Ruling out QCD phase transition as a PBH origin of LIGO/Virgo events

JI, P. D. Serpico, G. Franco Abellán. arXiv: 2204.07027
The QCD phase transition behind a PBH origin of LIGO/Virgo events?

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PBHs: Intro

Primordial Black Holes (PBHs) were firstly discussed in the 60s and 70s by Zeldovich & Novikov and Carr & Hawking

DM

While there is no shortage of DM particle candidates in extensions of the SM, there is no guarantee nor observational indication that DM is made of microscopic fundamental particles.

A non-particle candidate corresponds to **PBHs**.

Other

But also very interesting objects in the context of supermassive black holes (SMBHs), LIGO-VIrgo coalescing events, inflation etc.

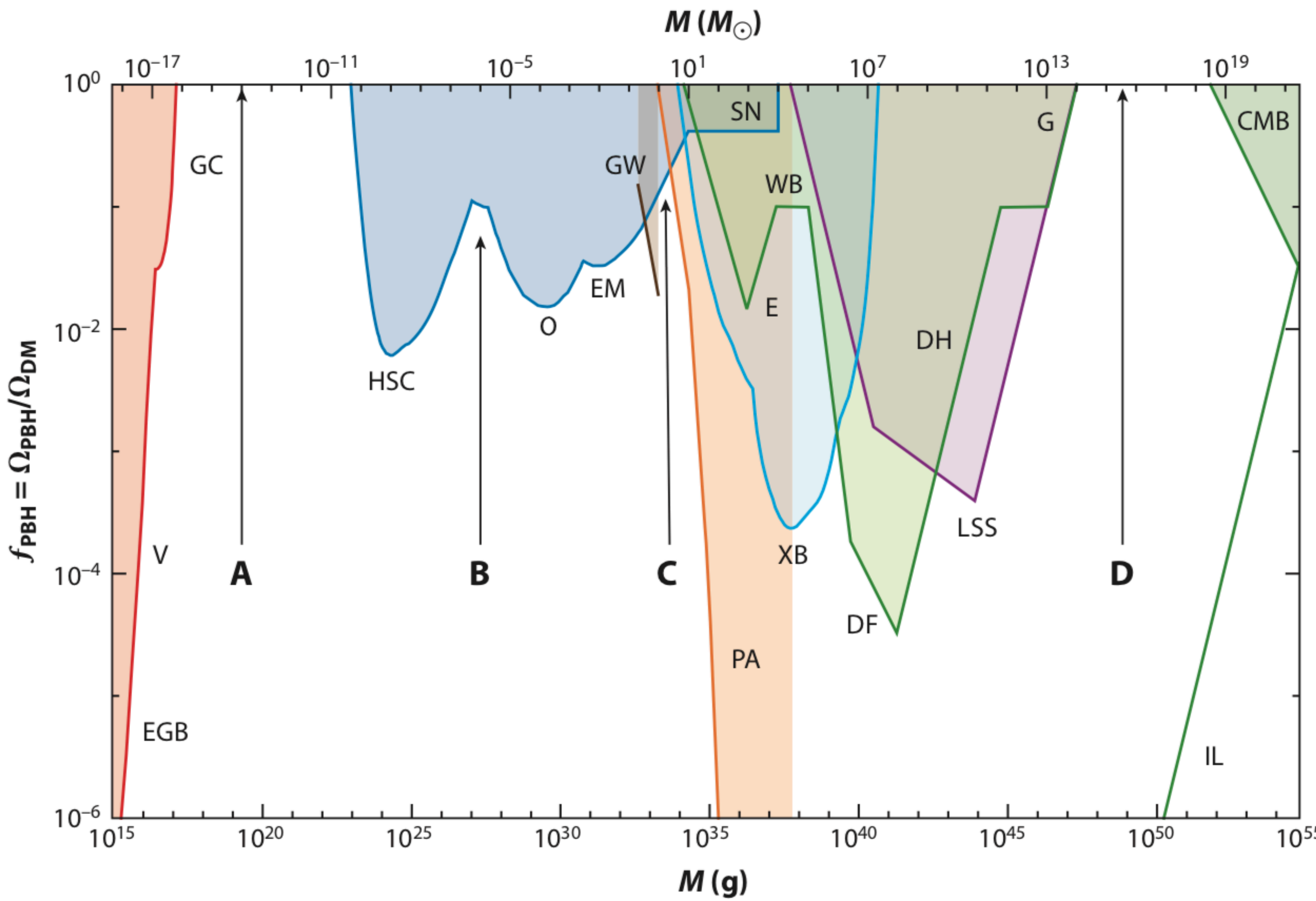
Several formation mechanisms considered in the literature, although typically assumed to be formed from the gravitational collapse of large overdensities in the early universe.

Gravitational collapse is stronger than pressure gradients.

PBHs span a wide range in mass $\Longrightarrow$ Can be associated to a number of signatures!

PBHs as DM:

Carr and Kühnel, Annual Review of Nuclear and Particle Science 70, 355–394 (2020)



Constraints on f (M) for a monochromatic mass function from evaporations (red), lensing (dark blue), gravitational waves (GW) (brown), dynamical effects (green), accretion (light blue), cosmic microwave background distortions (orange), and large-scale structure (purple). There are four mass windows (A, B, C, D) in which PBHs could have an appreciable density.

