The interplay between Primordial Black Holes and Leptogenesis

Marco Chianese

6 June 2024, PLANCK 2024 conference, Lisbon, Portugal

based on Calabrese, MC, Gunn, Miele, Morisi and Saviano, PRD 107 (2023) and PRD 109 (2024)

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NAP Theory

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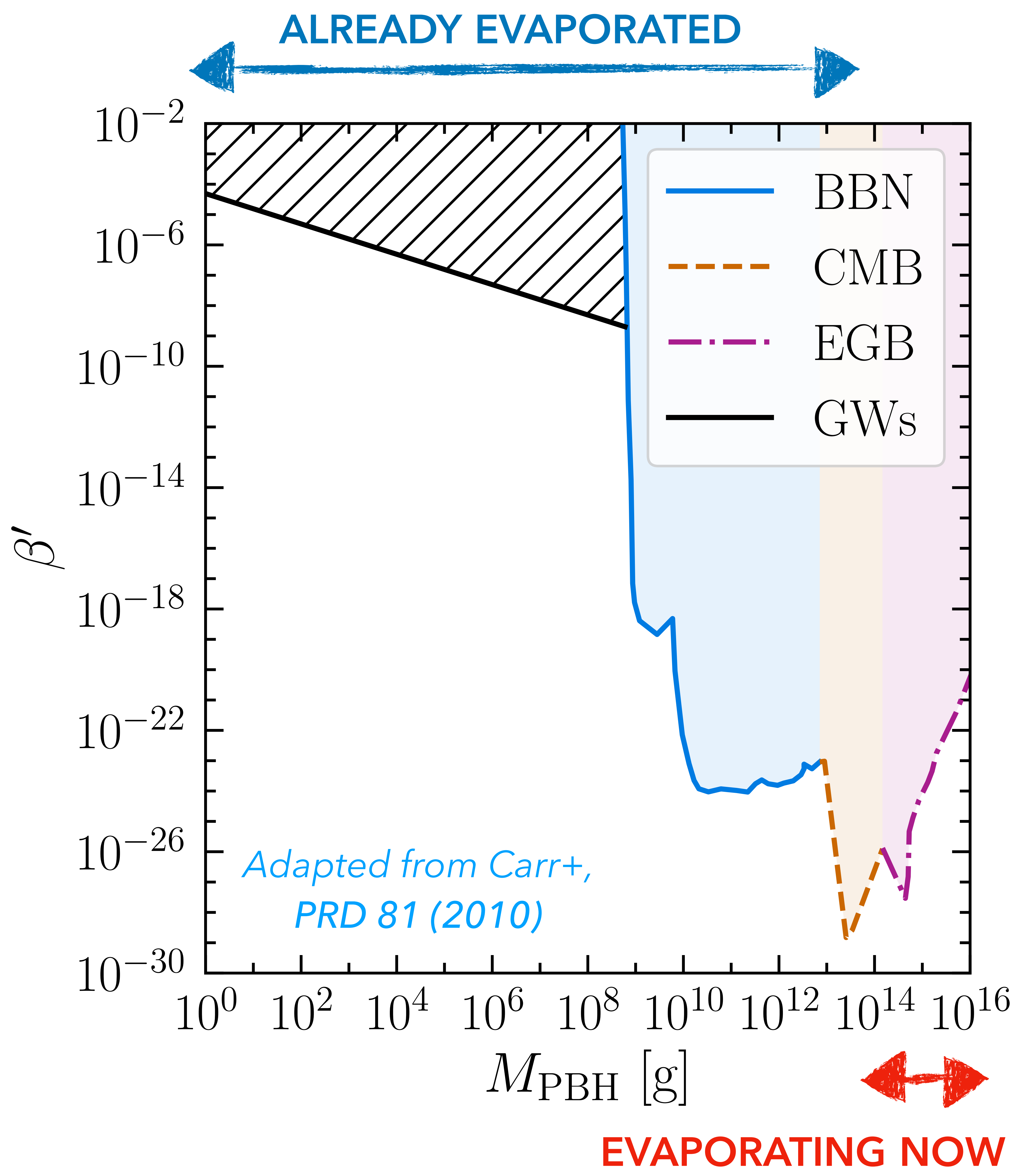
Primordial Black Holes (PBHs)



- ✦ Formed at $T_{\rm form}$ after inflation with an abundance

$$\beta'(M_{\rm PBH}) = \gamma^{1/2} \, \frac{\rho_{\rm PBH}(T_{\rm form})}{\rho_R(T_{\rm form})}$$

- ✦ Hawking radiation: emission of particles with a mass $m \leq T_{\rm PBH} \simeq 10 \left(10^{15} \text{ g}/M_{\rm PBH}\right) \text{MeV}$
- ✦ The evaporation lifetime is $\simeq 4 \times 10^{17} \left(M_{\rm PBH}/10^{15}\text{g}\right)^3 \text{s}$

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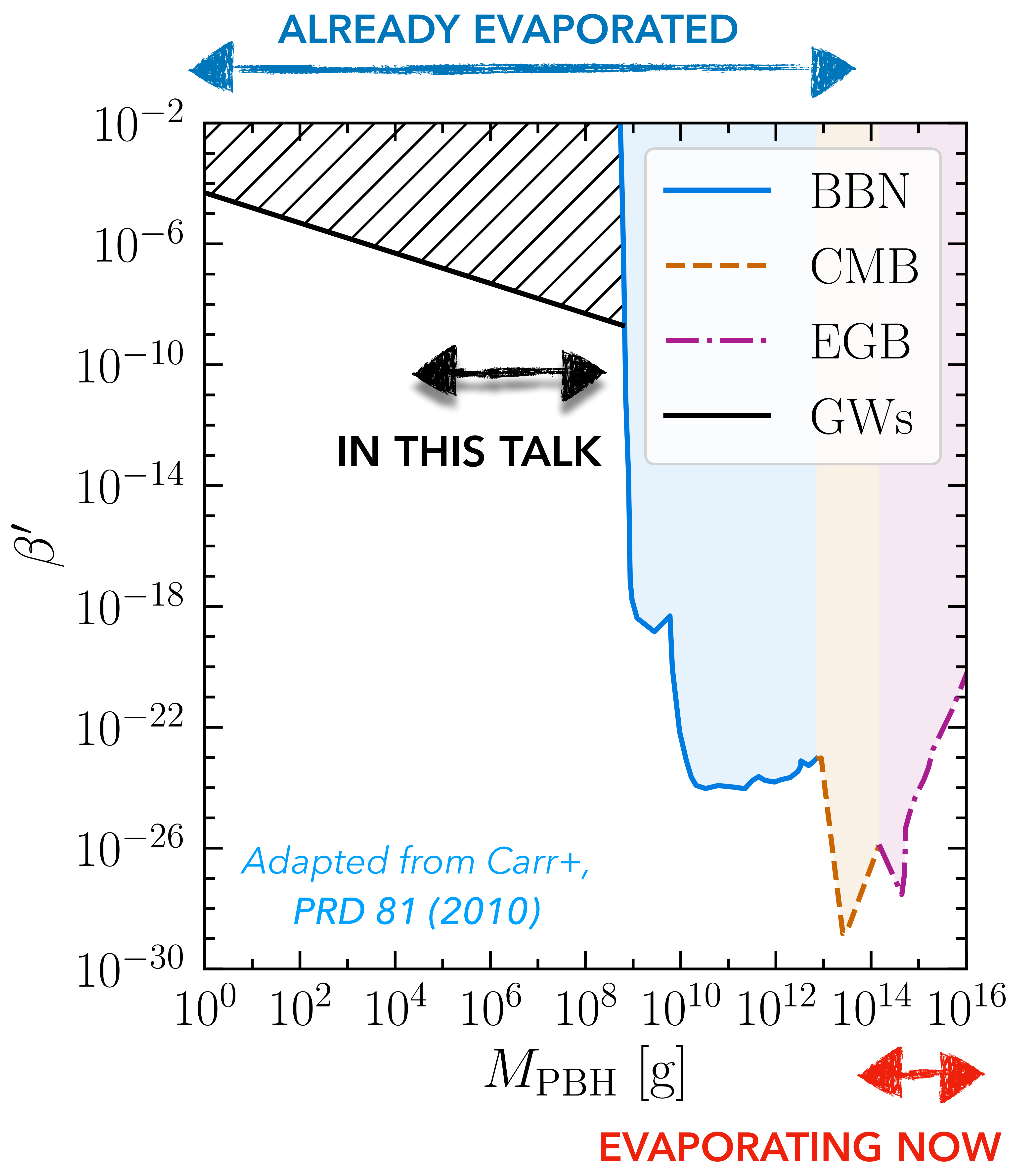

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IN THIS TALK

✦ Light PBHs ($M_{\rm PBH} \lesssim 10^9$ g) strongly modify the parameter space of leptogenesis

