Science with a next-generation Very Large Array

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Summary

Inspired by dramatic discoveries from the Jansky VLA, ALMA, and the VLVA, a plan to pursue a large collecting area radio telescope that will open new discovery space from proto-planetary disks to distant galaxies is being developed by NRAO and the science community. Building on the superb cm observing conditions and existing infrastructure of the VLA site, the current vision of the ngVLA will be an interferometric array with more than 10 times the sensitivity and spatial resolution of the current VLA and ALMA, that will operate at frequencies spanning ~1.2. – 116 GHz.

The ngVLA will be optimized for observations at wavelengths between the exquisite performance of ALMA at submm wavelengths, and the future SKA-1 at decimeter to meter wavelengths, thus lending itself to be highly complementary with these facilities. As such, the ngVLA will open a new window on the universe through ultra-sensitive imaging of thermal line and continuum emission down to milliarcecond resolution, as well as deliver unprecedented broad band continuum polarimetric imaging of non-thermal processes.

The ngVLA Science Working Groups have identified five Key Science Goals for the ngVLA through a community-driven exercise led by the ngVLA Science Advisory Council.

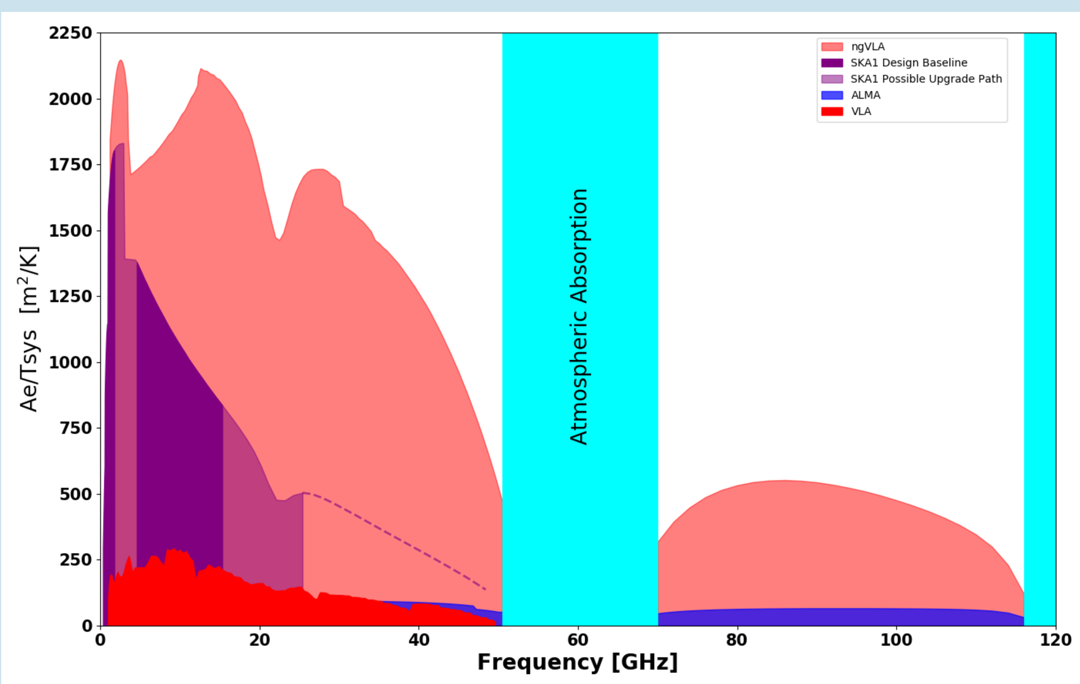


Figure 1: A comparison of sensitivity for a number of radio, mm, and sub-mm dish arrays expected to be operational in the 2030's. The ngVLA nicely sits between the decimetric and submm wavelengths covered by SKA1 and ALMA, respectively.

