భారతీయ సాంకేతిక విజ్ఞాన సంస్థ హైదరాబాద్
भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

InPTA
Indian Pulsar Timing Array

Indian Pulsar Timing Array (InPTA) : Joining the global hunt for nanoHz gravitational waves

Shantanu Desai, IIT Hyderabad

What happened on June 29, 2023?

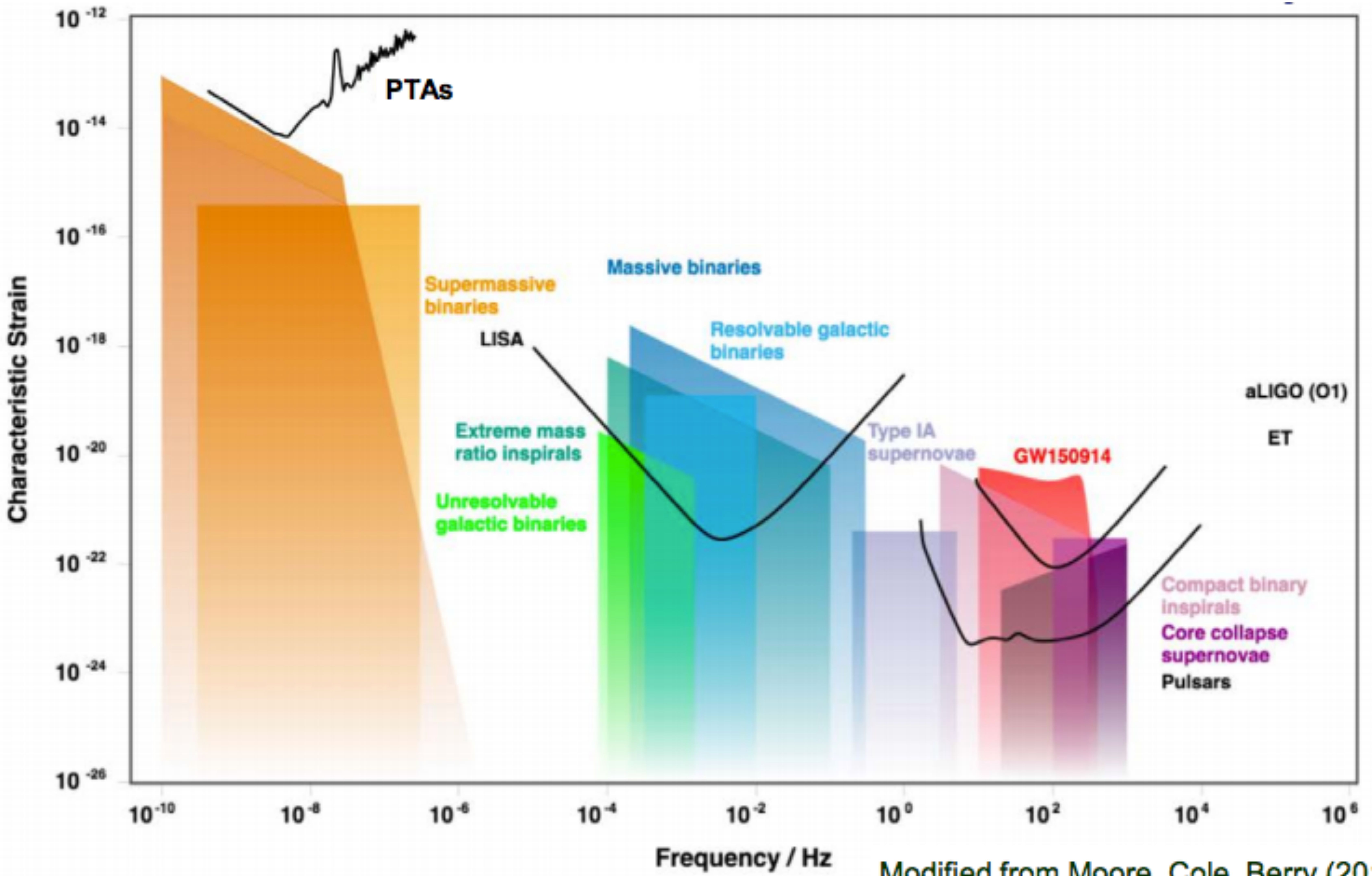
18 coordinated papers by NanoGrav, PPTA, InPTA, EPTA, CPTA announcing evidence for nanoHz GW background

> Papers with Science Results > 150 citations

- New York Times. "The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find." ↗
- Washington Post. "In a major discovery, scientists say space-time churns like a choppy sea." ↗
- National Public Radio (NPR). "Scientists have found signs of a new kind of gravitational wave. It's really big. ↗ "
- Scientific American. "First Evidence of Giant Gravitational Waves Thrills Astronomers." ↗
- Astrobites. "Drop the Bass: Evidence for a Gravitational Wave Background from a Galaxy-sized Detector." ↗
- CBS News. "For the first time ever, scientists 'hear' gravitational waves rippling through the universe." ↗
- ABC News. "Scientists have finally 'heard' the chorus of gravitational waves that ripple through the universe." ↗

- PBS. "PBS NewsHour for June 29th, 2023." ↗
- The Guardian. "Astronomers detect 'cosmic bass note' of gravitational waves." ↗
- BBC News. "Northern Ireland scientist's role in black hole shock-waves find." ↗
- New Scientist. "Gravitational waves produce a background hum across the whole universe." ↗
- The Globe and Mail. "Scientists report cosmic hum that may come from clusters of massive black holes." ↗
- UK Today News. "Gravitational waves produce a background hum across the whole universe." ↗
- BBC Science Focus. "Groundbreaking gravitational wave discovery could unlock our Universe's deepest mysteries." ↗
- Popular Science. "Astronomers used dead stars to detect a new form of ripple in space-time." ↗
- Reuters. "Scientists discover that universe is awash in gravitational waves." ↗
- Wired. "At Last, There's Evidence of Low-Frequency Gravitational Waves." ↗
- National Geographic. "Colossal gravitational waves -- trillions of miles long -- found for the first time." ↗
- The Wall Street Journal. "Black Hole at the Heart of Our Galaxy Is on Crash Course, Space-Time Ripples Reveal." ↗

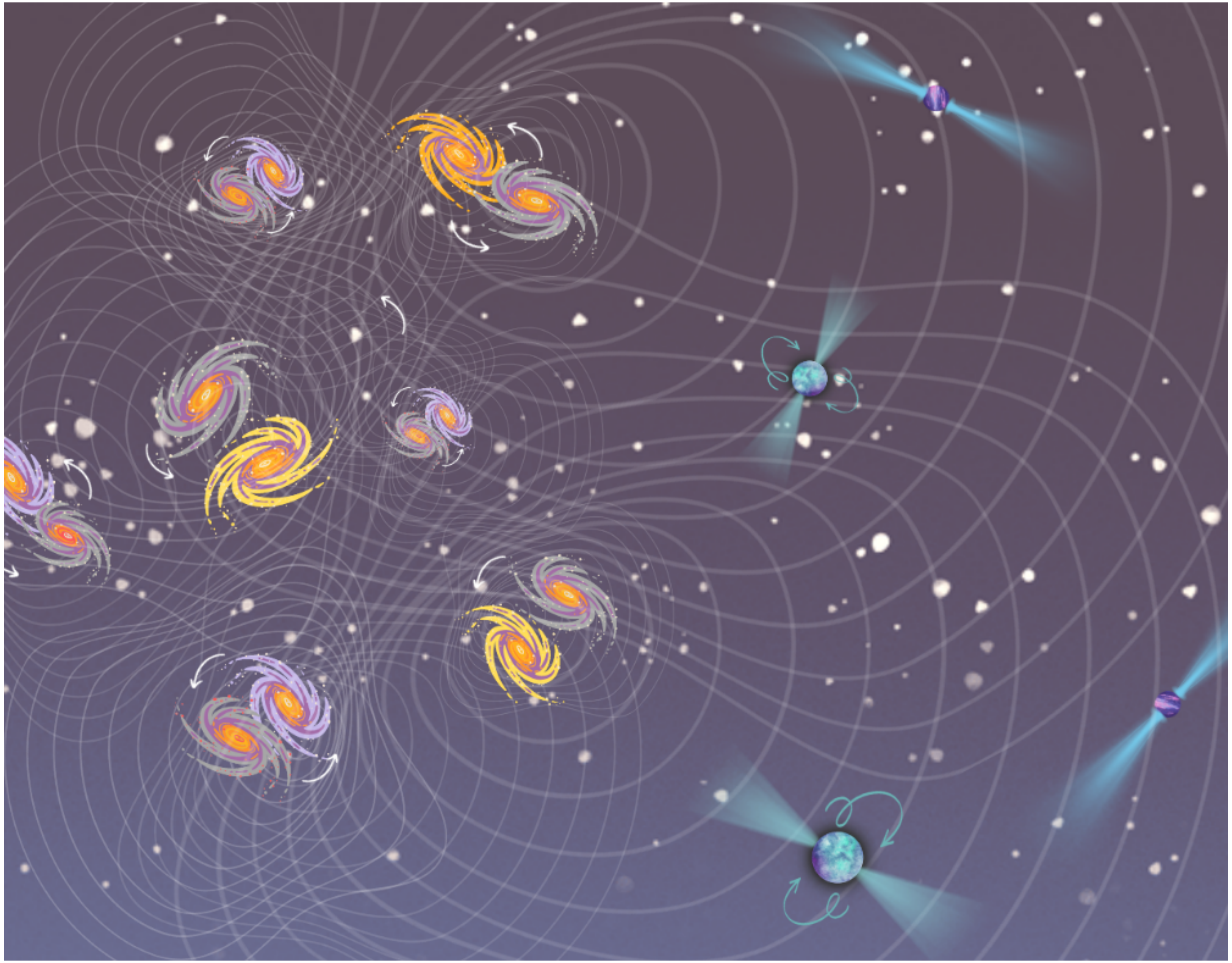
Sensitivity of PTAs in GW spectrum



Modified from Moore, Cole, Berry (2014)

Mingarelli & Mingarelli (2018)

