NCRA • TIFR

InPTA
Indian Pulsar Timing Array

The Indian Pulsar Timing Array: An Overview

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tifr

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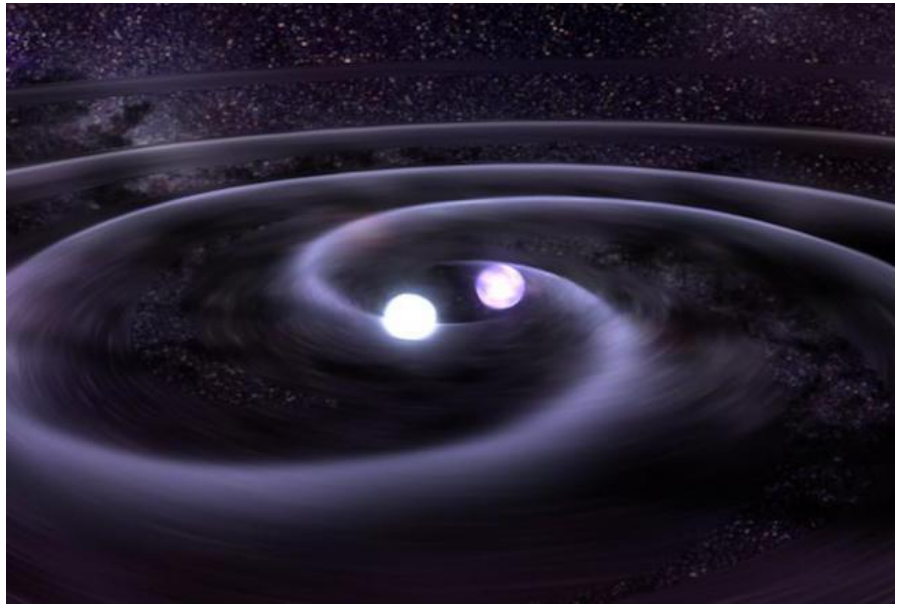
OCAMI

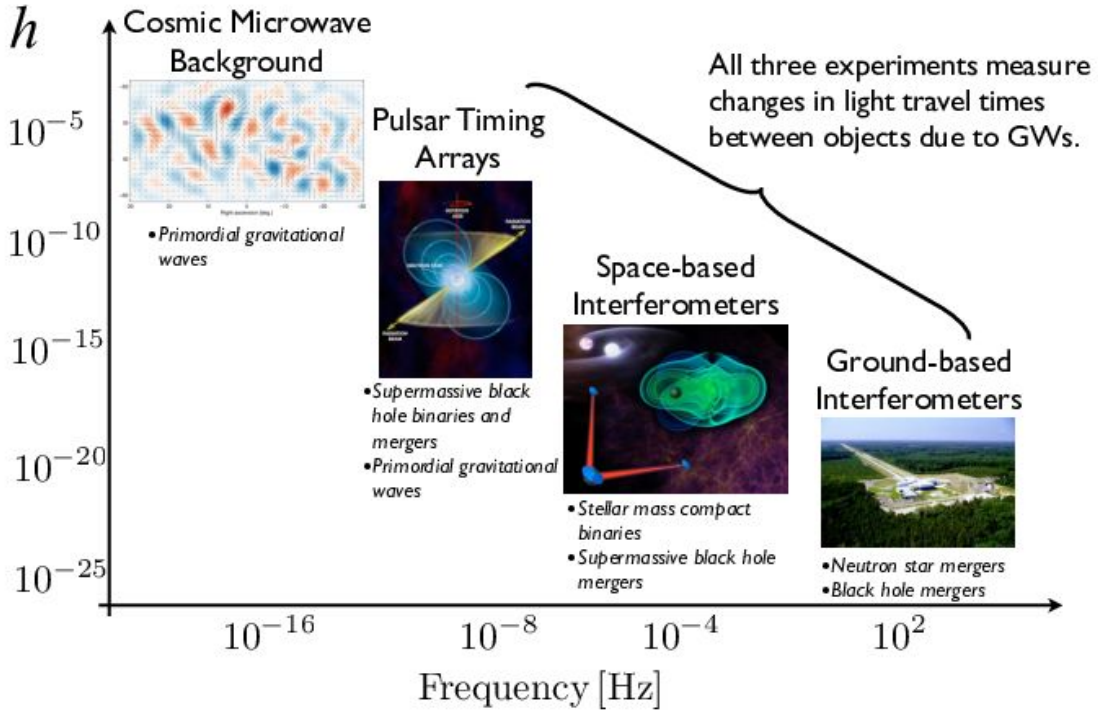
Gravitational Waves

- Heaviside proposed GWs in 1865
- Einstein's formulation in 1918
- Weber's attempt at detection with Weber cylinders during 1958–1970
- Indirect evidence of GWs in a binary pulsar by Hulse & Taylor 1974
- Direct evidence of short wavelength GWs by LIGO/Virgo in 2015
- First emerging evidence for GWB from PTAs in 2023