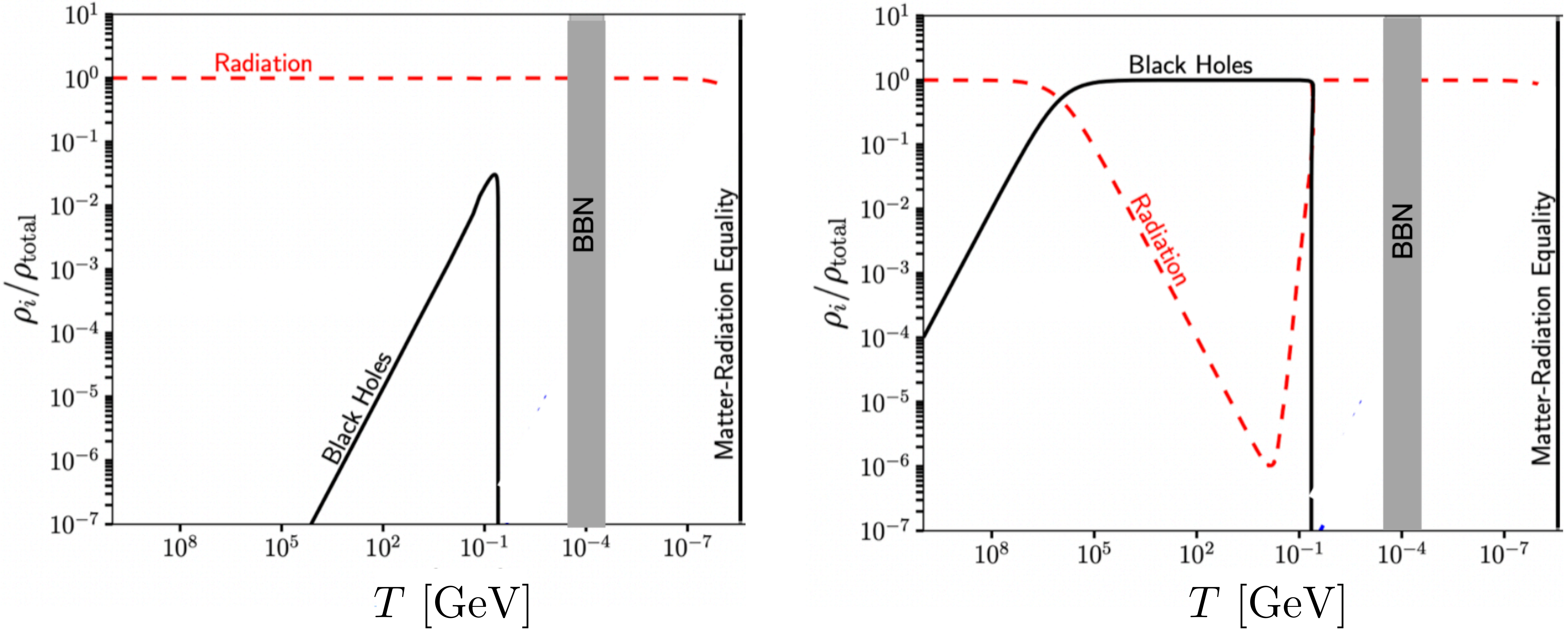
✦ Interesting interplay and mutual exclusion limits between PBHs and leptogenesis

Non-standard cosmology from PBHs

Depending on their abundance, PBHs could induce a matter-dominated period before evaporation

Small PBH abundance ($\beta \sim 10^{-13}$)

PBHs dominate before evaporation ($\beta \sim 10^{-7}$)



*Adapted from Hooper+, **JHEP 08 (2019)***

Leptogenesis landscape

Baryogenesis via Leptogenesis: the *seesaw Lagrangian* naturally satisfies the Sakharov conditions to produce an L asymmetry which is then converted into a B asymmetry via sphalerons

$\mathcal{O}(1\ \mathrm{GeV})$ $\mathcal{O}(10^3\ \mathrm{GeV})$ $\mathcal{O}(10^6\ \mathrm{GeV})$ $\mathcal{O}(10^{12}\ \mathrm{GeV})$ → M_R

Leptogenesis via oscillations

*Akhmedov, Rubakov & Smirnov, **PRL 81 (1998)**; Asaka & Shaposhnikov, **PLB 620 (2005)**; Asaka, Eijima & Ishida, **JHEP 1104 (2011)** …*

Resonant Leptogenesis

*Pilaftis & Underwood, **Nucl. Phys. B 692 (2004)**; Abada, Aissaoui & Losada, **Nucl. Phys. B 728 (2005)** …*

Intermediate-scale Leptogenesis

*Racker, Rius & Pena, **JCAP 1207 (2013)**; Moffat, Petcov, Pascoli, Schulz & Turner, **PRD 98 (2018)** …*

High-scale Leptogenesis

*Fukugida & Yanagida, **PLB 17 (1986)**; Buchmuller, Di Bari & Plumacher, **New J.Phys. 6 (2004)**; Barbieri, Creminelli, Strumia & Tetradis, **Nucl. Phys. B 575 (2000)** …*

*Incomplete list…see interesting reviews: Buchmuller+, **Annals Phys. 315 (2005)**; Sheng Fong+, **Adv.High Energy Phys. (2012)**; Davidson+, **Phys.Rept. 466 (2008)***

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Resonant Leptogenesis

+ PBHs

*Calabrese, MC, Gunn, Miele, Morisi, Saviano, **PRD 109.103001 (2024)***

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*Calabrese, MC, Gunn, Miele, Morisi, Saviano, **PRD 107.123537 (2023)***

*PBH & Leptogenesis: Fujita+, **PRD 89 (2024)**; Hamada+, **Prog. Theor. Exp. Phys. (2017)**; Morrison+, **JCAP 05 (2019)**; Perez-Gonzalez+, **PRD 104 (2021)**; Datta+, **JCAP 08 (2021)**; Jyoti Das+, **JCAP 11 (2021)**; Bernal+, **PRD 106 (2022)**; Schmitz+, **PLB 849 (2024)**; Ghoshal+ **JHEP 02 (2024)**; Barman+, **2405.15858***

Leptogenesis and PBHs

PBHs can affect leptogenesis in different ways depends on their mass M_{PBH} and abundance β'

ADDITIONAL NON-THERMAL SOURCE TERM

$$a\mathcal{H}\frac{\mathrm{d}n_N}{\mathrm{d}a} = -(n_N - n_N^{\mathrm{eq}})\ \Gamma_N^T + n_{\mathrm{PBH}}\ \Gamma_N^{\mathrm{PBH}}$$

if $T_{\mathrm{PBH}} > M$

contribution from thermal plasma

contribution from PBH evaporation

Studied for $M_{\mathrm{PBH}} < 10^5$ g in:
Perez-Gonzalez+, PRD 104 (2021)
Bernal+, PRD 106 (2022)

ENTROPY INJECTION

$$\frac{\mathrm{d}\mathcal{S}}{\mathrm{d}a} = -\frac{f_{\mathrm{SM}}}{T(a)}\frac{\mathrm{d}\ln M_{\mathrm{PBH}}}{\mathrm{d}a}\rho_{\mathrm{PBH}}$$

Dilution of any pre-existing relic at evaporation

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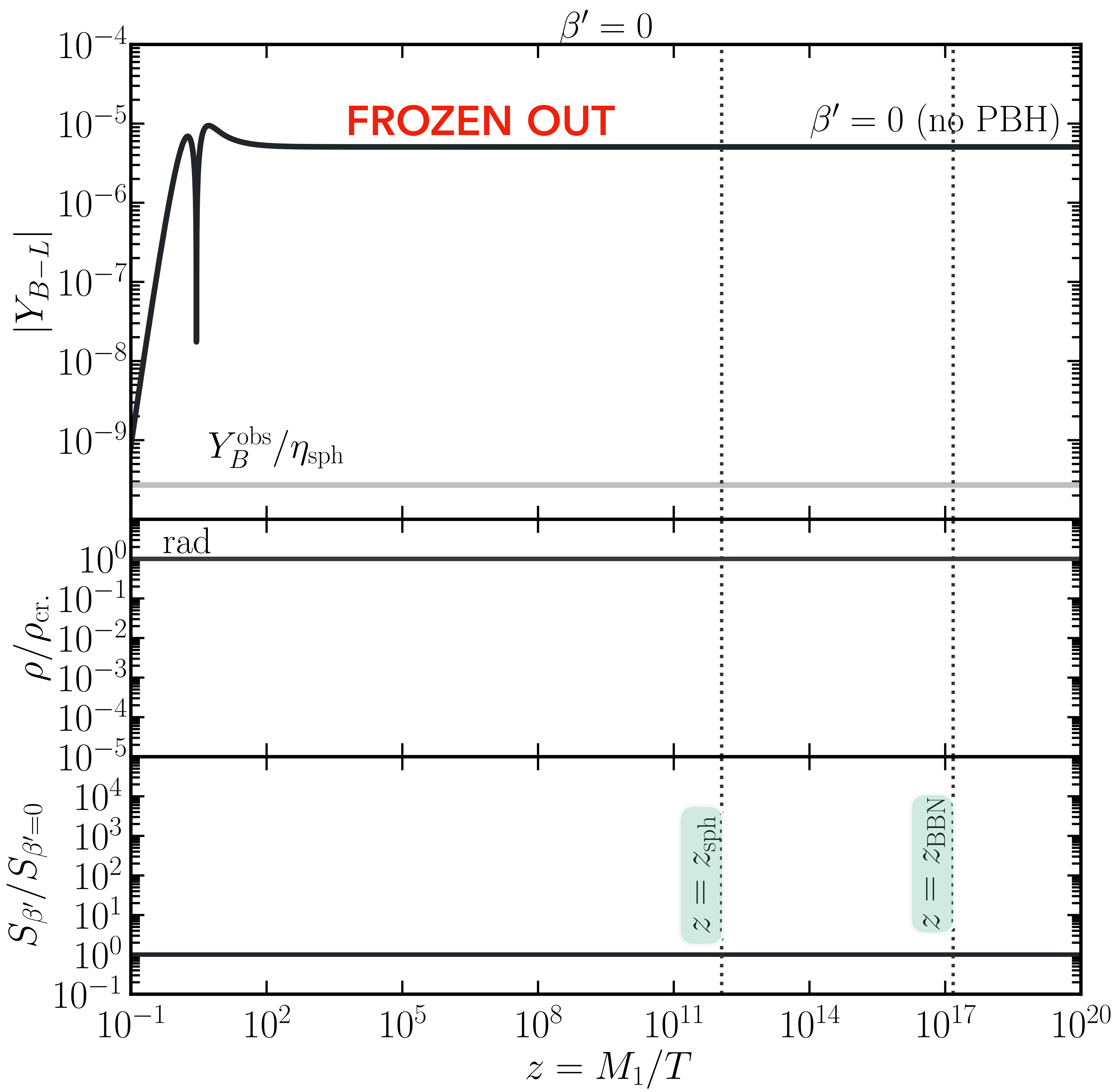
Dilution of any pre-existing relic at evaporation

In our works we focus on $10^5 \leq M_{\rm PBH}/{\rm g} \leq 10^9$

- ✦ No efficient production of RHNs ($10^4 \lesssim T_{\rm PBH}/{\rm GeV} \lesssim 10^8$)
- ✦ Evaporation after sphalerons but before BBN

