Pulsar Timing Arrays: The Next Window to Open on the Gravitational-Wave Universe

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[on behalf of Chiara Mingarelli and the NANOGrav collaboration]

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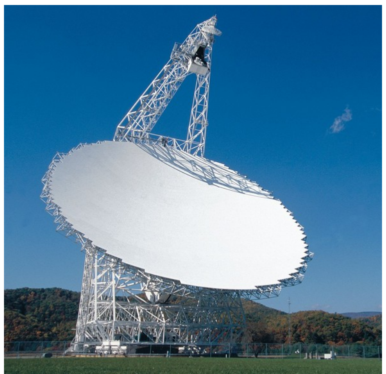
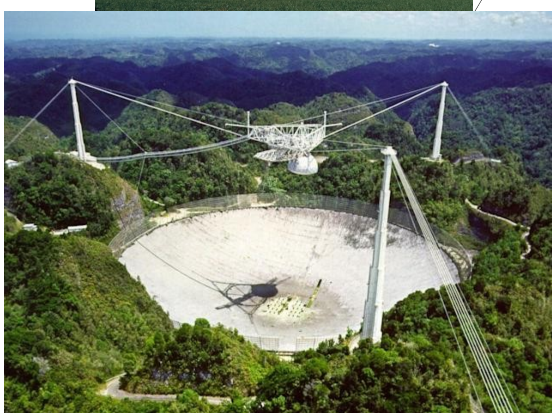
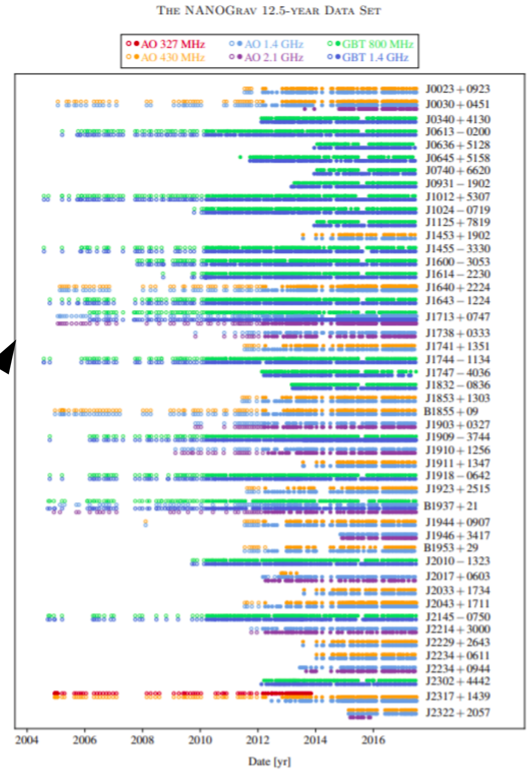
NANOGrav Physics Frontiers Center

Observation/Timing from Green Bank and Arecibo (VLA and CHIME to come)

