

The dynamic universe: realizing the potential of time domain and multimessenger astrophysics

Edited by

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The dynamic universe: realizing the potential of time domain and multimessenger astrophysics

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The dynamic universe: realizing the potential of classical time domain and multimessenger astrophysics

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In parallel with the multi-messenger revolution, major advances in time-domain astronomy across multiple science disciplines relevant to astrophysics are becoming more urgent to address. Aside from electromagnetic observations of gravitational wave events and explosive counterparts, there are a number of “classical” astrophysical areas that require new thinking for proper exploration in the time domain. How NASA, NSF, ESA, and ESO consider the 2020 USA Decadal Survey within the astronomy community, as well as the worldwide call to support and expand time domain and multi-messenger astrophysics, it is crucial that all areas of astrophysics, including stellar, galactic, Solar System, and exoplanetary science participate in the discussion, and that it not be made into an exclusive preserve of cosmological, high-energy, explosive and transient science. Time domain astronomy is used to explore many aspects of astrophysics—particularly concerning ground- and space-based mission science goals of exploring how the Universe works, understanding how did we get here, and are we alone. Time domain studies are already built into the core operations of many currently operating and future space telescopes (e.g., Roman, PLATO) as well as current and planned large areal ground-based surveys (e.g., Rubin). Time-domain observations designed for one scientific purpose, also lead to great discoveries in many other science areas. The recent advent of user-friendly hardware, software, observational approaches, and online data infrastructure has also helped make time domain observations especially suitable and appealing for citizen science projects. We provide a review of the current state of TDAMM alerts and observational protocols, revealing a wide array of software and applications, much of which is incompatible. Any conversation regarding TDAMM astrophysics should include all aspects of the field, including those aspects seen as classical applications.

KEYWORDS

time-domain astronomy, multi-messenger astronomy, time-series observations, phase-resolved observations, multi-wavelength observations

1 Introduction

1.1 Time-domain astronomy

Time-Domain Astronomy (TDA) is not a novel concept. Astronomers have been making observations as a function of time for over a century. Even before that time, scientists such as Galileo Galilei (Standish and Nobili, 1997) and Tycho Brahe recorded observations of the sun, moon, stars, and supernovae over time, noting changes in their structures and positions.

However, Today, there seems to be an inherent bias in TDA, associating these observations predominantly with high-energy cosmological events that are often explosive and infrequent for any given object. However, before the term TDA was coined and added to the lexicon of astronomer-speak, observations in time existed, had other names, and involved all aspects of astronomy from Solar System objects to stars to AGN. Such observations were called time-series data, light curves, or phase-resolved spectroscopy to name a few. These temporal observations include periodic, quasi-periodic, and stochastic variations in brightness, spectrum, and/or position. Some published examples are given in Cortie (1915); Gordon and Kron (1947); Kollath (1990); Powell et al. (1969); Mason et al. (1982).

1.2 Multi-messenger astronomy

Likewise, Multi-messenger Astronomy (MMA) as used today, generally seems to require the inclusion of, or at least the possibility of, particles and gravitational waves to be a part of the messenger group. Multi-wavelength astronomy, from its humble beginnings of simultaneous or contemporaneous measurements covering a few wavelengths of light (e.g., optical and IR) moved into a golden era with the advent of UV and X-ray rocket observations, space telescopes, and simultaneous use of space and ground-based telescopes. All aspects of astrophysical research are involved in multi-messenger (wavelength) studies, some are time-sampled while others are static non-explosive phenomena. Solar System science might also be considered here, being the only branch of astrophysics where sample-return is a viable option. Some examples are Herbig (1970); Schulte-Ladbeck and Hopp (1990); Belle et al. (2005). Of course, multi-wavelength astronomy, in terms of multi-color observations, has been around for over 100 years as well, for example, Shapley (1920); Sandage et al. (1969).

2 Considerations for time domain and multi-messenger astronomy (TDAMM)

2.1 Planning across astrophysical science

In parallel with the multi-messenger revolution, major advances in time-domain astronomy across multiple science areas relevant to astrophysics are becoming more urgent to address. Aside from electromagnetic observations (EM) of Gravitational Wave (GW) events and particle measurements for explosive counterparts, there are a number of “classical” astrophysics areas that require new thinking for proper exploration in the time domain. As the

astronomy community and NASA, in particular, consider the 2020 USA Decadal Survey’s recommendations to support and expand time domain and multi-messenger astrophysics,¹ it is crucial that all areas of astrophysics, including stellar, galactic, Solar System, and exoplanetary, participate in the discussion, and that it not be made into an exclusive preserve of high-energy, GW, and transient explosive cosmological science. For example, the NASA Kepler mission was designed for exoplanet transit observations, but excelled as well in other astrophysical studies. Cross-discipline discussions greatly helped both science areas reach new goals. Time-domain astronomy is used to explore many aspects of astrophysics—particularly concerning many of astronomy’s primary science goals of exploring how the Universe works, understanding how did we get here, and are we alone. Time domain observations are built into the core operations of Swift, TESS, Roman, PLATO, and other missions. Any conversation regarding TDAMM needs to include *all* aspects of astrophysics’s goals. If we have learned anything, time-domain observations designed for one scientific purpose, also lead to great discoveries in many other science areas. With the high alert volumes expected in the near future, it will be even more important to share information across domain boundaries. Early alerts will be poorly classified with initial follow-up observations possibly being of low interest to the original team, i.e., the source was not what was expected. However, such observations may perhaps be of high value to those interested in this particular source.

2.2 Definition and scope

Not all observations that happen across time necessarily require new considerations regarding new time-domain thinking. Just because some phenomena are observed with a light curve or a series of spectra does not mean they need to be included in these discussions. The specific requirements and factors that come into play in order to place a science case in the TDA category are:

- Time-sensitive observations: Certain phenomena can only be observed at certain times, whether those times are predictable or stochastic. This naturally includes traditional Target of Opportunity-type observations, such as GW events, explosive phenomena like supernovae, the beginning of a rare eclipse, flares, special stellar configurations (like microlensing) or other unpredictable events. It also applies to predictable but rare phenomena, which have similar difficulties when it comes to planning and coordinating observations, which we can call Rare Predictable Targets (RPTs), like long-period eclipsing multiple star systems, disk eclipsing systems, transiting and eclipsing planet observations, or eccentric-orbit non-transiting planet observations where the periastron passage is rarely observable that offer rare opportunities for key observations. Often, different types of time-sensitive scientific goals require different

¹ <https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020>

kinds of time-sensitive observations (e.g., rapid response vs. cadence observations) and these may change during the evolution of a given target.

- **Multi-facility coordination:** There are a number of science cases that require observations across multiple facilities simultaneously or in a specific sequence. For example, Roman + Rubin panchromatic investigations of exoplanet transits to disentangle transit signals from stellar variability (Limbach et al., 2023). While such observations do not necessarily have to take place at a specific time, the coordination in time across facilities means that such campaigns share many of the same observing and coordination difficulties as other time-domain astronomy efforts. These observations often involve multiple wavelengths (i.e., panchromatic observations), observing modes and/or instruments (photometry and spectroscopy), messengers (photons, gravitational waves, neutrinos, or cosmic rays), and both ground-based and space-based facilities.
- **Multi-mode monitoring or monitoring with a single technique at regular cadence:** For some predictable events and many stochastic events, there is often a period after an event where monitoring across many facilities and multiple channels can provide valuable insight. This monitoring effort can sometimes share some of the time constraints of the other two considerations, such as a minimum cadence of subsequent observation or a need for continuous observation inaccessible to a single ground-based facility. The monitoring period depends on the science goals and might last for a preset time frame (days or years), until a given event occurs (e.g., when a microlensing event ends), or might be indefinite. Monitoring also often involves a similar type of multi-facility coordination, but also data sharing, both for the alerts and for the subsequent follow-up data.

2.3 TDAMM key issues

Given the considerations above for how TDAMM operates across all of astrophysics, there are key issues that need to be addressed as part of any TDAMM initiative.

- **Communication/Coordination—**There are various electronic systems for managing the flow of data between various participants in TDAMM. These include observatories that generate alerts (e.g., LIGO, Rubin), alert brokers (e.g., ANTARES), transient marshals or Target and Observation Managers (TOMs) (e.g., the Supernova Exchange, GROWTH, ExoFOP), observing schedulers (e.g., the Las Cumbres Observatory network scheduler), coordination facilitators such as Treasure Map, and other tools. Can these systems talk to each other quickly and efficiently, are they publicly accessible and documented, and can all participants connect properly to them?
- **Alerts—**How universally are alerts being designed, generated, and dispersed? Are the standards, protocols, and terminology the same across relevant facilities? That includes NASA and other space missions, ground-based assets, laboratory and data

center facilities, international partners, and dispersed multi-institution observing networks, as well as citizen scientists. Are the alert brokers part of that same conversation?

- **Monitoring—**How should monitoring campaigns be organized and administered? Certain monitoring science cases include specific needs for cadence, SNR, duty cycle, wavelength coverage, spatial or spectroscopic resolution, etc.? Is there a role for decentralized networks in which voluntary observing contributions may be sufficient (e.g., citizen science or Pro-Am collaborative networks), or do we need to build up more robust versions of hierarchically controlled observing networks, such as LCO or EHT? Note, there are social networks coordinating collaborations as well as hardware/software networks providing autonomous connections.
- **Participation—**How can all potential observers participate in campaigns, including ToOs, RPTs, and monitoring campaigns? Observers want to know that they will be properly credited, with paper co-authorships, citations, acknowledgments, or other mechanisms that are agreed upon ahead of monitoring campaigns? How are diversity and equity brought into the participation?
- **Data Sharing—**How do we best take advantage of and encourage the community to share data and information to maximize the efficient use of limited resources and minimize duplication and overlapping use of those same resources? As an example, within the exoplanet community and the TESS Follow-up Observing Program, the public NASA Exoplanet Archive (ExoFOP) service has been critical to help organize such efforts; how do we best expand that approach into a community-wide paradigm regardless of the specific scientific area? Existing surveys (e.g., SDSS) developed operational models before “Big data” and TDAMM were forefront. It is likely that support in terms of software and funds will be needed to have these valuable surveys brought into the mix.
- **Existing Data—**An insufficiently appreciated component of TDA is prior knowledge of the sky. Historical data become more, not less, important in the era of time-sensitive science. When an event (ToO or RPT) occurs, what did that field look like beforehand, across all relevant wavelengths, timescales, and angular size scales? To do the best possible science with space and ground facilities, we need to ensure that space-based and ground-based time-domain data are reserved as well. Surveys in the time domain have often been inadequately archived, with many data sets lost forever. At the moment, many optical sky surveys such as ASAS, ASAS-SN, Evryscope, ATLAS, CRTS, and others are in some cases only partially archived, without long-term storage and access plans at federal agency levels. Other data sets, e.g., DASCH (over a century of photographic plates), are still in the process of being digitized and only exist as photographic plates.
- **Archiving—**To address existing data sets, NASA archives must be involved in TDA discussions from the beginning. The archival data might exist at many different repositories, operated by different agencies, with different data access protocols. Support for archiving and serving such data sets should be included in TDAMM funding models, and the

existence of these data must be realized as part of the broader TDAMM program formulation.

- **Training**—Access to and familiarity with the many new tools and services is far from uniform, creating a diversity and equity issue across astrophysics. Support for community outreach and training opportunities will be an important aspect of any successful program.
- **Citizen Science**—TDA also lends itself especially well to pedagogically impactful and scientifically productive citizen science projects. Indeed, perhaps the first large-scale citizen science project, observation and timing of the 1715 May 3 solar eclipse popularized by Edmond Halley (Pasachoff, 1999), was arguably a TDA program. TDA projects such as asteroid occultations (Cazeneuve et al., 2023) and exoplanet transit observations (Perrocheau et al., 2022) have enjoyed considerable involvement of citizen scientists. The technical simplicity of such observations allows amateur astronomers with minimal astrophysical knowledge and only modest observational experience to contribute scientifically meaningful data. Moreover, the recent advent of commercially available complete observational systems with built-in software for uploading observations to online repositories² substantially facilitates the curation of citizen science datasets.

3 The current state of tools

While many areas of astronomy (not just time domain science) can benefit from the tools developed for MMA, often MMA use cases have the most stringent rapid communication requirements. This has meant that the existing transient follow-up ecosystem infrastructure must be overhauled with MMA in mind. However, with often minimal extra effort, these tools can and should be made to serve the entire astronomical community. Significant efforts are already underway. Here we discuss the MMA use case to establish the tools currently being modified or developed, and then outline how they can or are being adapted for other areas of time domain or more general astronomy.

3.1 The multimessenger astronomy workflow: GW170817 as a case study

In Figure 1 we show a flow chart featuring a simplified version of some of the discoveries and communications surrounding GW170817. Below we discuss a more updated and generic version of a similar process.

3.1.1 The alert

Gamma rays are detected by several satellites, a merger of two neutron stars is detected by LIGO-Virgo-Kagra (LVK), and an alert is automatically generated and sent by various messaging systems. The NASA General Coordinates Network (GCN)³ sends machine-readable Notices, often nearly instantaneously via information

from satellites. Meanwhile the GCN Circulars require a human to write them, but are not machine readable. Traditionally, both have been sent via email, but they are now being sent by Kafka, a more robust messaging platform.⁴ Additionally, LVK alerts are sent via Hopskotch,⁵ a Kafka-based messaging system created by the SCIMMA (Scalable Cyberinfrastructure for Multimessenger Astronomy)⁶ group funded by the NSF. Nearly any message can be sent via Hopskotch, but an extension of it, HERMES,⁷ provides an Application Programming Interface (API), graphical user interface, and a schema so that users know expected variable names. HERMES blends human and machine-readability so that users can specify machine-readable variable names to be sent in Javascript Object Notation (JSON), and free-text, and users can refer to named variables in the text.

3.1.2 The search

A GW event may be localized to hundreds or thousands of square degrees, so a search must be initiated to find the electromagnetic (optical/IR) counterpart. Some groups tile a broad area with large-format detectors, while others employ a galaxy-targeted approach. In the latter case, groups have special software to receive LVK alerts, and automatically generate a prioritized list of galaxies within the localization region. This is often done within a Target and Observation Manager (TOM)—web-based software that allows users to initiate automated observations, manage their data, and communicate about them. Whether a tiling or galaxy-targeted approach is used, users can trigger observations with their TOMs, which can then reduce, manage, and allow users to process the search data.

The planned and completed search pointings can be reported to the Treasure Map (Wyatt et al., 2020).⁸ The Treasure Map uses Aladin Lite to visualize probability contours on the GW localization region, which can be overplotted on one of dozens of sky surveys, e.g., Pan-STARRS, DSS, or H-alpha surveys. Planned and completed search areas, displayed as multiple detector footprints on the sky, are also overlaid. This allows any group to coordinate their search to avoid duplication. Other targets (e.g., information about galaxies or candidates) can also be overlaid.

3.1.3 Candidates

During a search, dozens or hundreds of candidates may be found. These are reported via the TNS, GCNs, and HERMES. Plugins for the TOM toolkit allow users to automatically parse machine-readable HERMES messages and ingest new candidates. For telescopes with APIs, with the click of a button, these can be dispatched for vetting observations from the TOM, including photometry and spectroscopy. This is reduced and displayed in the TOM, which can then be reported back to the community via the messaging services. Photometry and spectra can be sent over a Kafka

² <https://www.unistellar.com/citizen-science/>

³ <https://gcn.nasa.gov>

⁴ GCN Classic has also offered socket connection since 1993, and VOEvent for 10 years. GCN Circulars now also offer a web form for submission, and are developing an API for compatibility with HERMES.

⁵ <https://hop.scimma.org>

⁶ <https://scimma.org>

⁷ <https://hermes.lco.global>

⁸ <https://treasuremap.space>

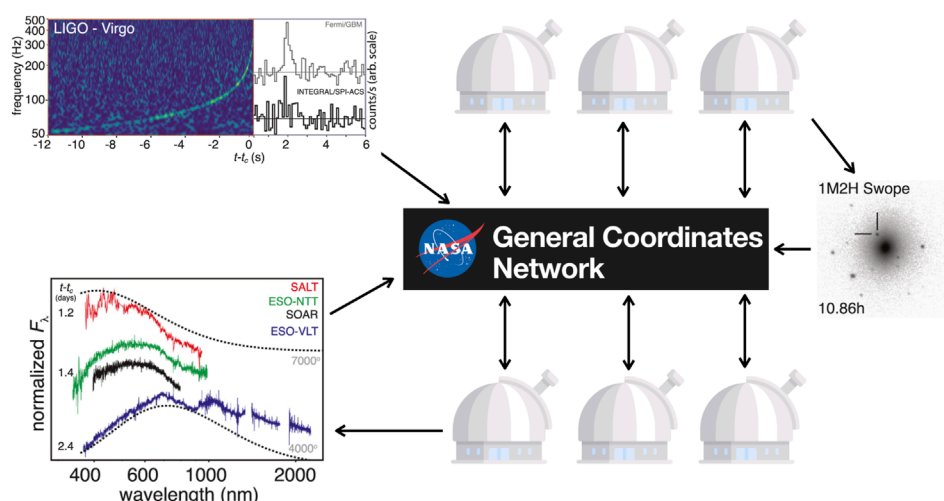


FIGURE 1

Simplified flow chart of a subset of the messaging and discoveries from GW170817. Aspects of the figure are adapted from Figure 2 of [Abbott et al. \(2017\)](#). After the initial discovery of gamma rays by Fermi and gravitational waves from LIGO and Virgo, messages detailing the discoveries were sent to a private version of NASA's General Coordinates Network (GCN), although this was delayed for about 1.5 h. These messages were read by individual observatories and observers who triggered a search for the electromagnetic counterpart, and reported the results back to GCNs. Each communication introduced latency, from the up to 20 min delays from GCNs, to humans reading the messages, manually triggering telescopes, reducing the data, and writing a text version of the results. The optical counterpart was discovered (right), nearly 11 h after the initial discovery in gamma rays. This was reported to GCNs, resulting in follow-up observations, including spectra (bottom left), taken 1.2, 1.4, and 2.4 days after discovery. Every step in this process is now faster, more robust, more machine readable, and more efficient, thanks to improvement in existing tools like TOMs and GCNs, and new tools like Treasure Map and Hermes.

topic in HERMES, which will automatically show up in other users' TOMs if properly configured. By pooling data, the community can find the true counterpart faster, since they can combine photometry to reveal color and increases in brightness or compare spectroscopic information.

3.1.4 The electromagnetic counterpart

Finally, once the candidates have been vetted and the true, well-localized EM counterpart to the GW event is found, this is reported to the TNS, GCNs, and HERMES. Many astronomers will target this event, and data can be shared nearly instantaneously by the above mechanisms.

3.2 Use of the tools for non-MMA science

3.2.1 Messaging

Many areas of transient science have reported their findings to various messaging systems for decades, sometimes segregated by type. For example, new comets and minor planets are usually reported to the Minor Planet Electronic Circulars. GRBs, gravitational wave events, and high energy sources are usually reported to the GCNs. Supernovae are reported to the Transient Name Server (TNS),⁹ and their AstroNotes. High-energy neutrinos are reported in GCN Notices and Circulars, as are low-energy neutrinos from SNEWS and Super-Kamiokande. Meanwhile some

variable stars, novae, and some supernovae are reported to the Astronomer's Telegrams (ATELs).¹⁰ This has resulted in the unfortunate situation where different information on a target is reported to different systems, sometimes even under different names. For example, the gamma rays from GW170817 were first detected and eventually given the name GRB 170817A. Then gravitational waves were reported to an embargoed form (at the time) of the GCN Notices and Circulars as GW170817.¹¹ Possible counterparts were then reported to the GCN Circulars and sometimes ATELs, often given arbitrary names, like SSS17a. Finally when the kilonova counterpart was confirmed, it was reported to the TNS and given the name AT 2017gfo, which was not always used in subsequent communications to other services ([Abbott et al., 2017](#)). Users had to monitor at least five services and sub-services to get the whole picture, and this was hindered by the fact that most of the hundreds of messages generated were not machine readable.

Different transient communities are locked into different messaging services partly by historical accident, partly because of limitations of the services, and partly because that's where the community expects to get information. For example, not many services can handle moving objects, but the Minor Planet Center,¹² which issues MPECs, is specialized for this. GCNs Notices were designed for rapid reporting of X-ray and gamma ray information,

¹⁰ <https://astronomerstelegram.org>

¹¹ The archive of the embargoed GCNs are at <https://gcn.gsfc.nasa.gov/other/G298048.gcn3>

¹² <https://www.minorplanetcenter.net>

⁹ <https://www.wis-tns.org>

and are machine readable, but not very human-readable. The parallel GCN Circulars are human-readable, but not machine-readable. Neither service has an API (though one is being developed). The TNS is custom-built for supernovae (though it is expanding), and is machine readable, but has a separate system for longer-form human-readable messages, AstroNotes (which is not machine readable but can be cross-referenced). ATELS are not machine-readable and lack an API.

Some existing services are adding new functionality. For example, the TNS is beginning to process Fast Radio Bursts. The GCNs are moving to a Kafka-based system and adding an API. But a new system (Hopskotch and HERMES) has been developed from the ground up to overcome the limitations of previous systems. Hopskotch is a Kafka-based messaging service with built-in Identity and Access Management (IAM). It imposes no structure on messages, and users can create new topics, so that users can send any kind of message, not just discovery reports, as has been traditional. HERMES is a layer on top of Hopskotch, which adds structure to support standardization and machine readability. It is backed by an API so that it can easily be built into TOM systems, but also has a standalone web-based user interface. The same message can have both machine and human-readable components, sent via JSON. To overcome the distributed information problem, users can browse any Kafka topic, including GCNs and HERMES messages in the same place, with integrated search. Users can simultaneously send a single message to multiple systems (currently HERMES/Hopskotch, GCNs, and the TNS). The HERMES version of the message has machine readability, but a text-only message is sent to systems that do not support it.

HERMES is designed to be useful for all of astronomy, not just MMA. Named variables are as generic as possible, and where specific ones are necessary for a subfield (e.g., a cross-reference to a GW event), they are not required. Users can add additional machine readable key/value pairs if there are new needs that the developers did not consider. Moving targets are also supported. Cross-linking to other messages, or adding document object identifiers (DOIs), or other references are also supported.

3.2.2 The TOM toolkit

There are many examples of TOM systems built for a specific purpose (e.g., SkyPortal, YSE-PZ, the Supernova Exchange). Recognizing the need to not keep reinventing the wheel, Las Cumbres Observatory developed the TOM Toolkit¹³ to allow any user in any area of astronomy to create their own TOM. Emphasis is placed on modularity so that users can swap out components that suit their needs (e.g., support for moving targets, cross-referencing to SIMBAD, alert broker plug-ins). The code is open-source so that users can add new modules or improvements, which is then reviewed by the development team before it is included in the broader toolkit. Documentation and support are also prioritized to encourage adoption. TOMs have been built with the TOM toolkit in many areas of astrophysics, including supernovae, gravitational wave events, microlensing, near earth objects, AGN,

gravitational wave events, variable stars, observatory support, and cosmology.

The TOM Toolkit has built-in support for Hopskotch and HERMES, so that the users of one TOM can click a button and immediately share photometry that shows up on a different TOM. This is done by writing to and reading from a Hopskotch topic. This can be made to work with any TOM, regardless of whether it was built with the TOM Toolkit. Support for the instant sharing of spectroscopy is in the works.

The TOM Toolkit also has native broker integration. ZTF discoveries are currently shared via Kafka, as LSST discoveries will be. Alert brokers ingest these alerts, and allow searching, filtering, and inferences derived from machine learning. So directly in their TOM, users can see new discoveries filtered by certain criteria, and then add a new target to their TOM and send it to observatories for additional observations with a few clicks.

3.2.3 The treasure map

In addition to gravitational wave events, Treasure Map is adding support for neutrino localizations and searches. It also supports joint localizations between GRBs and GW events. In principle, support could be added for other poorly localized astrophysical phenomena, such as GRBs, Fast Radio Bursts, or comets. Other areas of transient science could use the tool for, e.g., planning their observations, or seeing where their targets are located on the sky, and what has been detected across the EM spectrum in those regions.

4 Conclusion

Major advances in time-domain astronomy across multiple science disciplines relevant to astrophysics are becoming more urgent to address. Multi-messenger astrophysics (e.g., GW and particles) are beginning what will no doubt become a major revolution in our understanding of the Universe. However, aside from electromagnetic observations of gravitational wave events and explosive counterparts related to cosmological events, there are a number of “classical” astrophysical areas that require new thinking for proper exploration in the time domain. Time domain studies are already built into the core operations of many currently operating and future space telescopes as well as current and planned large areal ground-based surveys. Any conversation regarding TDAMM astrophysics should include all aspects of the field, including those aspects seen as classical applications. As a community, we want to assure that each type of TDAMM activity is supported, as we will learn even more about our Universe by being broadly inclusive of all TDAMM science.

New tools are being developed for MMA research to solve several problems limiting the rapid sharing of information in that field. Many of these tools are being developed with flexibility in mind, so that they can be used by any area of astrophysics. However, this will only succeed if there is wide adoption by the community. This requires community outreach, and support from federal funding agencies. A particular hurdle is that NASA is mandated to support space-based missions, while the National

¹³ <https://lco.global/tomtoolkit/>

Science Foundation supports ground-based research. We must ensure that groups funded by either agency work together to make interoperable tools. Finally, long-term support is necessary to enable new functionality, battle code rot, and increase interoperability.

Author contributions

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Fundamental physics studies in time domain and multi-messenger astronomy

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The era of time domain and multi-messenger astronomy is not only leading to the development of a much broader set of detectors and instruments for astrophysical observations, but is also providing the means for astronomy to tie directly to cutting-edge studies in physics. In this manner, fundamental physics (theory and experiment) coupled with a strong theoretical understanding of astrophysical phenomena (guided by high-performance computing simulations) can tie directly to the amazing new observations in astronomy. This paper discusses how physics, astrophysical models, and observations can not only help astronomy probe fundamental physics but guide the needs for next-generation astrophysical missions.

KEYWORDS

supernova, nuclear physics, plasma physics, radiation transport, atomic physics

1 Introduction

Time Domain and Multi-Messenger (TDAMM) astronomy is one of the fastest-evolving fields in astronomy, with new discoveries occurring annually both through the discovery of new phenomena (e.g., new classes of transients) and the availability of new observational regimes (different photon-energy band or new messengers like dust, gravitational waves, and neutrinos). With the rapid growth of data, astronomers can now leverage an abundant and diverse set of data. But to take advantage of this data, astronomers must understand the uncertainties and biases of each diagnostic.

The uncertainties are driven by uncertainties in the observations (e.g., instrumentation techniques) and the process by which we interpret them which includes uncertainties in the analysis procedures, our understanding of the fundamental physics behind the phenomenon, and the numerical issues in the modeling. The biases can only truly be understood if we have a comprehensive model that connects the different diagnostics. This requires detailed multi-physics models, often requiring the coupling of simulations from multiple codes running on the latest advances in supercomputers. It also requires improving the fidelity of the physics models used in these codes. As such, TDAMM astronomy provides an ideal conduit between the latest advances fundamental physics and astrophysical phenomena.

As an example of one such phenomena, we consider the growing set of diagnostics that constrain the supernova engine (Fryer et al., 2023a). Type Ib, Ic and all II supernovae are believed to be driven by the energy released when the core of a massive star collapses down to a proto-neutron star. The gravitational potential energy released is $GM_{\text{PNS}}^2/r_{\text{PNS}} \sim 10^{53} \text{erg}$ (where $M_{\text{PNS}} \sim 1M_{\odot}$ and $r_{\text{PNS}} \sim 20\text{--}30\text{km}$), more than enough to power a $\sim 10^{51} \text{erg}$ supernova explosion. But converting the energy released to explosion energy has proven to be a challenge of a lifetime;

initially proposed by Zwicky (1938), the current convection-enhanced paradigm was not developed until Herant et al. (1994) demonstrated its potential. Three decades later, scientists still work on understanding this convective engine. The difficulty lies in the fact that the growth of the convection is critical to its success and resolving this convection is not only well beyond the capability of brute-force, high-resolution simulations with high performance computing (both current and for the foreseeable future), but beyond our current understanding of convective instabilities (Fryer and Young, 2007; Fryer et al., 2021).

But a number of observations could help us constrain the growth and nature of this convection. The outward mixing of the ^{56}Ni synthesized in the engine, observed in both the gamma-rays and infra-red lines of SN 1987A (for a review, see Hungerford et al., 2003), provided the first clues of this engine. Observations of the ^{44}Ti distribution in Cassiopeia A confirmed this convective engine (Grefenstette et al., 2017). But these observations were limited to single events and, as we obtain observations of more systems, we can better understand both the characteristics of this engine and its dominance in the population of observed supernova explosions. Astronomers can tap a diagnostics to probe the supernova engine (Fryer et al., 2023a). Photons across a broad wavelength range provide a myriad of constraints, providing indirect (e.g., supernova light-curves) and direct (e.g., gamma-rays) clues into the nature of the engine. Additional constraints, such as the compact remnant mass distribution also improve our understanding. The most direct observations are rare, e.g., gravitational waves and neutrinos, but a Milky Way supernova with these observables will provide the foundation for our understanding of this engine. Tying these results with the large number of supernova light-curves and spectral observations will allow us to study the core-collapse engine as a broad population.

Connecting all these observations requires a series of cutting edge simulations, as well as a deep understanding of the theory behind these simulations, the fundamental physics required in these simulations, and of the observations providing insight into the problem. At this time, much work needs to be done to improve our physics understanding, the codes that implement this physics to study complex phenomena, and our interpretation of the simulations from these calculations so that we can best connect them to the observations. Understanding the observations also requires characterizing the uncertainties in both instrumentation and analysis tools. Most scientists focus on one narrow aspect of this problem and, to move forward, we must train scientists to break out of their stove-pipes and understand a more holistic picture of how we will use the upcoming flood of TDAMM data to understand astrophysical transients. In turn, our improved understanding of the process from fundamental physics to observed phenomena will help guide the priorities for next-generation detectors (both ground- and space-based) to maximize the science gain from these missions.

Instead of focusing on a single problem as we did here with the supernova engine, this paper will focus on a series of fundamental physics studies and their ties to observations: nuclear physics and nucleosynthetic yields (Section 2), radiation hydrodynamics and its effect on shocked emission (Section 3), and plasma physics and its importance in spectra (Section 4). With these three examples, we demonstrate just how interconnected and important fundamental

physics studies (both theory and experiment) are to the upcoming TDAMM era. We discuss that future in Section 5.

2 Nuclear physics and nucleosynthesis

A broad range of nuclear physics is important to TDAMM phenomena including nuclear cross-sections, neutrino physics and the behavior of matter at extreme conditions (nuclear densities, $\sim 10^{14}\text{gcm}^{-3}$, and temperatures above 10 MeV). In this section, we discuss the role of nuclear physics on observations constraining the formation of elements in the universe. The coupling between physics experiment to astrophysics observation is not direct. In most cases, it requires implementing physical models into a series of astrophysical studies (each requiring both detailed simulations and a theoretical understanding) that then tie to observations. This complex path means that experts across multiple fields must work together to do a complete study. Figure 1 diagrams this complex path. In the rest of this section we will discuss, for a variety of astrophysical observations, how these studies tie together to produce a full system study.

Before we do specific examples, let's discuss some sample science goals. For instance, science goals include: studying the neutrino signal and probing neutrino physics, studying properties of neutron stars, and understanding the origin of the heavy elements. For this discussion, we will focus on nucleosynthetic yields and, in particular, the study of the production of elements up to the iron peak (although we will discuss heavy element production, rapid and slow neutron capture elements briefly at the end of this section). We can also focus on a single observed constraint: e.g., dust grains formed in supernova explosions, yields in supernova remnants, and stellar abundances measuring multiple yields. With these observations, we identify the properties of the phenomena and the fundamental physics probed through these observations. In this section, we will limit ourselves to the three observations: dust grains, supernova remnants, and stellar abundances. We will discuss the full system studies needed for each of these observations separately and then show how they all tie together at the end of this section.

2.1 Supernova remnants

Supernova remnants provide an ideal window nucleosynthetic yields which, in turn, will improve our understanding of stellar evolution, supernova explosions and, ultimately, nuclear physics. But the connection between supernova-remnant observation to fundamental physics requires many steps and modeling everything from the stellar evolution through collapse to remnant evolution multiple modeling steps including 3 calculations require high-performance computing. Figure 2 highlights the high-performance computing steps.

2.1.1 Stellar evolution simulations

Massive stars produce many of the elements up through the iron peak. Stars are powered through a series of nuclear burning phases where the ashes of one phase becomes the fuel of the next. For most stars above $\sim 8 M_{\odot}$, this series of burning proceeds until an iron core builds up in the center. Iron peak elements are among the most

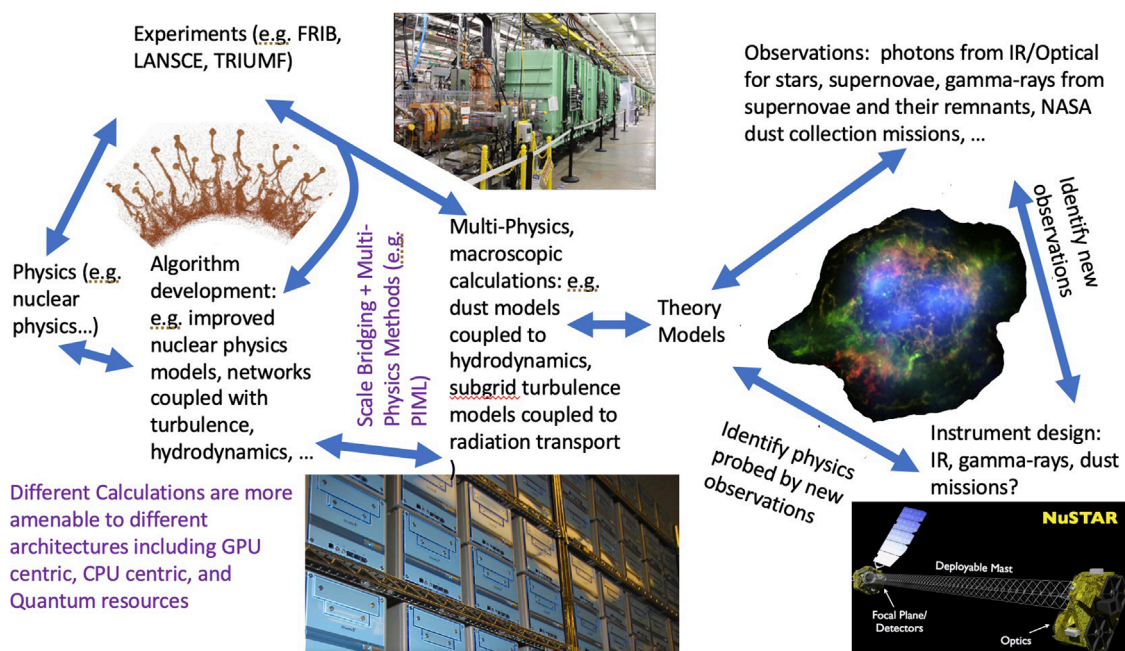


FIGURE 1

Nuclear Physics: This diagram shows the broad connection between fundamental physics fields and astrophysical phenomena studying nucleosynthesis and nuclear physics. To tie to observations, a great deal more physics must be included in the simulations, requiring the development of multi-physics algorithms. For example, dust grain studies require coupling both materials physics (e.g., density functional theory) and nuclear physics. Scientist leverage these fundamental studies to develop algorithms used in physics simulation that ultimately get implemented into macroscopic high-performance computing calculations used to compare to experiment. These macroscopic calculations are often needed to model the experiments successfully. The cycle from fundamental physics, algorithm development, macroscopic codes and experiment helps to fine-tune the codes. But there is another cycle from macroscopic simulations to astrophysical simulations to instrument design for observatories. Astrophysical observations, through macroscopic simulations of astrophysical phenomena can then feed back into the fundamental physics just as experiment does. The figures from bottom left moving clockwise are: the space simulator (Warren et al., 2003) Beowulf cluster (precursor for modern commodity computing) where the first 3-dimensional supernova simulations were run (Fryer and Warren, 2002), simulations of turbulent mixing (Ellinger et al., 2012), an image of the Facility for Rare Isotope Beams (FRIB <https://frib.msu.edu/index.php>), an image of Cassiopeia A including both Chandra observation (Hwang et al., 2004) the ^{44}Ti decay emission from NuSTAR (Grefenstette et al., 2017), and an image of the NuSTAR satellite (Harrison et al., 2013). The FRIB image is adapted from in wikipedia (FRIBcomm) ~ https://en.wikipedia.org/wiki/Creative_Commons.

bound and fusion beyond this point requires, instead of releases, energy. At the end of star's life, this nuclear burning determines the structure of the star.

Because of the large timescales in stellar evolution, these stars are modeled implicitly, meaning that the hydrodynamics is not followed in first principles. Instead, much of the physics is modeled either using a sub-grid or approximate method including: sub-grid models to mimic convection, simplified (gray) transport schemes with approximate opacity implementations. But these implementations are guided by high performance computing calculations as shown in Figure 2. Nuclear cross-sections can make a difference in these models. In particular, astronomers have focused on the $^{12}\text{C}(\alpha, \gamma)$ cross section (Woosley and Heger, 2021). We may be able to probe this physics directly through stellar observations, but most of the constraints arise from then following the collapse of these stars to study their remnants (both the supernova ejecta studied here and the compact remnants—black holes and neutron stars).

2.1.2 Collapse and explosion simulations

As the iron core grows, it contracts in a balance between the thermal and electron supporting the core and gravitational forces compressing it. At some point, the core becomes so dense that

electrons begin to capture onto protons (producing a neutron and a neutrino), reducing the electron degeneracy pressure, causing the core to compress further and, ultimately, resulting in a runaway collapse (). This collapse proceeds until the core reaches nuclear densities where neutron degeneracy pressure and nuclear forces halt the collapse, forming a proto-neutron star causing the core to bounce. After the bounce shock fails, a region above the proto-neutron star becomes convectively unstable. Neutrinos from the hot proto-neutron star (which continues to grow with convection), deposit energy into the convective region. When this energy is sufficient to overcome the ram pressure of the infalling star, an explosion is launched. The innermost ejecta is heated to extreme temperatures, driving further nuclear burning that produces many of the iron peak elements (as well as intermediate elements such as ^{44}Ti) in the supernovae.

Simulations of this explosion depend detailed hydrodynamics, neutrino transport and neutrino cross-sections, the behavior of matter at nuclear densities and, potentially, magnetic fields (e.g., middle panel of Figure 2). Because the explosion depends sensitively on the strength of the convection, its growth rate is critical. Unfortunately, numerical viscosity (dependent on the resolution of the simulations) is far too high in current simulations to accurately

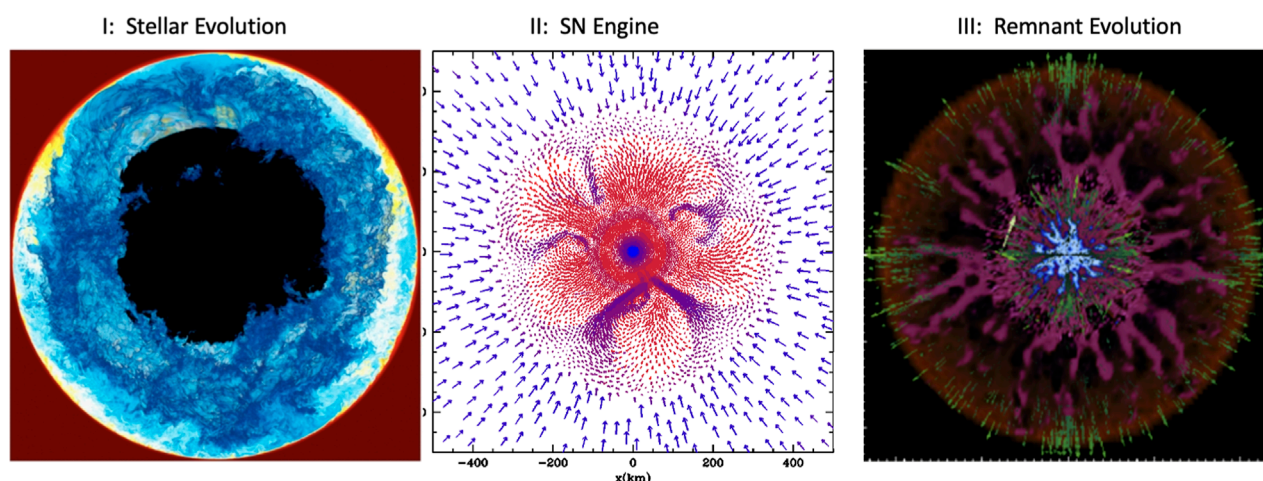


FIGURE 2

Nucleosynthetic yield simulations from stellar evolution to ejection typically require the combination of a series of high-performance calculations including (from left to right) detailed studies of stellar convection (Herwig et al., 2014), multi-dimensional models of the collapse, convection and explosion of supernovae (Fryer and Warren, 2002) and stellar explosions (Ellinger et al., 2013). Ideally, these simulations are connected not simply by taking the output of one calculation to connect to the other. Instead, the most impactful studies use these calculations to understand the basic physics behind these processes and then use this understanding to guide the next phase of study. This is required of the stellar convection simulations, the results of which must be distilled into a prescription for convection into stellar evolution codes capable of modeling stellar evolution through the evolution of the star which is many orders of magnitude longer than a typical eddy turnover time.

capture this growth rate (Fryer and Young, 2007; Fryer et al., 2021). Indeed, the resolution of all current models are many orders of magnitude too low to capture this growth rate. Without a better physical understanding of the convection, no simulation can make quantitative predictions to compare to data. The computing power needed for such simulations is not obtainable over next century unless some new method (e.g., quantum computing) provides viable. An alternate approach is to better understand the growth of convection and implement this physics using sub-grid models (e.g., Reynolds Averaged Navier Stokes solutions). But, at this time, the current state of these models leads to large uncertainties in the nature of the convection (Fryer et al., 2018; Couch et al., 2020; Fryer et al., 2021). The exact yields in these calculations also rely on the nuclear masses.

2.1.3 Remnant phase and emission simulations

Once the explosion is launched, the supernova blastwave moves out through the star and into the circumstellar medium. As the shock moves through the star, it drives further nuclear burning, further changing the composition of the ejecta. The characteristics of the circumstellar medium (also set by the stellar evolution models) set the deceleration and shocks in the expansion of the supernova blastwave. The reverse shock can then reheat the expanding material, causing it to emit. It is this emission that we observe in the X-ray when observing supernova remnants (Chevalier, 1974).

Our ability to model hydrodynamical effects is critical to tying to the observations. Both the mixing and the propagation of the reverse shock will determine what we observe (right panel of Figure 2). But the observations also depend on the emission properties of the atoms. In supernova remnants, local thermodynamic equilibrium (LTE, a simplifying assumption made in many opacity calculations) is not valid. Inferring abundances from supernova remnants will

require detailed models of non-LTE calculations for the emission (Reynolds, 2008). We will discuss this further in Section 4.

The exception to this additional complexity is the observation of radioactive isotopes (e.g., ^{44}Ti). Radioactive isotopes emit through the decay of the isotope [e.g., $^{44}\text{Ti} \rightarrow (\text{Electron Capture}) ^{44}\text{Sc} \rightarrow (\text{Electron Capture}, \beta^+ \text{ decay}) ^{44}\text{Ca}$]. The decays produce excited nuclear states that produce gamma-rays independent of the whether the material has been shock-heated by the reverse shock. The NuSTAR satellite was able to map the ^{44}Ti distribution by observing 2 of its decay photons (at the edge of NuSTAR's sensitivity) and this map confirmed that the convective engine was responsible for the explosion producing this remnant (Grefenstette et al., 2017). But, as we can see from the 3 sets of simulations needed to calculate yields (Figure 2, even tying remnant observations of the relatively simple ^{44}Ti emission requires advances in multiple physics (nuclear matter, neutrinos, nuclear cross-sections, turbulence, atomic physics) and modeling methods (sub-grid convection models, transport schemes). This doesn't even include the fact that additional models are needed to tie the fundamental physics experiments to the theory.

Figure 1 shows how these all fit together: fundamental physics theory models help code-developers derive better nuclear physics calculations and new computational physics algorithms for macroscopic, multi-physics codes. For many nuclear physics experiments, the multi-physics codes are not needed to interpret the data. The experiments both constrain the nuclear physics models (e.g., Hartree-Fock solutions) and can guide the development of nuclear network calculations. In some experiments (e.g., NIF studies of cross-sections for isomeric states), multi-physics codes are needed to analyze the data. Code-developers work with computer scientists/hardware experts to design new algorithms to develop codes both to model these experiments and to model astrophysical observations (often-times, the same code can do both). But these

computationally expensive multi-dimensional models are limited in the accuracy of their physics (low resolution, incomplete physics) and the number of calculations. To tie to observations, we must develop a theoretical understanding of the simulations to derive predictions for observations.

For example, based on an understanding of the supernova explosion using multi-dimensional models run on supercomputers, Magkotsios et al. (2010) simulated a series of simplified trajectories to determine how details of the explosion and the uncertainties in nuclear cross-sections can affect the ^{44}Ti yield. With this work, we can study observations, inferring both the asymmetries and strength of the shock from the yields. Further, this work demonstrated that the ratio of ^{44}Ti to ^{56}Ni (which varies dramatically with the details of the explosion shock and mass ejection) could help shed light into the supernova explosion mechanism and, ultimately, the nuclear physics.

Although we learn a great deal ^{44}Ti distribution alone, the ratio with respect to ^{56}Ni can be even further constraints. Unfortunately, we observe ^{56}Fe (the decay product of ^{56}Ni), not ^{56}Ni itself, in supernova remnants and it can be confused with the iron in the star when it first formed (Ellinger et al., 2013): a solar metallicity, $20 M_{\odot}$ has $\sim 0.2 M_{\odot}$ of iron at formation. Understanding the total iron distribution requires further multi-dimensional simulations coupled with theoretical models. These studies have driven further observations with JWST (Milisavljevic et al., 2024) to better locate the iron. Ultimately, these studies will identify the need for further observations and new telescopes and instrumentation. But if successful, supernova remnants could provide a strong probe of the supernova engine and the nuclear physics behind it.

The amount of work needed to do accurate models of the ^{44}Ti production is daunting. Fortunately, if we work with the physics community, astronomy can leverage the work of these physics fields. For example, the fluid dynamics community is actively improving sub-grid models for turbulence, testing their models against a growing list of experiments [e.g., Livescu et al. (2009); Duraisamy et al. (2019)]. In addition, the nuclear physics community is continuously improving the nuclear cross-sections combining nuclear theory and experiment (e.g., for ^{44}Ti Vockenhuber et al., 2008), reducing the uncertainties from nuclear physics.

As complex as it is to study ^{44}Ti , other yields are even more complex. It is difficult to observe stable isotopes unless they are shock heated. And it is even more difficult to get exact abundances without understanding the out-of-equilibrium setting the atomic level-states that determine the observed line-strengths. However, these yields have the potential to provide even greater insight into the explosion and the stellar progenitor (Braun et al., 2023).

2.2 Dust grains

Nucleosynthetic yields, particularly specific isotopes and isotope ratios, can be probed by studying dust grains formed in the supernova ejecta. These grains can be incorporated into meteorites that are then analyzed to determine detailed yields [e.g., Nittler and Ciesla (2016)]. Isotopic ratios are ideally suited to direct comparisons of nuclear cross-sections and dust grains provide a powerful messenger to probe nuclear physics and the supernova engine.

Many studies of dust grains assume the composition of the dust grain can be tied directly to the nucleosynthetic yields in

the explosion. But to truly study dust grains, scientists must understand the formation of these grains to better determine the subset of exploding material that is likely to form dust. Although modeling of dust grains is starting to include results of supernova models (Sarangi and Cherchneff, 2013; Sarangi and Cherchneff, 2015; Brooker et al., 2022), advances in both the incorporation of supernova mixing and dust grain production and destruction are needed to tie these observations to the supernova engine.

Not only do these studies rely on much of the physics needed to study yields in supernova remnants, but it also requires a detailed understanding of the materials physics behind dust grain production and formation. This includes detailed density function theory (DFT) models calibrated by detailed molecular dynamics (MD) and, where possible, quantum molecular dynamics (QMD) calculations. Again, fortunately for astronomy, there have been great advances in this field both in improving these models (Hickel et al., 2012; Afzalian et al., 2021) leveraging everything from AI to quantum computing. As with supernova remnants, the study of dust is a Herculean effort, but astronomers can make great strides if they work with the materials physics community to improve their models.

2.3 Stellar abundances

The Sloan Digital Sky Survey and the Sloan Extension for Galactic Understanding and Exploration have dramatically increased the spectral observations of stars (Ahumada et al., 2020). With intensive follow-up observations, astronomers have begun to amass a large number of stellar abundance patterns. Combined with models, we can use these patterns to study nucleosynthetic yields and the explosions and fundamental physics that make them.

Unfortunately, these are some of the most indirect observations we will discuss in this paper. Not only do we need to capture all of the physics from a single supernova explosion, but we will need to combine it with stellar populations and galaxy models to determine how these yields mix (over multiple supernovae) into the observed stars. Although these observations and the theory development behind them are important and could provide hints, much more work must be done to infer properties of supernovae, stars or nuclear physics from these observations.

2.4 Benefit of tying it together

All of this data has its limitations: e.g., detailed supernova remnant data or dust grains are limited to a handful of events. Stellar abundances measurements rely on uncertain calculations, but there is much more data. Combining all of this data will help provide a more complete picture of the nature of supernova explosions and the nuclear physics behind nucleosynthetic yields.

2.5 Heavy element production

In this section, we did not discuss the potential to probe slow- and rapid-neutron-capture elements. Tying the observations of these yields to nuclear physics also requires a much better understanding of the processes behind their production, distribution and detection

and most studies to date either underestimate or outright ignore the uncertainties in these processes. The first step in moving these studies forward is to identify the physics processes and, as we have done above for supernova yields, identify the dominant uncertainties that must be addressed to advance this field to a more quantitative state. But this discussion is beyond the scope of this paper.

3 Radiation hydrodynamics and shocked emission

Core-collapse supernovae are the observed phenomena from the explosion of a massive star, powered by the potential energy release in the collapse of the core. 99% of this energy ($\sim 10^{53}$ erg) is released in the form of neutrinos. During the first year of emission, the bulk of the remaining energy ($\sim 10^{51}$ erg) remains in kinetic energy. For most supernovae, only 1% of 1% of the total energy released (10^{49} erg) produces the observed photon emission. At such a small fraction, a number of sources could contribute to this emission: decay of radioactive elements (e.g., thermonuclear supernovae are powered by the decay of ^{56}Ni), an additional power source post-launch of the shock (e.g., a magnetar, fallback accretion) or, what has been realized as increasingly more important, shock heating converting kinetic energy to thermal energy that then powers the photon emission.

The evidence that shock heating can be an important component in the observed UV, Optical and IR (UVOIR) emission arises from a number of events that must be understood. For many decades, type II supernova light-curves have been believed to be powered by shock heating that occurs when the supernova propagates through the star. But recent observations of both shock breakout (Alp and Larsson, 2020) and early-time Swift UV emission (Brown et al., 2014) have shown that shock interactions occur as the blast wave pushes through the circumstellar medium. For example, if XMM has truly detected prompt X-rays from type II supernovae (Alp and Larsson, 2020), then it is extremely likely that shock interactions are pumping up the ejecta temperature. In addition, Swift UV observations of the pre-peak supernova emission (Brown et al., 2014) demonstrate that shocks continue to occur driving bright UV long after we'd expect from typical adiabatic cooling. Coupled with the fact that a large fraction of superluminous supernovae are believed to be produced by shock heating and not through the onset of an additional engine (Chatzopoulos et al., 2013). For these supernovae, shock interactions must be strong enough to convert up to 10% of the supernova's kinetic energy into emission.

Most supernova light-curve calculations assume a homologous outflow (without hydrodynamic effects), focusing on the details of radiation transport (e.g., detailed transport methods, atomic physics and out-of-equilibrium effects). Following the format of Figures 1, 3 shows the additional physics studies required to understand shock heating effects in supernovae. The key physics missing in most astrophysics calculations is the coupling of the radiation to the matter and the effects of the matter interactions (i.e., shocks) on the radiation source term.

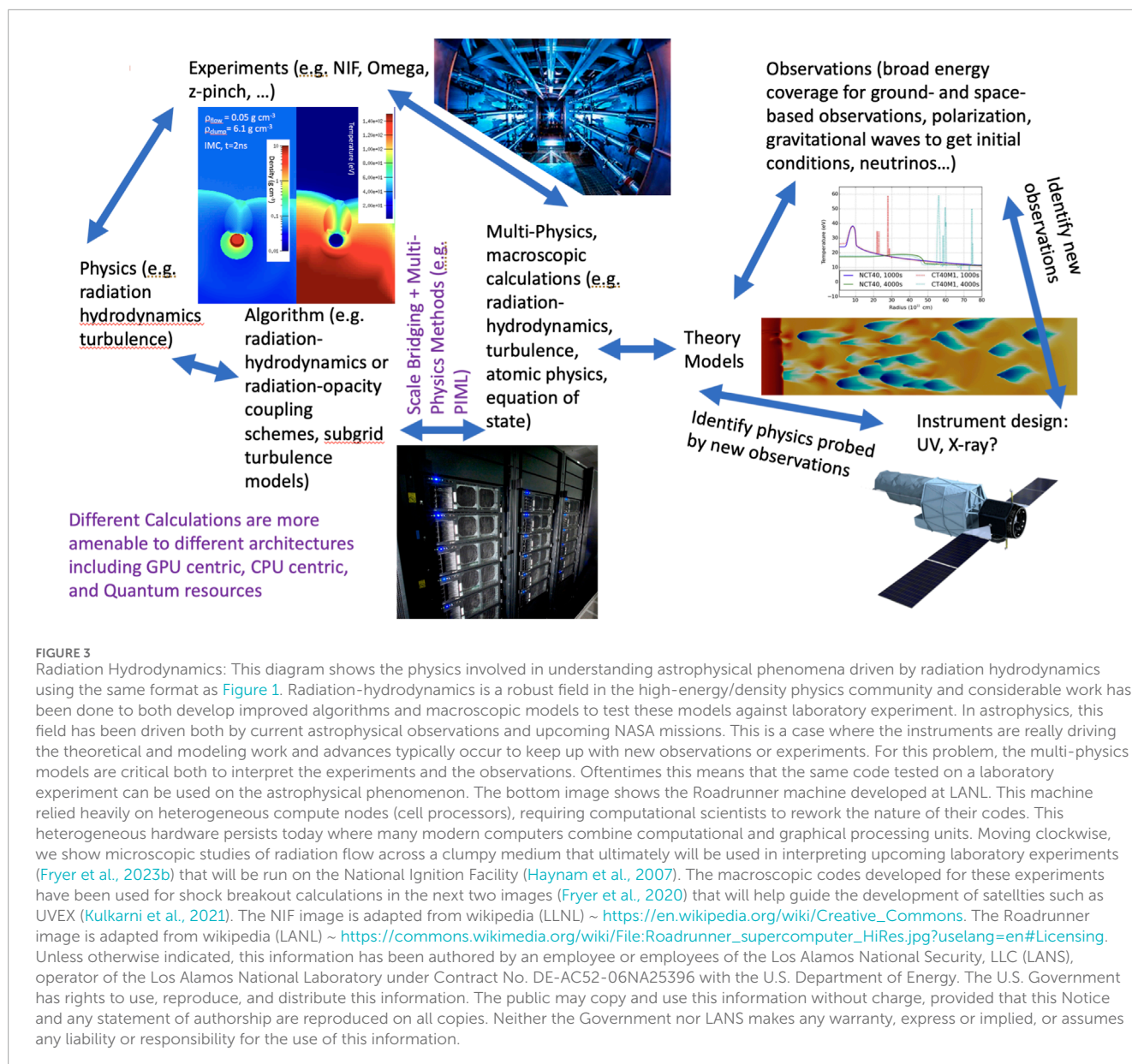
Radiation-hydrodynamics, including turbulence effects, is an active area of research. For example, the XFlows experiment program at LANL (Johns et al., 2023) is currently running

experiments at the National Ignition Facility to study the flow of radiation around an inhomogeneous medium. These experiments are used to validate existing codes and ultimately design subgrid algorithms that can be used in problems where we can not resolve the inhomogeneities (e.g., turbulent flows in shock breakout or early-time supernovae). Here, fundamental physics works tightly with algorithm development to produce codes that simulate the experiments. With the guidance from experimental data, we fine-tune our numerical models that can then be used to model supernova emission. The results of these calculations can, in turn, can be theoretically understood to conduct comparisons with astrophysical observations, further validating the codes (feeding back into the fundamental and algorithmic models of this physics). Ultimately, these calculations can be used to both design and maximize the science for upcoming telescopes and satellite missions (e.g., <https://www.ipac.caltech.edu/project/uvex>).

4 Plasma physics and spectra

In Section 3 we ignored many of the details of the emission processes. For many calculations, it is assumed that both the electrons and atomic energy states are in thermal equilibrium. Although this is a reasonable assumption at early times in a supernova explosion, the thermalization timescale increases as the ejecta expands and its density, and hence the particle collision rate, decreases. Collisions are what allow particles to reach an equilibrium state and, as the collision rate decreases, the equilibrium assumptions used in many astrophysical studies no longer hold. Unfortunately, Out of equilibrium physics plays an important role in many astrophysical observations. For example, particle acceleration in astrophysical shocks can produce a subset of highly energetic particles that either produce energetic (X-ray, gamma-ray) photons and/or are observed as cosmic rays or high-energy neutrinos. As atoms and their excitation levels fall out of equilibrium, it also becomes increasingly difficult to infer material properties from spectral features. This physics is studied by a broad range of scientists including laboratory experimentalists and space weather physicists. Figure 4 shows the interplay of these fields and how they might improve the astronomy and high-energy astrophysics.

High-energy astrophysics has suffered the most from not working closely with the physics experts. For example, the cosmic ray field relied too heavily on diffusive particle transport methods, not realizing that particle transport can be strongly affected by magnetic fields (Giacinti and Sigl, 2012; Ahlers, 2014; Fitz Axen et al., 2021). Unfortunately, this lack of understanding led this field to drastically mis-characterize the nature of their observations. Similarly, the simple models used to produce gamma-rays in GRB jets could lead to misleading interpretations of the jet properties. Fortunately, there are an increasing number of particle-in-cell and other plasma kinetic calculations of particle acceleration and astronomers can leverage these codes to model this physics at higher fidelity. But we also need to understand the limitations of these numerical approximations and this is where working closely with the plasma physics community is essential. For instance, many of the early models reduced the ratio of the proton to electron mass to make the simulation more tractable on limited computing resources, but this is known to alter the final electron energy



distribution and astrophysics studies are beginning to study these uncertainties in their applications (Rassel et al., 2023).

Further problems lie in simply understanding the origin of the accelerated electrons. Astronomers still rely on simple diffusive shock acceleration models (Reynolds, 2008) despite both plasma theory (Fan et al., 2010) and observations (Grefenstette et al., 2015) suggested this model is insufficient to explain all of the energetic electrons in remnants. Active work is involved to both improve diffusive shock acceleration models. But implementing more sophisticated models is essential to pushing this field forward and working closely with plasma physicists can accelerate this progress.

Fortunately, considerable progress has been made in both the plasma physics and high-energy density/physics fields as well as those of heliophysics and space weather. A growing set of plasma physics codes have been developed and reviews already exist discussing the advantages and disadvantages of the different techniques. Astronomers can leverage this

knowledge in their calculations, improving the fidelity of their simulations that will improve the accuracy of the interpretation of astrophysical phenomena.

5 The future of TDAMM

Many of the physics models used in astronomy are derived from an era where simplifications were essential under the current calculational power. But just as computing resources have advanced considerably, so too has the ability to model the fundamental physics. TDAMM astrophysics is pushing astronomy to a regime where including these physics advances is essential to understanding the phenomena we are facing. In some aspects of some problems, astrophysics has advanced more than the field itself, and building these ties will lead to advances on both sides. TDAMM can be the conduit to make these ties.

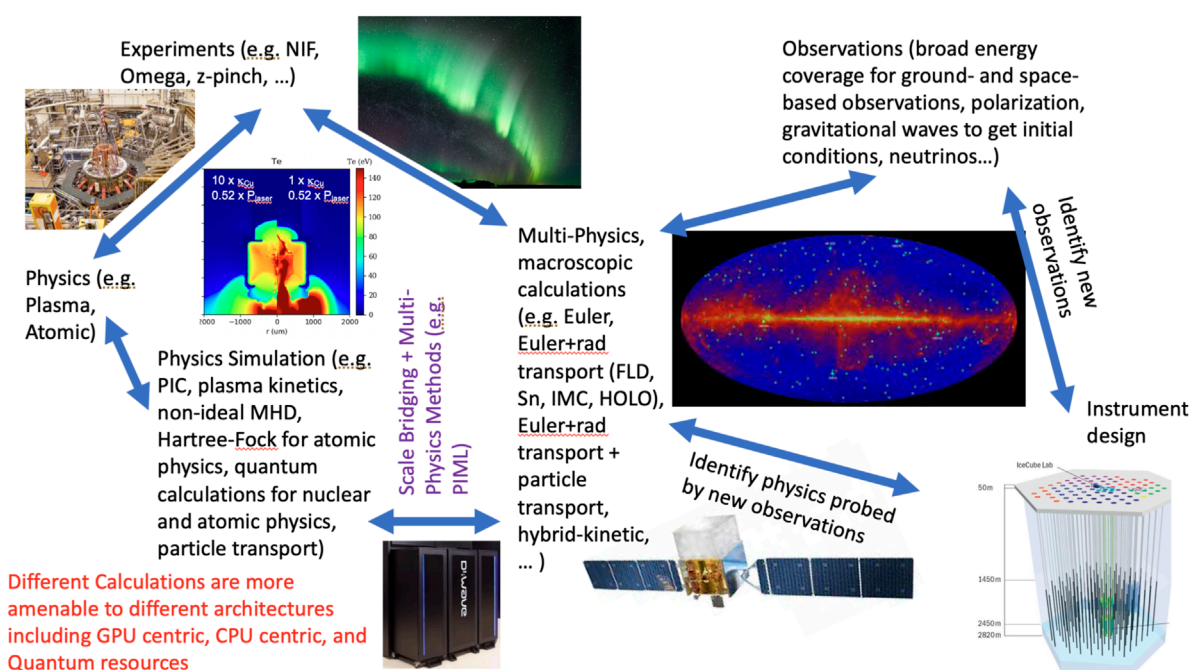


FIGURE 4

Plasma Physics: This diagram shows how plasma physics affects astrophysical observations following the format of Figure 1. There exist a wide range of problems where the emission arises from nonthermal emission from shock-accelerated electrons including astrophysical jets and supernova remnants, particle acceleration in extreme magnetic fields or particles emitted in the decay of radioactive isotopes. Nonthermal electrons are also produced in solar flares and there is a broad community of plasma physicists working in heliophysics and space weather. Nonthermal electrons are also produced in the laboratory; for example, in laser-driven experiments. Astronomy can leverage the research in laboratory experiments, fusion science and heliophysics to both better understand the physics and take advantage code developments in plasma physics (as well as an understanding of their numerical limitations). Plasma physics and atomic physics tie together closely and understanding both is essential for astrophysics (for instance late-time spectral features in kilonovae and supernovae). Although much progress has been made to bridge scales between the fundamental plasma and atomic physics and macroscopic calculations, these studies stress computing. It may be that quantum computing can eventually play a role in these studies, but this will require an entirely new style of coding, again testing the expertise of computational scientists. In the bottom left, we show the D-Wave machine (one such quantum computer). Moving clockwise, we show a simulation of a laser-driven hohlraum for experiments at the Rochester Omega facility or the National Ignition Facility, the Fusion Pilot Plant at the Princeton Plasma Physics Laboratory <https://www.pppl.gov/> and the aurora borealis (produced from nonthermal electrons from the solar wind interacting with the earth's magnetosphere—NOAA). Astrophysics sources include pulsar winds, hot stars, and jetted outflows as seen in the Fermi map of the sky (NASA/DOE/Fermi LAT Collaboration). Finally we show images of both the Fermi (Atwood et al., 2009) and the high-energy neutrino IceCube (IceCube Collaboration et al., 2006) telescopes. The D-wave image is adapted from wikipedia (Oleg Alexandrov) ~ <https://creativecommons.org/licenses/by-sa/4.0/>.

But the breadth of the connections that must be made to build these ties is enormous. Bringing together these fields is not as simple as bringing together an expert in a particular physics discipline and an astronomer. It requires bringing together experimental, theory and simulation experts in that physics discipline and tying it together with simulation, theory, observation and instrumentation experts in astronomy. And, on the simulation side, you also have to bring in algorithm and hardware experts. Ultimately, we must train scientists that can span all these fields to work with these experts.

Especially in computational physics, astronomy already leads the training of such broad scientists which is why you see astronomers in leading roles in the computer facilities and software development at national laboratories and in industry. Astronomy also has developed scientists that have a broad understanding of physics and experimental/observational uncertainties. But achieving the fidelity needed to drive forward many of the TDAMM goals requires much more continuous connections and will not only require focused funds at NASA for this work but better interagency collaboration.

Probably the most neglected connection lies in Astronomy's ties to experimental physics. Laboratory astrophysics can not only strive to reproduce astrophysical conditions studying turbulence, radiation flow, dust production, plasma properties and nuclear physics, but because a lot of the observed diagnostics are similar, close collaboration between experimental scientists and astronomy observers could lead to advances in our analysis techniques. For example, experimental scientists are now using spectral diagnostics with increasing frequency and they could definitely benefit from the intense effort astronomers have committed in inferring properties from spectra.

Astronomy has one additional strength to help advance physics: public support. No facility developed in physics has claimed the attention of the public like the launch of JWST, the release of a new Chandra image or the image of the event horizon for the Event Horizon Telescope. The public doesn't get excited about PREX (Reed et al., 2021) probing neutron skins until they realize that this experiment allows us to study the properties of neutron stars. Astronomy is well known to be the gateway drug into physics, attracting the next-generation of scientists and the public into

physics, astronomy and computational modeling. And TDAMM science is at the forefront of this effort.

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Conflict of interest

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Multi-messenger astrophysics of black holes and neutron stars as probed by ground-based gravitational wave detectors: from present to future

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The ground-based gravitational wave (GW) detectors LIGO and Virgo have enabled the birth of multi-messenger GW astronomy via the detection of GWs from merging stellar-mass black holes (BHs) and neutron stars (NSs). GW170817, the first binary NS merger detected in GWs and all bands of the electromagnetic spectrum, is an outstanding example of the impact that GW discoveries can have on multi-messenger astronomy. Yet, GW170817 is only one of the many and varied multi-messenger sources that can be unveiled using ground-based GW detectors. In this contribution, we summarize key open questions in the astrophysics of stellar-mass BHs and NSs that can be answered using current and future-generation ground-based GW detectors, and highlight the potential for new multi-messenger discoveries ahead.

KEYWORDS

gravitational waves, time-domain astronomy, multi-messenger astrophysics, GW170817, LIGO and VIRGO

1 Introduction

The discovery of the binary NS merger GW170817 during the second observing run (O2) of the LIGO (LIGO Scientific Collaboration et al., 2015) and Virgo (Acernese et al., 2015) GW detectors kicked off a new era in multi-messenger astrophysics (MMA; Figures 1, 2). In addition to marking the first direct detection of a GW chirp from a binary NS merger (Abbott et al., 2017c), GW170817 also represents the first astrophysical event to be observed with GWs and a completely independent messenger, namely,

electromagnetic waves. Indeed, GW170817 was the first direct association of a NS-NS merger with a short gamma-ray burst (GRB), an IR-optical-UV kilonova, and an electromagnetic afterglow observed from radio to X-rays (see Abbott et al., 2017e, and references therein).

The rich multi-messenger data collected for GW170817 (Figure 1), together with detailed modeling and simulations, have painted the most detailed picture yet of a binary NS merger, impacting a variety of fields beyond gravitational physics and including nuclear physics (e.g., Bauswein et al., 2017; Kasen et al., 2017; Margalit and Metzger, 2017; Annala et al., 2018; Radice et al., 2018b; Abbott et al., 2018c; Côté et al., 2018; De et al., 2018; Most et al., 2018; Rezzolla et al., 2018; Capano et al., 2020), relativistic astrophysics (e.g., Shibata et al., 2017; Lazzati et al., 2018; Ruiz et al., 2018; Lazzati et al., 2021), stellar evolution and population synthesis (e.g., Dominik et al., 2013; Kruckow et al., 2018; Vigna-Gómez et al., 2018), and cosmology (e.g., Abbott et al., 2017a; Baker et al., 2017; Creminelli and Vernizzi, 2017; Ezquiaga and Zumalacárregui, 2017; Sakstein and Jain, 2017; Chen et al., 2018).

As of today, the LIGO and Virgo detectors have reported highly-significant discoveries of ~ 100 compact binary coalescences (Abbott et al., 2023a). The detections are dominated by binary BH mergers. Two highly-significant NS-NS mergers (GW170817 and GW190425; Abbott et al., 2017c; 2020a) and a few BH-NS merger candidates have been identified (Abbott et al., 2021a), but GW170817 remains the only GW event with a secure electromagnetic counterpart association. While revolutionizing the field of GW-MMA, the discovery of GW170817 highlighted many open questions that remain to be answered. To this end, the LIGO and Virgo collaborations have developed plans for further improvements in sensitivity of these detectors that will fully exploit what is possible at these existing facilities (hereafter, post-O5 or A# era, Figure 3; Abbott et al., 2018a; Fritschel et al., 2023). Several new frontiers in MMA will also come on the horizon with these envisioned sensitivity upgrades for the LIGO detectors (which include an expanded network with LIGO India—hereafter LIGO Aundha—expected to be operational starting in the early 2030; Iyer et al., 2023). However, it is likely that the full discovery potential of MMA will be realized only with next-generation ground-based GW detectors such as Cosmic Explorer (hereafter, CE) and the Einstein Telescope (hereafter, ET), envisioned to become operational in the 2030s and requiring new facilities and longer interferometer arms (Figures 2, 3; Branchesi et al., 2023; Evans et al., 2023). Here, we review the major open questions in the field of MMA as enabled by ground-based GW detectors (Sections 2–3), and briefly discuss the short-to-long term potential of this field (Section 4).

We stress that, while this work highlights topics in MMA for which observations of GWs and light are critical, the field of MMA is broader and includes messengers such as cosmic rays and neutrinos (e.g., Particle Physics Project Prioritization Panel, 2023, and references therein). Here, we mention these other probes only briefly. We also stress that our discussion is centered on the science enabled by ground-based GW detectors operating in the few Hz to few kHz GW frequency regime. However, the GW spectrum is much broader, and fundamental contributions to its exploration are being provided by Pulsar Timing Arrays (Detweiler, 1979; Agazie et al., 2023; EPTA Collaboration et al., 2023; Reardon et al.,

2023; Xu et al., 2023), and will be provided in the future by space-based instruments such as LISA (Amaro-Seoane et al., 2023) and DECIGO (Kawamura et al., 2011).

2 MMA of compact binary mergers: key open questions

2.1 Diversity of NS-NS/BH-NS mergers and r-process yields

GW170817 remains so far the only event seen in both GWs and electromagnetic emission. An associated GRB (170817A) was detected about 2 s after the merger by the *Fermi*/GBM and *Integral* satellites (Figure 1; Abbott et al., 2017b; Savchenko et al., 2017). About 11 h after the GW detection, an optical counterpart was identified by the Swope Supernova Team (Figure 1; Coulter et al., 2017). Via extensive multi-wavelength observations carried by several teams, this counterpart was recognized to be a kilonova—a quasi-thermal fast-fading transient associated with r-process nucleosynthesis occurring in the neutron-rich debris created by the merger itself (Chornock et al., 2017; Cowperthwaite et al., 2017; Drout et al., 2017; Evans et al., 2017; Kasliwal et al., 2017; Nicholl et al., 2017; Pian et al., 2017; Smartt et al., 2017; Soares-Santos et al., 2017; Tanvir et al., 2017; Valenti et al., 2017; Villar et al., 2017). The kilonova detection also enabled the arcsec localization of GW170817, and hence the identification of its host galaxy and measurement of its redshift (Hjorth et al., 2017; Im et al., 2017; Levan et al., 2017; Palmese et al., 2017; Pan et al., 2017). Located only ≈ 40 Mpc away, GW170817 is the closest short GRB with known redshift identified as of today. As the radio-to-X-ray follow-up observations of the GW170817/GRB 170817A afterglow revealed, GW170817 also brought the first ever direct detection of a relativistic jet observed off-axis (Figure 1, JvLA and *Chandra* insets), and proved that relativistic jets are much more complex than typically assumed for cosmological short GRBs (for which the on-axis view prevents a detailed study of the jet structure; Alexander et al., 2017; Haggard et al., 2017; Hallinan et al., 2017; Margutti et al., 2017; Troja et al., 2017; Mooley et al., 2018b; Margutti et al., 2018; Mooley et al., 2018a).