Benchmark scenarios

Calabrese+ (w/ MC), **PRD 107.123537 (2023)**

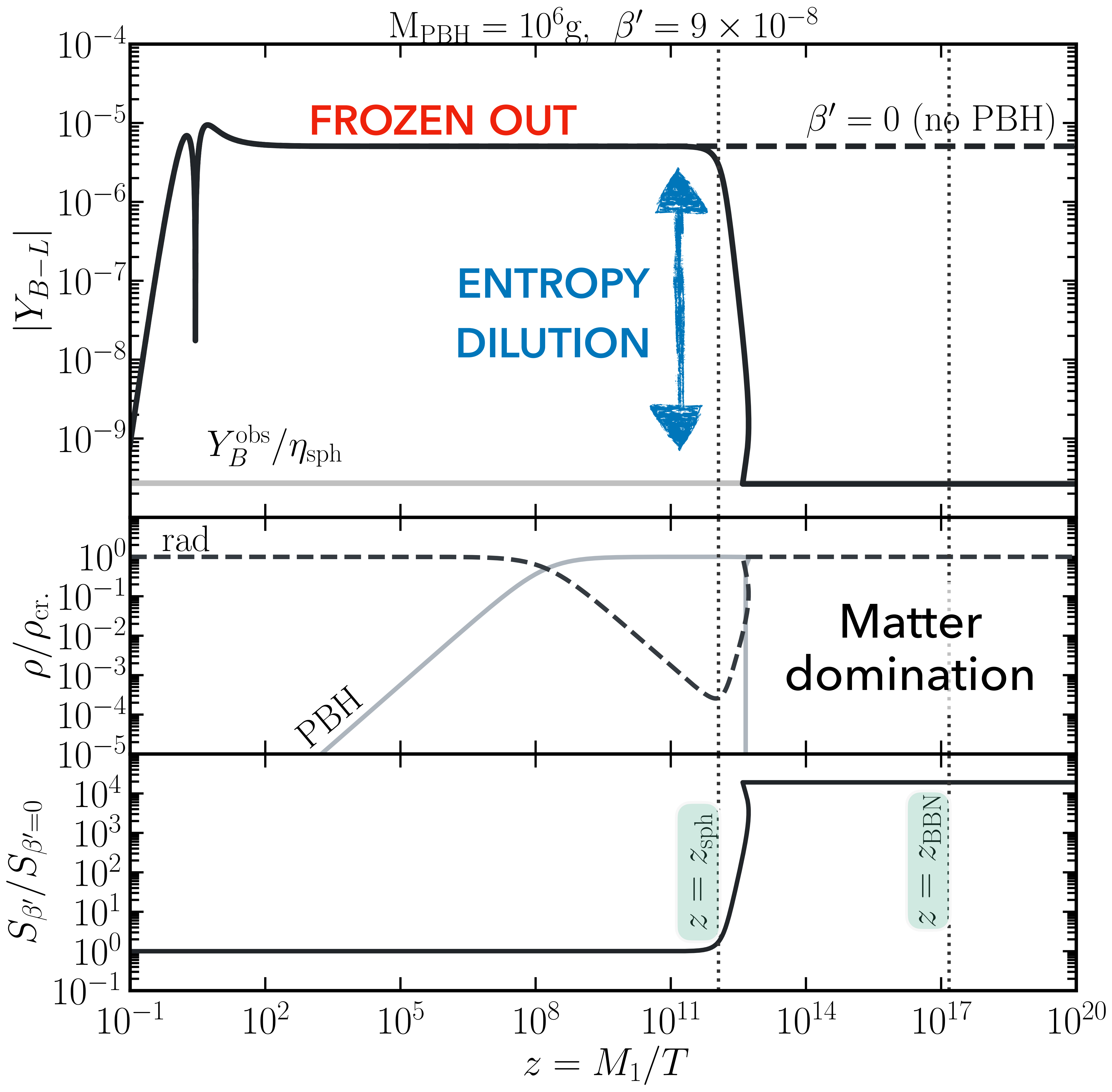


STANDARD LEPTOGENESIS SCENARIO

- ✦ The $B - L$ yield freezes-out before being converted to B at $z = z_{\rm spbh}$, leading to a **higher baryon asymmetry**
- ✦ **Standard** cosmology with a radiation-dominated universe
- ✦ The comoving entropy S is simply **constant**

Benchmark scenarios

Calabrese+ (w/ MC), ***PRD 107.123537 (2023)***

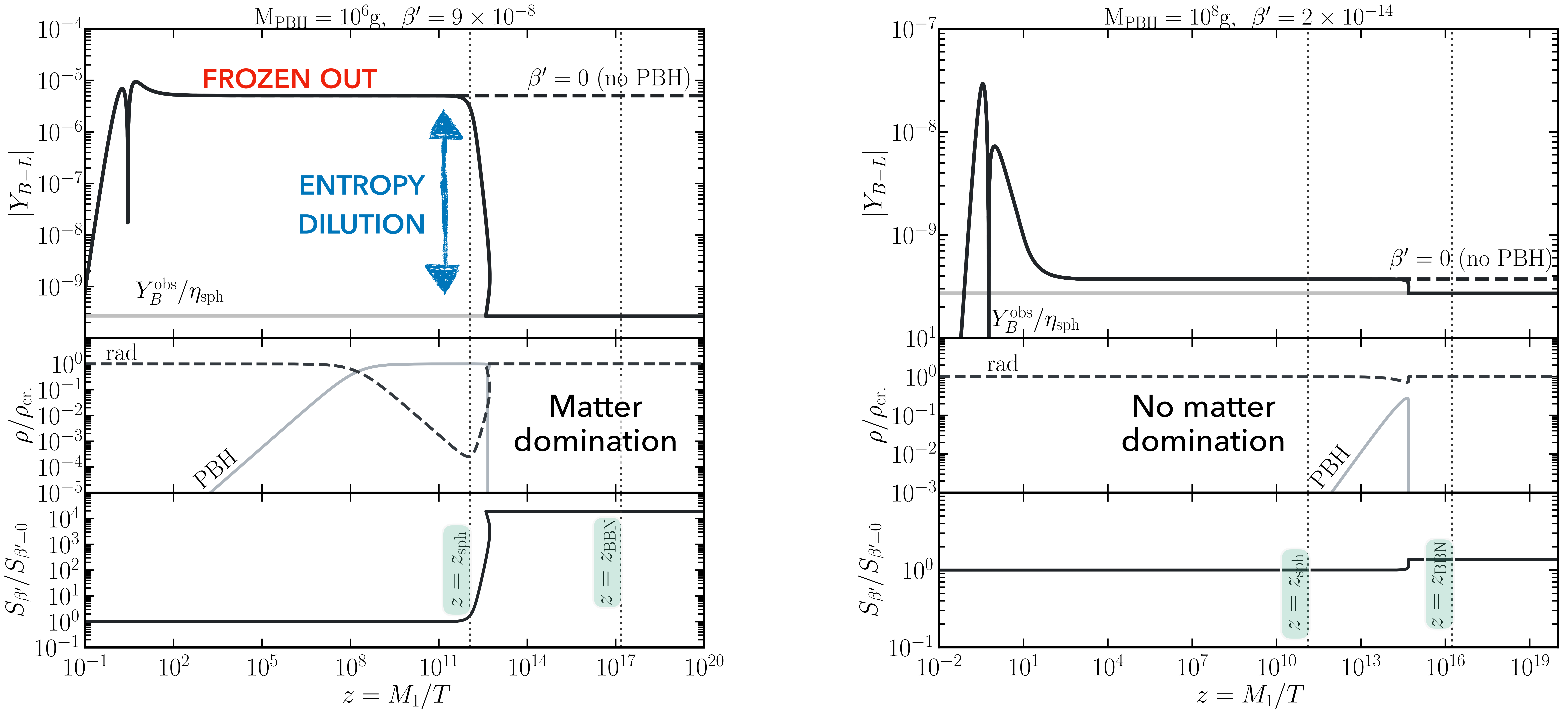


PBH-MODIFIED LEPTOGENESIS SCENARIO

- PBHs evaporate after sphaleron freeze-out at $z = z_{spbh}$, leading to the **observed baryon asymmetry**
- **Non-standard** cosmology with a matter-dominated epoch which ends before BBN at $z = z_{BBN}$
- The comoving entropy S is **not constant** due to the full evaporation of PBHs

Benchmark scenarios

Calabrese+ (w/ MC), ***PRD 107.123537 (2023)***



Large entropy production from PBH evaporation

Non-negligible effect even if PBHs never dominate!

Our models for thermal leptogenesis

- Type-1 seesaw $\mathcal{L} \supset -Y_{\alpha i}\overline{L}_\alpha \tilde{\phi} N_i - \frac{1}{2}\overline{N_i^C} M_{ij} N_j + \text{h.c.}$ $\longrightarrow$ $m_\nu \simeq -v^2 Y \frac{1}{M} Y^T$
- Casas-Ibarra parametrization for the Yukawa couplings: $Y = \frac{1}{v}\sqrt{\hat{M}}\, R\, \sqrt{\hat{m_\nu}}\, U^\dagger_{\text{PMNS}}$
- Normal ordering with $m_1 \simeq m_2$ since $\Delta m^2_{\text{sun}} \ll \Delta m^2_{\text{atm}}$ $\longrightarrow$ the only phase in R is $z_{13} = x + i\, y$

For further details see also: Hambye & Teresi, ***PRL 117 (2016)****; Giudice+,* ***Nucl. Phys. B 685 (2004)***

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Resonant Leptogenesis

- Degenerate RHNs: $M \sim M_1 \sim M_2$ with $\Delta M/M \ll 1$
- Mass range $M_1 \in [1, 10^3]$ GeV
- Free parameters $\{x,\ y,\ M,\ \Delta M\}$ with massless m_1

High-scale Leptogenesis

- Hierarchical RHNs: $M_1 \ll M_{2,3}$
- Mass range $M_1 \in [10^{10}, 10^{16}]$ GeV
- Free parameters $\{x,\ y,\ M,\ m_h\}$ with $m_h = m_3$

