NEHOP 2024

How Primordial Black Holes constrain leptogenesis

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Università degli Studi di Napoli Federico II

Based on works

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Phys.Rev.D 107 (2023) 12, 123537

IP3

Durham University

in collaboration with

Stefano Morisi, Marco Chianese, Ninetta Saviano, Roberta Calabrese, Gennaro Miele

And work in preparation in collaboration with

Jessica Turner, Yuber Perez-Gonzalez, Lucien Heurtier

Primordial Black Holes constrain (resonant) leptogenesis

$$M_N < 10^3\,\mathrm{GeV}$$

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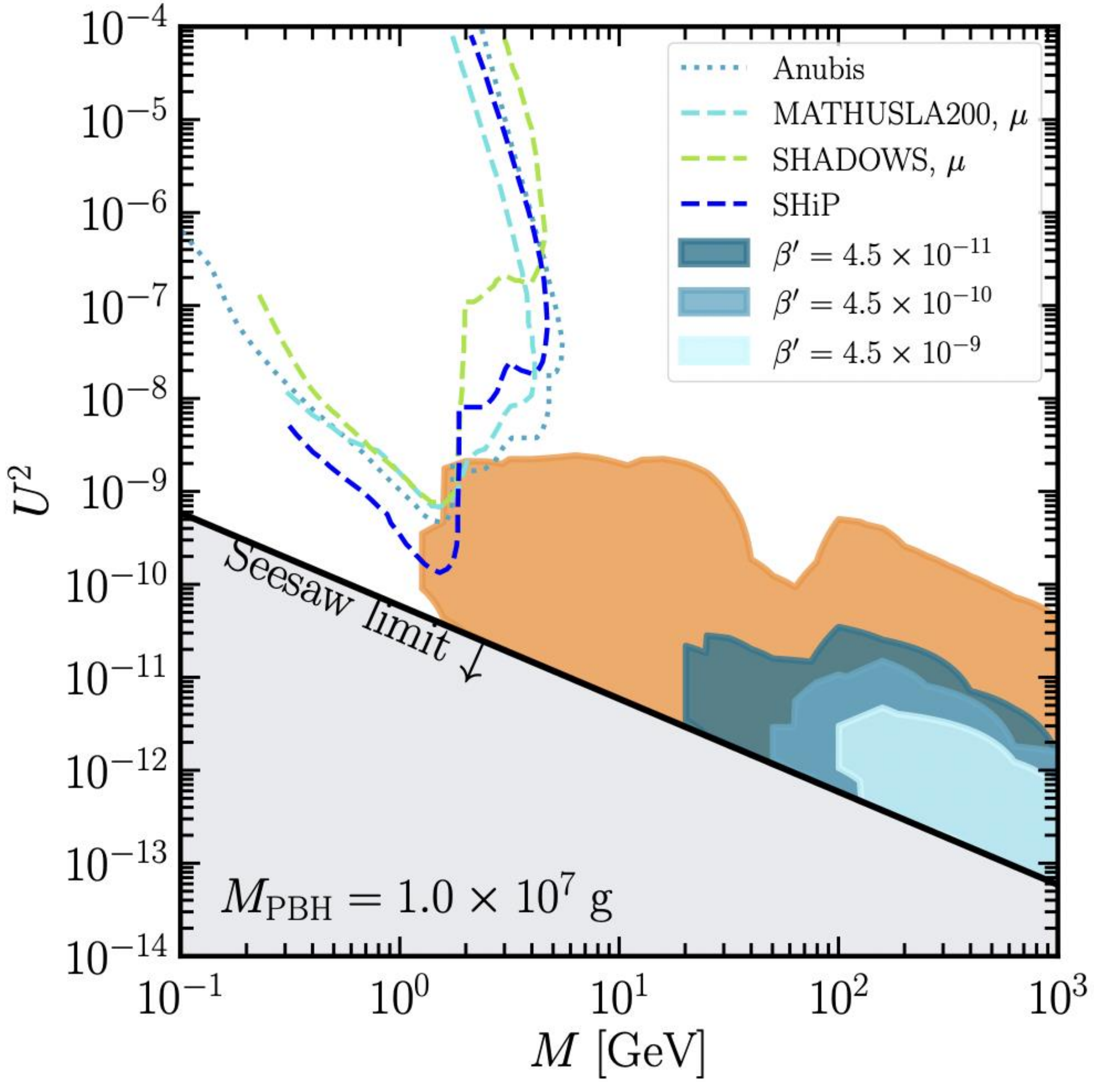

