Probing the Universe using Pulsar Timing Arrays

with the European Pulsar Timing Array data

https://docs.google.com/presentation/d/1LU7FxaK8XofzDoKCdy5JmwgiAVpjONorGFEkvZTFUZA/edit?usp=sharing

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Credit: OzGrav/Swinburne, Carl Knox

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- Context
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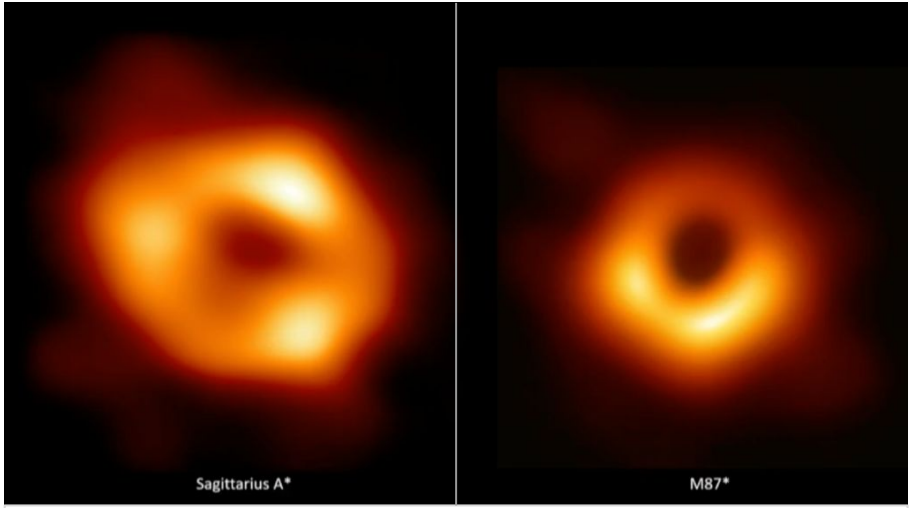
Context

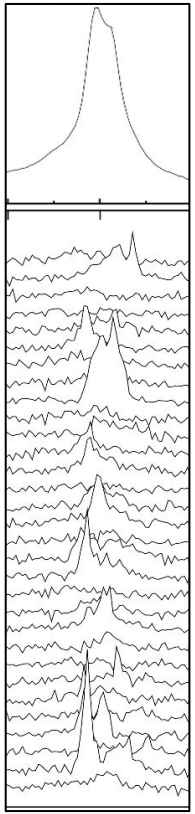
- **Gravitational Waves (GW)**
  - **GWs** are predicted by Einstein's theory of **General Relativity**
  - They are **perturbations** of the **geometry (curvature)** of **space time radiated** by **massive binary systems**
  - They were **first detected in 2015** by the **LIGO/Virgo Collaboration**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

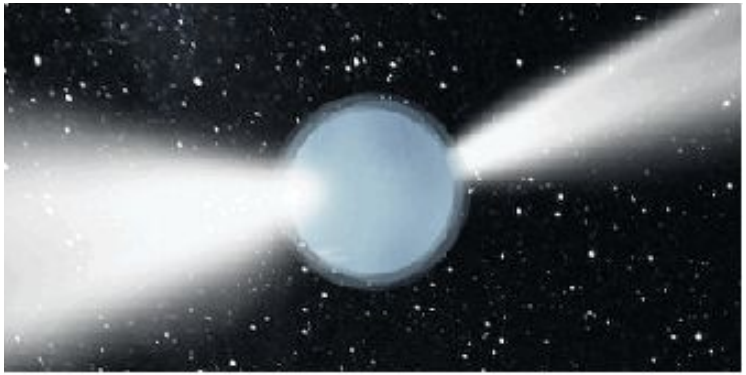


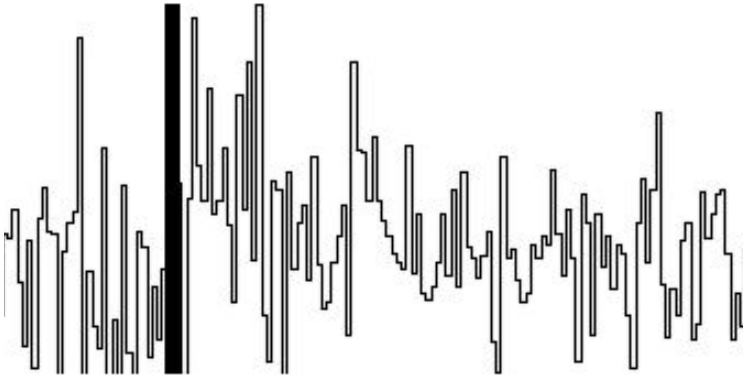
Credit : Event Horizon telescope collaboration

- **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





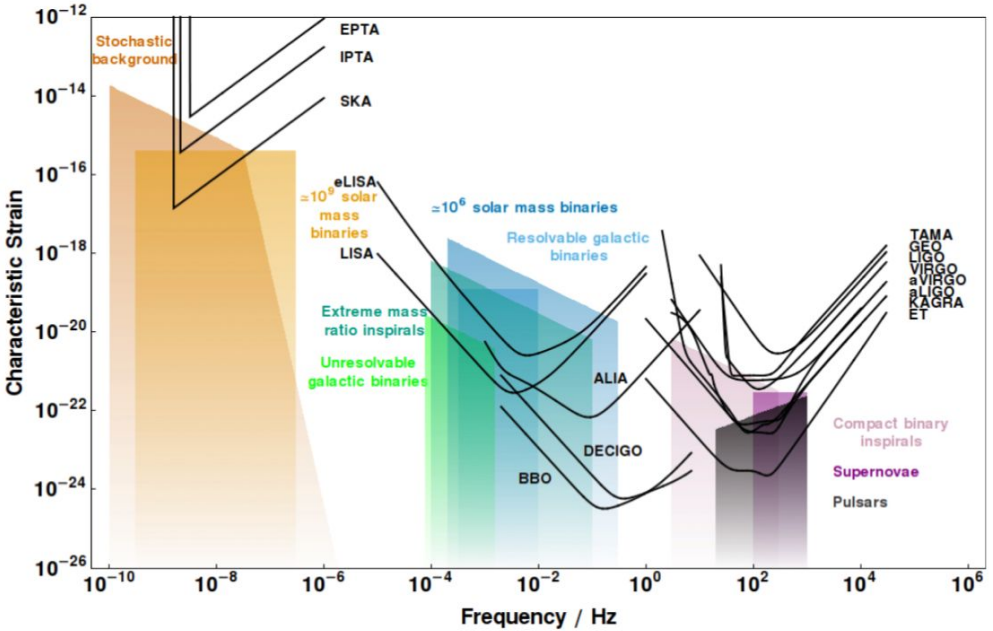


- **Millisecond pulsars (MSP)**
  - **Pulsars** are very dense, highly magnetized and **rapidly rotating neutron** stars emitting beams of EM radiation making them appear on Earth as **series of pulses**
  - A **MSP** is an **old neutron** star that got **spun up (recycled)** by stealing gas and angular 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