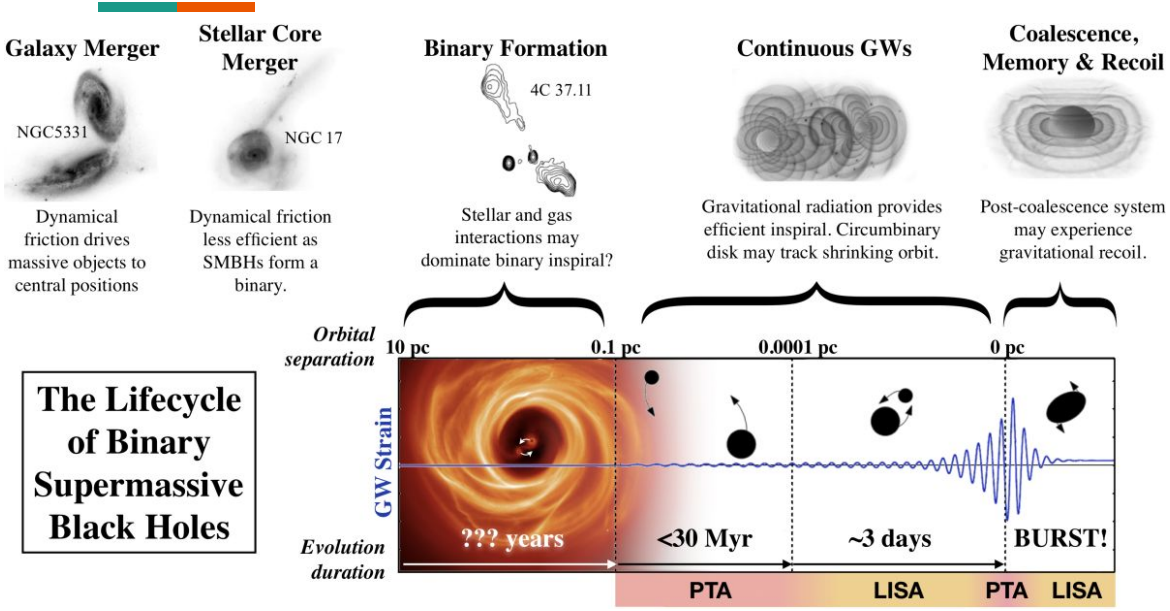
Credit: GSFC

GW spectrum & detectors

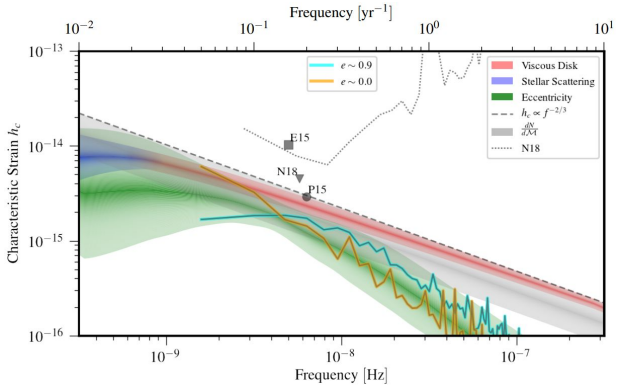


Credit: NANOGrav

GWs from SMBHBs



Credit: Burke-Spolaor et al. 2019, ARAA



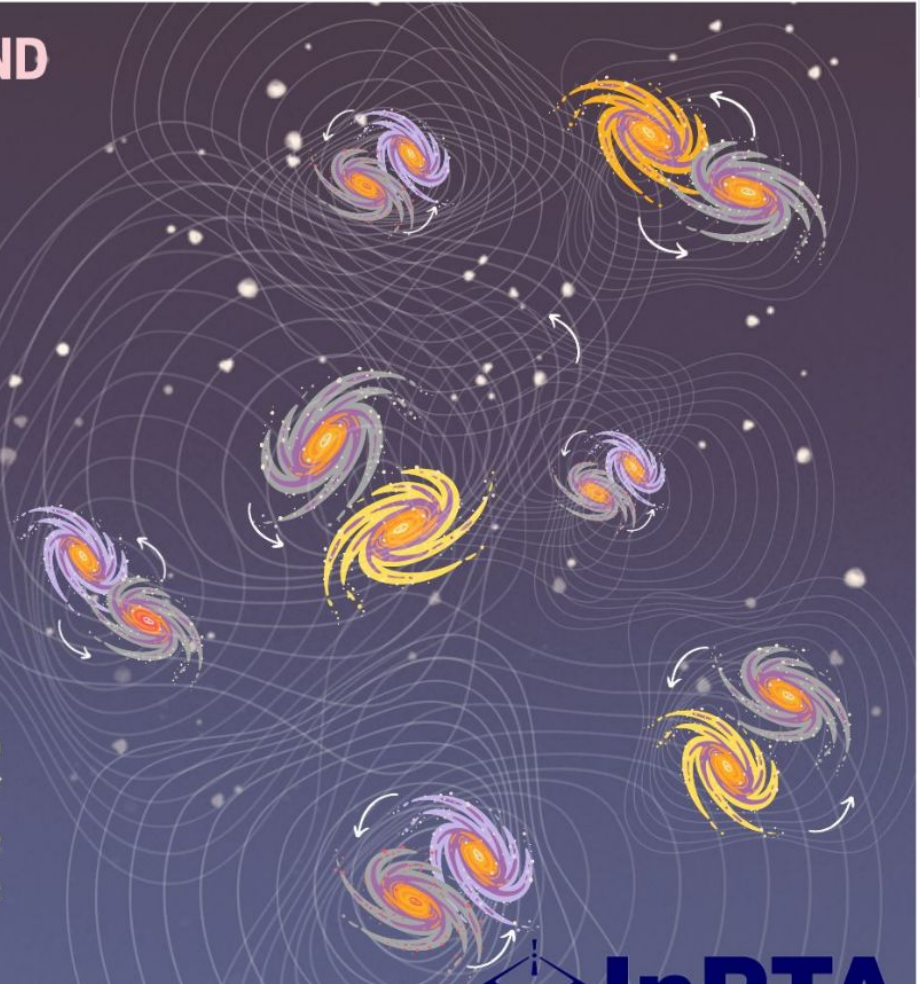
Spectrum of SGWB

$$h_c \sim 10^{-15} \left(\frac{f}{yr}\right)^{-2/3}$$

Jaffe & Backer 2003, ApJ

THE GRAVITATIONAL WAVE BACKGROUND

These waves stretch along for many light years, and cannot be detected by experiments such as LIGO, VIRGO or KAGRA, which have been detecting gravitational waves from merging black holes only 10s of times the mass of the sun



As black holes merge all across the universe, in every direction in the sky, these waves overlap and form a background