Gravitational waves from supermassive black holes at pulsar timing arrays

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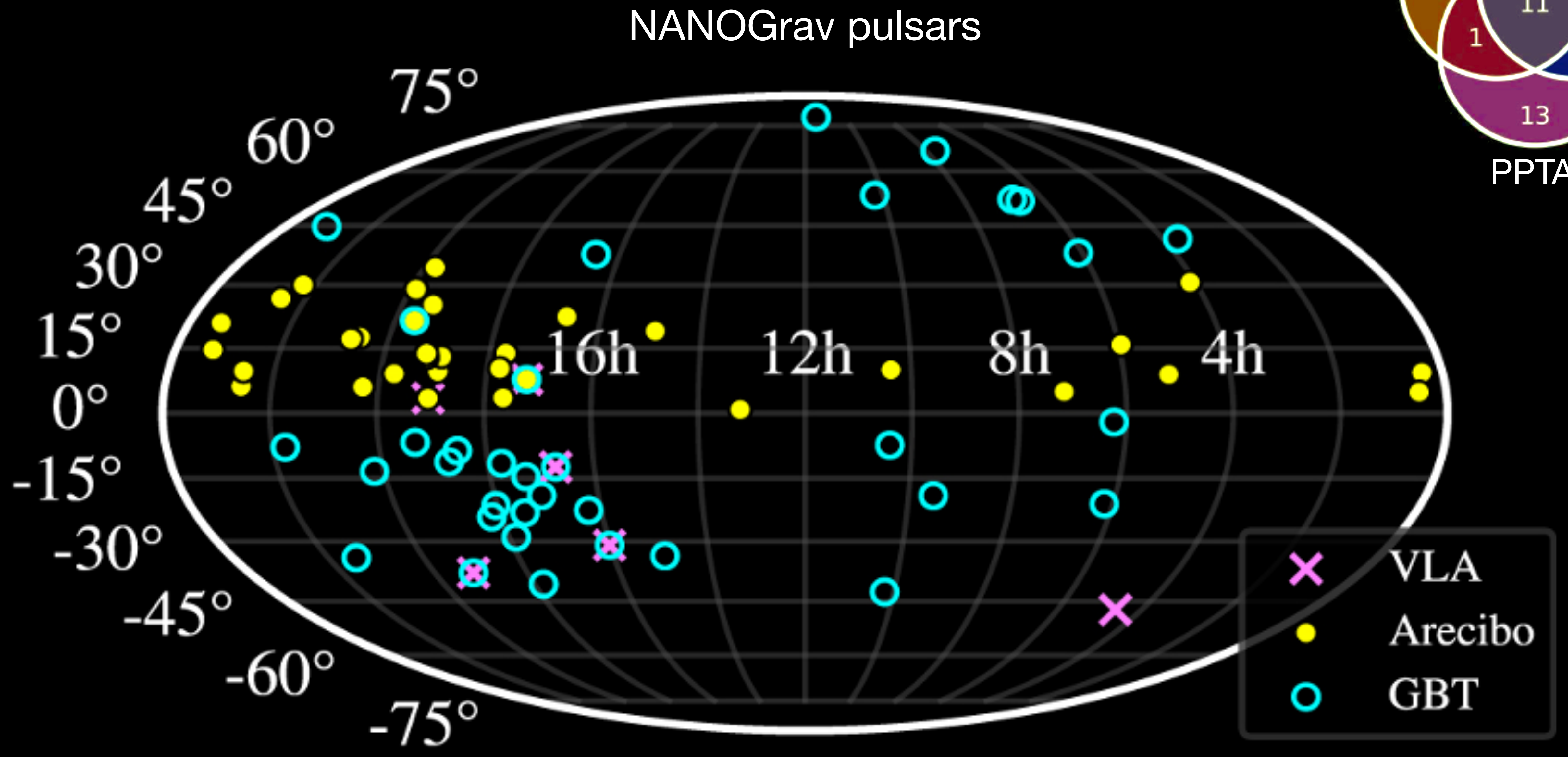
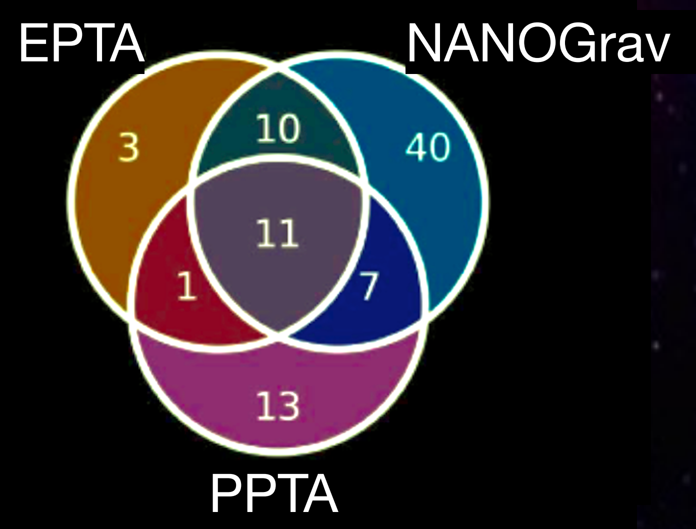
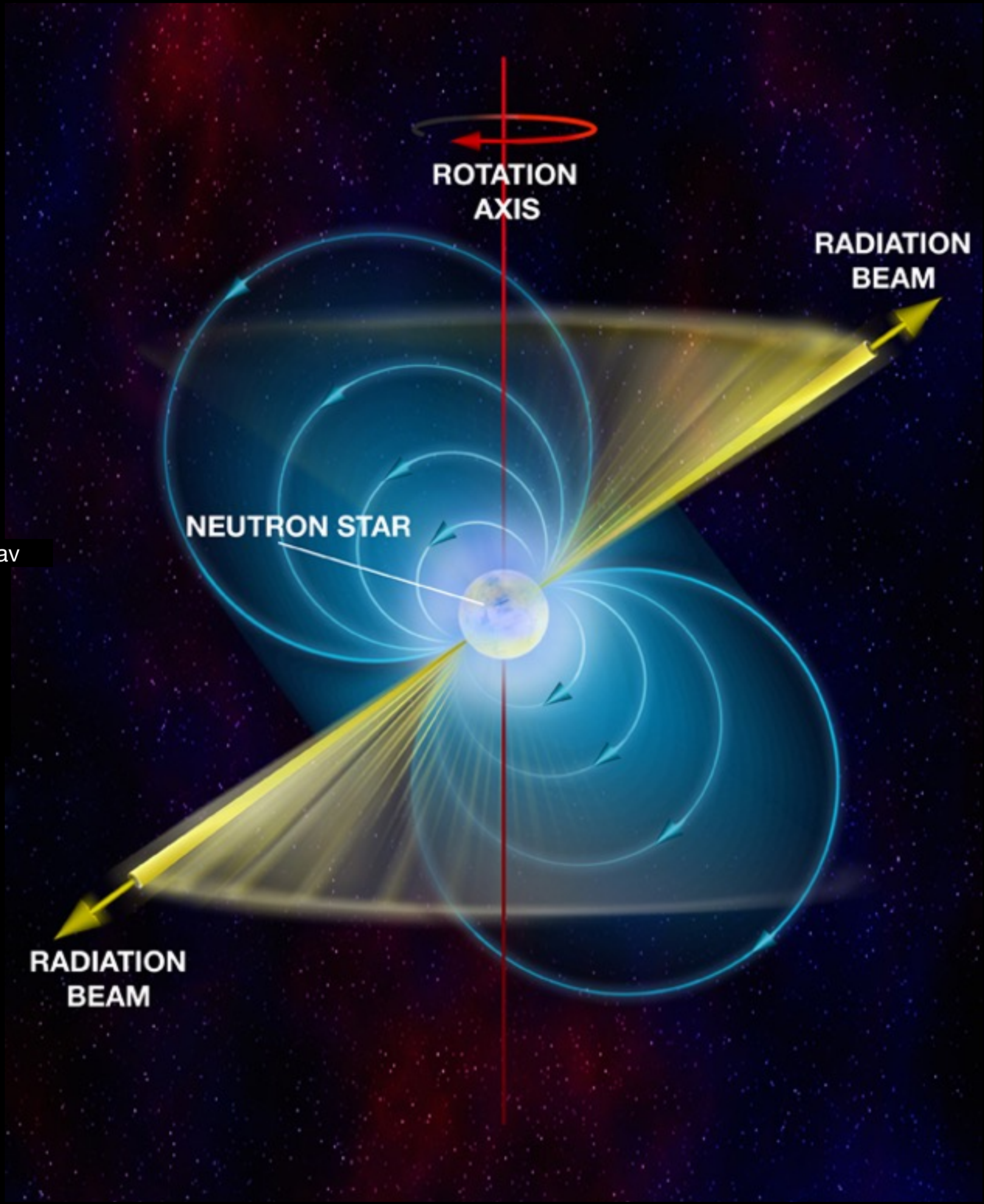
Pulsar timing arrays

- Measure **timing series** from a set of millisecond pulsars.
- GWs induce noise in that is **correlated** between pulsars.

