Summary of the latest EPTA results

the European Pulsar Timing Array collaboration

Groupement de recherche
Ondes gravitationnelles

EPTA

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16 Oct 2023 - Meudon
Gdr - Ondes gravitationnelles


Credit: OzGrav/Swinburne, Carl Knox

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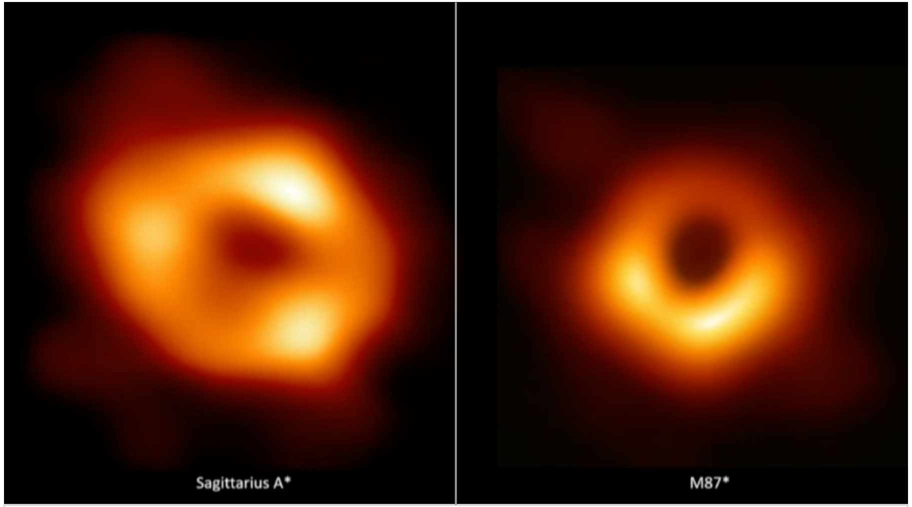
Introduction

- Context
- The EPTA + InPTA collaboration

Context

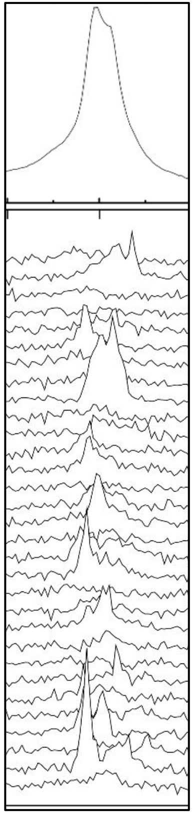
- **Gravitational Waves (GW)**
  - **GWs** are predicted by Einstein's theory of **General Relativity**
  - They are **perturbations** of the **geometry (curvature)** of **space time radiated** by **massive binary systems**
  - They were **first detected in 2015** by the **LIGO/Virgo Collaboration** who detected a GW **signal** produced by **two merging stellar black holes**

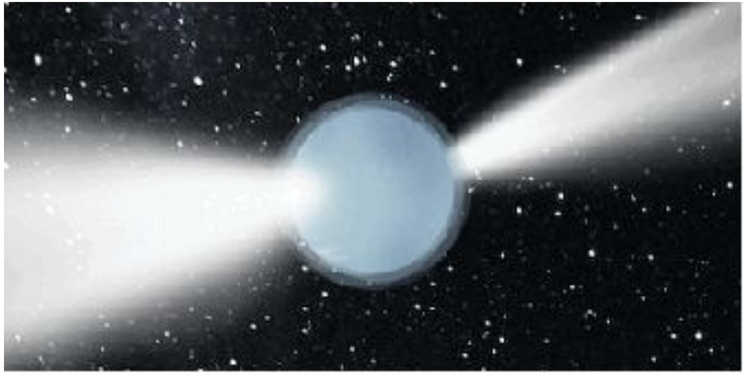


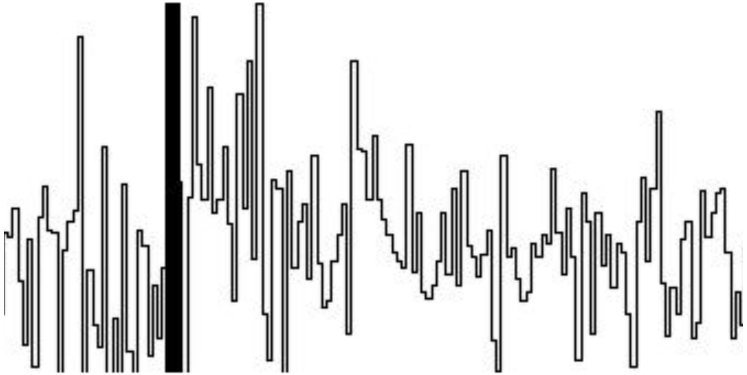
Credit : Event Horizon telescope collaboration

- **Super Massive Black Hole Binaries (SMBHB)**
  - **SMBHBs** are **binary systems** of **Super Massive Black Hole (SMBH)** that we find at the **center of galaxies**
  - Such systems are produced by **Galaxy merger** but have **never been directly observed**
  - We **could detect** the **GWs** produced by **SMBHBs** using **pulsars**

Context





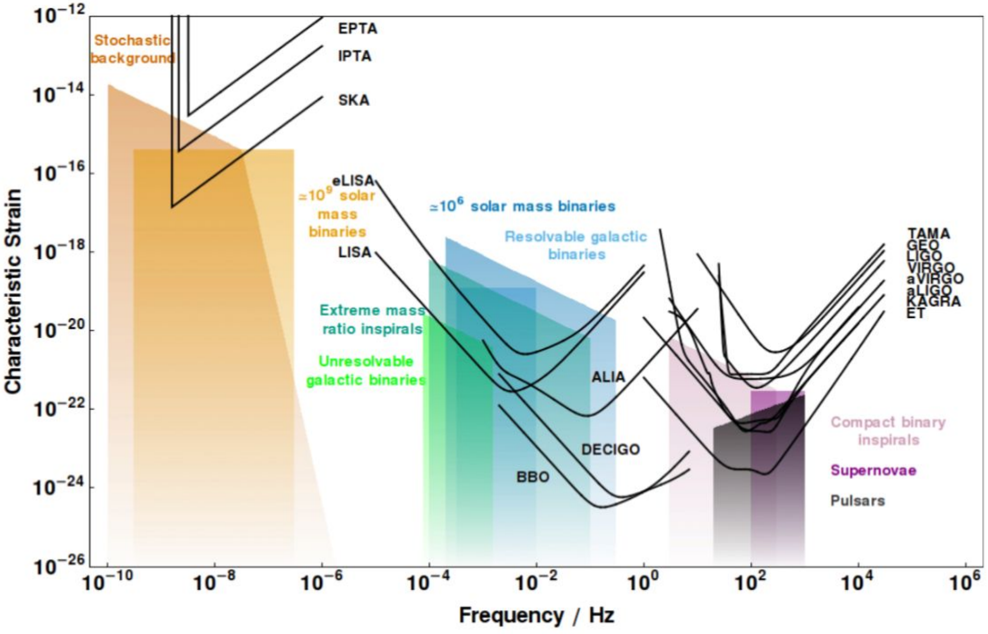


- **Millisecond pulsars (MSP)**
  - **Pulsars** are very dense, highly magnetized and **rapidly rotating neutron** stars emitting beams of EM radiation making them appear on Earth as **series of pulses**
  - A **MSP** is an **old neutron** star that got **spun up (recycled)** by stealing gas and angular momentum to its binary companion
  - We observe them in the **radio frequency band**
  - MSPs are **very stable in their rotation**, allowing us to do **precise timing measurements** and use them as **clocks**

