Dynamics of the very early universe: towards decoding its signature through primordial black hole abundance, dark matter, and gravitational waves

(Based on Phys.Rev.D **108** (2023) 6, 063523; Phys.Rev.D **109** (2024) 2, 023521; e-Print: 2403.16963; JCAP 07 (2024) 002 and e-Print: 2407.18246**)**

In collaboration with Suvashis Maity , Dr. Essodjolo Kpatcha, Dr. Nilanjandev Bhaumik, Prof. Yann Mambrini, Prof. L. Sriramkumar, and Prof. Debaprasad Maity.

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Outline of the talk

Motivation:
Observational difficulty in the early Universe and introduction to the reheating phase

Goal:

- Discuss the standard background dynamics of reheating: perturbative reheating.
- Possibilities of PBH reheating
- Comparison between monochromatic and the extended mass function.
- Particle production from a single BH and dark matter parameter space from evaporating BHs
- Decoding the early universe through Primary Gravitational waves (PGWs)
- Constraining the reheating phase through scalar induced secondary gravitational waves with NANOGrav 15-year data.
- Quantum correction on Hawking evaporation and its effect on dark matter production

Conclusions

Observational challenges in probing the early Universe

Our knowledge about the cosmic history of the Universe

Cosmic microwave background (CMB)

Provides evidence for an early inflationary phase with

- Energy scale $\sim 10^{16}$ GeV
- Duration $\Delta t_{inf} \geq 10^{-36}$ Sec

Big-Bang Nucleosynthesis (BBN)

Predicts quantities such as light-element abundances

- Energy scale $E_{BBN} \sim 1$ MeV
- Time scale $t_{BBN} \sim 1$ Sec

- There is a massive gap in terms of energy (and time) scale between the periods of inflation and BBN, which is poorly understood from both theory and observation

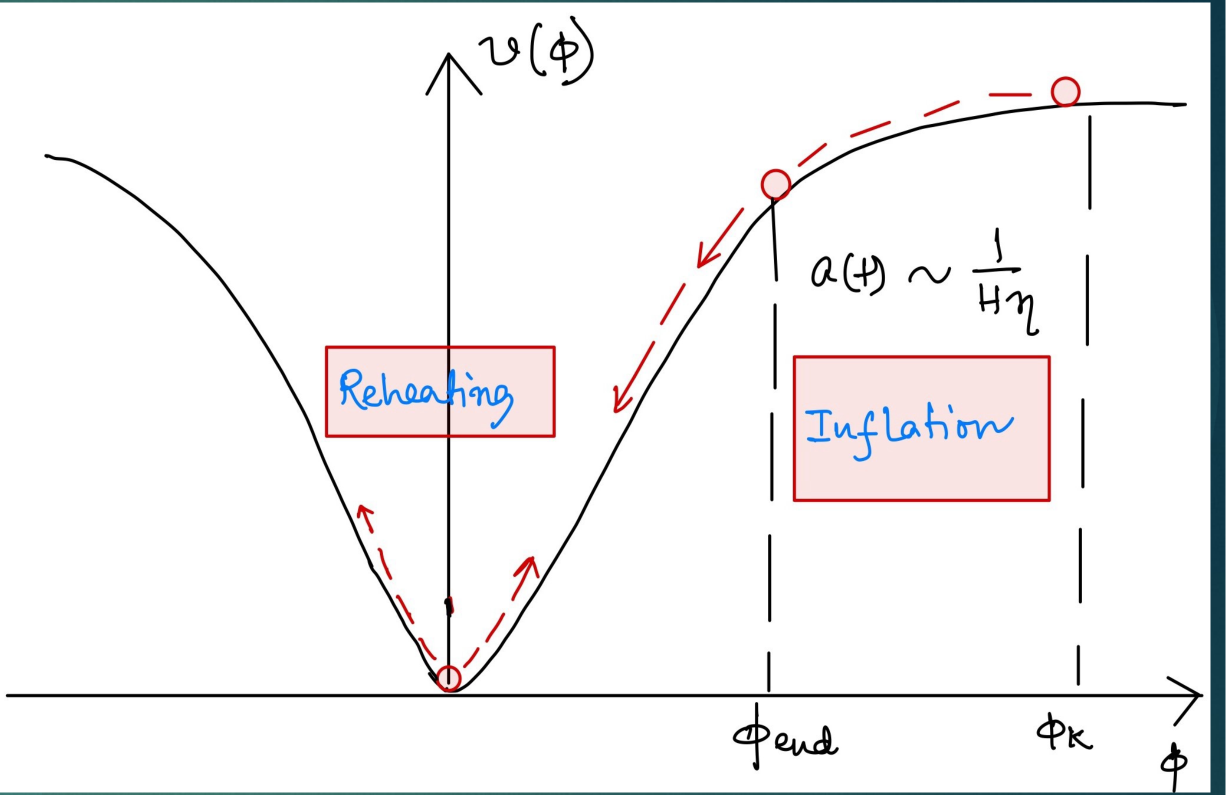
Why do we need reheating phase?

- ❑ The end point of inflation

❖ The universe is cold, dark, and dominated by the homogeneous inflaton field.

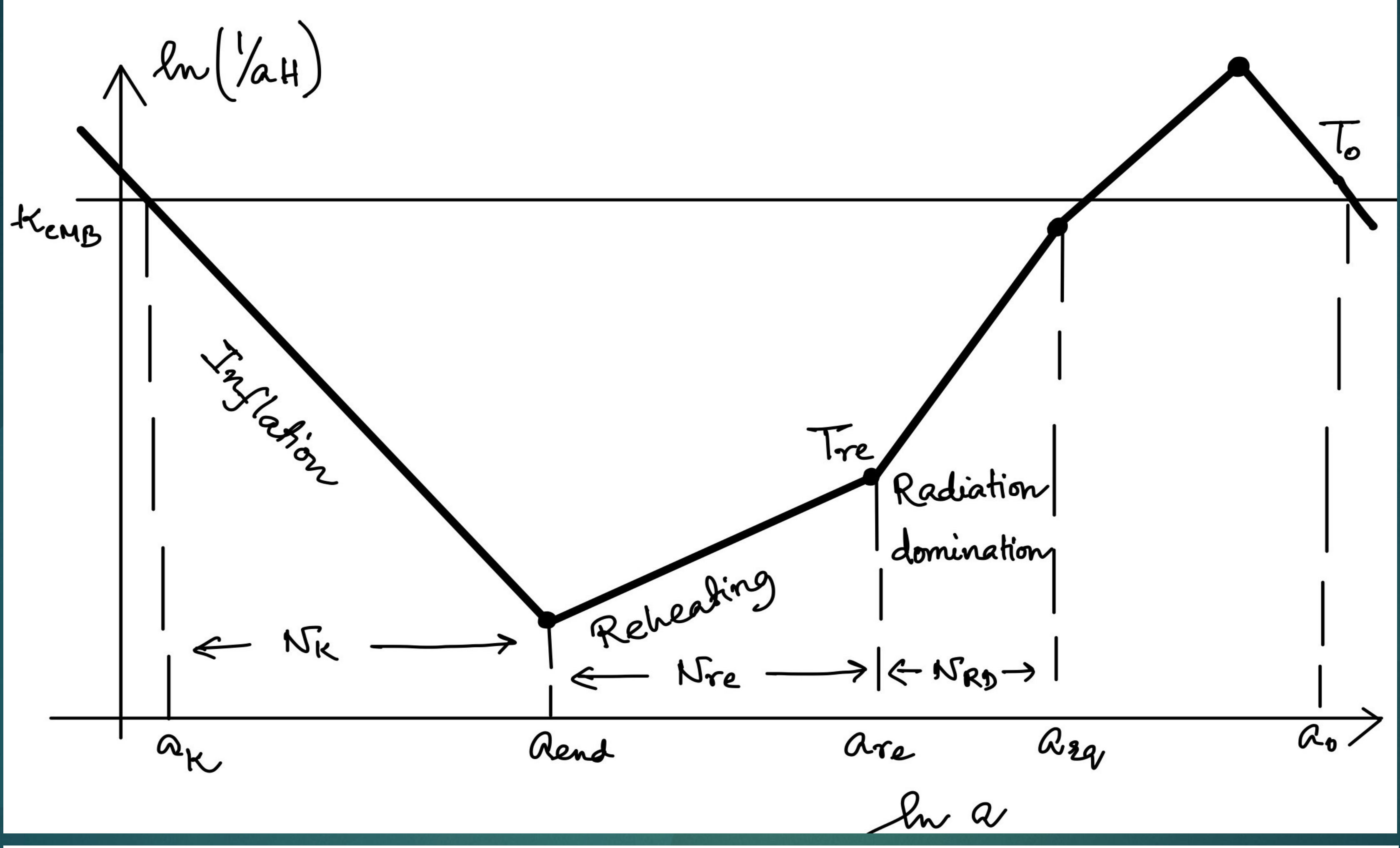
- ❑ How does the Universe transition to a the hot, thermalized, radiation-dominated state after inflation, which is required for nucleosynthesis.

- ❑ Reheating!



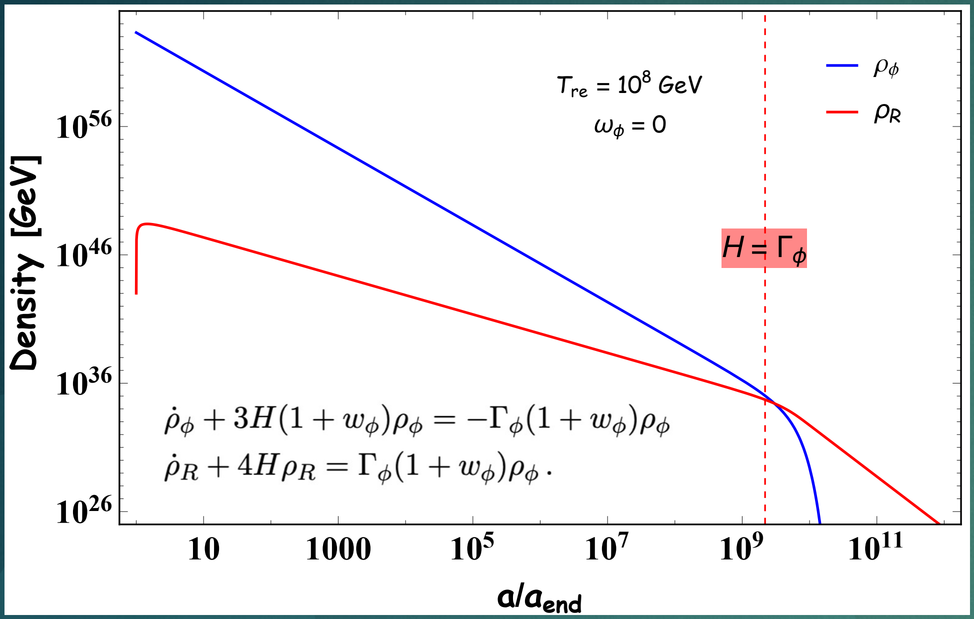
- ❑ Natural consequence after inflation: fill the empty space with matter (**generate entropy**)

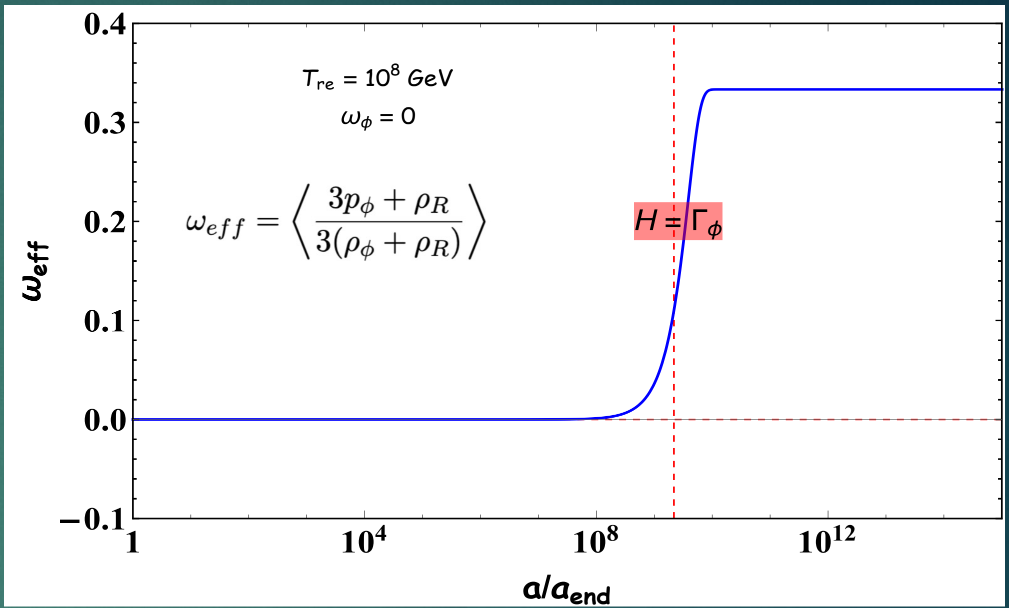
Schematic diagram of the evolution of the comoving Hubble radius



❖ We need to understand how the modified expansion history influences the prediction for cosmological observables.

