Primordial Black Hole versus Inflaton: Two Chief Systems of the World

(Based on JHEP 09 (2023) 012, and arXiv:2305.10518, in collaboration with Dr.Debaprasad Maity, Prof. Yann Mambrini, Dr. Essodjolo Kpatcha)

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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: Inflaton reheating
  - Discuss the background dynamics of reheating with PBHs
  - Possibilities of PBH reheating
  - Comparison between monochromatic and the extended mass function
  - Particle production from a single BH
  - DM matter production from PBH evaporation
- Conclusion

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

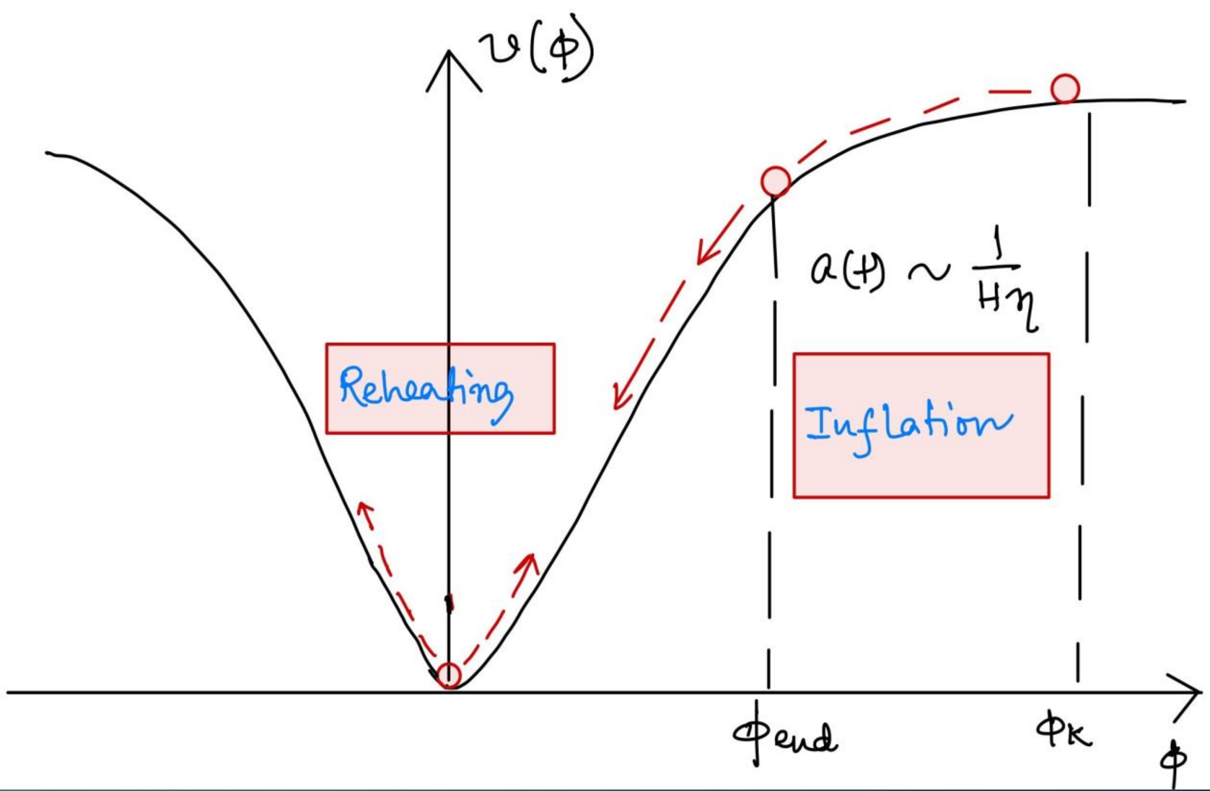
Why do we need reheating phase?

- ❑ The end point of inflation

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

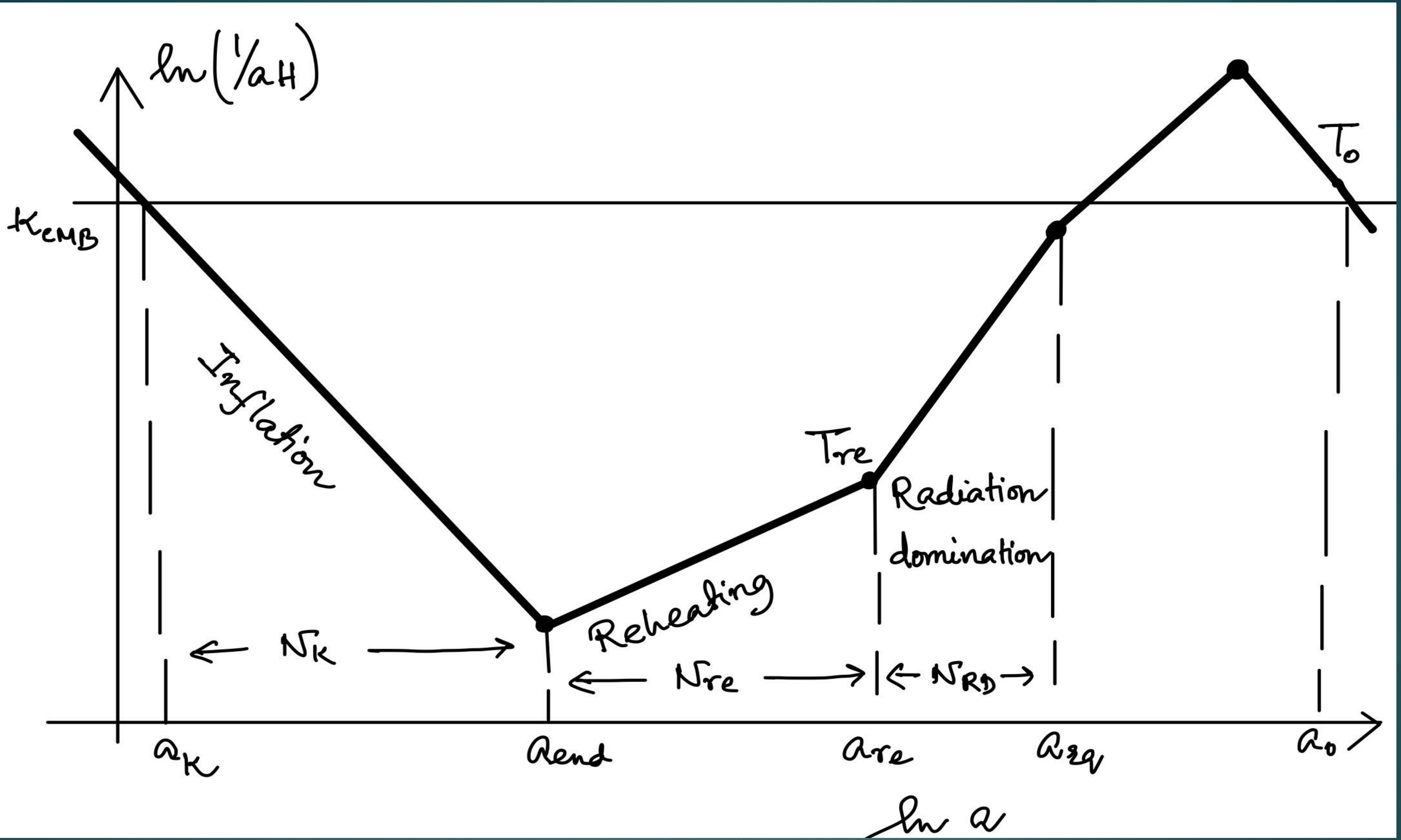
- ❑ How does the Universe transition to a the hot, thermalized, radiation-dominated state after inflation, which is required for nucleosynthesis.

