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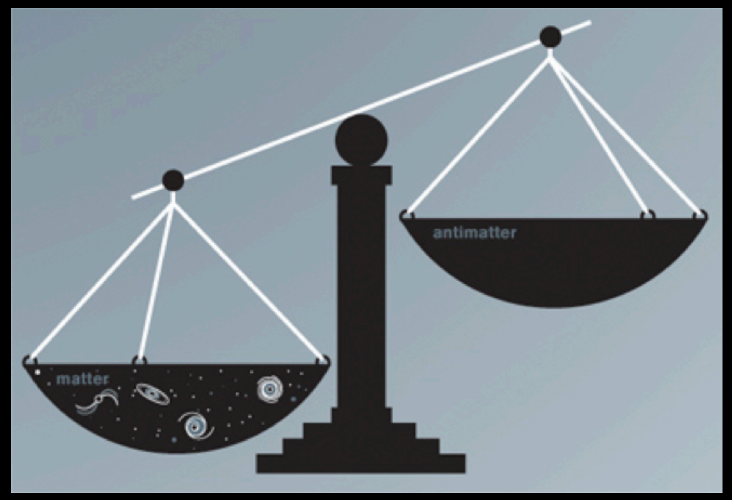
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

INFN Istituto Nazionale di Fisica Nucleare

PANTHEON

Leptogenesis in the light of Primordial Black Holes



Ninetta Saviano

INFN (NA)

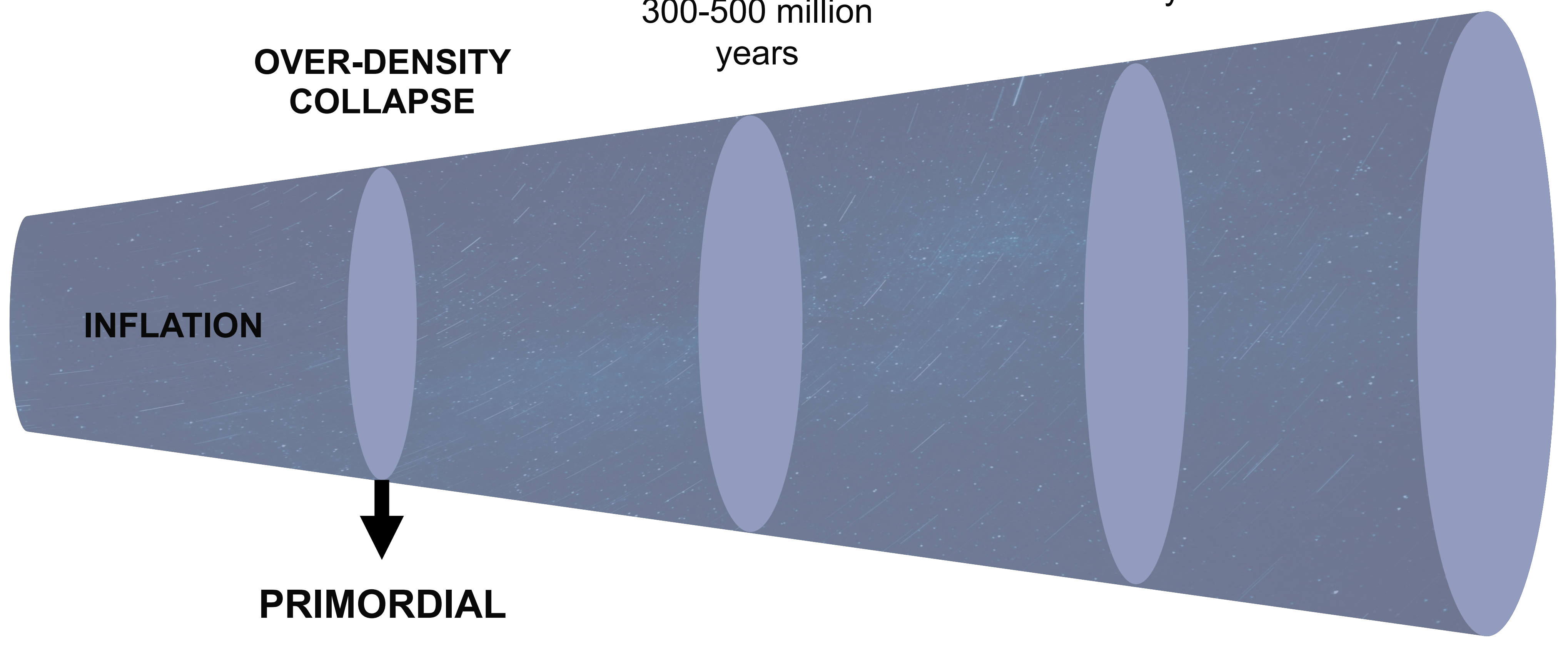
Based on PRD 107.123537 and on PRD 109.103001 in collaboration with R. Calabrese,M. Chianese, J. Gunn, G. Miele, S. Morisi

INVISIBLES24

4 July 2024

Genesis of Primordial Black Holes

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



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)

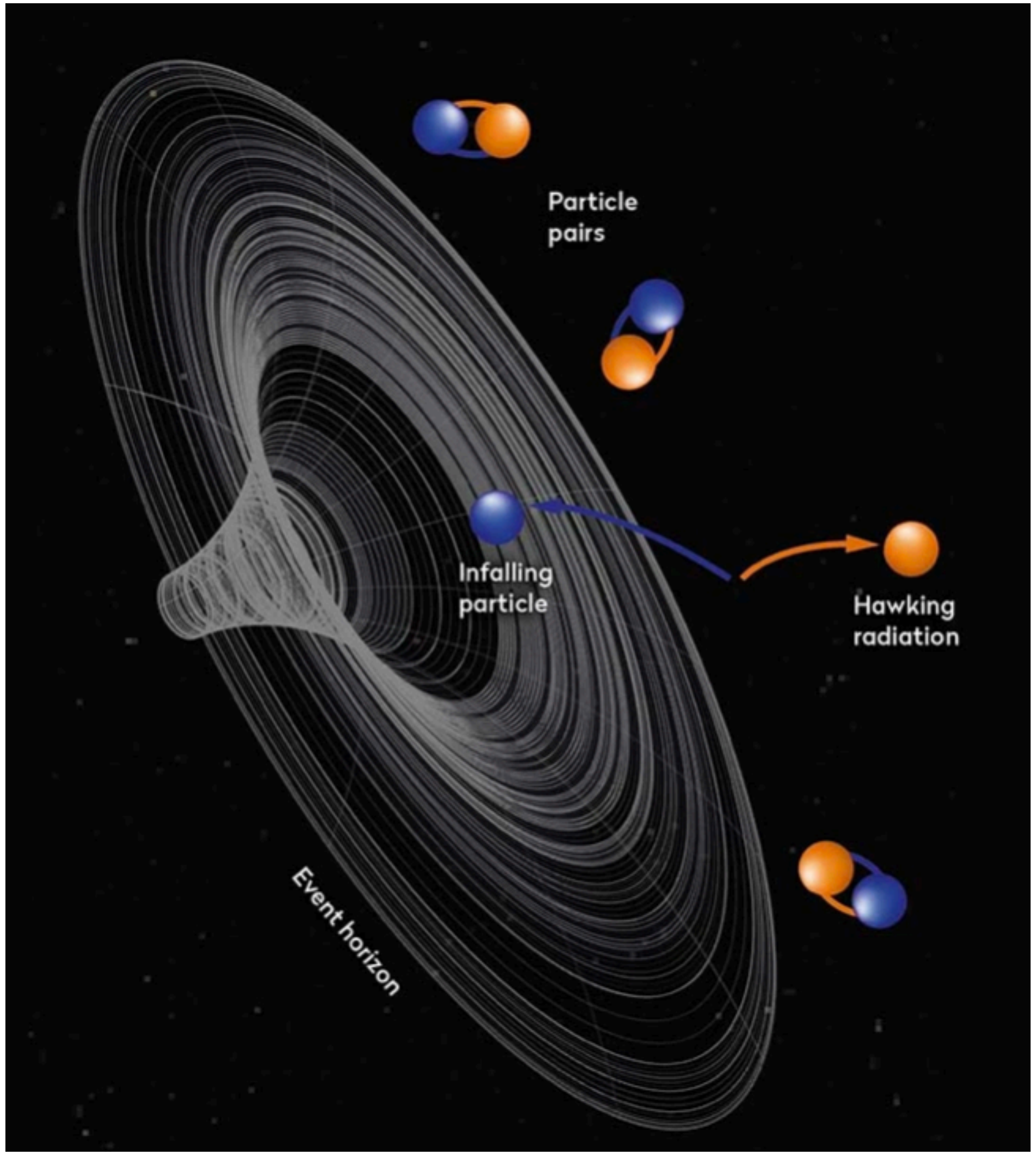
Properties of PBHs

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

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

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:

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

Surface gravity

for neutral and non-rotating BHs

✦ **Emission of all the elementary particles with $m \leq T_{\rm BH}$**

✦ The evaporation lifetime is: $\tau_{\rm BH} \approx 4.07 \times 10^{17} \left(\frac{M_{\rm BH}}{10^{15}\ {\rm g}}\right)^3 {\rm s}$

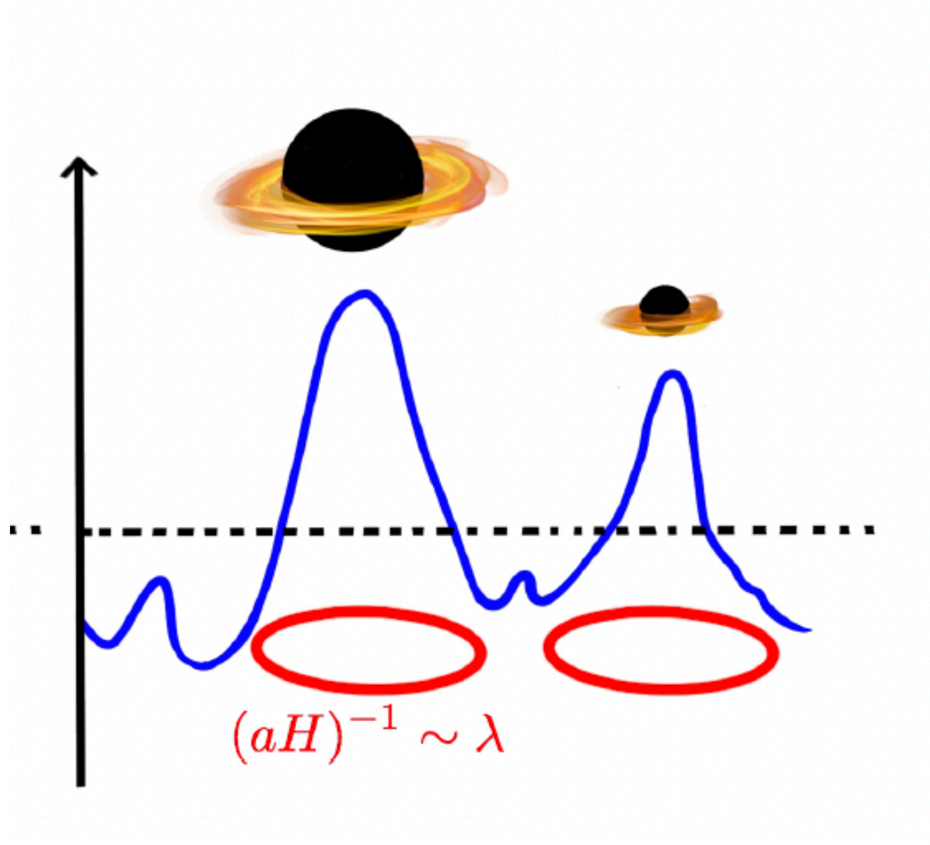
✦ **The lower the PBH mass, the earlier it evaporates**

✦ Negligible and undetectable for astrophysical black holes!

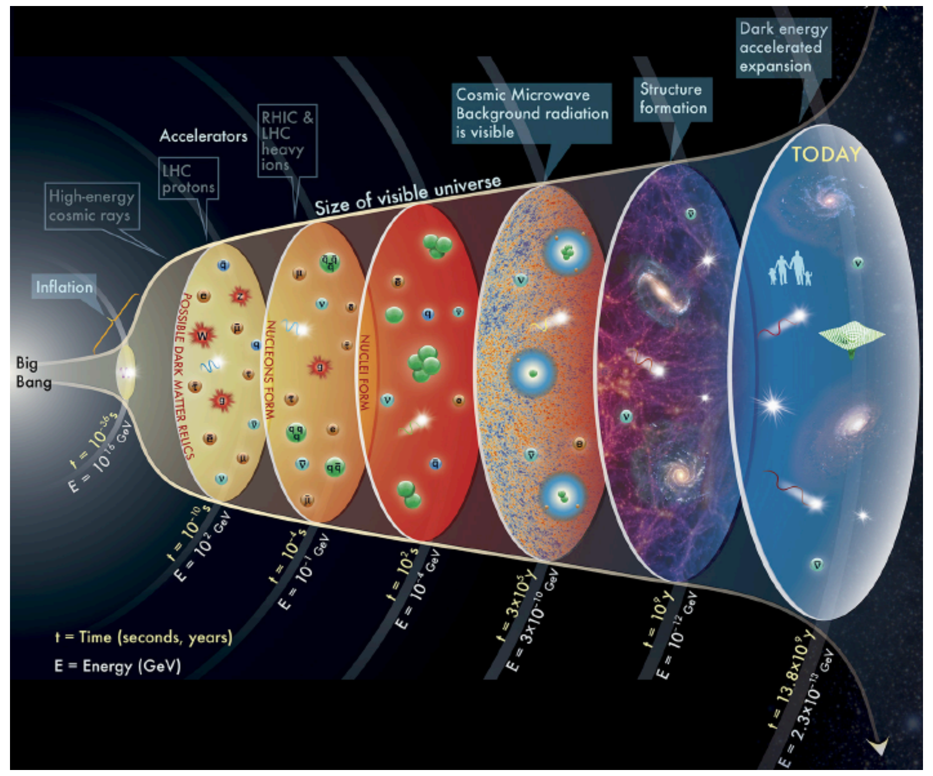
Hawking, Nature 248 (1974); Carr, ApJ. 206 (1976);
Hawking, Comm. Math. Phys. 43 (1976); Page, PRD 13 (1976)

