16th of September 2024, GEMMA2

The low-frequency gravitational wave sky: Pulsar Timing Arrays


D. Futselaar

EPTA

INTERNATIONAL PULSAR TIMING ARRAY

IPTA

C. Tiburzi

INAF-OAC

ISTITUTO NAZIONALE DI ASTROFISICA

INAF

OAC

Osservatorio Astronomico di Cagliari

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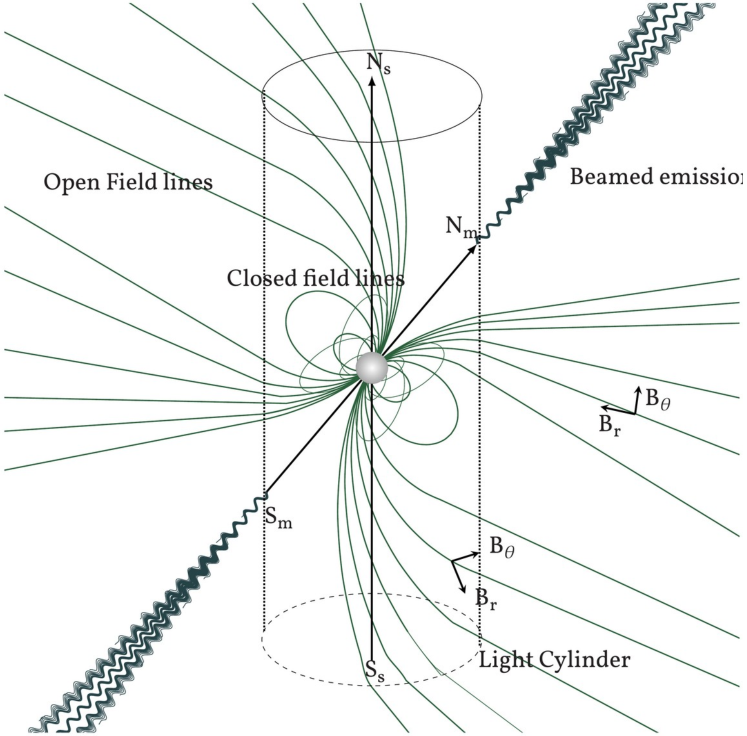
- Millisecond pulsars and Pulsar timing
- Pulsar Timing Arrays and the GW background
- The European PTA, and the 3σ GWB detection
- The future – EPTA-DR2+ and IPTA DR3

Pulsars in a nutshell

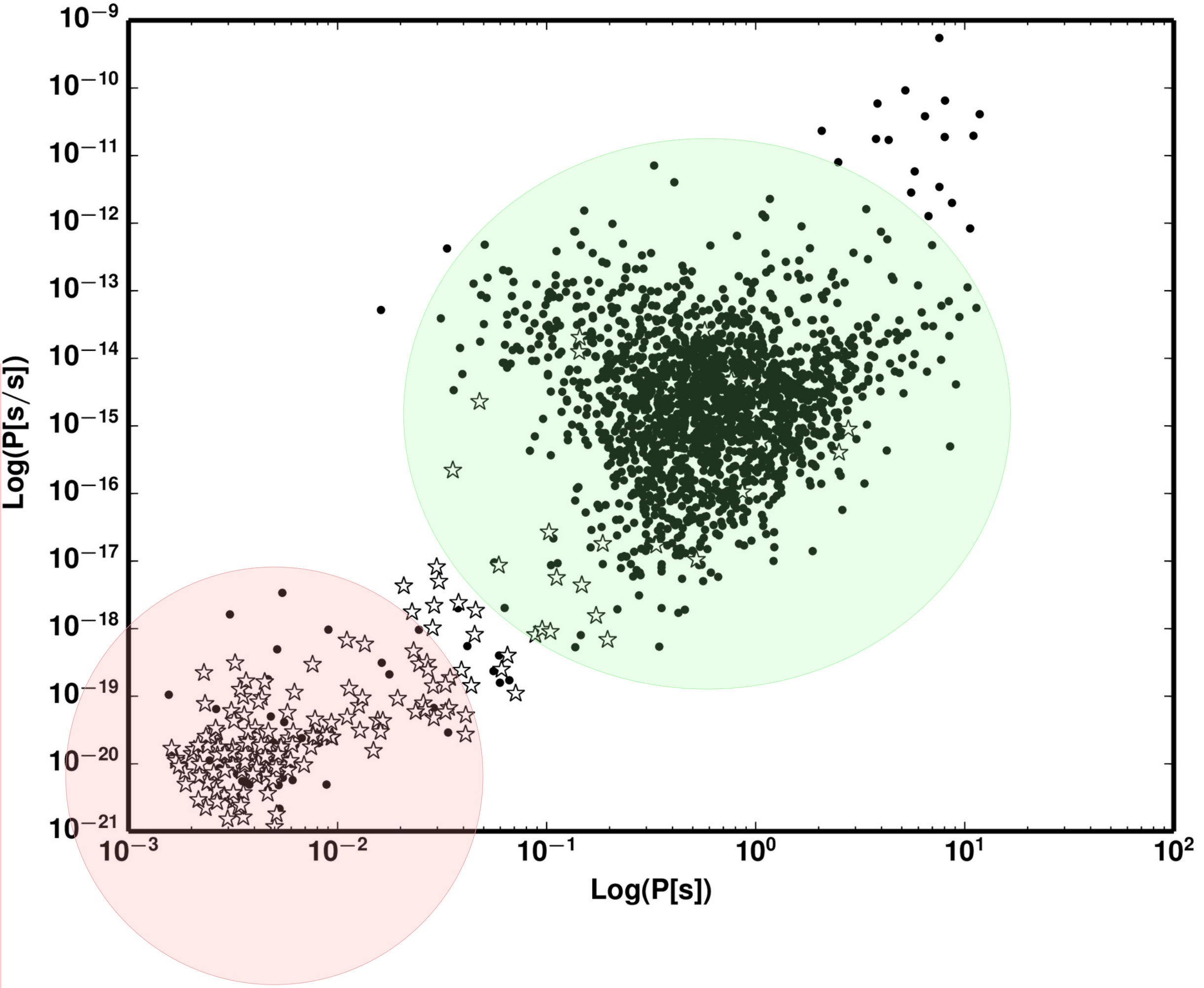
- **Pulsars** are highly-magnetized (~10^{12-14} G), fast-rotating (up to ~10^{-3} sec) **neutron stars**;
- They produce **two beams of emission**, radiating their rotational kinetic energy, mostly visible at radio wavelengths;
- Under particular geometric conditions, the observer collects the radio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



