NATIONAL RADIO ASTRONOMY OBSERVATORY

Shami Chatterjee, on behalf of the NANOGrav Collaboration

Gravitational Waves and Pulsar Timing

NANOGrav

NSF

Associated Universities, Inc.

ngVLA
The Next Generation Very Large Array

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.

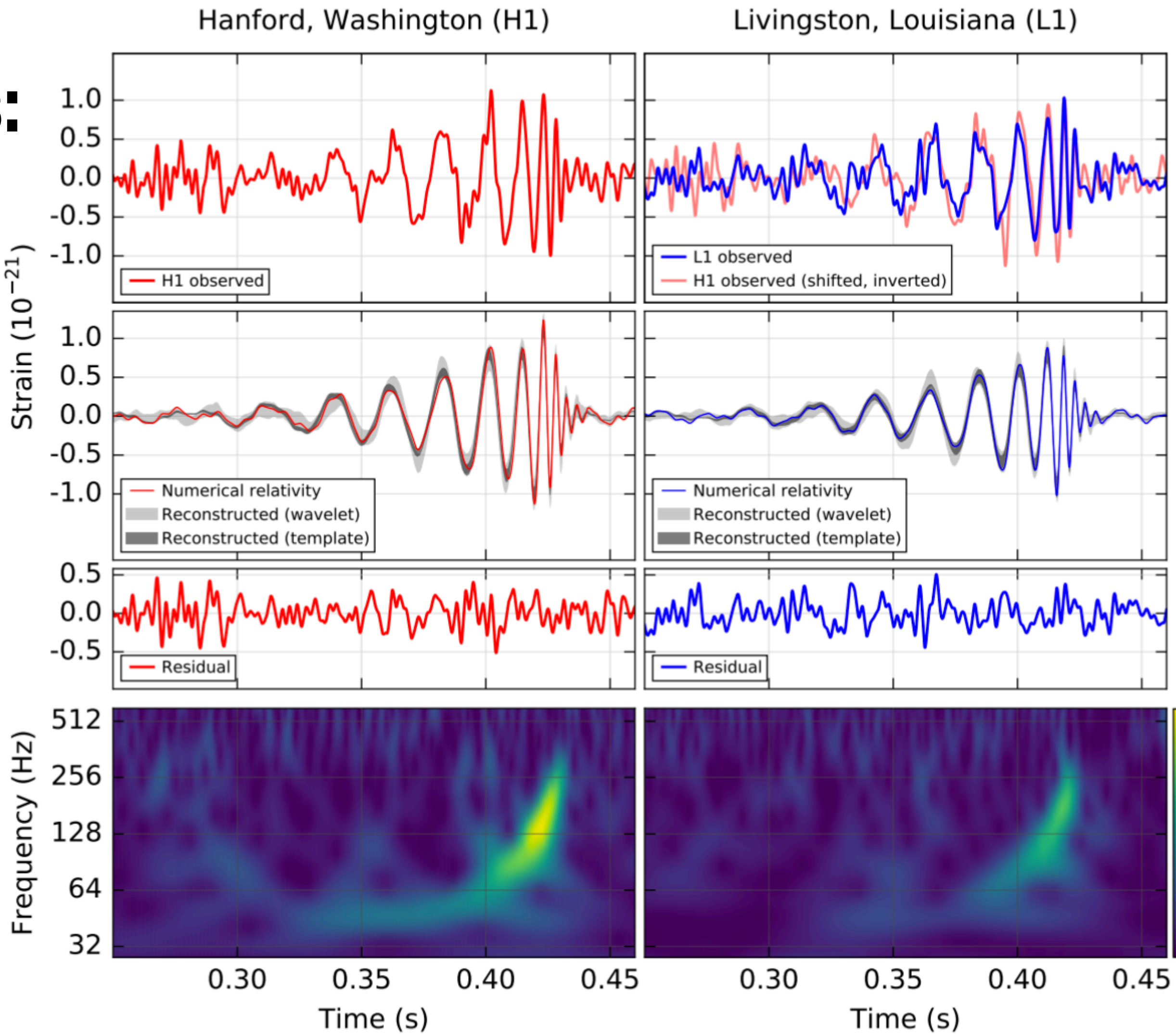
Gravitational Waves: A New Window on the Universe

LIGO detection:

→ GWs directly observed!