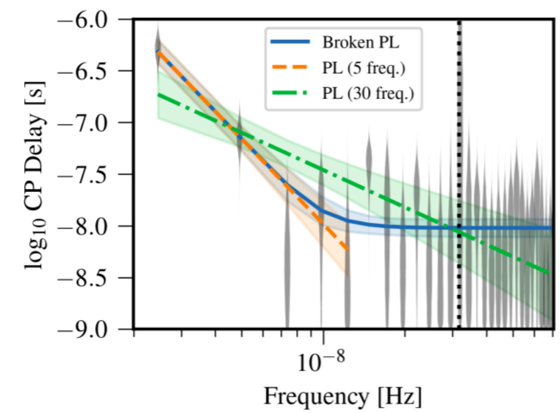


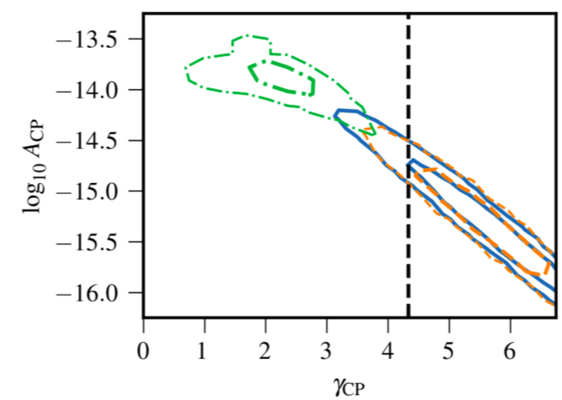




Pulsar Timing Array

Data analysis

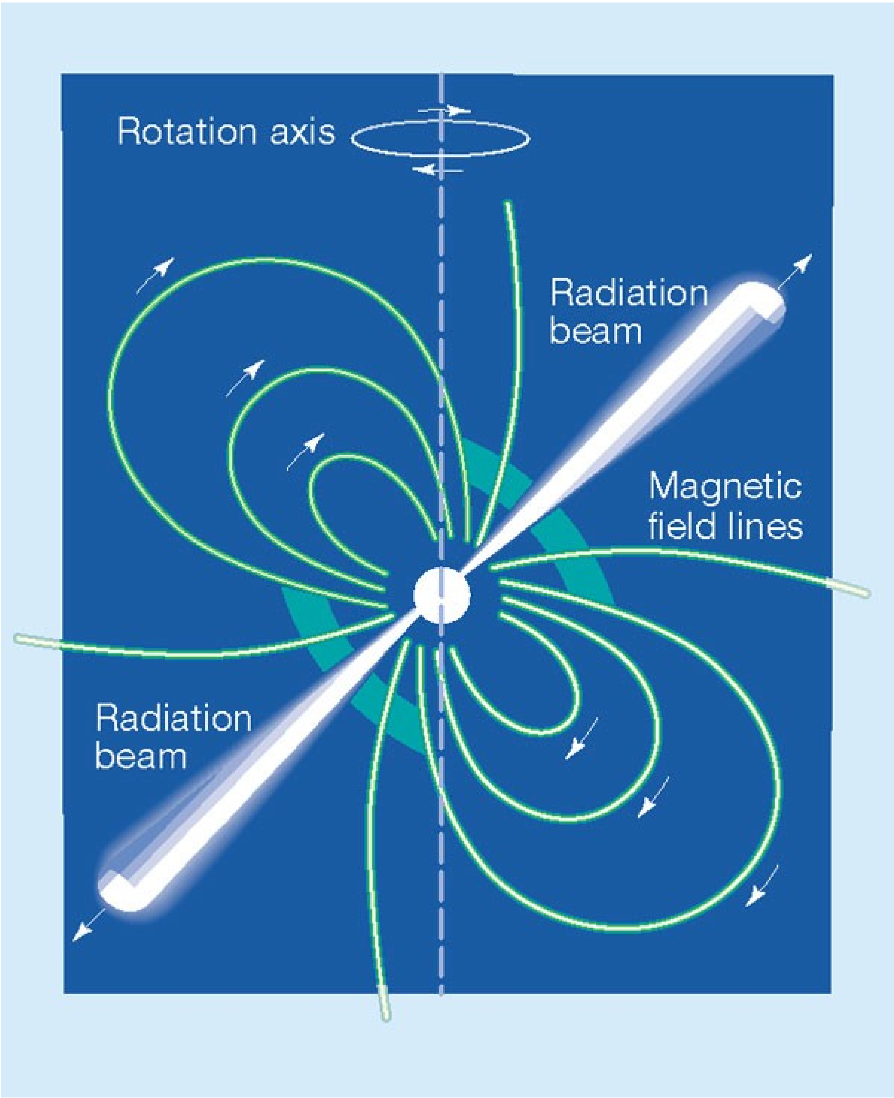


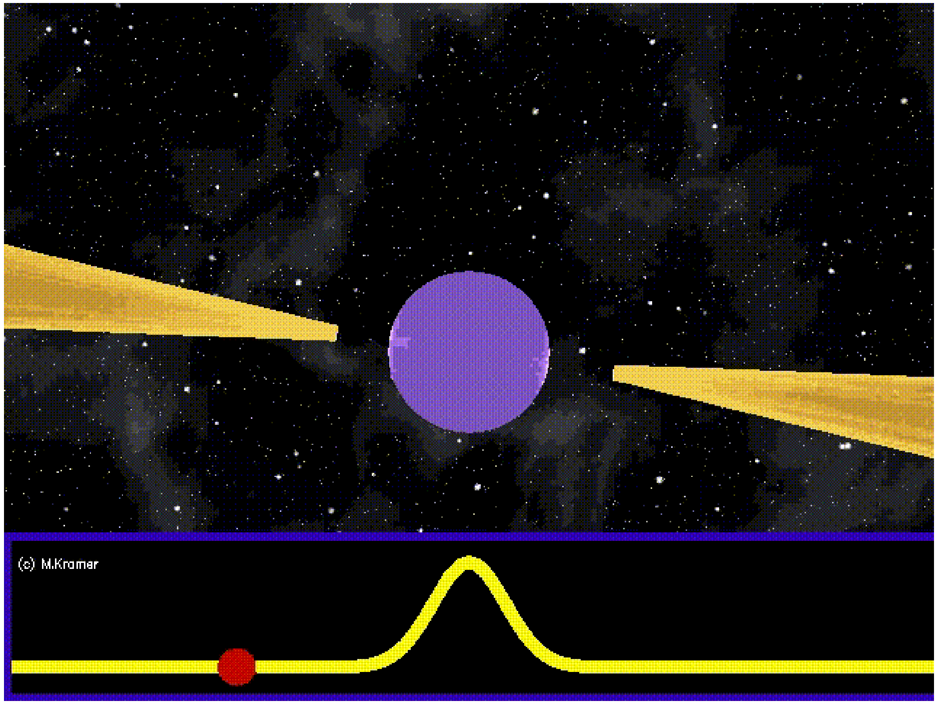


Motivation/ Scientific Impact

Astrophysical Interpretation

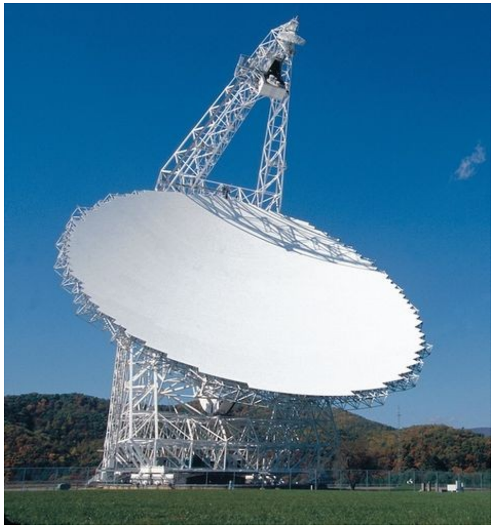
Pulsar Timing

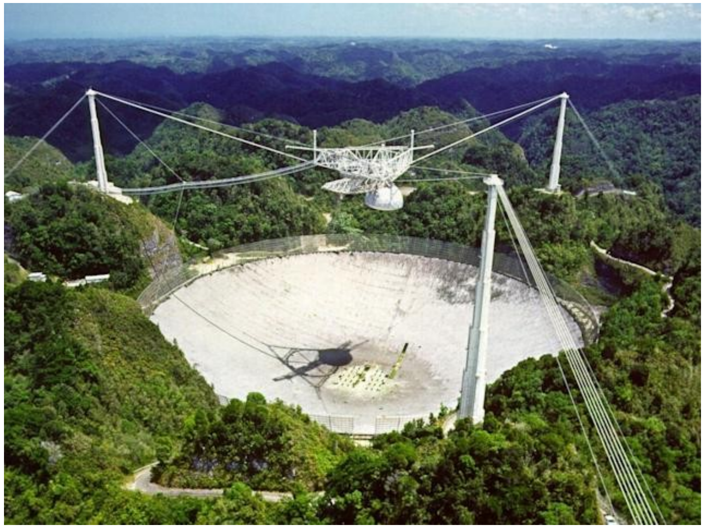


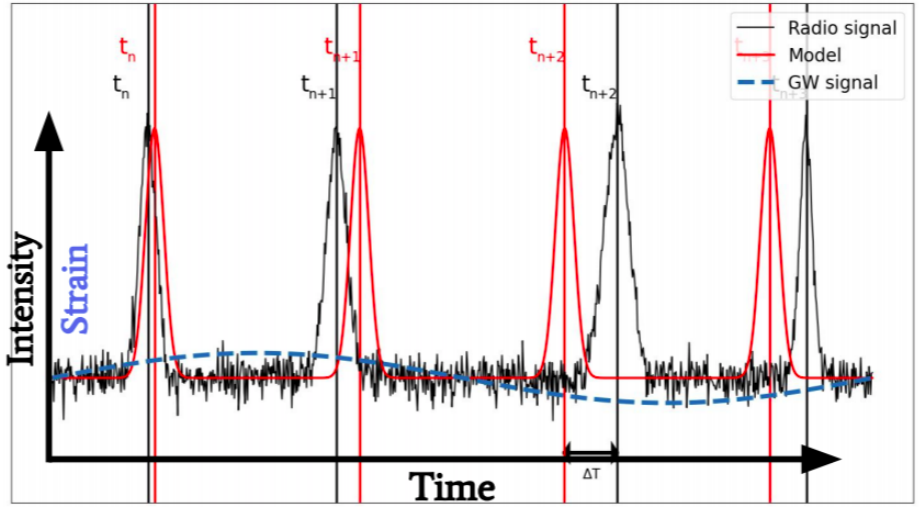


Credits: M. Kramer

Pulsar Timing

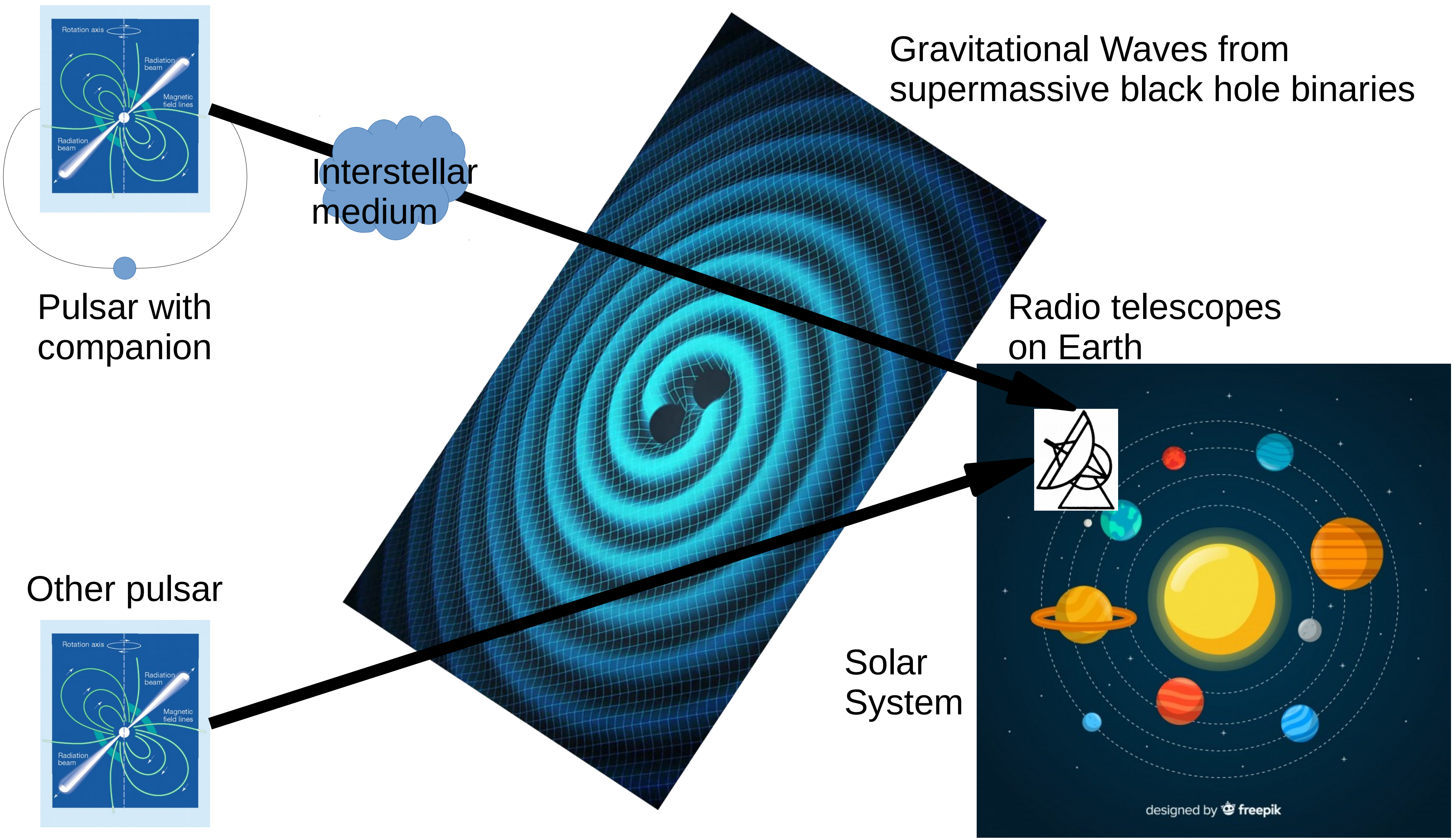




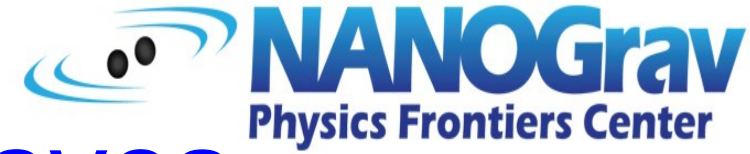


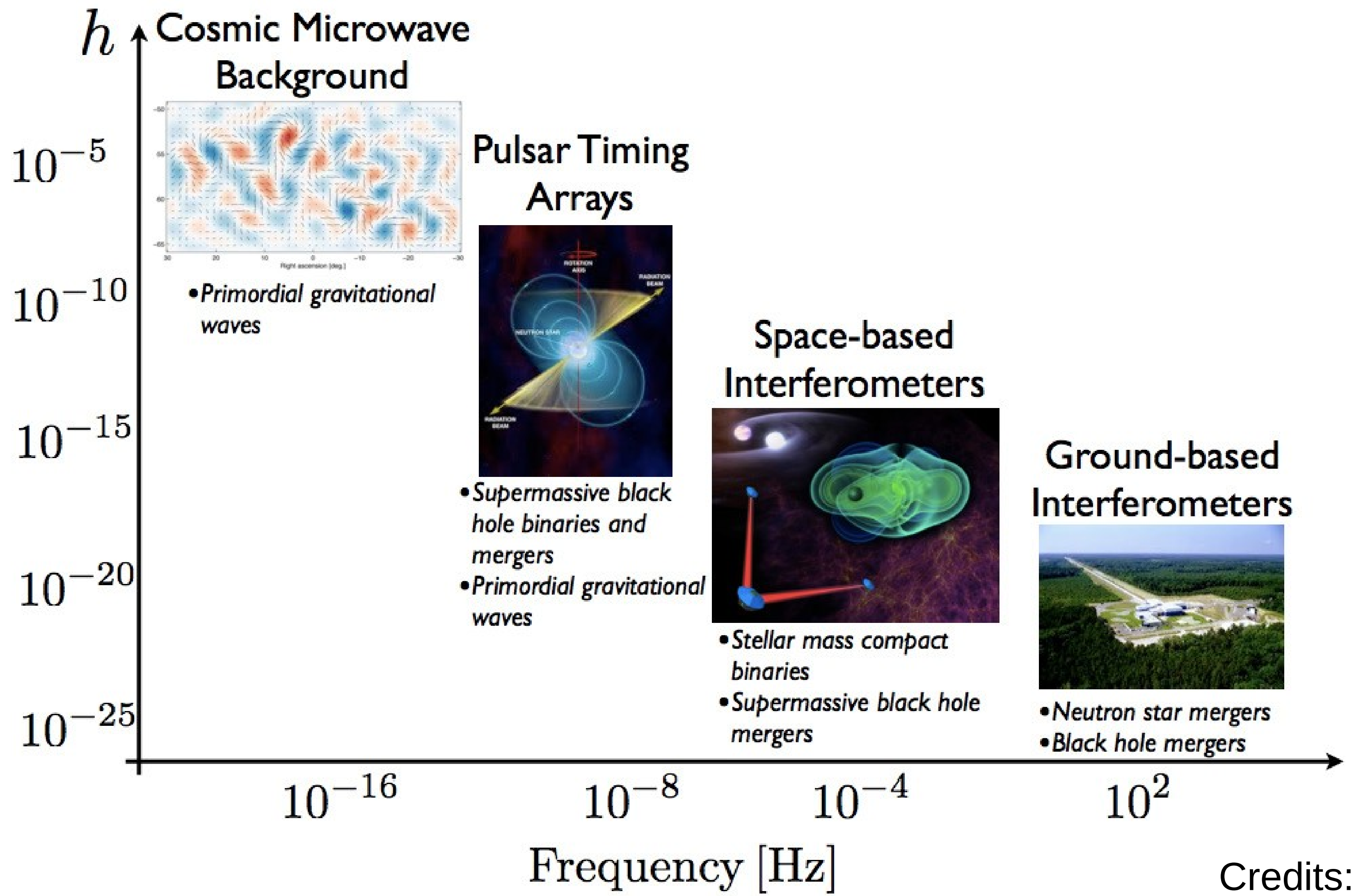
Credits: M. Falxa

Gravitational Waves



