Gravitational Waves and Pulsar Timing Arrays: The Best Gravitational Waves

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MONASH University
Australian National University
THE UNIVERSITY of ADELAIDE
THE UNIVERSITY OF MELBOURNE
THE UNIVERSITY OF WESTERN AUSTRALIA
AAO
CSIRO

About me

- Born in small town in Canada
- Ph.D. in the U.S.
- Moved to Sydney, Australia for a postdoc
- Now faculty at Swinburne in Melbourne

Main research interests:

- Timing millisecond pulsars to search for (and study) gravitational waves (MeerKAT and Murriyang)
- Fast Radio Bursts (ASKAP)

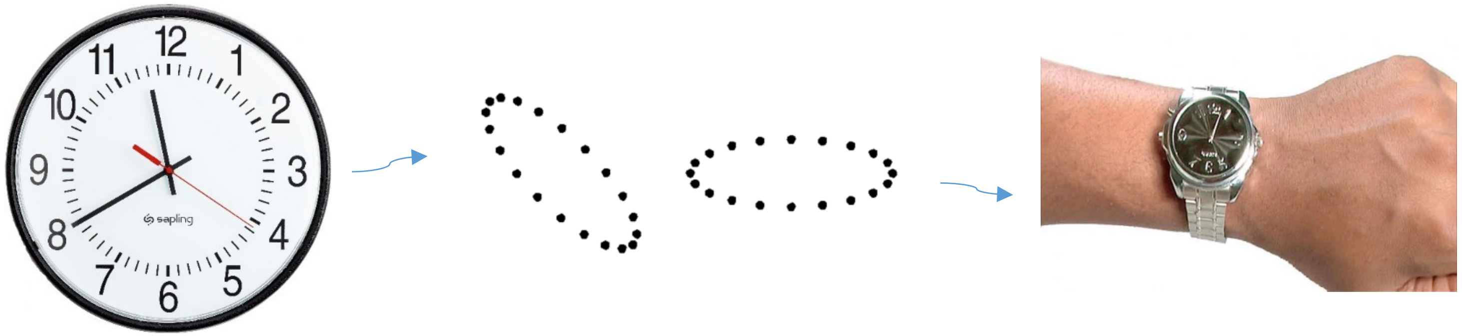
Outline

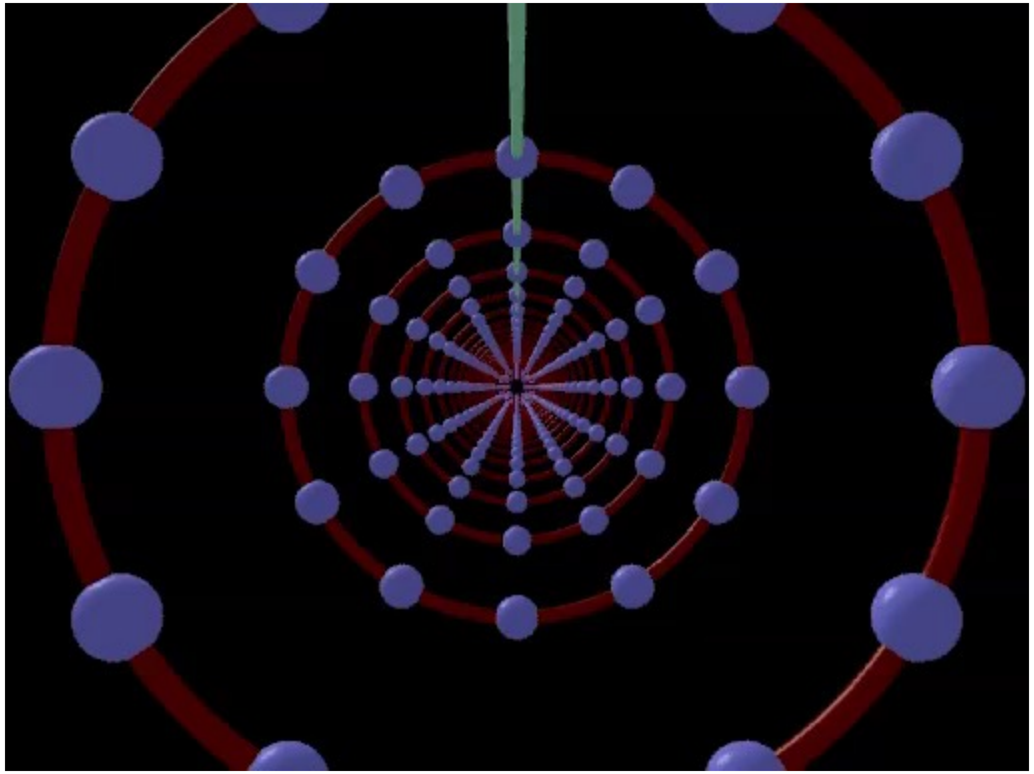
- Introduction to gravitational waves
- How pulsar timing arrays work
- Pulsar Timing Array Science
- The MeerKAT Pulsar Timing Array

Gravitational waves

- Fluctuations in curvature that propagate at the speed of light

- Experiment in the lab:

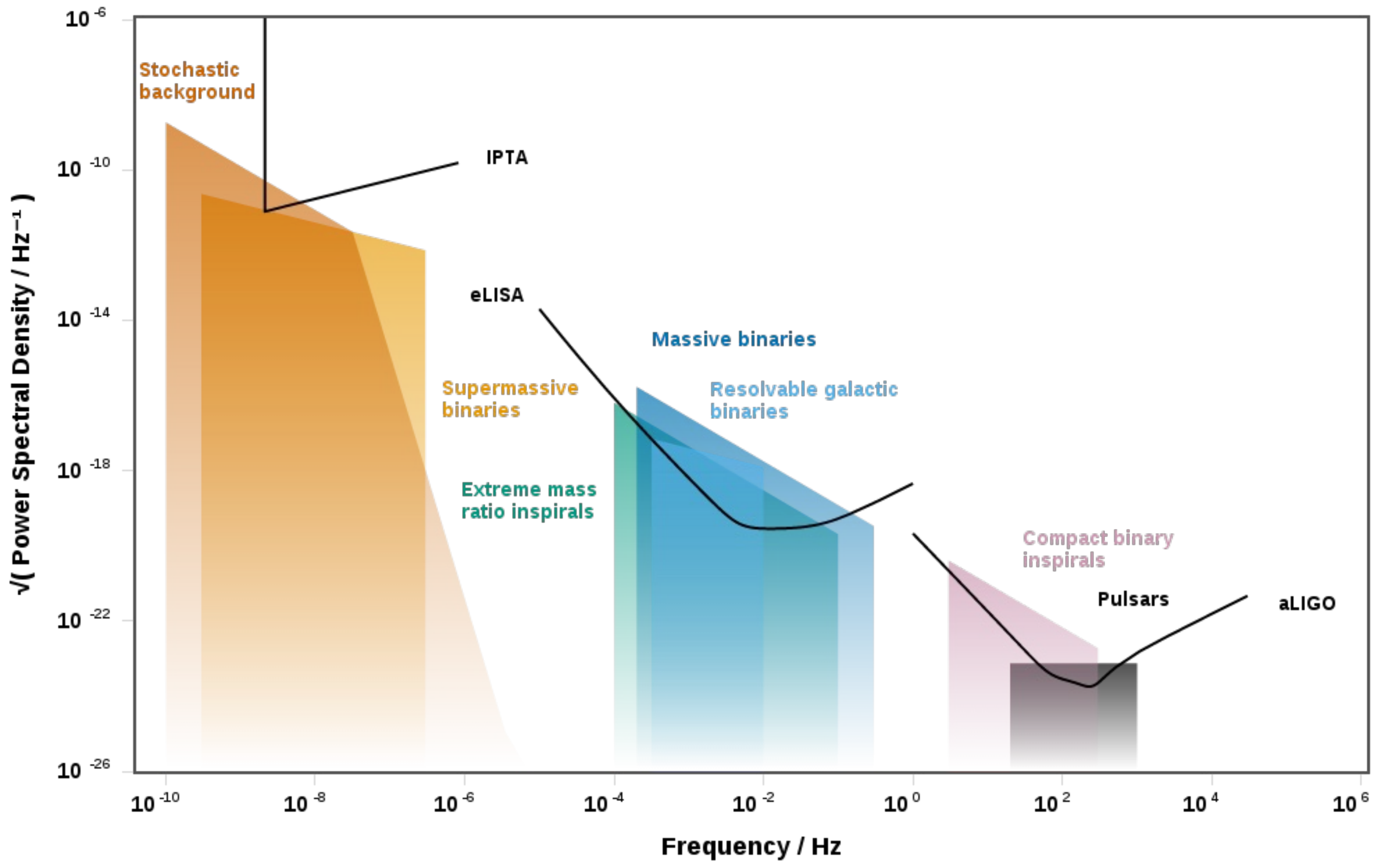




- Using an accurate clock, record when you measure ticks.
- Passing gravitational waves contract and expand space between observer and the clock.
- Measure deviation from expected time -> Detected gravitational waves.

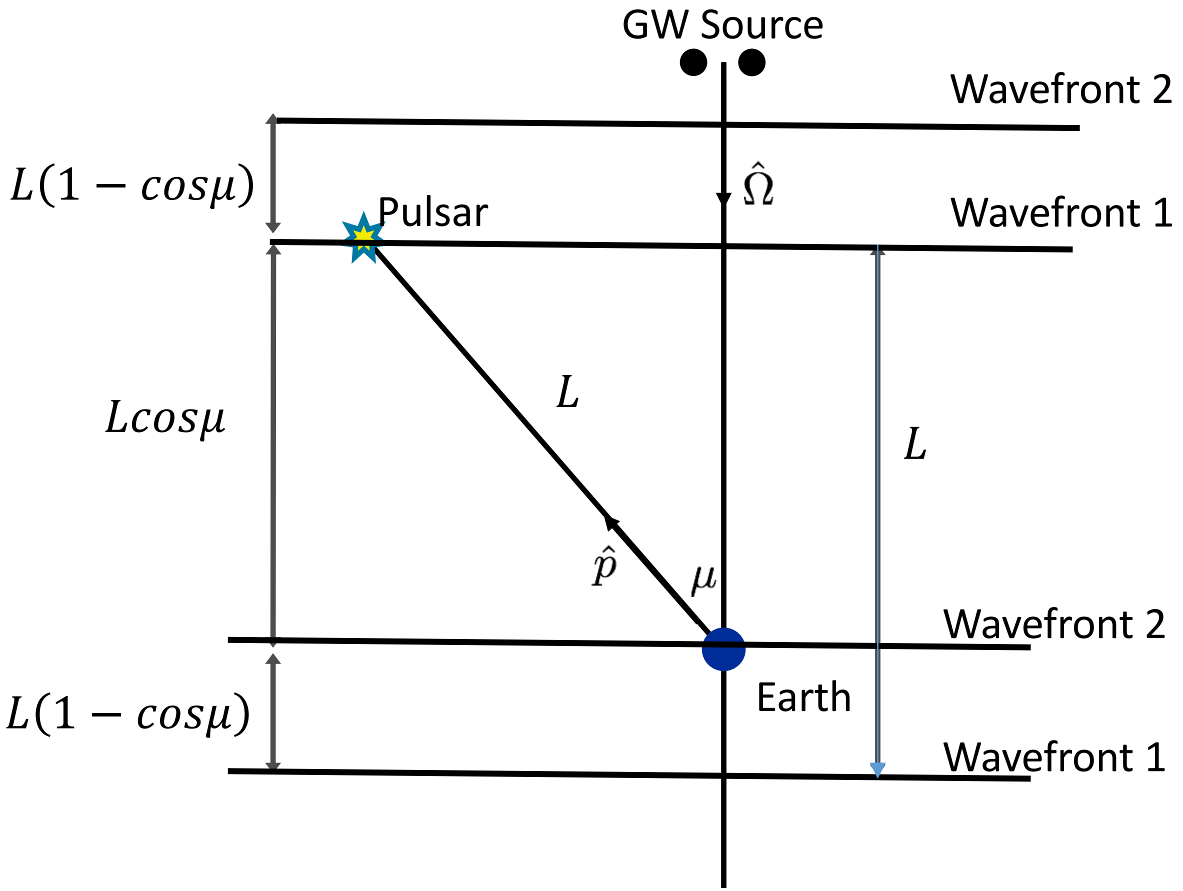
Credit: L. Lentati

The gravitational-wave spectrum



Credit: Chris Berry

Gravitational-wave geometry



- Perturbation at the pulsar at a time t_p:
- Perturbation at the Earth at a time t_e:

$$t_p = t_e - L(1 - cos\mu)$$

- Measure the difference between the two:

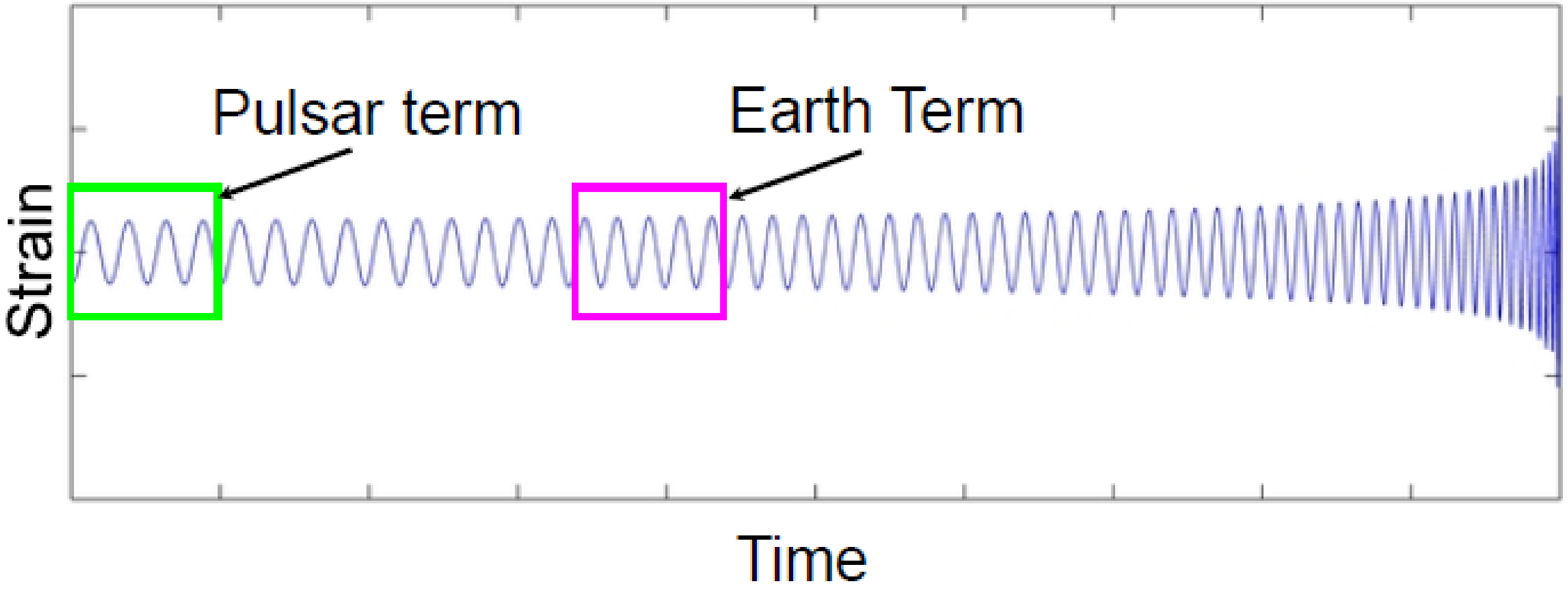
$$\Delta h_{ij} = h_{ij}(t_p, \widehat{\Omega}) - h_{ij}(t_e, \widehat{\Omega})$$

Credit: L. Lentati

Delay term is purely geometric

$$t_p = t_e - L(1 - cos\mu)$$

- L ~ 1 kpc, can potentially see frequency evolution over very large time scales.