Context

For a large population of SMBHBs in the Universe, we focus on two categories of signals:

- **Gravitational wave background** (GWB)
- **Continuous GWs** (CGWs)



Credits : Gravitational-wave sensitivity curves, C J Moore et al., 2014

Context

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

For a large population of SMBHBs in the Universe, we focus on two categories of signals:

- **Gravitational wave background** (GWB)
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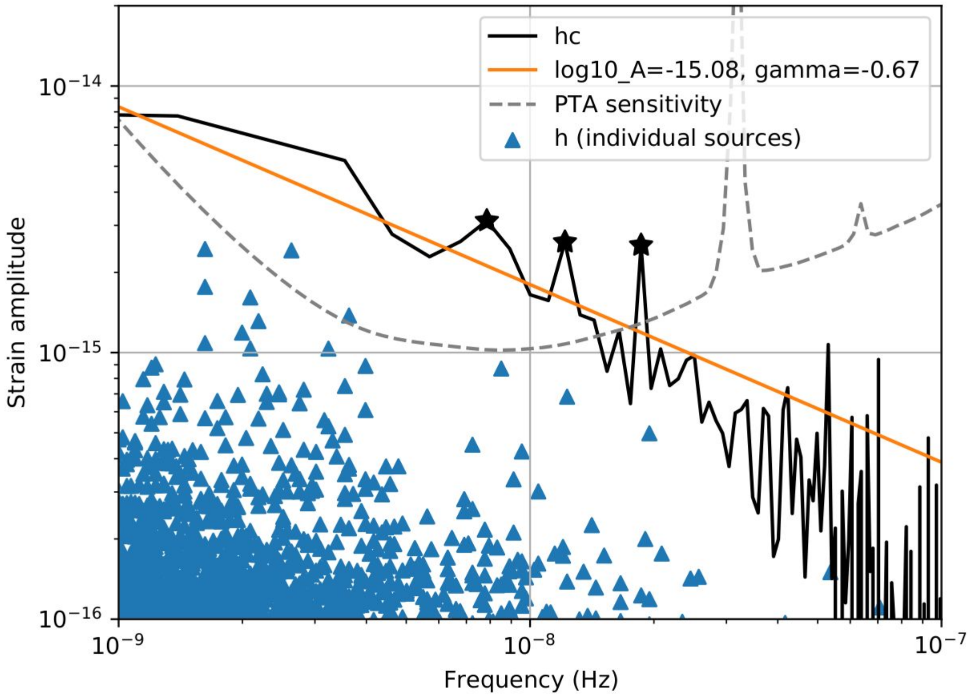
Data analysis for GW detection



The EPTA + InPTA collaboration

Partner telescopes:

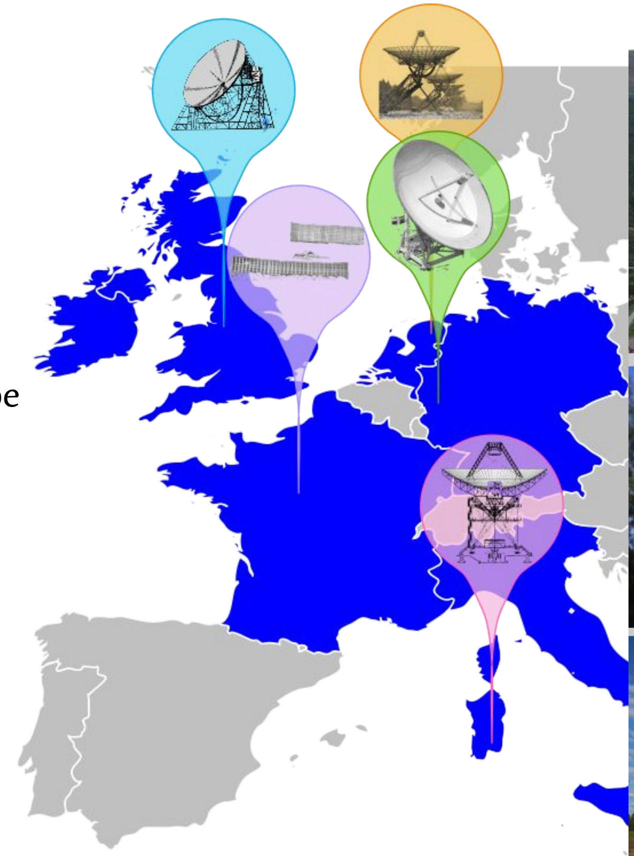
- Effelsberg
- Lovell
- Nancay Radio Telescope
- Sardinia Radio Telescope
- Westerbork Synthesis Radio Telescope

+

GMRT in India

+

Large European Array for Pulsars (**LEAP**)
Low Frequency Array (**LOFAR**)

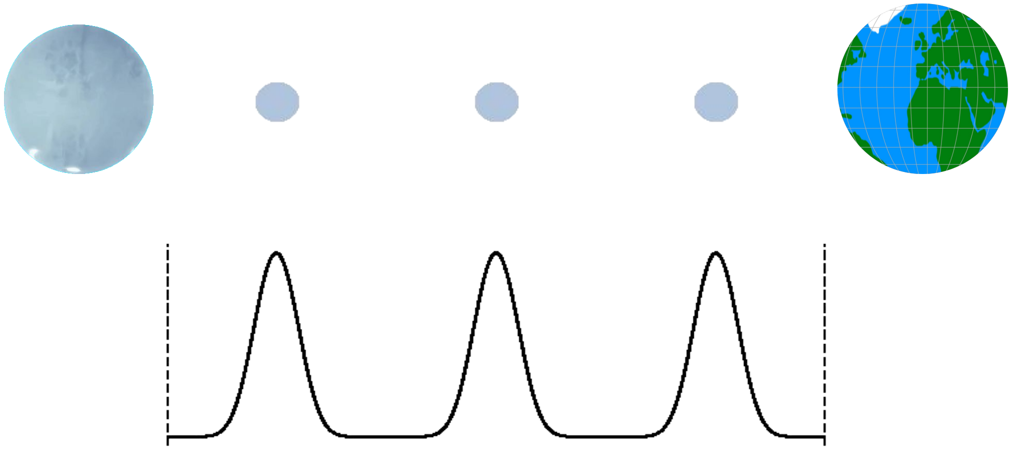


The Pulsar Timing Array

- Timing model and timing residuals
- Pulsar timing array
- The Hellings-Downs correlation
- Data analysis methods

