Supermassive Black Holes and Merging Galaxies: Low-Frequency Gravitational Wave Detection with Pulsar Timing Arrays

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Workshop III: Source inference and parameter estimation
IPAM, November 15, 2021

UWM

NANOGrav
Physics Frontiers Center

Gravitational Wave Spectrum

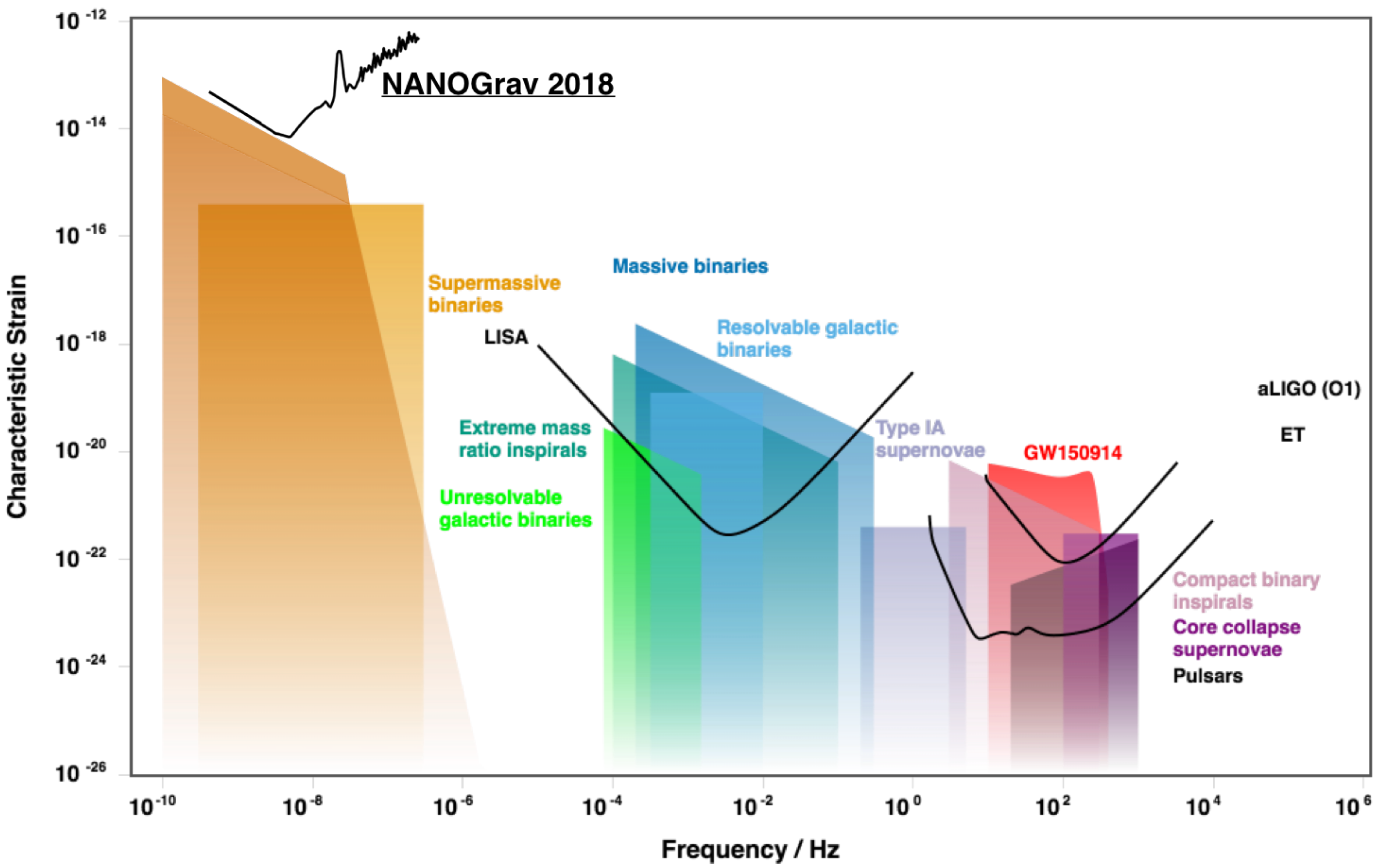


Figure credit: Moore, Cole, Berry (2014); modified by S.R. Taylor

Pulsars

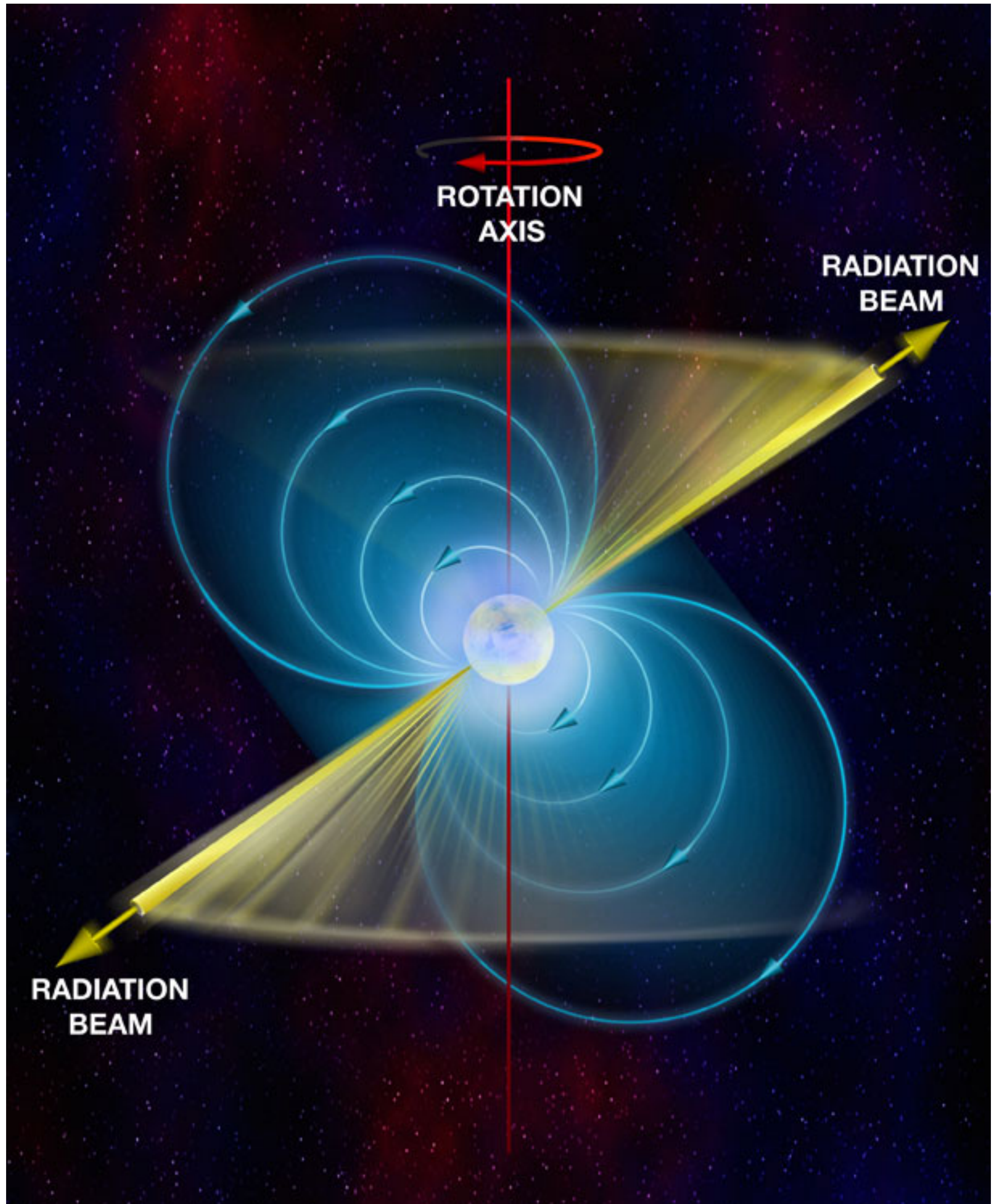
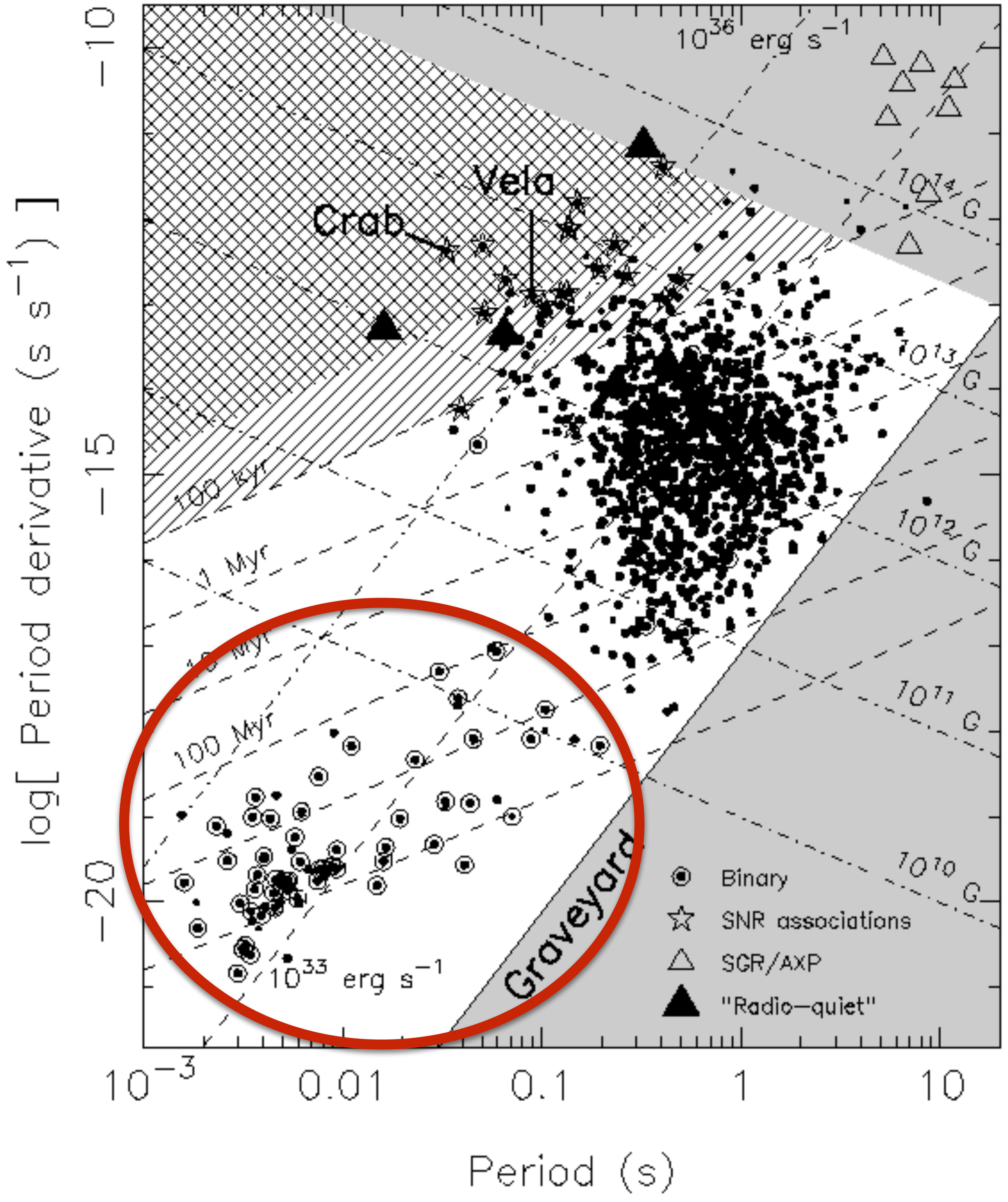