Credit: L. Lentati

Redshift to residuals

So far only one frequency, one source.

Total red shift obtained by integrating over all frequencies and all sky

$$z(t) = \int df \int_{S^2} d\Omega \, z(t, f, \Omega)$$

Also we don't observe redshift. We observe a fluctuation in the residuals left after subtracting a timing model from data

$$\mathrm{r}(t) = \int_0^t dt' z(t')$$

Credit: L. Lentati

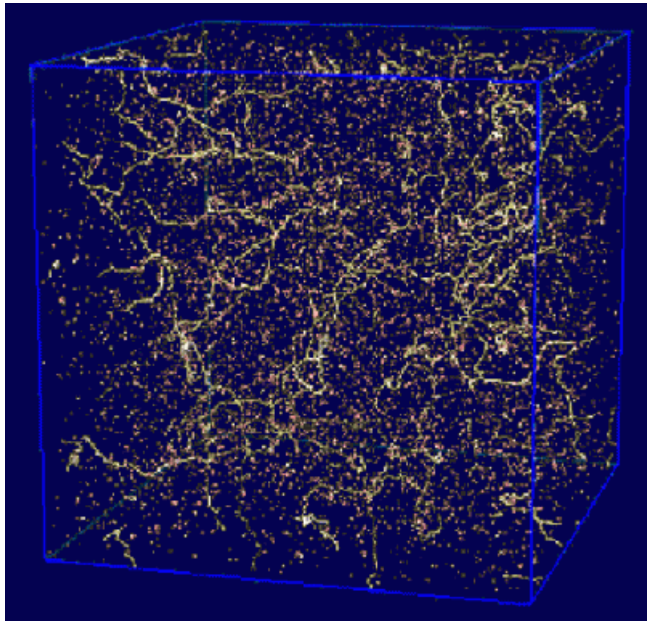
Sources of GWs in the nHz band

- *Sensitive to GWs with frequencies between 3 and 300 nHz (get TOAs every week for 10 years)*

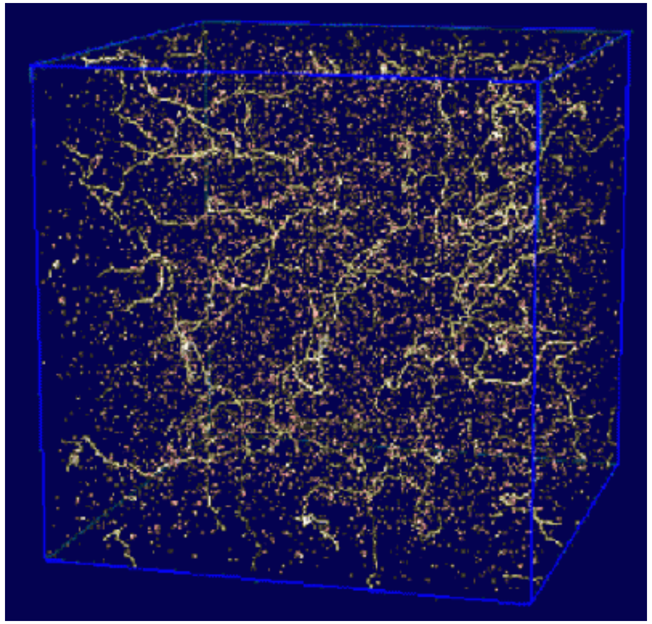
- **Massive Black Hole Binaries** (Jaffe & Backer 2003, Sesana et al. 2008,2013,2015; Ravi et al. 2012,2014,2015)

- **Cosmic Strings and Super Strings** (Damour & Vilenkin 2005, Sanidas et al. 2012, Lentati et al. 2015)

- **Early-Universe Signals** (Witten 2007, Caprini et al. 2010, Lasky et al. 2016).



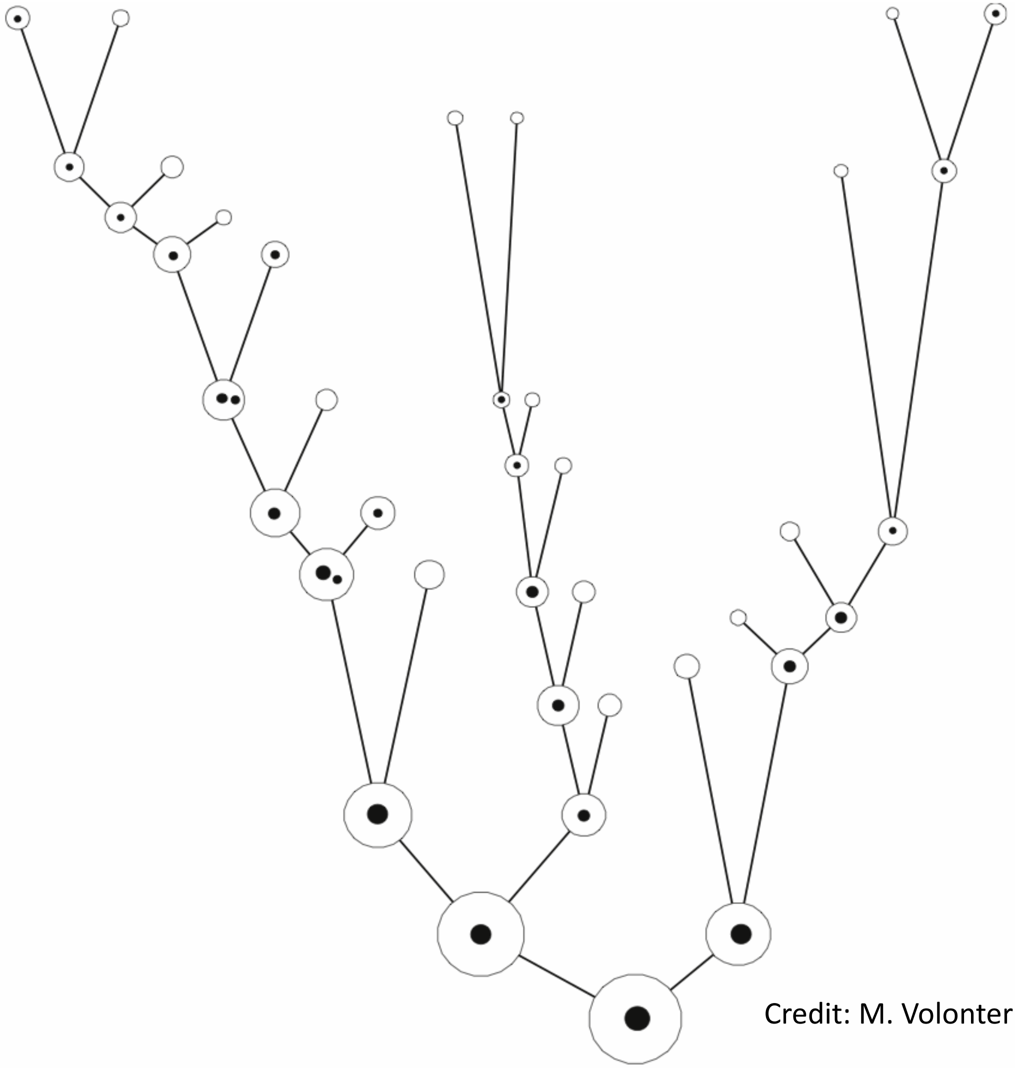
Types of sources in the nHz band



- *Sensitive to GWs with frequencies between 3 and 300 nHz (get TOAs every week for 10 years)*
- **Stochastic backgrounds**
- **Single sources** (Arzoumanian et al 2015, Zhu et al. 2015, Babak et al. 2016, Aggarwal et al. 2019)
- **Gravitational wave memory** (Wang et al. 2015, Madison et al. 2015)

A recipe for producing a GWB

- Black holes formed early in the universe at the centres of the first galaxies
- After galaxies merge, black holes dynamically dragged to centre
- When MBHs get close, they become prodigious emitters of GWs
- After merger, resultant BH gains mass through accretion (Quasar phase)
- Process repeats many times for each current galaxy (10?)



Credit: M. Volonteri

Why care about supermassive black holes?

- **How do galaxies form?** Why do today's galaxies look the way they do? What did the first galaxies look like?
- **What is the cause/effect of supermassive black holes and galaxy evolution?**
- **When galaxies merge, what happens to their SMBHs?**
  - Too close together to resolve using optical telescopes.
  - Reside in dense environments.
- **Gravitational waves enable us to study the centres of galaxies invisible otherwise!**

One problem..

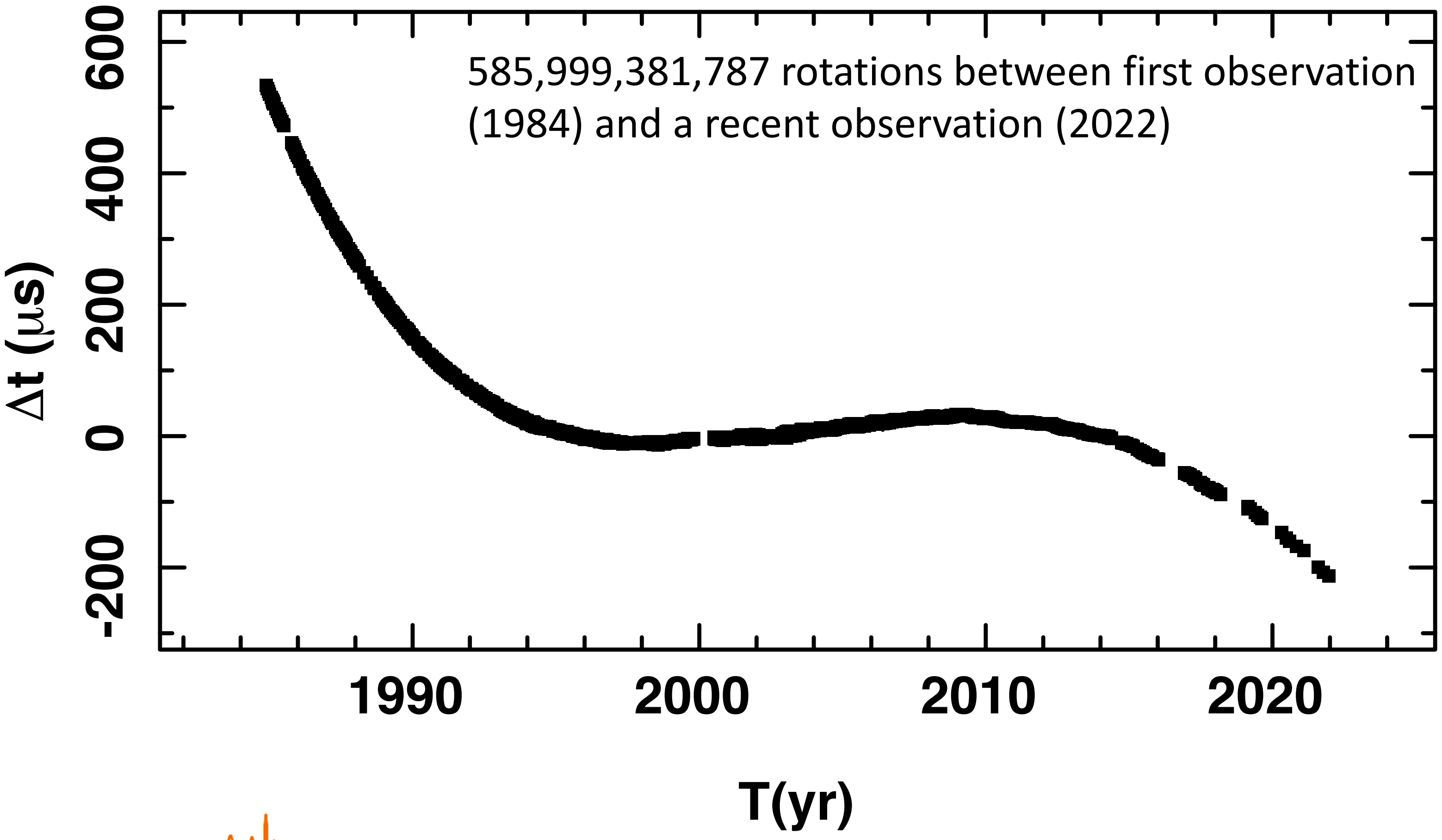
- Expected length change:

Width of an atomic nucleus on one meter baseline

- Need *very* accurate clock
- Or huge distances…

The joy of pulsar timing

- **Phase coherent**: sensitive to effects that only manifest as small Doppler shifts
- **Millisecond pulsars** sensitive to the smallest of perturbations
- **Timing noise:** spin irregularities manifest as red noise in arrival times
- GW strain: h
- $h \sim \Delta t/T \sim 10^{-3}\,s/10^{9}\,s = 10^{-12}$

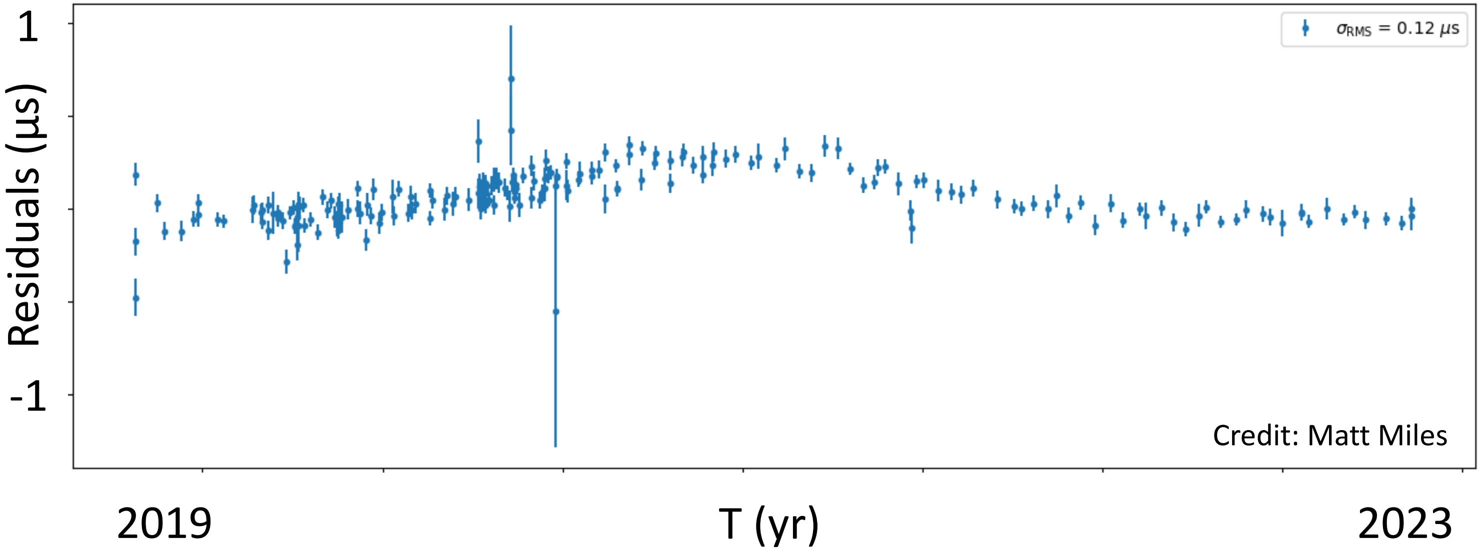


Using pulsars to detect Gravitational Waves

- Distant: ~ 1 kpc = 3×10^{19} meters

- Change in path length from GWs:

- ~ few hundred meters = ~ 100 ns

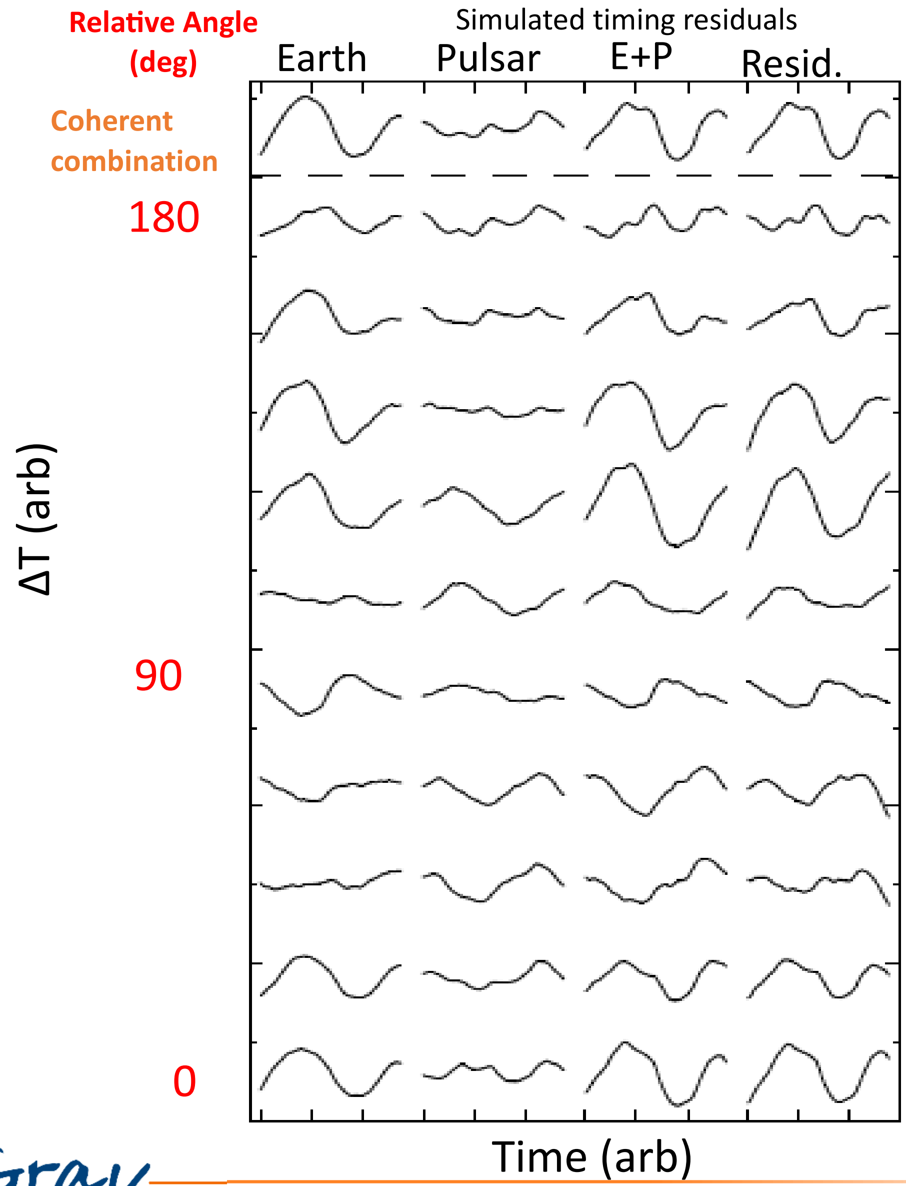


Credit: Matt Miles

A Stochastic Background

The **stochastic background** is the superposition of GWs from many sources

Background induces **red power spectrum** in residuals (more power at lowest frequency of GWs).

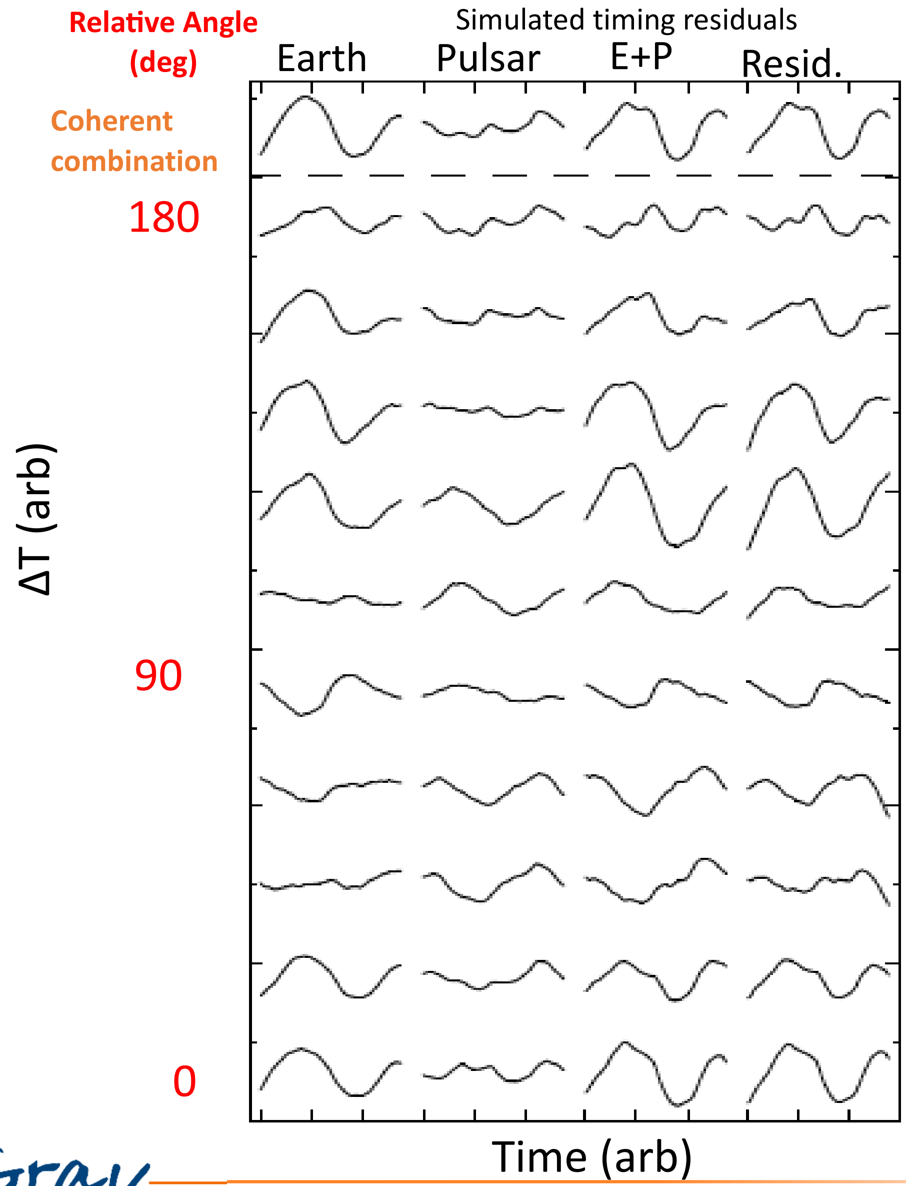


A Stochastic Background

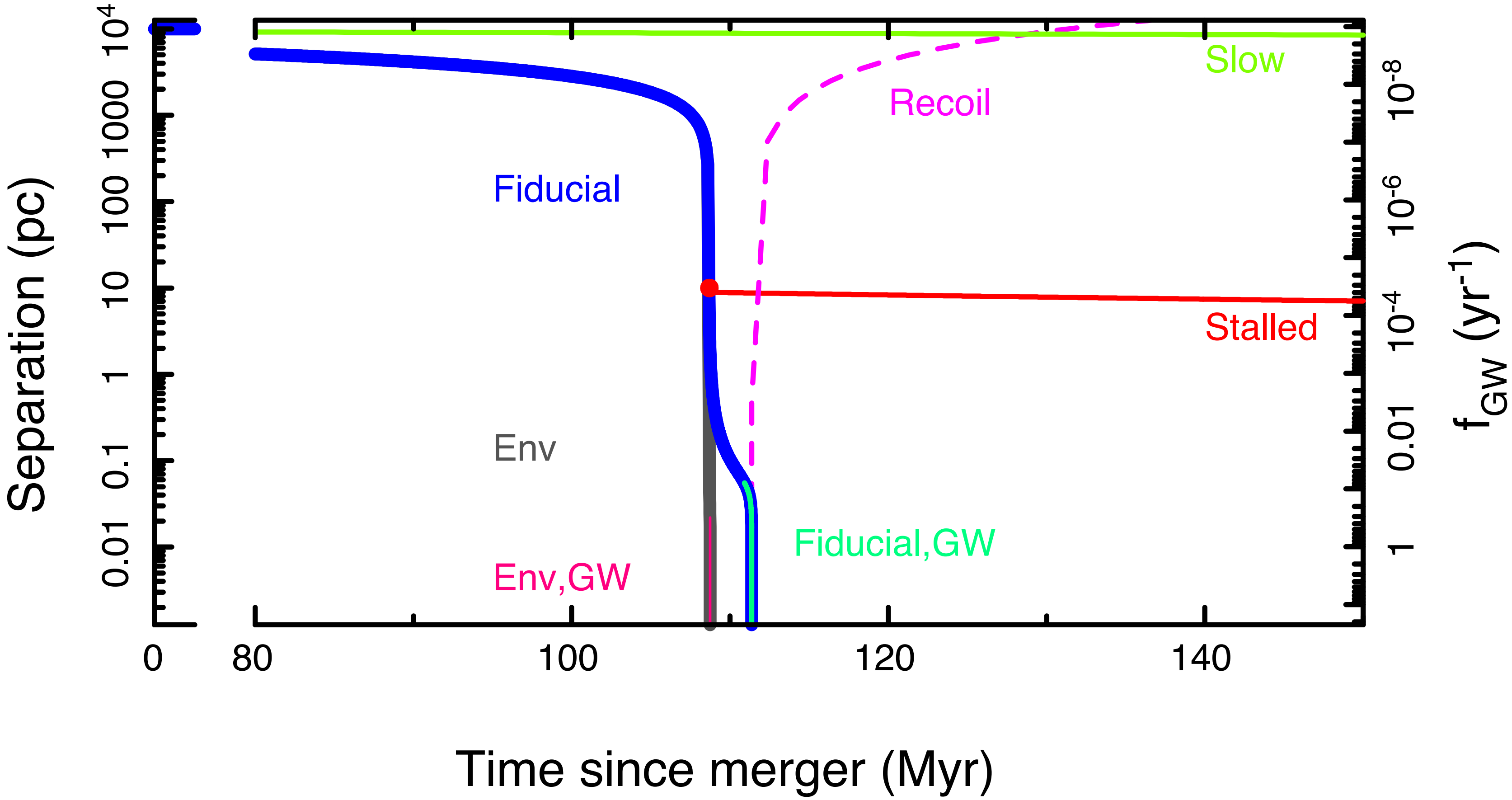
The background is characterized by a **characteristic strain amplitude spectrum** $h_c(f)$ with **amplitude** A_c (10^{-15})and spectral index α (-2/3).

$$\boxed{h_c(f) = A_c f^{\alpha}}$$

RMS contributions to residuals ~**20 ns** over 5 years: need to combine signal from a group of pulsars (pulsar timing array, PTA).



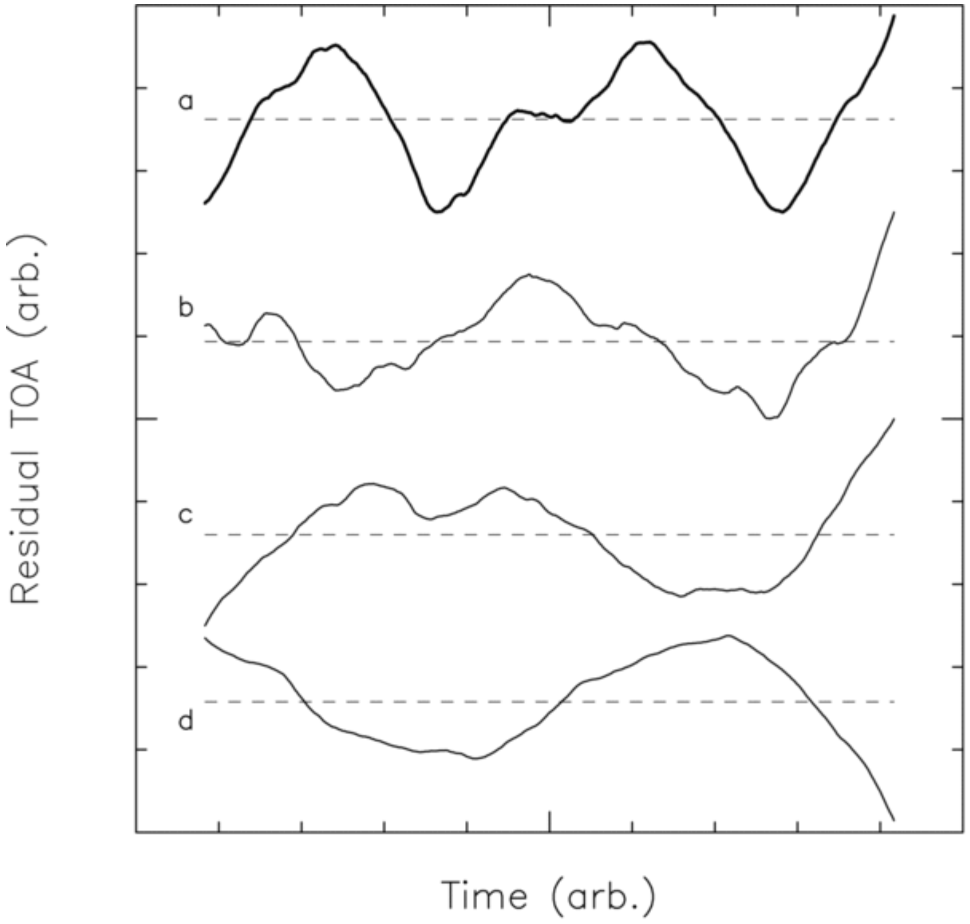
Astrophysical processes that impact GWB amplitude



