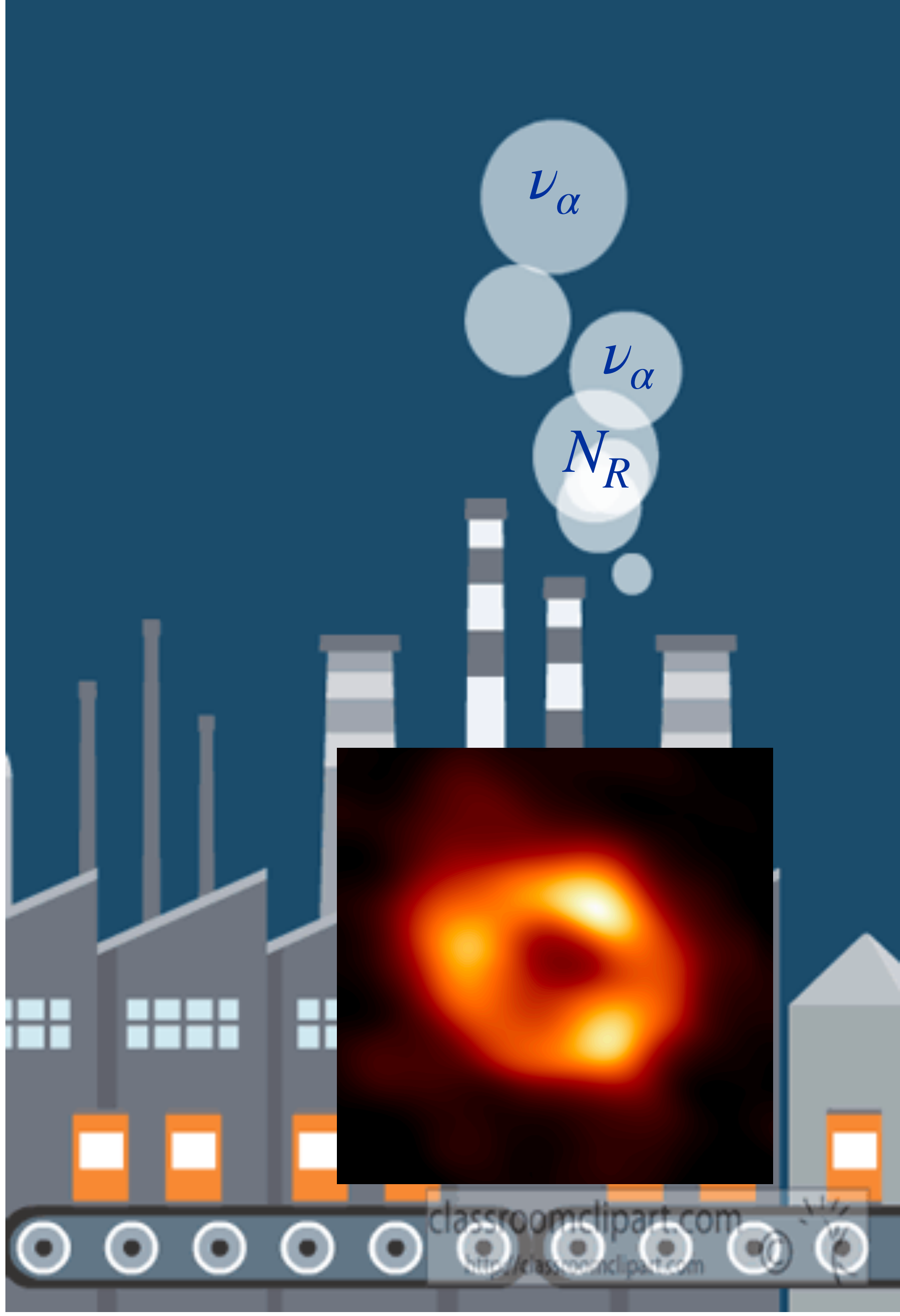
Leptogenesis looking into the abyss: The effects of Primordial Black Hole evaporation

Yuber F. Perez-Gonzalez

NEHOP, June 20th, 2023

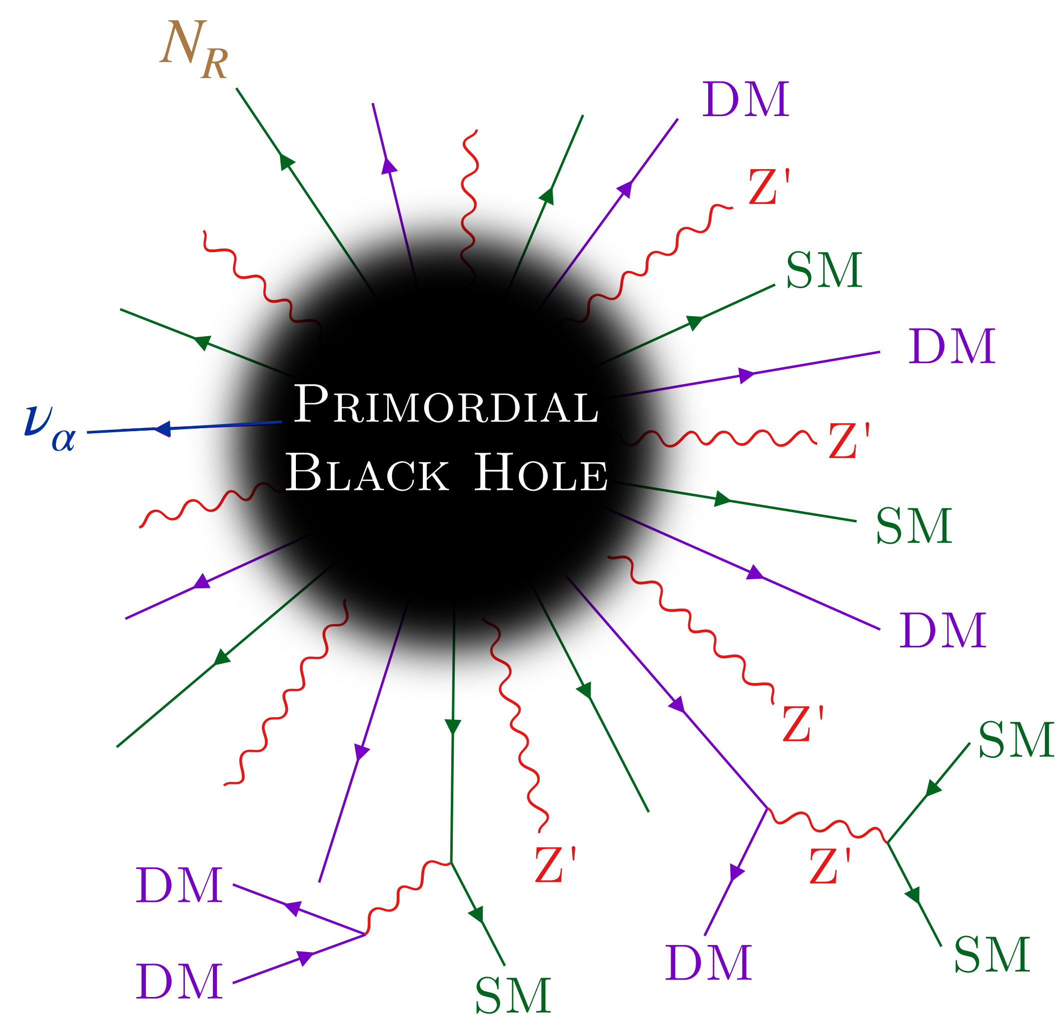


EHT Collaboration

Durham University
IP3

What's the impact of having evaporating Primordial Black Holes for Leptogenesis models?

- ✤ PBHs — Formation/Evaporation
- ✤ Massive Neutrino Emission from PBHs
- ✤ Interplay between PBHs ↔ Leptogenesis
- ✤ In progress

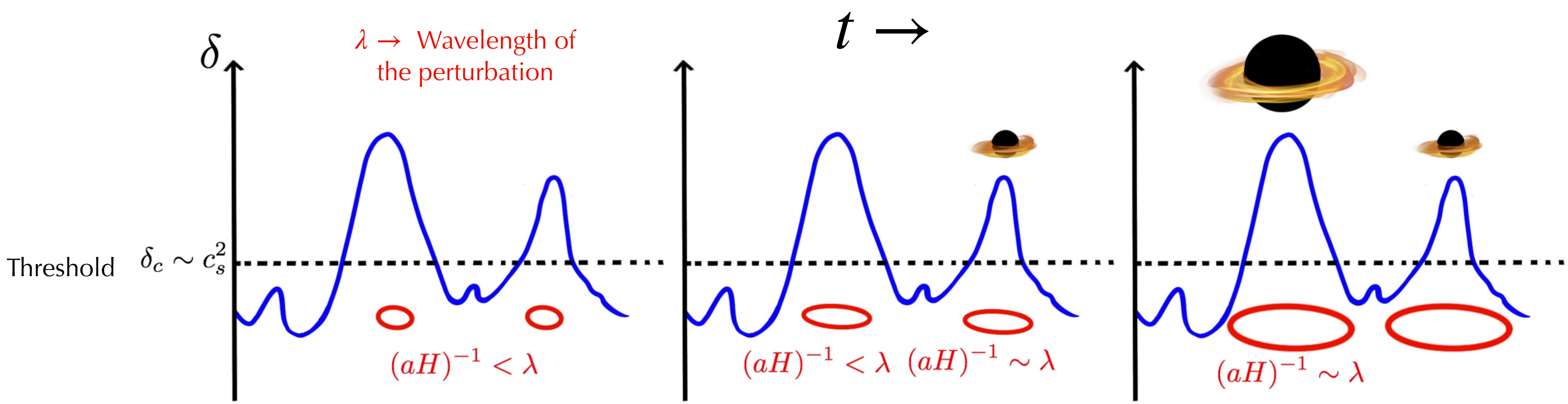


Formation

$$M_{\mathrm{BH,i}} \propto \underbrace{\frac{4\pi}{3}\rho\frac{1}{H^3}}_{\text{Mass contained in the horizon}}$$

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}$$

- Bubble collisions
- Pressure reduction
- Collapse of density fluctuations



Taken from Villanueva-Domingo, Mena, Palomares-Ruiz 2103.12087

Fraction of the total energy in PBH

$$\beta = \frac{\rho_{\mathrm{PBH}}}{\rho_{\mathrm{tot}}}$$

PBH form when the density perturbation enters the Hubble horizon

Carr et al. 2002.12778

See previous talks

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Fraction of the total energy in PBH

$$\beta = \frac{\rho_{\mathrm{PBH}}}{\rho_{\mathrm{tot}}}$$

Assume a monochromatic mass distribution

All PBHs with the same mass

$M_{\mathrm{BH},i}$, β

PBH form when the density perturbation enters the Hubble horizon

See previous talks

Carr et al. 2002.12778

Evaporation

Schwarzschild BH

Hawking Instantaneous Spectrum

$$\frac{d^2N_i}{dp\,dt} = \frac{g_i}{2\pi^2}\frac{\sigma_{s_i}(M,p,\mu_i)}{\exp[E_a(p)/T]-(-1)^{2s_i}}\frac{p^3}{E_a(p)}$$

BH Temperature

$$T = \frac{\hbar c^3}{8\pi G M k} \sim 1\ \mathrm{GeV}\left(\frac{10^{13}\ \mathrm{g}}{M}\right)$$

*Hic depositum est, quod mortale fuit Isaaci Newtoni

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Absorption cross section

BH Temperature $T = \frac{\hbar c^3}{8\pi GMk}$

$$\sim 1\ \mathrm{GeV}\left(\frac{10^{13}\ \mathrm{g}}{M}\right)$$

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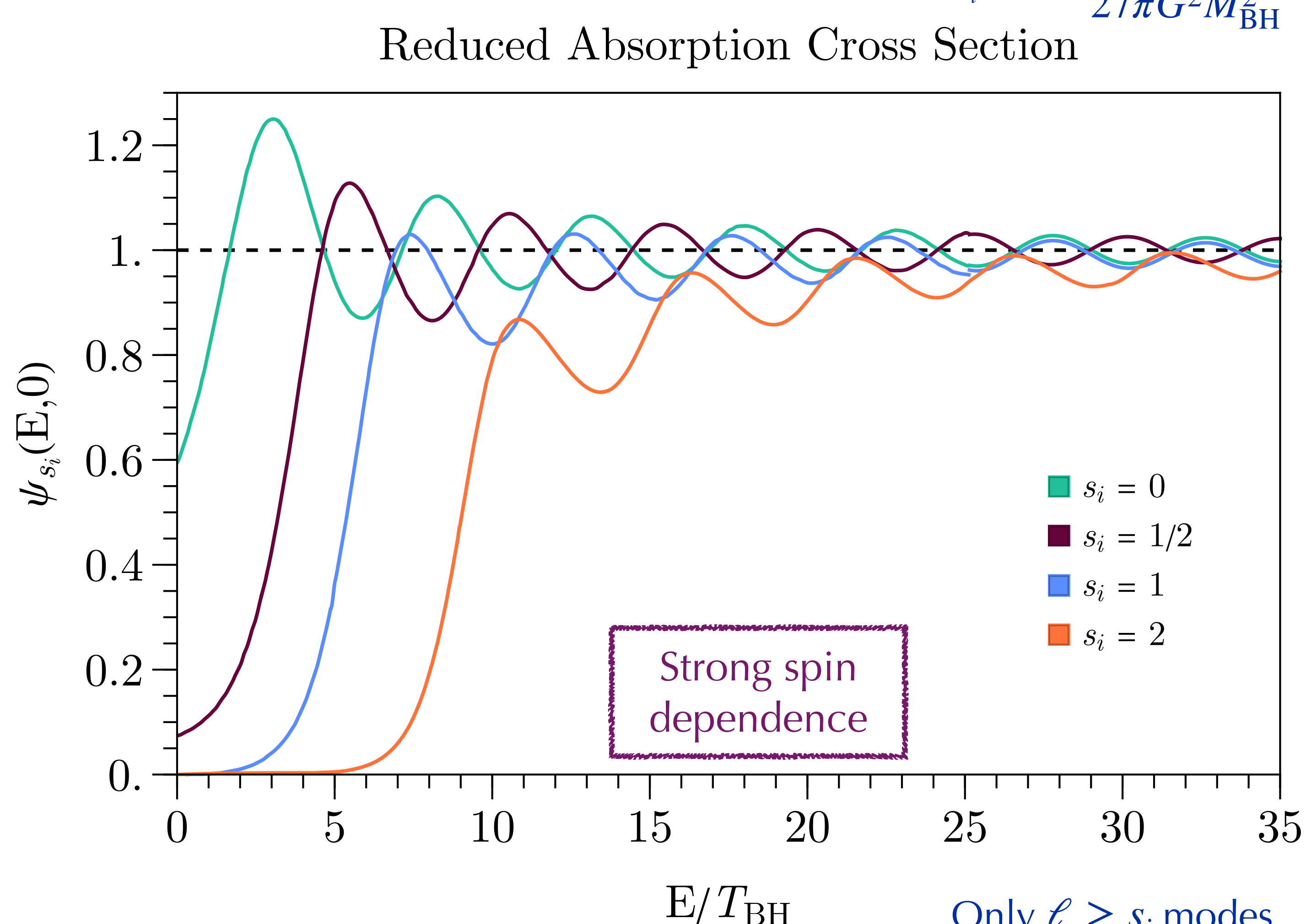
$$\psi_{s_i}(E) \equiv \frac{\sigma_{s_i}(E)}{27\pi G^2 M_{BH}^2}$$



Only $\ell \geq s_i$ modes

Why is interesting the particle production via evaporation?

DM production
(Besides PBH-DM)

- Purely Gravitationally interacting DM
- Modify Freeze-In/Freeze-out mechanisms

Fujita et al, 1401.1909
Lennon et al, 1712.07664
Morrison et al,1812.10606
Hooper, Krnjaic, McDermott, 1905.01301
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Bernal et al, 2010.09725, 2011.12306, …
Cheek, Heurtier, YFPG, Turner 2107.00013, 2107.00016, 2212.03878
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Baryon Asymmetry

- Modifying Baryogenesis scenarios
- Leptogenesis scenarios
- Producing a local asymmetry at PBH formation
- Connections with PBH-DM

Baumann, Steinhadt, Turok, 0703250
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Dark Radiation

- Production of hot gravitons
- Testable from future measurements on $\Delta N_{\rm eff}$

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See talks of Isabella, Nicolás, Andrew, Luca

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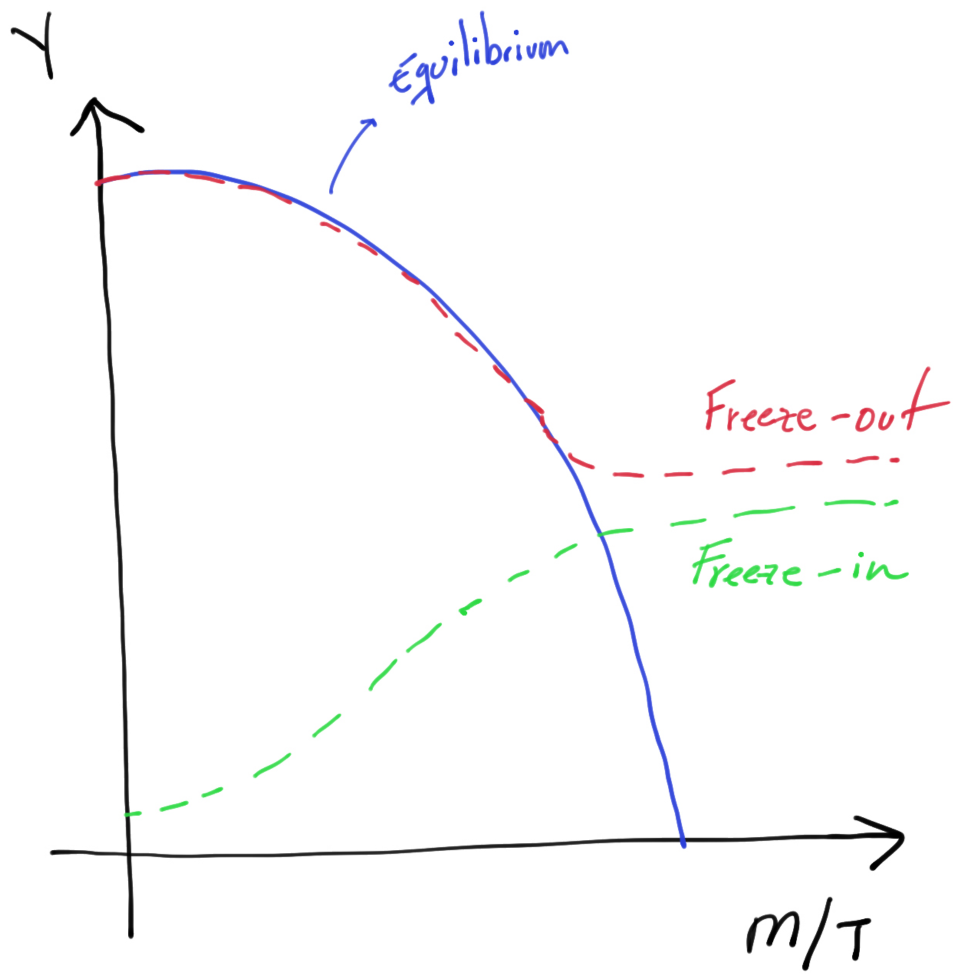
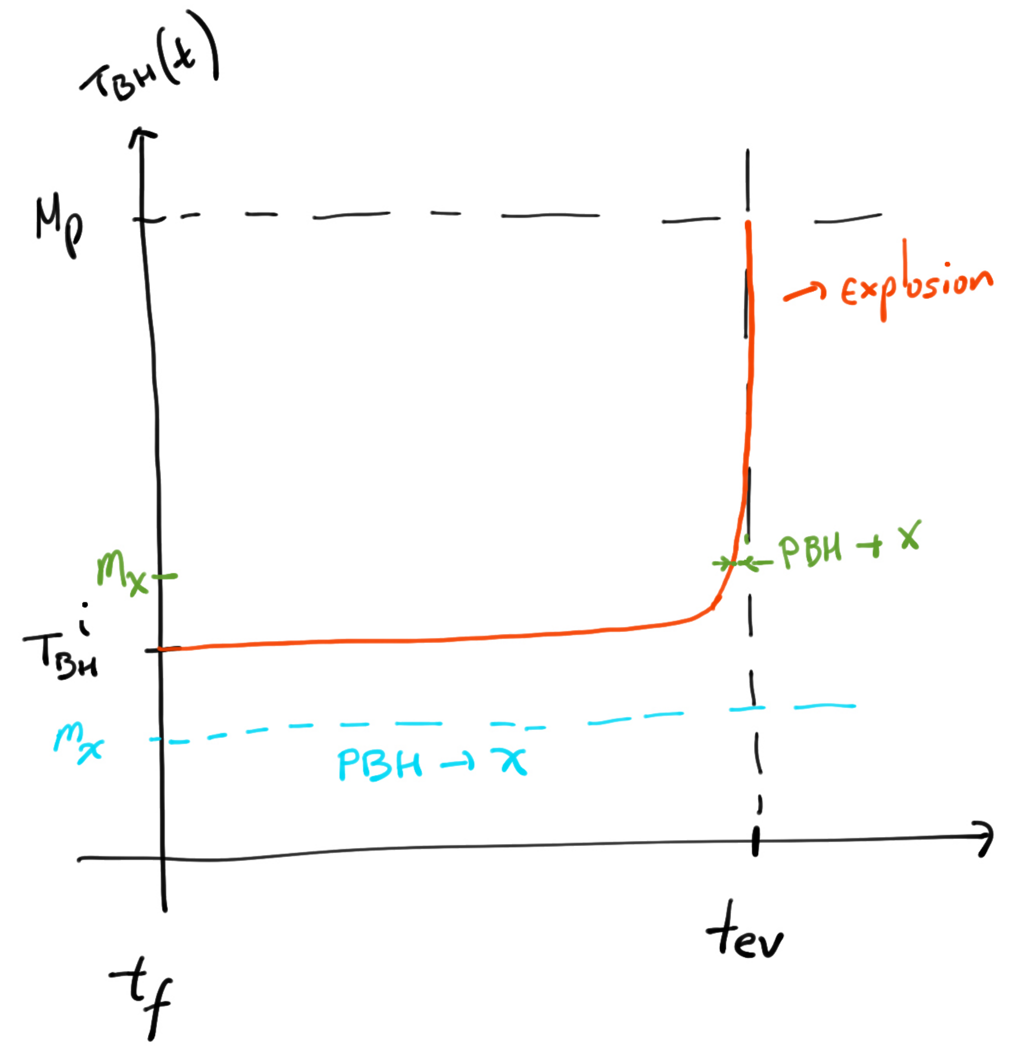
(Thermal) Particle decoupling



Abundances depend on masses and interactions

Hawking Evaporation



Abundances depend on masses and PBH parameters

- ❖ Modified Cosmology
- ❖ Particle production
- ❖ Entropy dilution

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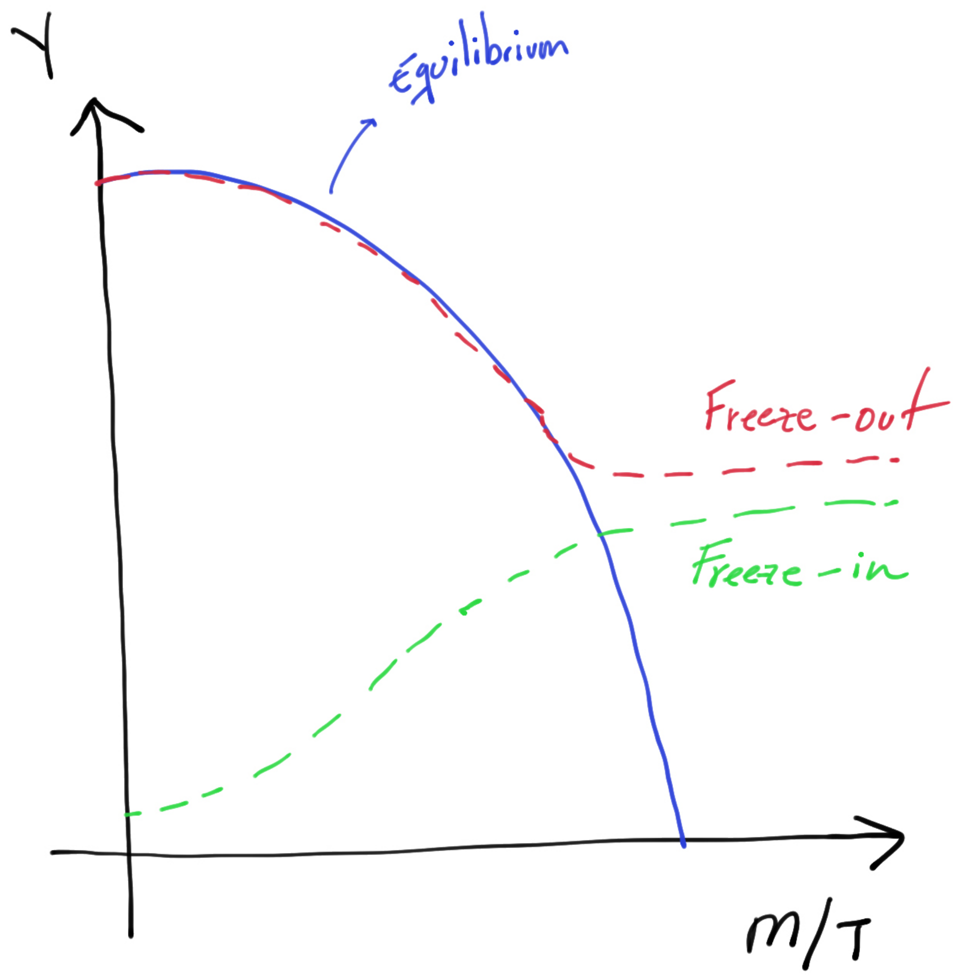

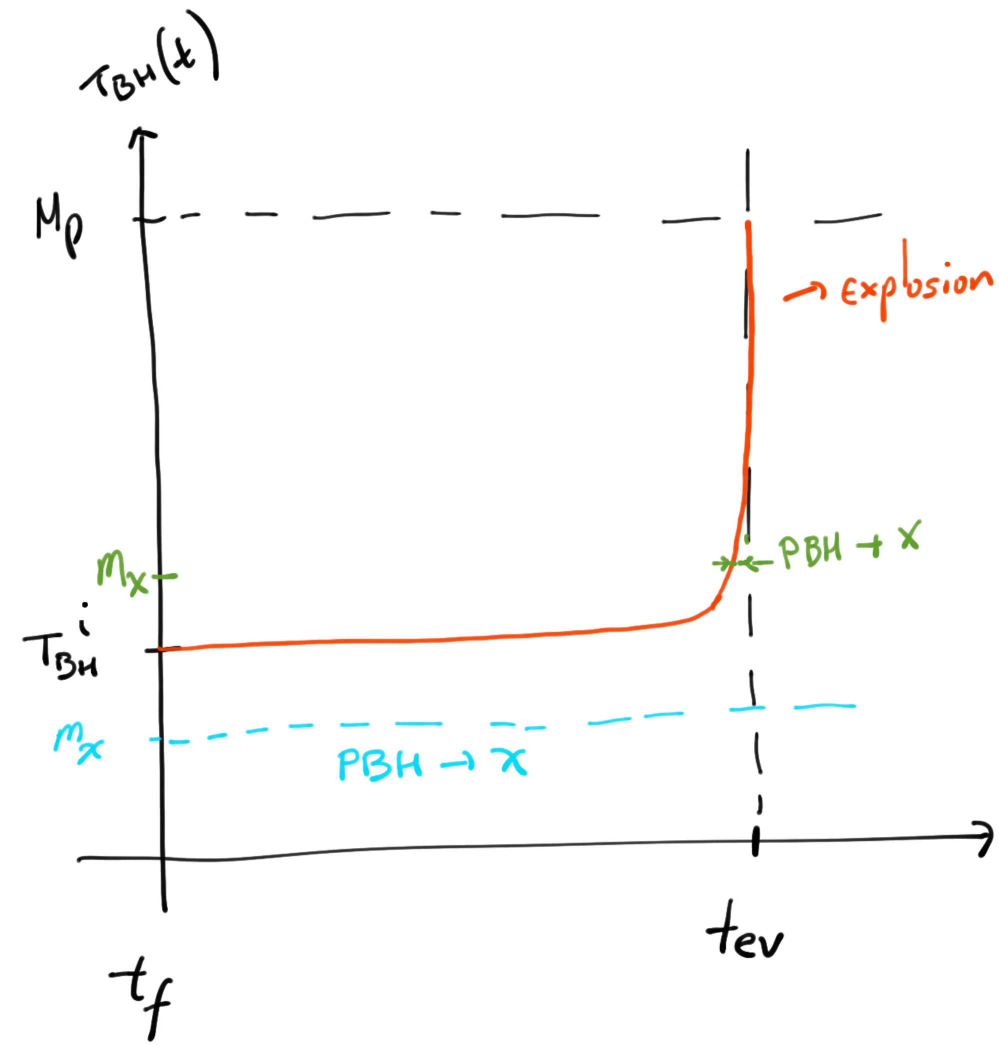

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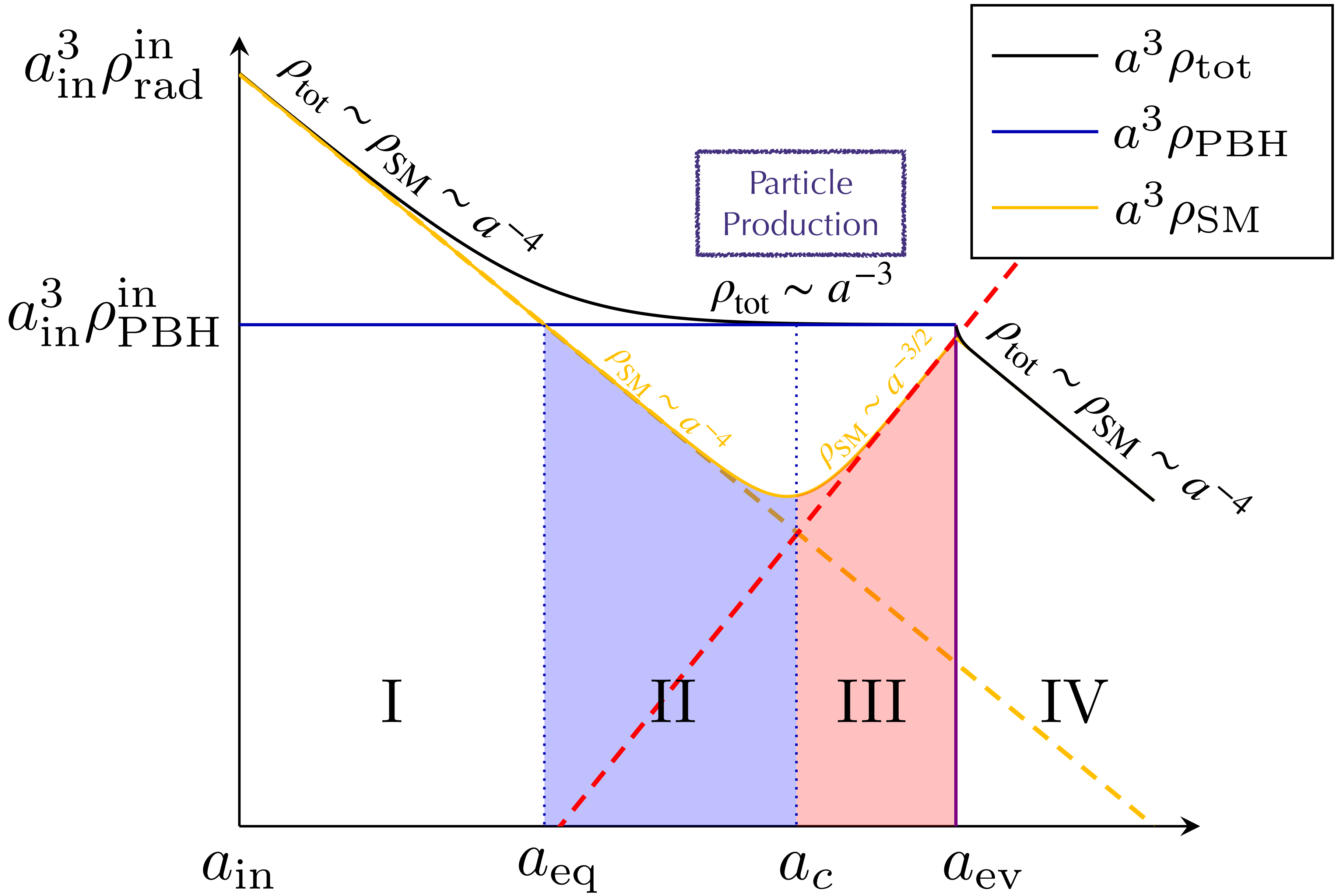
Abundances depend on masses and interactions

Interplay??

