Searching for a Gravitational Wave Background with Pulsar Timing Arrays

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University of Wisconsin-Milwaukee

JENAS Workshop, Sapienza University
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Gravitational Wave Spectrum

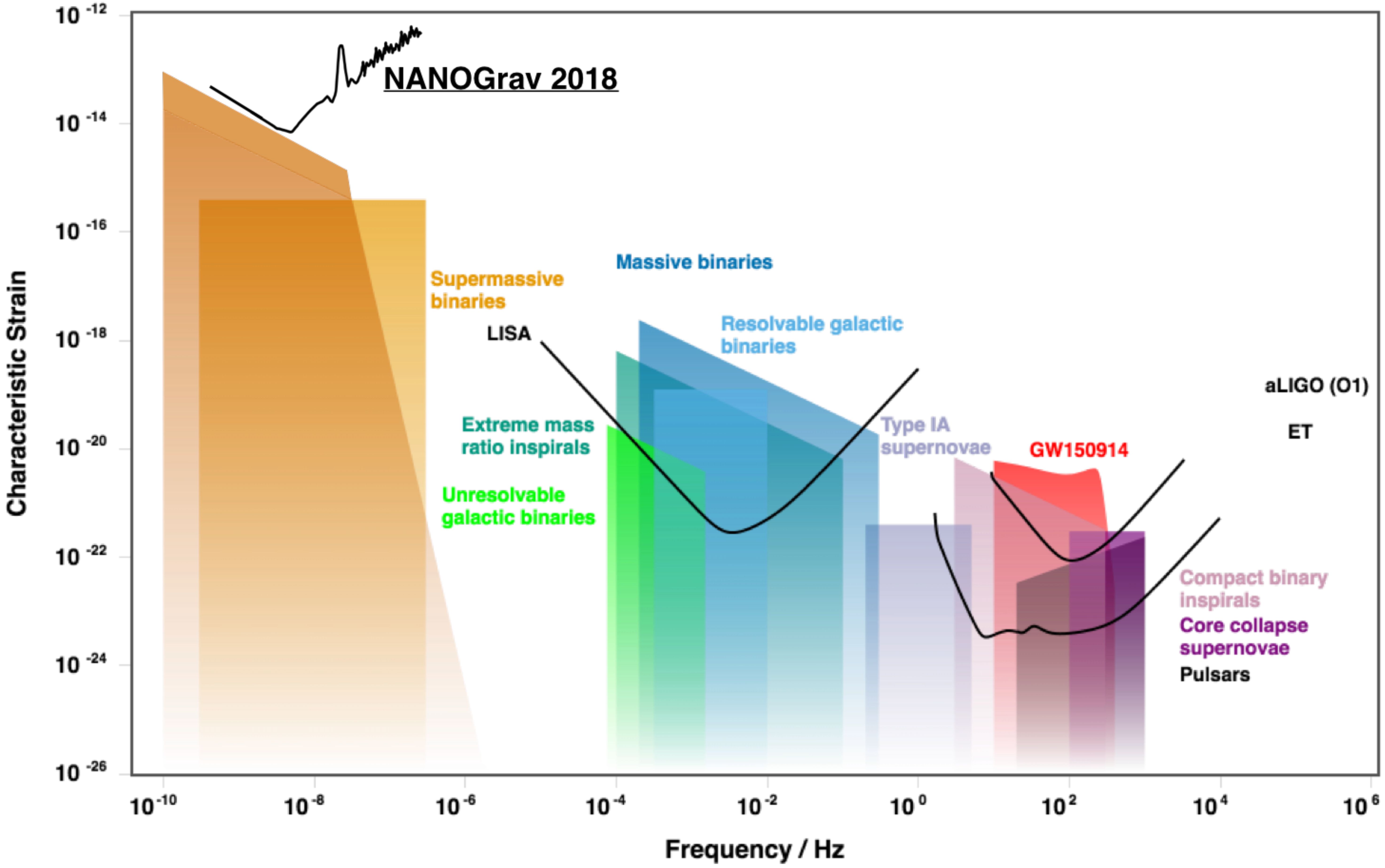

Figure credit: Moore, Cole, Berry (2014); modified by S. Taylor

Recently NANOGrav, the EPTA, the InPTA, the PPTA, and the CPTA all published papers where they present evidence for a gravitational wave background.

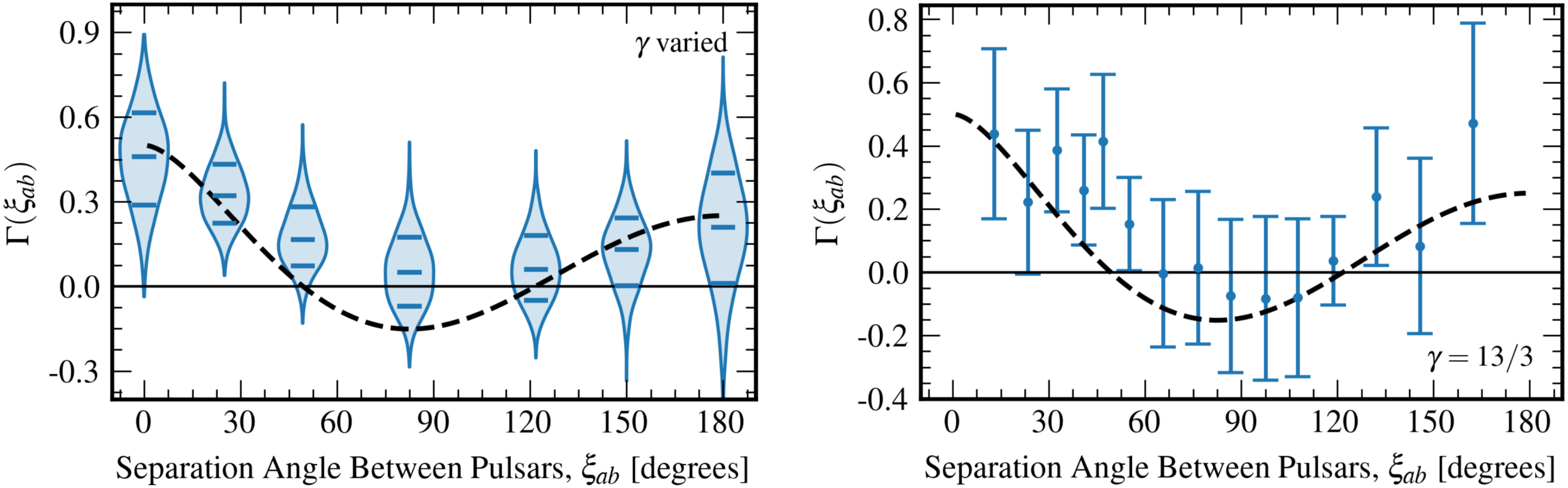

Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L8 (2023).

How do pulsar timing arrays detect gravitational waves?

What evidence is there that pulsar timing arrays have found nanohertz gravitational waves?

What could be producing this signal? And how can we determine the source?

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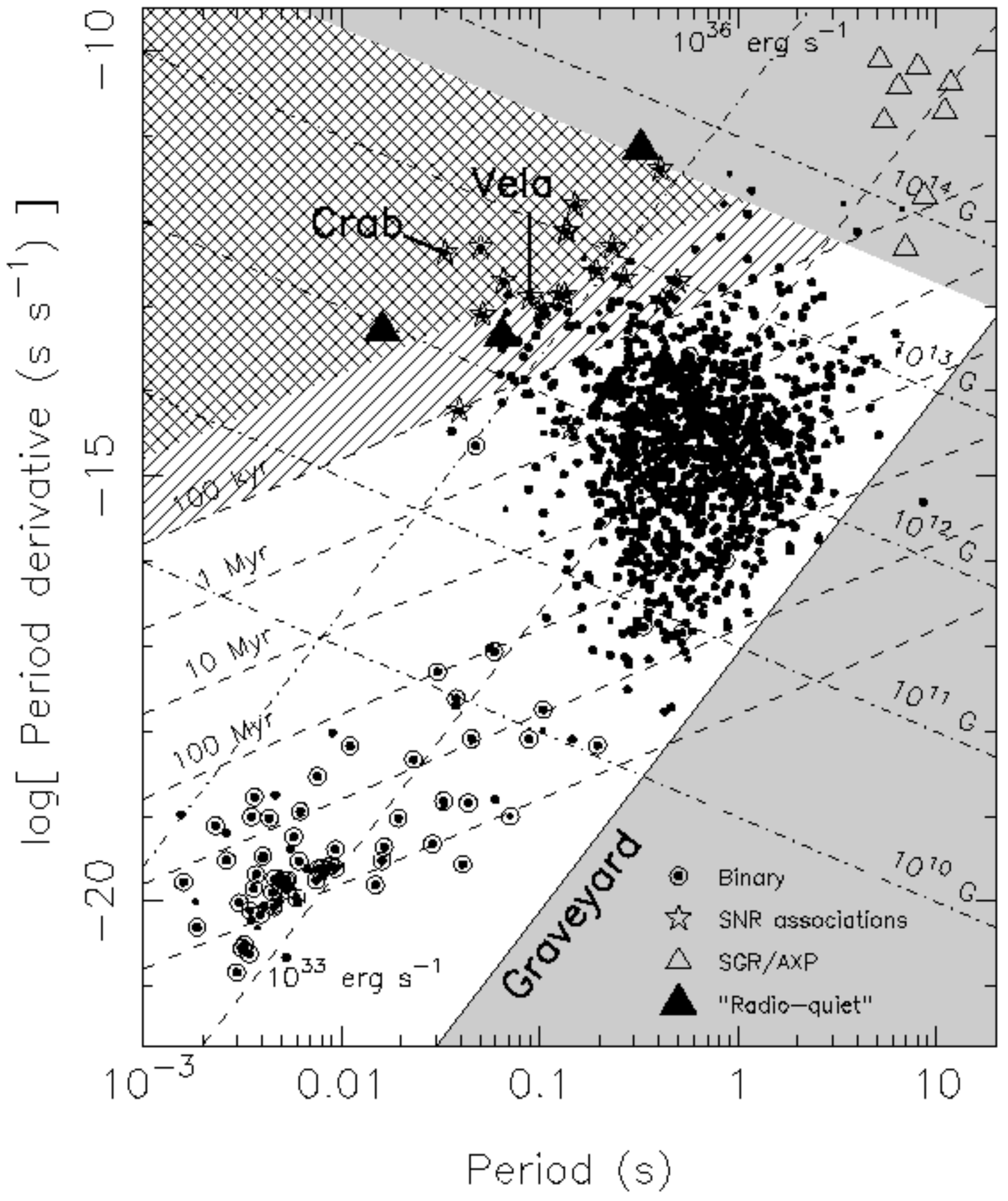
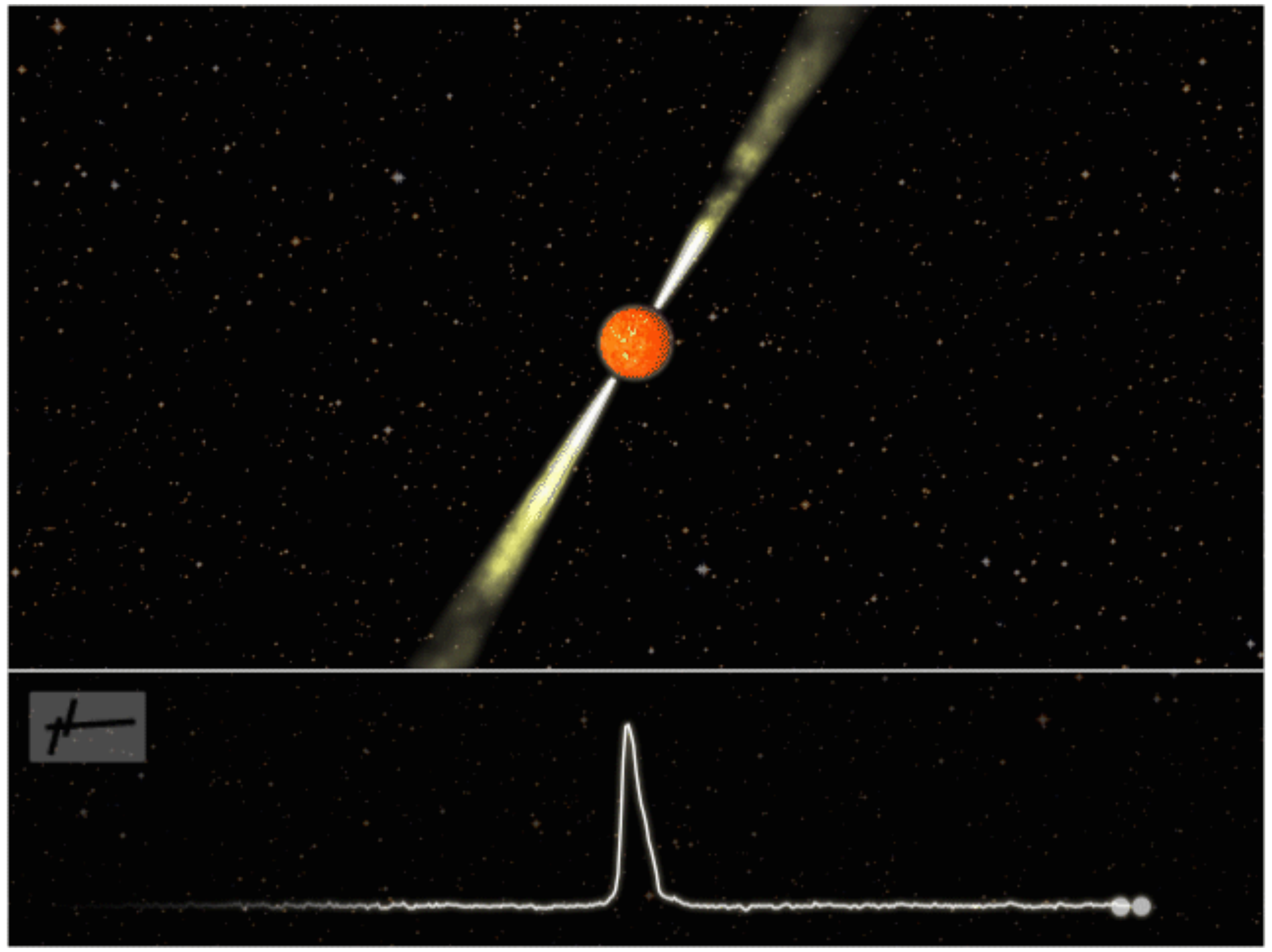
Pulsars



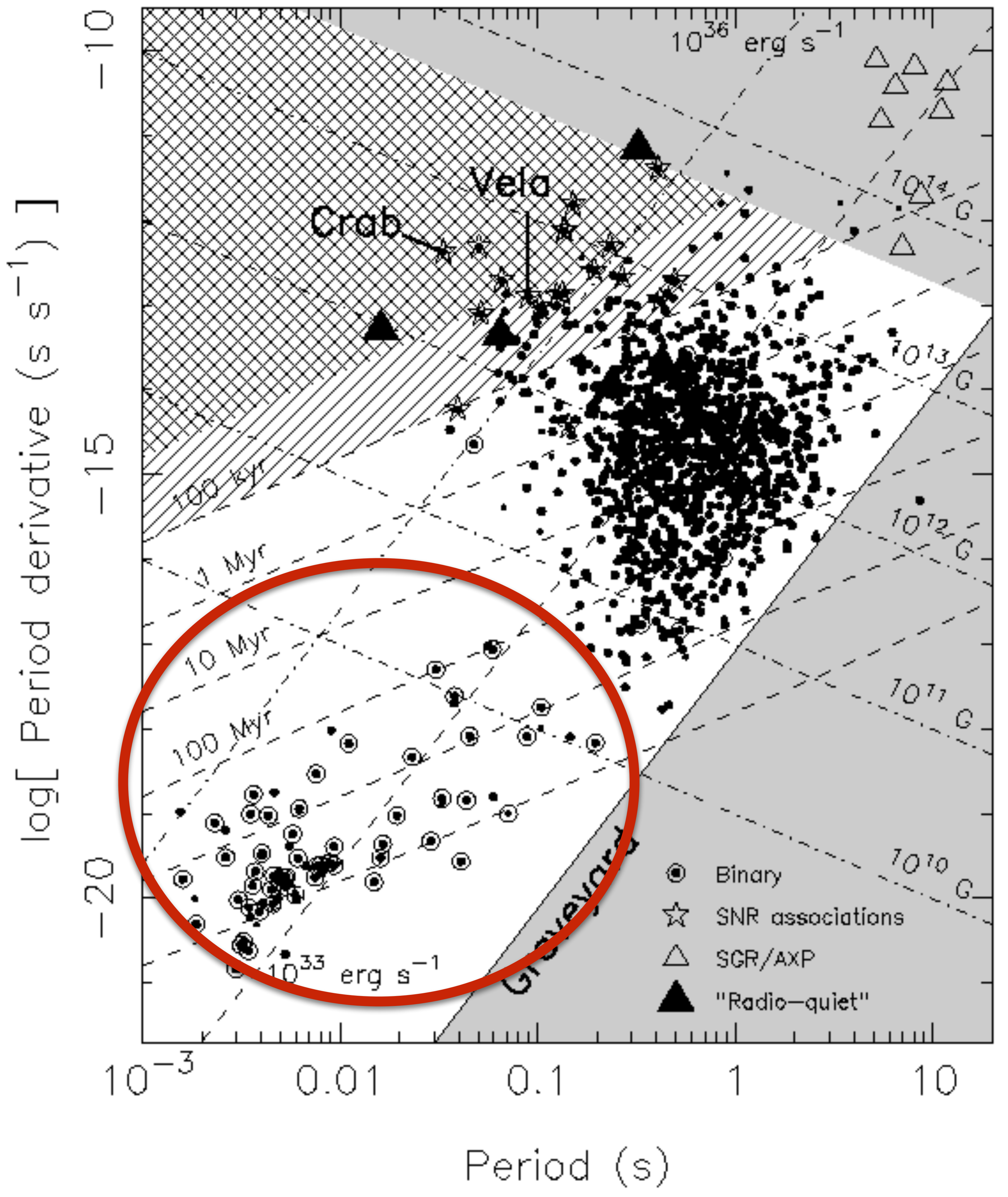
From the *Handbook of Pulsar Astronomy* by Lorimer and Kramer

Observed times of arrival are fit to a **timing model** to produce residuals.



