On the road to the detection and interpretation of the nano-Hertz Gravitational Waves with Pulsar Timing Arrays (?)

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ASTRON, *the Netherlands Institute for Radio Astronomy*

On behalf of…

EPTA

INTERNATIONAL PULSAR TIMING ARRAY

8ème Assemblée Générale du GdR Ondes Gravitationnelles
Marseille - 15 Oct 2024

Link to Gslides

GIGA Advancing Gravitational Wave Astrophysics

erc European Research Council

ASTRON Netherlands Institute for Radio Astronomy

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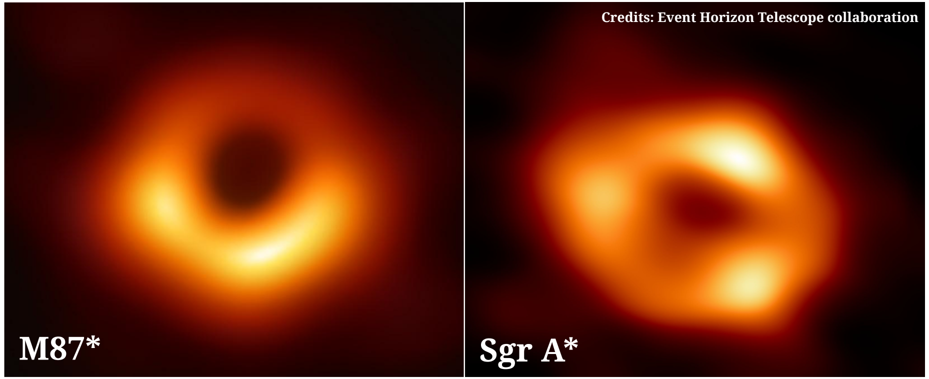
Key concepts - The Supermassive Black Hole Binaries (SMBHBs)



(Super)massive black holes:

- M ~ 10^6 - 10^{10} $M_\odot$
- Thought to be present in the center of all massive galaxies
- Among them, binary systems might emit GWs

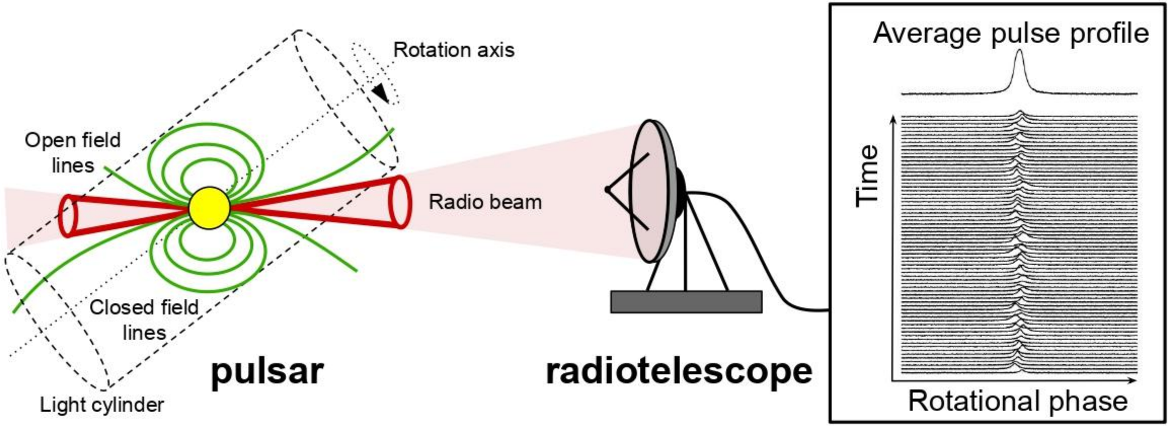
SMBHBs at the GW-emission stage are formed after

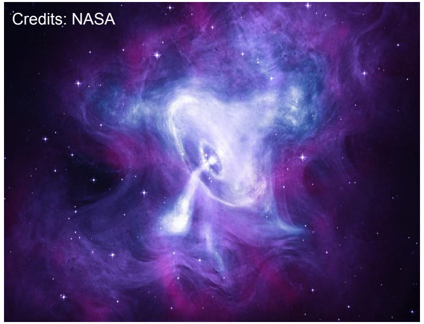
- The merger of their host galaxies
- Their sink to the centre of the remnant galaxy until the sub-parsec scales
    - Dynamical friction to parsec scales & (hydro)dynamical interaction with the dense background of stars and gas

They are expected to be the loudest sources of GWs at sub-microhertz frequencies !

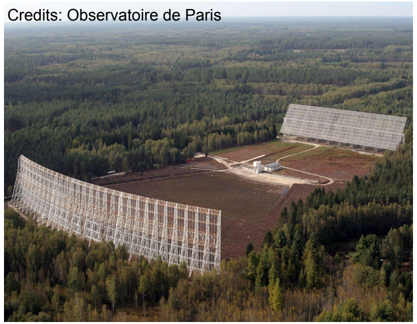
Key concepts - Pulsars

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

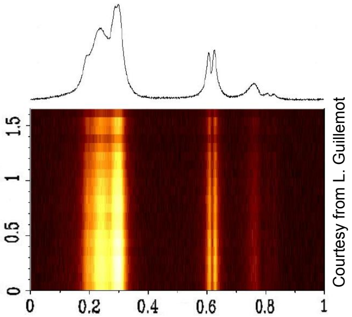




Crab pulsar in X-ray, Optical & IR



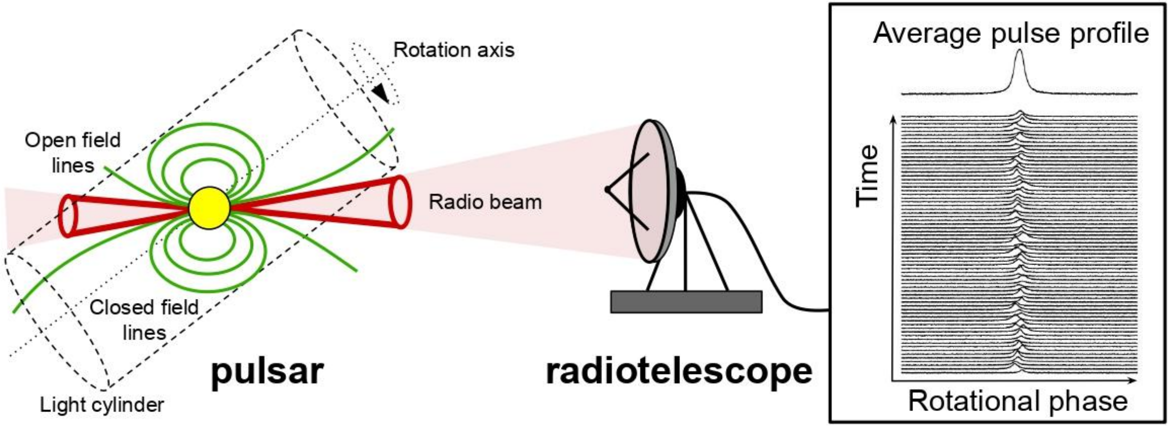
Nançay Radio Telescope (NRT)



Real Obs. from the NRT

Key concepts - Pulsars

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

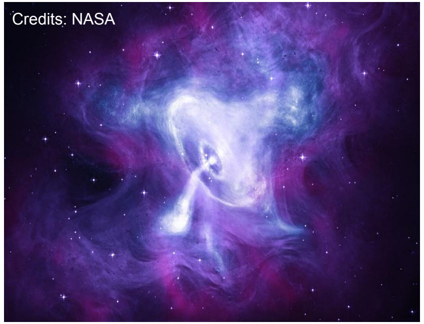


Important facts

- Millisecond pulsars have the most stable spinning frequency
  $\dot{P} \sim 10^{-20}$ s.s^{-1}, or ~ 10^{-12} s/10yr

- More than 600 MSPs known today

→ *With precise timing, we could use them as cosmic clocks to probe for GWs !*



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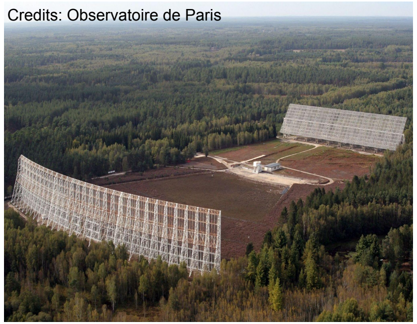

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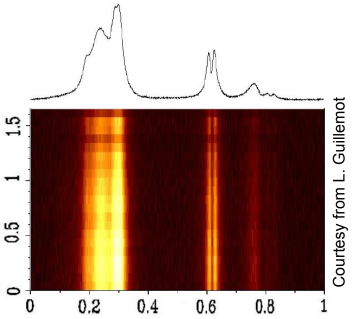
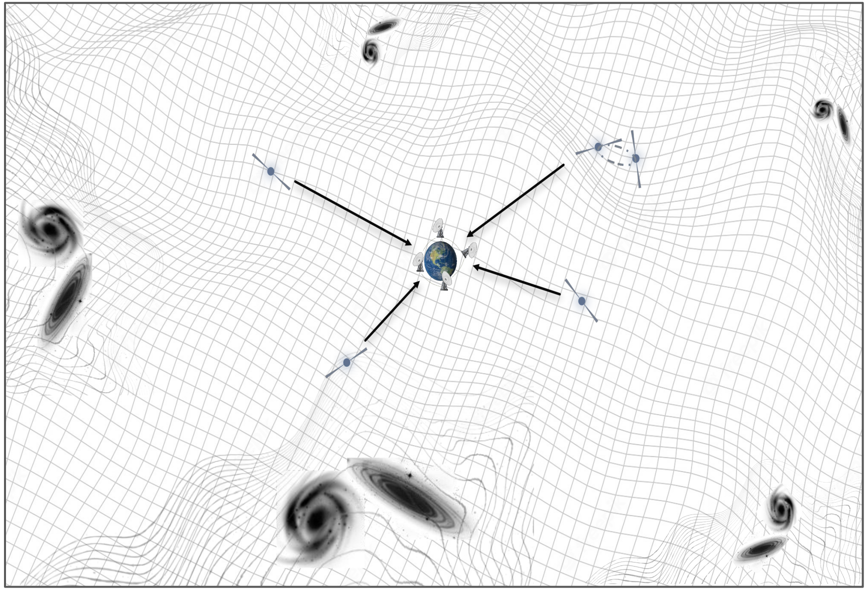