Image credit: Bill Saxton, NRAO/AUI/NSF



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

Pulsar Timing Arrays

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

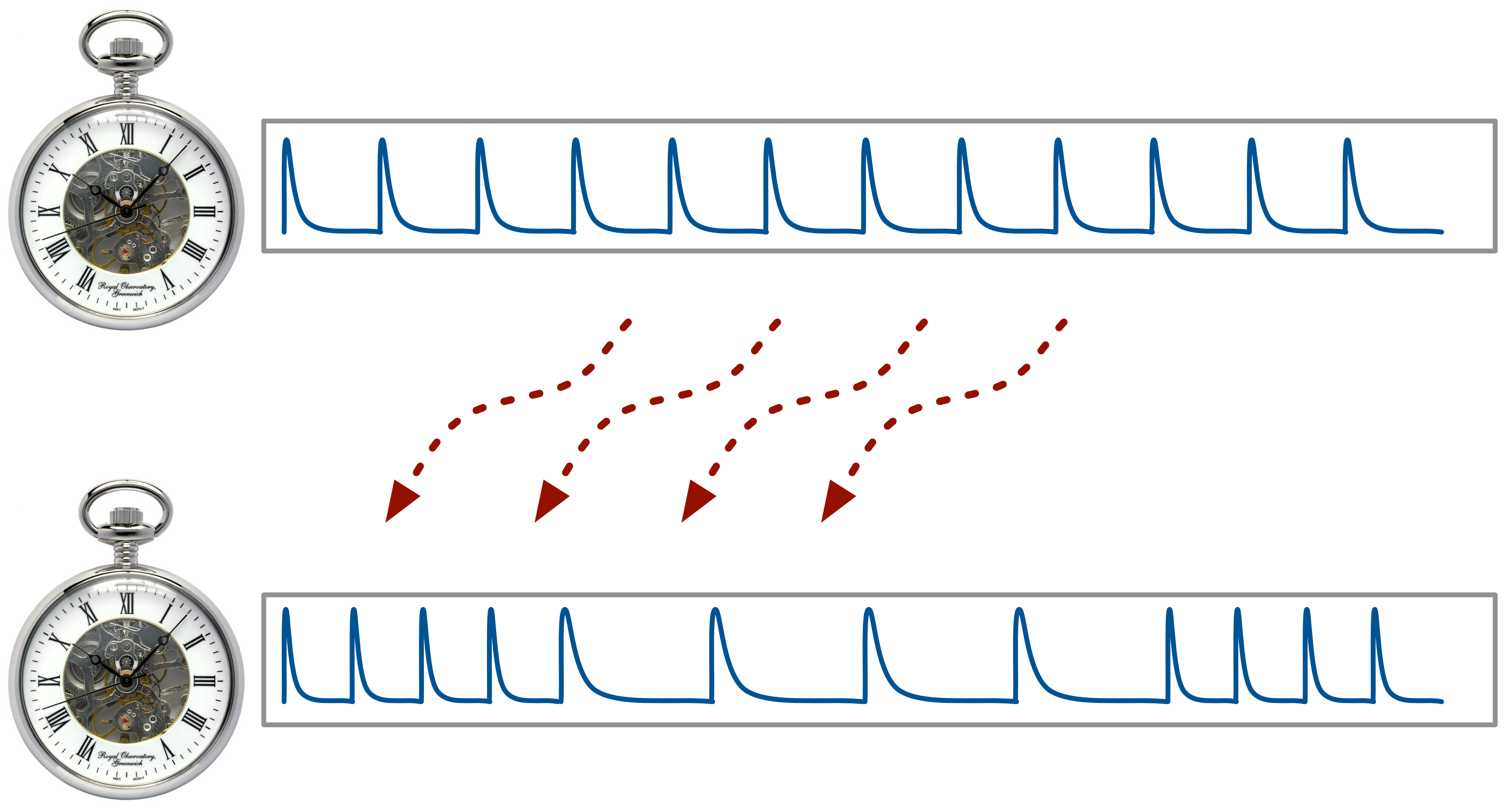


Image credit: S. Chatterjee

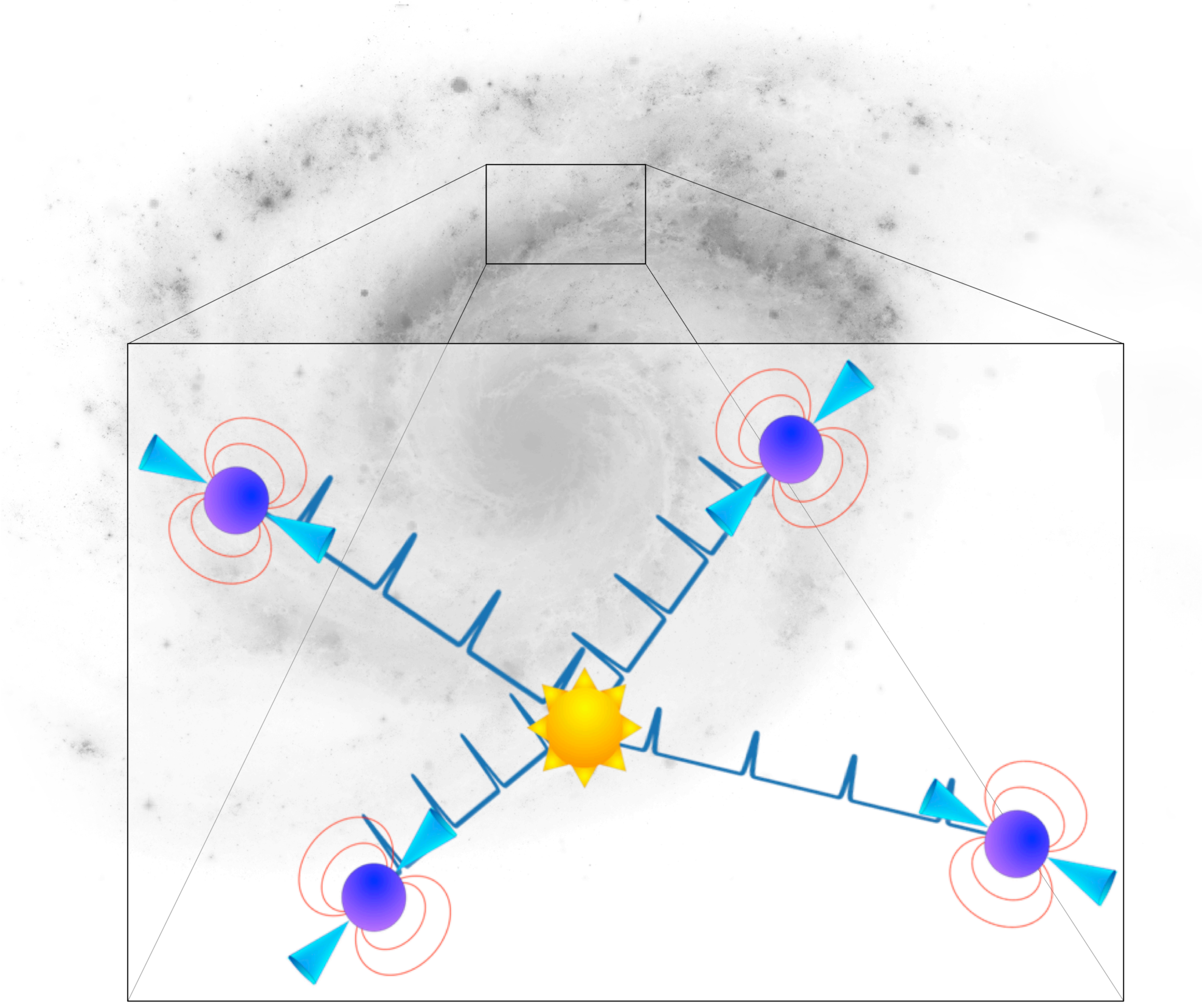


Image credit: J. Hazboun; NASA

Pulsar Timing

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

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

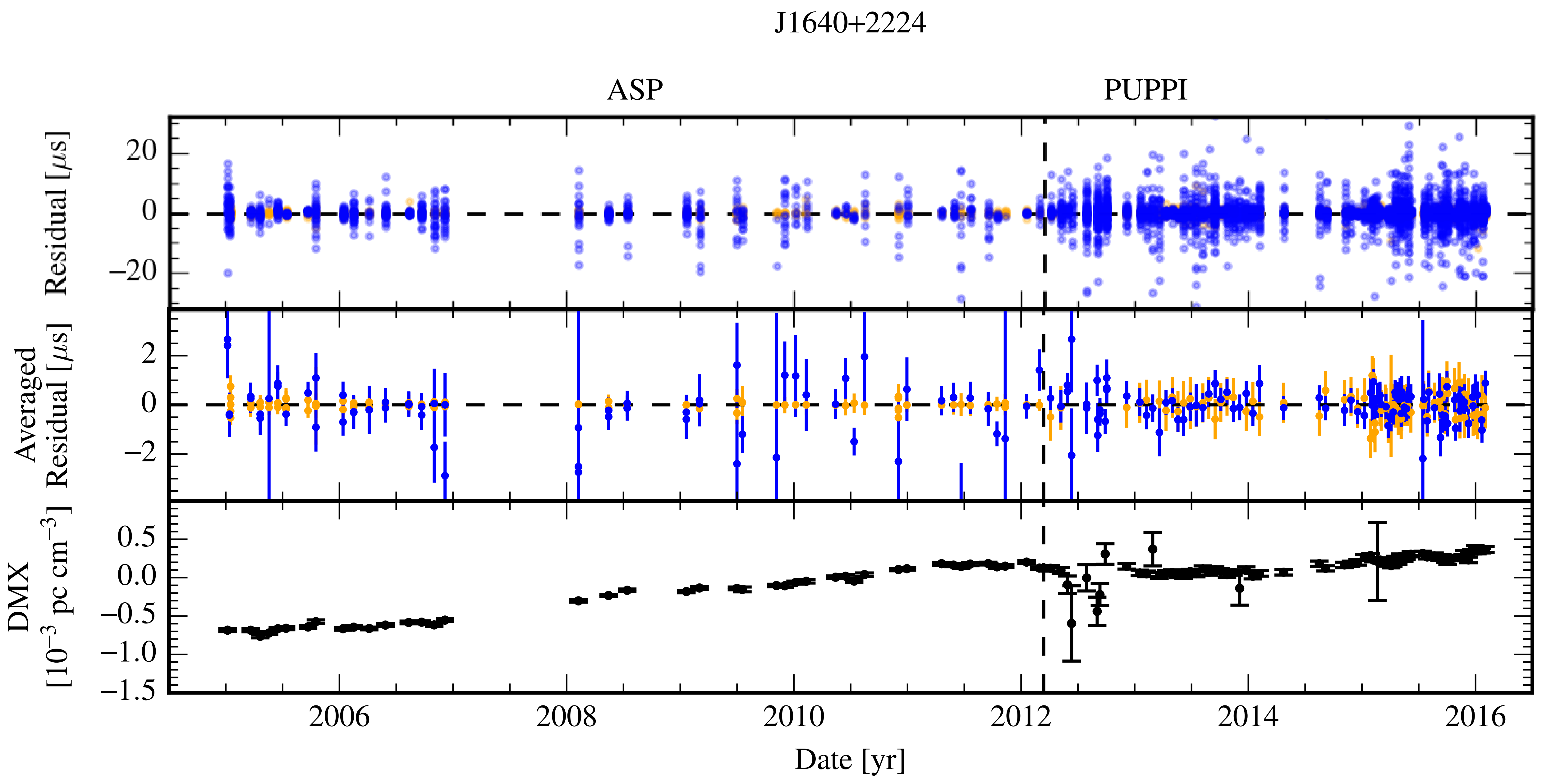
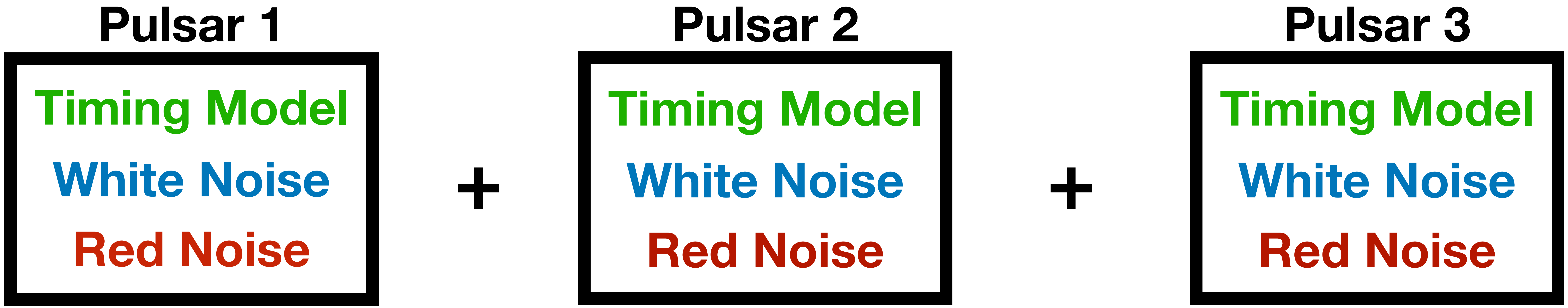
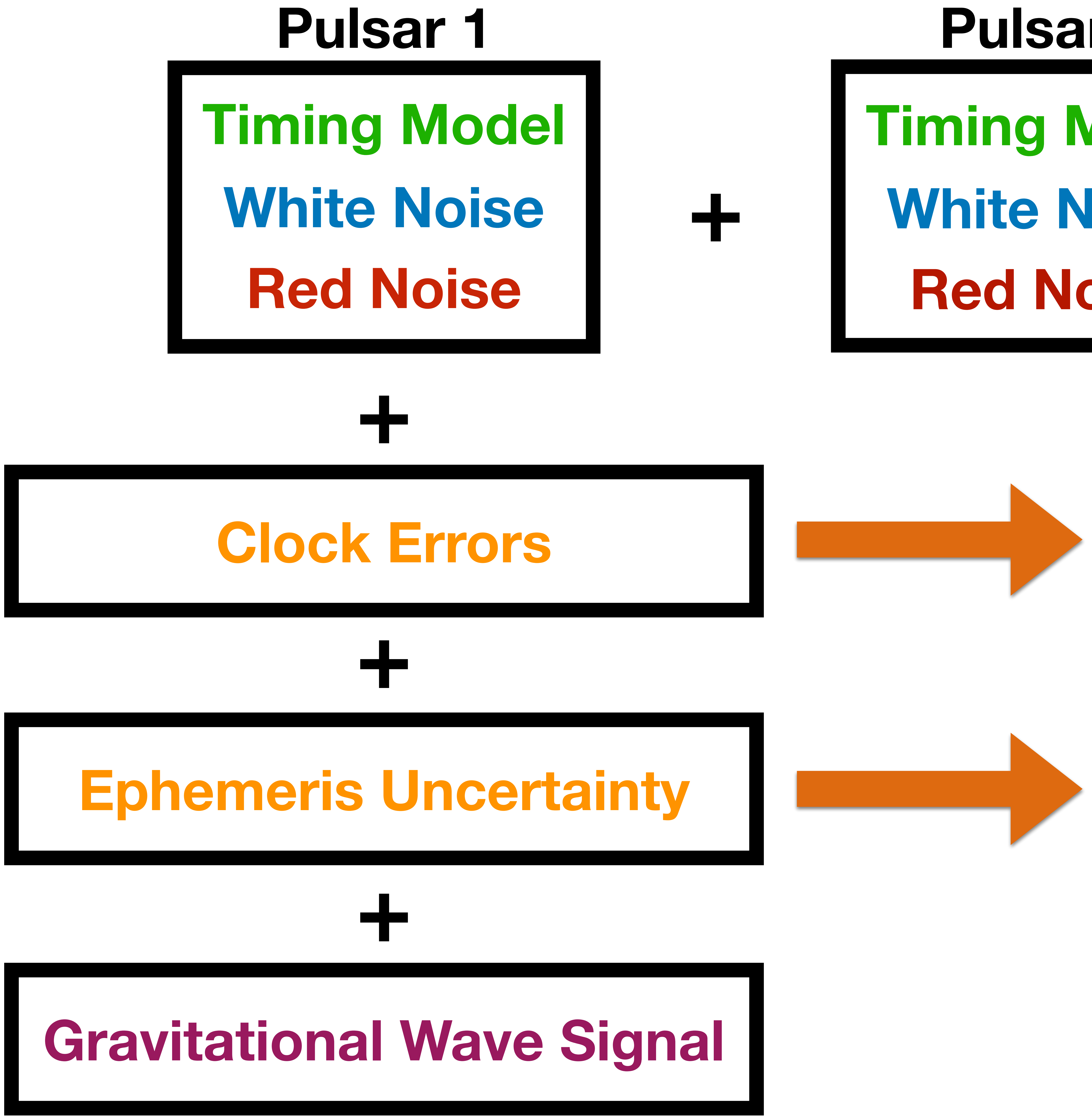


Figure credit: Z. Arzoumanian et al. (2018)

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


Pulsar 1
Timing Model
White Noise
Red Noise
+
Pulsar 2
Timing Model
White Noise
Red Noise
+
Pulsar 3
Timing Model
White Noise
Red Noise



Hobbs et al., MNRAS 427, 4 (2012)
Hobbs et al., MNRAS 491, 4 (2020)

Champion et al., ApJL 720, 2 (2010)
Caballero et al., MNRAS 481, 4 (2018)
Guo et al., MNRAS 489, 4 (2019)
Roebber, ApJ 876, 1 (2019)
Vallisneri et al., ApJ 893, 2 (2020)

Supermassive Black Hole Binaries

Stochastic GW Background

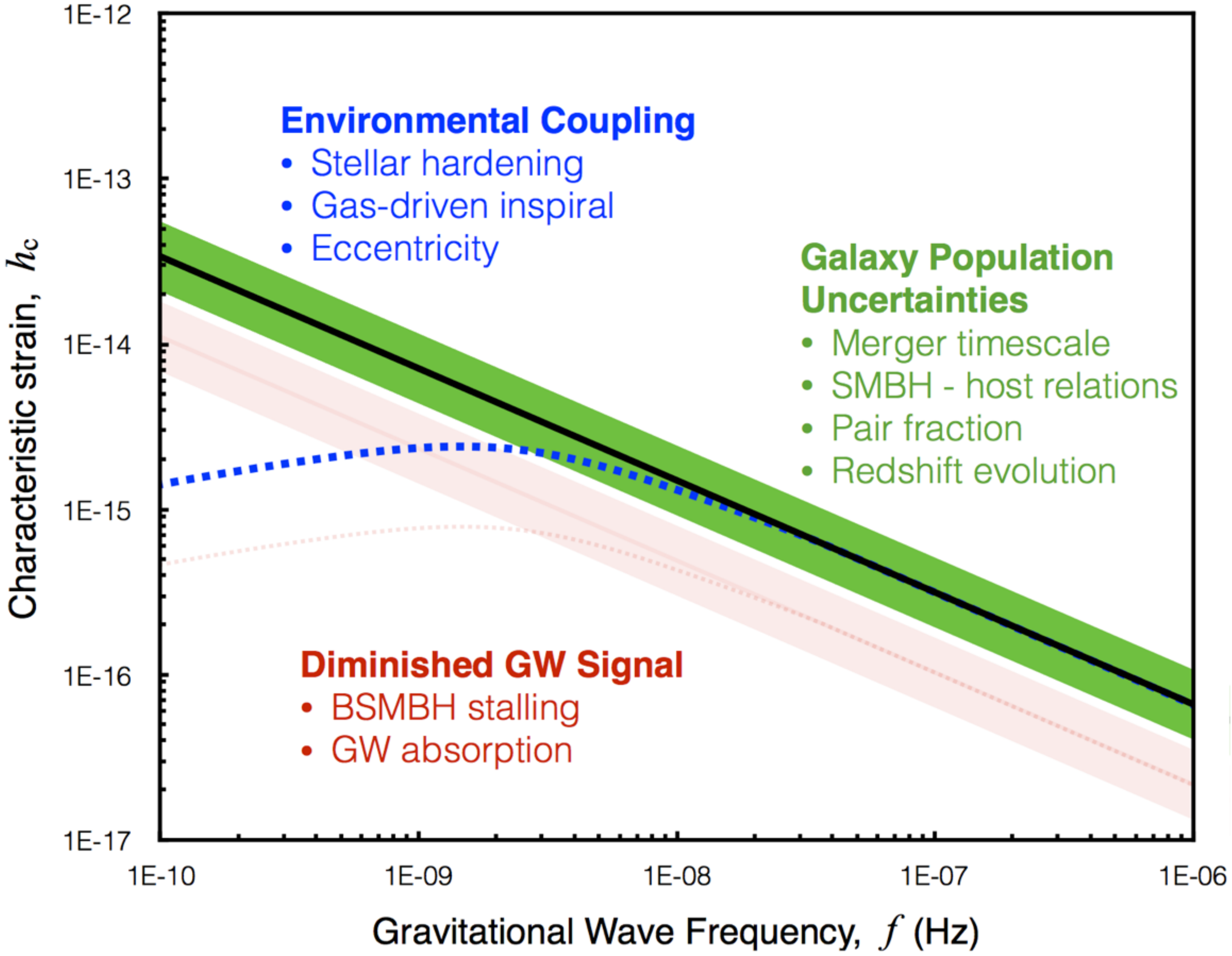


Image credit: S. Burke Spolaor 2015

The GWB from supermassive binary black holes is predicted to have a power-law power spectrum (Phinney, 2001):

$$P_{\rm gw}(f) = \frac{A_{\rm gw}^2}{12\pi^2}\left(\frac{f}{f_{\rm yr}}\right)^{-13/3}$$

This assumes circular binaries evolving only due to GW emission.

GWB Signal Model

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

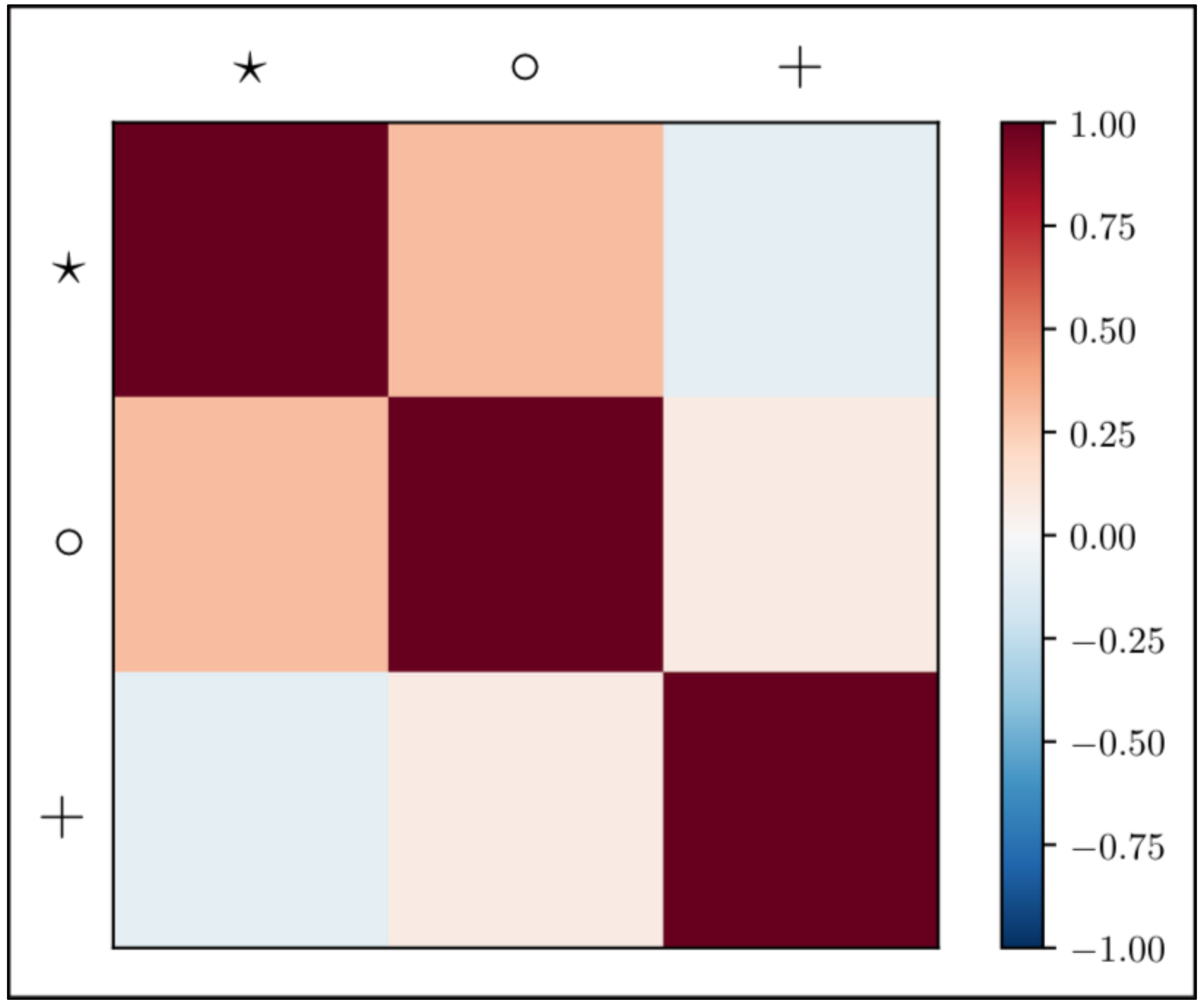
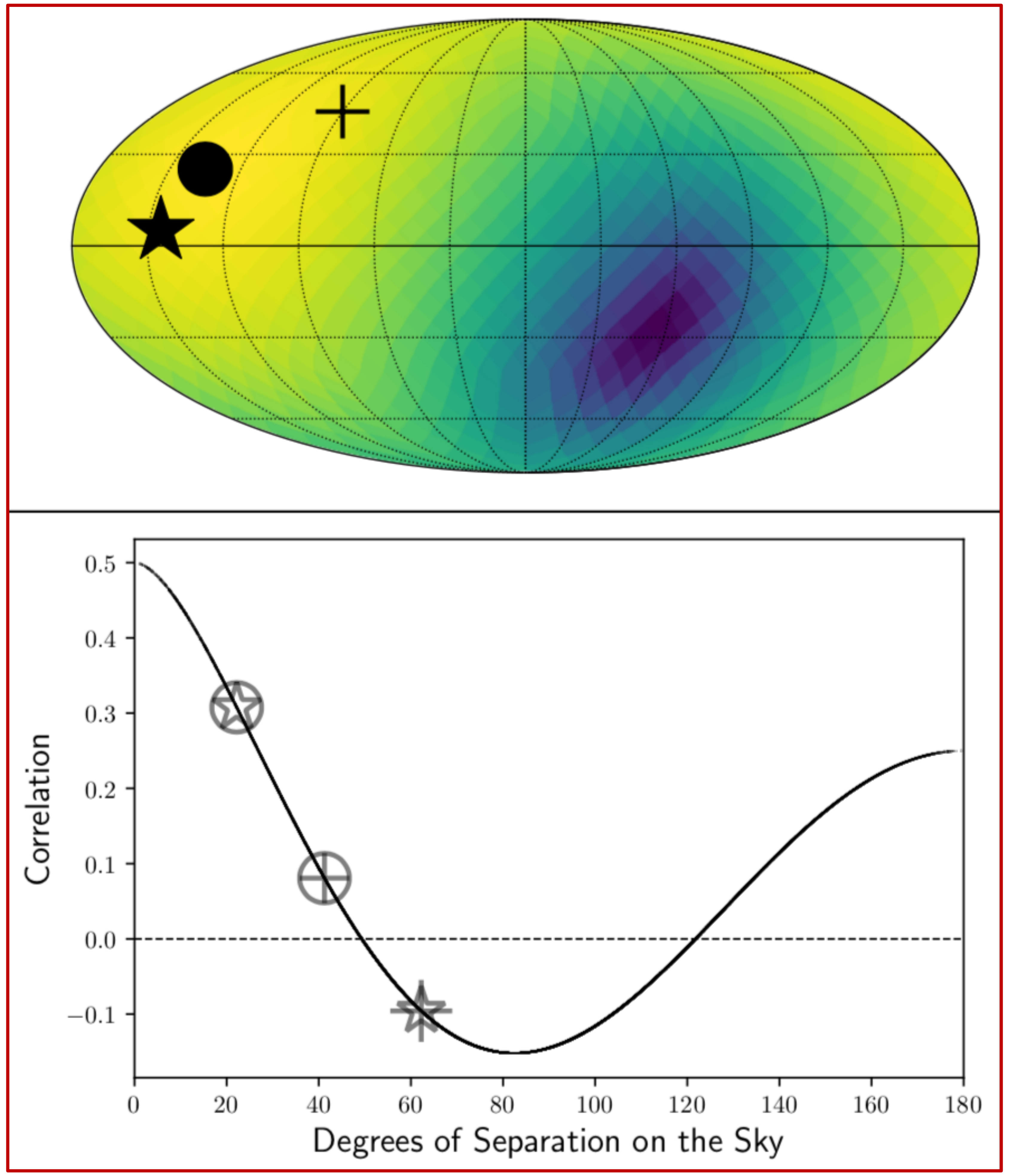


Figure credit: J. Hazboun



GWB Signal Model

We can search for the GWB in a couple of different ways:

- Search for a common red process in all of the pulsars that has the same power spectrum, ignoring the cross-correlations

- Search for a common red process in all of the pulsars and look for the Hellings-Downs correlations

