9th of April 2025, ACME WORKSHOP

The low-frequency gravitational wave sky: Pulsar Timing Arrays

EPTA

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INAF

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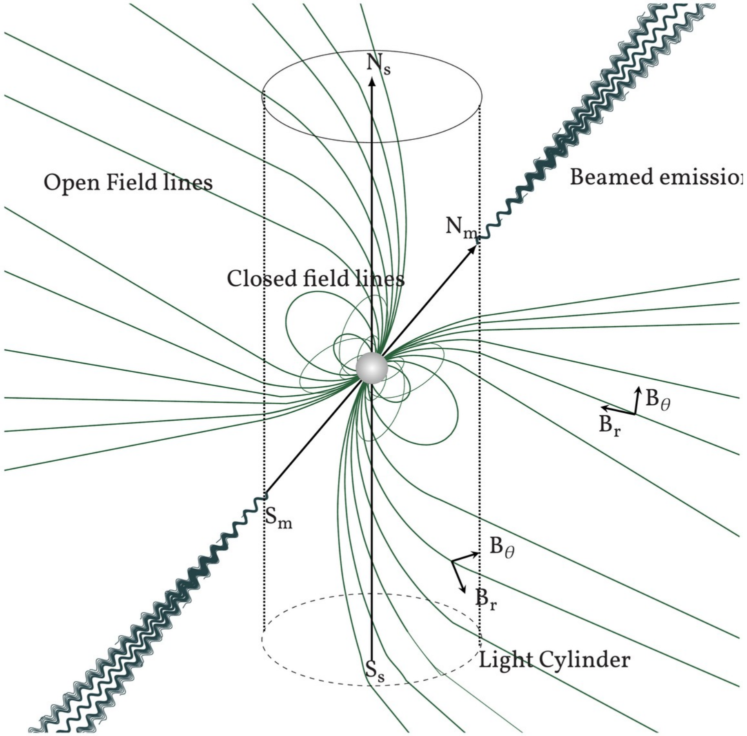
Contents

- Millisecond pulsars and Pulsar timing
- Pulsar Timing Arrays and the GW background
- The European PTA, and the 3σ GWB evidence
- The future – EPTA-DR2$_{low}$, the Solar wind, EPTA DR3 and IPTA DR3

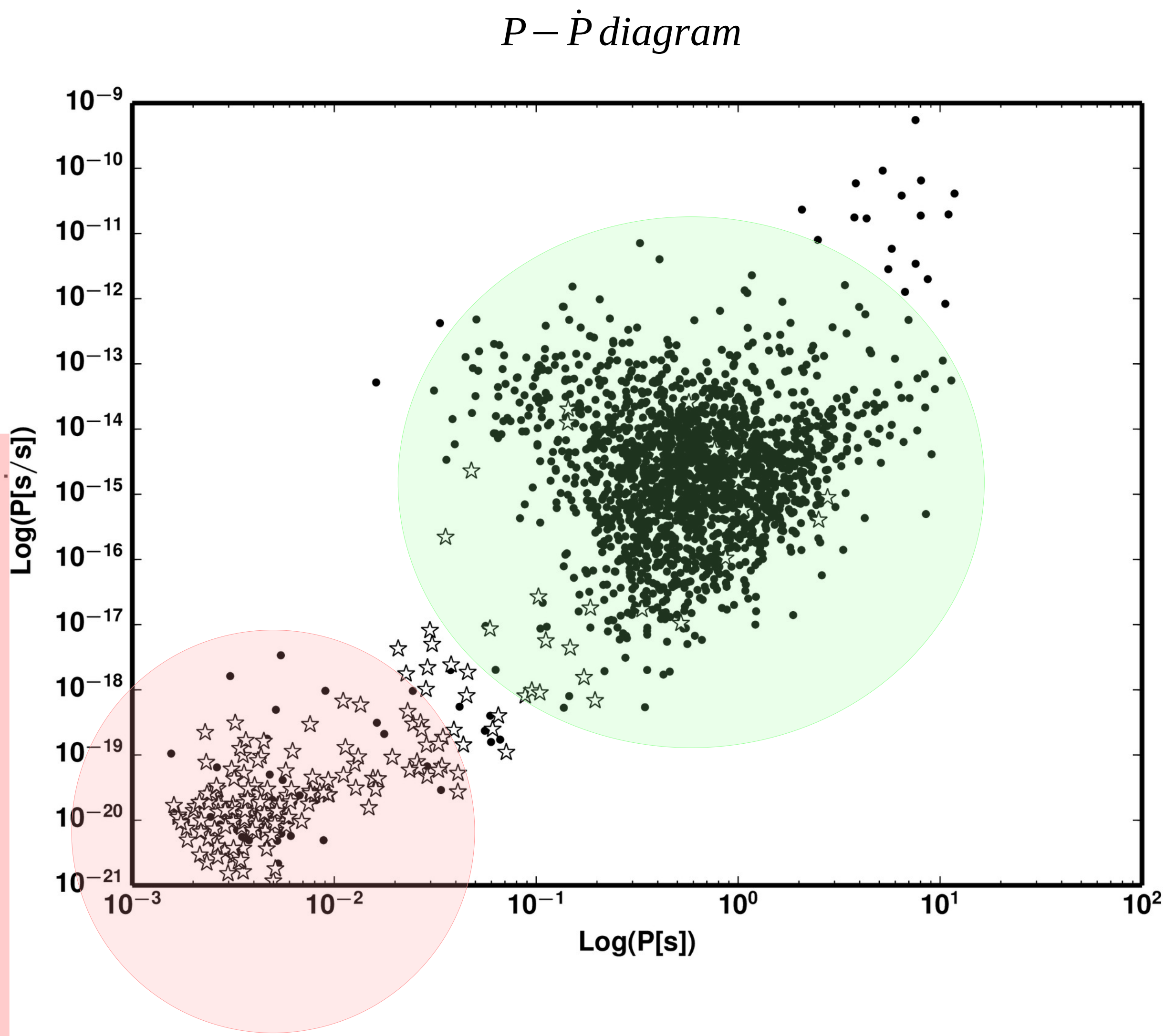
Pulsars in a nutshell

- **Pulsars** are highly-magnetized (~$10^{12\text{-}14}$ G), fast-rotating (up to ~10^{-3} sec) **neutron stars**;
- They produce **two beams of emission**, radiating their rotational kinetic energy, mostly visible at radio wavelengths;
- Under particular geometric conditions, the observer collects the radio beam radiation as a periodic signal (**“Lighthouse Effect”**)



Shaifullah 2017

The detectors: (milli)second pulsars



Normal pulsars

Millisecond pulsars

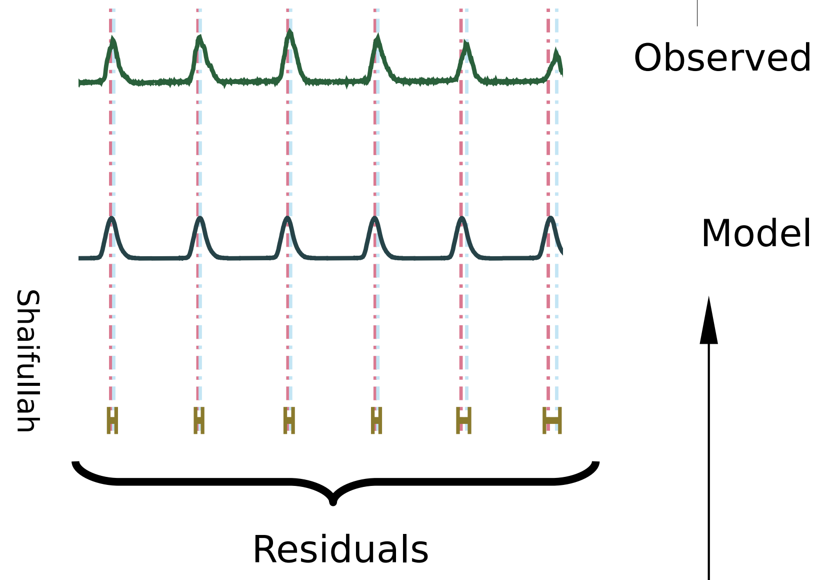
Far more stable than the normal pulsars, MSPs are targeted detector sources of PTAs

Data from PSRcat

Pulsar timing

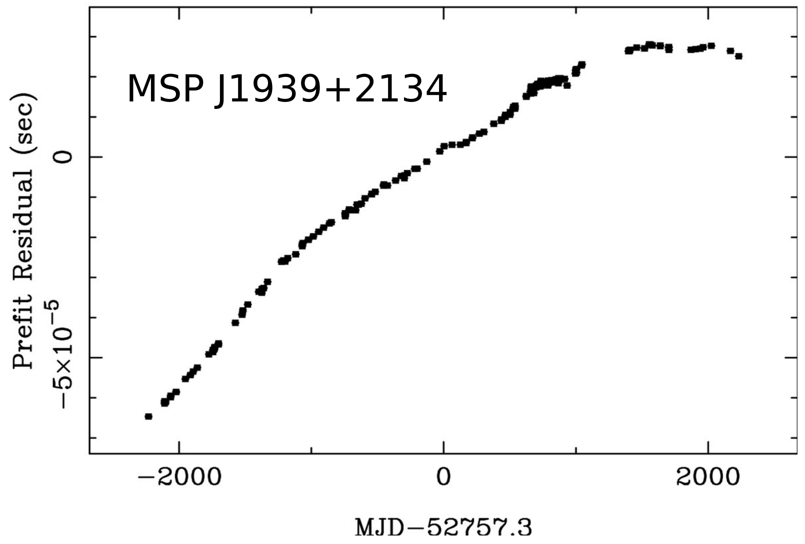
It is possible to predict the **arrival times** of a pulsar's radiation on the Earth once that its **ephemeris** are known. **Millisecond pulsars are characterized by the smallest "timing residuals"**, and hence are the **"most precise" sources** among pulsars

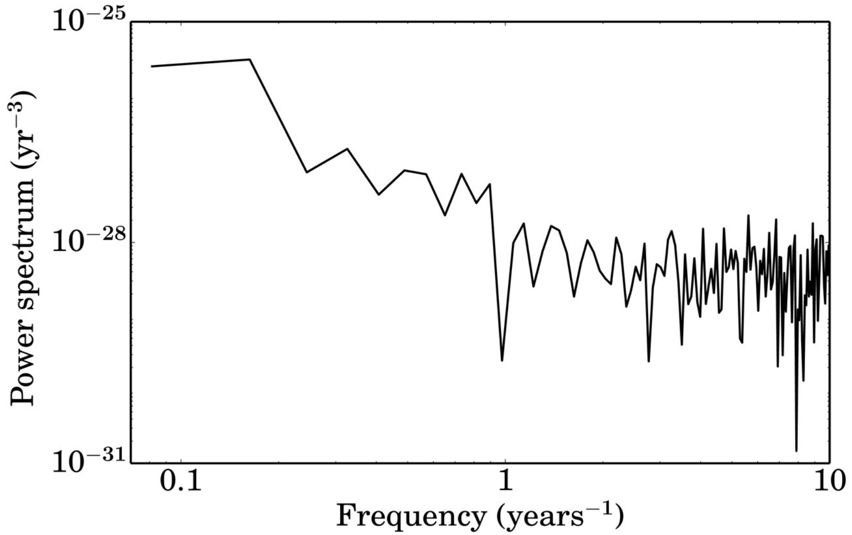
Pulsar	J1012+5307
Right Ascension	10:12:33.437521
Declination	+53:07:02.29999
DM	9.02314
Spin frequency	190.2678376220576
Spin freq. derivative	-6.20063E-16
Proper motion RA	2.609
Proper motion DEC	-25.482
BINARY	ELL1
Orbital period	0.604672722901
Rotation Measure	2.98
Solar Wind	Spherical, $n_0 = 4$
Companion mass	0.16
Clock reference	TT(BIPM2019)
SSE	DE440
[TBC]	



Pulsar timing

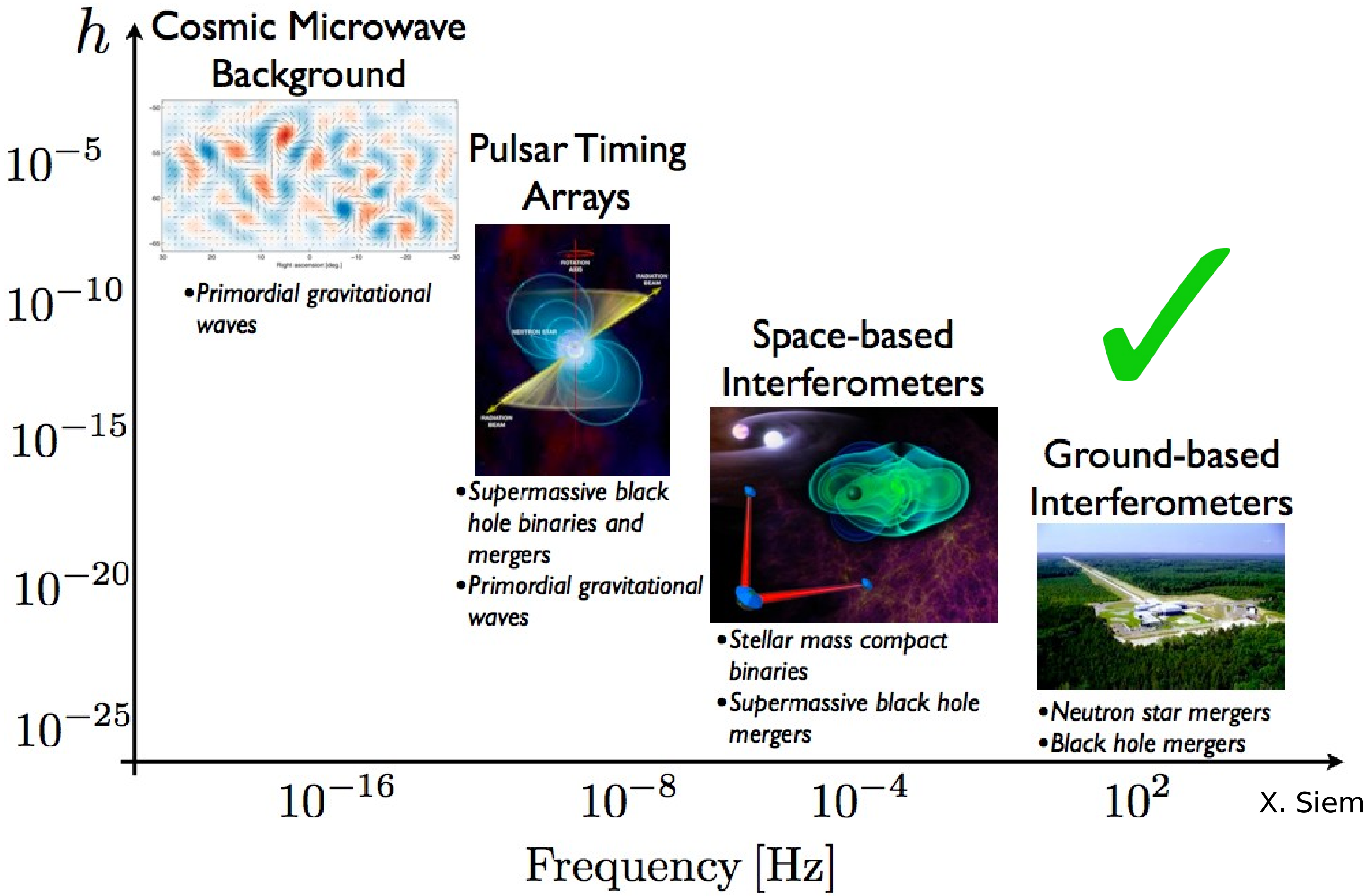
Long-term, non-modeled effects can perturb the ToAs and appear as ‘red noise’ in the timing residuals, an excess of power at low frequencies in the power spectrum





