The importance of LOFAR in characterising the nanohertz gravitational wave background

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ASTRON, *the Netherlands Institute for Radio Astronomy*

On behalf of…

EPTA

INTERNATIONAL PULSAR TIMING ARRAY
IPTA

Netherlands Astronomy Conference 2025
Berg en Dal, the Netherlands - 26 March 2025

GIGA
Advancing Gravitational Wave Astrophysics

erc
European Research Council

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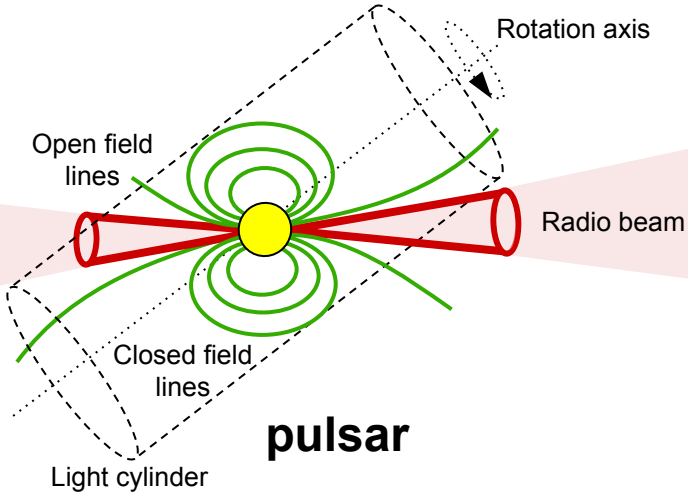
Link to Gslides

Pulsars

Neutron stars with strong magnetic fields that **spin rapidly** and **emit radio beams** along their magnetic axes



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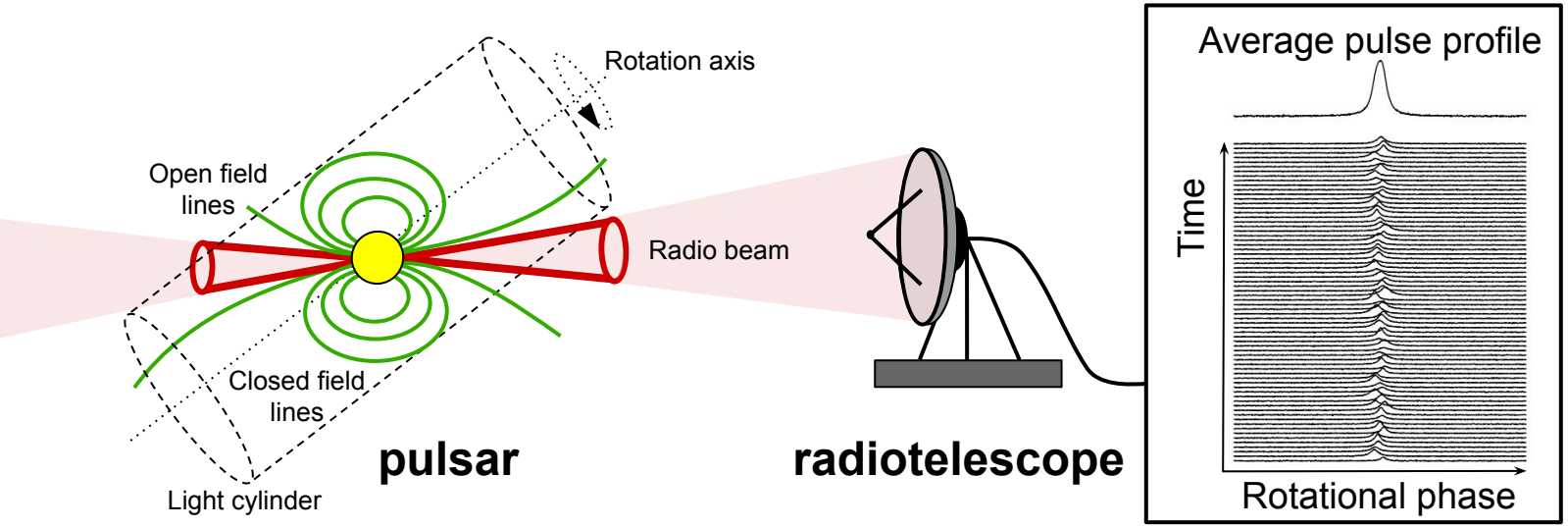
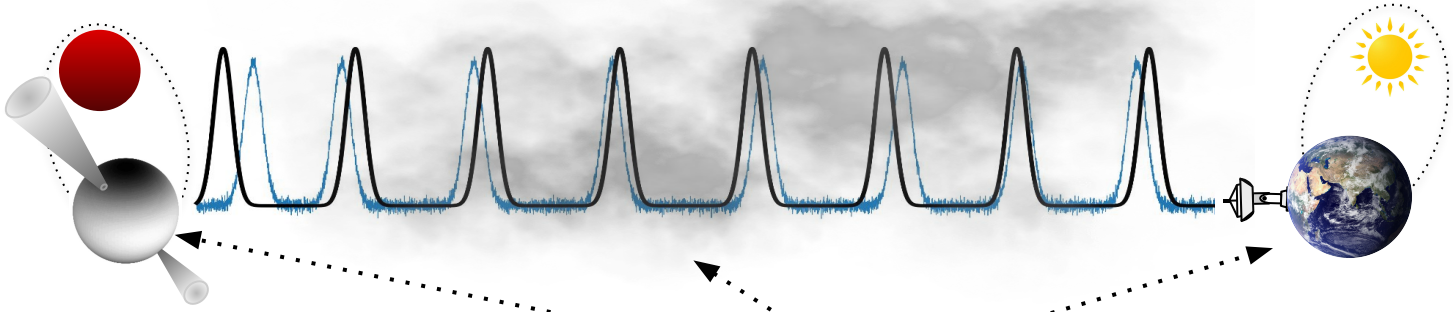


Precision pulsar timing



$$t_e^{psr} = t_a^{obs} - \Delta_B - \Delta_{ISM} - \Delta_\odot$$

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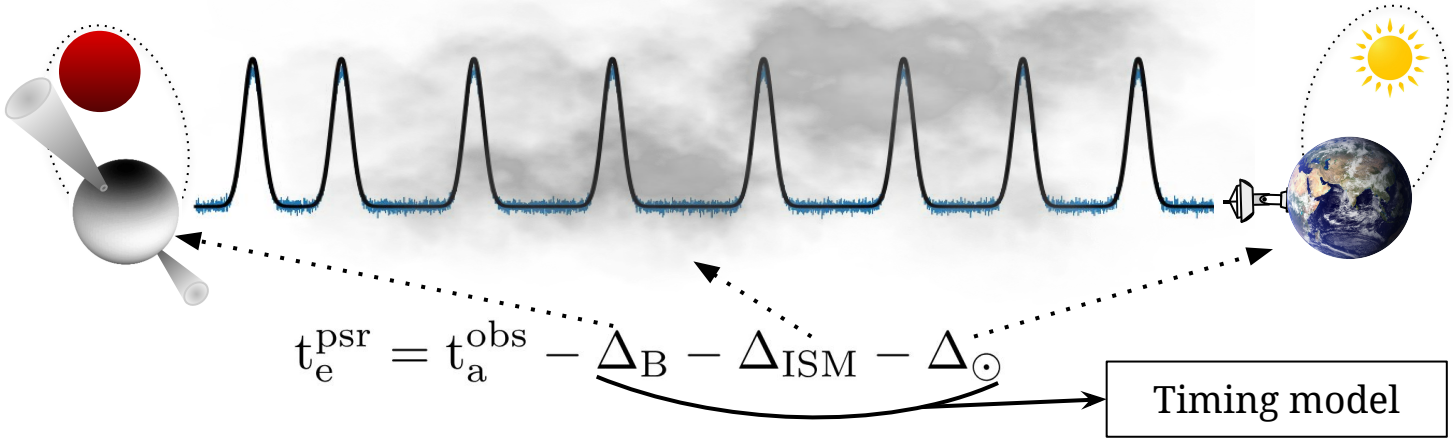
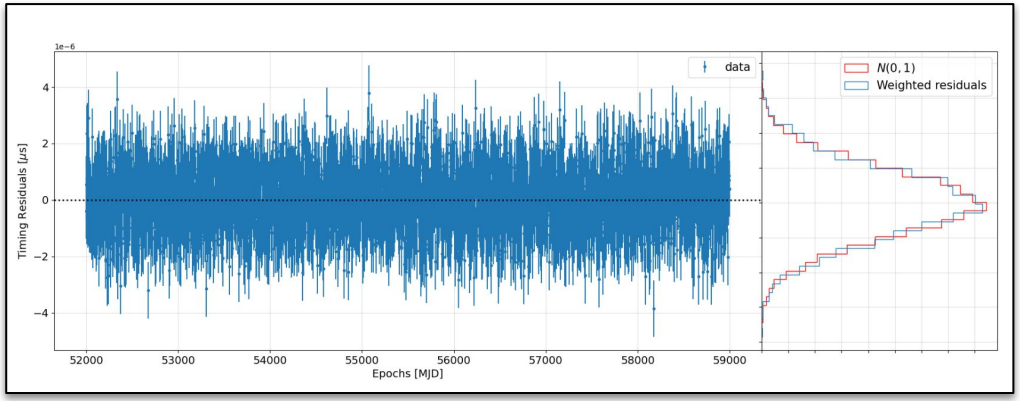


$$t_e^{psr} = t_a^{obs} - \Delta_B - \Delta_{ISM} - \Delta_\odot$$

Timing model

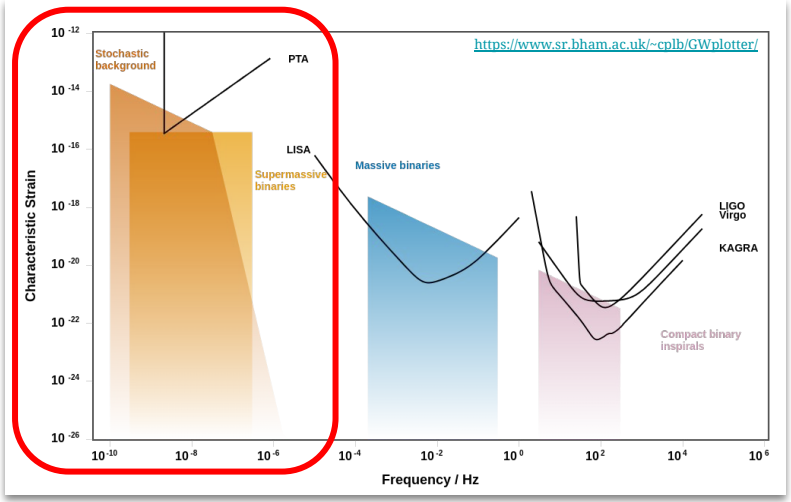
Timing residuals



$RMS_{rés}$ ~ 100 ns - 5 μs, with 10 - 30 yr of data !

Pulsar Timing Arrays (PTAs)

A nano-Hertz gravitational wave detector



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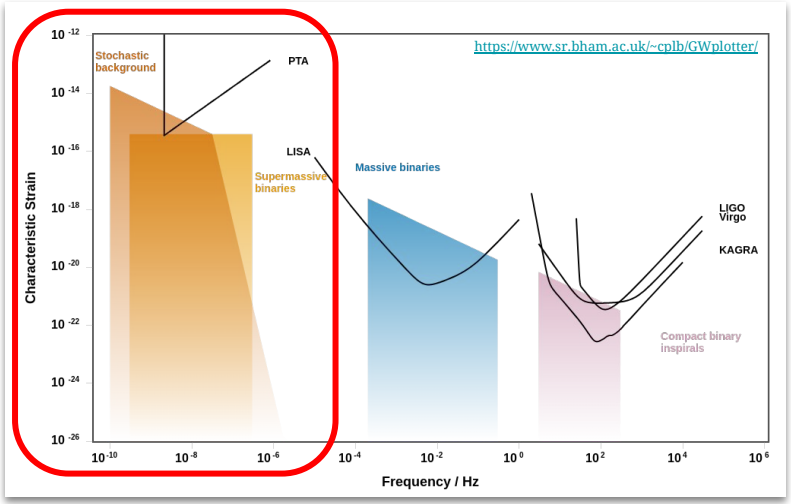
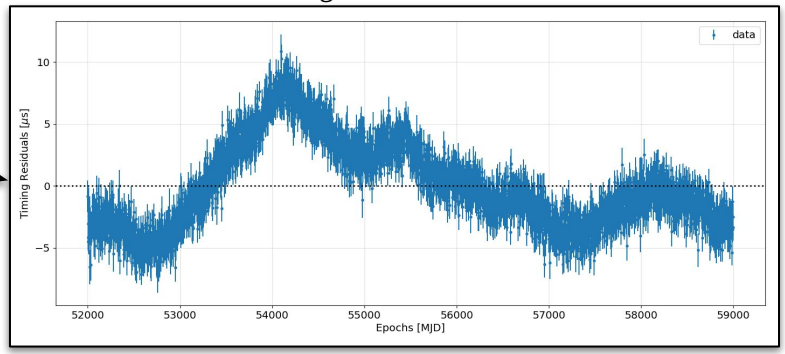
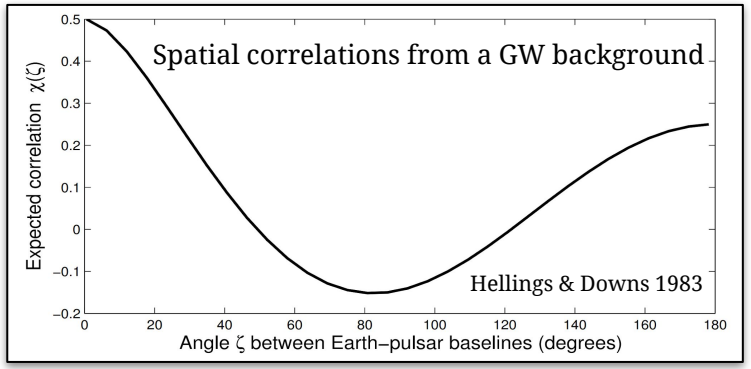


