Primordial Black Holes: dark matter and gravitational waves

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Introduction: a very brief overview

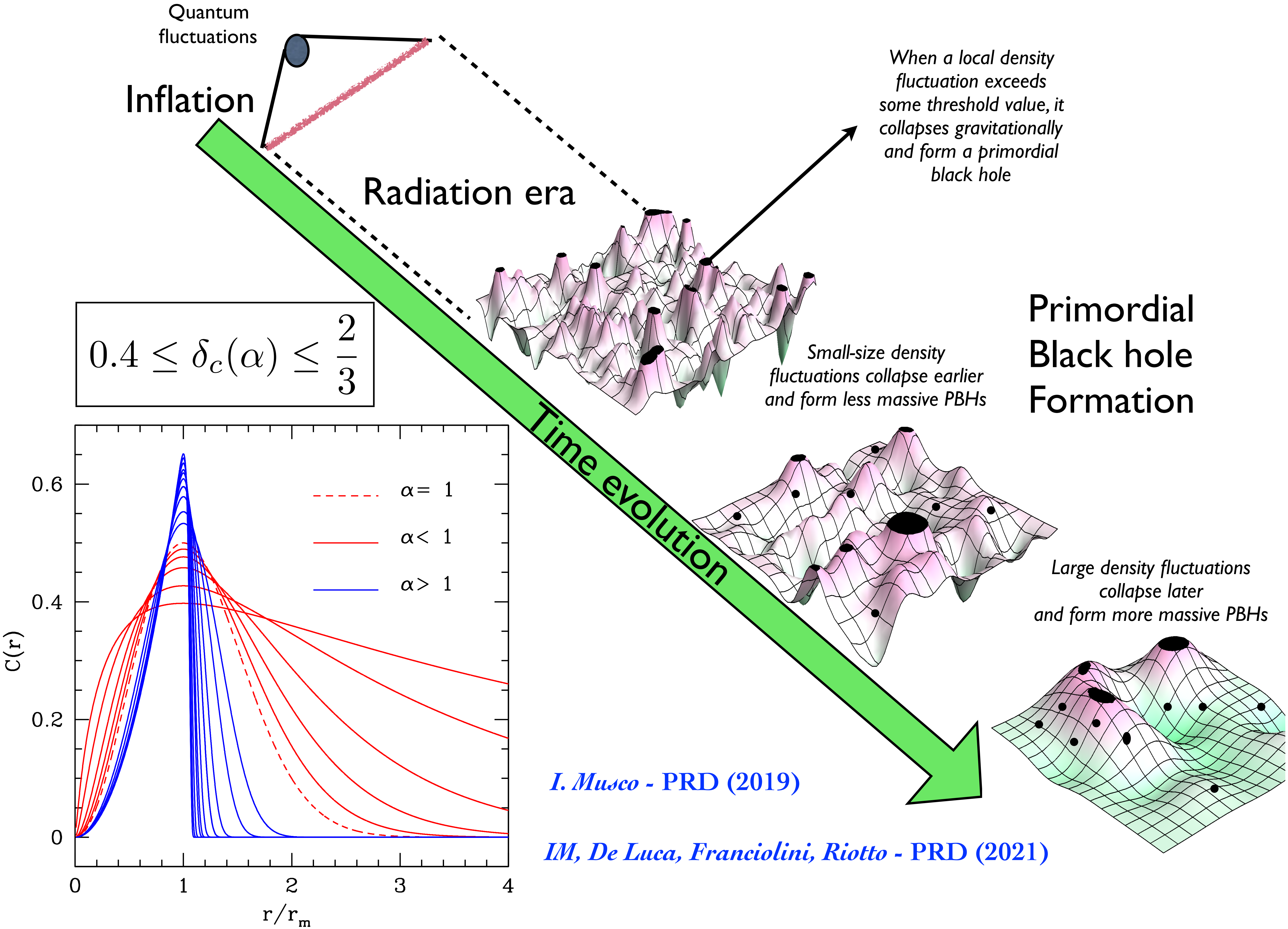
- **Primordial Black Holes (PBHs)** [**Zeldovich & Novikov** (1967), **Hawking** (1971)] could form from the collapse of cosmological perturbation during the radiation dominated era.

$$p = \frac{\rho}{3}$$

- **PBHs could span a large wide range of masses and if not evaporated** [BH evaporation **Hawking** (1974)]: PBHs with $M > 10^{15}\, g$ are interesting candidates for dark matter, intermediate mass black holes and the seeds of supermassive black holes.