→ Black holes exist!

→ Interesting astrophysical observations enabled by a new band.



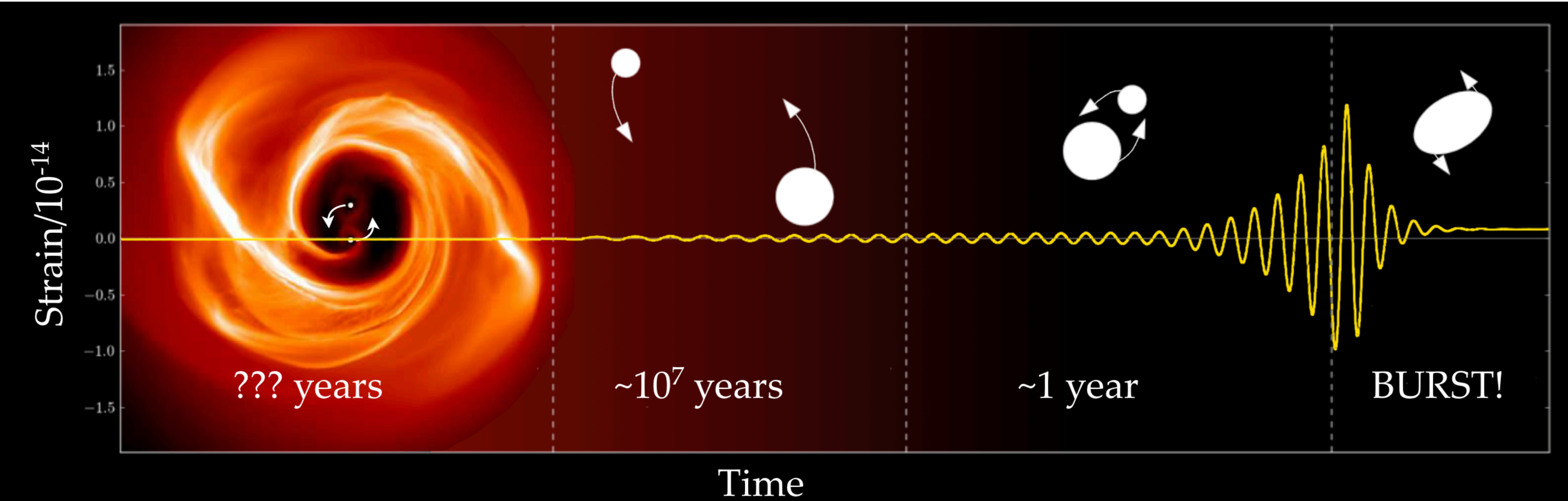
Gravitational Waves: A New Window on the Universe

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.



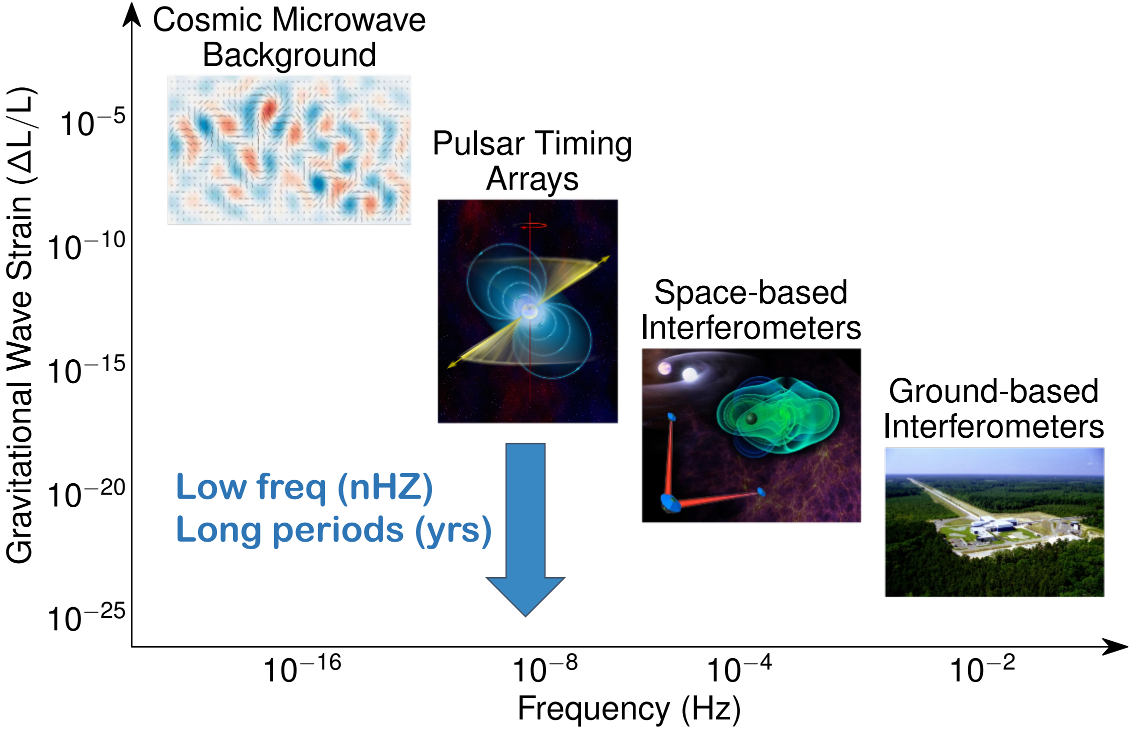
Gravitational Waves: A New Window on the Universe