Auto-correlations only

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

Auto-correlations and cross-correlations

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

North American Nanohertz Observatory for Gravitational Waves

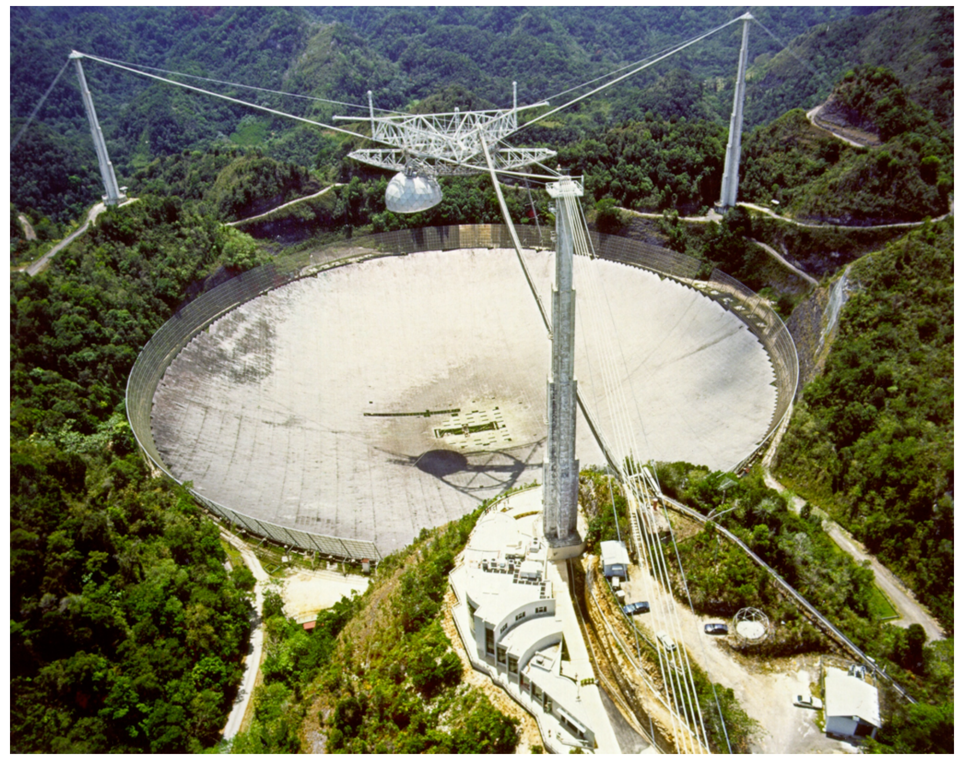




Image credits: NRAO/AUI, NAIC,
CHIME Collaboration

The International Pulsar Timing Array

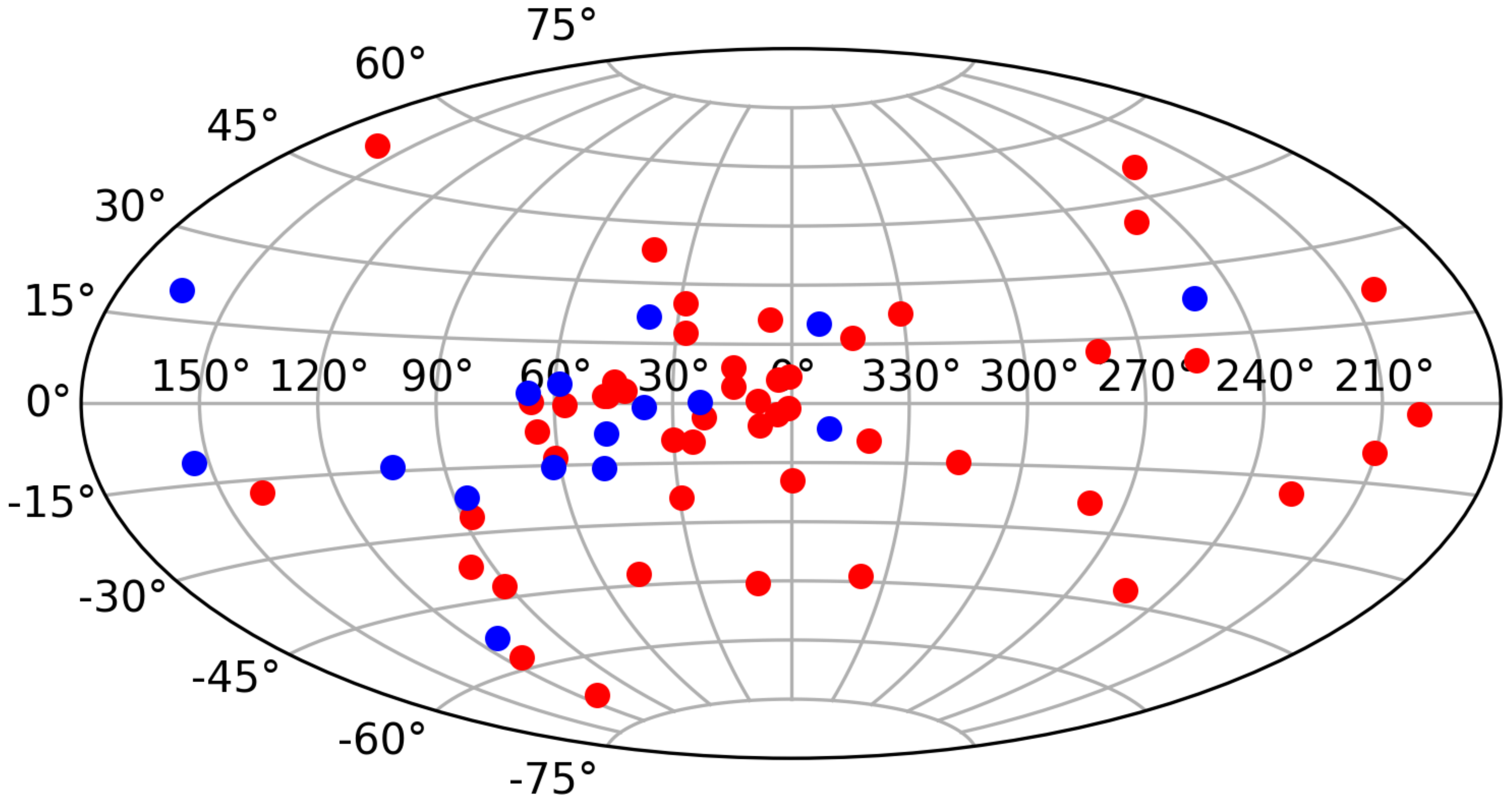
Image credits: NRAO/AUI, NAIC, EPTA,
ATNF/CSIRO, Google maps

The International Pulsar Timing Array

The IPTA has released two data sets that combine observations made by the EPTA, PPTA, and NANOGrav:

- DR1: 49 millisecond pulsars, observed for up to 27 years (J. Verbiest et al. 2016)

- DR2: 65 millisecond pulsars, observed for up to 29.4 years (B. Perera et al. 2019)

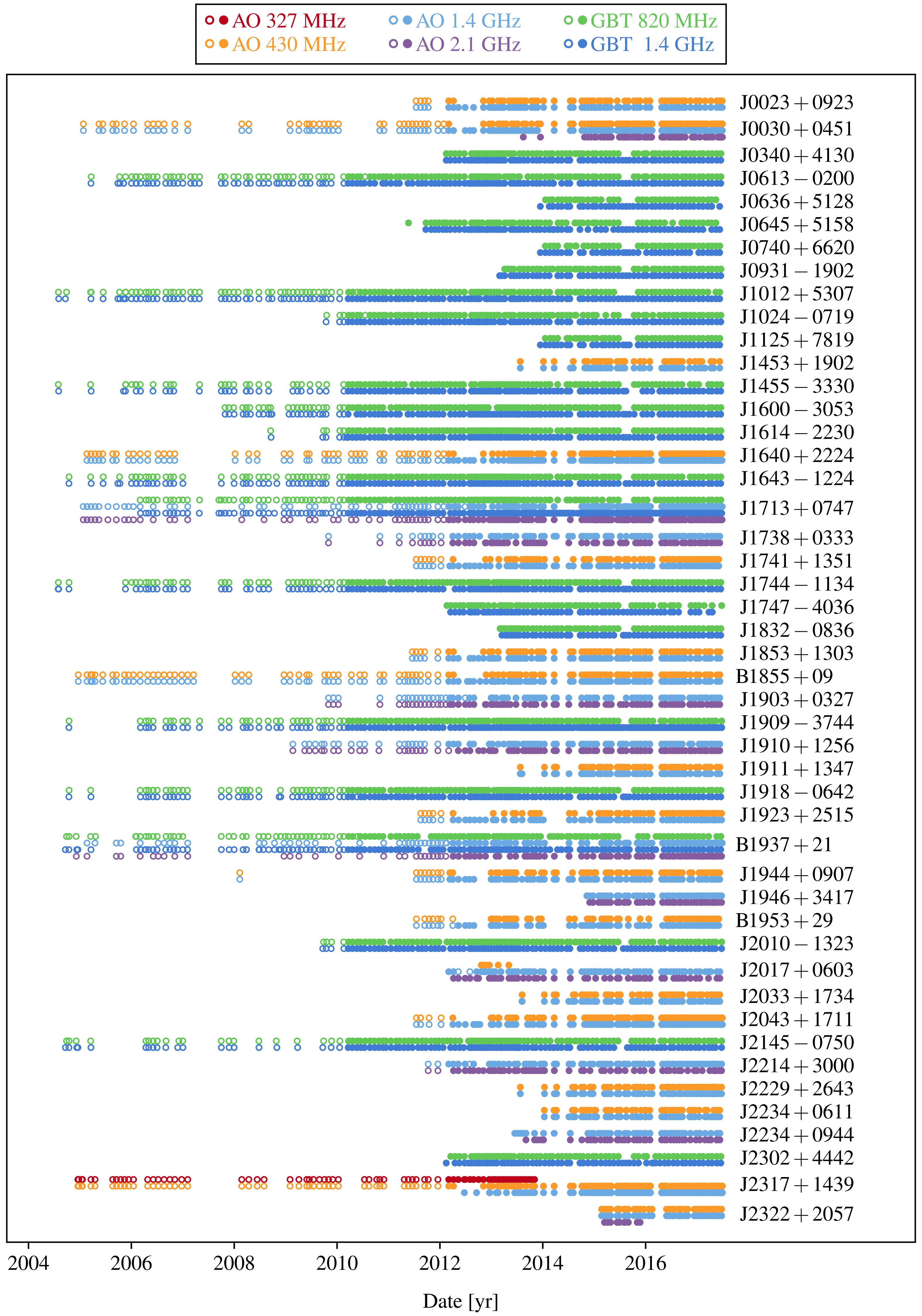


B. Perera et al. 2019

NANOGrav 12.5-yr Data Set

M. Alam et al. (NANOGrav collaboration), “The NANOGrav 12.5-year Data Set: High-Precision Timing of 47 Millisecond Pulsars,” *ApJS* 252 (2021). Lead author: M. DeCesar

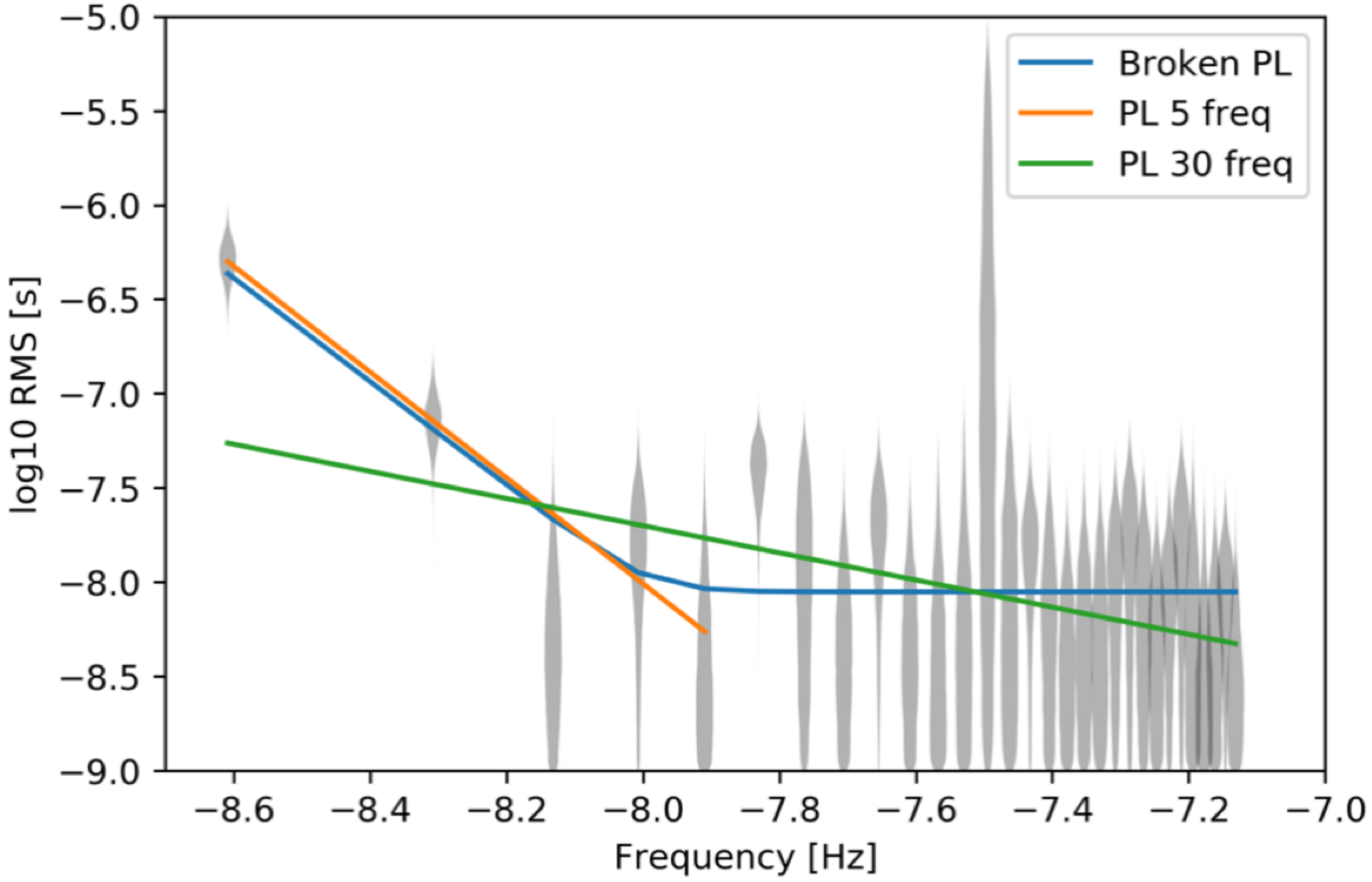
M. Alam et al. (NANOGrav collaboration), “The NANOGrav 12.5-year Data Set: Wideband Timing of 47 Millisecond Pulsars,” *ApJS* 252 (2021). Lead author: T. Pennucci

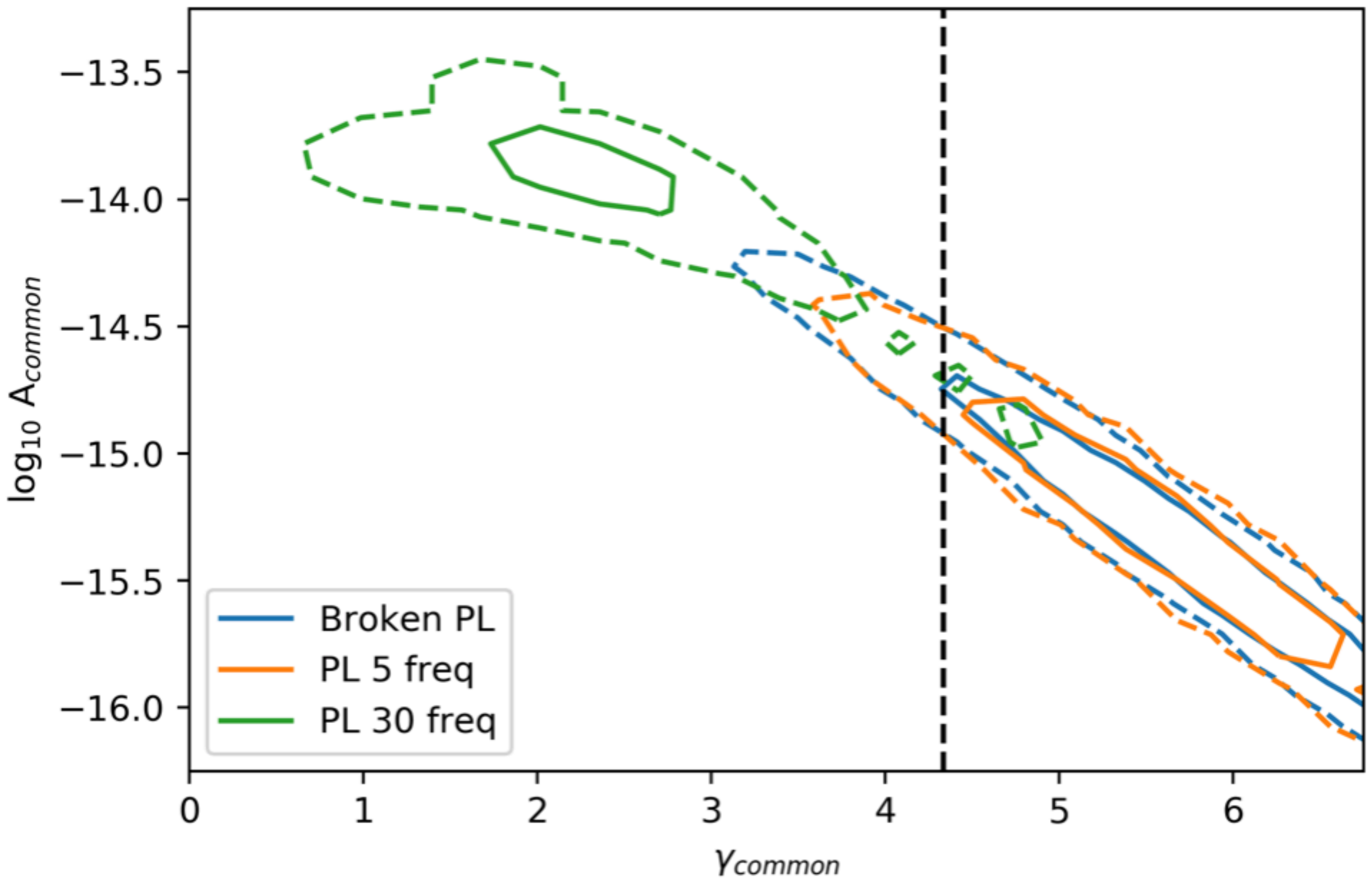


Latest data set contains 47 pulsars observed for up to 12.9 years (45 pulsars used for GW searches)

Two data sets produced: one using conventional narrowband timing, the other using new wideband timing