- **Slow galaxy mergers (green)**
- **Recoil of SMBH after merger (purple)**
- **Stalled mergers (red)**
- **Environmentally driven mergers (grey/red)**
- **Low occupation fraction of seed SMBH in early universe**

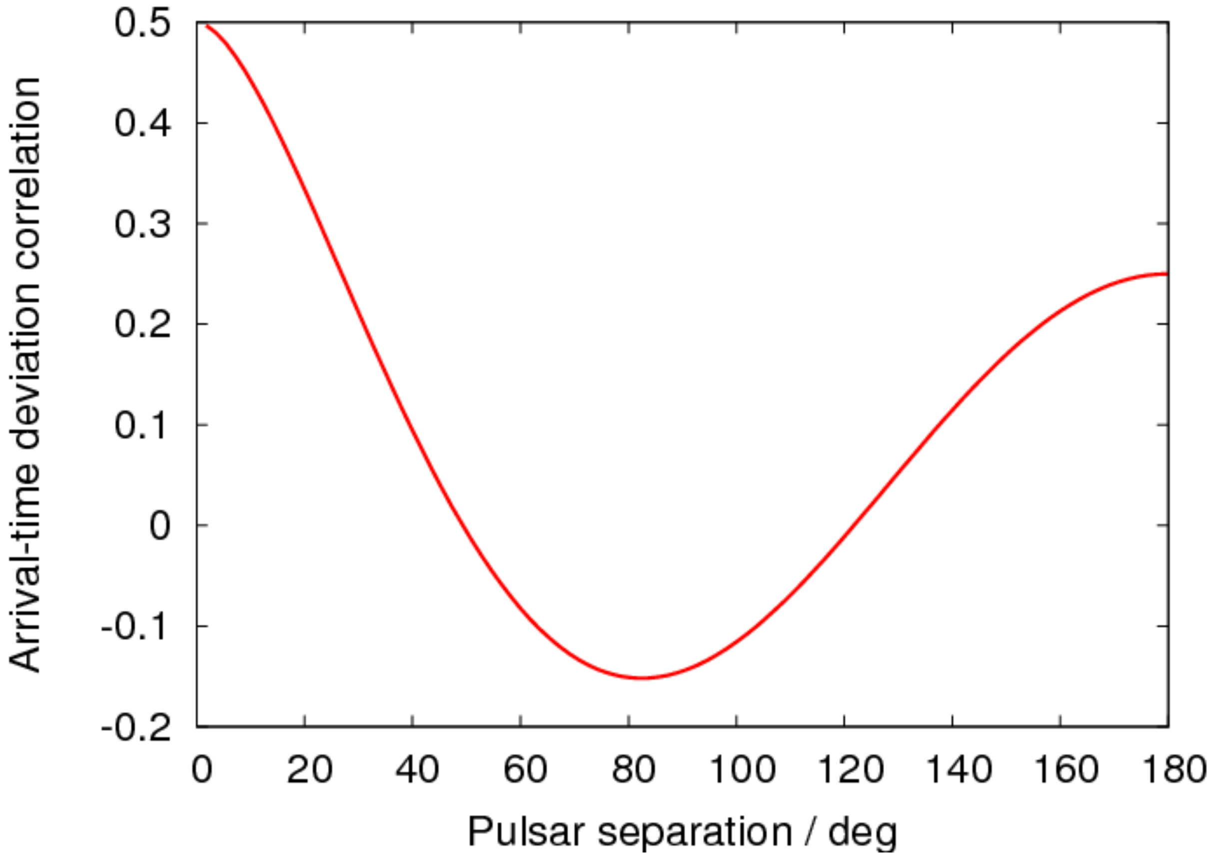
Common red process

- Gravitational wave background includes a contribution that has a spatial correlation, but also a process that has no spatial correlation
- This process is expected to be **statistically identical** between pulsars
  - Different realisation of the same process
- In PTA experiments with small numbers of pulsars or pulsars with varied levels of sensitivity the first evidence for the GWB might be this common red process



Four realisations of the same process (Shannon & Cordes 2010)

How do we detect a background?



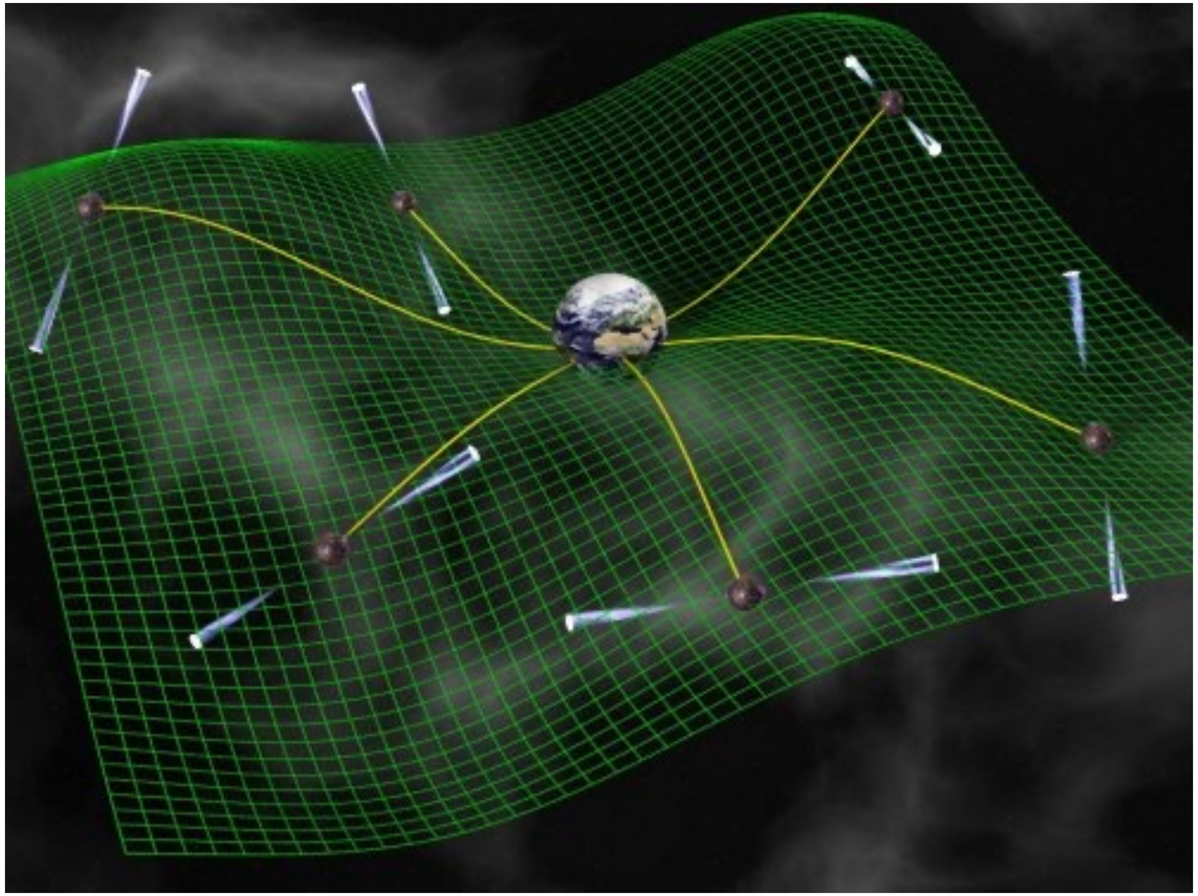
Problem: Other sources of noise can look like gravitational waves (e.g., pulsar spin noise)

Solution: Search for correlation in arrival times between multiple pulsars:
Pulsar Timing Array

Gravitational waves and pulsar timing

- Signal has quadropolar correlation between pulsars (pulsar timing array, PTA)

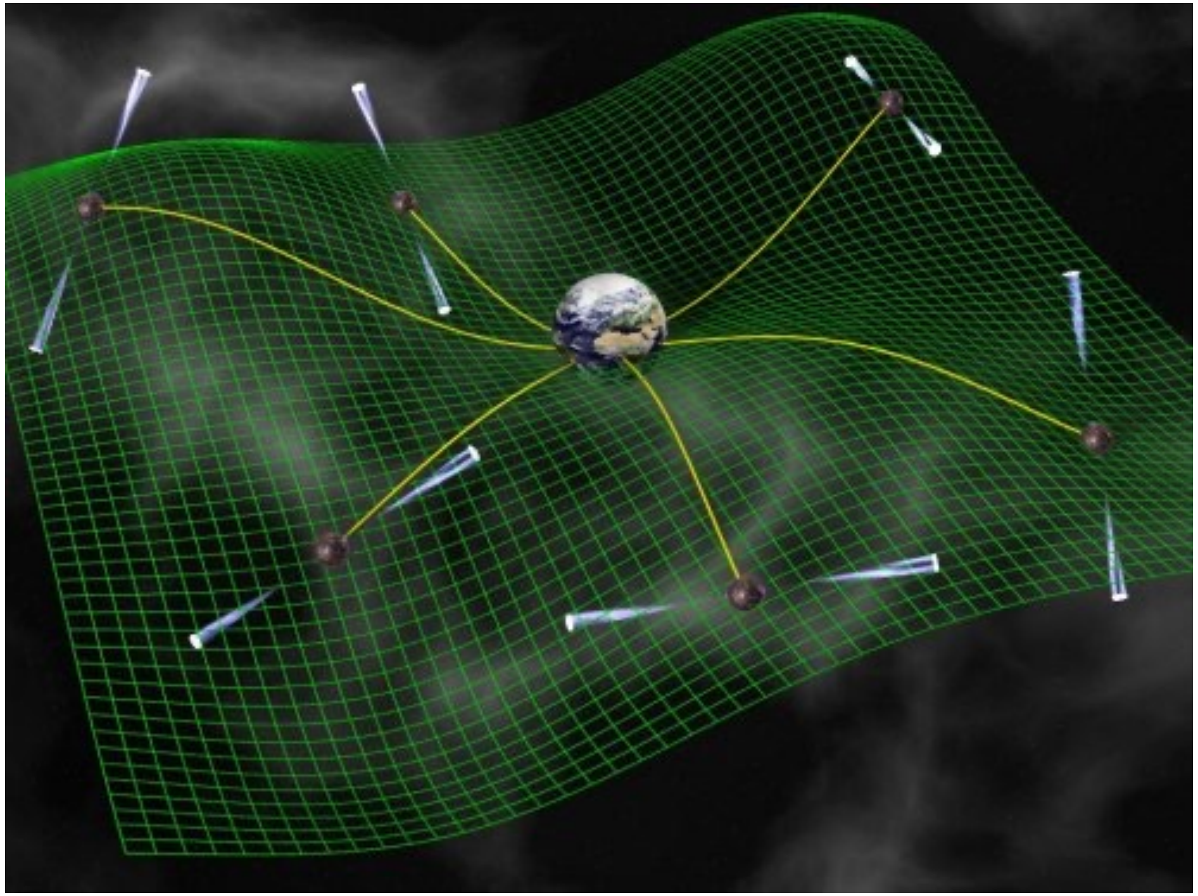
- Groups working together:
  - Europe (EPTA)
  - North America (NANOGrav)
  - Australia (Parkes PTA; PPTA)
  - **MeerKAT Pulsar Timing Array/**India/China
  - International Pulsar Timing Array (IPTA)



Gravitational waves and pulsar timing

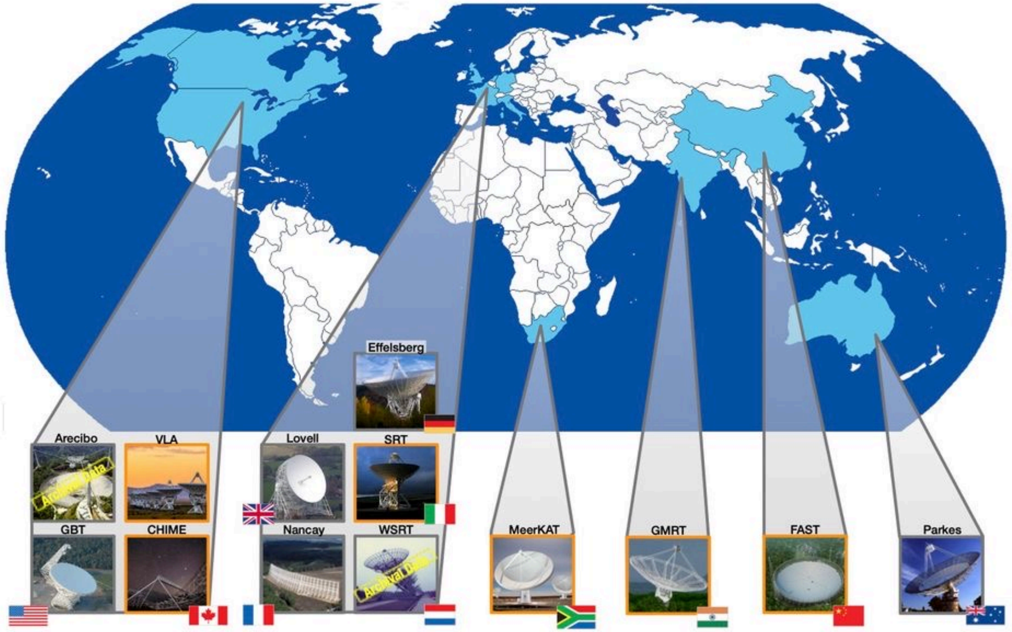
- Signal has quadropolar correlation between pulsars (pulsar timing array, PTA)

- **Differences to laser interferometers/CBC:**
    - Nanohertz frequency
    - Different path to detection
        - Ephemeral versus gradual (PTA)
    - Single realisation of both signal and noise
    - Imperative to model ”detector noise” and search for GW simultaneously
        - Only one realization of both



What has been found so far?

