Primordial Black Hole Reheating in Post-inflationary Universe

Donald E. KPATCHA (IJCLab & UAM-CSIC)

IHP, Paris Workshop on PBHs & GWs

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in collaboration with: Y. Mambrini, D. Maity and M. R, Haque

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Outline

1. Introduction
2. Primordial Black Holes Reheating
3. Implications for Dark Matter
4. Conclusions

Introduction

- PBHs are theoretical black holes that could have formed in the early universe, for e.g. from the gravitational collapse of overdense regions
- No evidence for PBHs, but their existence could be interesting, e.g. insights into the conditions of the early universe and the processes that led to their formation, for reheating phase, and for explaining DM
- Reheating is a phase, thought to have occurred after cosmic inflation and just before the hot Big Bang phase $\rightarrow$ leading to the creation of particles and radiation

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- **Two well studied reheating scenarios:**

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- **What if the hybrid scenario drives the reheating ?**

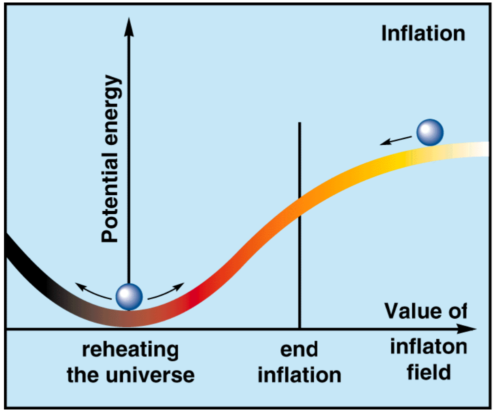
- **In this talk, i discuss the details of reheating dynamics in the presence of PBH**
  - **the implications for the reheating temperature**
  - **comment on the parameter space that could be compatible with dark matter relic abundance**

- **Two well studied reheating scenarios:**

► **Inflaton ϕ**

reheating

[JGB, astro-ph/9906497]



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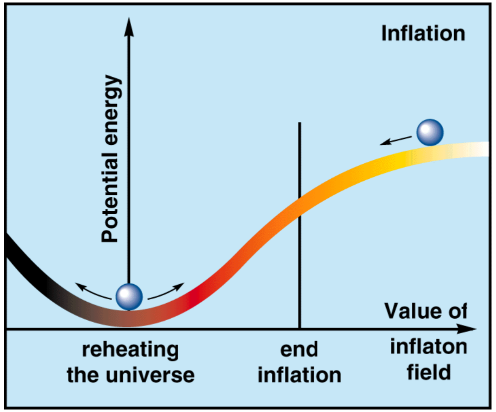

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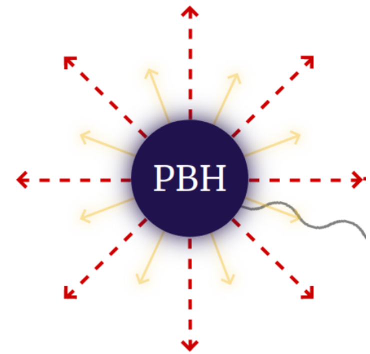

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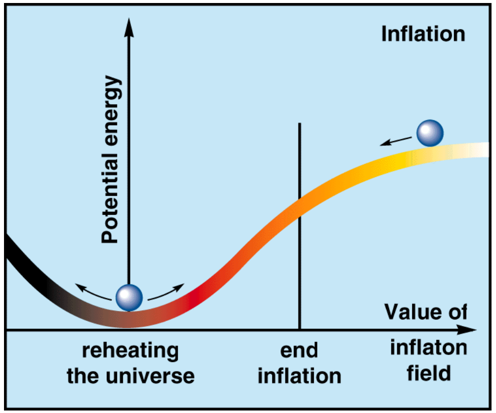

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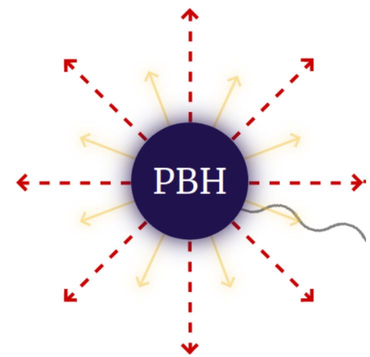

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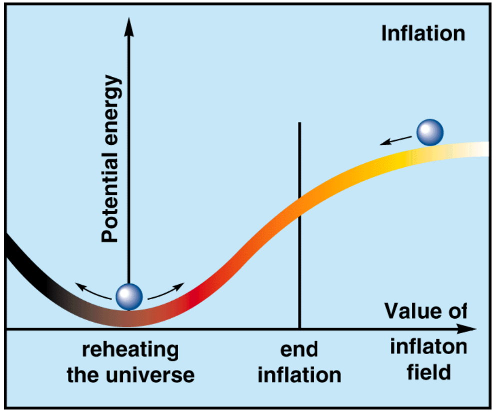

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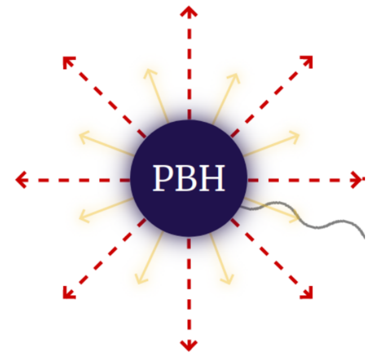

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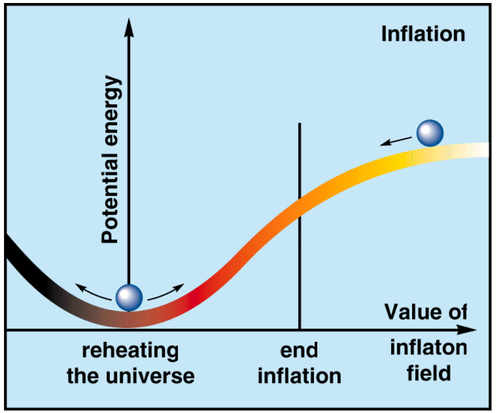

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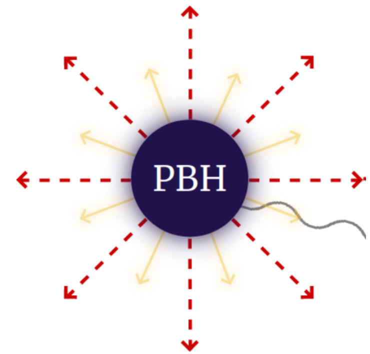

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Reheating with inflaton ϕ + PBH

- Inflaton ϕ decays via $y_\phi \bar{f} f \phi$, the potential $V(\phi) = \lambda M_P^4 \left(\frac{\phi}{M_P}\right)^n$, and equation of state $\omega_\phi = \frac{n-2}{n+2}$
- Evaporating monochromatic Schawrzchild PBH with:
  - initial mass $M_{\rm in} = \omega_\phi^{3/2} 4\pi \frac{M_P^2}{H_{\rm in}}$. We consider $1\,{\rm g} \lesssim M_{\rm in} \lesssim 10^9\,{\rm g}$
  - initial energy density fraction $\rho_{\rm BH}^{\rm in} = \beta\, \rho_{\rm tot}^{\rm in}$. We impose GWs constraints on β
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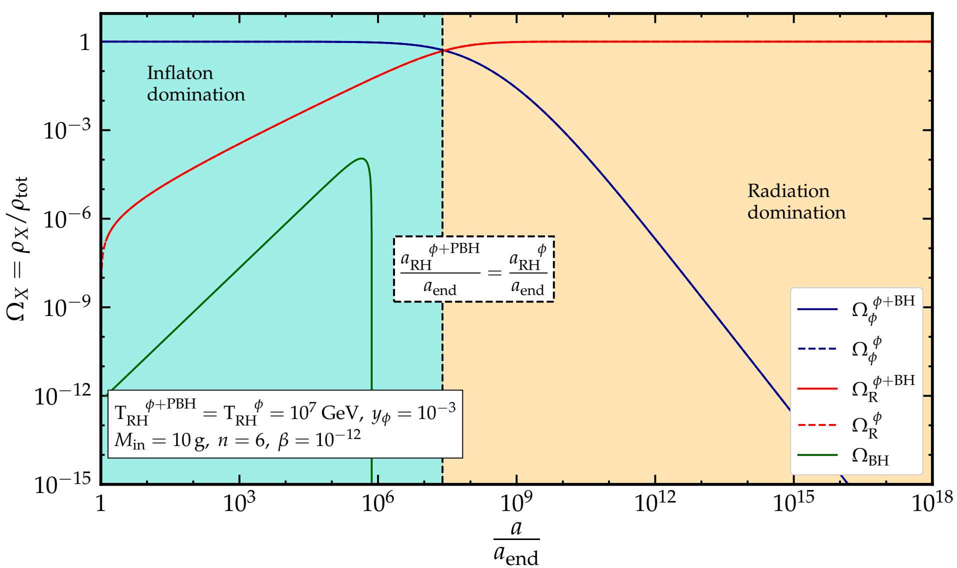

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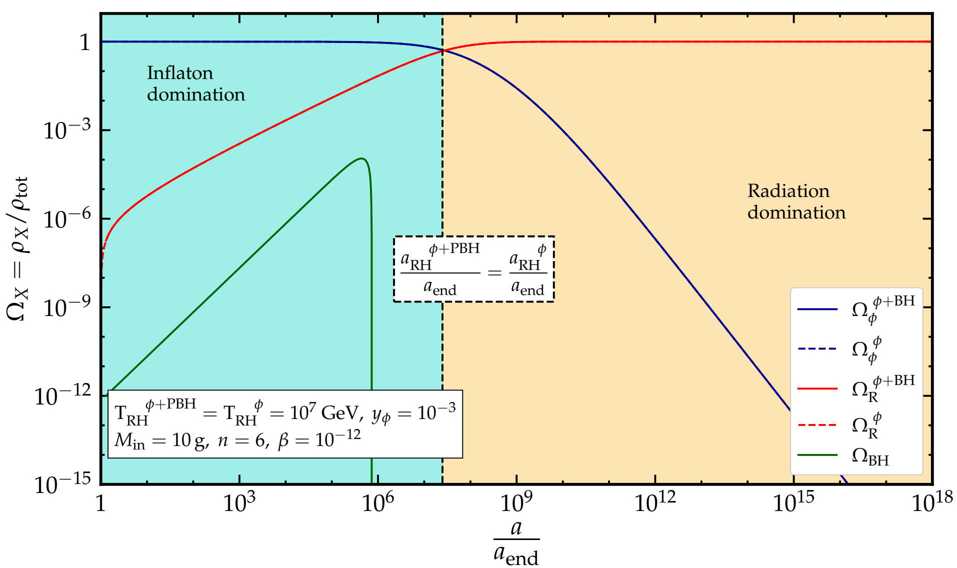