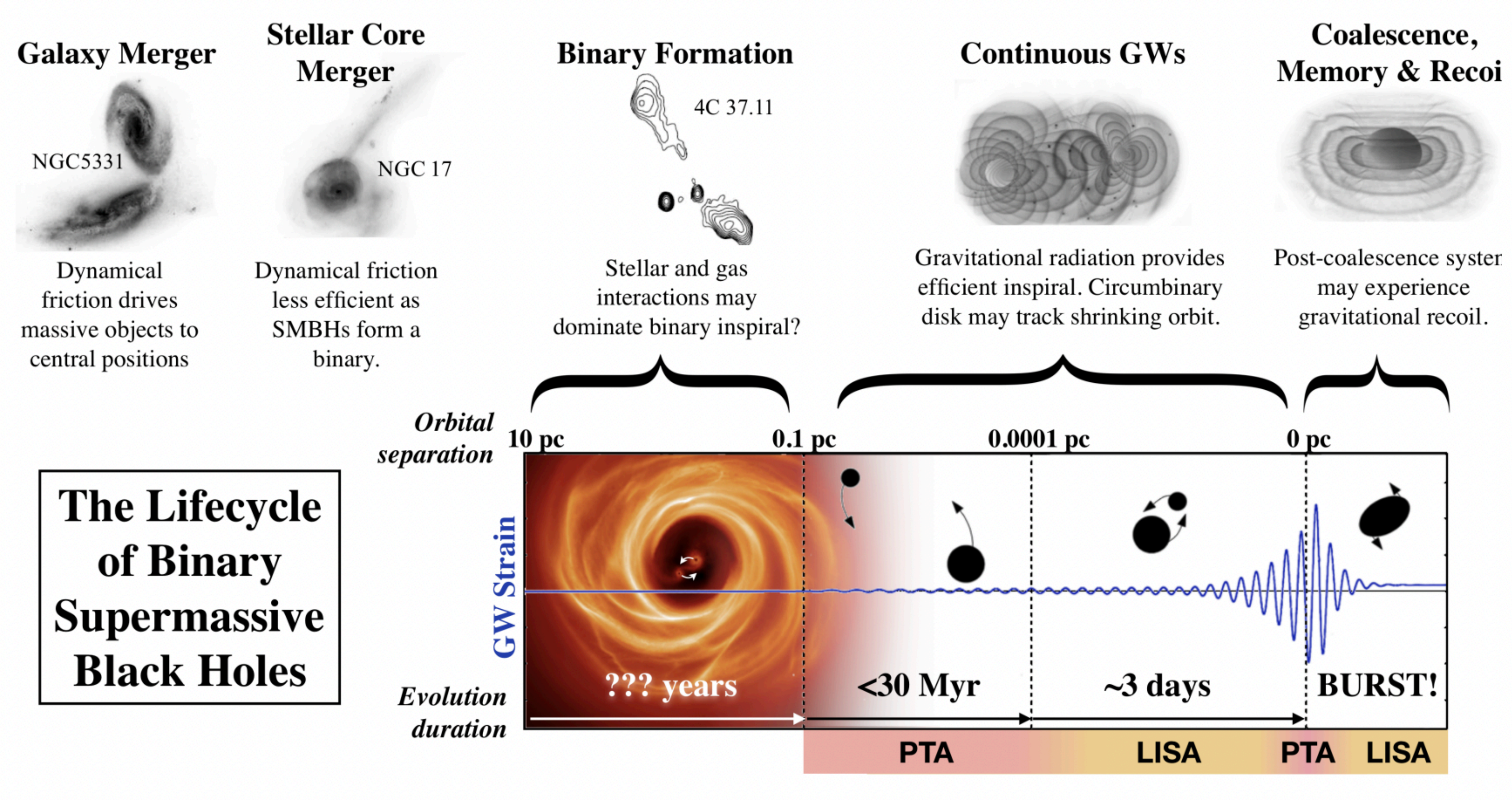
Most favored model for GWB

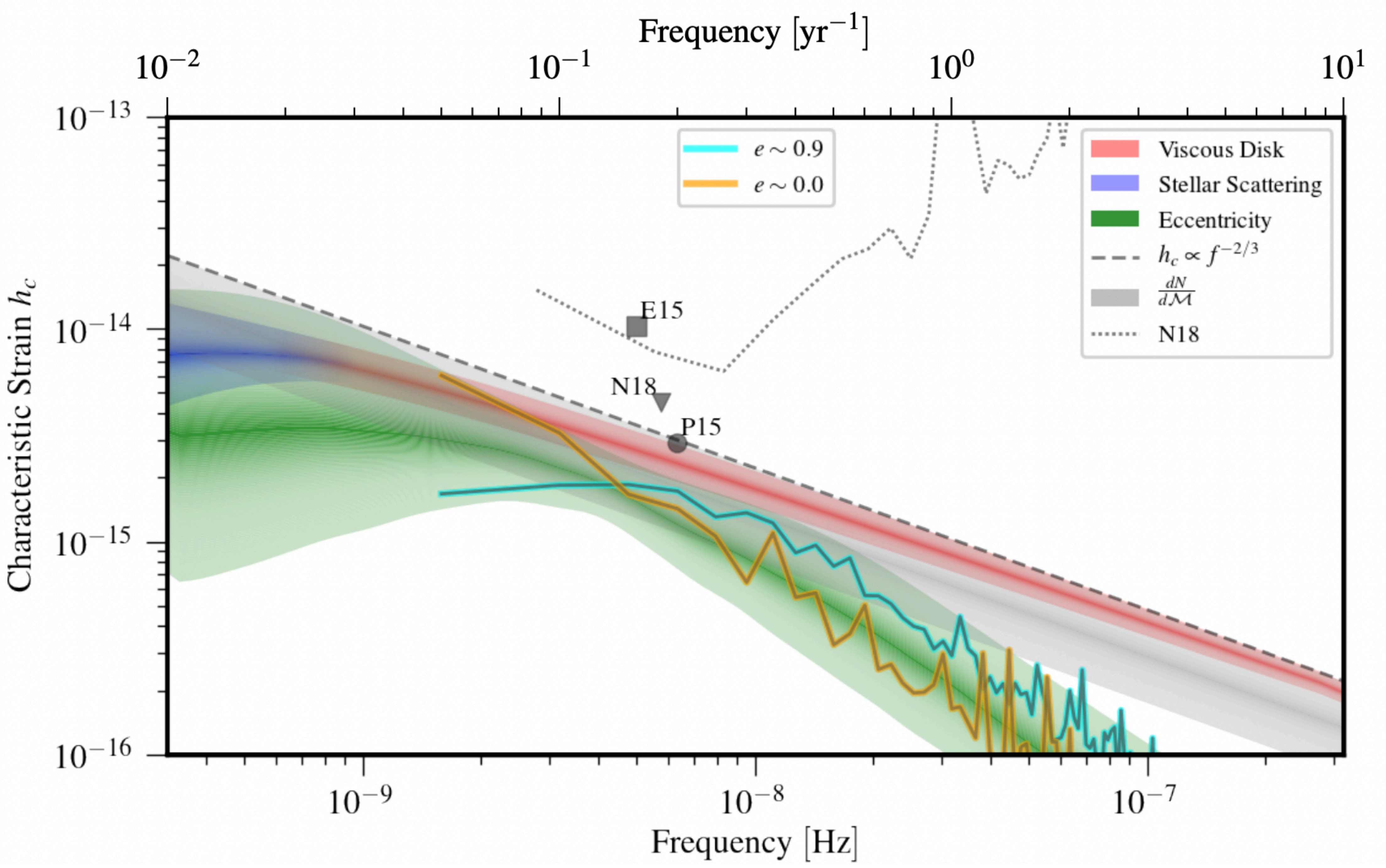


Superposition of supermassive black hole binaries

Credit : Neel Kolhe

GWs from SMBH binaries





$$h_c(f) = A_{1yr}\left(\frac{f}{1yr}\right)^{\alpha}$$

$$\alpha = -2/3$$

S. Burke-Spoalar et al *ARAA* 27, 5 (2019)

Timing Residuals due to Gravitational Waves

- **A passing GW, travelling in z-direction induces a fluctuation in the observed pulse frequency**

$$\frac{\nu_0 - \nu(t)}{\nu_0} = \frac{\alpha^2 - \beta^2}{2(1+\gamma)} \Delta h_+(t) + \frac{\alpha\,\beta}{1+\gamma} \Delta h_\times(t)$$

where α,β,γ are direction cosines to x,y,z axes.

Each term contains and earth and a pulsar term

S. Detweiler ApJ 234, 1100 (1979)

- **GW induced residuals**

$$R(t) = \int_0^t \frac{\nu_0 - \nu(t')}{\nu_0} \delta t'$$

Aim of PTAs is to look for such residuals

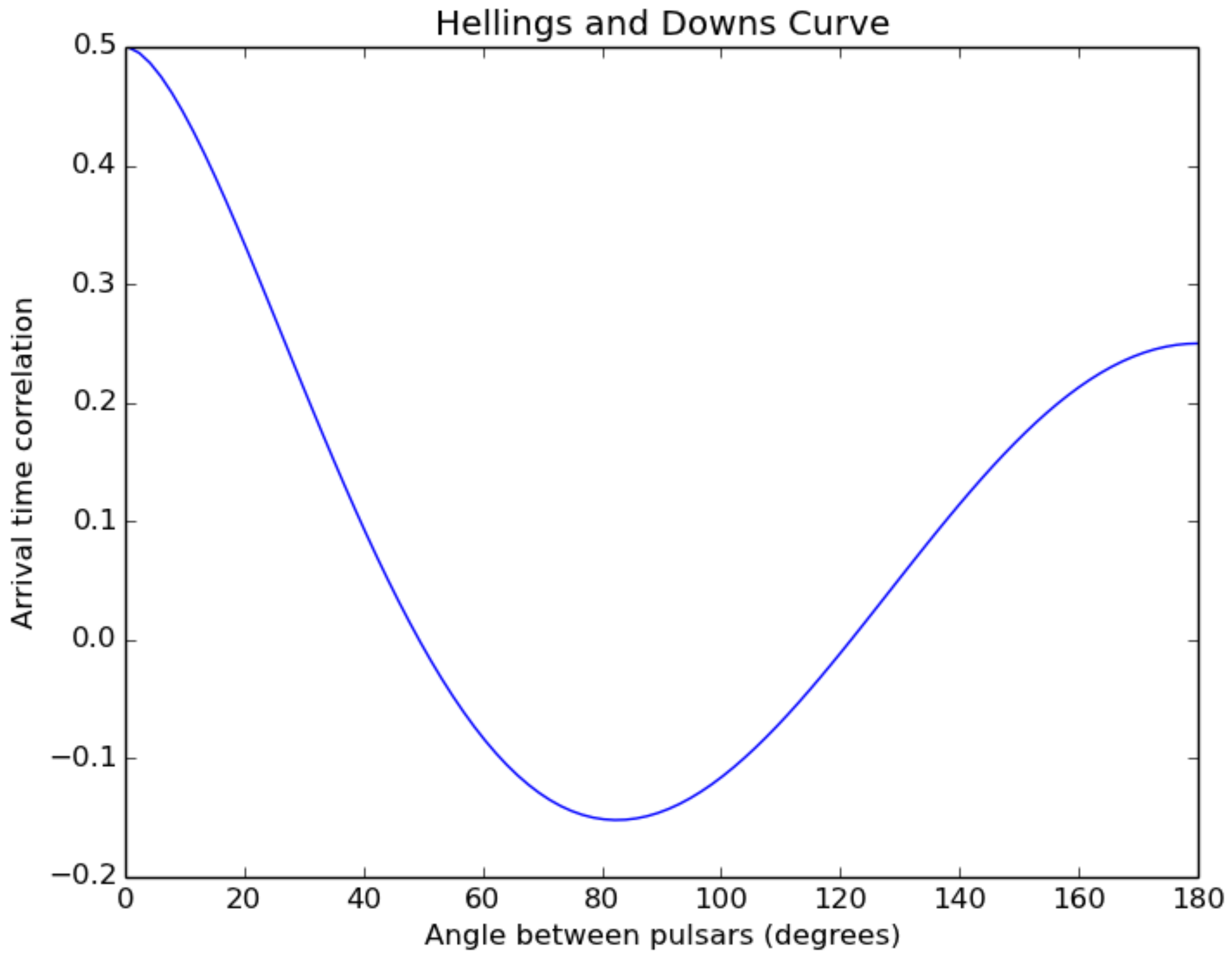
Smoking Gun Signature of GWB

- Stochastic GW background due to SMBH binaries manifests as a common red noise

$$P(F|A,\gamma) = \Gamma(\zeta_{ab})\frac{A^2}{12\pi^2}\left(\frac{f}{yr^{-1}}\right)^{-\gamma}$$