Primordial Black Holes constrain (resonant) leptogenesis

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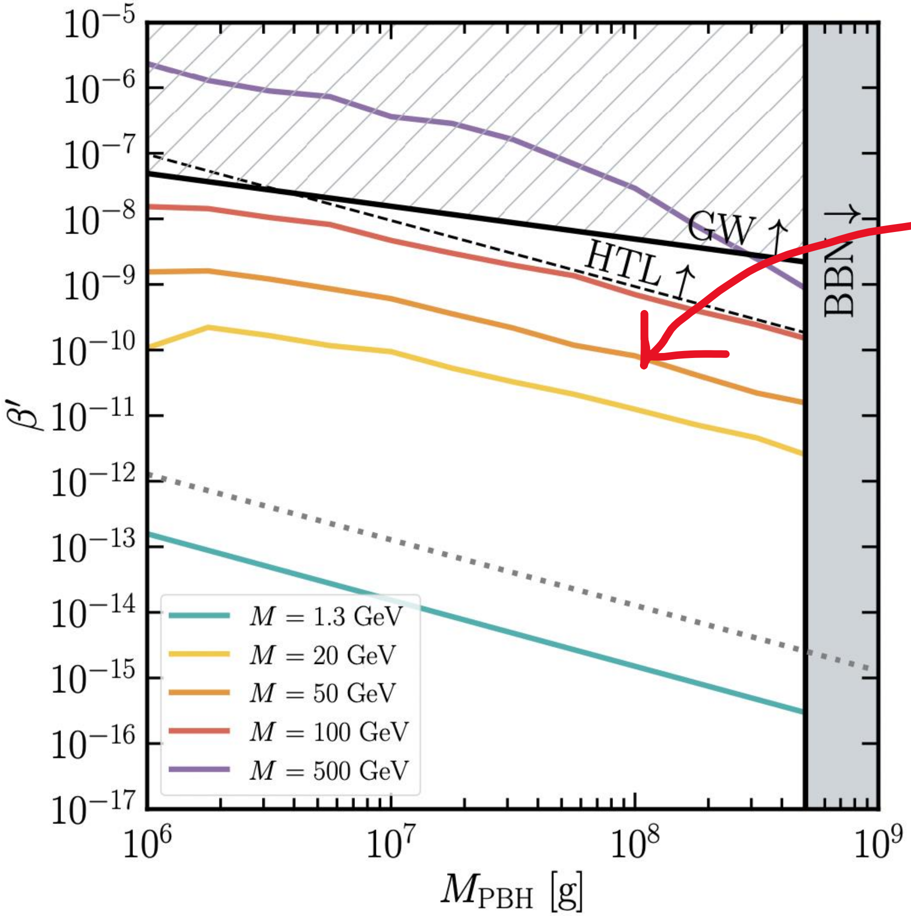