hum of gravitational waves. This thrumming hum is called as the stochastic gravitational wave background, and it has been the ongoing goal of PTA experiments to detect it.

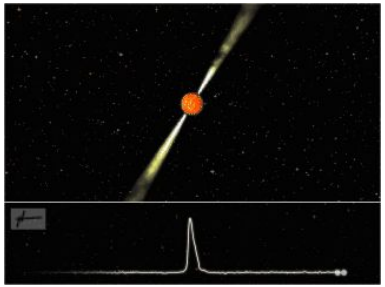
• Neel Kolhe

Infographics credit: Neel Kolhe (InPTA)

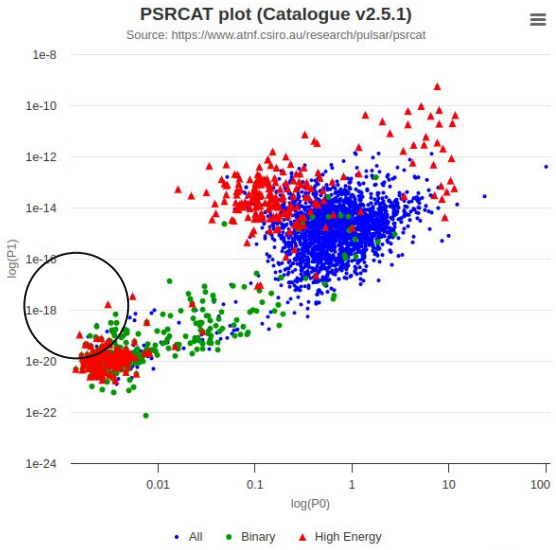
InPTA
Indian Pulsar Timing Array

Pulsars!!

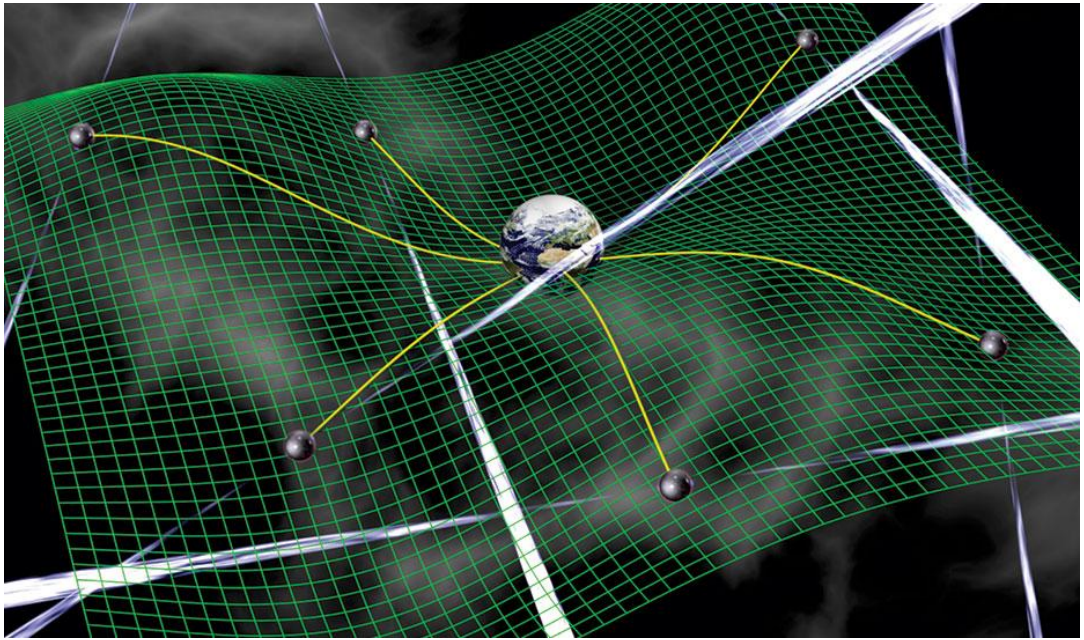
- Highly magnetised neutron stars (1.4 $M_{\odot}$ and r~10 km)
- Around 3700+ discovered till date
- Fast and extremely stable rotators - millisecond pulsars (MSPs)
  - Low B (~10^9 G) and extremely stable period below ~30 ms
  - High precision measurements of the pulse arrival time (< 1 μs)
  - Usually found in binaries



