



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



Indian-Japanese Pulsar Timing Array: 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

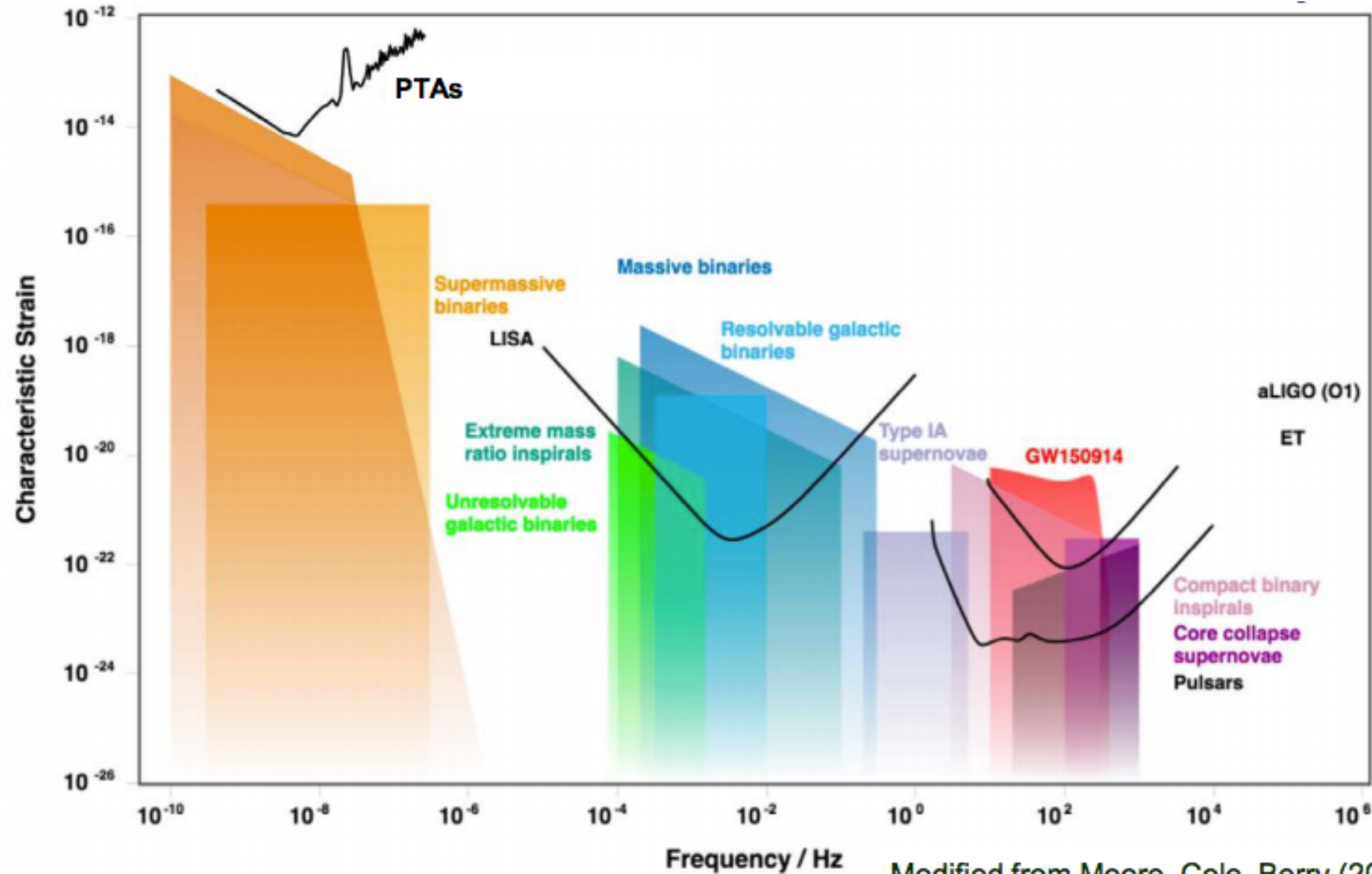
> Papers with Science Results > 150 citations

- 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."](#) ↗
- Astrobit.es. ["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."](#) ↗

Confirmed by MeerKAT in Dec 2024

Sensitivity of PTAs in GW spectrum

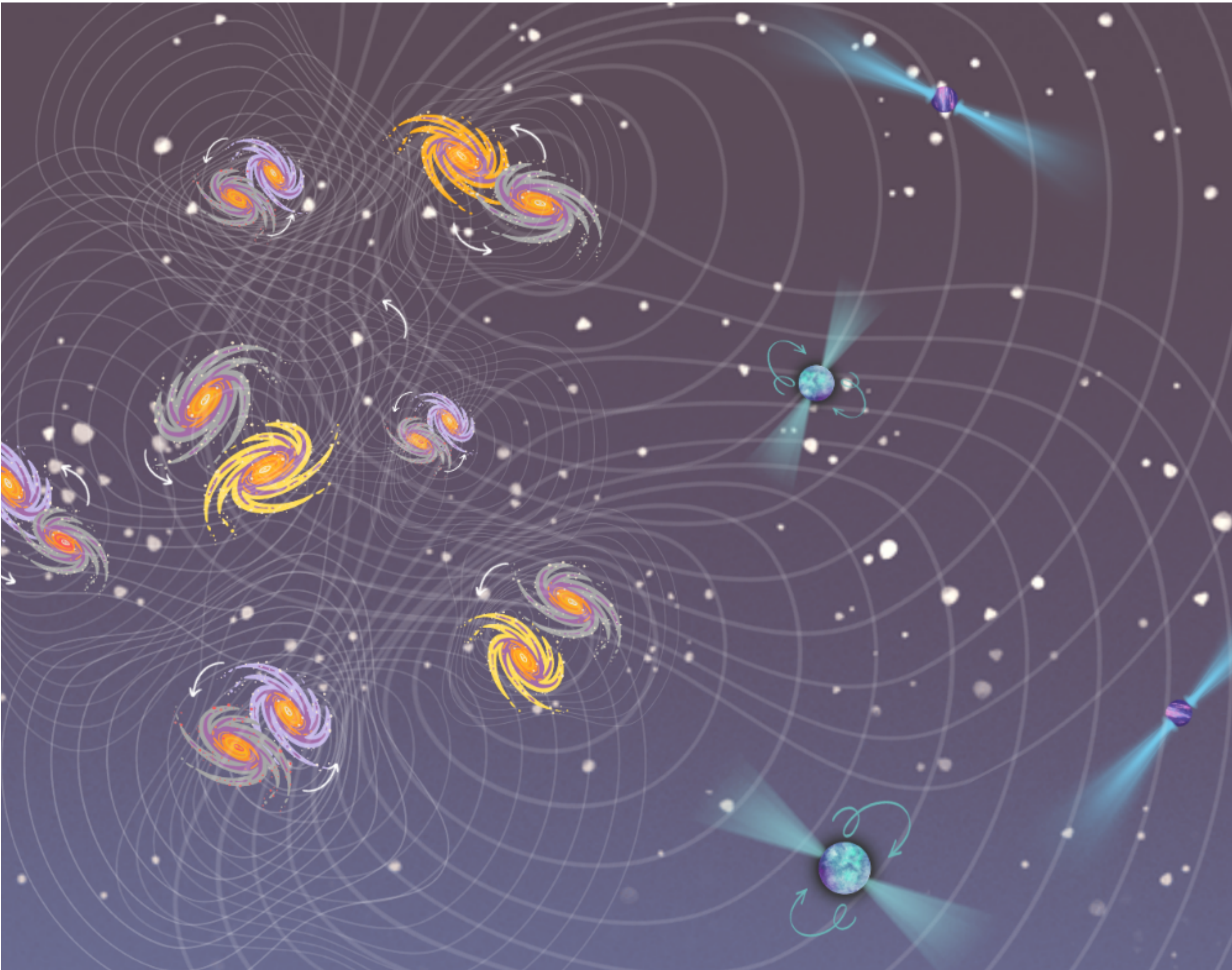


Modified from Moore, Cole, Berry (2014)

Mingarelli & Mingarelli
(2018)

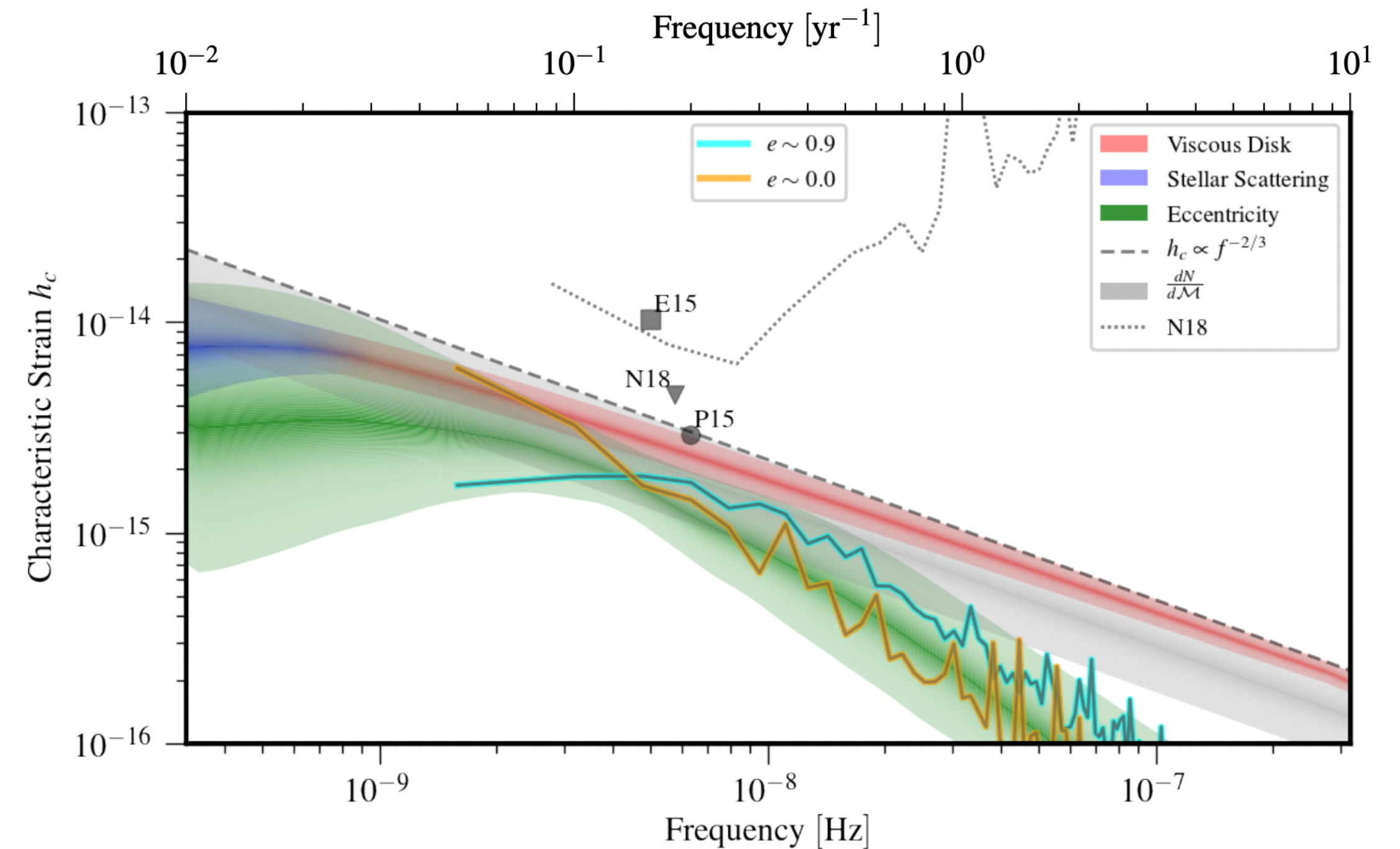
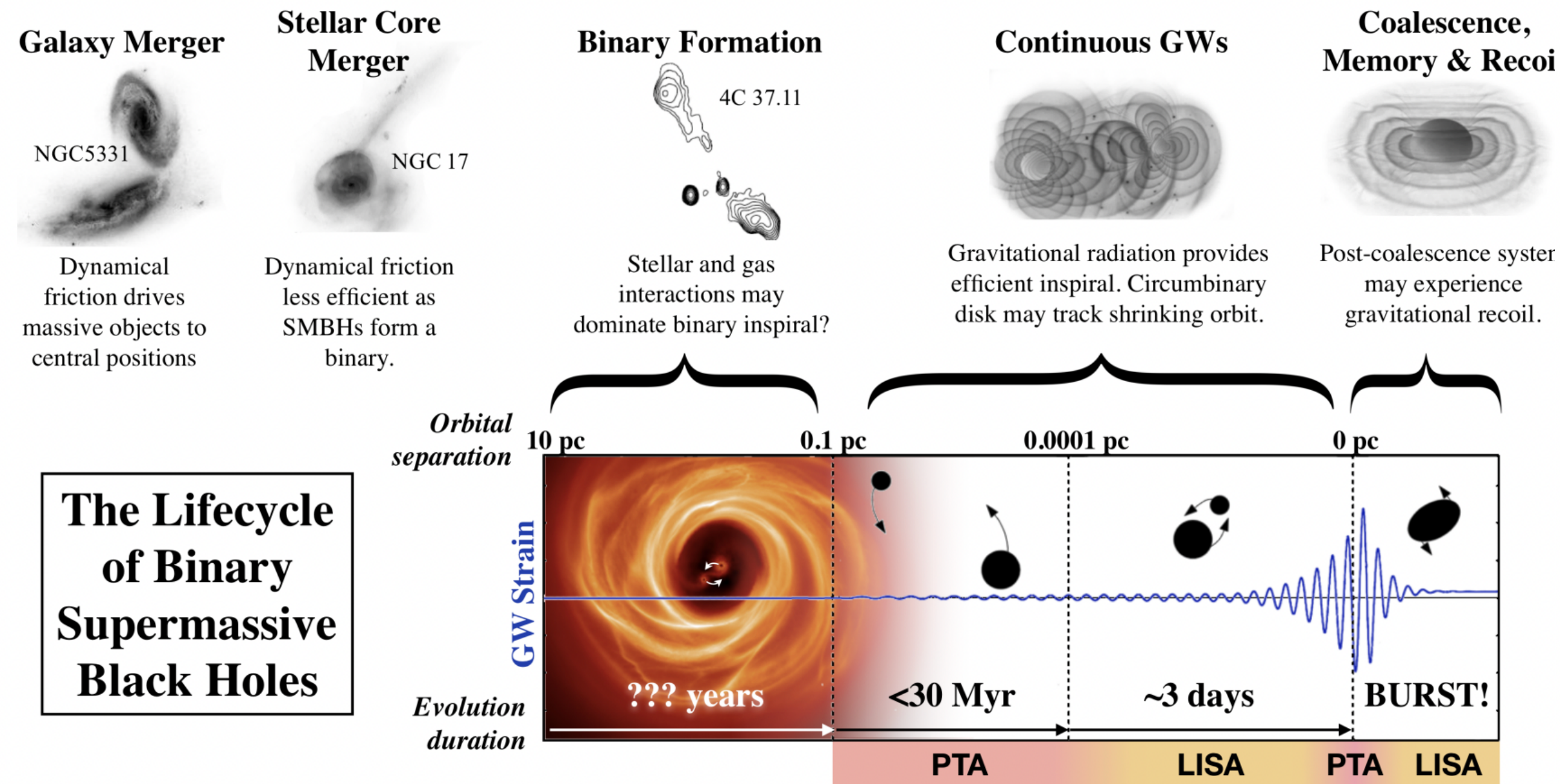
Most favored model for GWB