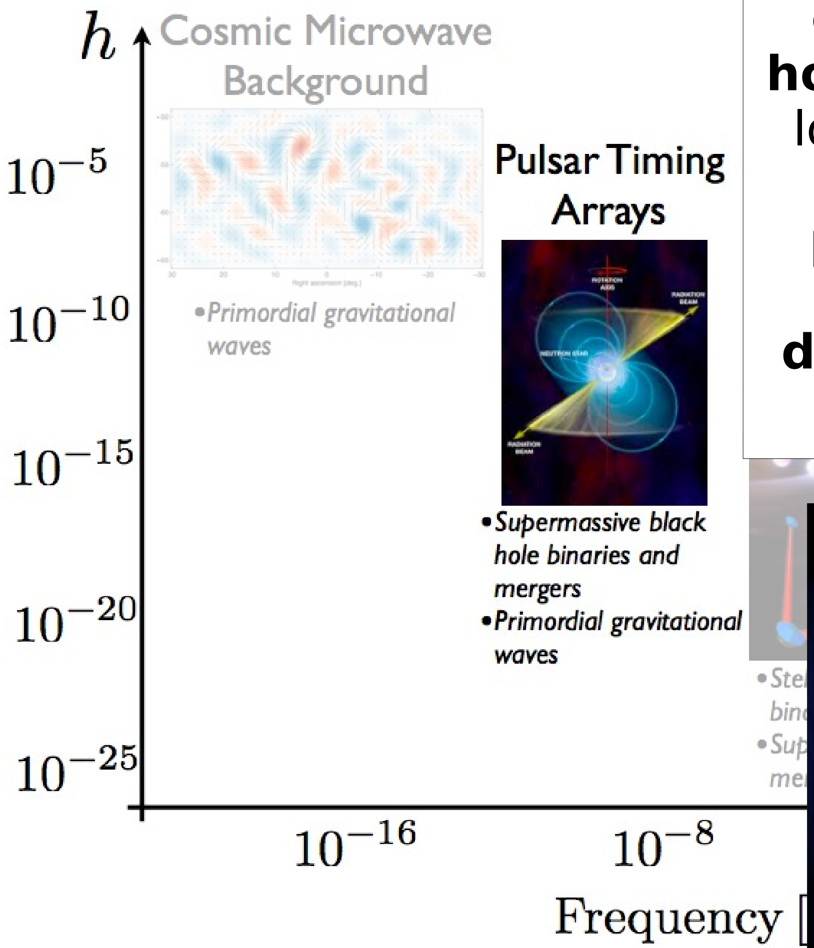
Red noise can be caused by turbulent ionised **interstellar medium**, **spin noise**, **instrumentation** issues, incorrect **planetary ephemeris**, incorrect **time standards**, **gravitational waves** or **unknown effects**

The Gravitational wave spectrum



X. Siemens

The Gravitational wave spectrum



Most likely source of nHz GWs are **coalescing supermassive black-hole binaries** (SMBHB), whose energy loss at separations <1pc is driven by GW emission. Such GW emission perturbs the space-time around the Earth and the pulsars, and **induce deviations in the expected arrival times of the radiation pulses**

Expected functional shape of timing residuals

Prediction for the **functional shape of timing-residuals** affected by the gravitational-wave emission from a coalescing supermassive black-hole binary (Jenet et al. 2004):

$$R(t)=\frac{1}{2}(1+\cos(\mu))[r_{+}(t)\cos(2\psi)+r_{x}(t)\sin(2\psi)]$$

Expected functional shape of timing residuals

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$$R(t)=\frac{1}{2}(1+\cos(\mu))[r_{+}(t)\cos(2\psi)+r_{x}(t)\sin(2\psi)]$$

GW polarization angle

$$r_{+,x}(t)=r^{E}_{+,x}(t)-r^{p}_{+,x}(t)$$

Earth term

$$r^{E}_{+,x}(t)=\int_{0}^{t} h^{E}_{+,x}(\tau)\,d\tau$$

Polarization of the GW

GW strain at Earth

Pulsar term

$$r^{p}_{+,x}(t)=\int_{0}^{t} h^{p}_{+,x}\left[\tau-\frac{d}{c}(1-\cos(\mu))\right]d\tau$$

Distance to the pulsar

GW strain at the pulsar

Opening angle between the GW source and the pulsar relative to Earth

PTAs: the nanoHertz window for GWs

Most likely, the first form in which nHz GWs will be detected by PTAs will be that of a **gravitational wave background (GWB)**, created by the incoherent superposition of GW emission from the cosmic population of merging SMHBHs

$$h_c(f) = A\left(\frac{f}{yr^{-1}}\right)^{\alpha=-2/3}$$

Phinney 2001
("[...] it is straightforward to show that...",
Sesana 2013)

$$P_{GWB}(f) = \frac{A^2}{12\pi^2}\left(\frac{f}{yr^{-1}}\right)^{2\alpha-3=-13/3}$$

Detweiler 1979
Jenet+2005/2006

1) Different for different sources of the GWB (see Burke-Spolaor 2015);

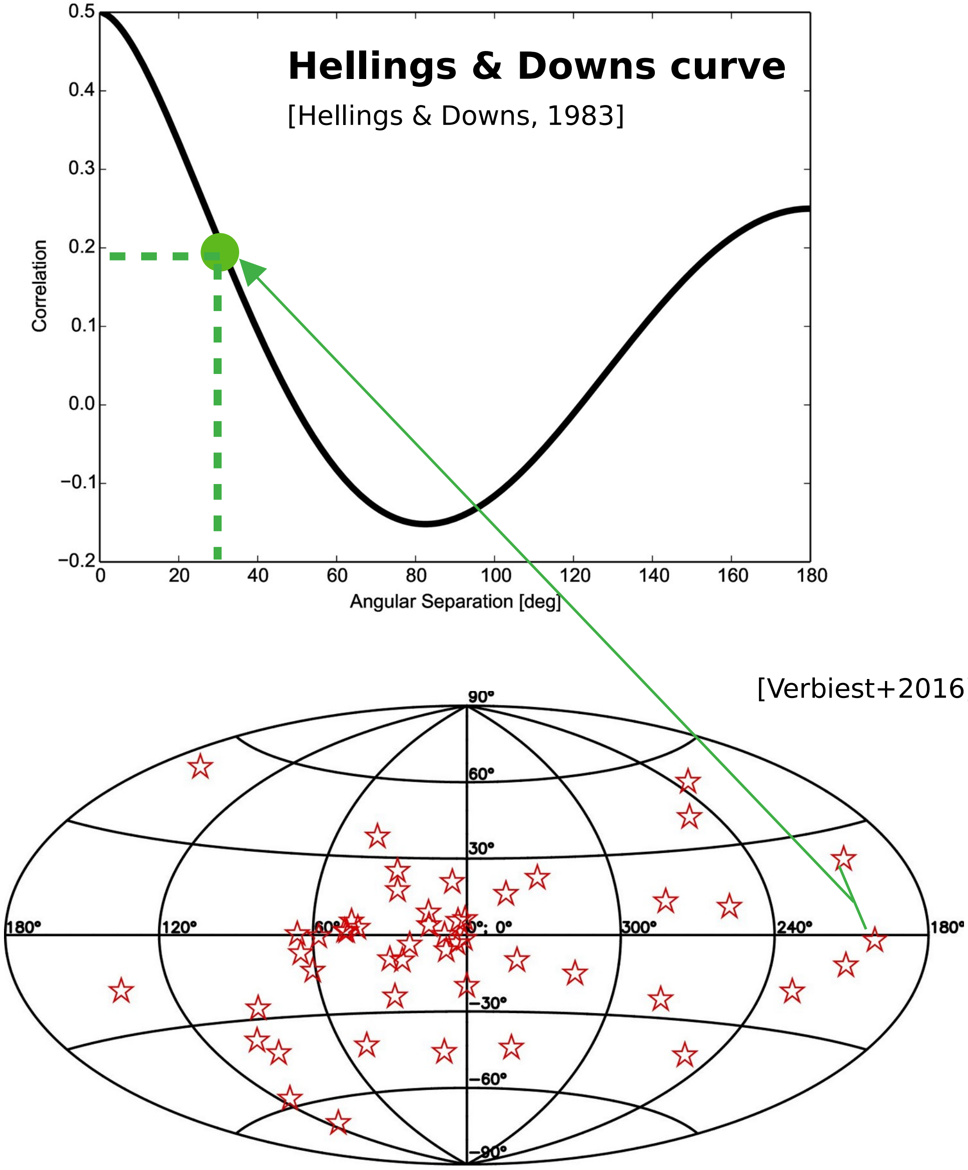
2) It assumes fully GW-driven merger (see Vigeland & Siemens 2016)

3) It assumes circular SMBHB without environmental influence

"RED" POWER SPECTRUM

PTAs: the nanoHertz window for GWs

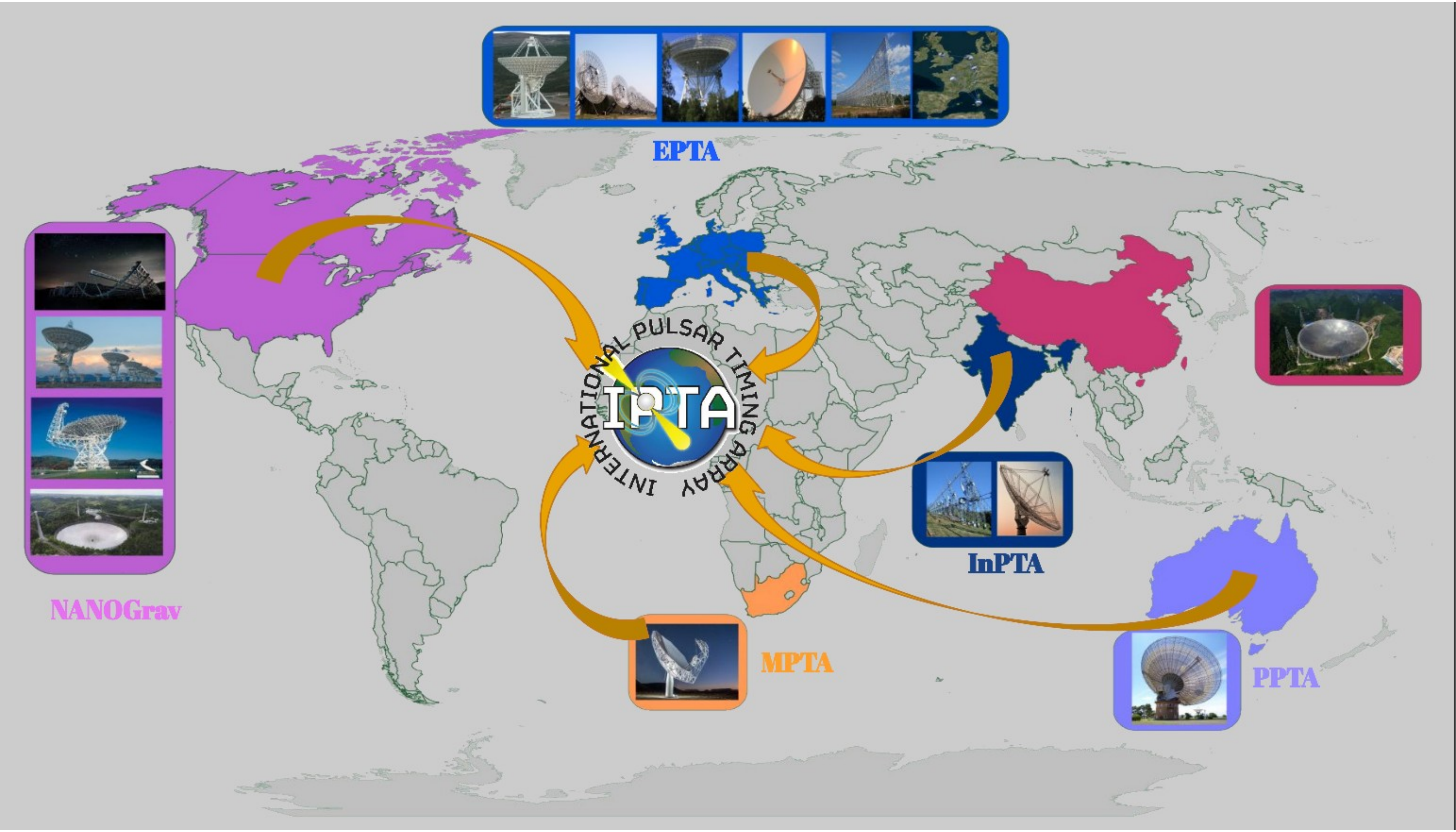
In **Pulsar timing arrays**, the timing residuals from an ensemble of very stable millisecond pulsars are ***spatially correlated*** to detect the nanoHertz GWB



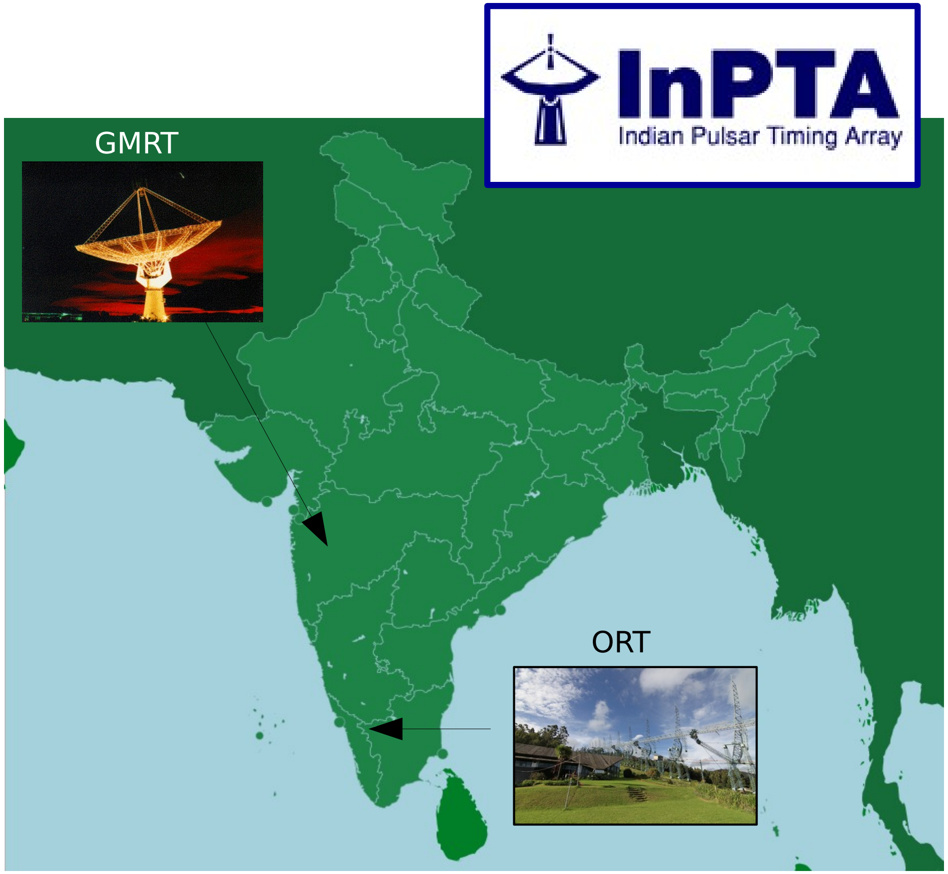
$$\begin{cases} \zeta(\theta_{ij}) = \frac{3}{2} x \log(x) - \frac{x}{4} + \frac{1}{2} \\ x = [1 - \cos(\theta_{ij})] \end{cases}$$

[Hellings & Downs, 1983]