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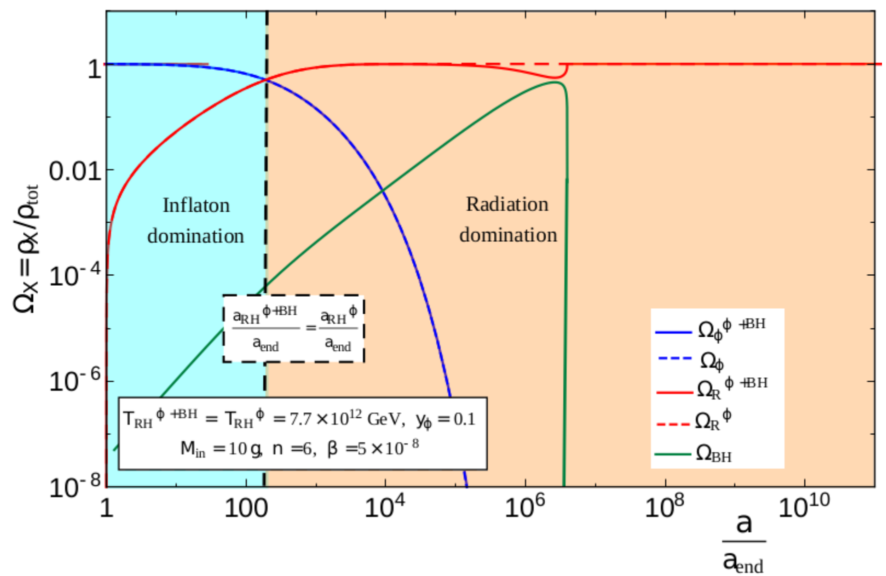
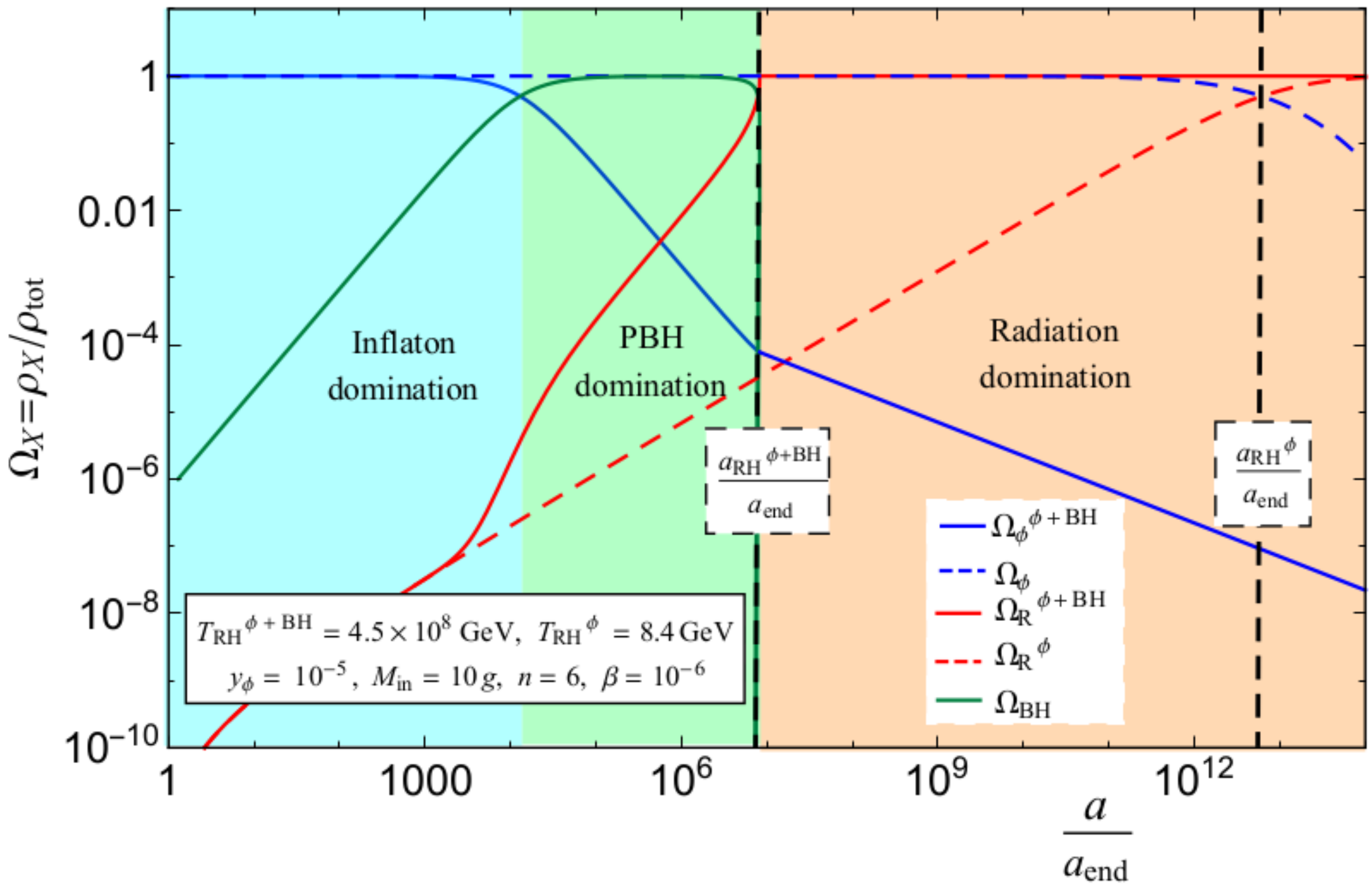
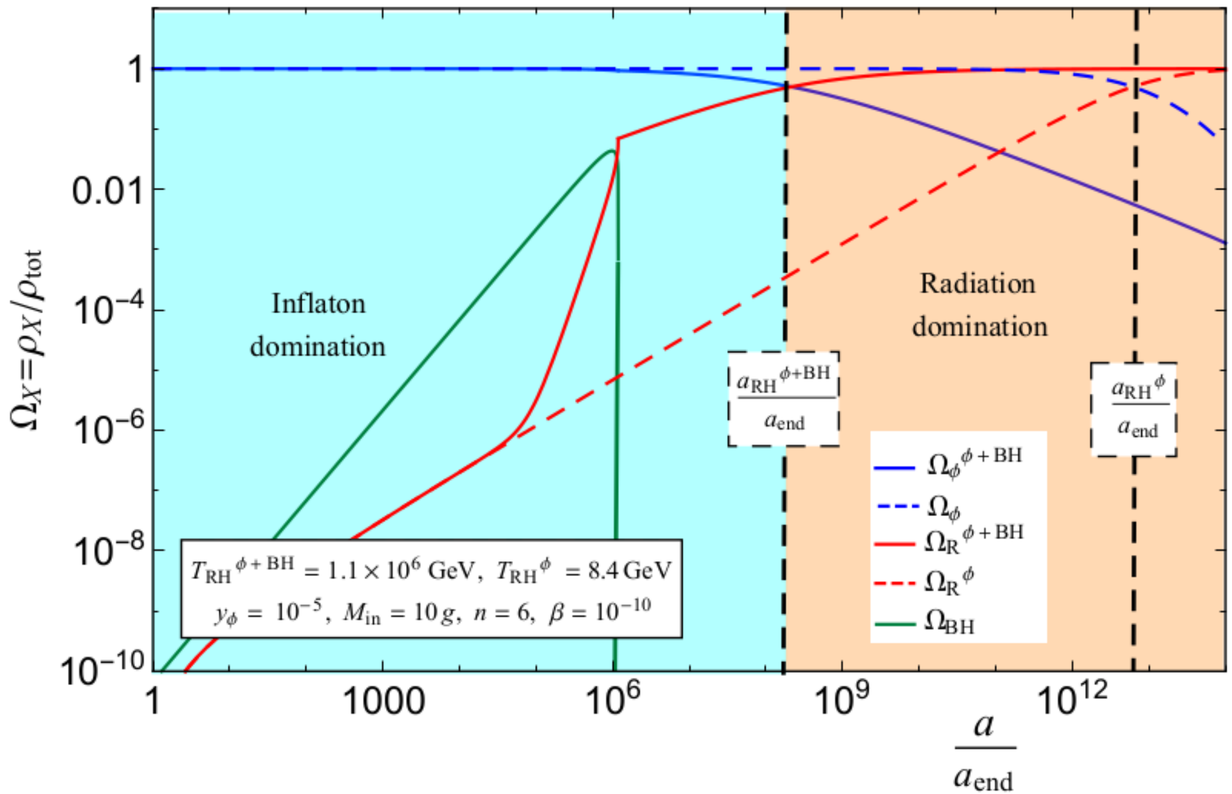


PBH evaporation completes AFTER reheating

▶ **Reheating with PBH domination**



- **Even if PBH do not dominate, the evaporation can dominate the reheating process**



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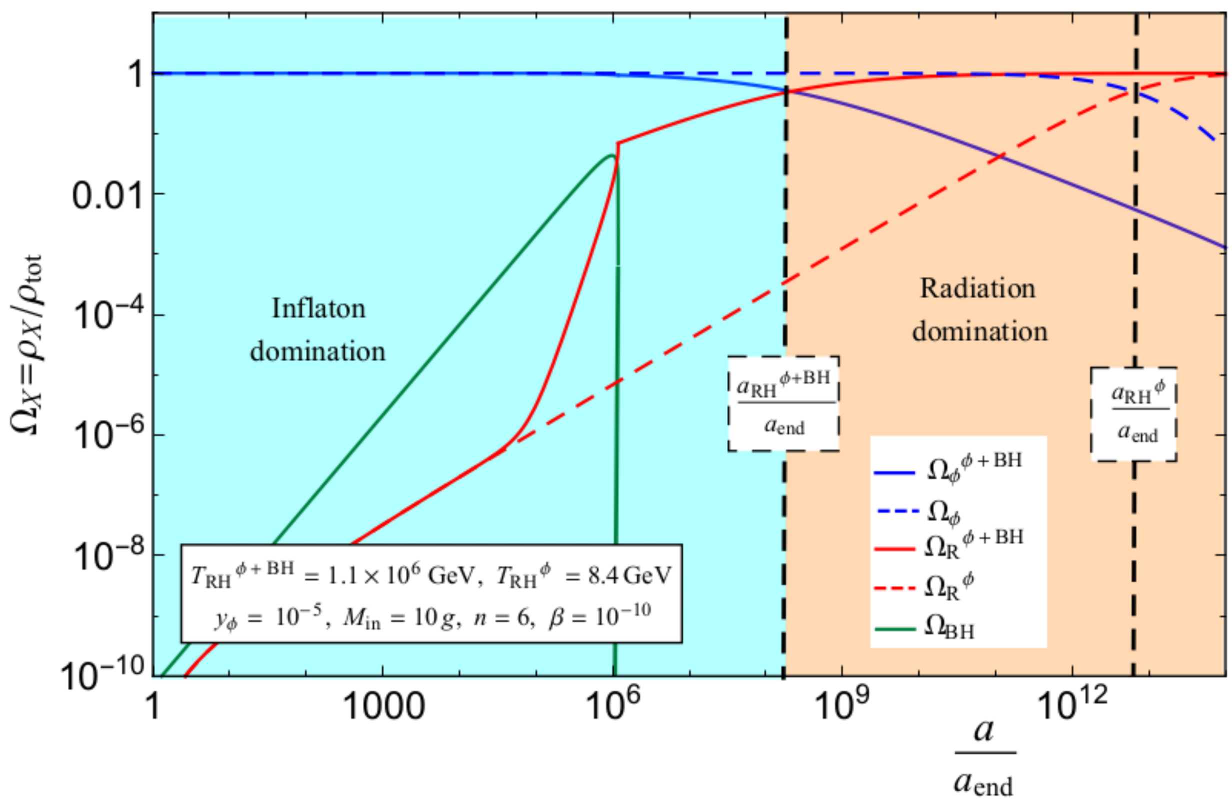