Gravitational Waves





Credits: SKA

Types of noise

Model all noises/signals as Gaussian processes to simplify likelihood computation:

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

Note: timing model marginalized

$$\Sigma^{\alpha} = \Sigma^{\alpha}_{WN} + \Sigma^{\alpha}_{RN} + \Sigma^{\alpha}_{DM} + \Sigma^{\alpha\beta}_{GW}$$

white noise: $S_{WN} = E^2(\sigma^2 + Q^2) + C$

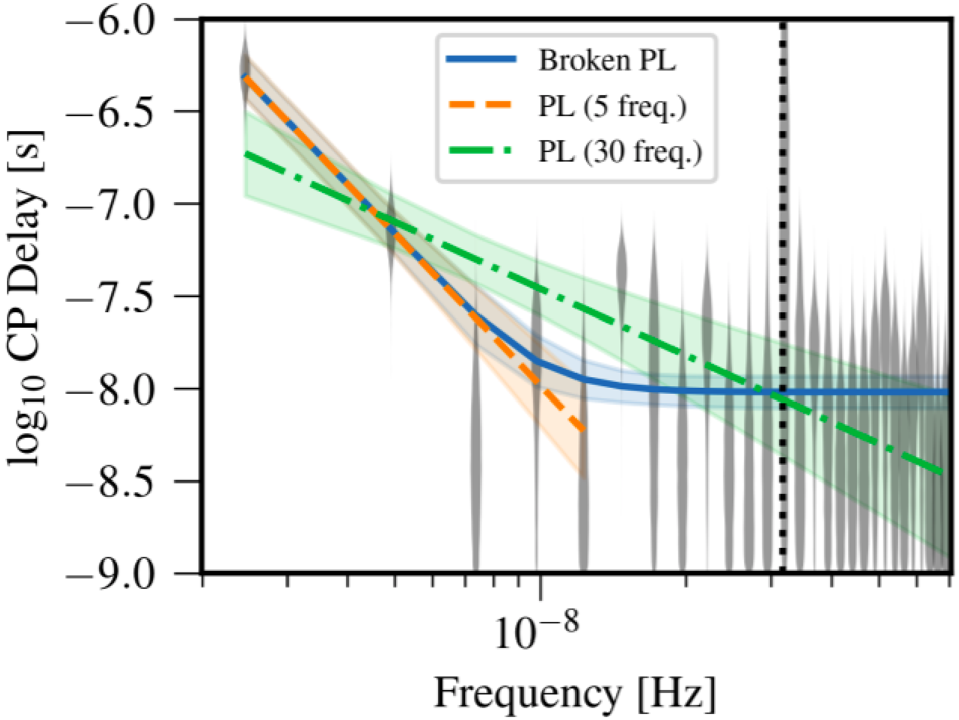
red noise: $S_{RN} = A^2_{RN} f^{-\gamma_{RN}}$

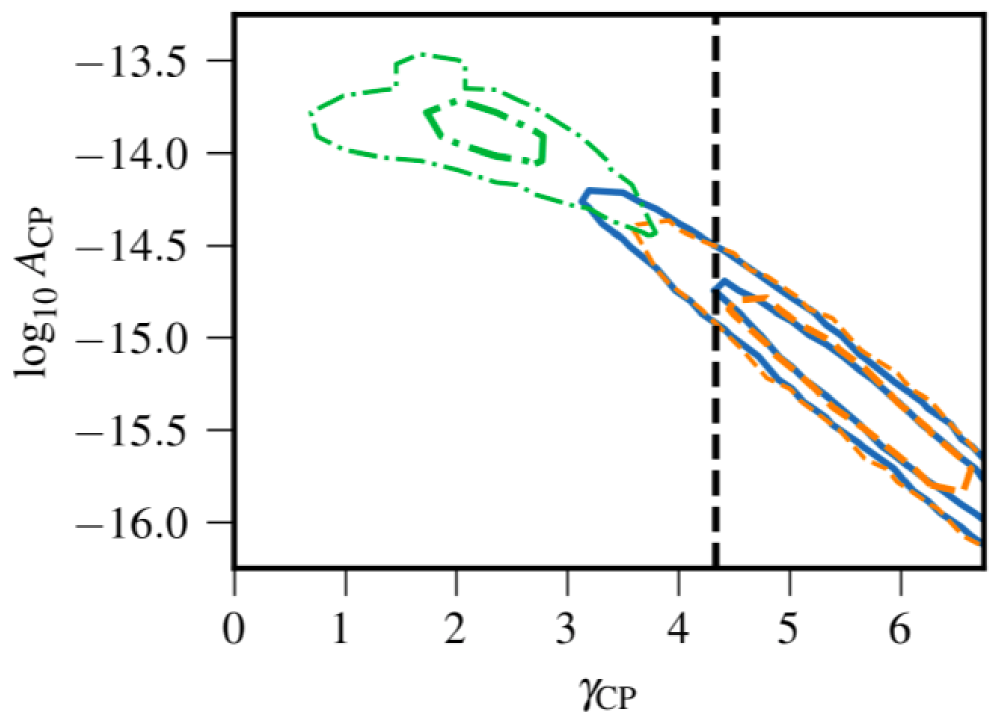
dispersion measure: $S_{DM} = \frac{K_{DM}}{\nu^2} A^2_{DM} f^{-\gamma_{DM}}$

