Gravitational Leptogenesis and Primordial Gravitational Waves during PBH-induced Reheating

NEHOP 2024

Suruj Jyoti Das

Institute for Basic Science

Based on:
arXiv: 2403.05626

Collaborators: B. Barman, M.R. Haque, Y. Mambrini

LHC Physics - CERN Bulletin

Baryon Asymmetry (from BBN and CMB) : $\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6.1 \times 10^{-10}$.

How to generate?

Sakharov conditions:

- B / L violation.
- C and CP violation.
- Departure from equilibrium.

How to generate?

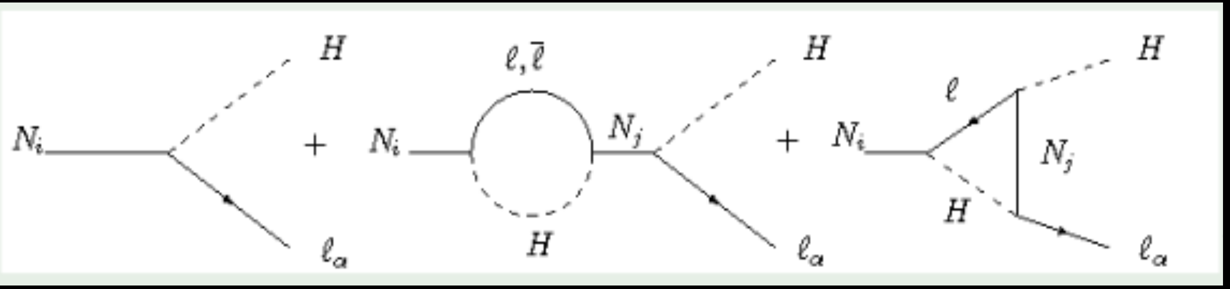
Sakharov conditions:

- B / L violation.
- C and CP violation.
- Departure from equilibrium.

Baryogenesis through leptogenesis:

$$M_{N_i}\overline{N_i^c}\,N_i - y_N^{ij}\,\overline{N_i}\,\widetilde{H}^\dagger L_j$$

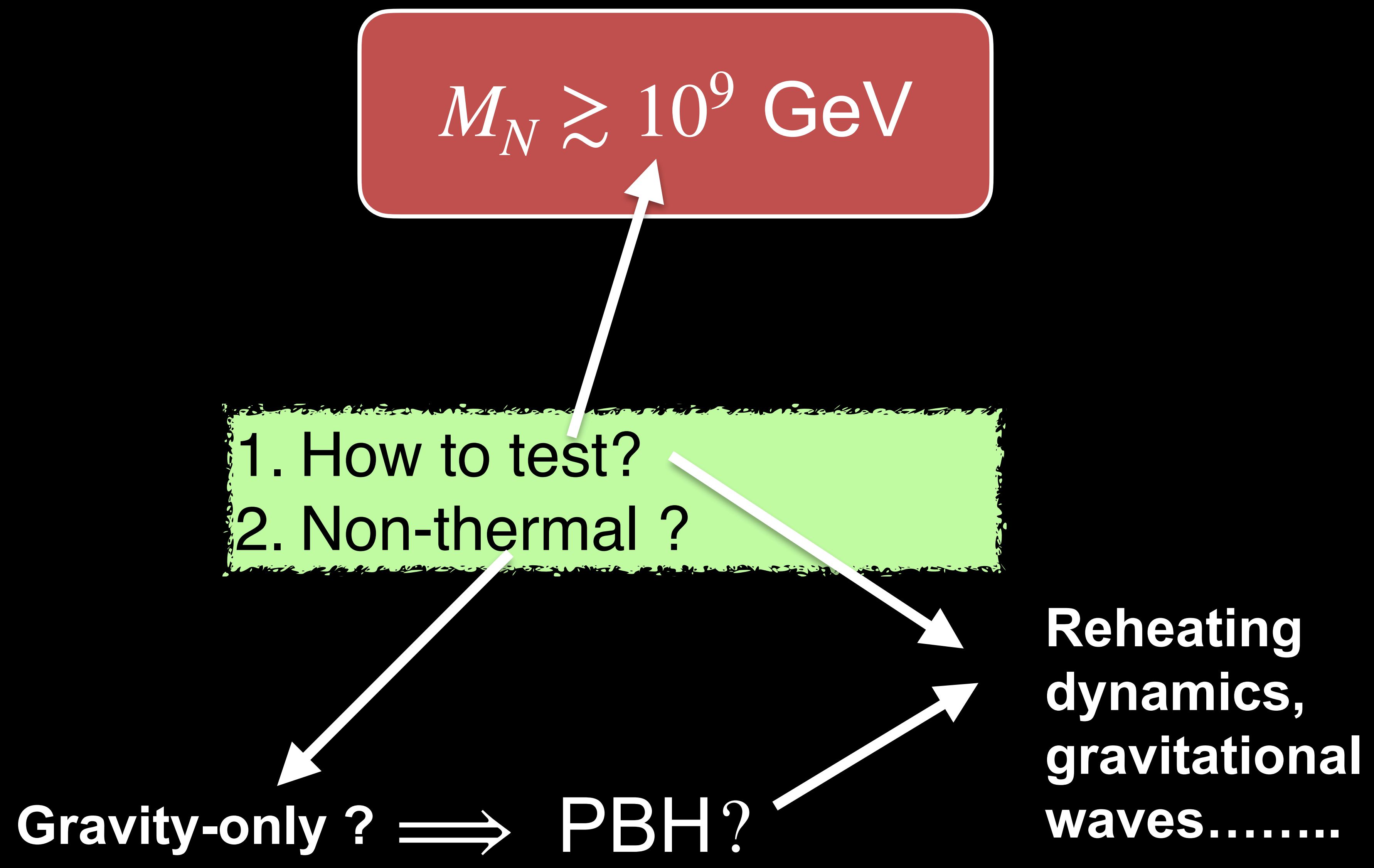
Around T~ M_N



Decay of right handed neutrinos $\epsilon_{\Delta L} \neq 0$

Sphalerons

η_B


$M_N \gtrsim 10^9$ GeV
1. How to test?
2. Non-thermal ?
Reheating dynamics, gravitational waves……..
Gravity-only ? $\Longrightarrow$ PBH?

Outline of the talk

- PBH-induced reheating and leptogenesis.
- Graviton mediated leptogenesis.
- Imprints on primordial gravitational waves.
- Summary & Outlook.

The tale of Primordial Black Holes…

Collapse of large inhomogeneities

Collapse of cosmic string loops

Bubble collisions

etc etc…

PBH mass at formation :

$$M_{\rm BH}(T_{\rm in}) = \gamma M_H = \gamma \frac{4\pi}{3} \frac{\rho_R(T_{\rm in})}{H^3(T_{\rm in})}$$

mass enclosed in horizon

Black hole temperature :