- ❑ Reheating!



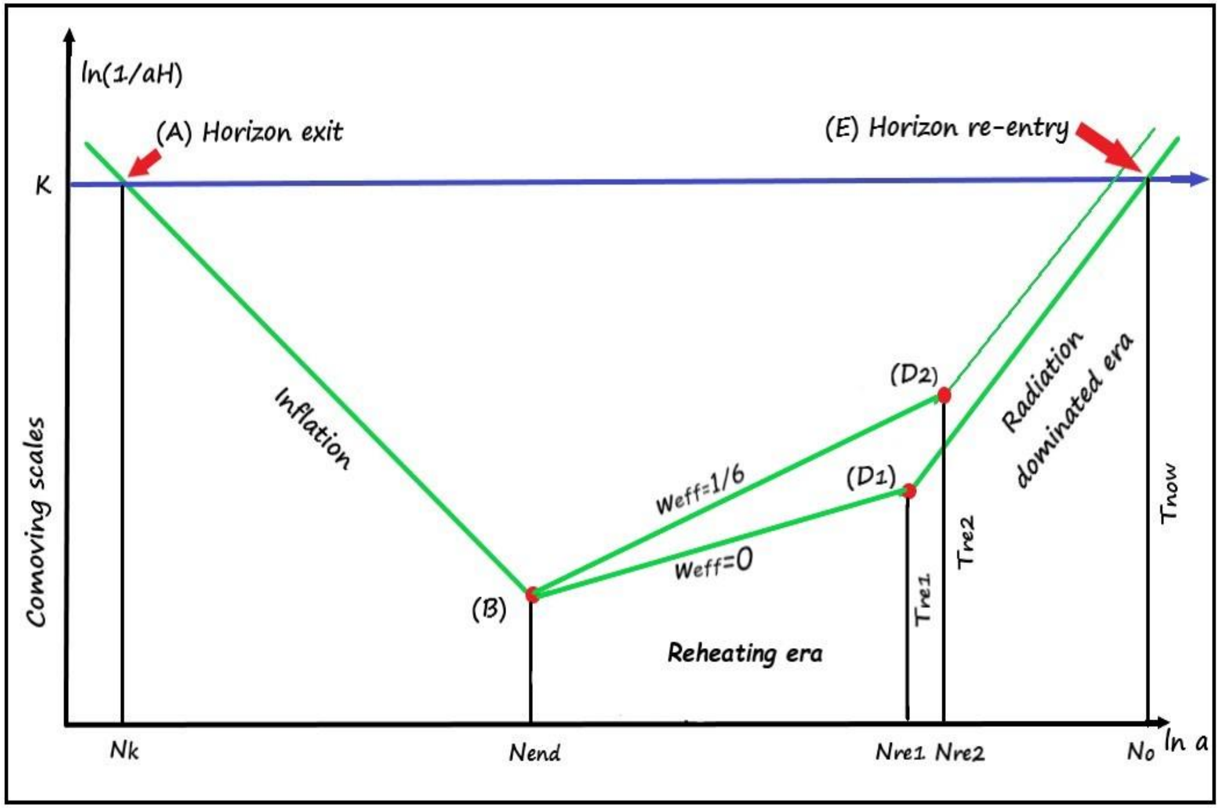
- ❑ Natural consequence after inflation: fill the empty space with matter (**generate entropy)**

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.

Reheating phase with different inflaton equation of state



- Try to understand the connection between the inflationary and reheating parameters

$$(\mathbf{n_s}, \mathbf{r}, \mathbf{N_{re}}, \mathbf{T_{re}}, \mathbf{w_{eff}})$$

- Two important parameters: duration and temperature

$$N_{re} = \frac{4}{(1-3\omega_{eff})}\left[-\frac{1}{4}ln\left(\frac{45}{\pi^2 g_{re}}\right) - \frac{1}{3}ln\left(\frac{11 g_{s,re}}{43}\right) - ln\left(\frac{k'}{a_0 T_0}\right) - ln\left(\frac{V_{end}^{1/4}}{H_k}\right) - N_k\right]$$

$$T_{re} = \left(\frac{43}{11 g_{s,re}}\right)^{\frac{1}{3}}\left(\frac{a_0 T_0}{k'}\right) H_k e^{-N_k} e^{-N_{re}}$$

L. Dai, M. Kamionkowski, and J. Wang Phys. Rev. Lett. **113**, 041302

Reheating: Possible interaction between inflaton and radiation (s/f)

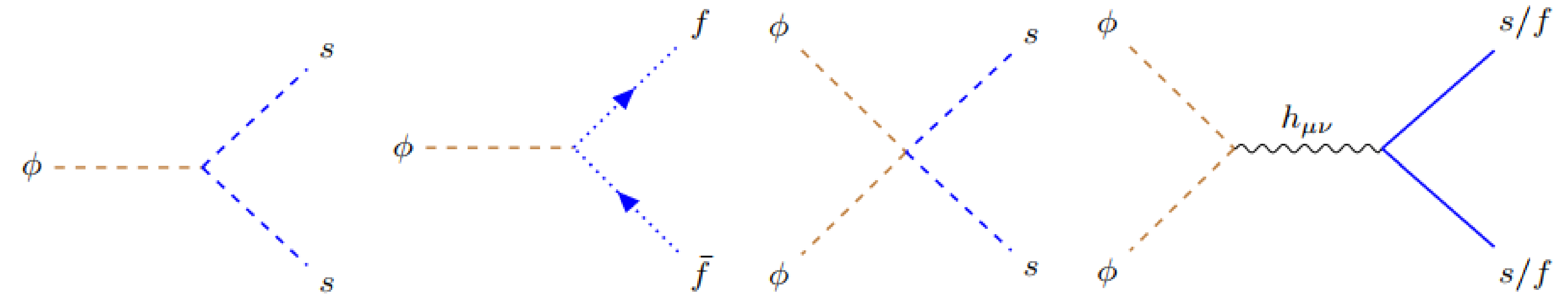


Figure: Fynmann diagram for all possible interactions between inflaton (Φ) and radiation (R)