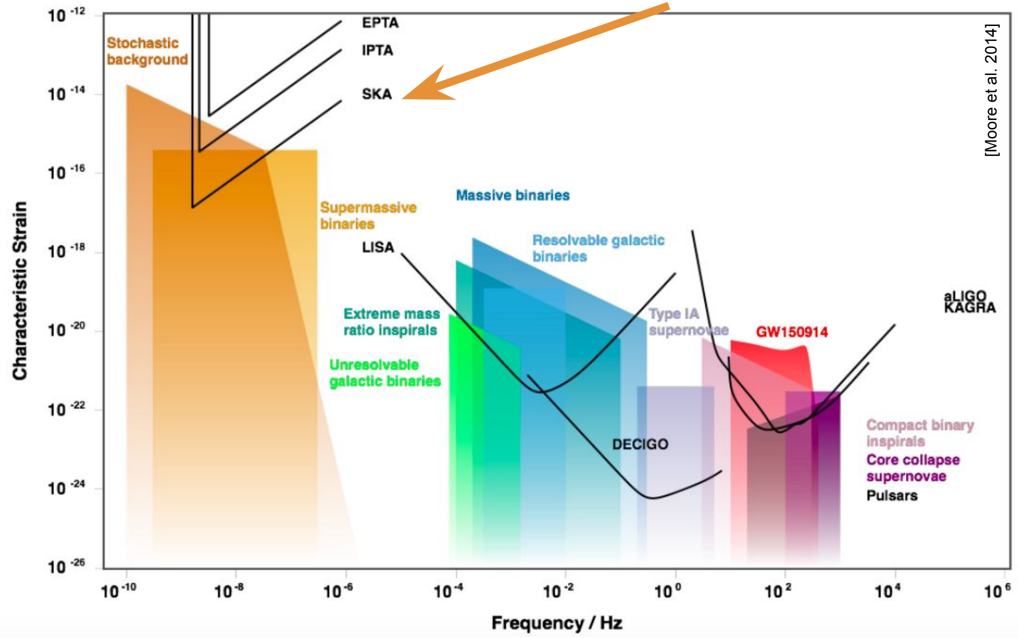
Real Obs. from the NRT

Pulsar Timing Arrays (PTAs) in a nutshell

A galactic-scale gravitational wave detector



probing at the **very-low frequencies**



The SMBHB signal in the PTA band

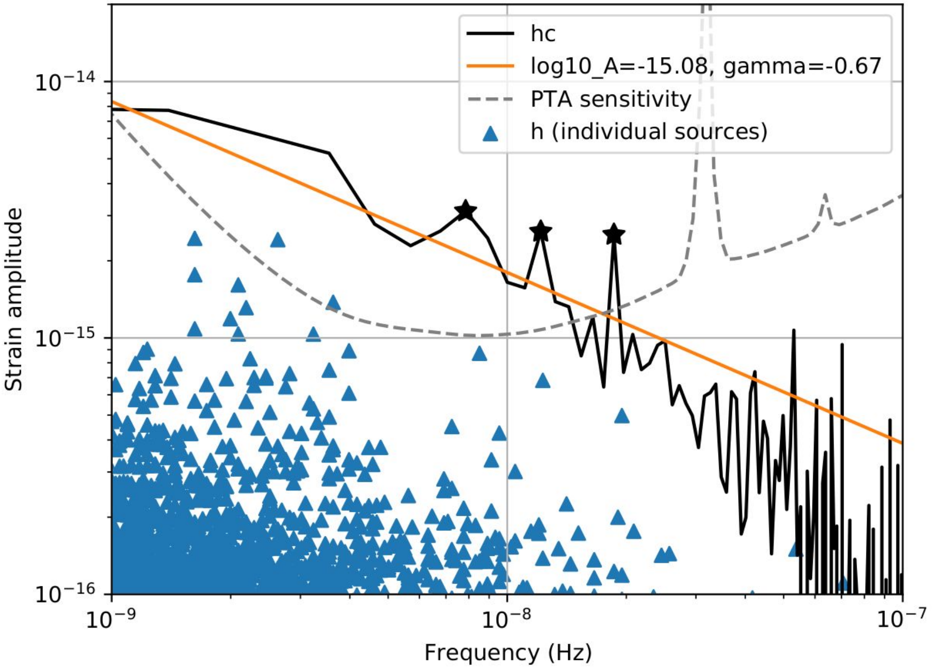
From a large population of SMBHBs, two main types of signals:

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

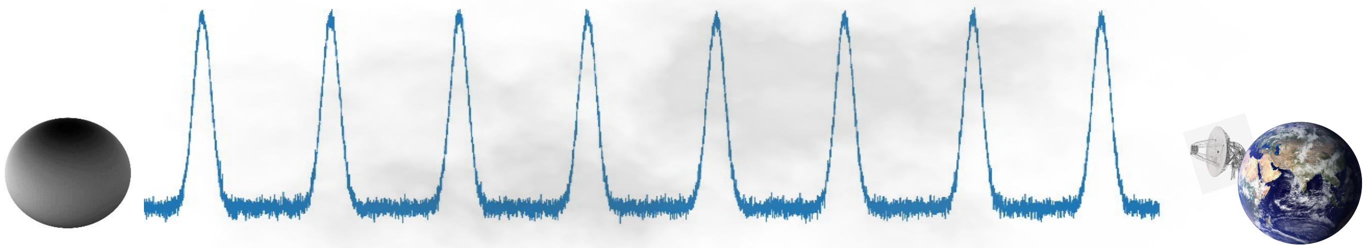
For a GW-driven population of circular SMBHBs:

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

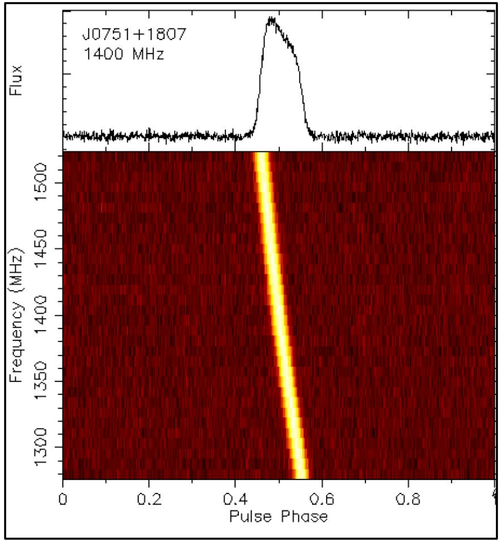
Credits: M. Falxa



Pulsar radio signal



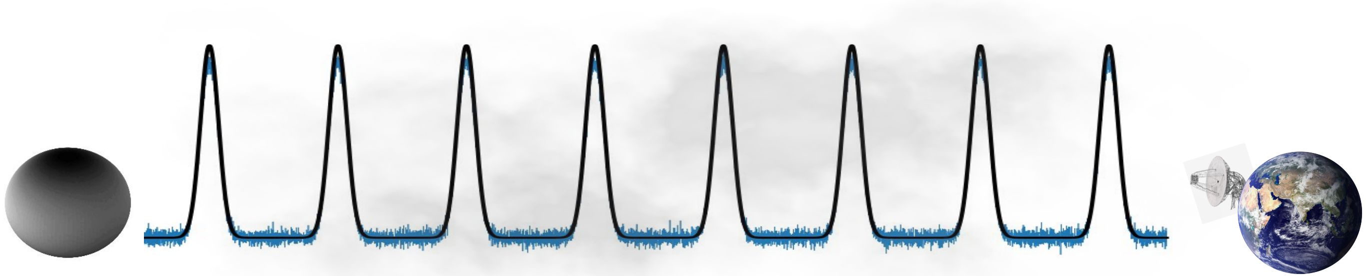
MSPs look very stable, but some effects impact the observed regularity…



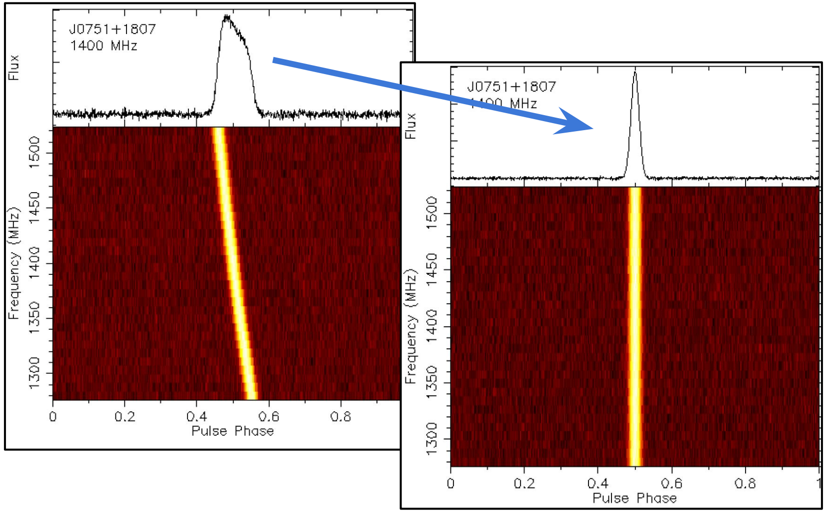
… e.g., dispersion from the interstellar medium

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

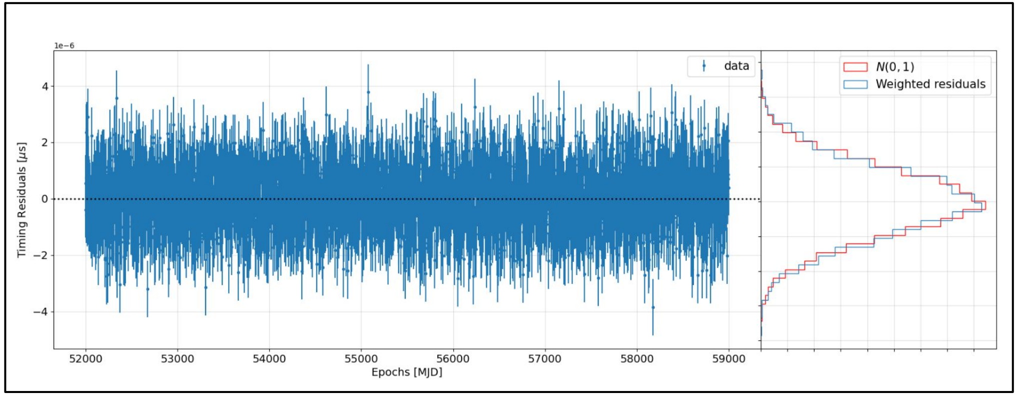
Pulsar Timing data



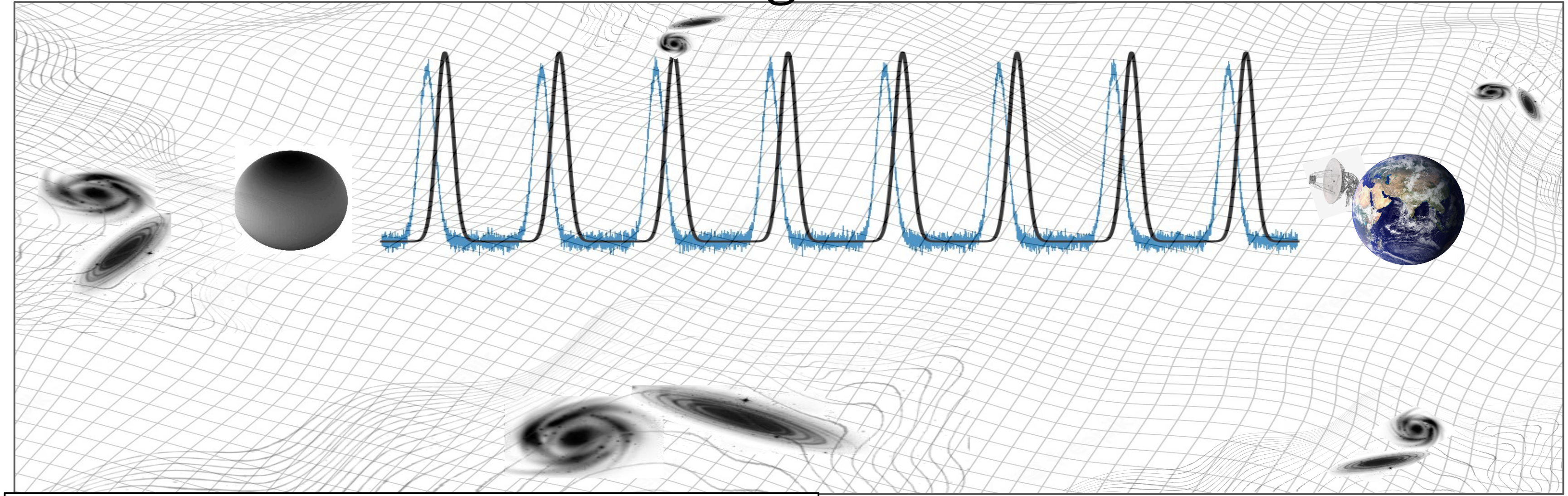
Pulsar timing => fit a timing model to predict **times of arrival**, minimizing the **timing residuals**

