Implications for heavy primordial black holes from pulsar timing arrays

arXiv:2306.17836

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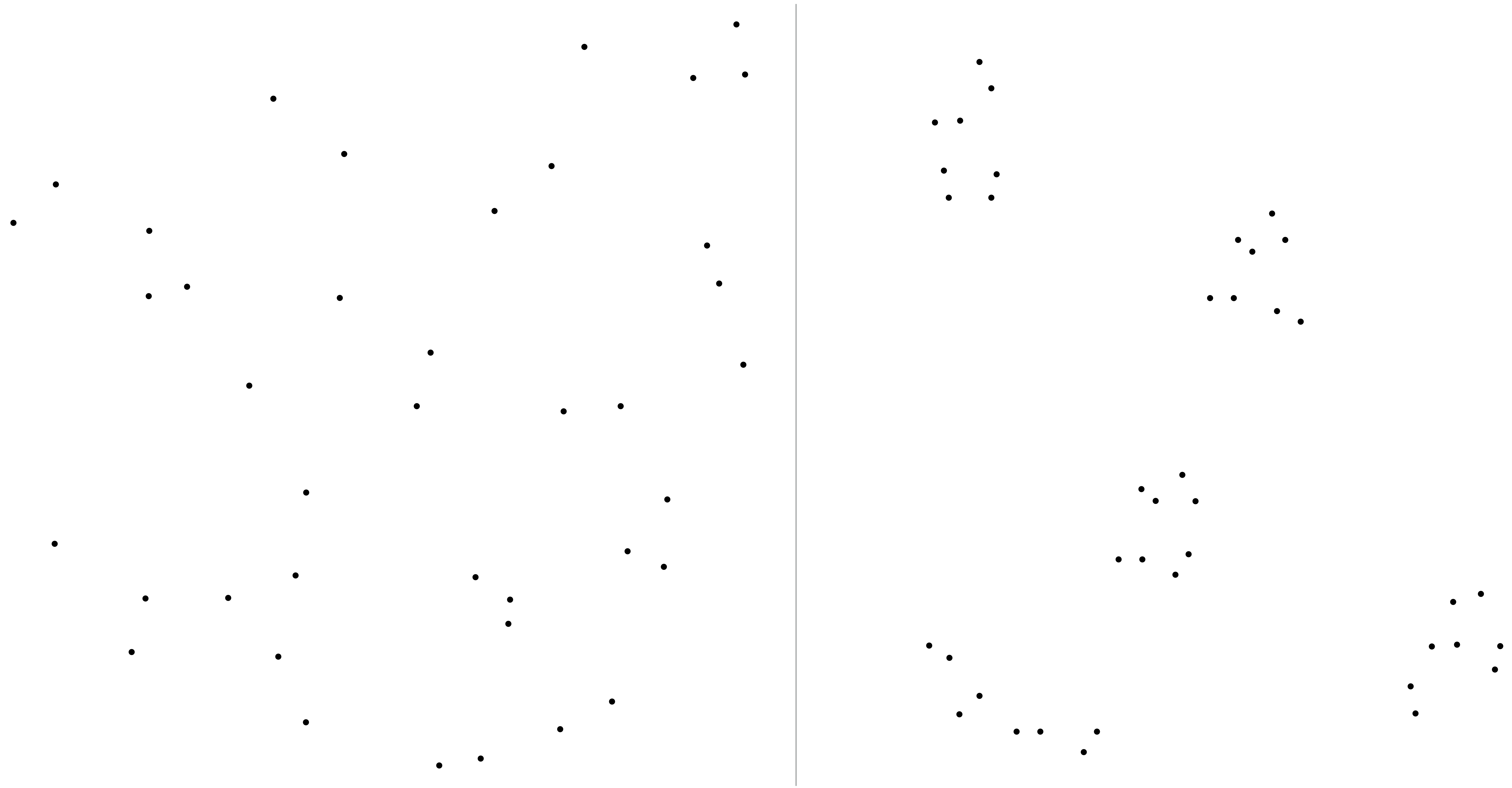
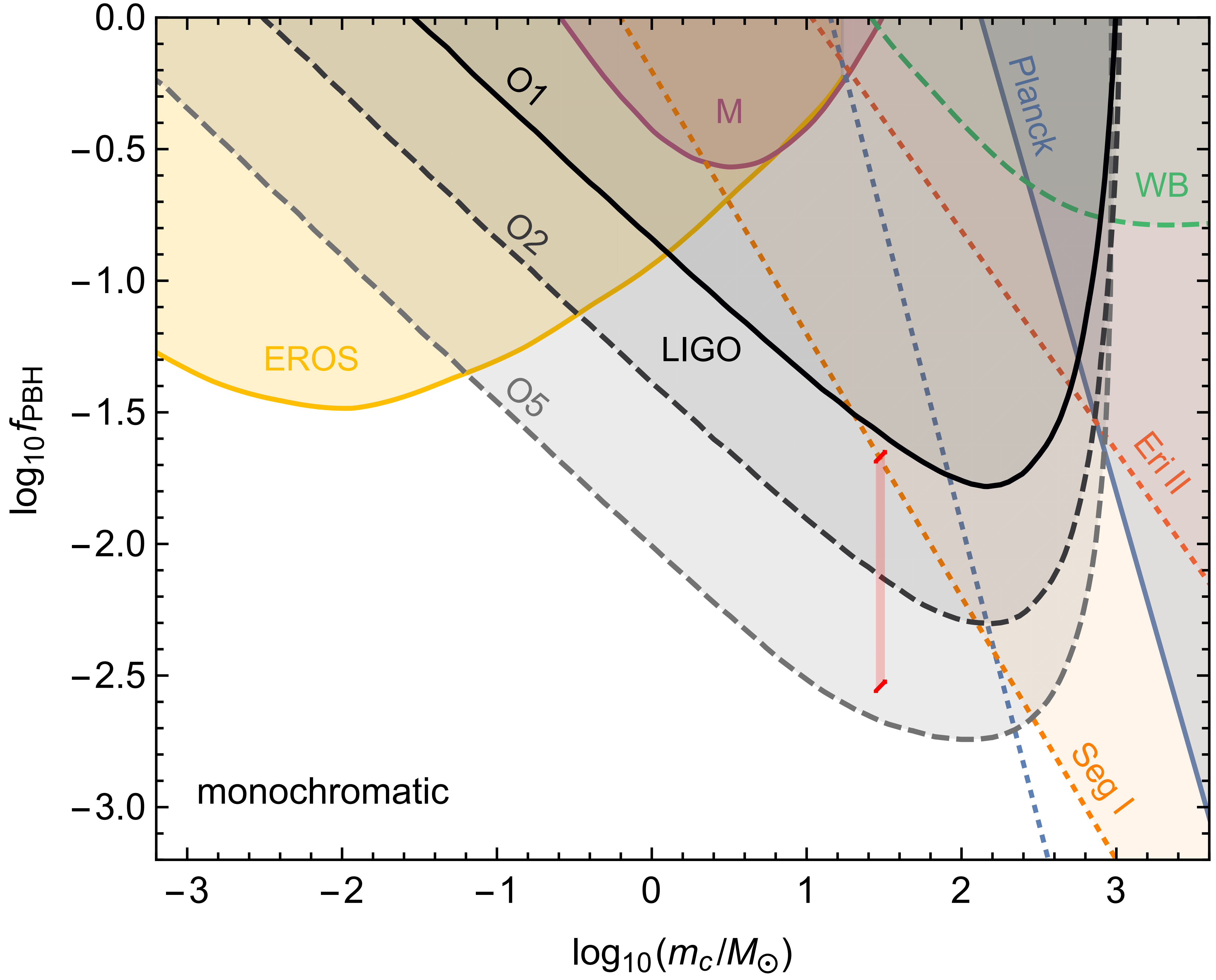