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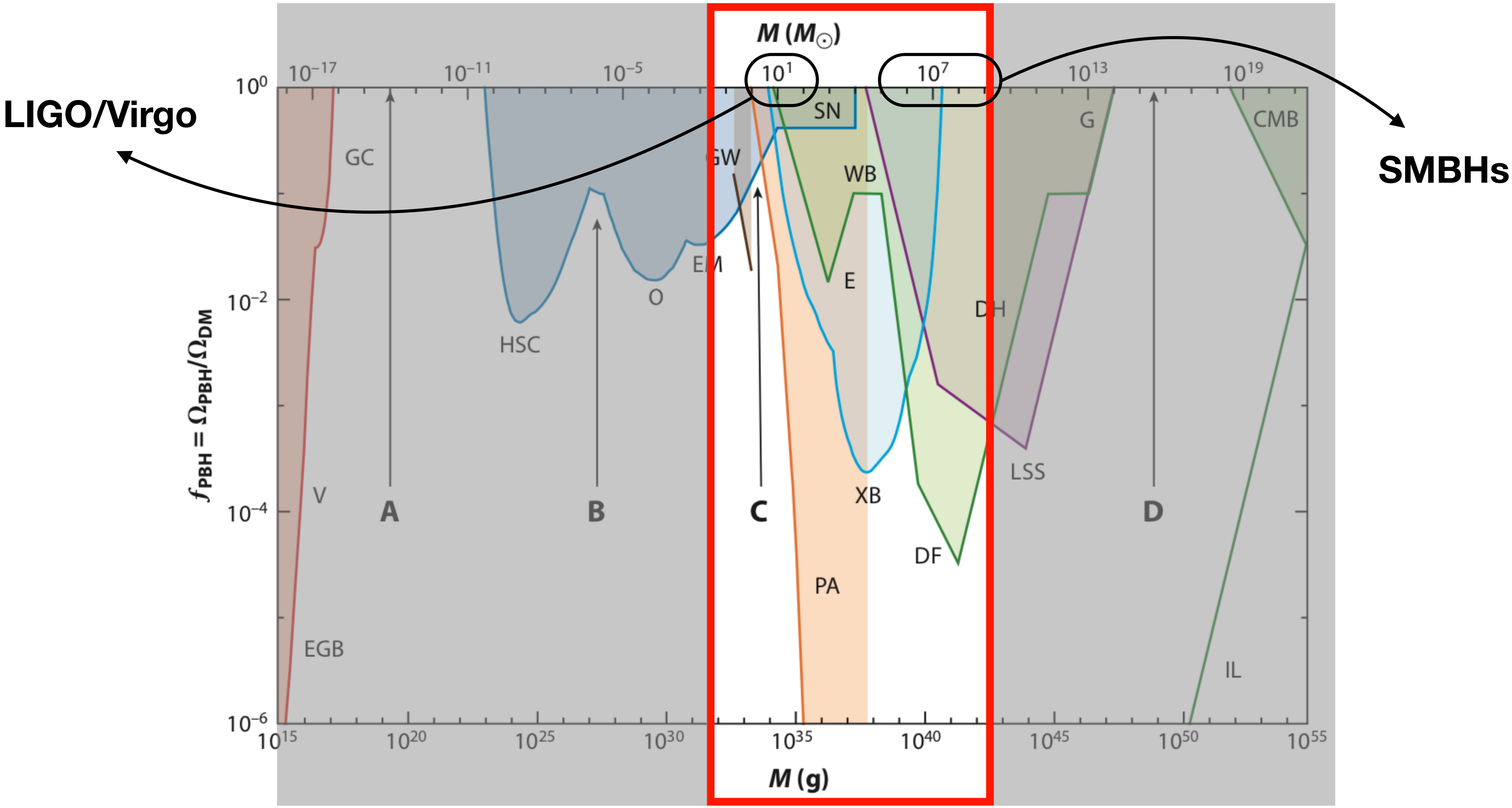

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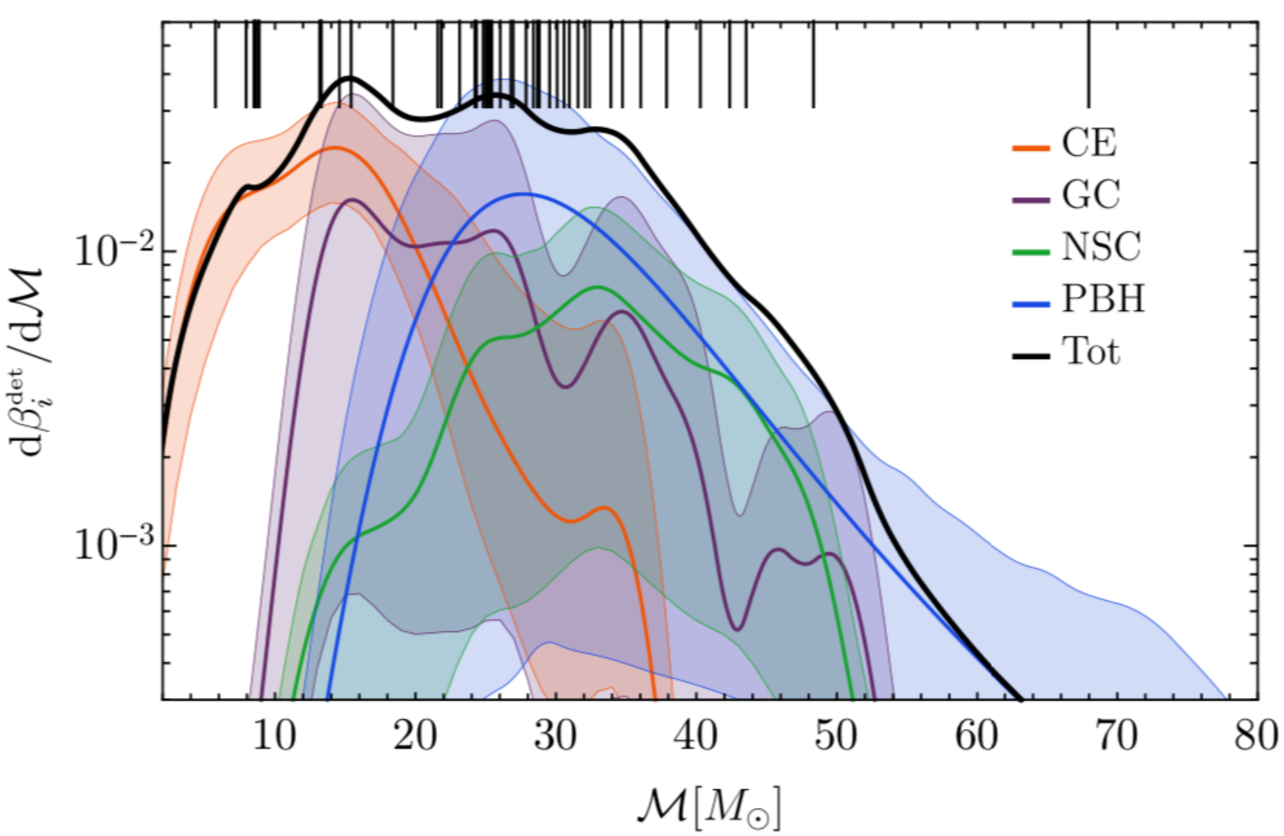
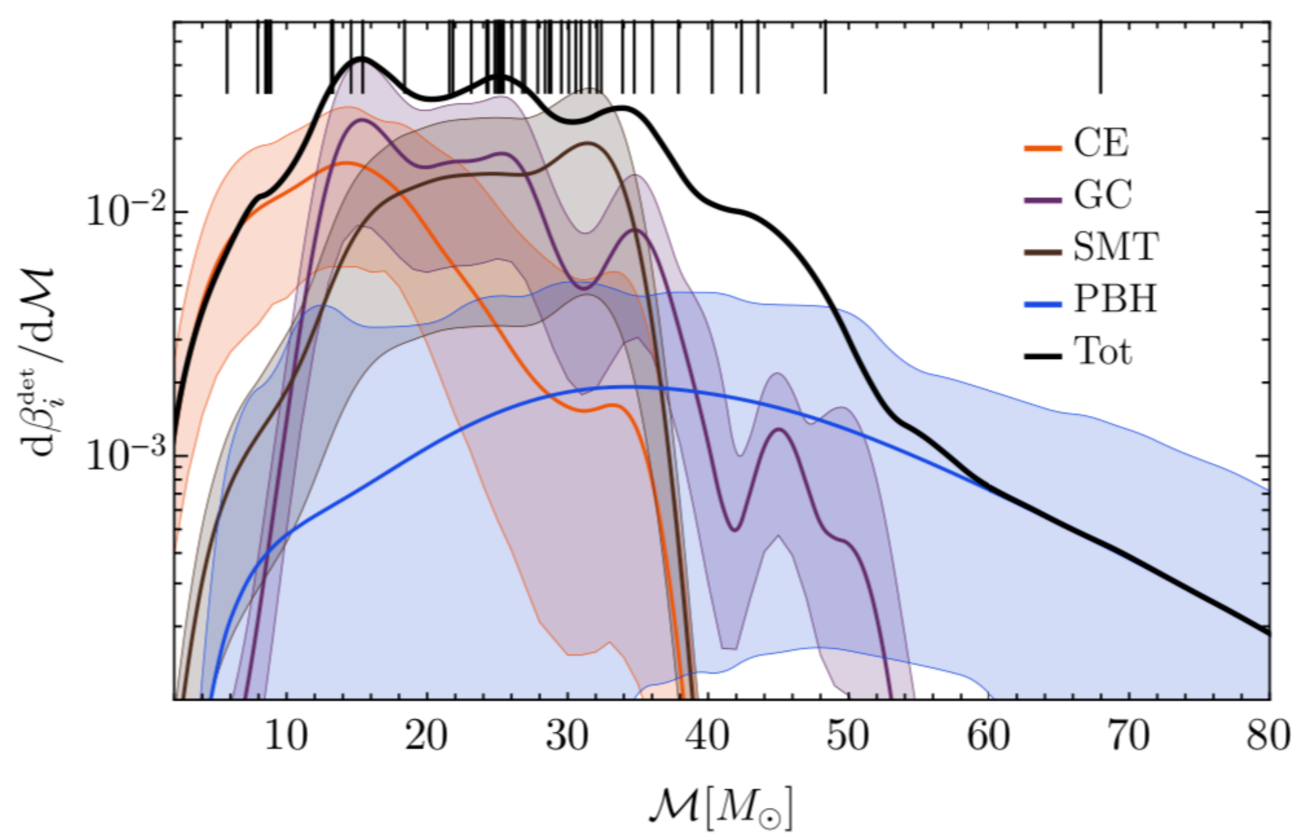
Intro/Motivation

