

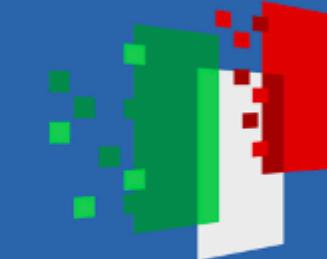


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PANTHEON

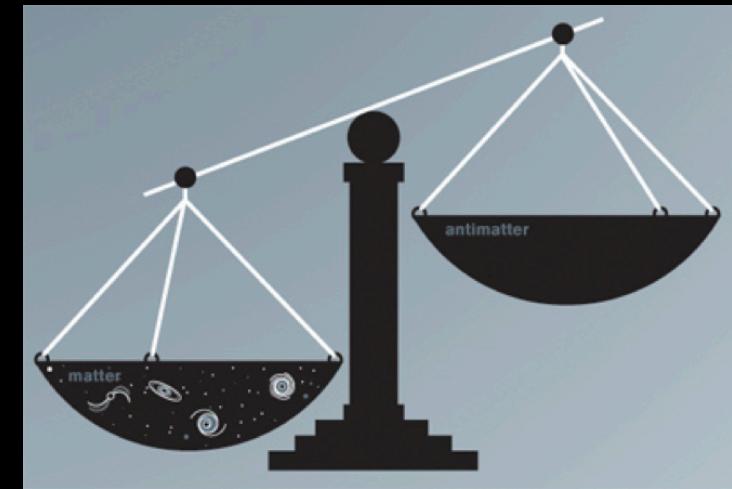


Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



Istituto Nazionale di Fisica Nucleare

Leptogenesis in the light of Primordial Black Holes



Ninetta Saviano

INFN (NA)

Based on PRD 107.123537 and on PRD 109.103001 in collaboration with R. Calabrese, M. Chianese, J. Gunn, G. Miele, S. Morisi

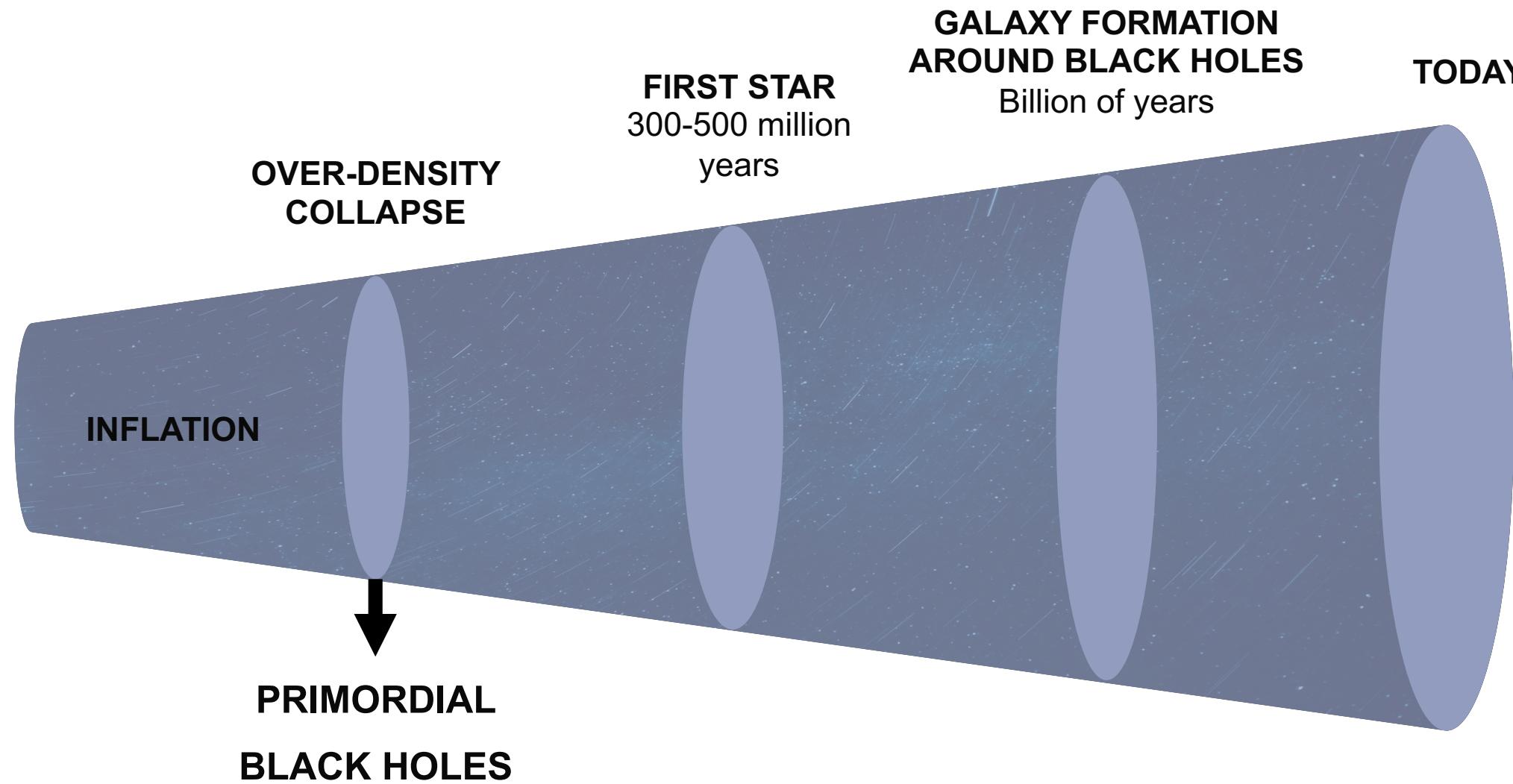


Neutrino Frontiers: Neutrinos in cosmology, non-standard neutrino physics and neutrino anomalies

July 01-05 2024

Genesis of Primordial Black Holes

Primordial Black Holes: *Black Holes generated at earlier than star formation times and therefore not of stellar origin.*



Properties of PBHs

- ◆ Black holes formed immediately after inflation in the very early Universe
- ◆ They can form with any mass: $M_{\text{PBH}} \in [0.1, 10^{50}] \text{ g}$
- ◆ They can have charge and spin
- ◆ DM candidates for $M_{\text{PBH}} \gtrsim 10^{15} \text{ g}$
- ◆ Different from astrophysical Black Holes (BHs):

$$M_{\text{BH}}^{\text{astro}} \gtrsim 10^{33} \text{ g}$$

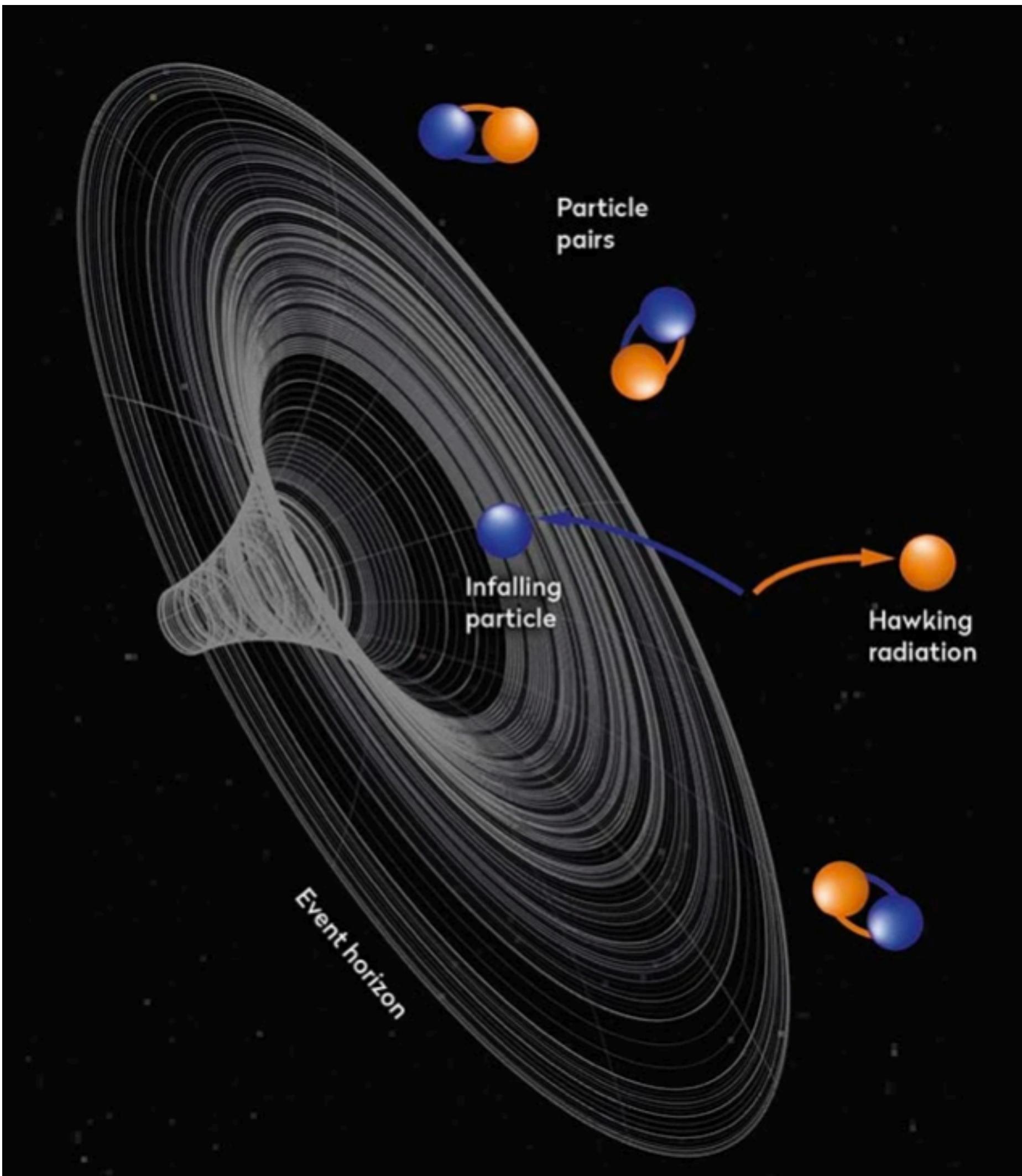
1966: their existence first proposed by Zel'dovich and Novikov

mid-1970s: the concept was picked up and developed by *Hawking and Carr.*

(For the first time the Black Hole name appears)

Hawking Evaporation

Due to a mixture of quantum and general relativity effects, the PBH can emit particles



- ◆ The emission is a black-body-like spectrum with a temperature:

$$T_{\text{BH}} = \frac{\kappa}{2\pi} \rightarrow T_{\text{BH}} = \frac{\hbar c^3}{8\pi G k_B M_{\text{BH}}} = 10.6 \left(\frac{10^{15} \text{ g}}{M_{\text{BH}}} \right) \text{ MeV}$$

Surface gravity

for neutral and non-rotating BHs

- ◆ Emission of all the elementary particles with $m \leq T_{\text{BH}}$

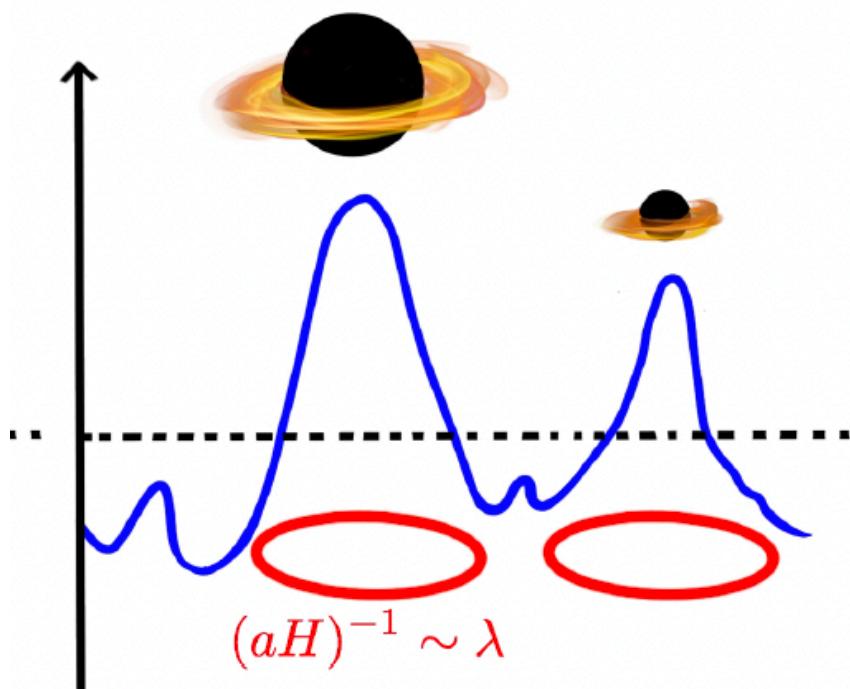
- ◆ The evaporation lifetime is:

$$\tau_{\text{BH}} \approx 4.07 \times 10^{17} \left(\frac{M_{\text{BH}}}{10^{15} \text{ g}} \right)^3 \text{ s}$$

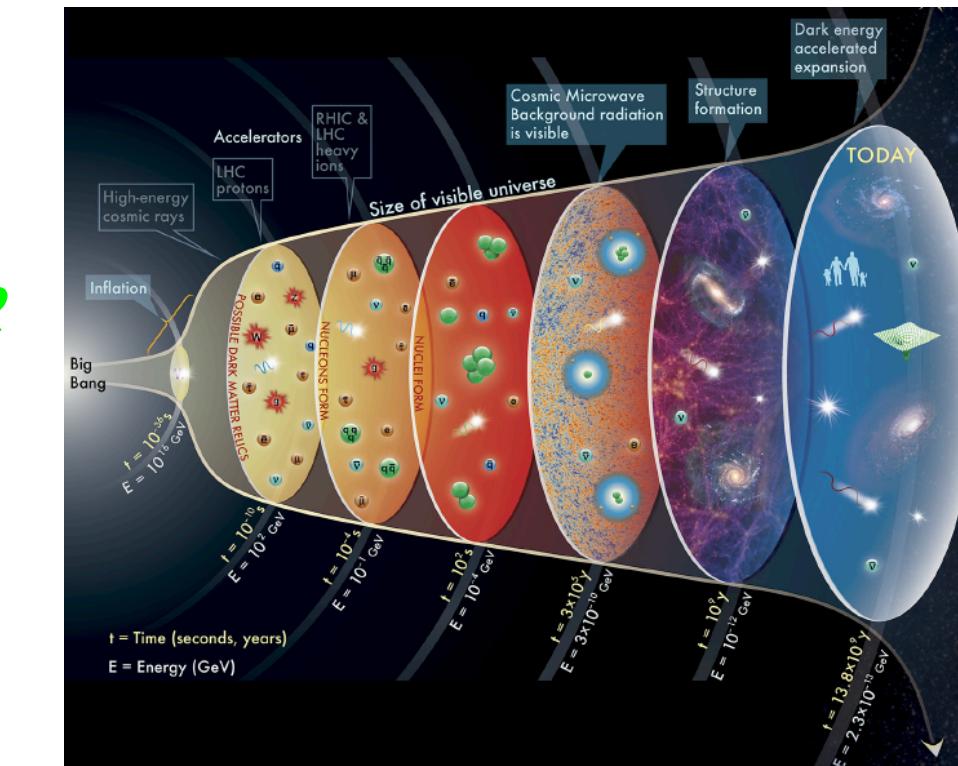
- ◆ Negligible and undetectable for astrophysical black holes!