Credit: Joeri van Leeuwen

Pulsars



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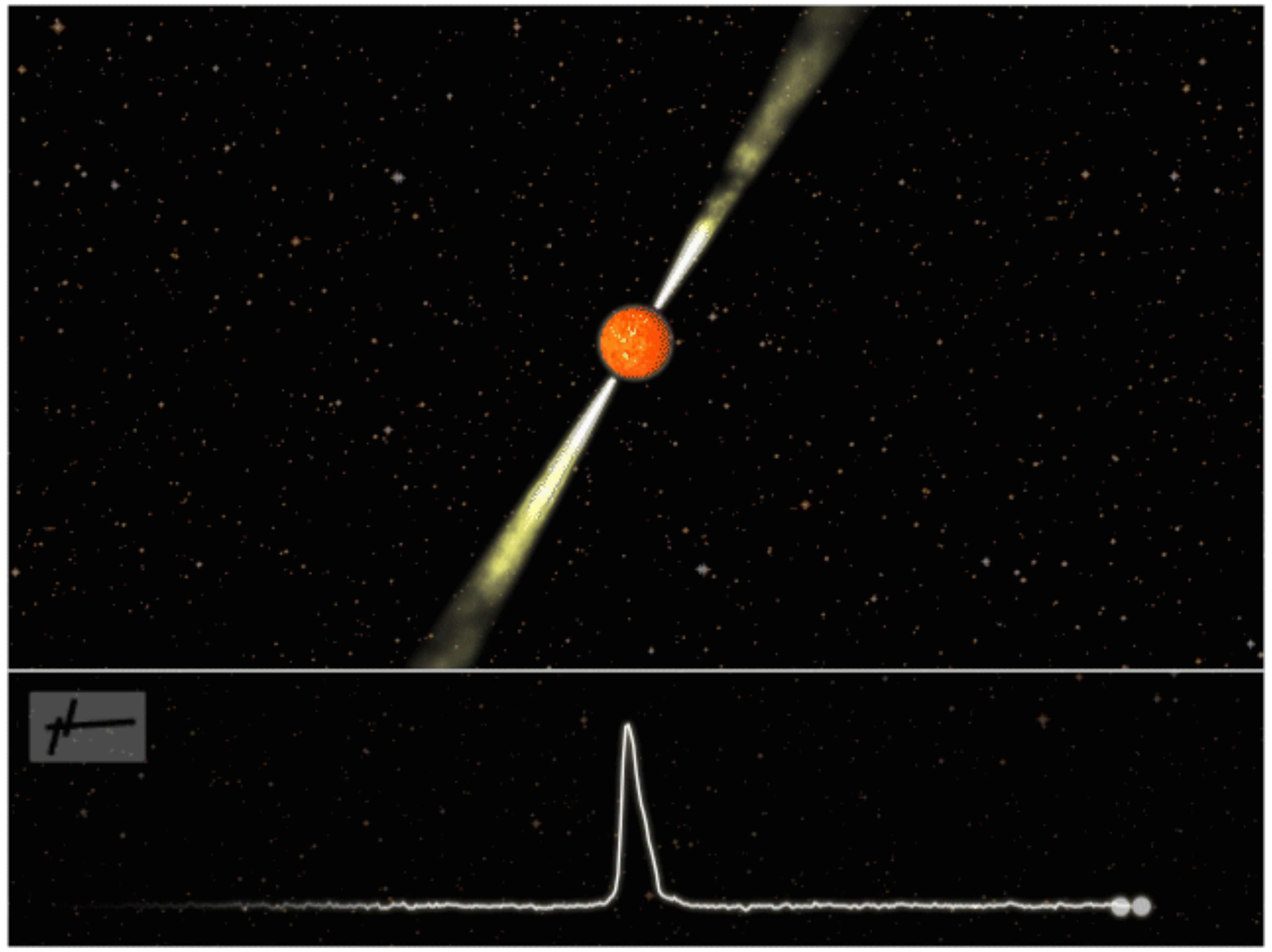

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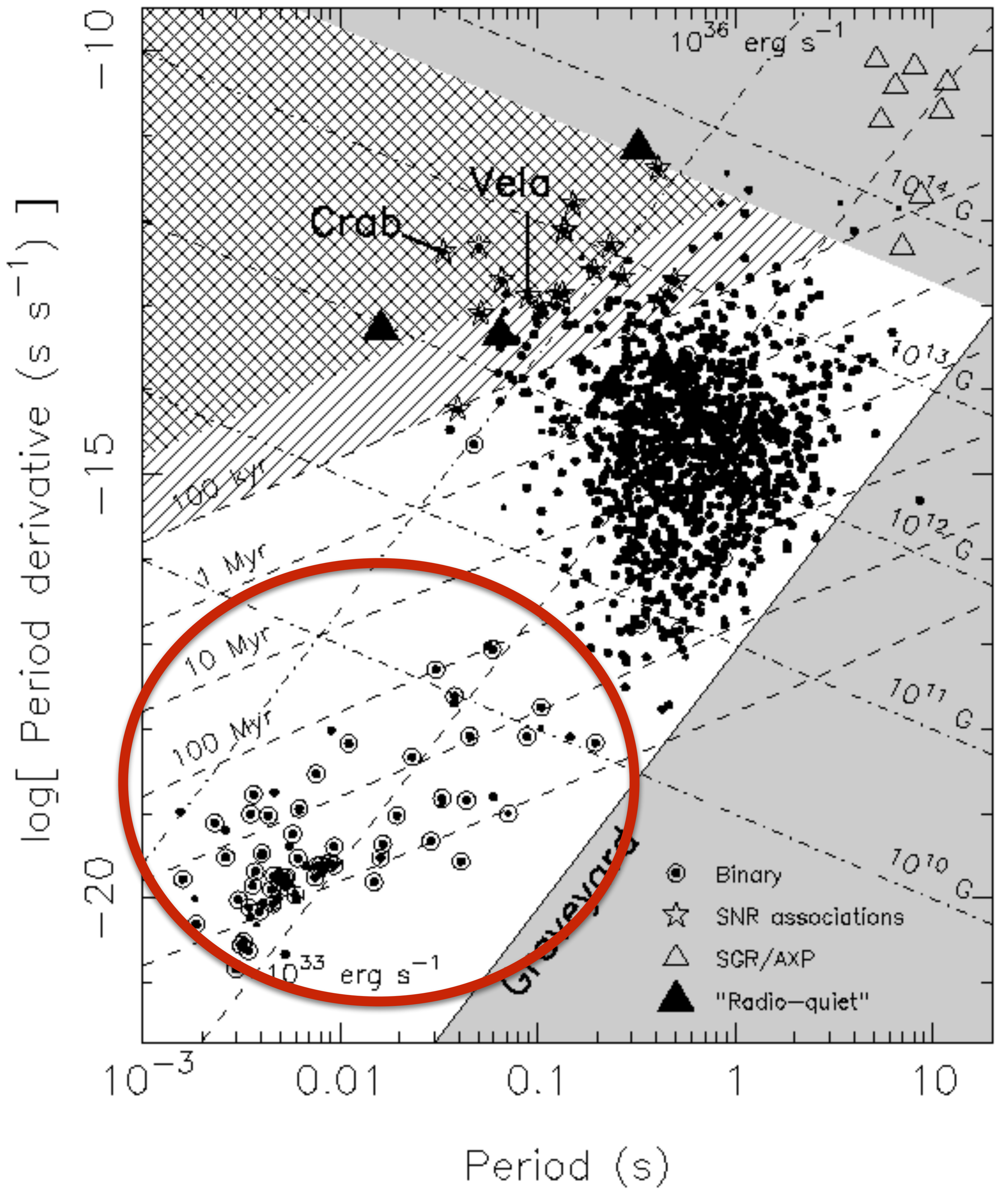
Pulsars



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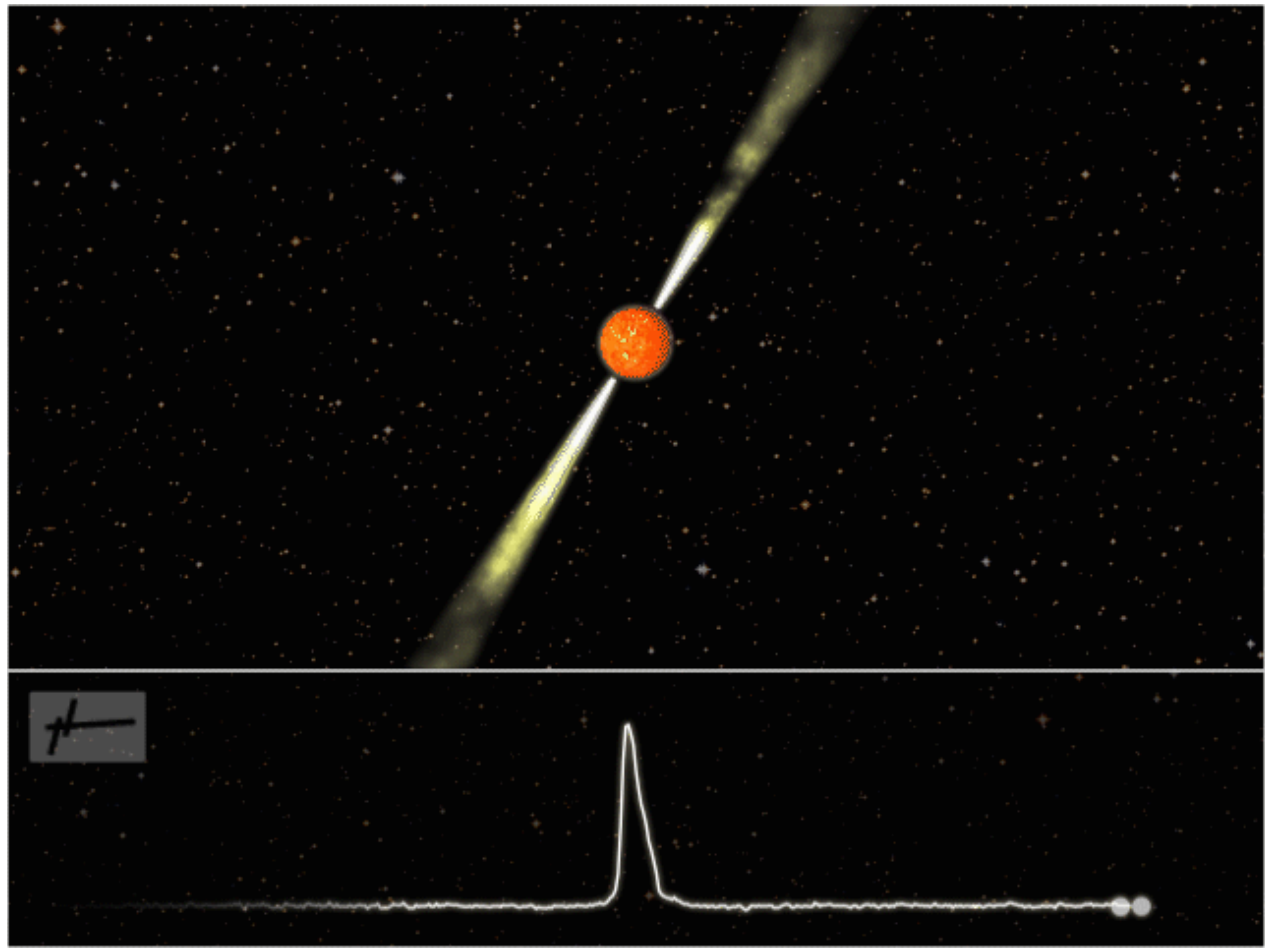


Credit: Joeri van Leeuwen

Pulsar mass measurements can be used to constrain the NS equation of state.

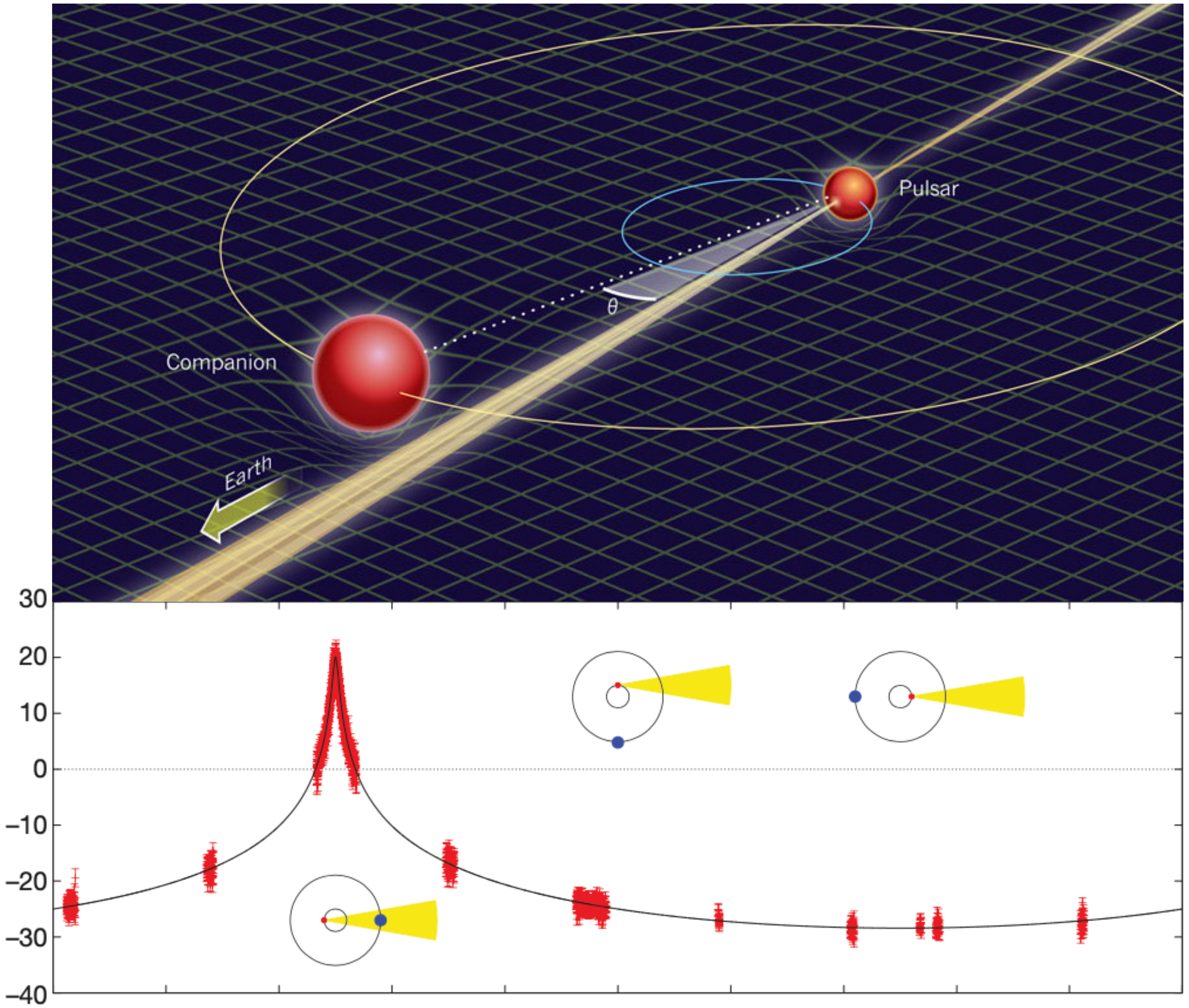


Figure credit: Demorest et al., Nature 467, 1081-1083 (2010)

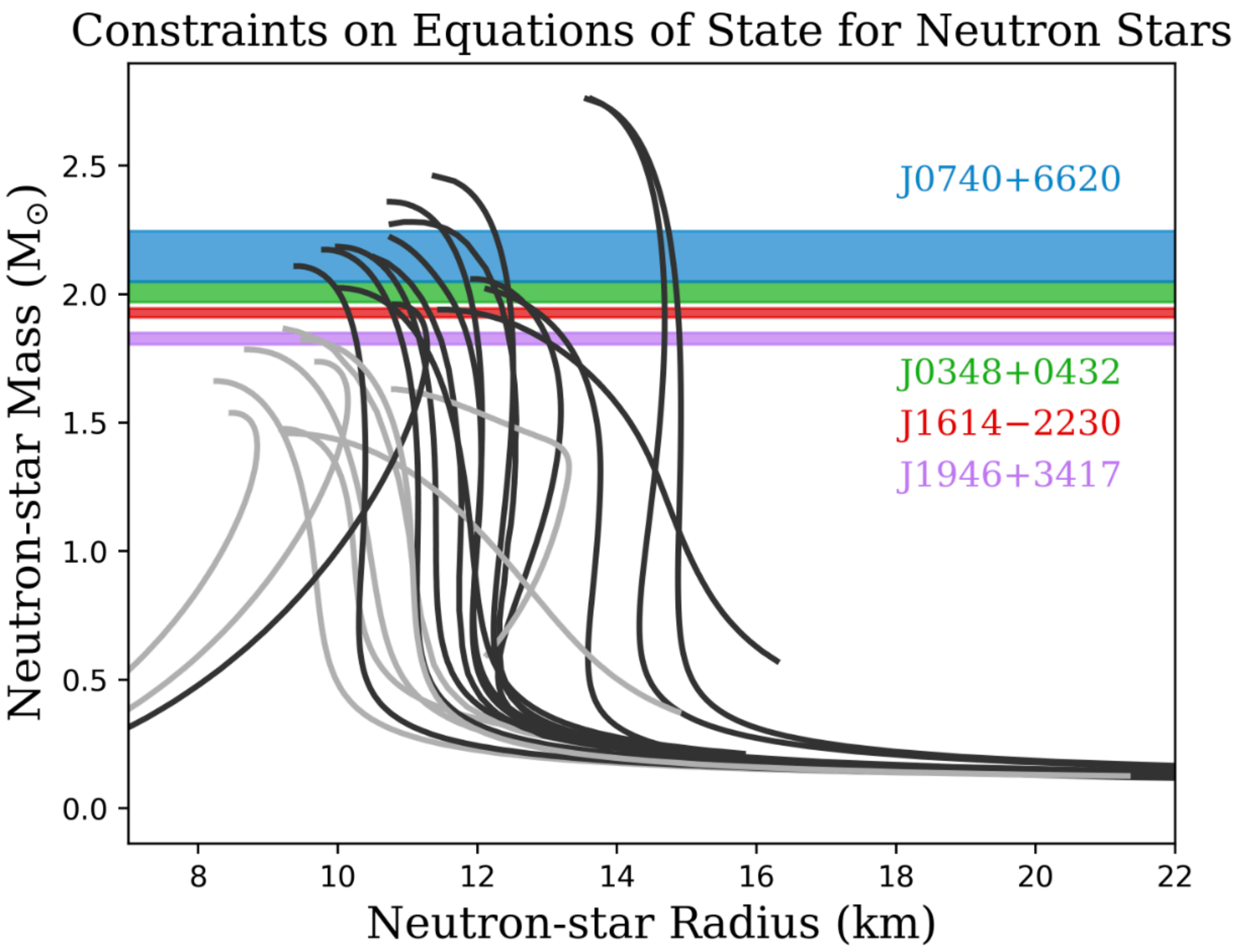


Figure credit: Fonseca et al., arXiv:1903.08194 (2019)