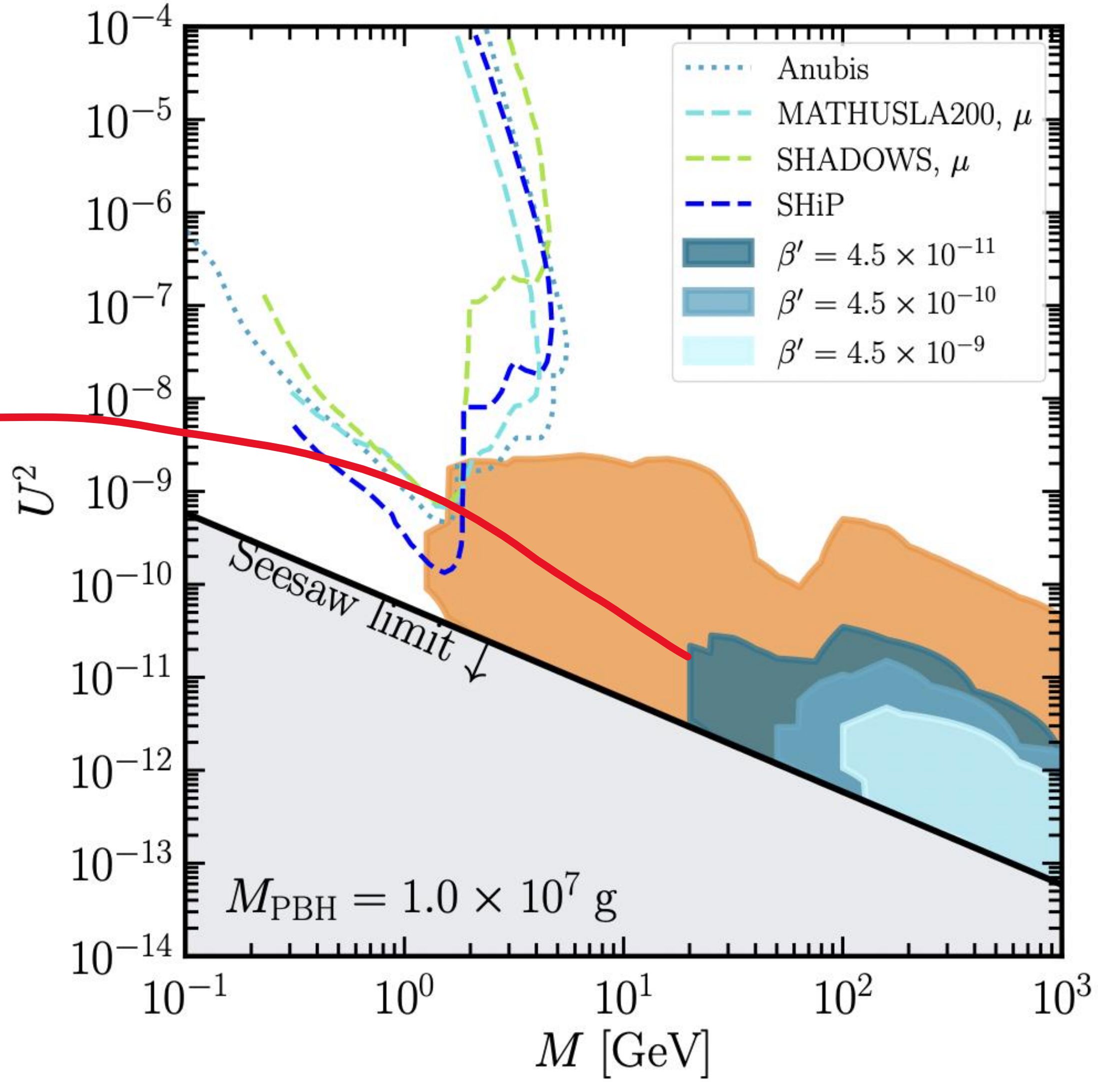

Leptogenesis - overview

$$\mathcal{L}_{\rm seesaw} = \frac{1}{2}\bar{N}_i^c \hat{M}_{ij} N_j - Y_{\ell i}\bar{L}_\ell \tilde{\phi} N_i + {\rm h.c.},$$

10^{-2}

10^{16}

Low scale

$M_N(\mathrm{GeV})$

High scale

Leptogenesis - overview

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New gauge singlets, HNLs/RHNs

10^{-2} ⟷ 10^{16}

Low scale — $M_N(\text{GeV})$ — High scale

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Occurs at very high temperatures

Theoretically appealing

Far beyond the reach of direct detection

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New gauge singlets, HNLs/RHNs

Leptogenesis is difficult to constrain at all scales

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10^{-2} $\longleftrightarrow$ 10^{16}

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Leptogenesis at low scales

$$\begin{pmatrix} M_{N_1} & 0 & 0 \\ 0 & M_{N_2} & 0 \\ 0 & 0 & M_{N_3} \end{pmatrix}$$

$$M_{N_i} \approx M_{N_j} \; , \; M_{N_k}$$

$$M_{N_i} - M_{N_j} = \Delta M_{ij}$$

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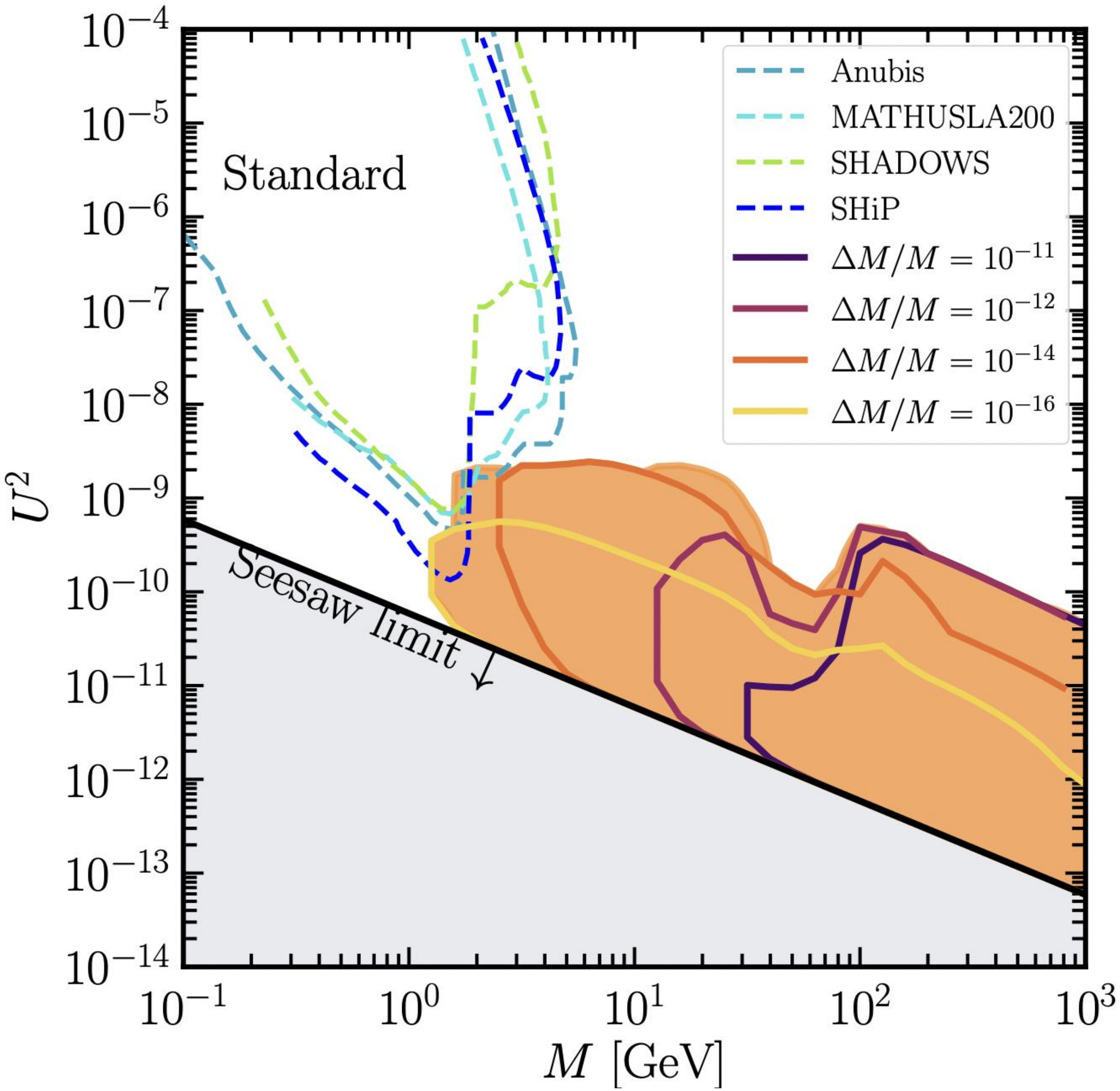

