Synergies between Cosmic Explorer and the ngVLA

Eric Murphy (NRAO); Tony Beasley (NRAO); Alessandra Corsi (TTU); Rachel Osten (STScI, JHU)

SUMMARY

We highlight the scientific synergies between the next generation gravitational wave detector Cosmic Explorer (CE; Evans et al. 2021), and the next generation Very Large Array (ngVLA; Murphy et al. 2018). The ngVLA is being designed as a transformative radio array providing an order of magnitude improvement in both sensitivity and angular resolution over existing radio facilities. It is envisioned to start full operations around ∼2038 (Figure 1), a timescale well aligned with that of CE. CE and the ngVLA can bring multi-messenger astronomy to its full potential —a priority recognized by the National Academies' 2020 Decadal Survey on Astronomy and Astrophysics.

Key question(s) and impact of the ngVLA-CE tandem

How common is GW170817? Building a golden sample of GW170817-like events in the local universe — CE is expected to detect $\approx$ 20 binary neutron star (BNS) mergers per year at $z \lesssim 0.06$ ($\lesssim$ 270 Mpc) with localization areas $\lesssim 0.1\,\mathrm{deg}^2$ (Evans et al. 2021; Figure 2, left), optimally matched to the ngVLA FOV at 2.5 GHz ($\approx 0.17\,\mathrm{deg}^2$ [1]). For BNSs located at $\lesssim$ 270 Mpc, the ngVLA can detect GW170817-like jets (2.5 GHz peak isotropic-equivalent luminosity density of $\approx 2 \times 10^{26}$ erg/s/Hz; Alexander et al. 2017; Hallinan et al. 2017; K. P. Mooley, E. Nakar, et al. 2018; Makhathini et al. 2021) at the $\gtrsim 10\sigma$ level in just 1 hr. BNSs at $\lesssim$ 270 Mpc are also well within the estimated reach of 1-m class OIR telescopes for kilonova detections ($\lesssim$ 400 Mpc; Petrov et al. 2022). Hence, CE working with the ngVLA and other facilities across the electromagnetic spectrum will be able to place each BNS on its multi-messenger matrix (Figure 3), linking BNS progenitors and remnants (stable NSs, unstable NSs, and promptly-formed BHs) to the properties of their slow (optical kilonova) and fast ejecta (radio and X-ray emitting jets and kilonova tails). This will be done free of selection biases related to using optical localizations to enable follow-up from radio to X-rays. At a rate of 20 events per year, CE can build a golden statistical sample of multi-messenger events that can be used to shed light on how jets are formed and launched in BNSs, how the presence/absence of successful jets is related to the nature of the merger remnants (stable NSs versus promptly-formed BHs), and how the structure (energy and speed profile as a function of polar angle) of these jets is shaped by the kilonova ejecta itself (Kenta Hotokezaka and Piran 2015; Lazzati, Perna, et al. 2018; Lazzati and Perna 2019).

Kilonova ejecta radio afterglows and nature of the merger remnant — Deep ngVLA observations (say 30 hrs on source per epoch) would enable studies of GW170817-like ejecta up to several years after the merger with 3σ sensitivities of $\approx 0.1\,\mu$Jy. This will extend to distances $\lesssim$ 220 Mpc the model constraints set by current searches for a kilonova radio afterglow in GW170817 (40 Mpc; Balasubramanian, Corsi, Kunal P. Mooley, Brightman, et al. 2021; Balasubramanian, Corsi, Kunal P. Mooley, Kenta Hotokezaka, et al. 2022). The detection of a late-time kilonova radio afterglow (Ehud Nakar and Piran 2011; Kenta Hotokezaka, Kiuchi, et al. 2018; Kathirgamaraju, Giannios, and Beniamini 2019) would help constrain the NS EoS (Nedora, Radice, et al. 2021) and the nature of the merger remnant (NS versus prompt BH formation; e.g., Nedora, Radice, et al. 2021; Sarin et al. 2022). See Figure 4 (left) for the GW170817 example.