$$\gamma = 13/3$$

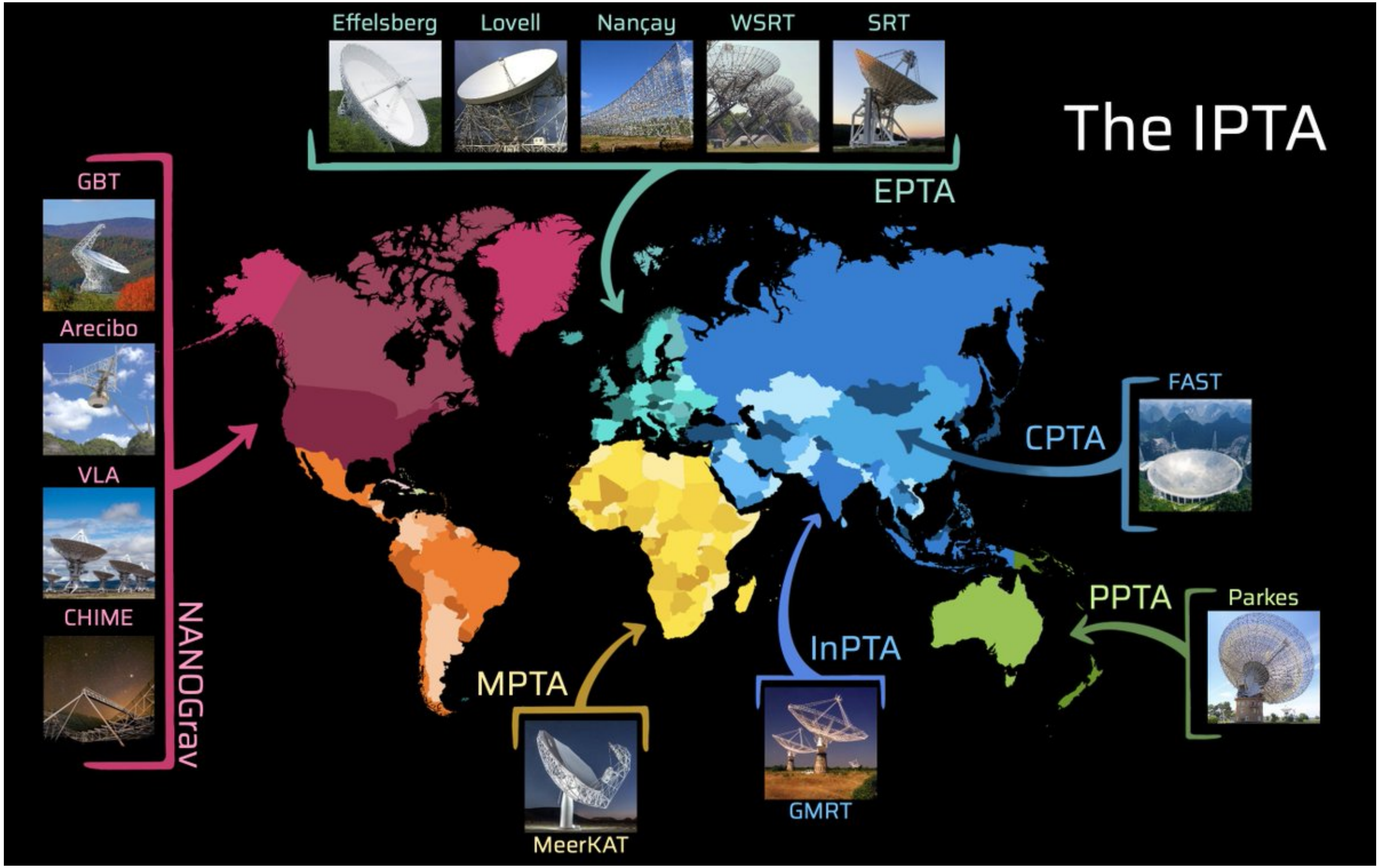
- Residuals due to SMBH binary GW background are correlated with quadrupole nature (HD correlation)



R.Hellings & G. Downs ApJL 265, L39-(1983)

B. Allen & J. Romano arXiv:2308.05847

International Pulsar Timing Array



NanoGrav 67 MSPs : 15 years

EPTA 25 MSPs : 24 years

PPTA 30 MSPs : 28 years

InPTA 20 MSPs : 7 years

Credit : Thankful Cromartie

InPTA Consortium

InPTA
Indian Pulsar Timing Array

NCRA • TIFR

tifr

RRI

熊本大学
Kumamoto University

- Indo-Japanese collaboration (~ 40 members)
- Started in 2015 (SD involved since 2018)
- Observing 22 millisecond pulsars Cadence 10-14 days
- Observations done using the upgraded GMRT which is highly sensitive to low frequency (2018-present)
- Submit observing proposal every 6 months.

Main goal of InPTA is to characterize and distinguish the slowly varying ISM induced noise form GW signal

Observations with Upgraded GMRT

- Low frequency of observations:
  - The uGMRT covers 300 – 800 MHz complementing other PTAs operating above 800 MHz
- High Sensitivity :
  - The InPTA uses phased arrays with new wideband feeds between 300 – 1500 MHz
- Concurrent observations between 300 – 500 and 1260 – 1460 MHz

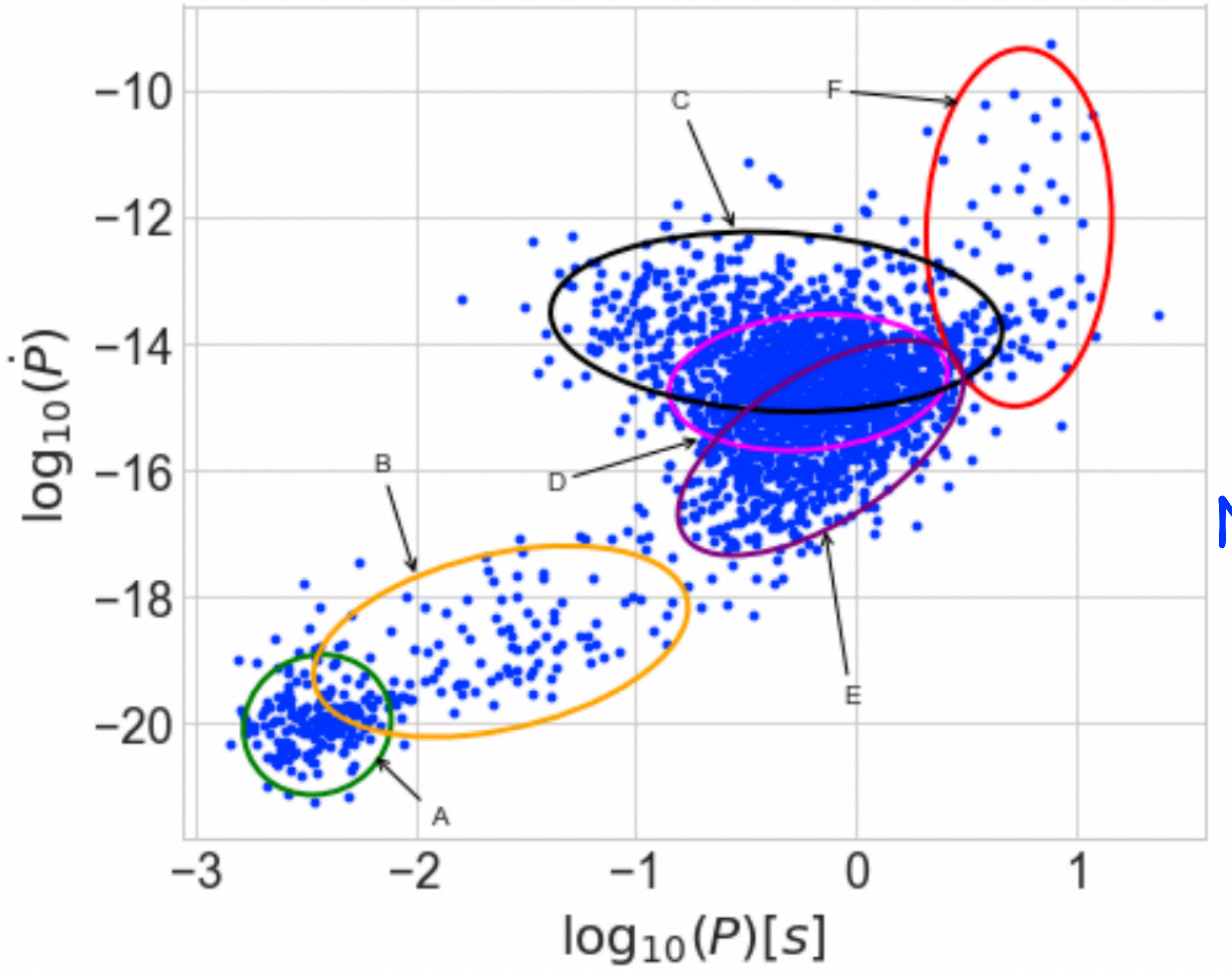
These niche capabilities are very useful for precision DM measurements and characterizing effects of inter-stellar medium for precision timing and complementing other PTAs