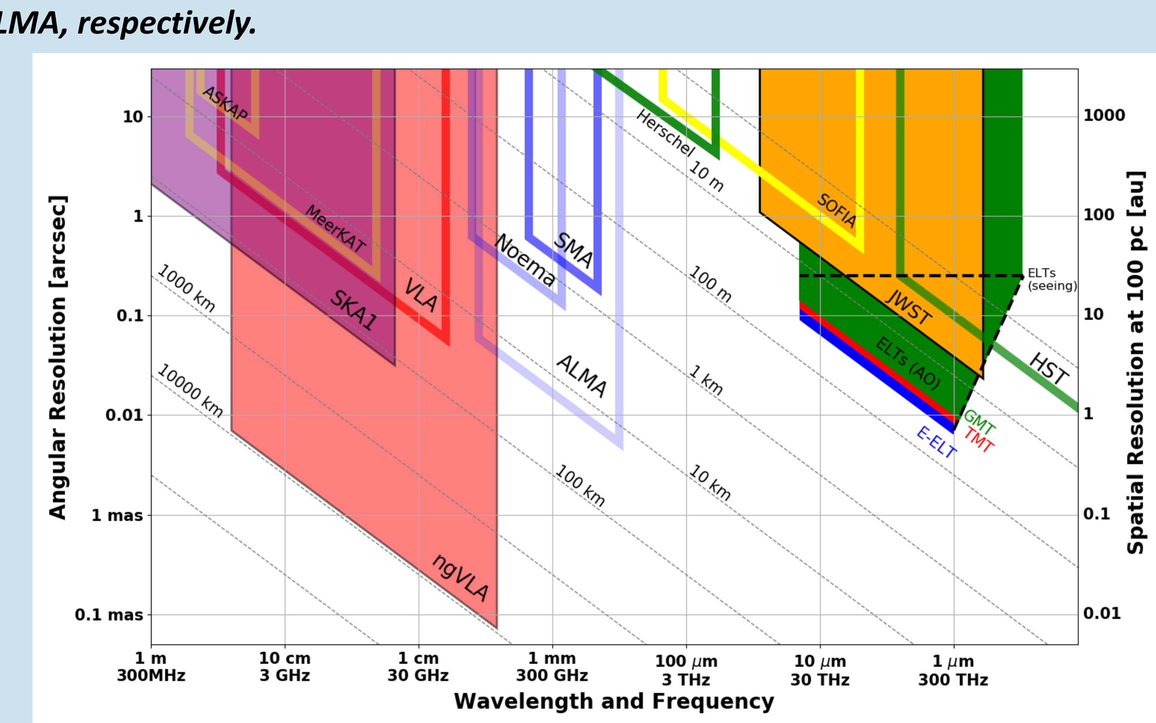


Figure 2: A comparison of achievable angular resolutions for a number of existing and expected facilities spanning the electromagnetic spectrum. The ngVLA will achieve AU-scale resolution for the nearest star-forming regions to study the formation of rocky planets.