As the sensitivity of the LIGO detectors continues to improve steadily compared to the O2 run (Figure 3), one of the biggest priorities in the field of MMA is the collection of a larger sample of GW170817-like multi-messenger detections: going from 1 to ~ 10 (nearby) events localized by GW detectors to less than 100 deg^2 by the post-O5/A# era is a must (Petrov et al., 2022; Abbott et al., 2018a, see also Section 4). Increasing the sample of nearby, extensively monitored events is key to answering some fundamental questions left open by GW170817 such as, are NS-NS mergers the only site or one of many sites of r-process nucleosynthesis; are the heaviest of the heavy elements synthesized in those mergers; does the yield of various heavy elements match the Solar abundance (e.g., Eichler et al., 1989; Bauswein et al., 2013b; Metzger, 2019; Arcones and Thielemann, 2023; Setzer et al., 2023, and references therein). More generally, nearby multi-messenger detections are critical to understanding what is the possible zoo of electromagnetic counterparts of NS-NS and BH-NS systems (blue *versus* red kilonovae, choked *versus* successful and structured *versus* top-hat

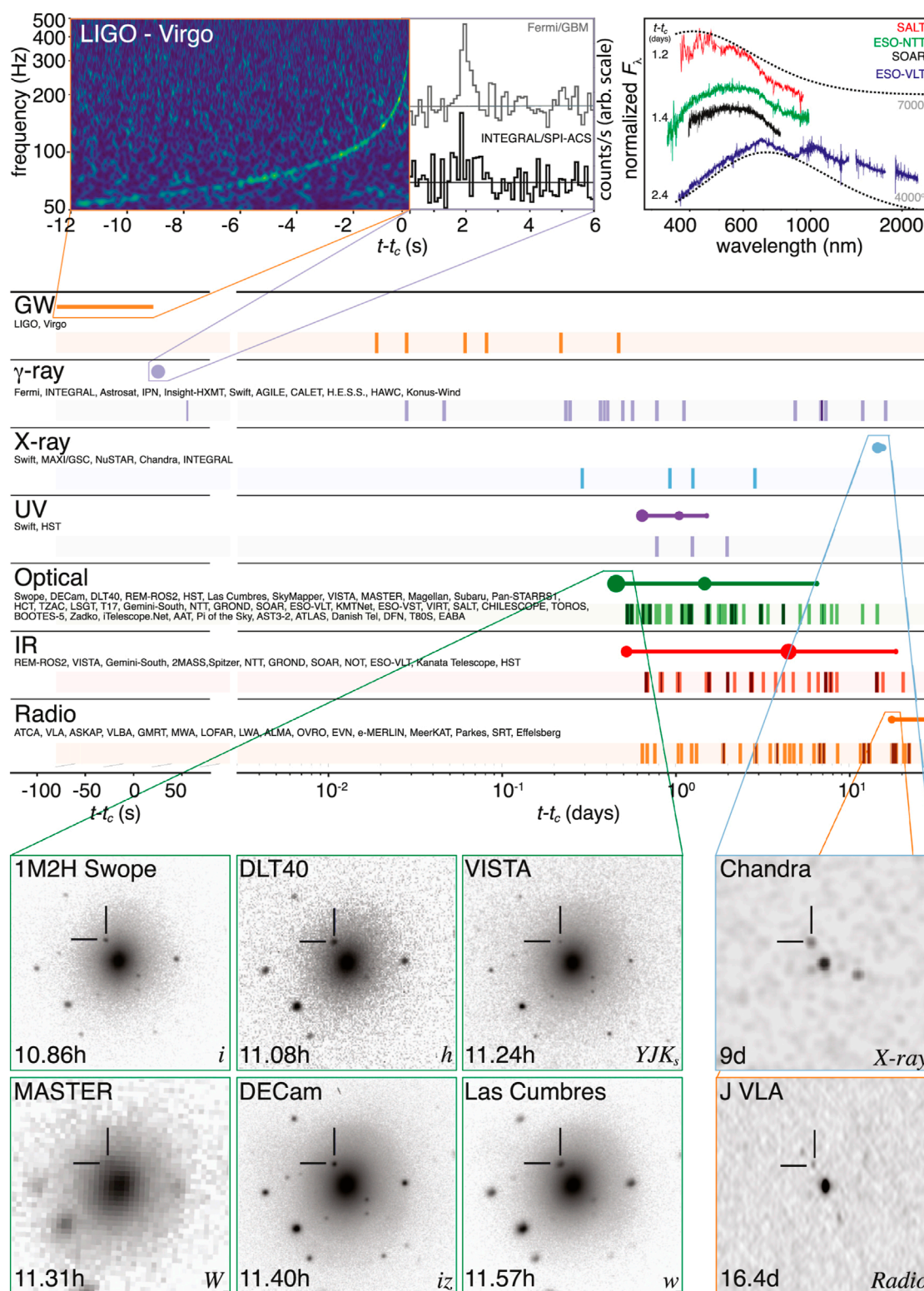


FIGURE 1

Figure reproduced from Abbott et al. (2017e). Timeline of the discovery of GW170817, its associated GRB 170817a, and its associated kilonova SSS17a/AT 2017gfo. The follow-up observations are shown by messenger and wavelength relative to the time of the GW event. The shaded dashes represent the times when information was reported in a GCN Circular. The names of the relevant instruments, facilities, or observing teams are collected at the beginning of the row. Representative observations in each band are shown as solid circles with their areas approximately scaled by brightness; the solid lines indicate when the source was detectable by at least one telescope. Magnification insets give a picture of the first detections in GWs, and in the gamma-ray, optical, X-ray, and radio bands.



FIGURE 2

Aerial views of the LIGO Hanford (left) and Livingston (center) observatories (credits: Caltech/MIT/LIGO Lab; [LIGO Scientific Collaboration et al., 2015](#)). We also show an artist's impression of a Cosmic Explorer (CE) observatory (credits: Angela Nguyen, Virginia Kitchen, Eddie Anaya, California State University Fullerton; [Evans et al., 2023](#)).

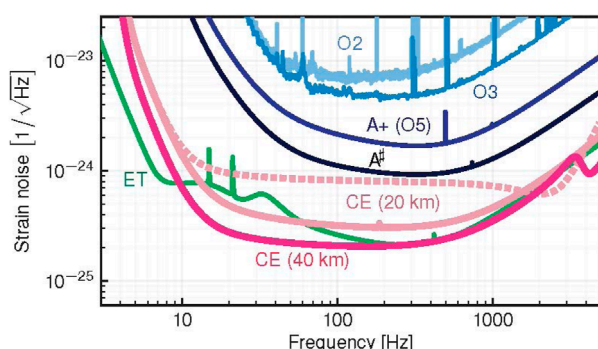


FIGURE 3

Figure adapted from [Evans et al. \(2023\)](#). Measured sensitivity of LIGO in its second (O2) and third (O3) observing runs, and estimated sensitivities of LIGO A+ (also referred to as LIGO O5 sensitivity; [Abbott et al., 2018a](#)), LIGO A# ([Fritschel et al., 2023](#)), ET ([Branchesi et al., 2023](#)), and the 20 km and 40 km CE detectors ([Evans et al., 2023](#)). We note that by reconfiguring several smaller optics, the 20 km detector could be operated either in a broad-band mode (solid) or a kilohertz-focused mode (dotted).

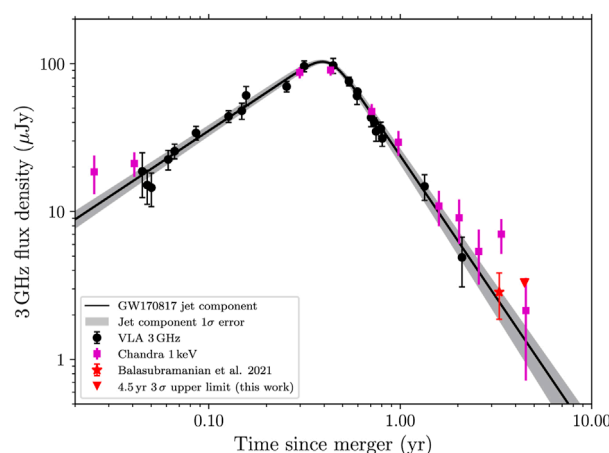


FIGURE 4

Figure reproduced from [Balasubramanian et al. \(2022\)](#). 3 GHz radio light curve of GW170817 (black dots, red star and red triangle) plus extrapolation of the X-ray observations to the radio band (purple squares), together with the best fit model and corresponding error (black line and gray shaded area) representing the emission from the relativistic jet.

jets), and what is the range of circum-burst medium densities in relation to the properties of the host galaxies (e.g., [Bloom et al., 2002](#); [Fong and Berger, 2013](#); [Barnes et al., 2016](#); [Hotokezaka et al., 2016](#); [Radice et al., 2016](#); [Bovard et al., 2017](#); [Lazzati and Perna, 2019](#); [Margalit and Metzger, 2019](#); [Nakar, 2020](#); [Ascenzi et al., 2021](#); [Raaijmakers et al., 2021](#); [Camilletti et al., 2022](#); [Fong et al., 2022](#); [Gottlieb and Nakar, 2022](#); [Perna et al., 2022](#); [Gompertz et al., 2023a](#); [Colombo et al., 2023](#); [Nouri et al., 2023](#)).

Ultimately, a diverse sample of multi-messenger detections of nearby and well-localized NS-NS and BH-NS systems will enable us to map the properties of the progenitors as probed by GWs (especially in terms of total mass, mass ratio, and Equation of State, hereafter, EoS; [Abbott et al., 2018c](#); [2019a](#), and references therein), to the properties of their merger ejecta and of the circum-merger environment as probed by electromagnetic observations ([Margalit and Metzger, 2019](#), and references therein). Joint multi-messenger analysis will then shed light on the physical processes that determine such mapping (e.g., [Radice et al., 2018a](#), and references therein).

2.2 Short GRB jets and central engines

The association of GW170817 with a GRB and an off-axis radio-to-X-ray afterglow ([Section 2.1](#); [Figure 4](#)) has demonstrated how GW observations can open the way to directly linking GRB progenitors to their relativistic jets. However, we are still far from fully understanding the physics behind the workings of GRB central engines and their jets, especially in terms of emission processes, jet composition and structure, and the role of magnetic fields.

Because in a compact binary merger the amplitude of the emitted GWs depends mildly on the orientation of the binary, GW detections can enable the study of off-axis GRB jets that may otherwise go undetected and/or unrecognized as off-axis events via electromagnetic observations alone ([Lazzati et al., 2017](#); [Granot et al., 2018b](#); [Bartos et al., 2019](#); [Dichiara et al., 2020](#); [Matsumoto and Piran, 2020](#); [Schroeder et al., 2020](#); [Grandorf et al., 2021](#); [Ricci et al., 2021](#); [Eddins et al., 2023](#); [Ghosh et al., 2024](#)). This is key to shedding light on the jet structures that, in turn,

are determined by complex processes involving the GRB central engines (that power the jet itself), and the interaction of the jets with the neutron-rich debris surrounding the merger sites (e.g., Rossi et al., 2002; Aloy et al., 2005; Bromberg et al., 2011; Nakar and Piran, 2018; Lazzati et al., 2018; Lazzati and Perna, 2019; Gottlieb et al., 2021; Sharan Salafia and Ghirlanda, 2022; García-García et al., 2023; Pavan et al., 2023, and references therein). As demonstrated by ~50 years of GRB observations, the structure of relativistic jets is largely masked in high-luminosity cosmological GRBs, whose electromagnetic emission is dominated by fast jet cores observed on-axis. In fact, the prompt γ -ray emission of the off-axis GRB 170817A was energetically weaker by about three orders of magnitude than the weakest cosmological short GRB (Fong et al., 2015). Its afterglow showed a behavior substantially different from the power-law-decaying afterglows of cosmological GRBs, with a delayed onset and a rising light curve observed from radio to X-rays (Figure 4 Alexander et al., 2017; Haggard et al., 2017; Hallinan et al., 2017; Margutti et al., 2017; Troja et al., 2017; D'Avanzo et al., 2018; Mooley et al., 2018b; Margutti et al., 2018; Mooley et al., 2018a; Makhathini et al., 2021; Balasubramanian et al., 2022). While extensive multi-band observations and detailed modeling have allowed us to link these unusual properties of GRB 170817A with a structured jet observed off-axis (Lazzati et al., 2018), significant uncertainties remain. Specifically, the polar profile (distribution of energy as a function of polar angle) of the GW170817 outflow remains highly debated, with analytical functions including Gaussian, power-law, and exponential profiles, as well as numerically-simulated profiles, all providing plausible fits to the data. In the radio band, future observations of off-axis GRB light curves combined with polarization measurements and Very-Long Baseline Interferometry (VLBI) can help shed light on both the jet structure and the largely unknown structure of magnetic fields within shocked ejecta (e.g., Ghisellini and Lazzati, 1999; Sari, 1999; Corsi et al., 2018; Gill and Granot, 2018; Granot et al., 2018a; Mooley et al., 2018a; Ghirlanda et al., 2019; Gill and Granot, 2020; Teboul and Shviv, 2021, and references therein).

The origin of the γ -rays in GRB170817a remains equally debated: while the structured outflow model can explain why a GRB was detected even if off-axis (Lazzati et al., 2017), a mildly relativistic shock breakout of a cocoon from the merger's ejecta is also possible (Gottlieb et al., 2018). Future multi-messenger observations of off-axis GRBs (including potential coincident detections between GW signals and sub-threshold GRBs; Kocevski et al., 2018; Magee et al., 2019; Tohuvavohu et al., 2020; Fletcher et al., 2023), will greatly help settle these debates (Lazzati, 2020; Beniamini et al., 2022; Bošnjak et al., 2022).

While the LIGO-Virgo-KAGRA detectors (Figure 2, left and central panel) continue to improve their sensitivity to GWs from GRBs (Abbott et al., 2021b; 2022b), these searches will undergo a leap forward when next-generation GW detector such as CE and ET, with $\approx 10\times$ the sensitivity of the current LIGO detectors (Figure 2, right panel; Figure 3), will probe the population of NS-NS mergers up to the star formation peak (and beyond for BH-BH mergers, Figure 5; Branchesi et al., 2023; Evans et al., 2023; Gupta et al., 2023a). With these next-generation detectors, we can expect each short GRB observed by satellites such as *Fermi* (Thompson and Wilson-Hodge, 2022) and *Swift* (Gehrels et al., 2004) to have a counterpart in GWs (Ronchini et al., 2022).

The direct mapping of GRBs to their progenitors—something inaccessible to electromagnetic observations alone—is key to shedding light on the conditions that enable the launch of successful relativistic jets, especially in relation to the properties of the progenitors (including whether BH-BH mergers make GRBs; Loeb, 2016; Connaughton et al., 2016; Dai et al., 2017; Perna et al., 2018; 2019; Veres et al., 2019; Graham et al., 2023) and the nature of the central engines (BHs *versus* long- or short-lived NSs; Bucciantini et al., 2012; Giacomazzo and Perna, 2013; Bauswein et al., 2013a; Giacomazzo et al., 2013; Mösta et al., 2020, see also Section 2.4). Systematic measurements of the delay times between GW mergers and GRBs, in addition to providing stringent fundamental physics tests, will further our understanding of the GRB jet launching mechanisms, of the physics of the jet breakouts from the surrounding medium, and of the dissipation and radiation mechanisms as related to the unknown composition of jets (Granot et al., 2017; Shoemaker and Murase, 2018; Zhang, 2019; Lazzati, 2020).

Probing directly and systematically the progenitor of short GRBs observed in γ -rays will also shed light on whether the phenomenological classification of GRBs in short/hard and long/soft as related to two different classes of progenitors (compact binary mergers and collapsars, respectively) holds in all cases. In fact, this classification scheme has been challenged by observations of long GRBs associated with kilonovae or lacking supernova counterparts to very deep limits, and short GRBs showing potential supernova bumps in their light curves (Della Valle et al., 2006; Fynbo et al., 2006; Ahumada et al., 2021; Troja et al., 2022a; Rastinejad et al., 2022; Rossi et al., 2022; Yang et al., 2022; Barnes and Metzger, 2023; Gompertz et al., 2023b). In the future, deep GW observations of these peculiar GRBs will provide the definitive word on the nature of their progenitors and likely settle current classification debates (Dimple et al., 2023).

2.3 Electromagnetic precursors to compact binary mergers

Electromagnetic emission from GW170817 was probed only after the GW merger (starting from about 2 s after; Figure 1) with the detection of γ -rays. Hence, as of today, the pre-merger phase remains unexplored in terms of potential electromagnetic counterparts. As the sensitivity and number of ground-based GW detectors increase, GW observations of an in-spiraling system can provide the advance notice required to capture light from the moments closest to merger (Figure 6; see also Cannon et al., 2012; Singer and Price, 2016; Messick et al., 2017; Chan et al., 2018; Zhao and Wen, 2018; Sachdev et al., 2020a; Magee et al., 2021; Nitz and Dal Canton, 2021; Nitz et al., 2020; Borhanian and Sathyaprakash, 2022; Banerjee et al., 2023; Chatterjee and Wen, 2023; Hu and Veitch, 2023; Miller et al., 2023).

Multi-messenger observations of the moments just before the merger could probe several highly-debated astrophysical scenarios (see Wang and Liu, 2021, for a recent review, and references therein). From a theoretical perspective, models predict the possible existence of pre-merger electromagnetic signatures via a variety of mechanisms including two-body electromagnetic interactions, resonant NS crust shattering, magnetic reconnection and particle

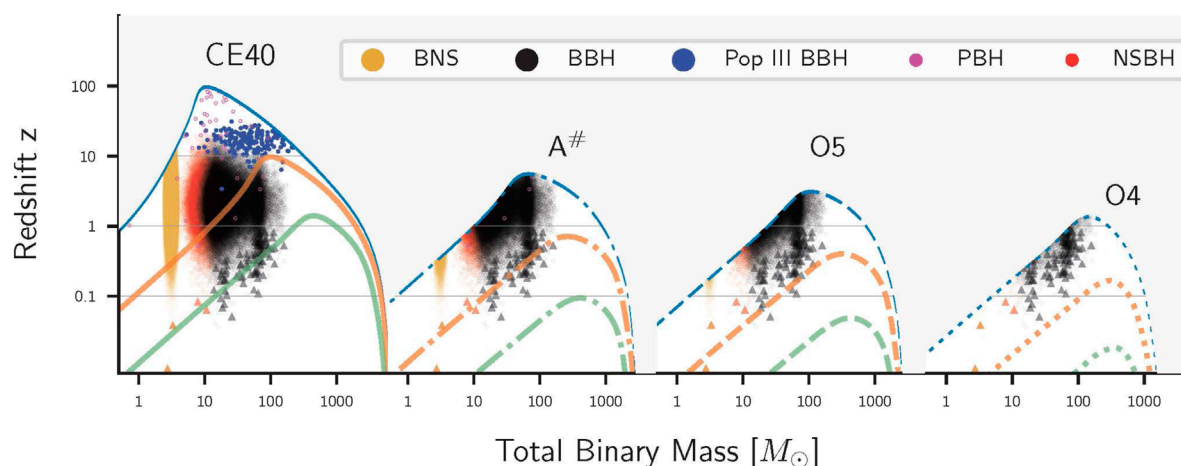


FIGURE 5

Figure adapted from [Evans et al. \(2023\)](#). The reach of current and future ground-based GW detectors for compact binary mergers (NS-NS mergers in gold; BH-NS mergers in red; and BH-BH mergers in black; see [Section 2.5](#)) is represented as a function of total binary mass and redshift at various signal-to-noise ratio (SNR) thresholds (blue lines for SNR 8; orange lines for SNR 100; and green lines for SNR 1000). The population of observed compact-object binaries is plotted with small triangles. We use dotted lines for LIGO at its O4 sensitivity; dashed lines for LIGO at its projected O5 sensitivity, also referred to as LIGO A+ ([Abbott et al., 2018a](#)); and dash-dotted lines for LIGO at its projected post-O5 A# sensitivity (the ultimate performance of current LIGO detectors envisioned for the post-O5 era; [Fritschel et al., 2023](#)). CE40 ([Evans et al., 2023](#)), a next-generation GW detector concept, can expand the cosmic horizon of NS-NS mergers, and enable observations of new populations including mergers from Population III BHs (blue dots), and speculative primordial BHs (magenta dots).

acceleration through the revival of pulsar-like emission during the in-spiral phase, the decay of tidal tails, the formation of fireballs or wind-driven shocks (e.g., [Goldreich and Lynden-Bell, 1969](#); [Vietri, 1996](#); [Hansen and Lyutikov, 2001](#); [Moortgat and Kuijpers, 2006](#); [Roberts et al., 2011](#); [Lai, 2012](#); [Metzger and Berger, 2012](#); [Piro, 2012](#); [Tsang et al., 2012](#); [Penner et al., 2012](#); [Medvedev and Loeb, 2013](#); [Metzger and Zivancev, 2016](#); [Suvorov and Kokkotas, 2019](#); [Beloborodov, 2021](#); [Sridhar et al., 2021](#); [Most and Philippov, 2023b](#); [Cooper et al., 2023](#)). It has also been suggested that in the late in-spiral phase of a NS-NS or BH-NS merger in which one NS is a magnetar, the tidal-induced deformation may surpass the maximum that the magnetar's crust can sustain, driving a catastrophic global crust destruction that releases magnetic energy as a superflare with energy hundreds of times larger than giant flares of magnetars ([Zhang et al., 2022](#)). Numerical studies support the conclusion that electromagnetic flares may be observed before the merger ([Palenzuela et al., 2013](#); [Most and Philippov, 2020, 2022, 2023a](#)). A key related open questions is whether NS mergers may power a fraction of fast radio bursts (FRBs; [Lorimer et al., 2007](#); [Thornton et al., 2013](#); [Zhang, 2014](#); [Williams and Berger, 2016](#); [Paschalidis and Ruiz, 2019](#); [Rowlinson et al., 2019](#); [Zhang, 2020](#); [Wada et al., 2020](#); [Chen Z.-L. et al., 2023](#); [Pan et al., 2023](#)).

Observationally, while high-energy precursors have been observed in short (and long) GRBs ([Lazzati, 2005](#); [Burlon et al., 2008, 2009](#); [Troja et al., 2010](#); [Zhong et al., 2019](#); [Wang et al., 2020](#); [Petroff et al., 2022](#); [Dichiara et al., 2023](#)), it is still a matter of debate whether these precursors have a different origin from that of the GRB itself, or are rather just a manifestation of the variable GRB emission ([Charisi et al., 2015](#); [Xiao et al., 2022](#)). Searches for electromagnetic precursors have been carried in coincidence with compact binary mergers identified by LIGO and Virgo during O2/O3 having a non-negligible probability

to contain a NS ([Stachie et al., 2022](#)). While these searches found no significant candidate precursor signals, open questions discussed above can be explored in future searches with improved sensitivity, potentially aided by GW early alerts and localizations, and extending across the electromagnetic spectrum (from radio to γ -rays; [Figure 6](#)).

2.4 Nature of the merger remnant and neutron star EoS

After a NS-NS merger, a compact remnant is left over. The nature of such a remnant—either a NS or a BH—is thought to depend primarily on the masses of the binary components (i.e., total mass of the system and mass ratio) and on the EoS of nuclear matter (e.g., [Ravi and Lasky, 2014](#); [Piro et al., 2017](#); [Shibata and Hotokezaka, 2019](#)). If a NS remnant is formed (as opposed to a prompt BH formation), its lifetime could range from short lived (hypermassive NS supported only temporarily against gravity by differential rotation), to long lived (supramassive NSs supported against gravity by uniform rotation), to indefinitely stable ([Beniamini and Lu, 2021](#); [Margalit et al., 2022](#); [Wang et al., 2024](#)). GWs can be used to probe the post-merger remnant via a variety of yet-to-be detected signals and, when paired with electromagnetic observations, can greatly help us understand the astrophysics of the post-merger phase.

GWs produced by oscillations of the hot, extremely dense remnant may come into reach with improved ground-based detectors (e.g., [Bauswein et al., 2012](#); [Clark et al., 2014](#); [Bauswein and Stergioulas, 2015](#); [Clark et al., 2016](#); [Krolak et al., 2023](#)). The formation of a hypermassive NS is expected to give off quasi-periodic GWs of frequencies $\approx 2-4$ kHz, while GWs from

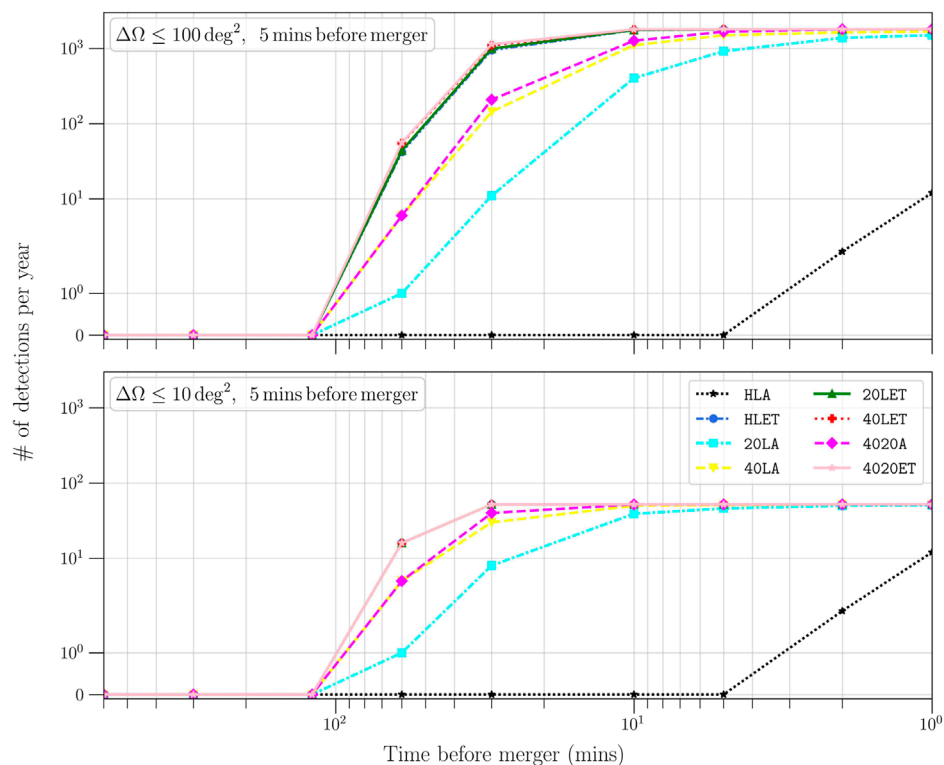


FIGURE 6

This Figure is based on the simulations presented in Gupta et al. (2023a), for GW detector networks containing zero to three next-generation observatories. The HLA network contains the two current LIGO detectors (Hanford and Livingston) operating at the upgraded A# sensitivity (Figure 3), plus the LIGO Aundha at A# sensitivity. The 20LA and 40LA networks represent configurations with a single 20 km-long arms CE detector operating in the context of an upgraded (A# sensitivity) LIGO network with locations in Livingston and Aundha. The HLET network is one with a single next-generation GW detector (ET) operating together with LIGO Hanford and LIGO Livingston at their upgraded A# sensitivity. The 4020A network represents the CE reference configuration as described in (Evans et al., 2023), with one 40 km-long and one 20 km-long next-generation detectors plus LIGO Aundha at A# sensitivity. The 20LET and 40LET networks represent a single CE detector (either 20 km or 40 km) operating with LIGO Livingston and the ET. Finally, the 4020 ET is the reference CE configuration operating with ET. For these networks, we calculate the signal-to-noise ratio of NS-NS systems at 1, 2, 5, 10, 30, 60, 120, 300, 600 min before merger (data points) for events that are localized within 100 deg^2 (top) or 10 deg^2 (bottom) at 5 min before merger, in 1 year. If the network signal-to-noise ratio is > 10 at the considered time before merger, then the binary is included in the count. We assume a local merger rate density of $320 \text{ Gpc}^{-3} \text{ yr}^{-1}$, but note that this rate is subject to large uncertainties ($10\text{--}1700 \text{ Gpc}^{-3} \text{ yr}^{-1}$; Abbott et al., 2023b). There are no events satisfying the imposed criteria at > 120 min before the merger given the assumed low-frequency cut-off of 5 Hz for all the detectors (results could be improved if ET reaches sub-5-Hz sensitivity). We also note that all events with $\Delta\Omega \leq 10 \text{ deg}^2$ at 5 min before merger are located at $z < 0.2$; and, all events with $\Delta\Omega \leq 100 \text{ deg}^2$ at 5 min before merger are located at $z < 0.5$. Finally, all events detected 5 min before merger (with no restrictions on the localization accuracy) lie at $z < 0.9$.

quasi-normal modes of promptly-formed BHs are found at higher frequencies of $\approx 6.5\text{--}7 \text{ kHz}$ (Shibata and Taniguchi, 2006; Breschi et al., 2022). Hence, post-merger GW observations can be used to constrain the yet-uncertain EoS of NS matter in a way complementary to measurements of the tidal deformation of the NSs during the late in-spiral phase (e.g., Flanagan and Hinderer, 2008; Chatziioannou et al., 2017; Landry, 2023). Simulations indicate that oscillations of a deformed, differentially rotating massive NS emit a GW spectrum with a pronounced peak generated by the fundamental quadrupolar oscillation mode, whose frequency correlates with the radius of the non-rotating NS (Bauswein et al., 2012). More specifically, the frequency of this mode is proportional to the square root of the mean density (Bauswein et al., 2012). Hence, for a given remnant mass (approximately given by the total binary mass), the peak frequency is determined by the radius. In turn, the determination of the dominant post-merger GW frequency can provide an upper-limit for the maximum

mass of non-rotating NSs, with implications for the NS mass distribution and, indirectly, electromagnetic counterparts (Margalit and Metzger, 2017; Ai et al., 2020; Bernuzzi, 2020). It has also been suggested that in compact binary mergers where short-lived NSs are formed after the merger, the quasi-periodic oscillations of the remnants may imprint quasi-periodic modulations of the γ -rays emitted in the associated GRBs (Chirenti et al., 2023). As of today, the viability of this process remains debated (Most and Quataert, 2023).

After the early (dynamical) GW-driven phase, the (secular) evolution of remnants that did not collapse to BHs is driven by viscous magnetohydrodynamics processes and neutrino cooling (Piro et al., 2017; Bernuzzi, 2020). Mapping observationally NS-NS progenitors to their remnants via their GW and electromagnetic emission offers an unprecedented opportunity to understand this complex interplay of gravitational, nuclear, weak and electromagnetic interactions (Beniamini and Lu, 2021;

Margalit et al., 2022; Wang et al., 2024). In the case of GW170817, the presence of an electromagnetic counterpart disfavors a prompt BH formation. The velocity, total mass, and electron fraction of the blue kilonova ejecta (as constrained from the observations) support the idea that the merger formed a rapidly spinning hypermassive and magnetized NS, with a 0.1–1 s lifetime (Metzger et al., 2018). In this interpretation, the lifetime of the GW170817 merger remnant is short because a long-lived remnant would have injected a rotational energy of a few $\approx 10^{52}$ erg into the ejecta, which can be excluded from observations (Radice et al., 2020). However, an interpretation of GW170817 in the context of a long-lived (days to months) remnant with a small dipole magnetic field (so as to minimize the energy injected into its outflows) cannot be excluded (Ai et al., 2018; Yu et al., 2018).

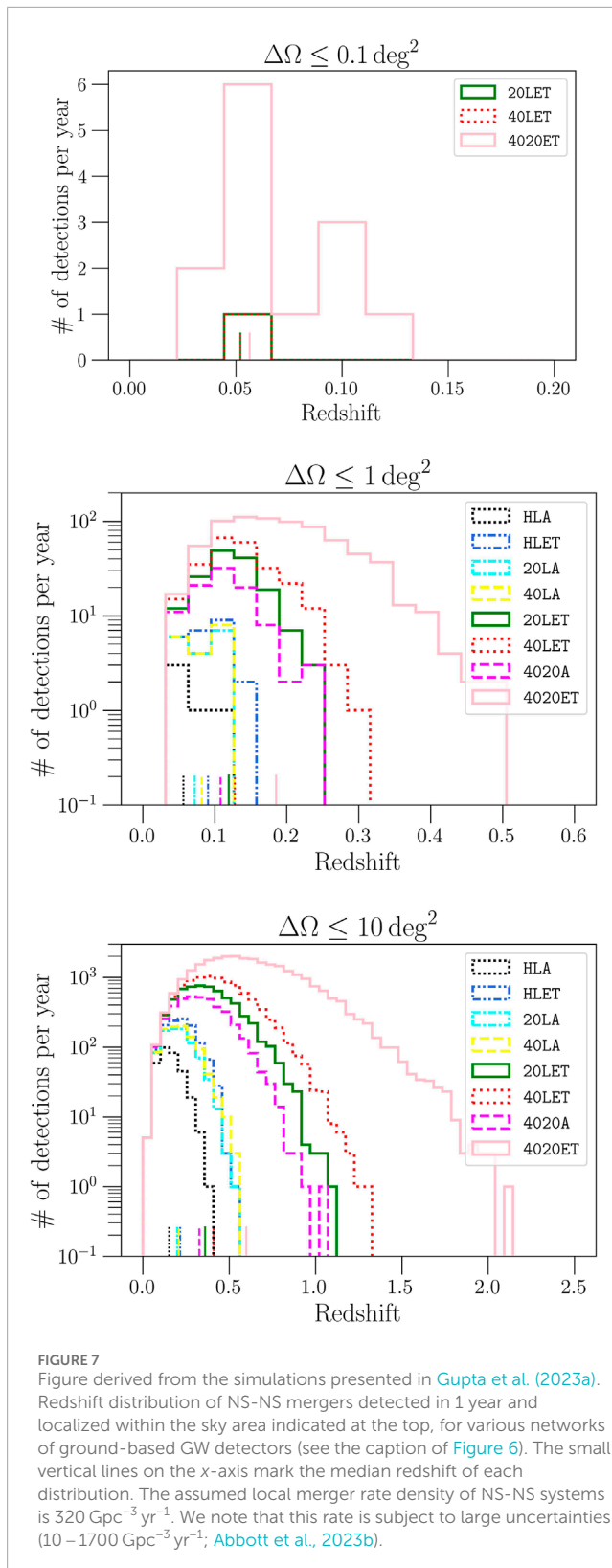
Overall, post-merger scenarios involving long-lived or stable NSs formed in compact binary mergers have been proposed to explain various features in GRB light curves and have received new attention after GW170817. Proposed electromagnetic signatures of long-lived remnants range from brighter-than-normal magnetar-powered kilonovae, to early-time X-ray afterglow plateaus and late-time radio and X-ray flares (Nakar and Piran, 2011; Rowlinson et al., 2013; Hotokezaka et al., 2018; Bartos et al., 2019; Kathirgamaraju et al., 2019; Nedora et al., 2021; Ai et al., 2022; Sarin et al., 2022; Sadeh et al., 2024; Wang et al., 2024). Proposed GW signatures include oscillation modes of a short-lived hypermassive NS, bar-mode instabilities, and rapid spindown powered by magnetic-field induced ellipticities (e.g., Lai and Shapiro, 1995; Owen et al., 1998; Cutler, 2002a; Shibata, 2005; Corsi and Mészáros, 2009; Hotokezaka et al., 2013; Ciolfi and Rezzolla, 2013; Dall’Osso et al., 2015; Clark et al., 2016). Several observing campaigns aimed at identifying electromagnetic or GW signatures of long-lived remnants have been conducted for both GW170817 and other short GRBs, and promise to become more constraining of proposed models with next-generation GW and electromagnetic instrumentation (e.g., Coyne et al., 2016; Horesh et al., 2016; Abbott et al., 2017d; 2019b; Sowell et al., 2019; Schroeder et al., 2020; Balasubramanian et al., 2021; Bruni et al., 2021; Abbott et al., 2021c; Grandorf et al., 2021; Balasubramanian et al., 2022; Troja et al., 2022b; Hajela et al., 2022; Eddins et al., 2023; Grace et al., 2023; Krolak et al., 2023; Ghosh et al., 2024). By probing the mass of the post-merger remnants in a systematic fashion, next-generation GW detectors like CE and ET could also probe models of supernova engines (Fryer, 2023).

2.5 Compact binary merger population properties

As the number of NS-NS, BH-NS, and BH-BH detections increases following the improvement in sensitivity of the LIGO, Virgo, and KAGRA detectors (Figure 3, 7), MMA studies based on single-event analyses will be crucially complemented by statistical studies of larger source samples. While interesting individual events and outliers will enable probing the most extreme systems, joint analyses of a large number of compact binaries will yield an exquisite characterization of the properties of the bulk of the population. These analyses can constrain key population properties such as

merger rates, mass distributions, r-process yields, properties of the GRB jets, etc. (e.g., Biscoveanu et al., 2020b; Chen et al., 2021; Abbott et al., 2023b; Biscoveanu et al., 2023; Delfavero et al., 2023), while enabling comparison with similar constraints derived from observations via other messengers (e.g., Belczynski et al., 2021; Landry and Read, 2021; Fishbach and Kalogera, 2022; Mandel and Broekgaarden, 2022; Liotine et al., 2023). On the longer term, the study of NS-NS mergers is likely to see an even more substantial shift from single-event analyses to population inference and statistical studies. In fact, next-generation GW detectors may enable us to probe the properties of NS-NS mergers across cosmic history and galactic environments (Figure 5), measure the time delay distribution between formation and merger (Safarzadeh et al., 2019), and thereby infer the history of chemical evolution in the Universe even beyond the reach of electromagnetic astronomy (Chruślińska, 2022). For the loudest and best-localized BH-BH binaries, the uncertainty volume will be small enough to confidently identify the host galaxy even in absence of a counterpart (Vitale and Whittle, 2018; Borhanian and Sathyaprakash, 2022). The ability of GW detectors to precisely measure masses, distances and sky positions of thousands of mergers per year is key to this end (Vitale and Evans, 2017; Gupta et al., 2023a; Evans et al., 2023, see Figure 7).

Increased detection rates of compact binary mergers containing the heaviest stellar-mass BHs will also shed light on crucial open questions in stellar astrophysics, especially when combined with electromagnetic surveys. Theory predicts the existence of a gap in the BH mass distribution because of pair-instability supernova (Fowler and Hoyle, 1964; Barkat et al., 1967; Woosley, 2017). This mechanism should produce a dearth of BH-BH binaries with components in the mass range $\sim 50 - 135 M_{\odot}$ (e.g., Belczynski et al., 2016). The largest uncertainty on the lower end of this “mass gap” comes from uncertainties on the nuclear reaction rate $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ (Farmer et al., 2019). The mass gap can be contaminated from hierarchical mergers of lower-mass BHs (Fishbach et al., 2017; Gerosa and Berti, 2017; Gerosa and Fishbach, 2021; Tagawa et al., 2021; Ford and McKernan, 2022) and from other formation channels with possible characteristic electromagnetic signatures, including stellar collisions in young stellar clusters (Costa et al., 2022; Ballone et al., 2023); the core collapse of rapidly rotating massive stars from progenitors with helium cores $\geq 130 M_{\odot}$ (“collapsars”), which could lead to long GRBs, r-process nucleosynthesis, and GWs of frequency $\sim 0.1 - 50$ Hz from non-axisymmetric instabilities (Siegel et al., 2022); super-Eddington accretion in isolated binaries (van Son et al., 2020); or more exotic scenarios, such as accretion onto primordial BHs (De Luca et al., 2021; De Luca and Bellomo, 2023). Several astrophysical scenarios predict the possibility of mergers between BHs on the “far side” of the mass gap (Mangiagli et al., 2019; Hijioka et al., 2021; Santoliquido et al., 2023). The observation of such mergers with next-generation GW detectors could allow us to measure the location of the upper end of the mass gap. Since the “width” of the mass gap is to a good approximation constant as a function of the uncertain nuclear reaction rates (e.g., Farmer et al., 2019), these constraints will also inform us about the location of the lower end of the mass gap. Theoretical predictions should also be compared with the already evident “bump” in the observed mass distribution of BH-BH mergers at



$\sim 35 M_{\odot}$ that cannot be explained by Poisson noise alone (Farah et al., 2023). Ultimately, the combination of GW observations and electromagnetic transient surveys can give important insight into nuclear reaction rates and supernova physics (Farmer et al., 2020; Karathanasis et al., 2023).

2.6 Impact of GW-enabled MMA on cosmology

Observations of GWs from well-localized compact binary mergers can measure absolute source distances. When coupled with an independent determination of redshift through an electromagnetic counterpart, they provide constraints on the Hubble constant (H_0) and hence the expansion history of the Universe (e.g., Schutz, 1986; Holz and Hughes, 2005; Dalal et al., 2006; Sathyaprakash and Schutz, 2009; Nissanke et al., 2010; Del Pozzo, 2012; Abbott et al., 2017a; Mukherjee et al., 2021a; Jin, 2023; Mancarella et al., 2023; Chen et al., 2024). Absolute distance measurements at low redshifts, as those enabled by GW observations, can constrain dark energy when combined with observations of the primary anisotropies in the cosmic microwave background (e.g., Hu, 2005). We note that, in modified theories of gravity that predict a non-trivial dark energy equation of state and deviations from general relativity in the propagation of GWs across cosmological distances, the effect of the modified GW propagation can dominate over that of the dark energy equation of state, potentially becoming observable with next-generation GW observatories (e.g., Belgacem et al., 2018; Mukherjee et al., 2021c; Afroz and Mukherjee, 2023).

Multi-messenger observations of GW170817 allowed for a measurement of the Hubble constant using the GW detection of the NS-NS merger combined with the optical identification of the host galaxy (Abbott et al., 2017a). The GW measurement returned a value of $H_0 = 70_{-8}^{+12} \text{ km s}^{-1} \text{ Mpc}^{-1}$. While this measurement is not sufficiently precise to significantly impact the current debate on the tension between different measurements of H_0 (Freedman, 2021; Freedman and Madore, 2023; Kamionkowski and Riess, 2023), its importance as a measurement completely independent of both the Planck cosmic microwave background and the local Cepheid-supernovae distance ladder measurements has been widely recognized. The dominant source of uncertainty in the H_0 measurement via GWs is the degeneracy between the binary viewing angle and the source distance. Hence, an independent determination of the viewing angle is of great importance (Nakar and Piran, 2021). For this reason, and as demonstrated by GW170817 itself, VLBI observations of the afterglow radio centroids and images of compact binary mergers are key to improve the H_0 measurement (Mooley et al., 2018a; Ghirlanda et al., 2019; Chen H.-Y. et al., 2023; Govreen-Segal and Nakar, 2023). Hotokezaka et al. (2019) estimate that 15 more localized GW170817-like events (with comparable signal-to-noise ratio and favorable orientation), having radio images and light curve data, can resolve the current Hubble tension, as compared to 50–100 GW events necessary in the absence of radio data. An accurate measurement of the Hubble constant from standard siren GW cosmology also requires a robust peculiar velocity correction of the redshift of the host galaxy (Nimonkar and Mukherjee, 2024).

It is important to note that a substantial fraction of sources detected by a given GW network over a certain timescale may not have associated transient electromagnetic counterparts. However, multi-messenger studies can still be relevant as they provide advantages related to incorporating host galaxy information. Indeed, it is possible to carry out a measurement of H_0 using a statistical approach that incorporates the redshifts of all potential host

galaxies within the GW three-dimensional localization region (Chen et al., 2018). This technique yields an H_0 measurement that has a greater uncertainty than that which can be achieved via direct counterpart identifications, but still informative once many detections are combined (Chen et al., 2018). The statistical approach also implies that, in the absence of a counterpart, only those GW events with small enough localization volumes yield informative H_0 measurements. Another proposed statistical technique exploits the clustering scale of the GW sources with galaxies of known redshift, and will be applicable also to the high redshift GW sources detectable with next-generation GW detectors (Mukherjee et al., 2021b; Cigarrán Díaz and Mukherjee, 2022; Mukherjee et al., 2022). In summary, with GW detectors of improved sensitivity able to observe farther and to localize better, galaxy surveys and statistical approaches for the measurement of H_0 are likely to become more and more relevant (Ye and Fishbach, 2021; Borghi et al., 2023; Dalang and Baker, 2023; Ghosh et al., 2023). In the era of next-generation GW detectors, other statistical techniques that do not require host galaxy information nor electromagnetic counterpart identifications may complement the constraints on cosmology as determined via these MMA techniques, particularly for the population of BH-NS mergers (Colombo et al., 2023; Shiralilou et al., 2023).

3 New frontiers in MMA

NSs and stellar-mass BHs, in isolation, in binary systems, and/or overall as populations, can be sources of GW signals that are very different from the compact binary merger signals already detected by LIGO and Virgo. We have mentioned some of these signals in the context of the nature of the post-merger remnant question left open by GW170817 (Section 2.4). Here, we expand our discussion to a zoo of yet-to-be-detected signals that may reveal the physics behind a suite of extreme astrophysical phenomena, and open new ways of doing MMA that include inference of population properties via correlations between the GW signals and other (electromagnetic) observables such as galaxy counts and the cosmic microwave background (e.g., Ando et al., 2013; Mukherjee et al., 2020b; a; Agarwal et al., 2022; De Lillo et al., 2022; Balaudo et al., 2023; De Lillo and Suresh, 2023; De Lillo et al., 2023; Perna et al., 2023; Yang et al., 2023).

Rotating NSs are thought to produce quasi-periodic GWs that can last for millions of years (and hence are usually referred to as continuous GWs), arising from time-varying mass quadrupoles supported by elastic or magnetic stresses (Melosh, 1969), or current quadrupoles known as “ r -modes” (Andersson, 1998; Lindblom et al., 1998; Glampedakis and Gualtieri, 2018). Accreting NSs (low-mass X-ray binaries), which are thought to become millisecond pulsars after accretion ends, can also be driven to non-axisymmetry by lateral temperature gradients (Bildsten, 1998; Ushomirsky et al., 2002), internal magnetic distortion (Melosh, 1969; Bonazzola and Gourgoulhon, 1996; Cutler, 2002b), or magnetic bottling of accreted material (Melatos and Payne, 2005), hence emitting GWs. Continuous GW emission will help reveal properties of NSs such as composition (EoS), internal magnetic field, and viscosity, in addition to unveiling NSs that cannot be observed electromagnetically (e.g., Bonazzola and Gourgoulhon,

1996; Bildsten, 1998; Owen et al., 1998; Andersson and Kokkotas, 2001; Owen, 2005; Glampedakis and Gualtieri, 2018; Gittins et al., 2021; Morales and Horowitz, 2022; Riles, 2023, and references therein). Current searches for continuous GWs produced by spinning NSs with asymmetries improve with every LIGO-Virgo-KAGRA run (e.g., Abbott et al., 2022c) and dozens of known millisecond pulsars could come into the reach of next-generation GW detectors (Woan et al., 2018; Gupta et al., 2023a; Evans et al., 2023), with the potential of many more thanks to upcoming or next-generation electromagnetic facilities such as the next-generation Very Large Array (ngVLA; Murphy and ngVLA Science Advisory Council, 2020) and the Square Kilometre Array (Kalogera et al., 2019; Evans et al., 2023; Pagliaro et al., 2023; Riles, 2023; Wette, 2023). Detection by next-generation instruments also looks promising for bright low mass X-ray binaries such as Scorpius X-1 (Gupta et al., 2023a; Evans et al., 2023).

Impulsive, energetic NS events other than binary mergers can also produce bursts of GWs. For example, magnetar γ -ray flares (possibly accompanied by FRBs; Abbott et al., 2022d; Abbott et al., 2022d; Ball and Frey, 2023) and pulsar glitches (e.g., Abbott et al., 2022a) are the targets of current searches for GW signals in LIGO-Virgo-KAGRA data. While near-future detector upgrades could probe GW signals expected in the most optimistic scenarios (Corsi and Owen, 2011), next-generation GW observatories are likely to probe a wider range of possible GW outcomes (Evans et al., 2023). We stress that the detection of normal modes of NSs such as so-called “ f -modes” will measure the cold NS EoS and masses of a population different from that seen in compact binary mergers, and combined with electromagnetic observations will yield information on internal magnetic fields (Evans et al., 2023).

Core-collapse supernovae are also thought to generate bursts of GWs from the dynamics of hot, high density matter in their central regions. Next-generation GW detectors are expected to be sensitive to supernovae within the Milky Way and its satellite galaxies (Kalogera et al., 2019; Srivastava et al., 2019; Szczepańczyk and Zanolin, 2022; Evans et al., 2023; Gossan and Hall, 2023), while some extreme supernovae, such as collapsars with cocoons, could generate GWs that could come into reach with current generation GW detectors (e.g., Siegel et al., 2022; Abbott et al., 2020b; Gottlieb et al., 2023, and references therein). The detection of a core-collapse event in GWs would provide a unique channel for observing the explosion's central engine and the (hot) EoS of the newly formed compact remnant. A nearby supernova could also provide a spectacular multi-messenger event via a coincident neutrino detection (e.g., Bionta et al., 1987; Janka, 2017; Chang et al., 2022; Abbasi et al., 2023; Guarini et al., 2023).

Finally, a stochastic GW background can be generated by a large variety of phenomena of cosmological (Caprini and Figueroa, 2018) and/or astrophysical origin. The detection of a cosmological stochastic background would be of fundamental importance for our understanding of the early Universe. While current GW detectors are not optimized for the detection of a stochastic background of cosmological origin, a fraction of the parameter space in various scenarios is compatible with a detection by future detectors (Caprini et al., 2016; Caprini and Figueroa, 2018; Barish et al., 2021). Astrophysical backgrounds contain key information about the distribution of mass, redshift, and other properties of their corresponding source populations (e.g., Mukherjee and Silk, 2020;

Yang et al., 2021). The merger rate of NS-NS mergers as estimated from current observations suggests that distant, unresolvable binary NSs create a significant astrophysical stochastic GW background (Abbott et al., 2018b), adding to the contribution from BH-BH and BH-NS binaries. In addition to compact binary coalescences of BHs and NSs, rotating NSs, magnetars, and core-collapse supernovae can all contribute sub-dominant stochastic backgrounds (e.g., Owen et al., 1998; Ferrari et al., 1999; Buonanno et al., 2005; Regimbau and de Freitas Pacheco, 2006; Regimbau, 2011; Rosado, 2012; Renzini et al., 2022). Overall, the ability to detect and subtract GW foregrounds, and to detect sub-dominant stochastic backgrounds, is critical to unveil potential new avenues for MMA using stochastic GW signals (e.g., Biscoveanu et al., 2020a; Sachdev et al., 2020b; Sharma and Harms, 2020; Mukherjee and Silk, 2021; Zhou et al., 2022; Bellie et al., 2023; Zhong et al., 2023).

4 Discussion

As discussed in Section 2.1, going from one GW170817-like event to ~ 10 well-localized NS-NS mergers detected in GWs and enjoying extensive electromagnetic follow-up represents a goal of the utmost importance for the current generation of ground-based GW detectors. It is also critical that the observational resources required to carry out a systematic electromagnetic follow up of NS-NS and BH-NS systems remain available. In fact, in the case of GW170817, observations from radio to γ -rays involving space-based and ground-based detectors with field of views (FOVs) ranging from tens of square degrees to a fraction of a square degree (Abbott et al., 2017e, and references therein), all proved essential to shed light on the different ejecta components (from the slow neutron-rich debris powering the kilonova to the structured jet emitting from radio to X-rays; e.g., Burns, 2020; Margutti and Chornock, 2021, and references therein). Going forward, it is clear that the more GW detectors improve their localization capabilities, enabling deep follow-up observations across the electromagnetic spectrum with instruments of different FOVs (Figure 7), the larger the impact of new GW detections on the field of MMA.

Improvements in sensitivity to ground-based GW detectors will enable us to reach a GW localization accuracy of $\sim 10 \text{ deg}^2$ (matched to the field of view of the Vera C. Rubin Observatory, hence greatly simplifying the hunt for kilonovae; Ivezić et al., 2019; Andreoni et al., 2022; Gupta et al., 2023b; Figure 7) for hundreds to thousands of NS-NS mergers per year with median redshifts of $z_{\text{median}} \approx 0.15$ for networks containing three 4 km-long LIGO detectors at sensitivities comparable to that of the so-called A# configuration (the ultimate performance of current LIGO detectors envisioned for the post-O5 era; Fritschel et al., 2023); $z_{\text{median}} \approx 0.2$ for networks containing at least one next-generation GW detector (with sensitivity $\sim 10 \times$ that of the LIGO detectors in their projected O5 configuration); and up to a $z_{\text{median}} \approx 0.6$ for an international network with three next-generation GW detectors. A network of ground-based GW detectors including one (three) next-generation instrument(s) could enable localizations of tens (hundreds and up to $\sim 10^3$) of nearby NS-NS mergers per year to $\lesssim 1 \text{ deg}^2$ (Figure 7; see also Evans et al., 2023; Gupta et al., 2023a). This, in turn, will allow sensitive tiling observations of the GW error regions

with radio (and X-ray) telescopes (such as the ngVLA), as well as IR telescopes (such as Nancy Grace Roman Space Telescope; McEnery, 2019), independently of a previous identification of an optical counterpart via larger FOV optical telescopes. This capability is likely to prove critical to probe the higher-mass NS-NS and BH-NS systems that may be characterized by red and dim kilonovae, but still be accompanied by (potentially off-axis) radio-to-X-ray jet afterglows (Chase et al., 2022; Gupta et al., 2023b; Andreoni et al., 2024).

It is fundamental to realize that the same improvement in sensitivity that enables GW detectors in a network to localize nearby compact binary mergers to exquisite accuracy (as discussed above), also enables such detectors to see farther compact binary merger events extending the reach of MMA to higher redshifts (see Sections 2.2, 2.5, 2.6 and Figure 7), as well as to unveil new sources of GW emission (see Sections 2.1, 2.4, 2.3, and 3). Indeed, as evident from the maximum redshift in the distributions in Figure 7, only networks of next-generation detectors can extend the reach of GWs to the peak of star formation ($z \approx 1-2$) for GW events localized to $\lesssim 10 \text{ deg}^2$. Space missions such as *Fermi* and *Swift*, Roman, and future NASA programs focused on the transient and time-variable Universe, are key to ensure continued progress in the electromagnetic follow-up of these events (National Academies of Sciences, Engineering, and Medicine, 2023; Sambruna et al., 2023). From the ground, the Rubin Observatory, the Extremely Large Telescopes, and the ngVLA will provide follow-up capabilities for GW events that are key to enable MMA to reach its full potential over the next decade and beyond (Beasley et al., 2019; Chornock et al., 2019; Corsi et al., 2019; Lazio et al., 2019; Murphy et al., 2023; National Academies of Sciences, Engineering, and Medicine, 2023). The IceCube-Generation 2 neutrino observatory will help constrain emission models for high-energy neutrinos in nearby NS-NS mergers and potentially open the way for discoveries across three different messengers (Aartsen et al., 2021; National Academies of Sciences, Engineering, and Medicine, 2023; Mukhopadhyay et al., 2024). Multi-band GW data sets formed with the LISA space-based GW detector can also impact MMA studies of compact binary mergers (see Sesana, 2016; Vitale, 2016; Amaro-Seoane et al., 2023, and references therein).

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AC: Writing-review and editing, Writing-original draft, Project administration, Funding acquisition, Conceptualization. LB: Writing-review and editing, Writing-original draft. EB: Writing-review and editing, Writing-original draft. ME: Writing-review and editing, Writing-original draft. IG: Writing-review and editing, Writing-original draft. KoK: Writing-review and editing, Writing-original draft. KeK: Writing-review and editing, Writing-original draft. AN: Writing-review and editing, Writing-original draft. BO: Writing-review and editing, Writing-original draft. BR: Writing-review and editing, Writing-original draft. Jocelyn Samantha JR: Writing-review and editing, Writing-original draft. BS: Writing-review and editing, Writing-original draft. DS: Writing-review and editing, Writing-original draft.

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Conflict of interest

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How do nuclear isomers influence the gamma-ray bursts in binary neutron star mergers?

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Neutron star mergers are astrophysical “gold mines,” synthesizing over half of the elements heavier than iron through rapid neutron capture nucleosynthesis. The observation of the binary neutron star merger GW170817, detected both in gravitational waves and electromagnetic radiation, marked a breakthrough. One electromagnetic component of this event, the gamma ray burst GRB 170817A, has an unresolved aspect: the characteristics of its prompt gamma-ray emission spectrum. In this work, we investigate that gamma-ray spectra in such GRBs may be influenced by de-excitations from isomeric transitions. Our study begins with a review of current knowledge on GRB structure and of r-process nucleosynthesis in neutron star collisions, focusing on the role of nuclear isomers in these settings. We then test our hypothesis by developing criteria to select representative isomers, based on known solar element abundances, for modeling GRB spectral characteristics. We integrate these criteria into an interactive web page, facilitating the construction and analysis of relevant gamma-ray spectra from isomeric transitions. Our analysis reveals that three isomers— ^{90}Zr , ^{207}Pb , and ^{89}Y —stand out for their potential to impact the prompt GRB spectrum due to their specific properties. This information allows us to incorporate nuclear isomer data into astrophysical simulations and calculate isomeric abundances generated by astrophysical r-processes in neutron star mergers and their imprint on the detected signal.

KEYWORDS

binary neutron mergers, gamma-ray bursts, rapid neutron capture nucleosynthesis, nuclear isomers, isomeric transition

1 Introduction

The collision of two neutron stars injects massive amounts of matter at high energy into the surrounding environment and release an enormous amount of energy that can be detected as gravitational waves and light, emitted across the electromagnetic spectrum on various timescales (Friedman and Stergioulas, 2020).

The first detection of gravitational waves (GW) from a binary neutron star (BNS) collision, named GW170817 (Abbott et al., 2017a), was accompanied by a weak, off-axis γ -ray burst (GRB 170817A) (Abbott et al., 2017b), matter outflow (Moharana and Piran, 2017) and an optical-to-infrared transient (AT2017gfo), called a kilonova (Arcavi et al., 2017), that emitted a broad array of electromagnetic (EM) radiation (Nakar et al., 2018), in accord with the predictions for radioactive decay of elements. Analysis of the data gathered from this collision provided us with a wealth of new insights into many yet unknown aspects of a neutron star (Potekhin, 2010), such as its internal structure and radius (Abbott et al., 2018), the amplification of the magnetic fields during merger (Abdalla et al., 2020), and the

outflow of matter during the collision process (Wu and MacFadyen, 2018). Further theoretical studies of this twin detection in GW and EM radiation allowed scientists to identify for the first time an element heavier than iron, namely strontium (Watson et al., 2019), thus confirming BNS mergers as sites where heavy elements are formed (Hotokezaka et al., 2018). These discoveries established neutron star mergers as veritable “gold mines,” because more than half of all the elements heavier than iron can be forged in the collision (Nedora et al., 2021) through the rapid-process (r-process) nucleosynthesis, the dominant mechanism through which neutrons are promptly captured by seed nuclei to build up heavier elements before they radioactively decay (Cowan et al., 2021).

The detection of the accompanied GRB 170817A signal (Goldstein et al., 2017; Savchenko et al., 2017) also unambiguously confirmed compact binary mergers as sources of gamma-ray bursts (GRB) (Beniamini et al., 2019; Wu and MacFadyen, 2019). However, one of the puzzling questions that still remains is the mechanism of the highly collimated short GRB (Kisaka et al., 2018; Nathanail, 2018; Matsumoto et al., 2019).

During the collision, a large amount of highly relativistic matter is projected outwards, along the axis of rotation. These particles are trapped, collimated and accelerated to near-light speed by strong magnetic fields amplified during the merger, and are carried to long distances, spanning entire galaxies. In their travel, these particles might convert kinetic energy into γ -ray (EM) energy through synchrotron emission, inverse Compton processes and dissipation due to internal shocks. Although great strides have been made in understanding the nature of GRB emission, one open issue remaining is the interpretation of the radiative mechanisms responsible for the prompt GRB spectrum. At the beginning, the γ -ray energies have a different origin than the synchrotron radiation, suggesting that a more complex model is required to fit the data. This emission might contain as well γ -ray photons from nuclear decay of the heavy elements produced in the ejecta (Janiuk, 2014). The heavy nuclei produced in this outflow of matter by the r-process nucleosynthesis are stripped of electrons, and many of them are unstable. While still in excited nuclear states, some of these nuclei can be trapped by the strong magnetic field and beamed to high velocities. The radioactive decay of these unstable isotopes will release nuclear energy in form of γ -ray, neutrino and particle products in the jet. While the neutrino will escape freely, the electrons will annihilate with the positrons, and the other particles will be thermalized through collisions, Coulomb forces and inverse Compton scattering, producing additional γ -rays.

A portion of these newly formed, highly excited heavy isotopes will be in isomeric, metastable nuclear states with lifetimes long enough to enable them to be distinguished from other nuclear states. The nuclear isomers that retain their metastable characteristics in highly energetic astrophysical environments such as BNS mergers are called astromers (Misch et al., 2021a) and may play a significant role in determining not only the abundance of the elements in the Universe (Misch et al., 2021b), but also the spectral appearance of GRBs from such events. Scientists have started to consider the influence of astromers in the r-process nucleosynthesis in connection with the light-curve of the EM signal from the ejecta of BNS mergers (Reifarth et al., 2018; Si and Ma, 2020). However, this aspect is still in its infancy, and none has explored their connection to GRB γ -ray emission.

One aspect that remains unexplained is the non-thermal γ -ray spectrum of the prompt emission. Our research aims to bridge this gap by investigating whether γ -ray de-excitations from isomeric transitions of excited nuclei created in the r-process nucleosynthesis during BNS mergers can contribute to the spectrum of the GRBs associated to these events. An accurate understanding of this γ -ray emission through isomeric transition is challenging because we have limited knowledge of the nuclear physics that operates the r-process nucleosynthesis of heavy elements during a BNS collision in the presence of isomers. Similar to the stable elements, isomers are thought to conglomerate around the “magic numbers” of neutron shell closure and can lead to a change in the elemental abundances produced in nucleosynthesis, or even influence the path of the nuclear reactions (Misch et al., 2021c). Our endeavor to connect isomeric γ -ray de-excitations with the observed GRB spectrum is feasible, although ambitious. To calculate the emission from such transitions, we must know the species of nuclides inside the merger ejecta, and their abundances. Moreover, the fate of the γ -ray photons generated through isomeric decay will be sensitive to the thickness of the ejecta, and will be affected by superpositions with the γ -rays generated through fission, annihilation radiation, synchrotron emission and thermalization, as well as by the line broadening caused by the Doppler effect during the relativistic expansion of the jet.

Our paper is organized as follows: we begin with a discussion on GRB properties, and continue with introducing known facts about the r-process nucleosynthesis in BNS collisions, as well as the concept of isomeric transition. We continue with presenting our compilation of the relevant isomeric elements likely to be created during the r-process, from Garg et al. (2023). We explain our criterion of selecting representative isomers, accounting for the typical time of the r-process, the time necessary for the jet to form and break through the ejecta surrounding the merger, and the time of the GRB burst. We carefully cross-correlate the identified isomers with the cosmic abundance of elements observed in the Solar System (Lodders, 2019) and estimate the number of isomers created relative to the number of baryons in the ejecta. We implement our selection criteria in a Python program embedded into an interactive web page, accessible as an open-source shareable data application. We analyze this data, constructing a set of relevant γ -ray spectra and light-curves associated with the most promising isomers. In a later work, we will refine our model and will compare our results with GRB170817A as well as with other GRBs thought to have originated from double neutron star mergers.

Our new connection between the GRB emission from known astrophysical sites of r-process nucleosynthesis such as BNS mergers and the γ -ray signature of isomeric transition might be a step forward towards explaining spectral features in past and future GRB detections from compact sources. The information we provide can be also incorporated into detailed astrophysical simulations, in order to calculate with accuracy the characteristic isomeric abundance produced by BNS collisions and to generate light curves that can be then validated by comparison with detected GRB data. This is just the beginning and much remains to be learned about the impact of isomers on the creation of heavy elements in astrophysical nucleosynthesis r-processes and on the physics of GRB. Our study could contribute to the elucidation of the intriguing mechanism behind the spikes in the spectrum of the GRB. Although besides

strontium, there is currently no reported detection of elements created during BNS mergers in the light curves from GRB 170817A (Savchenko et al., 2017), future combined GW/GRB detections, with more sensitive instruments, will occur. These detections will be needed to elucidate the mechanisms behind γ -ray emission in the GRB spectrum, and distinguish the role played by isomeric transition, thus validating or disproving our hypothesis.

2 GRB structure

Gamma ray bursts (GRBs) have been a focal point of research since their initial observation in 1973 by the Vela satellite (Klebesadel et al., 1973). It is agreed that their γ -ray emission follows roughly the same pattern, starting with a short, spectrally hard burst, followed by a longer tail of spectrally softer emission, and ending with a long-lasting multi-wavelength afterglow (Li and Paczynski, 1998; Lamb et al., 2022). Despite the detection of over 12,000 GRBs since their discovery, and extensive research on this topic, the jet formation mechanism remains elusive (Burns and Fryer, 2023; Valverde et al., 2023).

Based on the observed time frame of the γ -ray emission, astronomers have categorized GRBs in two groups: long (> 2 s) and short (< 2 s) bursts. The short-duration GRBs are considered to originate when two compact objects merge, while long GRBs could result from a collapsing massive star, or supernova. However, recent discoveries of long-duration bursts such as GRB 211211A (Mei et al., 2022; Rastinejad et al., 2022) and GRB 230307A (Dai et al., 2023) show evidence that they are consistent with the detection of an associated kilonova. Their spectra present extreme variability, flares and quasi-periodic substructure, characteristic to the formation of a neutron star remnant prior to the final collapse (Chirenti et al., 2023; Most and Quataert, 2023; Veres et al., 2023). These discoveries point towards a new class of long GRBs originating from mergers of neutron stars.

The mainstream explanation of the GRB engine is centered on the Blandford-Znajek mechanism. This theory requires the existence of a black hole (BH) surrounded by an accretion disk. The accretion disk supports large-scale aligned magnetic fields, which thread through the central black hole. This magnetic field extracts spin energy from the black hole, directing it into a low-mass jet, and accelerating it to relativistic speeds (Blandford and Znajek, 1977). Numerical simulations do report that during the collision of two neutron stars, the jet is formed after the remnant collapses to a black hole (Pavan et al., 2021). An alternative explanation for the GRB engine is a fast-spinning, strongly magnetized neutron star, called a magnetar, that can dump its rotational energy into the Poynting flux, who transports the energy of the magnetic fields in form of electromagnetic radiation from the star to the jet. This mechanism could accelerate a small amount of matter to very high energies, producing the relativistic jet. Indeed, other numerical simulations prove that magnetars formed as remnants of BNS mergers are viable engines able to launch GRBs and power kilonovae (Salafia et al., 2019; Mösta et al., 2020).

The current understanding of GRB production involves a compact star (either a magnetar or a black hole with an accretion disk) generating a large amount of highly relativistic particles. These particles extract energy from the compact object through

the Poynting flux, carrying them over large distances. During their travel, the stream of particles become optically thin and might experience shocks, and convert their kinetic energy into internal energy. The observed γ -rays are subsequently emitted through synchrotron radiation or inverse Compton processes when relativistic electrons are being accelerated in magnetic fields (Salafia et al., 2019; Burgess et al., 2020).

The GRB 170817A jet was detected at $t_0 = 1.75$ s after the peak in the GW signal, and lasted around $t_j = 2$ s, starting with an initial spike in γ -ray energy of about 0.5s, followed by a broader and less intense tail (Burgess et al., 2020). Its γ -ray emission was less luminous than known short-duration GRBs, leading scientists to infer that the emission was off-axis (He et al., 2018), and subsequently scattered while passing through the merger ejecta, with a peak in photon energy of about 5MeV and a narrow half-opening of $\approx 2.1^{+2.4}_{-1.4}$ degrees, viewed at an angle of 23^{+5}_{-3} degrees (Cao et al., 2023; Hayes et al., 2023; Salafia et al., 2023). This model classified GRB 170817A as a typical short GRB, favoring a quasi-universal jet structure, with the differences being caused by extrinsic factors, such as density of the particles in the jet, viewing angle or interaction with the surrounding medium (Salafia et al., 2019).

Numerical simulations showed that the time delay between the merger and the start of the jet was due to 1) the time necessary for engine activation and 2) the time for the jet to break out of the surrounding environment (Pavan et al., 2021). After a careful examination, it was shown that the time delay should include three terms, namely 1) the time to launch the jet, 2) the time for the jet to break out from the surrounding medium and 3) the time to reach the emission site. The fact that the time delay for GRB 170817A correlates with the pulse duration was interpreted to indicate that the time delay is dominated by the duration for the jet to travel to the emission radius, estimated to be at large distance ($\approx 10^{15}$ cm) from the progenitor (Zhang, 2019). As consequence, the time delay cannot be used to diagnose the jet launching mechanism.

In this model, the γ -rays are produced far away from the engine, in the circumstellar region populated by the outflow of gas ejected during the merger, driven by magnetic fields. The radiation was released from a broad outflow with a large opening angle, and subsequently collimated, partly by the large-scale, ordered magnetic field, and partly due to the ultra-relativistic motion of the particles in the jet (Cao et al., 2023). Relativistic outflows are strongly beamed, such that the observer sees only the beaming angle, proportional to $1/\Gamma$, where Γ is the Lorentz factor, a measure of the relativistic effects experienced by objects moving close to the speed of light. The estimated values for the Lorentz factor of the bulk matter in the jet are very large, between 100 and 1,000 (Ravasio et al., 2023). Particles accelerated to such relativistic speeds possess extremely high energy and emit synchrotron radiation in strong magnetic fields.

Nonetheless, many GRB spectra deviate from the expectations of this synchrotron emission. For example, the light-curves of the prompt emission are irregular. One of the hypothesis is that this variability is due to internal shocks (Kisaka et al., 2018; Salafia et al., 2019; Lazzati, 2020). Relativistic jets can generate shock waves because the inner engine produces inhomogeneities, and shells of particles in the jet travel at different velocities. However, the internal shock model of GRBs is inefficient in converting the kinetic energy of the particles in the jet into γ -ray radiation, known as the “low-efficiency problem.” This was replaced with a model in which a

“fireball,” moving at a relativistic speed, is launched by a fast-rotating black hole or magnetar. In this case, the internal shocks are supplemented with the external shock mechanism (Piran, 1999; Beniamini et al., 2016; Cao et al., 2023). Because the velocity of the particles in the jet is larger than the speed of sound, the beamed ejecta will form a cocoon when it plows through the surrounding medium and this interaction modulates the synchrotron radiation (Gottlieb et al., 2018). The jet and cocoon combination forms a “structured” jet, which avoids the underlying mechanism. A structured jet has a uniform, ultra-relativistic core, surrounding by a power-law decaying wind, forming a two-jet component, with a relativistic core and a slightly slower outer jet (Salafia and Ghirlanda, 2022). To explain photon energies greater than 10 GeV, this double-jet picture is modified into a narrow, off-axis jet with a high Lorentz factor, and a wide, on axis jet with a small Lorentz factor, the interaction between them forming reverse shock regions that could explain the GeV flares observed in some GRBs (Fraija et al., 2023a).

This way, a unified picture of both short and long GRBs from compact binary mergers emerges, based on a structured jet launched by a common central engine, which avoids the underlying mechanism (Kasliwal et al., 2017; Gottlieb et al., 2023). The peak luminosity distribution of the long and short GRBs could be also fitted to a triple power law, implying that both types of GRBs could be produced by the same mechanism (Fraija et al., 2023b; Li et al., 2023). But if indeed the γ -ray emission took place in an optically thin region, far away from the central engine, the shock emission components are suppressed, and some other mechanisms may be at play (Ravasio et al., 2023). For example, recent simulations show that before the emergence on the jet from the neutron star remnant formed after the BNS merger, a UV/blue precursor signal is generated, that can “seed” the ultra relativistic GRB jet (Combi and Siegel, 2023).

Spectral data alone might not be enough to discern between various models and to assess their viability. Polarization measurements of the GRB prompt emission, in principle, have the potential to address many of these questions. However, such measurements have only been obtained for a limited number of bursts and thus have limited statistical significance (Wang and Lan, 2023). Looking ahead, joint detections of GW/GRB events, coupled with polarization data from the accompanying GRB, will help understand these astrophysical phenomena.