gravitational waves: $S_{GW} = \Gamma_{\alpha\beta} A^2_{GW} f^{-\gamma_{GW}}$

Van Haasteren & Vallisneri 2014

Common process – NANOGrav 12.5



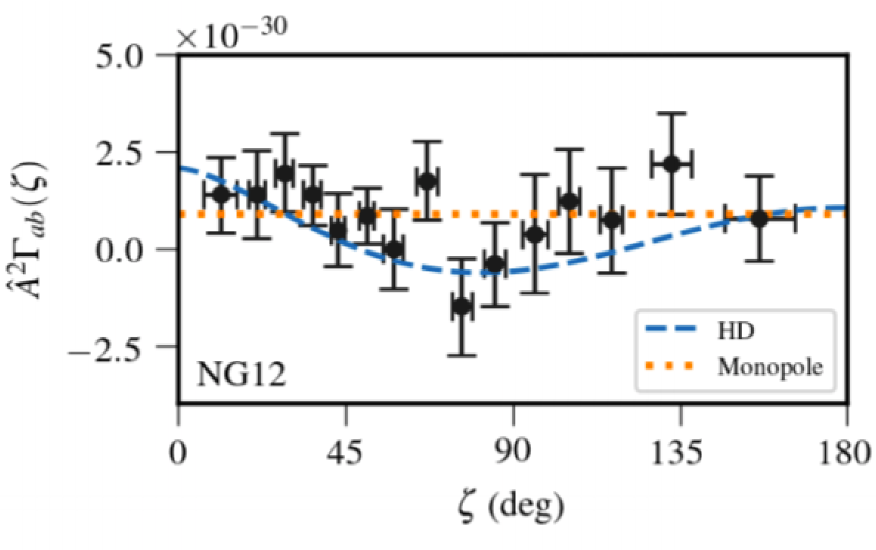


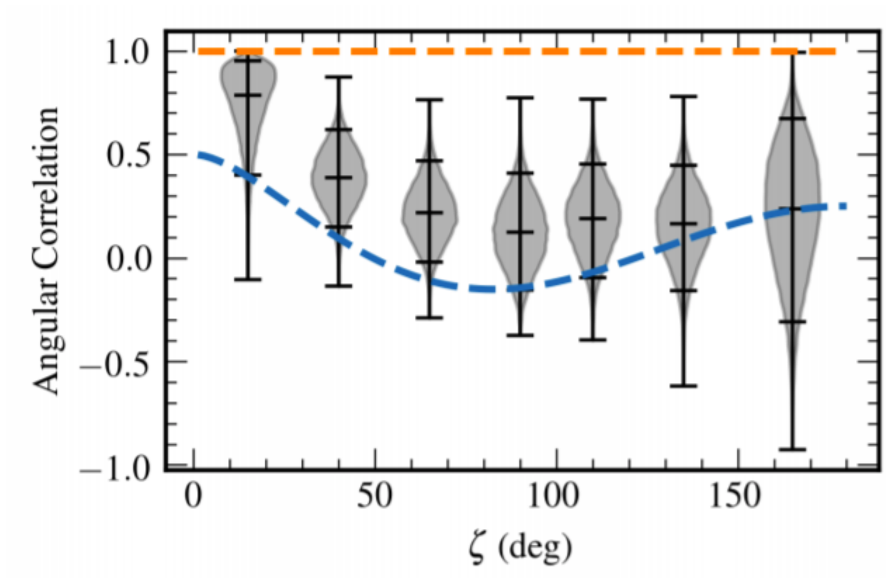
$$S_{ij}(f) = \Gamma_{ij} \frac{h_c^2}{12\pi^2 f^3} \qquad h_c(f) = A_{\rm GWB} \left(\frac{f}{f_{\rm yr}}\right)^{\alpha} \qquad \gamma = 3 - 2\alpha$$

At fixed γ = 13/3, amplitude: 1.9 +/– 0.6 e-15 (at 1/yr)

NANOGrav (Simon) 2020

Hellings-Downs correlation – NANOGrav 12.5





S/N ~ 1

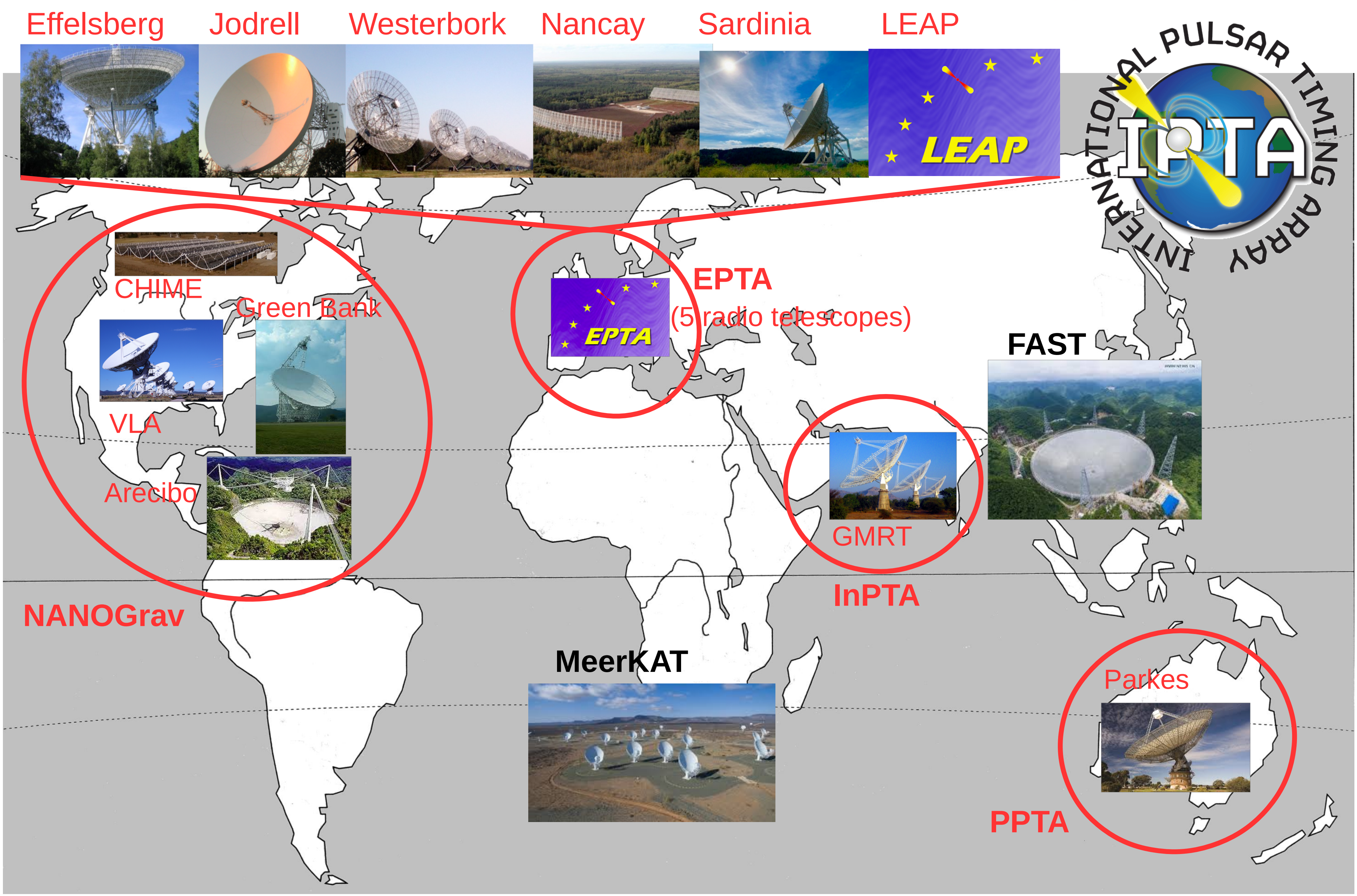
Bayes factor ~ 4.4

Evidence for HD correlation is not significant → No detection of GWs !