Timing residuals with GWs

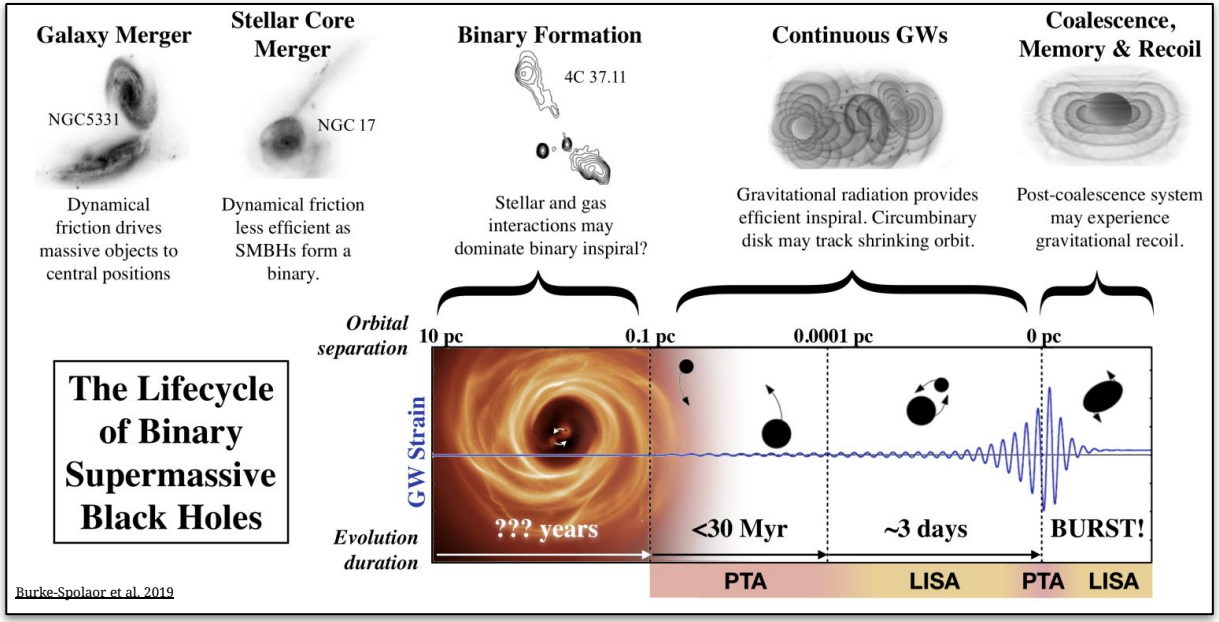




Pulsar Timing Arrays (PTAs)

A nano-Hertz gravitational wave detector

Main source: The supermassive ($M \geqslant 10^8\ M_\odot$) black hole binaries



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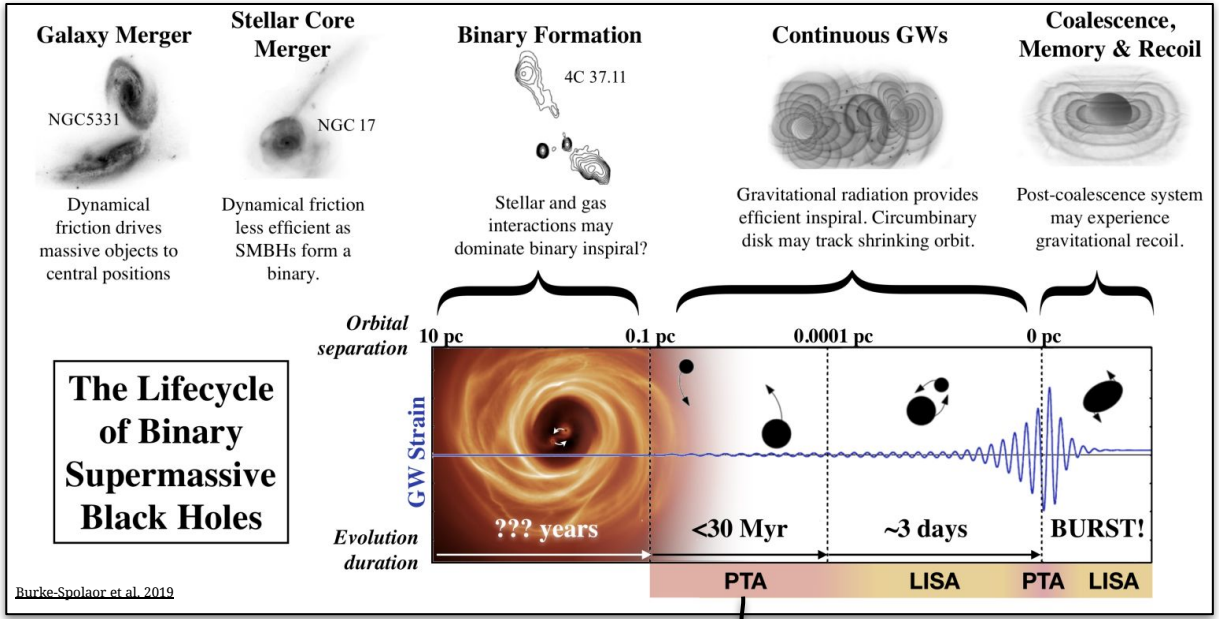
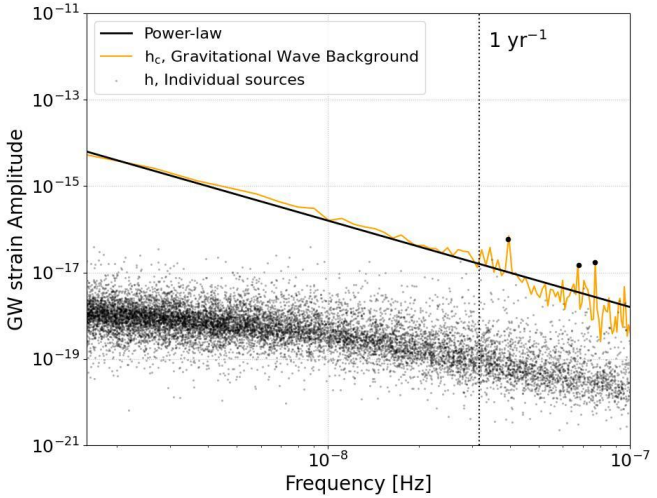
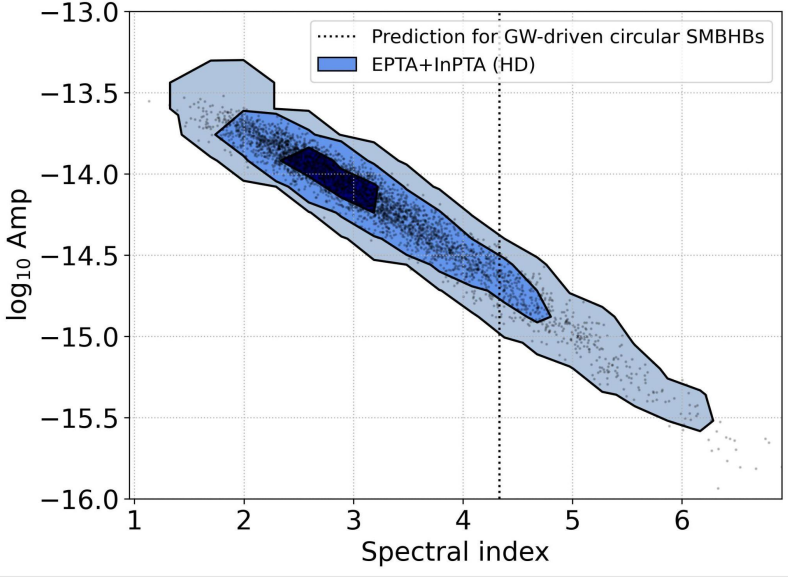




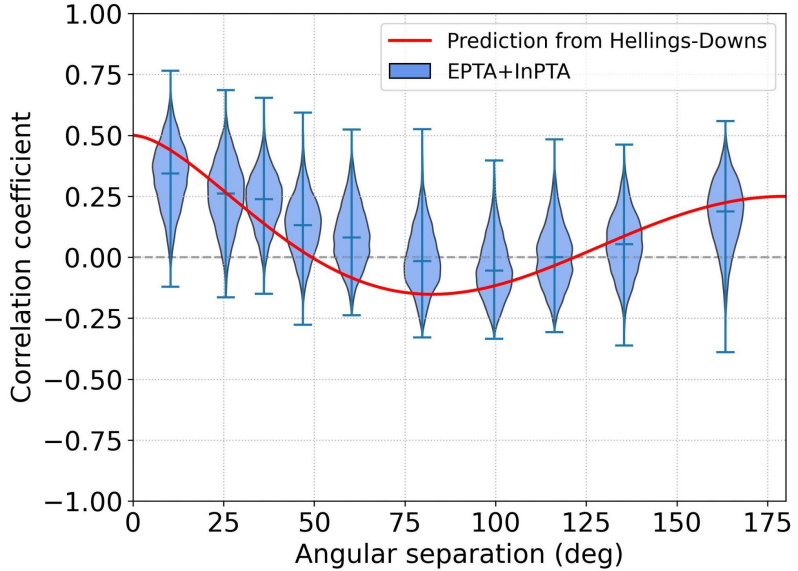
<u>PTAs observe all the nearby population</u> ($z \leqslant$ ~ 1-2)

Results from the European and the Indian PTAs in 2023

Power-law PSD, $S(f) \propto A^2.f^{-\gamma}$



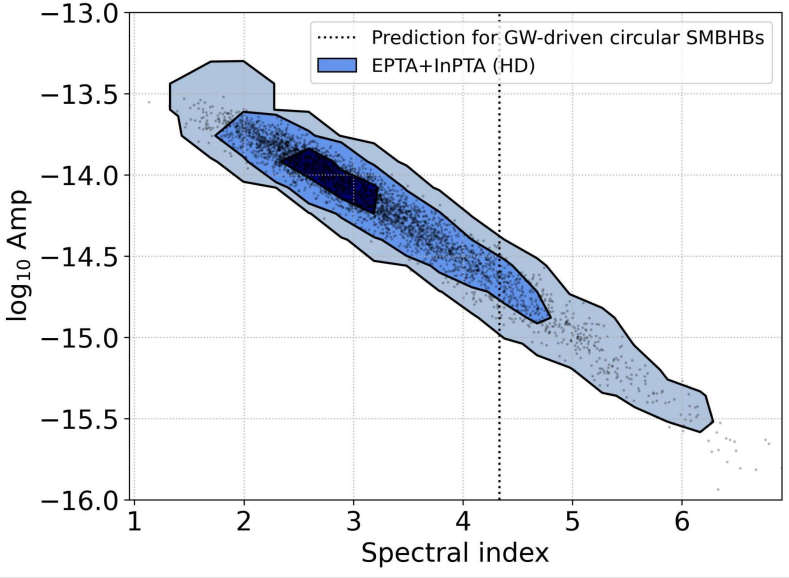
Spatial correlations



EPTA

Results from the European and the Indian PTAs in 2023

Power-law PSD, $S(f) \propto A^2.f^{-\gamma}$



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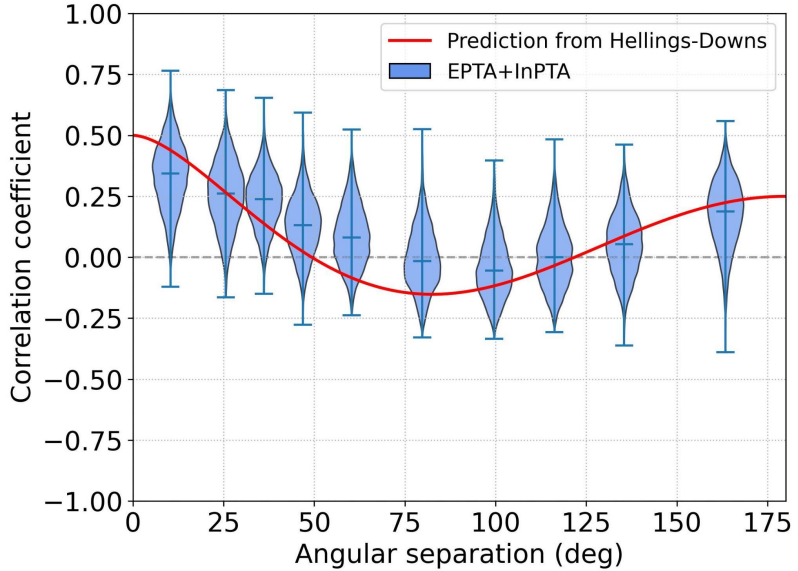


