The NANOGrav 15-year GWB Analysis

Sarah Vigeland
University of Wisconsin-Milwaukee

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

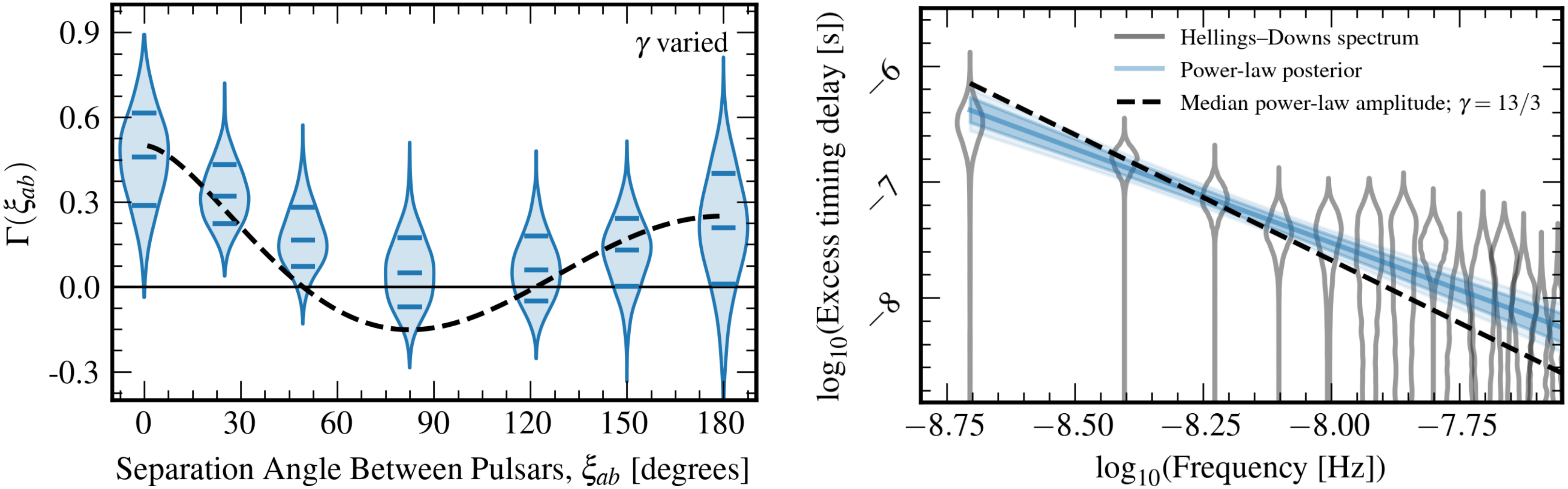
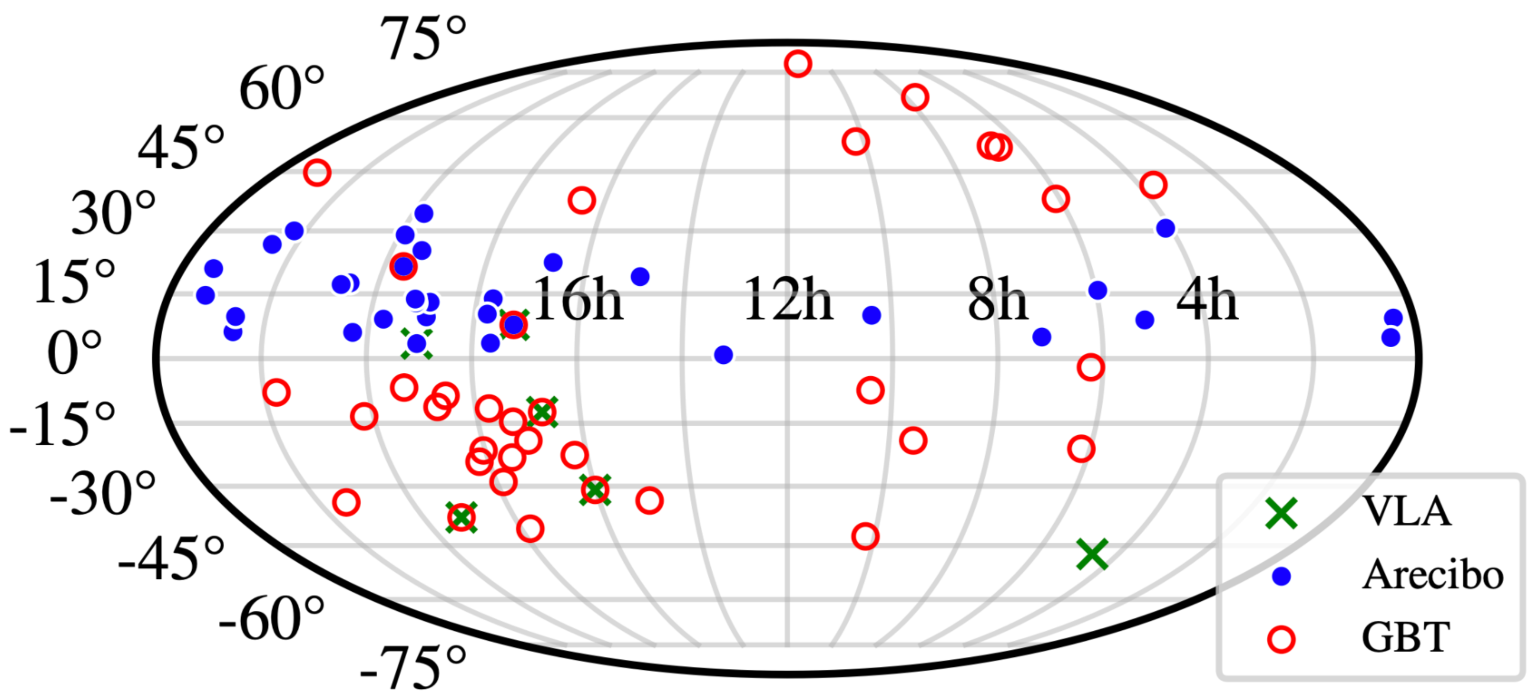


Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L8 (2023).

The NANOGrav 15-year Data Set



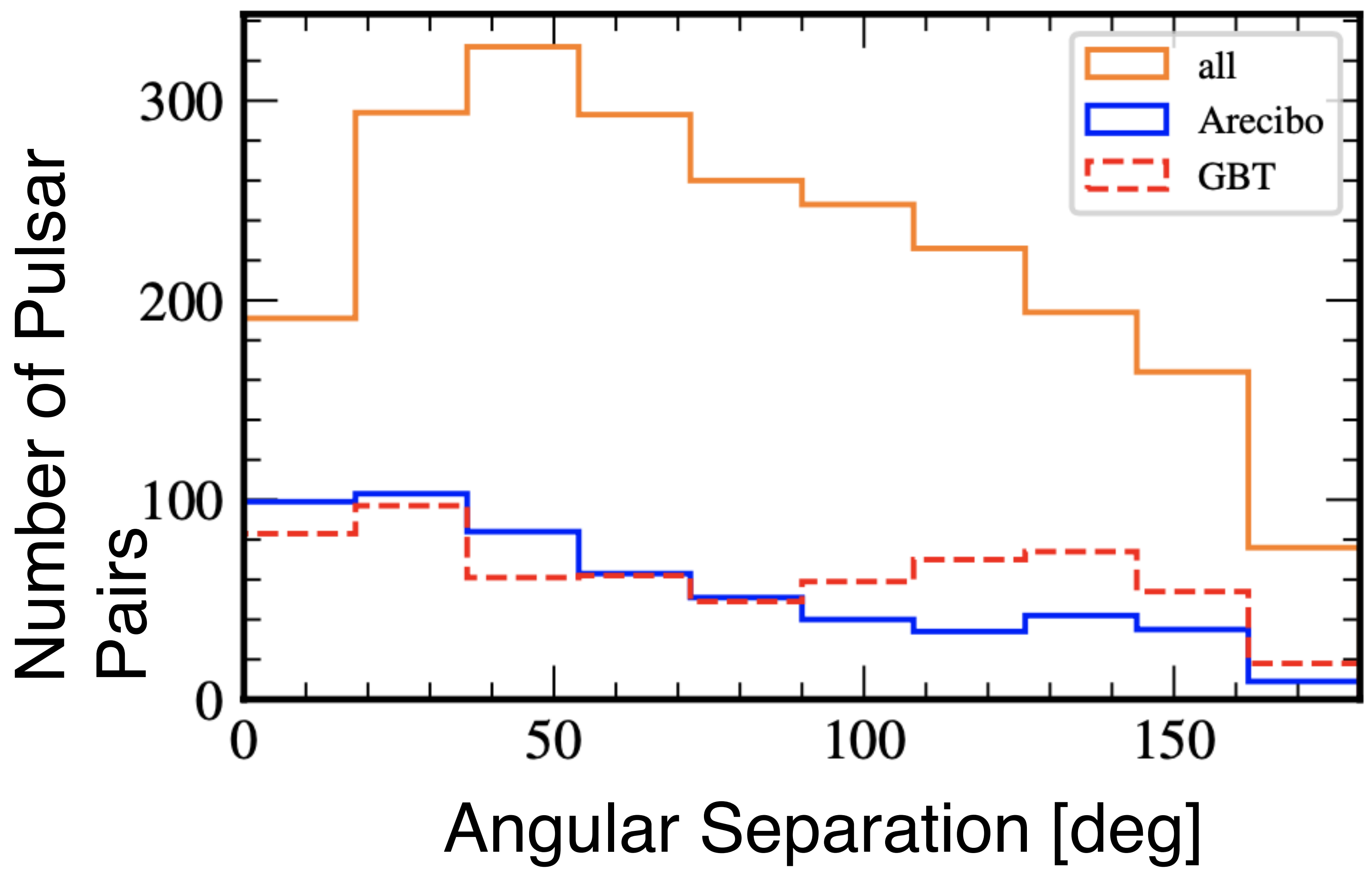


Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L8 (2023).

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.

Pulsar Timing

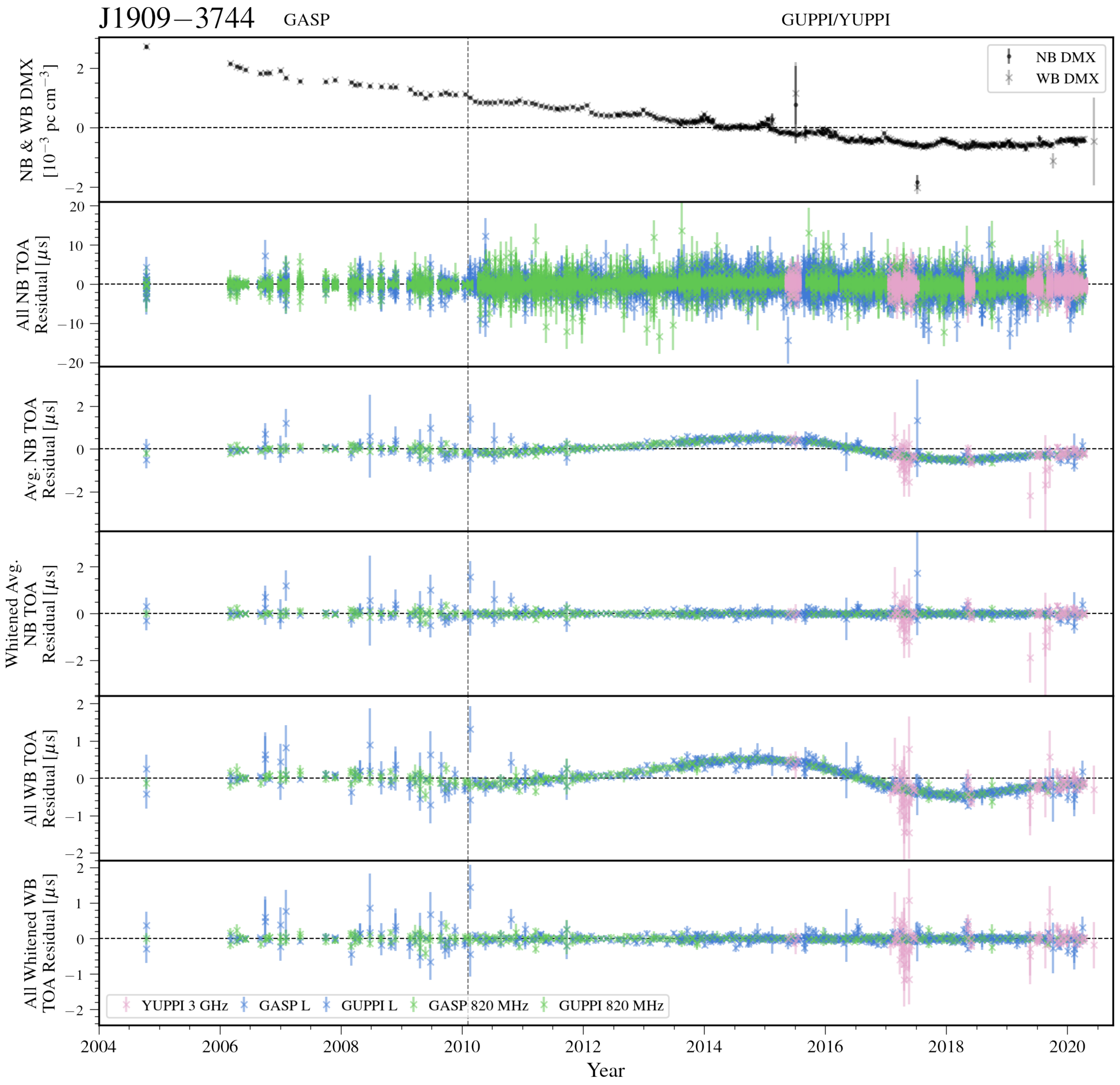
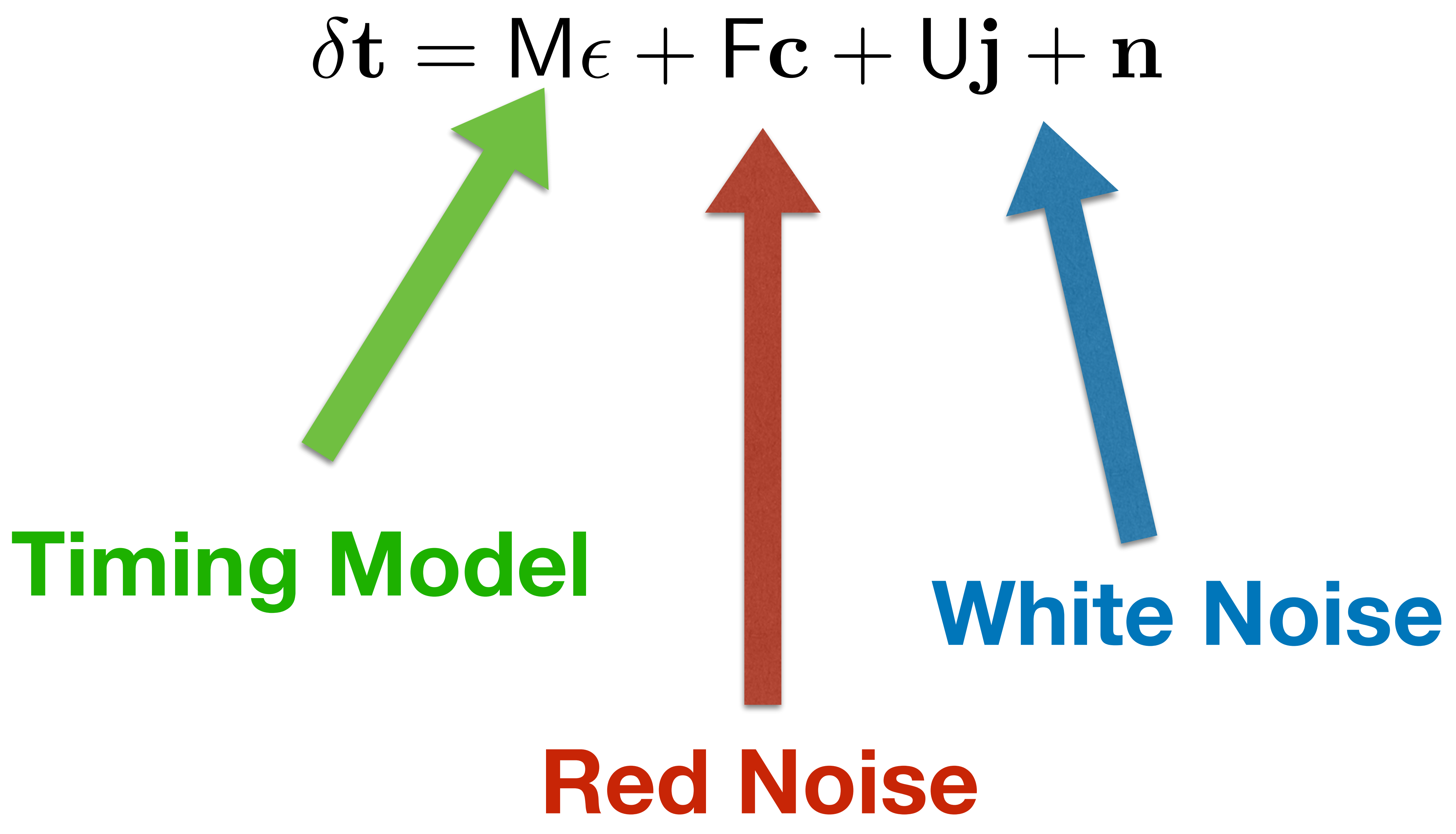


Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L9 (2023).

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



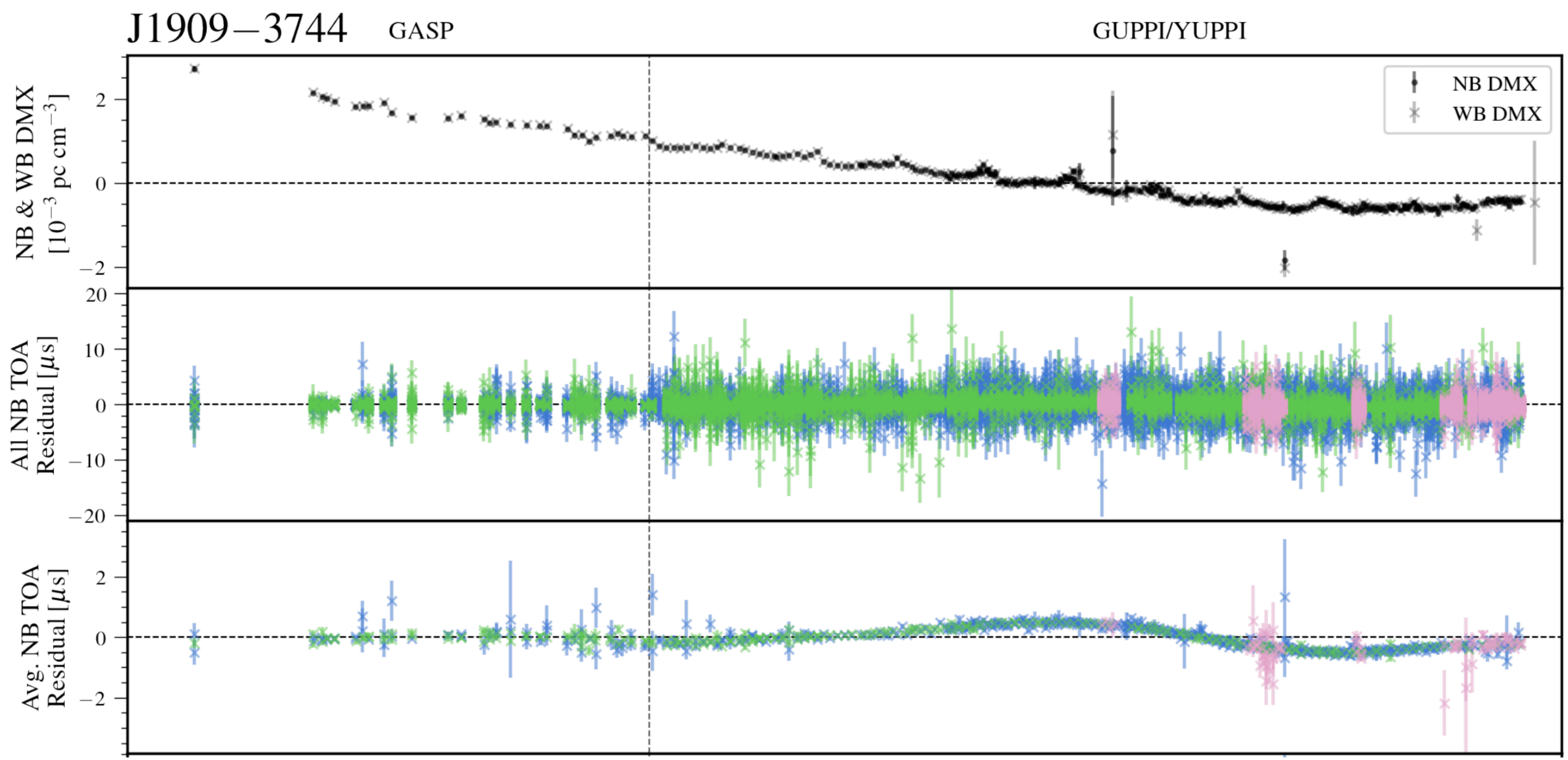
$$\delta \mathbf{t} = \mathsf{M}\epsilon + \mathsf{F}\mathbf{c} + \mathsf{U}\mathbf{j} + \mathbf{n}$$