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

$$
\Gamma^{gr}_{\phi\phi\to ss} = \frac{\rho_\phi m_\phi}{1024\pi M_p^4}(1+2f_B(m_\phi/T))\,,
$$

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

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]

Perturbative Reheating set up

- The effective equation of state is time-dependent $w_{\rm eff} = \frac{3\, w_\phi\, \rho_\phi + \rho_R}{3\, (\rho_\phi + \rho_R)}$
- Standard Boltzmann equation for two components: Infaton + Radiation

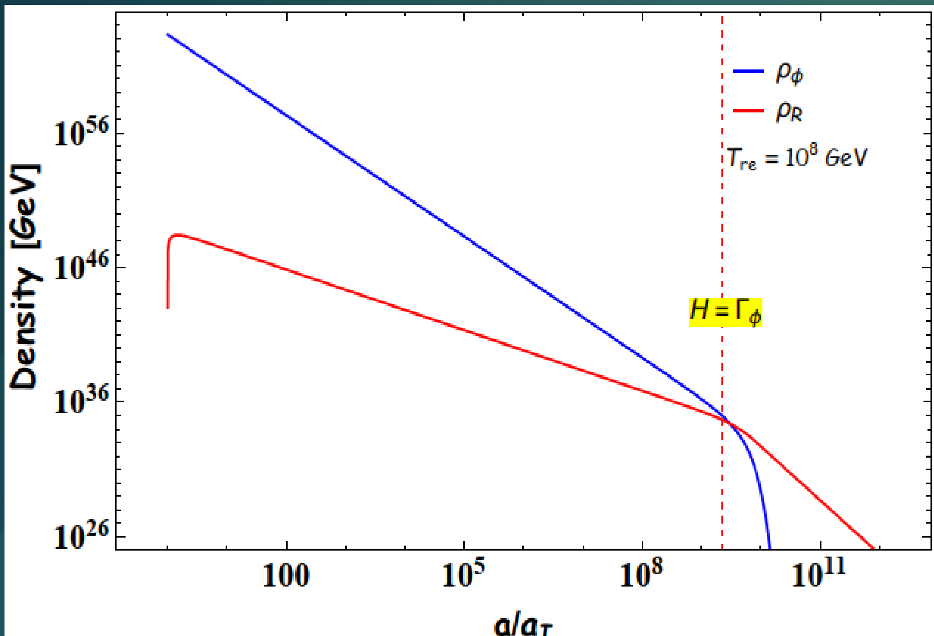
$$\dot{\rho}_\phi + 3\, H\ (1+\omega_\phi)\ \rho_\phi + \Gamma_\phi\, \rho_\phi\, (1+\omega_\phi) = 0$$

$$\dot{\rho}_r + 4\, H\, \rho_r - \Gamma_\phi\, \rho_\phi\, (1+\omega_\phi) = 0$$

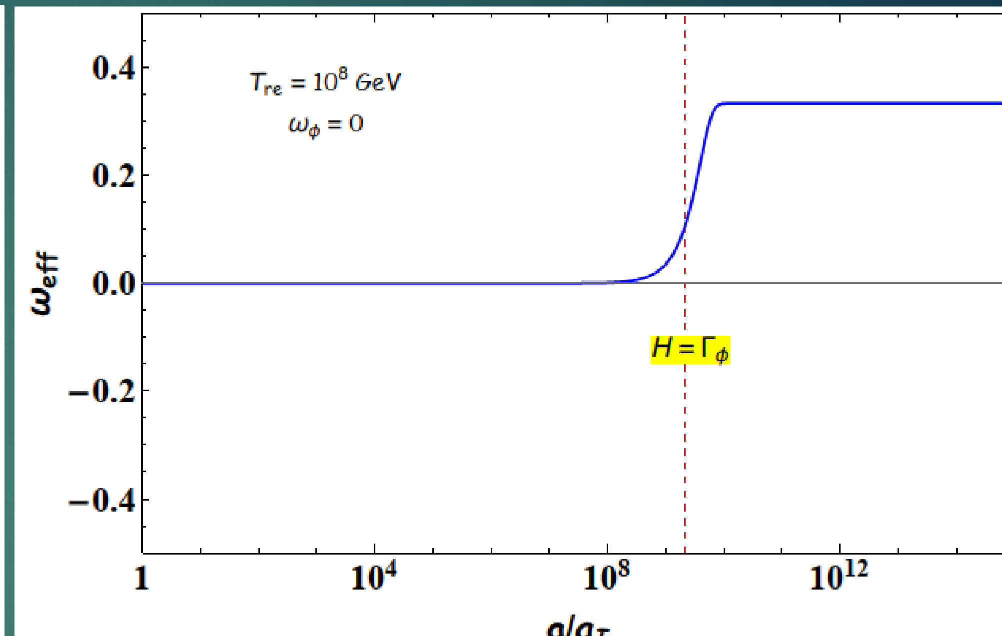
- Initial conditions: $\rho_\phi(A=1) = \frac{3}{2} V_{end}(\phi) \ ; \ \rho_R(A=1) = 0$
- Reheating temperature is identified at the point of $H(t_{re}) = \Gamma_\phi$
- Reheating temperature : $T_{re} = T_{rad}^{end} = \left(\frac{30}{\pi^2 g_*(T)}\right)^{1/4} \rho_R(\Gamma_\phi, A_{re}, n_s^k)^{1/4}$
- From entropy conservation : $T_{re} = \left(\frac{43}{11 g_{s,re}}\right)^{\frac{1}{3}} \left(\frac{a_0 T_0}{k'}\right) H_k e^{-N_k} e^{-N_{re}}$
- Connecting the above equations, one can estimate reheating parameters for a given initial condition.

D. Maity and P. Saha Phys. Rev. D **98**, 103525
Md R. Haque, D. Maity, and P. Saha Phys. Rev. D **102**, 083534

Perturbative Reheating: evolution of density components and EoS parameter



Evolution of the individual density component



Behavior of effective equation of state parameter with normalized scale factor

Averaging over one oscillation $\omega_\phi = \frac{P_\phi}{\rho_\phi} = \frac{\langle \phi V'(\phi) \rangle - \langle 2V \rangle}{\langle \phi V'(\phi) \rangle + \langle 2V \rangle} = \frac{n-1}{n+1}$, assuming $V(\phi) \sim \phi^{2n}$.

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.