NANOGrav (Simon) 2020

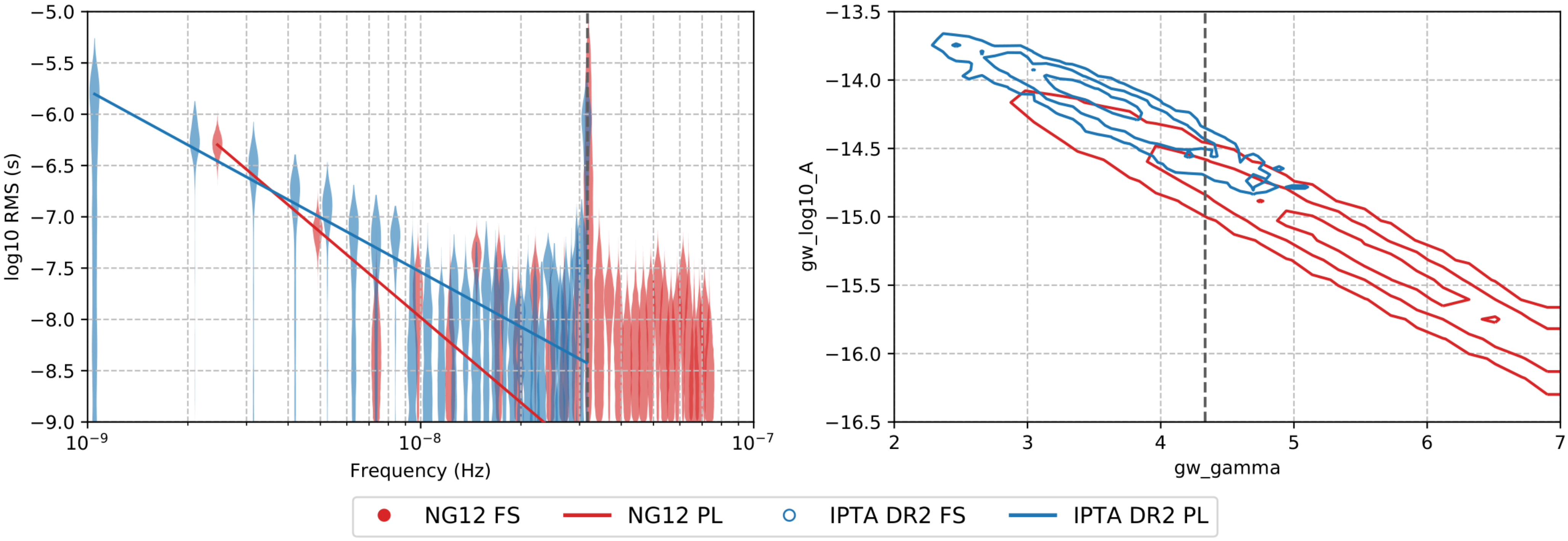
The International Pulsar Timing Array

NANOGrav
Physics Frontiers Center



Common process – IPTA DR2

PRELIMINARY

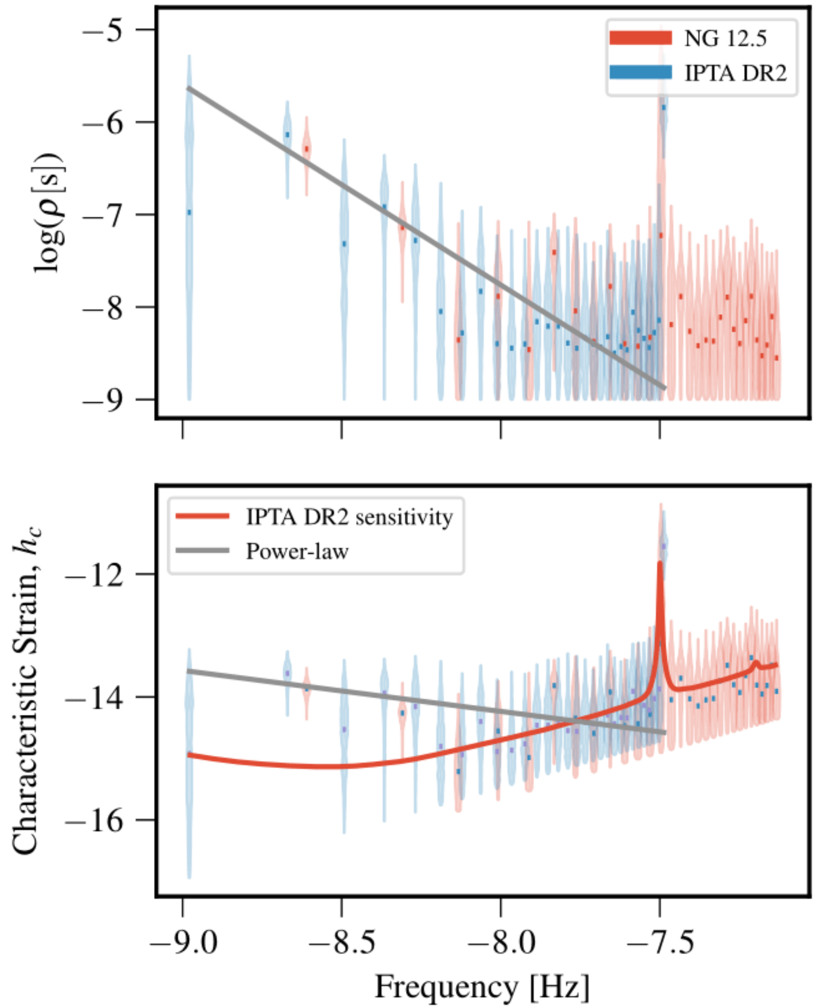


NG12: At fixed γ = 13/3, amplitude: 1.9 +/– 0.6 e-15 (at 1/yr)
IPTA DR2:At fixed γ = 13/3, amplitude: 2.8 +/– 0.8 e-15 (at 1/yr)

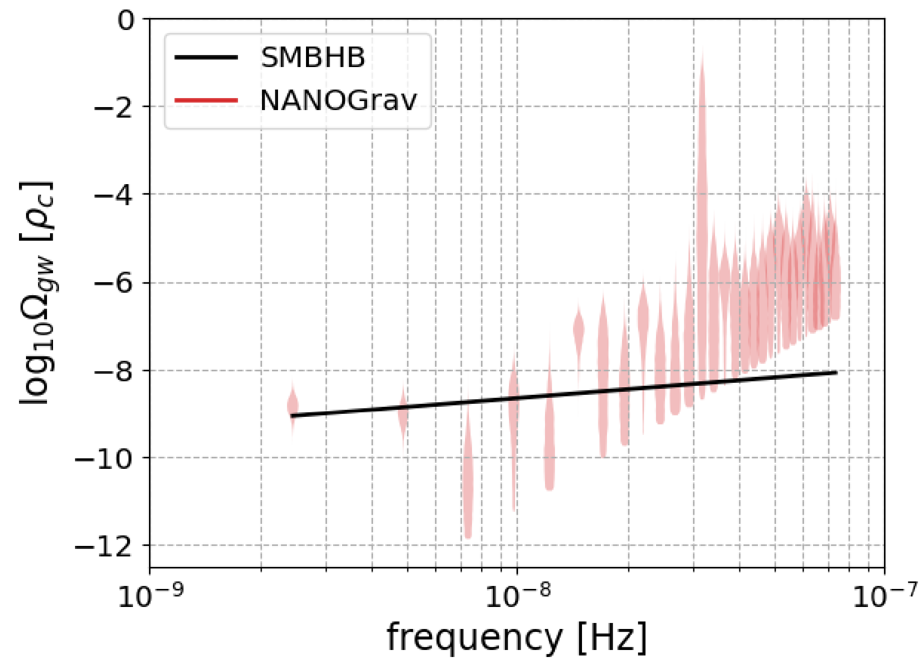
IPTA DR2: Perera et al. 2019
GWB analysis: in prep.