Credit: ASTRON

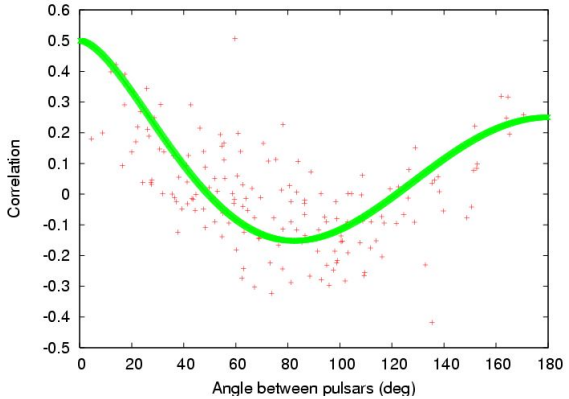


Pulsar Timing Arrays



Credit: David Champion

Pulsar arrival times will be correlated with quadrupole nature: Hellings & Downs correlation

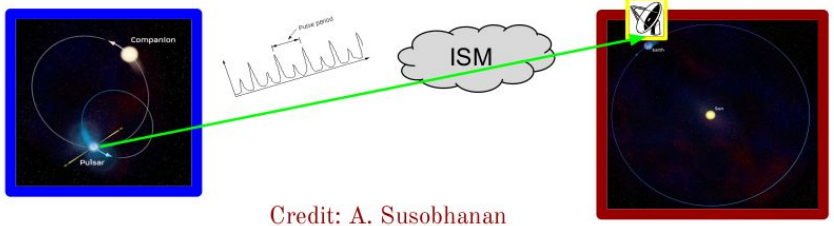


Credit: Andrea Lommen

High Precision Pulsar Timing

$$t_{obs} = t_{em} + \Delta_{Binary} + \Delta_{DM} + \Delta_{SolarSystem} + t_{clock} + \Delta_{GW} + \ldots$$

(Hobbs et.al. 2006)



Credit: A. Susobhanan

Credit: P. Freire

Clocks (mostly binary pulsars) are moving (Pulsar ephemeris delays)

Observer (Earth) is moving
Revolution (SSB delay) + Rotation
(local clock delays)

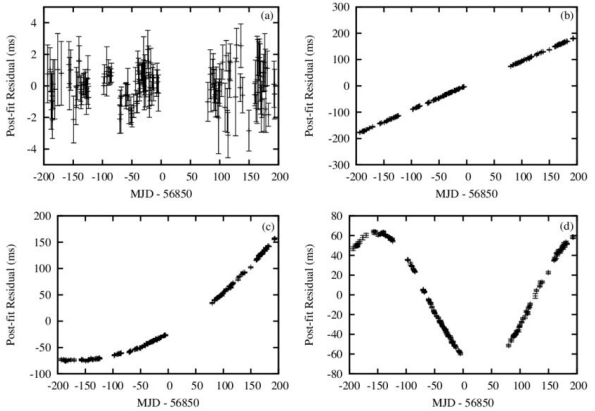
Planets in the SS are moving
(SS ephemeris delays)

Oceans of ISM to cross!