Significance

Bayesian

$$\mathcal{B}^{\mathrm{HD}}_{\mathrm{CURN}} = 65$$

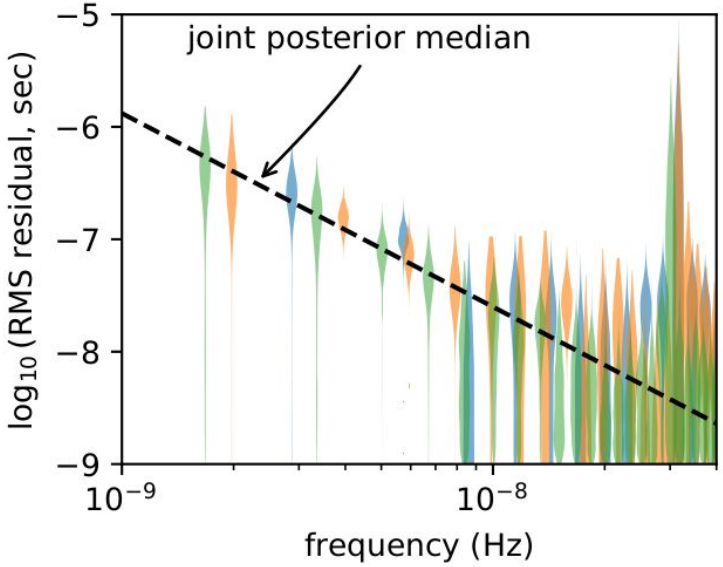
Frequentist

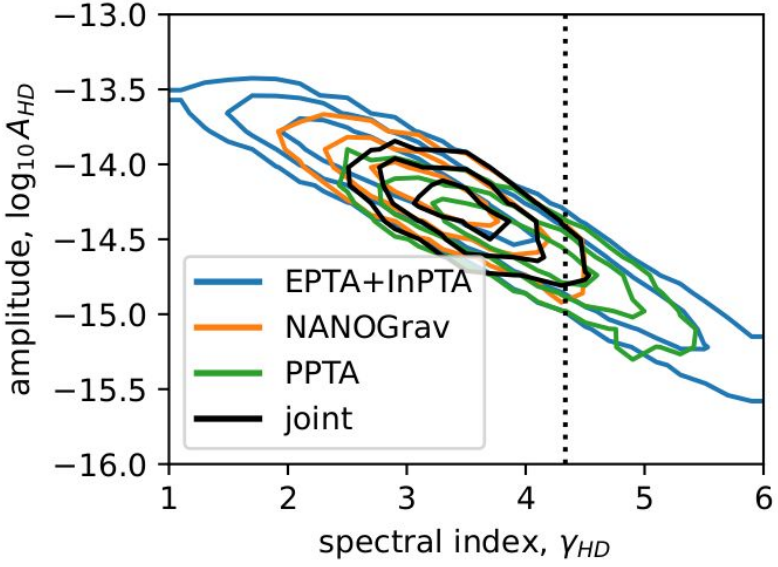
$$\mathrm{S/N}^{\mathrm{HD}} = 4.1^{+2.7}_{-1.7}$$

➡ p-val < 1e-4 ($\geq 3.5\sigma$)

IPTA 2024 - Comparing results against other PTAs

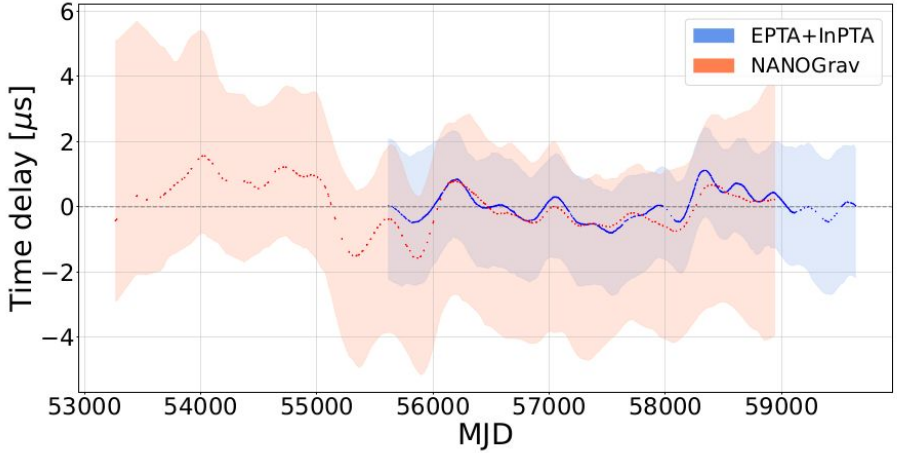
- Agazie et al. 2024 (10.3847/1538-4357/ad36be)
- Perform rigorous checks from published results & re-analyzing data
- Comparing
  - GWB & noise measurements
  - GWB sensitivity
  - Significance for HD correlations
- Forecasting IPTA significance

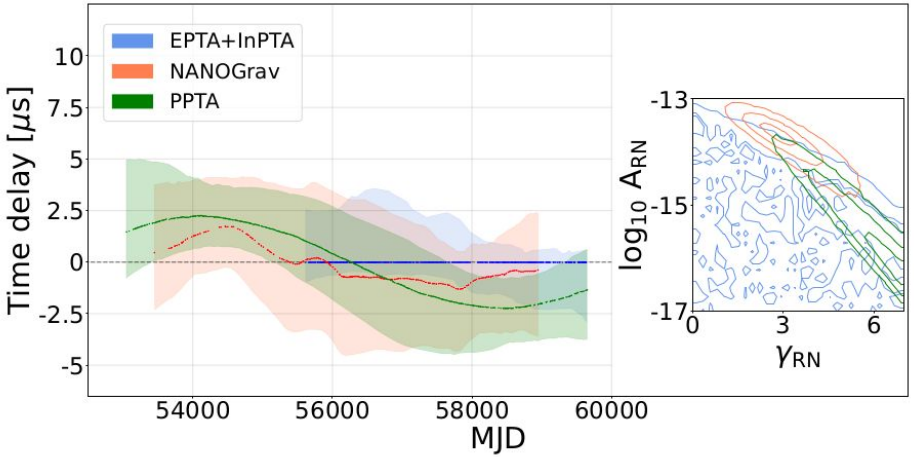




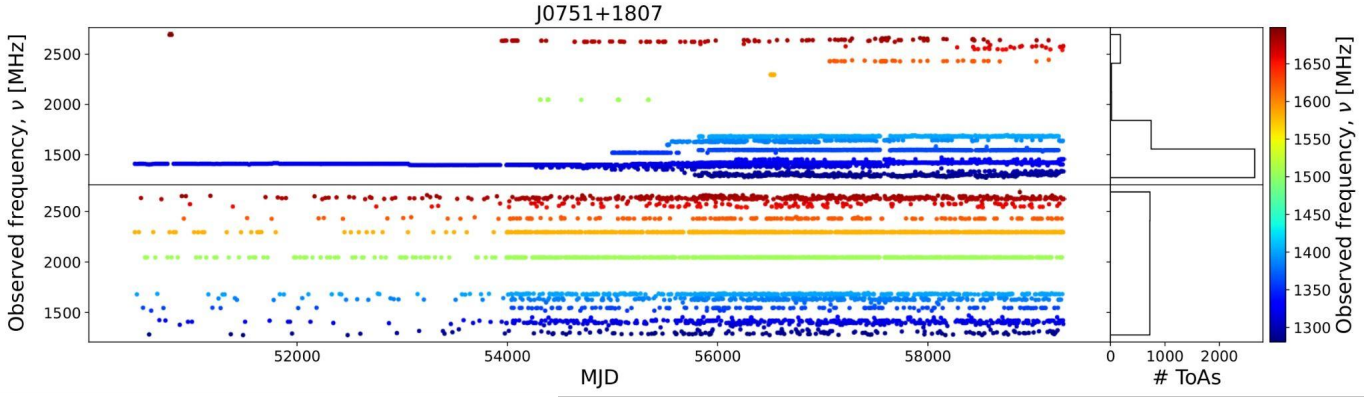
Some slight issues ?

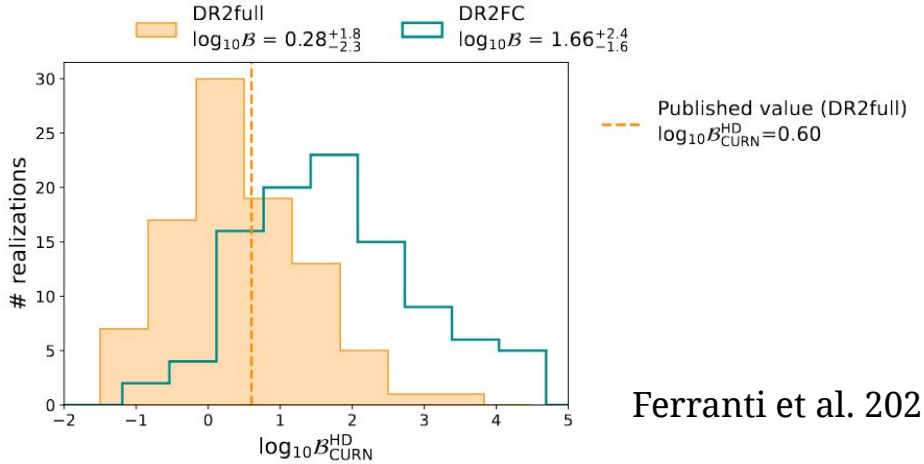
Some interesting cases for the noise properties





More issues ? **Different** results for **different** EPTA data set versions





Ferranti et al. 2025

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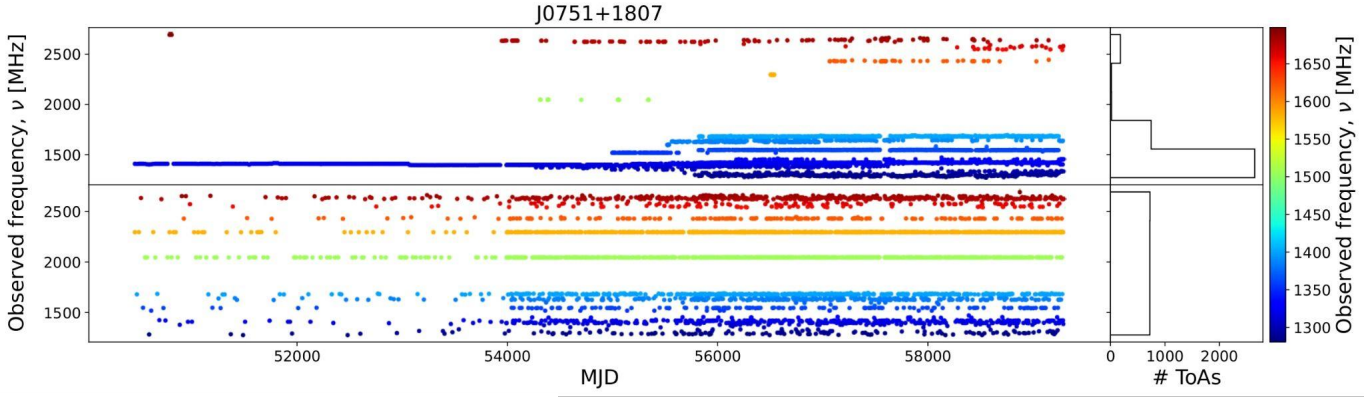
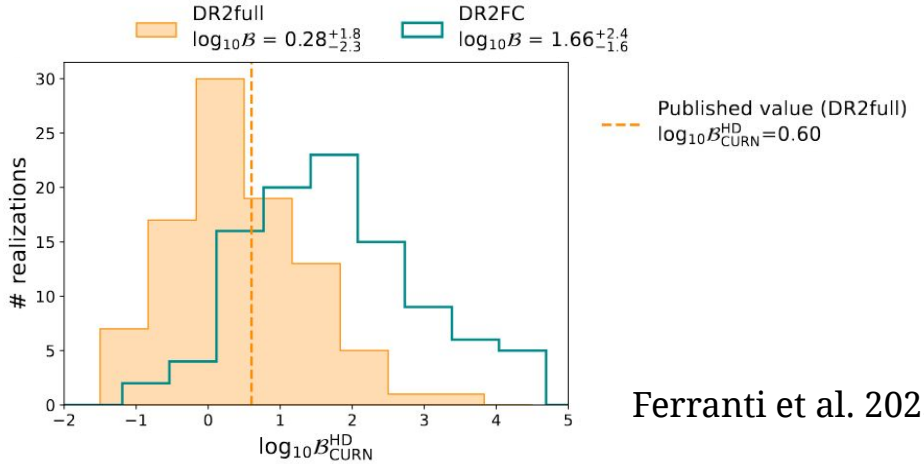
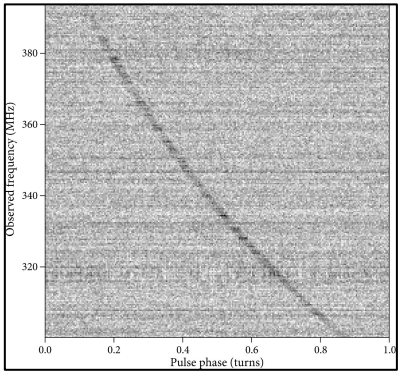


