Introduction to Pulsar Timing Arrays

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useful resources

Review articles:

- Burke-Spoloar, et al (2015), “The astrophysics of nanohertz gravitational waves,” *The Astronomy and Astrophysics Review.*
- Lommen (2015), “Pulsar timing arrays: the promise of gravitational wave detection,” *Rep. Prog. Phys.* **78** 124901.

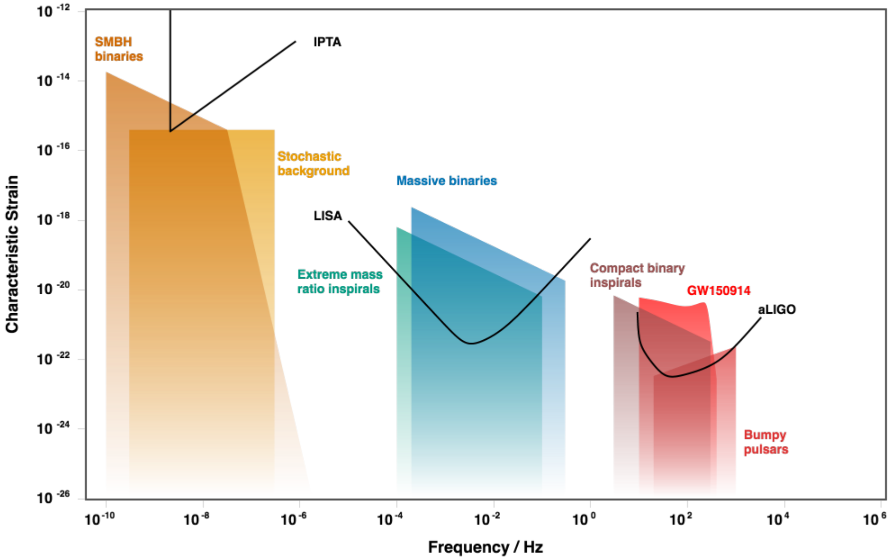
Textbook:

Taylor (2022), *The Nanohertz Gravitational Wave Astronomer*, CRC Press.

arXiv:2105.13270

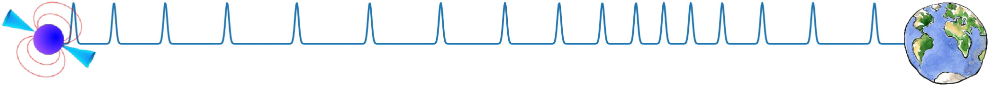
PTAs can detect nHz GWs by monitoring millisec radio pulsars

PTAs are sensitive to **low** frequency GWs

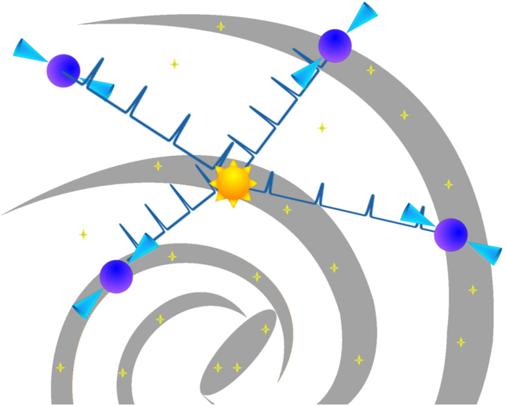


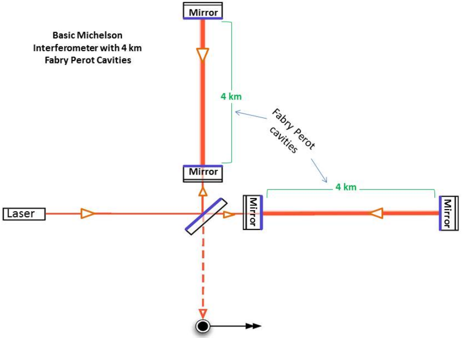
GWs change the distance between the pulsars and observer

PTAs look for variations in the **times of arrival** (TOAs) of pulses



The detector is the pulsars!





a timing model tells us when to expect the pulses to arrive

$$\tau_{\text{expected}} = F(\text{spin evolution; position; proper motion; orbital motion; other effects})$$

(see Ross Jennings' talk)