Pulsar Timing

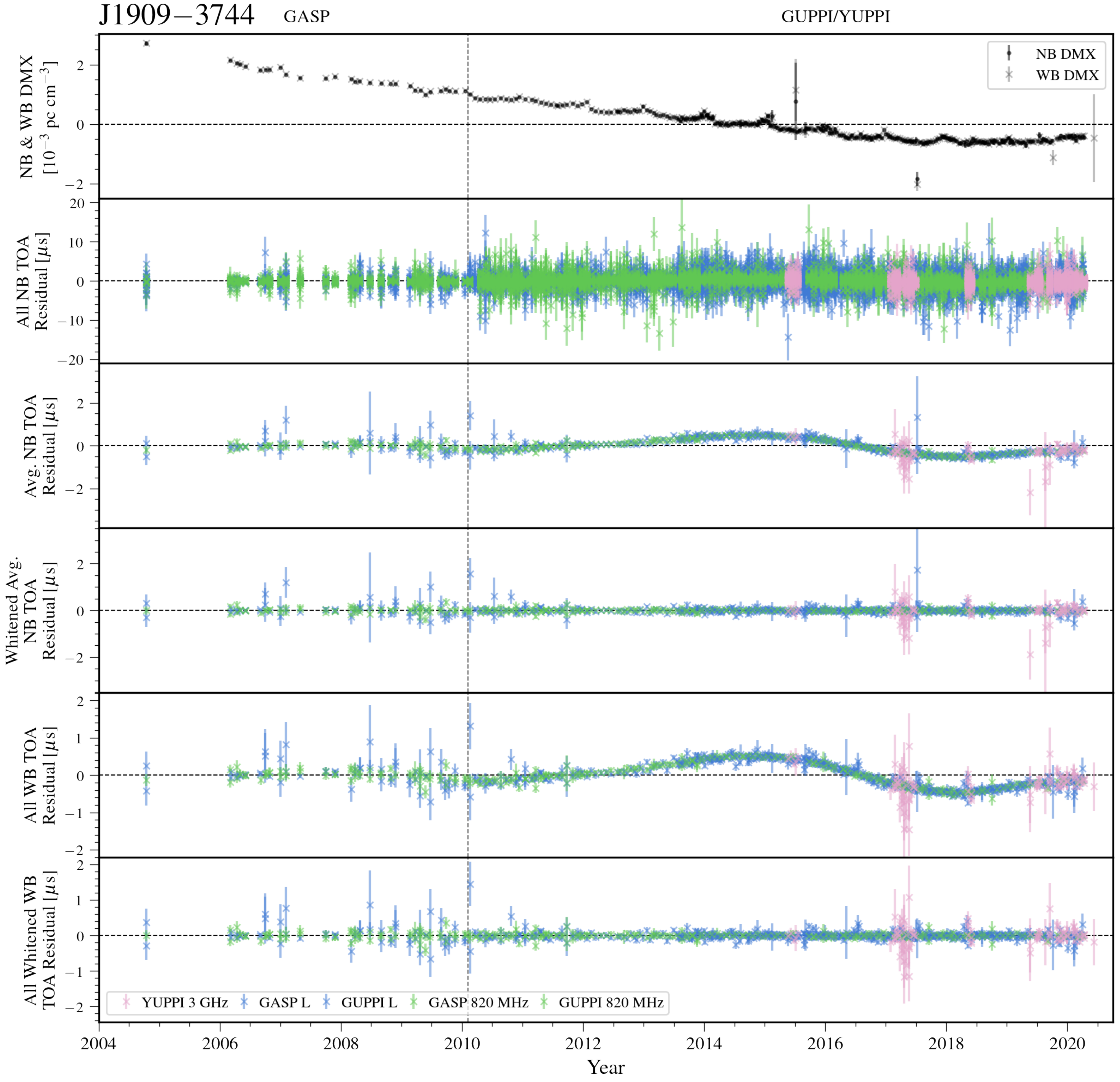


Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L9 (2023).

Observed times of arrival are fit to a **timing model** to produce residuals.

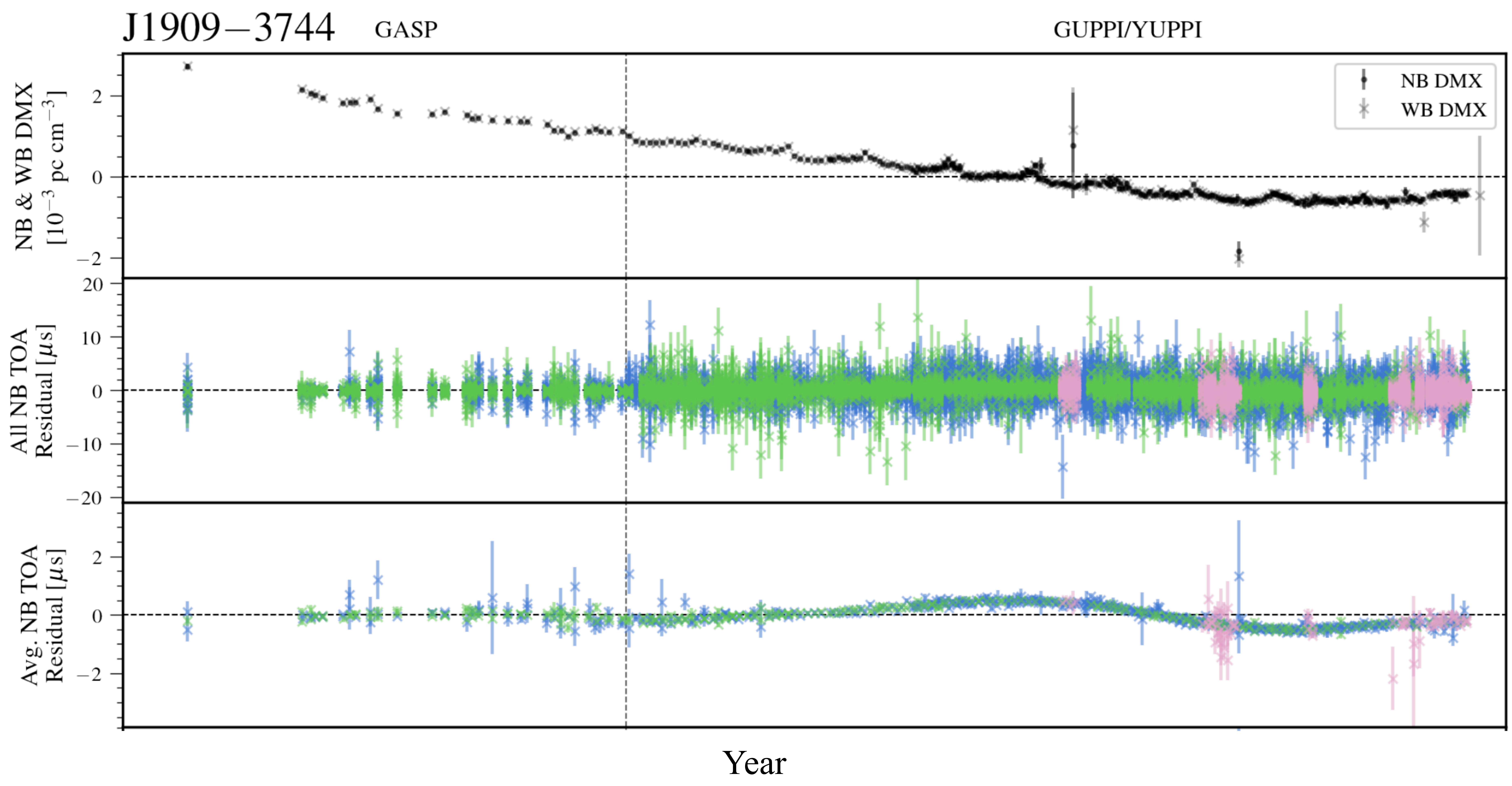
$$\delta\mathbf{t} = \mathsf{M}\epsilon + \mathsf{F}\mathbf{c} + \mathsf{U}\mathbf{j} + \mathbf{n}$$

Timing Model

White Noise

Red Noise

Pulsar Timing



Dispersion measure variations

Residuals

Averaged residuals

Noise Budget

Lead: Jeff Hazboun

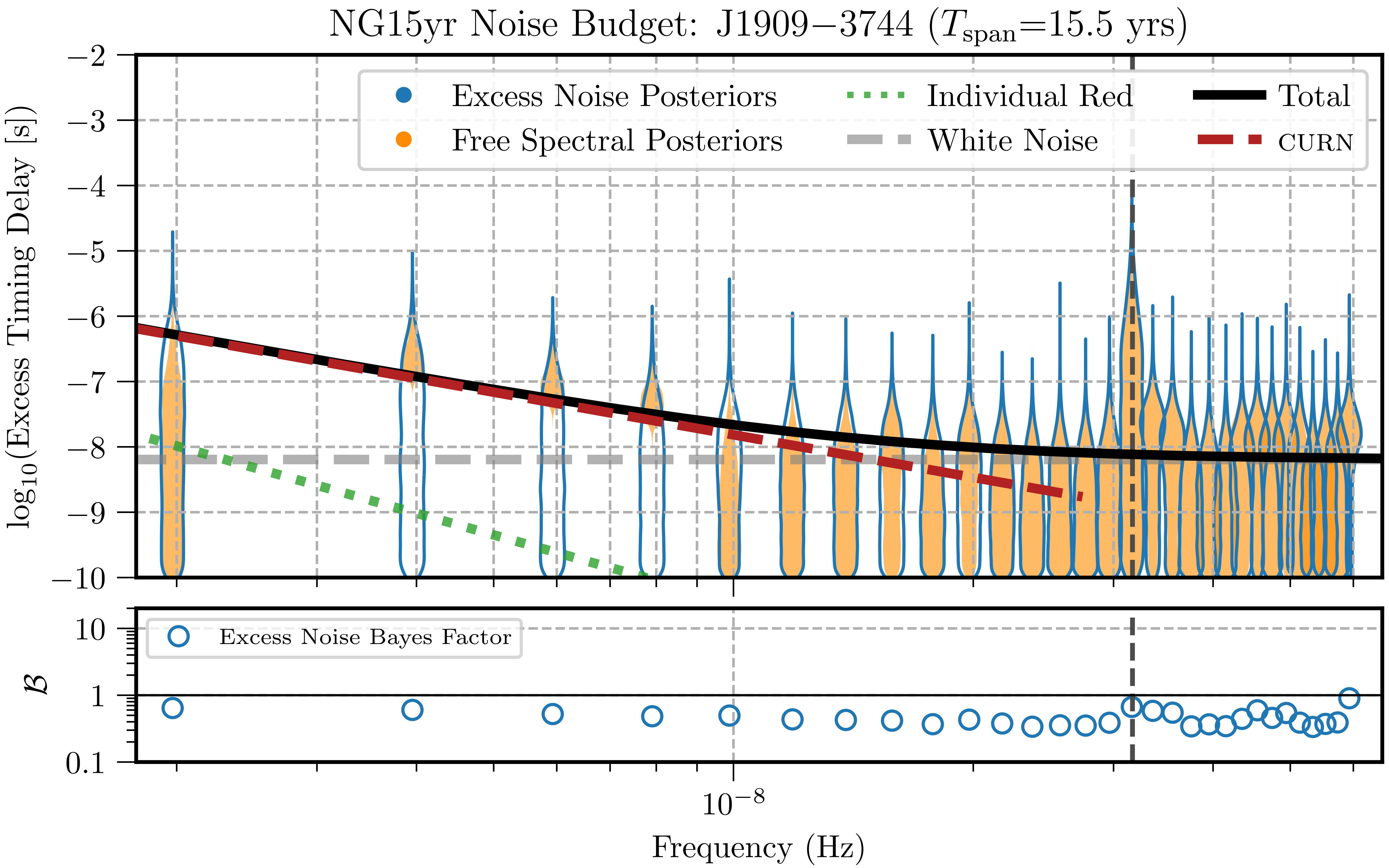
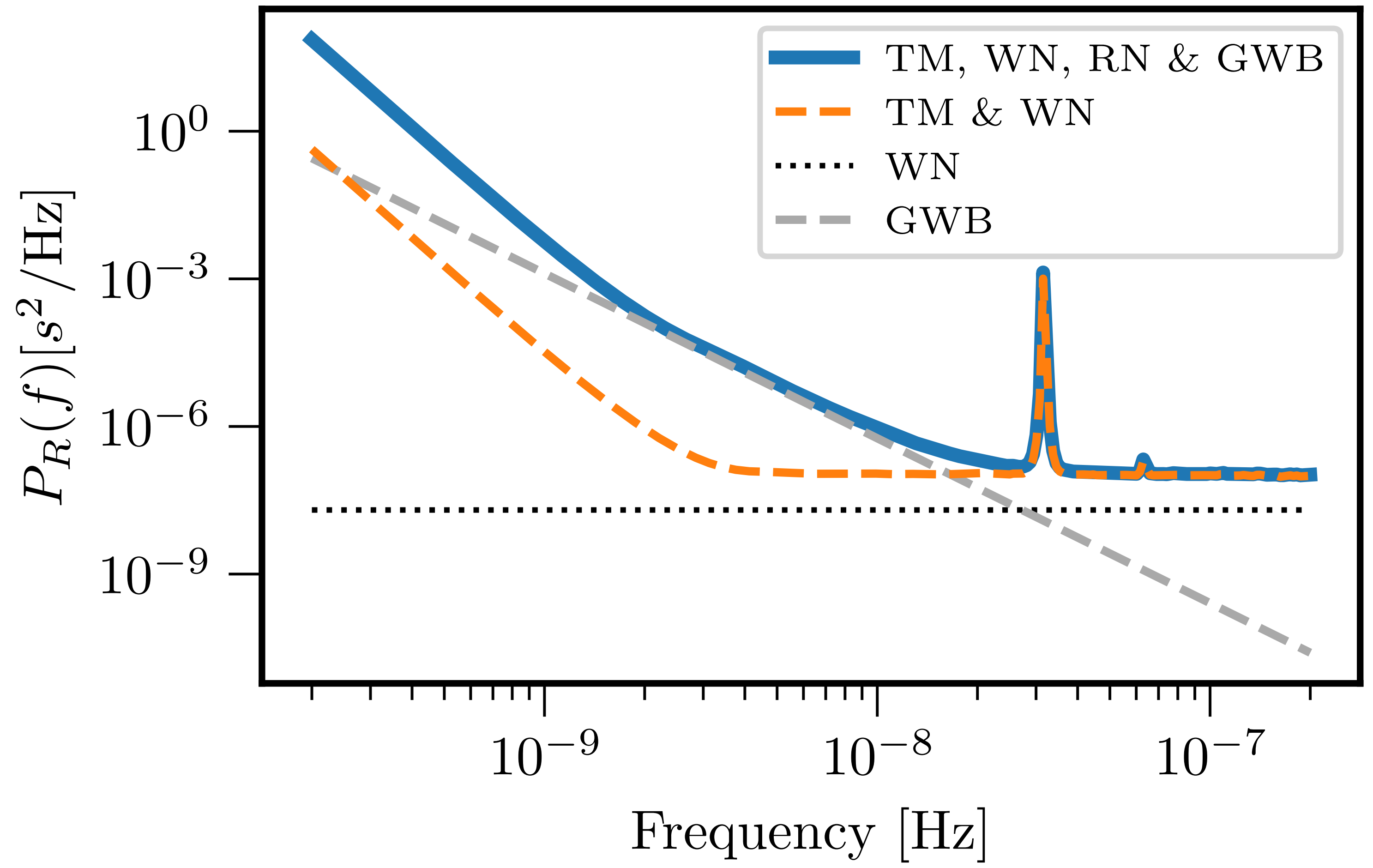
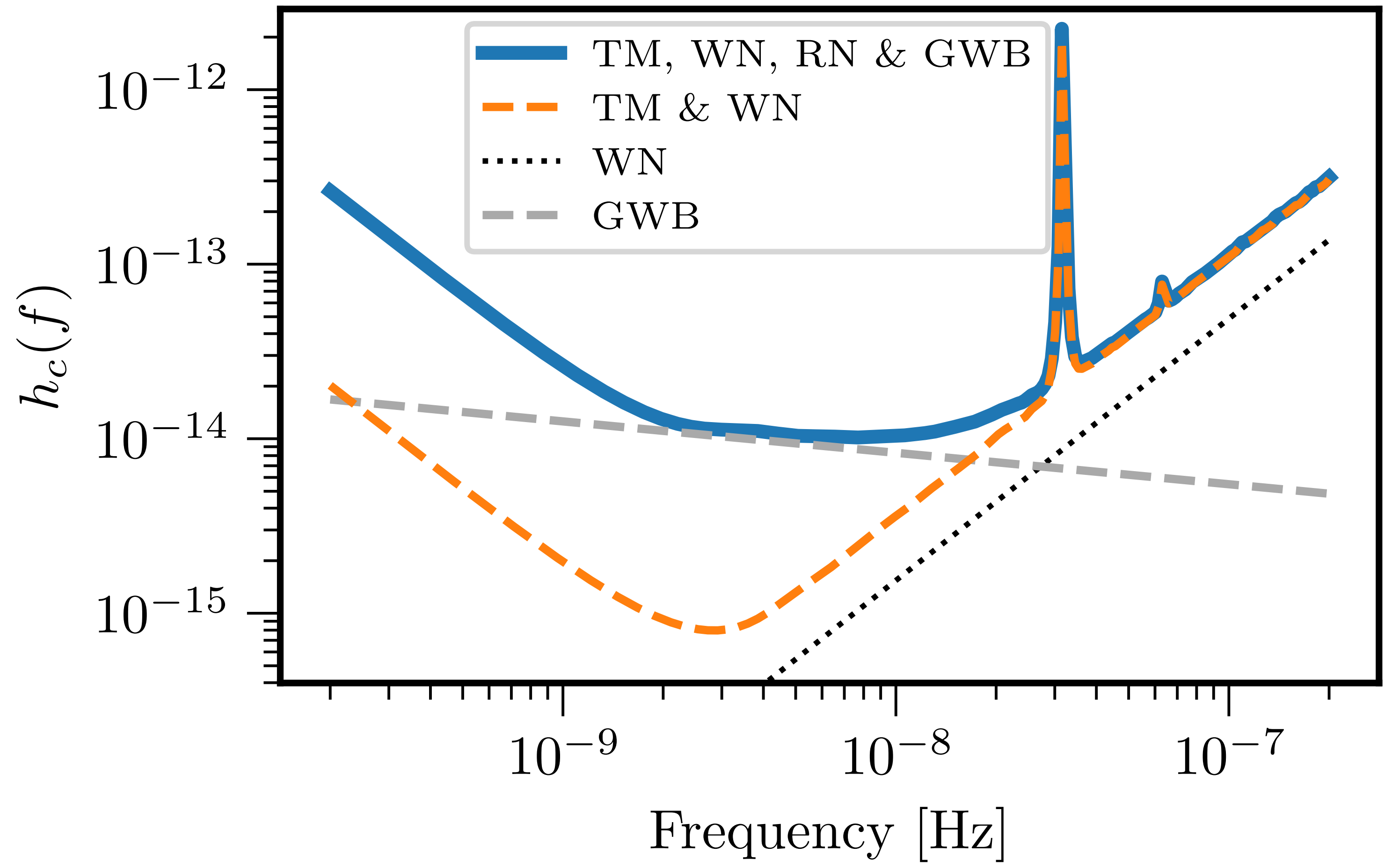


Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L10 (2023).