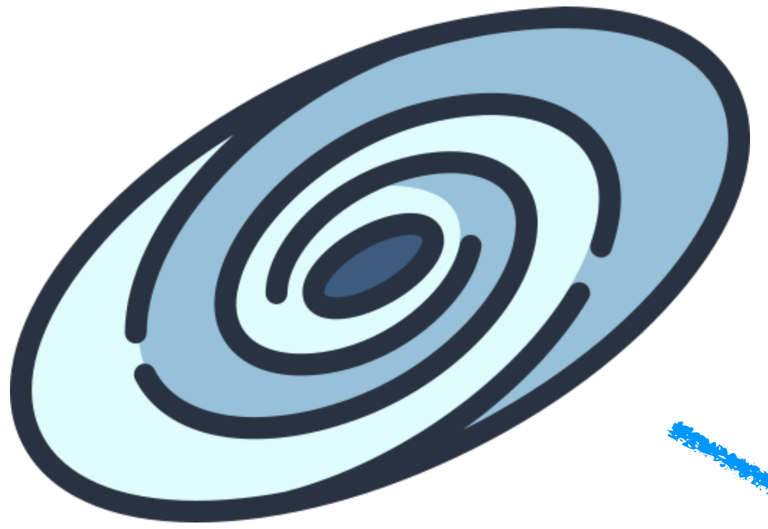
Current big interest in PBHs

Formation mechanism

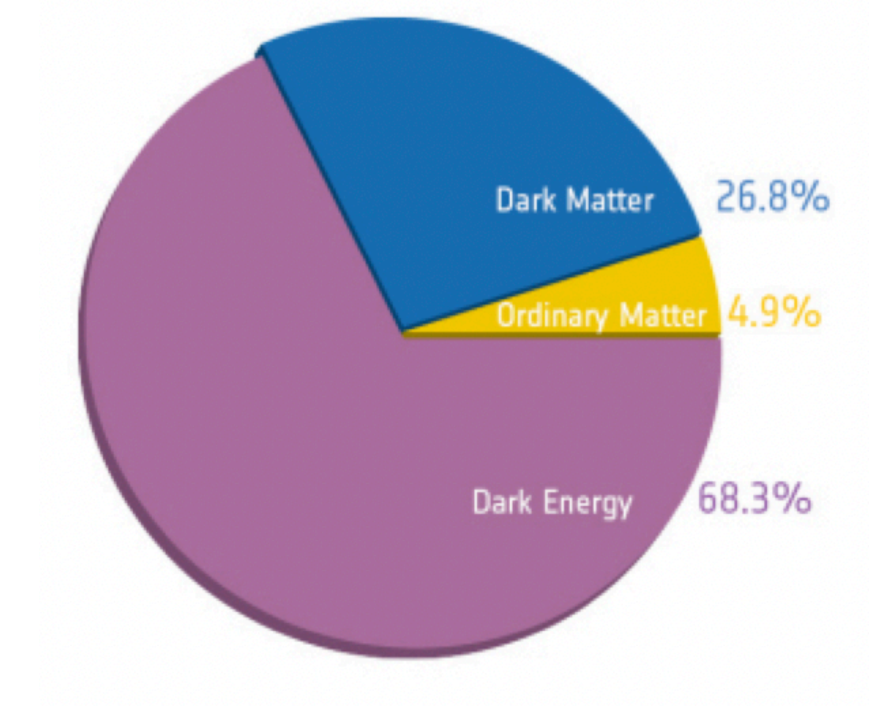


Early Universe

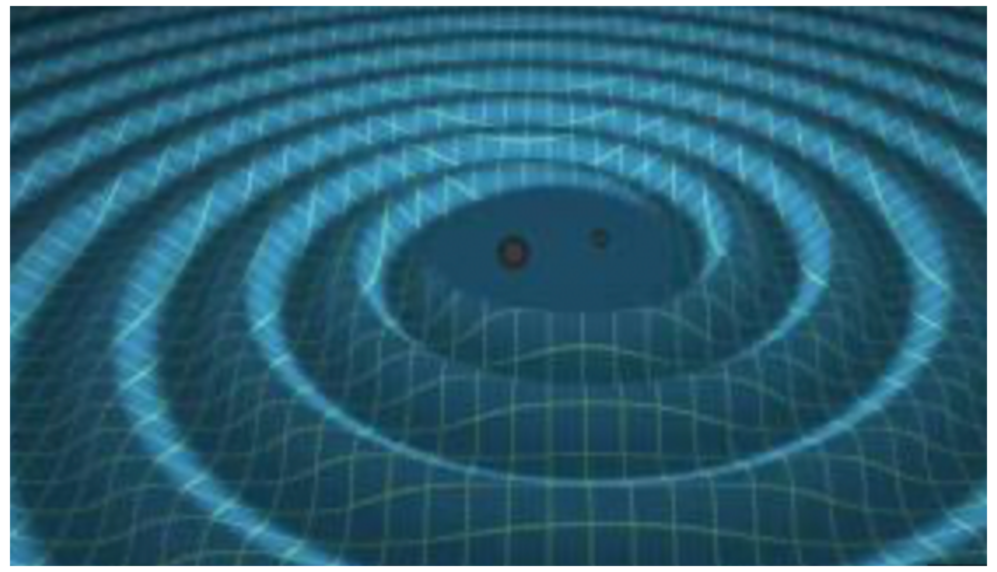




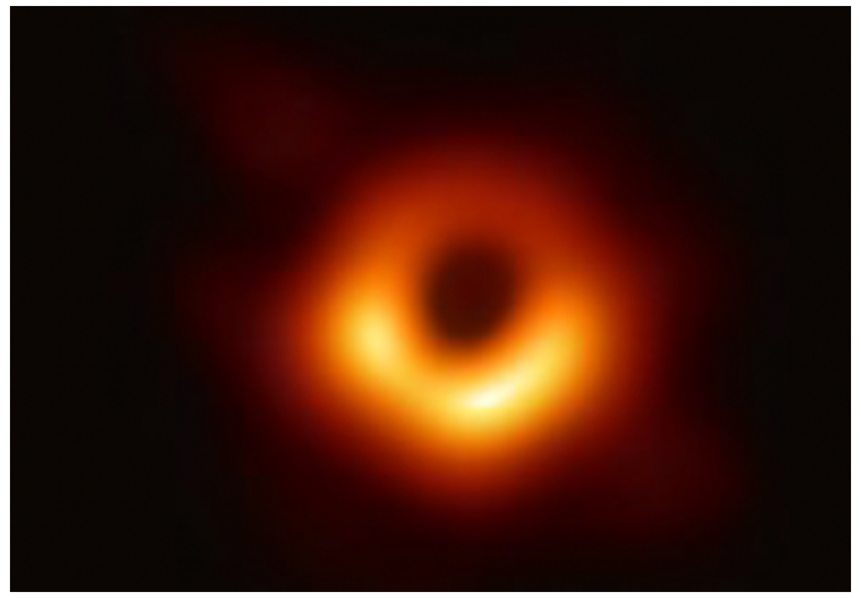
Dark Matter



Gravitational waves



Astrophysical issues



Current big interest in PBHs

Formation mechanism

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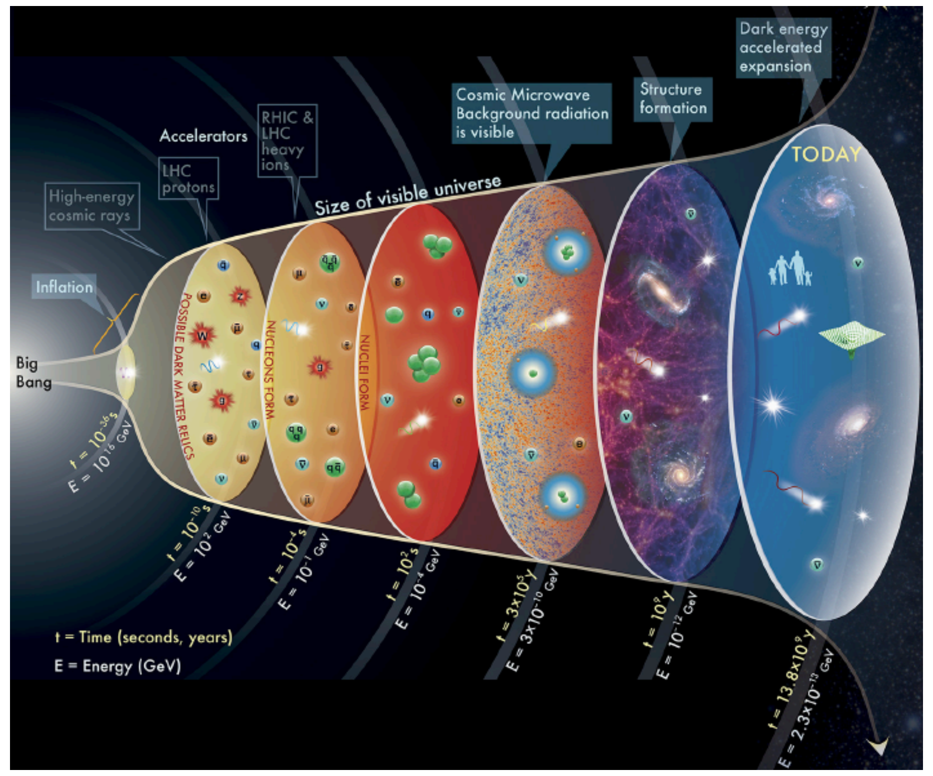
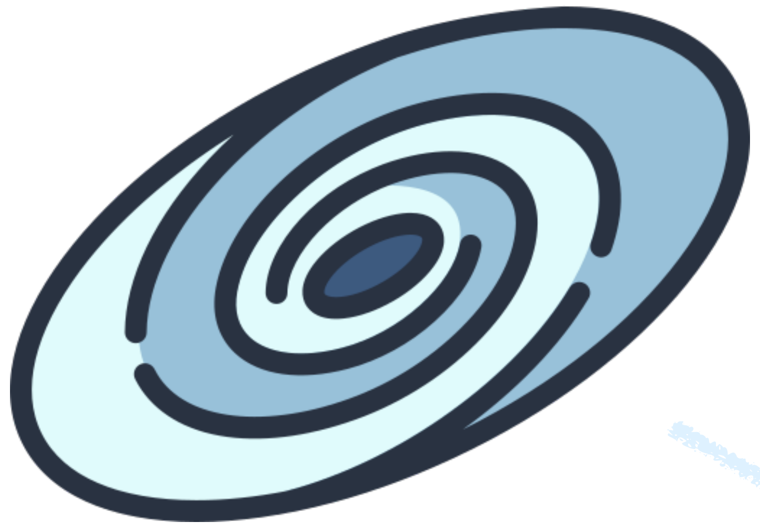


In this talk: Leptogenesis



Dark Matter

Gravitational waves

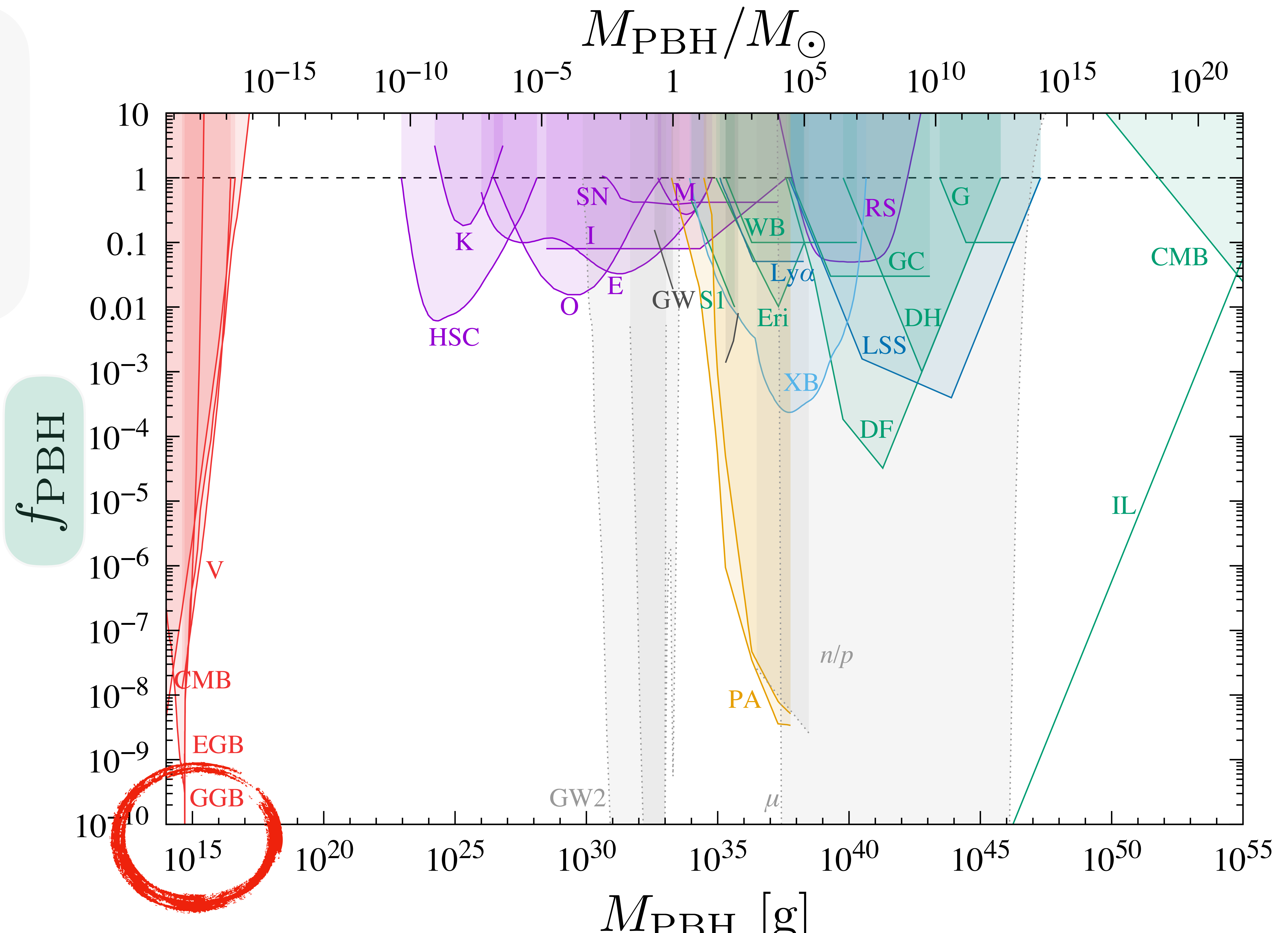
Astrophysical issues

PBH constraints

- Lensing
- Accretion
- CMB distortions
- LSS
- Dynamical effects
- Gas
- Evaporation

PBH today abundance

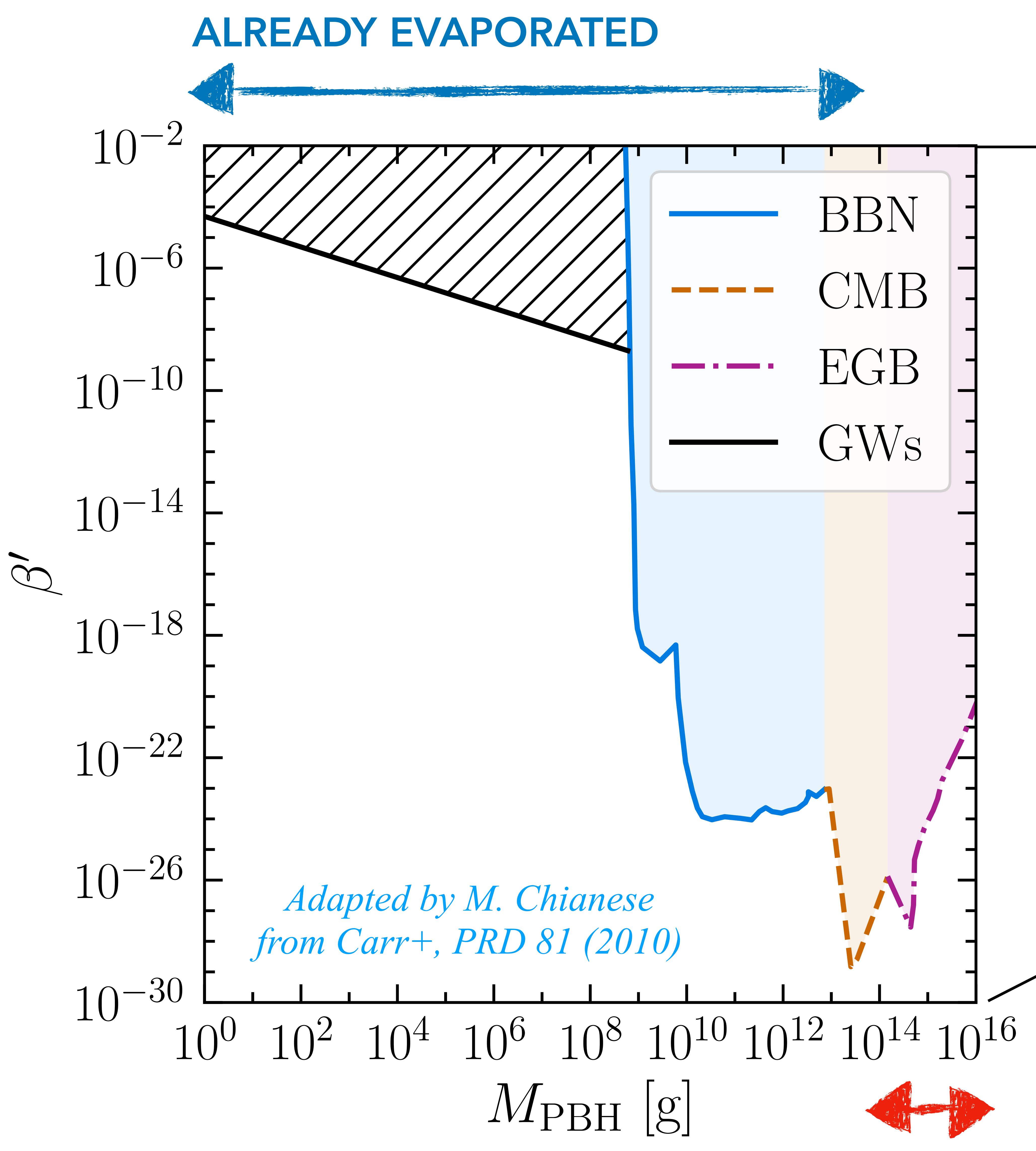
$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}}$$