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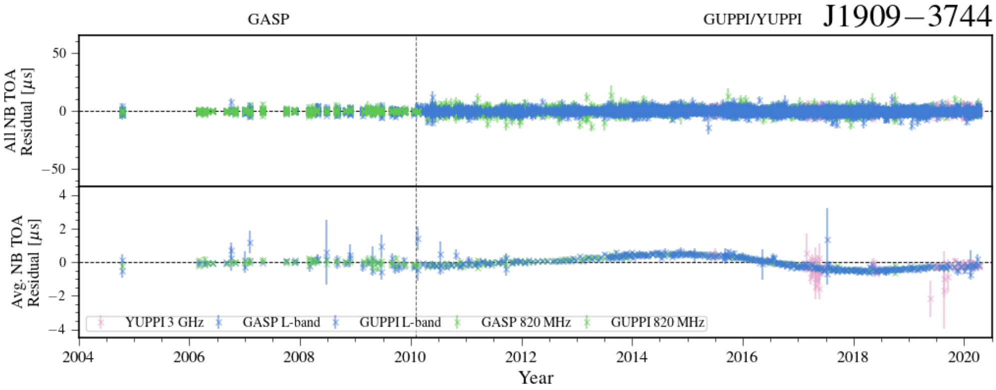
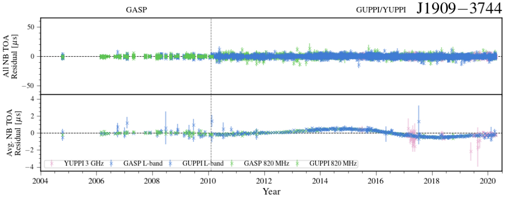
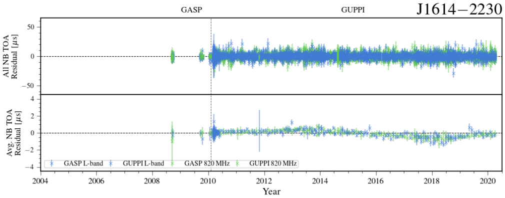
The key data product is the TOA residual

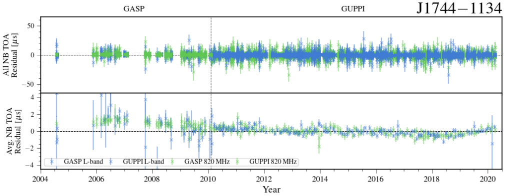
$$R(t) = \tau_{\text{measured}} - \tau_{\text{expected}}$$

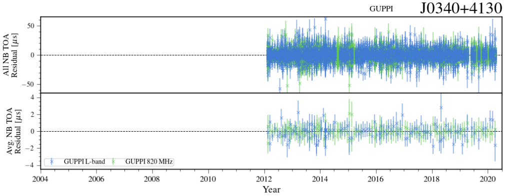


Not all pulsars have the same T_{obs} or noise level









GWs induce TOA residuals in pulsar data

- TOA residual

$$R(t) = \frac{1}{2}\frac{p^a p^b}{\left(1+\hat{\Omega}\cdot\hat{p}\right)}\int_0^t \mathrm{d}t' \left[h_{ab}(t',0) - h_{ab}(t'-L/c, L\hat{p})\right]$$

- line of sight projection
    - $\hat{\Omega}$ – GW direction
    - $\hat{p}$ – pulsar direction

- GW Earth term
- GW pulsar term
    - $L\,\hat{p}$ – pulsar location

To detect a **deterministic** GW signal...

... just calculate $R(t)$ for each pulsar and look

To detect a **stochastic** GW signal...

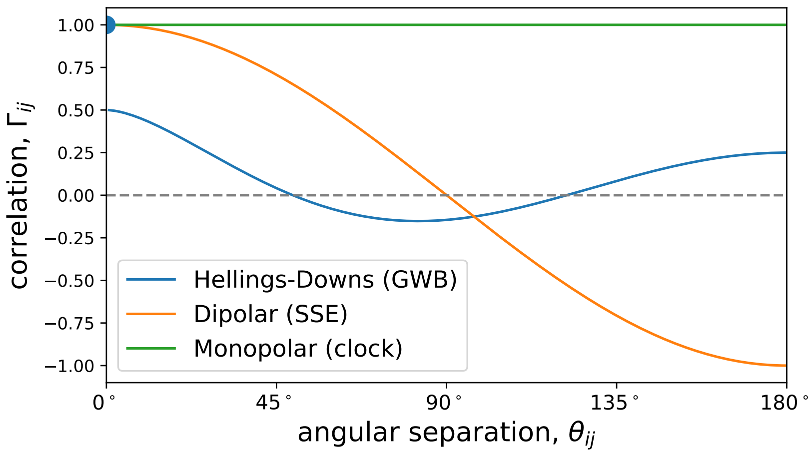
... we need to know the spectral properties of R

and how the signal in pulsar-i correlates to pulsar-j

$$S_R(f)_{ij} = \Gamma_{ij} \, \frac{h_c^2(f)}{12\pi^2 f^3}$$

cross-power spectral density of the timing residuals

The shape of the **overlap reduction function**, Γ_{ij}, depends on the source of the stochastic timing residuals