The International Pulsar Timing Array

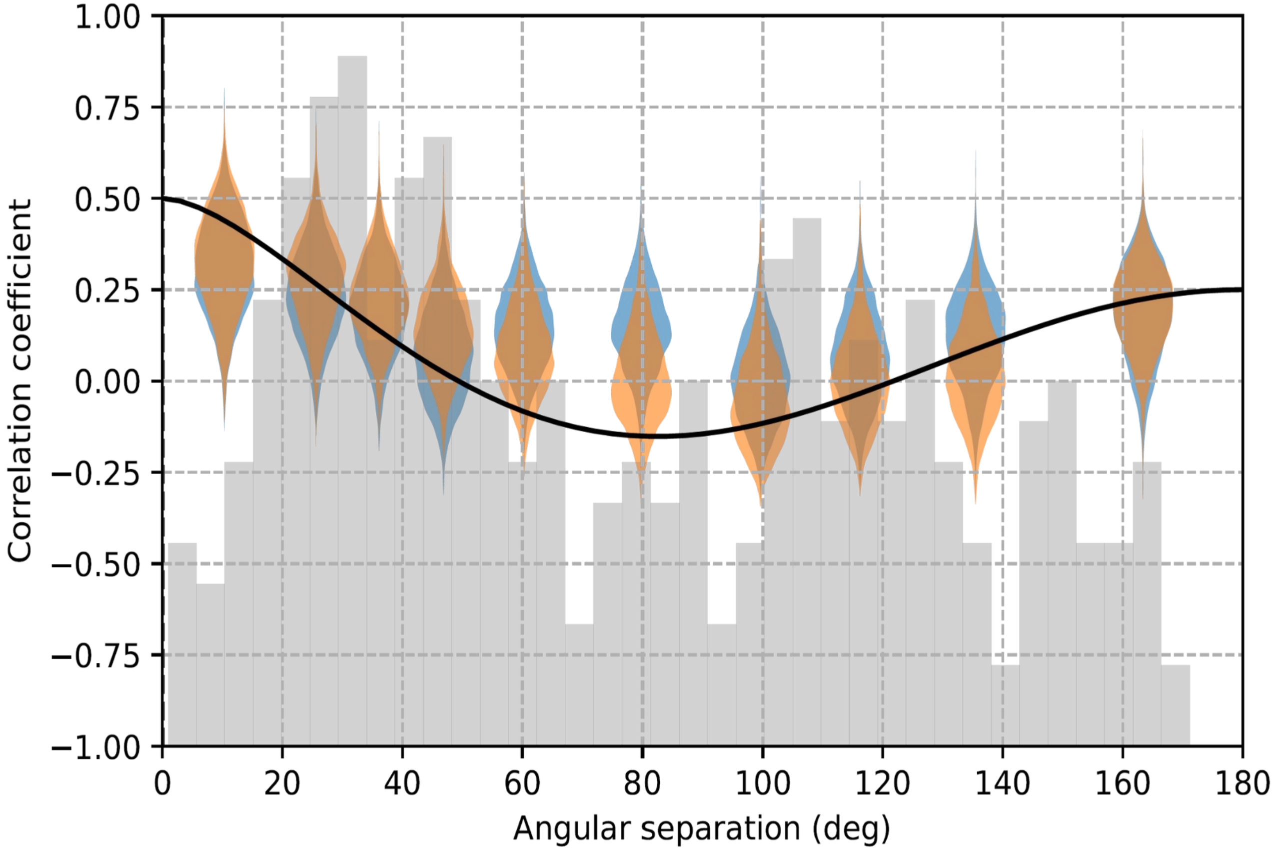



EPTA
WSRT †
JBO
EFF
SRT
NRT
LEAP
EPT


InPTA
Indian Pulsar Timing Array
GMRT
ORT

First indication of a GWB signature in the EPTA data

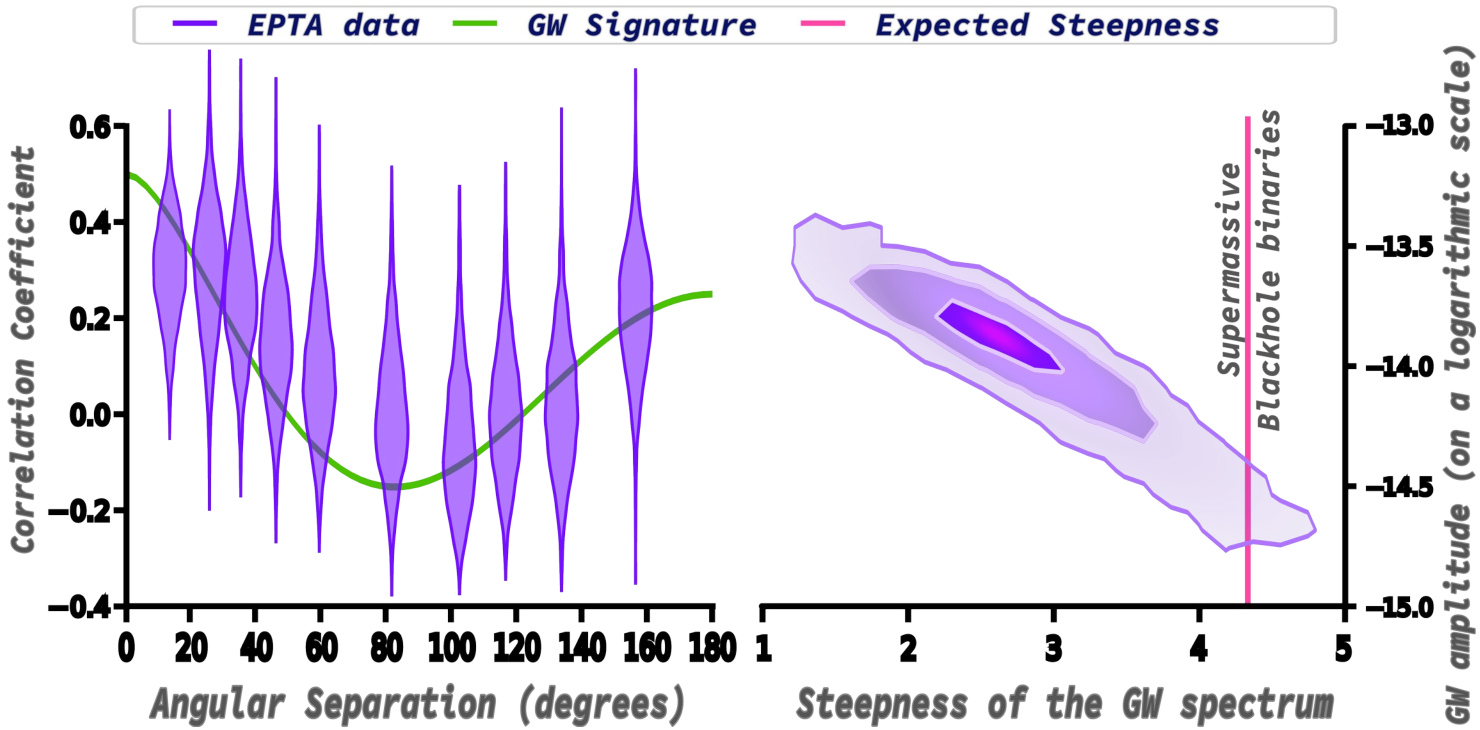
[Antoniadis+2023 III]



25 pulsars, ~3σ signal, lower than the targeted 5σ detection threshold, using the most recent **10.3 years of the EPTA+InPTA dataset**

First indication of a GWB signature in the EPTA data

[EPTA III]

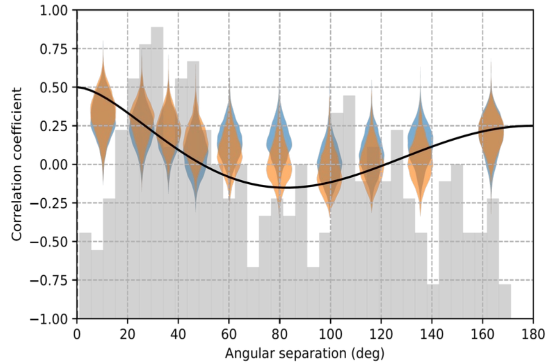


Strain amplitude for the GWB spectrum at 1/1yr ~ $\mathbf{2.5^{\pm 0.7} \times 10^{-15}}$ for a spectral index fixed to -13/3

If the GWB index is left free, the spectrum is flatter and the signal louder ($\mathbf{Log(A) = -13.94^{+0.23}_{-0.48}}$ and $\mathbf{\gamma = 2.71^{+1.18}_{-0.73}}$) than expected for circularly inspiralling SMBHBs

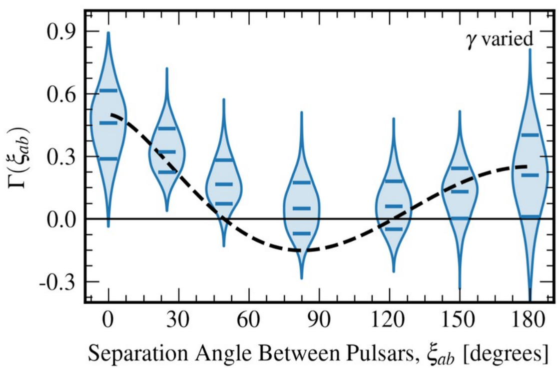
Consistency with the other PTA collaborations

[EPTA III]



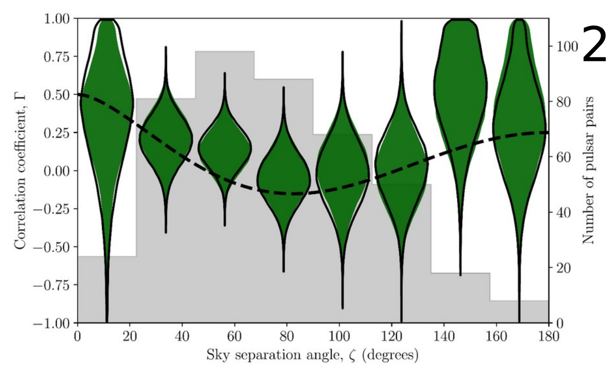
3σ

[Agazie+2023 I]

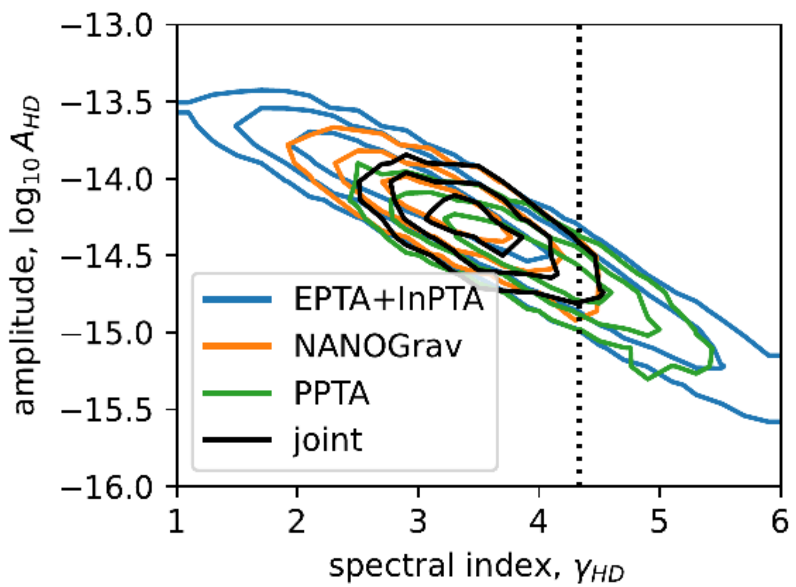


3.5-4σ

[Reardon+2023]



2σ



[IPTA 2023]

Implications

To date, **the origin of the observed signal is unaddressed** in all of the PTAs due to the poor constraints offered by both the signal's spectrum and HD curve.

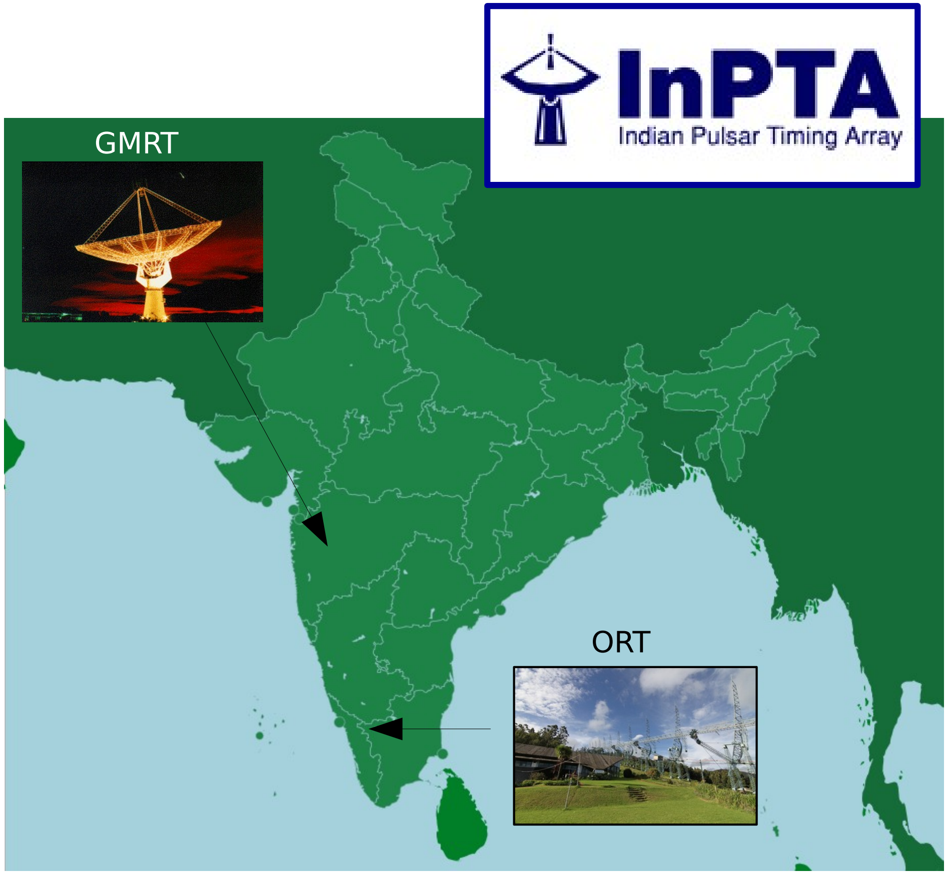
One of the first accessible considerations will probably be offered by the continuity of the spectrum, and the directionality of the signal:

All of the potential **cosmological sources** (cosmic strings, inflation, primordial magnetic fields, ultra-light dark matter...) give **stationary, isotropic and Gaussian** backgrounds, with **continuous** spectra