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 $\epsilon(M_{\rm BH})$: $\epsilon(M_{\rm BH}) = \sum g_j\, \epsilon_j(z_j)$

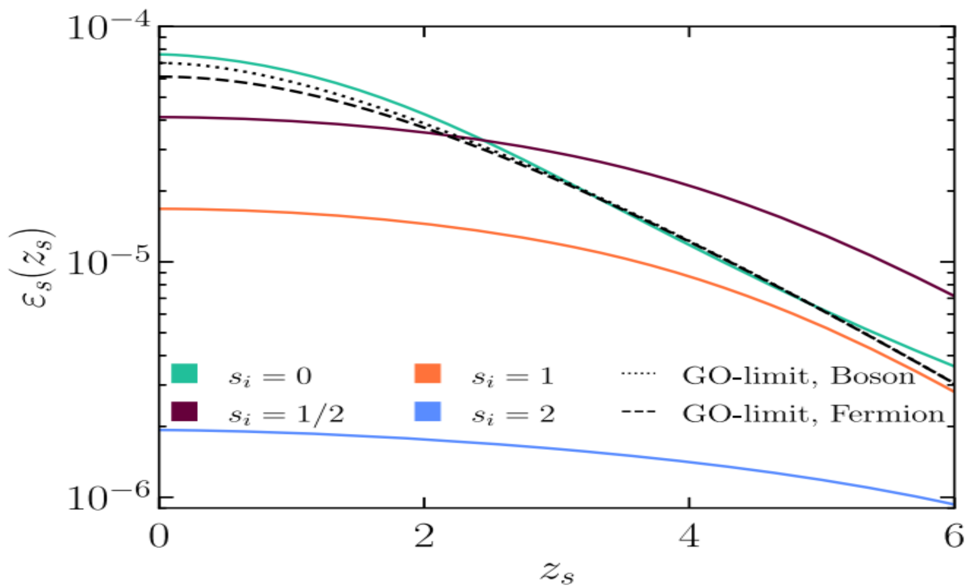
$$E_j = \sqrt{m_j^2 + p^2} \qquad z_j = m_j / T_{\rm BH}$$

- Evaporation function for massless particles in the *geometrical-optics* limit

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

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)

PBH evolution

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 :

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

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

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

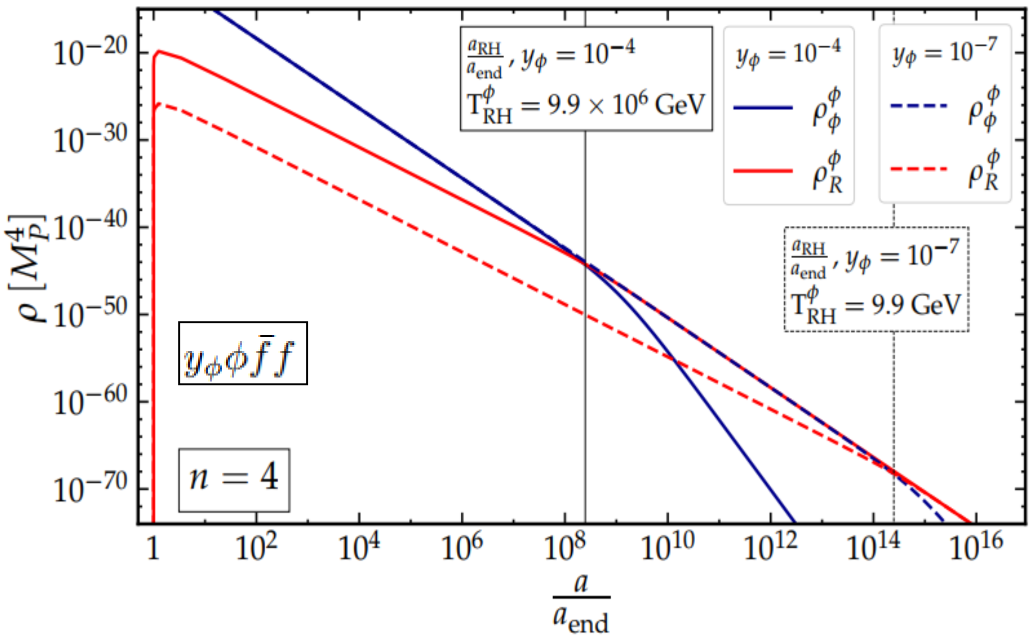
- Friedmann equation: $\rho_\phi + \rho_R + \rho_{\rm BH} = 3H^2 M_P^2$

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

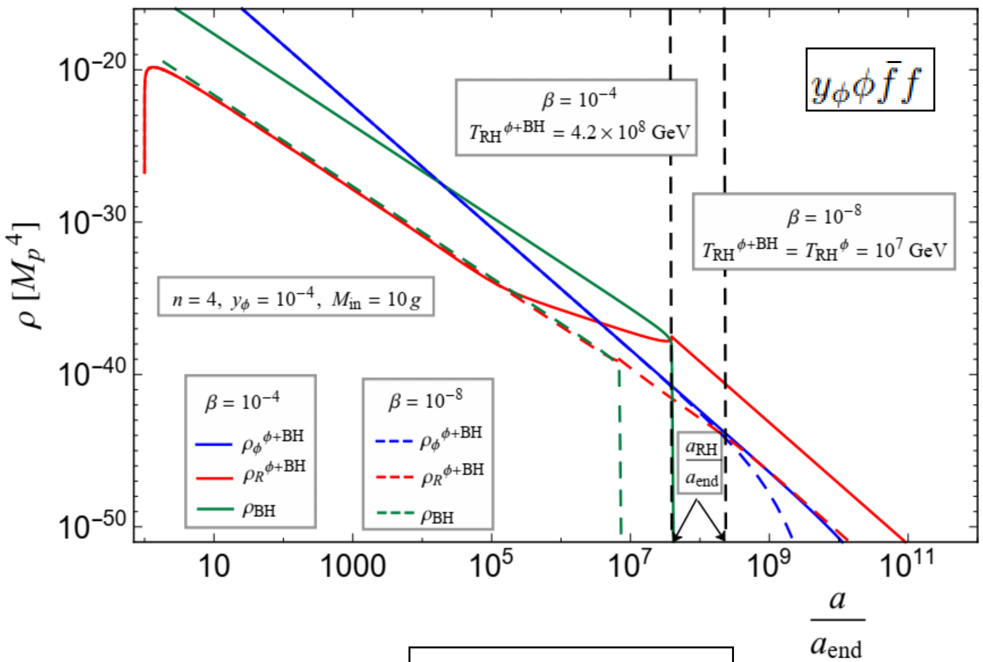
- Lifetime of the BH : $t_{\rm ev} = \frac{1}{\Gamma_{\rm BH}}$ $\quad \Gamma_{\rm BH} = 3\epsilon \frac{M_P^4}{M_{\rm in}^3}$