G. Franciolini et al. Phys. Rev. D **105**, 083526

A scenario with PBHs in the stellar mass range is especially interesting in the light of LIGO/Virgo observations of BBHs.

Even if pretty constrained, if PBHs with masses $M_{\rm PBH} \sim \mathcal{O}(10) M_\odot$ contribute a fraction $f_{\rm PBH} \simeq \mathcal{O}(10^{-3})$, PBHs could explain a significant fraction of events, improving fits to inferred mass distribution!





Intro/Motivation

JI, P. D. Serpico, G. Franco-Abellán. JCAP07(2022)009

PBH production models are hardly predictive on its mass distribution…

One may wonder if there is any actual physically motivated shape, which could be amenable to observational tests.

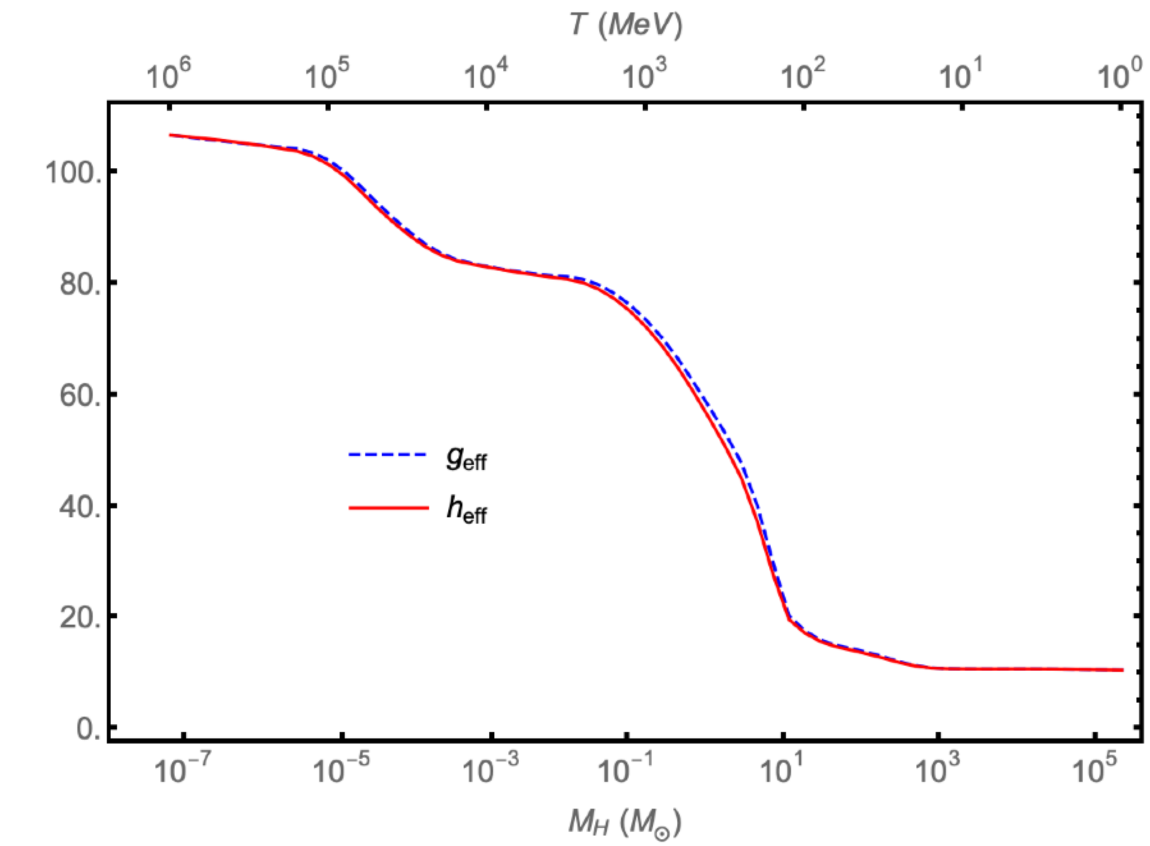
- YES! In the stellar mass range ⟶ QCD phase transition
  - K. Jedamzik, Physics Reports 307, 155 (1998)
  - B. Carr et al. Phys. Dark Univ. 31, 100755 (2021)
  - K. Jedamzik, Phys. Rev. Lett. 126, 051302 (2021)
  - etc.
- Also, at higer masses ⟶ e^+e^- annihilation

This implies a peculiar mass function with physically motivated features extending up to $M_{\rm PBH} \sim 10^7\, M_\odot$

➡ Assess viability of “best motivated” scenario in light of current constraints.