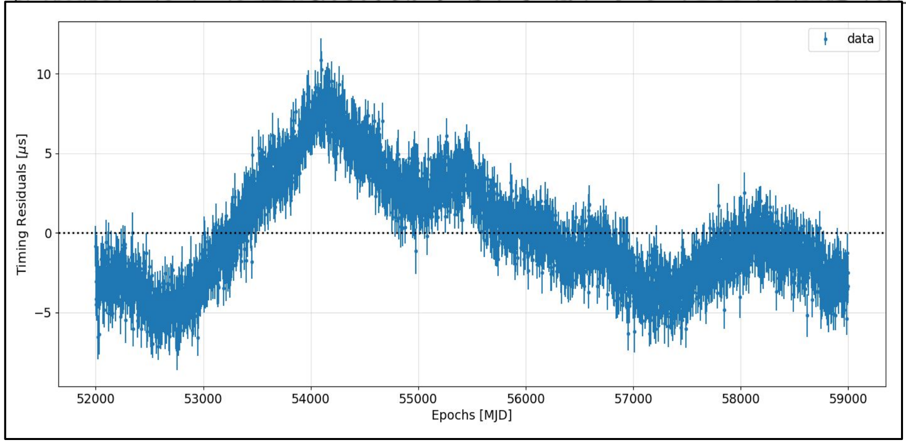


Timing residuals = $ToA_{obs} - ToA_{pred}$



Pulsar Timing data with GWs





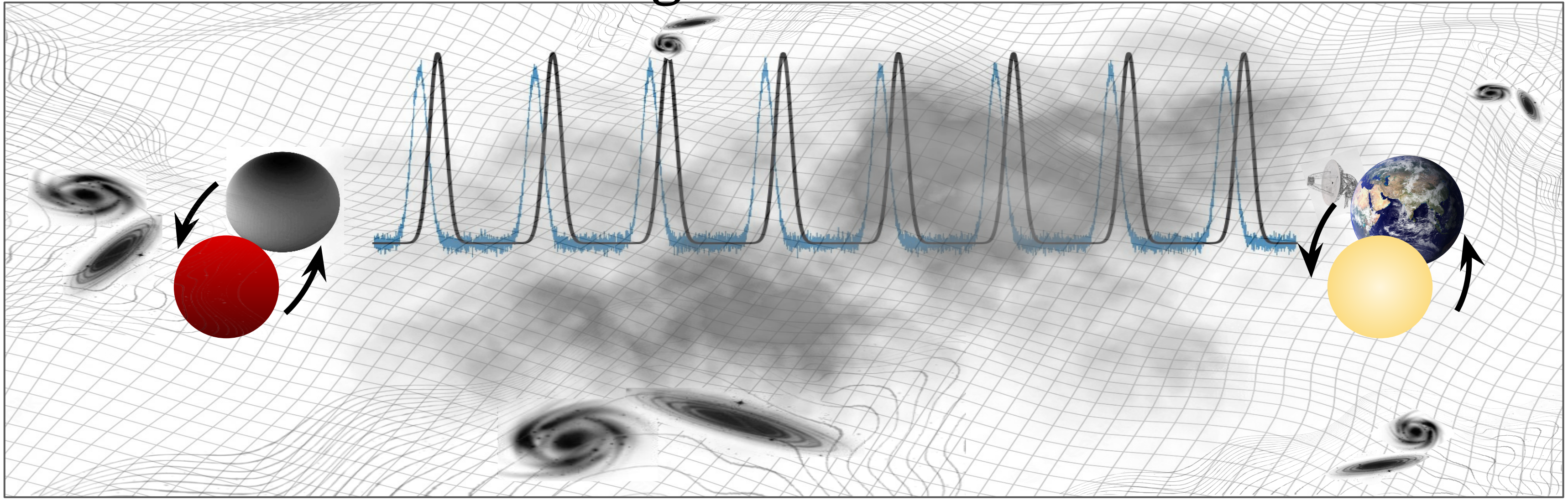
GWB modelling:

Red (long-term) process described with a
binned GP power-law Power Spectral Density

$$S_P^{\mathrm{GWB}}(f) = \frac{A_{\mathrm{GWB}}^2}{12\pi^2} \left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-\gamma_{\mathrm{GWB}}} \mathrm{yr}^3$$

$\gamma_{\mathrm{GWB}} = 13/3$ for Circular & GW-driven SMBHBs

Pulsar Timing data with GWs + noise



Spin noise ?

Unmodelled objects ?

Time-varying dispersion from the ISM ?

Time-varying scattering from the ISM ?

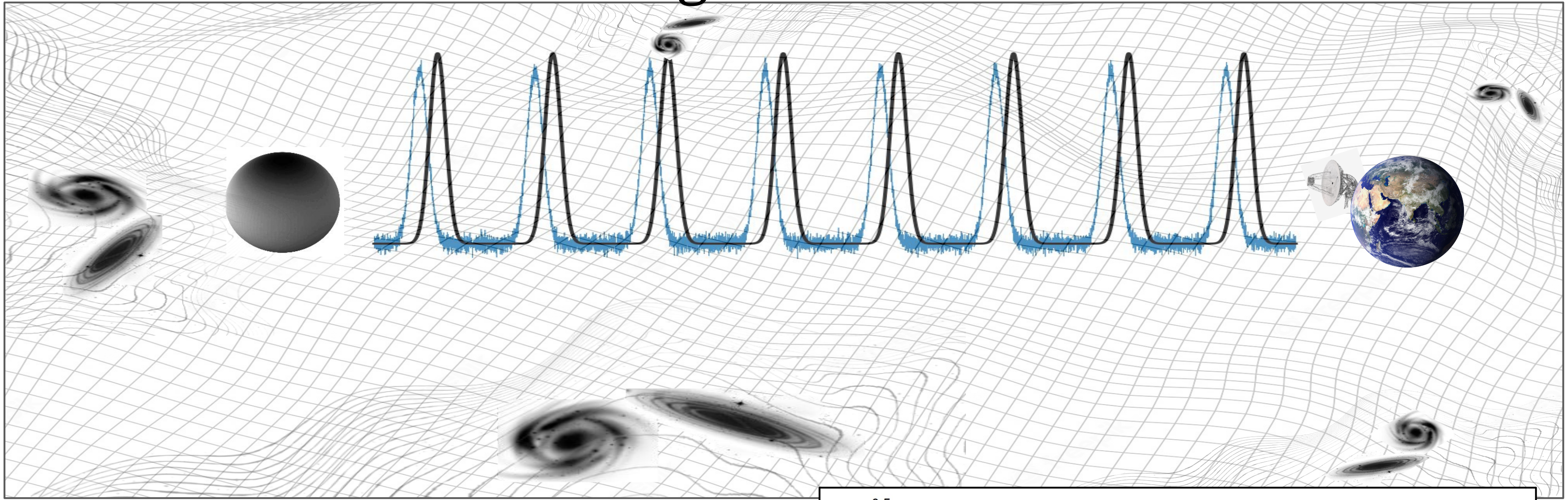
Time-varying dispersion from the Solar winds ?

Errors in the solar system barycenter position ?

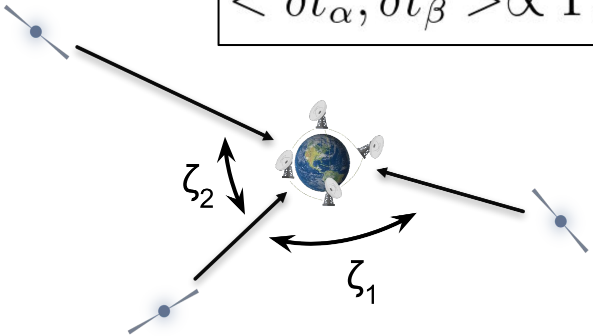
… ?

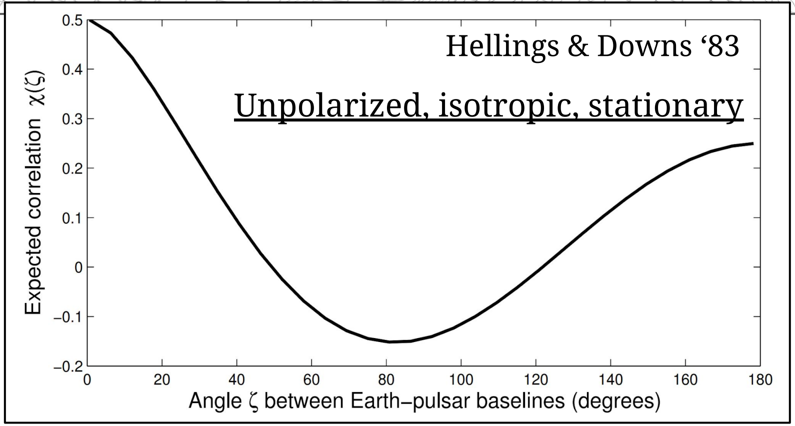
Stochastic GWB + deterministic signals ?

Constraining the GWB with PTAs



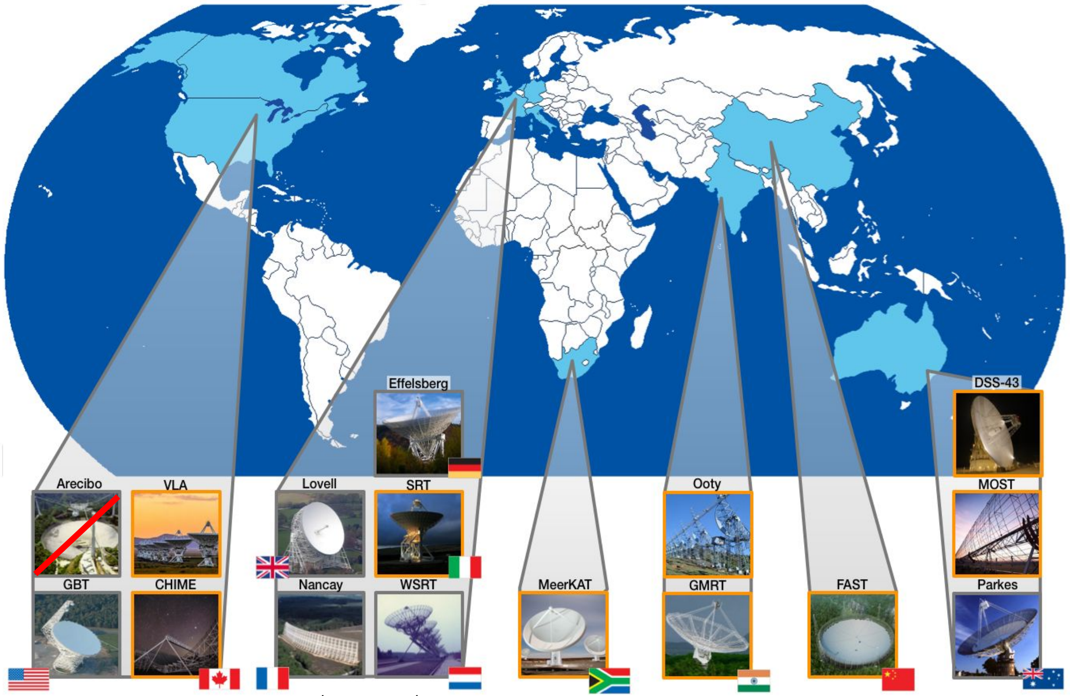
$$< \delta\vec{t}_\alpha, \delta\vec{t}_\beta > \propto \Gamma_{\alpha\beta}(\zeta_{\alpha\beta})$$





Context - PTAs around the world

INTERNATIONAL PULSAR TIMING ARRAY



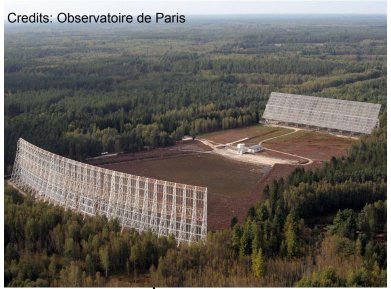
From NANOGrav's website

+ LEAP/LOFAR/NenuFAR

NANOGrav EPTA InPTA Indian Pulsar Timing Array PPTA

Context - The European Pulsar Timing Array (EPTA)

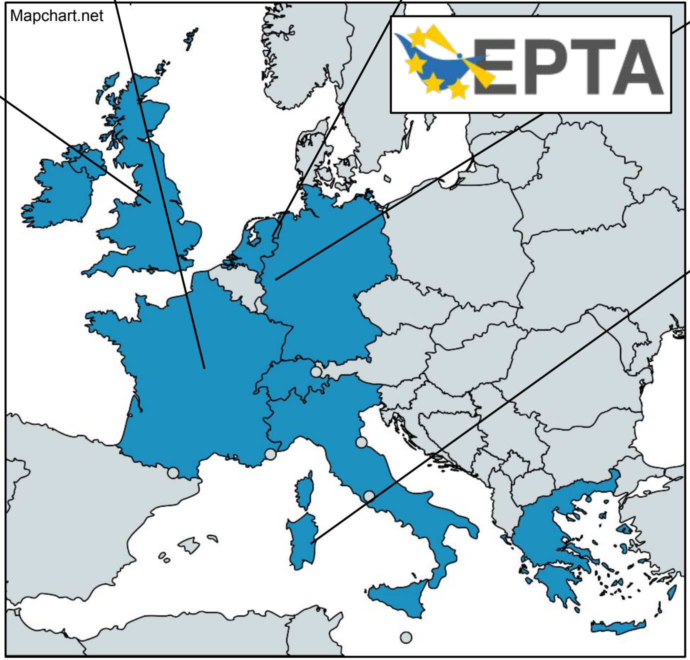

Credit: Anthony Holloway, Jodrell Bank


Credits: Observatoire de Paris


Credits: ASTRON

Member institutes in

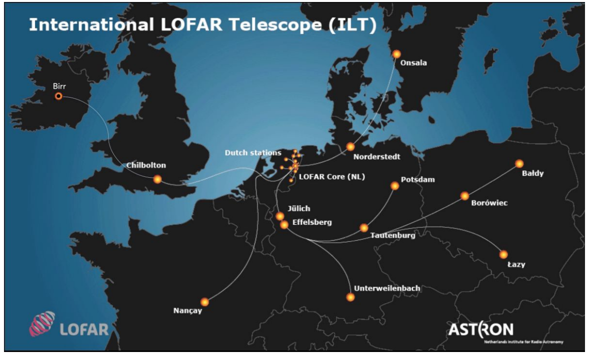
- China
- France
- Germany
- Greece
- Ireland
- Italy
- Netherlands
- Switzerland
- UK