Dispersive delays + scattering delays

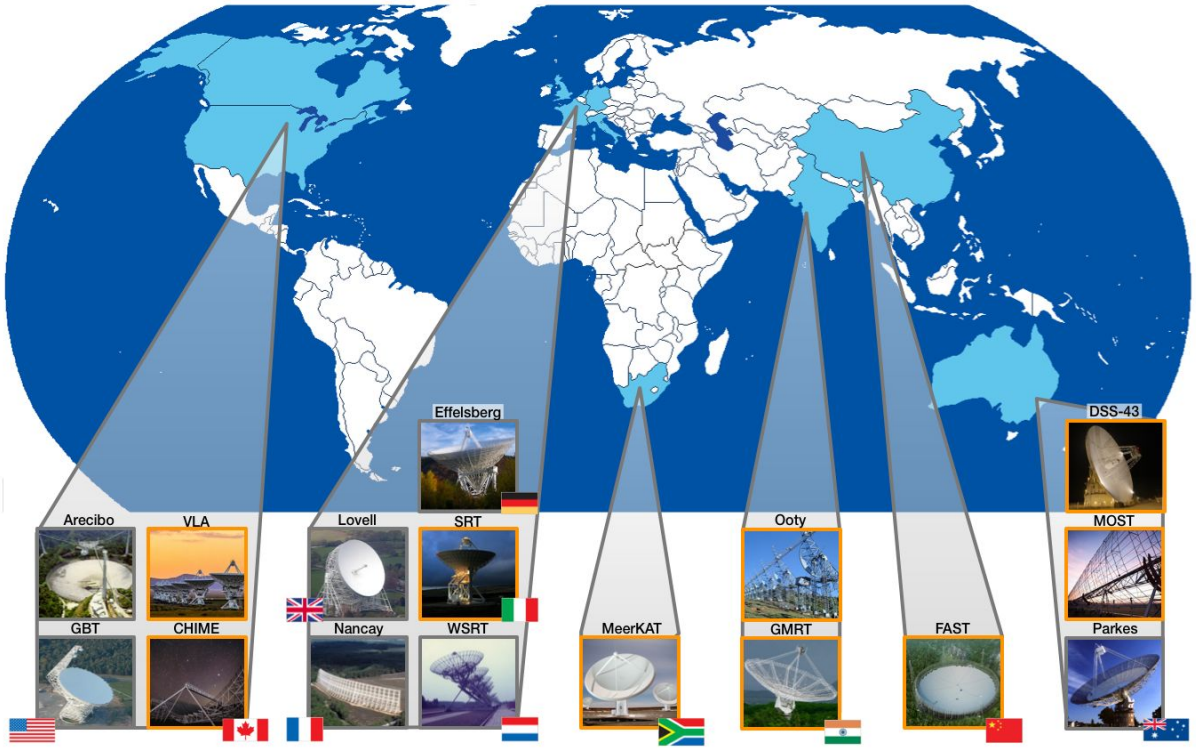
Credit: Pratik Tarafdar

$$T_{resid} = T_{obs} - T_{model}$$



Credit: Lorimer & Kramer 2005

International Pulsar Timing Array



NANOGrav: 67 MSPs, 15 years

EPTA: 25 MSPs, 24 years

InPTA: 20 MSPs, 7 years

PPTA: 30 MSPs, 18 years

MPTA: 89 MSPs, ~5 years

InPTA Consortium

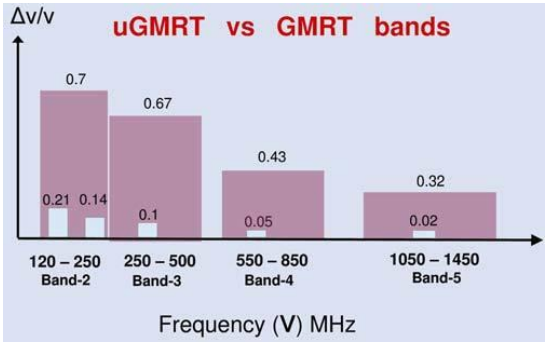
- Indo–Japanese Collaboration (~45 members)
- Started in 2015 with GMRT and ORT observations
- Observes 22 pulsars with a cadence of 10–14 days
- Observations are done with the upgraded GMRT from 2018 onwards

Photo taken during a busy week at IMSc, Chennai

Unique strength of InPTA: Highly sensitive observations at low Radio frequencies with uGMRT

The upgraded GMRT

- An array of 30 dishes, 45m diameter
- uGMRT covers a unique ~300 – 800 MHz range
- Complements observations by PTAs at higher frequencies
- Low- frequency wider bandwidth -> better precision in measuring and correcting ISM noise
- We use 300–500 and 1260–1460 MHz receivers of uGMRT simultaneously for regular observations
- An observation every 10-14 days

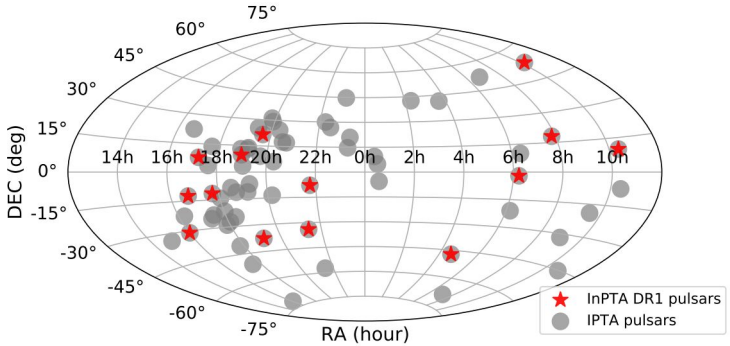


Gupta et al. 2017

InPTA
Indian Pulsar Timing Array

First data release from InPTA

- 22 pulsars with a cadence of ~15 days
- Data span ~3.5 years
- High precision ToAs from two different techniques: Narrowband and Wideband
- Epoch-wise DM for all pulsars using both these techniques