Pulsar Timing Arrays

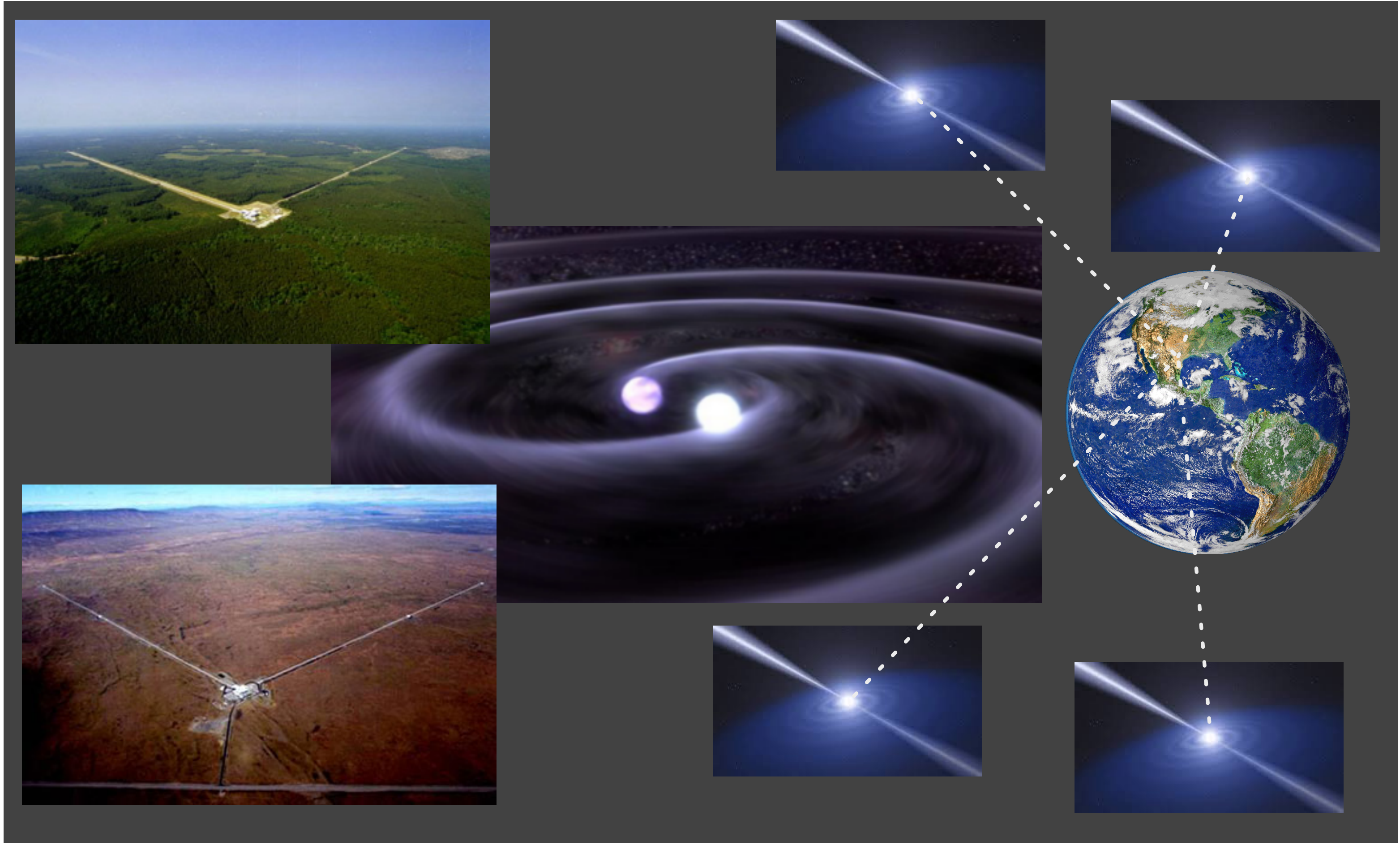
→ Supermassive binary black hole mergers.