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

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

S. Detweiler ApJ 234, 1100 (1979)

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

Each term contains an earth and a pulsar term

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

Aim of PTAs is to look for such residuals

- GW induced residuals

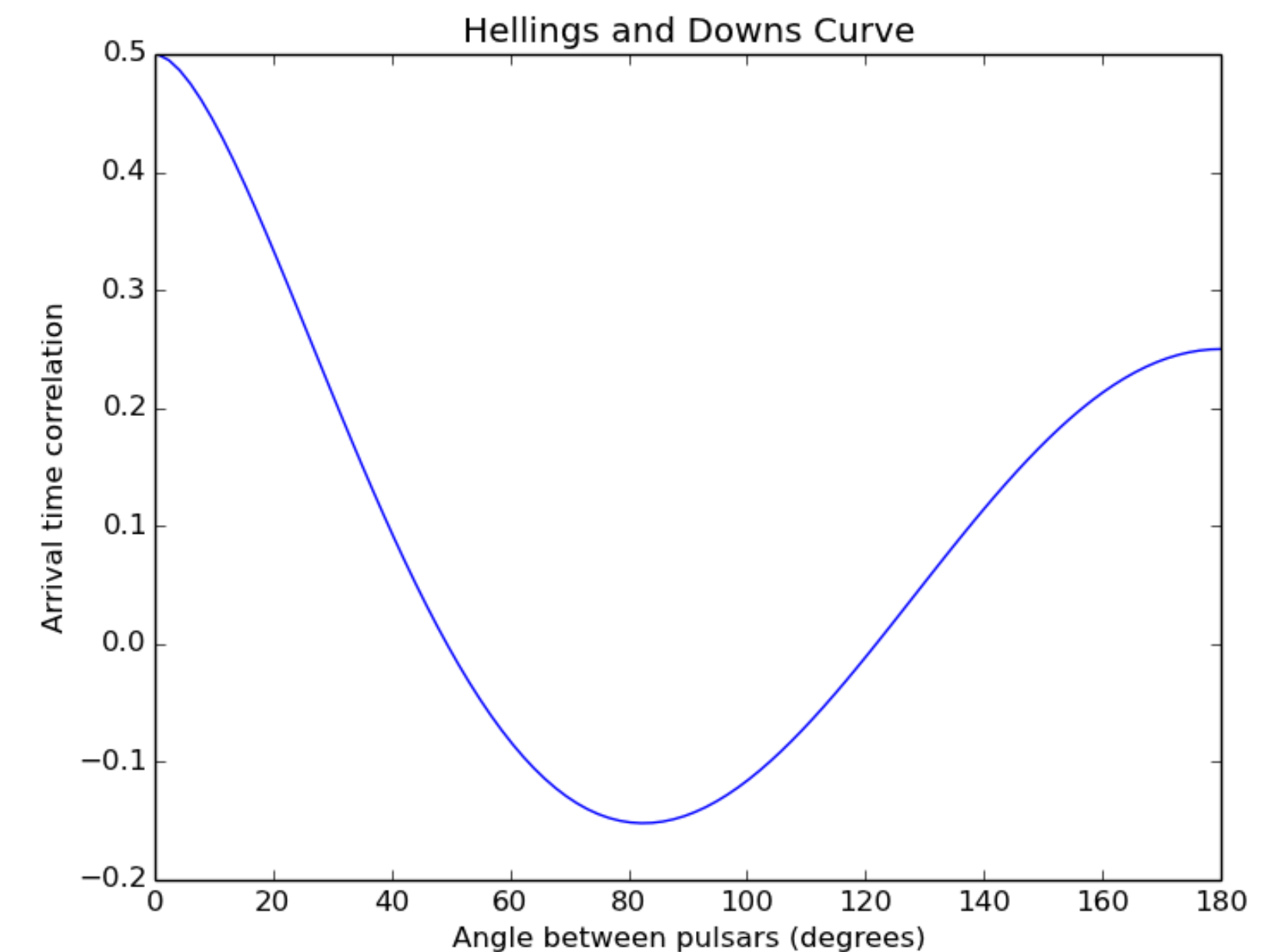
Smoking Gun Signature of GWB

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

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

$$\gamma = 13/3$$

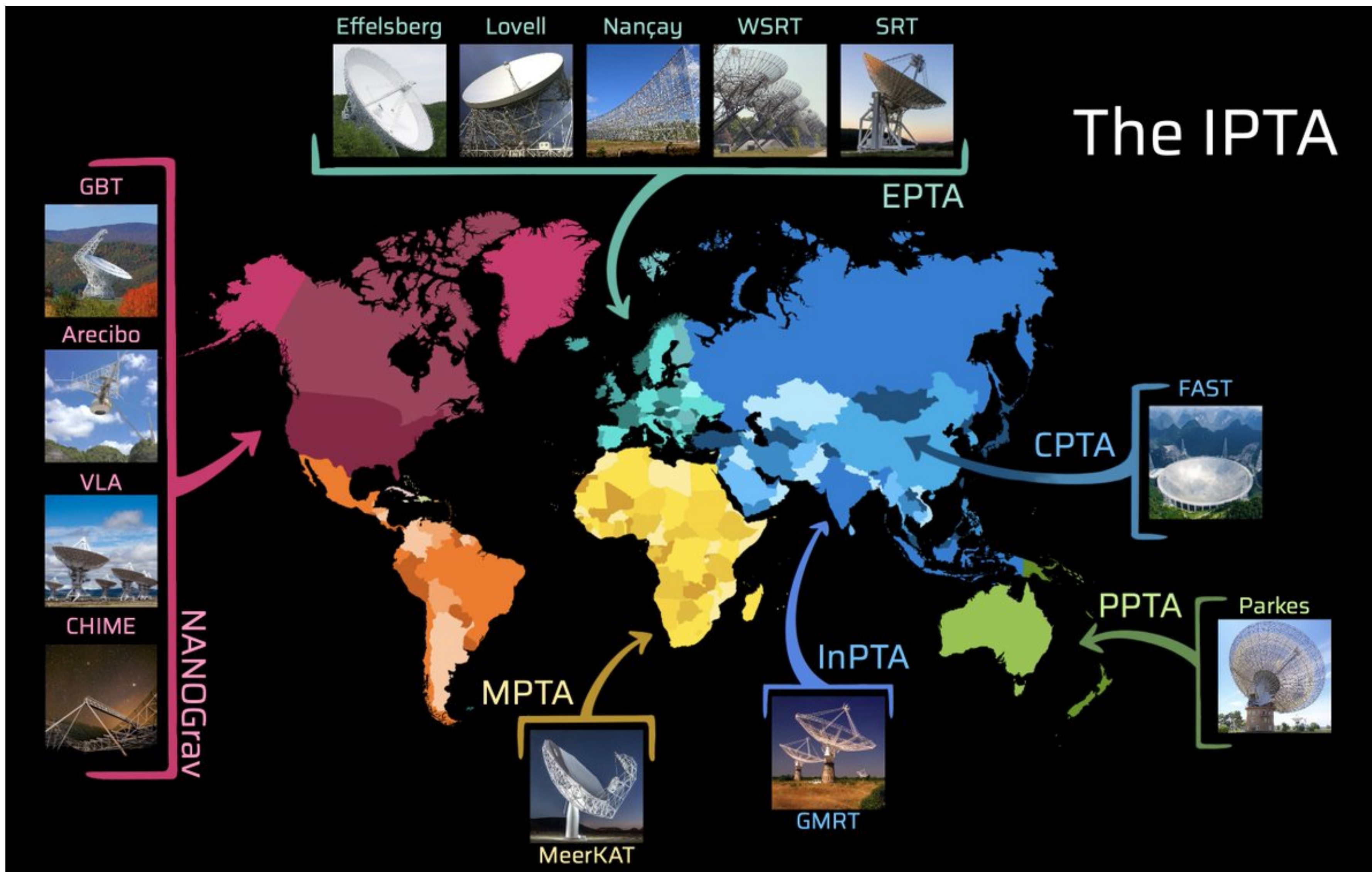
- Residuals due to SMBH binary GW background are **correlated** with **quadrupole** nature (HD correlation)



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

B. Allen & J. Romano arXiv:2308.05847

International Pulsar Timing Array (2023)



NanoGrav 67 MSPs : 15 years

EPTA 25 MSPs : 24 years

PPTA 30 MSPs : 28 years

InPTA 20 MSPs : 7 years

MPTA 83 MSPs : 4.5 years

InPTA Consortium



- Indo-Japanese collaboration (~ 50 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 from GW signal

Observations with Upgraded GMRT

Joshi et al 2018, Joshi et al 2022



- 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

First Data Release (DR1) in 2022

Second Data Release (DR2) in 2025

Third Data Release planned in 2027

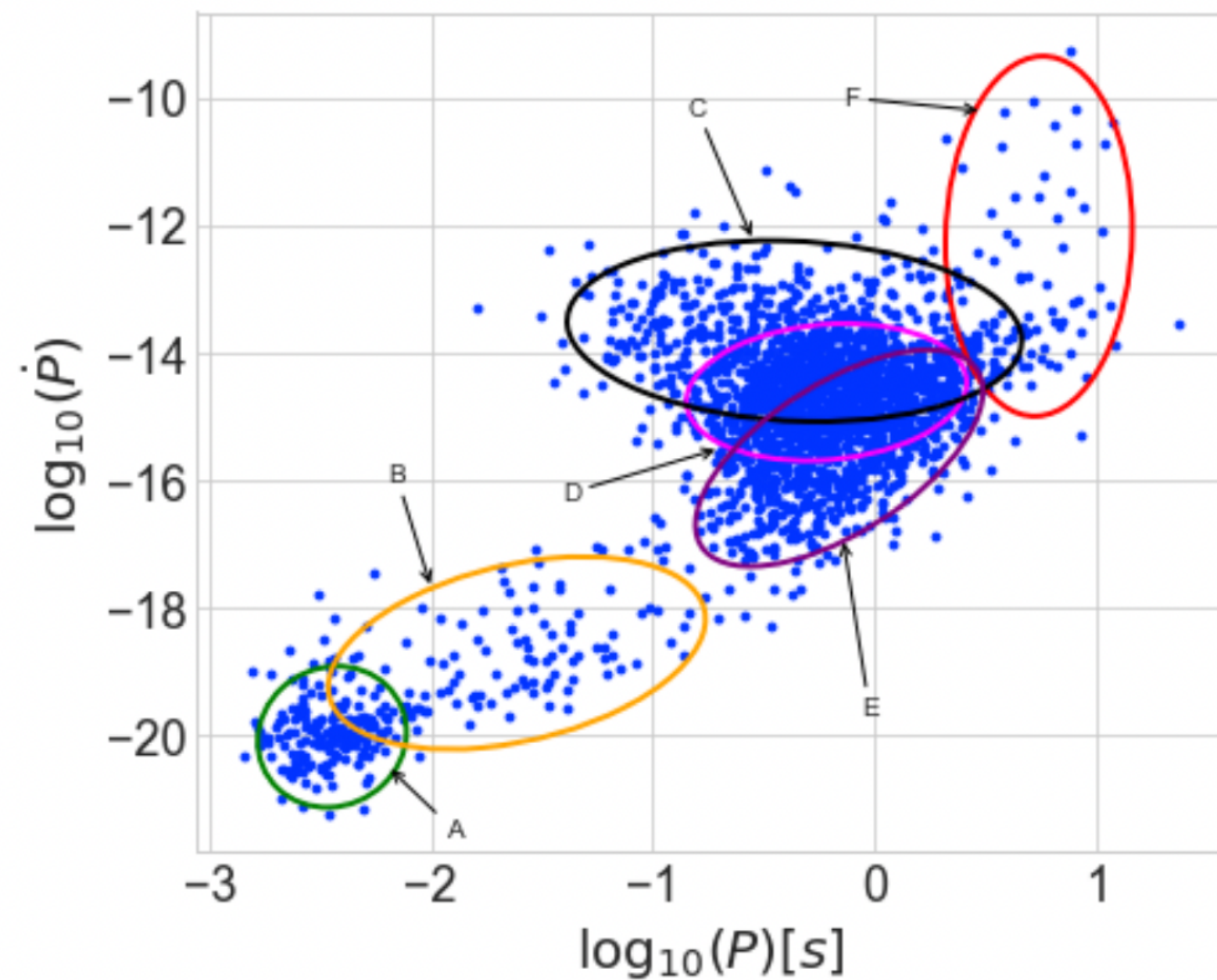
Millisecond Pulsars as Probes of GWs

Pulsars are highly magnetised rotating neutron stars ($M \sim 1.4 M_{\text{sun}}$ $R \sim 10$ 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