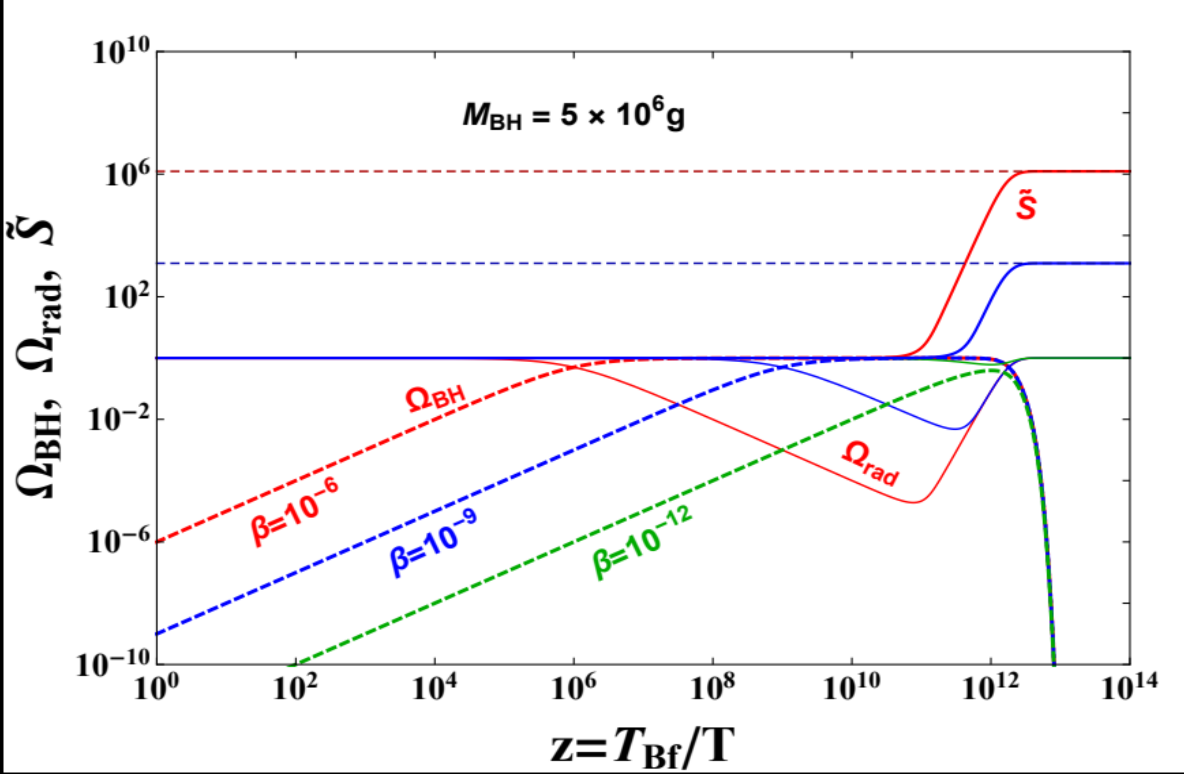
$$T_{\rm BH} = \frac{1}{8\pi G M_{\rm BH}} \approx 1.06 \left(\frac{10^{13}\ {\rm g}}{M_{\rm BH}} \right) {\rm GeV}$$

Initial PBH fraction : $\beta = \frac{\rho_{\rm BH}(T_{\rm in})}{\rho_{\rm Rad}(T_{\rm in})}$

Hawking evaporation :

$$\frac{dM_{BH}}{dt} \approx -5.34 \times 10^{25} \boxed{\varepsilon(M_{BH})} \left(\frac{1\ {\rm g}}{M_{BH}} \right)^2 g s^{-1}$$

PBH evanescence : $T_{\rm ev} \approx \left(\frac{9 g_*(T_{\rm BH})}{10240} \right)^{\frac{1}{4}} \left(\frac{M_{\rm Pl}^5}{M_{\rm in}^3} \right)^{\frac{1}{2}}$



May **dominate** before evaporating
(Talk by Dan)

- $M_{in} \gtrsim 10^{15} g$ can be a DM candidate.
- $M_{in} \lesssim 10^{15} g$ can lead to DM-genesis, matter-antimatter asymmetry.

Ultralight PBHs $\lesssim 10^9$ g

Particles produced from PBH:

$$\mathcal{N} = \frac{g_{X,H}}{g_{\star,H}} \begin{cases} \frac{4\pi}{3}\left(\frac{m_{\rm in}}{M_{\rm pl}}\right)^2 & \text{for } M_X < T_{\rm BH}^{\rm in}, \\ \frac{1}{48\pi}\left(\frac{M_{\rm pl}}{M_X}\right)^2 & \text{for } M_X > T_{\rm BH}^{\rm in}, \end{cases}$$

Baryon asymmetry:

$$Y_B(T_0) = \frac{n_B}{s}\Big|_{T_{\rm ev}} = \mathcal{N}_{N_1}\,\epsilon_{\Delta L}\,a_{\rm sph}\,\frac{n_{\rm BH}(T_{\rm ev})}{s(T_{\rm ev})}$$

CP asymmetry

PBH formation & evaporation during the reheating era ?

$$V(\phi) \propto \phi^n$$

$$M_{in} = \frac{4}{3}\pi\gamma H_{\rm in}^{-3}\rho_\phi(a_{\rm in})$$

Inflaton energy density

$$w(\phi) = \frac{n-2}{n+2}$$

PBH domination: $\beta > \beta_c \simeq \left(7.6 \times 10^{-6}\right)^{\frac{4w_\phi}{1+w_\phi}} \left(\frac{1\,\mathrm{g}}{M_{\mathrm{in}}}\right)^{\frac{4w_\phi}{1+w_\phi}}$ → depends on the inflaton background

PBH domination: $\beta > \beta_c \simeq (7.6 \times 10^{-6})^{\frac{4w_\phi}{1+w_\phi}} \left(\frac{1\,\mathrm{g}}{M_{\rm in}}\right)^{\frac{4w_\phi}{1+w_\phi}}$ → depends on the inflaton background

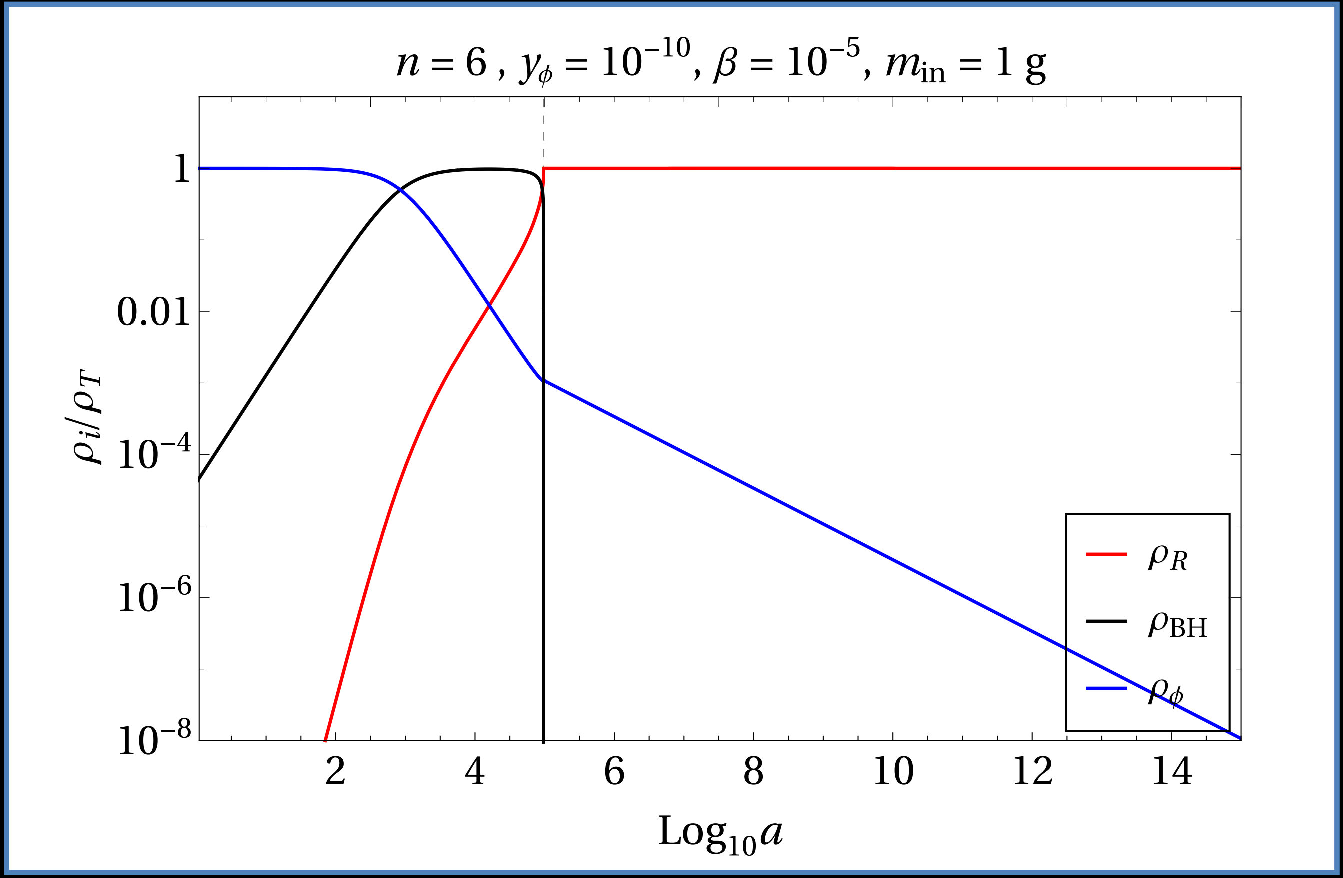
Reheating from PBH?

