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Gravitational waves from supermassive black holes at pulsar timing arrays

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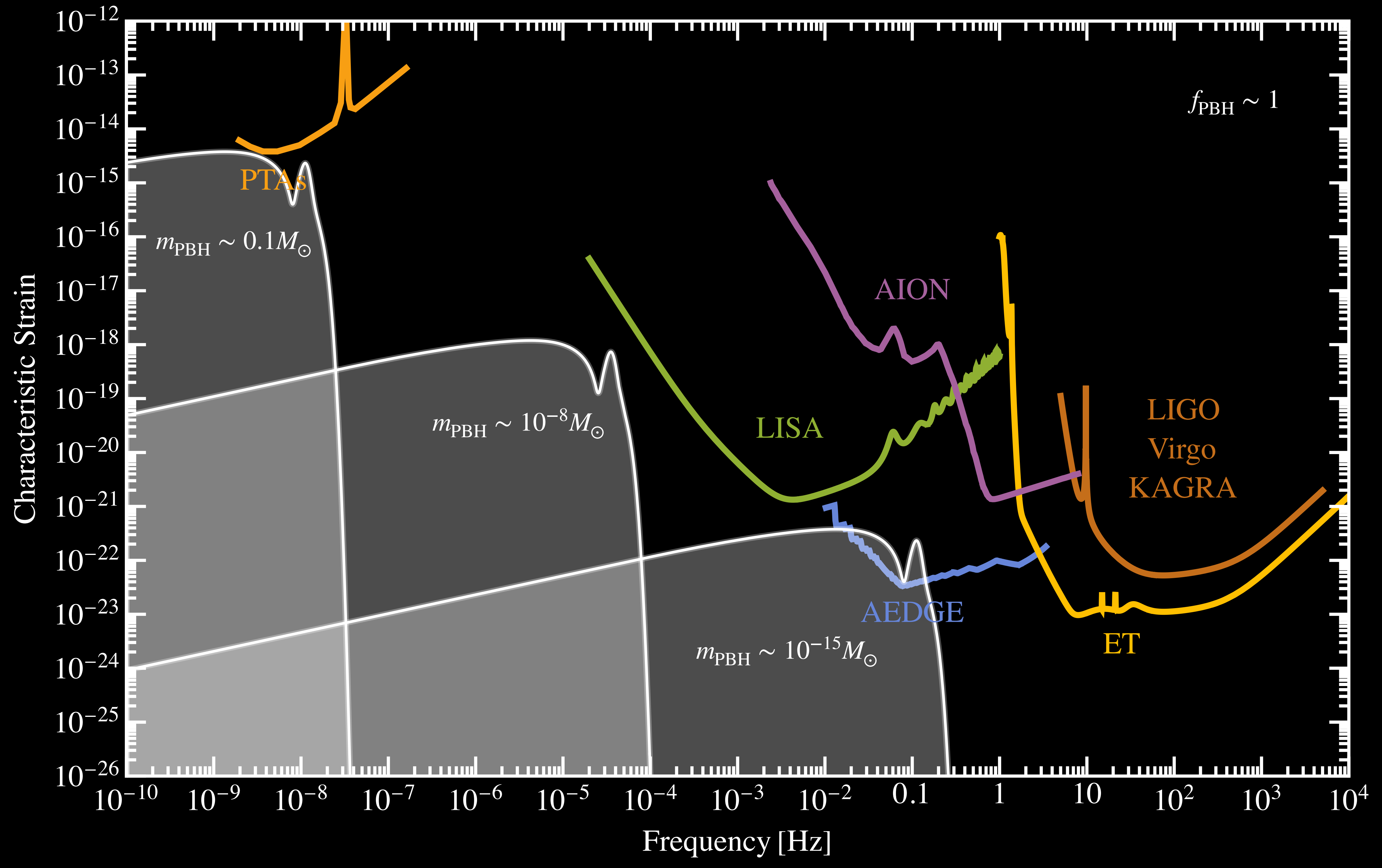
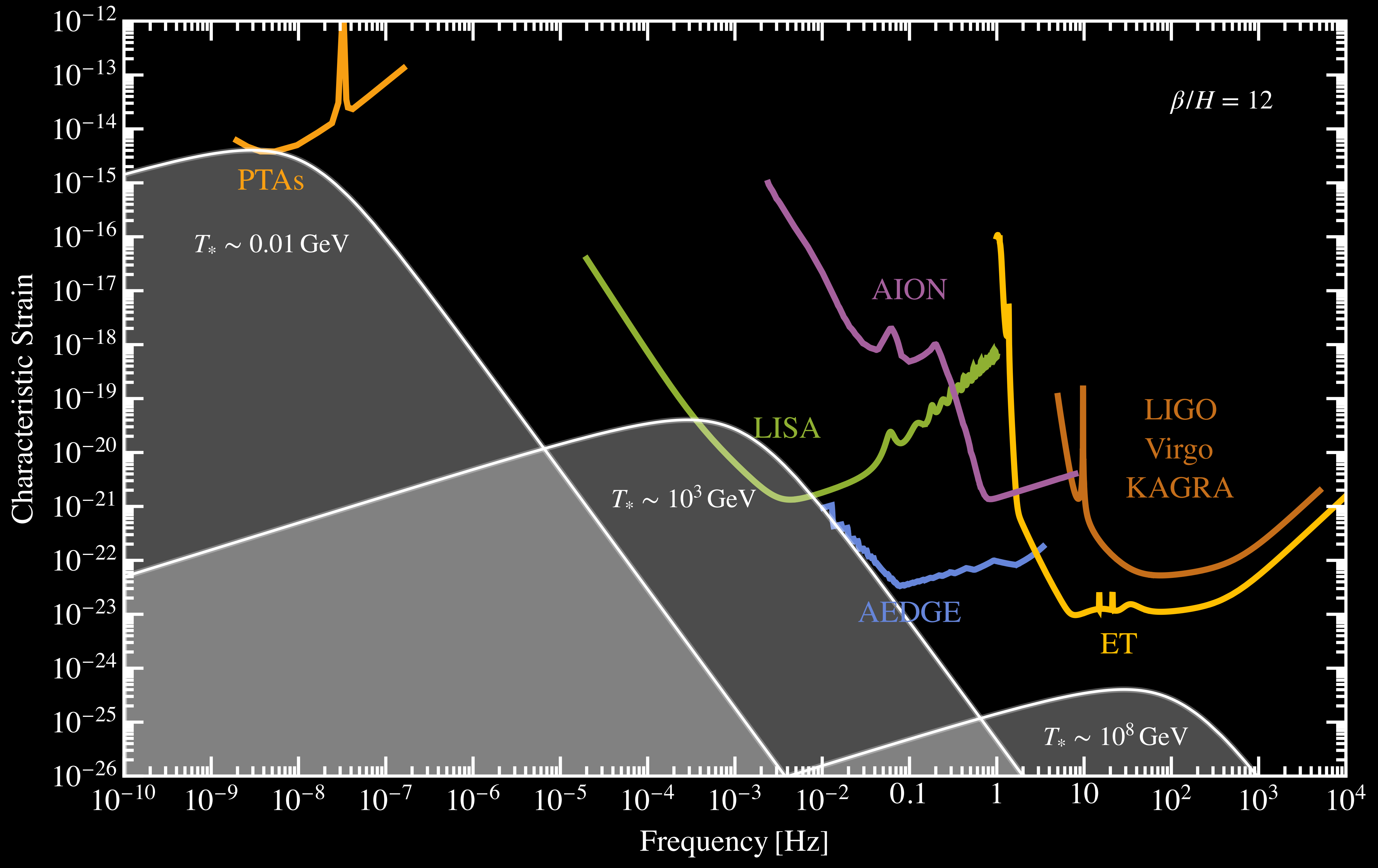
Warsaw, 27 June 2025

Scalar-induced GWs

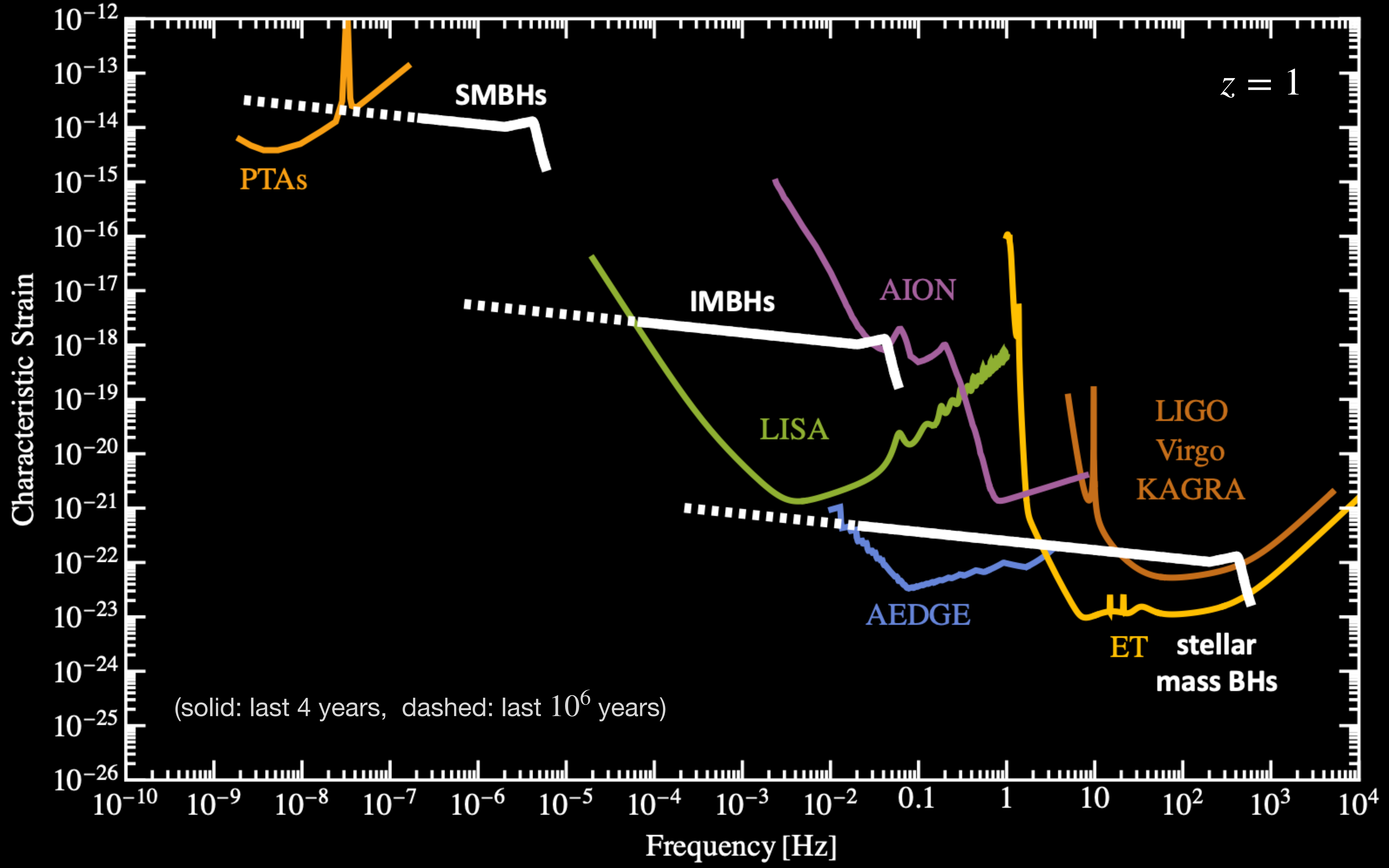


GWs from phase transitions



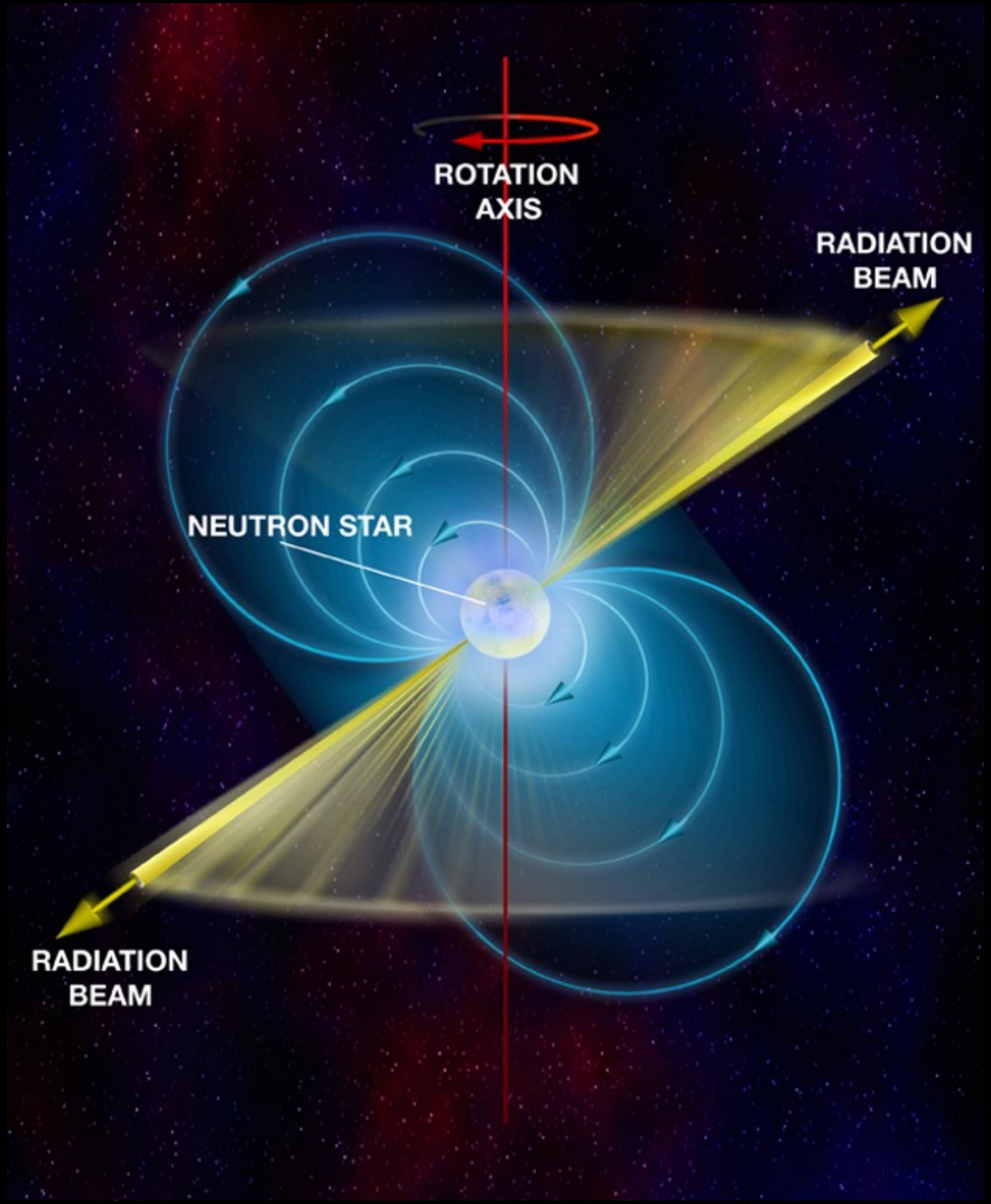
cosmic strings, domain walls etc…

Black hole binaries



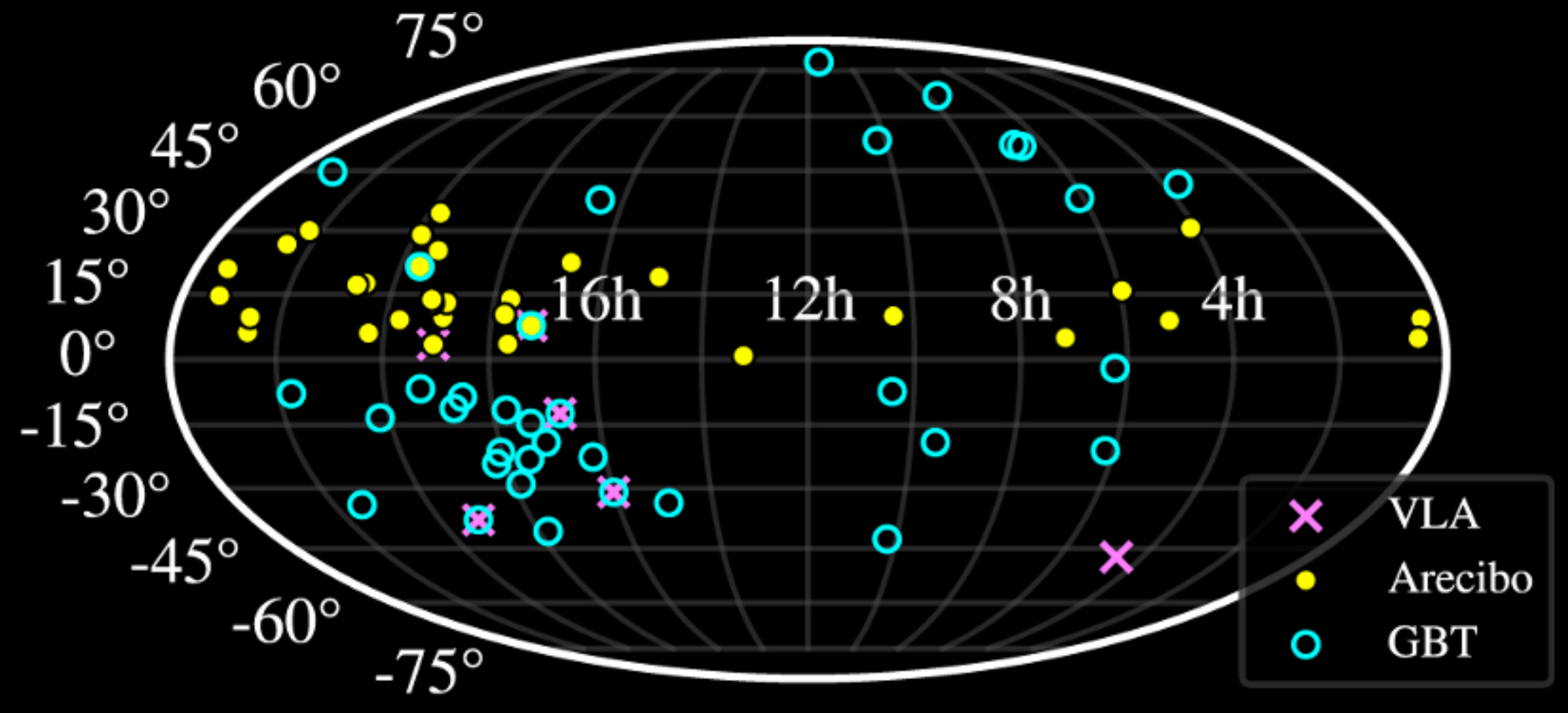
- Formation of SMBHs
- Standard sirens, gravitational lensing, cosmological parameters
- Dark matter effects: halo mass function, environmental effects, seeds for SMBHs