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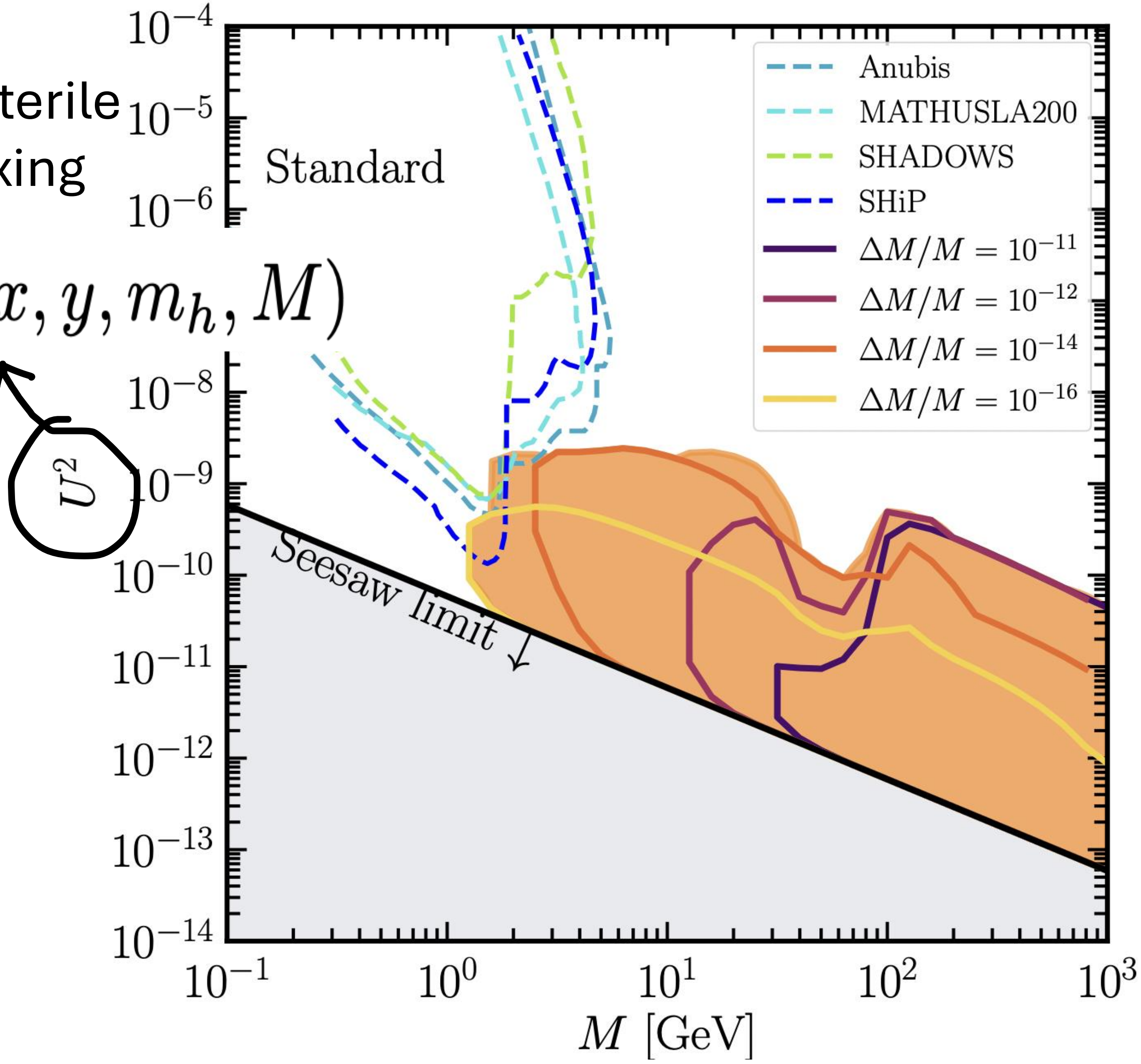
Total active-sterile neutrino mixing