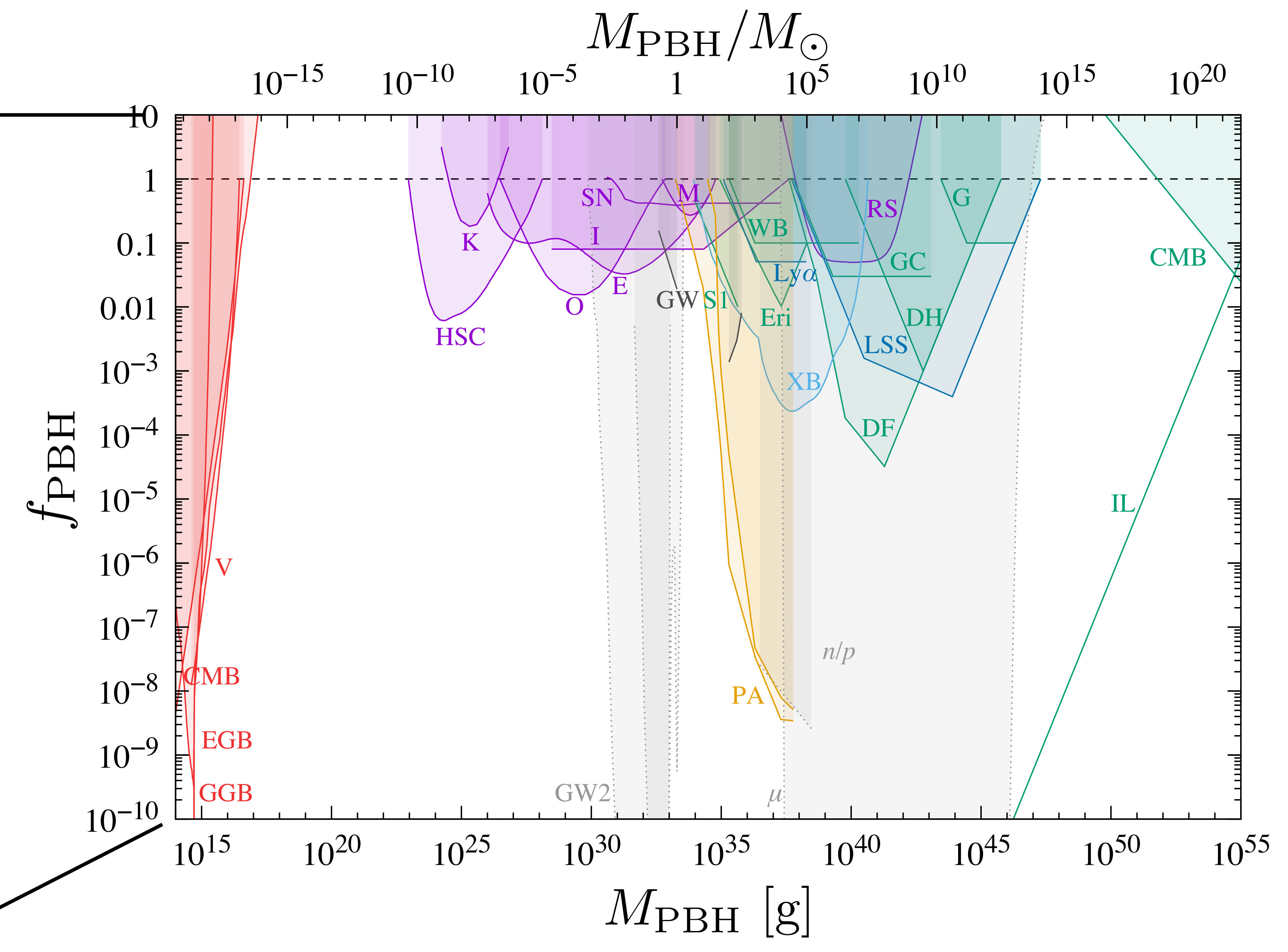


EVAPORATING NOW

$f_{\rm PBH} = 1$	$f_{\rm PBH} < 1$
PBHs are all the DM	PBHs are DM-subcomponent

PBH constraints

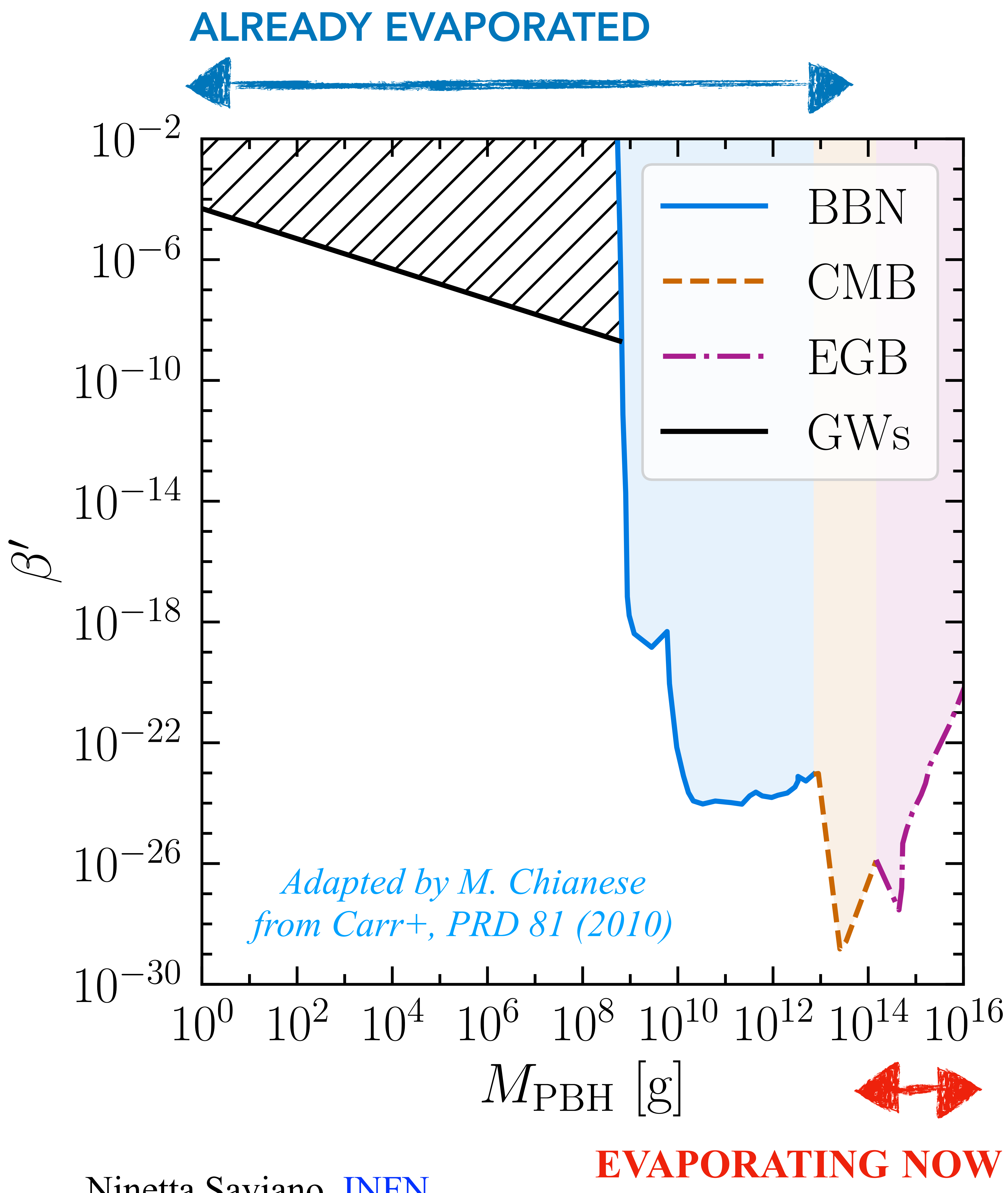




PBH cosmological abundance

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

PBH constraints



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

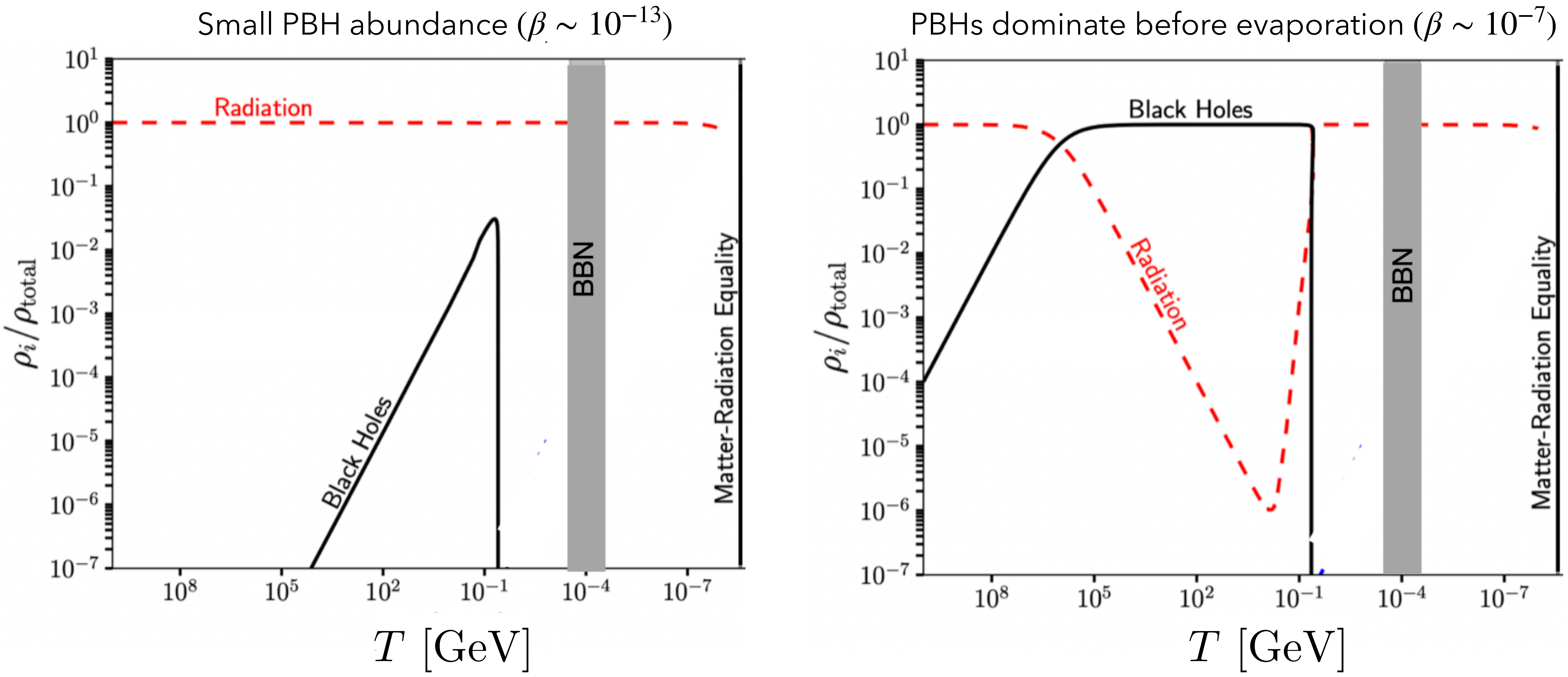
$$\beta'(M_{\rm PBH}) = \gamma^{1/2}\,\frac{\rho_{\rm PBH}(T_{\rm form})}{\rho_R(T_{\rm form})}$$

IN THIS TALK

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

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

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

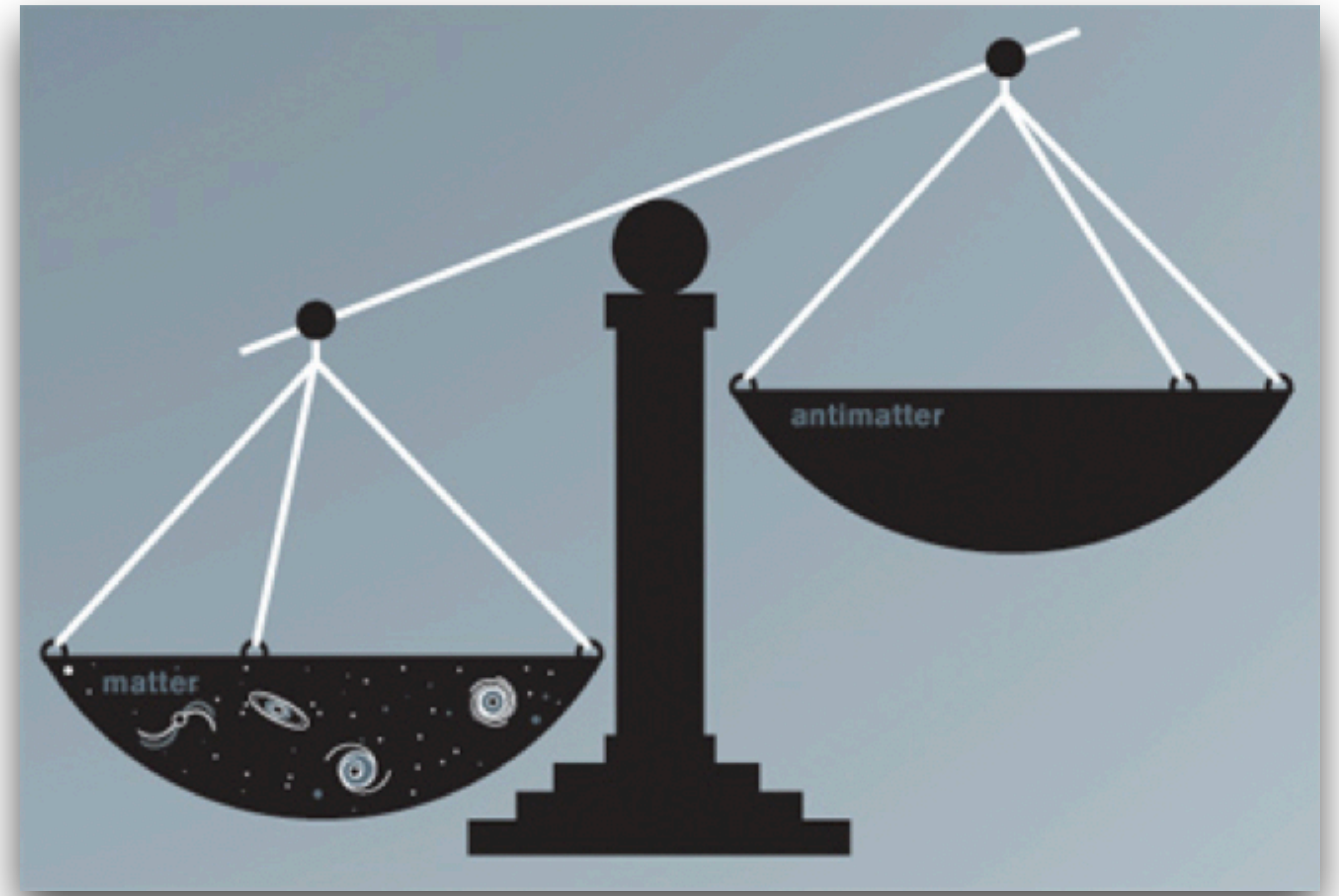
inferred independently by BBN and CMB (see PLANCK coll.)