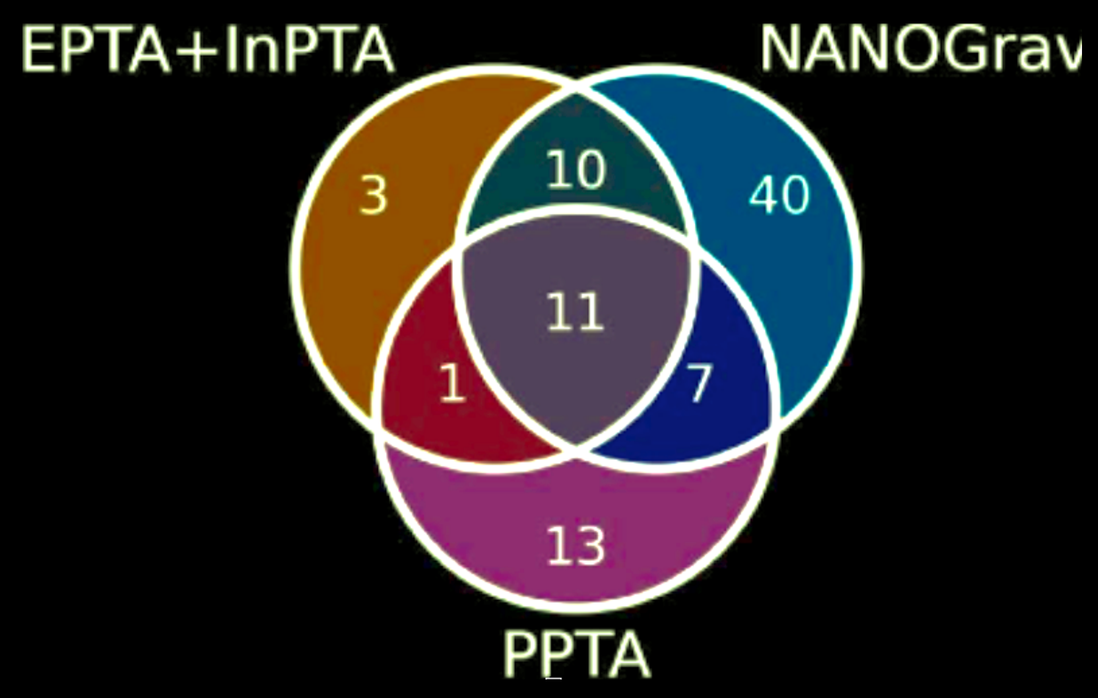
Pulsar timing arrays



- **Timing series** from a set of millisecond pulsars.
- GWs induce noise in the timing that is **correlated** between pulsars.
- Frequency range limited by observation time:

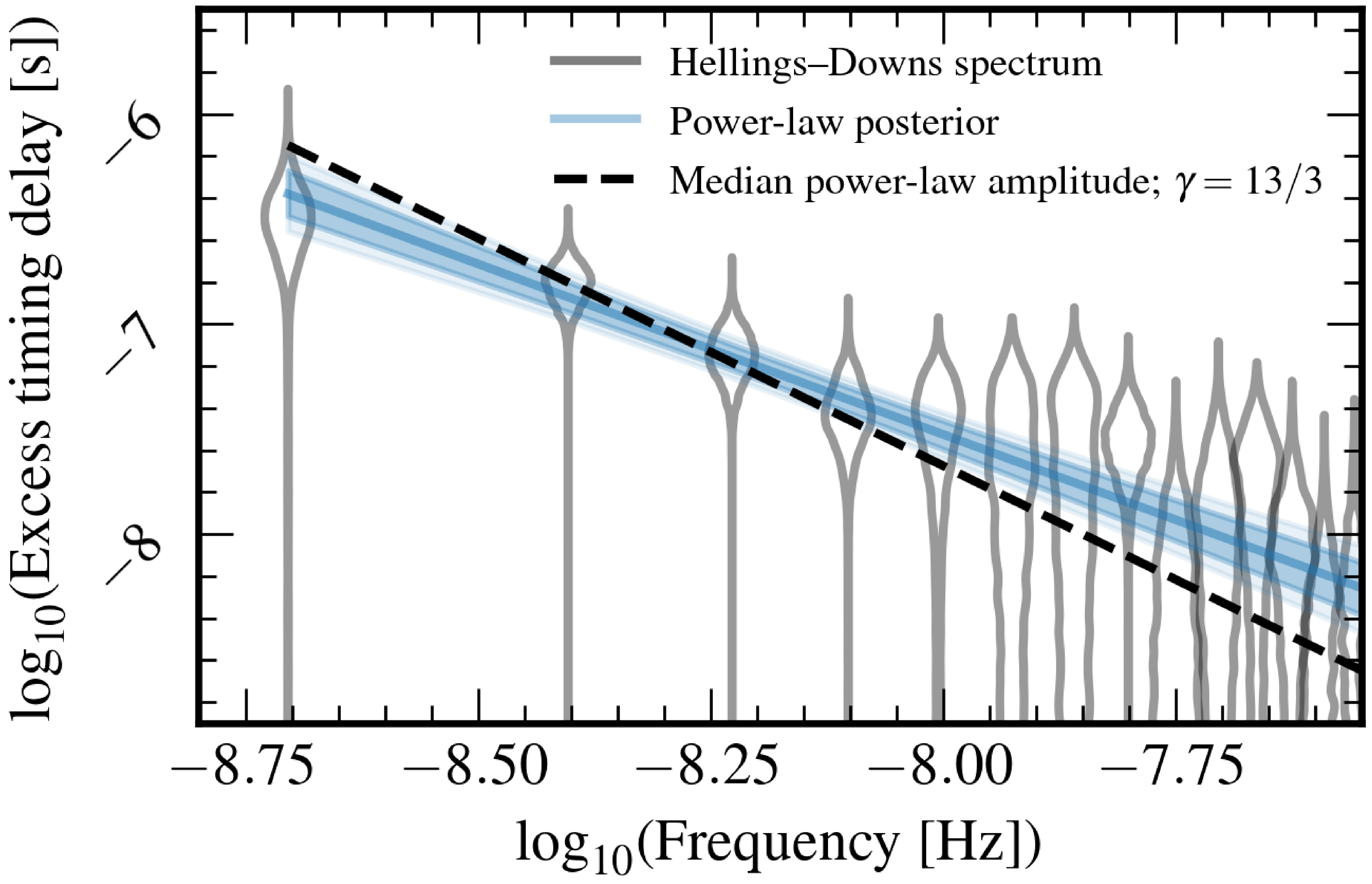
$$(2\pi D)^{-1} \sim 0.001\,\mathrm{nHz} \quad \text{but} \quad 1/T_{\mathrm{obs}} \sim \mathrm{nHz}\,.$$

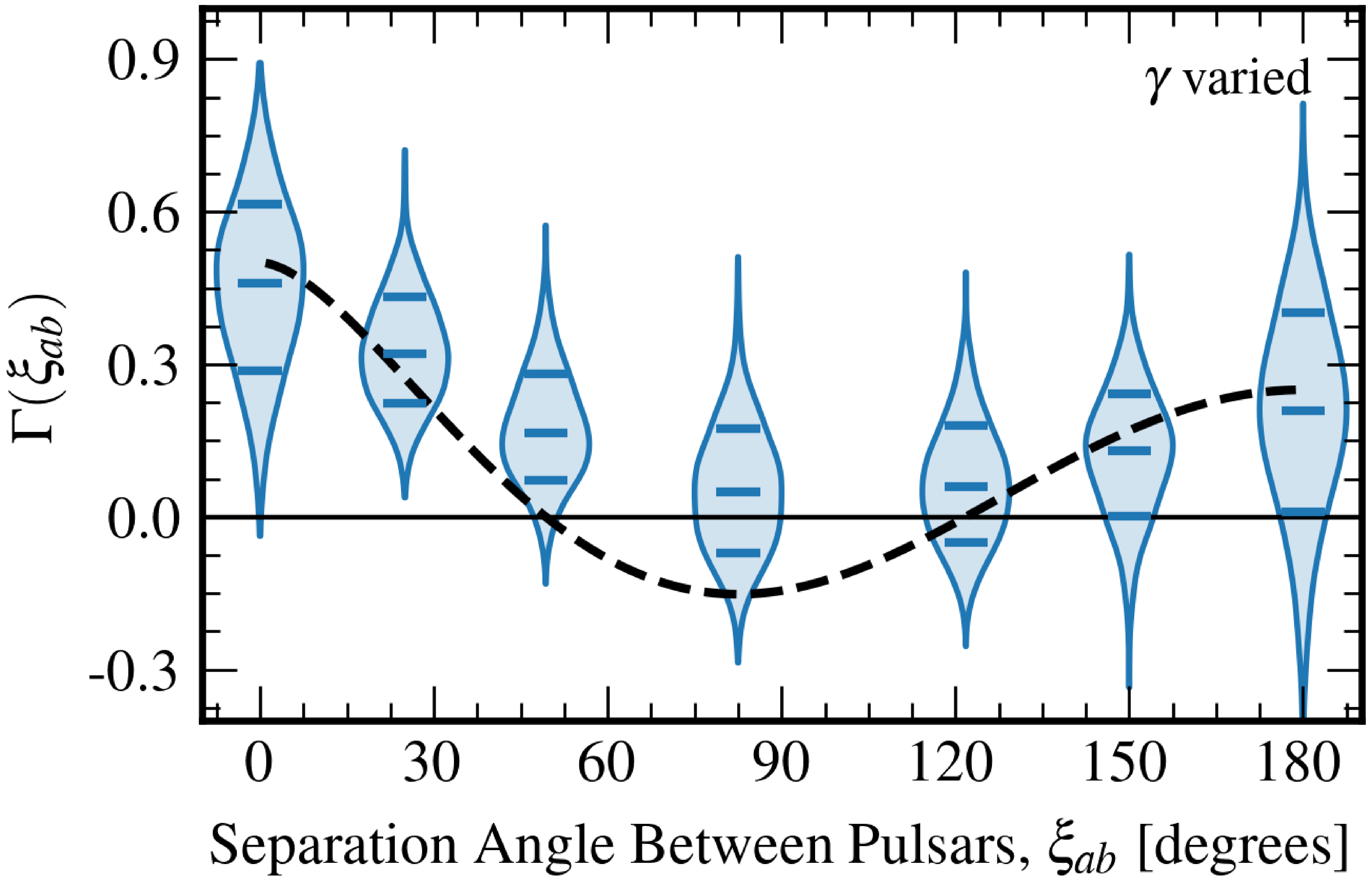




Strong evidence for a nHz GW background at PTAs

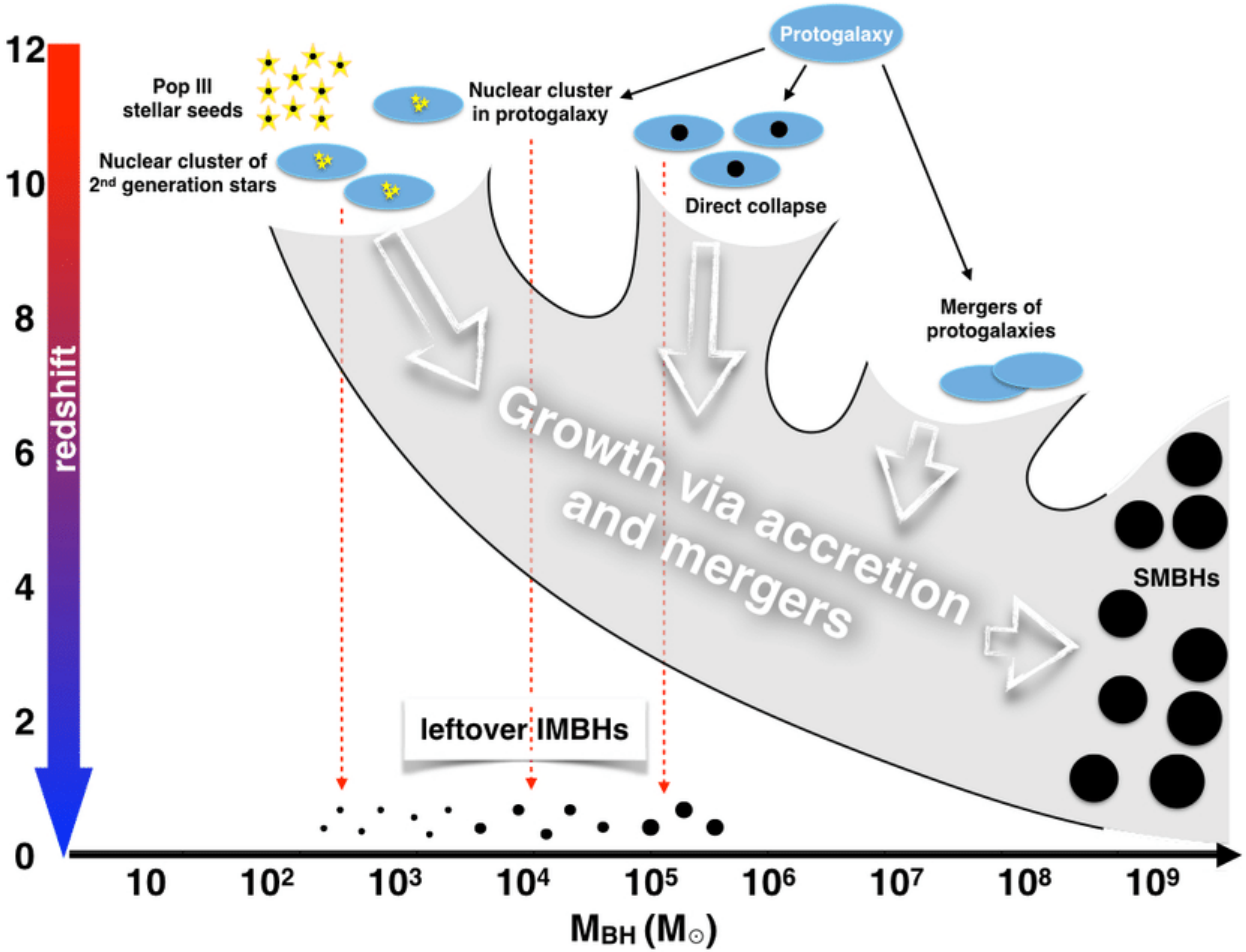
[NANOGrav, *ApJ. Lett.* 951 (2023), arXiv:2306.16213]