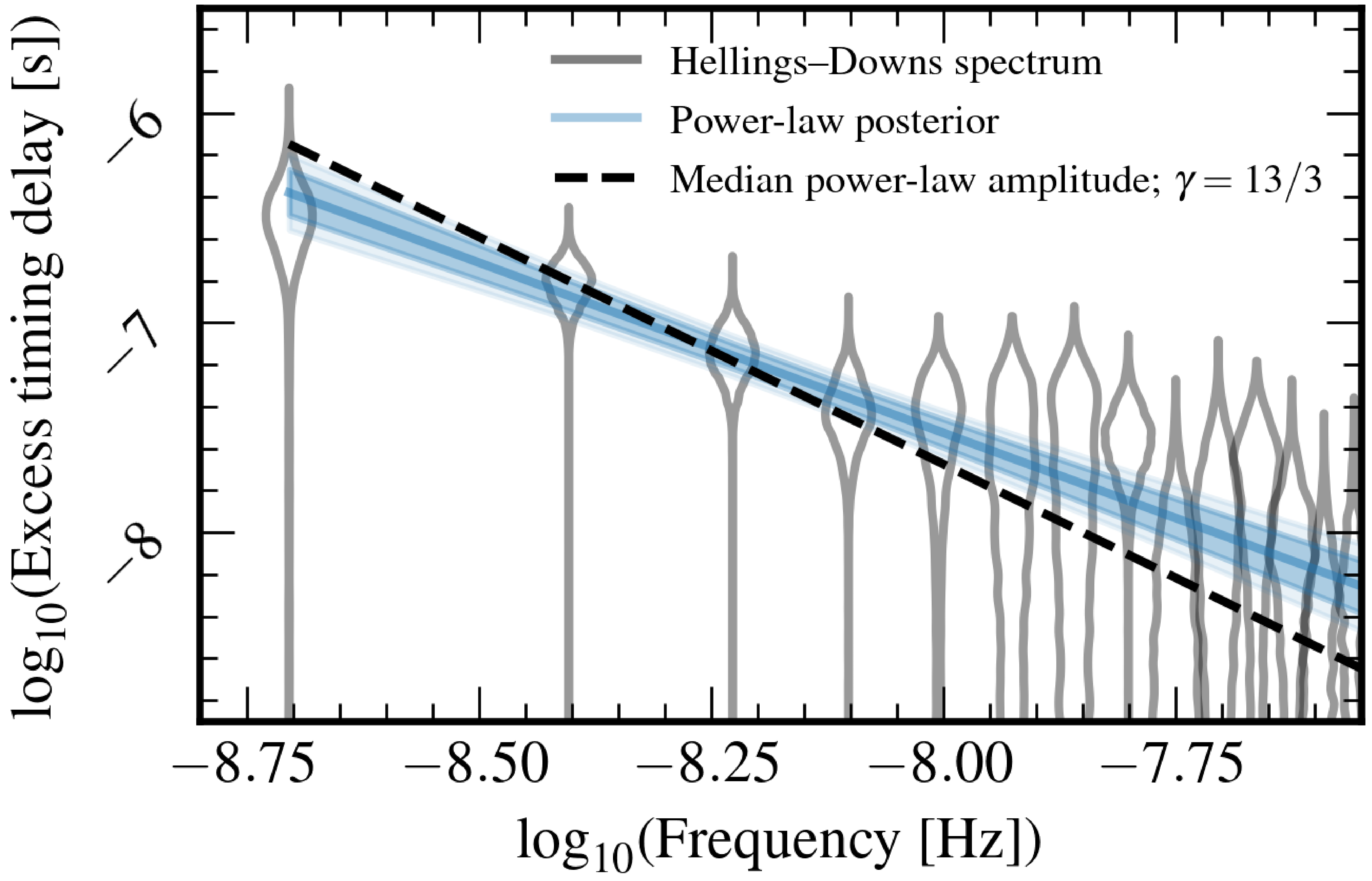


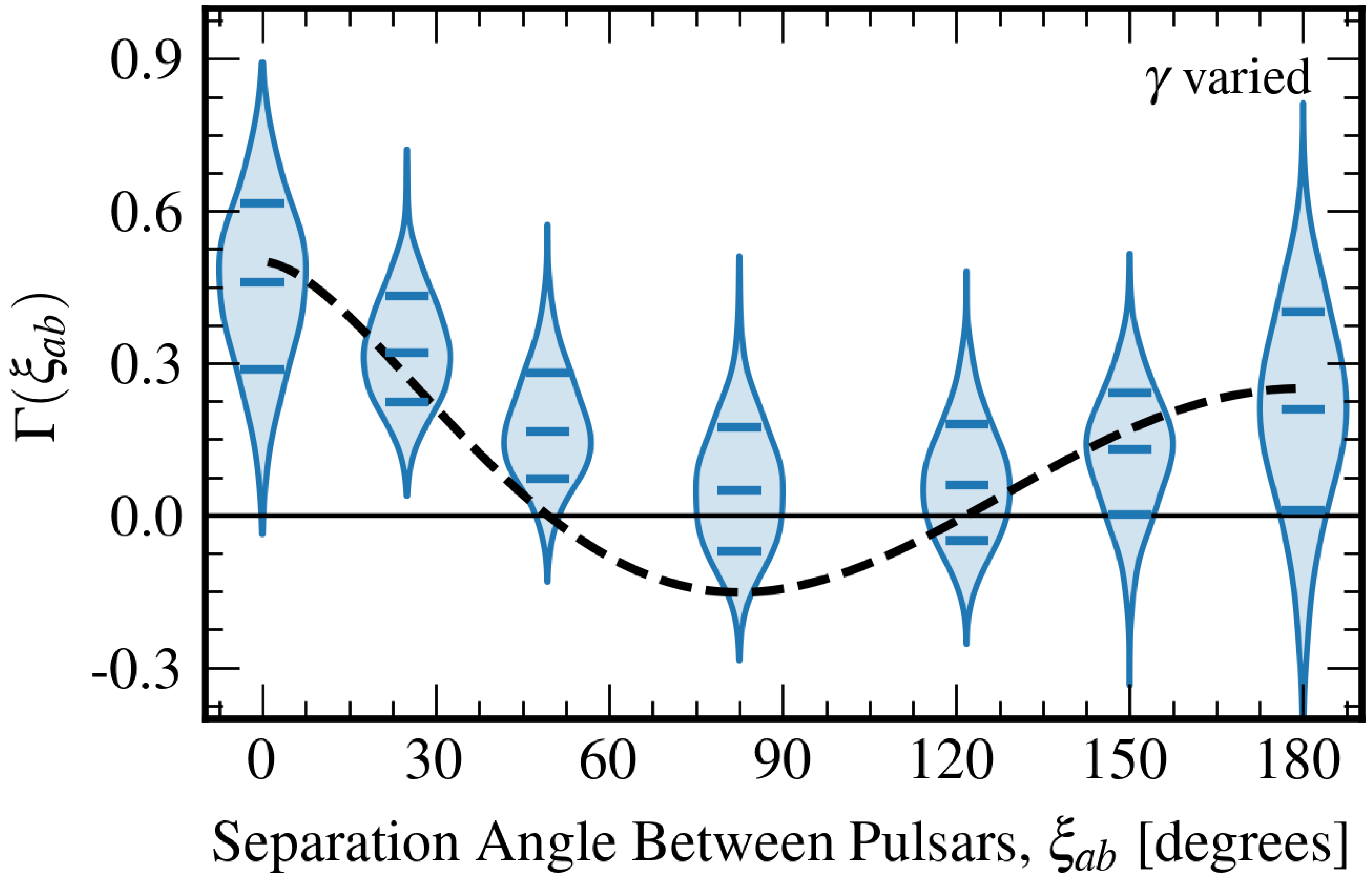




Strong evidence for a GW background at PTAs

[NANOGrav, ApJ. Lett. 951 (2023)]