Current big interest in PBHs

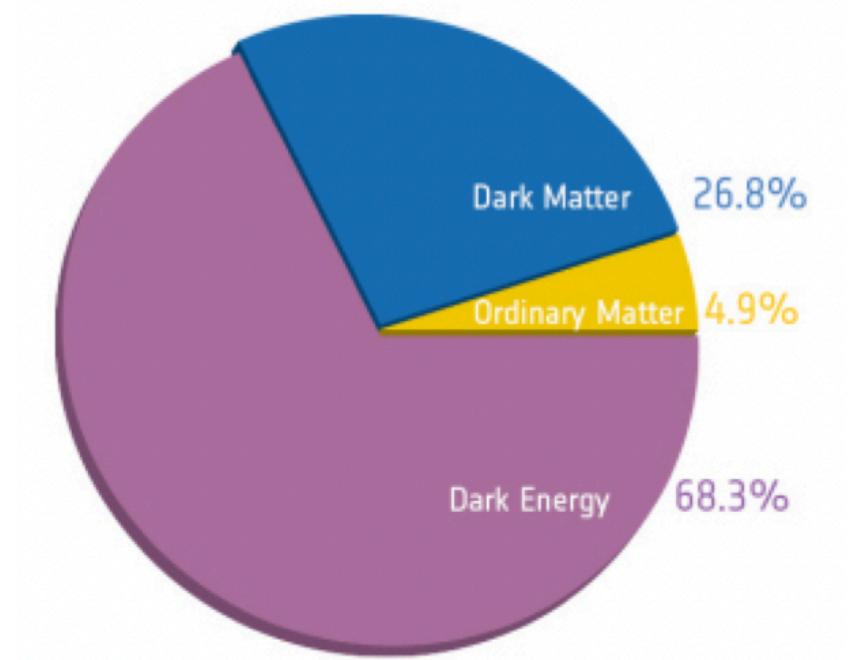
Formation mechanism



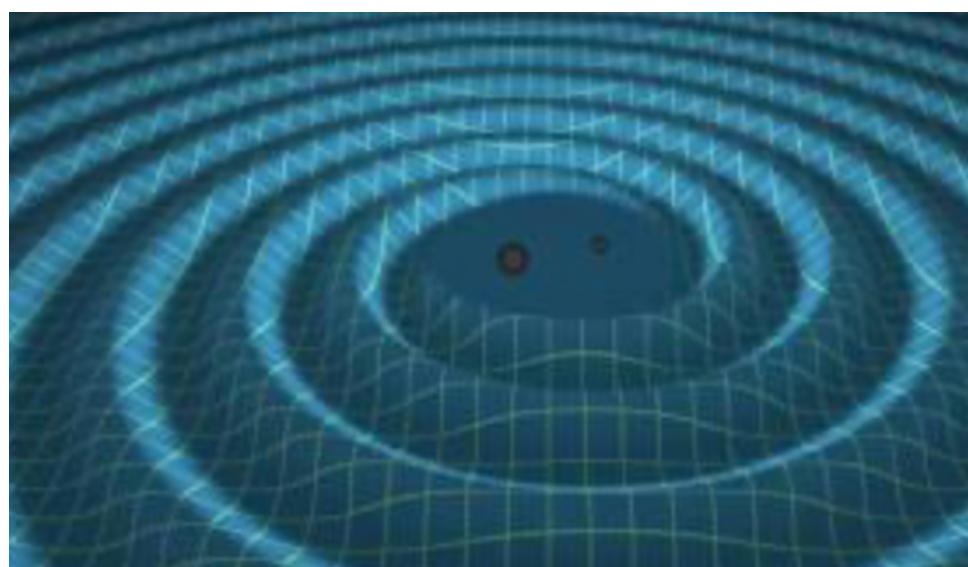
Early Universe



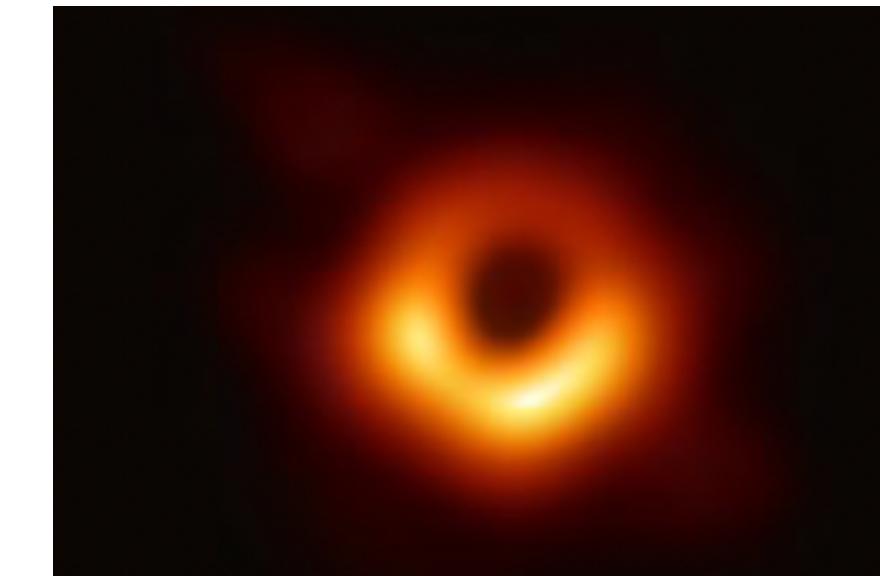
Dark Matter



Gravitational waves

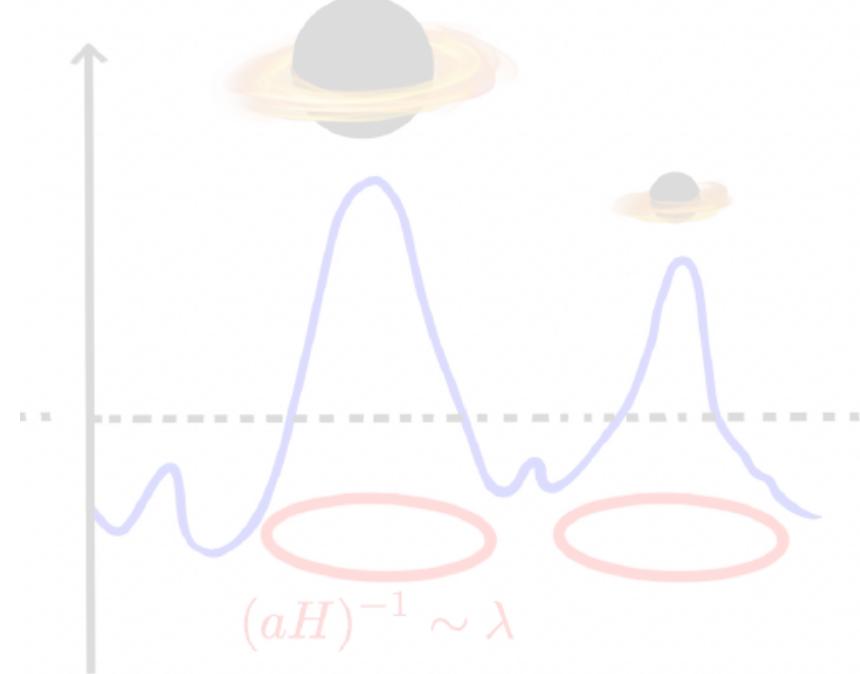


Astrophysical issues



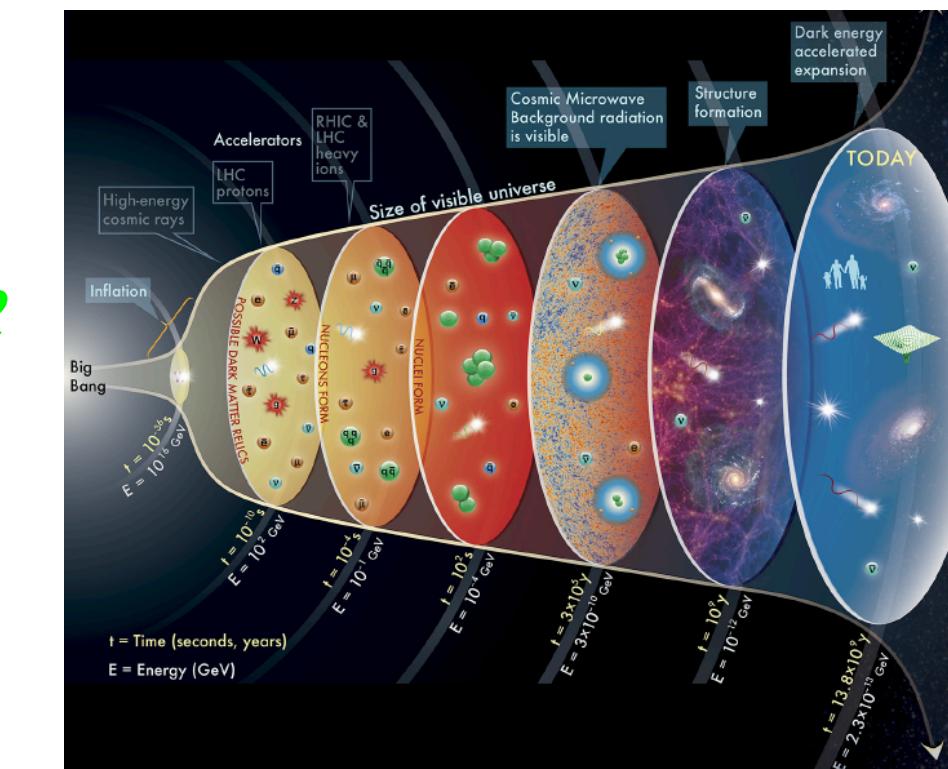
Current big interest in PBHs

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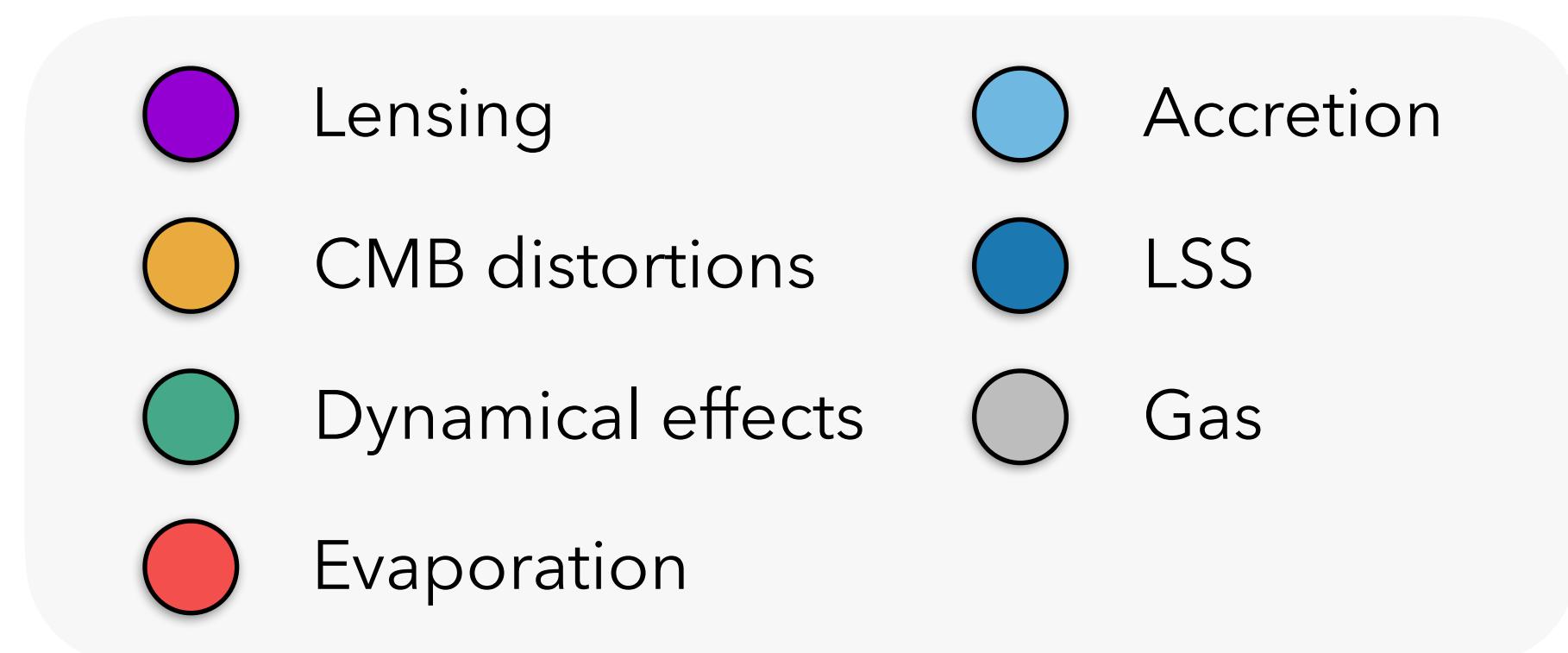


Early Universe

*In this talk:
Leptogenesis*



PBH constraints

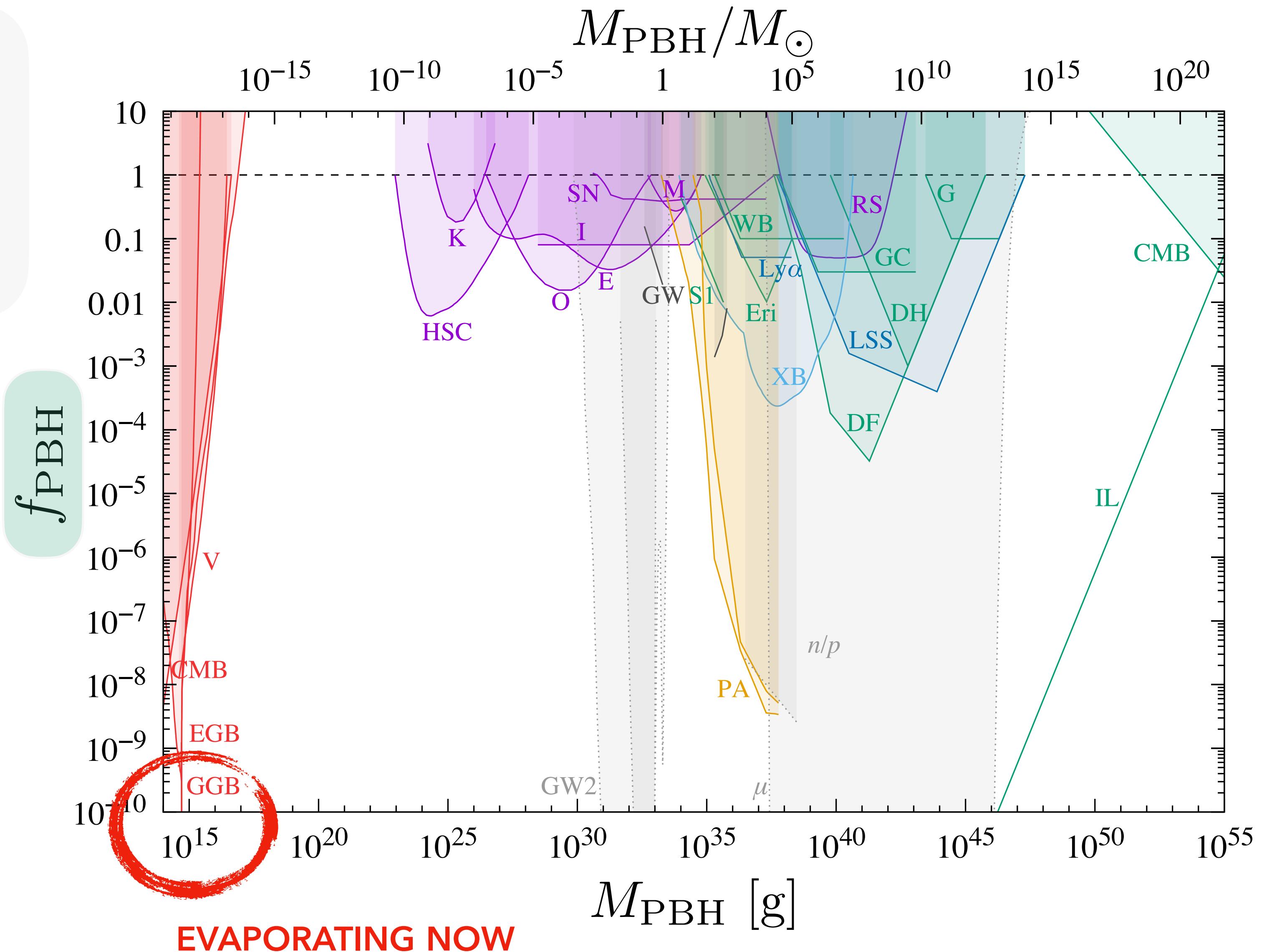


PBH today abundance

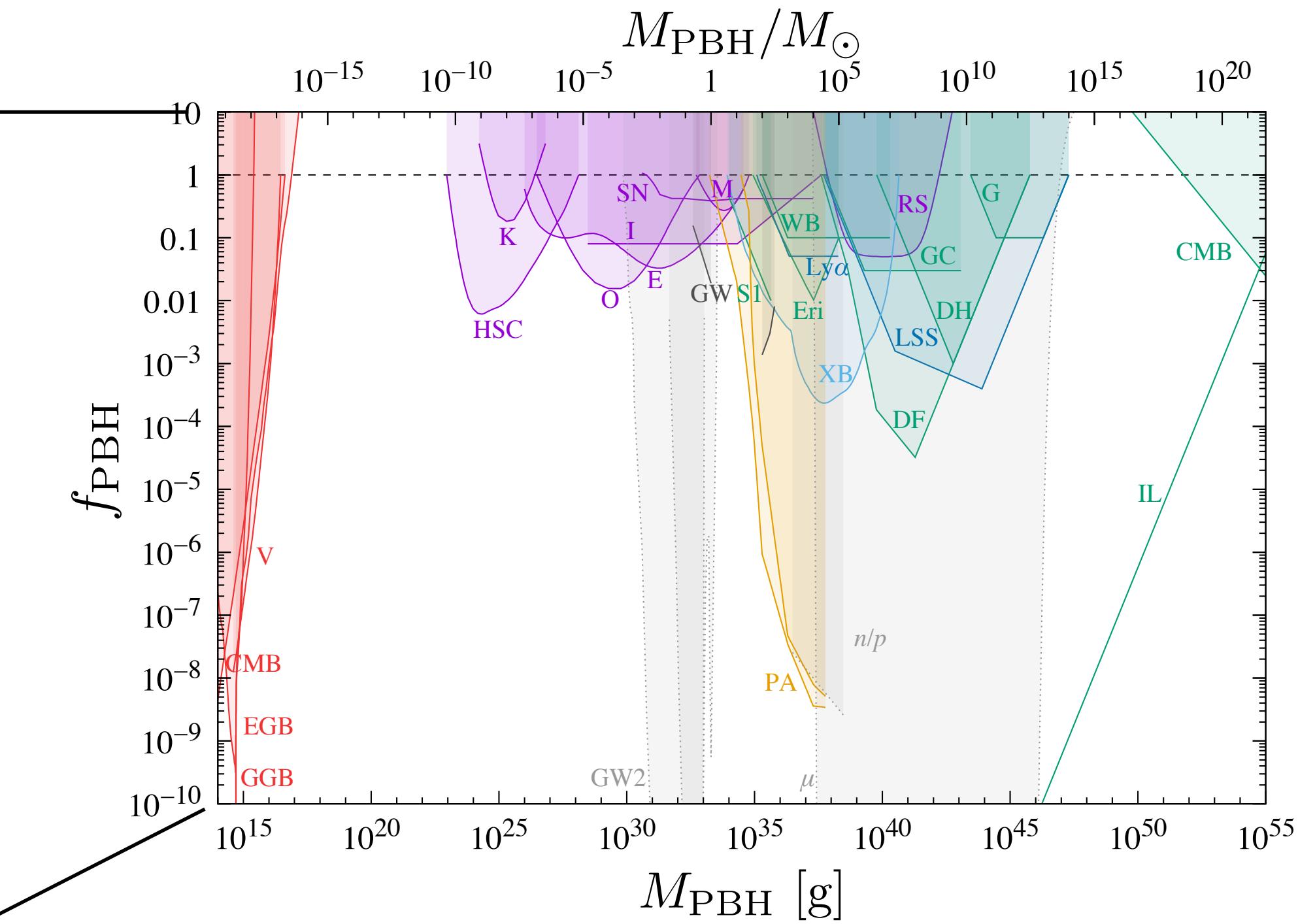
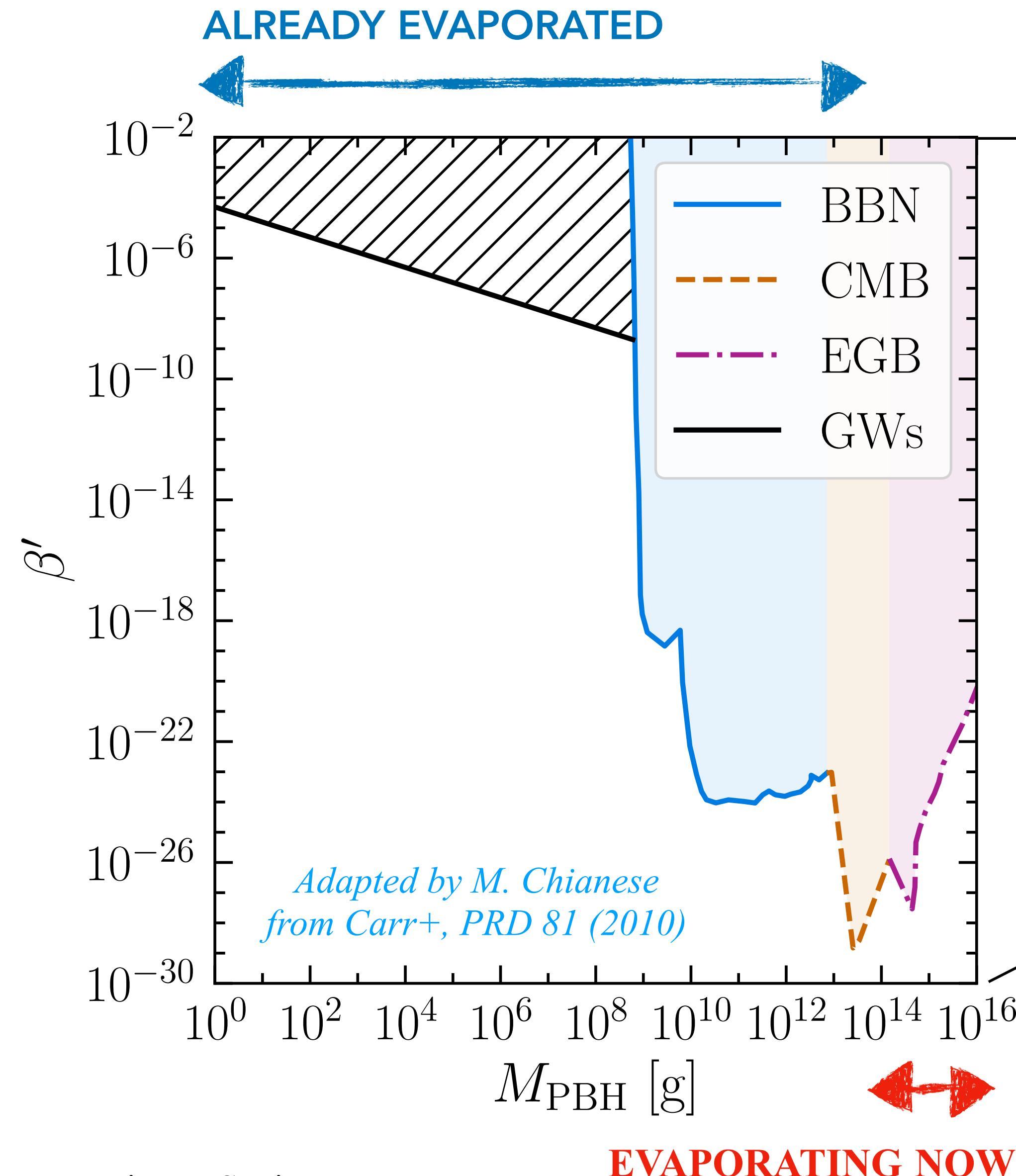
$$f_{\text{PBH}} = \frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}}$$