Perturbative Reheating: evolution of density components and equation of state parameter





- Evolution of the individual density components

- Behavior of effective equation of state parameter with normalized scale factor

- Assuming potential $V(\phi) \propto |\phi|^{2n}$, averaging over one oscillation we have $\langle \dot\phi^2 \rangle \simeq \langle \phi V'(\phi) \rangle$

$$\rho_\phi \simeq \frac{1}{2}\langle \dot\phi^2 \rangle + \langle V(\phi) \rangle = (n+1)\,\langle V(\phi) \rangle$$
$$P_\phi \simeq \frac{1}{2}\langle \dot\phi^2 \rangle - \langle V(\phi) \rangle = (n-1)\,\langle V(\phi) \rangle$$

→

$$\omega_\phi = \left(\frac{n-1}{n+1} \right)$$

→

$$\omega_{eff} = \left\langle \frac{3p_\phi + \rho_R}{3(\rho_\phi + \rho_R)} \right\rangle$$

Reheating: Some possible interactions between inflaton and radiation (s/f)

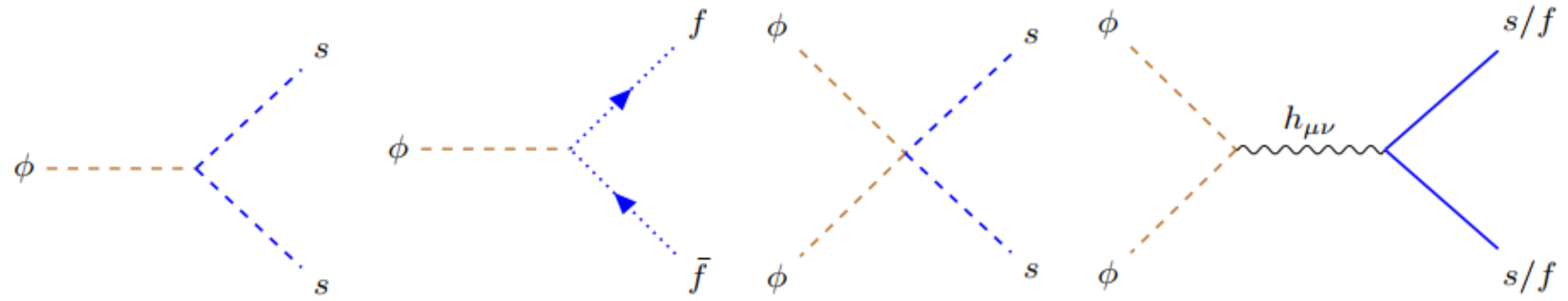


Figure: Feynmann diagram for all possible interactions between inflaton (Φ) and radiation (s/f)

$$
\Gamma_{s/f} = \begin{cases} \Gamma_{\phi\to ss} = \frac{(g_1^r)^2}{8\pi m_\phi(t)}\left(1+2f_B(m_\phi/2T)\right), & \text{for} \quad g_1^r \phi s^2 \\ \Gamma_{\phi\phi\to ss} = \frac{(g_2^r)^2 \rho_\phi(t)}{8\pi m_\phi^3(t)}\left(1+2f_B(m_\phi/T)\right), & \text{for} \quad g_2^r \phi^2 s^2 \\ \Gamma_{\phi\to \bar{f}f} = \frac{(h^r)^2}{8\pi} m_\phi(t)\left(1-2f_F(m_\phi/2T)\right), & \text{for} \quad h^r \phi \bar{f} f \end{cases}
$$

$$
\Gamma^{gr}_{\phi\phi\to ss} = \frac{\rho_\phi m_\phi}{1024\pi M_p^4}\left(1+2f_B(m_\phi/T)\right), \quad f_{B/F}(z) = \frac{1}{e^z \mp 1}
$$

$$
\Gamma^{gr}_{\phi\phi\to ff} = \frac{\rho_\phi m_f^2}{4096\pi\pi M_p^4 m_\phi}\left(1-2f_F(m_\phi/T)\right),
$$

M. R. Haque and D. Maity [Phys.Rev.D 107 (2023) 4, 043531].
Y. Mambrini and K. A. Olive [Phys.Rev.D 103 (2021) 11, 115009].

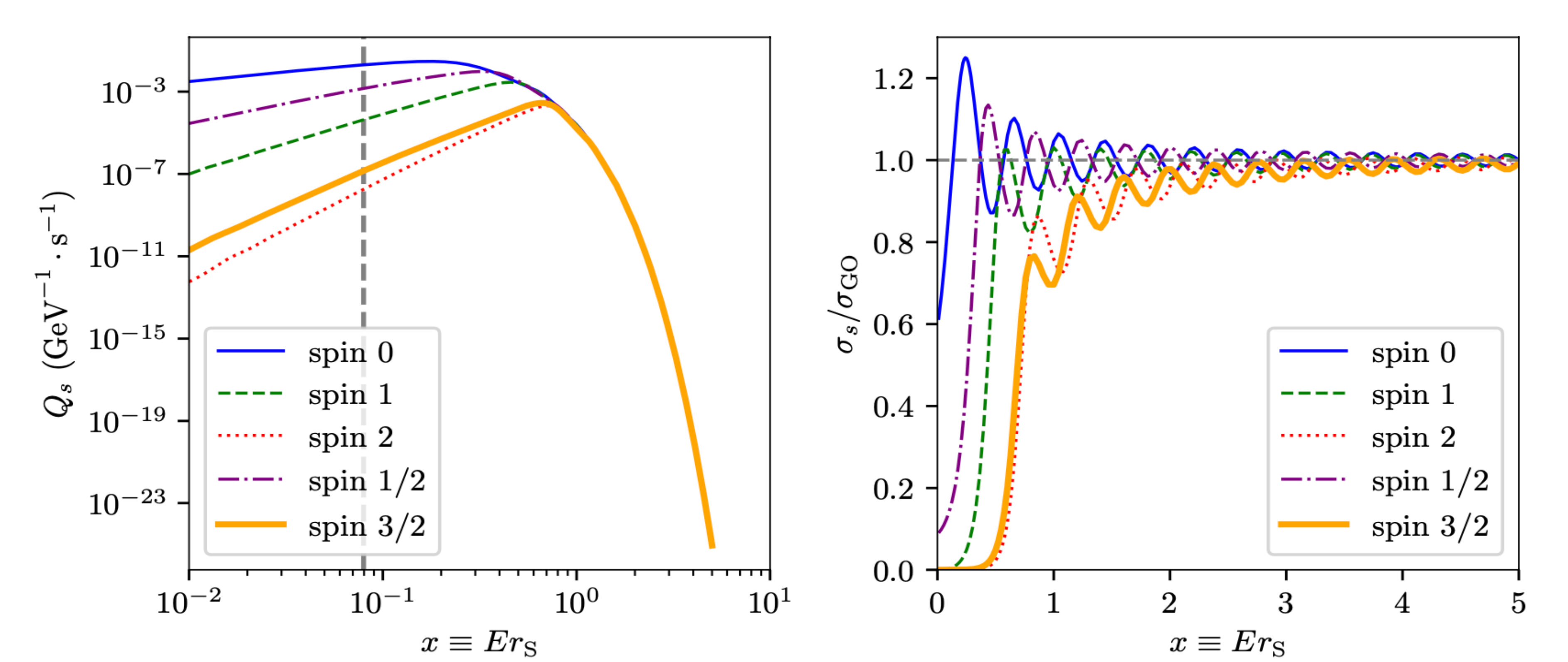
PBH formation during reheating : possibilities

- The production of PBHs from inflation usually requires the existence of a short period of ***ultra-slow-roll*** that produces a peak in the primordial power spectrum of scalar curvature perturbations.

- Perturbations that were generated during the late inflationary era can get resonantly amplified and collapse into black holes before the Universe is reheated. Depending on the reheating temperature, the PBH mass fraction can peak at different masses.

- Bubble collision during phase transition and in principle that can happen during reheating.

Energy spectrum



Left: Energy spectrum of the emitting particles. Right: absorption cross-section in high energy limit

$$Q_s(E, M_{BH}) \equiv \frac{d^2 N_s}{dt dE} = \frac{\Gamma_s}{e^{E/T_{BH}} - (-1)^{2s}}$$

$$\sigma_s \equiv \frac{\pi \Gamma_s}{E^2}, \quad \sigma_{GO} \equiv \frac{27}{4} \pi r_S^2$$

A. Cheek, L. Heurtier, Y. F. Perez-Gonzalez and J. Turner, Phys. Rev. D 105 (2022).
A. Arbey and J. Auffinger, Eur. Phys. J. C 79, 693 (2019).

Primordial Black Hole evaporation

- The rate of change of the BH mass : $$\frac{dM_{\rm BH}}{dt} = -\sum_j \int_0^\infty E_j \frac{\partial^2 N_j}{\partial p\, \partial t}\, dp = -\epsilon(M_{\rm BH}) \frac{M_P^4}{M_{\rm BH}^2}$$

- The mass-dependent evaporation function. $\epsilon(M_{\rm BH})$: $$\epsilon(M_{\rm BH}) = \sum g_j\, \epsilon_j(z_j)$$

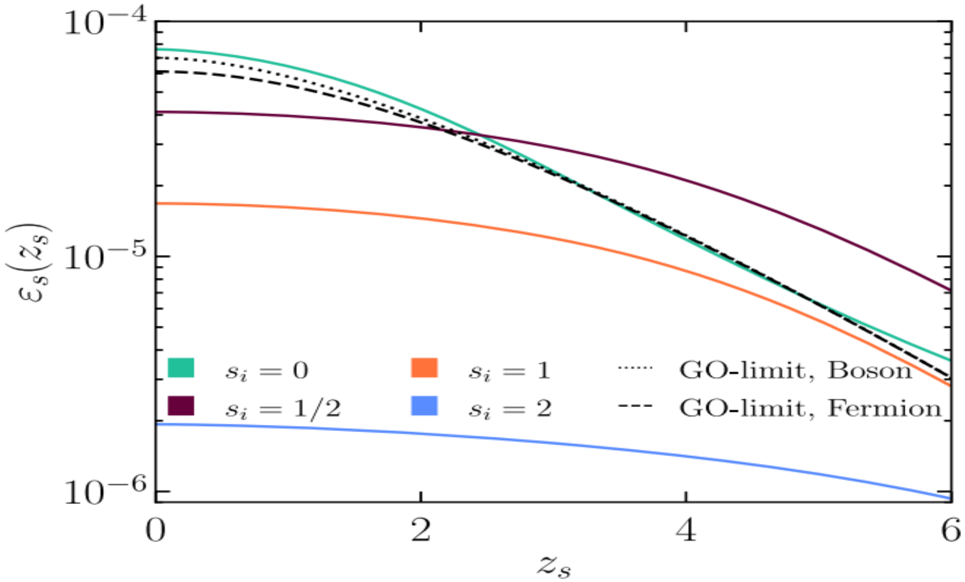
$$E_j = \sqrt{m_j^2 + p^2}\,, \quad z_j = m_j / T_{\rm BH}$$

- Evaporation function for massless particles

$$\epsilon_j(0) = \frac{27}{4} \frac{\xi\, \pi\, g_j}{480}$$

and total evaporation function

$$\epsilon = \frac{27}{4} \frac{g_*(T_{\rm BH}) \pi}{480}$$



Compare the evaporation function with the function to the to the geometric optics limit

A. Cheek, L. Heurtier, Y. F. Perez-Gonzalez and J. Turner, Phys. Rev. D 105 (2022).
A. Arbey and J. Auffinger, Eur. Phys. J. C 79, 693 (2019).

Evolution of the PBHs

Dependency on the evolution of the PBHs

1. PBH mass distribution

$$f_{\rm PBH}(M) = \delta(M - M_{\rm in})$$

2. Formation mass

$$M_{\rm in} = \gamma\, M_H = \gamma \frac{4\pi}{3} \frac{\rho(t_{\rm in})}{H^3(t_{\rm in})} = 4\pi\gamma \frac{M_P^2}{H(t_{\rm in})}$$

❖ Collapse efficiency : $\gamma = w^{3/2}$

3. Total energy falls into BH at the point of formation

$$\beta = \frac{\rho_{\rm BH}(t_{\rm in})}{\rho_{\rm tot}(t_{\rm in})}$$

$$\rho_{\rm tot} = \rho_\phi + \rho_R$$

B. J. Carr and S. W. Hawking, Mon. Not. Roy. Astron. Soc. **168**, 399 (1974)

Restriction on the PBH parameters

- Minimum allowed PBH mass bounded by the size of the horizon at the end of inflation

$$M_{\rm in} \gtrsim H_{\rm end}^{-3}\rho_{\rm end} \sim \frac{M_P^3}{\sqrt{\rho_{\rm end}}} \simeq 1{\rm g} = M_{\rm min}$$

- Maximum allowed mass can be calculated from the PBH mass variation with respect to time

$$\frac{dM_{\rm BH}}{dt} = -\epsilon \frac{M_P^4}{M_{\rm BH}^2} \quad \longrightarrow \quad t_{\rm ev} \simeq 1\ {\rm s}\left(\frac{M_{\rm in}}{10^8\ {\rm g}}\right)^3$$

- Allowed mass range for ultralight PBHs : $1{\rm g} \lesssim M_{\rm in} \lesssim 10^8{\rm g}$

- Restriction on β : Induced gravitational waves (GWs) sourced by the density fluctuation due to the inhomogeneities of the PBH distribution is not in conflict with the BBN constraints on the effective number of relativistic species

$$\beta < 1.1 \times 10^{-6}\left(\frac{w^{3/2}}{0.2}\right)^{-\frac{1}{2}}\left(\frac{M_{\rm in}}{10^4\ {\rm g}}\right)^{-17/24}$$

S. W. Hawking, Commun. Math. Phys. **43**, 199 (1975)
G. Dom`enech, C. Lin, and M. Sasaki, JCAP **04**, 062 (2021)

Reheating set up (with PBH)

- Boltzmann equations :

$$\dot{\rho_\phi} + 3H(1+w_\phi)\rho_\phi = -\Gamma_\phi\rho_\phi\,(1+w_\phi)$$

$$\dot{\rho}_R + 4H\rho_R = \Gamma_\phi\rho_\phi(1+w_\phi) - \frac{\rho_{\rm BH}}{M_{\rm BH}}\frac{dM_{\rm BH}}{dt}\,\theta(t-t_{\rm in})\,\theta(t_{\rm ev}-t)$$

$$\dot{\rho}_{\rm BH} + 3H\rho_{\rm BH} = \frac{\rho_{\rm BH}}{M_{\rm BH}}\frac{dM_{\rm BH}}{dt}\,\theta(t-t_{\rm in})\,\theta(t_{\rm ev}-t)$$

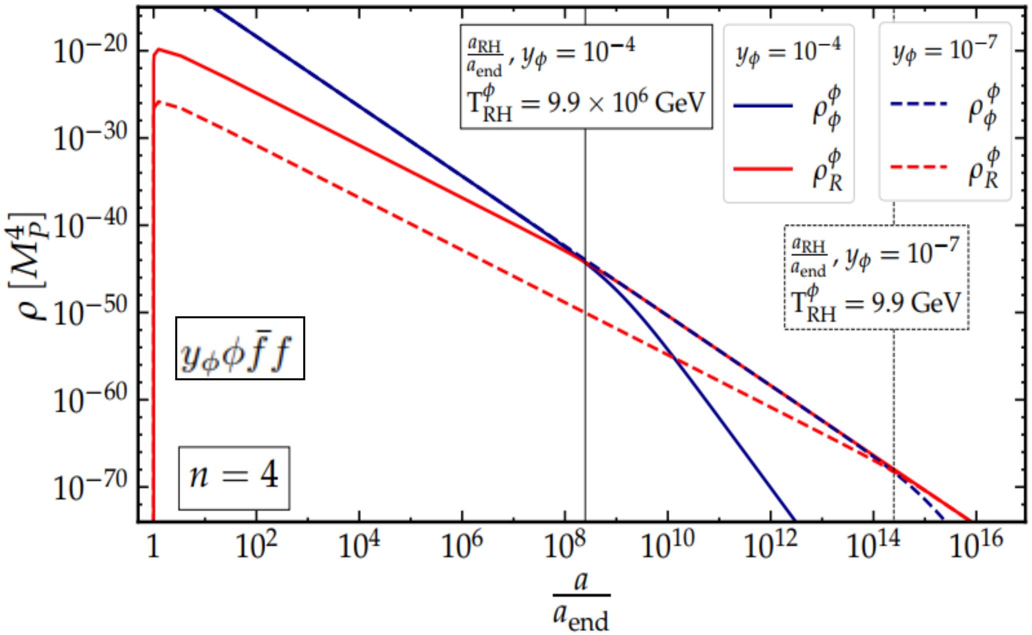
- Friedmann equation: $\rho_\phi + \rho_R + \rho_{\rm BH} = 3H^2M_P^2$

- Mass reduction: $\frac{dM_{\rm BH}}{dt} = -\epsilon\frac{M_P^4}{M_{\rm BH}^2}$ → $M_{\rm BH} = M_{\rm in}\left(1-\Gamma_{\rm BH}(t-t_{\rm in})\right)^{\frac{1}{3}}$