- **What are the implications for $T_{\rm RH}$? $\rightarrow$ two classes of solutions depending on y_ϕ, ω_ϕ and $M_{\rm in}$**

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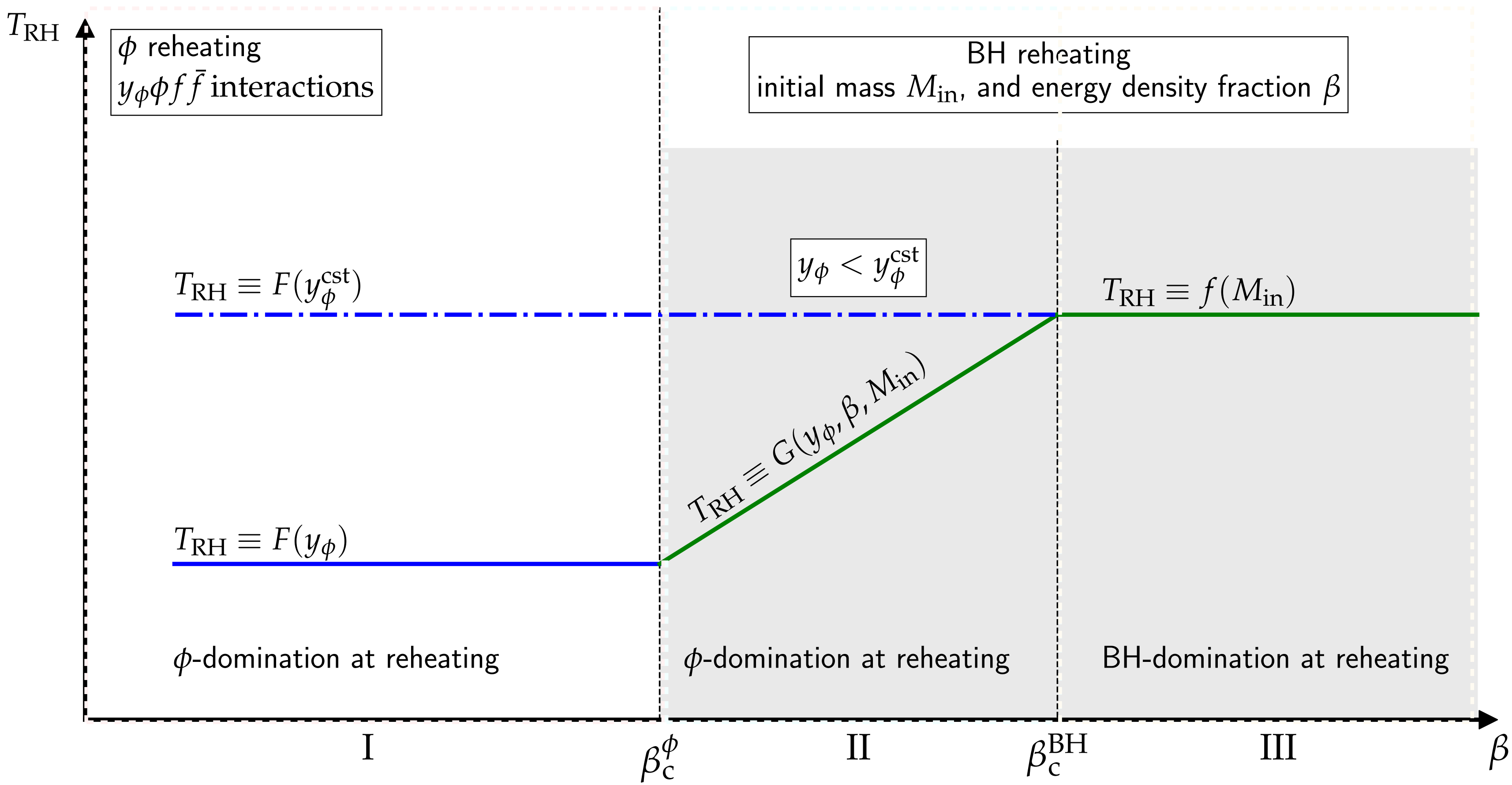

$T_{\rm RH} \sim \left(\frac{30\lambda}{g_T \pi^2}\right)^{\frac{1}{4}} \left(\frac{y_\phi^2}{8\pi}\right)^{\frac{n}{4}} \left(\frac{\alpha_n}{M_P^4}\right)^{\frac{n}{4}} M_P$ $\quad$ $T_{\rm RH} \sim M_P \left(\frac{M_P}{M_{\rm in}}\right)^{\frac{3-3\omega_\phi}{2-6\omega_\phi}} \beta^{\frac{3+3\omega_\phi}{12\omega_\phi - 4}}$ $\quad$ $T_{\rm RH} \sim \left(\frac{90\epsilon^2}{g_T \pi^2}\right)^{\frac{1}{4}} \left(\frac{M_P}{M_{\rm in}}\right)^{\frac{3}{2}} M_P$

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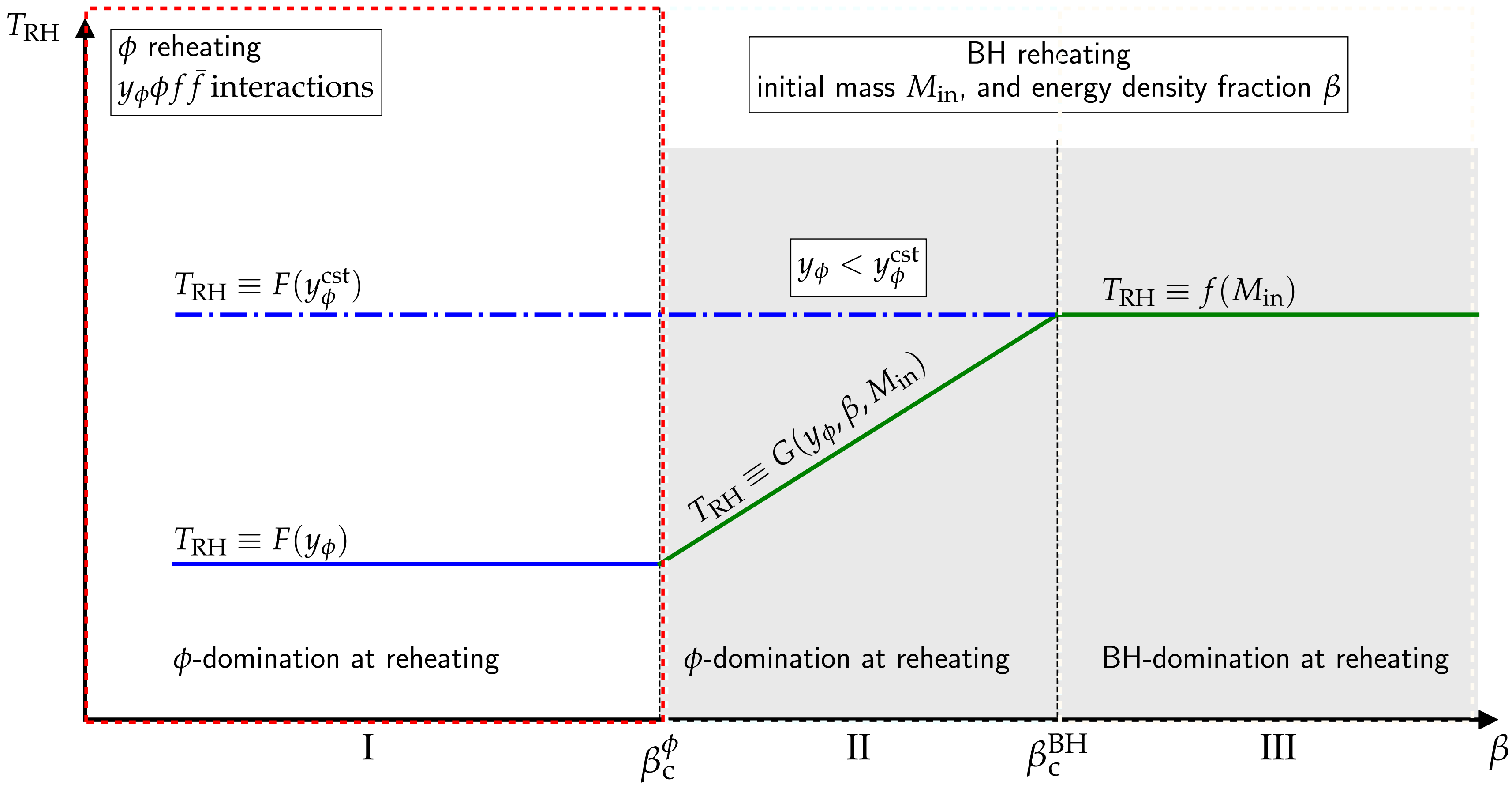