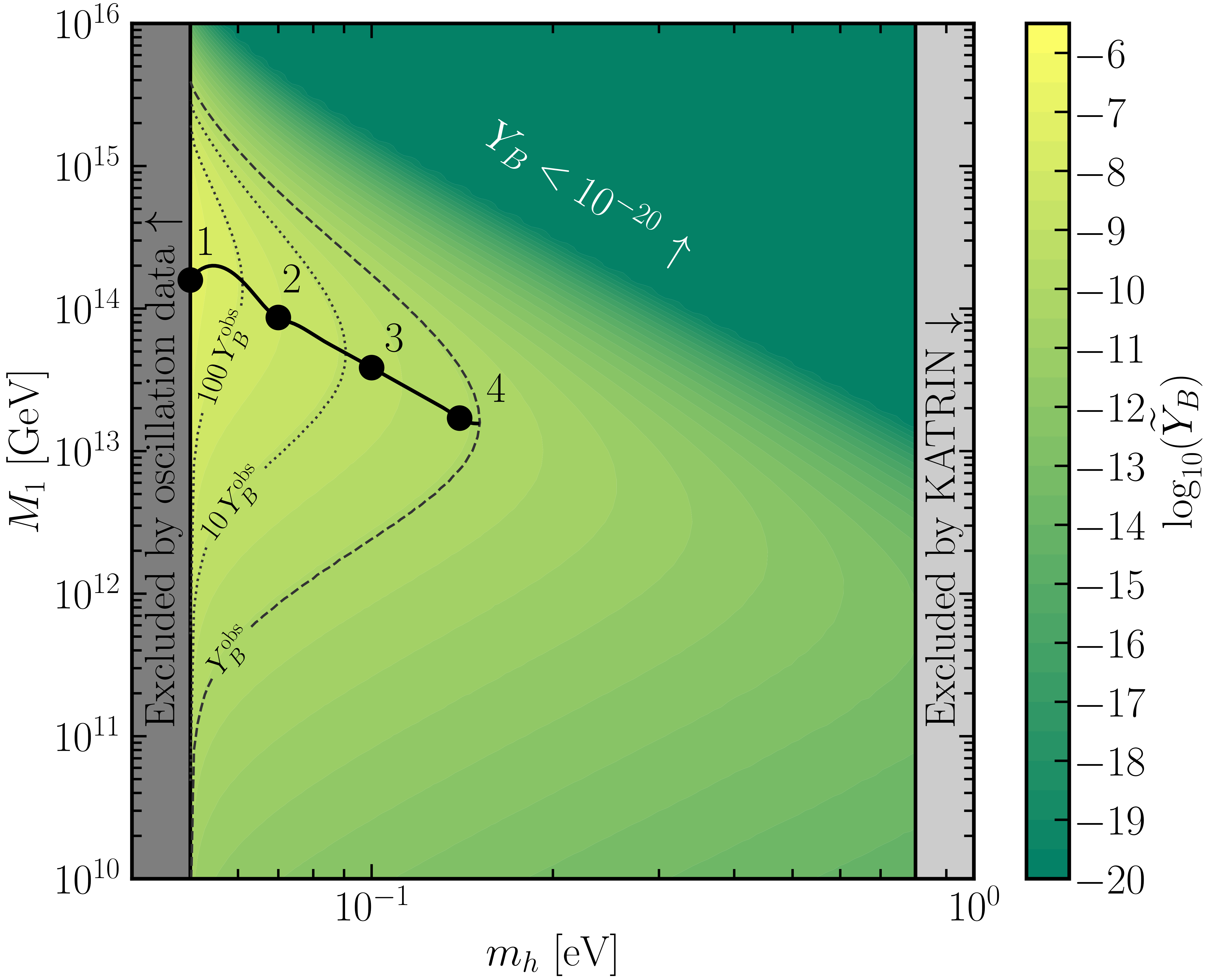
We scan the leptogenesis parameters to find the ones maximizing the baryon asymmetry!

*For further details see also: Hambye & Teresi, **PRL 117 (2016)**; Giudice+, **Nucl. Phys. B 685 (2004)***

High-scale Thermal Leptogenesis (HTL)

Calabrese+ (w/ MC), **PRD 107.123537 (2023)**

$$\tilde{Y}_B(m_h, M_1) = \max_{x,y} Y_B(x, y, m_h, M_1)$$



Parameters maximum the baryon asymmetry

Bench. pt	m_h [eV]	M_1 [GeV]	$\tilde{Y}_{\rm B}$
1	0.05	1.5×10^{14}	1.5×10^{-6}
2	0.07	1.0×10^{14}	3.6×10^{-9}
3	0.10	4.0×10^{13}	5.5×10^{-10}
4	0.14	2.0×10^{13}	1.2×10^{-10}

Dashed line: *contour for $\tilde{Y}_B$ matching the observed value*

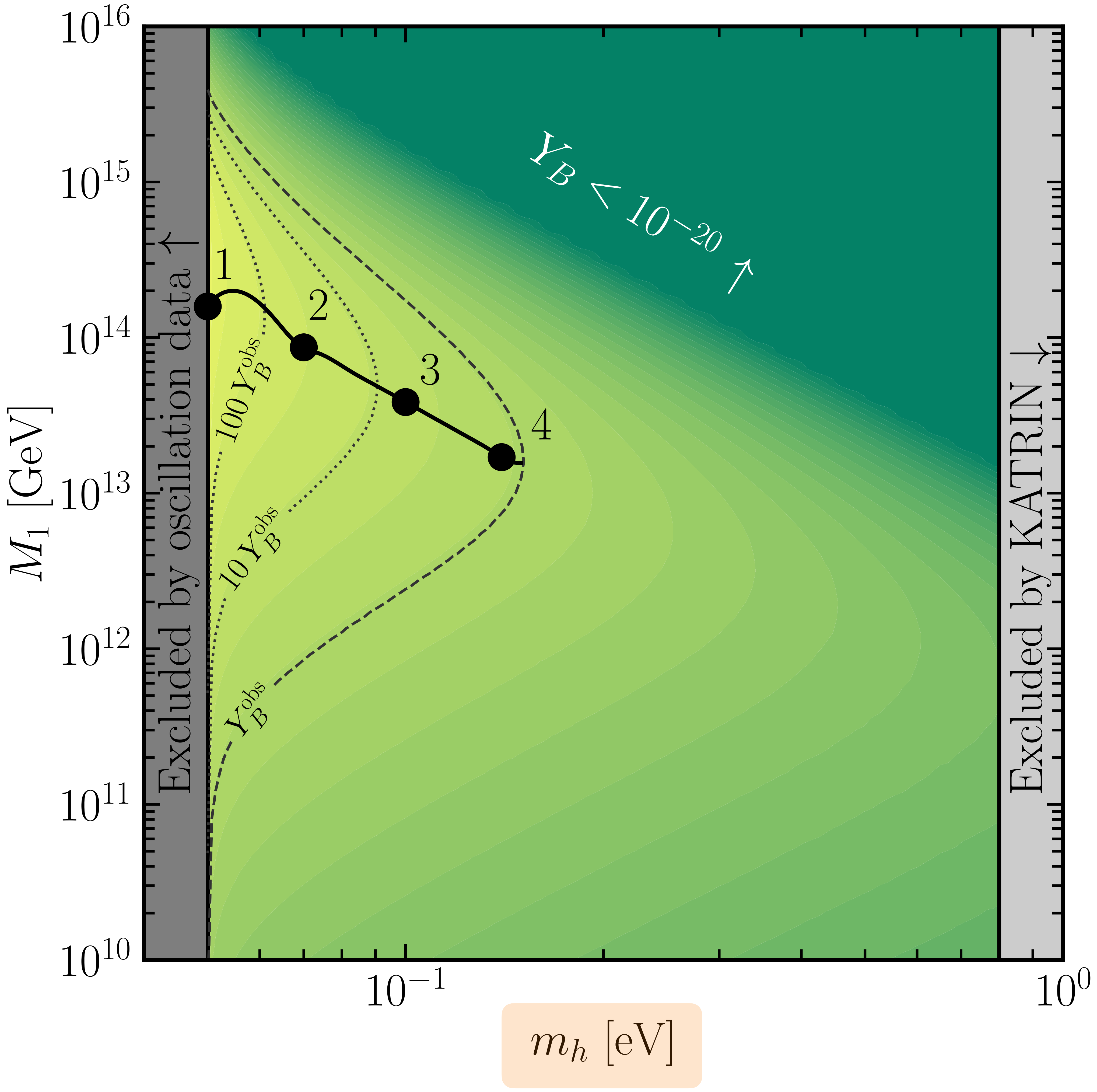
Dotted lines: *contours for increasing the ratio $\tilde{Y}_B$ / $Y_B^{\rm obs}$*