$f_{\text{PBH}} = 1$
PBHs are
all the DM

$f_{\text{PBH}} < 1$
PBHs are
DM-subcomponent



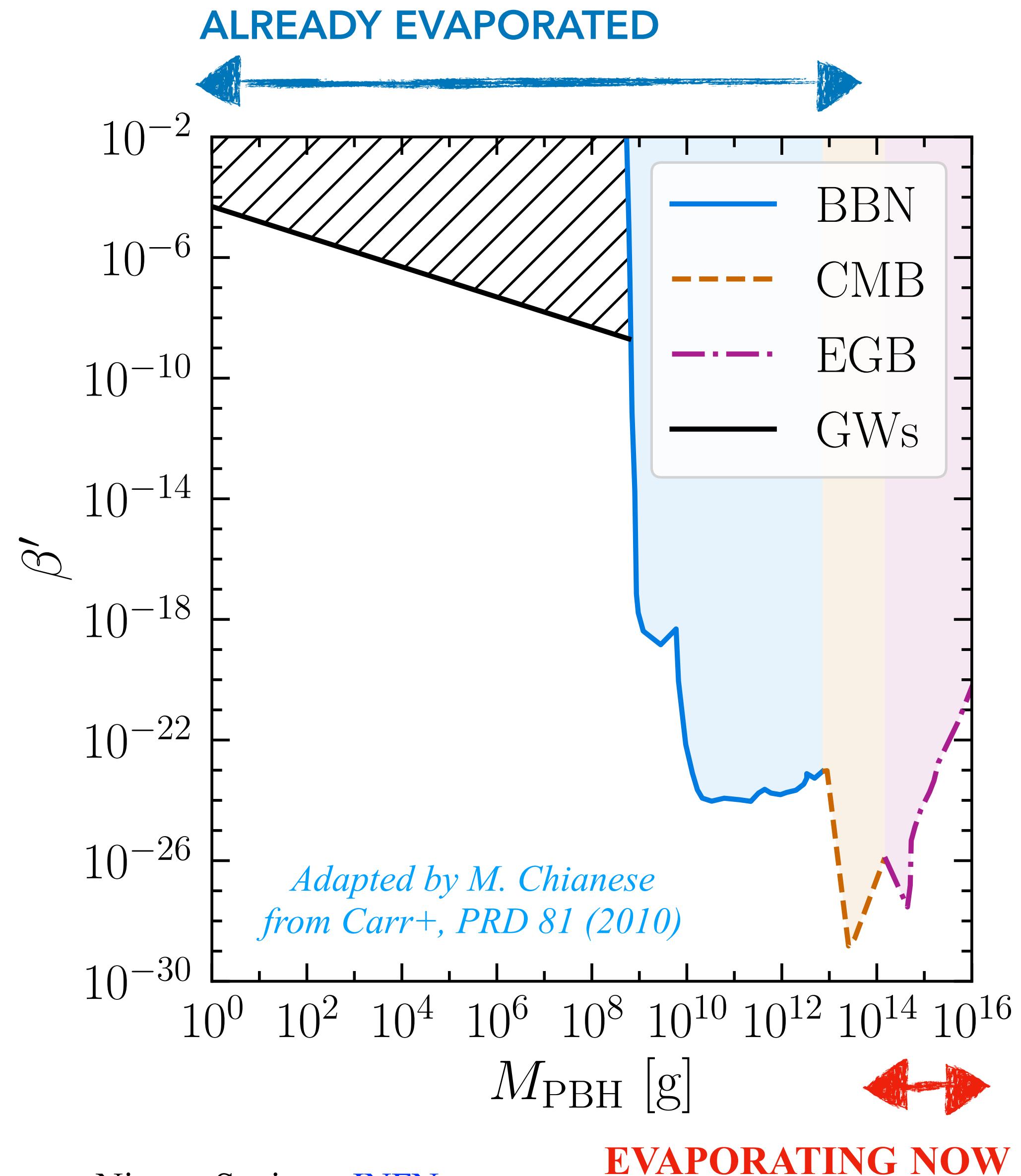
PBH constraints



PBH cosmological abundance

$$\beta'(M) = \gamma^{1/2} \frac{\rho_{\text{PBH}}(T_{\text{form}})}{\rho_{\text{R}}(T_{\text{form}})}$$

PBH constraints



- ◆ Formed at T_{form} after inflation with an abundance

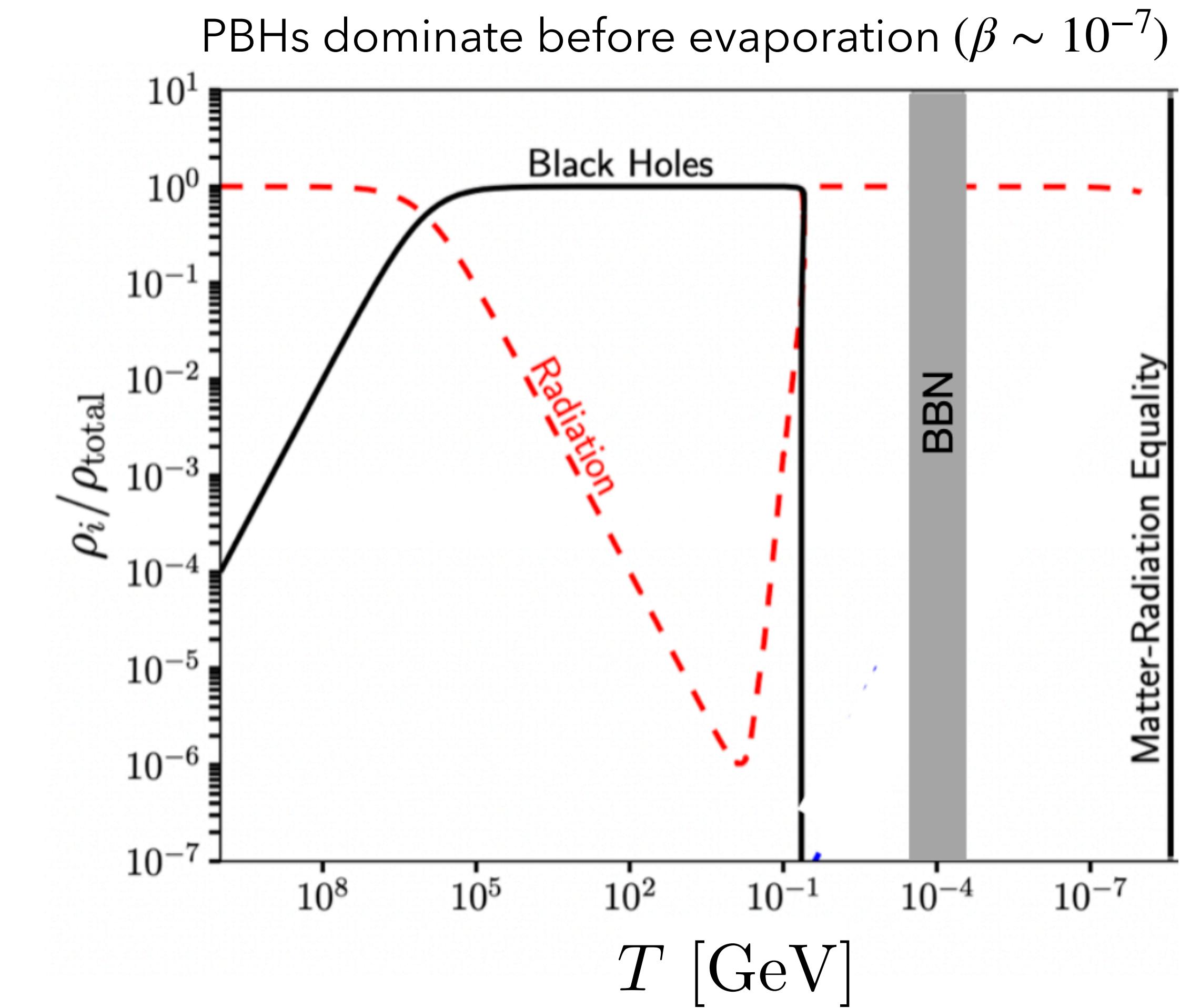
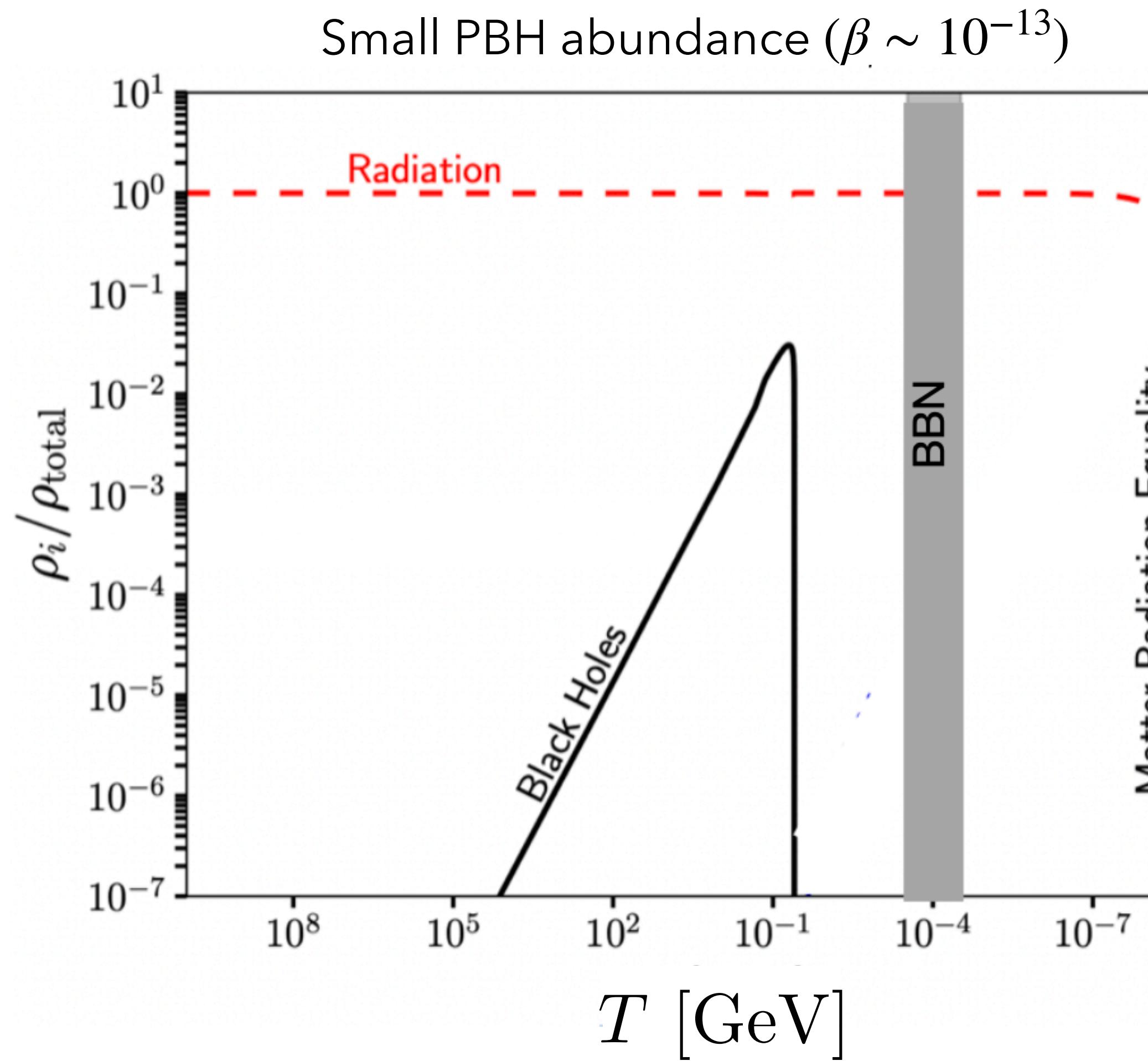
$$\beta'(M_{\text{PBH}}) = \gamma^{1/2} \frac{\rho_{\text{PBH}}(T_{\text{form}})}{\rho_R(T_{\text{form}})}$$

IN THIS TALK

- ◆ Light PBHs ($M_{\text{PBH}} \lesssim 10^9$ 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



Adapted from Hooper+, JHEP 08 (2019)

Baryogenesis

BARYON ASYMMETRY OF THE UNIVERSE (BAU)

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

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

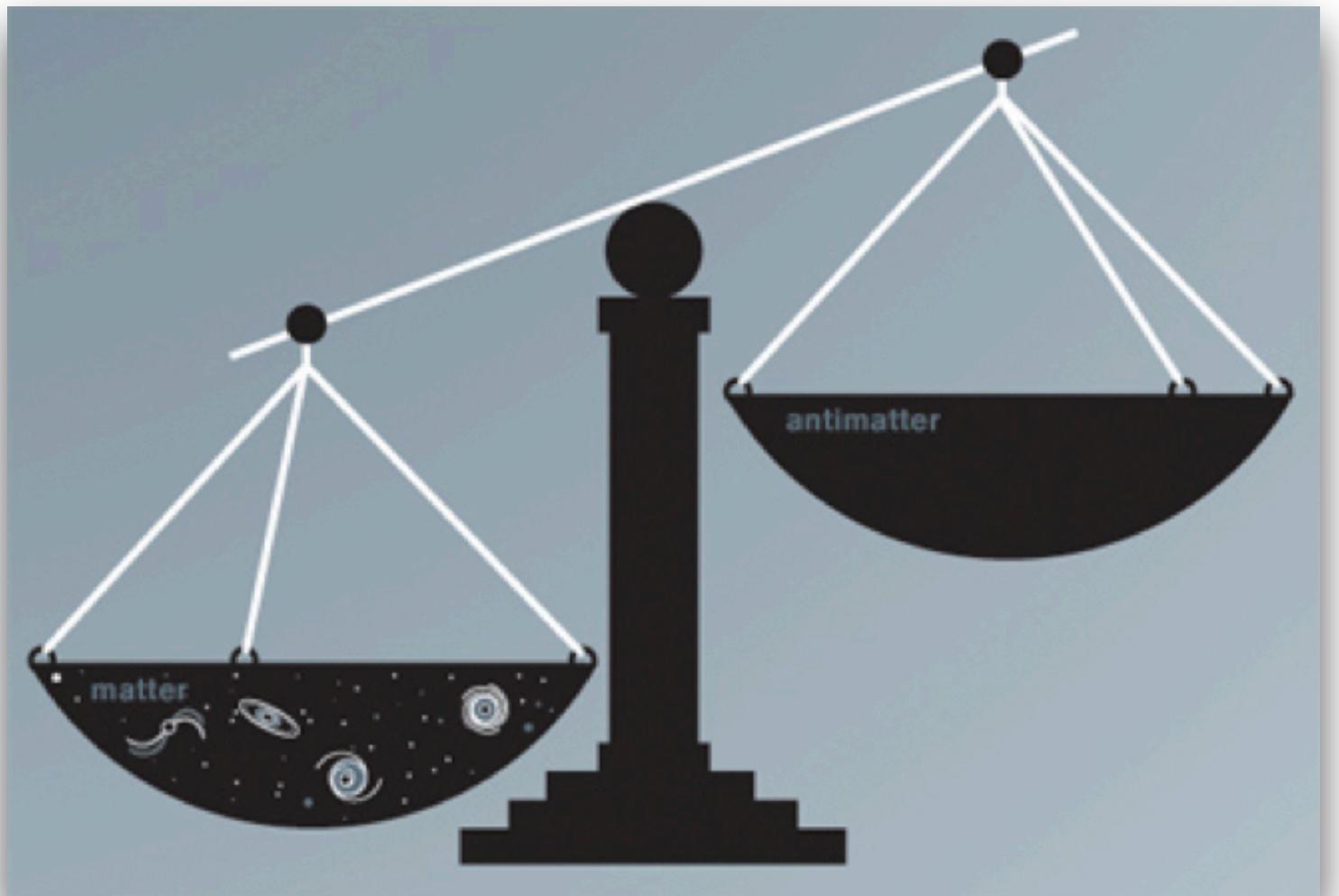
inferred independently by BBN and CMB (see PLANCK coll.)