Outline

- Gravitational waves from PBH binaries
- Merger rate and signal prediction
- Complementary constraints
- Results

Gravitational waves from PBH binaries

- Originally mostly considered for $\mathcal{O}(M_\odot)$ PBHs
- Huge interest after first GW observation by LIGO
  - Possible explanation of LIGO observations (mass distribution)
  - Constraints from GWB and merger rate
- Less investigated for pulsar timing arrays
  - Studies focussed on scalar-induced GWB associated with PBH formation, not GWB from PBH binaries
  - One study for NANOGrav 12.5 yr dataset, but misses crucial point → conclusions wrong
    Atal et al. 2012.14721



Radial, Vaskonen, and Veermäe 1707.01480

Merger rate of PBH binaries

- 2 nearest neighbor PBHs decouple from Hubble expansion, tidal forces from third PBH prevent head-on collision Nakamura et al. astro-ph/9708060, Raidal, Vaskonen, and Veermäe 1707.01480

- $\mathrm{d}n_3(x, y) = \frac{n_{\mathrm{PBH}}}{2}\, \mathrm{e}^{-\frac{4\pi}{3} y^3 \delta_{\mathrm{dc}} n_{\mathrm{PBH}}} (4\pi\, n_{\mathrm{PBH}}\, \delta_{\mathrm{dc}})^2\, x^2\, y^2\, \mathrm{d}x\, \mathrm{d}y$
- Clustering: Local density of PBHs around given one is enhanced by factor $\delta_{\mathrm{dc}} \sim n_{\mathrm{PBH,loc}}/n_{\mathrm{PBH}} > 1$

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- $R(t) = \int_0^{\tilde{x}} \mathrm{d}x \int_x^{\infty} \mathrm{d}y\, \frac{\partial^2 n_3}{\partial x\, \partial y}\, \delta(t - \tau(x,y))$

$$\propto \frac{\delta_{\mathrm{dc}}^{16/37}}{\tilde{x}^3\, \tilde{\tau}} \left(\frac{t}{\tilde{\tau}}\right)^{-34/37} \left(\Gamma\left[\frac{58}{37}, \frac{4\pi}{3}\tilde{x}^3 \delta_{\mathrm{dc}} n_{\mathrm{PBH}} \left(\frac{t}{\tilde{\tau}}\right)^{3/16}\right] - \Gamma\left[\frac{58}{37}, \frac{4\pi}{3}\tilde{x}^3 \delta_{\mathrm{dc}} n_{\mathrm{PBH}} \left(\frac{t}{\tilde{\tau}}\right)^{-1/7}\right]\right)$$

- Clustering increases overall rate and decreases timescale for mergers

Multiple merger steps

Bringmann, PFD et al. 1808.05910

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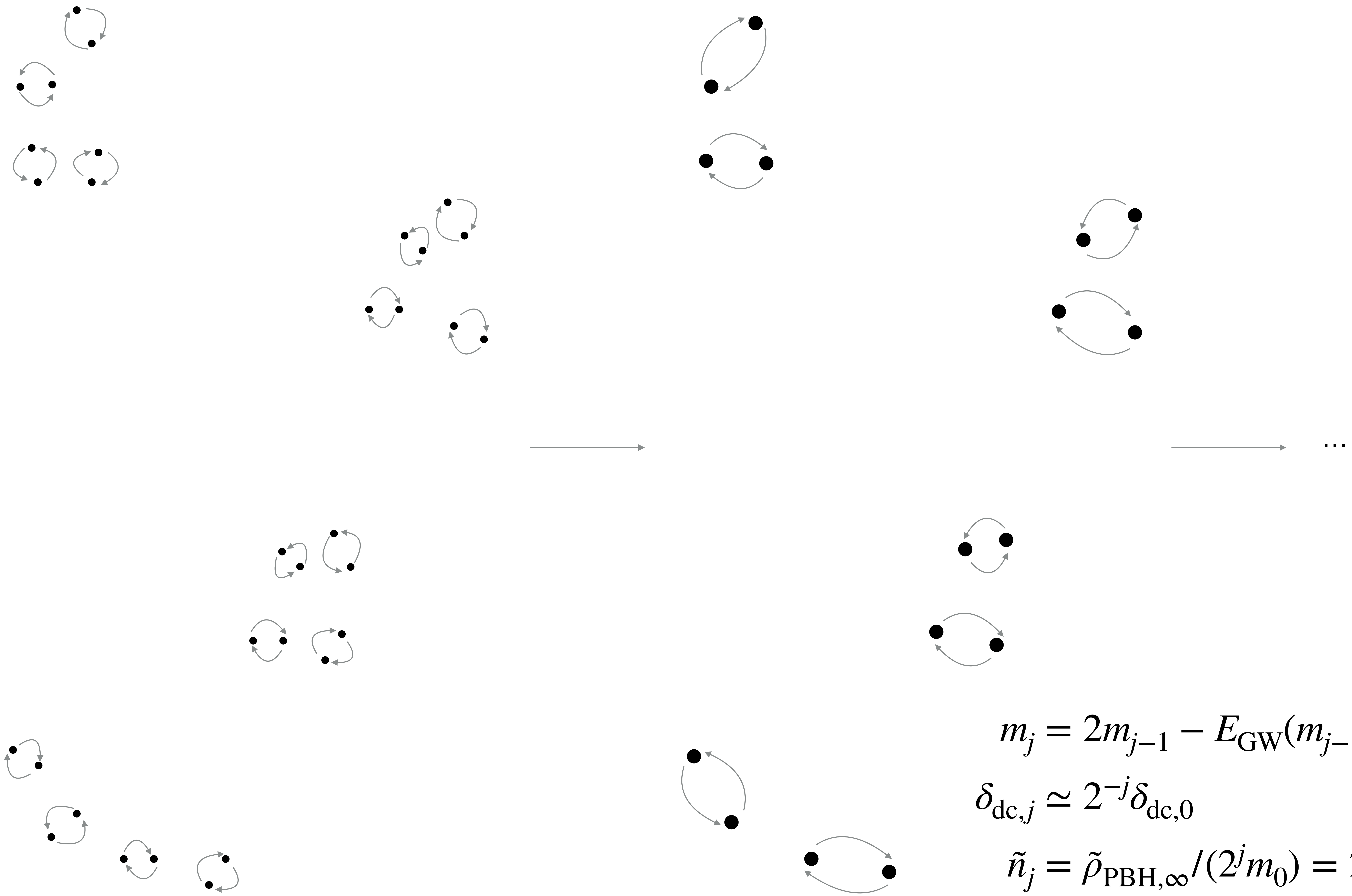