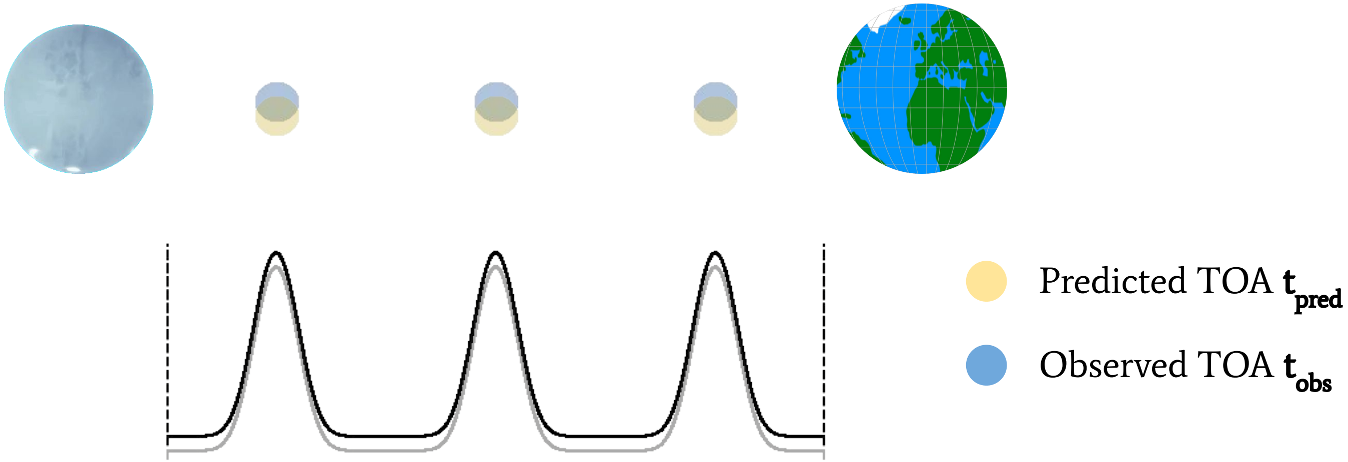
The Pulsar Timing Array (PTA)

Millisecond pulsars are very stable.



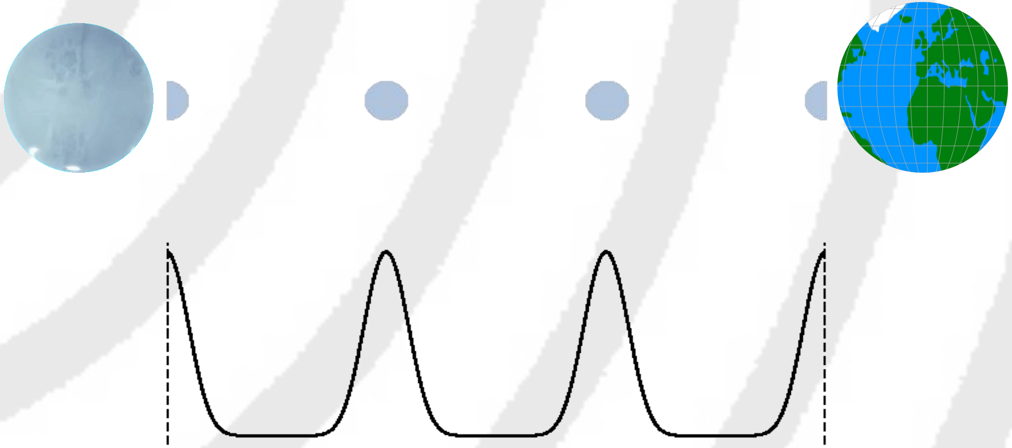
The Pulsar Timing Array (PTA)

We can fit a **timing model** to predict the **time of arrival** (TOA) of the **pulses**.



The Pulsar Timing Array (PTA)

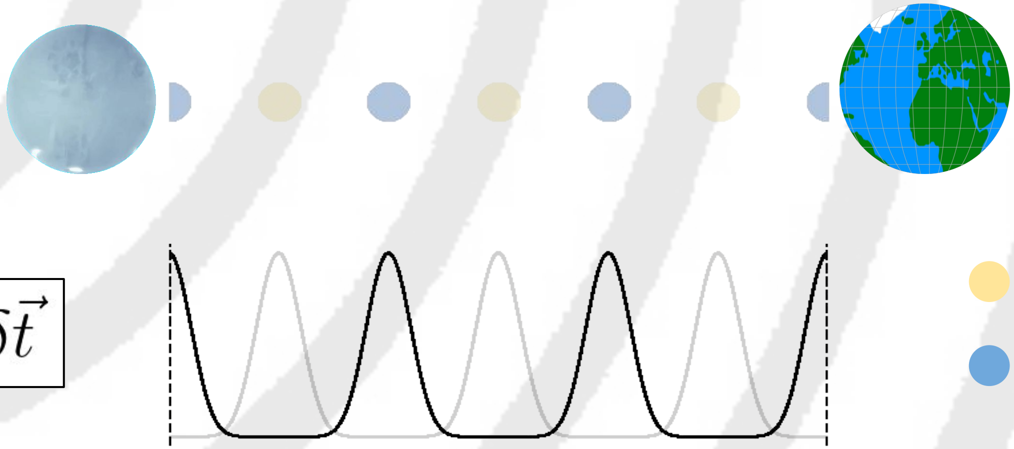
The **gravitational wave** signal **modulates** the expected **TOAs** of pulses...



The Pulsar Timing Array (PTA)

The **gravitational wave** signal **modulates** the expected **TOAs** of pulses...