$\longleftrightarrow$

SAKHAROV CONDITIONS

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

Present in the SM, but not sufficient…



Baryogenesis

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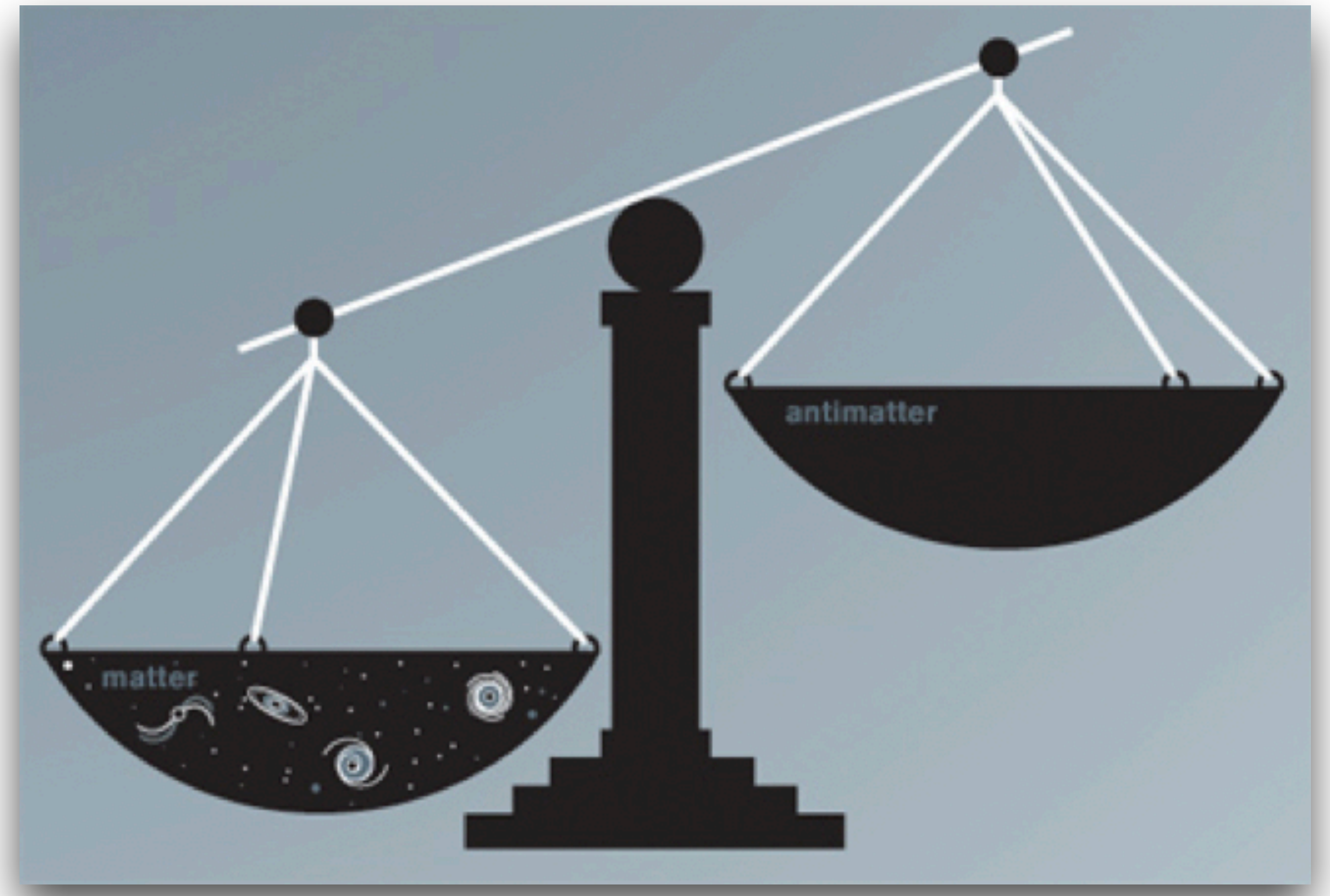
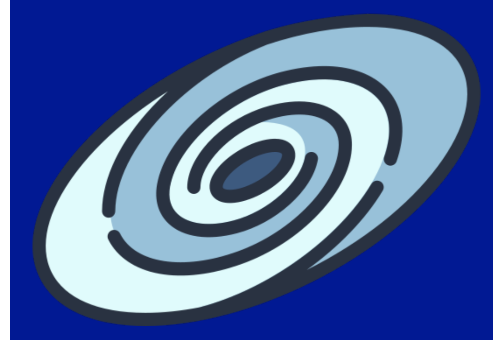


The democratic feature of PBHs can also lead to observed matter antimatter asymmetry.



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

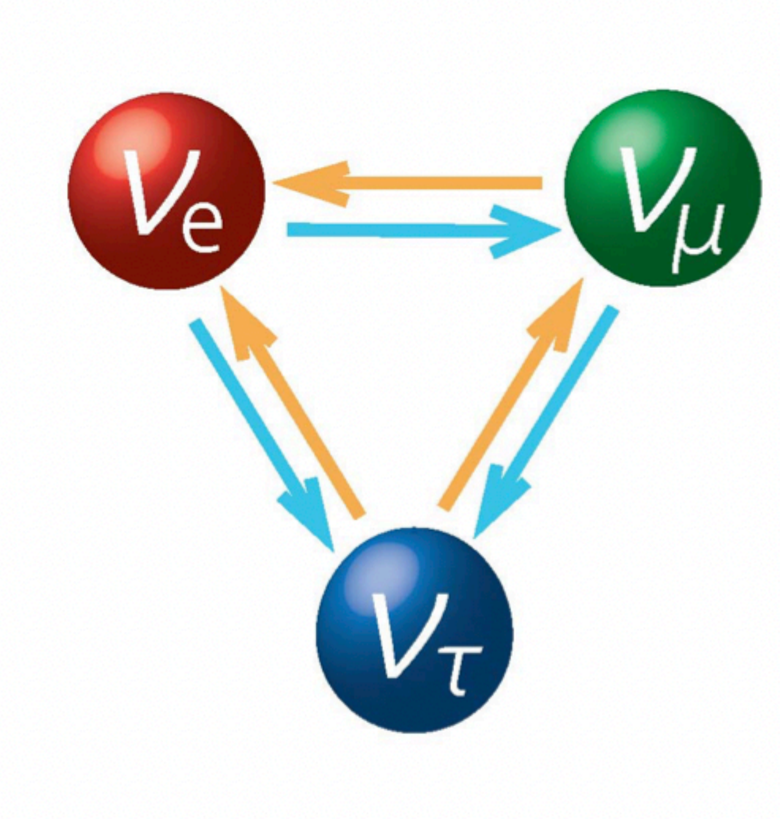
Simple and elegant explanation of the cosmological matter-antimatter asymmetry

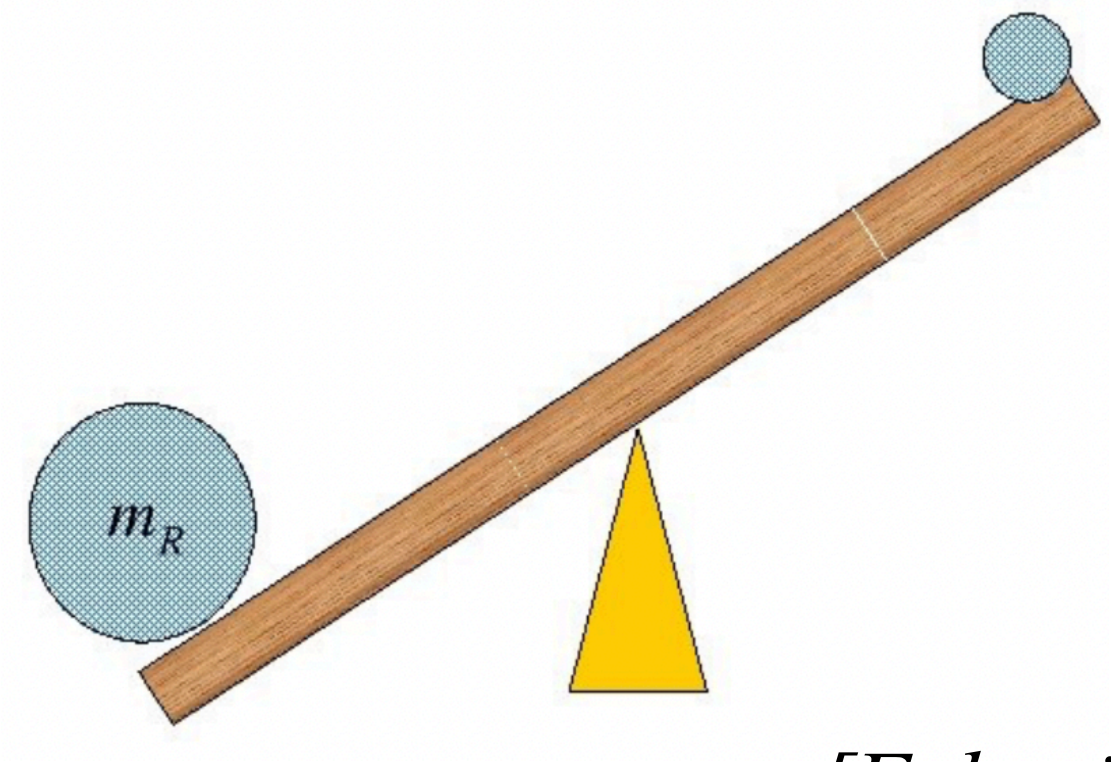
The seesaw Lagrangian naturally satisfies the Sakharov conditions in the leptonic sector!

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

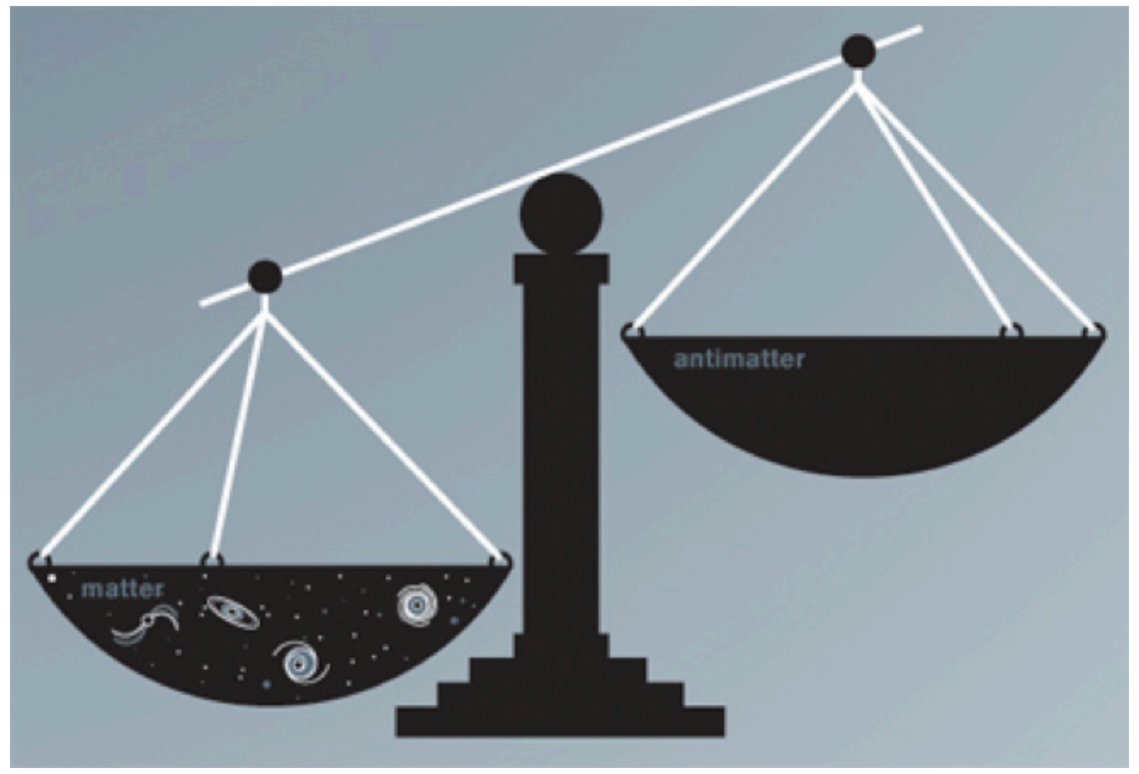
Right-Handed Neutrinos (RHNs)

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





[Fukugita, Yanagida '86]



Leptogenesis landscape

$\mathcal{O}(1\ \text{GeV})$ $\mathcal{O}(10^3\ \text{GeV})$ $\mathcal{O}(10^6\ \text{GeV})$ $\mathcal{O}(10^{12}\ \text{GeV})$ → 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) , P. Hernández et al. (2015)…

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); Roulet[1], Covi and Vissani (1997) 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)

Leptogenesis landscape

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

M_R

Leptogenesis via oscillations

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Resonant Leptogenesis

+ PBHs

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

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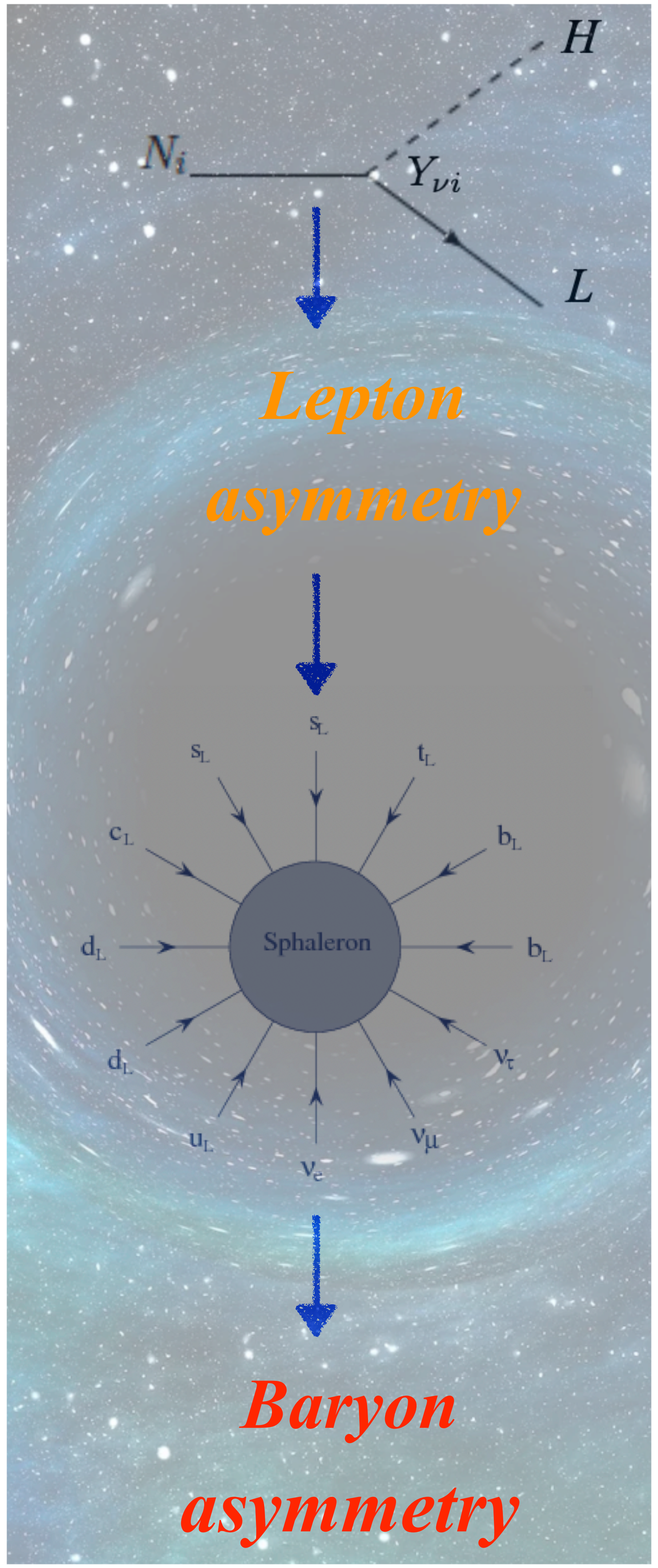
Calabrese, Chianese, Gunn, Miele, Morisi, Saviano, ***PRD 107.123537 (2023)***