- Concerted efforts in Australia (Parkes Pulsar Timing Array), Europe (European Pulsar Timing array) and North America started in the mid-2000s.
- Searches have become more sensitive
  - Longer timing baselines
  - Larger number of pulsars
  - More sensitive instrumentation/observatories

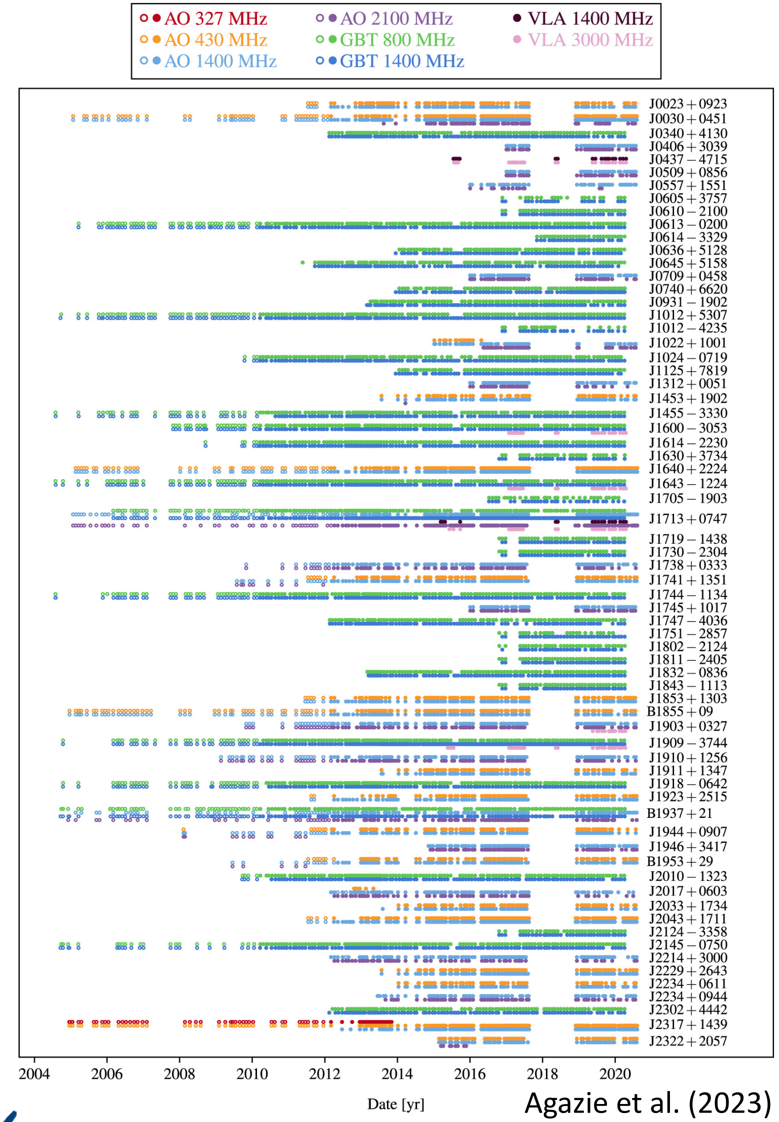


Credit: IPTA

Latest gravitational wave searches

Data sets:

- NANOGrav 15-year data set (Agazie et al. 2023)
  - 65 pulsars observed with Arecibo, Green Bank, and Very Large Array telescopes in North America
- PPTA DR2: 18-year data set (Reardon et al. 2023)
  - 30 pulsars observed with *Murriyang*
- Techniques:
  - Bayesian model selection using *Enterprise*
  - Marginalise over pulsar dependent (red/white) noise terms
  - Search for systematic errors in the solar system ephemeris using *Bayesephem*

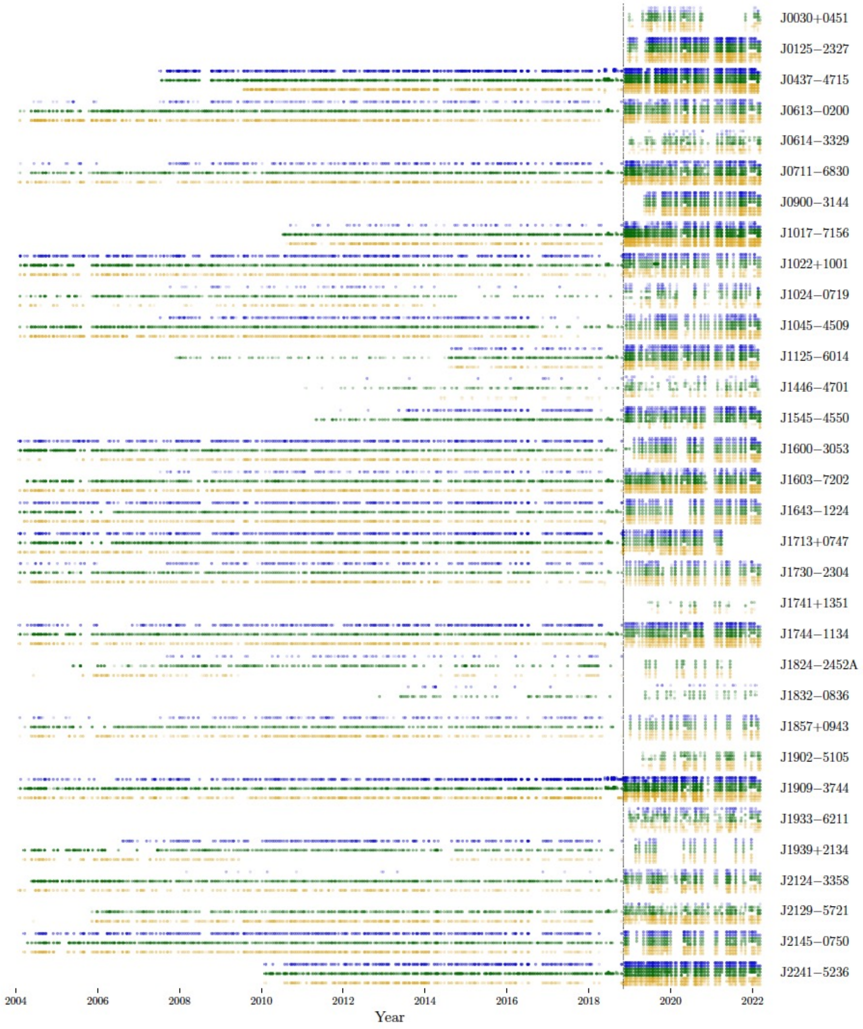


Agazie et al. (2023)

PPTA data set

- 26 pulsars
- 2004-2018

- Data release (Zic et al. 2023)
- Noise models (Reardon et al. 2023b)
- Some common pulsars with NANOGrav, including some of the best timing pulsars



Zic et al. (2023)

Setting the stage

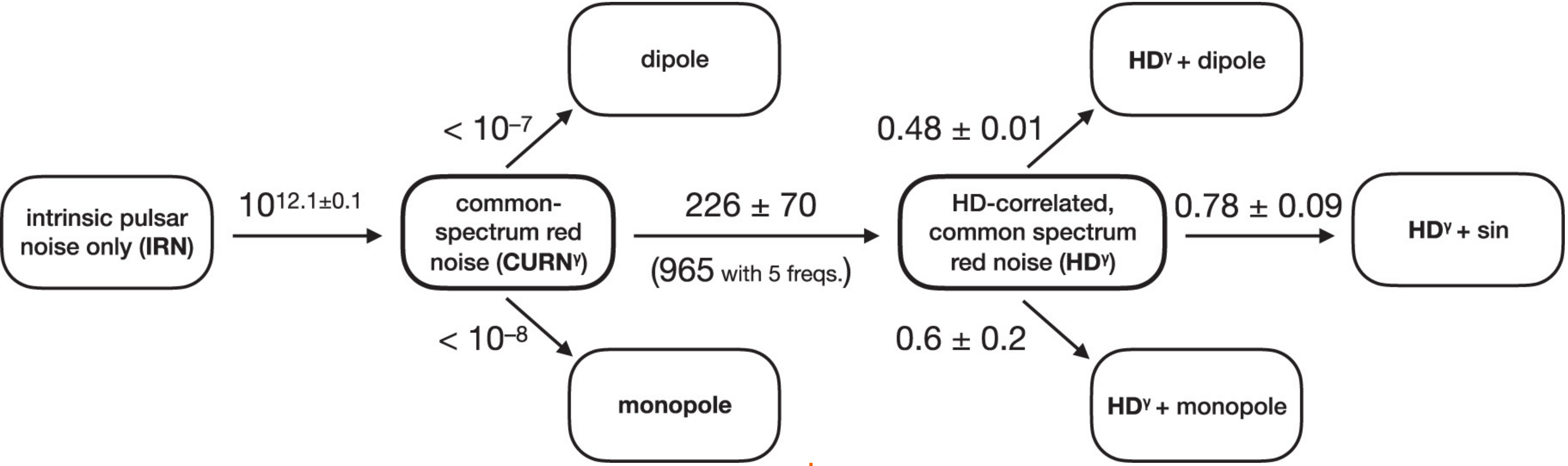
- All PTAs find significant *Bayesian* evidence for common red process in their analysis
- Modest evidence for Hellings-Downs correlations
- Side-by-side comparison of PPTA and NANOGrav results

Search methodology

Is there evidence for a common-spectrum $\gamma = 13/3$ process?
Yes, strong evidence.

Is there evidence for a spatially correlated $\gamma = 13/3$ process?
No strong evidence for HD correlations, decisive evidence against monopole and dipole.

Is there evidence for a second $\gamma = 13/3$ process on top of HD?
Little evidence either way.



intrinsic pulsar noise only (IRN)

$10^{12.1\pm0.1}$

common-spectrum red noise (CURN$^\gamma$)

$< 10^{-7}$

dipole

$< 10^{-8}$

monopole

226 ± 70

(965 with 5 freqs.)

HD-correlated, common spectrum red noise (HD$^\gamma$)

