Case study: NANOGrav 12.5-yr analysis for an isotropic stochastic GW background

Joe Romano, Texas Tech University

Saturday, 23 July 2022

(HUST GW Summer School 2022, Lecture 4)

The NANOGrav 12.5-year Data Set: Search For An Isotropic Stochastic Gravitational-Wave Background

ABSTRACT

We search for an isotropic stochastic gravitational-wave background (GWB) in the 12.5-year pulsar-timing data set collected by the North American Nanohertz Observatory for Gravitational Waves. Our analysis finds strong evidence of a stochastic process, modeled as a power-law, with common amplitude and spectral slope across pulsars. Under our fiducial model, the Bayesian posterior of the amplitude for an $f^{-2/3}$ power-law spectrum, expressed as the characteristic GW strain, has median 1.92×10^{-15} and 5%–95% quantiles of $1.37\text{–}2.67 \times 10^{-15}$ at a reference frequency of $f_{\rm yr} = 1\ {\rm yr}^{-1}$; the Bayes factor in favor of the common-spectrum process versus independent red-noise processes in each pulsar exceeds $10,000$. However, we find no statistically significant evidence that this process has quadrupolar spatial correlations, which we would consider necessary to claim a GWB detection consistent with general relativity. We find that the process has neither monopolar nor dipolar correlations, which may arise from, for example, reference clock or solar system ephemeris systematics, respectively. The amplitude posterior has significant support above previously reported upper limits; we explain this in terms of the Bayesian priors assumed for intrinsic pulsar red noise. We examine potential implications for the supermassive black hole binary population under the hypothesis that the signal is indeed astrophysical in nature.

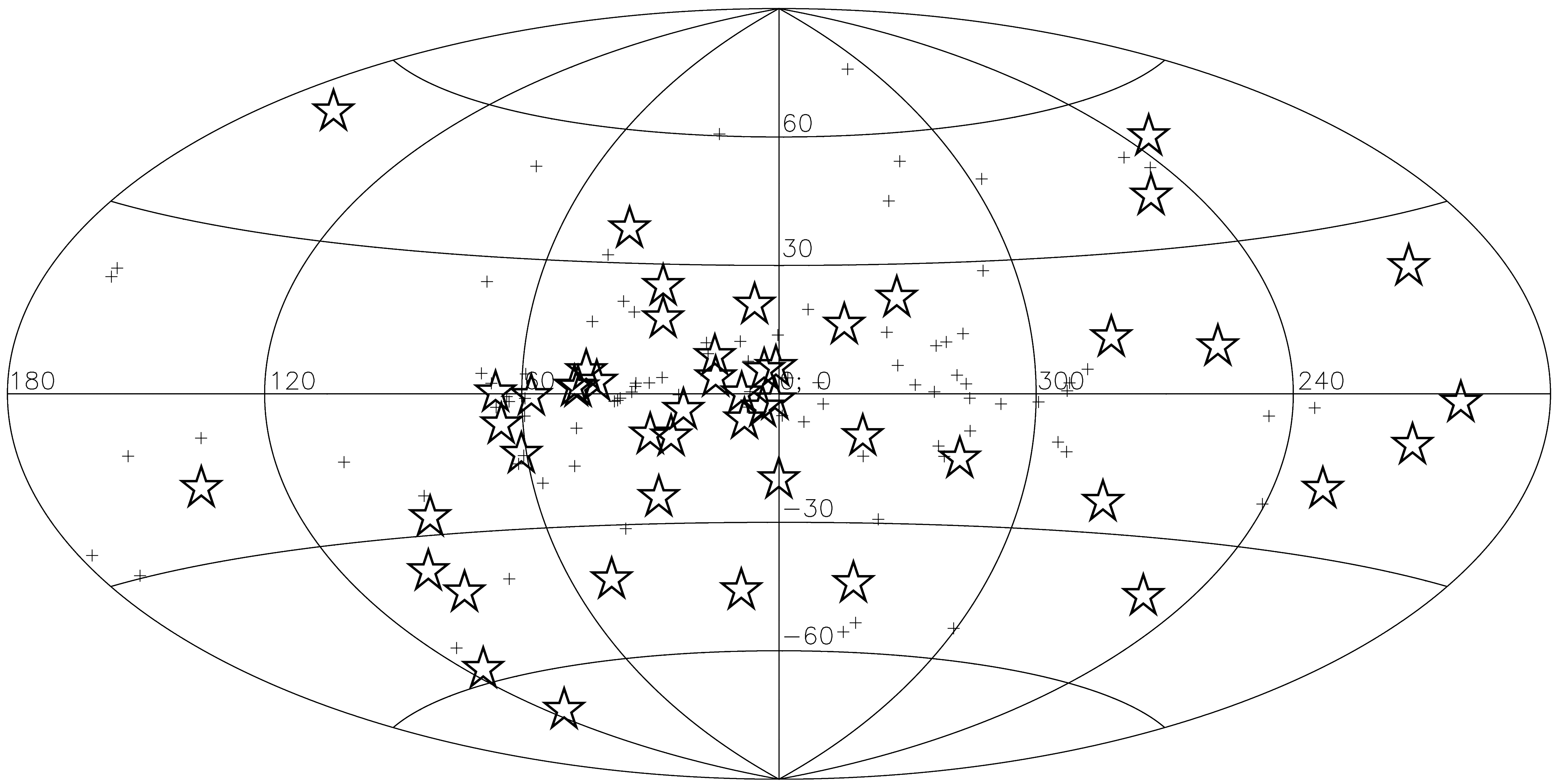
Keywords: Gravitational waves – Methods: data analysis – Pulsars: general