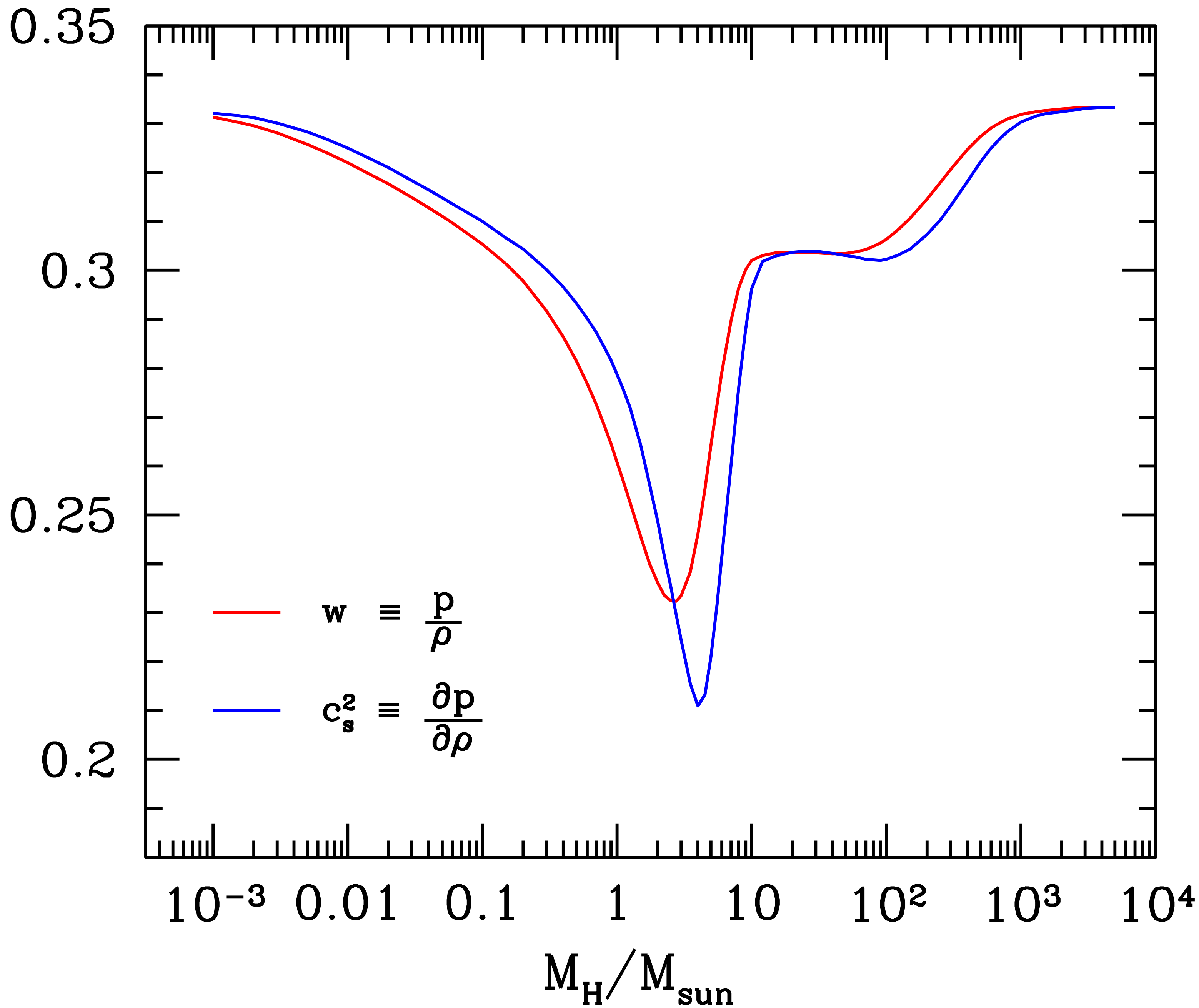
- **Numerical hydrodynamical simulations in spherical symmetry** of a cosmological perturbation, characterized by an amplitude δ, have shown:

  - $\delta > \delta_c \ \Rightarrow$ PBH formation
  - $\delta < \delta_c \ \Rightarrow$ perturbation bounce
  - $\delta_c \sim c_s^2 \equiv \dfrac{\partial p}{\partial \rho}$ (**Carr 1975**)


Quantum fluctuations
Inflation
Radiation era
When a local density fluctuation exceeds some threshold value, it collapses gravitationally and form a primordial black hole
Primordial Black hole Formation
Small-size density fluctuations collapse earlier and form less massive PBHs
Large density fluctuations collapse later and form more massive PBHs
Time evolution
$0.4 \leq \delta_c(\alpha) \leq \frac{2}{3}$
$\alpha = 1$
$\alpha < 1$
$\alpha > 1$
C(r)
r/r_m
0
0.2
0.4
0.6
1
2
3
4
I. Musco - PRD (2019)
IM, De Luca, Franciolini, Riotto - PRD (2021)