3 r-process nucleosynthesis and isomers

The r-process consists of a series of reactions in which nuclei capture neutrons rapidly, leading to the creation of heavy elements. This process is believed to occur at high temperatures, in extremely neutron-rich environments. While the r-process was long associated with supernovae, recent studies indicate that BNS mergers, with their more neutron-rich environments, are likely the predominant sites for heavy r-process element production (Just et al., 2015; Perego et al., 2021; Rosswog and Korobkin, 2022). More than half of the heavy elements found in nature are produced through the r-process, some elements forming exclusively or almost so by this mechanism (Cowan et al., 2021). The detailed pathways of producing these heavy elements are still unsettled (Pogliano and

Larsen, 2023) and the lack of confidence in the neutron capture rate predictions makes the calculation of final abundances in the r-process difficult (Kajino et al., 2019).

The r-process operates in two distinct phases: an initial period in which neutron captures dominate, and a subsequent state characterized by β -decay, leading to the creation of new elements with increasingly heavier proton numbers. The timescale for neutron capture is significantly faster than that of β -decay. Neutrons are absorbed rapidly until a statistical equilibrium is reached, a point known as “neutron drip line,” where neutron separation energy becomes zero. Here, a neutron shell closure is reached, known as “freeze-out,” where rapid neutron capture ceases (Just et al., 2015). This occurs when the neutron-rich environment becomes depleted, and the neutron capture rate drops significantly. At this stage, the nucleus is no longer able to capture neutrons effectively, marking the end of the rapid neutron capture phase and leading to a shift towards β -decay, where neutrons in the nucleus transform into protons, creating new elements. These nuclei, formed post freeze-out, act as seeds for subsequent r-processes, continuing to capture neutrons and forming increasingly heavy nuclei. “Kinks” in the r-process occur at neutron number shell closures, specifically around $N = 50, 82$, and 126 . At these points, nuclei are more stable and resist further neutron capture, leading to an accumulation of material. These kinks influence the distribution of elements produced in the r-process, leading to observable patterns in the abundance of elements. The r-process culminates at the “magic number” $N = 184$, that marks the third r-process peak, signaling the completion of neutron capture and β -decay. This happens at about $t_r = 1.34$ s since the beginning of the process, when unstable elements with large atomic mass, $A \approx 240$, are created (Eichler et al., 2015). This instability leads to fission, where the heavy nuclei split into smaller ones, typically in the $A < 140$ range, releasing additional neutrons and a significant amount of energy, detected as observable electromagnetic emission associated with neutron star mergers.

The r-process produces a variety of heavy elements, in agreement with the Solar System abundance. Within the energetic collision environment of BNS mergers, a diverse range of conditions leads to various nuclear nucleosynthesis products. Extremely high densities favor the formation of heavy nuclei, while high temperatures tend to produce lighter nuclei. During the coalescence phase, matter is dynamically ejected due to angular momentum conservation within milliseconds, moving at mildly relativistic speeds. This tidal ejecta, dense and moderately heated, retains its original low electron fraction, facilitating the “strong” r-process nucleosynthesis leading to heavier elements (Just et al., 2015). The production of heavy elements in this ejecta competes with its rapid expansion, that reduces the neutron density and temperature. During collision, temperatures reach values high enough to dissociate nuclei into free nucleons, and neutrinos become the primary cooling mechanism. At this point, amplified magnetic fields and neutrino winds eject neutron-rich material along the rotation axis, potentially enhancing the production of heavy elements that can be trapped in the jet (Perego et al., 2014; Shibata and Hotokezaka, 2019). The remnant formed after the merger acquires a neutron rich accretion disk, heated to high temperature by friction and irradiation with neutrinos, favoring the continuation of the r-process (Curtis et al., 2022).

Considering all components—dynamic ejecta, neutrino winds, and outflows from accretion disks—compact binary mergers produce the heaviest r-process nuclei, contributing significantly to the solar r-process abundance (Fujibayashi et al., 2023). The early dynamic ejecta, emerging from the spiral arms, stay very neutron rich and lead to strong r-processes, while the late ejecta will produce weaker r-processes. Simulations suggest that the mass ratio of the binary affects the range of elements produced, leading to variations in the r-process products across different events (Pogliano and Larsen, 2023; Ristić et al., 2023). If the magnetic field is amplified to large values, it will drive winds toward the disk, enhancing the production of heavier elements. These studies also show that the outflow from the remnants can produce a blue kilonova, indicating the presence of heavy elements (Curtis et al., 2024). Observations of kilonovae suggest also that the amount and distribution of r-process products can differ from event to event (Gompertz et al., 2018). As astrophysical models of compact binary mergers become more sophisticated and our understanding of neutron-rich nuclei improves, we move closer to accurately predicting the variety and abundance of heavy elements produced in these cosmic events, shedding light on their contribution to the universal abundance of elements (Banerjee et al., 2020; Perego et al., 2021; Rosswog and Korobkin, 2022; Kobayashi et al., 2023; Ristić et al., 2023).

Predictions indicate that γ -ray emissions from neutron star mergers might include photons from the radioactive decay of heavy isotopes produced in the r-process (Li, 2019; Gillanders et al., 2023). Those isotopes can find their way in the GRB jets, carried by neutrino cooling winds and by the magnetic field (Fujimoto et al., 2004; Janiuk, 2014; Janiuk, 2019). They can power the γ -ray bursts and extend the plateau of their γ -energy emission (Ishizaki et al., 2021). Direct measurements of these photons could potentially serve as a probe for the r-process nucleosynthesis (Korobkin et al., 2019; Terada et al., 2022). This must be supplemented with more robust knowledge of the properties of exotic, neutron-rich nuclei to reduce present nuclear uncertainties, that make it difficult to definitely measure the distribution of heavy isotopes (Sun et al., 2005).

The GW170817/GRB 170817A/AT2017gfo event was identified as a site of r-process nucleosynthesis, observed in the kilonova's electromagnetic spectrum (Hotokezaka et al., 2018; Domoto et al., 2021). Although the r-process nucleosynthesis was confirmed by the observations of this event, no trace of individual elements has been identified, except for strontium (Watson et al., 2019). The high density of the spectroscopic lines of the photons expected to be emitted during the r-process, together with the large velocity of the material ejected during the collision produces line blending and smooths the spectra. This uncertainty complicates the accurate quantification of the heavy element abundances associated with a GRB (Gillanders et al., 2023). Nuclear data is essential to predict the specific elements that are created in an observed astrophysical environment, and to connect observed abundances and kilonova features to astrophysical conditions and constraints on the nucleosynthesis sites (Terada et al., 2022).

Isomers, which are metastable excited states of the same atomic nucleus, can significantly influence γ -ray emission, and not accounting for them may lead to underestimations of the emission (Chen et al., 2021). If the corresponding lifetimes are of the same order of magnitude as the timescales of the environment, isomers must be treated explicitly (Reifarth et al., 2018). In the energetic

environment of the collision, isomers may either accelerate their decay, slow it down and act as energy storage, or remain unaffected in their half-life (Misch et al., 2021a; Misch et al., 2021b; Misch et al., 2021c). Particularly, isomers could contribute to the early, blue component of kilonova emissions, as observed in GW170817 (Si and Ma, 2020), potentially allowing outflow towards heavier masses via isomeric branches (Sun et al., 2005). Near the magic numbers $A \approx 80, 130, 195$ marking the “waiting point” where the r-process temporarily slows down, the excitation energy and the number of isomers increase (Garg et al., 2023). As a result, these points accumulate a higher concentration of nuclei, including isomeric states, that become preferentially populated at these three main peaks of the r-process (Sun et al., 2005; Sun, 2008). An important question to answer is how do isotopes reach the isomeric excited state, because promoting nucleons to excited states is hindered due to nuclear recoil (Mossbauer effect, Jain et al., 2021). To achieve excitation, the energy of the γ -ray photon must exceed the transition band energy. Isomer activation can occur either through the capture of higher-energy γ -ray photons or via nuclear excitation through thermal excitation at high temperatures (Crawford et al., 2023; Misch and Mumpower, 2024). Moreover, when nuclei move at relativistic speeds, they can reach isomeric states by absorbing radiation in ultraviolet and X-rays (Budker et al., 2021). Internal conversion, involving the ejection of an inner orbital electron, competes with γ -ray emission, unless the nuclei are in a completely ionized state, a condition found in the atmosphere of the merger (Misch et al., 2021a).

Understanding these intricate nuclear processes in the astrophysical environment of a neutron star merger and their imprint in the emitted EM radiation from BNS mergers not only sheds light on the complex mechanisms of r-process nucleosynthesis but could also enhance our knowledge of GRB's γ -ray emission.

4 Methods

Although uncertainties persist in the r-process calculations and their dependency on the astrophysical environment, there is a general agreement that it occurs within a few seconds. Reference Eichler et al. (2015) indicates that at $t = 1.34$ s, the timescale for neutron capture exceeds that of β -decay, marking the end of the r-process. The γ -rays emitted following the r-process are initially trapped within the ejecta and can only be detected after they successfully diffuse through it (Barnes, 2020). Most of these photons transfer heat and become thermalized, losing their characteristic spectral information. However, the similar timing observed between the completion of the r-process ($t_r \approx 1.34$ s) and the delay in the γ -ray burst GRB 170817A ($t_0 = 1.75$ s) offers a compelling suggestion: the γ -ray emission from this event may include photons from the de-excitation of heavy elements formed via r-process nucleosynthesis, from parts of the ejecta exposed to the jet funnel.

It has been previously suggested that emissions from binary neutron star mergers may include gamma rays from nuclear decay (Wang et al., 2020). Additionally, it has been shown that β -decaying isomer states are more strongly populated than the ground states in stellar environments (Banerjee et al., 2018). We propose that a large fraction of these heavy elements is excited into isomeric states and subsequently ejected within the magnetically and neutrino driven

wind outflows from the jet engine, contributing to the collimated jet. This de-excitation process is likely to contribute to the γ -ray spectrum observed in GRBs. Thus, we put forth the hypothesis that a BNS collision serves as an efficient γ -ray “factory,” where the primary “raw materials” are the heavy isotopes in their isomeric states, synthesized through r-process nucleosynthesis within the highly energetic and neutron-rich environment of the ejecta. Their presence may be observed in the γ -ray emissions through distinct multipolarity signatures, influenced by the spin angular momentum carried by the radiation.

To test this hypothesis, we utilized the Atlas of Nuclear Isomers (Garg et al., 2023), a comprehensive database of experimental data for all known isomers to date. This resource includes known properties of each isomer, such as excitation energies, half-lives, decay modes, spins and parities, and energies and multipolarities of isomeric transitions. In our analysis, we processed over 2,500 isomers and identified which isotopes produced in the r-process are likely to have significant isomeric states that are relevant for γ -ray production, based on the following two initial criteria:

- We start by converting the digital database for the known isomers (Garg et al., 2023) from its original format into an Excel file to enable compatibility with Python.
- We focus only on heavy elements produced in r-process nucleosynthesis and limit our choice to isotopes heavier than iron, starting with an atomic mass number greater than 56.
- From these isomers, we select only those that decay via 100% isomeric transitions, because such decays are most relevant for γ -ray emission and do not alter the chemical properties.

Our next task was to determine the initial quantity of individual isotopes for each element produced and to correlate this value with the respective isomeric form. To achieve this, we relied on estimations of the various types of ejecta present in a neutron star collision (Fujimoto et al., 2004; Just et al., 2015):

- The early dynamic ejecta emerging from the tidal interaction of the merging neutron stars, typically ranges between $10^{-4}M_{\odot}$ and $10^{-2}M_{\odot}$, depending on the mass ratio and composition (Abbott et al., 2017c; Dietrich and Ujevic, 2017).
- The neutron-rich mass ejected along the rotational axis by the magnetized wind from the merger remnant, is estimated to about $3.5 \times 10^{-3}M_{\odot}$, based on an outflow mass rate of $0.1M_{\odot}/s$ (Perego et al., 2014; Nedora et al., 2021).
- The post-merger ejecta surrounding the remnant is calculated to be around $0.1M_{\odot}$ (Shibata and Hotokezaka, 2019; Fujibayashi et al., 2023).

To approximate the mass contributing to isomeric decay, we focused on the mass of the magnetized wind. Additionally, we incorporated a proportion of the mass from both the early dynamic ejecta and the post-merger outflow, that aligns with the jet. The exact angular distribution of the ejecta within the jet remains uncertain, varying with the parameters of the merger. However, the multi-wavelength afterglow of GW170817 suggests a stratified geometry of the ejecta, as indicated in (Lazzati et al., 2018). Models range from a top-hat to isotropic fireball geometry, but evidence increasingly supports a structured composition (Kasliwal et al., 2017; He et al.,

TABLE 1 The estimated fractions of each element created in merging neutron stars (Johnson, 2019).

Fraction	Element
0.25	Se, Br, Kr, Rb, Sr, Y, Zr, Nb, Sn, Ba, Ce, Tl, Bi
0.50	Mo, Pd, Cd, Te, La, Pr, Nd, Hf, Ta, W, Hg
0.75	Ru, In, Sb, Sm, Yb, Lu
1.00	Rh, Ag, I, Xe, Cs, Eu, Gd, Tb, Dy, Ho, Er, Tm, Re, Os, Ir, Pt, Au, Pb, Th, U

2018; Lazzati et al., 2018). The post-merger ejecta, which constitutes the majority of the material, is propelled primarily by the shock at the contact surface during the merger of the two neutron stars. Due to the accumulation of tidal ejecta near the equatorial plane of the binary, this outflow is predominantly directed along the polar axis (Salafia et al., 2018). Considering an isotropic ejecta as a starting point, with matter uniformly distributed around the merger site, the mass encompassed within the half-opening angle θ_0 corresponds to the fraction of the spherical surface area covered by the jet $A_j = \Omega r_0^2$, where $\Omega = 2\pi(1 - \cos\theta_0)$ is the solid angle of the jet’s cone and r_0 is the radius from the central engine at which the jet forms. Thus, the effective mass in the jet is:

$$M_{\text{eff}} = M_{\text{ejecta}}(1 - \cos\theta_0), \tag{1}$$

where M_{ejecta} is the ejecta mass. This formula takes into account that the jets emanate from both poles.

After calculating the quantity of material expected to influence γ -ray production in the jet, our next step is to calculate the initial number of isotopes. This involves the following steps:

- We rely on the atomic abundances and the mass fractions for the specific isotopic composition in our Solar System, as detailed in Table 9 of Lodders (2019). We start with the heavy elements that begin forming near the first peak of the r-process, around atomic weight $A = 80$, namely with strontium.
- We estimate the fraction of each element produced in merging neutron stars (see Table 1), based on Supplementary Table S1 in the Supplementary Material from Johnson (2019). A revised estimation is found in Busso et al. (2022).
- We calculate the quantity of baryons for each element, rescaled to the abundance of heavy elements baryons, assuming that neutron star collision produce mainly these heavy elements.
- We rescale this quantity back to only 10% of the matter in the jet assumed to be converted into heavy elements through the r-process (Abbott et al., 2017c).
- From the calculated number of baryons for each element produced via the r-process in the jet, we determine the number of atoms and the corresponding mass abundance, in terms of solar mass.
- We normalize the number of atoms for each element to the total number of atoms in the jet. This normalization eliminates the dependence on the effective mass, and will allow to simply scale

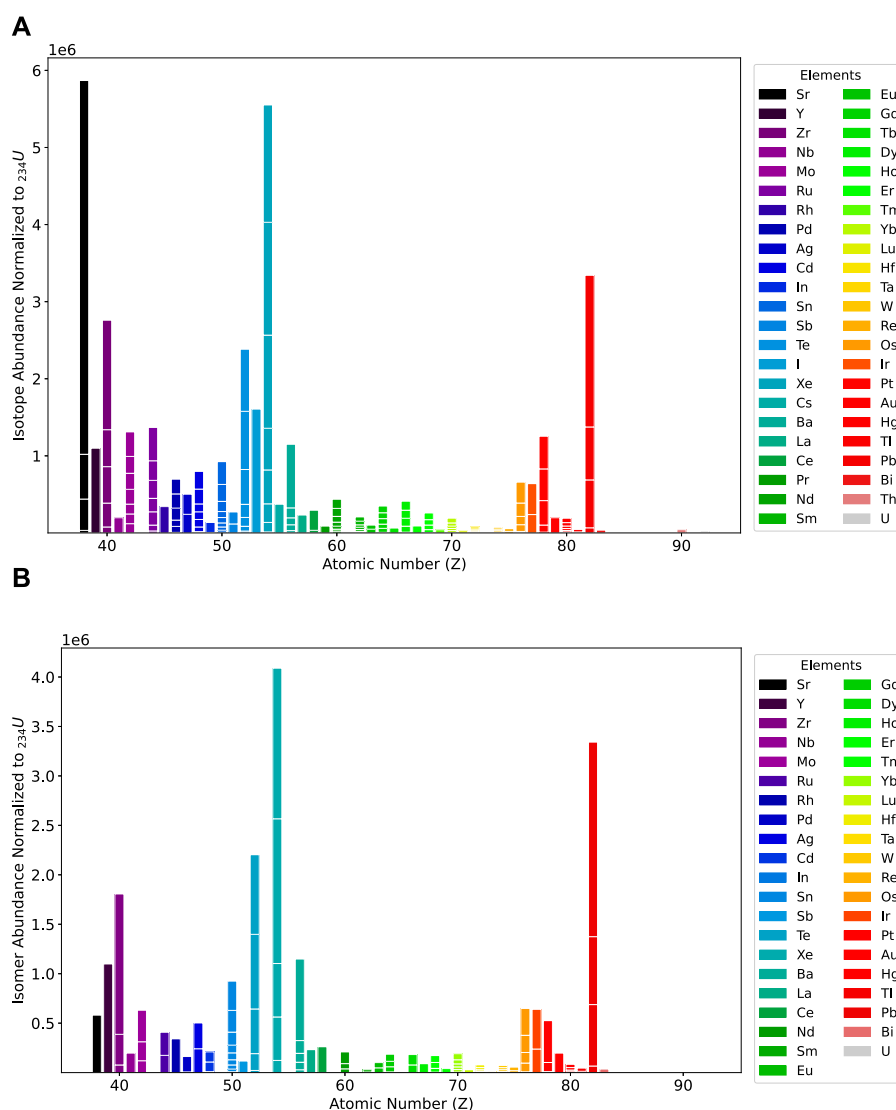


FIGURE 1

Abundances of heavy elements in BNS merger ejecta starting with strontium, plotted against atomic number Z , normalized to the lowest number of atoms ($^{92}_{234}\text{U}$), and stacked by atomic mass number. (A) Isotopes abundance per atom of ($^{92}_{234}\text{U}$) created in BNS merger ejecta. Note: vertical axis $\times 10^6$. (B) Isomer abundance per atom of ($^{92}_{234}\text{U}$) created in BNS merger ejecta. Note: vertical axis $\times 10^6$.

the contribution of each isotope to the γ -ray production in the jet.

- Lastly, we select among these heavy elements the atoms that admit the previously identified isomeric states, to obtain the type and number of isomers relevant for γ -ray production.

Research on mass ejection and nucleosynthesis in BNS mergers indicates that the temperature of the dynamical ejecta typically exceeds 10 GK (Fujibayashi et al., 2023), equivalent to approximately 0.86 MeV. Moreover, during the merger process, shock heating can generate temperatures as high as 100 MeV at the contact layer between the colliding stars. The collision dislodges neutron-rich material, which is subsequently carried into the jet by the neutrino cooling winds and magnetic fields from the polar region. The post-merger ejecta undergo heating due to temperature inversion caused by differential rotation, reaching temperatures

around 40 MeV. Isomeric states of the r-processes elements created in the ejecta of neutron star mergers could be populated due to these high temperatures, according to the Boltzmann distribution:

$$N_{i,0} = N_{\text{count}} e^{-\frac{\Delta E}{kT}}. \quad (2)$$

here, ΔE represents the energy difference between the isomeric and ground states, k is the Boltzmann constant, and T denotes the temperature of the ejecta. Besides nuclear excitation at high temperatures, the isomeric states can also be activated through absorption of γ -ray photons, or interaction with ultraviolet and X-rays, for nuclei moving at relativistic speeds. In a future work, after a more detailed analysis of the properties of the matter in the jet, we will refine the number of isomers at specific excitation energies.

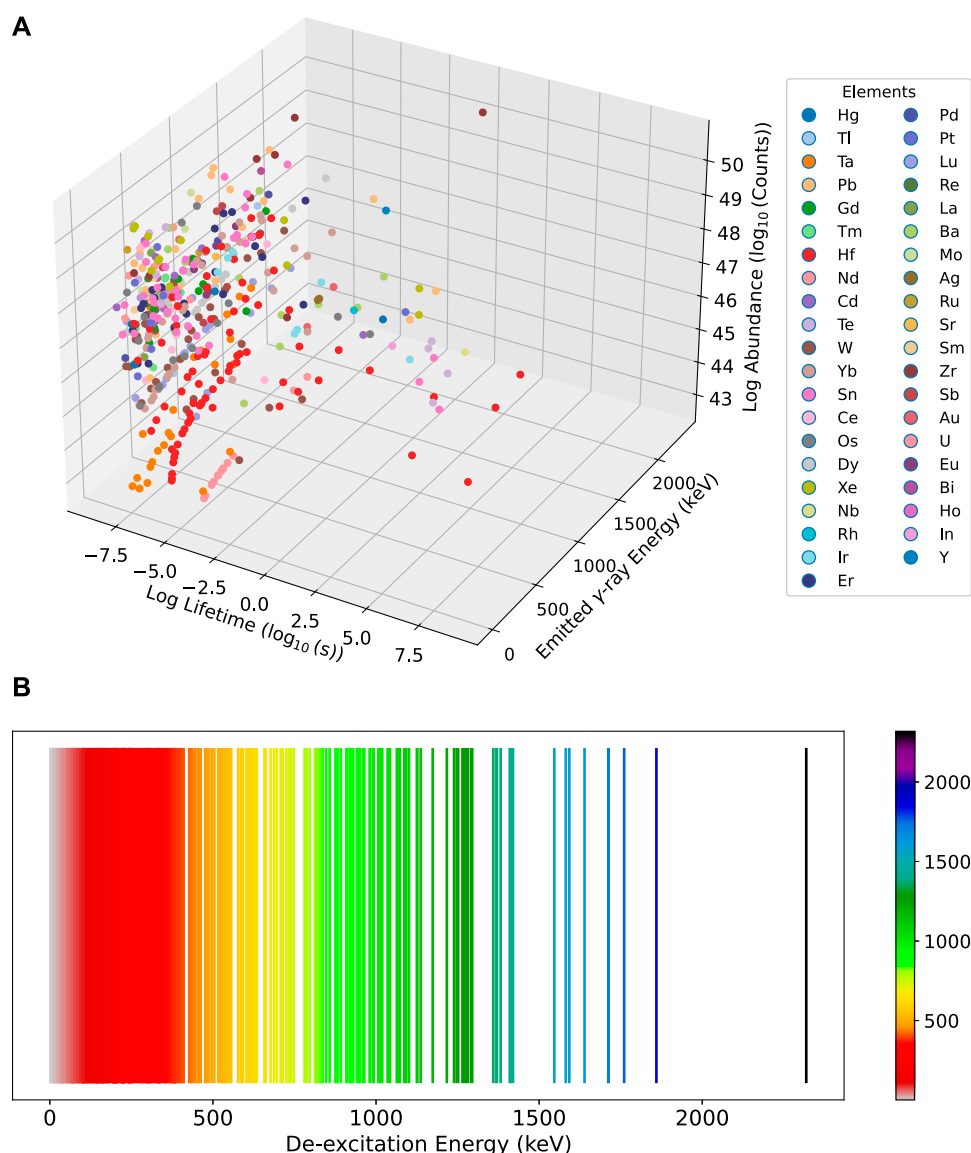


FIGURE 2

(A) Logarithmic abundance of isomers in the jet vs. logarithm of the lifetime ($T_{1/2}$) and the corresponding emitted E_γ . (B) The spectra of the emitted γ -ray radiation for all the isomers in the jet.

- In the cases where an isotope admits an isomer that has multiple decay pathways, the energy contribution from each decay is weighted according to the probability P_i of that specific pathway,

$$P_i = \frac{1}{N} \frac{E_{\gamma,i}}{\langle E_\gamma \rangle}, \quad (3)$$

where N is the total number of isomeric decays allowed for a particular isotope in isomeric state, i is the decay path, $E_{\gamma,i}$ the energy of the decay path, and $\langle E_\gamma \rangle$ the mean value of the energies. This

holds, because the probability of each decay path is proportional to its γ -ray energy (Garg et al., 2023).

- We calculate the number of γ -ray radiation events ΔN_i occurring within a chosen time interval Δt for each isomer identified, using the decay law:

$$\Delta N_i = N_{i,0} e^{-\lambda t} (1 - e^{-\lambda \Delta t}) \quad (4)$$

here, $\lambda = \ln(2)/T_{1/2}$ is the decay constant, with $T_{1/2}$ being the half-life of the isomer. We focus on isomers with terrestrial half-life between

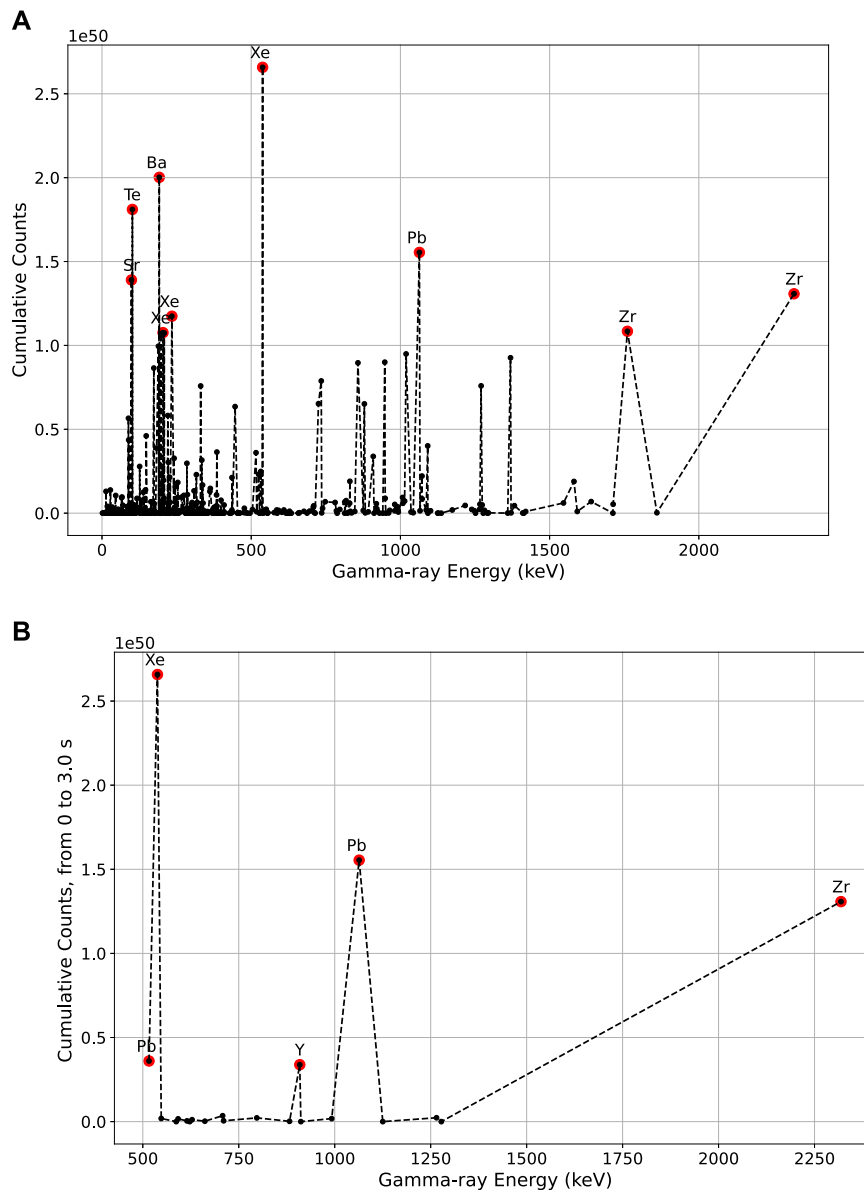


FIGURE 3

Isomer de-excitations spectra, represented as cumulative counts vs. γ -ray energy, $t \leq 3$ s. (A) Isomer de-excitations spectra for $t \leq 3$ s, with top elements highlighted. Vertical axis $\times 10^{50}$. (B) Selected isomer γ -ray spectra ($T_{1/2} \geq 10 \mu\text{s}$, $E_\gamma \geq 500$ keV). Vertical axis $\times 10^{50}$.

$t_0 - t_r \leq T_{1/2} \leq t_j$, assuming that the γ -rays emitted by isomeric de-excitation between the end of the r-process and the start of the jet will be reabsorbed.

- Finally, we combine the number of decays (or counts) ΔN_i for all the isomers within a given time interval to obtain the cumulative output from all isomeric decays for each specific de-excitation energy.

To construct the light curve that captures the contribution of isomeric γ -ray de-excitation to the temporal evolution of the GRB's intensity, we proceed as follows:

- For each isomer, we multiply the number of counts ΔN_i calculated with Eq. 4, by the γ -ray energy released per decay for consecutive time intervals, to obtain the evolution of the intensity in time, in increments of Δt .
- Then, we calculate the luminosity emitted for each time bin, by summing the emitted intensities for all the isomers and dividing by Δt .
- We calculate the specified emission area as $A = \Omega_j r^2$, where r is the estimated radius at which the jet is emitted, and its collimation angle is $\theta_j = (1/r)^p$, where $p \approx 0.22$ (Lloyd-Ronning et al., 2020).
- Lastly, we divide the luminosity calculated by the relevant area, to obtain the flux of γ -ray.

TABLE 2 The isomers within the selected criteria.

Fraction	Element	Lifetime (s)	Energy (keV)
206	Pb	1.25×10^{-4}	516.18
132	Xe	8.37×10^{-3}	538.2
89	Y	15.66×10^{-3}	908.96
207	Pb	0.805×10^{-4}	1,063.656
90	Zr	0.809	2,319

We have outlined the methods employed for building an interactive tool for analyzing data related to the complex process behind the contribution of isomeric transitions to the GRB spectrum, and to construct the light curve that captures the contribution of isomers to the temporal evolution of the GRB's intensity.

5 Results

To facilitate the data analysis of nuclear isomers with γ -ray emission relevant to GRBs, we developed an interactive web interface using Streamlit, an open-source Python library designed for creating shareable data applications. Our application, retrievable at <https://isomersearchengine.streamlit.app>, allows users to filter the data according to specific criteria through interactive sidebars. It also provides functionalities to plot relevant graphs and download the selected data for further analysis. This streamlined approach significantly enhances the efficiency and accessibility of our nuclear isomer data analysis tool.

We started our data analysis by estimating the amount of matter containing r-process elements that can contribute to the overall γ -ray decays occurring within the jets from neutron star mergers, a crucial quantity necessary to calculate the isotope count. We considered a jet of typical geometry, with an initial half opening angle of approximately $\theta_0 = 20^\circ$ when the jet forms (Dai et al., 2023). Using Eq. 1 with this value for θ_0 , we found that the effective mass in the jet is $M_{\text{eff}} \approx 6\% M_{\text{ej, ejecta}}$. In this case, the early ejecta contributes minimally, with a mass of maximum $6 \times 10^{-4} M_\odot$. The more significant contribution, of $6 \times 10^{-3} M_\odot$ arises from the post-merger ejecta. Therefore, adding the mass of the magnetized wind to the dynamic and post-merger ejecta expected to impact the jet, we obtain an effective mass $M_{\text{eff}} \approx 10^{-2} M_\odot$. This effective mass contains 1.2×10^{55} baryons, among which we assume that only 10% contribute to the formation of heavy elements (Abbott et al., 2017c). This approach allowed us to determine the amount of matter containing r-process elements that can contribute to the overall decay processes occurring within the jet. Our assumption is based on the premise that the ejecta is spherically-symmetric and that relevant γ -ray emission influencing the GRB's energetic output comes from the matter within this conical section of the jet. This model provides only an approximate estimate of the matter distribution within the jet. A detailed investigation of the matter distribution as a function of the angle, which is essential for a more precise understanding,

is beyond the scope of this study and will be the subject of future work.

We determine the initial number of isotopes in M_{eff} and select among these heavy elements the isotopes that admit isomers with 100% isomeric transitions, then calculate their abundance. Our analysis of the ejecta impacting the jet revealed that approximately 35% of the mass comes from the wind, about 5% originates from tidal interactions, and the remaining 60% is attributed to the outflow. Considering the different contributions to the ejecta and their respective temperatures, the average temperature of the ejecta is approximately $T = 59 \text{ MeV}$. We infer from Eq. 2 that for this average temperature, more than 96% of the heavy isotopes formed in the ejecta will have their isomeric energy levels populated. This provides only a rough estimate, because we did not account for the isomers activated through other processes. We mediate the number of isomers for each emitted γ -ray energy with the probability of de-excitation using Eq. 3.

We plot in Figure 1 the abundances of heavy elements, starting with strontium, as a function of the atomic number Z according to the predicted Solar System abundances, first for the isotopes (Figure 1A), and then for their corresponding isomers (Figure 1B). These are shown relative to the abundance of $^{92}_{234}\text{U}$, which has the lowest number of atoms ($^{92}_{234}\text{U} = 2.51662 \times 10^{44}$ atoms). The number of different isotopes for each Z is indicated within each bar, and the legend on the right lists the type of atoms. Strontium is the most abundant isotope, followed by xenon and lead, while in isomeric state only xenon and lead keep their contribution.

In Figure 2A, we present the abundance of isomers on a logarithmic scale, plotted against the emitted γ -ray energy and the logarithm of the de-excitation time, providing an intuitive overview of all the isomers created in a BNS merger ejecta. This is complemented by the complete de-excitation spectra shown in Figure 2B. We observe that the majority of isomers de-excite in less than (10 μs) and have their de-excitation energies below 500 keV. These emissions are likely reabsorbed by the medium within the jet, and are most likely not contributing to its overall energy budget. Observational data and models of GRBs indicate that the peak γ -ray energy ranges between 500 keV and 2 MeV. Consequently, isomers emitting within this energy range merit further investigation. In Figure 3A, we present the isomers energy spectrum as cumulative counts of de-excitations occurring within a time interval of 3s, highlighting all the isomers with the largest de-excitations counts, over 10^{50} . We note that $^{132}_{\text{Xe}}$, with a de-excitation energy of 538.2 provides the most substantial contribution to the overall emission. We further narrow down our selection to isomers with de-excitation times exceeding 10 μs and energies greater than 500 keV, and present them in Figure 3B, highlighting now the five isomers with the largest de-excitations counts. We list the identified isomers in Table 2, detailing their lifetimes, atomic mass number, and their emitted γ -ray energies.

We proceed to illustrate in Figure 4A the γ -ray intensity emitted over time, by the de-excitation of the five isomers selected, from 0 to 3s, calculated as $\text{Intensity}(t) = E_\gamma \times \text{Counts}(t)$. We observe minimal intensity contribution from the $^{206}_{\text{Pb}}$ isomer, while $^{132}_{\text{Xe}}$ peaks around $t \approx 5 \text{ ms}$ before steeply declining. Both of these isomers have de-excitation energies around 500 keV. Factoring in the electron-positron annihilation process, expected to be frequent within the

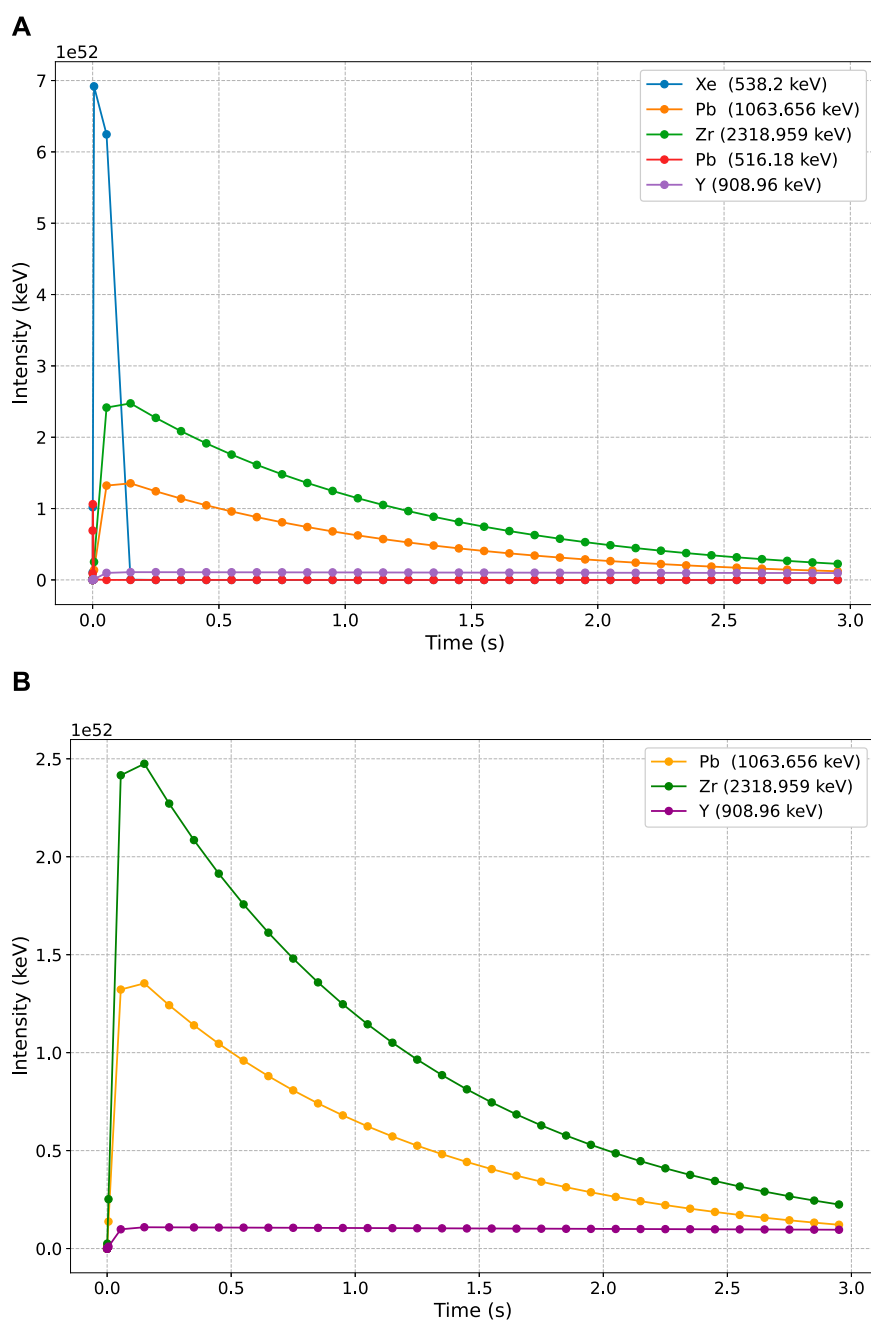


FIGURE 4

Evolution of the emitted γ -ray intensity, for the isomers relevant to GRBs, up to $t \leq 3$ s. **(A)** Evolution of the intensity for top 5 isomers, with $E_\gamma \geq 500$ keV. Vertical axis $\times 10^{52}$. **(B)** Evolution of the intensity for top 3 isomers ($E_\gamma \geq 1,000$ keV). Vertical axis $\times 10^{52}$.

jet and releasing 1.022 MeV, it becomes challenging to differentiate the signal from these isomers from that of the annihilation process. Consequently, our focus will shift to isomers with de-excitation energies above 1 MeV and de-excitation times of seconds, specifically ^{89}Y , ^{207}Pb , and ^{90}Zr , as these characteristics make their signals more distinguishable and relevant to our study. In Figure 4B, we show the intensity evolution of these three isomers. Notably, all three exhibit a peak at approximately 0.15s, followed by a rapid decline. Based on these observations, we identify ^{90}Zr , ^{207}Pb and ^{89}Y as prime

candidates to account for the hard prompt γ -ray emission observed in GRBs.

Lastly, we construct the light curves, which requires estimating the radius at which the jet originates from the central engine, which is still uncertain (Cao et al., 2023). In Figure 5, we compare the evolution of the total luminosity over time from all isomers against the luminosity specifically from the three selected isomers, displayed on a logarithmic scale. Initially, there is a notable burst in luminosity, attributed to the rapid de-excitation of isomers with lifetimes under

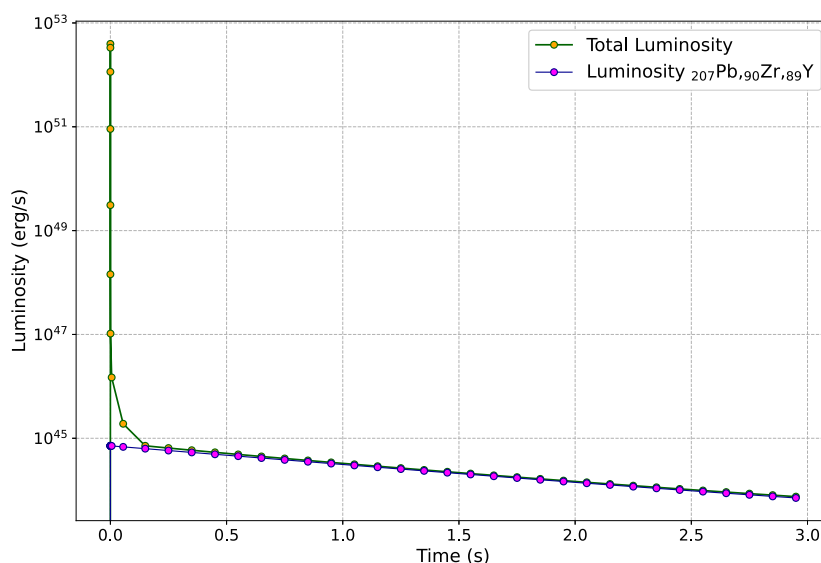


FIGURE 5
Comparison of total luminosity from all isomers against the luminosity specifically from the three selected isomers, displayed on a logarithmic scale.

1 μ s. However, after about 0.1s, the emission comes prominently from $_{132}\text{Xe}$ and the three key isomers, $_{90}\text{Zr}$, $_{207}\text{Pb}$, and $_{89}\text{Y}$, indicating their potential significant contribution to the jet. We note that the peak luminosity emitted by the selected isomers is $L_{(\text{Pb,Zr,Y})}^{\text{max}} \approx 7.15 \times 10^{44} \text{ erg/s}$ lower than that of the peak luminosity of typical GRB ($L_{\text{GRB}}^{\text{max}} \approx 10^{50} \text{ erg/s}$). This value represents the ‘true’ luminosity of the γ -ray photons that are emitted by isomeric transitions within the jet, and no further adjustment with the beaming factor is necessary. To calculate the flux at the GRB emission (in CGS units), we adopt the assumption that the jet forms at a distance of $5 \times 10^6 \text{ cm}$ from the central engine (Salafia et al., 2020), with a half-opening angle of $\theta_0 = 20^\circ$ and the emission occurs once the jet extends to about 10^9 cm from the central engine. By this stage, the collimation angle of the jet is approximately 6.23° , covering a surface area of $A_{\text{jet}} = 3.72 \times 10^{16} \text{ cm}^2$. For these values, we obtain a peak flux of $F_{(\text{Pb,Zr,Y})}^{\text{max}} \approx 1.92 \times 10^{28} \text{ erg/(s} \cdot \text{cm}^2)$.

Our findings present an analysis of isomeric abundances and their energy spectrum within the jet. We identify the top three relevant isomers with the potential to influence GRB gamma-ray emission. By examining the luminosity and flux generated by these isomers, we provide a foundational understanding of their contribution to the prompt emission phase of GRBs. It is important to note that our calculations while not accounting for the Doppler boost, likely present an upper-bound estimate. This is because we have assumed that all elements within the jet are in isomeric states that de-excite exclusively through isomeric transitions. Additionally, we treated the ejecta as isotropic and structurally uniform, without considering the diverse components and their respective r-process element abundance. This study paves the way for deeper investigations into the complex dynamics of these cosmic phenomena.

6 Conclusion

In this study, we relied on the knowledge that neutron star mergers play a crucial role in creating elements heavier than iron through r-process nucleosynthesis. The starting point of our investigation was the binary neutron star (BNS) merger GW170817, a milestone event observed both in gravitational waves and electromagnetic radiation. The prompt gamma-ray emission spectrum of the accompanying gamma ray burst (GRB 170817A) continues to be an open question. We proposed a novel idea, namely that the γ -ray spectrum of such GRBs may include contributions from γ -ray de-excitations due to isomeric transitions.

Our research starts with a comprehensive examination of the current understanding of GRB structure, coupled with an investigation into r-process nucleosynthesis during neutron star collisions. We make a case for the addition of isomers within these astrophysical phenomena. To investigate the role played by isomeric transitions within the GRB emission, we created an interactive web page designed to facilitate a thorough analysis of their potential impact on the GRB γ -ray spectra. This platform allows for interactive data filtering, detailed visualization of radiation spectra, and light curve modeling. We began by selecting representative isomers and estimating their initial quantities, using known solar element abundances and factoring in the quantity of matter expected to influence on gamma-ray production. Subsequently, we computed the number of gamma-ray radiation events for each isomer. This data was then utilized to construct both the radiation spectrum and the light curve, tailored specifically to the time interval of GRB 170817A. We identified three isomers, $_{90}\text{Zr}$, $_{207}\text{Pb}$, and $_{89}\text{Y}$, whose abundance, de-excitation energy, and lifetime make them prime candidates for contributing to the prompt GRB spectrum. This approach provides

a comprehensive method for examining the γ -ray characteristics of GRBs from similar astrophysical events.

Moving forward, our next goal is to refine our methods and compare the theoretical spectra and light curves predicted by our model against actual observations of GRBs from r-process sites. This comparison will be crucial in testing our assumptions and validating our model, thus deepening our understanding of the GRB emission spectra. In upcoming work, we plan to expand our selection of nuclear isomers to include elements lighter than strontium, and to pursue a more detailed analysis of the matter distribution and temperature in the jet. These improvements will allow us to achieve a more precise calculation of isomeric abundance in the major production sites of elements, apply our model to long GRBs, and incorporate these findings into astrophysical simulations. This last step will provide us with accurate calculations of isomeric abundance in astrophysical r-processes and will enable us to identify the precise contribution of isomeric transitions to the γ -ray signatures of GRBs, thus enhancing our understanding these astrophysical events.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://github.com/Powell222/Isomer_Search_Engine.

Author contributions

MH: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project

administration, Supervision, Visualization, Writing—original draft, Writing—review and editing. JP: Data curation, Formal Analysis, Funding acquisition, Software, Writing—review and editing.

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Conflict of interest

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Rapid multi-band space-based optical timing: revolutionizing accretion physics

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Optical timing with rapid, seconds-to-minutes cadences with high photometric precision and gap-free long baselines is necessary for an unambiguous physical picture of accretion phenomena, and is only possible from space. Exoplanet-hunting missions like Kepler and TESS have offered an outstanding new window into detailed jet and accretion physics, but have been severely hampered by incomplete calibration and systematics treatments and, most especially, a monochromatic single wide bandpass. Advances made using Kepler and TESS survey data, when considered alongside detailed, expensive multi-color experiments done from the ground, reveal the enormous potential of a space-based multi-color optical timing mission with a high energy focus.

KEYWORDS

AGN-active galactic nucleus, blazars, time domain, accretion, black holes

1 Introduction

During its prime mission from 2009–2013, the *Kepler* spacecraft fulfilled its brief spectacularly, discovering thousands of extrasolar planets. Its success was due to three major properties of the mission tailored to the search for exoplanet transits: rapid, 30-min cadence of the observations, a long and uninterrupted ~4 year baseline, and unprecedented photometric precision. The lack of seasonal and diurnal gaps, so often the bane of ground-based monitoring campaigns, enabled a full temporal sampling space. The properties that made the mission such an exemplary planet-finder also raised the potential for it to study variable high-energy phenomena in unexplored parameter spaces as well. A number of investigations into active galactic nuclei (AGN) and other accreting systems took place, but were hampered significantly by instrumental systematics that required complex bespoke reduction techniques often difficult to reproduce. To a large extent, this was due to the non-exoplanet applications requiring more complete calibration than needed for detecting the strictly periodic point-source variation that characterizes exoplanet transits; see [Smith \(2019\)](#) for a complete discussion, and [Howell \(2020\)](#) for a summary of *Kepler* results, including those beyond exoplanets.

The successor to *Kepler*, the Transiting Exoplanet Survey Satellite (TESS) was launched in 2018 with the same high precision, rapid cadence, and monolithic bandpass (with a redder central wavelength) as its predecessor, but with a few key differences, including the release of early-stage full frame images (FFIs) for the entire survey region and a much larger, nearly all-sky survey footprint, with the tradeoff of shorter baselines (27 days–1 year, depending on ecliptic latitude). From the start, TESS made itself more amenable to non-exoplanet science applications by releasing flexible support software for reduction (e.g., Lightkurve [Lightkurve Collaboration et al., 2018](#), originally designed for K2 data) and calibration products for the FFIs. Nonetheless, TESS systematics make time domain analysis

of stochastically varying sources like AGN quite challenging, especially when stitching light curves across many 27-day sectors. Fortunately, TESS supported user-created reduction software as part of its guest observer program, resulting in a proliferation of pipelines for both generic and highly customized science applications. Still, many works publish light curves that are badly affected by systematics.

In addition to challenging systematics due to electronics and background light, both missions also have a single white-light bandpass. While an efficient choice for transient and exoplanet searches, this prohibits the vast amount of astrophysics present in cross-band correlations at rapid timescales. Because these investigations require significant resources with existing instruments, almost all experiments at high cadence are done in expensive single object case studies.

2 Potential high-energy applications of multi-colored space-based timing

2.1 Searching for binary supermassive black holes

A confident census of the separations, mass ratios, and spins of binary supermassive black holes is an important prior for the multimessenger detections of binary inspirals through gravitational waves, both the stochastic background of orbiting binary pairs as seen by pulsar timing arrays like NANOGrav (Agazie et al., 2023) and in future signals expected from the upcoming LISA observatory (Amaro-Seoane et al., 2017). One potential signal is periodicity in AGN light curves due to Doppler boosting of an orbiting pair, periodic accretion episodes in the mini-disks, or precessing jets (e.g., D’Orazio et al., 2015; Ryan and MacFadyen, 2017; Charisi et al., 2018; Combi et al., 2022); observed candidates of each of these have been put forth in varying numbers (e.g., Graham et al., 2015; Liu et al., 2016; Britzen et al., 2018; Liao et al., 2021). However, the red noise nature of accretion disk and jet variability can lead to false positives in searches for binaries, which are seriously exacerbated by gaps in light curves. As the following examples demonstrate, far less ambiguous signatures of binary AGN are possible with high-cadence, uninterrupted monitoring, and adding color information increases the confidence even more.

Self-lensing flares, wherein a foreground massive black hole gravitationally lenses the emission from the mini-disk around the background hole in an orbiting pair, is a periodic signal that occurs at a predictable phase of a doppler-boosted periodic oscillation, and is not degenerate with other physical explanations (D’Orazio and Di Stefano, 2018). Only one such candidate exists currently, and it is from Kepler data, which was capable of capturing the approximately week-long flare event with very high significance (Hu et al., 2020).

As shown by (D’Orazio and Di Stefano, 2018), when the background accretion disk is near enough to be lensed as a source of finite size, multi-band light curves would provide a very sensitive probe of the structure of that accretion flow, a totally unique observable of the fueling of binaries. If the background disk is a point source, lensing is, as usual, achromatic; this would make the self-lensing flare completely distinct from other AGN flares.

The technique of “varstrometry” has recently been used with *Gaia* data to locate binary AGN candidates (at much larger separations than the self-lensing or periodicity techniques) using astrometric noise: two AGN will vary independently, so even when they are convolved in a low-resolution image, the image’s centroid will shift as one or the other AGN becomes brighter (Liu, 2015; Shen et al., 2019; Hwang et al., 2020). This method has successfully recovered a large number of known close binaries, and led to the discovery of many new binaries (e.g., Chen et al., 2022), although the technique is also useful for discovering lensed images of single quasars (e.g., Shen et al., 2021; Springer and Ofek, 2021). Rapid monitoring will allow for tighter constraints on astrometric noise, as well as noise at different variability timescales, and reveal a wider population of astrometrically-varying binary candidates. Furthermore, adding colors to the “varstrometry” method widens the discovery space even further; as the centroid shifts, so will the peak wavelength at which the convolved source is varying. This will lead to distinct centroids in different wavebands, as shown by Liu (2015) and Liu (2016). The achromaticity of gravitational lensing also suggests that multi-color varstrometry is likely to be able to differentiate between binary AGN pairs and lensing as the underlying cause of the shifting light center.

2.2 Relativistic jet physics in blazars

Blazars vary significantly at a huge variety of timescales, from a few minutes to a few years, in every waveband in which they have been studied. A vast literature exists focused on simultaneous monitoring of blazars across the full electromagnetic spectrum, with the most frequent goal being the determination of the origin of the two peaks of the blazar spectral energy distribution (SED). The lower-energy peak can span the radio to UV (so-called “low-synchrotron peak” or LSP blazars) or X-ray (“high-synchrotron peak”; HSP) wavebands, while the higher energy peak extends blue-ward from a trough after the low energy peak, including the gamma ray spectral region. The physical origin of the low-energy peak is well understood as synchrotron emission from electrons in the relativistic jet powered by the supermassive black hole. The gamma ray emission in the high-energy peak could come from leptonic processes like Compton-upscattered thermal photons from the accretion disk or obscuring torus (external Compton models; Sikora et al., 1993) or upscattered synchrotron photons from the jet itself (self-Compton models; Mastichiadis and Kirk, 1997). Alternatively, the gamma ray emission could come from hadronic processes such as pion decay or proton-synchrotron radiation (e.g., Böttcher et al., 2009; Reimer, 2012). Self-compton models imply that a strong correlation between variations in the lower and higher energy peaks would be expected, while hadronic models might suggest a weak or no correlation.

Within the optical band, multi-color monitoring has been used in a large number of ground-based surveys with semi-daily to weekly sampling over many years to study the physics of blazar flares. Bonning et al. (2012) showed convincing evidence for a shift in the low energy peak of the blazar 3C 454.3 over a 24 h flaring period in 2009 using multi-band optical-IR SMARTS monitoring, and reported a redder-when-brighter trend in flat-spectrum radio

quasars (FSRQs). Recent ground-based studies have found a bluer-when-brighter trend in many blazars, as well as using the rapid minutes-scale variability to determine upper limits on black hole masses, a very challenging quantity to measure in beamed targets like these (Chang et al., 2023; Li et al., 2024). Other studies have found that whether a source becomes bluer or redder when brightening depends on its optical spectral classification as an FSRQ or a BL Lac object (Zhang et al., 2023). The amount and color lag properties of so-called “microvariability” on minutes-to-hours timescales can be used to study the uniformity of particle flow within the jets and meaningfully constrain the amount of turbulence present (Marscher, 2014; Roy et al., 2023). The degree to which the color index changes on rapid timescales can also determine whether a rapidly-varying jet angle due to precession or a wobbling jet (and therefore a changing bulk Doppler factor) is contributing to the observed variability (Agarwal et al., 2016; Marchesini et al., 2016). These discoveries, however, have taken place in detailed, observationally expensive monitoring campaigns of single objects, requiring global networks of ground-based telescopes to avoid diurnal and weather-dependent gaps. Space-based timing, especially from TESS, has enabled discoveries of rapid quasi-periodicities in the optical jet emission has led to speculation about the nature of fluid instabilities in the jet boundaries, such as the kink instability (Jorstad et al., 2022; Tripathi et al., 2024a; b). However, as the TESS spacecraft has only a single wide bandpass, no color index information is present, preventing the use of these data for studying rapid inter-band lags in large samples.

2.3 Detailed physics of accretion flows

Accretion disks around supermassive black holes radiate primarily in the UV and optical, and are conceived as a series of annuli radiating like local blackbodies, decreasing in temperature with distance from the hole. This has led to enormous efforts to map accretion disks and track variations moving through accretion disks with simultaneous, multi-color modeling, to great effect. Edelson et al. (2015) and the STORM team conducted a monumental effort to monitor the Seyfert galaxy NGC 5548 with Swift and daily with HST in the X-ray, UV, and a range of optical wavebands. The results are spectacular, showing a clear signal of UV-optical lags agreeing with this general thermal annuli accretion disk theory, but with surprising results for the size of the accretion disk and with possible implications for the geometry of the broad-line region. Further studies of individual objects with multiband, daily monitoring by STORM have led to even further insights, including detailed maps of accretion disk temperature fluctuations with both temporal and spatial resolution (De Rosa et al., 2015; Cackett et al., 2023; Neustadt et al., 2024).

The unique insights offered by these studies cannot be overstated: this is the only direct observable into the behavior of matter in the extreme environments of AGN disks, except for direct imaging of accretion flows by, for example, the Event Horizon Telescope (Event Horizon Telescope Collaboration et al., 2019; The Event Horizon Telescope Collaboration, 2023), or deep *Chandra* imaging of gas near the Bondi radius (Baganoff et al., 2003; Wong et al., 2011; Russell et al., 2015; Bambic et al., 2023), which is only possible for a handful of nearby objects.

With cadence on minutes timescales like those afforded by TESS, but in the multiple colors explored with STORM, such insights would extend to the smallest regions of the optical disk, reaching into the most extreme space-time environments of the accreting matter. Ray tracing simulations indicate that at these scales, different wavelengths may trace the space-time environment itself (e.g., Bromley et al., 1997).

When combined with simultaneous X-ray monitoring, multi-band timing experiments provide unique information about the geometry and location of the X-ray corona, a major contested question in AGN physics. A wealth of longer-baseline, lower-cadence X-ray/UV/optical campaigns have provided conflicting results in the question of the origin of variations: do flares initiate in the corona, which is located above the disk like a “lamp-post”, and get reprocessed successively by the accretion disk at different radii, or do flares initiate in the disk through magnetic reconnection or bulk accretion flow variations, and propagate inward to the corona (For a recent review, see Cackett et al. (2021)).? The advent of very rapid X-ray timing with experiments like NICER (Gendreau et al., 2012), which has joint programs with TESS already, offers the possibility of simultaneous, rapid multi-band optical and X-ray experiments that probe this relationship at the smallest relevant physical scales.

2.4 Other applications

In addition to the science cases discussed in detail here, there are numerous other applications to AGN and accretion physics. Variability has been identified as an important means of identifying potential dwarf AGN; that is, actively accreting intermediate mass black holes (IMBHs) (Baldassare et al., 2020), and indeed many low-mass AGN have been noted in TESS light curves (Burke et al., 2020; Treiber et al., 2023). Rapid, highly photometrically accurate space-based timing is well-equipped to build a census of these objects orthogonal to those found in expensive radio and X-ray imaging searches. This is important, because the occupation fraction of AGN in dwarf galaxies has major implications for the nature of black hole seeds in the early Universe (see Greene et al., 2020, for a review).

Transients also offer a tantalizing peek into accretion physics, especially those associated with tidal disruption events (TDEs) in which a massive black hole consumes a stellar object, producing a temporary accretion flow and resulting in a large, multi-wavelength flare (Evans and Kochanek, 1989; Gezari, 2021). TESS has seen a number of such events (e.g., Holoien et al., 2019), and has detected other interesting fast nuclear transients (including some repeating anomalous signals) in galaxies (e.g., Payne et al., 2023). Color information provides much more physical interpretability than monochrome transient detection, including characterization of the transient’s evolution and information that helps constrain the nature of the disrupted star.

3 Conclusion: the impact of a rapid, multicolor space-based high-energy satellite

Despite their original design goal of finding and determining the orbital parameters of exoplanets, the *Kepler* and TESS

missions' rapid optical timing with high photometric precision and uninterrupted space-based monitoring were powerful tools for exploring the high energy astrophysics of accretion and jets. Observers in these areas overcame major data reduction challenges in order to use these instruments, driven mainly by the missions' original design goals (see Smith, 2019, for a detailed description of challenges). Among the biggest obstacles to achieving complete pictures of the phenomena under investigation are the monolithic one-color bandpasses of the experiments and the daunting uncalibrated systematics that mimic stochastic astrophysical signals; others include the large pixel size (contributing to crowding, a major issue for faint sources) and a bright limiting magnitude that severely hampers extragalactic sample sizes.

It is my perspective that a survey mission with many of the properties of *Kepler* and TESS, but with high-energy applications in mind, would provide major leaps forward in all of the science applications listed here. A mission with ~ 10 – 30 minute cadence, multiple optical colors, and a deeper limiting magnitude, even at the expense of sky coverage (for example, limited to small, well-studied extragalactic fields) and with careful calibration geared towards recovering stochastic signal is a natural next step towards space-based high energy astrophysics in the optical regime, following an existing budget-friendly template, that would offer outstanding science returns. All extragalactic applications would benefit substantially from deeper limiting magnitudes than those probed by the exoplanet missions, due to enormous increases in sample size at magnitudes > 20 even with reduced sky coverage. Rapid cadence offers an unprecedented window into jet and accretion disk phenomenology only accessible before with intensive global ground-based campaigns. Color information opens up a wide range of phenomenologies through the study of interband lags and leads, while also breaking degeneracies in searches for close binary AGN pairs, the source population for low-frequency gravitational waves. I urge the rest of the time domain community to consider what such a mission could do for their respective fields!

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Light travel time effects in blazar flares

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In this study, a model for light travel time effects for emission from a plasma blob in a blazar jet is presented. This calculation could be incorporated into more complex models with particle acceleration and radiation mechanisms, but as presented here, it is agnostic to these mechanisms. This model includes light travel time effects for an expanding or contracting blob. As examples, this model is applied to a flare observed by VERITAS and MAGIC from Mrk 421 in 2013 and a flare observed by the *Fermi* Large Area Telescope from 3C 454.3 in 2010.

KEYWORDS

BL Lacertae object: general, BL Lacertae objects: individual (Mrk 421), quasars: general, quasars: individual (3C 454.3), gamma-rays: general, gamma-rays: galaxies, time-domain astronomy

1 Introduction

Blazars are active galactic nuclei (AGN) with relativistic jets moving close to our line of sight. They are routinely detected at all wavelengths, from radio to γ -rays, and often extremely variable at all wavelengths as well. Consequently, a complete understanding of blazars requires a deep understanding of the time domain. The *Fermi* Large Area Telescope (LAT) is extremely useful for this since it monitors the entire sky in ≈ 30 MeV to 100 GeV γ -rays every 3 h. Observations by the LAT can be supplemented with observations by many other observatories, for instance, by *Swift* in space in the optical and X-rays and on the ground by MAGIC, H.E.S.S., and VERITAS at very high-energy (VHE) γ -rays, Very Long Baseline Array, TANAMI, Effelsberg, Owens Valley Radio Observatory in the radio, and SMARTS and the GASP-WEBT consortium in the optical (among others). The loss of *Fermi* will be a major blow to the study of blazars, especially considering there is no planned observatory that can replace its capabilities.

Blazar variability is often analyzed in terms of flares, explained by particle acceleration and radiative cooling in a homogeneous one-zone nonthermal plasma “blob.” Extensive time-dependent modeling analysis has been performed on flares (e.g., Boettcher et al., 1997; Kirk et al., 1998; Chiaberge and Ghisellini, 1999; Dermer and Schlickeiser, 2002; Joshi and Böttcher, 2011; Dotson et al., 2015; Zacharias, 2023). Particle acceleration could be from a diffusive shock or magnetic reconnection. Leptonic radiation processes include synchrotron, typically at low energies, and Compton scattering of a number of radiation fields at high energies. Hadronic processes may also be included (e.g., Petropoulou and Mastichiadis, 2012; Diltz et al., 2015). Light travel time effects are sometimes, though not always, ignored, implicitly assuming that the acceleration and/or radiative timescales are much larger than the light-crossing timescale.

Observationally, flares are often characterized in terms of an exponential rise and decay (e.g., Nalewajko, 2013; Meyer et al., 2019; Roy et al., 2019; Bhatta et al., 2023). Flares are often analyzed in terms of symmetry, among other properties, with symmetric flares having the same rising and decaying timescales. Symmetric flares are often taken as an indication that flare variability is dominated by light travel time rather than particle acceleration or cooling. Most blazar flares, but not all, are consistent with being symmetric within the uncertainties.

Here, a simple model that takes into account light travel time effects for emission from a plasma blob in a blazar jet is explored. The simple model is agnostic as to the particle acceleration and radiation mechanisms, assuming only that the acceleration and radiative timescales are much less than the light-crossing timescale. In [Section 2](#), a simple model from a non-expanding blob is explored, which will result in a symmetric light curve. This should be a good approximation for the majority of blazar flares that show no evidence of asymmetry. Next, in [Section 3](#), a model for a blob that can have a size that changes with time is explored. This could reproduce asymmetric flares, while still being agnostic as to the exact acceleration and radiation mechanisms. Finally, the discussion is provided in [Section 4](#).

2 Flare from a constant size blob

2.1 Formalism

Consider a homogeneous blob. If the emission of the entire blob is changing simultaneously, the observer will see the portion of the blob closer to the observer before the portion of the blob that is farther away. This effect was explored by [Chiaberge and Ghisellini \(1999\)](#) and [Joshi and Böttcher \(2011\)](#) and described by [Zacharias and Schlickeiser \(2013\)](#) for a spherical blob with constant size (see also [Finke and Becker, 2014](#); [Finke and Becker, 2015](#)). A blob in a blazar jet will be moving at a high relativistic speed, but all quantities of the blob in the observer's frame are used, so no relativistic transformations are necessary.

The emitting blob is considered to be centered on $x = R$ with a two-dimensional cross-sectional surface described by $(R - x)^g + y^g = R^g$, where (x, y) are the standard Cartesian coordinates. The observer is in the $-x$ direction. See [Figure 1](#) for an illustration of the geometry. The three-dimensional surface is created by rotating this surface around the x -axis. The blob will then have a volume given by

$$V = 2\pi \int_0^R dx R^2 \left[1 - \left(\frac{x}{R} \right) \right]^{2/g} \\ = 2\pi R^3 \int_0^1 d\tilde{x} (1 - \tilde{x}^g)^{2/g}. \quad (1)$$

Here, $g = 2$ corresponds to the case of a sphere. For a constant-size blob with this geometry and an intrinsic time-series light curve $F(t)$ starting at $t = 0$, the observed flux as a function of the observer's time t_{obs} is

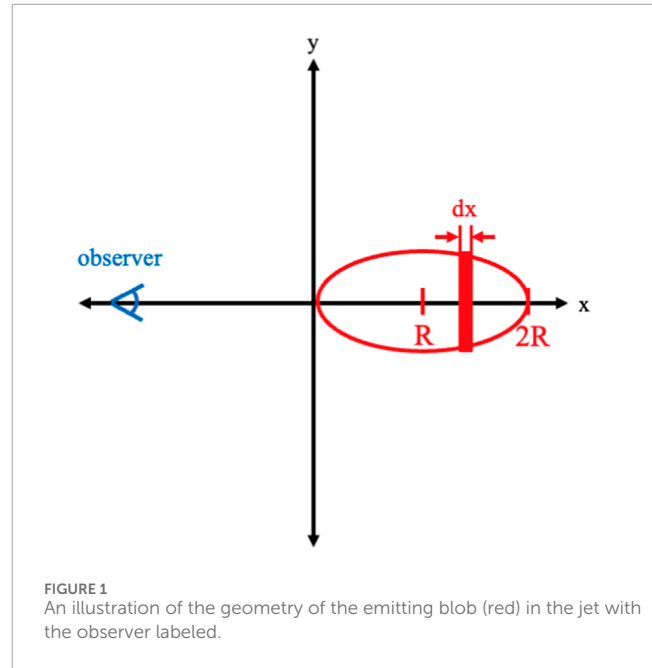
$$F_{\text{obs}}(t_{\text{obs}}) = \frac{\pi c}{V} \int_0^{\min(2R/c, t_{\text{obs}})} dt F(t_{\text{obs}} - t) \\ \times [R^g - |R - tc|^g]^{2/g}. \quad (2)$$

For the spherical case $g = 2$, [Eq. 2](#) gives the result from [Zacharias and Schlickeiser \(2013\)](#) and [Finke and Becker \(2015\)](#)

$$F_{\text{obs}}(t_{\text{obs}}) = \frac{3c}{R} \int_0^{\min(2R/c, t_{\text{obs}})} dt F(t_{\text{obs}} - t) \\ \times \left[\frac{tc}{2R} - \left(\frac{tc}{2R} \right)^2 \right]. \quad (3)$$

For the shortest possible flare,

$$F(t) = F_0 \delta(t - t_0), \quad (4)$$



where F_0 is the fluence of the flare and $\delta(x)$ is the usual Dirac delta function. From [Eq. 2](#), we obtain

$$F(t_{\text{obs}}) = F_0 \frac{\pi c}{V} [R^g - |R - (t_{\text{obs}} - t_0)c|^g]^{2/g} \\ \times H\left(t_{\text{obs}} - t_0; 0, \frac{2R}{c}\right). \quad (5)$$

Here, the step function [Eq. 6](#) is used.

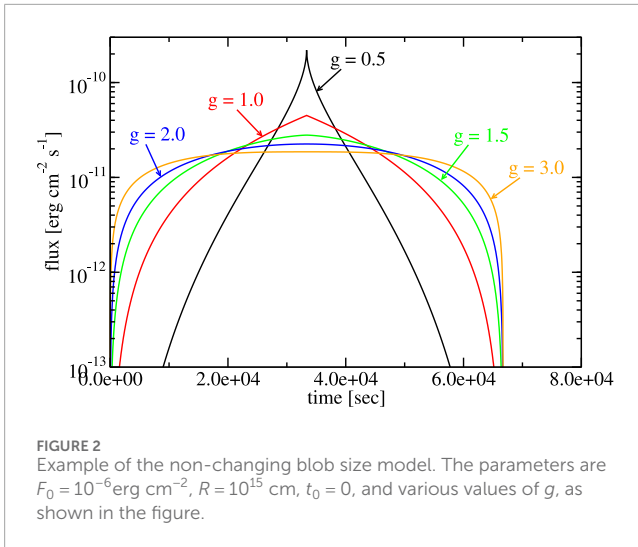
$$H(x; a, b) \equiv \begin{cases} 1 & a < x < b \\ 0 & \text{otherwise} \end{cases}, \quad (6)$$

The solution using [Eq. 5](#) has four free parameters: F_0 , R , g , and t_0 . This model creates a symmetric flare, with the rising and falling timescales being equal. If light travel time is indeed the only source of variability in a flare, the shape of the light curve should be the same at all energies (wavelengths and frequencies), although the normalization would be different. So if one has a light curve flux at energy E_1 , $F(E_1, t)$, the flux at E_2 would be $F(E_2, t) = r_1 F(E_1, t)$, where r_1 is another free parameter that is constant with time; $F(E_3, t) = r_2 F(E_1, t)$, where r_2 is another free parameter; and so on. Each additional light curve adds another free parameter.

[Figure 2](#) shows this model's light curve plotted for different values of the parameter g . This parameter can control the general shape of the flare. For lower values of g , it becomes more peaked.

This model can be a more physically motivated way of computing the size scale from a flare, although it should be clear that the size scale found here (R) is in the observer frame, not the frame co-moving with the jet, as is often desired.

As described in [Section 1](#), a large number of blazar flares do indeed appear to be symmetric, so this simple model should be able to provide a good fit to a large number of blazar flare light curves. This model is next applied to two bright, well-observed γ -ray flares taken from the literature.



2.2 April 2013 flare from Mrk 421

A highly detailed multiwavelength campaign on the high synchrotron-peaked BL Lac object Mrk 421 took place in April 2013, as reported by Acciari et al. (2020). During this time, the source was very bright, and several extremely bright flares were observed. Here, the simple light travel time model for a non-expanding blob is applied to the flare on 15 April 2013 (MJD 56397), as observed in the γ -rays by MAGIC and VERITAS. This bright flare was also captured in a similar detail in the X-rays by *NuSTAR*, but that is not explored here.

A Markov chain Monte Carlo analysis was performed (Foreman-Mackey et al., 2013) with the model described above in Section 2.1 on the 0.2–0.4 TeV, 0.4–0.8 TeV, and > 0.8 TeV light curves for the flare from Mrk 421 on 15 April 2013. The data are taken from Acciari et al. (2020). The result can be seen on the left side of Figure 3, and model parameters are given in Table 1. The model appears to be a reasonably good fit to the data, although it misses some of the points at early and late times. The light curves at the different energy ranges do look very similar, indicating that the light travel time may dominate the variability for this flare.

The fit deviates substantially from a spherical blob, with the fit resulting in $g \approx 0.60$, versus $g = 2$ for a spherical blob. There is no real reason to think that the shape of the blob is spherical; this is often used just for simplicity. The resulting radius of the blob, $R \approx 3 \times 10^{15} \text{ cm}$, is consistent with that observed in previous blazar modeling.