0.48 ± 0.01

HD$^\gamma$ + dipole

0.78 ± 0.09

HD$^\gamma$ + sin

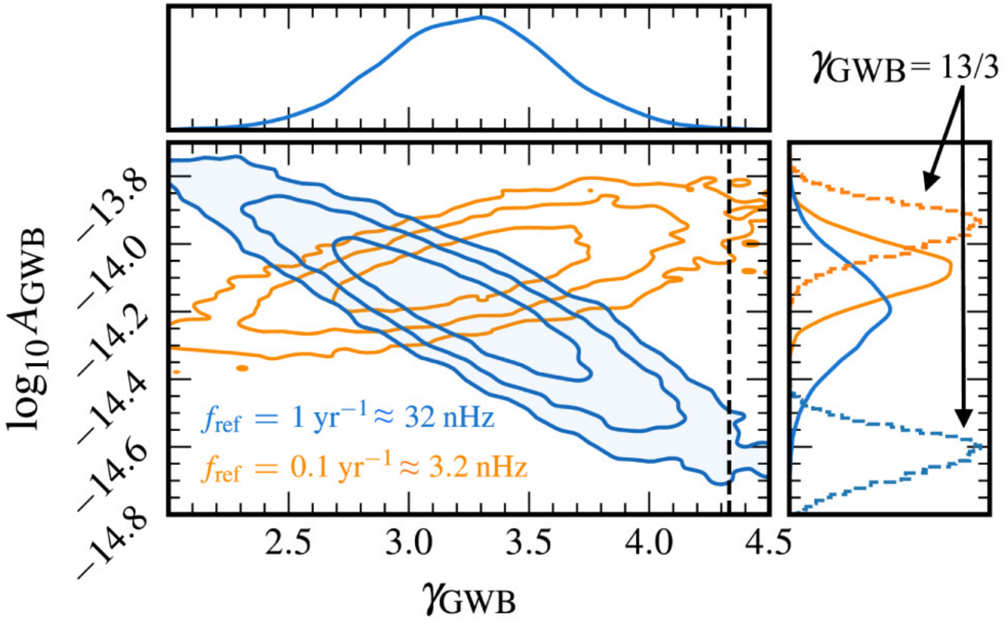
0.6 ± 0.2

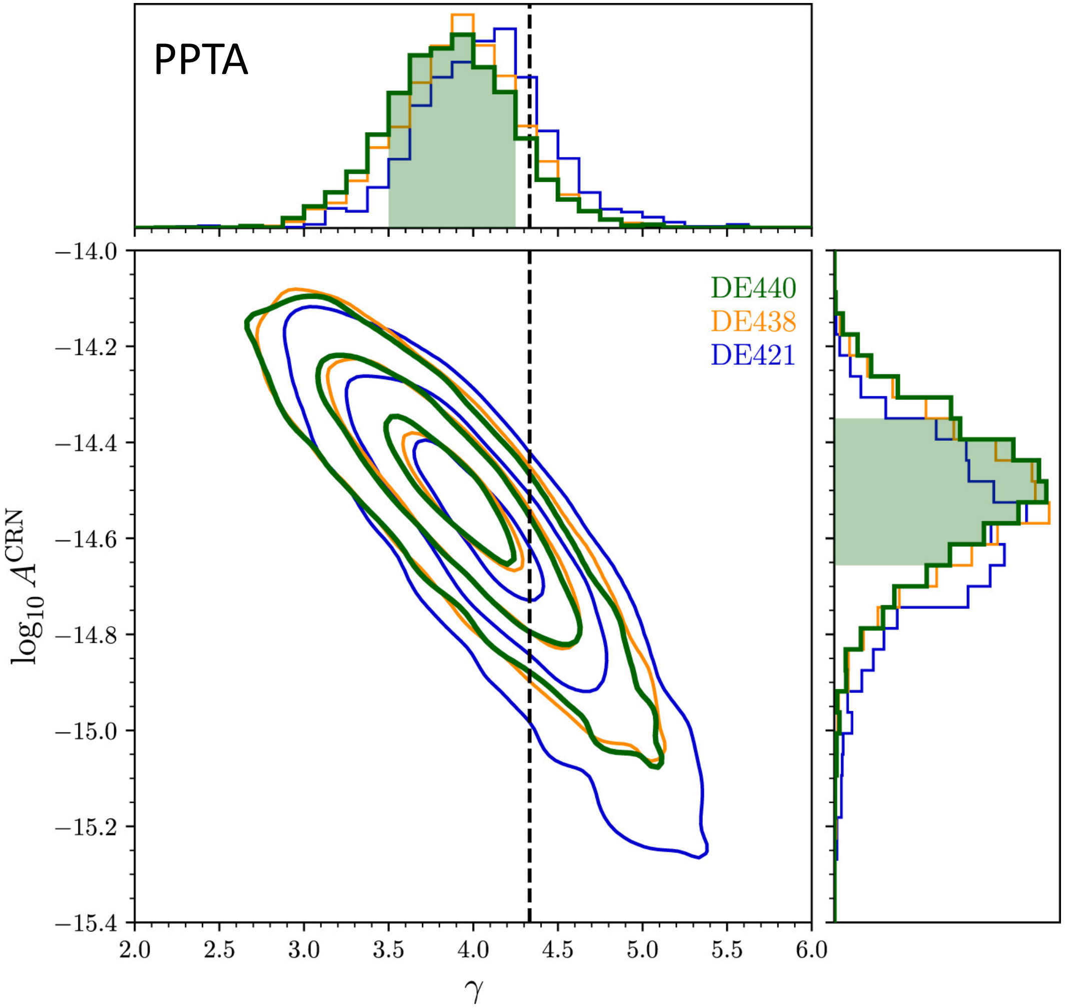
HD$^\gamma$ + monopole

Agazie et al. 2023

Common red noise

NANOGrav



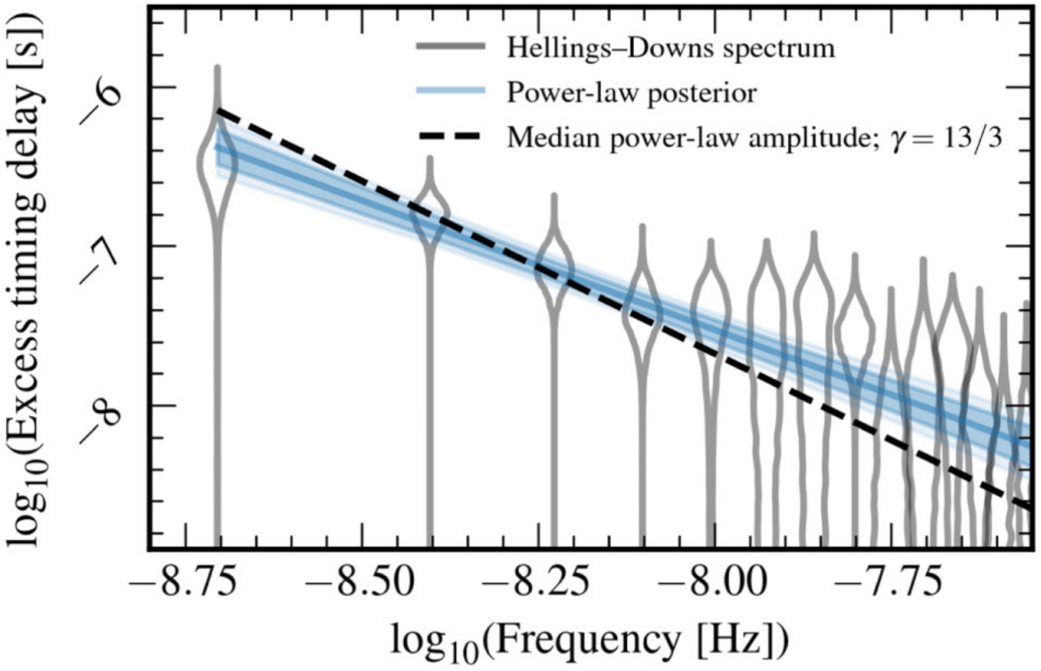


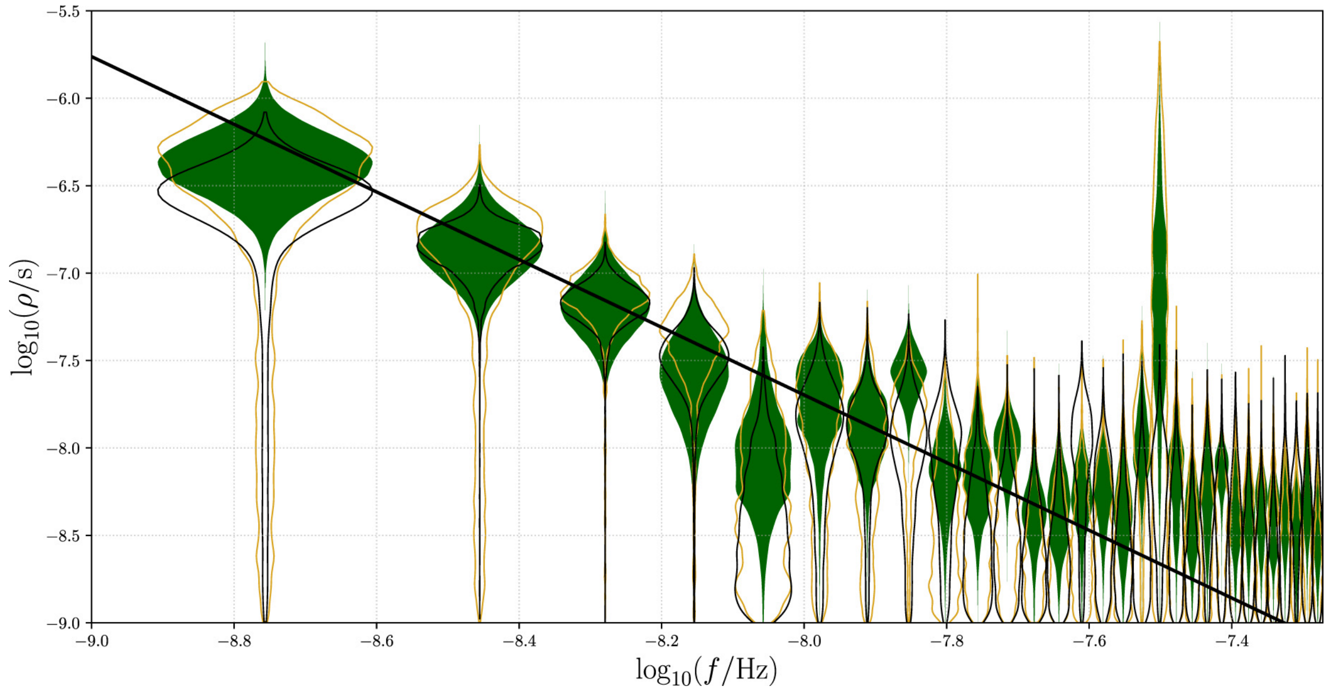
Posterior probability distributions: probability of a model parameter given the data.

A: amplitude of the CRN

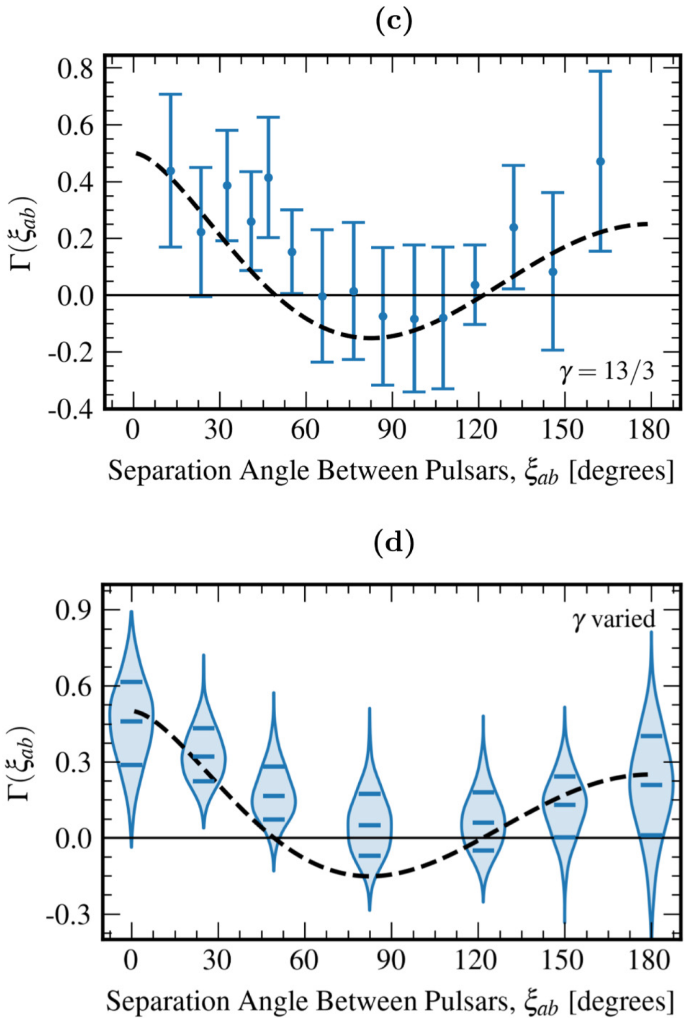
Ɣ: spectral index of the CRN

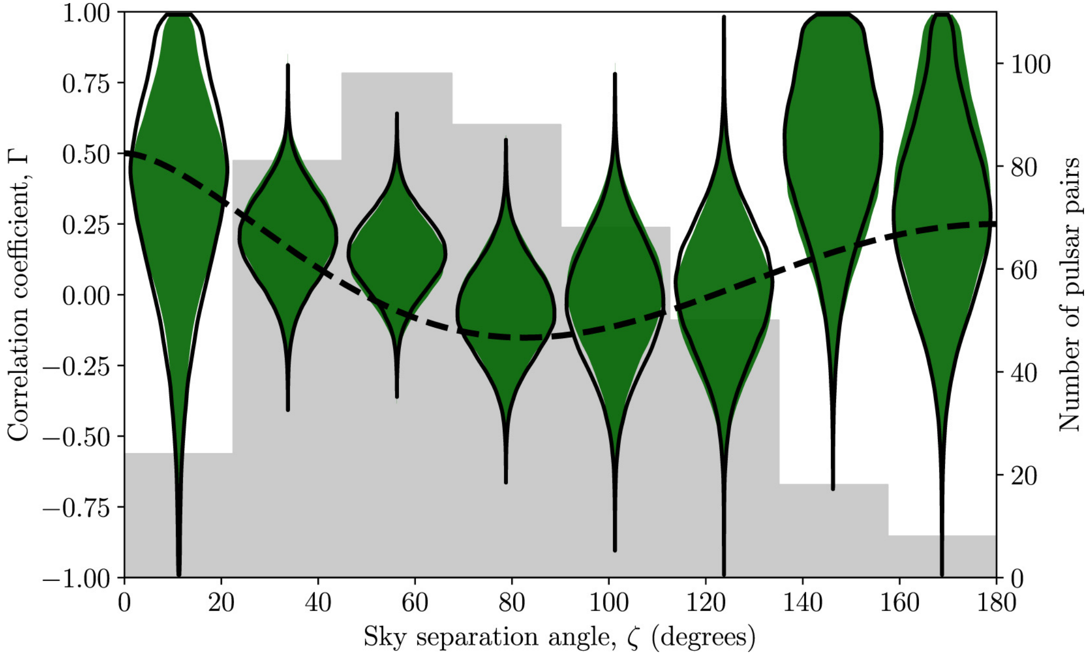
Spectrum of common noise





Search for correlations

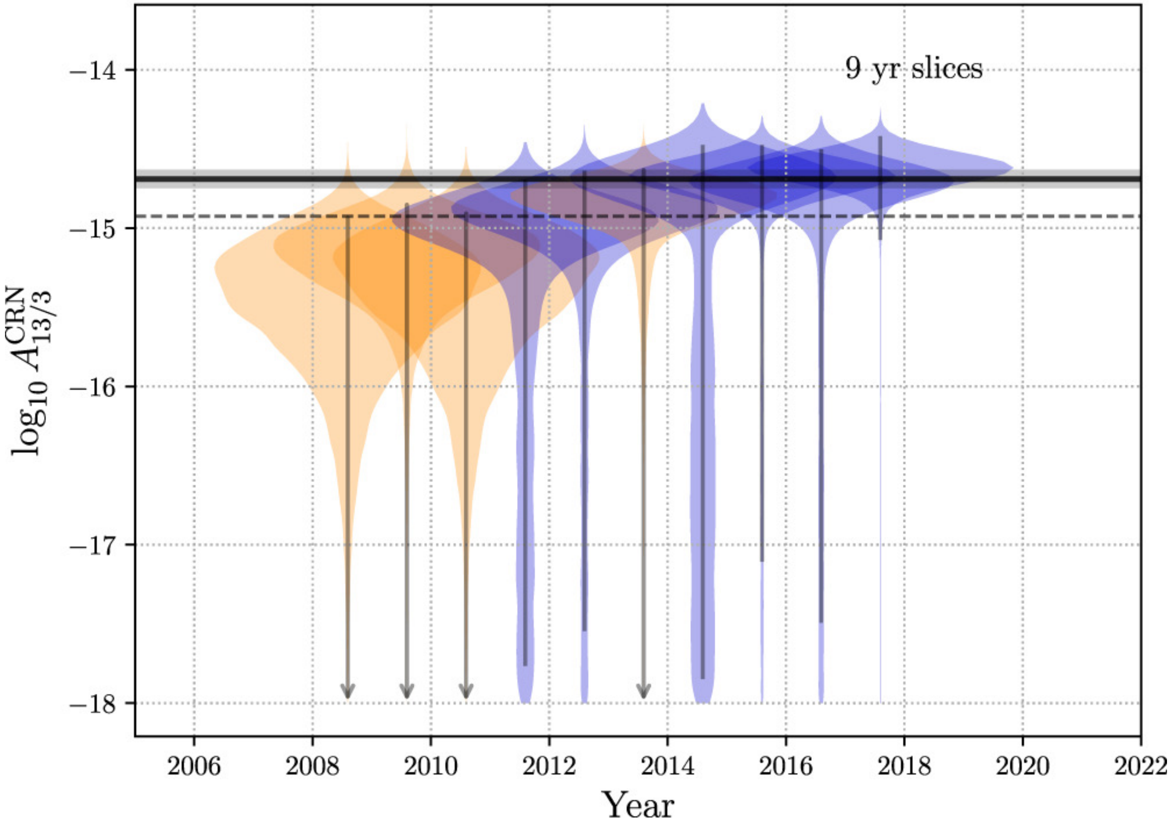




2-4 sigma evidence for a gravitational wave background

Weird things in PPTA data

- Previous upper limits on GWB inconsistent with loudness of common red noise signal
- Signal appears to be growing in amplitude with time

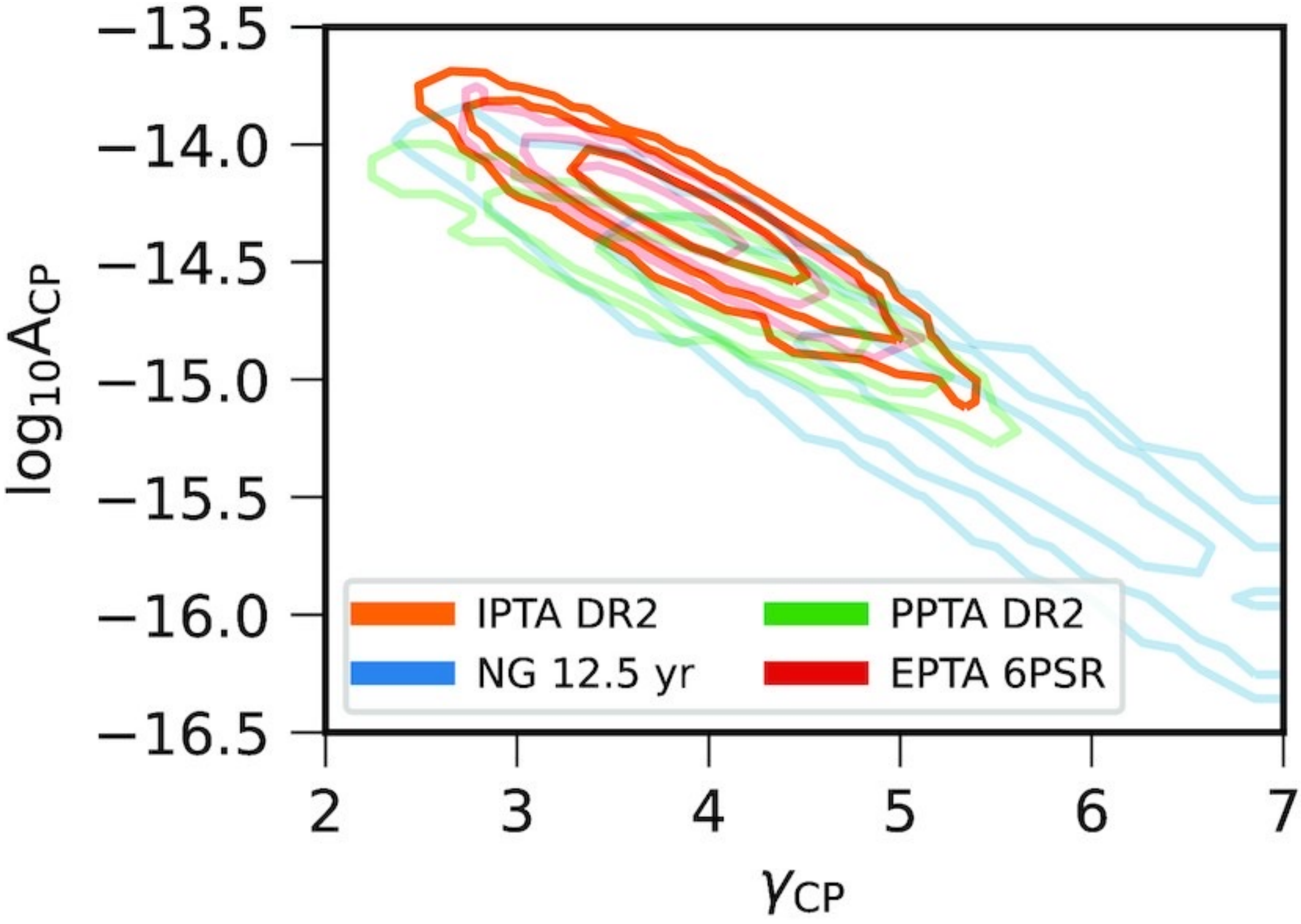


Reardon et al. (2023)