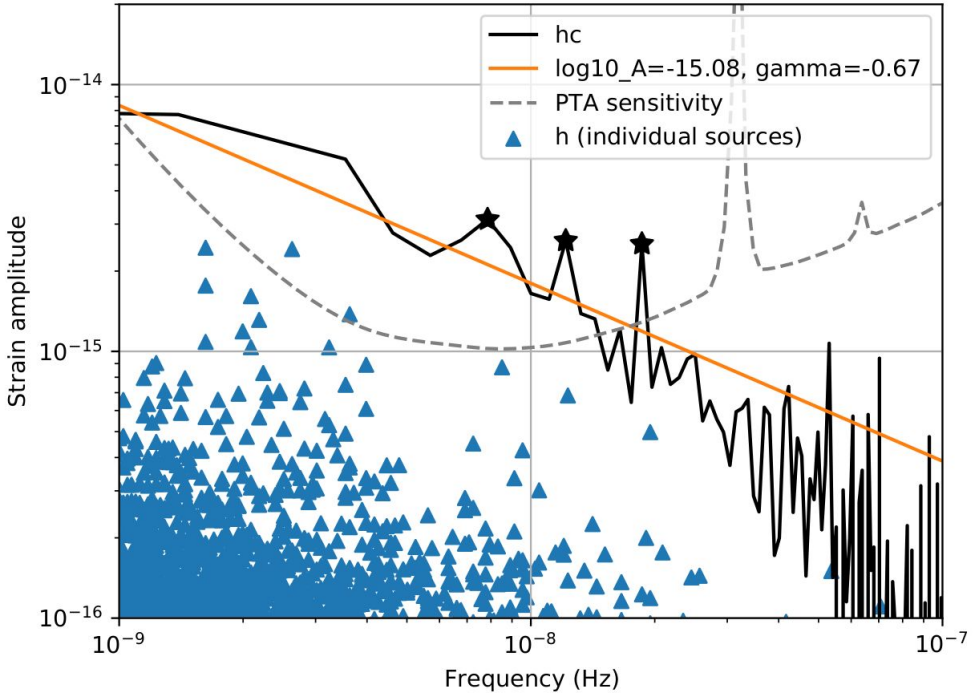
Context

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

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

Data analysis for GW detection

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



The EPTA + InPTA collaboration

Partner telescopes:

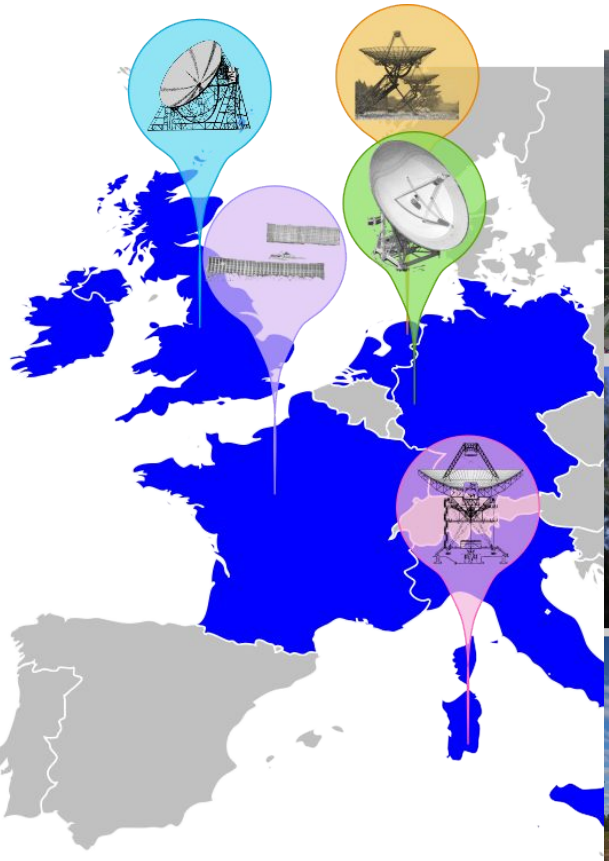
- Effelsberg
- Lovell
- Nancay Radio Telescope
- Sardinia Radio Telescope
- Westerbork Synthesis Radio Telescope