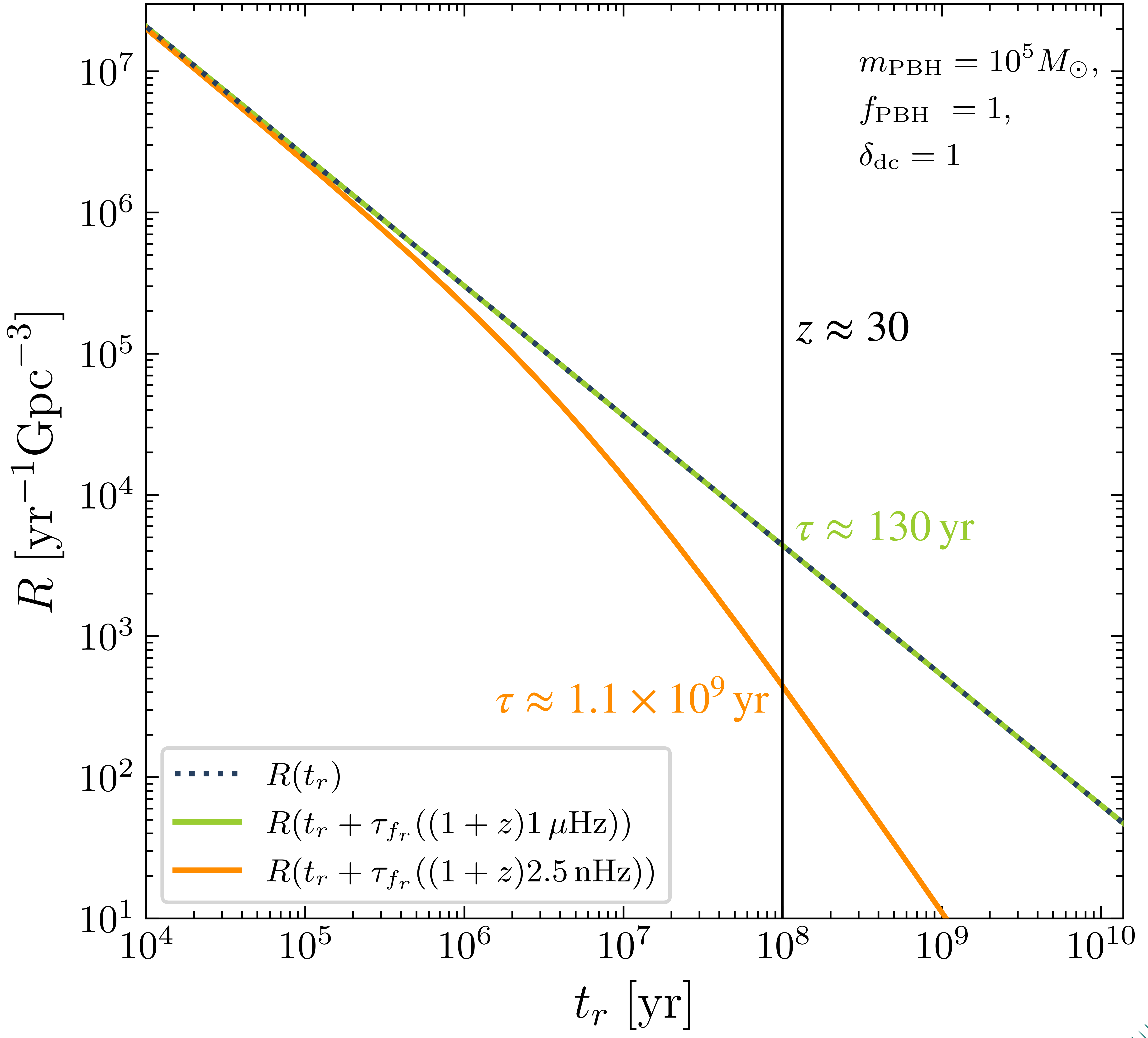
$$m_j = 2m_{j-1} - E_{\rm GW}(m_{j-1}) \sim 1.9^j m_0$$

$$\delta_{{\rm dc},j} \simeq 2^{-j}\delta_{{\rm dc},0}$$

$$\tilde{n}_j = \tilde{\rho}_{{\rm PBH},\infty}/(2^j m_0) = 2^{-j}\tilde{n}_0$$

Early emission of low frequencies

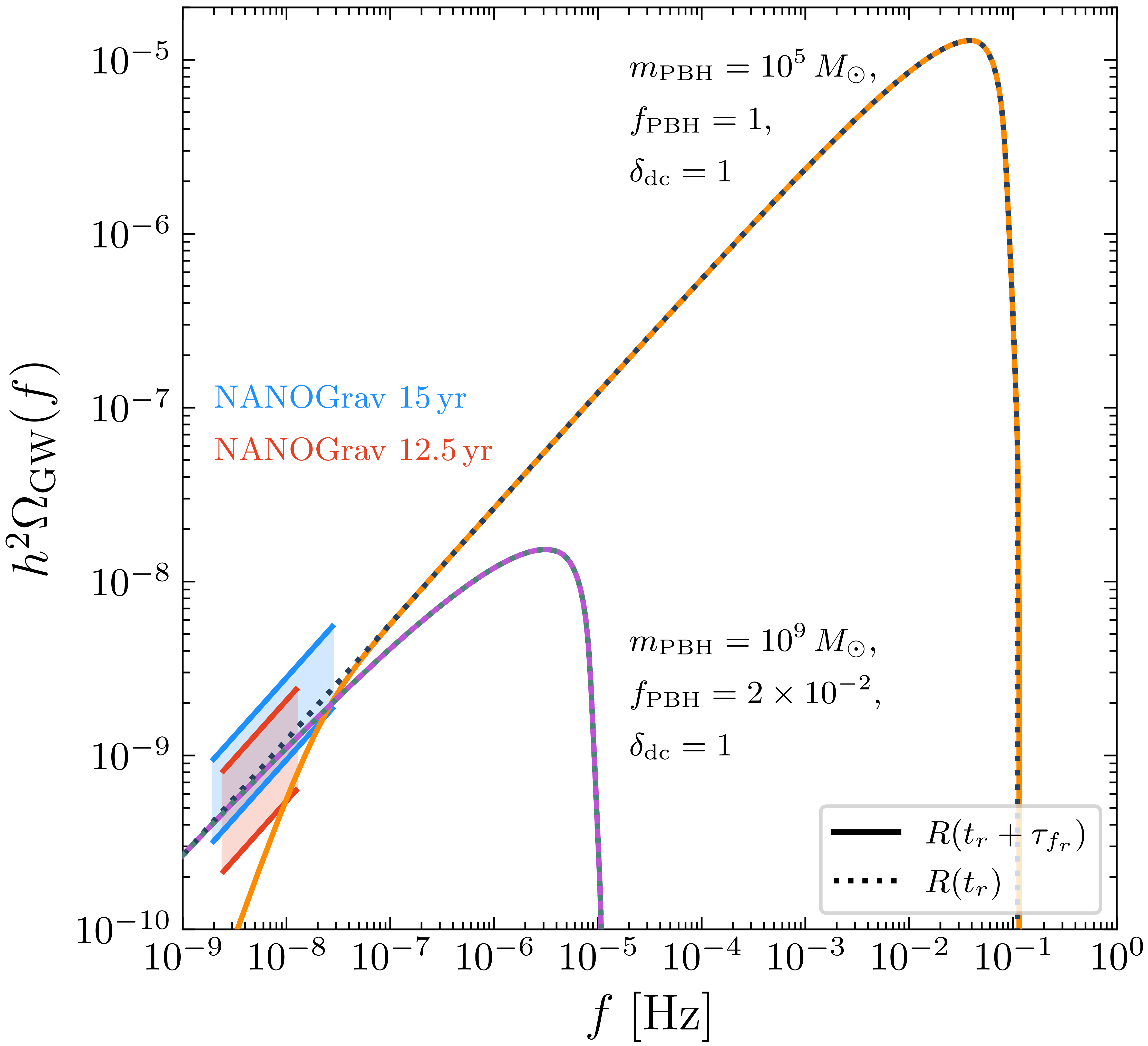
- Time until coalescence for frequency $f_{\rm r} = (1+z)f$ is $\tau_{f_{\rm r}} \propto f_r^{-8/3}\,(G\,m_{\rm PBH})^{-5/3}$
- Low frequencies can be emitted long before merger
- Emission rate can be obtained from merger rate $R(t) \to R(t+\tau_{f_{\rm r}})$