The **astrophysical sources** (the SMBHBs) give **deviations from isotropy and continuous spectra** due to the influence of individual, loud and close SMBHBs (therefore, the resulting spectrum would broadly follow a broken powerlaw)

https://www.epta.eu.org/


EPTA
WSRT †
JBO
EFF
SRT
NRT
EPT
LEAP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EPTA
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LOFAR
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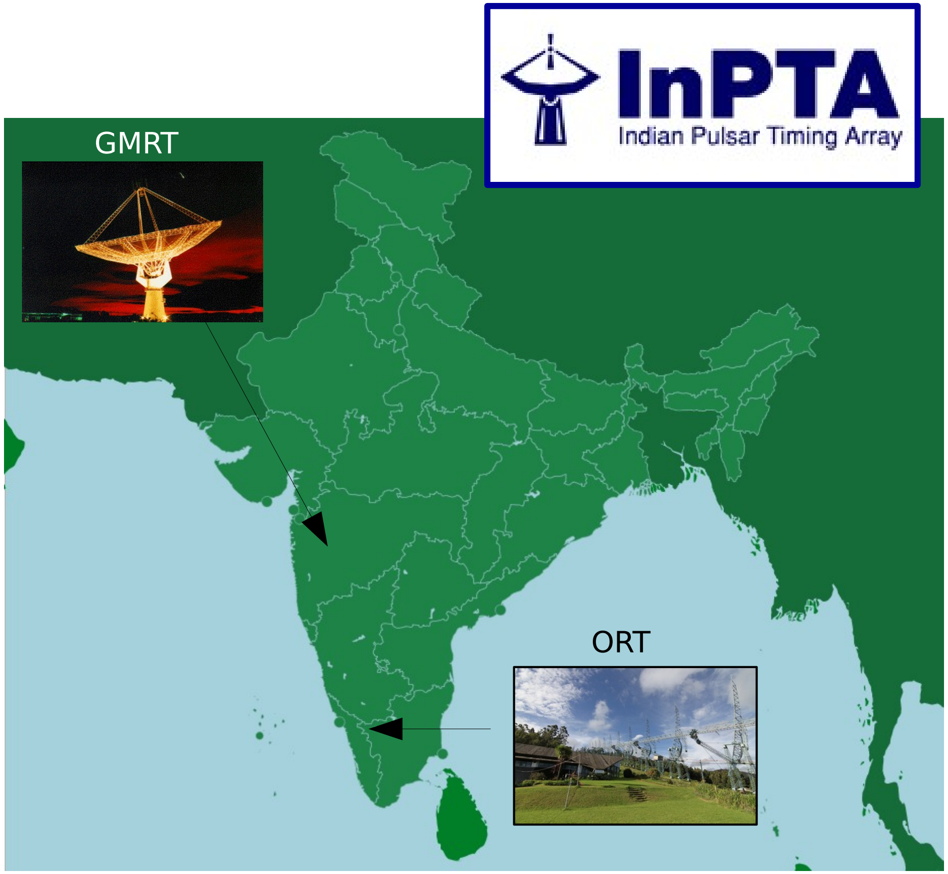
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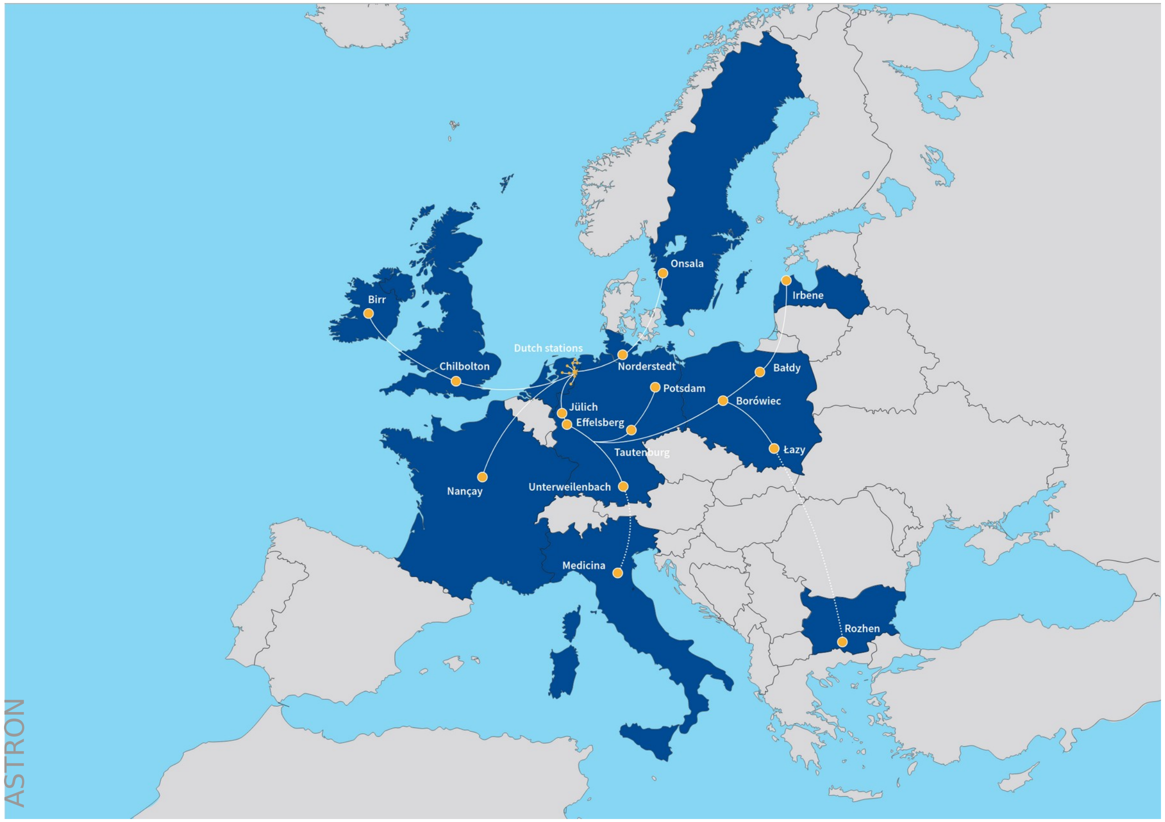
LOFAR, the LOw Frequency ARray



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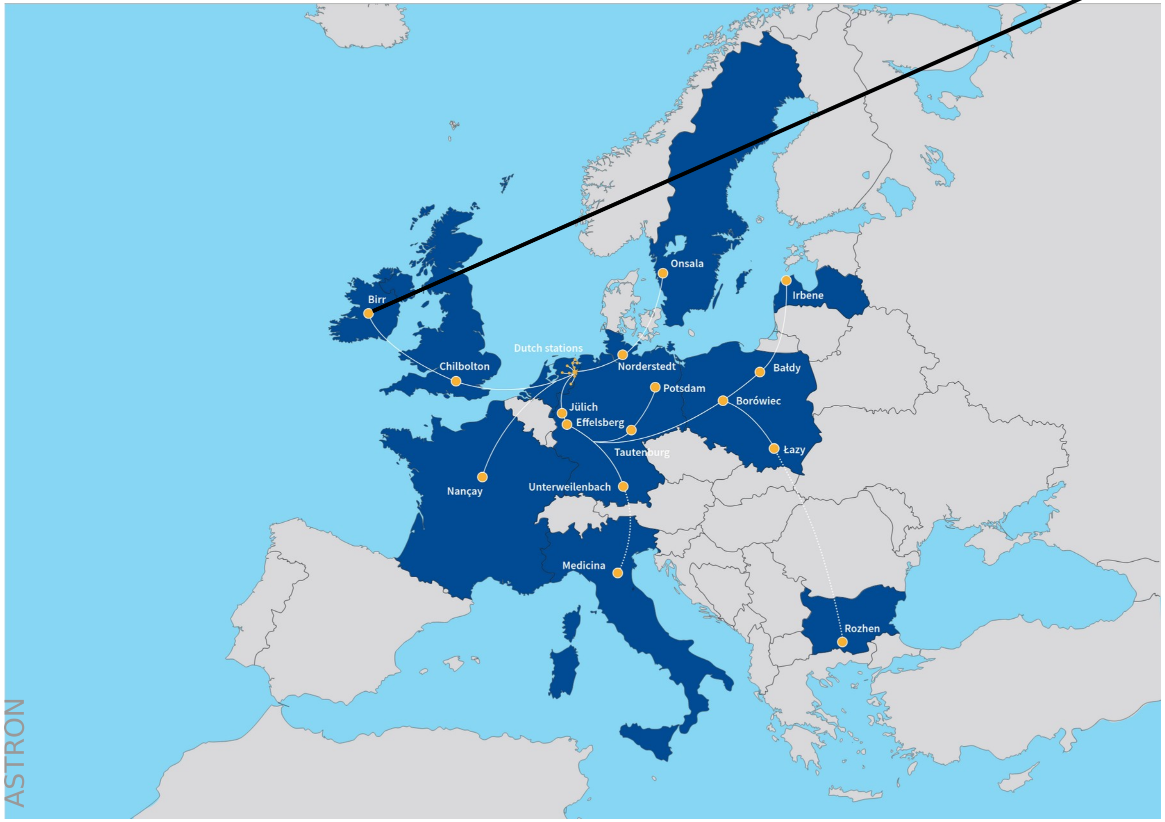
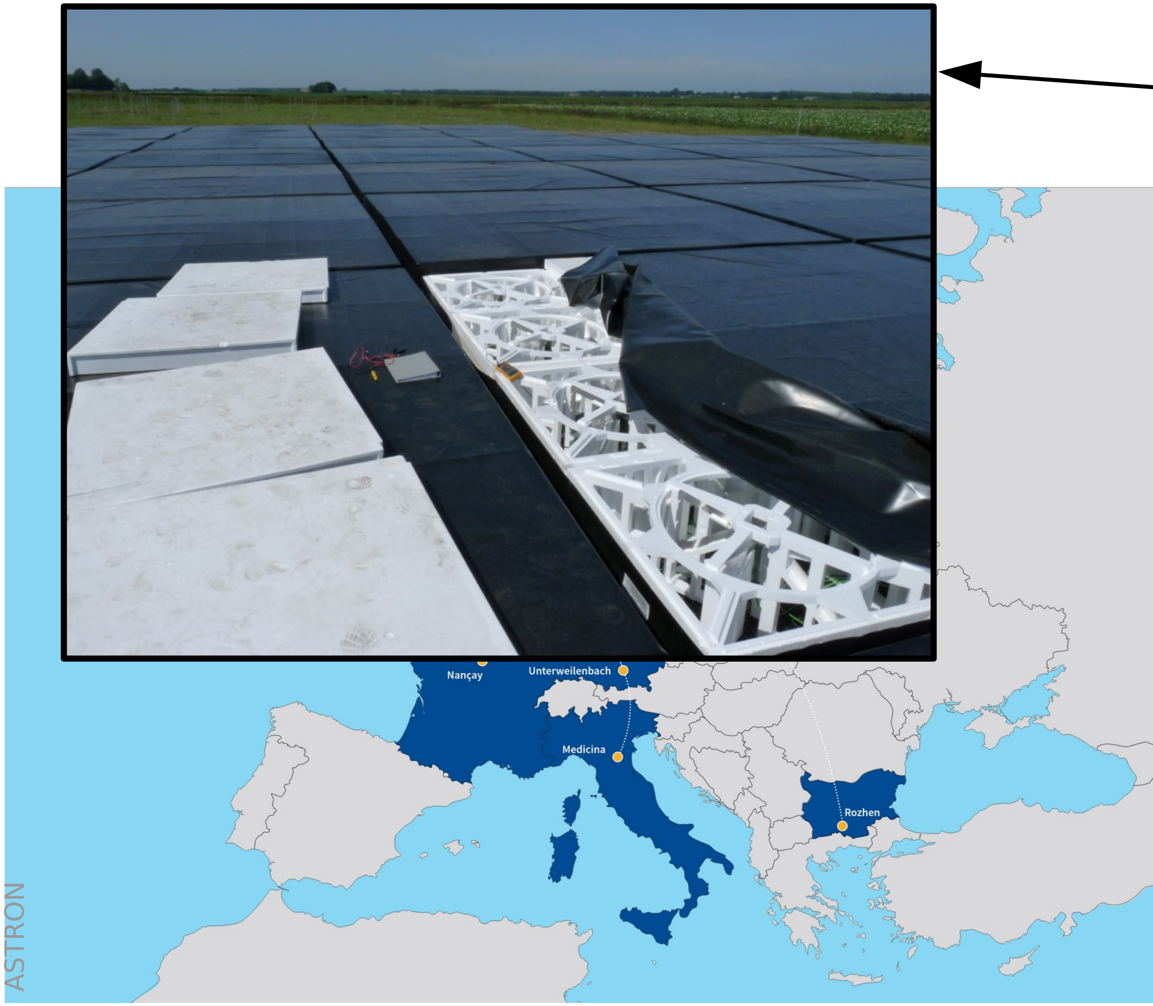
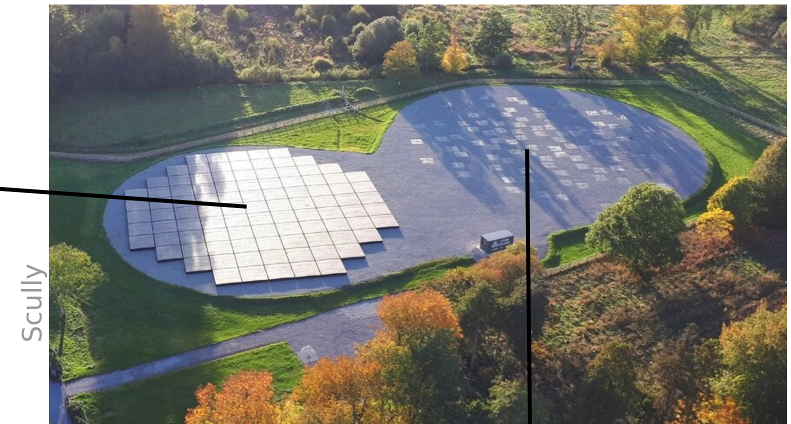