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 & PBH



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

ADDITIONAL NON-THERMAL SOURCE TERM

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

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

contribution from thermal plasma — *contribution from PBH evaporation*

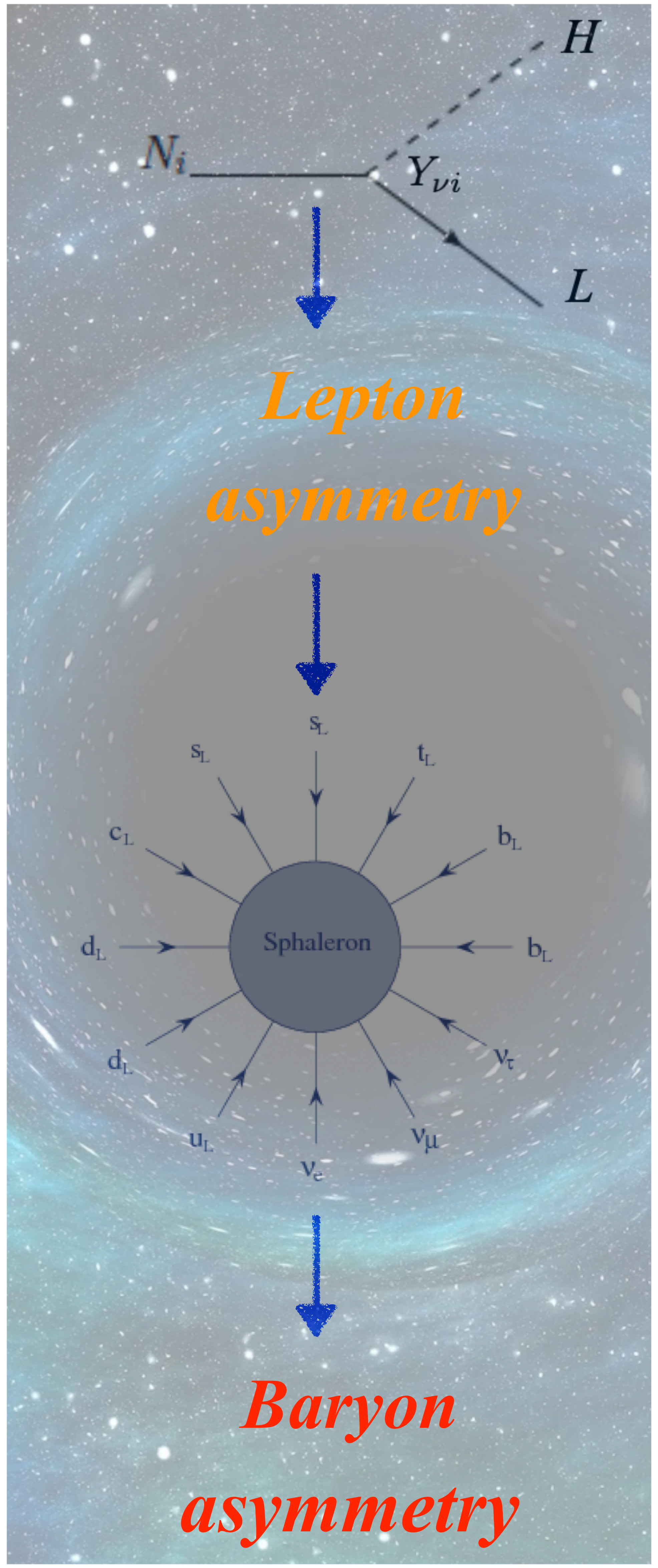
Studied for $M_{\mathrm{PBH}} < 10^5$ g in:
Perez-Gonzalez+, PRD 104 (2021), Bernal+, PRD 106 (2022)

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

Leptogenesis & PBH



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

ADDITIONAL NON-THERMAL SOURCE TERM

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

contribution from thermal plasma — contribution from PBH evaporation

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ENTROPY INJECTION

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

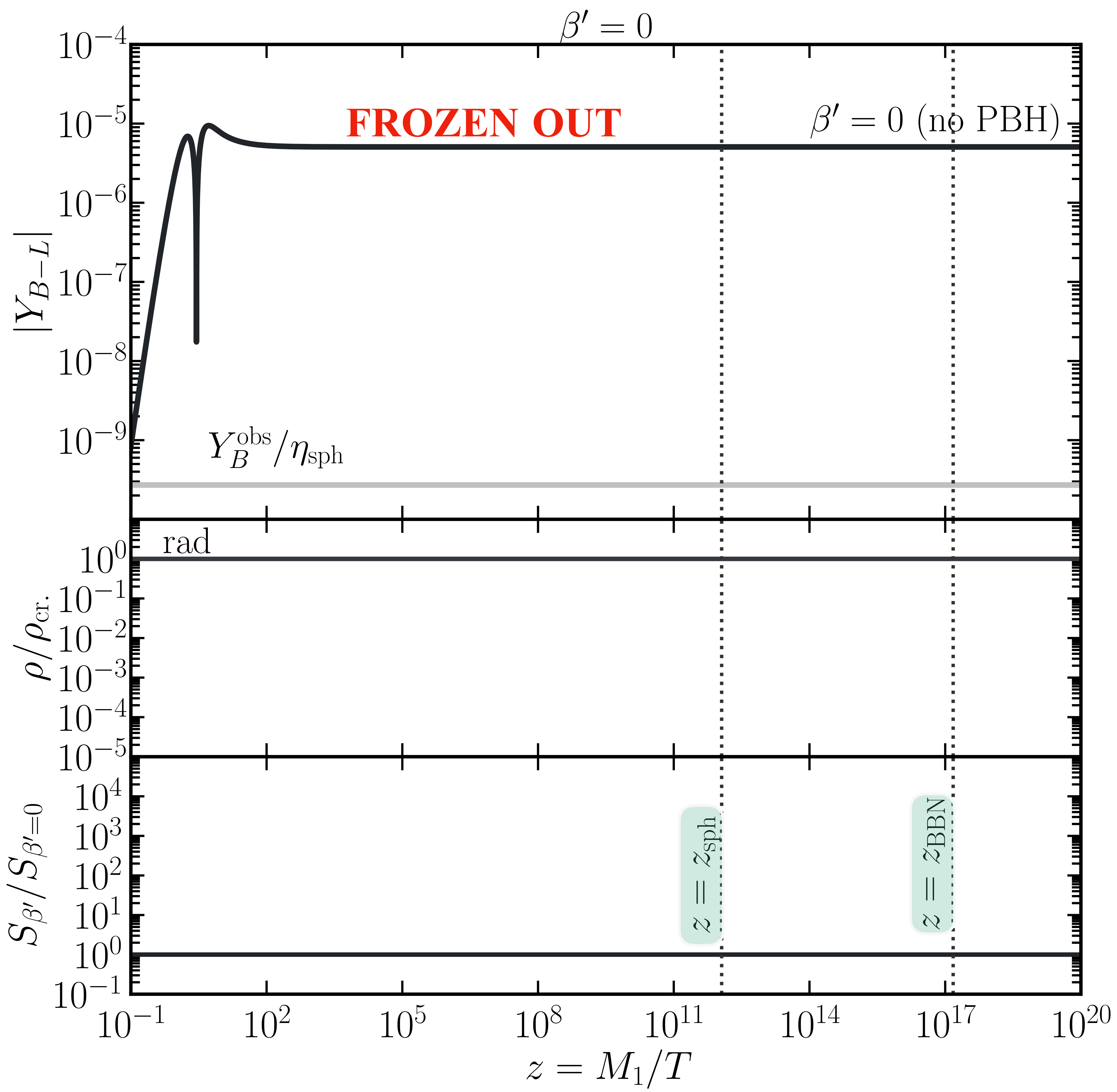
Dilution of any pre-existing relic at evaporation

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

- ✦ 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/ NS), **PRD 107.123537 (2023)***

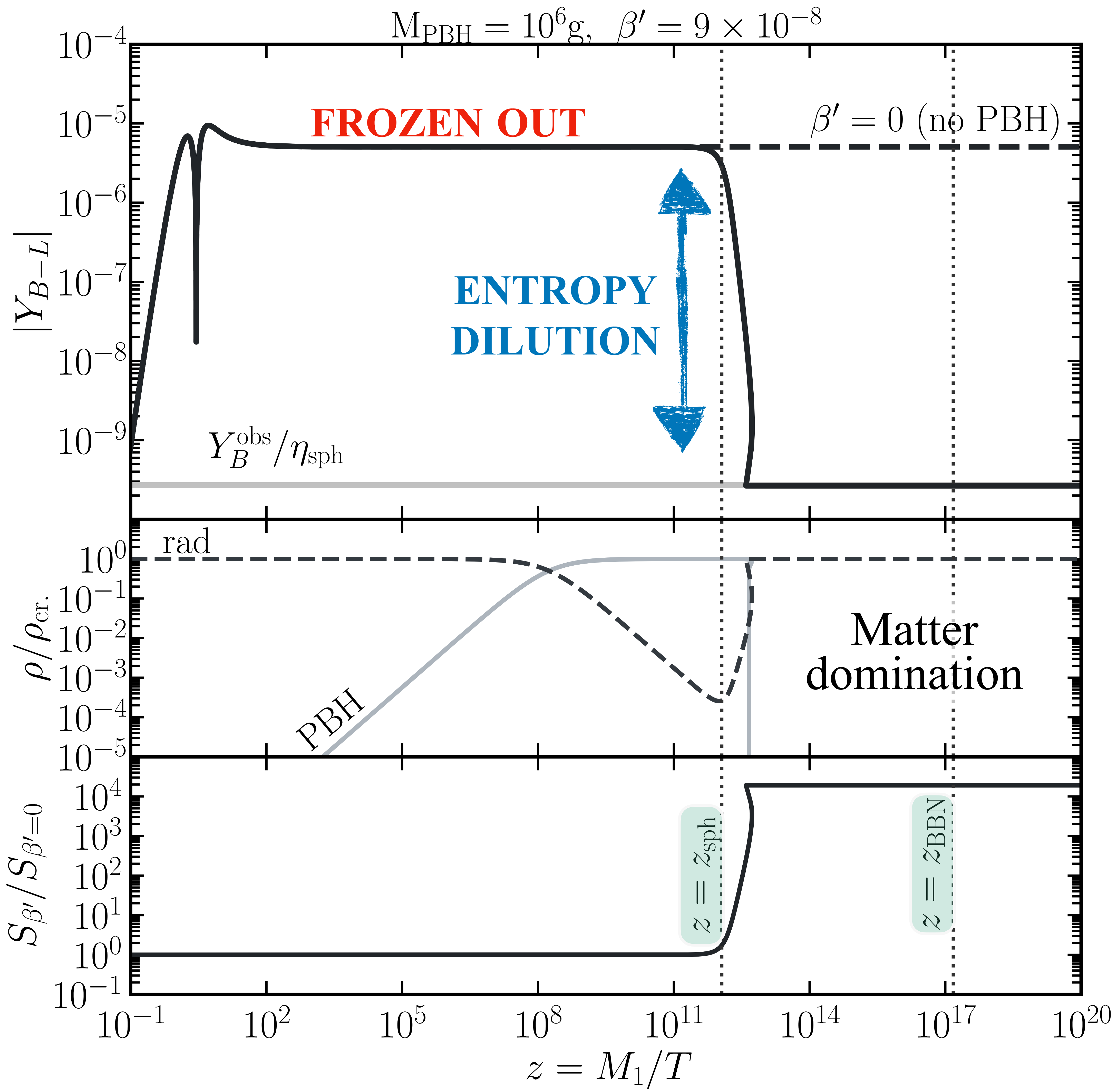


STANDARD LEPTOGENESIS SCENARIO

- ✦ 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/ NS), ***PRD 107.123537 (2023)***