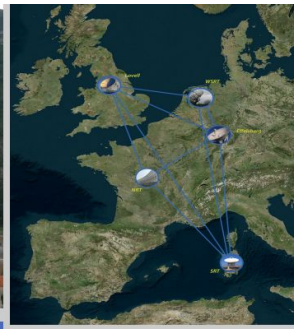
+

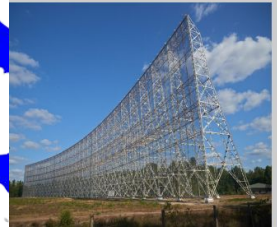
GMRT in India

+

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





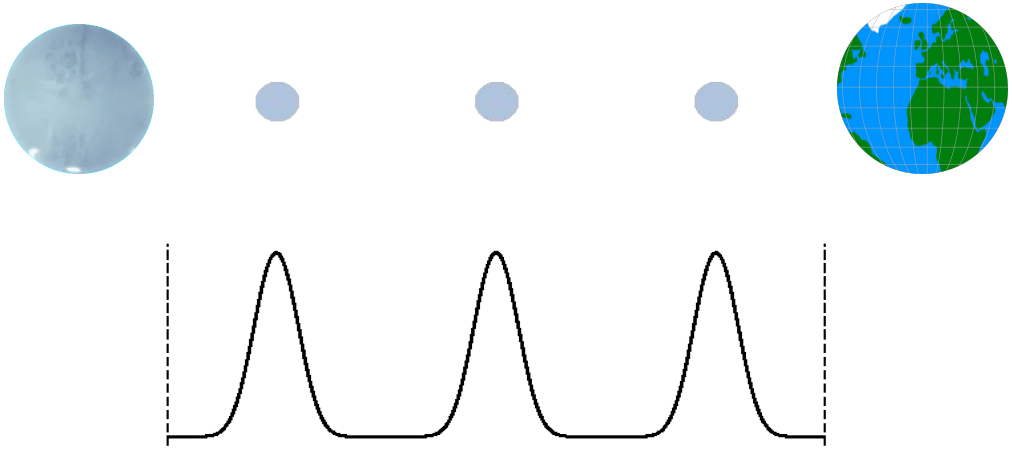


The Pulsar Timing Array

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

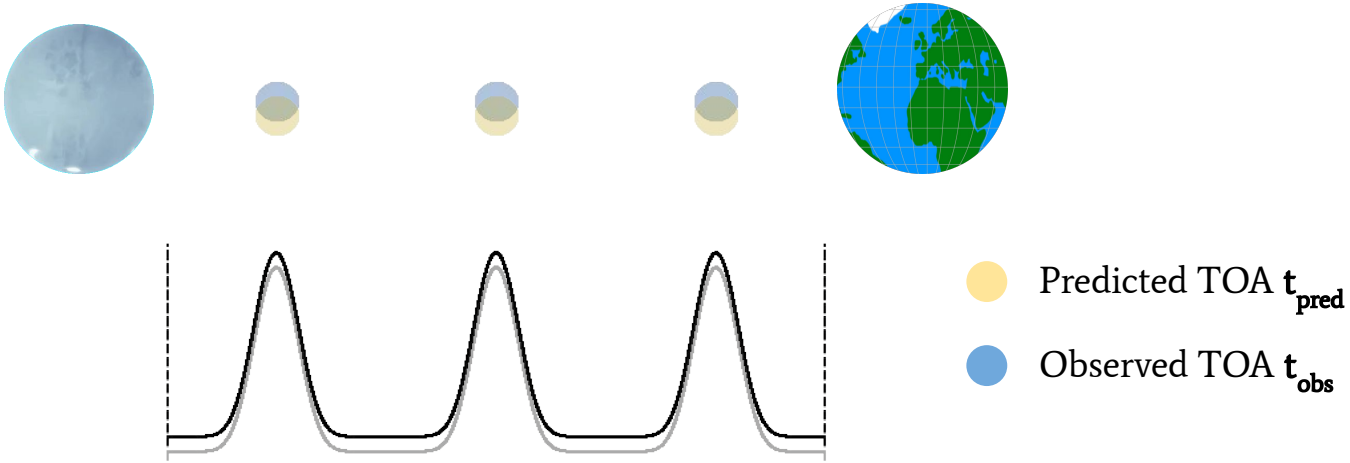
The Pulsar Timing Array (PTA)

Millisecond pulsars are very stable.



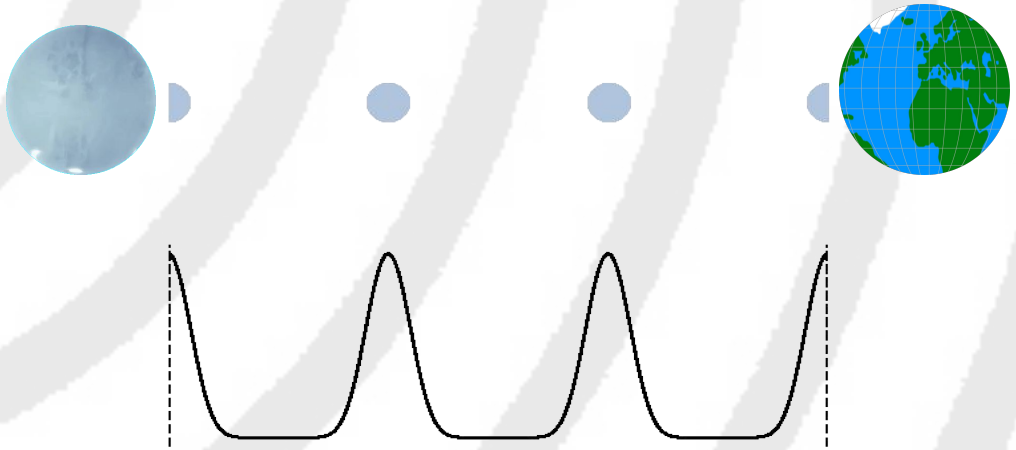
The Pulsar Timing Array (PTA)

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



The Pulsar Timing Array (PTA)

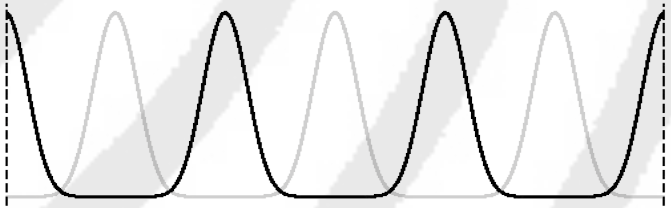
The **gravitational wave** signal **modulates** the expected **TOAs** of pulses...



The Pulsar Timing Array (PTA)