Solid line: *contour maximizing the baryon asymmetry Y_B*

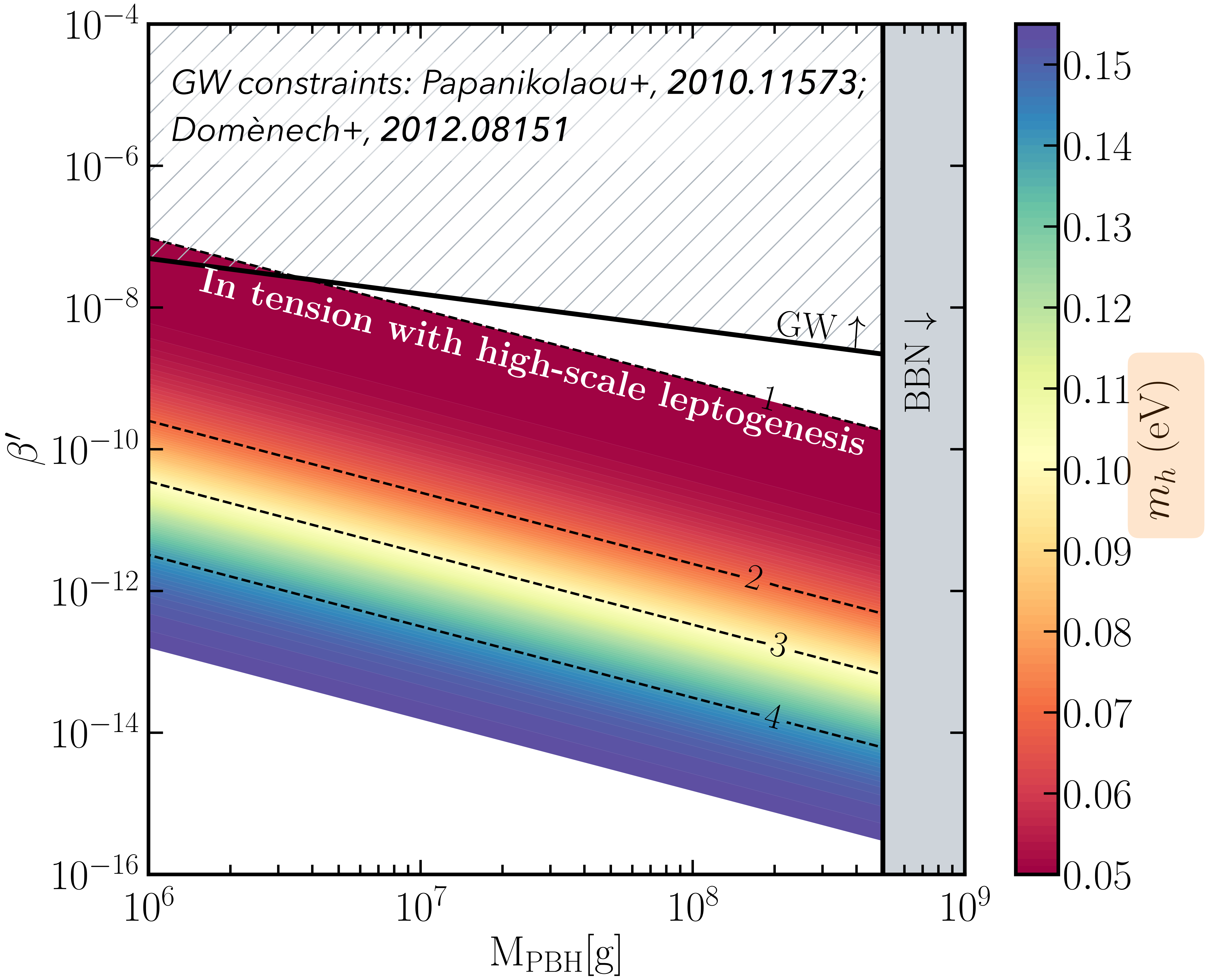
PBH-HTL constraints

Calabrese+ (w/ MC), **PRD 107.123537 (2023)**

Strong interplay with active neutrinos scale m_h



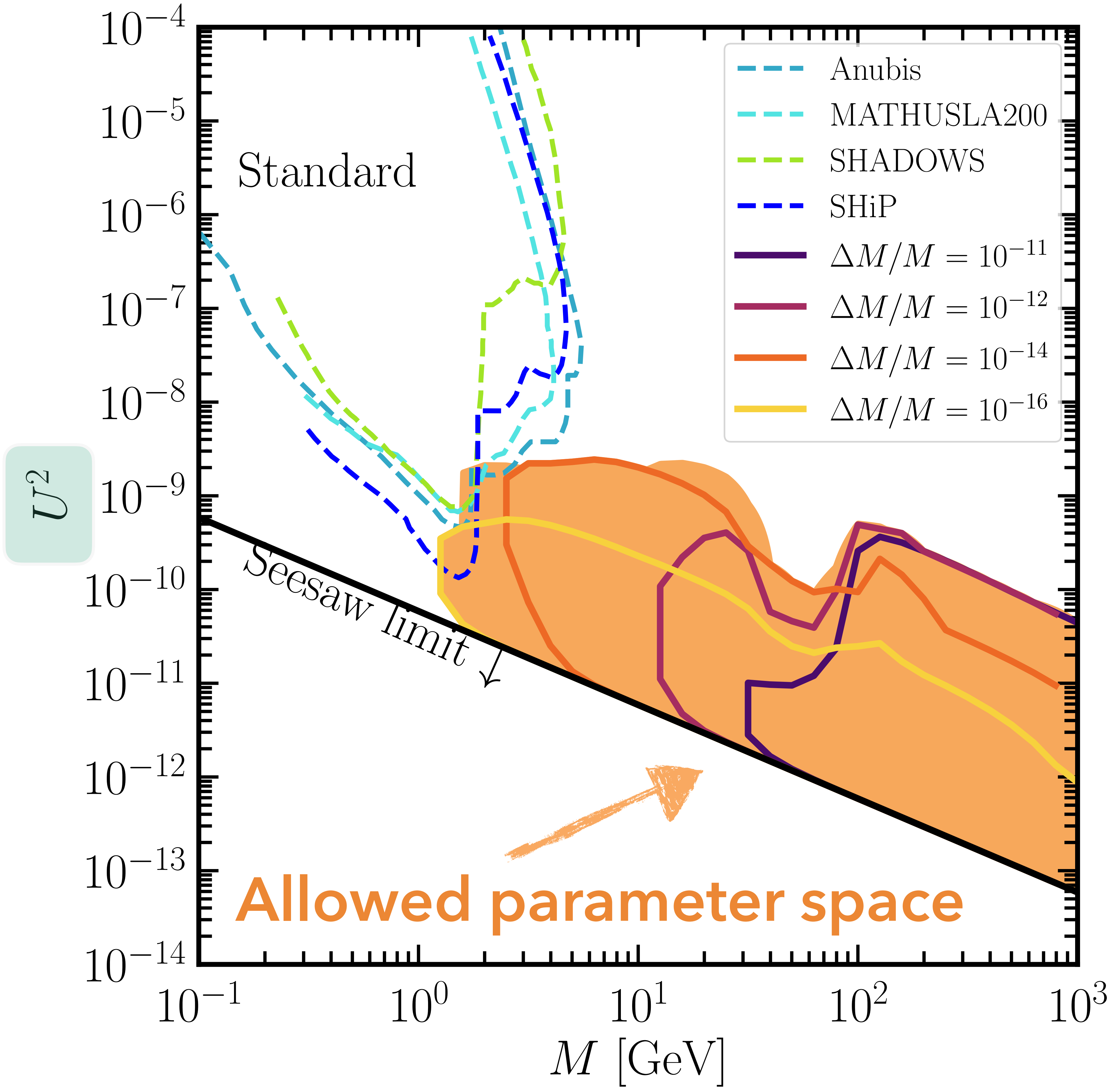
Mutual exclusion limits between PBHs and HTL

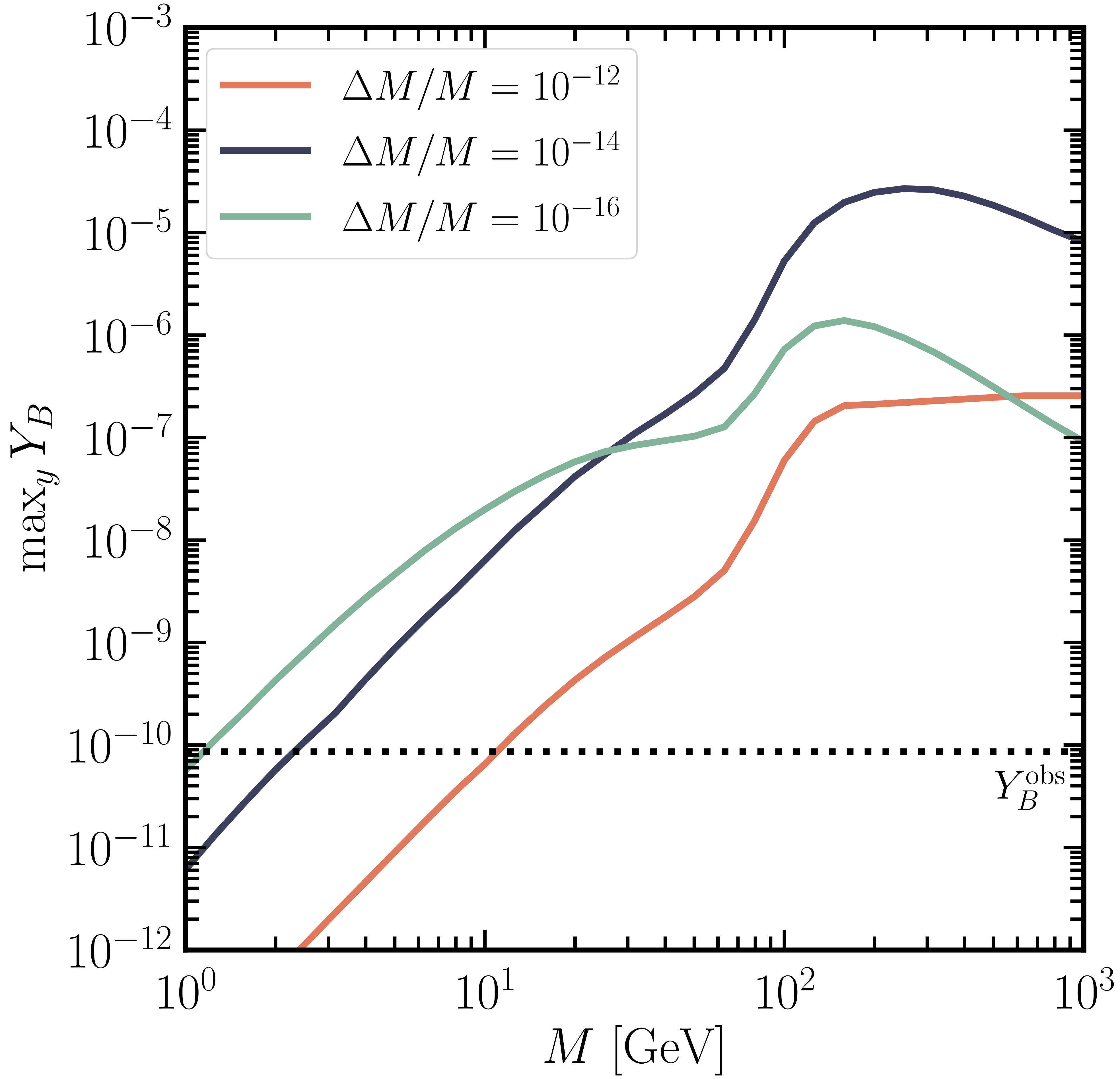


Resonant leptogenesis

Calabrese+ (w/ MC), **PRD 109.103001 (2024)**

Active-sterile mixing $U^2 = \sum_{\alpha N} |U_{\alpha(N+3)}|^2 = \frac{m_2 - m_3}{2} \frac{\Delta M}{M^2} \cos(2x) + \frac{(m_2 + m_3)}{M} \cosh(2y)$ for $m_1 = 0$