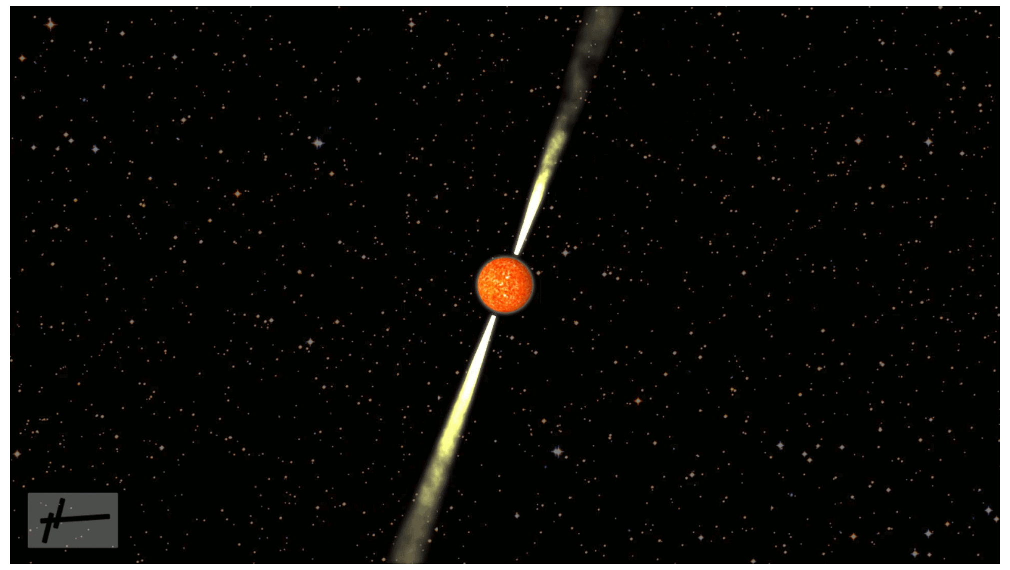
Arzoumanian et al 2020 ApJL 905 L34

arXiv:2009.04496v1 [astro-ph.HE] 9 Sep 2020

NANOGrav + EPTA + PPTA = IPTA

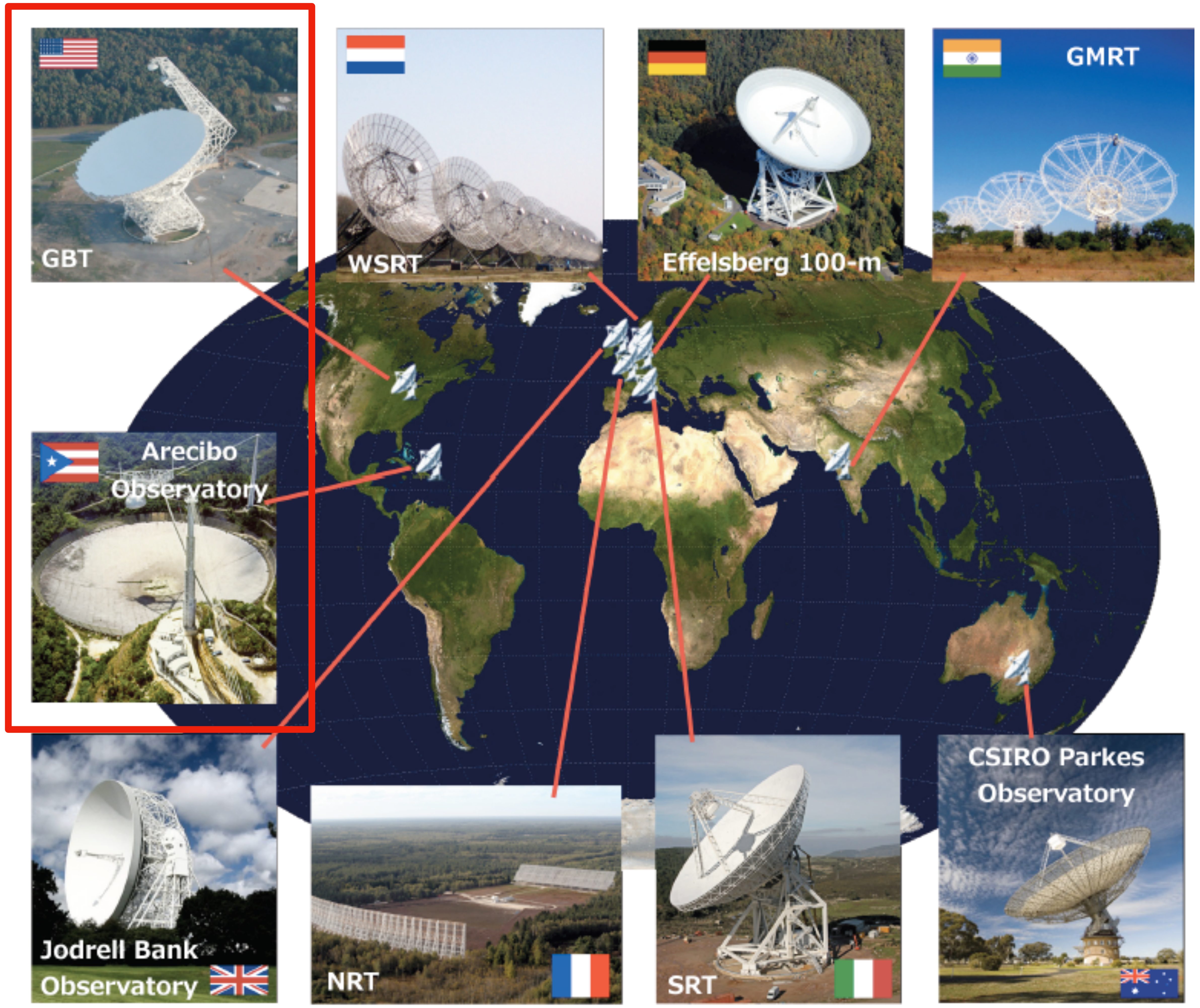
sky map of ~50 IPTA millisecond pulsars



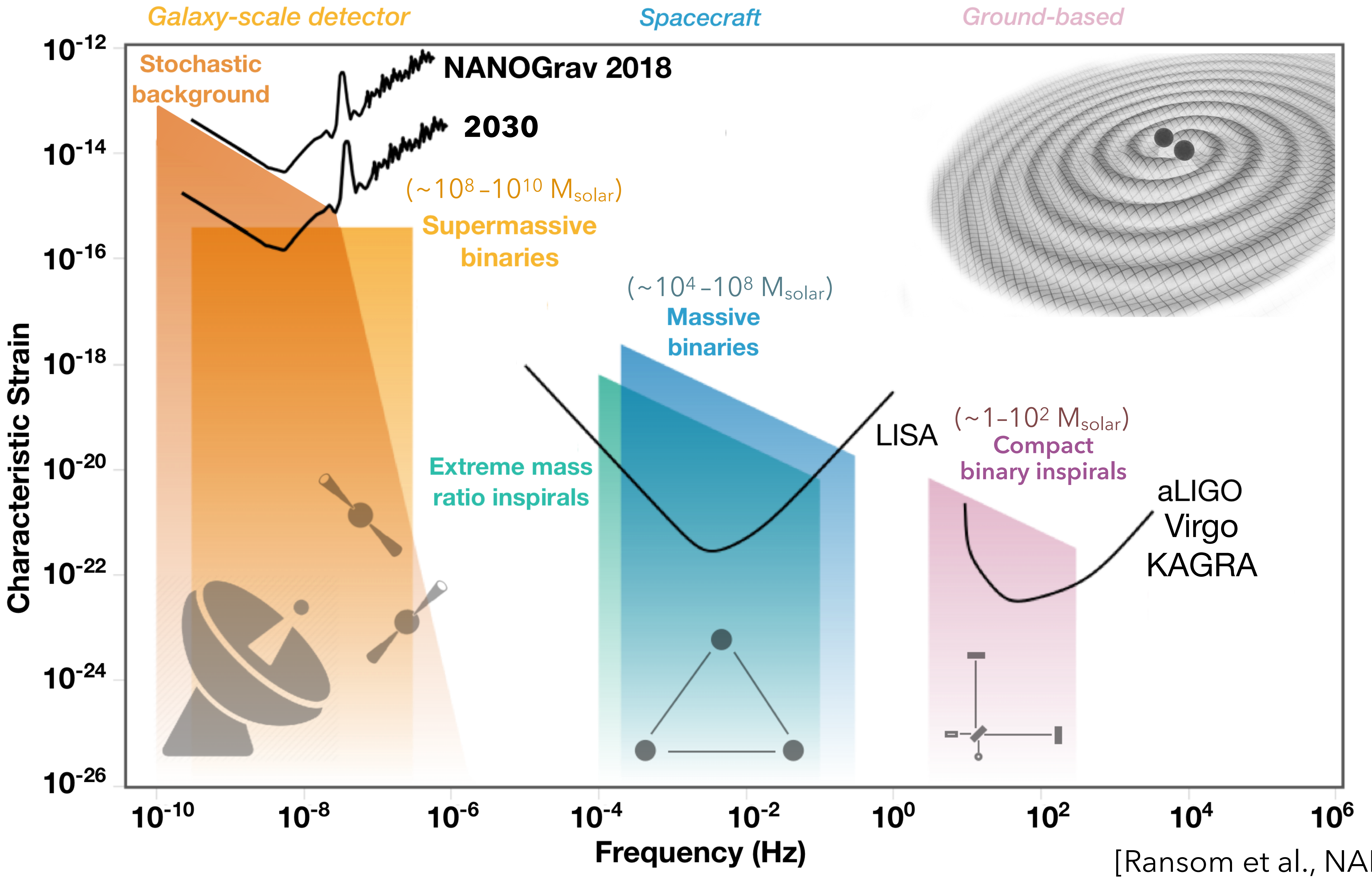


Nature's most precise clocks!