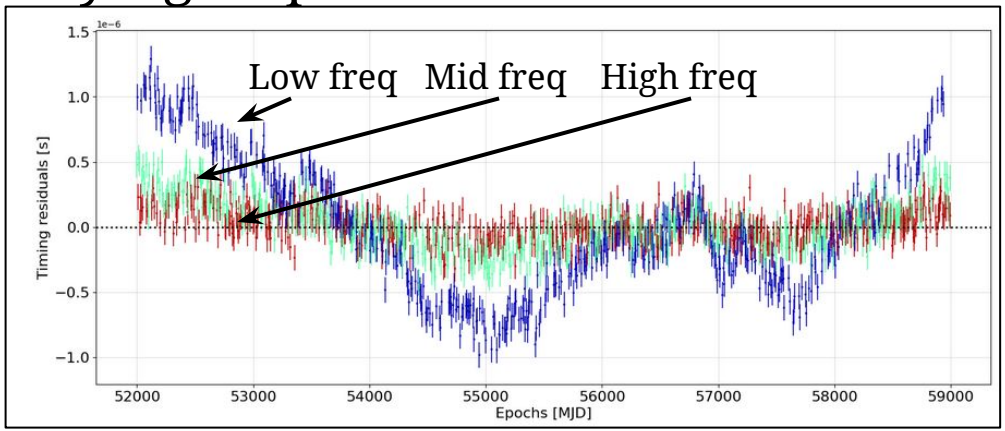


Ferranti et al. 2025

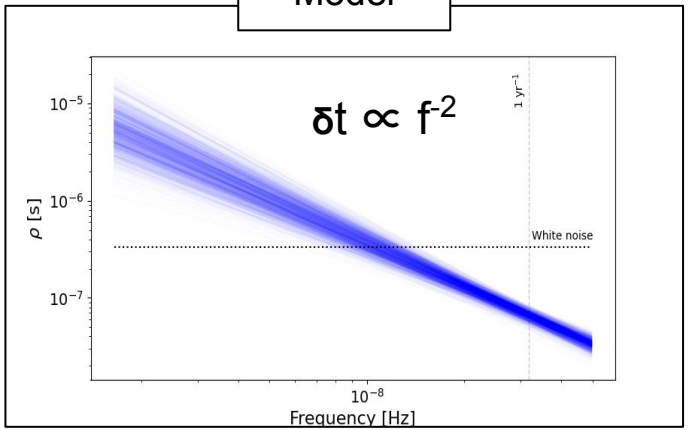
<u>We need to improve the data & noise models !</u>

The time-varying dispersion measure



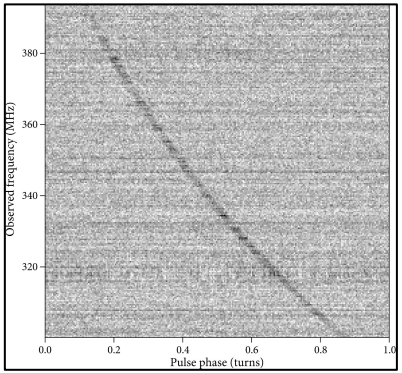


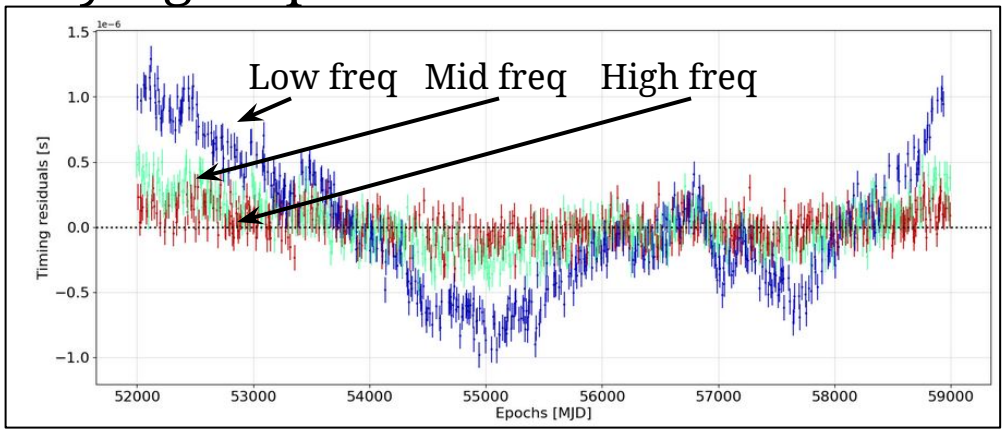
Model



Expected to probe structures of electron density
→**Kolmogorov turbulences**

The time-varying dispersion measure





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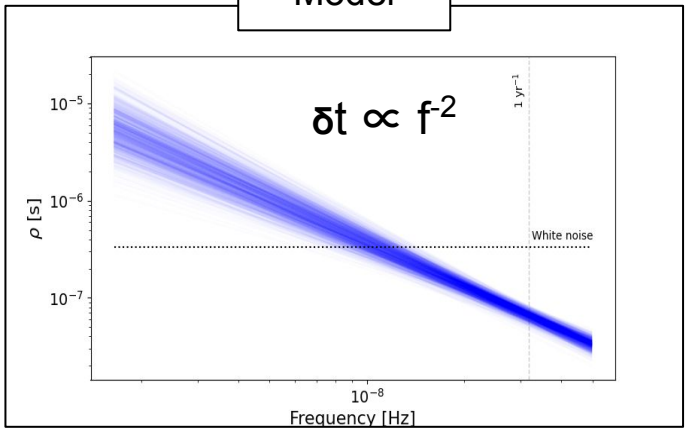


Expected to probe structures of electron density
→**Kolmogorov turbulences**

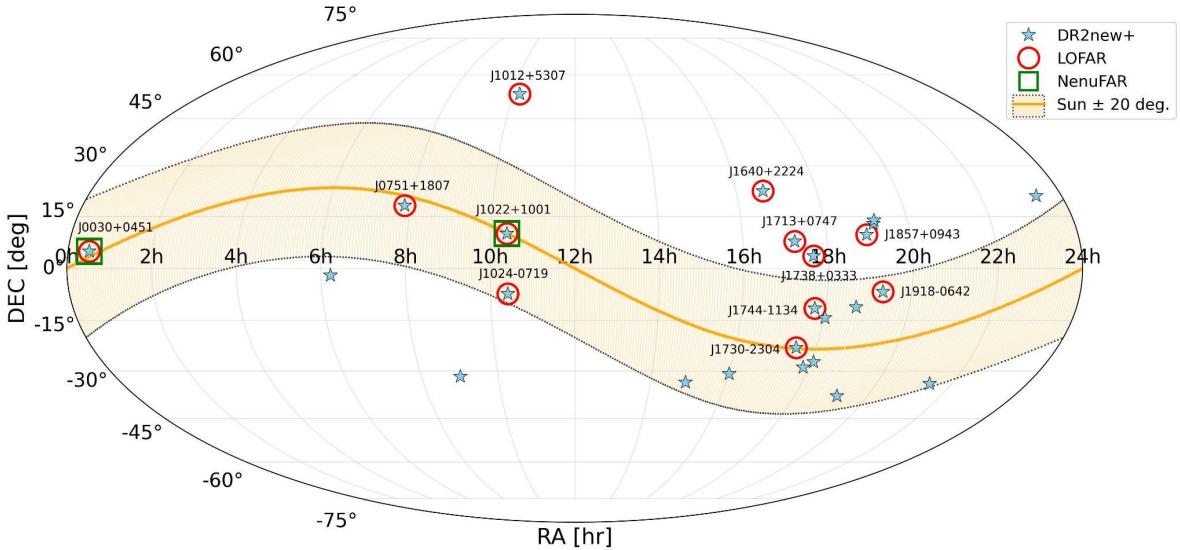
See Selah Melfor's poster for more insights !

We need low-freq. data → LOFAR & NenuFAR !

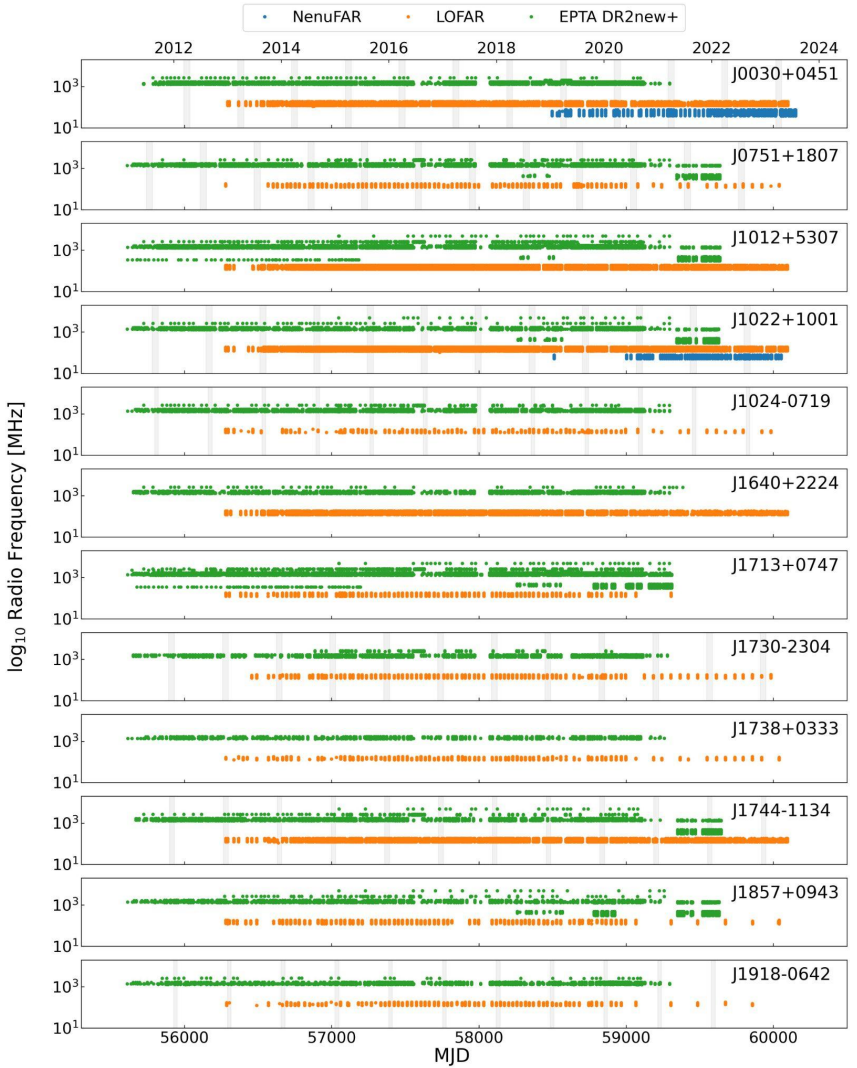
Combine data from EPTA DR2 & LOFAR/NenuFAR

Combining the second data-release of the European Pulsar Timing Array with low-frequency pulsar data

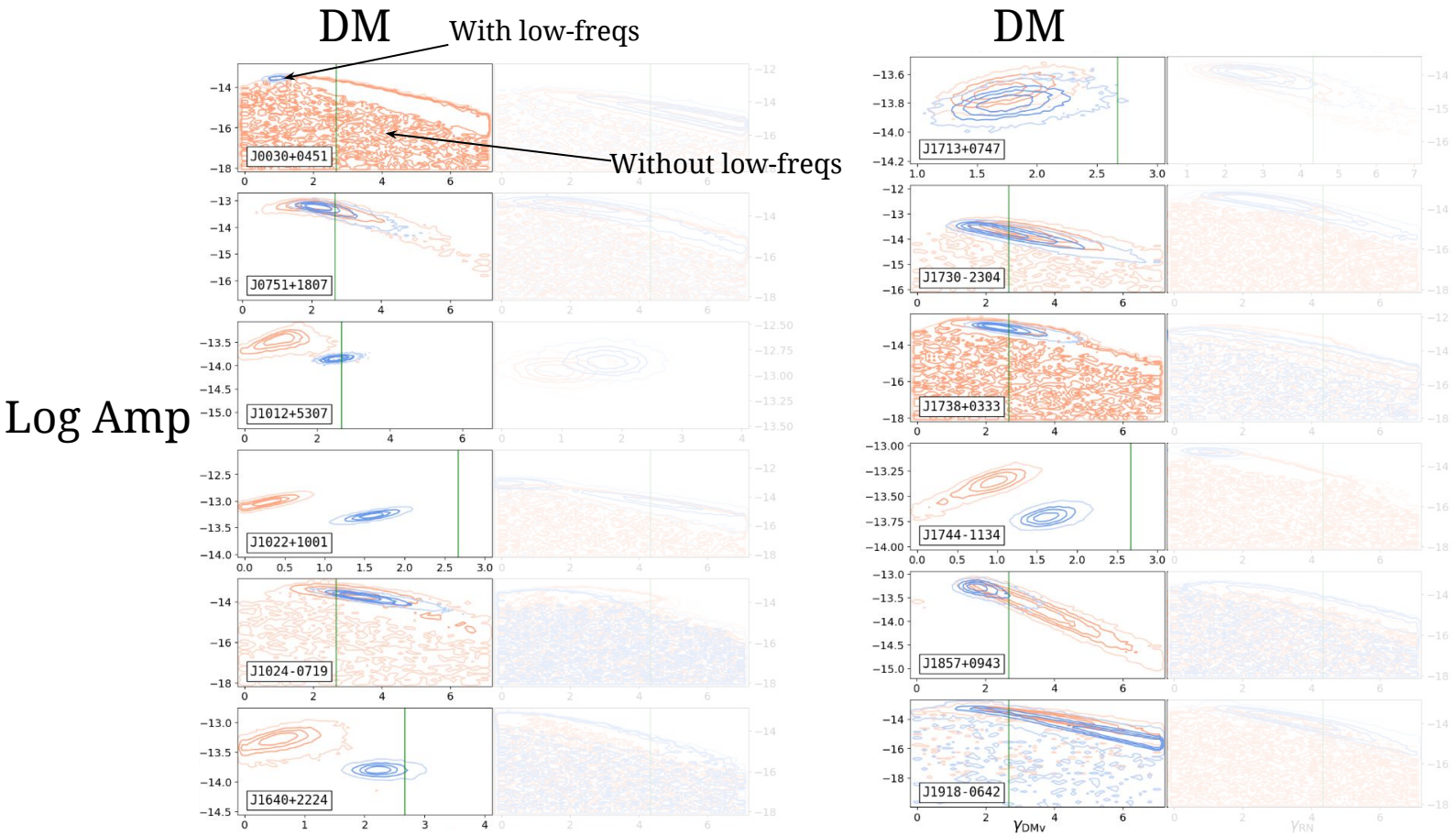
F. Iraci[1,2,⋆], A. Chalumeau[3,⋆⋆], C. Tiburzi[2], J. P. W. Verbiest[4], A. Possenti[2], S. C. Susarla[5], M. A. Krishnakumar[6], G. M. Shaifullah[7,8], and friends