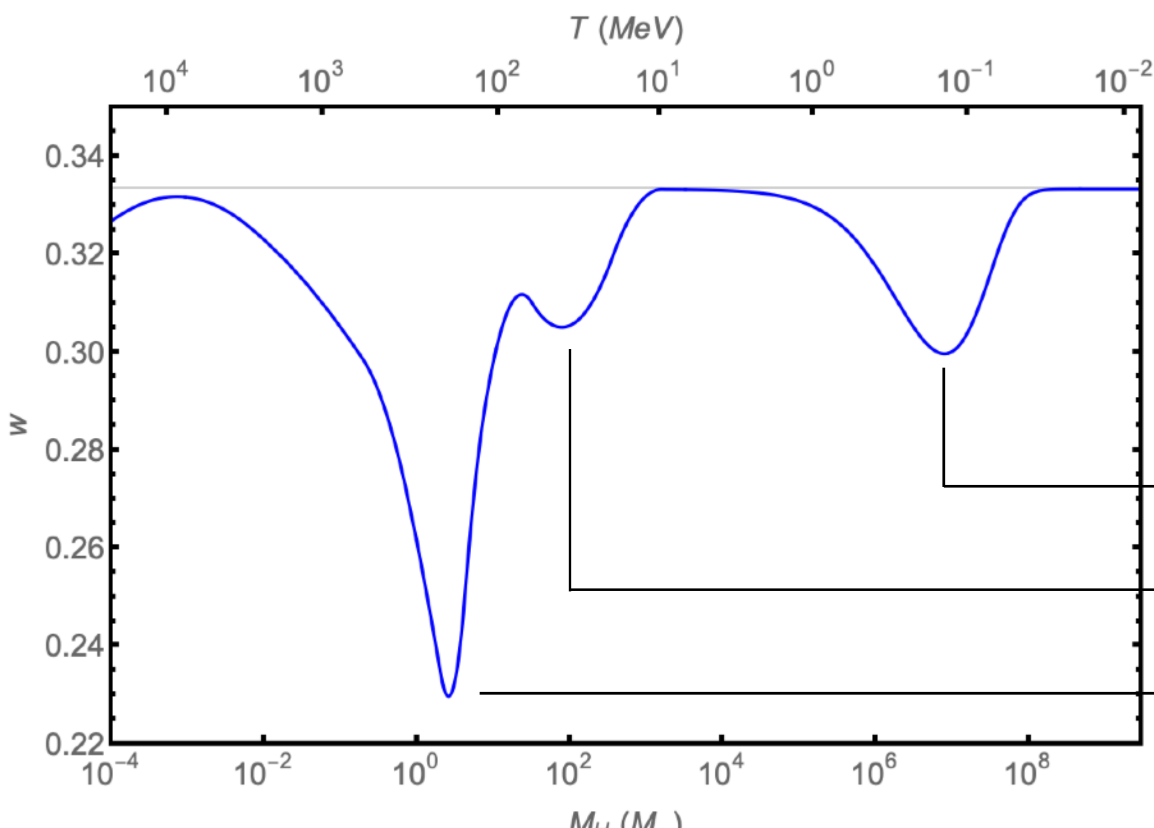
➡ Check resulting PBH abundance in LIGO/Virgo mass range $\Longrightarrow \boxed{f_{PBH} \sim \mathcal{O}(10^{-3})???}$

Equation of state in the early universe



$$g_{\rm eff}(T) \equiv \frac{30\rho}{\pi^2 T^4}\,,$$
$$h_{\rm eff}(T) \equiv \frac{45 s}{2\pi^2 T^3}\,,$$

$$P = sT - \rho \xrightarrow{w \,\equiv\, P/\rho} w(T) = \frac{4h_{\rm eff}(T)}{3g_{\rm eff}(T)} - 1$$



e^+e^- annihilation

Pion and muon annihilation

QCD phase transition

The power spectrum

The thermal history is not enough to obtain an allowed mass function! But we can play with the **power spectrum (PS)** to derive interesting scenarios.

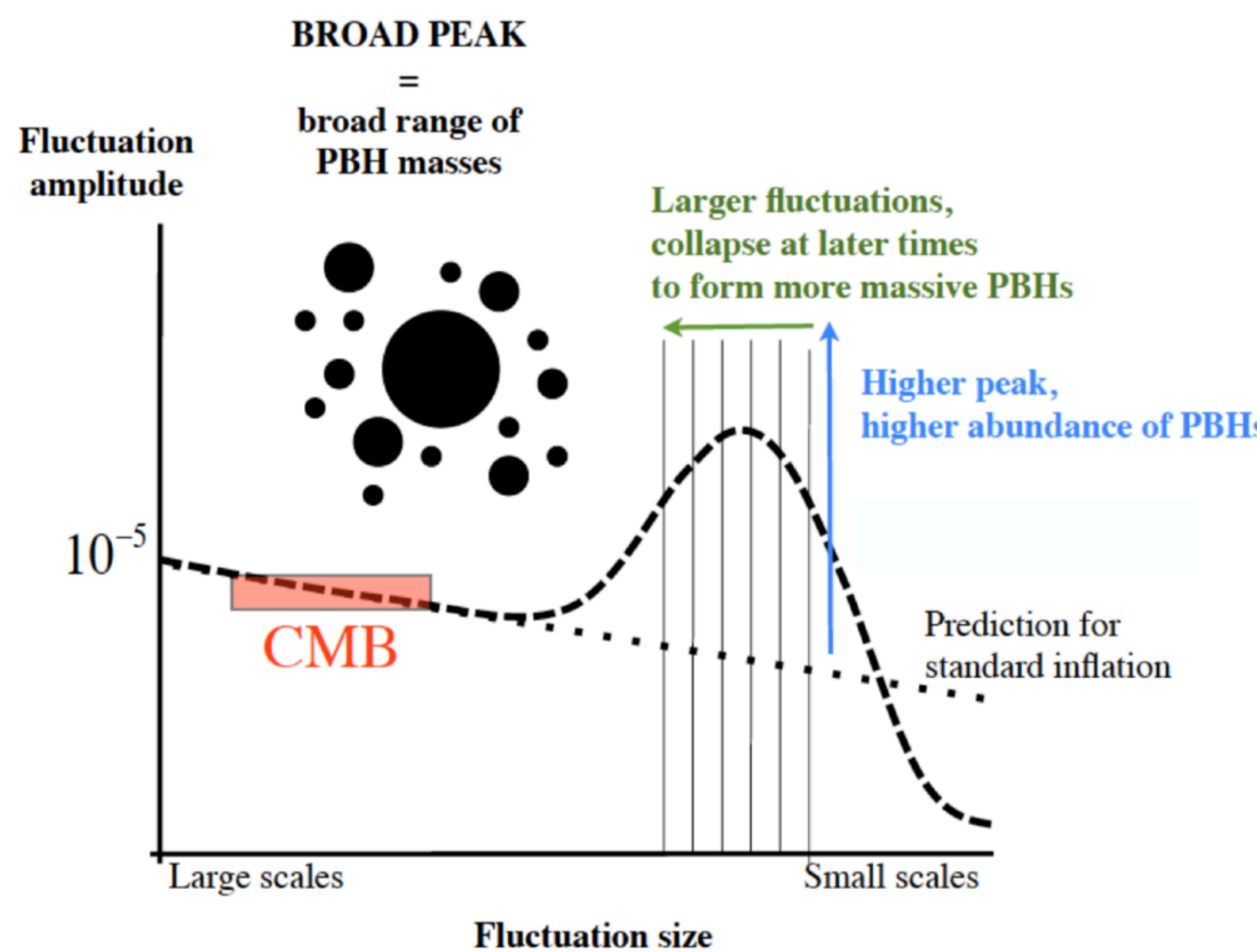
If PS was as small as the one extrapolated from CMB fit $\Longrightarrow$ negligible production of PBHs…