Common spectrum red noise **+** Hellings-Downs angular correlations

Supermassive black holes



Galaxy merger

↓

SMBH pair

↓

(dual) AGN

↓

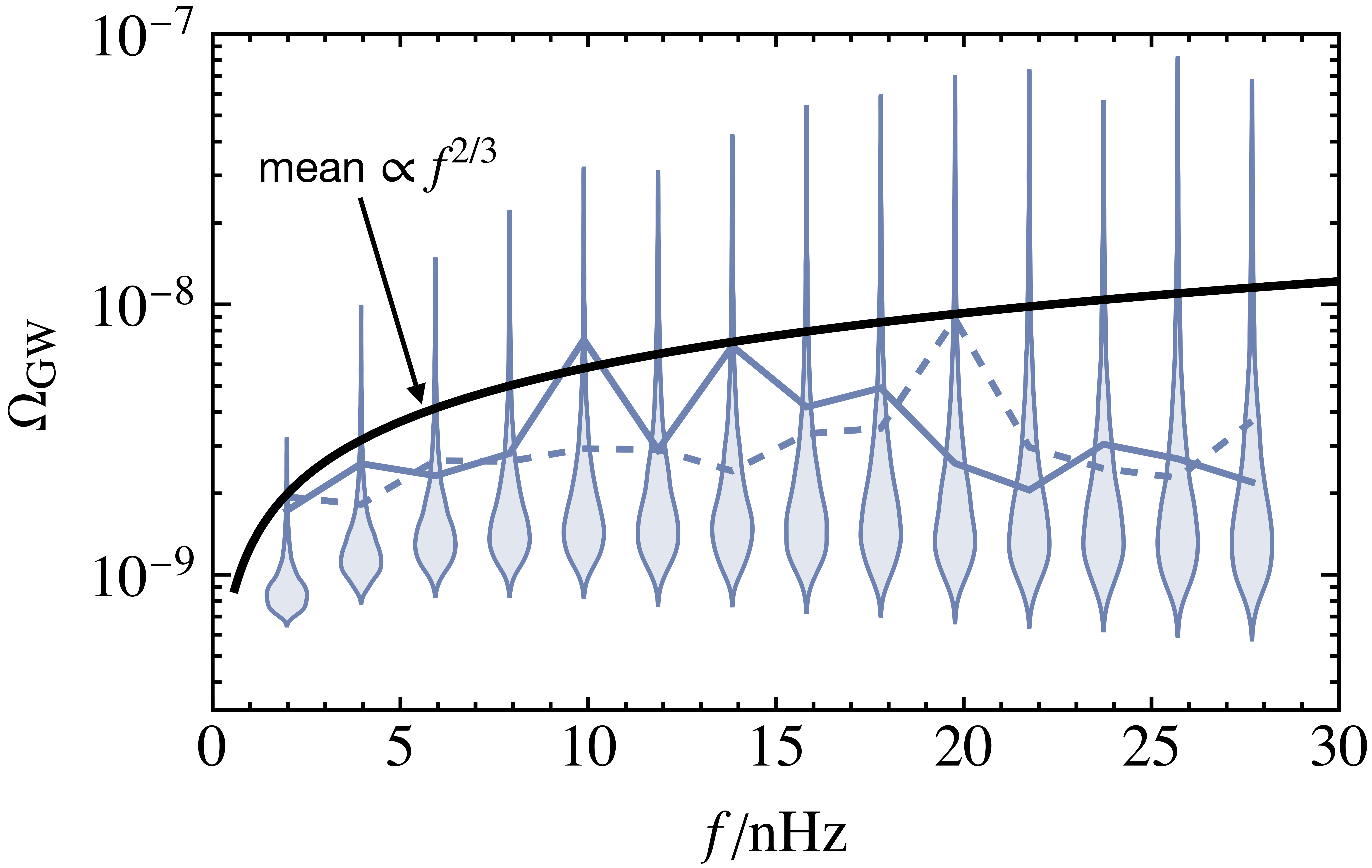
GW driven binary

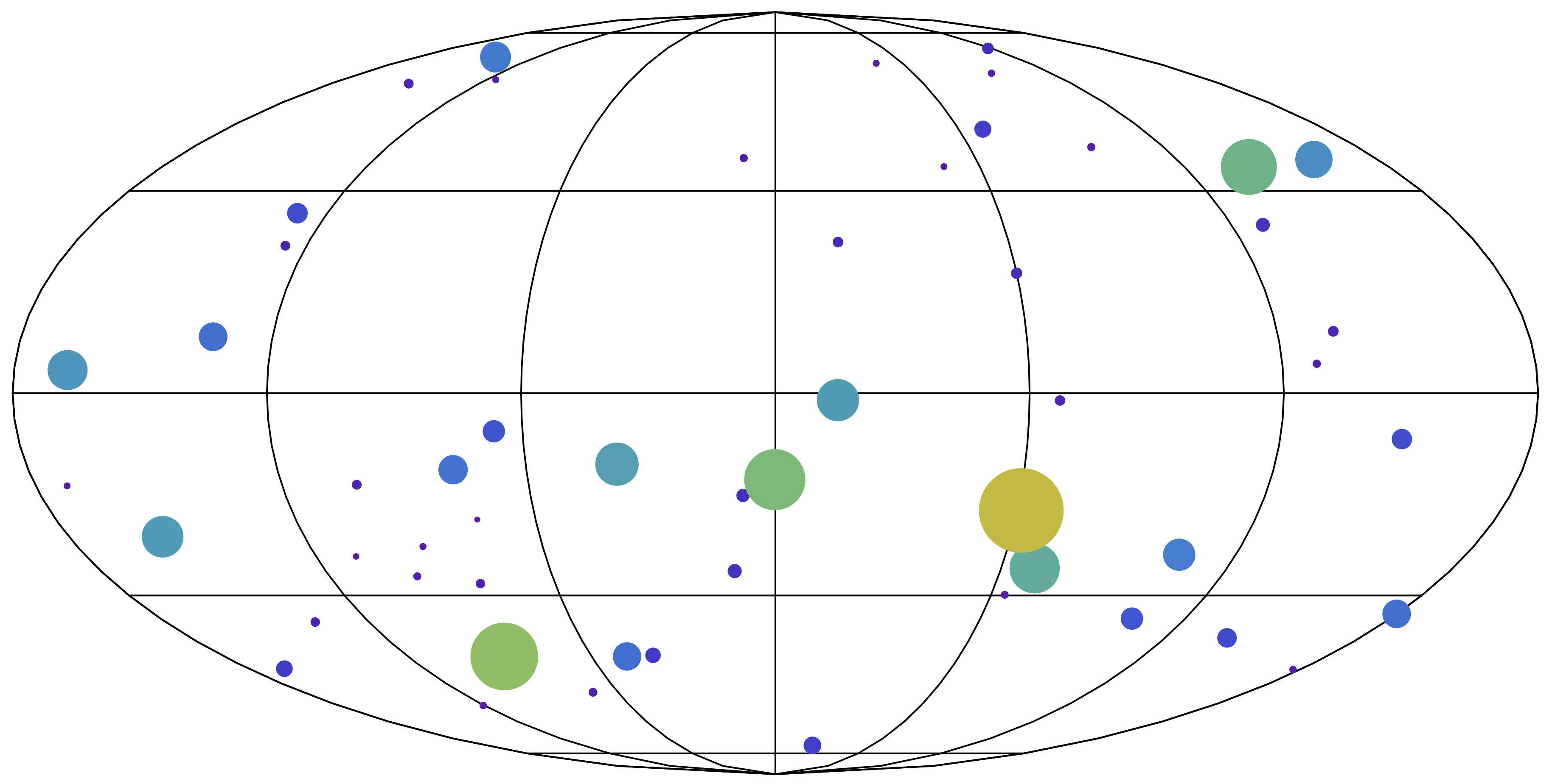
$$\tau_{\rm GW} = \frac{5}{256}(1+z)\left[(1+z)f\right]^{-\frac{8}{3}}\mathscr{M}^{-\frac{5}{8}}$$

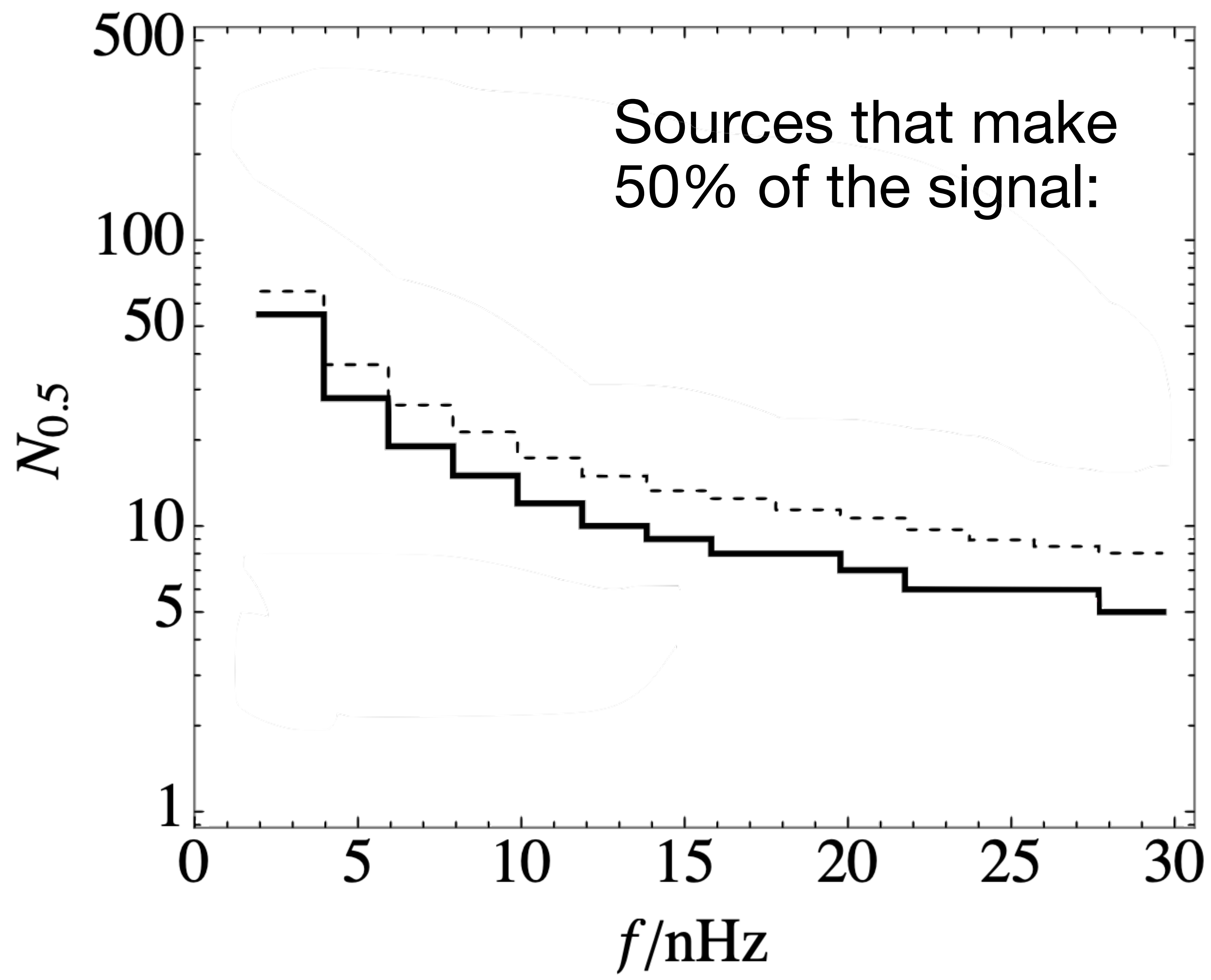
$$\approx \frac{4\times10^4\,{\rm yr}}{(1+z)^{\frac{5}{3}}}\left[\frac{f}{10\,{\rm nHz}}\right]^{-\frac{8}{3}}\left[\frac{\mathscr{M}}{10^9 M_\odot}\right]^{-\frac{5}{8}}$$

SMBH GW background

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







SMBH GW background

contribution from one binary

$\Omega_{\rm GW}^{(1)} \propto (\mathscr{M} f)^{10/3} D_L^{-2}$

$$\langle \Omega_{\rm tot} \rangle = \int \mathrm{d}\lambda \frac{\mathrm{d}t_c}{\mathrm{d}\ln f} \Omega^{(1)}$$

merger rate

$\mathrm{d}\lambda \propto \mathrm{d}R_{\rm BH}$

binary evolution

$\propto (1+z)\mathscr{M}^{-5/3} f^{-8/3}$

$\Longrightarrow$ PDF of binary parameters

Generate realizations of the binary population:

$$\Omega_{\rm tot}(f_i) = \sum_{j=1}^{N(f_i)} \Omega_j^{(1)}$$

Too slow for accurate construction of the PDF of $\Omega_{\rm tot}$ needed for the fit:

$$\mathscr{L} = \prod_{j=1}^{N_f} \int \mathrm{d}\Omega_{\rm tot} P_{\rm data}(\Omega_{\rm tot} \,|\, f_j) P_{\rm model}(\Omega_{\rm tot} \,|\, f_j, \vec{\theta}) \,.$$

- **NANOGrav**: Gaussian approximation.
- **EPTA**: a small number of realization.

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, central limit theorem does not hold,

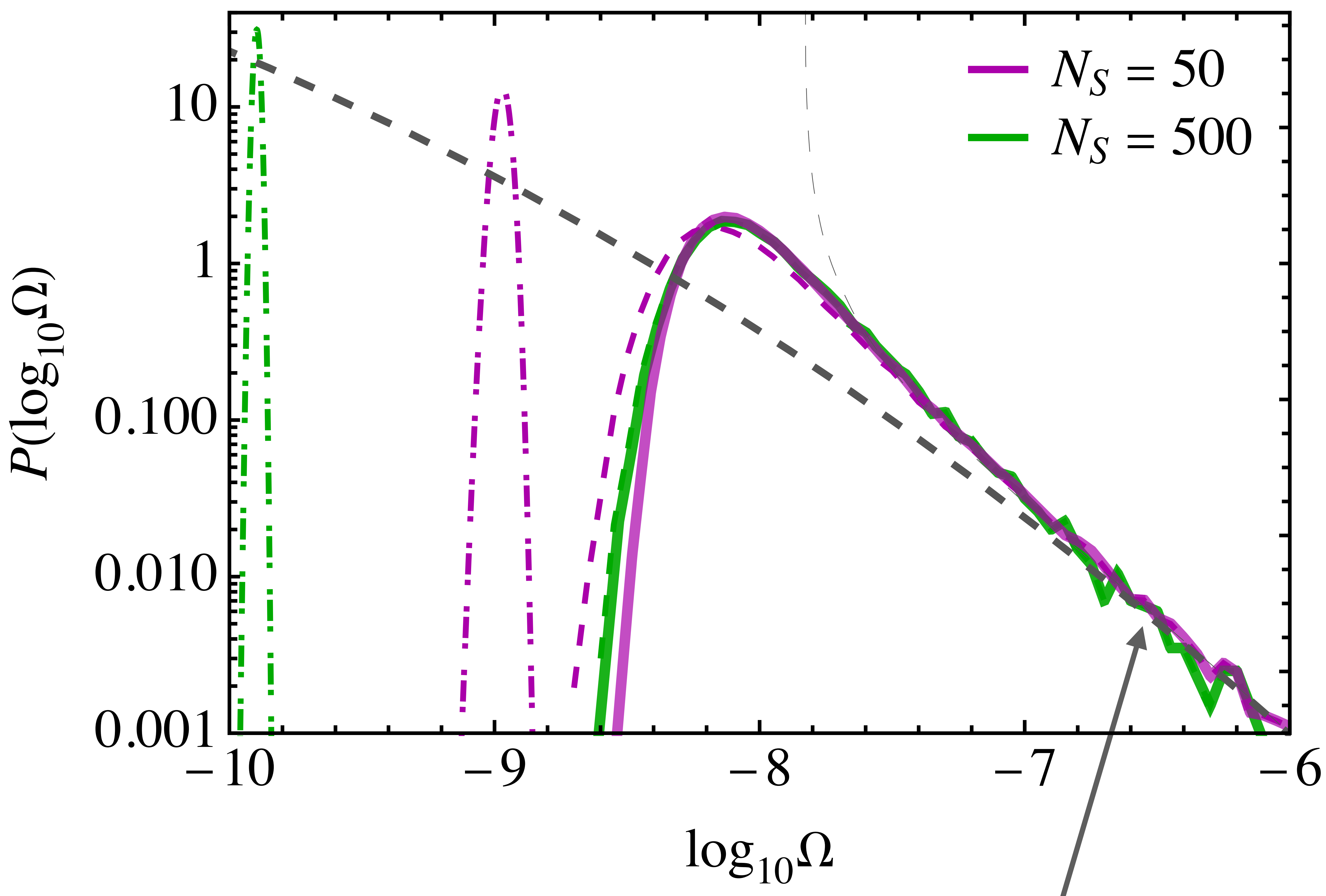
PDF of $\Omega_{\rm tot}$ is not Gaussian.

$$\Omega_{\rm tot} = \Omega_{\rm weak} + \Omega_{\rm strong}$$

weak sources, $\Omega_{{\rm GW},j} < \Omega_{\rm thr}$ follow a narrow Gaussian

strong souces generated from $P^{(1)}$

PDF of $\Omega_{\rm tot}$



$\bar{N}P^{(1)}(\Omega) \propto \Omega^{-5/2}$

long tail caused by nearby binaries

SMBH merger rate

probability that the SMBH pair merges

merger rate of halos (from EPS formalism or large scale simulations)

the distribution of SMBH masses in halos of mass $M_{\mathrm{v},j}$:

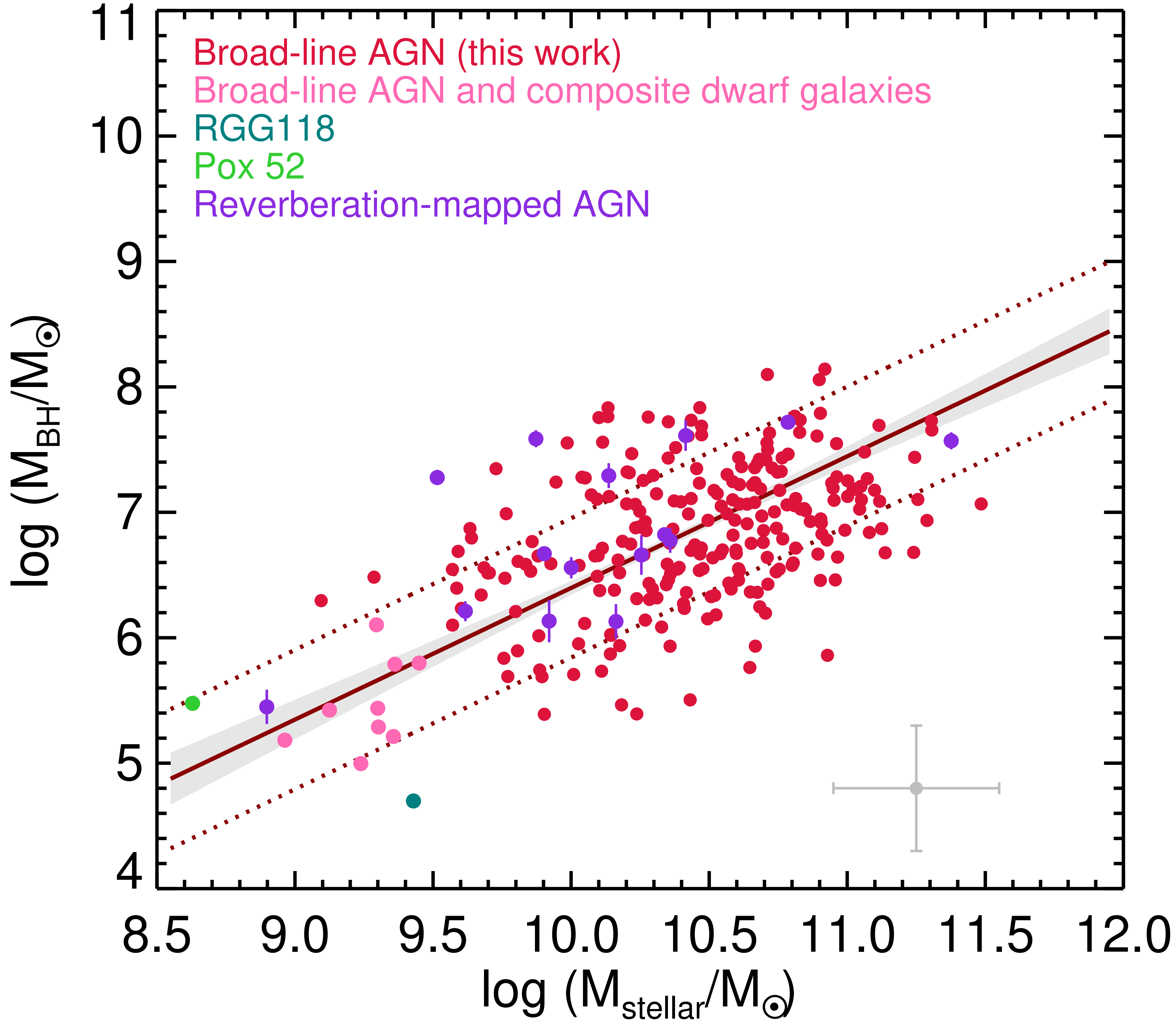
1. halo mass - stellar mass
2. stellar mass - BH mass

$$\frac{\mathrm{d}R_{\mathrm{BH}}}{\mathrm{d}m_1\mathrm{d}m_2} = p_{\mathrm{BH}} \int \mathrm{d}M_1\mathrm{d}M_2 \, \frac{\mathrm{d}R_h}{\mathrm{d}M_1\mathrm{d}M_2} \prod_{j=1,2} \frac{\mathrm{d}P(m_j \,|\, M_j)}{\mathrm{d}m_j}$$