Case 1: $\beta > \beta_c$

$$\rho_\phi = \rho_{\rm end} \left(\frac{a_{\rm end}}{a}\right)^{\frac{6n}{n+2}}$$

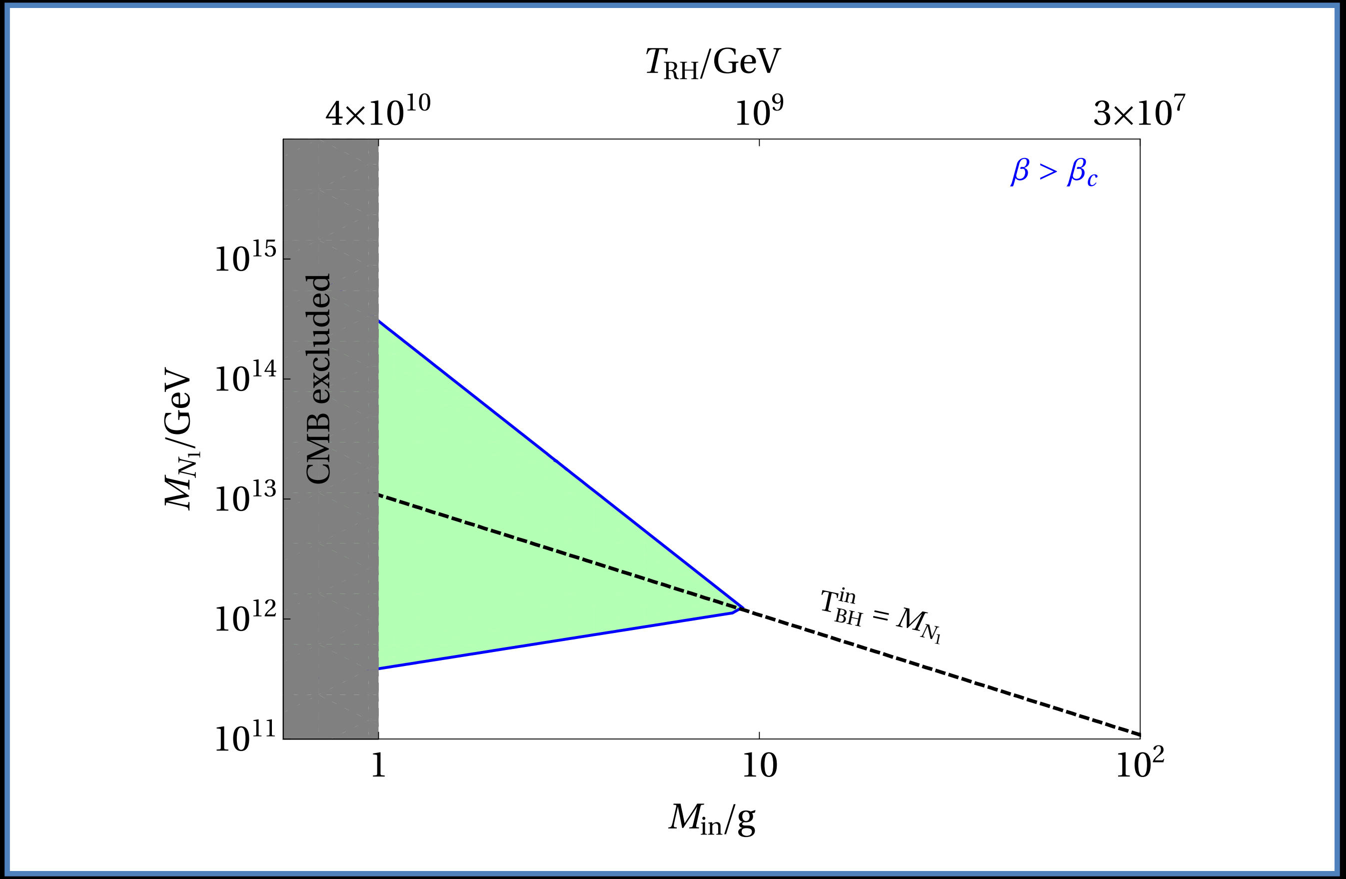
PBH can dominate for n > 2

$$T_{\rm RH} = T_{\rm ev}$$



Leptogenesis, Case I

$$Y_B(T_0) \simeq 8.7\times10^{-11}\,\delta_{\rm eff}\left(\frac{m_{\nu,\,\rm max}}{0.05\,\rm eV}\right)\begin{cases}\left(\frac{M_{N_1}}{3.7\times10^{11}\,\rm GeV}\right)\times\left(\frac{1\rm g}{M_{\rm in}}\right)^{\frac{1}{2}}, & M_{N_1} < T_{\rm BH}^{\rm in}\\ \left(\frac{3\times10^{14}\,\rm GeV}{M_{N_1}}\right)\times\left(\frac{1\rm g}{M_{\rm in}}\right)^{\frac{5}{2}}, & M_{N_1} > T_{\rm BH}^{\rm in},\end{cases}$$

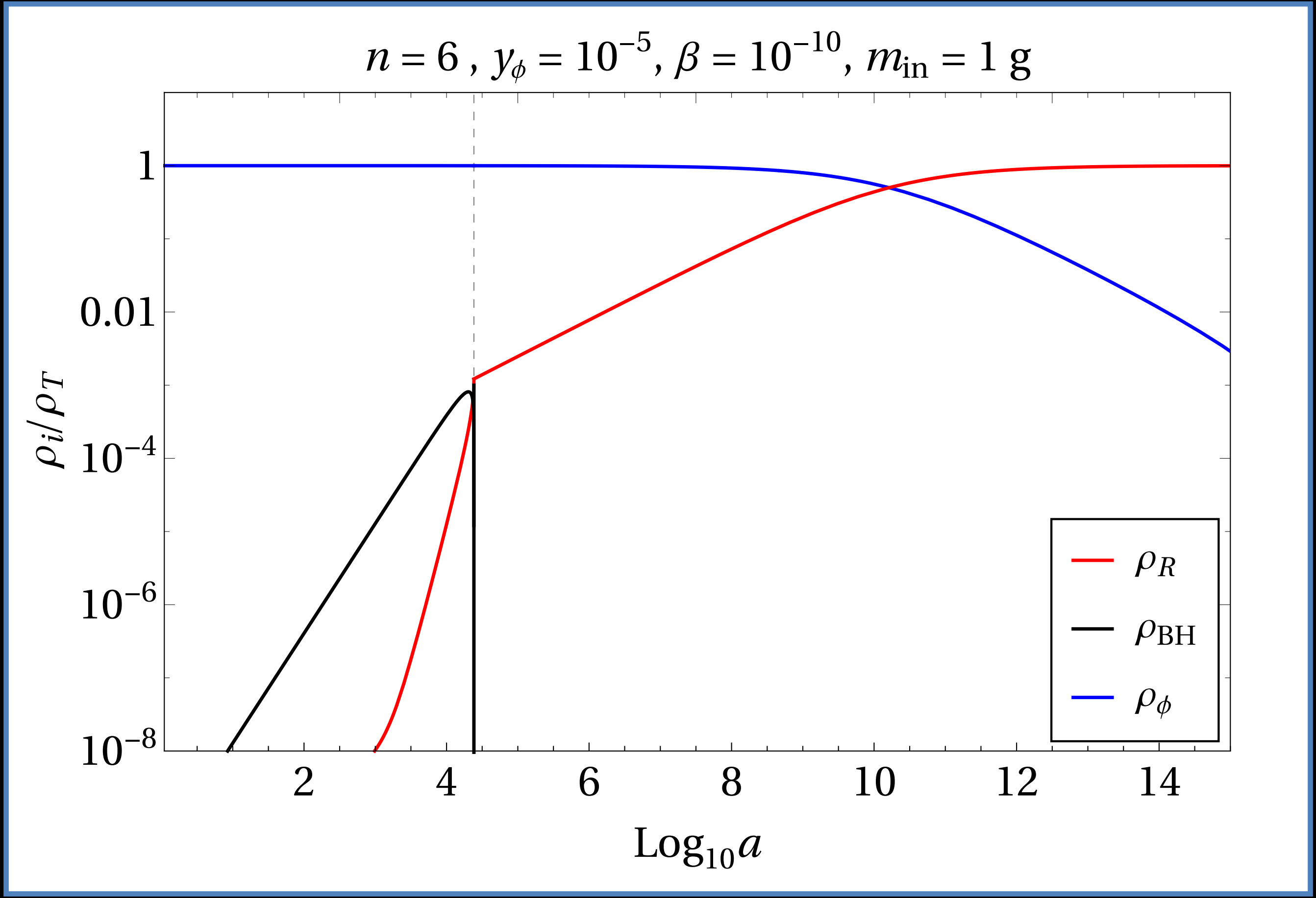


Case 2: $\beta < \beta_c$

PBH can reheat if:

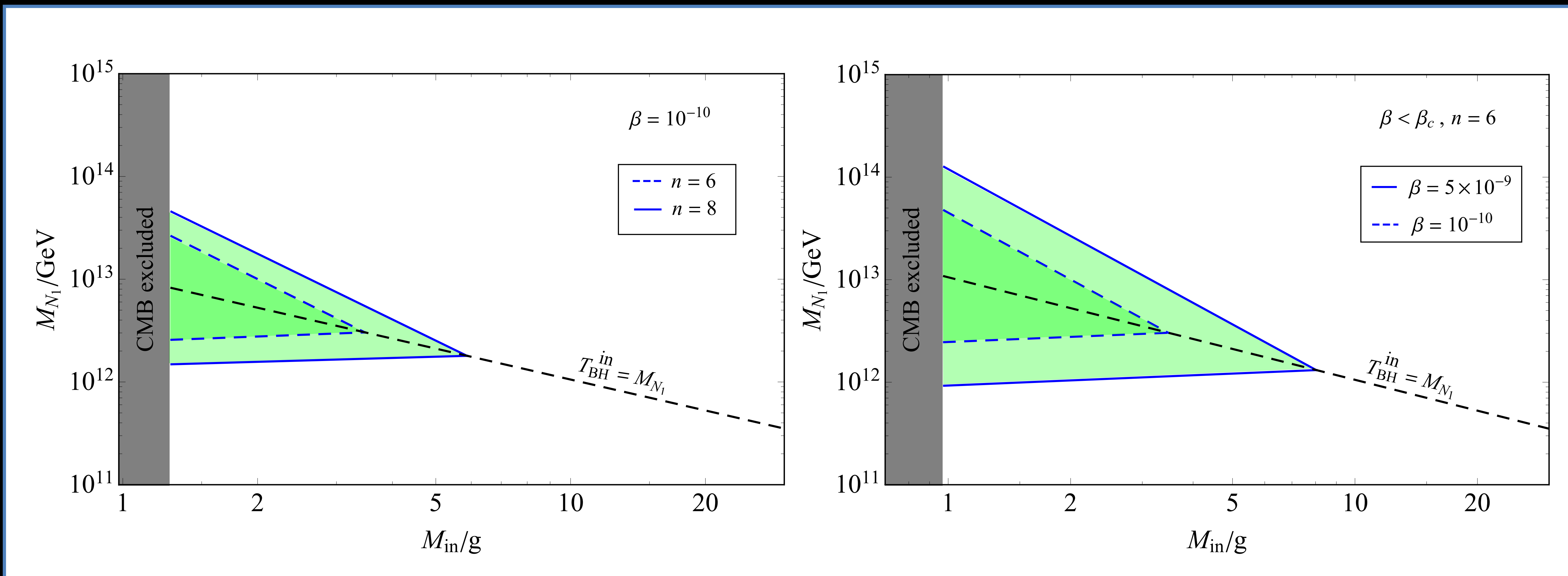
a) Inflaton coupling is small enough,

b) $w_\phi > 1/3$.



$$T_{\rm RH} \simeq (48\pi^2)^{1/4}\, \beta^{\frac{3(1+w_\phi)}{4(3w_\phi-1)}} \left(\frac{\epsilon}{2\,(1+w_\phi)\,\pi\,\gamma^{3w_\phi}} \right)^{\frac{2}{4(1-3w_\phi)}} \left(\frac{M_P}{M_{\rm in}} \right)^{\frac{6(1-w_\phi)}{4(1-3w_\phi)}} M_P\,.$$

Leptogenesis, Case II

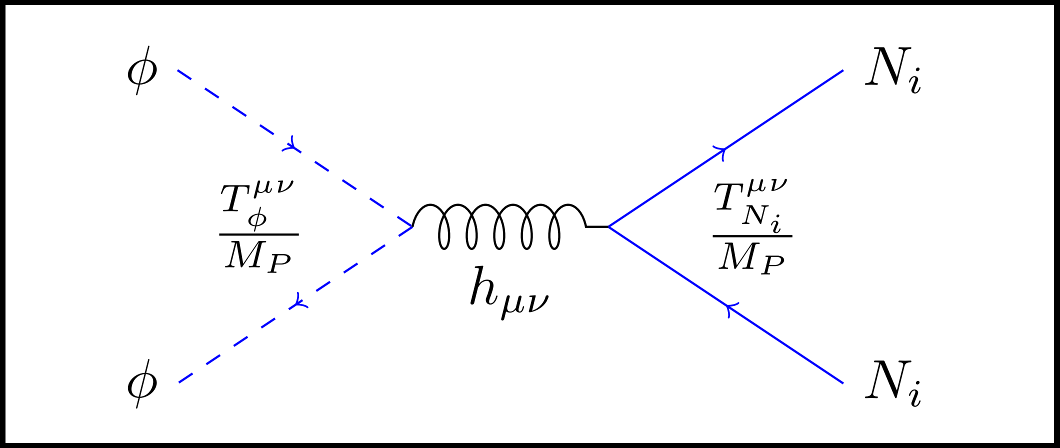


$$Y_B(T_0) \simeq 8.7 \times 10^{-11}\, \delta_{\rm eff} \left(\frac{m_{\nu,\,\rm max}}{0.05\,{\rm eV}}\right) \mu\, \beta^{\frac{1}{4}}$$

$$\begin{cases} \left(\frac{M_{N_1}}{6.5\times10^8\,{\rm GeV}}\right) \times \left(\frac{M_P}{M_{\rm in}}\right)^{\frac{1-w_\phi}{2(1+w_\phi)}} , M_{N_1} < T_{\rm BH}^{\rm in} \\ 7\times10^{18} \left(\frac{6.5\times10^8\,{\rm GeV}}{M_{N_1}}\right) \times \left(\frac{M_P}{M_{\rm in}}\right)^{\frac{5+3\,w_\phi}{2\,(1+w_\phi)}} ,\ M_{N_1} > T_{\rm BH}^{\rm in} \end{cases}$$

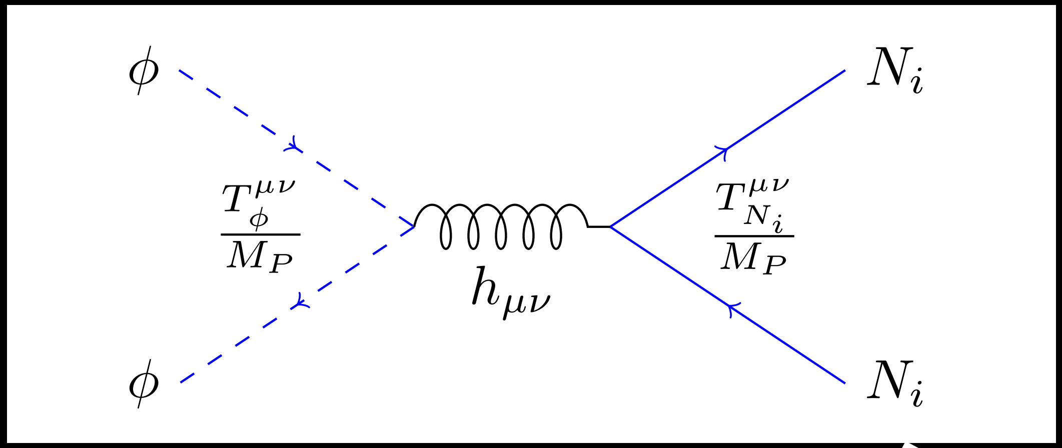
Graviton mediated scattering?