Using Galactic Center Pulsars to Test of Gravity

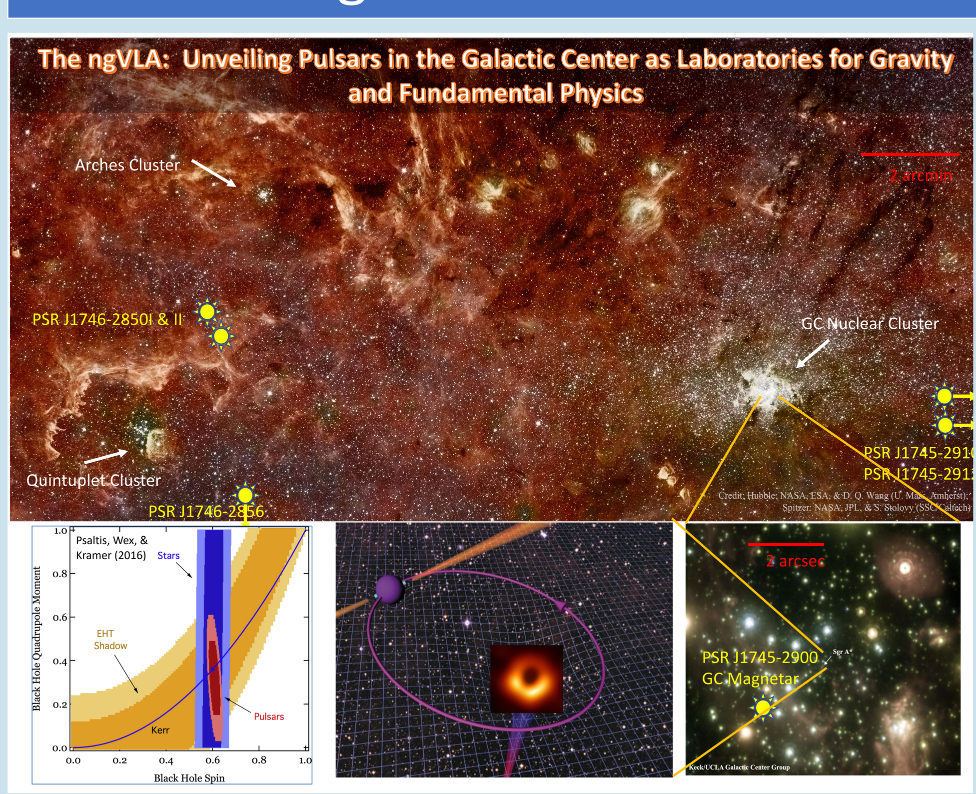


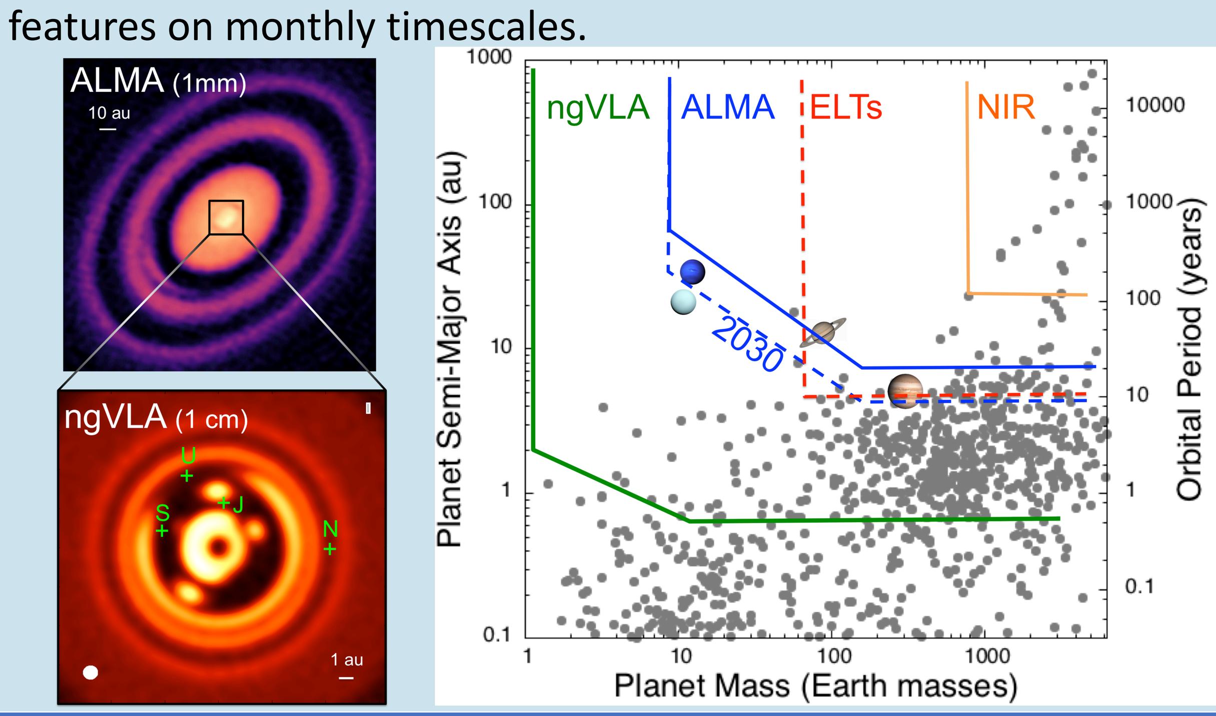
Figure 6: The pulsar distribution near the Galactic Center. Despite being the highest density in the Galaxy and multiple searches at sensitivities comparable to the VLA, only a few pulsars are known though ~1000 are predicted. By discovering pulsars around Sgr A*, the ngVLA will provide new opportunities to test theories of gravity to a previously impossible precision.