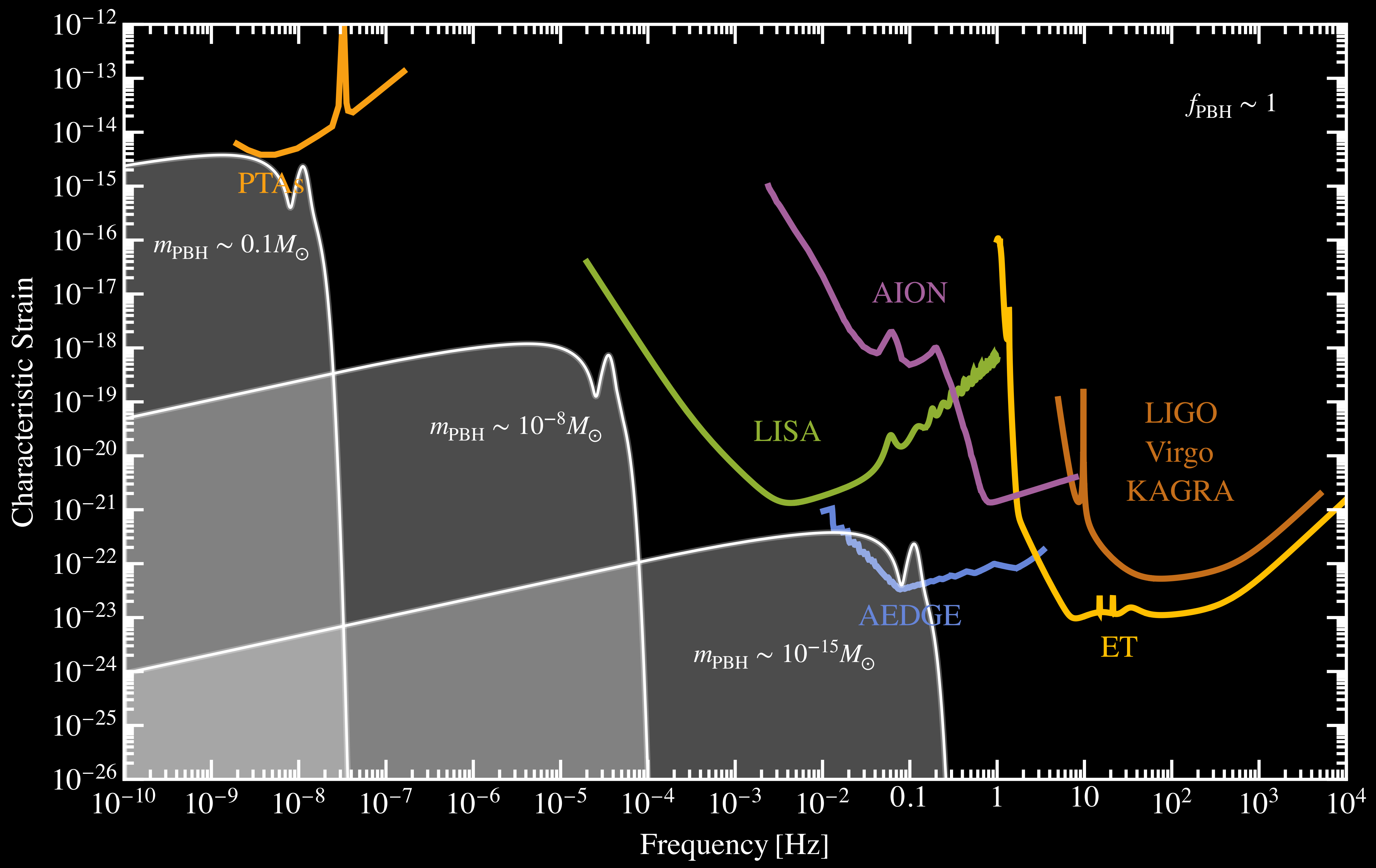




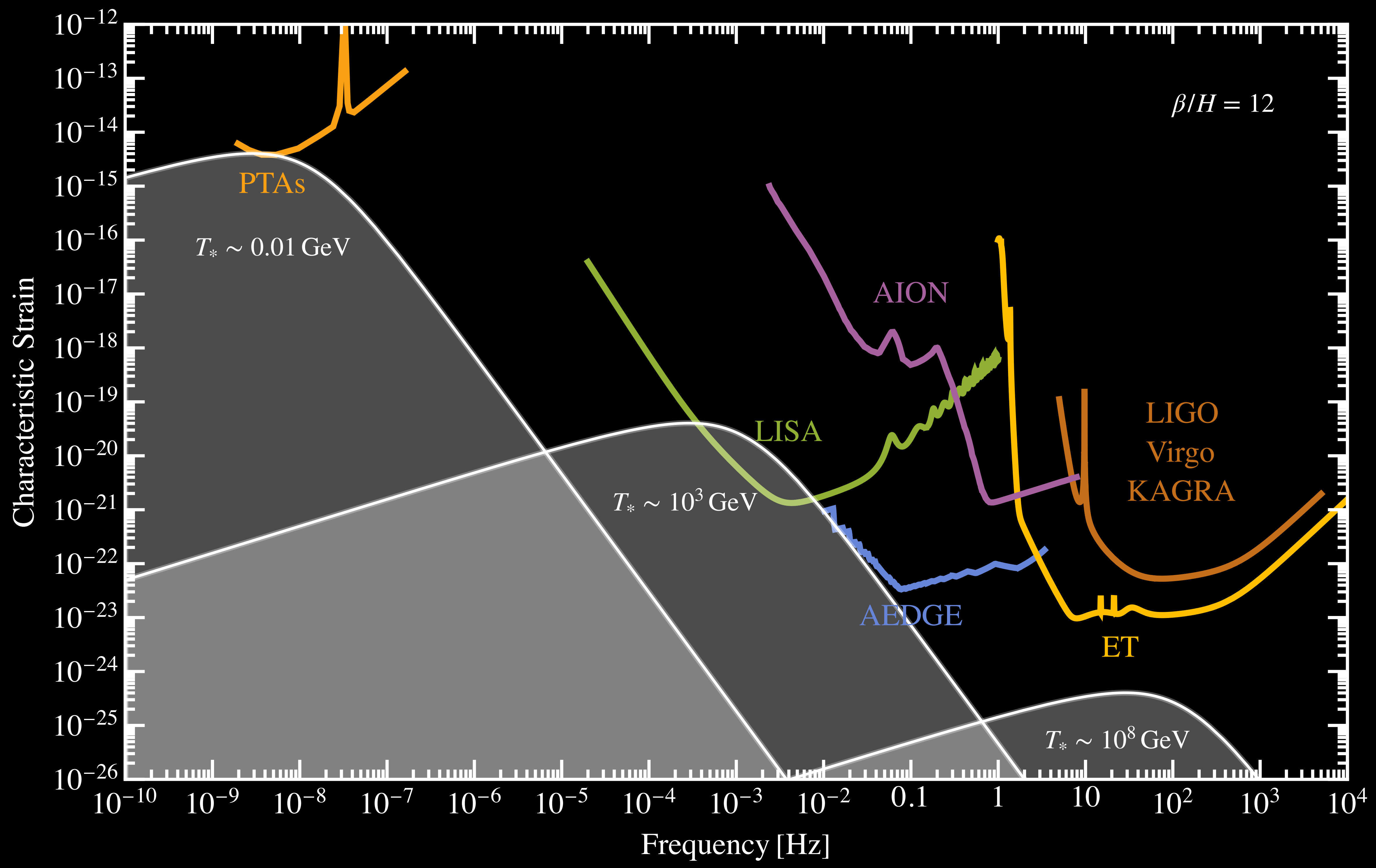
Common spectrum red noise + Hellings-Downs angular correlations

Cosmological sources

Scalar-induced GWs

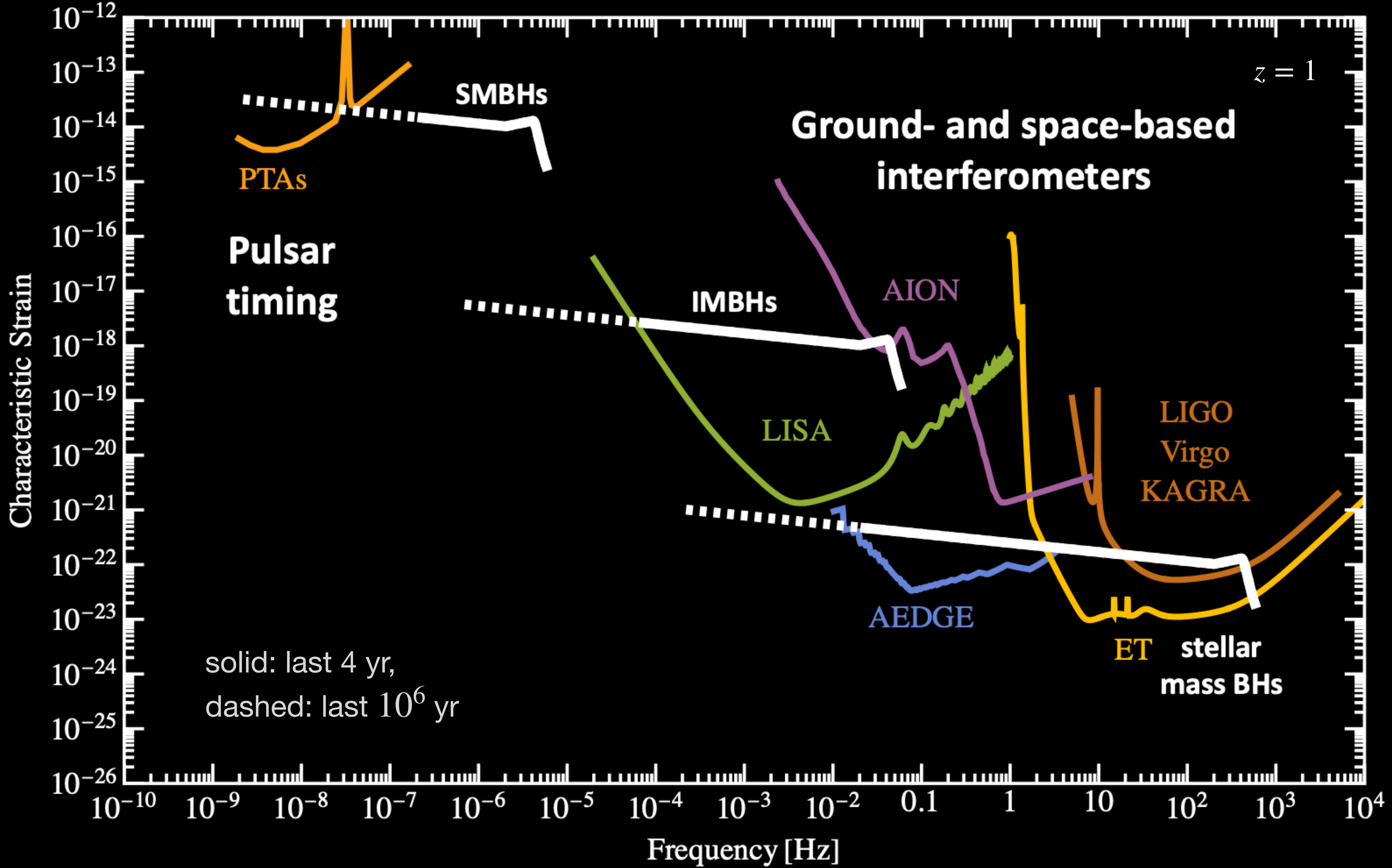


GWs from phase transitions



cosmic strings, domain walls etc.