Shaifullah 2017

The detectors: (milli)second pulsars

$P - \dot{P}$ *diagram*



Normal pulsars

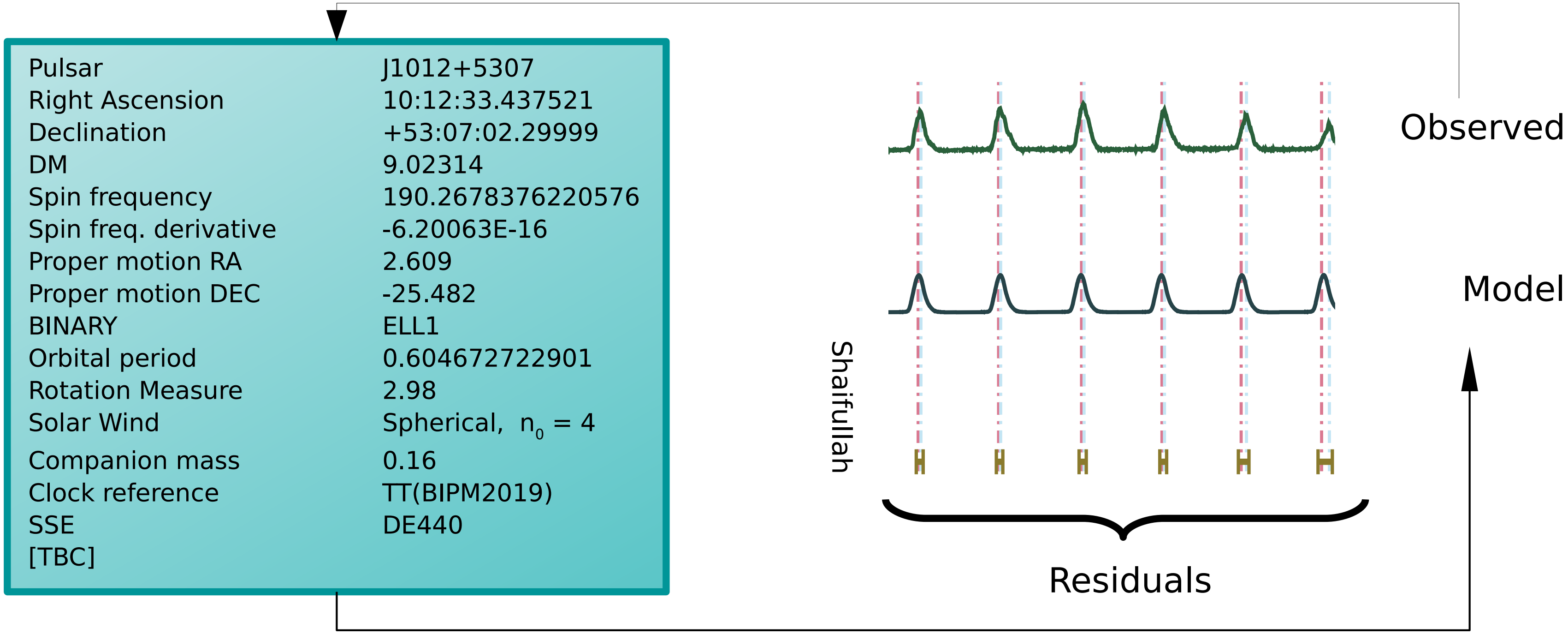
Millisecond pulsars

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

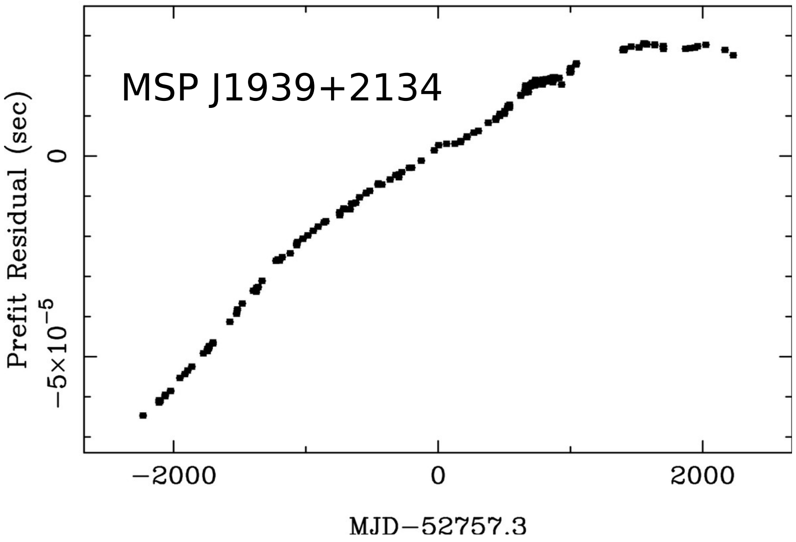


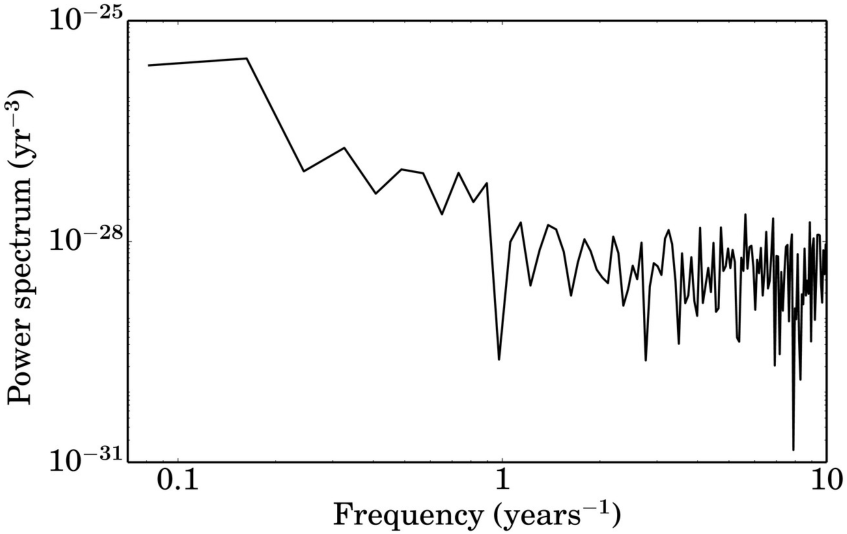
Pulsar	J1012+5307
Right Ascension	10:12:33.437521
Declination	+53:07:02.29999
DM	9.02314
Spin frequency	190.2678376220576
Spin freq. derivative	-6.20063E-16
Proper motion RA	2.609
Proper motion DEC	-25.482
BINARY	ELL1
Orbital period	0.604672722901
Rotation Measure	2.98
Solar Wind	Spherical, $n_0 = 4$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