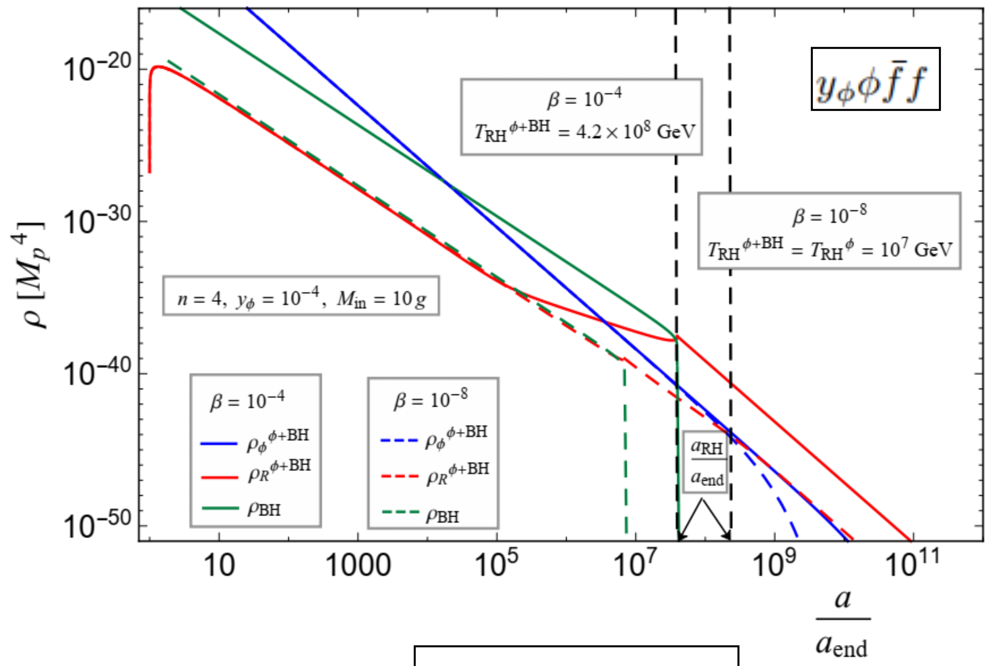
- Lifetime of the BH : $t_{\rm ev} = \frac{1}{\Gamma_{\rm BH}}, \quad \Gamma_{\rm BH} = 3\epsilon\frac{M_P^4}{M_{\rm in}^3}$

M. R. Haque, E. Kpatcha, D. Maity and Y. Mambrini, Phys.Rev.D **108** (2023) 6, 063523.

Evolution of the energy densities (with and without PBH)



Without PBH



With PBH

$$\rho_\phi \propto a^{-3(1+w_\phi)}, \quad \rho_R^\phi \propto a^{-\frac{3}{2}(1+3w_\phi)}, \quad \rho_R^{BH} \propto a^{-\frac{3}{2}(1-w_\phi)}$$

$$\rho_{BH}(a) = \beta \rho_{end} \left(\frac{4\pi\sqrt{3}\gamma M_P^3}{M_{in}\sqrt{\rho_{end}}} \right)^{\frac{2w}{(1+w)}} \left(\frac{a_{end}}{a} \right)^3 \times \left[1 - \frac{2\sqrt{3}\epsilon}{1+w} \frac{M_P^5}{M_{in}^3 \sqrt{\rho_{end}}} \left(\frac{a}{a_{end}} \right)^{\frac{3}{2}(1+w)} \right]^{\frac{1}{3}}$$

M. R. Haque, E. Kpatcha, D. Maity and Y. Mambrini, Phys.Rev.D **108** (2023) 6, 063523.

PBH reheating (PBH domination)

- ❑ Condition for the PBH domination :

$$\beta_c = \left(\frac{\epsilon}{(1+w_\phi)2\pi\gamma}\right)^{\frac{2w_\phi}{1+w_\phi}} \left(\frac{M_P}{M_{\rm in}}\right)^{\frac{4w_\phi}{1+w_\phi}}$$

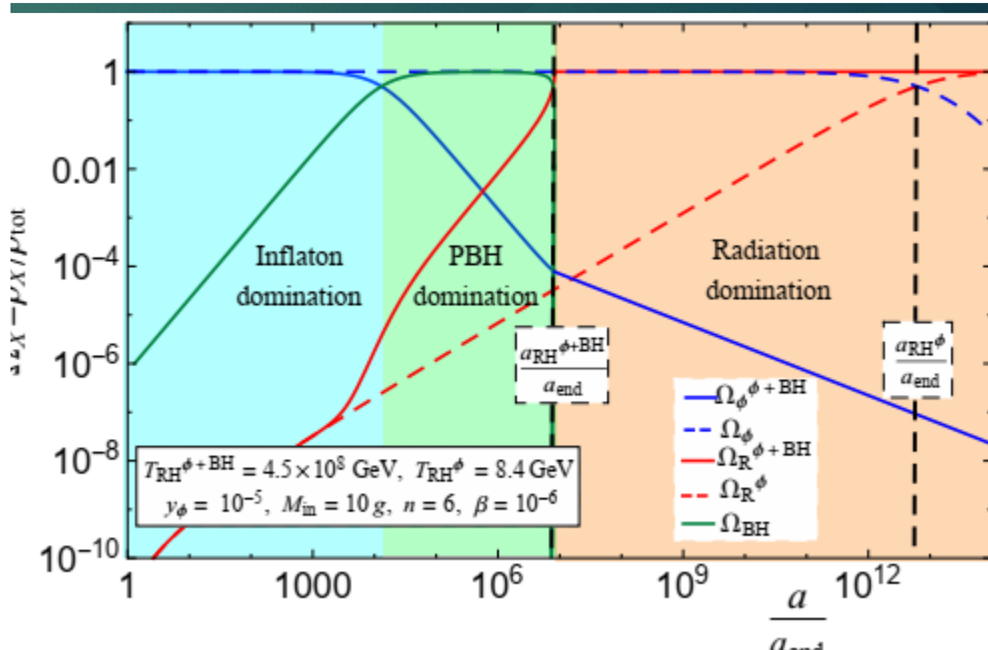
- ❑ PBH dominates reheating process

$$\Gamma_\phi \rho_\phi (1+w_\phi) < -\frac{\rho_{\rm BH}}{M_{\rm BH}} \frac{dM_{\rm BH}}{dt}$$

- ❑ Reheating temperature :

$$\Gamma_{\rm BH} = H \quad \Rightarrow \rho_{\rm RH} = 3M_P^2 \Gamma_{\rm BH}^2$$

$$T_{\rm RH} = M_P \left(\frac{3\,\epsilon^2}{\alpha_T}\right)^{\frac{1}{4}} \left(\frac{M_P}{M_{\rm in}}\right)^{\frac{3}{2}}$$



Evolution of the normalized energy densities as a function of scale factor

M. R. Haque, E. Kpatcha, D. Maity and Y. Mambrini, Phys.Rev.D **108** (2023) 6, 063523.

PBH reheating (without PBH domination)

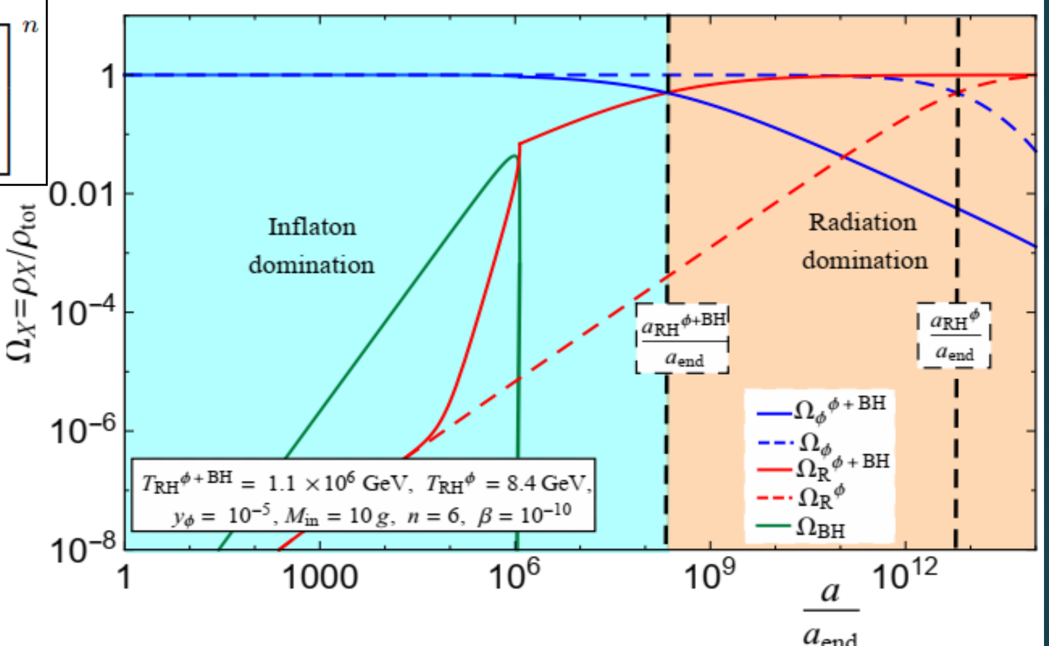
❑ Condition for the PBH reheating :

$$\beta^{n<7} \gtrsim \beta^{\phi}_{\rm crit} = \delta \times \left(\frac{y_\phi^2}{8\pi}\right)^{\frac{6w_\phi-2}{3-3w_\phi}} \left(\frac{M_P}{M_{\rm in}}\right)^{\frac{2-2w_\phi}{1+w_\phi}} \times \lambda^{\frac{3w_\phi-1}{3w_\phi+3}} \left(\frac{\alpha_n}{M_P^4}\right)^{\frac{6w_\phi-2}{3-3w_\phi}}$$

$$\lambda = \left(\frac{\Lambda}{M_P}\right)^4 \left(\frac{2}{3\,\alpha}\right)^{\frac{n}{2}} \quad V(\phi) = \Lambda^4 \left[1 - e^{-\sqrt{\frac{2}{3\,\alpha}}\frac{\phi}{M_P}}\right]^n$$

❑ Reheating temperature :

$$T_{\rm RH} \sim M_P \beta^{\frac{3}{4}\frac{1+w_\phi}{3w_\phi-1}} \left(\frac{M_{\rm in}}{M_P}\right)^{\frac{3}{2}\frac{1-w_\phi}{3w_\phi-1}}$$



Evolution of the normalized energy densities as a function of scale factor

M. R. Haque, E. Kpatcha, D. Maity and Y. Mambrini, Phys.Rev.D **108** (2023) 6, 063523.

PBH reheating (Case for the extended mass distribution)

- PBH number density and energy density :

$$n_{\rm BH}(t) = \int_0^\infty f_{\rm PBH}(M,t)dM\,,$$
$$\rho_{\rm BH}(t) = \int_0^\infty M f_{\rm PBH}(M,t)dM$$

- Conservation of the infinitesimal PBH comoving number density

$$a^3(t)dn_{\rm BH} \equiv a^3 f_{\rm PBH}(M,t)dM = a_{\rm in}^3 f_{\rm PBH}(M_i,t_i)dM_i$$

- Friedmann Boltzmann equation for different energy components:

$$\dot{\rho}_{\rm BH} + 3H\rho_{\rm BH} = \frac{a_{\rm in}^3}{a^3}\int_{\widetilde{M}}^\infty \frac{dM}{dt} f_{\rm PBH}(M_i,t_i)dM_i$$
$$\dot{\rho}_R + 4H\rho_R = \Gamma_\phi\rho_\phi(1+w_\phi) - \frac{a_{\rm in}^3}{a^3}\int_{\widetilde{M}}^\infty \frac{dM}{dt} f_{\rm PBH}(M_i,t_i)dM_i$$

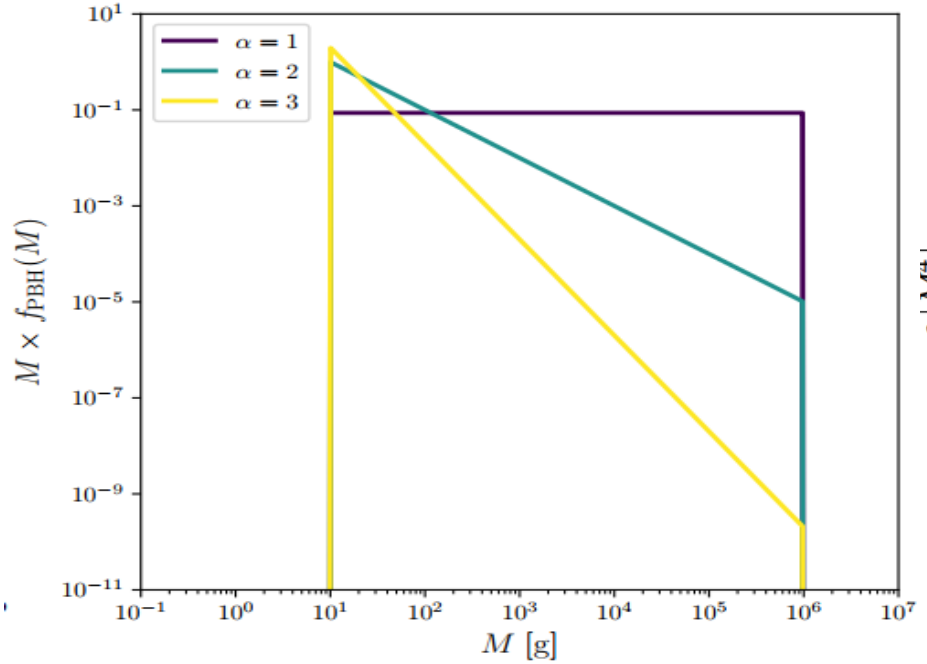
A. Cheek, L. Heurtier, Y. F. Perez-Gonzalez, and J. Turner, (2022), arXiv:2212.03878 [hep-ph].