Joshi et al 2018, Joshi et al 2022

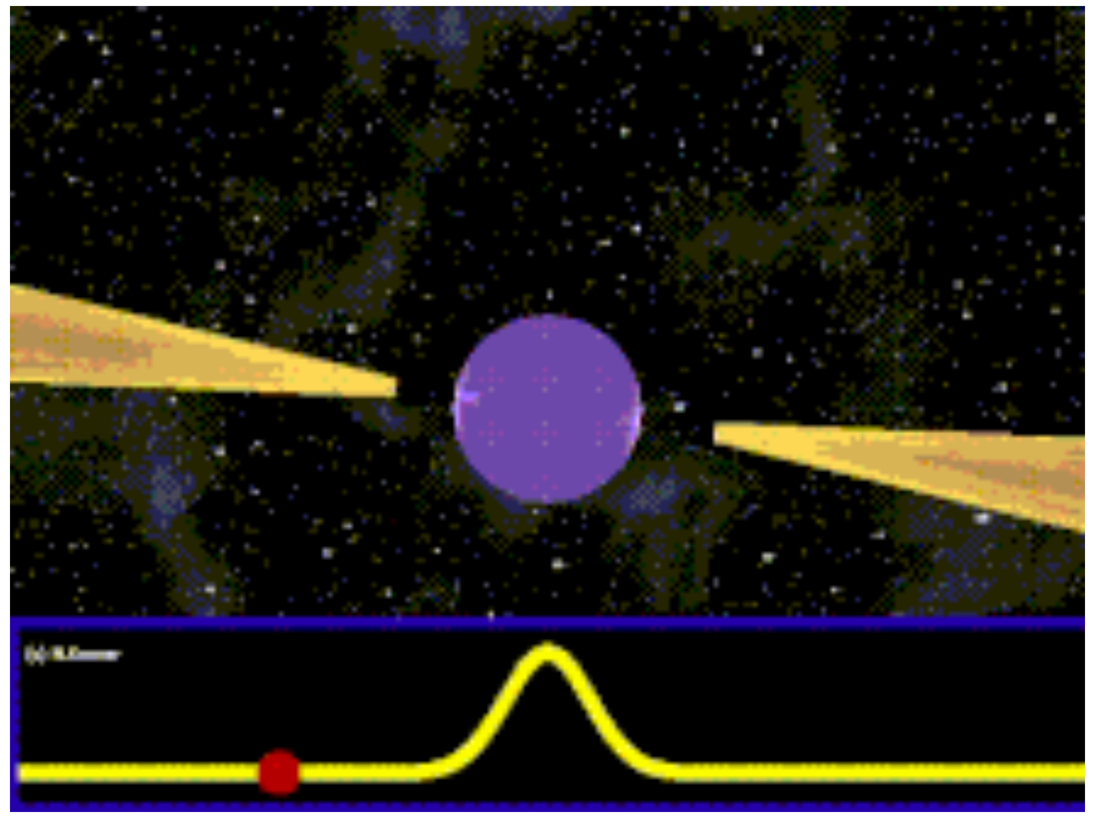
Millisecond Pulsars as Probes of GWs

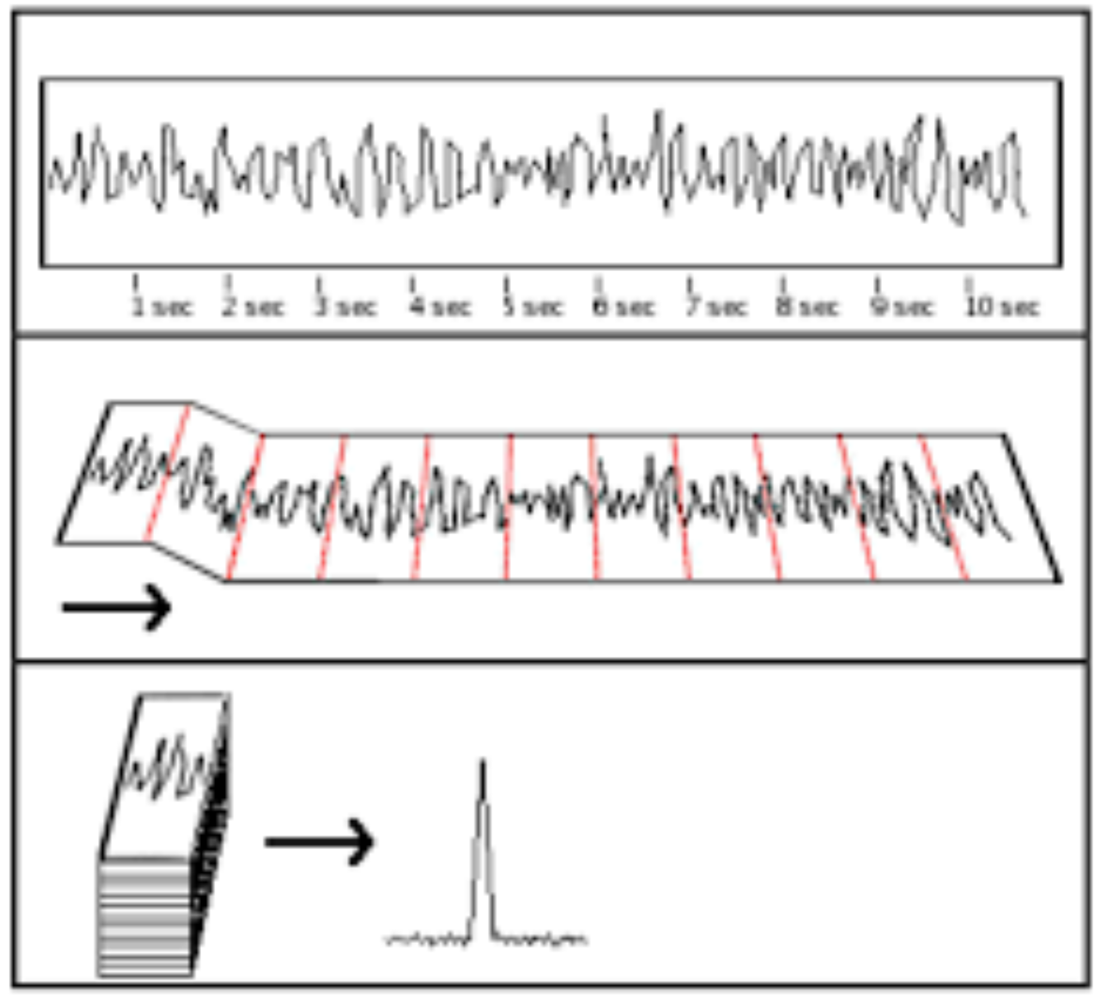
Pulsars are highly magnetised rotating neutron stars ($M \sim 1.4 M_{sun}$ $R \sim 10$ km)
Millisecond pulsars are subset with $P \sim 10$ ms, $B \sim 10^9$ G
Extremely stable periods ~ 1 part in 100 quintillion

This makes them very important for the detection of gravitational waves



Reddy & SD
New Astronomy 91, 101673 (2022)