→ Primordial GWs.

➔ Complementary to other ground- and space-based GW detectors.



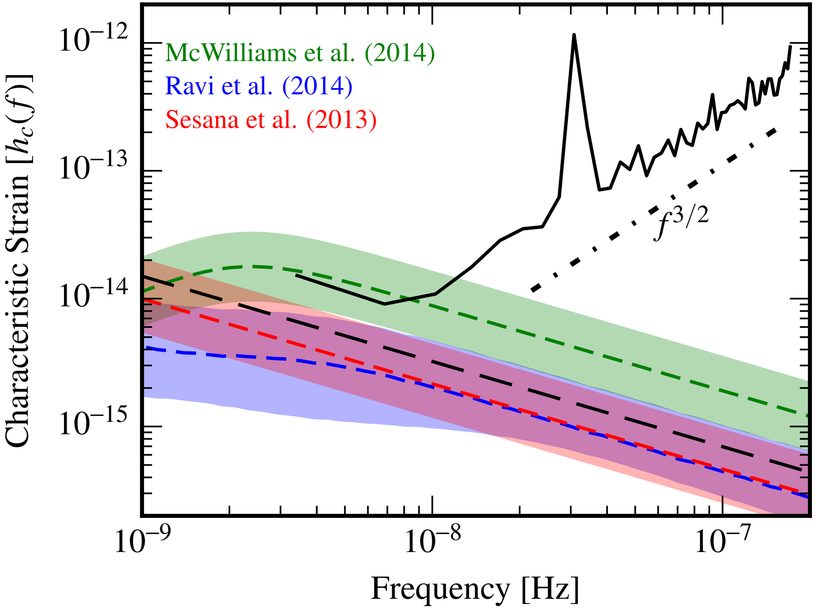
Aside: What is a Pulsar Timing Array?



Pulsar Timing Arrays and NANOGrav

- North American Nanohertz Observatory for Gravitational Waves.
- 9 yr data release:
  (Arzoumanian et al. 2016)

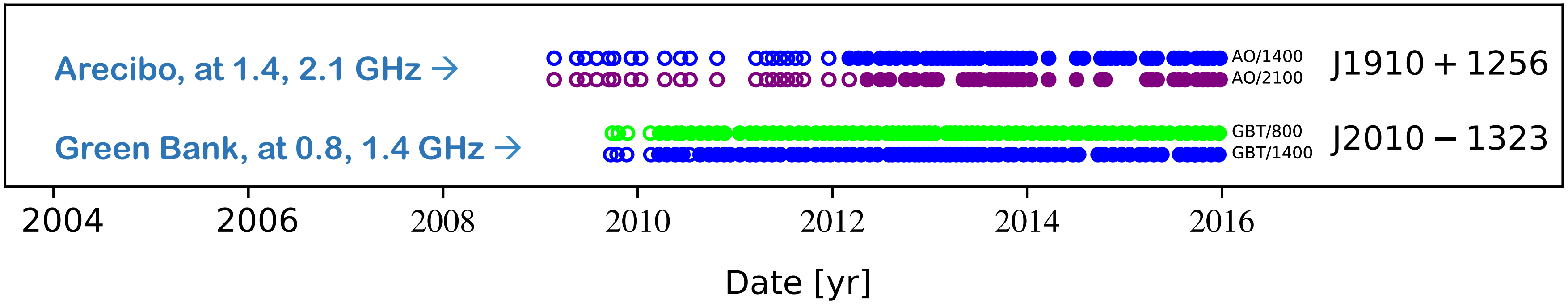
  → History of mass assembly
  in the early universe.
  → Astrophysics of BH mergers.
  → Already constraining current
  theoretical models.