Extended Vs monochromatic mass distribution

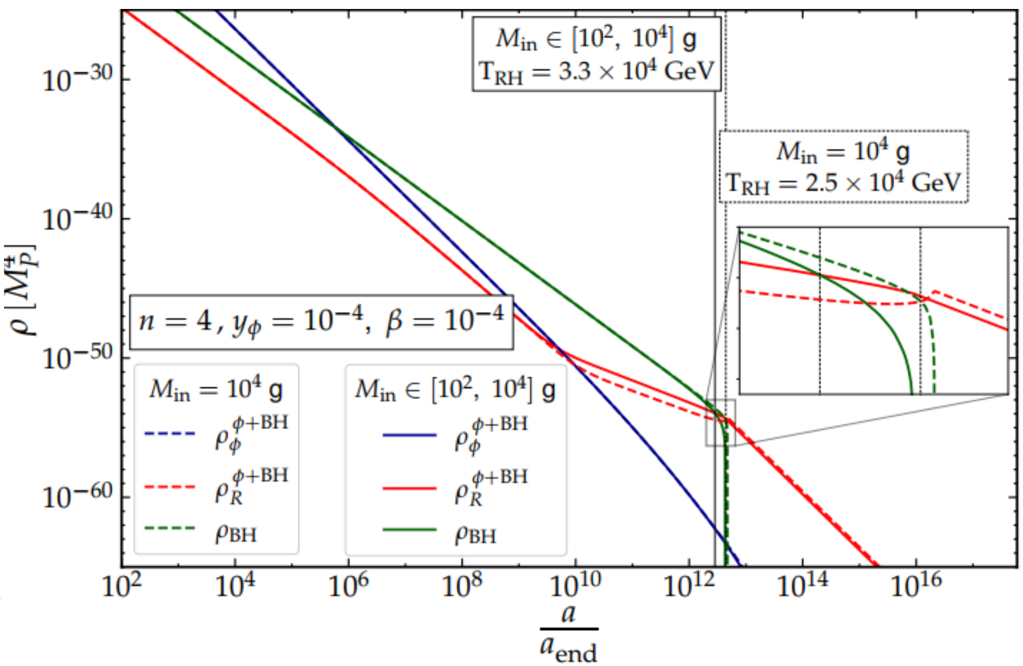
- Power-law mass function :

$$f_{\rm PBH}(M_i,t_i) = \begin{cases} C M_i^{-\alpha}, & \text{for } M_{\rm min} \le M_i \le M_{\rm max} \\ 0, & \text{otherwise}. \end{cases}$$

$$\alpha = \frac{2+4w}{1+w}$$



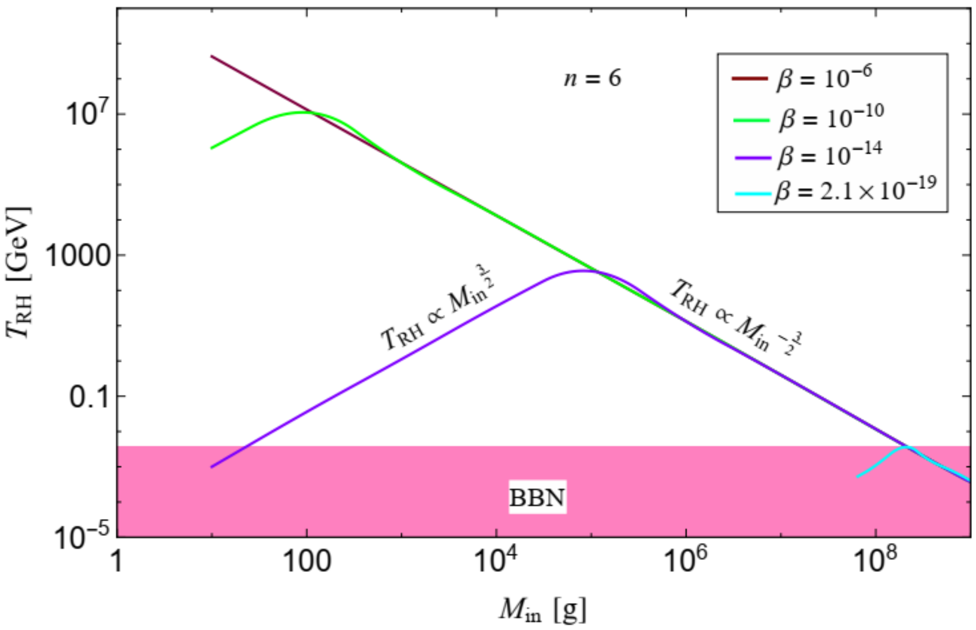
Power law mass distribution as a function of PBH mass

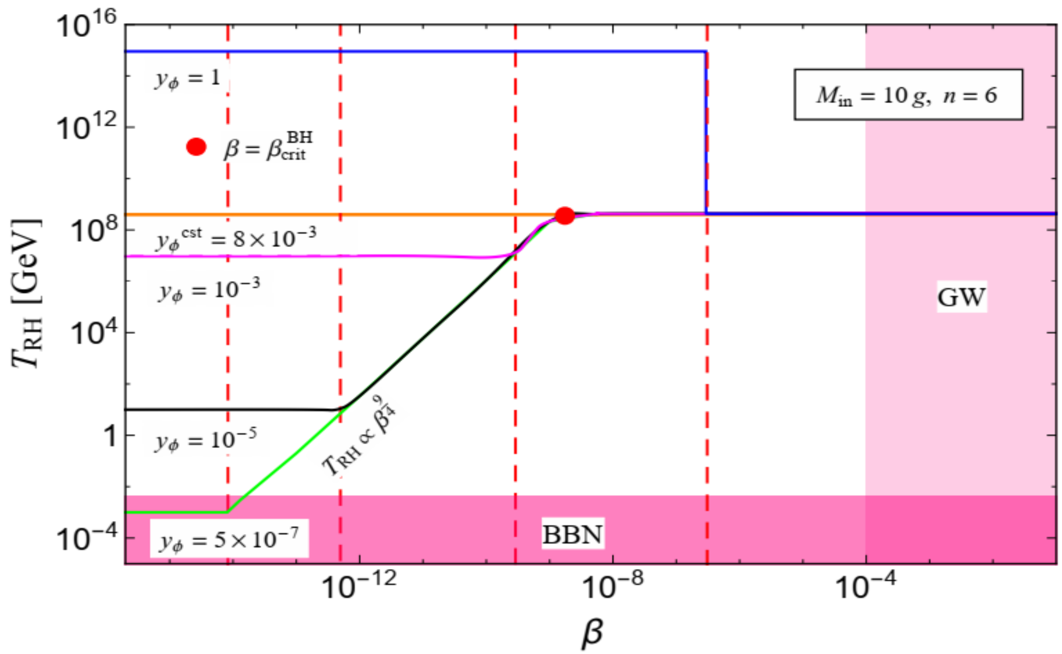


Evolution of the energy densities as a function of scale factor

B. J. Carr, Astrophys. J. **201**, 1 (1975).
M. R. Haque, E. Kpatcha, D. Maity and Y. Mambrini, Phys.Rev.D **108** (2023) 6, 063523.

Inflaton reheating vs PBH reheating





Reheating temperature as a function of initial BH mass

Evolution of the reheating temperature as function of β

M. R. Haque, E. Kpatcha, D. Maity and Y. Mambrini, Phys.Rev.D **108** (2023) 6, 063523.

Particle production from a single BH

- The emission rate of a particle of species *j* : $$\frac{d^2N_j}{dtdE} = \frac{27}{4}\pi R_S^2 \times \frac{g_j}{2\pi^2}\frac{E^2}{e^{\frac{E}{T_{\rm BH}}} \pm 1}$$

$$R_S = \frac{M_{\rm BH}}{4\pi M_P^2} \qquad T_{\rm BH} = \frac{M_P^2}{M_{\rm BH}} \simeq 10^{13}\left(\frac{1\text{g}}{M_{\rm in}}\right)\ \text{GeV}$$

- If the mass of the emitting particles less than the BH temperature at its formation time

$$N_j^{m_j<T_{\rm BH}^{\rm in}} = \int_{t_{\rm in}}^{t_{\rm ev}} \frac{dN_j}{dt} = \frac{15 g_j \zeta(3)}{g_* \pi^4}\frac{M_{\rm in}^2}{M_P^2} \simeq 10^8\left(\frac{M_{\rm in}}{1\text{ g}}\right)^2$$

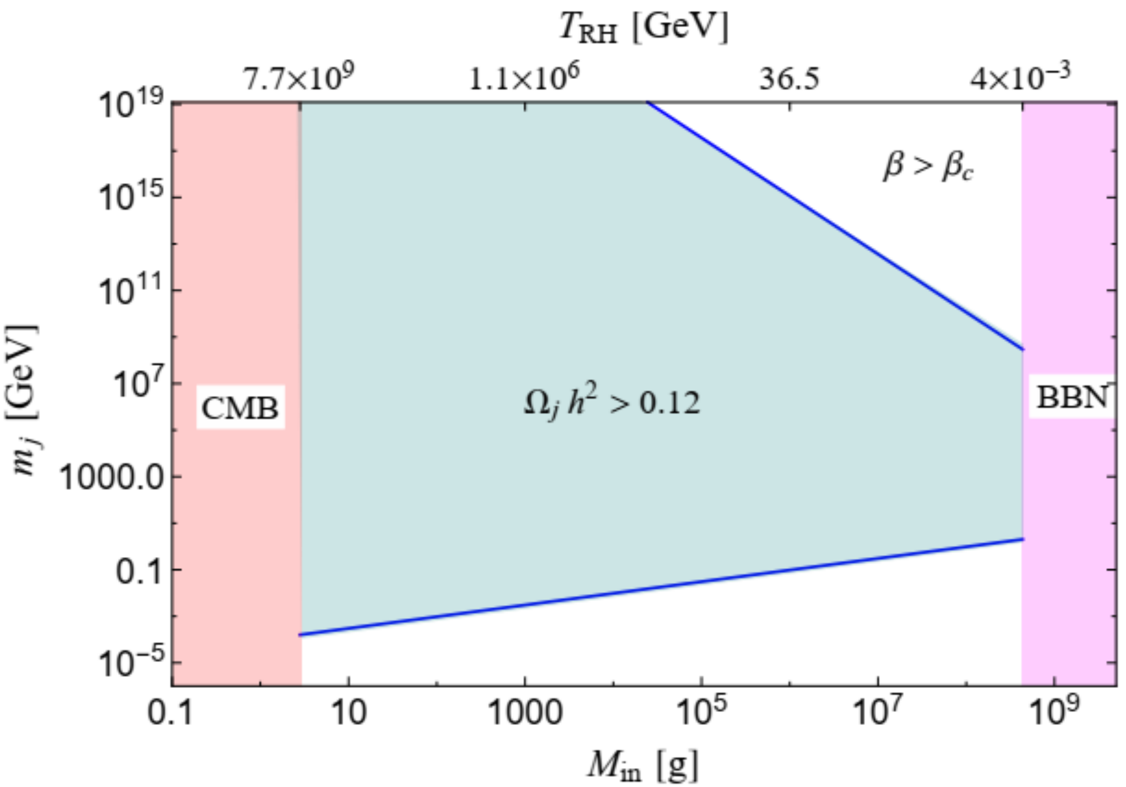
- For mass $m_j > T_{\rm BH}^{\rm in}$: $$N_j^{m_j>T_{\rm BH}^{\rm in}} = \int_{t_j}^{t_{\rm ev}} \frac{dN_j}{dt} = \frac{15 g_i \zeta(3)}{g_* \pi^4}\frac{M_P^2}{m_j^2} \simeq 10^{14}\left(\frac{10^{10}\text{GeV}}{m_j}\right)^2$$

- DM relic abundance of the species *j* today :

$$\Omega_j h^2 = 1.6 \times 10^8\,\frac{g_0}{g_{\rm RH}}\,\frac{N_j \times n_{\rm BH}(a_{\rm ev})}{T_{\rm RH}^3}\left(\frac{a_{\rm ev}}{a_{\rm RH}}\right)^3 \frac{m_j}{\text{GeV}}$$

Y. Mambrini, Particles in the dark Universe, Springer Ed., ISBN 978-3-030-78139-2 (2021)

DM parameter space: PBH reheating (PBH domination)



$$m_j < T_{\rm BH}^{\rm in} \Rightarrow \frac{\Omega_j h^2}{0.12} \simeq \sqrt{\frac{10^8 {\rm g}}{M_{\rm in}}}\frac{m_j}{1\ {\rm GeV}} \Rightarrow m_j \propto \sqrt{M_{\rm in}}$$

$$m_j > T_{\rm BH}^{\rm in} \Rightarrow \frac{\Omega_j h^2}{0.12} \simeq \left(\frac{10^8 {\rm g}}{M_{\rm in}}\right)^{\frac{5}{2}} \left(\frac{1.1\times10^{10}{\rm GeV}}{m_j}\right) \Rightarrow m_j \propto M_{\rm in}^{-5/2}$$

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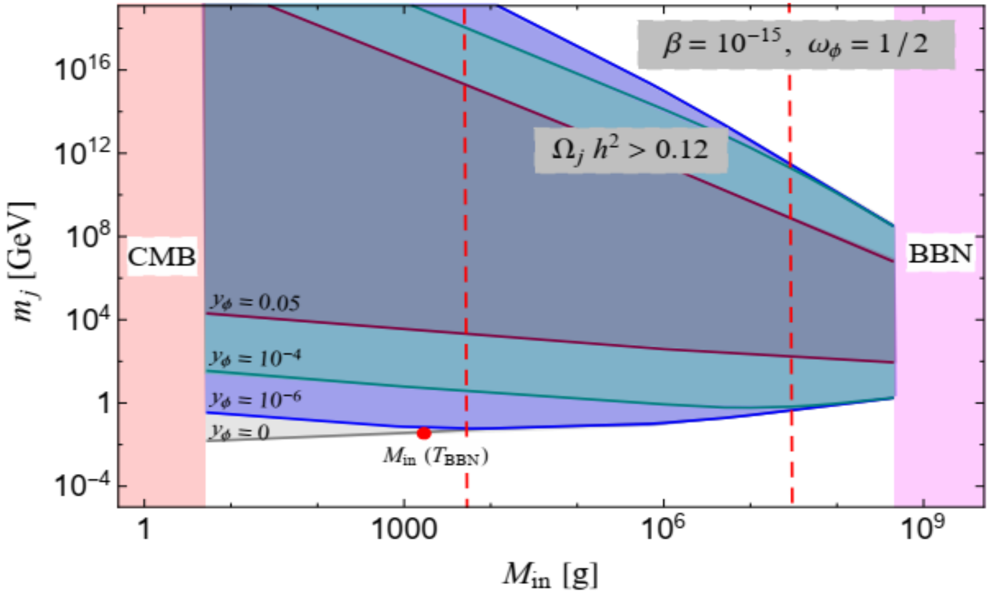
DM parameter space: PBH reheating vs Inflaton reheating



$m_j < T_{\rm BH}^{\rm in}$

Inflaton reheating	PBH reheating
$m_j \propto M_{\rm in}^{-1/3}$	$m_j \propto M_{\rm in}^{1/6}$

$m_j > T_{\rm BH}^{\rm in}$

Inflaton reheating	PBH reheating
$\Omega_j h^2 \propto M_{\rm in}^{-5/3} m_j^{-1}$	$\Omega_j h^2 \propto M_{\rm in}^{-13/6} m_j^{-1}$

$m_j < T_{\rm BH}^{\rm in}$:

$$\frac{\Omega_j h^2}{0.12} \simeq 2\times 10^{30}\beta \left(\frac{M_p}{M_{\rm in}}\right)^{\frac{1+3\,w_\phi}{1+w_\phi}} \left(\frac{M_P}{T_{\rm RH}}\right)^{\frac{3\,w_\phi-1}{1+w_\phi}} \frac{10^{13}\,{\rm GeV}}{m_j} \quad \text{(Inflaton reheating)}$$

$$\frac{\Omega_j h^2}{0.12} = 2.8\times 10^{8}\, \mu_j \beta^{\frac{1}{4}} \frac{g_0 g_j}{g_{\rm RH}^{\frac{1}{4}}\, g_*(T_{\rm BH})} \left(\frac{M_P}{M_{\rm in}}\right)^{\frac{1-w_\phi}{2+2w_\phi}} \frac{m_j}{\rm GeV} \quad \text{(PBH reheating)}$$