Shaifullah

Pulsar timing

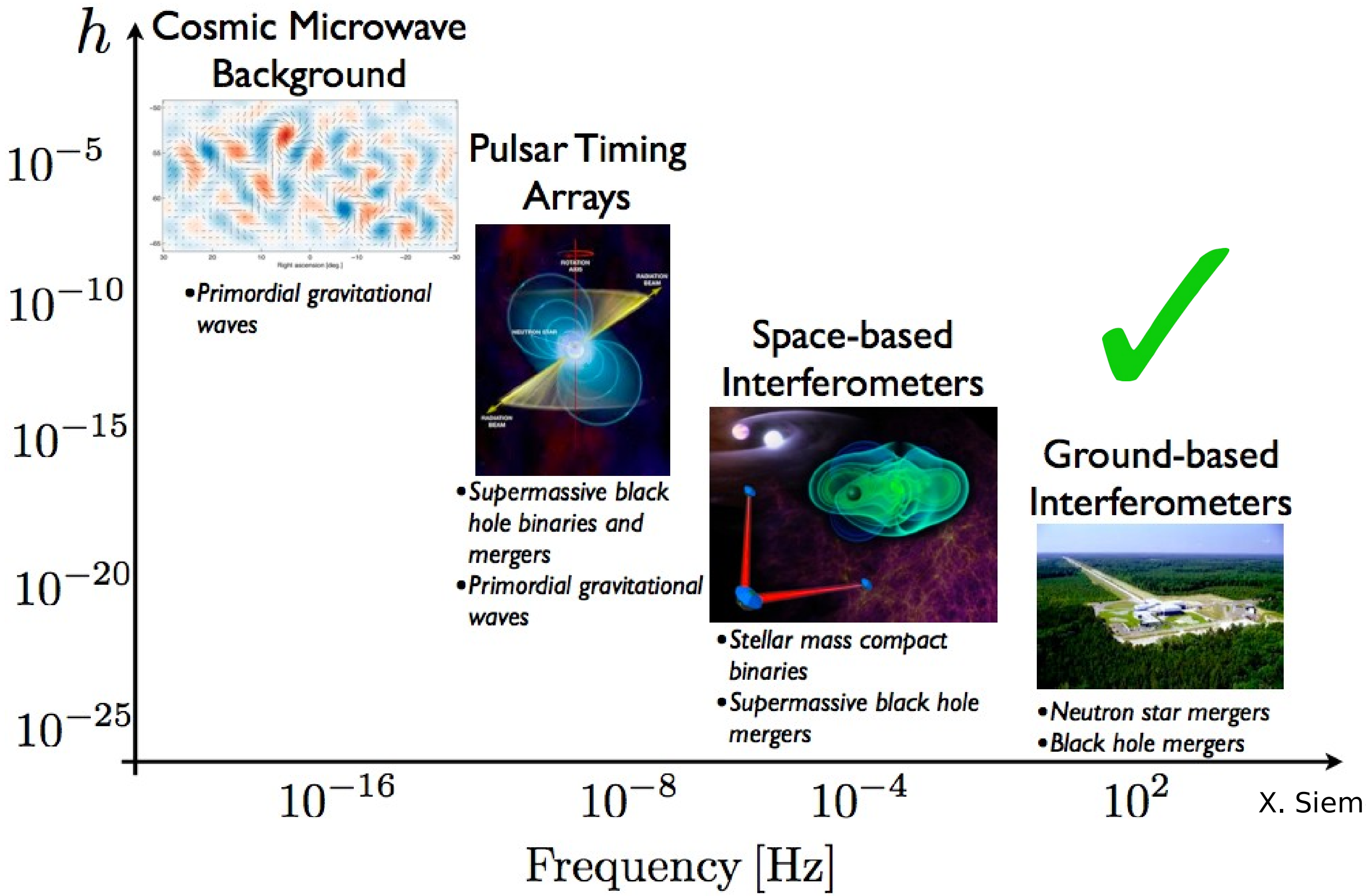
Long-term, non-modeled effects can perturb the ToAs and appear as ‘red noise’ in the timing residuals, an excess of power at low frequencies in the power spectrum





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**

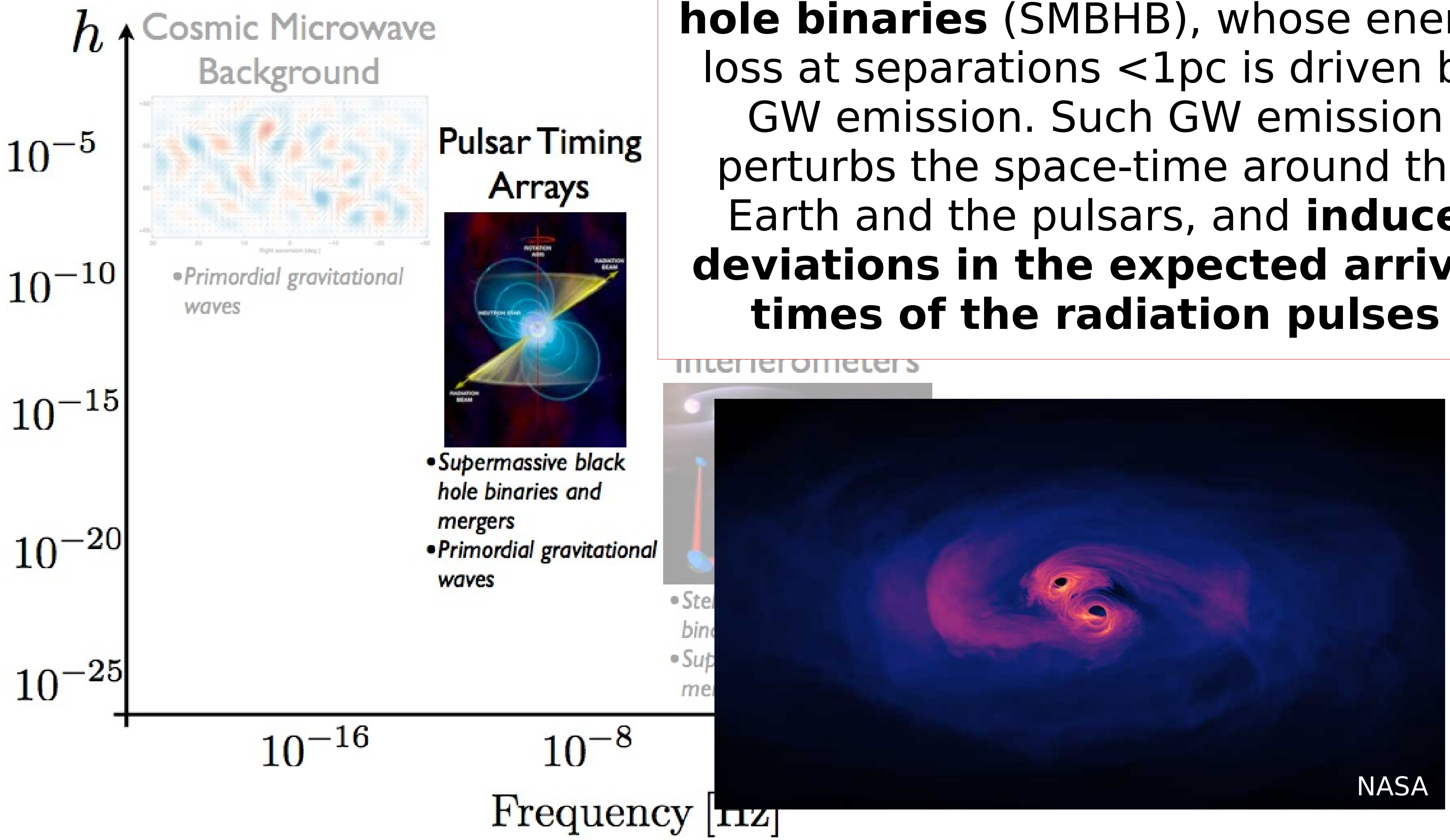
The Gravitational Wave spectrum



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 affected by GW emission from a SMBHB

