Synergies between Cosmic Explorer and the ngVLA

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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 in a network with the European Einstein Telescope (ET) is expected to detect a few 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 a few 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) 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

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

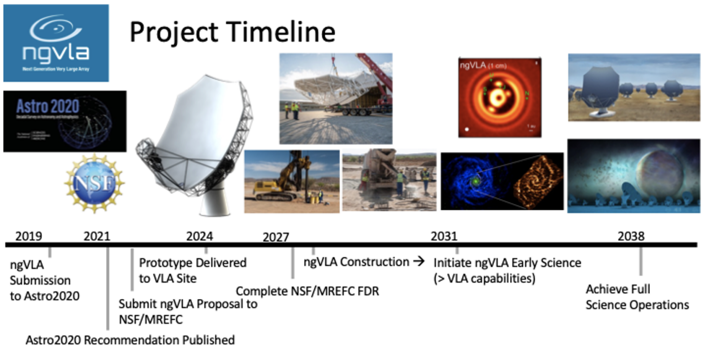
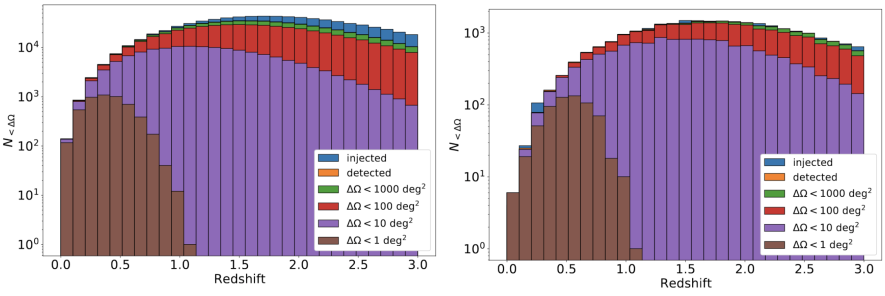


Figure 1: *ngVLA projected timeline. The ngVLA should achieve full science operations around the time that CE becomes operational. It will have ten times the sensitivity of the VLA (cm wavelengths) and ALMA (mm wavelengths), and continental-scale baselines providing sub-milliarcsecond-resolution. The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



(e) ET+2CE, all angles

(f) ET+2CE, $\theta_v < 15°$

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).*

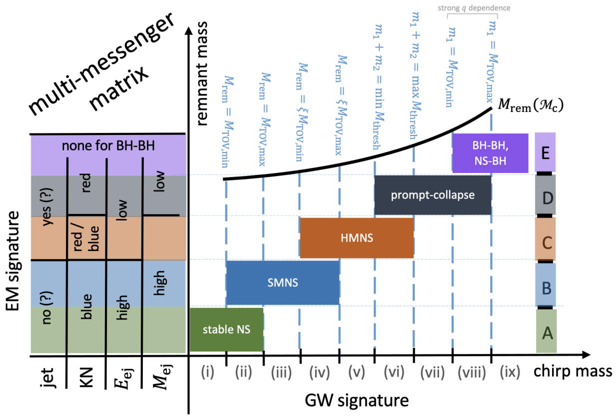


Figure 3: *Figure from Margalit and Metzger 2019. "Multi-Messenger Matrix" relating the range of expected electromagnetic counterparts of binary neutron star mergers (vertical axis) to the binary mass (horizontal axis) and merger remnants leading to qualitatively different predictions for the luminosity, 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.*

formation; e.g., Nedora, Radice, et al. 2021; Sarin et al. 2022). See Figure 4 (left) for the GW170817 example.

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 plus the ET 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 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 $10^{29} - 2 \times 10^{30}$ erg s^{-1} Hz^{-1}; Fong et al. 2017). The ngVLA will map a $\lesssim 10$ 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 ($z \approx 0.7 - 2.3$).

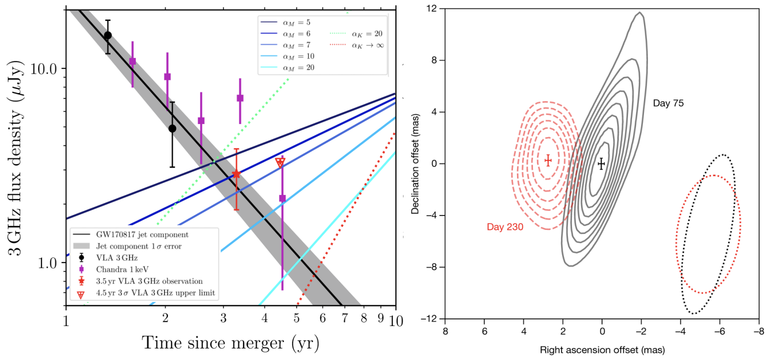


Figure 4: *LEFT: Figure from Balasubramanian, Corsi, Kunal P. Mooley, Kenta Hotokezaka, et al. 2022. Different kilonova radio afterglow models (solid lines of different shades of blue) are shown for GW170817. These models correspond to different energy-velocity profiles of the kilonova ejecta. For an 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.*

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