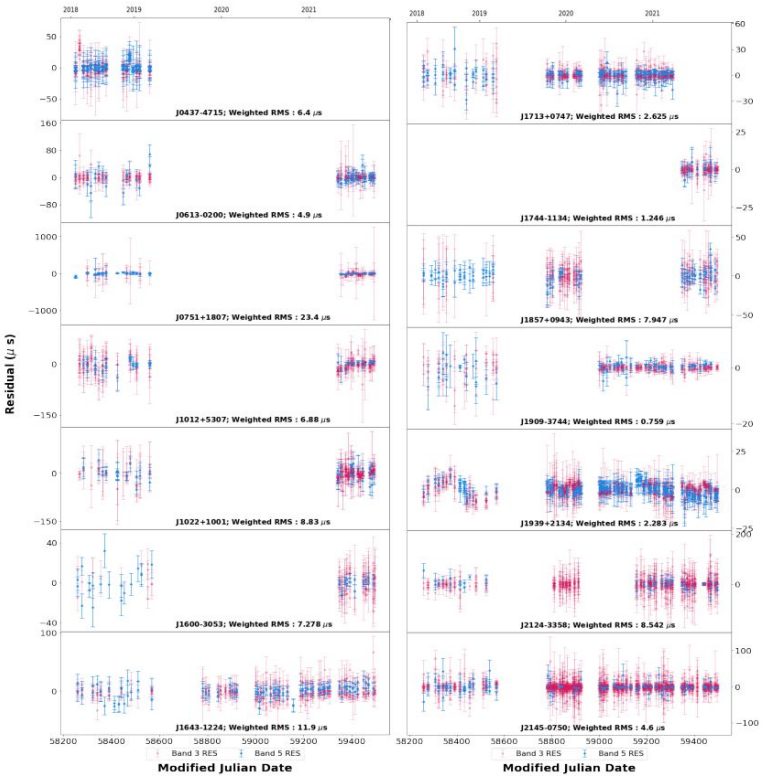


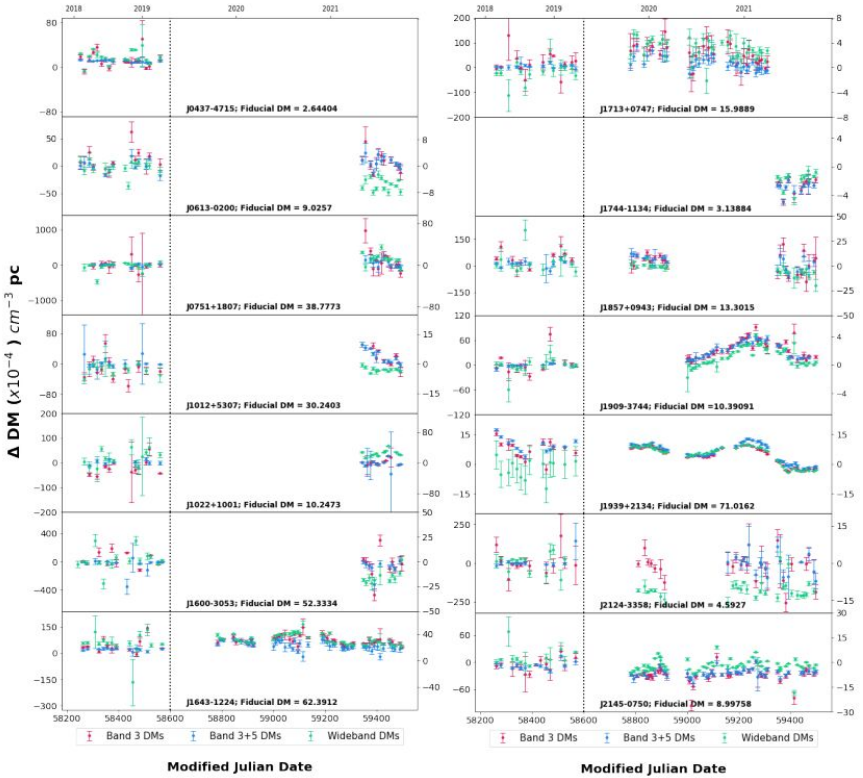
Tarafdar et al. 2022, PASA

- J0437-4715
- J0613-0200
- J0751+1807
- J1012+5307
- J1022+1001
- J1600-3053
- J1643-1224
- J1713+0747
- J1744-1134
- J1857+0943
- J1909-3744
- J1939+2134
- J2124-3358
- J2145-0750

InPTA
Indian Pulsar Timing Array

DR1 Results



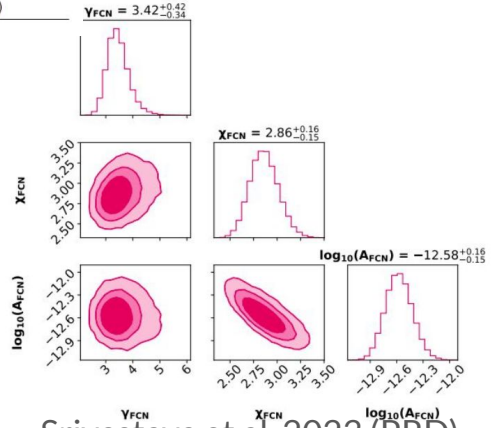


Noise Analysis

- Noise sources can be instrumental, pulsar spin and ISM
- They are modelled as Gaussian random processes
- Individual noise contributions will be modelled and removed while searching for HD correlation
- Significant amount of computing power is required
- One pulsar analysis will take 2-3 days, and GWB search about a month on clusters

Noise (abrev.)	Parameters	Priors (or fixed val.)
White Noise	EFAC	$\mathcal{U}(0.1,5)$
(WN)	EQUAD [s]	$\log_{10}\mathcal{U}(10^{-9},10^{-5})$
Achromatic red-noise	A_{RN}	$\log_{10}\mathcal{U}(10^{-18},10^{-10})$
(RN)	γ_{RN}	$\mathcal{U}(0,7)$
DM variations	A_{DM}	$\log_{10}\mathcal{U}(10^{-18},10^{-10})$
(DMv)	γ_{DM}	$\mathcal{U}(0,7)$
Scattering variations	A_{Sv}	$\log_{10}\mathcal{U}(10^{-18},10^{-10})$
(Sv)	γ_{Sv}	$\mathcal{U}(0,7)$
Free chromatic noise	A_{FCN}	$\log_{10}\mathcal{U}(10^{-18},10^{-10})$
(FCN)	γ_{FCN}	$\mathcal{U}(0,7)$
	χ_{FCN}	$\mathcal{U}(0,7)$