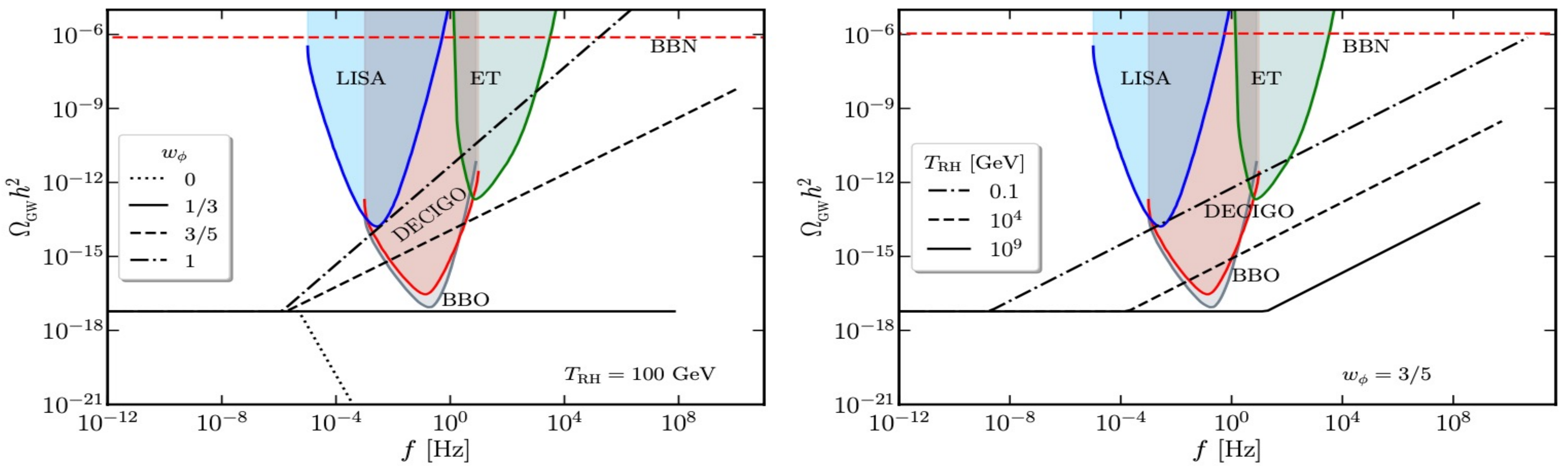
$m_j > T_{\rm BH}^{\rm in}$:

$$\frac{\Omega_j h^2}{0.12} \simeq 2\times 10^{30}\beta \left(\frac{M_p}{M_{\rm in}}\right)^{\frac{1+3\,w_\phi}{1+w_\phi}} \left(\frac{M_P}{T_{\rm RH}}\right)^{\frac{3\,w_\phi-1}{1+w_\phi}} \frac{10^{13}\,{\rm GeV}}{m_j} \quad \text{(Inflaton reheating)}$$

$$\frac{\Omega_j h^2}{0.12} = 1.7\times 10^{45} \mu_j \beta^{\frac{1}{4}} \frac{g_0 g_j}{g_{\rm RH}^{\frac{1}{4}} g_*(T_{\rm BH})} \left(\frac{M_P}{M_{\rm in}}\right)^{\frac{5+3w_\phi}{2+2w_\phi}} \frac{\rm GeV}{m_j} \quad \text{(PBH reheating)}$$

M. R. Haque, E. Kpatcha, D. Maity and Y. Mambrini, Phys.Rev.D **109** (2024) 2, 023521.

Decoding the phase of reheating through primary gravitational waves



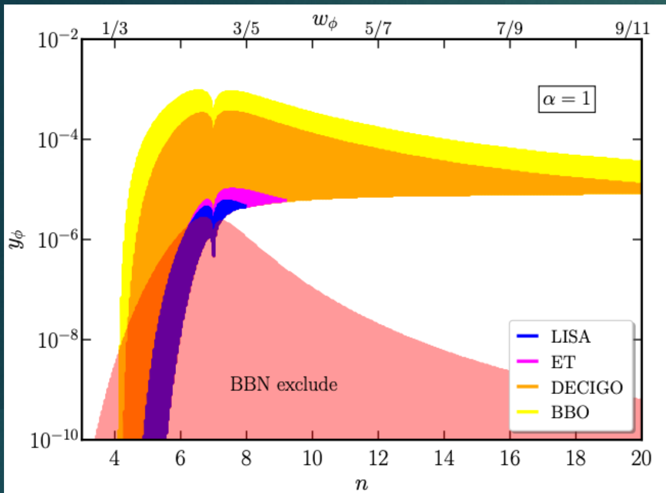
❖ In the domain $k \gg kre$: $\Omega_{GW}(k)\, h^2 \simeq \Omega_R\, h^2 \, \frac{H_I^2}{12\,\pi^2 M_{Pl}^2} \frac{4\,\gamma^2}{\pi} \Gamma^2 \left(1 + \frac{\nu}{\gamma}\right) \left(\frac{k}{2\,\gamma\, k_{re}}\right)^{n_{GW}}$

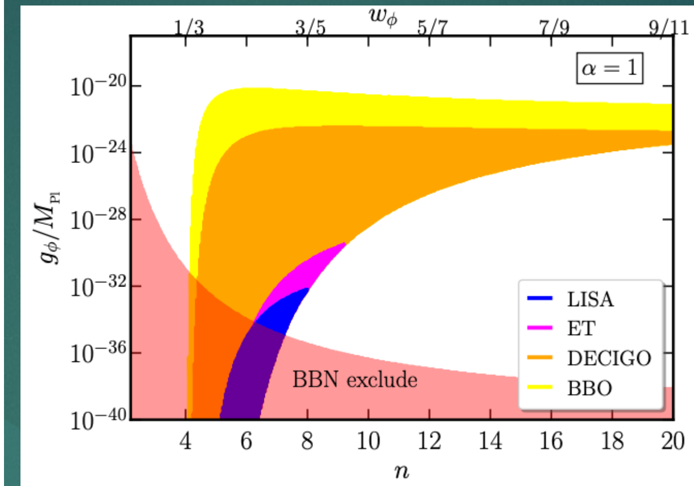
❖ In the domain $k \ll kre$ $\Omega_{GW}(k)\, h^2 \simeq \left(\frac{g_{r,0}}{g_{r,eq}}\right)^{1/3} \Omega_R\, h^2 \frac{\mathcal{P}_T(k)}{24} \simeq \Omega_R\, h^2 \frac{H_I^2}{12\,\pi^2 M_{Pl}^2}$

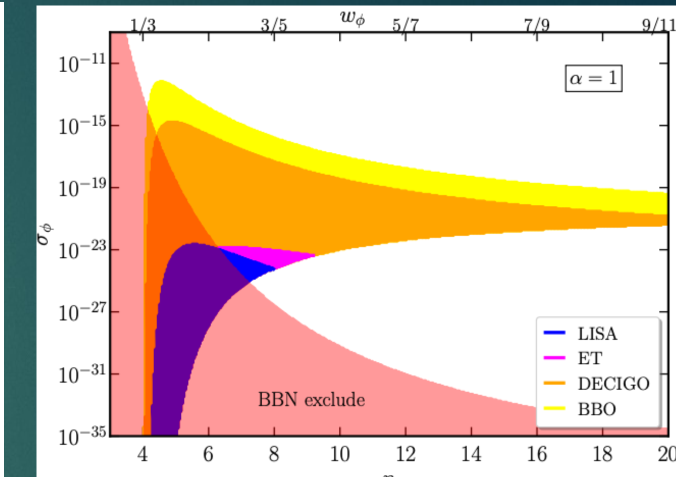
❖ Index of this spectrum : $n_{GW} = 1 - \frac{2\,\nu}{\gamma} = -\frac{2\,(1 - 3\,w_\phi)}{1 + 3\,w_\phi}$

M. R. Haque, D. Maity, T. Pal and L. Sriramkumar, Phys. Rev. D **104**, 063513 (2021).

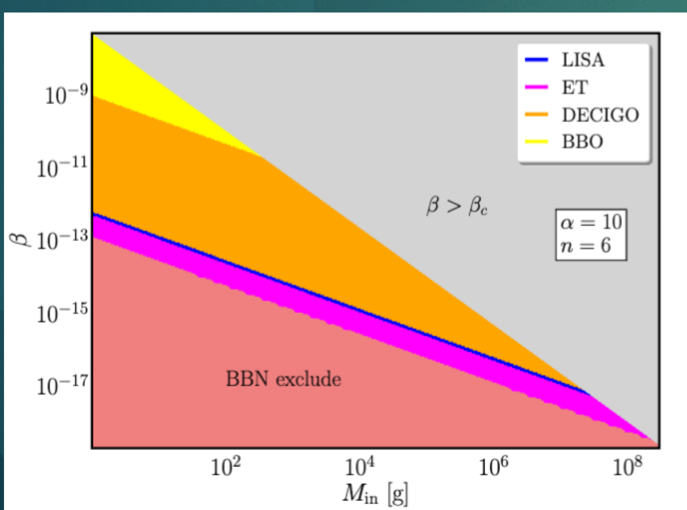
The possible probing range of different couplings between the inflaton and SM particles and PBH parameters considering PGWs

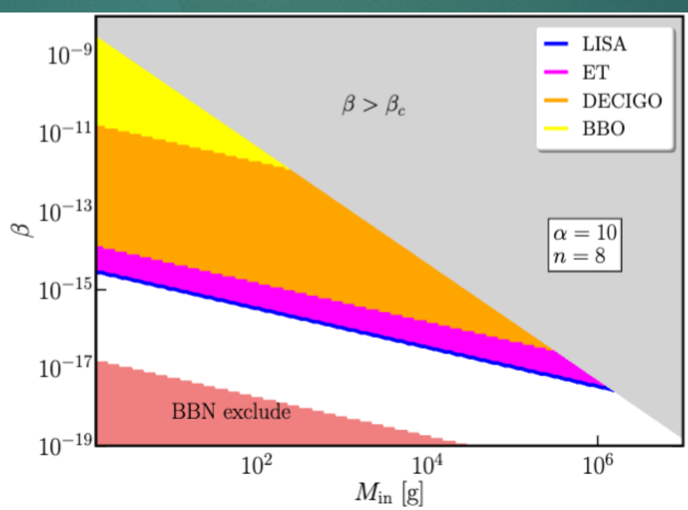






- ❖ Inflaton decays into pair of fermion $\mathcal{L}_{\rm int} \supset y_\phi \phi \bar{f} f \quad \phi \to \bar{f} f$
- ❖ Inflaton decays into pair of scalar $\mathcal{L}_{\rm int} \supset g_\phi \phi b b \quad \phi \to bb$
- ❖ Inflaton scattering process $\mathcal{L}_{\rm int} \supset \sigma_\phi \phi^2 b^2 \quad \phi\phi \to bb$





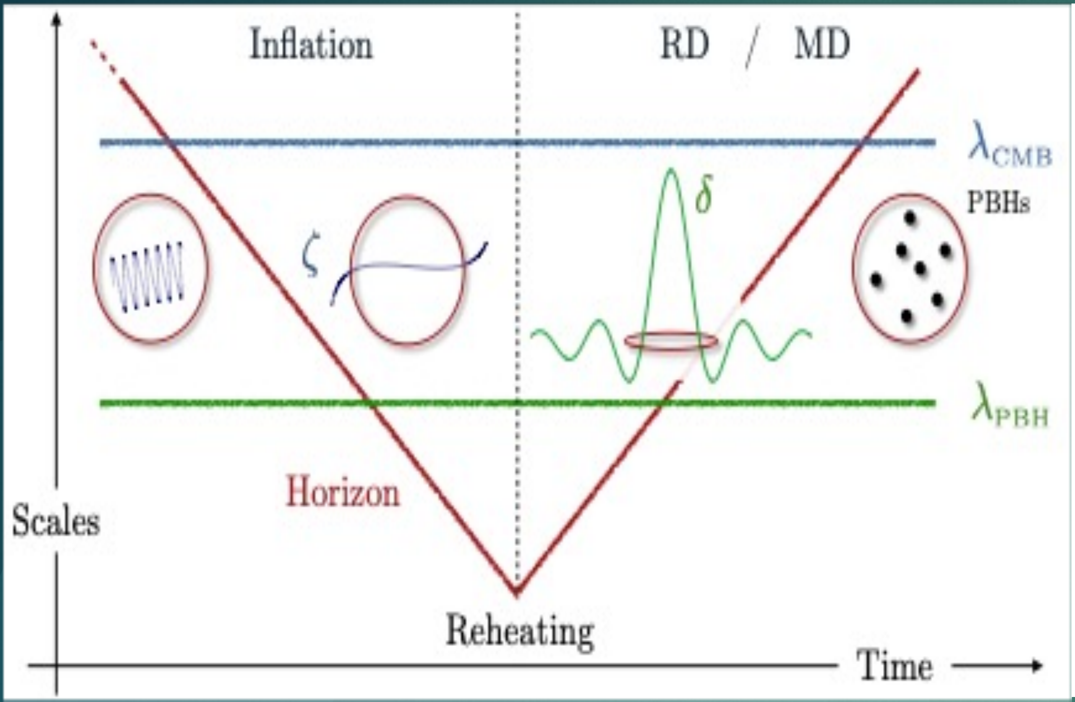
$$\rho = \left[2\, t_{\rm obs} \int_{f_{\rm min}}^{f_{\rm max}} {\rm d}f \left(\frac{\Omega_{\rm GW}(f)h^2}{\Omega_{\rm noise}(f)h^2} \right)^2 \right]^{1/2}$$

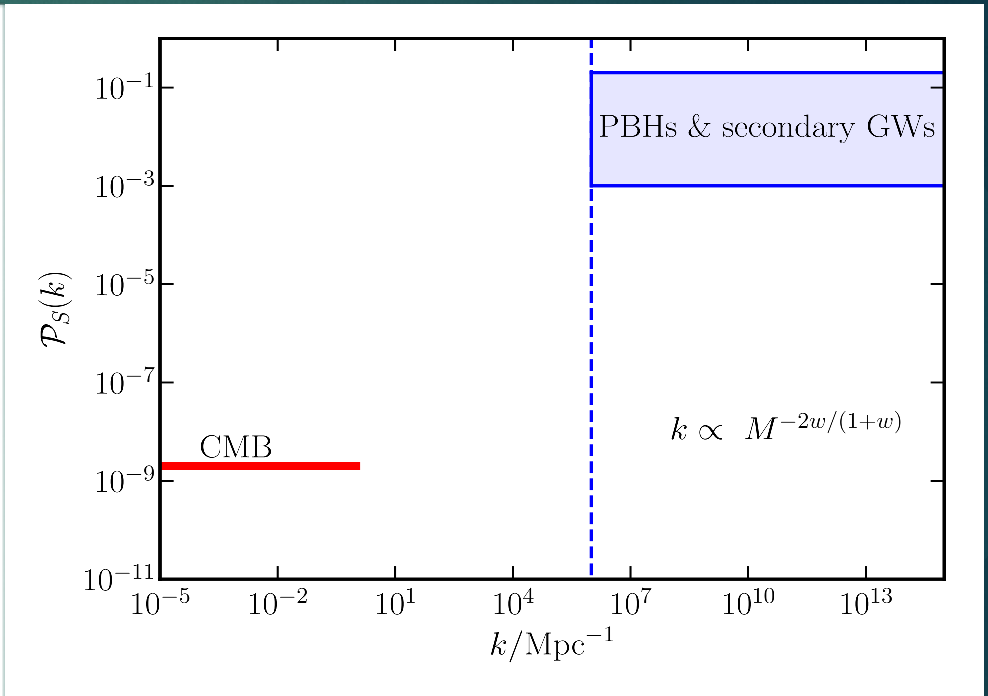
Detectors	frequency (Hz)	$t_{\rm obs}$ (years)	$\rho_{\rm th}$
LISA	$10^{-5} - 1$	4	10
ET	$1 - 10^4$	5	5
DECIGO	$10^{-3} - 10^2$	4	10
BBO	$10^{-3} - 10^2$	4	10

Reheating through evaporation of PBHs

S. Maity, M. R. Haque, arXiv 247.18246..

Formation of primordial black holes (PBHs) during post-inflationary era





- ❖ A schematic representation of the standard PBH formation scenario. The green line indicates the comoving scale of perturbations generated during inflation responsible for the PBH formation, much smaller than the CMB scales indicated in blue.
- ❖ The amplitude of the perturbations on small scales required to forms PBHs.