Timing Model

Red Noise

White Noise

Pulsar Timing

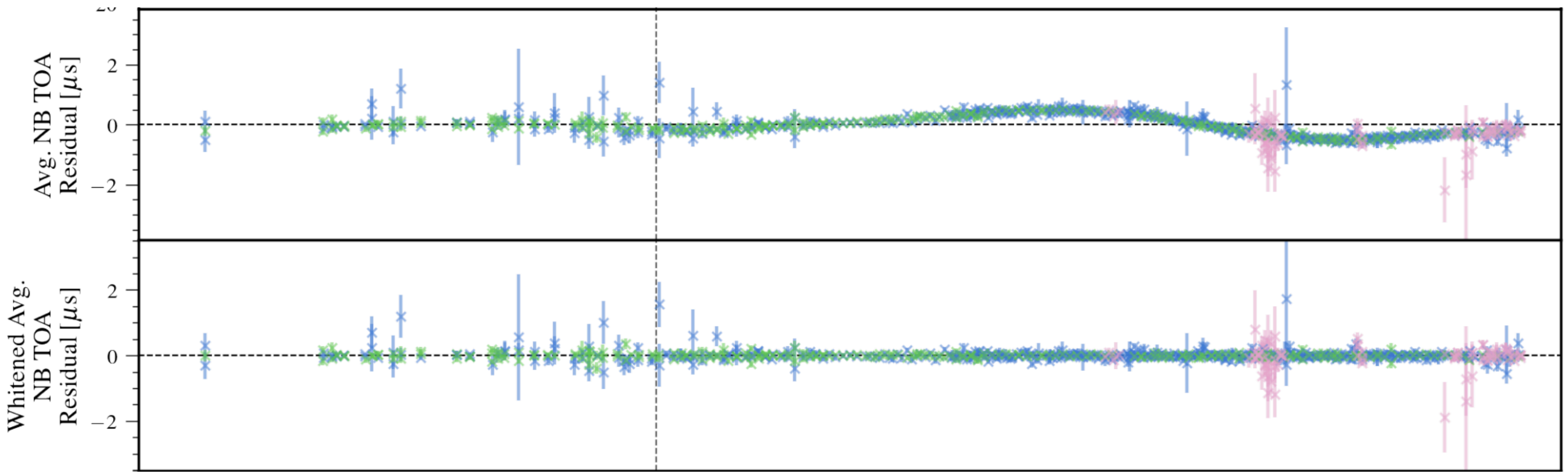


Dispersion measure variations

Residuals

Averaged residuals

Pulsar Timing



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

Fourier basis

$f = 1/T_{\mathsf{obs}}, 2/T_{\mathsf{obs}}, \ldots$

amplitude coefficients

Pulsar 1

Timing Model
White Noise
Red Noise

+

Pulsar 2

Timing Model
White Noise
Red Noise

+

Pulsar 3

Timing Model
White Noise
Red Noise

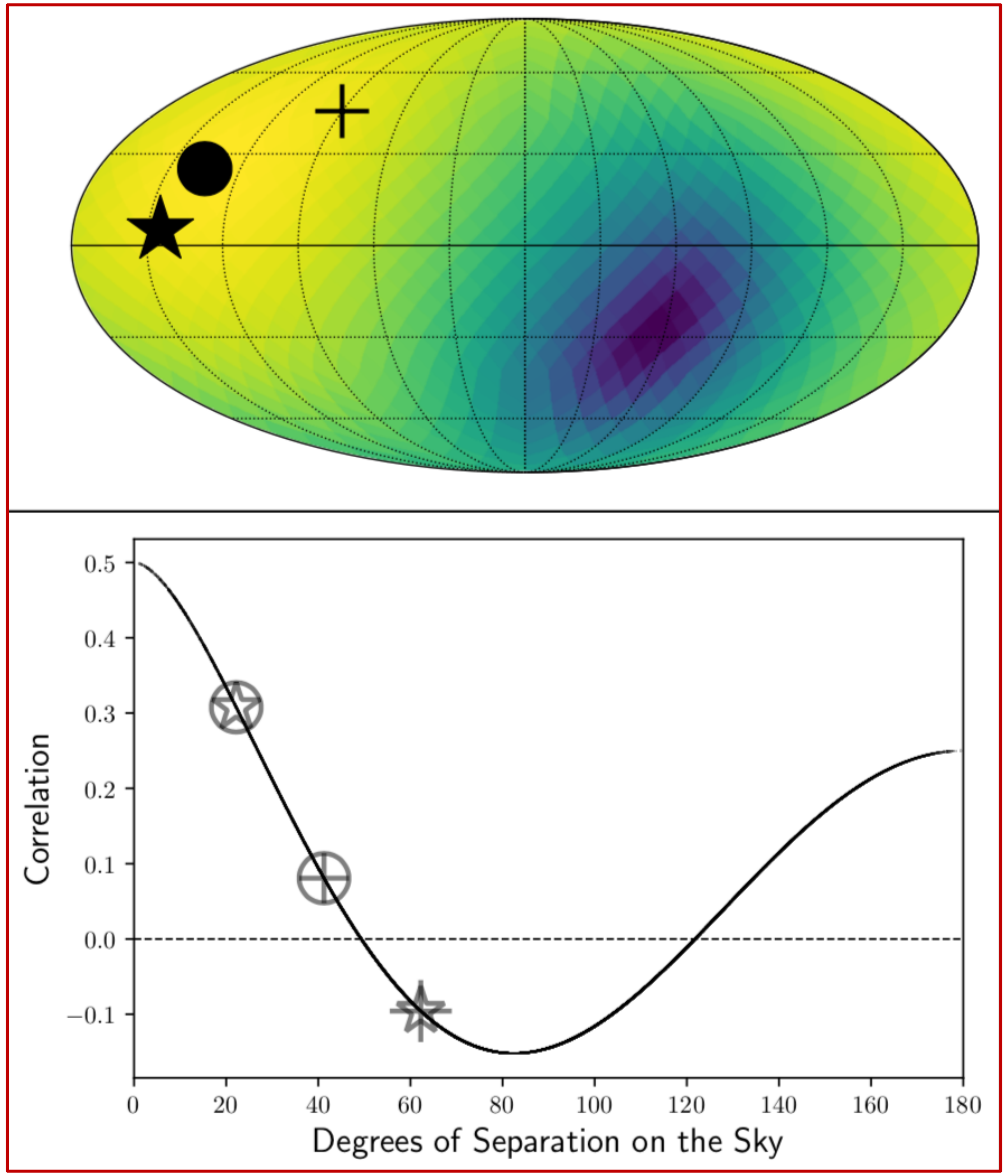
+

Common sources of noise

+

Gravitational Wave Signal

GWB Signal Model



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

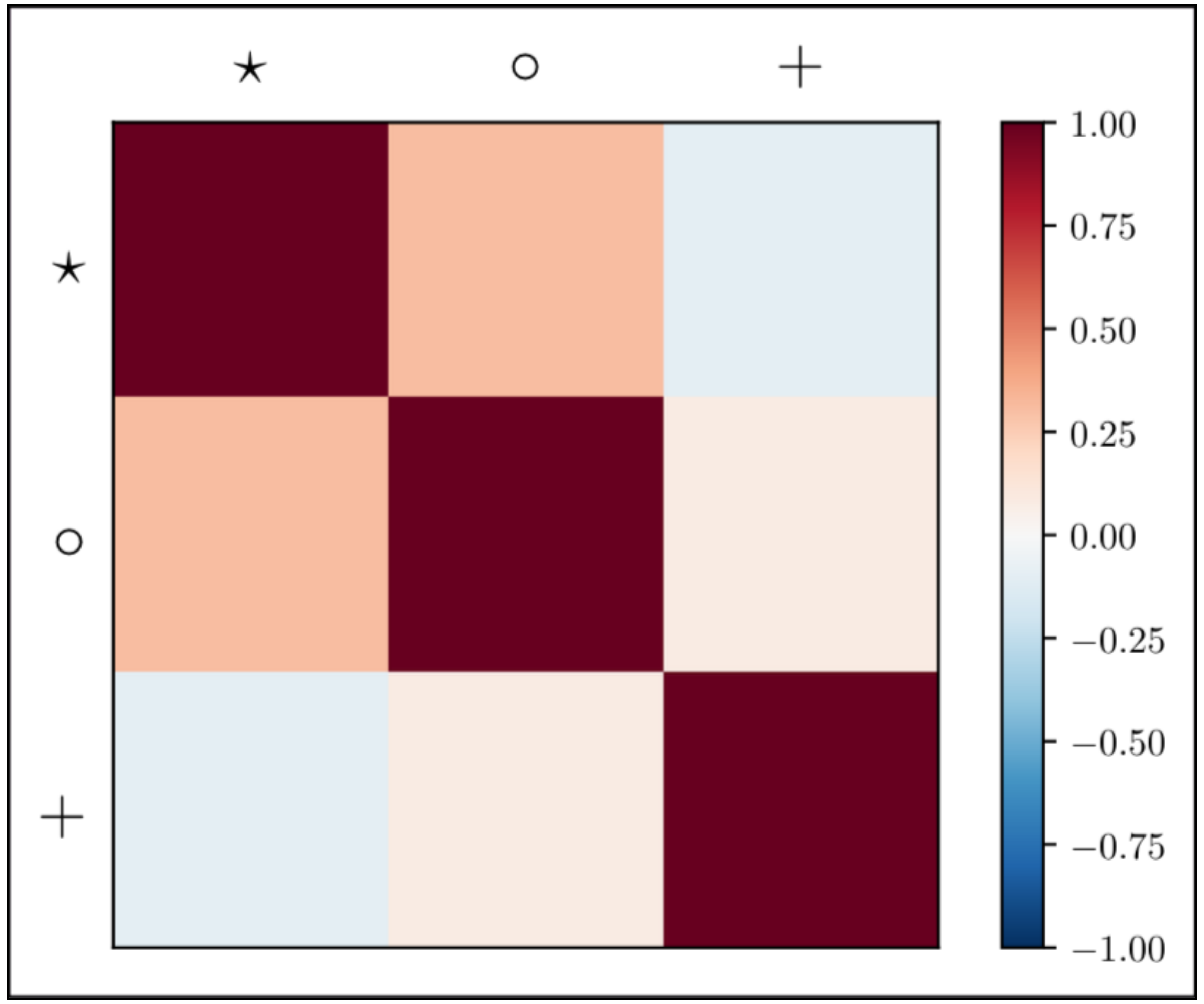


Figure credit: J. Hazboun

GWB Signal Model

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

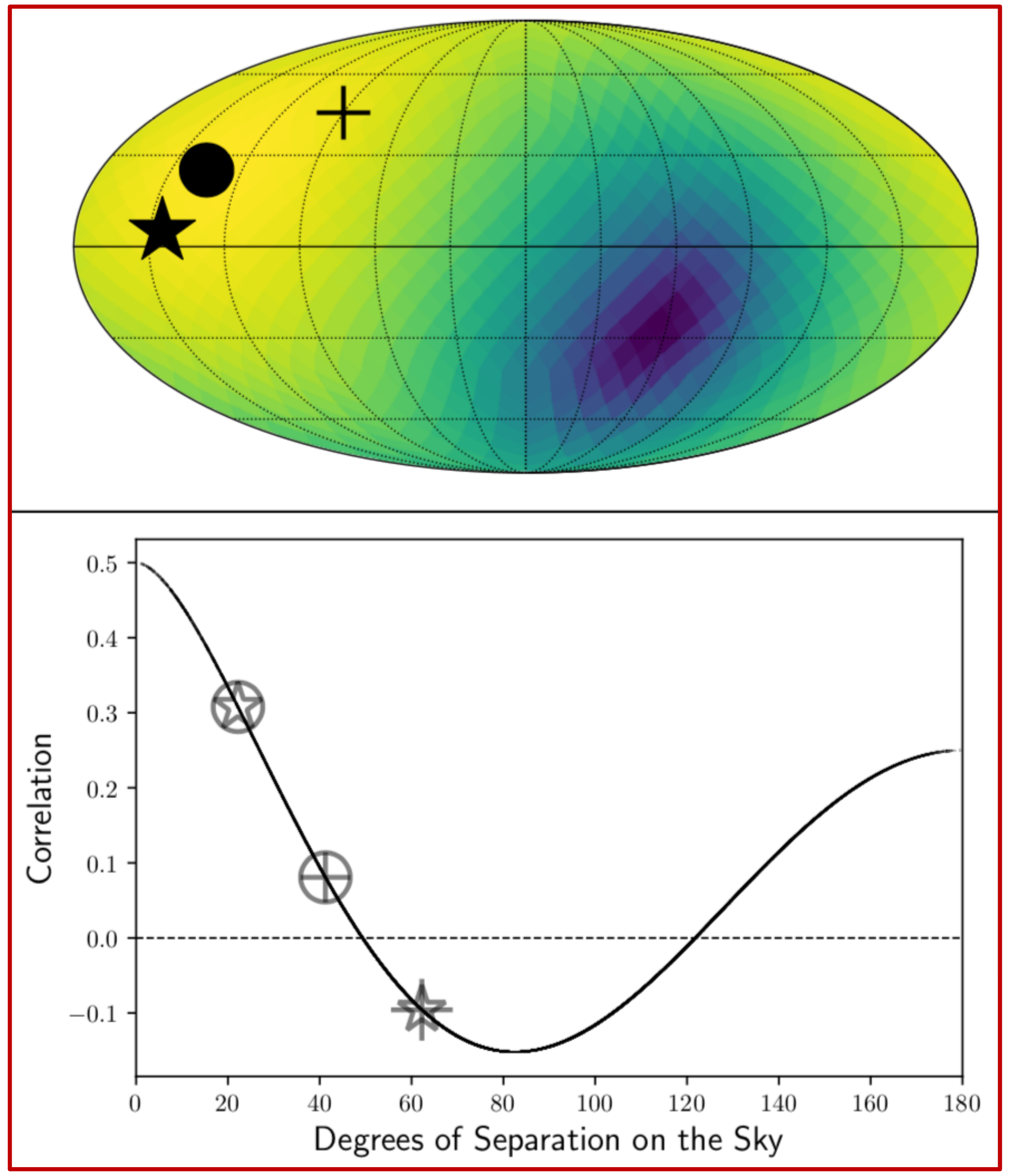


Figure credit: J. Hazboun

Auto-correlations only

$$\begin{pmatrix} \langle \delta t_1 \delta t_1^T \rangle & 0 & \dots & 0 \\ 0 & \langle \delta t_2 \delta t_2^T \rangle & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \langle \delta t_N \delta t_N^T \rangle \end{pmatrix}$$

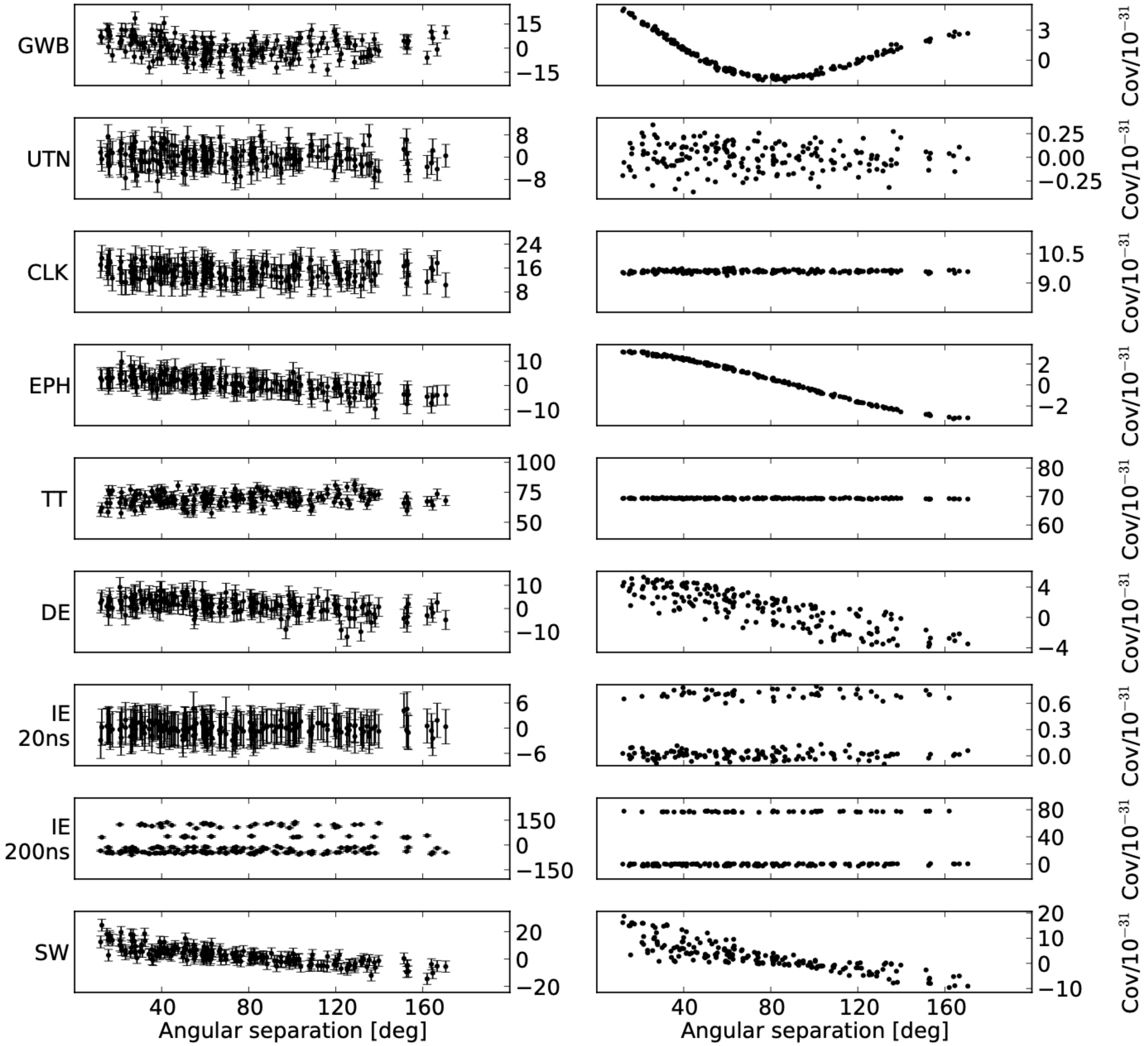
Auto-correlations and cross-correlations

$$\begin{pmatrix} \langle \delta t_1 \delta t_1^T \rangle & \langle \delta t_1 \delta t_2^T \rangle & \dots & \langle \delta t_1 \delta t_N^T \rangle \\ \langle \delta t_2 \delta t_1^T \rangle & \langle \delta t_2 \delta t_2^T \rangle & \dots & \langle \delta t_2 \delta t_N^T \rangle \\ \vdots & \vdots & \ddots & \vdots \\ \langle \delta t_N \delta t_1^T \rangle & \langle \delta t_N \delta t_2^T \rangle & \dots & \langle \delta t_N \delta t_N^T \rangle \end{pmatrix}$$

Correlated Noise Sources

Some noise sources can induce a common spatially-correlated signal (clock error, ephemeris error, etc.)