Common process – IPTA DR2

PRELIMINARY

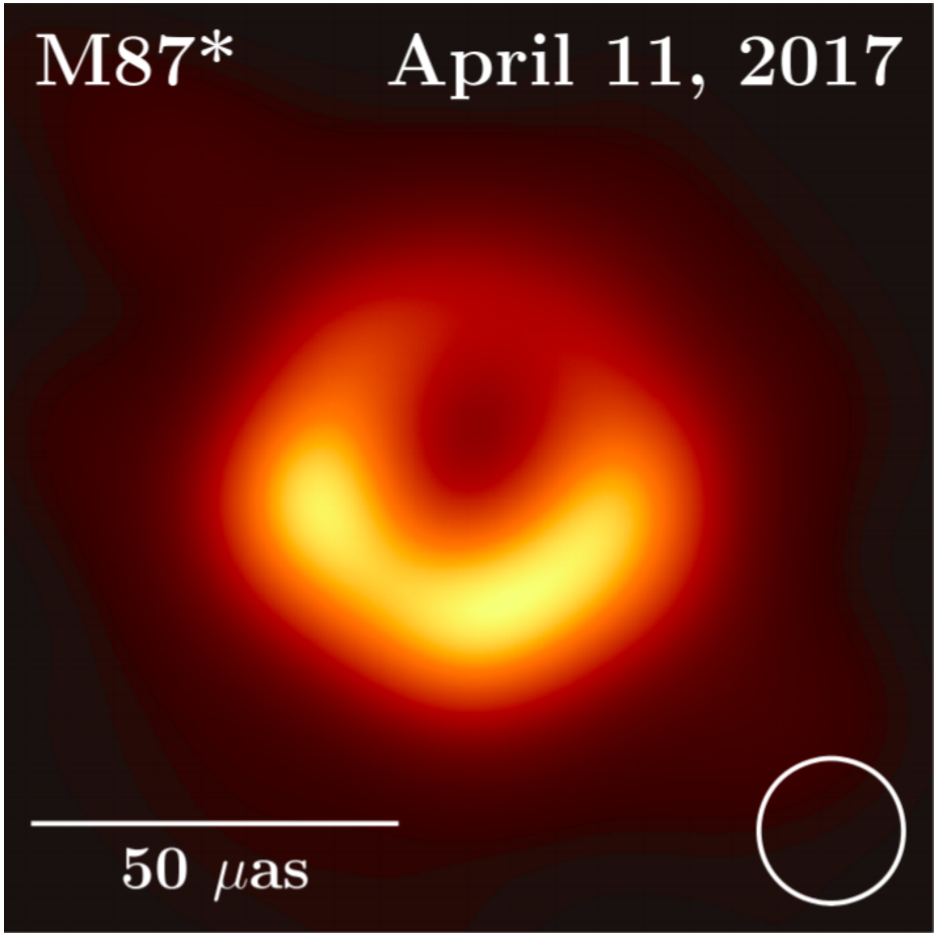


$$S_{ij}(f) = \Gamma_{ij}\frac{h_c^2}{12\pi^2 f^3} \qquad \gamma = 3 - 2\alpha$$

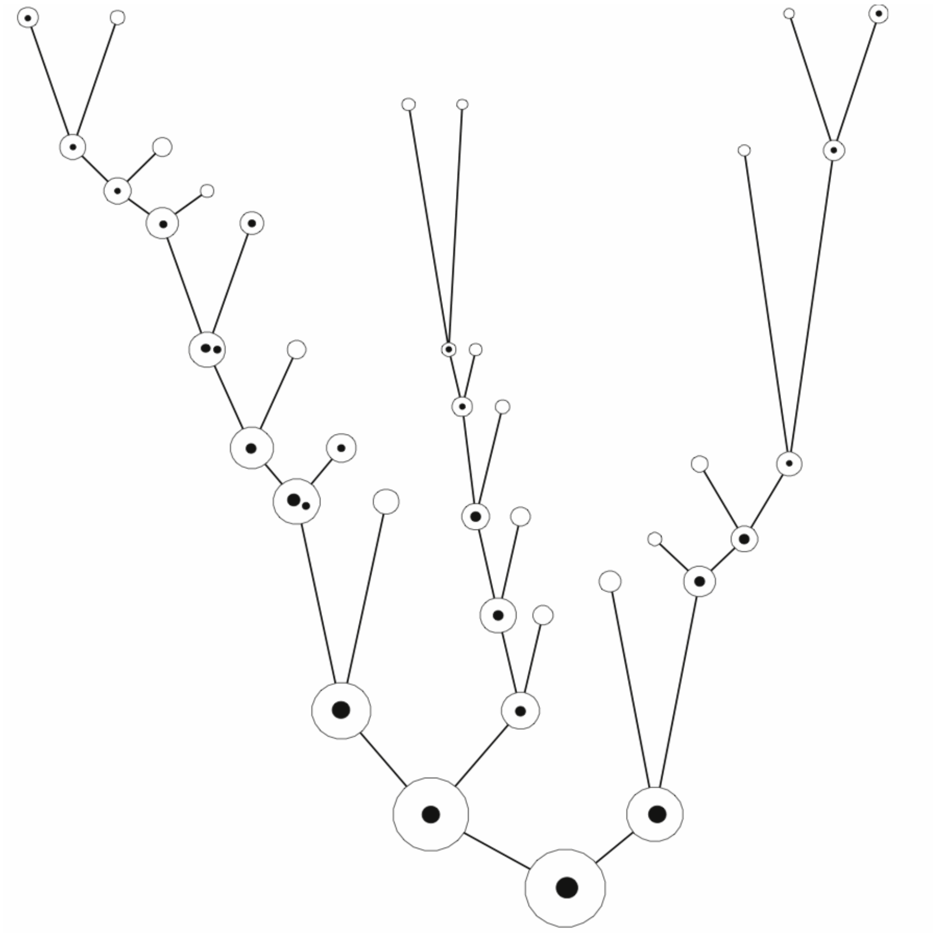


$$h_c(f) = A_{\rm GWB}\left(\frac{f}{f_{\rm yr}}\right)^{\alpha} \qquad \Omega_{GW} = \frac{\pi}{4}\frac{f^2 h_c^2}{G\rho_c}$$

Supermassive black holes



Credits: EHT



Credits: M. Volonteri

Parametric model

- Population of SMBHB $n_c(z,M)$
- Analytic description with 16 / 5 eff + 3 parameters

- Energy emission of individual binary dE/df
- Eccentricity, stellar density

$$h_c^2 = \frac{4G}{\pi c^2 f} \int_0^\infty dz \int_0^{\bar{M}} d\mathcal{M} \; n_c(z, \mathcal{M}) \frac{dE}{df}$$

Chen et al. 2017, 2019

Black hole binary – Galaxy Merger

- How many galaxies are there?
- Galaxy Stellar Mass Function

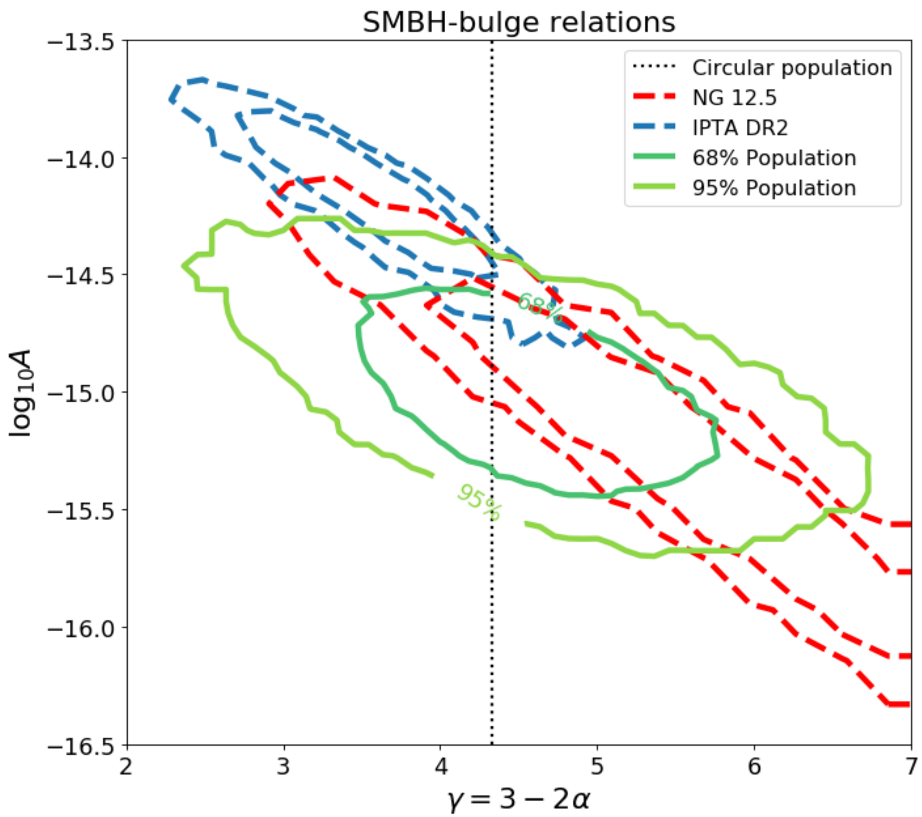
- What fraction of galaxies are in pairs?
- Pair Fraction

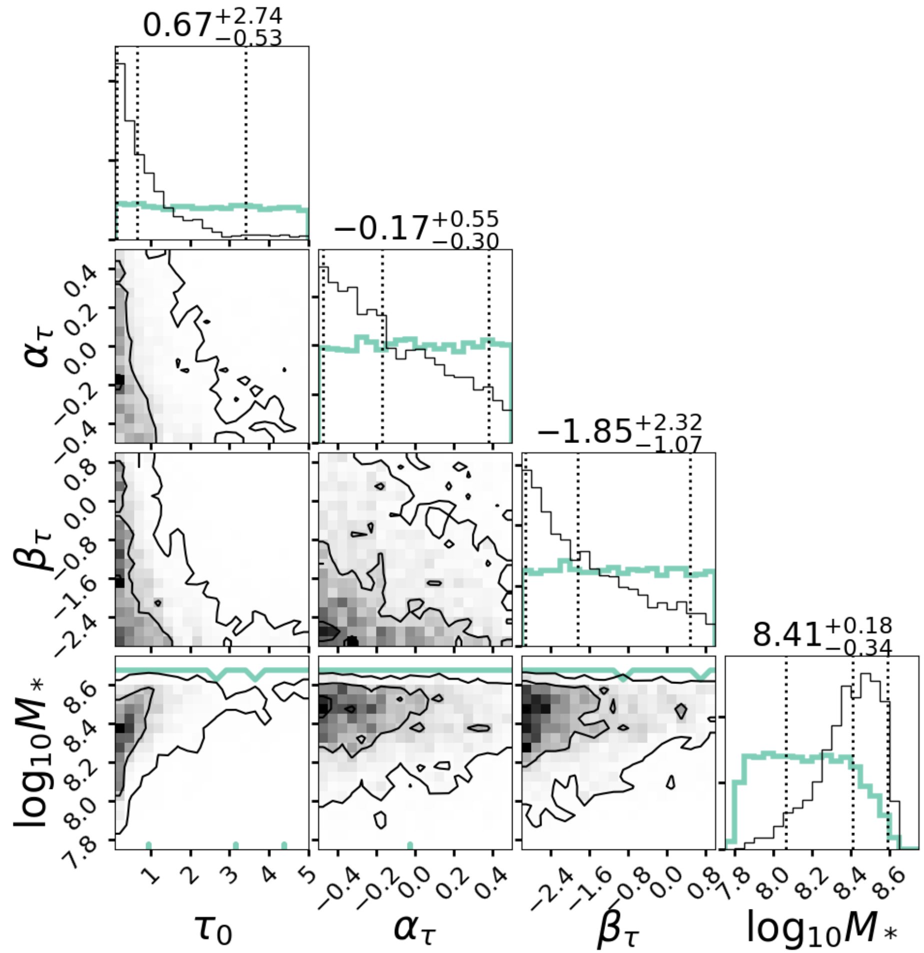
- How long does the merger take?
- Merger Time Scale

- What is the relation between a SMBH and its host galaxy?
- $M_G - M_{BH}$ relation