NANOGrav 12.5-yr GWB Search





Z. Arzoumanian et al. (NANOGrav collaboration), ApJL 905, L34 (2020)
Lead author: J. Simon

NANOGrav 12.5-yr GWB Search

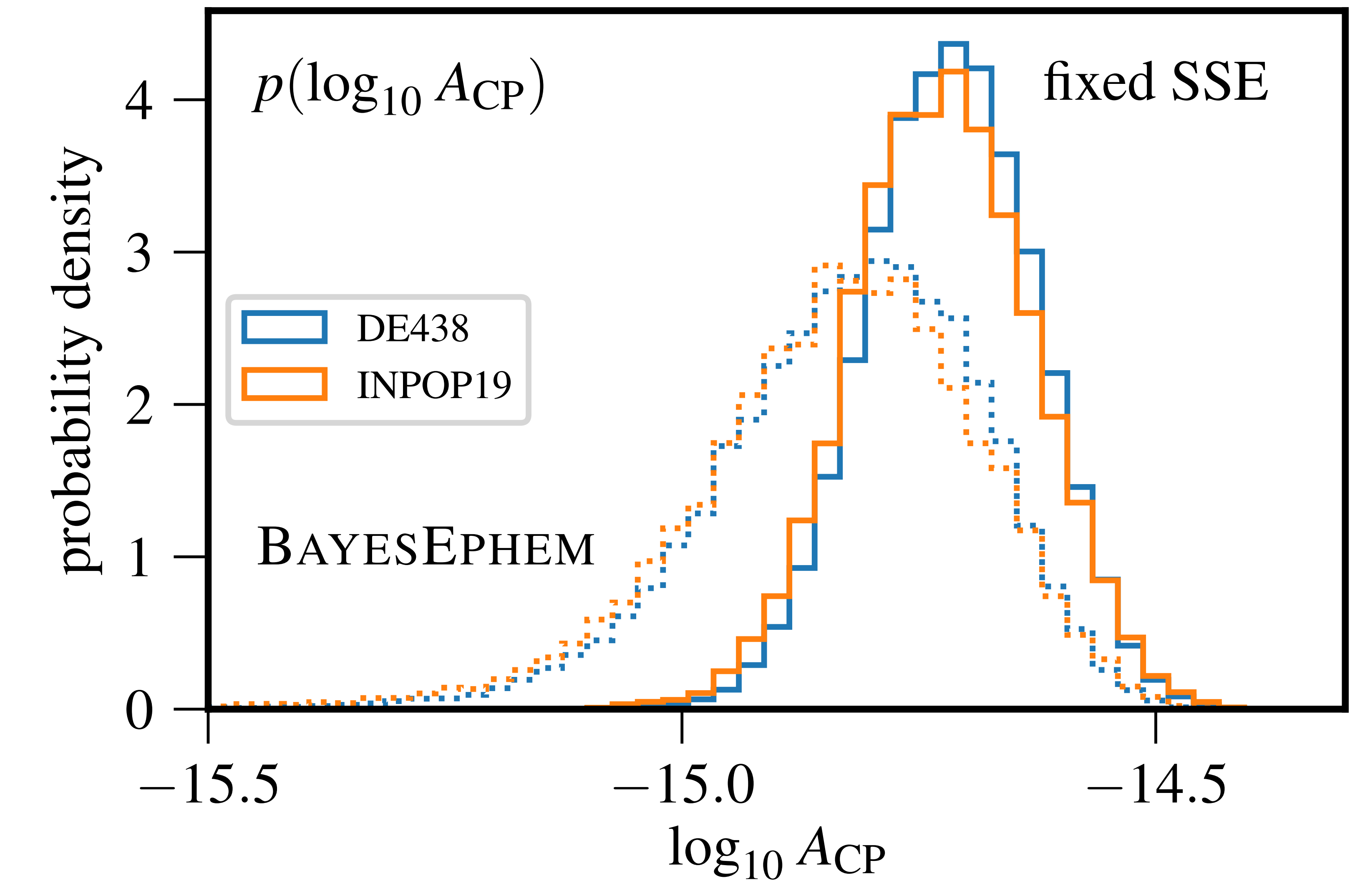
Is there evidence
for a common-amplitude
$\gamma = 13/3$ process?
Yes, strong evidence.

$$h_c(f) = A_{\rm GWB}\left(\frac{f}{f_{\rm yr}}\right)^{-\gamma}$$

pulsar intrinsic noise only → **common-amplitude process**

$\log_{10}$ BF = **4.5** [DE438]
4.2 [INPOP19a]
2.4 [BayesEphem ≡ BE]

median $A_{\rm CP}$ = $1.96\ 10^{-15}$ [DE438]
$1.88\ 10^{-15}$ [INPOP19a]
$1.53\ 10^{-15}$ [BE]



Slide courtesy J. Simon. Figures from Z. Arzoumanian et al. (2020)

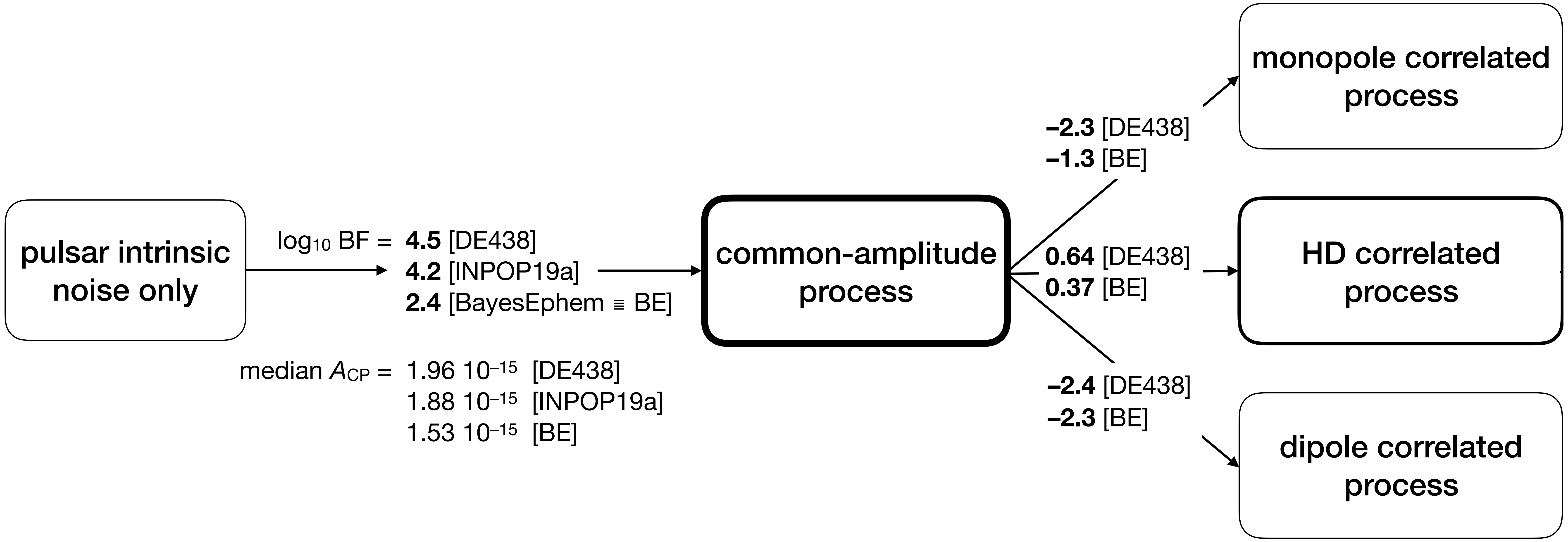
NANOGrav 12.5-yr GWB Search

Is there evidence for a common-amplitude $\gamma = 13/3$ process?

Yes, strong evidence.

Is there evidence for a spatially correlated $\gamma = 13/3$ process?

No strong evidence for HD correlations, moderate evidence against monopole and dipole.



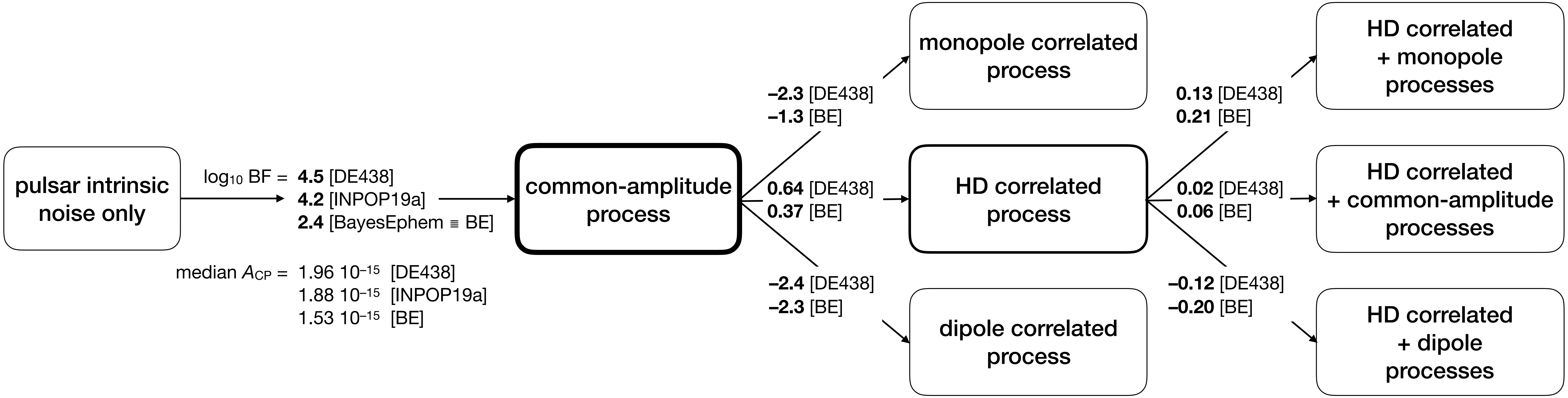
Slide courtesy J. Simon. Figures from Z. Arzoumanian et al. (2020)

NANOGrav 12.5-yr GWB Search

Is there evidence for a common-amplitude $\gamma = 13/3$ process?
Yes, strong evidence.

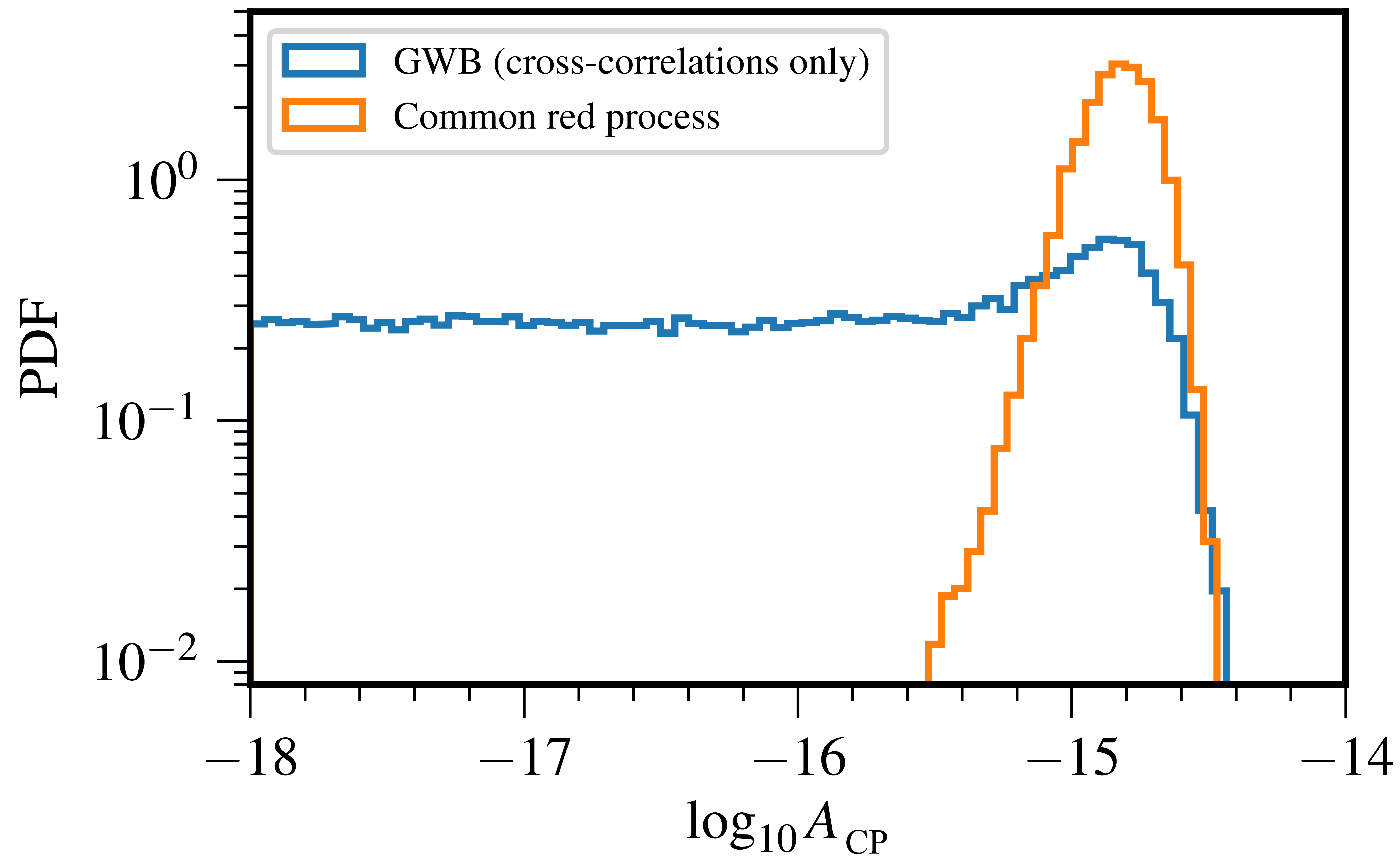
Is there evidence for a spatially correlated $\gamma = 13/3$ process?
No strong evidence for HD correlations, moderate evidence against monopole and dipole.

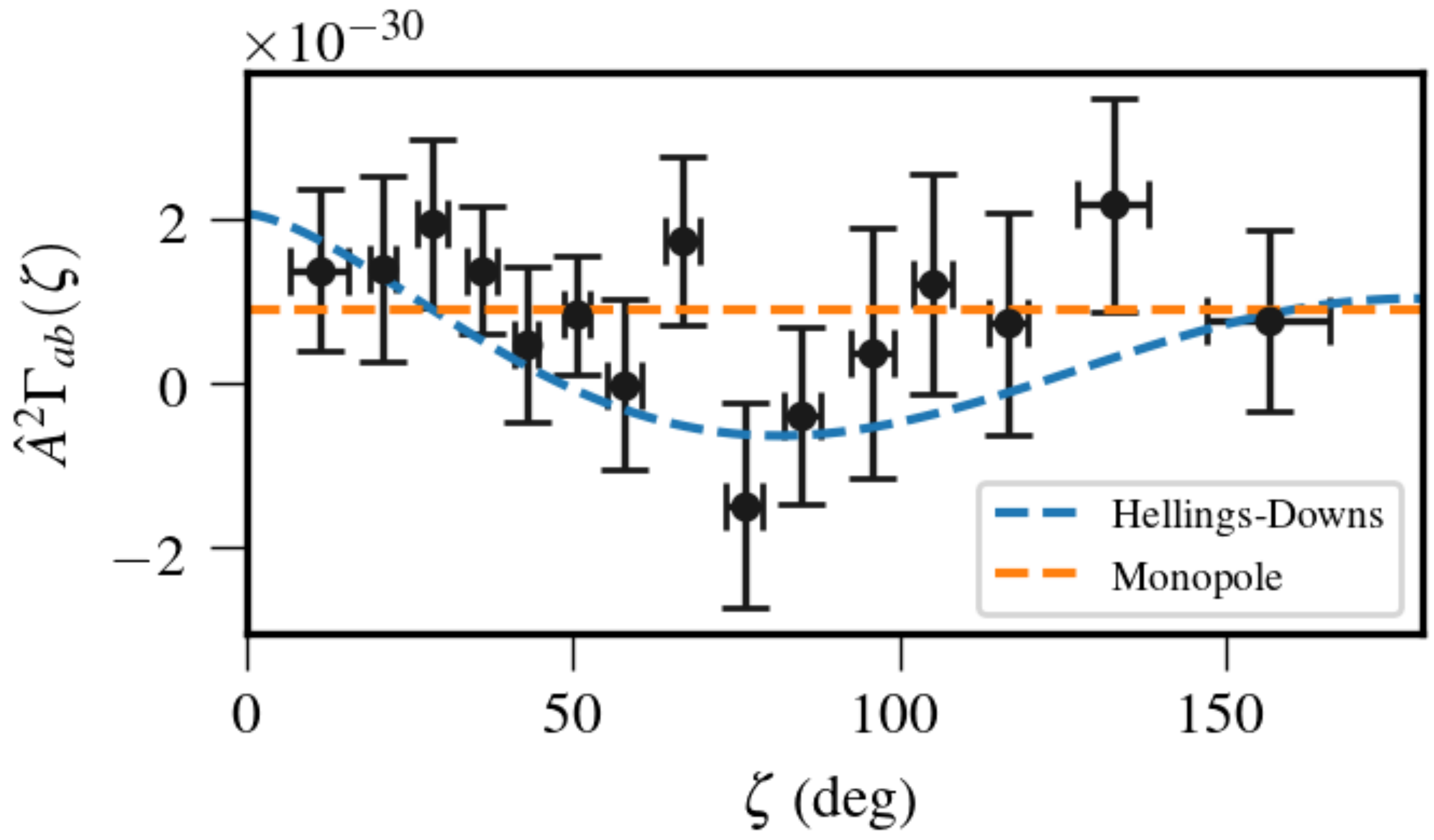
Is there evidence for a second $\gamma = 13/3$ process on top of HD?
Little evidence either way.



Slide courtesy J. Simon. Figures from Z. Arzoumanian et al. (2020)