Equation of State of the Early Universe: QCD Phase-transition

- Significant softening of the equation of state (lattice QCD simulations)
- Introducing an intrinsic scale



$$\rho = \frac{\pi^2}{30} g_{\rm eff}(T) T^4$$

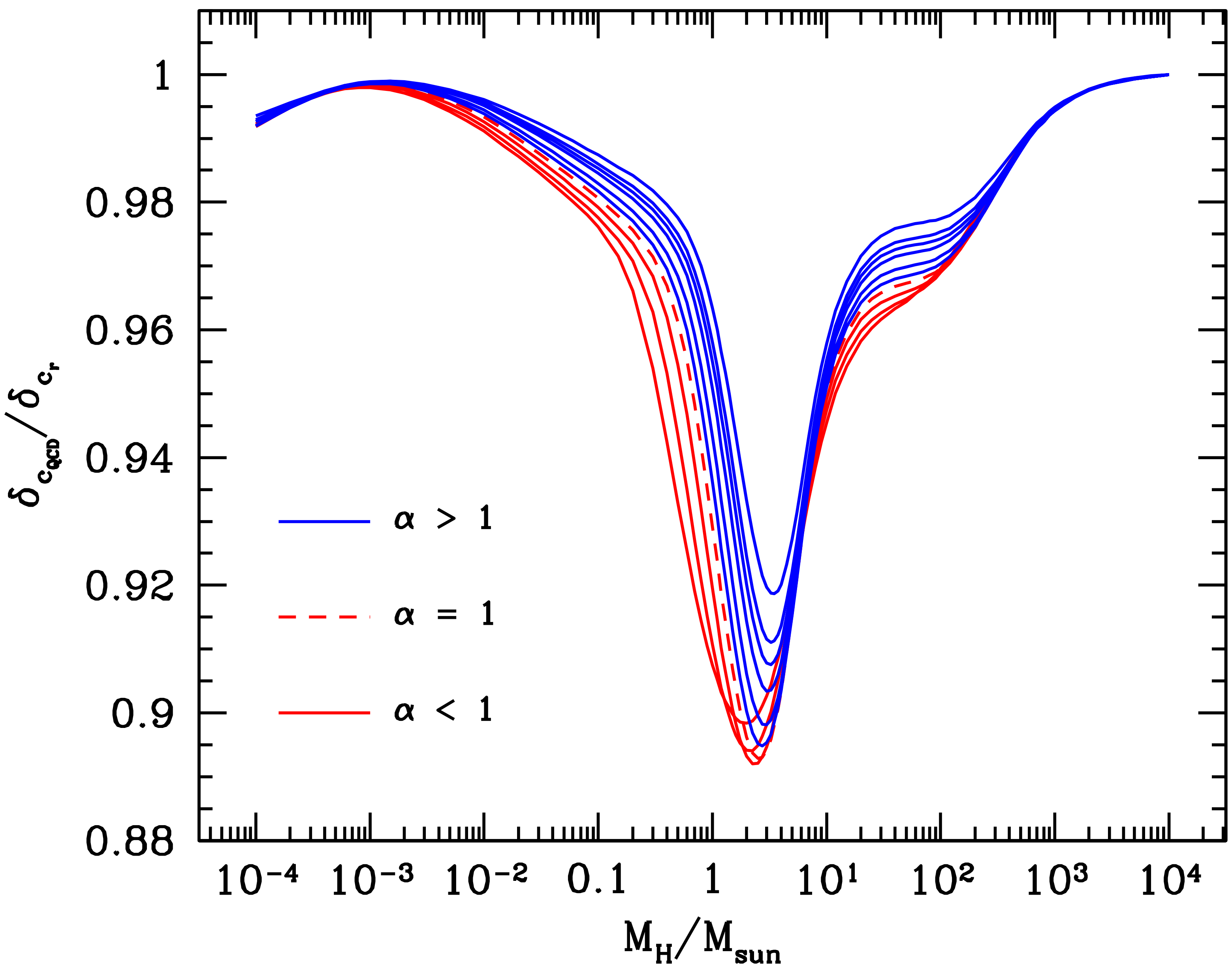
$$s = \frac{2\pi^2}{45} h_{\rm eff}(T) T^3$$

$$p = sT - \rho = w(T)\rho$$

$$w(T) = \frac{4h_{\rm eff}(T)}{3g_{\rm eff}(T)} - 1$$

$$c_s^2(T) = \frac{\partial p}{\partial \rho} = \frac{4(4h_{\rm eff} + T h'_{\rm eff})}{3(4g_{\rm eff} + T g'_{\rm eff})} - 1$$