+ LEAP

+ NenuFAR &

Credits: Hannah Currivan - I-LOFAR



Results from the European and the Indian PTAs in 2023

- Paper 1: The EPTA DR2 & timing analysis. DOI: 10.1051/0004-6361/202346841
- Paper 2: The noise analysis.
  DOI: 10.1051/0004-6361/202346842
- Paper 3: GWB search.
  DOI: 10.1051/0004-6361/202346844
- Paper 5: Implications for SMBHB, DM and the early Universe.
  DOI: 10.1051/0004-6361/202347433
- Paper 5: Continuous GW search.
  DOI: 10.1051/0004-6361/202348568
- Paper 6: Ultralight DM search.
  DOI: 10.1103/PhysRevLett.131.171001

The second data release from the European Pulsar Timing Array

III. Search for gravitational wave signals

J. Antoniadis, P. Arumugam, S. Arumugam, S. Babak, M. Bagchi, A.-S. Bak Nielsen, C. G. Bassa, A. Bathula, A. Berthereau, M. Bonetti, E. Bortolas, P. R. Brook, M. Burgay, R. N. Caballero, A. Chalumeau, D. J. Champion, S. Chanlaridis, S. Chen★, I. Cognard, S. Dandapat, D. Deb, S. Desai, G. Desvignes, N. Dhanda-Batra, C. Dwivedi, M. Falxa, R. D. Ferdman, A. Franchini, J. R. Gair, B. Goncharov, A. Gopakumar, E. Graikou, J.-M. Grießmeier, L. Guillemot, Y. J. Guo★★, Y. Gupta, S. Hisano, H. Hu, F. Iraci, D. Izquierdo-Villalba, J. Jang, J. Jawor, G. H. Janssen, A. Jessner, B. C. Joshi, F. Kareem, R. Karuppusamy, E. F. Keane, M. J. Keith, D. Kharbanda, T. Kikunaga, N. Kolhe, M. Kramer, M. A. Krishnakumar, K. Lackeos, K. J. Lee, K. Liu, Y. Liu, A. G. Lyne, J. W. McKee, Y. Maan, R. A. Main, M. B. Mickaliger, I. C. Niţu, K. Nobleson, A. K. Paladi, A. Parthasarathy, B. B. P. Perera, D. Perrodin, A. Petiteau, N. K. Porayko, A. Possenti, T. Prabu, H. Quelquejay Leclere, P. Rana, A. Samajdar, S. A. Sanidas, A. Sesana, G. Shaifullah, J. Singha, L. Speri, R. Spiewak, A. Srivastava, B. W. Stappers, M. Surnis, S. C. Susarla, A. Susobhanan, K. Takahashi, P. Tarafdar, G. Theureau, C. Tiburzi, E. van der Wateren, A. Vecchio, V. Venkatraman Krishnan, J. P. W. Verbiest, J. Wang, L. Wang and Z. Wu.

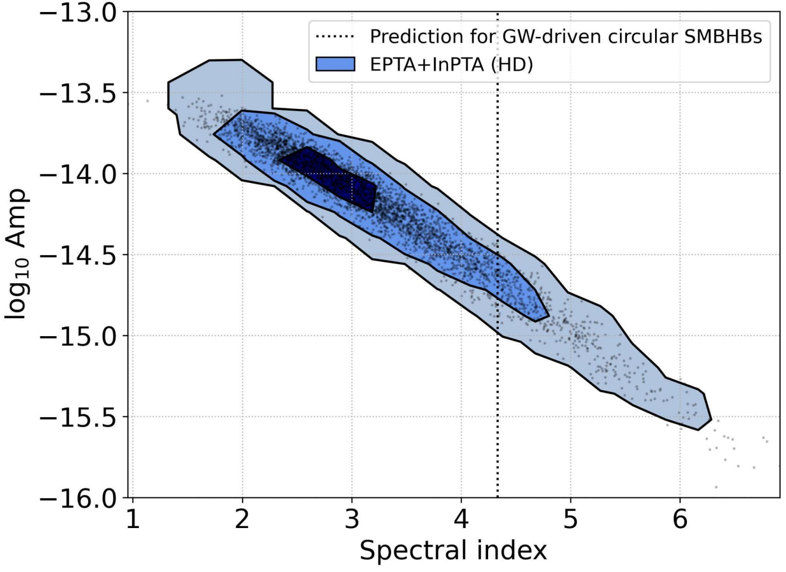
Dataset made of EPTA DR2 + InPTA DR1

High contribution from France:

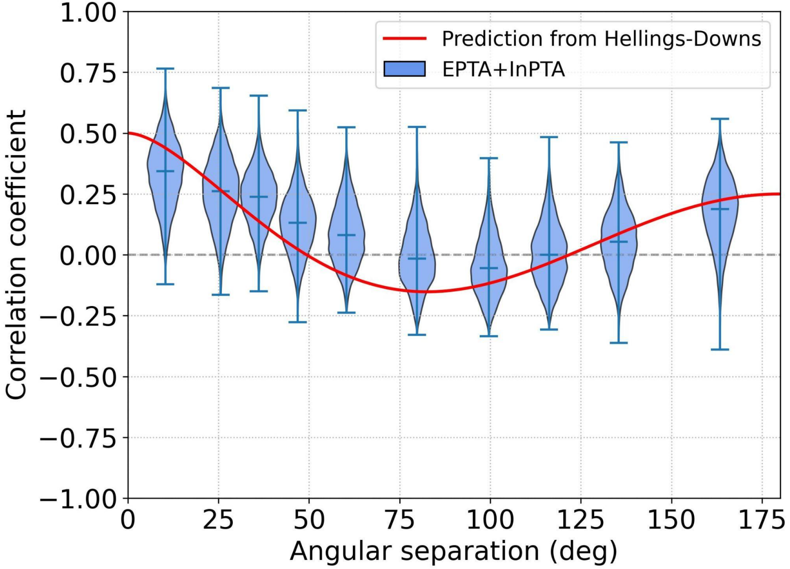
- From APC: **S. Babak**, **A. Chalumeau** (+LPC2E), **M. Falxa**, **A. Petiteau** (+ CEA), **H. Quelquejay-Leclere**, **D. Steer**
- From LPC2E/OBSPM: **A. Berthereau**, **I. Cognard**, **J.-M. Griessmeier**, **L. Guillemot**, **G. Theureau**
- > 50% of data from Nançay Radio Telescope !

EPTA+InPTA 2023 - Evidence for the Gravitational Wave Background

Power-law PSD



Spatial correlations



EPTA+InPTA 2023 - Evidence for the Gravitational Wave Background

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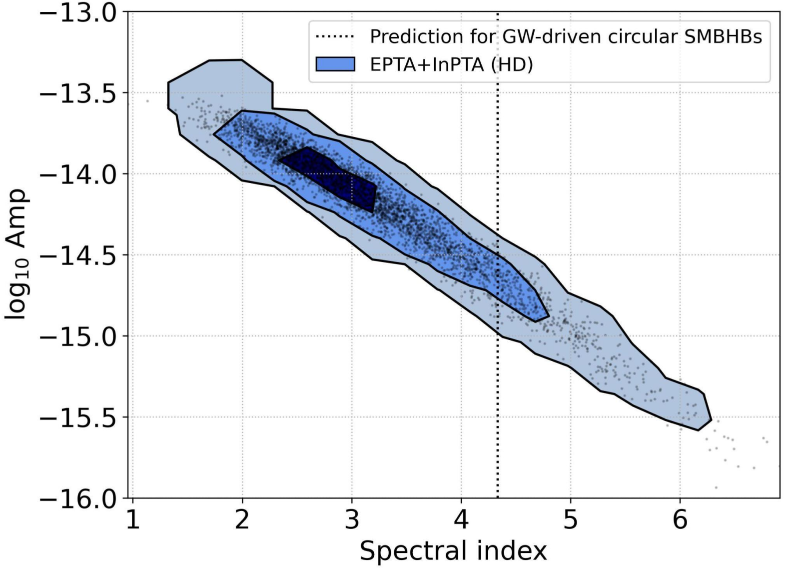

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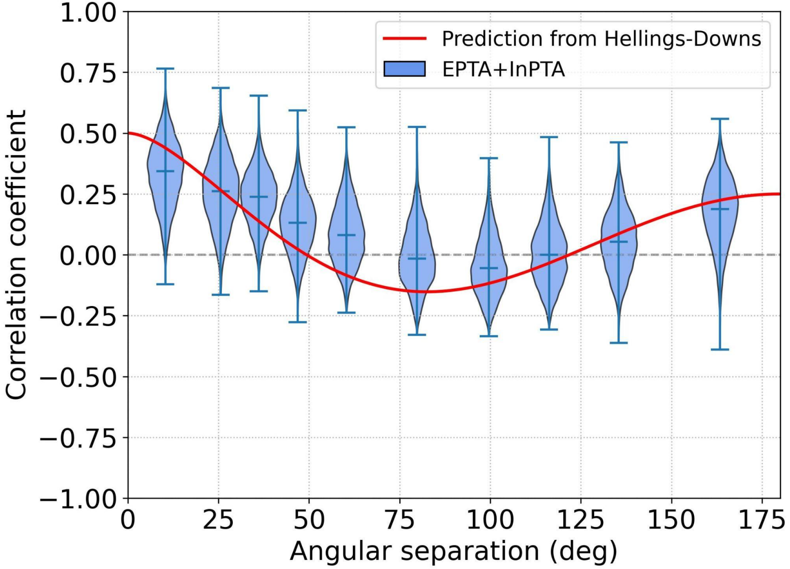


Significance

Bayesian

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

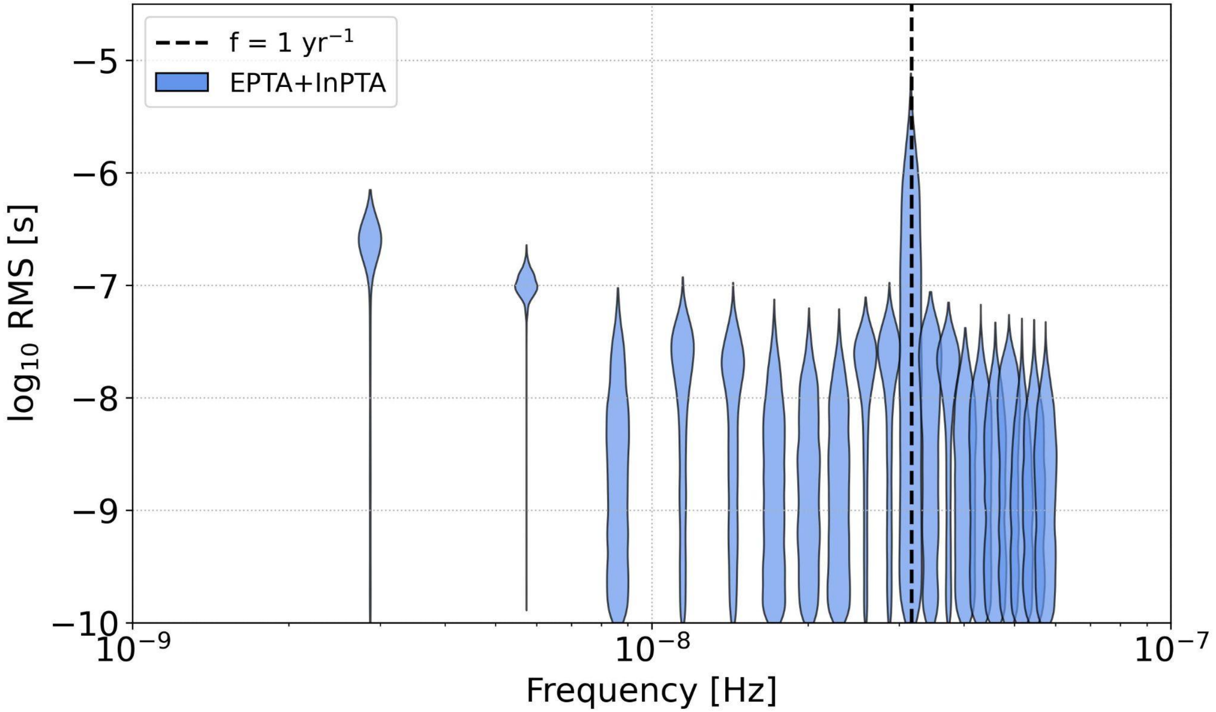
Frequentist

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

→ p-val < 1e-4 (≥ 3.5σ)