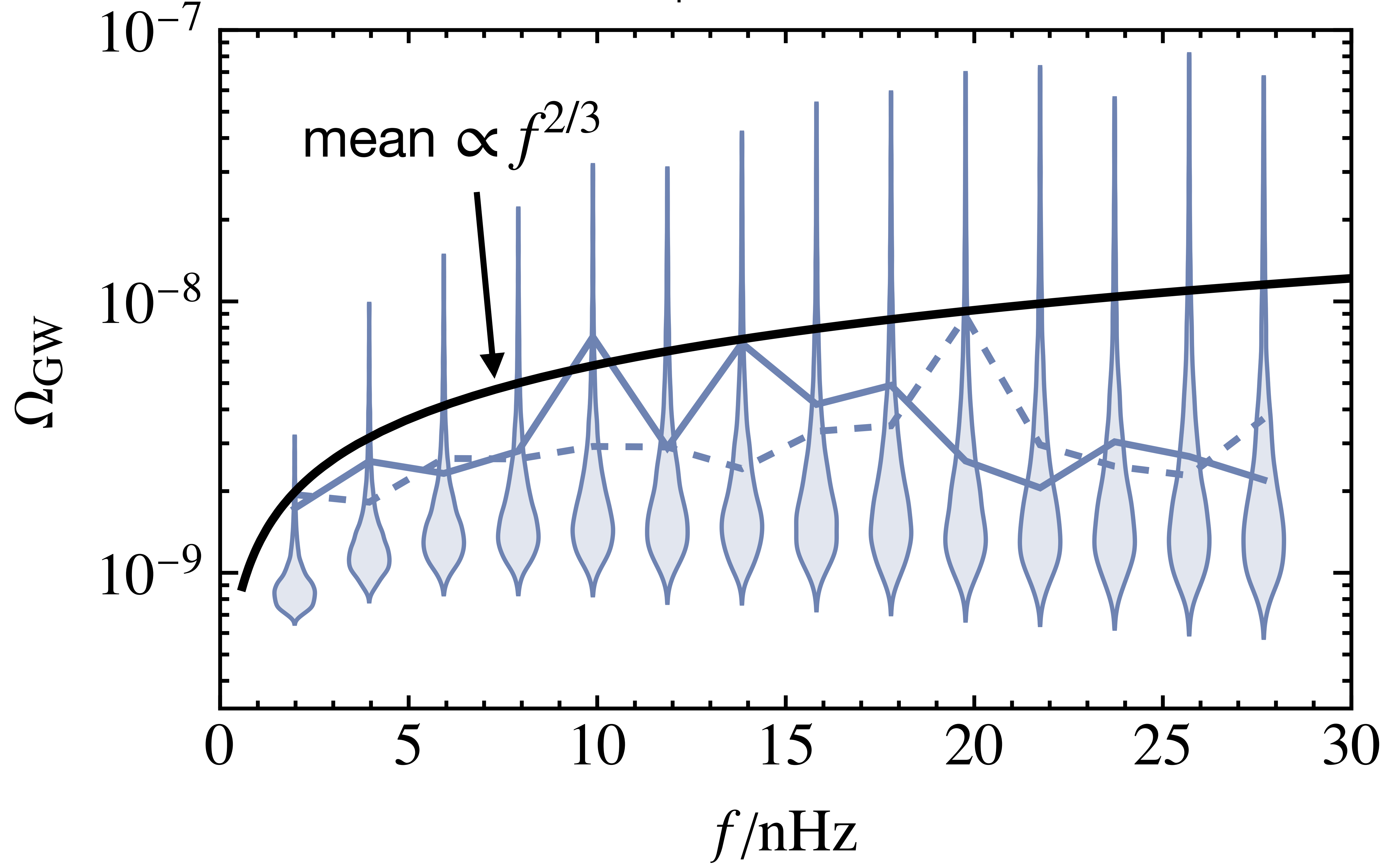
Black hole binaries



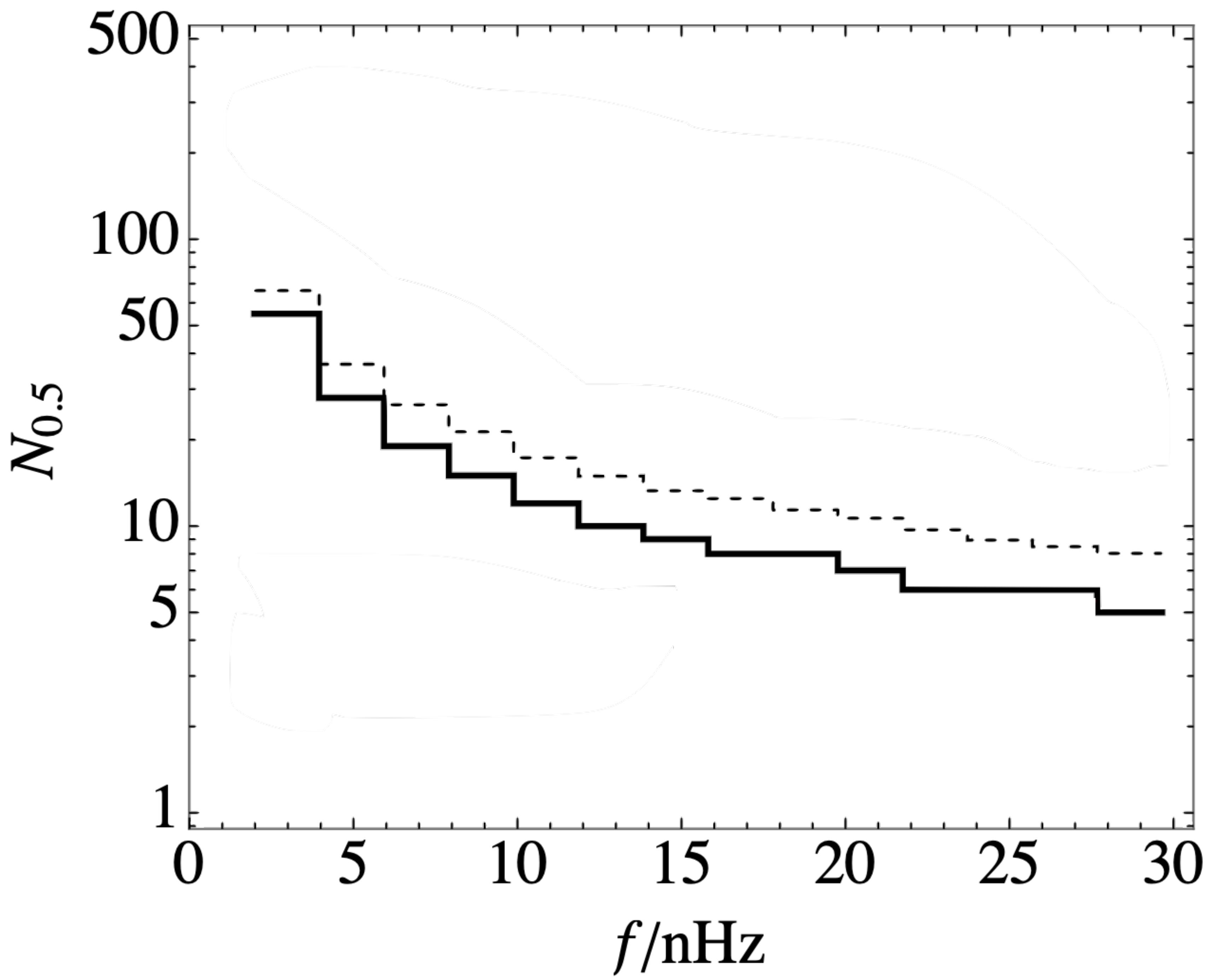
SMBH GW background

$$\Omega_{\rm tot}(f_i) = \sum_j \Omega^{(1)}_{{\rm GW},j} \quad \text{where} \quad \Omega^{(1)}_{\rm GW} \propto (\mathscr{M} f)^{10/3} D_L^{-2}$$

- **Solid and dashed curves:** two realizations of the background.
- **Violins**: distribution of the possible realisations.



Sources that make 50% of the signal:



SMBH GW background

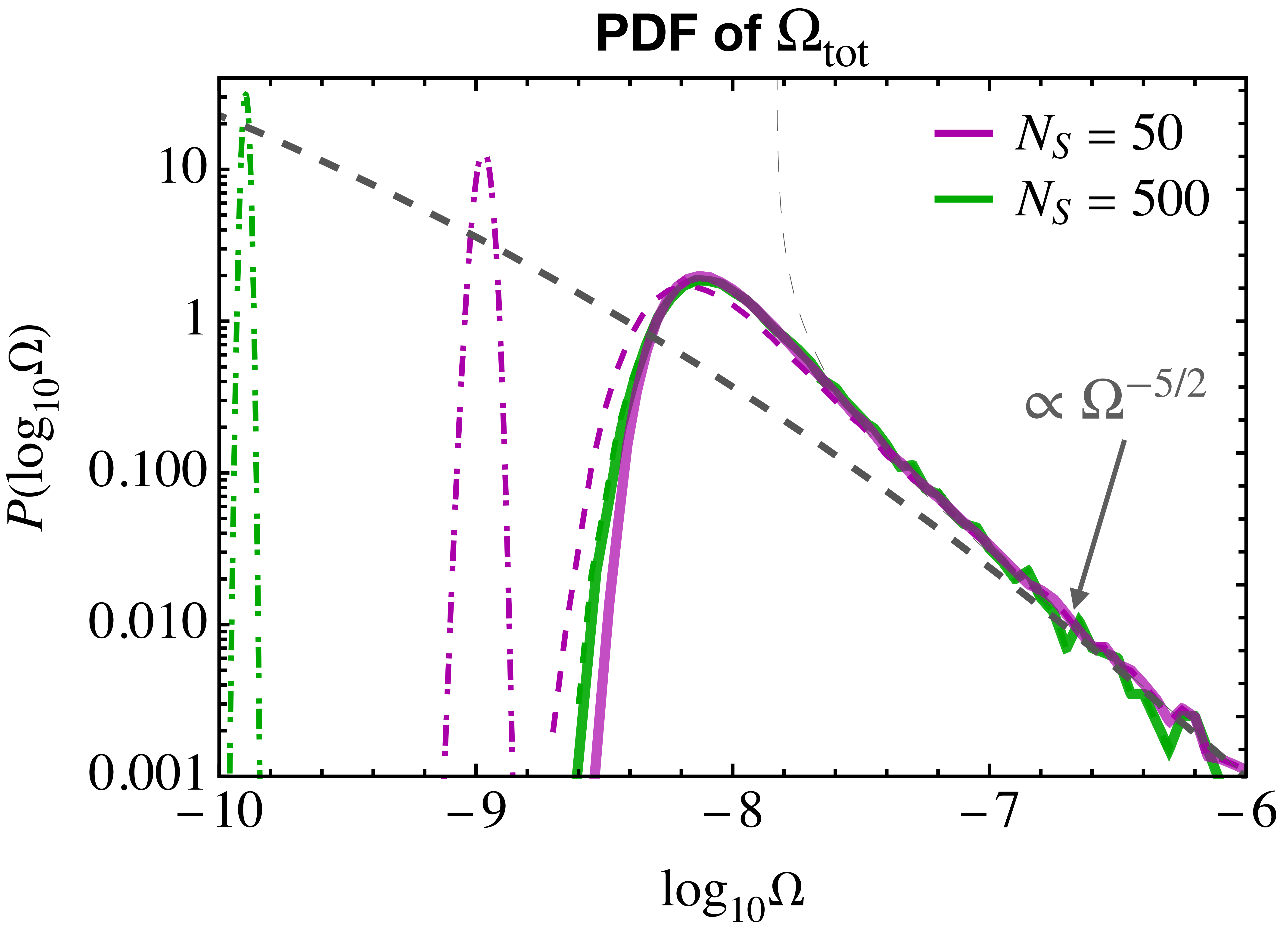
[Ellis et. al., *PRD* 109 (2023); *A&A* 676 (2023)]

$$P^{(1)}(\Omega) \propto \int \mathrm{d}\lambda \frac{\mathrm{d}t}{\mathrm{d}\ln f_r} \delta(\Omega - \Omega^{(1)})$$

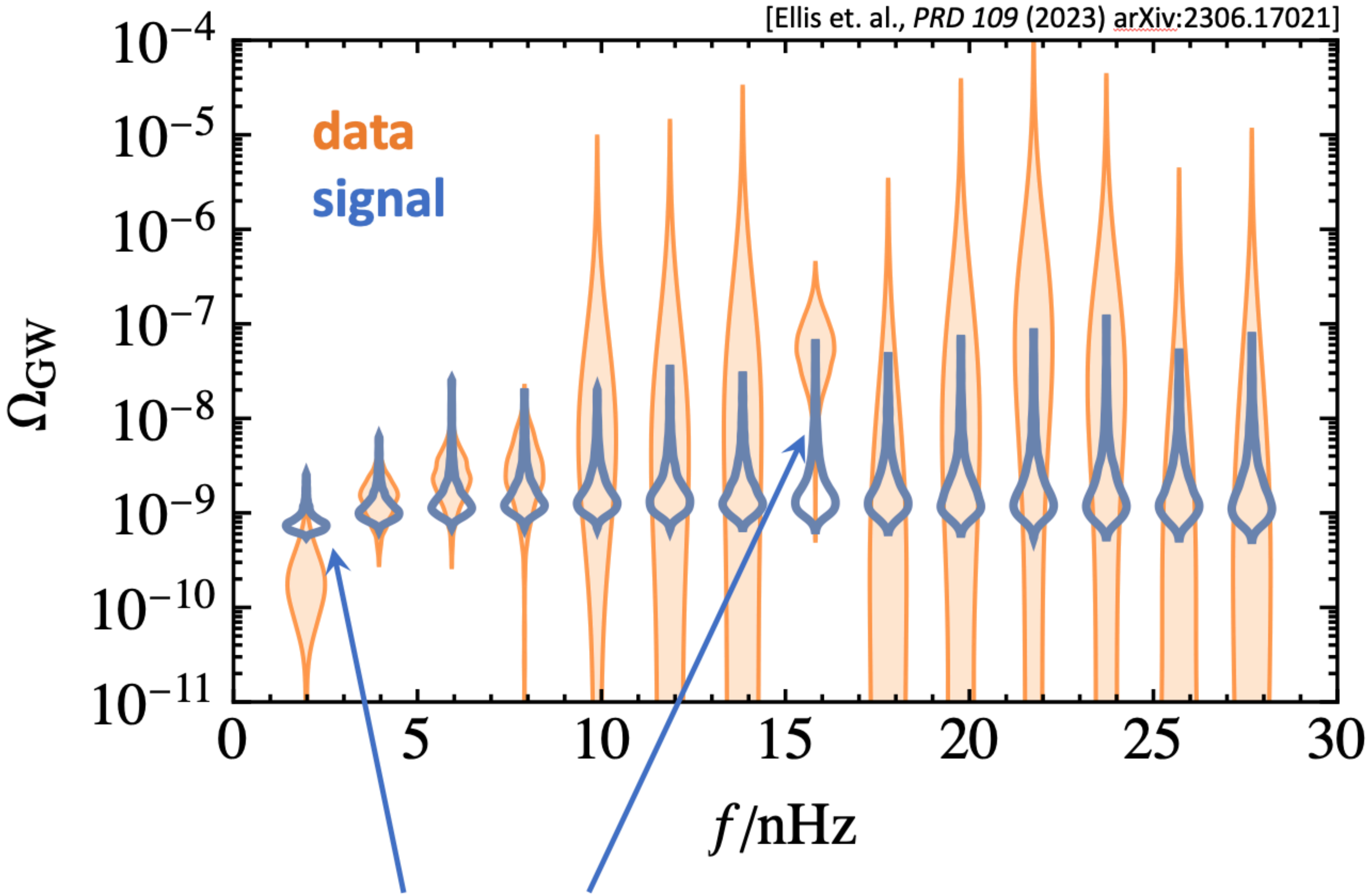
$P^{(1)}(\Omega)$ has a shallow power-law tail, caused by nearby binaris,

central limit theorem does not hold,

PDF of Ω_{tot} is not Gaussian.



PTA fit: GW driven binaries



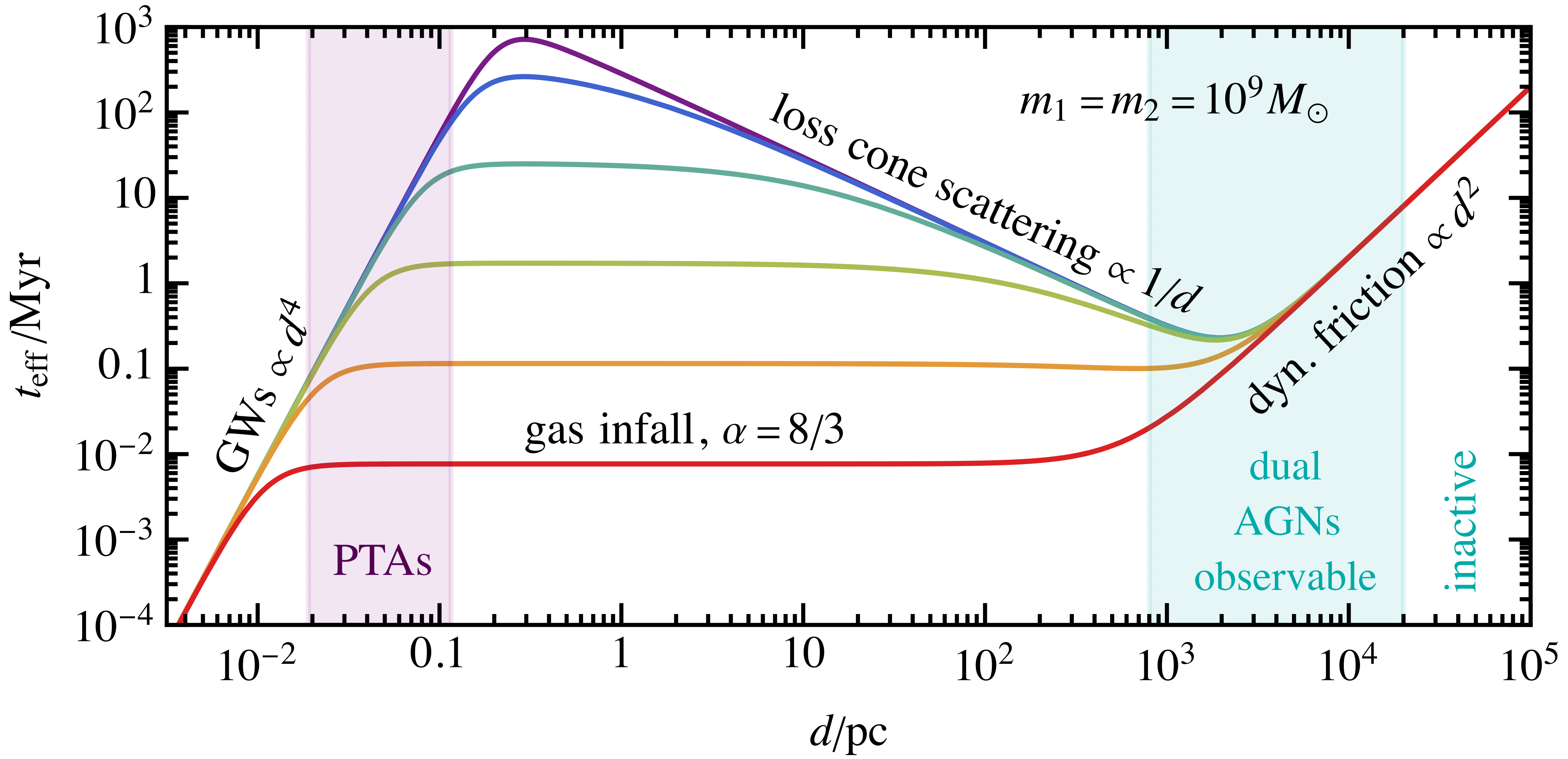
GW driven evolution gives
too flat spectrum.