PFD et al. 2306.17836

Gravitational wave background

- GWB from binary mergers cf. Phinney astro-ph/0108028
- $\Omega_{\rm GW} = \frac{f}{\rho_{\rm crit}} \int_0^{t_0} {\rm d}t \left(R(t-\tau_f) \frac{{\rm d}E_{\rm GW}}{{\rm d}f_{\rm r}} \right)_{f_{\rm r}=(1+z)f}$
- Power-laws for spectrum ${\rm d}E_{\rm GW}/{\rm d}f_{\rm r}$ describing inspiral, merger, and ringdown Ajith et al. 0710.2335
- Effect of early emission of low frequencies can be important if PBHs are relatively light for PTA explanation



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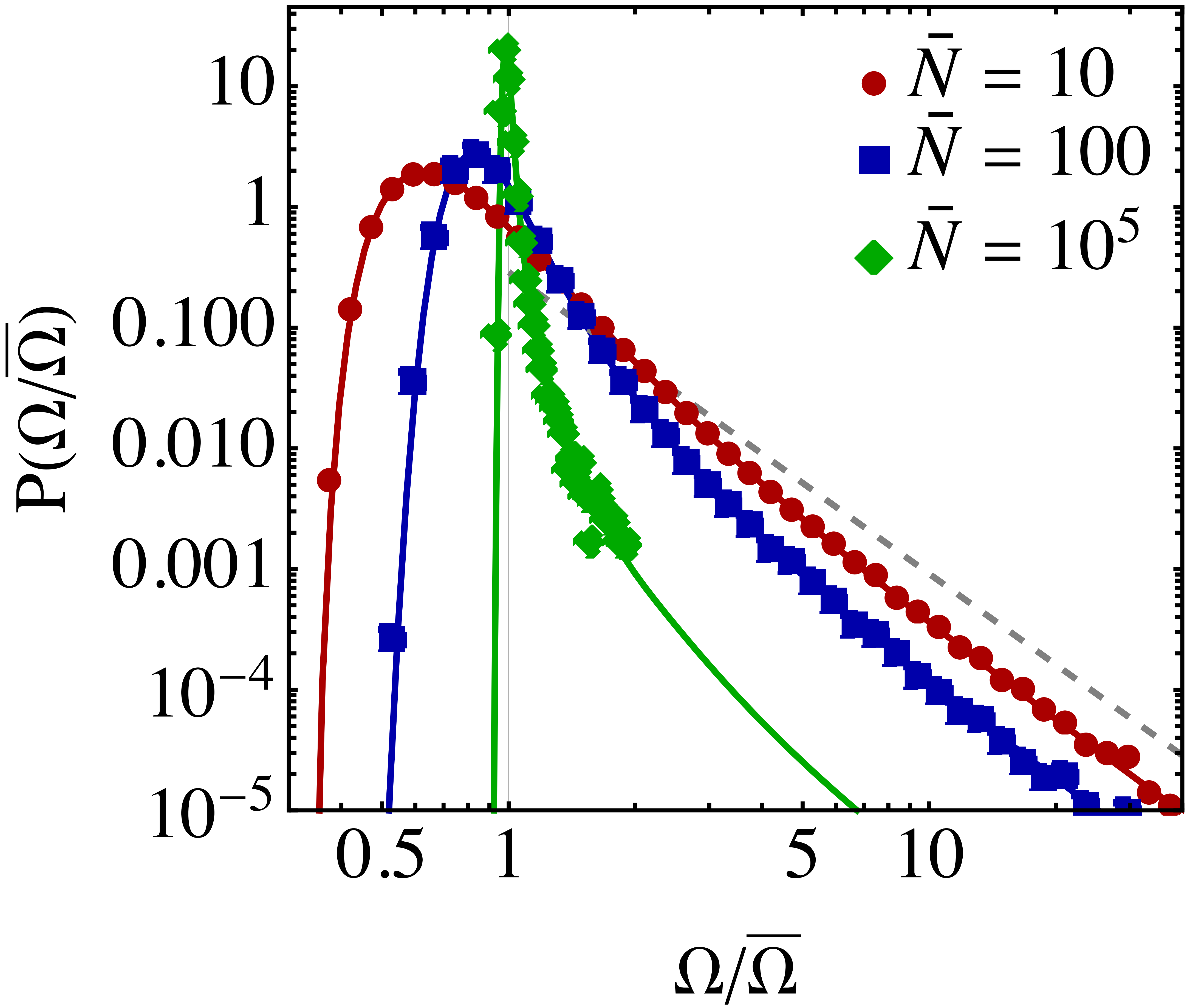
Stochastic GWB or individual sources?

Uncertainties in signal prediction

- Gravitational wave background consists of set of merging binaries, only truly stochastic GWB if number of binaries sufficiently large
- Local energy density in GWs is stochastic function of model parameters distributed around global average



Ellis et al. 2301.13854

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Uncertainties in signal prediction

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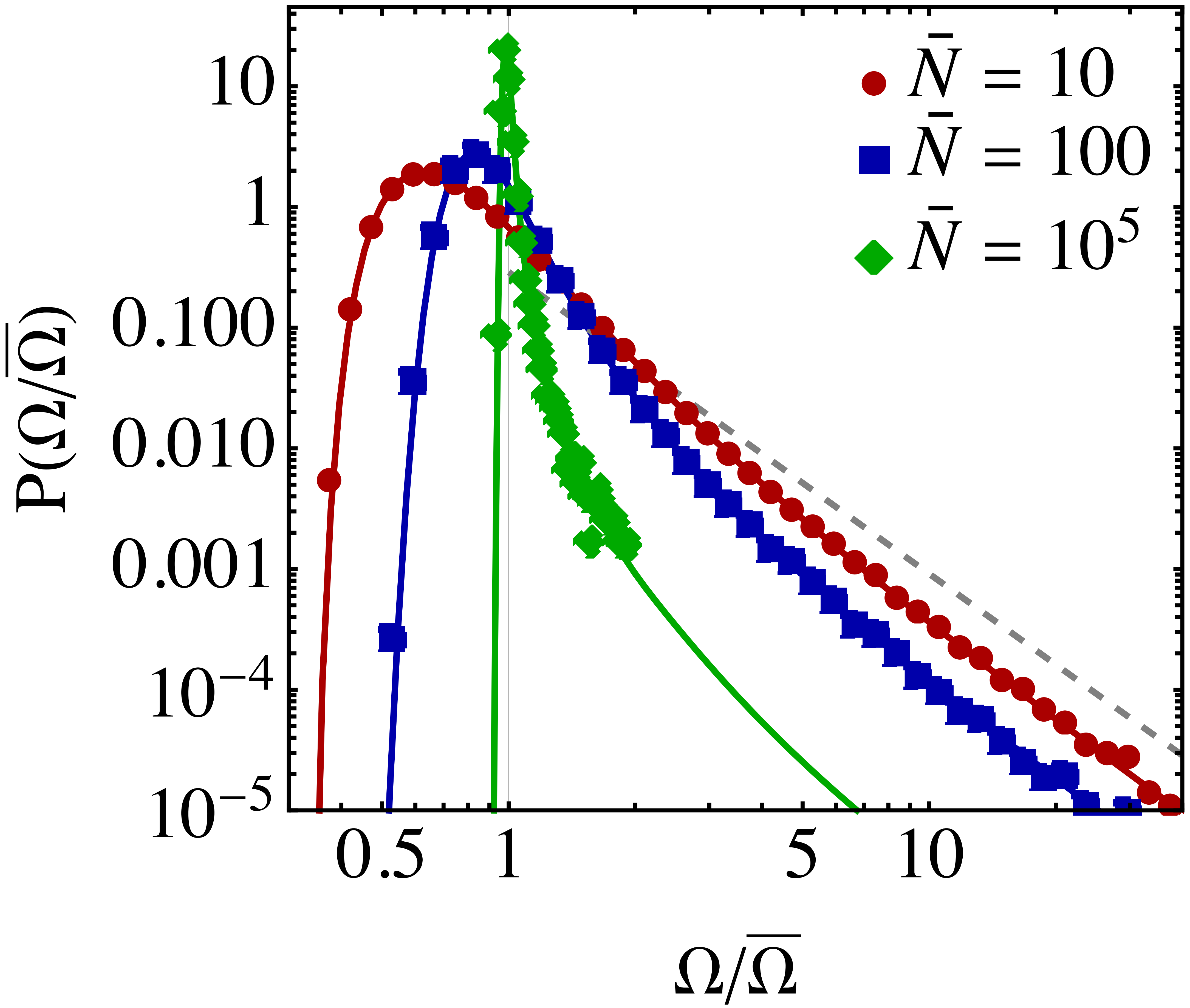
- Local energy density in GWs is stochastic function of model parameters distributed around global average
- Uncertainties in signal prediction depend on expected number of binaries $\bar{N}$:
  - $\bar{N} \gg 1$: observed signal close to global average
  - $\bar{N} \sim \mathcal{O}(\text{few})$: considerable uncertainty
  - $\bar{N} \ll 1$: no signal in most realizations
- We use global average and show regions where treatment is not appropriate