Timing Residual = Measured ToA - Predicted ToA

Data

Model of Pulsar

InPTA Data Release I

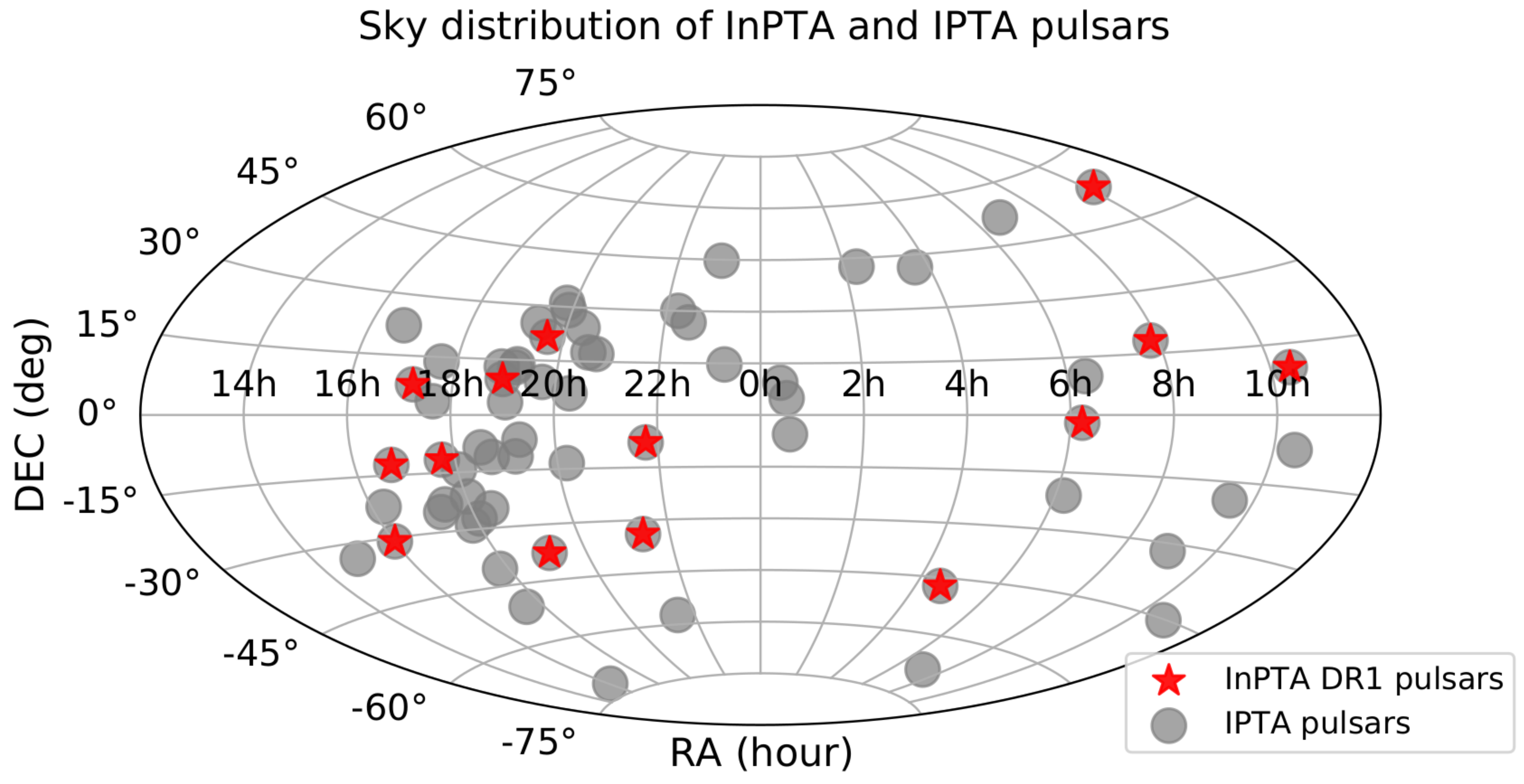
5-22 pulsars observed every 15 days

Epoch-wise high precision Dispersion Measure from traditional narrowband timing

+

Wideband DMs

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



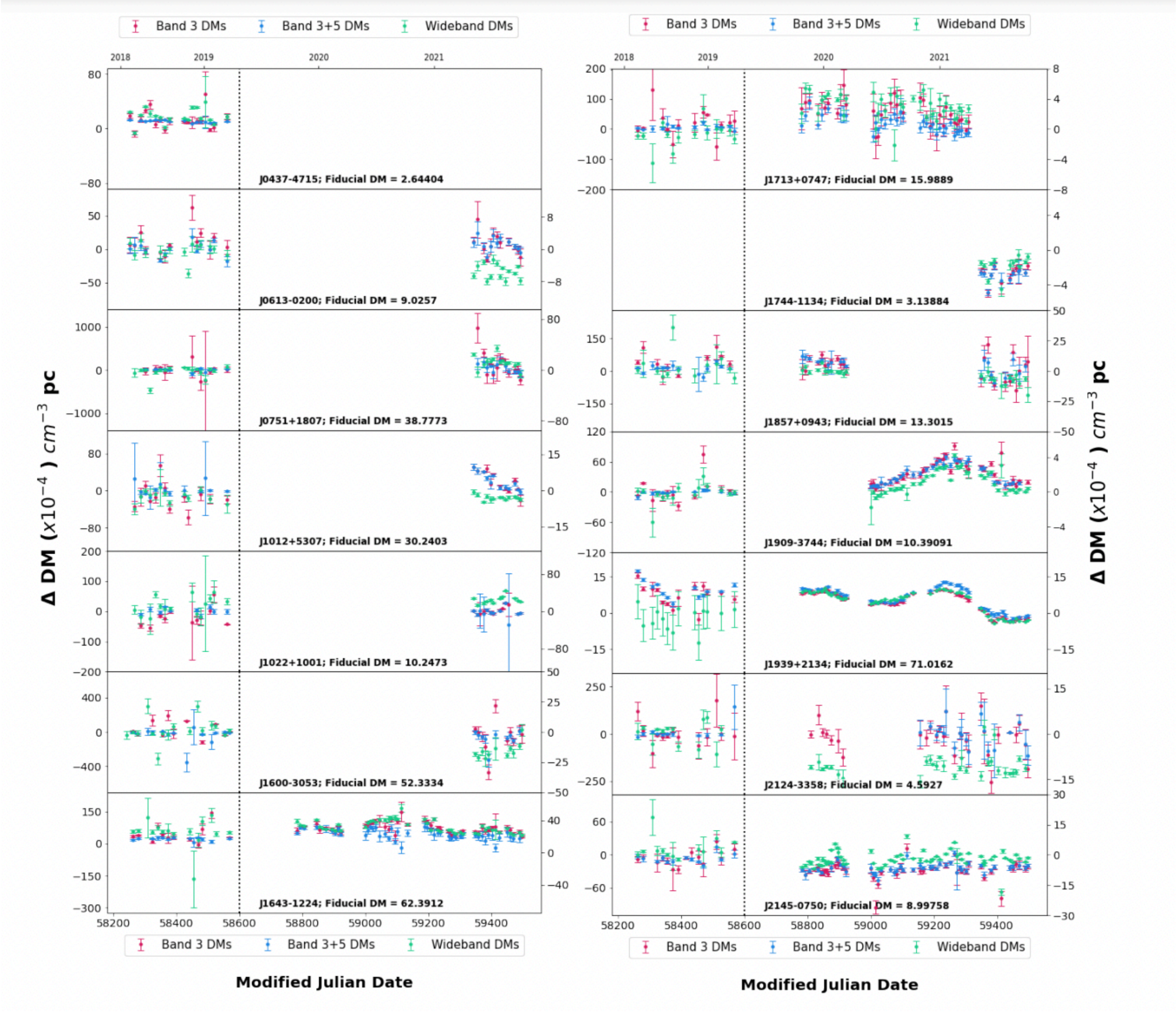
Narrowband TOAs

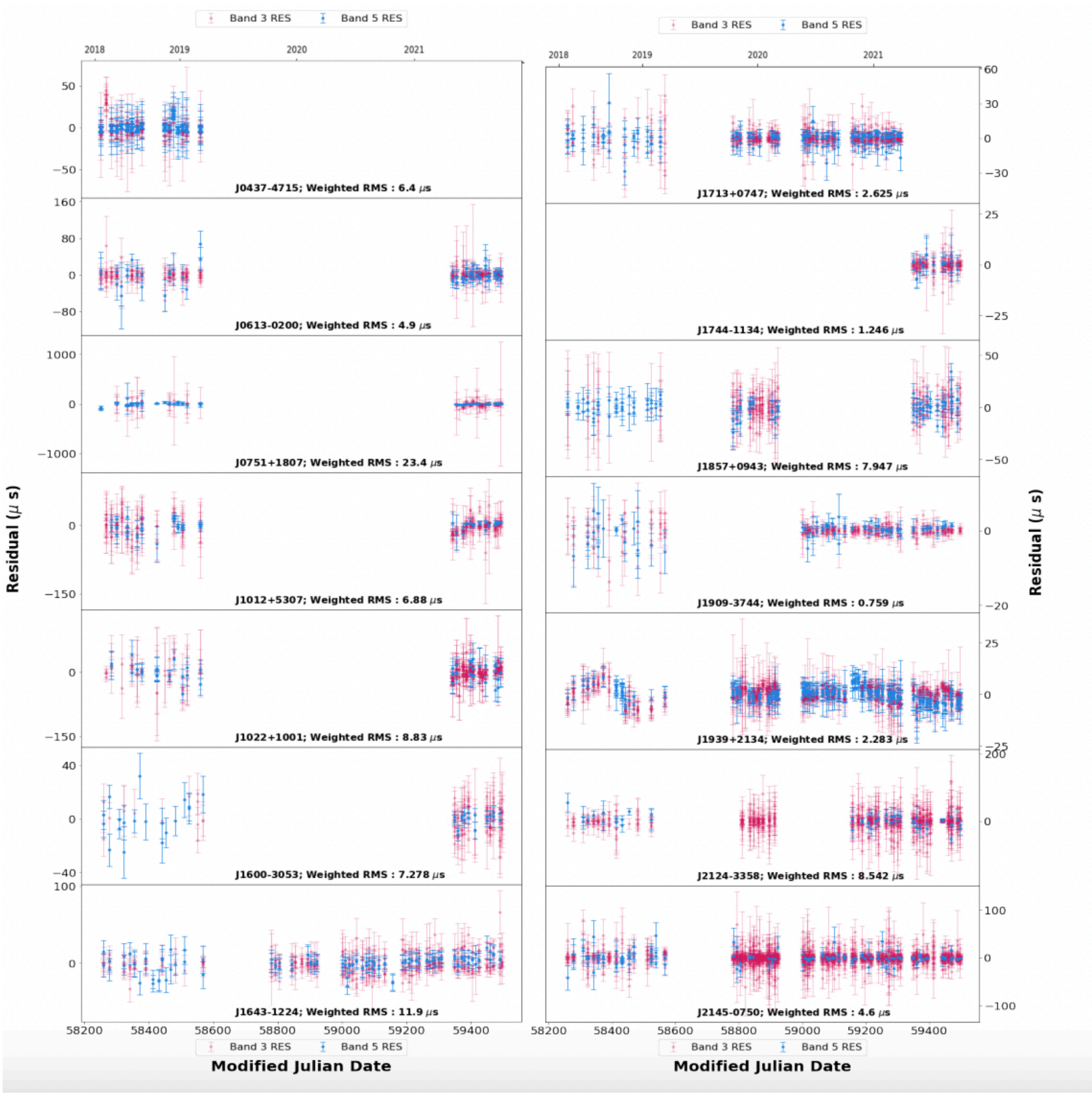
+

Wideband TOAs

P. Tarafdar et al PASA 39, 53 (2022)

InPTA DR1 Results





Noise Sources

- Contributes to systematic deviation in the residuals
- Deterministic - rotational , positional or binary model
- Stochastic - White noise, Efac, Equad
- Stochastic - Red Noise
  - Wander in Neutron Star rotation rate - spin noise
  - Variations in dispersion induced by varying electron content along the line of sight - DM noise $\sim \nu^{-2}$
  - Variation in scattering in the ISM - scattering noise $\sim \nu^{-4.4}$
- Red noise
  - Covariant with GW signal
  - Much larger than GWs

Stochastic GW background manifests itself as a stochastic red noise process

Noise Model Definitions

- White Noise $\sigma^2 = EFAC^2 \times (\sigma_{TOA}^2 + EQUAD^2)$
- Correlated red noise (Time correlated signal in Fourier domain)