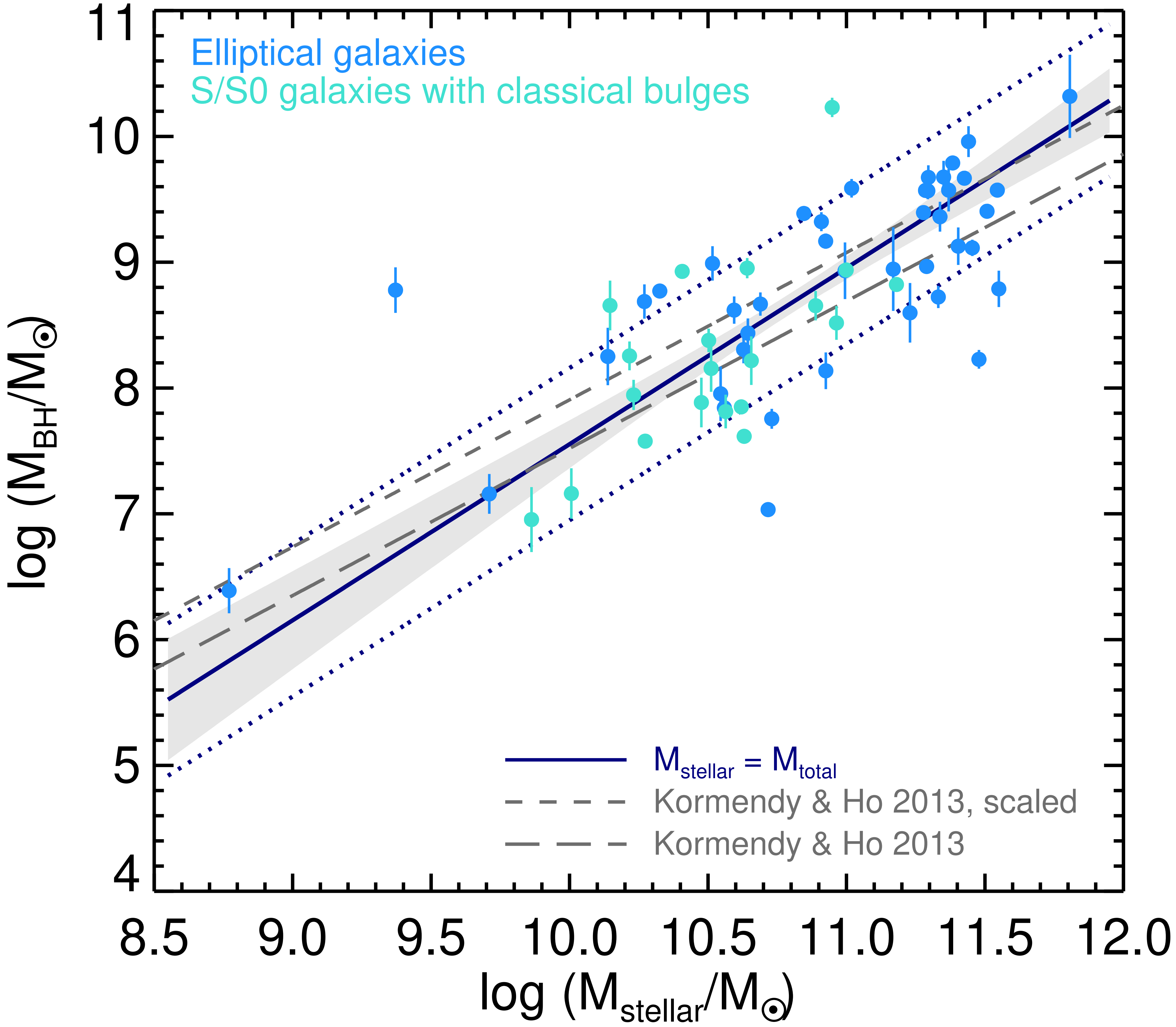
Stellar mass - BH mass relation

[Reines & Volonteri, *ApJ* 813 (2015)]

local AGNs:



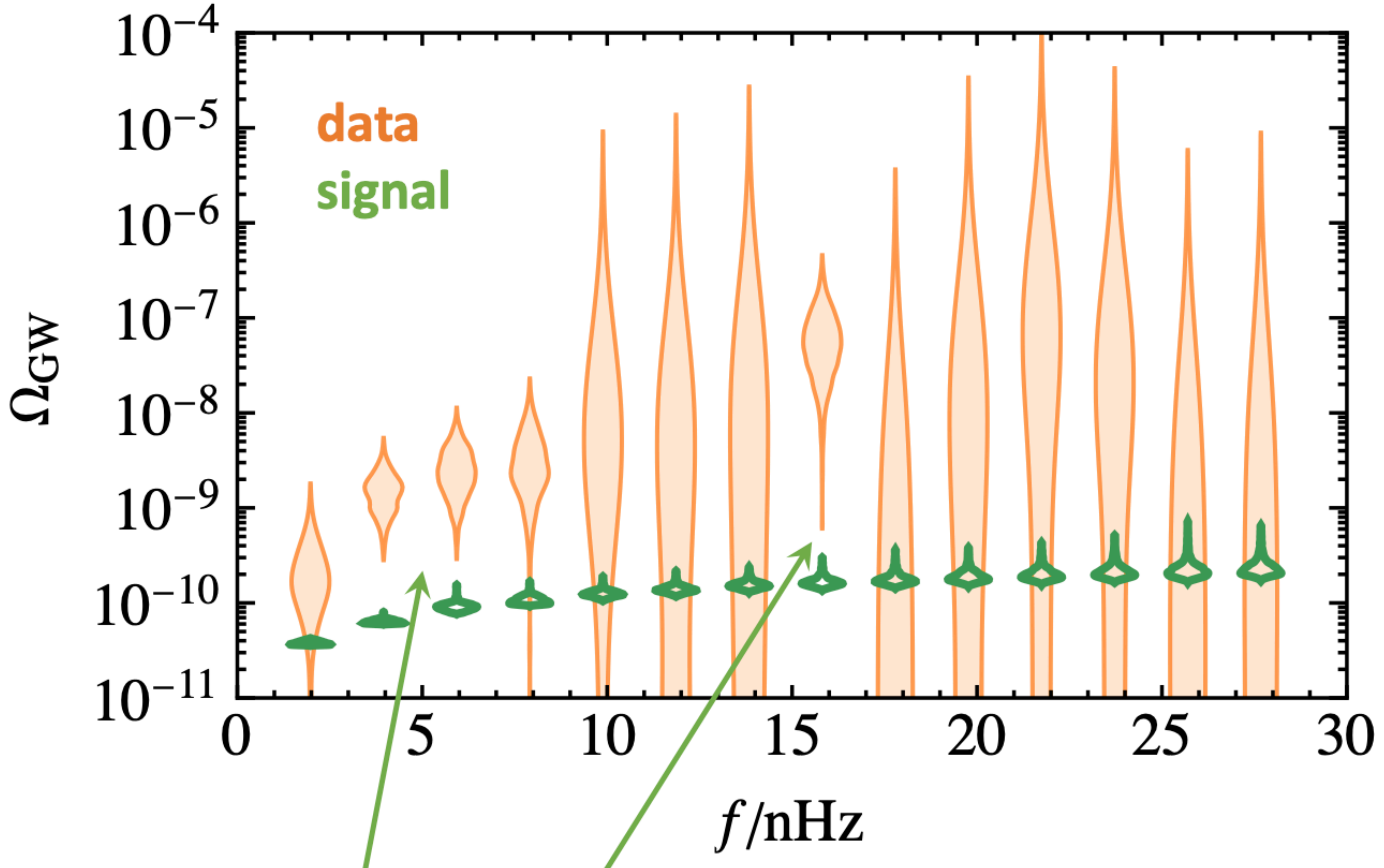
local inactive galaxies:



PTA fit: GW driven binaries

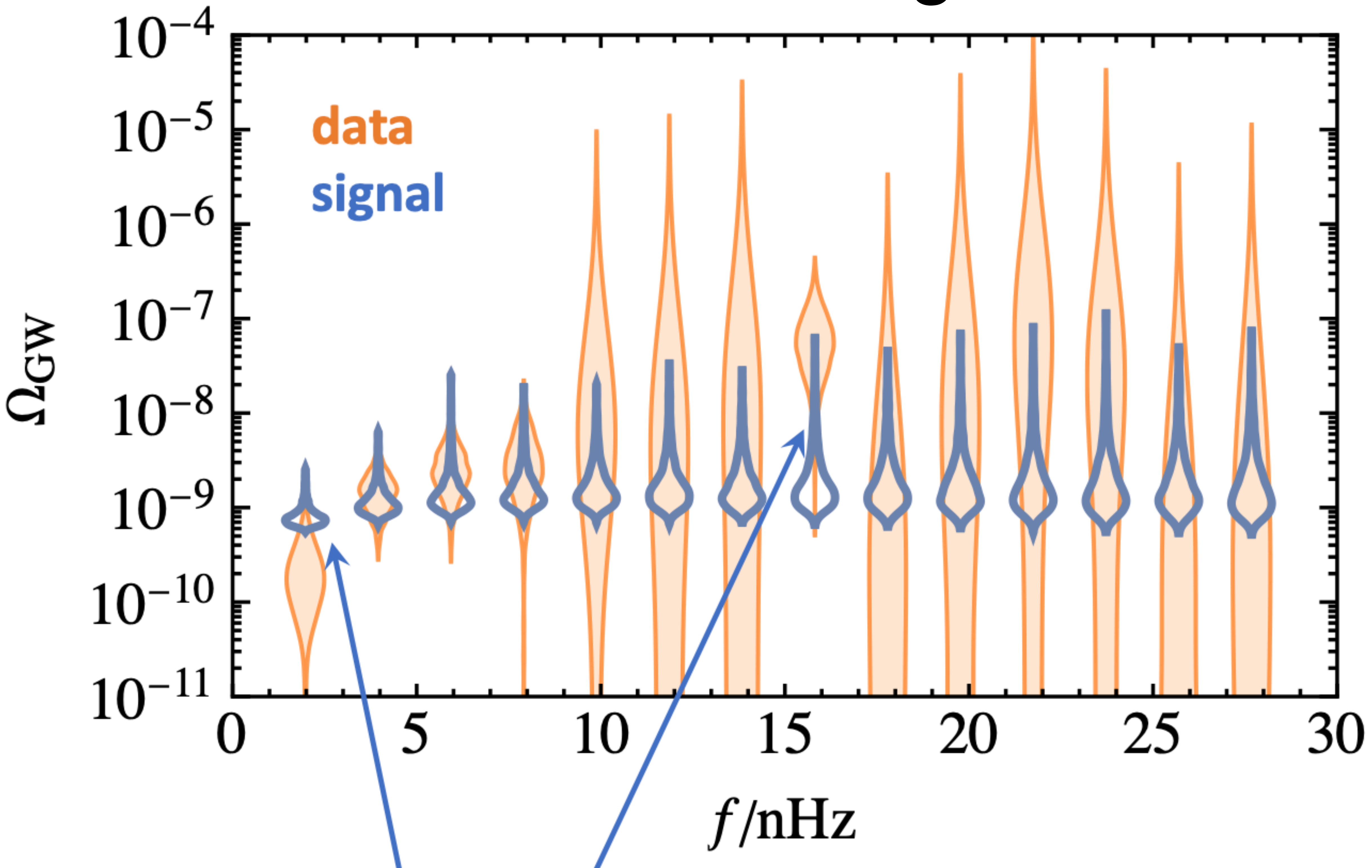
[Ellis et. al., *PRD* 109 (2023)]

local AGNs:



Local AGN relation gives
too small amplitude.

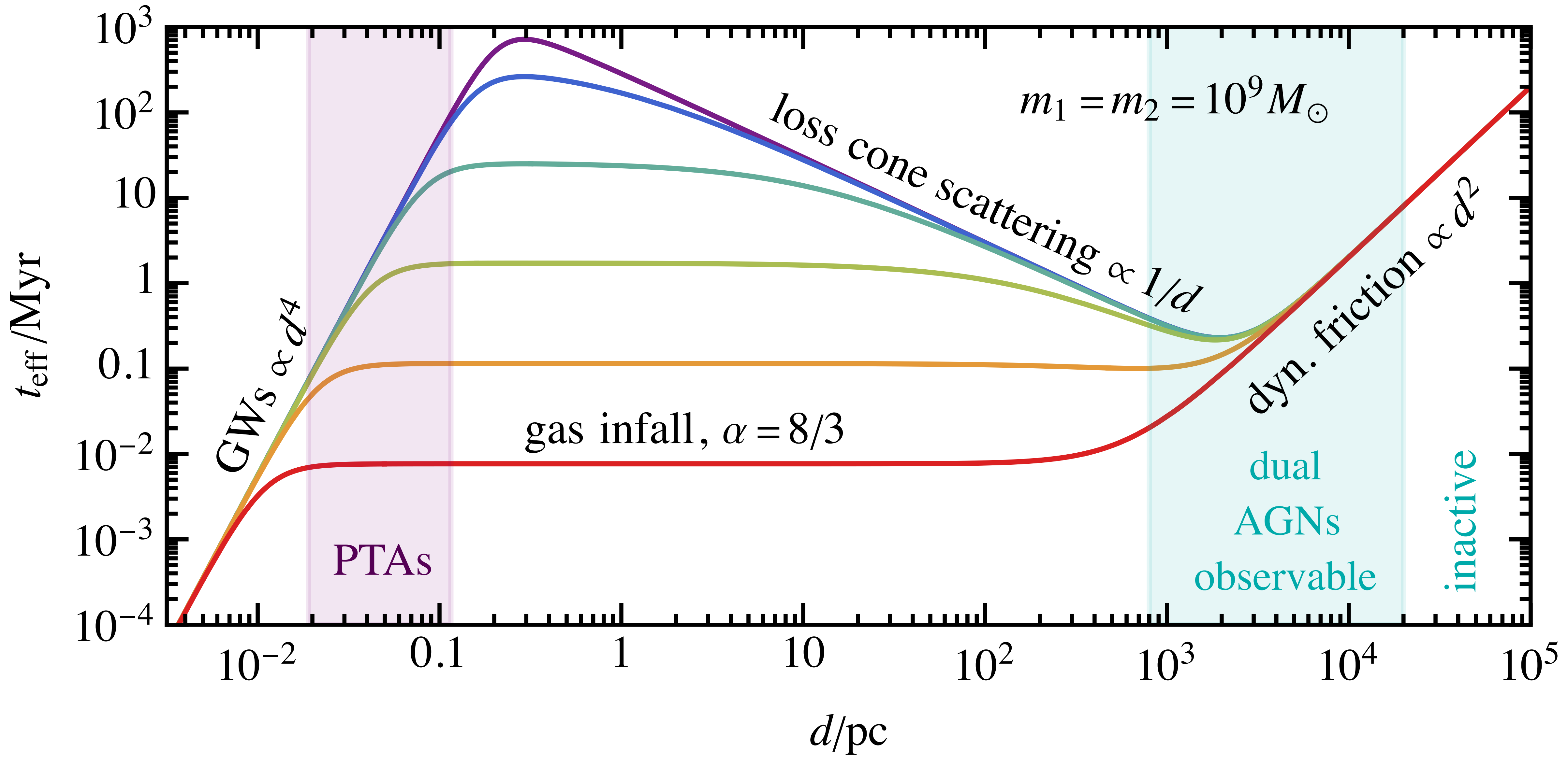
local inactive galaxies:



GW driven evolution gives
too flat spectrum.

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

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

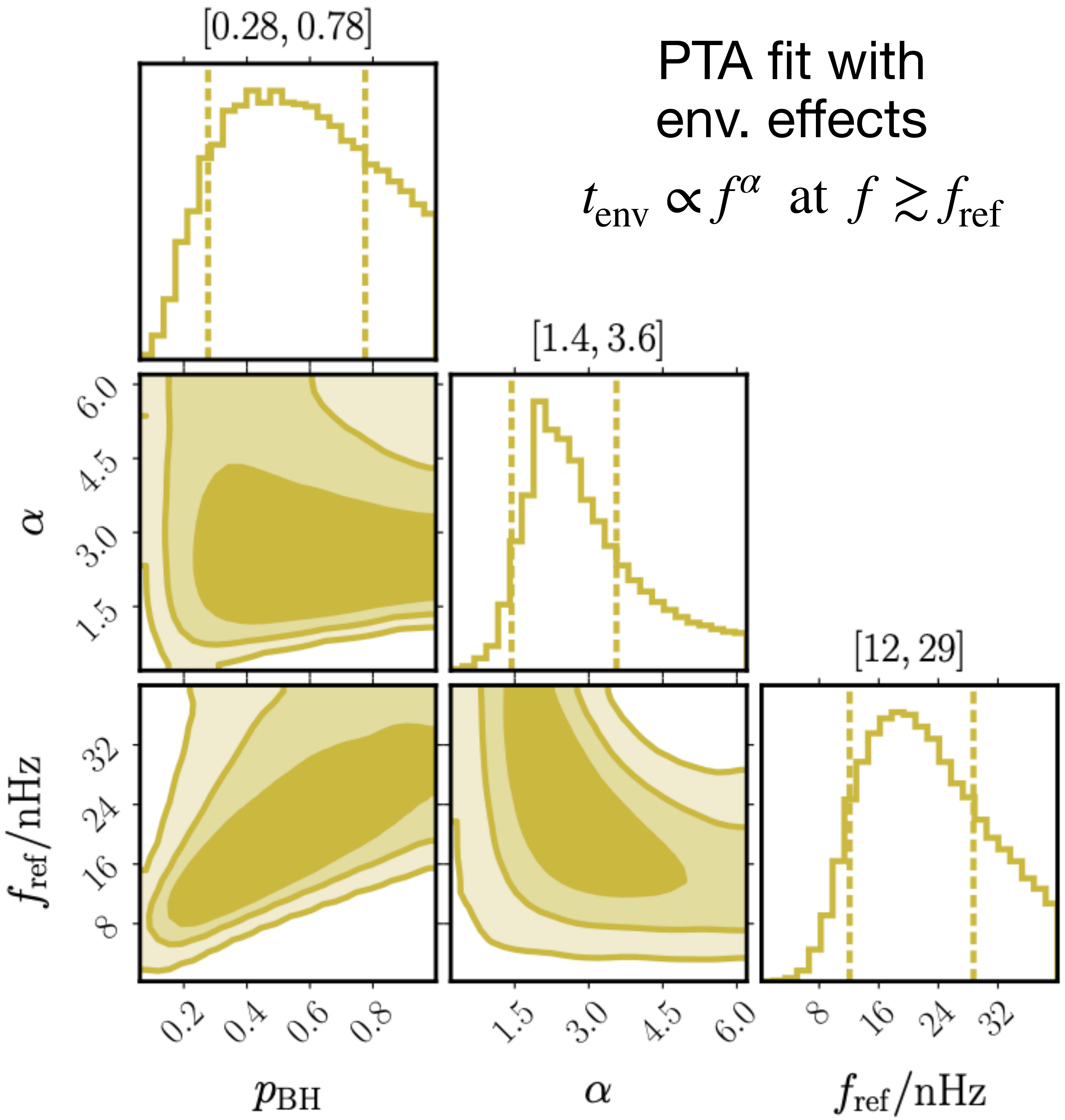
- Shorter residence time:

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

- Signal from single binary spreads over multiple frequencies.