Expected timing-residuals shape induced by GW emission from a SMBHB (Jenet et al. 2004):

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

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

Earth term

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

Pulsar term

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

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)

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

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

Detweiler 1979
Jenet+2005/2006

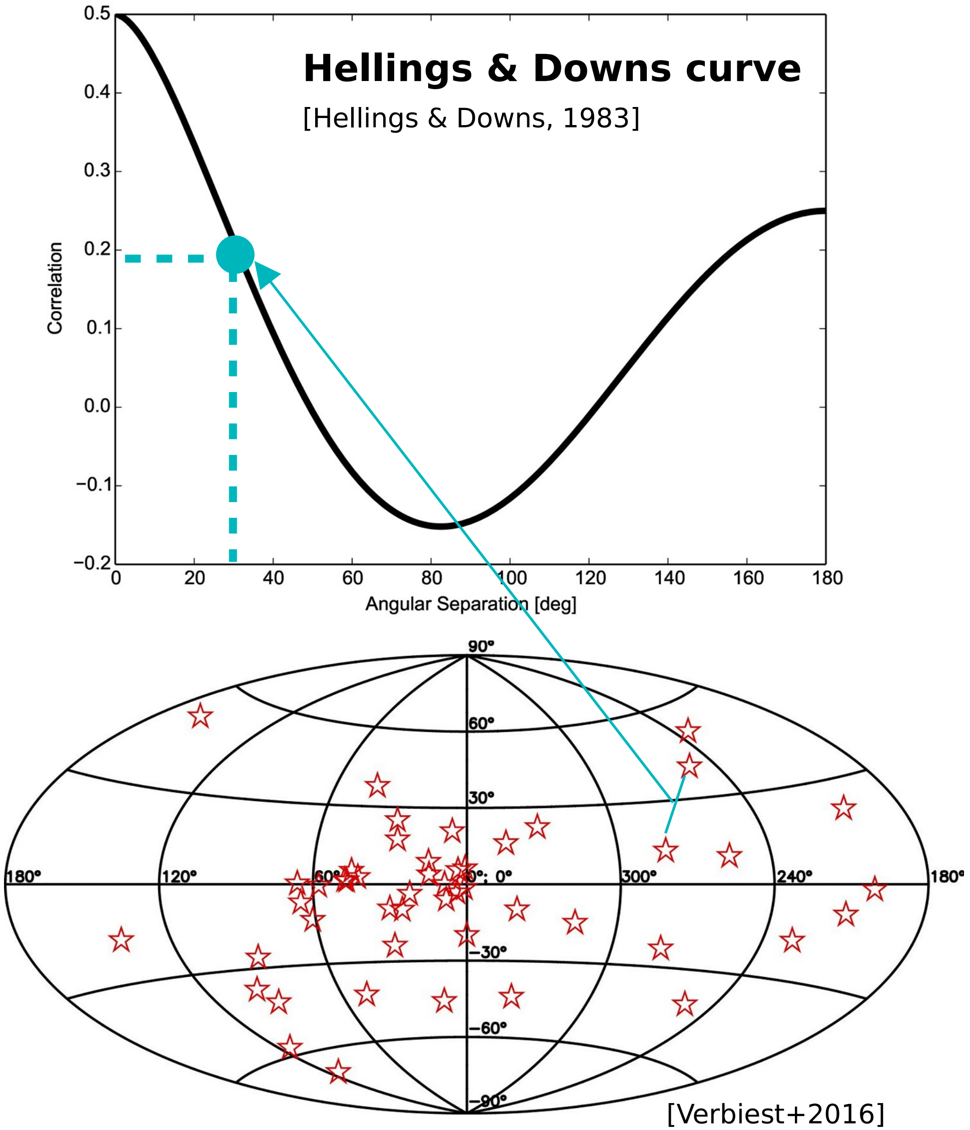
"RED" POWER SPECTRUM

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

$$\left\{\begin{aligned} &\zeta(\theta_{ij}) = \frac{3}{2}\,x\log(x) - \frac{x}{4} + \frac{1}{2} \\ &x = [1 - \cos(\theta_{ij})] \end{aligned}\right.$$

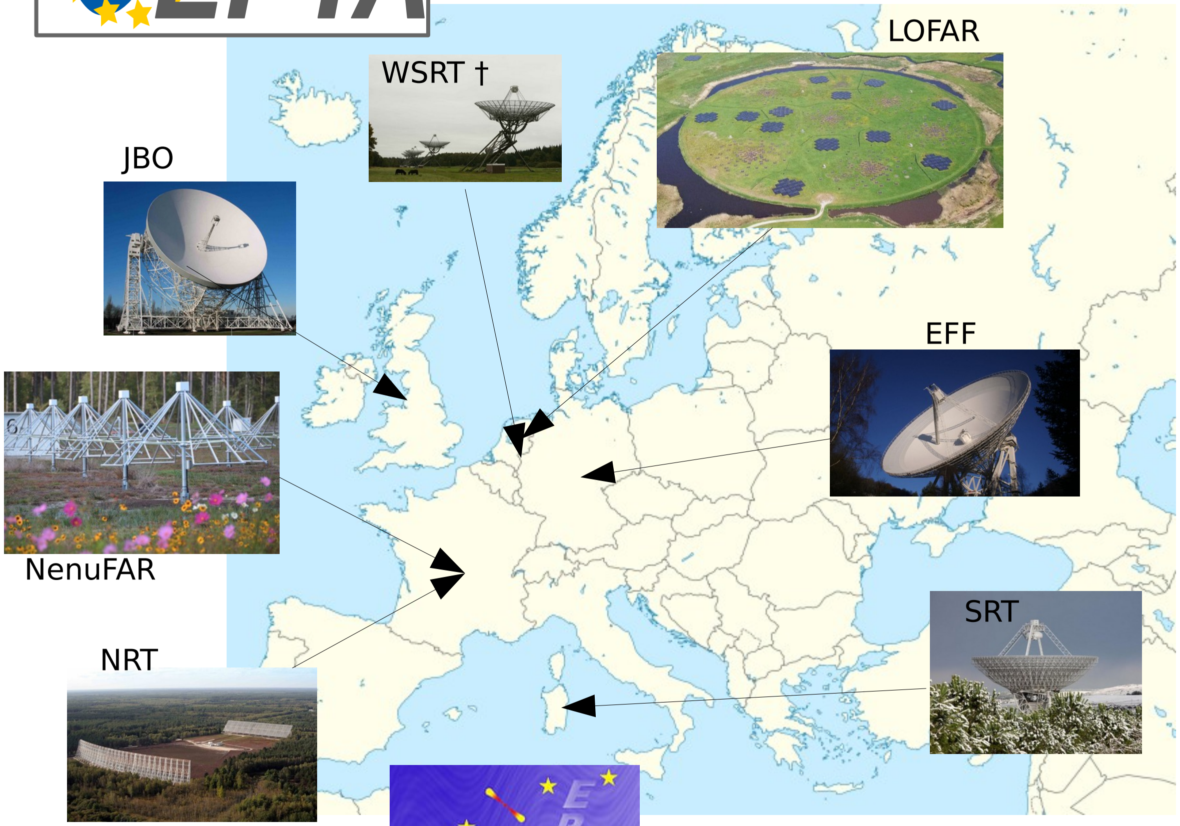
[Hellings & Downs, 1983]