J1939+2134



We used PARAMGanga (IIT Roorkee) and PARAMSeva (IIT Hyderabad)

Srivastava et al. 2023 (PRD)

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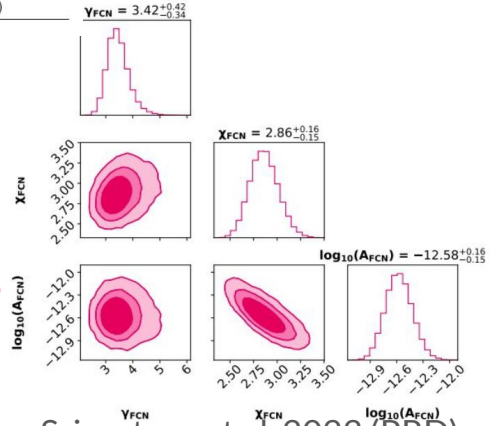

For more on Noise Analysis, listen to Aman's talk on Wednesday at 14:45

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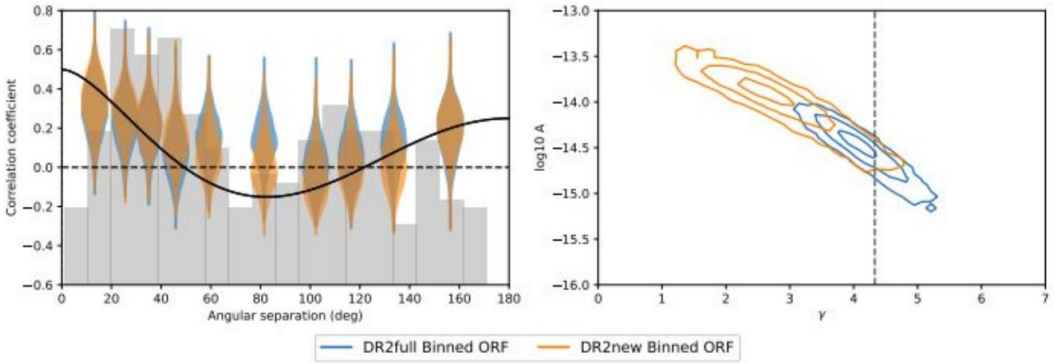
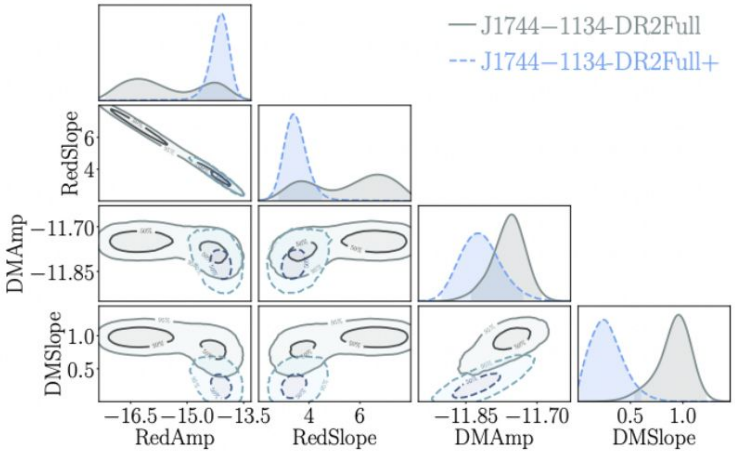
Srivastava et al. 2023 (PRD)

EPTA+InPTA results

- EPTA (25PSRs, 24yrs) and InPTA (14 PSRs, 3.5yrs) data were combined
- Low RF InPTA data helped model the chromatic and achromatic noise better