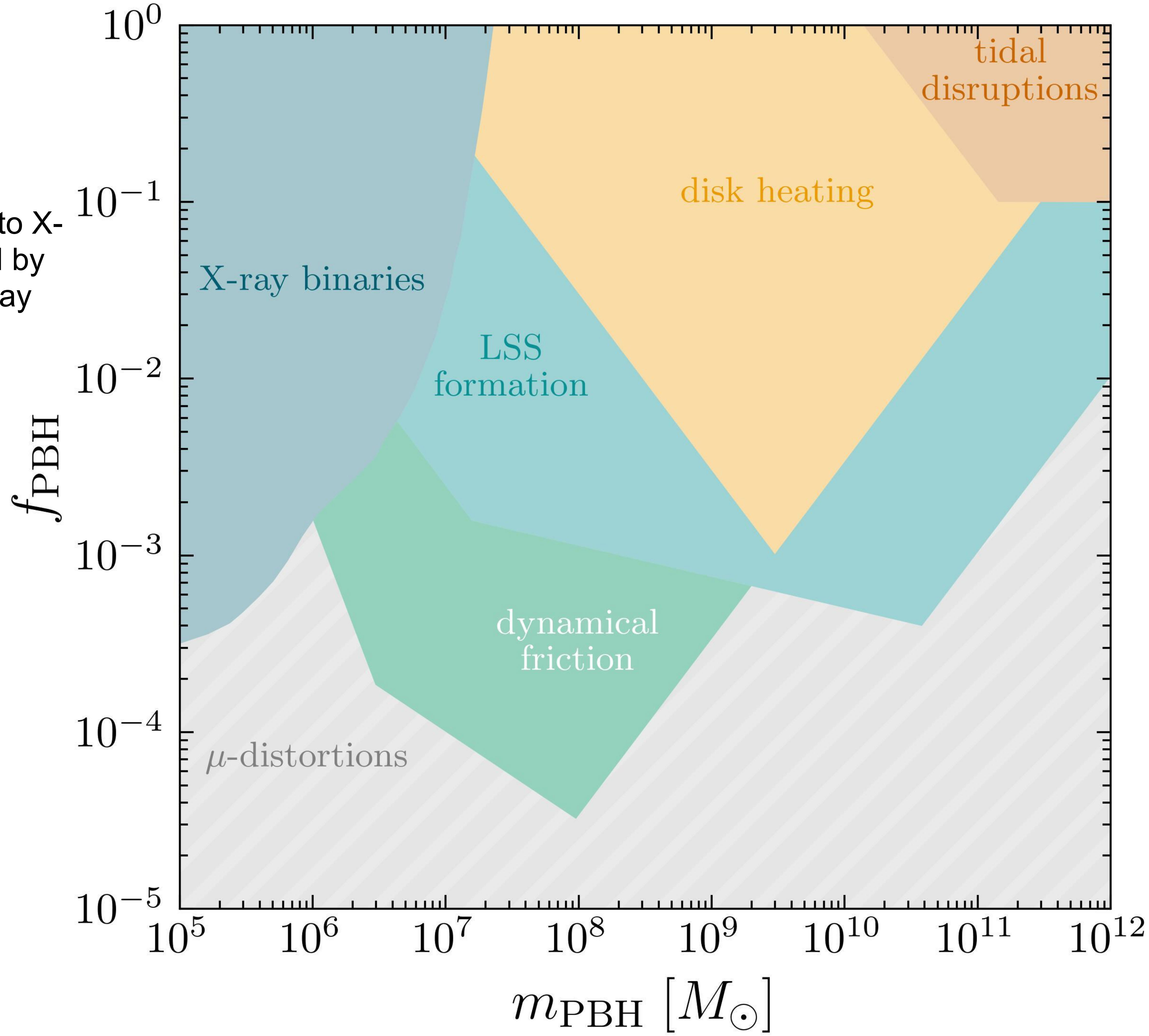
Ellis et al. 2301.13854

PTA data analysis

- Implemented (global) GWB as model in PTArcade Mitridate et al. 2306.16377
- Fitted NANOGrav 12.5 yr and 15 yr datasets using ceffyl Lamb, Taylor, and van Haasteren et al. 2303.15442
- Validated using enterprise and enterprise-extensions Ellis et al. 2020, Taylor et al. 2021
- For constraints added additional SMBHB power-law