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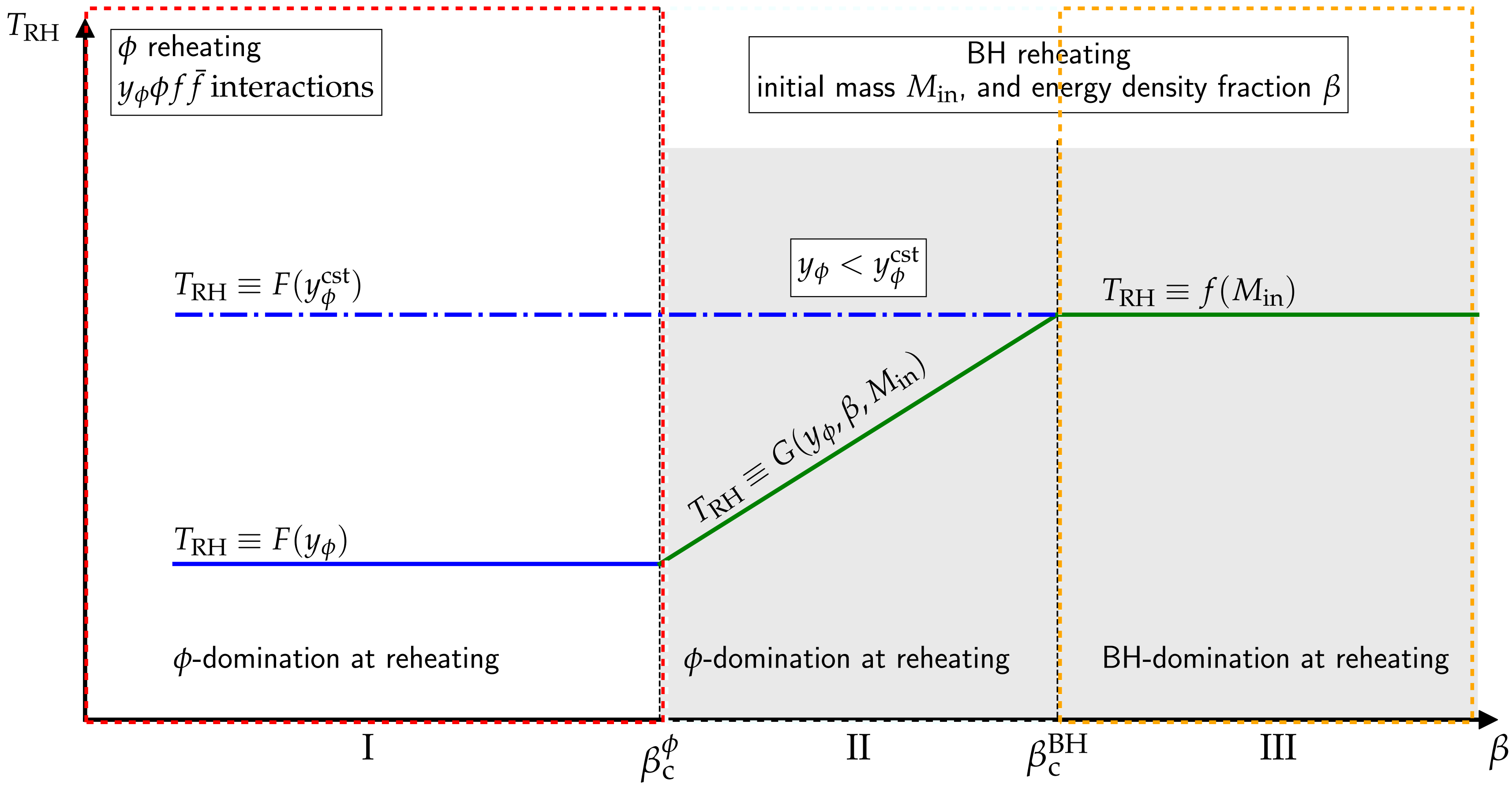

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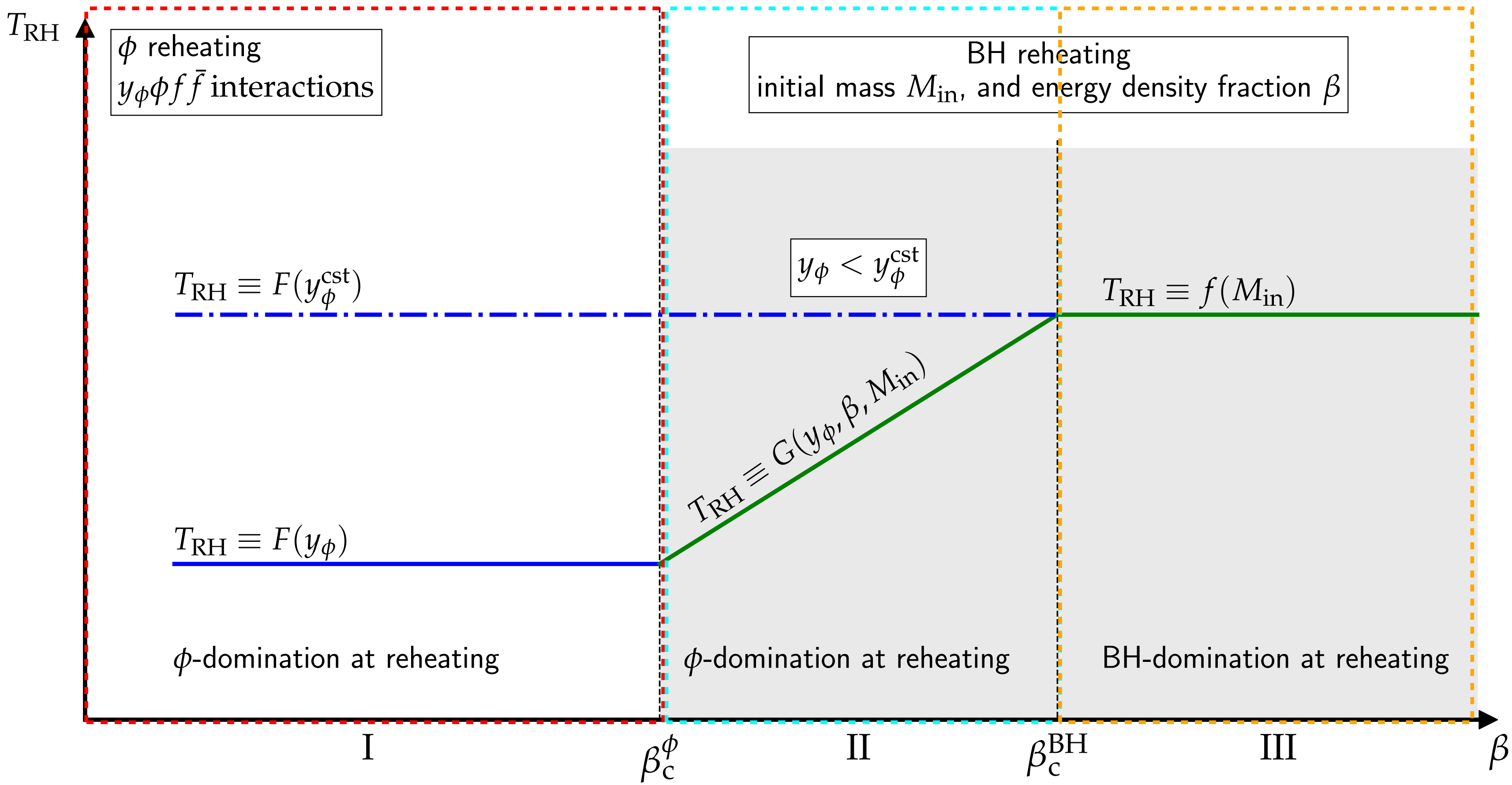

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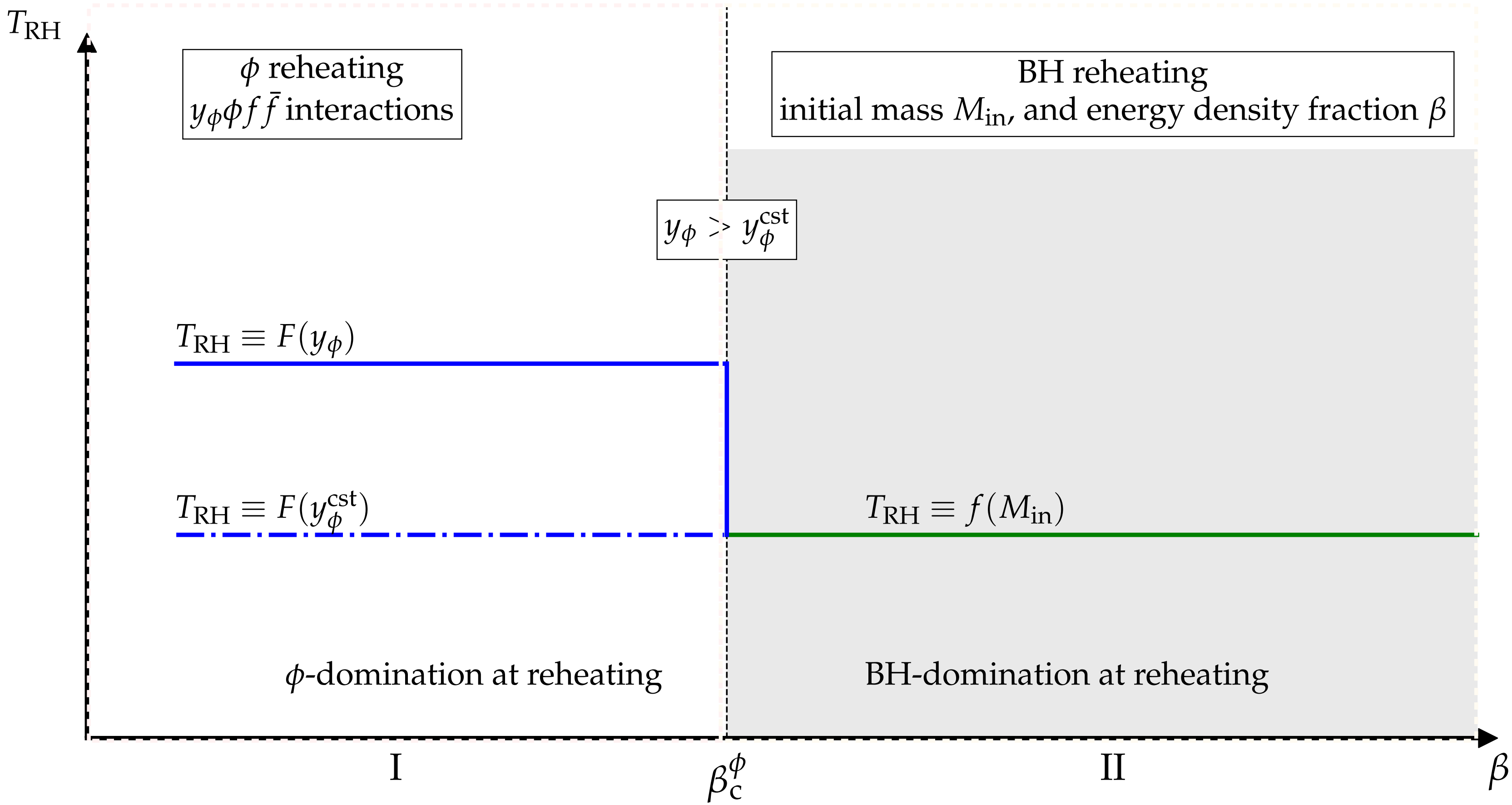