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

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

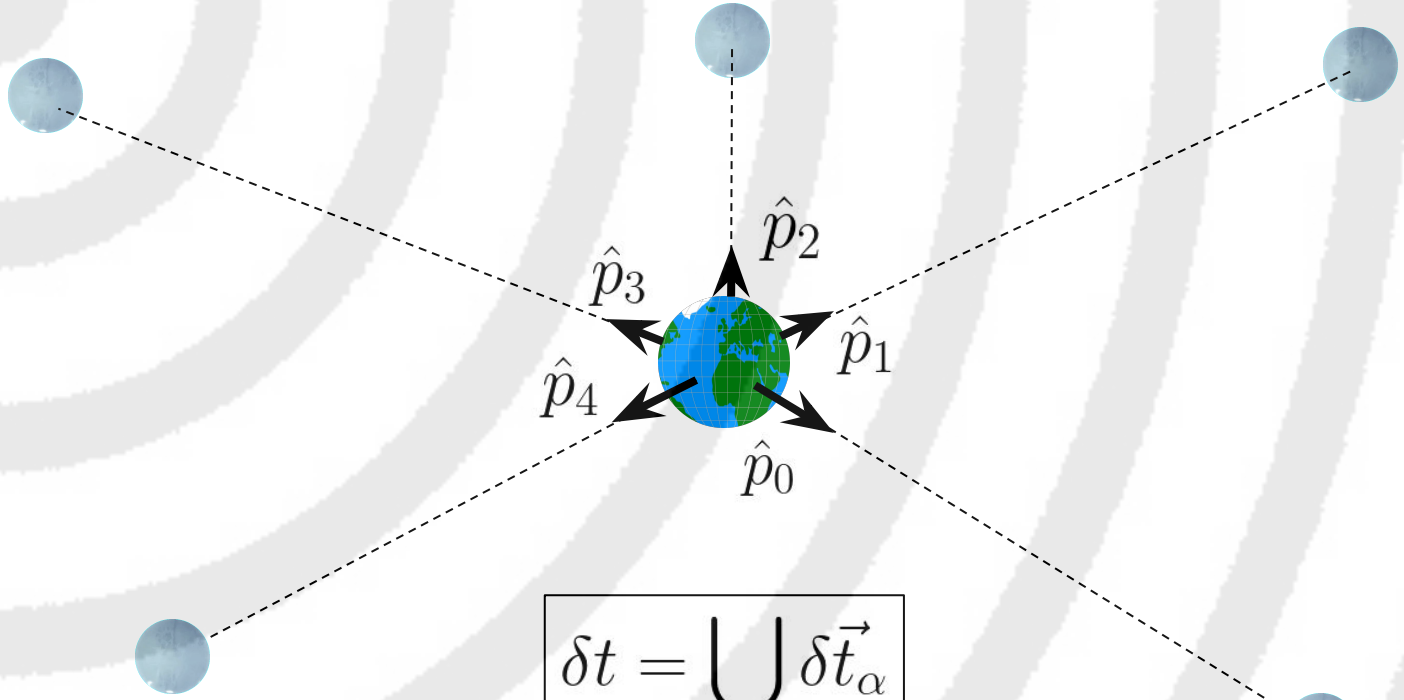


without GW t_{pred}

with GW t_{obs}

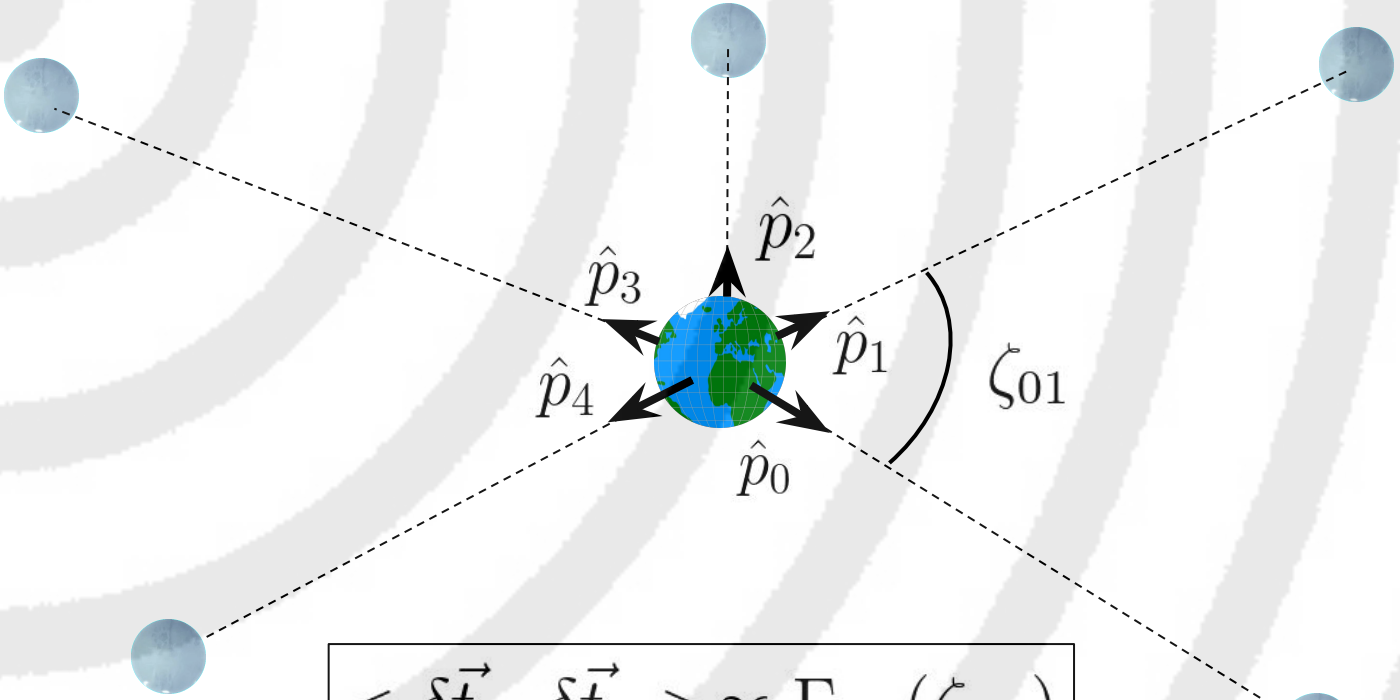
...the measured differences are the **timing residuals**

The Pulsar Timing Array (PTA)



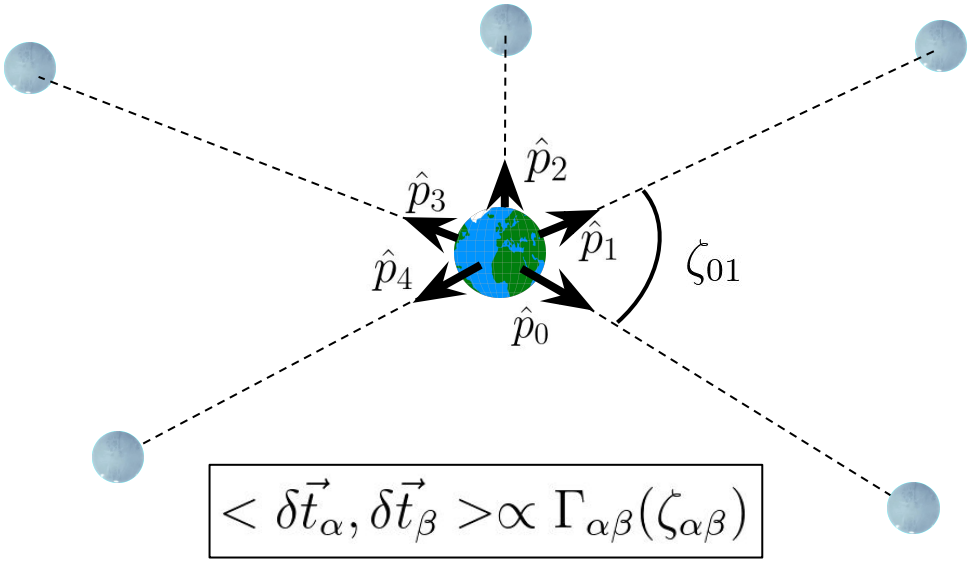
$$\delta t = \bigcup_{\alpha} \delta \vec{t}_{\alpha}$$

The Pulsar Timing Array (PTA)



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

The Pulsar Timing Array (PTA)



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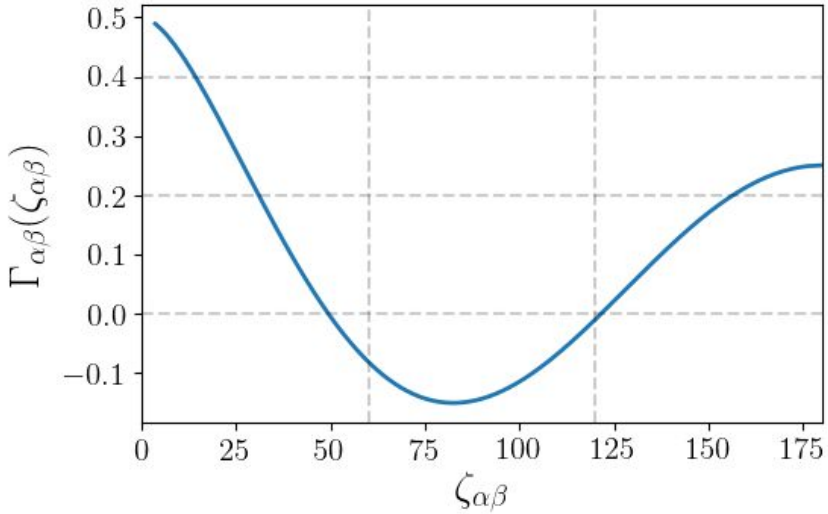
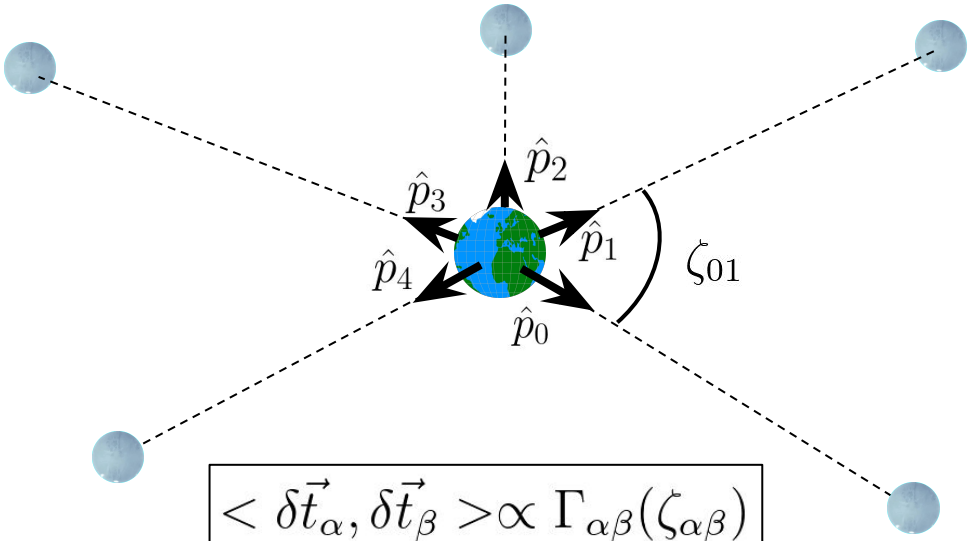