[1] https://ngvla.nrao.edu/system/media_files/binaries/130/original/ngVLA-Project-Summary_Jan2019.pdf?1548895473

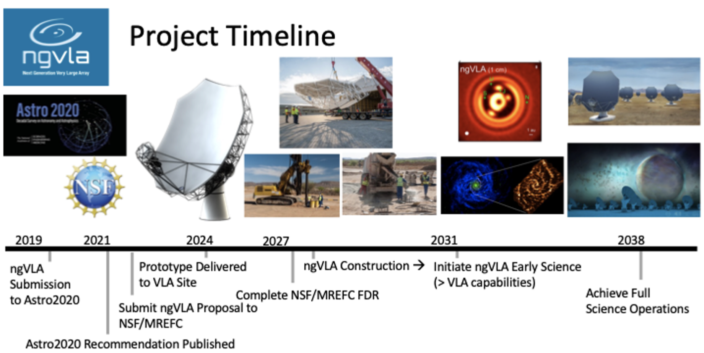
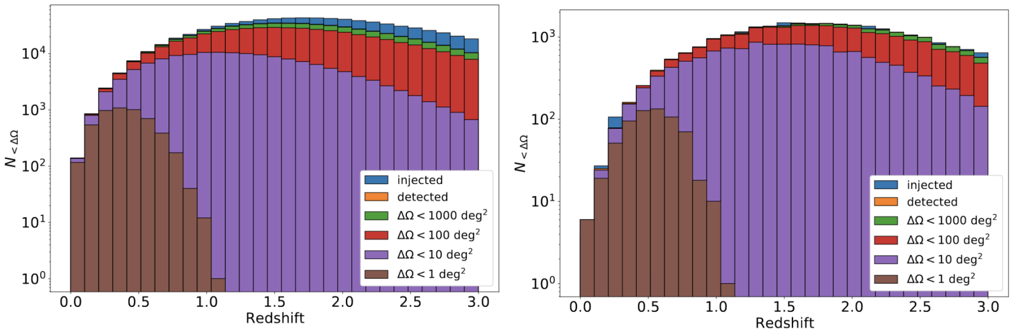


Figure 1: *ngVLA projected timeline. The ngVLA should achieve full science operations around the time that CE becomes operational. It will have ten times the sensitivity of the VLA (cm wavelengths) and ALMA (mm wavelengths), and continental-scale baselines providing sub-milliarcsecond-resolution. The ngVLA bridges the gap between ALMA and the Square Kilometer Array (longer wavelengths).*



(e) ET+2CE, all angles

(f) ET+2CE, θ_v < 15°

Figure 2: *Figure from Ronchini et al. 2022. Redshift distribution of sky-localization uncertainties (90% credible region) for the ET+2CE network in 1 year at 85% duty cycle. All (small) BNSs viewing angles are plotted on the left (right).*

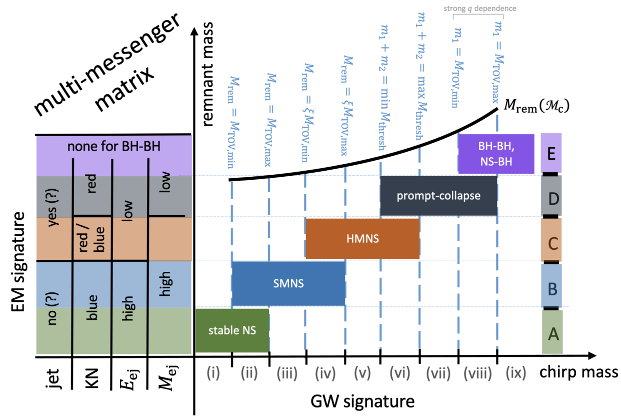


Figure 3: *Figure from Margalit and Metzger 2019. "Multi-Messenger Matrix" relating the range of expected electromagnetic counterparts of binary neutron star mergers (vertical axis) to the binary mass (horizontal axis) and merger remnants leading to qualitatively different predictions for the luminosity, color, and kinetic energy of the kilonova emission, as well as the possible presence or absence of ultra-relativistic GRB jets and their energy and speed profiles.*