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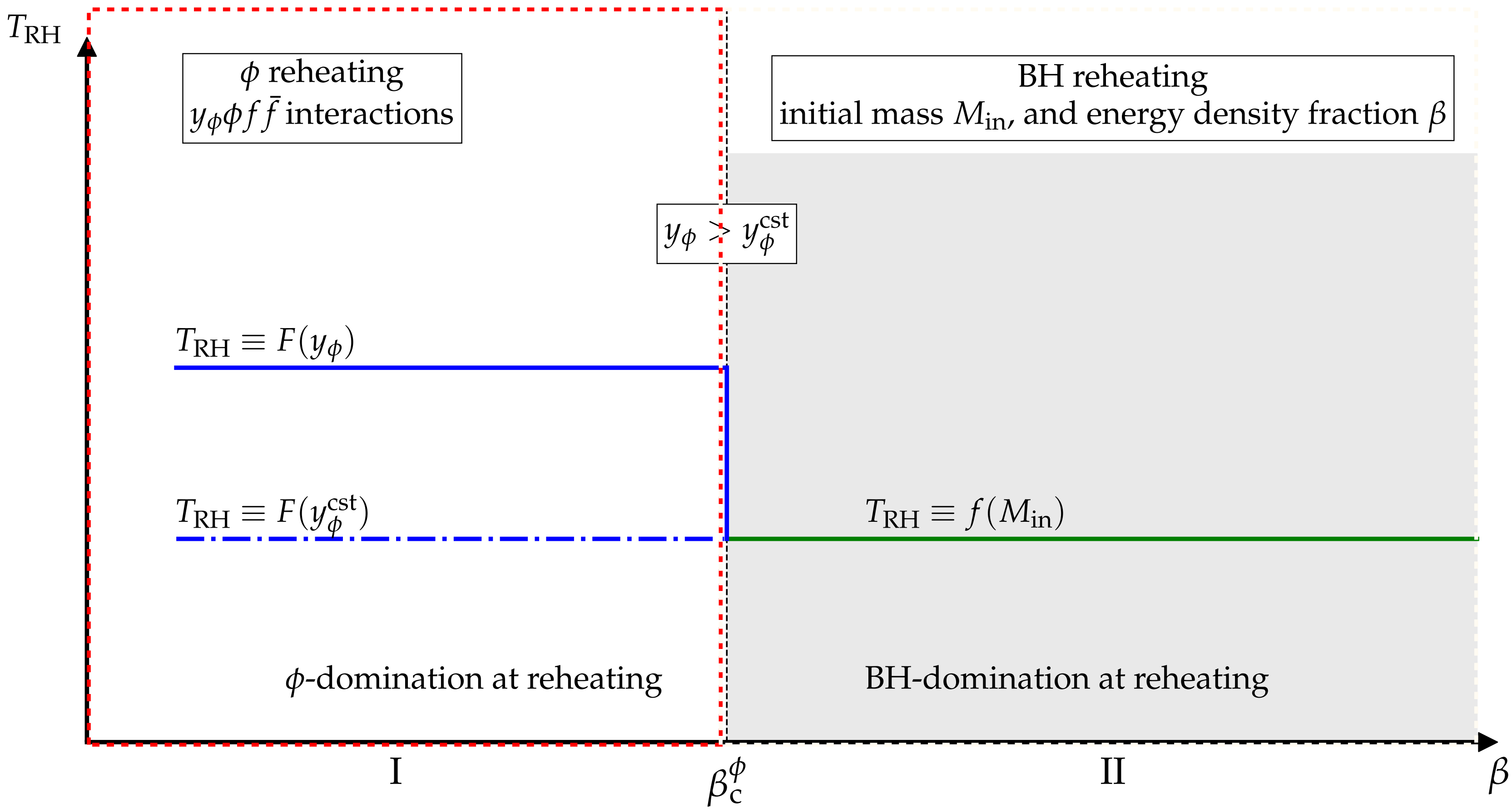

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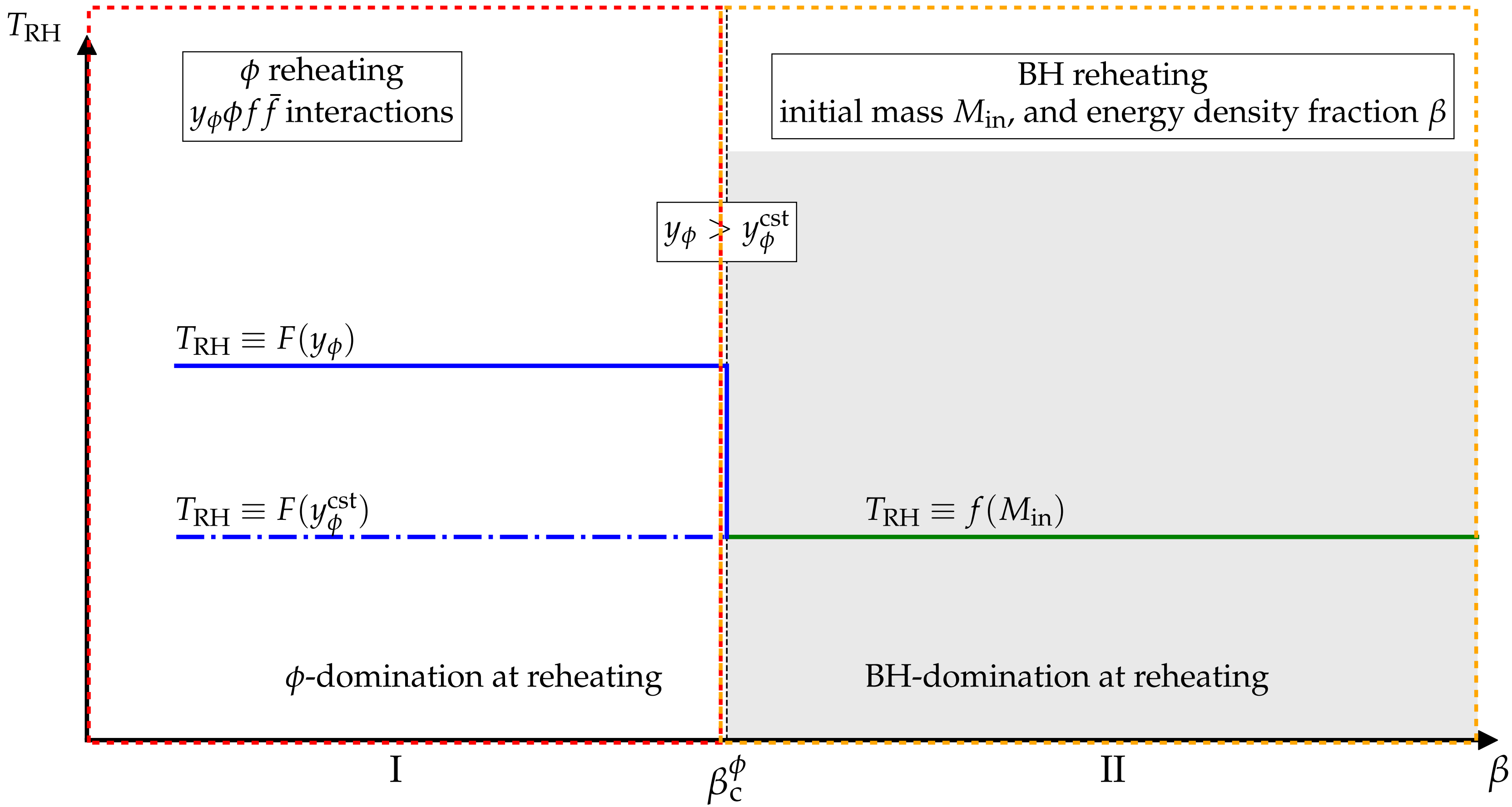
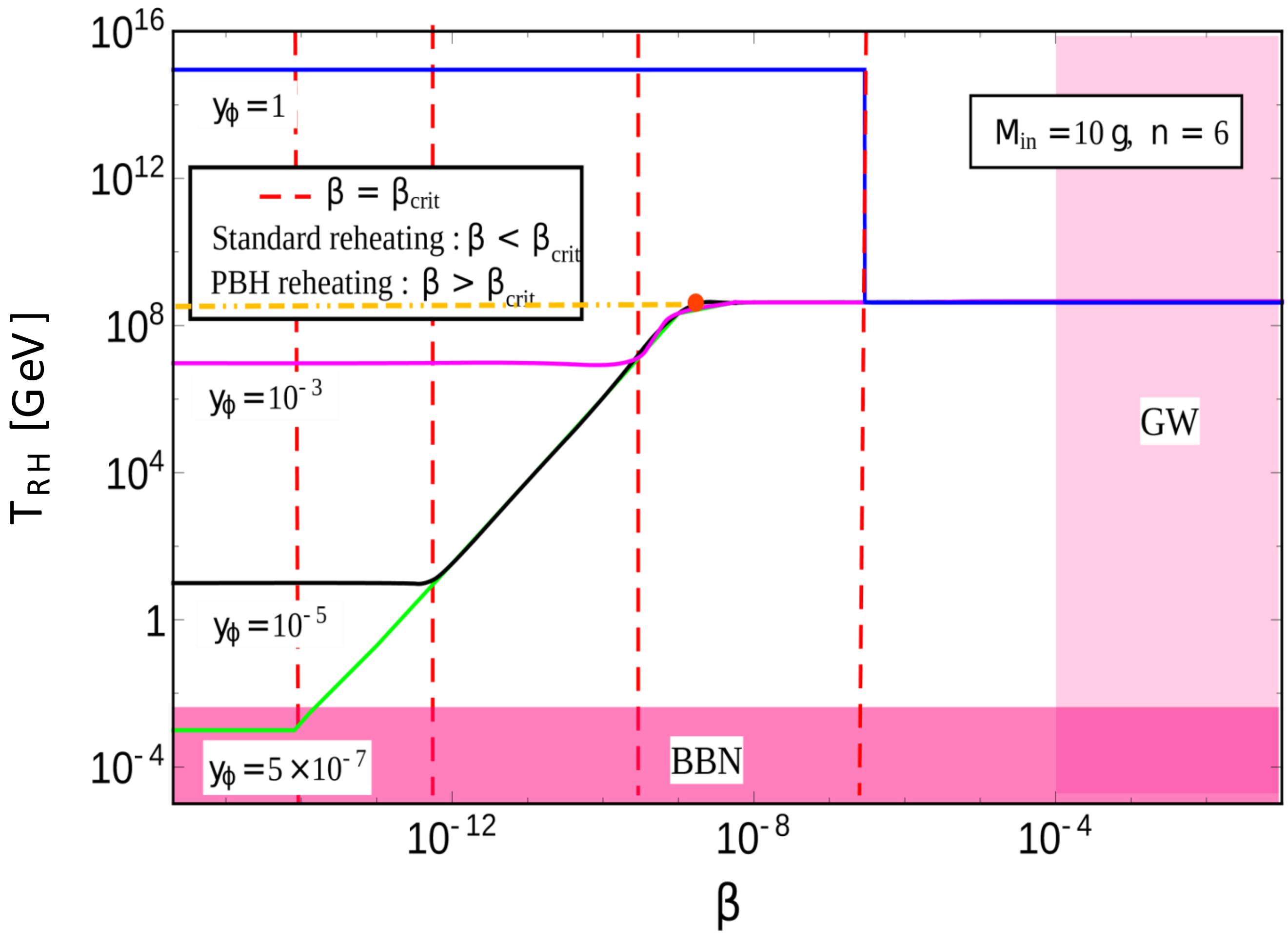