2.3 November 2010 flare from 3C 454.3

In November 2010, 3C 454.3 exhibited a bright γ -ray outburst detected by the *Fermi*-LAT, which was the brightest γ -ray flare from a blazar up to that point (Abdo et al., 2011). The non-expanding blob model is also applied to the 0.1–1.0 and > 1.0 GeV light curves of the brightest flare from this outburst. The result can be seen on the left side of Figure 4, and the parameters are given in Table 2. As can be seen, the model does not provide a particularly good fit to the

data. Furthermore, the shape of the light curve at the two different energy ranges is quite different, indicating that the simple light travel time model may not be a good approximation for this burst. It is interesting to note that the fit results at $g \approx 2$ are consistent with the spherical geometry for the emitting region.

3 Flare from a blob that is changing size

3.1 Formalism

Here, I generalize the light travel time effect for an expanding or contracting axisymmetric blob, which, to the best of my knowledge, has not been explored before. In this case, $R \rightarrow R(t)$. The solution for a constant-size blob δ function, Eq. 5 above, can be used as a Green's function for the case of the expanding blob (letting $F_0 \rightarrow 1$):

$$G(t_{\text{obs}}, t_0) = \frac{\pi c}{V(t_0)} [R(t_0)^g - |R(t_0) - (t_{\text{obs}} - t_0)c|^g]^{2/g} \times H\left(t_{\text{obs}} - t_0; 0, \frac{2R(t_0)}{c}\right). \quad (7)$$

The solution for the expanding/contracting blob will then be

$$F_{\text{obs}}(t_{\text{obs}}) = \int_0^{t_{\text{obs}}} dt_0 F(t_0) G(t_{\text{obs}}, t_0), \quad (8)$$

where again $F(t_0)$ is the intrinsic light curve of the blob. Substituting the Green's function, Eq. 7, in Eq. 8, one gets

$$F_{\text{obs}}(t_{\text{obs}}) = \pi c \int_{\max(0, t_{\min})}^{t_{\text{obs}}} dt_0 \frac{F(t_0)}{V(t_0)} \times [R(t_0)^g - |R(t_0) - (t_{\text{obs}} - t_0)c|^g]^{2/g}, \quad (9)$$

where $t_{\min}$ is defined by $t_{\text{obs}} < t_{\min} + 2R(t_{\min})/c$, based on the step function in Eq. 7, which can be determined once $R(t)$ is specified. Eq. 9 can be rewritten with the substitution $t = t_{\text{obs}} - t_0$, leading to

$$F_{\text{obs}}(t_{\text{obs}}) = \pi c \int_0^{\min(t_{\max}, t_{\text{obs}})} dt \frac{F(t_{\text{obs}} - t)}{V(t_{\text{obs}} - t)} \times [R(t_{\text{obs}} - t)^g - |R(t_{\text{obs}} - t) - tc|^g]^{2/g}. \quad (10)$$

Here $t_{\max}$ is defined by $t_{\max} < R(t_{\max})/c$ and must be determined once $R(t)$ is specified. For a blob that is neither expanding nor contracting, i.e., $R(t)$ is constant, Eq. 10 is reduced to Eq. 2.

The blob length scale is considered to expand as

$$R(t_0) = R_0 \left(1 + \frac{t_0 - t_{\min}}{T}\right)^a, \quad (11)$$

where R_0 , T , and a are free parameters. For this parameterization for $R(t_0)$, in Eq. 9, $t_{\min} = t_{\text{obs}} - 2R_0/c$. In Eq. 10, $t_{\max}$ does not have a closed-form solution and so must be solved for numerically.

For a δ -function intrinsic flux, as used in the constant size case, the expanding blob would simplify to the constant size case. This is because only the flux at one infinitesimally small instant will be seen by the observer, so any change in the blob's size will not make a difference. So, the intrinsic light curve is considered to be a Gaussian,

$$F(t_0) = \frac{F_0}{\sqrt{2\pi}\sigma_t} \exp\left(-\frac{(t_0 - t_{\min})^2}{2\sigma_t^2}\right). \quad (12)$$

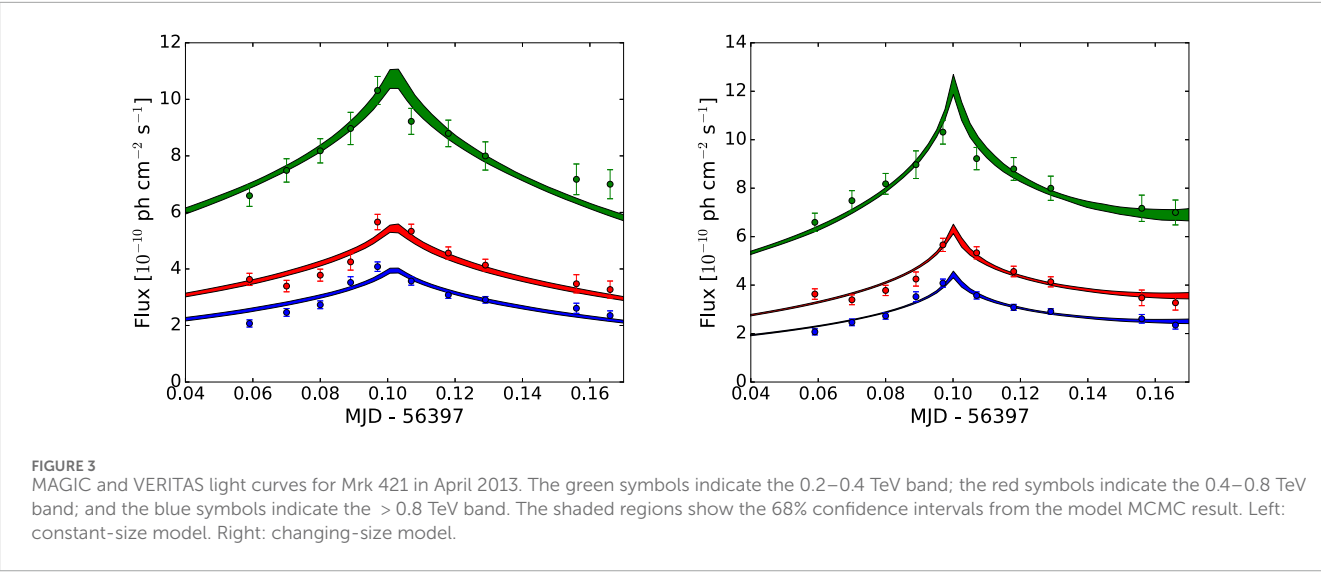


TABLE 1 Model parameters for fits to the April 2013 flare from Mrk 421.

Parameter	Constant-size blob	Changing-size blob
t_0 or $t_{\min}$ [MJD]	$56395.0^{+0.4}_{-0.3}$	56395.7 ± 0.3
$\log_{10} F_0$ [erg cm $^{-2}$]	$-4.59^{+0.04}_{-0.08}$	$-4.42^{+0.29}_{-0.17}$
σ_t [days]	-	$1.77^{+0.31}_{-0.26}$
$\log_{10} R_0$ [cm]	$15.46^{+0.10}_{-0.19}$	15.55 ± 0.09
T [days]	-	3.09 ± 0.45
a	-	$2.7^{+2.1}_{-1.8}$
g	$0.60^{+0.08}_{-0.03}$	0.49 ± 0.04
r_1	0.51 ± 0.01	0.51 ± 0.02
r_2	0.36 ± 0.01	0.36 ± 0.01
χ^2/dof	56/24	24/21

This model then has free parameters F_0 , R_0 , g , $t_{\min}$, σ_t , a , and T , along with any ratios for light curves at other wavelengths (r_2 and r_3). For $\sigma_t \rightarrow 0$, it is well-known that a Gaussian reduces to a Dirac δ function, so Eq. 12 reduces to Eq. 4. This means that the constant-size model is nested with the changing-size model, with the changing-size model having three additional free parameters.

Examples of light curves with this model are shown in Figure 5 for different values of the parameter a . Changes in a can account for flare asymmetry, allowing this model to explain a wide variety of flares with an emitting blob that changes in size.

One prediction of this model is that the light curves for a source at different wavelengths, produced by the same emitting region, should have the same overall shape. This means that if one observes simultaneous light curves at different wavelengths and their overall spaces are not consistent with

one another, this model alone is not sufficient. The light curves may differ due to different radiative properties or mechanisms at different wavelengths or contamination by other emitting regions.

3.2 April 2013 flare from Mrk 421

The changing-size model described above is applied to the April 2013 flare from Mrk 421. The result can be seen on the right side of Figure 3 and Table 1. The model does appear to provide a better fit. Since $a > 0$, this indicates the blob is expanding rather than contracting. A likelihood ratio test indicates that the constant-size blob model is rejected in favor of the changing blob model at 4.8σ significance. Since the light curves at different energies are so similar,

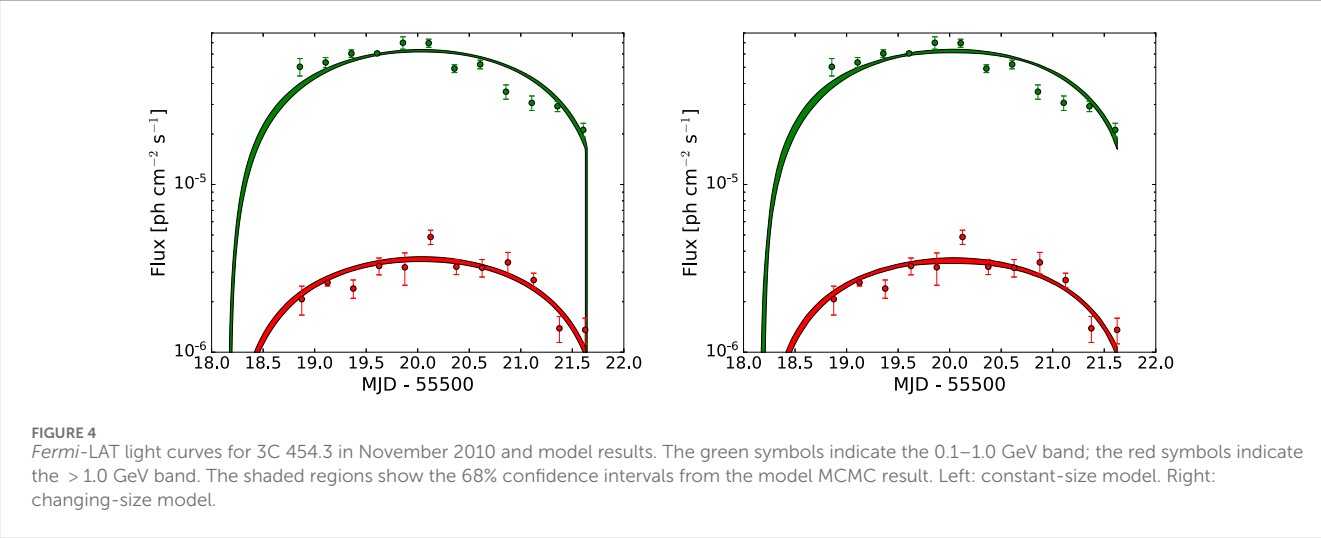


TABLE 2 Model parameters for fits to the November 2010 flare from 3C 454.3.

Parameter	Constant-size blob	Changing-size blob
t_0 or $t_{\min}$ [MJD]	$55518.17^{+0.03}_{-0.01}$	$55518.17^{+0.03}_{-0.01}$
$\log_{10} F_0$ [erg cm $^{-2}$]	$1.13^{+0.01}_{-0.01}$	$1.13^{+0.01}_{-0.04}$
$\log_{10} \sigma_t$ [s]	-	$1.97^{+0.90}_{-0.68}$
$\log_{10} R_0$ [cm]	$15.68^{+0.01}_{-0.01}$	$15.68^{+0.01}_{-0.01}$
T [days]	-	$7.8^{+2.5}_{-2.7}$
a	-	$-0.66^{+2.78}_{-3.51}$
g	2.07 ± 0.11	$2.08^{+0.11}_{-0.10}$
r_1	0.057 ± 0.02	0.057 ± 0.03
χ^2/dof	87/19	86/16

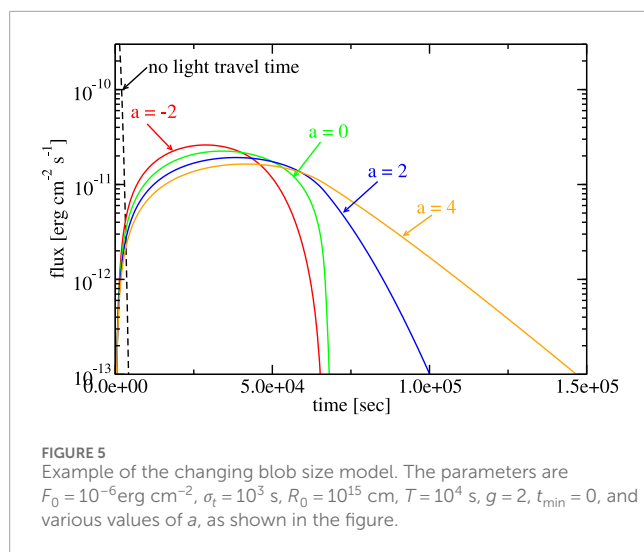
this is a reasonably strong indication that the variability is dominated by the light travel time for this flare.

3.3 November 2010 flare from 3C 454.3

The changing-size model is also applied to the November 2010 flare from 3C 454.3. The model can be seen over-plotted with the data in Figure 4, and the resulting parameters can be seen in Table 2. The model does not appear to provide a significantly better fit and indeed looks very similar to case of the non-expanding blob. This is confirmed with the likelihood ratio test, which indicates that the changing blob model is preferred at $10^{-7}\sigma$ over the non-expanding model, which any reasonable researcher would interpret as the more complicated model is not significantly preferred over the simpler one. The reason for this is that, unlike the flare in Mrk 421 explored above, the light curve shapes for the different *Fermi*-LAT energy bins are quite different (indeed, as noted by Abdo et al., 2011). This is an indication that flare shape is not dominated by light travel time effects and that a more complicated model is needed to explain it.

4 Discussion

A simple model has been described for light travel time effects in blazar flares, where the emitting region could be changing in size (either expanding or contracting). The change in size of the region can lead to an asymmetry in the light curve, i.e., different rising and decay timescales. The constant-size model uses an instantaneous turning on and off of emission, i.e., a Dirac δ function for intrinsic emission. The expanding blob model assumes a narrow Gaussian for the intrinsic emission. Although unrealistic, these models should be good approximations for flares where the particle acceleration and energy loss timescales are much less than the light travel timescale for the “blob.” For many flares, including asymmetric flares, light travel time effects alone should be able to account for the flare. Observing at multiple wavelengths is a good way to confirm or rule out this model. If the flares have the same shape at different wavelengths, which can be explained by this model, this is a good indication that the variability is dominated by light travel time. However, if the light curve shapes during the flare are different



at different wavelengths, this could be an indication that other processes are important. For instance, it could be an indication that the particle acceleration and energy loss timescales are not much smaller than the light travel timescale and hence cannot be neglected, although here one must be careful. For instance, in comparing optical emission and γ -ray emission in FSRQs, one must be careful to take into account the emission from the “blue bump,” i.e., from the accretion disk.

This story is complicated by recent observations by the *Imaging X-ray Polarimetry Explorer* (IXPE). Simultaneous observations of Mrk 421 (Di Gesu et al., 2023) and PG 1553+113 (Middei et al., 2023) reveal optical polarizations that are significantly different than X-ray polarizations measured by the IXPE. Mrk 421 and PG 1553+113 are both high synchrotron-peaked blazars, so both their optical and X-ray emissions are thought to be from synchrotron emission. One possible explanation is that the electrons producing the optical synchrotron can travel a larger distance from the acceleration site than the electrons producing the X-ray synchrotron since the lower-energy optical-emitting electrons will have a longer energy loss timescale than the higher-energy X-ray emitting electrons (Zhang et al., 2024). In this case, one would indeed expect the optical emission region to be larger than the X-ray emission region, and thus the optical would have a larger variability timescale, and likely a time delay, relative to the X-ray emission. In any case, light travel time effects, such as those described here, would need to be taken into account in accurate time-dependent modeling calculations.

As two examples, this model was applied to the April 2013 flare from the BL Lac Mrk 421, as observed by MAGIC and VERITAS, and to the November 2010 flare from the FSRQ 3C 454.3, as observed by the *Fermi*-LAT. In the case of the Mrk 421, the expanding blob model provides a good fit to the data and is preferred over the constant-size model with a significance of 4.8σ . This flare was extremely bright, and the data were quite good. A more complicated model would probably not provide a better description of the data. For the flare from 3C 454.3, neither model provides a particularly good reproduction of the data and the changing size model is not significantly preferred over the constant-size model.

The models here could be usefully applied to studies of light curves that make up multiple flares (Meyer et al., 2019; Roy et al., 2019; Bhatta et al., 2023). Since most flares are symmetric, the constant-size blob model should be sufficient to explain most flares. The parameter g can have a substantial impact on the shape of the flare, and varying it could probably describe most flares (Figure 2). The fits can be used to at least put an upper limit on the size scale of the flare (the parameter R). Care should be taken since this size scale is in the observer’s frame. In the frame co-moving with the blob, the size scale could be larger by a factor of the Doppler factor. Furthermore, the data from most flares are not as good as the data for the flares explored here. So a lack of improvement in the fit for most flares could be due to the large uncertainty in the data and may not be due to the flare being dominated by light travel time effects.

Although these models do not contain any information about particle acceleration or radiation mechanisms, light travel time, as discussed here, can be incorporated into such models. To some extent, light travel time effects have been incorporated into more complicated models already (Chiaberge and Ghisellini (1999); Joshi and Böttcher, 2011; Zacharias and Schlickeiser (2013)). The formalism described here will be incorporated into more complicated models in future work.

Particle-in-cell simulations indicate that magnetic reconnection in blazar jets could create “plasmoids,” i.e., magnetized, nonthermal plasma of various sizes with accelerated, radiating particles (e.g., Petropoulou et al., 2018). Christie et al. (2019) performed time-dependent modeling of emission from plasmoids created by magnetic reconnection in a blazar jet. They included light travel time effects between different plasmoids but did not include the light travel-time effects within the plasmoid. The light travel-time effect described here could be integrated into their model to take into account intra-plasmoid light travel time, including for a plasmoid that is changing in size. If the plasmoids are not changing in size rapidly during a flare, the flares could be more symmetric than previously assumed, affecting γ -ray observations and the inferred flare timescales (Meyer et al., 2021).

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

JF: writing—original draft and writing—review and editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships

that could be construed as a potential conflict of interest.

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Active galactic nuclei: global perspective and time-domain implications

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A view of the global structure of active galactic nuclei (AGN) is presented herein following the detection of blue-shifted warm absorber (WA) and ultrafast outflow (UFO) absorption features in their X-ray spectra. A straightforward interpretation of these features suggests the presence of magnetohydrodynamic winds off the underlying accretion disks spanning a wide range of a few to $\sim 10^6$ Schwarzschild radii. UFOs are associated with wind segments closest to a black hole, with decreasing ionization absorber species associated with these wind segments at increasingly larger distances; eventually, the wind segments at the largest distances are sufficiently cool and dusty to be associated with the AGN tori, as suggested in the past. Furthermore, spectroscopic X-ray observations at a sufficient resolution allow estimates of the mass fluxes of these winds, showing that they increase with radius. As a consequence, the mass flux of the underlying accretion disk must decrease toward the accreting black hole, eventually reaching a value smaller than that needed to convert the flow into an X-ray hot advection-dominated accretion flow; it is suggested that this hot segment of the accretion flow is responsible for the observed AGN X-rays (and galactic X-ray binaries) in place of the *ad hoc* corona assumed thus far. This work indicates that the properties of this component that are reflected in its relative luminosity to the viscous disk O-UV component depend on the source luminosity in broad agreement with the observations.

KEYWORDS

black hole, accretion, accretion disks, magnetohydrodynamic wind, active galactic nuclei

1 Introduction: main components of the spectral energy distribution of active galactic nuclei

Sixty years after their discovery, quasars and more broadly active galactic nuclei (AGN) continue to puzzle scientists. Although observational and theoretical advancements over the years have sharpened our views regarding these objects, a comprehensive, low-parameter picture of their associated structures and properties is lacking. Following the discovery of quasars and their association with luminous radio sources, it was shown early on that the efficiency of their radiation must be higher than that of nuclear burning; as such, they are likely powered by the more efficient process of matter accretion onto a black hole (Lynden-Bell, 1969), likely though dissipation in an accretion disk. Following this, the seminal work on accretion disks and their spectral appearance was developed by Shakura and Sunyaev (1973) (hereafter SS73; see also Kubota and Done (2018) for more recent models).

The accretion disks described in SS73 have steady states and generally thin geometric structures that are in vertical hydrostatic equilibrium with azimuthal velocities

much higher than the poloidal and radial velocities ($V_\phi \gg V_z > V_r$). Matter sinks slowly toward a black hole, transferring its angular momentum outward, while locally dissipating the fraction of its kinetic energy released from infinity in addition to that transferred outward along the smaller radii with the angular momentum. The dissipated energy along the radius r , given approximately by $\dot{E} \approx GM\dot{M}/r$, is considered to be emitted in the black body form of temperature T , such that $\sigma T^4 = 3GM\dot{M}/(8\pi r^3)$ (the factor $(3/8\pi)$ results from including both the energy released from infinity to r and that transferred outward by the viscous stresses; Novikov and Thorne (1973); Shapiro and Teukolsky (1986); Frank et al. (1985)). The resulting spectrum is then a superposition of the black-body spectra of radial temperature dependence $T \propto r^{-3/4}$.

This results in a feature broader than that of a single black body with luminosity per logarithmic frequency $\nu L_\nu \propto \nu^{4/3}$, maximum temperature set by the accretion rate $\dot{M}$, and black hole mass M (in reality by the value of the innermost stable circular orbit (ISCO); $R_{\text{ISCO}} \approx 2 - 6M$ depending on the value of the black hole spin). This feature is commonly referred to as the big blue bump (BBB) because it dominates the overall emission and peaks in the ultraviolet (UV) region of the electromagnetic spectrum in most quasars.

By introducing the value of the Eddington accretion rate $\dot{M}_E = L_E/c^2$, where L_E is the Eddington luminosity given by $L_E \approx 1.3 \times 10^{46} M_8 \text{ erg/s}$ ($M_8 = (M/10^8 M_\odot)$), and the normalized accretion rate $m = \dot{M}/\dot{M}_E$, the maximum temperature associated with the BBB is obtained as $T \approx 10^5 (\dot{m}/M_8)^{1/4} = 10^7 (\dot{m}/M_1)^{1/4}$. For AGN with high luminosity and masses in the range of $10^8 - 10^9 M_\odot$, this feature peaks in the UV part of the spectrum; for galactic accreting black holes of mass only a few solar masses, this feature peaks in the soft X-ray spectral band, in agreement with observations.

Additional observations have shown that aside from the above multitemperature black-body feature, the spectra of accreting black holes almost universally include harder ($> 2 \text{ keV}$) X-rays (with exceptions being the tidal disruption events (TDEs) that exhibit very little emissions above $E > 2 \text{ keV}$); these are generally in the accordance with a power law with the photon spectra $dN/dE \propto E^{-\Gamma}$ with $\Gamma \sim 1.5 - 2.5$ and an (apparent whenever it is detected) exponential cut-off at $E \sim 50 - 100 \text{ keV}$. The origin of this higher energy component is attributed to an *ad hoc* hot ($T_e \sim 10^9 \text{ K}$) corona, which produces the observed X-rays by Comptonization of the disk photons through the hot electrons. The properties of the corona (electron temperature T_e , Thomson depth τ and geometry, and resulting luminosity) are not given *a priori* but are chosen so as to account for specific observations.

In addition to their X-ray and O-UV continua, the AGN spectra exhibit prominent line emissions. These comprise two general groups, i.e., broad permitted lines (typically of $\Delta V \sim 10,000 \text{ km/s}$) such as C IV, Ly α , N V, Mg II, H α , and H β as well as narrow and typically forbidden lines ($\Delta V \sim 2,000 \text{ km/s}$) such as O III. It is generally considered that the line velocities represent the dynamics of the plasma emissions in the gravitational field of a black hole, implying that the broad lines are emitted closer to the gravitating object than the narrow ones. The issues of their origin as well as physical, kinematic, and dynamic properties have been the subjects of numerous studies, resulting in several interesting correlations (Sulentic et al., 2000, 2017) whose origins are not yet firmly established. To further increase the AGN diversity, a

large proportion of them exhibit narrow permitted lines, thereby producing two line-based categories as type 1 (broad permitted lines) and type 2 (narrow permitted lines).

Observations of the type 2 AGN (Seyfert 2 galaxies) in polarized light have shown the existence of broad line components; however, these are observed only in polarized light, suggesting that their broader component closer to the AGN center is blocked from direct view by a structure of significant height-to-radius (h/r) ratio. The properties of this component indicated a cold, potentially dusty/molecular structure of toroidal shape called the “AGN torus”; this feature was then added as one of the important components of AGN phenomenology (Antonucci, 1993). The dusty, molecular make-up of these tori implies that they must be cool ($T \sim 10 - 100 \text{ K}$) structures that do not produce their own radiation but apparently intercept and reprocess a large fraction of the AGN UV and X-rays into infrared (IR) rays. The major problem with this notion is their large h/r ratios given their low temperatures compared to the local virial ones with temperatures $\geq 10^7 \text{ K}$. Although these tori are hailed as the crux of the unification of types 1 and 2 AGN, further observations over the years appear have indicated a more complex structure (Netzer, 2015).

Finally, in addition to the X-ray to far-infrared (FIR) spectral components that are attributed to features associated with their accretion disks (which we are unable to resolve spatially), AGN are invariably detected at radio frequencies ($\sim 1 \text{ GHz}$). These emissions are generally associated with largely resolvable, ubiquitous jets that apparently originate near the AGN centers and span distances of the order of parsecs to megaparsecs. Interestingly, the radio emissions vary widely among the different AGN as a fraction of their bolometric luminosity; despite the small values of these fractions ($L_r/L_{\text{bol}} \sim 10^{-3} - 10^{-6}$), they are employed as yet another discriminator to separate the classes. Hence, depending on the value of this ratio, the AGN are distinguished as radio loud (RL) ($L_r/L_{\text{bol}} \sim 10^{-3}$) and radio quiet (RQ) ($L_r/L_{\text{bol}} \sim 10^{-6}$). The radio flux of the RL AGN spectra connects smoothly with that of the FIR, contrary to that of the much weaker flux of the RQ AGN that appears completely separate (Figure 1). Furthermore, RL AGN have been detected by the Fermi-LAT at energies of $E_\gamma \approx 10 \text{ GeV}$ and even tera electron volts on occasion, and the γ -ray flux dominates the entire spectral energy distribution (SED) in many cases (Figure 1B). This feature, along with the differences in their L_r/L_{bol} ratios, imply that RL AGN are endowed with additional non-thermal components aside from those that produce the FIR to X-ray spectra, which are absent in the RQ AGN.

Based on these multiwavelength facts, it is interesting to put together an all-inclusive AGN scheme, such as the well-known one by Urry and Padovani (1995) shown in Figure 1 and its variations. Although this may be useful in providing a broad picture of the AGN, it has little reference to the underlying physics. Clearly, the AGN are multiwavelength, multiscale objects presenting observers with a multitude of facts even for a relatively narrow frequency band that roughly spans one decade (e.g., see the recent review by Netzer (2015)). Although each of these sets is important in its own right to the specific subfield, the following questions need to be addressed: Are all facts equally important to the global AGN picture? Are the properties of a given spectral band independent of those of other bands or are they interrelated? Is there a small number parameter comprehension of the global AGN structure?. It is the goal of this

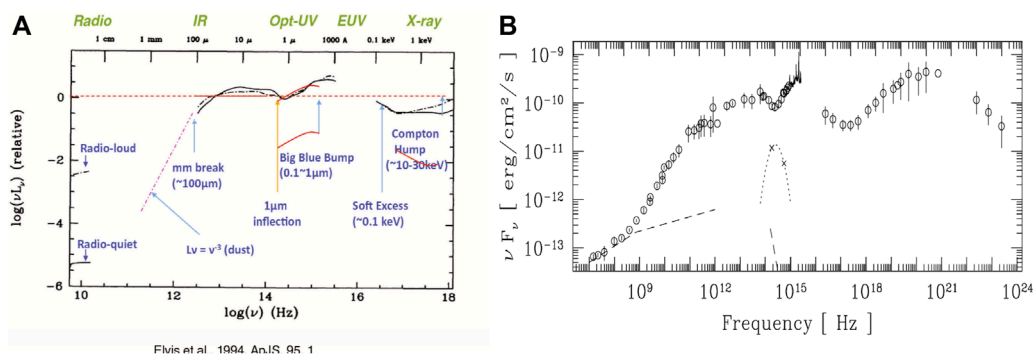


FIGURE 1

(A) General form of the AGN SEDs (both RL and RQ) from radio to X-ray frequencies. (B) SED of the RL AGN 3C 273, indicating continuous flux from radio to γ -ray range.

work to indicate the path to this global picture. To the best of the author's knowledge, the first attempt in this direction was the work of Boroson (2002), where principal component analysis (PCA) was employed on a set of 87 nearby RL and RQ AGN to formulate a 2D parametrization of the AGN according to their fractional Eddington luminosity values, L/L_E , and accretion rates $\dot{M}$. This analysis was driven by the radio loudness and also the properties of the Fe II[O III], He II, and H β components that were employed to provide estimates of the black hole mass. Although this analysis provides the global location of the AGN in the $L/L_E - \dot{M}$ diagram, insights concerning the relative importances of the individual spectral AGN bands are also important.

With respect to this last issue, considering that the AGN luminosity is driven by the black hole potential, it is expected that the contributions of the individual components would decrease with frequency, as implied by the spectral shape of the accretion disk. The fact that the FIR and line emissions have comparable luminosity values with the higher energy continuum determines that the former subtend a significant fraction of the latter's solid angle, thereby setting the structure of the large-scale AGN geometry.

This finding becomes more complicated with the relative contributions and geometries of the O-UV and X-ray components. Based on the models that assume the O-UV emissions to be caused by a disk (of the SS73 type or otherwise) that reaches the ISCO of the black hole, this broad and multicolor component should be dominant, as in the case of most AGN. As noted earlier, the X-ray emissions are attributed to the corona, whose geometry as well as spectral properties and luminosity in particular are typically chosen to fit the data. However, this picture has been challenged by microlensing observations; Morgan et al. (2010) showed that the X-ray emitting region was ≈ 10 times smaller than that of UV emissions, despite the fact that the BBB luminosity was larger than that for X-rays (i.e., the ratio $R_{UVX} = L_{BBB}/L_X > 1$), thereby violating the qualitative accretion disk rule that the smallest disk radii emit the most radiation. It is of additional interest that this ratio, which is usually presented as the logarithmic slope of the AGN flux between 2500 Å and 2 keV and referred to as α_{OX} , is not constant. Despite the complications of the overlying galaxy in the determination of the true BBB luminosity, α_{OX} has been found to depend on the source

luminosity at 2500 Å (Strateva et al., 2005), implying the presence of as yet incomprehensible physics that determines its value.

Significant insights may be obtained on the issue of the dependence of R_{UVX} values on the source luminosity from observations of galactic X-ray sources; these indicate that the ratio of fluxes between the multicolor black-body disk (their BBB equivalent) and power-law-based hard X-ray components depends on the source luminosity: at high values of the source luminosity, the spectrum is dominated by the multicolor quasithermal disk component, with the harder X-ray component being subdominant and having high energy spectral index values of $\Gamma > 2$. At lower source luminosities, the multicolor disk spectrum becomes subdominant with hard X-ray index values of $\Gamma < 2$, indicating that the same source can exist in two different states (Esin et al., 1997, 1998). A similar behavior in the AGN would then account for the results of Strateva et al. (2005) if the sources at the highest values of L_{UV} , which exhibit the most negative values of α_{OX} , have the highest Eddington ratios.

The following section provides a brief review of the scaling employed in relation to the broader class of accretion problems, along with some data that evidence the presence of magnetohydrodynamic (MHD) winds off the entire extent of the AGN accretion disks. Furthermore, the presence of these winds is shown to imply a decreasing disk accretion rate toward the black hole and its conversion to a hot advection-dominated accretion flow (ADAF) that accounts for the AGN X-ray emissions and their effects on the relative AGN UV and X-ray luminosities. Finally, the concluding section presents some general comments and observations regarding the overall AGN properties and future directions to be pursued for their deeper understanding.

2 AGN/X-ray binaries accretion disks and winds

2.1 Accretion/outflow unification along the mass scale

As discussed in Kazanas et al. (2012), for problems regarding accretion or winds in the gravitational field of a black hole, it

is convenient to normalize the radius by their Schwarzschild radius $x = r/r_s, r_s = 2GM/c^2 \approx 3 \times 10^5 M_\odot$ cm, the luminosity by their Eddington luminosity $L_E = 2\pi m_p c^3 (r_s/\sigma_T) \approx 1.3 \times 10^{38} M_\odot$ erg/s (where m_p and σ_T are the proton mass and Thomson cross section, respectively), and the accretion rate by their corresponding Eddington rate, i.e., $\dot{m} = \dot{M}/\dot{M}_E$ (where $\dot{M}_E = L_E/c^2$). These scalings then indicate that as long as the flow velocities are proportional to the Keplerian ones $v \propto v_K = c(2x)^{-1/2}$, the Thomson depth of the flows τ is independent of the black hole mass and depends only on $\dot{m}$ and the dimensionless radius x , such that $\tau = r_s \sigma_T n_0 \approx \dot{m}$ for $x \approx 1$ with n_0 being the density normalization near the horizon. The universality of the X-ray properties of the AGN and galactic X-ray binaries, which involve mainly their Thomson depths, argues favorably for this point of view.

This scale invariance is broken by processes including absorption, the BBB disk emission, and AGN tori temperatures, whose properties scale with the black hole mass and x . The maximum temperature associated with the BBB, assuming $x \approx 1$, is given by $T_{BBB} \approx 10^5 (\dot{m}/M_8)^{1/4} = 10^7 (\dot{m}/M_1)^{1/4}$. For high-luminosity AGN with masses in the range of $10^8 M_\odot$ to $10^9 M_\odot$, this feature peaks in the UV part of the spectrum; for galactic accreting black holes of mass only a few solar masses, the feature peaks in the soft X-ray spectral band, in agreement with observations. Similarly, the tori temperatures scale as $T_{tor} \sim 300 (\dot{m}/M_8^3)^{1/4} x_6^{-1/2}$ K, where $x_6 = (x/10^6)$.

For the BBB, X-rays, and their corresponding scalings that are in broad agreement with observations over the black hole mass range of eight decades, it is reasonable to consider that the accretion of a black hole can be studied along the accreting black hole mass scale using a reasonably small number of parameters. The tori temperatures are also in broad agreement with observations, but their luminosities depend on the physical characteristics; their apparent absence in the galactic X-ray sources depend on the sizes of their accretion disks, as discussed later.

2.2 Wind structure and ionization

One of the more significant discoveries of the ASCA, Chandra, and XMM-Newton is the presence of blue-shifted absorption features in the X-ray spectra of $\geq 50\%$ of the AGN, whose origins lie in the photoionization of the outflowing plasma by the AGN continuum. The X-ray absorbers are of particular interest because of their wide range of ionization states (Fe XXVI to Fe II) and corresponding range of outflow velocities from $v \sim 300$ – 500 km/s (referred to as warm absorbers (WA) (Reynolds and Fabian, 1995)) to $v > 10,000$ km/s (referred to as ultrafast outflows (UFOs) (Tombesi et al., 2010)). A similar fraction of the AGN spectra was also found by the Hubble space telescope (HST) to exhibit UV absorbers (Crenshaw et al., 2003), indicating the ubiquitous presence of winds in accreting black holes.

2.2.1 Absorption measure distribution

The wide ranges of ionization states and velocities have prompted the consideration of different regions with various values for their ionization parameter $\xi = L_{ion}/n(r)r^2 = L_{ion}/N_H r$ (where L_{ion} and $n(r)$ are the ionizing luminosity and plasma density, respectively) and velocity v . In this respect, Holczer et al. (2007)

and Behar (2009) offered a different approach: they assumed a continuous variation of the absorber equivalent width given by $N_H(r)$ as a function of the ionization parameter ξ , i.e., $N_H(r) \sim \xi^\alpha$, or more specifically what they called the absorption measure distribution, $AMD = dN_H/d\log \xi \propto \xi^\alpha$, to derive a value for the parameter α through a global fit of the values of N_H of the ions over a wide ξ range. Incidentally, by virtue of the definition of ξ , the AMD also implies a power-law range for the plasma density $n(r)$ along the line of sight (LoS) of the observer in the form $n(r) \propto r^{-s}$, with $s = (2\alpha + 1)/(\alpha + 1)$. The analysis of five AGN by Behar (2009) indicated values of $\alpha \approx 0$ – 0.3 , implying values of $s \approx 1$ – 1.25 . These values indicate that the ionization parameter $\xi(r) \propto r^{(2-s)}$ decreases with distance r from the accreting black hole, implying that the lower ionization species occur at larger distances and therefore have lower velocities. This indeed appears to be the case since we generally have $v(r) \propto r^{-1/2}$ in accretion/wind problems. The radial dependence of the wind column is then given by $N_H(r) \approx r^0 - r^{-0.25}$, which is a rather slow variation that allows discernible absorption even for the lowest ξ ions.

Clearly, these scalings are very different from those expected for radiatively or thermally driven winds that are generally considered in AGN. The latter, which are driven from regions of limited extent but high luminosity L or temperature T , develop a radial density dependence steeper than $n(r) \propto r^{-2}$ as the wind accelerates with $n(r) \propto r^{-2}$ asymptotically, implying that the wind ionization increases with distance while the asymptotic column density $N_H(r) \propto r^{-1}$ decreases sufficiently fast to preclude a significant column for the ions forming at the largest distances (highest ξ ions). The winds uncovered by these ionization structure studies are obviously distinctly different from those reported by Tombesi et al. (2013) if they are to conform to the relations discussed above; in fact, they are consistent with the winds launched by the rotation of the magnetic fields that thread the AGN accretion disks across their full extent (Blandford and Payne, 1982; Contopoulos and Lovelace, 1994). These range from near the black hole to the length of its sphere of influence, namely, 10^5 – $10^6 r_s \sim 1$ pc, i.e., out to the AGN tori; in fact, as proposed by Konigl and Kartje (1994), these MHD winds are the AGN tori. These winds are the solutions of the axisymmetric MHD equations under self-similar conditions, which is a reasonable assumption considering their great radial extent. Their power-law density scalings are a consequence of the self-similarity, along with their angular (poloidal) distribution given by the equation of transverse momentum balance or Grad-Safranov equation.

2.2.2 Wind ionization structure

Assuming a power-law radial wind density provided by the accretion disk MHD wind models of Contopoulos and Lovelace (1994), Fukumura et al. (2010a, 2010b) computed the ionization structures of the winds with the density parameter $s = 1$, i.e., $\alpha = 0$. The results of these calculations are shown in Figure 2B and depict the ionic columns of several Fe ions, namely, Fe XXV, Fe XVII, Fe XIII, and Fe III, as functions of ξ or r . It can be seen that while the distance of the maximum column among these ions increases with decreasing ionization state, the maximum value remains independent of r or ξ , in broad agreement with the data.

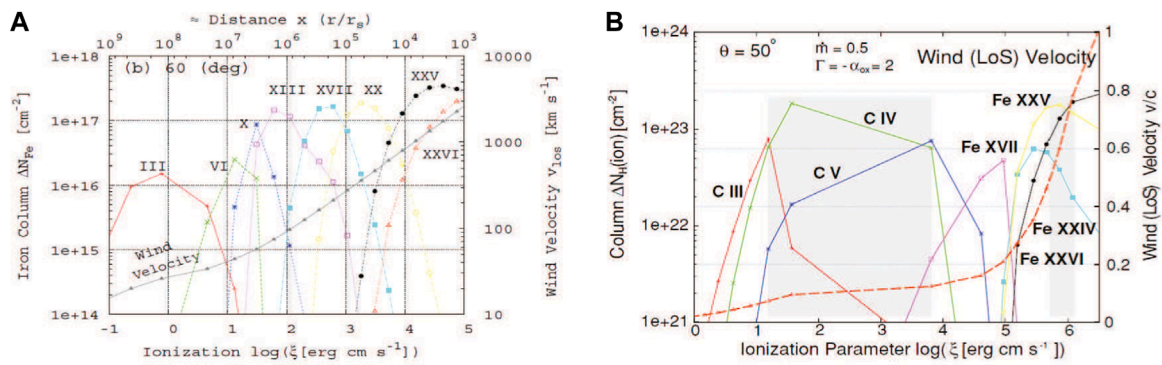


FIGURE 2

(A) Ionization structure of a wind having a density profile with $p = 1$ as a function of ξ and distance from the black hole. The wind velocity with distance r is given by the dashed line. (B) Ionization structure of the same wind but with an ionizing flux $\times 10$ smaller. The shaded region indicates the ξ range over which C IV and C V can be found, showing that reduction of the ionizing flux can increase the outflow velocities.

Fukumura et al. (2010b) showed the ionization structures of these winds with the X-ray luminosity decreased relative to that of the BBB (which is used to set the normalizations of the accretion disk and wind densities at the inner disk edge, i.e., $x = 1$). The decrease in the ionizing flux (for a given density as a function of r) decreases the location of occurrence of a given ion, thus increasing its corresponding velocity. Hence, when all other conditions are equal, according to these considerations, the broad absorption line quasi-stellar objects (BAL QSOs) must be associated with the AGN of the reduced X-ray relative to the UV fluxes, a fact that is generally consistent with the observations.

To further test the notion that much of the absorber phenomenology can be accounted for by the photoionization of a given MHD outflow when given the ionizing luminosity, Fukumura et al. (2018) employed the same type of MHD wind model to derive a global fit to the data of the galactic X-ray binary GRO 1655-40, a source exhibiting blue-shifted features with high S/N ratio. In accordance with the proposed notion, because the bolometric source luminosity (including that of the quasithermal BBB component) is also the ionizing luminosity for black holes of $M \sim 10M_{\odot}$, given the same value of the outflow Thomson depth τ as that of the AGN (τ is independent of the black hole mass), the outflow is fully ionized to a larger distance; as a result, ions with the highest ionizations, such Fe XXVI and Fe XXV, also occur at velocities of $v \sim 2,000$ km/s, while ions with lower ionizations like Ne X have velocities of only $v \sim 300$ km/s (Figure 3).

2.3 L_{UV}/L_X ratio

One of the most important consequences of the specific values of the wind density profiles $n(r)$ obtained by Behar (2009) and employed in the models of Fukumura et al. (2010a) is the wind mass flux, especially its radial dependence that is given in dimensionless units by

$$\begin{aligned} \frac{\dot{M}(x)}{\dot{M}_E} &= \dot{m}(x) \approx r_S n_0 \sigma_T x^2 x^{-p} x^{-1/2} = \dot{m}_0 x^{3/2-p} \\ &= \dot{m}_0 x^{\beta} \quad \beta = 3/2 - p. \end{aligned} \quad (1)$$

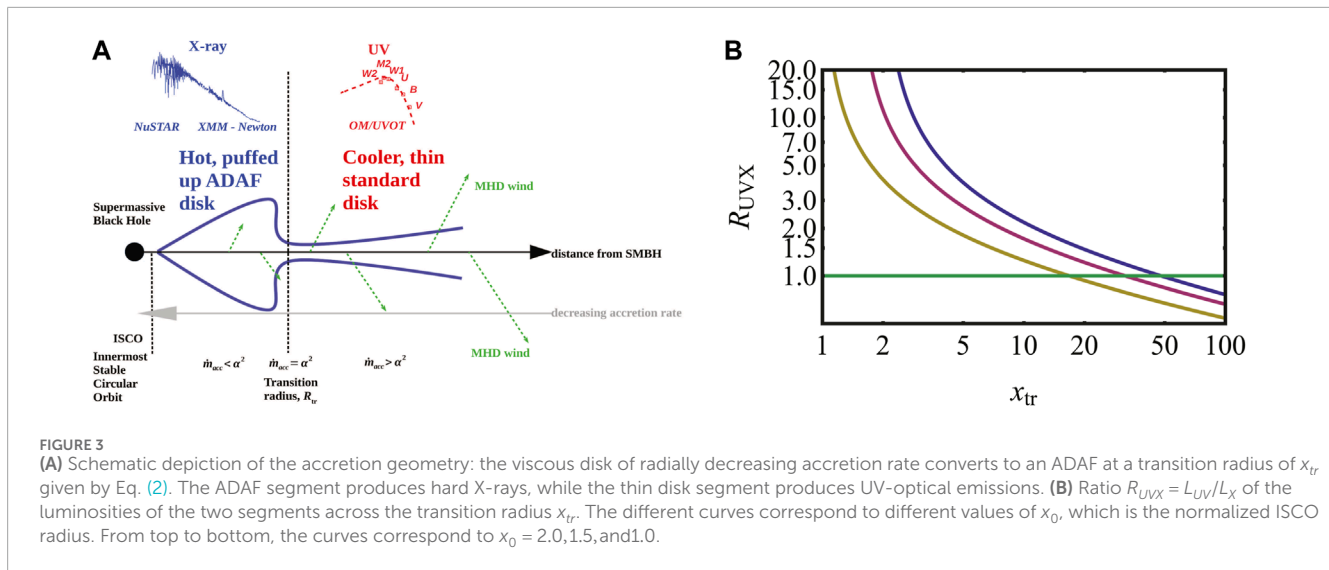
It is interesting to note that for $p < 3/2$, the wind mass flux increases with distance from the black hole. This behavior implied by the absorber observations is allowed within the MHD disk wind approach of Contopoulos and Lovelace (1994) and is crucially related to the possibility of wind launching across the entire disk domain.

At the same time, the mass flux in the disk, i.e., its accretion rate, decreases toward the black hole, implying that the disk deviates from that of the standard SS73 (Tombesi et al., 2013; Luminari et al., 2020) and that the disk loses most of its available matter and angular momentum to the wind. This provides the possibility of converting the inner segments of the disk to an ADAF (Narayan and Yi, 1994) or rather an ADvection Inflow-Outflow Solutions (ADIOS) (Blandford and Begelman, 1999). As noted by Narayan and Yi (1994), this occurs when the local dimensionless accretion rate $\dot{m}(x) < \alpha^2$, where α is the (local) disk viscosity coefficient.

These considerations bring consistency to the picture of the X-ray binary disks as functions of their luminosities, as described in Esin et al. (1997, 1998); these authors conjectured the presence of an ADAF in the inner flow regions based on observations and that its size decreased with increasing luminosity, i.e., with increasing $\dot{m}$. Equation (1) then implies that there is a transition radius at $x = x_{tr}$ such that

$$\dot{m}_0 x_{tr}^{\beta} = \alpha^2, \quad \text{or} \quad x_{tr} = \left(\frac{\alpha^2}{\dot{m}_0} \right)^{1/\beta} \quad (2)$$

and that for $x > x_{tr}$, the disk geometry is that of the standard black body emitting accretion disk of luminosity L_{UV} ; here, we assume an AGN of sufficiently large black hole mass to emit in the UV. However, for $x < x_{tr}$, the disk geometry is that of the geometrically thick hot ADAF/ADIOS, which is the main source of X-ray emission. It is worth noting that such a geometry is supported by recent X-ray polarimetric observations (Krawczynski et al., 2022; Gianolli et al., 2023; Tagliacozzo et al., 2023). These considerations then allow separate computations of the quasithermal viscous disk emission and X-ray emission by accounting for the efficiency of the hot/ADAF being proportional to $\dot{m}(x)$ and the presence of an inner edge to this disk segment at the ISCO of $x = x_0 \approx 1$ (depending on the value of the black hole spin), which limits its efficiency; it is assumed that



there is no X-ray production in the free-falling segment of the flow interior to x_0 . Under these conditions, the following expressions are obtained for L_{UV} and L_X .

$$L_X \propto \int_{x_0}^{x_{tr}} \frac{\dot{m}(x)^2}{x^3} \left[1 - \left(\frac{x_0}{x} \right)^{1/2} \right] x dx, \quad (3)$$

$$L_{UV} \propto \int_{x_{tr}}^{\infty} \frac{\dot{m}(x)}{x^3} x dx, \quad (4)$$

It should be noted that the ratio of the quantities of Eqs 3, 4, $R_{UVX} = L_{UV}/L_X$, depends mainly on the dimensionless accretion rate $\dot{m}_0$ and value of x_{tr} given by Eq. (2). It should also be noted that for a sufficiently large value of $\dot{m}_0$, L_X can nominally vanish as the X-ray emitting disk segment $[x_0, x_{tr}]$ is “squeezed” to near zero. This notion is consistent with statements on recent observations of the X-ray transient source MAXI J1820 + 070, whose corona contracted as the source luminosity increased (Kara et al., 2018).

According to the proposed notion, the general fact is that for bright AGN, $L_{UV} > L_X$ is indicative of the dimensionless accretion rates. On the other hand, at sufficiently low values of $\dot{m}_0$, the X-ray luminosities may be comparable to those of the thermal components, indicating a value close to fifty for x_{tr} , as shown in Figure 3.

Figure 3A presents a schematic representation of the disk structure including the standard and ADAF components along with the corresponding spectra of each segment. Their given shapes are only indicative and can be calculated more accurately if the size of the X-ray region is given along with the electron heating rates.

3 Discussion: timing implications

We present a global perspective of the AGN physics and resulting SED components within the framework of a single parameter, namely, the dimensionless accretion rate. It should be noted that the single most important feature of this entire scheme is the radial decrease of the disk accretion rate effected by the MHD winds launched across the entire disk domain. These apparently remove and eject most of the mass available for accretion onto the black

hole (along with the angular momentum) to infinity to provide the observed phenomenology of the X-ray emission, BBB, and FIR molecular tori. It is important to note that within the present framework, these components are not independent but related via the same global MHD winds that extend over six decades in terms of radius. The X-ray absorber observations and their corresponding wide x_i ranges are crucial for developing and establishing this notion, which help determine the dependence of their density on distance from the black hole through the AMD.

The wide radial ranges of these winds also imply a very wide range of the AGN time-domain properties. Unfortunately, human limitations cannot capture the entire range of AGN variations. In this respect, the scale invariance of the column densities allows scaling of the variability studies of accreting galactic black holes to the properties of the AGN brethren. As much as this scaling may be reasonable, it is not clear to this author that such an extrapolation would indeed be valid. However, time-domain studies that could even refute such scaling would be invaluable in probing the physics underlying the accretion dynamics.

Time reverberation studies by Kara et al. (2021) and the references therein have provided much information for probing the near-black-hole geometry. Despite much efforts, the preferred model of a lamppost over a thin viscous disk cannot reproduce the entire phenomenology. The picture of the accretion flow given in Figure 3 along with the underlying physics of the radially variable accretion rate may provide novel insights on the geometries and physics to be tested with this technique.

Finally, the tidal disruption of stars by the AGN black holes (Chan et al., 2019 and references therein) can lead to interesting phenomena that could provide additional tests to the above picture. First of all, a stellar disruption will provide additional mass for accretion and also ejection. In either case, one can expect novel phenomena: higher accretion rates should modify the SEDs, while ejection of matter through the winds of roughly constant columns should have different observables if launched in vacuum. Of great interest here would be the variation of the properties of the absorbers following such an event (Pasham et al., 2024). Sufficient sensitivity and spectral resolution will also enable

mapping of the interaction phase space along the LoS of the observer. Furthermore, studies on the line emission properties will offer a broader picture of the results of such interactions. The future of time-domain studies thus looks very promising.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Radio transients from compact objects across the mass spectrum in the era of multi-messenger astronomy

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Compact objects across the mass spectrum—from neutron stars to supermassive black holes—are progenitors and/or central engines for some of the most cataclysmic phenomena in the Universe. As such, they are associated with radio emission on a variety of timescales and represent key targets for multi-messenger astronomy. Observations of transients in the radio band can unveil the physics behind their central engines, ejecta, and the properties of their surroundings, crucially complementing information on their progenitors gathered from observations of other messengers (such as gravitational waves and neutrinos). In this contribution, we summarize observational opportunities and challenges ahead in the multi-messenger study of neutron stars and black holes using radio observations. We highlight the specific contribution of current U.S. national radio facilities and discuss expectations for the field focusing on the science that could be enabled by facilities recommended by the 2020 Decadal survey such as the next generation Very Large Array (ngVLA).

KEYWORDS

gravitational waves, high energy neutrino astrophysics, radio astronomy, radio array, black holes, supermassive binary black holes, neutron star binaries, AGN -active galactic nucleus

1 Introduction

The study of compact objects across the mass spectrum—from neutron stars with masses comparable to that of the Sun to supermassive black holes at the center of galaxies hundreds of thousands to billions times more massive—has entered a golden era. Indeed, electromagnetic observations of transients associated with compact objects are being enriched, if not revolutionized, by observations of completely independent messengers, namely, gravitational waves and high-energy neutrinos (e.g., [Abbott et al., 2017b](#); [IceCube Collaboration et al., 2018a](#)). While currently multi-messenger studies of compact objects remain limited to a relatively small number of sources, continued effort and investment in the field can greatly impact our understanding of the physics of compact objects across the whole mass spectrum of neutron stars and black holes. Indeed, the mass spectrum of neutron stars and black holes includes regions that are currently poorly characterized,

such as the mass range where the dividing line between neutron stars and stellar-mass black holes (the lower mass gap, e.g., Abbott et al., 2020b; Gupta et al., 2020) lies, and the mass range thought to be populated by intermediate-mass black holes (e.g., Abbott et al., 2020a; Greene et al., 2020; Abbott et al., 2024). Improved gravitational-wave and particle detectors envisioned to be operational in the next decade and beyond are key to opening new opportunities for multi-messenger discoveries ahead. At the same time, it is critical that our observational capabilities across the bands of the electromagnetic spectrum continue to improve in parallel with that of gravitational-wave and particle detectors. Otherwise, we will soon reach a stage at which multi-messenger studies of transients associated with compact objects will be limited by the sensitivity of electromagnetic facilities rather than by the horizon distances of gravitational-wave and particle detectors (the current major limitation).

In this short review, we discuss the role that the radio band of the electromagnetic spectrum plays in multi-messenger studies of compact objects, focusing on the science enabled by current and future U.S. national radio facilities. Our paper is organized as follows. In Section 2, we briefly summarize the past and present of time-domain multi-messenger astronomy done with radio observations; in Section 3, we discuss some future opportunities that have great potential for enabling new discoveries and conclude.

2 The radio contribution to multi-messenger studies of compact objects

Radio observations play a key role in all three scientific priorities for the coming decade identified in the *Pathways to Discovery in Astronomy and Astrophysics for the 2020s* report (hereafter, Astro 2020; National Academies of Sciences Engineering and Medicine, 2021), and are critical to the “New Windows on the Dynamic Universe” science priority area. This priority includes using “time-resolved multi-wavelength electromagnetic observations from space and the ground with non-electromagnetic signals to probe the nature of black holes, neutron stars, and the explosive events and mergers that give rise to them.” In fact, radio wavelength observations play a crucial role in the study of black holes and neutron stars, as emission in this band probes the presence of fast, non-thermally emitting ejecta largely independently of geometric effects. Radio wavelength observations also are critical for enabling very high-resolution observations that can either resolve the ejecta and/or enable proper motion measurement of the source structure (unveiling fast jet components via observations of superluminal motion). Several recent observational results demonstrate the central role played by observations in the radio band in multi-messenger discoveries that are revolutionizing the way we study the cosmos. We briefly summarize these key discoveries in what follows.

2.1 Radio observations and gravitational-wave astronomy

The multi-messenger discovery of GW170817 (Abbott et al., 2017b), a binary neutron star merger for which

the gravitational-wave siren was unveiled by LIGO (LIGO Scientific Collaboration et al., 2015) and Virgo (Acernese et al., 2015), initiated what can be considered a revolution in time-domain multi-messenger astronomy of stellar-mass compact objects. GW170817 was accompanied by a short γ -ray burst (GRB; Abbott et al., 2017a), and extensive follow-up identified its kilonova counterpart—a quasi-thermal transient associated with r -process nucleosynthesis occurring in the merger neutron-rich debris (Chornock et al., 2017; Coulter et al., 2017; Cowperthwaite et al., 2017; Drout et al., 2017; Evans et al., 2017; Kasliwal et al., 2017; Nicholl et al., 2017; Pian et al., 2017; Smartt et al., 2017; Soares-Santos et al., 2017; Tanvir et al., 2017; Valenti et al., 2017; Villar et al., 2017). The kilonova identification enabled the arcsec localization of GW170817 and measurement of its distance at approximately 40 Mpc (Hjorth et al., 2017; Im et al., 2017; Levan et al., 2017; Palmese et al., 2017; Pan et al., 2017). Subsequent X-ray-to-radio follow up probed the GRB afterglow (Alexander et al., 2017; Haggard et al., 2017; Hallinan et al., 2017; Margutti et al., 2017; Troja et al., 2017; Mooley et al., 2018a; Mooley et al., 2018b; Margutti et al., 2018). The radio band, in particular, proved unique. Extensive monitoring of GW170817 with the Karl G. Jansky Very Large Array (VLA) revealed a steady increase of the optically thin 3 GHz flux during the first ≈ 100 d since merger (Hallinan et al., 2017; Mooley et al., 2018a; Mooley et al., 2018b)—something very different from the power-law decaying radio afterglows of cosmological short GRBs. The sensitivity of the VLA was essential to probe the rising part of the afterglow light curve without interruptions that affected, e.g., the X-ray band due to the Sun’s proximity. The resolution provided by the VLA in its most extended configurations was essential to avoid contamination of the measured radio flux from the nearby, radio-emitting core of the host galaxy NGC 4993 (e.g., Hallinan et al., 2017; Levan et al., 2017). Radio monitoring, including importantly Very Long Baseline Interferometry (VLBI) observations (Mooley et al., 2018a; Ghirlanda et al., 2019), proved critical to establish that the delayed afterglow was produced by an off-axis structured jet—the first off-axis jet to be securely identified after about 20 years since the discovery of GRB afterglows (Costa et al., 1997).

Overall, radio observations of compact binary mergers containing at least one neutron star can constrain the ejecta structures (energy-speed distributions), the viewing geometries, the densities of the media around the merger sites, the structure of the magnetic field, and provide hints on the nature of the merger remnant (e.g., Nakar and Piran, 2011; Metzger and Bower, 2014; Fong et al., 2016; Horesh et al., 2016; Mooley et al., 2018a; Mooley et al., 2018b; Corsi et al., 2018; Dobie et al., 2018; Hotokezaka et al., 2018; Lazzati et al., 2018; Kathirgamaraju et al., 2019; Gill and Granot, 2020; Liu et al., 2020; Balasubramanian et al., 2021; Makhathini et al., 2021; Nedora et al., 2021; Teboul and Shviv, 2021; Balasubramanian et al., 2022; Nedora et al., 2023; Sadeh et al., 2024). Looking to the future, as the sensitivities of the LIGO, Virgo, and KAGRA detectors continue to improve (Akutsu et al. 2019; Abbott et al., 2021; Abbott et al., 2022), a collection of a larger sample of multi-messenger detections with deep radio follow-up observations would shed light on many currently open questions (e.g., Corsi et al., 2024). For example, what is the diversity of radio counterparts to compact binary mergers? Do all neutron star binary mergers power jets? As the horizon of multi-messenger studies of neutron star binary mergers reaches the peak of star formation with

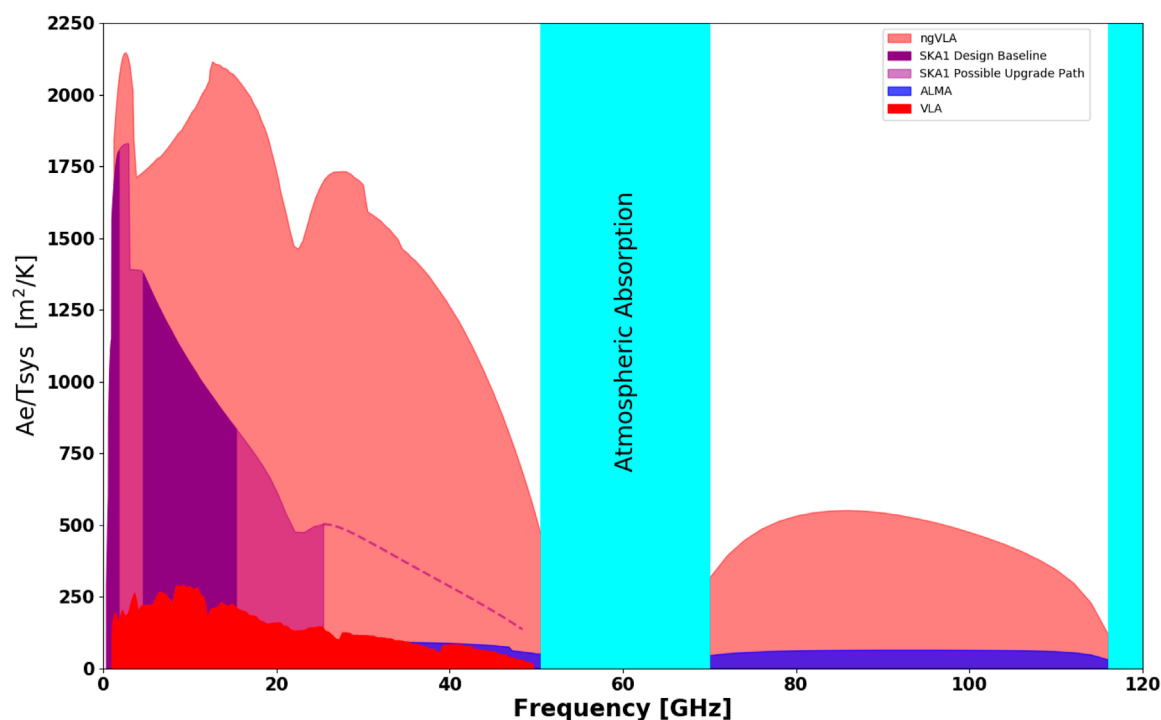


FIGURE 1

This Figure is an updated version of Figure 9 in Selina et al. (2018). The effective collecting area for the ngVLA is plotted versus frequency and compared to that for other existing (VLA and ALMA) or planned (SKA; Braun et al., 2019) facilities. Compared to the VLA, the ngVLA will have 10× the sensitivity and 10× the resolution at comparable frequencies. As highlighted by Murphy E. et al. (2018), this implies that with the ngVLA it will become possible to map a ~ 10 deg² region (i.e., the localization uncertainty expected by gravitational wave detectors when ngVLA is operational) to a depth of ~ 1 μ Jy/bm at 2.5 GHz in ~ 10 hrs.

next-generation, ground-based gravitational-wave detectors such as Cosmic Explorer and the Einstein Telescope ($\sim 10 \times$ the sensitivity of LIGO detectors; Branchesi et al., 2023; Evans et al., 2023; Gupta et al., 2023), it would be possible to link each short GRB radio afterglow to a progenitor (as probed in gravitational waves) and understand the physics behind such mapping (e.g., Ronchini et al., 2022). Key to this end is that the sensitivity and resolution of PI-driven national radio arrays, such as the VLA, continue to increase in parallel with the improving sensitivity of gravitational-wave detectors (§3).

Radio observations also promise to be critical for extending multi-messenger studies of gravitational wave sources to the highest end of the mass spectrum of compact objects, i.e., the region populated by supermassive black holes found at the center of galaxies (Volonteri et al., 2021). Pulsar timing arrays (PTAs), such as the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), and the Laser Interferometer Space Antenna (LISA) are opening, or will soon open, complementary observational windows on massive black-hole binaries. While PTAs currently probe the stochastic gravitational-wave background from massive black-hole binary populations, over the next decade, both PTAs and LISA will detect individual black hole binaries. Multi-messenger studies of these massive black holes in binaries are critical to constrain, on large scales, the merger rate of massive galaxies and, on smaller scales, the dynamics of stars and gas in galactic cores (e.g., Burke-Spolaor et al., 2019; Arzoumanian et al., 2021; Mangiagli et al., 2022; Amaro-Seoane et al., 2023; Arzoumanian et al., 2023; Agazie et al., 2023;

D’Orazio and Charisi, 2023; Liu et al., 2023; Stegmann et al., 2023). Currently, the uncertainties that affect the dynamics of massive black-hole binaries leave open various scenarios predicting different delay times between the galaxy mergers and the black-hole coalescences. This delay time determines, e.g., the LISA detection rate, and depends critically on the residence time (or how long the binary stays) at parsec-scale separations (Katz et al., 2020; DeGraf et al., 2024). The residence time at a given separation can in turn be constrained via radio observations. In fact, when one or both black holes are actively accreting, their AGN jets produce radio emission and jet cores trace the location of the black holes at small separations (1 pc–100 pc), which are spatial scales that can be sampled via very long baseline radio interferometry (VLBI, Burke-Spolaor, 2011; Breiding et al., 2021). Radio wavelength observations also can probe jets that may form right before, during, and after the merger phase, via the interaction between the plasma surrounding the black holes and the magnetic fields, as well as jets originating from accretion on the black holes or their final merger remnant (Schnittman, 2011; Bogdanović et al., 2022).

2.2 Radio observations and high-energy neutrino astronomy

Neutrino astronomy has boomed in recent years, as multi-messenger observations of high-energy neutrinos have

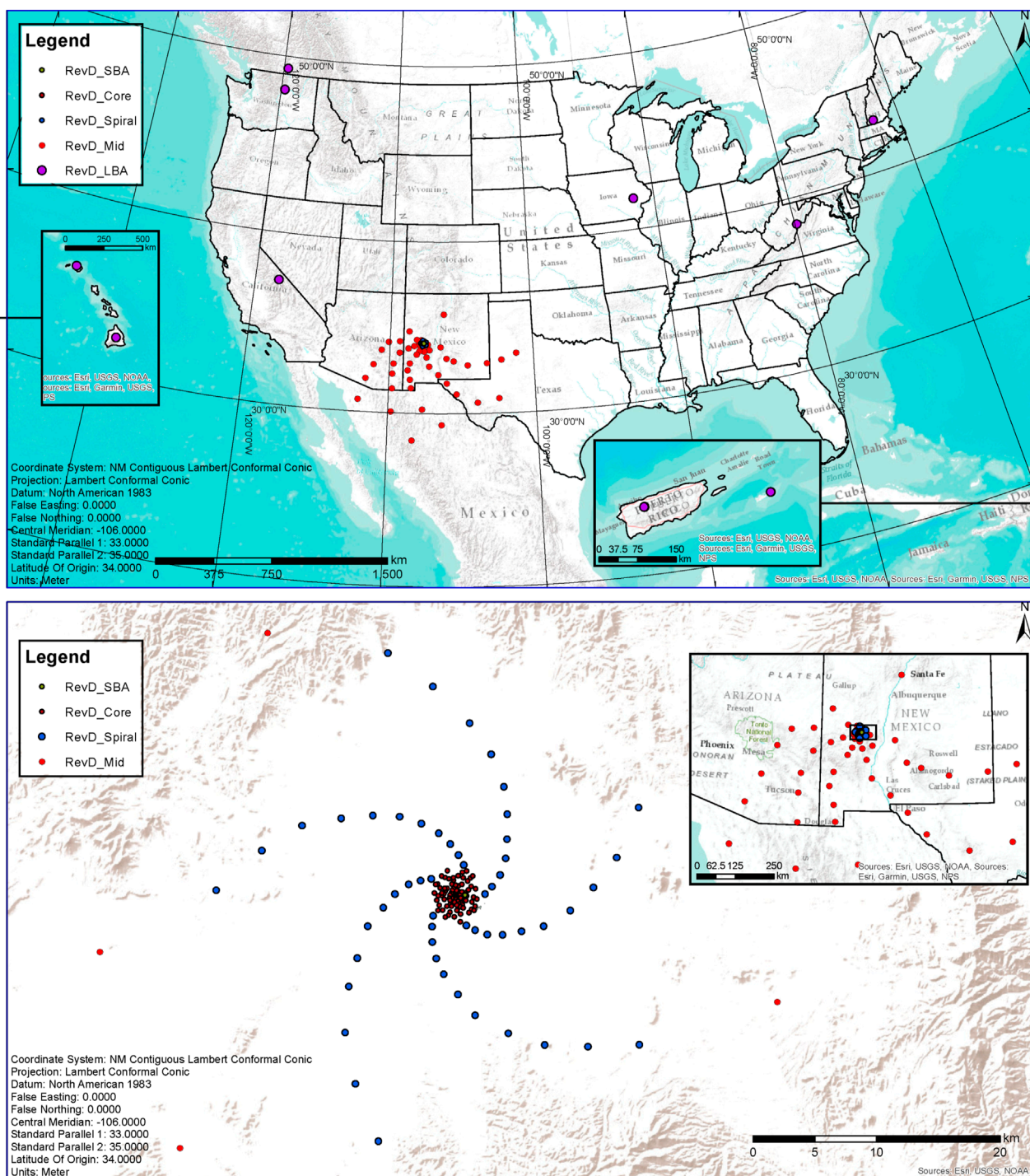
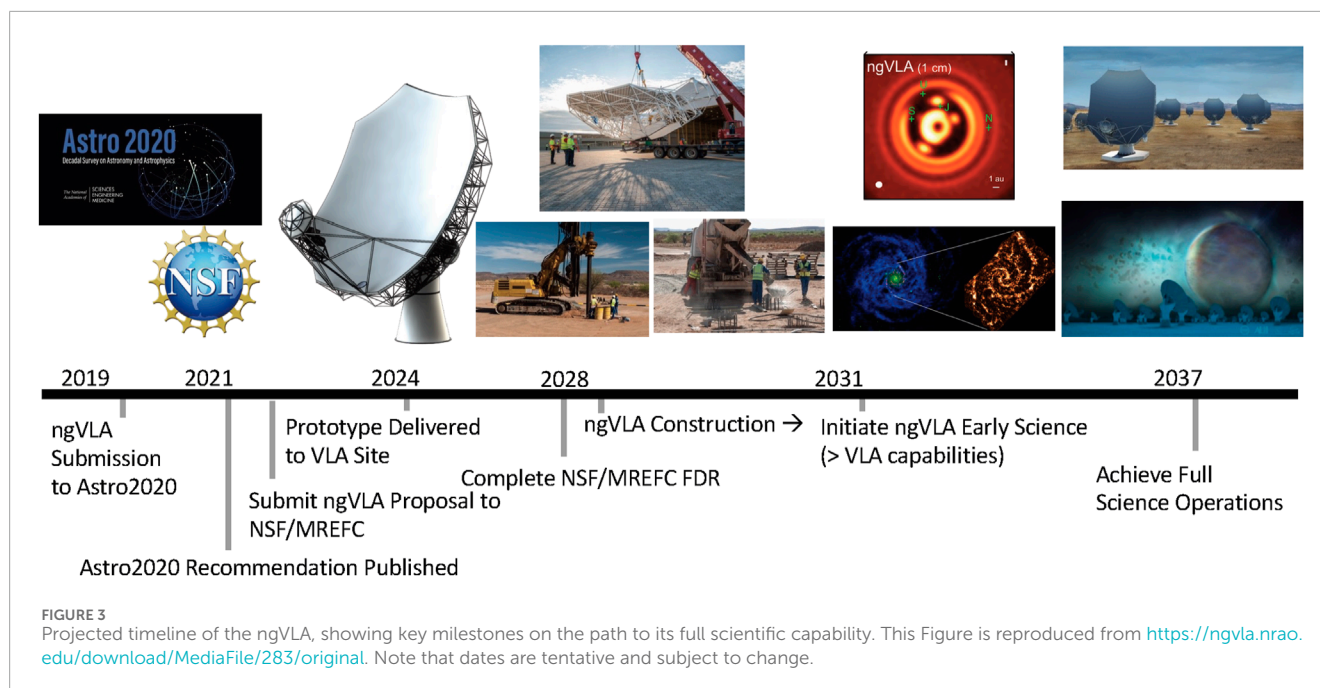


FIGURE 2

This Figure is reproduced from [Murphy \(2022\)](#). Top: A potential configuration layout for the ngVLA showing all 263 antennas spread across the North American Continent. The Array is centered at the current VLA site on the plains of San Agustin in New Mexico. The legend associates each antenna with a logistical sub-component of the full array. Each of the long-baseline stations (purple dots) consists of three antennas. Bottom: A zoom-in of the main array showing the five-arm spiral pattern (54 18 m antennas) and dense core (114 18 m antennas). The maximum baseline of the spiral and core antennas is 29.3 and 4.3 km, respectively. The 19 6 m Short Baseline Array antennas are located within the central core.

been enabled by the IceCube detector ([Aartsen et al., 2017b](#)). Cosmic neutrinos are produced when accelerated cosmic rays (high-energy nuclei) interact with radiation fields

(photons) or with matter. Because neutrinos can traverse the Universe without being deflected by magnetic fields, they can pinpoint the astrophysical sources that produce them.