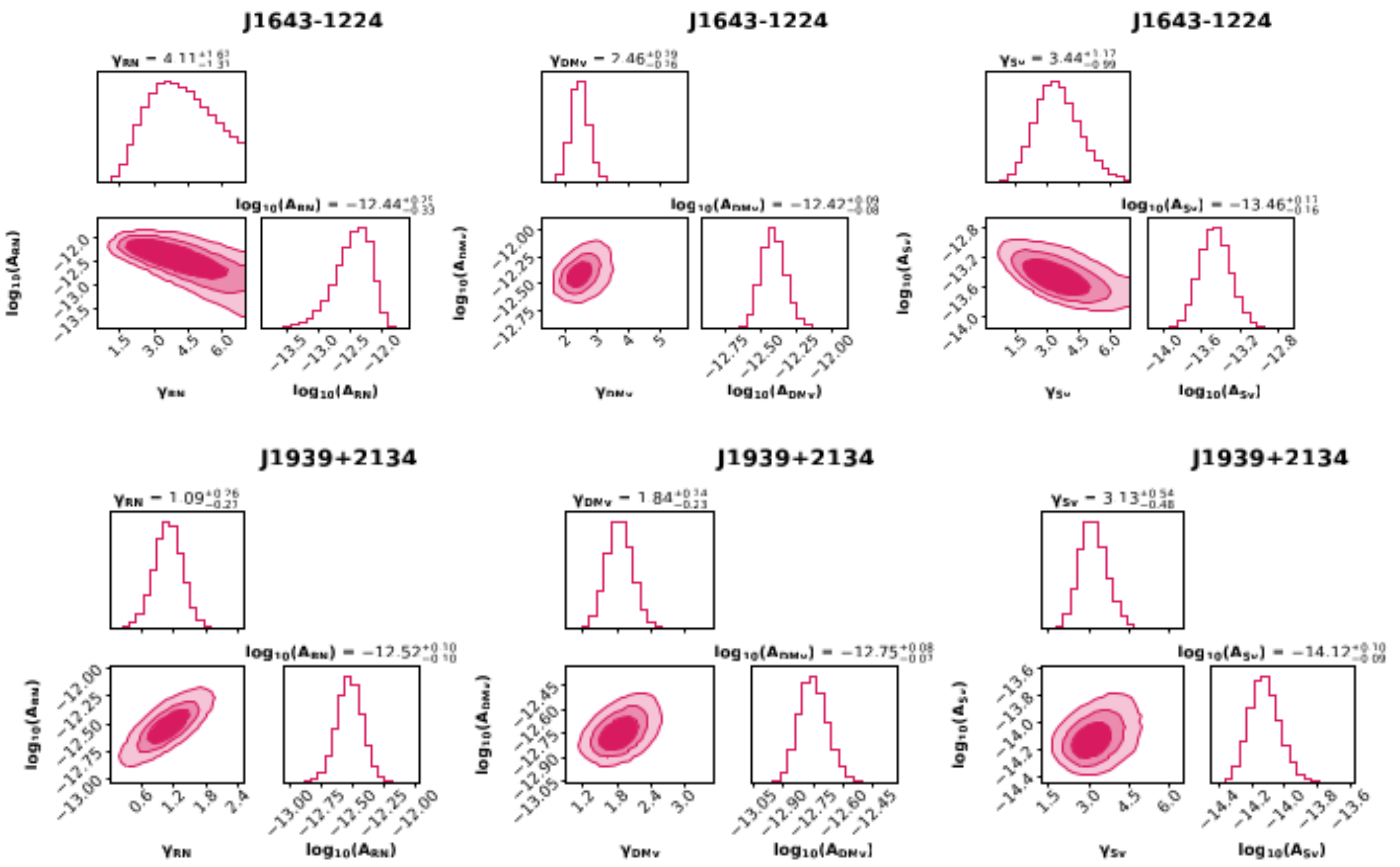
$$\delta t(t_i) = \sum_{l=1}^{n} [X_l \cos(2\pi t_i f_l) + Y_l \sin(2\pi t_i f_l)]$$

Power Spectral Density $S(\gamma) = \frac{A^2}{12\pi^2} \left(\frac{f}{yr^{-1}}\right)^{-\gamma}$

- Spin Noise Hyperparameters : l =1,....n, A,γ
- Chromatic DM and Scattering Noise : $F_{il}^{chrom} = F_{il} \times \left(\frac{\nu_i}{1.4GHz}\right)^{-\chi}$
- Chromatic noise hyperparameters : l =1,....n, A, γ,χ=2,4, free

Noise Modelling

Single Pulsar noise analysis of 14 pulsars using InPTA DR1 dataset
Noise model selected using Bayesian evidence (using dynesty)
Parameter Estimation using PTMCMC



DM variations present in 8 pulsars
Scattering variation present in 4 pulsars

A. Srivastava, SD, et al Physical Review D108, 023008 (2023)

EPTA+ InPTA Results

- EPTA+InPTA data combination used 25 pulsars (InPTA provided 14)
- InPTA provided noise models of ISM noise improving the ability to remove noise which mimics the GW signal from combined DR2full+ data

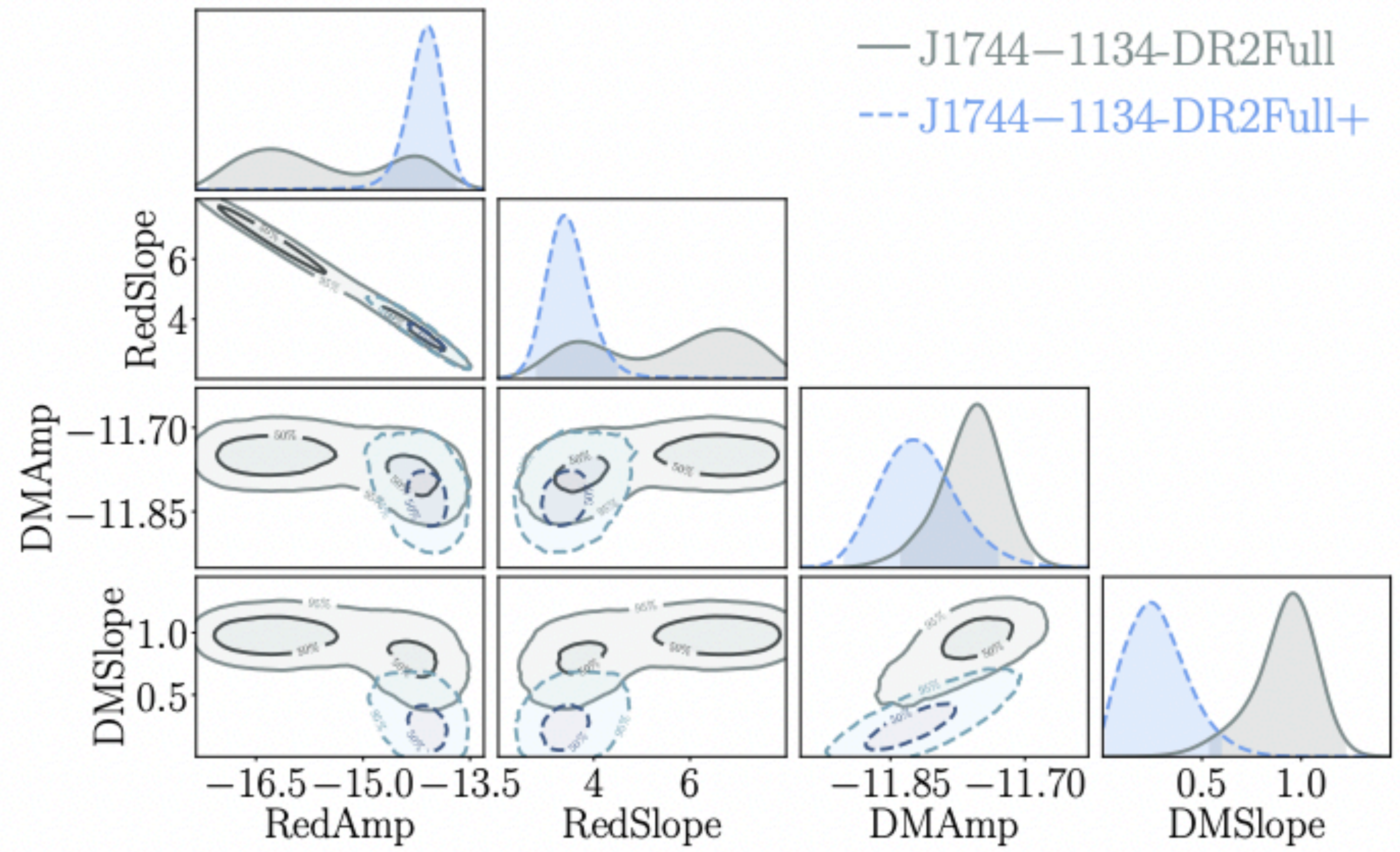


Fig. 5. Red and DM noise models for PSR J1744−1134 using DR2full and DR2full+ datasets. The inclusion of InPTA data allows a better constraint on the achromatic noise.

Antoniadis et al 2023 A & A [in press]

InPTA/EPTA Comparison

- Comparison of EPTA alone noise models with InPTA+EPTA noise models done using the Tensiometer package (written by Marco Raveri former SISSA Ph.D student) in a team led by Subhajit Dandapat (TIFR)
- Results from EPTA and EPTA+InPTA broadly in agreement Noise models in tension for few pulsars

Table 6. Estimated tension (Z-score in sigma) between the DR2full and DR2full+ datasets for the red and DM noise models. Instances with significant tension are highlighted.

Pulsar	Model	RN-RN	DM-DM
J0613−0200	DM+RN	0.74	**2.97**
J0751+1807	DM	X	0.63
J1012+5307	DM+RN	0.02	0.04
J1022+1001	DM+RN	0.08	0.52
J1600−3053	DM	X	**4.64**
J1713+0747	DM+RN	0.01	0.14
J1744−1134	DM+RN	0.20	**2.29**
J1857+0943	DM	X	0.05
J1909−3744	DM+RN	0.05	**4.39**
J2124−3358	DM	X	0.84