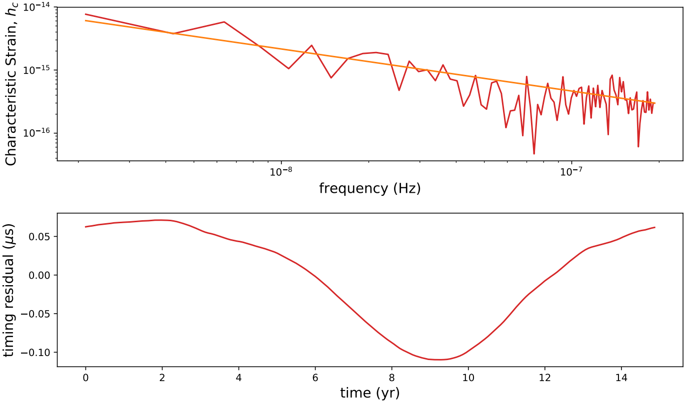
The spectrum of h_c depends the source of the stochastic timing residuals

$$h_c(f) = A_c \left(\frac{f}{\mathrm{yr}^{-1}}\right)^{\alpha}$$

GWB from SMBHB

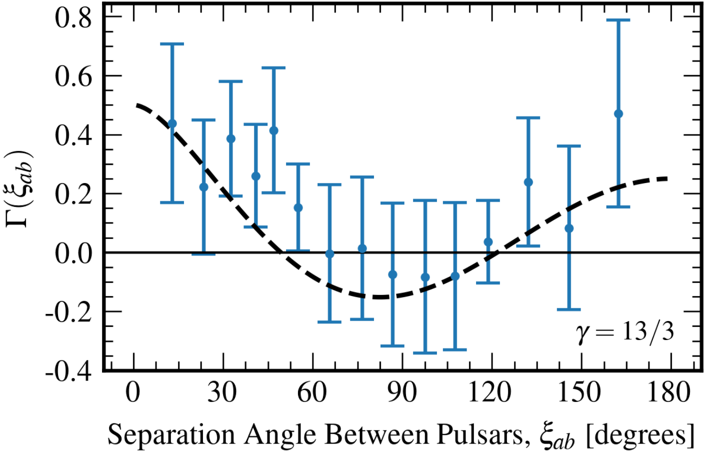
$$\alpha = -2/3$$

$$\implies S_R \sim f^{-13/3}$$



(see Phinney 2001)

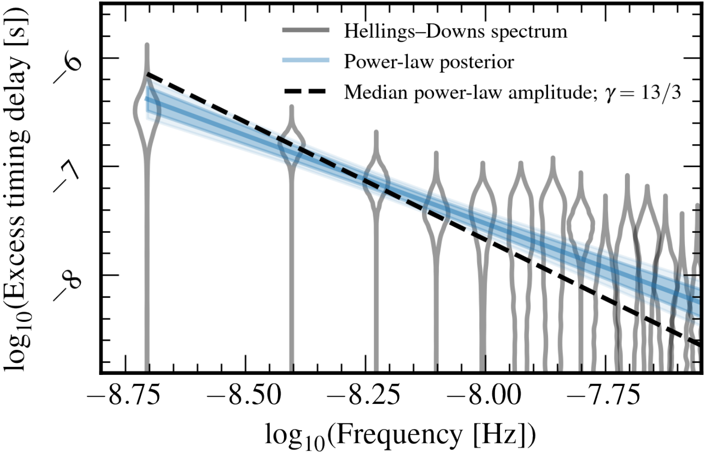
NANOGrav observed Hellings-Downs inter-pulsar correlations



(see Sarah Vigeland's talk to learn how)

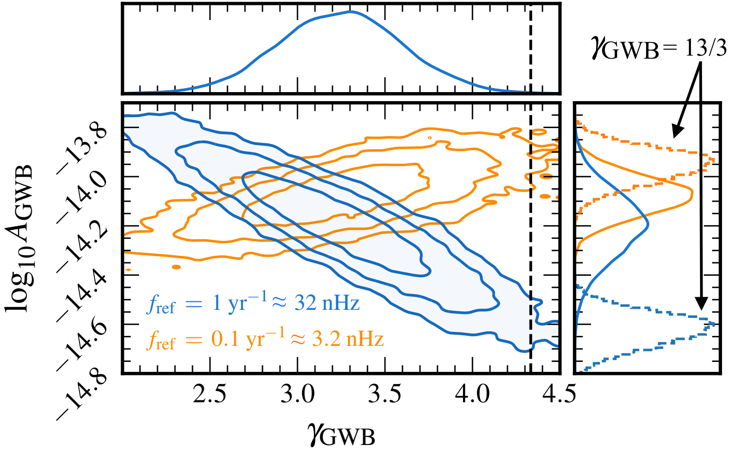
(NANOGrav collaboration, arXiv:2306.16213)

The spectrum observed by NG agrees with a powerlaw...