PS should be enhanced!
Ideally at

$$k_{\rm QCD} \gg k_\bullet \gg k_{\rm CMB}$$

$$M_{QCD} \ll M_{cut} \ll M_{CMB}$$

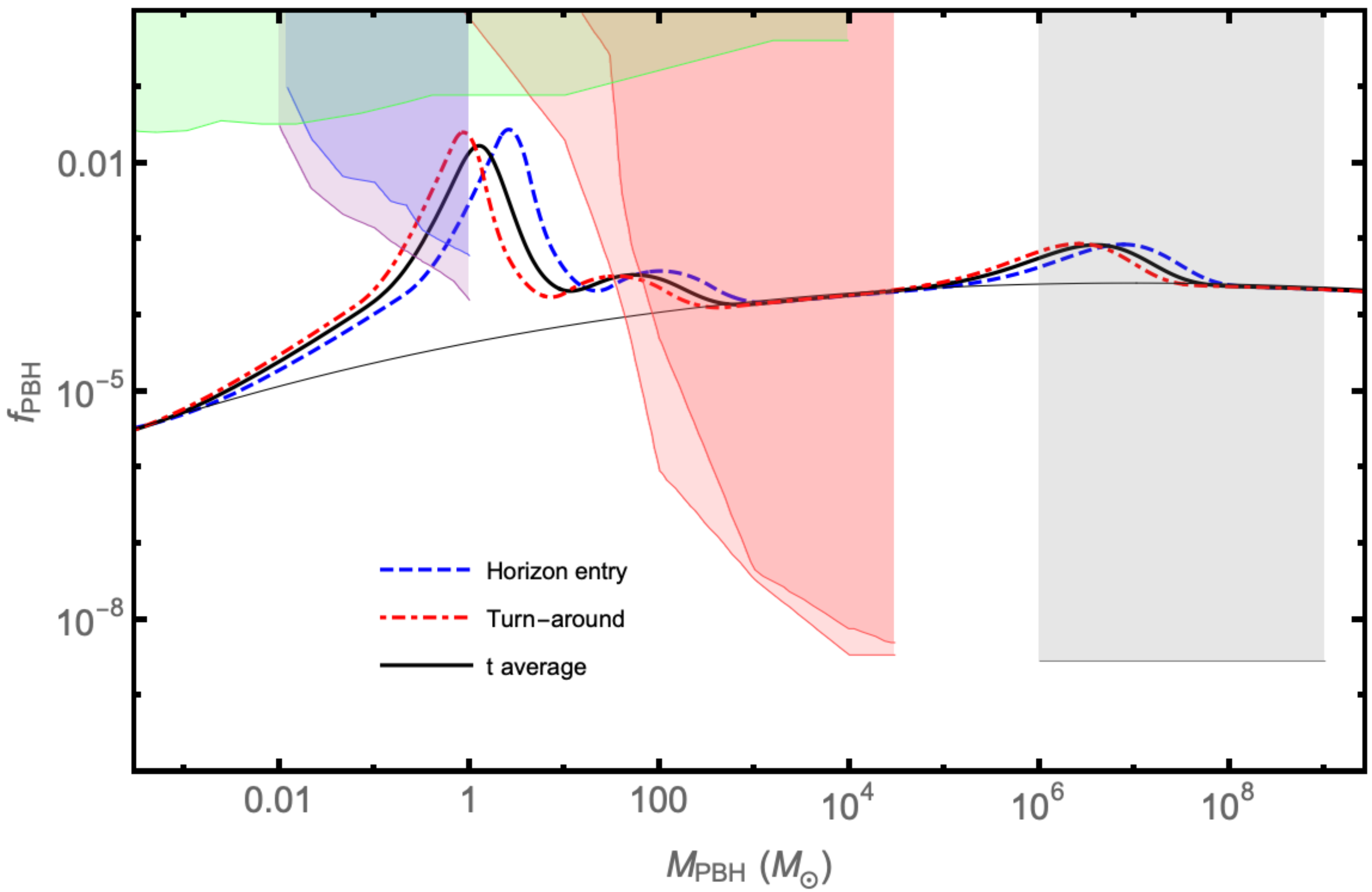
$$M_{\rm cut} = \left(\frac{k_\bullet}{10^6 {\rm Mpc}^{-1}}\left(\frac{g_*}{10.75}\right)^{1/12} 17^{-1/2}\right)^{-2} M_\odot$$



Results: Quasi-flat spectrum

Clearly, in tension with several bounds!!

$$\int_{M_{\rm min}}^{M_{\rm max}} {\rm d}M \frac{\psi_p(M)}{f_{\rm mono}^{\rm max}(M)} = 1$$