Other recent searches

- EPTA: 20 pulsars
- IPTA DR2: 42 pulsars
  - Signal strength depends on amplitude of GWB

- Searches provide mostly consistent results in common red noise
- All provide only modest evidence for GWB



Next steps: GW searches

- Detection of GWB will require convincing detection of Hellings-Downs correlation

- Existing PTAs
  - Better characterization of noise
  - Extended timing baselines

- International Pulsar Timing Array
  - Sensitivity scales strongly with number of pulsars
  - Combine EPTA, NANOGrav and PPTA data sets
  - IPTA-DR2 analysis completed
    - NANOGrav 9 year data set and PPTA 2015 data set
  - IPTA-DR3

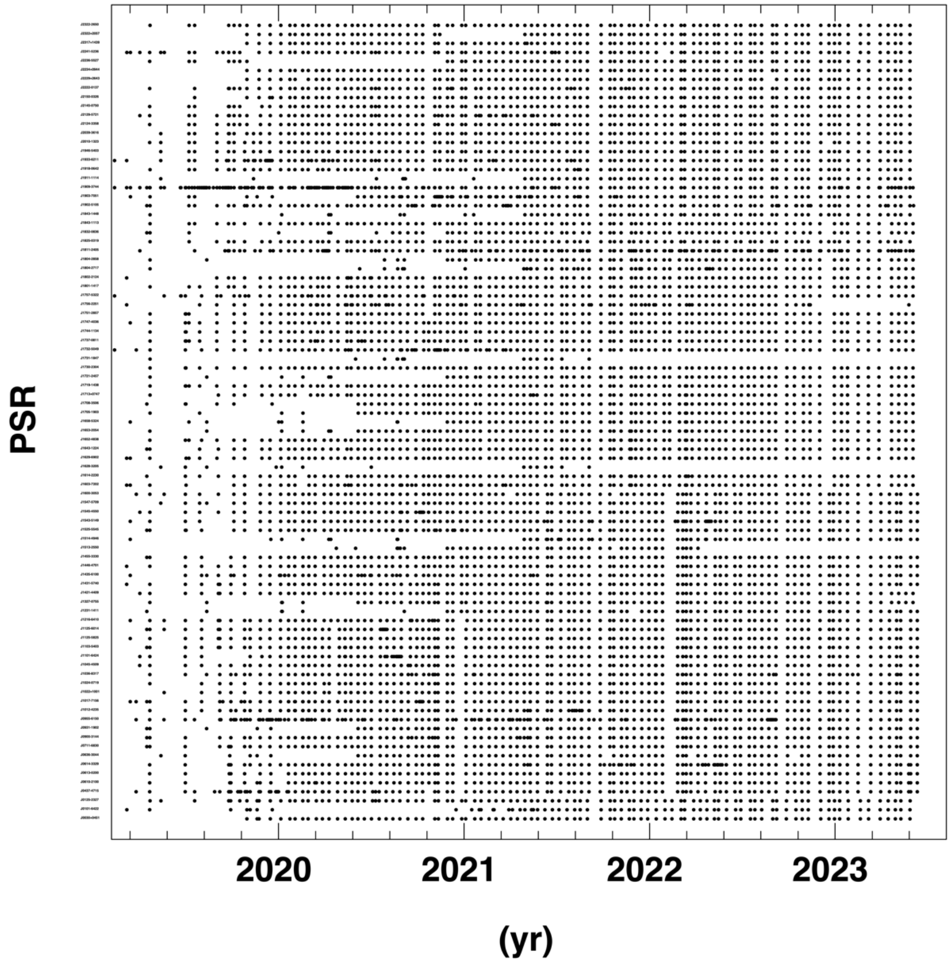
Improving Sensitivity

Detection of GWB will require convincing detection of Hellings-Downs correlation

- **New facilities**
  - Increase sensitivity
  - MeerKAT/FAST
- **Improved instrumentation**
  - Wide (radiofrequency) bandwidth receiving systems
- **Improvements in algorithms/systems**
  - Better understand systematics / improve calibration of the signal
  - Coordination between facilities
- **More pulsars**
  - Large-area sky surveys for new pulsars

MeerKAT Pulsar Timing Array

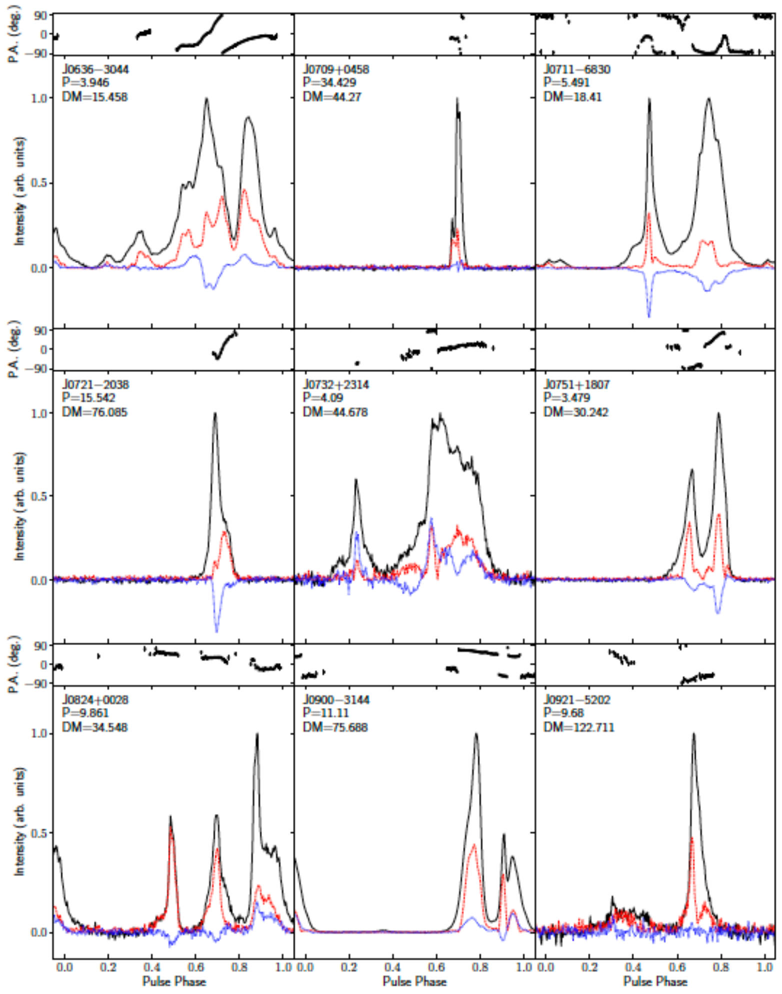
- Regular observing started in Feb 2019
- MeerTime MSP timing:
  - ~ 10,000 observations of 190 pulsars in ~ 600 hours
  - Observations with L-band (900-1.7 GHz)
  - Typically observe in standard pulsar timing “fold” mode
    - Occasional observation in search/baseband mode to study single pulses



OzGrav

MeerTime MSP program: first projects

- Pulsar census (Spiewak et al., submitted)
  - Homogenous study of 187 MSPs
  - Observe all MSPs at least 4-6 times
  - Study of MSP emission
  - Determine MSPs suitable for monitoring with MeerKAT and the SKA
- Pulse jitter (Parthasarathy et al. 2021)
- First data release (Miles et al. 2023)



Spiewak et al., Submitted

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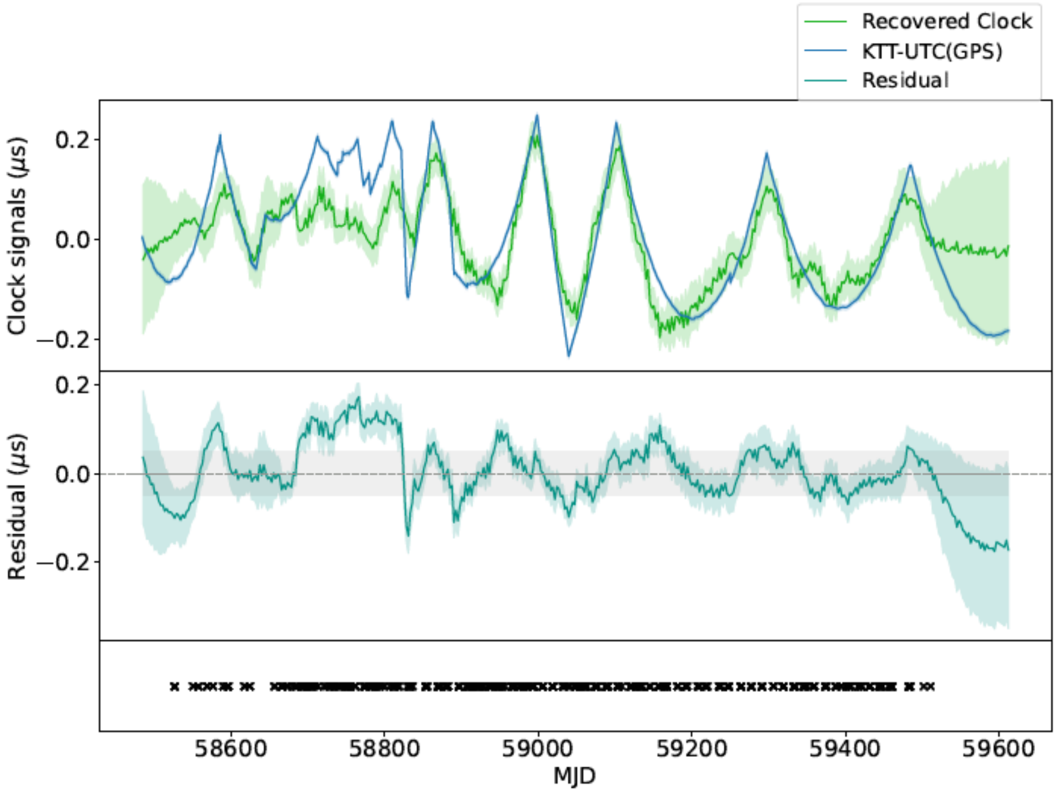


Forecasting array sensitivity

Estimate by S/N (ρ) by match filtering with Hellings-Downs correlation

- Model signals in noise in Fourier domain
- Sum over all pulsar pairs (*ij*)
- Sum over all fluctuation frequencies (*k*)
- Each channel provides an atom of S/N^2

- P_p: pulsar noise model
- P_g: GW power spectral density
- χ_{ij}: Hellings-Downs correlation func

$$\chi_{ij} = \frac{3}{4}\left(1 - \cos(\theta_{ij})\right) \log\left(1 - \cos(\theta_{ij})\right) - \frac{1}{8}\left(1 - \cos(\theta_{ij})\right) + \frac{1}{2}$$

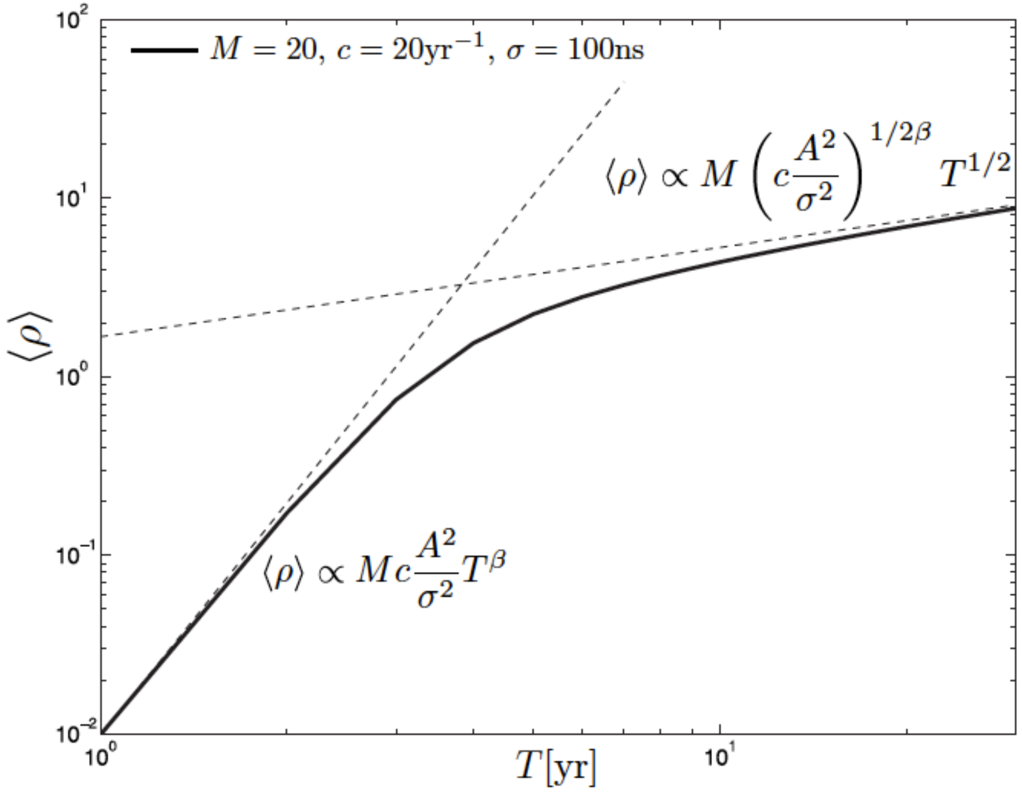
Signal to noise ratio

$$\rho^2 = \sum_{i=1}^{N_p-1} \sum_{j=i+1}^{N_p} \chi_{ij}^2 \sum_{k=1}^{N_f} \frac{P_g^2(f_k)}{P_{p_i}(f_k) P_{p_j}(f_k)},$$

OzGrav

MeerTime MSP strategy: motivation

- **Weak signal:** signal dominated by measurement noise in cross correlations
  - Fast increase in S/N
- **Strong signal:** Dominated by self noise in cross correlations
  - Signal only increases slowly with time
- *In both regimes the S/N increases linearly with number of pulsars*