$$\vec{t}_{obs} - \vec{t}_{pred} = \delta\vec{t}$$

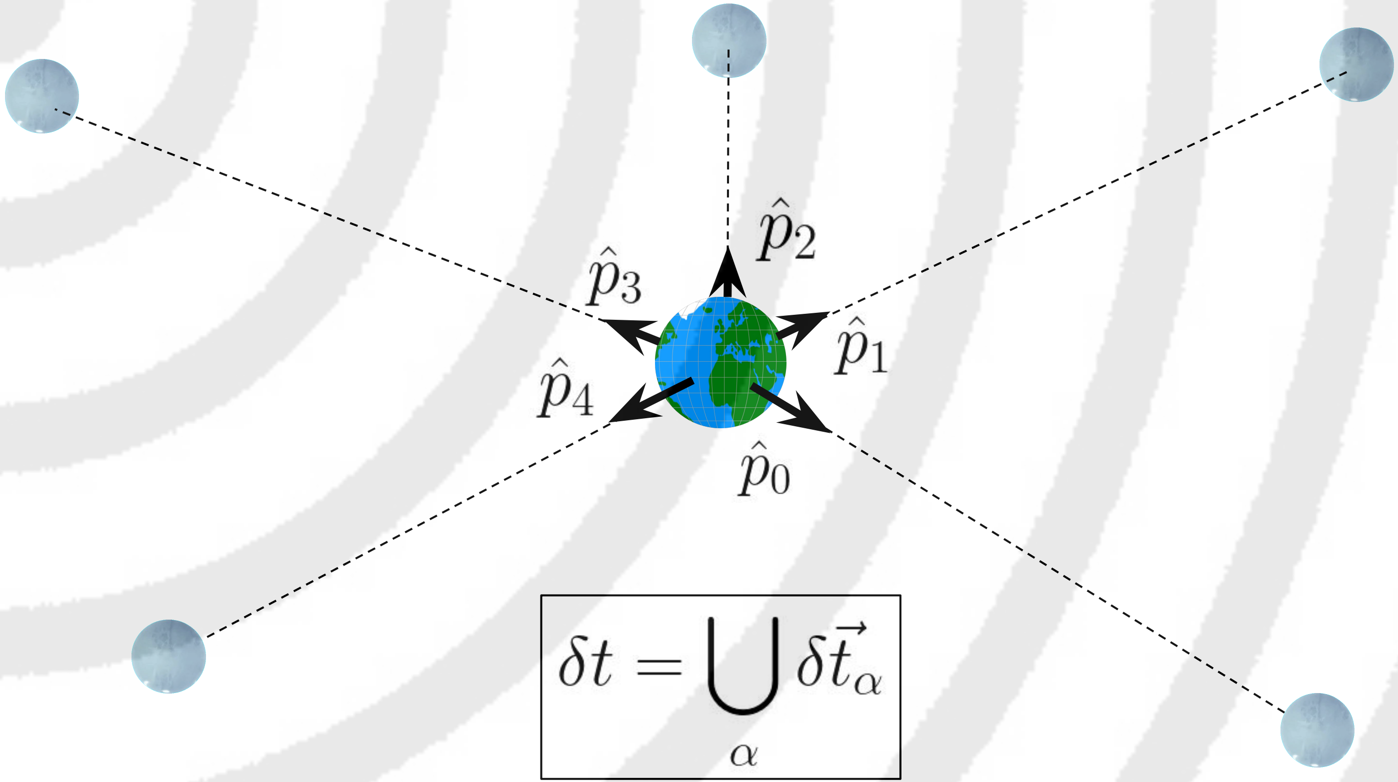


without GW $\mathbf{t}_{\mathbf{pred}}$

with GW $\mathbf{t}_{\mathbf{obs}}$

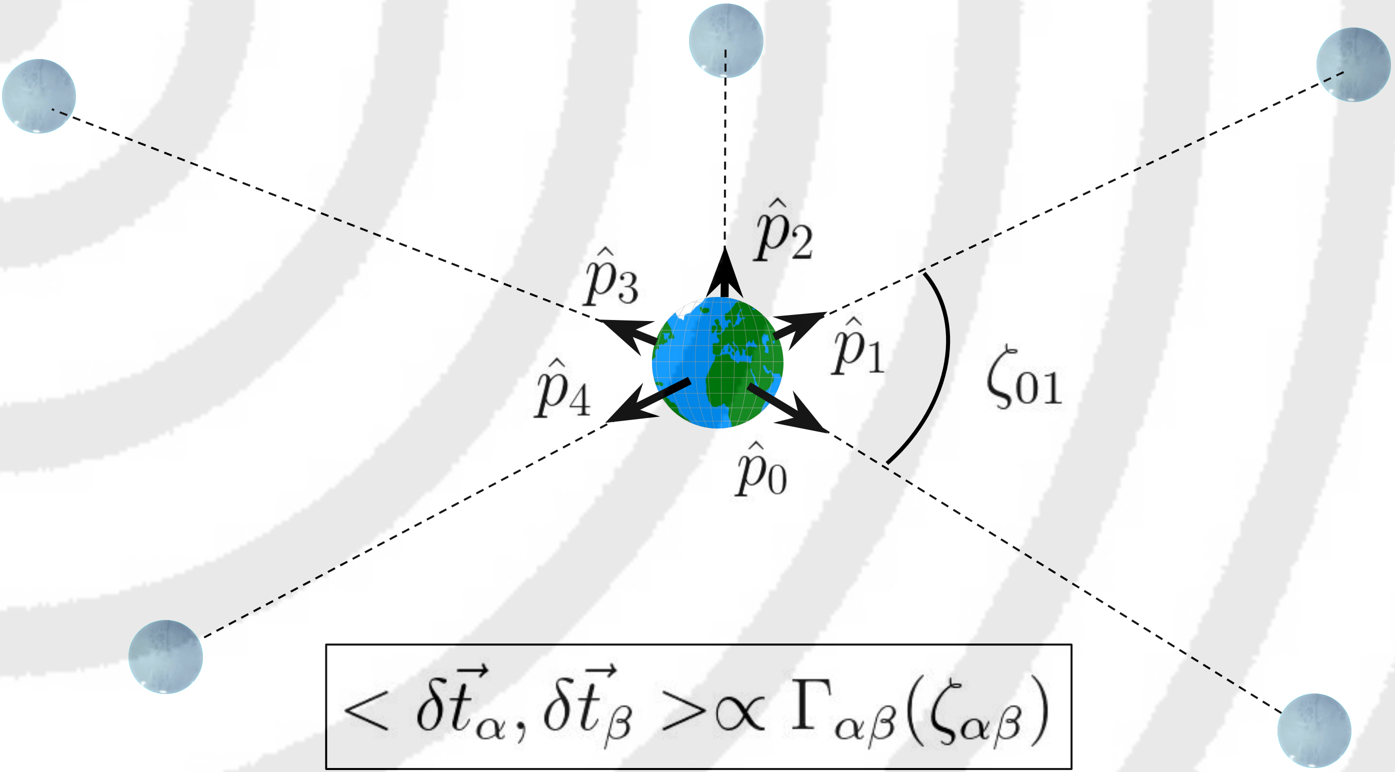
...the measured differences are the **timing residuals**

The Pulsar Timing Array (PTA)



$$\delta t = \bigcup_{\alpha} \delta \vec{t}_{\alpha}$$

The Pulsar Timing Array (PTA)



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

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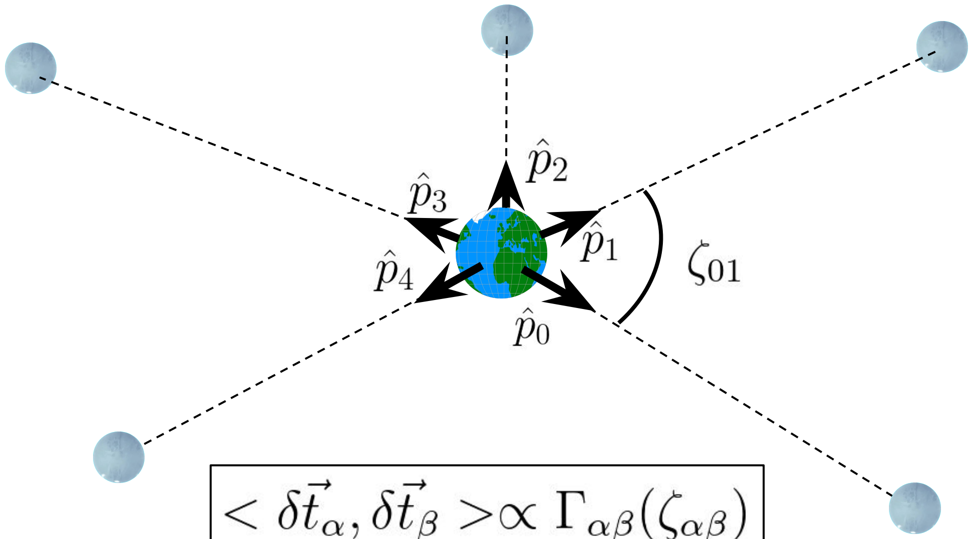