EPTA+InPTA 2023 - Evidence for the Gravitational Wave Background

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

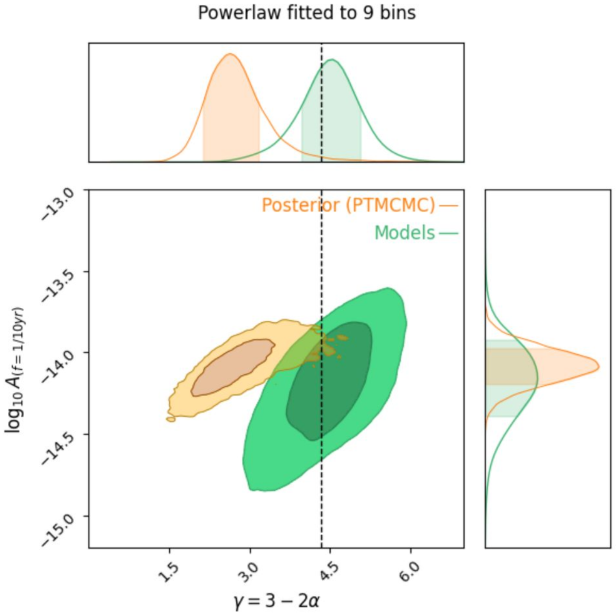


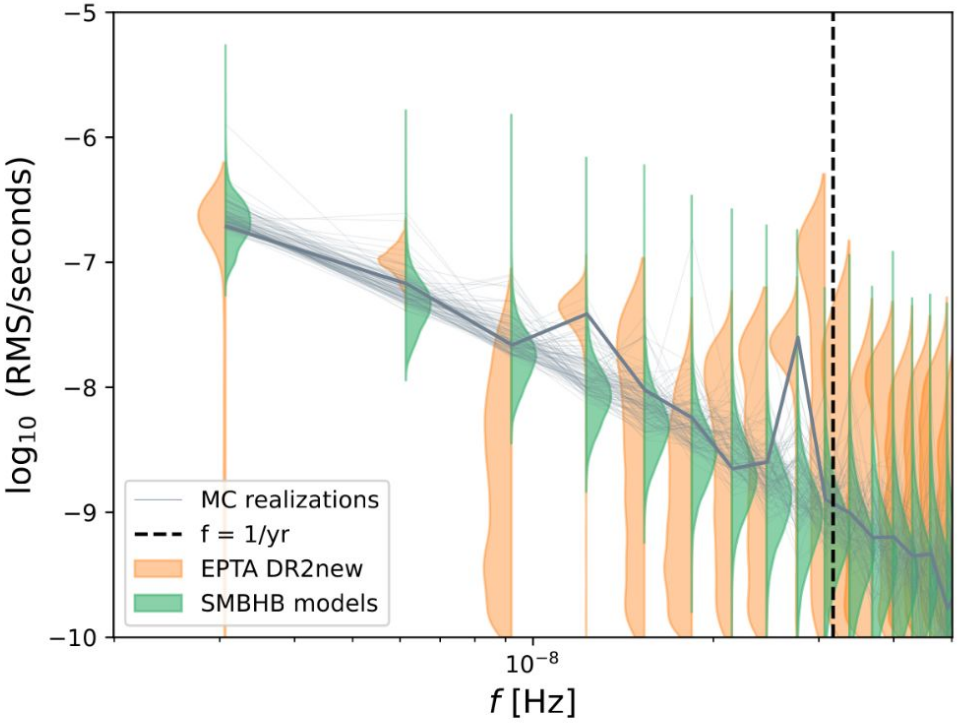
- Only **few frequency bins** are **well constrained**
- Excess of **power** at **low frequencies**

EPTA+InPTA 2023 - Interpretation of the measurement

1. Comparison with empirical models based on observations

324k MC realizations to capture signal variance & resolvable sources





EPTA+InPTA 2023 - Interpretation of the measurement

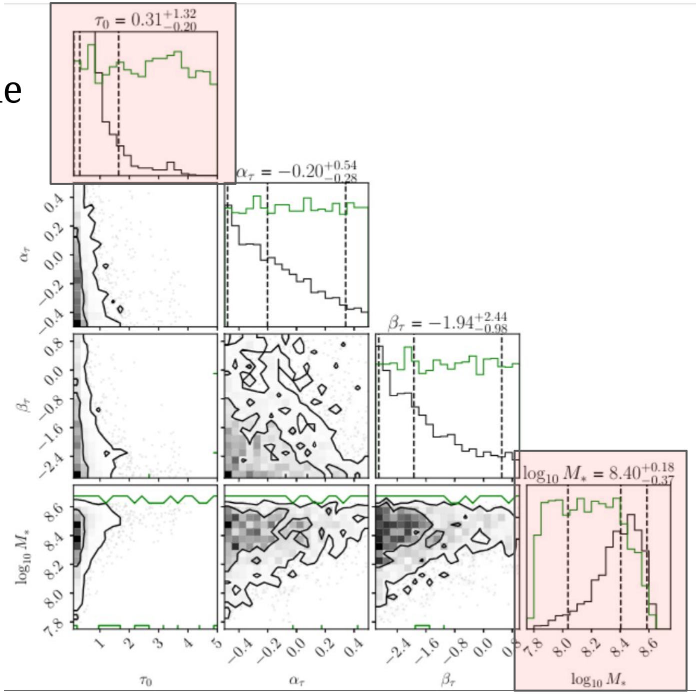
1. Comparison with empirical models based on observations

2. SMBHB inference from PTAs

Signal is informative → SMBHB are massive and merge frequently

Merging timescale

$M_{BH} - M_{bulge}$ norm



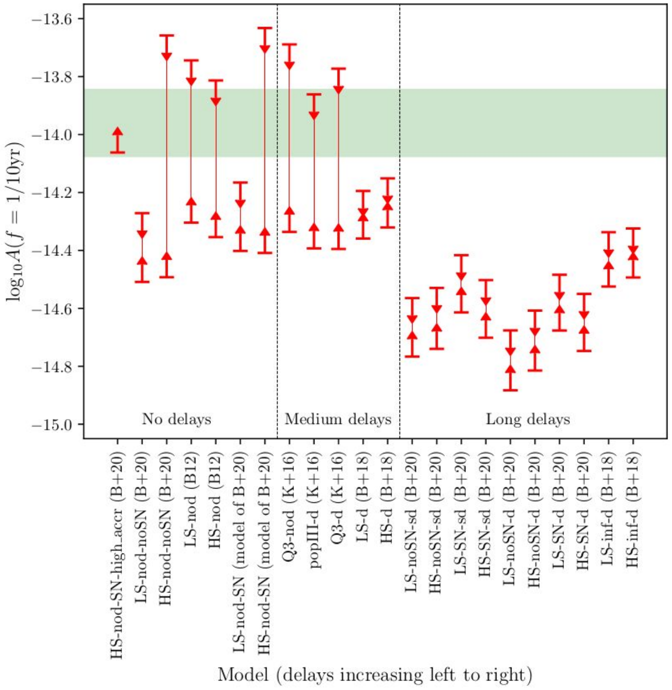
EPTA+InPTA 2023 - Interpretation of the measurement

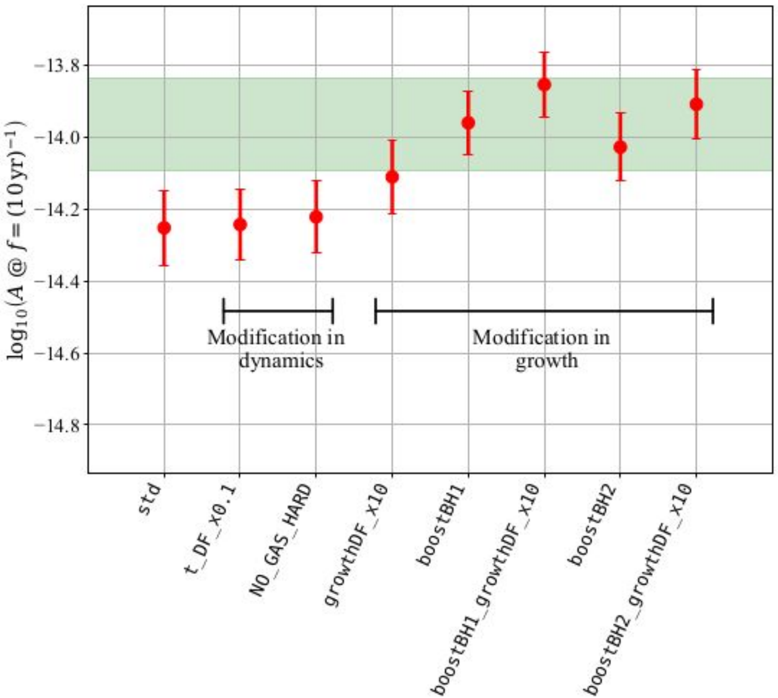
1. Comparison with empirical models based on observations

2. SMBHB inference from PTAs

3. Comparison with semianalytical models

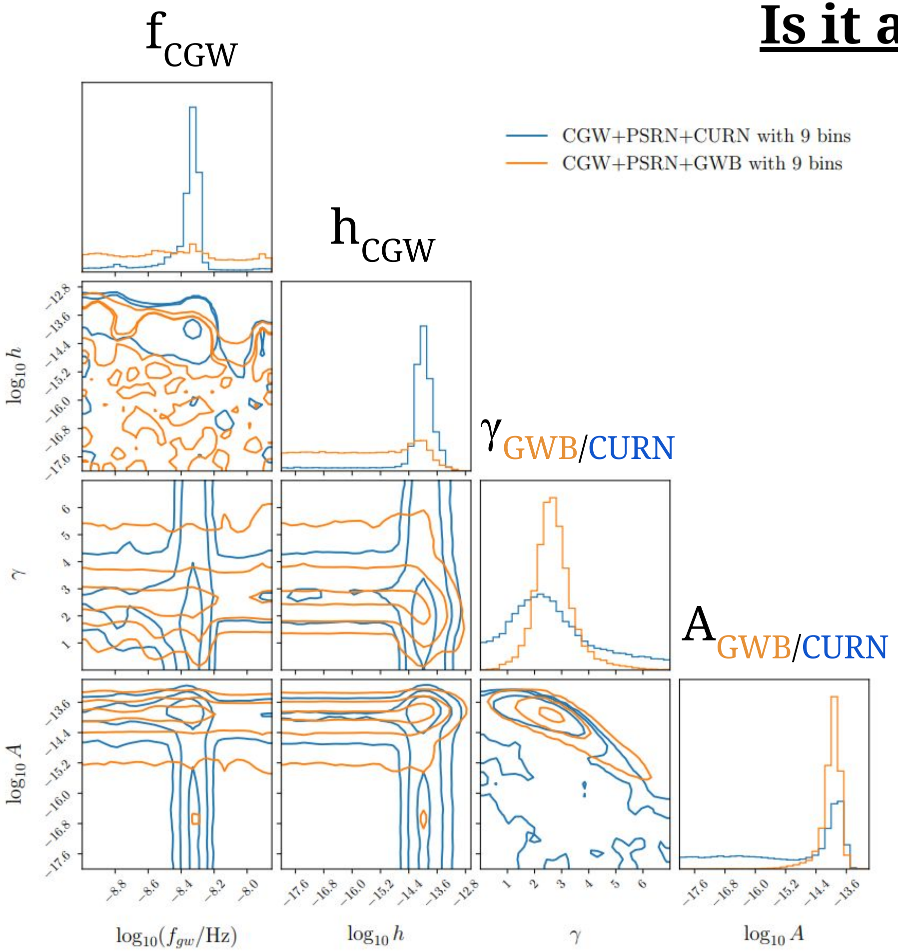
$\Rightarrow$ **hard to reproduce the observed amplitude**



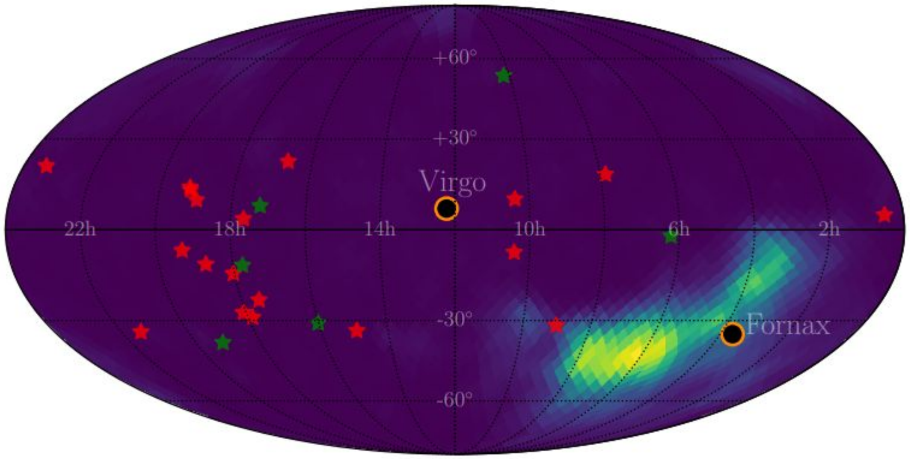


EPTA+InPTA 2023 - Interpretation of the measurement

Is it a continuous wave ?