$(\Delta T_p / T_p < 10^{-14})$

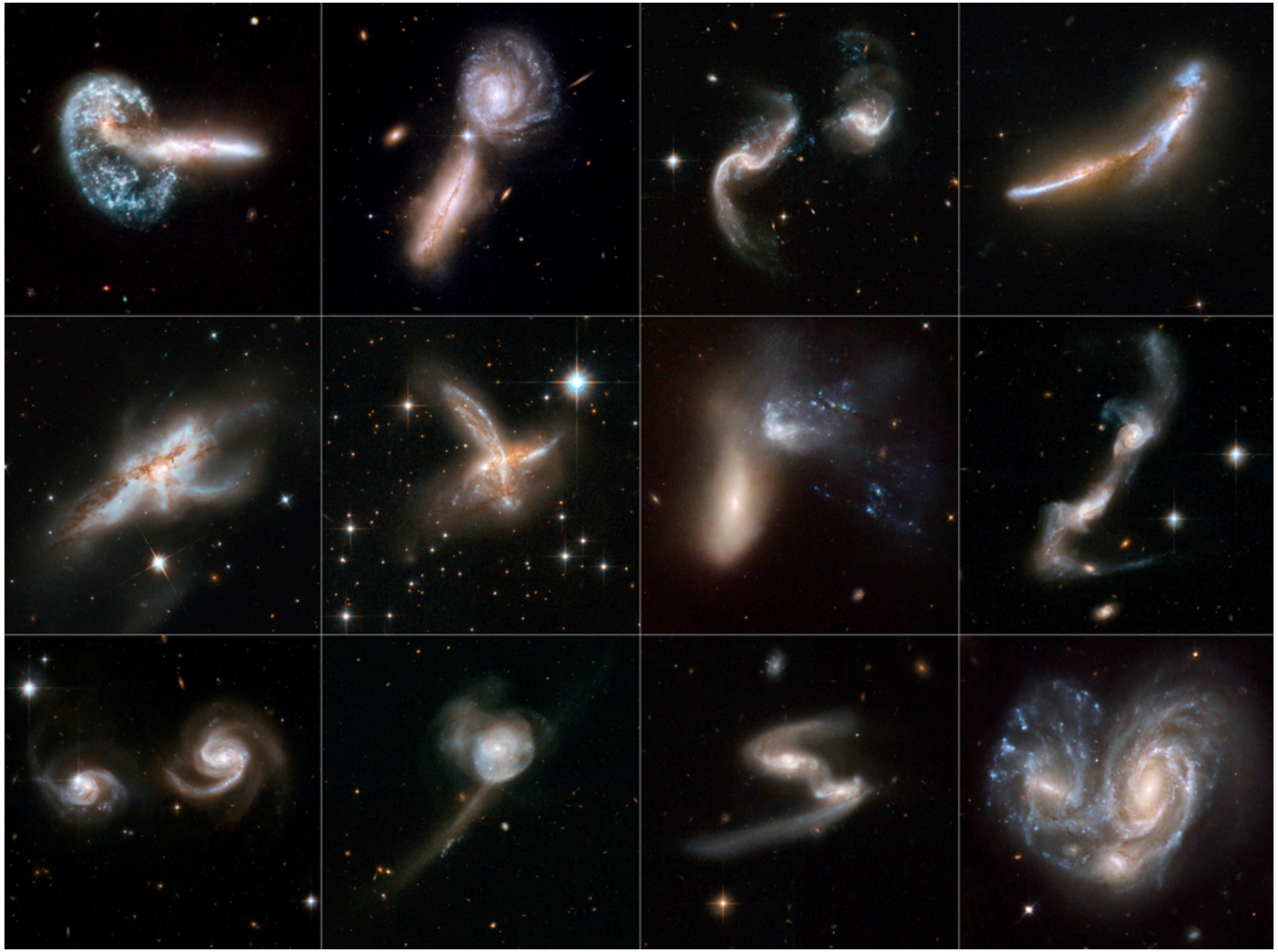


Recall: GW spectrum

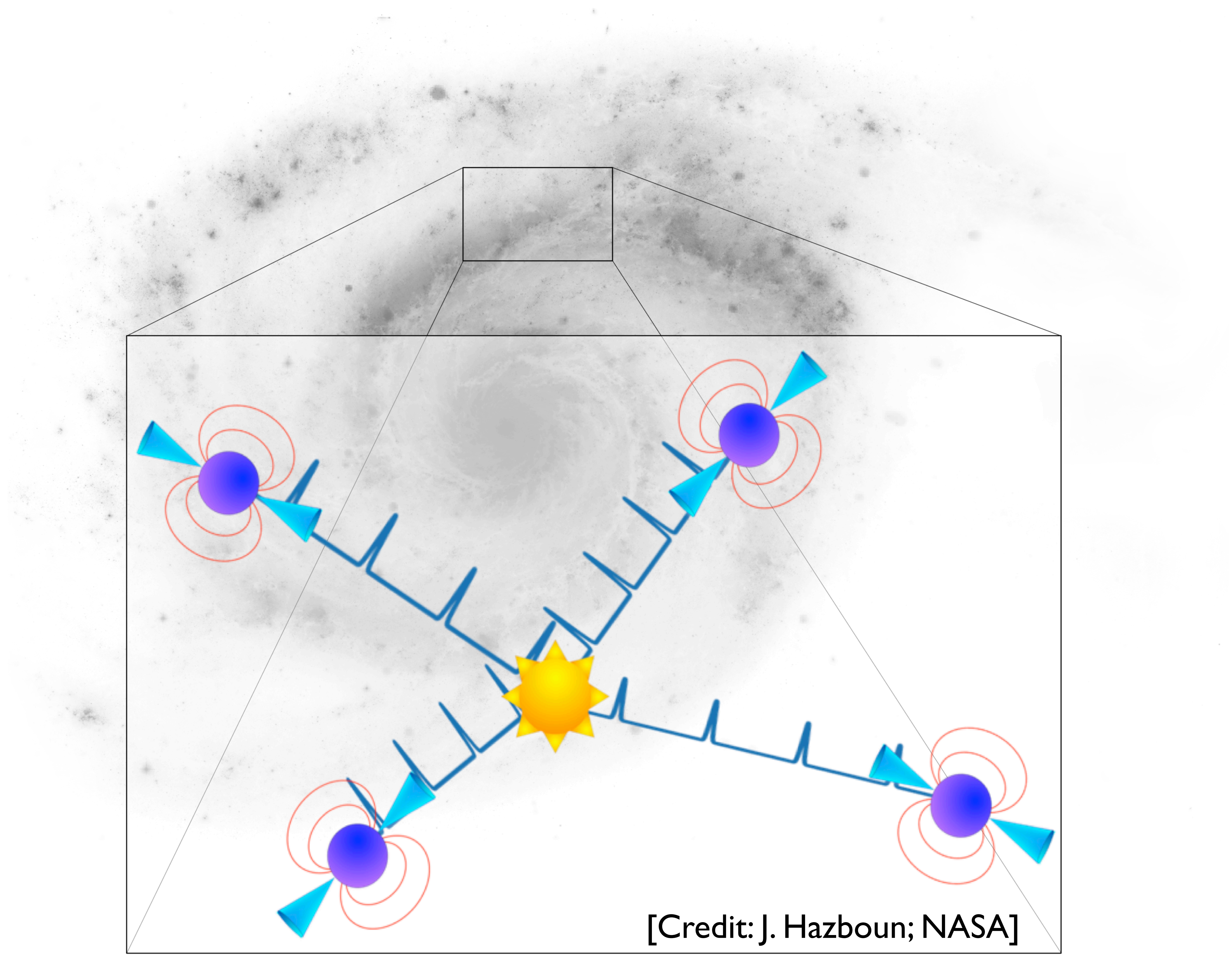


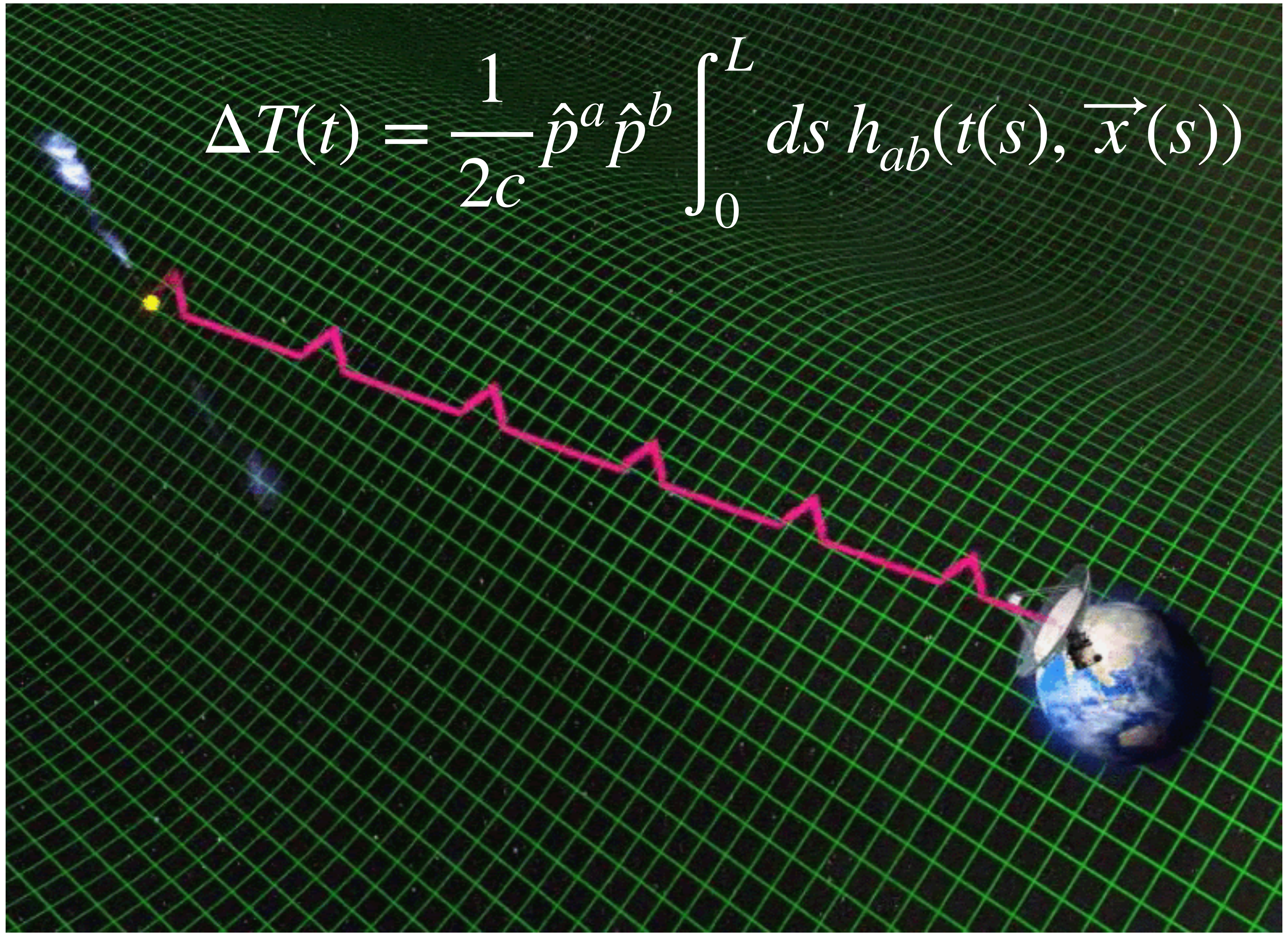
[Ransom et al., NANOGrav Astro2020]