G. Franciolini, arXiv:2110.06815 [astro-ph.CO].

Formation of the PBHs during reheating

❖ We assume that the inflationary scalar power spectrum with a broken power law is given by

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\rm S}\left(\frac{k}{k_*}\right)^{n_{\rm S}-1} + A_0 \begin{cases} \left(\frac{k}{k_{\rm peak}}\right)^4 & k \leq k_{\rm peak} \\ \left(\frac{k}{k_{\rm peak}}\right)^{n_0} & k \geq k_{\rm peak} \end{cases}$$

where $A_{\rm S}$ and $n_{\rm S}$ are the amplitude and spectral index of the power spectrum at the CMB pivot scale of $k_* = 0.05\,{\rm Mpc}^{-1}$.

❖ We shall assume that the threshold value of the density contrast for the formation of PBHs is given by following analytical expression

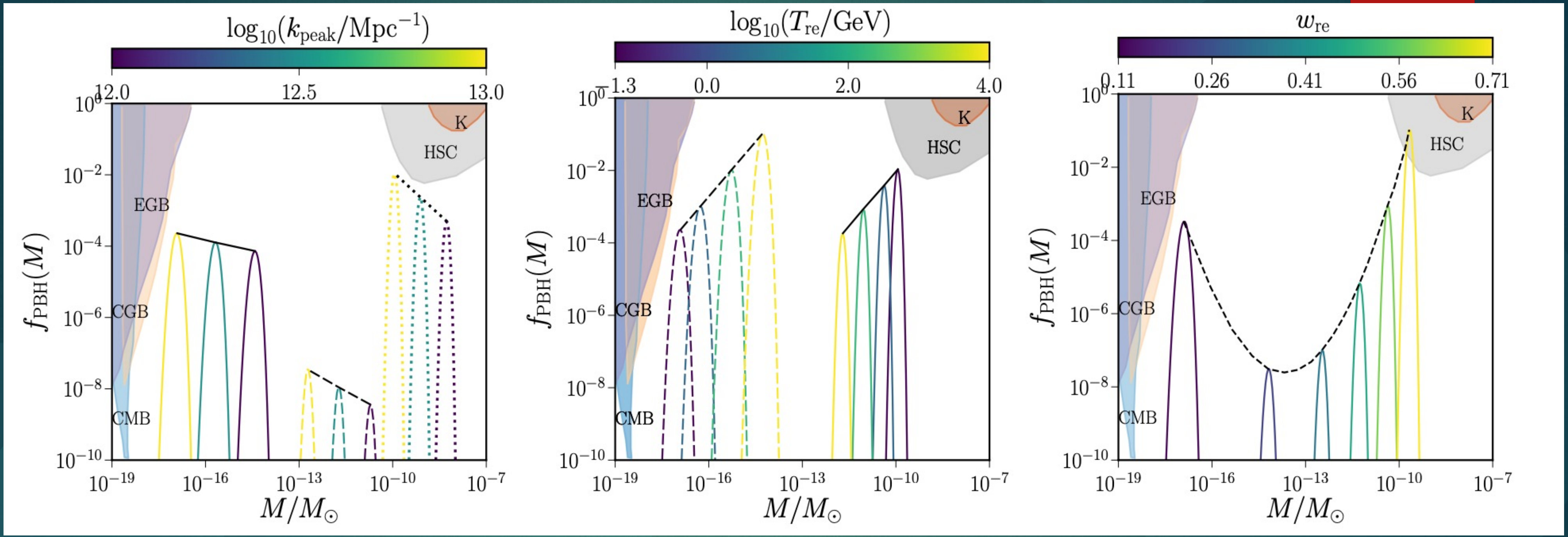
$$\delta_{\rm c}^{\rm an} = \frac{3\,(1+w_{\rm re})}{5+3\,w_{\rm re}}\,\sin^2\left(\frac{\pi\,\sqrt{w_{\rm re}}}{1+3\,w_{\rm re}}\right)$$

❖ Fraction of the dark matter contributed from PBH today

$$f_{\rm PBH}(M) = \beta(M)\,\frac{\Omega_{\rm m}\,h^2}{\Omega_{\rm c}\,h^2}\left(\frac{g_{s,\rm eq}}{g_{s,\rm re}}\right)\left(\frac{g_{\rm re}}{g_{\rm eq}}\right)^{\frac{1}{1+w_{\rm re}}}\left(\frac{T_{\rm re}}{T_{\rm eq}}\right)^{\frac{1-3\,w_{\rm re}}{1+w_{\rm re}}}\left(\frac{M}{\gamma\,M_{\rm eq}}\right)^{-\frac{2\,w_{\rm re}}{1+w_{\rm re}}}$$

T. Harada, C.-M. Yoo, and K. Kohri, Phys. Rev. D **88**, 084051 (2013).

Formation of the PBHs during reheating

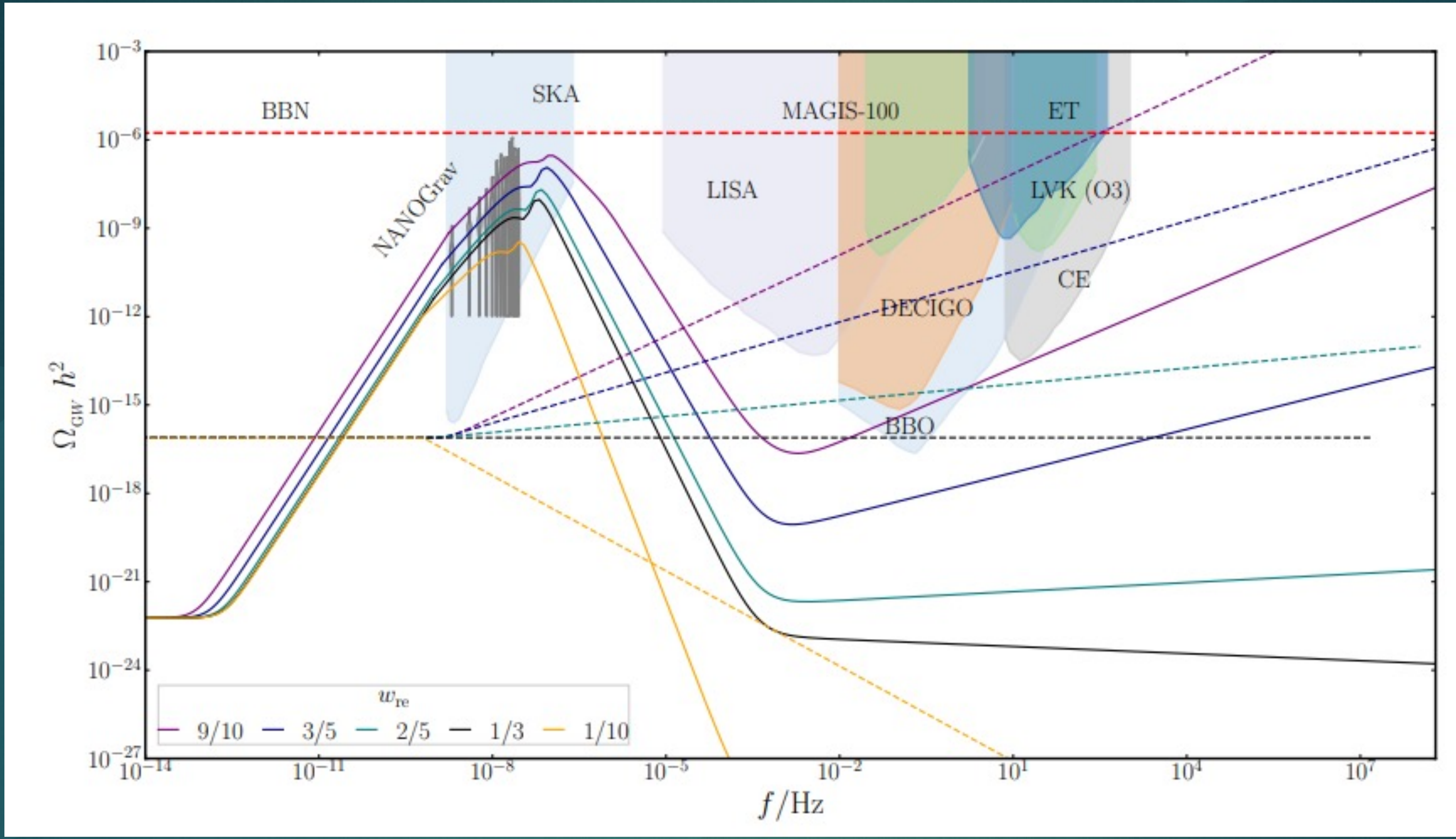


❖ $f_{\rm PBH}$ is plotted as a function of $M/M_\odot$. For the left plot we fix $w_{\rm re} = (1/9, 1/3, 2/3)$ and for the middle plot we fix $w_{\rm re} = (1/9, 2/3)$. For right panel T_{re} = 50 MeV.

$$f_{\rm PBH}(M) \propto T_{\rm re}^{\frac{1-3\,w_{\rm re}}{1+w_{\rm re}}} M^{-\frac{2\,w_{\rm re}}{1+w_{\rm re}}}$$

S. Maity, N. Bhaumik, M. R. Haque, D. Maity and L. Sriramkumar, arXiv 2403.16963.

Generation of scalar induced secondary GWs during the epoch of reheating



The dimensionless spectral energy density of primary and secondary GWs today have been plotted for a given reheating temperature and different values of the parameter describing the equation of state during reheating

S. Maity, N. Bhaumik, M. R. Haque, D. Maity and L. Sriramkumar, arXiv 2403.16963.

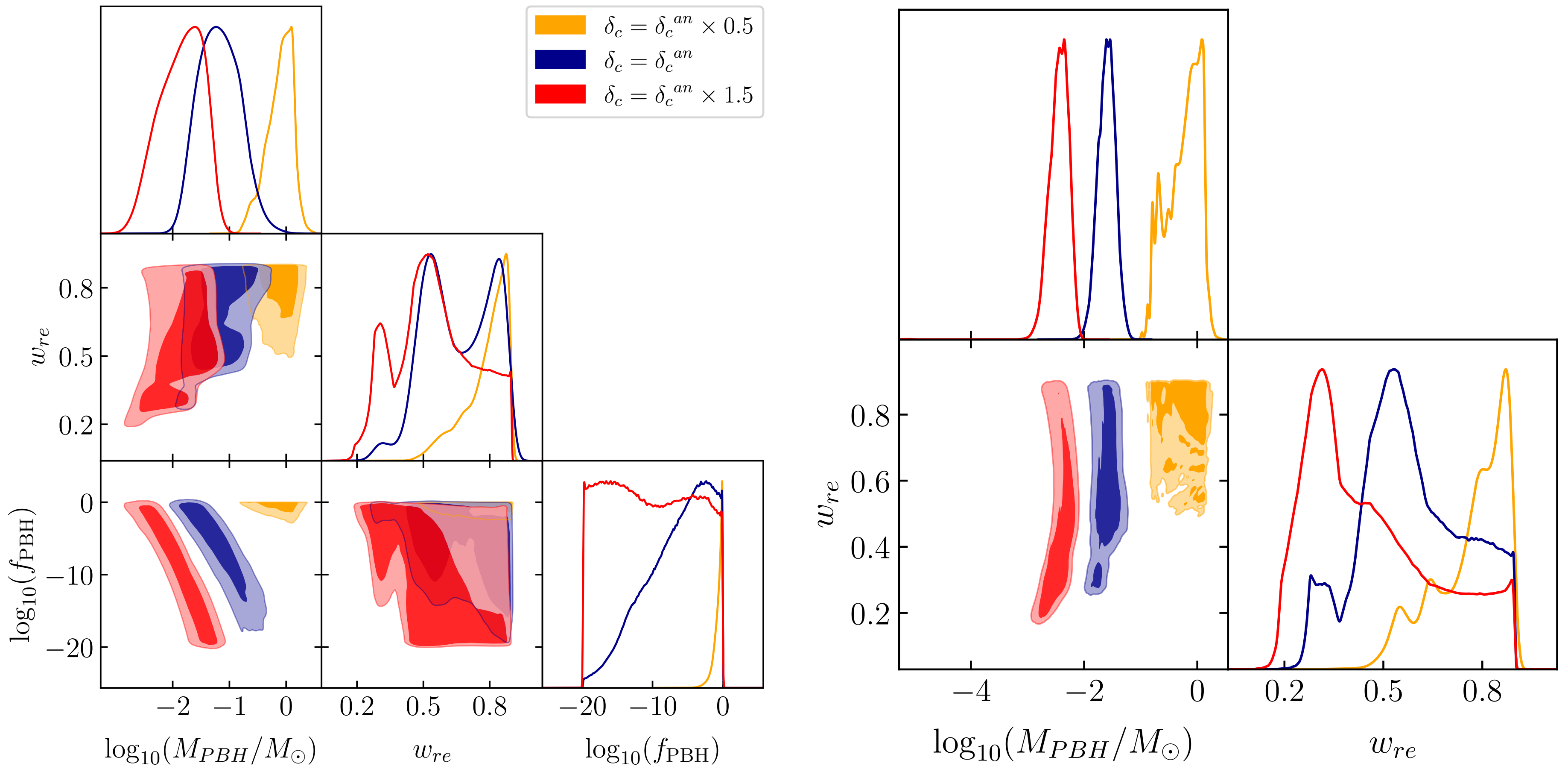
Best-fit values

Model	Parameter	Prior	Mean value		
R4pF	$\log_{10}\left(\frac{k_{\rm peak}}{\rm Mpc^{-1}}\right)$	$[6, 9]$	$7.62^{+0.35}_{-0.41}$		
	$\log_{10}(A_0)$	$[-3, 0]$	$-1.23^{+0.38}_{-0.66}$		
	$w_{\rm re}$	$[0.1, 0.9]$	0.52 ± 0.23		
	n_0	$[-3.0, -1.5]$	-2.26 ± 0.43		
R3pF	$\log_{10}\left(\frac{k_{\rm peak}}{\rm Mpc^{-1}}\right)$	$[6, 9]$	$7.54^{+0.36}_{-0.44}$		
	$\log_{10}(A_0)$	$[-3, 0]$	$-1.26^{+0.26}_{-0.64}$		
	$w_{\rm re}$	$[0.1, 0.9]$	$0.55^{+0.39}_{-0.14}$		
			$\mathbf{0.5\, \delta_c^{an}}$	$\boldsymbol{\delta_c^{an}}$	$\mathbf{1.5\, \delta_c^{an}}$
R3pB	$\log_{10}\left(\frac{M}{M_\odot}\right)$	$[-6, 3.5]$	$-0.12^{+0.28}_{-0.15}$	$-1.18^{+0.35}_{-0.39}$	$-1.85^{+0.49}_{-0.30}$
	$\log_{10}(f_{\rm PBH})$	$[-20, 0]$	$-0.67^{+0.68}_{-0.16}$	$-6.6^{+6.5}_{-1.9}$	$-10.2^{+8.2}_{-9.6}$
	$w_{\rm re}$	$[0.1, 0.9]$	$0.78^{+0.11}_{-0.030}$	$0.66^{+0.23}_{-0.19}$	0.55 ± 0.17
R2pB	$\log_{10}\left(\frac{M}{M_\odot}\right)$	$[-6, 3.5]$	$-0.24^{+0.38}_{-0.45}$	$-1.60^{+0.16}_{-0.14}$	$-2.45^{+0.20}_{-0.13}$
	$w_{\rm re}$	$[0.1, 0.9]$	$0.77^{+0.13}_{-0.038}$	0.59 ± 0.16	$0.464^{+0.095}_{-0.25}$

The best-fit values arrived upon comparison with the NANOGrav 15-year data.