Sensitivity Curves





The power spectrum of the residuals is the inverse of the noise-weighted transmission function.

We can write this in terms of the characteristic strain:

$$S(f) = \frac{P_R}{\mathcal{R}} = 12\pi^2 f^2 P_R(f)$$

$$h_c(f) \equiv \sqrt{f S(f)} = \pi f^{3/2} \sqrt{12 P_R(f)}$$

Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L10 (2023).

Pulsar Timing Arrays

Gravitational waves induce correlated changes in the pulse times of arrival:

$$z(t, \hat{\Omega}) = \frac{1}{2} \frac{\hat{p}^i \hat{p}^j}{1 + \hat{\Omega} \cdot \hat{p}} \Delta h_{ij}$$

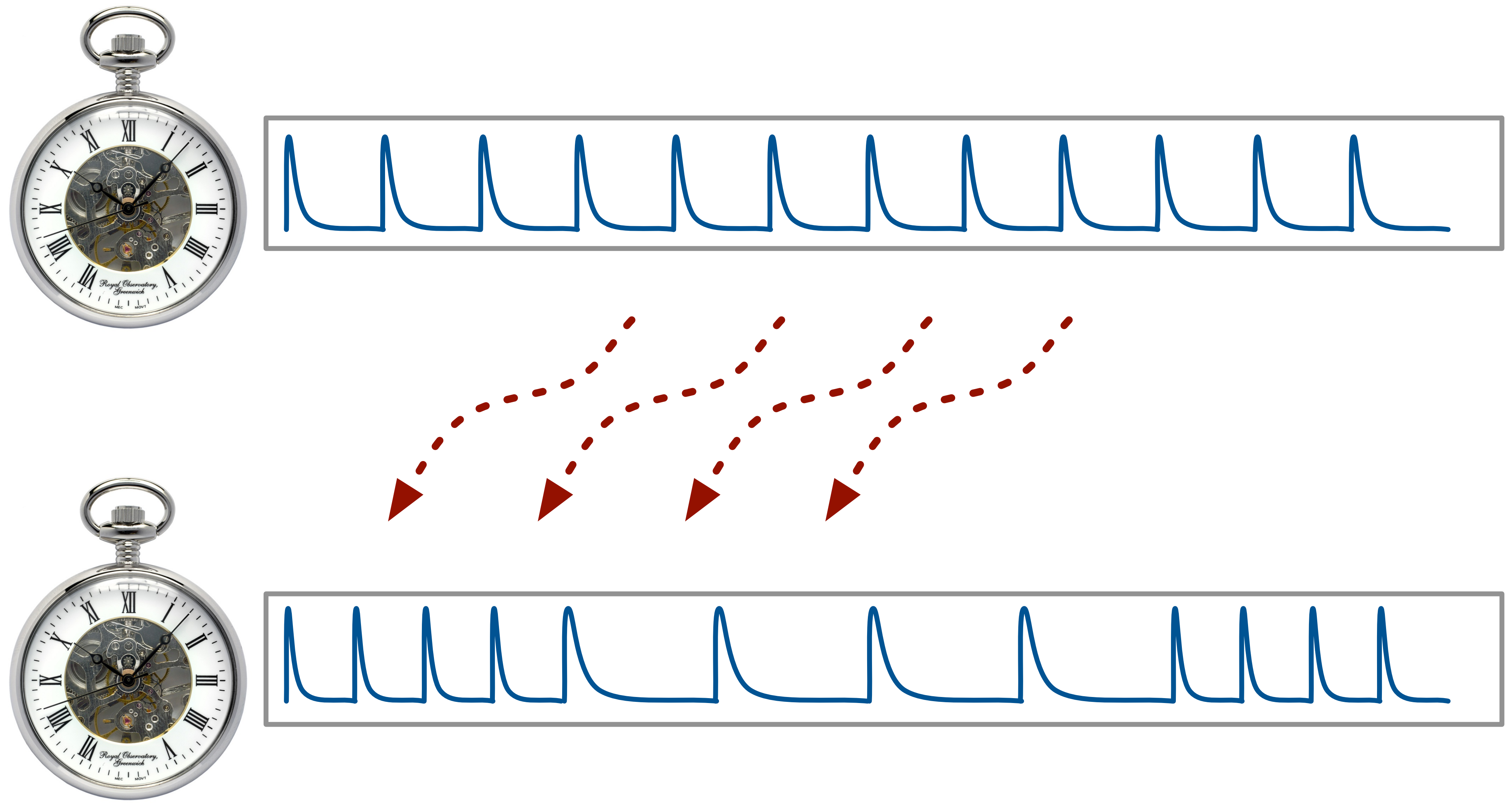


Image credit: S. Chatterjee

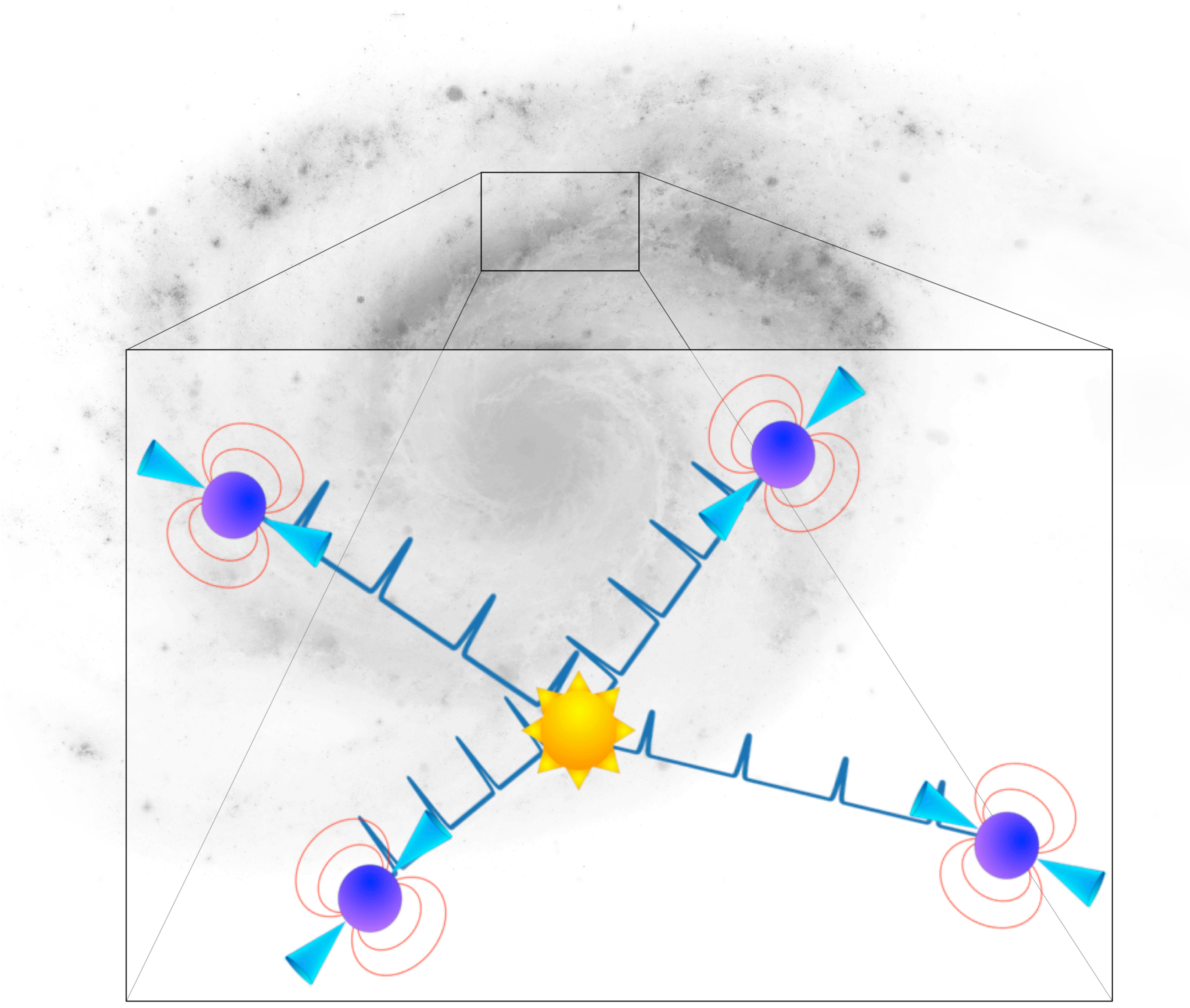


Image credit: J. Hazboun; NASA

Lovell

Nançay

WSRT

SRT

Effelsberg

EPTA

GBT

Arecibo

VLA

CHIME

NANOGrav

FAST

CPTA

Parkes

PPTA

MeerKAT

MPTA

GMRT

InPTA

IPTA

Image credit: H. T. Cromartie

Pulsar 1

Timing Model
White Noise
Red Noise

\+

Pulsar 2

Timing Model
White Noise
Red Noise

\+

Pulsar 3

Timing Model
White Noise
Red Noise

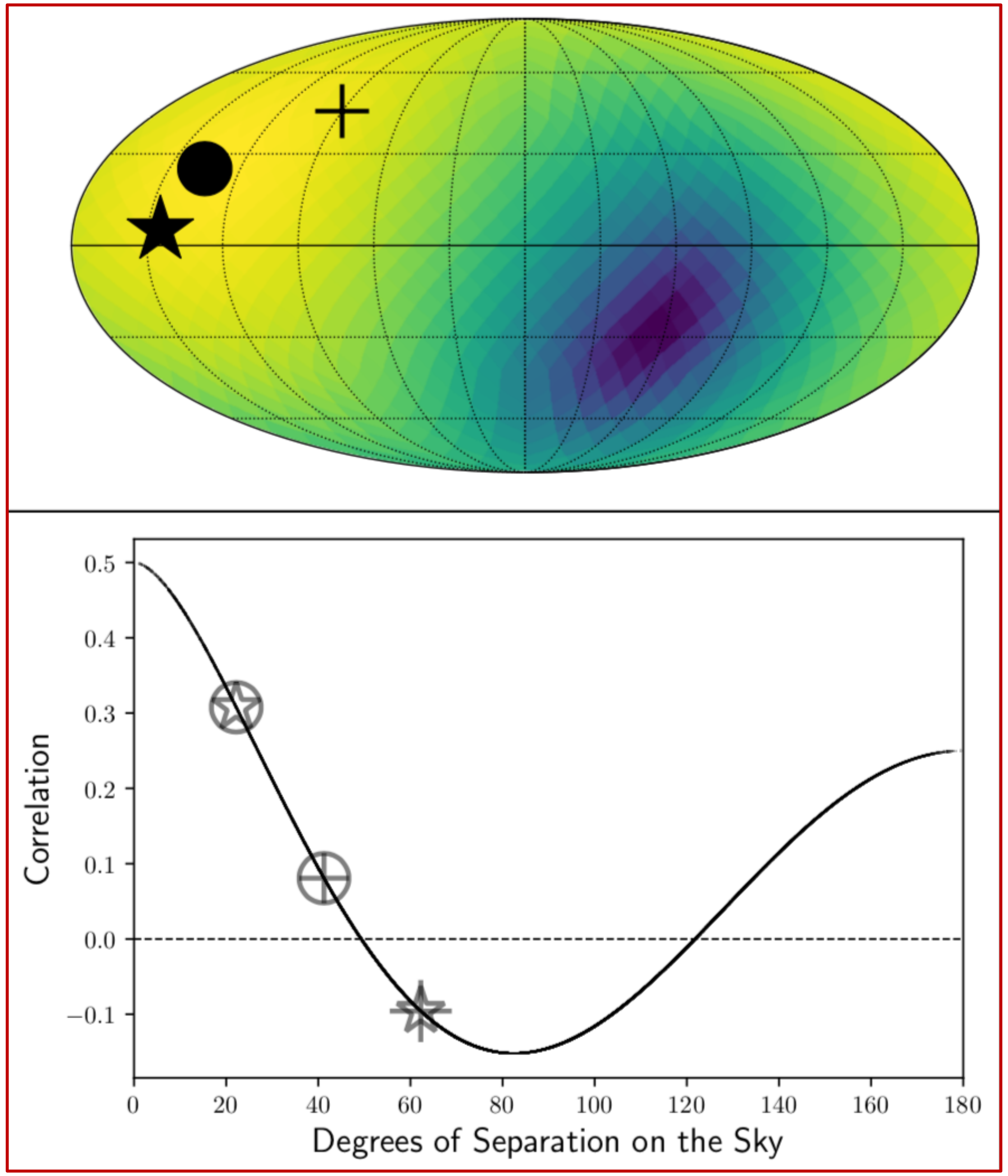
\+

Common sources of noise

\+

Gravitational Wave Signal

GWB Signal Model



Gravitational waves induce correlated changes in the pulse times of arrival (Hellings & Downs, 1983).