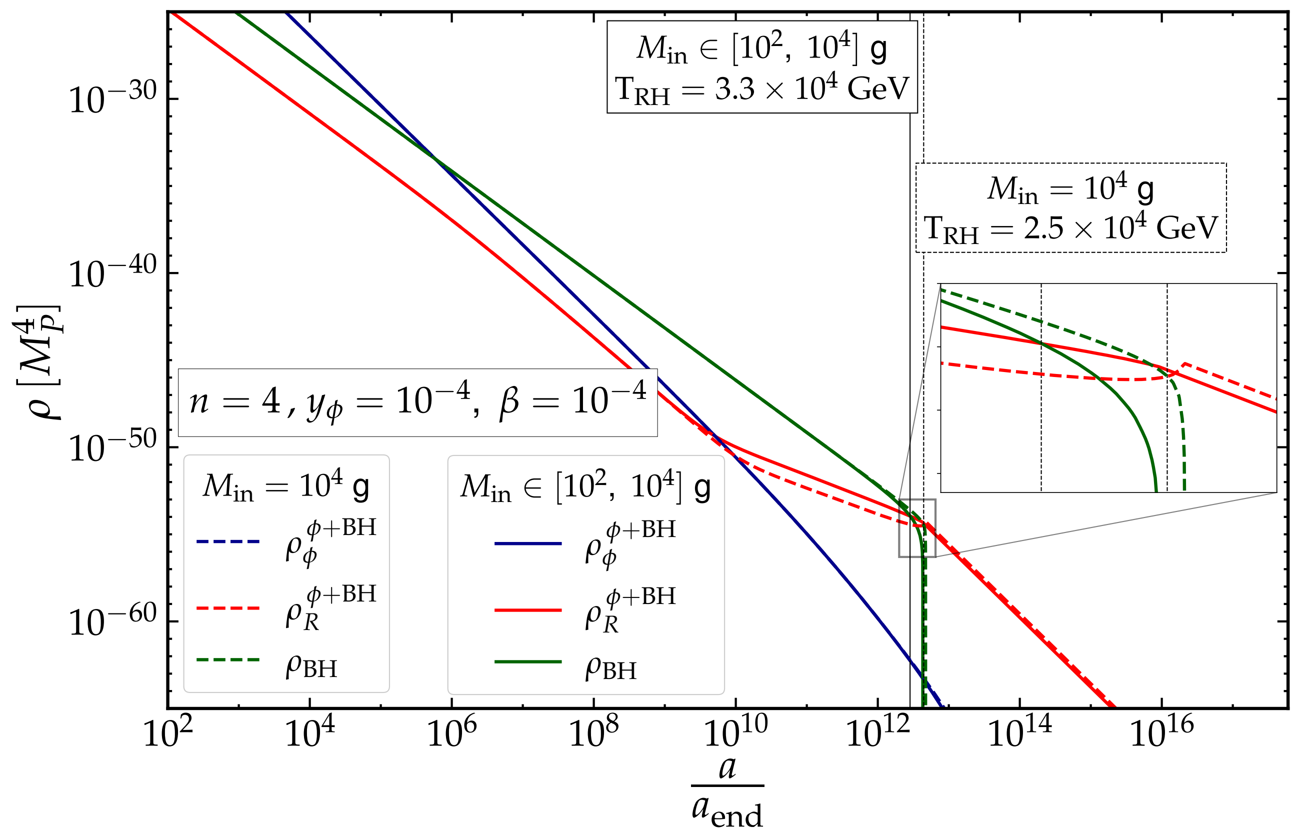
- **For example:** $\omega_\phi = 1/2$, $M_{\rm in} = 10\,{\rm g}$ $y_\phi^{\rm cst} \simeq 3.3\times 10^{-3}$ $\beta_{\rm c}^{\rm BH} \sim 1.2\times 10^{-9}$ $\beta_{\rm c}^{\phi} \propto y_\phi^{\frac{4}{3}}\,(M_{\rm in}/M_P)^{-\frac{2}{3}}$



Extended mass case

- We found comparable reheating temperature as for monochromatic case.

  For e.g. $\omega = 1/3$



Explaining Dark Matter

- **Assuming: $\phi \to$ SM, and PBH $\to$ SM + DM, and no interactions between DM and ϕ or SM**

- $\omega_\phi = 1/2$

- **Two distinct allowed regions:**

$$10^{-5}\ \mathrm{GeV} \lesssim m_j \lesssim 1\,\mathrm{GeV}, \quad \text{for } m_j < T_{\mathrm{BH}}^{\mathrm{in}}$$

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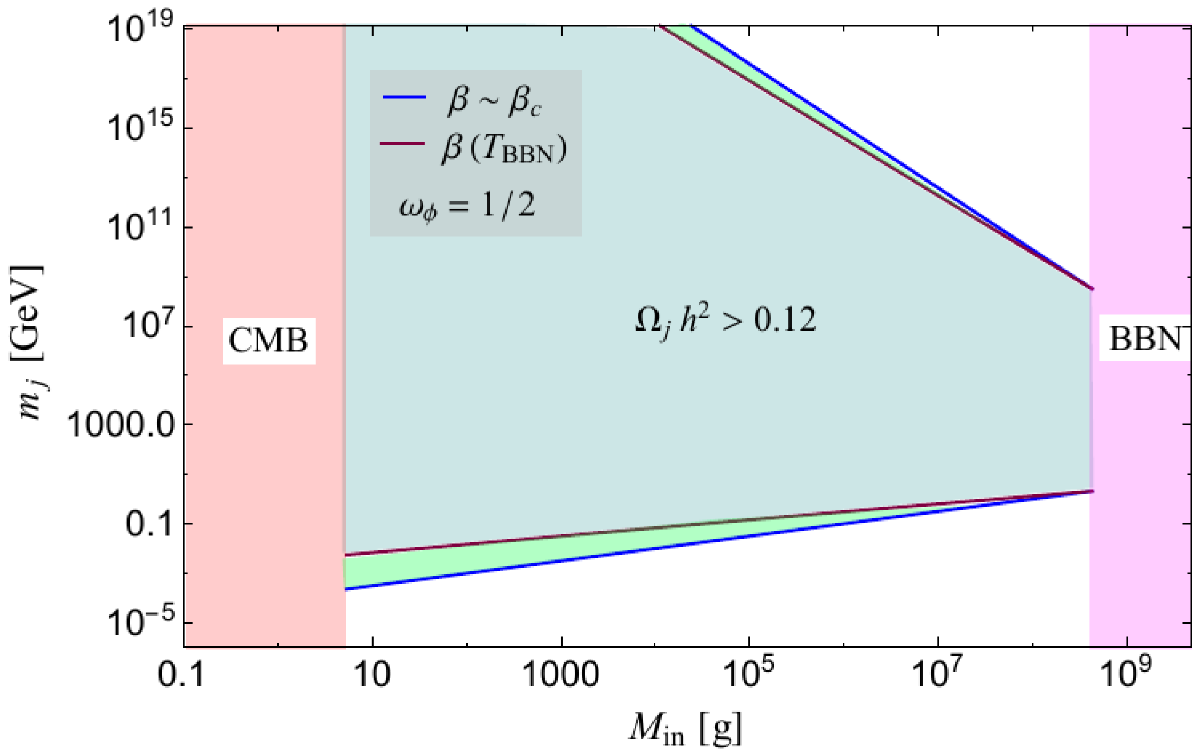

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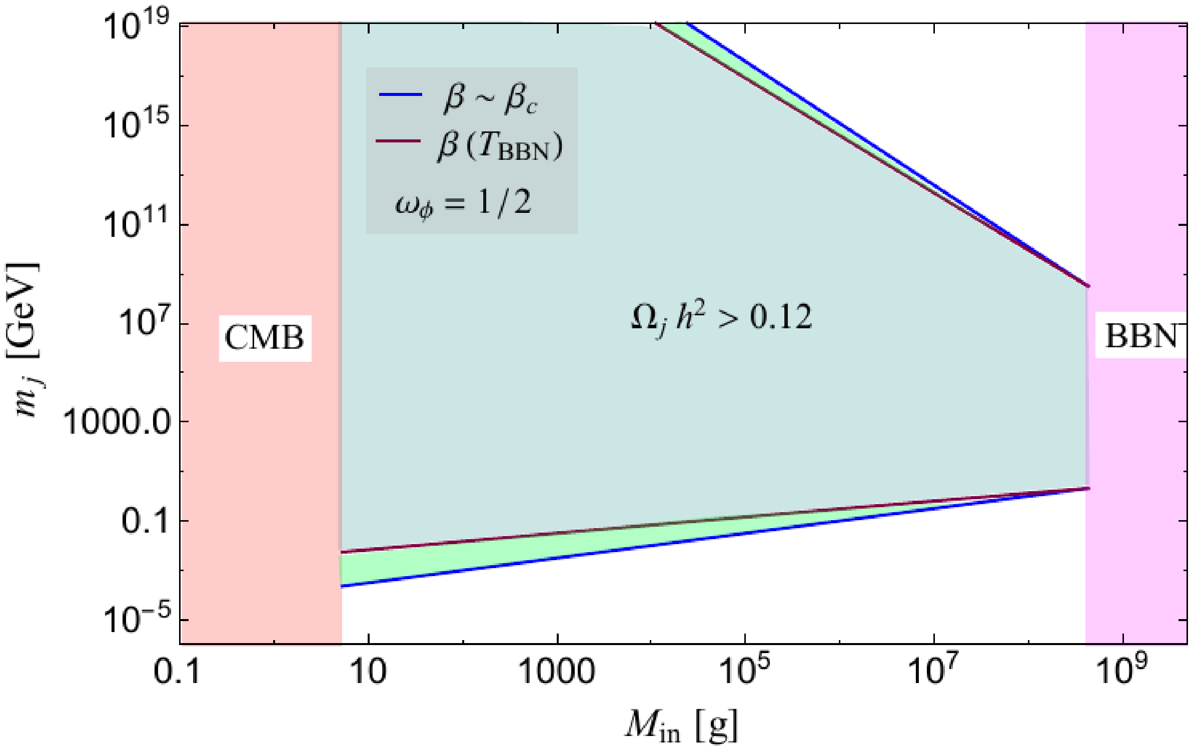

