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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 an 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 Shaviv, 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

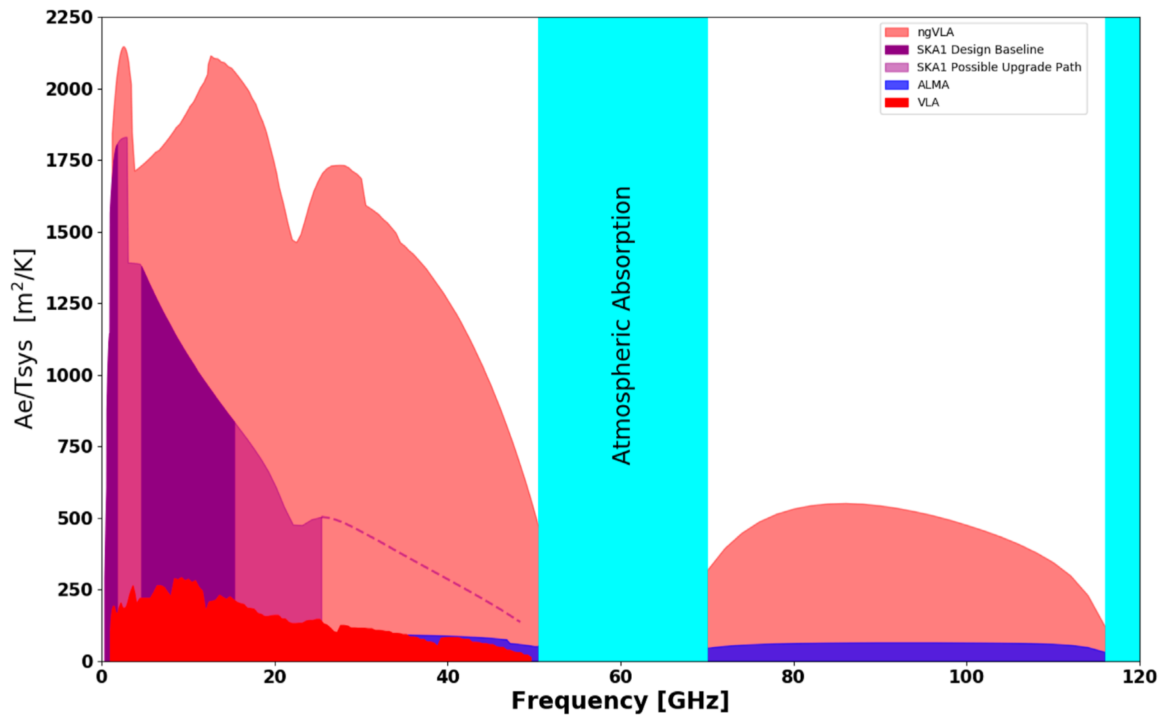

FIGURE 1
This Figure is an updated version of Figure 9 in Selina et al. (2018). The effective collecting area for the ngVLA is plotted versus frequency and compared to that for other existing (VLA and ALMA) or planned (SKA; Braun et al., 2019) facilities. Compared to the VLA, the ngVLA will have 10×the 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 deg^{2}region (i.e., the localization uncertainty expected by gravitational wave detectors when ngVLA is operational) to a depth of ~1 μJy/bm at 2.5 GHz in ~10 hrs.

next-generation, ground-based gravitational-wave detectors such as Cosmic Explorer and the Einstein Telescope (≈10× 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