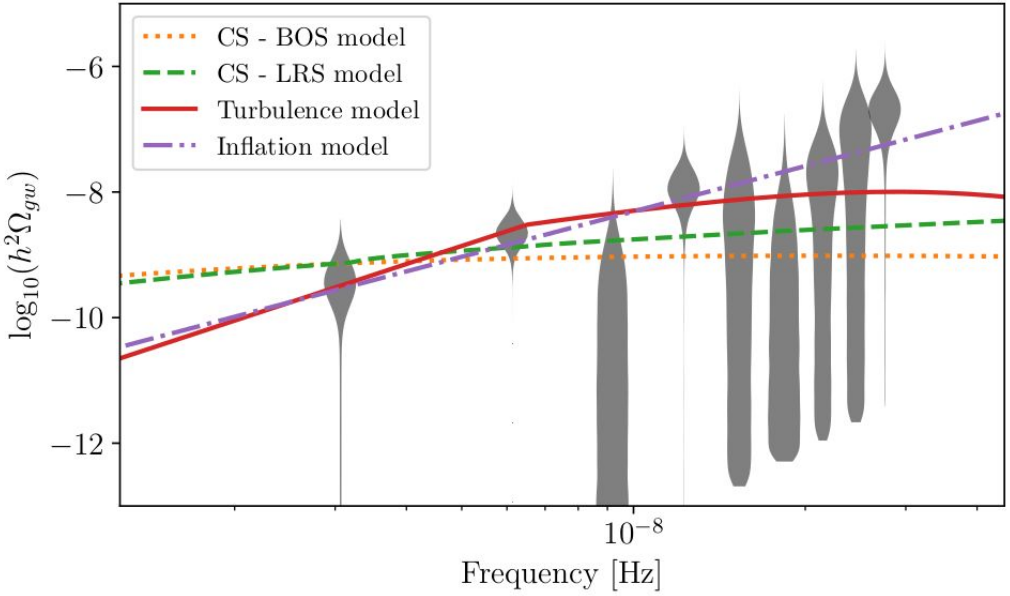
- **CGW candidate** around **5 nHz**
- **Chirp mass** loosely constrained
- Adding **HD** correlated **GWB absorbs** the feature



EPTA+InPTA 2023 - Interpretation of the measurement

Implications for early Universe sources & Dark Matter

GWB measured with high amplitude –> **Models generally needs to be boosted**

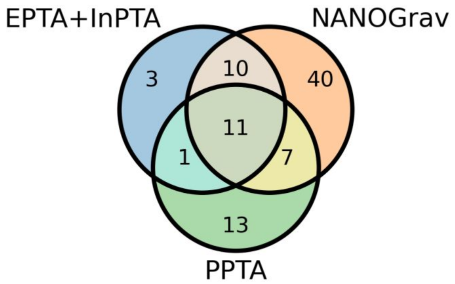


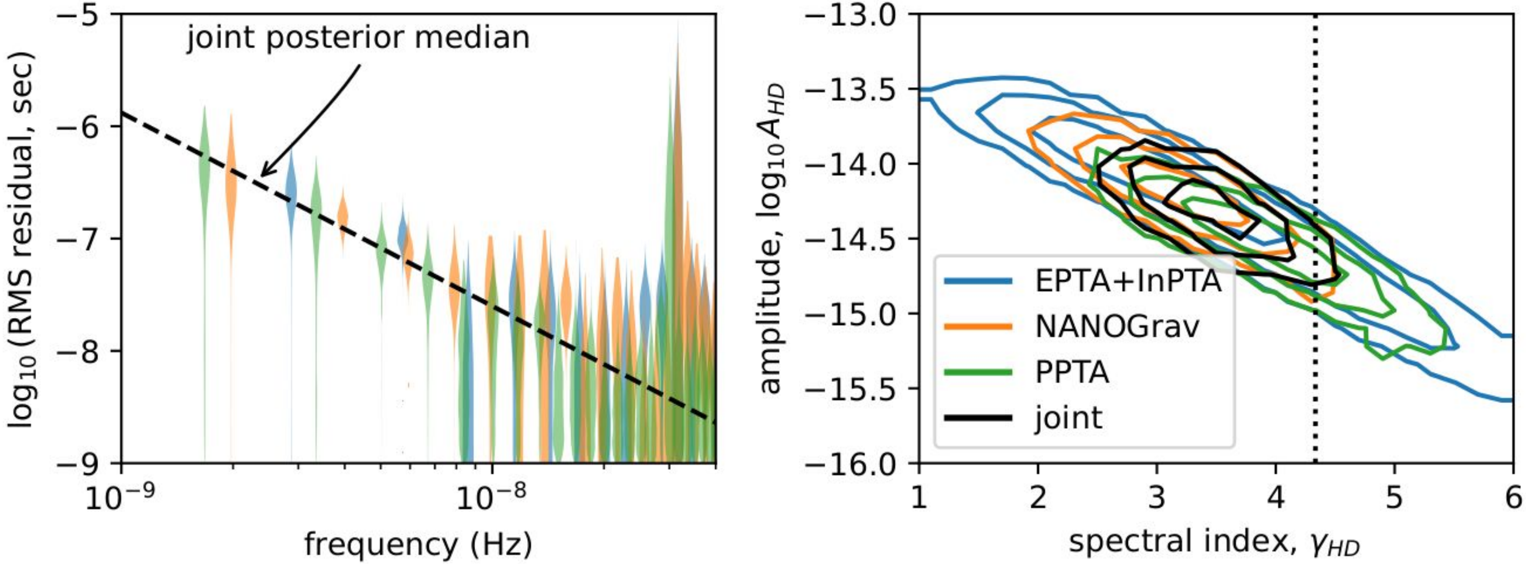
Cosmic strings	⇒ Data consistent with string tension @ -11 < $\log_{10}$ Gμ < -9.5
QCD phase transition	⇒ Require high energy density or scale close to the horizon at QCD epoch
Primordial inflationary GWs	⇒ Require non-standard inflationary scenarios(not consistent with slow roll inflation)
Primordial scalar curvature perturbations	⇒ Require excess at small scales to not violate CMB constraints

Fuzzy DM	⇒ ULDM particles with mass −24eV < $\log_{10} m_\phi$ < −23.4eV can only make up at most **30-40 % of the total DM energy density.**