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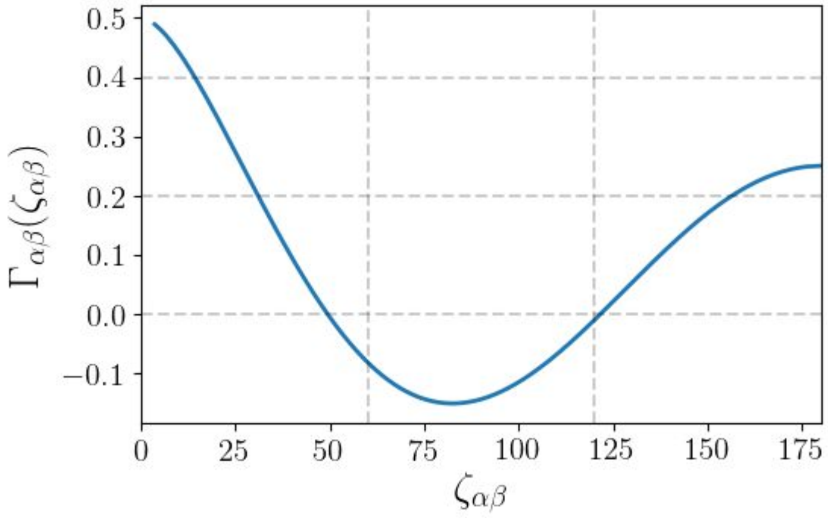
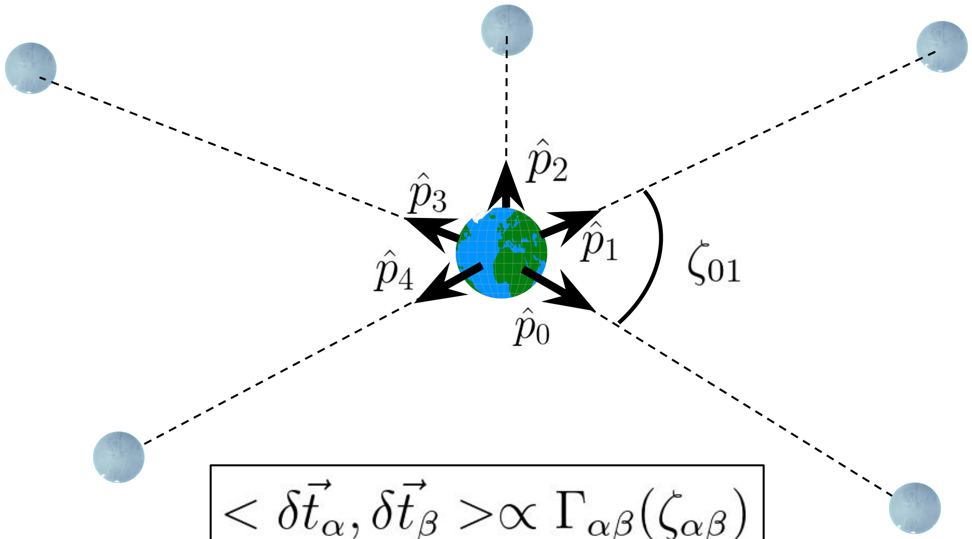


Hellings-Downs correlation pattern

The Pulsar Timing Array (PTA)



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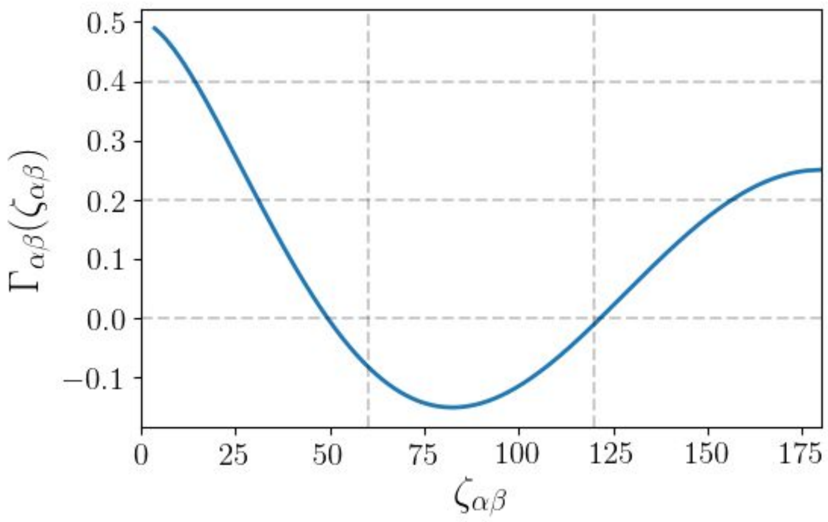


Hellings-Downs correlation pattern

with a PSD of $S_{\alpha\beta}(f) \propto f^{-13/3}$ → for circular SMBHB induced GW background

Data analysis

- Fit a **timing model** to **predict the TOAs** and get the **timing residuals**
- Build a **noise** model: **white** noise, **red** noise, **dispersion variation** noise
- **Noises** are modelled as **gaussian processes**, encoded in the **covariance matrix C**
- **Bayesian** analysis (set **prior probability** for parameters)

Posterior probability :

$$p(\delta t|\vec{\theta}) = \frac{1}{\sqrt{\det(2\pi \mathrm{C})}} \exp\left(-\frac{1}{2}\delta t^T \mathrm{C}^{-1} \delta t\right) \Pi(\vec{\theta})$$

Residuals:

$$\delta t \rightarrow \delta t - \sum_{i=1}^{N_{\mathrm{signals}}} s_i(\vec{\lambda}_i)$$

→ <u>Deterministic signals</u> (CGW, ephemeris, ...)

Data analysis

- **Bayesian** analysis for **model selection**
- Estimate the **Bayes factor** to evaluate the **significance** of **Hellings–Downs spatial correlations**
- The **Bayes factor** is defined as the **ratio of the evidences**

$$\mathcal{Z}_M = \int d\vec{\theta}_M p_M(\delta t|\vec{\theta}_M) \quad \longrightarrow \quad \boxed{\mathcal{B}^A_B = \frac{\mathcal{Z}_A}{\mathcal{Z}_B}}$$

Data analysis

- The covariance matrix is made of **diagonal autocorrelated terms Σ^{α}** describing the **intrinsic noise properties** of pulsars and **cross correlated terms $\Sigma^{\alpha\beta}$** describing the **common correlated signals** (like the stochastic GW background)