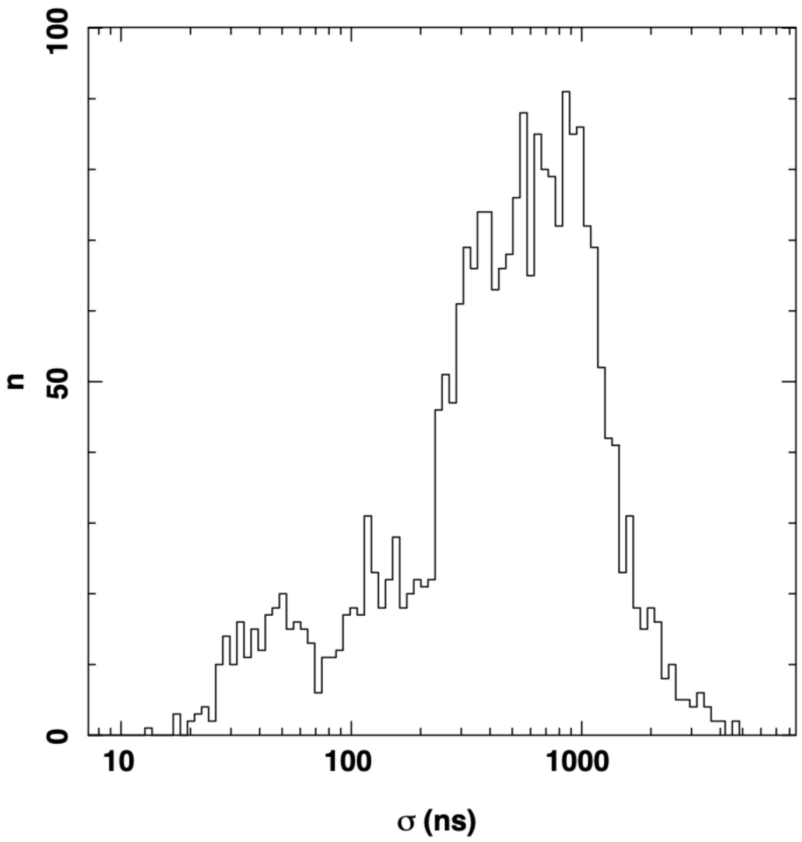


Siemens et al. (2013)

Current observations/strategy

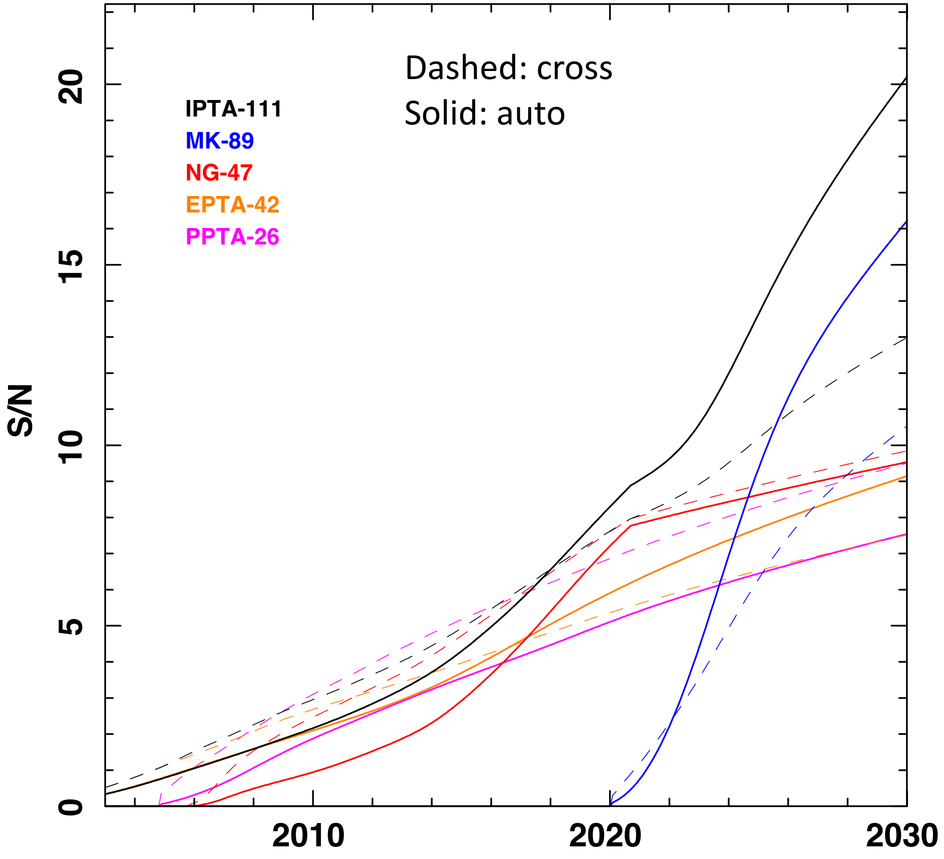
- Time as many pulsars as possible to (median) sub-microsecond precision
  - If 1 μs is achieved in < 256 s, observe for 256 seconds
  - Tailor integration times to achieve 1 μs precision
  - Don't observe pulsars where sub-1 μs takes longer than ~2000 s.
- As of 2023 July: 83 pulsars pass this
  - Most are South of δ < 0°

Histogram of all PTA TOAs



Assessing the array sensitivity

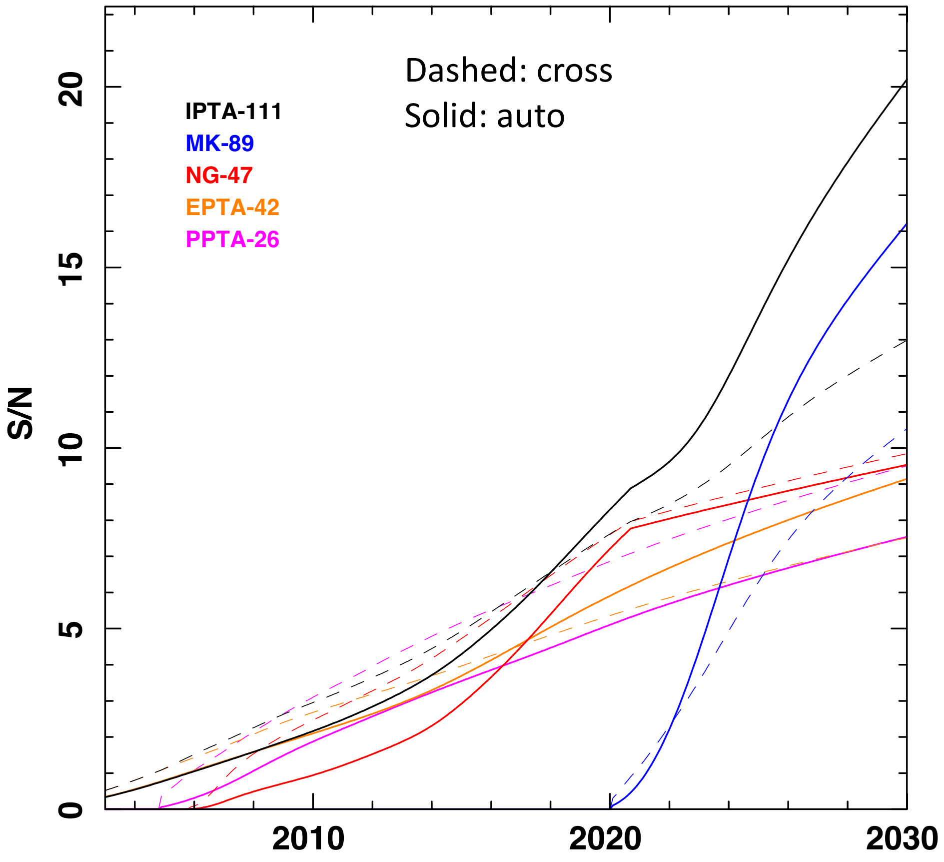
- 80 pulsars can be observed in 11 hours of integration time (286 hours per year with fortnightly cadence)
- Compare sensitivity to other PTAs
  - Noise models from Goncharov+20 (PPTA) and Alam+20 (NANOGrav) for red noise
- Create simple IPTA
  - Include pulsars from single timing array which gives “best” precision”
  - *Assume $A_{gw,yr}$*: $2\mathrm{x}10^{-15}$
    - Level of purported common red noise in NANOGrav data



NANOGrav and IPTA curve assume Arecibo MSPs are not observed elsewhere

Assessing the array sensitivity

- Initially Increases rapidly because of large number of well-timed pulsars
- Continues to increase rapidly because of large total number of pulsars
- Despite shorter timing baselines, MPTA will be contributing to international sensitivity on the time scale of MeerKAT
- Will provide legacy data sets for SKA

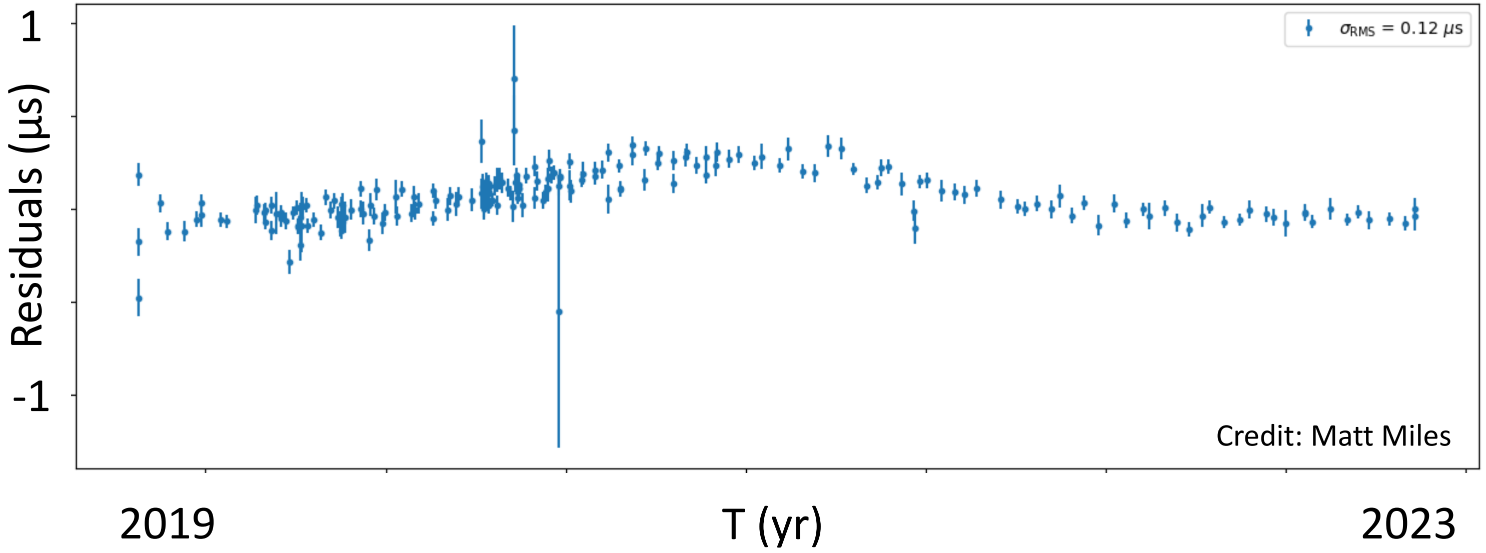


NANOGrav and IPTA curve assume Arecibo MSPs are not observed elsewhere

MeerKAT MSP timing update

- Extended data set: Feb 2019 – Jan 2023
- Data reduced using same approach as in Miles et al. (2023)
- Search for astrophysical noise processes
    - DM variations f^{-2}
    - Scattering noise $f^{-4} - f^{-6}$
    - Solar wind
    - Jitter noise
- Important to have best noise model in search for gravitational waves
- Hierarchical inference using standard methodology

Frequency averaged residuals: corrected for DM and stochastic solar wind

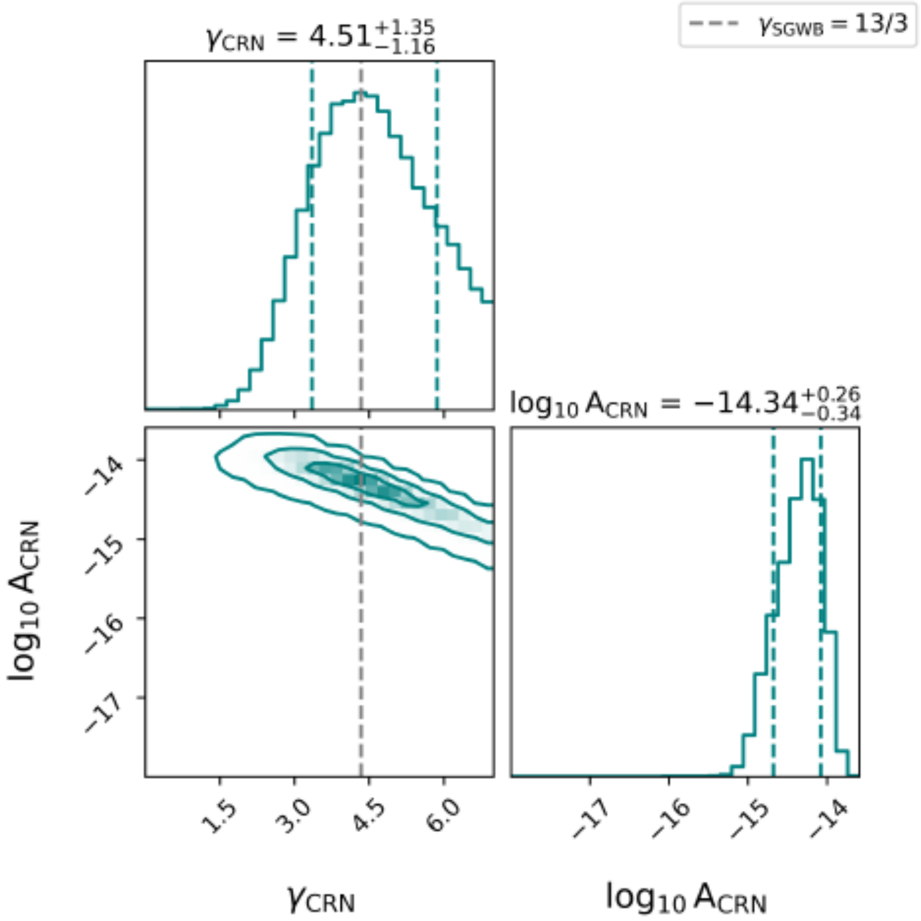


Credit: Matt Miles

Strong achromatic red noise observed in best millisecond pulsars
CRN stronger than in older data setss

MeerKAT MSP timing update

- Extended data set: Feb 2019 – Jan 2023
- Data reduced using same approach as in Miles et al. (2023)
- Search for astrophysical noise processes
  - DM variations f^{-2}
  - Scattering noise $f^{-4} - f^{-6}$
  - Solar wind
  - Jitter noise
- Important to have best noise model in search for gravitational waves
- Hierarchical inference using standard methodology



Miles, PhD Thesis (2023)

Summary

- Nanohertz gravitational waves provide a new tool to study the Universe
- Pulsar timing arrays can be used to search for such signals
- New facilities / longer datasets /more pulsars will enable us to detect GWs with pulsars.
- MeerKAT to play pivotal role