- GW emission circularises binaries.

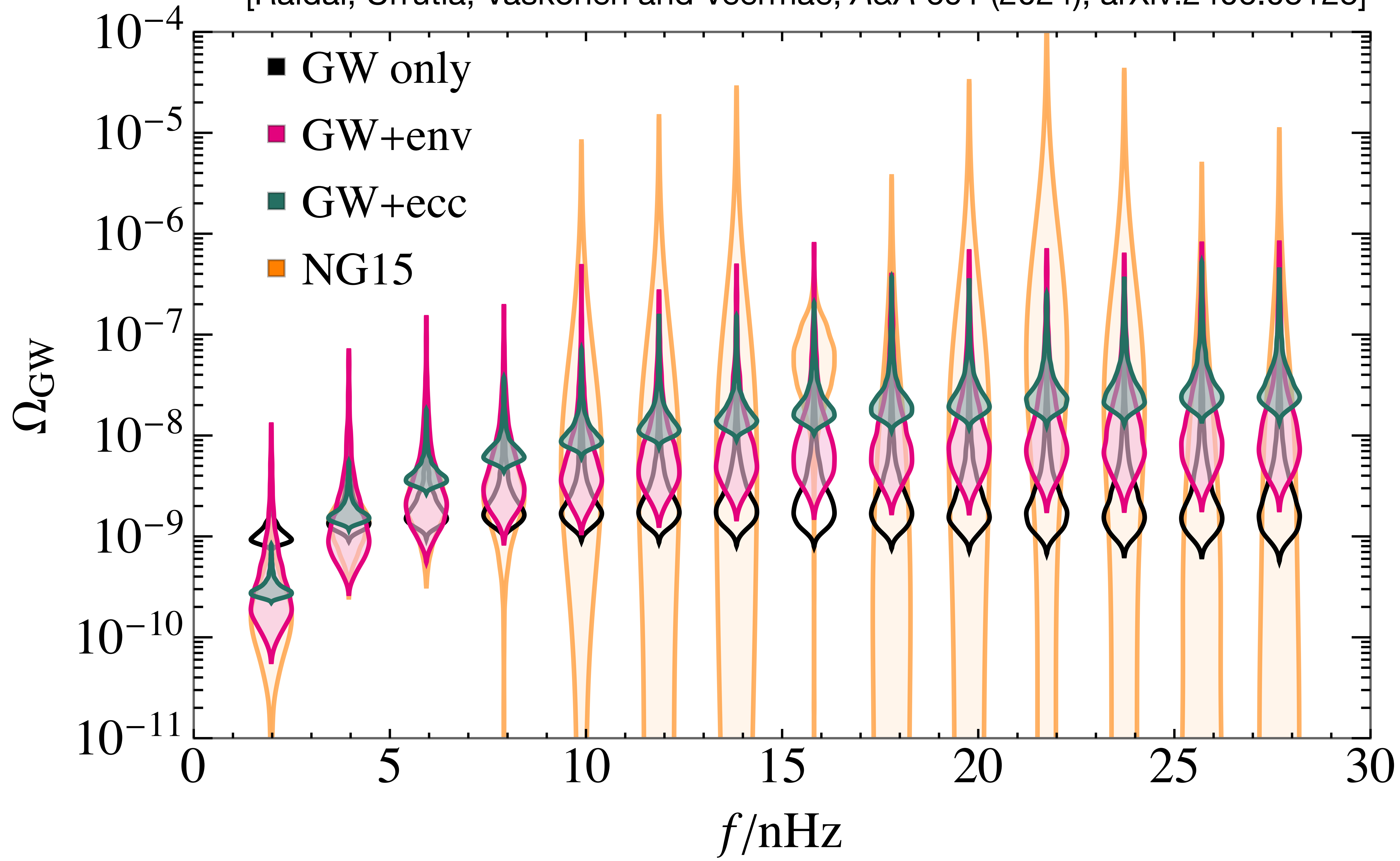
PTA fit: Low-frequency suppression



PTA fit with env. effects

$t_{\rm env} \propto f^{\alpha}$ at $f \gtrsim f_{\rm ref}$

[Raidal, Urrutia, Vaskonen and Veermäe, *A&A* 691 (2024), arXiv:2406.05125]



Large eccentricities, $\langle e \rangle \gtrsim 0.6$, or strong env. effects, $f_{\rm ref} \gtrsim 10\,\mathrm{nHz}$, are preferred.

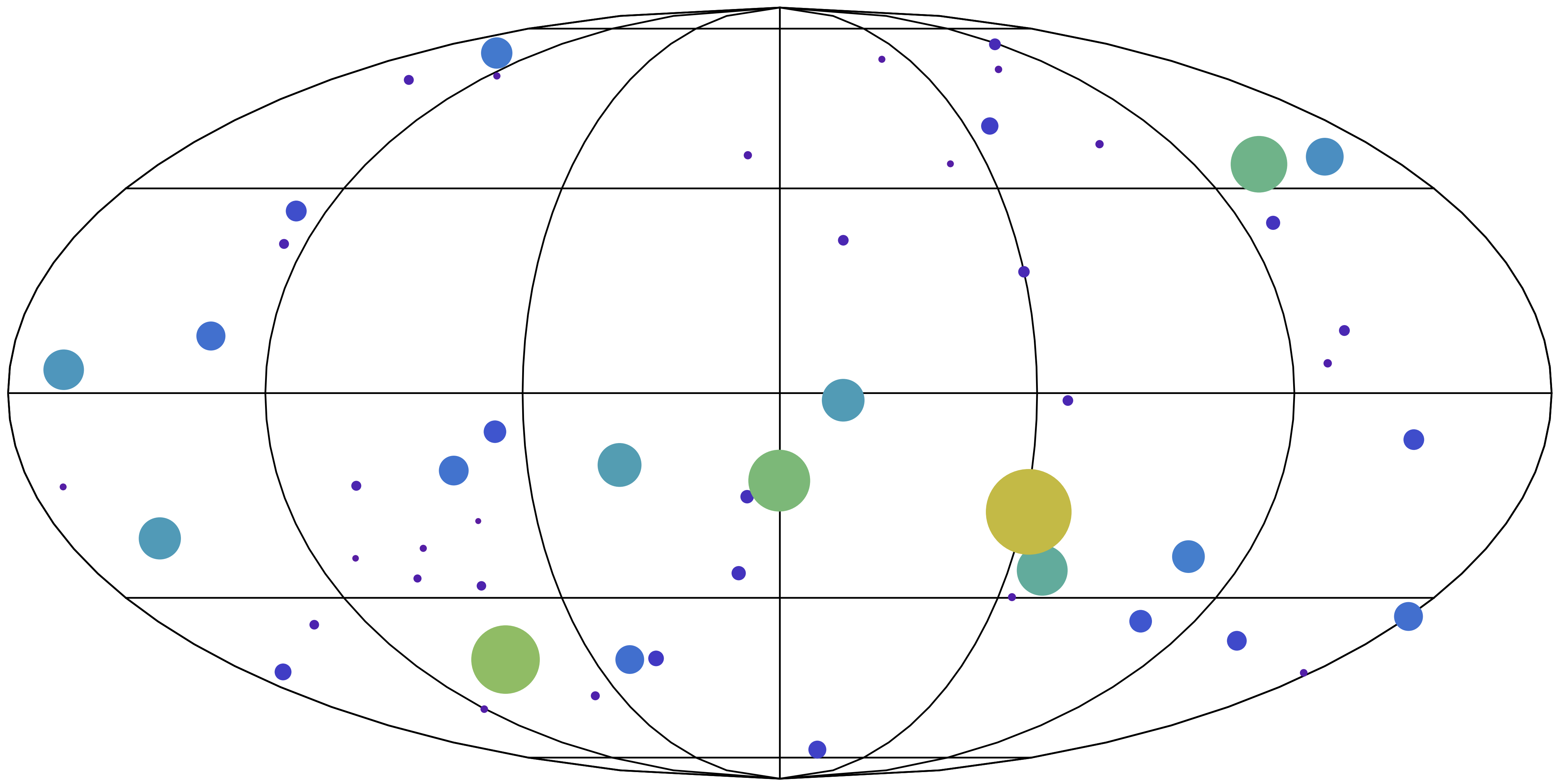
Anisotropies

$$\Omega_{\mathrm{GW}}(\hat{x}) = \sum_j \Omega_{\mathrm{GW},j}\,\delta^2(\hat{x} - \hat{x}_j) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} c_{lm} Y_{lm}(\theta, \phi)$$

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |c_{lm}|^2 \quad \sim$$

a measure of fluctuations in the power spectrum on the angular scale $\theta \approx 2\pi/l$

$$\frac{C_l}{C_0} = \sum_{i,j} \frac{\Omega_i \Omega_j}{\Omega_{\mathrm{tot}}^2} P_l(\hat{x}_i \cdot \hat{x}_j)$$

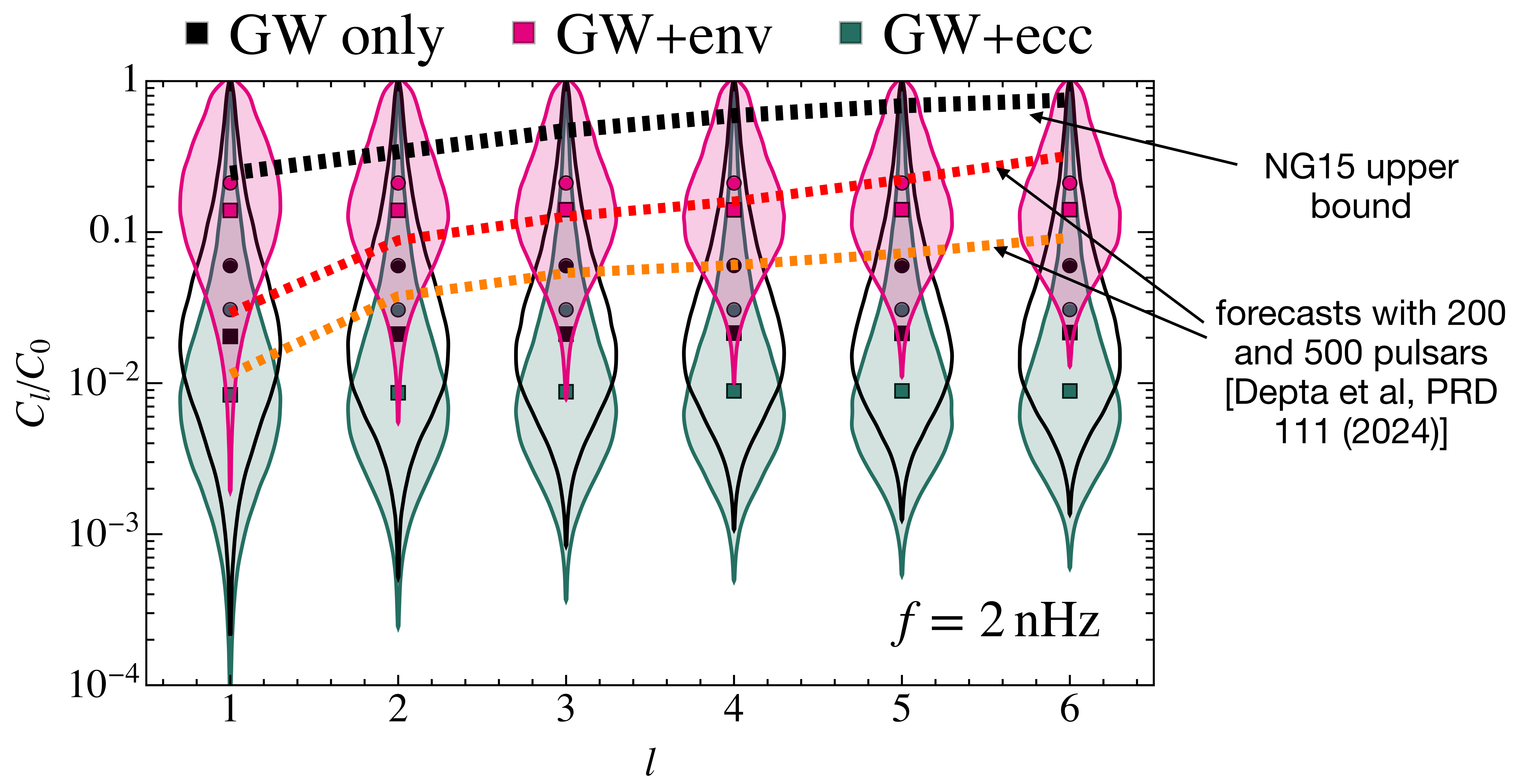


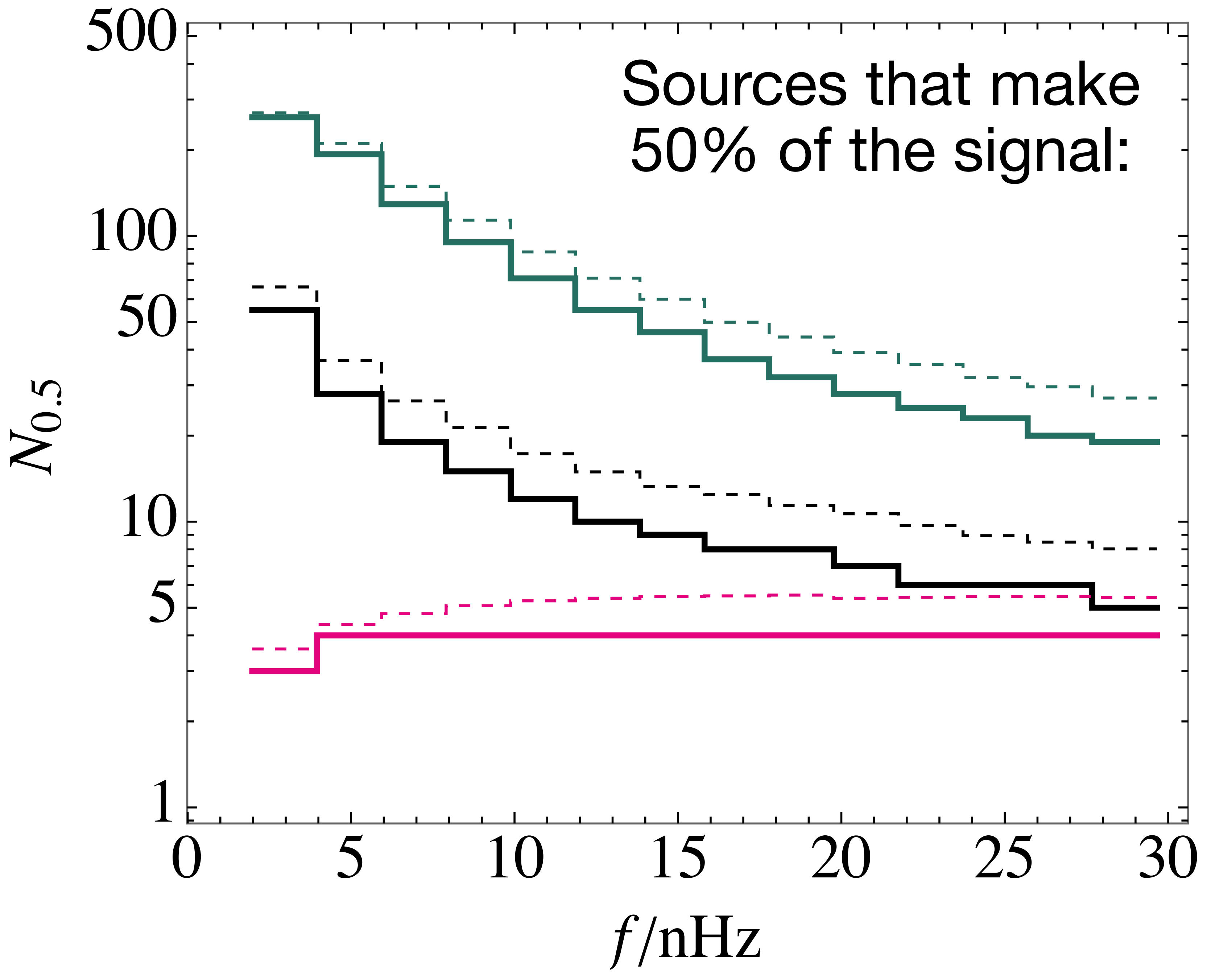
1. single source: $C_l = C_0 = \Omega_{\mathrm{tot}}^2/(4\pi)$