SAKHAROV CONDITIONS

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

Present in the SM, but not sufficient...



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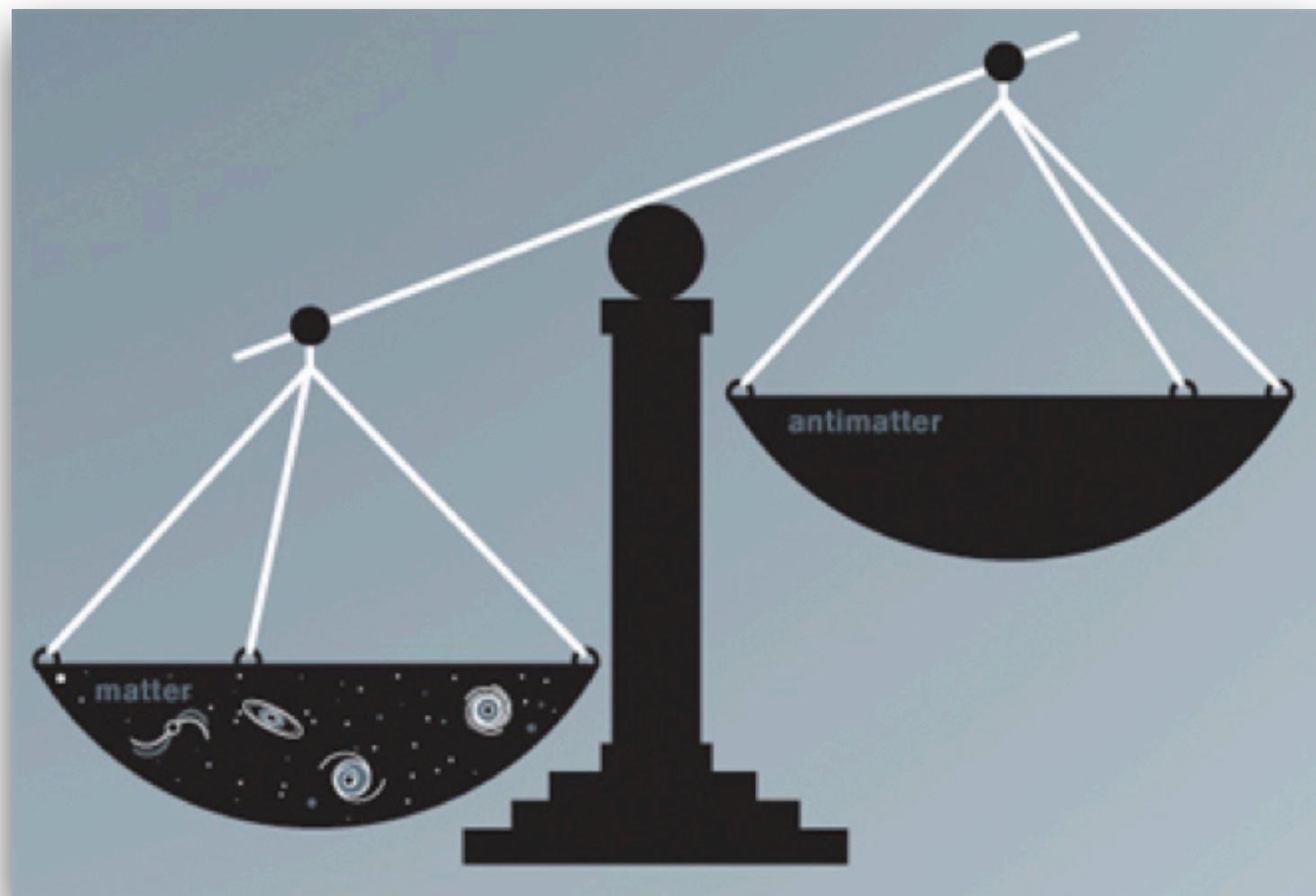
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SAKHAROV CONDITIONS

- ◆ Baryon number violation
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Present in the SM, but not sufficient...



The democratic feature of PBHs can also lead to observed matter antimatter asymmetry.



Idea already explored in the seminal papers of Hawking and Carr:
heavy, new particles from PBH evaporation, could decay violating CP and baryon number.

Leptogenesis

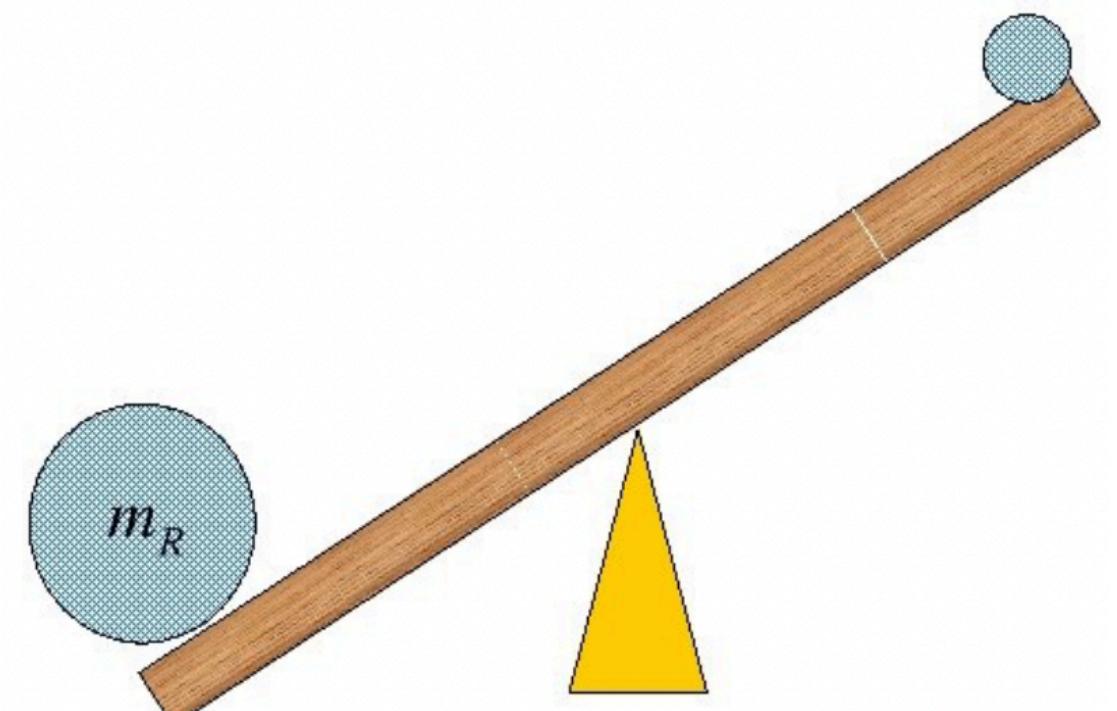
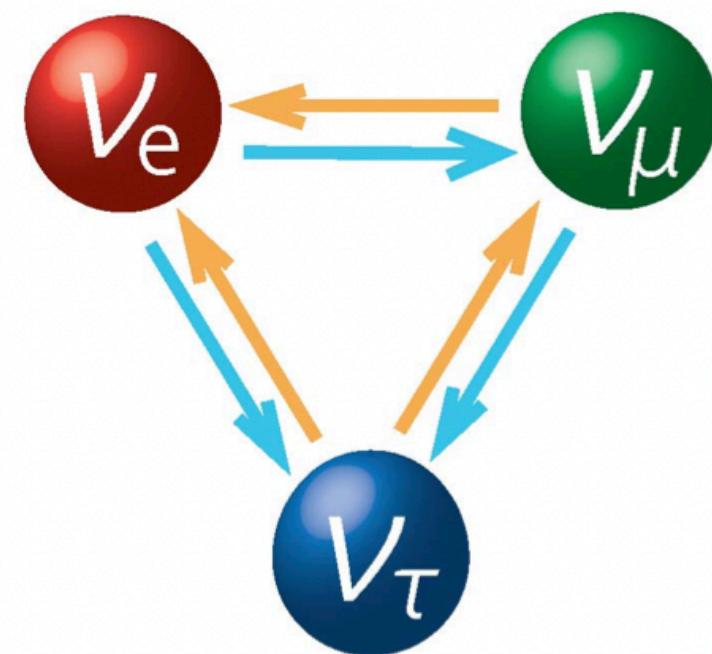
Simple and elegant explanation of the cosmological matter-antimatter asymmetry

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

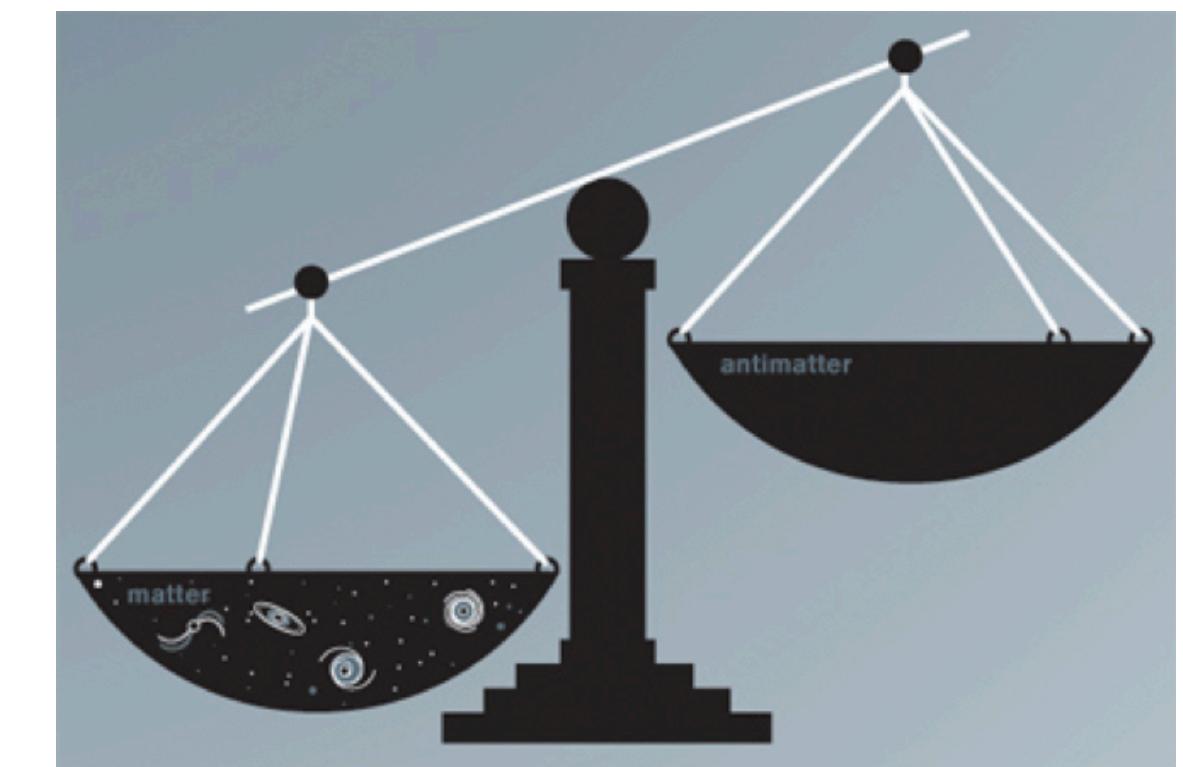
$$\mathcal{L} \supset -Y_{\alpha i} \overline{L}_\alpha \tilde{\phi} N_i - \frac{1}{2} \overline{N}_i^C M_{ij} N_j + \text{h.c.}$$

Right-Handed Neutrinos (RHNs)

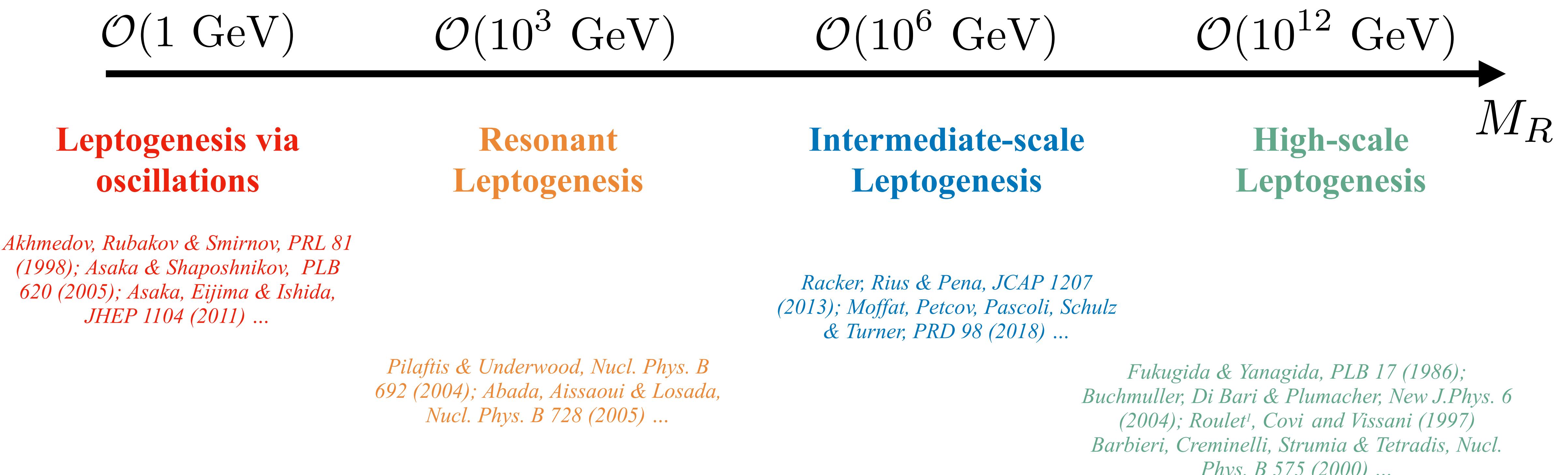
- ◆ L violation due to the Majorana nature of RHNs;
 $L \rightarrow B$ via sphaleron
- ◆ C and CP violation due to Dirac Yukawa couplings
- ◆ Departure from thermal equilibrium when $\Gamma_N < \mathcal{H}$



[Fukugita, Yanagida '86]