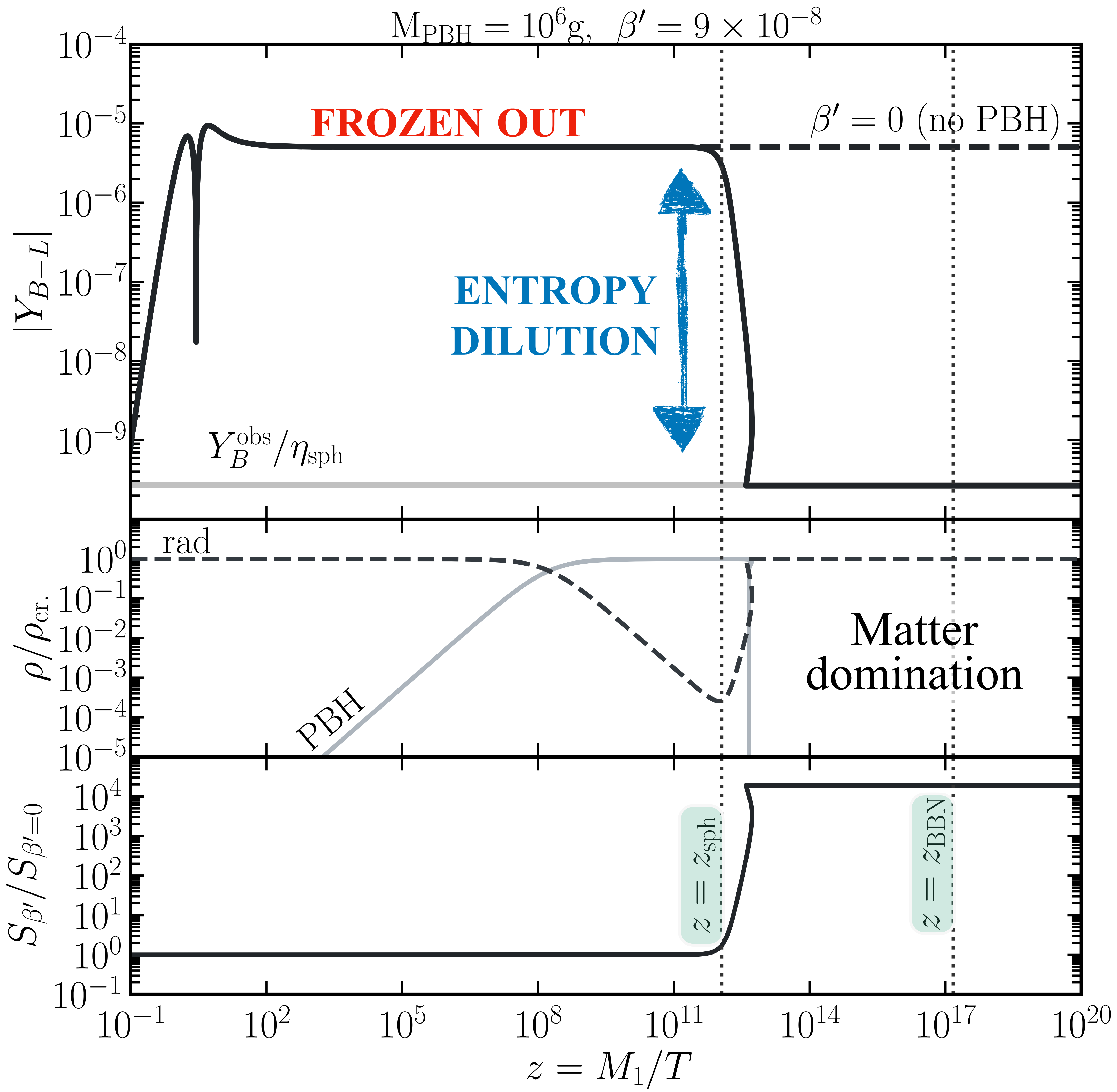


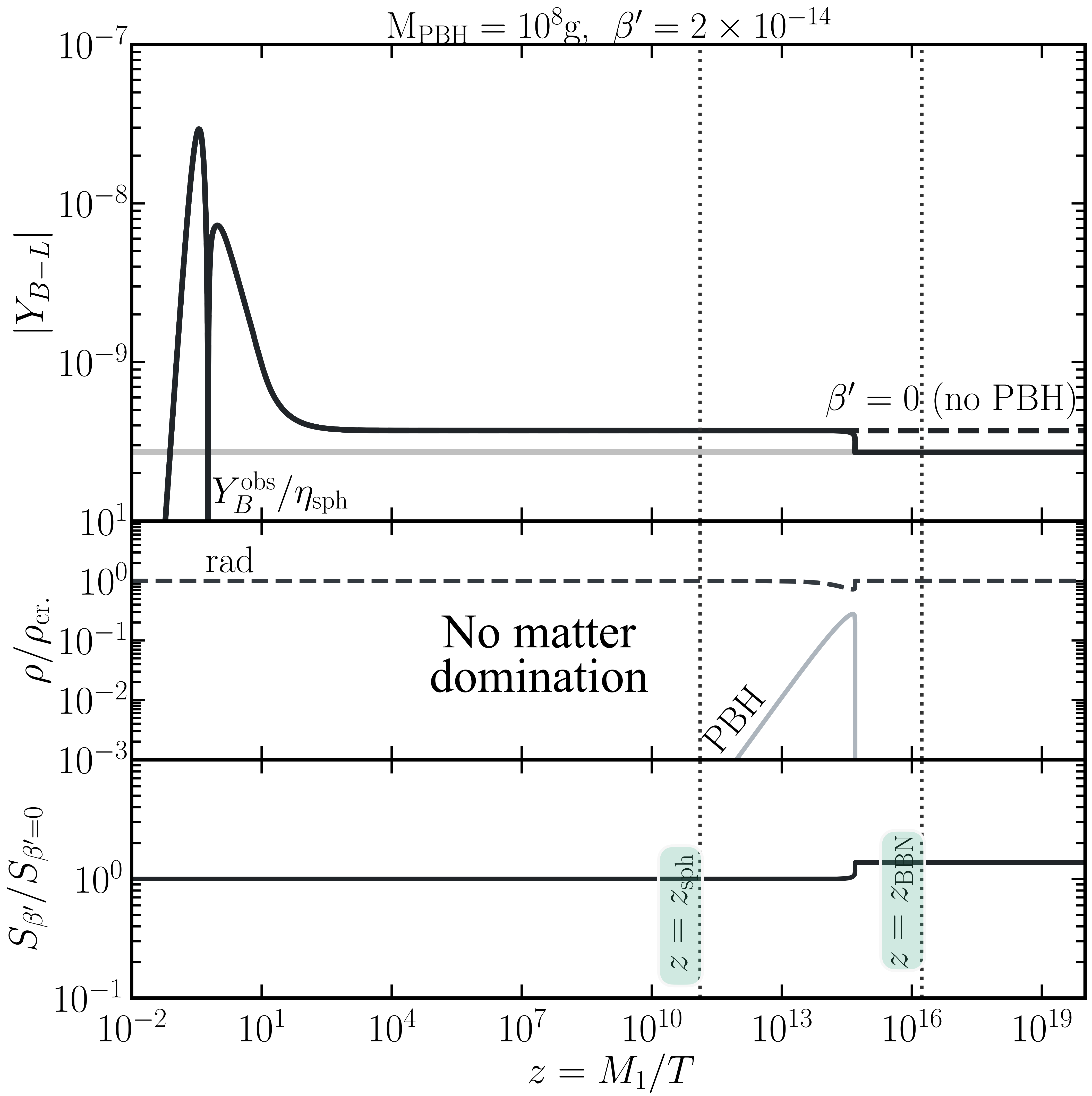
PBH-MODIFIED LEPTOGENESIS SCENARIO

- ✦ 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/ 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 $\mathcal{L} \supset -Y_{\alpha i}\overline{L}_\alpha \tilde{\phi} N_i - \frac{1}{2}\overline{N_i^C} M_{ij} N_j + \text{h.c.}$ ⟶ $m_\nu \simeq -v^2 Y \frac{1}{M} Y^T$

✦ 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 $\Delta m^2_{\text{sun}} \ll \Delta m^2_{\text{atm}}$ ⟶ the only phase in R is $z_{13} = x + i\, y$

Our models for thermal leptogenesis

- Type-1 seesaw $\mathcal{L} \supset -Y_{\alpha i}\overline{L}_\alpha \tilde{\phi} N_i - \frac{1}{2}\overline{N_i^C} M_{ij} N_j + \text{h.c.}$ ⟶ $m_\nu \simeq -v^2 Y \frac{1}{M} Y^T$
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- Normal ordering with $m_1 \simeq m_2$ since $\Delta m^2_{\text{sun}} \ll \Delta m^2_{\text{atm}}$ ⟶ 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 $m_h = m_3$

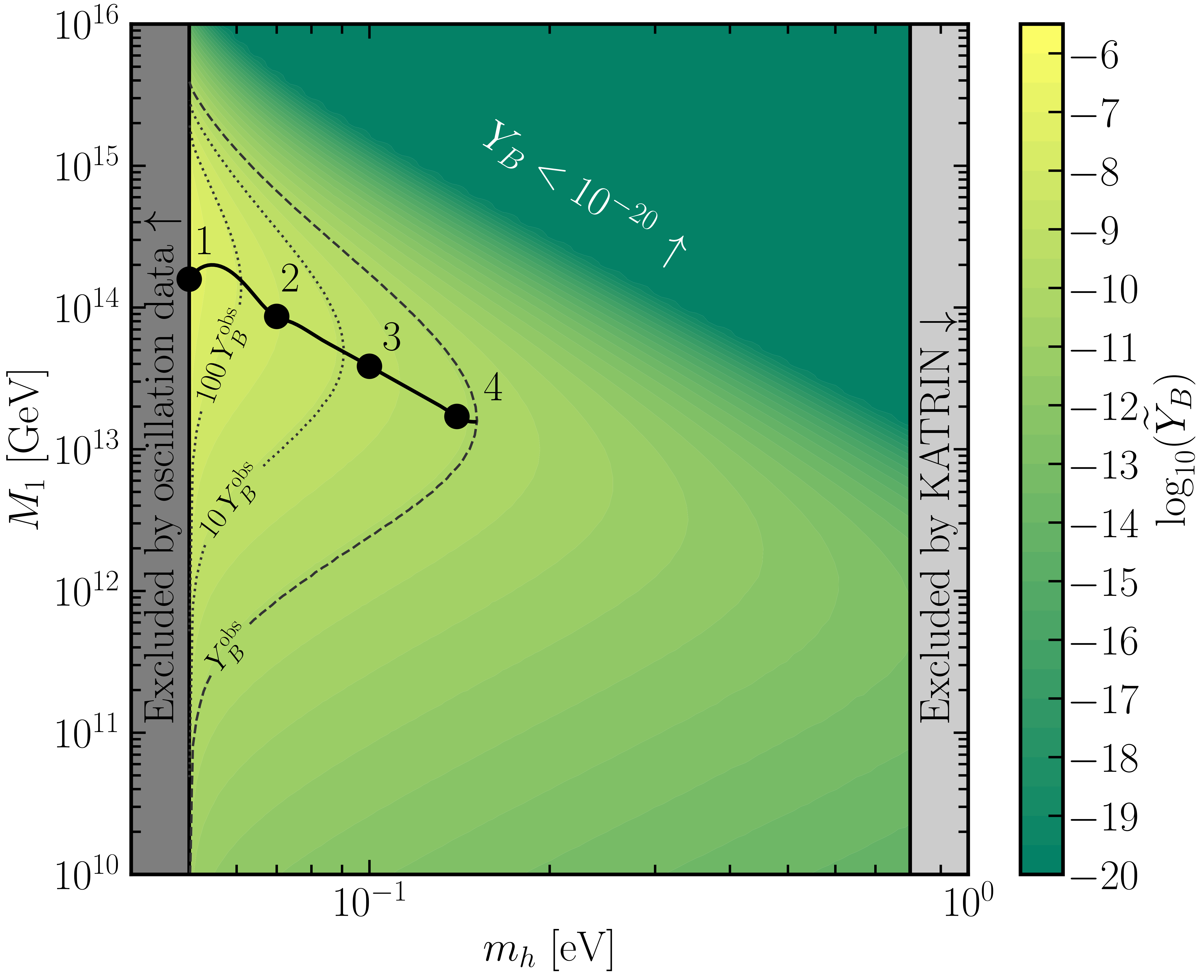
We scan the leptogenesis parameters to find the ones maximizing the baryon asymmetry!

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

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^{obs}

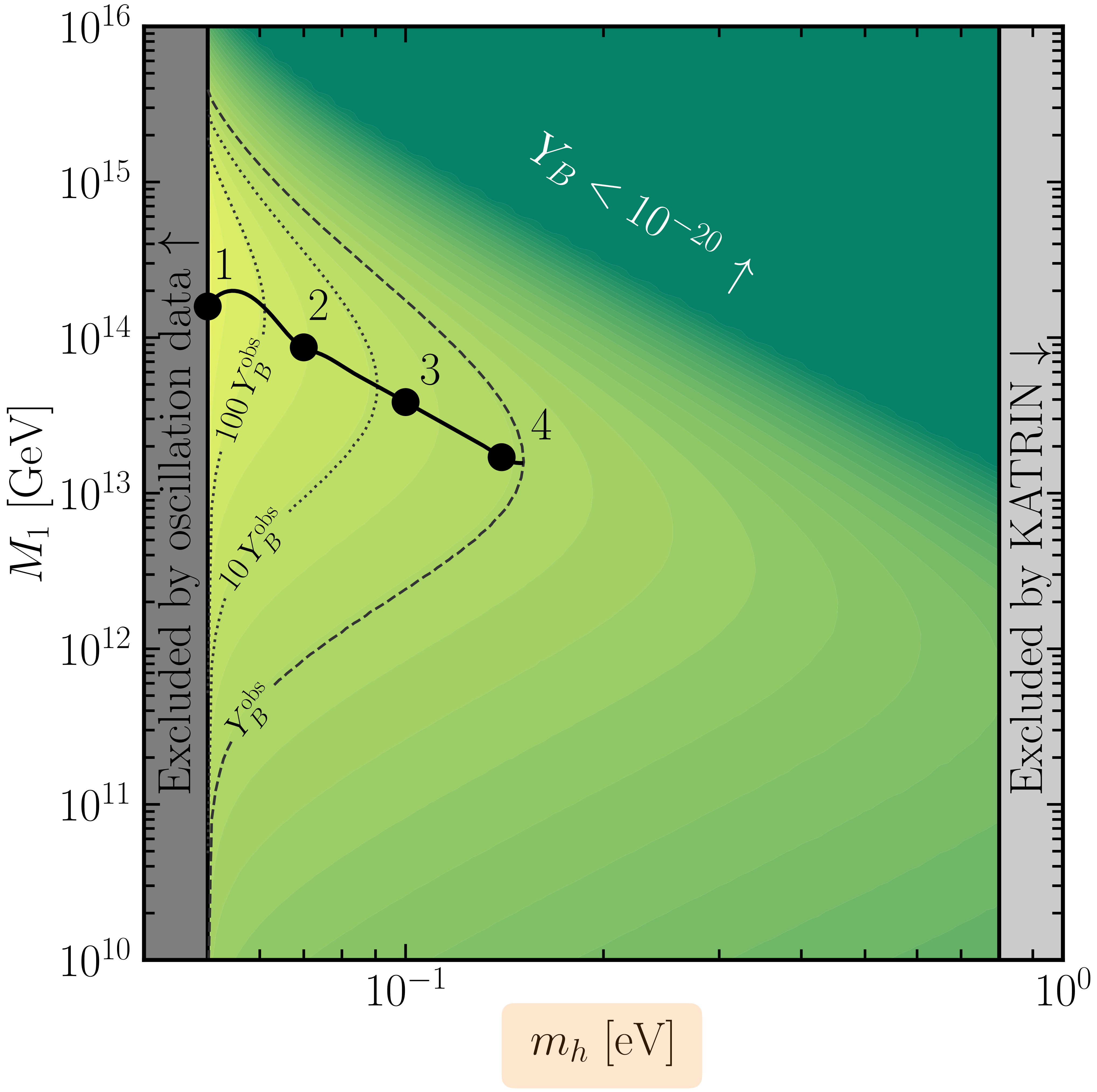
Solid line: contour maximizing the baryon asymmetry Y_B

For each value of M_1, the final baryon asymmetry increases for decreasing m_h.