Chen et al. 2019

Astrophysical interpretation



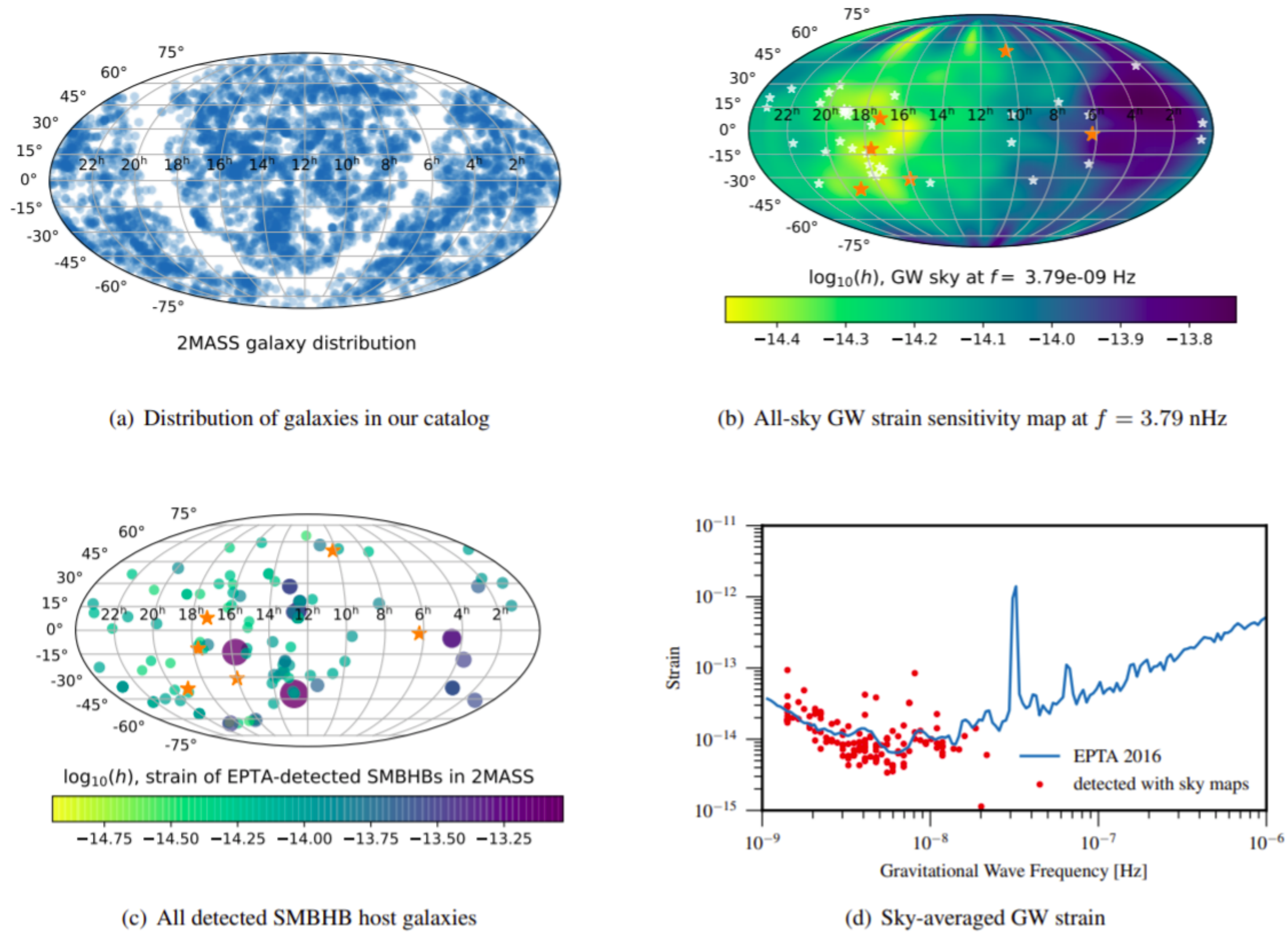


Credits: A. Sesana, SC

$\Phi_{BHB,0} \approx$ 1e-4 Mpc^{-3}

Middleton et al. 2021

Galaxy catalogues



(a) Distribution of galaxies in our catalog

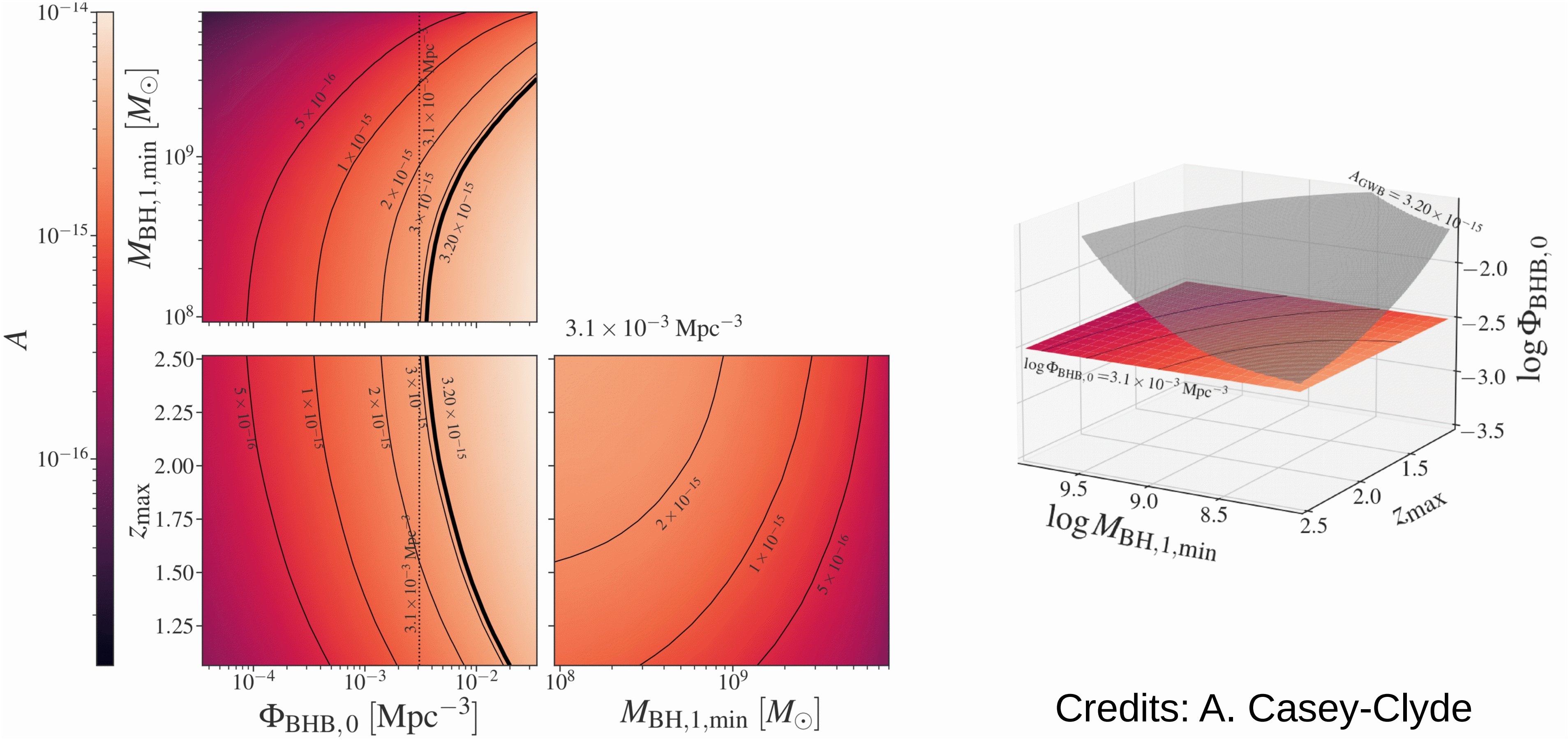
(b) All-sky GW strain sensitivity map at $f = 3.79$ nHz

(c) All detected SMBHB host galaxies

(d) Sky-averaged GW strain

Mingarelli et al. 2017

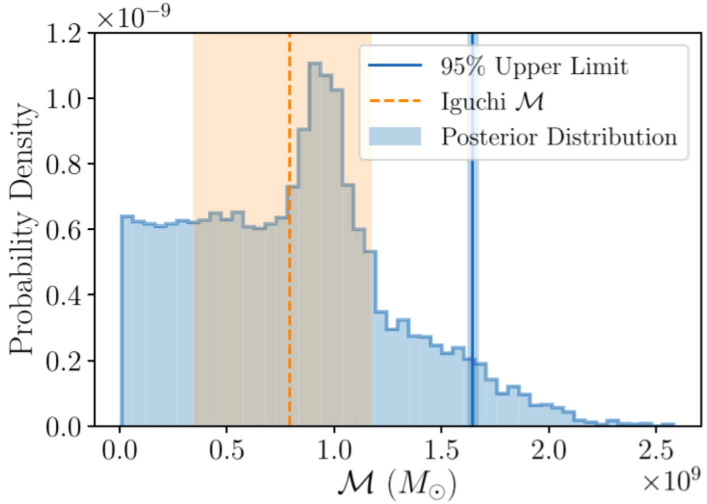
Astrophysical interpretation



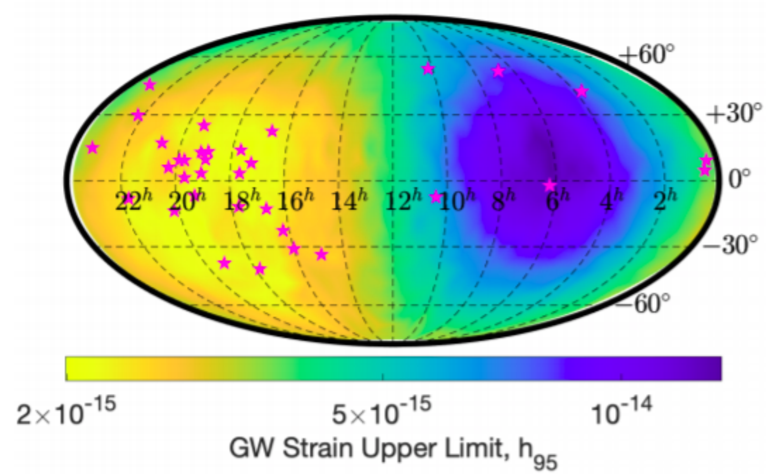
Credits: A. Casey-Clyde

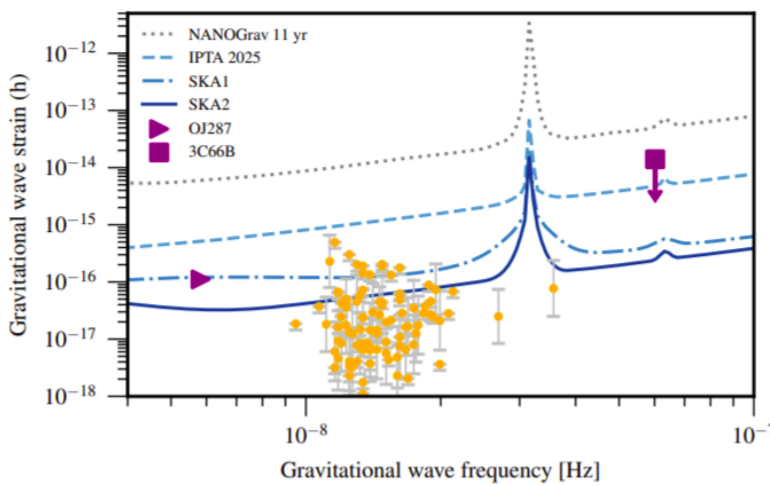
$\Phi_{BHB,0} \approx 3e\text{-}3\ Mpc^{-3}$