Primary source of GWs for pulsar timing array searches



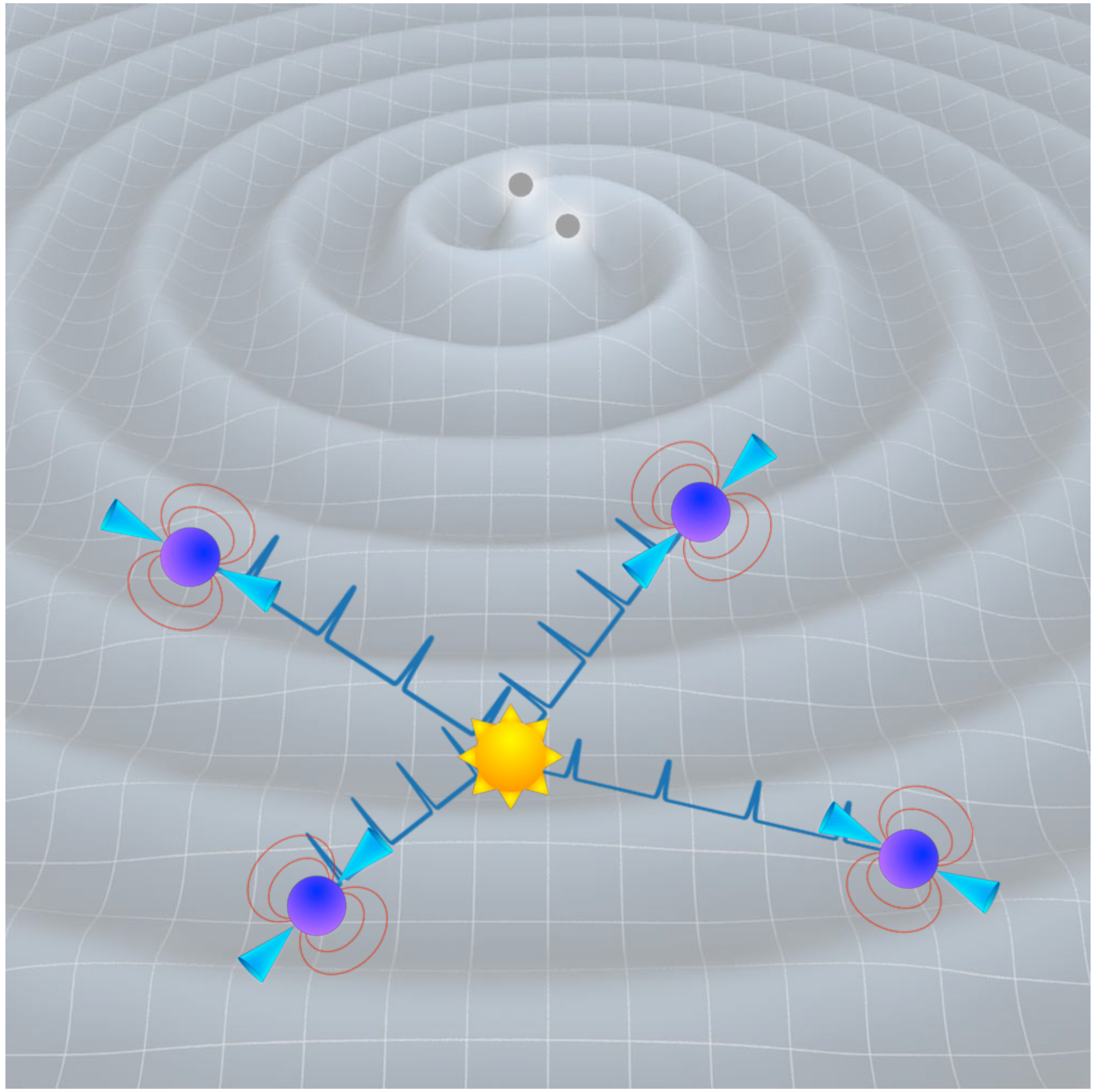
PTA as a galactic-scale GW detector

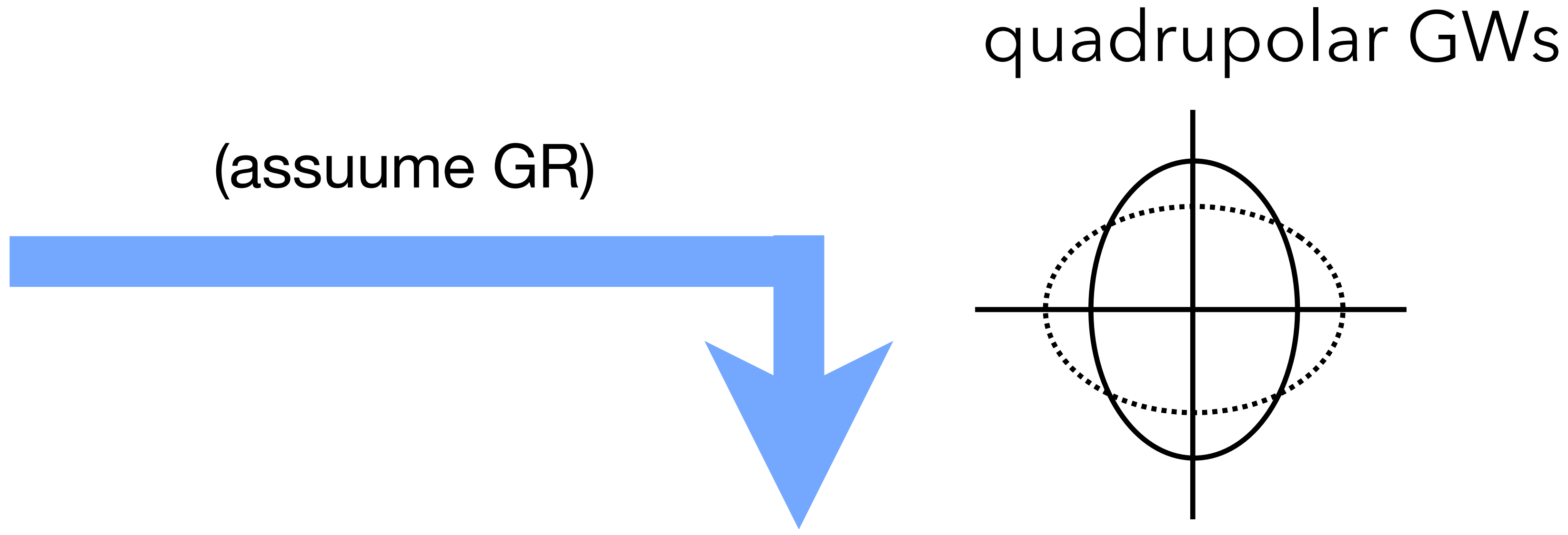


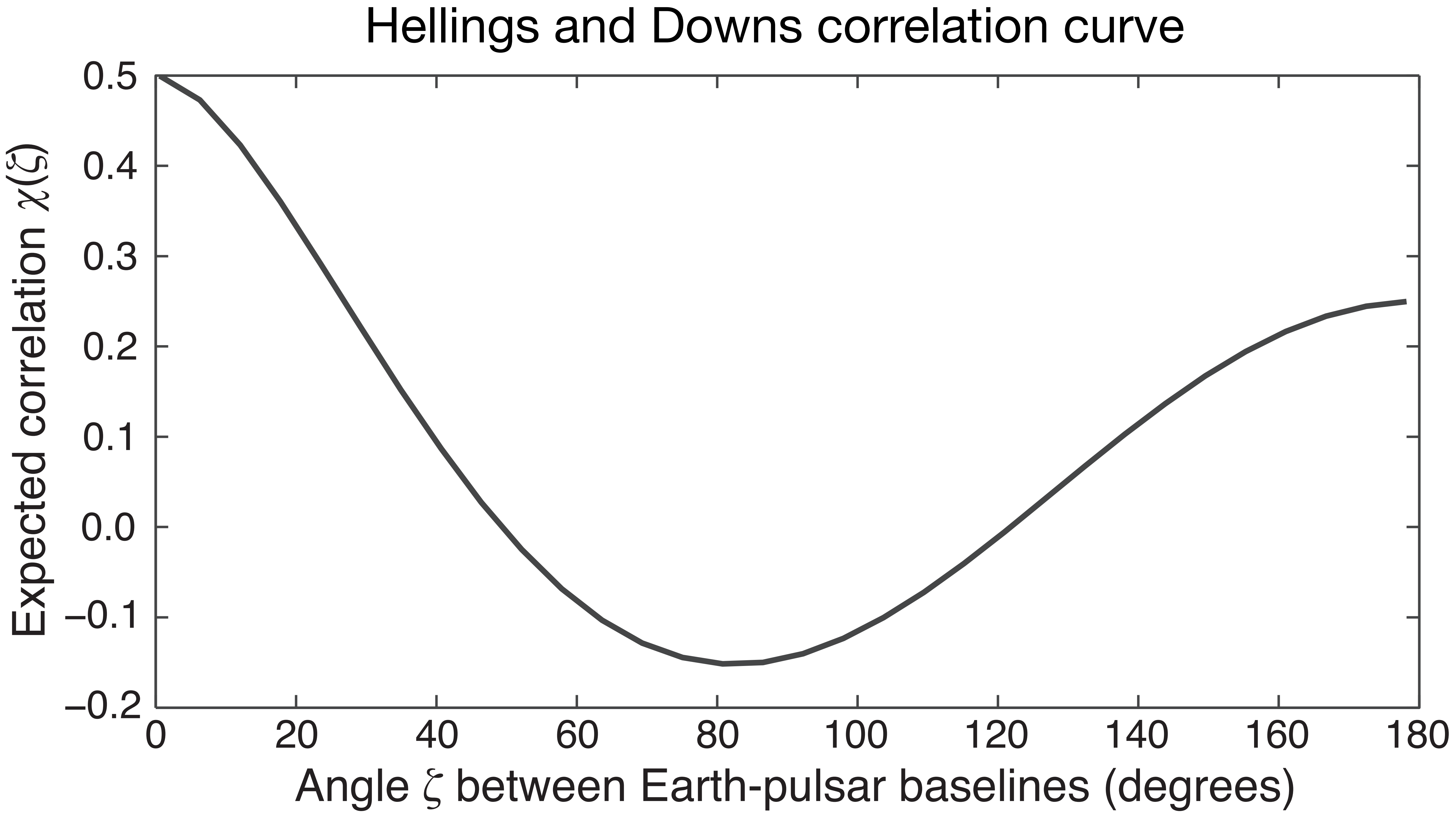


GWs **perturb the arrival times** of pulses -> look for the presence of GWs in the **timing residuals**

GW perturbations are correlated across pulsars



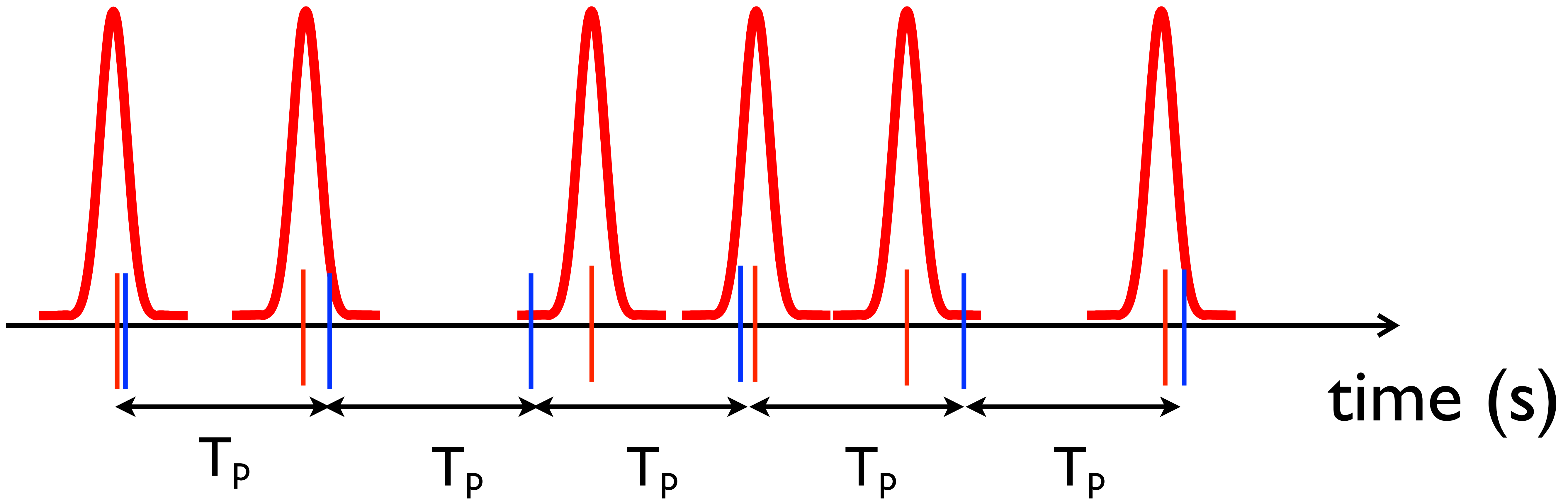


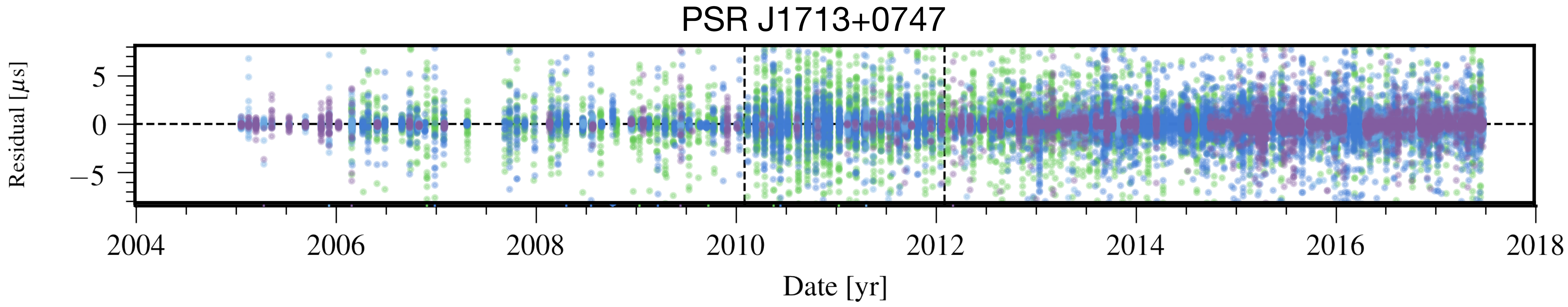


Timing residuals are the data for PTA analyses

$$\text{timing residual} = \text{observed arrival} - \text{predicted arrival}$$
$$= \text{unmodeled deterministic processes} + \text{noise sources} + \text{GW signals}$$

timing model





Signal + noise models for the 12.5-yr analysis

Pulsar 1		Pulsar 2		Pulsar N
Timing Model White Noise Red Noise	+	Timing Model White Noise Red Noise	+ … +	Timing Model White Noise Red Noise