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  - The reheating temperature T_{RH} can change drastically in the presence of PBH
  - Interestingly this can happen without PBH ever dominating the energy budget of the universe
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- PBH can affect the standard post-inflation reheating dynamics
  - The reheating temperature T_{RH} can change drastically in the presence of PBH
  - Interestingly this can happen without PBH ever dominating the energy budget of the universe
- PBH can can simultaneously reheat the universe and explain the right amount of relic abundance
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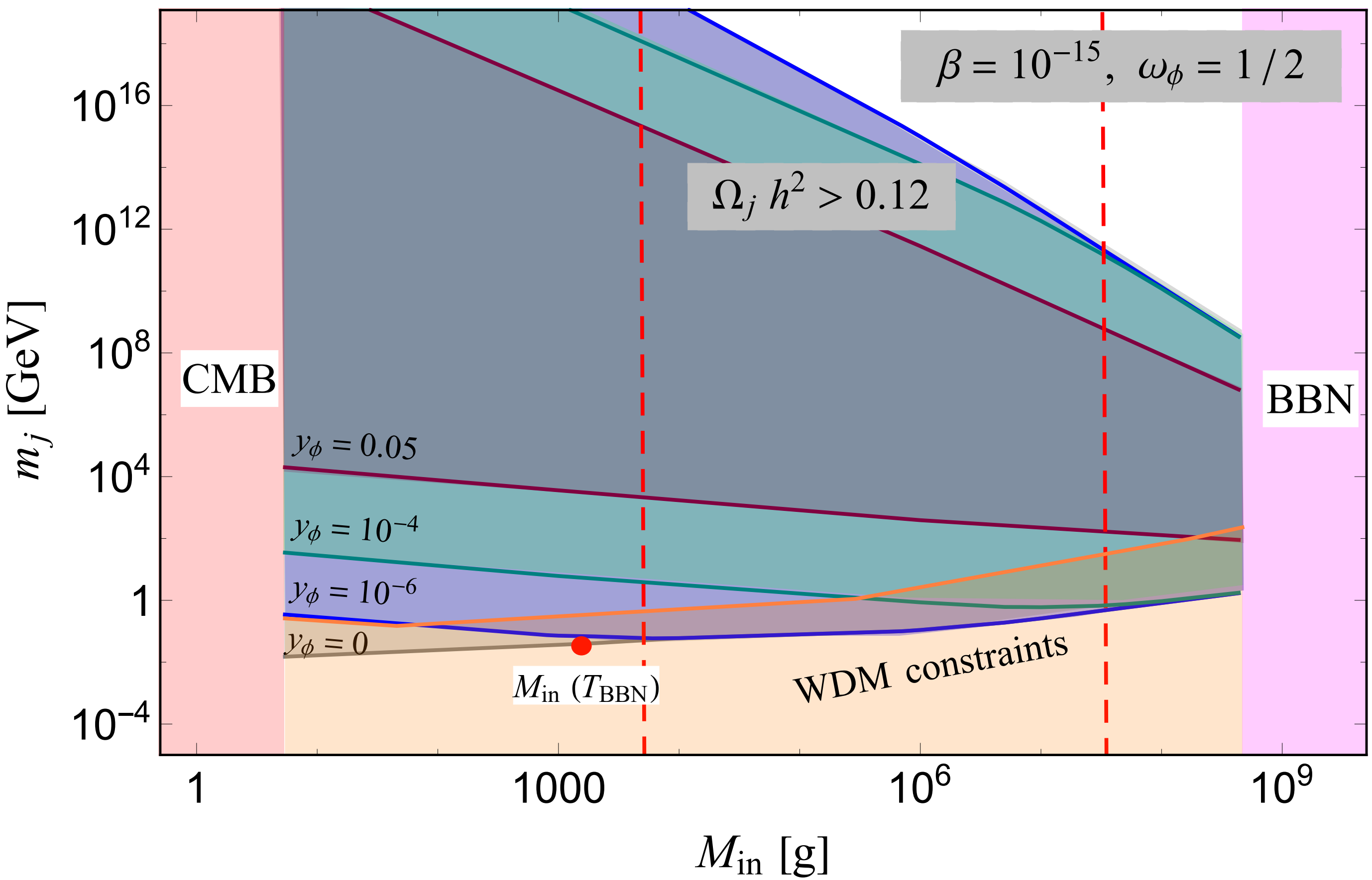
THANK YOU !

Warm DM constraints



- λ is constrained by CBM [Drewes, Kang and Mun, JHEP 11 (2017), 072]

$$\lambda = \quad \alpha_1^n \left(\frac{3\pi^2 r A_{\mathscr{R}}}{2}\right)^4 \left[\frac{n^2+n+\sqrt{n^2+3\alpha(2+n)(1-n_s)}}{n(2+n)}\right]^n$$

$A_{\mathscr{R}} \sim 2.19 \times 10^{-9}$ = amplitude of the scalar perturbations, r = tensor-to-scalar ratio, and n_s = spectral index

- The field value at the end of the inflation can be written as

$$\phi_{\rm end} = \frac{M_P}{\alpha_1} \ln\left(\frac{n}{\sqrt{3\alpha}}+1\right).$$

$$V(\phi_{\rm end}) = \frac{\lambda\, M_P^4}{\alpha_1^4}\left(\frac{n}{n+\sqrt{3\alpha}}\right)^n$$

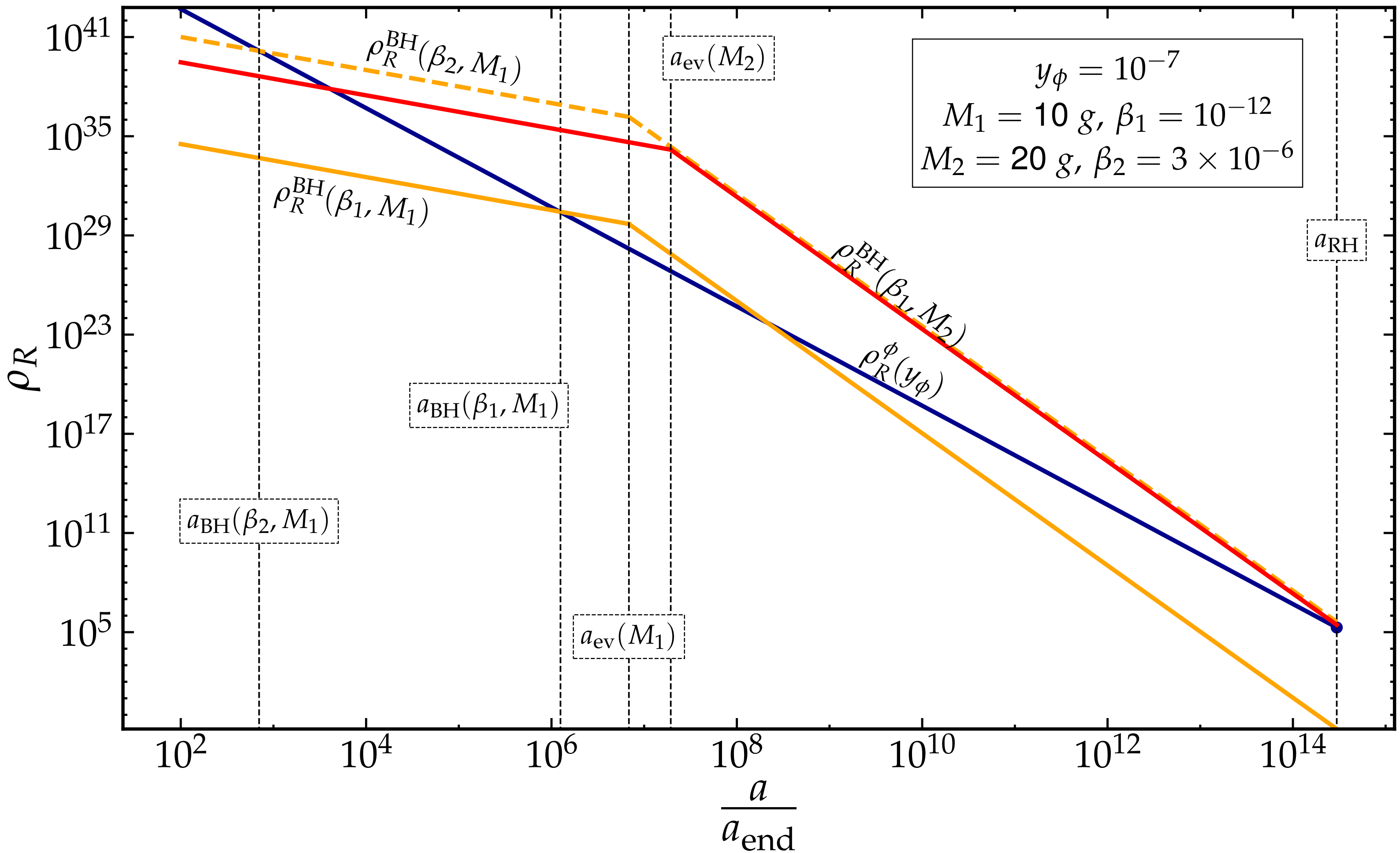
- Energy density at the end of inflation is then

$$\rho_{\rm end} = \frac{3}{2} V(\phi_{\rm end}) = \frac{3\lambda\, M_P^4}{2\,\alpha_1^4}\left(\frac{n}{n+\sqrt{3\alpha}}\right)^n.$$

- Inflaton decay to fermions rate

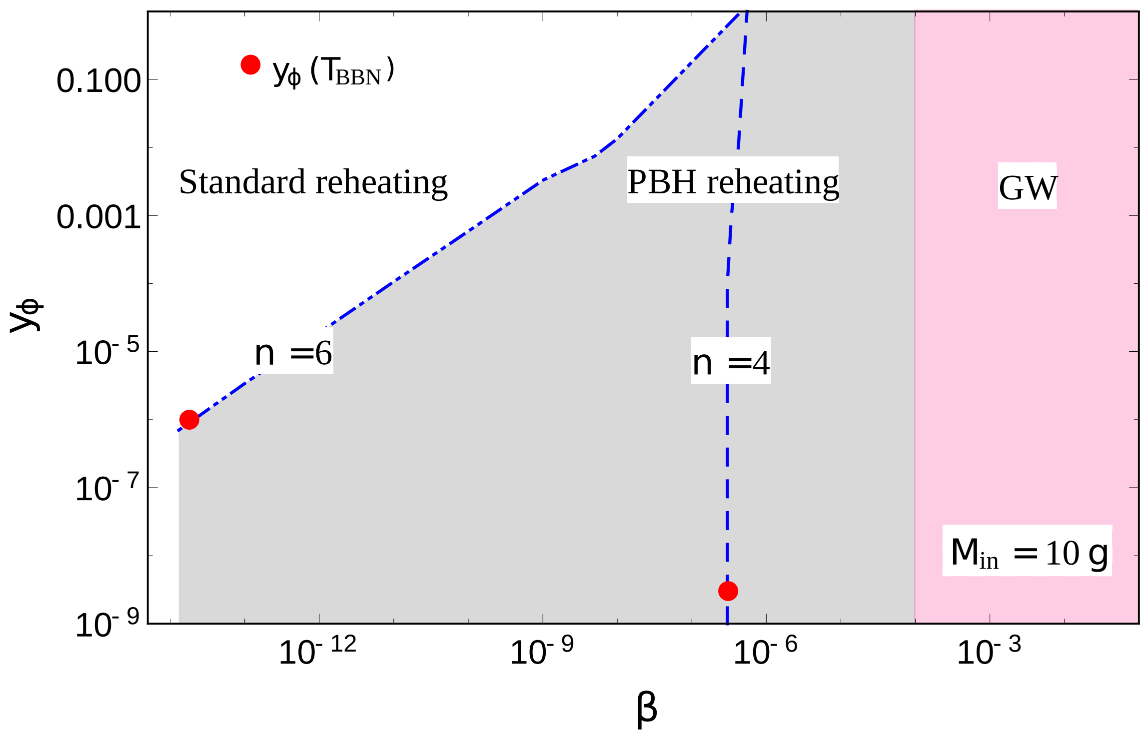
$$\Gamma_\phi = \gamma_\phi \left(\frac{\rho_\phi}{M_P^4}\right)^\ell, \quad \gamma_\phi = \sqrt{n(n-1)}\lambda^{1/n} M_P \frac{y_\phi^2}{8\pi}, \quad \ell = \frac{1}{2} - \frac{1}{n}$$