Tag	**Simulated effect**	**GWB-like spectrum**
S_{gwb}	GWB	Y
S_{utn}	Uncorrelated red noise	Y
S_{clk}	Stochastic clock-like errors	Y
S_{eph}	Stochastic ephemeris-like errors	Y
S_{tt}	Difference between TT(BIPM2013) and TT(TAI)	N
S_{de}	Difference between DE421 and DE414	N
S_{ie}	Instrumental errors	N
S_{sw}	Solar wind	N



Tiburzi et al., MNRAS 455, 4 (2015)

Non-Einsteinian Polarization Modes

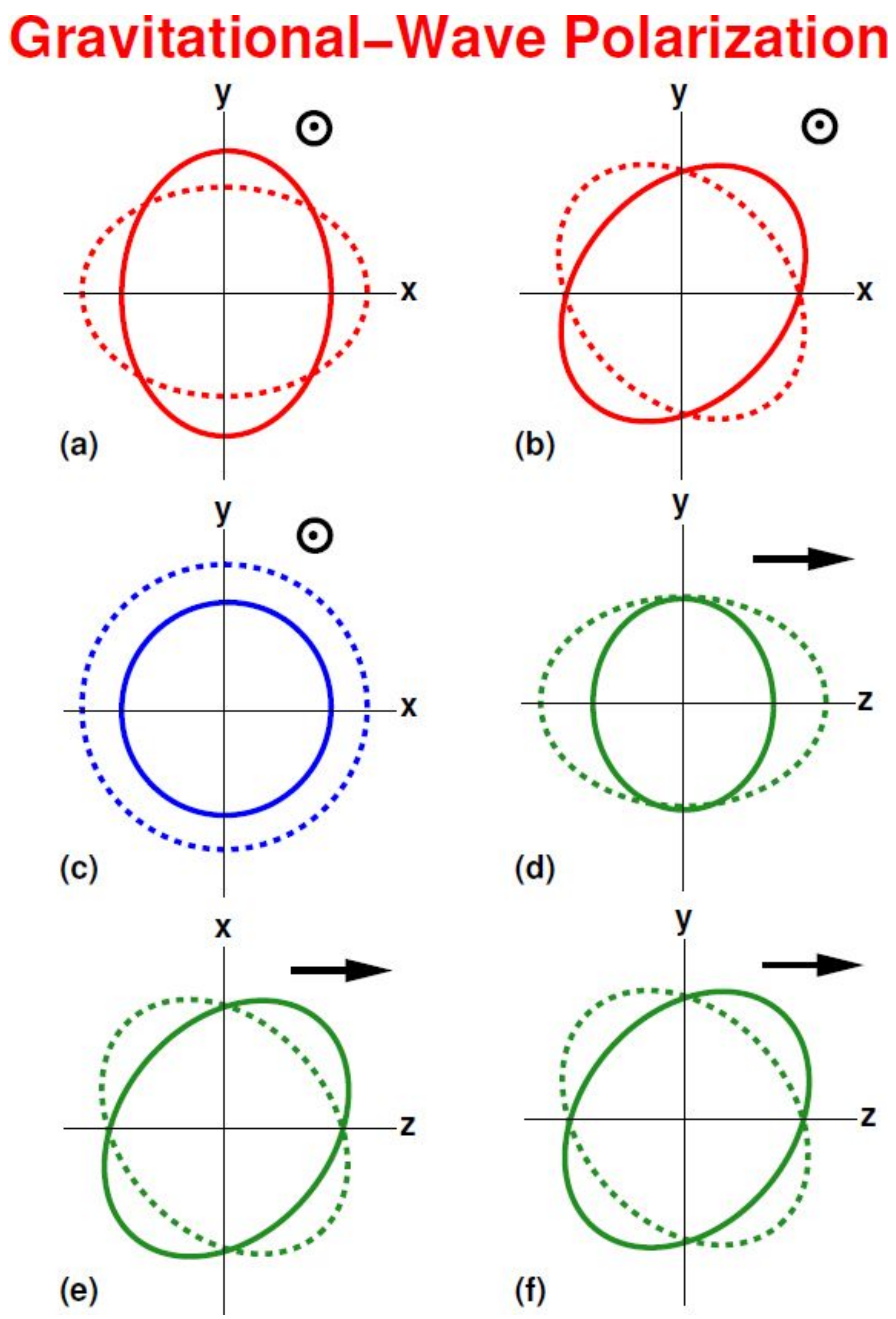
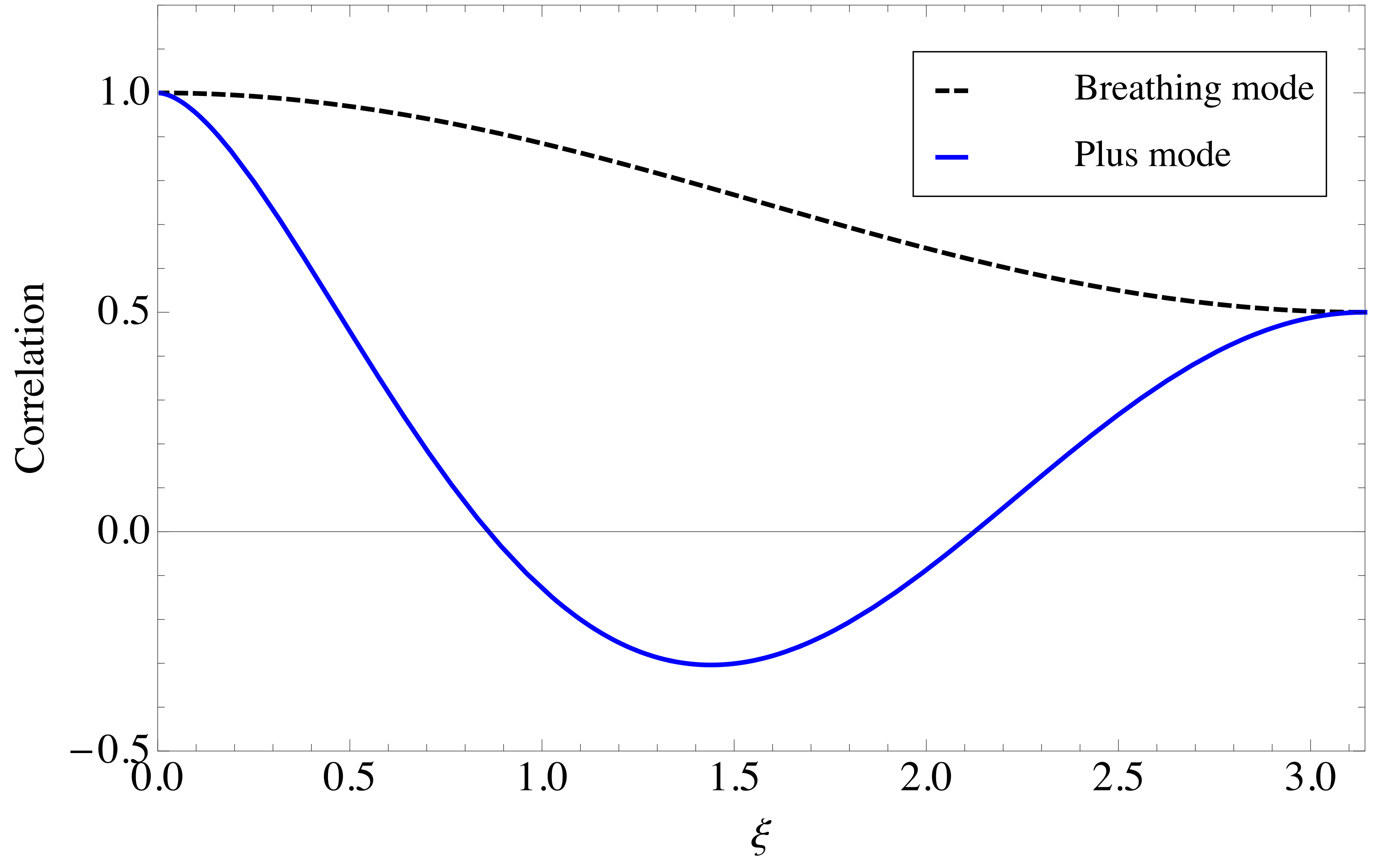


Figure credit: C. Will (2014)

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)



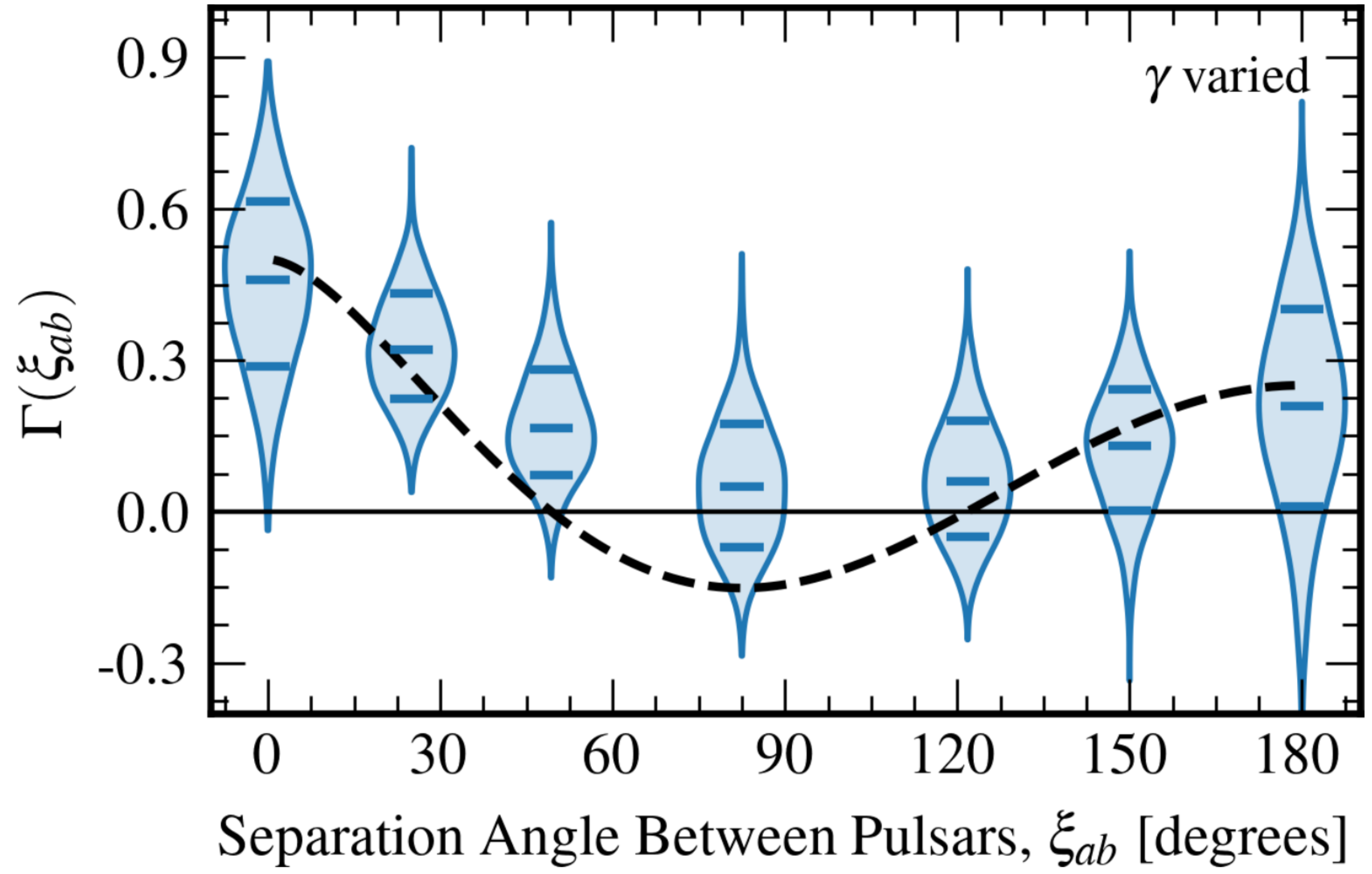
Chamberlin & Siemens (2012)

Evidence for HD Correlations

Bayesian analyses prefer a common red process with HD correlations.

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

Leads: Sarah Vigeland and Stephen Taylor

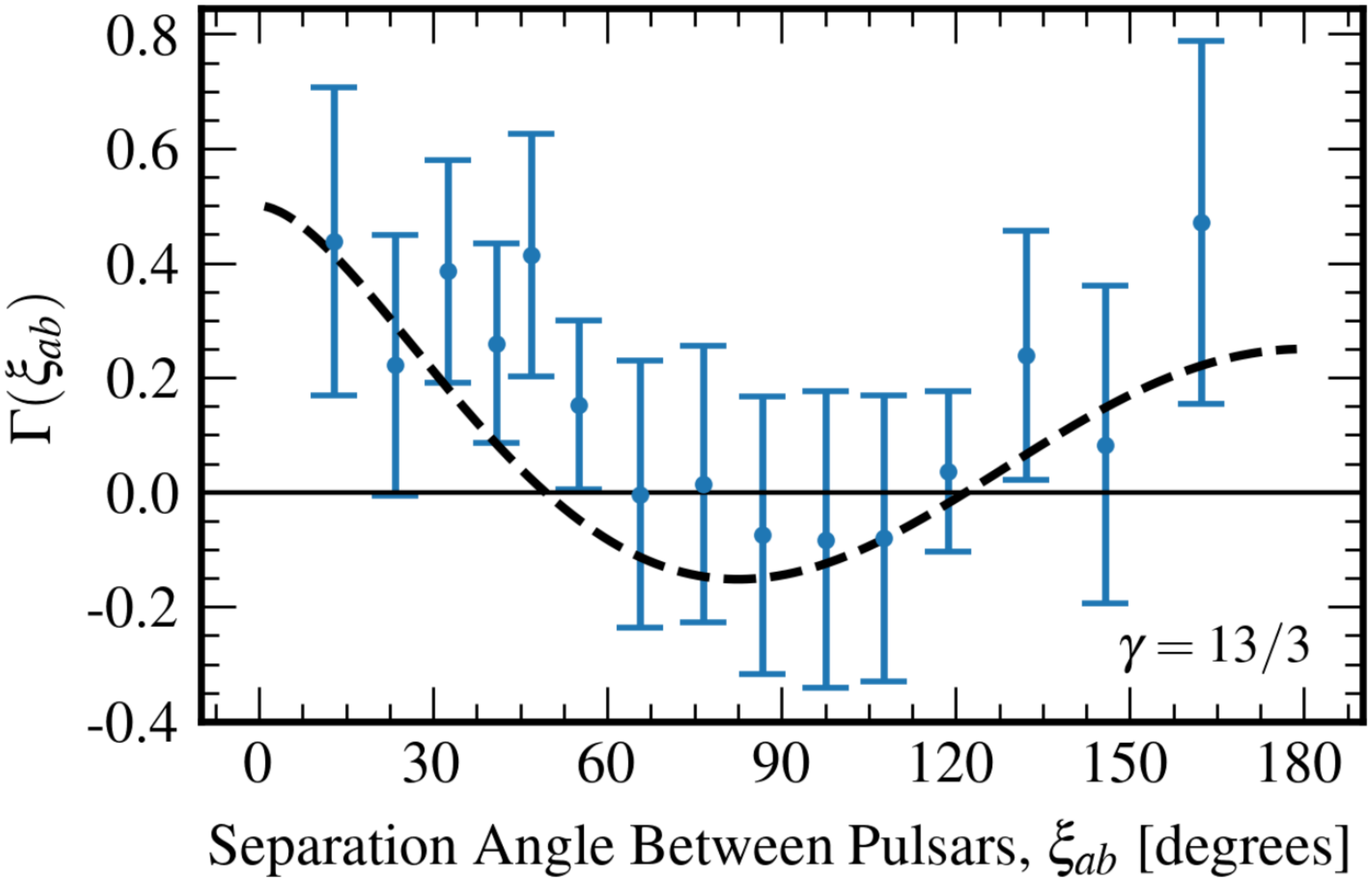


intrinsic pulsar noise only **(IRN)** $\xrightarrow{10^{12.1\pm0.1}}$ common-spectrum red noise **(CRN)** $\xrightarrow{226 \pm 70}$ HD-correlated, common spectrum red noise **(HD)**

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.