Combined data
EPTA DR2 / InPTA DR1
+
LOFAR & NenuFAR

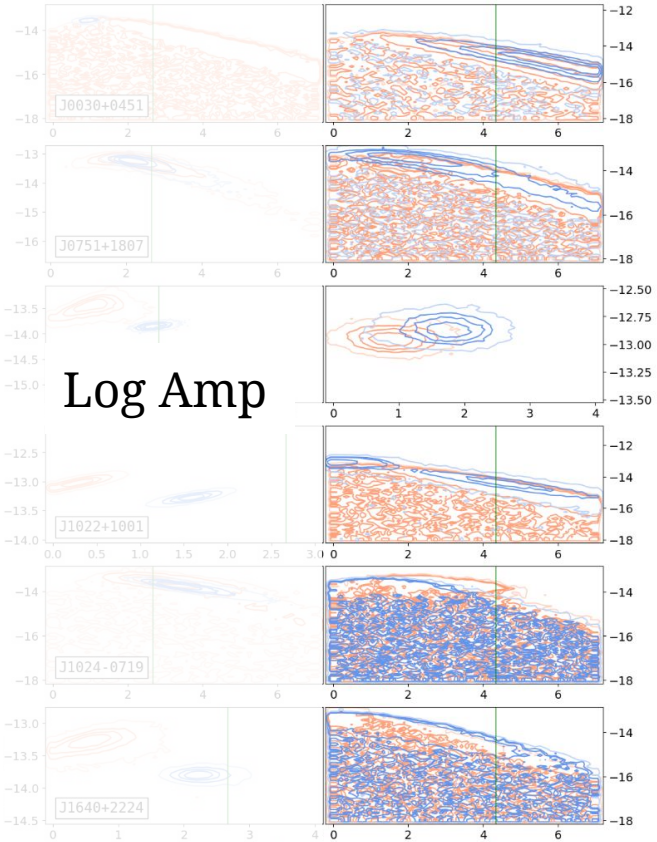


Results - DM variations



Results - Red noise

RN



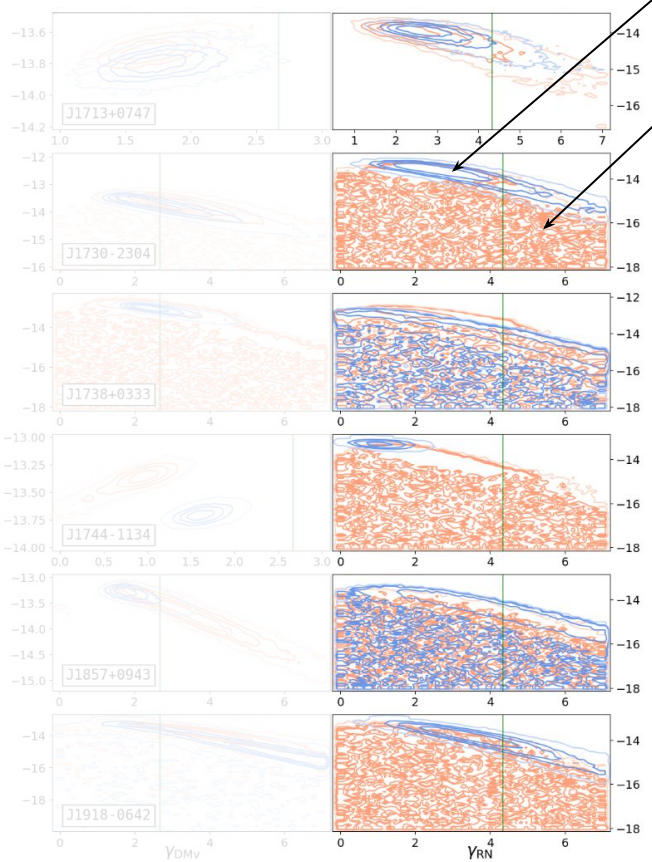
Log Amp

Spec. Idx

RN

With low-freqs

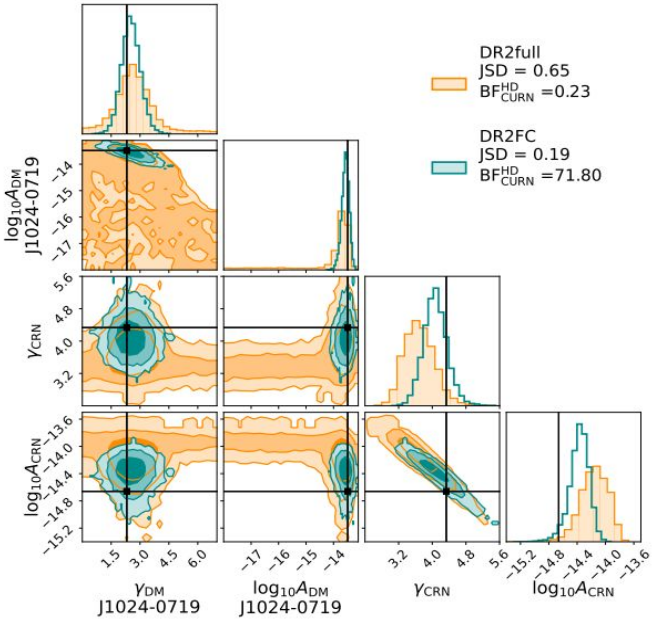
Without low-freqs



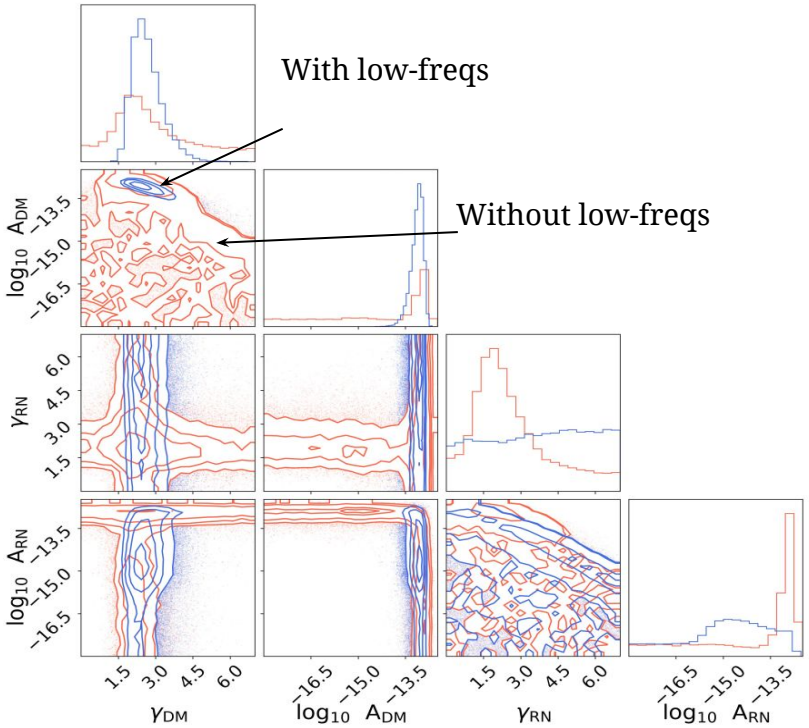
Spec. Idx

Results - RN vs. DMv

Ferranti et al. 2025 (simulations)



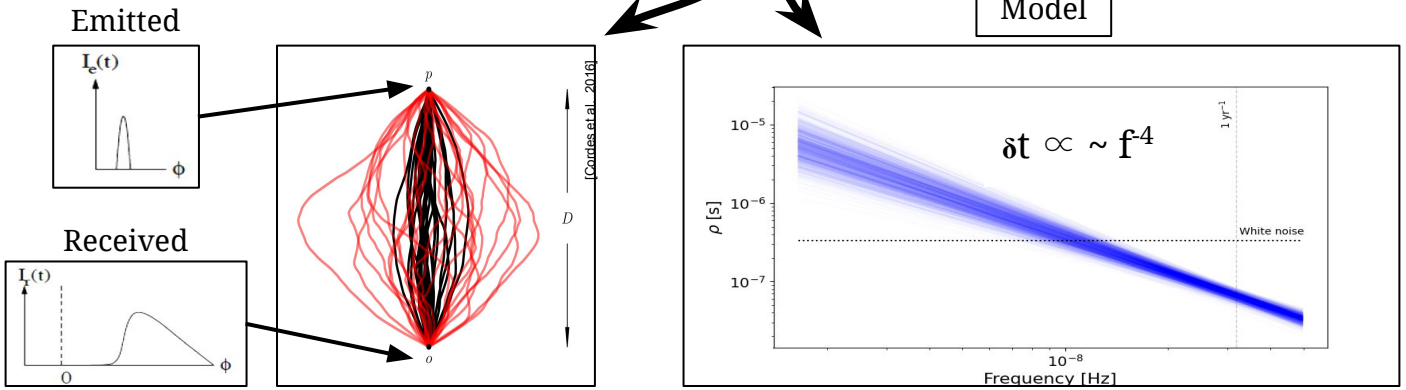
PSR J1738+0333



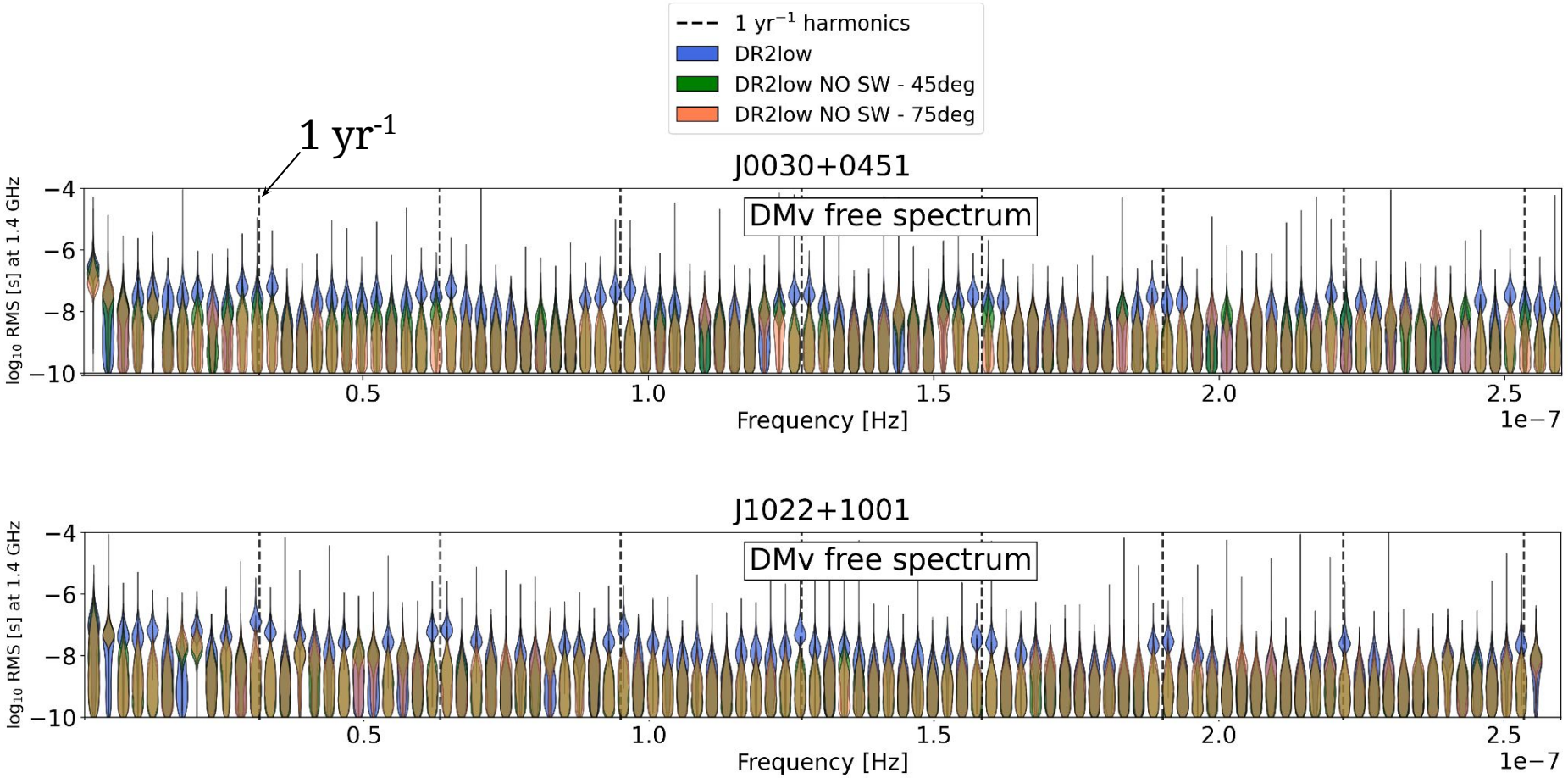
Results - Model selection between chosen components