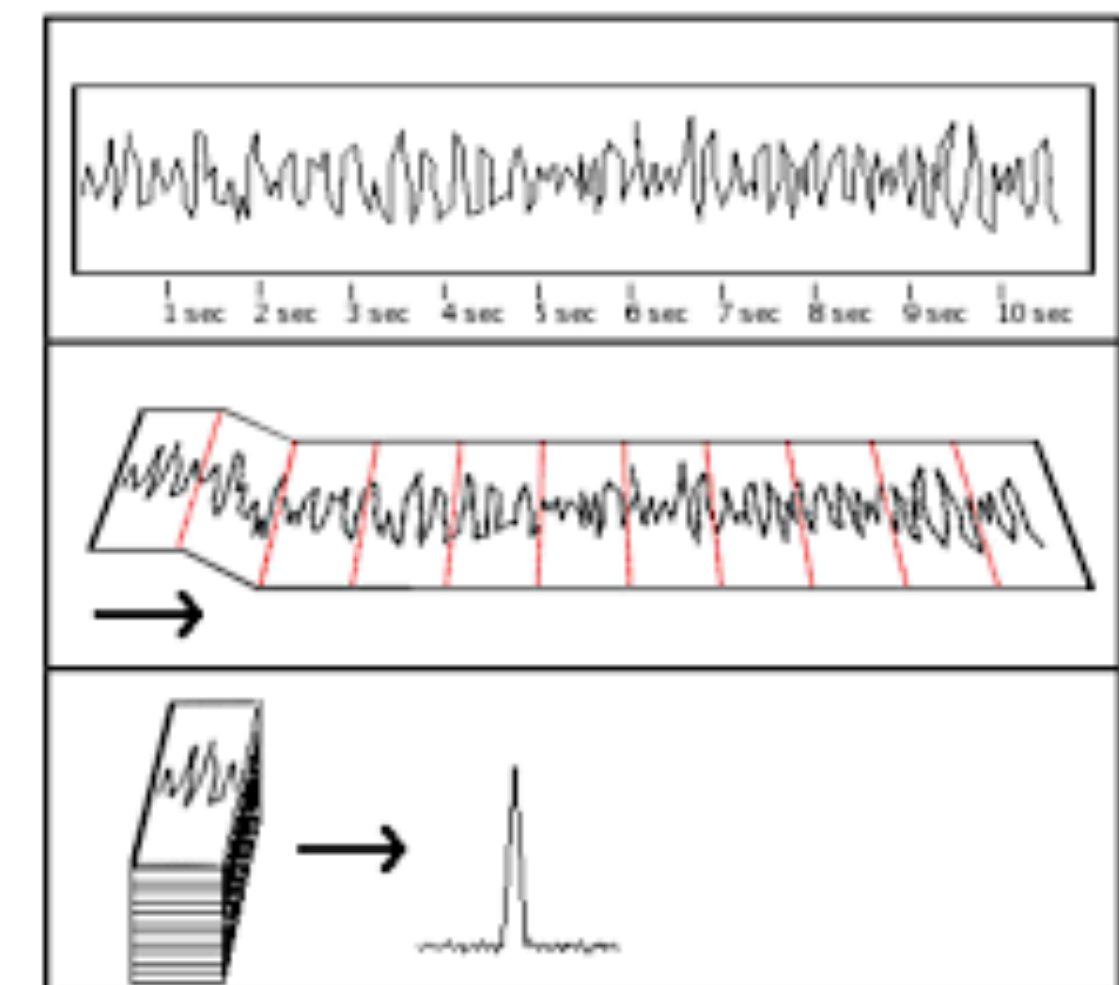
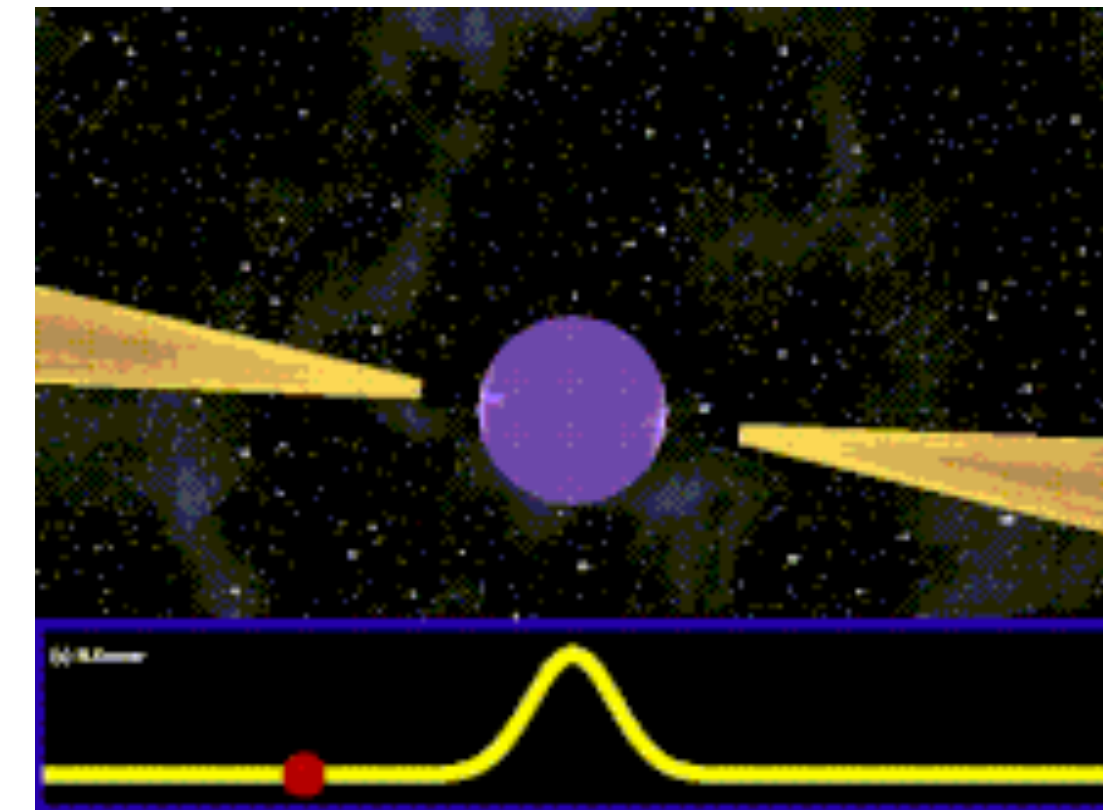


Reddy & SD
New Astronomy 91, 101673 (2022)