Pulsars in the Galactic Center represent clocks moving in the space-time potential of a super-massive black hole and would enable qualitatively new tests of theories of gravity. They offer the opportunity to constrain the history of star formation, stellar dynamics, stellar evolution, and the magneto-ionic medium in the Galactic Center. The ngVLA's combination of sensitivity and frequency range will probe much deeper into the likely Galactic Center pulsar population to address fundamental questions in relativity and stellar evolution.

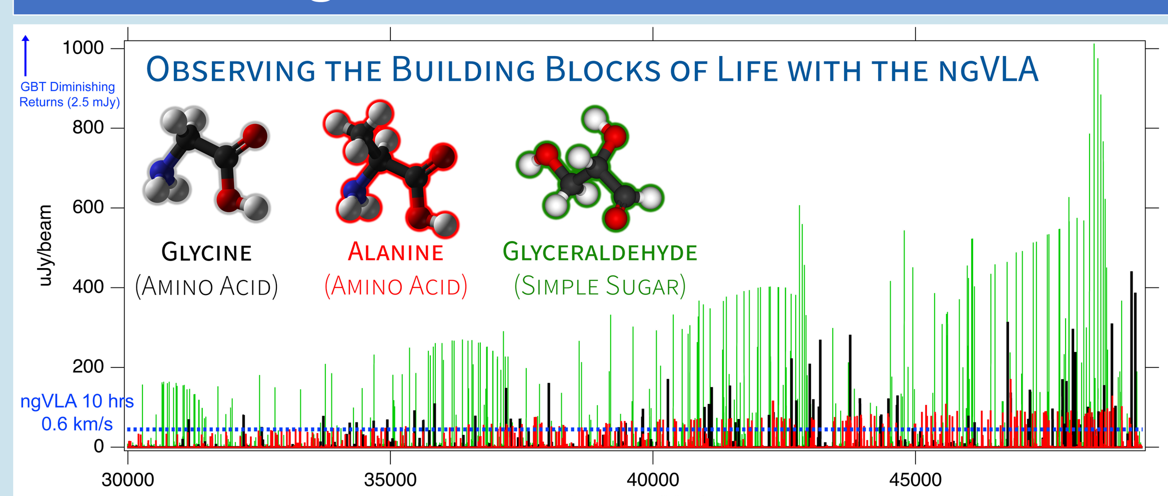
Unveiling the Formation of Solar System Analogs on Terrestrial Scales

The ngVLA will measure the planet initial mass function to 1 – 5 Earth masses and unveil the formation of planetary systems similar to our Solar System by probing the presence of planets on orbital radii as small as 0.5 AU at a distance of 140 pc. The ngVLA will also reveal circum-planetary disks and sub-structures in the distribution of millimeter-size dust particles created by close-in planets and will measure the orbital motion of these features on monthly timescales.

Figure 3: *Top-left* – ALMA 1mm observations of HD163296 with a resolution of 0.04" (4 au at *d*=101 pc) revealing gaps and rings indicative of the presence of Saturn-like planets (Liu et al. 2018; Zhang et al. 2018). *Bottom-left* – Simulated 1 cm ngVLA observations of the innermost 24 au region at 0.01" (1 au) resolution, assuming the presence of (J)upiter-, (S)aturn-, (U)ranus-, and (N)eptune-like planets. *Right* – The distribution of exoplanets around mature stars and young planets embedded in circumstellar disks probed by current NIR telescopes (orange box), future ELTs (red box), ALMA & ALMA2030 (blue boxes), and the ngVLA (green box). The ngVLA will discover many hundreds of planets with orbital periods < 10 yr, allowing for temporal monitoring and characterization of their orbital motions.



Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry



The ngVLA will detect predicted, but as yet unobserved, complex prebiotic species that are the basis of our understanding of chemical evolution toward amino acids and other biogenic molecules. The ngVLA will enable the detection and study of chiral molecules, testing ideas on the origins of homochirality in biological systems. The detection of such complex organic molecules will provide the chemical initial conditions of forming solar systems and planets.

Figure 4: Simulations of three biogentic molecules in a typical hot core source, based on existing upper limits, assuming *T* = 80 K, *dV* = 3 km/s, and a 5" source. The ngVLA's sensitivity to detect these lines *for the first time* in a 10 hr integration is shown as a dashed blue line. For comparison, diminishing returns with GBT integrations start around 2.5 mJy; to detect any new molecules below that limit would require 100s to 1000s of hours.

Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present

The ngVLA will provide a 10x improvement in depth and area for cold gas surveys in galaxies to early cosmic epochs, and will enable routine sub-kiloparsec scale resolution imaging of the gas reservoirs. The ngVLA will afford a unique view into how galaxies accrete and expel gas and how this gas is transformed inside galaxies by imaging their extended atomic reservoirs and circum-galactic regions, and by surveying the physical and chemical properties of molecular gas over the local galaxy population. These studies will reveal the detailed physical conditions for galaxy assembly and evolution throughout the history of the Universe.

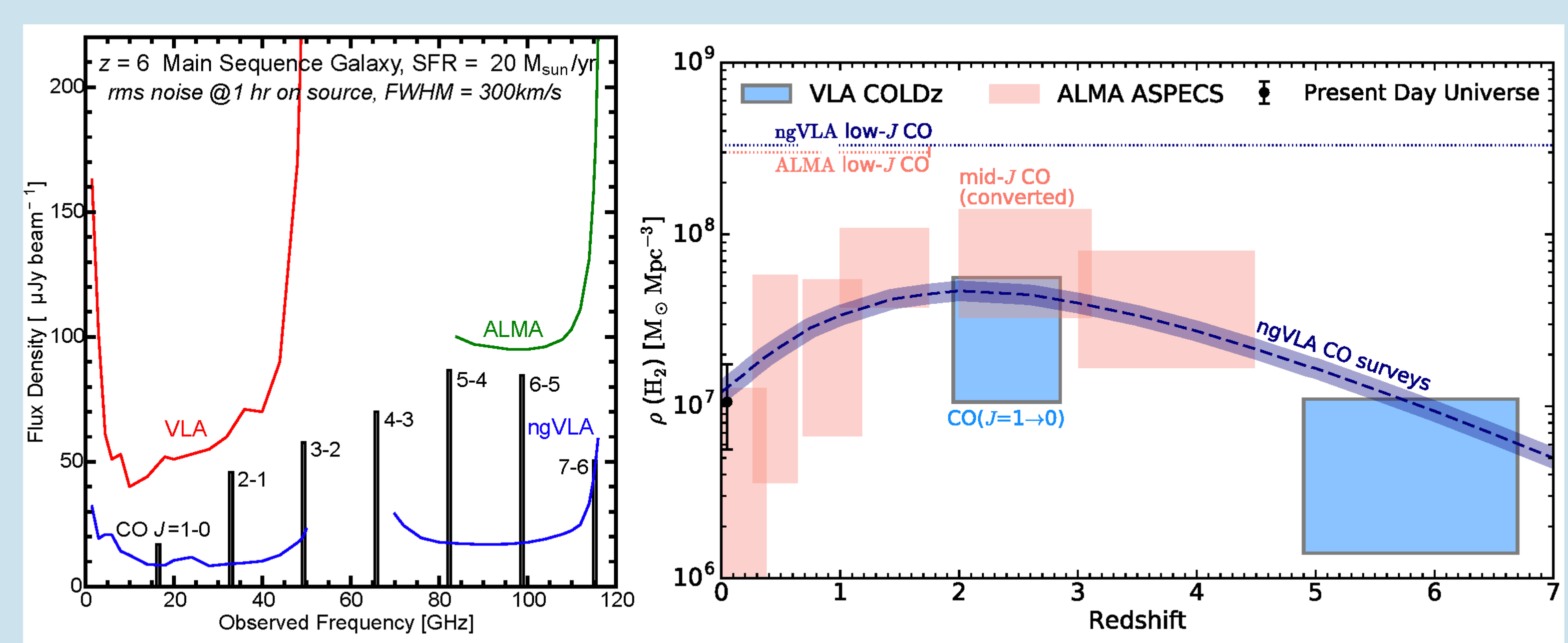
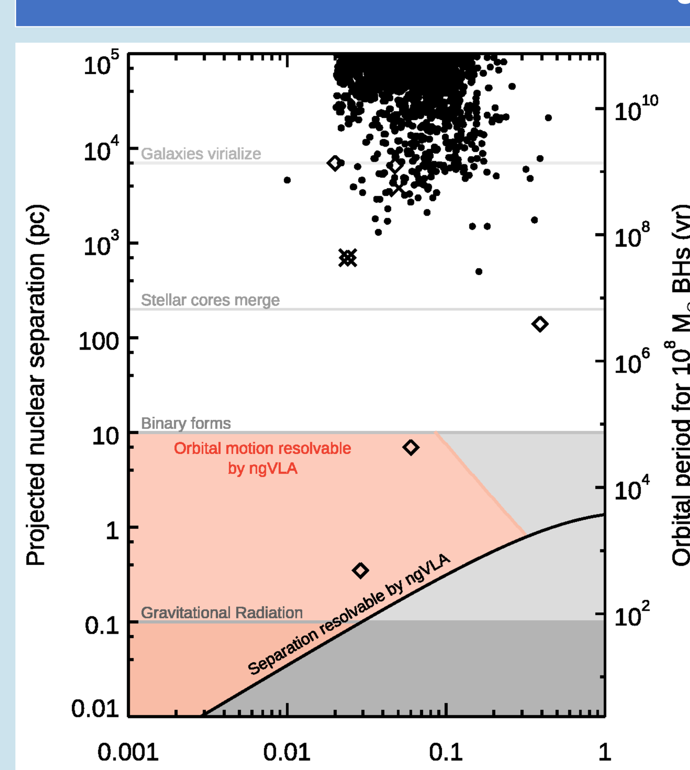