$$\sqrt{-g}\,\mathscr{L}_{\rm int} = -\frac{1}{M_P}\,h_{\mu\nu}\left(T^{\mu\nu}_{\rm SM} + T^{\mu\nu}_{\phi} + T^{\mu\nu}_{X}\right)$$



Graviton mediated scattering?

$$\sqrt{-g}\,\mathscr{L}_{\rm int} = -\frac{1}{M_P}\,h_{\mu\nu}\left(T^{\mu\nu}_{\rm SM} + T^{\mu\nu}_{\phi} + T^{\mu\nu}_{X}\right)$$

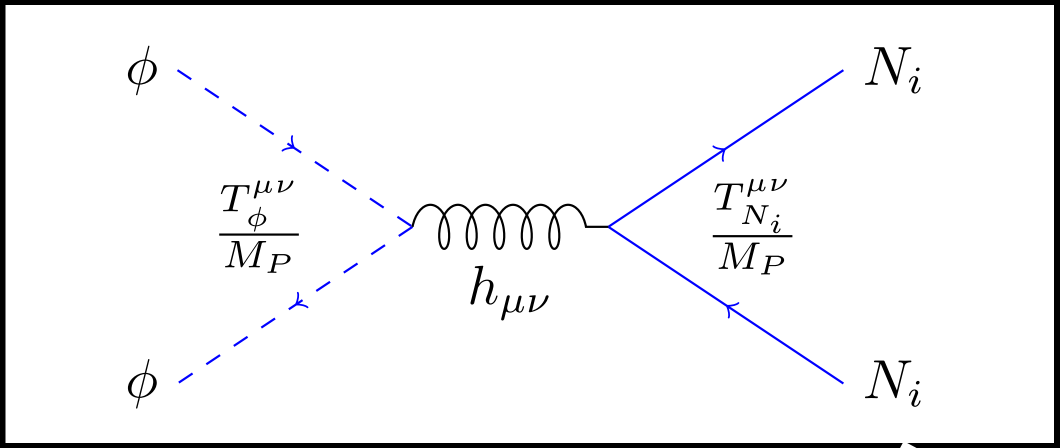


Production of N_1 : $$\frac{dn_{N_i}}{dt} + 3\,H\,n_{N_i} = R^{\phi^n}_{N_i}$$

$$\frac{\rho^2_{\phi}}{4\pi M_P^4}\,\frac{M^2_{N_i}}{m^2_{\phi}}$$

Graviton mediated scattering?

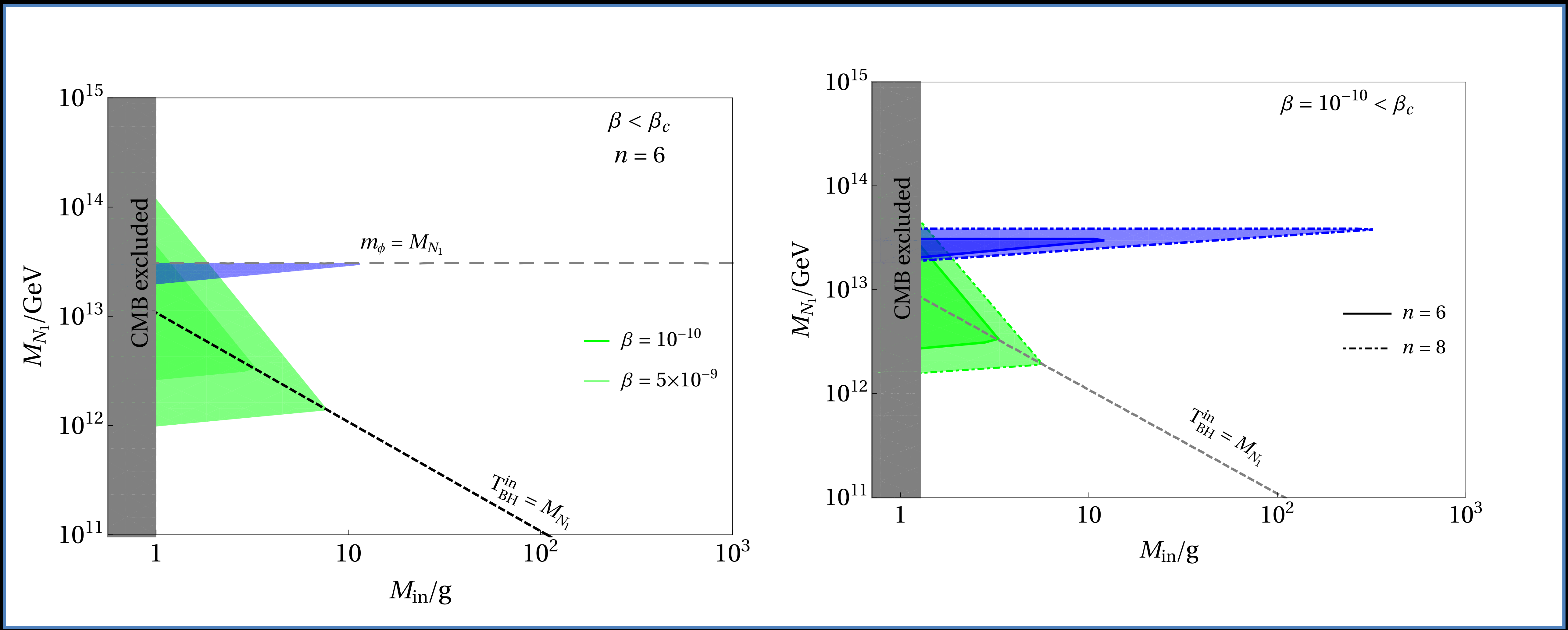
$$\sqrt{-g}\,\mathscr{L}_{\rm int} = -\frac{1}{M_P} h_{\mu\nu}\left(T^{\mu\nu}_{\rm SM} + T^{\mu\nu}_{\phi} + T^{\mu\nu}_{X}\right)$$



Production of N_1 : $$\frac{dn_{N_i}}{dt} + 3\,H\,n_{N_i} = R^{\phi^n}_{N_i} \rightarrow \frac{\rho_\phi^2}{4\pi M_P^4}\frac{M_{N_i}^2}{m_\phi^2}$$

Case I: Gets diluted because of PBH domination

Case II: $$n_{N_1}(a_{\rm RH})\Big|_{\beta<\beta_c} \propto \frac{M_{N_1}^2\sqrt{3}\,(n+2)\,\rho_{\rm RH}^{\frac{1}{2}+\frac{2}{n}}}{24\,\pi\,n(n-1)\lambda^{\frac{2}{n}}\,M_P^{1+\frac{8}{n}}}\left(\frac{\rho_{\rm end}}{\rho_{\rm RH}}\right)^{\frac{1}{n}}$$



Opens up larger PBH mass window for Case 2

Primordial Gravitational waves from Inflation

Sourced by tensor perturbations

$$ds^2 = a(\tau)\left[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j)\right]$$

Transfer function

$$P_T(k) = rA_s(k_*)\left(\frac{k}{k_*}\right)^{n_T}$$

$$\Omega_{\rm GW}(k) = \frac{1}{12H_0^2}\left(\frac{k}{a_0}\right)^2 T_T^2(\tau_0, k)P_T(k)$$

Constrained from CMB

For single-field slow roll inflation models: $n_T = -r/8 \simeq 0 \implies \Omega_{\rm GW}h^2 \sim 10^{-16}$

(too faint and scale-invariant...)