Timing Residual = Measured ToA - Predicted ToA

Data

Model of Pulsar



InPTA Data Release I

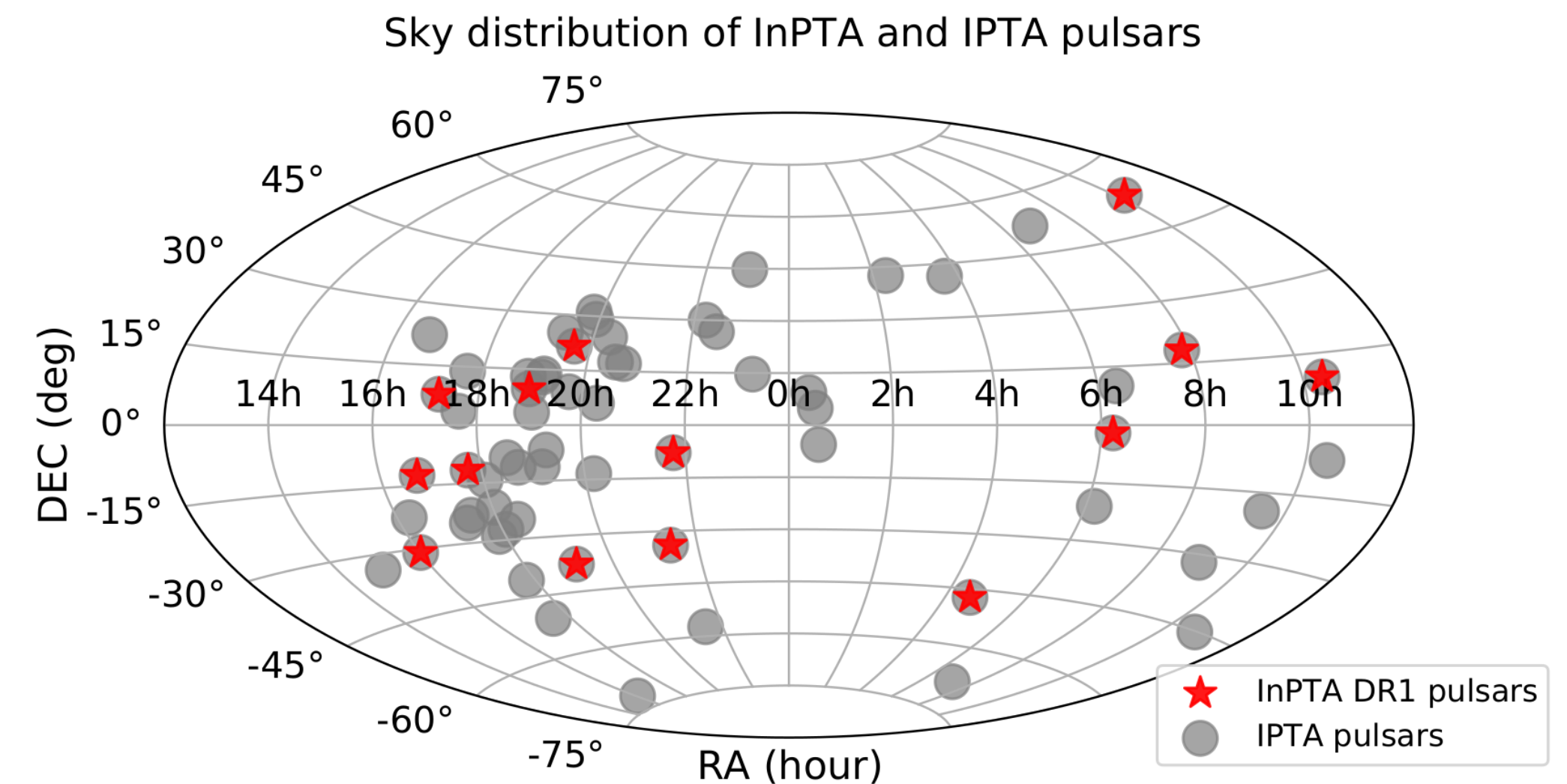
14 millisecond pulsars

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

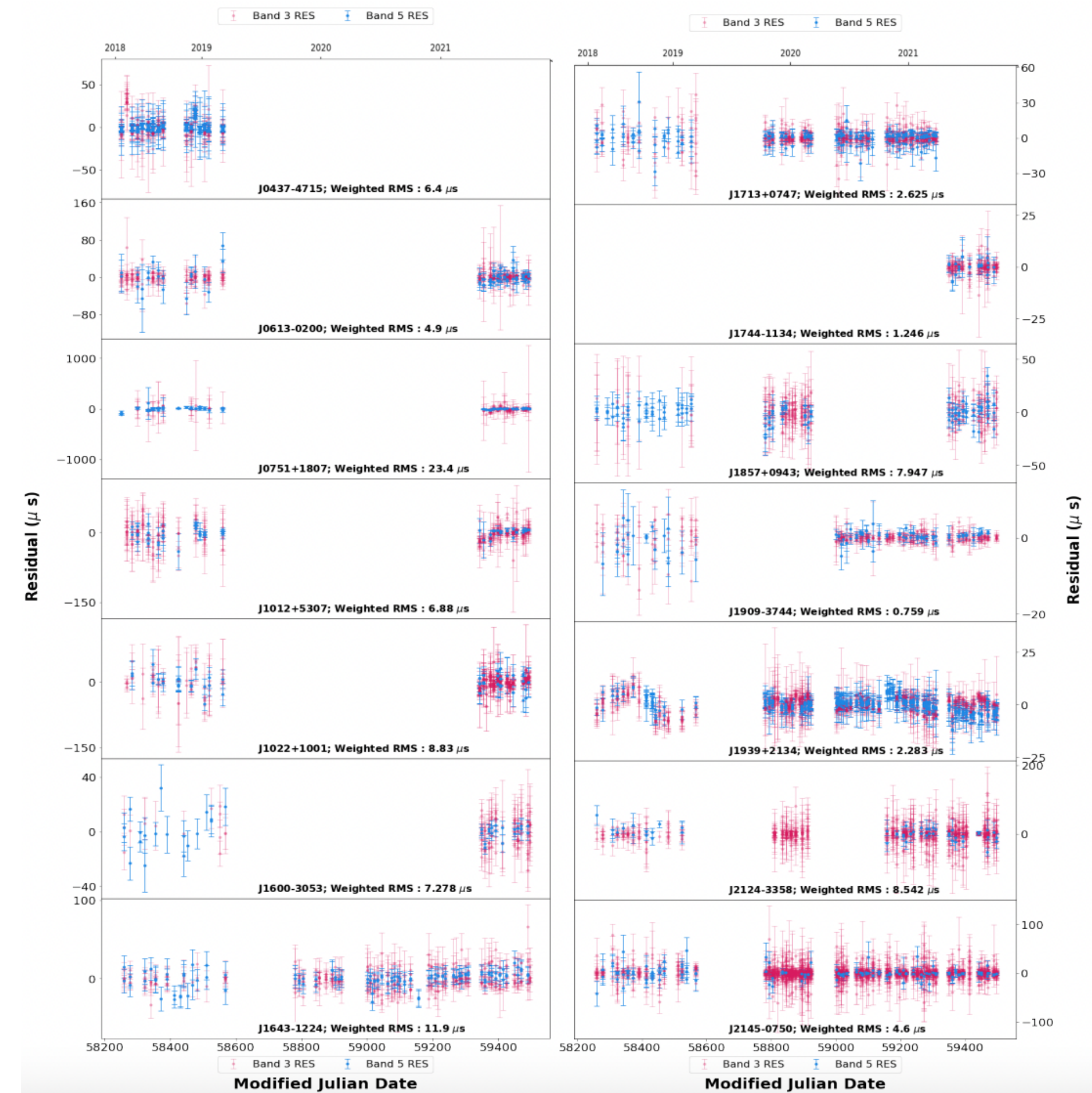
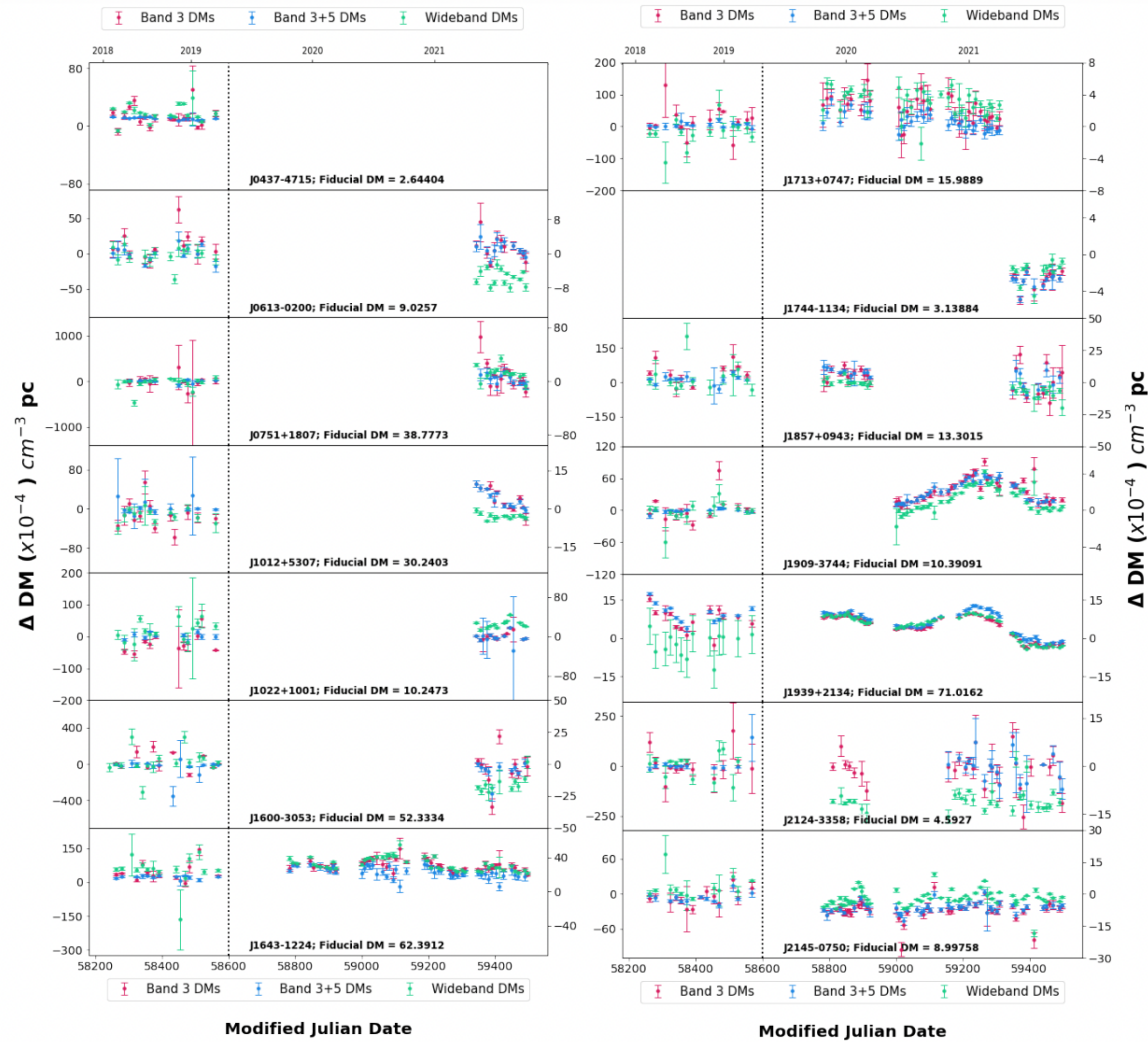


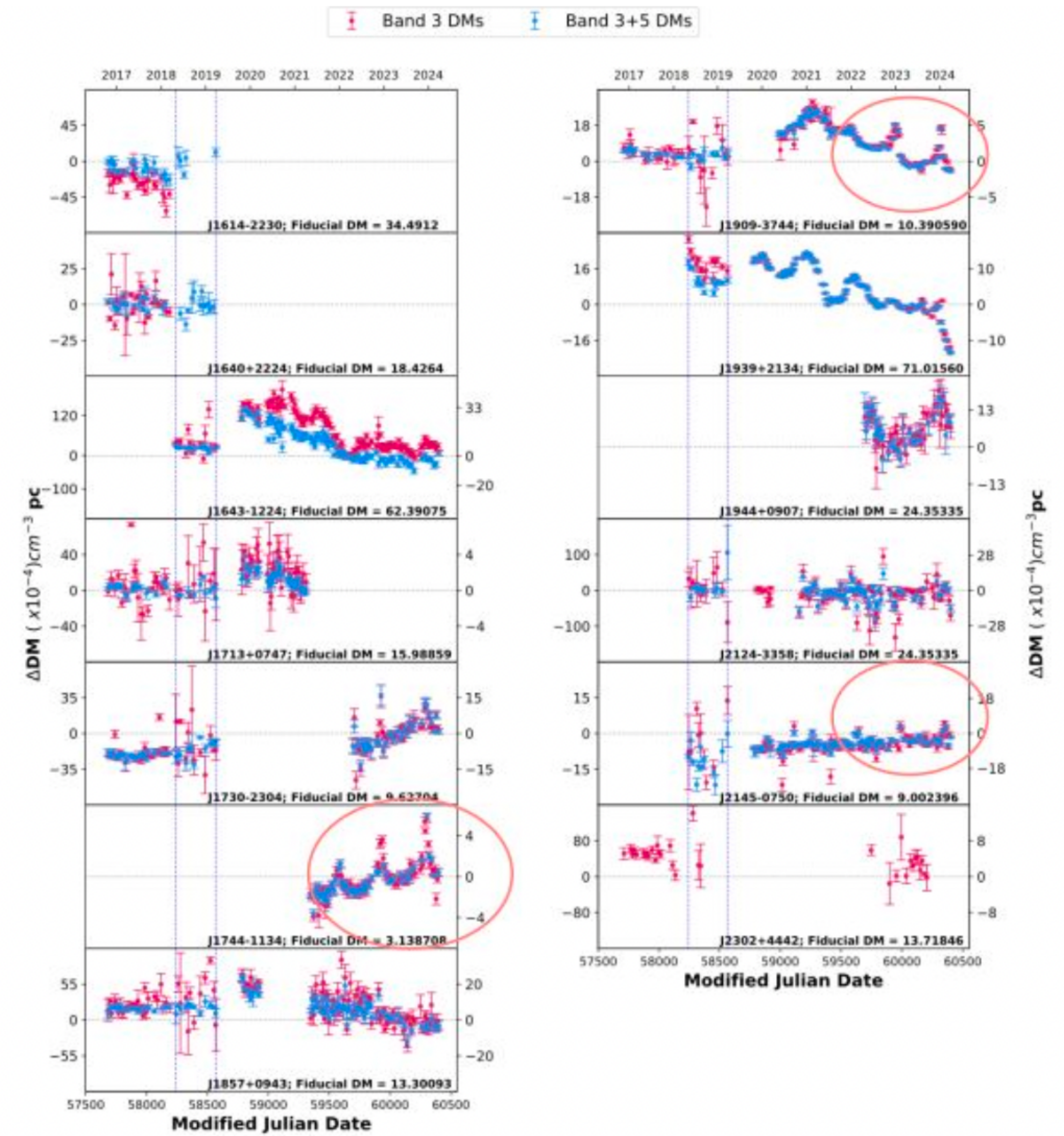
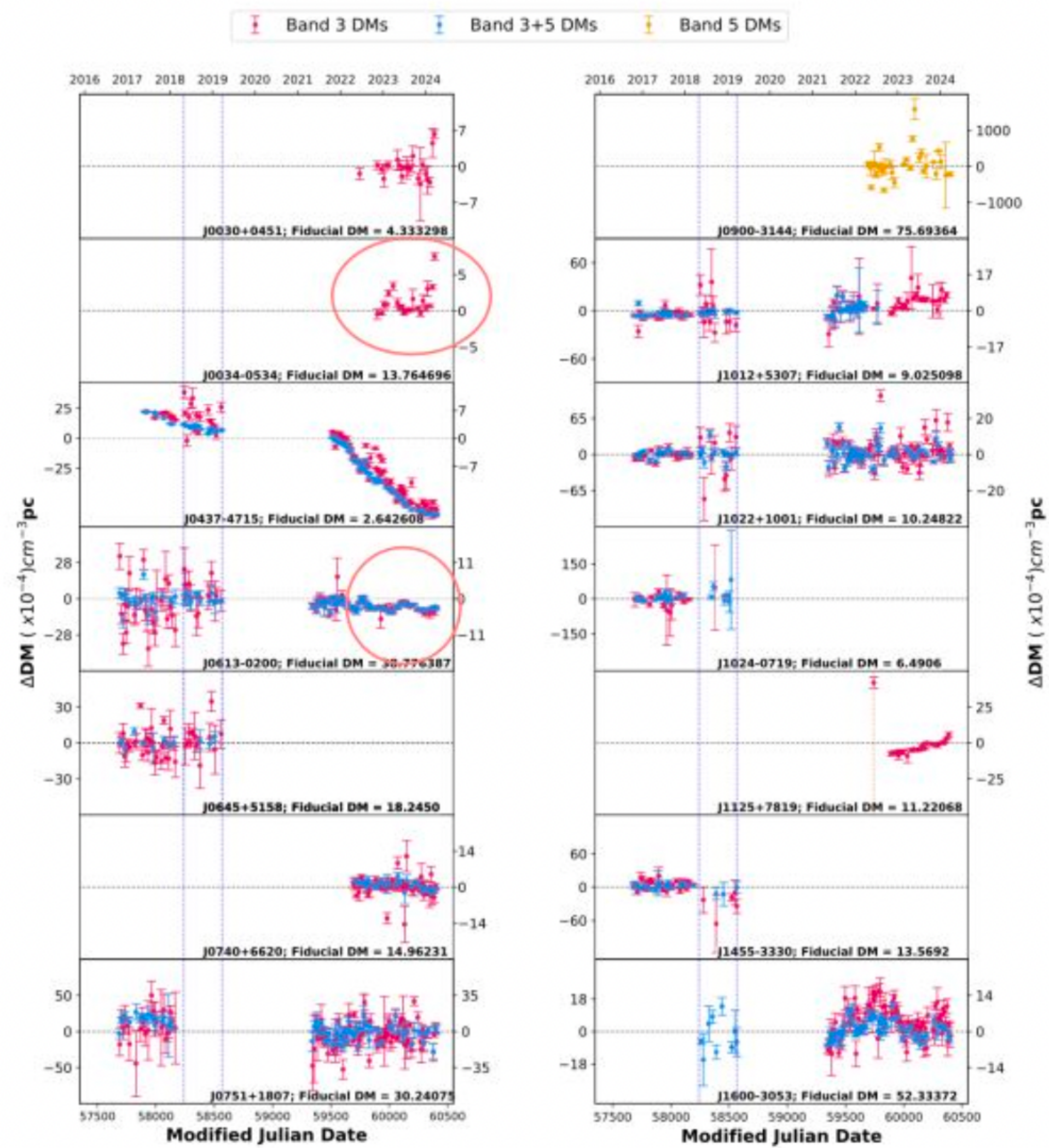
Narrowband TOAs

+

Wideband TOAs

InPTA DR1 Results





- High DM precision : $10^{-6} - 10^{-5} \text{ pc cm}^{-3}$
- PSRs J0034-0534, J0613-0200, J1744-1134 , J1909-3744 and J2145-0750 show annual trend due to solar wind
- PSR J1125+7810 show interesting DM event at MJD 59741 having $\Delta DM \sim 0.042 \text{ pc cm}^{-3}$

Noise Sources

- Contributes to systematic deviation in the residuals
- Deterministic - rotational , positional or binary model
- Stochastic - White noise, E_{fac}, E_{quad}
- 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