Pulsar	EPTA+InPTA+LOFAR+NenuFAR			EPTA+InPTA		
J0030+0451	RN13	DMv100	$CN_4$77	RN10	X	X
J0751+1807	X	DMv92	$CN_4$38	X	DMv50	X
J1012+5307	RN87	DMv20	$CN_4$100	RN100	DMv47	X
J1022+1001	RN98	DMv99	$CN_4$99	RN30	DMv100	X
J1024−0719	X	DMv18	X	X	DMv15	X
J1640+2224	RN54	DMv40	$CN_4$40	X	DMv47	X
J1713+0747	RN73	DMv74	$CN_4$12	RN73	DMv72	X
J1730−2304	RN18	DMv52	X	X	DMv11	X
J1738+0333	RN29	DMv28	X	X	DMv24	X
J1744−1134	RN22	DMv100	$CN_4$31	RN19	DMv98	X
J1857+0943	RN87	DMv99	X	X	DMv92	X
J1918−0642	RN36	DMv24	$CN_4$42	X	DMv75	X

Model



Results - Solar winds



Conclusions & Prospects

- LOFAR & NenuFAR allowed to significantly improve the characterization of noise in the EPTA/InPTA data
- But it also reveals some limitations in the current models

- Work in progress…
  - to apply advanced SW models
  - to better understand IISM properties with simulations (**see Ruggero Valdata's poster !**)
  - to better understand IISM properties with real data (**see Selah Melfor's poster !**)

- The upcoming IPTA DR3 will include LOFAR, NenuFAR & CHIME data to also improve the robustness of the GW measurements

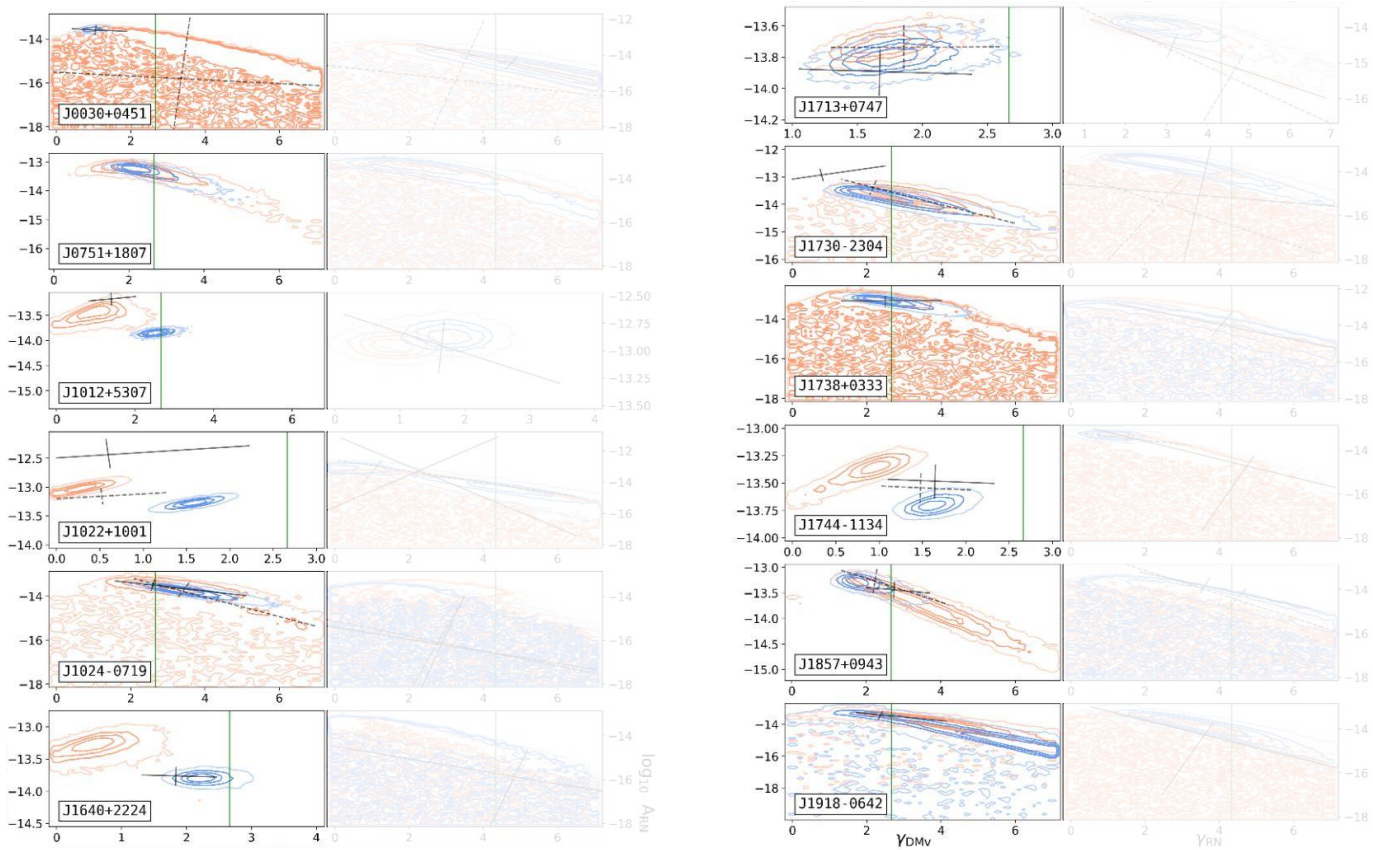
Thank you !

