Gravitational Waves and Pulsar Timing

Shami Chatterjee, on behalf of the NANOGrav Collaboration
Bottom line summary

• Pulsar timing arrays will detect low-frequency gravitational waves. **Risks:** Telescope access, continuity, funding. **Rewards:** A new window on the GW spectrum.

• ngVLA can incorporate PTA science: “Pulsars and Gravity”. Phased sub-arrays, frequency coverage, computation needs.

= No tall poles in the requirements, compared to existing design concepts.
Gravitational Waves: A New Window on the Universe

LIGO detection:
→ GWs directly observed!
→ Black holes exist!
→ Interesting astrophysical observations enabled by a new band.
Gravitational Waves: A New Window on the Universe

- Supermassive binary black hole mergers
  - Mass assembly in the early Universe.
  - GWs at much lower frequencies (nHz).
  - Continuous emission, bursts with memory; Stochastic background from superposition.

Diagram:

- Strain/10^{-14}
  - ??? years
  - ~10^7 years
  - ~1 year
  - BURST!

Time
Gravitational Waves: A New Window on the Universe

Pulsar Timing Arrays

→ Supermassive binary black hole mergers.

→ Primordial GWs.

→ Complementary to other ground- and space-based GW detectors.
Aside: What is a Pulsar Timing Array?
Pulsar Timing Arrays and NANOGrav

• North American Nanohertz Observatory for Gravitational Waves.

• 9 yr data release: (Arzoumanian et al. 2016)

→ History of mass assembly in the early universe.
→ Astrophysics of BH mergers.
→ Already constraining current theoretical models.

\[
\begin{align*}
10^{-12} & \quad 10^{-13} \\
10^{-14} & \quad 10^{-15} \\
10^{-9} & \quad 10^{-8} & \quad 10^{-7}
\end{align*}
\]

Characteristic Strain [\(h_c/f\)]

\[f^{3/2}\]

McWilliams et al. (2014)
Ravi et al. (2014)
Sesana et al. (2013)
Pulsar Timing Arrays and NANOGrav

Building and operating a Galactic-scale GW detector:

- 46 pulsars observed at Arecibo Observatory and the Green Bank Telescope.
- Timed ~monthly at at least two frequency bands to mitigate pulse dispersion and weather in the interstellar medium.
11 Years of Operation

Improving the detector:

- More pulsars added to the array each year.
- Ongoing searches for high-quality pulsars.
- Higher cadence to improve sensitivity.
- Wider bandwidths to mitigate propagation effects (dispersion, scintillation, scattering).
- Distributed all over the sky to improve “PSF”.
- Multi-site data management infrastructure.

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The International Pulsar Timing Array

- Parkes PTA, European PTA.
- Partners in India, China, South Africa coming on board.

- Current model: competition + cooperation.
- US leadership depends on telescope access.
PTA Science in the ngVLA era

- Detection of the stochastic GW background – before ngVLA. ngVLA timeframe – from detection to science with GWs.

- Anisotropy of the GW background.
- Individual GW sources: continuous waves, bursts with memory.
- Electromagnetic counterparts.
- Exotic physics? String theory, dark matter models, etc.

(Roger Blandford talk: don’t be ashamed of exotic physics!)
Pulsar Timing Arrays and ngVLA

• Sensitivity: 2x GBT is plausible.
  → Shared use with ~20% of ngVLA (more for some targets).
  → Sole use with sub-arrays observing multiple targets.

• Integration time: Does not keep dropping with sensitivity.
  → Pulsars have “jitter” – need at least N pulses to measure
    a precise pulse time of arrival.
  → Nominal ~0.5 hr per target per observation.

= Sub-array capability is essential.
Pulsar Timing Arrays and ngVLA

- Frequency coverage:
  Can avoid dual frequency observations with wide enough bandwidth. Need access to lower frequencies (1–4 GHz or 2–8 GHz).

TOA uncertainty in $\log_{10}(\text{us})$ for “perfect” pulsars ($S_f \sim f^a$).

TOA uncertainty in $\log_{10}(\text{us})$ for more realistic pulsars.

(Work by Michael Lam)
Pulsar Timing Arrays and ngVLA

- Sensitivity: ~20% sub-arrays.
- Frequency and bandwidth: 1–4 or 2–8 GHz.
- Integration time: 0.5 hr per target per epoch.
- Cadence: ~ weekly measurements.
- Sources: 100 “good” pulsars distributed over the sky.

**Strawman observing program:**
100 targets, all sky, 20% ngVLA at 2–8 GHz for 0.5 hr per week.
= Only 10 hrs per week.
But: sustained, long term program.
Constraints on the ngVLA design

- Multiple, independently phased, sub-array beams. Scales with fraction of array available - up to 10 sub-arrays, say.

- Wide bandwidths and low frequency coverage. Down to 1 GHz; with larger instantaneous bandwidth, maybe 2 GHz.

- Computation capability for coherent de-dispersion, fast dump of beam. 50 μs sampling, 0.5 MHz channels.
Constraints on the ngVLA design II

• Polarization calibration of phased sub-array beams. Need full-Stokes – good to ~10%? Better is better, of course.

• Clock stability – short term and long term. Consistent with (less restrictive than) VLBI, long baseline requirements.

• Data management and curation for legacy-scale surveys. Continuity of measurement and long-term availability.
Constraints on the ngVLA design

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None of these are “tall poles” for the current ngVLA design concepts.
PTAs, ngVLA, and other radio telescopes

Other telescopes can time pulsars.
- GBT, Arecibo: the future is uncertain, especially on decade timescales.
- FAST: limited sky and can’t share sensitivity on multiple targets.
- CHIME: useful for monitoring of propagation effects.

- SKA, MeerKAT: critical for coverage in the Southern hemisphere, but limited observing time, and we need all-sky coverage for the future of PTA science, beyond the initial detection of the stochastic background.
PTAs, ngVLA, and other facilities

On the ngVLA timescale, several other synergistic facilities:

- Optical, IR, X-ray telescopes (JWST, LSST, ELTs, Lynx, etc.)
  Electromagnetic counterparts to individual GW sources.

- aLIGO, VIRGO, LISA
  Complementary windows on the GW spectrum.
  Massive multi-national projects.
Swept under the rug?

- What about a dedicated telescope or array? No significant advantages compared to ngVLA sub-arrays.

- What about pulsar searches? Computationally intensive to search wide fields of view at high time and frequency resolution, but a significant discovery space. → FAST, SKA, hybrid imaging-based searches.
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