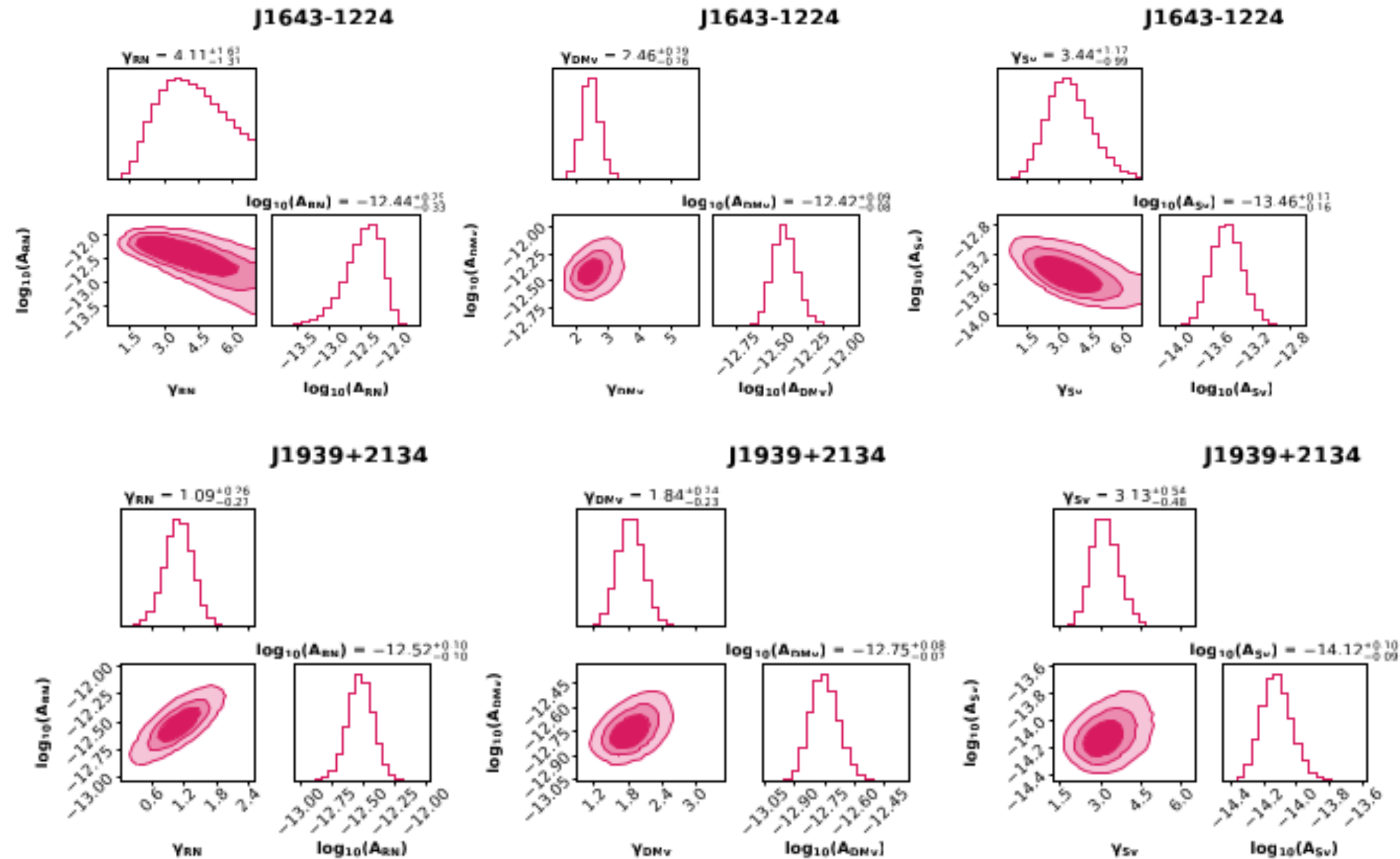
Stochastic GW background manifests itself as a stochastic red noise process

Noise 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

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

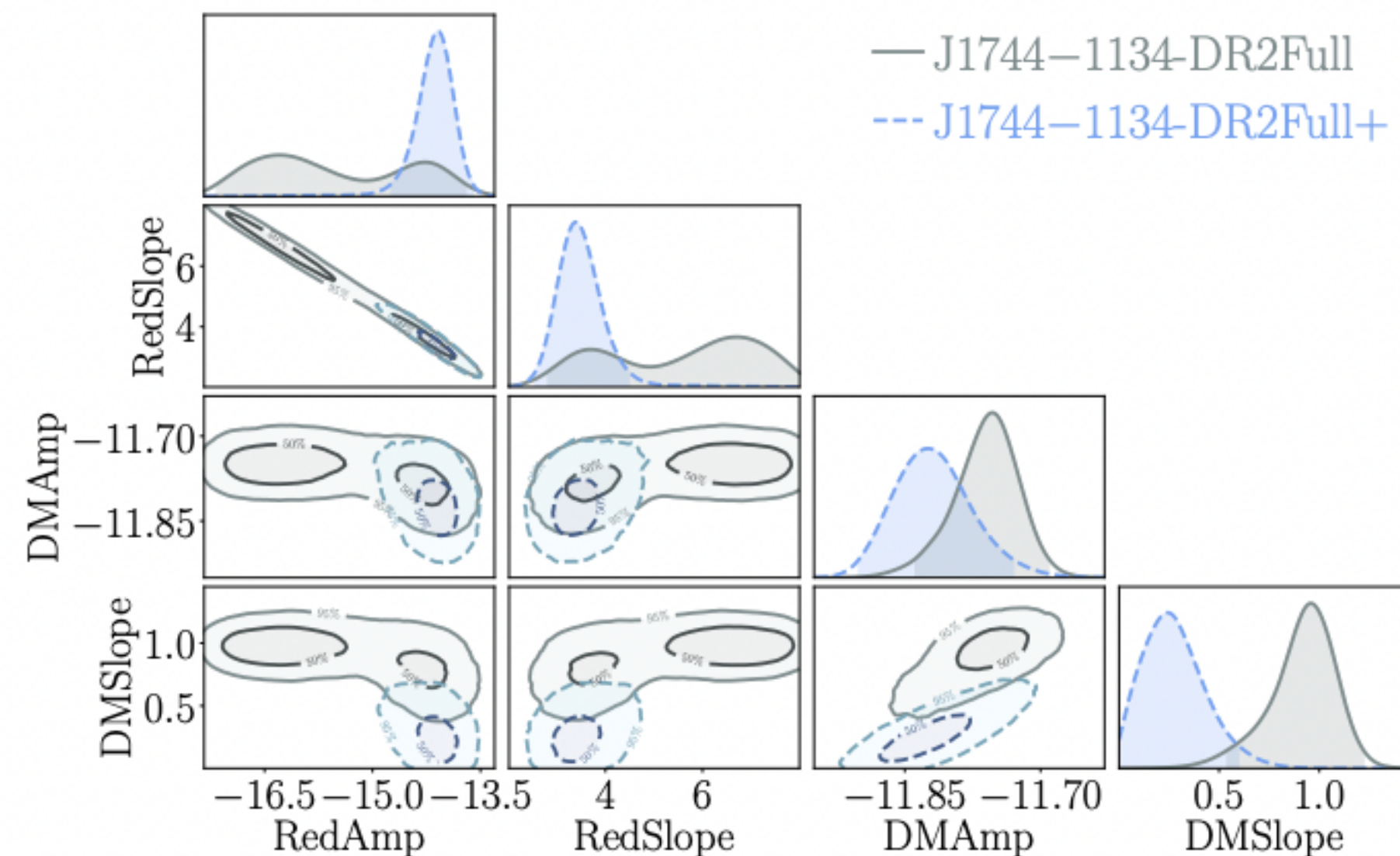
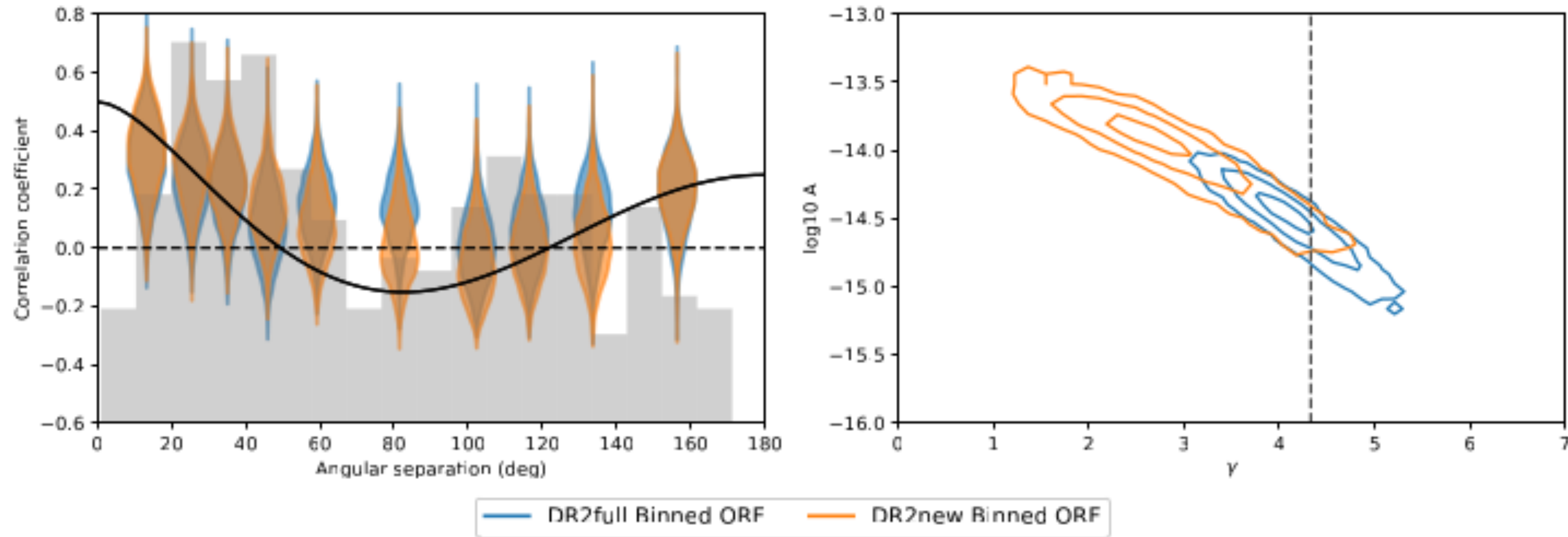


Fig. 5. Red and DM noise models for PSR J1744–1134 using DR2full and DR2full+ datasets. The inclusion of InPTA data allows a better constraint on the achromatic noise.

InPTA+EPTA Evidence for Hellings-Downs Correlation

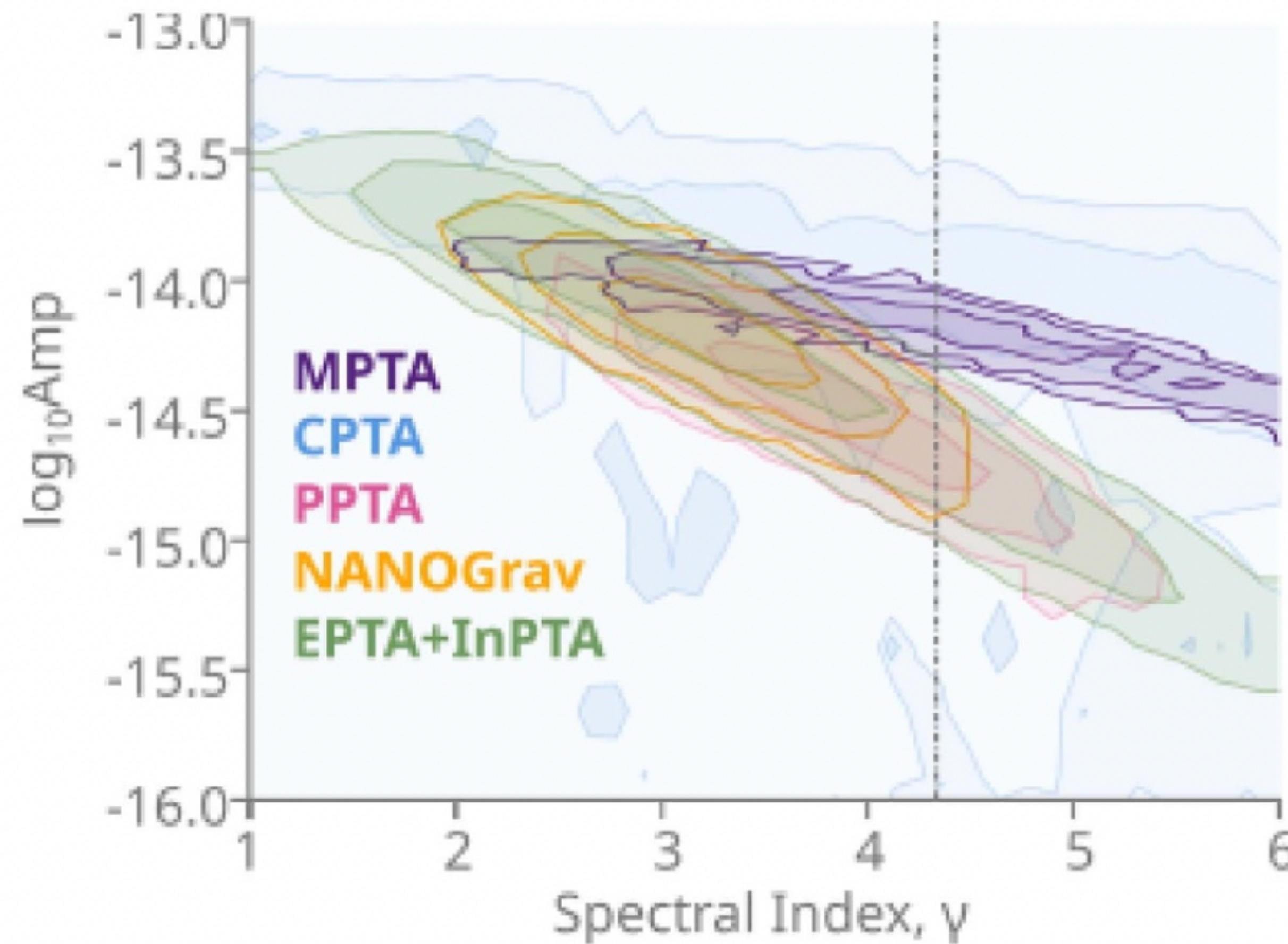


Analysis of InPTA+EPTA dataset done on supercomputers at IIT Hyderabad by Aman Srivastava