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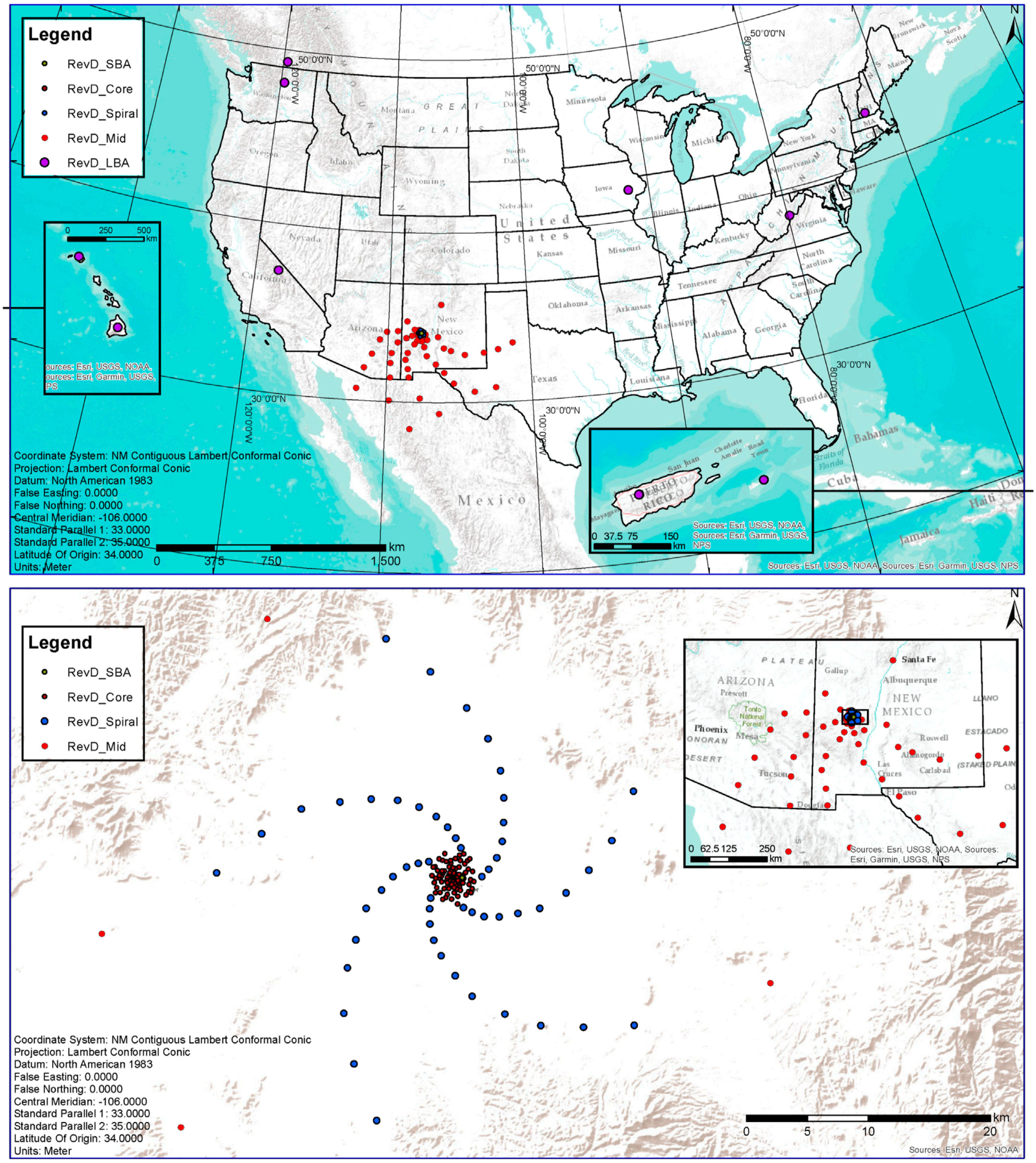

FIGURE 2
This Figure is reproduced from Murphy (2022). Top: A potential configuration layout for the ngVLA showing all 263 antennas spread across the North American Continent. The Array is centered at the current VLA site on the plains of San Agustin in New Mexico. The legend associates each antenna 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.

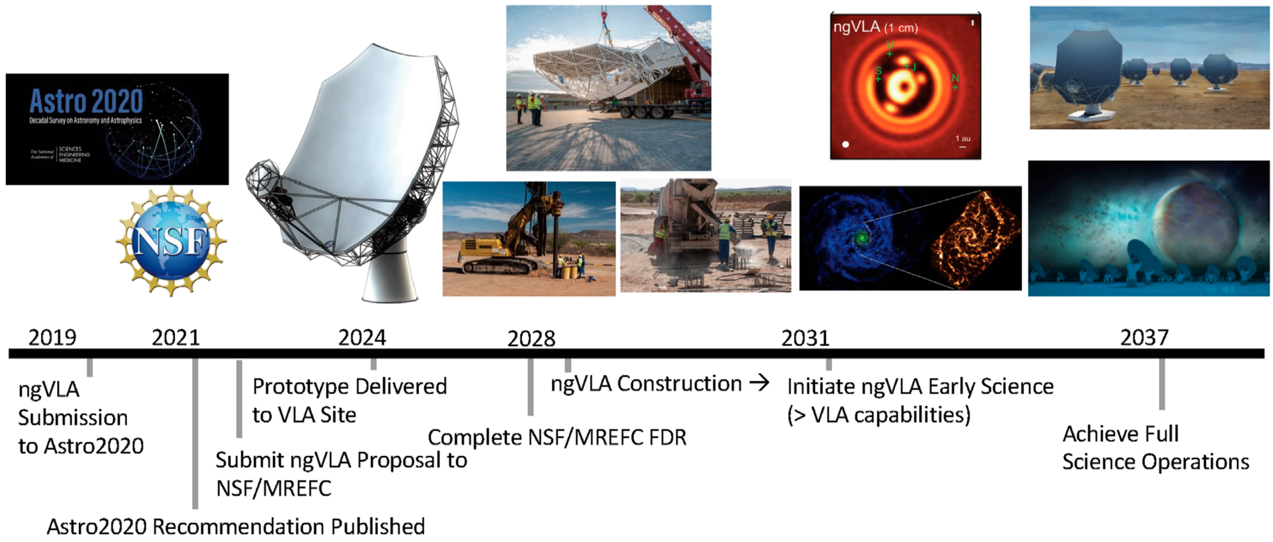

FIGURE 3
Projected timeline of the ngVLA, showing key milestones on the path to its full scientific capability. This Figure is reproduced from https://ngvla.nrao.edu/download/MediaFile/283/original. Note that dates are tentative and subject to change.

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 Kheirandish, 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 TXS 0506 + 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 TXS 0506 + 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 TXS 0506 + 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 ≈10× 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 k m (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 band[1].

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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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