Hellings-Downs correlation pattern

The Pulsar Timing Array (PTA)



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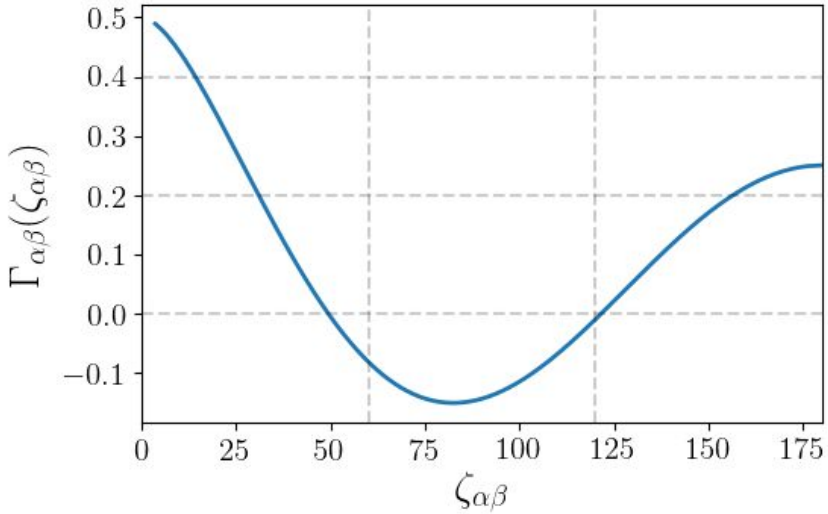
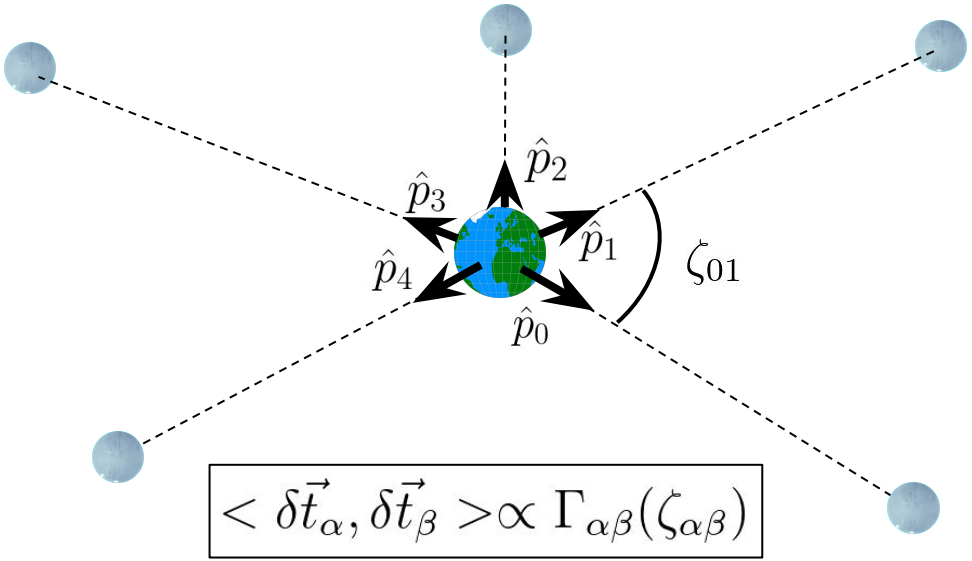


Hellings-Downs correlation pattern

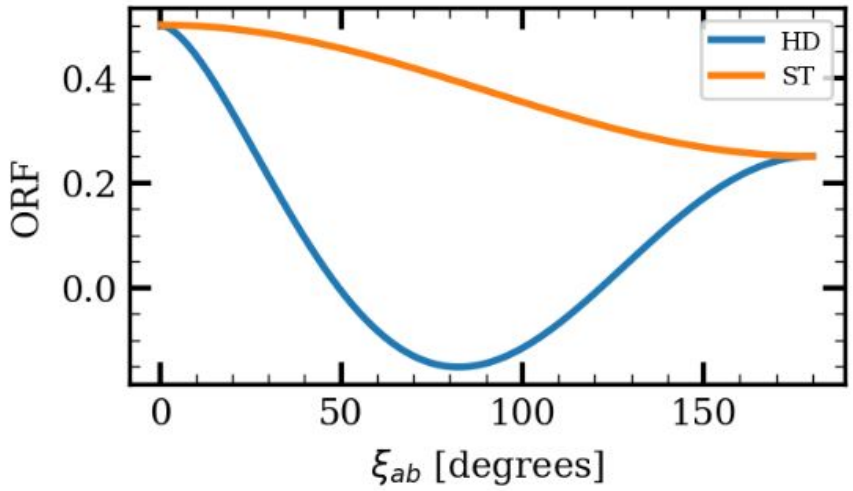
with a PSD of $S_{\alpha\beta}(f) \propto f^{-13/3}$ → for circular SMBHB induced GW background

The Pulsar Timing Array (PTA)

Non-Einsteinian polarization modes also searched for ! (2310.12138)