NANOGrav 12.5-yr GWB Search



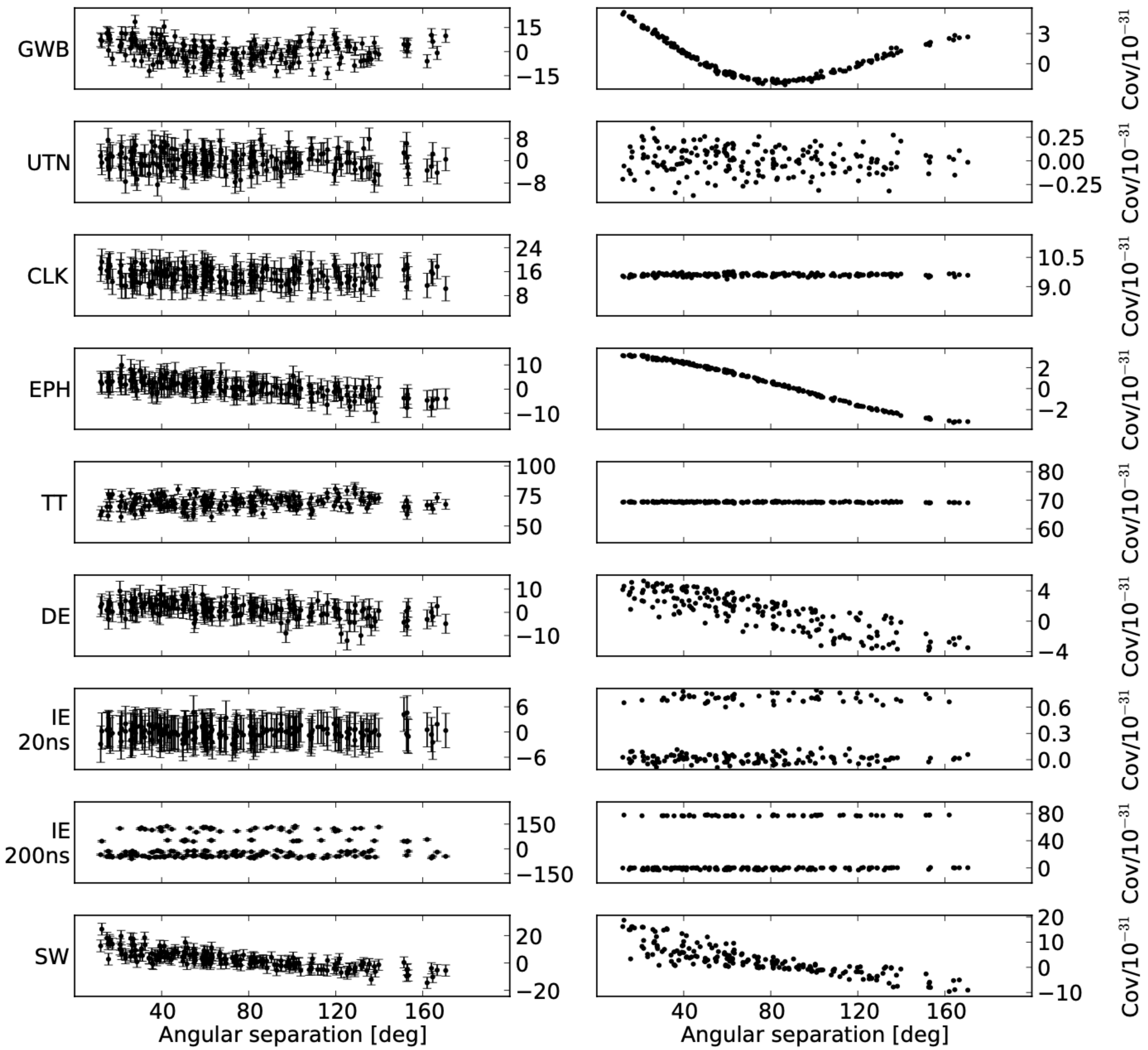


Z. Arzoumanian et al. (2020)

Assessing Spatial Correlations

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

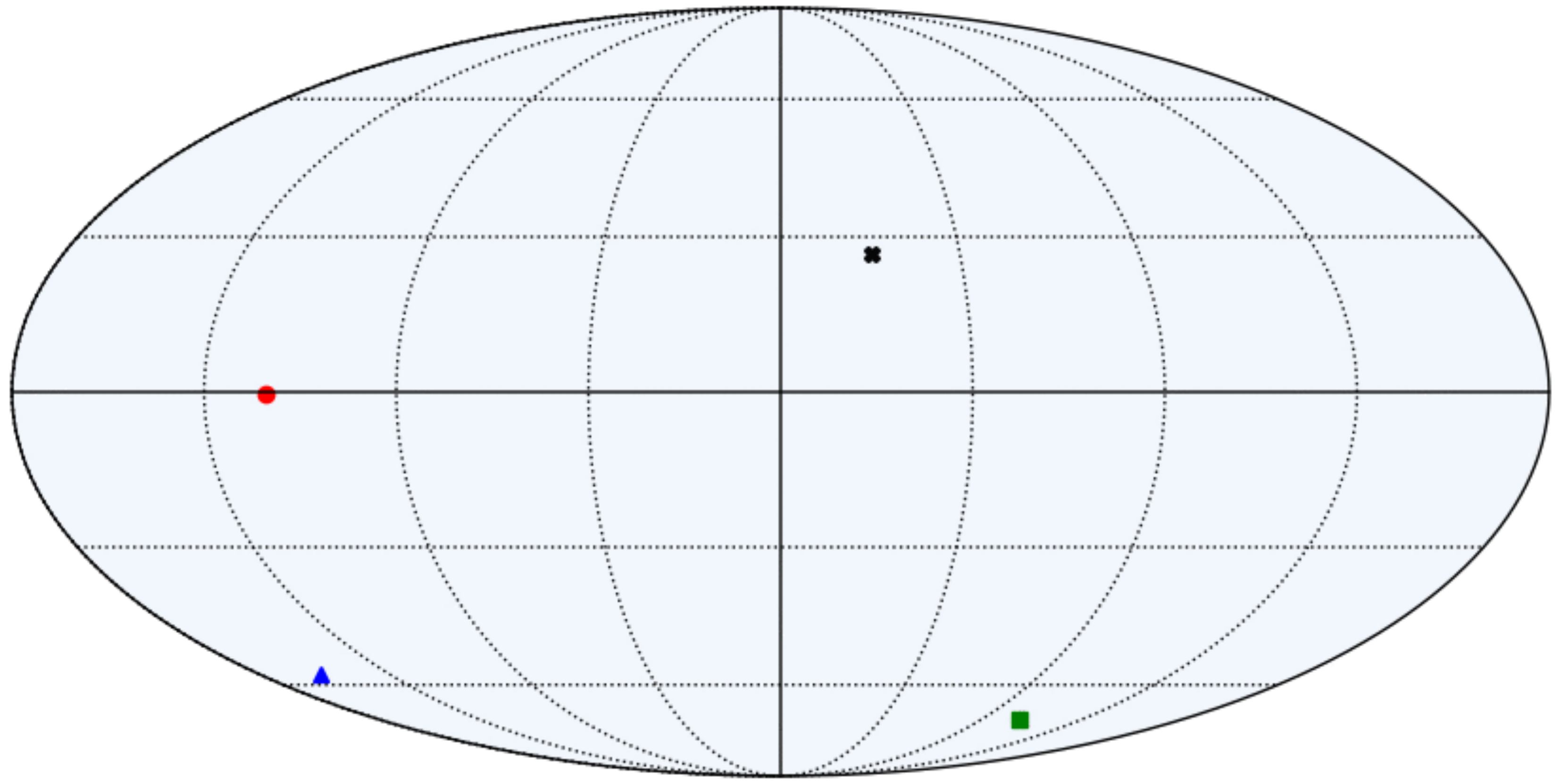
Tag	Simulated effect	GWB-like spectrum
S_{gwb}	GWB	Y
S_{utn}	Uncorrelated red noise	Y
S_{clk}	Stochastic clock-like errors	Y
S_{eph}	Stochastic ephemeris-like errors	Y
S_{tt}	Difference between TT(BIPM2013) and TT(TAI)	N
S_{de}	Difference between DE421 and DE414	N
S_{ie}	Instrumental errors	N
S_{sw}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



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

Phase Shifts and Sky Scrambles

We can calculate the false alarm probability using sky scrambles and phase shifts (Cornish & Sampson 2016; Taylor et al. 2017) to compute the SNR distribution when we break the spatial correlations.



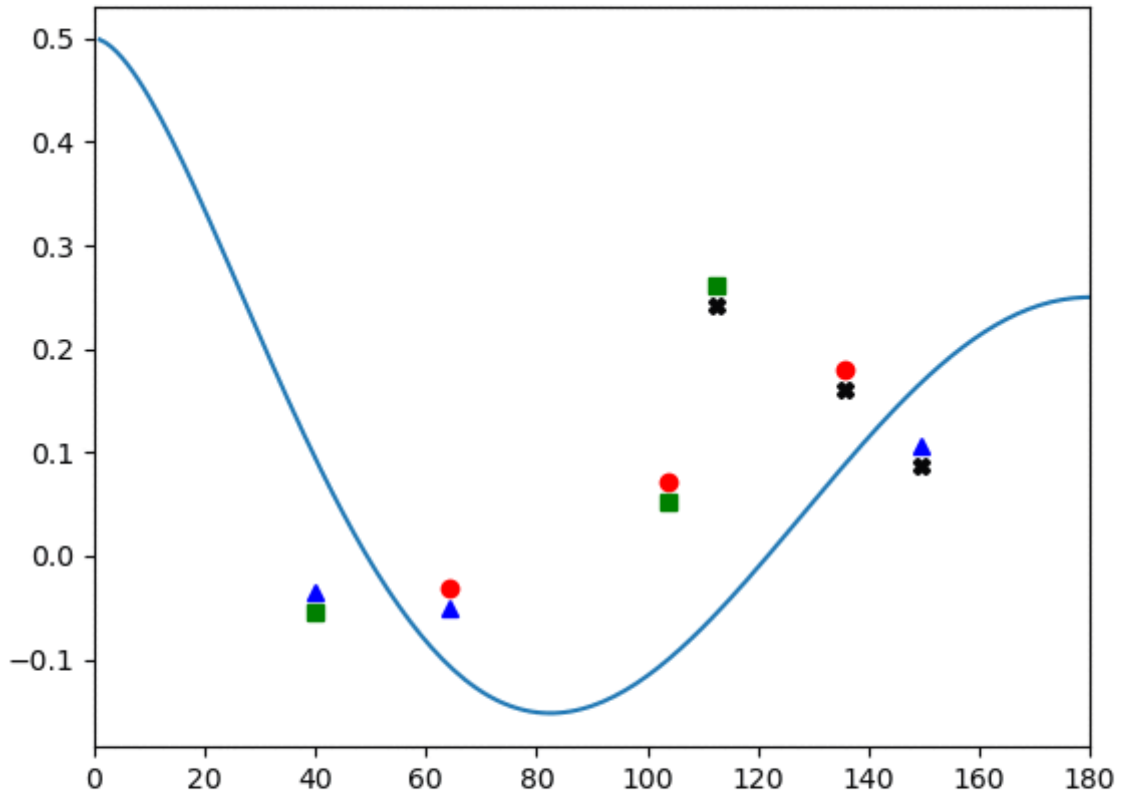
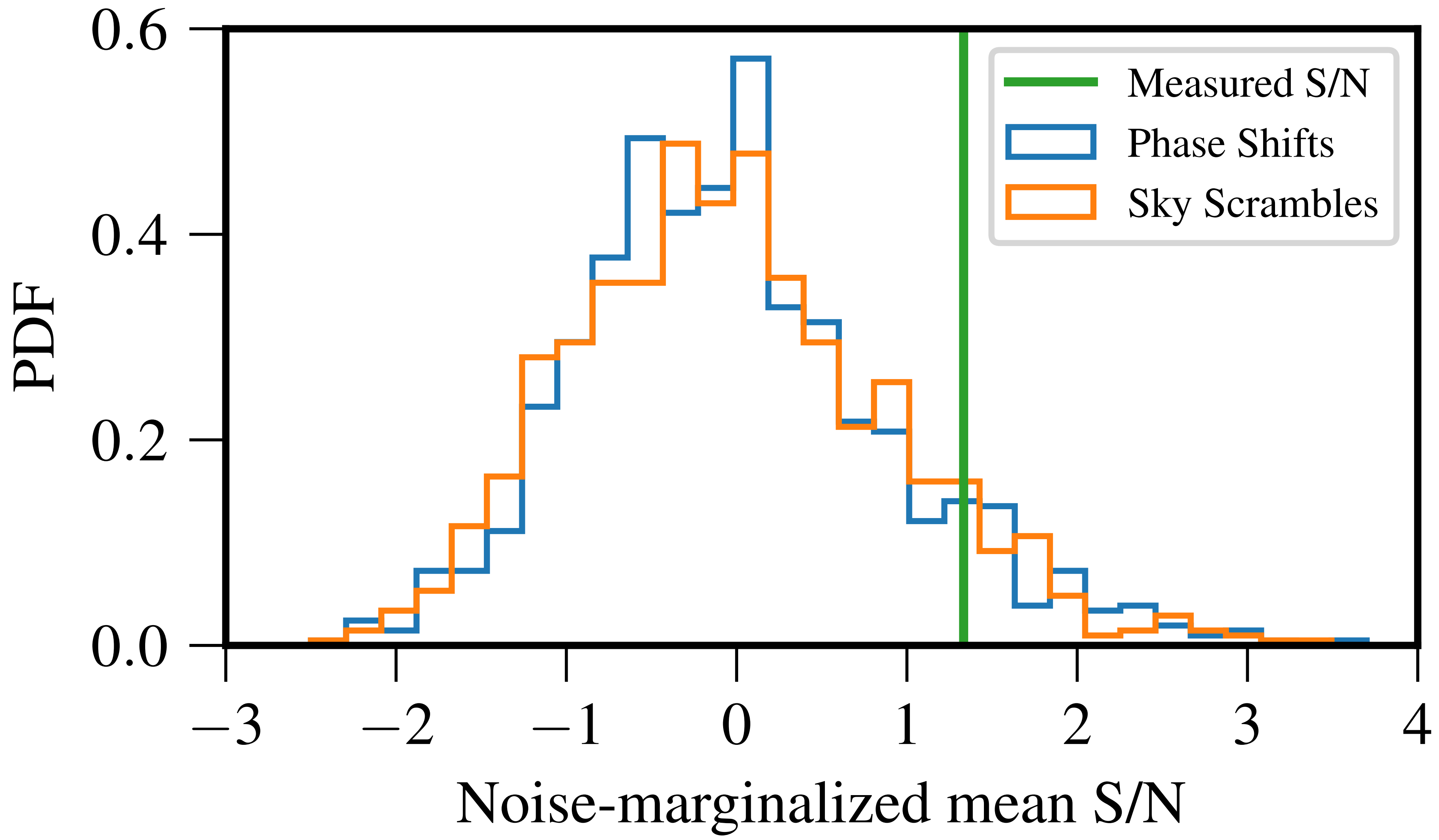
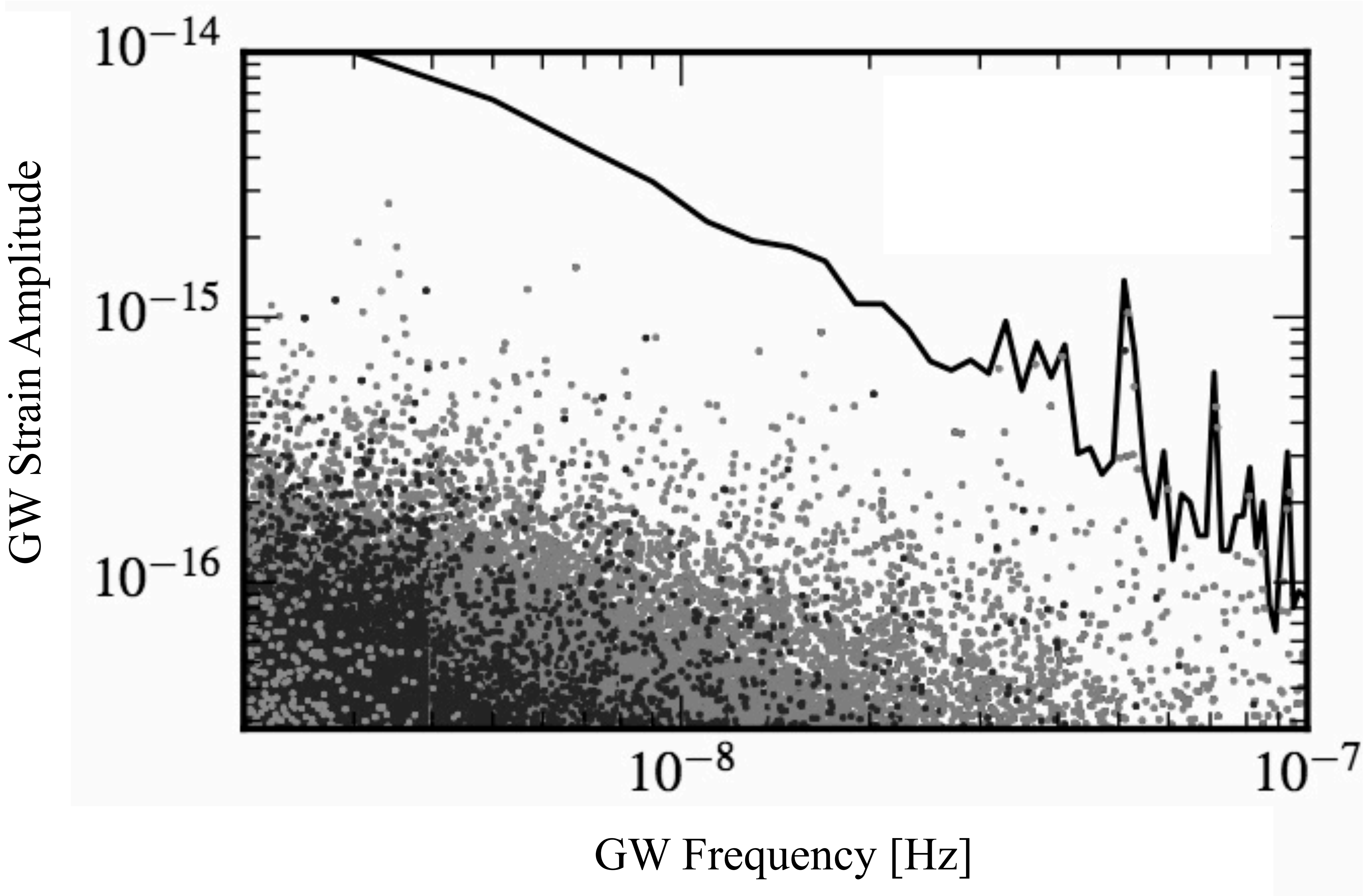


Figure credit: N. Cornish



Z. Arzoumanian et al. (2020)

NANOGrav 12.5-yr GWB Search



The stochastic GWB:

- ✓ Appears in many pulsars
- ? Quadrupole cross-correlations between different pulsars (Hellings-Downs curve)
- ? Power spectrum is power-law with spectral index -13/3 (if produced by circular SMBHBs)

Figure credit: J. Simon

Population Inference

The GWB from supermassive binary black holes is predicted to have a power-law power spectrum (Phinney, 2001):

$$P_{\rm gw}(f) = \frac{A_{\rm gw}^2}{12\pi^2}\left(\frac{f}{f_{\rm yr}}\right)^{-13/3} = \frac{h_c^2(f)}{12\pi^2 f^3}$$

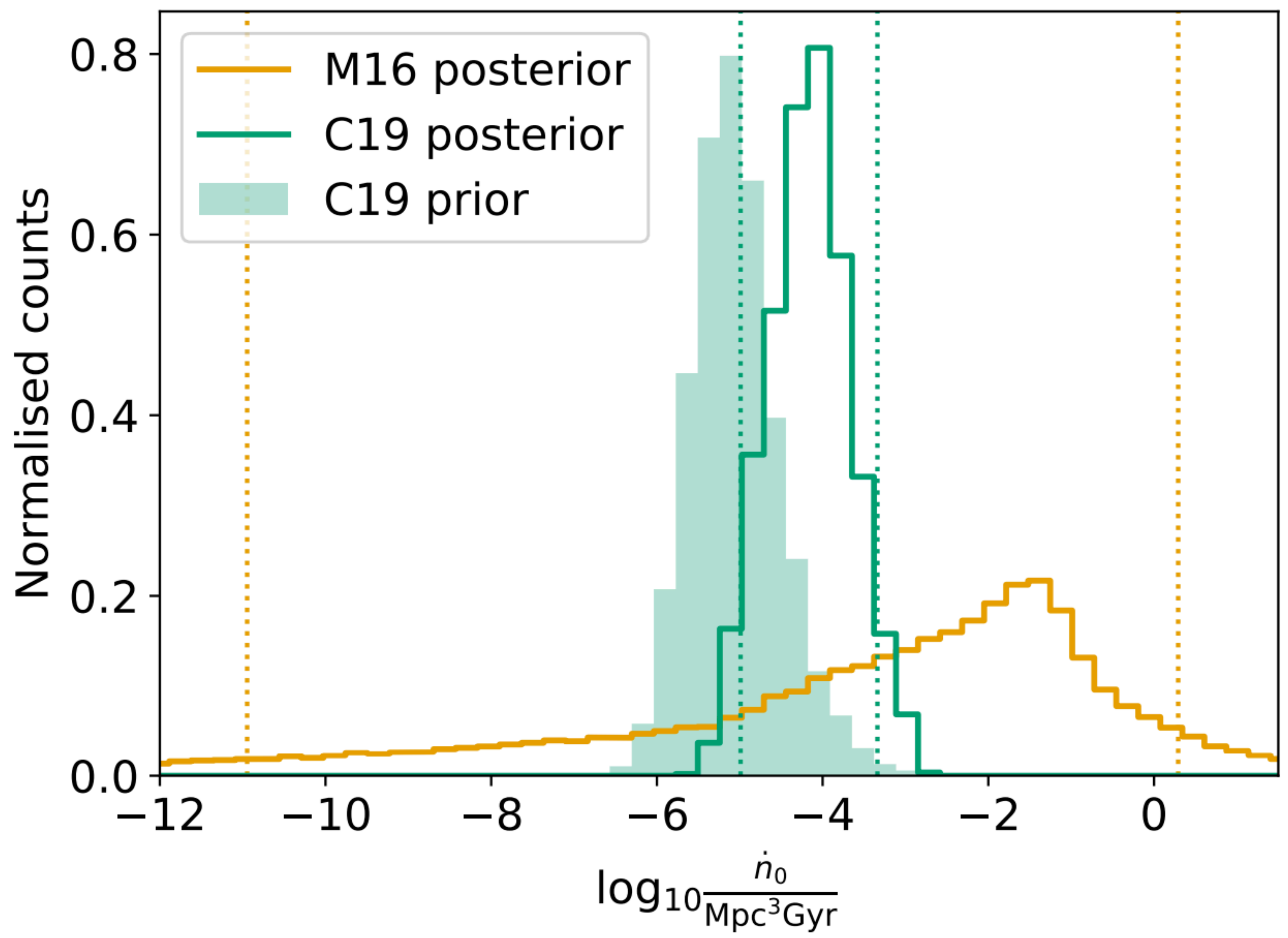
$$h_c^2(f) = \frac{4G^{5/3}}{3\pi^{1/3}c^2} f^{-4/3} \int d\mathcal{M} \int dz\ (1+z)^{-1/3}\mathcal{M}^{5/3}\frac{d^2 n}{dz\ d\mathcal{M}}$$