- ❖ Modified Cosmology
- ❖ Particle production
- ❖ Entropy dilution

PBHs: Rise and Fall

In a PBH dominated Early Universe



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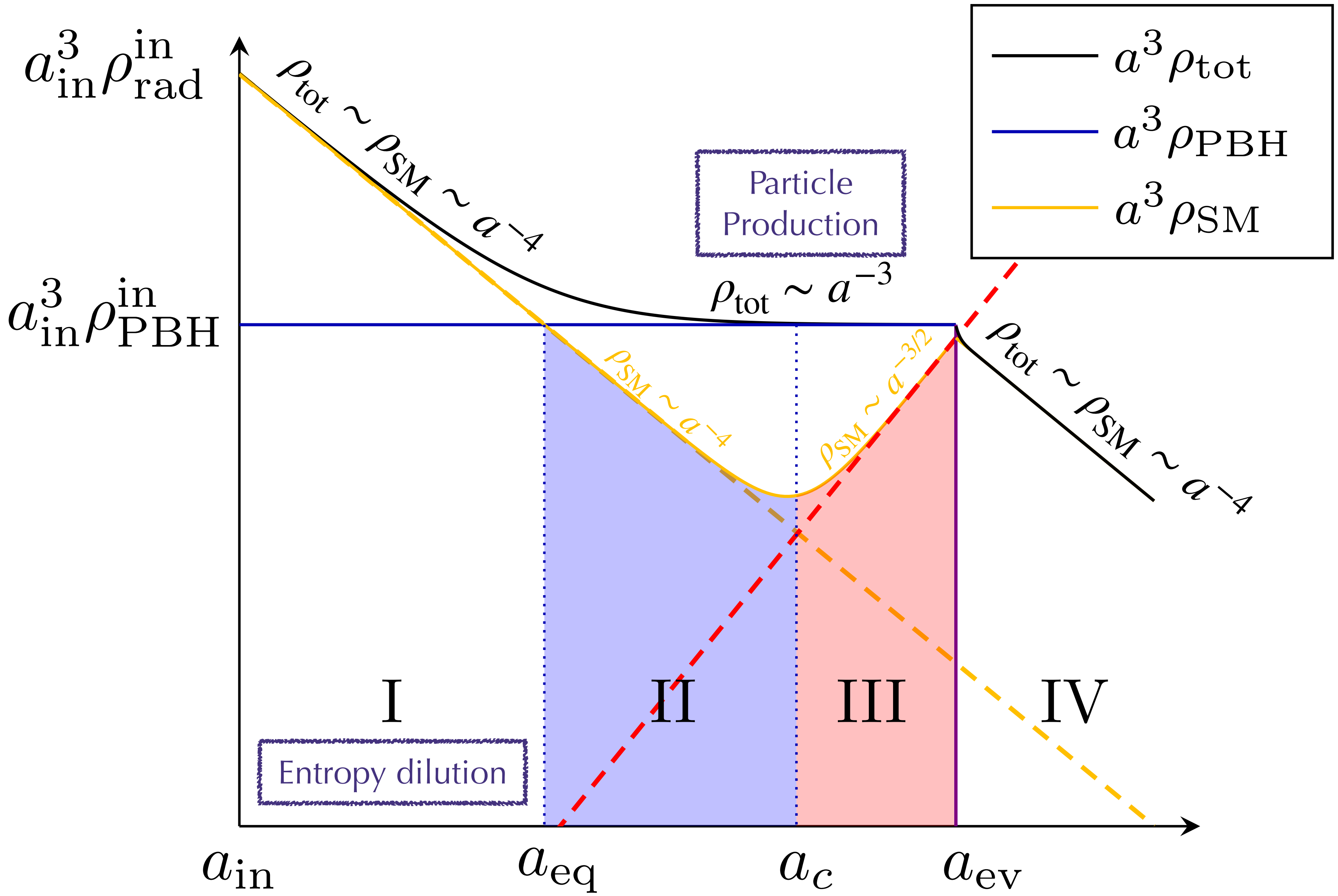

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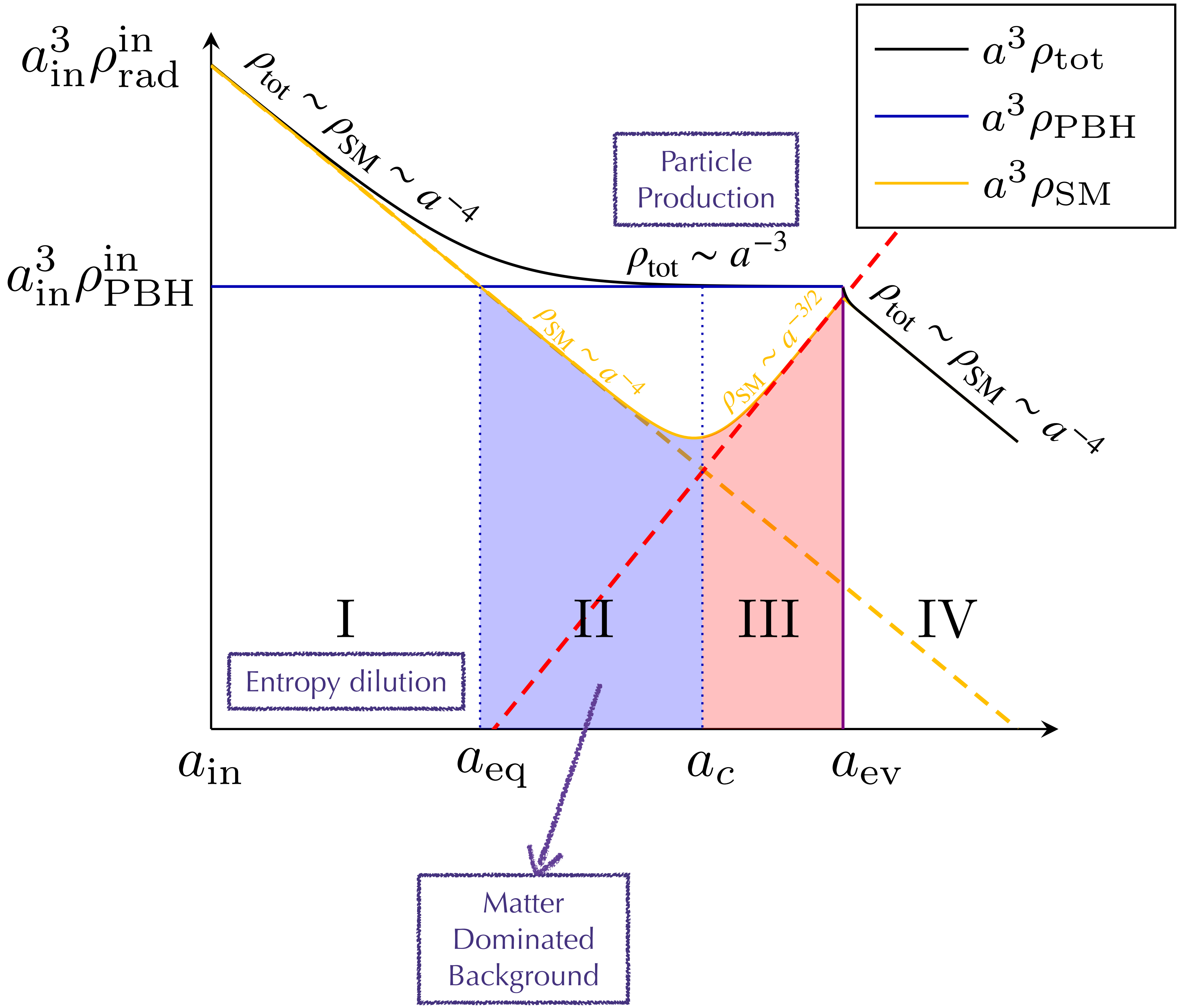

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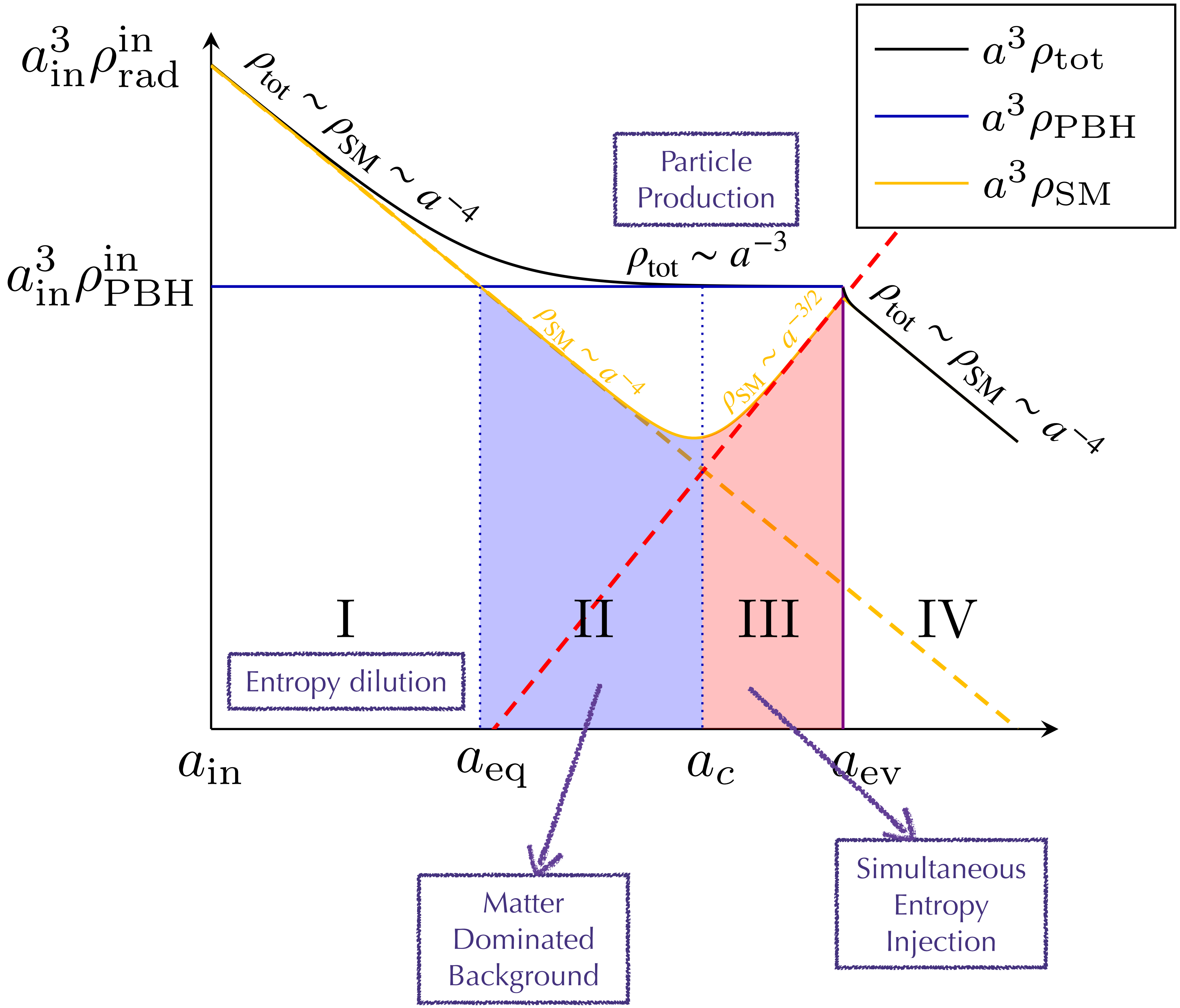

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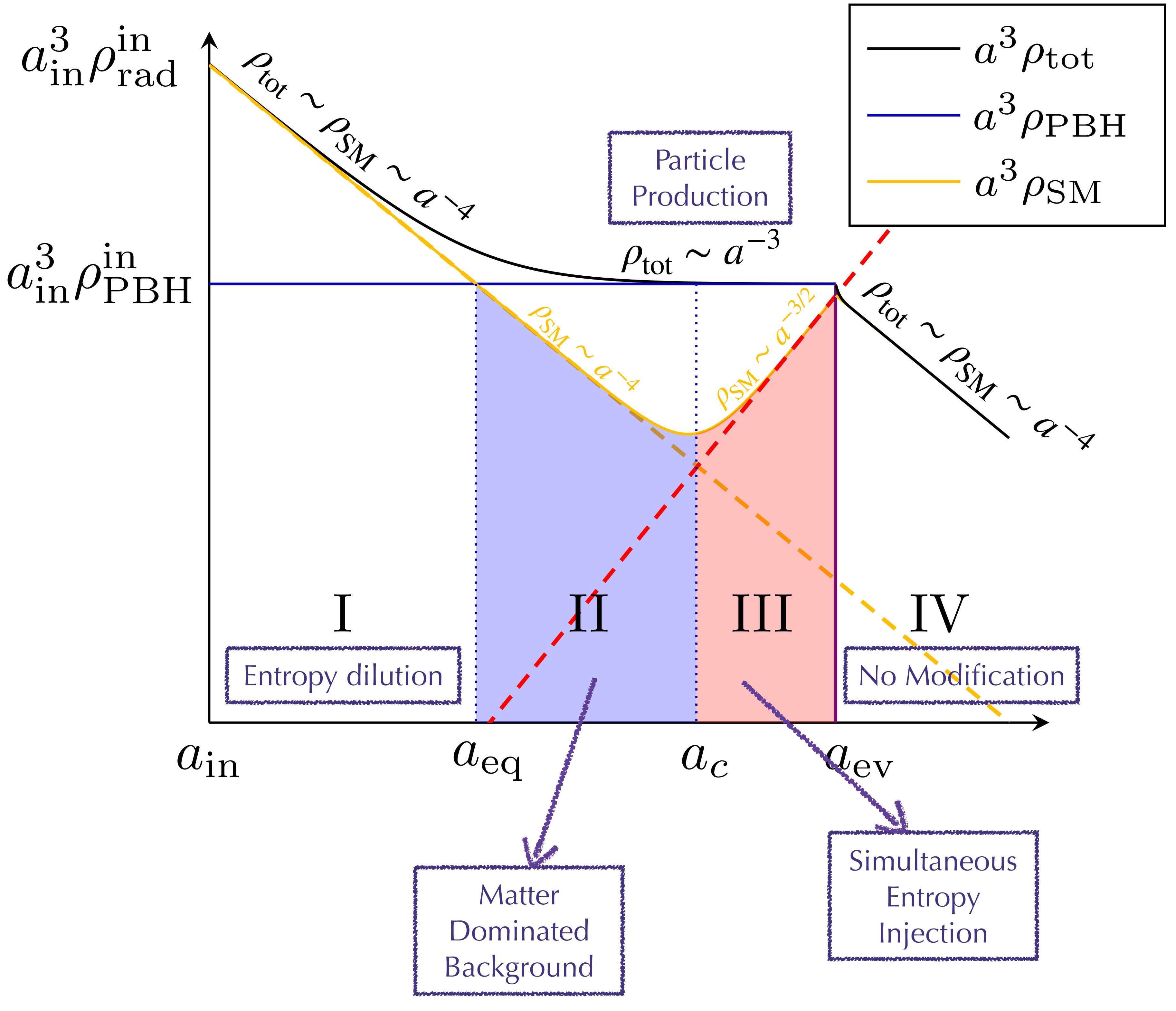

What about neutrino emission?

In the SM…

B. Carr, 1976

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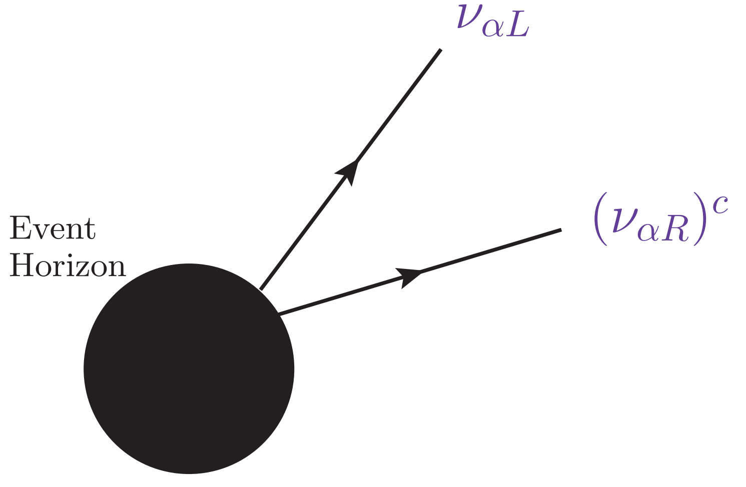


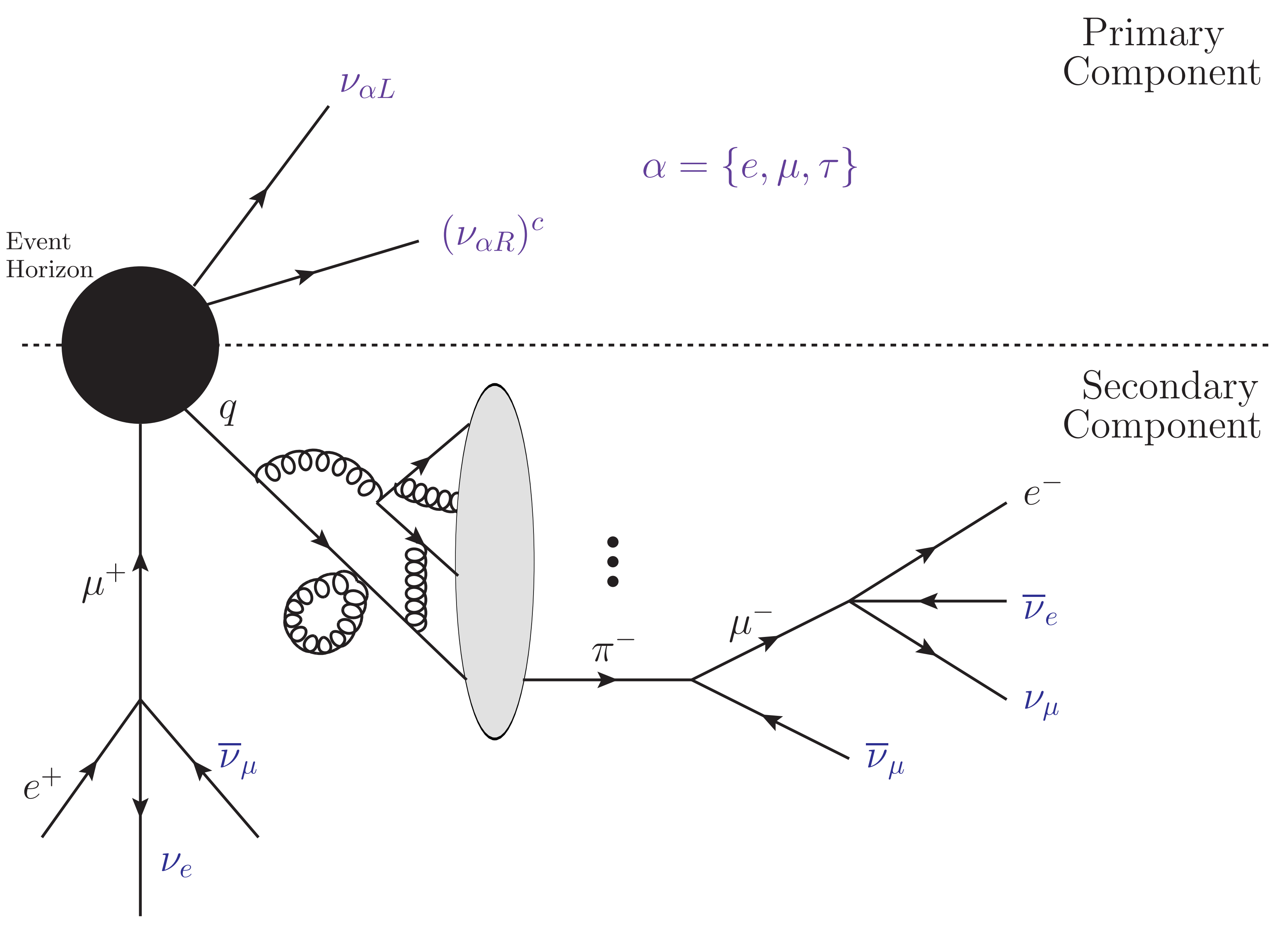
$\alpha = \{e, \mu, \tau\}$

Primary Component

B. Carr, 1976

What about neutrino emission?

In the SM…



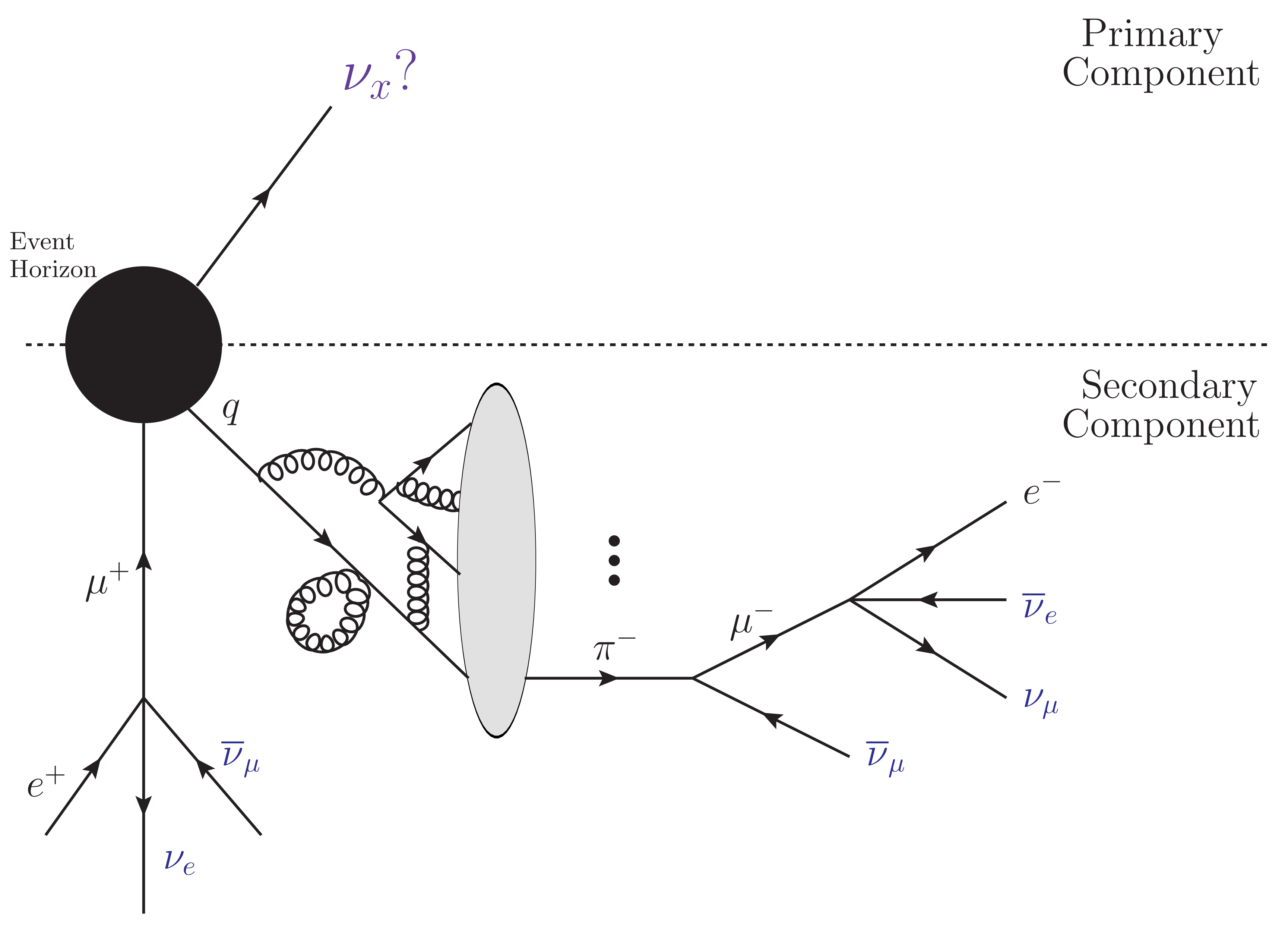
Constraints on the diffuse neutrino flux

B. Carr, 1976

J. MacGibbon, 1991
F. Halzen,9502268
Bugaev, 0005295

What is the state of the emitted neutrino?

Neutrinos are massive



Weak Interaction

What is the state of the emitted neutrino?

Weak interactions

ν_e ν_μ ν_τ

Hawking Effect

ν_1 ν_2 ν_3

What is the state of the emitted neutrino?

Weak interactions

$$n \rightarrow p^+ + e^- + \overline{\nu_e}$$

Interaction mediated by a gauge boson

Associated with a charged lepton

Flavor eigenstate

ν_e ν_μ ν_τ

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Hawking Effect

$$\langle 0_- | b_i^\dagger b_i | 0_- \rangle = \Gamma_{lm} \left[\exp\left(E_a / T_{\rm BH} + 1 \right) \right]^{-1}$$

Particle definition in a curved
spacetime is observer dependent

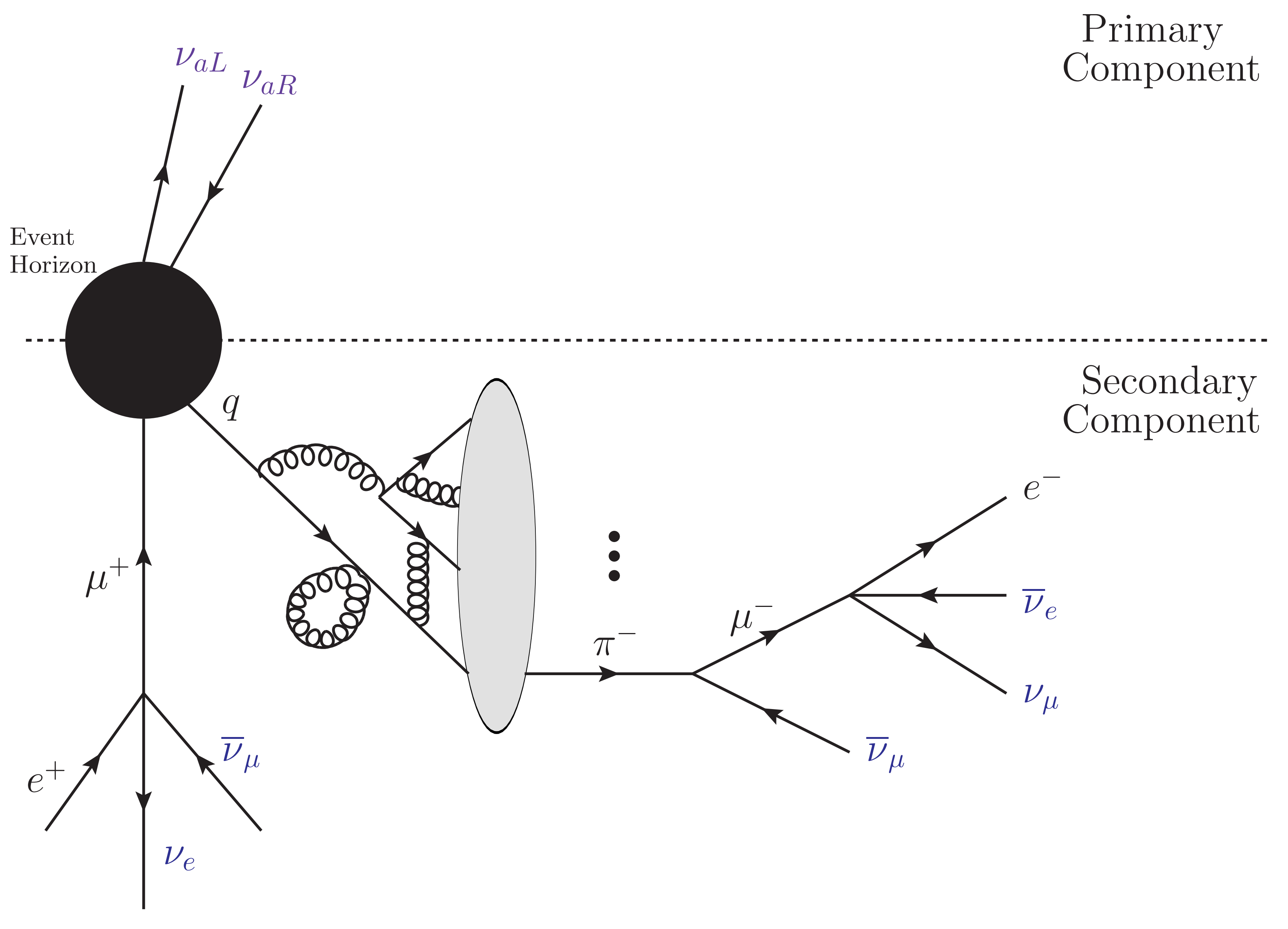
Particles with well-
defined kinematical
properties