Bayes factor for Hellings-Downs correlation of ~ 60

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

Combined Results from all PTAs (2023)



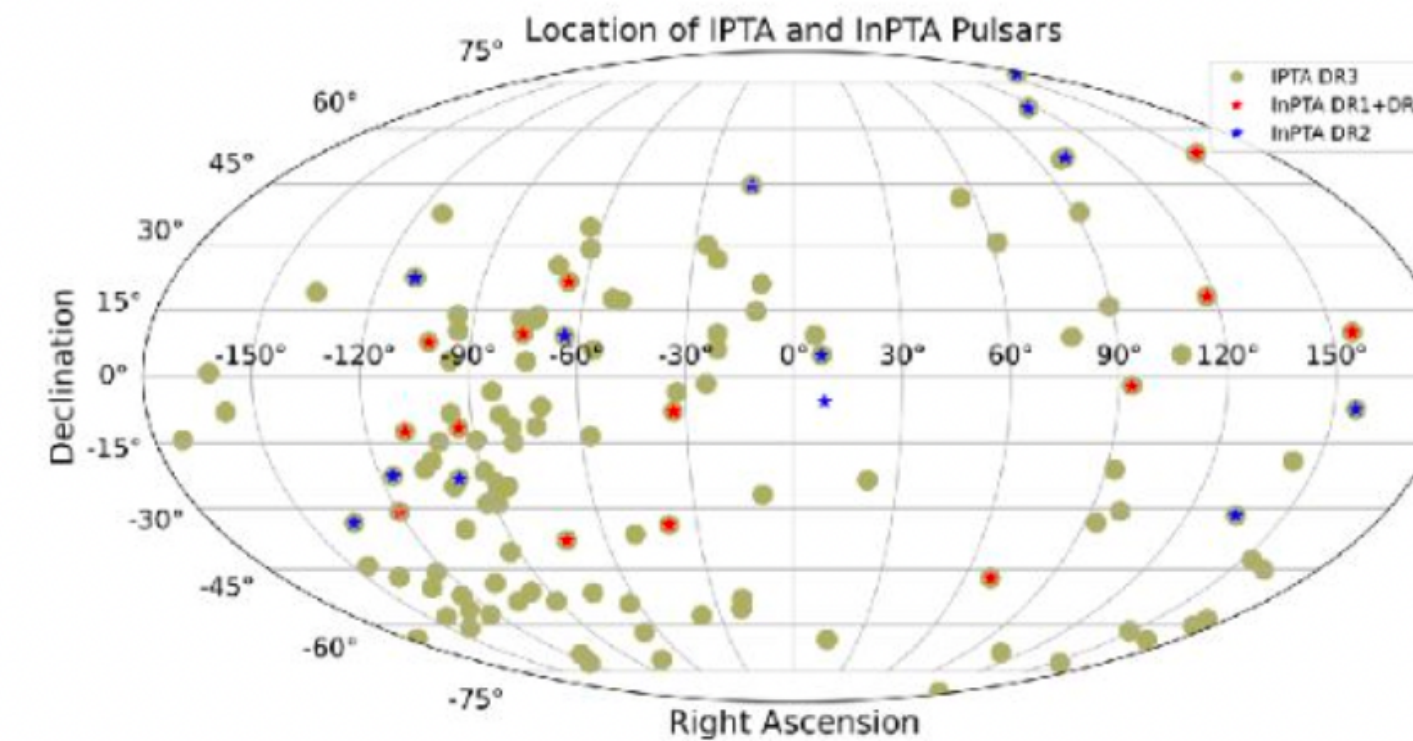
InPTA Data Release II

14 InPTA-DR1 MSPs +

- | | |
|--------------|--------------|
| • J0030+0451 | • J1455-3330 |
| • J0034-0534 | • J1614-2230 |
| • J0645+5158 | • J1640+2224 |
| • J0740+6620 | • J1730-2304 |
| • J0900-3144 | • J1944+0907 |
| • J1024-0719 | • J2302+4442 |
| • J1125+7819 | |

= Total 27 pulsars

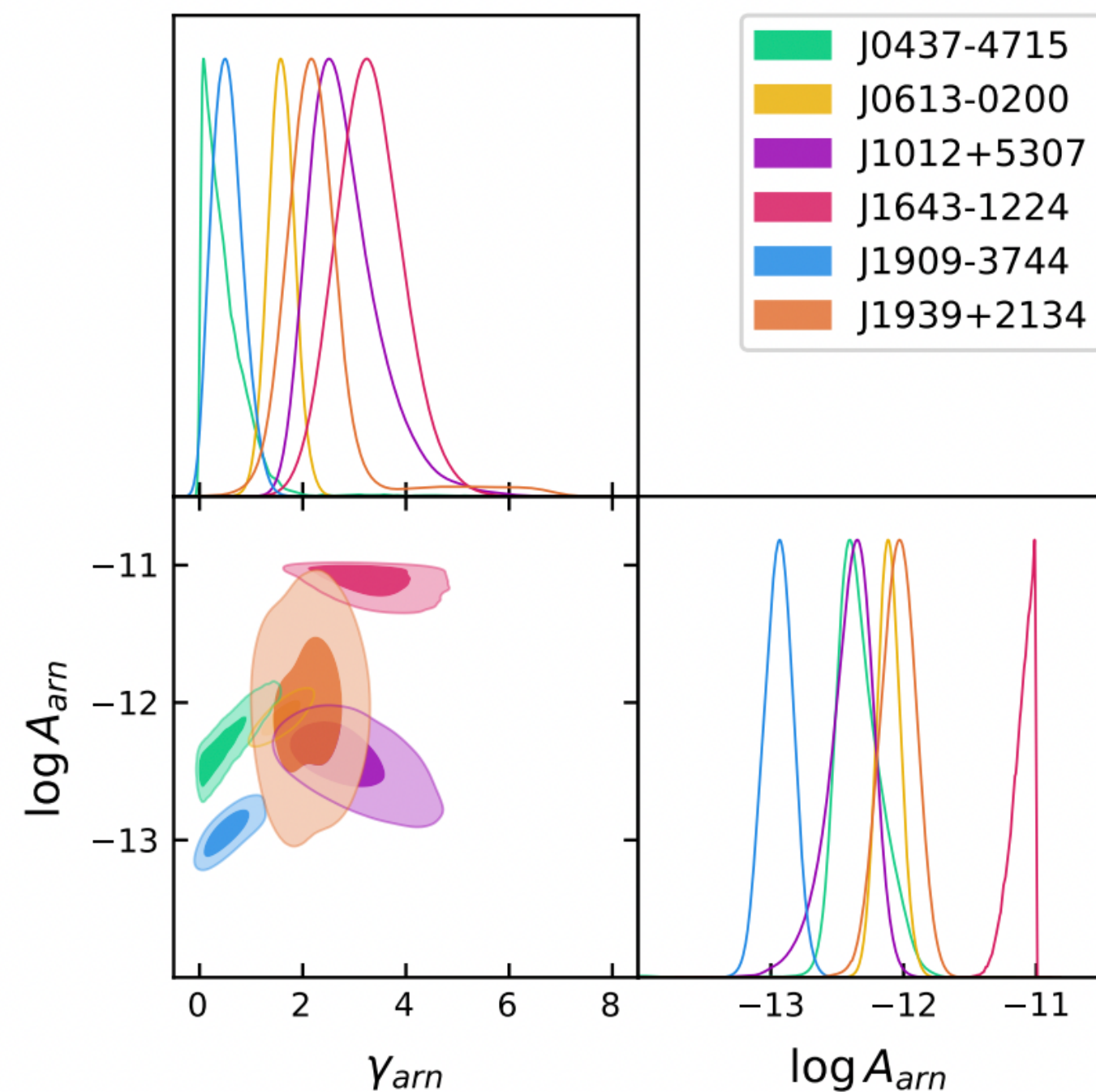
- InPTA-DR2 includes dataset from early 2017 to early 2024.
- Includes concurrent observations of two sub-arrays: **Band 3 (300-500 MHz)** and **Band 5 (1260-1460 MHz)** of the uGMRT.
- High-precision Dispersion measure (DM) and Narrowband sub-banded Time-of-Arrivals (ToAs).
- Timing models obtained using ~ 7 years time baseline data.



InPTA DR2 Noise Analysis

- Noise as a Stationary Gaussian Process - White Noise + ARN+DMGP+ FCN
- Taylor Series model for Solar wind.
- Anderson-Darling test for Gaussianity of noise-subtracted residuals : Gaussian

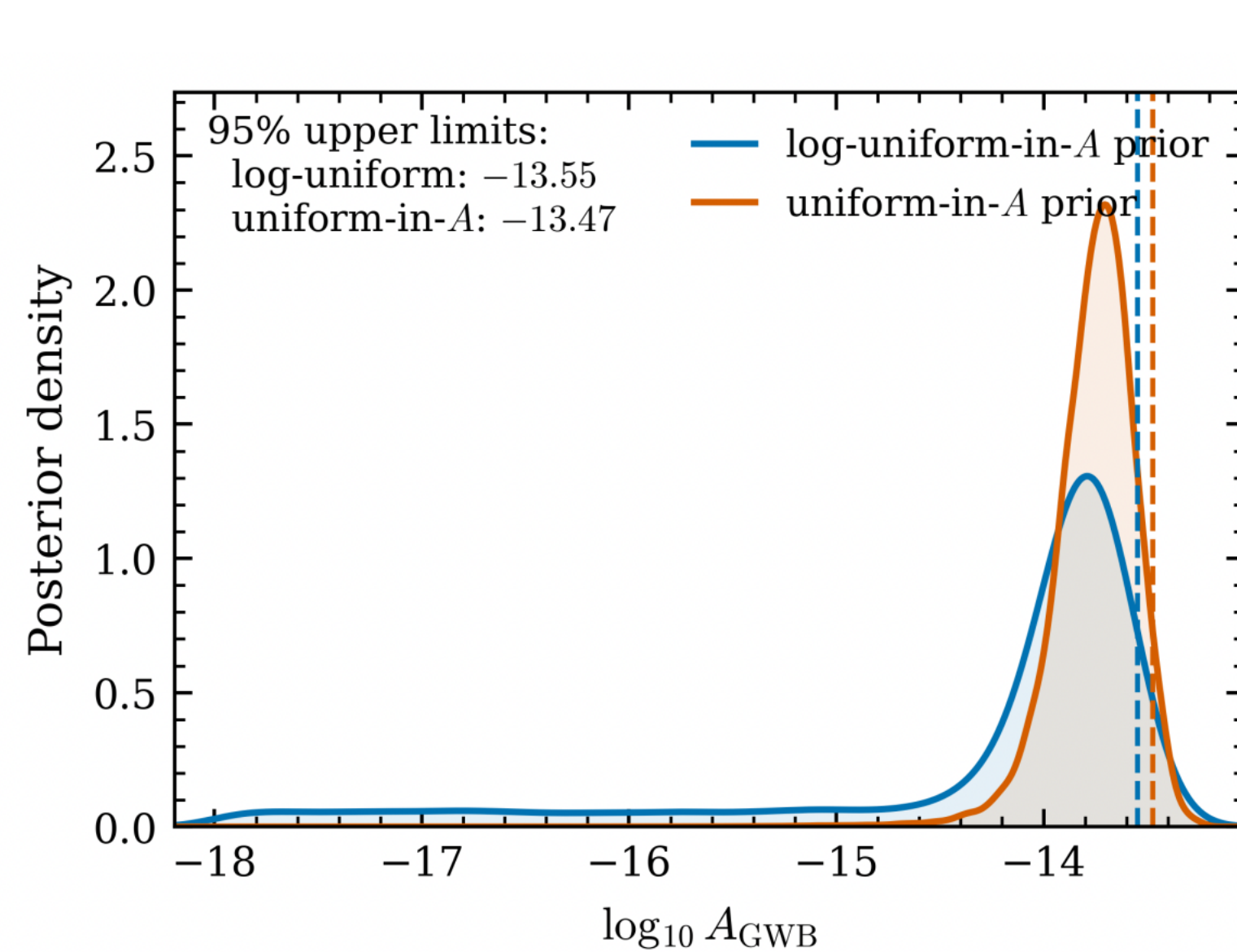
(Gaussian : 15 pulsars, Nearly Gaussian 8 pulsars, Non-Gaussian 4 pulsars)