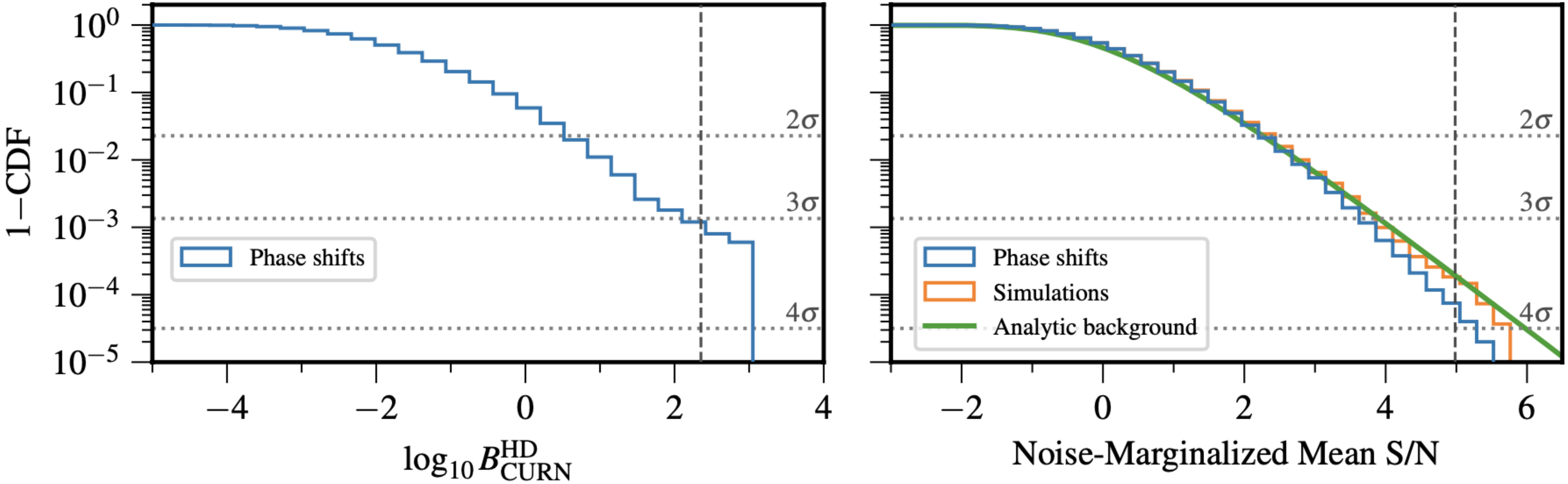
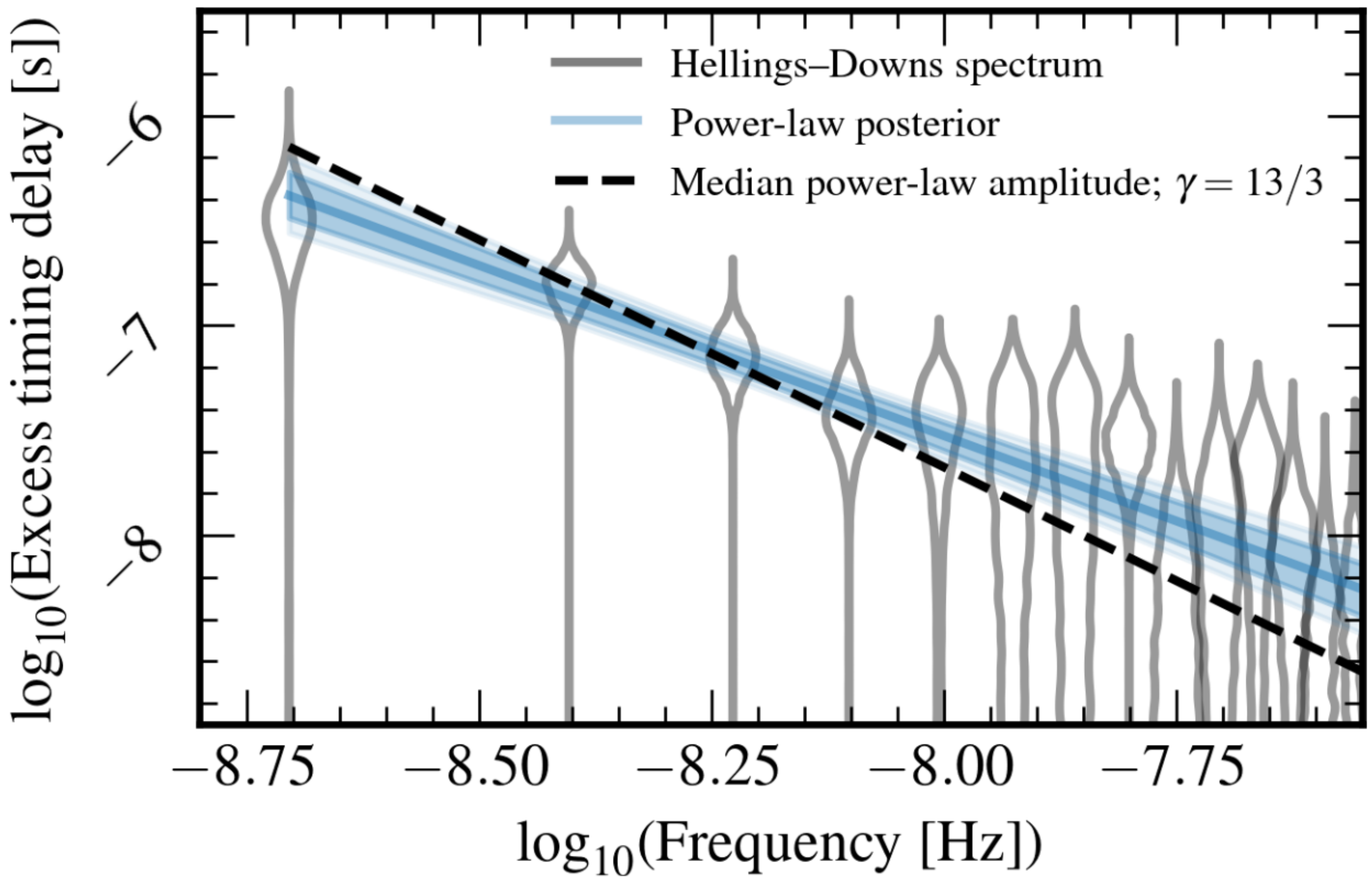


Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L8 (2023).

Spectral Characterization



Evidence of a common spectrum process with HD correlations.

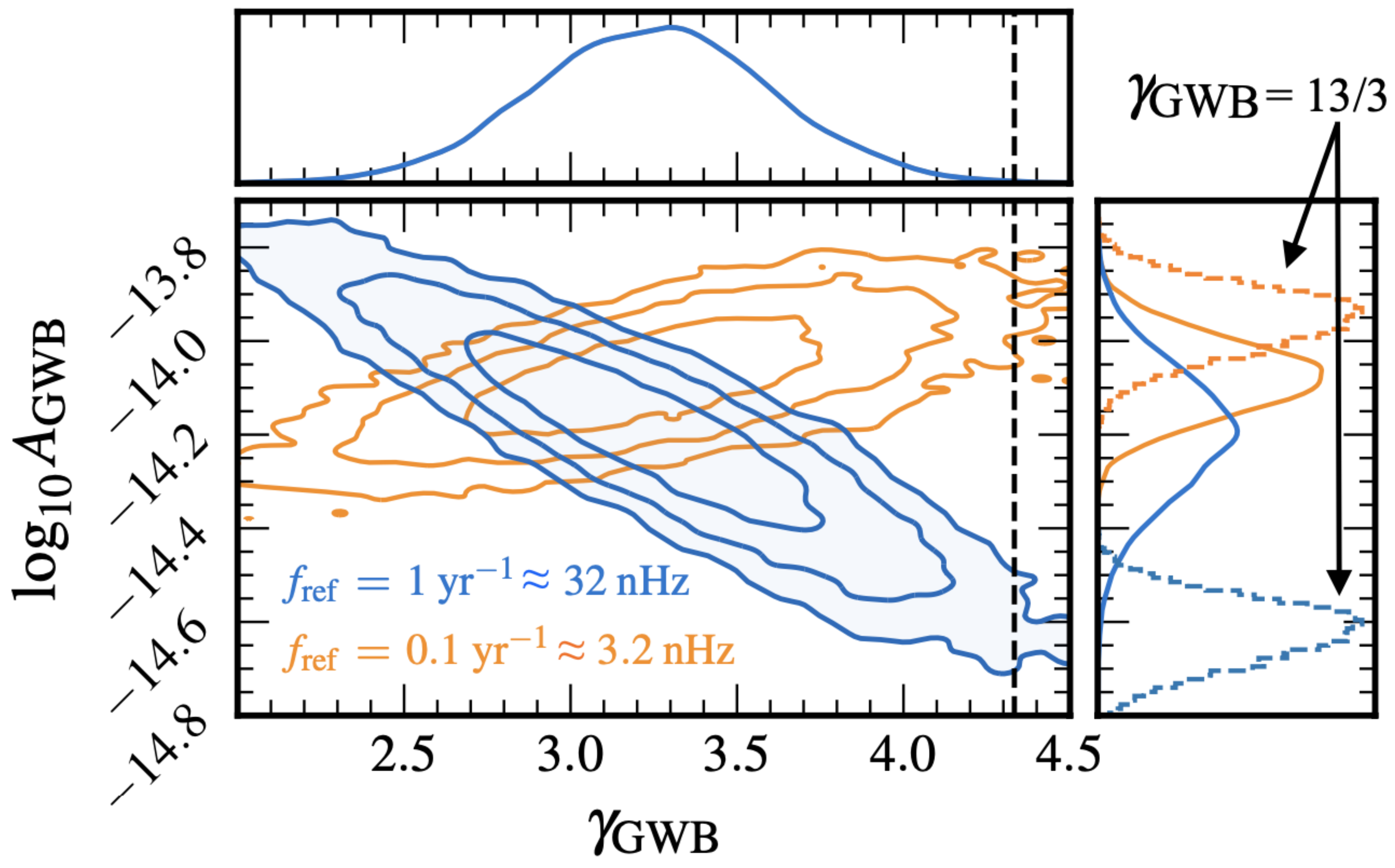
Spectrum transitions to flat at ~28 nHz (14 freq bins).

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.