Identifying the sources of high-energy neutrinos can also shed light on their parent cosmic rays and the physics behind their acceleration (e.g., Ahlers and Halzen, 2018; Halzen and Khairandish, 2022).

IceCube has discovered an extra-galactic diffuse flux of cosmic high-energy neutrinos (IceCube Collaboration, 2013). The radio band offers key insights for understanding the role of stellar-mass compact objects and their jets as sources of high-energy neutrinos and contributors to the high-energy neutrino background. While stacking analyses have shown that transients such as cosmological GRBs do not contribute a major fraction of the all-sky neutrino flux (Aartsen et al., 2017a; Abbasi et al., 2022; IceCube Collaboration et al., 2023; Lucarelli et al., 2023), theoretical models suggest that radio-emitting but γ -ray-dark, choked jets may lead to efficient high-energy neutrino production (e.g., Murase, 2015; Senno et al., 2016; Esmaili and Murase, 2018; Senno et al., 2018; Chang et al., 2022). Recently, Guarini et al. (2023) have emphasized that, while a significant fraction of the explosion energy of astrophysical transients associated with collapsing massive stars can be emitted in the infrared-optical-ultraviolet band, the optical signal alone is not optimal for neutrino searches. Instead, neutrino emission is strongly correlated with radio emission arising from either strong circumstellar medium interactions or with the presence of a central engine (e.g., Corsi et al., 2014; Corsi et al., 2023). Perhaps one of the most exciting prospects for future multi-messenger detections of stellar-mass compact objects would be to identify compact binary mergers containing neutron stars that could be probed not only via gravitational waves and radio light (as for the case of GW170817) but also via high-energy neutrino counterparts (e.g., Albert et al., 2017; Aartsen et al., 2020; Abbasi et al., 2023b; Mukhopadhyay et al., 2024). The last would probe dissipation mechanisms in relativistic outflows driven by the mergers (Albert et al., 2017; Abbasi et al., 2023a; Matsui et al., 2023).

The identification of the cosmic neutrino IceCube-170922A from the known blazar TXS0506 + 056 (IceCube Collaboration et al., 2018a) has also established a link between high-energy neutrinos and supermassive black holes in AGNs with jets aligned with our line of sight (γ -ray emitting blazars). Additional associations of high-energy neutrinos with sources other than blazars, such as the Seyfert II galaxy NGC 1068 (IceCube Collaboration et al., 2022) and a few tidal disruption event (TDE) candidates (e.g., Stein et al., 2021), leave open the debate on the relative role of potential γ -ray bright and γ -ray dark (or jet-quiet) high-energy neutrino emitters (Senno et al., 2017; Franckowiak et al., 2020; Kreter et al., 2020; Murase et al., 2020; Plavin et al., 2020; Kimura et al., 2021; McDonough et al., 2023; Murase and Stecker, 2023). In fact, IceCube identified a six-month-long cluster of events from TXS0506 + 056 in 2014–2015 that was not accompanied by increased γ -ray activity. Both the 2014–2015 neutrino flare and the IceCube-170922A neutrino event from TXS0506 + 056 are associated with intervals of enhanced radio emission (IceCube Collaboration et al., 2018b). In July 2019, the high-energy neutrino event IC190730A was found spatially coincident with the bright flat-spectrum radio quasar PKS 1502 + 106. While PKS 1502 + 106 was not found to be in a particularly elevated γ -ray state, it exhibited a bright radio outburst at the time of the neutrino detection. In 2022, the IceCube neutrino event IC220225A was identified in spatial coincidence with the flat-spectrum radio quasar PKS 0215 + 015 in a high optical and γ -ray state accompanied by a bright radio outburst (Eppel et al., 2023a; Eppel et al., 2023b).

In AGN jets, radio emission is a good proxy for the general jet activity (Hovatta et al., 2021). An increase in the radio flux density before a γ -ray flare could signal a long-term increase in the total jet power. Statistical studies aimed at understanding the connection between radio-loud AGNs and high-energy neutrinos are particularly important. For example, Plavin et al. (2020)

investigated the association of neutrinos with radio-bright AGN and found an average increase of radio emission at frequencies above 10 GHz around neutrino arrival times for several AGNs. [Plavin et al. \(2021\)](#) found a 3σ significance for the correlation between the IceCube point-source likelihood map and the VLBI radio fundamental catalog of AGN. [Hovatta et al. \(2021\)](#) found that observations of flares in OVRO-monitored blazars (at 15 GHz) at the same time as a neutrino events are unlikely to be random coincidences. [Suray and Troitsky \(2024\)](#) highlighted how IceCube neutrinos with energies over 200 TeV previously found to be associated with bright radio blazars are significantly more likely to be accompanied by flares of lower-energy events, compared to those lacking blazar counterparts. On the other hand, [Zhou et al. \(2021\)](#) investigated the possibility that radio-bright AGN are responsible for the TeV–PeV neutrinos detected by IceCube using 3,388 radio-bright AGN selected from the Radio Fundamental Catalog and found that stacking analyses show no significant correlation between the whole catalog and IceCube neutrinos. In summary, it is clear that radio plays an important role in shedding light on supermassive black holes as sources of high-energy neutrinos, though a larger number of high-confidence multi-messenger detections are needed to clarify the exact link between radio emission and sources high-energy neutrinos.

3 Discussion

Among the so-called “Large Programs That Forge the Frontiers,” the Astro2020 report recognized as essential that “the Karl Jansky Very Large Array (VLA) and Very Long Baseline Array (VLBA), which have been the world-leading radio observatories, be replaced by an observatory that can achieve roughly an order of magnitude improvement in sensitivity compared to those facilities. The Next Generation Very Large Array (ngVLA) will achieve this, with a phased approach where design, prototyping, and cost studies are completed and reviewed in advance of commencing construction.” Indeed, the ngVLA promises to be a key facility enabling studies of radio emission from sources of gravitational waves and high-energy neutrinos described in [Section 2](#) to be extended to the larger distance horizons ([Ahlers and Halzen, 2014](#); [Aartsen et al., 2021](#); [Evans et al., 2023](#); [Gupta et al., 2023](#); [Corsi et al., 2024](#)).

The ngVLA ([Murphy E. J. et al., 2018](#)) is being designed as an interferometric array of 263 antennas with $\approx 10\times$ greater sensitivity and spatial resolution than the current VLA and ALMA, operating in the frequency range of 1.2 GHz–116 GHz ([Figures 1–3](#)). The ngVLA configuration includes an ≈ 4 km diameter core consisting of 114 antennas centered at the current VLA site; a five-arm spiral of 54 antennas with a maximum baseline of ≈ 40 km (i.e., similar to the current VLA A-configuration); a set of 46 mid-baseline antennas that achieve a maximum baseline length of ≈ 1000 km; and, finally, a long-baseline antenna stations with ten sites spread across the North American Continent (for a maximum baseline of 8,857 km), each site equipped with three antennas. Hence, the ngVLA will greatly expand current U.S. VLBI capabilities by both replacing existing VLBA antennas/infrastructure with ngVLA technology and providing additional stations on 1000 km baselines to bridge the gap between the ≈ 40 km VLA-like baselines and the ≈ 9000 km VLBA-like or Continental baselines. Plans are already underway

to lay out a community-led plan for enabling a smooth transition from the VLA/VLBA to the ngVLA. To this end, a Transition Advisory Group (TAG)—a group of 18 members of the U.S. and international astronomical community—is working to develop, quantitatively assess, and evaluate a set of possible VLA/VLBA-to-ngVLA transition options prioritized based on their scientific promise (given the scientific opportunities for the coming decade), of their cost, and their technical/personnel impacts.

Based on the summary of §2, we expect the ngVLA to begin operations at the culmination of a phase of rapid growth in gravitational-wave and high-energy neutrino astronomy. The detection of radio emission from cataclysmic multi-messenger sources associated with neutron stars and black holes across the mass spectrum can enable their precise localization, help measure their energetics, and provide clues on their surrounding environments. The combination of multi-messenger information will provide a complete picture of the life-cycle of massive stars, the micro-physics of their explosive deaths, and the formation and evolution of neutron stars, stellar-mass black holes, and supermassive black holes. The future of multi-messenger astronomy looks bright, and it is key that the U.S. keeps a leading role in enabling this multi-messenger science in the radio band¹.

Author contributions

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

¹ library.nrao.edu/public/memos/ngvla/NGVLA_19.pdf

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A two-step strategy to identify episodic sources of gravitational waves and high-energy neutrinos in starburst galaxies

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Supermassive black hole (BH) mergers with spin-flips accelerate energetic particles through their relativistic precessing jets, producing high-energy neutrinos and finally gravitational waves (GWs). In star formation, massive stars form in pairs, triplets, and quadruplets, allowing second-generation mergers of the remnants with discrepant spin directions. The GW data support such a scenario. Earlier, we suggested that stellar mass BH mergers (visible in M82) with an associated spin-flip analogously allow the acceleration of energetic particles, with ensuing high-energy neutrinos and high-energy photons, and finally produce GWs. At cosmic distances, only the GWs and the neutrinos remain detectable. In this study, we generalize the argument to starburst and normal galaxies throughout their cosmic evolution and show that these galaxies may dominate over active galactic nuclei (AGN) in the flux of ultra-high-energy particles observed at Earth. All these sources contribute to the cosmic neutrino background, as well as the GW background (they detected lower frequencies). We outline a search strategy to find such episodic sources, which requires including both luminosity and flux density.

KEYWORDS

neutrinos, starburst, galaxies, black hole mergers, gravitational waves, particle acceleration

1 Introduction

Searches for identifying the source of a given high-energy neutrino or gravitational wave (GW) event usually try to find both coincidences in direction on the sky and some temporal coincidence, like excess emission at the same time. One of the best candidates for very high-energy particle acceleration is the effect of relativistic precessing jets during the merger of two black holes (BHs). Such an event has been proposed to be identified in the starburst galaxy M82, due to the action of the precession of a pair of powerful jets emanating from two stellar mass BHs prior to their merger (Kronberg et al., 1985; Allen and Kronberg, 1998; Biermann et al., 2018). As we will show, these jets match in their power the observed minimum of jet power of active galactic nuclei (Punsly and Zhang (2011)), and so they can be quite efficient in producing ultra-high-energy cosmic ray (UHECR) particles, and as a consequence high-energy neutrinos. In such a discussion, it is important to note that energetic neutrinos might be highly boosted in the direction of the jet at the time of emission, and so additional selection effects operate Kun et al. (2021) and Becker Tjus et al. (2022).

1.1 Binary star orbital angular momentum evolution

An important question is regarding the possibility of most or all stellar mass BHs being born with near maximal rotation. There are two obvious mechanisms to get them to rotate fast:

The first mechanism acts when the newly formed massive star has a rapidly rotating core, which remains in sufficiently high rotation until the star blows up as a supernova (SN), and the BH is formed (Chieffi and Limongi, 2013; Limongi and Chieffi, 2018; Limongi et al., 2020). This requires that angular momentum transport is small throughout the star and also that the wind does not remove a significant quantity of rotational angular momentum throughout the life of the star.

The second mechanism is plausible via tidal locking since most massive stars reside in binaries, triples, or even quadruple systems. In the following, we will work through the requirements for this path. This implies that during their evolution, binary stars get close enough to actually achieve tidal locking (Chini et al., 2012; Chini et al., 2013a; Chini et al., 2013b).

We will show that the removal of orbital angular momentum by the winds of the two stars is a key aspect.

For didactic simplicity, we consider two stars of equal mass M at a distance of $2r$ from each other orbiting in a circle with period P . Then, the total orbital angular momentum is given by

$$J_{orb} = \pi^{-1/3} M^{5/3} G_N^{2/3} P^{1/3}, \quad (1)$$

where G_N is Newton's constant of gravitation and the radial scale r can be connected to the other measures of the system by

$$r = \frac{1}{2\pi^{2/3}} M^{1/3} G_N^{1/3} P^{2/3}. \quad (2)$$

It follows that the time changes are given by

$$\frac{\dot{J}_{orb}}{J_{orb}} = \left(\frac{5}{3} \frac{\dot{M}}{M} + \frac{1}{3} \frac{\dot{P}}{P} \right), \quad (3)$$

and

$$\frac{\dot{r}}{r} = \left(\frac{1}{3} \frac{\dot{M}}{M} + \frac{2}{3} \frac{\dot{P}}{P} \right). \quad (4)$$

The loss of orbital angular momentum by a wind is given by

$$\dot{J}_{orb} = 2 \dot{M} r v_\phi (1 + \varepsilon_{W,B}), \quad (5)$$

where the term $\varepsilon_{W,B}$ describes the loss by the torque of the magnetic field (Weber and Davis, 1967), their Eq. 9), and v_ϕ is the rotational velocity of the flow. In this study, we assume that the orbital radius acts as a lever arm. It follows that the temporal evolution of the orbital radius is given by

$$\frac{\dot{r}}{r} = 2 \frac{\dot{M}}{M} \left(\varepsilon_{W,B} - \frac{1}{2} \right). \quad (6)$$

Next, we need to put this into context: the angular momentum transport from both stars is given by Weber and Davis (1967) in their Eqs. 8, 9

$$\dot{J}_{orb} = 2 \left(4 \pi r^2 \rho v_r v_\phi r + B_r B_\phi r^3 \right), \quad (7)$$

where v_r is the radial velocity and the ratio of the second term and the first term gives $\varepsilon_{W,B}$. The first term corresponds to $2 \dot{M} r v_\phi$ above.

It follows that for mass loss, and so for $\frac{\dot{M}}{M} < 0$, the orbital separation will increase for the case of no magnetic fields. However, for $\varepsilon_{W,B} > 1/2$, the orbital separation will decrease. For equipartition in the wind, $\varepsilon_{W,B} \approx 1$. If magnetic fields were really strong, it would allow a lever arm even larger than the orbital radius $\varepsilon_{W,B} > 1$.

We conclude here that magnetic winds are the key for driving massive binary stars together, allowing locked-in rotation. This gives rotation with the speed close to what had been assumed in the simulations of Limongi and Chieffi (2018) and Limongi et al. (2020).

The ratio of the magnetic term to the flow term can be written as the inverse of two Alfvén–Mach numbers:

$$M_{A,r} = \frac{v_r(r_*) \sqrt{4 \pi \rho(r_*)}}{B_r(r_*)}, \quad (8)$$

and

$$M_{A,\phi} = \frac{v_\phi(r_*) \sqrt{4 \pi \rho(r_*)}}{B_\phi(r_*)}, \quad (9)$$

where r_* is the radius, density ρ , rotational velocity v_ϕ , and tangential magnetic field B_ϕ are evaluated. In the long distance limit, here v_r goes to a constant, ρ as $1/r^2$, v_ϕ as $1/r$, B_r as $1/r^2$, and B_ϕ as $1/r$. It follows that $M_{A,r} \sim r$, and $M_{A,\phi} \sim 1/r$ so that the product $M_{A,r} M_{A,\phi} \sim 1$. Then,

$$\varepsilon_{W,B} = \frac{1}{M_{A,r} M_{A,\phi}} \sim 1. \quad (10)$$

In a number of OB stars compiled by Chini et al. from Chini et al. (2012), Chini et al. (2013a), and Chini et al. (2013b), a typical orbital period is approximately 4 days, with quite a spread. The initial typical radius of these stars is approximately $10^{12.2}$ cm, which is almost independent of mass (Chieffi and Limongi, 2013), and so the inferred typical initial surface velocity is approximately 300 km/s, just the high velocity used in these calculations (Limongi and Chieffi, 2018). Surface magnetic fields are of order 10^3 G

(Walder et al., 2012); however, the observational evidence suggests that some massive stars rotate more slowly with age rather than faster, as argued here. That could happen, if the local angular momentum is maintained so that the core rotates faster with time, and the outer parts of a star rotate more slowly with time. To obtain a quantitative estimate for $\varepsilon_{W,B}$, we have to adopt some further numbers: $v_r \approx 2000$ km/s, and for the magnetic field near the surface, we adopt a low estimate of $B_r \approx B_\phi \approx 100$ G. For the mass loss, we take $10^{-5} M_\odot \text{ yr}^{-1}$. This gives an estimate of $\varepsilon_{W,B} \approx 1$. If the magnetic fields were any stronger, $\varepsilon_{W,B}$ would be larger, and then the orbital angular momentum loss would be yet stronger, allowing the two stars to get closer even faster. However, if the magnetic fields were significantly weaker, this preponderance of the magnetic fields in removing orbital angular momentum would disappear, the two stars in a binary system would move apart, rotate ever more slowly, and the spin of the resulting BH might be far below maximal. The scant data (Walder et al., 2012) suggest that of the massive stars, not all end up producing a rotating BH, rotating near maximum; only some do. The fraction of massive stars in binaries that do produce a rotating BH is unknown at present.

However, there is the other option, mentioned at first above, that the cores of all massive stars are rotating fast right from the formation, allowing the surface to rotate much more slowly, and hence deceiving any observer. This will be relevant also for all massive stars in binary systems that do not tighten their orbit over time.

We will focus here on those stars that do produce a BH rotating near the maximum allowed. All well-observed radio supernovae (RSNe) seem to share a common property that the product of the magnetic field and the radius ($B \times r$) has the same value in the wind (Biermann et al., 2018; Biermann et al., 2019), comparing different radial scales r and different RSNe in one galaxy, M82, as well as in different galaxies. Furthermore, we note that this value is consistent with what has been observed around the SMBH in the galaxy M87 EHT-Coll. et al. (2019). Furthermore, the wind/jet power derived is consistent with the minimum jet power for radio-loud optically selected quasars (Punsly and Zhang, 2011). In many of the cases, the central SMBH is believed to be near maximum rotation (Daly, 2019), EHT-Coll. et al. (2019). In this study, we explain this property also in stellar mass BHs as a result of the central BH rotating near maximum at the beginning (Chieffi and Limongi, 2013; Limongi and Chieffi, 2018; Limongi et al., 2020), possibly reducing its angular momentum quite rapidly.

1.2 Angular momentum of the black hole

For all models, the final predicted BH angular momentum is approximately

$$J_{BH*} \geq 10^{51.1} \left(\frac{M_{BH*}}{10 M_\odot} \right)^2 \text{ erg s} \approx 10^{50.9} \left(\frac{M_{BH*}}{10 M_\odot} \right)^2 \text{ erg s} = J_{BH,max}. \quad (11)$$

If there is excess of angular momentum, it has to be dissipated before a BH can even form, even if near maximal rotation. There are several possibilities:

- First option: A small initial BH mass near its spin limit grows and sheds all excess angular momentum during growth

through tidal gravitational torque or through magnetic torque. As massive star explosions are very clumpy, this might produce GWs. No such waves have yet been detected.

- Second option: The collapse first forms a binary BH (BBH) or a binary of a BH and a neutron star. At each radius, the angular momentum contained matches the limiting number allowed for that mass. This implies that we have maximal differential rotation, for BBHs near maximal individual spins are plausible—individual spin-down has been shown to be slow (King et al., 1999). This option would produce a high-frequency GW event, and none has been seen as yet, that could be attributed to such a scenario for certain. On the other hand, three events have been seen with low mass partners LIGO/VIRGO-Coll. et al. (2021), which could be neutron stars or BHs. The sum of the two partners is consistent with the lowest mass BHs known. The aligned spin before the merger is consistent with 0 in all three cases, which is expected in such a scenario. A bright SN showing the explosion of a very massive star is implied to accompany the final merger of the two fragments turned BH or neutron star.
- Third option: There is a burst of ejected excess angular momentum and energy via magnetic fields: this is akin to a proposal by Bisnovatyi-Kogan (1970), and in many papers later, such as Bisnovatyi-Kogan and Moiseenko (2008). He proposed that this is the mechanism involved in explosion of massive stars to make a SN.
- Fourth option: A collapse into a Kerr geometry, with $(J_{BH} c)/(M_{BH}^2 G_N) > 1$, is allowed (Joshi et al., 2020). This is still an astrophysical BH (i.e., lot of mass compacted in small volume, with no event horizon). There are powerful mechanisms as to how such (a naked singularity) configuration very rapidly gives away angular momentum and settles to a rotating BH with a horizon. Here, one gets the required burst-like energy also from high angular momentum decay.

All options listed here lead to formation of a BH in near maximal rotation, a state which may last only a short time. So we will assume near maximal rotation for now, and revisit these arguments later again. If there is no excess to start with, the angular momentum can still be very close to maximal according to the simulations of Limongi et al. (2020).

2 Black hole mergers, supernovae, and other episodic events

In this study, we focus on stellar mass BH mergers, as one example of a short injection of energetic particles, recognizable via the cone of precessing jets, that clean out the interstellar medium (ISM) (e.g., source 41.9 + 58 in the starburst galaxy M82, Kronberg et al. (1985); Allen and Kronberg (1998); Biermann et al. (2018)).

2.1 Source 41.9 + 58, a second-generation stellar mass black hole merger?

The compact radio source 41.9 + 58 sits at the apex of a triangular region without radio emission opening south, with a less

regular region without radio emission to the north (Kronberg et al., 1985); a detailed image is shown in Biermann et al. (2018). The difference can be understood as the result of projection effects since the disk of M82 is slightly tilted relative to the line of sight. This can be interpreted as the action of a pair of two-sided precessing jets emanating from two coalescing active rotating BHs of stellar mass (Kronberg et al., 1985; Biermann et al., 2018). As most massive stars sit in stellar binary systems, triples, and often even quadruples, each close binary system will interact such that their spins can be expected to align, while distant binaries resulting from two first-generation mergers of two stars or BHs each can be expected to yield very different spin directions. Magnetic winds help bring two stars or two BHs together by removing orbital angular momentum. The large cone of precession results in the case that the two BHs initially have vastly different spin directions and the BHs slowly align their spin directions before their actual merger (Gergely and Biermann, 2009). This topology is inconsistent with an explosion in a stratified atmosphere since that always leads to a stem-like outflow (extensive literature is given in Biermann et al. (2018)). Such stem-like outflows are in fact seen as filaments above and below the disk of M82 (Biermann et al., 2018).

Could there be other such features hidden in the radio map of the inner region of M82 (Kronberg et al., 1985)? If a large proper motion were to be allowed, then there are a number of possibilities that allow an interpretation of another such double-cone feature, with source 44.0 + 59.5 a speculative option.

So the detection of one such source out of 43 yields a very uncertain estimate of their rate of 1 per 2,500 years in the starburst galaxy M82 (Biermann et al., 2018). M82 has a far infra-red (FIR) dominated luminosity of approximately $10^{10.6} L_{\odot}$ (Kronberg et al., 1985), and so that rate can be estimated to be correspondingly higher for a higher FIR luminosity.

2.2 Fraction of mergers among massive stars

In M82, we observe 43 compact sources (Kronberg et al., 1985), probably all of which are explosions of blue super giant (BSG) stars since the winds of red super giant (RSG) stars do not provide enough ram pressure to allow the quick formation of RSNe of the size as observed, of a few parsec (Kronberg et al., 1985; Allen and Kronberg, 1998; Allen, 1999; Biermann et al., 2018; Biermann et al., 2019). We find a single source, 41.9 + 58, which appears to be fully consistent with a second-generation BH merger. The FIR luminosity of M82 can be interpreted as a measure of the star formation rate. The SN rate for massive stars (i.e., all above a zero age main sequence (ZAMS) mass of approximately $10 M_{\odot}$) can be estimated to be within the range of 1 per 1.5 years and 1 per 5 years (Kronberg et al., 1985; Biermann et al., 2018), and so the rate of such second-generation mergers can be very crudely estimated to 1 in 1,000 of massive stars, with an error range of probably at least an order of magnitude.

2.3 Rate of mergers

Using a scaling with FIR luminosity yields a maximal rate of $10^{12}/10^{10.6} \times 1/2$, 500 per year, so approximately 1 in approximately 100 years at most. This is again an order of magnitude estimate only.

What is exactly the scenario of energetic particle injection? Powerful plasma jets precess and therefore continuously encounter new material to accelerate to ultra-high energies. This new material is fed to the central region of the starburst galaxy by friction in the interstellar medium (Toomre and Toomre, 1972; Wang and Biermann, 2000), in the model to consider any gaseous galaxy akin to an accretion disk Lüst (1952). Starburst galaxies often involve the merger of two galaxies, stirring up their ISM (Toomre and Toomre, 1972).

Then, the next question is the length of time of the active episode: for that, we use column 2 of Table 2 in Gergely and Biermann (2009), so the initial inspiral rate, scaling the expression in the last line, for the angle change, to $10 M_{\odot}$ and an equal mass binary, gives a time scale of 5 years, still a small fraction of 100 years. This implies that in our model, the injection of energetic particles due to the inspiral motion of active BHs is taken to last of order 5 years (this time scale scales linearly with mass). Therefore, the precessing motion makes the injection of new particles much more efficient for acceleration than in a non-moving jet. Thereafter, when the merged BH drives another pair of jets, injection of energetic particles continues, but at a much lower rate since the precessing motion has ceased, so the encounter with the new material is reduced.

This time scale is based on the initial stage, when GW emission becomes the dominant means to remove orbital angular momentum (Gergely and Biermann, 2009). We have proposed above that magnetic stellar winds, using the angular momentum lever arm of the orbital radius, remove sufficient orbital angular momentum to get the system to this point.

This time scale is short compared with the time scale between such events, as estimated above at order 100 years for the most luminous starburst galaxies and longer for starburst galaxies of lower FIR luminosity. Therefore, it appears possible, but fairly unlikely, that any starburst galaxy will experience many such activity episodes at the same time.

2.4 Episodic activity and corresponding energies

Therefore, for a starburst galaxy of an FIR luminosity L_{FIR} other than the maximum of $10^{12} L_{\odot}$, the time-scale between such episodes of injection is then correspondingly longer than 100 years, and hence is of order 100 years $\{10^{12} L_{\odot}/L_{FIR}\}$.

This implies that in any given flux density interval of a sample, those galaxies that have the highest FIR luminosity contribute the most, and therefore, are at the highest redshift. They have the highest probability to be in an active stage right now (in the observer frame), as compared to other galaxies at the same flux density, but at lower redshift. This is a key step in the argument proposed.

If BH spin energy drives powerful jets, it implies that the rotational energy is available, implying that for a final mass of $10 M_{\odot}$, we have $\{\sqrt{2} - 1\} M_{BH} c^2$ maximally available to drive a magnetic jet, replete with energetic particles. For a $10 M_{\odot}$ final mass, this is

some fraction of $10^{54.9} M_{BH,1}$ erg times an inefficiency factor that estimates what fraction of this energy goes into energetic particles. Allowing 1/3, this gives $10^{54.4} M_{BH,1}$ erg. Counting at first only the second-generation mergers happening every 2,500 years (note the uncertainty in this number), it implies that potentially we have a power input of $10^{43.8} M_{BH,1}$ erg/s, noting that this involves two such BHs. The minimum power required in M82 to clean out the ISM (Biermann et al., 2018) can be estimated as follows: first of all, the $P dV$ work can be estimated by using the numbers in Kronberg et al. (1985): The volume is a cone of approximately 50 pc baseline radius and approximately 30 pc height, giving a volume of approximately 10^5 pc³; the pressure can be estimated also from Kronberg et al. (1985) as approximately four times the magnetic field pressure (magnetic field, energetic particles, and thermal particles giving a pressure equal or larger than magnetic fields and energetic particles combined), so using a magnetic field strength of $10^{-3.7}$ G gives a pressure of $10^{-8.8}$ dyn. The total $P dV$ work is then $10^{51.7}$ erg. Since we are referring to the sweeping action of the precession cone, the time scale has to be that for changing the angle: as derived above, this yields 5 years for this time scale, assuming for reference again $10 M_{\odot}$, and so the associated power flow has to be of order $10^{43.5}$ erg/s for two jets, so $10^{43.2}$ erg/s for one jet. This is in fact consistent with the power flow derived from the quantity $(B \times r) = 10^{16.0 \pm 0.12}$ G $\times$ cm observed for the common magnetic field in young RSN (Biermann et al., 2018; Biermann et al., 2019); based on Kronberg et al. (1985), Allen and Kronberg (1998), and Allen (1999)), using the approach of Falcke and Biermann (1995)). This yields $10^{42.8}$ erg/s, easily within the errors of such a comparison. This derivation is independent of BH mass, as the consistency with the minimum power in radio quasars (Punsly and Zhang, 2011), and with the magnetic field in the M87 radio core EHT-Coll. et al. (2019). This is a consistency check on the power flow in the precessing jets. At this point, we can derive the time scale of angular momentum loss and energy loss: this can be determined by dividing the maximally available energy of $10^{54.9} M_{BH,1}$ by this luminosity derived here of $10^{42.8}$ erg/s, which gives $10^{12.1} s M_{BH,1}$; here, $M_{BH,1}$ is the mass of the BH in units of 10 solar masses. On this time scale, a maximally rotating BH loses angular momentum and energy, at the minimum. This shows that for a BH mass of $10^{6.6} M_{\odot}$, we reach the lifetime of the Universe. Curiously, this happens to be the mass of the SMBH in our Galactic Center, for which its rotation state is not yet known EHT-Coll. et al. (2022). The power derived here is slightly lower than the power output derived at the beginning, of $10^{43.5}$ erg/s for one BH; a simple interpretation may be that there are channels other than the magnetic jet itself to use up the rotational energy of the BH, e.g., via the Penrose process (Penrose and Floyd, 1971), or even simpler that the life time of the high spin of the BHs is just longer than the merging time scale; since many BHs get a kick at formation, they leave the galaxy, and the detections of RSNs in M82 may be limited by these objects just flying out. If this is the correct understanding, then all these rotating BHs are flying through the region around galaxies like M82 and lose most of the rotational energy out there.

If this rotational energy of a rotating BH is ejected via magnetic fields and energetic particles, in a relativistic wind or jet, could their contribution to energetic particles in intergalactic space surpass the contribution from super massive BHs (SMBHs)? The combined usable rotational energy of all these stellar mass BHs can be

estimated for our galaxy, following the summary of the data in Biermann et al. (2018), based on Diehl et al. (2006), using $10 M_{\odot}$ again as a reference for simplicity, as approximately $10^{62.4}$ erg, to be compared with the maximal useable rotation energy of our Galactic Center BH, assuming that it ever achieved this, as $10^{60.5}$ erg. This all depends on interpreting these stellar mass BHs beginning with a near maximal rotation state, as suggested by the commonality of the magnetic field in RSNs, and the simulations by Chieffi and Limongi (2013) and Limongi and Chieffi (2018); the argument has been given above in detail. If these stellar mass BHs also produce relativistic jets, the maximum energy particles may reach well beyond the ankle in the CR spectrum. By these same magnetic fields, they lose their rotation quite fast, in approximately $10^{4.2}$ yrs for a $10 M_{\odot}$ BH (above we derived a similar number, $10^{4.6}$ yrs, using energy output). Summed over the lifetime of our Galaxy, this corresponds to a power input of $10^{44.7}$ erg/s outside our Galaxy; today it is a factor of order 2 less and hence approximately $10^{44.4}$ erg/s. The Galactic CRs require an input of order $10^{41.0}$ erg/s (Gaisser et al., 2013), which gives an efficiency of approximately $10^{-3.5}$ for CR injection inside the CR disk. As the typical galaxy density is of order 10^{-2} Mpc⁻³ (Lagache et al., 2003), and an order of magnitude lower at the FIR luminosity of our Galaxy, using this efficiency, it yields a crude estimate of $10^{39.0}$ erg/s Mpc⁻³. This can also be checked directly with the density of SMBHs (e.g., Caramete and Biermann, 2010) of $10^{5.5 \pm 0.4} M_{\odot}$ Mpc⁻³, which corresponds to a maximally usable CR energy flow of $10^{38.2}$ erg/s Mpc⁻³, which is slightly less than the possible contribution from massive star BHs, but consistent within the uncertainties. On the other hand, SMBHs can accrete and power outflows also at the Eddington limit, yielding very much higher possible power inputs for a short time: using the same densities of SMBHs (Caramete and Biermann, 2010) and a time fraction of order 10^{-2} for high activity yields then approximately $10^{41.6}$ erg/s Mpc⁻³, still below the purely spin-down-based stellar mass BH power input, derived above, of $10^{44.4}$ erg/s. This can be compared with the average UHECR energy input worked out by, e.g., Waxman (1995) of $10^{37.1}$ Mpc⁻³ erg/s. The possible contribution from massive stars exceeds the AGN UHECR contribution, so massive star BHs may make a substantial contribution to UHECRs, in the case of initially high rotation, and relativistic jets, as implied by the M82 observations. This is fully consistent with new Auger results from Auger-Coll. (2024).

Finally, there is another consequence of this minimum loss time for angular momentum. In a star cluster of massive stars, these stars also lose orbital angular momentum via their magnetic winds, setting up a merger of massive stars to form a supermassive star (Spitzer (1969); Sanders (1970); Wang and Biermann (2000), which in turn may quickly form an SMBH of a mass close to that of the GC SMBH (Appenzeller and Fricke, 1972) focus on the explosion only). *A fortiori*, this also works for the merger of stellar mass BHs. This process can speed along the early formation of SMBHs, as observed by JWST (Übler et al., 2023).

2.5 Other sources of episodic activity

The classical episodic events that inject energetic particles are primarily SN explosions (e.g., Cox, 1972). However, normal SN explosions running through a former stellar wind give a maximal

particle energy of approximately $10^{17.5} Z$ eV, reaching the ankle but certainly do not go beyond (Biermann et al., 2018). The reason is that in such RSNe, the magnetic field in terms of $B \times r$ is observed to be always close to the measure $10^{16.0 \pm 0.12} \text{ G} \times \text{cm}$ (Biermann et al., 2018; Biermann et al., 2019), as extensively discussed above. In the well-observed sources, there is not clearly a large tail of this quantity on either side of this specific number. However, the selection effects could be large in such a tally. However, if these rotating BHs were to initiate a relativistic jet (Mirabel and Rodríguez, 1999), the particle energies accelerated could go much higher.

Other episodic sources are binary star systems with one BH, pulsars and pulsar winds, white dwarf SNe (SN Ia), active neutron stars in binary systems, and neutron star mergers.

It is important to add that a further source of episodic acceleration can be due to electric discharges (Gopal-Krishna and Biermann, 2024): winds and jets patterned after the Parker wind (Parker, 1958) carry an electric current. When the power varies with time, the electric current changes. This change builds up electric charges and fields following Maxwell's equations (Gopal-Krishna and Biermann, 2024), here the equation of continuity for electric currents which is contained in Maxwell's equations. These electric fields can discharge violently and produce acceleration of particles (see for the possibility of an electric discharge close to the central BH Aleksić et al. (2014)); in the limit of strong electric fields, this discharge acceleration produces a 1D momentum p spectrum of p^{-2} , quickly scattered to a 3D p^{-4} spectrum. This spectrum has been recognized in radio emission in radio filaments that may have undergone an electric discharge (Gopal-Krishna and Biermann, 2024), both galactic and extra-galactic. The magnetic irregularity spectrum excited by this steep particle spectrum also contributes to a good fit to the newest AMS data for Fe energetic particles (Allen et al., 2024), and presumably also for other primary elements like He, C, and O, with the difference that He, C, and O have spallation additions from higher elements and not only spallation losses like Fe.

2.6 Probability

The probability that a given starburst galaxy is ejecting, for instance, high-energy neutrinos right now (in the observer frame) runs with the FIR luminosity in our proposed model. Therefore, comparing all sources at some given flux density, those at the highest luminosity, therefore highest redshift, have the highest probability to contribute. As shown above, there is probably no case where multiple activity contributors are relevant at the same time.

To go beyond identifying most probable sources, say by working out the total neutrino background, we go one step further: once the sources are summed weighted by probability, we follow by adding all different flux density levels (*cf.* Caramete, 2016).

Clearly, a merger of two stellar mass BHs with the associate precession of jets aligning each with the spin of a BH is likely to accelerate particles to high energies so that interaction takes place, and neutrinos are emitted. At the very end of this stage, the two BHs will merge and emit a burst of GWs. It is important to note that due to boosting, the selection effects governing the detection of neutrinos and a burst of GWs are very different. So the detection of both due to the same episode of a source at about the same time is unlikely.

The main aspect in the analysis is that at any given flux density, the sources with the highest intrinsic luminosity, so highest redshift, have the highest probability to contribute. This would be the same conclusion for the other possibilities of episodic injection of energetic particles, such as SNe. However, if the energetic particles are stored and not ejected via the open precession cone, then the line of reasoning is valid only if most of the interaction happens right at the start, as has been argued already (Stanev et al., 1993; Biermann et al., 2001; Biermann et al., 2018; Allen et al., 2024).

2.7 Analogy of supermassive black hole mergers

This approach may be useful as well for AGN with central SMBHs since their activity is also episodic. Assuming that relativistic boosting is not stronger for minimum power AGN-BHs at near maximal rotation, then looking for the highest luminosity within a given flux density interval should also give a higher probability for the source to give either neutrinos or GWs. For many AGN, the FIR range has the highest probability to actually be strongly influenced by thermal dust emission (e.g., Chini et al., 1989a; Chini et al., 1989b), powered by the activity of the central SMBH. The flat spectrum AGN S5 1803 + 784 is a famous counter-example, with its FIR emission in line with a flat spectrum extrapolation from 5 GHz.

So we tentatively propose for AGN-BHs a similar observing strategy as for starburst galaxies, with a focus on the FIR: take spectra of all sources in the plausible search window on the sky, including the FIR continuum. Then, select a flux density interval and pick a sample of the highest luminosity sources among them. Try to verify whether any of them could be the source; if unsuccessful, pick another flux density interval, and repeat the exercise.

So a similar approach might be useful to test to select at any given flux density the highest luminosity sources, with two approaches; first, to go for the FIR dust emission, and second for the FIR flat spectrum extension.

2.8 An observational strategy

Consider the detection of a GW event, or alternatively the detection of a high-energy neutrino event, likely to be of astronomical origin. Then, first an area needs to be identified that may contain the galaxy with the source. Thereafter, take a spectral map of this area, which shows the approximate redshift for all sources.

Proceed as follows:

- i) Rank all candidate sources in FIR flux density.
- ii) Start with the galaxy at the highest flux density, and then define the (index j , here $j = 1$), the first sample (index i) by

$$\Sigma L_{\text{FIR},j,i} > L_{\text{FIR},M82} \frac{\tau_{3,4}}{\tau_{ep}}, \quad (12)$$

where $\tau_{3,4}$, the repetition time scale is, in our BH merger approach, 2, 500 years, and τ_{ep} , the length of the UHECR injection is, in our approach, the length of the time, during which the jets precess, 5 years. Thus, in this sample, there is a ≈ 100 percent expectation

that some galaxy is in an active phase of an episode. The size of the sample is one parameter. The chosen flux density interval needs to be large enough so that subsequent intervals do not overlap in combined probability of identification.

- iii) Then, rank within the sample all sources by FIR luminosity. The galaxy with the highest luminosity has the highest probability to be the real source.
- iv) Repeat, using the next group of galaxies (index j), and use the same size of the sample, by adjusting the next flux density boundary; for a Euclidean Universe, one choice could be stepping flux densities by a factor of $2^{-2/3}$ so that we get equal and large numbers at each step.

Check the candidates in the set for any sign of activity that may relate to the event chosen, like visible variability. Considering the observations of M82, a sign would be if a compact source changes structure or spectrum as 41.9 + 58 did. If there is no such sign, pick the next set of lower flux density, and repeat the exercise. Iterate the procedure, until successful, or until the observations run out of sensitivity.

Clearly, this needs a learning experience, different for every class of sources identified. We chose this model to emphasize the possibility for the maximal energy to go beyond the ankle, near 10^{18} eV, and do so with a high rate of injection into the acceleration process. Our model as proposed can be justified only for starburst galaxies, and it remains to be tested whether an analogous approach might also be helpful also for AGN.

3 Conclusion

We propose a model and a two-step strategy to identify sources for either high-energy neutrinos or GWs based on the concept that their production and emission from starburst galaxies are episodic, with the probability that the galaxy contains an emitter currently active in the observer frame running with the FIR luminosity, and the probability that we actually detect the emission running with the flux density. An analogous approach for AGN might be similar, but remains to be developed, justified, and tested.

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Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

MA: writing–review and editing. PB: writing–original draft. AC: writing–review and editing. RC: writing–review and editing. DF: writing–review and editing. LG: writing–review and editing. BH: writing–review and editing. IJ: writing–review and editing. PJ: writing–review and editing. PK: writing–review and editing. EK: writing–review and editing. AM: writing–review and editing. E-SS: writing–review and editing. TS: writing–review and editing.

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The role of magnetar transient activity in time-domain and multimessenger astronomy

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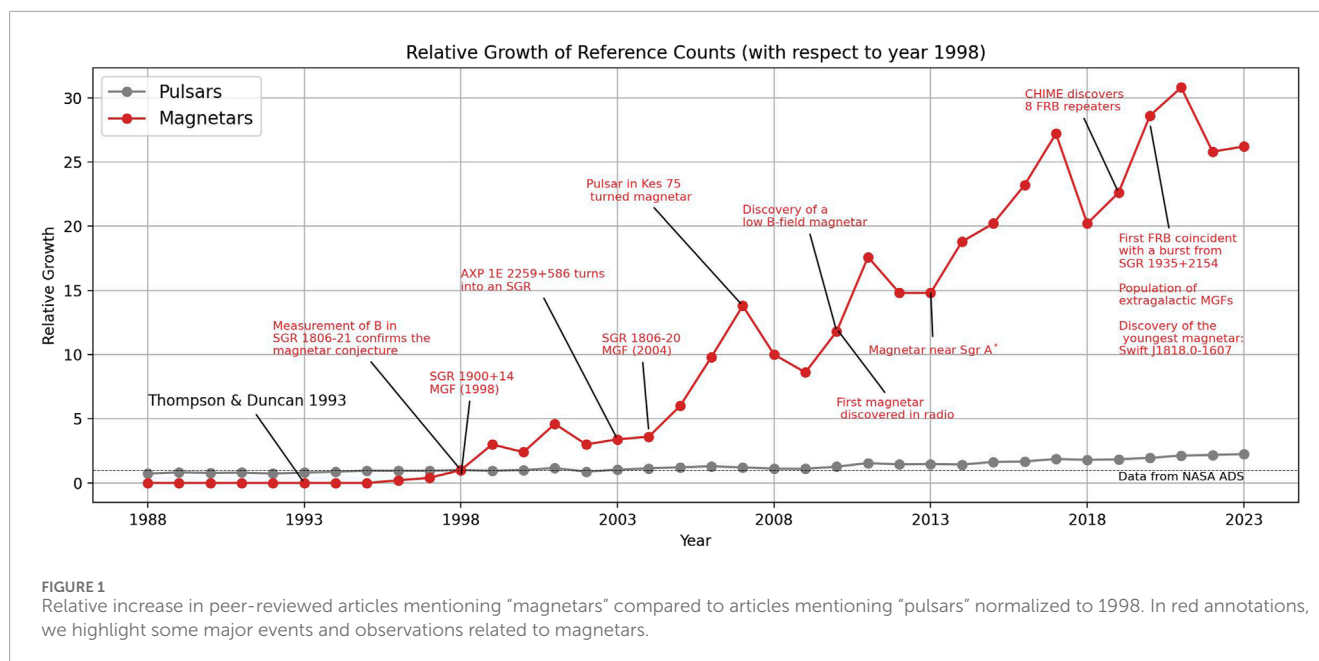
Time-domain and multimessenger astronomy (TDAMM) involves the study of transient and time-variable phenomena across various wavelengths and messengers. The Astro2020 Decadal Survey has identified TDAMM as the top priority for NASA in this decade, emphasizing its crucial role in advancing our understanding of the universe and driving new discoveries in astrophysics. The TDAMM community has come together to provide further guidance to funding agencies, aiming to define a clear path toward optimizing scientific returns in this research domain. This encompasses not only astronomy but also fundamental physics, offering insights into properties of gravity, the formation of heavy elements, the equation of state of dense matter, and quantum effects associated with extreme magnetic fields. Magnetars, neutron stars with the strongest magnetic fields in the universe, play a critical role in this context. We aim to underscore the significance of magnetars in TDAMM, highlighting the necessity of ensuring observational continuity, addressing current limitations, and outlining essential requirements to expand our knowledge in this field.

KEYWORDS

magnetars, TDAMM, time-domain, multimessenger, neutron star (NS)

1 Introduction

Over the last 2 decades, magnetars have been the subject of numerous comprehensive review articles. The work by [Mereghetti \(2008\)](#) delved into observational evidence distinguishing a unique class of isolated neutron stars (NSs)—powered by magnetic energy—termed magnetars, which encompass anomalous X-ray pulsars (AXP) and soft gamma repeaters (SGRs) ([Mereghetti et al., 2015](#)). Subsequently, in 2015, Mereghetti, along with Pons and Melatos, offered a second review focusing on persistent emission properties, exploring models explaining extreme magnetic field origins, evolutionary pathways, and interconnections with other neutron star classifications ([Mereghetti et al., 2015](#)). Additionally, in the same year, [Turolla et al. \(2015\)](#) provided a detailed overview of magnetar origins and evolution, emphasizing the critical role of theoretical modeling in understanding fundamental physics, constrained by both persistent and transient emission observations. Furthermore, the review by [Kaspi and Beloborodov \(2017\)](#) ([Kaspi and Beloborodov, 2017](#)) and 4 years later by [Esposito, Rea, and Israel \(2021\)](#)



(Esposito et al., 2021) updated the discourse on the magnetar population within our Galaxy. These reviews focused on high-energy (X-rays and above) persistent emission characteristics, temporal behavior, and transient activities, collectively enriching our understanding of these enigmatic celestial objects. Recently, Dell’Orso and Stella provided a review focused on newly born millisecond magnetars (Dall’Osso and Stella, 2022).

A clear trend emerging from each of these reviews is that, despite representing only a small fraction of the observed neutron star population, magnetars have been attracting the interest of many scientists from many different areas of astronomy and astrophysics, demonstrated by the relative increase in the number of publications mentioning “magnetars” over the past decades (Figure 1). The sheer number of reviews is the result of continued fundamental discoveries pertaining to the field of magnetars, which shape the understanding of the NS population at large and beyond. The most significant among them is the unification of AXP and SGR under the same name (Duncan, 1998) and progresses with the phenomenology of starquakes (Cheng et al., 1996), the observation of the extremely bright events called giant flares (when a magnetar outshines the Sun for a fraction of a second in hard X-rays) (Hurley et al., 1999; 2005), identification of a population of extragalactic magnetar flares masquerading as short gamma-ray bursts, the observation of new mysterious bright and intermittent galactic long-period radio pulsating sources, and finally the association between magnetars and fast-radio bursts (Mereghetti et al., 2020). Such observational evidence has been catalyzing studies and has increased the interest of a wider and deeper community. Several models predict gravitational wave emission from magnetars at birth and during giant flares, and many theoretical studies suggest that high-energy neutrinos are produced during those events. Furthermore, there are discussions on magnetars being the source of other types of isolated neutron stars, such as central compact objects (CCOs) and X-ray dim isolated neutron stars (XDINs), and transient event ultra-luminous X-ray sources (ULXs), super-luminous supernovae (SLNS), and fast X-ray transients (FXT).

This paper explores the significant role of magnetars in time-domain and multimessenger (TDMM) astronomy, focusing on their transient activity. The core aspect of this scope highlights the critical role of the high-energy space-based missions that have enabled inference built upon compelling evidence in the past several decades. This study aims to highlight the main characteristics of these missions, while also acknowledging their limitations, thereby proposing viable avenues for enhancing our ability to study these captivating celestial entities. Section 2 provides a brief introduction on the magnetar population, and Section 3 focuses on the fast-transient activity, discussing short bursts, storms, and flares. Section 4 delves into the multimessenger prospects for magnetars, discussing the expectations for the observation of gravitational waves and neutrinos.

2 Magnetars

The question of the conditions necessary to create and power a magnetar underpins the broad interest in these enigmatic celestial objects. To grasp the significance of this question, it is essential to first define a magnetar. Neutron stars are the compact remnants forged in the explosion of massive stars during a supernova event. With a mass typically ranging between about 1.2 and 2 times that of the Sun, the neutron-degenerate matter in NS is squeezed into a sphere that is approximately 10–20 km (6–12 miles) in diameter, reaching supra-nuclear densities in their interior and representing the densest form of matter known in the universe—about fourteen orders of magnitude denser than osmium, the densest element found on Earth. NSs are highly magnetized, which requires a dynamo-like amplification of an original magnetic field from stellar mergers (Schneider et al., 2019), fall-back dynamos (Barrère et al., 2022), or other mechanisms, like inverse cascading of helical and fractionally helical magnetic fields (Brandenburg, 2020). Differential rotation and rotation–convection coupling in the collapsing core of massive stars can also initiate this dynamo effect (Duncan and

Thompson, 1992), which continues in the convective inner structure of the newly formed rapidly rotating NS, and produce strong magnetic fields (Thompson and Duncan, 1993). Magnetars are ultra-magnetized NSs, with recorded (dipolar) magnetic fields of the order of 10^{14-15} G, usually found in isolation (i.e., not in binary systems) and sometimes associated to a nearby supernova remnant. Understanding the type of progenitor star(s) that can generate magnetars is key to understanding their nature and behavior, which ultimately gives access to the physical mechanisms involved in such extreme environments.

Studying the population of magnetars in our Galaxy, both alone and in comparison to the bigger population of isolated NSs, can shed light on their progenitors (Beniamini et al., 2019), and hence the conditions necessary for their formation. The main characteristics of the Galactic magnetar population are illustrated in Figure 2, in comparison to the wider pulsar population (Manchester et al., 2005, ATNF Catalog). Approximately thirty known high-energy emitting magnetars are found in our Galaxy, with the majority located within 1° from the Galactic plane, one in the Large Magellanic Cloud (Cline et al., 1982) and one in the Small Magellanic Cloud (Lamb et al., 2002). They are characterized by a high spin-down rate and slow rotation period, which together with their location in the plane, suggest that active magnetars are typically young, from approximately a hundred years [the youngest known is about 240 years old, discovered in 2020 (Esposito et al., 2020)] to a few tens of thousands of years, as shown in the top-left panel in Figure 2, in comparison with the much older population of pulsars. Except for PSR J1622-4950, which was discovered in radio in 2010 (Levin et al., 2010), all the other known “standard” young magnetars were discovered in the X-ray band, most of them through a first bright transient event. Through the observation and statistical study of the bursting activity of SGR 1806-20 Cheng et al. (1996) found evidence of the hypothesized solid crust on the magnetar surface (see for a similar association with FRBs, Totani and Tsuzuki, 2023). In fact, they found similarities between the magnetar burst energy and waiting time distributions and those for quakes on Earth caused by tectonic movements (Perna and Pons, 2011; Dehman et al., 2020). The discovery of fast radio bursts (FRBs) from galactic magnetars (Bochenek et al., 2020; CHIME/FRB Collaboration et al., 2020) in coincidence with their bursting (Mereghetti et al., 2020; Li et al., 2021) and possibly glitching activity (Younes et al., 2023; Ge et al., 2024) provide crucial information on the physical mechanisms that power these phenomena and the crustal and magnetospheric conditions that can produce FRBs. More recently, radio transient surveys have discovered a population of long-period galactic radio pulsars which are likely older magnetars (Caleb et al., 2022; Hurley-Walker et al., 2022; 2023; Beniamini et al., 2023; Rea et al., 2024). None of these have a high-energy counterpart yet, but given their highly variable nature in the radio and likely magnetar nature along with a possible connection to long-period FRBs (Beniamini et al., 2020), it is plausible that future X-ray and gamma-ray transients could be associated with high-energy monitors with sufficient angular resolution.

Several magnetars have been discovered in neighboring galaxies: NGC 253 (Sculptor galaxy), M31 (Andromeda galaxy), the M81-M82 group, and M83. Confirmation of pulsating emissions matching typical magnetar rotation periods would validate their identity. Extragalactic magnetars can be observed only during

the brightest flares, but an unequivocal association requires the detection of the pulsating emission, typically too fast-fading to be caught in time by sensitive instruments. However, the detection of the brighter short initial spike allows inferring the volumetric intrinsic rates of such phenomena associated with magnetars, providing important clues on their formation channels (Burns et al., 2021). The current population of extragalactic magnetar candidates includes only a handful of objects from nearby galaxies, limiting our constraints on the volumetric intrinsic rates. Such limitation needs more sensitive all-sky soft gamma-ray monitors with the ability to trigger more efficiently on these events.

3 Magnetars in time-domain astronomy

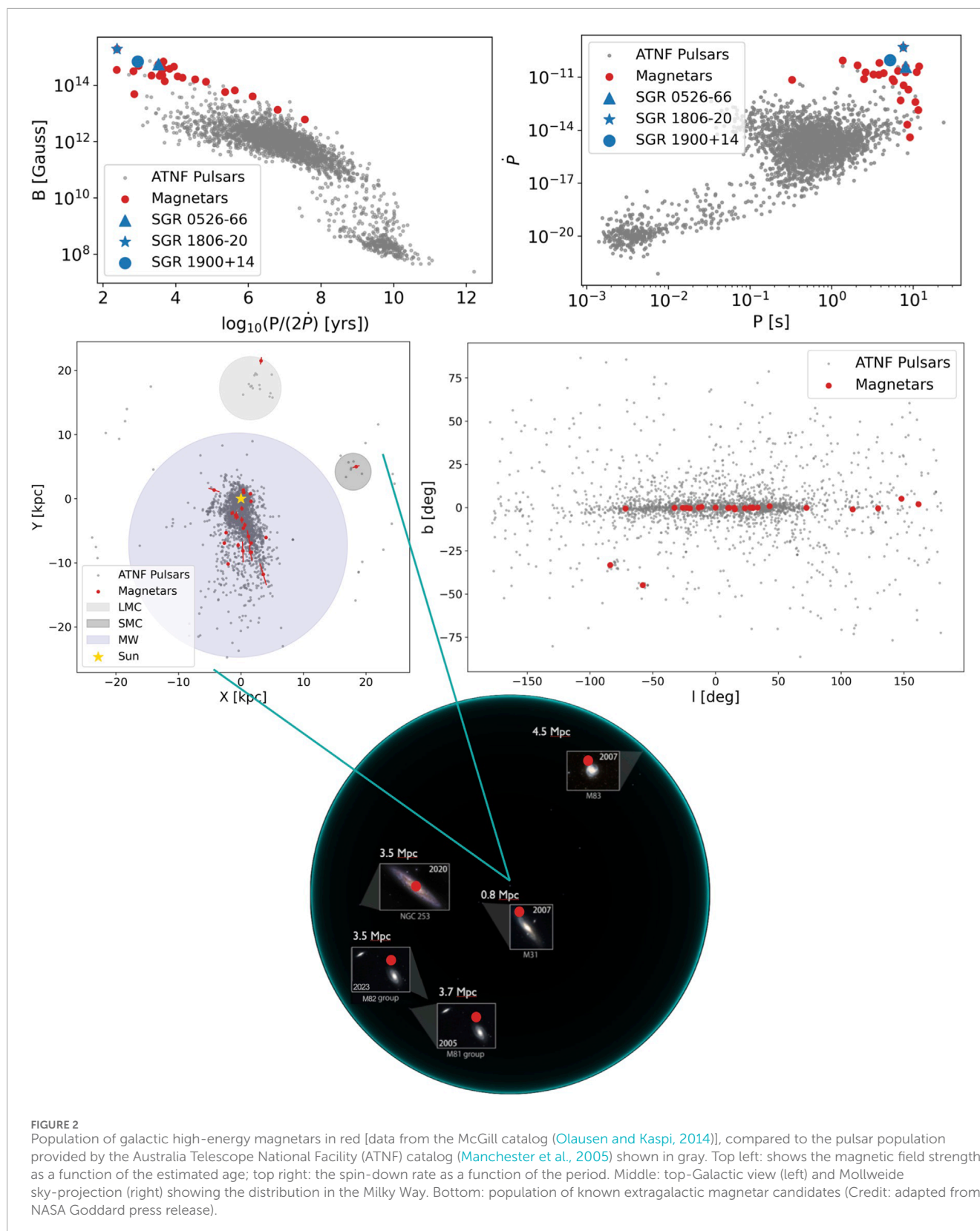
Magnetars show a variety of transient activities observable from soft X-rays up to medium-energy gamma-ray bands and differing in terms of timescales, energetics, and temporal and spectral evolution. Such activity includes outbursts, short bursts, burst storms, and flares, as illustrated in Figure 3.

Apart from the more prolonged outbursts, magnetars are also associated with short bursts of intense radiation, typically lasting only a fraction of a second. These short bursts, often observed in the hard X-ray spectrum, provide valuable insights into the extreme physical conditions prevailing in the vicinity of magnetars. The origins of these short bursts may be linked to the sudden release of magnetic energy or magneto-elastic energy from the crust. Short bursts are quasi-thermal, and broadband soft gamma-ray spectroscopy reveals that they are consistent with trapped fireballs within closed loops at low altitudes in the magnetosphere (van der Horst et al., 2012; Younes et al., 2014).

Magnetars are known for their outbursts, during which the quiescent/persistent X-ray emission increases by as many as three orders of magnitude. Typically these events are characterized by a faster (hours–days) flux rise, followed by a slower (week- to year-long) decay to return eventually to quiescence. Such temporal characteristics enable follow-ups and monitoring by sensitive pointing telescopes, providing accurate flux estimates. Crustal shifts due to magnetic stress are believed to cause magnetar outbursts. Short bursts and flares have been observed during outbursts, as well as isolated in time. Burst storms have been observed to happen at the onset of outbursts.

Magnetar burst storms (or burst forests) refer to periods of heightened and sustained activity, during which a magnetar emits a series of tens to thousands of bursts over a relatively short time frame of minutes to days. These episodes of magnetar burst storms contribute significantly to our understanding of the magnetar’s dynamic behavior. Studying these storms helps decipher the underlying processes that govern the interplay between the decaying intense magnetic field, the internal and external structure of the magnetar, and the radiative processes occurring in high-B-field regime close to the surface of the magnetar.

Magnetar flares represent another facet of their transient activity, characterized by sudden and intense increases in radiation across multiple wavelengths. Such events are characterized by an ms-long bright spike, followed by a dimmer (but still bright) periodic tail decaying in time. These flares are among the most energetic



events in the universe, releasing energy on the order of solar flares, but with magnitudes far surpassing those of solar flares Hurley et al. (1999, 2005); Israel et al. (2008). Typically classified in

intermediates flares (with $E_{iso} \sim 10^{41} - 10^{43}$ ergs, and giant flares (MGFs) ($E_{iso} \sim 10^{44} - 10^{47}$ ergs), magnetar flares are crucial to enhance our comprehension of the extreme conditions prevailing in

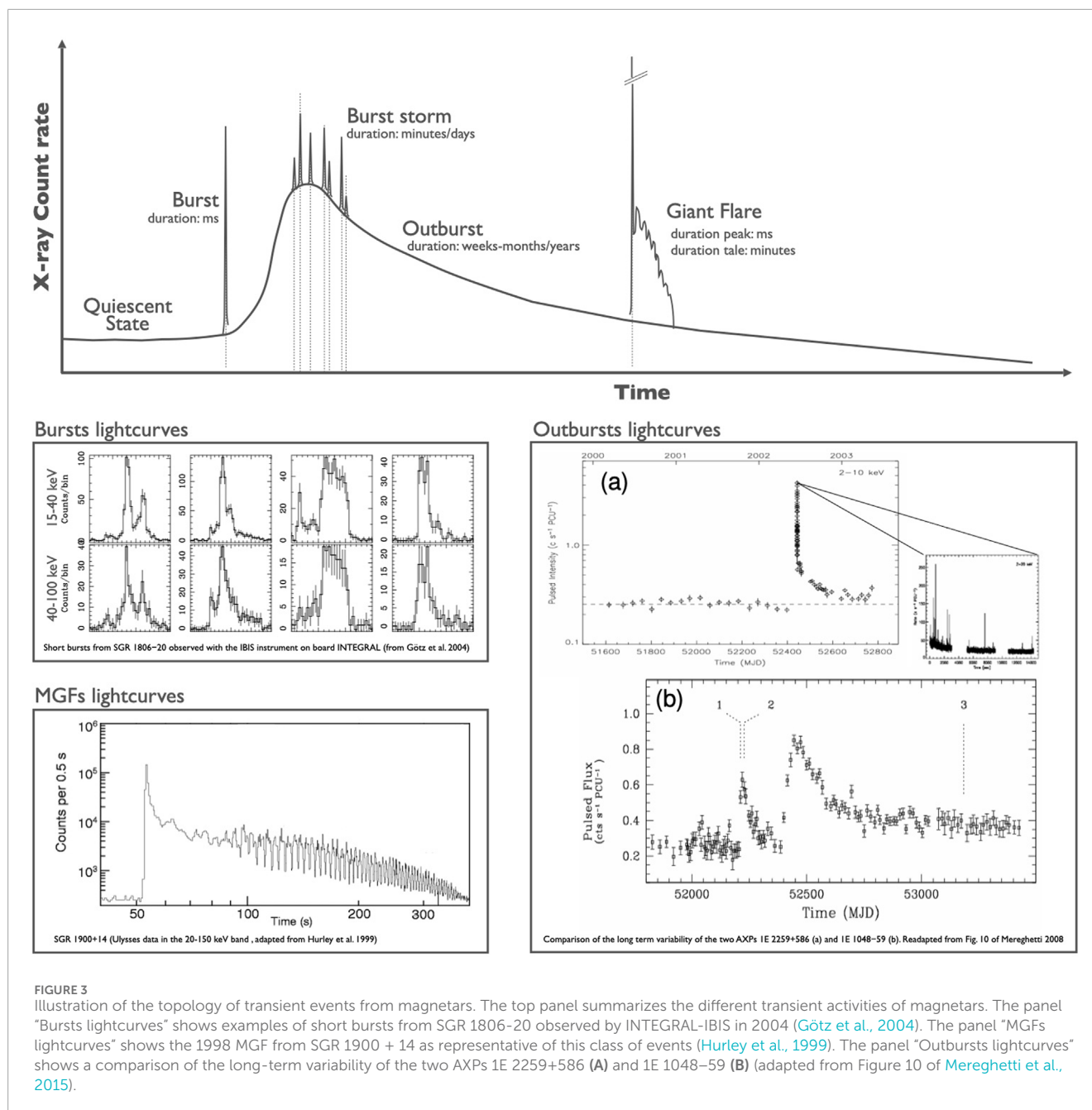


FIGURE 3

Illustration of the topology of transient events from magnetars. The top panel summarizes the different transient activities of magnetars. The panel "Bursts lightcurves" shows examples of short bursts from SGR 1806-20 observed by INTEGRAL-IBIS in 2004 (Götz et al., 2004). The panel "MGFs lightcurves" shows the 1998 MGF from SGR 1900 + 14 as representative of this class of events (Hurley et al., 1999). The panel "Outbursts lightcurves" shows a comparison of the long-term variability of the two AXPs 1E 2259+586 (A) and 1E 1048-59 (B) (adapted from Figure 10 of Mereghetti et al., 2015).

the vicinity of these celestial bodies and provides valuable data for refining models of magnetar behavior.

High-energy monitors, spectrometers, and fast-repointing instruments have enabled the observation of magnetars' dynamic transient activity since the 1980s. Major contributors including ROSAT (Truemper, 1982), CGRO (Gehrels et al., 1994), RXTE (Swank, 1999), and BeppoSAX (Boella et al., 1997) have been used earlier. Table 1 lists the major high-energy instruments that are currently contributing to monitoring and detection of magnetars' transient activity. High-energy instruments like the GBM on board Fermi, Konus on board WIND, BAT on board Swift, and the ACS on board INTEGRAL offer broad coverage of the soft gamma-ray band, making them valuable for detecting a wide range of transient events, including those from magnetars. Instruments like Chandra,

XMM-Newton, NuSTAR, and NICER provide high-angular resolution and are capable of discovering the precise locations of transient events, aiding in follow-up studies and multiwavelength observations; however, except for Swift with minute-scale reaction, the repointing time limits follow-ups to magnetar outbursts and burst storms. Figure 4 is a visual illustration of the available energy, timing, and sky coverage provided by the instruments listed in Table 1.

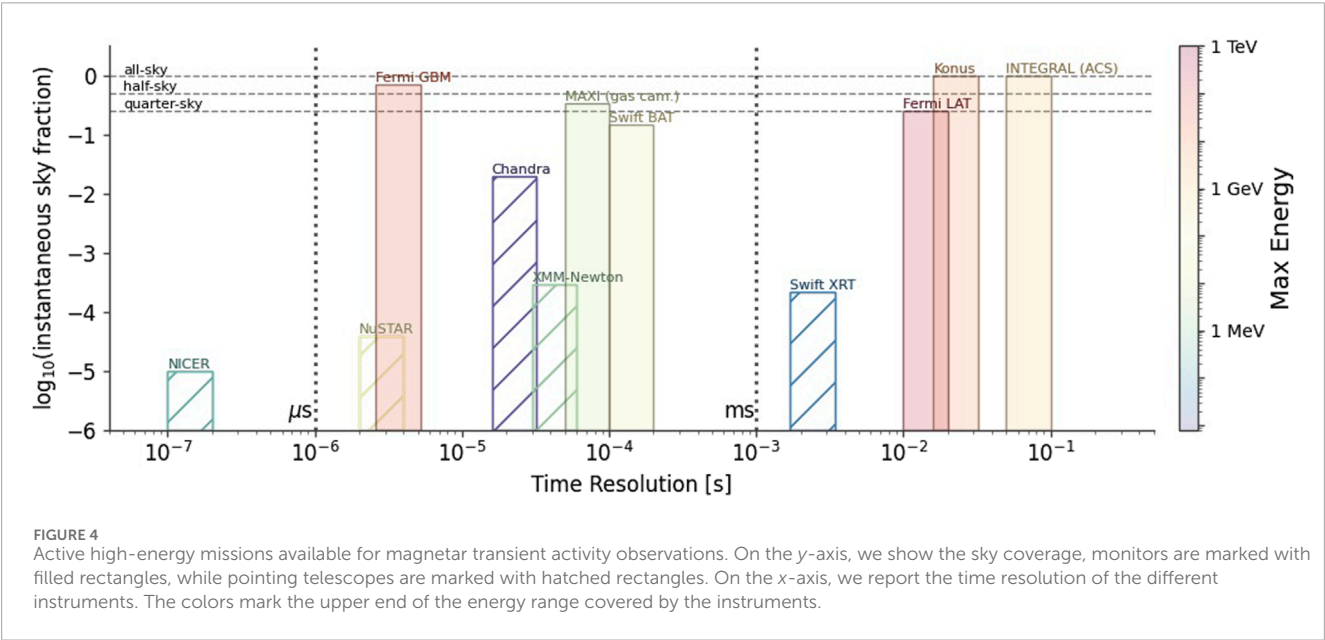
3.1 Outbursts

Most magnetars display periods of elevated X-ray emissions above their historical minimum level, sometimes by as many as

TABLE 1 Major high-energy instruments currently contributing to magnetar observations. Missions' figures of merit can be found on the NASA's High-Energy Astrophysics Science Archive Research Center (HEASARC). For the time property of INTEGRAL anti-coincidence shield (ACS), we referred to Savchenko et al. (2012).

Mission	FoV	Min. Repoint	Energy (keV)	Time Res. ^c	Launch
Konus-WIND	All-sky	–	20 – 20000	16 ms	1994
Chandra (HRC)	30' × 30'	< 5 days	0.1 – 10	16 μs	1999
XMM-Newton (PN)	27.5' × 27.5'	< 24 hours	0.2 – 12	30 μs	1999
INTEGRAL (ACS)	All-sky	–	> 80	50 ms	2002
Swift BAT	15%	–	15 – 350	100 μs	2004
Swift XRT	23.6' × 23.6'	Minutes	0.3 – 10	1.7 ms	2004
Fermi GBM	70% of sky	–	8 – 40000	2.6 μs	2008
Fermi LAT	25% of sky	–	(0.1 – 800) × 10 ⁶	10 ms	2008
MAXI (gas cam.)	1.5° × 160°	–	2 – 30	50 μs	2008
NuSTAR	10' ^a	< 24 hours	3 – 79	2 μs	2012
NICER	5' ^b	< 4 hours	0.2 – 12	100 ns	2017

^aFoV (50% resp.) at 10 keV.
^bNon-imaging.
^cThis is the highest temporal resolution reached in any mode of any instrument on-board.



three orders of magnitude in luminosity (Coti Zelati et al., 2018), i.e., magnetar outbursts. These epochs, which are typically observed concurrently to the onset of bursting activity (see below), are defined by extreme spectral–temporal variability to the soft and hard X-ray emissions in the form of harder spectra, pulse profile and fraction variation, timing noise, and glitches (Gavriil et al., 2004; Woods et al., 2007; Rea et al., 2009; Dib and Kaspi, 2014; Hu et al., 2020; Younes et al., 2022). At radio wavelengths, six

confirmed magnetars have shown transient *radio pulsed emission*, appearing around outburst epochs (Camilo et al. (2006); Lower et al. (2020b), or, in a few occasions, disappearing (Lower et al., 2023). For a few magnetars, the infrared to optical emissions have also been observed to vary (Tam et al., 2004). These outburst epochs last from months to years during which the multiwavelength properties usually return back to their pre-outburst states (Coti Zelati et al. (2018).

Magnetar outbursts are generally attributed to crustal shifts (e.g., due to stresses on the surface from internal B-field restructuring and perhaps decay), imparting a twist onto an external magnetic field loop [see (Turolla et al., 2015) and references therein]. The surface heating arises due to either energy deposition in the crust, e.g., from Hall wave avalanches (Thompson and Duncan, 1996; Beloborodov and Li, 2016), or bombardment of the surface by accelerated particles in a twisted external B-field (Beloborodov, 2009). Both models predict the formation of surface hotspots, which could explain the altered pulse shape and amplitude during magnetar outbursts as well as the harder spectra and increased X-ray power. Although in both cases the outburst is initiated by an elastic failure of the crust (Dehman et al., 2020), their evolution is dictated by different regions of the NS. For the external model, as the twisted fields “unwind,” magnetic energy is released in the form of radiation, typically leading to the shrinkage and cooling of the hotspot (Beloborodov, 2009), whereas if the heating is purely internal, the outburst decay is determined by crustal cooling scenarios heavily dependent on the micro- (e.g., crust impurity) and macro-physics [depth and total energy deposited in the crust (Brown and Cumming, 2009; Pons et al., 2009)].

Hence, given the abovementioned, multiwavelength follow-up studies of magnetar outbursts have distinctly revealed their highly dynamic nature; physics of plastic deformation of the crust, characteristics of the twisted B-field loops (twist magnitude, loop locale, and total volume), pair-production and particle acceleration required for the coherent radio emission, and the interconnection between all of these elements.

The high-energy properties of magnetar outbursts have been extensively studied with RXTE, XMM-Newton, Chandra, Swift/XRT, NuSTAR, and most recently NICER. Yet the most consequential results have come from the long-term monitoring previously afforded by RXTE (Dib and Kaspi, 2014) and currently conducted with XRT (Archibald et al., 2013; 2020) and NICER (Lower et al., 2020a; Younes et al., 2020b). Apart from the obvious benefit of such observational campaigns, i.e., the measurement of the period and period-derivative, and hence of the fundamental properties of the sources (magnetic dipole field strength, spin-down age, and spin-down power), continuous long-term monitoring of several bright magnetars from 1998 to 2012 revealed the common detection of some timing anomalies, mainly in the form of large spin-up (or on one occasion spin-down) glitches, at the onset of outbursts likely implying an internal trigger mechanism to these events (Archibald et al., 2013; Dib and Kaspi, 2014). Moreover, these monitoring campaigns revealed the delayed, erratic variability in the spin-down torque of these sources months to years after outburst onset, providing clues to the dynamics of the untwisting magnetospheric B-field lines (Woods et al., 2007; Younes et al., 2017; Archibald et al., 2020). Most recently, NICER (with the added benefit of the large effective area, relatively low background, and ease of repointing), through almost daily observations of the magnetar SGR 1830–0645, was able to resolve, for the first time, pulse peak migration which simplified the triple-peaked pulse profile at outburst onset to a single peak in 37 days (Younes et al., 2022). These results provide the strongest evidence yet for plastic motion of the crust, long theorized to drive magnetar outbursts. Finally, for the same reasons, NICER has been able to time fainter magnetars, especially around periods of strong X-ray and radio bursting activity.

Target of opportunity campaigns have been particularly revealing. A very recent example is provided by the FRB-emitting magnetar SGR 1935 + 2154, for which a double glitch event within 9 h was detected, bracketing the largest spin-down rate ever observed from an NS along with an FRB (Hu et al., 2024; Younes et al., 2023). This discovery has implications for the rate of superfluid material in a magnetar, outflowing plasma-loaded wind, production mechanism of FRBs in magnetars, and possibly gravitational wave emission.