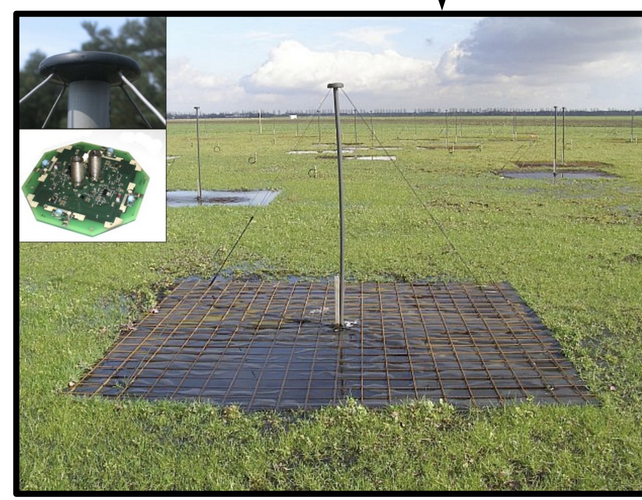
Scully

LOFAR, the LOw Frequency ARray

High **B**and **A**ntennae
100 – 240 MHz







Low **B**and **A**ntennae, <100 MHz

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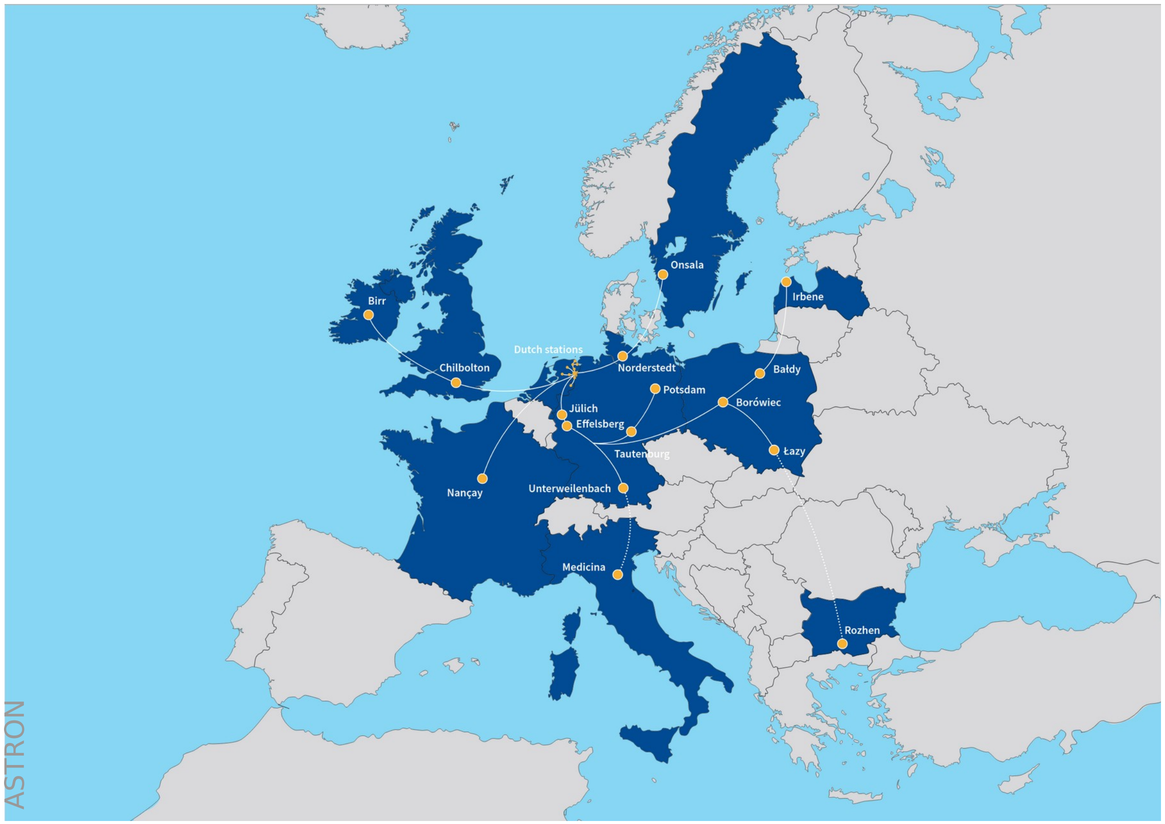
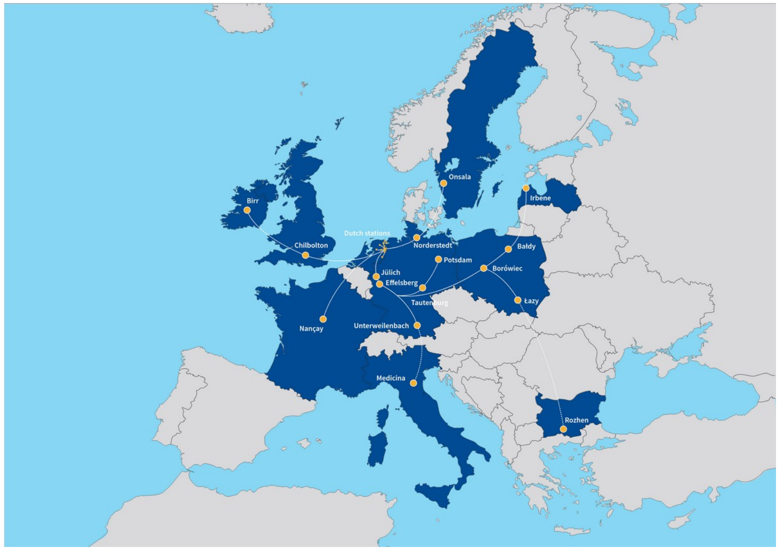
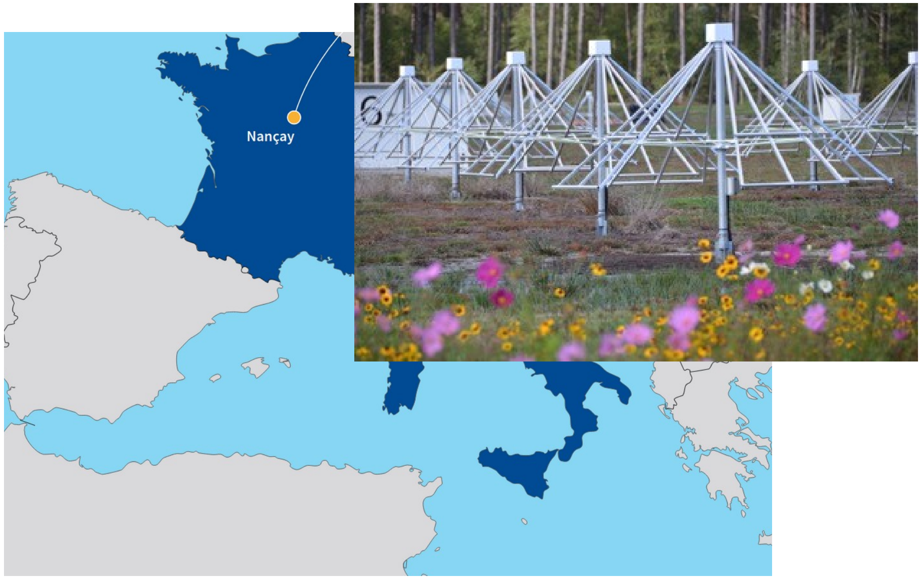


Station distribution:

- 24 stations in Exloo, NL (“LOFAR core”), with 48 HBAs and 96 LBAs each
- 14 “remote” stations in the NL, with 48 HBAs and 96 LBAs each
- 14 international stations in Ireland, UK, Sweden, Latvia, Poland, Germany, France + 2 upcoming in Italy and Bulgaria, with 96 HBAs and 96 LBAs each

LOFAR and NenuFAR, pulsar monitoring





LOFAR

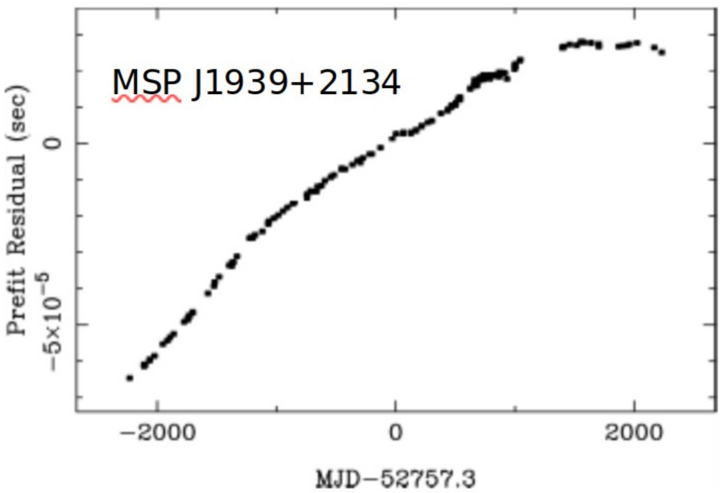
- HBAs, 110-190 MHz
- LOFAR core + German (6), French (1), Swedish (1), Irish (1) stations
- Pulsar observations ongoing since 2013
- >100 monitored pulsars
- >40 millisecond pulsars
- Weekly to (multi)monthly cadence

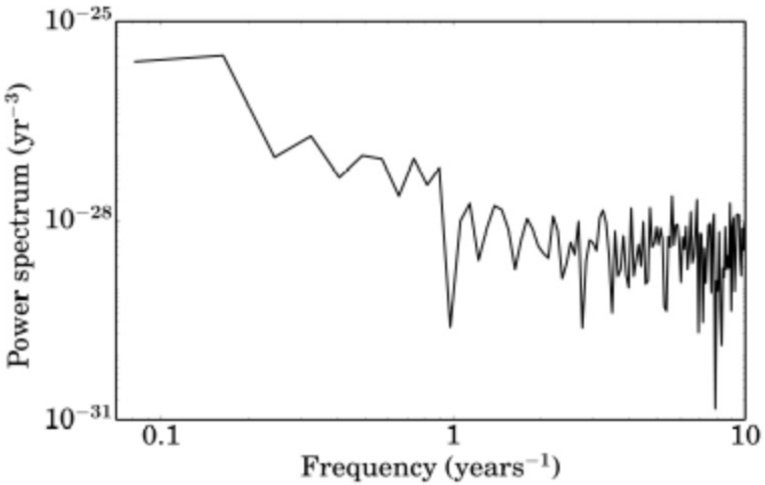
NenuFAR

- “Power-up” LBAs, 10-90 MHz
- Pulsar observations ongoing since 2019 with the NenuFAR Pulsar KP
- >40 monitored pulsars
- 4 millisecond pulsars
- Bi-weekly to monthly cadence

Low frequencies, why?

Long-term, non-modeled effects can perturb the ToAs and appear as 'red noise' in the timing residuals, an excess of power at low frequencies in the power spectrum





Red noise can be caused by turbulent ionised **interstellar medium**, **spin noise**, **instrumentation** issues, incorrect **planetary ephemeris**, incorrect **time standards**, **gravitational waves** or **unknown effects**

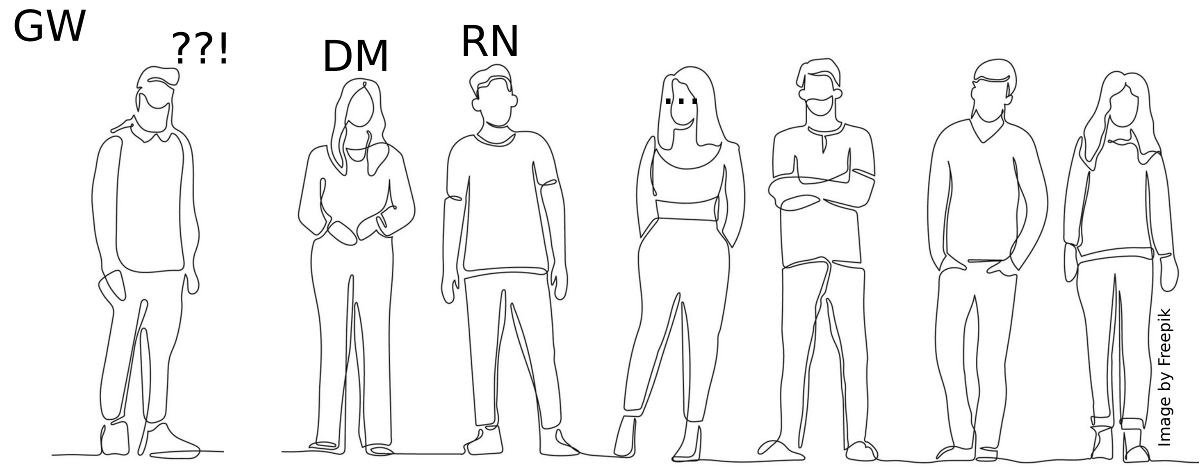
Get in line, GWs

GWs are not the only phenomena that perturb the regular arrival of a pulsar's radiation pulses.

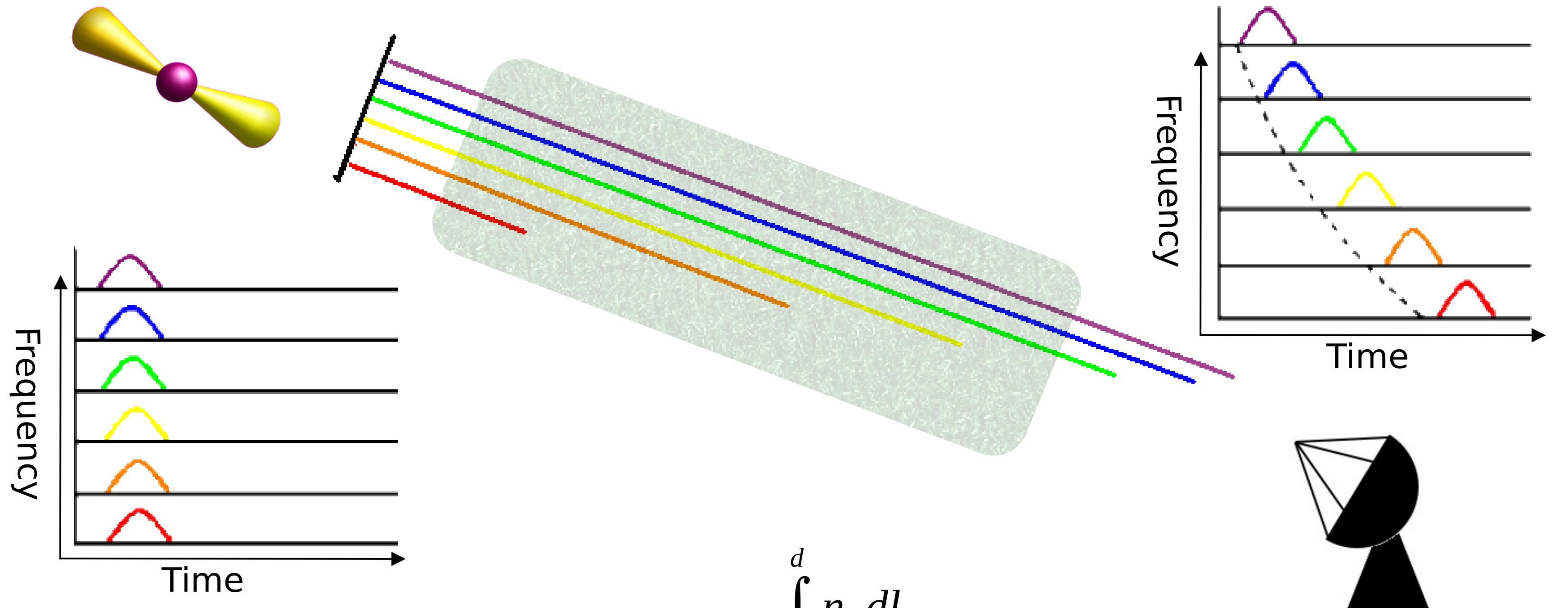
The biggest competitors are:

Intrinsic irregularities in the pulsar spin (**'Red noise'** tout-court, RN)

Variations in the plasma density along the LoS (**'DM noise'**)



Dispersion



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Companion mass	0.16
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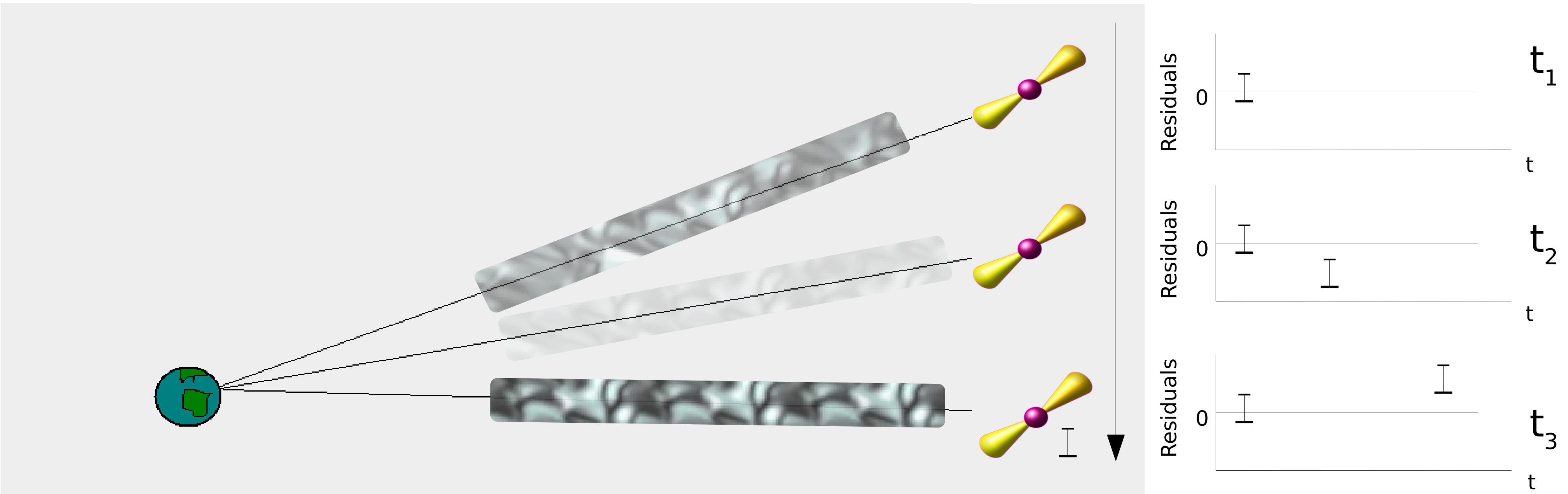
[TBC]	