$$U^2 = U^2(x, y, m_h, M)$$



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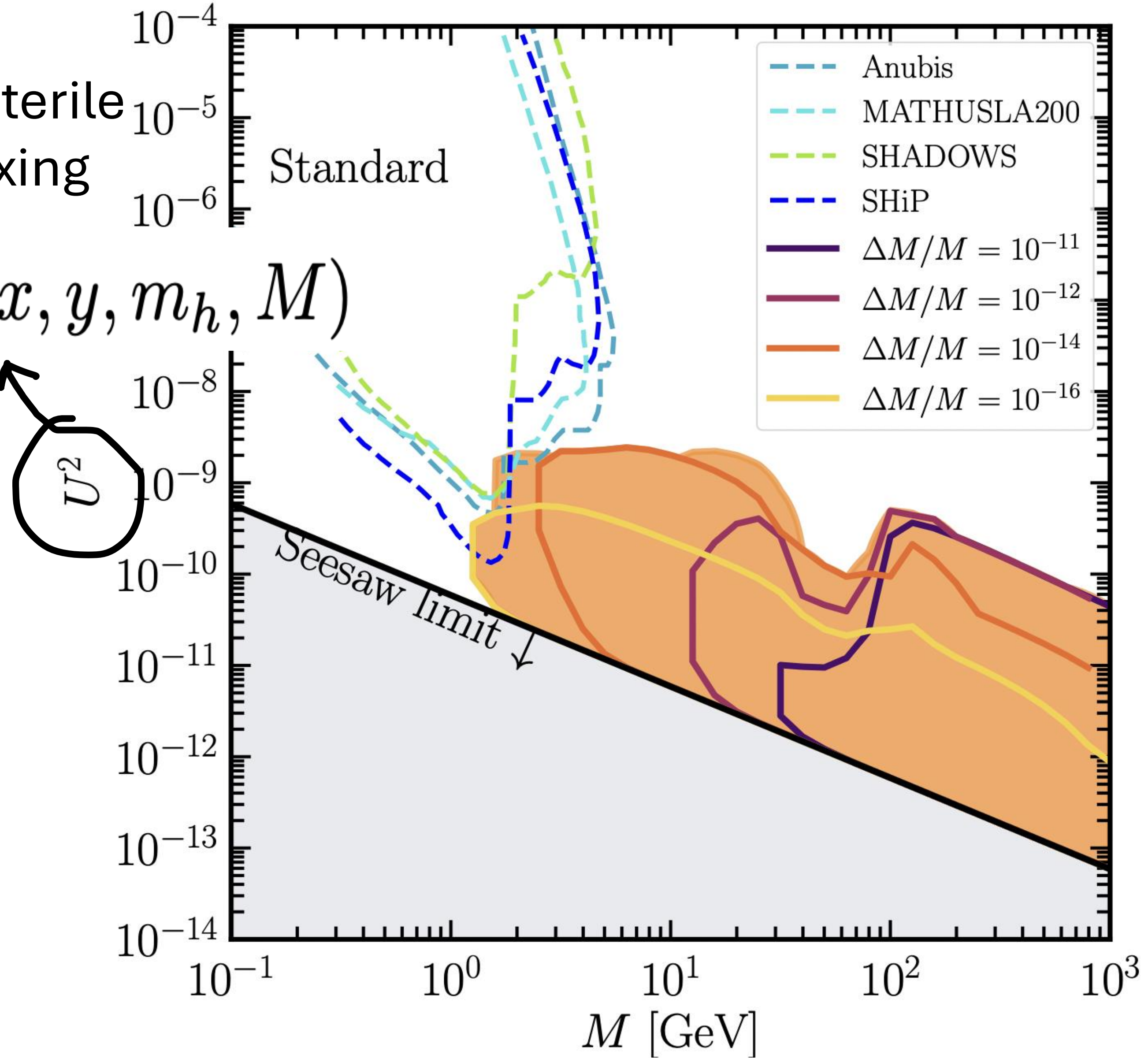
$$\Delta M_{ij} \approx \Gamma_{N_i}$$

Fine tuning?



How do PBHs affect leptogenesis?

Production of RHNs

Cosmological evolution

Entropy injection

Production of RHNs $\frac{\mathrm{dM_{PBH}}}{\mathrm{dt}} \propto M_{\mathrm{PBH}}^{-2}$

$$M_{N_i} \leq T_{\mathrm{PBH}}$$

Boosted RHNs
produced by PBH

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$$M_{\mathrm{PBH}} \leq 10^5 \mathrm{g}$$

Boosted RHNs decay seeding asymmetry

Boosted RHNs produced by PBH

sphalerons convert lepton asymmetry

$$\frac{\mathrm{dY_B}}{\mathrm{dt}} = \epsilon \Gamma_{N_i}^{\mathrm{PBH}} \mathcal{N}_{N_i}$$