Results - DM variations

DM

DM

Log Amp



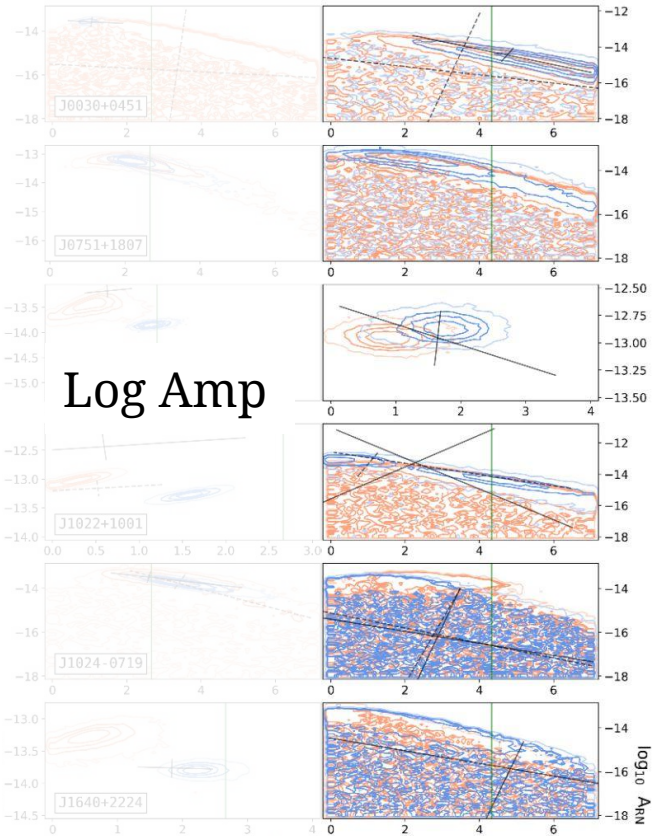
Spec. Idx

Spec. Idx

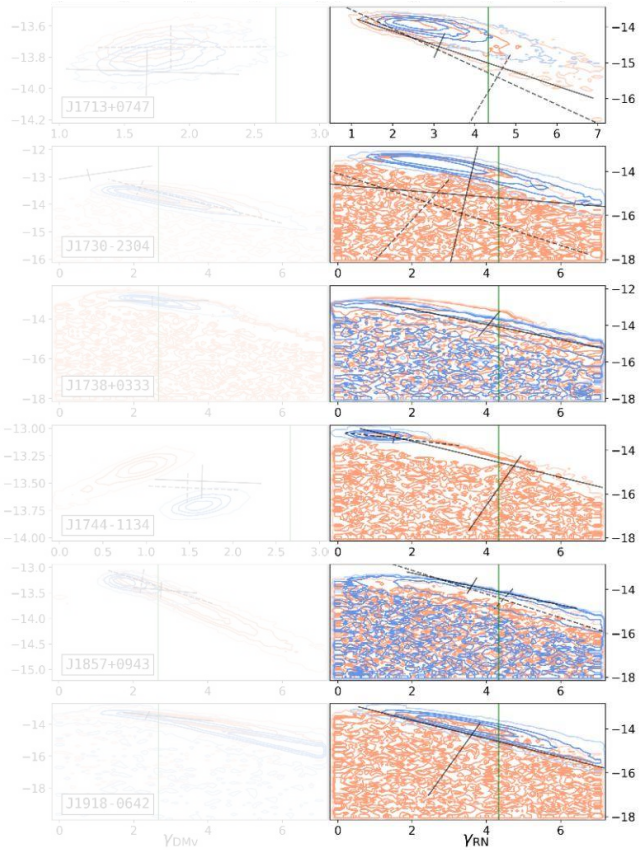
Results - Red noise

RN

RN



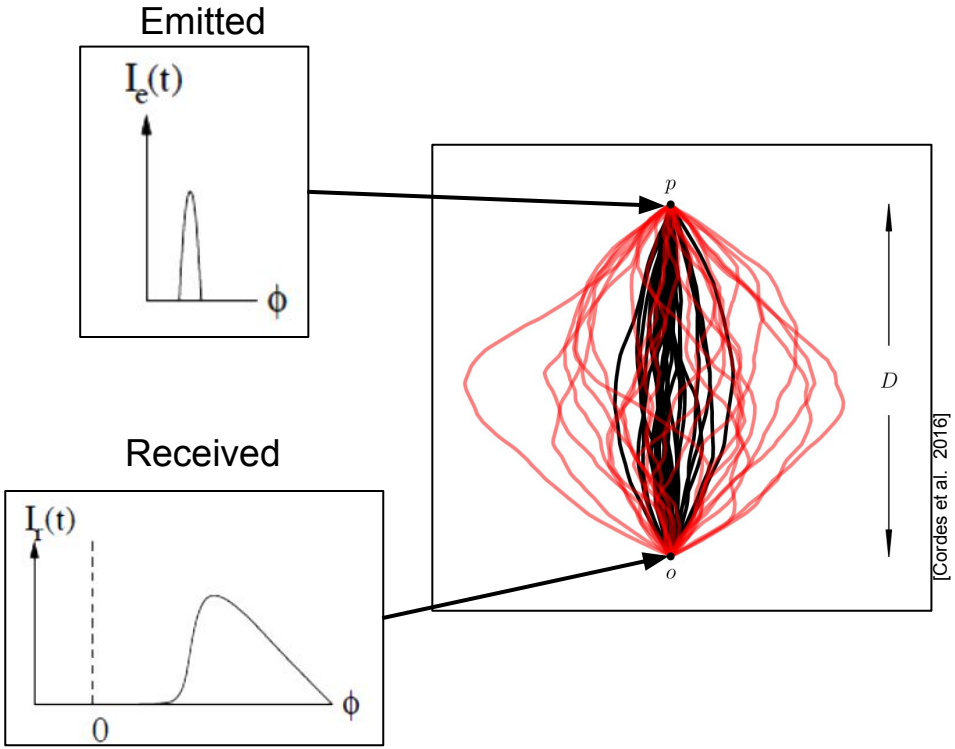
Log Amp

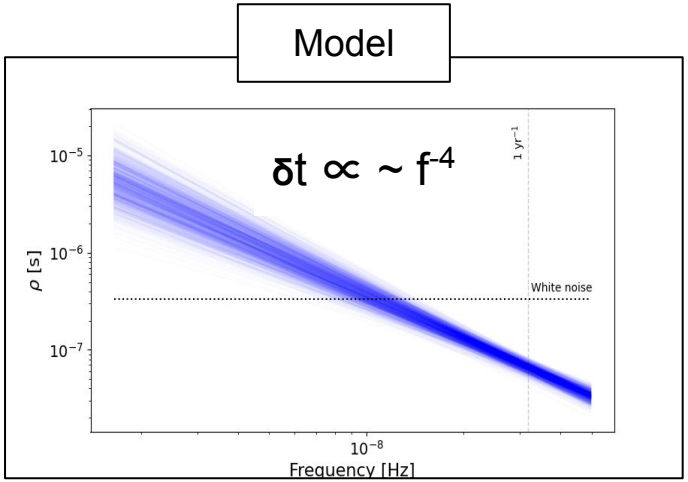


Spec. Idx

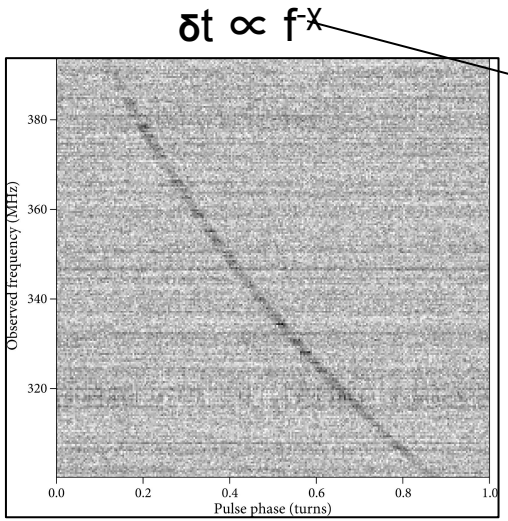
Spec. Idx

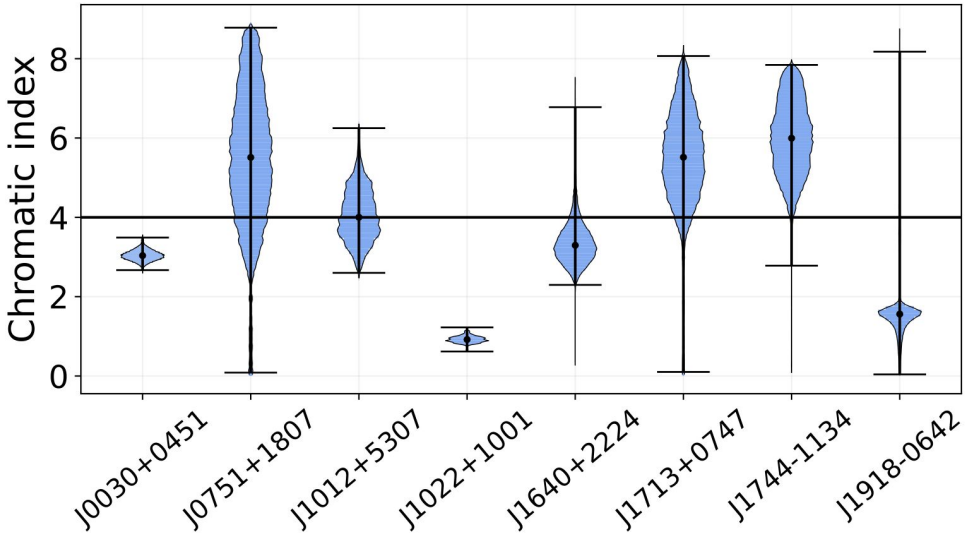
Building the noise model - The time-varying scattering delays (secondary effect)



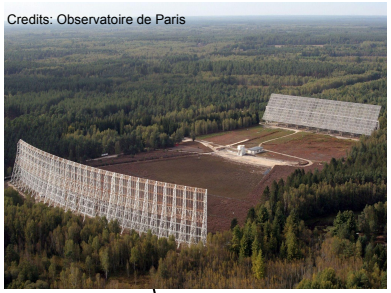


Results - Scattering variations ?



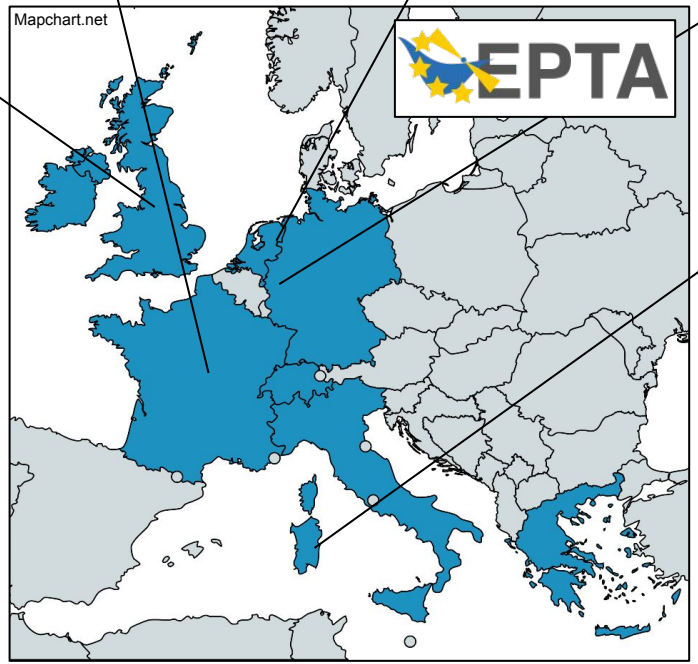


The European Pulsar Timing Array (EPTA)



Member institutes in

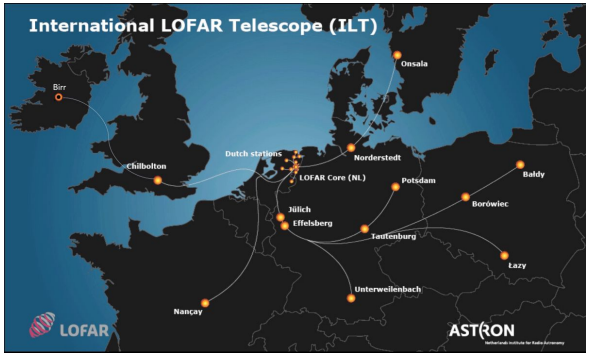
- China
- France
- Germany
- Greece
- Ireland
- Italy
- Netherlands
- Switzerland
- UK



\+

\+ NenuFAR &

Credits: Hannah Currivan - I-LOFAR

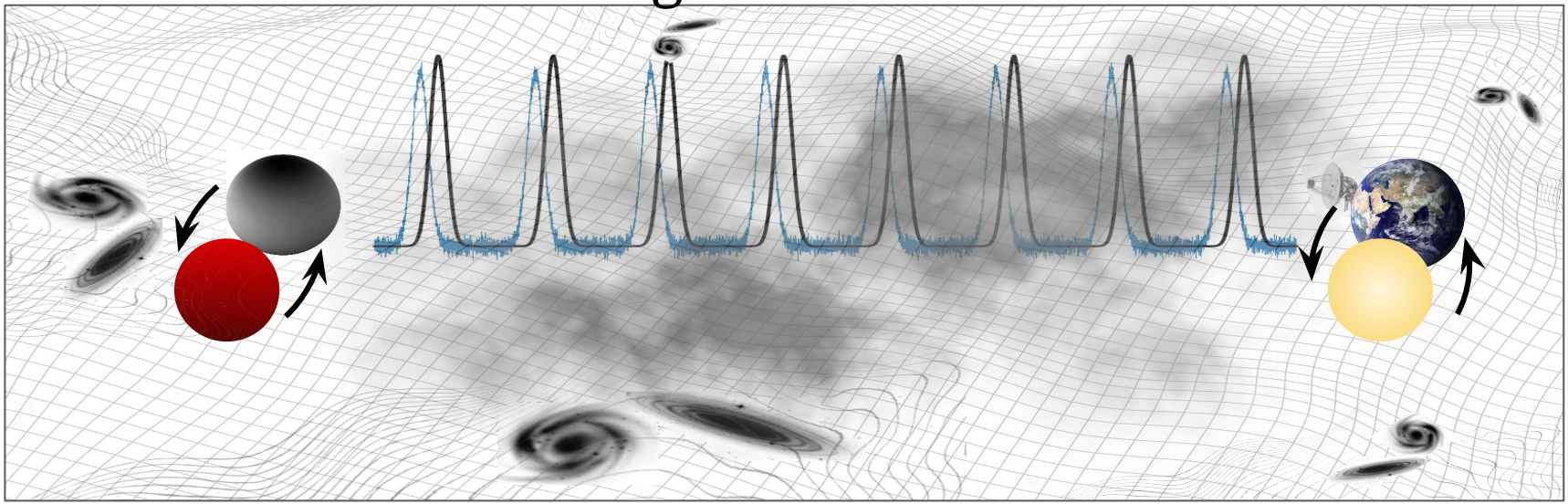


The International Pulsar Timing Array(s)

+ LEAP/LOFAR/NenuFAR

NANOGrav EPTA APT InPTA Indian Pulsar Timing Array CPTA PPTA

Pulsar Timing data with GWs + noise



Spin noise ?

Unmodelled objects ?

Time-varying dispersion from the IISM ?

Time-varying scattering from the IISM ?

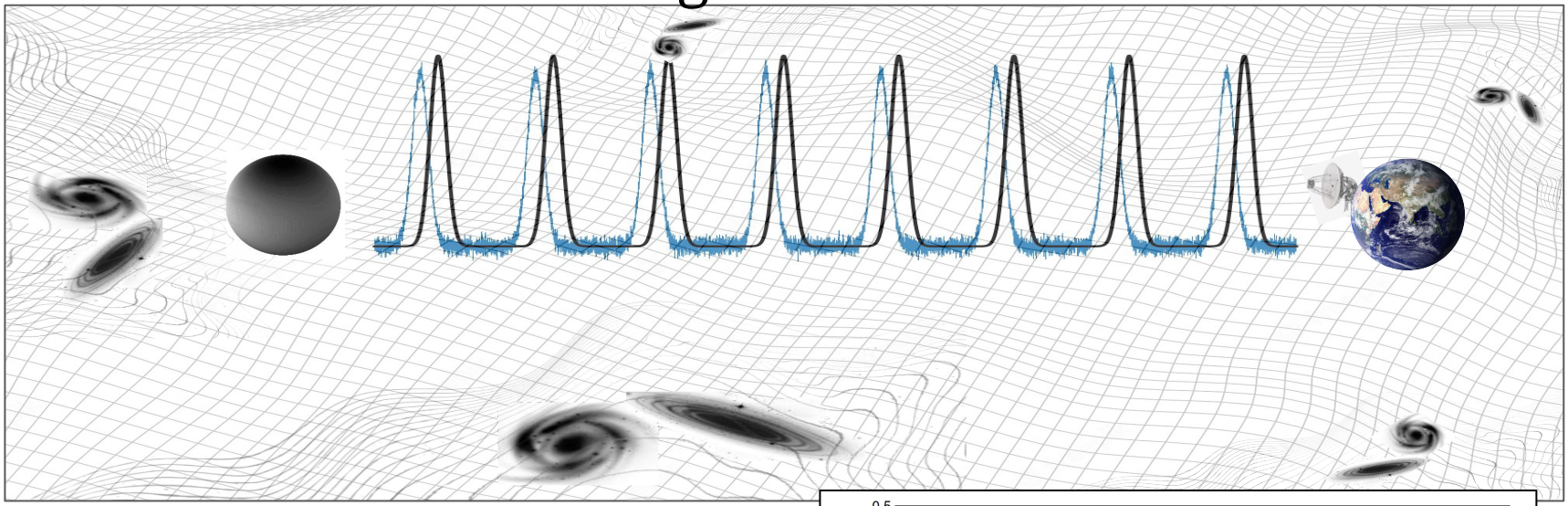
Time-varying dispersion from the Solar winds ?

Errors in the solar system barycenter position ?

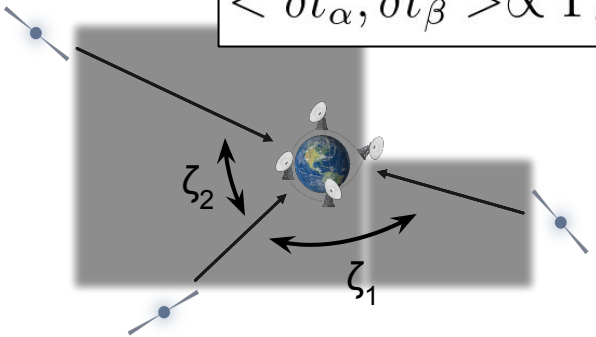
… ?

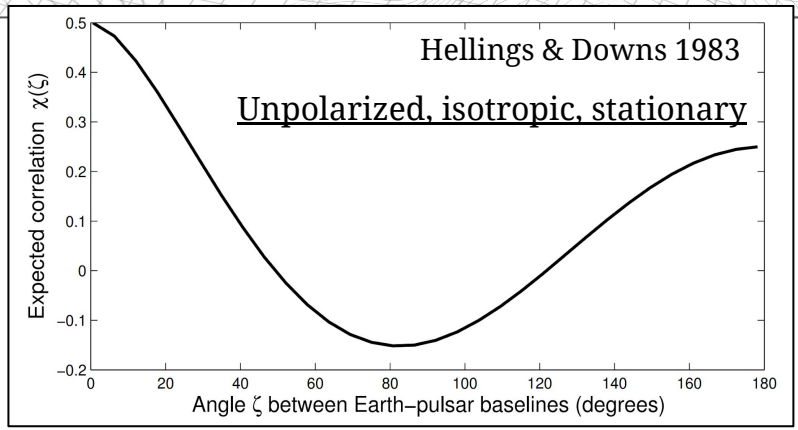
Stochastic GWB + deterministic signals ?