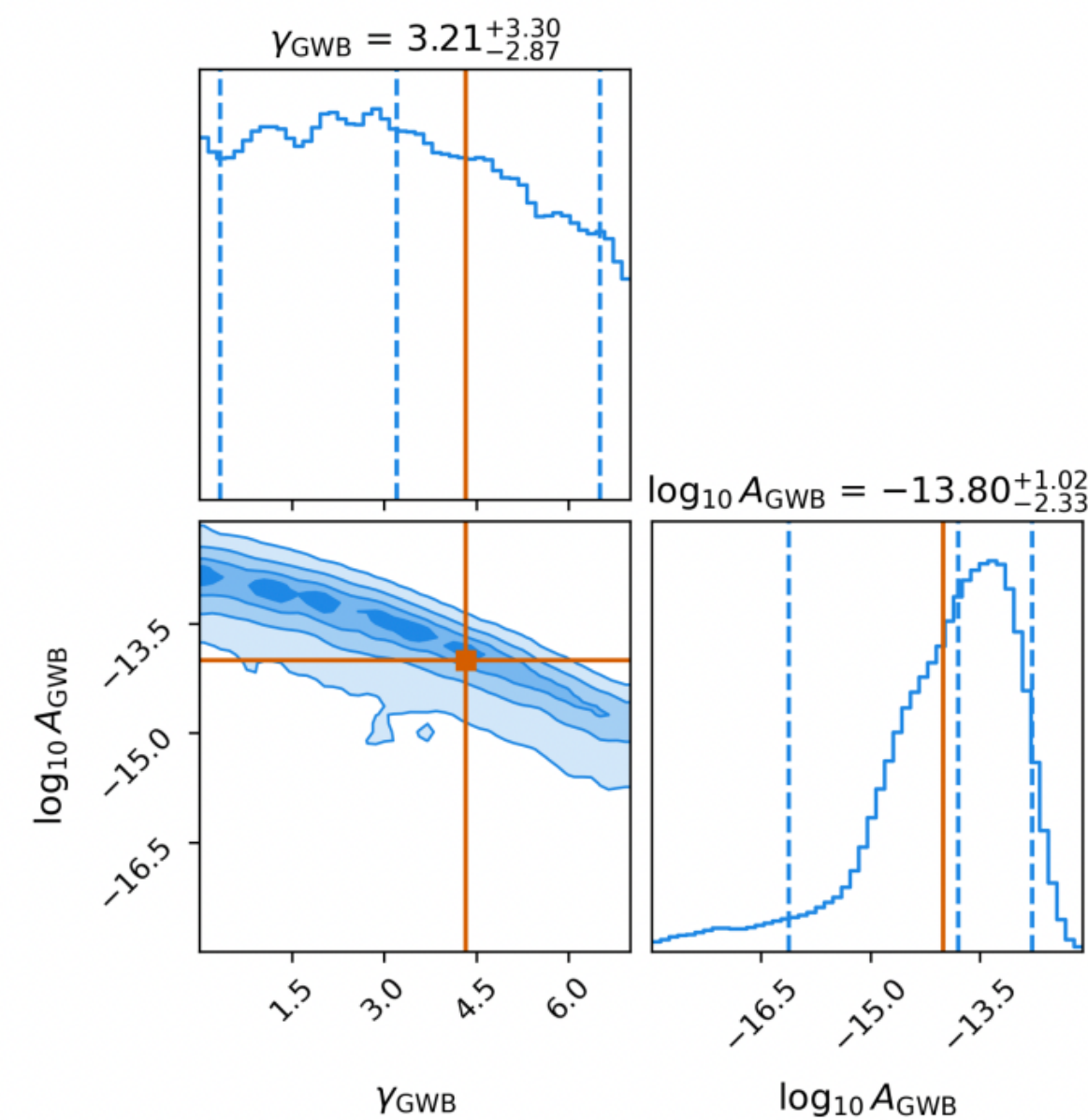
K. Nobleson, C. Dwivedi, SD et al
arXiv:2608.02808, JHEAP 53, 100594

InPTA DR2 Search for SGWB

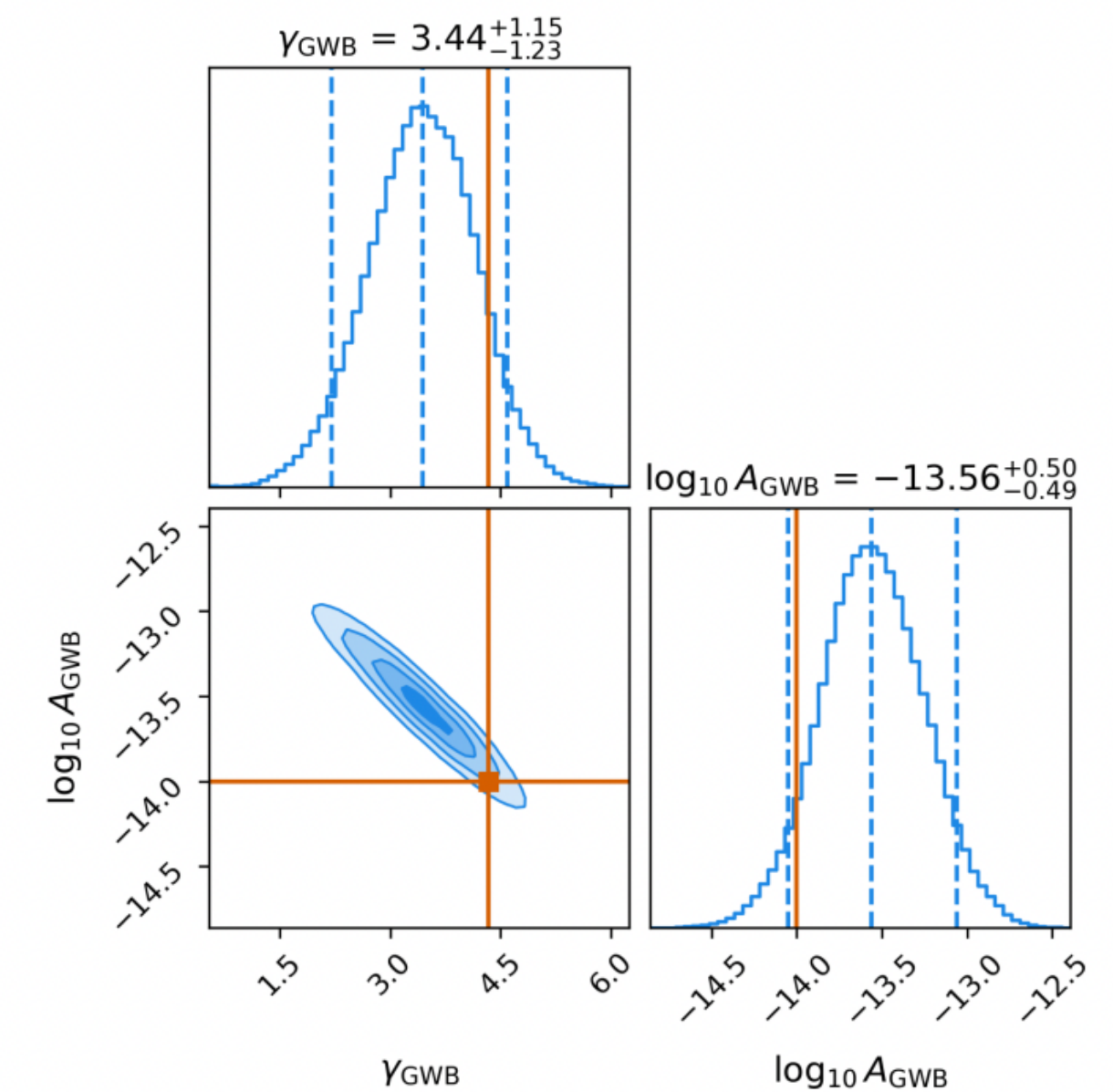
- Bayesian CURN Search reweighed to Hellings-Down model via importance sampling
- No significant common-process detection



(a) Full DR2 Upper Limit plot



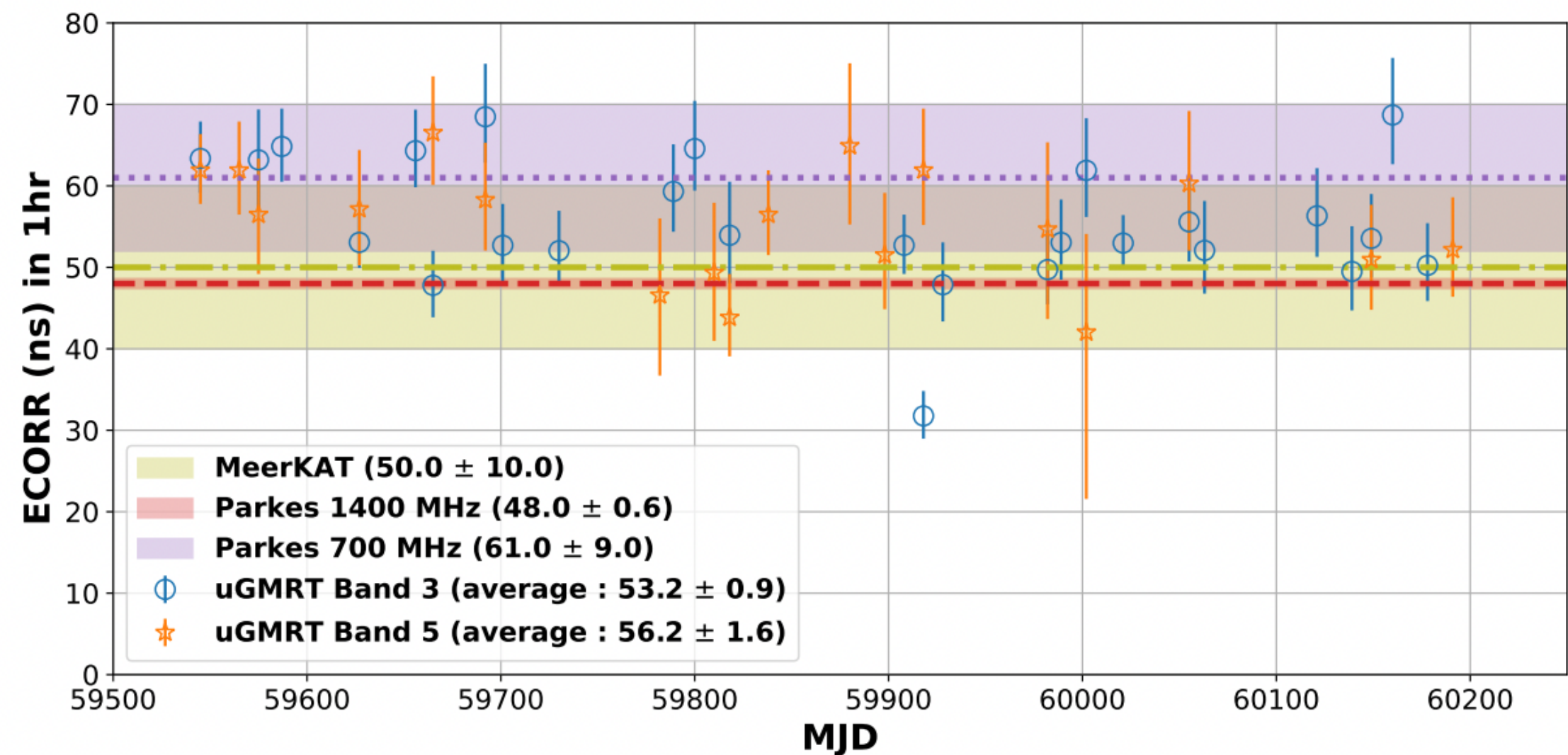
(a) 7-year baseline (validation)



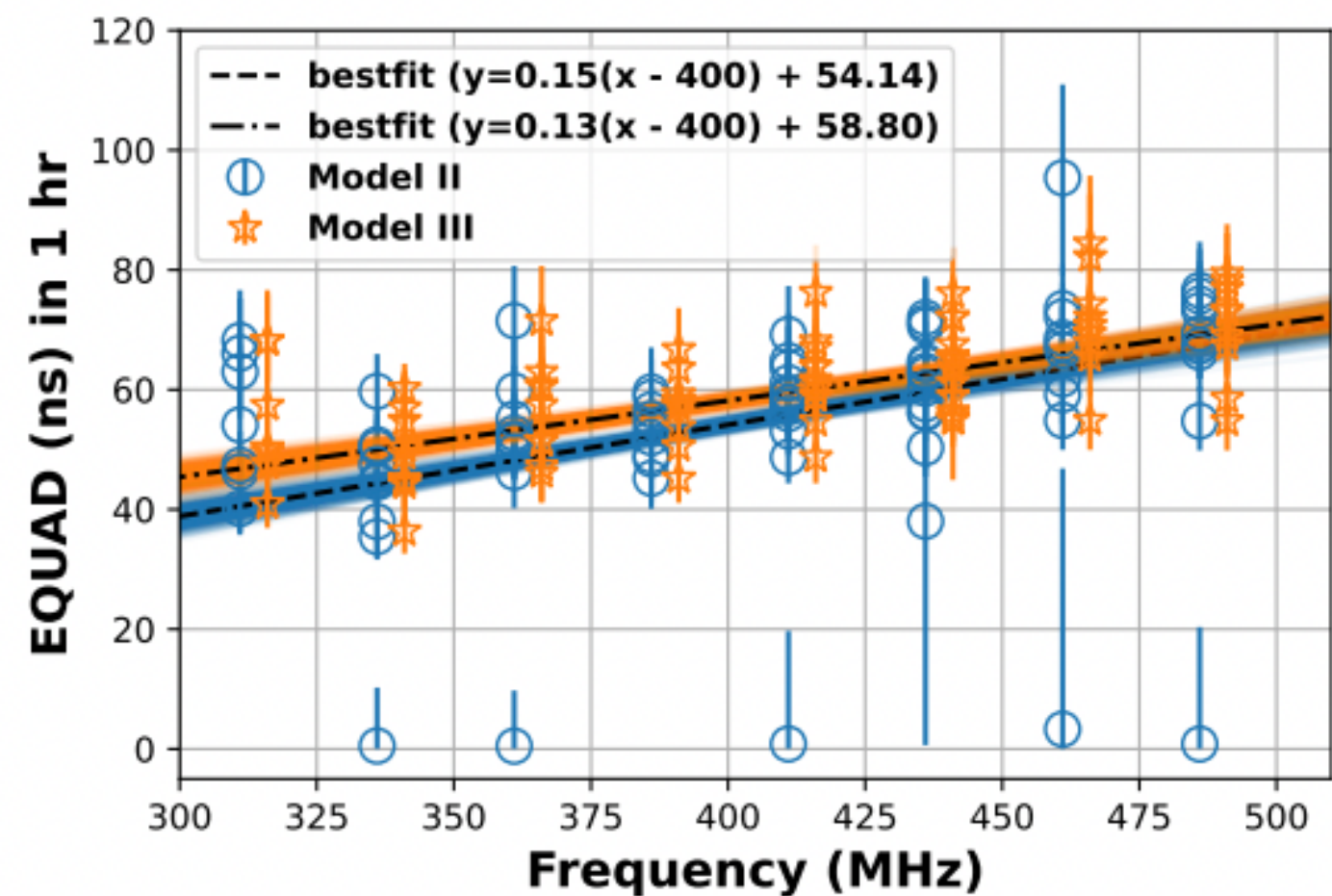
(b) 10-year baseline (forecast)

$$A_{\text{GW}} < 3.4 \times 10^{-14} (95 \% c.l.)$$

Jitter Measurements with PSR J0437–4715



First jitter measurement of this pulsar below 700 MHz
T. Kikunaga et al PASA, 41, 036 (2024)