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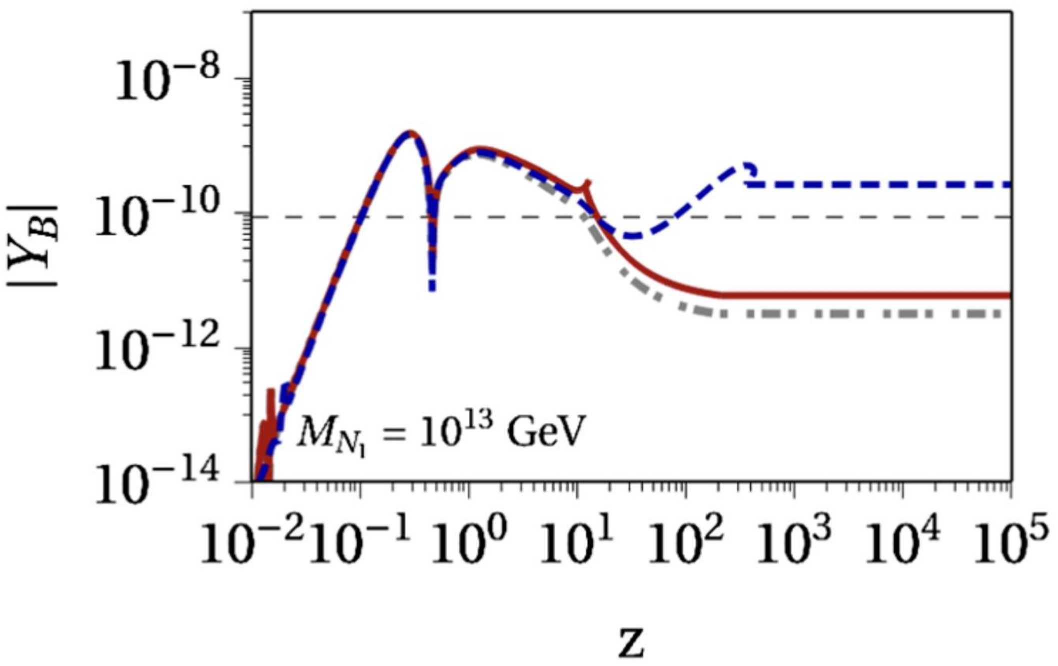
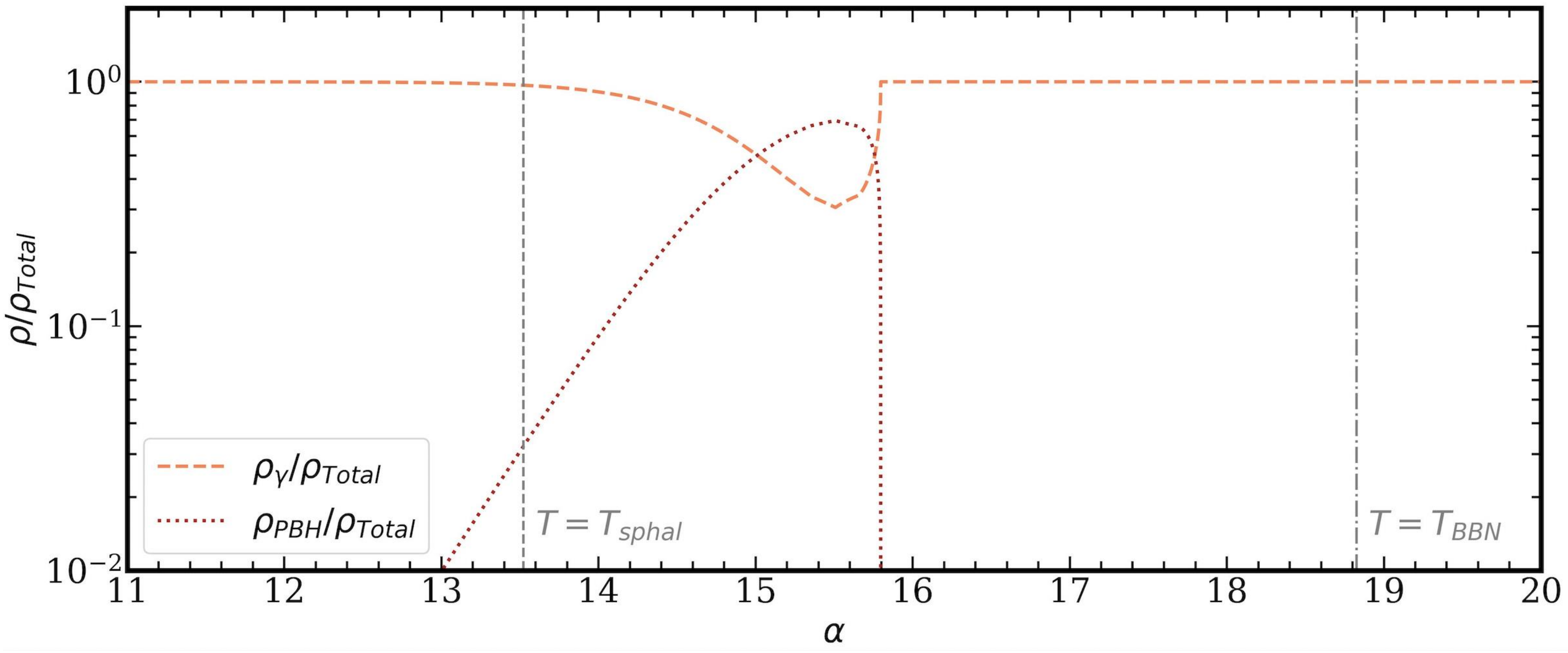
Perez-Gonzalez, Turner