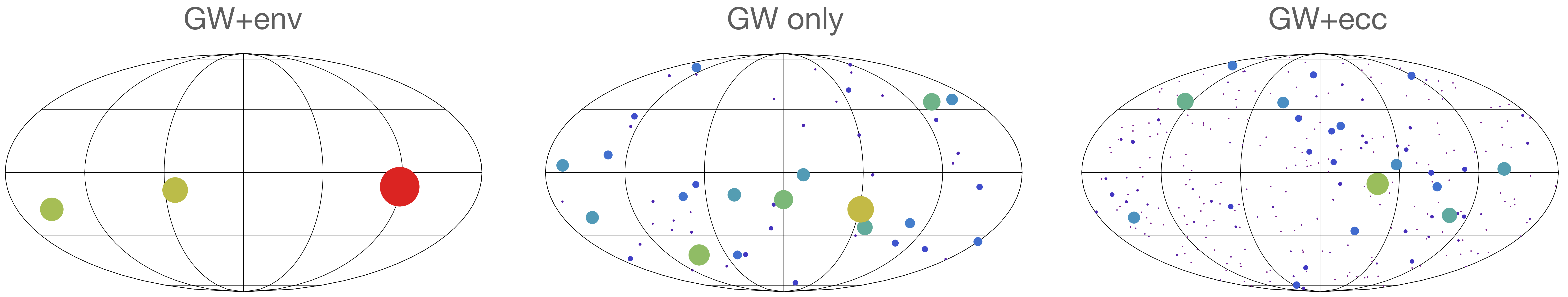
2. many sources: $C_{l>0} \ll C_0 = \Omega_{\mathrm{tot}}^2/(4\pi)$

Anisotropies

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



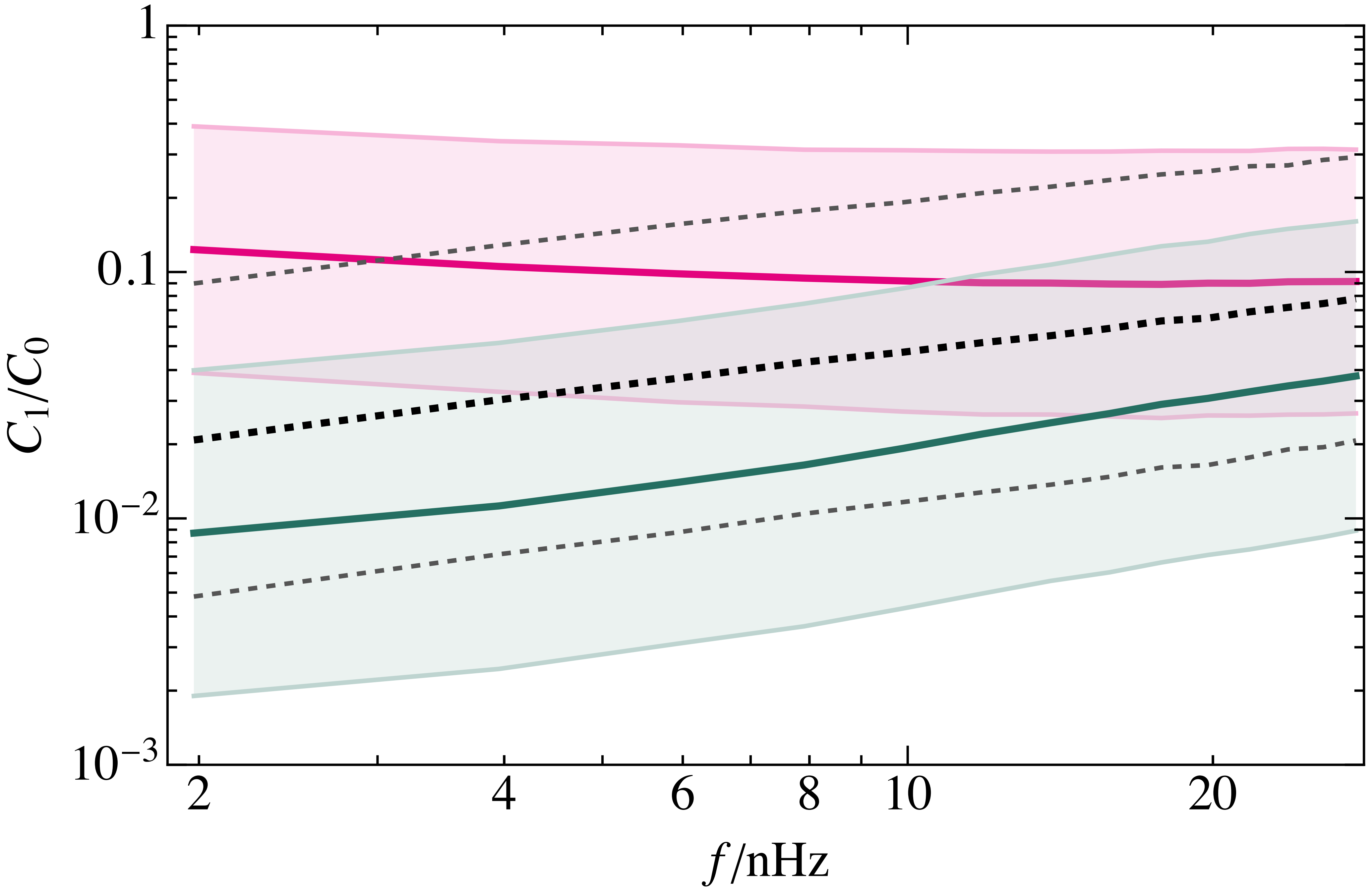




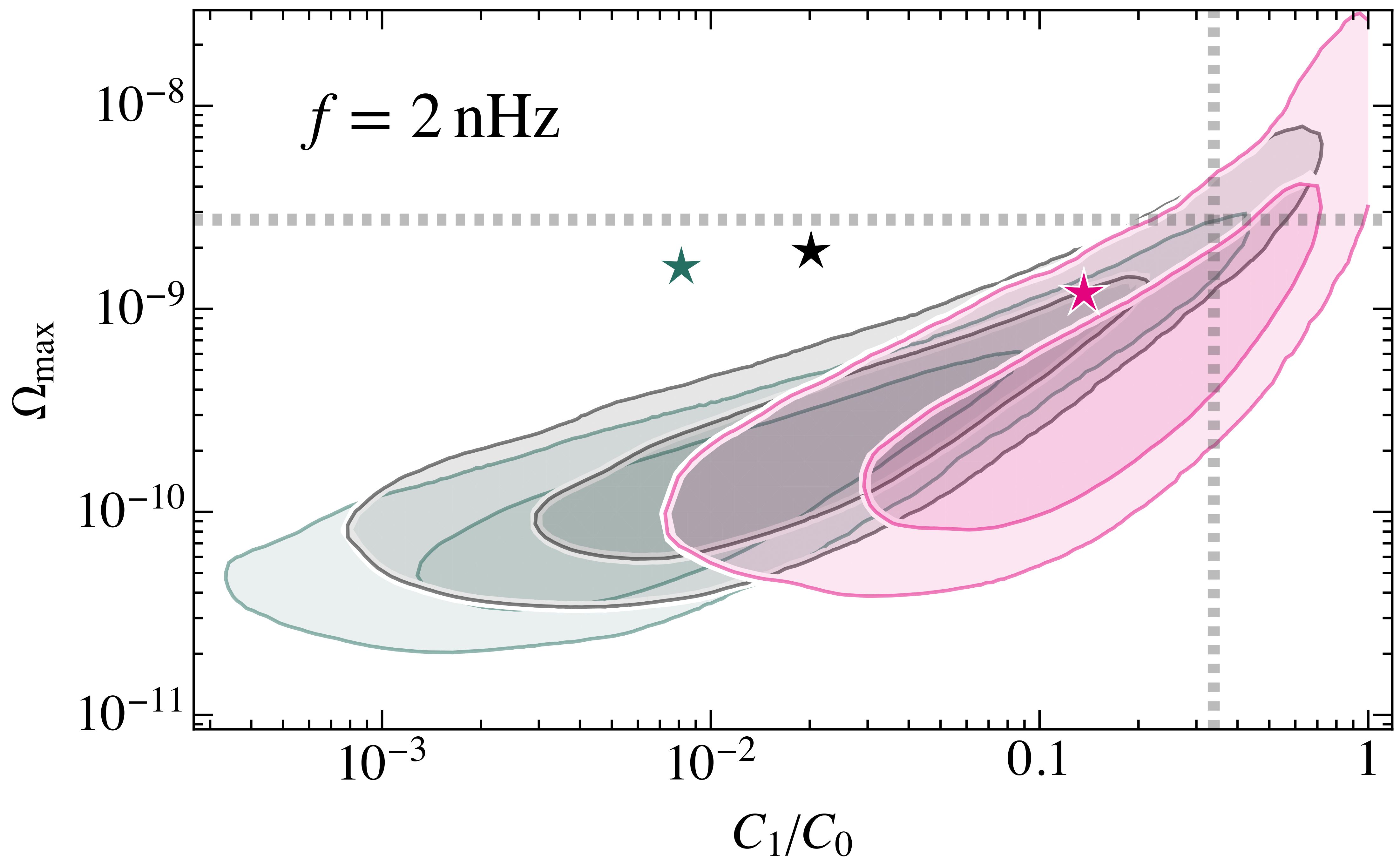
Anisotropies

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

Anisotropies change with frequency:



Anisotropies are correlated with the strongest binary contribution:



Coevolution of galaxies and SMBHs

[Ellis, Fairbairn, Urrutia and Vaskonen, arXiv:2410.24224]

Evolution by **mergers**:

$$M_J(M) = \left[\frac{\mathrm{d}n(z)}{\mathrm{d}M}\right]^{-1} \int_0^M \mathrm{d}M' \frac{\mathrm{d}n(z')}{\mathrm{d}M'} \frac{\mathrm{d}P(M,z\,|\,M',z')}{\mathrm{d}M} M_J(M')$$

M_J: halo mass, BH mass, stellar mass

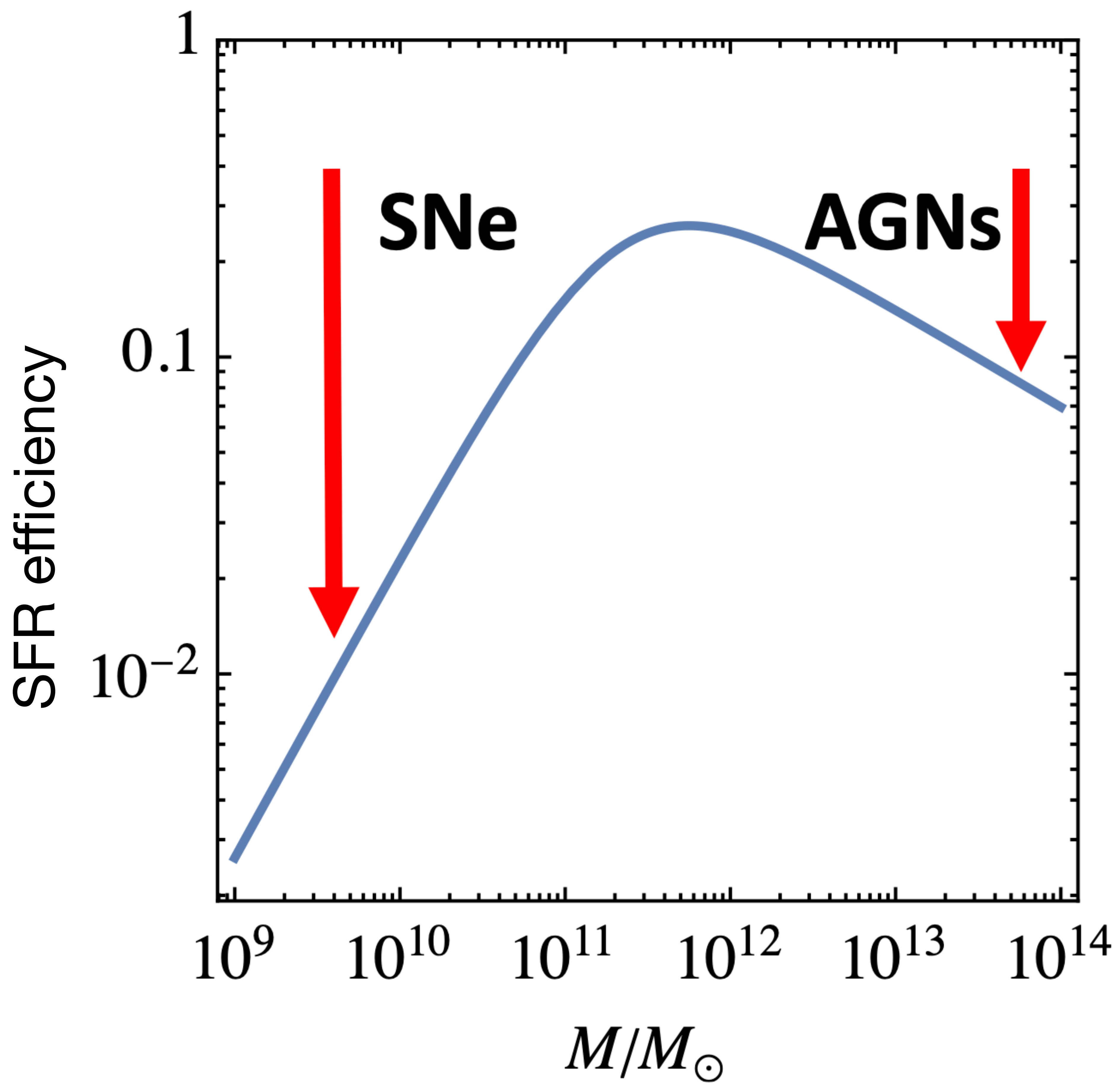
$\mathrm{d}P/\mathrm{d}M$: probability for $M' \to M$

BH **accretion** in heavy galaxies:

$$\dot{M}_{\rm BH}^{\rm merg} \simeq f_{\rm edd} \frac{2.2}{\rm Gyr} M_{\rm BH}$$

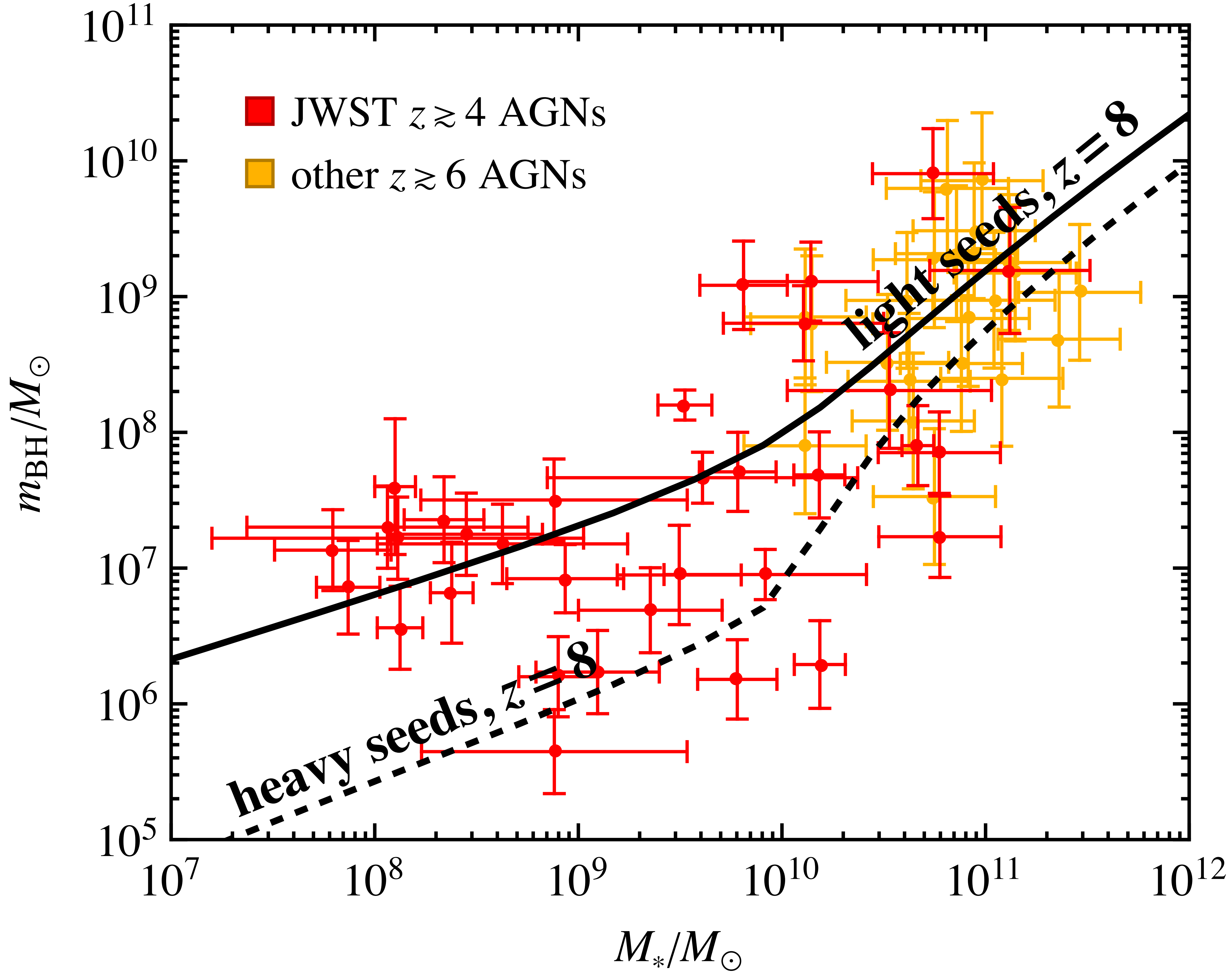
$f_{\rm edd}$: fraction of Eddington rate