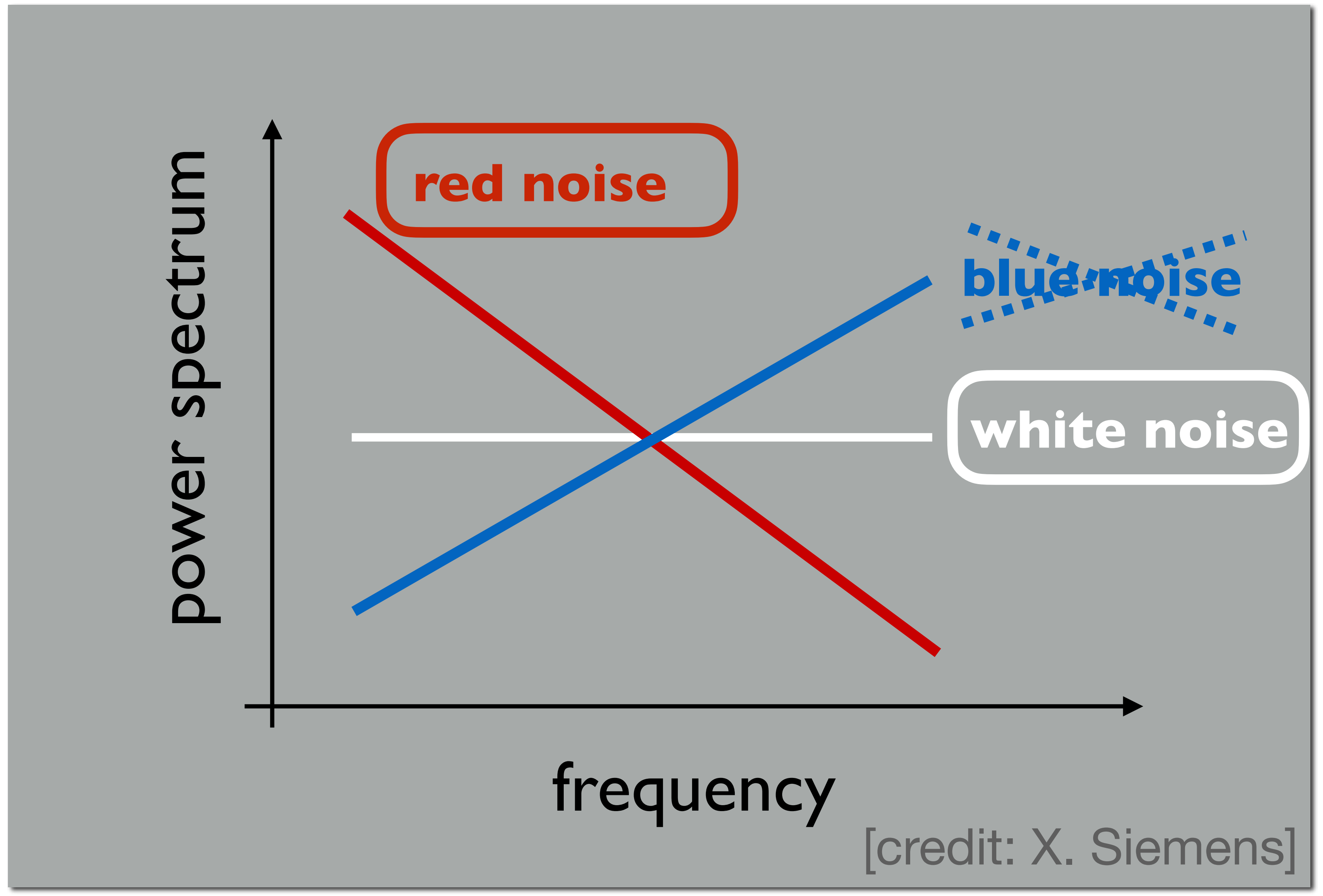
+

Uncorrelated red-noise process common to all pulsars

+

Correlated red-noise process across pulsars (monopole, dipole, or quadrupole)

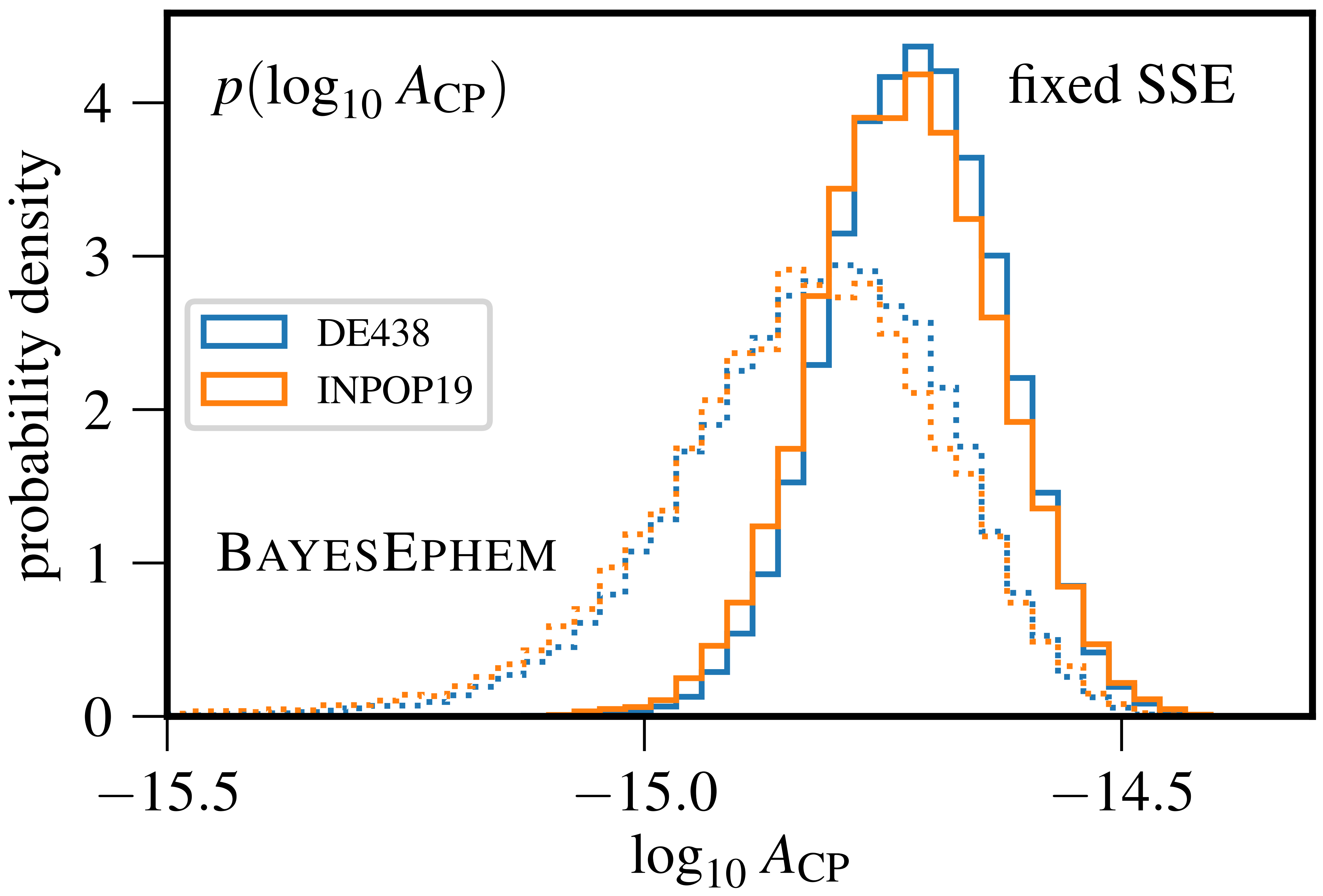
[credit: S. Vigeland]