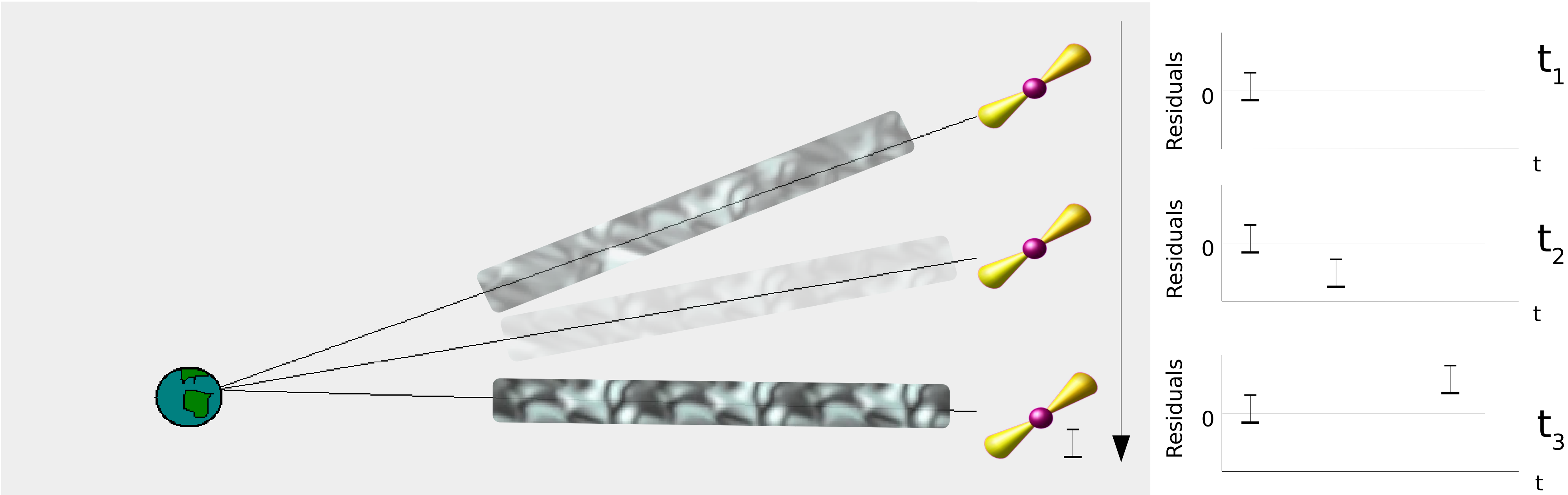
$$\Delta t = \frac{e^2}{2\pi m_e c} \frac{\int_0^d n_e \, dl}{f^2} \propto \frac{DM}{f^2}$$

$$DM = \int_0^d n_e \, dl$$

DM ‘noise’



DM 'noise'

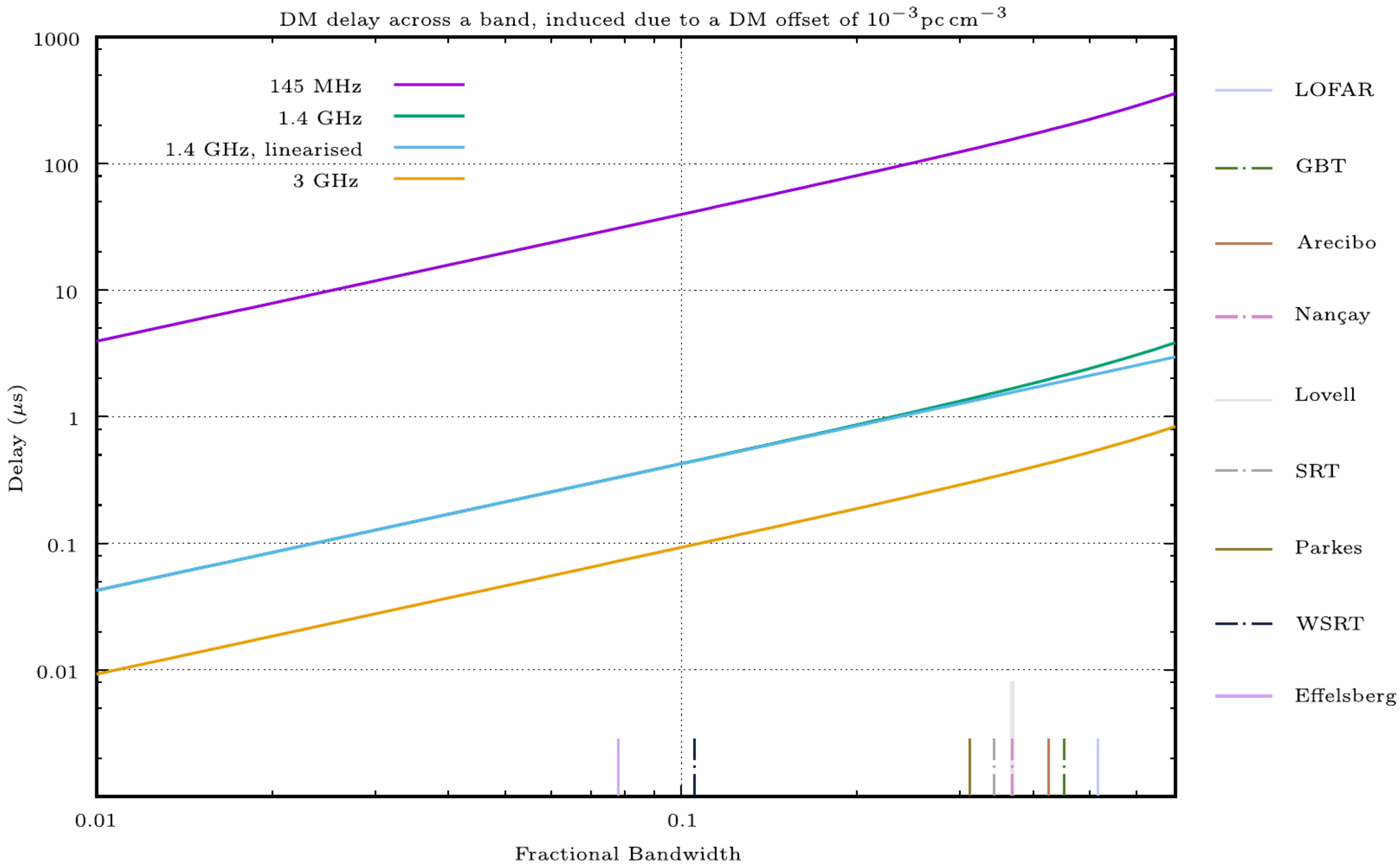


To neutralize this and other 'red' noise processes, PTAs use Bayesian-based software to **model their power spectra.**

However

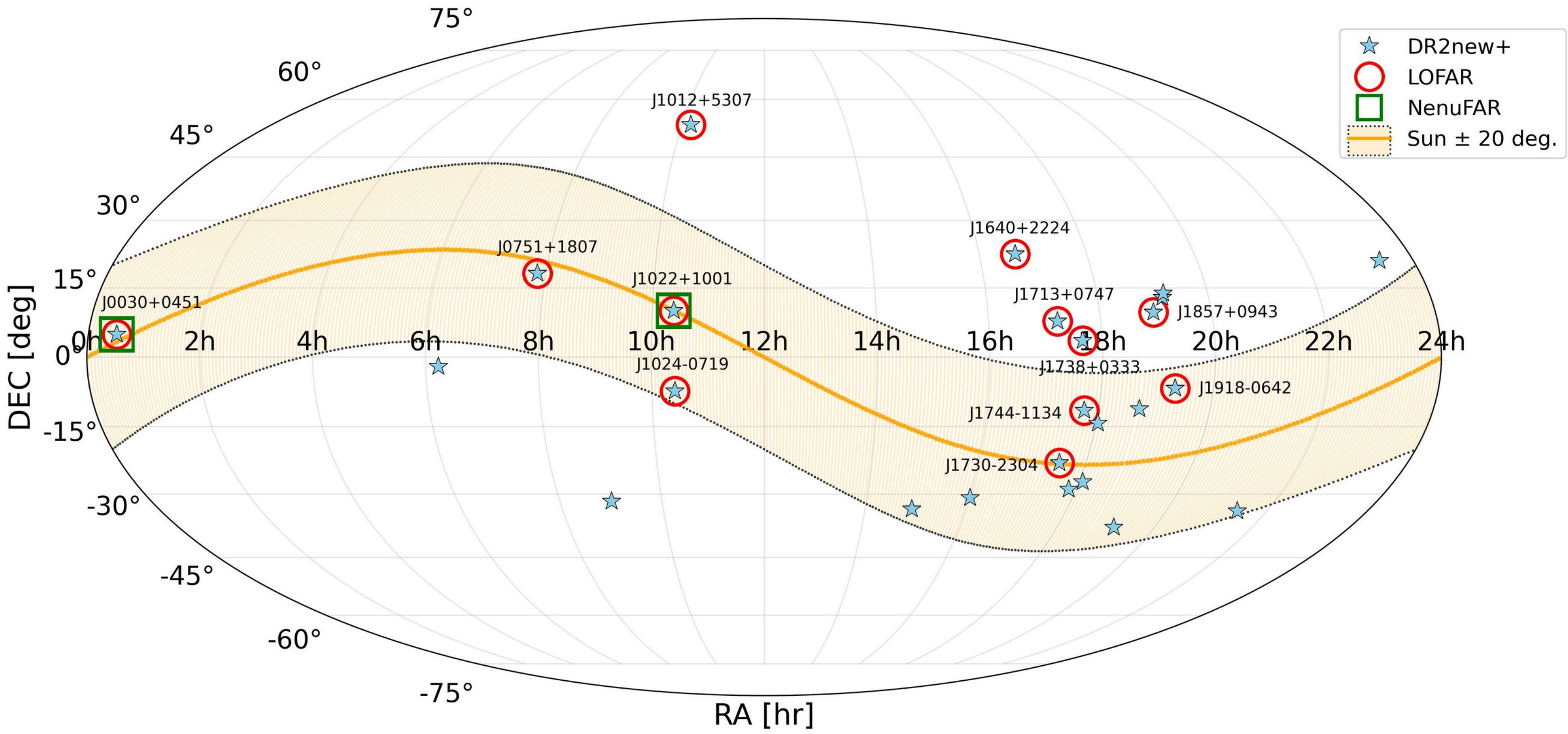
The bulk of PTA data is at **L-Band** where the **DM noise is present** but **cannot be calculated** because its signature is poor ($\propto DM/f^2$)

Low frequencies, why?