PBH Threshold during the QCD

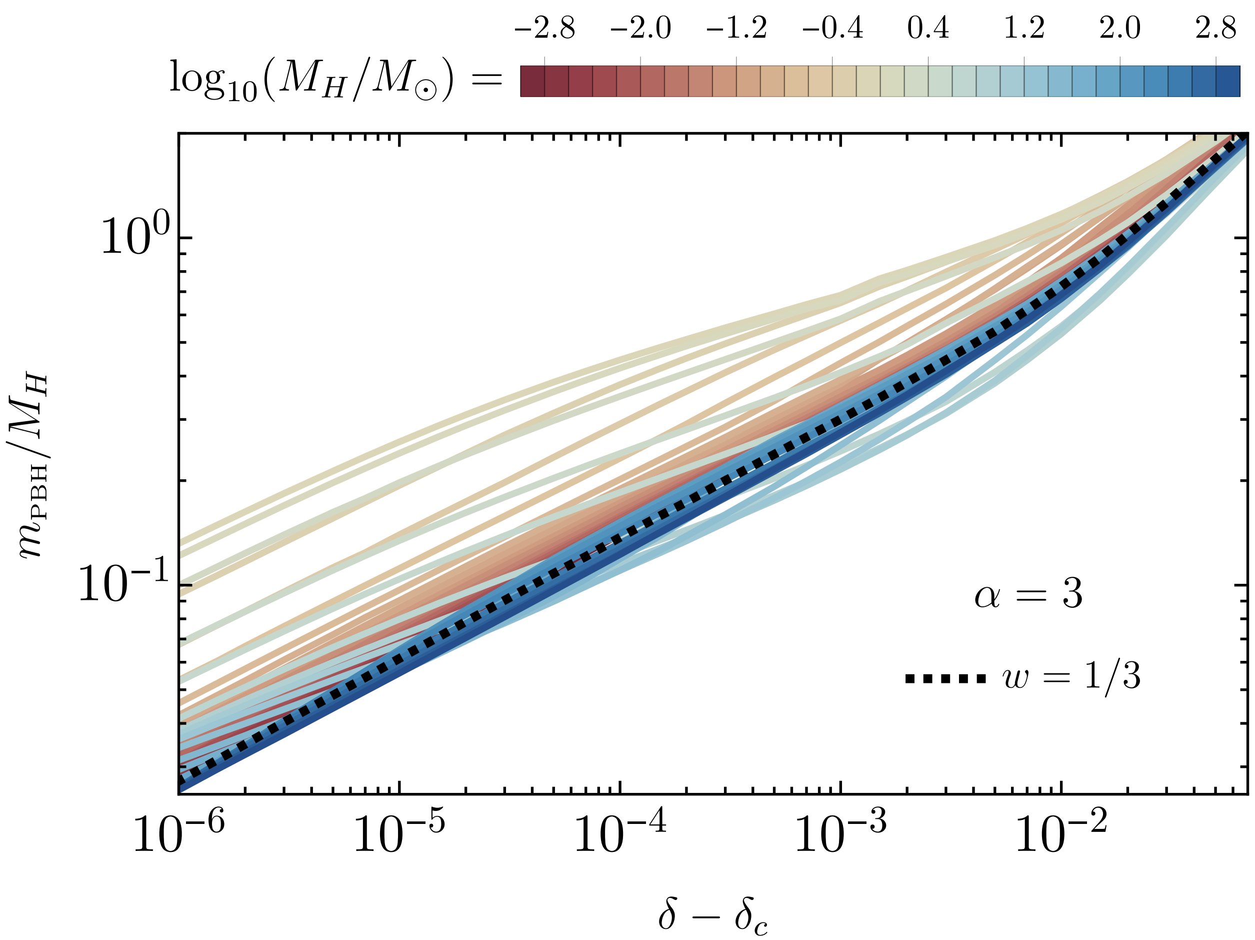


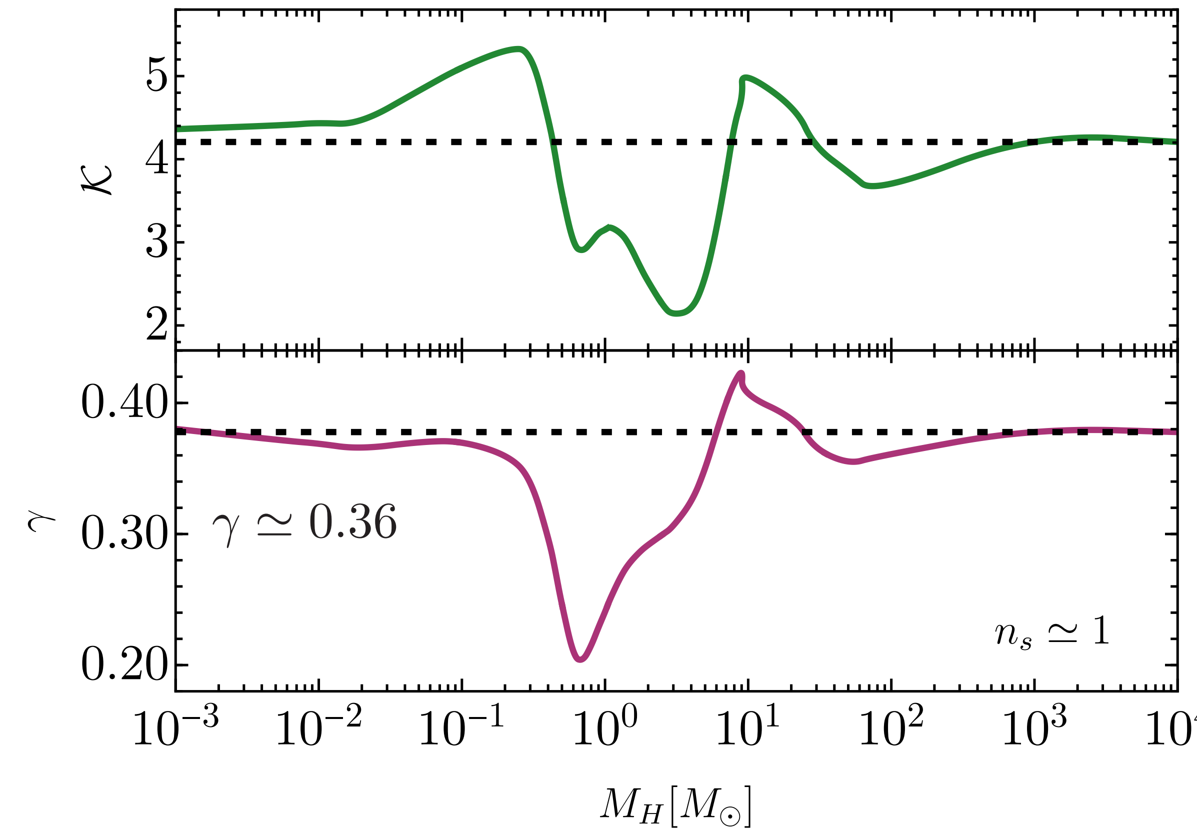
Depending on the shape, the threshold for PBH formation during the QCD phase transition is reduced about 10% around the minimum of ***w(T)***.

Significant enhancement of PBH formation around the solar mass scale: abundance increased of about O(3) with respect radiation!

IM, K. Jedamzik, Sam Young - in progress…

PBH Mass Spectrum





$$M_{PBH} = \mathcal{K}(\delta - \delta_c)^\gamma M_H$$

$$\delta_c(M_H), \gamma(M_H), \mathcal{K}(M_H)$$

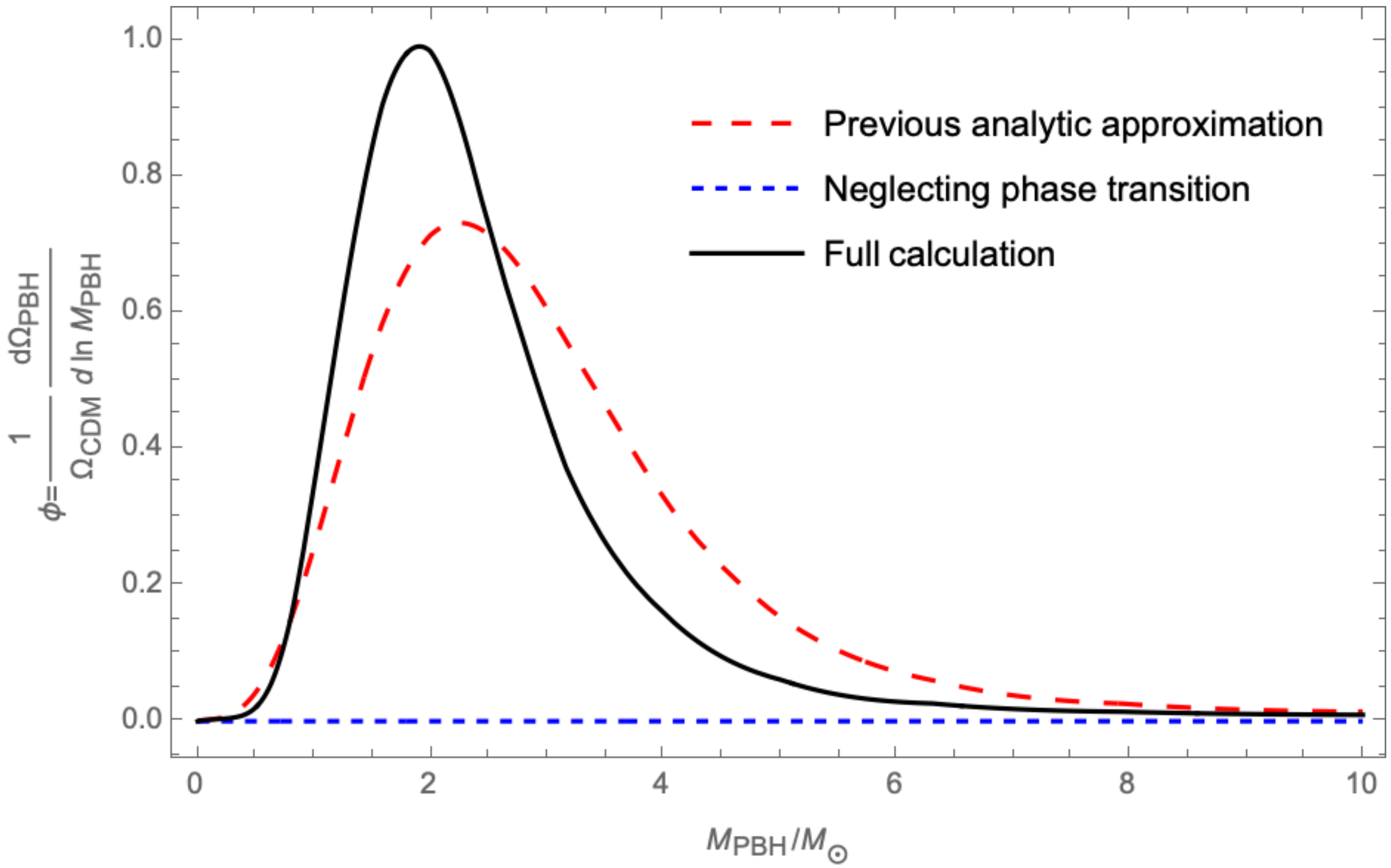
G. Franciolini, IM, P.Pani, A urbano - PRD (2022)