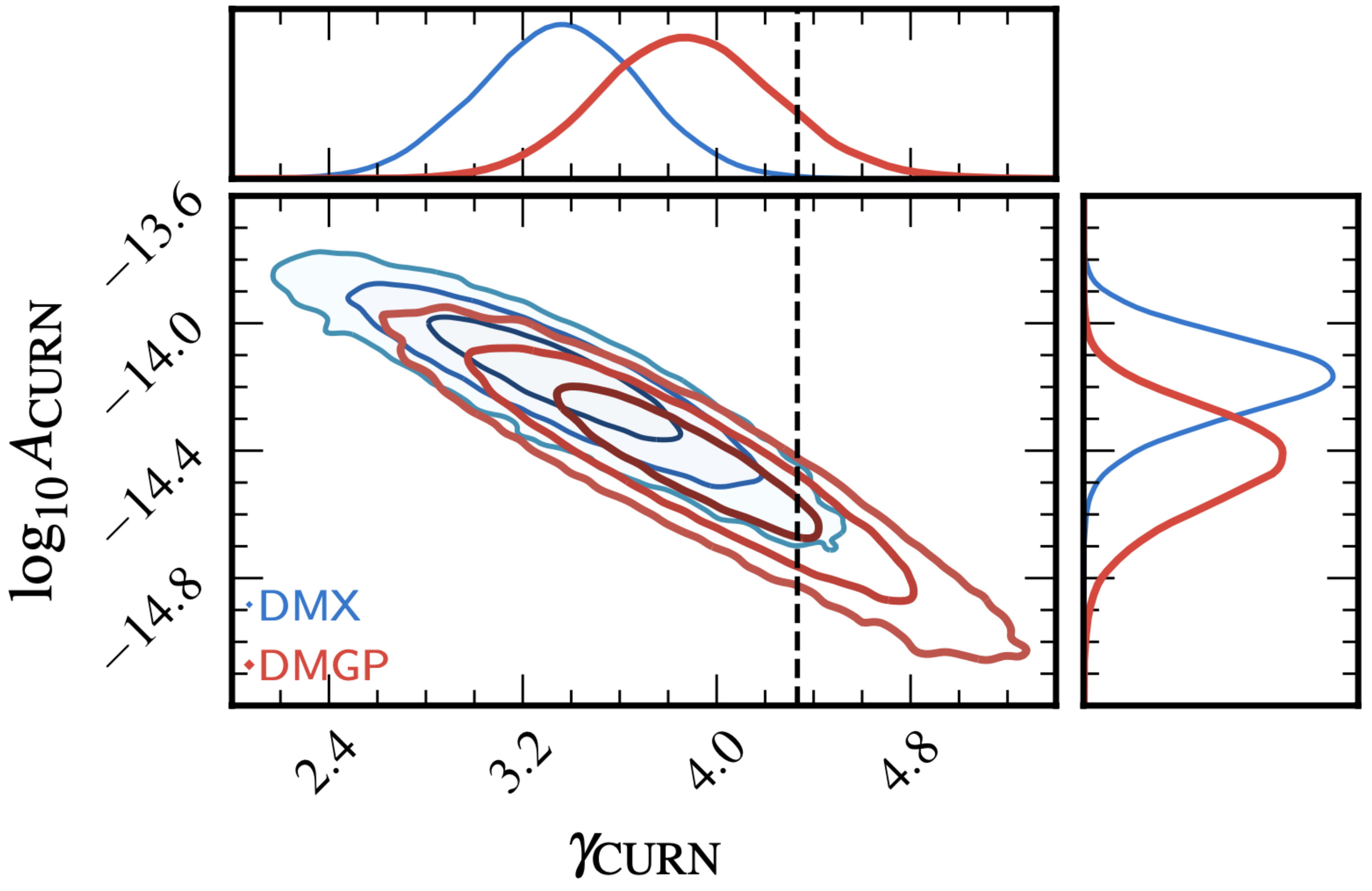
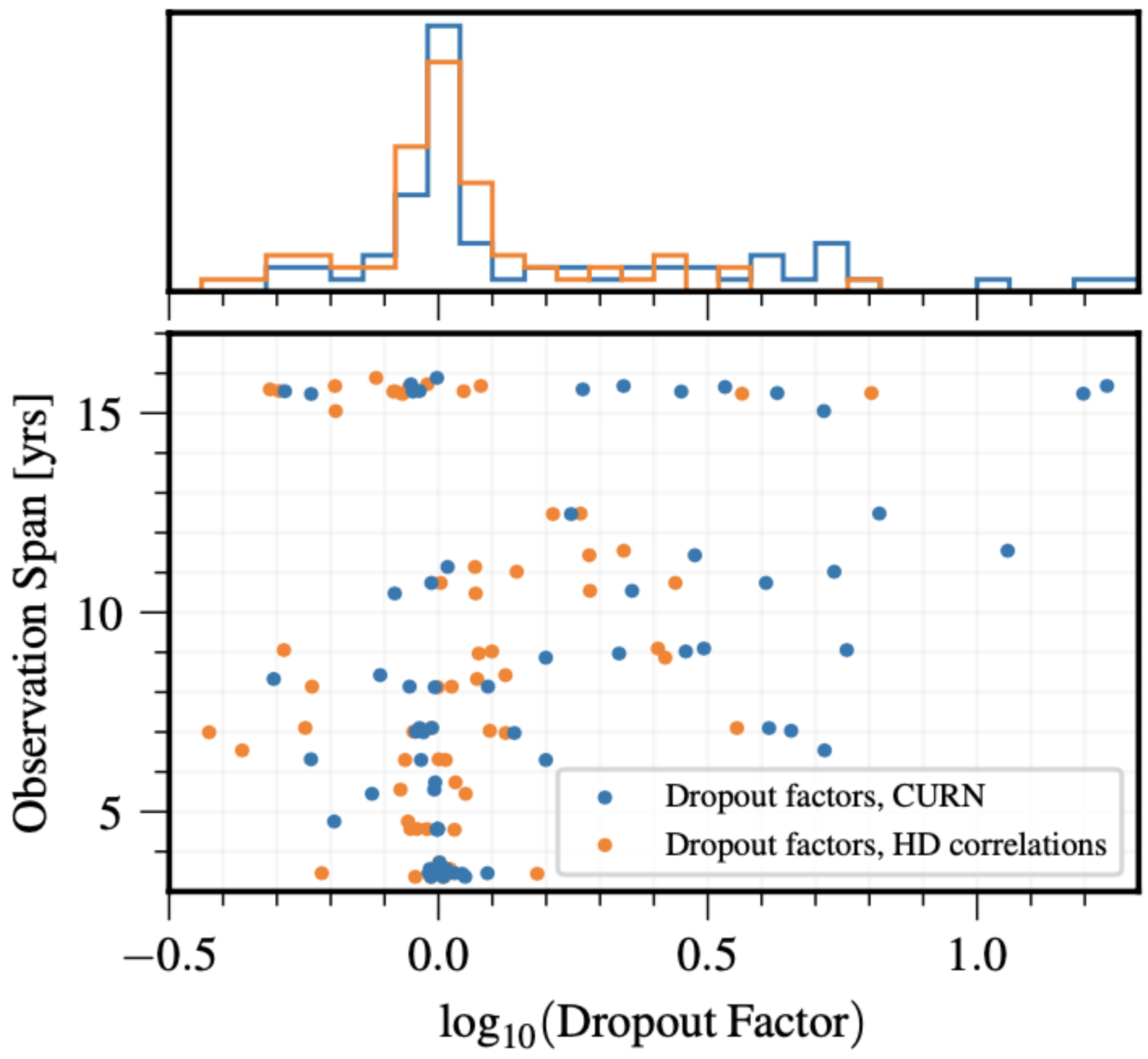


Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L8 (2023).

Cross-Validation: Dropout Analysis



A **dropout factor** measures how much each individual pulsar supports the presence of the common signal.

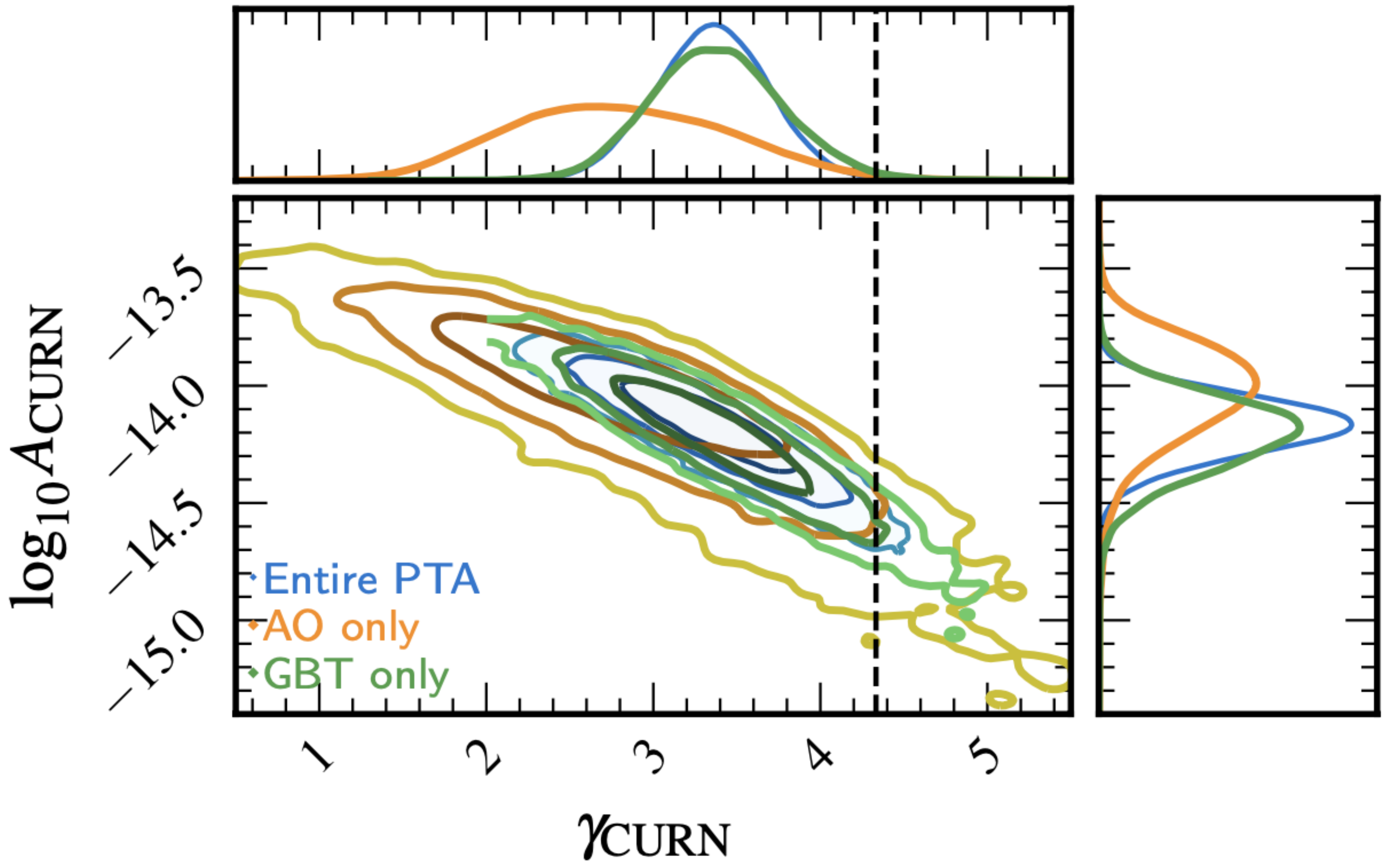
The analysis shows support for an uncorrelated common process in 20 pulsars (dropout factors > 2), while only one pulsar has a dropout factor < 0.5.

For the HD correlations only, seven pulsars show support (dropout factors > 2) while three have a dropout factor < 0.5.

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

Cross-Validation: Telescope Comparison

We split the data into two data sets: one containing only observations made with Arecibo, and one containing only observations made with Green Bank.

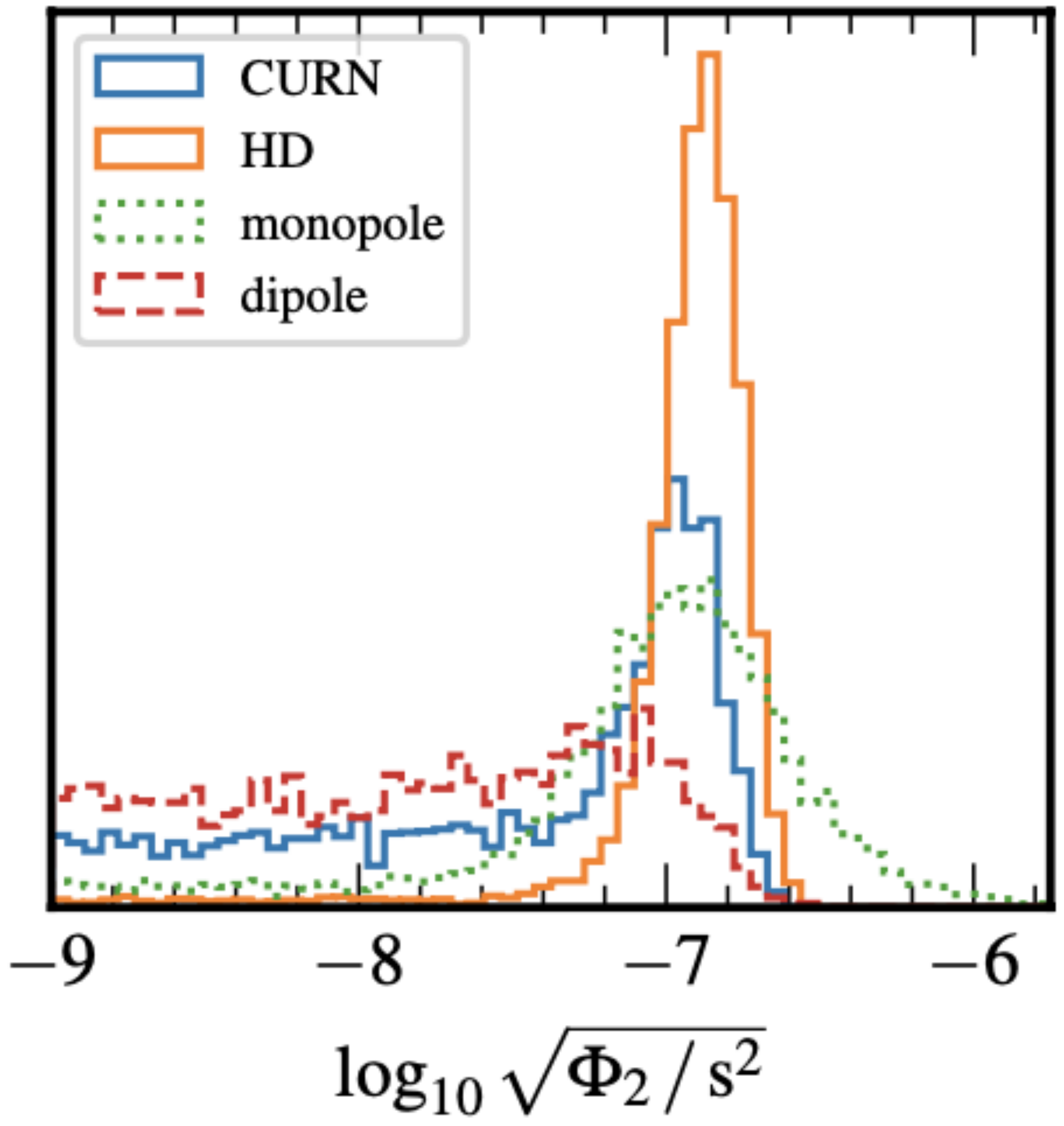


Both show evidence of a common process. Both show evidence of HD correlations at a reduced significance than the full data set.