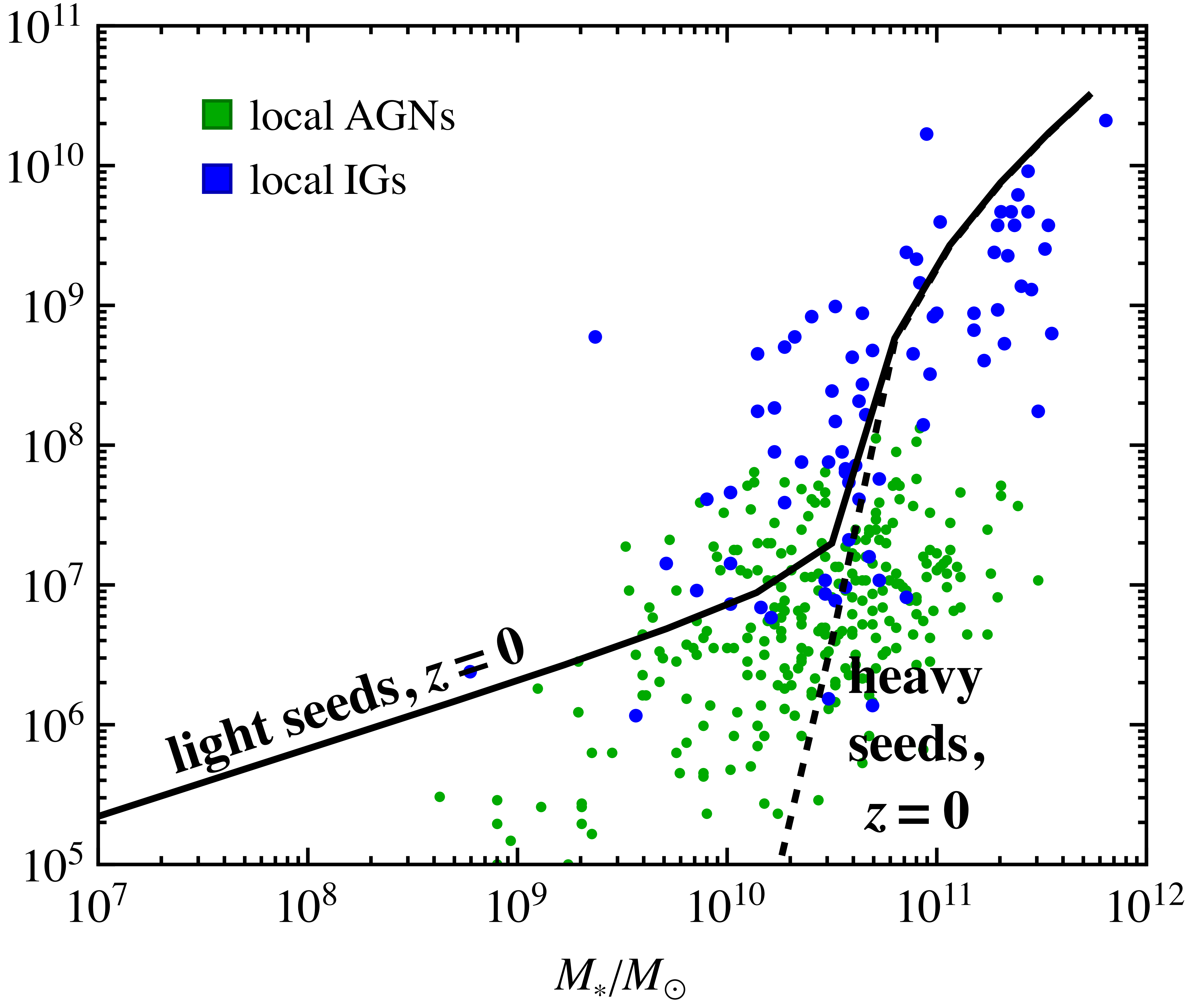
Star formation:



Coevolution of galaxies and SMBHs

[Ellis, Fairbairn, Urrutia and Vaskonen, arXiv:2410.24224]





Dark matter effects

Halo mass function in different DM models:

Fuzzy DM **Warm DM** **PBHs or axion miniclusters**

Dark matter effects

Starlight from JWST: Implications for star formation and dark matter models

Juan Urrutia[1,2,⋆], John Ellis[3,4,⋆⋆], Malcolm Fairbairn[3,⋆⋆⋆], and Ville Vaskonen[1,5,6,⋆⋆⋆⋆]

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May 16, 2025

ABSTRACT

We confront the star formation rate in different dark matter (DM) models with UV luminosity data from JWST up to $z \simeq 25$ and legacy data from HST. We find that a transition from a Salpeter population to top-heavy Pop-III stars is likely at $z \simeq 10$ and that beyond $z = 10 - 15$ the feedback from supernovae and active galactic nuclei is progressively reduced, so that at $z \simeq 25$ the production of stars is almost free from any feedback. We compare fuzzy and warm DM models that suppress small-scale structures with the CDM paradigm, finding that the fuzzy DM mass $> 4.5 \times 10^{-22}$eV and the warm DM mass > 1.5 keV at the 95% CL. The fits of the star formation rate parametrization do not depend strongly on the DM properties within the allowed range. We find no preference over CDM for enhanced matter perturbations associated with axion miniclusters or primordial black holes. The scale of the enhancement of the power spectrum should be $> 27\,\mathrm{Mpc}^{-1}$ at the 95% CL, excluding axion miniclusters produced for $m_a < 7.5 \times 10^{-17}$ eV or heavy primordial black holes that constitute a fraction $f_{\rm PBH} > \max[88 M_\odot/m_{\rm PBH}, 10^{-4}(m_{\rm PBH}/10^4 M_\odot)^{-0.09}]$ of DM.

To appear soon!

JWST SMBH Data Constraints on Fuzzy and Warm Dark Matter

John Ellis,[1,2,*] Malcolm Fairbairn,[1,†] Juan Urrutia,[3,4,‡] and Ville Vaskonen[3,5,6,§]

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[6] *Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Via Marzolo 8, 35131 Padova, Italy*

A semi-analytical model for the evolution of galaxies and supermassive black holes (SMBHs) within the ΛCDM paradigm has been shown to yield BH mass-stellar mass relations that reproduce both the JWST and pre-JWST observations of high-redshift SMBHs. Either fuzzy or warm dark matter (FDM or WDM) would suppress the formation of the smaller galactic halos that play important roles in fits to the high-redshift SMBH data. Our analysis disfavours FDM fields with masses $< 10^{-19}$ eV and WDM particles weighing < 12.5 keV, both at the 95% confidence level.

SMBH merger rate in different DM models:

binary populations at LISA and AEDGE

Star formation in different DM models:

UV luminosity function fits

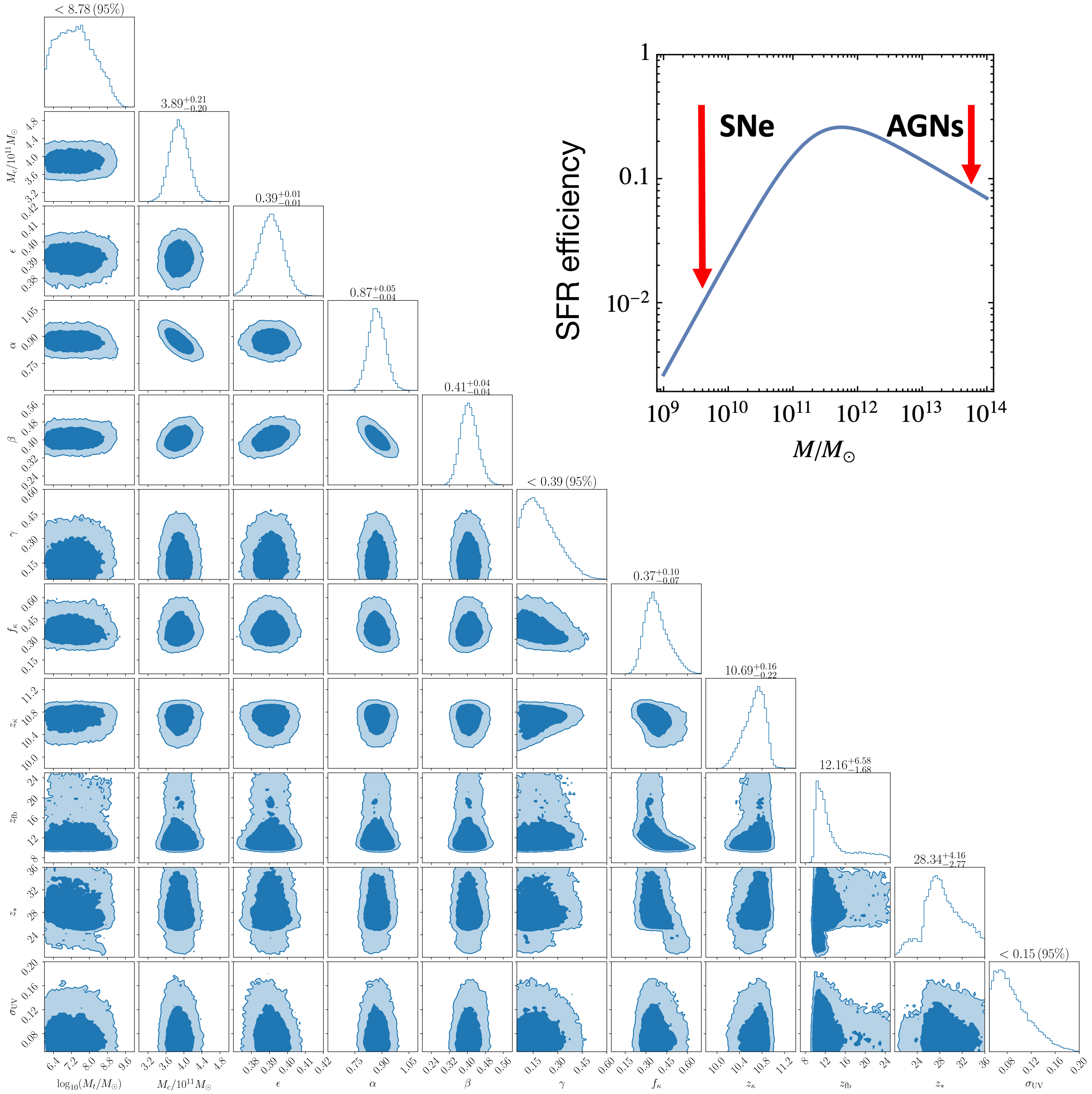
Growth of SMBHs in different DM models:

fits of stellar mass - BH mass relation

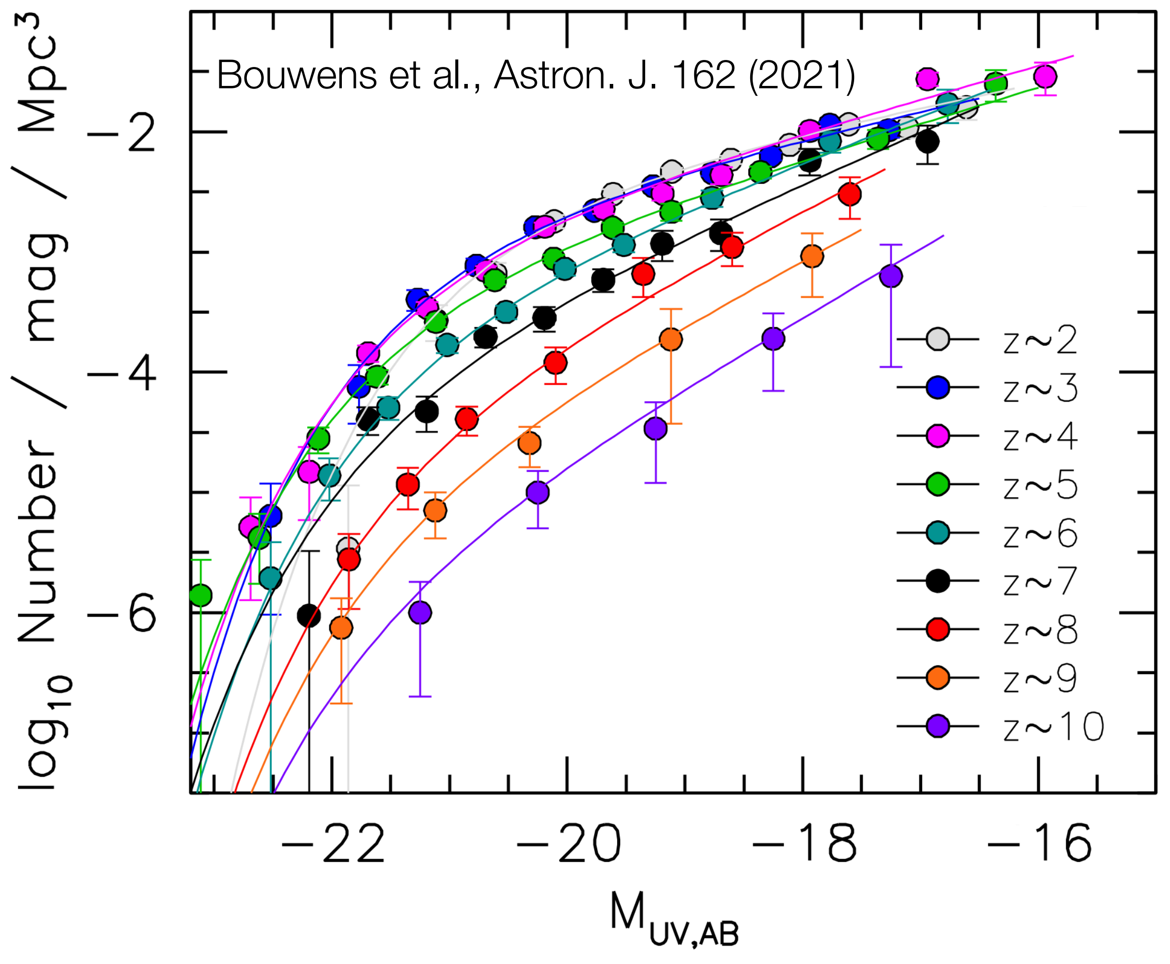
UV luminosity functions

[Ellis, Fairbairn, Urrutia and Vaskonen, arXiv:2504.20043]

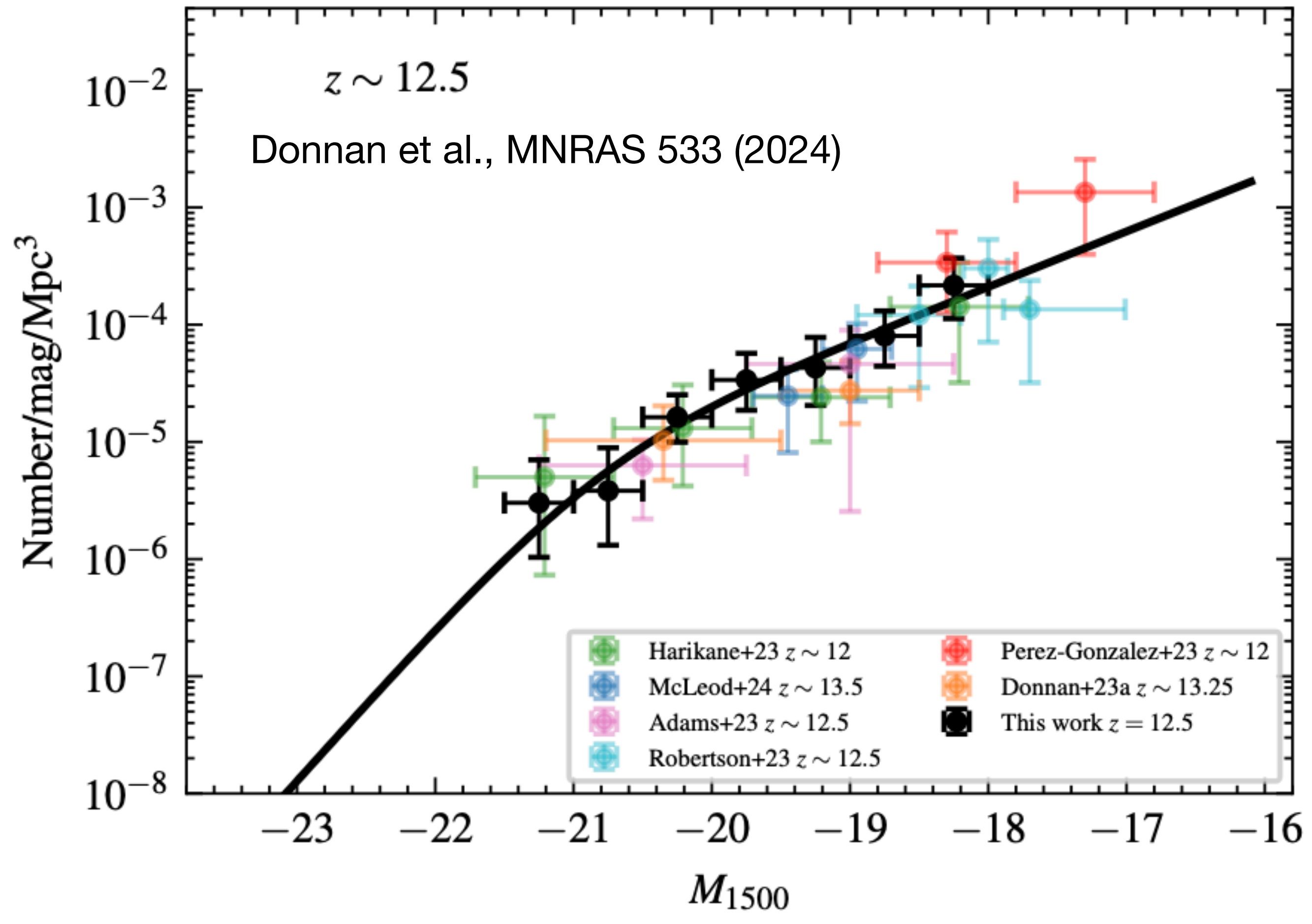
UVLF = the number density of galaxies as a function of their UV luminosity.