***IM, K. Jedamzik, Sam Young* - in progress…**

PBH mass distribution - QCD

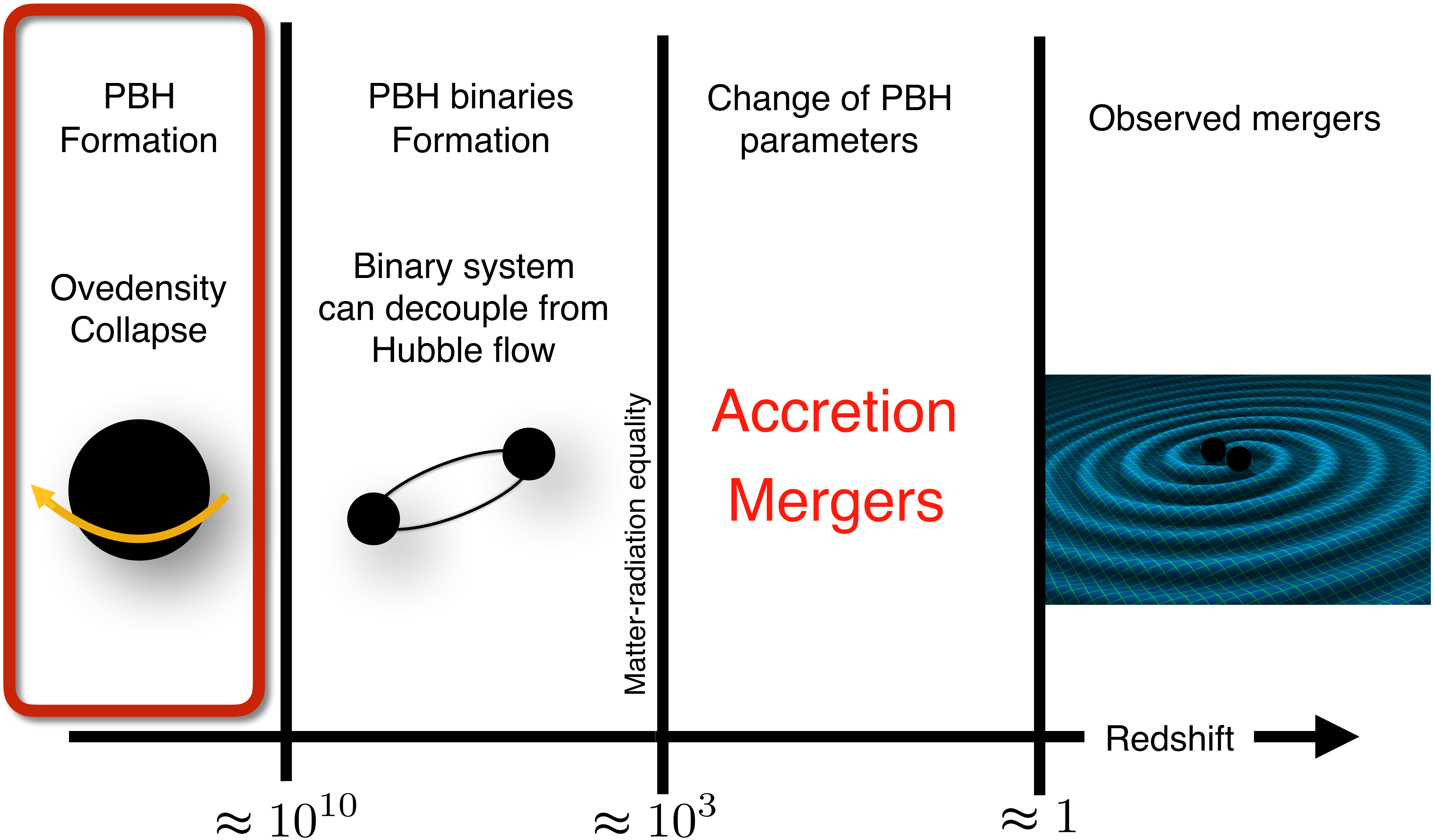
Mass Function ψ(mPBH): fraction of PBHs with mass in the infinitesimal interval of mPBH