Figure 5: *Left* – With its unparalleled sensitivity, the ngVLA will routinely detect molecular gas in "normal" star-forming galaxies at *z*=6, including the critical low-*J* transitions that remain inaccessible to ALMA. *Right* – The ngVLA will provide more than an order of magnitude improvement in our knowledge of the cold molecular gas density throughout cosmic time compared to the best efforts possible with the VLA (Riechers et al. 2019) and ALMA (Decarli et al. 2019) by providing direct access to low-*J* CO into the Epoch of Reionization.

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



The ngVLA will be the ultimate black hole hunting machine, surveying from the remnants of massive stars to the supermassive black holes (SMBHs) that lurk in the centers of galaxies. High-resolution imaging will separate low-luminosity black holes in our local Universe from background sources, providing critical constraints on their formation and growth for all sizes and mergers of black hole-black hole binaries. The ngVLA will also identify the radio counterparts to transient sources discovered by gravitational wave, neutrino, and optical observatories. Its high-resolution, fast-mapping capabilities will make it the preferred instrument to pinpoint transients associated with violent phenomena such as supermassive black hole mergers and blast waves.

Figure 7: Dual AGN and black hole binaries, with optical/NIR selected sources as dots, X-ray selected sources as X's, and radio selected sources as diamonds. The region above the solid black line would be resolvable by the ngVLA, while the region shaded in orange would have measurable proper motions over 5 years if detected at signal-to-noise of 100 (which for Eddington-limited AGN should be achievable in minutes with the ngVLA), at 40 GHz, for 10^8 solar mass black holes. (from Burke-Spolaor et al. 2018)

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