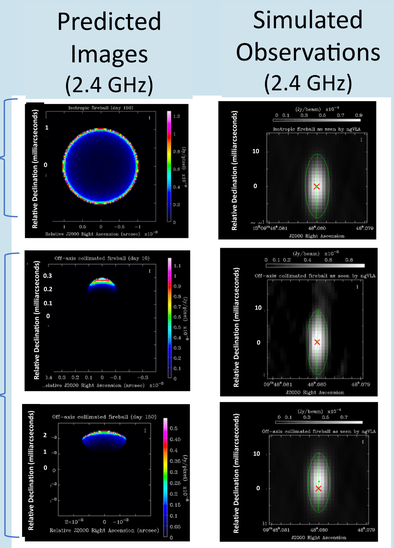
Formation and Evolution of Black Holes in the Multi-Messenger Astronomy Era

T. J. W. Lazio (Jet Propulsion Laboratory, California Institute of Technology), K. Alatalo (STScI), L. Blecha (Florida), B. D. Boizelle (Texas A&M), G. C. Bower (ASIAA), J. Braatz (NRAO), T. Bogdanovic (Georgia Institute of Technology), W. Brisken (NRAO), S. Burke-Spolaor (WVU), D. Carbone (Texas Tech), L. Chomiuk (Michigan State), F. Civano (Harvard-Smithsonian CfA), J. Comerford (Univ. Colorado, Boulder), J. Condon (NRAO), D. L. Coppejans (Northwestern), A. Corsi (Texas Tech), J. Darling (Univ. Colorado, Boulder), T. A. Davis (Cardiff), D. A. Frail (NRAO), K. Hall (Johns Hopkins), G. Hallinan (California Institute of Technology), J. J. Harwood (Hertfordshire), P. Kharb (NCRA-TIFR), A. Kimball (NRAO), A. Kirkpatrick (Kansas; Yale), E. G. Körding (Radboud), M. Lacy (NRAO), D. Lazzati (Oregon State), M. L. Lister (Purdue), X. Liu (UIUC), T. J. Maccarone (Texas Tech), B. D. Metzger (Columbia Astrophysics Lab.), J. C. A. Miller-Jones (ICRAR-Curtin), D. Mukherjee (Univ. degli Studi di Torino), K. Nyland (NRL), R. O'Shaughnessy (Rochester Institute of Technology), B. J. Owen (Texas Tech), P. Patil (NRAO), D. Pesce (NRAO; UVa), R. M. Plotkin (ICRAR-Curtin), I. Prandoni (INAF), V. Ravi (California Institute of Technology), M. Reid (Harvard-Smithsonian CfA), A E. Reines (Montana State), W Rujopakarn (Chulalongkorn), M. P. Rupen (Herzberg Astronomy & Astrophysics), D. J. Sand (Arizona), Y. Shen (UIUC), J. J. Simon (Jet Propulsion Laboratory, California Institute of Technology), G. R. Sivakoff (Alberta), J. Stader (Michigan State), G. B. Taylor (UNM), S. R. Taylor (California Institute of Technology), S. van Velzen (New York Univ.)

Merging Stellar Mass Black Holes, Gravitational Waves, and Electromagnetic Counterparts

A radio afterglow has been observed from the neutron star-neutron star (NS-NS) merger GW 170817. VLA observations have been instrumental in constraining the properties of the ejecta, and the ngVLA would be able to expand the accessible volume dramatically and resolve the afterglows from NS-NS and black hole-neutron star (BH-NS) mergers.

Imaging with the ngVLA would determine the speed distribution and distinguish between collimated relativistic fireballs observed off-axis and quasi-spherical relativistic ejecta. The magnetic field structure can be further constrained via full polarimetric imaging. Consider two extreme cases likely to "bracket" the possible outcomes:



Isotropic relativistic ejecta would appear in ngVLA images as ring-like: brighter near edges and dimmer near center

Isotropic merger ejecta at day 150 with energy $E_{iso} = 2.5 \times 10^{49}$ erg, expanding into medium of density $n = 6.8 \times 10^{-4}$ cm^{-3}

Collimated relativistic jets, having top-hat ejecta distributions, and with jet axes misaligned to observer would evolve in ngVLA images, with centroids of emission moving as jets propagate

Top-hat collimated (23°) fireball observed off-axis (39°) at day 10 with energy $E = 5.7 \times 10^{50}$ erg, ambient density $n = 3.2 \times 10^{-4}$ cm^{-3}

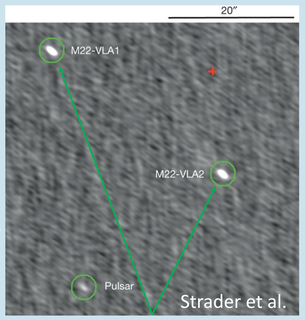
Same as Center row but as observed at day 150

Corsi et al., ngVLA Science Book

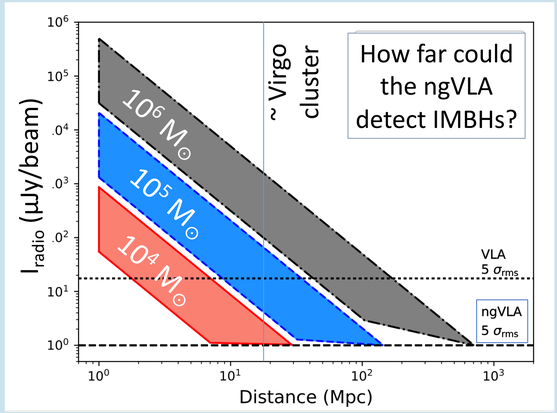
Large populations of stellar-mass and intermediate-mass black holes (IMBHs) could exist in local Universe:

- Identification of BHs in globular clusters could help resolve the origin of field vs. cluster for BH-BH merger events detected by LIGO-Virgo
- Do IMBHs exist?