Best fit merger efficiency:

$$p_{\rm BH} \approx 0.1$$

Low-frequency suppression

Environmental effects



- Shorter residence time:

$$\frac{\mathrm{d}t}{\mathrm{d}\ln f_b} = \frac{\mathrm{d}t_{\rm GW}}{\mathrm{d}\ln f_b}\left[1 + \frac{t_{\rm GW}}{t_{\rm env}}\right]$$

- GW-driven evolution takes over at small separations.

Eccentricities

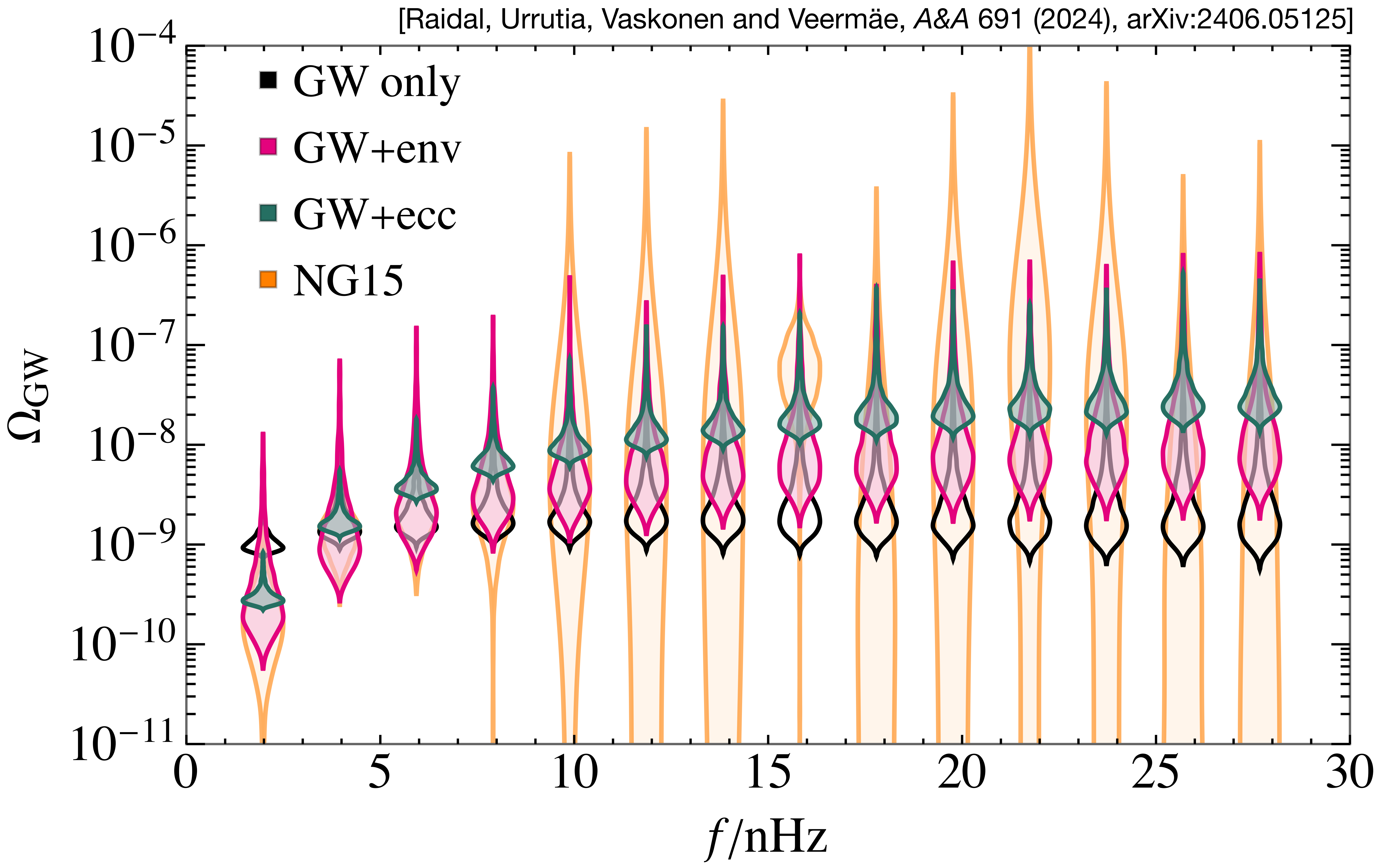
$$\frac{\mathrm{d}E_n}{\mathrm{d}t_r} = \frac{\mathrm{d}E_{\rm circ}}{\mathrm{d}t_r} g_n(e)\,, \quad \mathcal{F}(e) = \sum_{n=1}^{\infty} g_n(e) > 1$$

- Shorter residence time:

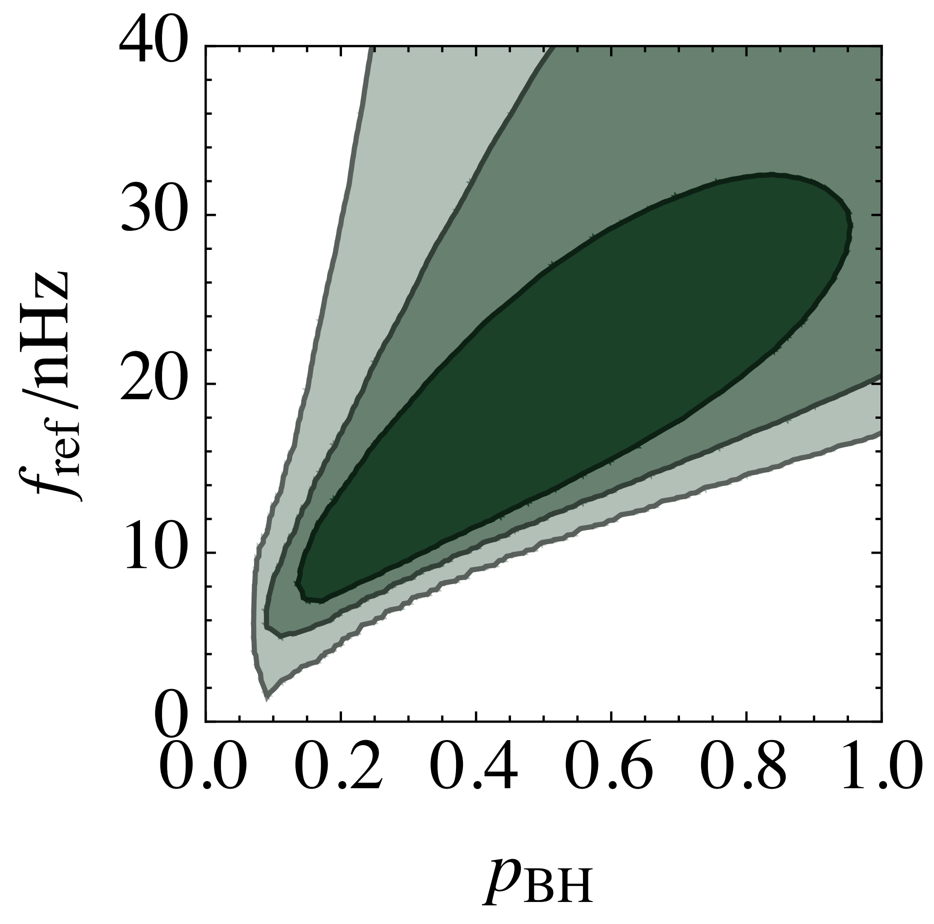
$$\frac{\mathrm{d}t}{\mathrm{d}\ln f_b} = \frac{\mathrm{d}t_{\rm circ}}{\mathrm{d}\ln f_b}\frac{1}{\mathcal{F}(e)}$$

- Signal from single binary spreads over multiple frequencies.
- GW emission circularises binaries.