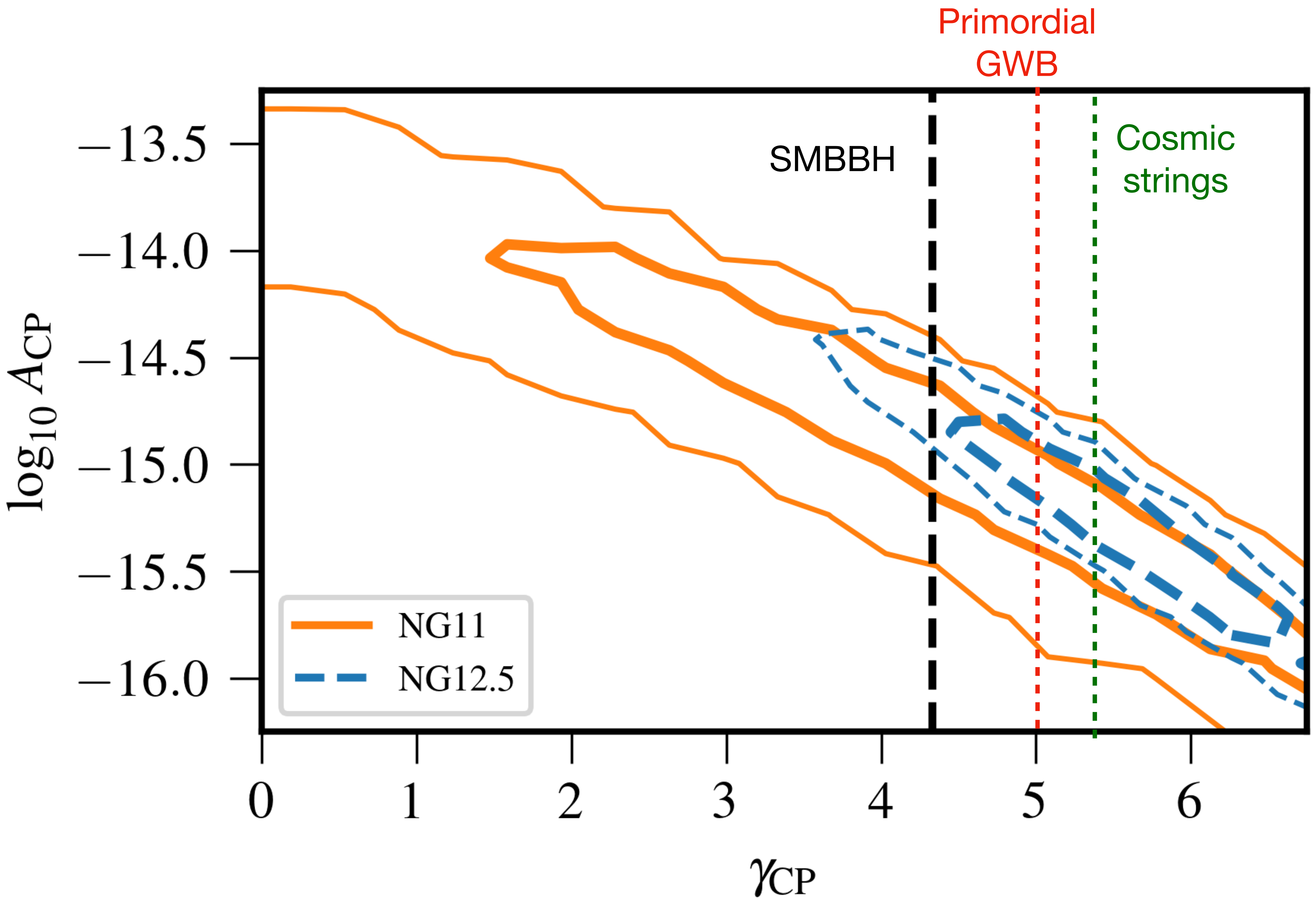


$$P(f) = \frac{A^2}{12\pi^2}\left(\frac{f}{f_{\rm yr}}\right)^{-\gamma} f_{\rm yr}^{-3}$$

The various signal+noise models are then assessed using both **Bayesian** and **frequentist** analyses (e.g., optimal CC statistic)

Result 1: Strong evidence for a common spectrum process for individual pulsar data (no correlations)



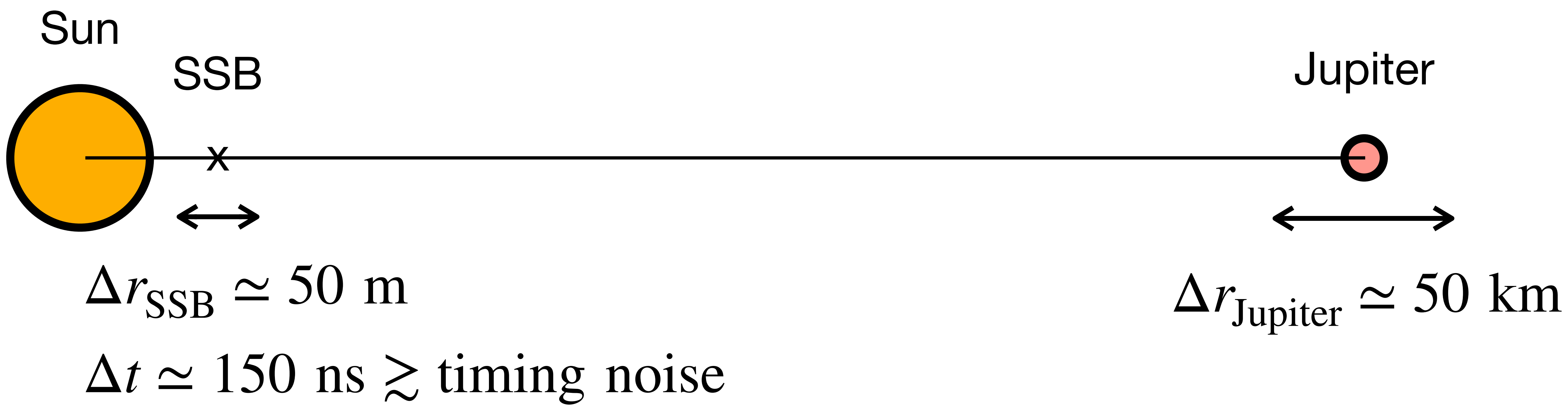


$A_{CP} = 1.92 \times 10^{-15}$ (median)

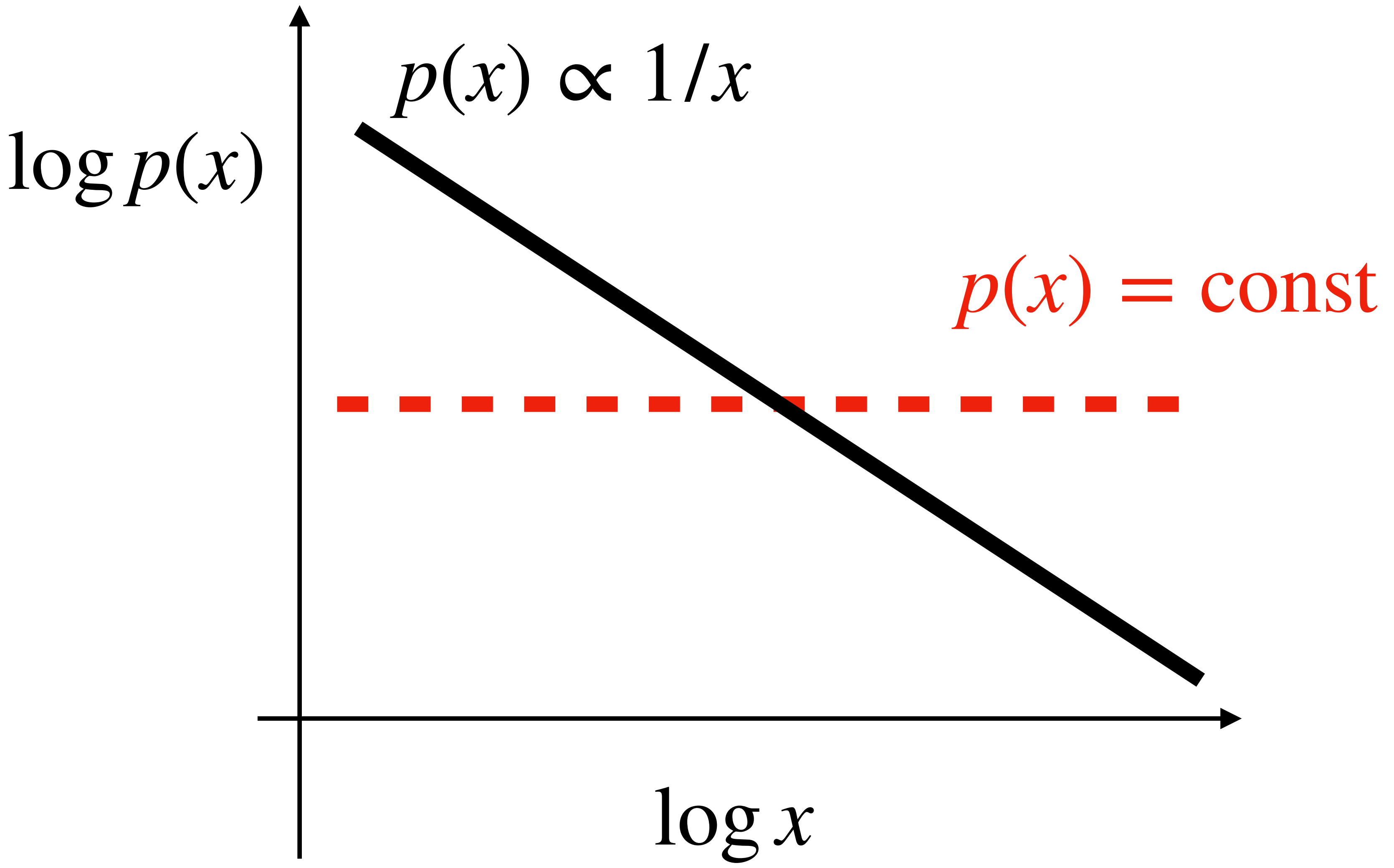
$4 \lesssim \gamma_{CP} \lesssim 7$ (2σ uncertainty)

Previous analyses had lower ULs due to differences in the analyses

1. Earlier **solar system ephemeris** models had relatively large **uncertainties** in the position of Jupiter, which needed to be **marginalized over**