Complementary constraints on PBHs

PBH accretion leads to X-ray flux, constrained by observations of X-ray binaries



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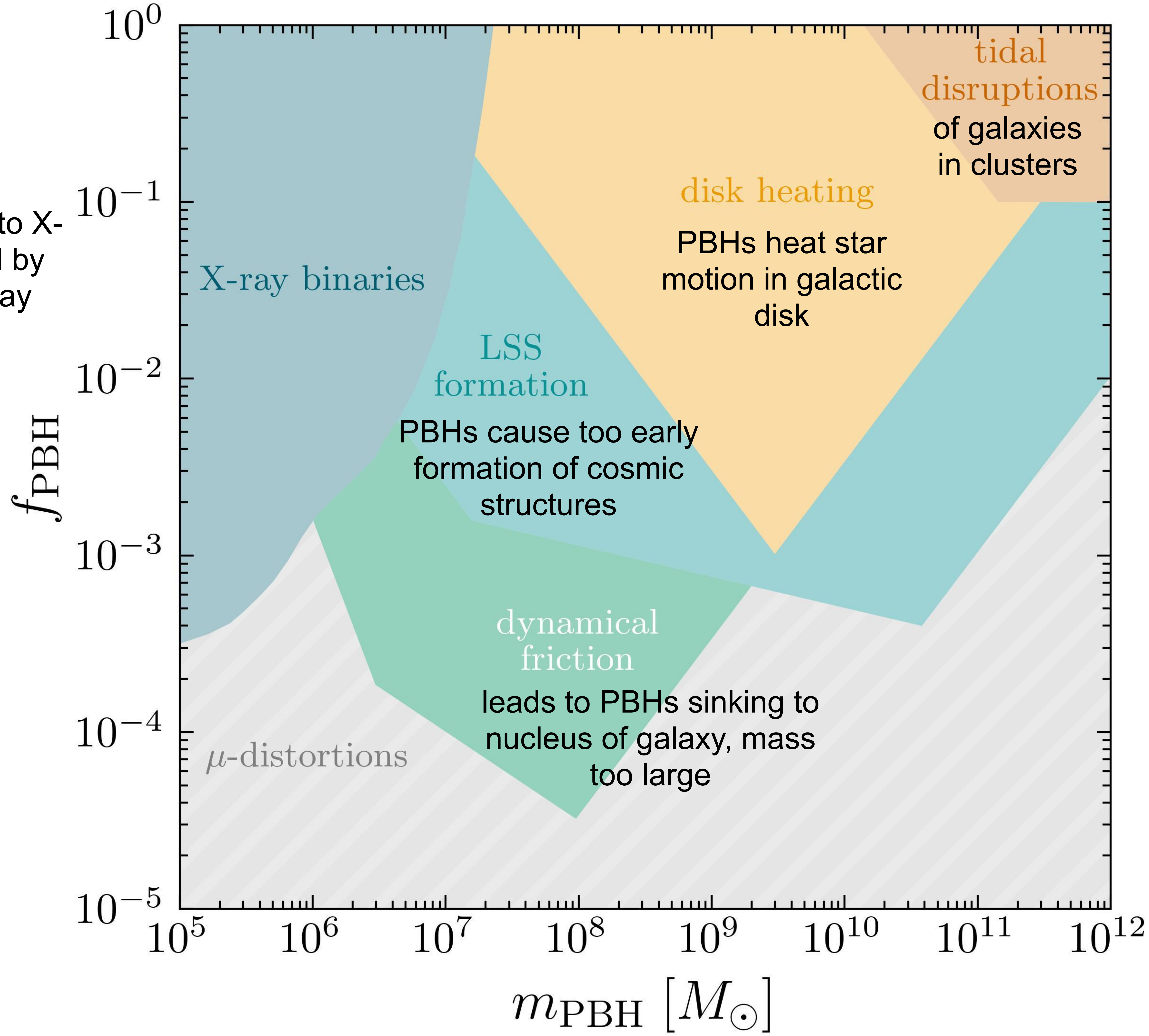

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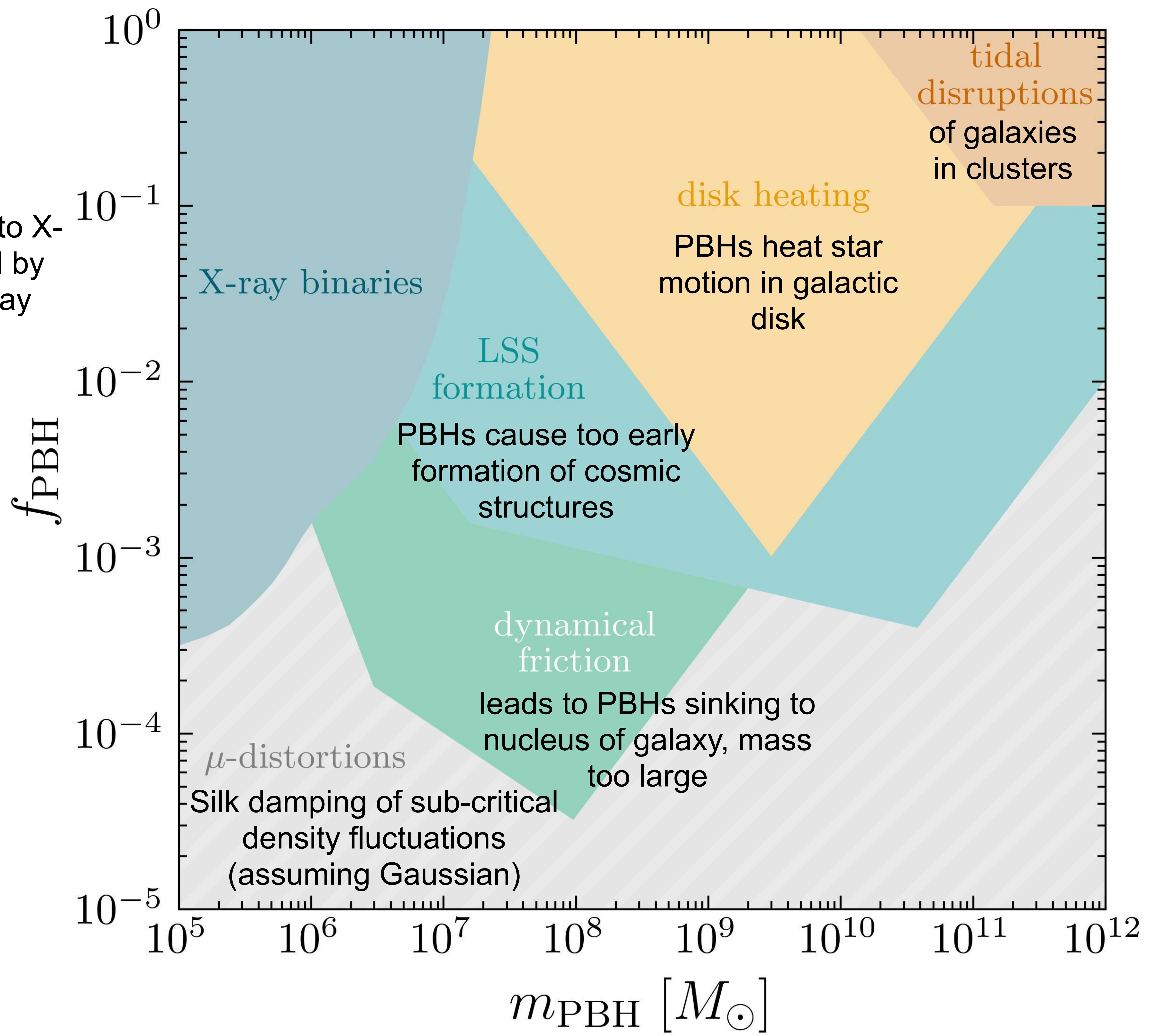