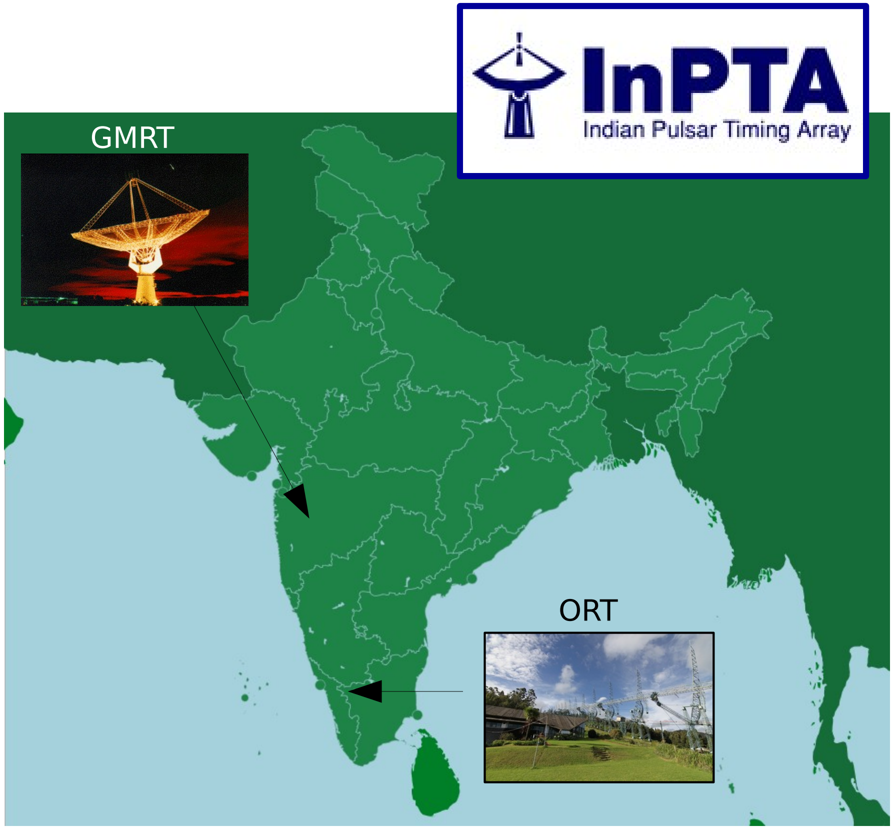
[Verbiest+2016]