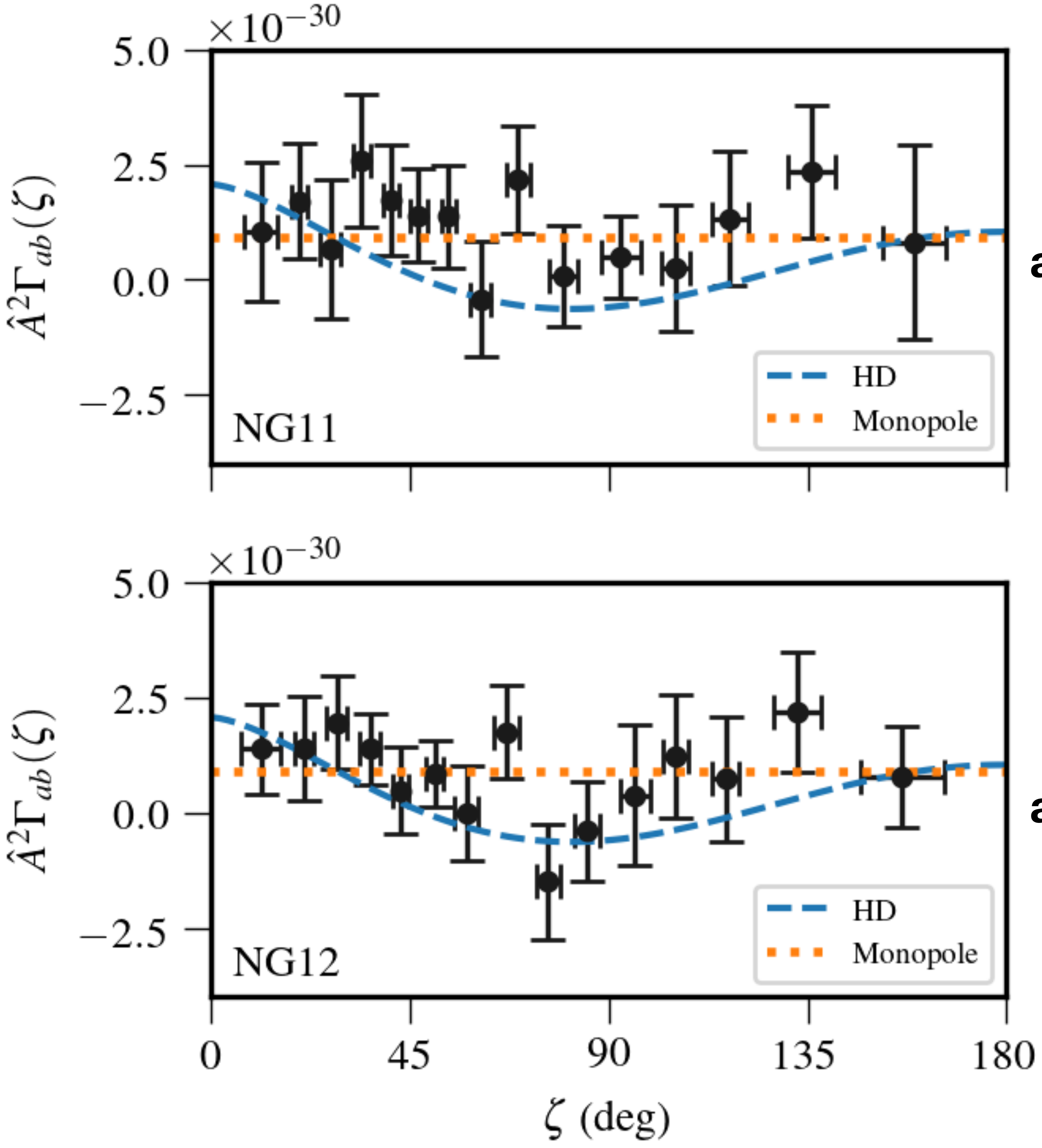


2. Previous analyses used **uniform priors** for the amplitude of **pulsar red noise**, which gave more weight to **larger pulsar noise**



NG 12.5-yr and 11-yr results consistent when analyzed in a similar manner

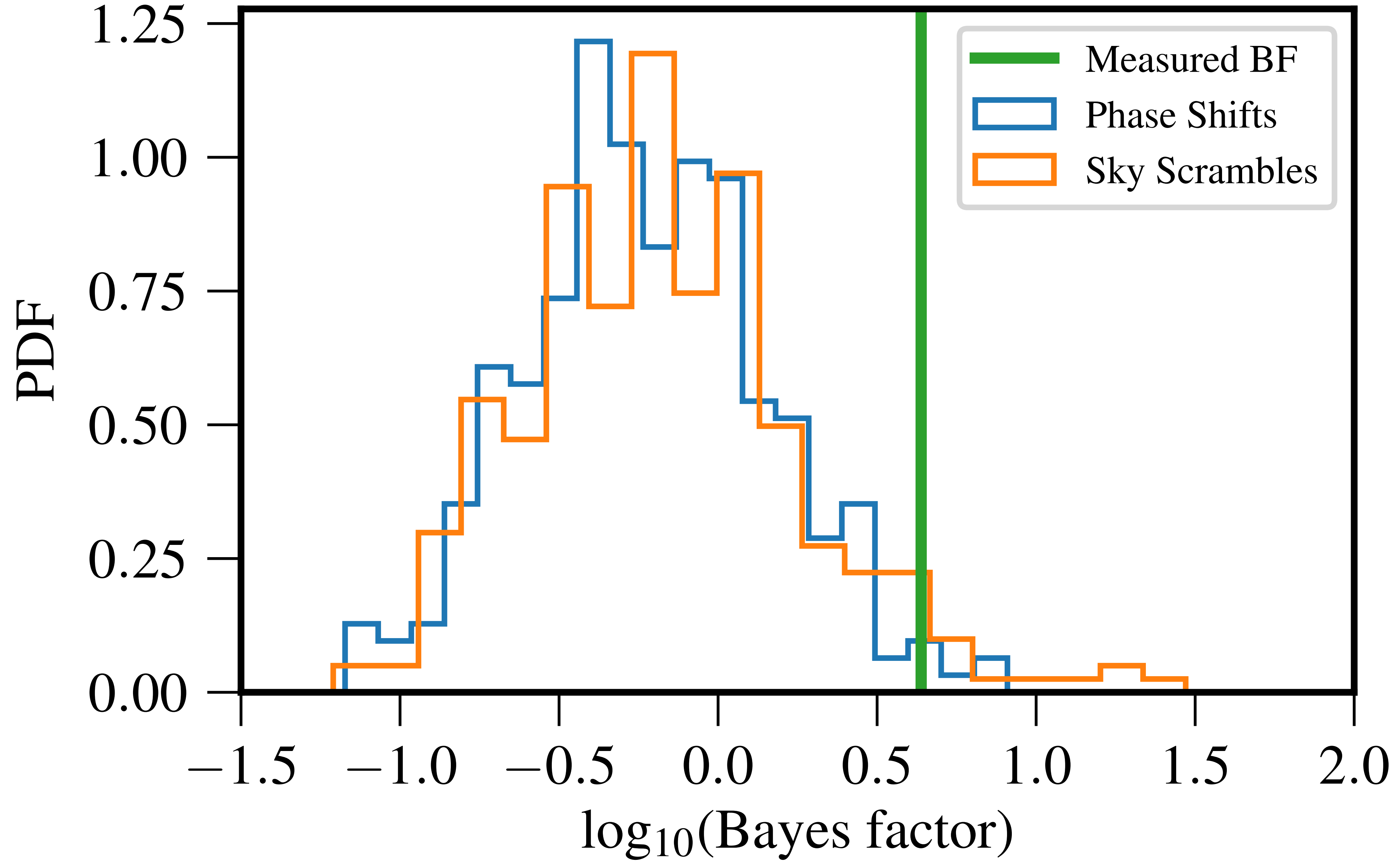
Result 2: No significant evidence of HD spatial correlations (Bayes factor in favor of HD correlations is only ~3:1 or ~1.5σ)



11-yr analysis

12.5-yr analysis

(compare against noise-only hypothesis)

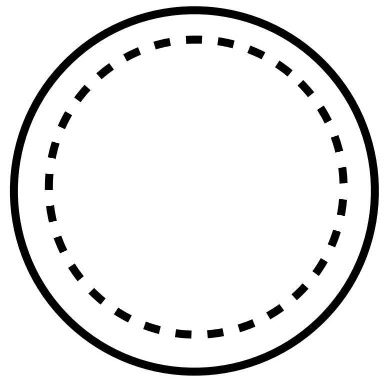


Chance of obtaining a BF ~3 from noise alone is **~5%**

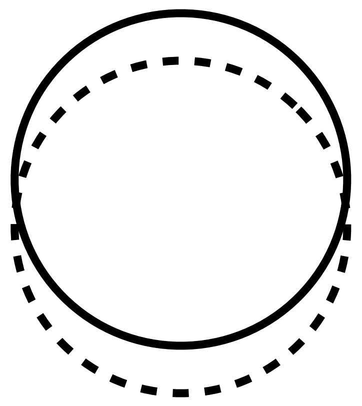
[pulsar timing GWB equivalent of time slides for transients]

Result 3: Monopole and dipole spatial correlations are disfavored (Bayes factors of ~100 to 200 against so ~3σ)

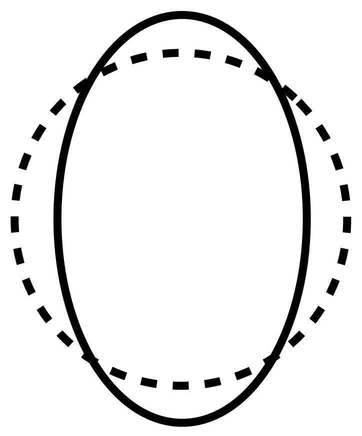
- **Monopole** correlations could be sign of a **clock offset** affecting all pulsars