- **Even when PBH do not dominate, their evaporation can dominate the reheating process**
  - **e.g: for quartic potential, $\beta \lesssim 3 \times 10^{-6}$ implies PBHs never dominate, BUT ...**



Results: y_ϕ versus β

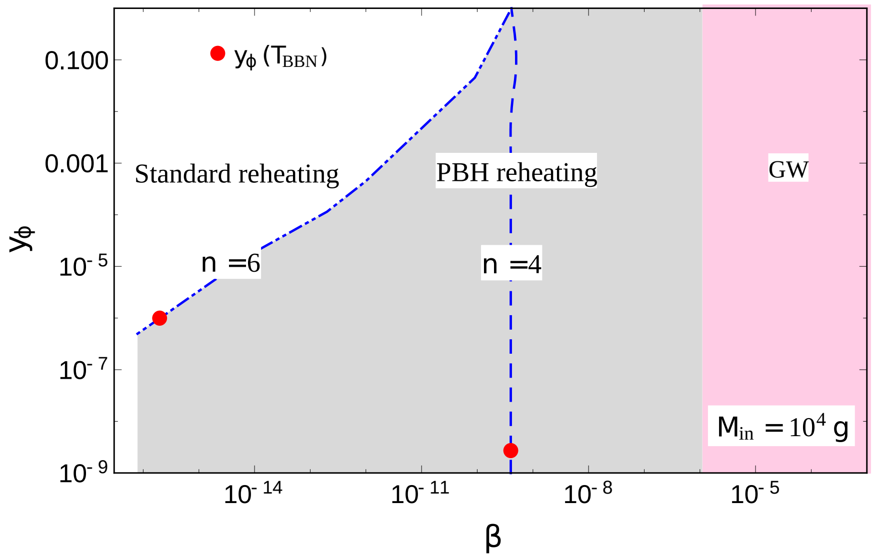
- **Summarizing, the dynamics is determined by: y_ϕ, β, and $M_{\rm in}$**



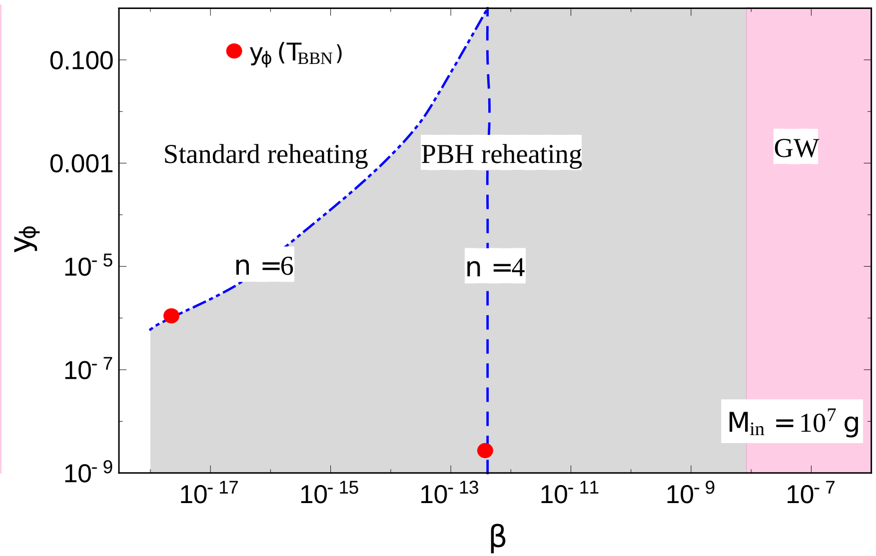
- $M_{\rm in} = 10\, g$
  - $n = 4: \; y_\phi^{\rm cst} = 6 \times 10^{-4}$

    $\beta_{crit}^{\phi} \simeq \beta_{crit}^{\rm BH} \sim 3 \times 10^{-7}$
  - $n = 6: \; y_\phi^{\rm cst} \sim 3.3 \times 10^{-3}$

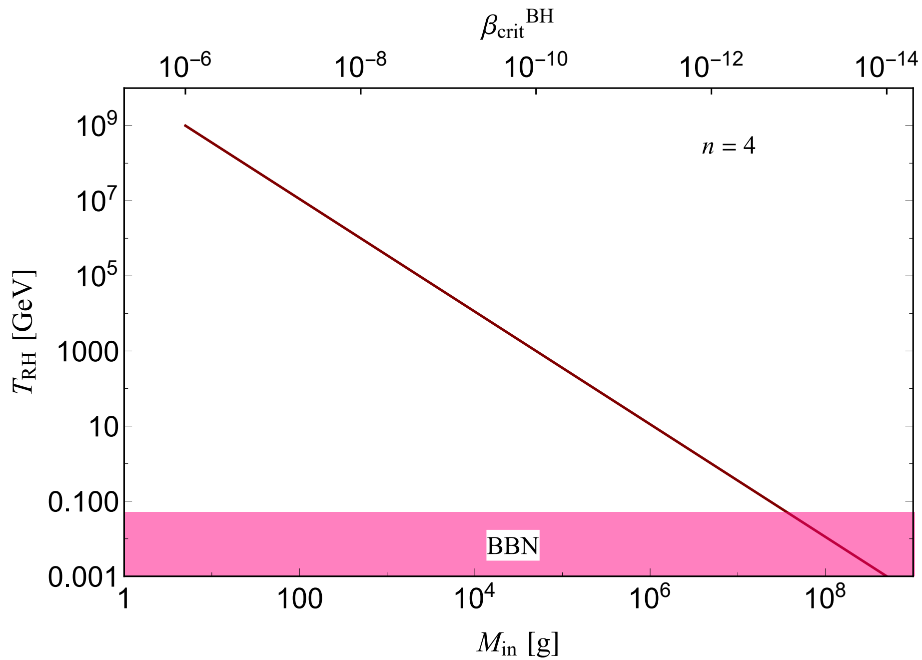
    $\beta_{crit}^{\phi} \propto y_\phi^{\frac{4}{3}}$, and $\beta_{crit}^{\rm BH} \sim 1.2 \times 10^{-9}$

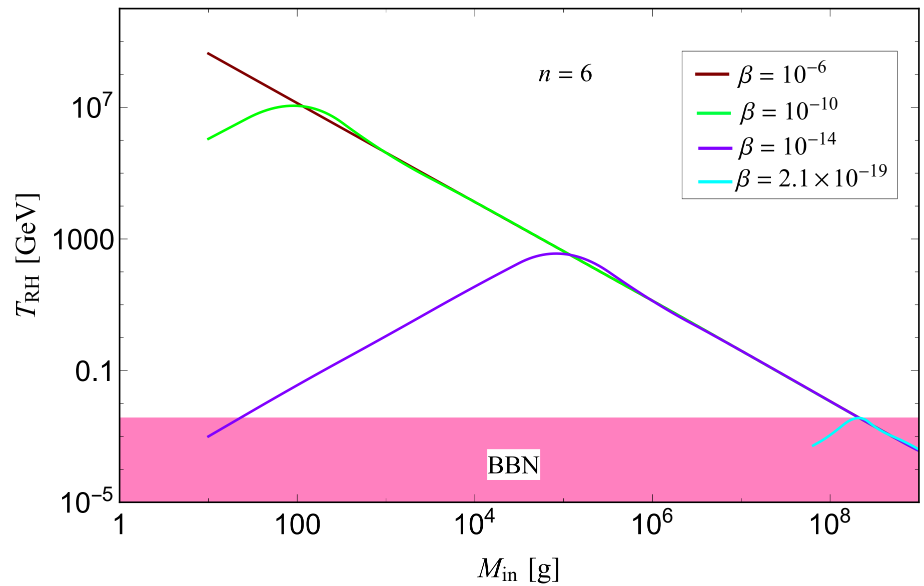


0.100
0.001
10^{-5}
10^{-7}
10^{-9}
y_ϕ
$y_\phi\,(T_{BBN})$
Standard reheating
PBH reheating
GW
n =6
n =4
$M_{in} = 10^4$ g
10^{-14}
10^{-11}
10^{-8}
10^{-5}
β



0.100
0.001
10^{-5}
10^{-7}
10^{-9}
y_ϕ
$y_\phi\,(T_{BBN})$
Standard reheating
PBH reheating
GW
n =6
n =4
$M_{in} = 10^7$ g
10^{-17}
10^{-15}
10^{-13}
10^{-11}
10^{-9}
10^{-7}
β


$\beta_{\rm crit}{}^{\rm BH}$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
$n = 4$
$T_{\rm RH}$ [GeV]
10^9
10^7
10^5
1000
10
0.100
0.001
BBN
1
100
10^4
10^6
10^8
$M_{\rm in}$ [g]


$n = 6$
$\beta = 10^{-6}$
$\beta = 10^{-10}$
$\beta = 10^{-14}$
$\beta = 2.1 \times 10^{-19}$
$T_{\rm RH}$ [GeV]
10^7
1000
0.1
10^{-5}
BBN
1
100
10^4
10^6
10^8
$M_{\rm in}$ [g]

Warm DM constraints

- Revisit of the typical limit on WDM of $m_{DM} \gtrsim 3\,\mathrm{keV}$ from structure formation or Lyman-α constraints since

$$p_{\rm ev} \sim T_{\rm BH}^{\rm in} \gg T_{\rm RH} \to \text{boost factor } \gamma = \frac{p_{\rm ev}}{T_{\rm RH}} \sim \frac{T_{\rm BH}^{\rm in}}{T_{\rm RH}} \implies \text{new limit } m^{\rm lim} \gtrsim 3\,\gamma\,\mathrm{keV}$$

E.g. $\omega_\phi = 1/2$

- $\beta > \beta_c^{\rm BH} \to \frac{m^{\rm lim}}{\rm GeV} \propto \left(\frac{M_{\rm in}}{M_P}\right)^{\frac{1}{2}}$
- $\beta_c^{\phi} < \beta < \beta_c^{\rm BH} \to \frac{m^{\rm lim}}{\rm GeV} \propto \beta^{-\frac{1}{4}} \left(\frac{M_{\rm in}}{M_P}\right)^{\frac{1}{6}}$
- $\beta < \beta_c^{\phi} \to \frac{m^{\rm lim}}{\rm GeV} \propto \left(\frac{T_{\rm RH}}{M_P}\right)^{-\frac{1}{9}} \left(\frac{M_{\rm in}}{M_P}\right)^{\frac{1}{3}}$