Mass eigenstate

ν_1 ν_2 ν_3

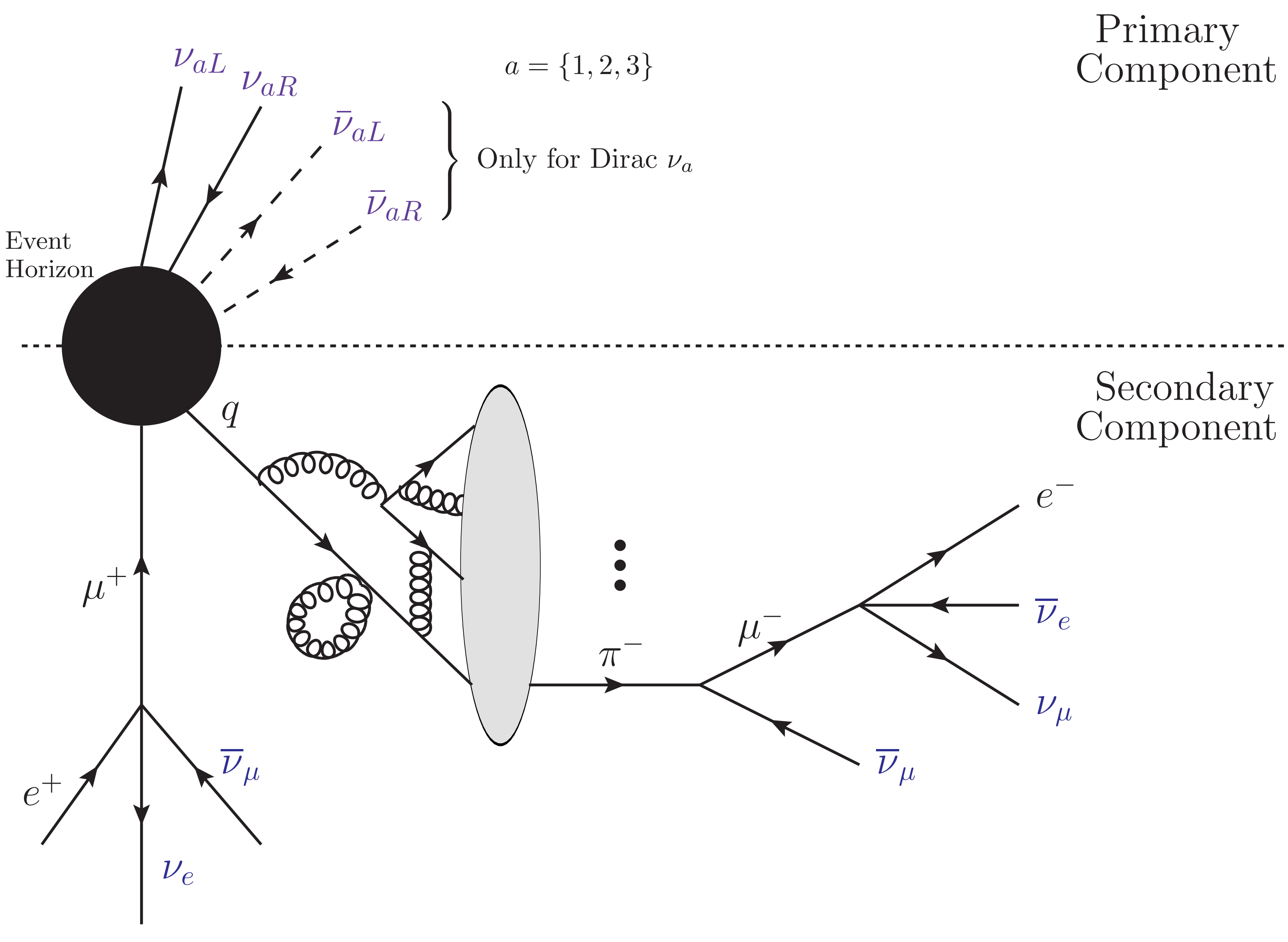
Dirac vs Majorana

Dirac vs Majorana



Majorana neutrinos

Dirac vs Majorana



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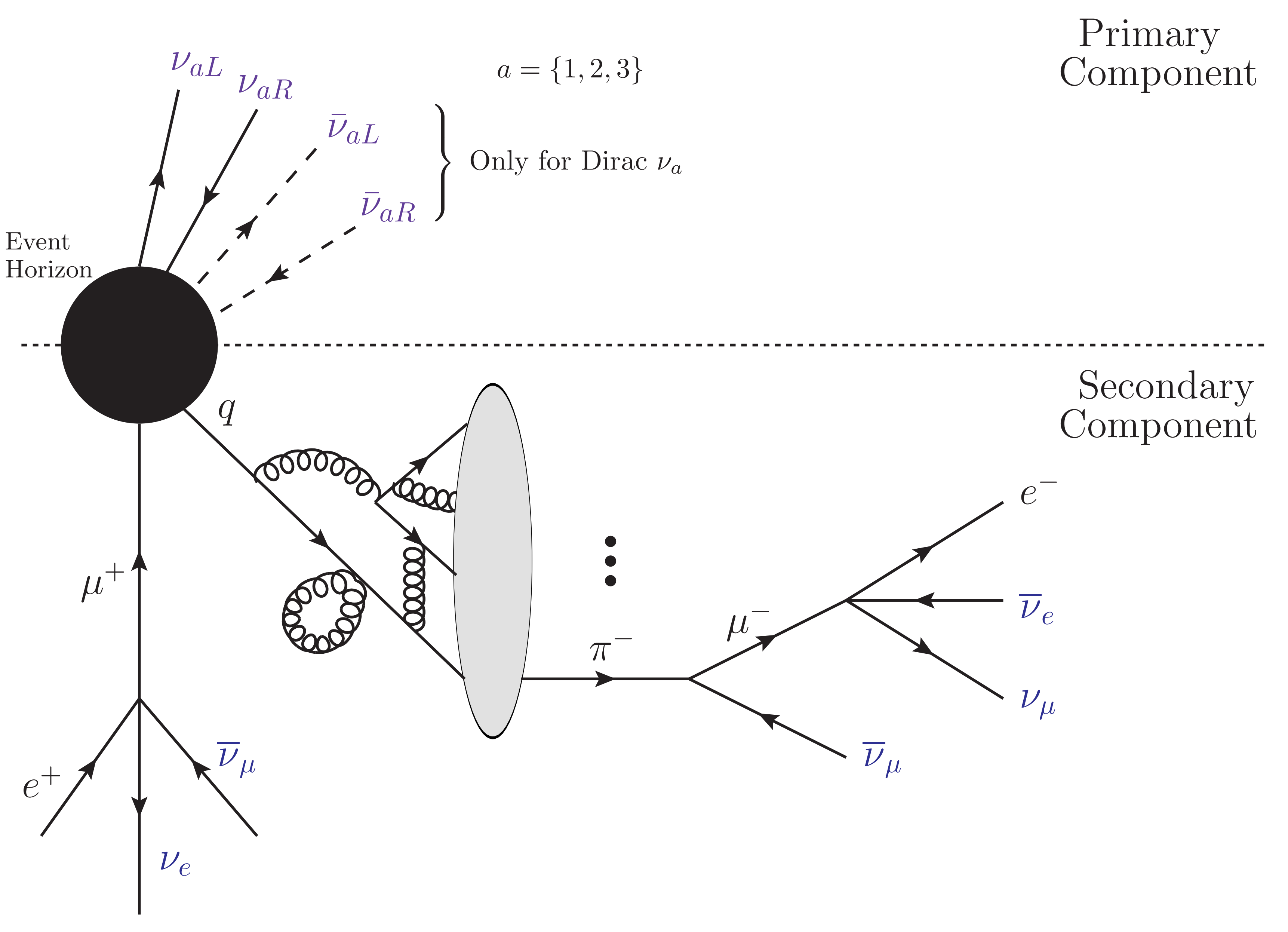


Dirac neutrinos

Phenomenological consequences?

Dirac neutrinos

VS

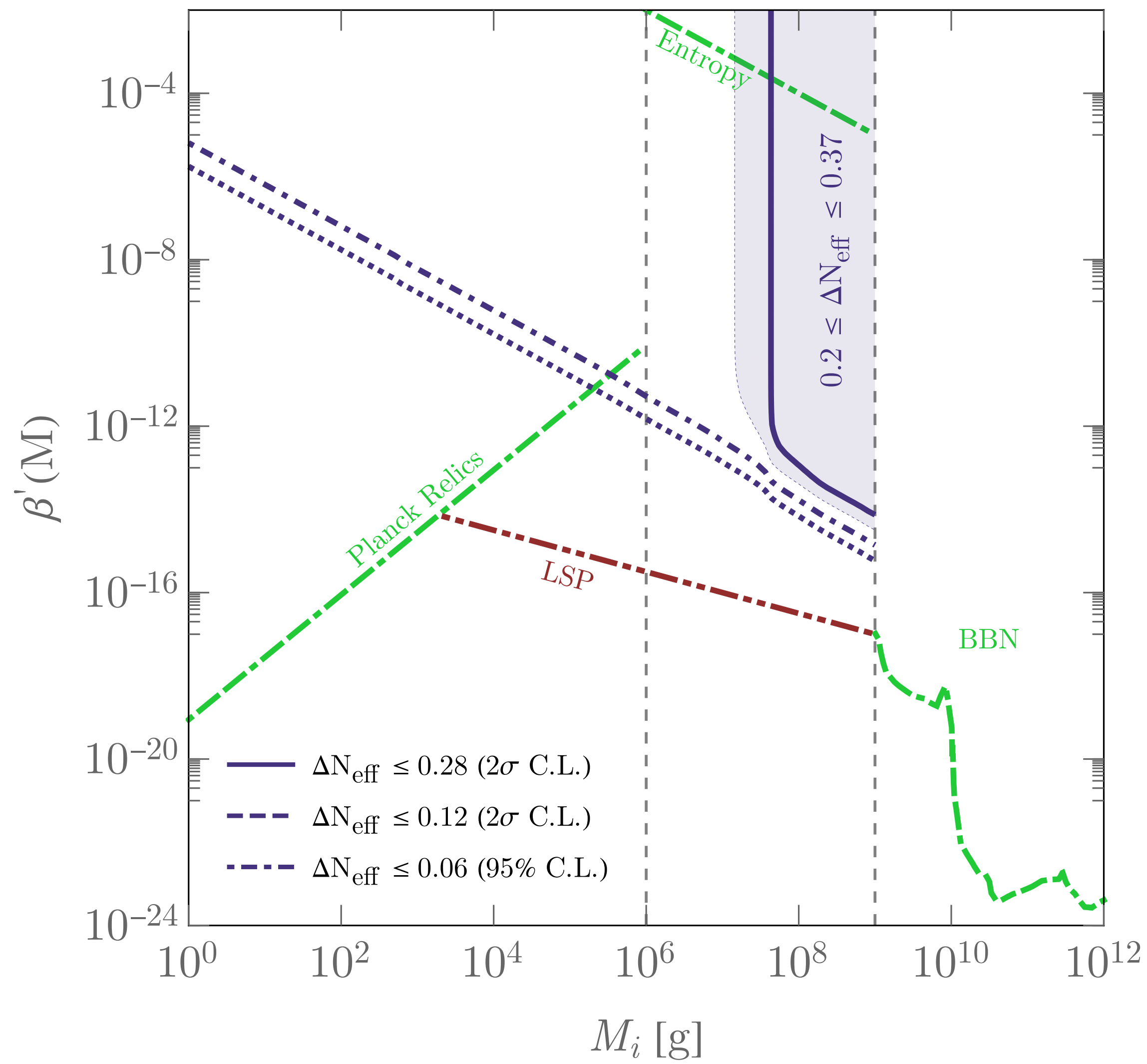
Majorana neutrinos

$$\sigma^{\nu}_{\rm abs}(+1/2) = \sigma^{\nu}_{\rm abs}(-1/2)$$

Production of light RH neutrinos!

Unruh, 1976

No helicity suppression



Heavy RH neutrinos

↓

PBH-induced Leptogenesis

Baumann, Steinhadt, Turok, 0703250
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Hooper and Krnjaic, 2010.01134
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YFPG and Jessica Turner, PRD 104(2021) 103021
Bernal, Fong, YFPG, Turner 2203.08823

Cecilia Lunardini, YFPG
JCAP08(2020)014

See Valentina's talk

Interplay between PBH and Leptogenesis

Based on:
YFPG and Turner: 2010.03565
Bernal, Fong, YFPG, Turner 2203.08823

Thermal Leptogenesis in a nutshell

Baryon asymmetry

$$\eta_{\rm CMB} = (6.23 \pm 0.17) \times 10^{-10}$$

$$\eta_{\rm BBN} = (6.08 \pm 0.06) \times 10^{-10}$$

Sakharov Conditions

- Baryon and Lepton number violation
- CP violation
- Departure from thermal equilibrium

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Type I seesaw:

$$-\mathscr{L} \supset \frac{1}{2} M_{N_i} \overline{N_i^c} N_i + \overline{\ell_\alpha} H^* Y_{\alpha i} N_i + \mathrm{H.c.}$$

$$m_\nu \sim \frac{Y_\nu^2 v^2}{M_N} \sim \mathcal{O}(0.1 \text{ eV})$$

$$Y_\nu = \frac{1}{v} U_{\text{PMNS}} \sqrt{m_\nu} R^T M_N^T$$

Casas, Ibarra, 2001

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Boltzmann Equations

$$\frac{dn_{N_i}}{dz} = D_i (n_{N_i} - n_{N_i}^{\rm eq})$$

$$\frac{dn_{\rm B-L}}{dz} = \sum_i \epsilon_i D_i (n_{N_i} - n_{N_i}^{\rm eq}) - \mathscr{W}_i\, n_{\rm B-L}$$

Washout

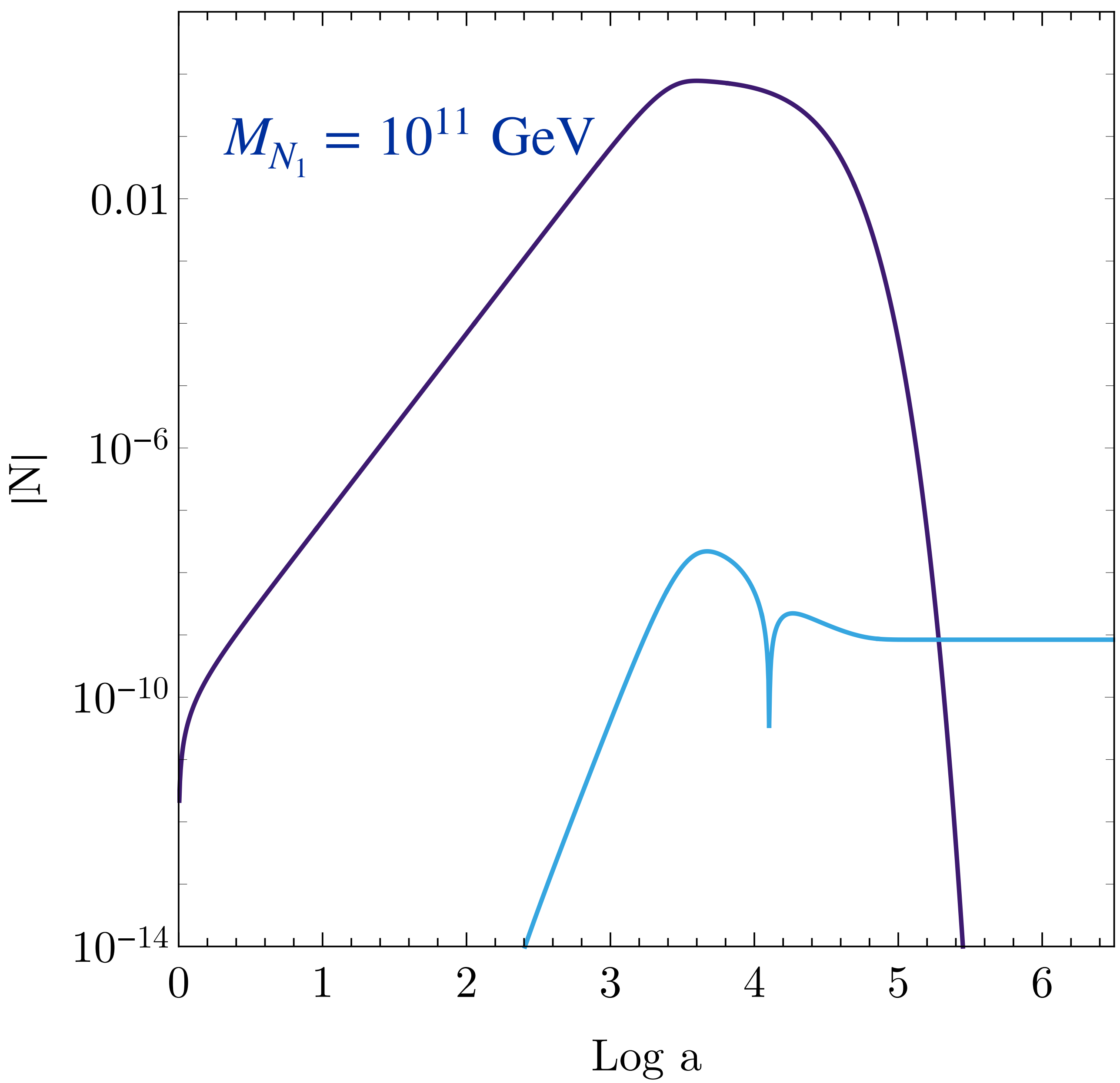
$$LH \leftrightarrow \overline{L}H$$

$$\Delta L = 2$$

Fukugida, Yanagida, ‘86

Thermal Leptogenesis in a nutshell

$$z \equiv \frac{M_{N_1}}{T}$$



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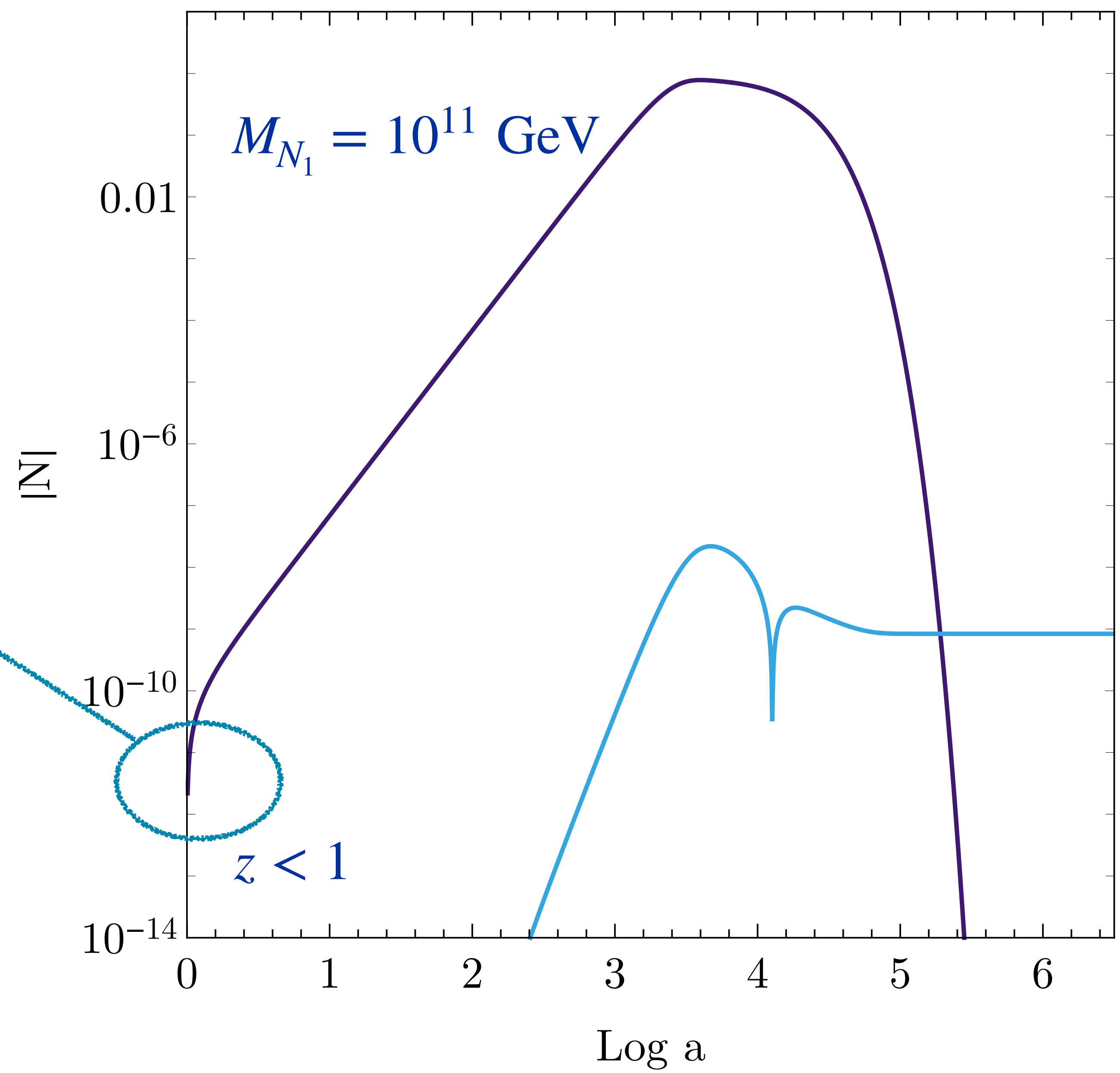
Thermal Leptogenesis in a nutshell

$z \equiv \frac{M_{N_1}}{T}$

At $T \sim M_N$
RH neutrinos are created

$LH \to N$

Initial abundance taken as zero



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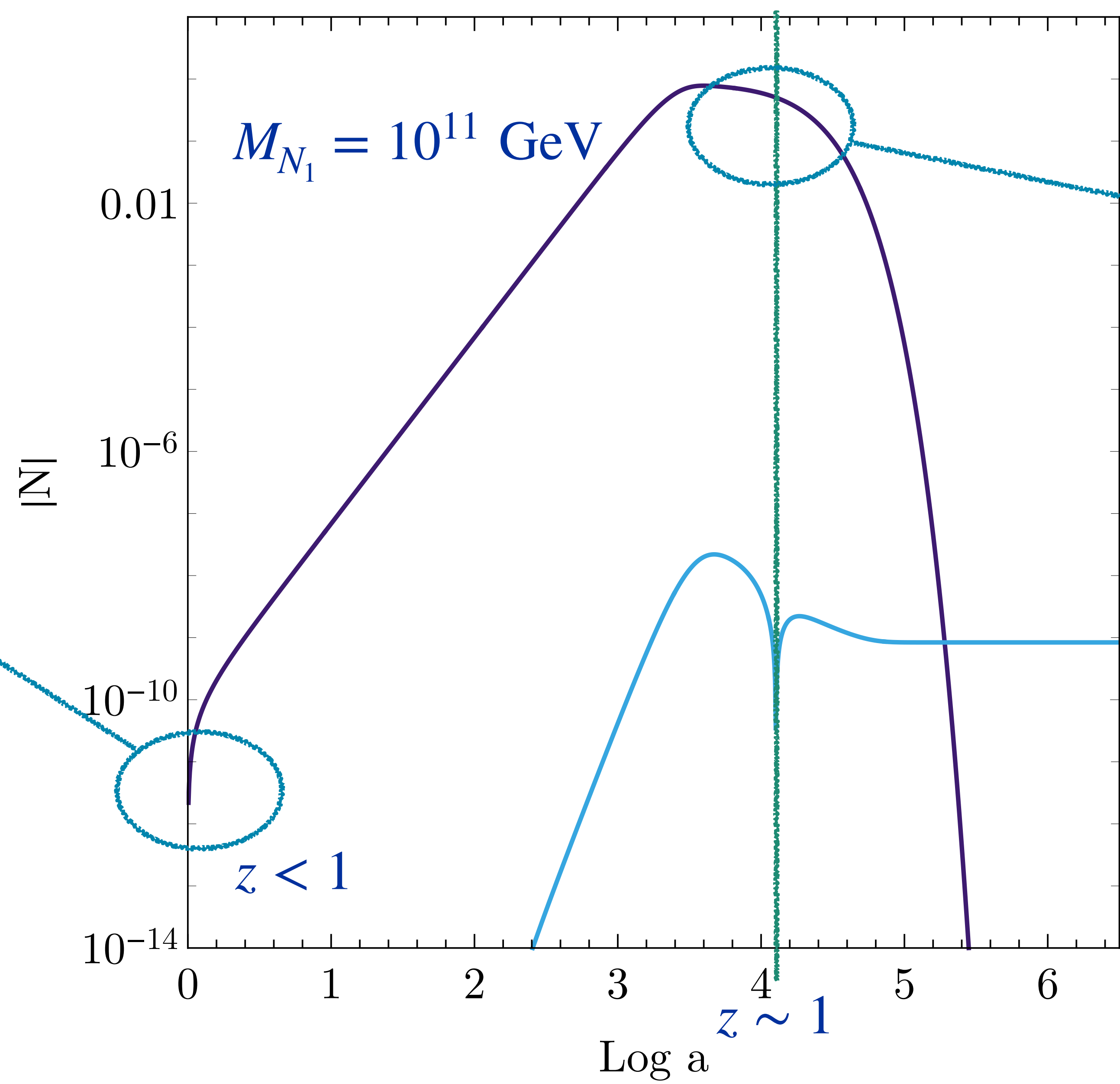

RH reaches equilibrium abundance

Initial abundance taken as zero

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Thermal Leptogenesis in a nutshell

$z \equiv \frac{M_{N_1}}{T}$

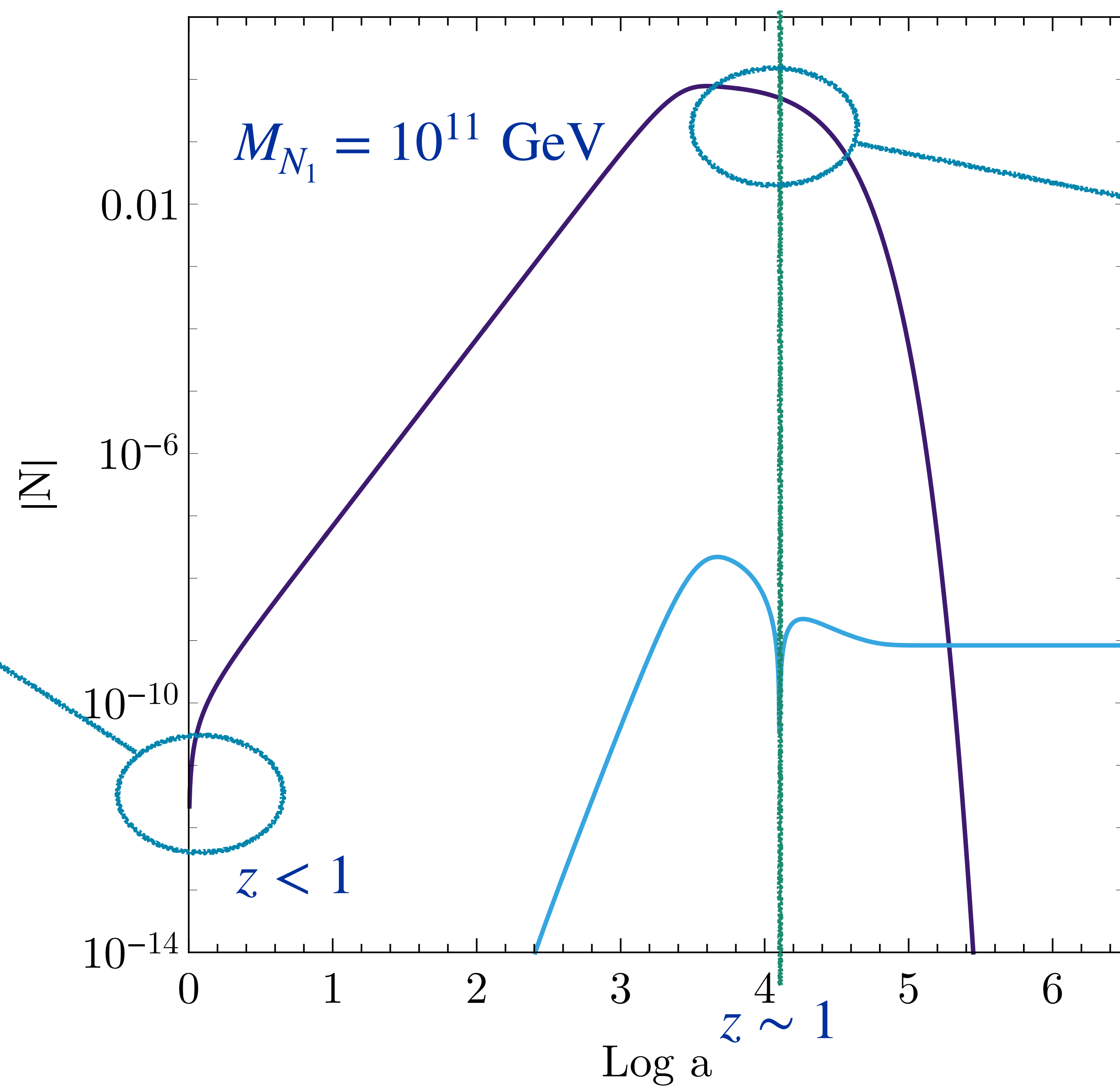
At $T \sim M_N$ RH neutrinos are created

$N \to LH$

$N \to \bar{L}H$

Lepton asymmetry is created

$LH \to N$



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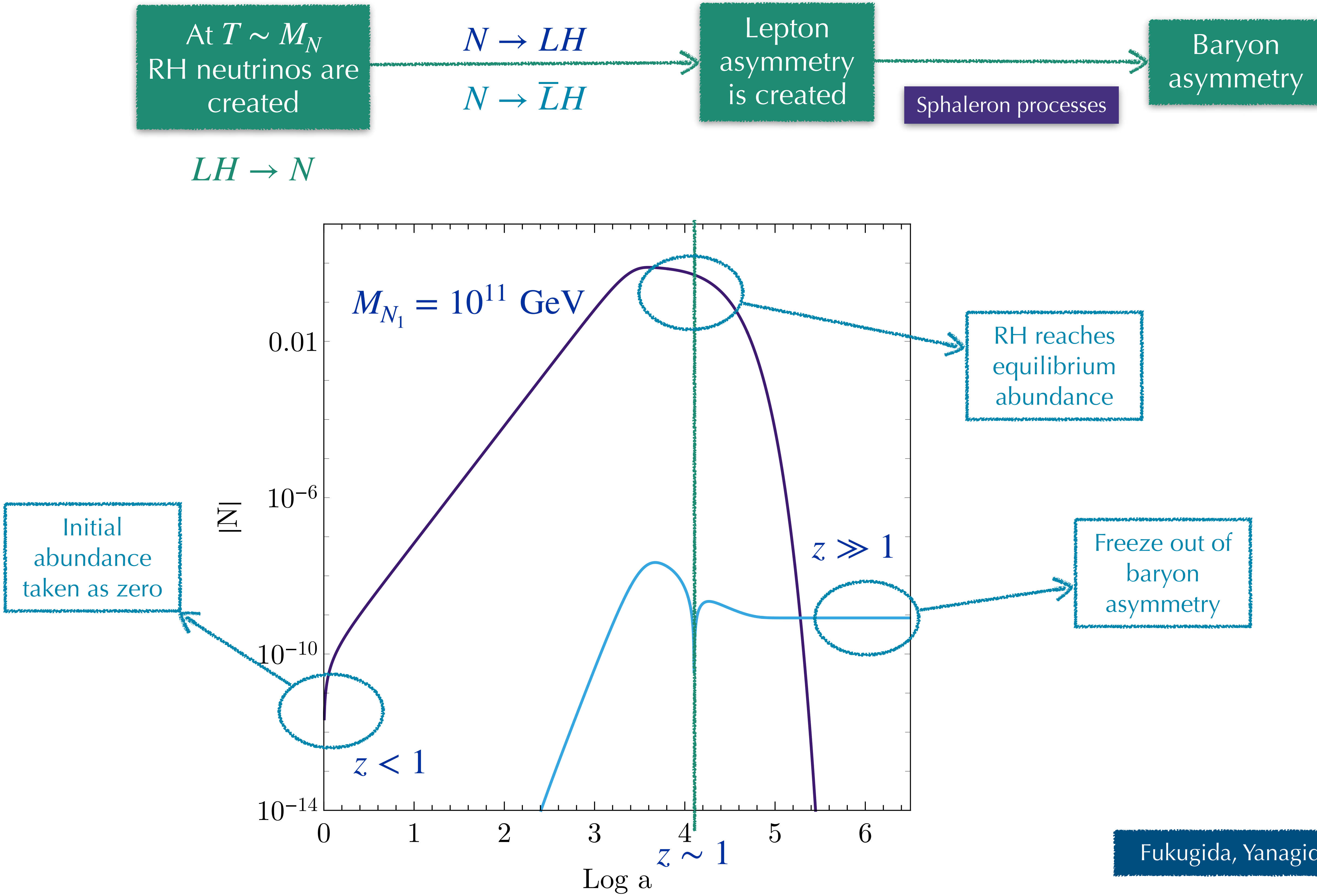