Standard siren cosmology with CE+ngVLA — The long-baseline configuration of the ngVLA will provide enough sensitivity and resolution for mapping directly the radio ejecta of BNS mergers as bright as GW170817 ($\approx 100\,\mu$Jy). Visibility analysis (Corsi et al. 2018) and measurement of the superluminal motion of the radio emission centroid (K. P. Mooley, Deller, et al. 2018; Ghirlanda et al. 2019; Figure 4, right) can distinguish off-axis collimated outflows from isotropic ones. As demonstrated in the case of GW170817, these types of measurements are critical to remove degeneracies between ejecta structure and viewing angle (Nedora, Dietrich, and Shibata 2023) and help improve the impact of gravitational wave observations on standard siren cosmology (K. Hotokezaka et al. 2019).

Linking BNS progenitors to their relativistic jets up to the peak of star formation — A network of CE detectors will measure the gravitational wave emission from every NS in the universe up to distances comparable to the peak of star formation or $z \approx 2$. In particular, hundreds to thousands of BNS gravitational wave detections per year within such redshift will be from small viewing angle events with gravitational wave localizations smaller that $10\,\mathrm{deg}^2$ (Figure 2, right). These systems will likely have radio afterglows comparable to those of short GRBs and hence $500 - 10^4$ times more luminous (isotropic-equivalent) than GW170817 (or radio luminosity densities in between $10^{29} - 2 \times 10^{30}\,\mathrm{erg\,s^{-1}\,Hz^{-1}}$; Fong et al. 2017). The ngVLA will map a $\lesssim 10\,\mathrm{deg}^2$ region to a depth of $\lesssim 1\,\mu$Jy (1σ) at 2.5 GHz within a $\lesssim 10$ hr epoch. Hence, nearly on-axis BNSs could be detectable at the $\gtrsim 5\sigma$ level for distances $\lesssim 4 - 18$ Gpc ($z \approx 0.7 - 2.3$).

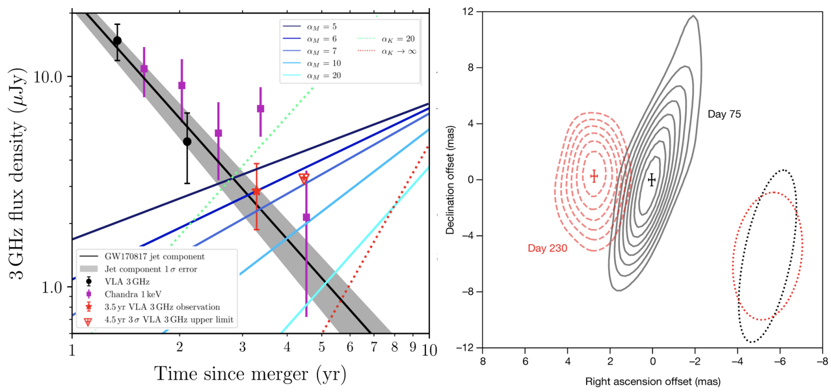


Figure 4: *LEFT: Figure from Balasubramanian, Corsi, Kunal P. Mooley, Kenta Hotokezaka, et al. 2022. Different kilonova radio afterglow models (solid lines of different shades of blue) are shown for GW170817. These models correspond to different energy-velocity profiles of the kilonova ejecta. For an equal mass ratio binary, a steeper energy-velocity distribution larger values of α_M in the Figure) correlates with a stiffer NS EoS for a given cold, non-rotating maximum mass . RIGHT: Figure from K. P. Mooley, Deller, et al. 2018. Superluminal motion of the GW170817 radio centroid.*

Bibliography

[1] K. D. Alexander et al. "The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. VI. Radio Constraints on a Relativistic Jet and Predictions for Late-time Emission from the Kilonova Ejecta". In: *ApJL* 848.2, L21 (Oct. 2017), p. L21. DOI: 10.3847/2041-8213/aa905d. arXiv: 1710.05457 [astro-ph.HE].