S. Maity, N. Bhaumik, M. R. Haque, D. Maity and L. Sriramkumar, arXiv 2403.16963.

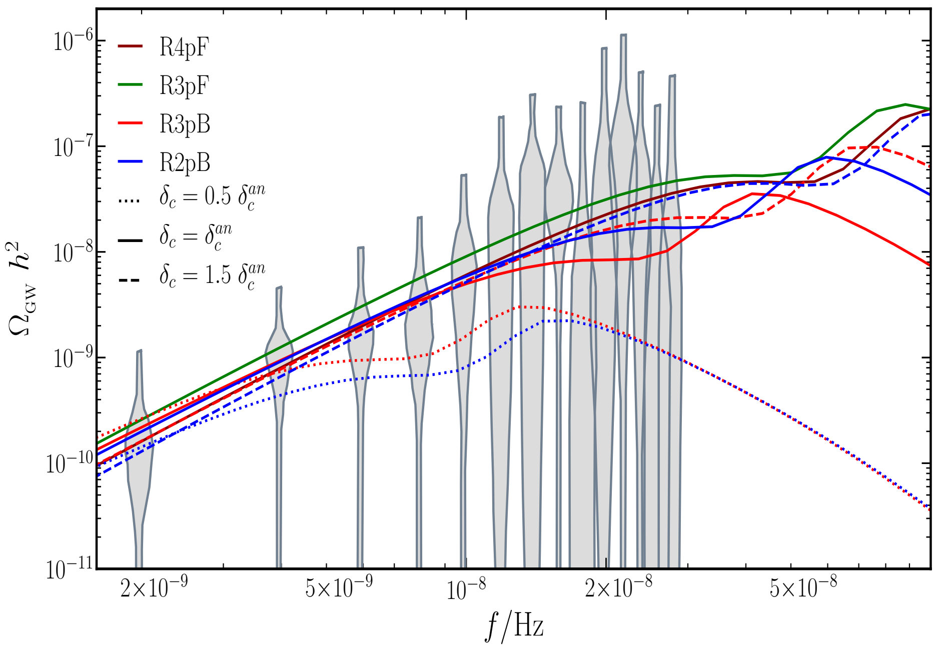
Constraints on the epoch of reheating

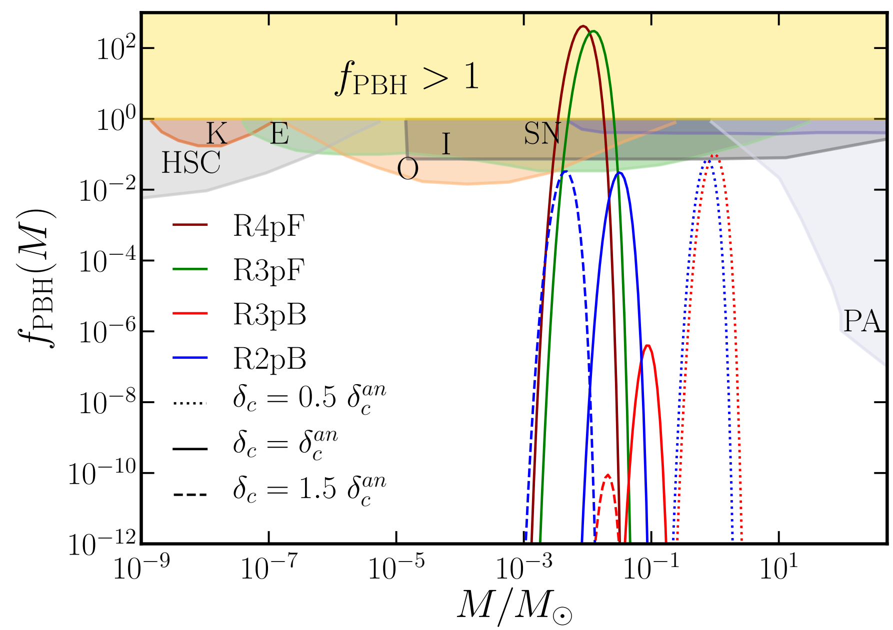


❖ we have plotted the marginalized posterior distributions of the parameters that have been arrived at upon comparing our model with the NANOGrav 15-year data.

S. Maity, N. Bhaumik, M. R. Haque, D. Maity and L. Sriramkumar, arXiv 2403.16963.

Spectrum of the secondary GWs and the formation of the PBHs with the best-fit values





- The dimensionless spectral energy density of the secondary GWs today $\Omega_{\rm GW}$ (f) is plotted for a given reheating temperature and the best-fit values of the parameters in the different models.
- The fraction of PBHs that constitute the dark matter density today is plotted for a given reheating temperature T_{re}=50 MeV and the best-fit values of the parameters in the different models.

S. Maity, N. Bhaumik, M. R. Haque, D. Maity and L. Sriramkumar, arXiv 2403.16963.

Bayesian evidence

Model X	Model Y	$\mathrm{BF}_{Y,X}$		
		$\delta_c = 0.5\,\delta_c^{\mathrm{an}}$	$\delta_c = \delta_c^{\mathrm{an}}$	$\delta_c = 1.5\,\delta_c^{\mathrm{an}}$
SMBHB	R2pB	$1.7 \pm .06$	260.04 ± 19.21	350.61 ± 27.36

❖ We obtain the marginalized likelihood in support of model Y and utilize it to evaluate the Bayesian factor against a reference model X.

❖ When $\delta_c = \delta_c^{an}$ and $\delta_c = 1.5\ \delta_c^{an}$, our comparison with the NANOGrav's 15-year data finds strong Bayesian evidence in favor of the scenario wherein PBHs are formed during reheating, resulting in the generation of secondary GWs rather than the SMBHB model.

S. Maity, N. Bhaumik, M. R. Haque, D. Maity and L. Sriramkumar, arXiv 2403.16963.

Quantum correction on the evaporation of PBHs

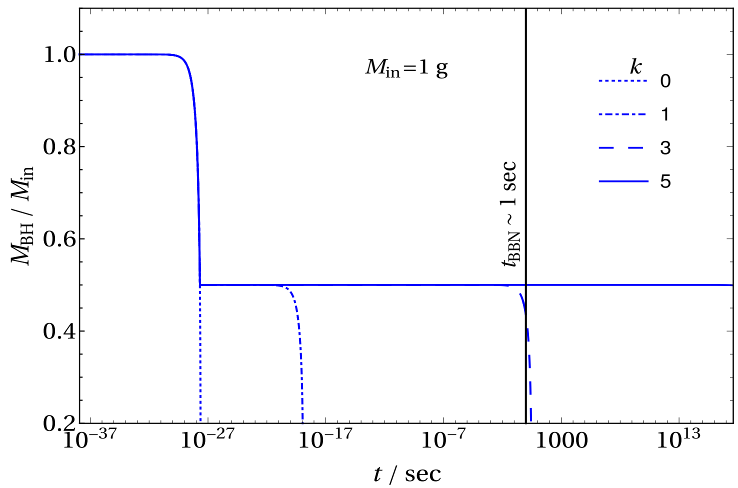
- During phase-I (standard Hawking evaporation)

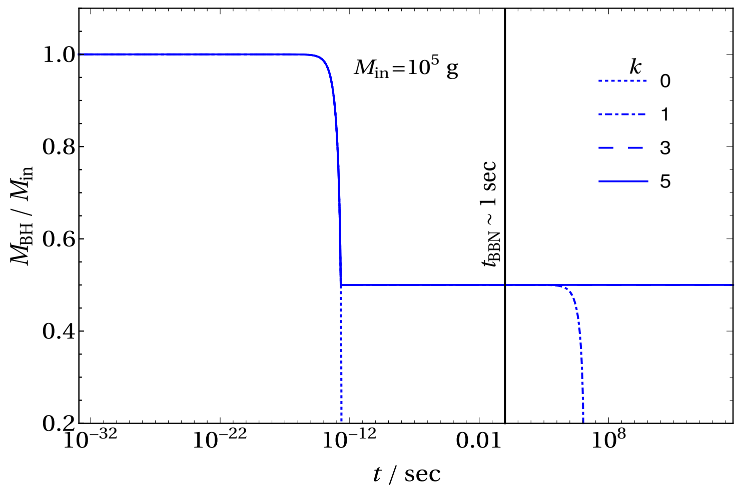
$$\frac{dM_{\rm BH}}{dt} = -\epsilon \frac{M_P^4}{M_{\rm BH}^2} \quad \Rightarrow \quad t_{\rm q} = \frac{1-q^3}{\Gamma^0_{\rm BH}}, \quad \Gamma^0_{\rm BH} = 3\epsilon M_P^4/M_{\rm in}^3$$

- During phase-II (Memory burden phase)

$$\frac{{\rm d}M_{\rm BH}}{{\rm d}t} = -\frac{\epsilon}{[S(M_{\rm BH})]^k}\frac{M_P^4}{M_{\rm BH}^2} \quad \Rightarrow \quad t^k_{\rm ev} \simeq \frac{q^{3+2k}}{2^k(3+2k)}\left(\frac{M_{\rm in}}{4.3\times 10^{-6}\ {\rm g}}\right)^{3+2k} 5.7\times 10^{-44}\ {\rm s}$$

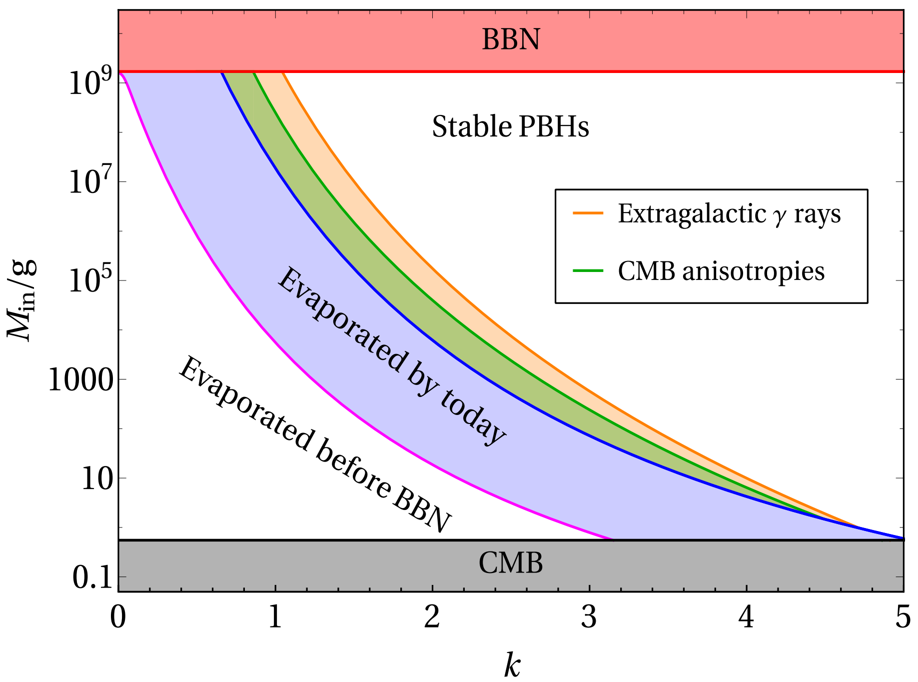
$$S = \frac{1}{2}\left(\frac{M_{\rm BH}}{M_P}\right)^2$$

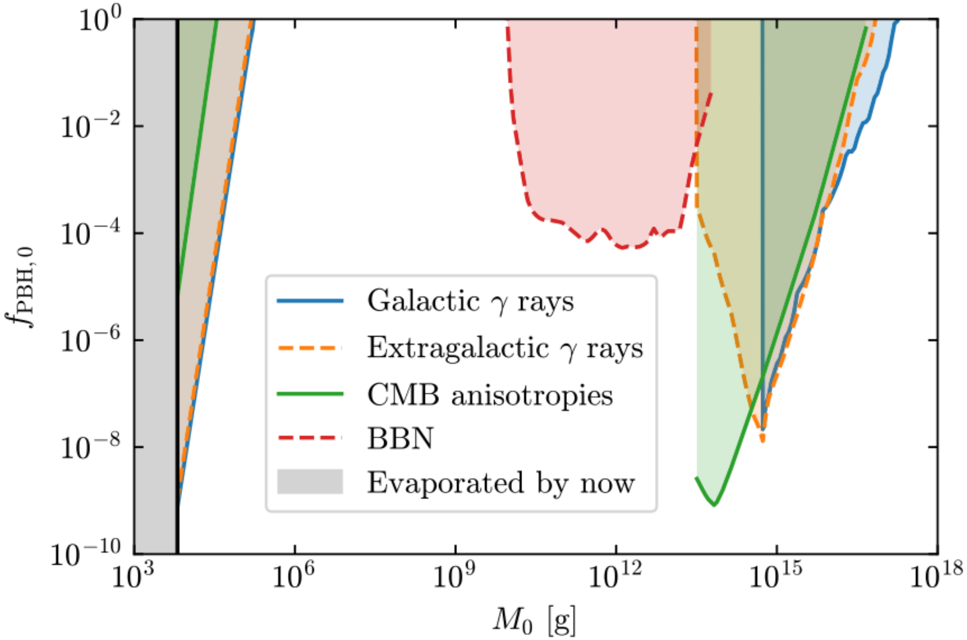




A. Alexandre, G. Dvali, and E. Koutsangelas, arXiv:2402.14069.
M. R. Haque, S. Maity, D. Maity, and Y. Mambrini, JCAP 07 (2024) 002.