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



Hellings-Downs correlation pattern

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

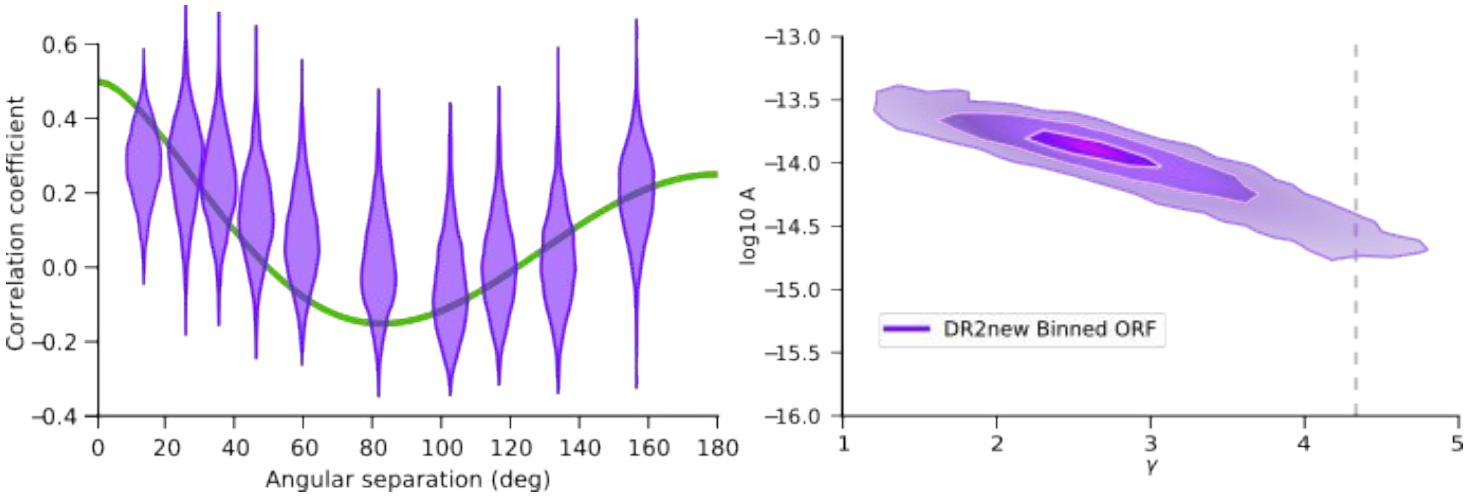
Results

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

Results EPTA DR2 + InPTA : Gravitational wave background

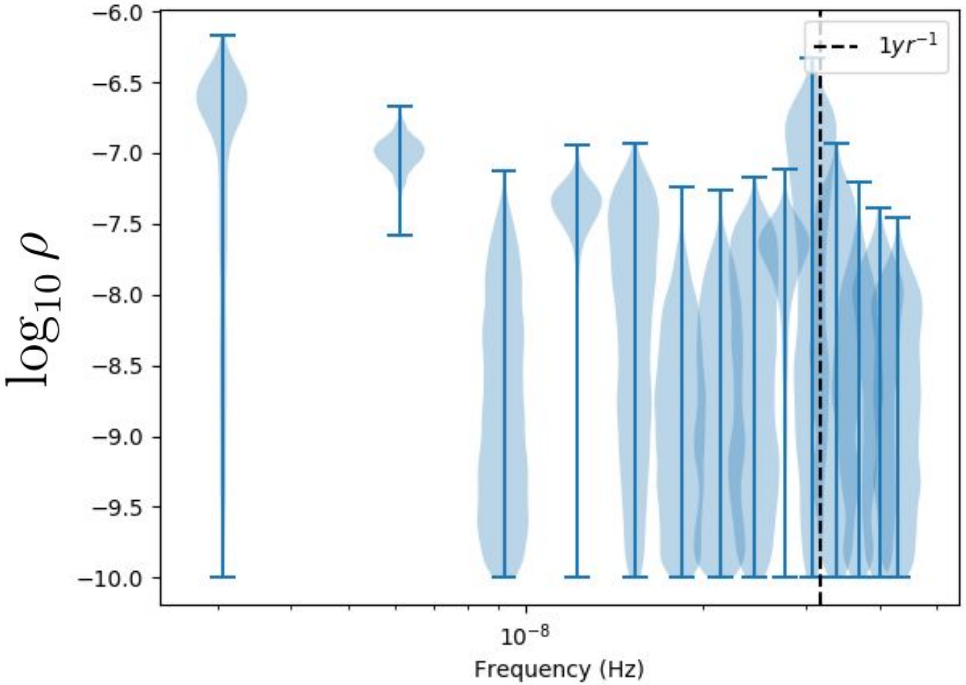
$$\mathcal{B}^{HD}_{CURN} = 65$$

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



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: EPTA/InPTA

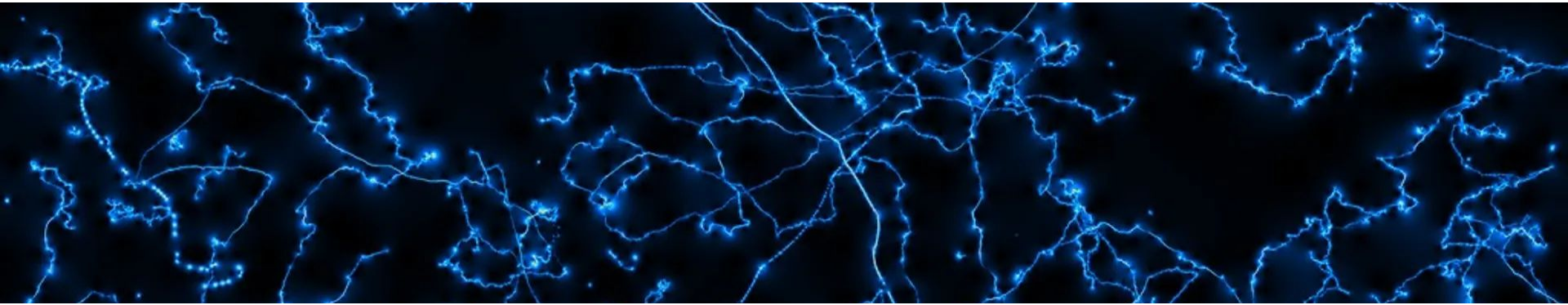
$$S^{HD}_{\alpha\beta}(f) = \Gamma_{\alpha\beta} \sum_i \rho_i^2 \delta_{f f_i}$$

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

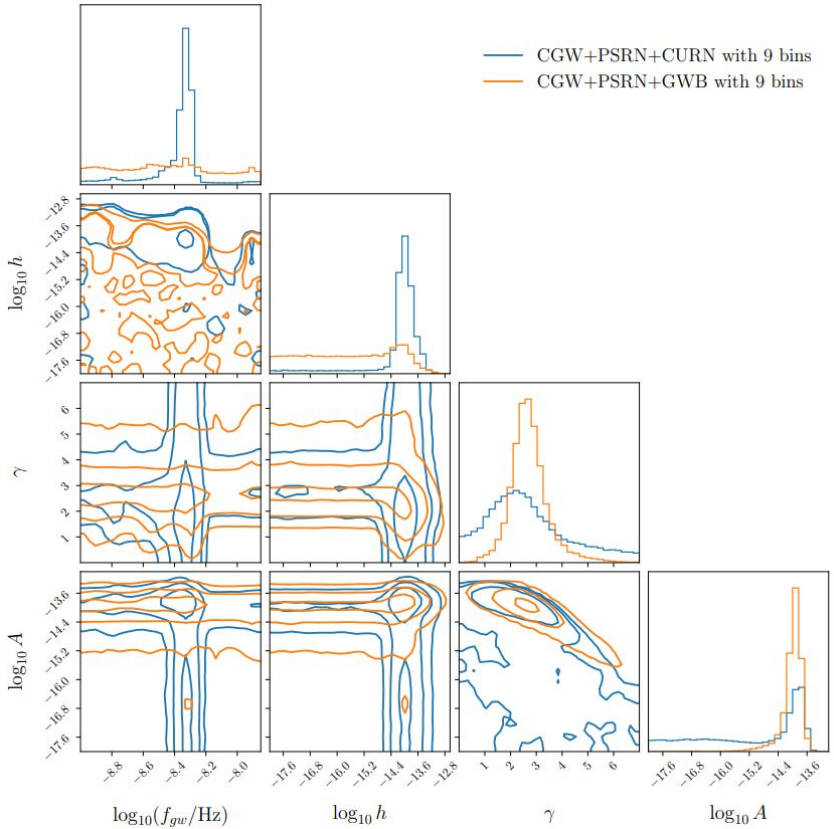
Results EPTA DR2 + InPTA : Other sources ?