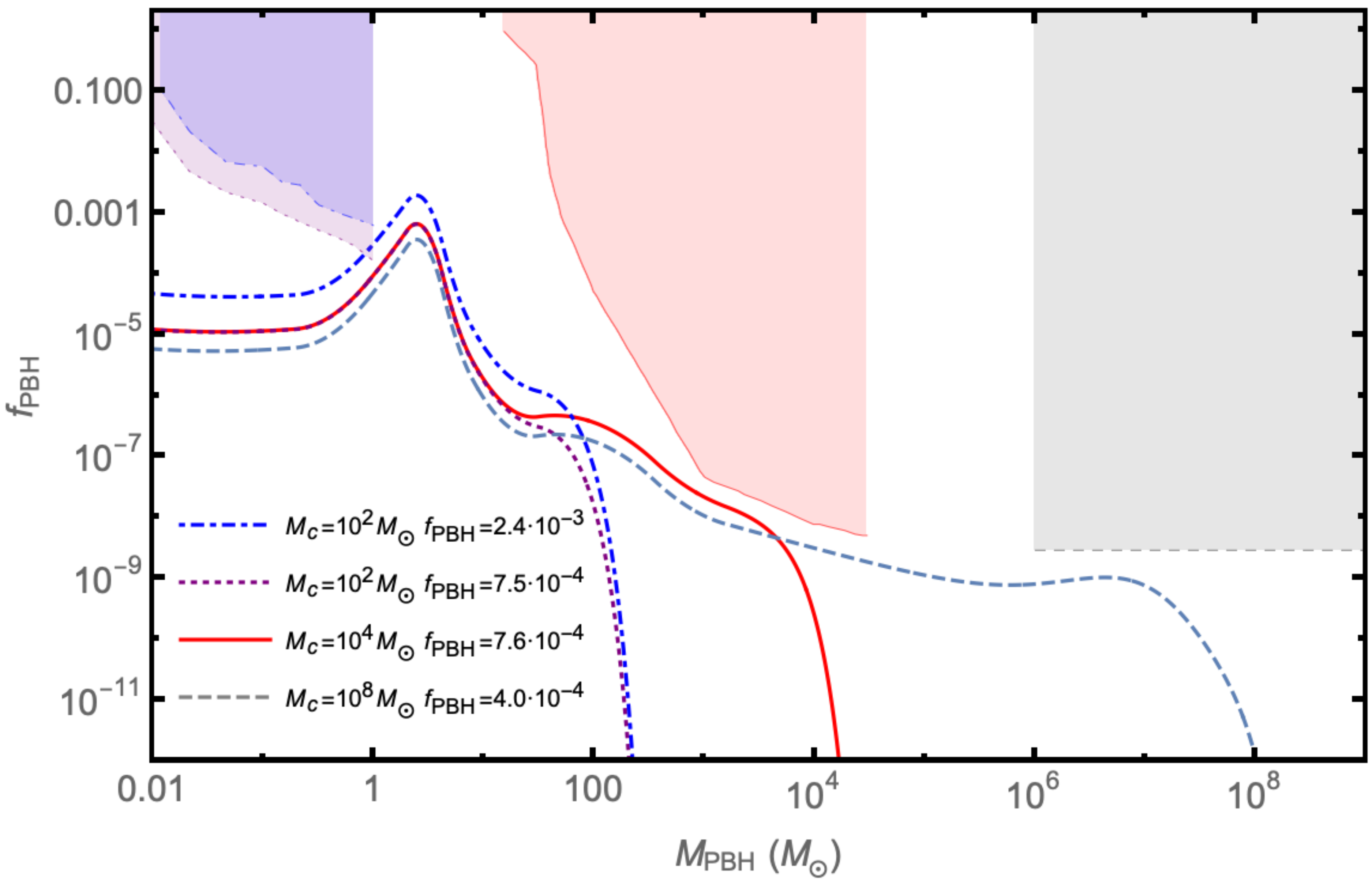


$$\sigma^2 = 0.0033 \left(\frac{M}{10 M_\odot} \right)^{n_M}$$

$$f_{\rm GW} \equiv \int_{5M_\odot}^{160 M_\odot} \psi_p(M) {\rm d}M$$

$$f_{GW} \sim 10^{-3}$$

Results: allowed models



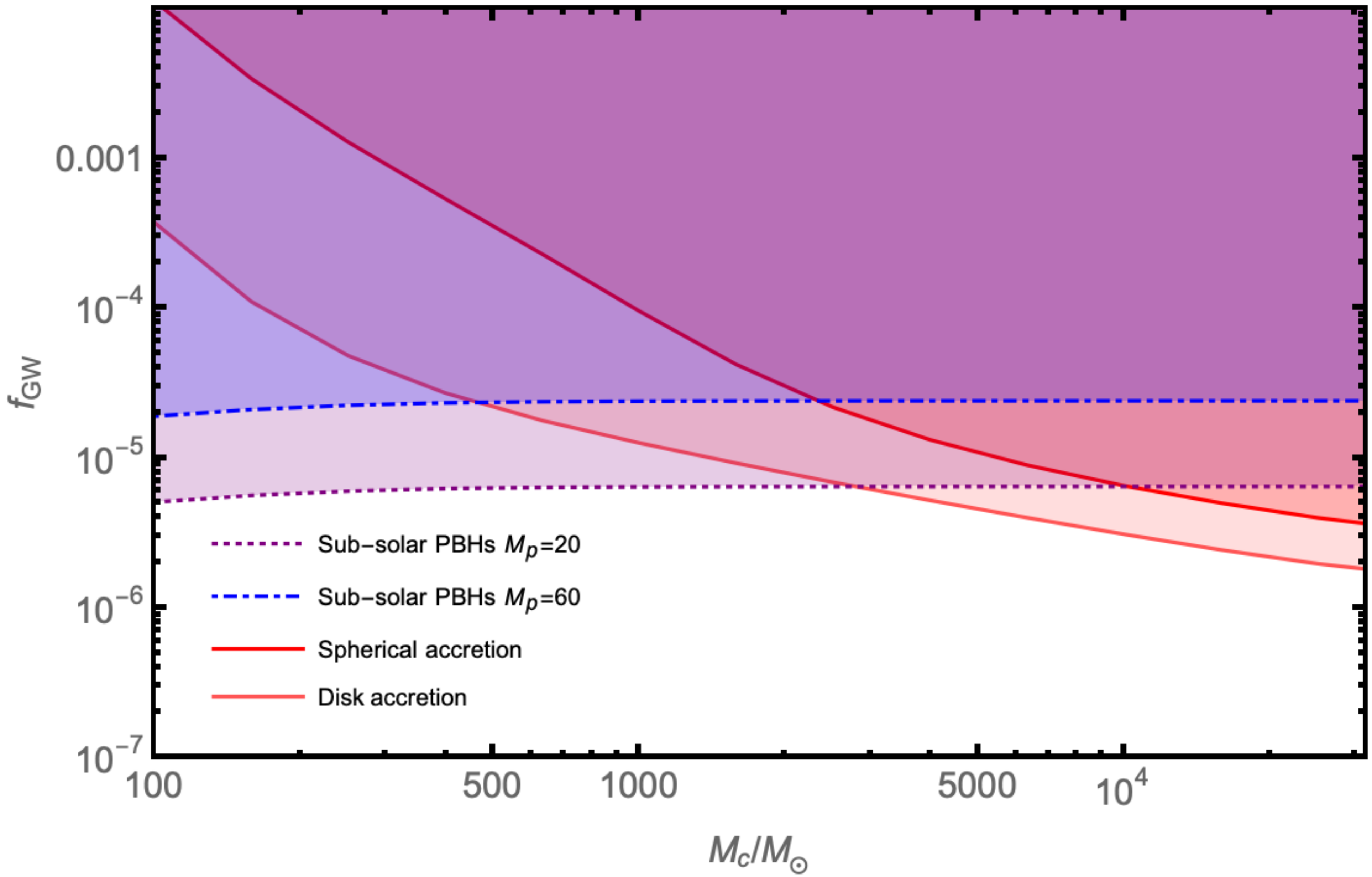
For $M_{cut} \gtrsim 10^6 M_\odot$:
Tension with SMBHs counting and μ distortion bound!

For $M_{cut} \gtrsim 10^4 M_\odot$:
Tension with CMB anisotropies bound!