The EPTA, and the 3σ GWB detection

EPTA

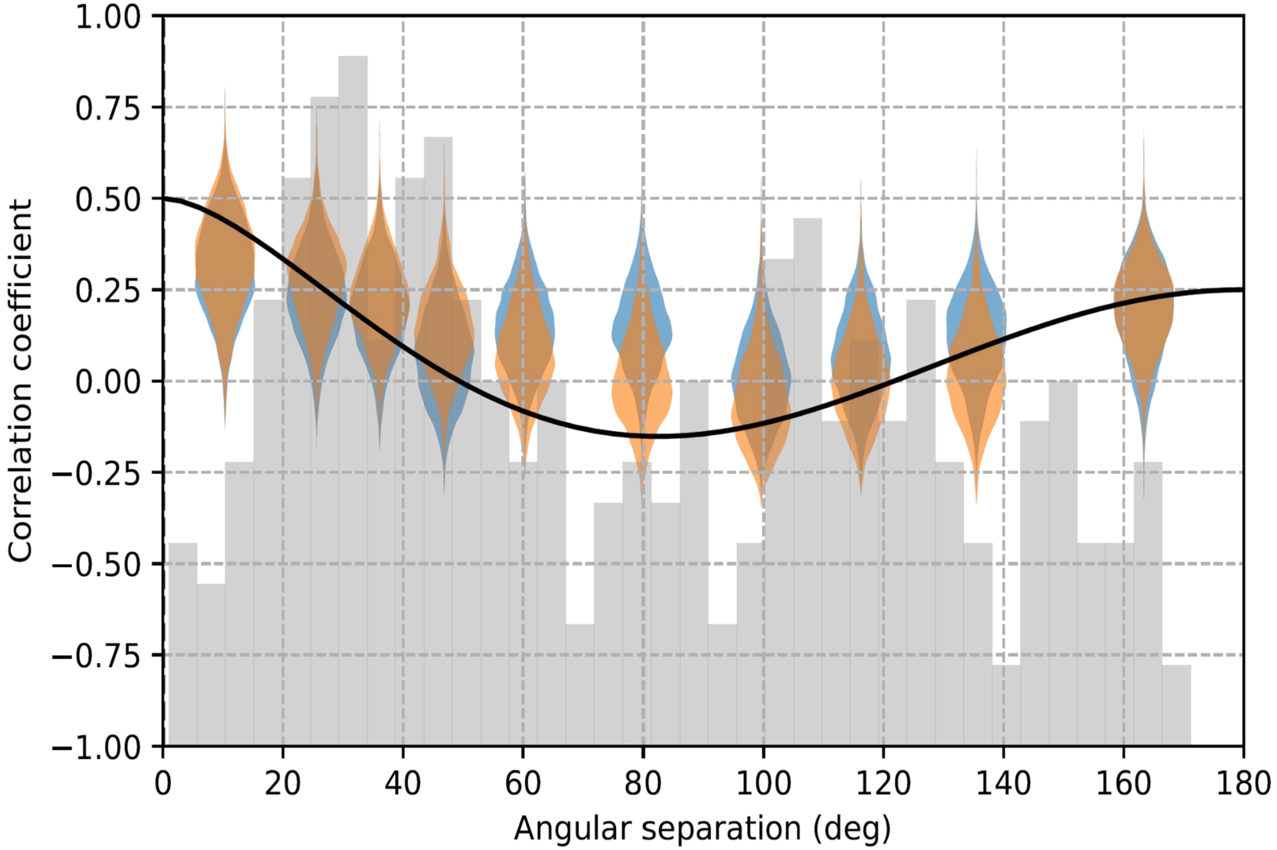


LEAP



First indication of a GWB signature in the EPTA data

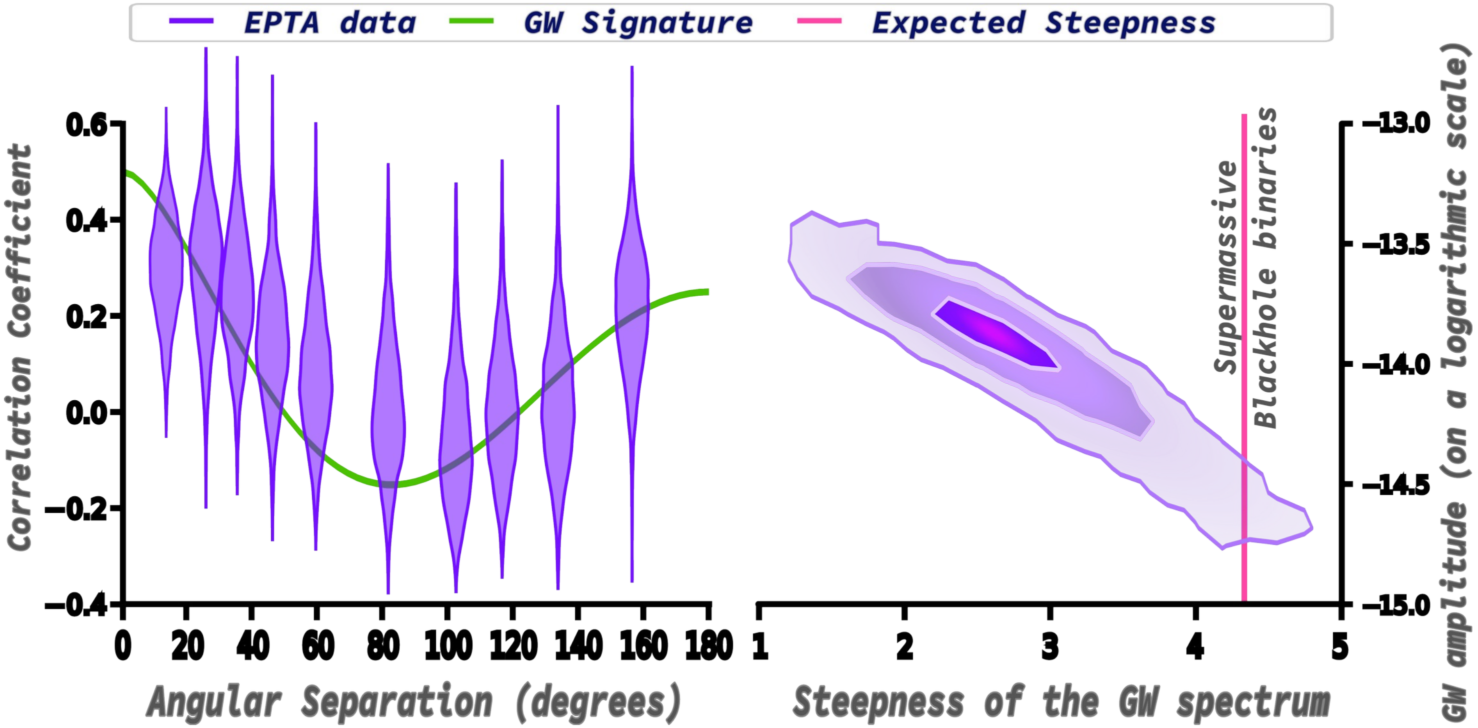
[Antoniadis+2023 III]



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

[Antoniadis+2023 III]

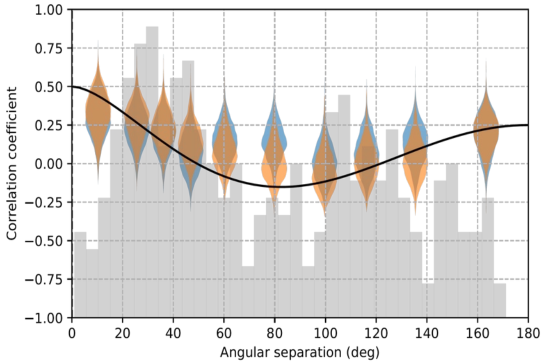


The **strain amplitude** for the expected GWB spectrum at the GW freq of 1/1yr ~ $\mathbf{2.5^{\pm 0.7} \times 10^{-15}}$ when the spectral index is fixed to -13/3. However, by leaving the GWB index free we derive a much **flatter spectrum and louder signal, $\mathbf{Log(A) = -13.94^{+0.23}_{-0.48}}$** and $\mathbf{\gamma = 2.71^{+1.18}_{-0.73}}$, than what expected for circularly inspiralling SMBHBs

Consistency with the other PTA collaborations

EPTA

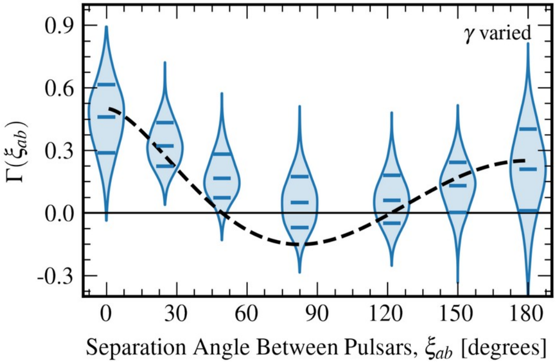
[Antoniadis+2023 III]



3σ

NANOGrav

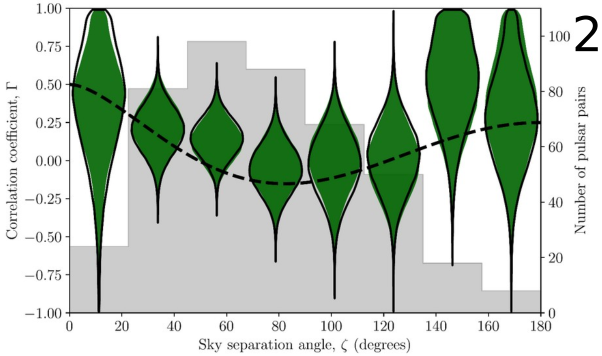
[Agazie+2023 I]



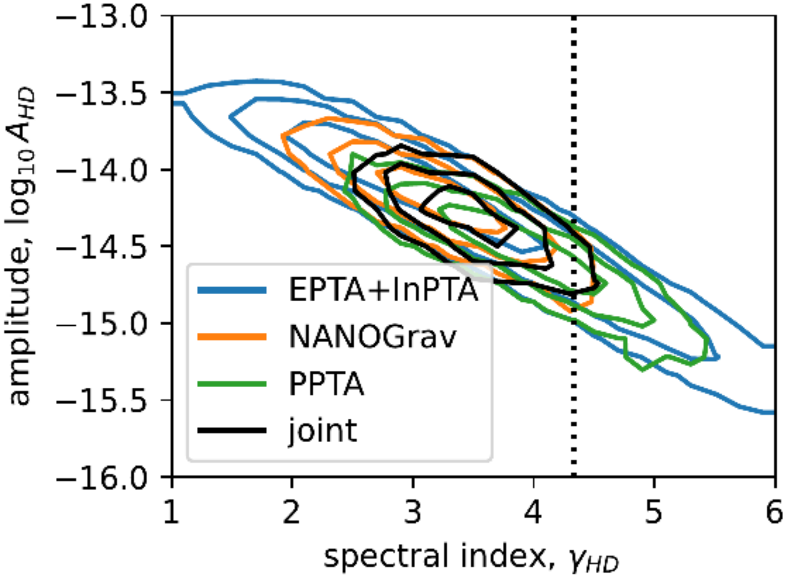
3.5-4σ

PPTA

[Reardon+2023]