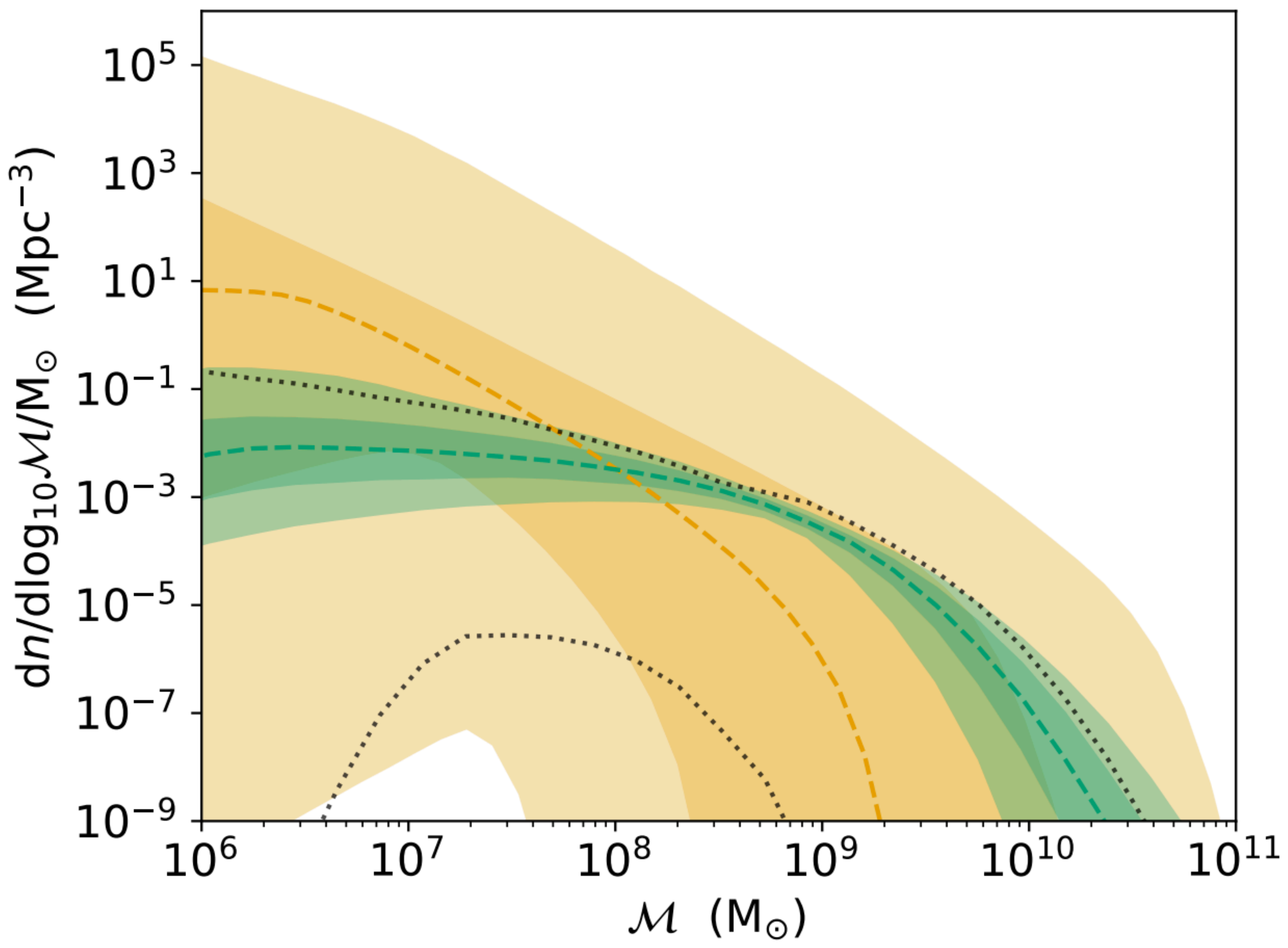
number density of sources per unit redshift per chirp mass interval

Population Inference

The number density of SMBHBs can be related to the merger rate:

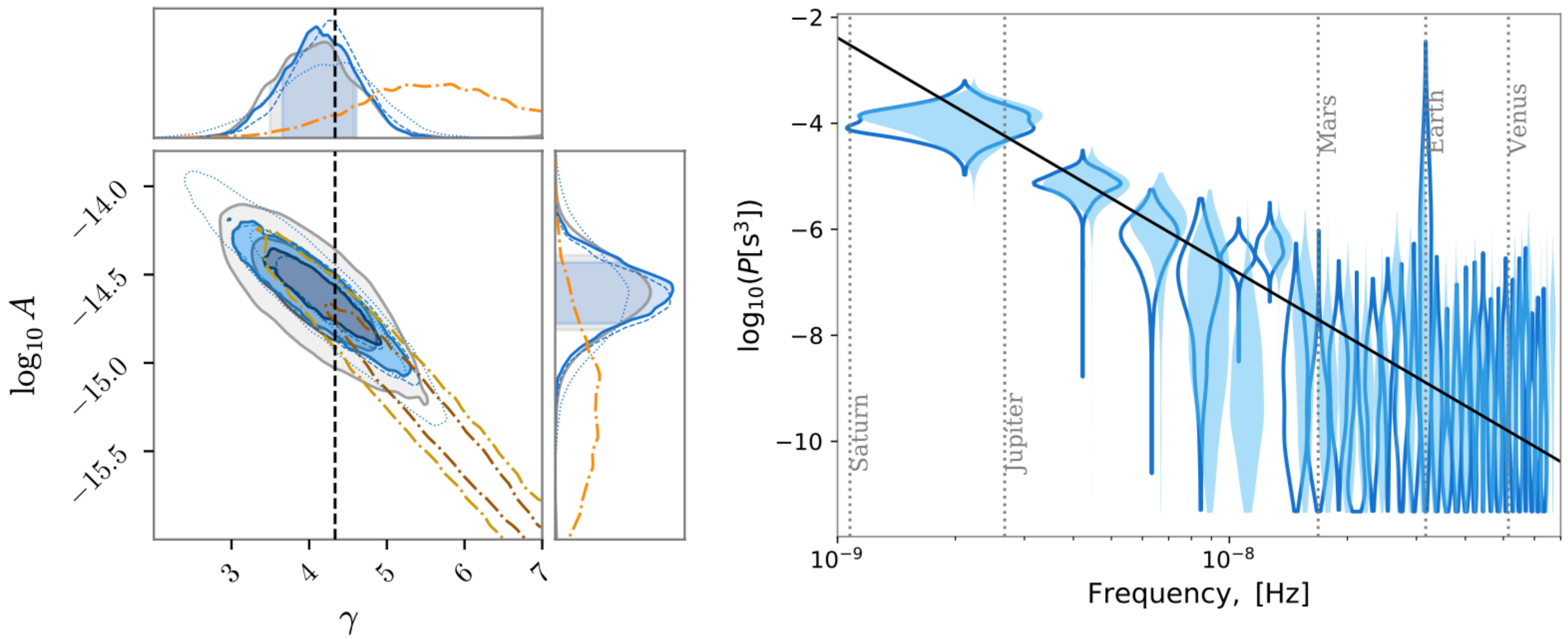
$$\frac{d^2n}{dz\, d\log_{10}\mathcal{M}} = \dot{n}_0 \frac{dt_R}{dz}\left[(1+z)^{\beta_z}\exp^{-z/z_0}\right]\frac{dn}{d\mathcal{M}}(\alpha, \mathcal{M}_*)$$



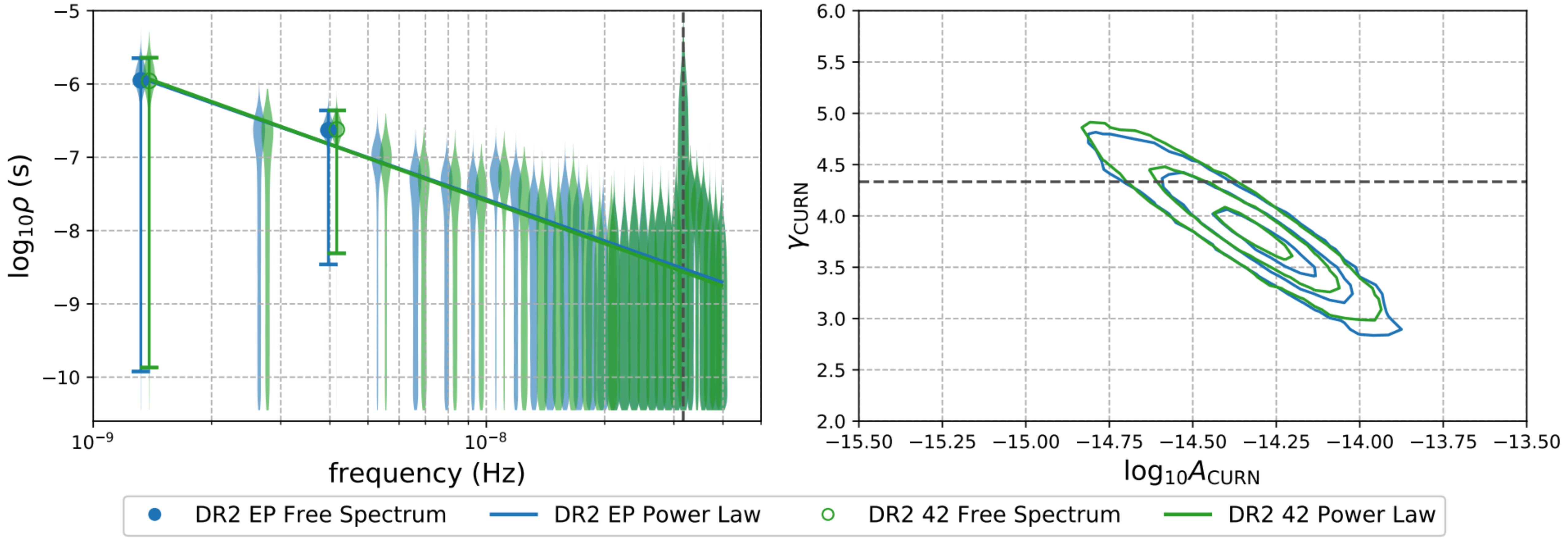


Middleton et al., MNRASL 502, 1 (2021)

Other PTAs are also see a similar common spectrum process in their recent data sets.



PPTA DR2, B. Goncharov et al., ApJL 917, L19 (2021)

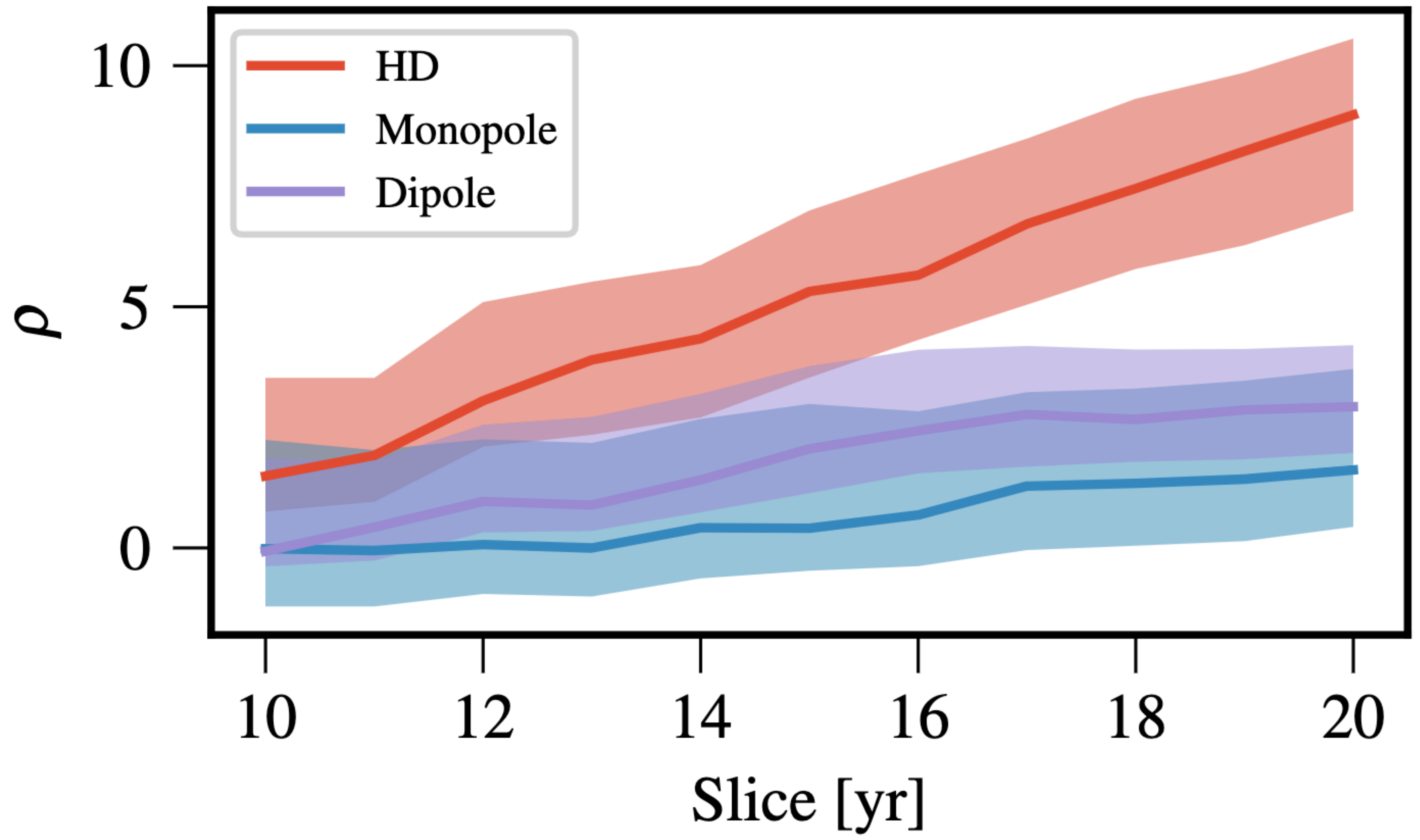


EPTA DR2, S. Chen et al., MNRAS 508 (2021)

What to Expect When You're Expecting a GWB

If what we are seeing is the GWB, we expect the significance of the spatial correlations to increase over the next several years (Siemens et al. 2013)

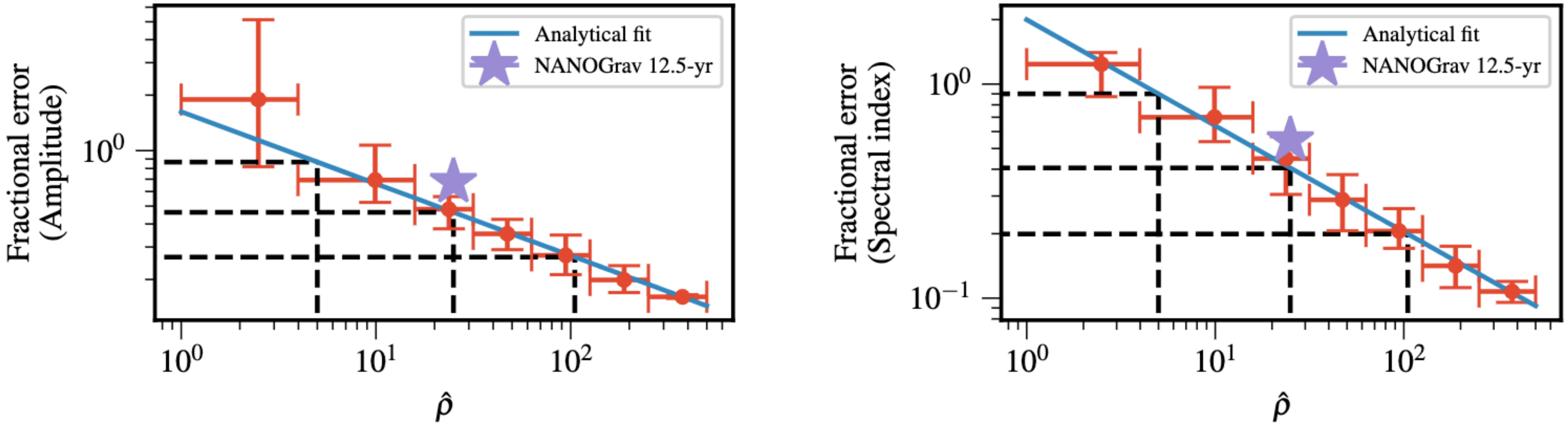
$$\langle \rho \rangle = \begin{cases} N_{\text{psrs}}\, T^{\gamma} & \text{(weak signal regime)} \\ N_{\text{psrs}}\, T^{1/2} & \text{(intermediate signal regime)} \end{cases}$$



N. S. Pol et al., ApJL 911, 34 (2021)

What to Expect When You're Expecting a GWB

If what we are seeing is the GWB, measurement of the amplitude and spectral index of the GWB will improve as the SNR increases.



N. S. Pol et al. (2021)

Individual SMBHBs

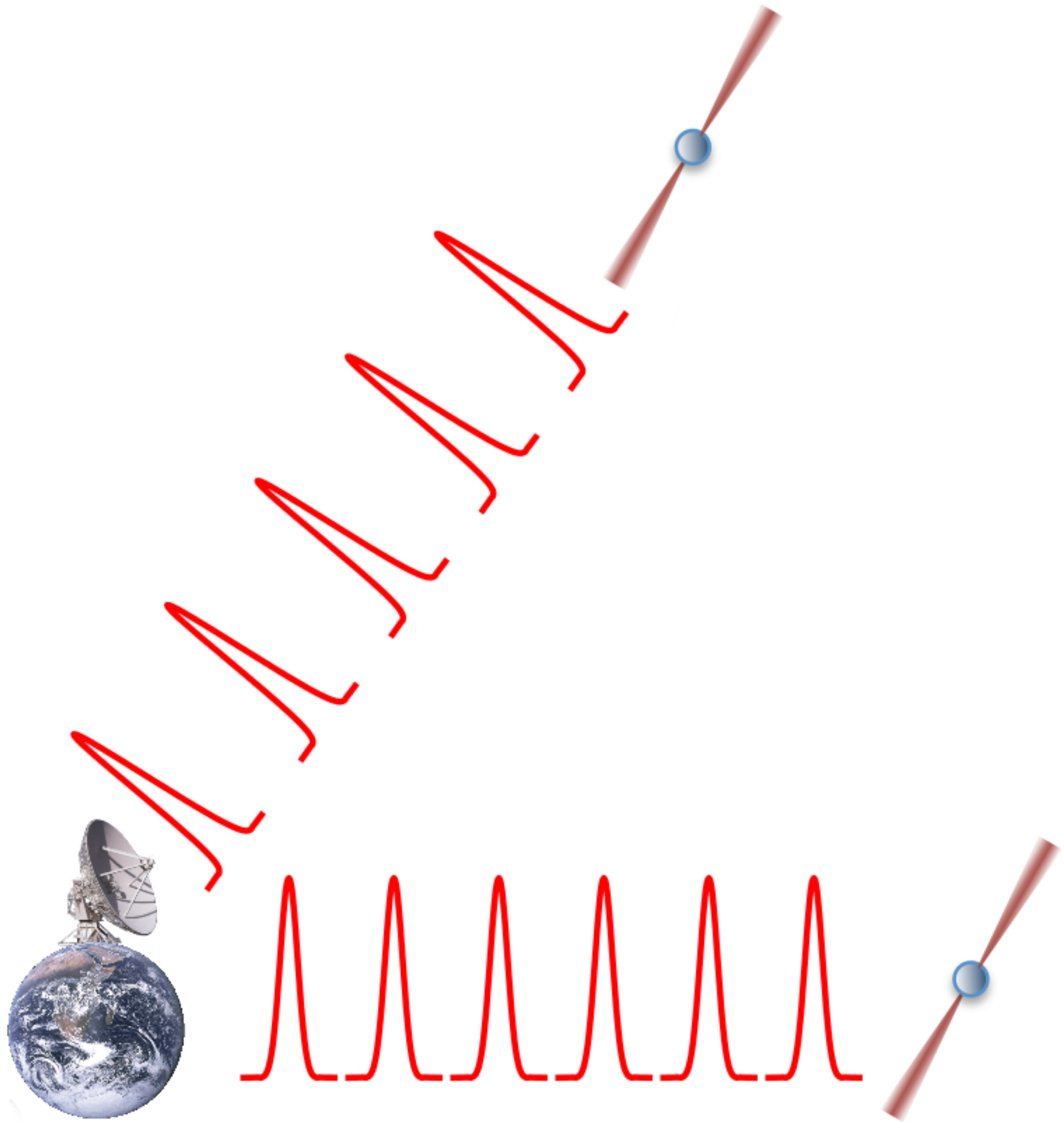
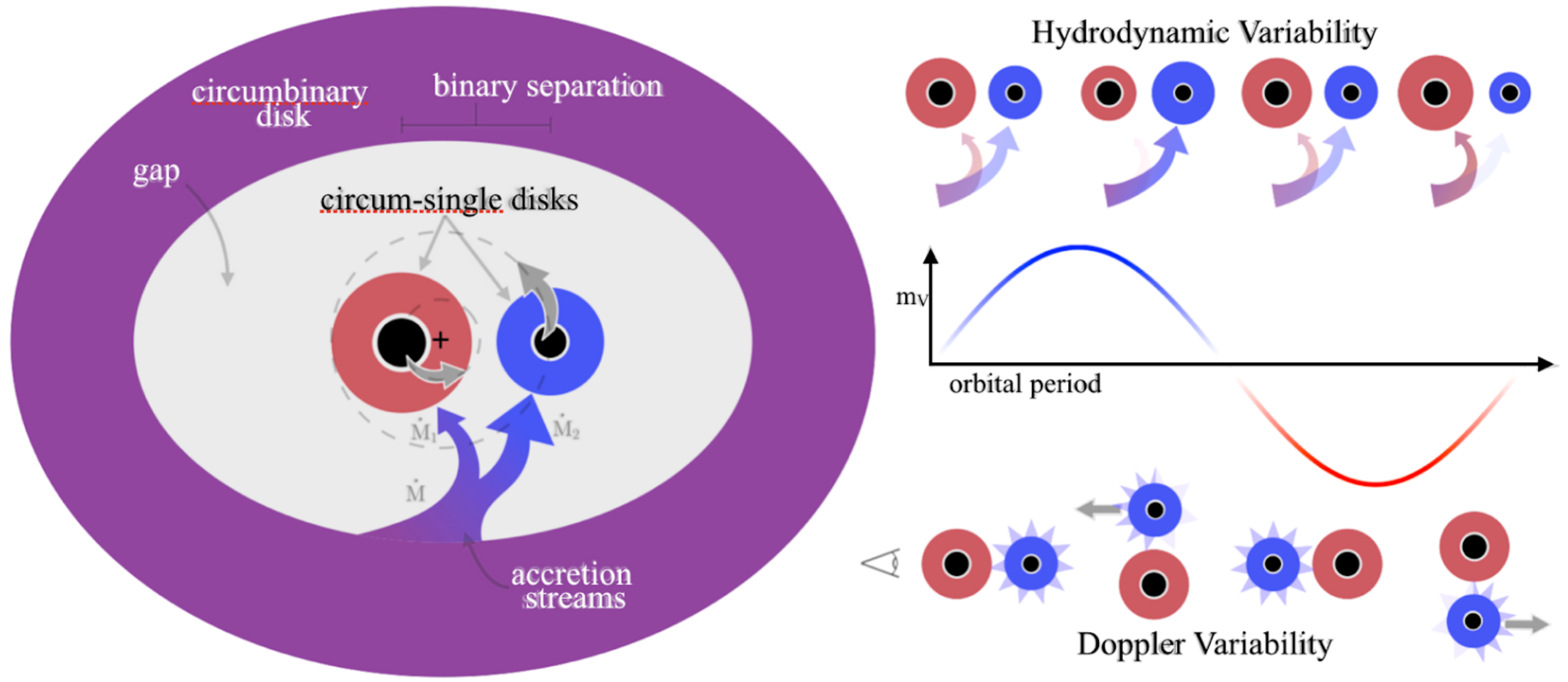