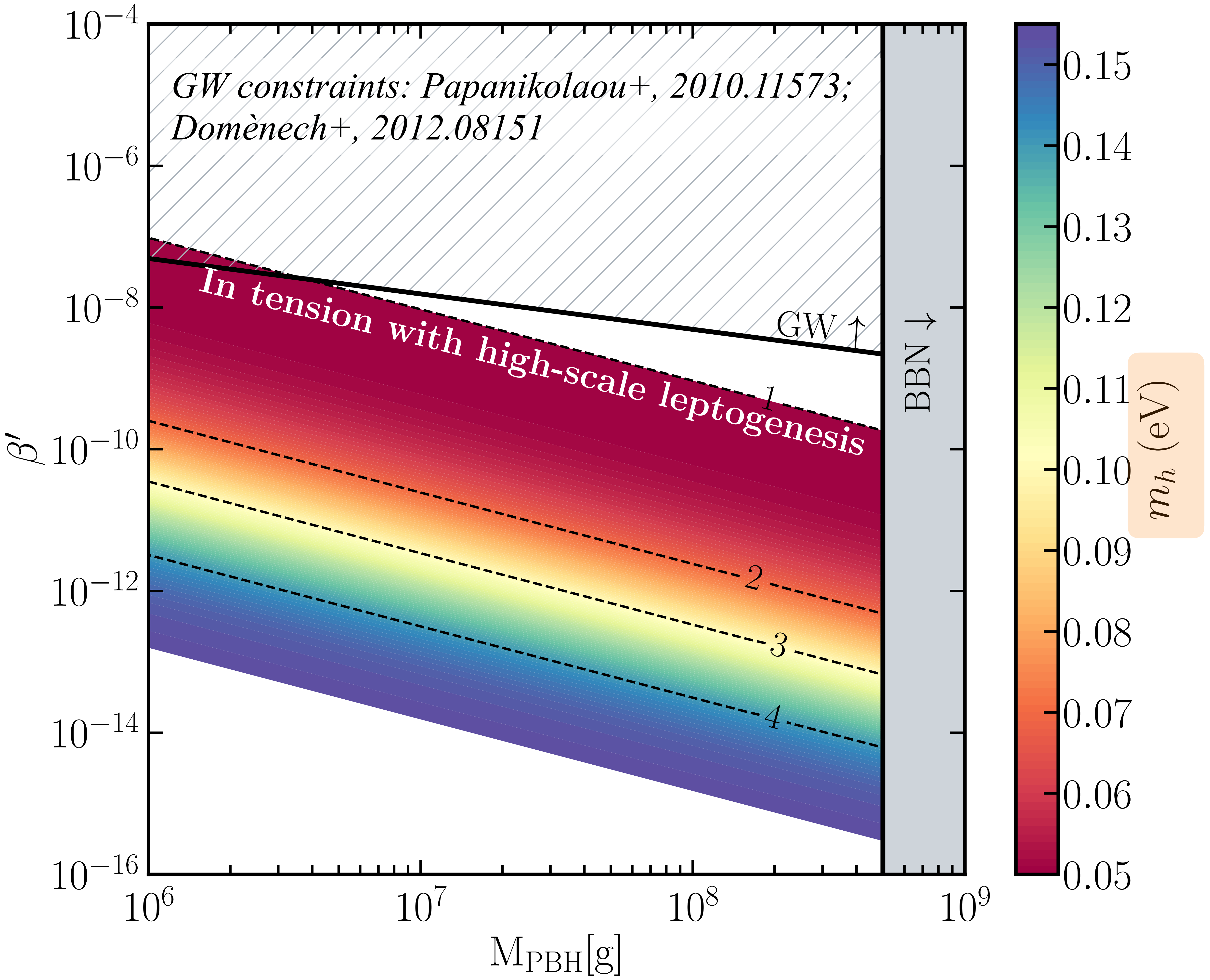
PBH-HTL constraints

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

Strong interplay with active neutrinos scale m_h



Mutual exclusion limits between PBHs and HTL

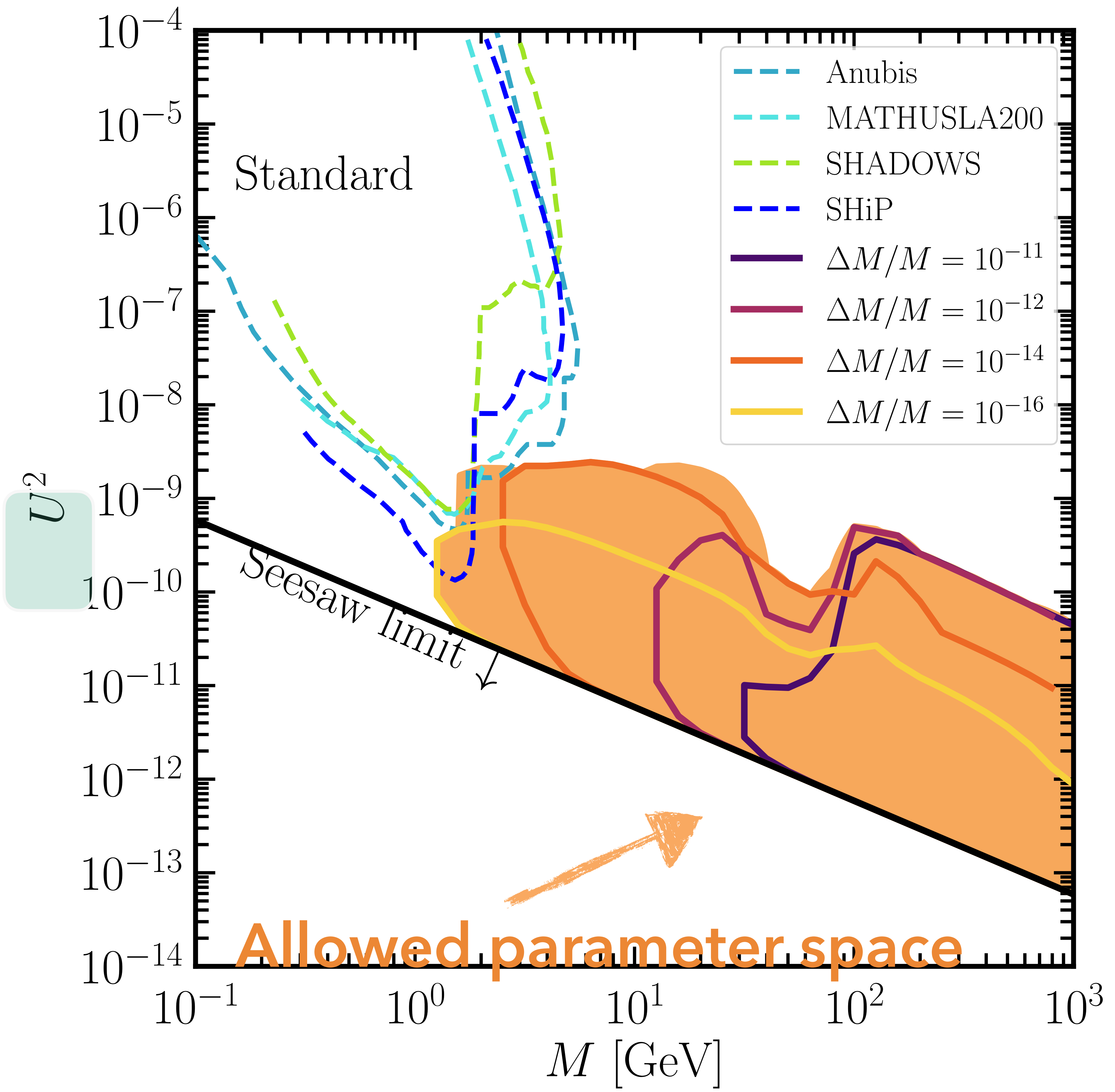


Higher the neutrino mass scale the stronger the constriants on PBH

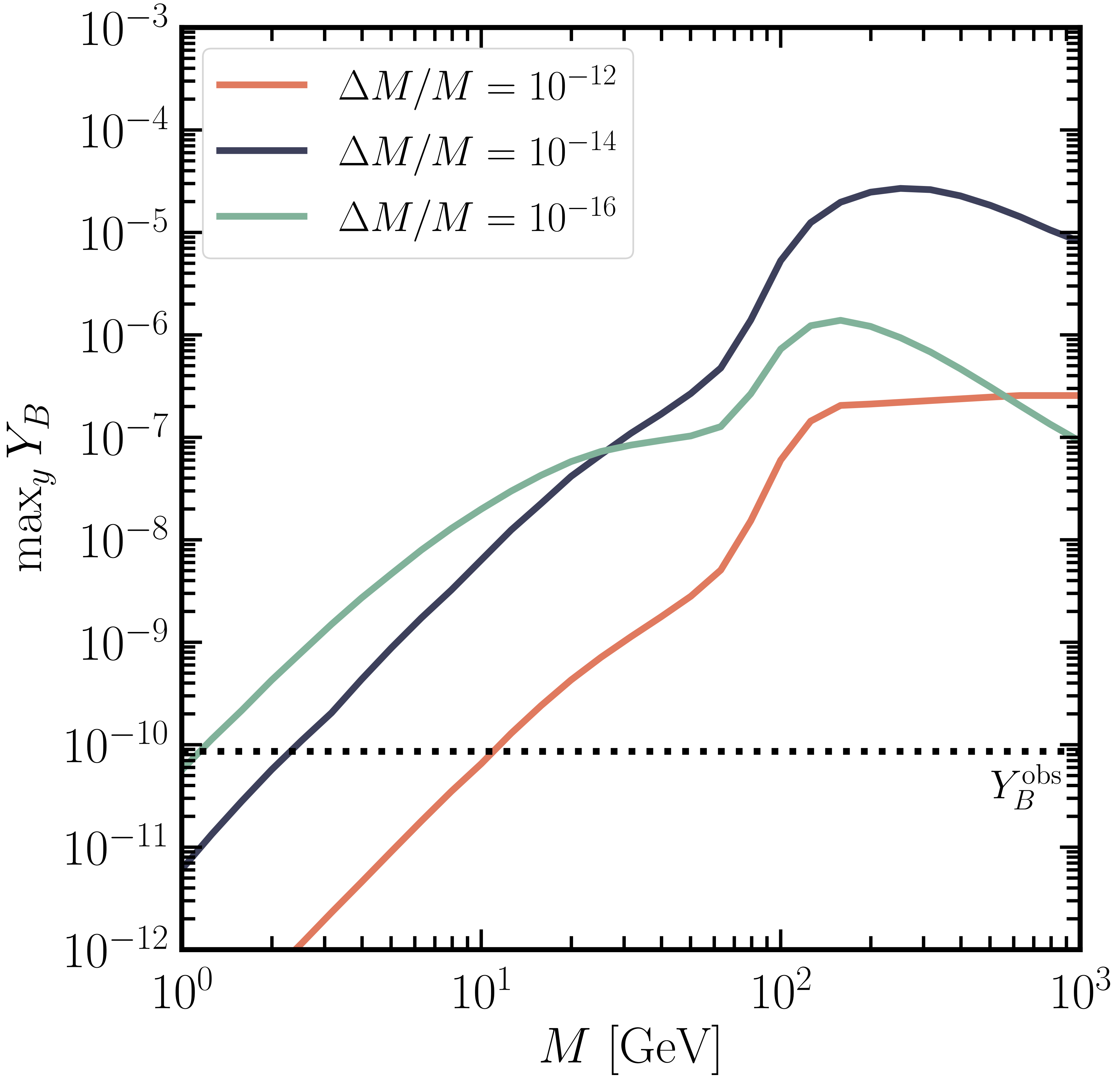
Resonant leptogenesis

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

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



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

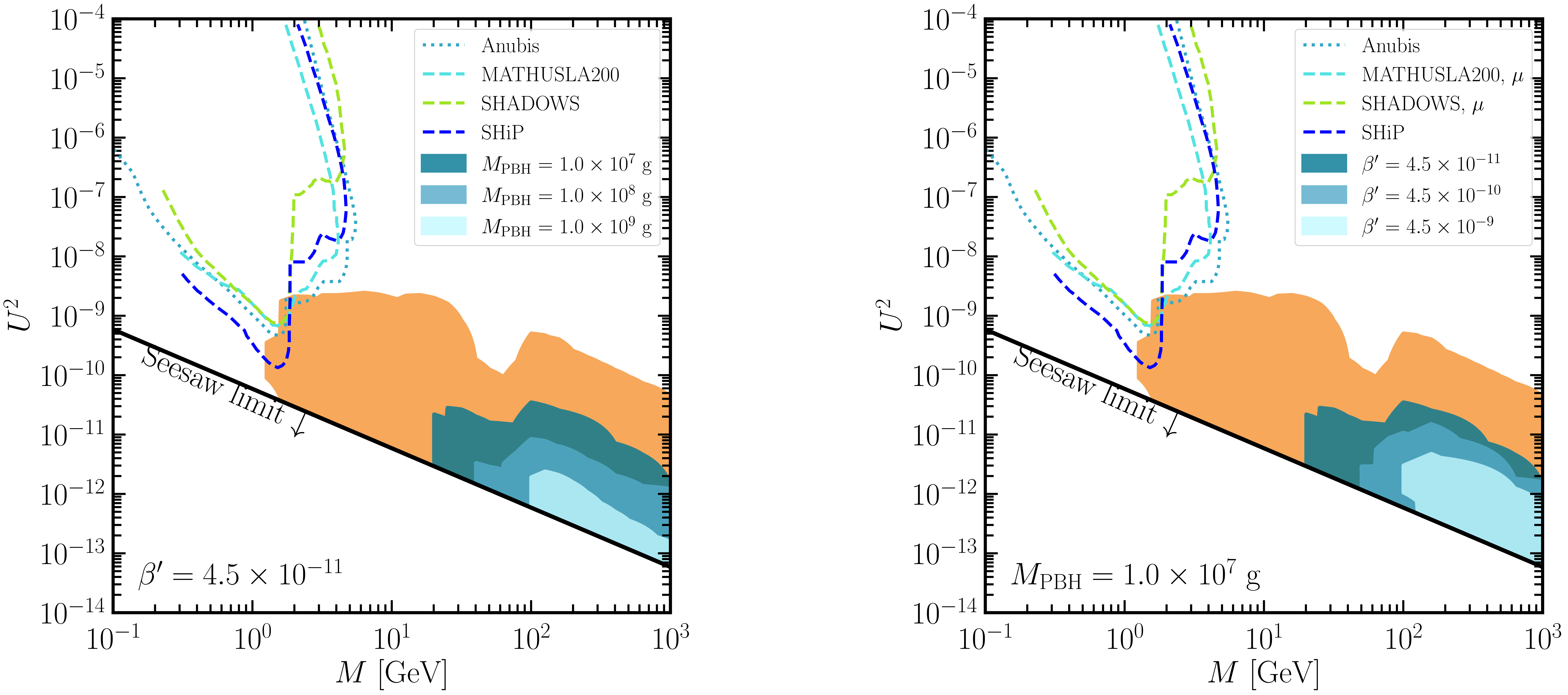


Maximum baryon asymmetry as a function of RHN mass

PBH impact

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

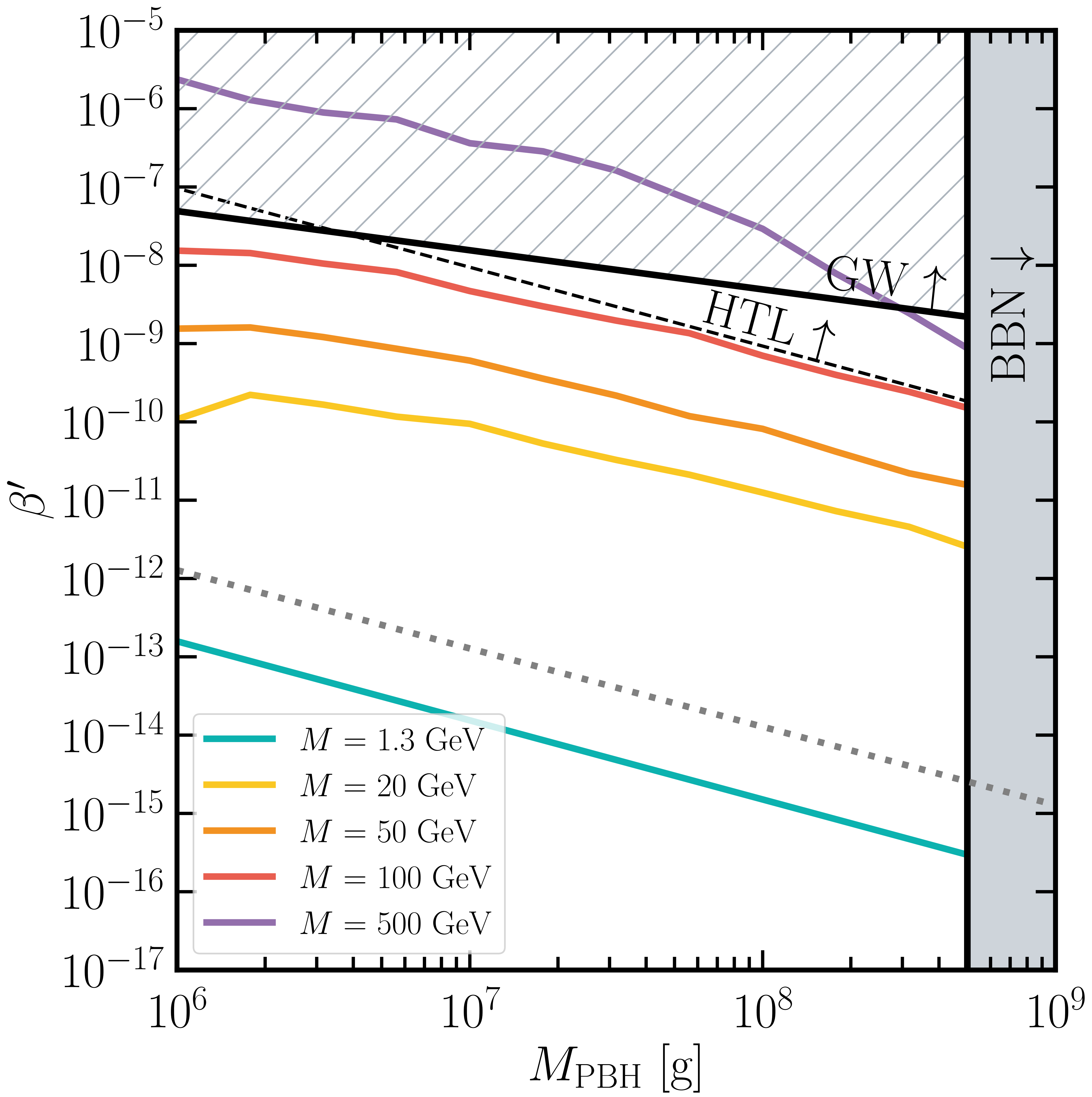
Shrinking the RHNs allowed region towards higher masses M and smaller mixing U^2



PBHs disfavor detection of Heavy Neutral Leptons (HNLs)!

PBH-leptogenesis constraints

Calabrese+ (w/ 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

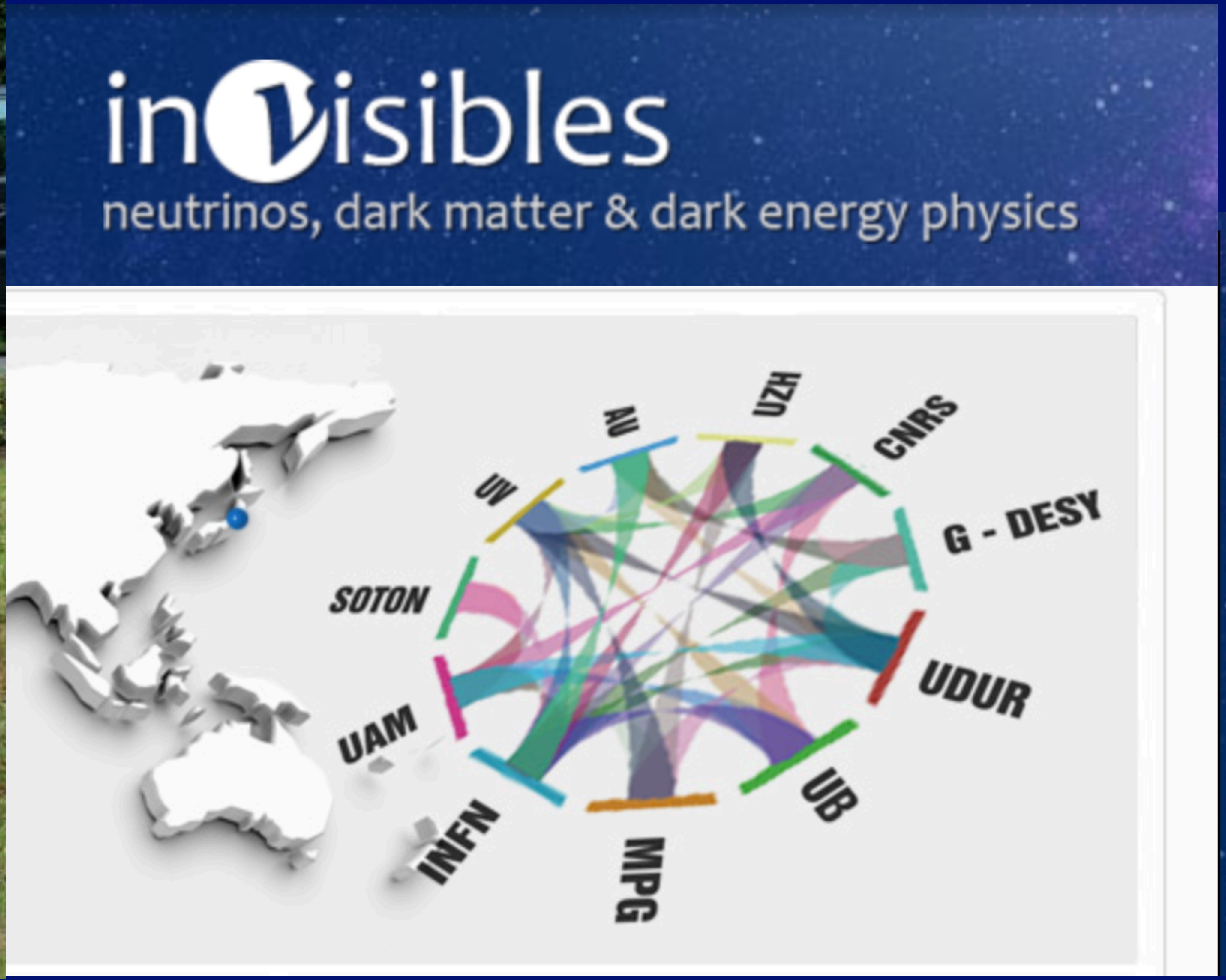
Conclusions

- ✦ 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.