Pulsar Timing Arrays and NANOGrav

Building and operating a Galactic-scale GW detector:

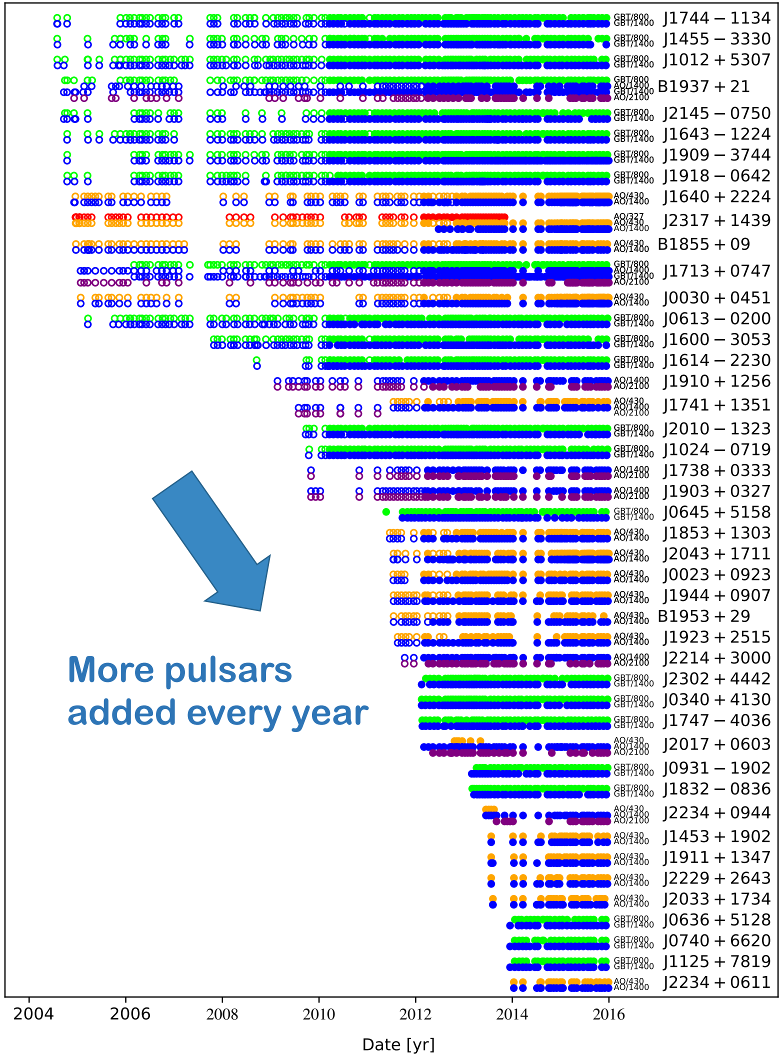
- 46 pulsars observed at Arecibo Observatory and the Green Bank Telescope.
- Timed ~monthly at at least two frequency bands to mitigate pulse dispersion and weather in the interstellar medium.