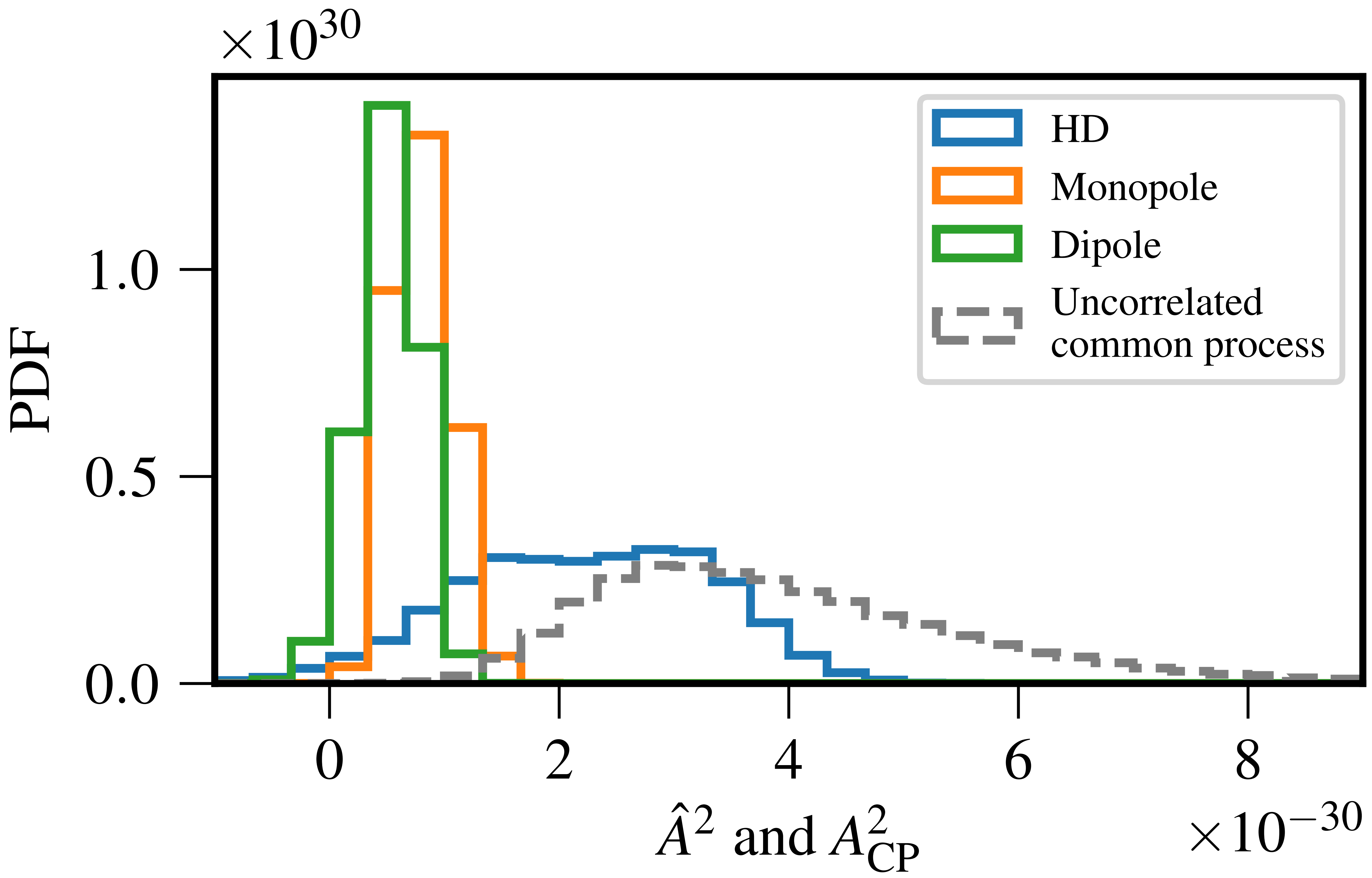


- **Dipole** correlations could be due to inaccurate determination of the **solar system barycentre**



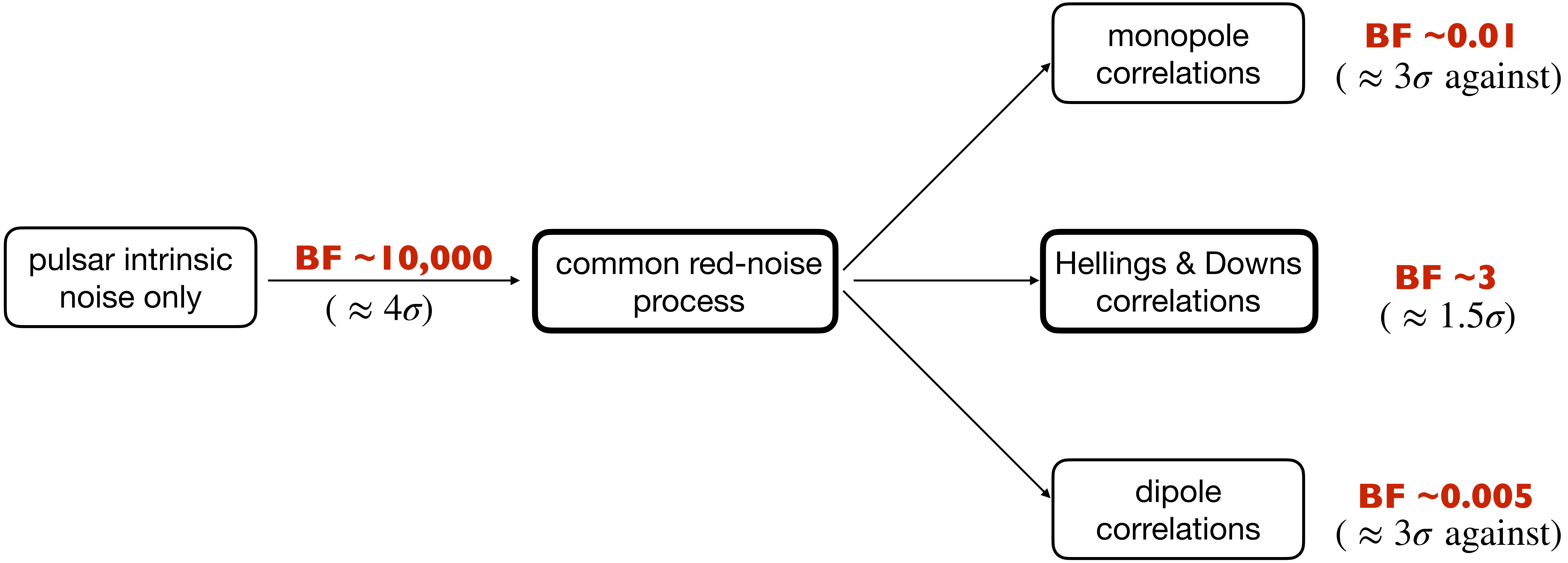
- **Quadrupolar (i.e., Hellings-Downs)** correlations are **expected from GR**





[pulsar timing GWB equivalent of LIGO-Virgo detector characterization]

Bayes factor model comparisons

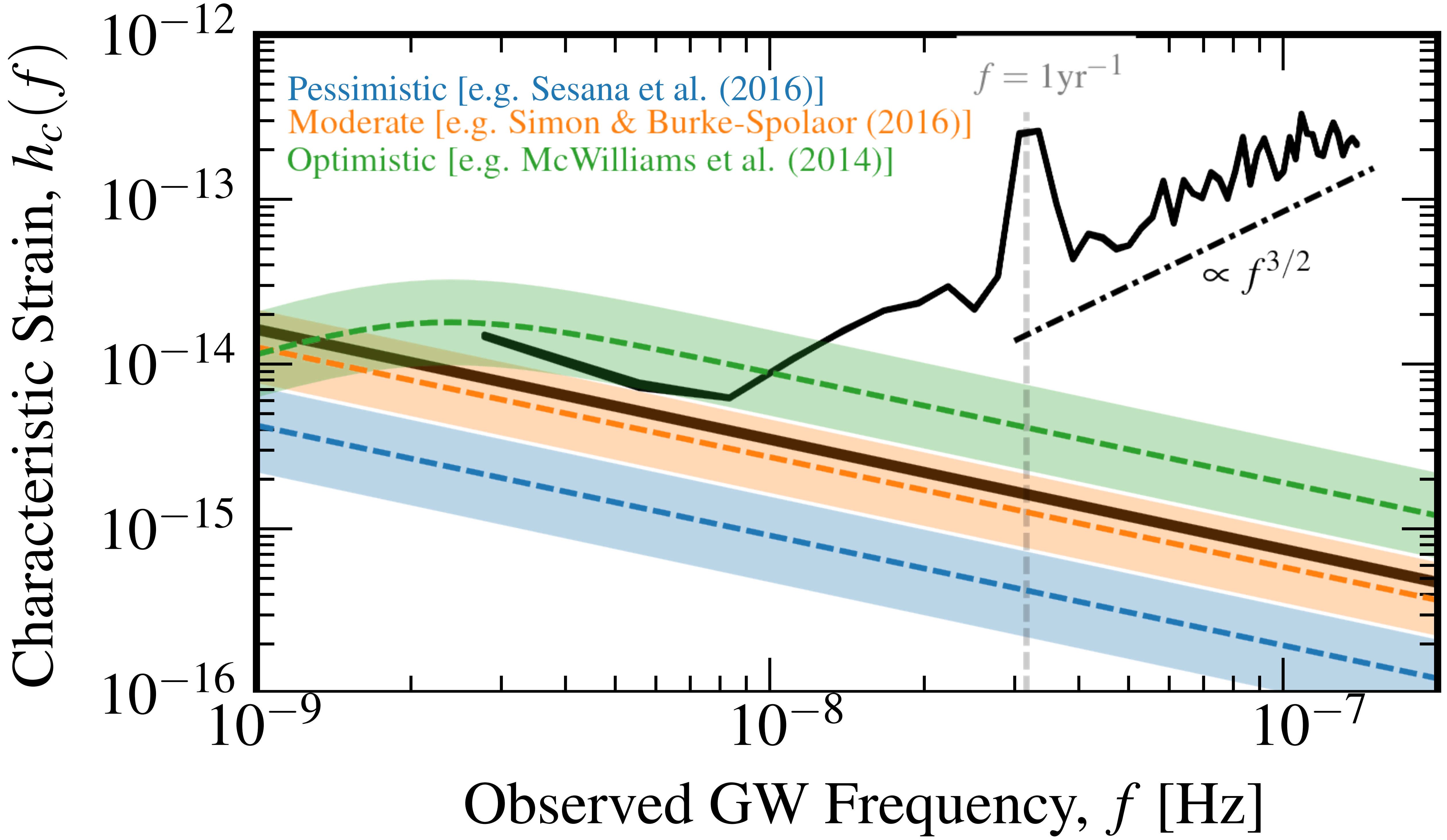


[credit: X. Siemens]

Astrophysical implications

- SMBBH models that were previously in tension with the NG 11-yr ULs are **no longer ruled out**
- Broad posterior for spectral index allows for **possible cosmological sources**
- Of order **50 papers** on the arXiv over the past 1.5 years
- NANOGrav is also analyzing the 12.5-yr data for **other potential sources of GWs**

(NG 11-yr stochastic analysis)



Summary

- **Strong evidence for an uncorrelated red-noise process common to all puslars** in the NANOGrav 12.5-yr data
- **No significant evidence for HD correlations**, but monopole and dipole correlations are disfavored
- **Larger data sets** (e.g., NG 15-yr) and **alternative analyses** (independent pipelines or data sets, e.g., IPTA) will either confirm or rule out these results (currently multiple confirmations fo the common spectrum process)
- Unlike the gold-plated detection of GW150914, the detection of a GWB will be a **gradual process**, with **more evidence accumulating over time**

Further investigations…

- Python code for simulating / recovering HD correlation:
  - romano_code4.ipynb
- Metronome-microphone PTA demo:
  - AJP paper: “An acoustical analogue of a galactic-scale gravitational-wave detector,” Lam et al., 2018 (https://aapt.scitation.org/doi/10.1119/1.5050190)
  - Code: https://github.com/nanograv/tabletop_pta/