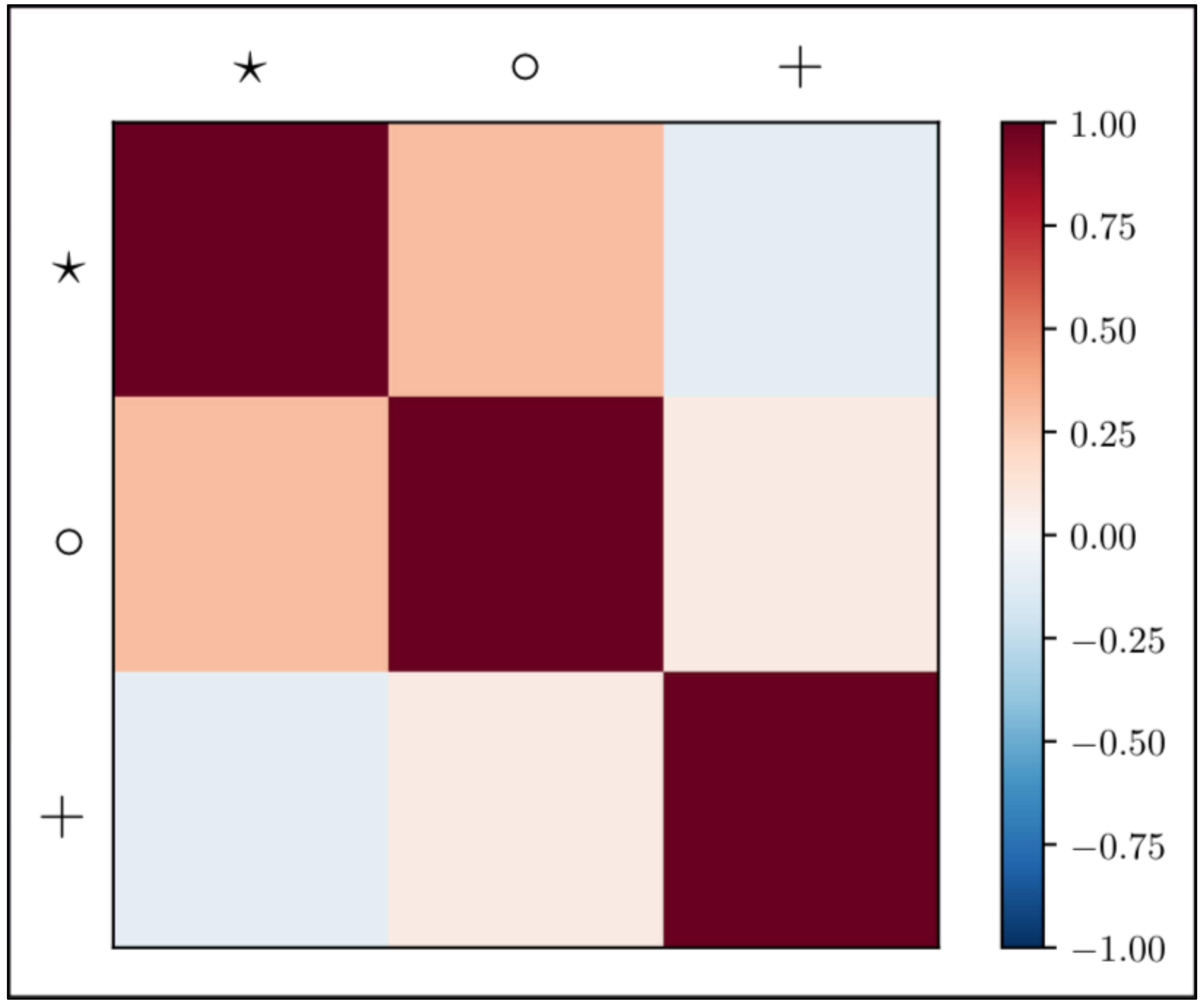


Figure credit: J. Hazboun

Non-Einsteinian Polarization Modes

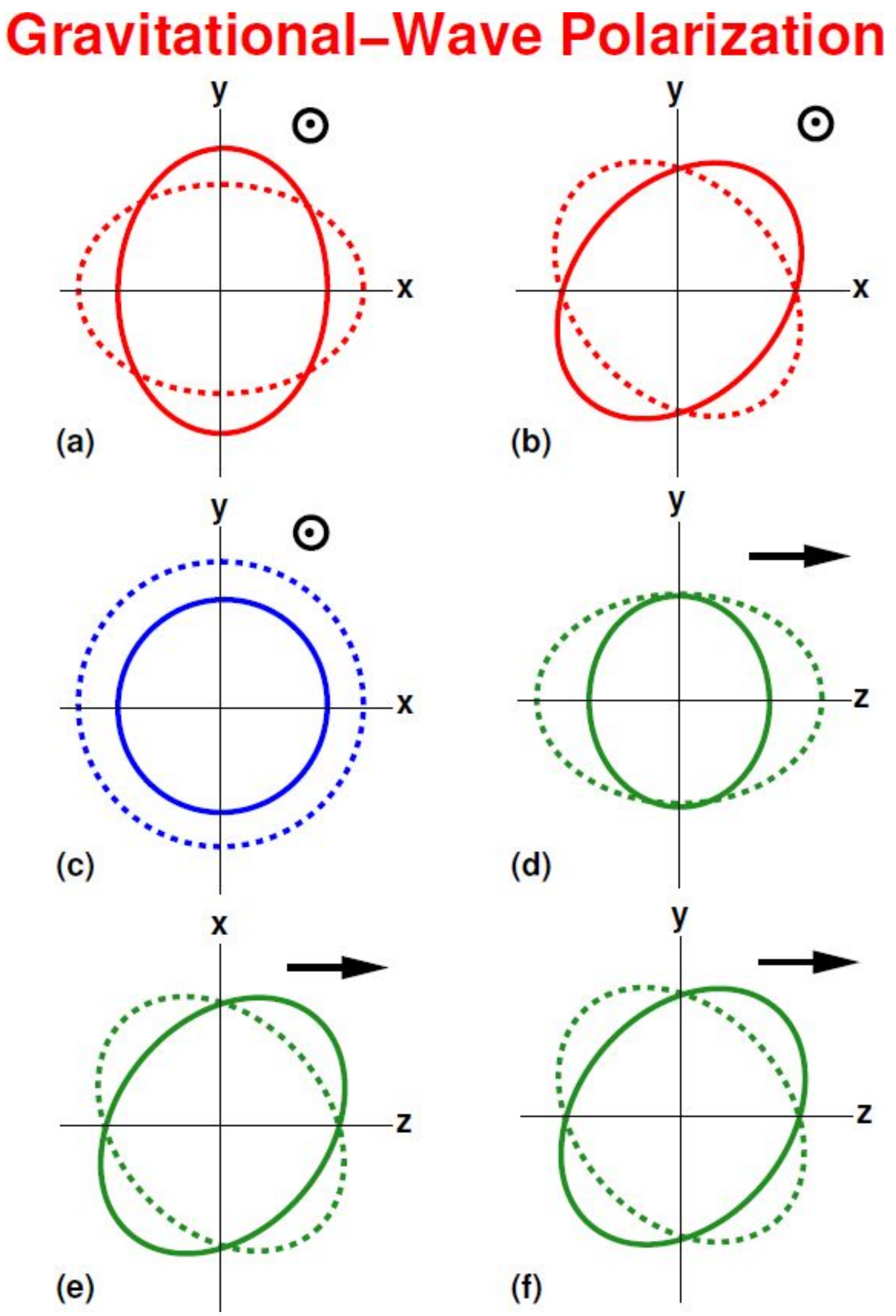


Figure credit: C. Will (2014)

In GR, there are only two GW polarizations. Alternate theories of gravity may allow other polarizations to exist.

PTAs can put constraints on the power in alternate polarizations (Chamberlin & Siemens 2012; Cornish, O'Beirne, Taylor, and Yunes 2018)

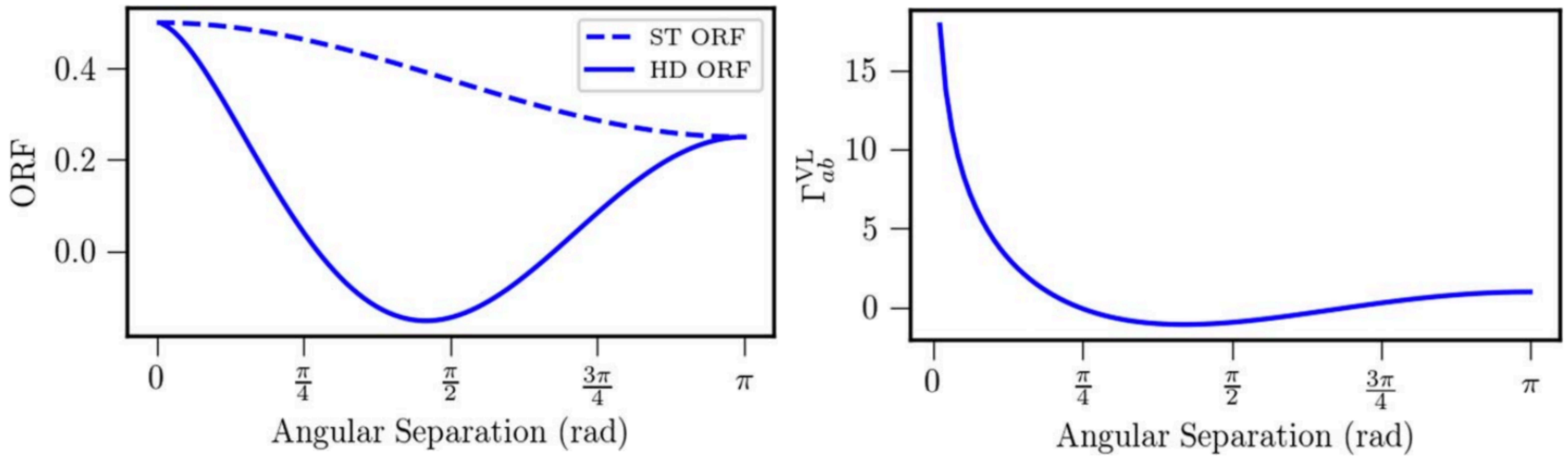
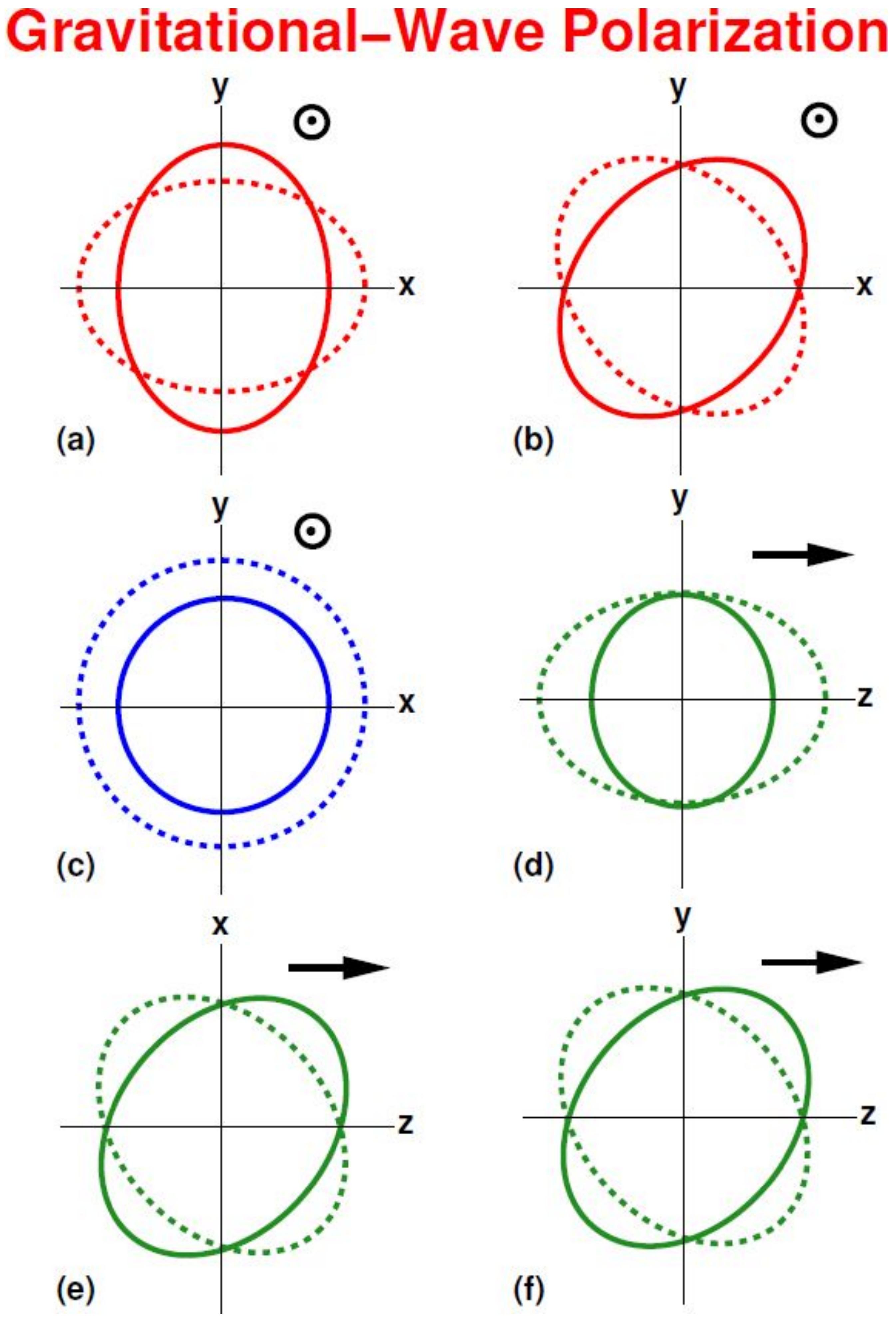


Figure credit: G. Agazie et al. (The NANOGrav Collaboration, lead Nima Laal), ApJL 923, L2 (2021).

Non-Einsteinian Polarization Modes



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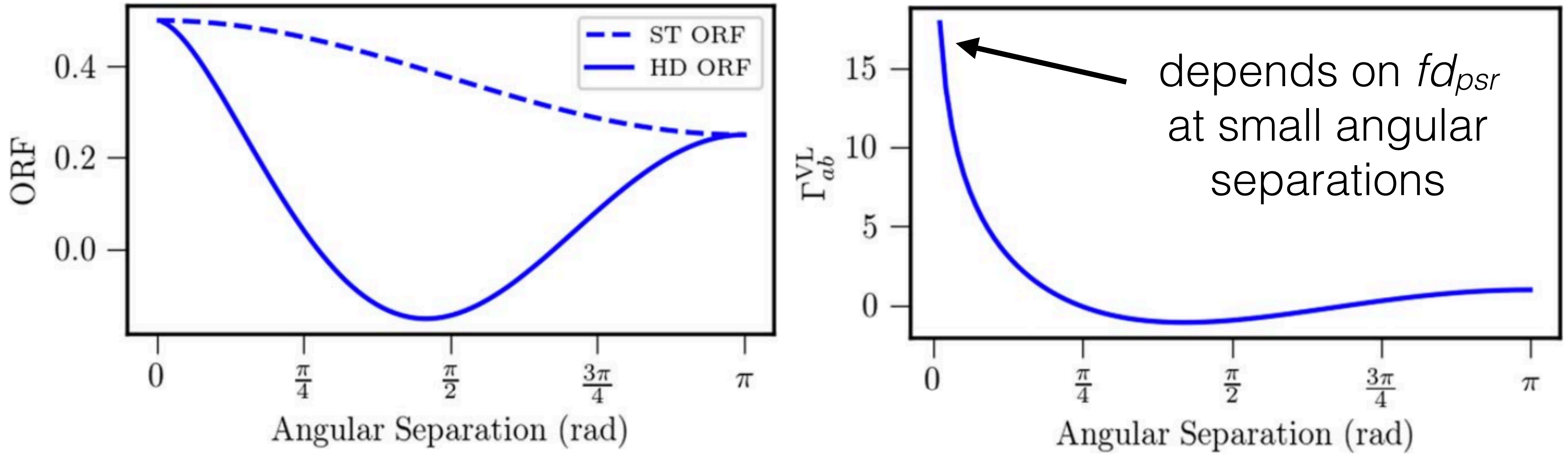


depends on fd_{psr} at small angular separations

Figure credit: G. Agazie et al. (The NANOGrav Collaboration, lead Nima Laal), ApJL 923, L2 (2021).

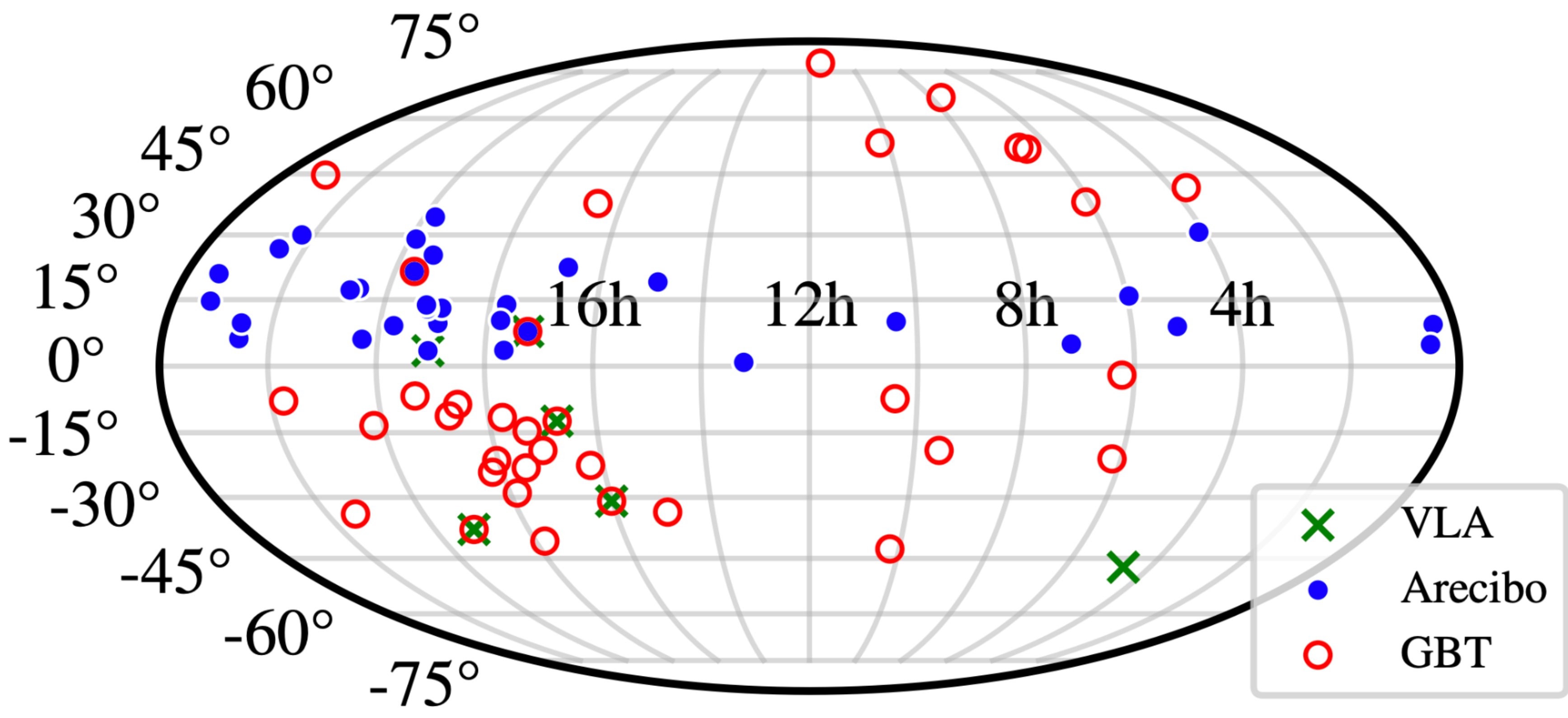
How do pulsar timing arrays detect gravitational waves?

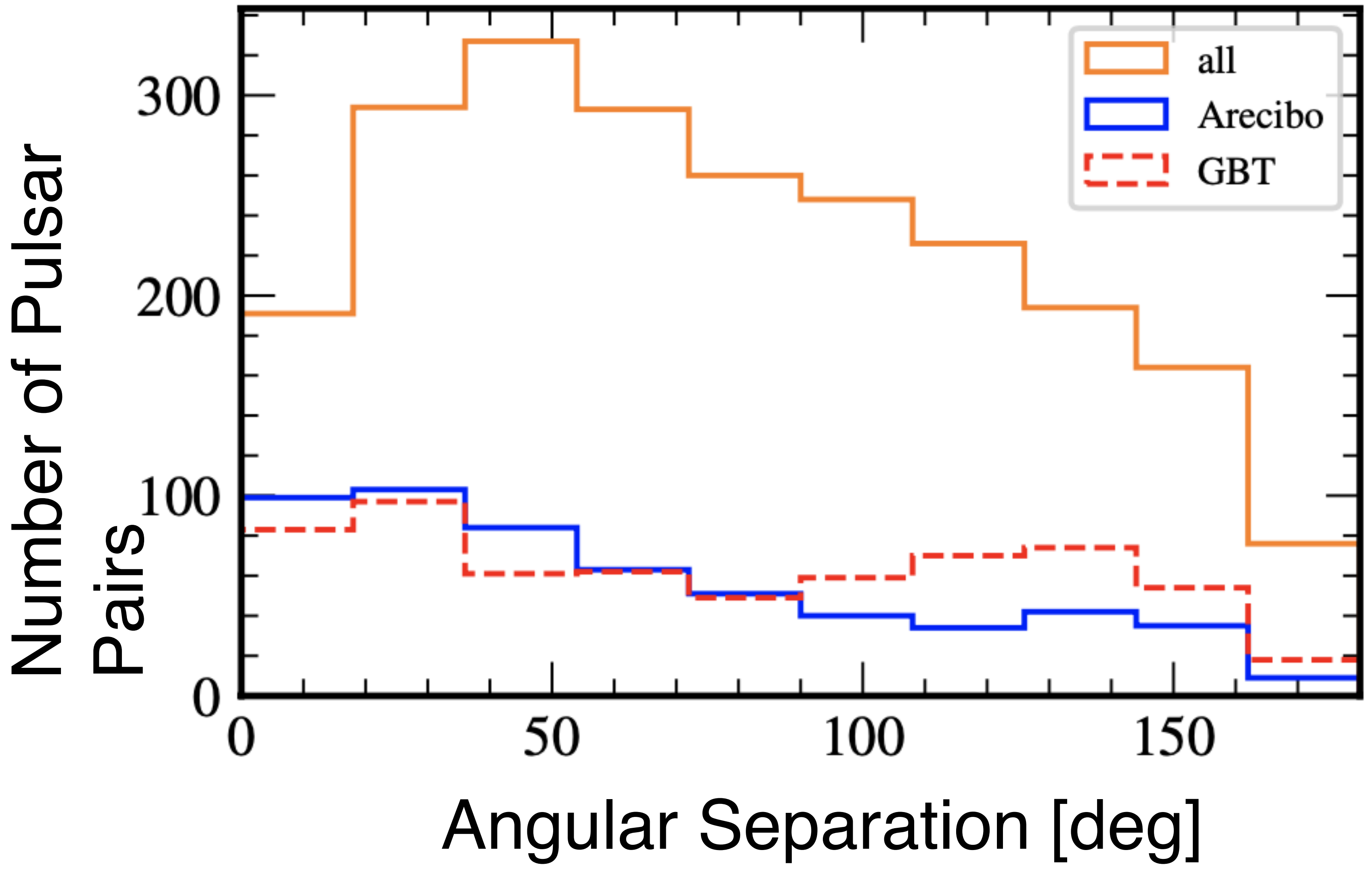
What evidence is there that pulsar timing arrays have found nanohertz gravitational waves?