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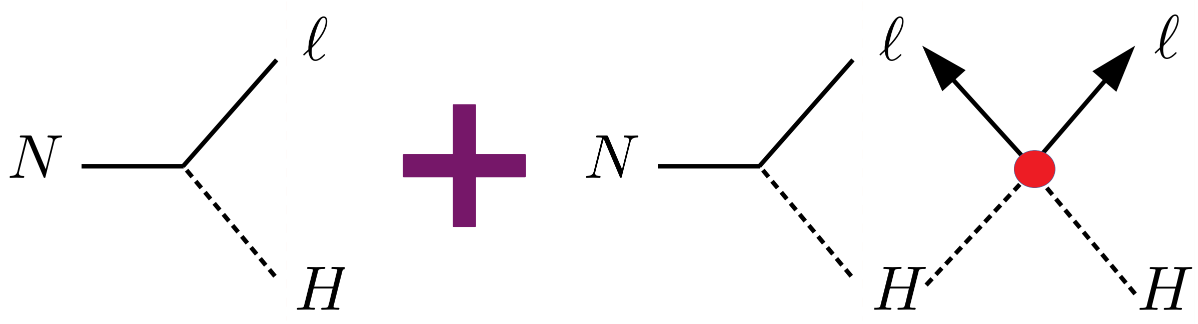
High Scale Leptogenesis

$M_N \gtrsim 10^{12}$ GeV

$M_{N_1} < M_{N_2} < M_{N_3}$

CP violation from interference



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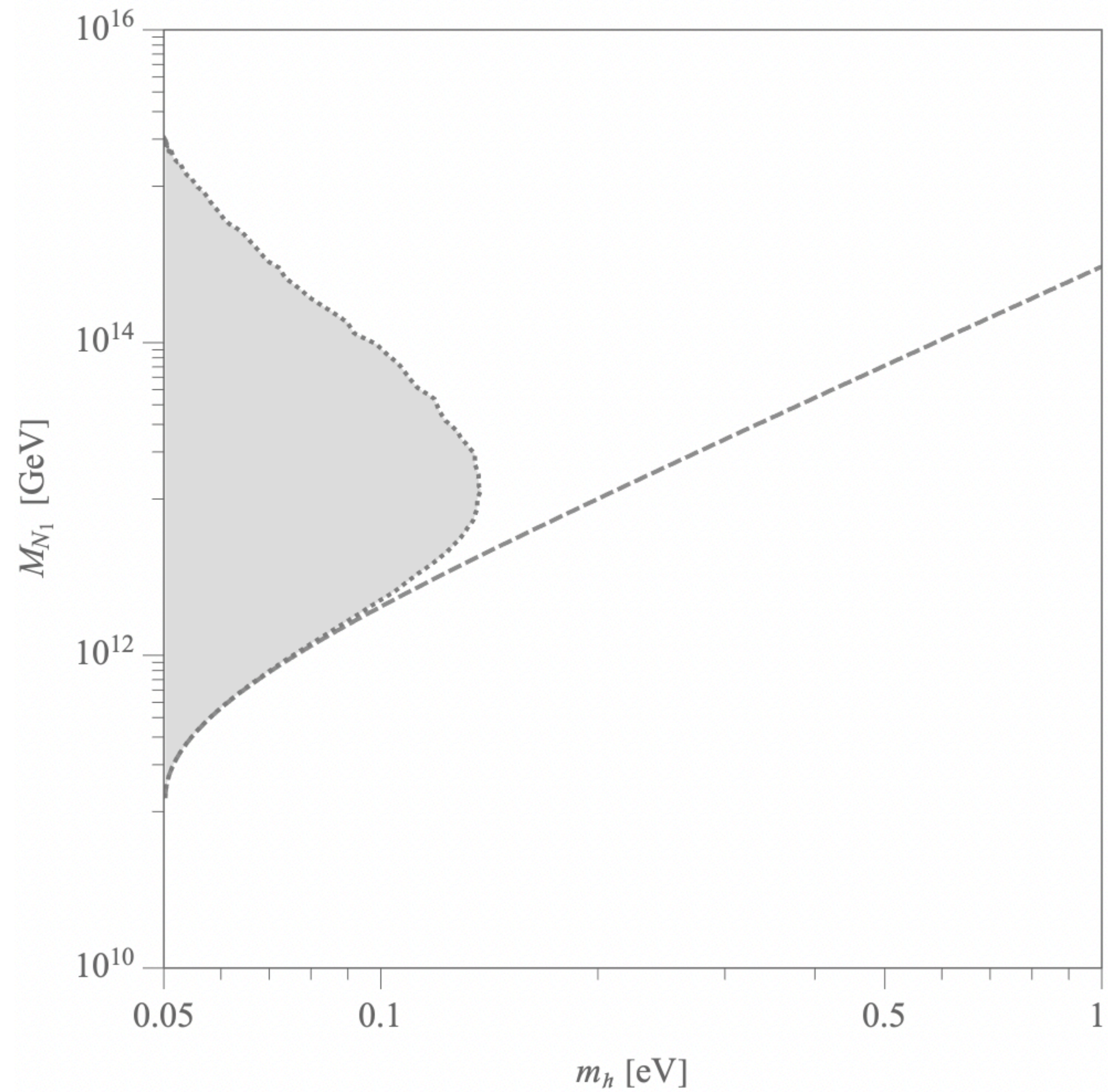

m_h = Heaviest neutrino mass

Maximizing over Yukawa parameters

Giudice *et al.*, 2004
Buchmuller *et al.*, 2005

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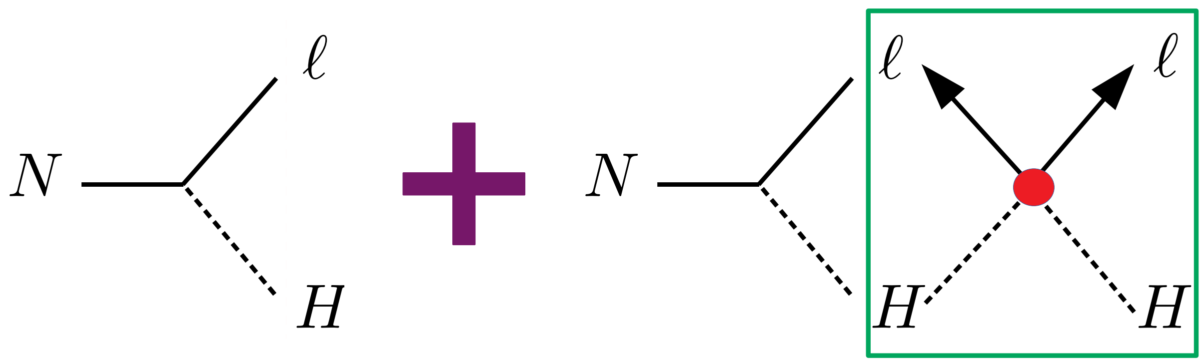

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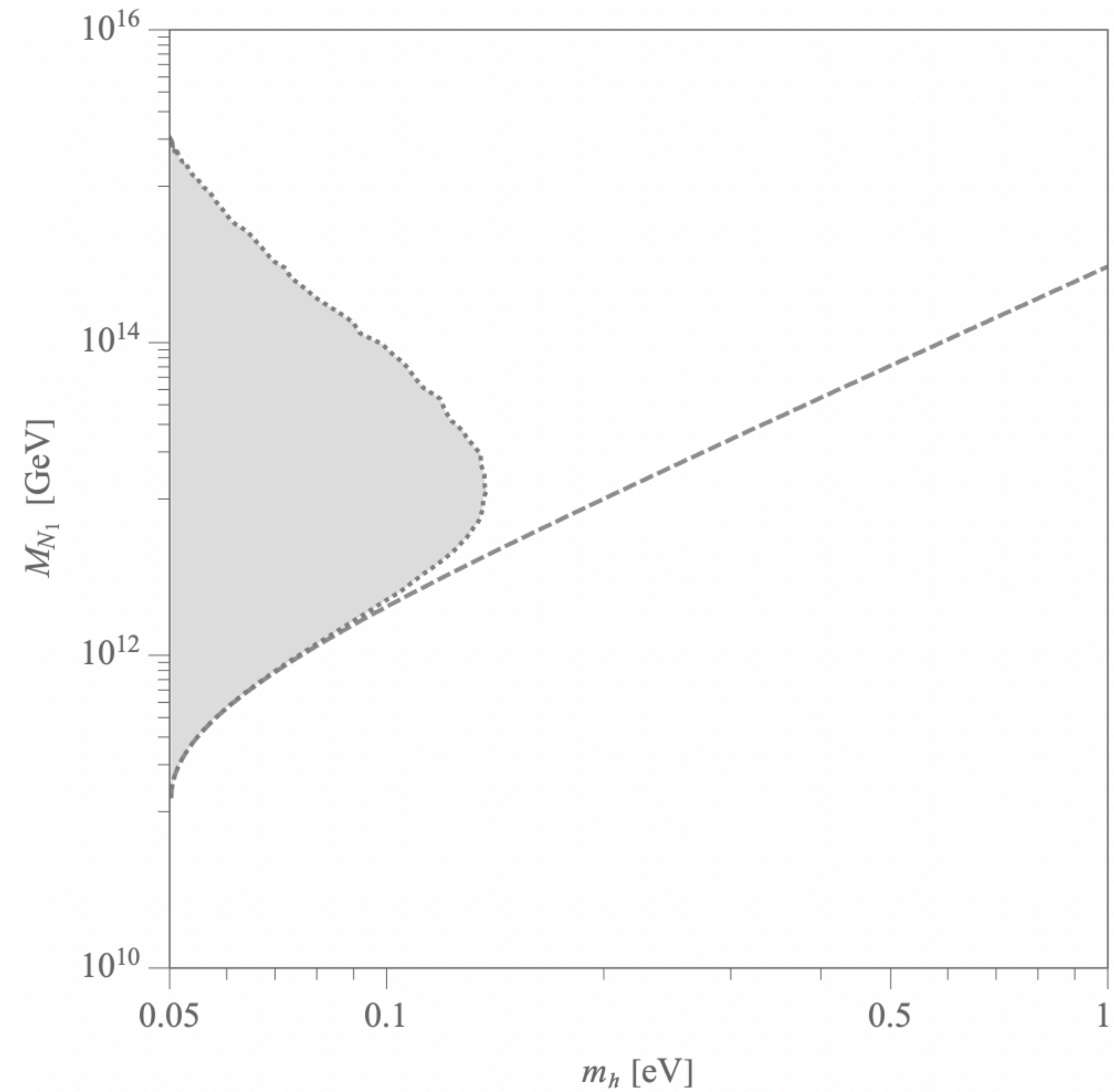

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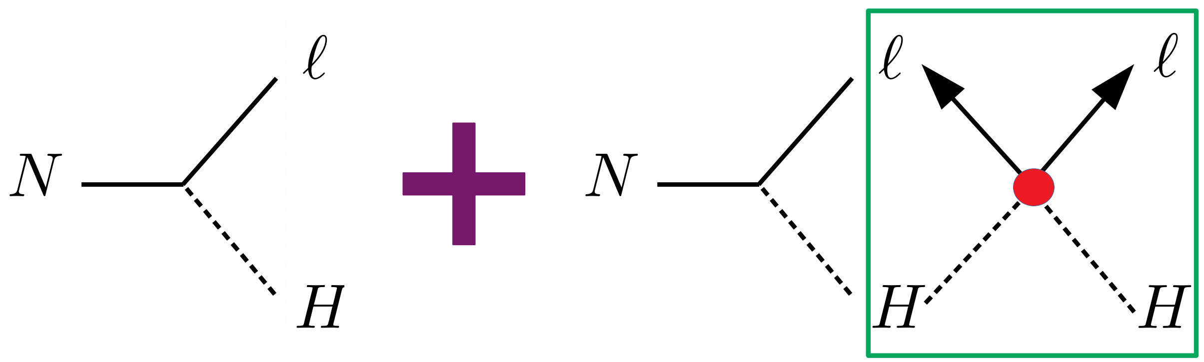

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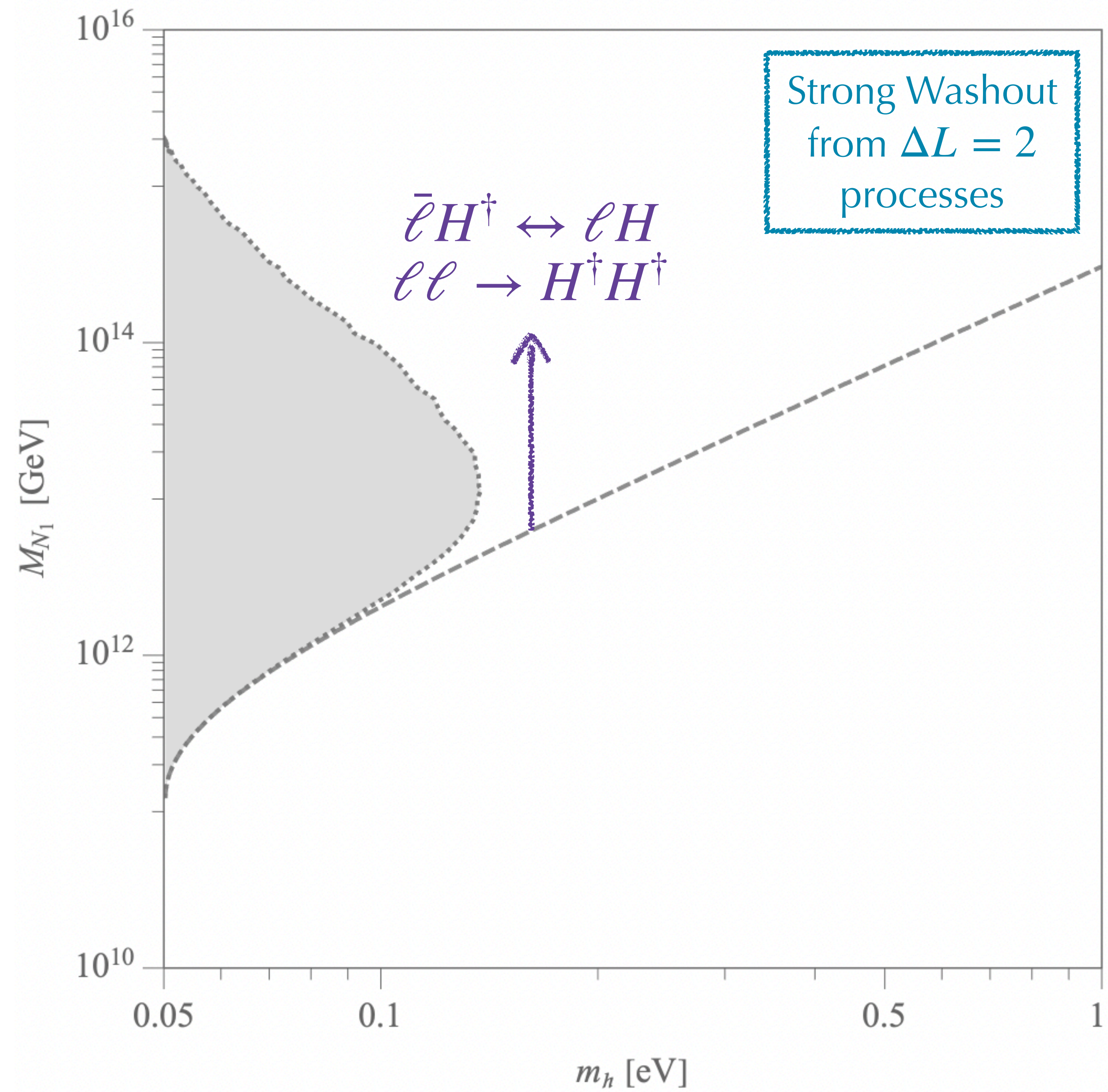

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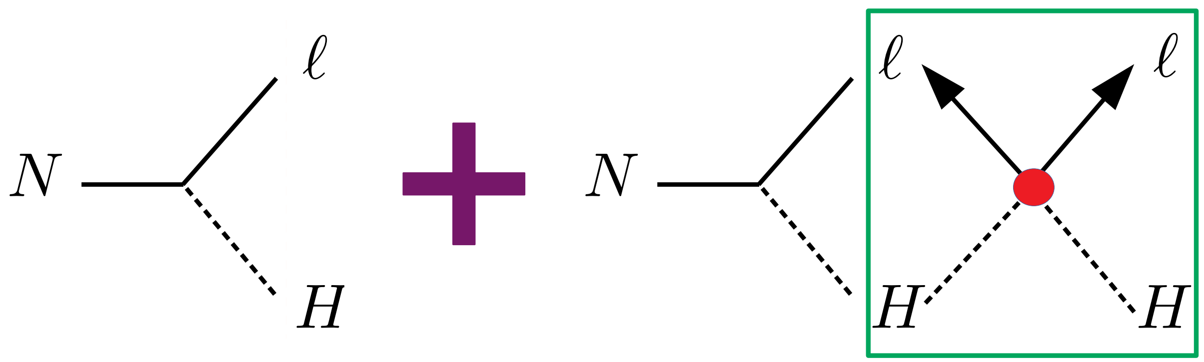

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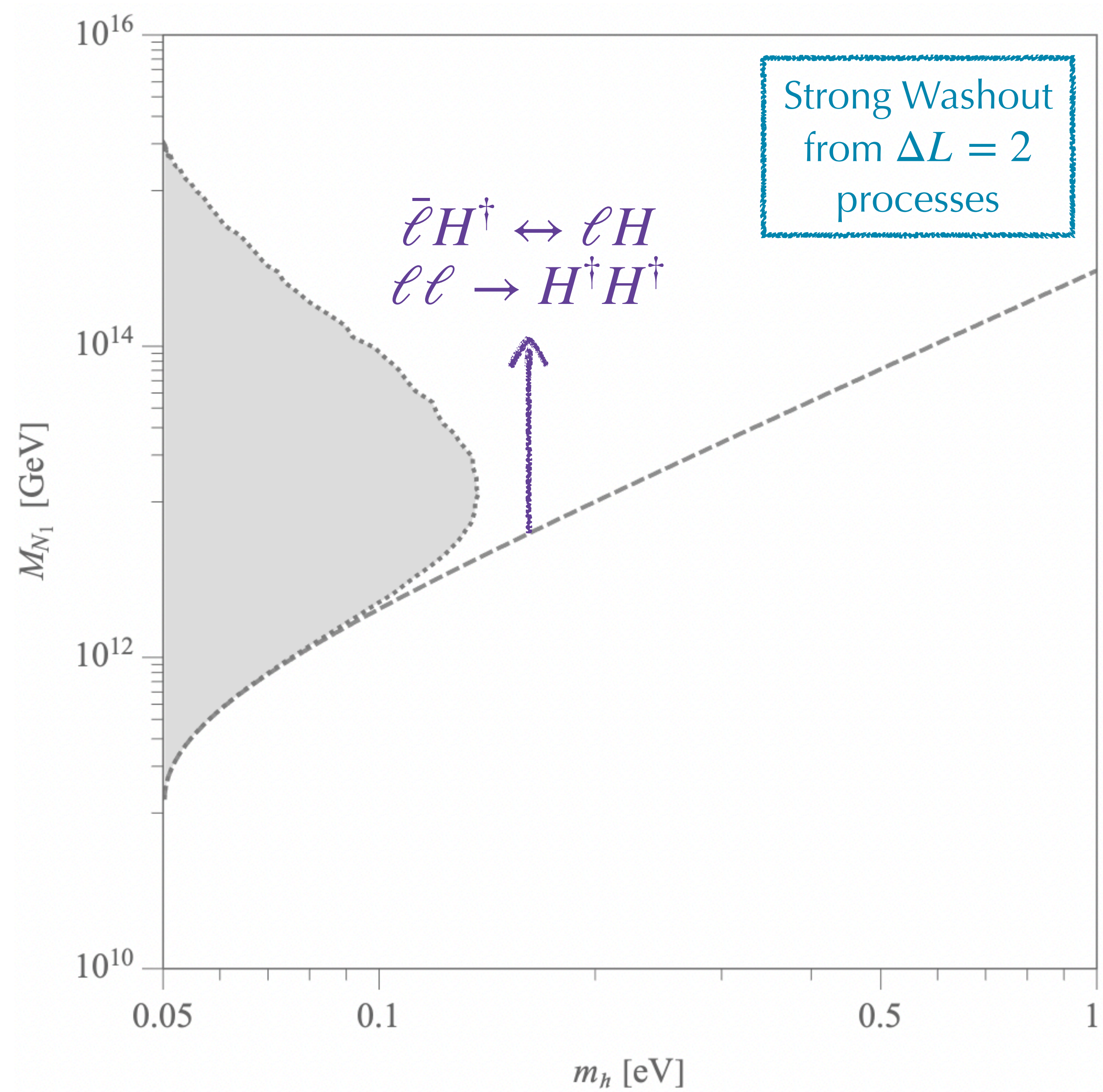

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Maximizing over Yukawa parameters

How to save HSL? → Produce RHNs after washout process have frozen out?

Giudice *et al.*, 2004
Buchmuller *et al.*, 2005

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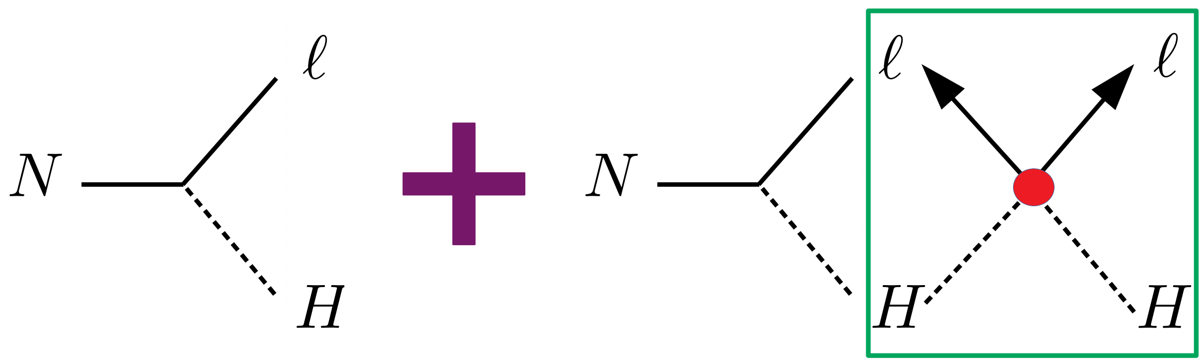

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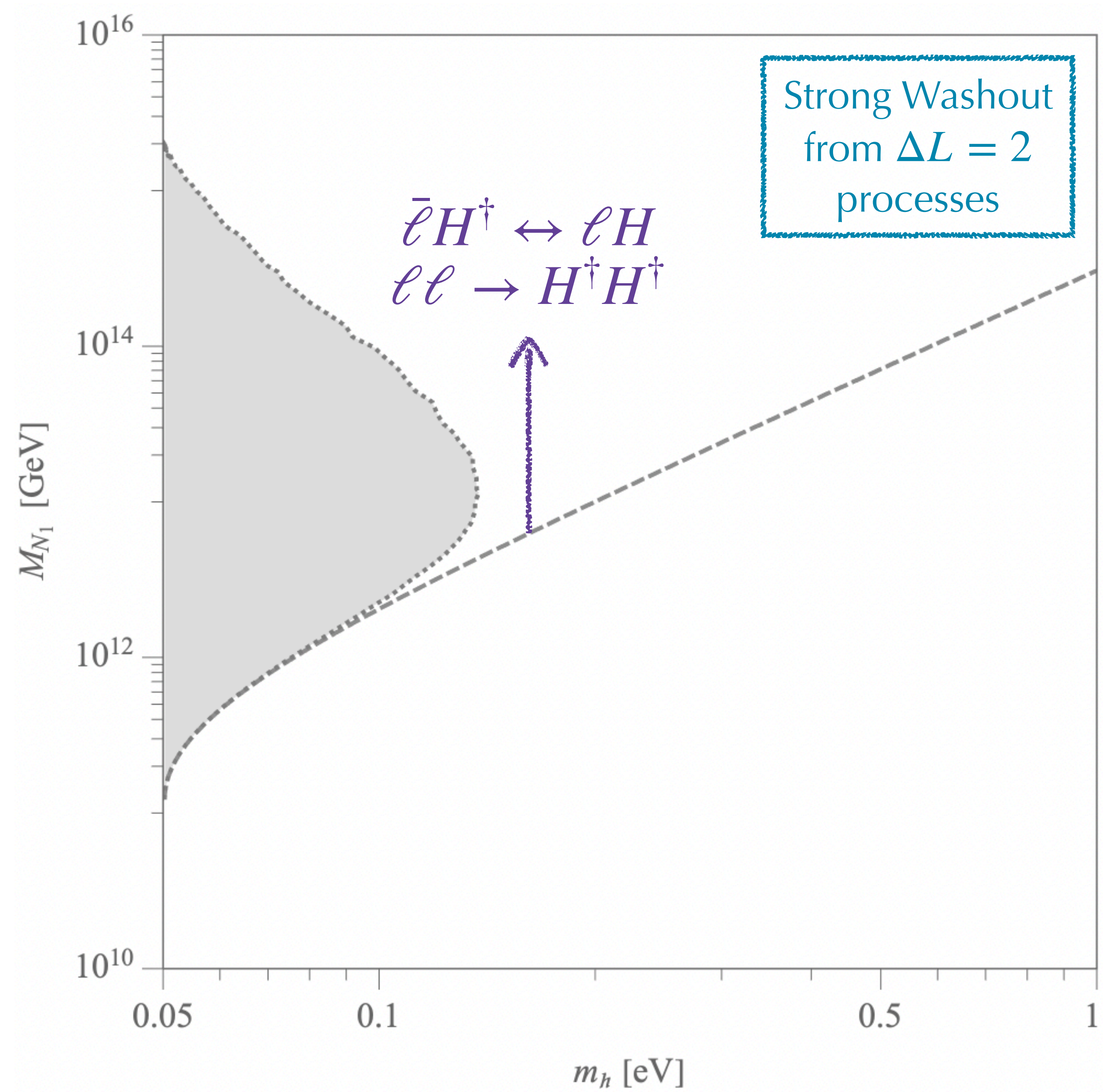
$$M_{N_1} \gtrsim 4 \left(\frac{0.1 \text{ eV}}{m_\nu}\right)^2 10^{12} \text{ GeV}$$



m_h = Heaviest neutrino mass

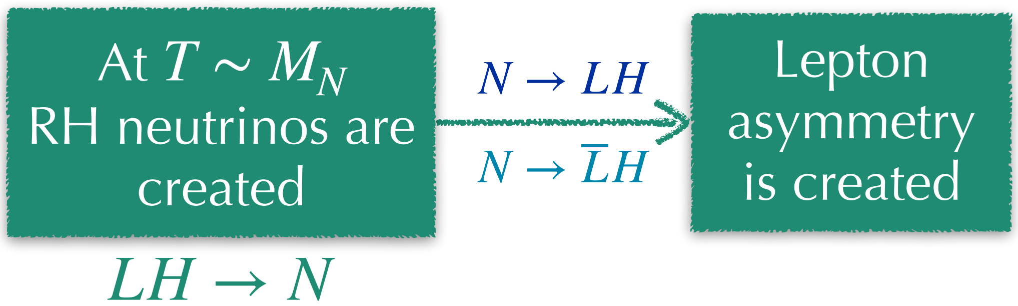
Maximizing over Yukawa parameters

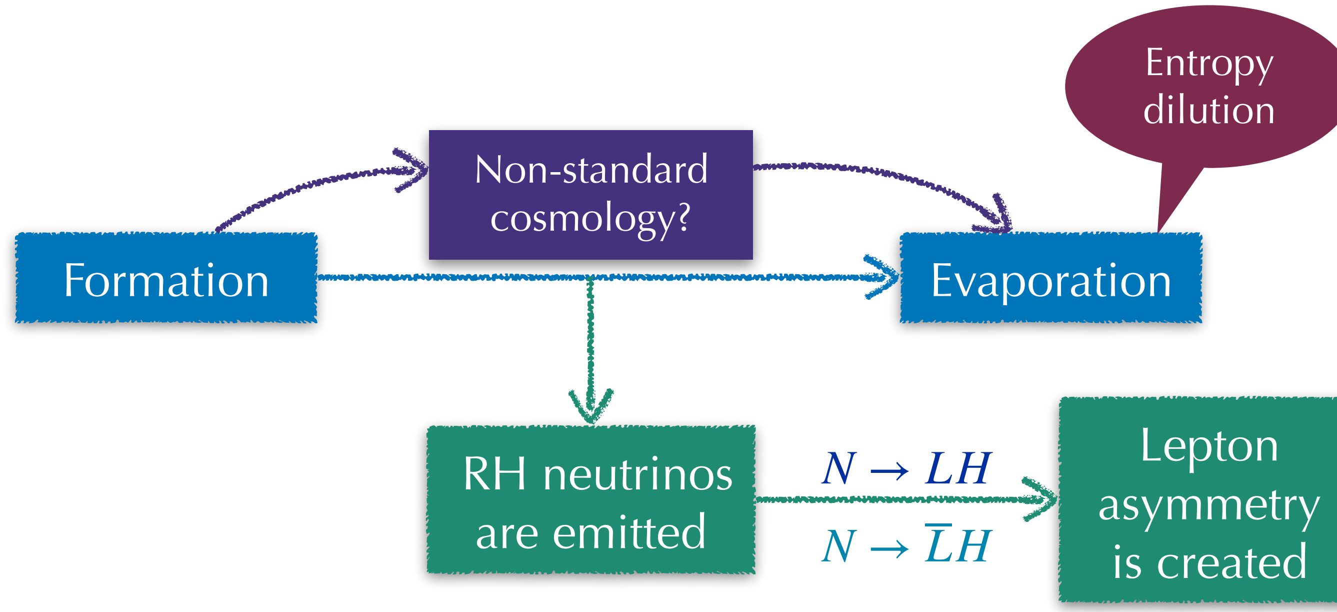
How to save HSL? → Produce RHNs after washout process have frozen out?