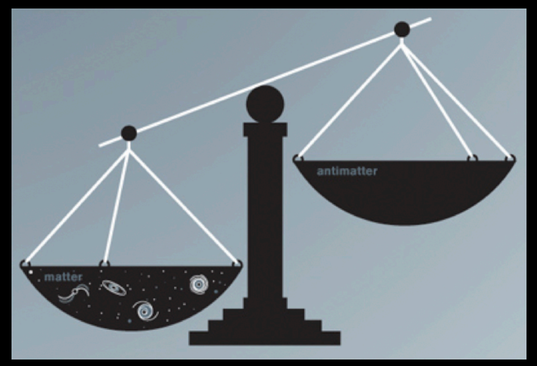
- ✦ We have placed **mutual exclusions limits** between minimal leptogenesis models and PBHs when the final baryon asymmetry is below the observed value.

Invisibles workshop 2013

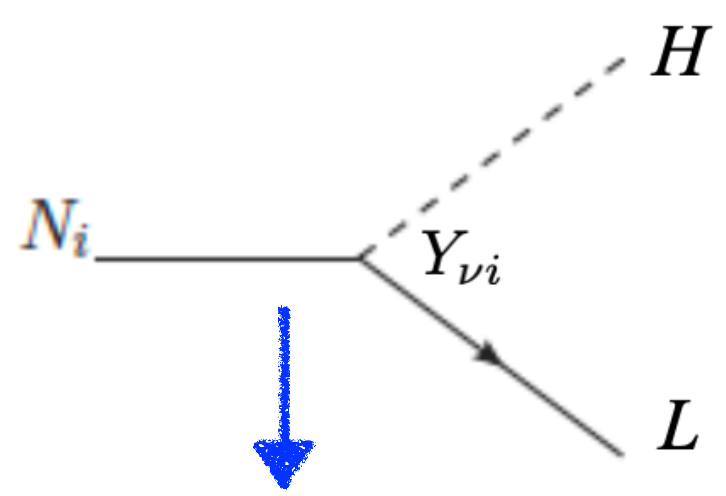


Thank you

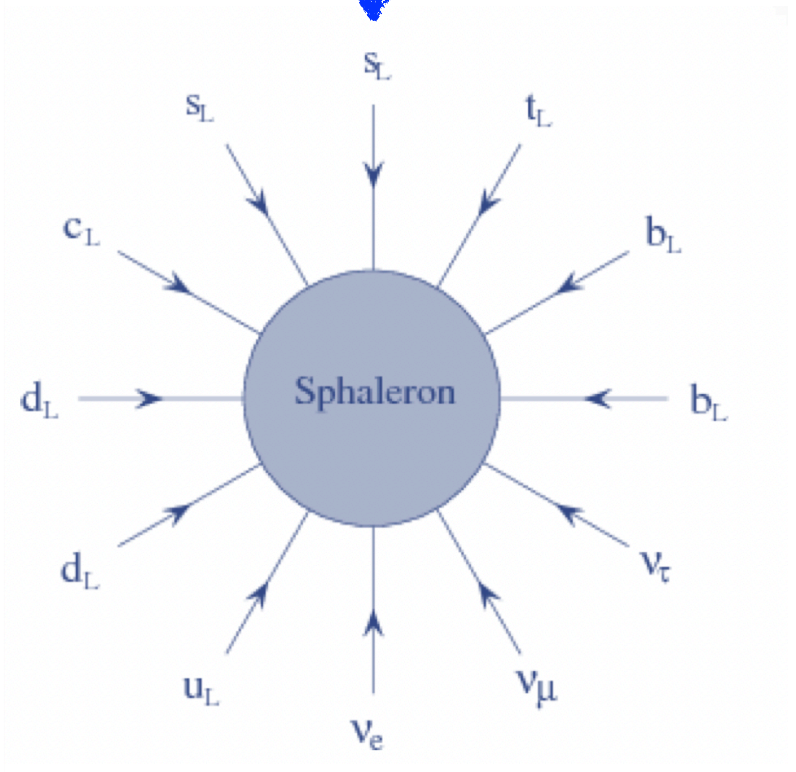
Thank you



Basic Step of Leptogenesis



Lepton asymmetry

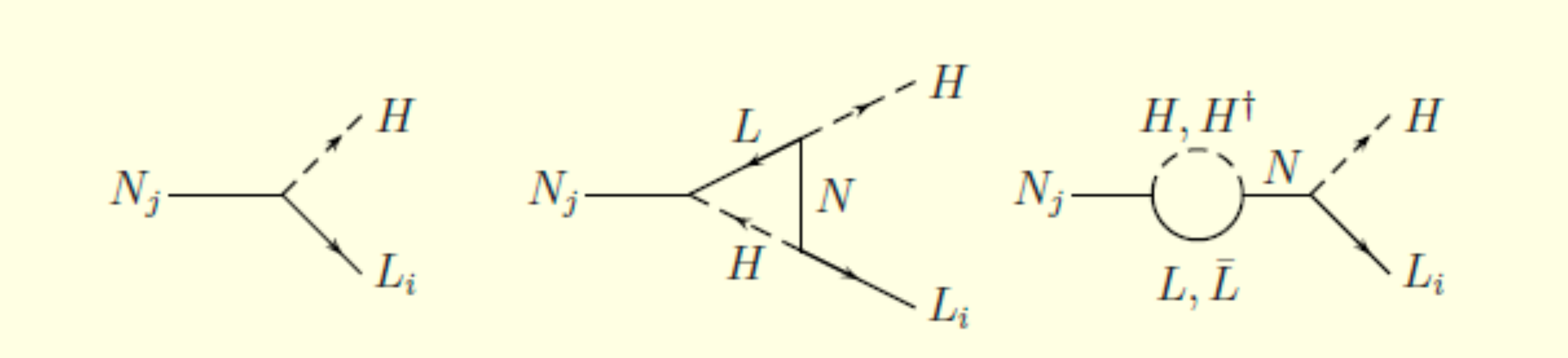


Baryon asymmetry

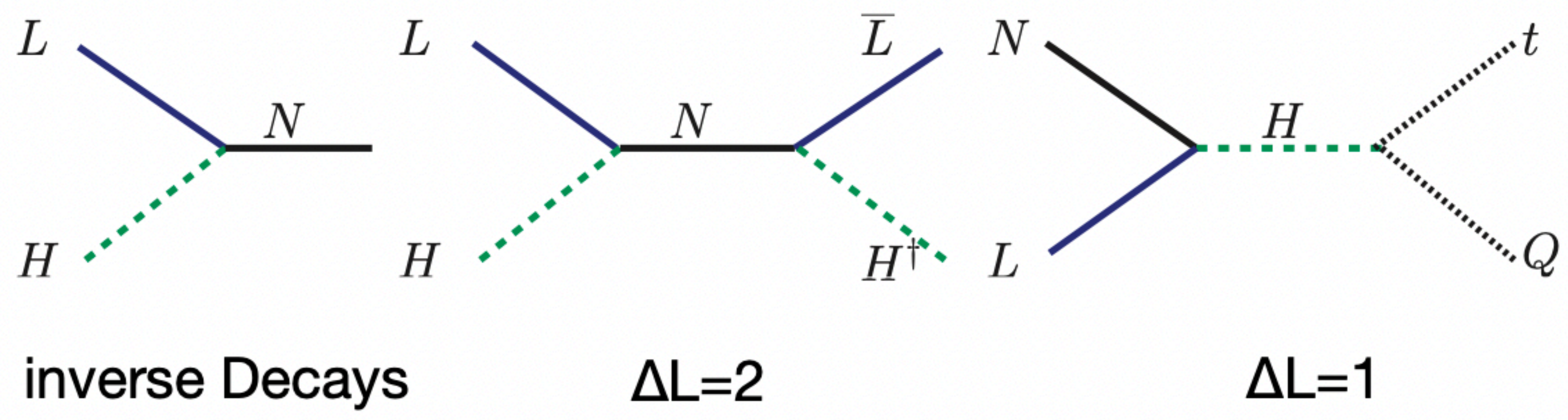
$$N \to LH / N \to \bar{L}H$$

$$\epsilon_i = \frac{\Gamma_i - \overline{\Gamma_i}}{\Gamma_i + \overline{\Gamma_i}}$$

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)***

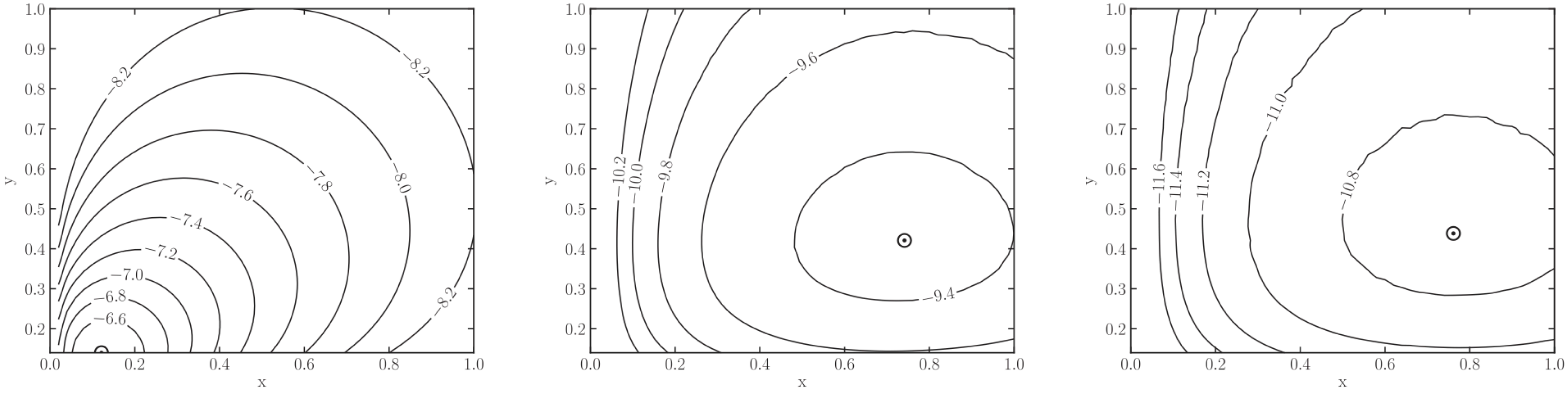


FIG. 1. The final baryon asymmetry Y_B as a function of x, y for $m_h = \sqrt{m^2_{\rm atm}} \approx 0.05$ eV (left panel), $m_h = 0.1$ eV (middle panel) and $m_h = 0.2$ eV (right panel), with $M_1 = 2.0 \times 10^{13}$ GeV. The contours are for constant $\log_{10} Y_B$ while the symbol $\odot$ indicates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

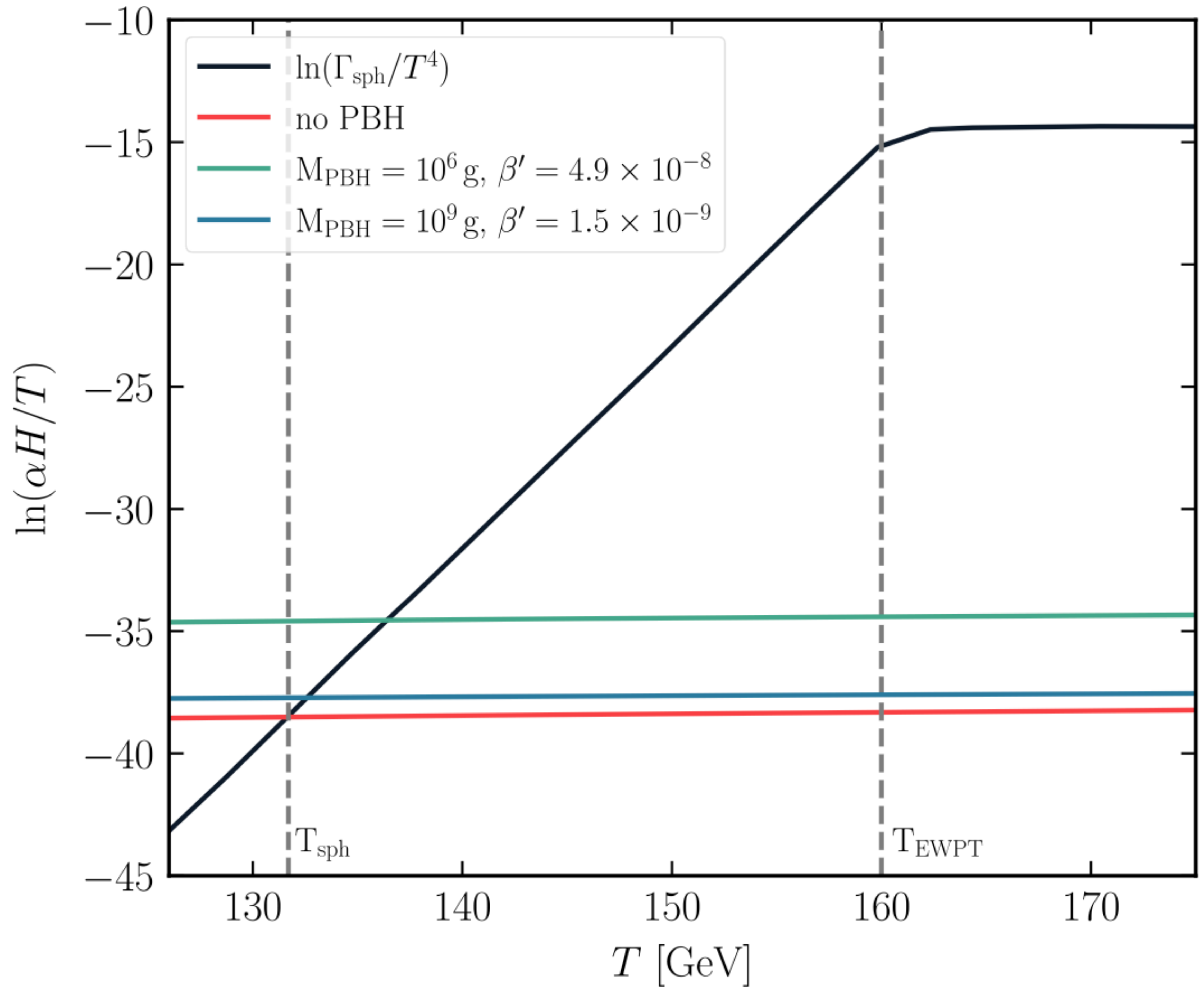


FIG. 5. The rate of sphaleron process (black line) as a function of the temperature. The colored lines show the Hubble rate for different scenarios with and without the presence of PBHs. The crossing between $\Gamma_{\rm sph}$ and H defines the temperature $T_{\rm sph}$ at which the sphaleron processes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

High-scale Leptogenesis: Boltzmann equations

Calabrese+ (w/ NS), ***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

Calabrese+ (w/ NS), ***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.