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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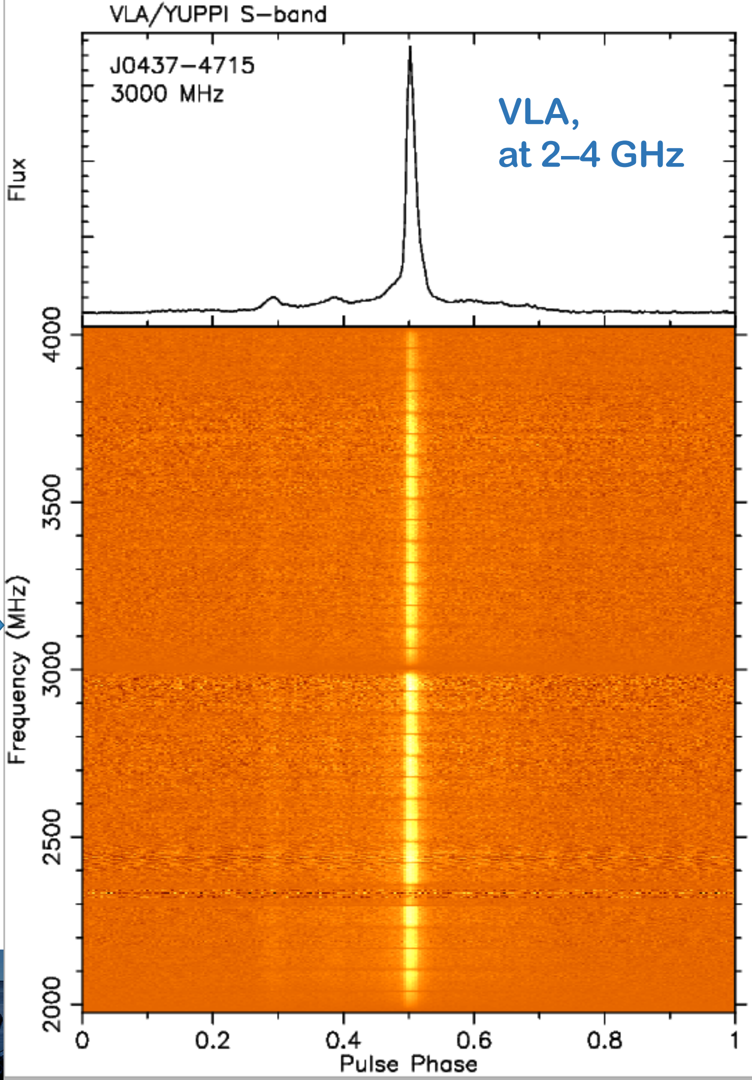
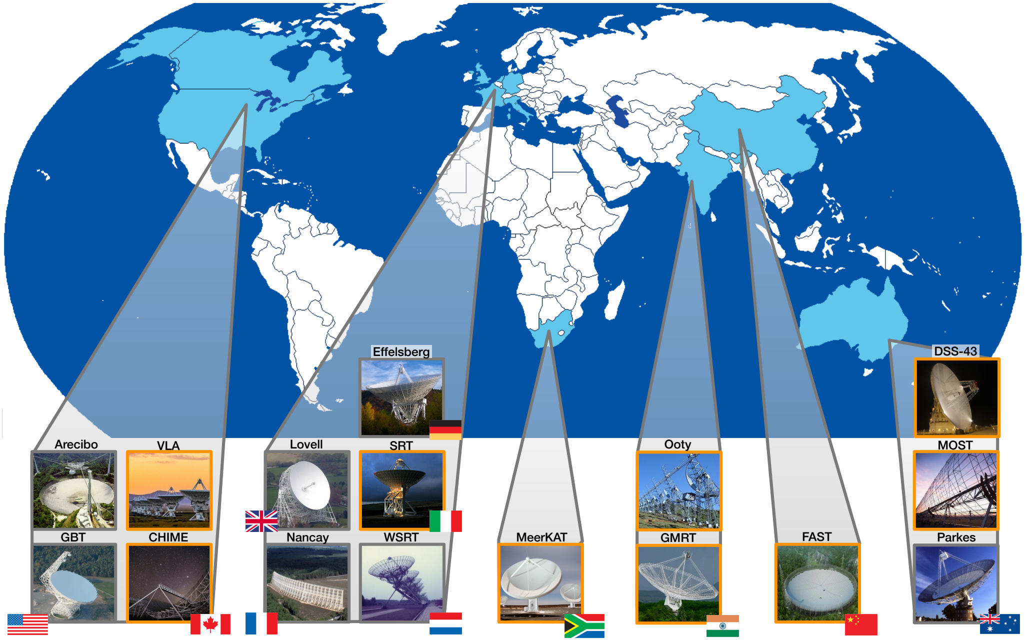