$$\psi(M_{\rm PBH}) = \frac{1}{\Omega_{\rm PBH}} \frac{{\rm d}\Omega_{\rm PBH}}{{\rm d}M_{\rm PBH}}$$



- The main effect is given by the modification of the threshold.
- The modified mass spectrum prides a pile up of PBHs on smaller masses.

PBH evolution

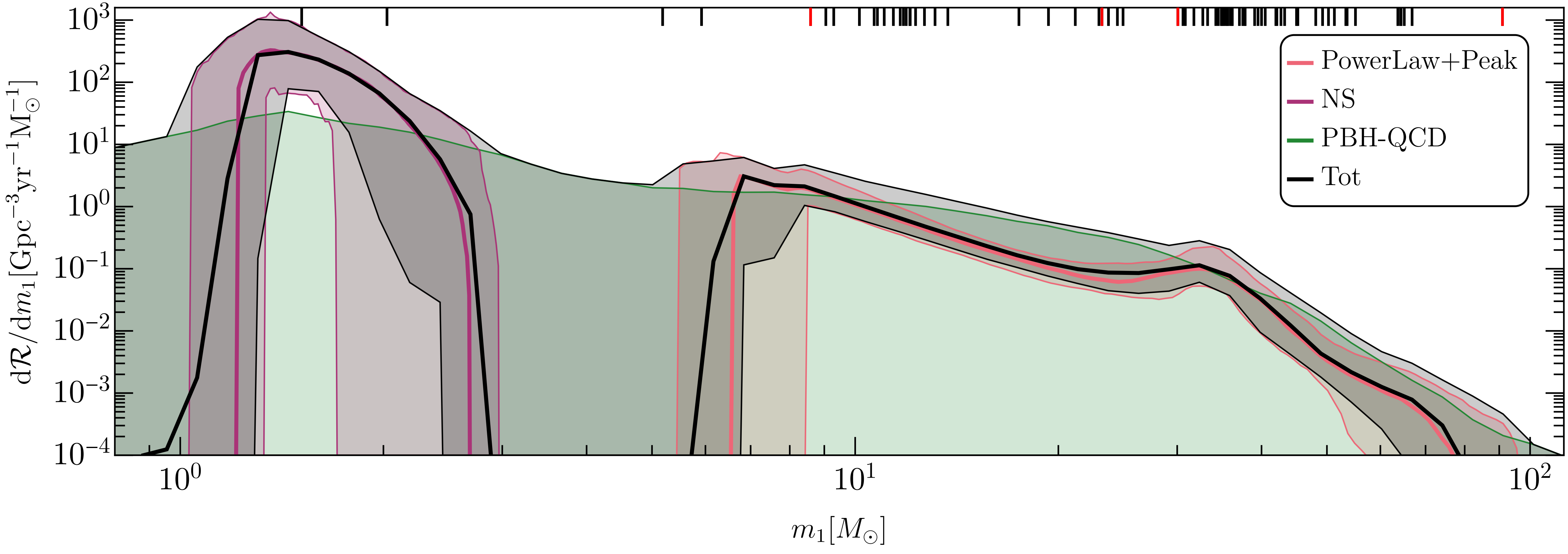


GWs from PBH mergers

G. Franciolini, IM, P.Pani, A urbano - PRD (2022)

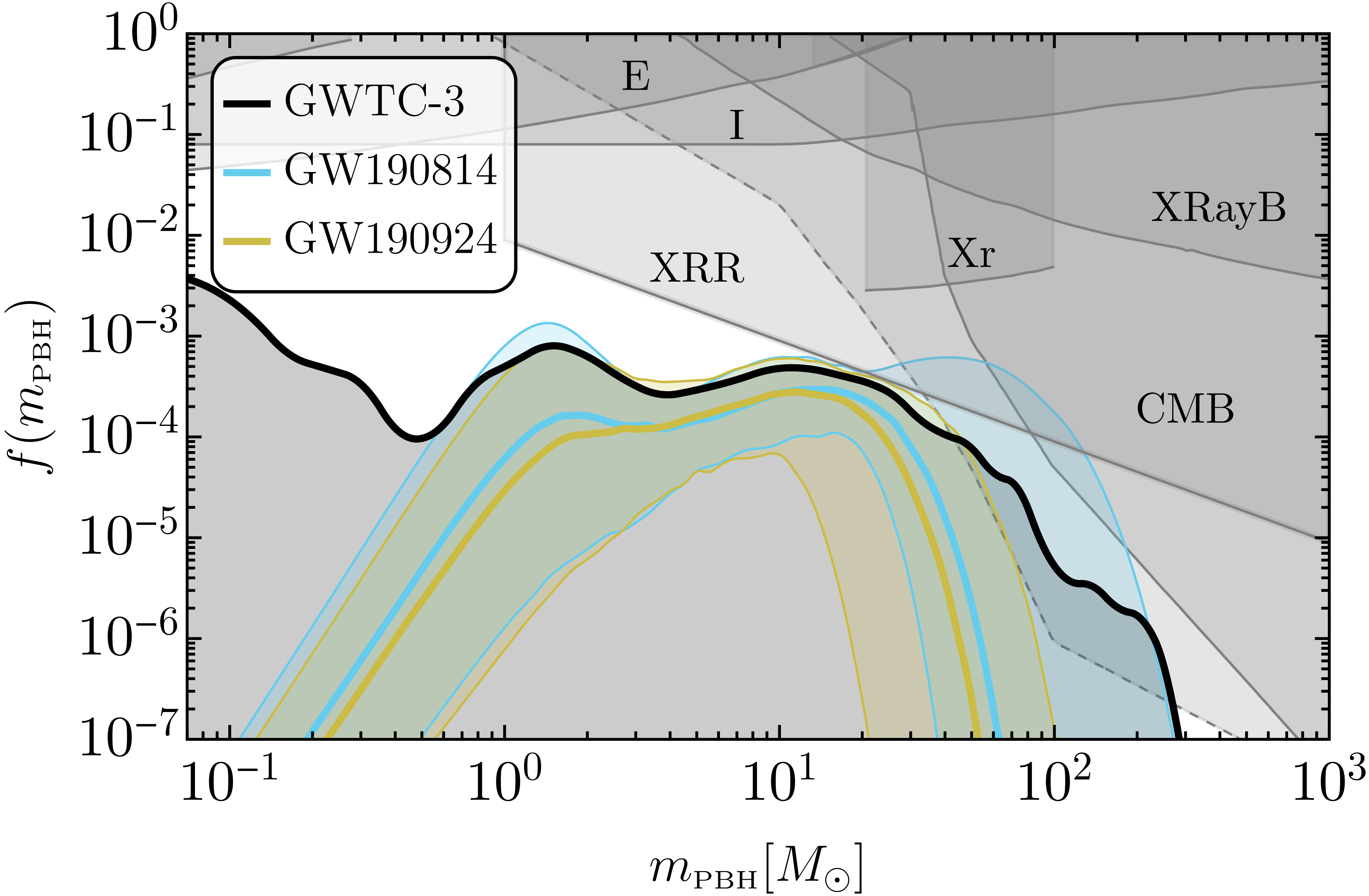
- Making **Bayesian inference analysis** we found that a sub-population of PBHs is compatible with the LVK catalog.

- PBHs give a natural explanation for the events in with BH mass gap: in particular GW190814 falling within the lower mass gap (predictions for O4 and O5).



PBH constraints

G. Franciolini, IM, P.Pani, A urbano - arXiv:2209.05959



Conclusions and future perspectives

- The **non linear threshold for PBH** and **the mass spectrum** could be fully computed from the relativistic numerical simulations.

- A softening of the equation of state **(QCD) significantly enhances the formation of PBHs**, with a **mass distribution peaked between 1 and 2 solar masses (**the range of heavy NSs and light BHs).

- This could gives **a sub-population of BH mergers compatible with the LVK catalog**, explaining mass gap events as **GW190814**.

- Our analysis predicts a **constraint on the abundance of DM in PBHs formed during the QCD (up to 0.1%)**, compatible with the current observational constraints.

- **In the future it would be very important to fully compute the gravitational waves emission associated to PBH formation (SECONDMENT at QMUL).**

- **3 Days international workshop in Rome (December 2023).**