Verbiest & Shaifullah 2018

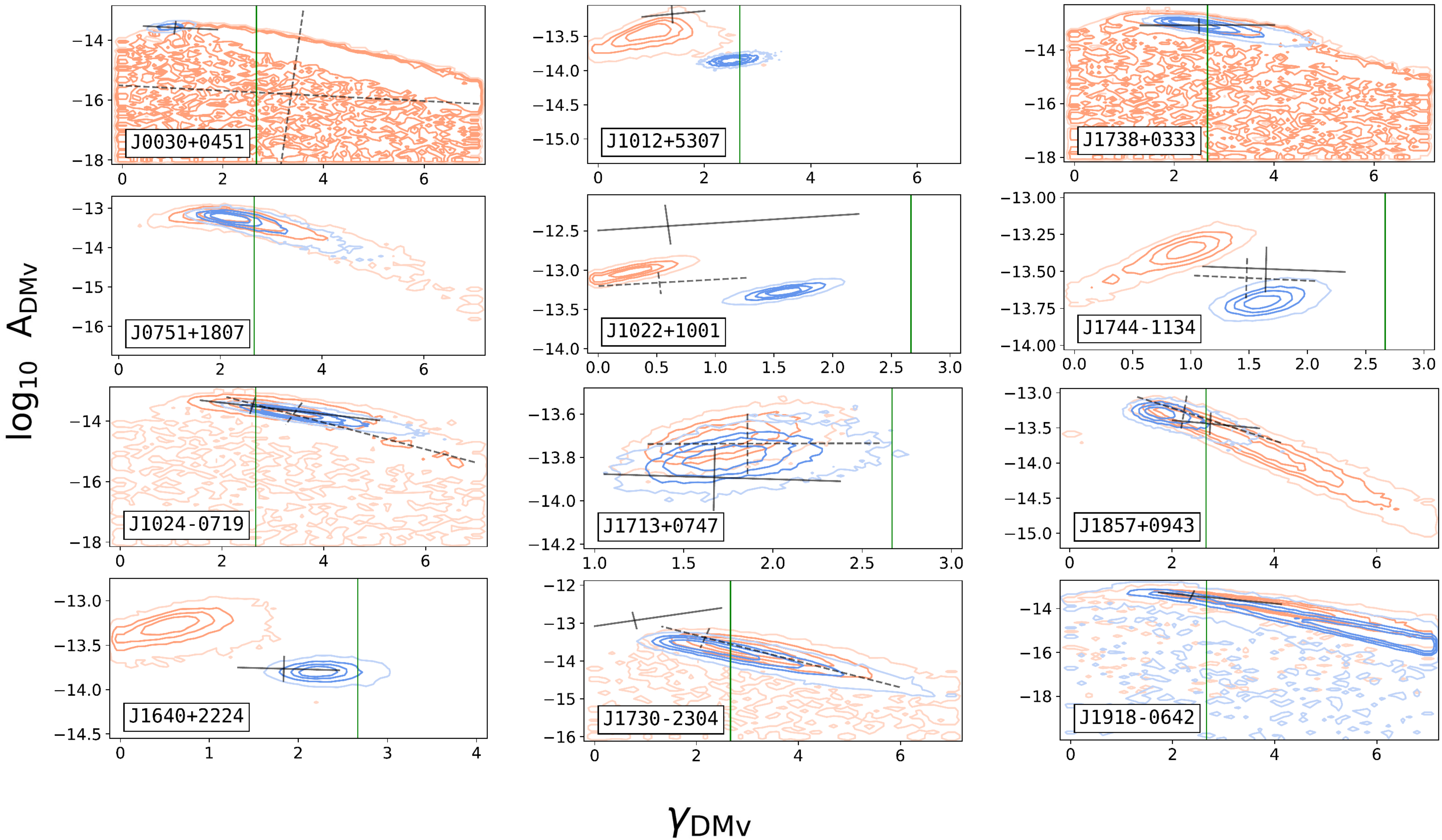
EPTA DR2$_{low}$



Iraci+, in prep

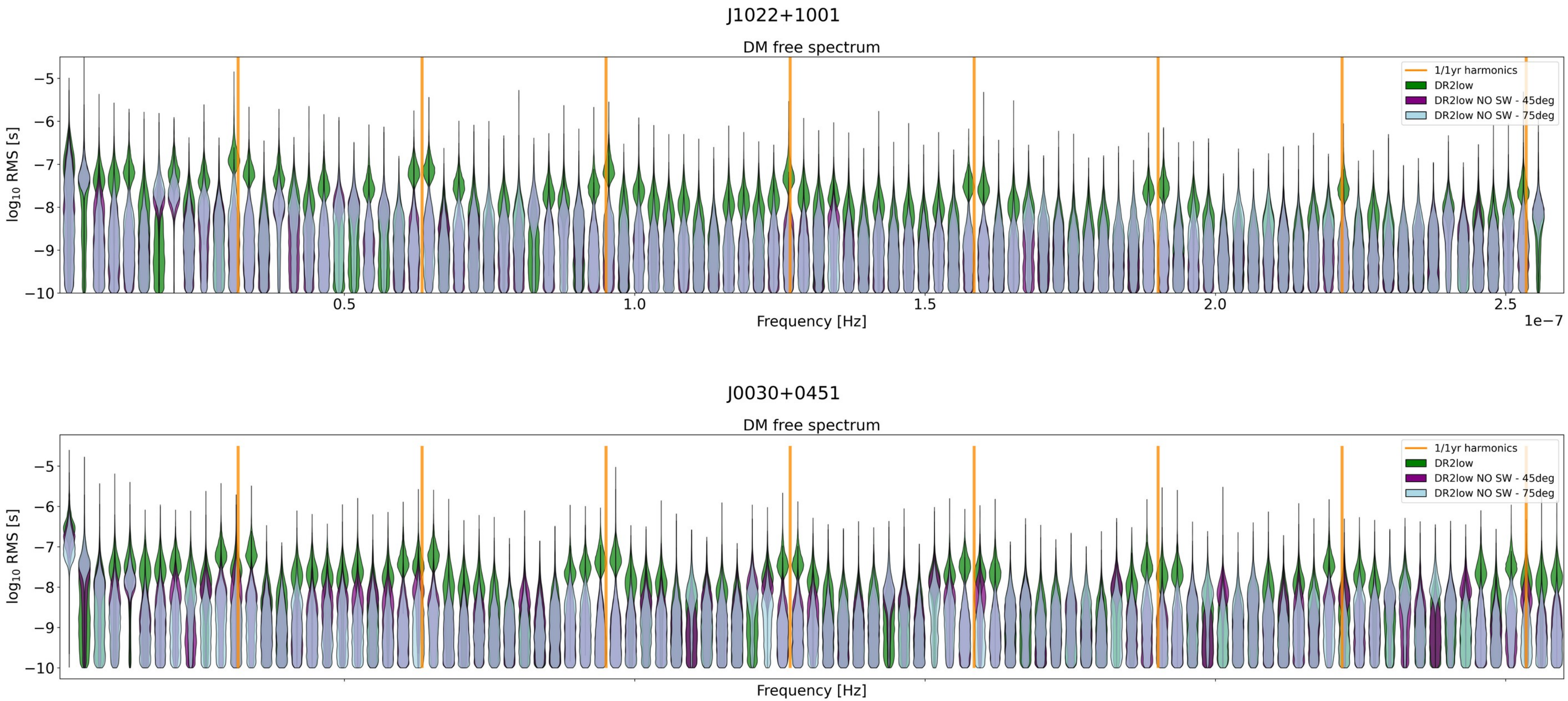
EPTA DR2$_{low}$

Iraci+, in prep

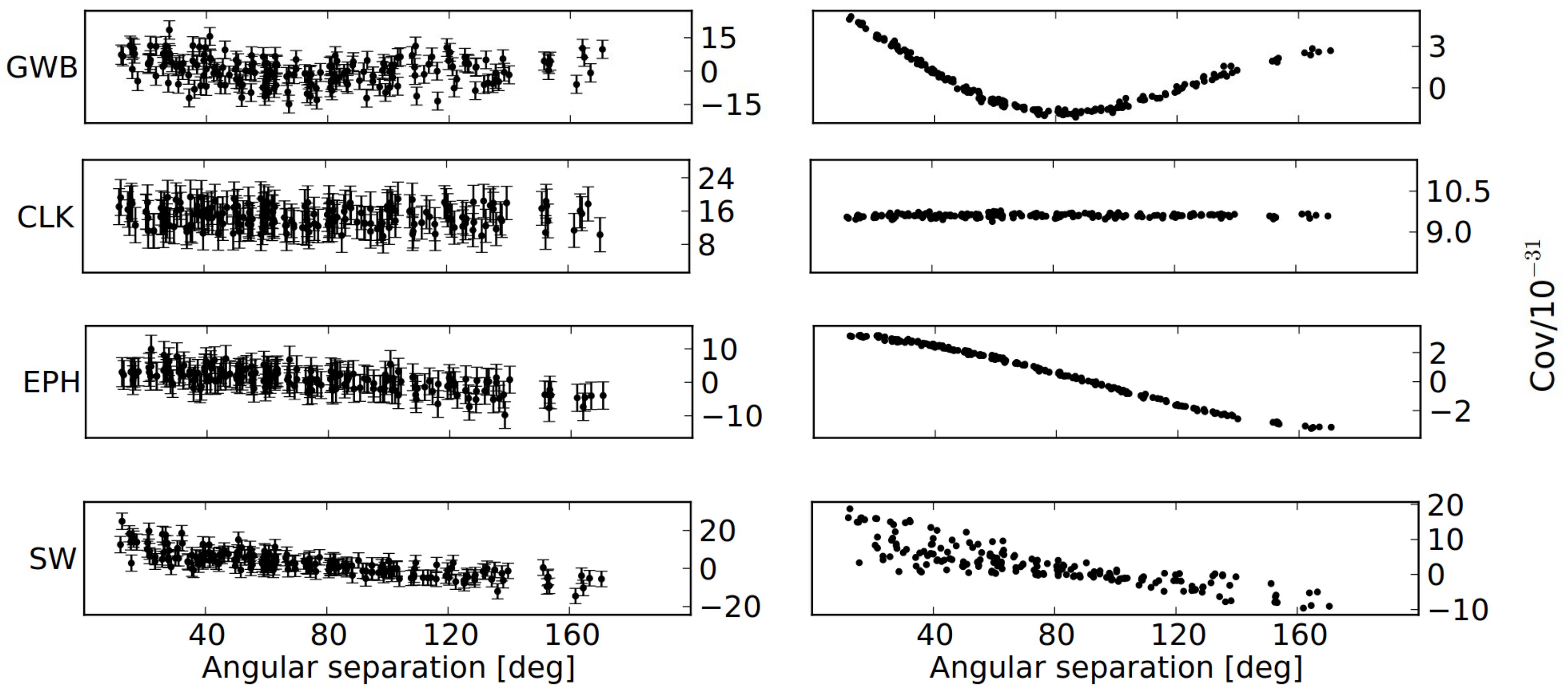


EPTA $DR2_{low}$

Iraci+, in prep

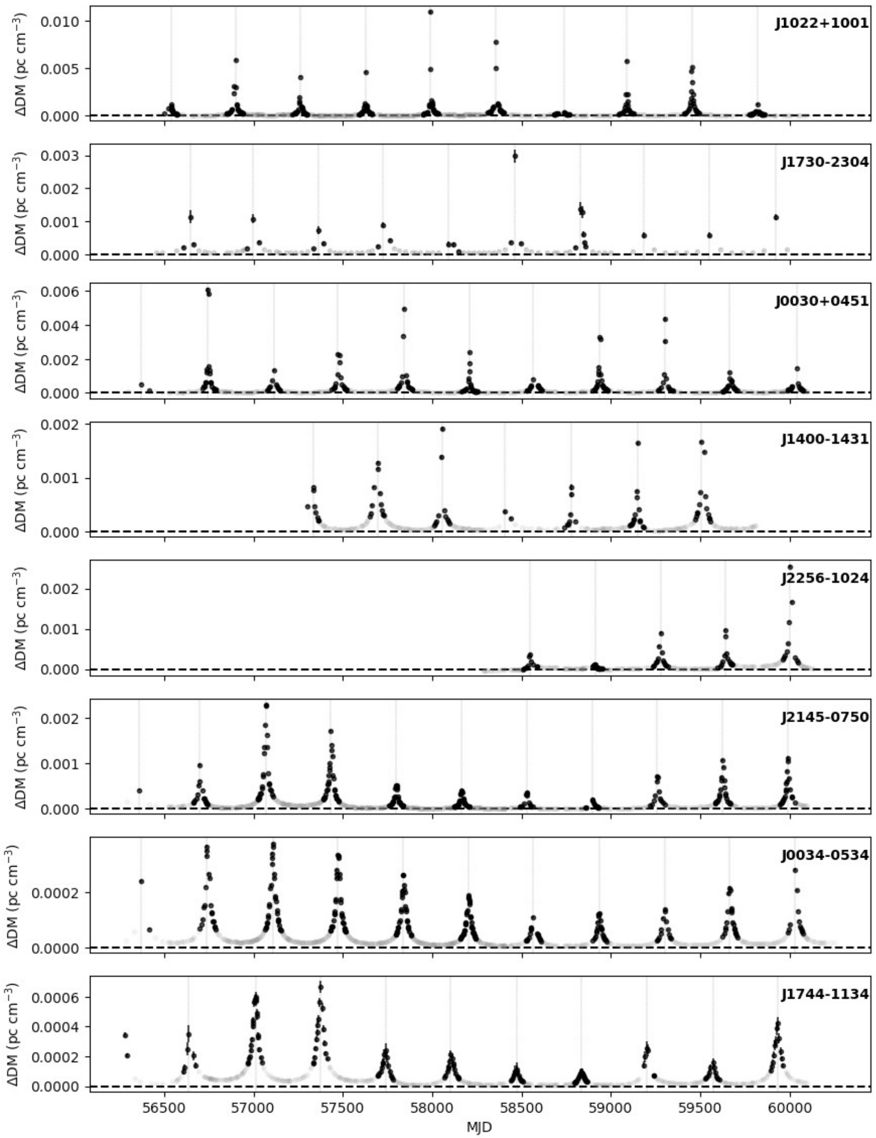


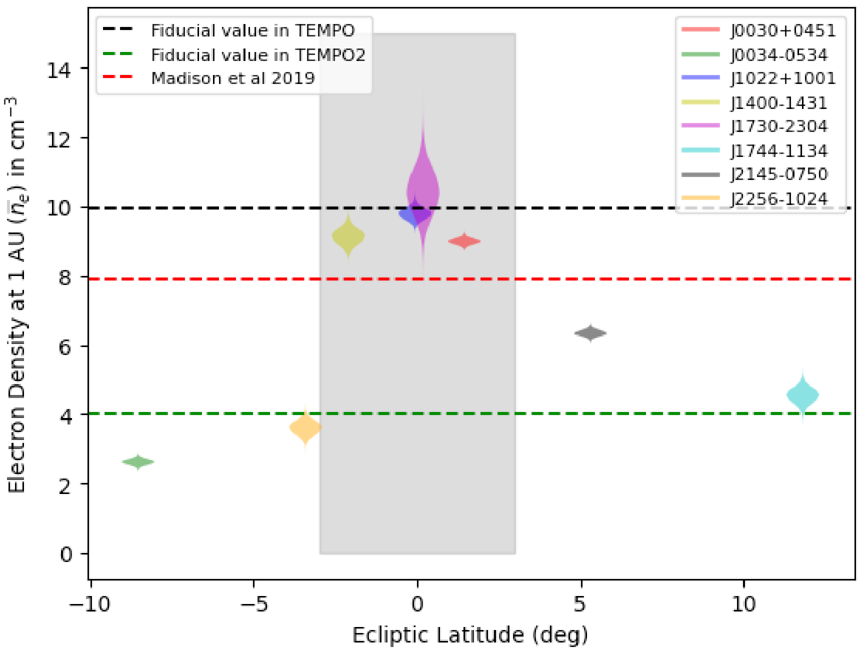
Tip-toeing around false detections



Tiburzi+2016

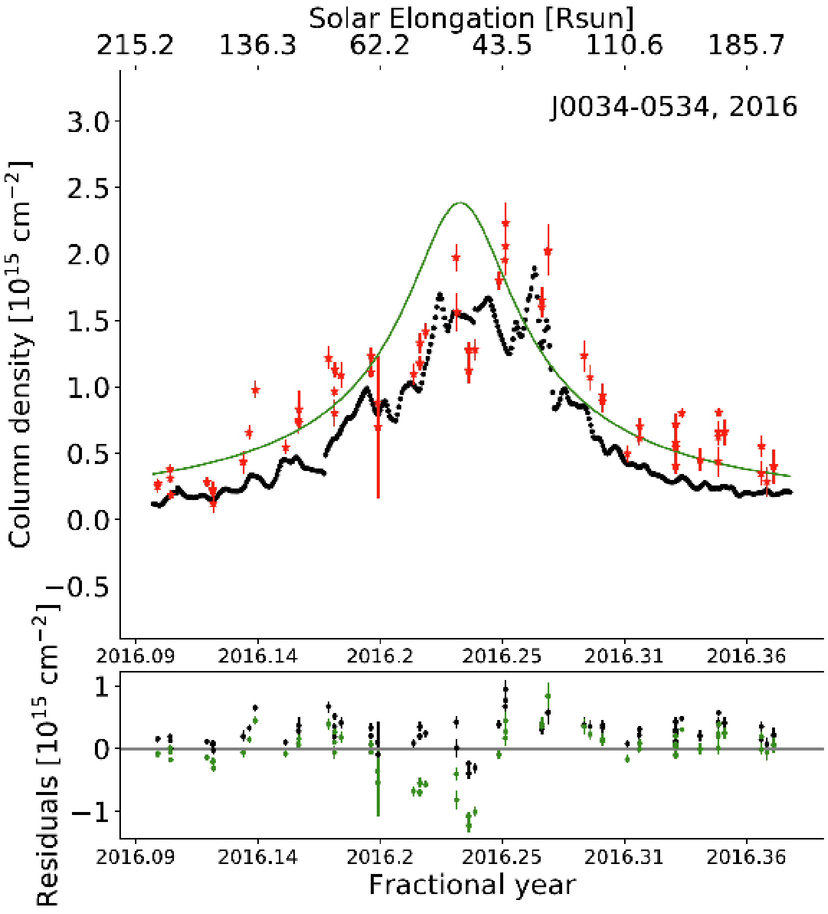
The enemy is in the house – the Solar wind