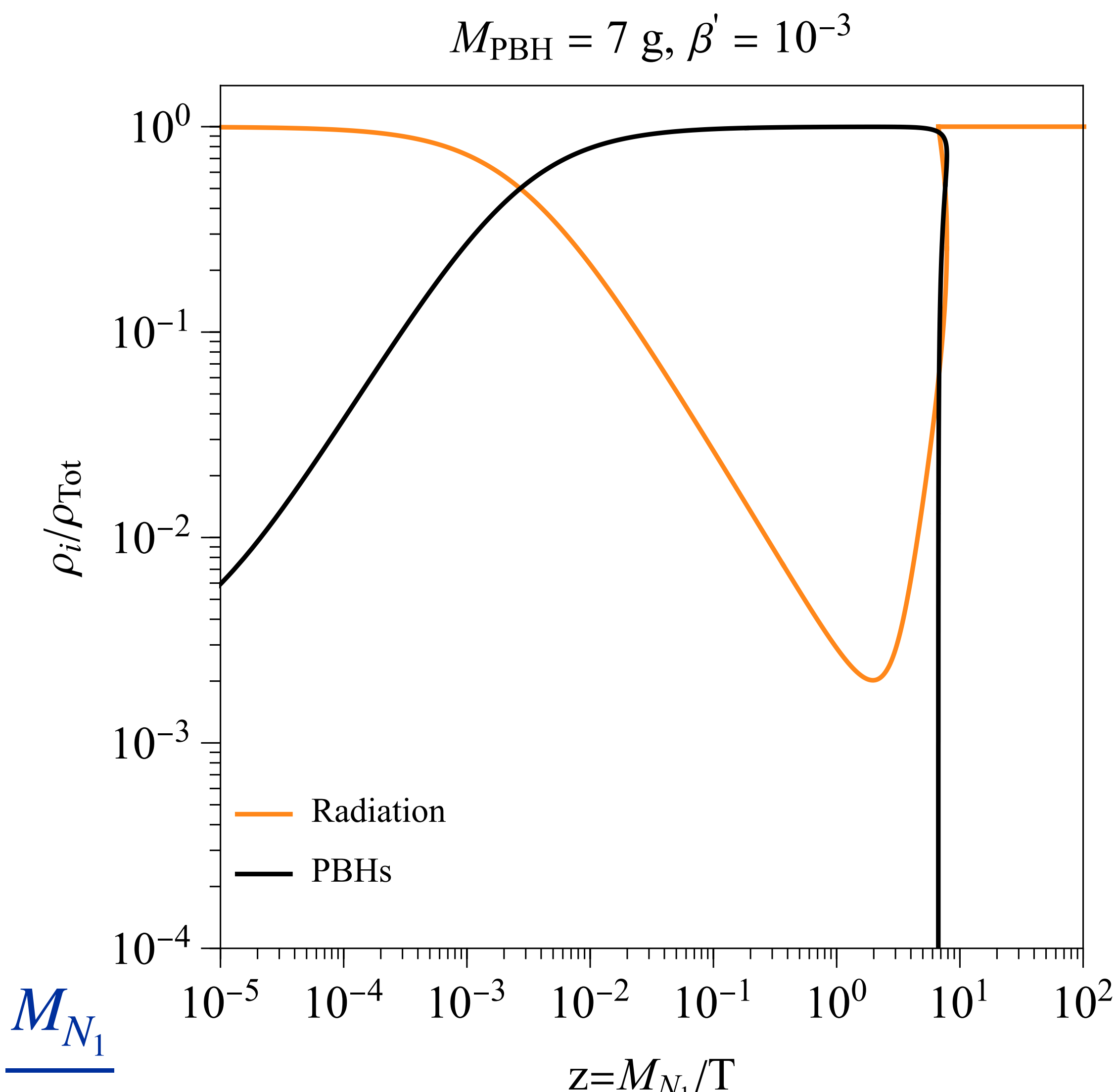
PBHs!

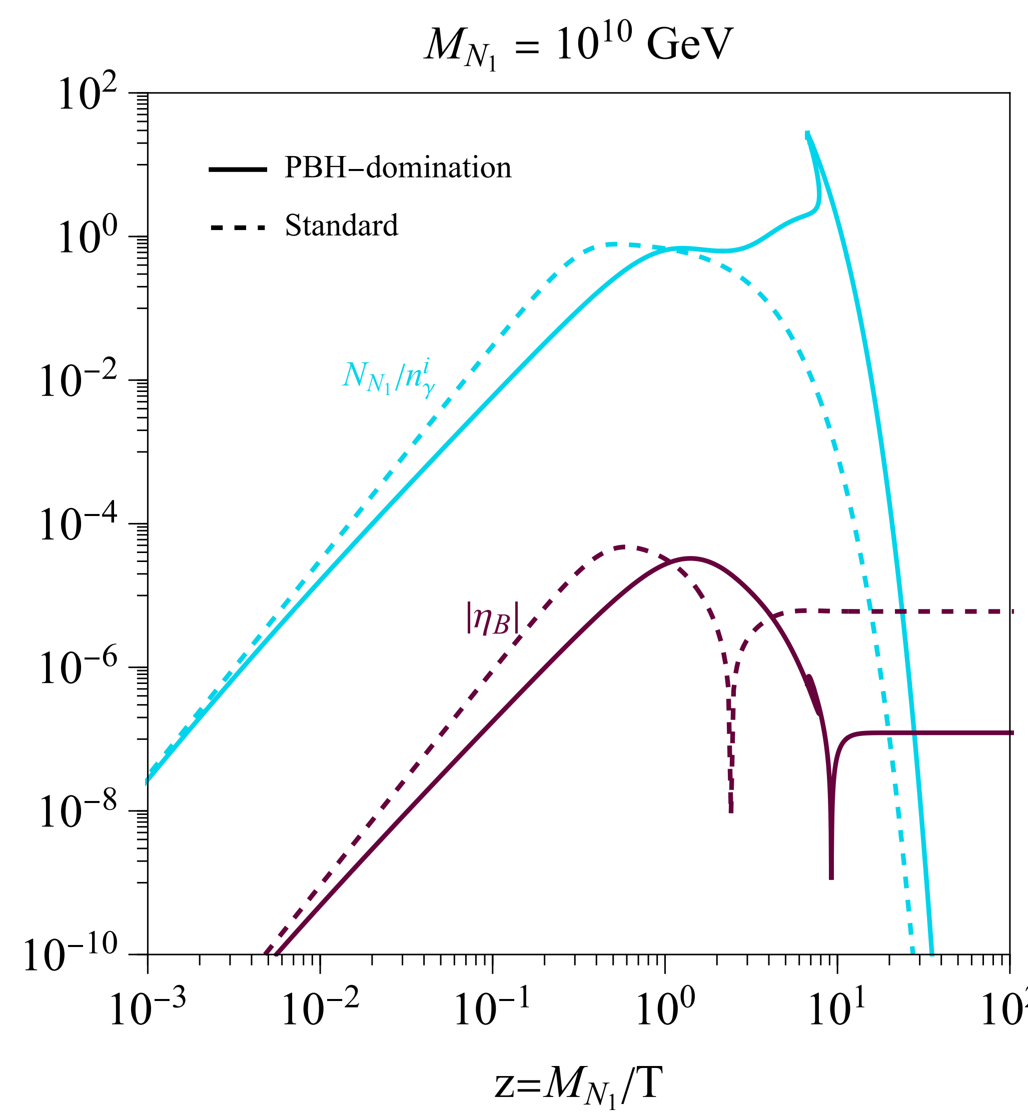
Giudice *et al.*, 2004
Buchmuller *et al.*, 2005

PBH + Leptogenesis





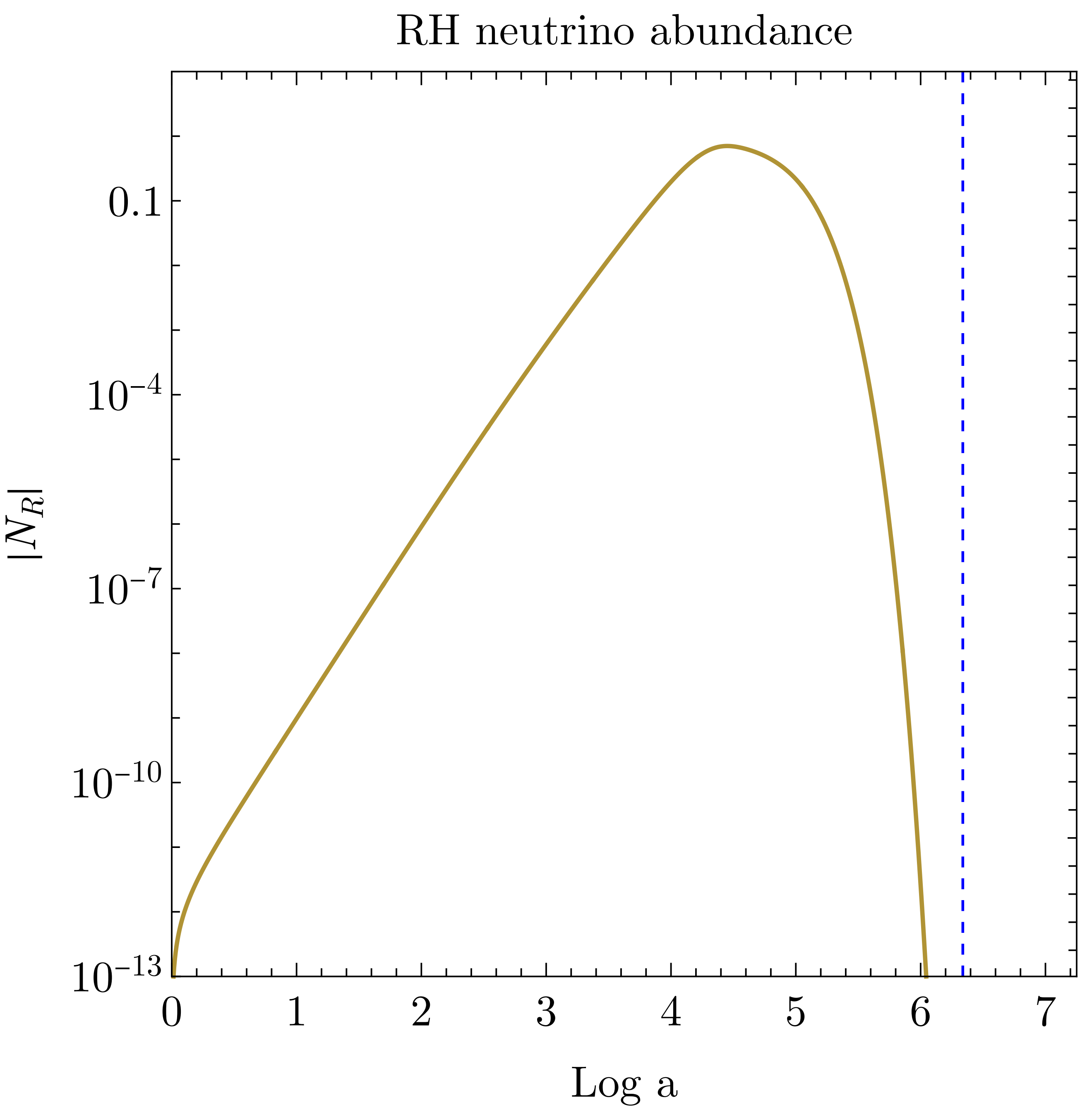


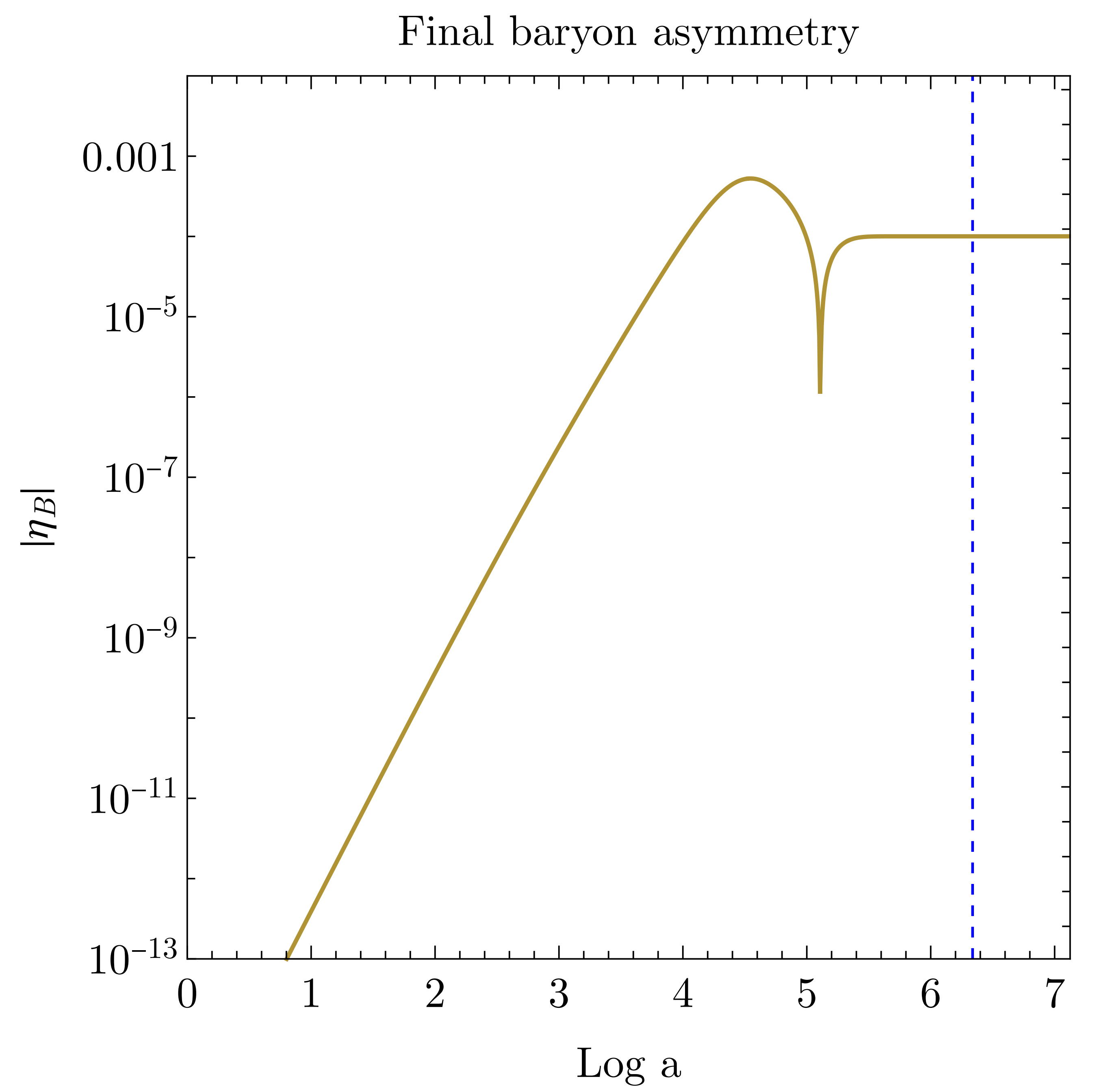


$$z_{\rm BH} \equiv \frac{M_{N_1}}{T_{\rm BH}}$$

Three scenarios

A. PBH evaporate before RHs are thermally produced (IV)
B. Evaporation happens during thermal leptogenesis (II-III)
C. PBH create a RH density after the thermal case (II-III)





$M_i = 1.7$ g
$\beta_i' = 10^{-3}$

$M_{N_1} = 10^{11}$ GeV

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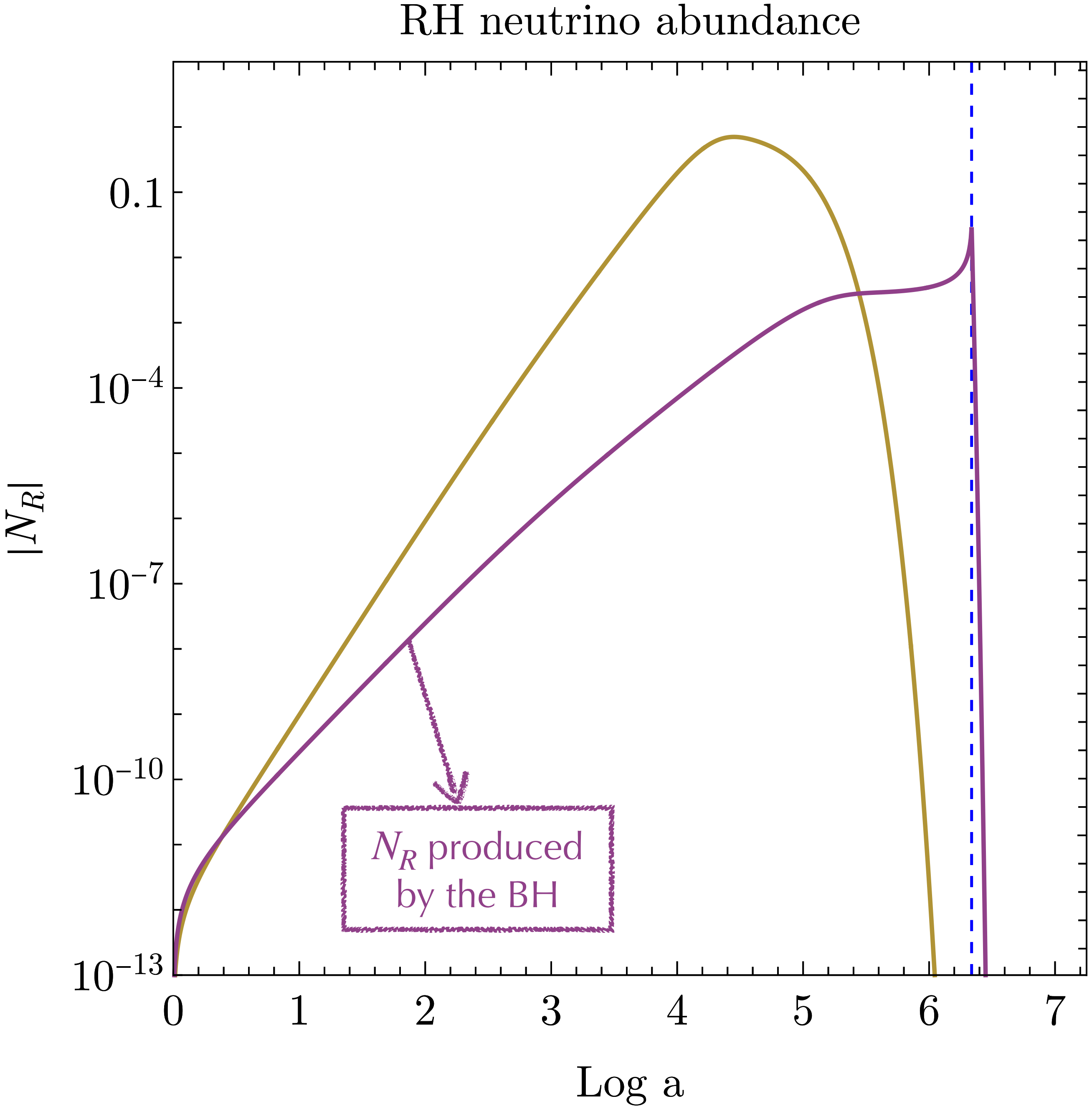

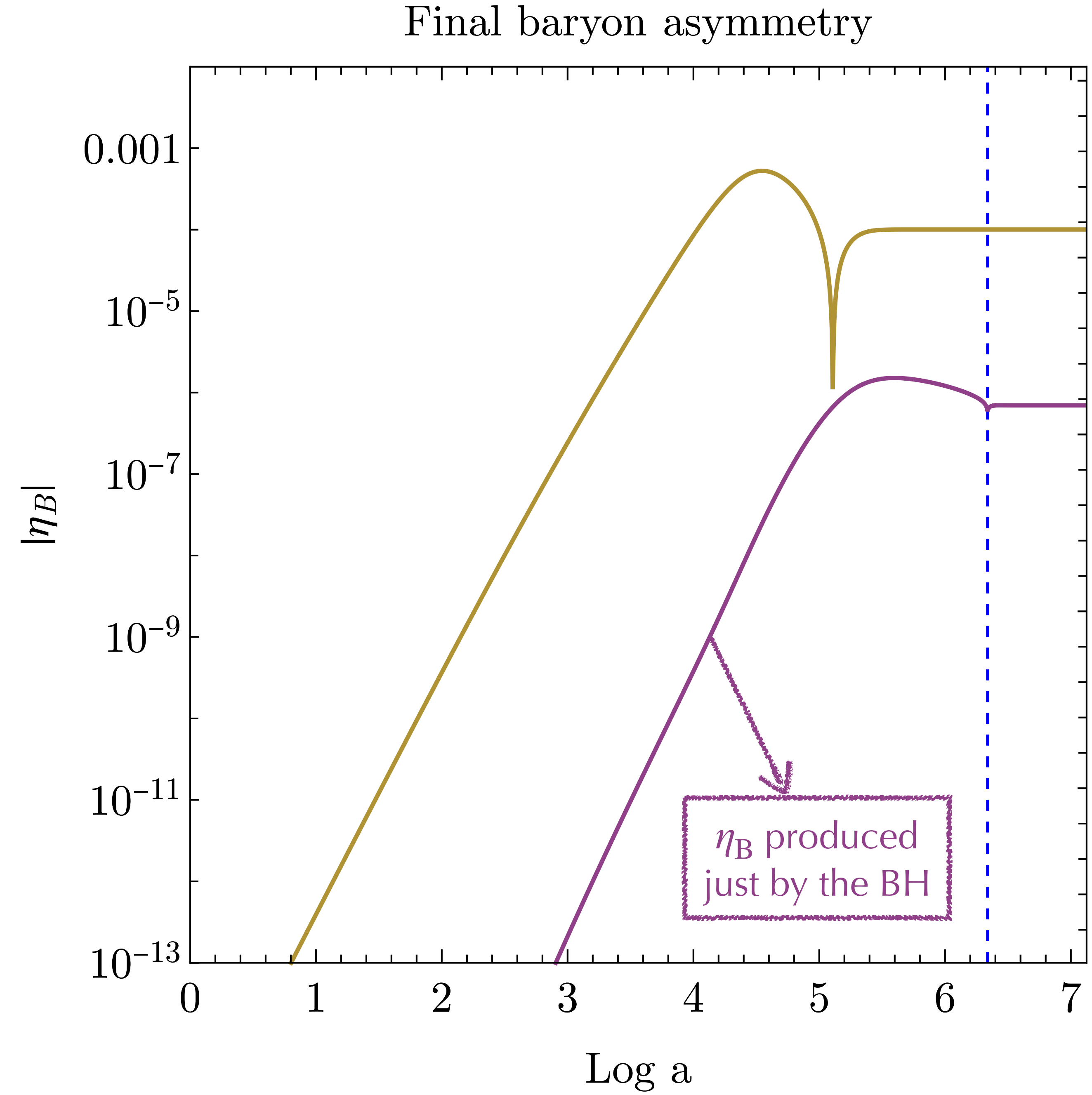

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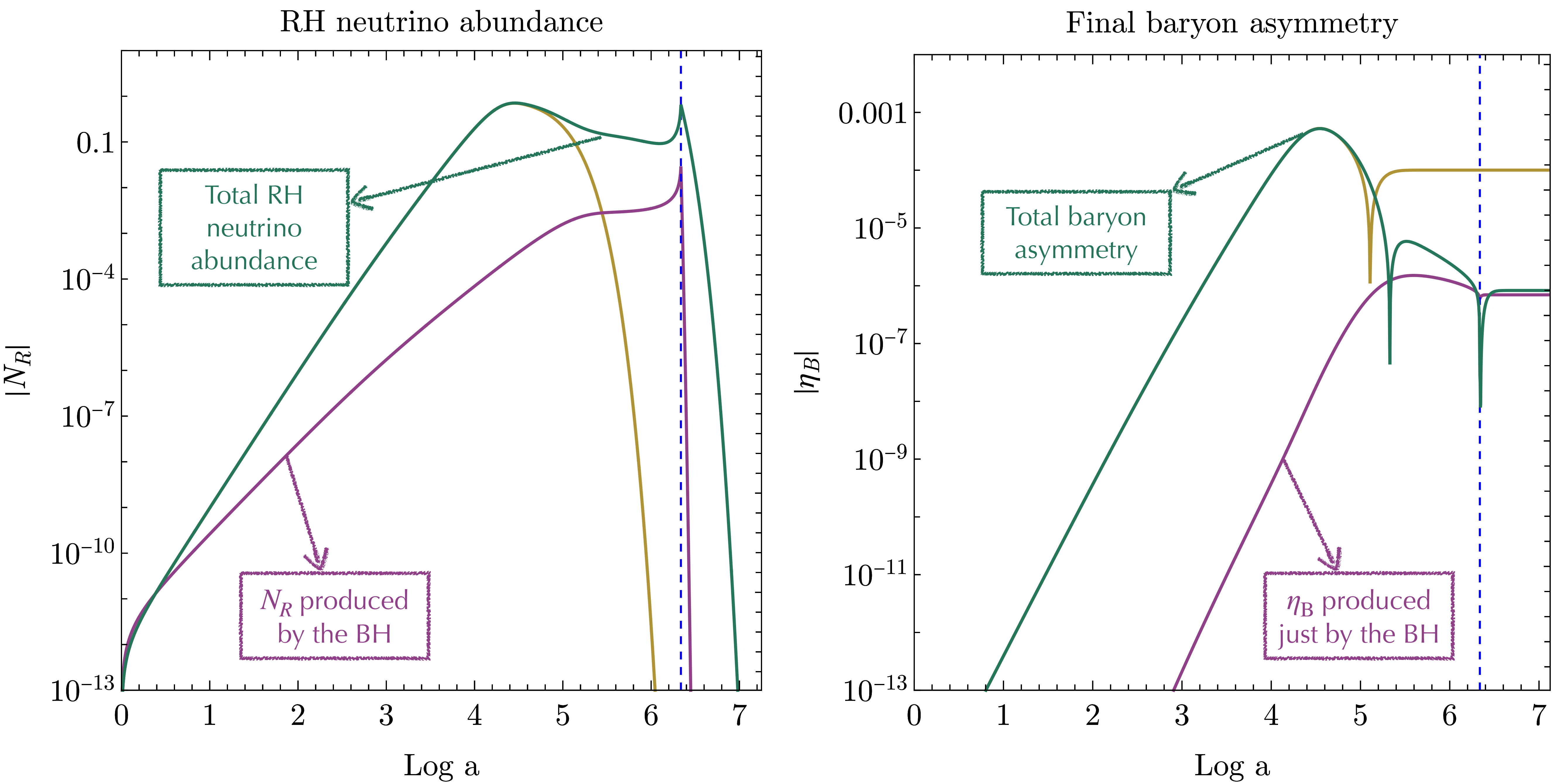

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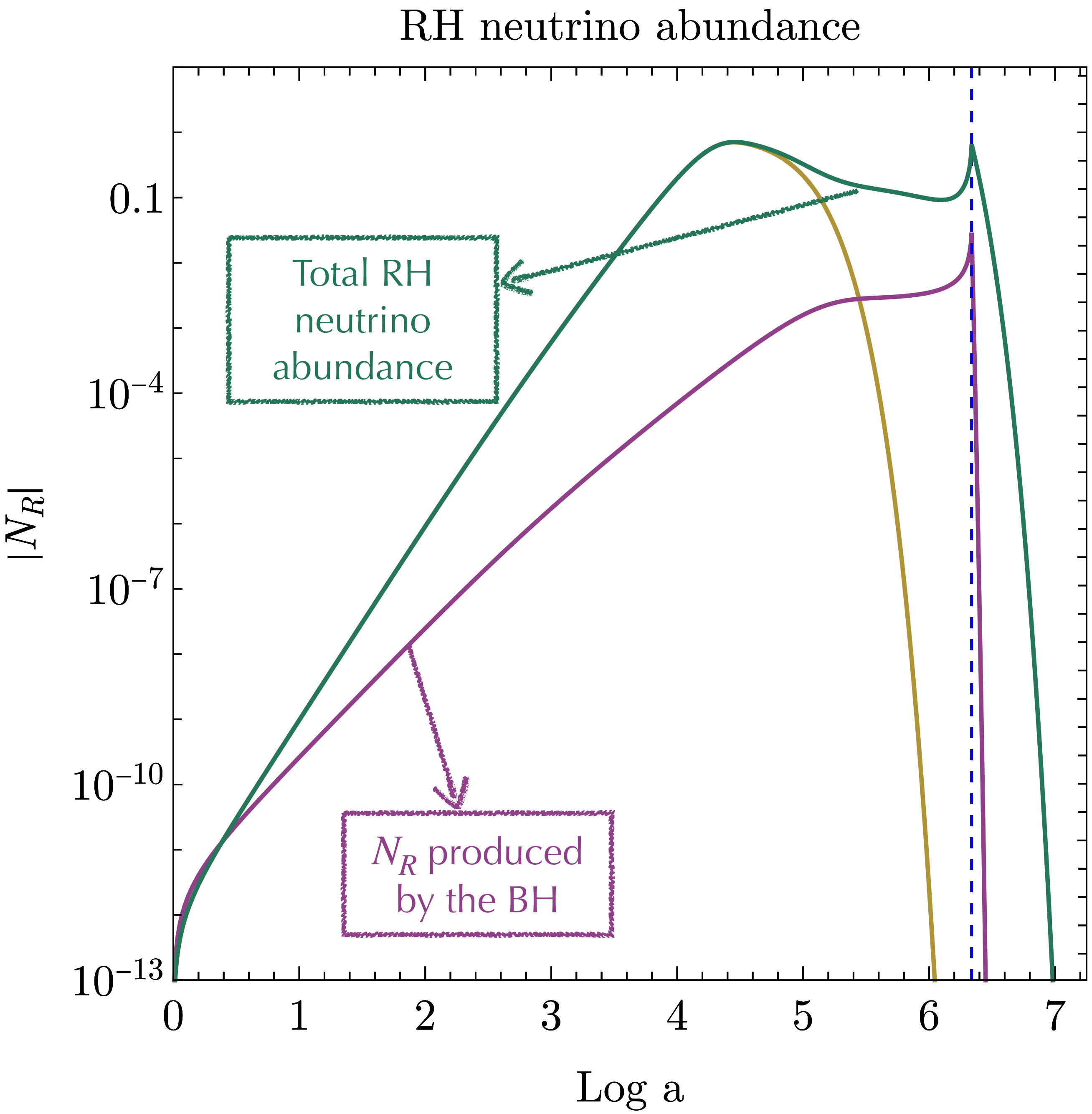