Figure credit: NANOGrav (modified)

Binary candidates can be identified by looking for light curve periodicities



Kelley et al. (2018), arXiv:1809.02138

Individual SMBHBs (“Continuous Waves”)

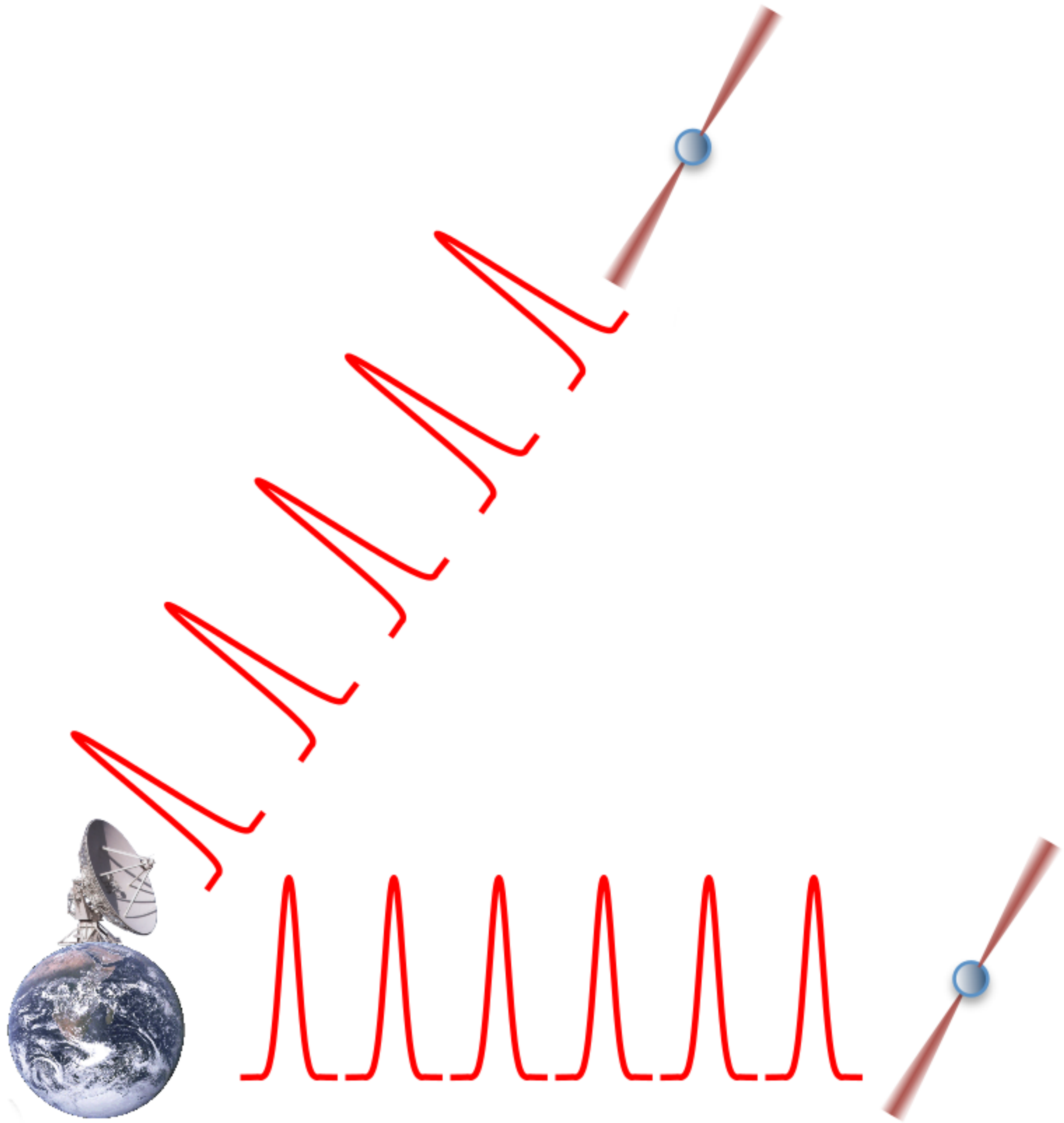
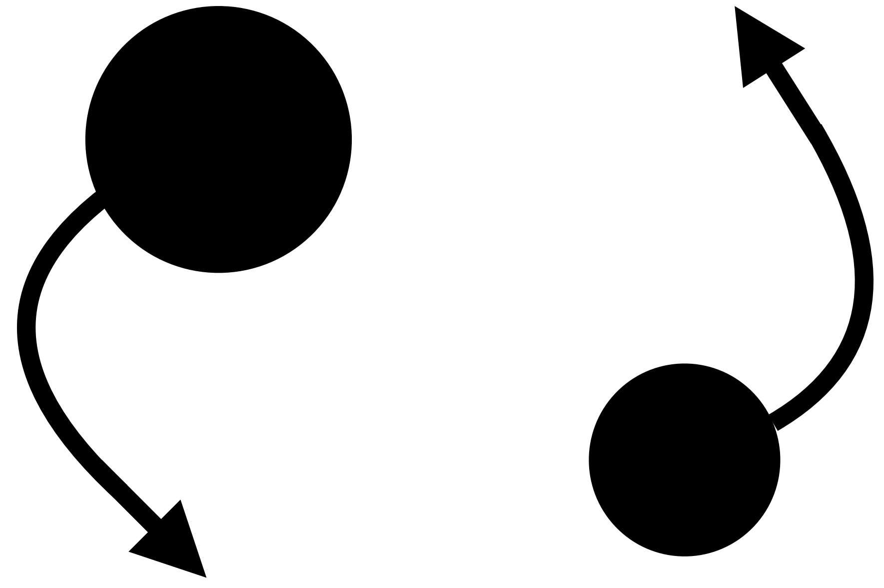


Figure credit: NANOGrav (modified)



$$s_{+,\times} = F^{+,\times}(\hat{\Omega})\ \left[s_{+,\times}(t_p) - s_{+,\times}(t_e)\right]$$

pulsar term

Earth term

Individual SMBHBs ("Continuous Waves")

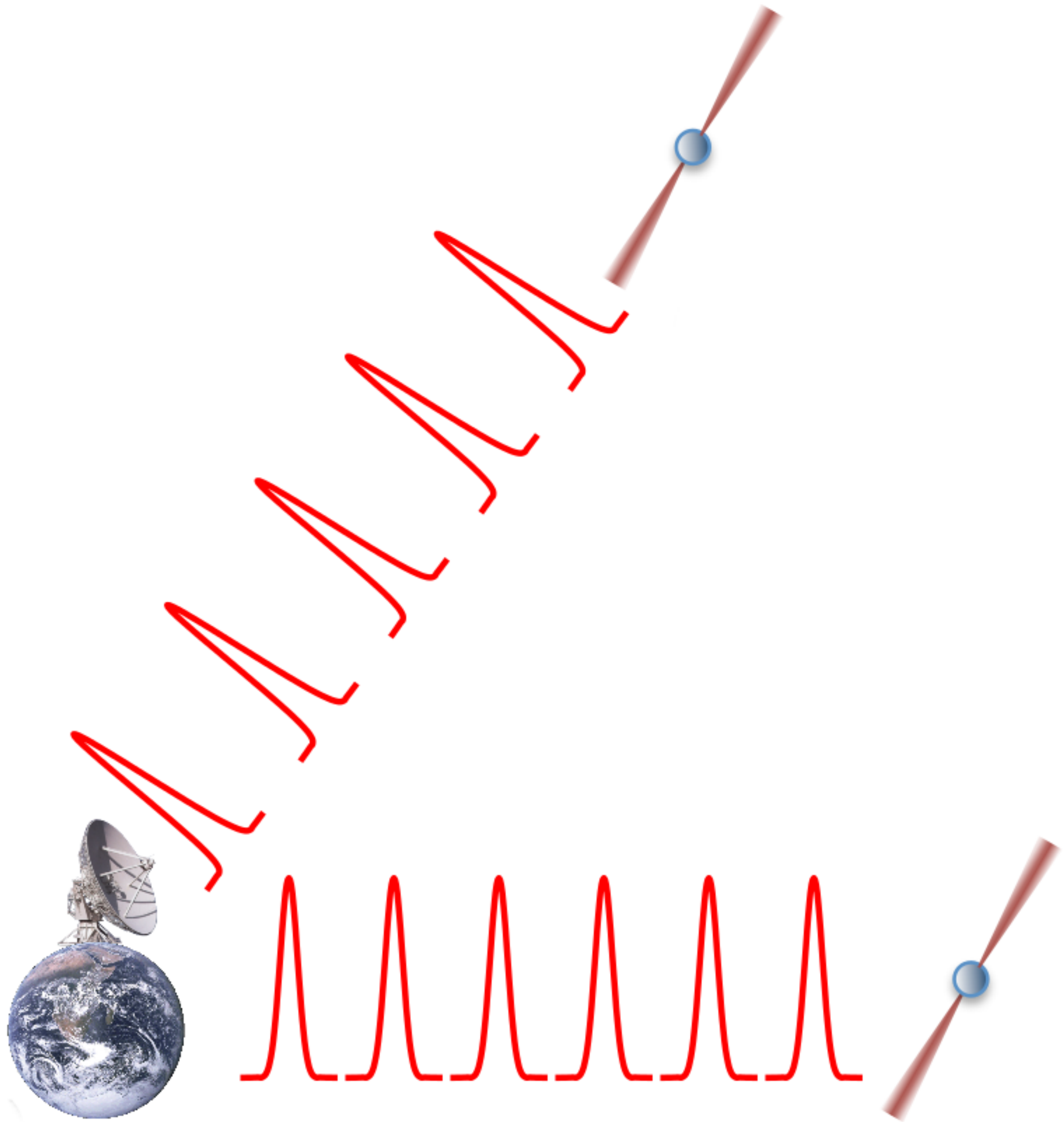
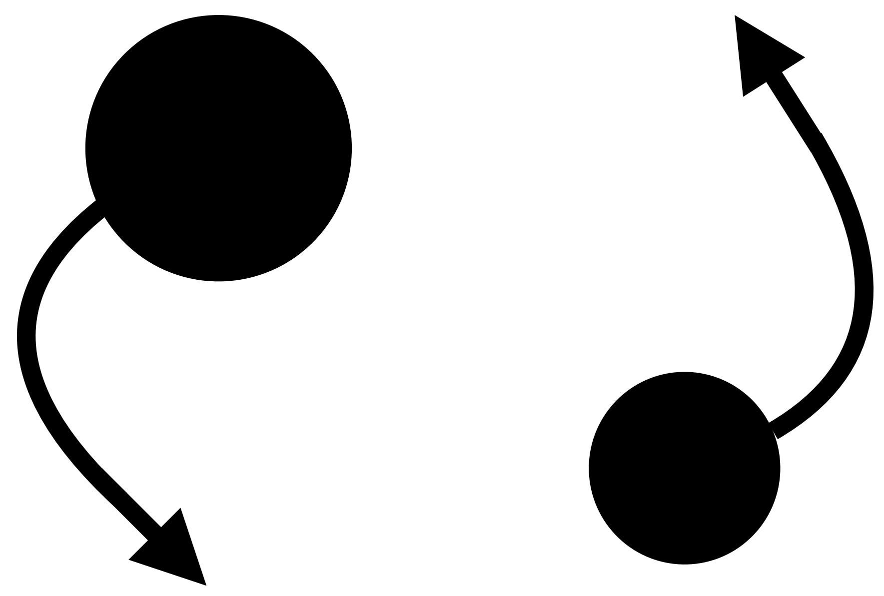


Figure credit: NANOGrav (modified)

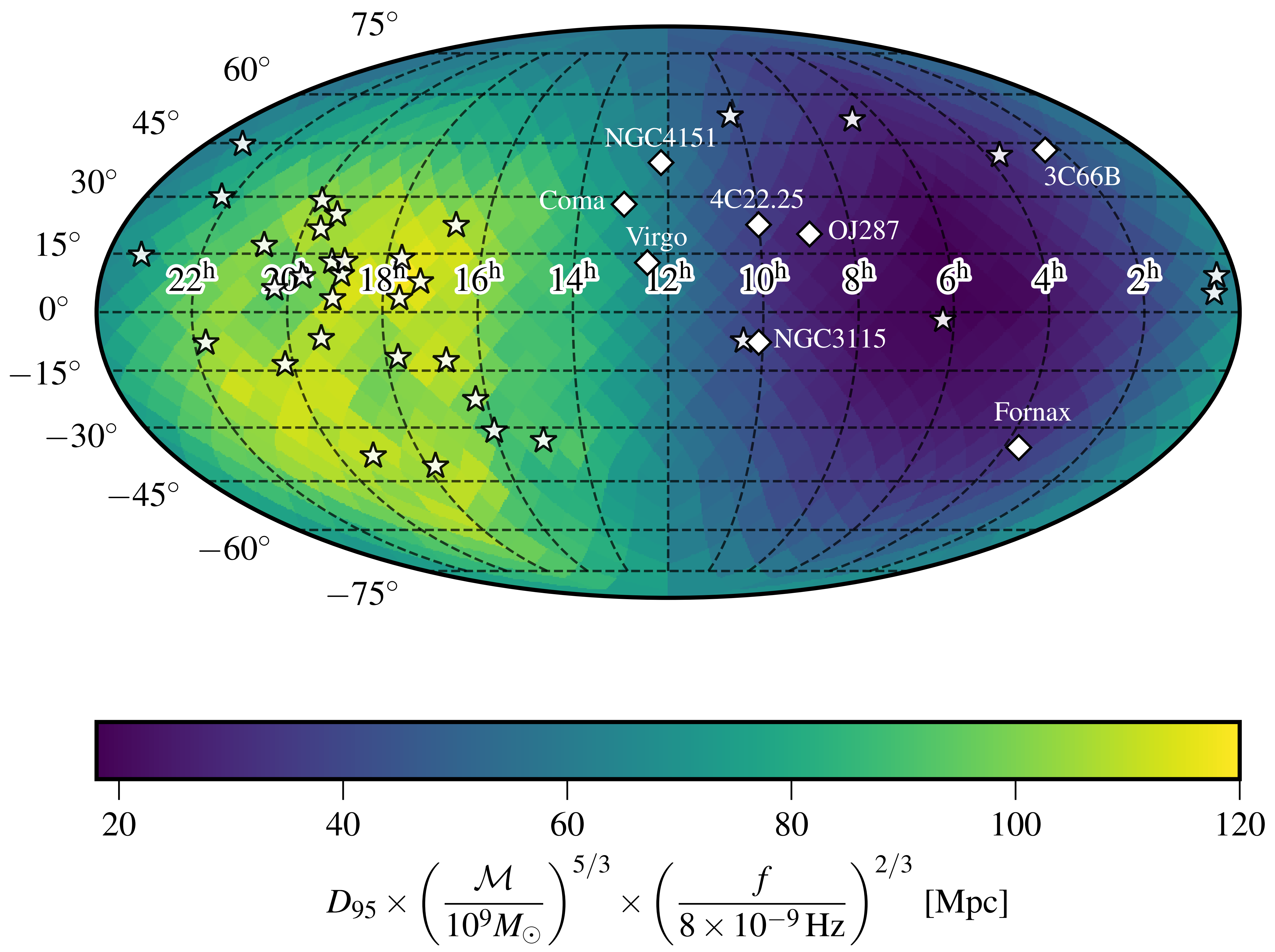


$$s_{+,\times} = F^{+,\times}(\hat{\Omega})\ \left[s_{+,\times}(t_p) - s_{+,\times}(t_e)\right]$$

$$t_p = t_e - L\left(1 + \hat{\Omega}\cdot\hat{p}\right)$$

$$\omega(t) = \omega_0\left[1 - \frac{256}{5}\mathcal{M}^{5/3}\omega_0^{8/3}(t - t_0)\right]^{-3/8}$$