2σ



[IPTA 2023]

Implications

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

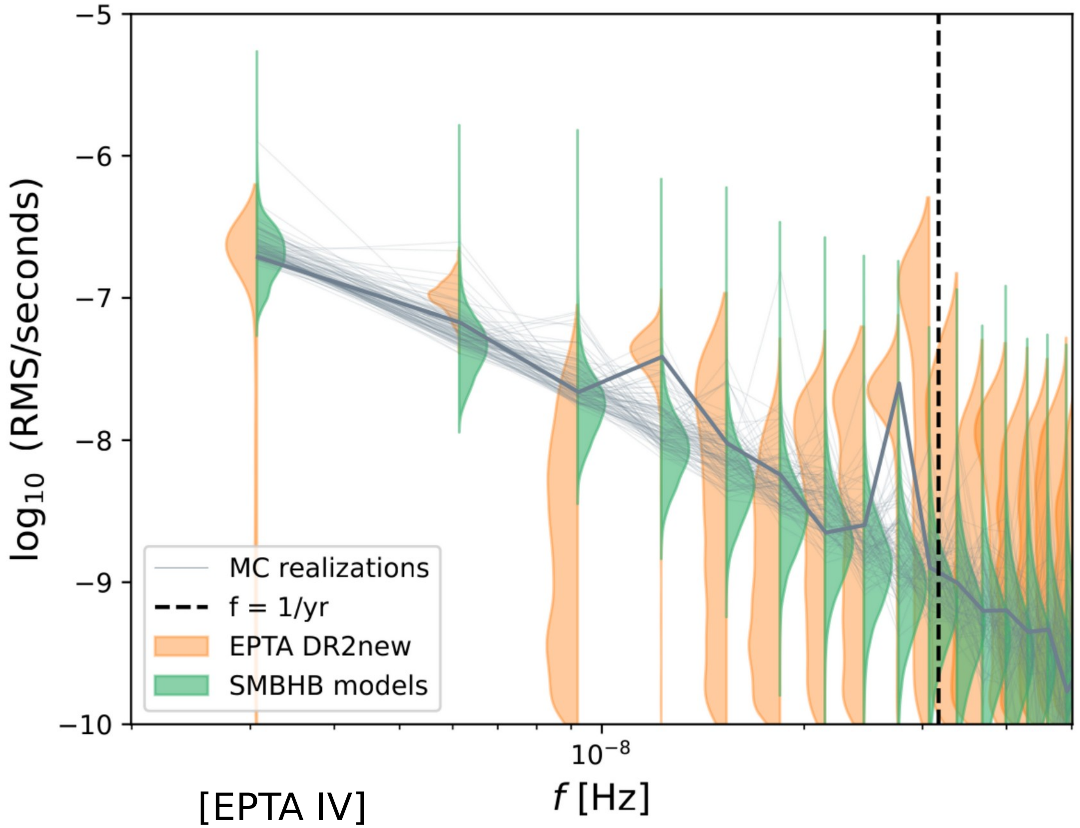
One of the first accessible considerations will be probably offered by the continuity of the spectrum, and the directionality of the signal:

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

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



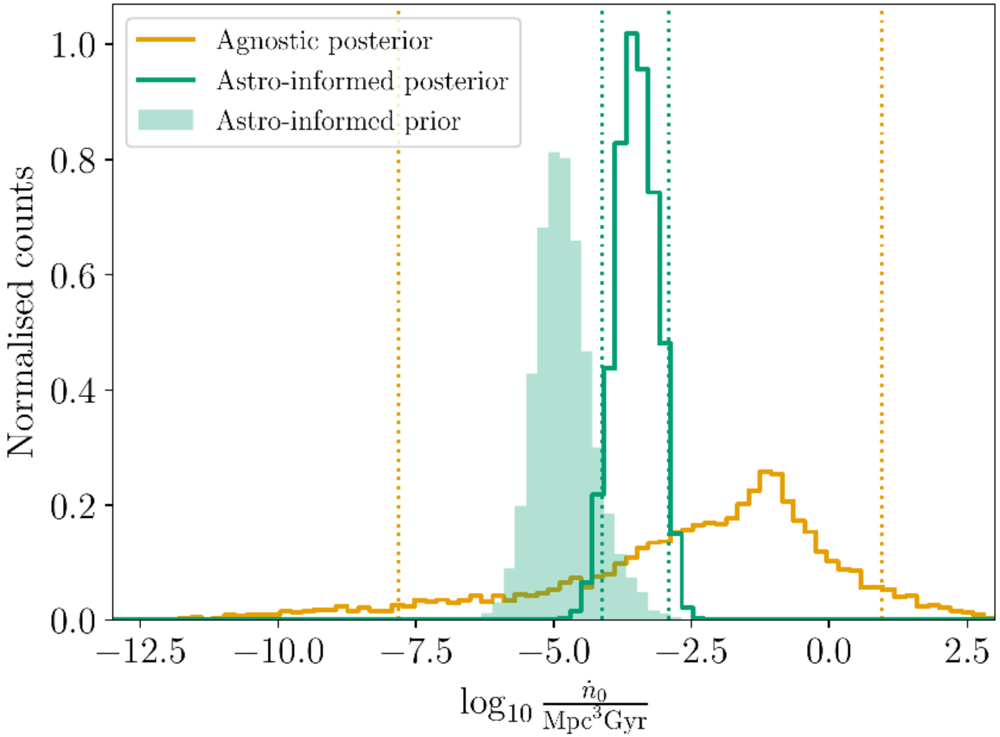
[EPTA IV]

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

Implications, SMBHBs

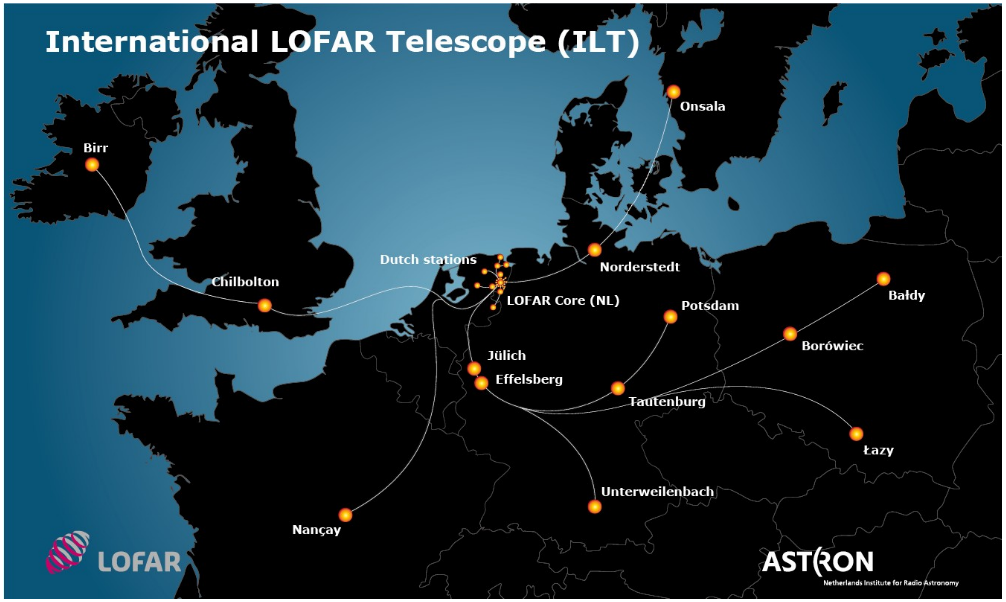
To constraint the properties of the potential SMBHB population, we use both an agnostic model, with minimal minimal assumptions about the underlying population, and an astrophysically-informed one, capturing the environment interaction and eccentric orbits