For $M_{cut} \lesssim \mathcal{O}(10^2) M_\odot$:
The cut is just above the QCD scale! Cutting below means renouncing the idea of a QCD-inspired scenario…

So can we explain LVC events?

$$f_{\mathrm{GW}} \equiv \int_{5M_\odot}^{160M_\odot} \psi_p(M)\mathrm{d}M$$ and PBH's contribution should be $f_{GW} \sim \mathcal{O}(10^{-3})$



$f_{GW} \lesssim 10^{-5}$

well below the amount required in phenomenological fits!!

In QCD-inspired scenarios, PBHs have at most a tiny contribution to LVC events.

CONCLUSIONS

We have assessed the viability of the scenario where a sizable PBH contribution to LVC mergers relies on a mass function shaped by early universe phenomena (QCD + e^+e^- annihilation).

This scenario is not viable unless and ad hoc **mass function evolution** and a **cutoff in power spectrum** very close to QCD scale is introduced by hand, which spoils its "naturalness" appeal.

On the other hand, an interesting feature is its very wide PBH mass function, from $M_{PBH} \sim 0.1 M_\odot$ to $M_{PBH} \sim 10^7 M_\odot$. Its viability would still require that CMB spectral distortion bounds can be relaxed $\Longrightarrow$ **non-Gaussianities**!

The search for BBH with a sub-solar mass BH may provide a better understanding of the heaviest BHs in universe!

Backup slides

PBH mass distribution

$$\beta = 2\int_{\delta_c}^{\infty} \mathrm{d}\delta \frac{M}{M_H} P(\delta)$$

$$\beta = \mathrm{erfc}\left(\frac{\delta_c}{\sqrt{2\sigma^2}}\right)$$

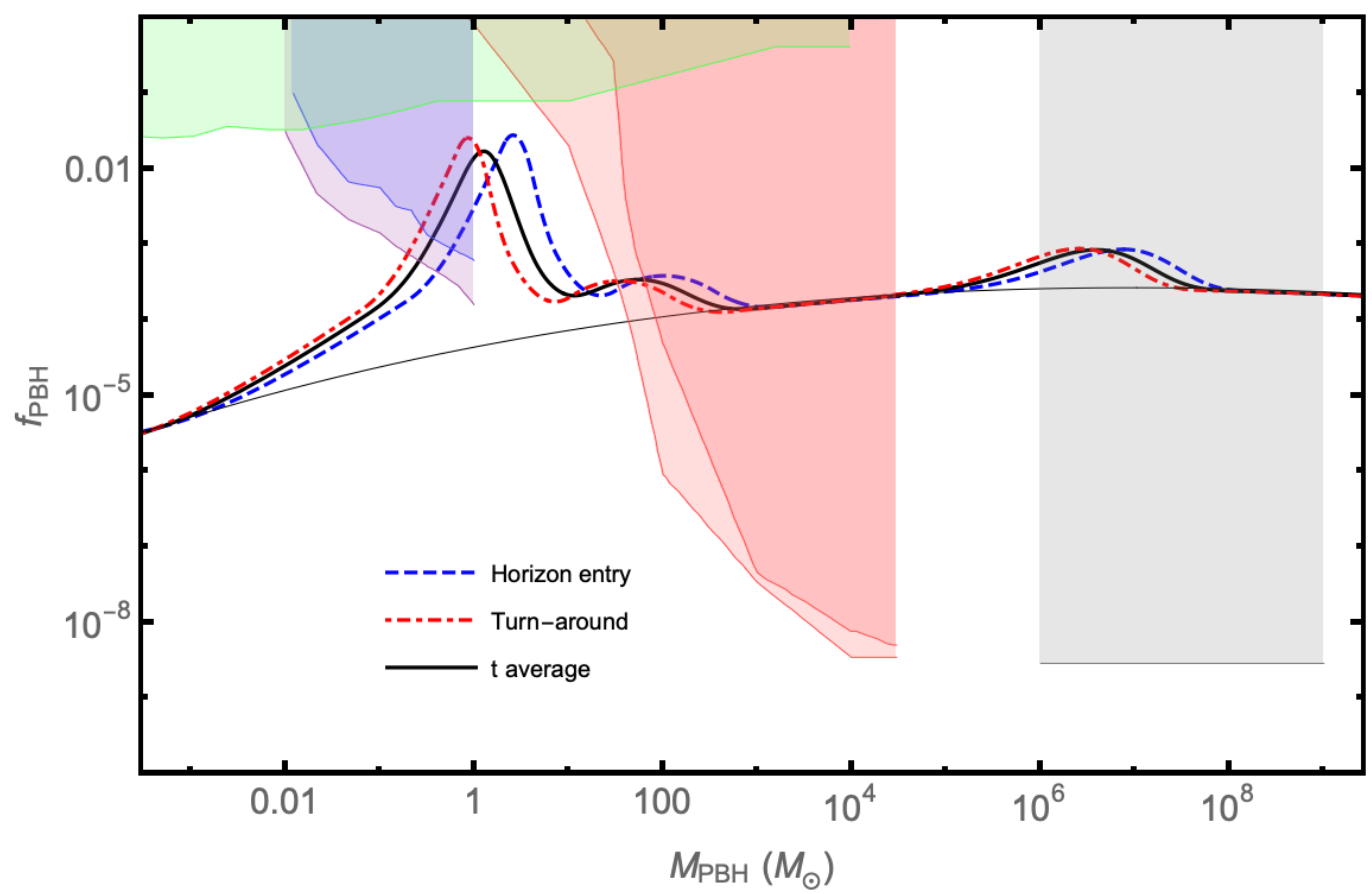
$$\sigma^2 = \int_0^\infty W(kR)^2 \mathcal{P}_\delta(k)\frac{\mathrm{d}k}{k}$$

where $\mathcal{P}_\delta(k) = \frac{16}{81}(kR)^4\mathcal{P}_\zeta(k)$

$$f_{\mathrm{PBH}} = \int \psi_p(M)\mathrm{d}M \equiv \int \left(\frac{M}{M_{\mathrm{eq}}}\right)^{-1/2} \frac{\beta(M)}{\Omega_{\mathrm{DM}}}\frac{\mathrm{d}M}{M},$$