M. Riajul Haque, E. Kpatcha, D. Maity and Y. Mambrini, [arXiv:2305.10518 [hep-ph]]

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. Riajul Haque, E. Kpatcha, D. Maity and Y. Mambrini, [arXiv:2305.10518 [hep-ph]]

PBH reheating (PBH domination)

- Condition for the PBH domination :

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

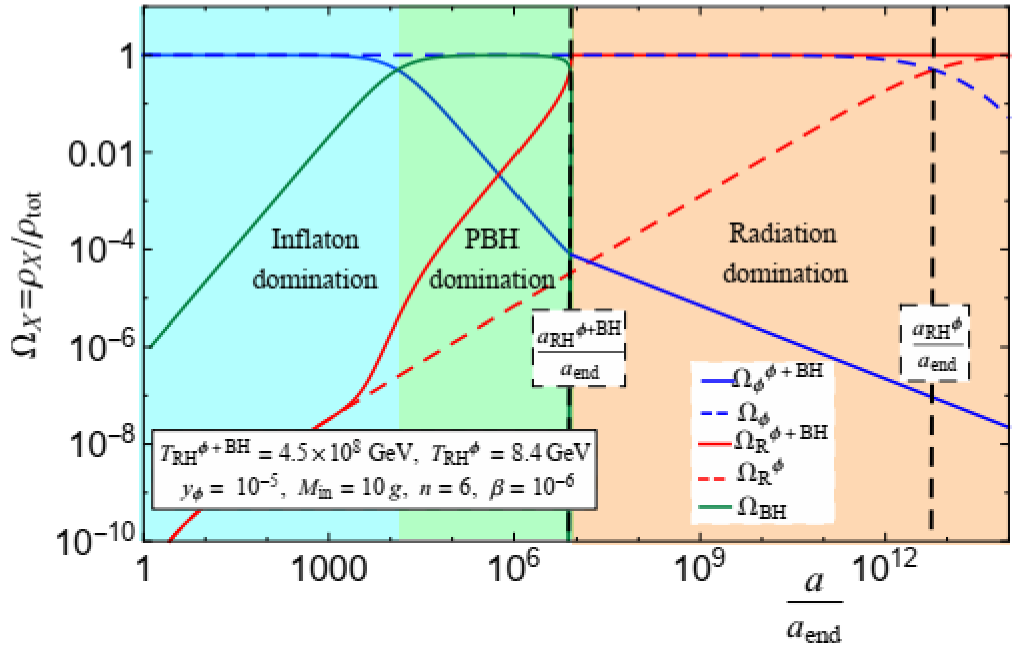
- PBH dominates reheating process

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

- 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. Riajul Haque, E. Kpatcha, D. Maity and Y. Mambrini, [arXiv:2305.10518 [hep-ph]]

PBH reheating (without PBH domination)

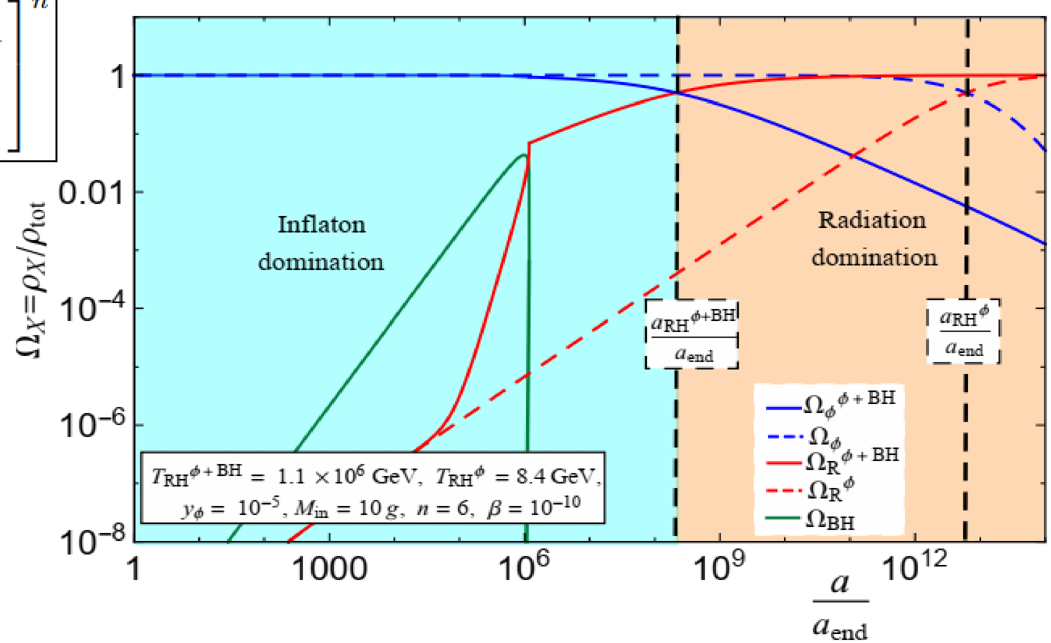
- Condition for the PBH reheating :

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

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

- 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. Riajul Haque, E. Kpatcha, D. Maity and Y. Mambrini, [arXiv:2305.10518 [hep-ph]]

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

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

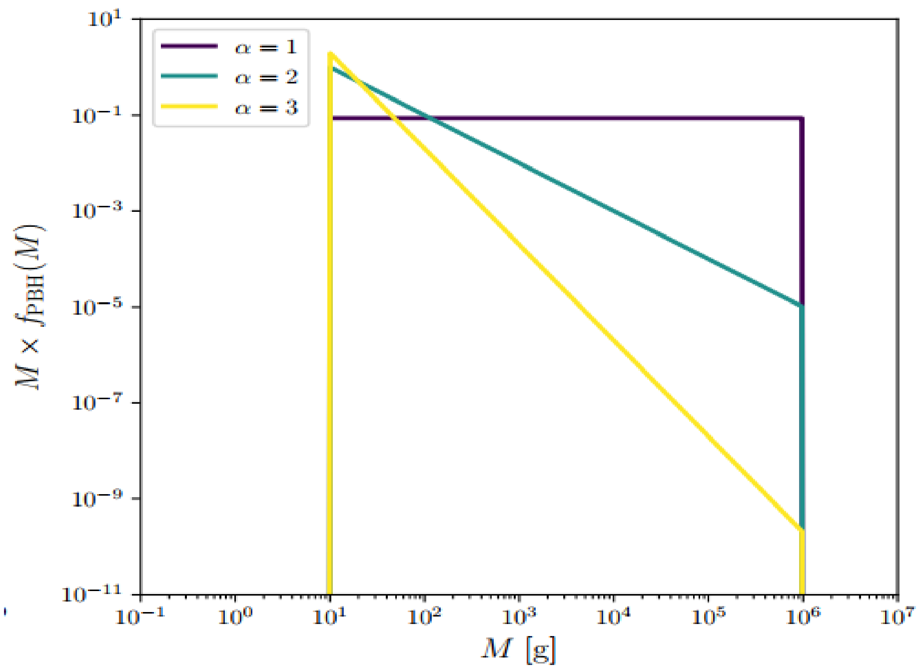
- Friedmann Boltzmann equation for different energy components:

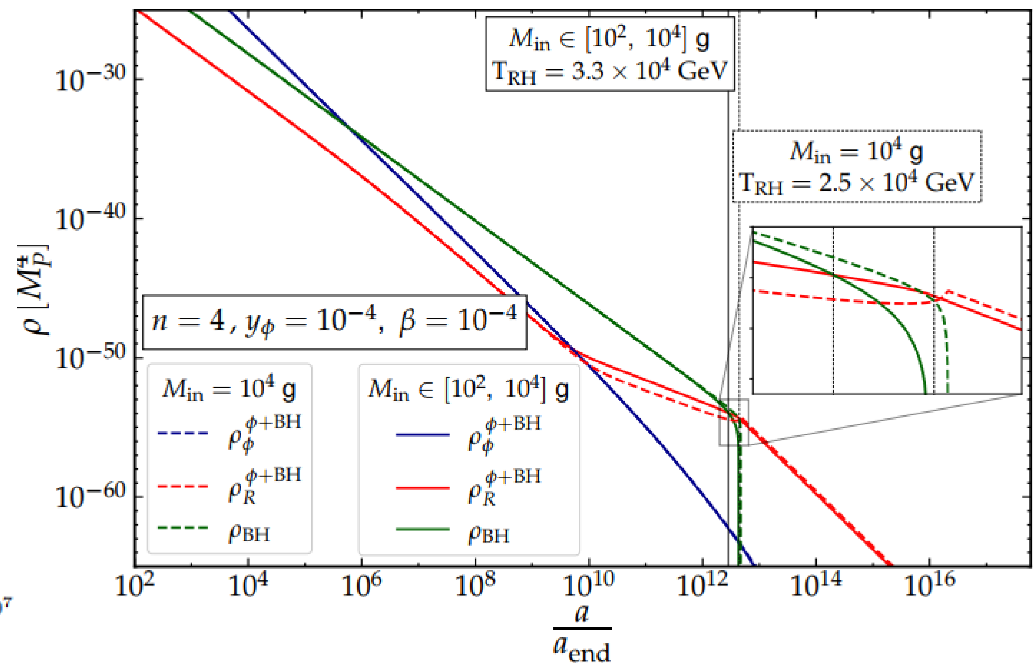
$$\dot\rho_{\rm BH} + 3H\rho_{\rm BH} = \frac{a_{\rm in}^3}{a^3}\int_{\widetilde M}^\infty \frac{dM}{dt} f_{\rm PBH}(M_i,t_i)dM_i$$
$$\dot\rho_R + 4H\rho_R = \Gamma_\phi\rho_\phi(1+w_\phi) - \frac{a_{\rm in}^3}{a^3}\int_{\widetilde M}^\infty \frac{dM}{dt} f_{\rm PBH}(M_i,t_i)dM_i$$

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 : $f_{\rm PBH}(M_i, t_i) = \begin{cases} C M_i^{-\alpha}, & \text{for } M_{\min} \le M_i \le M_{\max} \\ 0, & \text{otherwise}\,. \end{cases}$ $\quad \alpha = \dfrac{2+4w}{1+w}$