Primordial Gravitational waves from Inflation

Sourced by tensor perturbations

$$ds^2 = a(\tau)\left[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j)\right]$$

Transfer function

$$P_T(k) = r A_s(k_*)\left(\frac{k}{k_*}\right)^{n_T}$$

$$\Omega_{\rm GW}(k) = \frac{1}{12H_0^2}\left(\frac{k}{a_0}\right)^2 T_T^2(\tau_0, k) P_T(k)$$

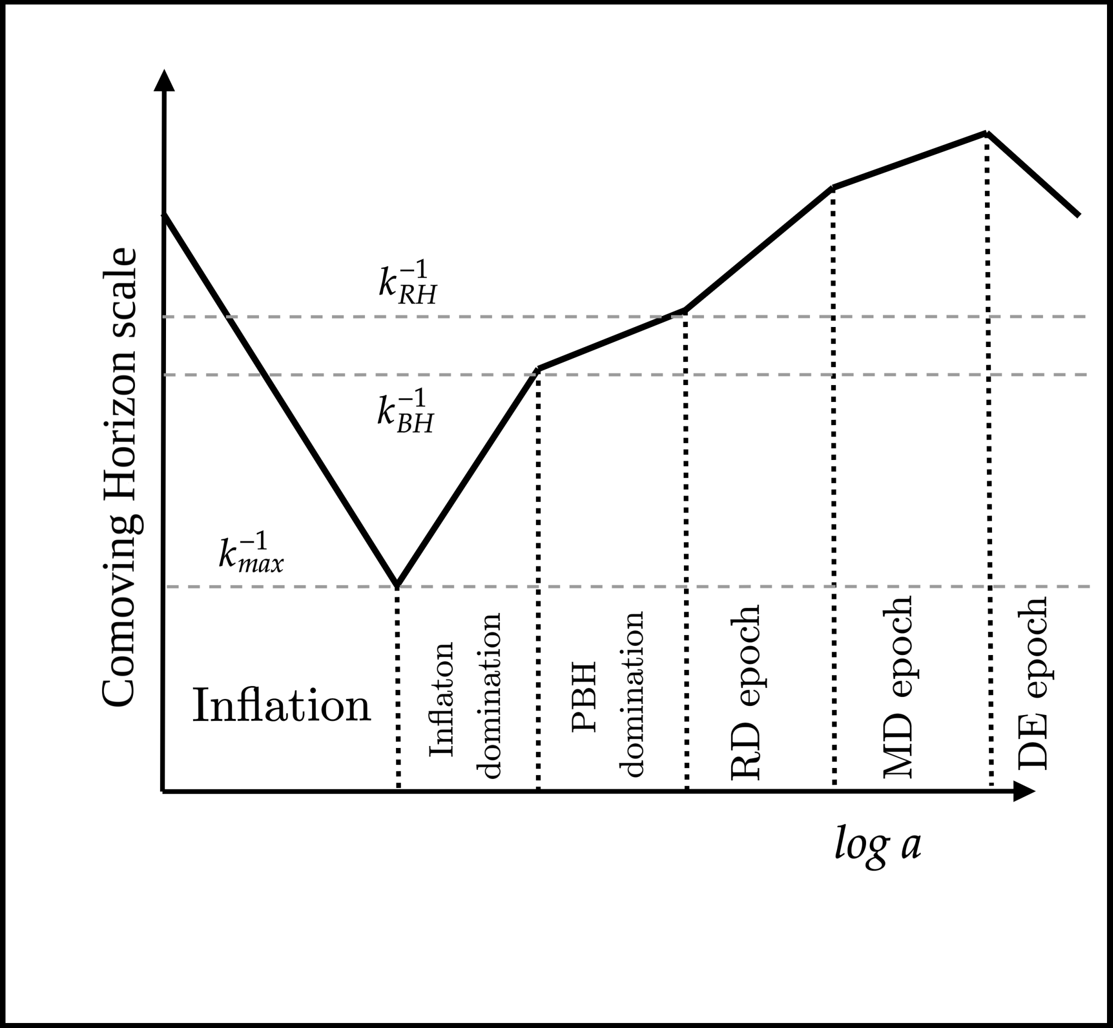
Constrained from CMB

For single-field slow roll inflation models: $n_T = -r/8 \simeq 0 \implies \Omega_{\rm GW} h^2 \sim 10^{-16}$

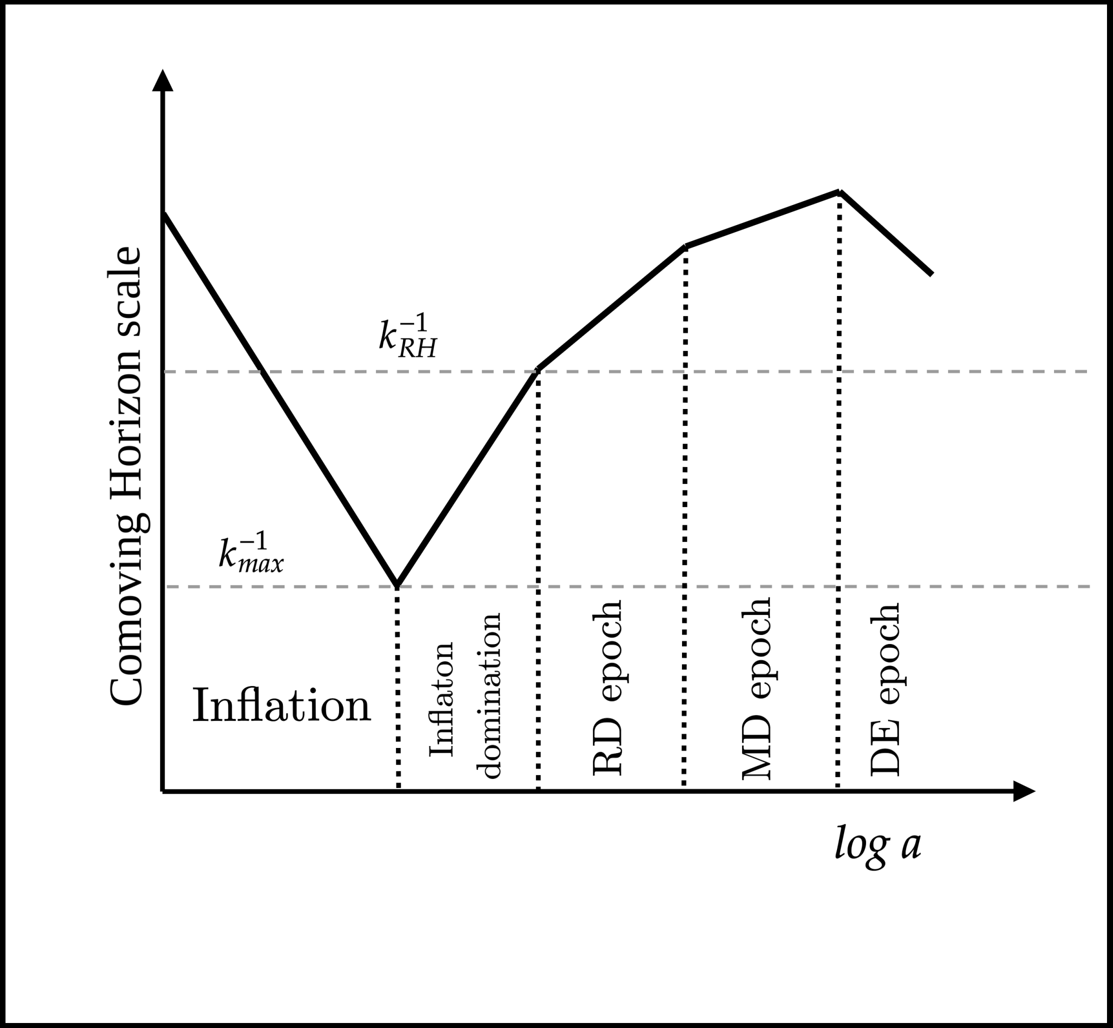
(too faint and scale-invariant...)

$T_T^2(\tau_0, k)$?