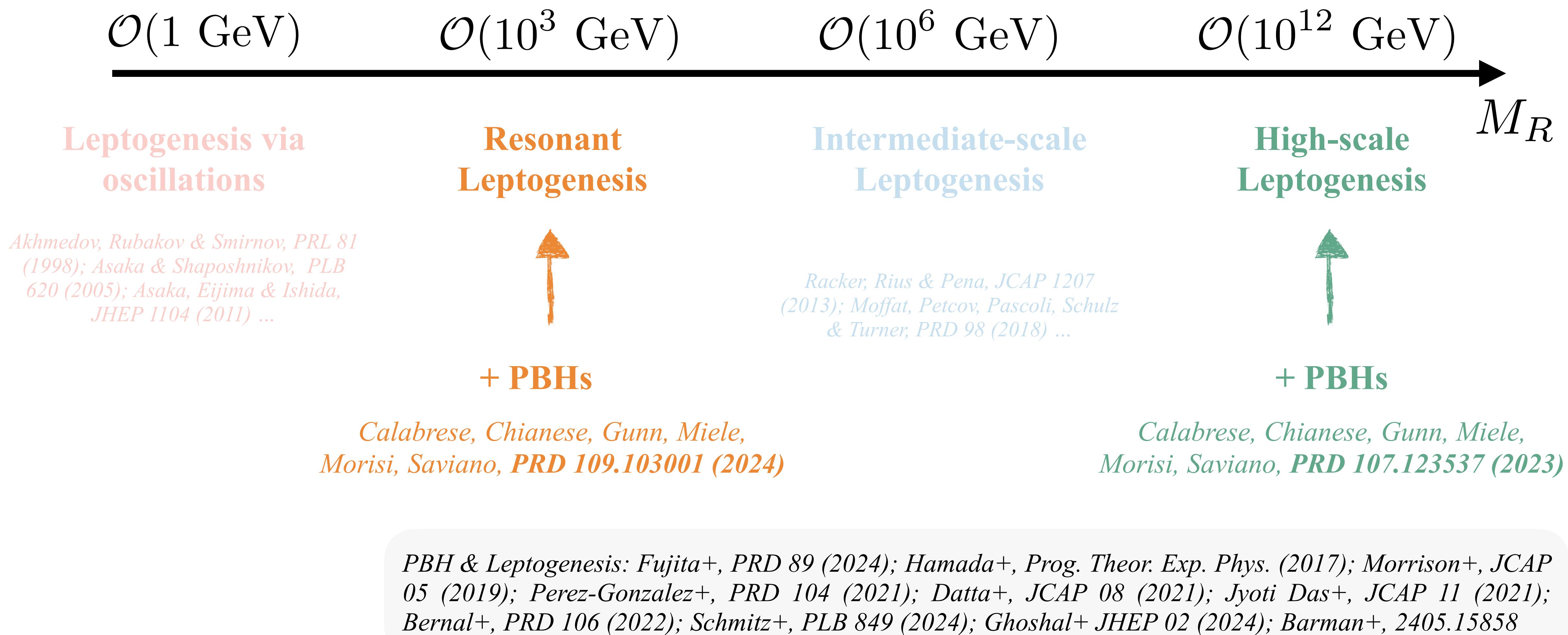


Leptogenesis landscape

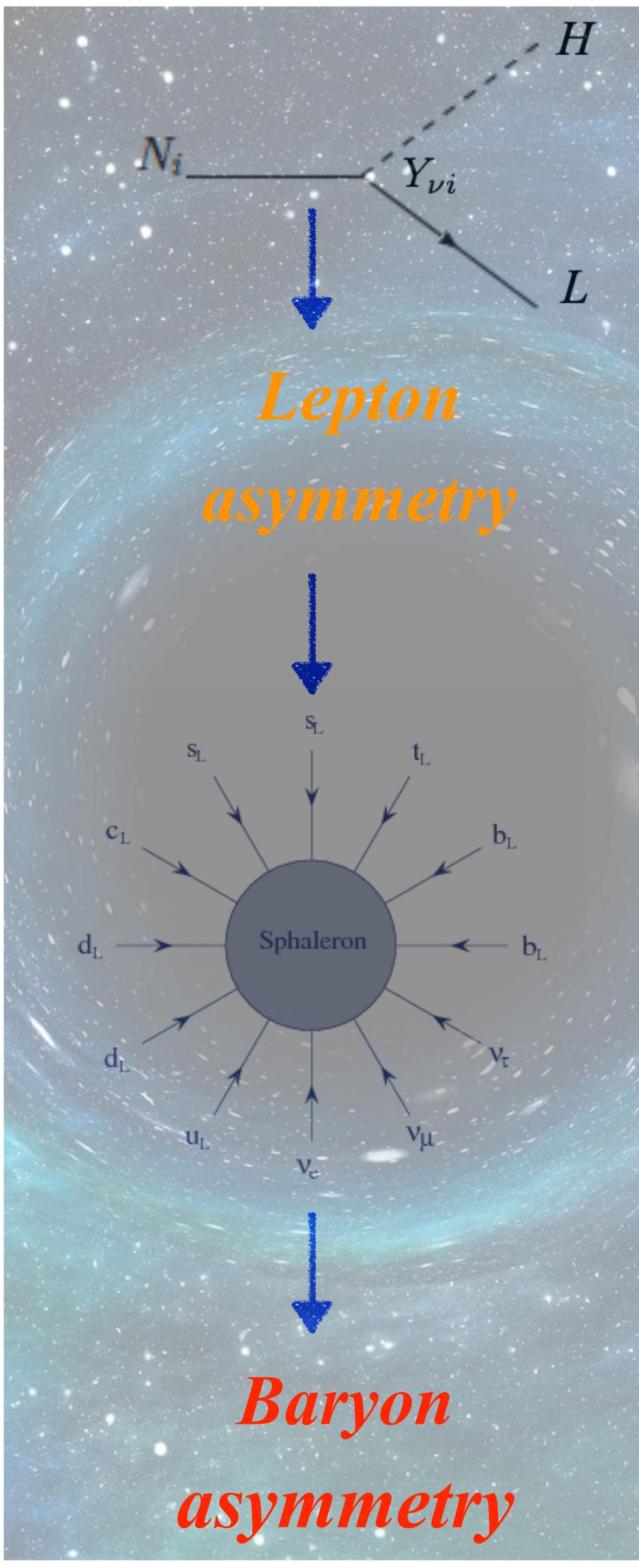


Incomplete list...see interesting reviews: Buchmuller+, Annals Phys. 315 (2005); Sheng Fong+, Adv.High Energy Phys. (2012); Davidson+, Phys.Rept. 466 (2008)

Leptogenesis landscape



Leptogenesis & PBH



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

ADDITIONAL NON-THERMAL SOURCE TERM

$$a\mathcal{H} \frac{dn_N}{da} = -(n_N - n_N^{\text{eq}}) \Gamma_N^T + n_{\text{PBH}} \Gamma_N^{\text{PBH}} \quad \text{if } T_{\text{PBH}} > M$$

contribution from thermal plasma

contribution from PBH evaporation

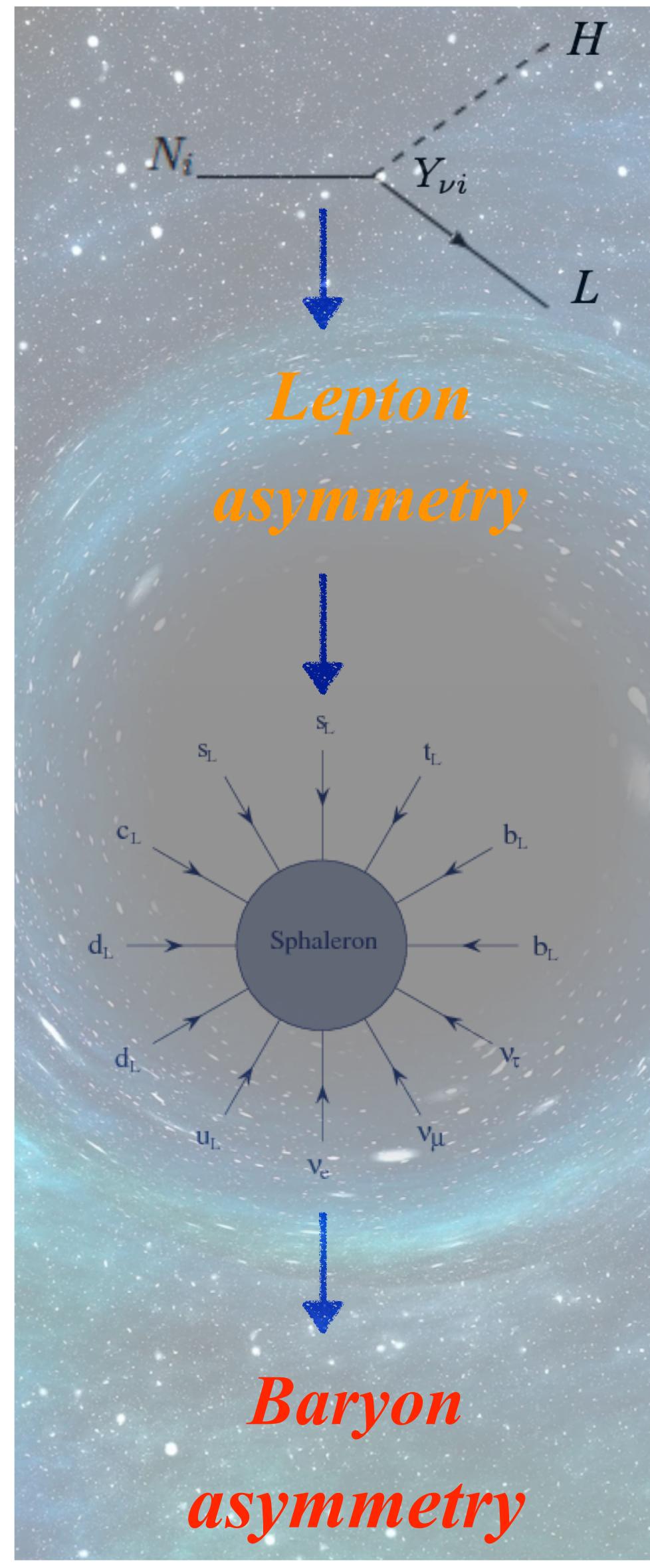
Studied for $M_{\text{PBH}} < 10^5$ g in:
Perez-Gonzalez+, PRD 104 (2021), Bernal+, PRD 106 (2022)

ENTROPY INJECTION

$$\frac{dS}{da} = -\frac{f_{\text{SM}}}{T(a)} \frac{d \ln M_{\text{PBH}}}{da} \rho_{\text{PBH}}$$

Dilution of any pre-existing relic at evaporation

Leptogenesis & PBH



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

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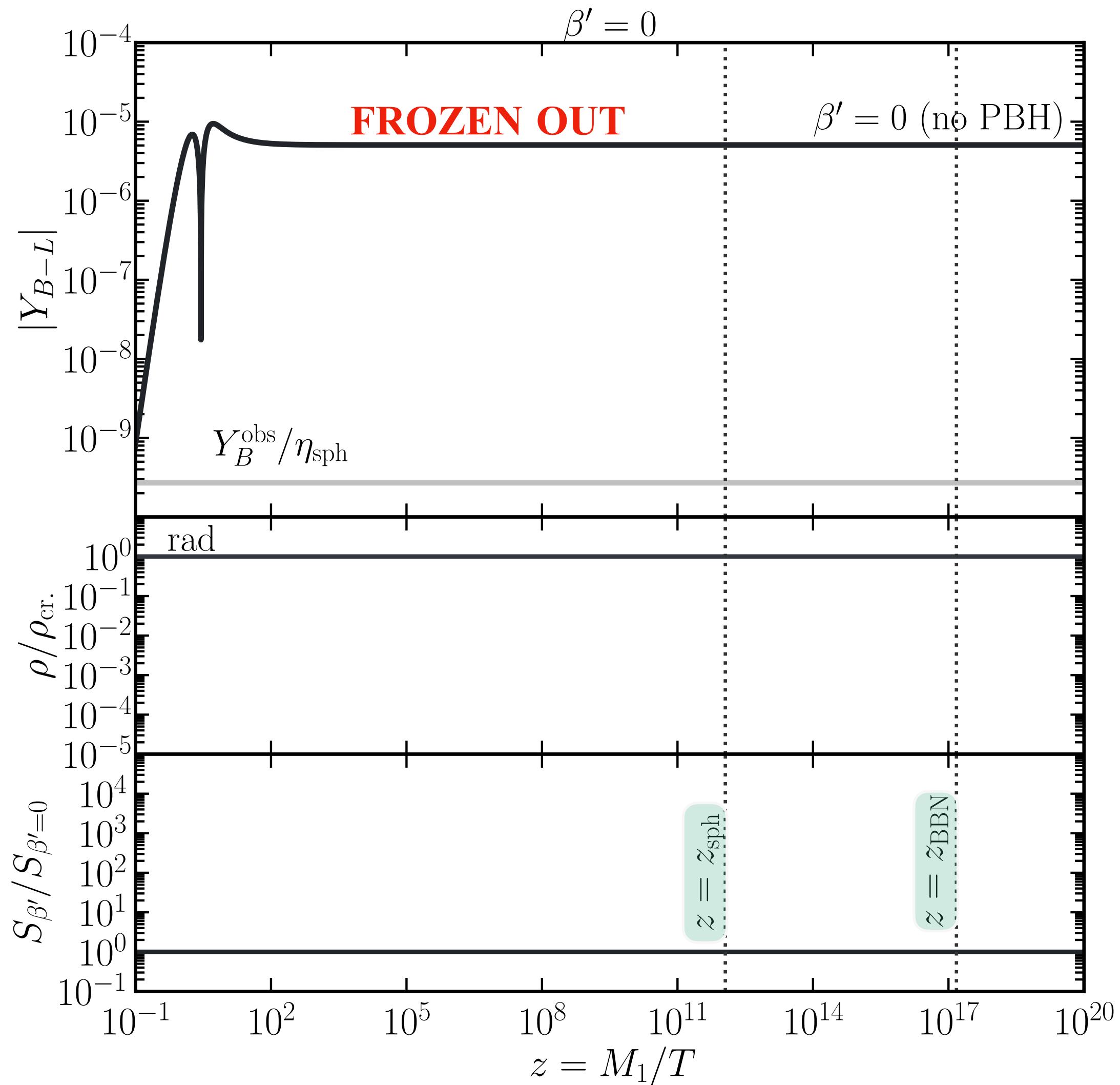
Dilution of any pre-existing relic at evaporation

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

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

Benchmark scenarios

Calabrese+ (w/ NS), PRD 107.123537 (2023)

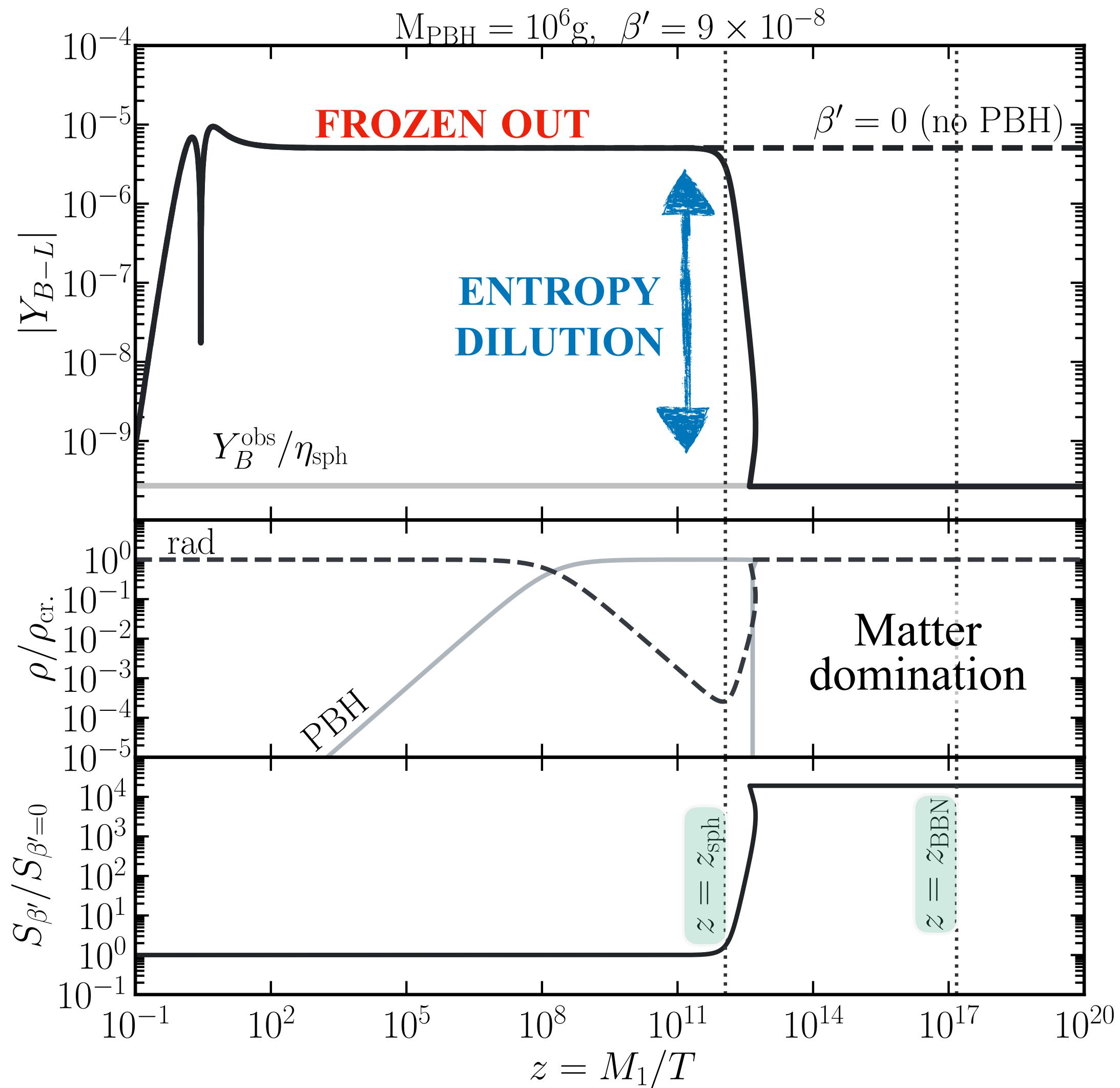


STANDARD LEPTOGENESIS SCENARIO

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

Benchmark scenarios

Calabrese+ (w/ NS), PRD 107.123537 (2023)