Arecibo: S/N 2.9
GBT: S/N 3.3
Full data set: S/N 5.0

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

Evidence for an Additional Correlated Process



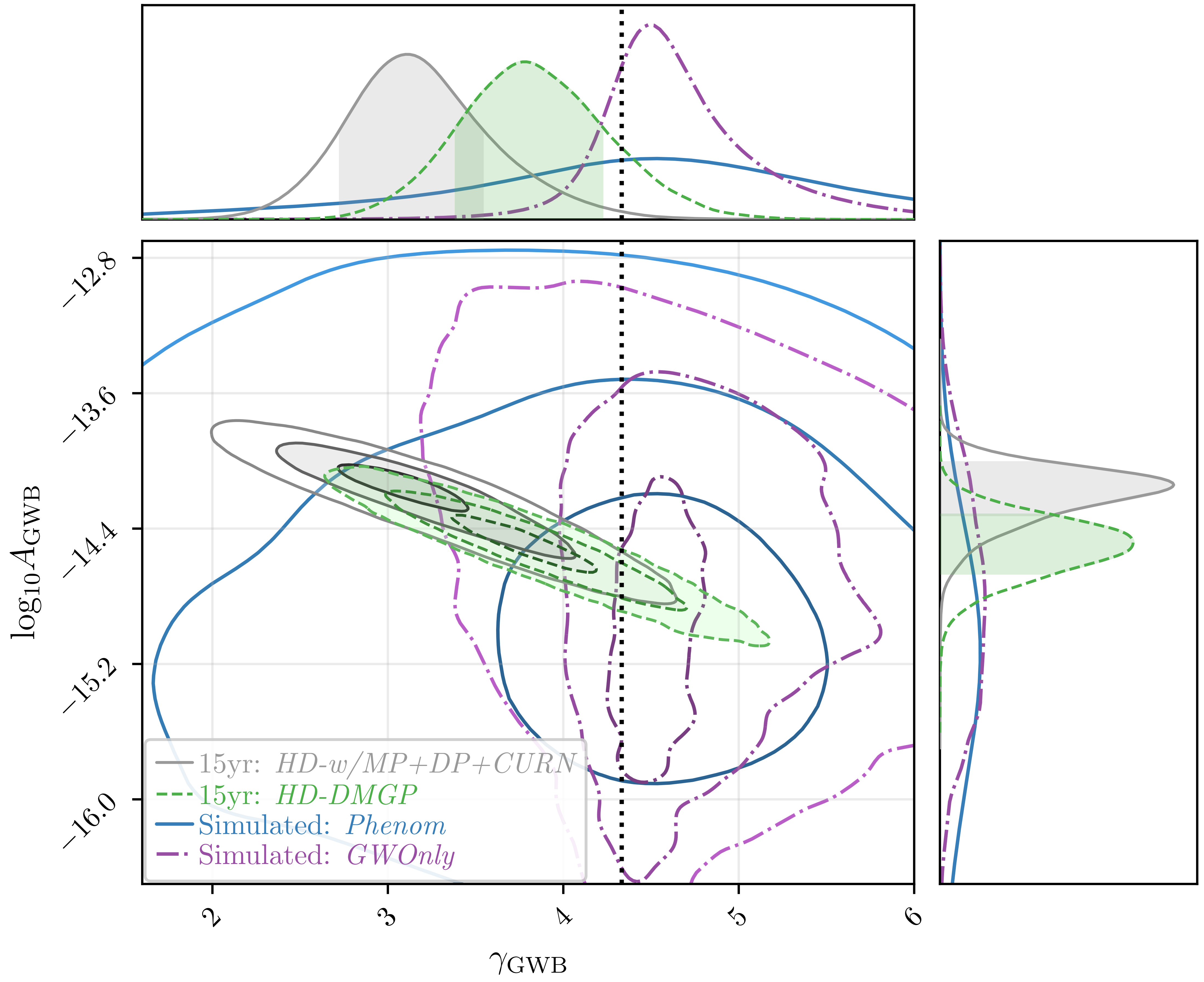
Some evidence that a monopole-correlated signal is present in addition to a HD-correlated signal.

Multiple component optimal statistic analysis (Sardesai & Vigeland 2023) shows preference for HD + monopole correlations over HD only.

Bayesian analyses have BF ~1-10 for monochromatic-monopole signal at f=4 nHz in addition to HD-correlated signal.

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

Implications for SMBBHs



Observed PSD is consistent with a GWB produced by SMBBHs

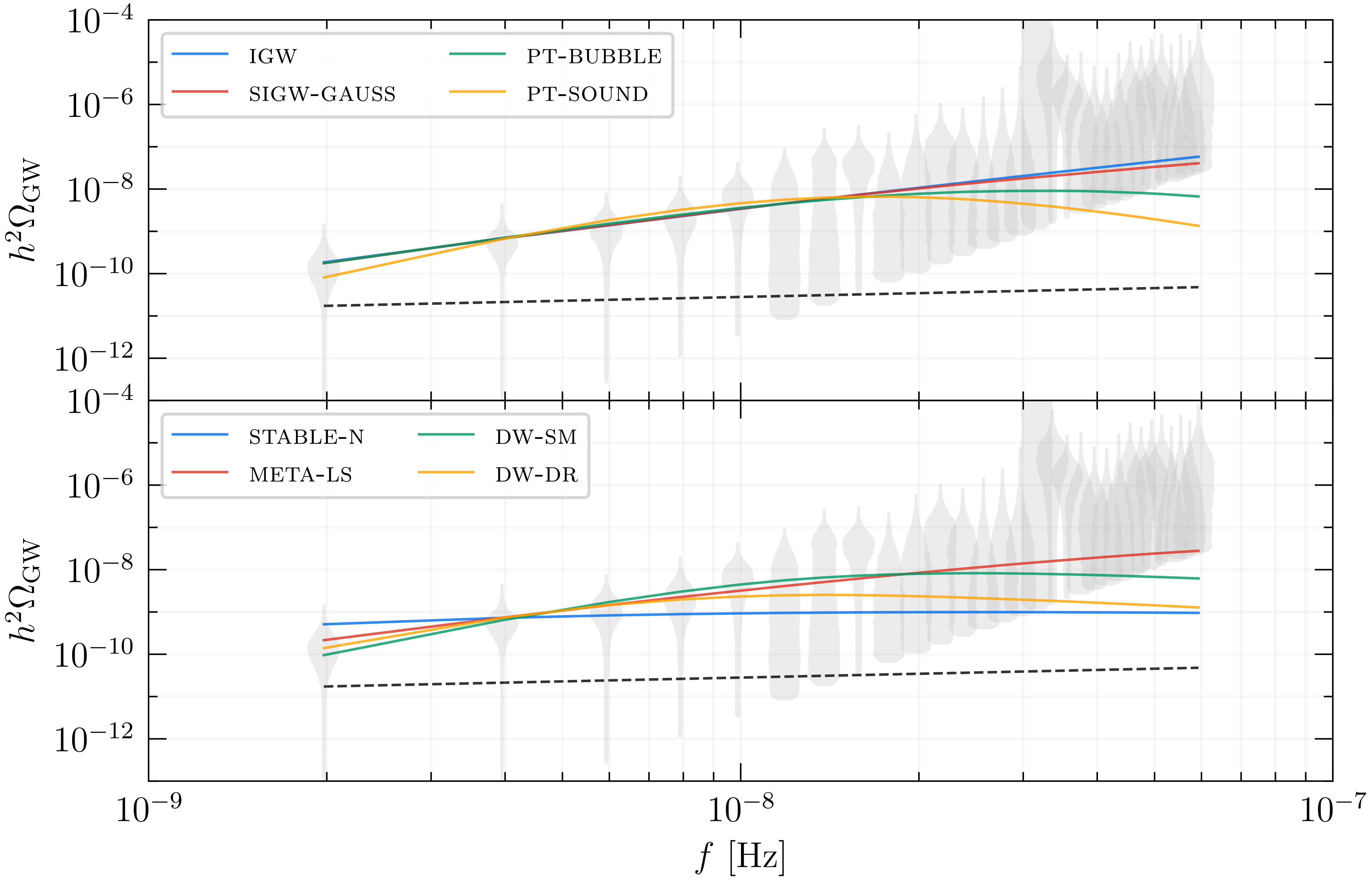
Some preference for interacting models versus GW-only evolution models

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

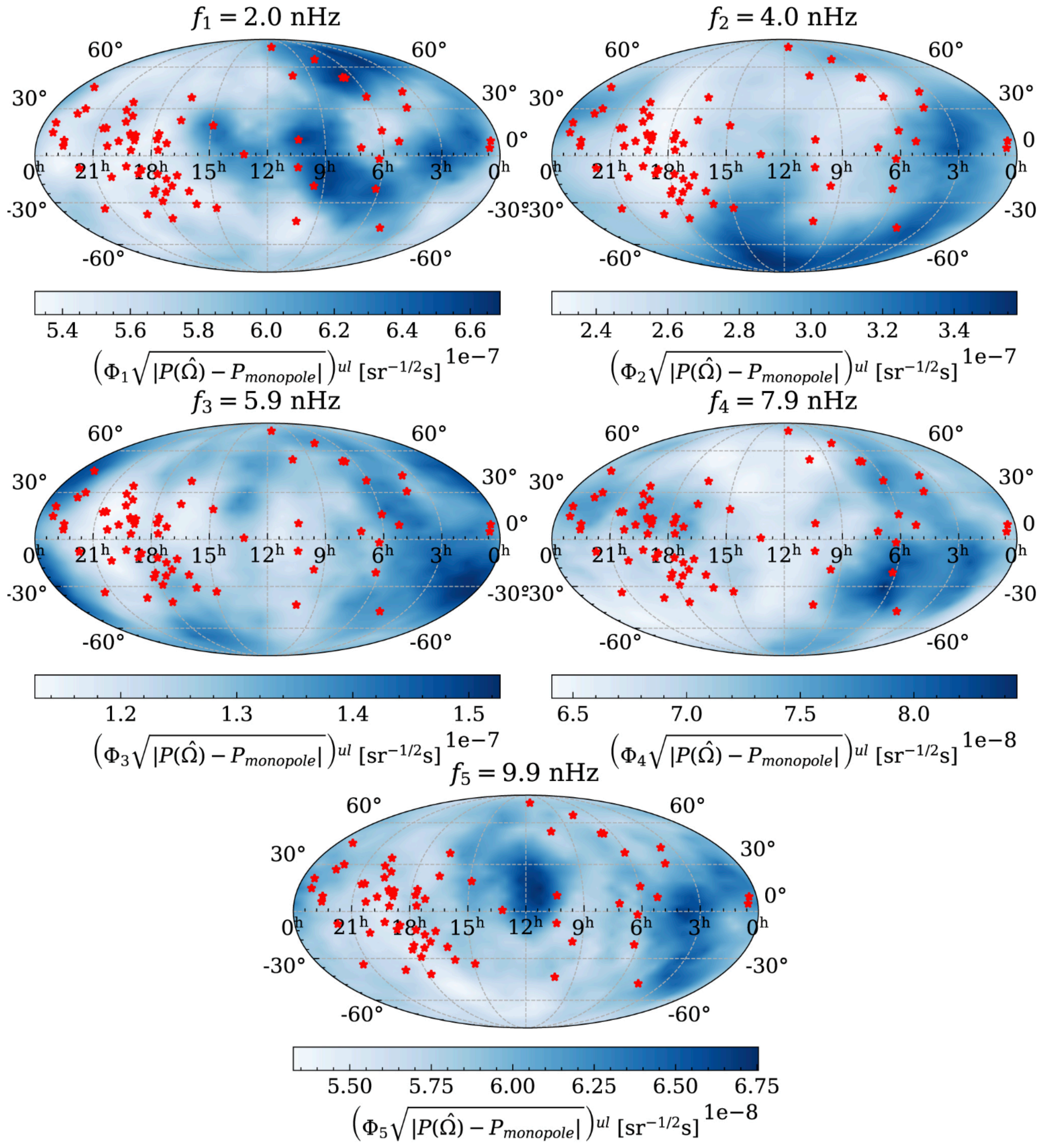


Observed PSD is also consistent with GWB produced by cosmic inflation, scalar-induced GWs, first-order phase transitions, and domain walls.

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.