Limits on the ultralight PBHs

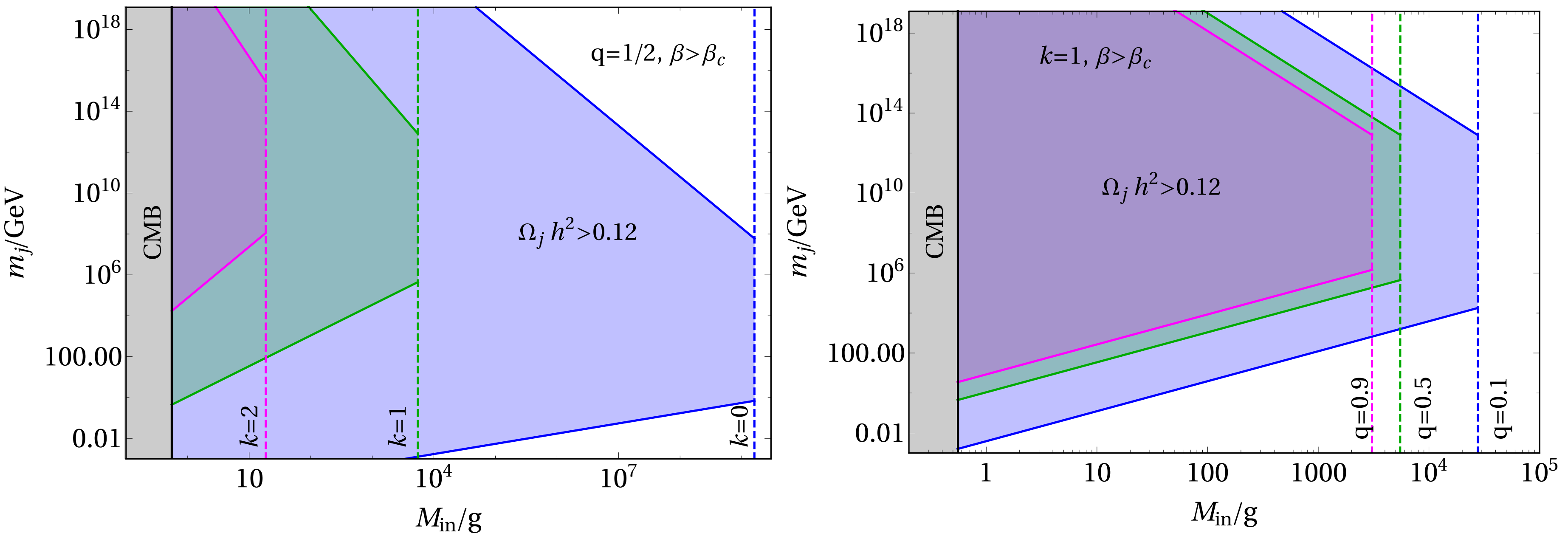




- ❖ Different limits on the formation mass as a function of *k* are plotted here.
- ❖ Constraints on $f_{\rm PBH}$ for $k=2$ is plotted here.

M. R. Haque, S. Maity, D. Maity, and Y. Mambrini, JCAP 07 (2024) 002.
V. Thoss, A. Burkert, and K. Kohri, arXiv:2402.17823.

Modified DM parameter space for evaporating PBHs in the PBH dominance scenario



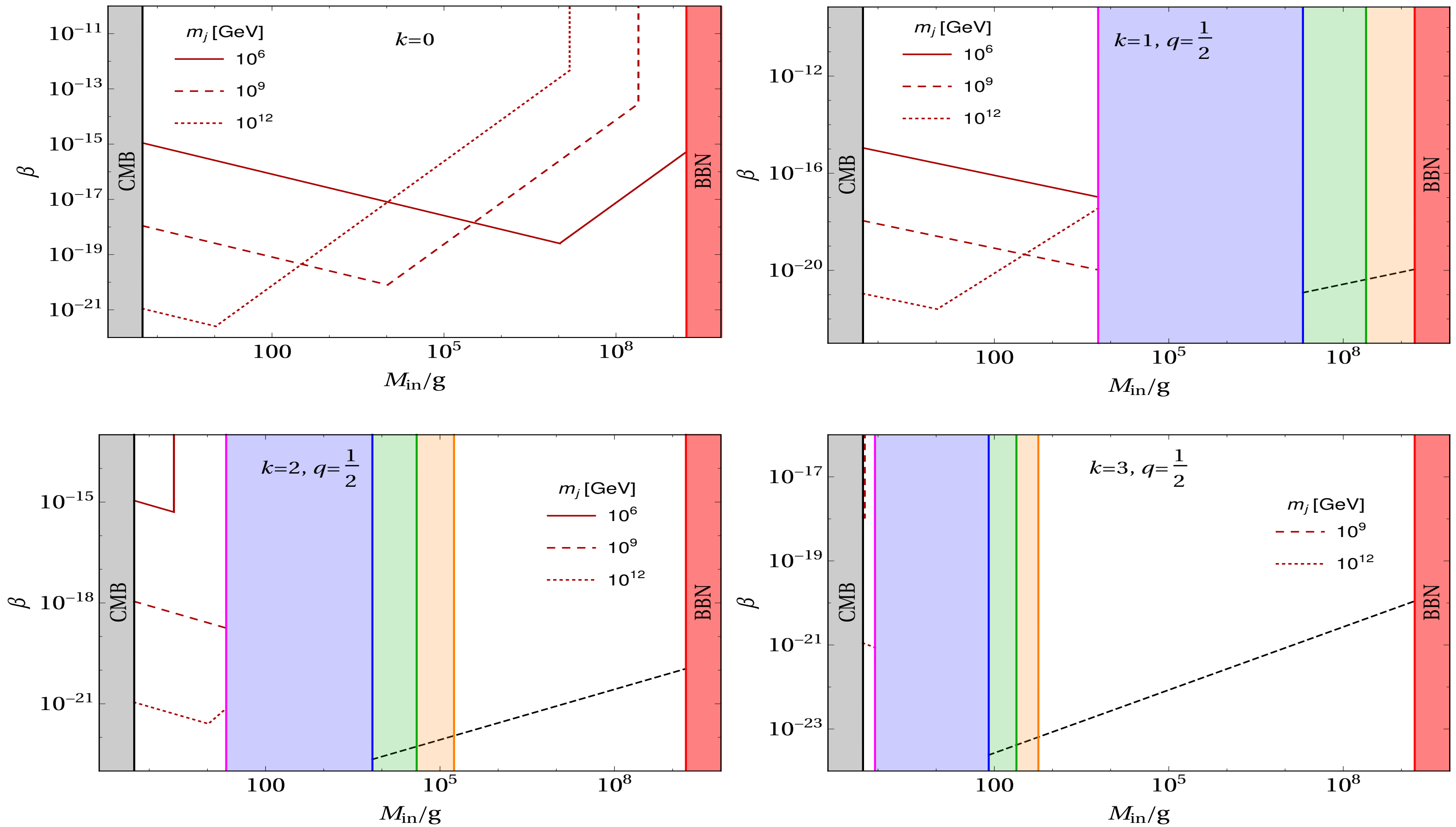
$$m_j < T_{\rm BH}^{\rm in} \Rightarrow \frac{\Omega_j h^2}{0.12} = 2.85 \times 10^6 \, \frac{\xi \, g_j}{q^2} \left(2^k(3+2k)\right)^{1/2} \left(\frac{M_P}{q\, M_{\rm in}}\right)^{\frac{2k+1}{2}} \frac{m_j}{\rm GeV}$$

$$m_j > T_{\rm BH}^{\rm in} \Rightarrow \frac{\Omega_j h^2}{0.12} = 1.64 \times 10^{43} \, \xi \, g_j \left(2^k(3+2k)\right)^{1/2} \left(\frac{M_P}{q\, M_{\rm in}}\right)^{\frac{2k+5}{2}} \frac{\rm GeV}{m_j}$$

The value of the dark matter mass is plotted here as a function of the formation mass of PBHs for the case where the evaporation happens during PBH domination.

M. R. Haque, S. Maity, D. Maity, and Y. Mambrini, JCAP 07 (2024) 002.

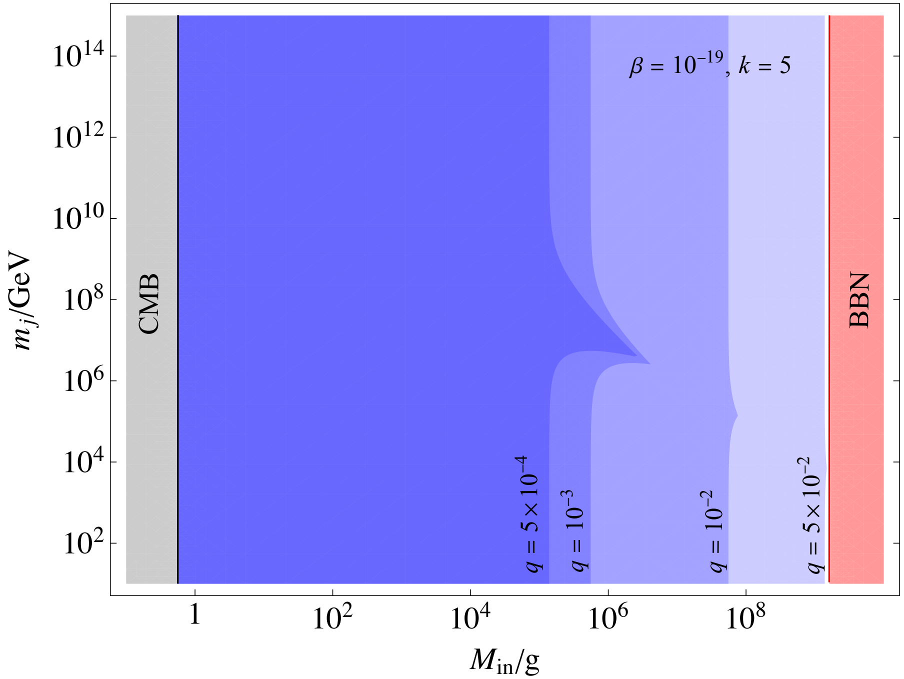
DM from the evaporating as well as stable PBHs for ultralight PBHs

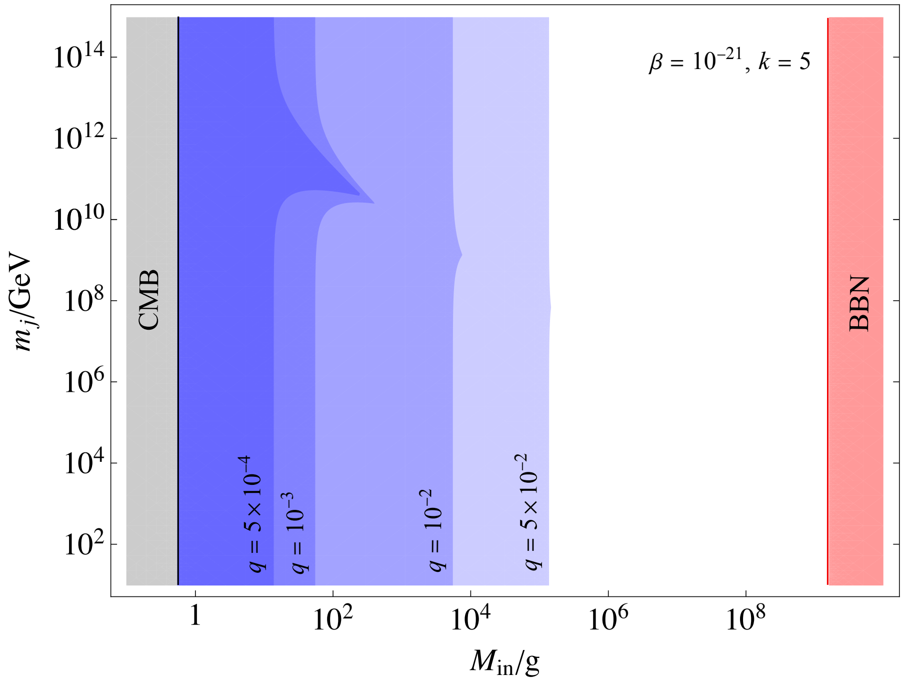


❖ The critical values of β corresponding to the total dark matter density are plotted in brown as a function of PBH mass when the dark matter is emitted from the evaporation of PBHs before BBN. The black dashed lines correspond to the critical β when the stable PBHs contribute to the total dark matter energy density.

M. R. Haque, S. Maity, D. Maity, and Y. Mambrini, JCAP 07 (2024) 002.

Dark matter from the stable PBHs with Hawking evaporation (phase-I) before BBN





$$\frac{\Omega_{\rm DM}\, h^2}{0.12} = 3.5\times10^{27}\,\beta\left(\frac{M_P}{M_{\rm in}}\right)^{1/2}\left[q + N_j\frac{m_j}{M_{\rm in}}\right]$$

$$N_j = \frac{15\,\xi\, g_j \zeta(3)}{g_*(T_{\rm BH})\,\pi^4}\begin{cases}(1-q^2)\frac{M_{\rm in}^2}{M_P^2}, & \text{for } m_j < T_{\rm BH}^{\rm in}\\ \frac{M_P^2}{m_j^2} - \frac{q^2 M_{\rm in}^2}{M_P^2}, & \text{for } \frac{T_{\rm BH}^{\rm in}}{q} > m_j > T_{\rm BH}^{\rm in}\end{cases}$$

Dark matter mass as a function of the PBH mass taking into account the contribution from both the evaporation product and the stable PBHs.

M. R. Haque, S. Maity, D. Maity, and Y. Mambrini, JCAP 07 (2024) 002.

Conclusions

- PBHs *does not have* to dominate over the inflaton density to affect the reheating. Even if they remain subdominant, the continuous entropy injection through their decay can notably change the reheating process, especially for low inflaton couplings to the particles in the plasma. If PBHs dominate the background dynamics ($\beta > \beta_c$), the reheating process becomes insensitive to the inflaton and the PBH fraction β. Therefore, it is the PBH mass M_{in} that solely controls the DM abundance as well as the reheating temperature $T_{\rm RH}$.

- We discuss in detail the reheating and DM parameter space in the background of the reheating phase dynamically obtained from two chief systems in the early Universe: the inflaton ϕ and the primordial black holes. The DM is assumed to be produced purely gravitationally from the PBH decay, not interacting with the thermal bath and the inflaton.

- The observations by the PTAs and their possible implications for the stochastic GW background offer a wonderful opportunity to understand the physics operating over a wider range of scales in the early universe.

- We compute the relic abundance of dark matter in the presence of Primordial Black Holes (PBHs) beyond the semiclassical approximation, which is assumed to suppress the black hole evaporation rate by the inverse power of its own entropy. We, include the possibility of populating the dark sector by the decay of PBHs to those fundamental particles, adding the contribution to stable PBH whose lifetime is extended due to the quantum corrections.

Thank You