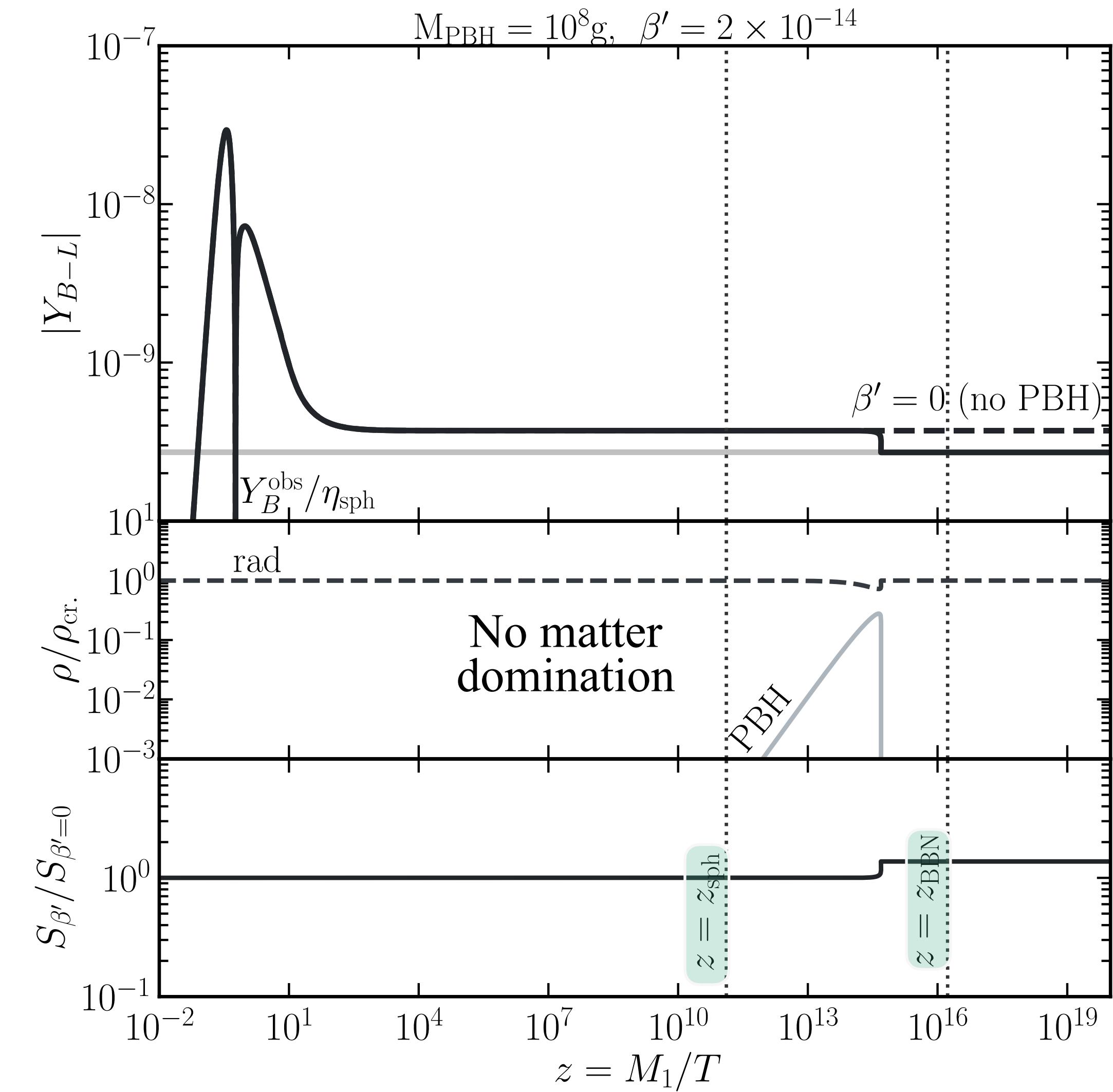
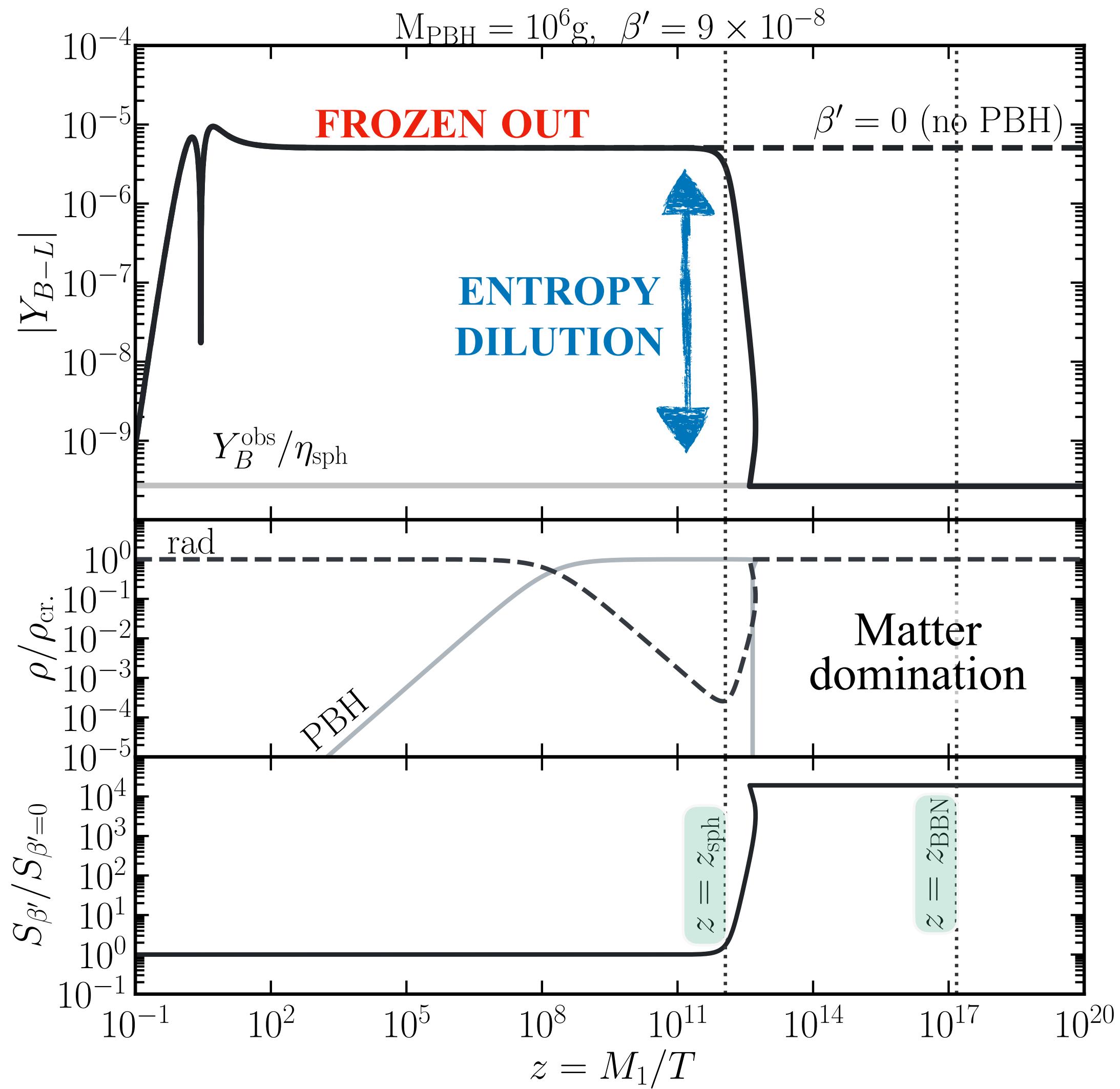


PBH-MODIFIED LEPTOGENESIS SCENARIO

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

Benchmark scenarios

Calabrese+ (w/ NS), 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: $Y = \frac{1}{v} \sqrt{\hat{M}} R \sqrt{\hat{m}_\nu} U_{\text{PMNS}}^\dagger$
- ♦ Normal ordering with $m_1 \simeq m_2$ since $\Delta m_{\text{sun}}^2 \ll \Delta m_{\text{atm}}^2$ \longrightarrow the only phase in R is $z_{13} = x + i y$

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- ♦ Normal ordering with $m_1 \simeq m_2$ since $\Delta m_{\text{sun}}^2 \ll \Delta m_{\text{atm}}^2$ \longrightarrow the only phase in R is $z_{13} = x + i y$

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

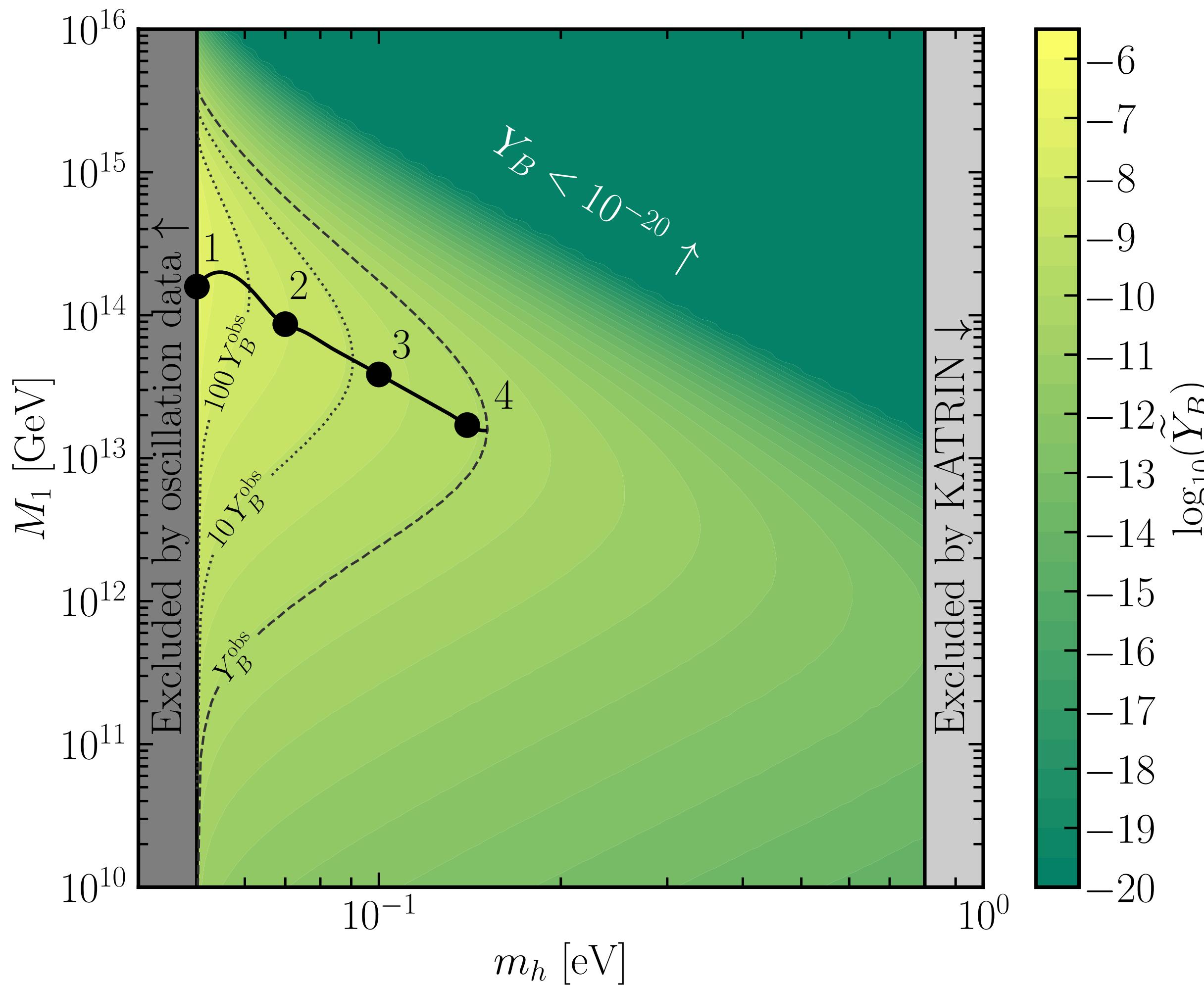
- ♦ Hierarchical RHNs: $M_1 \ll M_{2,3}$
- ♦ Mass range $M_1 \in [10^{10}, 10^{16}]$ GeV
- ♦ Free parameters $\{x, y, M, m_h\}$ with $m_h = m_3$

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

High-scale Thermal Leptogenesis (HTL)

Calabrese+ (w/ NS), PRD 107.123537 (2023)

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

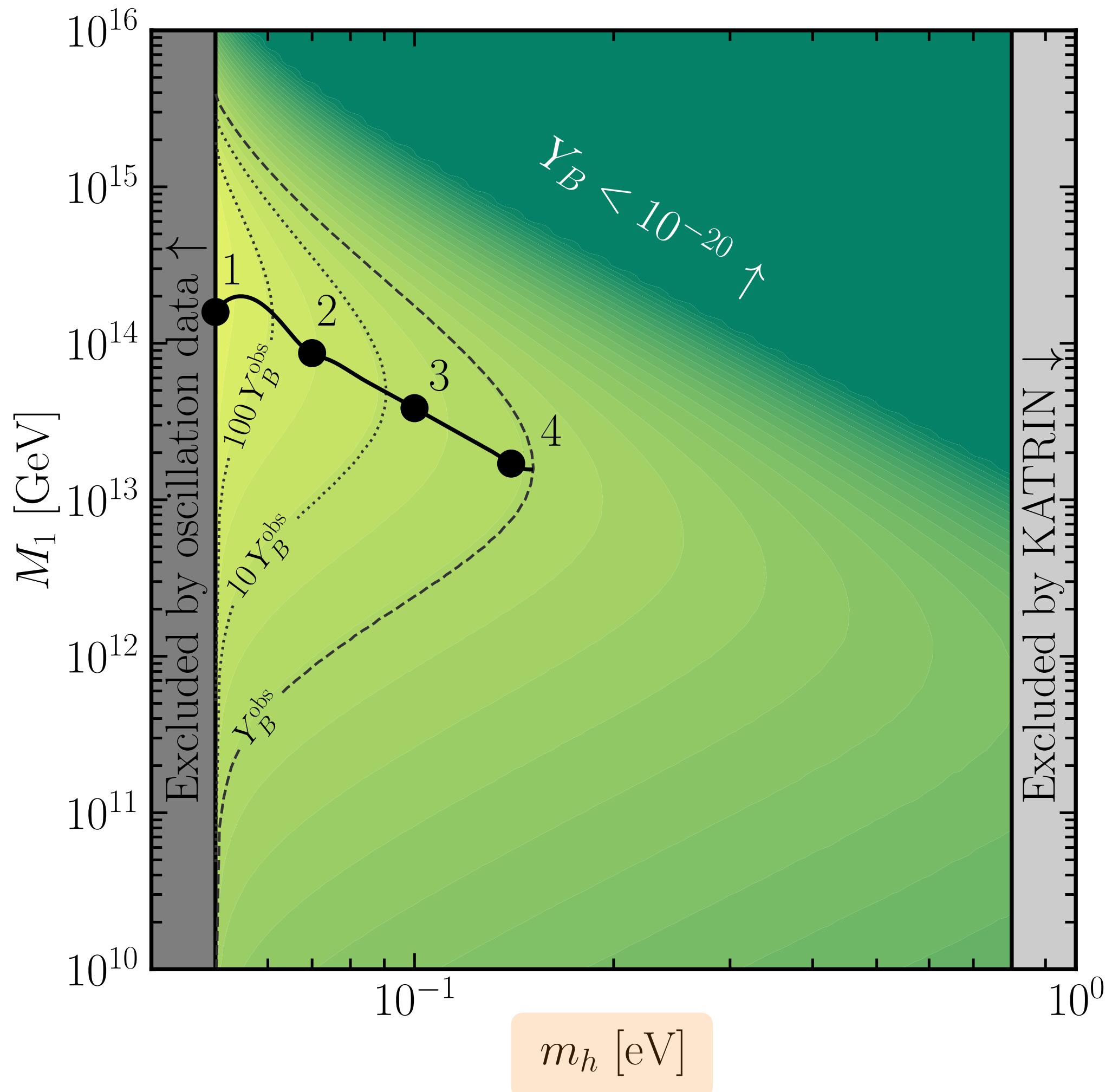


Parameters maximize the baryon asymmetry

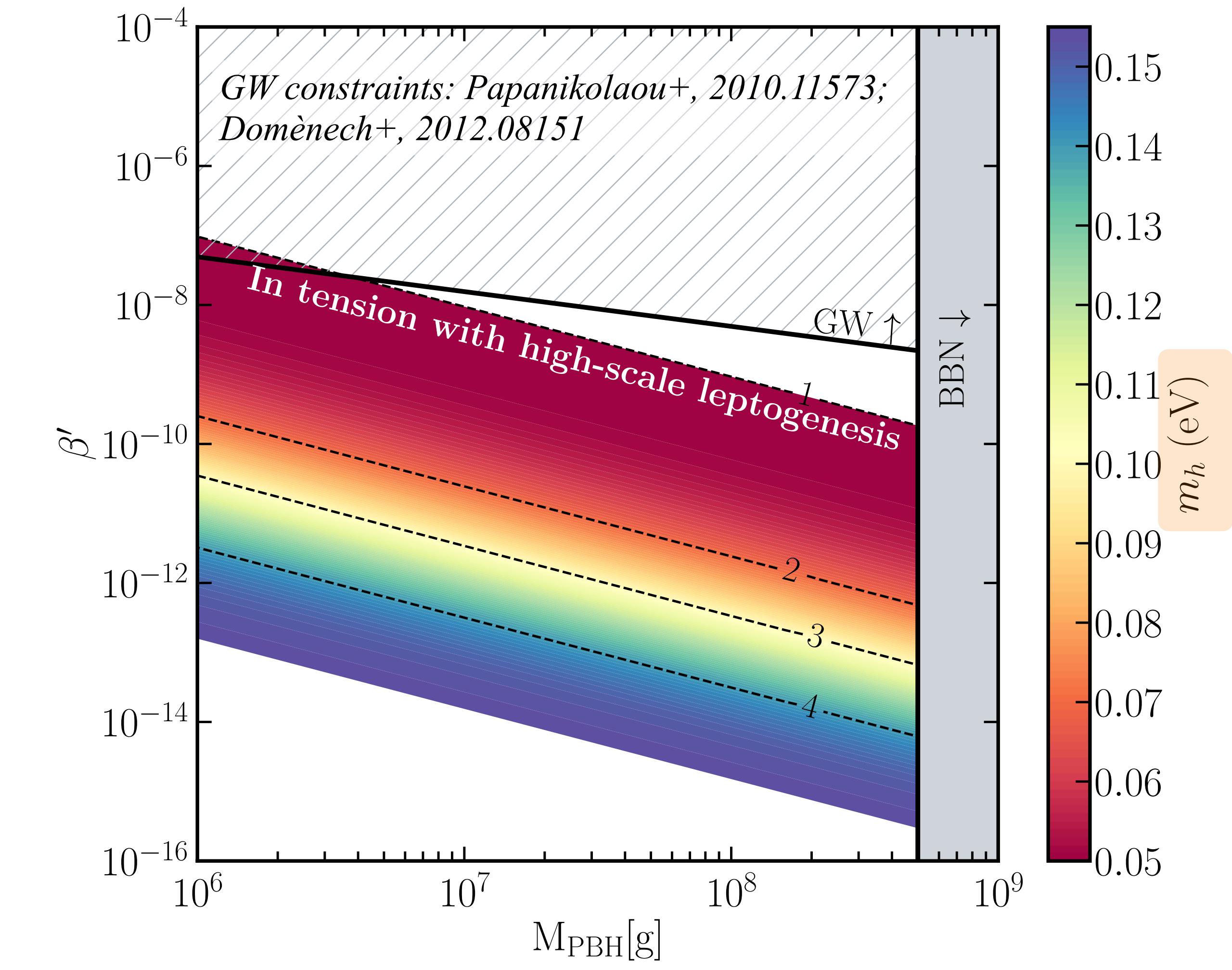
Bench. pt	m_h [eV]	M_1 [GeV]	\tilde{Y}_B
1	0.05	1.5×10^{14}	1.5×10^{-6}
2	0.07	1.0×10^{14}	3.6×10^{-9}
3	0.10	4.0×10^{13}	5.5×10^{-10}
4	0.14	2.0×10^{13}	1.2×10^{-10}