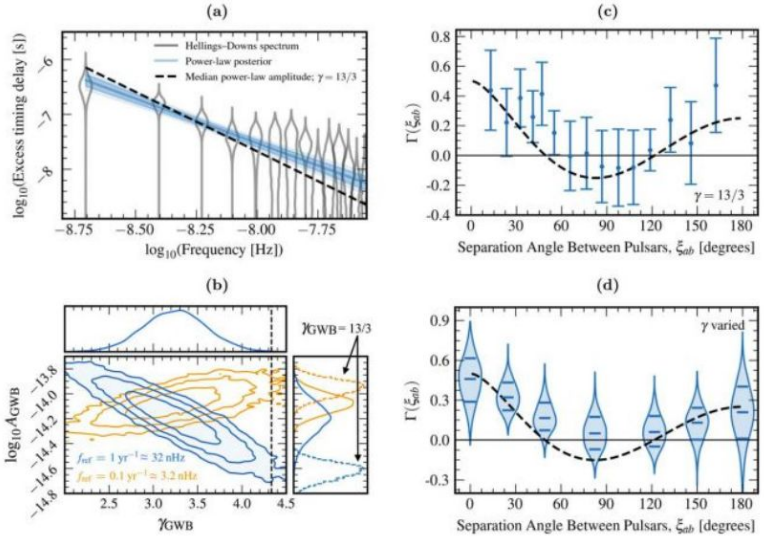


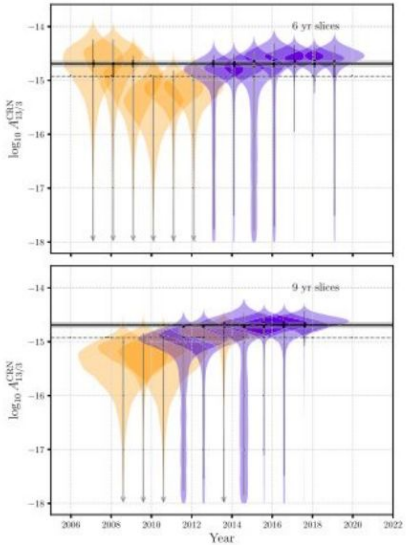
Antoniadis et al. 2023 A&A

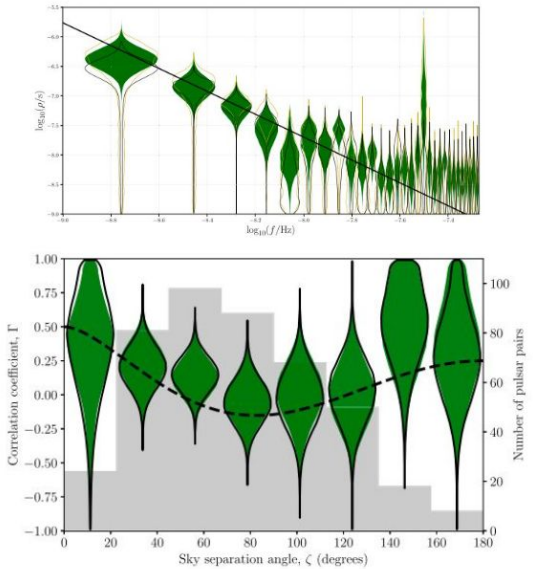
HD significance of ~3–3.5 sigma!

Results were announced together on 29 June 2023

NANOGrav and PPTA results







NANOGrav: Agazie et al. 2023 ApJL
HD Significance: 3.5 – 4 sigma

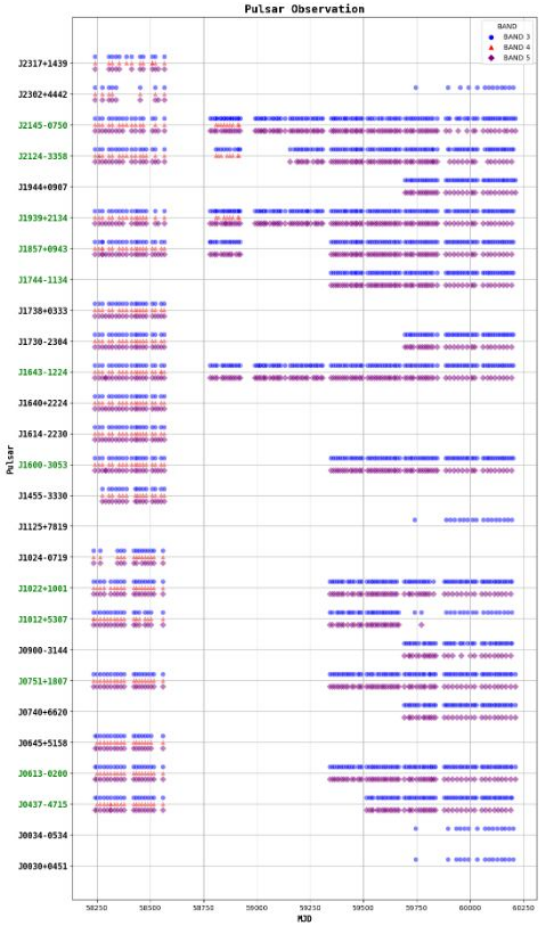
PPTA: Reardon et al. 2023 ApJL
HD Significance: ~2 sigma

Coordinated announcements from NANOGrav, EPTA, InPTA, CPTA and PPTA (18 articles in total)

InPTA
Indian Pulsar Timing Array

Moving ahead...

- **InPTA DR2** in full swing
- 27 MSPs spanning ~7 years
- Timing is almost over
- SPNA currently going on
- Submission expected before the end of Oct



IPTA Data Release 3

- The biggest ever combination of IPTA data
- A total of 114 pulsars will be combined from EPTA, InPTA, NANOGrav, PPTA and MPTA
- Early DR3 with a selected 20 pulsars are over
- SPNA is going on
- Expected to increase the sensitivity to SGWB
- Timeline is ~summer 2025

InPTA
Indian Pulsar Timing Array

New Frontiers

- SKA PTA in action ~2028
- Detection of individual sources? - Listen to Avinash Kumar' talk on Wednesday at 14:00
- Burst with memory?
- GWB anisotropy?
- Cosmological phase transitions?
- Cosmic strings?
- Primordial black holes, Dark matter candidates?

Summary

- A new window of long–wavelength GW astronomy opened up by the PTAs
- PTAs use a network of pulsars to look for characteristic red noise spectrum and spatial correlation
- The InPTA collaboration of Indo-Japanese researchers published their first data release of 3.5 years of uGMRT observations and combined it with the EPTA DR2
- The EPTA+InPTA has found significant evidence for CURN and 3 sigma evidence for spatial correlation → emerging evidence for GWB
- Similar evidences are observed by other PTAs
- InPTA DR2 is in full swing and would include ~7 years of high precision data from the uGMRT
- IPTA DR3 with a combination of all the PTA data sets are expected next year increasing the significance of evidence