Cosmological evolution

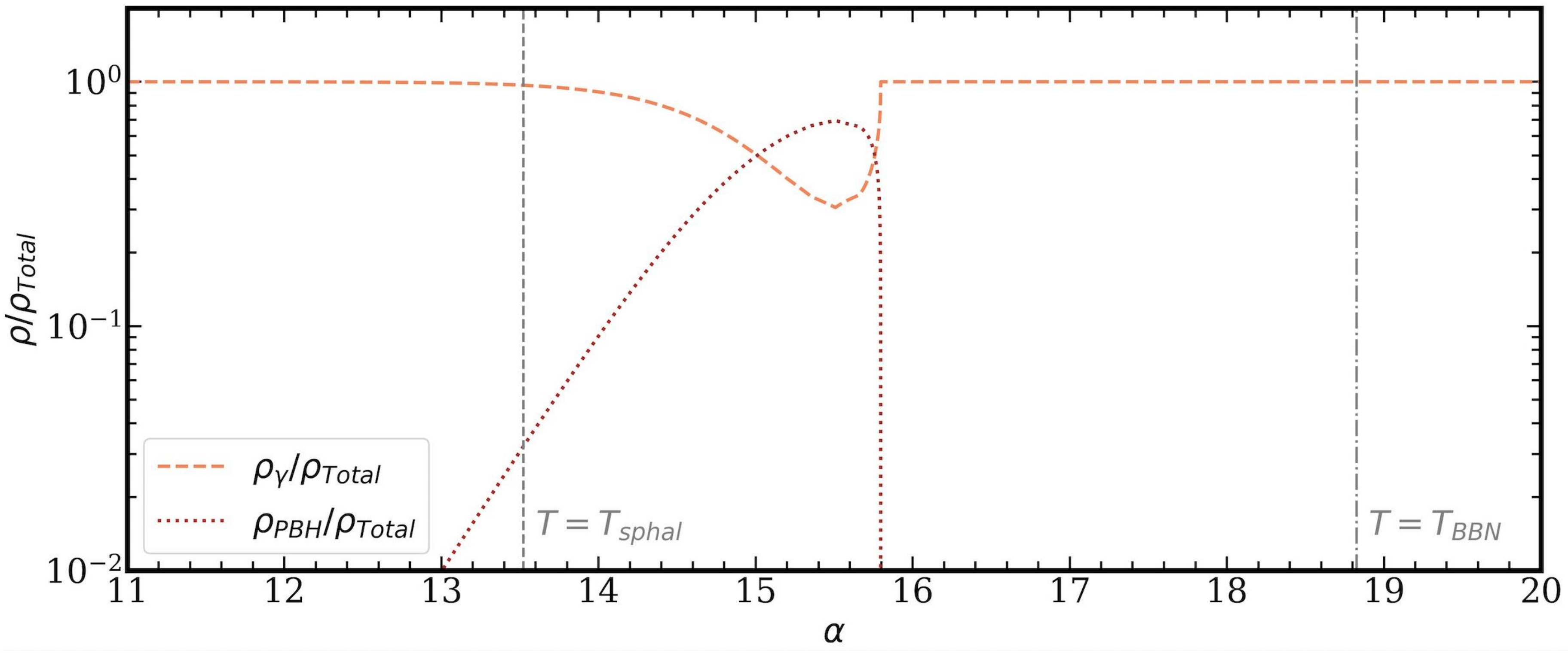
PBHs redshift like matter



Cosmological evolution

PBHs redshift like matter

Large populations dominate the energy budget



Cosmological evolution

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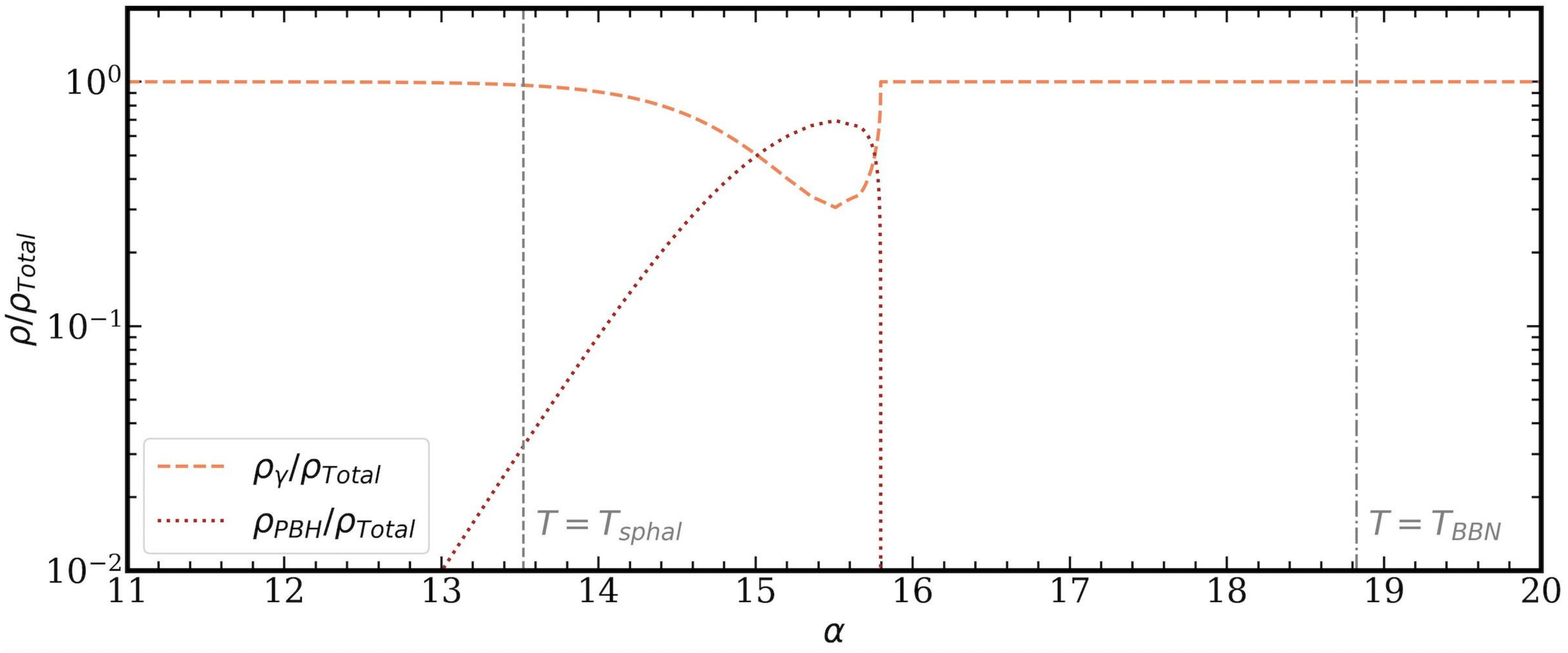