Long-term monitoring of magnetars in X-rays (in tandem with radio and infrared campaigns) is unquestionably fruitful. In this regard, continued operation of Swift and, especially, NICER is essential, and similarly, the operation of a satellite with a similar type of capabilities, such as Strobe-X, in the future (Ray et al., 2019).

3.2 Short bursts and burst storms

Short bursts are one of the most unique and defining properties of the magnetar population. These sub-second, bright hard X-ray flashes, capable of reaching luminosities of about 10^{42} erg s^{−1} (Figure 5), are easily identifiable by a suite of past and present large field-of-view hard X-ray monitors. They have played a crucial role in the inception of the soft gamma repeater class (Atteia et al., 1987; Kouveliotou et al., 1987; Laros et al., 1987) and cementing the anomalous X-ray pulsar (AXP) class as part of the same underlying population (Kaspi et al., 2003): NSs with activity driven by the extreme magnetic field strength (Duncan and Thompson, 1992; Paczynski, 1992). Magnetar short bursts can occur in isolation when one or few events are observed over the course of days, or, for the most active magnetars (which tend to be the youngest, Perna and Pons, 2011), during burst storms/forests when hundreds to thousands are emitted over the course of minutes to hours (Collazzi et al., 2015).

Due to the dimness of most magnetars during their quiescent state, the large absorbing column in their direction (being at low galactic latitudes), and the lack of adequate large field-of-view X-ray instruments¹, magnetars are rarely discovered through their persistent X-ray emission. This is plainly demonstrated through the discovery space of new magnetars in the last 20 years, which is fully dominated by the detection of short bursts, primarily with the Swift Burst Alert Telescope (BAT). The BAT is sensitive to short magnetar bursts and able to localize them to within few arcminutes. The rapid follow-up with the Swift X-ray telescope (XRT) confirms the activity through the detection of the (at the time) bright X-ray counterpart and provides arcsecond localization. Follow-up X-ray observations with the adequate time-resolution (which currently happens primarily with NICER) detects the pulse period of the source and its derivative, thus confirming the magnetar nature of the source (see, e.g., Ray et al., 2019, among numerous ATels of this kind). In summary, during its 20-year operation, the Swift telescope has enabled the discovery of more than double of the confirmed magnetar population in the galaxy and identified numerous new outbursts from the already known ones (Kaspi and Beloborodov,

1 eROSITA might detect few magnetars at the end of its full-sky survey, yet these will likely be marked as candidates as many might not be bright enough for pulsation detection.

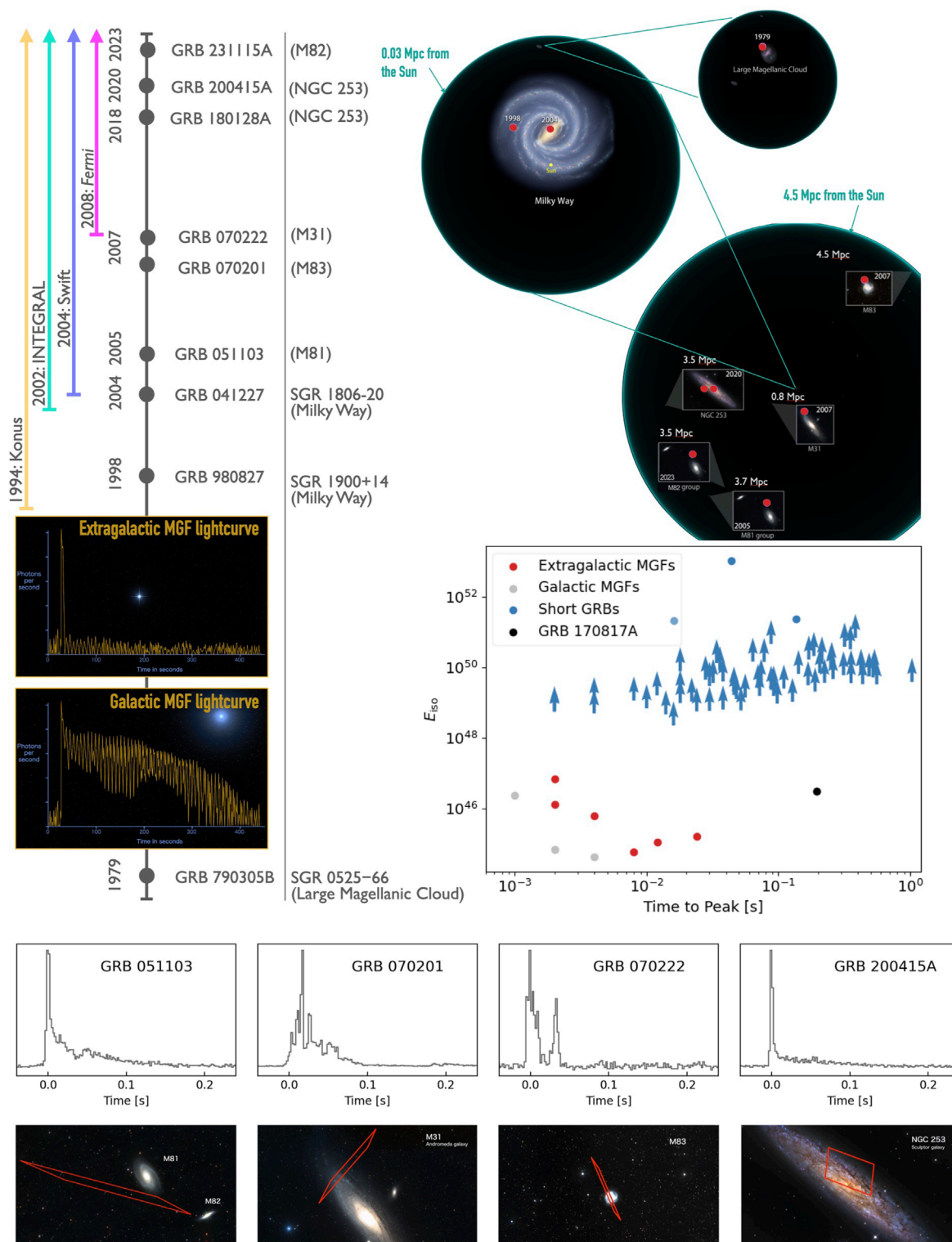


FIGURE 5

Illustration summarizing the current known population of MGFs and MGF candidates. The plot of the intrinsic energetic as a function of the rise time is the updated version of the plot presented in Ref. Negro and Burns (2023) with the addition of two more recent extragalactic identified events (see the text for more details). We also report the light curves and the IPN localizations for four of the MGF candidates identified in Burns et al. (2021). (Credit images: adapted from NASA Goddard).

2017; Esposito et al., 2021). The most significant among those discoveries is the identification of other classes of NSs as capable of showing magnetar-like activity, most noticeably high-B radio-pulsar (Archibald et al., 2016; Göğüş et al., 2016), CCOs Rea et al. (2016), and low-field magnetar Rea et al. (2010), as well as the discovery of a canonical magnetar with a bright X-ray wind nebula (Younes et al., 2016), a property typically attributable to rotation-powered pulsars (Kargaltsev et al., 2015). These discoveries have enabled a more comprehensive understanding of what constitutes a magnetar, observationally, and theoretically, the latter through magneto-thermal evolutionary studies of poloidal and toroidal/crustal fields in NSs (Pons et al., 2009; Viganò et al., 2013; Gourgouliatos et al., 2016; De Grandis et al., 2020; Igoshev et al., 2021; Dehman et al., 2023b; a).

Magnetar short bursts are also crucial for understanding the enigmatic FRBs (Section 4.3). Following the detection of a short X-ray burst coincident with an FRB-like radio emission from the magnetar SGR 1935 + 2154 (Bochenek et al., 2020; CHIME/FRB Collaboration et al., 2020; Mereghetti et al., 2020; Tavani et al., 2021; Li et al., 2021; Ridnaia et al., 2021), studies on the comparison of the spectral and temporal properties of the FRB-associated X-ray short burst to those without an FRB counterpart (which constitutes the overwhelming majority of short X-ray bursts) have shed light on the unusually hard spectrum of the X-ray burst that accompanies the FRB (Mereghetti et al., 2020; Younes et al., 2021). This likely pointed to an active region in the vicinity of the open-field line zone which permits the release of bright radio waves away from the presumably dense environment of the closed magnetosphere (Younes et al., 2021). Moreover, population-wide comparison of extragalactic FRBs and magnetar short bursts, such as duration, rate, and waiting time distribution, have shed some light on the origin of extragalactic FRBs (Cruces et al., 2021; Wei et al., 2021). Yet these have not been able to confirm what fraction of magnetar short bursts is indeed magnetars. This is partly due to our poor knowledge of the magnetar population in the Galaxy, and their activity cycle. Moreover, the detection of FRB 20200120E from a globular cluster in the nearby galaxy M 81 Bhardwaj et al. (2021) challenges the notion that most, if not all, FRBs have a magnetar central engine, unless these magnetars were formed through unconventional channels, e.g., accretion-induced collapse or the merger of two white dwarfs. X-ray observations of this FRB 20200120E with current X-ray instruments ruled out coincident short bursts that are at the high end of the burst fluence distribution ($L_X \geq 10^{42} \text{ erg s}^{-1}$) and approaching the luminosities of intermediate flares (Pearlman et al., 2023).

Several advances in the magnetar field could be achieved with modest effort and investment. For instance, we currently lack a comprehensive, preferentially live, catalog of magnetar short bursts; an essential first step to understanding the activity rate and cycle of the population as a function of, e.g., spin-down age and magnetic field strengths. This could inform population studies of FRBs and comparison to the magnetar population. Ensuring the continued operation of Swift (or a new Swift-like instrument) is crucial for continued discovery of new magnetars and other exotic sources that exhibit magnetar-like activity. For instance, the low-magnetic field magnetar, SGR 0418 + 5729, bears a striking resemblance to XDINs during quiescence (Haberl, 2007). None of the latter sources (known as the magnificent seven) have shown magnetar-like activity, yet this

could be due to their larger ages, implying a lower rate of activity than that of canonical magnetars. If XDINs are confirmed to be magnetars, this would have significant consequences on the number density of magnetars in the Milky Way and their formation rate, providing clues for the birth process of magnetars (Beniamini et al., 2019). New large FOV hard X-ray monitors that are capable of providing arcminute localization, preferentially equipped with sensitive follow-up X-ray instruments, e.g., NICER-like effective area, are key for continued scientific success in our understanding of the magnetar bursting and outburst phenomena. Additionally, next-generation X-ray instruments, such as HEX-P, AXIS, or Strobe-X, should be able to reach weaker short bursts in the nearby universe, further constraining the magnetar nature of nearby FRBs, including FRB 20200120E (Alford et al., 2024).

3.3 Magnetar giant flare spikes

In the 1970s, the debate on the origin of gamma-ray bursts (GRBs) was an outstanding question in astrophysics. Key pieces of information were that GRBs were not associated to known sources, none had been shown to repeat, and that their light curves had spiky but random behavior. The arrival of GRB 790305B was the first GRB localized to a known position (a supernova remnant in the Large Magellanic Cloud), was followed by a weaker GRB from the same position, and an incredibly bright spike was observed, followed by a periodic, exponentially decaying tail (Mazets et al., 1979). The tail period is approximately 8 s, complemented by a weaker interpulse occurring at a phase of 0.5 (Mazets et al., 1979; Cline et al., 1980). The rapid rise time of less than 0.25 ms was the fastest ever seen (Cline et al., 1980). This was the first Magnetar Giant Flare (MGF) seen and the first signal from a magnetar identified. Since then, two more flares have been identified from magnetars in the Milky Way (Hurley et al., 1999; Palmer et al., 2005). All three show similar characteristics, with tails lasting for hundreds of seconds. Due to their extreme luminosities, the spikes of these three giant flares saturated all viewing detectors.

MGFs are the most luminous transients created by magnetars. The crust of the magnetar may store significant elastic energy, which is released when the crust, stressed and powered by the internal magnetic field energy density, deeply and widely fractures (Lander et al., 2015). Magnetic reconnection may occur in the magnetosphere, releasing a bright spike where the plasma blows off on open field lines, followed by a periodic tail caused by the emission from a plasma fireball magnetically trapped on the rotating surface of the magnetar (Duncan and Thompson, 1992; Paczynski, 1992).

By building and characterizing a larger population of MGFs, it will be possible to place better constraints on their intrinsic rates, energetics distribution, and maximal energy release. The rates are of key importance to understand the possibility of detection via GWs during future observing runs (Abbott et al., 2019; Macquet et al., 2021) and the possibility that intermediate or giant flares may produce cosmological FRBs (Popov et al., 2018; Bochenek et al., 2020). The rates are key to understanding the formation channels and the fraction of magnetars that emit giant flares, allowing us to understand the processes which produce the most powerful magnets in the cosmos. The rates and energetics distribution will determine if the giant flares are the extreme events of the same

underlying population which produces SGR short bursts, or if they are fundamentally distinct. The maximal energy release can be related to the maximal surface magnetic field of magnetars.

Furthermore, a sample of events allows for testing of theories on the physical mechanisms that power the prompt spikes. However, galactic events saturate any reasonable GRB monitor, precluding spectral and temporal properties of the spikes at the brightest intervals. This saturation has prevented the study of whether giant flares only occur with single pulses or if they show the same internal pulse variability observed in typical and intermediate SGR short bursts.

Galactic events likely only occur every few decades. In order to substantially increase the sample size during our lifetimes, we must recover and study extragalactic events. These are also key events to study the spectral and temporal properties as they are often sufficiently far to avoid significant saturation effects on GRB monitors. Given the exceptionally high peak luminosities of their initial spikes, instruments with high sensitivity, such as the *Fermi* Gamma-ray Burst Monitor (Meegan et al., 2009) or the Swift Burst Alert Telescope [BAT: Barthelmy et al., 2005], can detect MGF emissions from magnetars located in galaxies possibly up to distances of 25 Mpc (Burns et al., 2021). However, the periodic tail “smoking gun” signature is not yet recoverable far beyond the Milky Way. Even with more sensitive detectors which can see the tails to the local group, the majority of events they detect will be seen only via their initial spikes.

Thus, identification of extragalactic giant flares requires reasonably precise localizations and comparison with nearby galaxy catalogs. Six candidate events at differing degree of significance have now been found: GRB 070201 from M31, GRB 051103 and 231115A from M82, GRB 070222 from M83, and GRB 180128A and GRB 200415A from NGC 253 (Frederiks et al., 2007; Ofek, 2007; Mazets et al., 2008; Ofek et al., 2008; Hurley et al., 2010; Burns et al., 2021; Roberts et al., 2021; Svinkin et al., 2021; Trigg et al., 2023). This spatial alignment method and expectation of extragalactic MGFs masquerading as cosmological short GRBs date back decades (Hurley et al., 2005). Only GRB 051103 and GRB 070201 were identified prior to 2020. Population analyses considering localizations of all short GRBs by Swift and the InterPlanetary Network (IPN) against galaxy catalogs failed to identify additional candidates. The discovery of GRB 200415A led to the development of an improved search method, weighting possible host galaxies by star formation rate and distance based on the brightness of the GRB, which identified GRB 070222 in archival data (Burns et al., 2021). Additionally applying selections to short GRBs including the rise time and duration, both preferentially shorter for MGFs, identified GRB 180128A (Trigg et al., 2023). Recently, INTEGRAL detected, localized to few arc minutes—which is orders of magnitude better than the second best-localized MGF—enabling rapid follow-up observations, and promptly identified GRB 231115A as an MGF (Mereghetti et al., 2023; Yin et al., 2023), which is the first giant flare with rapid follow-up observations. Further analysis of this event is ongoing. It is important to notice how, in this case, even in the absence of a pulsating tail, it was possible to unambiguously identify the origin of the event as an MGF, thanks to the precise localization. A well-constrained association to a nearby galaxy, in fact, allows for accurate

estimation of distances and hence intrinsic energetics of the burst, effectively excluding other typically more energetic progenitors.

Constructing a population of MGFs is key for several reasons. Study of galactic and extragalactic MGFs allows for more precise measures on rates and intrinsic energetic functions (Burns et al., 2021), which indicate if these giant flares are the extreme end of the SGR short burst distribution or fully distinct. These measures are also key to understanding if MGFs can power FRBs. The study of individual events provides precise temporal and spatial information for deep multimessenger searches. Recovery of the MGF signal, individually or stochastically (Macquet et al., 2021; Kouvatsos et al., 2022), allows measure of the f-mode frequency, giving an insight into the structure of NSs and their equation of state (Kunjipurayil et al., 2022). The study of extragalactic MGFs allows for careful (unsaturated) study of their temporal and spectral evolution, providing insights into their physical origin (Trigg et al., 2023). Lastly, identifying extragalactic MGFs is the easiest, possibly only way to study magnetars beyond the Magellanic Clouds.

All of these scientific results support the need for continuous, sensitive, all-sky monitoring of the gamma-ray sky. Reasonable localization accuracy is necessary to enable follow-up searches across and beyond the electromagnetic spectrum. The possible harder spectrum of brighter bursts may be key to driving sensitivity at higher energies than typical GRB monitors. Coverage of gamma-rays above the MeV regime is needed to search for more GeV flares, similar to the one found after GRB 200415A (Ajello et al., 2021), which may inform or reject the bow-shock origin proposed in Ajello et al. (2021).

3.4 Pulsating MGF tail from extragalactic magnetars

The initial spike of the three confirmed MGFs was closely followed by a bright ($L_X \approx 10^{43}$ erg s $^{-1}$) thermally emitting ($kT \approx 10$ keV) tail, declining quasi-exponentially below the sensitivity of large field-of-view hard X-ray monitors in approximately 300 s). The rotational motion of the NS induces periodic modulation to this tail at the star spin period, providing the smoking-gun evidence for the magnetar central engine of these extreme events.

These tails are thought to be generated due to the magnetosphere of the NS trapping a fraction of the energy released by the initial burst (likely when magnetic pressure overcomes the radiation pressure as emission from the initial spike abates). This trapped fireball of photon-pair plasma is optically thick and slowly releases energy from its surface as it cools and shrinks in size (essentially evaporating Thompson and Duncan, 1996). Observationally, the tail spectra in the 1–100 keV range are dominated by a thermal component with observed temperatures on the order of tens of keV, which decreases with time. A non-thermal component is also present, most prominently at early times and dominating the emission at higher energies (≥ 100 keV, Boggs et al., 2007).

The spectra of the time-integrated tails of the three MGF tails were compatible with a dominant blackbody component (kT of tens keV) and a subdominant power-law only emerging above 30–40 keV (Figure 4 of Hurley et al., 2005). The intrinsic total radiative energy of the three observed MGF tails hovers at approximately a few 10^{44} erg (Mereghetti, 2008), despite the fact that the energy

from their initial spikes varies by two orders of magnitude. This raises the intriguing question of whether MGF tails are standard candles. The current statistics of the available observations limits our capability to provide a meaningful answer. However, the relevance of this realization has important implications for both cosmology (providing a tool for more accurate distance measurements) and the measurement of the, largely unknown, magnetic Eddington limit (Turolla et al., 2015). Additionally, quasi-periodic oscillations (QPOs) at several differing frequencies have been discovered in the tail emission of the galactic MGFs of SGR 1900 + 14 and SGR 1806–20 (Israel et al., 2005; Strohmayer and Watts, 2005). If interpreted as oscillation modes in the NS crusts, these QPOs could be utilized to place limits on the dense matter equation of state, complementing other major efforts such as light curve modeling of millisecond pulsars by NICER (Miller et al., 2019; Riley et al., 2019) and the waveform modeling of the gravitational wave signal from double NS mergers (Abbott et al., 2017). Thus, expanding our ability to detect MGF tails beyond our galaxy and immediate neighborhood will substantially increase the sample size of these events, in turn providing crucial data to test these tails as an independent cosmological probe and infer the Eddington limit of highly magnetized NSs.

To this end, we simulate the possible detection of MGF tails with currently operating X-ray satellites, scaled to the extragalactic distance of 3.5 Mpc (e.g., the distance of the star-forming galaxies M82 and NGC 253). We assume an event like the 1998 MGF from SGR 1900+14 as presented in Feroci et al. (2001), in which the spectrum is modeled as a blackbody, with temperature decreasing over time. We use the effective areas of the instruments as presented in the left panel of Figure 6. The right panel of Figure 6 displays the number of expected signal counts as a function of a hypothetical repointing time starting at 60 s and integrating over the duration of the tail (300 s). In this time window, for most pointed X-ray telescopes, the expected background counts is on the order of a few (not included in our simple calculations, as detailed simulations are reserved for an upcoming publication). At 3.5 Mpc, all instruments are capable of detecting the tail assuming a relatively fast repointing, e.g., that of XRT aboard Swift. A NuSTAR or NICER-like instrument, under the same circumstances, could detect the tail up to approximately 35 Mpc. With an MeV-sensitive mission which could detect MGF spikes up to these distances and beyond, an X-ray follow-up instrument with the above capabilities could provide smoking-gun evidence for a population-size sample of MGF, paving the way for a major leap toward the understanding of these phenomena. On the other hand, a large field-of-view X-ray instrument such as eROSITA (Predehl et al., 2021) or one equipped with a sensitive lobster eye optic, such as Einstein Probe (Yuan et al., 2022), might be able to detect MGF tails independently and provide an estimate of “orphan” MGF tails where the spike emission is beamed away from the observer.

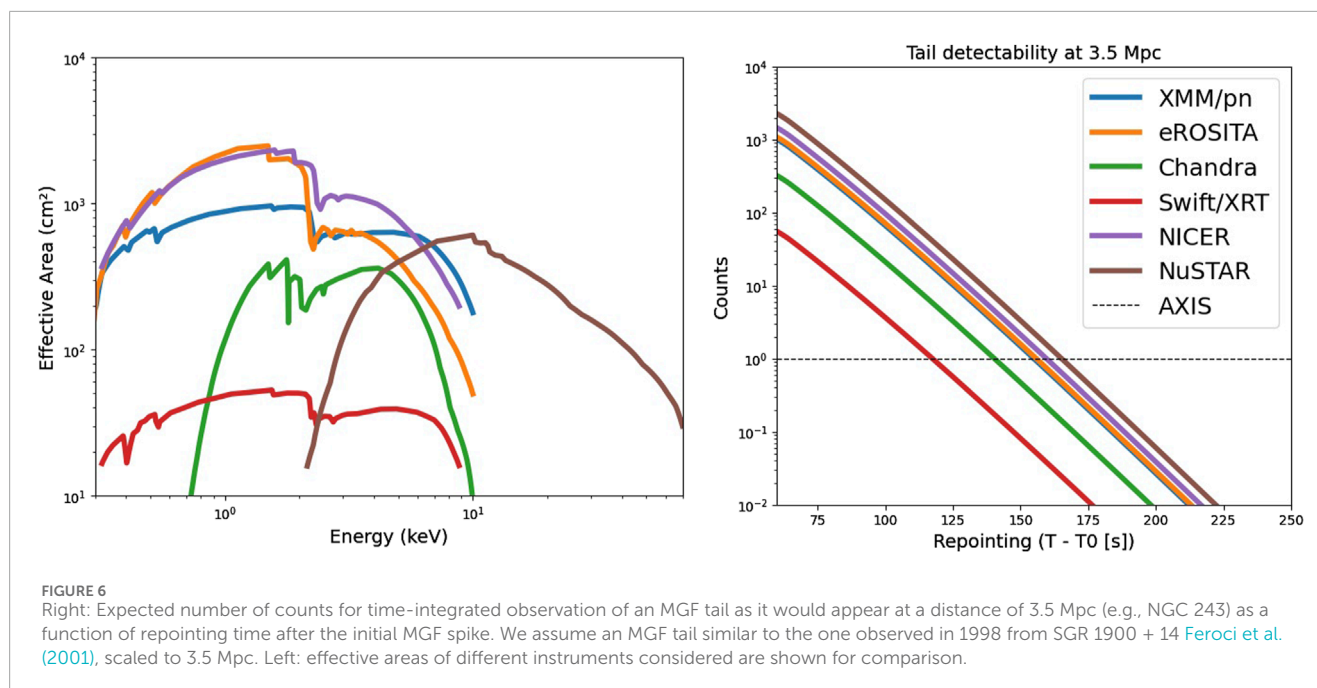
3.5 Polarization of magnetars’ bursts and flares

X-ray polarization of magnetars traces the magnetic field geometry as well as the shape, dimension, and physical state of the surface emitting region and exotic effects of quantum

electrodynamics (QED) that are expected to take place in the presence of extreme magnetic fields like those of magnetars. Despite the significant recent observational advancements made with the NASA’s IXPE mission (Weisskopf et al., 2022), the highly degenerate parameters space prevents from definitive conclusions on QED effects (Taverna et al., 2022; Zane et al., 2023). IXPE results, which focus primarily on persistent emission, highlight the need for further theoretical effort and advancements in numerical simulations to build more accurate models. Furthermore, the impossibility in decoupling QED effects on polarization from geometrical polarization expected when the emitting region is a small patch on the magnetar’s surface suggests the need for extending the range of measured polarization below 1 keV. Probing the polarization from the cooler X-ray radiation emitted from a wider portion of the surface is expected to be a better probe of QED effects. In this context, the further advancement of technologies like the ones developed for the Rocket Experiment Demonstration of a Soft X-ray Polarimeter (REDSOX) (Marshall et al., 2023), recently approved by the NASA, will be critical in this endeavor.

Extant models of magnetar burst polarizations are sparse (Taverna and Turolla, 2017) and are currently in development Wadiasingh et al. (2023). The combination of different outgoing photon angles sampled by the observer on a magnetic loop, however, is expected to reduce the time-averaged polarization of the bursts to approximately 30–60%. Polarization of bursts is also expected to be energy-, viewing-, and magnetic-geometry-dependent, with possible influences of gravitational lensing by the magnetar. Any actual observational constraints on burst polarization, combined with measured broadband spectra of high-energy monitors, can greatly inform the factors influencing burst polarization, such as magnetar viewing geometry, size of the active flux tube, and rotational spin phase of the burst. This, in turn, combined with other high-energy observations, can elucidate the active region and physics of the magnetar crust. As magnetar bursts are sporadic and unpredictable, catching a bright burst serendipitously in pointed observations is unlikely, unless a burst storm is ongoing, in which case, assessment of the polarization could be limited by counts statistics for individual short bursts or pile-up in case of extremely bright events. This can be observed with current instruments (such as IXPE) through the delayed X-ray emission from the very bright bursts scattered off dust layers along the line of sight. Such observations would be effective in the approximation that the dust scattering-induced polarization is negligible ($\sim 10^{-5}$ modulation), which is valid for small (arcminutes) scattering angles (see Appendix B.2 of Negro et al., 2023). A fast-pointing soft X-ray polarimeter or a sensitive monitor with polarization capability would greatly widen our observational portfolio, allowing for more modeling and better understanding of the processes involved in galactic magnetar burst activity.

In the context of MGFs, polarization observations would provide key information about the structure of the magnetar magnetosphere. Taverna and Turolla (2017) modeled the spectral and polarization properties of the 1–100 keV radiation emitted during the MGF tails, invoking a simplified “trapped-fireball” model, in which the electron-positron pair plasma is injected into the magnetosphere and remains trapped within the closed lines of the strong magnetic field. The linear polarization predicted by this model is very high (greater than 80% between 1 and 100 keV). Taverna and Turolla



(2017) adopted a similar model to predict the linear polarization from MGF tails, assuming a more realistic temperature distribution in the fireball, but integrating over wider energy ranges, finding a lower polarization degree, as high as 30% (1–30 keV) and 10% (30–100 keV) depending on the viewing angle with respect to the magnetic axis of the magnetar.

Such discrepancy in different predictions highlights how polarization measurements of MGF tails could help constrain the trapped-fireball model and potentially drive new theories to explain magnetar flares. Such observations are not possible in the soft X-ray band as IXPE could not repoint fast enough to catch the emission, while at higher energies, at which the future missions COSI and POLAR 2 will operate, theoretical predictions are lacking. COSI—the COMPTON Spectrometer and Imager ([Tomsick et al., 2023](#))—scheduled to launch in 2027, will be sensitive to soft gamma rays between 200 keV and 5 MeV and will have polarization capabilities for assessing galactic MGF tails. A dedicated study on the ability of the COSI to detect extragalactic MGFs is needed.

4 Magnetars in multimessenger astronomy

4.1 Gravitational waves from magnetar bursts and flares

Gravitational waves (GWs) from magnetars can be generated through various astrophysical processes that involve rapid changes in the mass distribution or extreme deformations of these highly magnetized NSs. The intense magnetic fields associated with magnetars significantly influence their dynamics and can give rise to GW emissions. This happens when the intense magnetic fields of magnetars undergo instabilities, causing dramatic reconfigurations.

The associated GW waveforms depend on the specifics of the starquake, and the characteristic frequencies are unknown. MGFs excite two different types of oscillations, the fundamental (of f-mode), which radiate GWs, and the shear modes or torsional modes, that manifest themselves with observable QPOs. The f-mode is thought to be excited when the magnetar's internal magnetic field rearranges itself, while QPOs are other oscillation modes most likely excited due to seismic vibrations and are longer-lived than the f-mode. QPOs have been detected in the tail emission of all three nearby MGFs ([Israel et al., 2005](#); [Strohmayer and Watts, 2005](#); [Strohmayer and Watts, 2006](#); [Watts and Strohmayer, 2006](#)), and, interestingly, QPOs in short repeated bursts from SGR J1550-5418 were also reported in 2014 by [Huppenkothen et al. \(2014\)](#). In general, however, the frequencies detected are disparate and the vibration modes are difficult to identify, given the numerous stellar parameters involved (magnetic field, mass, radius, composition, etc...) and the rarity of these events.

While GWs are generally anticipated to accompany energetic bursts, this expectation is especially pronounced and accessible in the case of MGFs, representing the most intense starquakes in magnetars. This expectation is predicated upon the assumption that mass redistribution can yield a GW luminosity that is a sizable fraction of the total radiative luminosity of $10^{45} - 10^{47}$ erg/sec in the initial spike. Such GW luminosities are readily accessible to LVK for magnetars in the Milky Way and in nearby galaxies. Despite these expectations, the detection of GWs from MGFs remains elusive, with none having been observed to date (see [The LIGO Scientific Collaboration et al., 2022](#), for the search in the previous LIGO-VIRGO-KAGRA observing run). In 2004, in occasion of the MGF from SGR 1806–20 ([Palmer et al., 2005](#)), the early LIGO interferometers reported only upper limits ([Abbott et al., 2007](#)) on a possible GW emission. The Gamma-ray Transient Network Science Analysis Group ([Burns et al., 2023](#)) pointed out that the current GW detector network is about two orders of

magnitude more sensitive than the first generation detector network, and another factor of 100 is expected within the next 20 years of upgrades. Such improvement from the GW front can lead the first detection of GWs from magnetars in Milky Way and beyond. In this context, the presence of wide field-of-view high-energy monitors with a fast turnaround is imperative to promptly detect electromagnetic counterparts. Such observations would constrain the total energy that can be radiated via GW, as well as the ratio between electromagnetic energy vs. GW energy during magnetar flares, providing major advances in our understanding of magnetars (and NSs in general), constraining the models of matter structure and behaviors in such extreme environments.

GWs are also likely produced during the birth of the magnetar. Section 3.3 described the relevance of observing a second MGF from the same magnetar, in terms of being the first source of repeating GRBs. However, another implication of repeating MGFs, as pointed out by Stella et al. (2005), is the requirement of a magnetic field above 10^{16} G of newly born magnetars. Such extreme internal field necessarily deforms the NS; if its moment of inertia has axes not aligned with the rotational axis, it would generate a week-long strong gravitational wave signal. The frequency of such a GW signal is dictated by the fast rotation period of the newly born magnetar. Stella et al. (2005) predicted the detection of such a GW signal by Advance LIGO-class detectors up to the distance of the Virgo Cluster (~ 2000 galaxies), where magnetars are expected to form at a rate of more than one magnetar per year. GW detections of newborn magnetars (Lander and Jones, 2020) have so far not been forthcoming.

Models predicting gravitational wave signals from magnetars (see Ciolfi and Rezzolla, 2012; Dall'Osso and Stella, 2022, and references therein) face considerable uncertainty due to our limited understanding of their internal magnetic field configurations and matter equations of state. This uncertainty spans from optimistic to pessimistic expectations. Further investigation into magnetars' transient activity holds promise in elucidating the underlying physics, potentially improving prediction reliability.

4.2 Neutrinos from magnetars

During the initial phases of a magnetar flare or burst, the intense release of energy can heat the NS's crust and interior. Subsequent cooling processes, involving neutrino emission, become prominent. Neutrinos, being weakly interacting particles, can escape the dense magnetar environment and carry away significant amounts of energy. We can distinguish between high-energy neutrinos, of GeV–TeV energy, detectable by instruments like the IceCube Observatory (IceCube Collaboration et al., 2006), and MeV neutrinos, like the ones produced in stellar processes and supernovae explosions, detectable by instruments like Super-Kamiokande (Walter, 2008). Both classes of neutrinos, when detected in coincidence with the electromagnetic counterpart, are a crucial aspect of multimessenger astronomy—which, in a sense, can be dated back to the detection of MeV neutrinos from SN 1987A (Blanco et al., 1987). In the context of magnetar bursts and flares, models have been developed to predict the emission of high-energy neutrinos, the detection of which would

provide important information about the flaring mechanism, as well as the crustal composition. In general, the production of neutrinos requires the presence of hadronic or photo-hadronic interactions. In MGFs, the neutrino fluxes depend on the baryon load, which is not well-constrained, due to uncertainties on the relative importance of thermal and non-thermal components (Ioka et al., 2005). Hence, detection of neutrinos from magnetars would be extremely insightful to understand their composition.

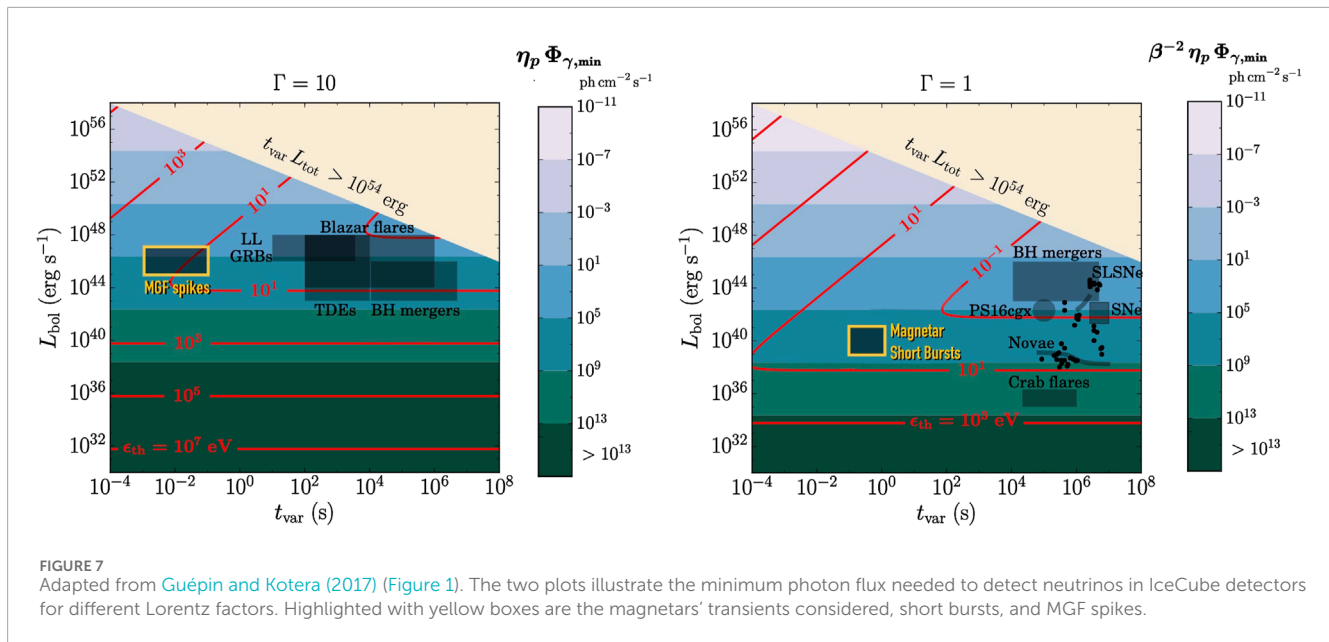
One can build the expectation of the high-energy neutrino yield knowing the expected photon flux of the outflow. This was done in Guépin and Kotera (2017), where they computed the minimum photon flux necessary for neutrino detection by IceCube, as well as the maximum neutrino energy expected, for a number of different sources of outflows (including magnetar bursts and flares). The study is generalized in terms of the intrinsic bolometric luminosity, the Lorentz factor, and the time variability of the emission. Figure 7 highlights the results for magnetars' transient activity. This study shows how neutrino detection is limited to only very nearby bright events, i.e., MGFs with a maximum luminosity distance of ~ 0.39 Mpc (minimum photon flux of $10^4 - 10^6$ ph cm $^{-2}$ s $^{-1}$ to have a neutrino detected in IceCube). The procedure followed by Guépin and Kotera (2017) is somewhat simplistic and assumes high hadronic yield and maximally efficient proton acceleration associated with relativistic outflows. This might be attained for MGFs, but it is unlikely for short bursts. Models predict relativistic outflows in the tails of MGFs (van Putten et al., 2016) as a necessary ingredient to reproduce the observed pulse fraction, offering therefore prospects for high-energy neutrino emission during the tail-phase of MGFs if proton acceleration is tenable. As pointed out by Ioka et al. (2005), if TeV neutrinos are detected, one would also expect detectable EeV cosmic rays and possibly TeV gamma-ray emission in coincidence. No claim of such detection has been made so far.

Ghadimi and Santander (2023) searched for high-energy neutrinos from galactic magnetars, performing a time-integrated search over 14 years of data collected by the IceCube Observatory (Aartsen et al., 2017). The results point out that a next-generation upgrade of the neutrino detector with improved sensitivity is in order, as the current IceCube capabilities are $\sim$ two orders of magnitude above the needed sensitivity to detect a stacked signal from all known magnetars. The creation of a magnetar burst catalog would be beneficial for targeted time-dependent neutrino searches anticipated in Ghadimi and Santander (2023) as future studies.

4.3 Link to fast radio bursts

FRBs are extragalactic flashes of radio emission of millisecond duration of isotropic-equivalent energies $10^{36} - 10^{41}$ erg, first² reported by Lorimer et al. (2007). Only recently (since about 2014) has their true astrophysical nature been accepted, over instrumental backgrounds or artifacts (Spitler et al., 2014). FRBs have now become a major interest of study and industry in radio astronomy

² Although possibly much earlier by Linscott and Erkes (1980).



(Caleb and Keane, 2021), with propagation effects particularly useful in cosmological probes (Zhou et al., 2014; Li et al., 2018) such as the baryon fraction of the intergalactic medium (Macquart et al., 2020). They are also, currently, an important topic in time-domain astronomy. Many future facilities prominently feature FRBs or radio transients more broadly, as one of their key science topics. Yet, as given below, there is an intimate association between magnetars and their soft gamma-rays short bursts.

Magnetars were initially proposed as the engines of the 2001 Lorimer burst among many models, although in the form of giant flares producing FRBs (Popov and Postnov, 2010; 2013). Yet various non-magnetar and exotic models were also proposed (Platts et al., 2019). As the first repeating FRB was discovered (Spitler et al., 2016), giant flares from “hyperactive” magnetars became a popular model (Beloborodov, 2017; Metzger et al., 2019) over cataclysmic events. However, statistics of waiting times and power-law distributions of fluence in repeating FRBs suggested much more similarity with magnetar short bursts (Wadiasingh and Timokhin, 2019). Yet, as of 2019, no FRBs were seen from many thousands of short bursts recorded from known magnetars in our local universe. Moreover, radio limits on the SGR 1806-20 giant flare in 2004 ruled out any contemporaneous bright radio flashes (Tendulkar et al., 2016); thus, it appears that giant flares do not necessarily produce FRBs. As suggested by Wadiasingh and Timokhin (2019); Wadiasingh et al. (2020), special conditions (e.g., charge starvation and pair cascades in the magnetosphere) must be satisfied such that not all short bursts produce radio emission (yet all FRBs would be associated with short bursts, as the FRB occurs in the beginning “clean” stage of the fireball created in short bursts). As FRBs result from coherent emission processes, and short bursts are incoherent, the energy contained in FRBs is generally expected to be a small fraction of the total energy observed in the quasi-thermal short bursts. The same conditions thought to be conducive to the production of FRBs (i.e., explosive pair production demanded by large coherent electric fields) likely are

also suitable for proton acceleration and the production of high-energy neutrinos at low altitudes in the magnetar magnetosphere (Herpay et al., 2008).

The situation was clarified dramatically in April 2020, when SGR 1935 + 2154 underwent a burst storm, emitting thousands of short bursts in the hard X-rays (Younes et al., 2020a; Palmer, 2020). In the waning hours of this storm, CHIME/FRB (CHIME/FRB Collaboration et al., 2020) and STARE2 (Bochenek et al., 2020) observed a bright radio flash consistent with an FRB from SGR 1935 + 2154. The radio burst was bright enough (energy $\sim 10^{36}$ erg isotropic equivalent) if placed at a cosmological distance to be similar to weaker extragalactic FRBs. Thus, at least a fraction of FRBs originate from magnetars. The burst featured a bright (10^{40} erg) and prompt hard X-ray short burst counterpart detected by INTEGRAL, HXMT-Insight, and Konus Wind (Mereghetti et al., 2020; Li et al., 2021; Ridnaia et al., 2021) (although not by Fermi-GBM and Swift-BAT due to Earth occultation). The HXMT-Insight light curve of the FRB-associated burst featured a 30–40 Hz quasi-periodic oscillation (Li et al., 2022), consistent with a low-order crustal torsional eigenmode of an NS, bolstering the case that FRBs are related to magnetar crustal dynamics and how that is transmitted to the magnetosphere (Wadiasingh and Chirenti, 2020). Moreover, the radio led features in the short burst counterpart by a few milliseconds, suggesting a magnetospheric origin to this radio burst, and perhaps all FRBs (Ge et al., 2023; Giri et al., 2023). More recent statistical “aftershock” analyses of extragalactic FRBs and SGR 1935 + 2154 have revealed similarities to each other and to earthquake dynamics (but not solar flare catalogs) (Totani and Tsuzuki, 2023; Tsuzuki et al., 2024), suggesting that the crustal dynamics on magnetars are key to understanding FRBs.

Radio activity in SGR 1935 + 2154 is also connected with torque and potentially interior dynamics of the magnetar. In October 2020, SGR 1935 + 2154 became radio-active again, exhibiting bright radio bursts (Kirsten et al., 2021) as well as a prolonged

episode of pulsar-like pulsed radio emission (Zhu et al., 2023). This is suggestive of conditions which are conducive to both phenomena and a magnetospheric origin of FRBs. For this episode, X-ray timing revealed a jump in the period of the magnetar Younes et al. (2023) i.e., a spin-down glitch, consistent with a baryon loaded wind extracting angular momentum from the star. More recently, Hu et al. (2024) have reported X-ray timing revealing two spin-up glitches separated by ~ 9 hours bracketing FRB-like radio bursts (Dong and Chime/Frb Collaboration, 2022; Maan et al., 2022) during an epoch of waning burst rate but high spin-down in October 2022. This result suggests a high superfluid fraction of the magnetar, with burst activity possibly triggering the first spin-up glitch. The glitch, in turn, possibly triggered the baryonic wind and magnetospheric conditions conducive for radio bursts.

There are many open questions concerning FRBs and the putative magnetar connection: Why do only a small fraction of magnetar short bursts result in an FRB-like emission? Why are some extragalactic FRB sources much more prolific FRB producers than galactic magnetars? What is the origin of long-timescale periodic activity windows in extragalactic FRBs (Rajwade et al., 2020; Chime/Frb Collaboration et al., 2020), and is this related to the recently reported galactic long-period magnetar candidates (Caleb et al., 2022; Hurley-Walker et al., 2022; 2023; Beniamini et al., 2023)? Can magnetars involved in NS mergers produce radio bursts (Cooper et al., 2023)? To answer these questions, further study of local magnetars and extragalactic magnetar signals correlated in time and sky location in multiple messengers will likely be crucial.

5 Summary and conclusion

We conclude by underscoring the critical role of continuous monitoring and real-time detection and alert capabilities in advancing our understanding of magnetars, as well as other transient events in the high-energy astrophysical landscape.

Long-term monitoring campaigns of magnetar outbursts, particularly in X-rays alongside radio and infrared observations, have yielded invaluable insights into the behavior of magnetars. Swift and NICER have played pivotal roles in this regard, with their continued operation being paramount for future discoveries. Sensitive, continuous monitoring of the high-energy sky plays a crucial role in detecting bursts and flares from magnetars, both alone and in concert with FRB monitoring, and possibly future GW and neutrino observations. Increased sensitivity of all-sky monitors could reveal MGF tail emission of extragalactic events, providing the unambiguous signature for a magnetar origin. At the same time, improved localizations could unambiguously exclude a cosmological origin of the detected gamma-ray burst (Mereghetti et al., 2023). Precise localizations may also allow for determination of repeat giant flares from individual magnetars in other galaxies, a question which has not been resolved directly in 50 years of monitoring the Milky Way. Capturing orphan MGF tail detection, where the spike emission is directed away from the observer, also requires ultra-fast repointing instruments or large field-of-view X-ray instruments equipped with sensitive optics. High-energy polarimetry offers a unique window into the physical processes driving magnetar transients, shedding light on magnetic

field configurations, emission mechanisms, and the nature of the emitting sources. The recent non-selection of LEAP—A Large Area burst Polarimeter—by NASA represents a missed opportunity to gather new insights from fast-transient polarization in the 50–500 keV energy range. In general, a wide-field polarimeter with sensitivity down to tens of keV would greatly contribute to enhancing our understanding of magnetar dynamics through the observations of nearby extragalactic MGFs and galactic intermediate flares.

The aging status of current instruments, including Konus, Swift, and Fermi, coupled with the decommissioning of AGILE and the impending decommissioning of INTEGRAL, underscores the urgency of advancements in technology and development of new missions to ensure uninterrupted coverage and enhanced capabilities for detecting fast transients. As technology evolves, there is optimism for improved sensitivity, localization, and monitoring capabilities, paving the way for further discoveries in the dynamic field of high-energy astrophysics.

Author contributions

MN: conceptualization, project administration, writing—original draft, and writing—review and editing. GY: writing—original draft and writing—review and editing. ZW: writing—original draft and writing—review and editing. EB: writing—original draft and writing—review and editing. AT: writing—original draft and writing—review and editing. MB: writing—original draft and writing—review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Multi-messenger emission characteristics of blazars

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Multi-messenger observations and theories of astrophysical objects are rapidly becoming a critical research area in the astrophysics scientific community. In particular, point-like objects such as BL Lacertae (BL Lac) objects, flat-spectrum radio quasars (FSRQs), and blazar candidates of uncertain type (BCUs) are of distinct interest to researchers studying the synchrotron, Compton, neutrino, and cosmic ray emissions sourced from compact objects. Notably, there is also much interest in the correlation between multi-frequency observations of blazars and neutrino surveys on source demographics. In this review, we look at such multi-frequency and multi-physics correlations of the radio, X-ray, and γ -ray fluxes of different classes of blazars from a collection of survey catalogs. This multi-physics survey of blazars shows that there are characteristic cross-correlations in the spectra of blazars when considering their multi-frequency and multi-messenger emission. In addition, a review of cosmic ray and neutrino emissions from blazars and their characteristics is presented.

KEYWORDS

high-energy astrophysics, multi-messenger astrophysics, supermassive black holes, blazars, active galactic nuclei, γ -ray, X-ray

1 Introduction

Active galactic nuclei (AGN) are the largest, most luminous, and persistent extragalactic objects observed in the Universe. These sources feature emissions across the full gamut of electromagnetic spectra, from radio to γ -ray up to ultra-high-energy cosmic rays. AGN, in general, encompass a large population of the high-energy γ -ray sources in the known Universe, comprising nearly 61.4% of the 5,064 γ -ray sources in the most recent completed update to the *Fermi*-LAT 4FGL catalog (Abdollahi et al., 2020). Blazars and other point-like objects such as misaligned AGN or radio galaxies (Abdo et al., 2010a) and Narrow-Line Seyfert 1 galaxies (D'Ammando, 2019), which feature similar emission patterns and mechanisms, play an essential role in our understanding of the high-energy Universe, potentially revealing crucial information about the evolutionary process of itself and the host galaxy. Blazars are of particular interest as they allow for direct observations of the relativistic jet emission and the resulting luminosity amplification due to the Doppler boosting of the emission. They are characterized by their extreme variability, high polarization, radio-core dominance, and superluminal velocities (Liu, 2009; Fan et al., 2016) and vary widely in time scales ranging from minutes to hours (intra-day variability), weeks to months (short-term variability), and months to years (long-term variability) (Wagner and Witzel, 1995; Gupta et al., 2016). They are known to show two prominent broad-spectral features: the first peak is the result of synchrotron radiation, and the second bump is potentially the

result of inverse-Compton emission (Gupta et al., 2016; Valverde et al., 2020) that dominates leptonic models. The corresponding hadronic models in blazar spectral energy distributions (SEDs) result from the higher-energy proton-synchrotron emission resulting from cascades of protons and pions in photo-meson productions (Böttcher, 2007; Cerruti, 2020). Blazars are categorized into two main subclasses, BL Lacertae (BL Lac) objects and flat-spectrum radio quasars (FSRQs) (Fan et al., 2016; Zhang and Fan, 2018; Kramarenko et al., 2021; Prandini and Ghisellini, 2022; Mohana A et al., 2023), along with a somewhat chameleon type of subclassification called *changing-look blazars* (Kang et al., 2024). The most notable differences between the two classes are the contrasts in emission lines. BL Lacs produce weakly peaked emission lines, while FSRQs produce very strong emission lines (Liu, 2009). The history of blazar unification has been a long-standing problem in AGN observations (Urry and Padovani, 1995; Fossati et al., 1998; Padovani et al., 2017; Rieger, 2019).

The *Fermi*-LAT collaboration (Atwood et al., 2009) has generated one of the most extensive catalogs of AGN in the high-energy regime (Ajello et al., 2020; Abdollahi et al., 2020; Ballet et al., 2023). A growing number of developing probe and mission concepts are dedicated to the multi-messenger aspects of observing these energetic objects with variable emissions. Additionally, when considering correlations of higher-energy observations with radio emissions of blazars, the joint Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE)-FERMI (Lister et al., 2011) catalog correlates these emission regimes observed by *Fermi*-LAT and MOJAVE collaborations. Similarly, on the lower end of the frequency spectrum, the MOJAVE (Lister et al., 2009) is stated as being a long-term program that observes the brightness and polarization of radio jets in AGN. Furthermore, sources are continuously added to the joint MOJAVE-FERMI AGN catalog (Kramarenko et al., 2021). Recommendations from the Pathways to Discovery in Astronomy and Astrophysics for the 2020s (Astro2020) (National Academies of Sciences and Medicine, 2023) have generated a number of products and

initiatives that prioritize science gaps for time-domain and multi-messenger (TDAMM) (ESA/ATG medialab, 2023) astrophysics. The γ -ray Transient Network Science Analysis Group (GTN SAG) (Burns et al., 2023) and various workshops and conferences solicit community synergy like that of the TDAMM workshop: The Dynamic Universe: Realizing the Science Potential of Time Domain and Multi-Messenger Astrophysics, was held following the recommendations from the National Academies of Sciences and Medicine (2023).

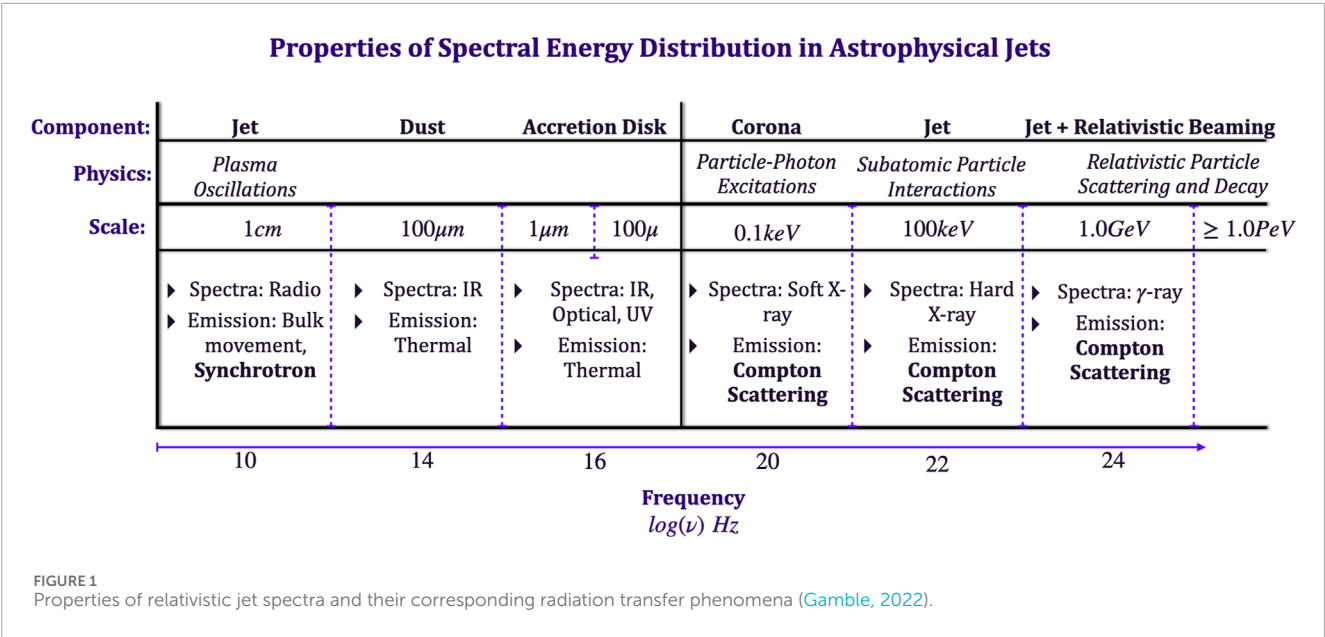
The remainder of this review is organized as follows: Section 2 provides a focused description of state-of-the-art physical characteristics of blazars and their emitted jets across a multi-physics regime looking at the intersecting physics of jet launching; Section 3 reviews current efforts that explore multi-spectral correlations and variability in blazars; and lastly, we end this paper with a discussion on multi-messenger science gaps, making parallels with other high-energy point-like objects that show similar emission characteristics as blazars. This section also highlights ongoing efforts and projects that attempt to reveal new areas of scientific interest in relation to a central black hole.

2 Multi-physics characteristics of blazars

2.1 Power spectrum

Relativistic jets comprise non-thermal emission within the AGN spectra, ranging from synchrotron sources of radio emission to higher-energy γ -ray and even cosmic ray emissions as can be seen in Figure 1. The power spectrum associated with synchrotron and self-synchrotron emission can be determined using Eq. 1 below

P(v) = (sqrt(3)*e^3*B*sin(alpha))/(m_e*c^2) * (v/v_c) * integral from v/v_c to infinity of K_5/3(eta) d eta, (1)



where the critical frequency, ν_c , is given by

$$\nu_c = \frac{3}{2} \gamma^2 \nu_G \sin \alpha, \quad (2)$$

with ν_G as the gyrofrequency. The parameters B, α , and ν are the magnetic field strength, pitch angle, and emission frequency, respectively. The integral in the synchrotron power function here is characterized by the modified Bessel function of the second kind $K_{5/3}(\eta)$, where η is defined as the ratio of the frequency to critical frequency ν_c . Additionally, their spectra can be determined using various observational data analysis methods and SED correlation schemes (Homan et al., 2021). Current data analyses from observational missions have shown that the SEDs of BL Lacs and FSRQs exhibit significant continuum variability in their observed frequency bands (Harris and Krawczynski, 2006; Abdollahi et al., 2020; Valverde et al., 2020; Mohana A et al., 2023). These spectral data can be connected back to the black hole–disk system to infer the local properties of the surrounding accretion disk (i.e., matter content, dust/plasma temperature, and particle accelerations/scatterings) but are limited in describing the gravitationally induced dynamics of the relativistic jet (Gamble, 2022).

2.2 Jet emission mechanisms

Currently, the mechanisms for relativistic jet emissions associated with AGN and other high-energy astrophysical objects like γ -ray bursts (GRBs) and microquasars are of interest in the astrophysics scientific community. Jet formation theory and emission is a major problem yet to be solved in high-energy astrophysics. One of the most widely argued models for describing this type of emission has been the Blandford–Znajek (BZ) process (Blandford and Znajek, 1977). This process describes the rotational energy extraction from black holes involving the torsion of magnetic field lines, resulting in Poynting flux-dominated outflows parallel to the rotation axis of the central object (Blandford and Znajek, 1977; Znajek, 1977).

$$L_{BZ} = f(\alpha_H) B_\phi^2 r_s^2 c 8\pi^{-1}, \quad (3)$$

where Eq. 3 provides the BZ luminosity. Here, we define the parameters α_H, B_ϕ , and r_s as the spin parameter of the black hole horizon, magnetic field strength in the ϕ -direction, and the corresponding Schwarzschild radius, respectively. The nature of such highly complex energetic emission mechanisms from these systems, which feature event horizons in rotating spacetimes, has been studied extensively over the last few decades (Williams, 2004; 1995; Pei et al., 2016; Toma and Takahara, 2016; King and Pringle, 2021; Gamble, 2022). Recent numerical and observational models incorporating magnetohydrodynamic (MHD) and general relativistic magnetohydrodynamic (GRMHD) methods have shown that a major contribution to jet outflows is from the poloidal magnetic field configurations from relativistic matter accreting onto the central object (Komissarov, 2005; Nathanail and Contopoulos, 2014; Koide, 2020; Akiyama et al., 2022). Unanswered questions on the relativistic nature of these jets involve figuring out how particles that make up the jet content are accelerated to ultra-relativistic speeds, of which the Lorentz factors are $\Gamma_{Lorentz} > 10$. What is the

origin of the relativistic particles that produce non-thermal radiation that we observe? Moreover, how do these jets become *matter-loaded*? Focusing on the theoretical aspects of jet formation mechanisms, fundamental questions continue to remain unresolved, one of which is the causal connection of the jet to the exterior Kerr spacetime. An application of the BZ process to alternatives or extensions of general relativity by Pei et al. (2016) has shown the versatility of the decade-old theory but, again, exhibits how the BZ process needs extensions to incorporate the sources of the magnetic fields it describes (Garofalo and Singh, 2021; King and Pringle, 2021).

As mentioned, a relativistic jet is described as a beam of light that carries linear momentum and, thus, is influenced by an appreciable amount of external angular momentum in both the non-relativistic and relativistic regimes. This angular momentum would then be dependent on the origin of an associated coordinate system, owing to the intrinsic gauge dependence of angular momentum in fundamental physics descriptions. If we then proceed to describe BL Lac and FSRQ blazars as energetic point sources, we can infer the physical characteristics of the jet emission as relativistic beams transported across galactic distances. These point sources should then inherently carry rotational symmetry corresponding to rotated field lines with respect to the host black hole (Gamble, 2022). The following equations of motion described in Eq. 4, specifically under the influence of curved spacetime near the jet-launching region, illustrate the complexities of jet launching from the supermassive black holes of blazar types. Here, the potentials parameterizing particle paths in this near-horizon region are defined, yielding a set of Hamilton–Jacobi equations for each direction. It is easy to see the expected symmetries in the particle paths for the t and ϕ directions. Here, the functions $R(r)$ and $V(\theta)$ in Eqs 6, 7 correspond to the traditional motions in the r and θ directions, respectively.

$$\Sigma \frac{dr}{d\lambda} = \pm \sqrt{R(r)}, \quad (4a)$$

$$\Sigma \frac{d\theta}{d\lambda} = \pm \sqrt{V_\theta(\theta)}, \quad (4b)$$

$$\Sigma \frac{d\phi}{d\lambda} = -(\alpha_H E - L/\sin^2\theta) + \alpha_H T/\Delta, \quad (4c)$$

$$\Sigma \frac{dt}{d\lambda} = -\alpha_H (\alpha_H E \sin^2\theta - L) + (r^2 + \alpha_H^2) T/\Delta, \quad (4d)$$

where the functions $T, R(r)$, and $V_\theta(\theta)$ are defined as

$$T \equiv E(r^2 + \alpha_H^2) - \alpha_H L, \quad (5)$$

$$R(r) \equiv T^2 - \Delta [m_0^2 r^2 + (L - \alpha_H E)^2 + Q], \quad (6)$$

$$V_\theta(\theta) \equiv Q - \cos^2\theta \left[\alpha_H^2 (m_0^2 - E^2) \frac{L^2}{\sin^2\theta} \right]. \quad (7)$$

Here, E and L are the particle energy and angular momentum, respectively, m_0 is the rest mass of a test particle, and Q is identified as Carter's constant. The functions $\Sigma = r^2 + \alpha_H^2 \cos^2\theta$ and $\Delta = r^2 - Mr + \alpha_H^2$ are defined from the components of the Kerr spacetime for a rotating black hole of arbitrary mass. Within the context of this discussion on blazar jet emission, it is logical to consider not only the particle distributions in jets but also the intrinsic geometry of particle paths moving at high Lorentz factors, specifically above $\Gamma_{bulk} \geq 10 - 10^2$. Additionally, there have been

efforts to incorporate non-equatorial instabilities that contribute to the e^-/e^+ pair production at γ -ray energies $\geq \text{GeV}$ around high-spin $\alpha_H \geq 0.8$ black hole horizons in a description of jet launching (Williams, 1995; Williams, 2004), thus removing some of the mystery of the physical mechanisms that cause some jets to twist and carry a proportionate amount of angular momentum from the black hole. It is then intuitive to think about how one can infer the mechanisms causing such polarization in the observed spectra. Observations of blazars and radio-loud AGN have shown that polarization states exist in the spectra from these sources (Homan et al., 2021; Liodakis et al., 2021).

3 Multi-spectral variability of blazars

3.1 Variability and flaring of VLBI-selected blazars

Observing the variability of blazars can reveal the necessary information to infer the composition of the jet emissions, the mechanisms behind the jet formation, and changes in the accretion rate of the accretion disk and can allow for the localization of the innermost emitting regions (Lawrence, 2016; Valverde et al., 2020). As the central supermassive black hole (SMBH) at the cores of blazars accretes matter and forms the surrounding accretion disk, it launches relativistic jets that emit across the electromagnetic spectrum (radio to γ -rays) (Gupta et al., 2016). Figure 2 shows such a distribution in the GeV energy flux associated with γ -ray emissions *versus* the very long baseline array (VLBA) flux for these radio–gamma correlated sources. This distribution shows a differentiation between high-synchrotron peak (HSP) BL Lacs that feature peaks in the range $\nu > 10^{15} \text{ Hz}$ and low-synchrotron peaked (LSP) BL Lacs that fall in the range $\nu < 10^{14} \text{ Hz}$ (Sahakyan, 2020). Refer to Giommi and Padovani (1994) and Abdo et al. (2010b) for more detailed descriptions comparing HSP and LSP signatures for BL Lacs.

Figure 3 shows that there exists a delayed variability in the radio emission for the blazar TXS 0506 + 056 (4FGL J0509.4 + 0542) compared to its higher-energy counterpart in the light curve at $E_{ph} > 1.07 \text{ GeV}$. This light curve, along with blazars in the MOJAVE-FERMI catalog, features this type of variability, where the radio and γ -ray emissions are correlated according to a respective time lag. There exists significant correspondence with the γ -ray flaring of TXS 0506 + 056 (4FGL J0509.4 + 0542) with neutrino incidence in the direction of this blazar (IceCubeFermi-LATMAGICAGILEASAS-SNHAWC et al., 2018). Analyzing the photo-meson production for HSP as stated above, such particle interactions within the jets of highly energetic sources like TXS 0506 + 056 (4FGL J0509.4 + 0542) and PKS 0735 + 178 (4FGL J0738.1 + 1742) (Prince et al., 2023) are a testament of the dynamic multi-messenger and multi-physics aspect of sources that feature extremely accelerated ejecta. The correlation between the radio and very high-energy (VHE) γ -ray emissions is a curious notion highlighting the new frontier of multi-messenger astrophysics in the modern era of astronomy. Additionally, HSP blazars with similar flaring characteristics are also likely to exhibit particle cascade mechanisms that produce cosmic rays (high-energy nucleons and charged particles). The 116 sources in the MOJAVE-FERMI-LAT 1FGL catalog are a prototypical example of the type

of variability blazars exhibit across multiple spectral frequencies. Note that the catalog only correlates VLBI-selected 15-GHz radio-loud sources with a significant correlation to their γ -ray peaks. The catalog is sourced from the study by Kramarenko et al. (2021), a decade of joint MOJAVE-Fermi AGN monitoring; localization of the γ -ray emission region that features 331 sources with down selection to N-blazars with significantly strong radio emission ($> = 80\%$) of the 331 catalogs of sources. Both blazar classes have been reported to present strong correlations between the radio and γ -ray emissions (Max-Moerbeck et al., 2014; Mufakharov et al., 2015; Fan et al., 2016), thus indicating that the production of these jet emissions coincides with a common mechanism. A more extensive overview of radio VLBI/ γ -ray catalogs of blazars: MOJAVE-FERMI-LAT 1FGL, National Radio Astronomy Observatory (NRAO) catalogs, Atacama Large Millimeter/submillimeter Array (ALMA), and Event Horizon Telescope results and simulations will be provided in subsequent papers focusing on more details of the cross-correlation in blazars. Figure 4 shows such intra-week variability at 15 GHz in the time domain. This variability illustrates the need for time-domain follow-up for energetic sources. We can see that on a month-to-month time scale, the correlation strength peaks at ~ 5 months. This suggests that there could be a significant observing campaign for follow-up observations. From a multi-physics perspective, improved time-dependent theoretical models and GRMHD simulations are needed to decipher such physics.

4 Discussion

4.1 Blazar parallels with γ -ray bursts

Given the nature of the high-energy emission characteristics of BL Lac and FSRQ blazars, it is additionally safe to compare them to GRBs. Both types of high-energy sources are considered to be sourced by compact objects (i.e., SMBH, X-ray binaries, neutron star mergers, core-collapse supernovae, and stellar mass black holes). Both energetic phenomena exhibit similar physical characteristics when considering their respective ejecta mechanisms. It is no coincidence that GRBs and blazar jets also feature similarities in the spectral peaks, illuminating commonalities in their respective radiation physics (Nemmen et al., 2012). A more detailed description of these physical comparisons can be found in works highlighting such comparisons (Lyu et al., 2014; Srinivasaragavan et al., 2023). An even more interesting recent inclusion in the “AGN zoo” is *changing-look blazars*. These are blazars that feature changes in their accretion processes, intrinsically changing from FSRQ-type to BL Lac and vice versa (Kang et al., 2024). This suggests that further investments in TDAMM science and its technological developments are needed to further elucidate the dynamical properties of AGN with blazar types, BL Lac, FSRQs, and BCUs.

4.2 Ground-based follow-up

4.2.1 ALMA: radio

Specifically, within the radio frequency regime, the ground-based ALMA (Wootten and Thompson, 2009) is extraordinary

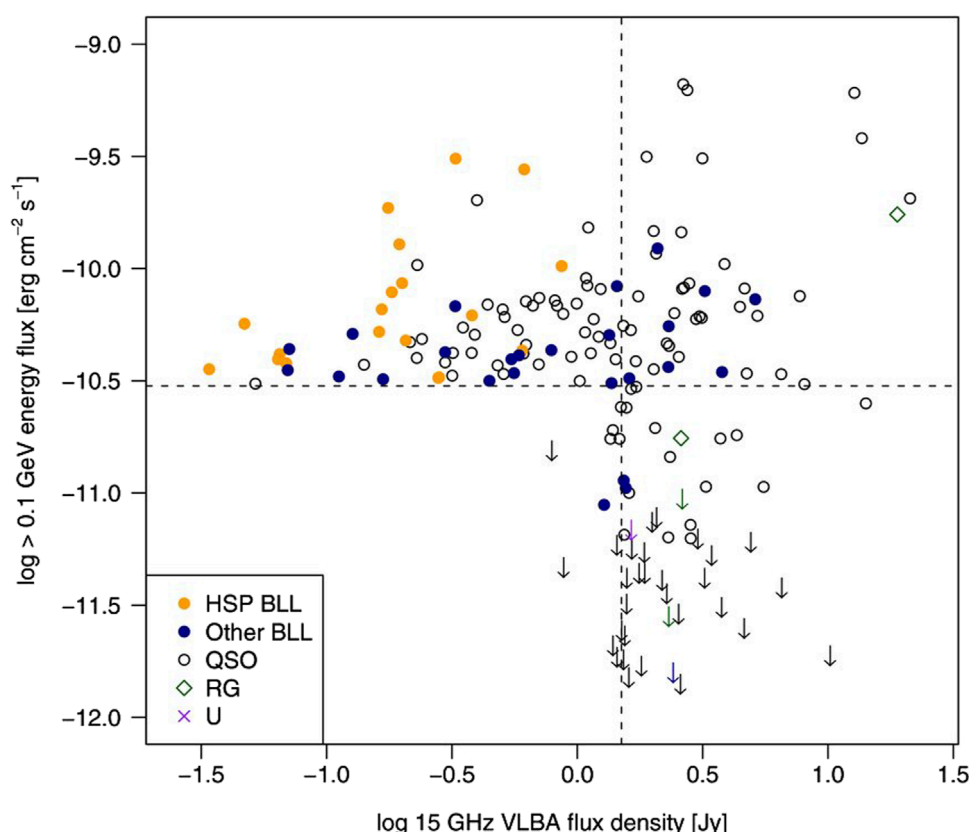


FIGURE 2

Plot of 11-month Fermi average $> 0.1\text{ GeV}$ energy flux vs 15-GHz VLBA flux density of the joint blazar samples given by [Lister et al. \(2011\)](#). The filled circles represent BL Lac objects, with the HSP objects in orange and others in blue. The open circles represent quasars, the green diamonds denote radio galaxies, and the purple crosses denote optically unidentified objects. Upper limits on the γ -ray fluxes are indicated by arrows. All of the BL Lac objects are detected by the LAT, with the exception of J0006-0623. The vertical dashed line indicates a sample radio limit of 1.5 Jy, and the horizontal dashed line indicates a γ -ray limit of $3 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$. The figure and caption are sourced from the MOJAVE-FERMI-LAT 1FGL catalog ([Lister et al., 2011](#)).

for observing, in general, AGN of different classifications as it provides a perspective of these high-energy objects in the radio and infrared spectrum. With its ground-breaking interferometric array of 66 high-precision antennas, its performance results in high-resolution images with the brightness sensitivity of a single-antenna array ([Brown et al., 2004](#)). LSP BL Lac objects offer a distinctive spectral climb when comparing their γ -ray peaks to their maximal synchrotron peaks ([Mohana A et al., 2023](#)), with blazars of type FSRQ almost exclusively falling under LSP ([Sahakyan, 2020](#)). Conversely, when analyzing the spectral correlation of HSP BL Lac objects with similar γ -ray energies, the correlation is not strong enough ($< 10\text{ GeV}$).

Quasar PKS 1549–79 was previously observed by [Oosterloo et al. \(2019\)](#) in order to analyze its radio jet, using millimeter- and very long baseline interferometry 2.3-GHz continuum observations. PKS 1549–79 is known as a radio-loud quasar, having a stronger radio emission and higher energy than the more common radio-quiet quasar ([Barvainis et al., 2005](#)). PKS 1549–79 is also the closest quasar that has been observed merging with an AGN in the first phases of its evolution. [Oosterloo et al. \(2019\)](#) also presented CO (1–0) and CO (3–2)

observations of its molecular gas. Their results showed that the massive outflow of $650 M_{\odot} \text{ yr}^{-1}$ confined to $r < 120 \text{ pc}$ of the inner galaxy suggests that the AGN drives this outflow. The radio-quiet quasar SDSS J0924 + 0219 was observed by [Badole et al. \(2021\)](#) using 45 of ALMA antennas and very large array (VLA). It is evident that analyzing both LSP and HSP blazars contributes to a more compounded description of blazar models when looking at the entire non-thermal spectra of blazars in the AGN zoo.