Dashed line: contour for \tilde{Y}_B matching the observed value
 Dotted lines: contours for increasing the ratio $\tilde{Y}_B / Y_B^{\text{obs}}$
 Solid line: contour maximizing the baryon asymmetry Y_B

Strong interplay with active neutrinos scale m_h



Mutual exclusion limits between PBHs and HTL



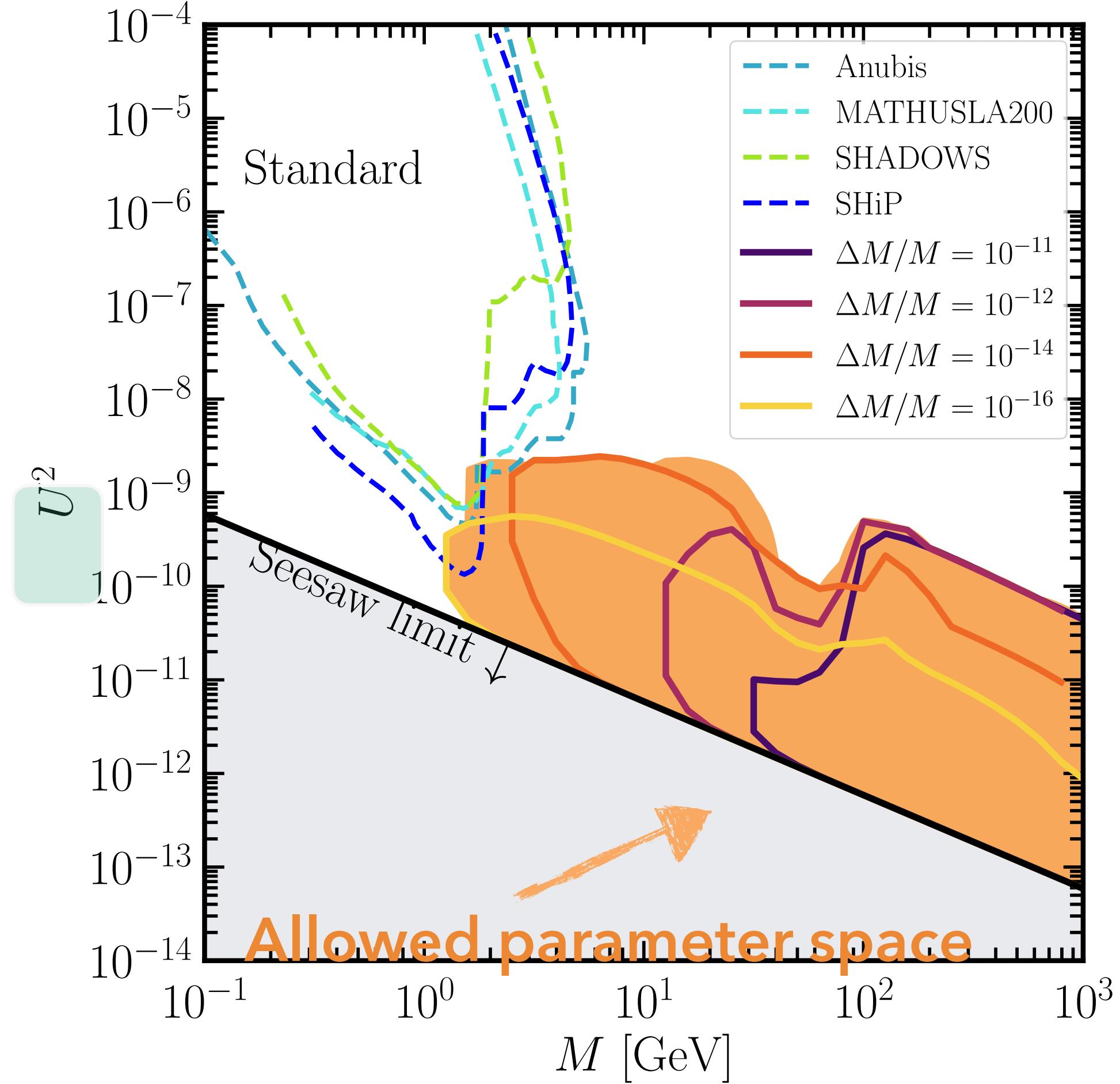
Higher the neutrino mass scale the stronger the constraints on PBH

Resonant leptogenesis

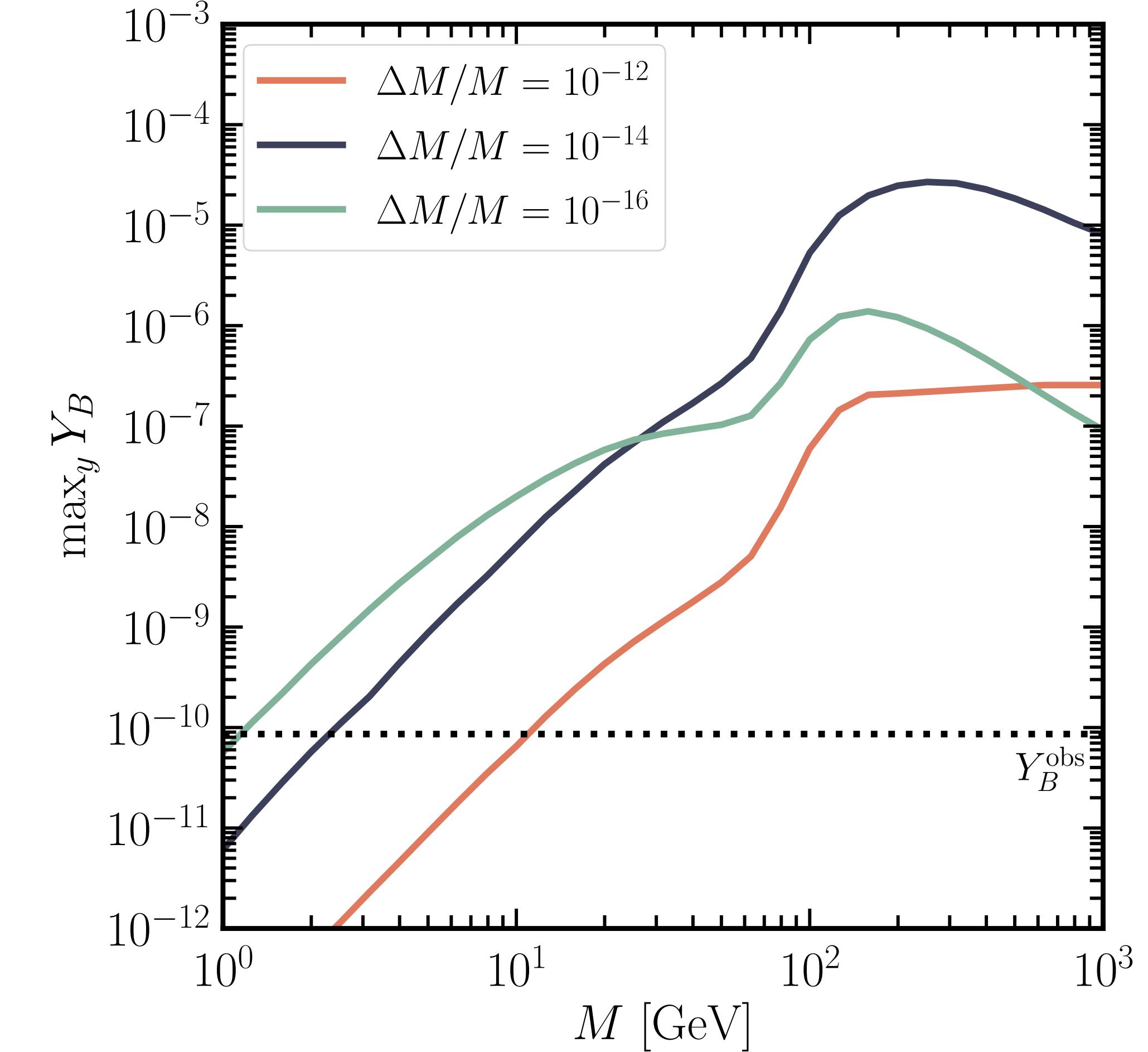
Calabrese+ (w/ NS), PRD 109.103001 (2024)

Active-sterile mixing

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

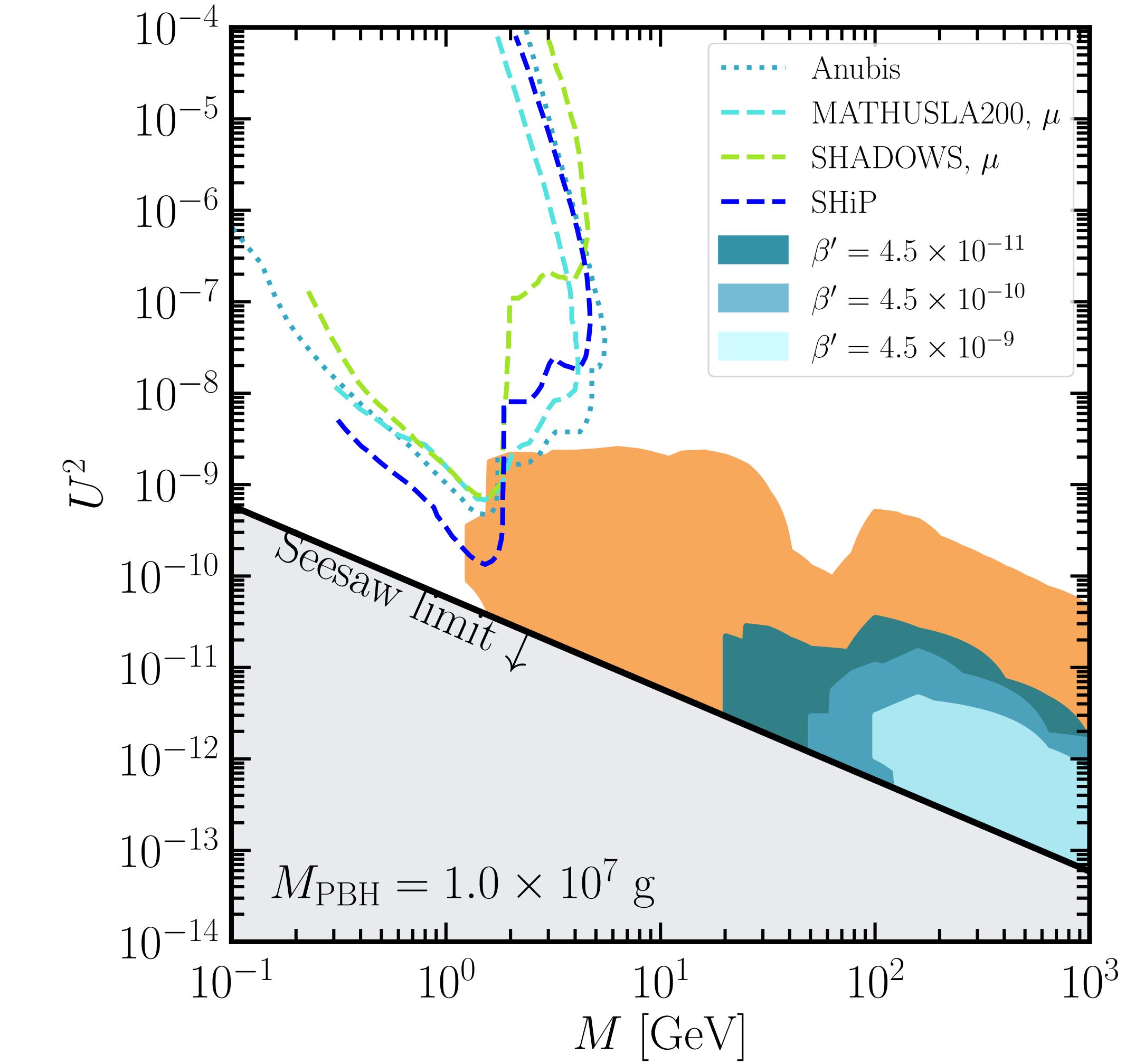
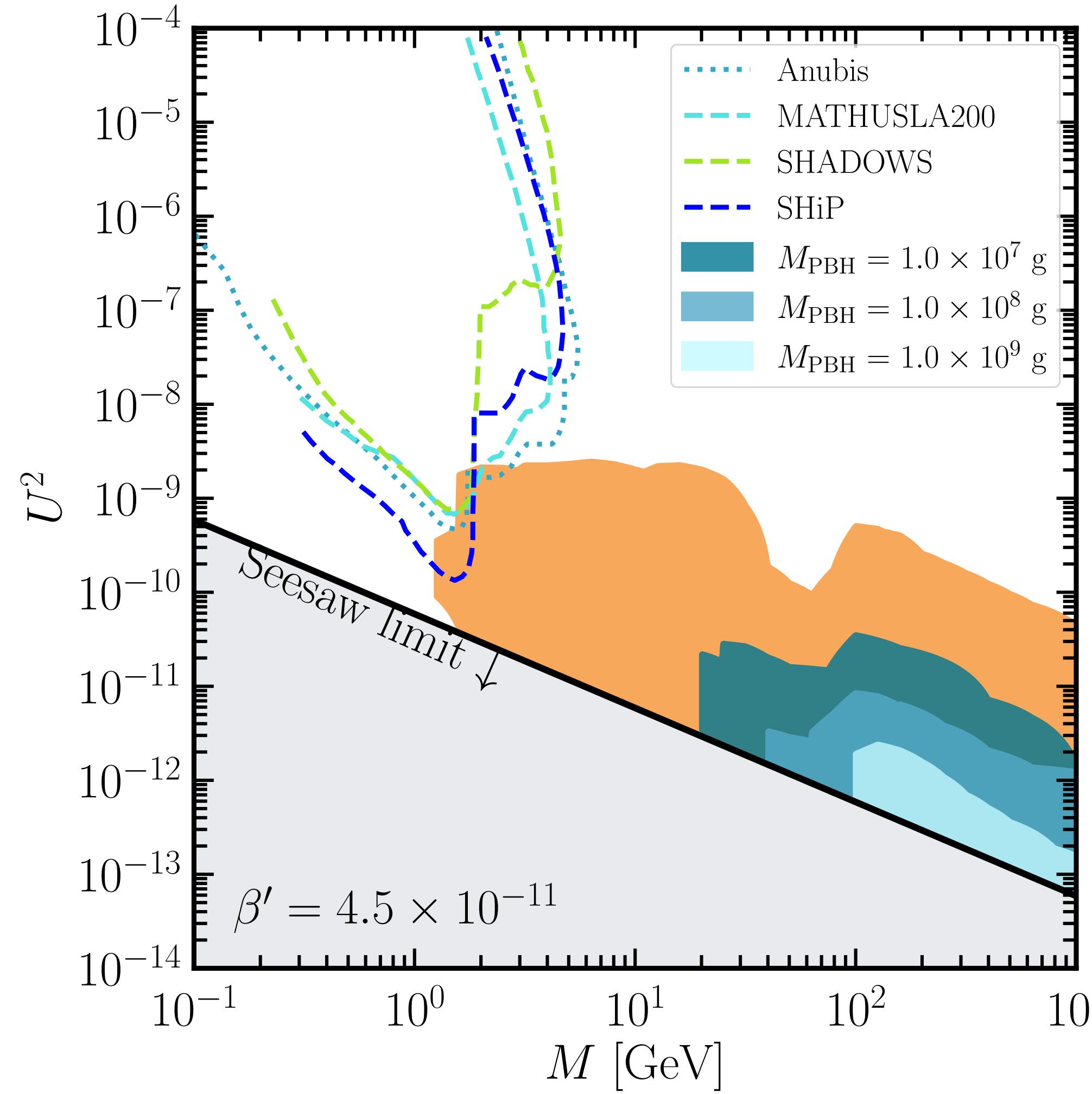


For the colored solid line lines the baryon asymmetry Y is equal to the observed one



Maximum baryon asymmetry as a function of RHN mass

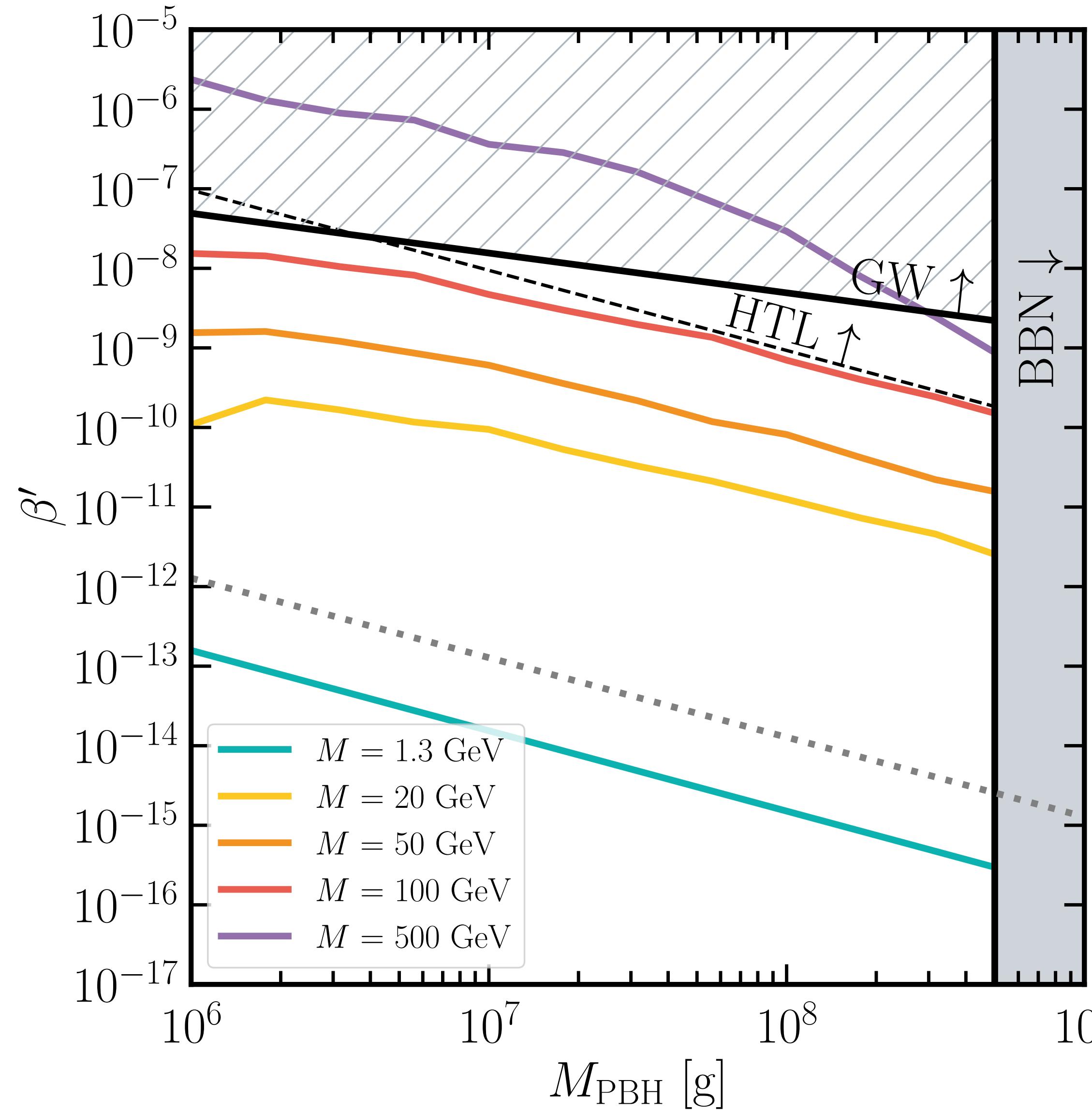
Shrinking the RHNs allowed region towards higher masses M and smaller mixing U^2



PBHs disfavor detection of Heavy Neutral Leptons (HNLs)!