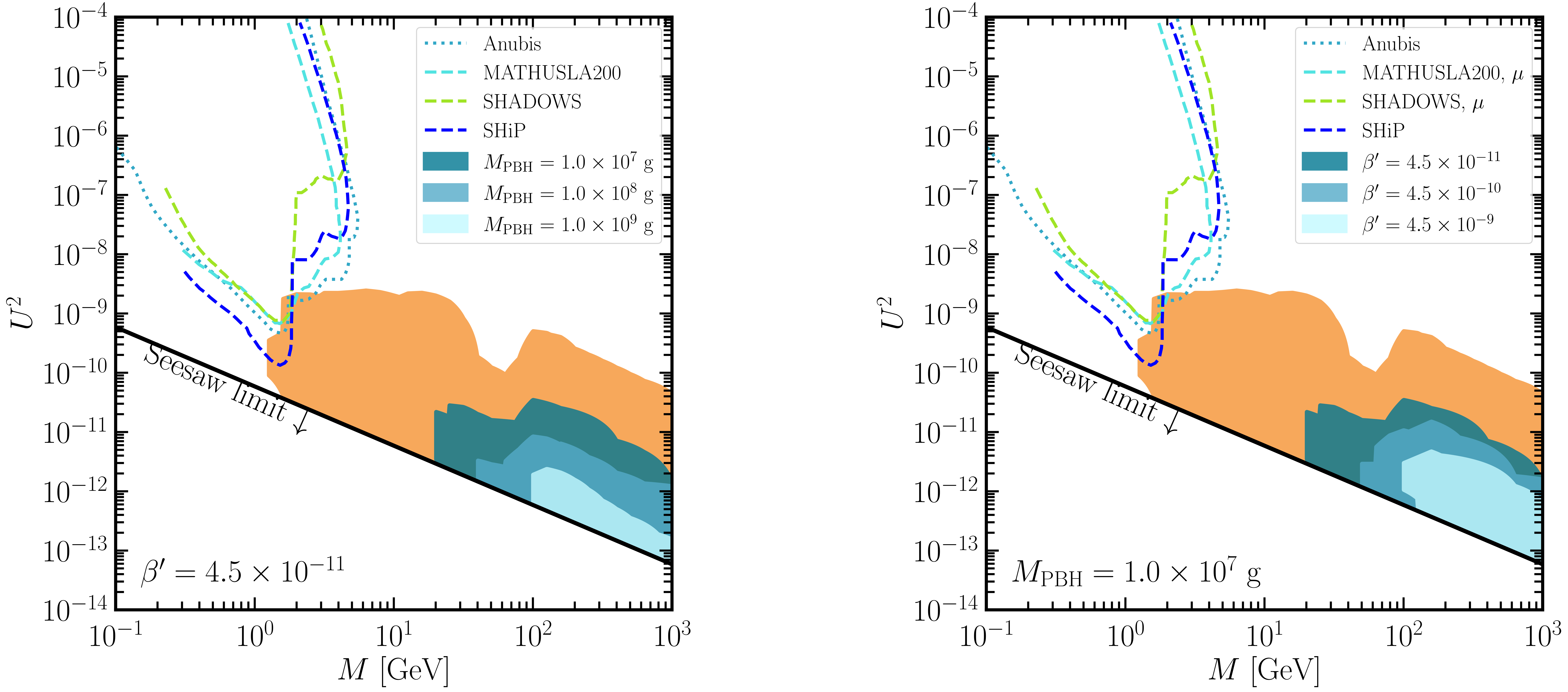


Maximum baryon asymmetry as a function of RHN mass

PBH impact

Calabrese+ (w/ MC), **PRD 109.103001 (2024)**

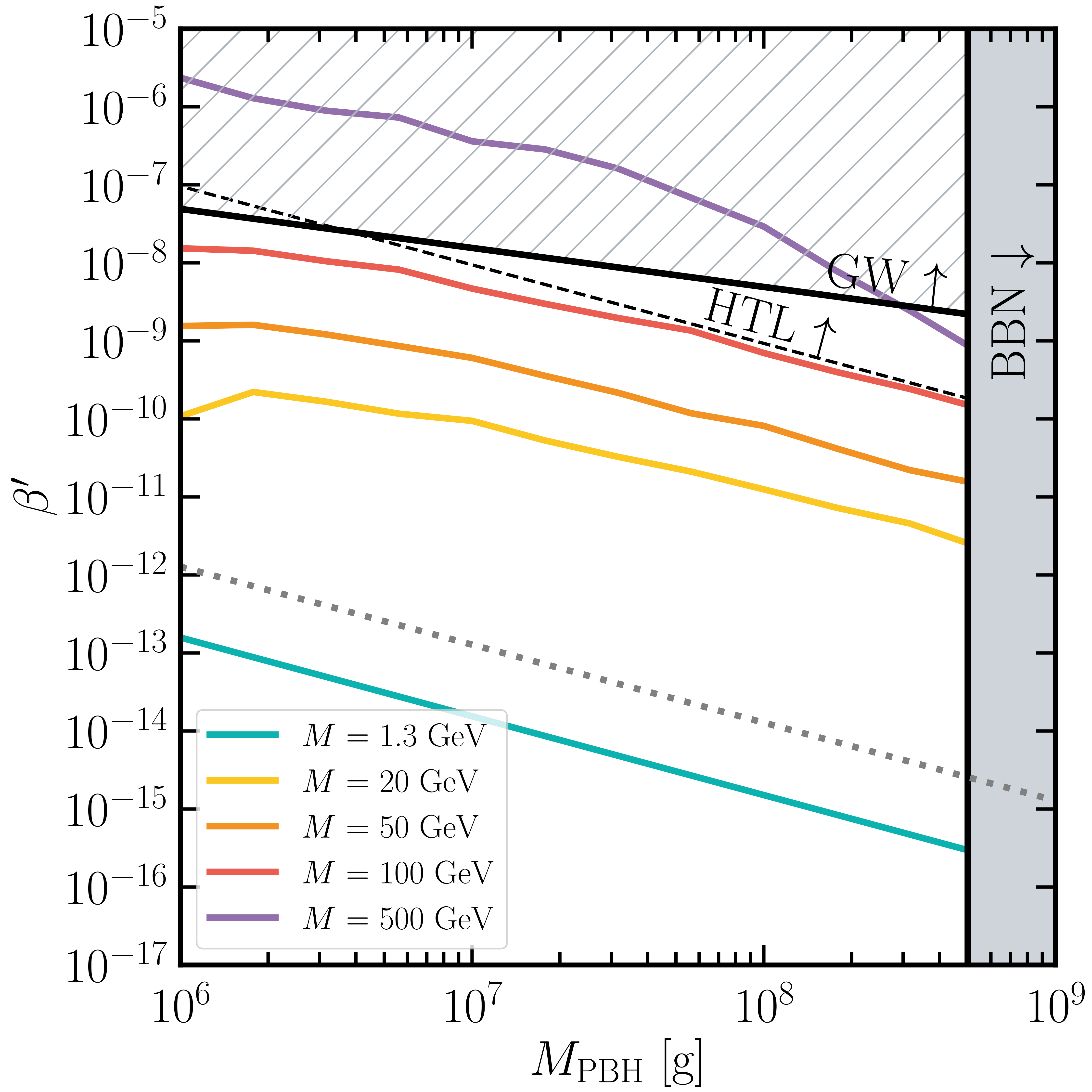
Shrinking the RHNs allowed region towards higher masses M and smaller mixing U^2



PBHs disfavor detection of Heavy Neutral Leptons (HNLs)!

PBH-leptogenesis constraints

Calabrese+ (w/ MC), **PRD 109.103001 (2024)**



- ✦ If light PBHs existed, then laboratory experiments might not be able to detect HNLs
- ✦ On the other hand, we can place constraints on PBH parameter space assuming future detection of HNLs at a given mass scale M

Dashed line: *most conservative constraints for High-scale Thermal Leptogenesis (HTL)*

Dotted line: *minimum PBH abundance for matter domination*

Solid lines: *constraints for different HNL masses*

Conclusions

- ✦ The **non-standard cosmology driven by PBHs** has strong effects on leptogenesis, e.g. entropy injection and dilution of the baryon asymmetry frozen after sphalerons.

- ✦ We have explored the parameter space of **high-scale and resonant leptogenesis** models in order to find the parameters maximizing the baryon asymmetry.

- ✦ We have placed **mutual exclusions limits** between minimal leptogenesis models and PBHs when the final baryon asymmetry is below the observed value.

Thanks for listening!

SUPPLEMENTAL MATERIAL

Baryogenesis via leptogenesis

BARYON ASYMMETRY OF THE UNIVERSE (BAU)

$$\eta = \left.\frac{n_B - n_{\bar{B}}}{n_\gamma}\right|_0 = (6.21 \pm 0.16) \times 10^{-10}$$

$$Y_{\Delta B} = \left.\frac{n_B - n_{\bar{B}}}{s}\right|_0 = (8.75 \pm 0.23) \times 10^{-11}$$

inferred independently by BBN and CMB (see PLANCK coll.)

⟷

SAKHAROV CONDITIONS

- ✦ Baryon number violation
- ✦ C and CP violation
- ✦ Out of equilibrium dynamics

Present in the SM, but not sufficient…

The **seesaw Lagrangian** naturally satisfies the Sakharov conditions in the leptonic sector!

$$\mathcal{L} \supset -Y_{\alpha i} \overline{L}_\alpha \tilde{\phi} N_i - \frac{1}{2} \overline{N_i^C} M_{ij} N_j + \text{h.c.}$$

Right-Handed Neutrinos (RHNs)

- ✦ L violation due to the Majorana nature of RHNs, then L → B via sphaleron
- ✦ C and CP violation due to Dirac Yukawa couplings
- ✦ Departure from thermal equilibrium when $\Gamma_N < \mathscr{H}$

High-scale Leptogenesis

Calabrese+ (w/ MC), **PRD 107.123537 (2023)**

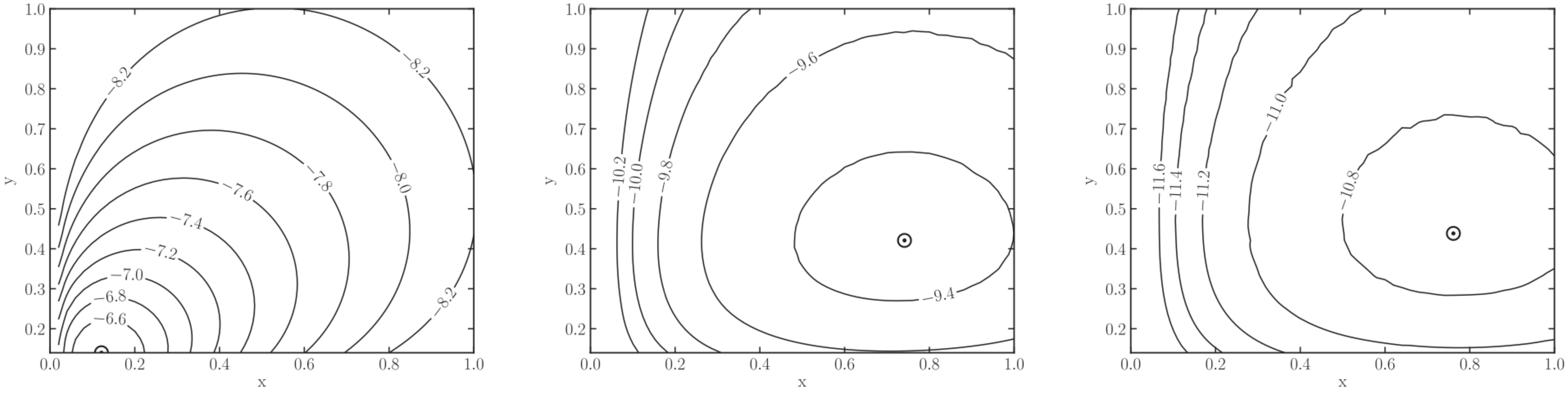


FIG. 1. The final baryon asymmetry Y_B as a function of x, y for $m_h = \sqrt{m^2_{\rm atm}} \approx 0.05$ eV (left panel), $m_h = 0.1$ eV (middle panel) and $m_h = 0.2$ eV (right panel), with $M_1 = 2.0 \times 10^{13}$ GeV. The contours are for constant $\log_{10} Y_B$ while the symbol $\odot$ indicates the point (x, y) which maximizes Y_B for the fixed values of m_h.