- **Continuous gravitational wave :** individual SMBHBs
- **Cosmic strings,**
- **Inflationary GWB**
- **And many more...**

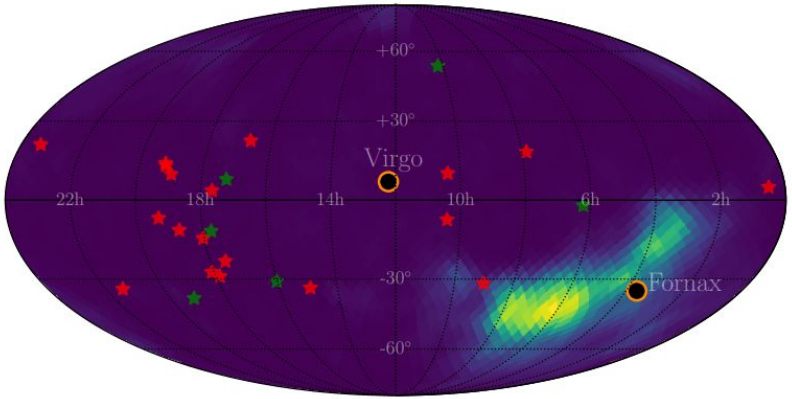
Credits : A simulated image of cosmic strings - Chris Ringeval



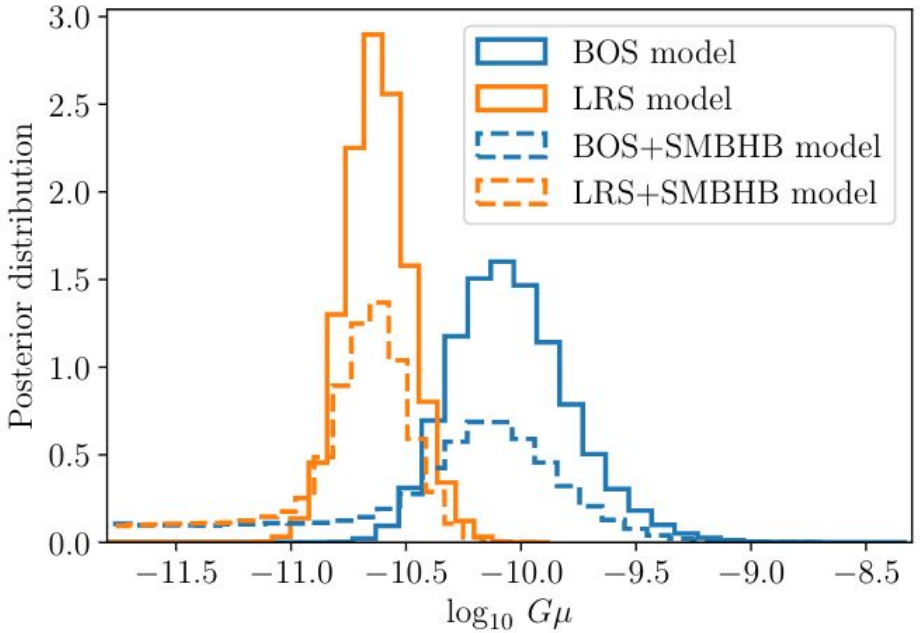
Results EPTA DR2 + InPTA : Continuous GW



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



Results EPTA DR2 + InPTA : Cosmic strings

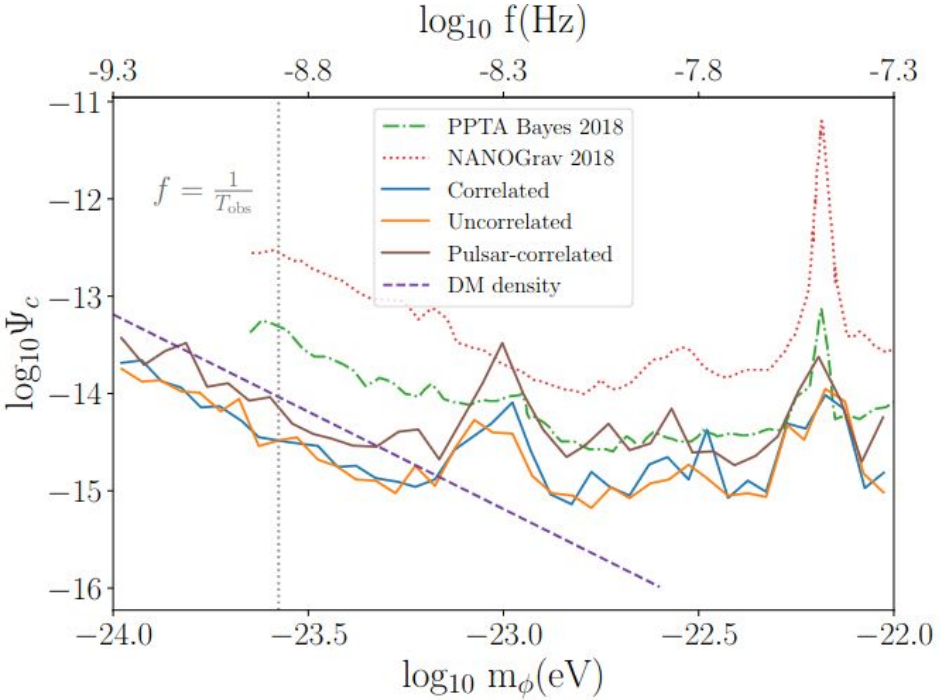


- **Cosmic strings** are **line-like topological defects** that may form after a **symmetry-breaking phase transition** in the **early Universe**
- They produce **GW bursts** through **cusps** and **kinks**
- The **sum** of **GW bursts** produces a **GWB**
- The **amplitude of burst** depends on the **string tension** **Gμ**

arXiv: 2306.16227: EPTA/InPTA

Results EPTA DR2 + InPTA : ULDM

$$\delta t_{\rm DM} = \frac{\Psi_{\rm c}(\vec{x})}{2m_\phi}[\hat{\phi}^2_{\rm E}\sin(2m_\phi + \gamma_{\rm E}) - \hat{\phi}^2_{\rm P}\sin(2m_\phi + \gamma_{\rm P})],$$