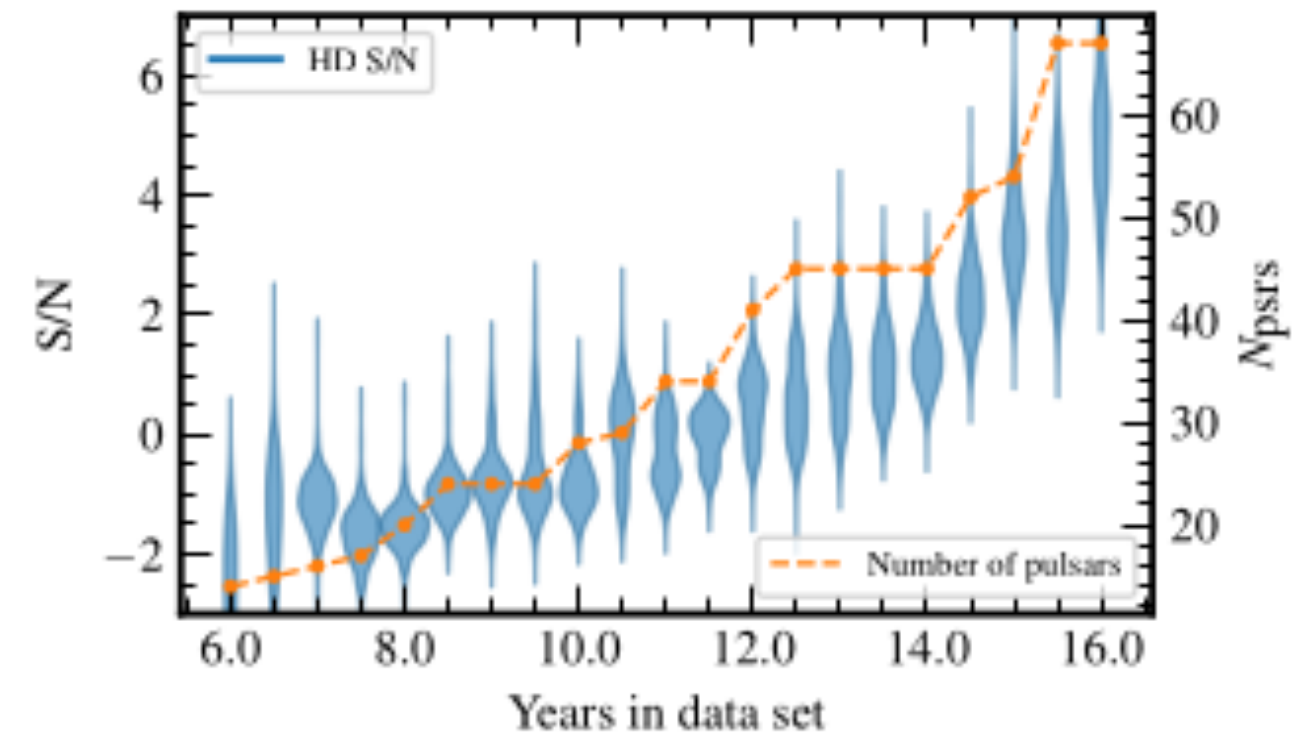
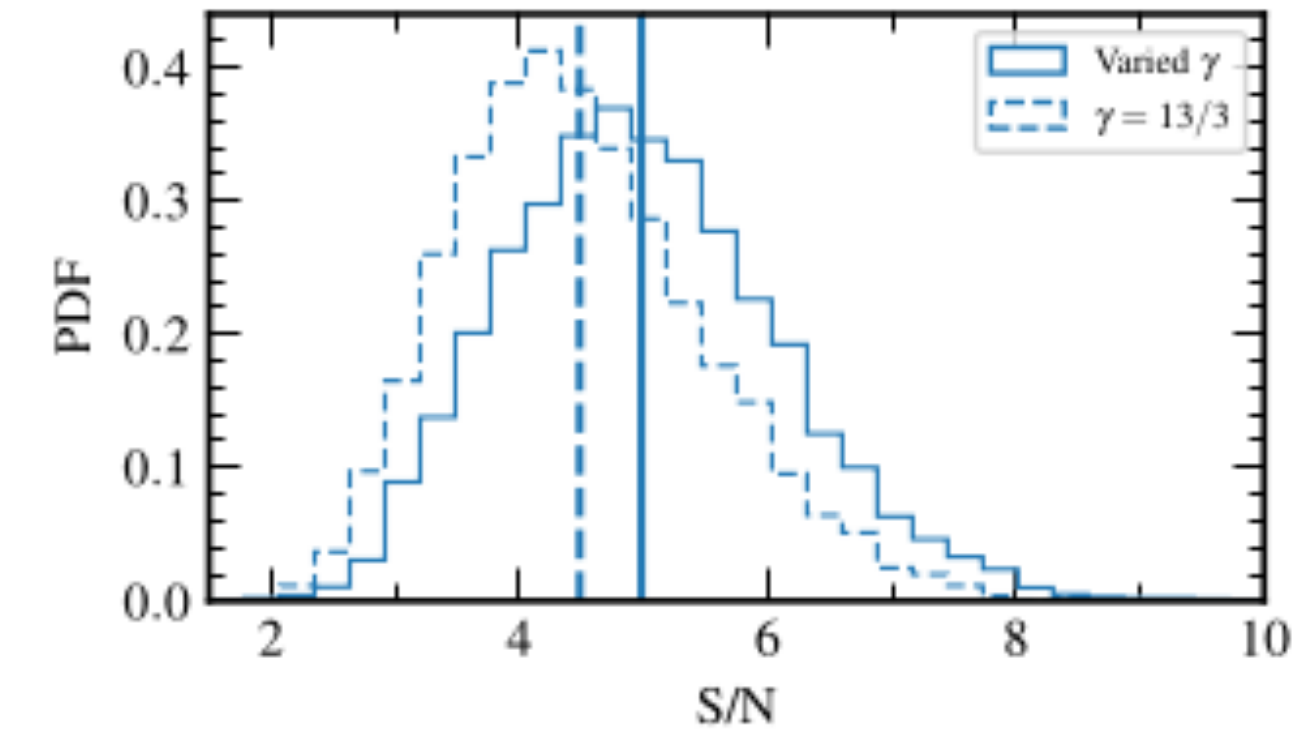
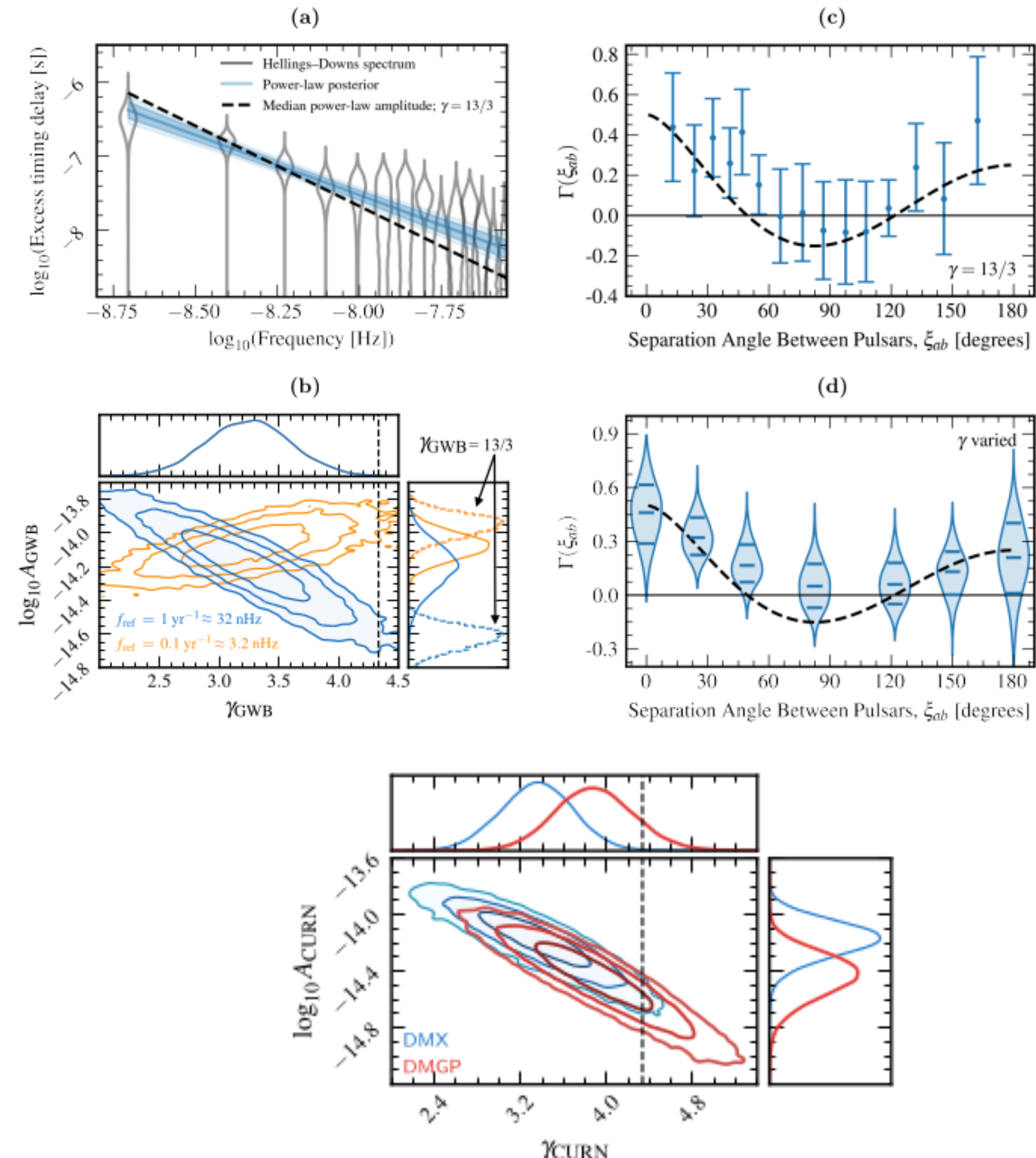
Jitter Measurements from J1744-1134
J. Jose [under review] (2026)

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 (2023) 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 $\sim 2.4 \times 10^{-15}$ @ 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**

Noise Model Definitions

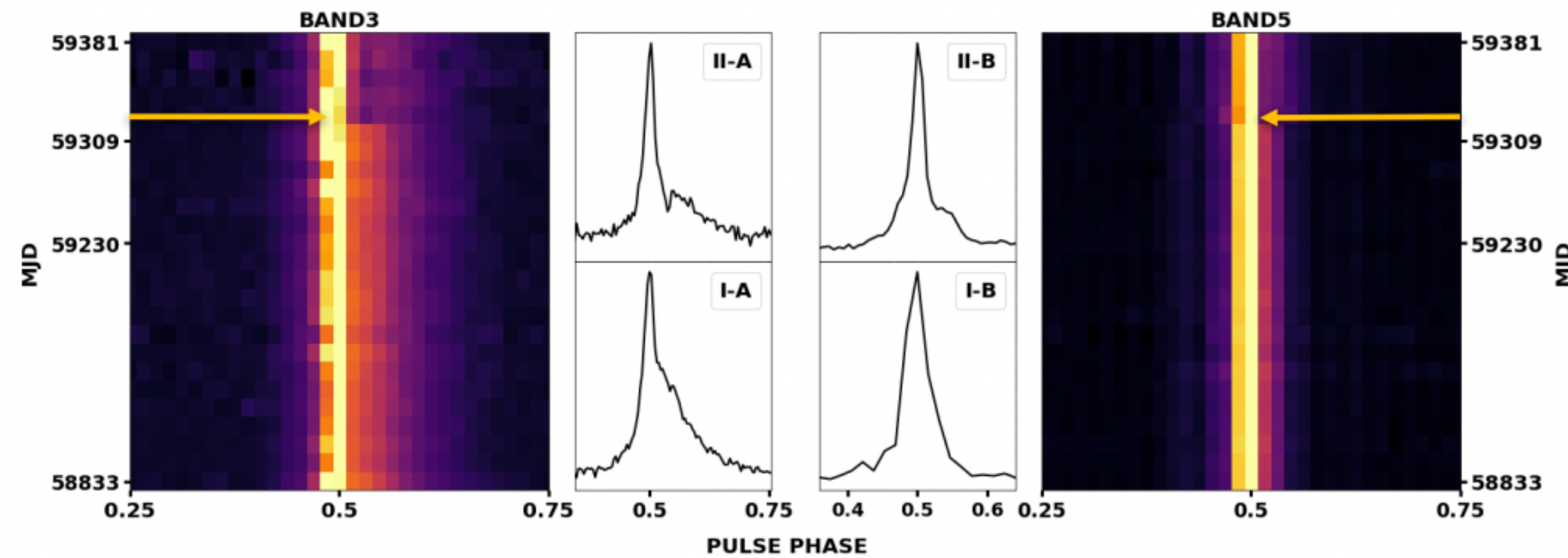
- **White Noise** $\sigma^2 = EFAC^2 \times (\sigma_{TOA}^2 + EQUAD^2)$
- **Correlated red noise** (Time correlated signal in Fourier domain)

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

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

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

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.