4.2.2 IceCube: neutrinos and cosmic rays

The flaring and variability of the blazar spectra listed in the MOJAVE-FERMI catalog, the *Fermi*-LAT catalogs, and various others that feature high-energy γ -ray emission from blazars residing in their active phases are important aspects for identifying the neutrino production from such sources (e.g., TXS 0506 + 056 (4FGL J0509.4 + 0542) and PKS 0735 + 178 (4FGL J0738.1 + 1742)). Analyzing the particle production mechanisms, we can see that the particle phenomenology associated with the electromagnetic and cosmic-ray producing interactions overlaps with their decay mechanisms as well. The photo-meson particle production in the

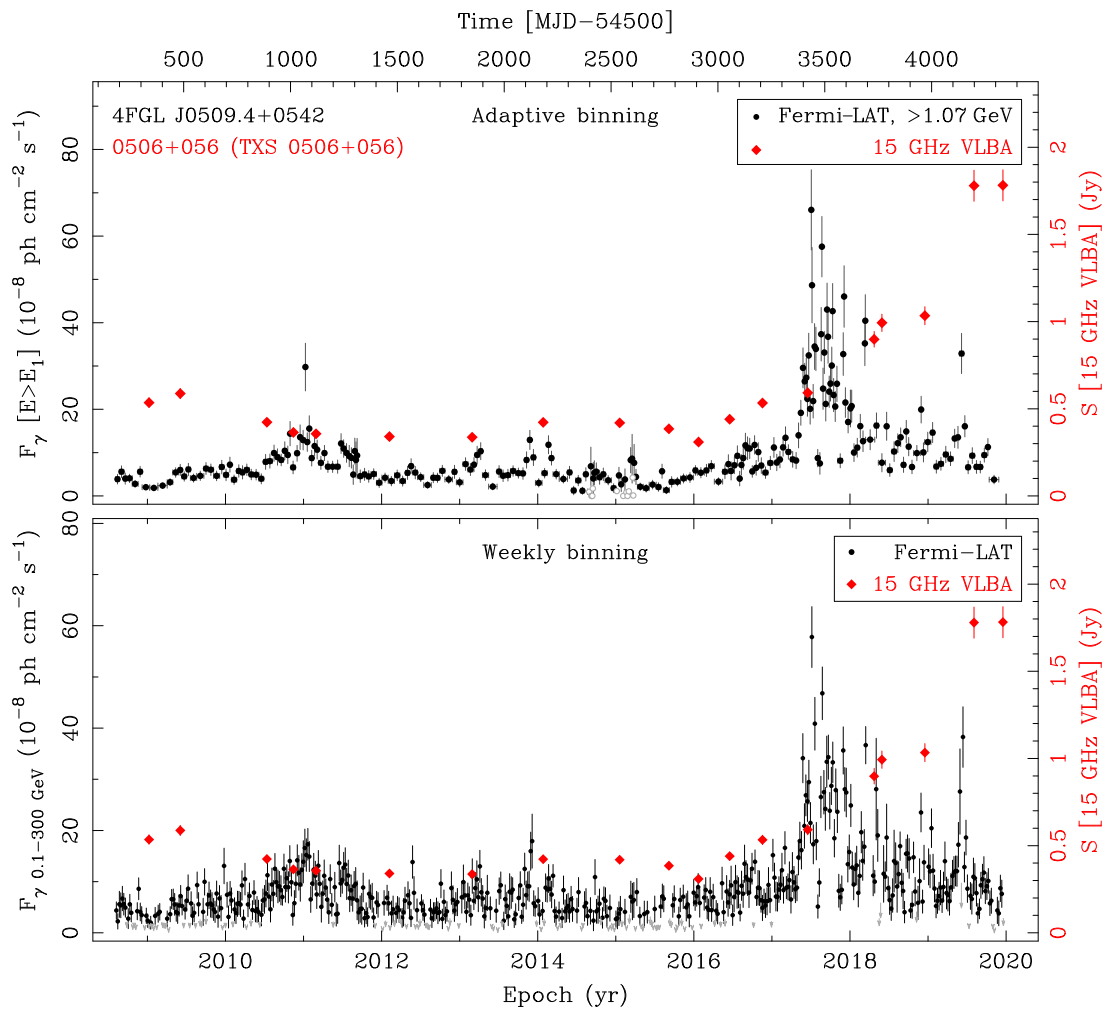


FIGURE 3
Intra-week variability overlap of the γ -ray emission at $E_{ph} > 1.07$ GeV (in black) and the VLBA radio emission at 15 GHz (in red) of the blazar TXS 0506 + 056 (4FGL J0509.4 + 0542). The two panels show the light curve with adaptive binning on the top and weekly binning on the bottom where the epoch spans 12 years. The multi-epoch light curve is sourced from the MOJAVE-FERMI-LAT 1FGL catalog (Lister et al., 2011).

accelerated environments of jets is shown in Eqs 8, 9, where protons scatter off photons to produce a cascade of charged and neutral pions (π^0, π^+, π^-).

$$\begin{aligned} p + \gamma &\rightarrow p' + \pi^0 \\ p + \gamma &\rightarrow n + \pi^+ \\ p + \gamma &\rightarrow p' + \pi^+ + \pi^- \end{aligned} \quad (8)$$

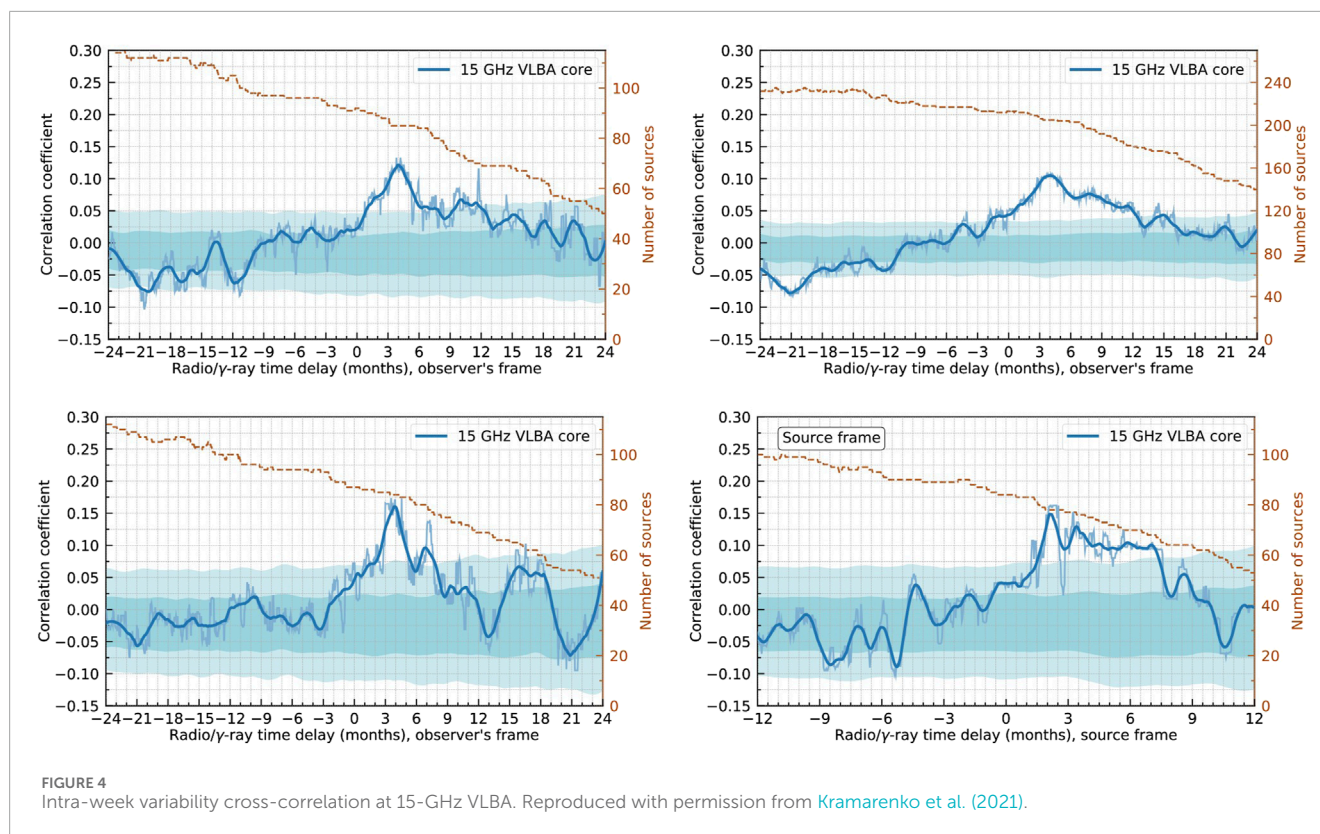
This interaction of accelerated protons with γ -ray photons provides a precursor to the neutral and charge pions. The subsequent decay of (π^-, π^+) into a cascade of muons (μ^+, μ^-) and neutrinos (ν_e, ν_μ) (of e^- and μ^+ types) and their respective symmetric (antimatter) pairs introduces the weak interaction into hadronic/meson blazar jet models.

$$\begin{aligned} \pi^0 &\rightarrow 2\gamma \\ \pi^+ &\rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \end{aligned} \quad (9)$$

Ultimately, the presence of these cascades detected by neutrino and Cherenkov telescopes is a prominent clue for finding relativistic protons in the jet (Muecke et al., 1999; Cerruti, 2020). The IceCube Neutrino Observatory (Aartsen et al., 2017) has made significant progress in detecting neutrinos of astrophysical origin emanating from blazars. Blazars, such as TXS 0506 + 056 (4FGL J0509.4 + 0542) and PKS 0735 + 178 (4FGL J0738.1 + 1742), have been extensively studied in recent years (Padovani et al., 2015; IceCubeFermi-LATMAGICAGILEASAS-SNHAWC et al., 2018; Prince et al., 2023). Multi-messenger observations and their follow-up have thus proven to be a powerful methodology for determining the VHE characteristics of blazars.

5 Conclusion

This focused review of blazars of type FSRQ, BL Lac, and BCU shows just how dynamic these point-like objects



are regarding their relativistic properties. The multi-physical nature of such astronomical objects suggests significant gaps in our understanding of their multi-messenger characteristics. The recommendations from the Astro2020 decadal survey offer an initiation of thoughts surrounding TDAMM science gaps. Further investments from the broader astronomy/astrophysics community are required to elucidate and decipher the true nature of blazars, their relativistic jet emission, and future multi-spectral analyses and missions. The utilization of unconventional thoughts and methodologies would prove useful in our quest to understand the energetic Universe. The synergy between radio (ALMA and MOJAVE), X-ray (IXPE, XRISM, Chandra, and SWIFT), γ -ray (VERITAS, *Fermi*-LAT, MAGIC, and H.E.S.S.), and cosmic-ray/neutrino (IceCube) observations plays an important role in the analysis and theoretical modeling of variable energetic blazars as it allows for more detailed observations of these objects.

Author contributions

RG: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing—original draft, and writing—review and editing. JF: conceptualization and writing—original draft. AB: conceptualization and writing—original draft. GS: conceptualization and writing—review and editing. IH: conceptualization and writing—review and editing. MJ: conceptualization and writing—review and editing.

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Conflict of interest

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NASA's astrophysics cross-observatory science support (ACROSS) initiative: enabling time-domain and multimessenger astrophysics

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The Astro2020 Decadal Survey recommended an investment in Time-Domain and Multimessenger Astrophysics (TDAMM) as the top-priority sustaining activity in space for the coming decade. One aspect of NASA's response to this recommendation is a pilot project, the Astrophysics Cross-Observatory Science Support (ACROSS) initiative, designed to provide support to both missions and observers as they pursue TDAMM science. Here, we present our observations of needs in the community and initial plans for ACROSS activities, including services to facilitate and improve cross-mission follow-up planning and execution; a multimessenger web portal with links to existing mission resources, community tools, and information targeted for TDAMM general observers; development of "Smart target-of-opportunity submission page" proof-of-concepts; and ongoing development of a potential TDAMM general observing competitive grant solicitation. As the ACROSS pilot phase begins, we invite discussion of our plans with both missions and observers to better understand their needs and concerns.

KEYWORDS

time domain, multimessenger, infrastructure, realtime, software

1 Introduction

Driven by the exciting firsts of 2017 – the first coincidence of a gravitational wave (GW) event, GW170817, with a short gamma-ray burst (GRB), kilonova, and off-axis jet ([Abbott et al., 2017](#)) and the first strong indication of an association between an astrophysical neutrino, IceCube-170922, and an active galactic nucleus (AGN), TXS 0506 + 056 ([IceCube Collaboration et al., 2018](#)) – the new capabilities encompassed by Time-Domain and Multimessenger Astrophysics (TDAMM) were called out highlighted by the Astro2020 Decadal Survey ([National Academies of Sciences, Engineering, and Medicine, 2023](#)) as the "highest priority sustaining activity" in space for the coming decade.

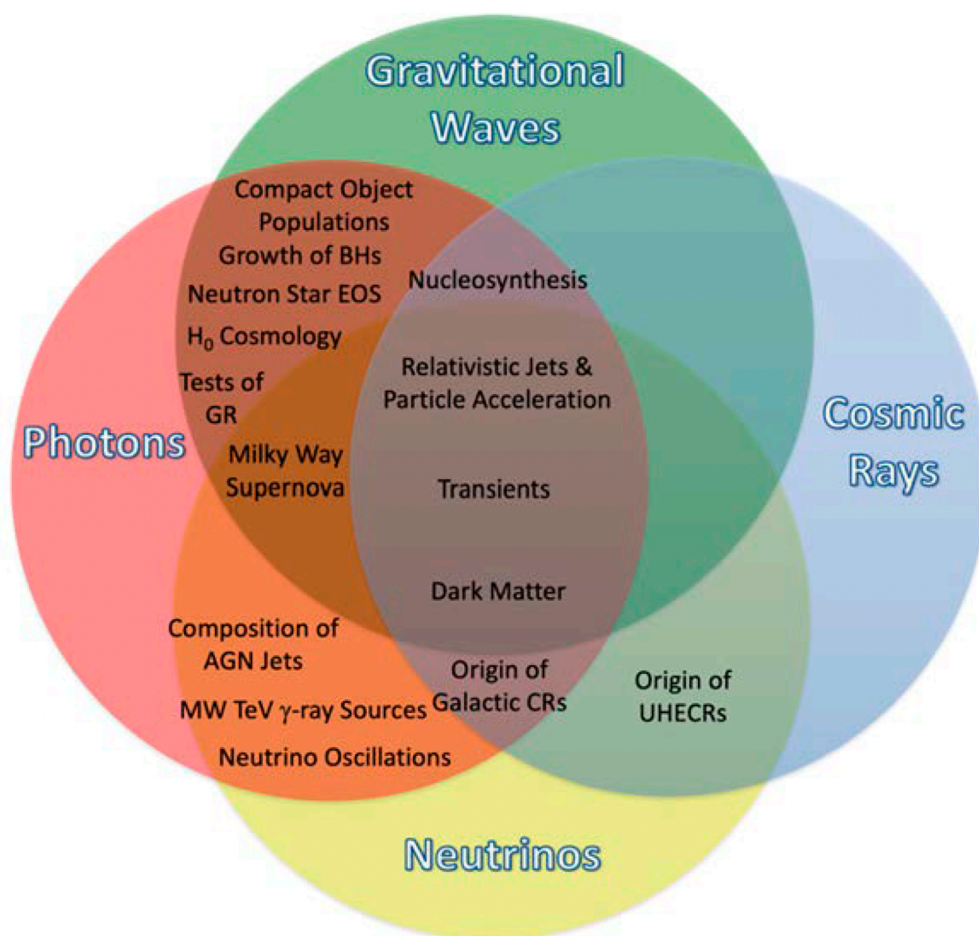


FIGURE 1

A schematic diagram indicating the science questions best answered by different combinations of messenger, emphasizing the range of critical science questions that are impacted by multimessenger observations (National Academies of Sciences, Engineering, and Medicine, 2023).

Much time-domain and multimessenger science can only be performed using space-based assets, thus creating a unique opportunity for NASA contributions. Astro2020 recognized that to “advance this science, it is essential to maintain and expand space-based time-domain and follow up facilities.” The landscape of science accessible via multimessenger observations is extremely rich, as indicated in Figure 1. In the coming years, exploration of this broad range of science will be enabled by NASA’s fleet in synergy with ground-based observatories spanning all messengers, as indicated in Figure 2. For NASA to meet the vision outlined in the Astro2020 Decadal Survey it must invest in the infrastructure needed to enable multimessenger and time-domain astronomy discoveries.

As was recognized by Astro 2020, a “suite of space-based electromagnetic capabilities [is] required to study transient and time-variable phenomena.” Numerous currently operating facilities that contribute to time-domain science are working to improve how they serve the time-domain astronomy community and expand how they can work collaboratively with other space and ground-based observatories. However, up until this point these collaborations between facilities have been largely bilateral and coordination has

generally been on an *ad hoc* basis. This has sometimes led to a failure to capture rare and exciting scientific opportunities arising from transients whose brightness fades on time scales of seconds to days, depending on the facilities required to observe them. For example, in the case of GRB 230307A, for the first time a late-time infrared spectrum resulting from r-process nucleosynthesis was measured. However, delays in localizing the event due to a lack of automated infrastructure meant that key observations were not made in the first few hours after the initial detection that would have helped to understand the evolution of the afterglow and the apparent kilonova emission (Burns et al., 2023). In 2019, NASA commissioned a Gravitational-Wave Electromagnetic (GW-EM) Task Force to assess the status of community resources. The study found that the extent to which observatories collaborate is inconsistent, is not especially well coordinated, and does not currently serve the science community as well as it could (Racusin et al., 2019).

General Observer Facilities (GOFs, e.g., the *Fermi* Science Support Center) exist to support the science community in using NASA’s space-based observatories. GOFs implement processes for community engagement, science prioritization, and proposal selection. Additionally, GOFs provide organizational, financial and

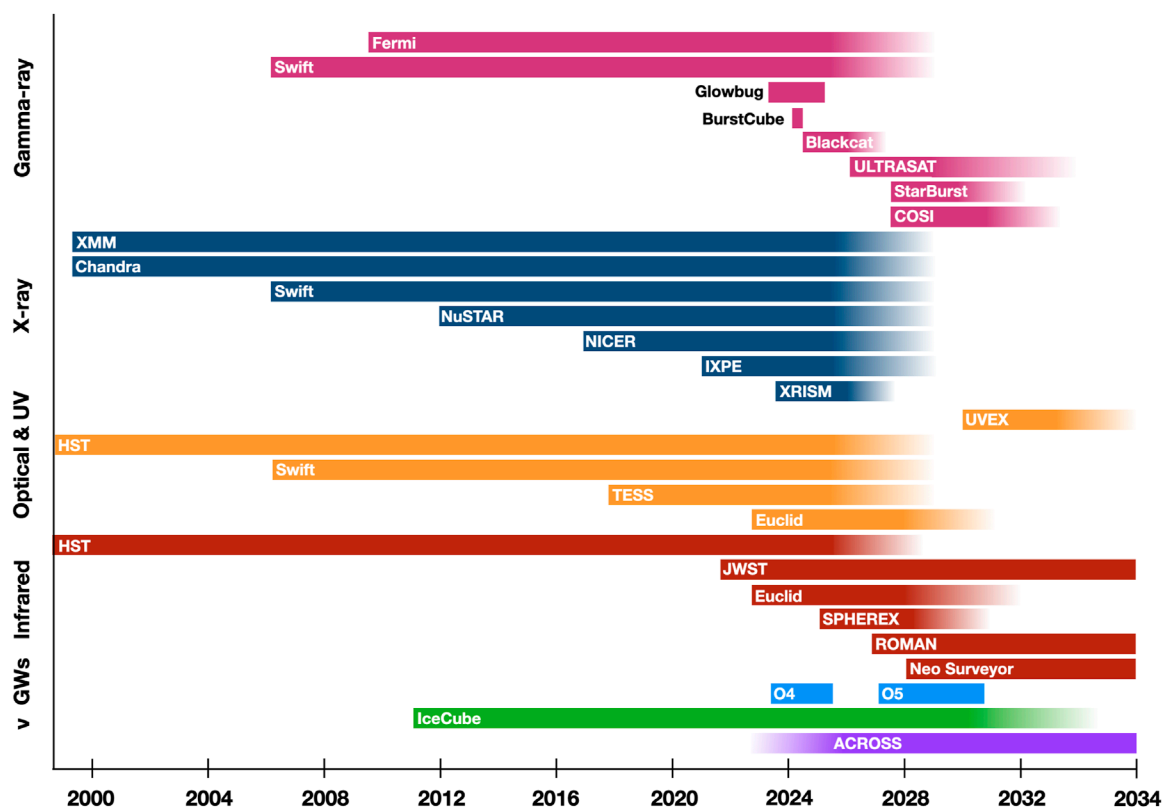


FIGURE 2

Multimessenger observatory timeline, showing that the ACROSS operations phase coincides with the next round of gravitational wave observations. NASA missions that are in their prime mission are shown as fading out after their prime mission completes; missions in their extended phase are shown to fade out beginning in 2025. Any of them may be extended, pending results of the 2025 Senior Review. GWs are based on current LVK plans (IGWN, 2024). The ACROSS pilot phase, discussed below in Section 3, is shown as a fade in, reaching an anticipated “initial operating capability” milestone in late 2025 that corresponds to the launch of the public web portal and tools, following which ACROSS would enter into a continuous improvement and sustainment phase.

technical resources (such as analysis tools, documentation, and tutorials) to improve the effectiveness and efficiency of scientific investigations involving NASA observatories. Although existing GOFs support many joint-observation programs, NASA's GOFs have been primarily organized to support investigations involving single observatories. Furthermore, rare and time-sensitive TDAMM science cases involving multiple observatories require a greater degree of collaboration and coordination than can be achieved by existing GOFs.

A recent workshop¹ on the scientific opportunities afforded by TDAMM was held in Annapolis, MD, August 22–24, 2022, with nearly 200 attendees in person and robust participation by another 150 attendees online. The workshop and its resulting white paper (Andrews et al., 2022) demonstrated the level of excitement in the community for opportunities to coordinate across instruments and wavelengths and across space and ground. A session on TDAMM infrastructure, covering space communications systems, alert systems, and data archives, showed that dedicated consideration of how to robustly ensure we have the capabilities to respond rapidly to rare but vital transient events is needed and

new structures may need to be built to enable broad access to these capabilities for the entire astrophysical community. Subsequent workshops in this series have been hosted by NOIRLab in 2023² and Louisiana State University in 2024³, emphasizing infrastructure and interdisciplinary science, respectively.

As one aspect of its response to the Astro2020 Decadal Survey's recommendations highlighting the importance of time-domain and multimessenger science and in light of the studies noted above, the NASA Astrophysics Division commissioned a 3-year study to investigate how to implement a GOF or similar facility that would address these issues. The study's charge for its first year was to focus on NASA's space-based observatories and to provide the following items.

1. A set of top-level requirements and architecture concept models for enabling a space-based follow-up observing capability.
2. Processes for TDAMM community engagement, proposal solicitations, and award management.

1 <https://pcos.gsfc.nasa.gov/TDAMM/TDAMM.php>

2 <https://noirlab.edu/science/events/websites/MMA2023>

3 <https://sites.google.com/view/3rd-tdamm-workshop/home>

3. A motivating set of TDAMM science cases and an analysis of the associated agreements, tools, process flows, and interfaces necessary to support those cases.
4. One or more implementation strategies for utilizing NASA assets to achieve an initial operating capability by FY26.
5. A best-value recommendation for a particular implementation strategy if more than one option is evaluated.

Subsequent years of the study are expected to expand the scope to consider opportunities to improve coordination with ground-based observatories, typically involving funding from multiple agencies, and with international facilities.

2 Literature review and stakeholder interviews

The study interviewed mission science operations teams, observers, and other stakeholders in the TDAMM enterprise, and reviewed the reports of previous studies into aspects of multimessenger follow-up and time-domain astronomy. Those interviews reinforced many of the findings of those previous studies, particularly those of the NASA GW-EM Task Force report and the 2019⁴ and 2022⁵ Senior Review reports. Those findings are summarized below. They motivate the main recommendation of this report: to launch a pilot initiative aimed at beginning to implement the required software infrastructure to improve mission coordination and observer workflows in a learn-by-doing model. This will allow rapid prototyping and changes in direction in response to ongoing stakeholder feedback.

2.1 Gravitational wave - electromagnetic counterpart task force

In an effort to enhance NASA's multimessenger astronomy capabilities and promote better collaboration between NASA missions and the wider scientific community, the NASA Astrophysics Division established the GW-EM Task Force in the spring of 2019. In addition to providing specific findings on the top-level capabilities of future missions in response to projected GW-EM scientific needs, the Task Force also identified several areas for improvement to maximize the scientific output of missions currently in operation or under development. These improvements include a) upgrading target-of-opportunity (ToO) capabilities, such as expanding the time allotted for ToOs and accelerating response times; b) fostering better communication and coordination within NASA missions, between NASA missions and observers, within the scientific community, and in liaison with the NSF; and c) making necessary modifications to Guest Observer (GO), Guest Investigator (GI), and Research and Analysis (R&A) programs.

Firstly, they recommended that NASA missions enhance their follow-up coordination to optimize the scientific yield from the entire NASA Astrophysics portfolio. For instance, they suggested that the *Swift* and Hubble Space Telescope missions adopt a rapid communication protocol for UV observations of GW counterparts. They also proposed a similar protocol for X-ray counterpart searches and follow-up involving *Swift*, NuSTAR, NICER, *Chandra*, XMM, IXPE, and XRISM. Furthermore, the task force encouraged gamma-ray burst monitors to collaborate for detections, sub-threshold searches, and localizations to facilitate the quick identification of neutron star (NS) mergers to initiate follow-up observations.

Improved communication with the broader astronomical community was also highlighted. The Task Force recommended the implementation of common reporting standards for planned and executed observations, and the detection of transient sources. These standards should ideally align with those adopted by NSF-funded (e.g., the Vera Rubin Observatory) and internationally funded (e.g., SKA) facilities. They also emphasized the importance of centralized, standardized data archiving, suggesting that all missions should store both data and data products in shared archives, utilizing modern application programming interfaces (APIs) and, where possible, common standards. They also encouraged improved advertisement of existing capabilities and development of new resources for cross-mission archival searches, both within NASA and between NASA missions and ground-based facilities.

In addition, they highlighted the potential of new scientific opportunities enabled by a funding mechanism supporting community efforts to improve existing tools such as the General Coordinates Network (GCN)⁶ (Barthelmy et al., 1995) and develop new resources/tools (e.g., Treasure Map⁷ (Wyatt et al., 2019), NASA Extragalactic Database (NED) Gravitational-Wave Follow-Up service⁸) to better coordinate the community and enable more effective follow-up observations and sub-threshold coincidence searches.

Finally, given the inherently multi-wavelength nature of time-domain and multimessenger science, joint observing proposals played an important role in GW170817, and will continue to do so for future discoveries. To improve opportunities for such joint programs in the future, the Task Force found that NASA should maintain an updated list of joint observing opportunities, make this list readily available to the community, and should pursue additional joint programs where scientifically relevant.

2.2 Key findings from other reports

In 2019, the Senior Review report highlighted the key importance of the existing NASA fleet for multimessenger astrophysics and encouraged NASA to investigate ways to better coordinate its operating missions to optimize their science return. Similar recommendations were voiced in the white paper produced by the first NASA TDAMM Workshop in August 2022 (Andrews et al., 2022). One scenario for the implementation of a

4 <https://science.nasa.gov/astrophysics/resources/documents/2019-senior-review-operating-missions/>

5 <https://science.nasa.gov/astrophysics/resources/documents/2022-senior-review-operating-missions/>

6 <https://gcn.nasa.gov/>

7 <https://treasuremap.space/>

8 <https://ned.ipac.caltech.edu/NED::GWFOverview/>

coordinating facility for multimessenger follow-up observations was presented by the Multimessenger Operational Science Support & Astrophysical Information Collaboration (MOSSAIC) collaboration (Sambruna et al., 2022), which is looking to serve as a community-oriented group aiming to highlight priorities for tool and coordination needs.

2.3 Response to GRB 221009A

There has yet to be a notable transformation in the way NASA conducts multi-mission follow-ups, particularly in dealing with exceptional and uncommon occurrences. This was evident during the investigation of the Brightest of All Time (BOAT), GRB 221009A, 5 years after the seminal events of 2017. Once again, the case of GRB 221009A showcased the community's capacity for self-organization and coordination (relying significantly on GCN) in executing an extensive follow-up endeavor. However, the systemic inefficiencies exacerbated the workload for both observers and science operations teams, while simultaneously missing out on potential scientific opportunities.

For instance, there remain challenges in predicting the necessary observational parameters weeks in advance for flagship missions. This has often resulted in under-prepared responses and less-than-optimal data collection. Furthermore, the lack of an automated GRB collation and association process to identify and consolidate observations means observers and science operations teams still need to manually determine the nature of events observed by *Swift* and *Fermi* (Burns et al., 2023). This process, unfortunately, results in delays in the initiation of the follow-up observations, causing a setback in scientific progress (for example, missing the early evolution of the GRB afterglow or, as mentioned above, the apparent kilonova in the case of GRB 230307A (Burns et al., 2023)).

However, amidst these shortcomings, there were promising signs as well. The use of Slack for rapid human-to-human communication and as an open forum greatly facilitated and accelerated information sharing and decision-making processes. Moreover, the timing of the 10th International Fermi symposium⁹ coinciding with the event turned out to be a fortunate coincidence, as it enabled a large number of relevant experts to work together in person, thereby greatly enhancing collaborative efforts and results. These positive aspects should guide our future responses, ensuring that the entire astronomical community can quickly react and collaborate in response to rare and unusual astronomical events, ideally without relying on the serendipity of attendance at a relevant topical conference or membership in the right Slack workspaces.

2.4 TDAMM and general observer facilities

One key finding of the study is that a potential TDAMM GOF differs significantly from mission GOFs. Mission GOFs exist to incentivize and support observers using NASA observatories. GOFs are active during the operations and sustainment phase of the NASA mission lifecycle. They implement community engagement

and proposal selection processes. GOFs provide scientific and technical expertise, financial resources, and technical resources for the community. Although NASA's mission GOFs have similar functions, their implementations vary across the fleet—the terms “science support center” (SSC) and “GOF” are used interchangeably (e.g., TESS SSC, *Fermi* SSC, *Swift* GOF, etc.). Although GOFs support some joint observing programs, GOFs are primarily scoped and organized to support their missions and generally do not have the resources or personnel to build coordination-focused tools.

In contrast, a TDAMM GOF does not have a “parent” mission organization or observatory to support. Rather, a TDAMM GOF should incentivize and foster cross-observatory science cases that exceed the capabilities of a single observatory or science team. While, as noted by the Astrophysics Advisory Committee (APAC)¹⁰ (Holley-Bockelmann, 2023), there is not yet a generally accepted definition of TDAMM science cases, multimessenger/multi-wavelength science cases with time-sensitive space-based follow-up are the motivating cases for the study. Science planning and execution of such science cases without the perception of bias requires willing participation of mission science teams.

2.5 Recommendations

In response to the findings described above, as well as similar recommendations for better communication and coordination presented in the Physics of the Cosmos Program Analysis Group (PhysPAG) Science Analysis Group (SAG) on Multimessenger Astrophysics (MMA)¹¹ Final Report (Brandt et al., 2020), the 2020 Decadal Review of Astronomy and Astrophysics (National Academies of Sciences, Engineering, and Medicine, 2023), and the Chandra Time Domain Working Group report (Miller et al., 2022), the primary recommendation of this study is to initiate the Astrophysics Cross-Observatory Science Support (ACROSS) pilot. Building upon these conclusions, ACROSS aims to facilitate “all-of-astronomy” science cases and streamline intricate, time-sensitive observing strategies that surpass the capabilities of any single observatory or mission team. In parallel with the pilot initiative, conversations with the community will continue and expand to include ground-based observatories (both triggering and follow-up) and international partners, to ensure that the pilot initiative's activities are fulfilling the community's needs.

In addition to the ACROSS pilot, both the Astro2020 Decadal Survey and the 2022 TDAMM workshop endorsed the idea of a persistent, community-led organization as a valuable forum for enumerating the driving science cases for NASA's TDAMM science support efforts and for providing feedback to NASA on the specific priorities and features needed by the community. The recently formed TDAMM Science Interest Group¹², chaired by members of the Physics of the Cosmos, Cosmic Origins, and Exoplanet Exploration Program Analysis Groups, is designed to fulfill that roll.

⁹ <https://indico.cern.ch/event/1091305/>

¹⁰ <https://science.nasa.gov/researchers/nac/science-advisory-committees/apac>

¹¹ <https://pcos.gsfc.nasa.gov/sags/mmzasag.php>

¹² <https://pcos.gsfc.nasa.gov/signs/tdamm-sig.php>

Given the rapid-development culture of TDAMM, we find that the best way to proceed in implementing the functions listed above is a pilot program that allows implementation and evaluation to proceed iteratively and rapidly, providing small but useful deliverables to the community to establish trust and build an understanding of the community's needs and adding deliverables and functionality as we go.

3 ACROSS pilot plans

The ACROSS pilot has been set up to determine how to better coordinate in realtime the coordinated observations of unexpected events like GW170817 and GRB221009A. ACROSS will serve as a center of excellence for TDAMM science, to aid observers and observatory science teams with planning and executing complex observing plans. To enable this, ACROSS will provide expertise, software tools, and critical realtime information through web pages and APIs. ACROSS will utilize an agile development process in order to respond to lessons learned and as plans evolve in response to ongoing interactions with and feedback from stakeholders.

Figure 3 illustrates the response to an interesting astrophysical event. The left panel focuses on the workflow to prepare follow-up observations by a single observatory: information about the initial detection is disseminated to the community via one of several alert systems, e.g., GCN. Interested observers respond by requesting follow-up observations by a specific observatory, either triggering a pre-approved ToO program or requesting director's discretionary time (DDT) observations. The observatory science team evaluates the request and, if approved, develops a new observation timeline that incorporates the requested observation. The constraints (and correspondingly the timelines) involved in developing a new plan vary widely between missions, from as short as minutes for a mission like *Swift* that has been designed for rapid follow-up, and whose ground systems have seen substantial effort to upgrade specifically for this purpose, to as long as weeks for flagship missions whose observing programs include numerous time-sensitive observations, or missions for which their technical constraints depend on the sequence of pointings. Once a new observing timeline is established, the updated sequence of commands must be uploaded to the observatory at the next available communications opportunity. Finally, the observatory executes the updated command sequence, carrying out the requested follow-up observations.

The center panel of Figure 3 illustrates how, in most cases, this sequence of steps is repeated independently by each mission in the NASA fleet. This is driven—at least in part—by NASA's competitive selection processes that deliver a fleet whose individual missions are optimized to carry out a specific set of science cases without dependence on other missions flying concurrently, which would add risk. Mission development and operations funding structures ensure efficient, focused, and lean science teams, but have unintended consequences. When a science event of mutual interest occurs, this siloed structure results in follow-up that is often *ad hoc*, inefficient, and less scientifically effective than it could be.

New infrastructure is required to fully realize the TDAMM science potential from past and future investments in NASA's Astrophysics fleet. The right panel of Figure 3 shows where the ACROSS pilot fits into this mission ecosystem, by providing tools

that improve situational awareness both across the fleet and for observers, as well as planning tools for observers and cross-mission follow-up decision support tools. A fleet becomes an observing system when supported by organizational, human, and technical infrastructure. TDAMM science cases drive requirements for essential cross-observatory science support infrastructure. However, once in place this infrastructure supports a wide range of science cases, amplifying the return on investment. The primary users of the support infrastructure are general observers and observatory (mission) science teams.

The goals of the ACROSS pilot are to (1) enable rapid and complete-as-possible information sharing between missions and with observers; (2) simplify the process for observers to request follow-up observations; (3) provide decision-support tools to assist observers and mission teams in evaluating and planning observations; and (4) engage the community to enable equitable access to TDAMM resources and science for all. To keep the scope of the pilot activities tractable, we will focus initially on a limited number of operating missions. These missions include the pointed X-ray missions *Swift*-XRT, NICER, NuSTAR, and IXPE (together providing a good mix of complementary and overlapping capabilities), the wide-field gamma-ray telescopes aboard the *Fermi* Gamma-ray Space Telescope and the *Swift*-BAT, and the Keck Observatory as an opportunity to prototype interfaces with ground-based facilities. The scope of the pilot will expand to include other missions as availability of resources and their interest allow. The notional schedules for the ongoing TDAMM study and the ACROSS pilot are shown in Figure 4. The objective is to have an initial operating capability of web-based ACROSS tools in time for the O5 observing run of the gravitational wave observatories, as shown in Figure 2. The following sections briefly describe the initial activities targeted at achieving these goals.

3.1 TDAMM toolkit

ACROSS is developing an API to expose and retrieve observatory state and status information as well as observing plans and history and (to the extent feasible) constraints on target observability. By providing this information via an API, it allows users to immediately incorporate necessary information flows into the products needed for their use cases. Another development activity in this API is to support new missions (and existing missions, if they so choose) by providing a toolkit for building ToO request submission and evaluation interfaces. Altogether, this TDAMM toolkit will facilitate streamlined, standardized, and automated submission of ToO requests, for example, based on input from transient brokers, enabling faster response times. The TDAMM Toolkit design is based upon the successful deployment of the *Swift* ToO API and website, but will be customizable for specific mission needs, enabling a streamlined, standardized, and automated workflow for ToOs, and critically an easy-to-deploy API interface that allows integration of ToO submission into third-party products such as the Target and Observation Monitor (TOM) Toolkit (Street et al., 2018) and SkyPortal (Coughlin et al., 2023). TOM Toolkit and SkyPortal, examples of tools widely used in the ground-based community, both already have the ability to submit ToO requests to *Swift*. The initial release of the toolkit will support

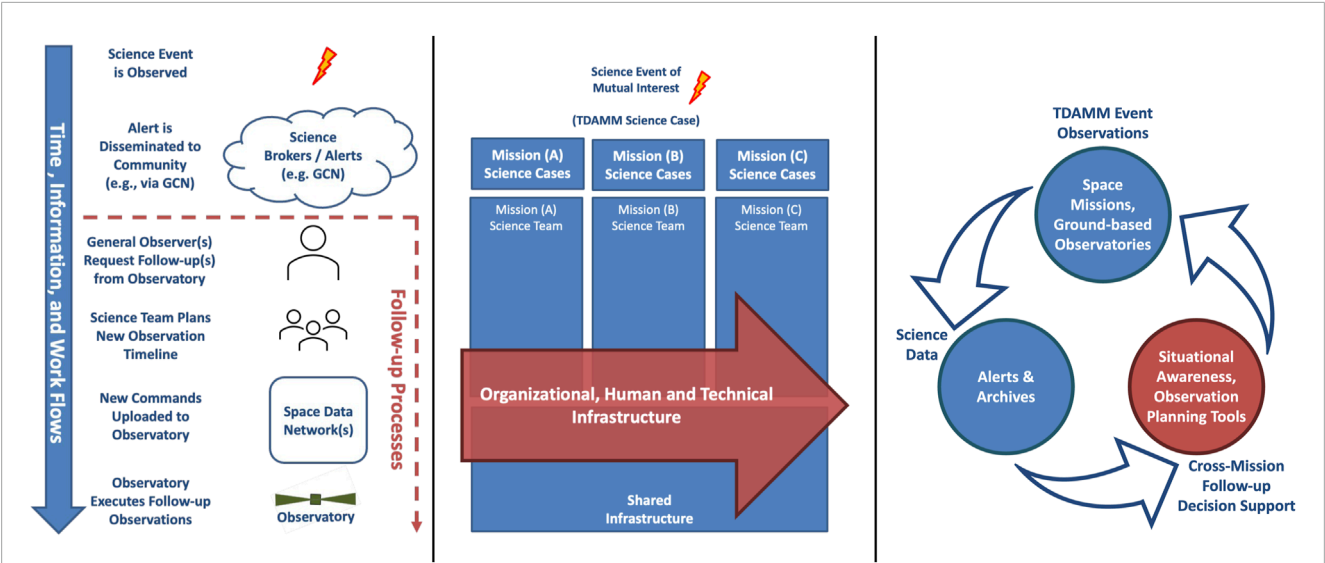


FIGURE 3 Typical follow-up response work flow for (left) one or (center) multiple observatories. The workflow indicated in the left panel is typically repeated for each mission in the center panel; ACROSS aims to improve the cross-cutting infrastructure that supports multi-mission planning and execution. (right) The role of ACROSS in the observing and follow-up ecosystem is to strengthen the cross-mission follow-up decision support infrastructure by providing situational awareness and observation planning tools.

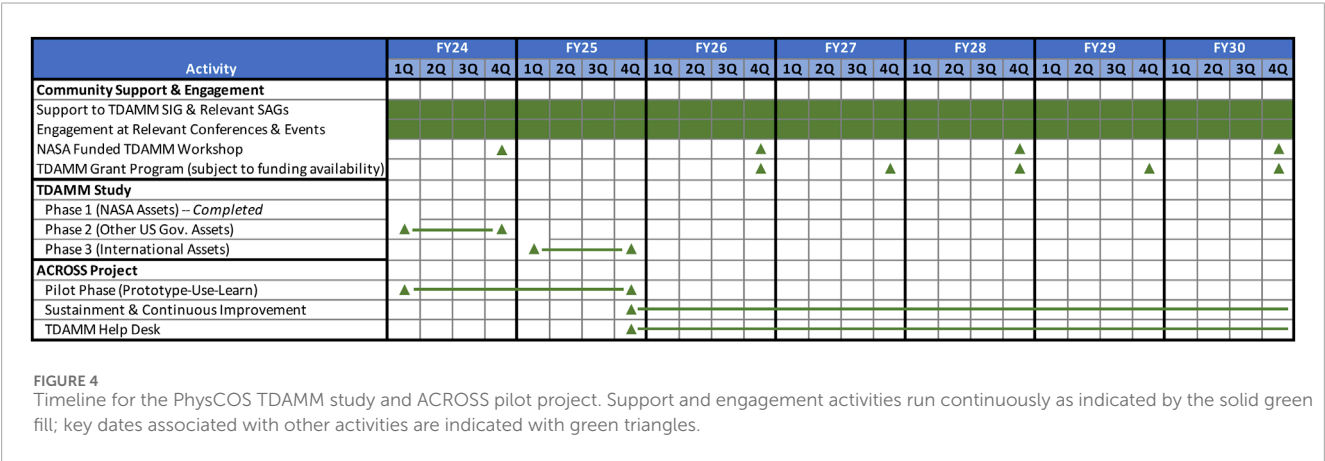


FIGURE 4 Timeline for the PhysCOS TDAMM study and ACROSS pilot project. Support and engagement activities run continuously as indicated by the solid green fill; key dates associated with other activities are indicated with green triangles.

simple API and web-based submission and evaluation interfaces for ToO requests. Later releases of the toolkit will incorporate cross-observatory science feasibility information streams and follow-up decision support tools. The TDAMM toolkit will be developed as an open-source project. As a proof of principle, the ACROSS pilot is providing the ToO API interface for BurstCube in 2024, and for StarBurst in 2025. Since these two wide-field GRB detectors are not pointed instruments, the interface enables a “download of opportunity” (DoO) to facilitate downlink of time-tagged event data from onboard buffers around times of interest for transients detected by other facilities.

Tasks to be executed during the ACROSS pilot period include:

1. Define the necessary state and status information and follow-up observation parameters.
2. Assess availability of state and status information parameters, by mission.

3. Define relevant observing and scheduling constraints.
4. Negotiate implementation resources and schedule, by mission.
5. Implement API state and status information streams.
6. Implement API for ToO construction/submission.
7. Deploy mission state and status information streams on publicly accessible cloud infrastructure.
8. Develop and deploy visualization and other situational awareness functions or applications.
9. Deploy mission ToO API on publicly accessible cloud infrastructure.

3.2 TDAMM web portal

To enable the TDAMM community to efficiently respond to new alerts and coordinate follow-up planning, the ACROSS pilot will develop, deploy, and maintain a web portal collecting in one

place all of the tools and information needed by the community. The web portal will include capability summaries for TDAMM-relevant observatories, links to ACROSS and community-developed tools, links to ToO submission pages for all missions, and links to funding opportunities, conferences, and workshops. The web portal will also include “Events of Interest” pages, both static (curated by humans) and dynamic (built from near-term observing plans and recent observation history for popular TDAMM events). Tasks to be executed during the ACROSS pilot period include:

1. Develop a conceptual design and layout for portal content.
2. Seek and obtain approval for a NASA domain URL.
3. Evaluate technical software implementation and cloud hosting options.
4. Implement a U.S. Web Design System (USWDS)¹³ compliant framework.
5. Populate framework with content.
6. Deploy web portal to publicly accessible cloud infrastructure.
7. Maintain web portal content.

3.3 TDAMM research announcement

A funding opportunity tailored to fill gaps in the tools and coordinated science observations needed to maximize the TDAMM science return from the NASA fleet is targeted for an initial call no later than 2026, subject to availability of funds. The scope and types of projects to be funded are to be examined during the pilot phase. There are three areas of scope to be considered.

1. A research announcement (RA) targeted specifically at development of tools or observing modes that will enable new science cases. Open questions to resolve include the criteria that would define the range of tools that would be considered eligible (for example, must the tool play a role in planning or conducting observations?) and the requirements on the deliverables. The pilot period will provide an opportunity to gain experience in defining tools and their development and delivery as the ACROSS team begins by prioritizing an initial list and identifying optimal acquisition strategies. That experience is expected to be useful in defining the criteria needed for a successful tools RA.
2. An opportunity for funding of DDT observations made by “rest of fleet” missions, like those provided by the flagships in response to DDTs. Open questions to resolve include avoiding creation of a perverse incentive that discourages applications to existing RAs, defining criteria for which DDTs are of sufficient interest to warrant financial support for the analysis and interpretation of the resulting data, determining which observers should be eligible for consideration for funding after a particular set of DDT observations are made, and determining an appropriate level of support to provide. If these questions can be satisfactorily resolved, this type of funding opportunity might be the most useful to implement first as it would both close a clear gap and provide valuable

experience that would likely inform construction of a cross-mission observing RA.

3. An RA designed to fill the gaps between existing mission calls and remove the risk of double jeopardy by explicitly supporting observing programs that require coordination between two or more observatories. Open questions to resolve include how to establish a pool of observing time across the fleet, what criteria would define eligible proposals, how many awards are anticipated, how to coordinate accepted programs across the missions involved, how to avoid overlap with existing mission RAs and bilateral agreements, and more. The pilot period will provide an opportunity to observe how mission teams interact with each other, particularly as enhanced coordination tools are rolled out, and will afford ACROSS team members an opportunity to more clearly define the remaining gaps such a call would fill.

Tasks to be executed during the ACROSS pilot include:

1. Develop an initial research announcement based on options identified in Phase 1 Study.
2. Elicit feedback from the NASA Astrophysics Division, mission, and community stakeholders.
3. Negotiate and refine implementation of the research announcement.
4. Funding permitting, execute initial call in 2026 in advance of the fifth observing run of the International Gravitational-Wave Observatory Network.

3.4 Community support

ACROSS will also provide support to the community in the form of a virtual help desk staffed by domain experts who can assist observers in submitting ToO requests and coordinating with observatory teams. Additional support in the forms of documentation, tutorials, and workshops will be provided to advertise the tools described above and lower the barriers to entry to their usage. ACROSS is working with the Physics of the Cosmos Program Office and the TDAMM SIG to organize another TDAMM-focused workshop targeted for September 2024, and anticipate providing a preview or introductions to some of the tools above at the workshop and solicit feedback on them.

3.5 Inter-observatory communications

Inspired by the need for coordination during the LIGO-Virgo-KAGRA (LVK) fourth observing run (O4), which began in May 2023, ACROSS initiated a meeting between representatives of the X-ray observatories of the NASA fleet (including XMM-Newton) to discuss the pre-approved gravitational-wave follow-up observing programs for each observatory. Participants gained an awareness of each program’s science objectives, triggering criteria and whether any dependencies or redundancies were likely among the programs. As an outcome of this meeting, ACROSS created a dedicated Slack channel for rapid, asynchronous communications among the participating science operations teams used to ensure

¹³ <https://designsystem.digital.gov/>

situational awareness and facilitate coordination should a high-priority gravitational-wave event occur. While the poorer-than-expected localizations achieved (and the lack of binary neutron star mergers) thus far by O4 have meant this channel has not yet proven its value, ACROSS has extended the model of using Slack communications channels to engage with missions and sets of missions for specific purposes. For example, ACROSS has established a channel with NuSTAR to discuss development of an interface to expose observation planning status information. ACROSS is open to supporting tools for communication between observatory operations teams to support observation planning going forward and are happy to discuss needs and opportunities to do so as they arise.

4 Conclusions and next steps

The first phase of NASA's TDAMM study was charged with focusing on the space-based observatories in the NASA fleet and to look at ways to improve coordination and community engagement in response to TDAMM science cases. The key findings were consistent with previous, similar studies. First, additional software infrastructure is needed to support both missions and the community by providing awareness of the fleet's observing plans and status. Second, this software infrastructure needs to extend to simplifying the process for requesting follow-up observations and providing decision-support tools to assist observers and mission teams. Third, a combination of software and human infrastructure is needed to enable equitable access to TDAMM science for the entire community. Finally, developing the above infrastructure in a new organization separate from but with close ties to the existing mission GOFs will enable it to focus on the needed cross-cutting infrastructure without interfering with their work. The primary recommendation of this study is to initiate the ACROSS pilot.

The ACROSS pilot provides the best path to proceed to rapidly implement and evaluate elements of the software infrastructure needed to support efficient follow-up coordination of time-domain and multimessenger triggers. The objective is to have an initial operating capability of web-based ACROSS tools in time for the O5 observing run of the gravitational wave observatories, as shown in Figure 2. In parallel, the TDAMM study continues through the pilot phase, enabling feedback from stakeholders—both mission teams and observers—to be solicited and incorporated continuously, and expanding the scope to explore and incorporate coordination with ground-based and international partners.

Data availability statement

The datasets presented in this article are not readily available because the raw data supporting the conclusions of this article consist of interviews with relevant stakeholders. Requests to

access the datasets should be directed to T. B. Humensky, thomas.b.humensky@nasa.gov.

Author contributions

TH: Conceptualization, Investigation, Project administration, Writing—original draft, Writing—review and editing, Methodology. CR: Conceptualization, Investigation, Methodology, Supervision, Writing—review and editing, Formal Analysis, Funding acquisition, Resources, Validation, Visualization, Writing—original draft. TB: Conceptualization, Investigation, Writing—review and editing. RC: Conceptualization, Investigation, Methodology, Writing—review and editing, Validation. SC: Conceptualization, Investigation, Methodology, Supervision, Writing—review and editing, Validation. FC: Investigation, Writing—review and editing, Validation. JD: Conceptualization, Investigation, Writing—review and editing. CH: Investigation, Validation, Writing—review and editing, Conceptualization. MH: Investigation, Writing—review and editing. JK: Investigation, Writing—review and editing, Conceptualization, Formal Analysis, Methodology, Project administration, Software, Supervision, Writing—original draft. DK: Investigation, Visualization, Writing—original draft, Writing—review and editing. JR: Investigation, Methodology, Validation, Writing—review and editing. BR: Investigation, Writing—review and editing. RS: Investigation, Methodology, Supervision, Validation, Writing—review and editing. JS: Investigation, Methodology, Writing—review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Cosmic ray contributions from rapidly rotating stellar mass black holes: cosmic Ray GeV to EeV proton and anti-proton sources

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In Radio Super Novae (RSNe) a magnetic field of $(B \times r) = 10^{16.0 \pm 0.12}$ Gauss $\times$ cm is observed; these are the same numbers for Blue Super Giant (BSG) star explosions as for Red Super Giant (RSG) star explosions, despite their very different wind properties. The EHT data for M87 as well for low power radio galaxies all show consistency with just this value of the quantity $(B \times r)$, key for angular momentum and energy transport, and can be derived from the radio jet data. We interpret this as a property of the near surroundings of a black hole (BH) at near maximal rotation, independent of BH mass. In the commonly used green onion model, in which a 2π flow changes over to a jet flow we interpret this as a wind emanating from the BH/accretion disk system and its surroundings. Near the BH collisions in the wind can produce a large fraction of anti-protons. In this scenario the cosmic Ray (CR) population from the wind/jet is proposed to be visible as EeV protons and anti-protons in the CR data to EeV energy, with a $E^{-7/3}$ spectrum. This can be connected to a concept of inner and outer Penrose zones in the ergo-region. The observed numbers for the magnetic field imply the Planck time as the governing time scale: A BH rotating near maximum can accept a proton per log bin of energy in an extended spectrum with the associated pions every Planck time.

KEYWORDS

cosmic Rays, acceleration, supernovae, black holes, magnetic fields, anti-protons

1 Introduction: energetic particles and black holes

Energetic particles, commonly called Cosmic Ray particles, or short just *Cosmic Rays* have been researched since their discovery in 1912 (with a recent review with many references in [Biermann et al. \(2018\)](#)); further important viewpoints and history are given by [Colgate \(1994\)](#), [Yodh \(1992\)](#), [Yodh \(2003\)](#), [Yodh \(2005\)](#), [Yodh \(2006\)](#). Cosmic Ray (short CRs) particles have been observed from below GeV, with stellar sources responsible up to a few EeV, as discussed here, and extragalactic sources up to a few hundred EeV. Many of them, both Galactic and extragalactic, can be traced to the activity of black holes.

The various possible sources of CRs were discussed in [Biermann et al. \(2018\)](#), [Biermann et al. \(2019\)](#), and earlier papers ([Biermann, 1993](#); [Biermann and Cassinelli, 1993](#); [Biermann and Strom, 1993](#); [Stanev et al., 1993](#); [Rachen et al., 1993](#)) with reviews in [Biermann \(1994\)](#), [Biermann \(1997\)](#). A main distinction, which we have made ([Stanev et al., 1993](#)), is to differentiate between SNe, that explode into their own wind, wind-SNe, and those that explode into the Interstellar Medium (ISM), ISM-SNe. It is also necessary to subdivide those two groups: There are Red Super Giant (RSG) stars with slow dense winds, and Blue Super Giant (BSG) stars that explode into tenuous fast winds, heavily enriched in the chemical elements of higher nucleon A and charge number Z . Furthermore, almost all massive stars are in binaries, or multiple systems ([Chini et al., 2012](#); [Chini et al., 2013a](#); [Chini et al., 2013b](#)), while the binary frequency is reduced for lower mass stars. This naturally explains the rapid change in the chemical composition of CRs all across the knee ([Stanev et al., 1993](#)), and a knee energy at about $10^{17.3 \pm 0.2}$ eV for Fe ([Stanev et al., 1993](#); [Biermann et al., 2018](#)); note that for the model worked out in 1993 the magnetic field in winds had not been known as well it is now, as today the magnetic fields are known to be stronger, and so all ensuing particle energies higher. Of those SNe that explode into the ISM, there are SN Ia that are exploding white dwarfs, and massive star SNe, that make neutron stars producing much lower particle energies. In the model of [Gaisser et al. \(2013\)](#) there is a Galactic component of near EeV protons, that matches the model in [Stanev et al. \(1993\)](#) using the better magnetic field numbers now known. A test has been made of this model in [Thoudam et al. \(2016\)](#). [Allen et al. \(2024\)](#) focusses on those SNe, that explode into fast winds: On this basis we discussed there the new highly accurate AMS data on CRs. The sum of the CRS arising from ISM-SNe and wind-SNe, and their secondaries, gives structure to the spectrum at low energies ([Stanev et al., 1993](#); [Biermann et al., 2019](#); [Allen et al., 2024](#)). The essential message ([Allen et al., 2024](#)) is that almost all CR elements contain spallation secondaries, and we identified a spallation sequence, from a small secondary component, like for CR O, to a dominant secondary component like CR ^3He . There is a large secondary component in CR protons.

The area around a rotating black hole (BH) has been observed by the [EHT-Coll \(2019a\)](#), [EHT-Coll \(2019b\)](#), [EHT-Coll \(2021a\)](#), [EHT-Coll \(2021b\)](#) and is found to be highly variable; in such a zone one may expect a population of energetic particles driven by stochastic processes, such as the second order Fermi process ([Fermi, 1949](#); [Fermi, 1954](#)), followed by reconnection and other mechanisms (e.g., [Meli and Mastichiadis, 2008](#); [Meli and Nishikawa, 2021](#); [Meli et al., 2023](#)). The particle energy may go up to the maximum which space allows for

the Larmor motion. In Radio Super-Novae (RSNe) a wind of typically $10^{-5} M_{\odot} \text{yr}^{-1}$ (a summary in [Biermann et al. \(2018\)](#)), a shock speed of about $0.1c$, and a magnetic field of $(B \times r) = 10^{16.0 \pm 0.12}$ Gauss $\times$ cm are implied by the radio observations ([Kronberg et al., 1985](#); [Allen and Kronberg, 1998](#); [Allen, 1999](#); [Biermann et al., 2019](#)); these are the same numbers for Blue Super Giant star explosions as for Red Super Giant star explosions, despite their very different wind properties ([Kronberg et al., 1985](#); [Allen and Kronberg, 1998](#); [Allen, 1999](#); [Kronberg et al., 2000](#); [Biermann et al., 2018](#); [Biermann et al., 2019](#)), as mentioned above. It is important to note that this latter quantity is independent of radial distance r ([Parker, 1958](#); [Weber and Davis, 1967](#)). In fact, the EHT data for M87 ([EHT-Coll, 2019b](#)) as well the low power radio galaxies ([Punsly and Zhang, 2011](#)) all show consistency with just this value of the quantity $(B \times r)$. The quantity $(B \times r)$ is key for angular momentum and energy transport, and can be derived from the radio jet data. We note that just recently the super-massive black hole in M87 experienced a merger with another black hole, with a spin-flip visible in the data ([Owen et al., 2000](#)); it might be possible that most, if not all radio galaxies evolve via many mergers of their central black holes as well as their host galaxies ([Rottmann, 2001](#); [Gopal-Krishna et al., 2003](#); [Gopal-Krishna et al., 2012](#); [Jaroschewski et al., 2023](#)). In the commonly used green onion model, in which a 2π flow changes over to a jet flow (on both sides) we interpret the observations of RSNe as a wind emanating from the black hole/accretion disk system and its near surroundings, after a stellar explosion which produced a rapidly rotating black hole (BH) ([Chieffi and Limongi, 2013](#); [Limongi and Chieffi, 2018](#); [Limongi and Chieffi, 2020](#)).

The goal of this paper (see [Table 1](#) for the run of the argument) is to understand the origin and the consequences of the quantity $(B \times r)$ showing the same number for stellar mass BHs and super-massive BHs, when we have reason to assume that in these cases the BH is rotating near maximum. Can we learn something about BHs from CR observations, and the answer we propose is “yes”. We will propose an origin of the numerical value of $(B \times r)$ as rooted in a property of rotating BHs.

1.1 Black holes

A better understanding of the nature of black holes (BHs) has been sought ever since Schwarzschild's discovery [Schwarzschild, 1916](#) of a solution of Einstein's equations ([Einstein, 1915](#)) with an essential singularity (black hole), and Kerr's generalization of the solution to a rotating BH ([Kerr, 1963](#); [Rees et al., 1974](#); [Rueda et al., 2022](#)). The most significant flaw is the failure to merge gravitational physics with quantum physics, with some convincing first steps ([Penrose and Floyd, 1971](#); [Bekenstein, 1973](#); [Bardeen et al., 1973](#); [Hawking, 1974](#); [Hawking, 1975](#); [Rueda and Ruffini, 2020](#); [Rueda and Ruffini 2021](#)); some early and recent books are [Misner et al. \(1973\)](#), [Misner et al. \(2017\)](#), [Rees et al. \(1974\)](#), [Joshi \(1993\)](#), [Joshi \(2007\)](#), [Joshi \(2011\)](#), [Joshi \(2014\)](#), [Joshi \(2015\)](#). The best hope to explore BH physics is to consider more detailed observations e.g. [Mirabel et al. \(2011\)](#). The goal of this paper is to further the understanding of BHs by exploring the observations of Super-Nova Remnants (SNRs) which are produced in those SN explosions which lead to BHs. These sources are referred to as Radio Super-Novae

TABLE 1 Run of arguments in this paper.

RSNe: Show $(B \times r) = 10^{16.0 \pm 0.12}$ Gauss $\times$ cm
M87 BH: the same numbers
Radio galaxies: low power with same numbers
SMBH spin: radio galaxies show high BH spin
Stellar evolution: simulations yield high BH spin
Proposal: in all cases RSN central BH high spin initially
Electric currents: in winds and jets driven by drift E^{-2} spectrum of protons and anti-protons
General Relativity: using radio observations using $(B \times r)$ constant with r same for all gives divergence of charged particle density near horizon
Collisions: of protons with protons gives anti-protons, spallation of heavier nuclei so their destruction
Prediction: E^{-2} source protons and anti-protons $E^{-7/3}$ for observer reaching EeV energies, identified from GeV to EeV

(RSNe). Numerous observational data have been obtained for these stellar explosions, which make BHs, at various wavelengths.

There are a number of samples of Radio Super Novae (RSNe): First is the large set of RSNe in the discovery paper (Kronberg et al., 1985), 28 sources certain, and 43 possible. Then there are the independent observations by the team of Muxlow, (Muxlow et al., 1994; McDonald et al., 2002; Muxlow et al., 2005; Muxlow et al., 2010), of the same population of RSNe in M82 (30 classified as SNR). There is the newly observed list of the M82 RSNe collected and analyzed in Allen and Kronberg (1998). Then there are the lists assembled in Biermann et al. (2018) of Red Super Giant (RSG) and Blue Super Giant (BSG) RSNe, all from the literature. For the RSNe collected in Biermann et al. (2018) we know the moment of explosion, with all accompanying information; the radio interferometric observations (VLBI) have followed the expansion to a radial scale of order 10^{16} cm. For the RSNe in M82 we have only estimates when the explosion occurred, but from ram pressure arguments (Biermann et al., 2019) one can show that these RSNe must have originated in most cases from the explosion of a Blue Super Giant (BSG) star; in these cases the expansion can be followed to a radial scale of order $10^{18.5}$ cm. All these RSNe are consistent with just different stages of the same kind of explosions, from RSG as well as BSG stars, for the large radial scales mostly BSG star explosions. Considering the independent data shown in the papers by Muxlow and his group (e.g., Muxlow et al., 1994; McDonald et al., 2002; Muxlow et al., 2005; Muxlow et al., 2010), they give the same value of $(B \times r)$, just with a larger error bar, as the data obtained and analyzed by Allen and Kronberg (1998). The collection in Biermann et al. (2019) is based on the Allen and Kronberg (1998) analysis and data. Moreover, there is an independent discussion using another data set of very energetic explosions by Soderberg et al. (2010), leading to about the same value for $(B \times r)$, as shown in Biermann et al. (2018).

It has been argued that very massive star SN lead to a BH by direct collapse, without leaving a visible trace (e.g.,

Smartt, 2009; Smartt, 2015; Van, 2017; Humphreys et al., 2020). These arguments are based on visual and infrared data, and are influenced by obscuration and selection effects. However, gamma-ray line data and radio data (e.g.; Diehl et al., 2006; Diehl et al. 2010; Diehl et al. 2011; Prantzos et al., 2011; Diehl, 2013; Siegert et al., 2016b; Biermann et al., 2018) clearly give much more accurate SN statistics data, unaffected by obscuration. These data show for instance [summarized in Biermann et al. (2018)], that Blue Super Giant star explosions happen in our Galaxy about once every 600 years, and in other galaxies at corresponding frequencies, scaled with the star formation rate, derivable from both far-infrared and radio observations, as they scale with each other (e.g., Tabatabaei et al., 2017).

These RSN range from RSG star explosions to BSG star explosions, which cover vastly different environments in density. Among the BSG star explosions they probably cover the entire range of masses [summarized in Biermann et al. (2018) based on the work of Chieffi and Limongi (2013), Limongi and Chieffi (2018), Limongi and Chieffi (2020)], which can be derived from the now many lists in LIGO/VIRGO-Coll (2019), LIGO/VIRGO-Coll (2021a), LIGO/VIRGO-Coll (2021b), LIGO/VIRGO/KAGRA-Coll (2021c). Of course, the lists of observed mergers of stellar mass BHs encompasses second generation mergers, and that is why the BH mass can reach relatively high values, up to four times the highest single BH mass.

The only common feature of all these explosions is that they form a BH, and the explosions happen into a wind. SN-explosions that make a neutron star explode into the ISM. Here we consider explosions into a wind: and yet, the quantity $(B \times r)$ is consistent with having the same value for all explosions. We note that the EHT data for M87 are consistent with the same number; the radio galaxy M87 harbors a central black hole with a mass approaching $10^{10} M_{\odot}$, suspected to be near maximal rotation (Daly, 2019; EHT-Coll, 2019b). The minimum jet powers in Punshly and Zhang (2011) are also consistent with the same values. So, we explore the possibility that this quantity is actually related to the BH in the sense that this quantity refers to a near maximal rotation of the black hole, independent of the mass, but with energetically negligible accretion.

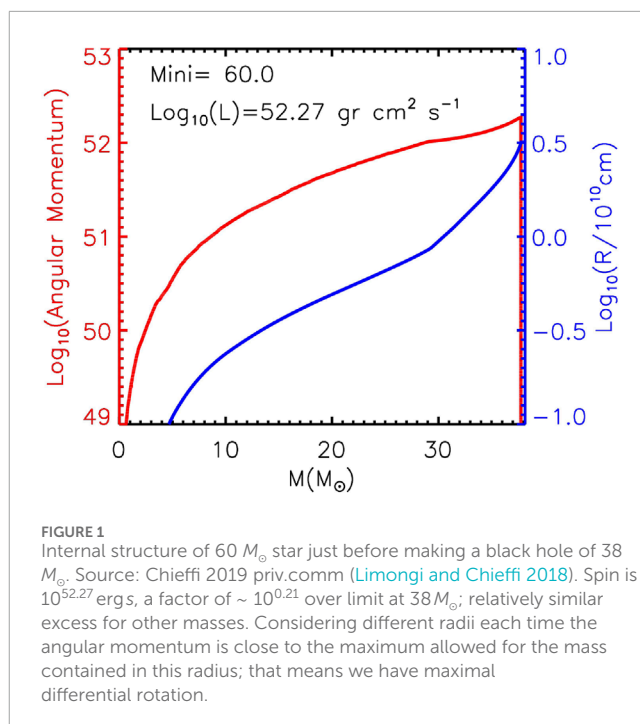
In the following we will assume that the physics around black holes scales such that fundamental principles carry over across all masses observed (Merloni et al., 2003; Merloni et al., 2006; Falcke and Markoff, 2004; Markoff et al., 2015; Gültekin et al., 2019); this is commonly referred to as the “Fundamental plane of black hole accretion”. Much of the accretion physics is mass-invariant. As a consequence we will assume the same physical concepts across all masses of black holes discussed in the following.

2 Radio super novae (RSNe) with freshly formed black holes (BHs)

Where do we witness the formation of black holes? In massive star Super Novae (SNe), from stars of an initial mass (Zero Age Main Sequence or ZAMS) above about $25 M_{\odot}$ (at Solar abundances: (Woosley et al., 2002; Heger et al., 2003; Chieffi and Limongi, 2013; Limongi and Chieffi, 2018; Limongi and Chieffi, 2020), best observable as Radio Super Novae (RSNe). The radio data can be interpreted as follows: We observe a Parker wind, as $(B \times r)$ follows

two rules i) $(B \times r) = \text{const}$ for a given RSN, over a range in radius, and also ii) that value is the same for different RSNs, in different galaxies and for very different radii r (Parker, 1958; Weber and Davis, 1967; Biermann et al., 2018; Biermann et al., 2019); the best data are obtained from the starburst galaxy M82 (Kronberg et al., 1985; Allen and Kronberg, 1998; Allen, 1999); the M82 sample can be checked also independently using the observations of Muxlow et al. (2005), and in other galaxies (Biermann et al., 2018); the radial range over which $(B \times r) = \text{const}$ covers a factor of over 100. The quantity is $(B \times r) = 10^{16 \pm 0.12} \text{ Gauss} \times \text{cm}$ (Allen and Kronberg, 1998; Allen, 1999; Biermann et al., 2019). Probably all the Radio-Super-Novae (RSNe) detected in M82 can be traced back to BSG stars, all of which make black holes. This argument is based on the wind ram pressure, which is very much larger for a BSG star than for a Red Super Giant (RSG) star (Biermann et al., 2019). A wind from a RSG star is not expected to reach such large radii as parsec scale in an environment at a pressure like in the starburst galaxy M82. An expansion as in ISM-Super Novae (Cox, 1972) (i.e., SN exploding into the Interstellar Medium (ISM), the most common SNe) would not allow the quantity $(B \times r)$ to be constant; various other proposed explosion scenarios have been worked through in Biermann et al. (2019); none of them allow to understand such a constant value for $(B \times r)$, independent of environment and of radius r . Furthermore, since the value of $(B \times r)$ is the same in all examples, in different locations in M82 as well as in different galaxies, also at a much earlier stage of RSN evolution, it is clear that the environment does not play a role in the expansion. The concept of a wind driven by a rotating compact object at its center (Parker, 1958; Weber and Davis, 1967) has been generalized (e.g., Chevalier, 1984), to neutron stars (Goldreich and Julian, 1969), to black holes (Blandford and Znajek, 1977) and to entire galaxies (e.g., Breitschwerdt et al., 1991). We note that the generic approach developed by Pacini and Salvati (1973) in their development phase 2 gives a relationship as shown by the observations here, $(B \times r) = \text{const.}$, with the difference that the magnetic field is too high by an order of magnitude; however, the approach of Pacini and Salvati (1973) was proposed for neutron stars which would be expected to yield somewhat different numbers as compared to BHs. Weiler and Panagia (1980) applied this approach to the observations of supernova remnants driven by the slowing down of a central neutron star, which they called “plerions”. Latest simulations are, e.g., those of Davis and Gammie (2020), White et al. (2020), Wong et al. (2021), Marszewski et al. (2021), Lucchini et al. (2022), Cho et al. (2023). Much of this work focusses on the Magnetically Arrested Disk (MAD) models (Igumenshchev et al., 2003; Narayan et al., 2003), also postulating that the driver of activity is the spin-down of the central black hole. Here we focus on what the observations tell us about a wind driven by the central object in RSNs, a rotating black hole. The well established idea of a central spinning object driving activity by spin-down starting with Parker (1958) is used here as well. The key difference here is the observation that the magnetic field in terms of $(B \times r)$ appears to be the same value for the RSNs observed.

In support of arguing that these RSNs contain BHs rotating near maximum, we note, that in radio galaxies it has been shown that the central BHs do rotate near maximum (Daly, 2019; EHT-Coll, 2019b), with the same magnetic field directly measured or the magnetic field inferred in terms of the quantity $(B \times r)$ (Punsly and Zhang, 2011) from the jet power (Falcke and Biermann, 1995; Falcke et al., 2004).



We wish to emphasize here that all these RSNs clearly derive from a spectrum of BH masses, as the black hole merger data as well as the optical stellar observations of original stars show (LIGO/VIRGO-Coll, 2019; LIGO/VIRGO-Coll, 2021a; LIGO/VIRGO-Coll, 2021b; LIGO/VIRGO/KAGRA-Coll, 2021c; Chini et al., 2012; Chini et al., 2013a; Chini et al., 2013b). So the quantity $(B \times r)$ does not depend on the BH mass at its center. Massive stars producing black holes almost all start in a binary, triple or quadruple system, allowing the final BH initially near maximum spin from a tidal lock in the tight binaries (Chini et al., 2012; Chini et al., 2013a; Chini et al., 2013b; Limongi and Chieffi, 2018; Limongi and Chieffi, 2020). Simulations suggest (Limongi and Chieffi, 2018; Limongi and Chieffi, 2020) that the black holes formed may reach a high rotation rate, possibly even slightly exceeding maximal just before a black hole is actually formed (see Figure 1).

3 The EeV cosmic ray proton component

At solar chemical abundances, stars $\geq 25 M_{\odot}$ Zero Age Main Sequence (ZAMS) mass evolve to RSG stars, while those $\geq 33 M_{\odot}$ ZAMS mass become BSG stars. Both classes of stars produce BHs (Limongi and Chieffi, 2018; Limongi and Chieffi, 2020). Stars between a ZAMS mass of about $\sim 10 M_{\odot}$ and $\sim 25 M_{\odot}$ produce neutron stars.

Magnetic fields (Kronberg, 1994; Kronberg, 2016) are observed in the winds of massive stars (e.g., Maheswaran and Cassinelli, 1992). Detailed further observation reveal, that massive stars are usually combined in binaries, triplets or quadruplets. This implies that these stars may lose orbital angular momentum efficiently, driving them progressively together - see the work in the group of Chini (Chini et al., 2012; Chini et al., 2013a; Chini et al., 2013b;

Barr Domínguez et al., 2013; Pozo Nunez et al., 2019). Tidal locking then ensures that their rotation increases, resulting in the high rotation rates used in the simulations of Limongi and Chieffi (2018), Limongi and Chieffi (2020). These simulations show that massive stars can eventually lead to BHs which initially rotate near the maximum allowed (Chieffi and Limongi, 2013; Limongi and Chieffi, 2018; Limongi and Chieffi 2020).