What could be producing this signal? And how can we determine the source?

The NANOGrav 15-year Data Set

Leads: Joe Swiggum and Thankful Cromartie





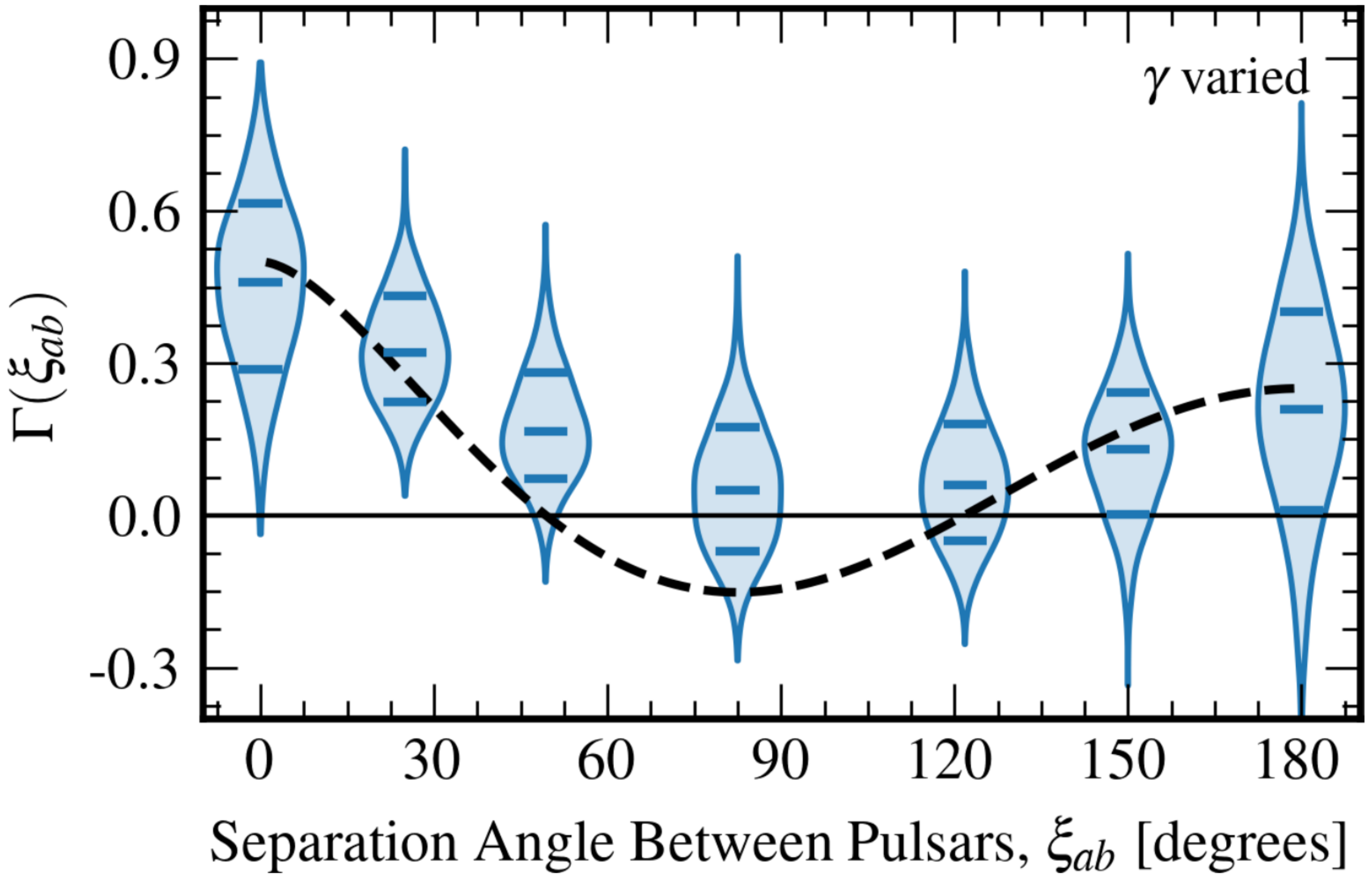
68 pulsars observed for up to 15.9 years (67 pulsars used for GW searches).

Observations made with the Arecibo Observatory, Green Bank Telescope, and Very Large Array.

Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L8 (2023).

Evidence for HD Correlations

Leads: Sarah Vigeland and Steve Taylor



Bayesian analyses prefer a common red process with HD correlations.

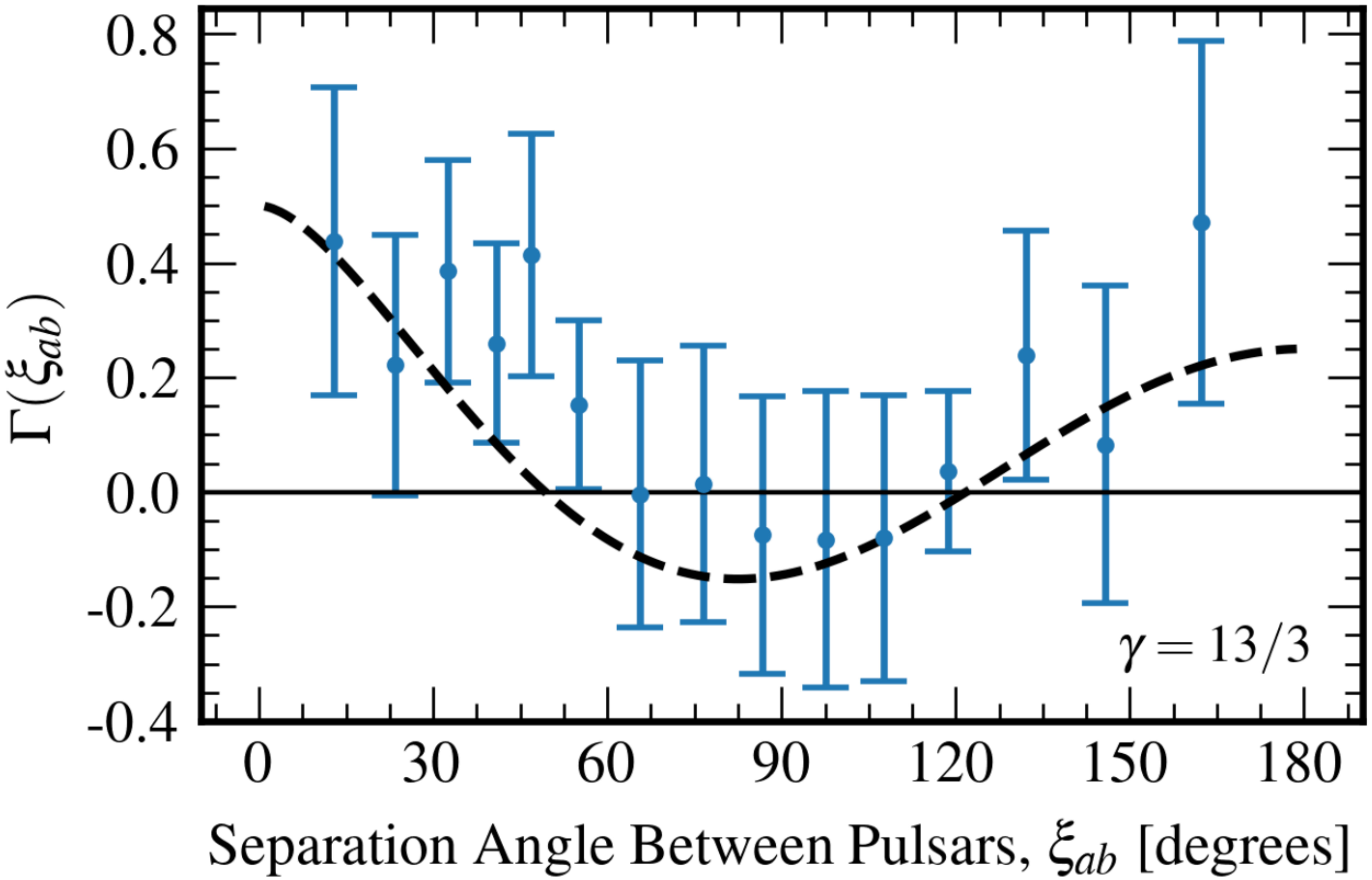
Bayes factor = 226 with a power-law model across f = 2 - 28 nHz.

intrinsic pulsar noise only (IRN) $\xrightarrow{10^{12.1\pm0.1}}$ **common-spectrum red noise (CRN)** $\xrightarrow{226 \pm 70}$ **HD-correlated, common spectrum red noise (HD)**

Bayes factors calculated using thermodynamic integration, product space sampling.

Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L8 (2023).

Evidence for HD Correlations



Frequentist optimal statistic used in two ways:

(1) detection statistic
(2) binned estimator

Binned estimator (left) includes pair covariance (Allen & Romano 2023).

Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L8 (2023).

HD Correlation Significance

The false alarm probabilities are ≈10^{-3} (3σ Gaussian-equivalent) for the Bayesian analysis and ≈10^{-4} (4σ Gaussian-equivalent) for the frequentist analysis.

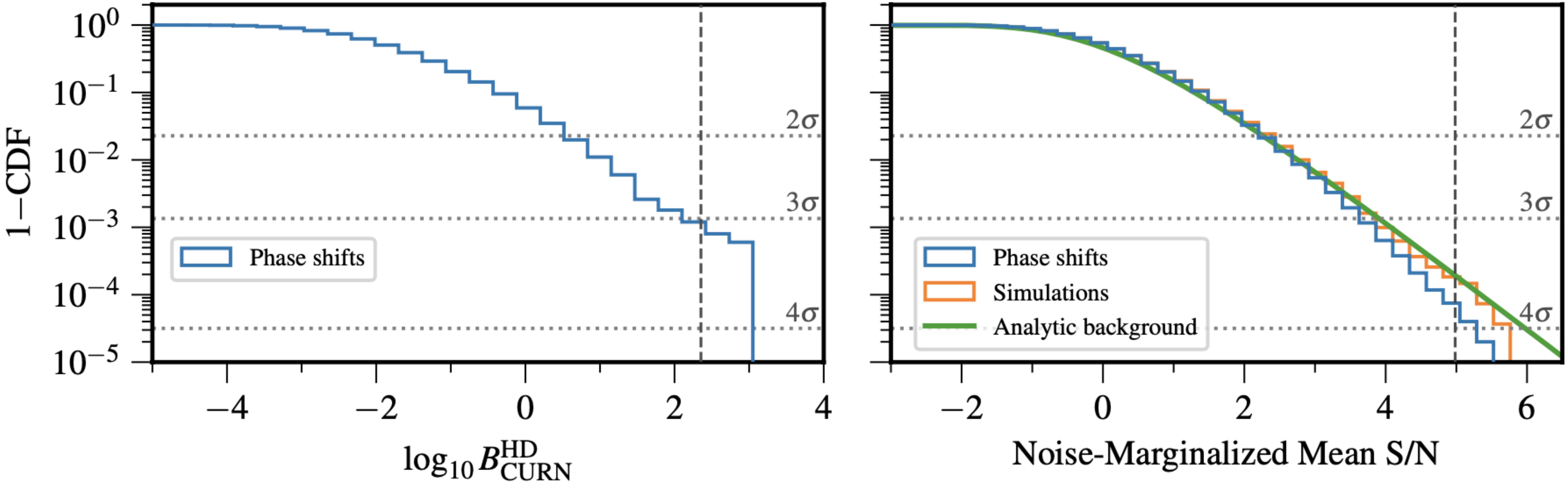
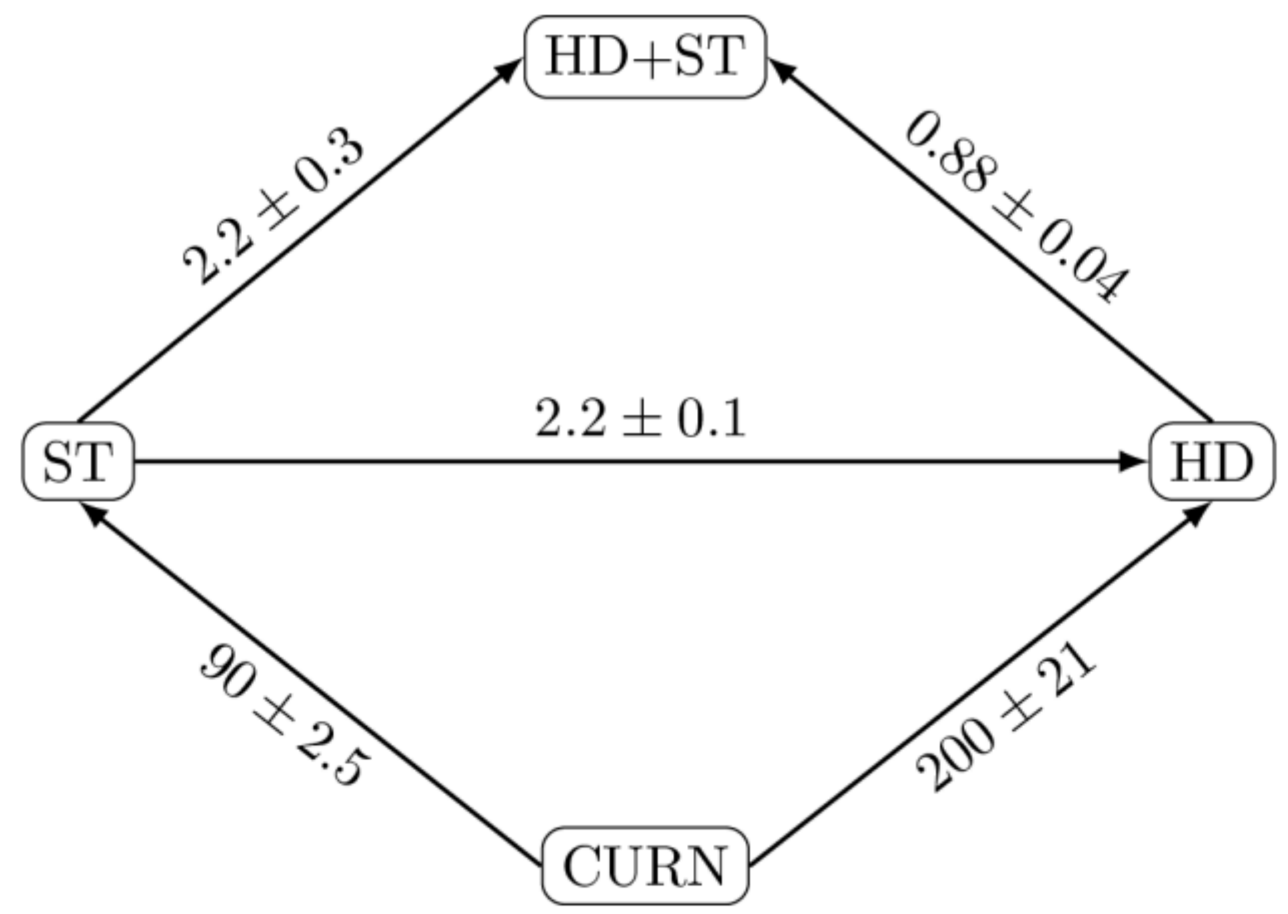
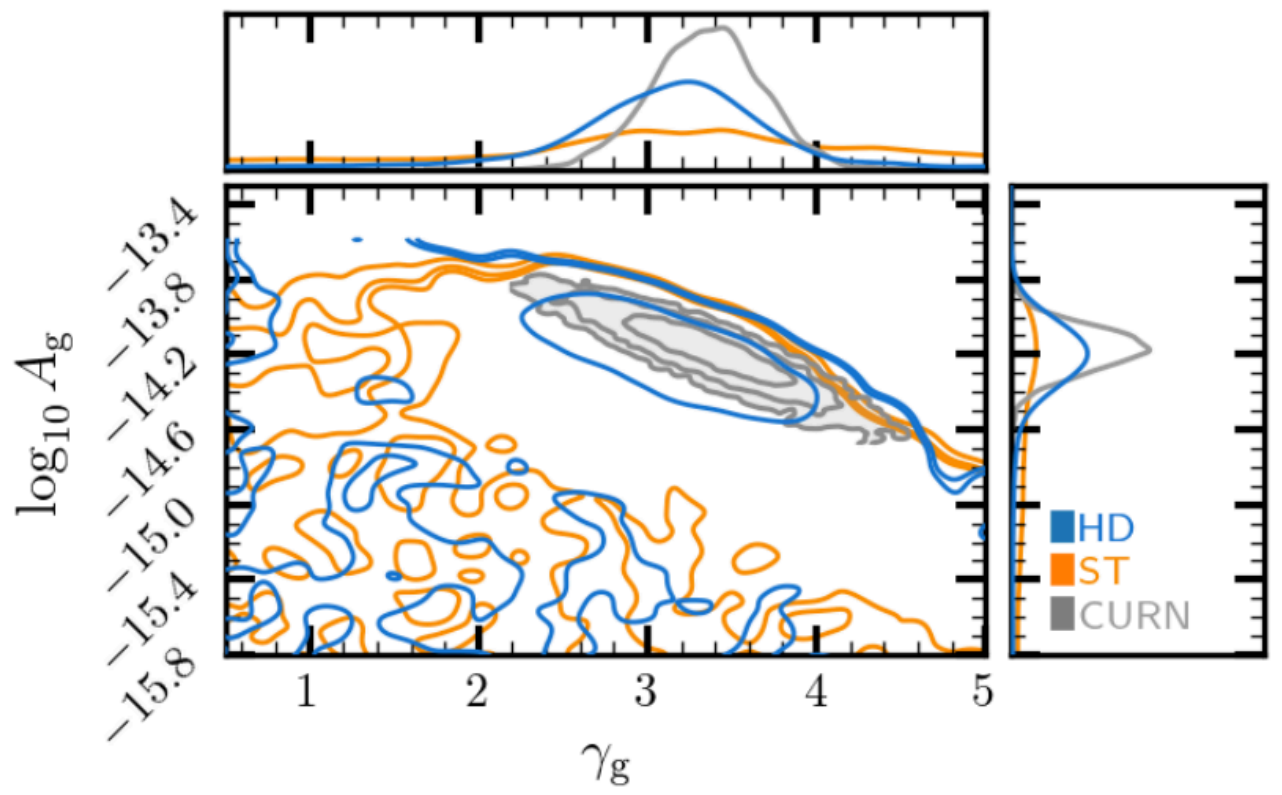


Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L8 (2023).