[2] Arvind Balasubramanian, Alessandra Corsi, Kunal P. Mooley, Murray Brightman, et al. "Continued Radio Observations of GW170817 3.5 yr Post-merger". In: *ApJL* 914.1, L20 (June 2021), p. L20. DOI: 10.3847/2041-8213/abfd38. arXiv: 2103.04821 [astro-ph.HE].

[3] Arvind Balasubramanian, Alessandra Corsi, Kunal P. Mooley, Kenta Hotokezaka, et al. "GW170817 4.5 Yr After Merger: Dynamical Ejecta Afterglow Constraints". In: *ApJ* 938.1, 12 (Oct. 2022), p. 12. DOI: 10.3847/1538-4357/ac9133. arXiv: 2205.14788 [astro-ph.HE].

[4] Alessandra Corsi et al. "Science with an ngVLA: Compact binary mergers as traced by gravitational waves". In: *arXiv e-prints*, arXiv:1810.07544 (Oct. 2018), arXiv:1810.07544. DOI: 10.48550/arXiv.1810.07544. arXiv: 1810.07544 [astro-ph.IM].

[5] Matthew Evans et al. "A Horizon Study for Cosmic Explorer: Science, Observatories, and Community". In: *arXiv e-prints*, arXiv:2109.09882 (Sept. 2021), arXiv:2109.09882. DOI: 10.48550/arXiv.2109.09882. arXiv: 2109.09882 [astro-ph.IM].

[6] W. Fong et al. "The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. VIII. A Comparison to Cosmological Short-duration Gamma-Ray Bursts". In: *ApJL* 848.2, L23 (Oct. 2017), p. L23. DOI: 10.3847/2041-8213/aa9018. arXiv: 1710.05438 [astro-ph.HE].

[7] G. Ghirlanda et al. "Compact radio emission indicates a structured jet was produced by a binary neutron star merger". In: *Science* 363.6430 (Mar. 2019), pp. 968–971. DOI: 10.1126/science.aau8815. arXiv: 1808.00469 [astro-ph.HE].

[8] G. Hallinan et al. "A radio counterpart to a neutron star merger". In: *Science* 358.6370 (Dec. 2017), pp. 1579–1583. DOI: 10.1126/science.aap9855. arXiv: 1710.05435 [astro-ph.HE].

[9] K. Hotokezaka et al. "A Hubble constant measurement from superluminal motion of the jet in GW170817". In: *Nature Astronomy* 3 (July 2019), pp. 940–944. DOI: 10.1038/s41550-019-0820-1. arXiv: 1806.10596 [astro-ph.CO].

[10] Kenta Hotokezaka, Kenta Kiuchi, et al. "Synchrotron Radiation from the Fast Tail of Dynamical Ejecta of Neutron Star Mergers". In: *ApJ* 867.2, 95 (Nov. 2018), p. 95. DOI: 10.3847/1538-4357/aadf92. arXiv: 1803.00599 [astro-ph.HE].

[11] Kenta Hotokezaka and Tsvi Piran. "Mass ejection from neutron star mergers: different components and expected radio signals". In: *MNRAS* 450.2 (June 2015), pp. 1430–1440. DOI: 10.1093/mnras/stv620. arXiv: 1501.01986 [astro-ph.HE].

[12] Adithan Kathirgamaraju, Dimitrios Giannios, and Paz Beniamini. "Observable features of GW170817 kilonova afterglow". In: *MNRAS* 487.3 (Aug. 2019), pp. 3914–3921. DOI: 10.1093/mnras/stz1564. arXiv: 1901.00868 [astro-ph.HE].

[13] Davide Lazzati and Rosalba Perna. "Jet-Cocoon Outflows from Neutron Star Mergers: Structure, Light Curves, and Fundamental Physics". In: *ApJ* 881.2, 89 (Aug. 2019), p. 89. DOI: 10.3847/1538-4357/ab2e06. arXiv: 1904.08425 [astro-ph.HE].