Search for resolvable supermassive black hole binaries for multi-messenger astronomy

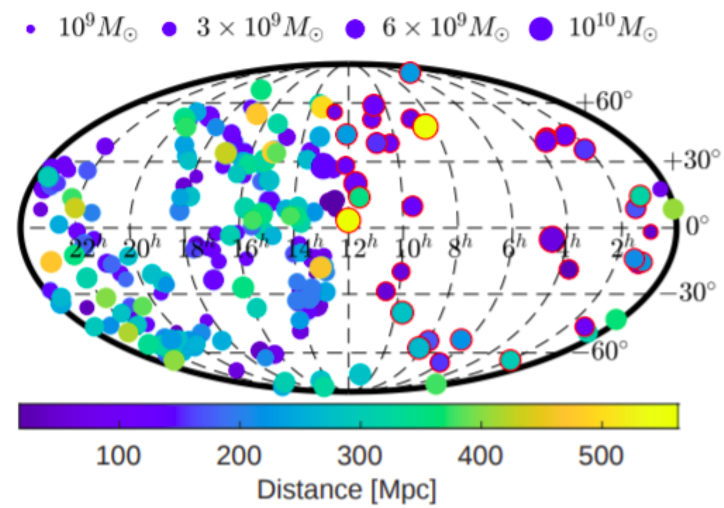


NANOGrav (Witt) 2020





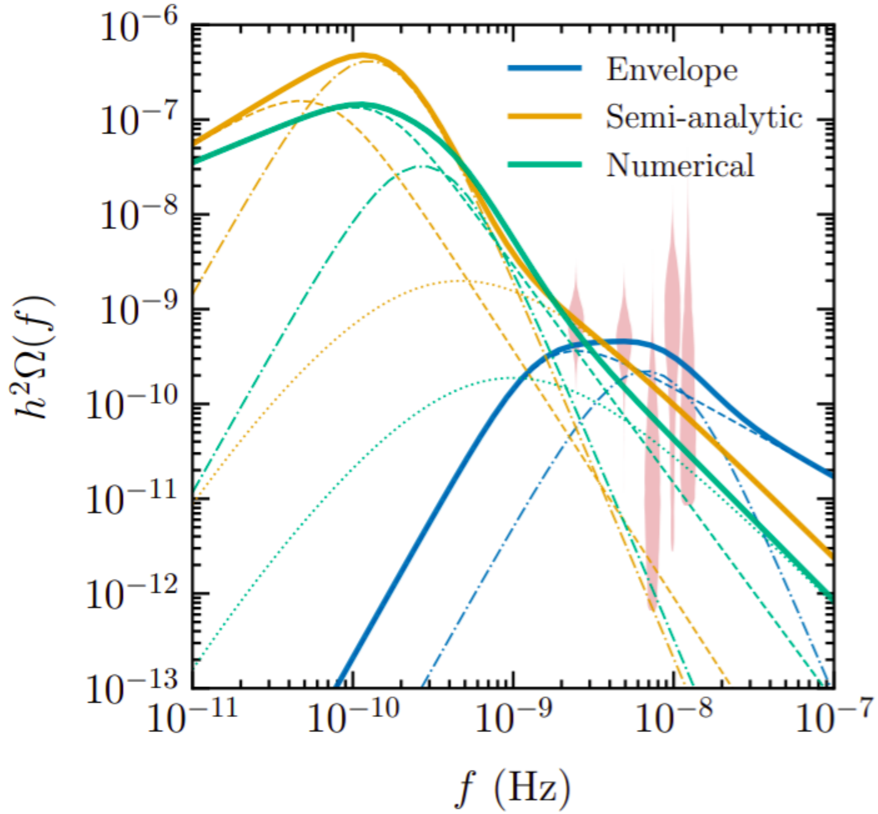
Xin et al. 2020, see also Mingarelli et al. 2017



NANOGrav (Charisi) 2021

Other NANOGrav work

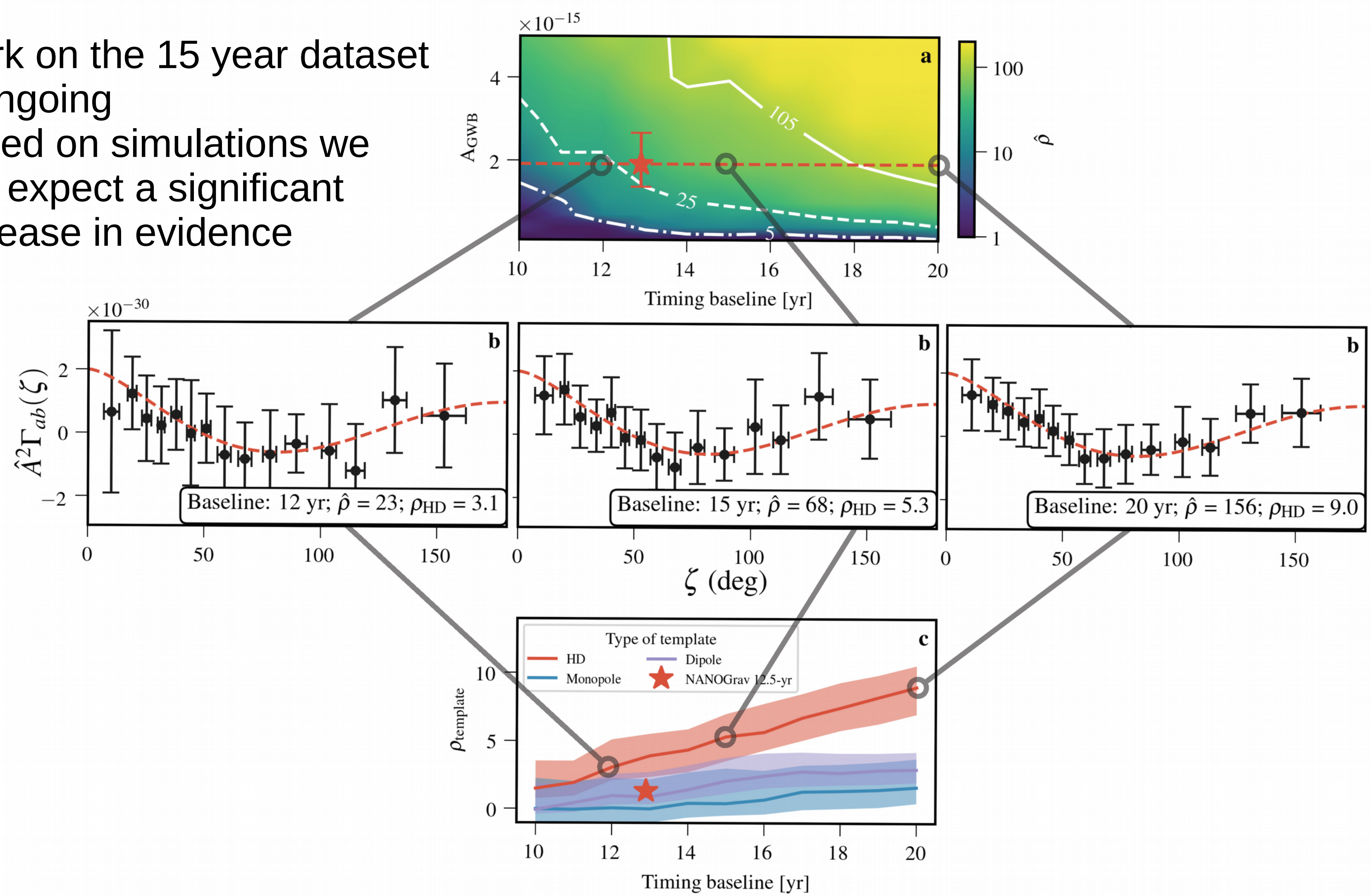
- Continuous GW: Caitlin Witt
- Burst of memory: Jerry Sun
- Fuzzy Dark Matter: Brendan Drachler
- Phase transitions: Andrea Mitridate
- Alternative GWB polarizations: Nima Laal
- Advanced noise model: Joseph Simon and Jeffrey Hazboun
- 15 year dataset + GWB search
- IPTA DR2 + DR3



NANOGrav (Mitridate) 2021

What to expect for the future ?

- Work on the 15 year dataset is ongoing
- Based on simulations we can expect a significant increase in evidence



Pol et al. (NANOGrav) 2021

Summary

- NANOGrav has detected a common process in its most recent 12.5year dataset with an amplitude of about 2e-15
- No significant evidence for Hellings-Downs → No GW detection yet !
- Other PTA collaborations have similar detections: IPTA DR2: 3e-15
- Interpretation with SMBHBs give a merger rate of 1e-4 – 1e-3 Mpc^{-3}
- Single resolvable SMBHBs possible to be detected for multi-messenger astrophysics
- A lot of other work done in NANOGrav
- Expecting a breakthrough very soon
- Preparation for the 15year dataset and IPTA DR3 work ongoing