No Evidence for Additional ST Modes

Leads: Dallas Degan and Nima Laal





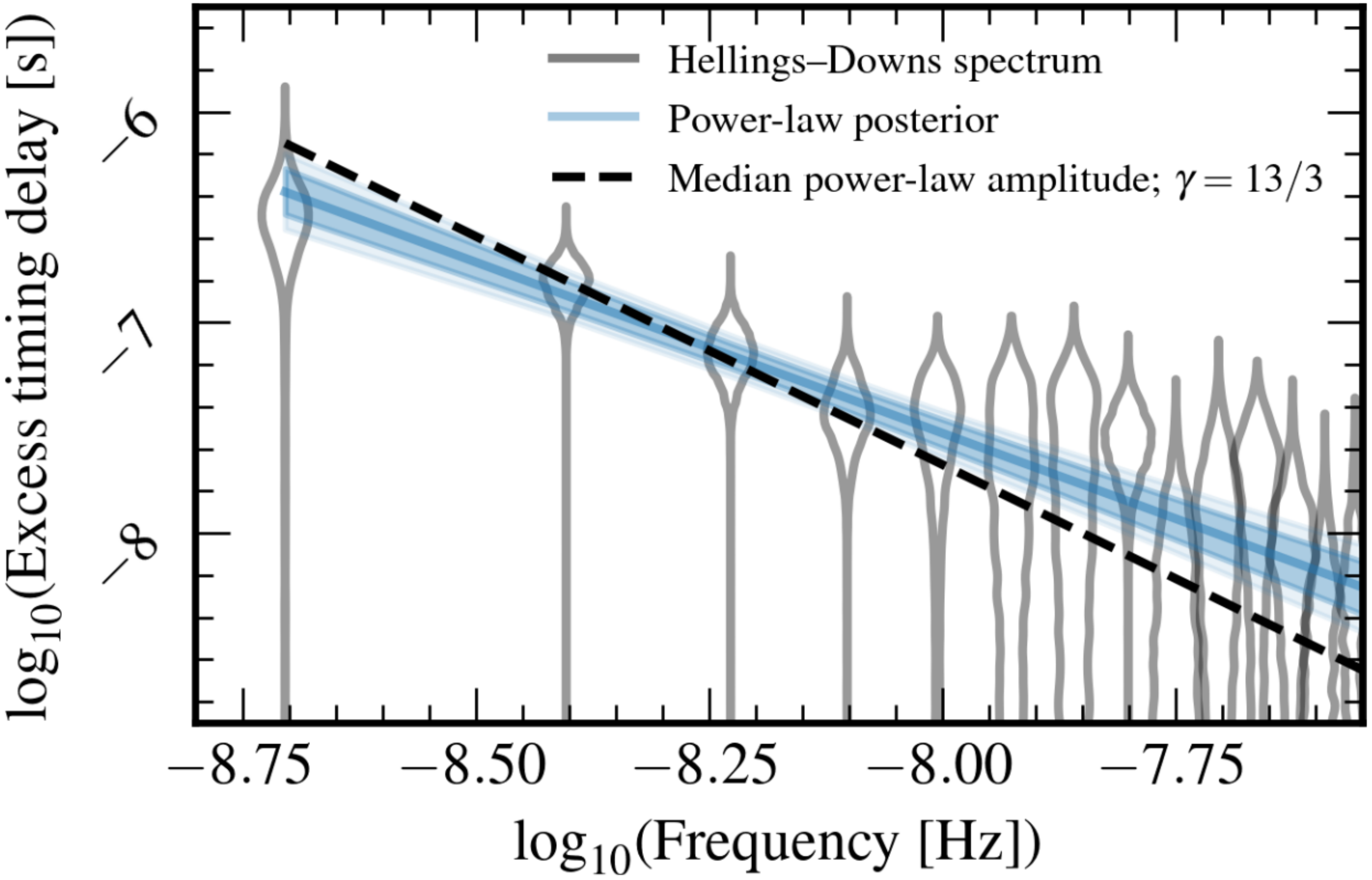
No evidence of ST modes in addition to TT modes in NANOGrav 15yr data set. TT modes-only preferred over ST modes-only.

Results are consistent with analysis by Chen, Wu, Bi, and Huang, arXiv:2310.11238.

NANOGrav analysis only searched for ST and TT modes because ORFs for SL and VL require knowledge of pulsar distances, which are not well-measured for all pulsars.

Figure credit: G. Agazie et al. (The NANOGrav Collaboration), arXiv:2310.12138

Spectral Characterization



Evidence of a common spectrum process with HD correlations.

Spectrum transitions to flat at ~28 nHz (14 freq bins).

Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L8 (2023).

Spectral Characterization

Under default data model, the power-law PSD exponent prefers <13/3 (circular SMBBHs).

Power-law parameter posteriors consistent when using different DM models, but using DMGP results in steeper spectral index.

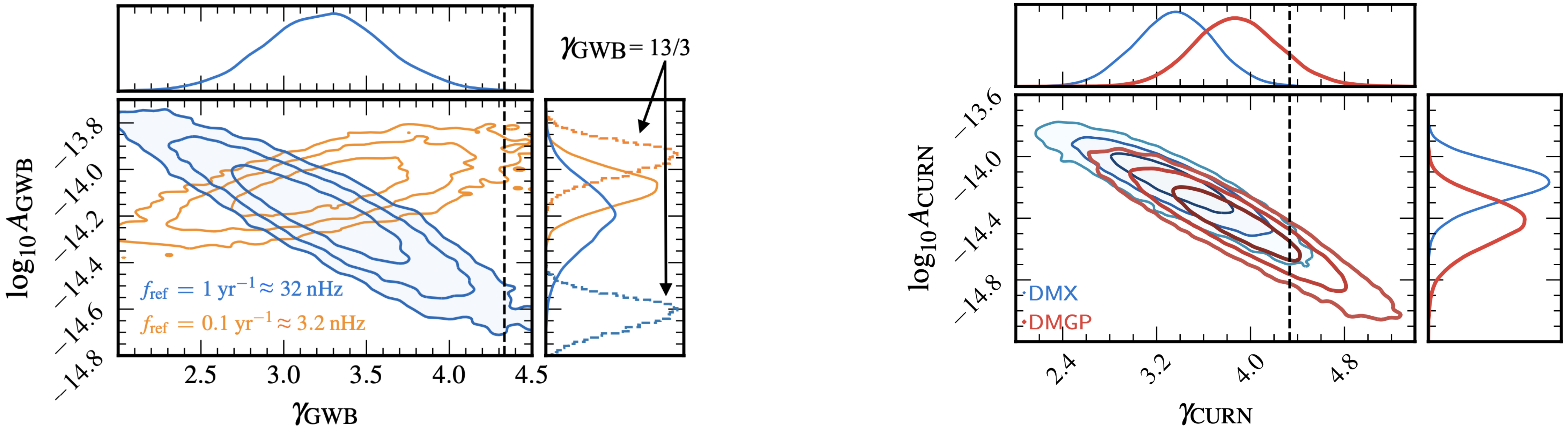


Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L8 (2023).

We coordinated the release of 18 papers from NANOGrav, the EPTA, the InPTA, the PPTA, and the CPTA.

arXiv:2306.16213 to 2306.16230

- The NANOGrav 15-year Data Set: Evidence for a Gravitational-Wave Background
- The second data release from the European Pulsar Timing Array III. Search for gravitational wave signals
- Search for an Isotropic Gravitational-wave Background with the Parkes Pulsar Timing Array
- Searching for the Nano-Hertz stochastic Gravitational wave background with the Chinese Pulsar Timing Array Data Release I
- The NANOGrav 15-year Data Set: Observations and Timing of 68 Millisecond Pulsars
- The NANOGrav 15-year Data Set: Detector Characterization and Noise Budget
- The NANOGrav 15-year Data Set: Search for Signals from New Physics
- The NANOGrav 15-year Data Set: Constraints on Supermassive Black Hole Binaries from the Gravitational Wave Background
- The NANOGrav 15-year Data Set: Search for Anisotropy in the Gravitational-Wave Background
- The NANOGrav 15-year Data Set: Bayesian Limits on Gravitational Waves from Individual Supermassive Black Hole Binaries
- The NANOGrav 15-year Gravitational-Wave Background Analysis Pipeline
- The second data release from the European Pulsar Timing Array I. The dataset and timing analysis
- The second data release from the European Pulsar Timing Array II. Customised pulsar noise models for spatially correlated gravitational waves
- The second data release from the European Pulsar Timing Array IV. Search for continuous gravitational wave signals
- The second data release from the European Pulsar Timing Array V. Implications for massive black holes, dark matter and the early Universe
- The second data release from the European Pulsar Timing Array VI: Challenging the ultralight dark matter paradigm
- The Gravitational-wave Background Null Hypothesis: Characterizing Noise in Millisecond Pulsar Arrival Times with the Parkes Pulsar Timing Array
- The Parkes Pulsar Timing Array Third Data Release

The IPTA has submitted a paper comparing the GWB results from the EPTA+InPTA, NANOGrav, and PPTA data sets.

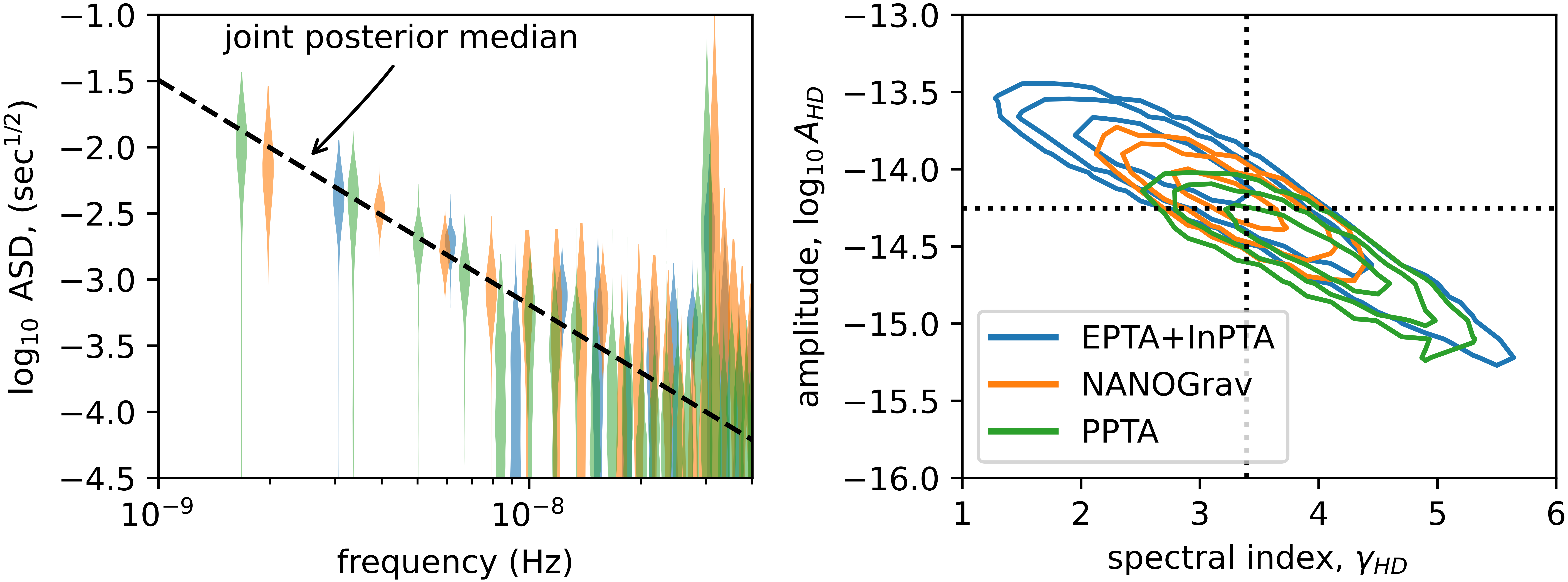


Figure credit: G. Agazie et al. (The IPTA Collaboration), arXiv:2309.00693

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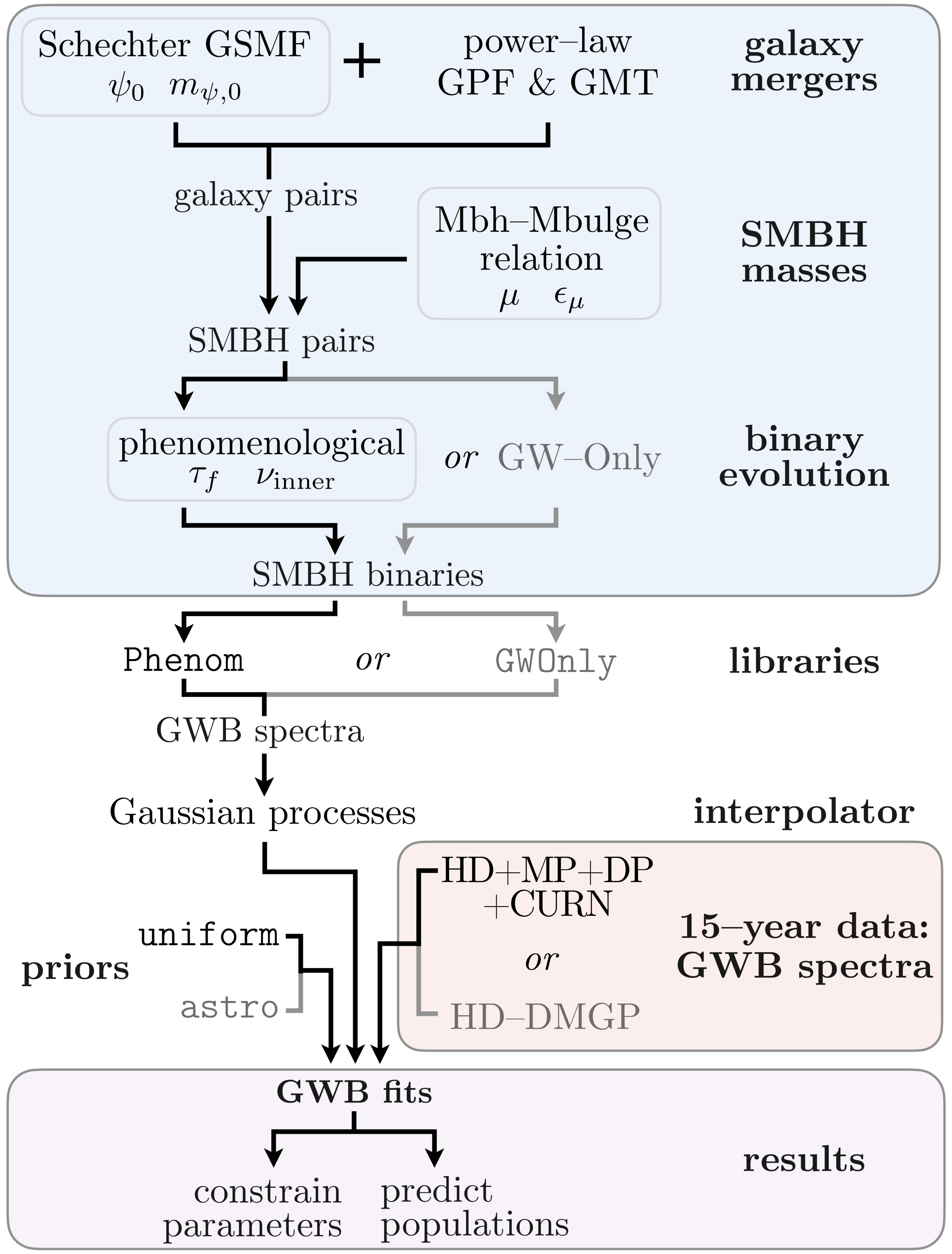
Supermassive Binary Black Holes

Image credits: J. Cuadra, D. Madison, S. Burke-Spolaor

Implications for SMBBHs



Step 1: Generate SMBBH populations

Start with galaxy mergers. Populate them with SMBHs. Evolve binaries from large separations.

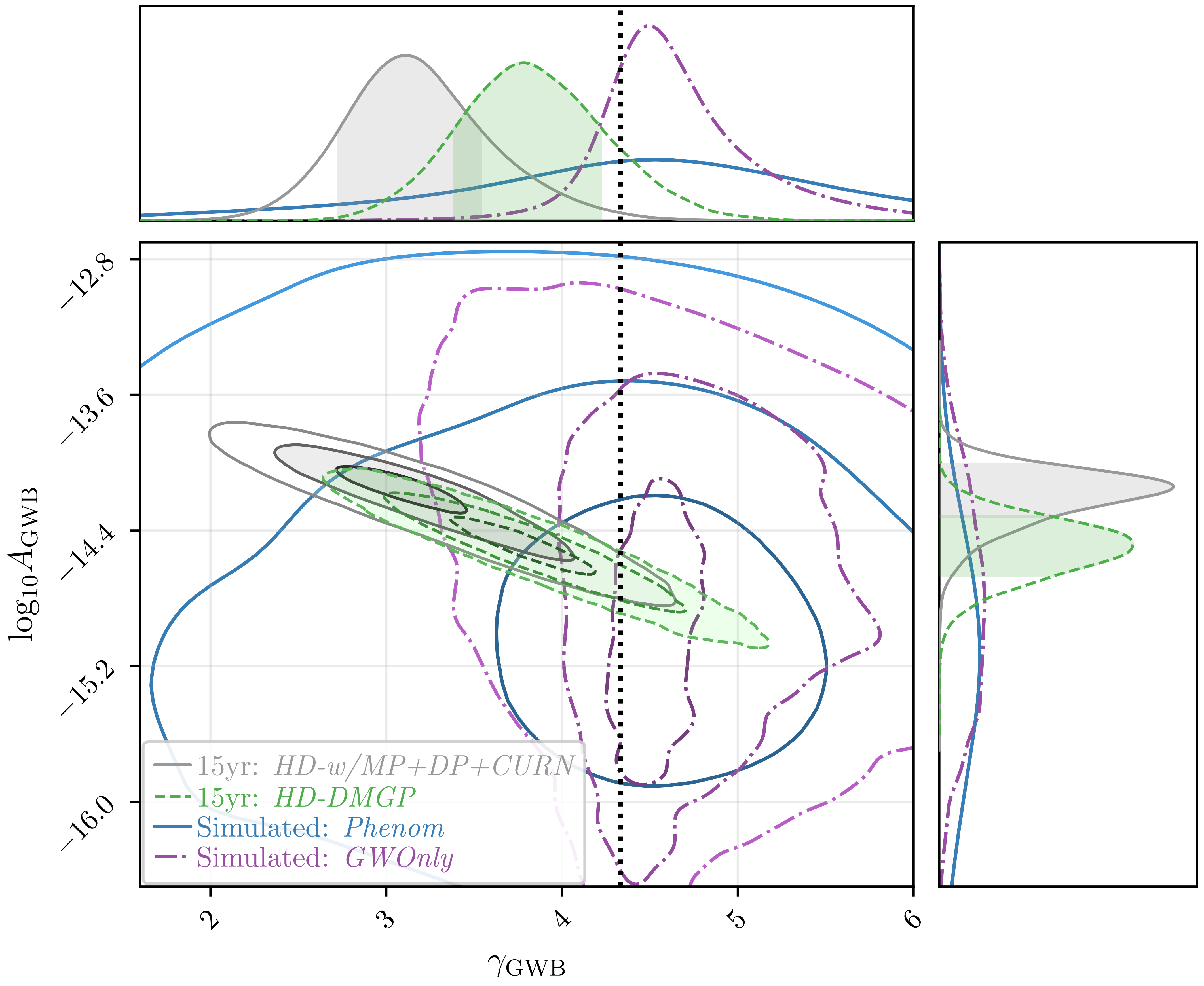
Step 2: Interpolate population synthesis models using Gaussian processes.