The VLA has found BH candidates in globular clusters; the ngVLA would find fainter BHs in Galactic globular clusters and probe nearby dwarf galaxies. With long baselines, the ngVLA could measure proper motions.



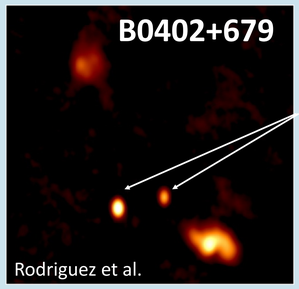
Candidate BHs in globular cluster M22



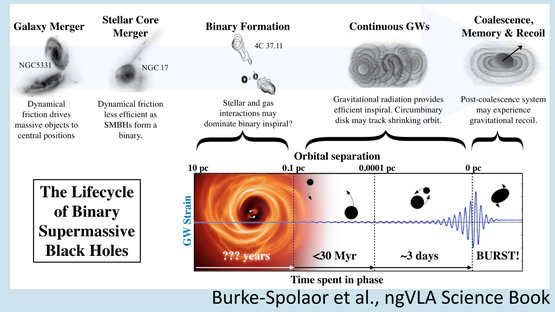
The ngVLA could detect IMBHs out to Virgo cluster for 10^4 $M_\odot$ IMBHs, out to 1 Gpc for 10^6 $M_\odot$ IMBHs. Assumes 1 hr observation at 8 GHz, IMBH with 2 keV-10 keV X-ray flux > 10^{-15} erg s^{-1} cm^{-2} and 10^{-5} L_{edd} < L_X < 10^{-3} L_{edd} (Plotkin & Reines, ngVLA Science Book)

Supermassive Black Hole Mergers

Dual (≲ 10 kpc separation) and binary (≲ 10 pc separation) supermassive black holes (SMBHs) should form during major galaxy mergers; in late stages of evolution, they should produce nHz and μHz gravitational waves, and, potentially, electromagnetic bursts as they merge.



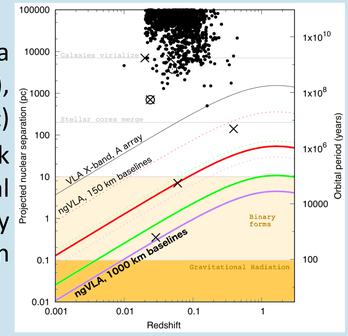
7 pc (*projected*) separation SMBH pair found with VLBA
How many more can be found? ngVLA would be prime search machine.



Burke-Spolaor et al., ngVLA Science Book

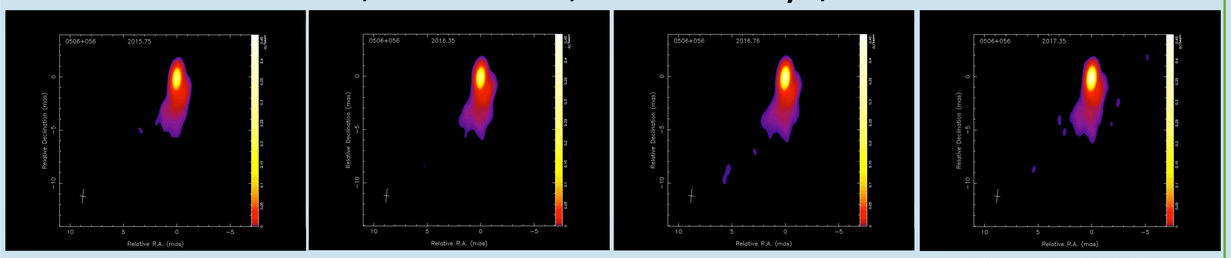
SMBH pairs mark on-going galaxy mergers and imminent SMBH coalescences and are strong probes of redshift-dependent merger rates, occupation fractions of dual SMBHs in galaxies, and post-merger evolution.

Dual AGN discovered via radio (X), X-ray (circle), optical/near-IR (dot)
Horizontal lines mark (approximate) critical stages in binary formation and evolution



Curves indicate ngVLA resolution at 10 GHz (**red**), 50 GHz (**green**), and 120 GHz (**purple**); dashed curves show resolution of 150 km baselines, solid curves show 1000 km extended baselines. The ngVLA has potential to resolve multi-messenger SMBH binaries in nearby Universe (curves that cross dark yellow region) at flux density levels inaccessible to the VLBA.

Black Holes, Neutrinos, Cosmic Rays, and Photons



Lister et al.; MOJAVE Program

TXS 0506+056, blazar associated with the TeV neutrino event IceCube 170922A. This sequence of VLBA images shows evolution of jet structure at 6 mon. intervals leading up to the neutrino event.

The ngVLA could be used to follow-up future high-energy neutrinos, distinguishing between potential candidate sources; investigating the jet structure of candidate sources, particularly for assessing whether jets directed toward the Earth (as in the case of TXS 0506+056) is required for detection of high-energy neutrinos; or tracking flux density changes indicative of potential future neutrinos from a candidate source.

The ngVLA could be used for similar future investigations of the sources of ultra-high energy cosmic rays.

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