(NANOGrav collaboration, arXiv:2306.16213)

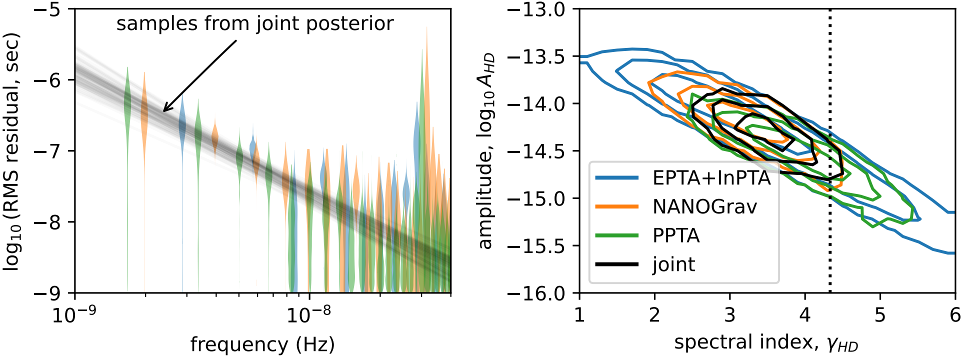
… but is in mild tension with canonical GWB from SMBHB



(see Luke Kelley's talk)

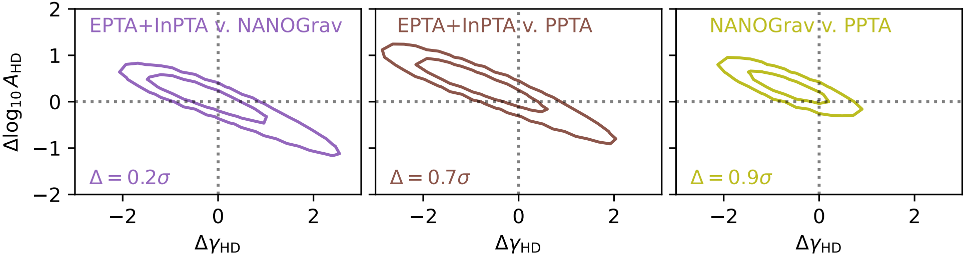
(NANOGrav collaboration, arXiv:2306.16213)

European+Indian PTAs and Parkes (Australian) PTA also published GWB results



(IPTA collaboration, arXiv:2309.00693)

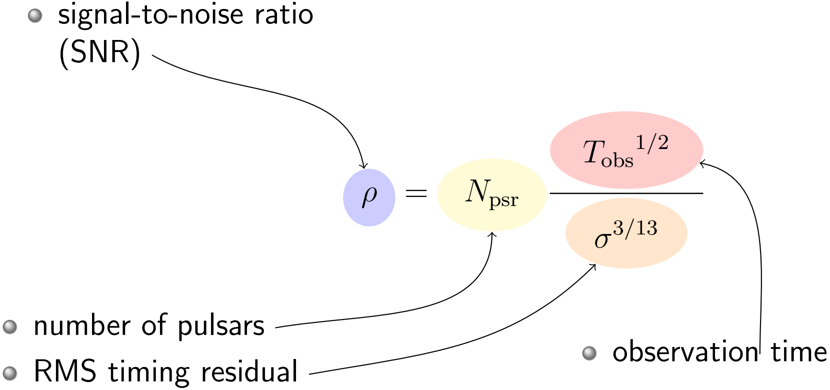
There is excellent agreement between the observed spectral characteristics by each PTA



(IPTA collaboration, arXiv:2309.00693)

If you want to make a PTA GW detector better

(see Siemens et al 2013)



- signal-to-noise ratio (SNR)

$$\rho = N_{\mathrm{psr}} \frac{{T_{\mathrm{obs}}}^{1/2}}{\sigma^{3/13}}$$

- number of pulsars
- RMS timing residual
- observation time

topic	arXiv #		topic	arXiv #
NANOGrav GWB	2306.16213			
EPTA+InPTA GWB	2306.16214		IPTA compare	2309.00693
PPTA GWB	2306.16215			
CPTA GWB	2306.16216			
			E+In data	2306.16224
NANOGrav data	2306.16217		E+In noise	2306.16225
NANOGrav noise	2306.16218		E+In SMBHB	2306.16226
NANOGrav new phys	2306.16219		E+In astro+	2306.16227
NANOGrav astrophys	2306.16220		E+In UL DM	2306.16228
NANOGrav anisotropy	2306.16221			
NANOGrav SMBHB	2306.16222		PPTA noise	2306.16229
NANOGrav pipeline	2306.16223		PPTA data	2306.16230