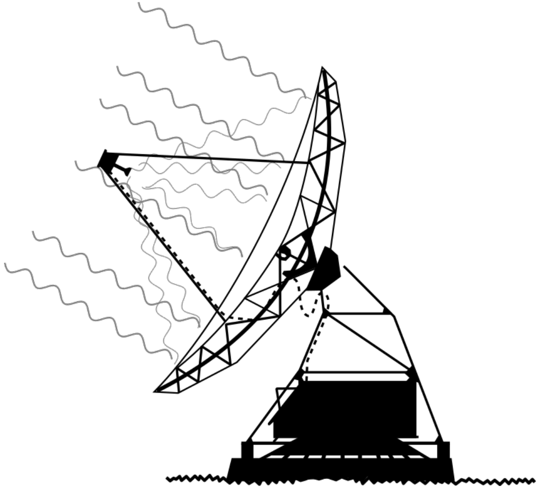
Common correlated signal

$$\mathbf{C} = \begin{bmatrix} \mathbf{\Sigma^0} & \Sigma^{01} & \dots & \Sigma^{0N} \\ \Sigma^{10} & \mathbf{\Sigma^1} & \dots & \Sigma^{1N} \\ \vdots & \vdots & \ddots & \vdots \\ \Sigma^{N0} & \Sigma^{N1} & \dots & \mathbf{\Sigma^N} \end{bmatrix}$$

No common correlated signal

$$\mathbf{C} = \begin{bmatrix} \mathbf{\Sigma^0} & 0 & \dots & 0 \\ 0 & \mathbf{\Sigma^1} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \mathbf{\Sigma^N} \end{bmatrix}$$

Data analysis



Credits: CAMRAS Tammo Jan Dijkema

White noise : measurement errors (radiometer noise) + systematics

$$S_{WN} = \sigma^2 \delta(f - f')$$

Red noise : low frequency noise on pulsar rotation

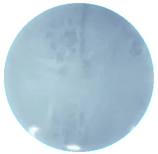
$$S_{RN} = A_{RN} f^{-\gamma_{RN}}$$

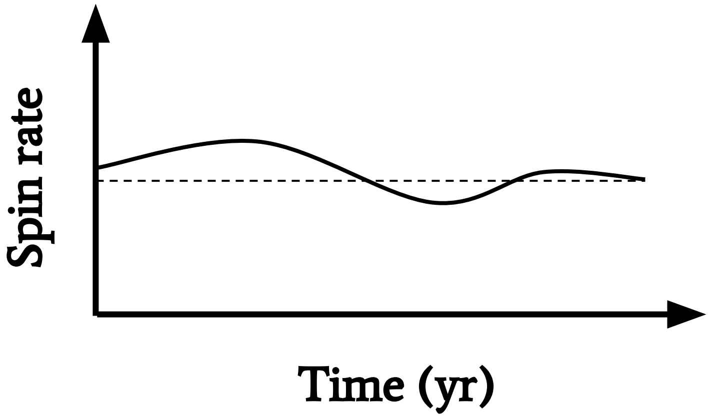
Dispersion noise : dispersion due to propagation through interstellar medium

$$S_{DM} = (\frac{K_{DM}}{\nu^2}) A_{DM} f^{-\gamma_{DM}}$$

$$\Sigma^\alpha = \sigma^2_{\alpha,WN}\delta_{ij} + \Sigma^\alpha_{RN} + \Sigma^\alpha_{DM} (+\Sigma^{\alpha\beta}_{GW})$$

Data analysis





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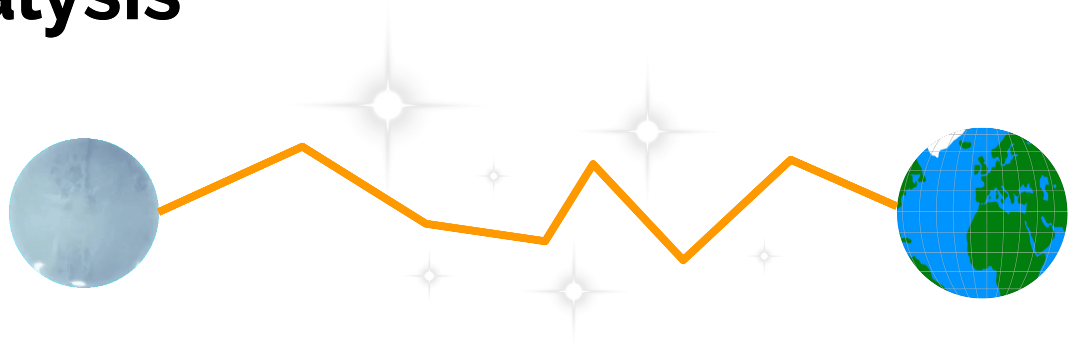

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Data analysis

Stochastic Gravitational Wave Background : noise term, correlated across pulsars in array

$$S_{GW} = \Gamma_{\alpha\beta} A_{GW} f^{-\gamma_{GW}}$$

White noise : measurement errors (radiometer noise) + systematics

$$S_{WN} = \sigma^2 \delta(f - f')$$

Red noise : low frequency noise on pulsar rotation

$$S_{RN} = A_{RN} f^{-\gamma_{RN}}$$

Dispersion noise : dispersion due to propagation through interstellar medium

$$S_{DM} = (\frac{K_{DM}}{\nu^2}) A_{DM} f^{-\gamma_{DM}}$$

$$\Sigma^{\alpha} = \sigma^2_{\alpha,WN}\delta_{ij} + \Sigma^{\alpha}_{RN} + \Sigma^{\alpha}_{DM} \boxed{(+\Sigma^{\alpha\beta}_{GW})}$$

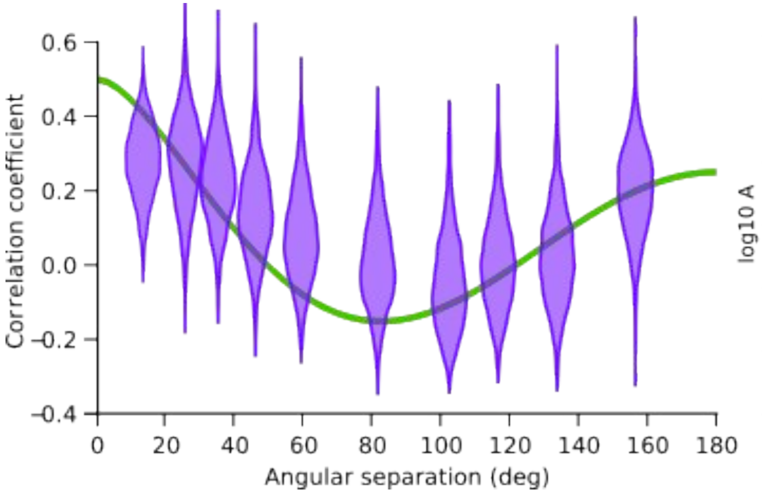
Results

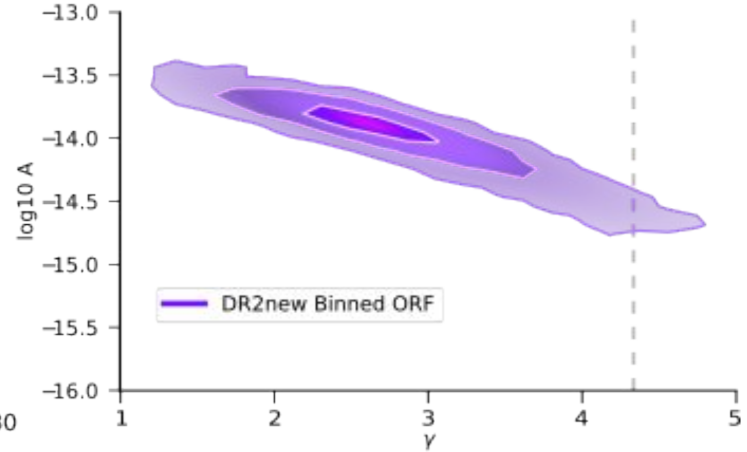
- The gravitational wave background
- Estimating the significance
- Other sources