[14] Davide Lazzati, Rosalba Perna, et al. "Late Time Afterglow Observations Reveal a Collimated Relativistic Jet in the Ejecta of the Binary Neutron Star Merger GW170817". In: *Phys.Rev.Lett.* 120.24, 241103 (June 2018), p. 241103. DOI: 10.1103/PhysRevLett.120.241103. arXiv: 1712.03237 [astro-ph.HE].

[15] S. Makhathini et al. "The Panchromatic Afterglow of GW170817: The Full Uniform Data Set, Modeling, Comparison with Previous Results, and Implications". In: *ApJ* 922.2, 154 (Dec. 2021), p. 154. DOI: 10.3847/1538-4357/ac1ffc. arXiv: 2006.02382 [astro-ph.HE].

[16] Ben Margalit and Brian D. Metzger. "The Multi-messenger Matrix: The Future of Neutron Star Merger Constraints on the Nuclear Equation of State". In: *ApJL* 880.1, L15 (July 2019), p. L15. DOI: 10.3847/2041-8213/ab2ae2. arXiv: 1904.11995 [astro-ph.HE].

[17] K. P. Mooley, A. T. Deller, et al. "Superluminal motion of a relativistic jet in the neutron-star merger GW170817". In: *Nature* 561.7723 (Sept. 2018), pp. 355–359. DOI: 10.1038/s41586-018-0486-3. arXiv: 1806.09693 [astro-ph.HE].

[18] K. P. Mooley, E. Nakar, et al. "A mildly relativistic wide-angle outflow in the neutron-star merger event GW170817". In: *Nature2018b* 554.7691 (Feb. 2018), pp. 207–210. DOI: 10.1038/nature25452. arXiv: 1711.11573 [astro-ph.HE].

[19] E. J. Murphy et al. "The ngVLA Science Case and Associated Science Requirements". In: *Science with a Next Generation Very Large Array*. Ed. by Eric Murphy. Vol. 517. Astronomical Society of the Pacific Conference Series. Dec. 2018, p. 3. DOI: 10.48550/arXiv.1810.07524. arXiv: 1810.07524 [astro-ph.IM].

[20] Ehud Nakar and Tsvi Piran. "Detectable radio flares following gravitational waves from mergers of binary neutron stars". In: *Nature* 478.7367 (Oct. 2011), pp. 82–84. DOI: 10.1038/nature10365. arXiv: 1102.1020 [astro-ph.HE].

[21] Vsevolod Nedora, Tim Dietrich, and Masaru Shibata. "Synthetic radio images of structured GRB and kilonova afterglows". In: *arXiv e-prints*, arXiv:2302.12850 (Feb. 2023), arXiv:2302.12850. DOI: 10.48550/arXiv.2302.12850. arXiv: 2302.12850 [astro-ph.HE].

[22] Vsevolod Nedora, David Radice, et al. "Dynamical ejecta synchrotron emission as a possible contributor to the changing behaviour of GRB170817A afterglow". In: *MNRAS* 506.4 (Oct. 2021), pp. 5908–5915. DOI: 10.1093/mnras/stab2004. arXiv: 2104.04537 [astro-ph.HE].

[23] Polina Petrov et al. "Data-driven Expectations for Electromagnetic Counterpart Searches Based on LIGO/Virgo Public Alerts". In: *ApJ* 924.2, 54 (Jan. 2022), p. 54. DOI: 10.3847/1538-4357/ac366d. arXiv: 2108.07277 [astro-ph.HE].

[24] S. Ronchini et al. "Perspectives for multimessenger astronomy with the next generation of gravitational-wave detectors and high-energy satellites". In: *A&A* 665, A97 (Sept. 2022), A97. DOI: 10.1051/0004-6361/202243705. arXiv: 2204.01746 [astro-ph.HE].

[25] Nikhil Sarin et al. "On the diversity of magnetar-driven kilonovae". In: *MNRAS* 516.4 (Nov. 2022), pp. 4949–4962. DOI: 10.1093/mnras/stac2609. arXiv: 2205.14159 [astro-ph.HE].