The Cosmic History



Case I



Case II

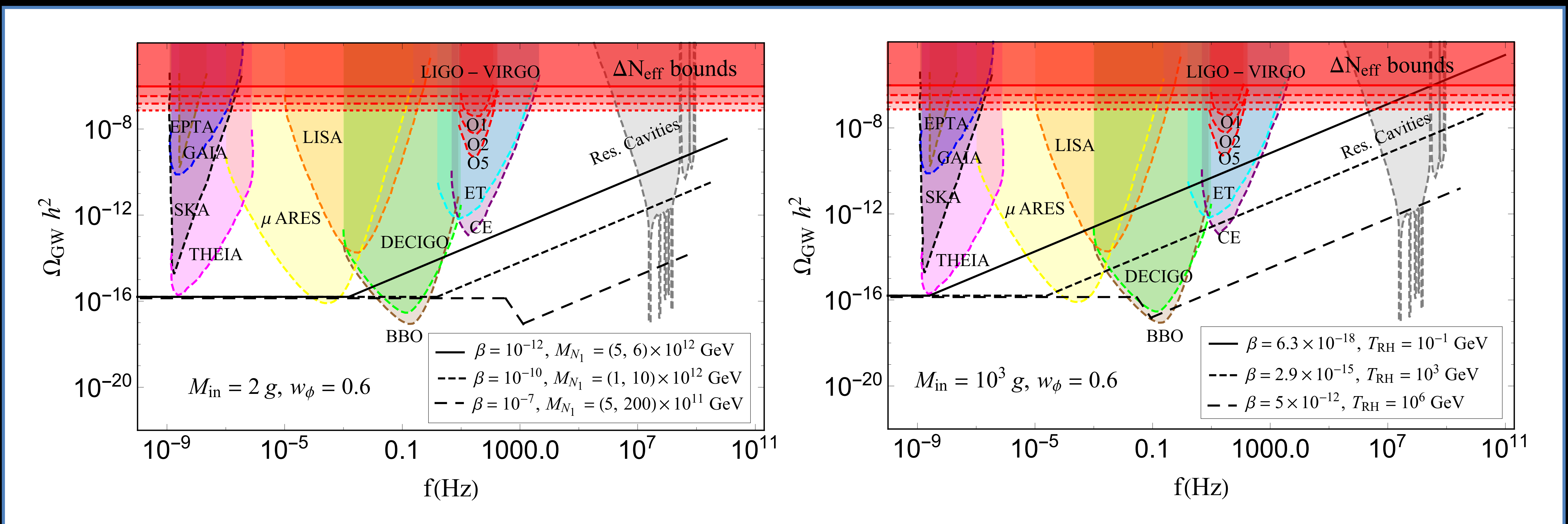
Gravitational wave spectrum

Case I

$$\Omega_{\rm GW}^{(0)} \simeq \Omega_{\rm GW,rad}^{(0)} \begin{cases} 1 & k < k_{\rm RH} \\ c_1 \left(\frac{k}{k_{\rm RH}}\right)^{-2} & k_{\rm BH} < k < k_{\rm RH} \\ c_2 \left(\frac{k}{k_{\rm BH}}\right)^{\frac{6\,w_\phi - 2}{1+3\,w_\phi}} & k_{\rm BH} < k < k_{\rm max} \end{cases}$$

Case II

$$\Omega_{\rm GW}^{(0)} \simeq \Omega_{\rm GW,rad}^{(0)} \begin{cases} 1 & k < k_{\rm RH} \\ \frac{\zeta}{\pi} \left(\frac{k}{k_{\rm RH}}\right)^{\frac{6\,w_\phi - 2}{1+3\,w_\phi}} & k_{\rm RH} < k < k_{\rm max}, \end{cases}$$



Constraints from $\Delta N_{\rm eff}$

GW : Extra relativistic degree of freedom:

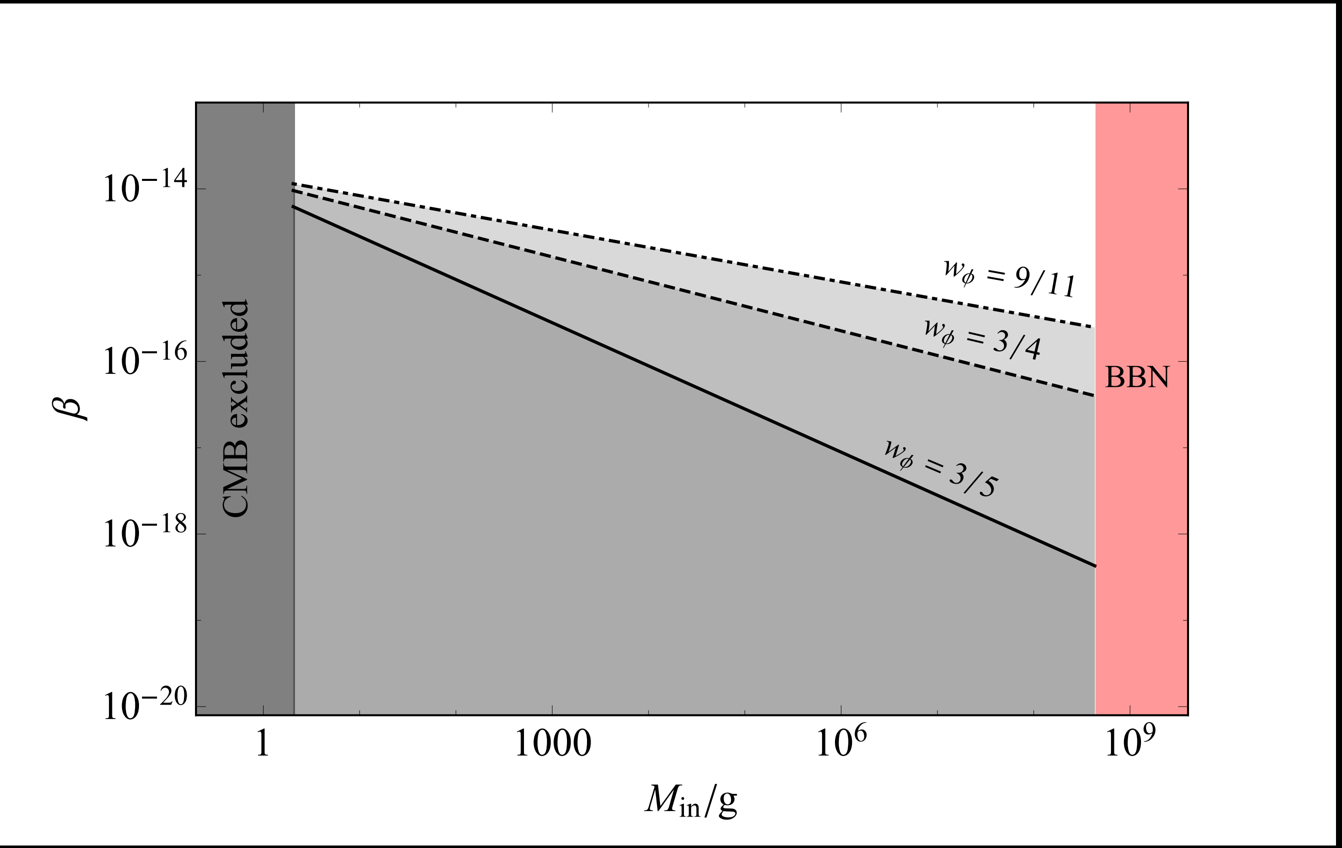
$$\rho_{\rm rad} = \rho_\gamma + \rho_\nu + \rho_{\rm GW} == \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 N_{\rm eff}\right]\rho_\gamma$$

$$\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{\rm SM} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}}\left(\frac{\rho_{\rm GW}(T)}{\rho_\gamma(T)}\right)$$

$$\int_{k_{\rm BBN}}^{k_{\rm max}} \frac{dk}{k}\Omega^{(0)}_{\rm GW} h^2(k) \simeq \Omega^{(0)}_{\rm GW,rad} h^2 \mu \left(\frac{k_{\rm max}}{k_{\rm RH}}\right)^{\frac{6w_\phi - 2}{1+3w_\phi}} \leq \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \Omega_\gamma h^2 \, \Delta N_{\rm eff}\,,$$

Lower bound on β:

$$\beta \geq \left(\frac{\Omega^{(0)}_{\rm GW,rad} h^2 \mu}{5.61 \times 10{-6}\, \Delta N_{\rm eff}}\right)\left(\frac{M_P}{M_{\rm in}}\right)^{\frac{2(1-w_\phi)}{1+w_\phi}} \times \left(\frac{1}{\mu^4 \alpha_{\rm T}} \frac{\rho_{\rm end}}{M_P^4}\right)^{\frac{3w_\phi - 1}{3(1+w_\phi)}}$$



Summary & Outlook

- PBH are enough to reheat the Universe.
- *Gravity-only* leptogenesis: from ultralight PBH & graviton mediated scatterings.
- Primordial GW from inflation modified and detectable across several bands of frequencies.
- Probable by $\Delta N_{\rm eff}$ future experiments.
- Details of reheating dynamics, other GW sources, connection with formation mechanisms….. ?