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

GWs from Individual SMBBHs

Leads: Bence Betsy and Neil Cornish

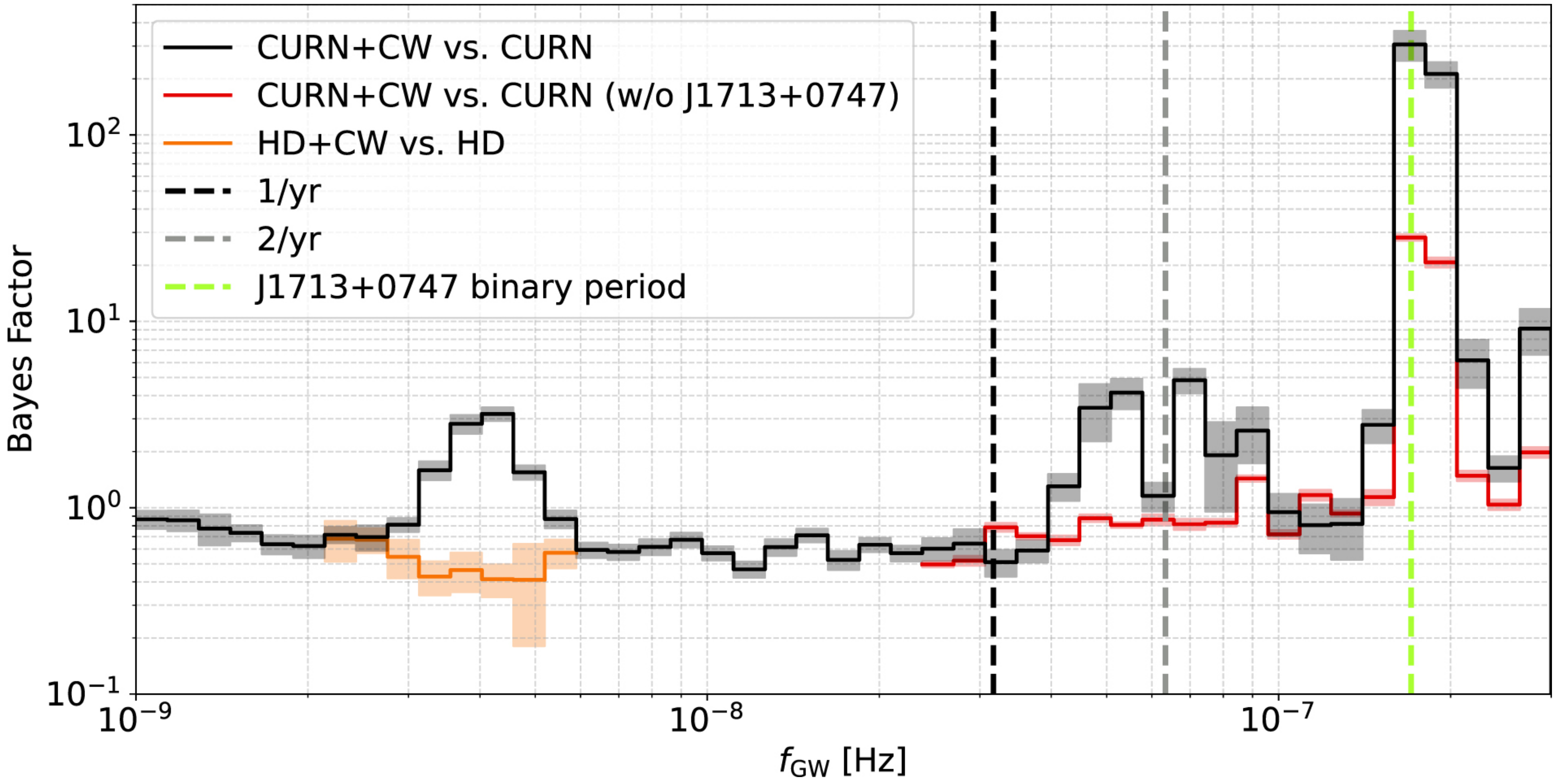


Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L50 (2023).

We searched for GWs from individual SMBBHs in circular orbits.

No significant evidence for GWs from individual SMBHBs in addition to a GWB.

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

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.

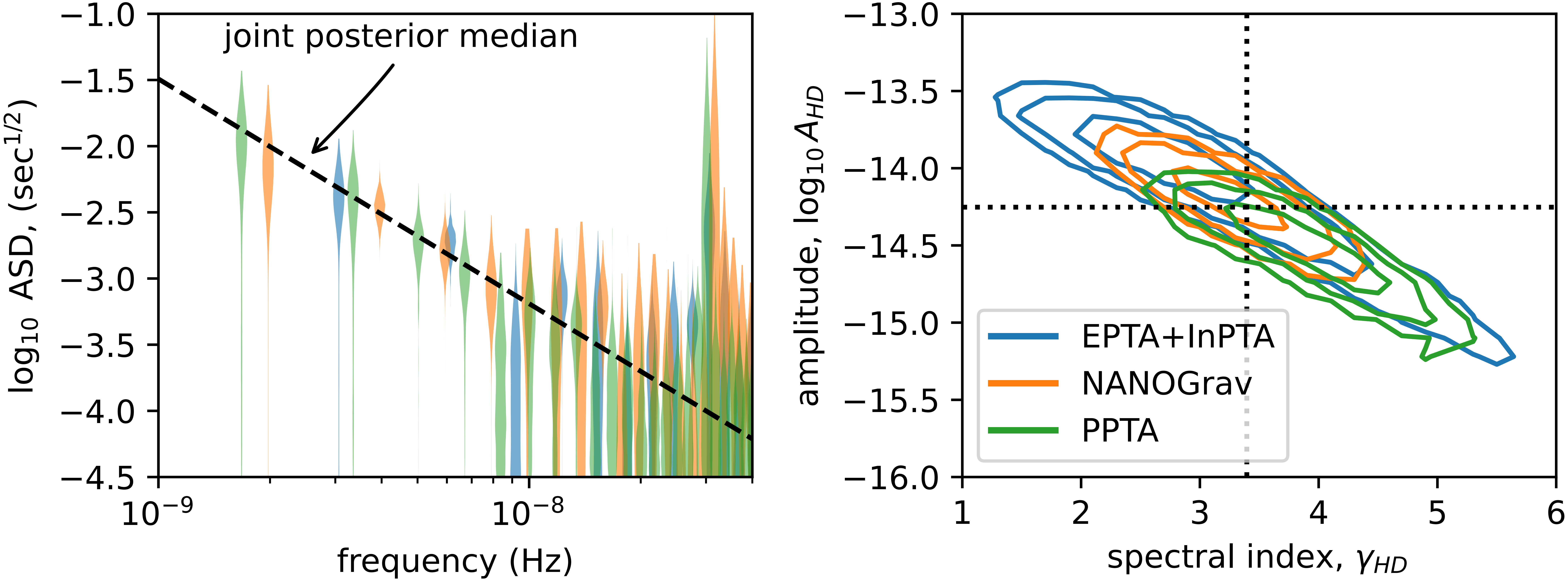
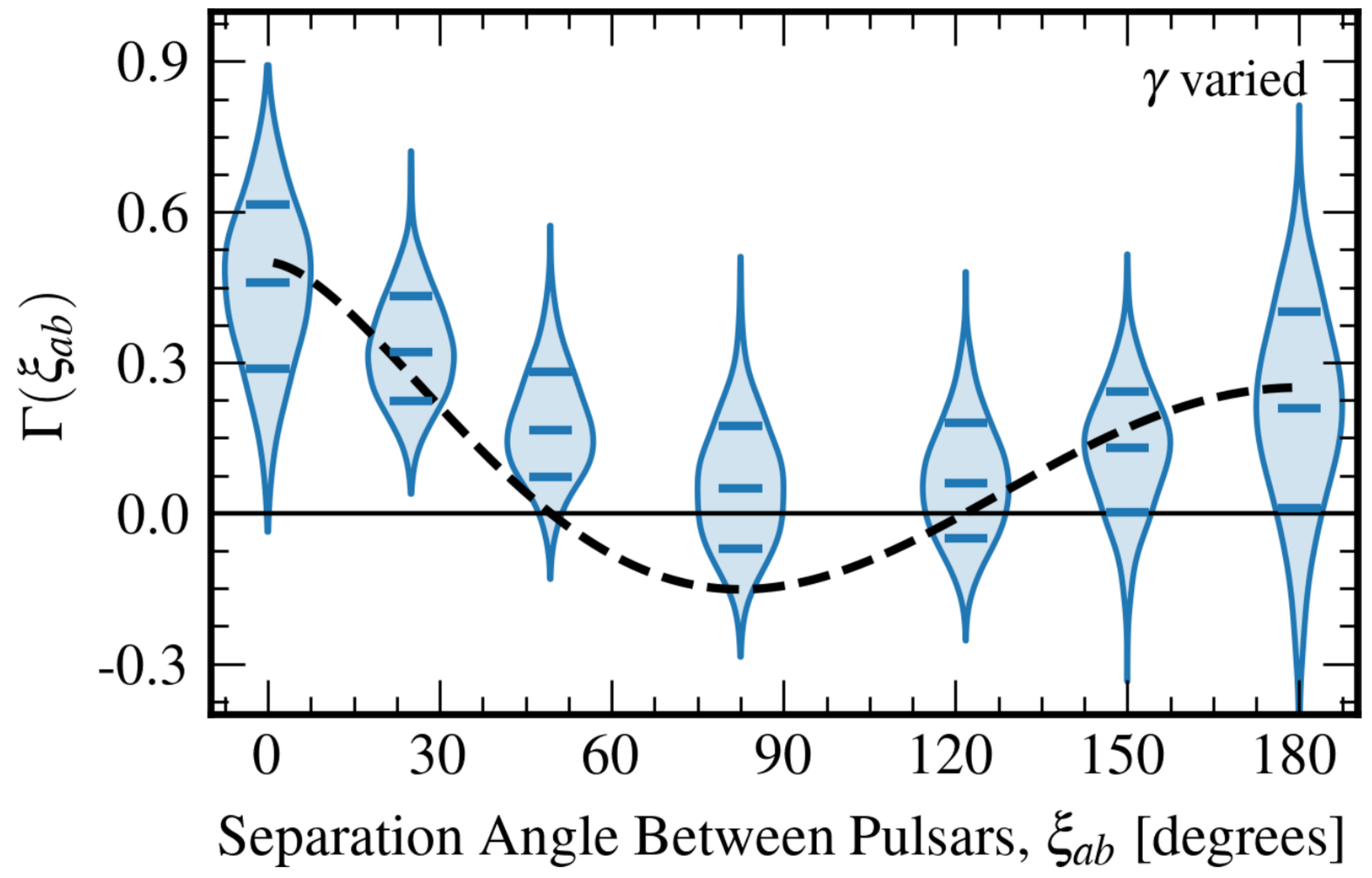
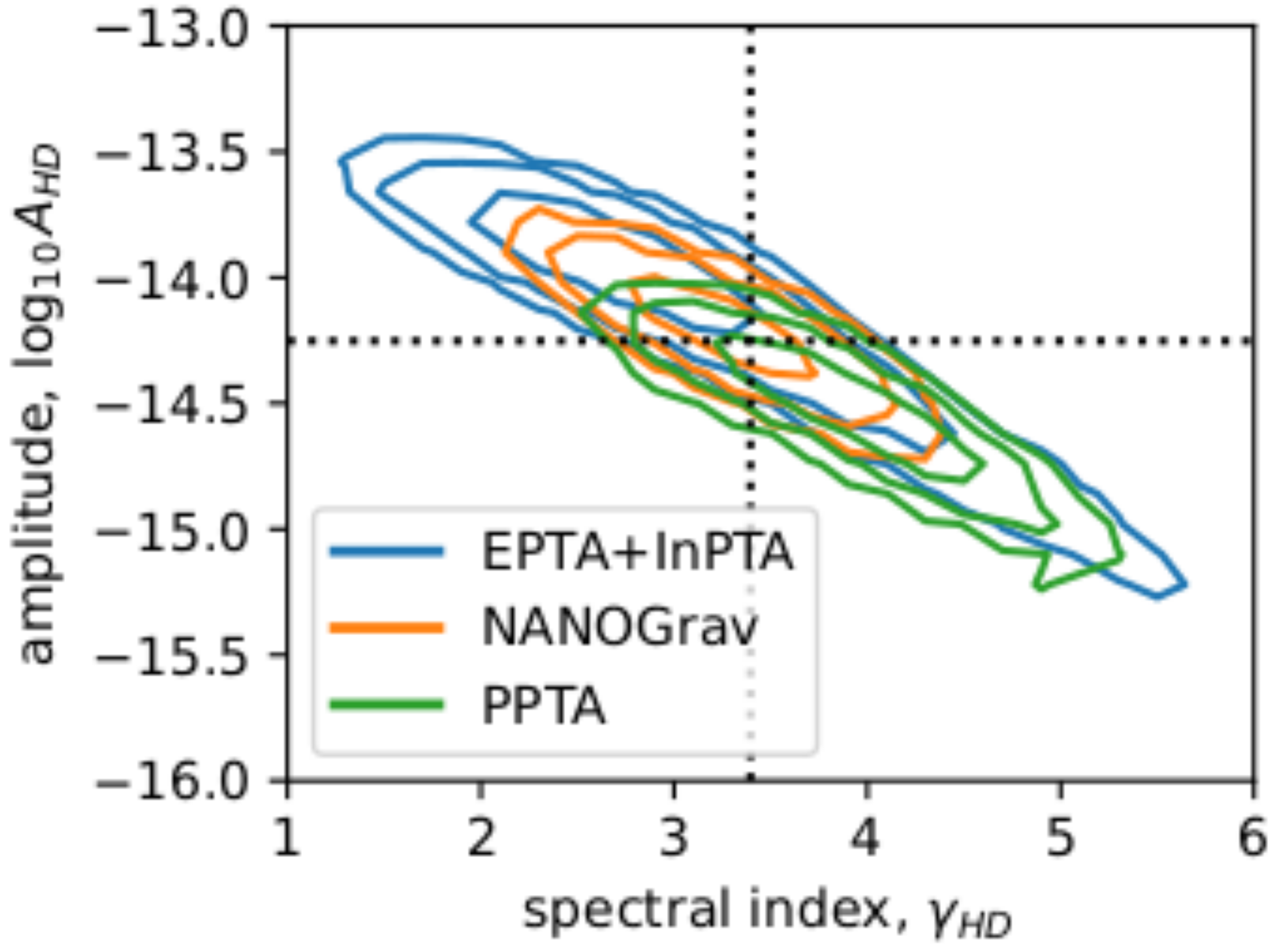


Figure credit: G. Agazie et al. (The IPTA Collaboration), arXiv:2309.00693

Conclusions





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 extends over low frequencies (2 - 28 nHz), and is consistent with an astrophysical population of SMBBHs, but exotic sources cannot be ruled out.