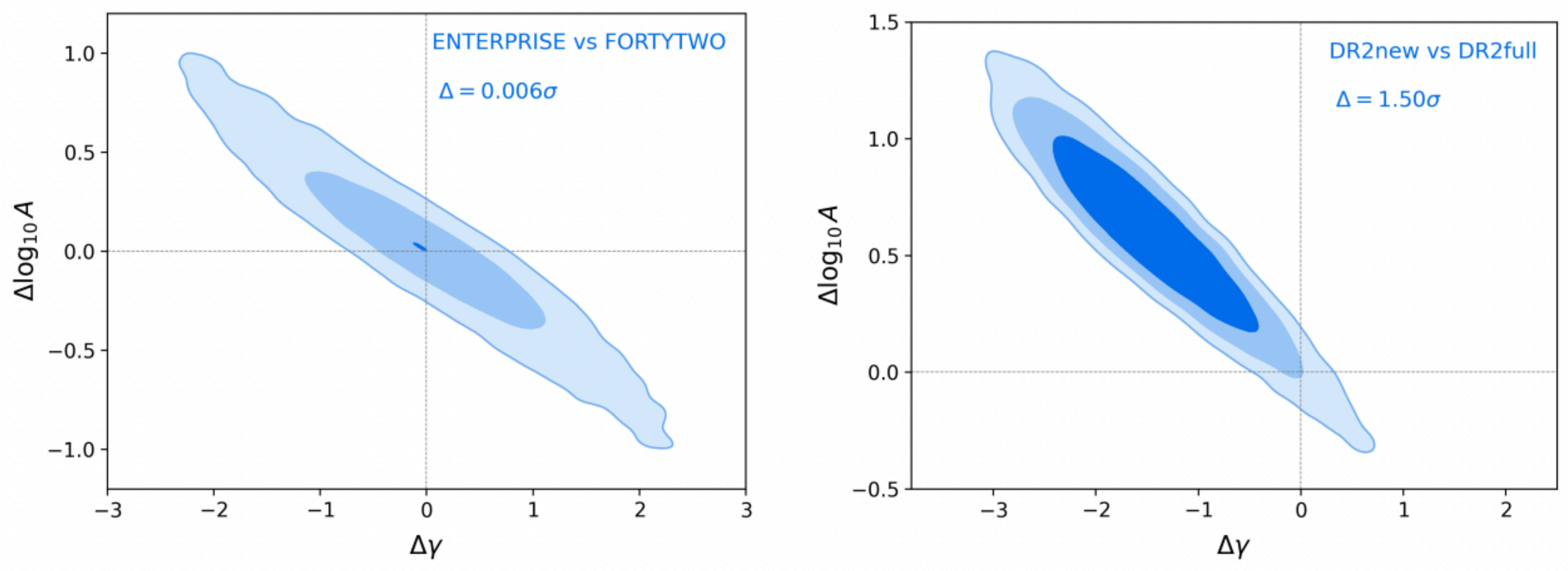
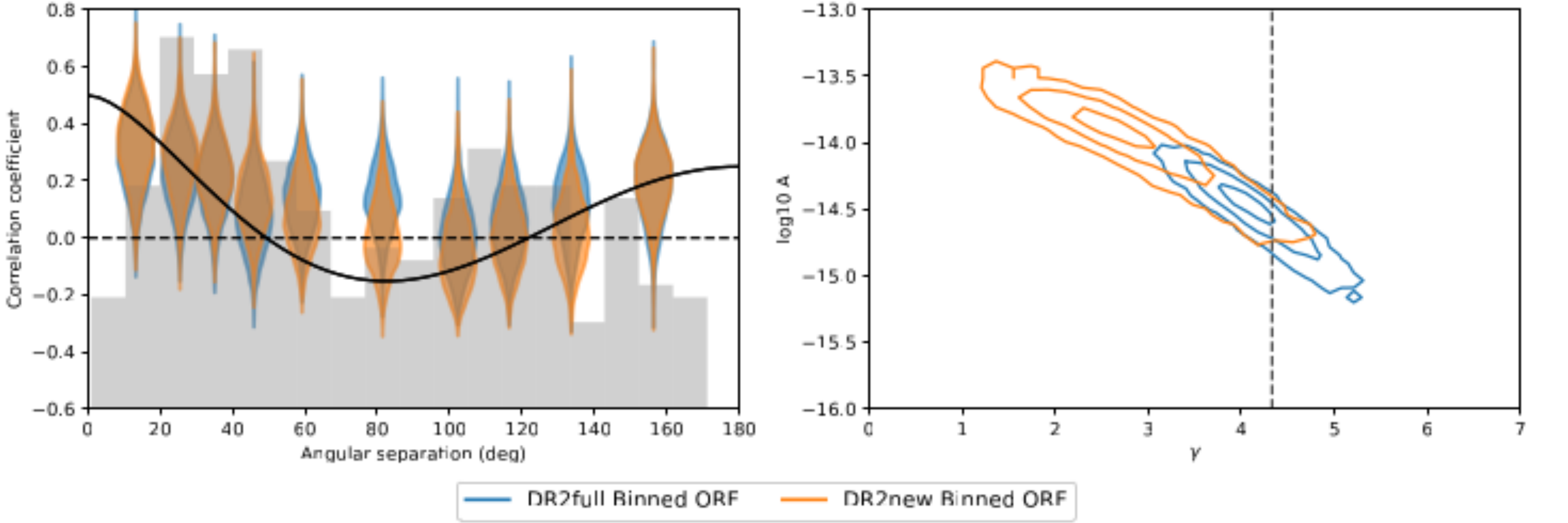


Fig. 2: Difference distributions between two posterior distributions originating from GWB processes. The left panel depicts the difference distribution between DR2new and DR2full data sets while employing the ENTERPRISE package. In comparison, the right panel shows the tension contour between ENTERPRISE and FORTYTWO software packages when we employ the DR2new data set. The plots contain three contours: 1σ, 2σ, and the Δ contours that correspond to the value of the computed tension.

- Tensiometer is also being used for comparison of results by the PTA experiments.

Antoniadis et al 2023 A & A [in press]

InPTA+EPTA Evidence for Hellings-Downs Correlation



Analysis of InPTA+EPTA dataset done on supercomputers at IIT Hyderabad by Aman Srivastava

Bayes factor for Hellings-Downs correlation of ~ 60

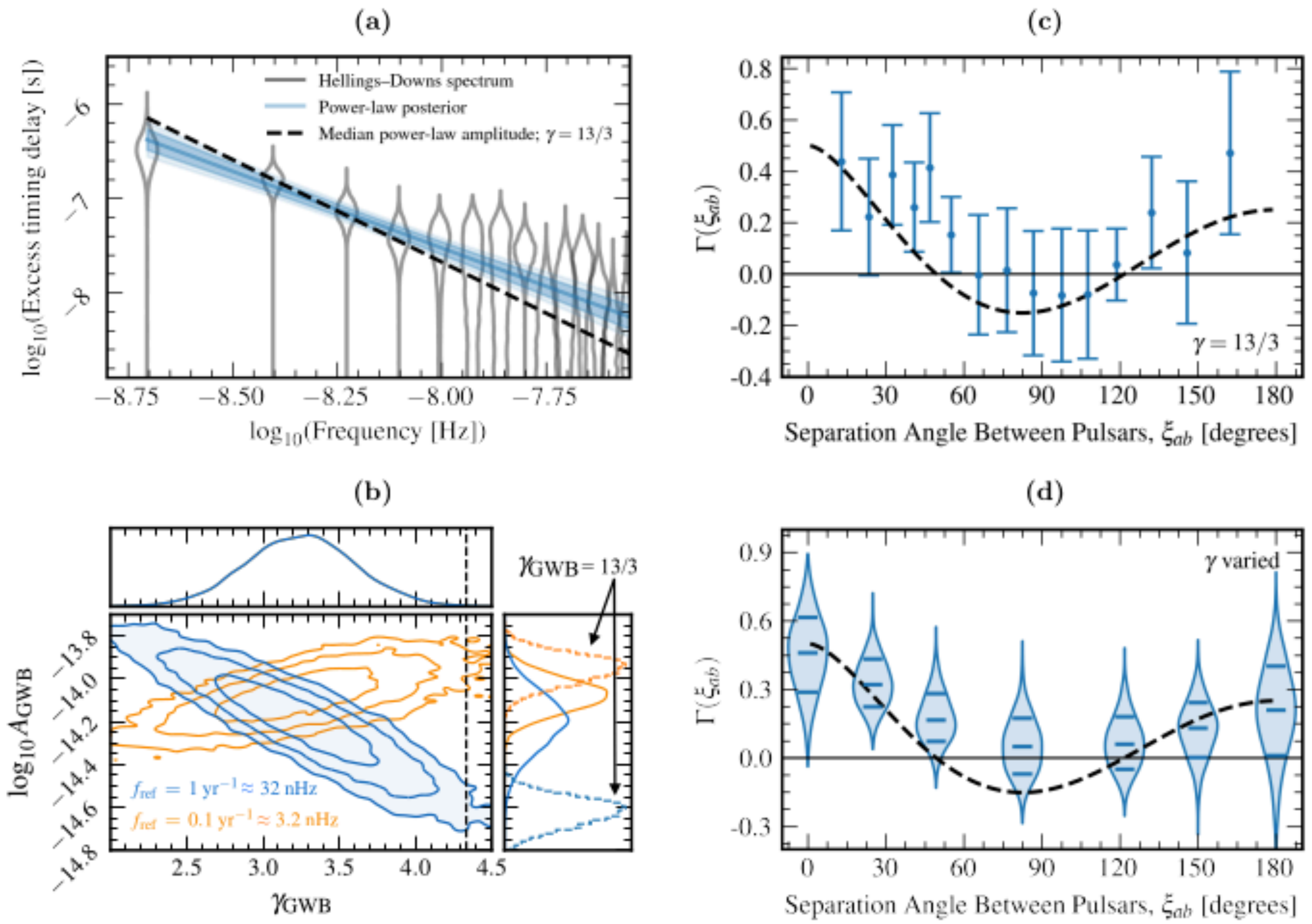
Frequentist p-value = 0.1% ($\geq 3\sigma$ significance)