Constraining the GWB with PTAs



$$< \delta\vec{t}_\alpha, \delta\vec{t}_\beta > \propto \Gamma_{\alpha\beta}(\zeta_{\alpha\beta})$$

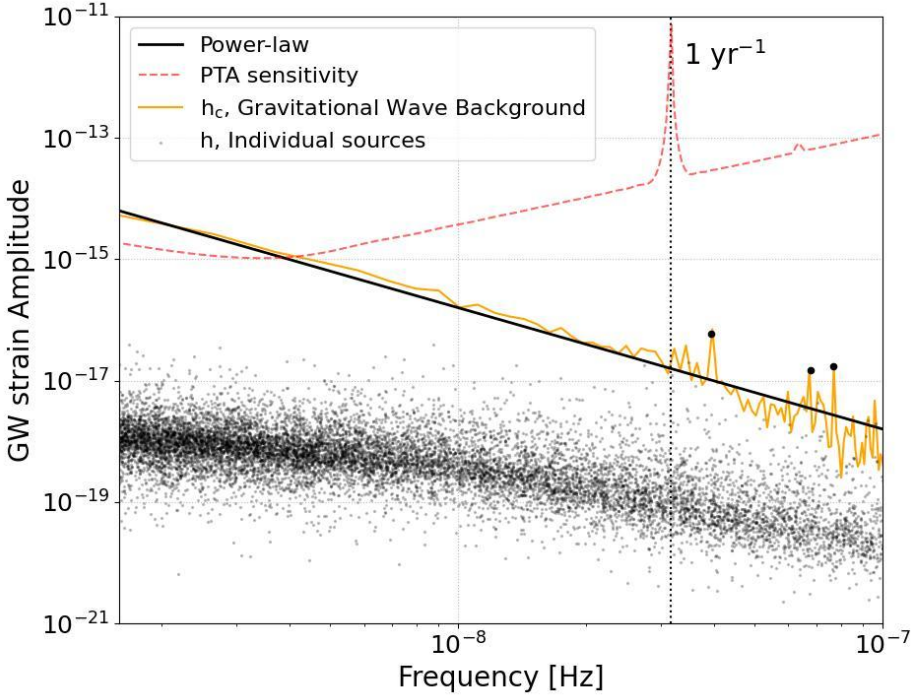




The SMBHB signal in the PTA band

From a large population of SMBHBs, two main types of signals:

- **The Gravitational Wave Background (GWB)**
- **The Continuous Gravitational Waves (CGWs)**



For a GW-driven population of circular SMBHBs:

$$h_c^{\mathrm{GWB}} \propto f^{-2/3}$$ Phinney 2001

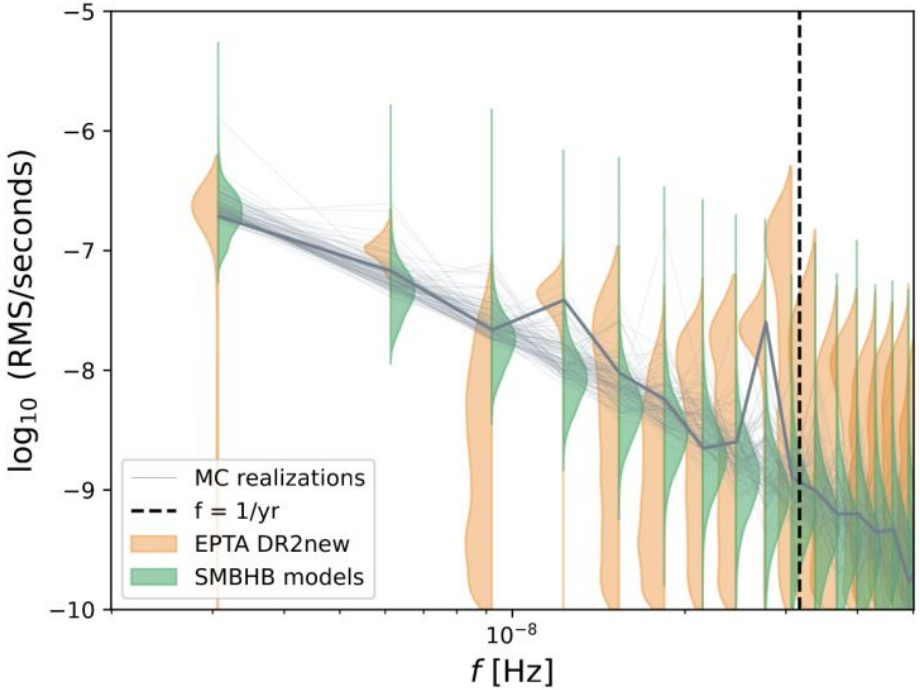
In the strong-signal regime, sensitivity towards GWB scales as

$$\mathrm{S/N}^{\mathrm{PTA}} \propto N_{psr}\sqrt{T}\left(\sqrt{c \times \Delta f_{\mathrm{rad}}}\right)^{1/\gamma}$$ Siemens et al. 2013 + Lorimer & Kramer 2004

Results from the European and the Indian PTAs in 2023

"Free-spectrum": Estimation of the PSD at each frequency bin

$S(f) = \rho(f)$

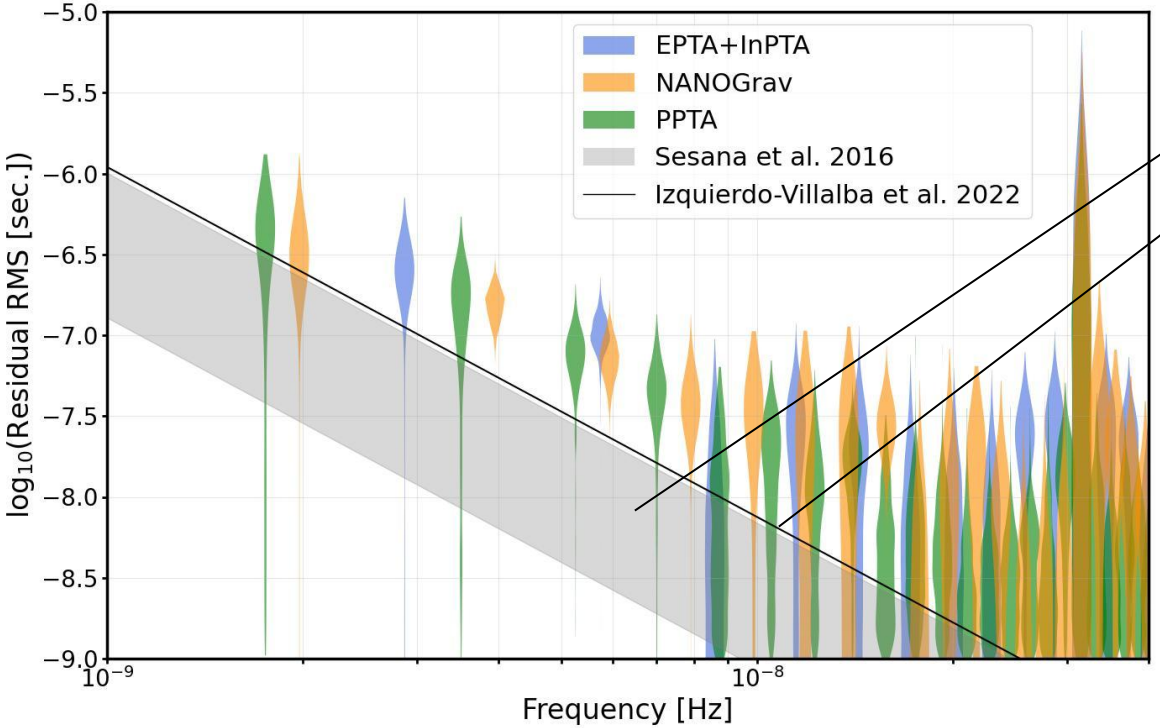


- Only **few frequency bins** are **well constrained**
- Excess of **power** at **low frequencies**

- Consistency with empirical SMBHB models

Current challenges for PTAs

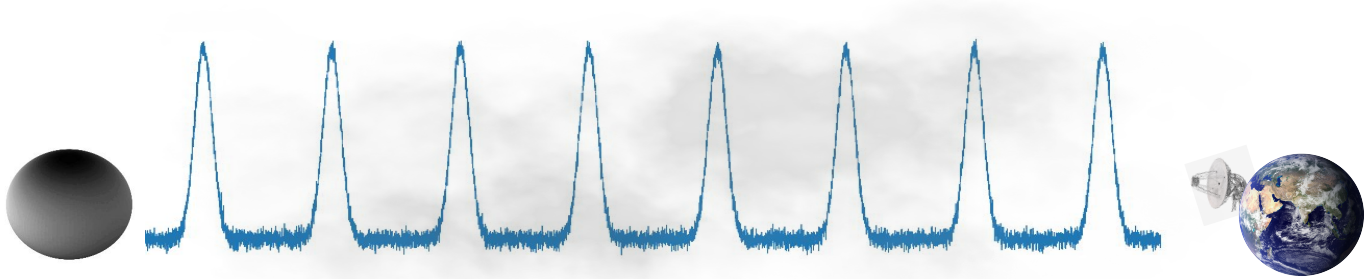
Some crucial points to understand: **Measurement vs. expectations ?**



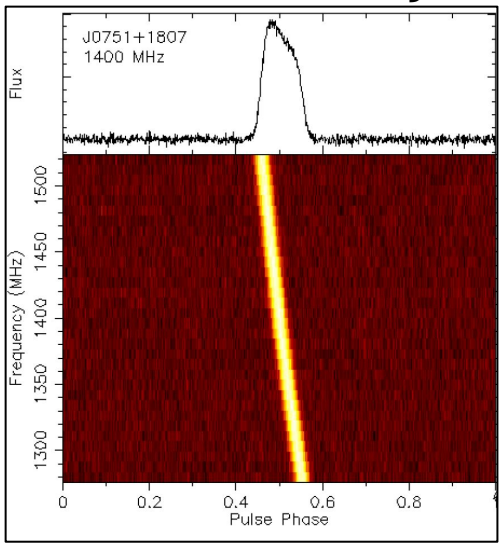
- **Measurements higher than predictions !**
- **Agreement could be obtained, after boosting gas accretion…**

… but such modification induces mismatch against key observational constraints
(e.g., quasar bolometric luminosity functions or the local black hole mass function)

Pulsar radio signal



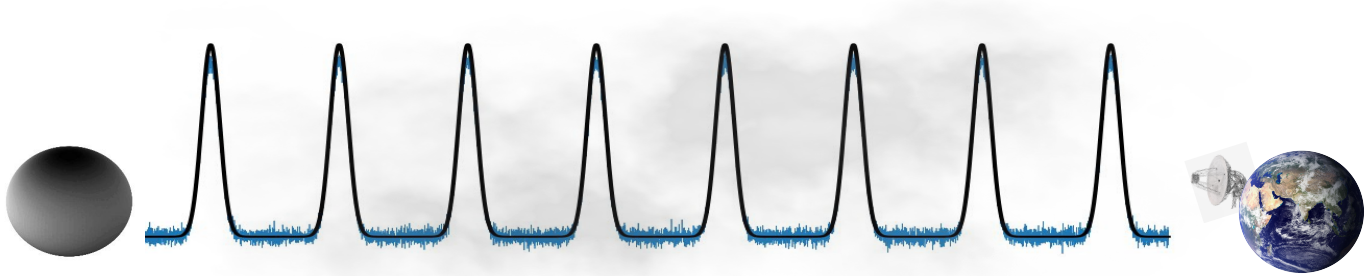
MSPs look very stable, but some effects impact the observed regularity…



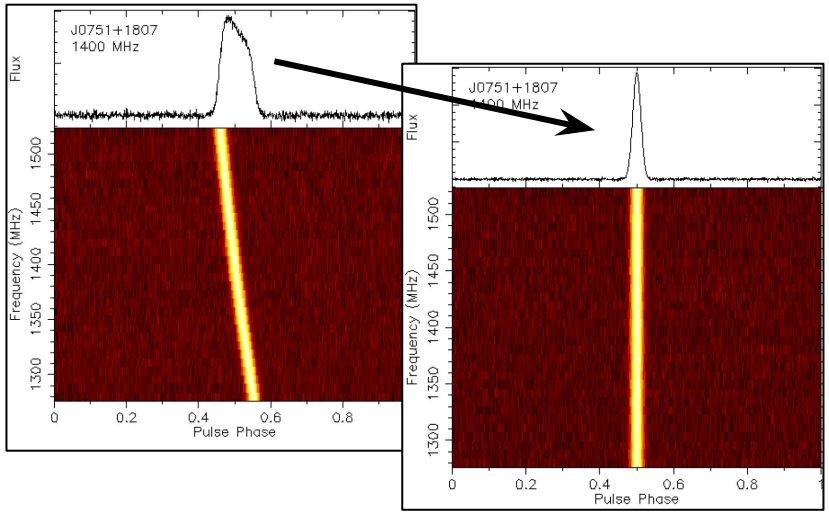
… e.g., dispersion from the interstellar medium

$$\delta t \propto 1 / \nu^2$$

Pulsar Timing data



Pulsar timing => fit a timing model to predict **times of arrival**, minimizing the **timing residuals**



Timing residuals = ToA_{obs} - ToA_{pred}