Somewhere in Edinburgh….

THANK YOU QUESTIONS?

BACK UP

$$\frac{\mathrm{d}^2\mathcal{N}_i}{\mathrm{d}p\,\mathrm{d}t} = \frac{g_i}{2\pi^2}\frac{\sigma_{s_i}(M_{\mathrm{BH}},\mu_i,p)}{\exp\left[E_i(p)/T_{\mathrm{BH}}\right]-(-1)^{2s_i}}\frac{p^3}{E_i(p)}$$

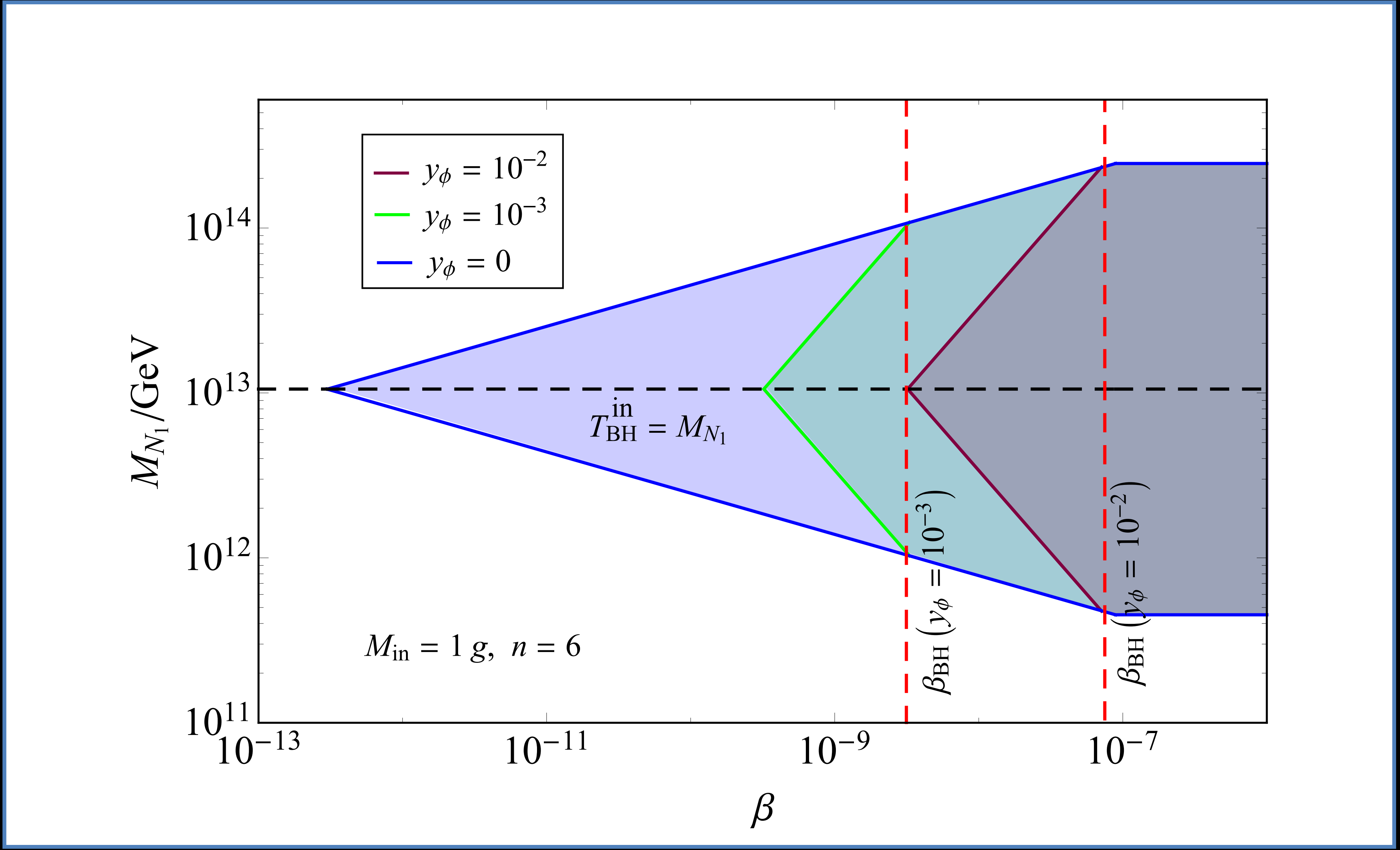
$$\frac{\mathrm{d}M_{\mathrm{BH}}}{\mathrm{d}t} \equiv \sum_i \left.\frac{\mathrm{d}M_{\mathrm{BH}}}{\mathrm{d}t}\right|_i = -\sum_i\int_0^\infty E_i\frac{\mathrm{d}^2\mathcal{N}_i}{\mathrm{d}p\mathrm{d}t}\mathrm{d}p$$

$$\left.n_{N_1}^{\phi^n}(a_{\mathrm{RH}})\right|_{\beta>\beta_c} \propto \frac{M_{N_1}^2\,M_P\,(n+2)\,48^{\frac{1}{n}}}{8\,\pi\,n(n-1)\lambda^{\frac{2}{n}}\,\beta}\left(\frac{\rho_{\mathrm{end}}}{M_P^4}\right)^{\frac{1}{n}}\left(\frac{M_P}{M_{\mathrm{in}}}\right)^{\frac{2+5n}{n}}\epsilon^2\,(\pi\gamma)^{-1+\frac{2}{n}}$$

$$\mu = \left(\frac{48\,\pi^2}{\alpha_T}\right)^{\frac{1}{4}}\left(\frac{\epsilon}{2\,(1+w_\phi)\,\pi\,\gamma^{3w_\phi}}\right)^{\frac{1}{2\,(1-3\,w_\phi)}}$$

$$c_1 = \left[\Gamma\left(\frac{5}{2}\right)\right]^2 / \pi \quad c_2 = (c\,\zeta/\pi))\ \left(k_{RH}/k_{\rm BH}\right)^2$$

$$m_\phi^2(t) = n\,(n-1)\lambda^{\frac{2}{n}}\, M_P^2 \left(\frac{\rho_\phi}{M_P^4}\right)^{\frac{n-2}{n}}$$



$$\frac{d\rho_\phi}{da} + 3\,(1+w_\phi)\,\frac{\rho_\phi}{a} = -\frac{\Gamma_\phi}{H}\,\left(1+w_\phi\right)\,\frac{\rho_\phi}{a}\,,$$

$$\frac{d\rho_R}{da} + 4\,\frac{\rho_R}{a} = -\frac{\rho_{\rm BH}}{M_{\rm BH}}\,\frac{dM_{\rm BH}}{da} + \frac{\Gamma_\phi\,\rho_\phi\,(1+w_\phi)}{a\,H},$$

$$\frac{d\rho_{\rm BH}}{da} + 3\,\frac{\rho_{\rm BH}}{a} = \frac{\rho_{\rm BH}}{M_{\rm BH}}\,\frac{dM_{\rm BH}}{da}\,,$$

$$\frac{dn_{N_1}^{\rm BH}}{da} + 3\,\frac{n_{N_1}^{\rm BH}}{a} = -n_{N_1}^{\rm BH}\,\Gamma_{N_1}^{\rm BH} + \Gamma_{{\rm BH}\to N_1}\,\frac{\rho_{\rm BH}}{M_{\rm BH}}\,\frac{1}{a\,H}\,,$$

$$\frac{dn_{B-L}}{da} + 3\,\frac{n_{B-L}}{a} = \frac{\epsilon_{\Delta L}}{a\,H}\left[\left(n_{N_1}^T - n_{N_1}^{\rm eq}\right)\,\Gamma_{N_1}^T + n_{N_1}^{\rm BH}\,\Gamma_{N_1}^{\rm BH}\right]$$

$$\frac{dM_{\rm BH}}{da} = -\epsilon\,\frac{M_P^4}{M_{\rm BH}^2}\,\frac{1}{a\,H}\,,$$

$$H^2 = \frac{\rho_\phi + \rho_R + \rho_{\rm BH}}{3\,M_P^2}\,.$$