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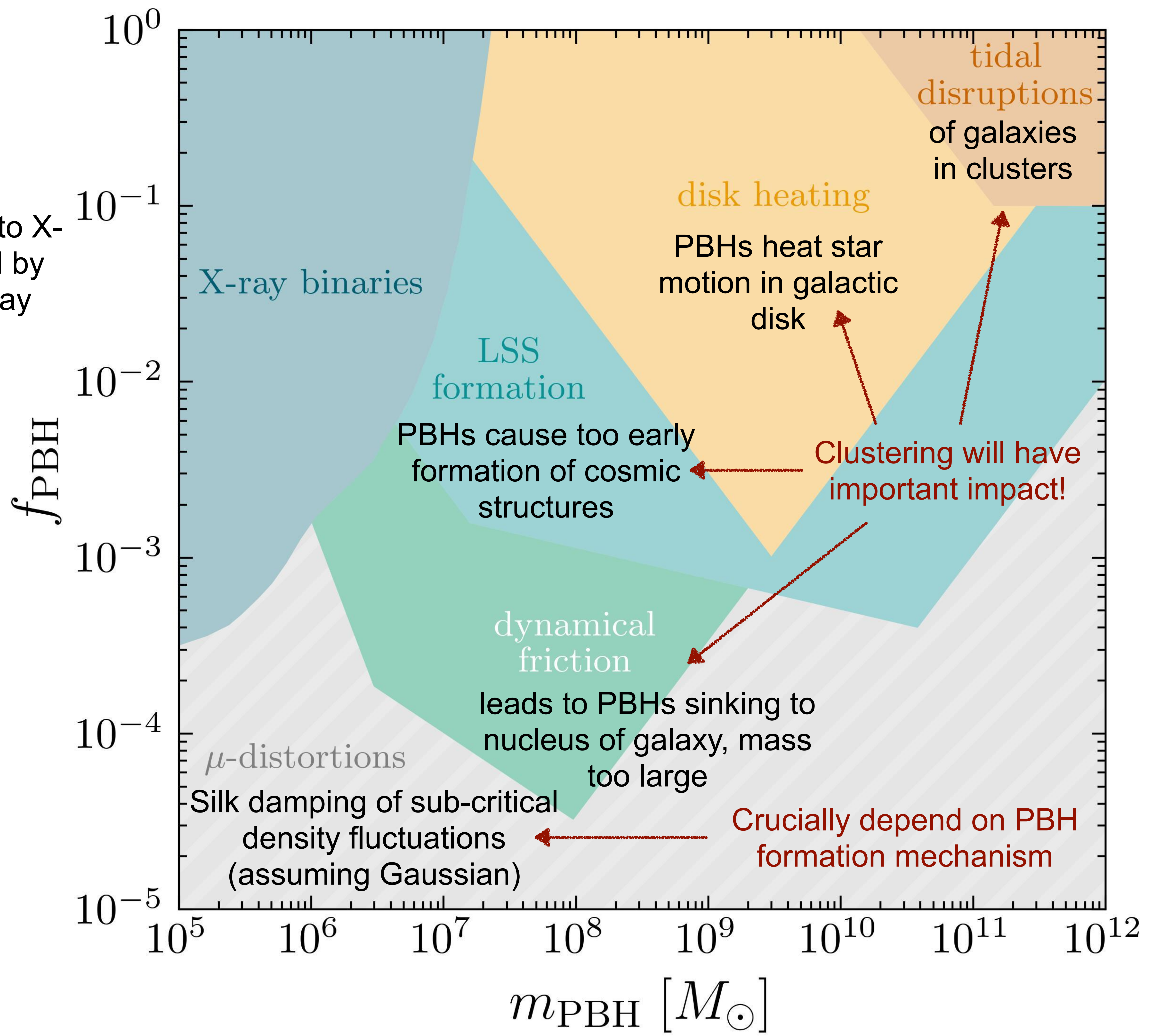
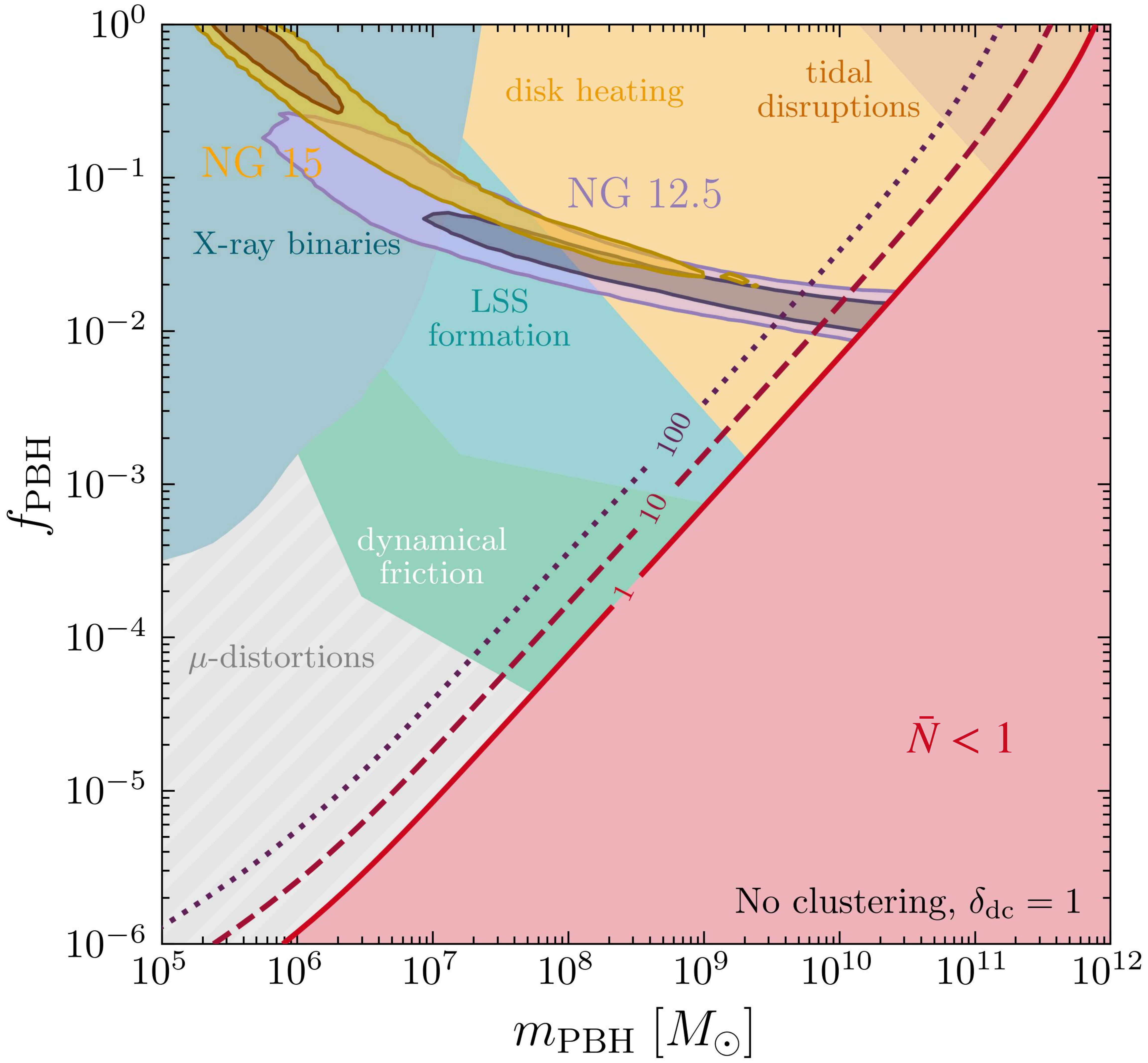