HST

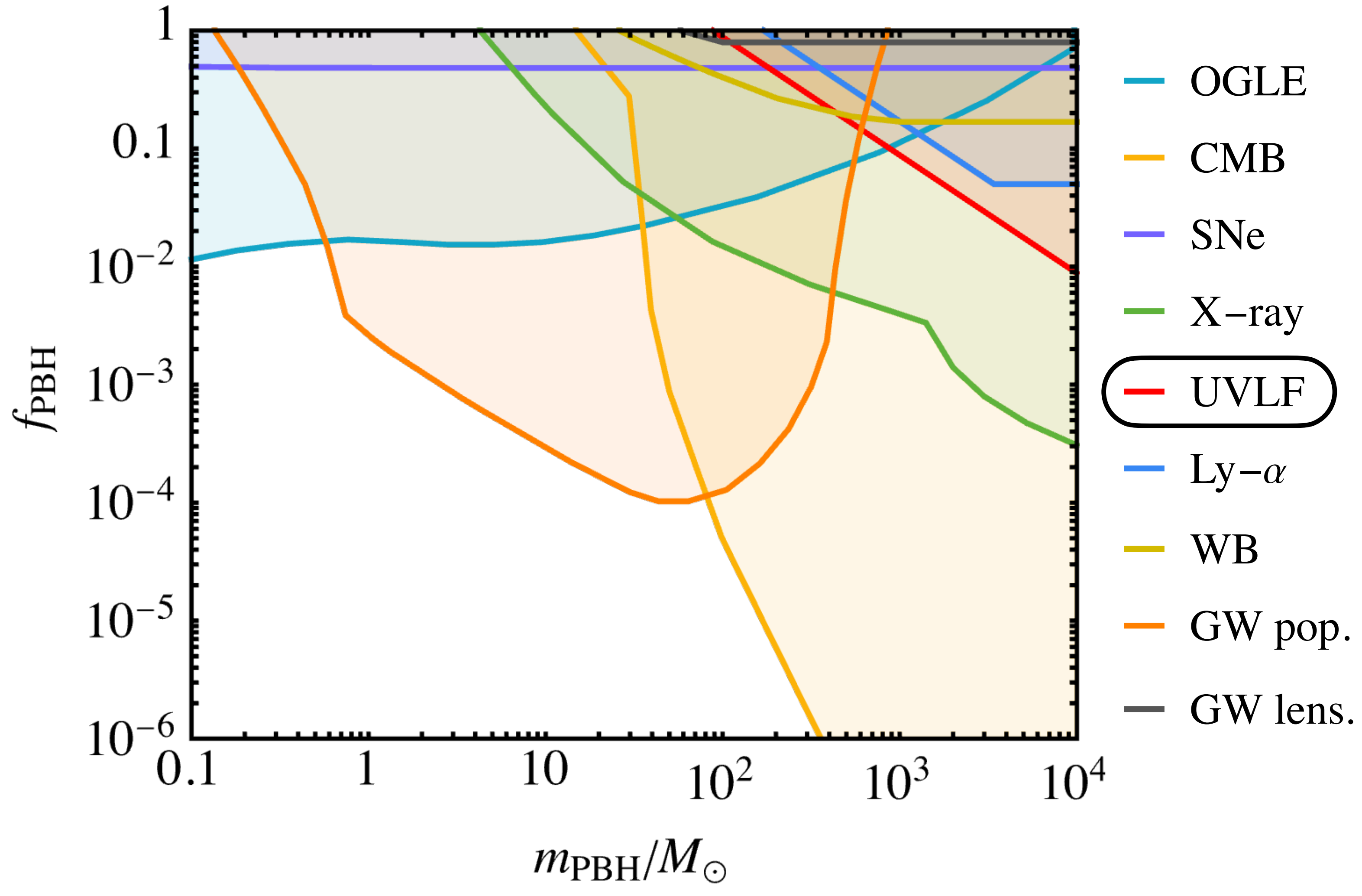


JWST



DM constraints from UVLF observations:

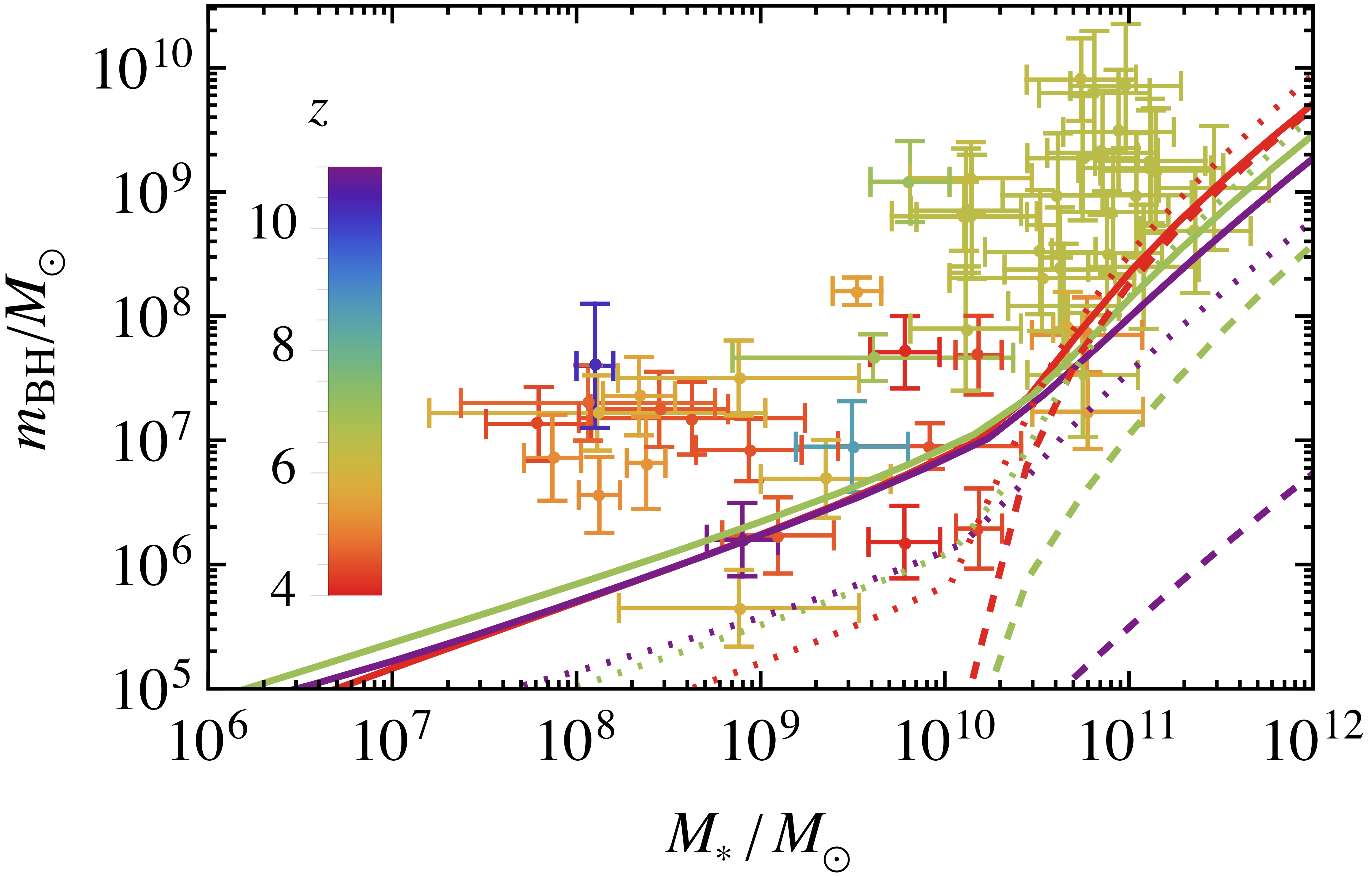
- $m_{\rm FDM} > 4.5 \times 10^{-22}\,\mathrm{eV}$
- $m_{\rm WDM} > 1.5\,\mathrm{keV}$
- $k_c > 27\,\mathrm{Mpc}^{-1}$



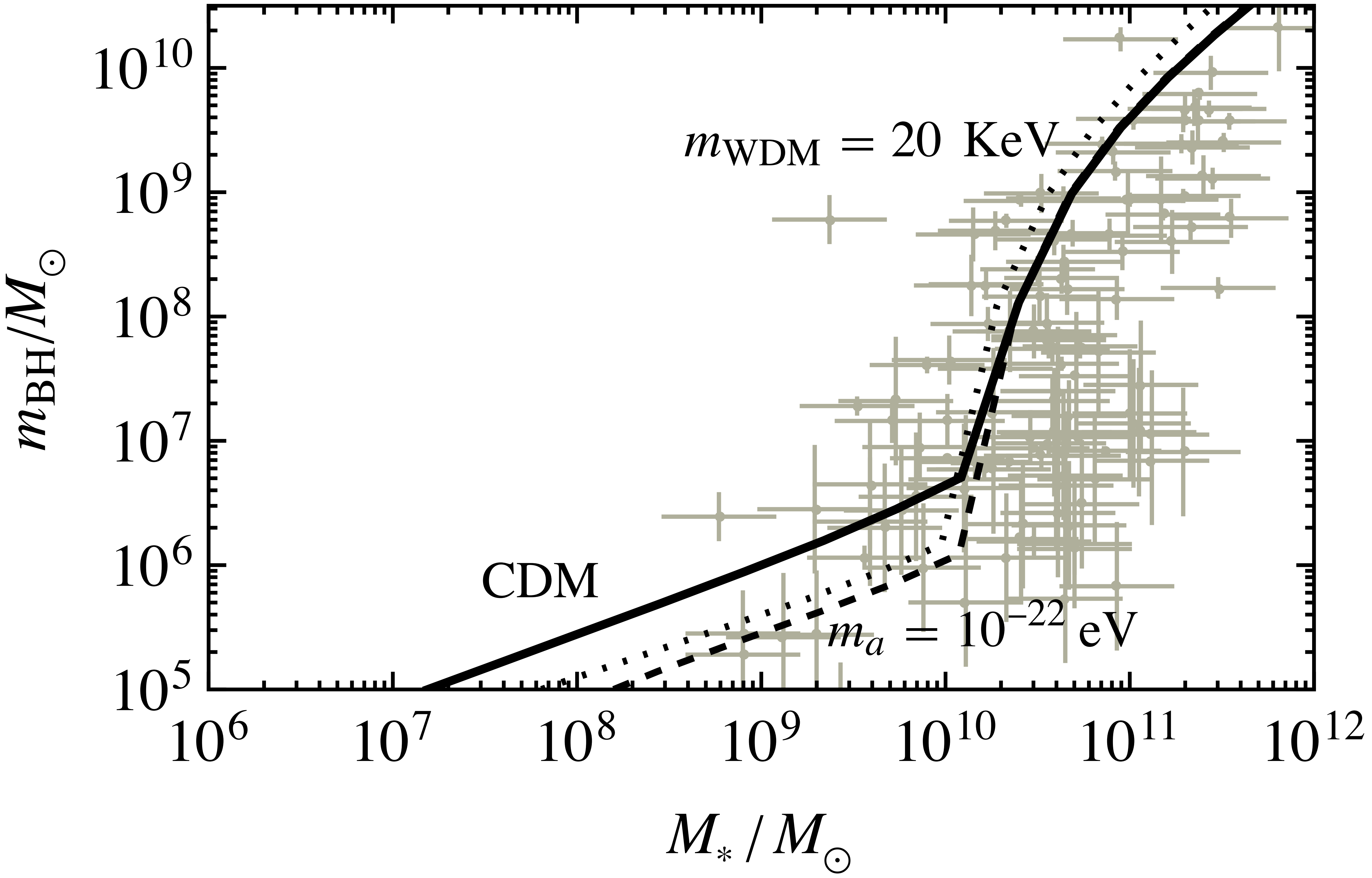
Stellar mass - BH mass relation

Same seed scenario, different DM models:

high-z SMBHs

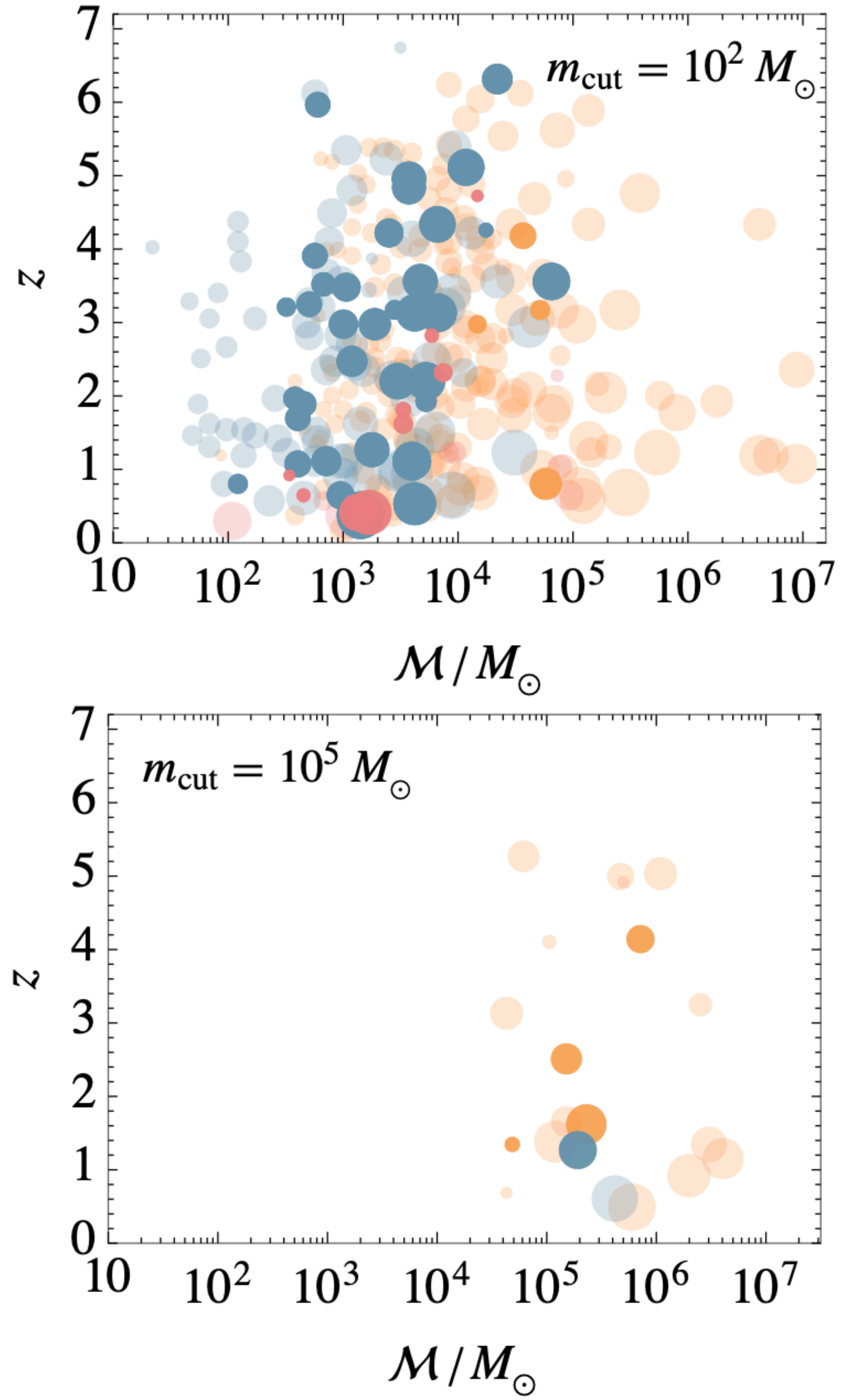


local SMBHs

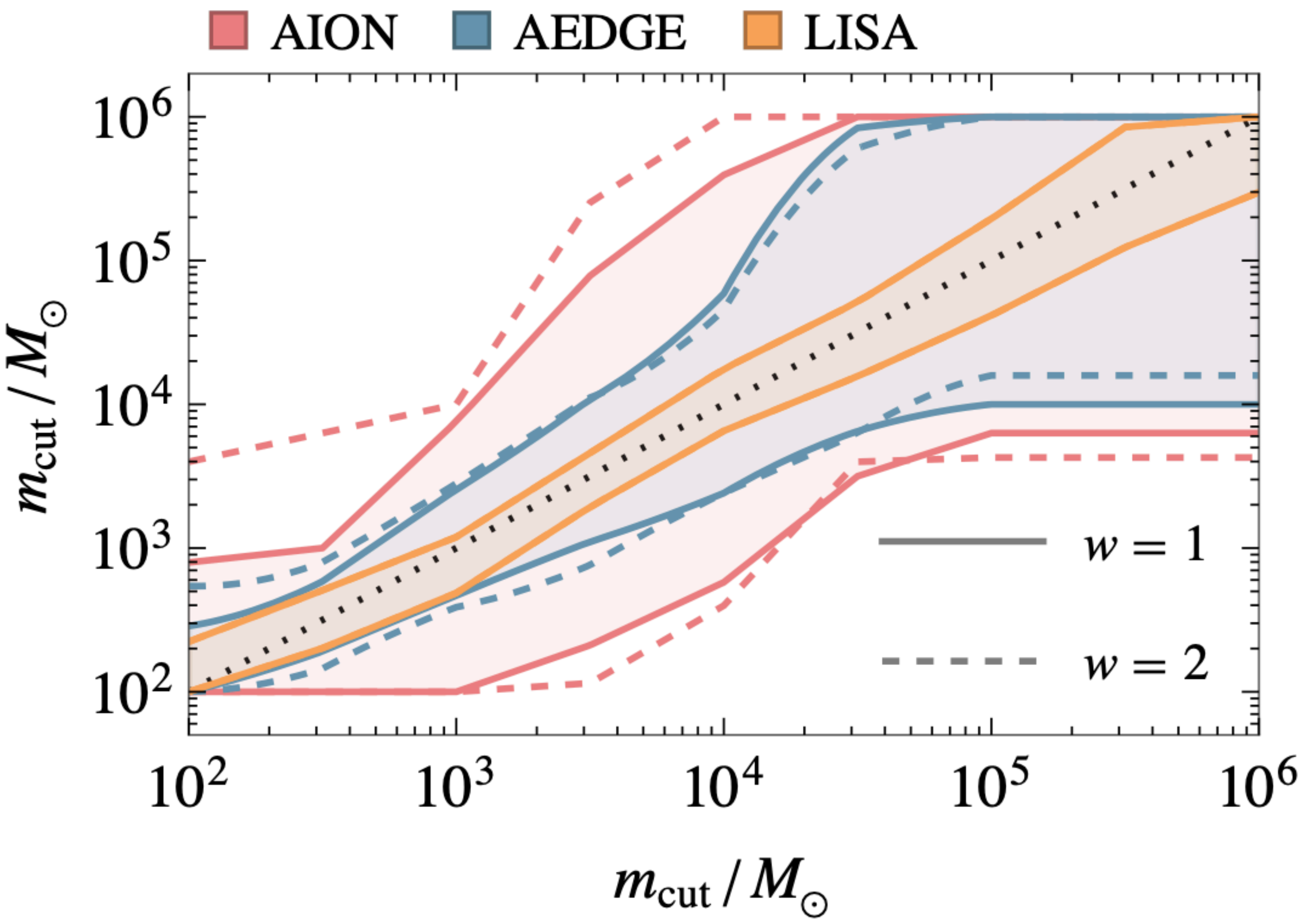


Probing SMBH seed scenarios

[Ellis, Fairbairn, Urrutia and Vaskonen, *ApJ* 964 (2024)]



Different seed scenarios (in CDM) can be distinguished by probing the IMBH population in GWs:



Summary

1. The PTA GW background is compatible with the local observations of SMBH-stellar mass relation.

2. The 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.

4. JWST and GW observations of SMBHs can be used to probe the nature of DM.