Step 3: Fit models to PTA data

Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 952, L37 (2023).

Implications for SMBBHs

Lead: Luke Kelley



Observed PSD is consistent with a GWB produced by SMBBHs

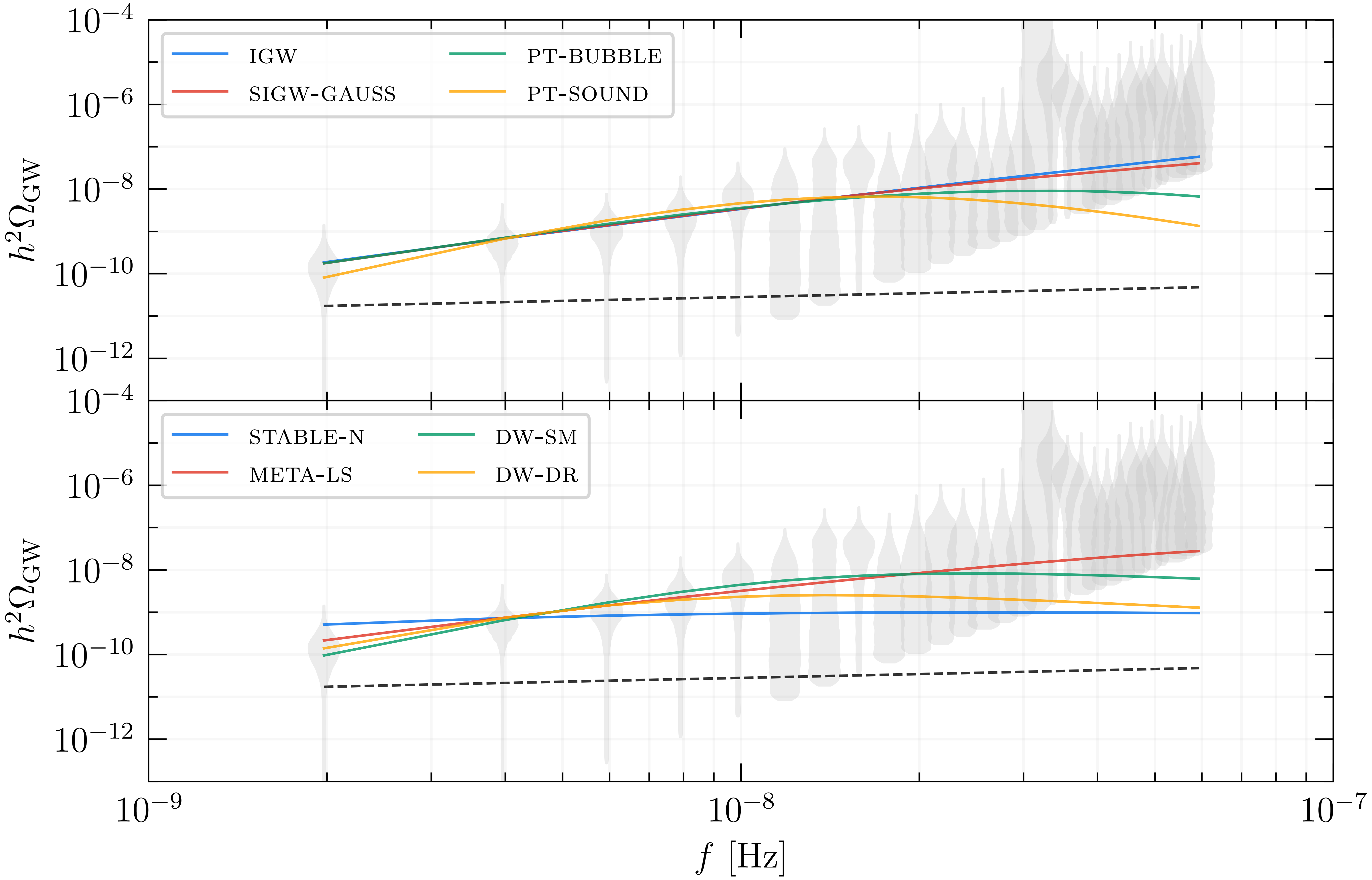
Some preference for interacting models versus GW-only evolution models

Amplitude is high, but within the range of expectations. Implies some combination of relatively high masses, high rates of galaxy mergers, and efficient binary inspiral

Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 952, L37 (2023).

Implications for New Physics

Leads: Andrea Mitridate and Kai Schmitz

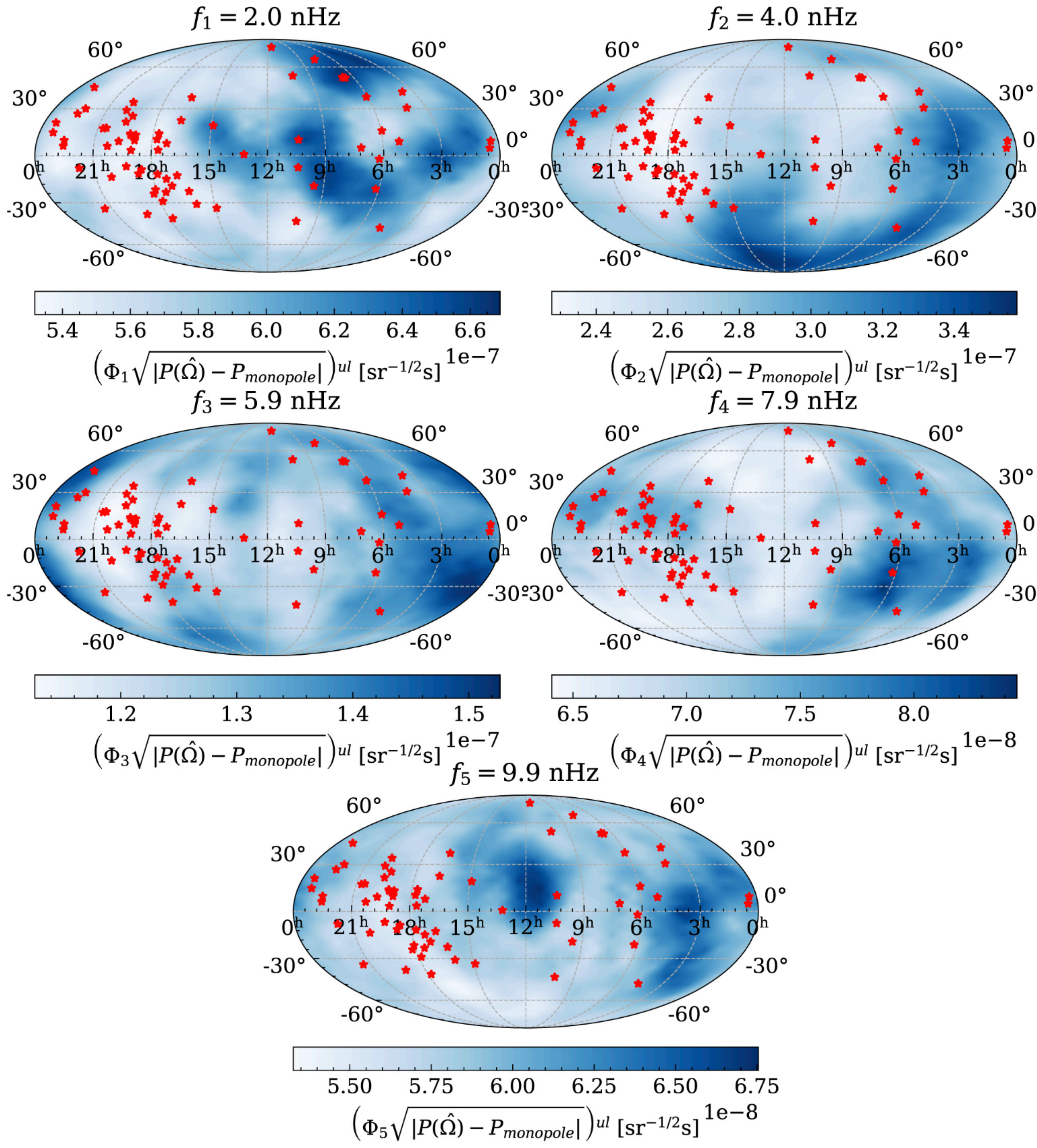


Observed PSD is also consistent with GWB produced by cosmic inflation, scalar-induced GWs, first-order phase transitions, and domain walls.

Figure credit: A. Afzal et al. (The NANOGrav Collaboration), ApJL 951, L11 (2023).

Limits on Anisotropy

Lead: Nihan Pol



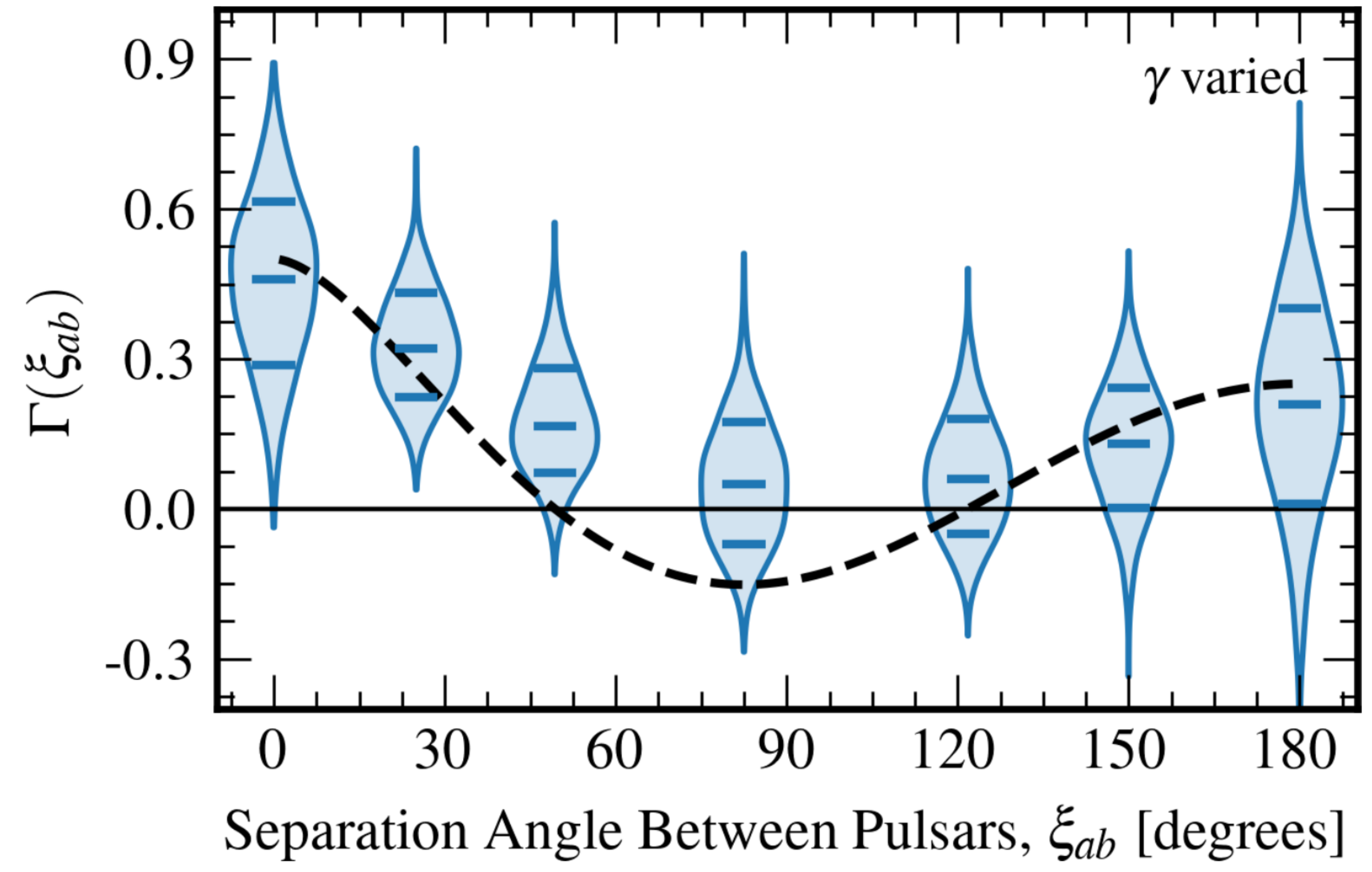
A GWB from SMBBHs should have some amount of anisotropy since it is made up of GWs from a finite number of individual binaries.

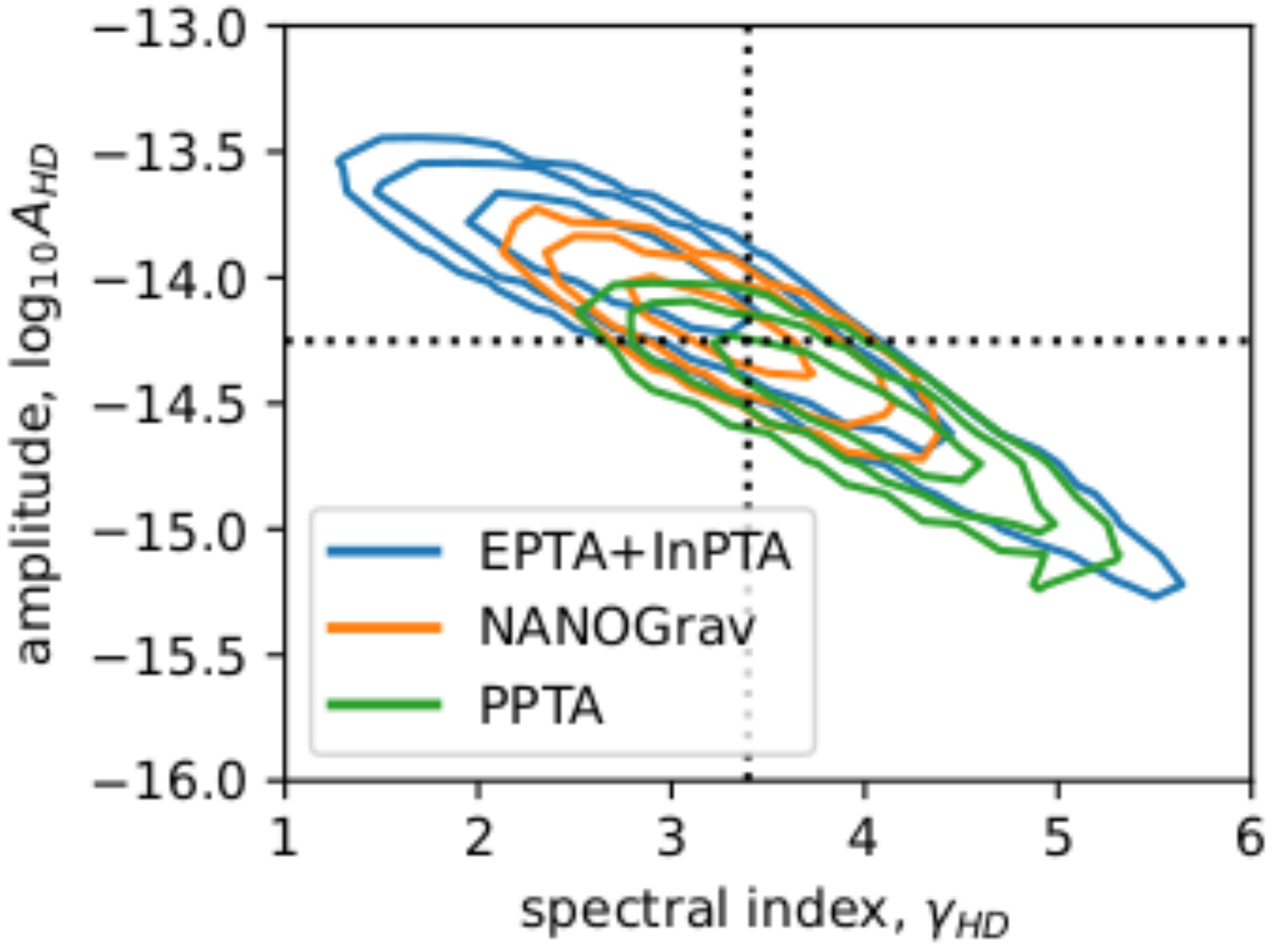
We place limits on the anisotropy of the GWB using the 15yr data set.

Simulations suggest future PTA data sets with ~20 years of data will be able to detect anisotropy (Pol, Taylor, and Romano 2022).

Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 956, L3 (2023).

Conclusions





Pulsar timing array collaborations have recently published evidence for a gravitational wave background at nanohertz frequencies.

The NANOGrav 15-year data set shows evidence of HD correlations with false alarm probabilities of 10^{-3} to 10^{-4} (3-4σ Gaussian equivalent).

This signal is consistent with an astrophysical population of SMBBHs, but is also consistent with new physics sources. More precise measurement of the spectrum, or measurement of anisotropy, can help us identify the source(s).