[EPTA IV]



Merger rate density

EPTA DR2+



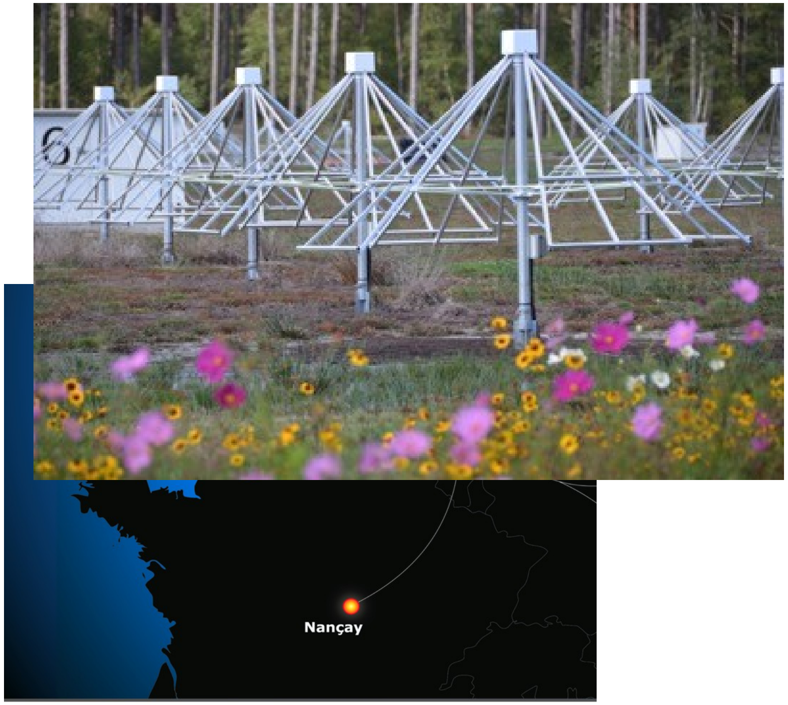
LOFAR, the LOw Frequency Array

Pulsar observations ongoing since 2013

>100 pulsars

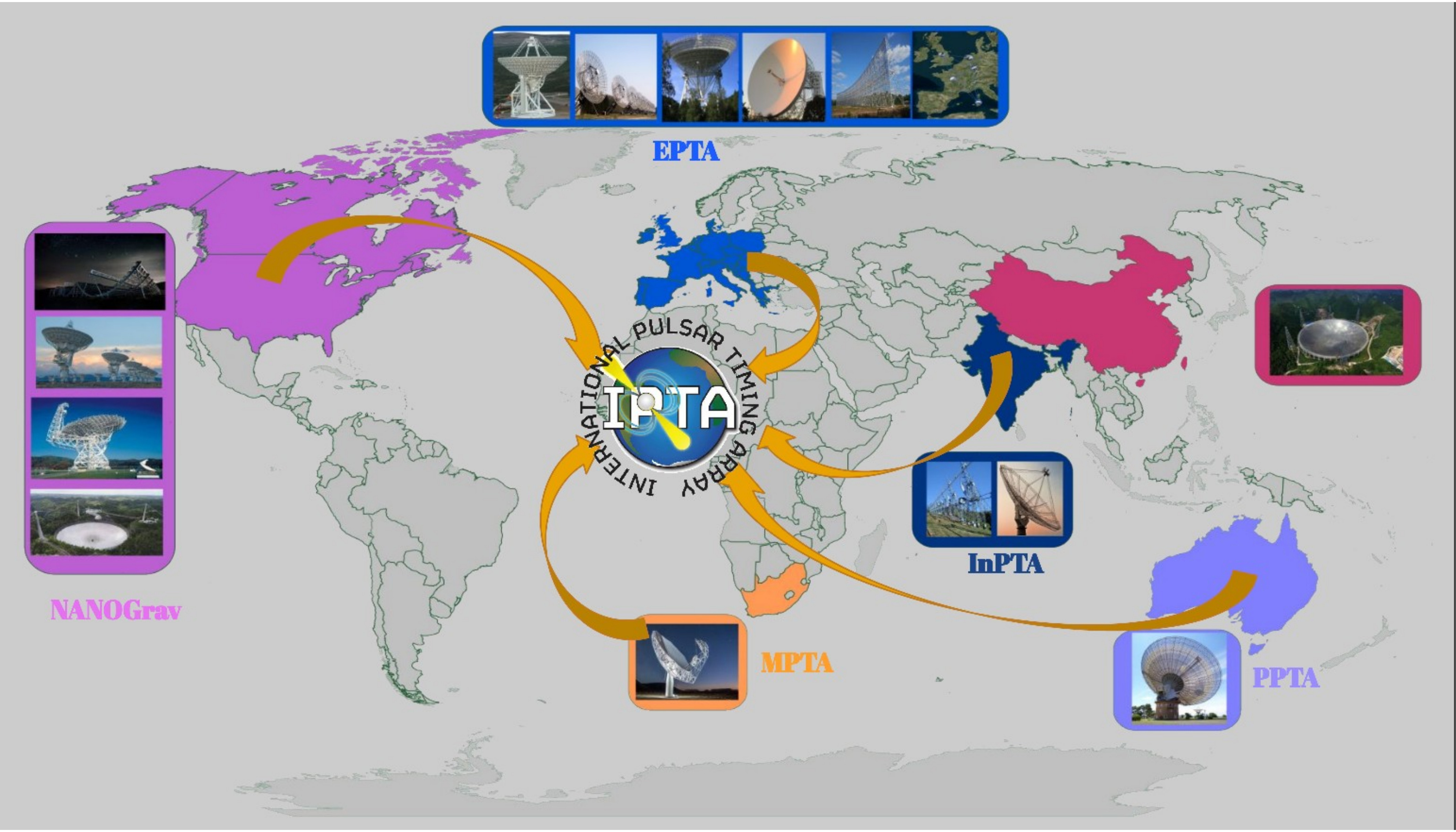
Weekly or monthly cadence

NenuFAR



IPTA, DR3

115 pulsars



Thank you for your attention