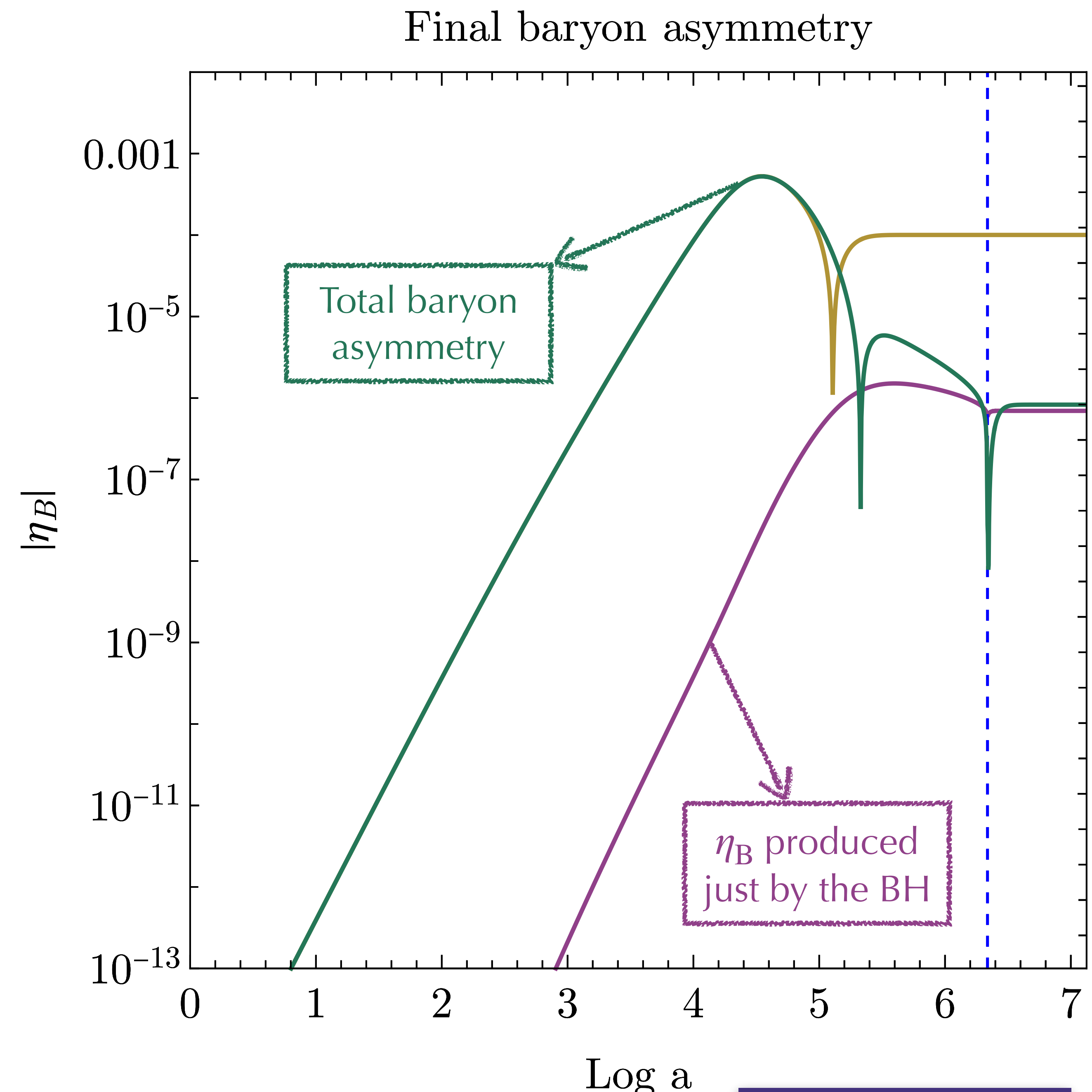

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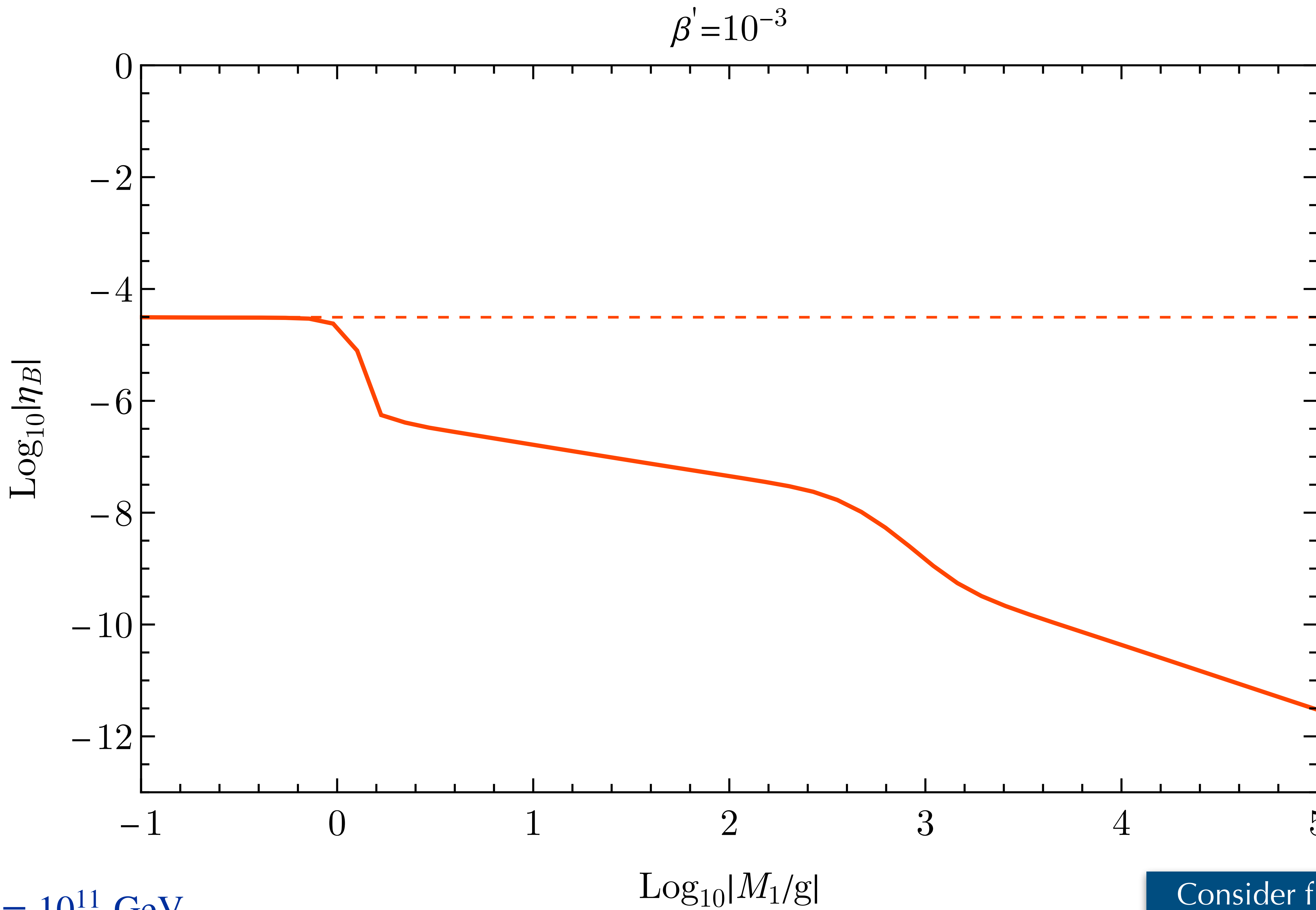
BH evaporation can diminish the asymmetry!

$$Y_\nu = \frac{1}{v} U_{\rm PMNS} \sqrt{m_\nu} R^T M_N^T$$



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Consider fine-tuned Yukawas

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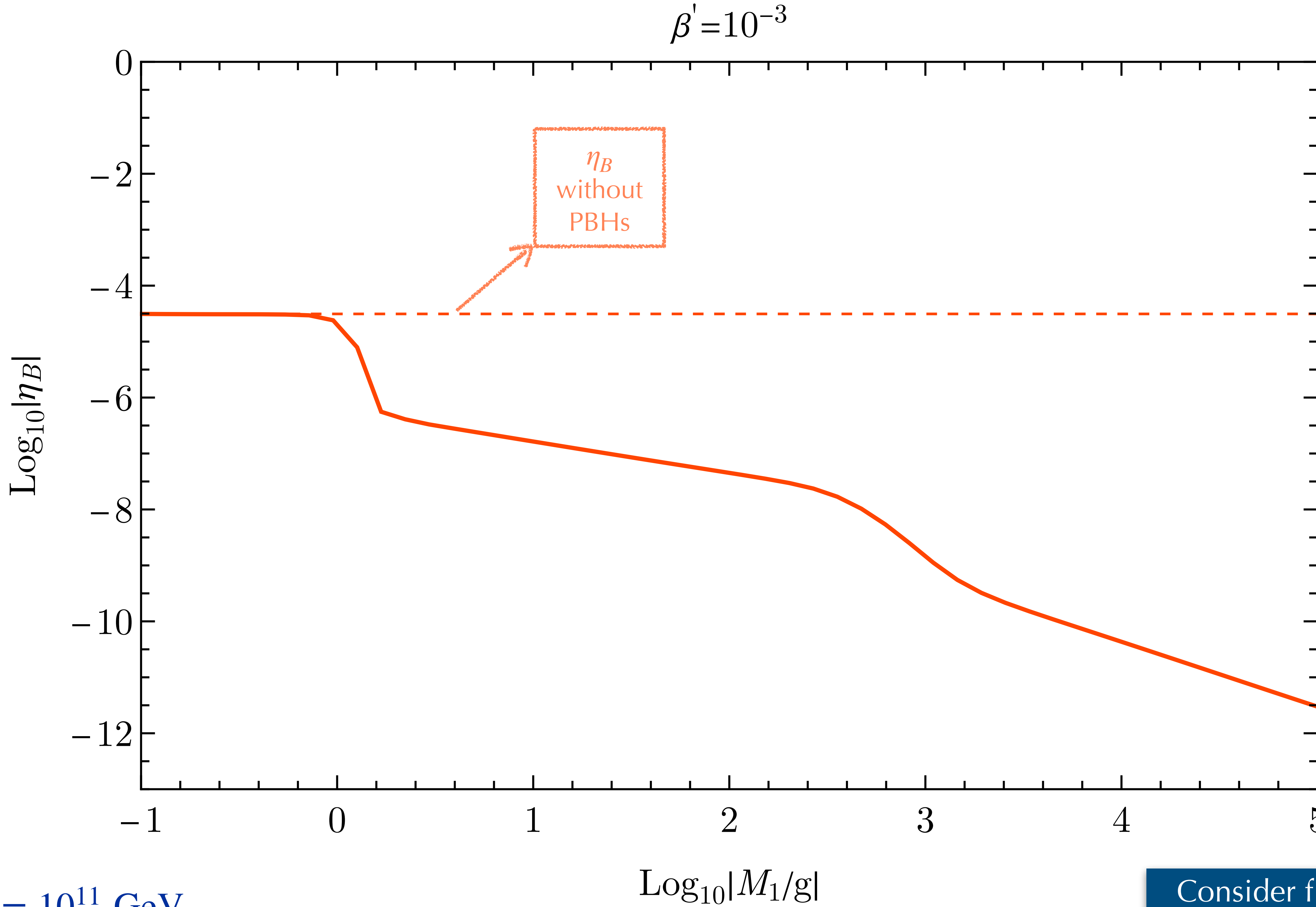

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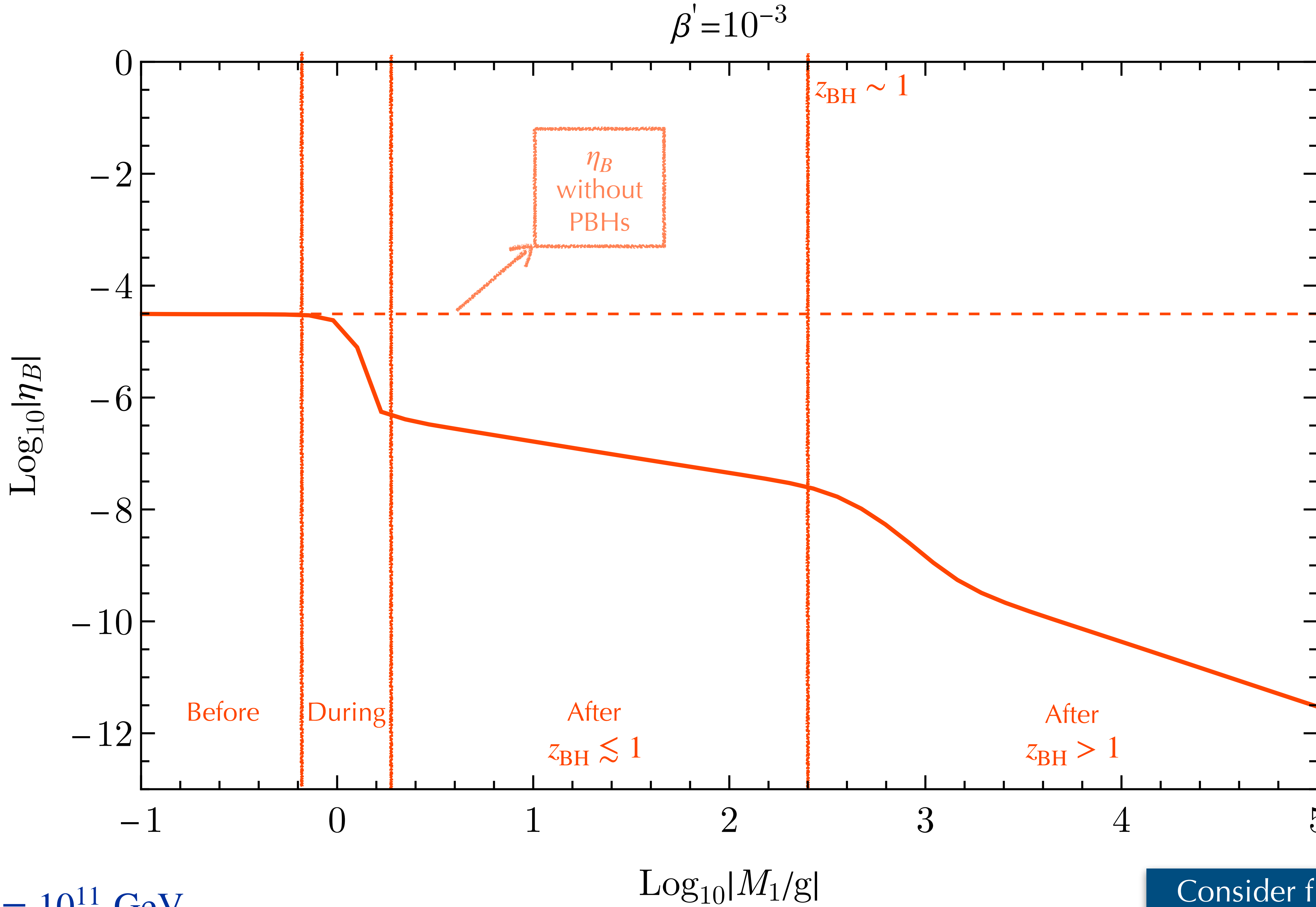

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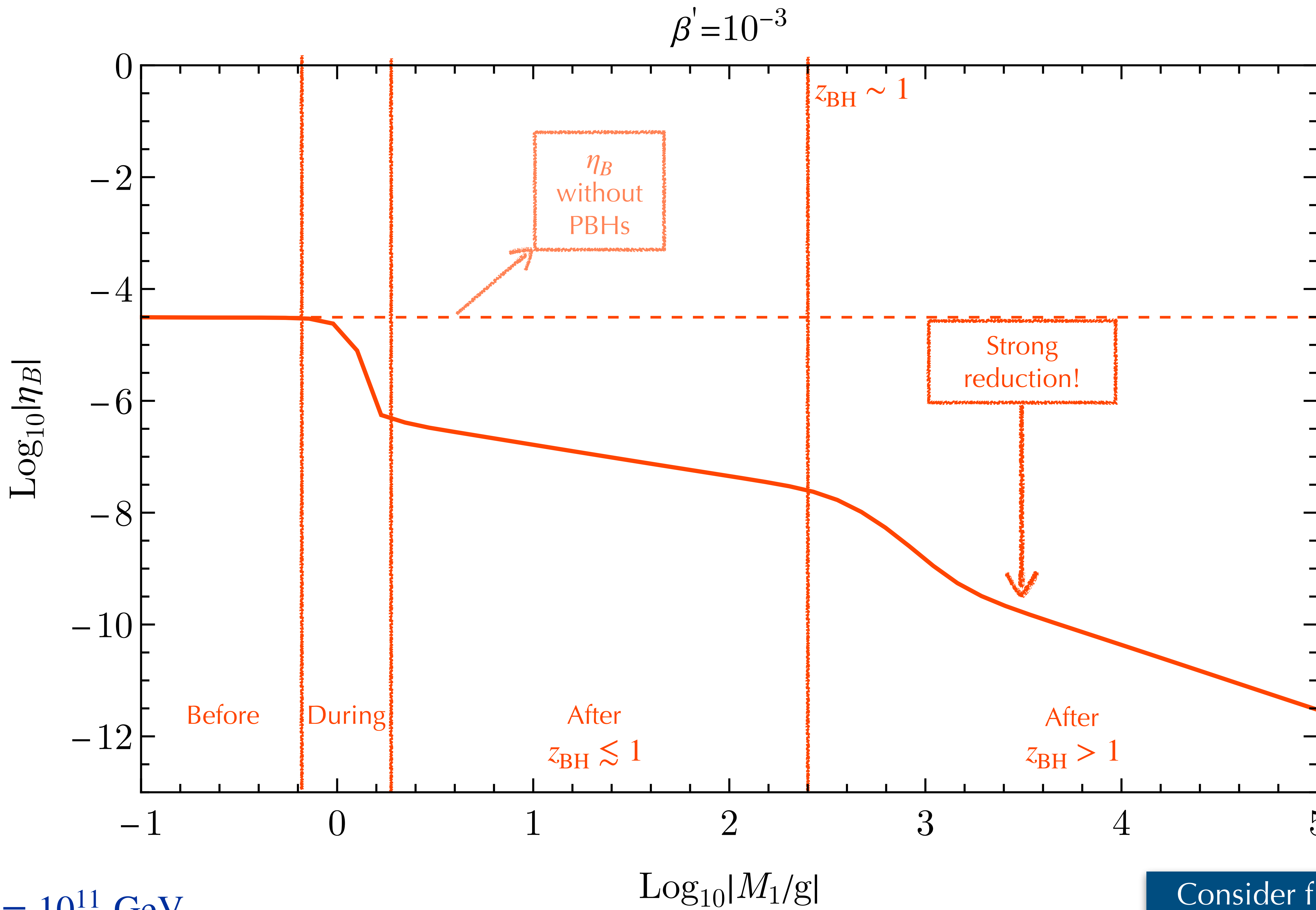

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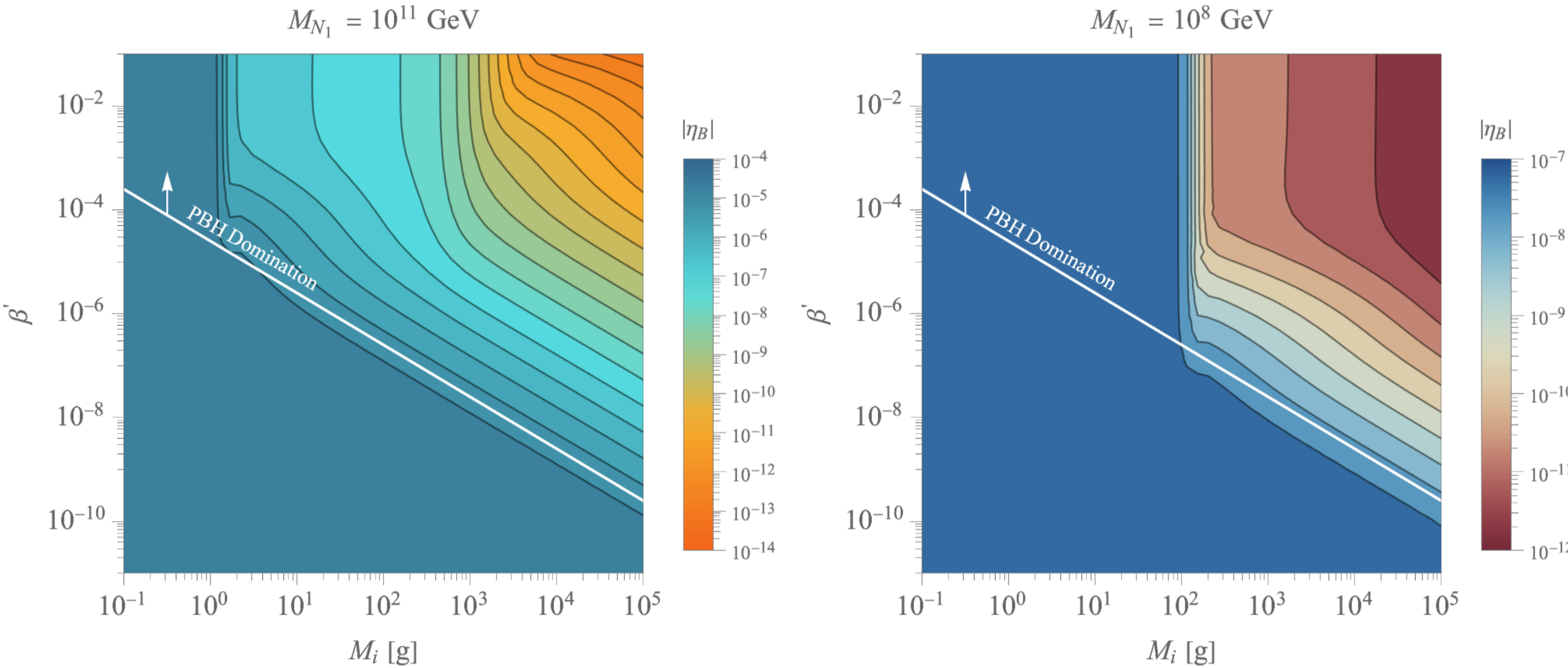
Consider fine-tuned Yukawas

Dependence on β'

How the depletion depends on the initial fraction?



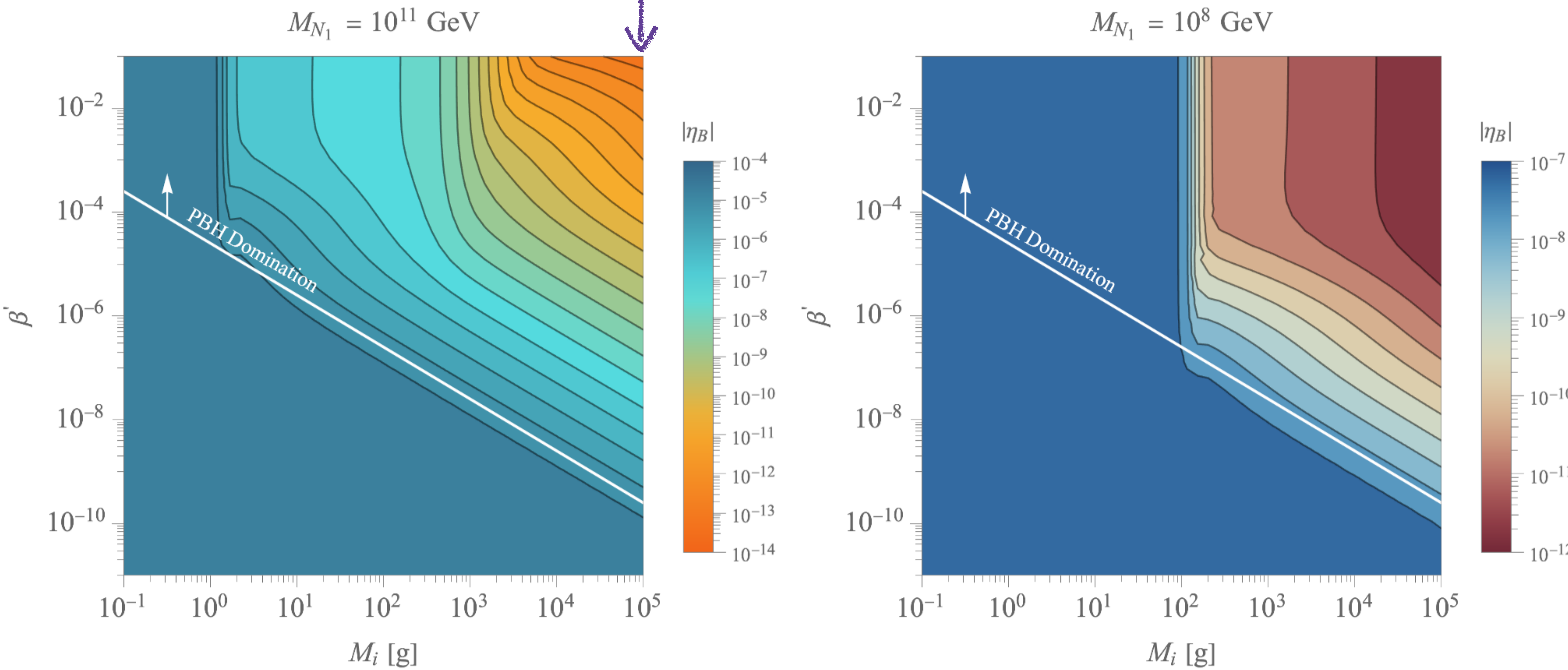
Entropy dilution is a generic and important feature to be taken into account

See also talks of Rome and Jacob

Dependence on β'

How the depletion depends on the initial fraction?

$T_{ev} \gtrsim 150$ GeV*



Entropy dilution is a generic and important feature to be taken into account

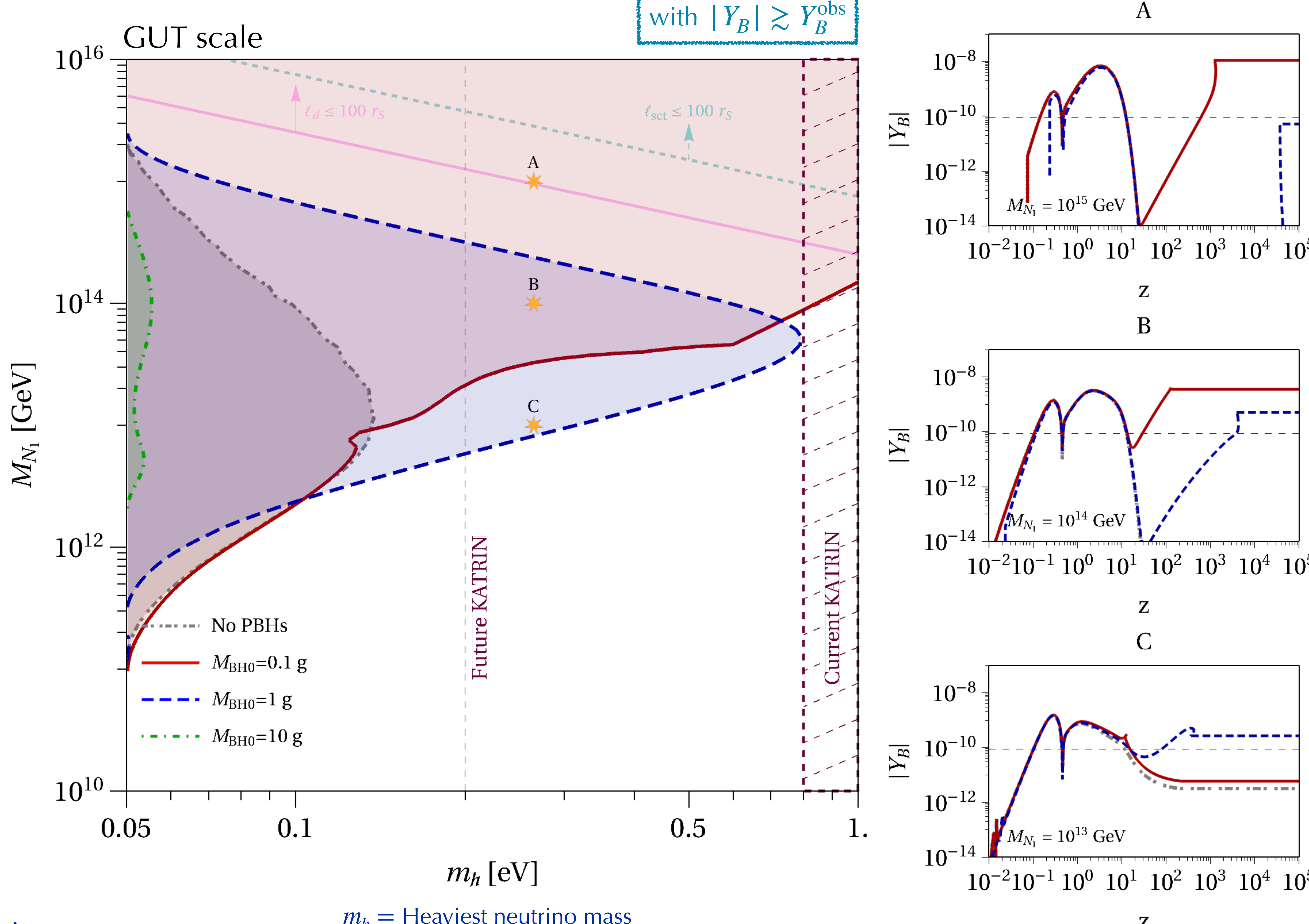
*Sphalerons in the SM plasma

Sphalerons active around PBHs
García-Bellido et al, 1904.11482
De Luca et.al., 2102.07408

See also talks of Rome and Jacob

Rescuing HSL

Colored Regions with $|Y_B| \gtrsim Y_B^{obs}$



m_h = Heaviest neutrino mass

Maximizing over Yukawa parameters

*Up to perturbativity

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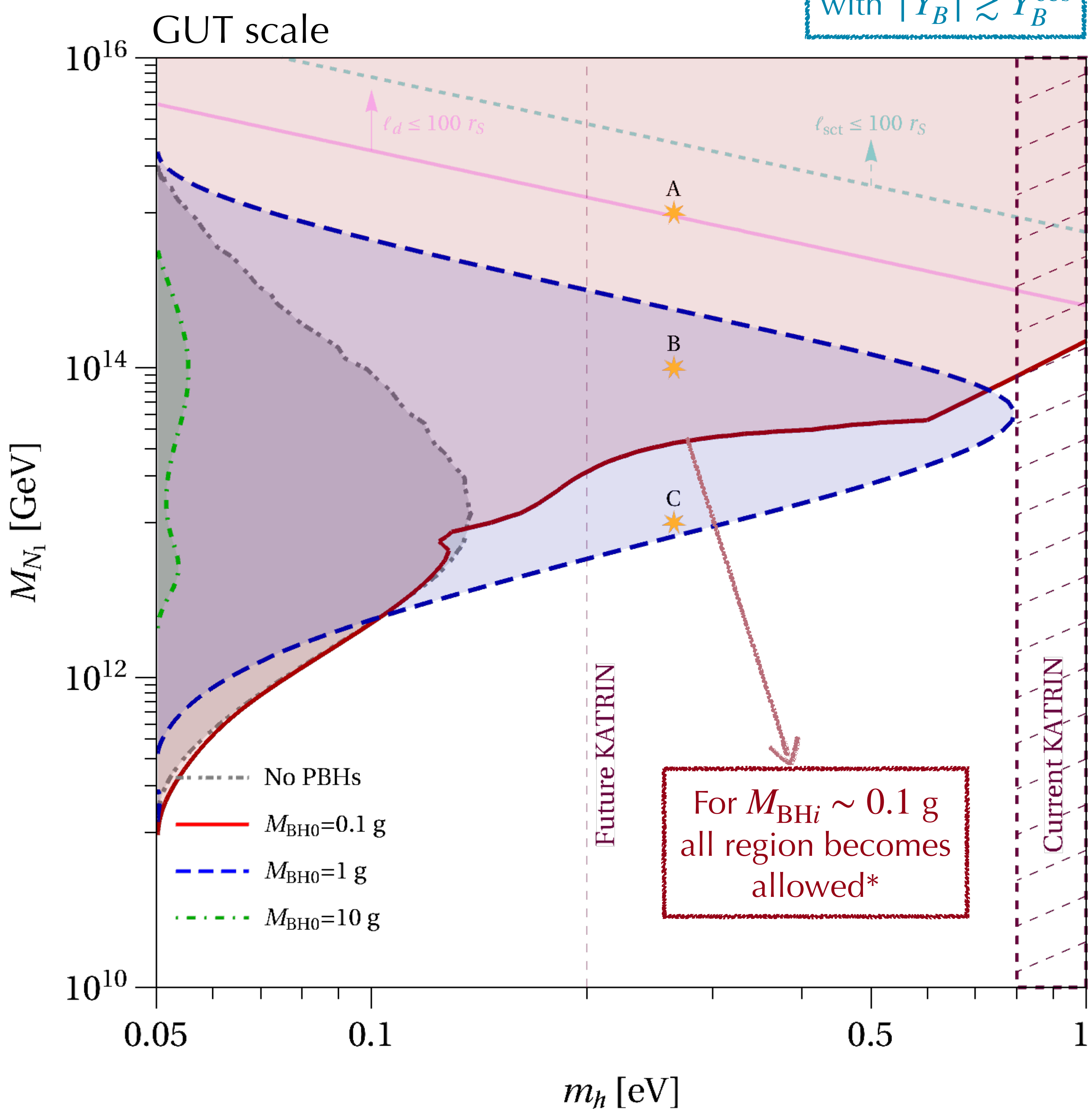