Limits on Individual SMBHBs



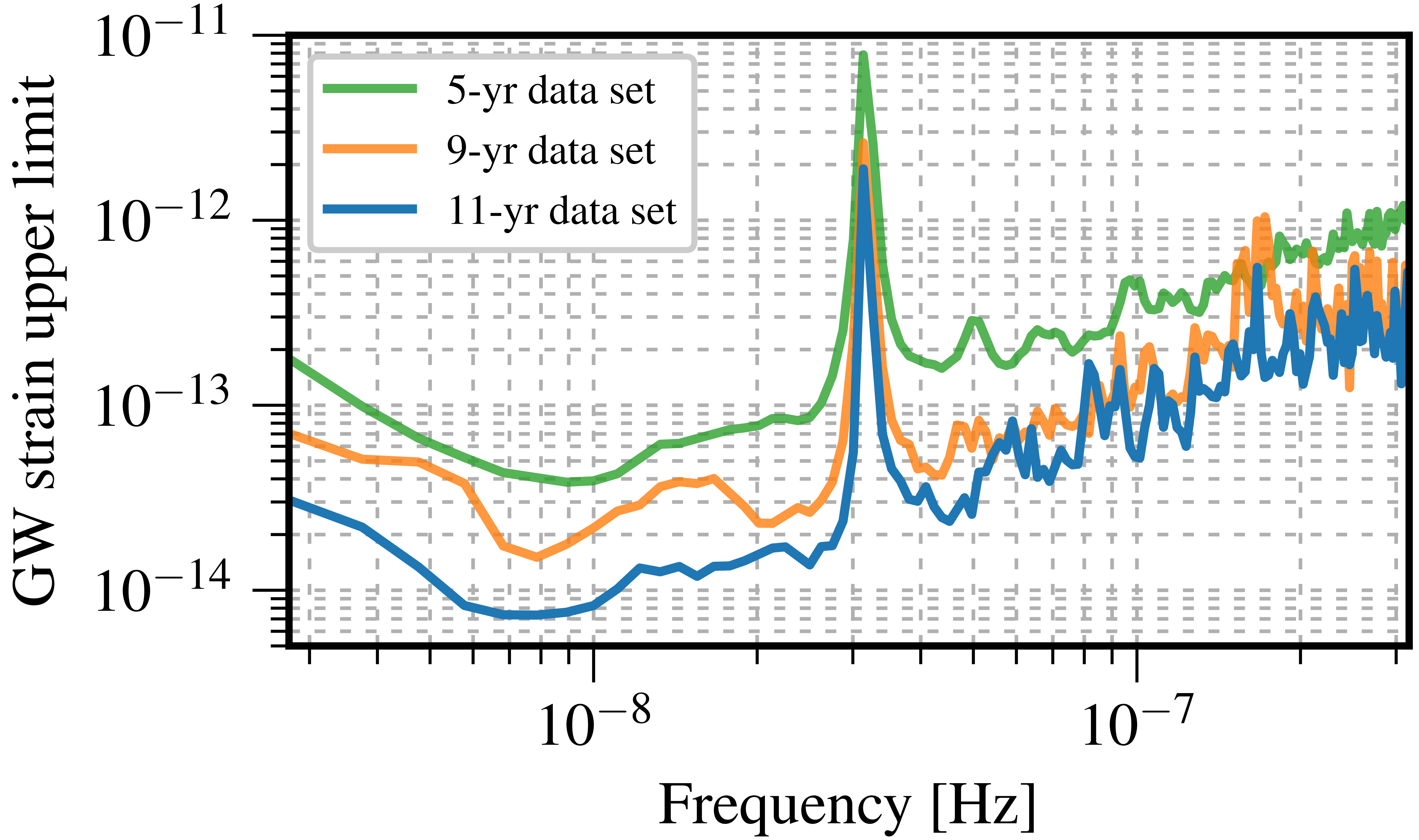
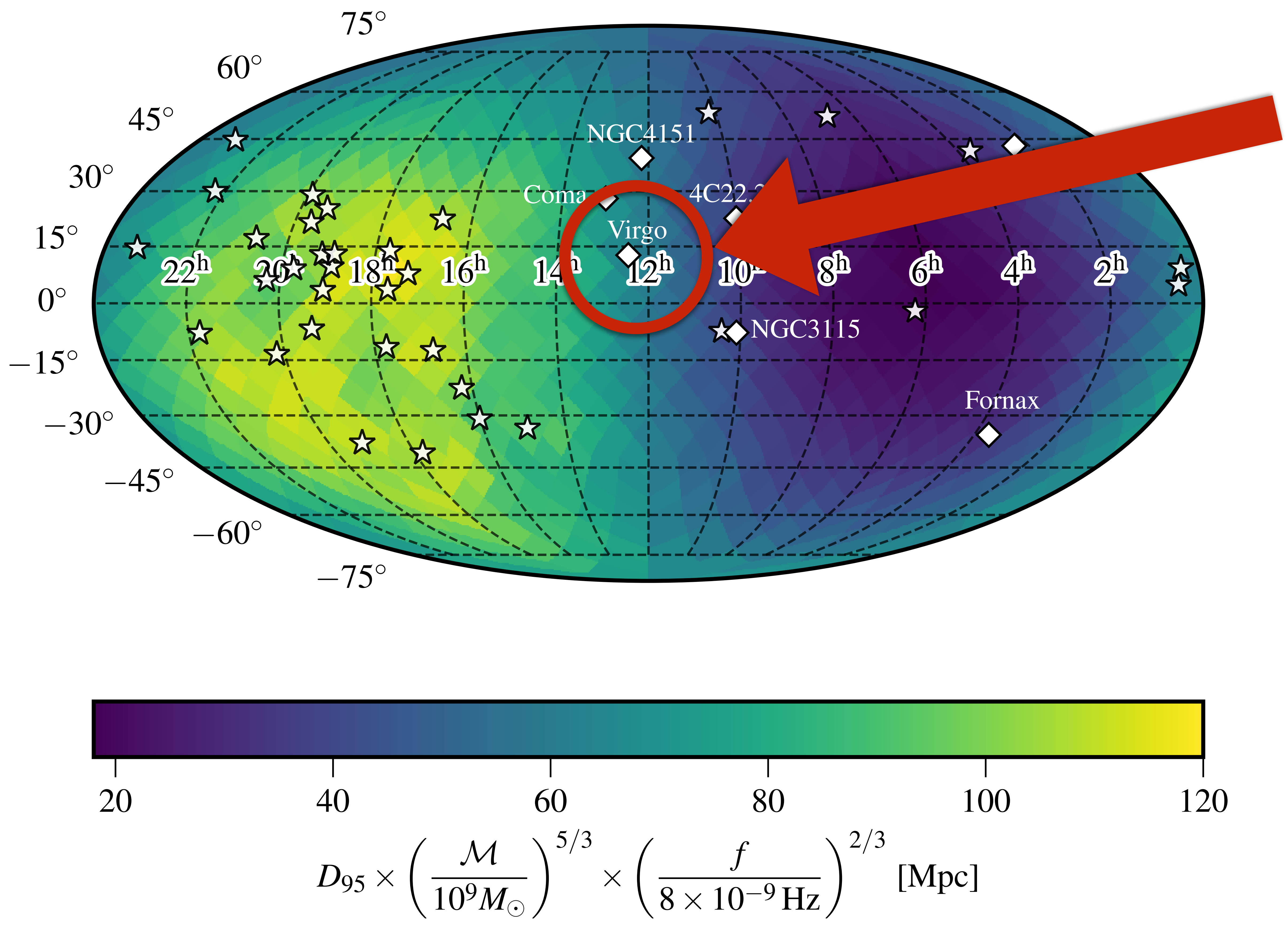


Figure credit: K. Aggarwal et al., ApJ 880, 2 (2019)
Lead author S. J. Vigeland

Limits on Individual SMBHBs



There are no SMBHBs in the Virgo Cluster with $\mathcal{M} > 1.6 \times 10^9$ $M_\odot$.

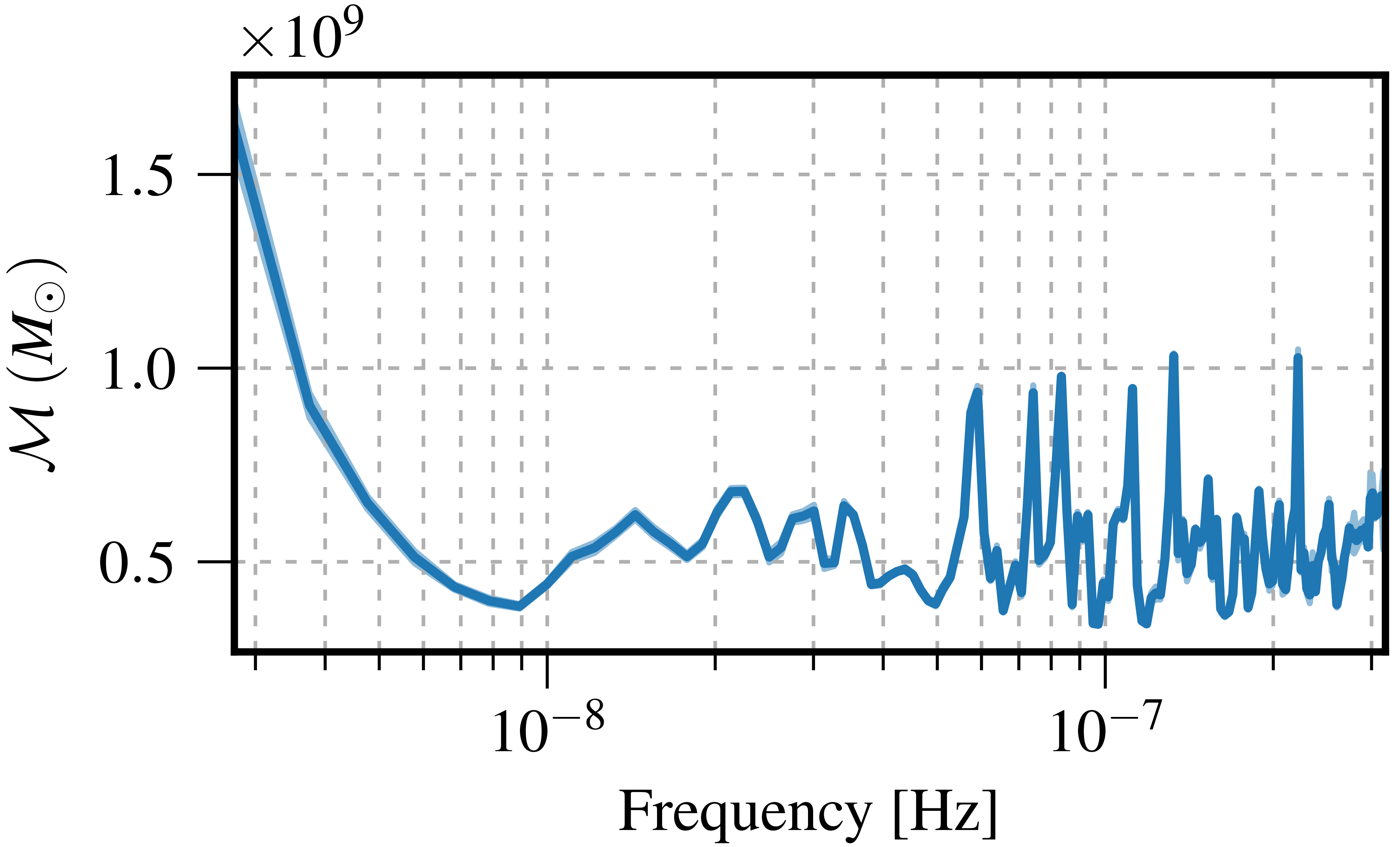


Figure credit: K. Aggarwal et al. (2019)

Constraints on Galaxy Mergers

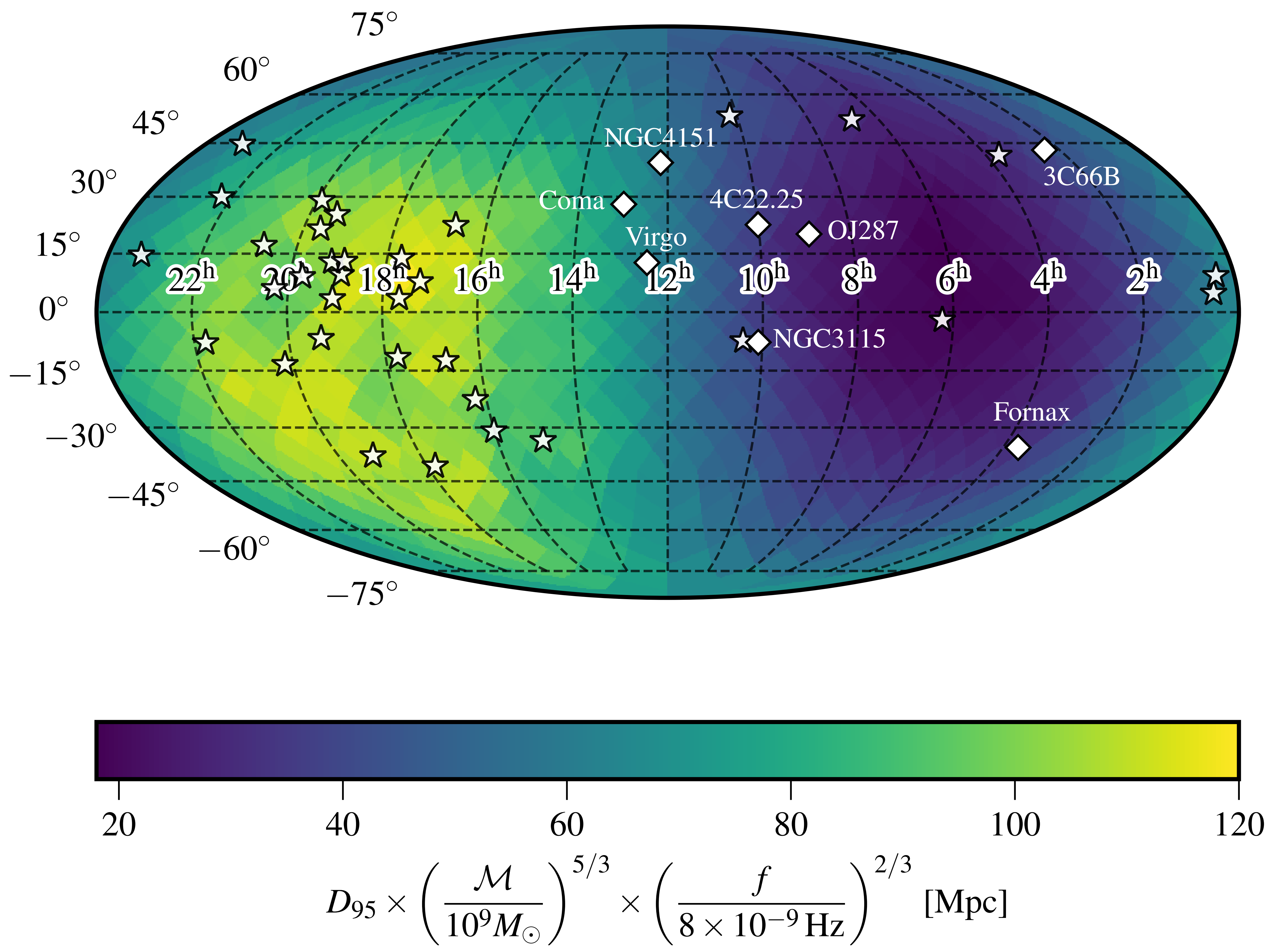


Figure credit: K. Aggarwal et al. (2019)

Major mergers involve two galaxies of similar masses. The resulting SMBBH will have a large mass ratio (q > 0.25).

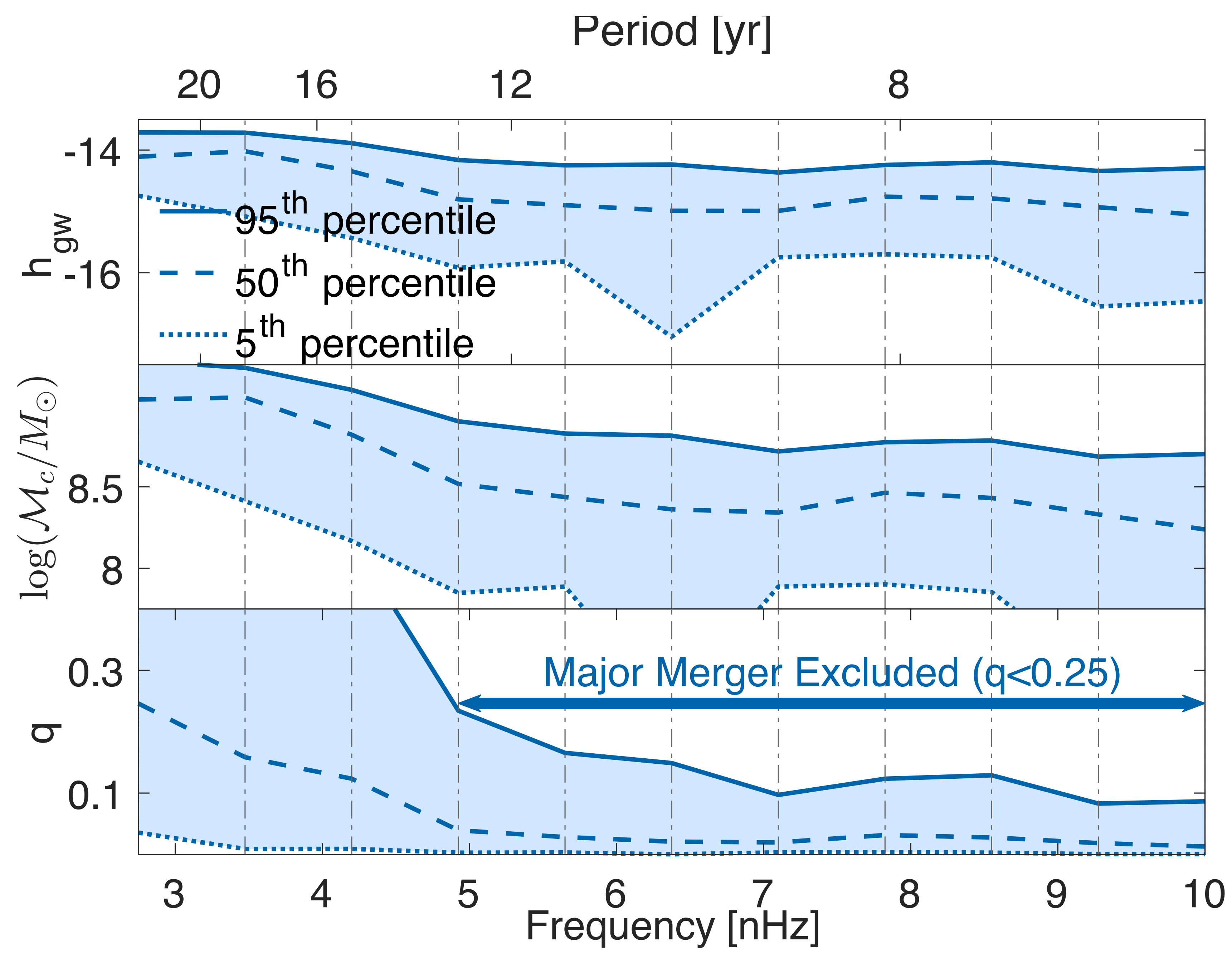


Figure credit: Z. Arzoumanian et al., ApJ 914, 2 (2021).
Lead author: M. Charisi

Conclusions

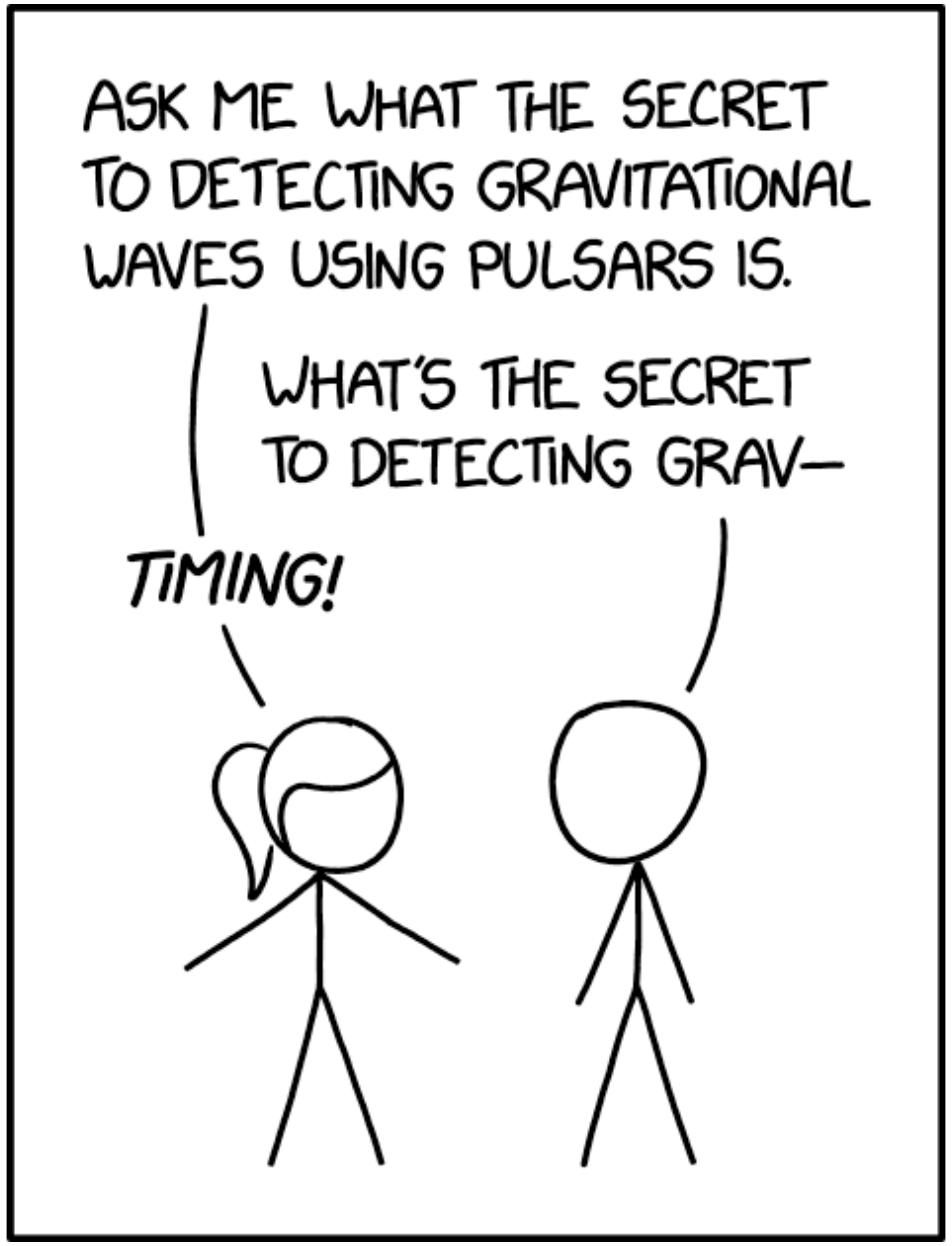


Figure credit: xkcd

- PTAs are sensitive to nanohertz GWs inaccessible to ground-based or space-based interferometers.

- PTAs are already putting constraints on the astrophysical properties of nearby SMBBHs.

- The most recent data from NANOGrav, the PPTA, and the EPTA show evidence for a common stochastic signal; however, there is not yet evidence for the spatial correlations characteristic of the GWB.