Sphaleron process

Calabrese+ (w/ MC), **PRD 107.123537 (2023)**

✦ In our scenario, the sphaleron processes go out of equilibrium during a matter-dominated epoch, but always after the electroweak phase transition.

✦ The sphaleron temperature $T_{\rm sph}$ is computed as

$$\frac{\Gamma_{\rm sph}(T_{\rm sph})}{T_{\rm sph}^3} = \alpha \mathcal{H}(T_{\rm sph})$$

with $\alpha \approx 0.1015$

see D'Onofrio+, *PRL 113 (2014)*

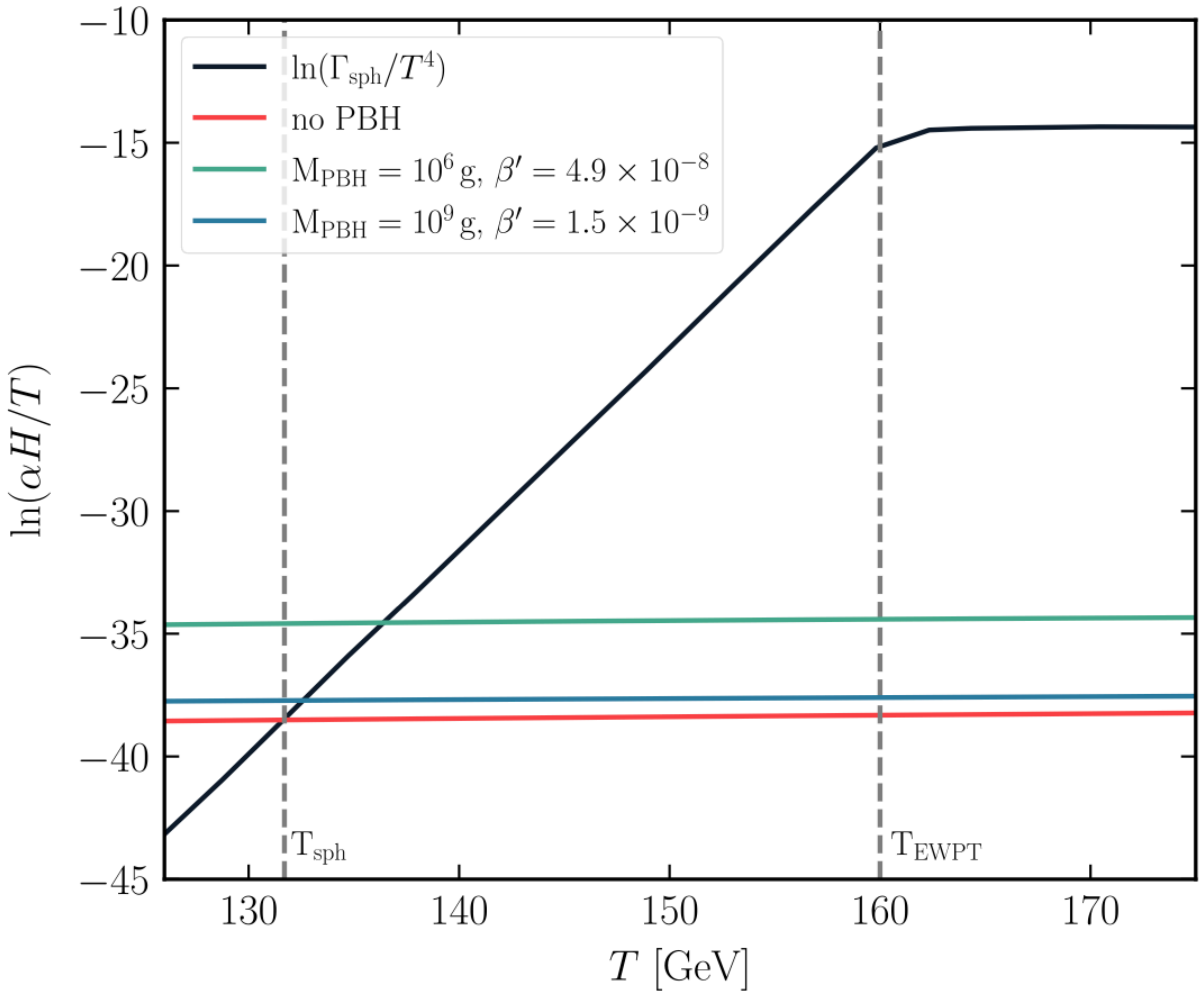


FIG. 5. The rate of sphaleron process (black line) as a function of the temperature. The colored lines show the Hubble rate for different scenarios with and without the presence of PBHs. The crossing between $\Gamma_{\rm sph}$ and H defines the temperature $T_{\rm sph}$ at which the sphaleron processes freeze-out. We find $T_{\rm sph} < T_{\rm EWPT}$ in the whole parameter space analyzed.

High-scale Leptogenesis: Boltzmann equations

For further details see Calabrese+ (w/ MC), ***PRD 107.123537 (2023)***

$$\frac{\mathrm{d}\mathcal{N}_{N_1}}{\mathrm{d}\alpha} = \ln(10)\frac{\Gamma^{\mathrm{th.}}_{N_1}}{H}(\mathcal{N}^{\mathrm{eq.}}_{N_1} - \mathcal{N}_{N_1})$$

$$\frac{\mathrm{d}\mathcal{N}_{\mathrm{B-L}}}{\mathrm{d}\alpha} = \frac{\ln(10)}{H}\left[\epsilon(\mathcal{N}_{N_1} - \mathcal{N}^{\mathrm{eq.}}_{N_1})\Gamma^{\mathrm{th.}}_{N_1} + \left(\frac{1}{2}\frac{\mathcal{N}^{\mathrm{eq.}}_{N_1}}{\mathcal{N}^{\mathrm{eq.}}_{\ell}}\Gamma^{\mathrm{th.}}_{N_1} + \gamma\frac{a^3}{\mathcal{N}^{\mathrm{eq.}}_{\ell}}\right)\mathcal{N}_{\mathrm{B-L}}\right]$$

- $1 \to 2$ decays of N_1, $N_1 \to \ell\phi^\dagger$ and its CP conjugate process $N_1 \to \bar{\ell}\phi$.
- $2 \to 1$ inverse decay modes like $\ell\phi^\dagger \to N_1$. These processes produce the N_1 population but only wash out the asymmetry.
- $2 \leftrightarrow 2$ scatterings mediated by N_1 exchange like $\ell\phi^\dagger \to \bar{\ell}\phi$, for which $\Delta L = 2$. These processes contribute to the washout and do not change the number density of N_1.

Resonant Leptogenesis: Boltzmann equations

For further details see Calabrese+ (w/ MC), ***PRD 109.103001 (2024)***

$$\frac{\mathrm{d}\mathcal{N}_{N_i}}{\mathrm{d}\alpha} = \frac{a^3 \ln(10)}{H}\left(1 - \frac{\mathcal{N}_{N_i}}{\mathcal{N}_N^{\mathrm{eq}}}\right)(\gamma_D + 2\gamma_{S_s} + 4\gamma_{S_t})$$

$$\frac{\mathrm{d}\mathcal{N}_{\Delta\ell}}{\mathrm{d}\alpha} = \frac{a^3 \ln(10)}{H}\sum_i \left[\epsilon^i_{\ell\ell}\left(\frac{\mathcal{N}_{N_i}}{\mathcal{N}_N^{\mathrm{eq}}} - 1\right)\gamma_D - P_{\ell\, i}\frac{\mathcal{N}_{\Delta\ell}}{\mathcal{N}_\ell^{\mathrm{eq}}}\left(2\gamma_D + 2\gamma_{S_t} + \frac{\mathcal{N}_{N_i}}{\mathcal{N}_{N_i}^{\mathrm{eq}}}\gamma_{S_s}\right)\right]$$