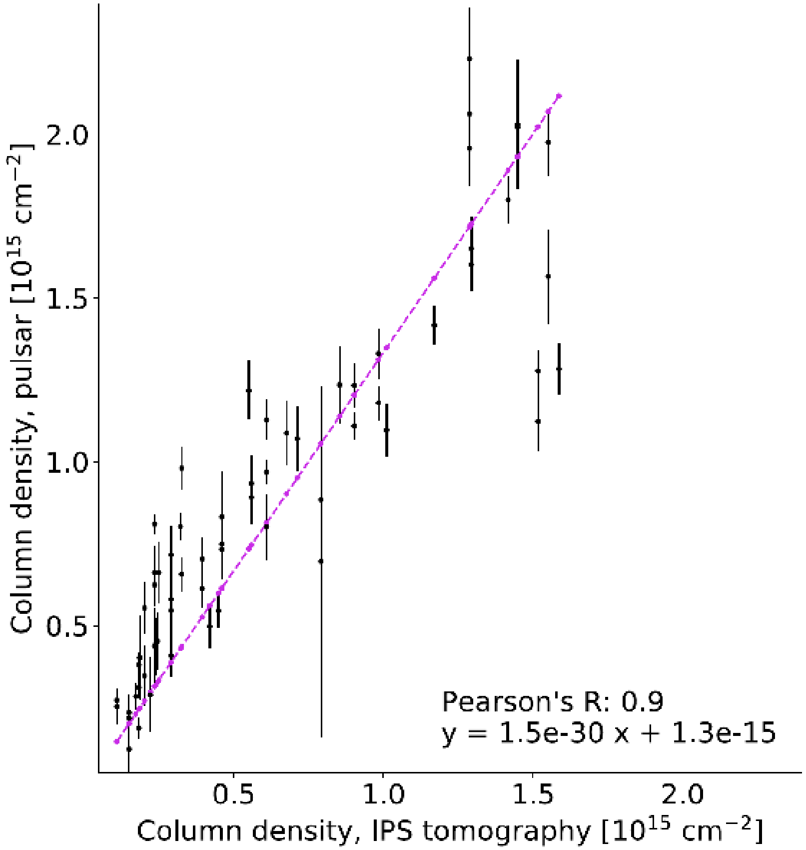




Susarla+2024

A way forward? – pulsar timing and space weather

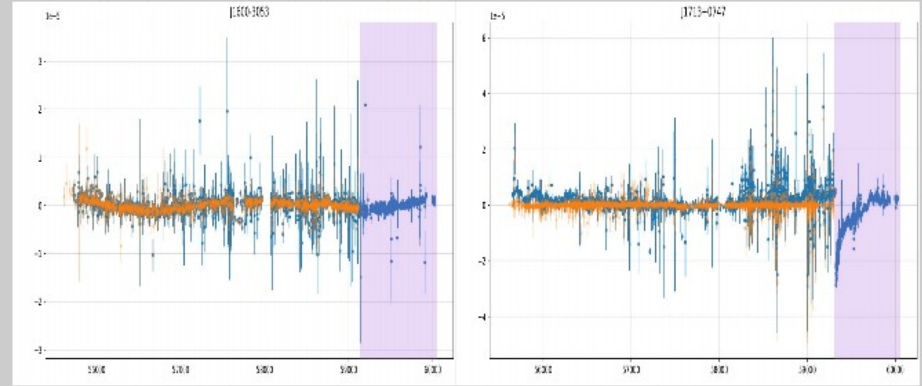


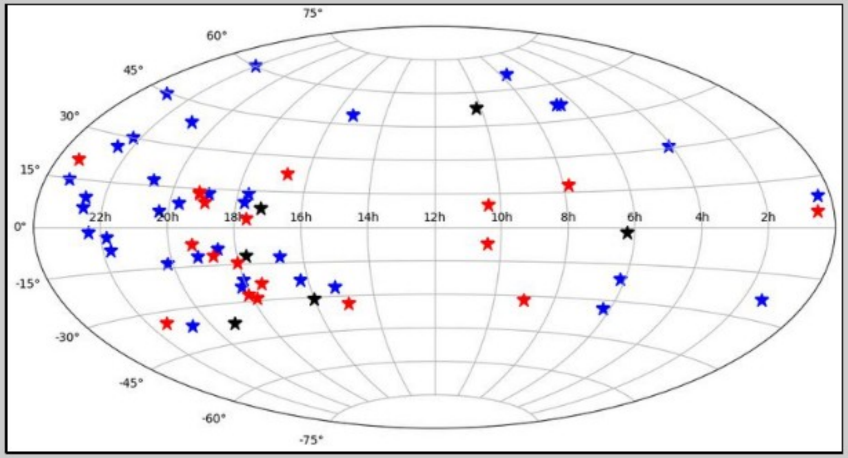


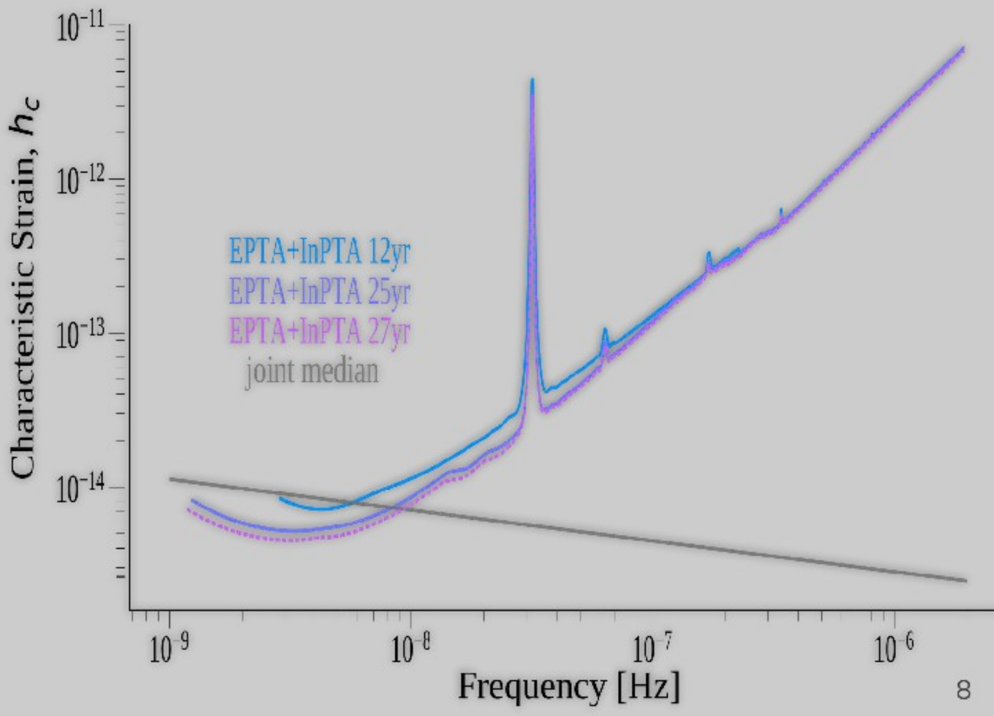
Tiburzi+2022, Shaifullah+2022

EPTA DR3

- New data up to 2024 January
- Expanding up to 60 best pulsars (~100 timed)
- Will commit data to IPTA for as many as feasible.
- Highest cadence (~3-7 days)
- Longest PTA dataset (~27 years)
- With InPTA, sensitive from 350 MHz up to 5 GHz
- Adding LOFAR and NENUFAR to go down to 20MHz.
- 7 operating telescopes - 25 MHz to 100 GHz







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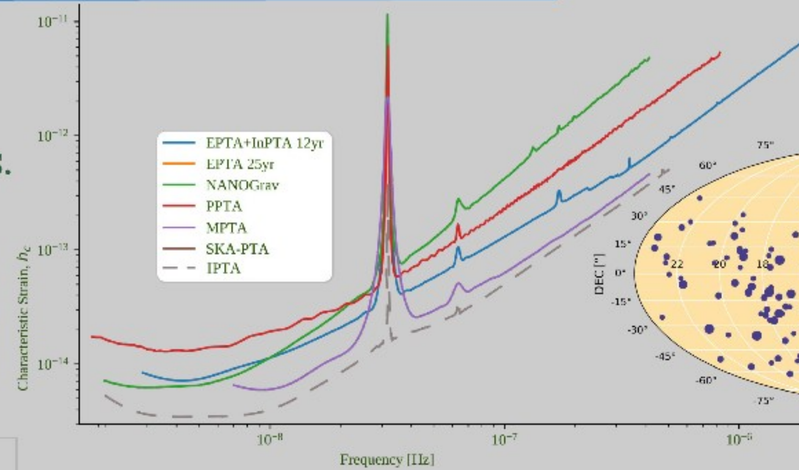
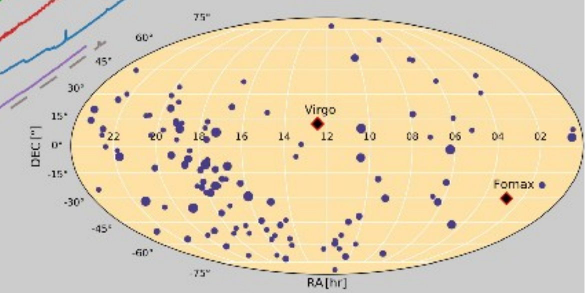
Courtesy of G. Shaifullah

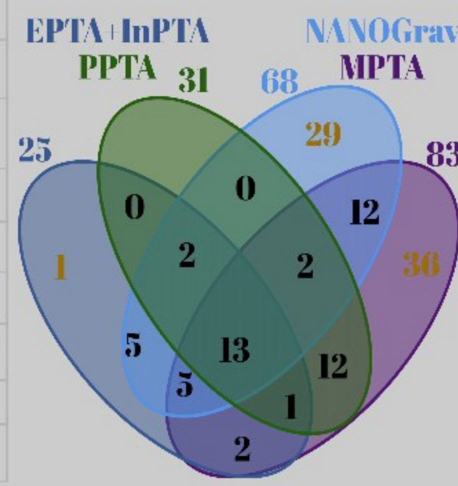
IPTA DR3

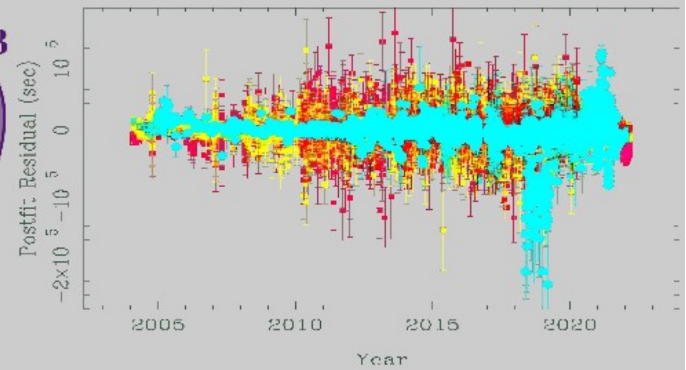
- **121 pulsars, down to <100 ns for a few pulsars**
- Greater sky coverage!
- More pulsar pairs for angular correlation searches.
- July,2024 – "Early Data Release" (eDR3), which includes the 20 best/longest-timed pulsars
- Dec, 2024 ~80 pulsars have been combined, first noise runs too!





PTA	Dataset	PSRs	Tspan (years)	$f_{GW,low}$ (nHz)	f_{radio} (MHz)
EPTA	DR2 / DR3	25 / +35	24.5	1.29	283 – 5107
	LOFAR + NENUFAR	17	9.6	–	30 – 190
NANOGrav	15-yr	68	15.9	1.99	302 – 3988
	CHIME	11	2.5		400 – 800
PPTA	DR3	24	18.1	1.75	704 – 4032
InPTA	DR1	15	3.5	9.05	300 – 1460
MeerKAT	DR2	88	4.5	7.04	856 – 1412
IPTA	DR3	121	~25/40	1.29/0.79	30 – 5107



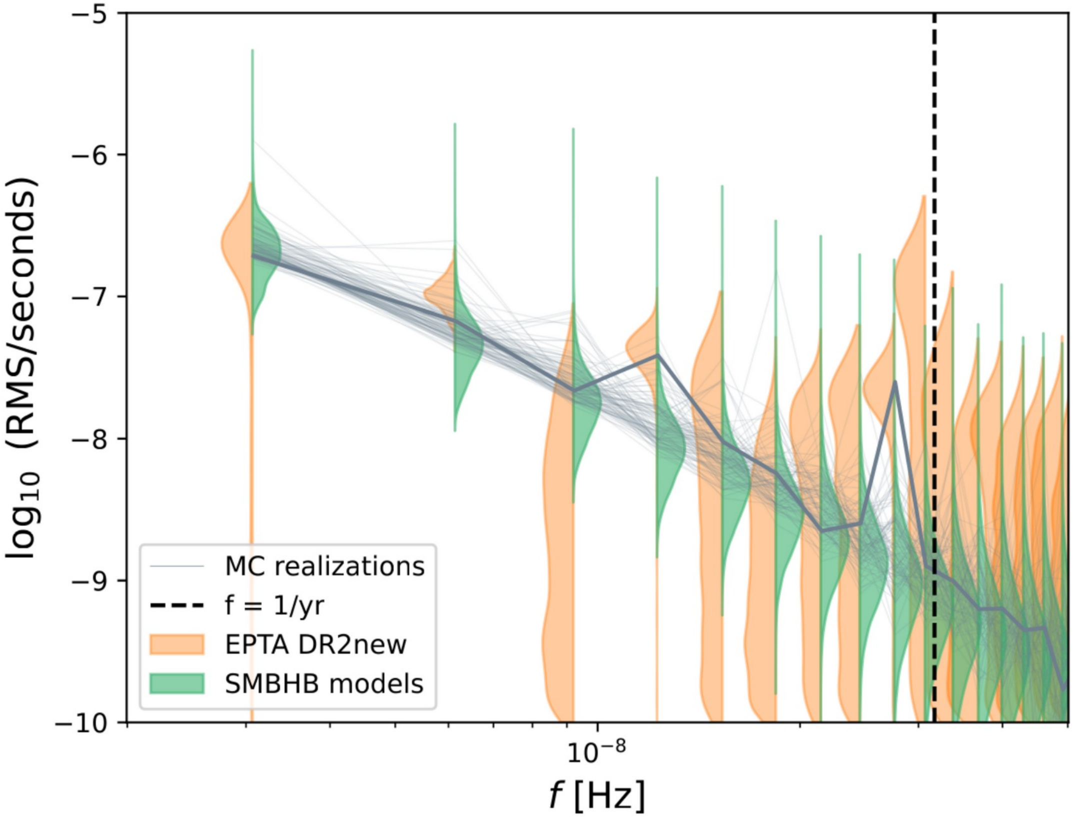


Courtesy of G. Shaifullah

Thank you for your attention

Implications, SMBHBs

The expected signal for circularly inspiralling SMBHB without environmental coupling has a spectrum of -13/3, while the recovered one is much flatter. This is compatible with the potential SMBHBs being eccentric and coupled with the gaseous and stellar surroundings



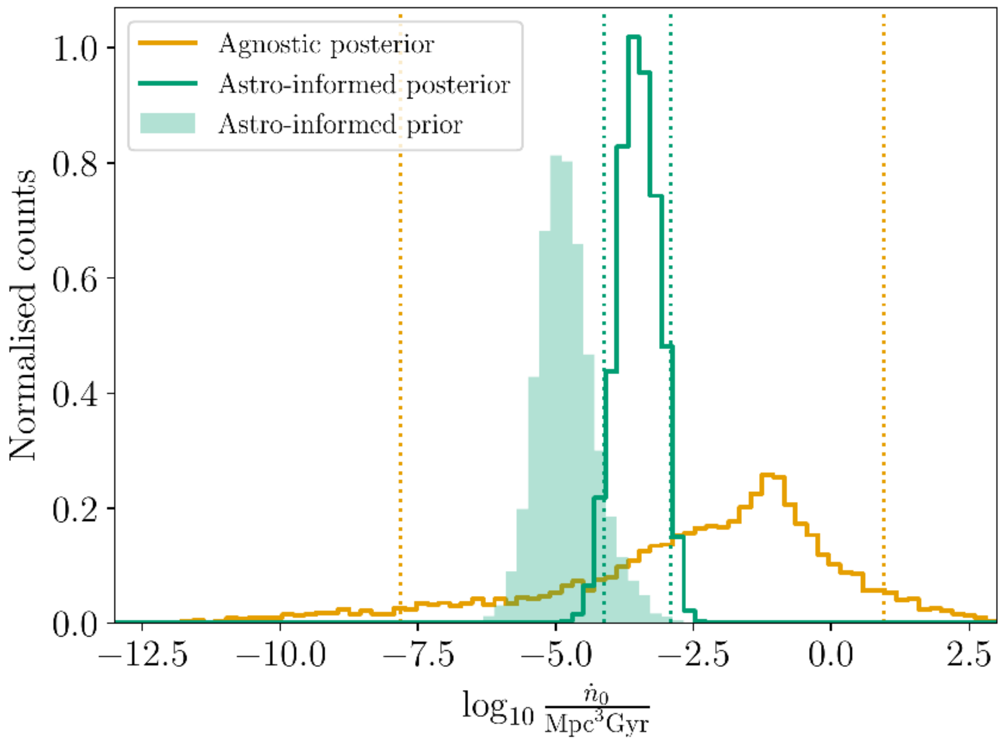
[EPTA IV]

The non-Gaussianity of the model's violins is induced by the sparse SMBHB distribution, that can sometimes produce exceptionally loud signals

Implications, SMBHBs

To constraint the properties of the potential SMBHB population, we use both an agnostic model, with minimal minimal assumptions about the underlying population, and an astrophysically-informed one, capturing the environment interaction and eccentric orbits

[EPTA IV]



Merger rate density