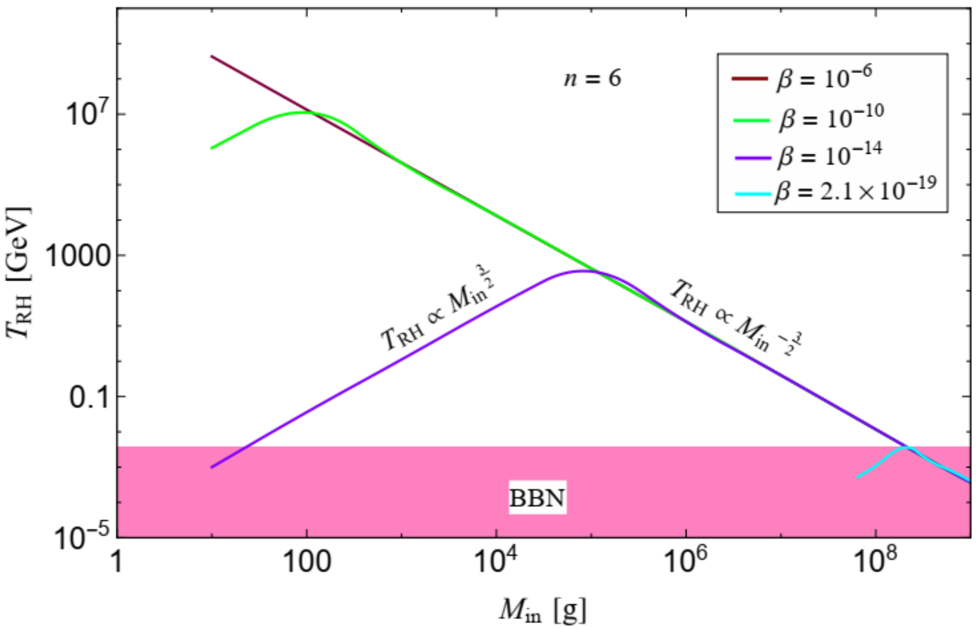


Power law mass distribution as a function of PBH mass

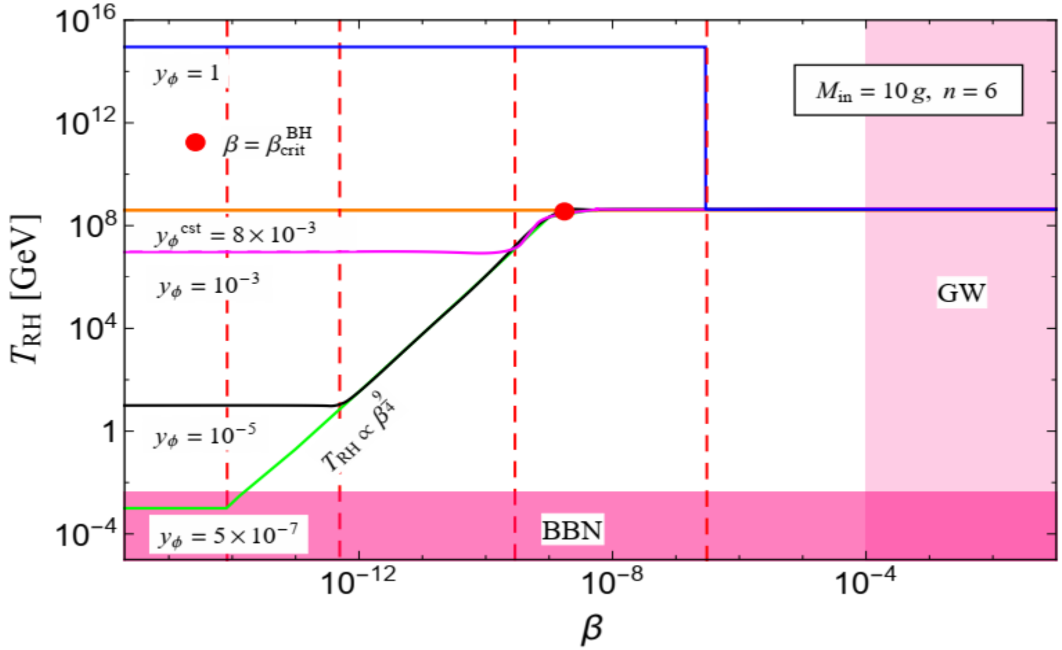
Evolution of the energy densities as a function of scale factor

B. J. Carr, Astrophys. J. **201**, 1 (1975)
A. Cheek, L. Heurtier, Y. F. Perez-Gonzalez, and J. Turner, (2022), arXiv:2212.03878 [hep-ph]

Inflaton reheating Vs PBH reheating



Reheating temperature as a function of initial BH mass



Evolution of the reheating temperature as function of β

M. Riajul Haque, E. Kpatcha, D. Maity and Y. Mambrini, [arXiv:2305.10518 [hep-ph]]

Particle production from a single BH

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

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

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

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

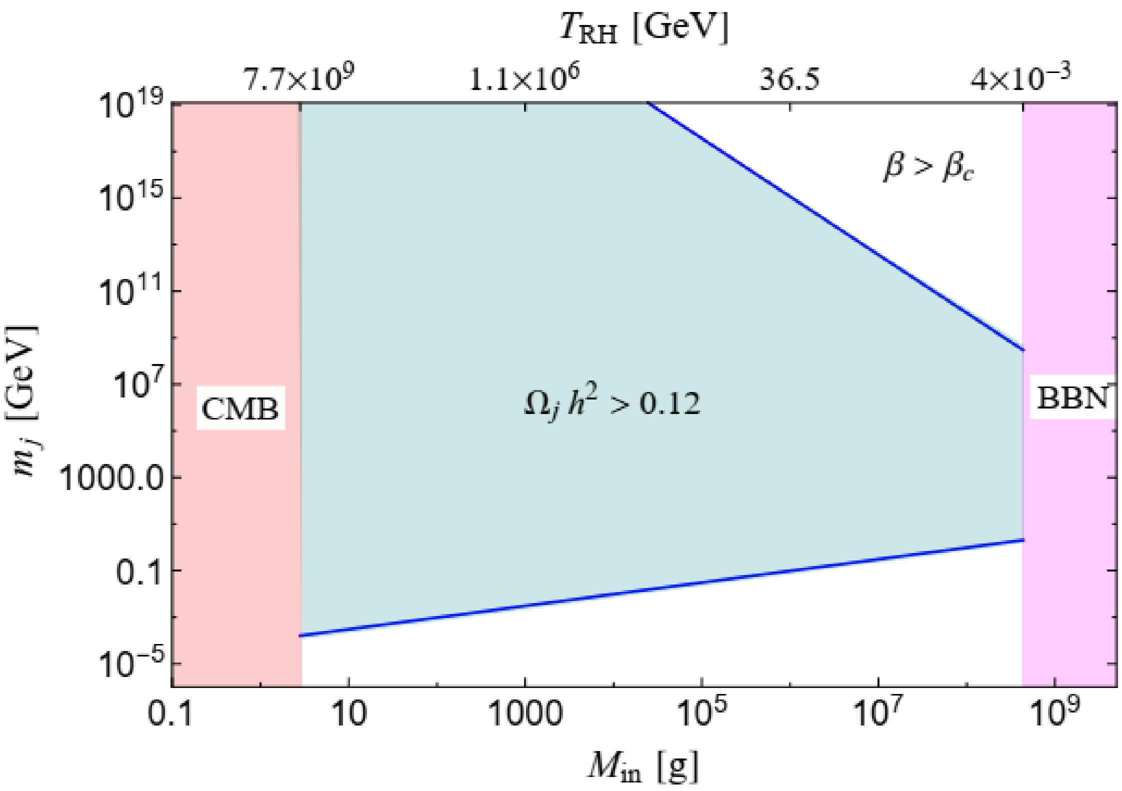
- For mass $m_j > T_{\rm BH}^{\rm in}$: $$N_j^{m_j>T_{\rm BH}^{\rm in}} = \int_{t_j}^{t_{\rm ev}} \frac{dN_j}{dt} = \frac{15 g_i \zeta(3)}{g_* \pi^4}\frac{M_P^2}{m_j^2} \simeq 10^{14}\left(\frac{10^{10}\rm GeV}{m_j}\right)^2$$

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

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

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

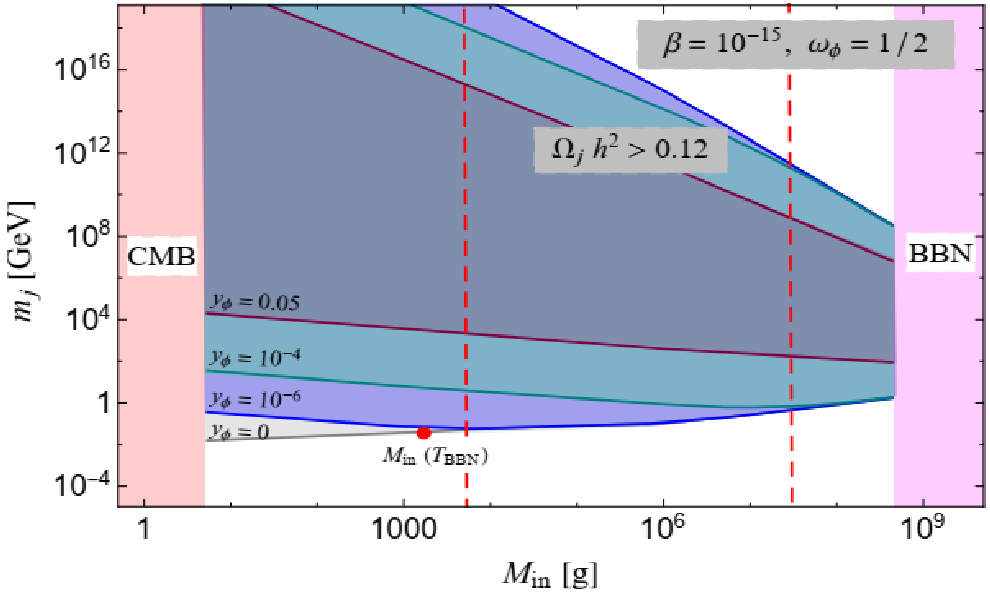
DM parameter space: PBH reheating (PBH domination)