The International Pulsar Timing Array

- 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

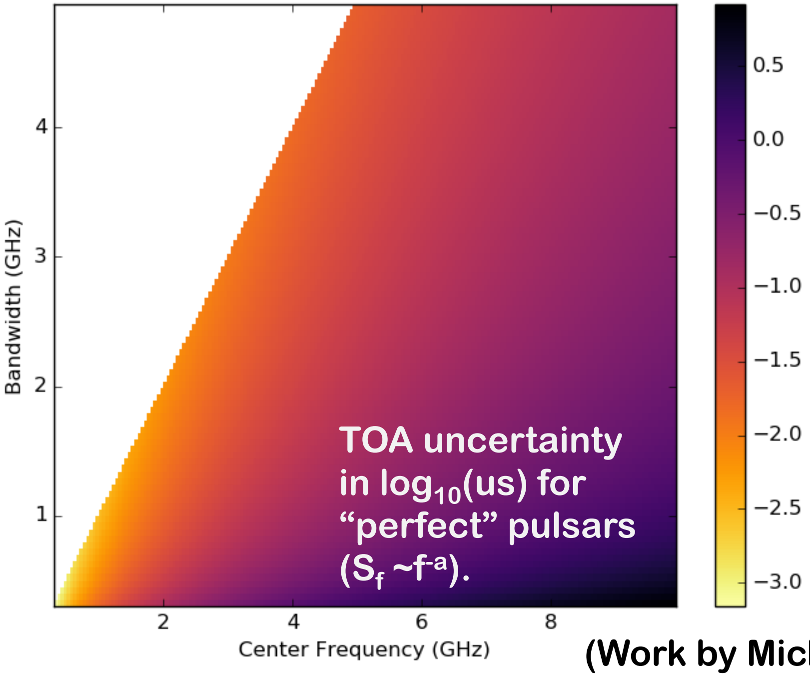
- Sensitivity: 2x GBT is plausible.
  → Shared use with ~20% of ngVLA (more for some targets).
  → Sole use with sub-arrays observing multiple targets.

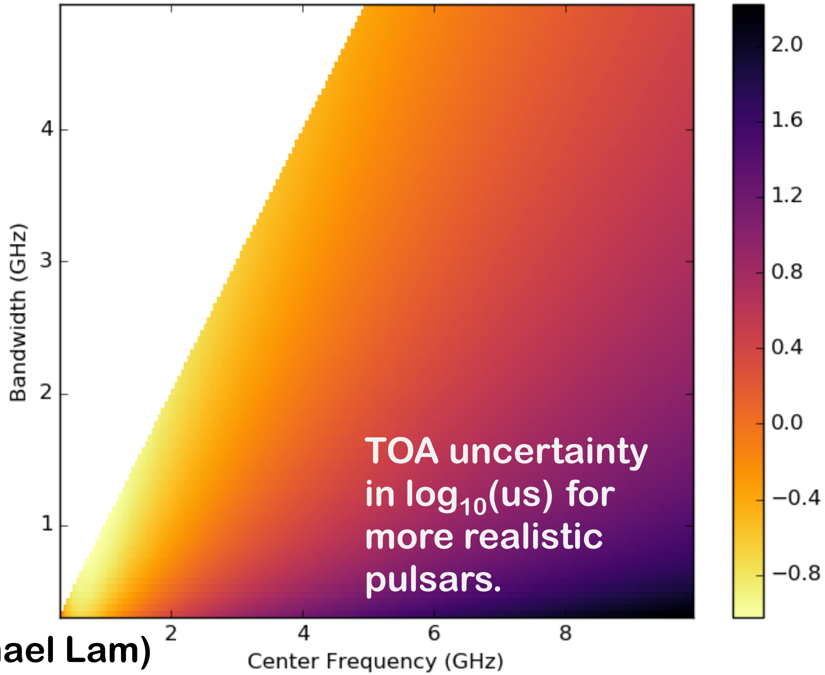
- Integration time: Does not keep dropping with sensitivity.
  → Pulsars have "jitter" – need at least N pulses to measure a precise pulse time of arrival.
  → Nominal ~0.5 hr per target per observation.

= 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).





(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

- Multiple, independently phased, sub-array beams.
- Wide bandwidths and low frequency coverage.
- Computation capability for coherent de-dispersion, fast dump of beam.
- Polarization calibration of phased sub-array beams.
- Clock stability – short term and long term.
- Data management and curation for legacy-scale surveys.

→ 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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