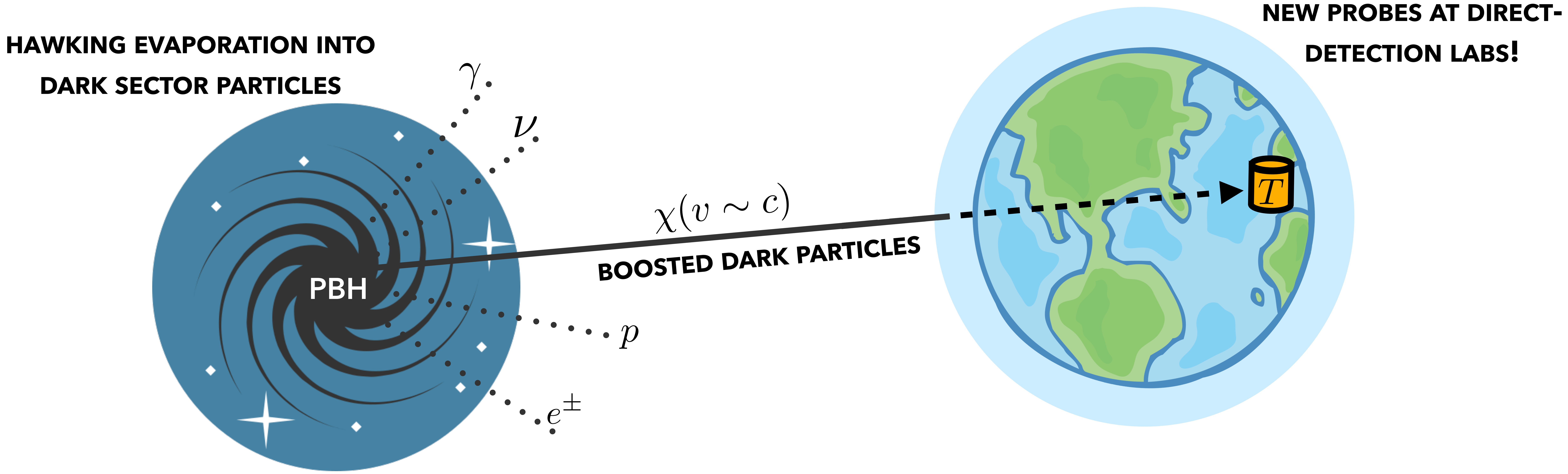
$$\frac{\mathrm{d}\mathcal{N}_B}{\mathrm{d}\alpha} = -\frac{\ln(10)}{H}\Gamma_B(T)(\mathcal{N}_B + \chi(T)\mathcal{N}_\Delta)$$

non-instantaneous sphalerons

- $1 \leftrightarrow 2$ (inverse) decays of $N_{1,2}$ and the Higgs, $N_{1,2} \leftrightarrow \ell\phi^\dagger$ and $\phi \leftrightarrow N_{1,2}\ell$, with γ_D denoting the corresponding reaction density.
- $2 \leftrightarrow 2$ scatterings with $\Delta L = 1$, involving (top) quark or gauge boson final states mediated by leptons or Higgs, with reaction densities γ_{S_s} and γ_{S_t} for s-channel and$t$-channel processes, respectively.
- $2 \leftrightarrow 2$ scatterings with $\Delta L = 2$, which are mediated by $N_{1,2}$. However, their contribution is negligible and therefore not considered here.

PBH evaporation into dark particles

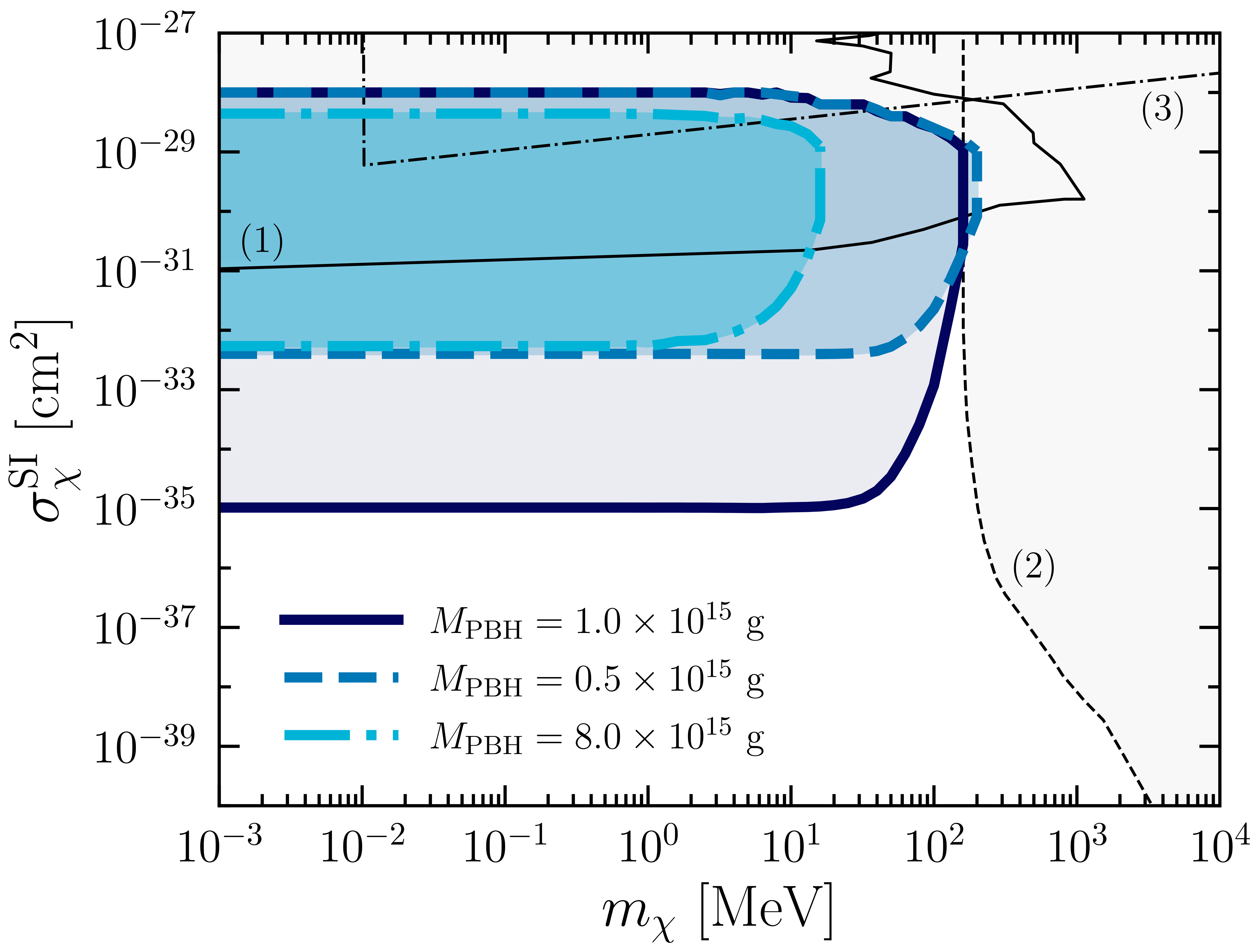
The ePBH-DM scenario: evaporating PBHs with a mass from $10^{14}$to 10^{18} grams are efficient sources of boosted light dark particles in the present Universe!



Calabrese, MC, Fiorillo, Saviano, ***PRD 105.L021302 (2022)***
Calabrese, MC, Fiorillo, Saviano, ***PRD 105.103024 (2022)***

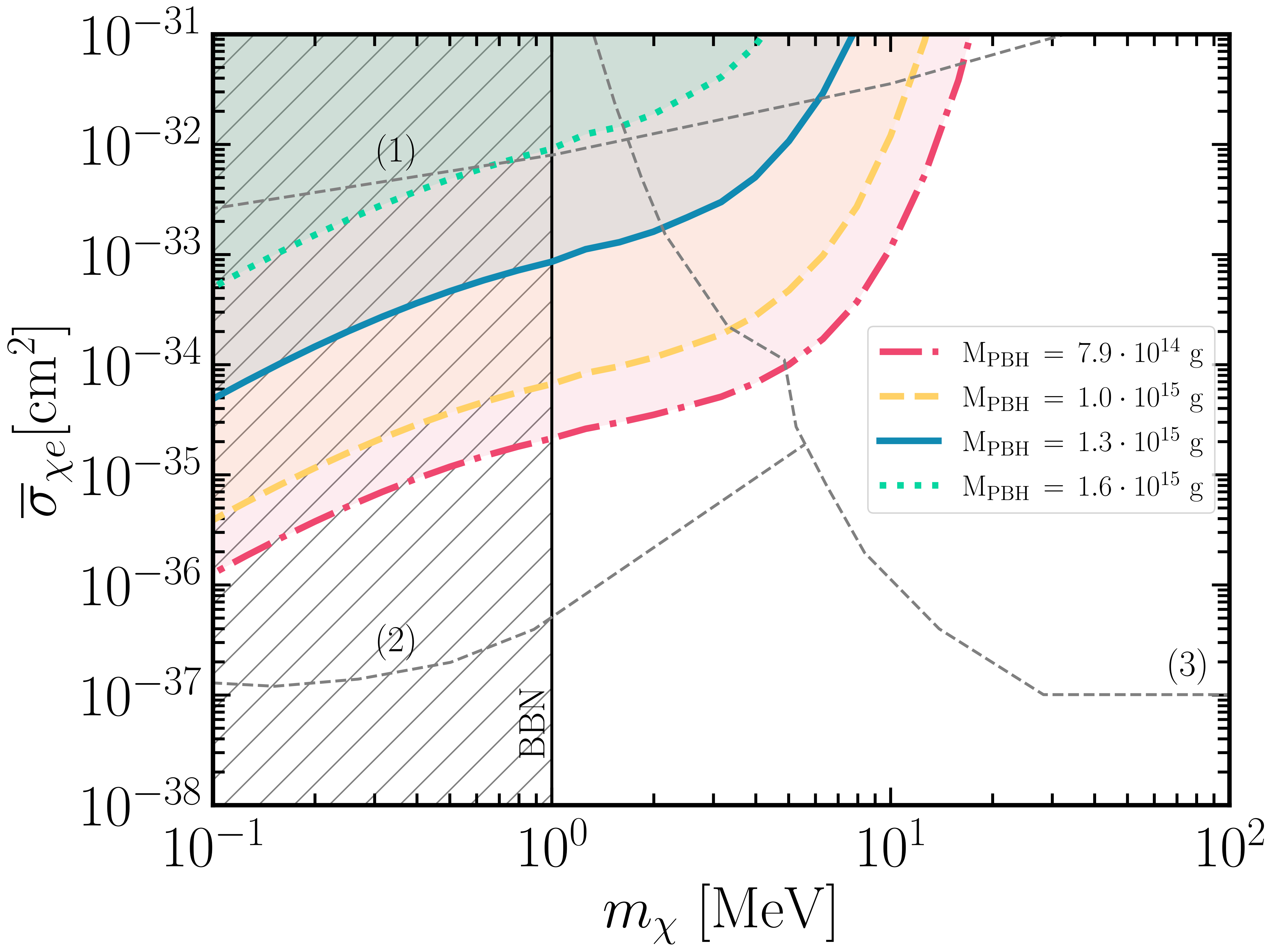
Constraints in the ePBH-DM scenario

DM-NUCLEON CROSS-SECTION AT XENON1T



Calabrese+ (w/ MC), ***PRD 105.L021302 (2022)***

DM-ELECTRON CROSS-SECTION AT SUPER-KAMIOKANGE



Calabrese+ (w/ MC), ***PRD 105.103024 (2022)***