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

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

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

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

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

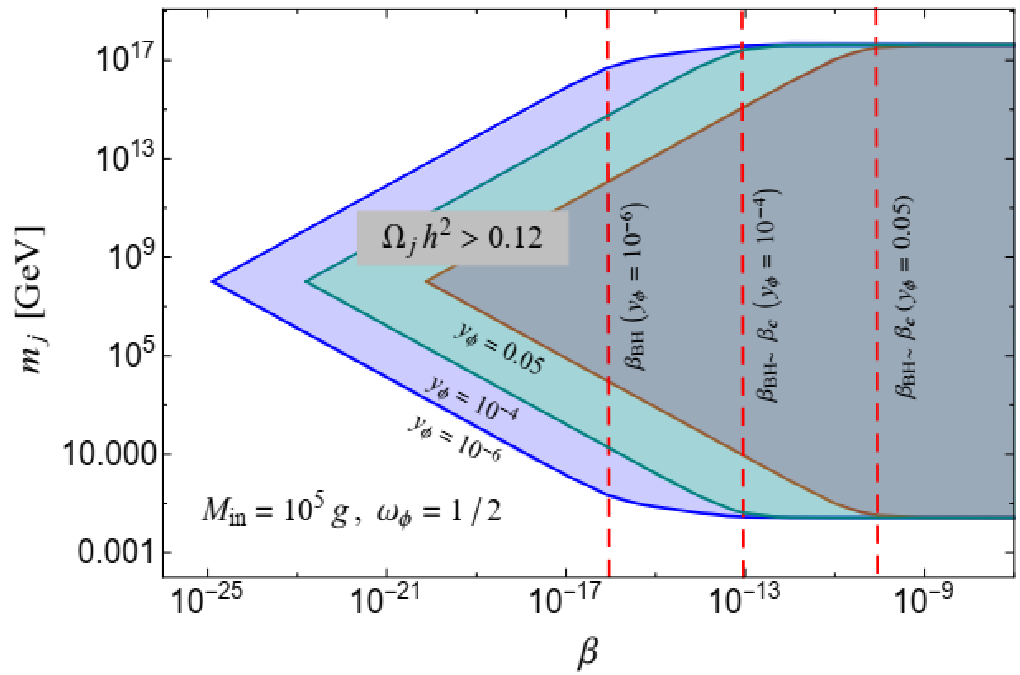
$$\frac{\Omega_j h^2}{0.12} = 2.8\times 10^{8}\ \mu_j \beta^{\frac14} \frac{g_0 g_j}{g_{\rm RH}^{\frac14}\, g_*(T_{\rm BH})} \left(\frac{M_P}{M_{\rm in}}\right)^{\frac{1-w_\phi}{2+2w_\phi}} \frac{m_j}{\rm GeV} \quad \text{(PBH reheating)}$$

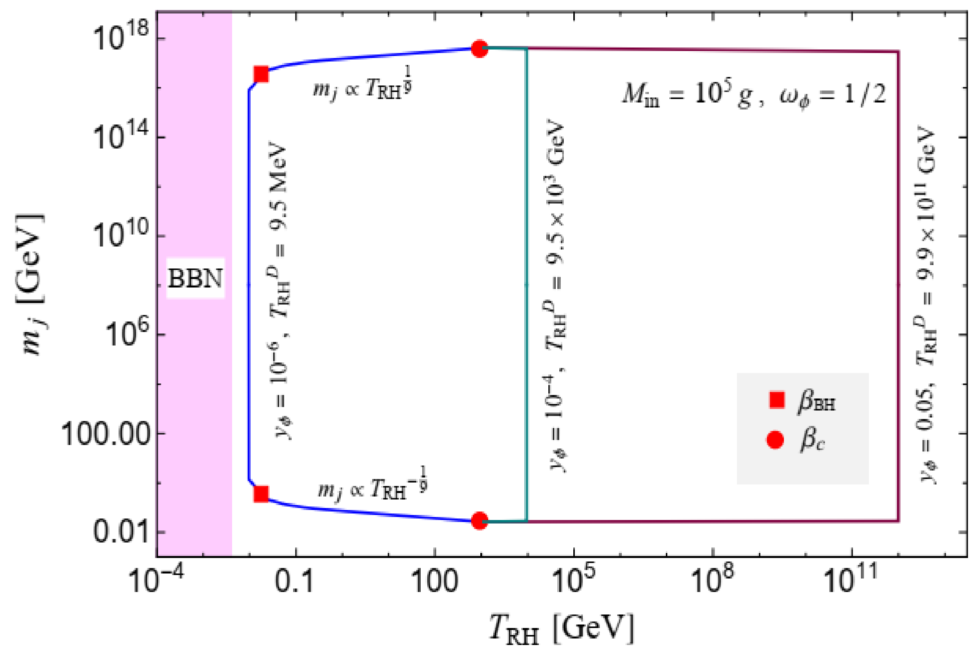
$m_j > T_{\rm BH}^{\rm in}$

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

$$\frac{\Omega_j h^2}{0.12} = 1.7\times 10^{45} \mu_j \beta^{\frac14} \frac{g_0 g_j}{g_{\rm RH}^{\frac14} g_*(T_{\rm BH})} \left(\frac{M_P}{M_{\rm in}}\right)^{\frac{5+3w_\phi}{2+2w_\phi}} \frac{\rm GeV}{m_j} \quad \text{(PBH reheating)}$$

DM parameter space: PBH reheating Vs Inflaton reheating





$$m_j < T_{BH}^{in} \Rightarrow m_j \propto T_{RH}^{\frac{1-3w_\phi}{3(1+w_\phi)}} \Rightarrow w_\phi = \frac{1}{2},\ m_j \propto T_{RH}^{-\frac{1}{9}}$$

$$m_j > T_{BH}^{in} \Rightarrow m_j \propto T_{RH}^{\frac{3w_\phi-1}{3(1+w_\phi)}} \Rightarrow w_\phi = \frac{1}{2},\ m_j \propto T_{RH}^{\frac{1}{9}}$$

Conclusion

- We have started our discussion with a brief description of the standard inflaton reheating.

- 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.

- 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_{RH}.

- 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.

Thank You