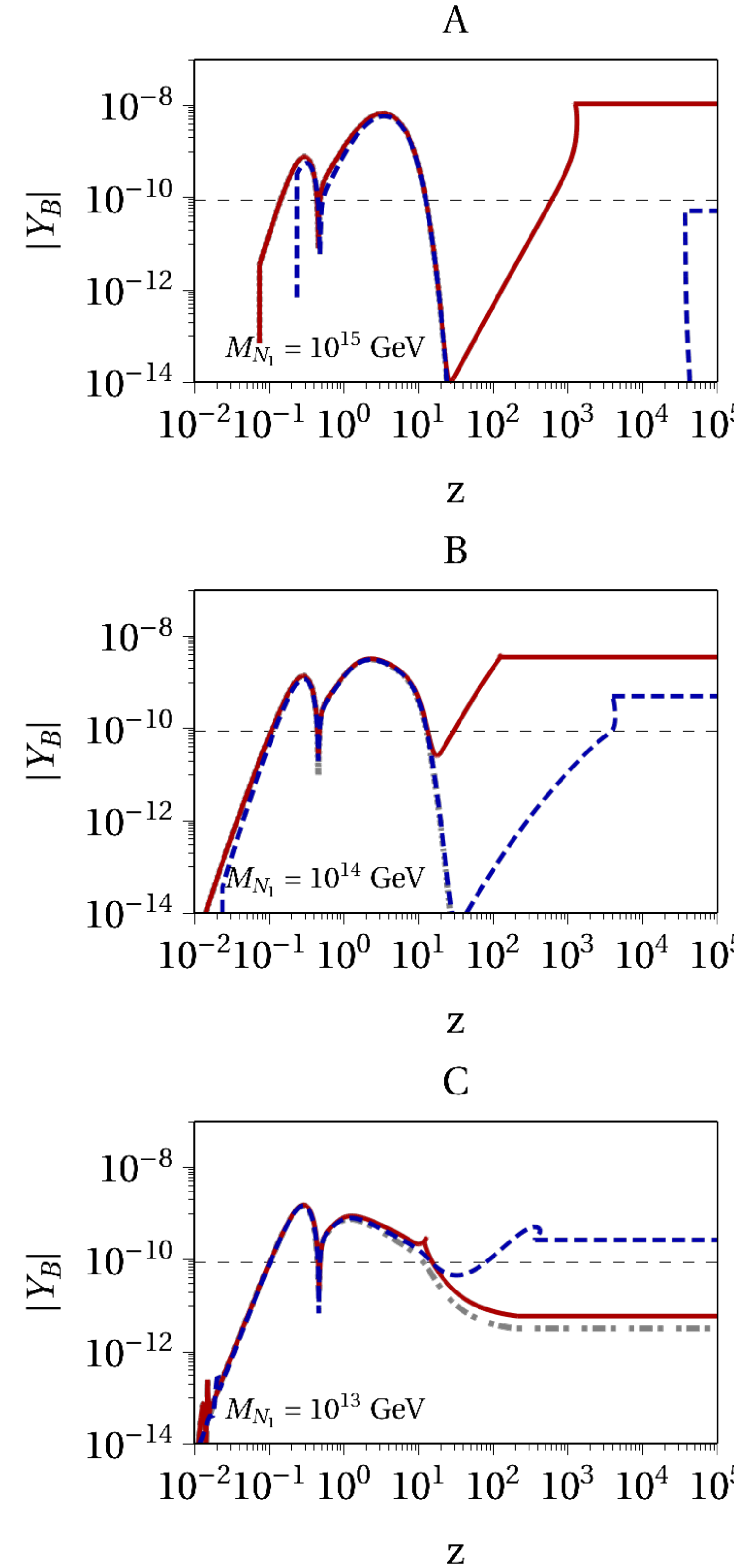

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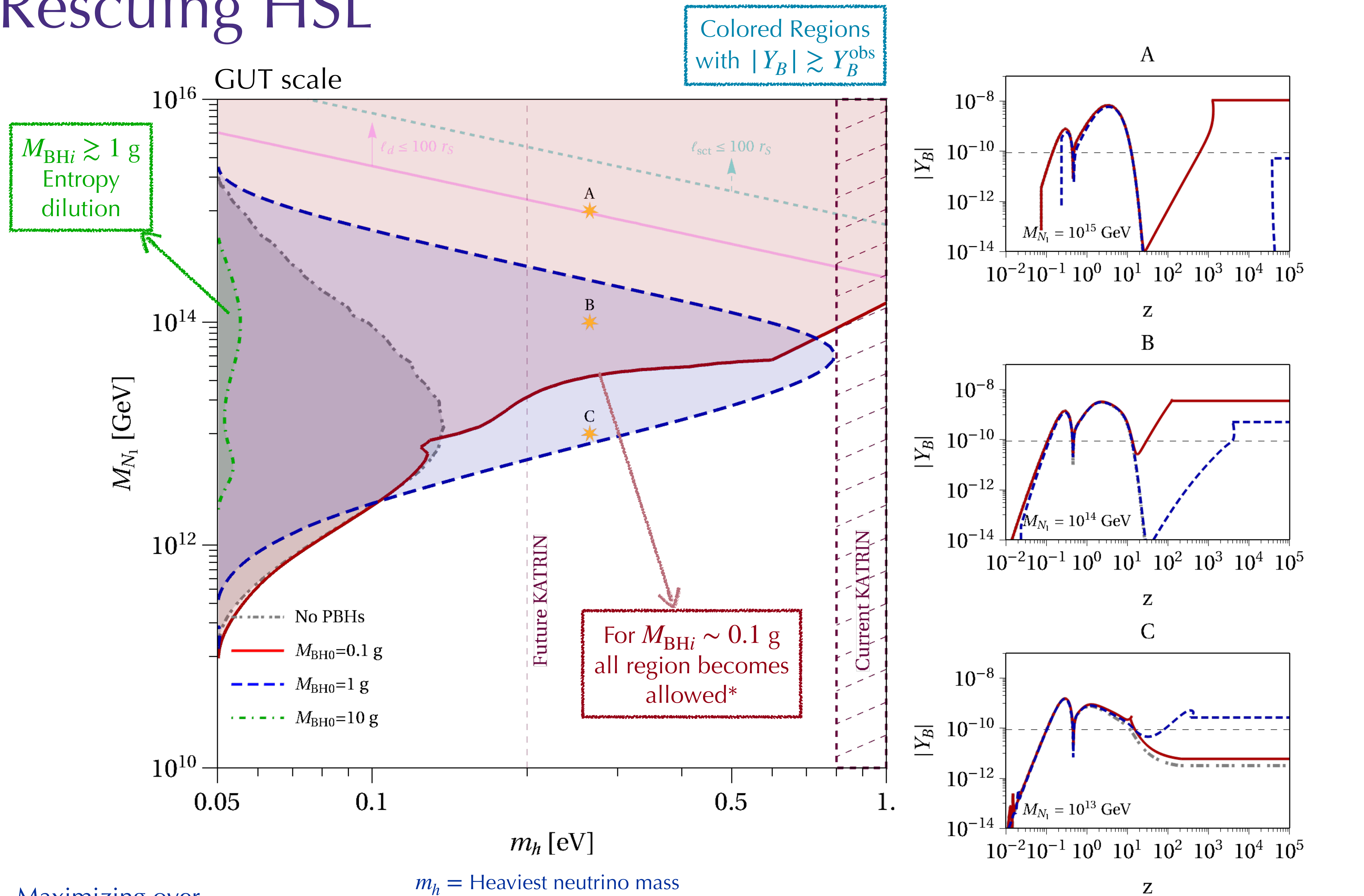

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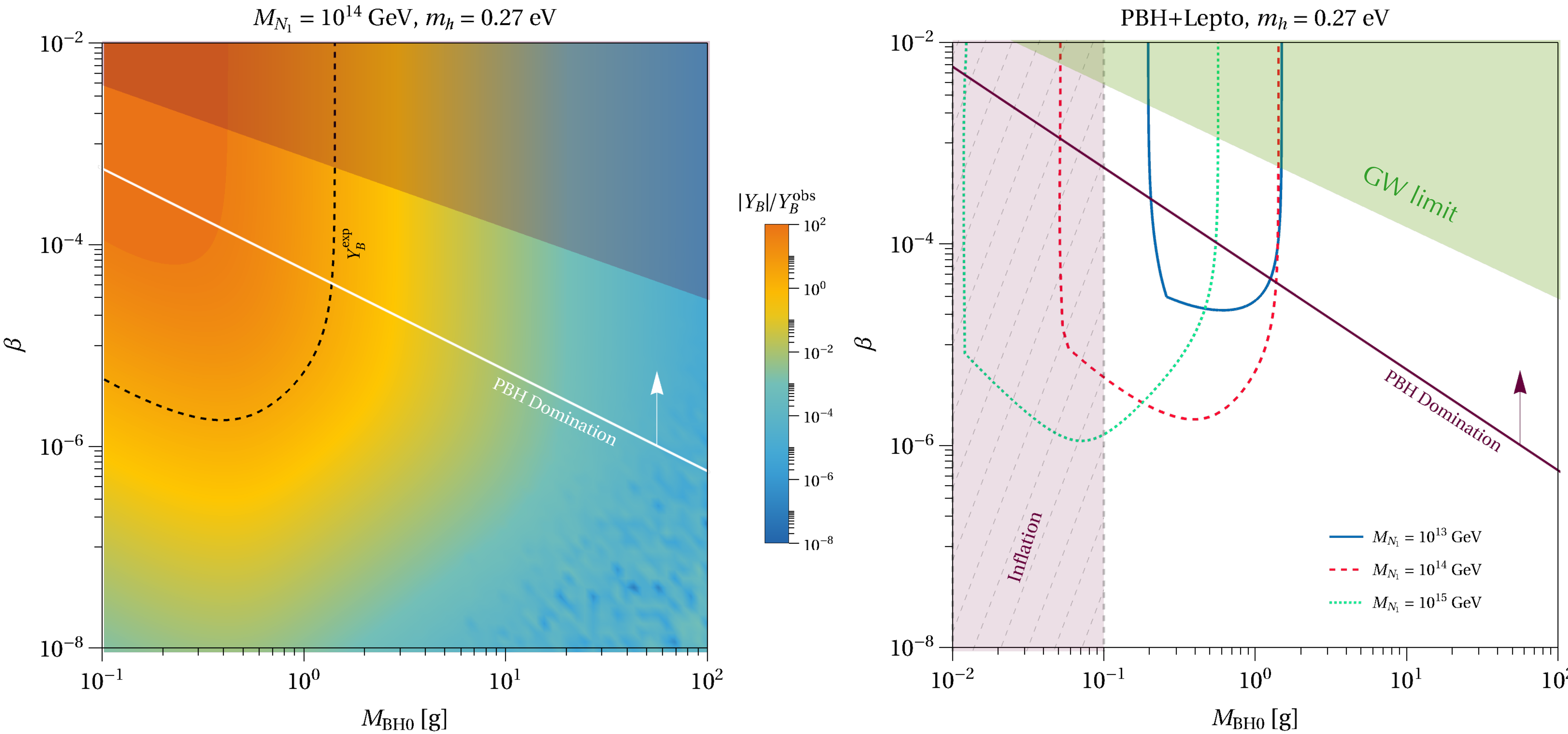
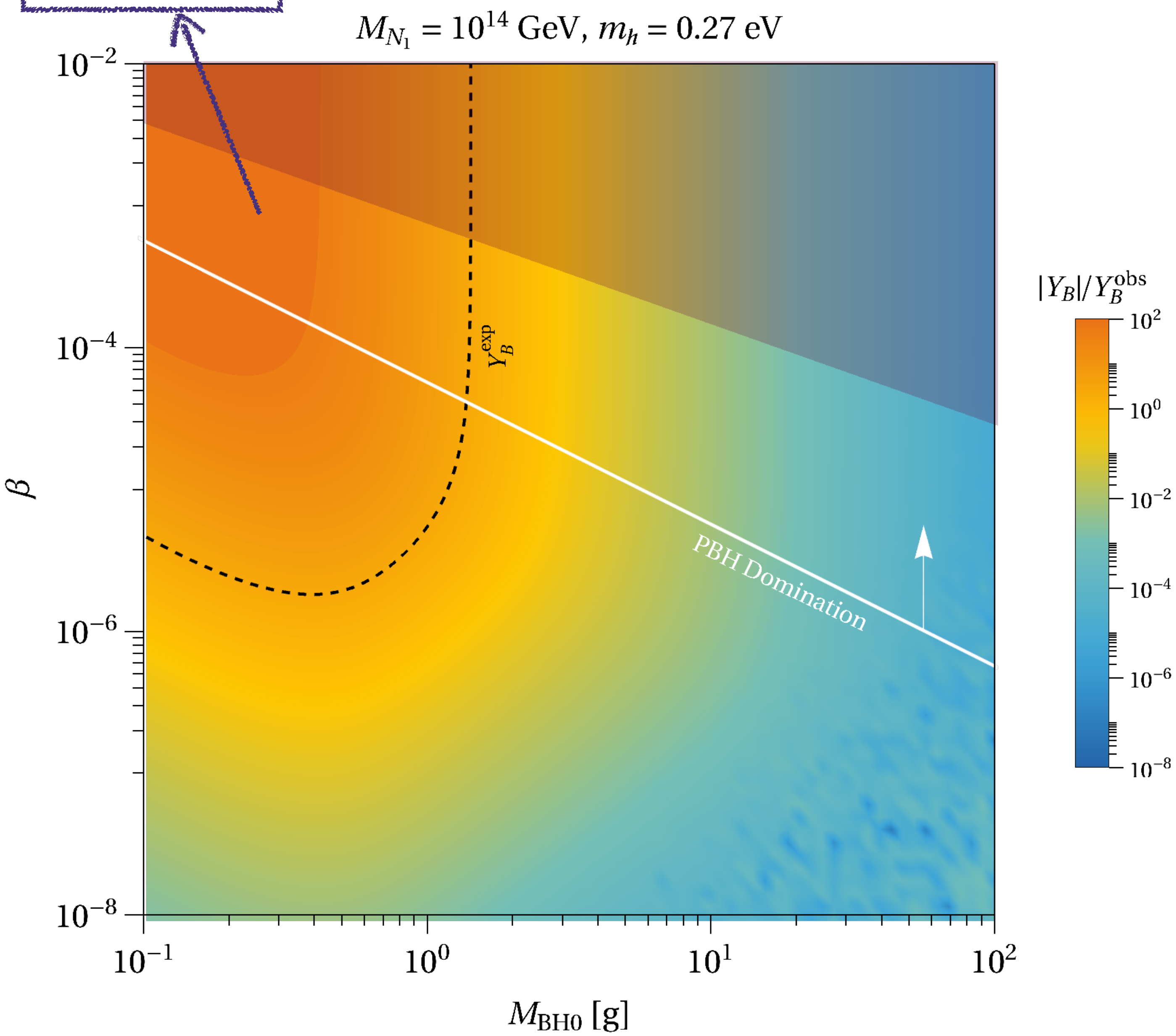
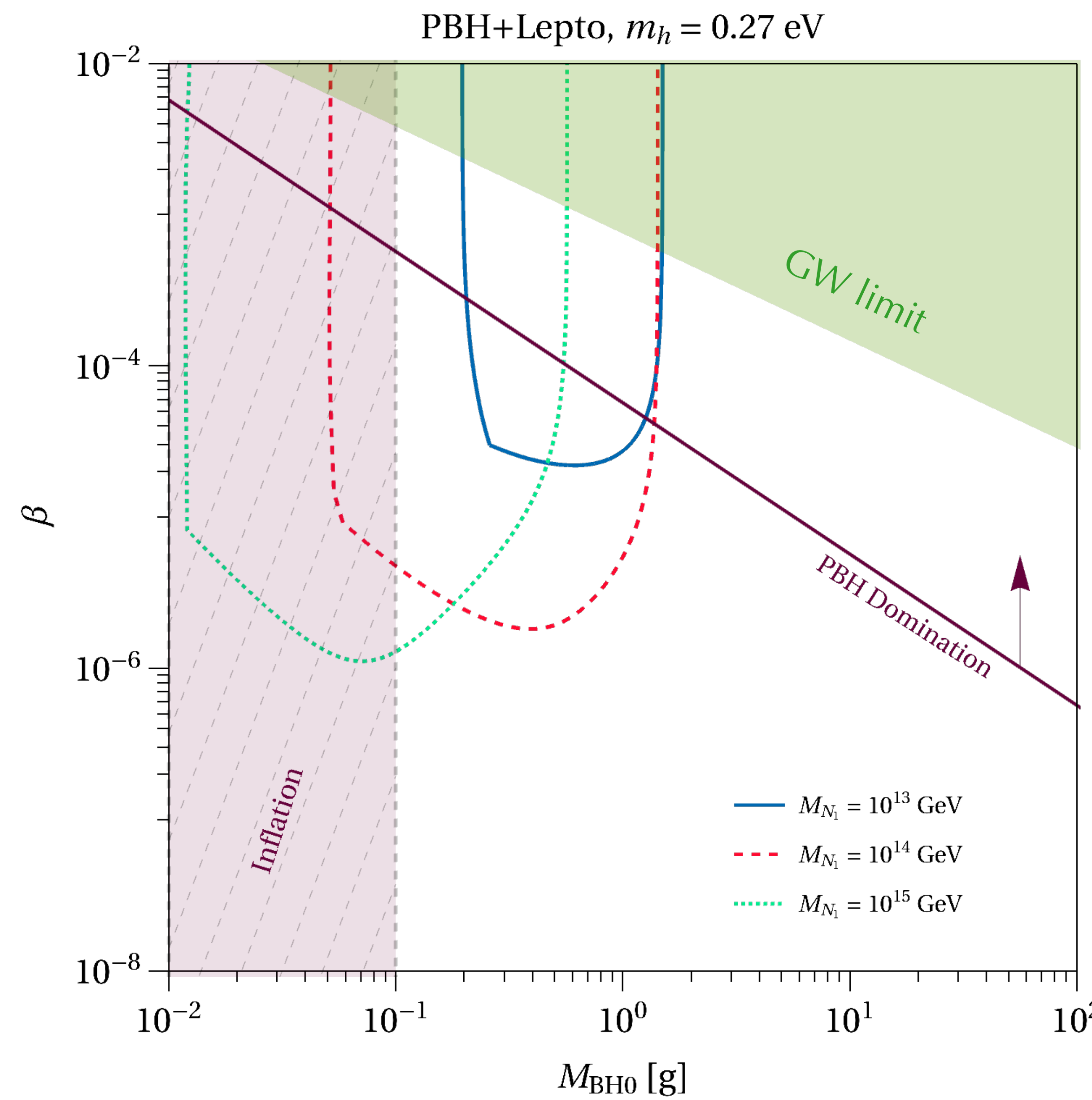


Rescuing HSL

$\mathcal{O}(10^6)$ enhancement





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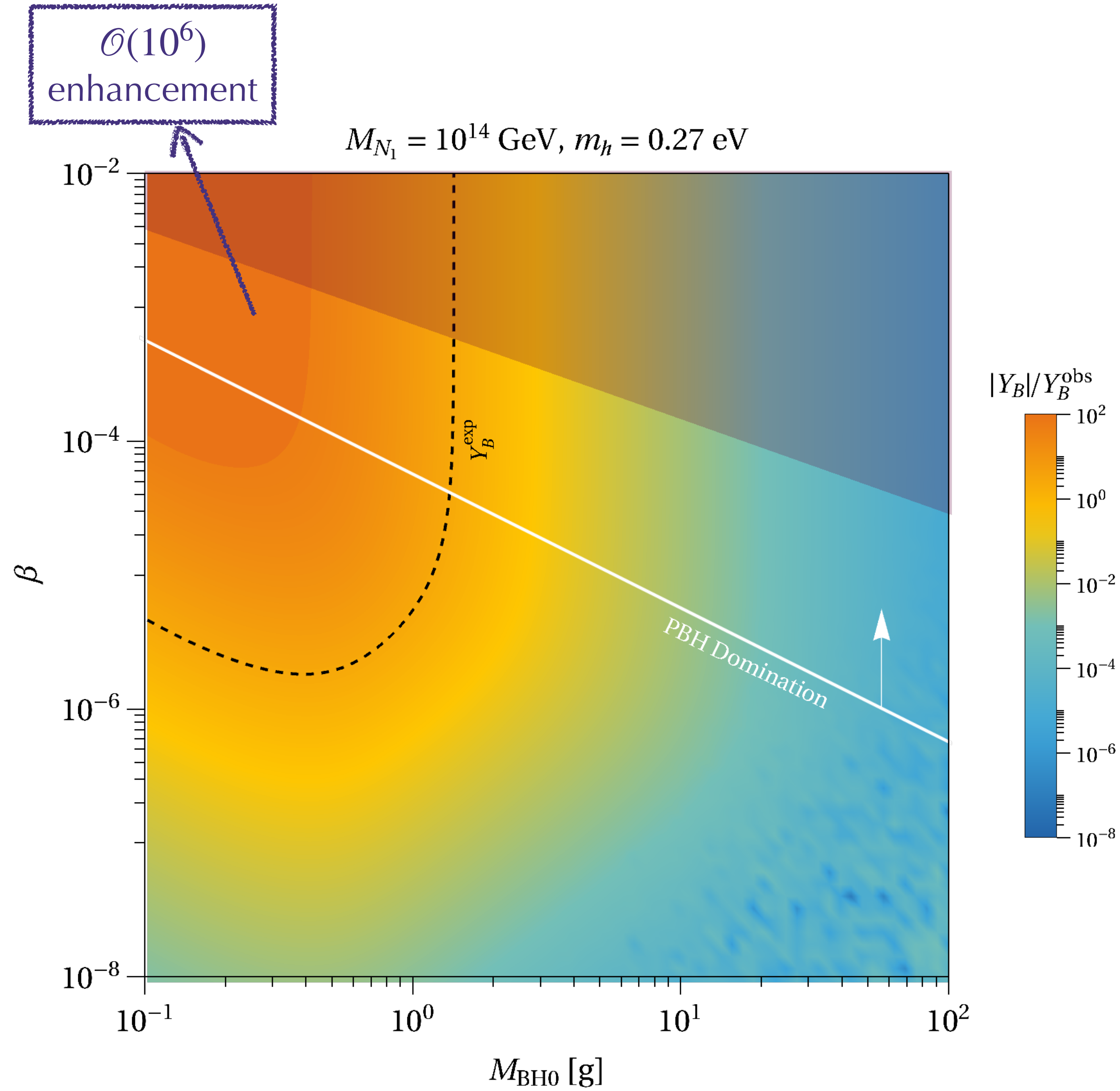

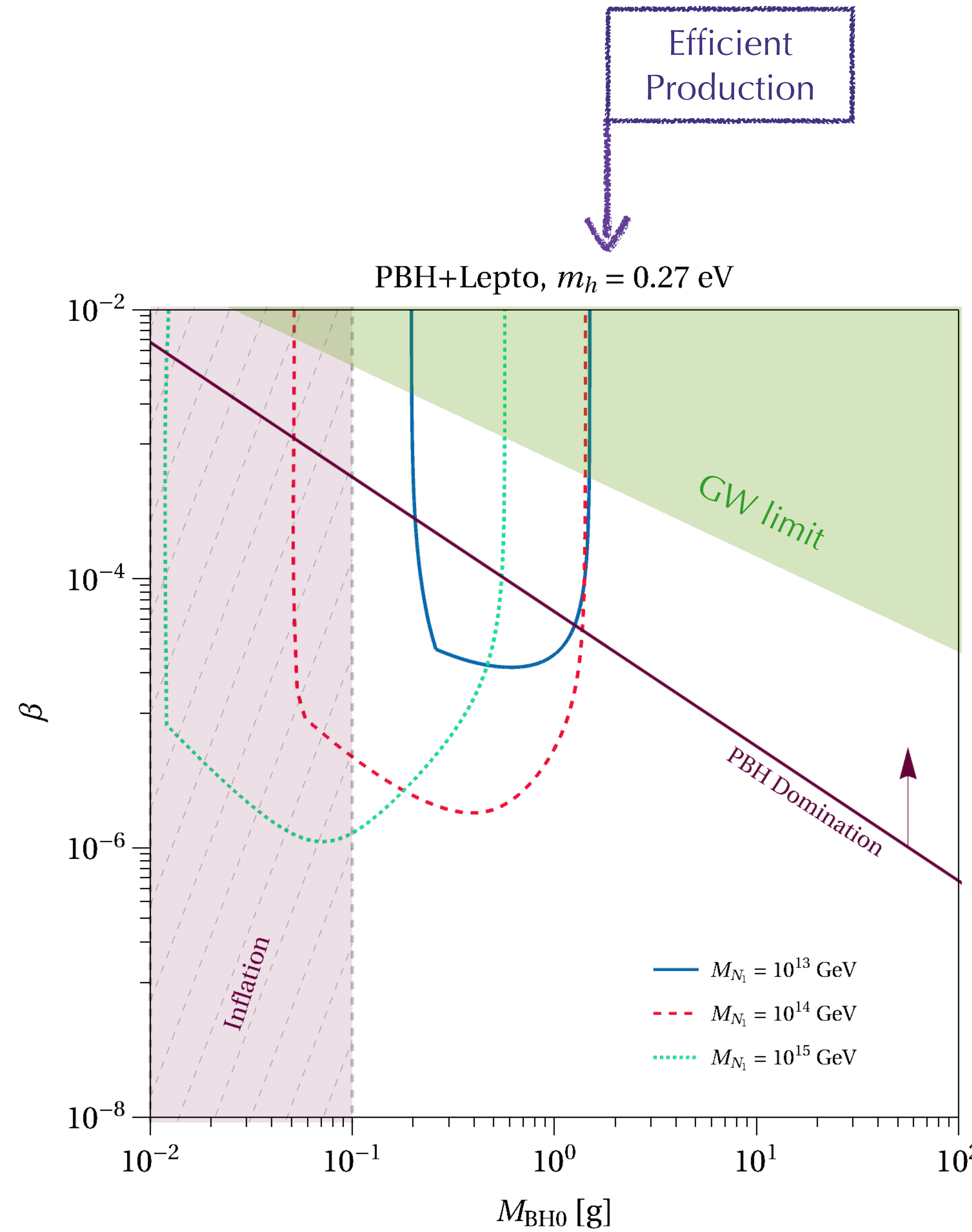

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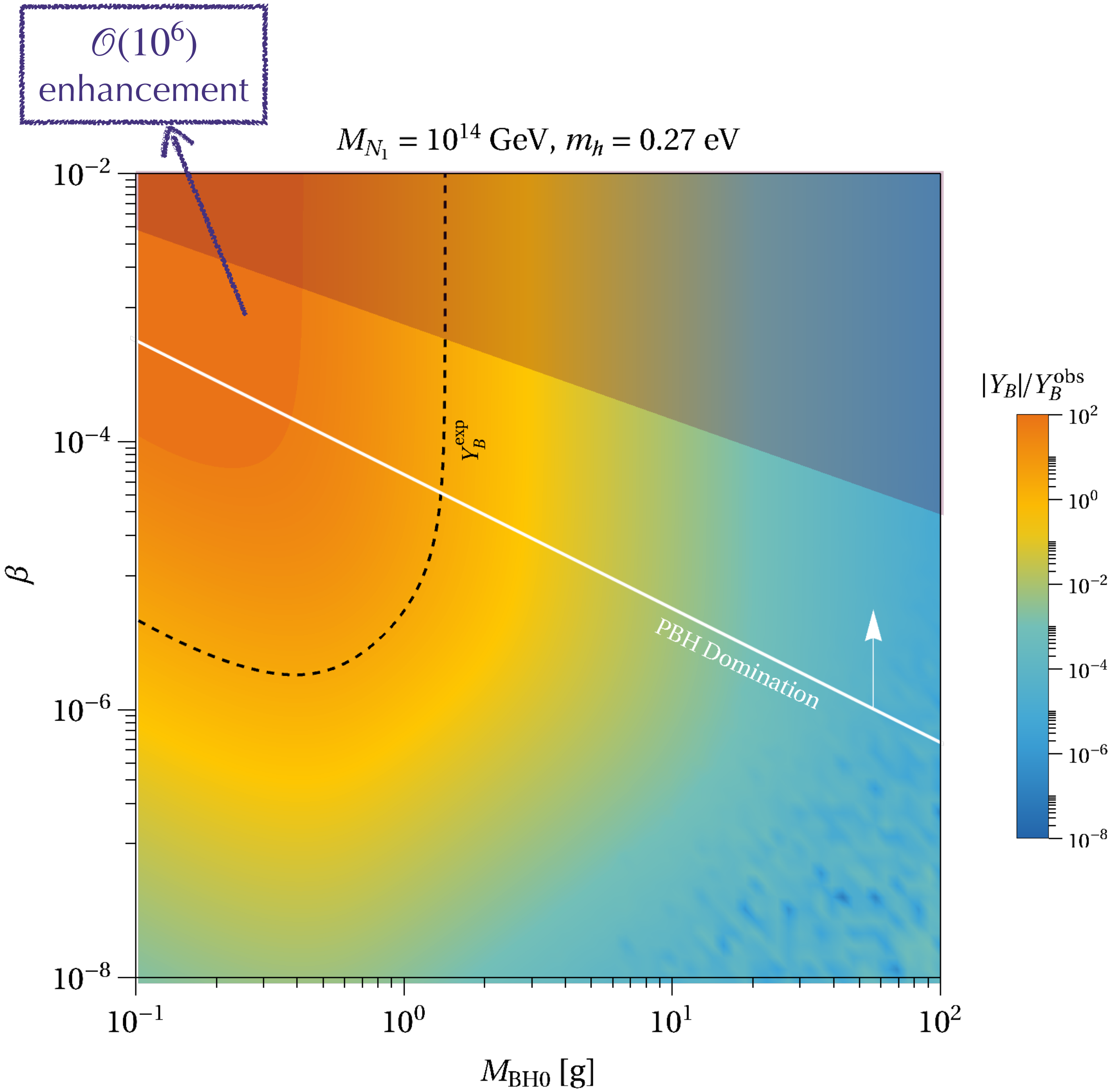
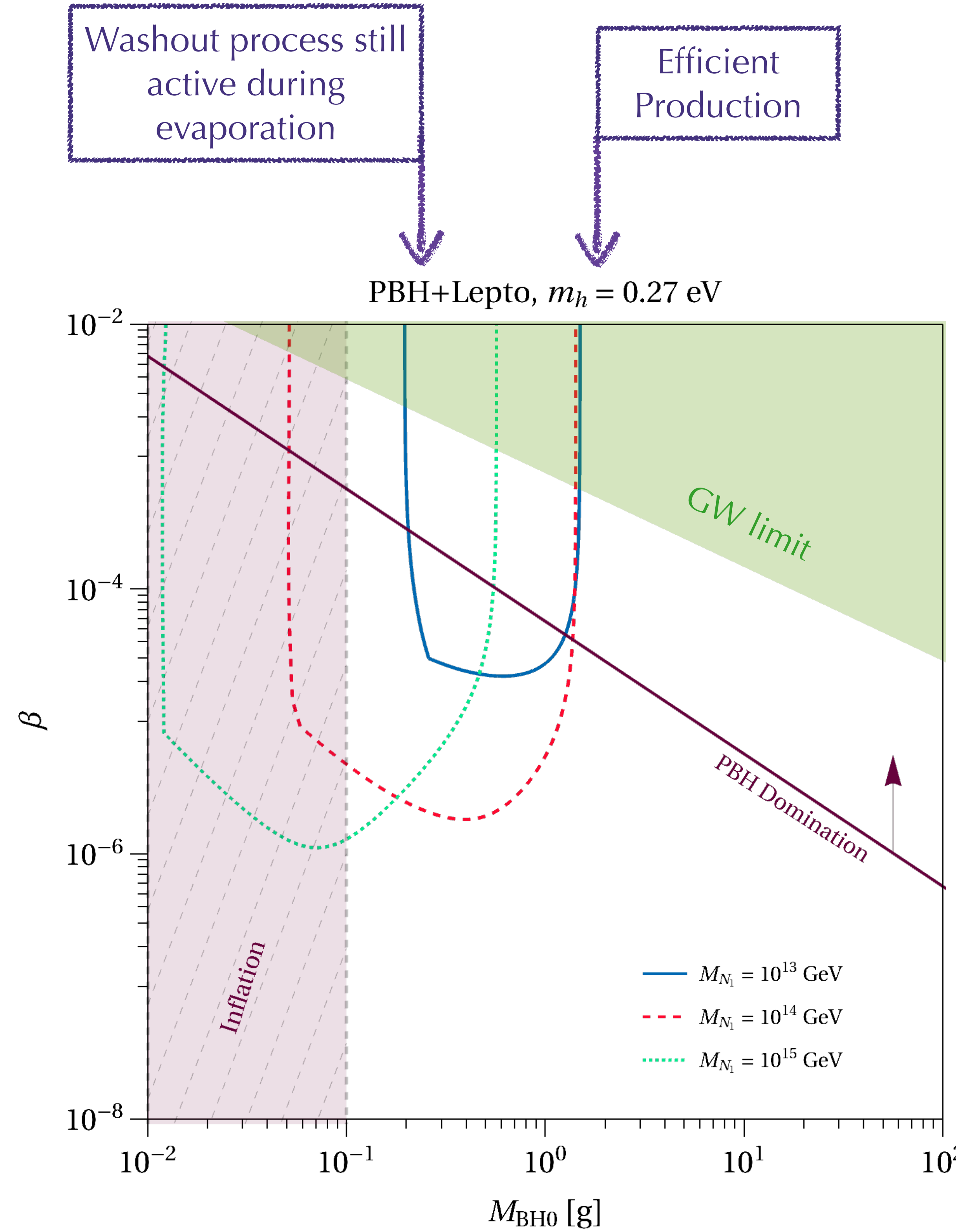