PBH-leptogenesis constraints

Calabrese+ (w/ NS), 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

The smaller the RHNs mass scale, the stronger the constraints on β'

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

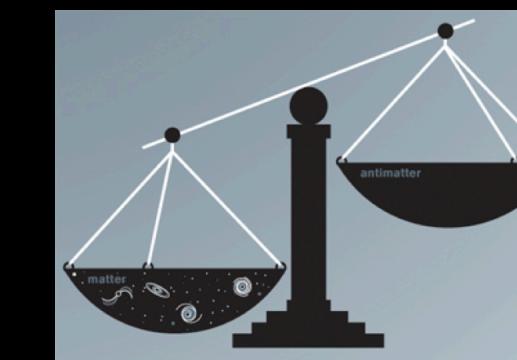
Dotted line: minimum PBH abundance for matter domination

Solid lines: constraints for different HNL masses

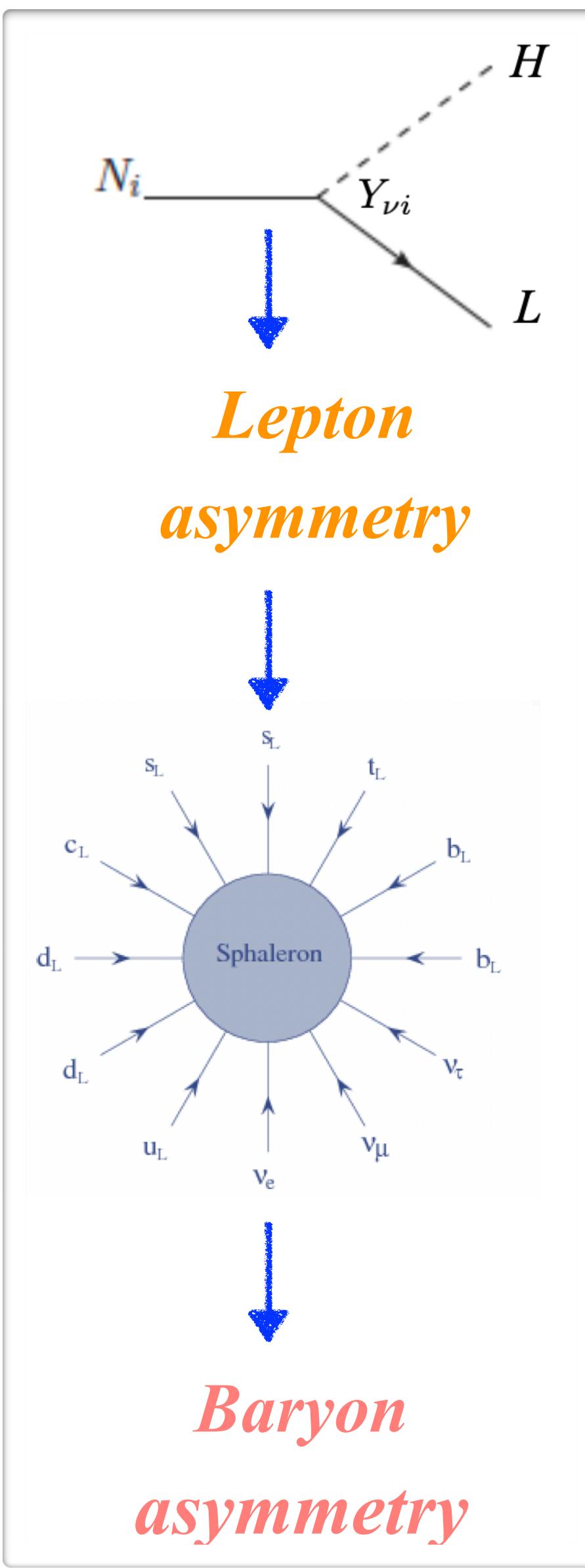
Conclusions

- ◆ 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.

Thank you



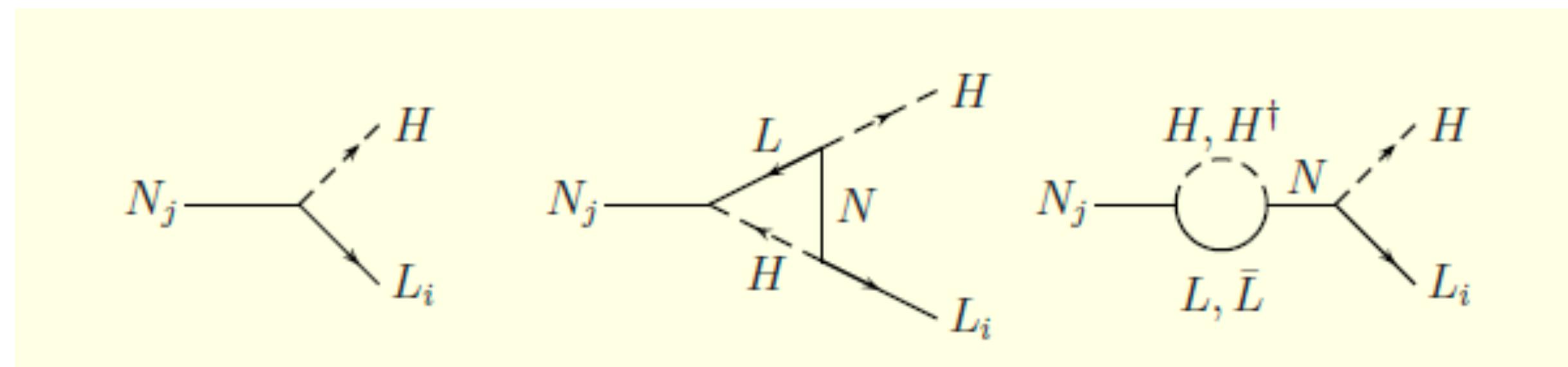
Basic Step of Leptogenesis



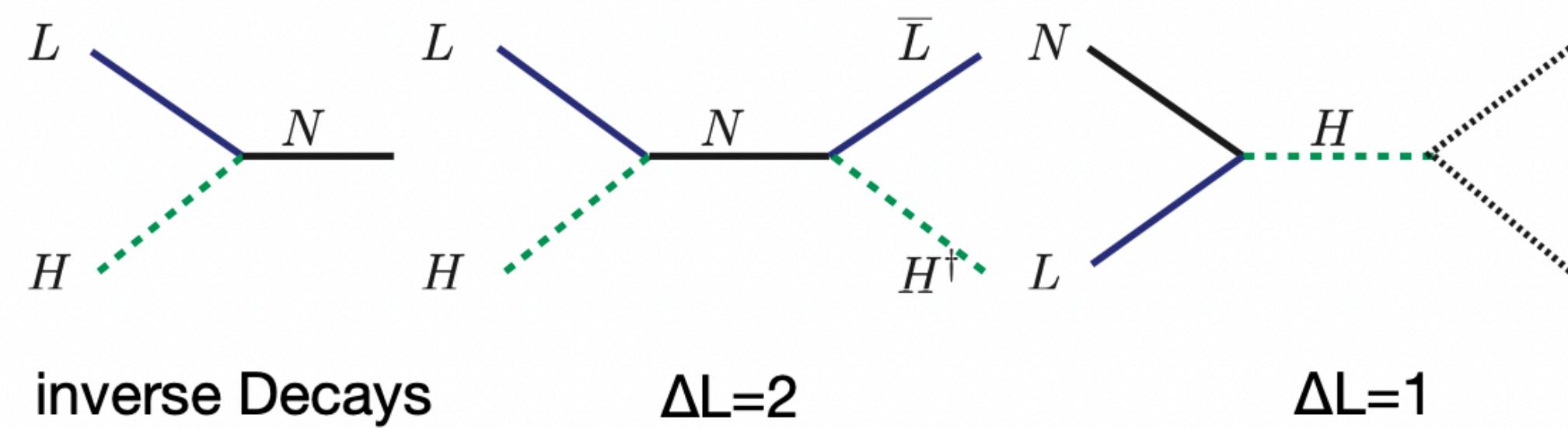
$$N \rightarrow LH / N \rightarrow \bar{L}H$$

$$\epsilon_i = \frac{\Gamma_i - \bar{\Gamma}_i}{\Gamma_i + \bar{\Gamma}_i}$$

CP asymmetry results from the interference between tree and 1-loop wave and vertex diagrams.



Partial washout of the asymmetry due to inverse decay and scatterings:



*Conversion of the left-over L asymmetry to B asymmetry at $T > T_{sph}$:
B - L conserved*

High-scale Leptogenesis

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

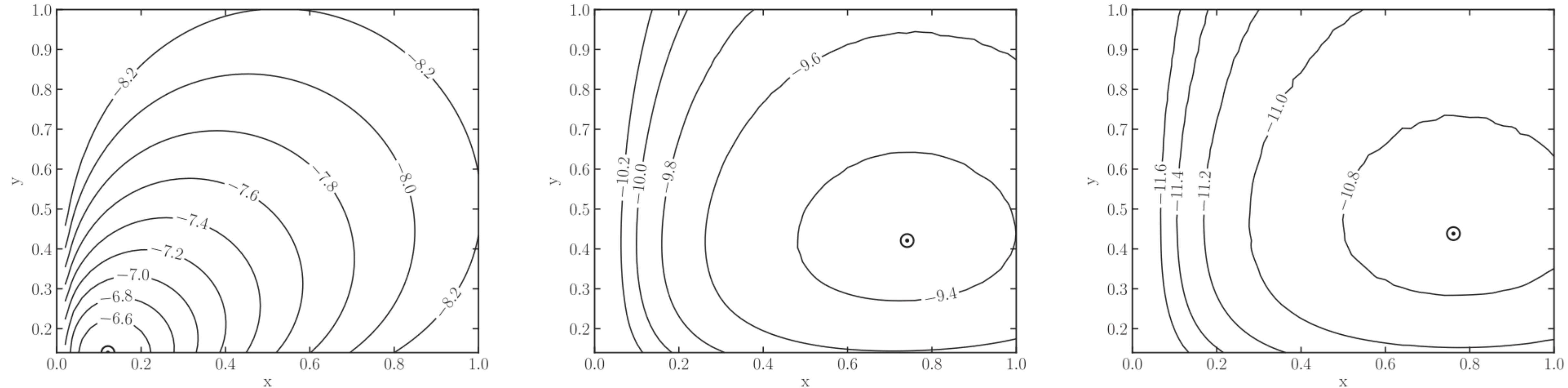


FIG. 1. The final baryon asymmetry Y_B as a function of x, y for $m_h = \sqrt{m_{\text{atm}}^2} \approx 0.05$ eV (left panel), $m_h = 0.1$ eV (middle panel) and $m_h = 0.2$ eV (right panel), with $M_1 = 2.0 \times 10^{13}$ GeV. The contours are for constant $\log_{10} Y_B$ while the symbol \odot indicates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

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

with $\alpha \approx 0.1015$

see D'Onofrio+, PRL 113 (2014)

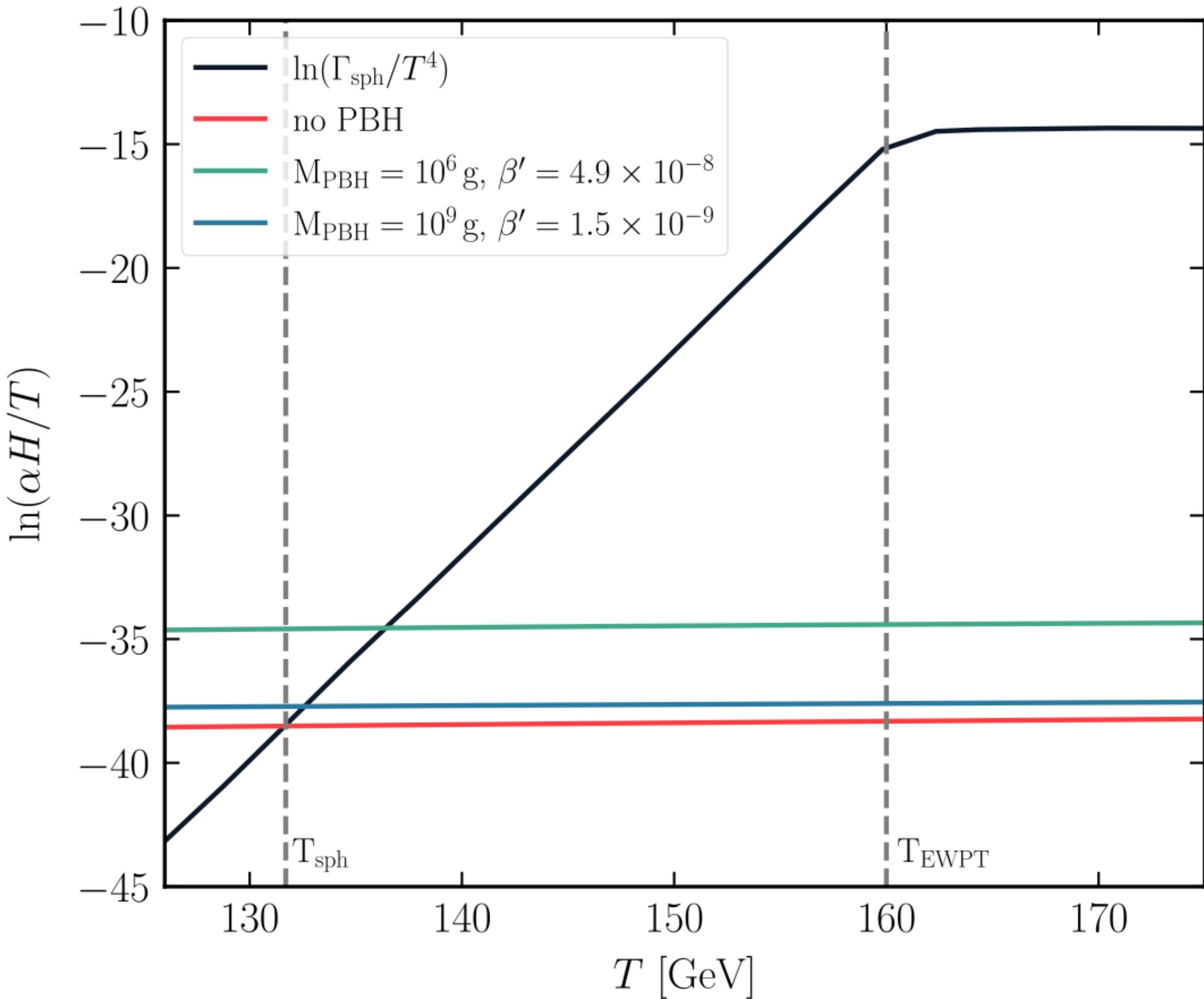


FIG. 5. The rate of sphaleron process (black line) as a function of the temperature. The colored lines show the Hubble rate for different scenarios with and without the presence of PBHs. The crossing between Γ_{sph} and H defines the temperature T_{sph} at which the sphaleron processes freeze-out. We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

High-scale Leptogenesis: Boltzmann equations

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

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

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

- ◆ $1 \rightarrow 2$ decays of N_1 , $N_1 \rightarrow \ell \phi^\dagger$ and its CP conjugate process $N_1 \rightarrow \bar{\ell} \phi$.
- ◆ $2 \rightarrow 1$ inverse decay modes like $\ell \phi^\dagger \rightarrow N_1$. These processes produce the N_1 population but only wash out the asymmetry.
- ◆ $2 \leftrightarrow 2$ scatterings mediated by N_1 exchange like $\ell \phi^\dagger \rightarrow \bar{\ell} \phi$, 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

Calabrese+ (w/ NS), PRD 109.103001 (2024)

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

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

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

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.