EPTA+InPTA 2023 - 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

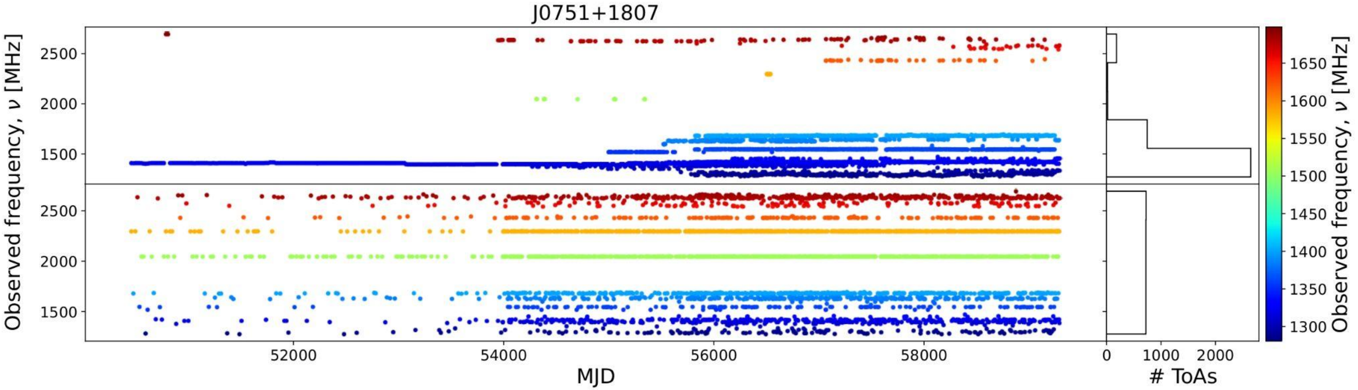


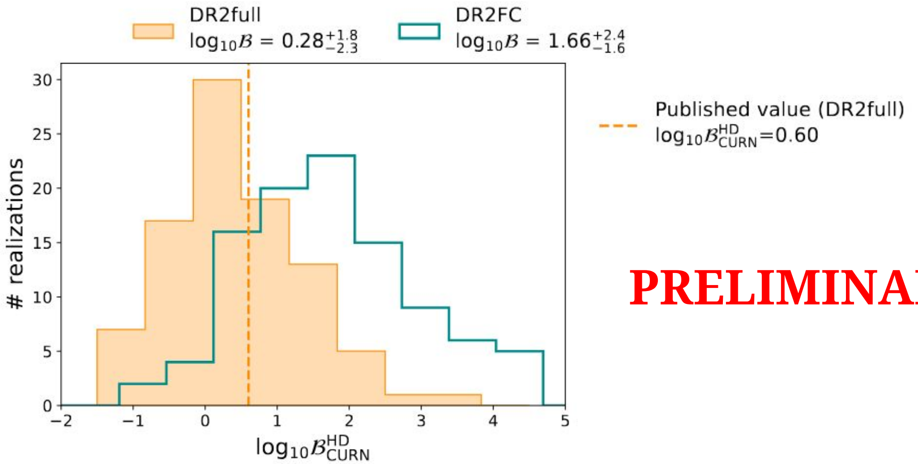


Current status and perspectives

Current challenges for PTAs

Some crucial points to understand: Implications of non-homogeneous data sets



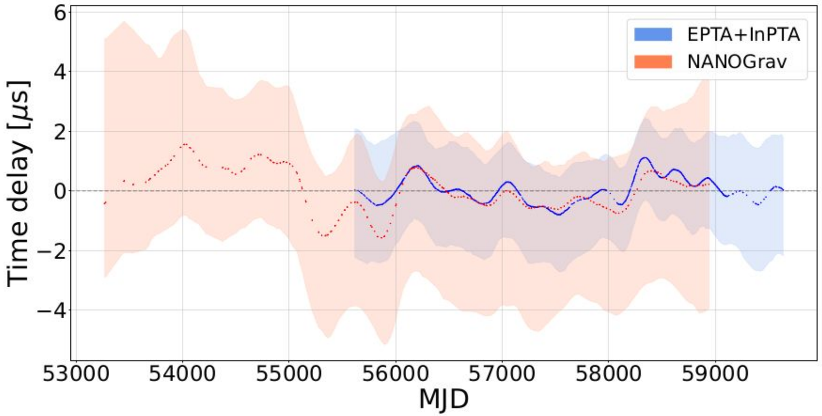


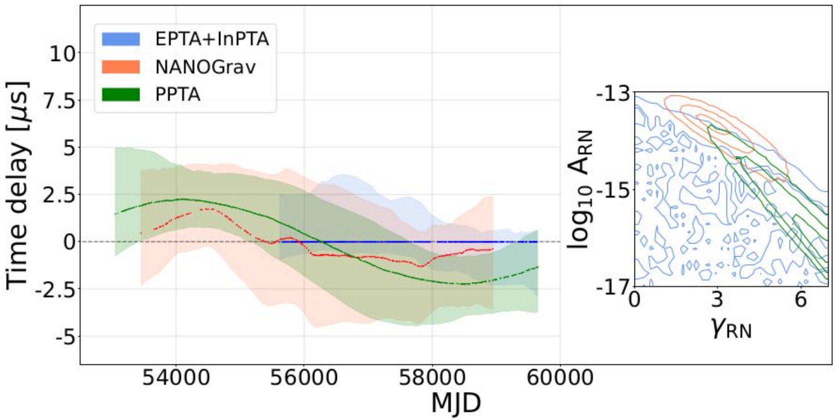
Courtesy from I. Ferranti & M. Falxa

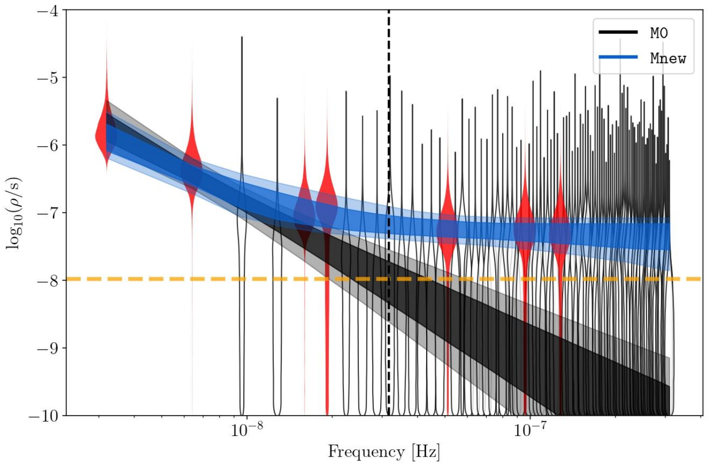
PRELIMINARY

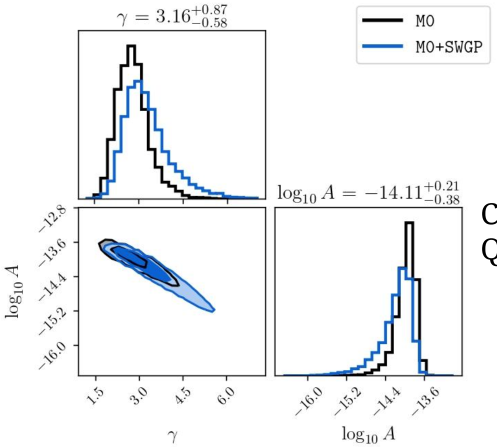
Current challenges for PTAs

Some crucial points to understand: Complexe noise properties







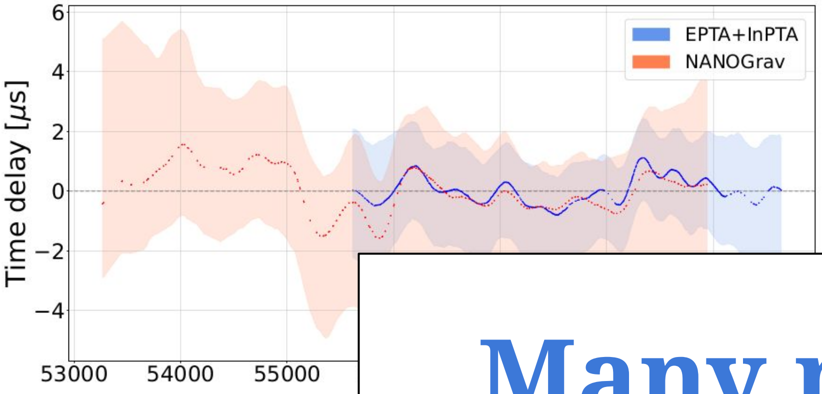


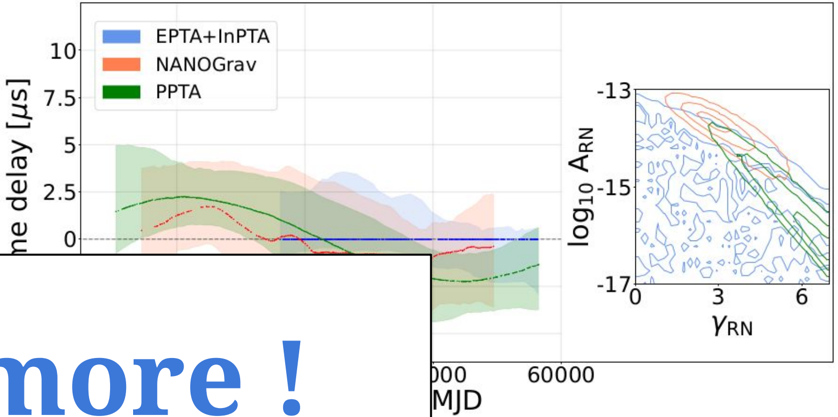
Courtesy from H. Quelquejay-Leclere

PRELIMINARY

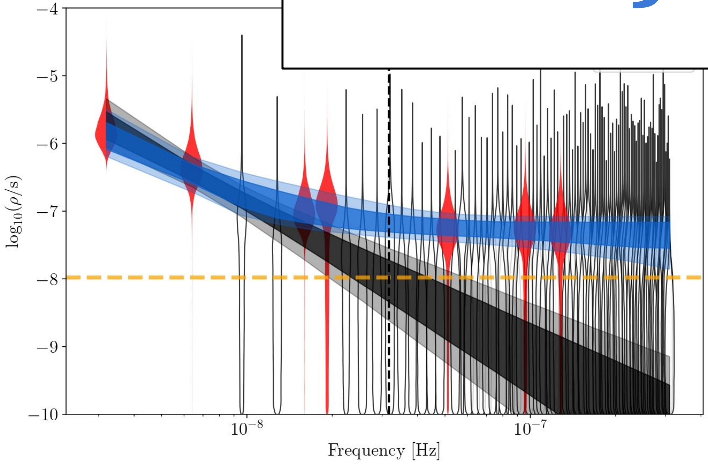
Current challenges for PTAs

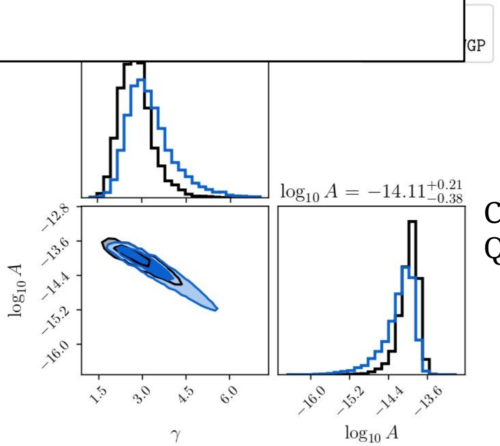
Some crucial points to understand: Complexe noise properties





Many more !





Courtesy from H. Quelquejay-Leclere

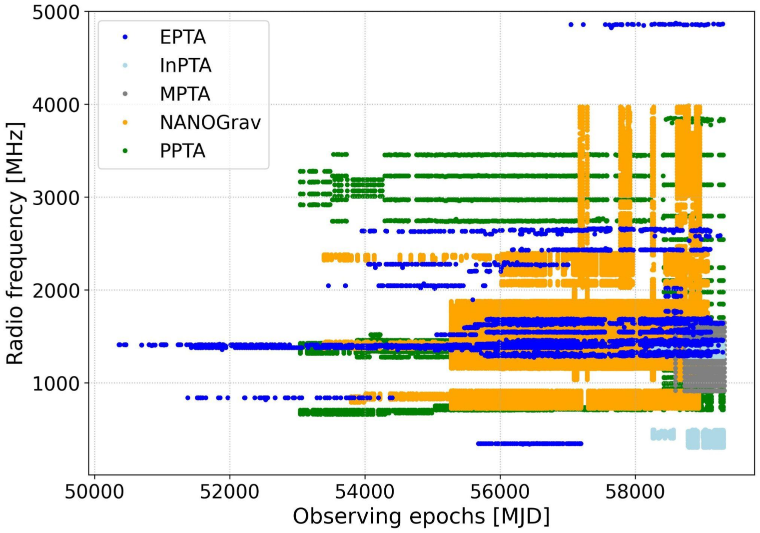
PRELIMINARY

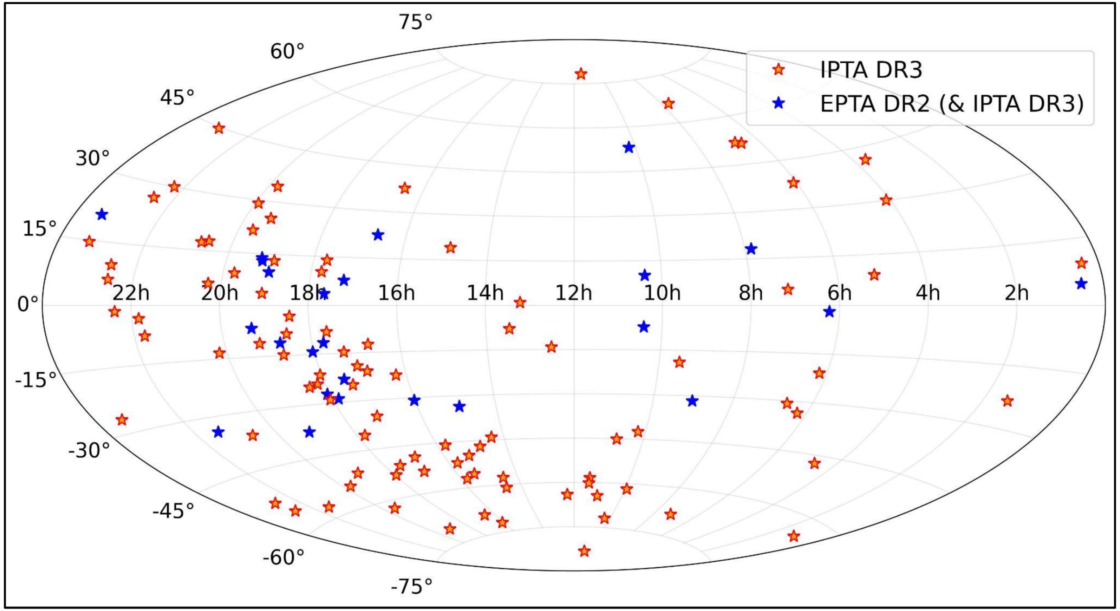
The International Pulsar Timing Array Third Data Release

Global effort is now mainly focused on the upcoming IPTA DR3

That will combine > 120 pulsars from **EPTA** (w/ **LOFAR & NenuFAR**), **InPTA**, **MeerKAT**, **NANOGrav** (w/ **CHIME**), and **PPTA**

More than 1e6 data points !





Conclusion

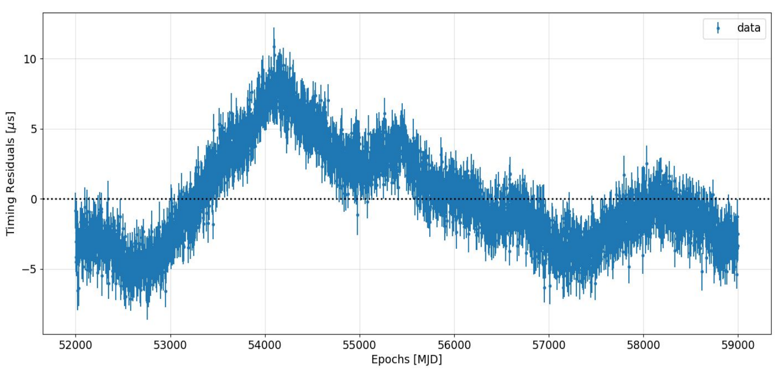
- **Strong evidence** for a **gravitational wave signal** in the EPTA+InPTA data
    - BF ~ 65 ; p-val ~ 3.5σ, **still not a formal detection**
    - **Main candidate** is the **stochastic GWB** from **SMBHBs**
        - But 1: It is hardly separated from a CGW source
        - But 2: it is currently **impossible to determine** the **exact origin** of this **GW signal**

- Exciting future in the **short** and **long** terms for PTAs
    - The **IPTA DR3** will combine of all the main data sets to **improve** our **sensitivity** and help us going further on understanding the origins of the signal
    - The **SKA** radio telescope will be a jump in **data quality** and **number of pulsars**

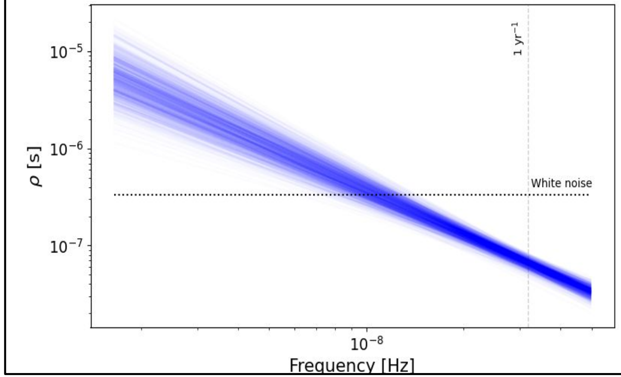
    - Measurements will be complemented by those from **gamma-ray pulsar timing** (Fermi) & **astrometric surveys** (Gaia)
    - **Multi Messenger Astrophysics** could be done having a single source detection

Thank you for your attention !