Results EPTA DR2 + InPTA : Gravitational wave background

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

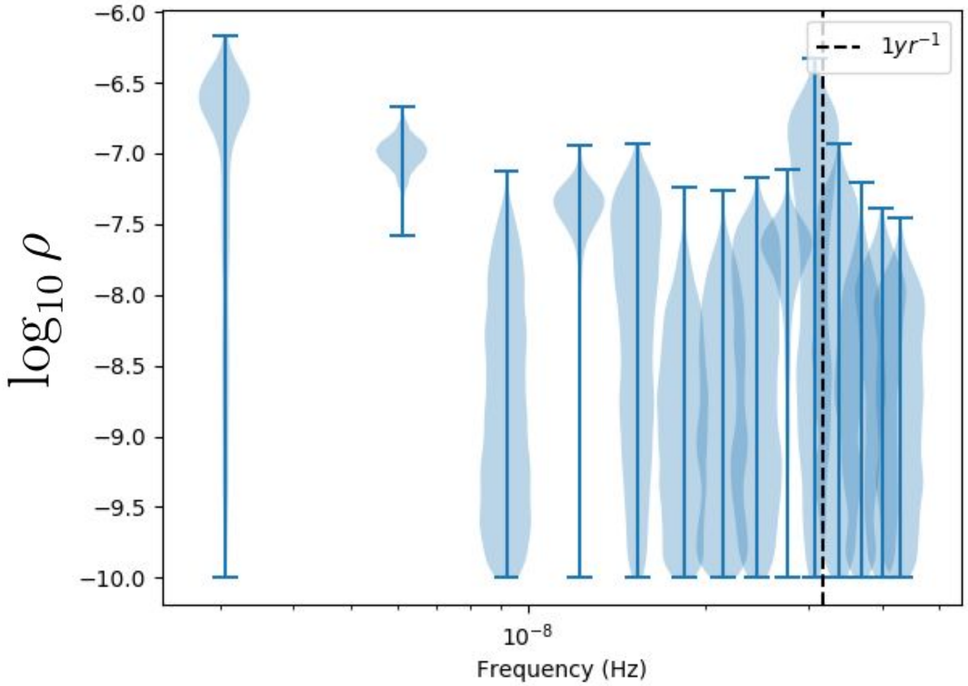
$$S^{SGWB}_{\alpha\beta} = \Gamma^{H-D}_{\alpha\beta} A^2_{GW} f^{-\gamma}$$





arXiv: 2306.16214 : ***The second data release from the European Pulsar Timing Array III. Search for gravitational wave signals, 2023***