We interpret the observed radio emissions as a wind, which is driven by a BH rotating near the maximum allowed via the Penrose/Blandford/Znajek mechanisms (Penrose and Floyd, 1971; Blandford and Znajek, 1977). This wind is thought of as keeping the energy and angular momentum transport processes functioning in the Radio Super-Novae (RSNe). The RSN data show that the slowest angular momentum transport time scale, derived from the afore-mentioned quantity $(B \times r) = 10^{16.0 \pm 0.12} \text{ Gauss} \times \text{cm}$, is $\sim 10^{3.7} \text{ yrs} (M_{\text{BH}}/M_{\odot})$, following (Parker, 1958) and (Weber and Davis, 1967). Here we interpret the magnetic field observed, with $(B \times r)$ a constant without any indication of the magnetic field's direction, as B_{ϕ} . The specific number for the angular momentum transport time-scale depends on three factors, which together amount to a term between unity and ten in the case of near maximal allowed rotation. As a compromise number here we adopt the value of 5, with a large uncertainty. From the connection of mass, irreducible mass, and spin, we can derive in the limit of near-maximal rotation that $(dM_{\text{BH}})/(M_{\text{BH}} dt) = (1/2)(dJ_{\text{BH}})/(J_{\text{BH}} dt)$, where J_{BH} is the angular momentum of the black hole. This gives a luminosity of $\sim 10^{42.8} \text{ erg/s}$, independent of BH mass in the mass range considered here. This corresponds to within a factor of unity to the Poynting flux energy flow (e.g., Nokhrina, 2020); such an interpretation suggests that the wind is split into a fast jet along the symmetry axis and a slower wind around it, i.e., over much of 4π (see the General Relativity Magneto-Hydrodynamic - GRMHD - simulations of Mościbrodzka et al. (2016), Davelaar et al. (2018), Porth et al. (2019)). The Super-Nova Remnant (SNR) data of Cas A in X-rays are compatible with this possibility (Hwang et al., 2004).

This is fully consistent with the voltage drop expected near a black hole (Lovelace, 1976; Kronberg et al., 2011). In Kronberg et al. (2011) the voltage near a black hole was worked out, and inserting the observed numbers corresponds to $10^{18.9} \text{ eV}$ independent of black hole mass. This value is consistent with the observed magnetic field strength in terms of $(B \times r)$.

To summarize the concept used here: When a massive star explodes, it explodes into its magnetic wind, which has pushed out a substantial fraction of its Zero Age Main Sequence (ZAMS) mass already prior to the explosion. A magnetic wind emanating from a compact object, here thought to be a rotating black hole, enhances the energy and angular momentum transport processes and provides an outward pressure. Thus all the primary CRs are accelerated in the SN shock, but an additional weaker "special" CR component is proposed to come from the environment of the compact object, which we identify as 3^* of Gaisser et al. (2013); but also refer to Thoudam et al. (2016). We propose that this component is currently also visible in data near EeV (see Auger-Coll, 2020a). This is indeed a small proton component, if we think of pop 3^* , in either Tables 2, 3 (Gaisser et al., 2013).

Noting that massive stars explode as SNe in our Galaxy on average about every 75 years (summarized in Biermann et al. (2018);

the error on these numbers is $10^{\pm 0.11}$: see Diehl et al. (2006), Diehl et al. (2010)), and those leading to BHs every 400 years (i.e., both RSG and BSG stars); we can check the energy budget. Here we take the numbers of Gaisser et al. (2013), which indicate that one needs to account for 10^{41} erg/s for CR production in our Galaxy. Following these authors, we adopt 10 percent of the kinetic energy as leading to CR production. This then suggests that every massive star which makes a neutron star produces 10^{50} erg in CRs, i.e., $\sim 5 \cdot 10^{40} \text{ erg/s}$, requiring $10^{50.8} \text{ erg}$ in CRs of those stars which make BHs to match the energy budget given by Gaisser et al. (2013). This is in accordance with numerous observations of massive star SN explosions (see, e.g., Pāvālaš, 2001), in that they produce about an order of magnitude more energy than the more common SNe which lead to neutron stars (Biermann et al., 2018). The CR production of SN explosions of type Ia has been discussed in Biermann et al. (2019).

In this work, we will use the Gaisser et al. (2013) tabular fits (their Table 3). In Gaisser et al. (2013) there is a population of protons, referred to as either "Pop. 3", with a cutoff energy of 1.3 EeV, a differential spectral index of 2.4, and a relative abundance of 0.002, or as "Pop. 3^* " with 1.5 EeV, 2.4, and 0.0017, respectively. For reference, we note that assuming a slightly flatter spectral index of $7/3 \approx 2.33$ lowers these relative abundances by a factor of about 4, i.e., to $0.002/4 = 0.0005$ or $0.0017/4 = 0.000425$.

The RSNe expand to about 1–2 pc (Kronberg et al., 1985; Allen and Kronberg, 1998; Allen, 1999) with an observed shock speed of $c/10$ (Biermann et al., 2018), giving a time scale of 10^9 to $10^{9.3} \text{ s}$, which in turn gives a total electromagnetic energy output of $10^{51.8}$ to $10^{52.1} \text{ erg}$, consistent with the numbers inferred above. This energy supply is similar to the SN mechanism of Bisnovaty-Kogan (1970), which is worked out in, (e.g., Bisnovaty-Kogan and Moiseenko, 2008), and many further papers. This is consistent with observations of the explosions of similar stars (in the starburst galaxy M82 Blue Super Giant stars, (Biermann et al., 2018; Biermann et al., 2019), mentioned above (see [Pāvālaš (2001)]), for an earlier demonstration of such energetics); these stars have a ZAMS (Zero Age Main Sequence) mass of $\geq 33 M_{\odot}$ at Solar chemical abundances (Limongi and Chieffi, 2018; Limongi and Chieffi, 2020). The observed RSN wind allows an energy flow of an energetic particle population of $\sim 10^{39.8} \text{ erg/s}$ at most, so the energy flow is down by $\sim 10^{-3}$ from the total energy flow. This corresponds to the CR population, "3" as well as " 3^* " in Gaisser et al. (2013). By fitting the Larmor motion diameter into the space available, we obtain a maximal energy of $(1/2)(e * B \times r) = 10^{18.15 \pm 0.12} \text{ eV}$, which is the same quantity which rules angular momentum flow. This also matches the Gaisser fit to the maximum proton energy in the range of 1.3–1.5 EeV (Gaisser et al., 2013).

These ideas are in good agreement with Auger. The relevant statement (Auger-Coll, 2020b) is that at energies below 1 EeV, even though the amplitudes are not significant, their phases determined in most of the bins are not far from the R.A. of the Galactic center - $RA_{\text{GC}} = -94^\circ$. This suggests a predominantly Galactic origin for anisotropies at these energies. The reconstructed dipole phases in energy bins above 4 EeV point instead to R.A.s that are almost opposite to the Galactic center R.A.: They suggest a possible extragalactic CR origin (cited nearly verbatim from Auger-Coll, 2020b). In the Gaisser et al. (2013) data analysis the components "3" or " 3^* " referred to above have a cutoff at 1.3 to 1.5 EeV, and this is the component

argued about here quite explicitly. Therefore this EeV CR proton component appears to be fully consistent with Auger data, and is in fact almost required by the data (see Figure 5 in Gaisser et al. (2013)). In a chemical composition analysis of the Auger data a proton component with such a cutoff is clearly detectable (see Figure 2 in Auger-Coll (2020a)). The mixed chemical composition around the knee and above was predicted in Stanev et al. (1993), is consistent with Gaisser et al. (2013), confirmed in Thoudam et al. (2016), and is visible in the new Auger data (Auger-Coll, 2020a).

4 Why this value of $(B \times r)$?

4.1 The magnetic field due to the convection

The magnetic field observed via non-thermal radio emission in the winds of massive stars (Abbott et al., 1984; Drake et al., 1987; Churchwell et al., 1992) can be attributed to the dynamo process working in the central convection zone of massive stars (Biermann and Cassinelli, 1993). The rotation and convection allows the magnetic field to be amplified right up to the stress limit. Then the magnetic field can meander in flux tubes through the radiative zone, and penetrate into the wind. The estimate gives the right order of magnitude, but does not allow to comprehend, that the resulting magnetic field observed in the post-shock region of the SN-explosion racing through the wind is the same number for very different stars, RSG and BSG stars, with extremely different wind properties.

4.1.1 The magnetic field due to the SN-shock

The magnetic field could be enhanced through the SN-shock itself, observed to be at a velocity of about $0.1 c$ for both RSG and BSG star explosions (Biermann et al., 2018). The Bell-Lucek mechanism (Lucek and Bell, 2000; Bell and Lucek, 2001) can certainly produce strong magnetic fields, but to give the same strength of the magnetic field in two very different types of winds is highly implausible; the ram pressure of the SN-shock in these two types of wind is orders of magnitude different due to the much higher density in RSG star winds than in BSG star winds, as they show about the same shock speed, and the same mass loss in the prior wind.

4.1.2 The magnetic field due to the central object

The central object and its immediate environment could also determine the magnetic field strength of the wind visible, just as in the Pacini and Salvati (1973) approach. The observations show that all RSNe show the same magnetic field in terms of $(B \times r)$, a constant for B_ϕ throughout a Parker wind (Parker, 1958), despite the fact that massive stars over a wide range of masses produce such SNe, including RSG stars with slow and dense winds (Biermann et al., 2018). Furthermore, the environment of the big black hole in the galaxy M87 also shows a magnetic field consistent with the same number in these terms (EHT-Coll, 2019b). This can speculatively attributed to the environment of a rapidly rotating black hole, rotating near maximum, and independent of the mass of the black hole. This magnetic field can be translated into a wind or jet power, and the magnetic

field observed corresponds to the minimum jet power in radio galaxies (Punsly and Zhang, 2011). So it is plausible to interpret this number as due to a pure spin-down power, as done in EHT-Coll (2019b). This implies that radio galaxies relatively quickly revert to pure spin-down power after a merger of two central super-massive black holes, as demonstrated by the X-shape of the radio galaxy Cen A (Gergely and Biermann, 2009; Gopal-Krishna et al., 2003).

4.2 Some important questions

At this point there are some important questions:

1: What is the reason for the observed specific number $(B \times r) = 10^{16.0 \pm 0.12}$ Gauss $\times$ cm? It can be written as an energy flow with $(B \times r)^2 c = \{\hbar c\}/e^2 \{m_X c^2\}/\tau_{Pl}$ with m_X close to the proton or neutron mass, and τ_{Pl} the Planck time (see, e.g., Rueda and Ruffini, 2021). Below, in the paragraph headed by “Frequency of the Penrose process” we will derive such a relationship based on angular momentum flow; this relationship supported by observations requires the Planck time, and so connects gravitation and quantum mechanics.

2: Is there a possible physical connection to a relationship between magnetic field and rotational frequency (here equivalent to radius at maximum spin) also well known for super-conducting spheres (Hirsch, 2014; Hirsch, 2019)?

3: Does this also explain that knee and ankle energy are independent of the mass of the star which explodes and makes a BH? This has in fact been proposed (e.g., Biermann, 1993; Biermann and Astroph, 1993; Biermann and Cassinelli, 1993; Biermann and Strom, 1993; Stanev et al., 1993; Biermann et al., 2018; Biermann et al., 2019). Finding the relationship between magnetic field and angular momentum transport, as explained here in this paper, provides this argument.

4: Do all BHs near maximal rotation have the same magnetic field in terms of $(B \times r)$ independent of mass? That does seem to be the case, comparing magnetic field strength numbers in RSNe and in M87 (EHT-Coll, 2019b) and the inferred energy flow in radio quasars (Punsly and Zhang, 2011). The relationship derived below supports this conclusion.

5: What is the magnetic field at lower spin? Here the Galactic Center SMBH will be a useful test. This will be derived in a subsequent paper. Some dependencies on spin are derived below.

6: What is the effect of electric drift currents (Northrop, 1963; Equation 1.79) allowed by an energetic population of E^{-2} particles? Such electric drift currents can occur in electrically neutral plasmas and can be extremely fast. This was worked out in Gopal-Krishna and Biermann (2024), where it was shown that electric gradient drift currents, electric fields, and violent discharges are quite common in variable jets and winds.

All this provides motivation for deeper study.

5 Angular momentum transport

Since the quantity $(B \times r)$ is strongly connected to angular momentum transport, we consider this next.

5.1 A Parker limit approximation

At first we consider a Parker limit approximation to understand what is required at the inner boundary even in the simple Newtonian limit approximation. In this case we can include the ϕ -dependence, which we cannot do in the GR approximation. We posit

$$r^2 B_r = B_0 r_H^2 H(r - r_H) \{\cos \theta\} \{\cos \phi\} \quad (1)$$

$$r B_\theta = -B_0 r_H^2 \delta(r - r_H) \frac{\sin \theta}{2} \{\cos \phi\} + B_1 r_H H(r - r_H) \frac{\sin \theta}{2} \{\sin \phi\} \quad (2)$$

$$r B_\phi = B_1 r_H H(r - r_H) \{\sin \theta\} \{\cos \theta\} \{\cos \phi\} \quad (3)$$

r_H is the radius of the horizon, assumed at first to be independent of θ . $H(r - r_H)$ is the Heaviside function, and its derivative is the δ -function $\delta(r - r_H)$. This allows the angular momentum transport $B_\phi B_r r^3$ to be of the same sign everywhere. This construction immediately allows the divergence equation to be satisfied, and avoids any requirement for a monopole. In this solution the magnetic field stops at r_H , and does not penetrate inside. It is obvious that the magnetic field could be expanded into a long series, just as in [Parker \(1958\)](#), but these are simple first terms. This results in

$$B_1 r_H H(r - r_H) [2 \cos^2 \theta - \sin^2 \theta] \{\cos \phi\} - B_1 r_H H(r - r_H) \frac{\{\cos \phi\}}{2} - B_0 r_H^2 \delta(r - r_H) \frac{\{\sin \phi\}}{2} = \frac{4\pi r^2}{c} j_r$$

This allows the surface integral of the radial current j_r to be zero, separately in θ and ϕ . It also shows that the electric current runs in the same direction, both at $\theta = 0$ and at $\theta = \pi$, both either outwards or inwards. The current scales with $+B_1$ near the two poles, and is negative with $-B_1$ at the equator, with negative values in a broad equatorial band.

$$-B_1 r_H \delta(r - r_H) \sin \theta \cos \theta \{\cos \phi\} - B_0 r_H^2 \frac{H(r - r_H)}{r^2} \frac{\cos \theta}{\sin \theta} \{\sin \phi\} = \frac{4\pi r}{c} j_\theta \quad (4)$$

and

$$\left[B_0 r_H^2 \frac{\delta(r - r_H)}{r - r_H} \frac{1}{2} + B_0 r_H^2 \frac{H(r - r_H)}{r^2} \right] \sin \theta \{\cos \phi\} + B_1 r_H \delta(r - r_H) \frac{\sin \theta \{\sin \phi\}}{2} = \frac{4\pi r}{c} j_\phi \quad (5)$$

Considering the δ -function as a narrow Gaussian this suggests a double-layer in the ϕ -current, plus an asymmetric term.

This clearly shows that already in this simple approximation we get a δ -function term, and even the derivative of a δ -function term for the electric current at the inner boundary. It also demonstrates that the density of the current carrying charged particles diverges at the boundary, which implies that collisions also diverge in this approximation. One part of the end-product of these collisions is accreted to the BH, and the other part is ejected in the wind with a known magnetic power flow independent of BH mass.

5.2 A General Relativity solution

Here we derive the angular momentum transport in the terms of General Relativity, so allowing to treat the behavior of the magnetic field close to the black hole, for any rotation. In this section we set the speed of light c to unity for simplicity.

The metric tensor elements for the Kerr metric are given in Boyer - Lindquist coordinates by

$$ds^2 = \frac{d\phi^2 \sin^2(\theta) ((a^2 + r^2)^2 - a^2 \sin^2(\theta) \Delta(r))}{\rho(r, \theta)^2} - \frac{(dt d\phi + dt d\phi) (2a G_N M_{BH} r \sin^2(\theta))}{\rho(r, \theta)^2} + d\theta^2 \rho(r, \theta)^2 + \frac{dr^2 \rho(r, \theta)^2}{\Delta(r)} + dt^2 \left(- \left(1 - \frac{2 G_N M_{BH} r}{\rho(r, \theta)^2} \right) \right) \quad (6)$$

where G_N is the universal gravitational constant, M_{BH} is the mass of the black hole and

$$\rho(r, \theta)^2 = r^2 + a^2 \cos^2(\theta), \quad \Delta(r) = r^2 - 2 G_N M_{BH} r + a^2. \quad (7)$$

The electromagnetic tensor is

$$F_{\mu\nu} = \begin{pmatrix} 0 & 0 & \tilde{E}_\theta(r, \theta) & 0 \\ 0 & 0 & \tilde{B}_\phi(r, \theta) & -\tilde{B}_\theta(r, \theta) \\ -\tilde{E}(r, \theta) & -\tilde{B}_\phi(r, \theta) & 0 & \tilde{B}_r(r, \theta) \\ 0 & \tilde{B}_\theta(r, \theta) & -\tilde{B}_r(r, \theta) & 0 \end{pmatrix}, \quad (8)$$

and the components of $F_{\mu\nu}$ are determined from the vector potential components A_μ

$$F_{\mu\nu} = \partial_\mu (\sqrt{g_{\nu\nu}} A_\nu(r, \theta)) - \partial_\nu (\sqrt{g_{\mu\mu}} A_\mu(r, \theta)). \quad (9)$$

The measured components of the electric and magnetic fields are related to the tilde components in $F_{\mu\nu}$ by the relations

$$\begin{aligned} \tilde{E}_\theta(r, \theta) &= E_\theta(r, \theta) \\ \tilde{B}_r(r, \theta) &= \sqrt{g_{\theta\theta} g_{\phi\phi}} B^r(r, \theta) \\ \tilde{B}_\theta(r, \theta) &= -\sqrt{g_{rr} g_{\phi\phi}} B^\theta(r, \theta) \\ \tilde{B}_\phi(r, \theta) &= \sqrt{g_{rr} g_{\theta\theta}} B^\phi(r, \theta) \end{aligned} \quad (10)$$

These expressions are based on the definitions of the electric and magnetic fields given in [Komissarov \(2004\)](#). They have the asymptotic forms given in [Weber and Davis \(1967\)](#). We are assuming that the r - and ϕ -components of the electric field are zero. The $E_\theta(r, \theta)$ component of the electric field can be determined for the case of a static magnetic field, $\partial \tilde{B} / \partial t = 0$, from the relation

$$(\nabla \times \tilde{E})_\phi = 0. \quad (11)$$

This relation requires that

$$E_\theta(r, \theta) = \frac{E_0}{\rho(r, \theta)}, \quad (12)$$

where E_0 is a constant. The $B^r(r, \theta)$ component of the magnetic field is obtained from the divergence relation

$$\nabla \cdot \tilde{B}(r, \theta) = 0. \quad (13)$$

For $B^\theta(r, \theta) = 0$ (Weber and Davis, 1967) this relation requires that

$$B^r(r, \theta) = \frac{B_0}{\sqrt{g_{rr}g_{\theta\theta}g_{\phi\phi}}}, \quad (14)$$

where B_0 is a constant. The remaining components of the magnetic field are undetermined. Based on observational radio data extensively discussed in Biermann et al. (2018), Biermann et al. (2019), we assume that

$$\sqrt{g_{rr}g_{\theta\theta}}B^\phi(r, \theta) = \text{constant} = B_{p0}. \quad (15)$$

Here both B^r and $B^\phi \sim \Delta^{1/2}$. The ratio between B_ϕ and B_r is given by the Parker model, and this indicates that $B_{p0}/B_0 \sim \chi/M_{BH}$, where χ is the dimensionless spin (i.e., maximum unity), so $\chi = a/M_{BH}$. Furthermore we assume that the total radial magnetic field energy is proportional to the available rotational energy, which results in $B_0 \sim \chi M_{BH}$, in the $\chi \ll 1$ approximation. From this it follows that $B_{p0} \sim \chi^2$. Using observations of radio loud quasars (Punsly and Zhang, 2011) we can check on the implications, since GR solutions and far-distant solutions have to be consistent in their dependence on χ and M_{BH} , namely, $L_{jet} \sim \chi^4$, independent of BH mass M_{BH} . Furthermore $E_0 \sim \chi^2 M_{BH}$ from the consistency requirement of the energy flow and angular momentum flow, worked out below.

The energy flux is obtained from the contraction of the covariant form of the Killing vector k_t^μ with the electromagnetic energy-momentum tensor

$$\mathcal{E}^\mu = T^{\mu\nu}(k_t)_\nu, \quad (16)$$

and the angular momentum flux is obtained from the contraction of the covariant form of the Killing vector k_ϕ^μ with the electromagnetic energy-momentum tensor

$$\mathcal{L}^\mu = T^{\mu\nu}(k_\phi)_\nu. \quad (17)$$

The r - and θ -spatial components of the energy flux and the angular momentum flux are given by

$$\begin{aligned} \mathcal{E}^r &= \frac{B_{p0} E_0 \Delta(r)}{\rho(r, \theta)^5} \\ \mathcal{E}^\theta &= 0 \\ \mathcal{L}^r &= \frac{B_0 B_{p0} \Delta(r)^{3/2}}{\rho(r, \theta)^5} \\ \mathcal{L}^\theta &= 0. \end{aligned} \quad (18)$$

The energy flux and the angular momentum flux are related via the expression

$$\mathcal{E}^r = \omega(r, \theta) \mathcal{L}^r, \quad (19)$$

where

$$\begin{aligned} \omega &= \frac{\tilde{E}_\theta}{\tilde{B}_r} \\ &= \frac{E_0}{B_0 \sqrt{\Delta}}. \end{aligned} \quad (20)$$

This is the same relation as the one in Equation 4.4 of Blandford and Znajek (1977). Here $\omega \sim \chi/M_{BH}$.

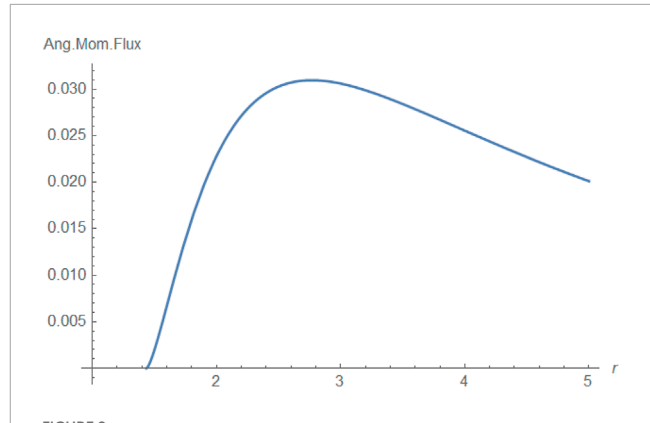


FIGURE 2
Radial component of the angular momentum flux vs the radius at the equator of the black hole ($\theta = \pi/2$). In this specific plot as in the next two plots in the abscissa the unit is the Kerr radius, in contradiction to the text, where r scales to the Kerr radius; so there r has as a minimum the Kerr radius $\{G_N M_{BH}\}/c^2$, but with c set to unity in this section. The ordinate is determined by the mathematical expression, setting all other constants to unity. The angular momentum per unit mass constant, a , is $a = 0.9$.

The location of the horizon is determined by the condition $\Delta(r) = 0$, so the flux components $\mathcal{E}^r$ and $\mathcal{L}^r$ vanish on the horizon. On the equator of the black hole ($\theta = \pi/2$) the radial component of the angular momentum flux reaches a maximum at a radius of slightly less than three horizon radii, Figure 2. These expressions are similar to the ones obtained by Blandford and Znajek (1977), but there are significant differences due to the differences between our model and theirs. In the BZ model both of the poloidal components of the energy flux are non-zero, while in our model both of the fluxes in the θ -direction (polar direction) are zero. The vanishing of the θ -component of the energy flux in our model is due to setting the r - and ϕ -components of the electric field equal to zero, and the vanishing of the θ -component of the angular momentum flux is due to setting the θ -component of the magnetic field equal to zero, following Weber and Davis (1967).

5.3 Calculation of energy extraction and angular momentum extraction

As seen by an observer at infinity the rate of energy extraction is given by

$$\dot{E}_{rad} = \int \mathcal{E}^r \rho(r, \theta)^2 d\Omega, \quad (21)$$

and the rate of angular momentum extraction is given by

$$\dot{L}_{rad} = \int \mathcal{L}^r \rho(r, \theta)^2 d\Omega, \quad (22)$$

where $d\Omega$ is the infinitesimal solid angle. The evaluation of these integrals gives (note that the radius r refers to the BH mass, so that spin a , radius r , and $G_N M_{BH}$ have the same unit in this section)

$$\begin{aligned} \dot{E}_{rad} &= \frac{4\pi B_{p0} E_0 (a^2 + r(r - 2G_N M_{BH}))}{r^2 \sqrt{a^2 + r^2}} \\ \dot{L}_{rad} &= \frac{4\pi B_0 B_{p0} (a^2 + r(r - 2G_N M_{BH}))^{3/2}}{r^2 \sqrt{a^2 + r^2}}. \end{aligned} \quad (23)$$

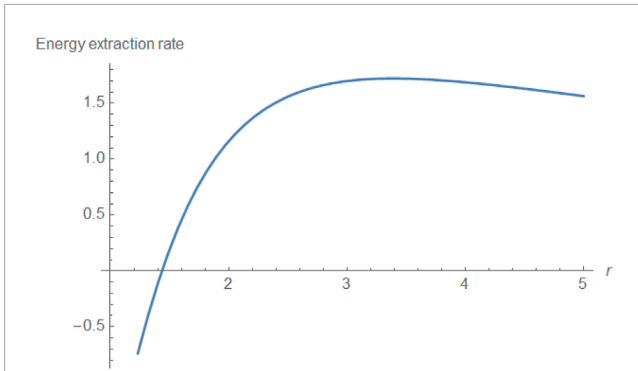


FIGURE 3
Radial component of the magnitude of the rate of energy extraction. The angular momentum per unit mass constant, a , is $a = 0.9$. All other constants are set equal to 1. The extrapolation to negative values of this extraction rate is without consequence for an observer, as this part of the curve is inside the horizon.

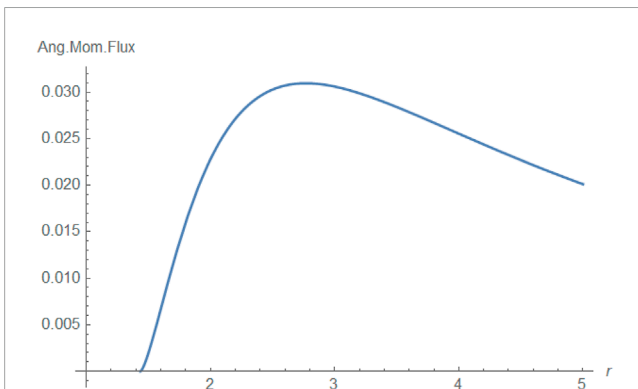


FIGURE 4
Radial component of the magnitude of the angular momentum extraction rate vs the radius. The angular momentum per unit mass constant, a , is $a = 0.9$. All other constants are set equal to 1. Here the radial range considered is very large to show how this angular momentum transport approaches a constant despite the simplicity of the model.

Here $\dot{E}_{rad} \sim \chi^4$, and $\dot{L}_{rad} \sim \chi^3 M_{BH}$, consistent with a derivation following (Weber and Davis, 1967; Falcke and Biermann, 1995).

Here the power is proportional to χ^4 and the angular momentum transport to $\chi^3 M_{BH}$. Since the power put out via magnetic fields is also proportional to B_0^2 Falcke and Biermann, 1995 this is consistent. The angular momentum transport by magnetic fields (Weber and Davis, 1967; Equation 9, integrated over $4\pi r^2$) runs as $B_0 \times B_{p0} \sim \chi^3 M_{BH}$, so this is also consistent. In these graphs (Figures 2–4) the lower limit of r is given by the condition $\Delta(r) = 0$, so for maximal spin, that radius is $r = \{G_N M_{BH}\}/c^2$, the Kerr radius.

5.4 Calculation of the current

The current can be calculated from the covariant divergence of the electromagnetic field tensor

$$\nabla_\mu F^{\mu\nu} = J^\nu \quad (24)$$

For the radial and theta components of the current this calculation gives

$$J^r = -\frac{4a^2 B_{p0} \sin(\theta) \cos(\theta) (a^2 + r(r - 2G_N M_{BH}))}{(a^2 \cos^2(\theta) + r^2)^3}$$

$$J^\theta = -\frac{2B_{p0} (a^2 \cos^2(\theta) (G_N M_{BH} - r) + r(2a^2 + r(r - 3G_N M_{BH})))}{(a^2 \cos^2(\theta) + r^2)^3} \quad (25)$$

The J^t and J^ϕ components are non-zero, but their expressions are much longer. The latter two components decrease much more rapidly with r than either J^r or J^θ .

5.5 Charge density

The expression for the charge density as obtained from the covariant divergence relation is given by

$$J^0 = \frac{2\sqrt{(2)} a^2 \sin(2\theta) (6a^4 E_0 \cos^2(\theta) - 20a B_0 G_N M_{BH} r \sqrt{a^2 + r(r - 2G_N M_{BH})})}{(a^2 + r(r - 2G_N M_{BH})) (a^2 \cos(2\theta) + a^2 + 2r^2)^{7/2}}$$

$$+ \frac{2E_0 r^3 (4G_N M_{BH} + 3r)}{(a^2 + r(r - 2G_N M_{BH})) (a^2 \cos(2\theta) + a^2 + 2r^2)^{7/2}}$$

$$+ \frac{2\sqrt{(2)} a^2 \sin(2\theta) (a^2 E_0 r (14G_N M_{BH} + 9r + 3(-2G_N M_{BH} + r) \cos(2\theta)))}{(a^2 + r(r - 2G_N M_{BH})) (a^2 \cos(2\theta) + a^2 + 2r^2)^{7/2}} \quad (26)$$

This shows that in terms of the local charge density we also get a divergence at the inner boundary, at the horizon. This is proportional to $\chi^4 M_{BH}^{-2}$. In more detail the leading terms with B_0 as well as E_0 run as $\chi^4 M_{BH}^{-2}$, while the terms with E_0 have two further terms running as $\chi^8 M_{BH}^{-2}$ and $\chi^6 M_{BH}^{-2}$. It follows that the density may get high enough for lots of energetic collisions.

Furthermore the term running with B_0 has the factor $\Delta^{-1/2}$, while the terms running with E_0 all have the factor Δ^{-1} . When Δ approaches a value small compared to radius r , and writing the spin parameter as $\chi = 1 - \delta\chi$ with $\delta\chi \ll 1$, then $\Delta = (r - r_g(1 + \sqrt{2\delta\chi})) \times (r - r_g(1 - \sqrt{2\delta\chi}))$. Writing the first term in brackets as δr , then Δ becomes $\delta r \times (\delta r + 2\sqrt{2\delta\chi})$. If we could constrain the collision rate then it follows that we could also constrain $\delta\chi$ to be a possibly small number.

To work out the numbers we note that B_{p0} is observed to be $10^{16.0 \pm 0.12} \text{ Gauss} \times \text{cm}$ (Biermann et al., 2018; Biermann et al., 2019); writing all other terms with their proper dimensions using the equatorial outer radius of the ergo-region of a $10 M_\odot$ BH, so $10^{6.4} \text{ cm}$, gives a charged particle density of about $10^{14.0} \text{ cm}^{-3}$, ignoring here the factors with some power of Δ , and adopting the limit $\chi \approx 1$.

This suggests that collisions could be an important process, and this is what we explore further.

5.6 Neutrinos from the ergo-region?

There is an inconsistency between what the mass transport is in the wind (assuming equipartition with the observed magnetic fields) and what accretion to the BH is needed to sustain the luminosity of $\sim 10^{43} \text{ erg/s}$, if one were to power this emission simply by accretion, as equality would require 100% efficiency. This inconsistency can

be resolved by considering the pure spin-down mode (Blandford and Znajek, 1977), which implies very little accretion. Here we note that in the pair production variant to the Penrose process, this could imply that the BH accretes predominantly particle/anti-particle pairs, most of which never get out. The creation of such pairs costs at least two proton masses in energy, but energetically pion production dominates by far (below we use a factor of about 30 based on the ratio of cross sections to make pions and to make proton-anti-proton pairs from p-p collisions). They are available from interaction with magnetic irregularities and non-linear waves, such as shock waves. In fact, from the mismatch in mass turnover, one might speculate that the energetic protons initiate a cascade process similar to the interaction of ultra high energy CR particles entering the atmosphere of the Earth. In such a cascade a very large number of secondary particles is produced. By analogy with the Penrose argument one may expect that half the cascade particles are directly on orbits falling into the BH; the other half are initially on orbits to escape. These particles interact with the magnetic field. At the outer boundary of the ergo-region, the particles may transfer a significant fraction of their energy and angular momentum to the magnetic fields and fall back down in accretion to the BH (see Penrose and Floyd, 1971). In processes such as $\bar{p}$'s colliding with p 's, pions and multiple neutrinos are produced. These neutrinos have a good chance to escape altogether. All this should be re-evaluated using proper frames (e.g., Bardeen et al., 1972; Shaymatov et al., 2015; Bambhaniya et al., 2021), although a collision-dominated gas with a magnetic field, in which some energetic particles have Larmor radii which are close to the scale of the system, is a challenge. What we present here is a detailed balancing of different particle species in the local frame.

Many different losses go into production of pions, which quickly decay into energetic electrons, positrons, photons and neutrinos. In the model proposed the photons are optically thick in their propagation. This is akin to the model published for blazars, and their neutrino emission in Kun et al. (2021). The electrons/positrons and neutrinos have a chance of escaping. Based on the ratio of cross-sections for p-p-collisions to make pions versus p-p-collisions to make proton-anti-proton pairs, about 30 times as much energy goes into an electron/positrons pair plasma from pion decay (ratio of cross sections and energy turnover), and neutrinos, as goes into proton-anti-proton pairs, in terms of what gets out. The neutrinos - in the model proposed - range from MeV to very much higher energy, and for those the IceCube data provide a serious upper limit, if the model is used at TeV energies and beyond. Other than an electron/positron plasma neutrinos could be a second main escape path. That is a main point of the model.

A check with data can be done: the proposal is consistent with IceCube-Coll et al. (2016), IceCube-Coll et al. (2021) and INTEGRAL data (Diehl et al., 2006; Diehl et al., 2010; Siebert et al., 2016a; Siebert et al., 2016b):

In the model proposed the cosmic ray flux of the component going to EeV energies is about $10^{-2.8}$ of the normal CR flux at GeV energies (numbers taken from Gaisser et al. (2013), Table 3, CR components 3 or 3*; pop three contains all elements (Table 2) and pop 3* contains only protons); correcting for a slightly flatter spectrum assumed here, anchored at EeV, gives about $10^{-3.4}$. This implies $10^{37.6}$ erg/s, again using Gaisser's et al. numbers for the entire Galaxy of 10^{41} erg/s. Falcke and Markoff (2013) give an estimate

of the accretion rate measured close to the central BH in our Galaxy, and it corresponds to a power of about $10^{37.8}$ erg/s, consistent with the number above. INTEGRAL (Siebert et al., 2016b) gives a positronium production of $10^{43.5} \text{ s}^{-1}$ in a very large region, with a scale height of several kpc and along the plane from a larger region than any other recognizable source class, corresponding to about $10^{37.5}$ erg/s, again consistent with the Gaisser et al. (2013) number. The papers by Diehl et al. support the point of view that there could be plenty more electrons and positrons that escape from the Galactic disk unseen. The production of a large number of electrons/positrons is demonstrated by observations of the BH V404 Cyg (Siebert et al., 2016a). The electron/positron pair plasma production in our Galaxy appears to be due to many sources, possibly the Galactic Center black hole (GC BH) and most probably many stellar/SN/BH sources, including microquasars and SN Ia supernovae (Martin et al., 2010; Prantzos et al., 2011; Prantzos, 2017; Mera Evans et al., 2022). Diehl et al. propose that all black holes produce an electron/positron pair plasma, often in outbursts. Based on gamma-ray line spectroscopy (Diehl et al., 2006; Diehl et al., 2010; Diehl, 2017) give a SN rate of those SNe making black holes in the Galaxy of about 1 SN per 400 years (again, with an uncertainty of $10^{\pm 0.11}$); this has been worked through in Biernmann et al. (2018); this includes both Red Super Giant and Blue Super Giant star progenitors, both of which produce black holes, or short BH-SNe. The time scale of the activity is at least 30 years (1 parsec at 0.1c), as observed numbers from Radio Super-Novae given in Biernmann et al. (2019), based on the M82 data of Radio Super-Novae (RSNe) (Allen and Kronberg, 1998; Kronberg et al., 1985; Kronberg et al., 2000). It ensues that each BH-SN contributes - again using the numbers in Gaisser et al. (2013) - about $10^{50.8}$ erg in CRs, as shown above. For this specific low level HE CR component this translates to $10^{47.4}$ erg, as well as $10^{48.9}$ erg in e^+e^- plasma and MeV neutrinos, by virtue of the 30 times larger cross section (p-p collisions making pions versus p-p collisions making $p\bar{p}$ pairs). This translates into a maximal flux, using the shortest reasonable time scale - of $10^{39.9}$ erg/s initially. The observed power of about $10^{37.5}$ erg/s in the Galactic Center region (by INTEGRAL) in electron/positron plasma means, if produced by a SN, that the activity could be down now by $e^{-400/30} \approx 10^{-5.8}$, for a possible initial power of $10^{43.3}$ erg/s for all SN contributors summed together. This in fact approximately matches the spin-down power seen in both M87 (EHT-Coll, 2019a; EHT-Coll, 2019b), many other radio galaxies in their minimum jet power (e.g., Punsly and Zhang, 2011), and in Radio Super-Nova Remnants interpreting them as driven by a relativistic wind from a spinning compact object, presumably a BH.

Using the starburst galaxy M82 (Kronberg et al., 1985; Allen and Kronberg, 1998; Kronberg et al., 2000) itself as our IceCube limit for point sources (IceCube-Coll et al., 2016; IceCube-Coll et al., 2020; IceCube-Coll et al., 2021) gives about $10^{-12.0}$ TeV events $\text{cm}^{-2} \text{ s}^{-1}$, assuming a E^{-2} spectrum, corresponding to a limit of about $10^{-11.0}$ erg $\text{cm}^{-2} \text{ s}^{-1}$ at GeV for a $E^{-7/3}$ spectrum assumed here for the relevant CR spectrum, where the Gaisser et al. (2013) numbers are anchored. This corresponds to a limiting luminosity at TeV of $10^{39.1}$ erg/s at the distance of M82, and $10^{33.9}$ erg/s at the distance of the Galactic Center. Since there is evidence from the Telescope Array et al. (2020) as well as Auger-Coll (2018), that both starburst galaxies M82 in the North and NGC253 in the South may have been detected in UHECRs, we assume that the detailed analysis

of recent Radio Super-Novae (RSNe) in M82 applies also to NGC253 (Kronberg et al., 1985; Allen and Kronberg, 1998; Kronberg et al., 2000), where the specific IceCube limit mentioned above applies and so a limit for all sources is $< 10^{39.1}$ erg/s. In M82 there are about 40 such sources (Kronberg et al., 1985), so the limit per source is $< 10^{37.5}$ erg/s, if all sources contribute equally. However, again, for a possible decay time of 30 years, only one source may contribute, and this possibility would imply a luminosity of $< 10^{39.1}$ erg/s for that one source. To within the large errors of such an estimate this is still consistent with the data, which give an expectation for a single contributing source at $10^{39.9}$ erg/s. Allowing for a slightly steeper spectrum would loosen these constraints, as would an even faster change with time of any single source. The age of the youngest source $41.9 + 58$ is sufficiently large so that it may have decayed already significantly. Of course, if the HE neutrinos were pointed in their emission, then their luminosity could be quite a bit higher without showing up in our observations.

To do a further test: Applying the same neutrino flux limit to possible sources in the Galactic Center (GC) region gives a limit of about $10^{5.1}$ times stronger, so $< 10^{34.4}$ erg/s. As shown above this is fully consistent with the rate of BH-SNe occurring; the expected flux reduction is $10^{-5.8}$ for an initial luminosity limit of $< 10^{40.3}$ erg/s, again consistent. One problem in such an argument is that the sources are known to be highly fluctuating (e.g., Siebert et al., 2016a). It is possible to repeat this exercise for the Cyg region, which is much closer than the Galactic Center. This gives a limiting luminosity of $10^{33.2}$ erg/s, and it is again consistent, since the BH-SN rate is very low near to us, 1 BH-SN per about 10^5 years, so predicting a huge reduction from the expected initial luminosity of $10^{39.9}$ erg/s worked out above; Cygnus might be close enough to provide an actual source of the Galactic EeV CRs identified by Gaissner et al. (2013).

5.7 Collisions

Analyses of particle collisions near to BHs and singularities have been carried out, (Patil et al., 2010; Patil and Joshi, 2011a; Patil and Joshi, 2011b; Patil and Joshi, 2012; Patil et al., 2012; Patil and Joshi, 2014; Patil et al., 2015; Patil et al., 2016; Liu et al., 2011; Banados et al., 2009; Banados et al., 2011). These papers did not have the benefit of insight provided by the RSN observations, the most detailed of which by Allen and Kronberg (1998), Allen (1999), Kronberg et al. (2000). The latter provide a newer solid foundation to develop the approach.

As an example, we calculate the particle density and flux for the ergo-region around a stellar mass BH of $10M_{\odot}$. The magnetic field, extrapolated to near the BH, at radius $R = 10^{6.4}$ cm, is about $10^{9.6}$ Gauss. In equipartition, $(B^2)/(8\pi) \approx nk_B T$, leading to a particle density of $n \approx 10^{21.6}$ cm $^{-3}$ at a weakly relativistic temperature of $\sim 10^{12}$ K. This, in turn, allows a flow of particles of $4\pi R^2 n c \approx 10^{46}$ s $^{-1}$. Interactions give a similar number, using a cross section of 10^{-27} cm 2 (valid for making proton-anti-proton pairs (Winkler, 2017; Reinert and Winkler, 2018); the inelastic cross-section is about 30 times higher well above threshold), as obtained from $4\pi R^3 n^2 \sigma c \approx 10^{47}$ s $^{-1}$, which is more than what is needed to explain the observations; as even a smaller cross-section could be accommodated. This latter quantity cannot be readily extrapolated to a higher BH mass, as we discuss below.

Using the general approach of EHT-Coll (2019b) we can show that this optical depth may reach order 10, independent of radius. This means that the interaction time to produce proton-anti-proton pairs is less than the residence time, possibly considerably less.

The observations show that $B = 10^{16.0 \pm 0.12}/r$ Gauss, with r in cm. This relationship has been observed over the range of radius from about $10^{18.5}$ cm down to order 10^{16} cm, with the highest resolution observations done by radio interferometry (VLBI). Using the analogy with the Solar wind (Parker, 1958; Weber and Davis, 1967) we extrapolate it down for the case of fast rotation. The EHT observations of M87 suggest that such an extrapolation is reasonable (EHT-Coll, 2019b): There the product $(B \times r)$ has about the same value as in RSNe at about five gravitational radii; the M87 black hole has been suspected to be in substantial rotation, perhaps near maximal (Daly, 2019; EHT-Coll, 2019b and later). The jet power of M87 is consistent with what is derived for RSNe using the available energy content of a maximally rotating black hole, and the time-scale derived from angular momentum transport (Weber and Davis, 1967). This suggests that the jet power far outside the ergo-region is already visible at five gravitational radii.

Putting in numbers as observed (EHT-Coll, 2019b) extrapolated to a stellar mass BH suggests that the production time scale for making proton-anti-proton pairs is safely of order < 1 of the resident time scale in the inner region around the ergo-region.

This argument works for stellar mass black holes, and we can speculate here that the model proposed would allow this to work also for more massive black holes.

5.8 Anti-protons

The concept is that the energetic particles are confined by the magnetic field and so stay in the ergo-region; the magnetic field is due to electric currents in the (weakly relativistic) thermal matter, which is held in the gravitational field. In momentum phase space there is a cone, inside of which all particles are on orbit to accrete to the BH. This is akin to arguments in Hills (1975), Bahcall and Wolf (1976), Frank and Rees (1976). In that approach, stars interact with molecular clouds to fill a cone in momentum phase space which allows accretion to a central BH. This is referred to as the *loss cone* mechanism. Here, charged particles interact with the magnetic fields (Strong et al., 2007; Moskalenko and Seo, 2019), and also with each other, to also finally accrete to the BH.

Given all the above arguments, what are the predictions in these scenarios? In these conditions, one can ask what the fraction of anti-protons $n_{\bar{p}}/n_p$ might be. The observed fraction of anti-protons is about $10^{-3.7}$ (AMS Coll, 2016), with a spectral shape dependence of about $E^{-2.7}$ for both protons and anti-protons. We assume that this spectrum changes for both towards a flatter spectrum at higher energy since at lower energies, both components have other contributions (see, e.g., Biermann et al., 2018). Could this match the observed flux of anti-protons? Fitting above 200 GeV, the CR flux is about 10^{-3} relative to other CR-populations from the similar SN-explosions. Using a spectrum such as $E^{-7/3}$, this modifies the factor of 10^{-3} to $10^{-3.3}$ to $10^{-3.4}$. However, at EeV, the sum of protons and anti-protons is observed, while at lower energy, anti-protons are observed separately. Thus, correcting the prediction by another factor of order two gives $10^{-3.6}$ to $10^{-3.7}$, which allows

the observed $10^{-3.7}$. Consequently, we propose a model to explain the flux, energy content, spectrum, maximal particle energy, and particle/anti-particle ratio of highly energetic protons. It follows then, that the spectrum of anti-protons continues all the way to ankle energies, with a spectral shape near $E^{-7/3}$. The energetic protons would approach the spectrum of the anti-protons at some energy slightly above PeV. AMS may well detect some of these anti-protons among its highest energy particles, around TeV.

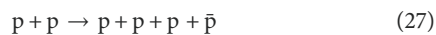
One may well ask whether anti-protons survive their path to us: Their cross-section to interaction is the same as for protons, and since we see protons at EeV (Auger-Coll, 2020a) without being able to distinguish protons and anti-protons, the particles detected may well contain anti-protons, in this proposal here possibly half.

If there are in fact large numbers of cascades, then many of the secondaries, including electrons and positrons might also escape, creating a funnel in the Galactic disk which allows them to flow out (see Diehl et al., 2006; Diehl et al., 2011; Diehl, 2013; Siebert et al., 2016b). The total positron production in a large region around the Galactic Center corresponds to a power on the order of $10^{37.1}$ erg/s. This is $10^{-4.6}$ of the maximal energetic particle flow, of order 10^{51} erg in about $10^{9.3}$ s (see above) even for a single massive star SN event, suggesting that much of the energy is vented out to the Galactic halo. Even allowing for a reduction by about a factor of 100, to account for the difference in CR electron fluxes from CR proton and Helium, would still leave a factor of $10^{-2.6}$. The contribution from the Galactic Center BH seems to be less than that which any possible surrounding sources could contribute.

In the balance between production of anti-protons from $p - p$ collisions, as well as $\bar{p} - \bar{p}$ collisions, the annihilation process $p - \bar{p}$ dominates. Those interactions will limit not only the $\bar{p}$ net production, but will also produce large numbers of neutrinos. On the other hand, the p vs $\bar{p}$ interaction decreases with energy, while the p vs p interaction cross-section to produce $p - \bar{p}$ pairs, rises with energy. These neutrinos will be crudely commensurate with the Poynting flux energy flow. They, however, could exceed the Poynting flux, if the production and immediate destruction of $\bar{p}$ greatly exceed the rate of accretion of $\bar{p}$, as this runs with the ratio of the cross sections. Consequently, this process could emit a significant fraction of the rotational energy of the BH via neutrinos.

We consider the following reactions: first for creating and annihilating anti-protons; here we include the primary protons. Note that these densities represent integrals over the momentum distribution, and the cross-sections include weighting due to the momentum phase-space distribution:

1)



with cross section

$$\sigma_{pr,p\bar{p}}; \quad (28)$$

protons have density n_p and anti-protons density $n_{\bar{p}}$;

2)



with cross-section

$$\sigma_{de,p\bar{p}}. \quad (30)$$

– The pions decay into neutrinos and other leptons.

3) The reaction



has the same cross section as above for protons,

$$\sigma_{pr,p\bar{p}}. \quad (32)$$

4) The production of anti-neutrons



has the cross section

$$\sigma_{\bar{n},p\bar{p}}. \quad (34)$$

There are corresponding analogous processes for producing or destroying protons.

The detailed balance equations are (adopting c as an approximate typical velocity for the particles):

$$\begin{aligned} \frac{dn_{\bar{p}}}{dt} = & \sigma_{pr,p\bar{p}} c n_p^2 - \sigma_{de,p\bar{p}} c n_{\bar{p}} n_p + \sigma_{pr,p\bar{p}} c n_p^2 \\ & - \sigma_{\bar{n},p\bar{p}} c n_{\bar{p}}^2 - \frac{n_{\bar{p}}}{\tau_{BH}}, \end{aligned} \quad (35)$$

and

$$\begin{aligned} \frac{dn_p}{dt} = & \sigma_{pr,p\bar{p}} c n_p^2 - \sigma_{de,p\bar{p}} c n_{\bar{p}} n_p + \sigma_{pr,p\bar{p}} c n_p^2 \\ & - \sigma_{n,p\bar{p}} c n_p^2 - \frac{n_p}{\tau_{BH}} + \frac{n_p}{\tau_{gal}}. \end{aligned} \quad (36)$$

Here the last term in the previous equation, and the last two terms in this equation, represent accretion to the BH, and accretion from the outside, from an accretion disk for instance. Accretion from outside constitutes positive baryon number accretion. If many secondaries are created and accreted, their net baryon number is zero. Baryon number accretion derives from both populations.

Initially, we assume that the accretion terms are negligible. By virtue of particles and anti-particles behaving the same in corresponding cross-sections, we can now consider two situations:

First we consider the case, where $n_{\bar{p}} \ll n_p$. In this case, the production of anti-protons via pair creation dominates, and for protons the reaction leading to neutron production dominates. So, in this case, the anti-protons grow in number, and the protons decrease in number. The situation is not stationary.

Next, the condition of exact stationarity can be required, and the two equations above can be subtracted from each other: By virtue of the symmetry of cross-sections between particles and anti-particles, the first three terms in the first equation are equal to the first three terms in the subsequent equation, leaving the fourth term. This gives

$$n_{\bar{p}}^2 \sigma_{\bar{n},p\bar{p}} - \sigma_{n,p\bar{p}} n_p^2 = 0. \quad (37)$$

By virtue of the equivalence between particles and anti-particles, the two cross-sections are identical and can be cancelled out. The result of the above operation is

$$n_{\bar{p}}^2 - n_p^2 = 0, \quad (38)$$

thus the density of protons and anti-protons is the same in stationarity, neglecting accretion both from outside and to the BH. This does not violate baryon number conservation since in this model, both protons and anti-protons are secondary; the baryon number is exactly zero.

It follows that the ratio of neutrino production via pion decay to $p\bar{p}$ pair-production runs with the ratio of the two cross-sections, which is large; however, the cross-sections have to be weighted with the momentum phase space distribution as noted above. It follows that the time scale for refilling the momentum phase space necessary to yield large interaction rates is key to the effective neutrino luminosity. Correspondingly, the ratio of neutron production to $p\bar{p}$ pair-production runs with the ratio of the two cross-sections, which is also large. The cross-section to make pions and ensuing neutrinos starts at small energy and is large, and so dominates over the neutron production. In this simplified picture creation and destruction balance, and so the momentum distribution adjusts itself to make the effective cross-sections match, moderated by the time scales of redistributing particles in momentum phase space.

Second, we allow for the accretion terms to be relevant. Then the difference of the two terms leads to

$$(n_p - n_{\bar{p}}) \left(\sigma_{n,pp} (n_p + n_{\bar{p}}) + \frac{1}{\tau_{BH}} \right) = \frac{n_p}{\tau_{disk}}. \quad (39)$$

This means if the sum of the neutron production and the BH net accretion is much larger than the outside accretion (from, e.g., an accretion disk), then the relative difference

$$(n_p - n_{\bar{p}})/n_p \quad (40)$$

is small. The anti-proton density approaches the proton density. Next consider the sum of the two equations: A solution is possible, in which the creation of secondaries is mostly balanced by destruction, with some accreting to the BH, and an even smaller number providing net loss of particles to the outside.

The pion decay leading to neutrino production can be approximated well by the approach of [Penrose and Floyd \(1971\)](#), leading to an accretion of neutrinos to the BH. It also leads to a corresponding luminosity of outgoing neutrinos.

In summary, the test is clearly to determine the anti-proton fraction at the EeV energy scale. If that fraction is half of the sum of protons and anti-protons, then the neutrino luminosity is predicted to be large, with most neutrinos near GeV energies. We observe TeV energies in neutrinos, and above.

5.9 The Penrose zones with magnetic fields

All these arguments depend on the Penrose process ([Penrose and Floyd, 1971](#), [Bardeen et al., 1972](#)). However, the main difference to the collisional Penrose process (e.g., [Bejger et al., 2012](#); [Hod, 2016](#); [Leiderschneider and Piran, 2016](#); [Schnittman, 2018](#)) is that in our approach, based on the magnetic field observations, particles are scattered by magnetic field irregularities frequently and throughout the ergo-region. We can write the spectrum of magnetic field irregularities $I(k)$ as energy density with wavenumber k , so that the mean free path can be written as

$$r_g \frac{B^2 / \{8\pi\}}{I(k)k} \quad (41)$$

where r_g is the Larmor radius of the motion of a charged particle. This mean free path is far smaller than the scale of the ergo-region except for the very highest particle energies, spanning more than nine orders of magnitude (from the values of $B \times r$) observed, as discussed above and in [Biermann et al. \(2018\)](#), [Biermann et al. \(2019\)](#).

Here we focus on the angular momentum transport and work out, how frequently the data show that the Penrose process happens; however, first we have to comment on orbits of particles versus the local 3D momentum phase space distribution.

5.9.1 Momentum phase space distribution

The near-BH region, the ergo-region (also referred to as the ergo-sphere, but is never actually anything near spherical, see [Figure 5](#)) and its immediate outer environment, is full of a strong magnetic field (near 10^{10} Gauss for a ten Solar mass BH, as observed [Biermann et al., 2018](#)), with a full spectrum of irregularities $I(k)$: Therefore the charged particle momentum phase space distribution is highly an-isotropic, and includes locally an extension to all possible orbits to EeV energies, the maximum allowed by the magnetic field. Magnetic field scattering remixes the orbits continuously in the locally non-rotating frame ([Bardeen et al., 1972](#)); the magnetic field and the particles at all energies refer to the rotation, and so carry angular momentum. Similar to stellar orbits in globular clusters ([King, 1966](#)), where the orbits are cut off by tidal forces, the phase space distribution cuts off where plunge orbits take all particles away. This is also akin to the loss-cone process ([Hills, 1975](#)) where stars are taken out of the distribution by going straight into a BH. So the angular momentum transport is governed on the outside of the ergo-region by a region with the thickness of scrambling the orbits by magnetic fields, which governs the ejection of particles carrying angular momentum, and anchoring the magnetic fields; so the thickness is strongly dependent on particle energy: we call this the outer Penrose zone: This consideration gives the angular momentum loss of the BH together with the ergo-region. The angular momentum transport on the inside of the ergo-region is governed by ubiquitous particle interaction, producing secondary protons and anti-protons with many more pions of either charge. The orbits are also scrambled in this zone by magnetic fields, but also by the new production of secondaries. Many of those particles going into the black hole carry less specific angular momentum than the BH itself ([Bardeen et al., 1972](#)), and so take angular momentum net from the BH. We dub this the inner Penrose zone. The balance between loss towards the outside in the outer Penrose zone and loss to the inside, the BH, on the inside in the inner Penrose zone gives the net angular momentum loss of the BH. At the highest particle energies the outer and inner Penrose zones might touch. Since the transport in this concept is given by secondary particles, the net transport to the outside is visible in the magnetic fields ([Biermann et al., 2018](#)) and also in electron-positron pairs ([Siegert et al., 2016a](#)), and, we posit, in pop 3* of [Gaisser et al. \(2013\)](#), which in this concept should carry an about equal number of anti-protons and protons. We note that all jets carry an electric current, driven by a proton-anti-proton pair plasma with a spectrum of E^{-2} ([Gopal-Krishna and Biermann, 2024](#)) to EeV energies, which we identify here with this CR population, steepened by an ISM Kolmogorov spectrum of magnetic irregularities in the Galactic disk, so 1/3. Variable jets drive an electric field, which upon

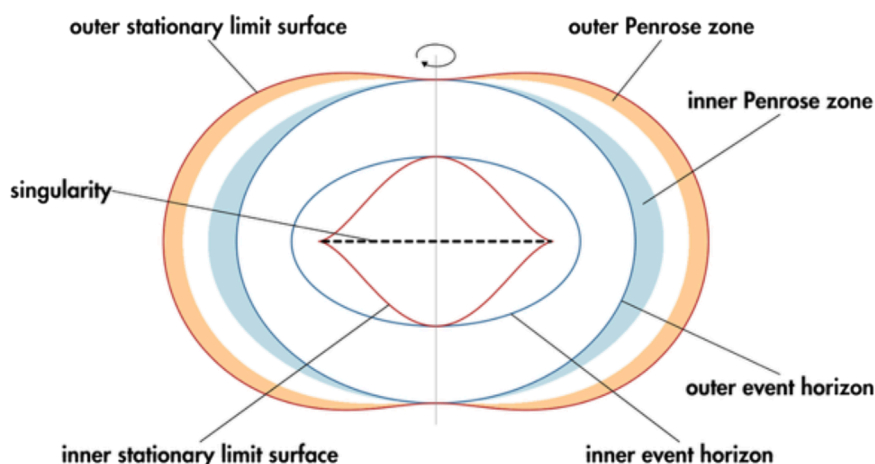


FIGURE 5

The key elements of the Kerr black hole with rotation parameter $a = 0.95$ are represented in a planar section containing the axis of rotation. The infinite curvature ring singularity appears from lateral side view as a segment. This is hidden inside a structure of two horizons, the outer horizon being the boundary of the Kerr black hole. Two stationary limit surfaces (where $g_{tt} = 0$) are positioned inside the inner horizon and outside the outer horizon, respectively. At the outer stationary limit surface the redshift is infinite and photons cannot counterrotate, while inside it they will always corotate, similarly to all the other particles, irrespective of their initial direction. The ergo-region, lying between the outer stationary limit surface and the outer event horizon, contains the outer and inner Penrose zones, attached to these limiting surfaces.

discharge drives particle energies much higher (Gopal-Krishna and Biermann, 2024). Such discharges have been seen ubiquitously as synchrotron radio filaments (Gopal-Krishna and Biermann, 2024; Yusef-Zadeh et al., 2022). One prediction in our model is that pop 3* of Gaissner et al. (2013) should be composed by an equal number of protons and anti-protons, and this may be detectable around and above TeV energies.

In Bardeen et al. (1972) their Figure 3 shows what fraction of velocity phase space - there simplified to equatorial orbits, so planar orbits - goes down into the BH. Because of the scrambling of charged particle orbits by the relatively strong magnetic fields there are in reality no orbits from or to infinity, within an interaction length of the horizon only orbits that either remain in the ergo-region or plunge down into the BH. Further inside the ergo-region all orbits are such that the particles remain in the ergo-region. So as soon as magnetic scattering or new particle creation by collisions puts an orbit into the plunge region of momentum phase space that particle is directly lost. Since this part of phase space is not generally a cone, instead of a “loss-cone” we refer to it as the “plunge region of momentum phase space”. That plunge region of momentum phase space exists only within an interaction length of the horizon, see the equation above, accounting both for magnetic scattering or particle collisions with creation of new particles. The magnetic scattering interaction length is rigidity dependent, depending on the Larmor radius scaling linearly with rigidity, and the spectrum of resonant irregularities $I(k)$. For a spectrum of $I(k) \sim k^{-\beta}$, this gives an interaction length scaling with the power of $2 - \beta$. For a Kolmogorov spectrum this gives an interaction scaling with rigidity to a $1/3$ power, lightning dominated turbulence gives a $5/3$ power, while shock dominated turbulence gives an interaction length independent of rigidity (Allen et al., 2024). Collisions of particles to create new particles, such as lots of pions, or proton-anti-proton pairs, produces the most particles on such an orbit. As both B'

and B^ϕ , the observed components, scale as $\Delta^{1/2}$, the Larmor radius diverges near the horizon, and so the scattering by the magnetic field is weakened; on the other hand, the charged particle density also diverges near the horizon, both clear from the expressions above. For the collision rate between protons with other protons, including secondary protons, to be faster than pion decay implies extraordinary densities, of order 10^{24} cm^{-3} or higher, easily possible with the expression above for the charged particle density. This means that near the horizon the injection of mostly new particles into the plunge orbit part of momentum phase space dominates over pure magnetic field scattering. This has been the main thrust here, that secondary particles go onto plunge orbits, and so determine the spin-down.

5.9.2 Frequency of the Penrose process

In pure spin-down angular momentum transport provides the main constraints:

The data show that the quantity $(B \times r)$ has the value $10^{16 \pm 0.12} \text{ Gauss} \times \text{cm}$ for both red supergiant and blue super-giant RNe (Biermann et al., 2018; Biermann et al., 2019); this value is consistent with the numbers for super-massive black holes (EHT-Coll, 2019b). Using Equation 9 of Weber and Davis (1967) this corresponds, as seen from afar, to an angular momentum transport of $10^{38.4 \pm 0.24} \text{ {ergs}}/\text{s}$ for a 10 Solar mass BH, and using the assumption, that at the outer radius of the ergo-region (at $10^{6.4} \text{ cm}$ on the equator) the radial magnetic field is equal to the tangential field. This is the angular momentum transport just via the magnetic field. This angular momentum transport is enhanced by thermal and non-thermal particles, and similar to the ISM we assume here that non-thermal particles give the same angular momentum transport as the pure magnetic field, and the thermal particles give the same as this sum, the magnetic field and non-thermal particles added together: This gives a factor of $f_{\text{ISM}} = 4$ over the pure magnetic field

case, for a final angular momentum transport of $10^{39.0 \pm 0.24} \{ \text{ergs} \} / \text{s}$. This number has to consistent with what particles transport.

How does this compare with what is carried by particles, also seen from afar? The argument starts with protons and anti-protons, so $10^{-23.8} \text{ g}$, at $10^{6.4} \text{ cm}$ with close to the velocity of light c , so $10^{-6.9} \text{ g cm}^2 \text{ s}^{-1}$ as a base unit of angular momentum. Extending the spectrum to EeV energies gives for an E^{-2} spectrum (Gopal-Krishna and Biermann, 2024) a factor of the natural log of the range, so about $f_{CR} = 10^{1.2}$. Considering that pions result energetically 30 times as often from p-p collisions as proton-anti-proton pairs adds another factor of $f_{\pi^+} = 10^{1.5}$ for a total angular momentum of $10^{-4.2} \text{ g cm}^2 \text{ s}^{-1}$. We will normalize these three factors to their nominal values, and write $f_{ISM} = 4 f_{ISM,0.6}$, $f_{CR} = 10^{1.2} f_{CR,1.2}$, and $f_{\pi^+} = 10^{1.5} f_{\pi^+,1.5}$. So $10^{-4.2} \text{ g cm}^2 \text{ s}^{-1}$ gets a factor of $f_{CR,1.2} f_{\pi^+,1.5}$. What time scale per such step is required to match the observed angular momentum transport? The implied time scale is the Planck time of $\tau_{Pl} = 10^{-43.3} \text{ s}$ (Planck, 1900), which yields here $10^{39.1} \{ \text{ergs} \} / \text{s}$, consistent with the number indicated by magnetic field observations, as derived above. This says, that the Penrose process happens most efficiently for an E^{-2} spectrum (also required for the electric current, and the large Debye length Gopal-Krishna and Biermann, 2024), and equally for each log bin of particle energy in the particle spectrum. It also says, that the Penrose process happens for a BH of any mass at near maximal rotation about 10^{46} times per second in terms of protons/anti-protons, and an order magnitude more often in terms of pions. This relies solely on the production of secondaries via collisions, and no accretion from far outside.

On the basis of observations discussed above we derive therefore the relationship

$$(B \times r)^2 = \frac{f_{CR} f_{\pi^+}}{f_{ISM}} \frac{m_p c}{\tau_{Pl}} \quad (42)$$

for a BH of any mass in nearly maximal rotation, and in pure spin-down, so without any accretion.

The outer radius of the ergo-region drops out, and so this relationship becomes independent of proximity to the BH, as long as the scale is outside the ergo-region. The term with the factors f_{CR} , f_{π^+} , and f_{ISM} , perhaps by coincidence, approximately equals $\{ \hbar c \} / e^2$. The observations leading to this relationship range from a few $M_\odot$, to about $10^{10} M_\odot$.

We emphasize that in this interpretation radio observations of the magnetic field close to what we have proposed are near maximally rotating black holes, require the Planck time to match with protons/anti-protons and pions in angular momentum transport. This interpretation allows to understand the strength of the magnetic field; the magnetic field is determined by this process. This argument is valid for any black hole in near maximal rotation, and without any accretion.

This leads to the question, whether this can be thought of as spontaneous emission of a black hole in the sense of Einstein (1917) and Feynman et al. (1963): Feynman Lectures of Physics, vol. I, p. 42.9). And if so, what qualifies as stimulated emission (see Falcke and Biermann, 1995; Gopal-Krishna and Biermann, 2024)? The magnetic field in terms of $(B \times r)$ is larger by the square-root of the ratio of the power of the source to the minimum power implied here (also observed Punsly and Zhang, 2011; Biermann et al., 2018; Biermann et al., 2019; EHT-Coll, 2019b). Therefore also in that case the Planck time is used.

5.9.3 Circular orbits in the inner Penrose zone

The lowest energies correspond to locally circular orbits in the inner Penrose zone (Bardeen et al., 1972). This zone is governed predominantly by the numerous pions and their decay products; secondary protons and anti-protons feed the acceleration to the maximal energy allowed, but are way down in number. As pion production is energetically about 30 times proton-anti-proton pair production, and pions have about 1/10 the rest mass of protons/anti-protons, it entails that pions are about 300 times as numerous as protons/anti-protons if produced sufficiently fast. Neutrinos escape, but electron/positrons are trapped by the magnetic fields. They lose energy rather quickly, but can also be accelerated again in the bath of many waves. We can derive this temperature crudely as follows: Charged particles are easily thermalized in any post-shock region: if the equation of state is relativistic then the speed of sound is given by $c_{rel}^2 = c^2/3$, so that the typical velocities are some fraction of the speed of light, post-shock easily $c/3$, which for pions corresponds to order 30 MeV. Basically pions dominate the thermodynamics despite their short life-time. This requires that all time scales, like for producing pions, must be faster, and the densities correspondingly high. The conditions that p-p collisions to make proton-anti-proton pairs are faster than pion decay requires densities above $10^{24.5}$ per cc, a charged particle density plausible close to the horizon by the expression above.

5.9.4 Observational tests

This argument, that requires the Planck time, is derived from radio observations and their interpretation.

A priori we do not know, how many of the secondary particles are released to the outside, but in the interpretation, that the pop 3* of Gaisser et al. (2013) and the particles driving an electric current in jets (Gopal-Krishna and Biermann, 2024) corresponds to the ejection of secondary protons and anti-protons from the Penrose zones around young stellar mass BHs, the strongest prediction to test is that AMS may be capable of determining these anti-protons and protons near to and beyond TeV. Annihilation of protons and anti-protons may also be detectable.

The electron-positrons detected by Martin et al. (2010), Prantzos et al. (2011), Siebert et al. (2016a), Siebert et al. (2016b), Prantzos (2017), Mera Evans et al. (2022) may correspond to just the population derived from pion production and decay.

6 Conclusion

In the scenarios proposed here, we predict anti-protons to be seen above TeV energies AMS-Coll. (2016) with the EeV proton component detected in fits of the cosmic ray data in Gaisser et al. (2013), Thoudam et al. (2016), Auger-Coll (2020a). These concepts lead us to a number of predictions and inferences:

- Massive stars, commonly found in multi-star systems, lose orbital angular momentum through magnetic winds.
- This, in turn, allows a tightening of the binary system, and by tidal locking to an increase of rotation. Alternatively the core of the nascent star may rotate fast and remain in fast rotation during its rapid evolution.

- Resulting BHs rotate initially near the maximum allowed value. This phase of high rotation is short-lived.
- RSNe of former Red Super Giant stars and Blue Super Giant stars can be interpreted as winds emanating from the direct environment of the ergo-region of a BH, which rotates near the maximum allowed value.
- The constancy of the value of the quantity $(B \times r)$, being independent of BH mass, in RSNe shows that protons can attain EeV energies.
- The quantity $(B \times r)$ gives an angular momentum loss time scale of the BH of $\sim 10^{3.7} \text{ yrs} (M_{\text{BH}}/M_{\odot})$, so is proportional to the mass of the BH, here scaled to one Solar mass. For super-massive BHs we obtain the same value of the quantity $(B \times r)$, directly from M87 observations (EHT-Coll, 2019b), and indirectly from the minimum power observed (Punsly and Zhang, 2011). The time scale of angular momentum loss exceeds the age of the universe for any such BH of mass larger than $10^{6.5} M_{\odot}$, assuming it started at near maximal rotation. This value is remarkably close to the mass of our Galactic Center BH (EHT-Coll, 2019b). It follows that without spin-up intermediate mass BH are expected to rotate slowly (Fuller and Lu, 2022).
- This quantity leads to a power outflow of $\sim 10^{42.8} \text{ erg/s}$, independent of BH mass. This is seen for low power radio galaxies Punsly and Zhang (2011). For stellar mass BHs this is far above the Eddington power.
- This power outflow comes purely from spin-down (Blandford and Znajek, 1977), and is thus a minimum, matching observations of radio-quasars (Punsly and Zhang, 2011).
- The wind emanating from the ergo-region injects a CR population with an observed spectrum of $E^{-7/3}$ (due to transport out of the Galaxy, pop 3* in Gaisser et al. (2013); Table 3) and a maximum energy at EeV level. This population is predicted to show a fraction of anti-protons, half. At such a high charged particle density as required to make anti-protons, all higher mass nuclei will be destroyed by spallation; this component is only protons and anti-protons in our proposal. This directly matches the argument about electric currents in jets being driven by a proton-anti-proton plasma with a spectrum of E^{-2} (Gopal-Krishna and Biermann, 2024). This is in addition to the stronger CR flux of all elements which is produced by SN-shocks (pop 1, 2 and 3 in Gaisser et al. (2013), Table 2). This destruction of heavier nuclei is actually a consistency check of our model, since the Gaisser et al. model (Gaisser et al., 2013) does not show such a heavy nuclei component, with this spectrum $E^{-7/3}$.
- This model provides a floor to the anti-proton spectrum seen by AMS and limits determined by HAWC AMS-Coll. (2016), HAWC-Coll. (2018) in the range of GeV to TeV. A consequence is that this component of the anti-protons should show a straight spectrum from near TeV energies all the way to EeV energies, with a $E^{-7/3}$ power law throughout.
- The model suggests that in the ergo-region there is a cascading, collisional production of energetic particles, producing an abundance of secondaries. An electron/positron plasma is a primary product from these collisions. These secondaries produce strong drift currents, and exchange energy and

angular momentum with the magnetic field (Gopal-Krishna and Biermann, 2024).

- The cascading might lead to a much higher production of anti-protons and protons than the number of protons actually accreted from far outside. Most of the anti-protons get annihilated in collisions with protons. In such a reaction, large numbers of neutrinos are produced, and those which escape can remove angular momentum. This could lead to an efficient reduction of rotational energy of the BH. This is possibly detectable as neutrinos with energies near GeV.
- This scenario can be connected to a concept of inner and outer Penrose zones in the ergo-region. The observed numbers for the magnetic field imply the Planck time as the governing time scale: A BH rotating near maximum can accept a proton of low specific angular momentum per log bin of energy with the associated pions every Planck time.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

MA: Writing–review and editing. PB: Writing–original draft, Writing–review and editing. AC: Writing–review and editing. RC: Writing–review and editing. DF: Writing–review and editing. LG: Writing–review and editing. G-K: Writing–review and editing. BH: Writing–review and editing. IJ: Writing–review and editing. Gopal-Krishna: Writing–review and editing. PJ: Writing–review and editing. PK: Writing–review and editing. EK: Writing–review and editing. AM: Writing–original draft, Writing–review and editing. E-SS: Writing–review and editing. TS: Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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