In progress

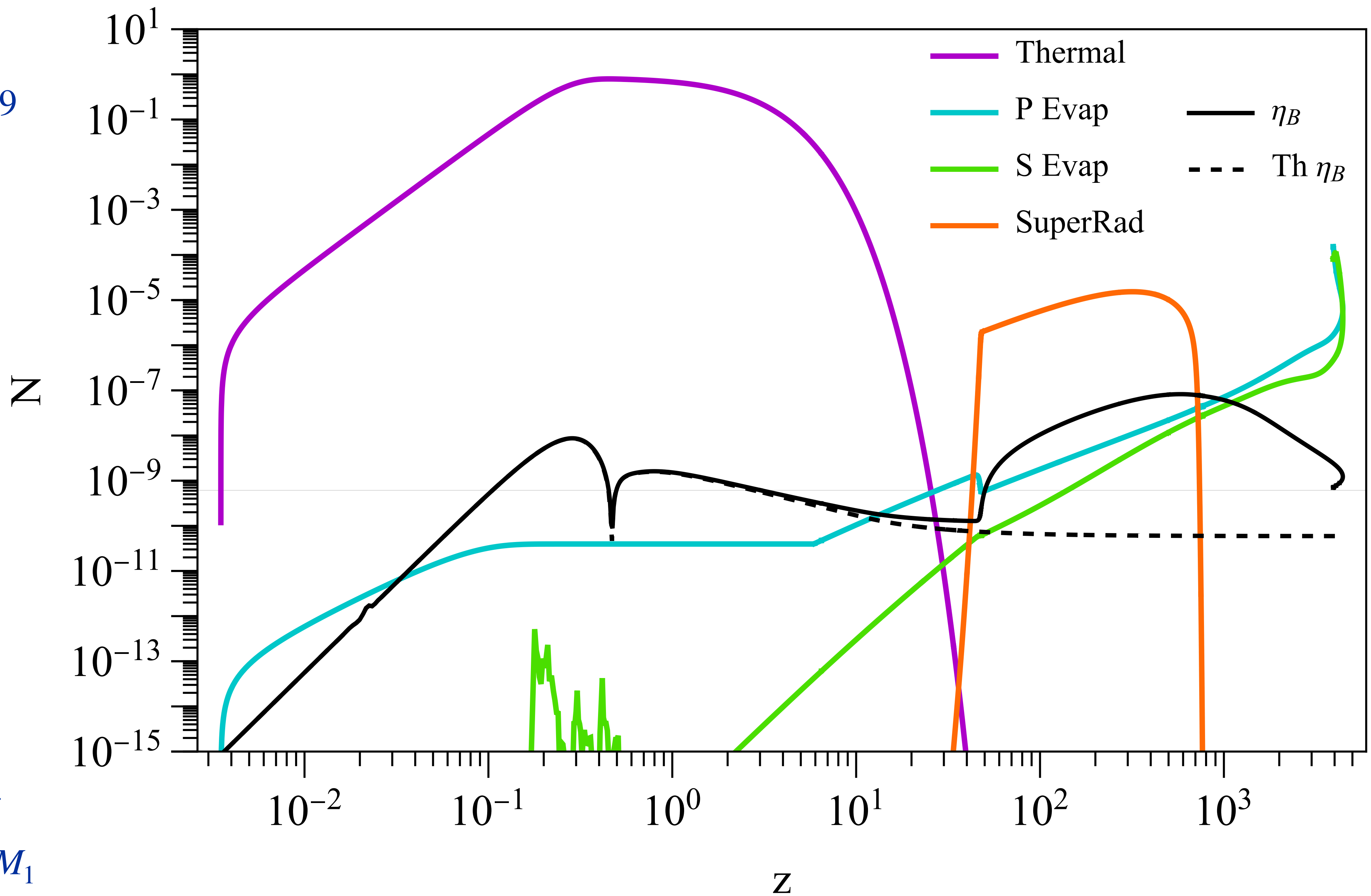
More "Baroque" Models

New possible phenomena → Superradiant enhancement?

Dark sectors containing scalar dofs

$\phi \to NN$

$M_1 = 4.6 \times 10^{12}$ GeV
$M_{\rm PBH} = 10$ g
$\beta' = 10^{-4}$
$a_\star = 0.999$



$g = 10^{-4}$
$M_\phi = 2.05 M_1$

See João's talk

Ghoshal, YFPG, Turner. 203X.XXXXX

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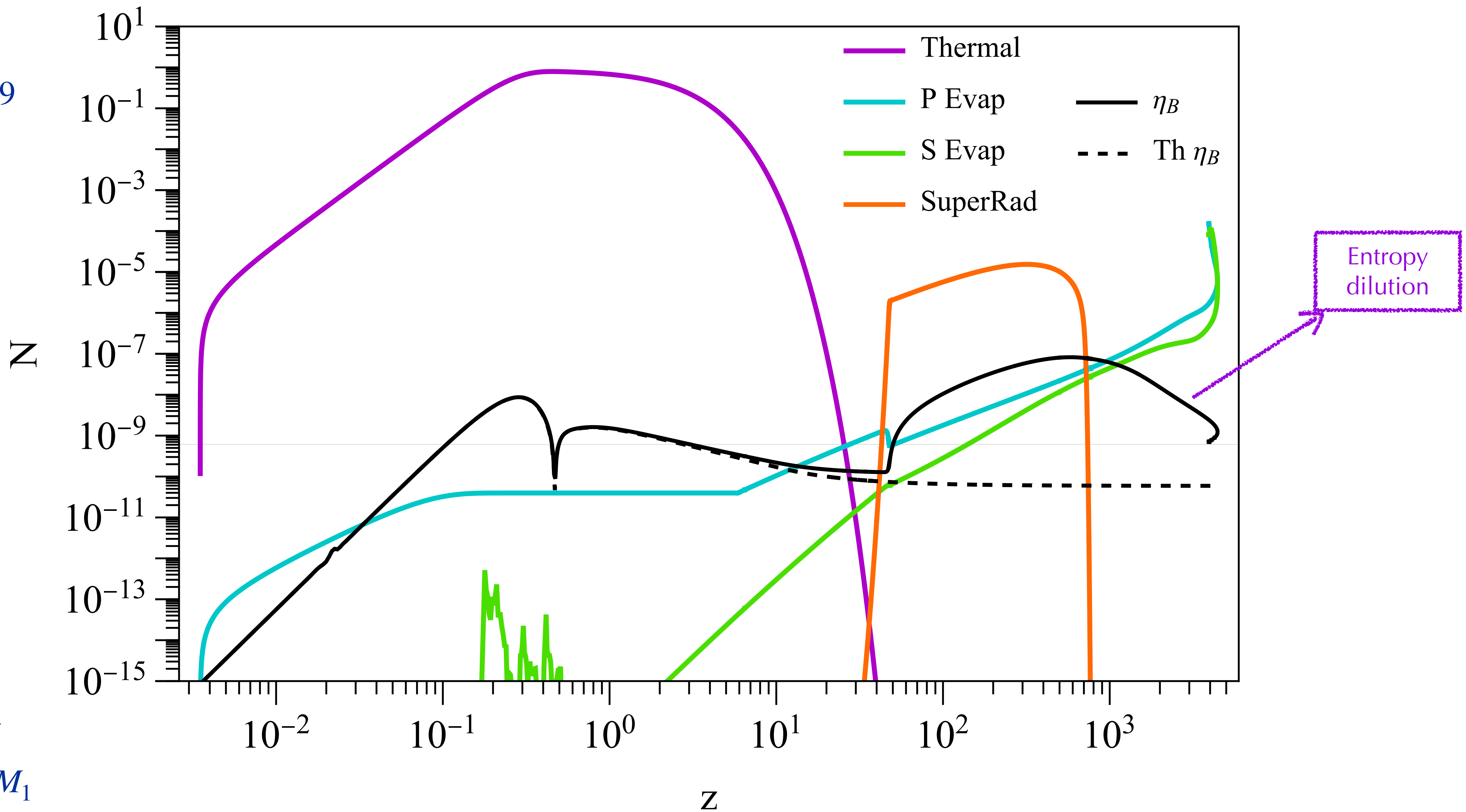

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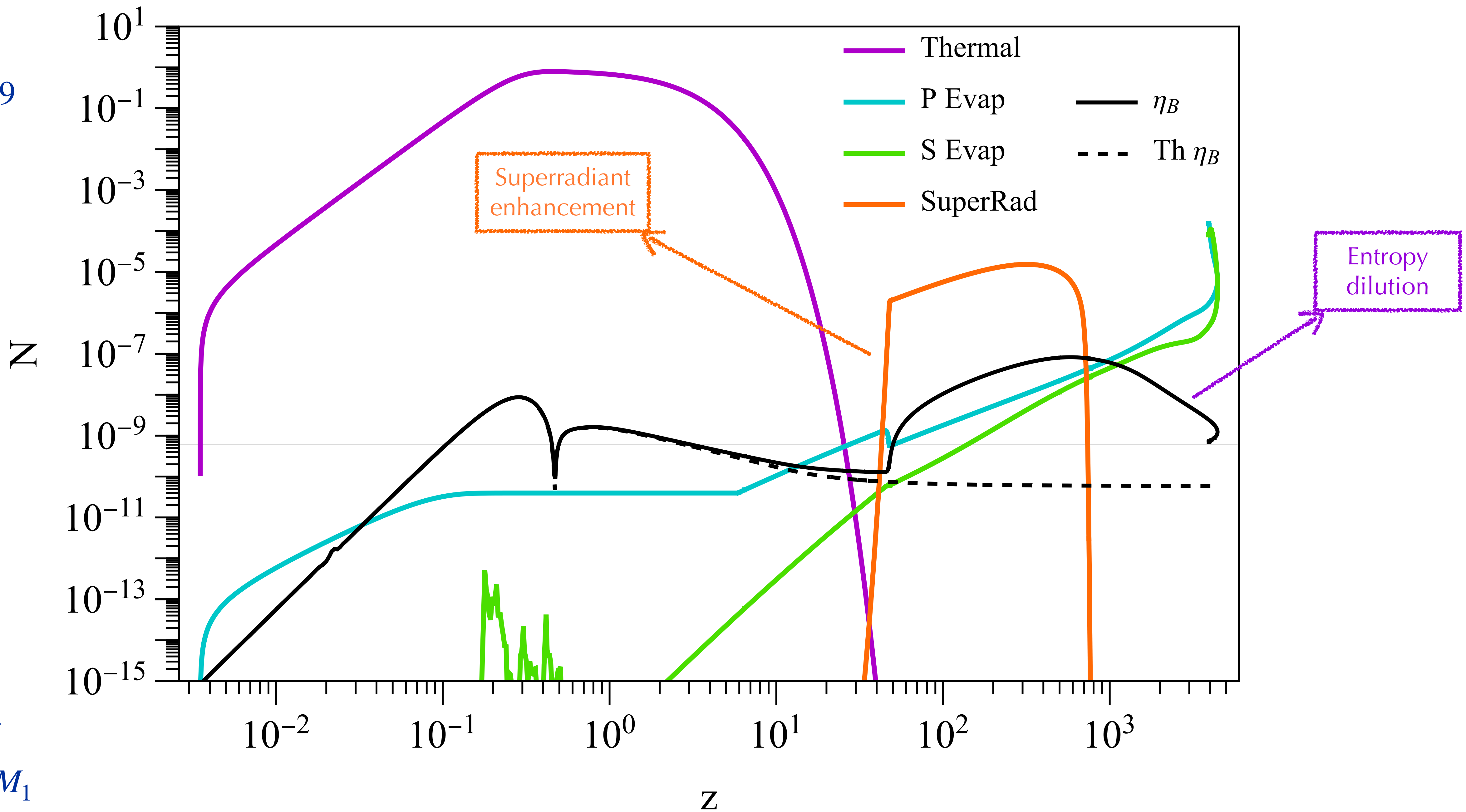

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Mass Distributions?

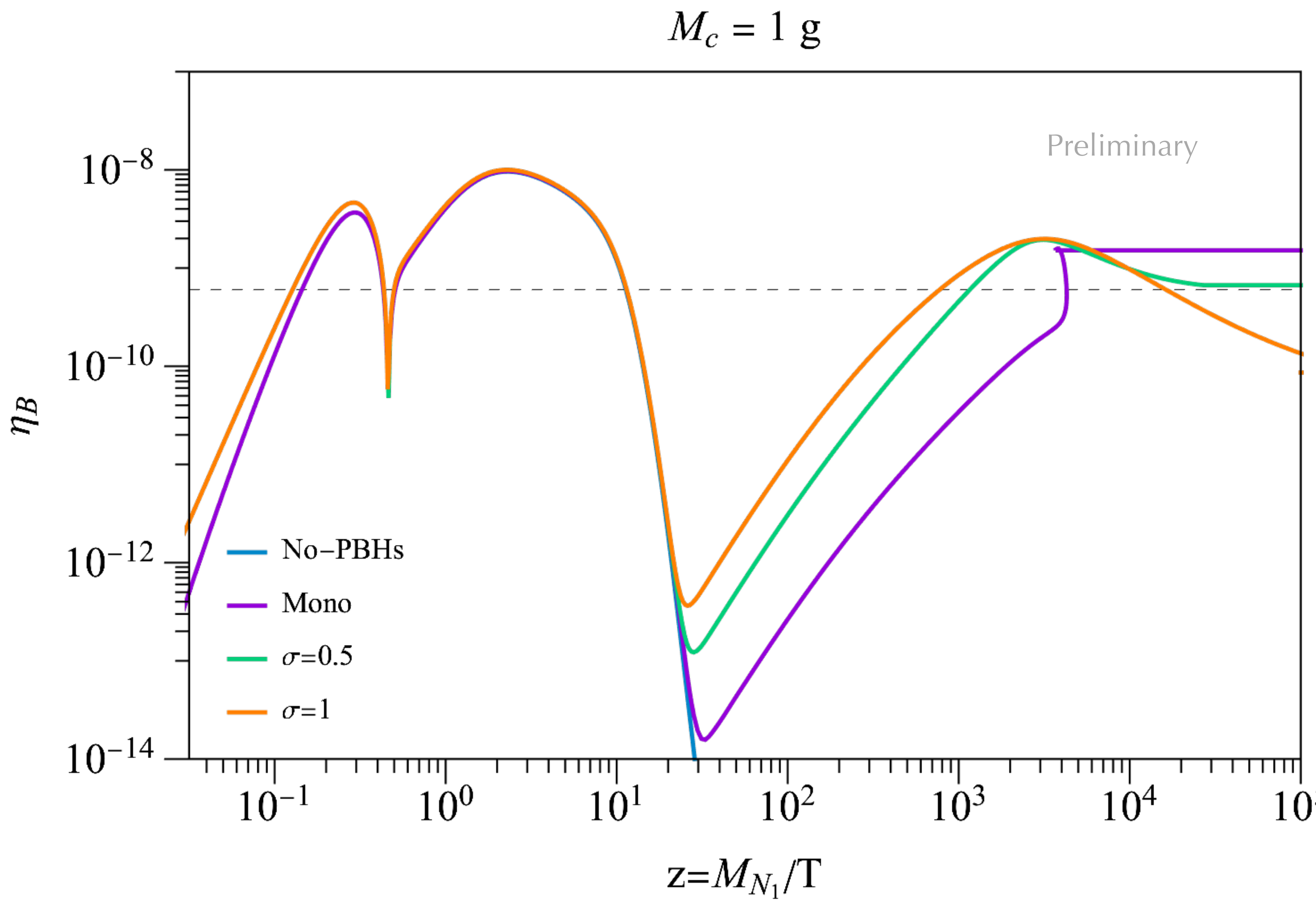
Dolgov, 93
Green, 2016
Kannike, 2017

Monochromatic approximation *too* approximated?

Connection with different formation mechanisms?

$$n_{\rm PBH} = \int dM\, f(M) \qquad f(M) = \frac{n_{\rm BH}}{\sqrt{2\pi}\sigma M}\exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$

Log-normal distribution



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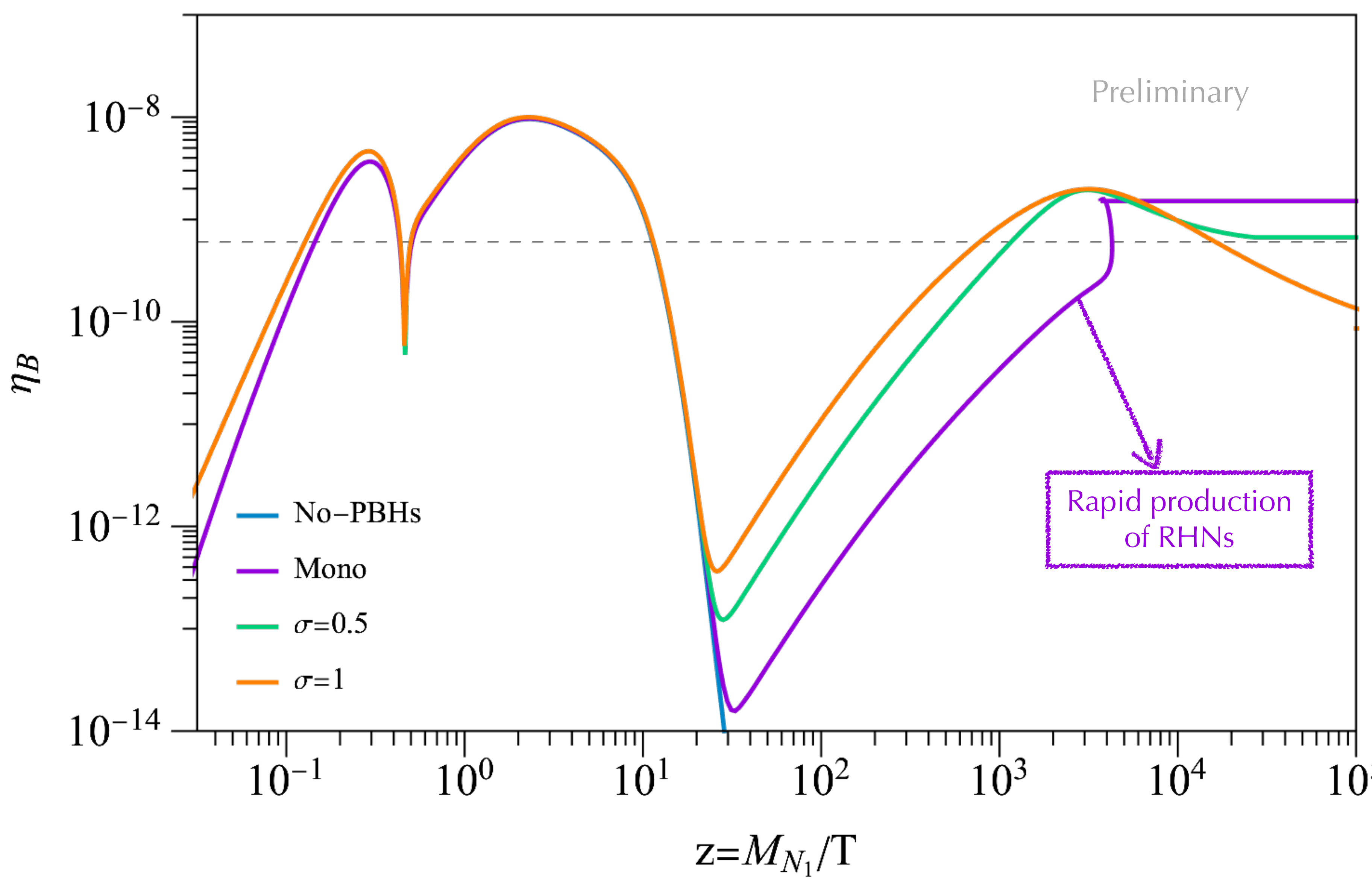
$M_c = 1$ g



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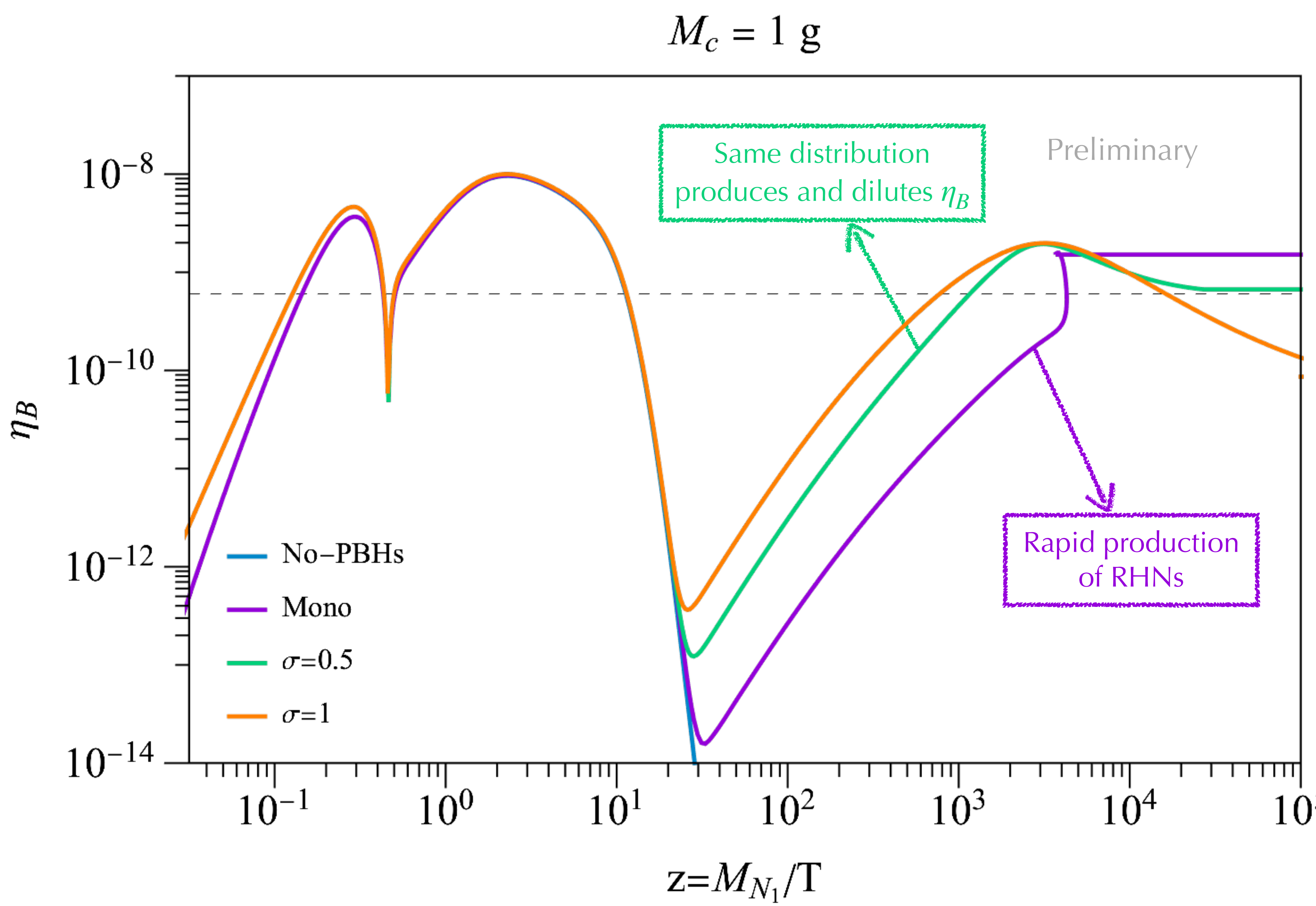

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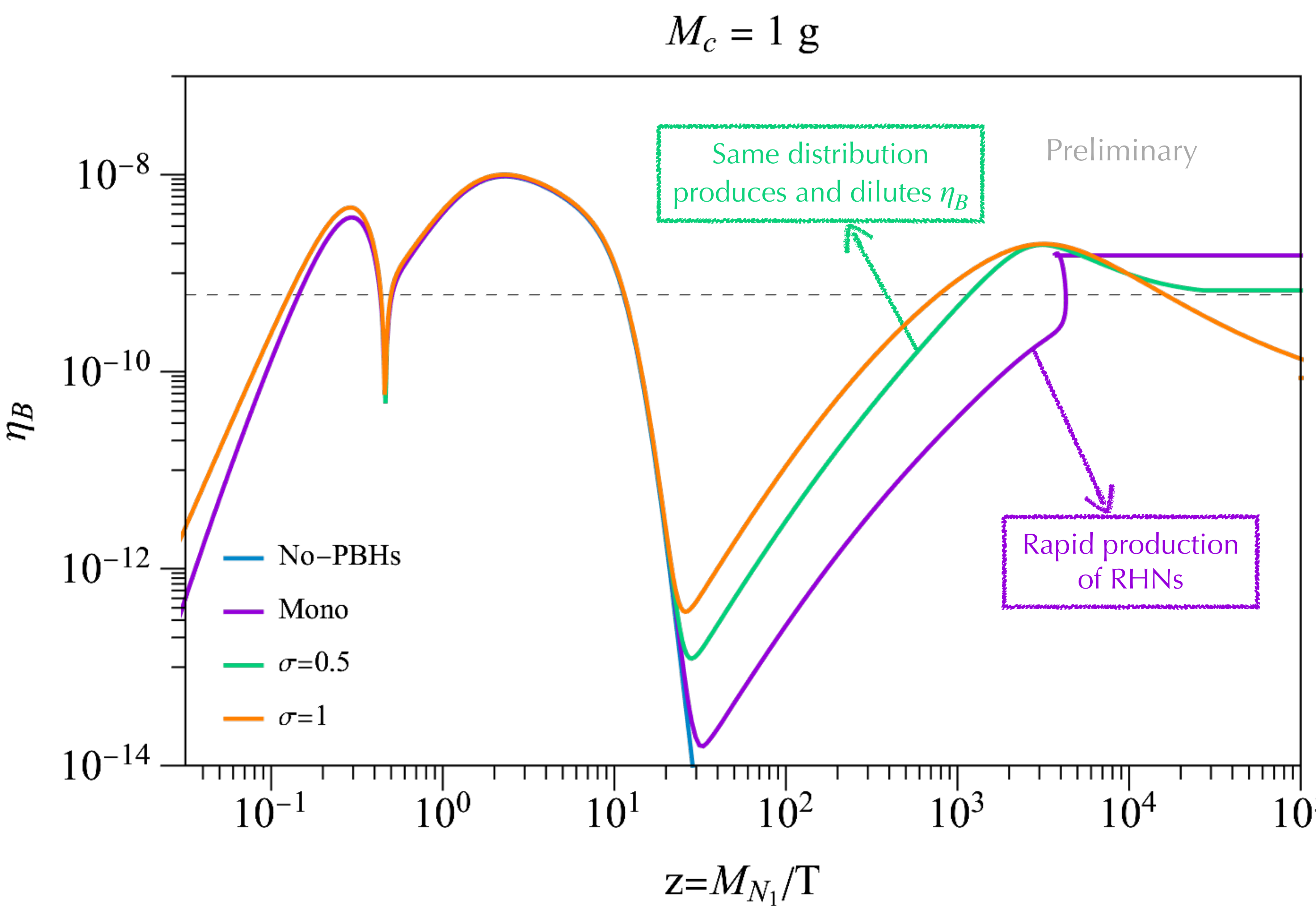

Having PBHs with different masses could have a distinct impact on the previous results

Conclusions

- PBH evaporation offers a unique mechanism to produce particles in the Early Universe
- The effects are threefold:
  - Universal particle emission
  - Modifying the Cosmological Background
  - Entropy dilution
- We explored the effects on leptogenesis assuming the existence of a PBH population
- Future directions:
  - Relating to "more realistic" PBH formation mechanisms (connected to PBH-DM?)
  - Kerr PBH $\longrightarrow$ Additional interesting properties!

Thank you!