RD $\Longrightarrow$ MD

$$M_{\mathrm{eq}} = 2.8\times 10^{17} M_\odot$$



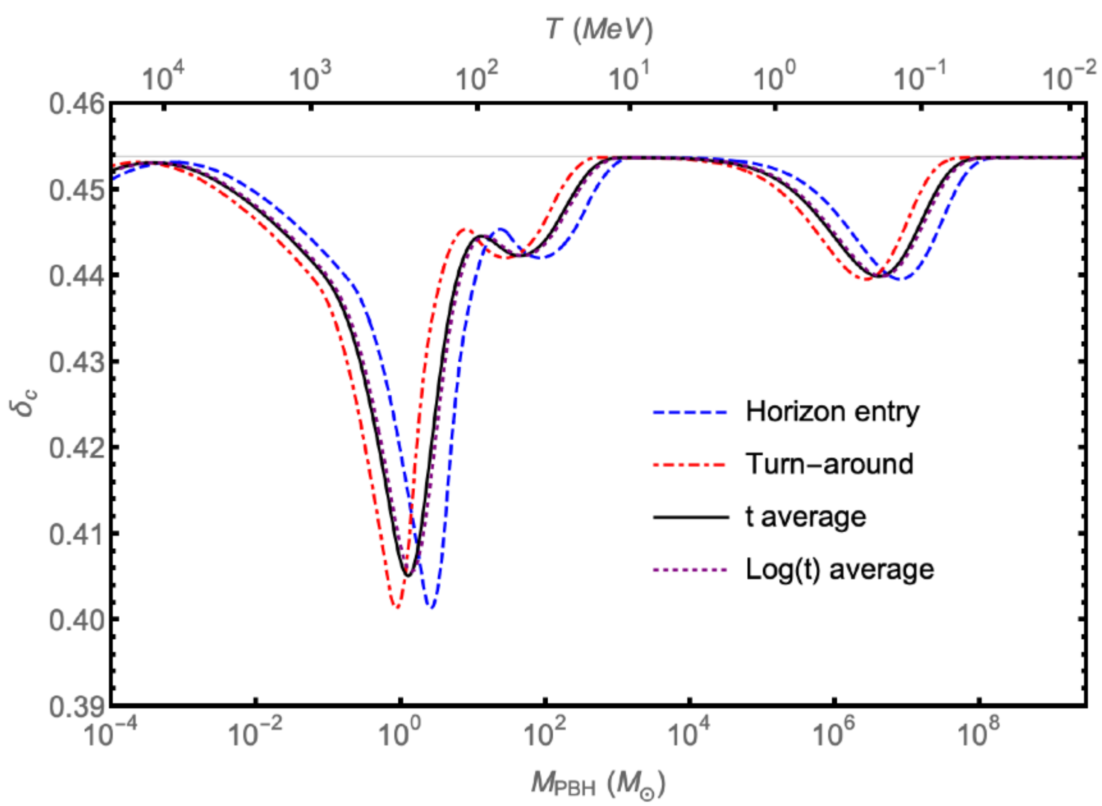
$$\sigma^2 = 0.0033\left(\frac{M}{10M_\odot}\right)^{n_M}$$

$$f_{\mathrm{GW}} \equiv \int_{5M_\odot}^{160M_\odot} \psi_p(M)\mathrm{d}M \sim 10^{-3}$$

PBH mass distribution

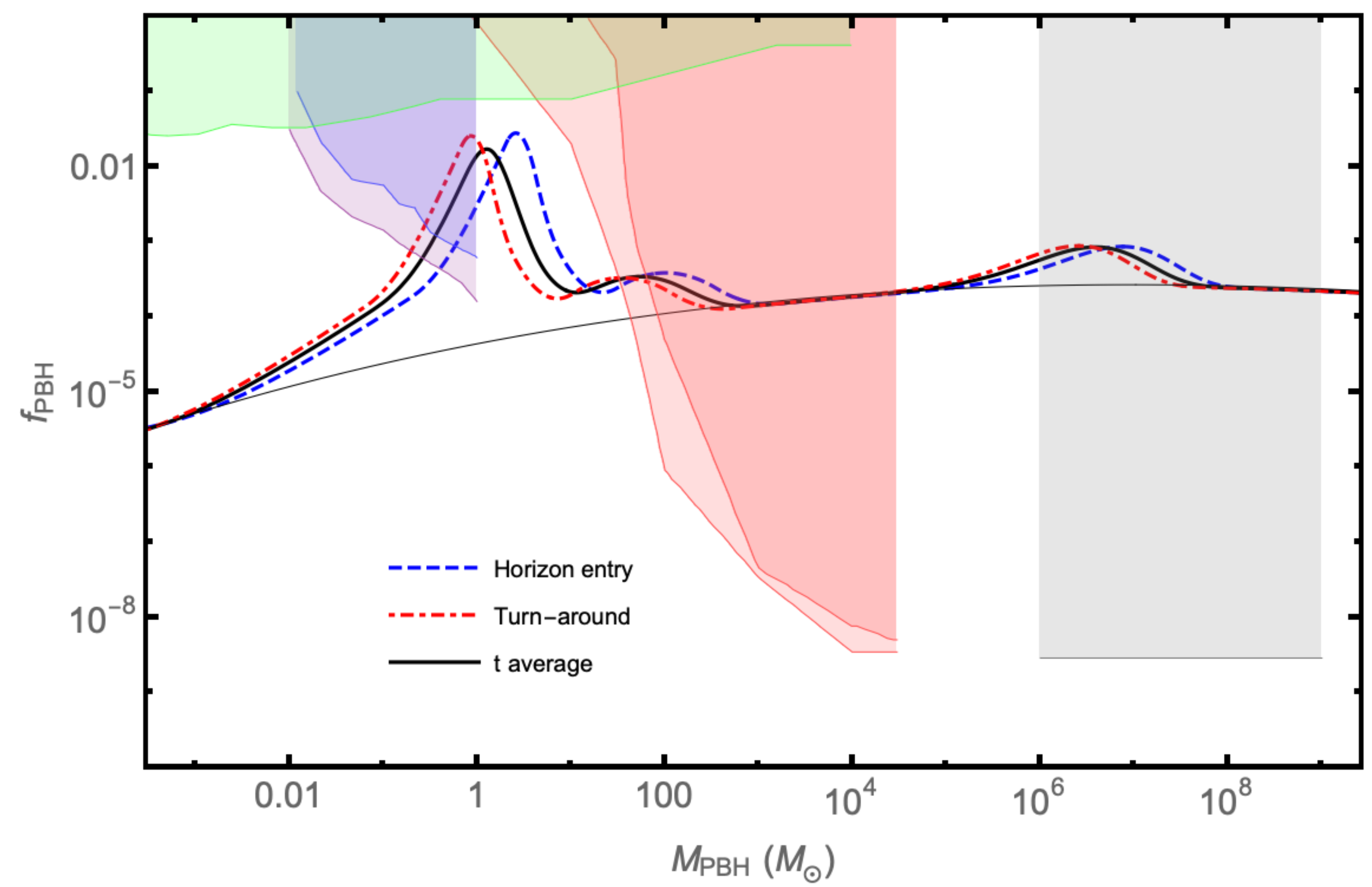
If PS was as small as the one extrapolated from CMB fit, we get a negligible production of PBHs…
Let's choose the simplest option a.k.a. (quasi-)scale invariance:

$$\boxed{\sigma^2 = 0.0033 \left(\frac{M}{10 M_\odot}\right)^{n_M}} \qquad f_{\rm GW} \equiv \int_{5M_\odot}^{160 M_\odot} \psi_p(M)\mathrm{d}M \sim 10^{-3}$$



$$\omega \iff \delta_c$$

I. Musco and J. C. Miller, Classical and Quantum Gravity 30, 145009 (2013).



Power spectrum at small scales