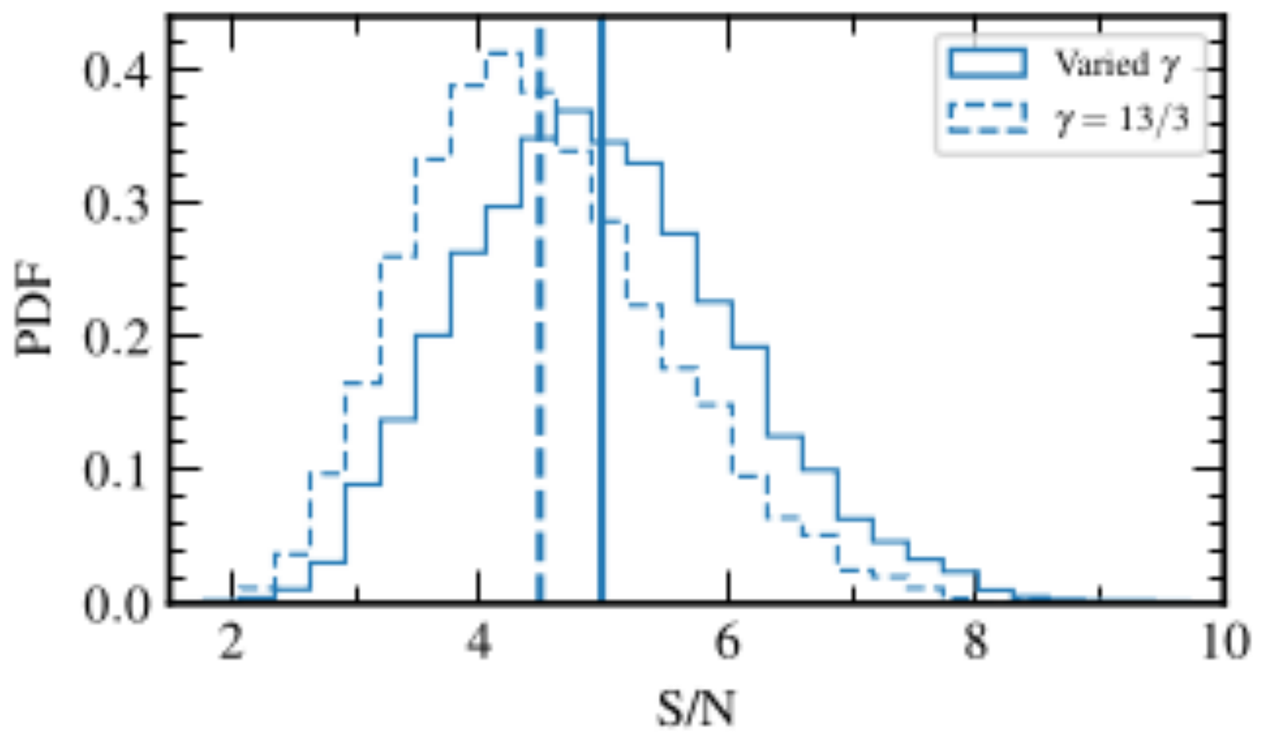
Conclusions

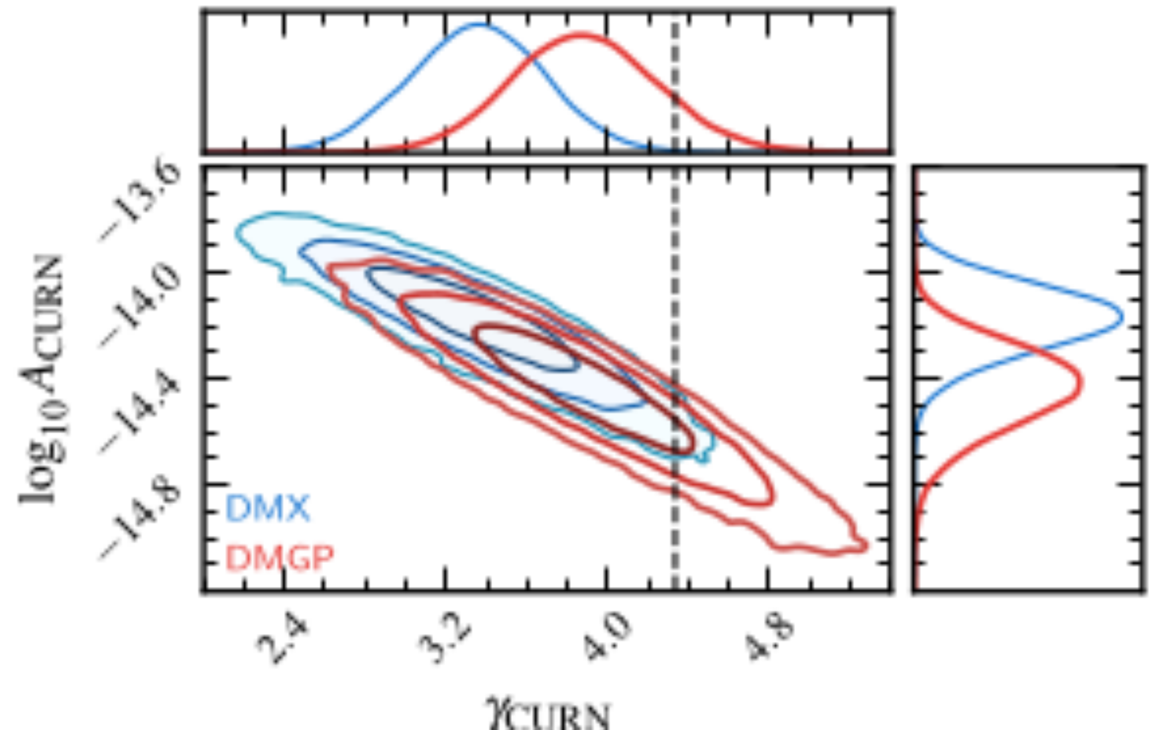
- A new window of GW astronomy has been opened by PTAs at ultra-long wavelengths by observation of red noise spectrum and spatial correlation.
- The InPTA collaboration using uGMRT observations (starting from 2018) combined its data with EPTA for joint analysis of 25 pulsar sample.
- EPTA+ InPTA has found significant evidence for CURN and 3σ evidence for spatial correlation suggestive of emerging evidence for GWB.
- Combination of data of all these experiments is in progress and the detection significance is likely to be enhanced with further observations.

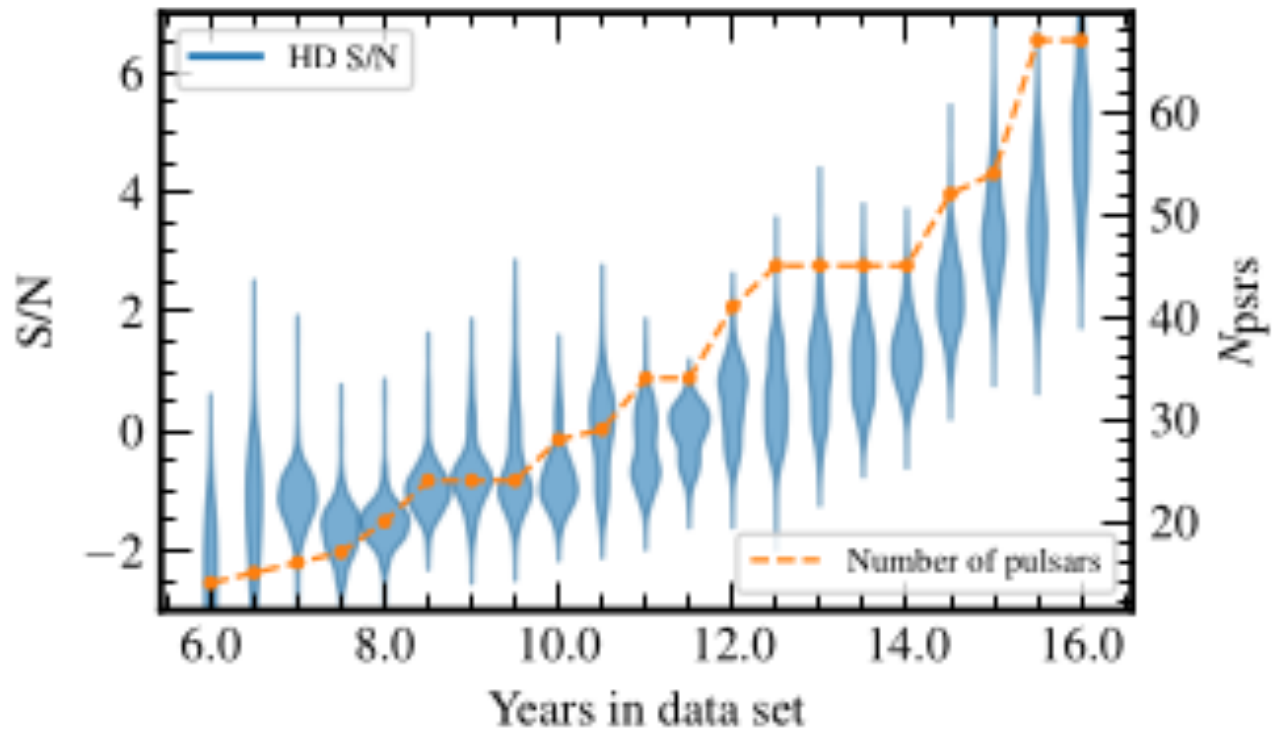
Stay tuned for more exciting results

(Backup) Results from NanoGrav









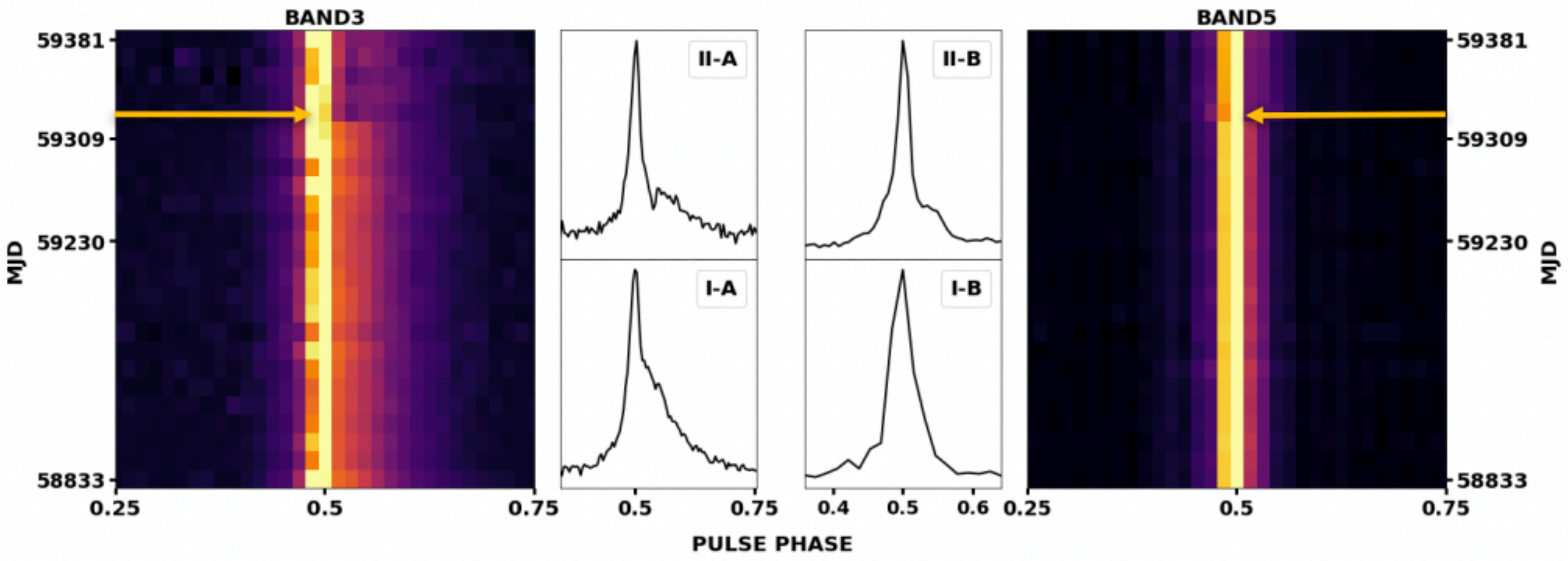
Agazie et al. ApJ, 951, L8 (2023)

(Backup) Summary of PTA results

- On June 29, CPTA, EPTA, InPTA, NANOGrav and PPTA published 18 papers presenting their latest data which presented for the first time evidence of ultra-low frequency GWs

- NANOGrav papers main results :
  - CRN at large significance over SPN (BF : 10^{14} ; SNR 7)
  - CRN significant over URN (BF : 200-1000; SNR 3.5-4)
  - HD significant (Bayesian SNR 3 ; Frequentist 3.5 to 4)
  - GWB amplitude ~ 2.4 X 10^{-15} @ 1 year^{-1}
  - GWB spectral index in mild tension with SMBHB 13/3 (2/3)
  - GWB sources could be other than SMBHB
  - DMGP model more consistent with SMBHB than DMX
    - InPTA low frequency data ?????
  - SNR grew with time
    - GWB slowly emerging as expected

Evidence for Profile Change in J1713+0747



J. Singha et al MNRAS 507, L57 (2021)

Figure 1. Profile changes observed at Band 3 and Band 5 before and after MJD 59321 are shown in this figure. The colour-map plots show the variation in profile with observation epochs indicated in MJD along the vertical axes for Band 3 (left plot) and Band 5 (right plot), respectively, where the profile change epoch is indicated by arrows. The plots in the center show the frequency and time collapsed profiles before (I-A and I-B) and after (II-A and II-B) the event for Band 3 (left plots) and Band 5 (right plots) as solid lines.