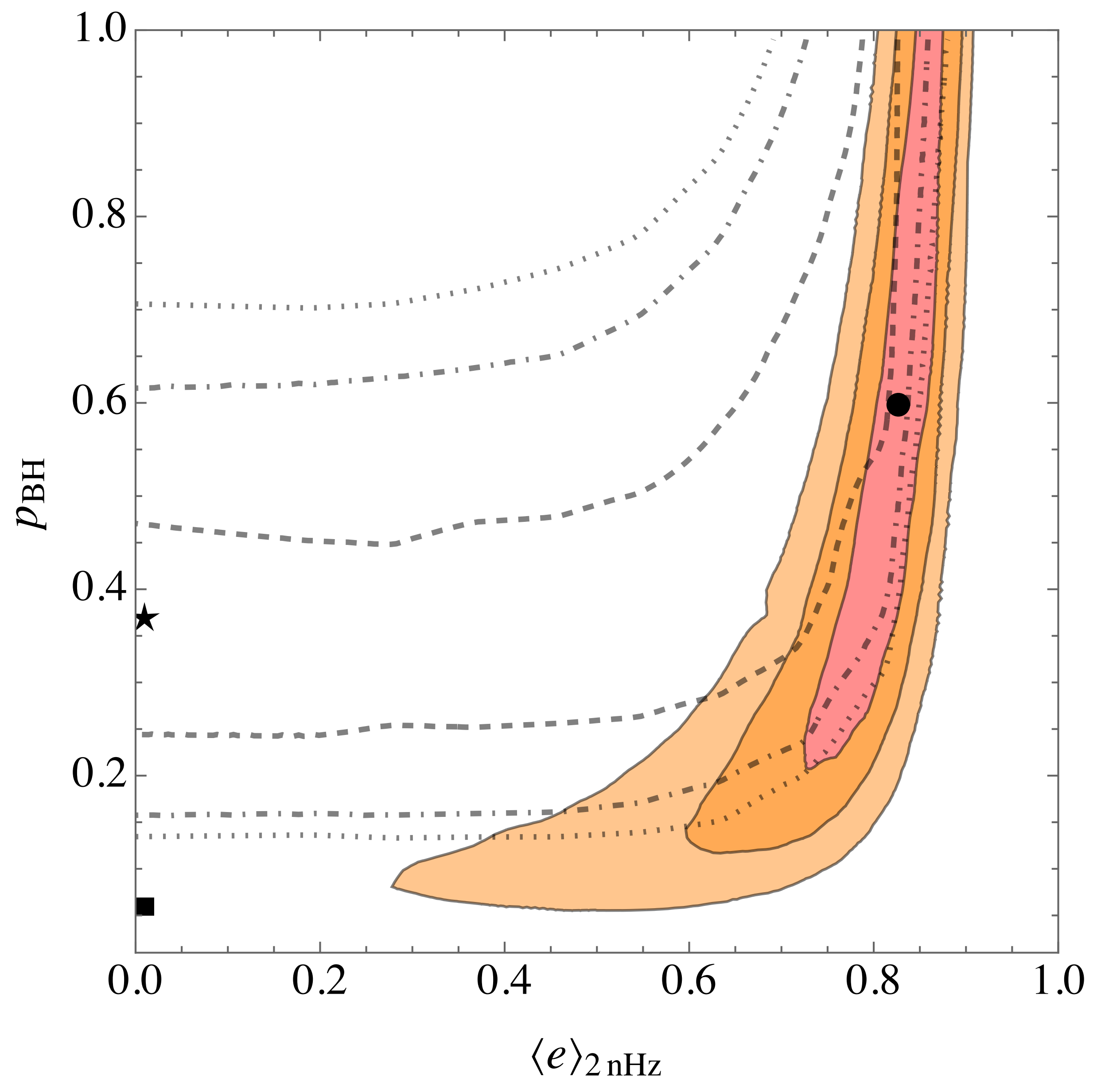
PTA fit: low-frequency suppression



env. effects at $f \gtrsim 5\,\mathrm{nHz}$

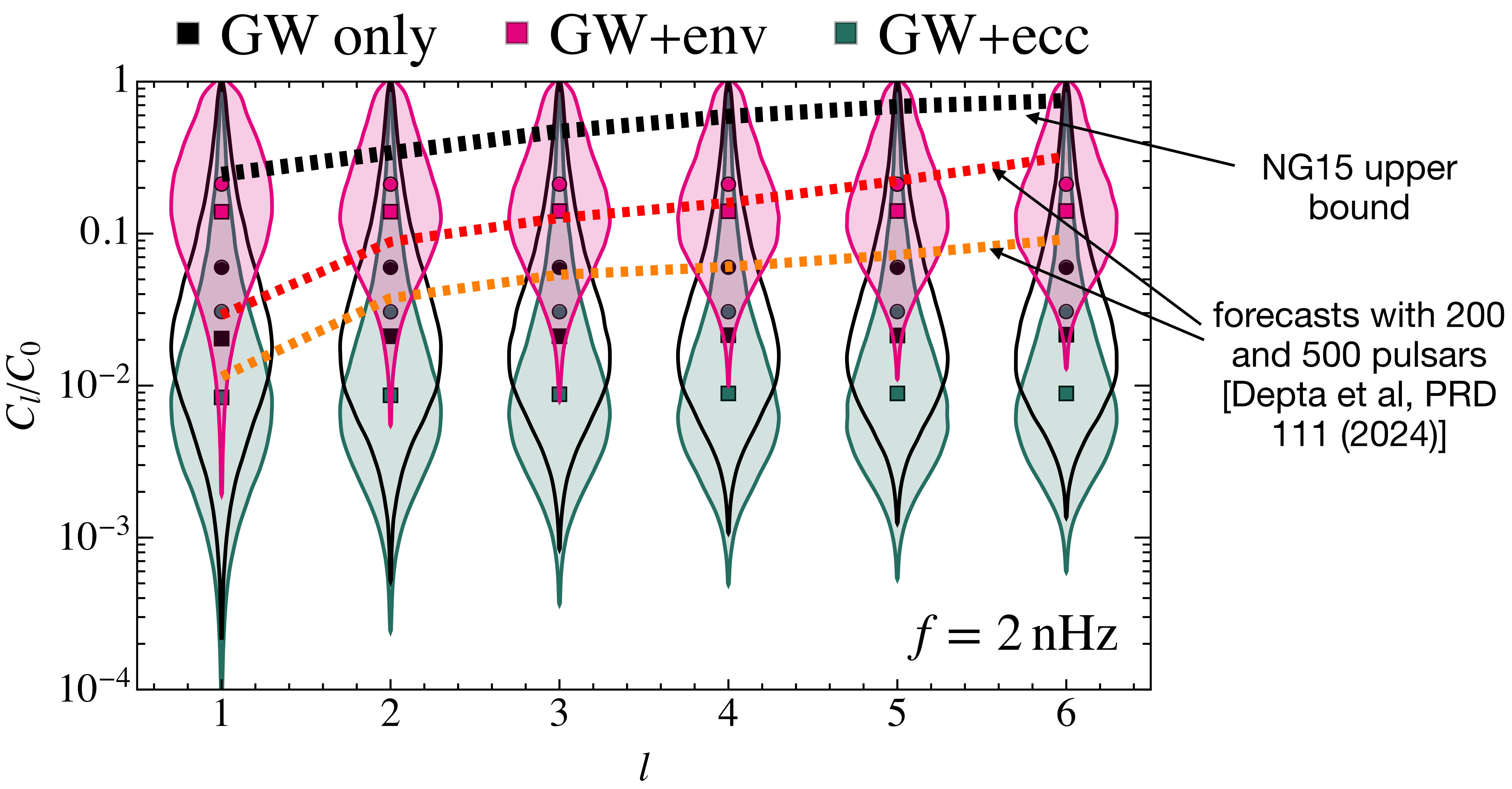


large eccentricities, $e \gtrsim 0.6$



Anisotropies

[Raidal, Urrutia, Vaskonen and Veermäe, arXiv:2411.19692]