Results EPTA DR2 + InPTA : Gravitational wave background

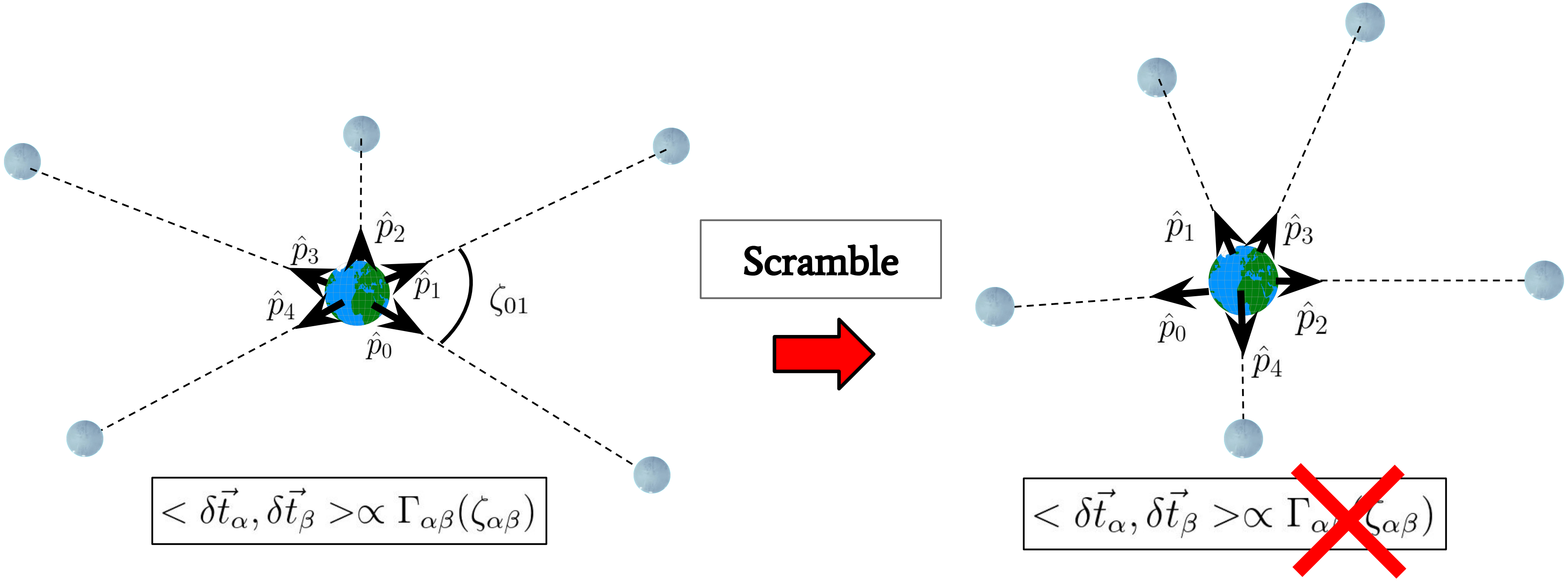


arXiv: 2306.16227: Sesana et al

$$S^{HD}_{\alpha\beta}(f) = \Gamma_{\alpha\beta} \sum_i \rho_i^2 \delta_{ff_i}$$

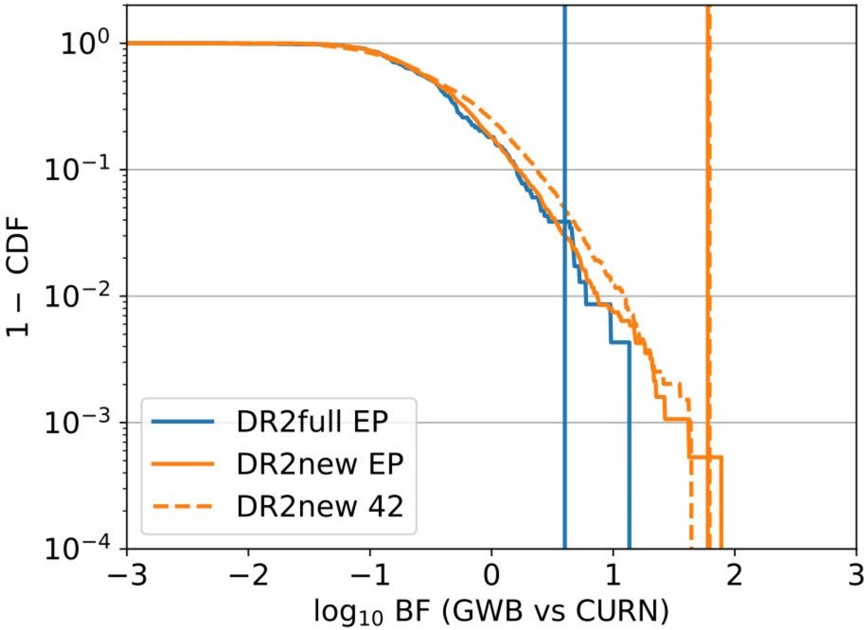
- **Free spectrum** gives a **probabilistic estimate of PSD**
- Only **few frequency bins** are **well constrained**
- Excess of **power** at **low frequencies**

Results EPTA DR2 + InPTA : Significance



How likely is it to observe $\boldsymbol{\Gamma_{\alpha\beta}}$ *given our data for a random configuration of pulsars ?*

Results EPTA DR2 + InPTA : Significance



arXiv: 2306.16214

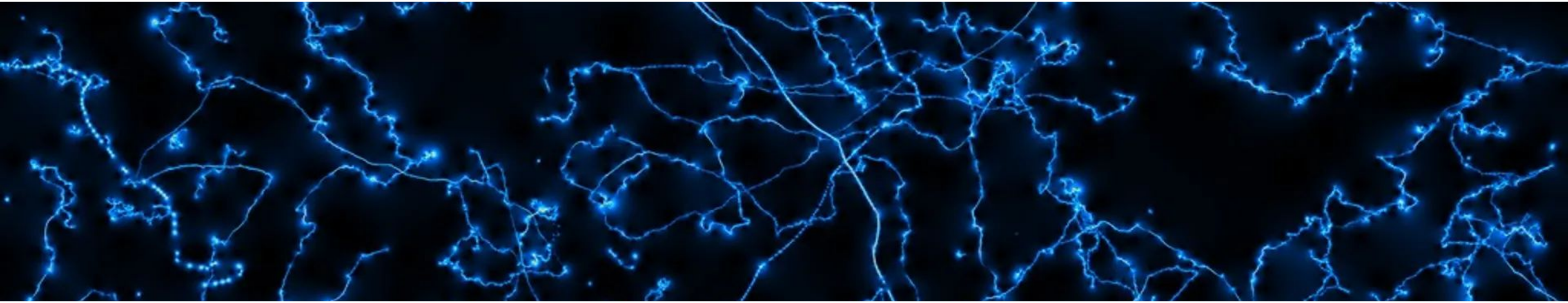
- We construct the **distribution** of **BF(HD/CURN)** under **null hypothesis (no GW)** by estimating **BF(HD/CURN)** for thousands of different **scrambles**
- We estimate the **p-value** from our actual measurement of **BF(HD/CURN)** with no scrambles

$$p \sim 3.5\sigma$$

Results EPTA DR2 + InPTA : Other sources ?

- **Continuous gravitational wave :** individual SMBHBs
- **Cosmic strings,**
- **Inflationary GWB,**
- **Next talk** on **tuesday :** ***Alternative interpretation of DR2 new,*** Hippolyte **Quelquejay-Leclere**

Credits : A simulated image of cosmic strings - Chris Ringeval

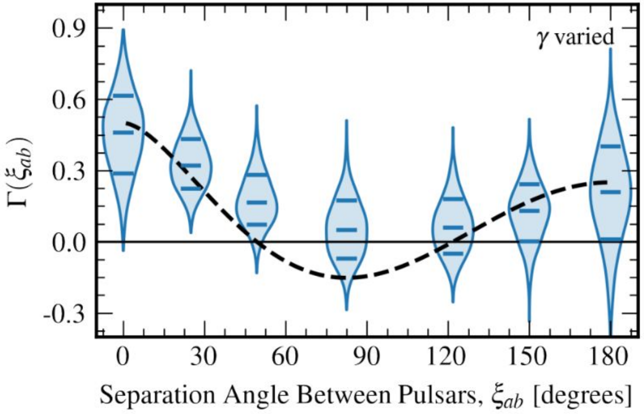


Conclusion

- There is **strong evidence** for a **gravitational wave signal** in the **second data release** of the **EPTA collaboration**
- The **p-value** for the presence of a **GW signal** is of **3.5σ**
- The **main candidate** for this signal is the **stochastic GWB** from **SMBHB**
- At the **current stage** it is **impossible to determine** the **exact origin** of this **GW signal**
- The **combination** of all **PTA datasets** for the **International PTA collaboration's 3rd data release** will **increase** our **sensitivity** and shed new light on the origins of this signal

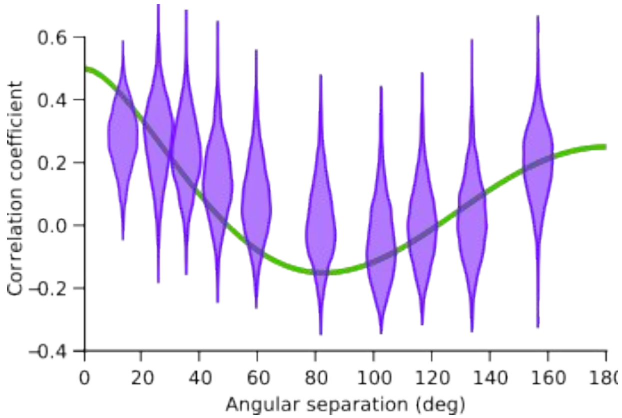
Thank you for your attention

NANOGrav, 2023
15 years, 70 PSRs
4σ



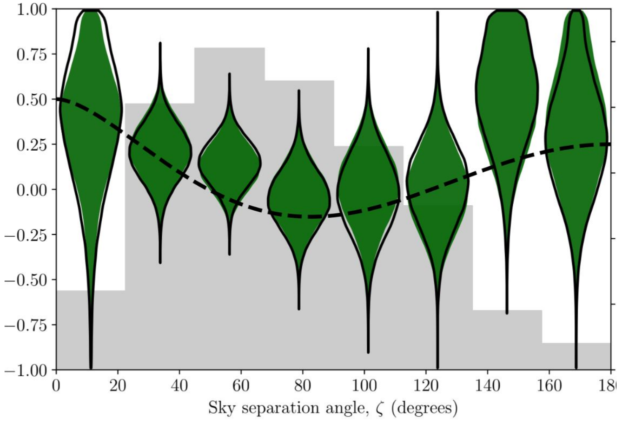
arXiv: 2306.16213

EPTA+InPTA, 2023
10.3 years, 25 PSRs,
3.5σ



arXiv: 2306.16214

PPTA, 2023
18 years, 32 PSRs
2σ



arXiv: 2306.16215