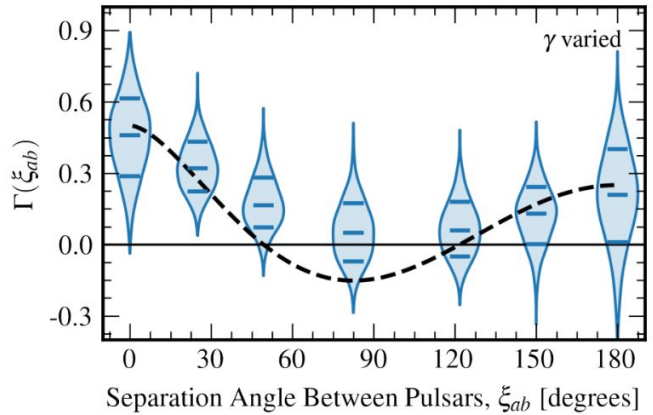
- **Ultra light dark matter interacting gravitationally** with **baryonic matter**
- **Axion-like field**
- **$10^{-24.0}$ eV ≲ m ≲ $10^{-23.3}$ eV**
- **Cannot make-up** for **100%** of the **observed dark matter**
- **Upper limit local density ρ ≲ 0.3 GeV/cm ^{3}**
- See : **2306.16228 (Smarra et al.)**

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

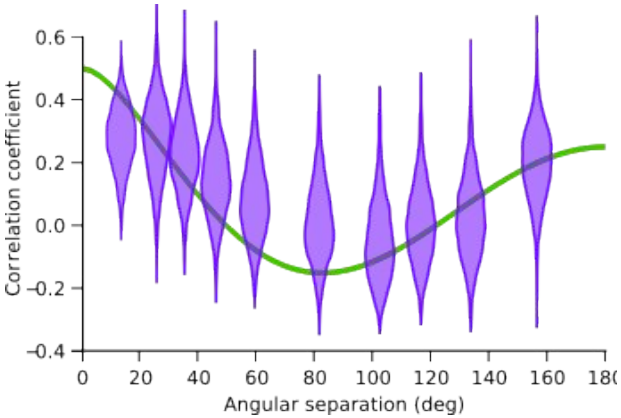
Thank you for your attention

NANOGrav, 2023
15 years, 70 PSRs
4σ



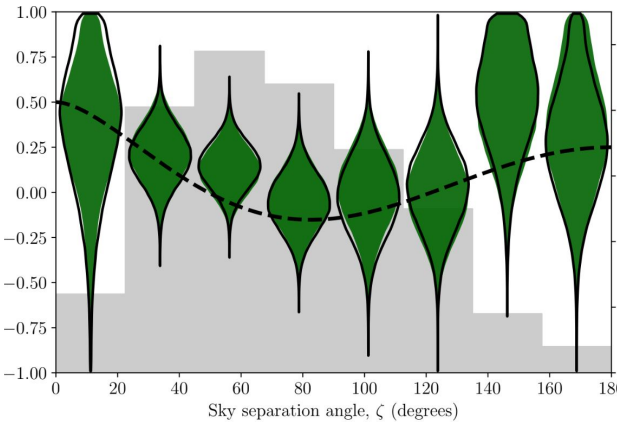
arXiv: 2306.16213

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



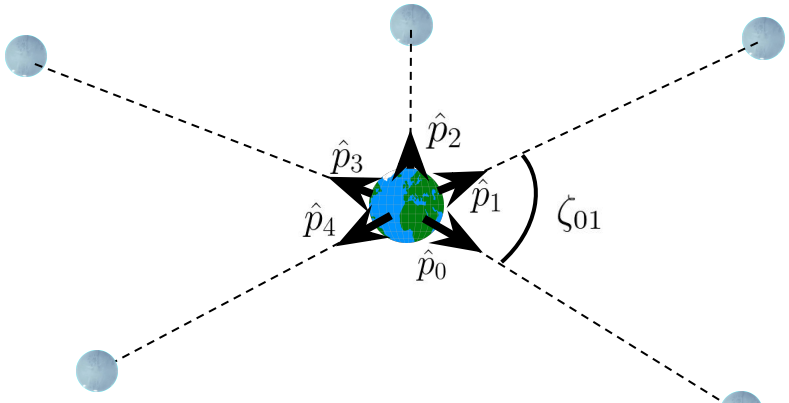
arXiv: 2306.16214

PPTA, 2023
18 years, 32 PSRs
2σ



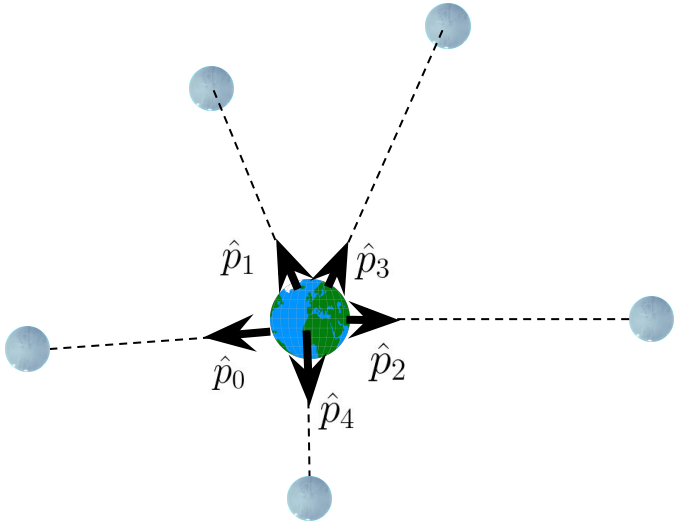
arXiv: 2306.16215

Results EPTA DR2 + InPTA : Significance



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

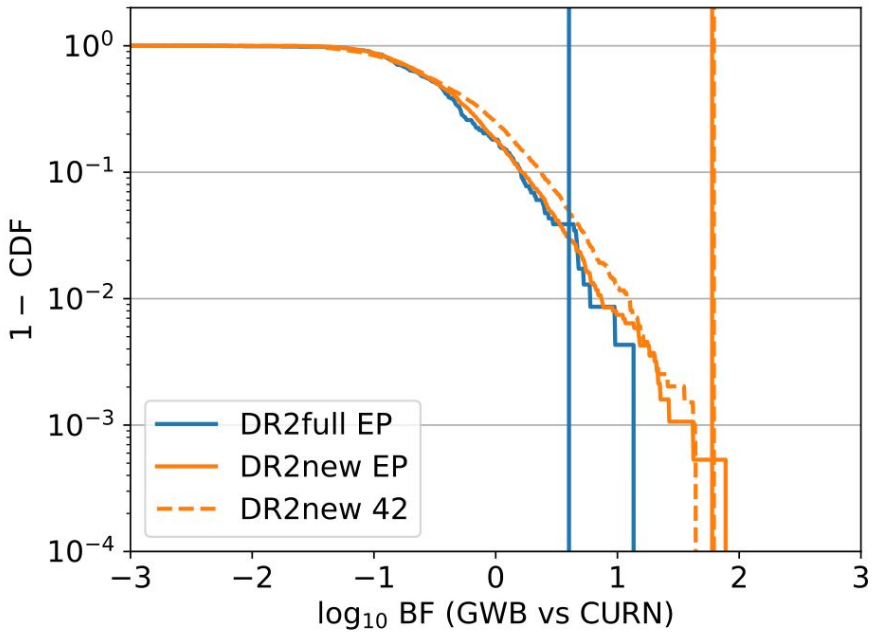
Scramble



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

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

Results EPTA DR2 + InPTA : Significance



- 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

$$p \sim 3.5\sigma$$

arXiv: 2306.16214