Results without clustering



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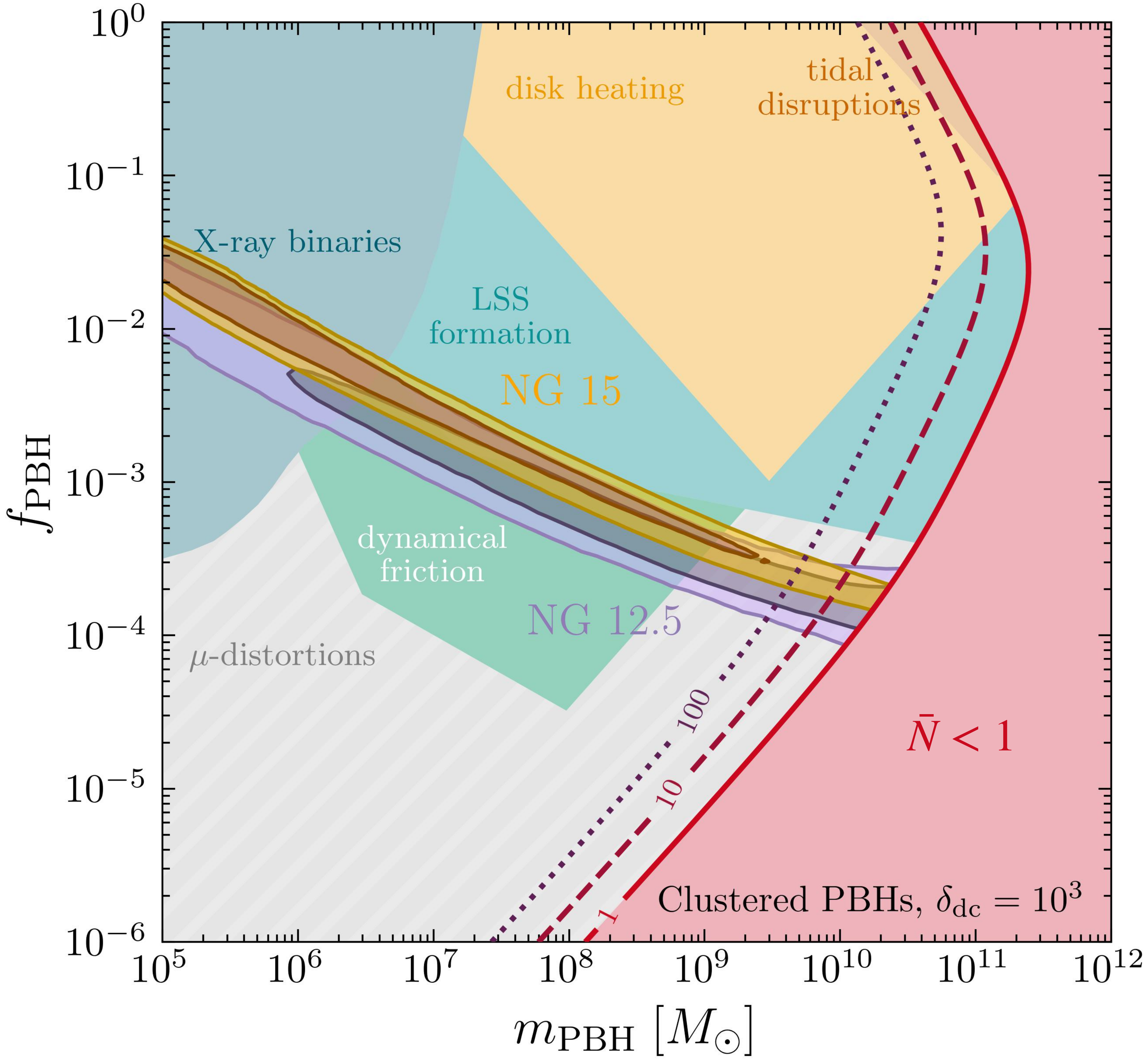

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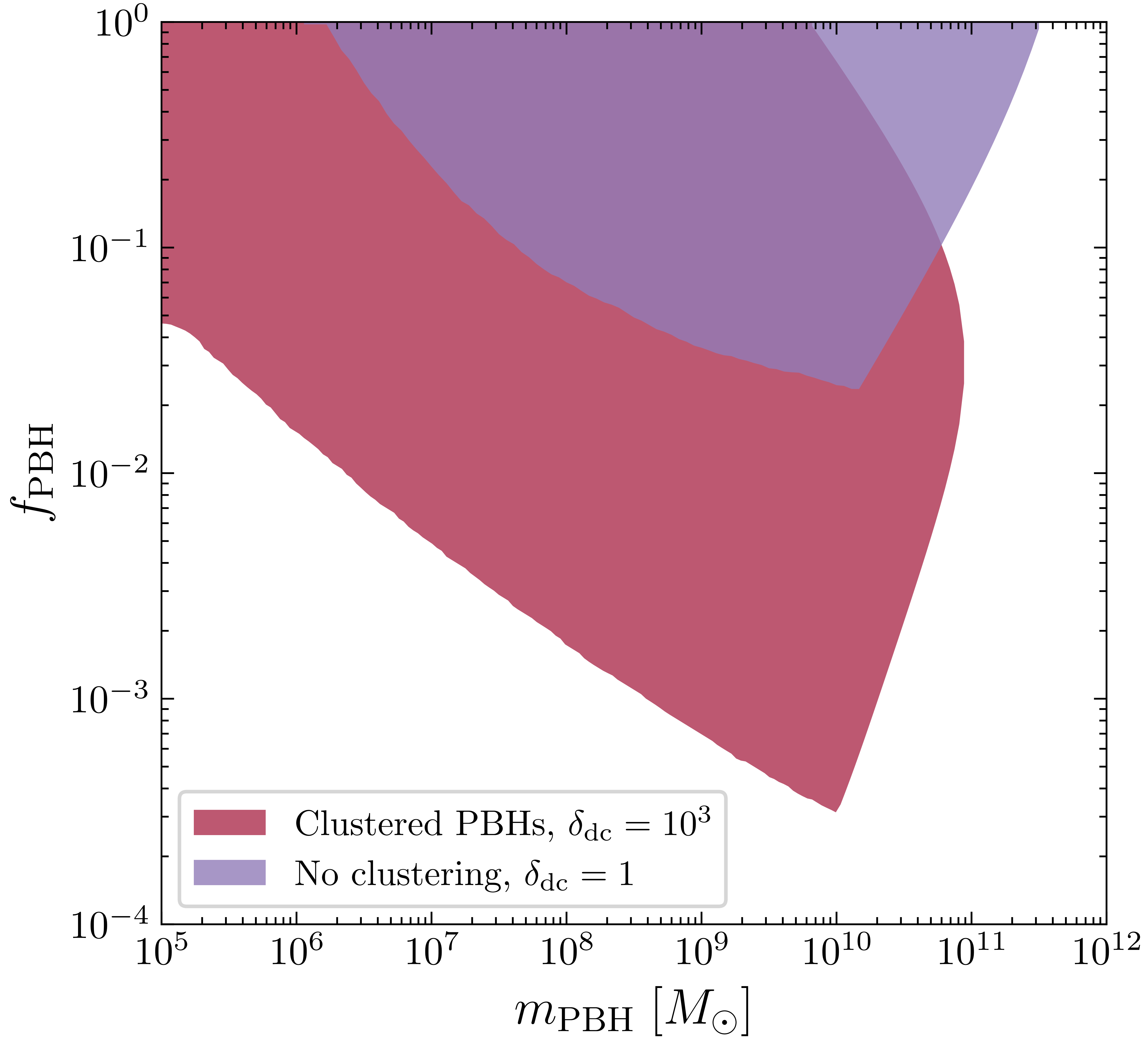
Constraints



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Conclusions

- Homogeneously distributed PBHs cannot explain PTA signal
- Clustering shifts signal region to smaller abundances and can help to alleviate complementary constraints $\rightarrow$ consistent explanation of PTA signal in terms of merging PBHs possible
    - μ-distortions can still be problematic
    - Is there a PBH formation scenario leading to clustering without μ-distortions?
- PTAs also place constraints on PBHs, can be derived with and without clustering

Thank you