Annexe 1 - Intrinsic red noise

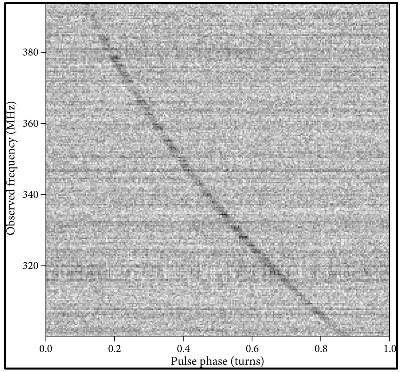


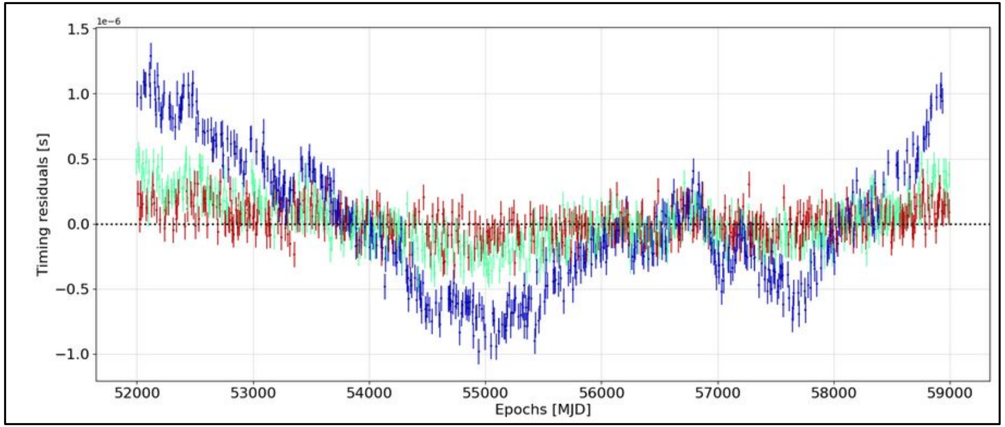
Model



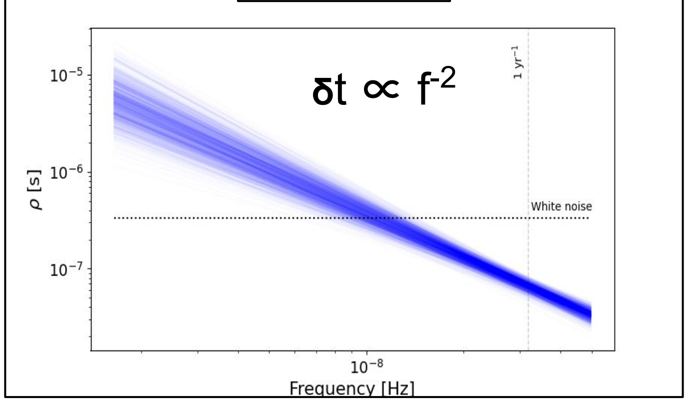
- Magnetospheric variability
  - Lyne et al. 2010
  - Tsang & Gourgouliatos 2013
- Pulsar's superfluid core / solid crust interactions
  - Cordes & Shannon 2010
- Superfluid turbulence
  - Melatos & Link 2014
- Influence of unmodelled objects in psr vicinity
  - Planets (Cordes 1993)
  - Asteroids (Shannon et al. 2013)
  - Companion (Bassa et al. 2016, Kaplan et al. 2016)
- …

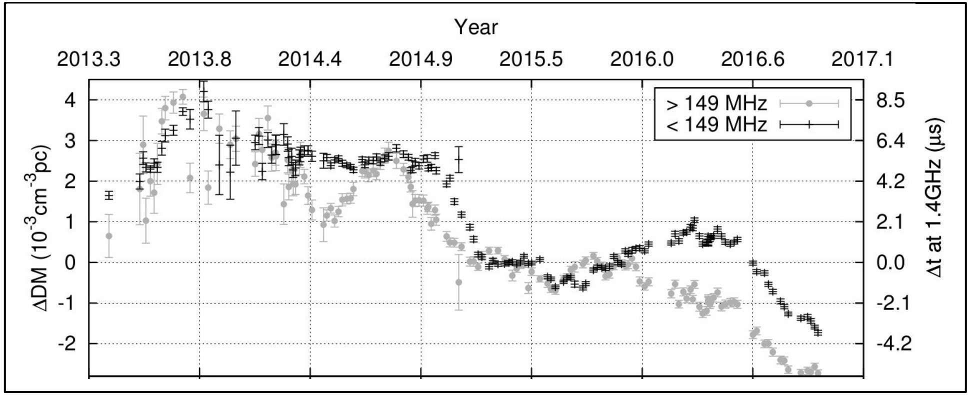
Annexe 2 - Time-varying dispersion





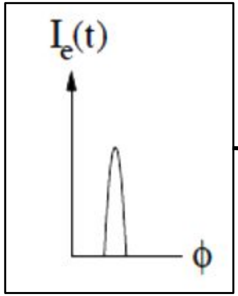
Model

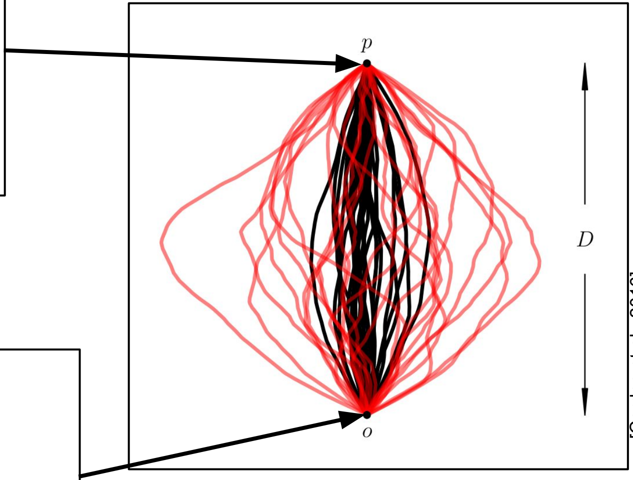




Annexe 3 - Time-varying scattering

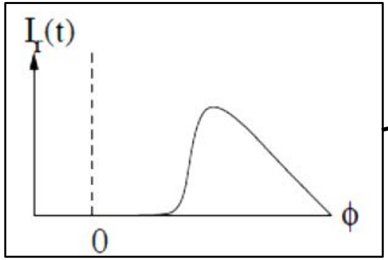
Emitted



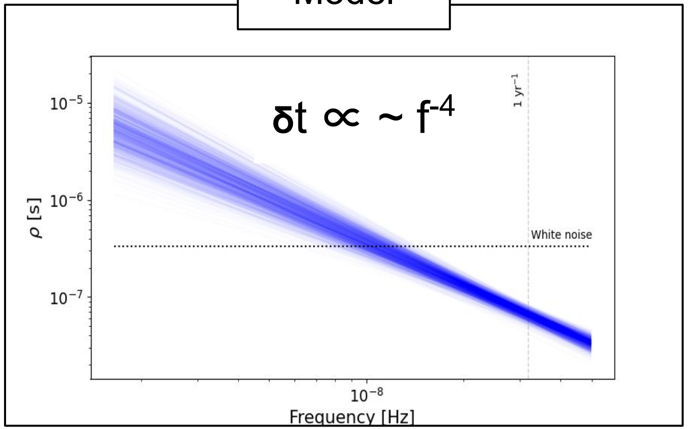


[Cordes et al. 2016]

Received

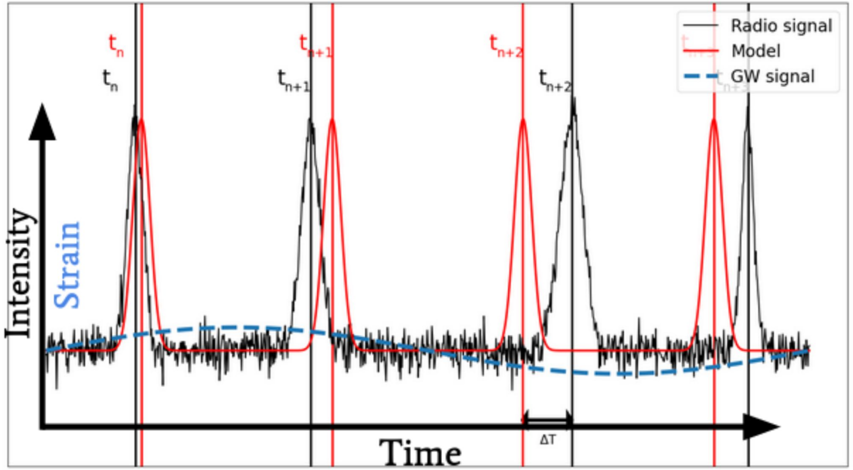


Model



Annexe 4 - Measuring GWs with PTAs

Gravitational waves *disturb the metric and induce* ***long term fluctuations*** *in pulses arrival times*



Credits: M. Falxa

GW signal in arrival times

Obs. & emitted pulsar spin frequency

$$\delta t_{\mathrm{GW}}(t_a) = \int_{t_e}^{t_a} \frac{\nu(t') - \nu_0}{\nu_0} dt' = \int_{t_e}^{t_a} \frac{\delta\nu}{\nu_0}(t')dt'$$

Emission & reception times of pulses

$$\frac{\delta\nu}{\nu_0} = \frac{\hat{n}_\alpha^i \hat{n}_\alpha^j}{2\,(1 + \hat{n}_\alpha.\hat{k})} \Delta h_{ij}$$

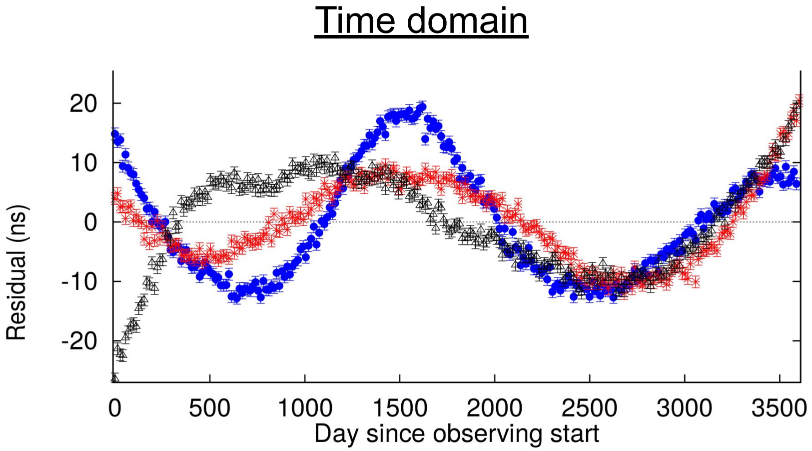
$$\Delta h_{ij} = h_{ij}(t_e) - h_{ij}(t_a)$$

Pulsar & GW source sky location

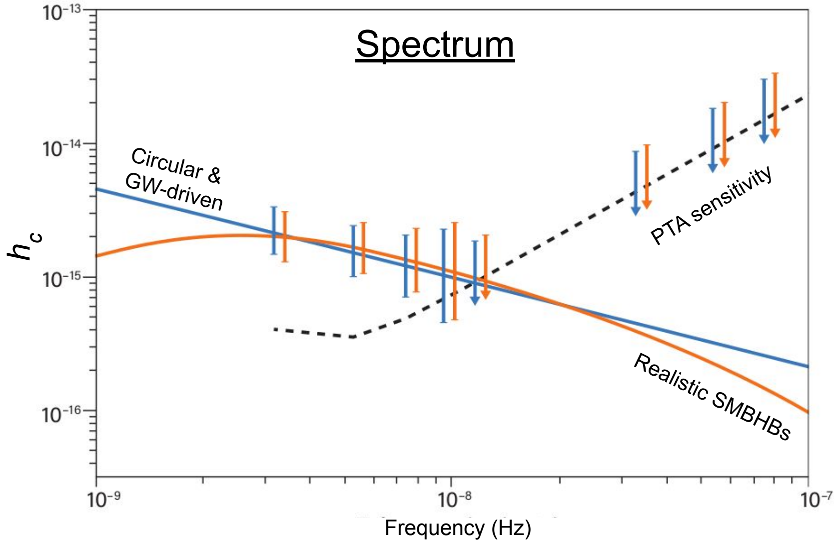
GW characteristic strain

Annexe 5 - The Gravitational Wave Background

*The stochastic **GWB** from the nearby population of **SMBHBs***



[Burke-Spolaor et al. 2019]



Credits: S. Chen

Annexe 6 - The EPTA DR2