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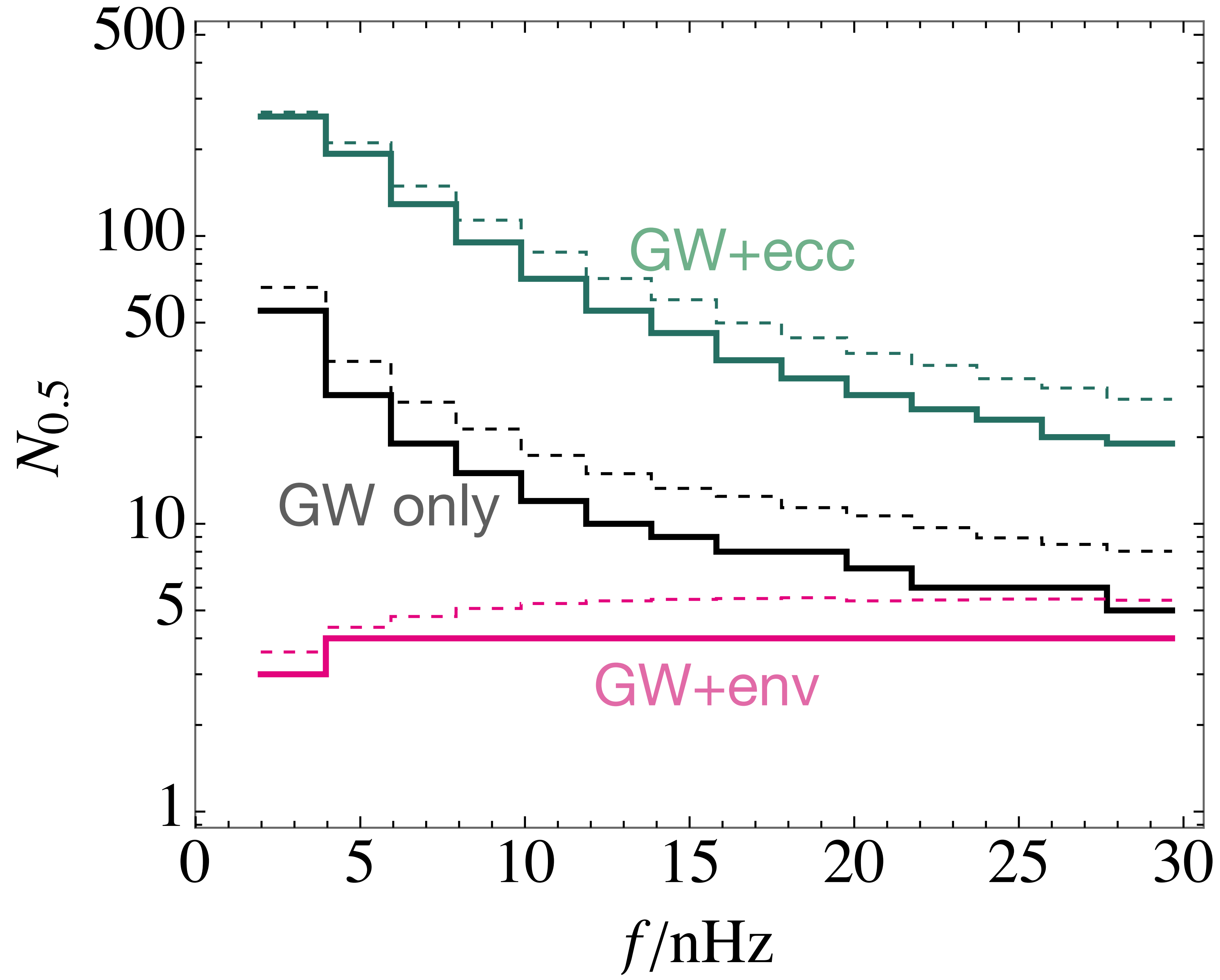
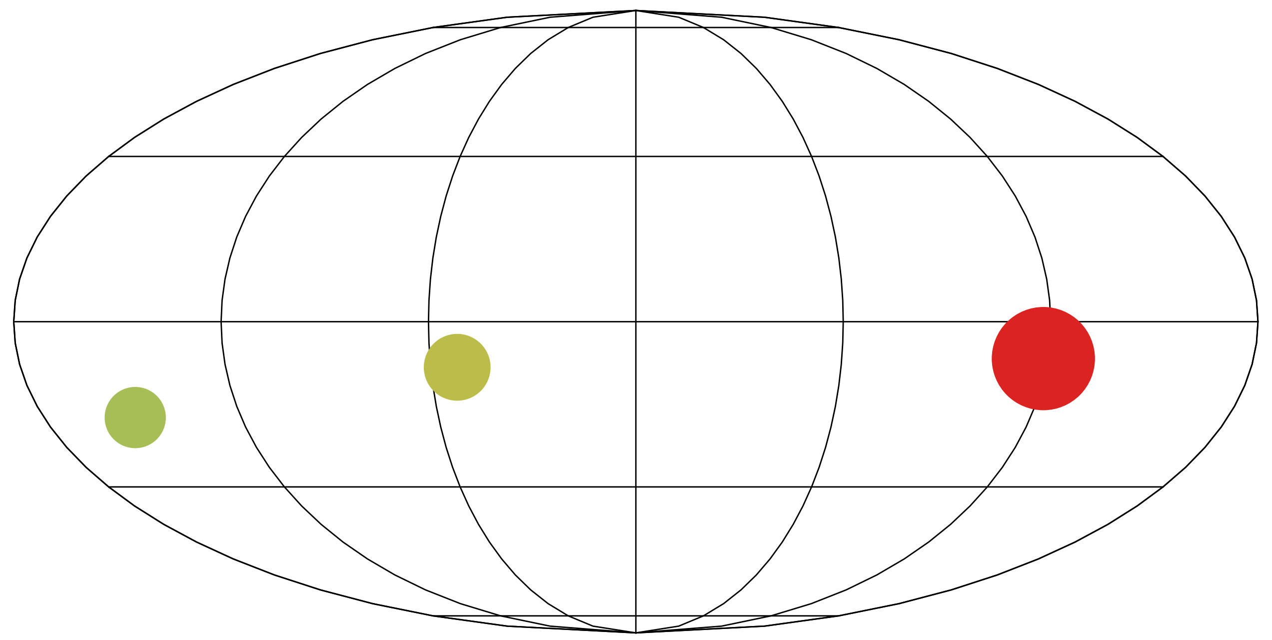
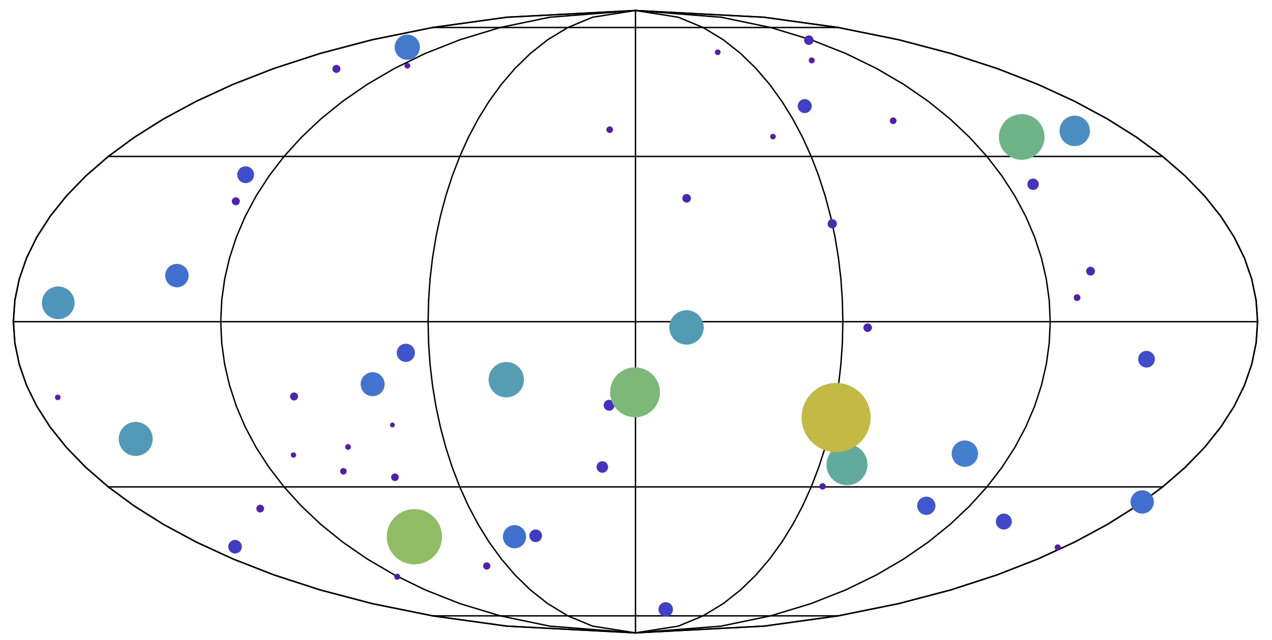


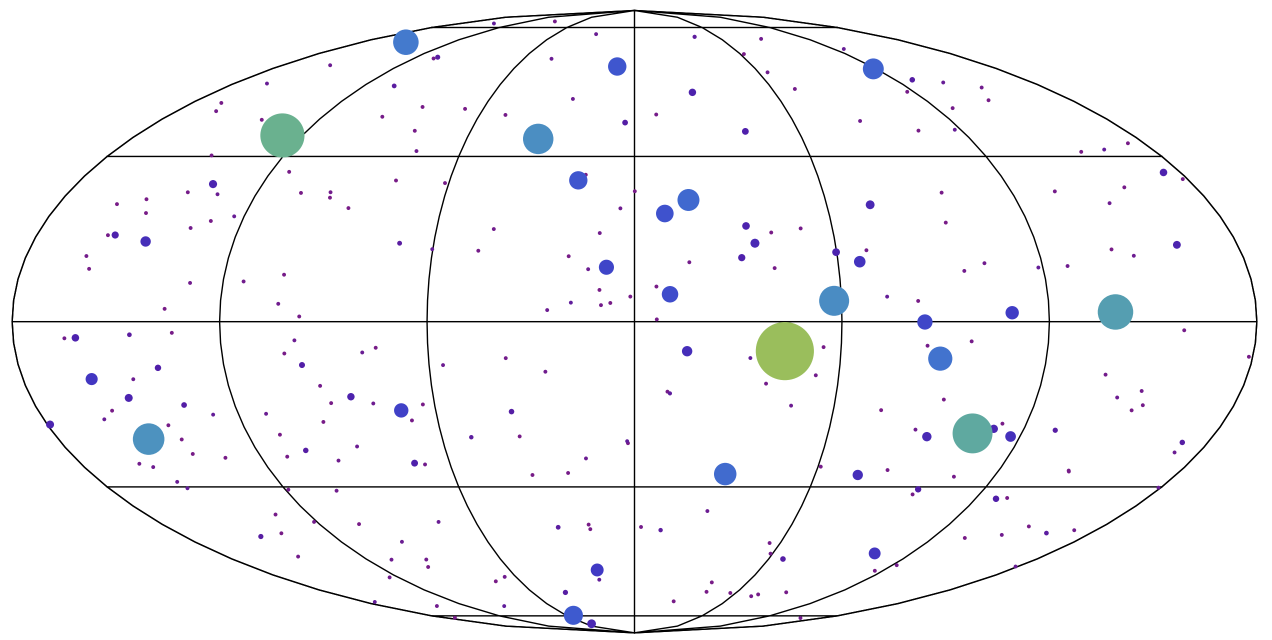
GW+env



GW only



GW+ecc



Summary

1. The PDF of SMBH GWB realizations has a power-law tail, $P(\Omega) \propto \Omega^{-5/2}$, arising from the possibility of having nearby sources.

2. The PTA GW spectrum shape indicates either strong environmental effects or highly eccentric binaries.

3. Spectral fluctuations and anisotropies provide a way to distinguish SMBH origin of the PTA signal from cosmological sources.