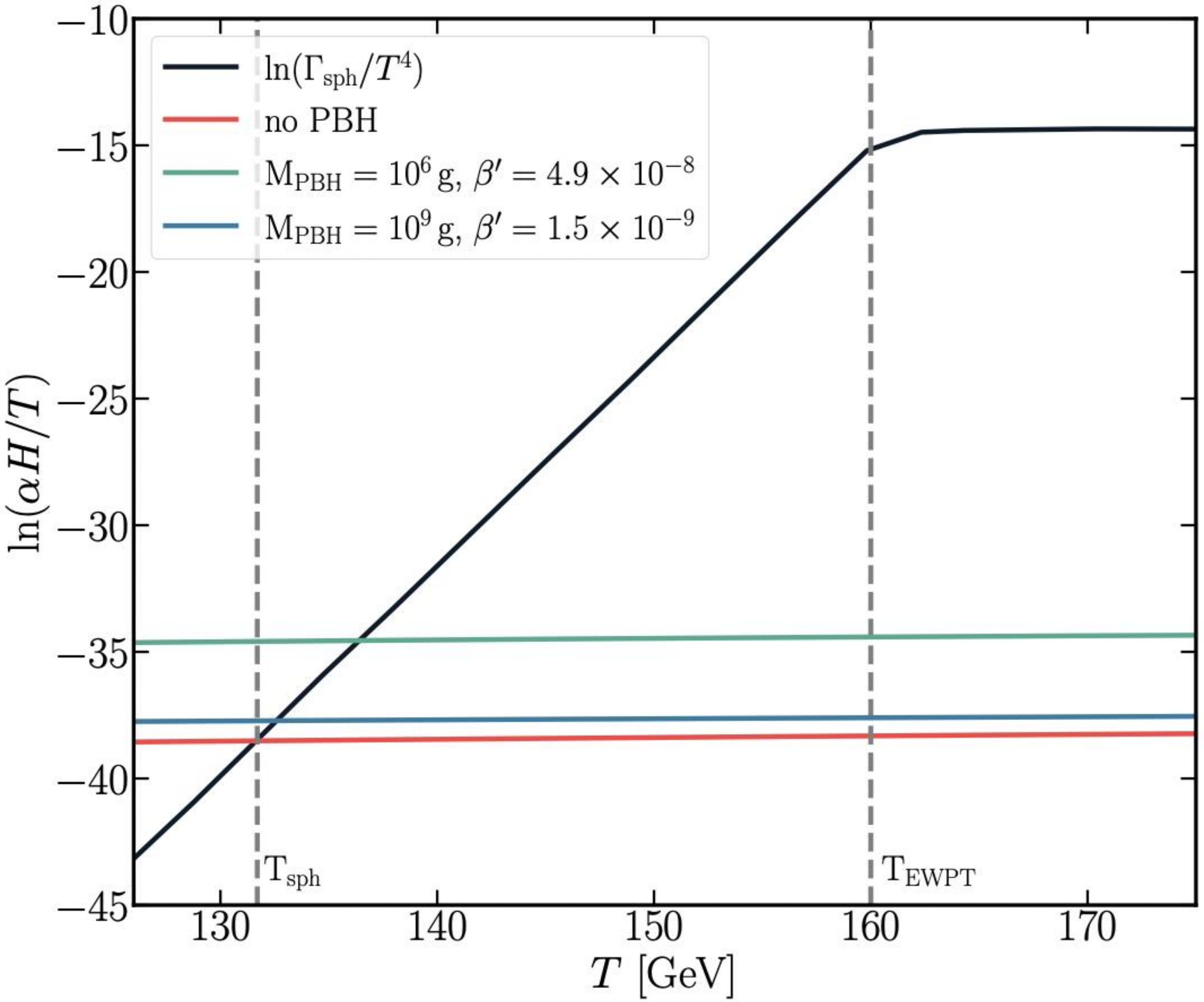
Increased Hubble rate close to evaporation



Sphaleron freeze-out

Black line is sphaleron rate

Crossing of black line with horizontal line shows freeze-out temperature



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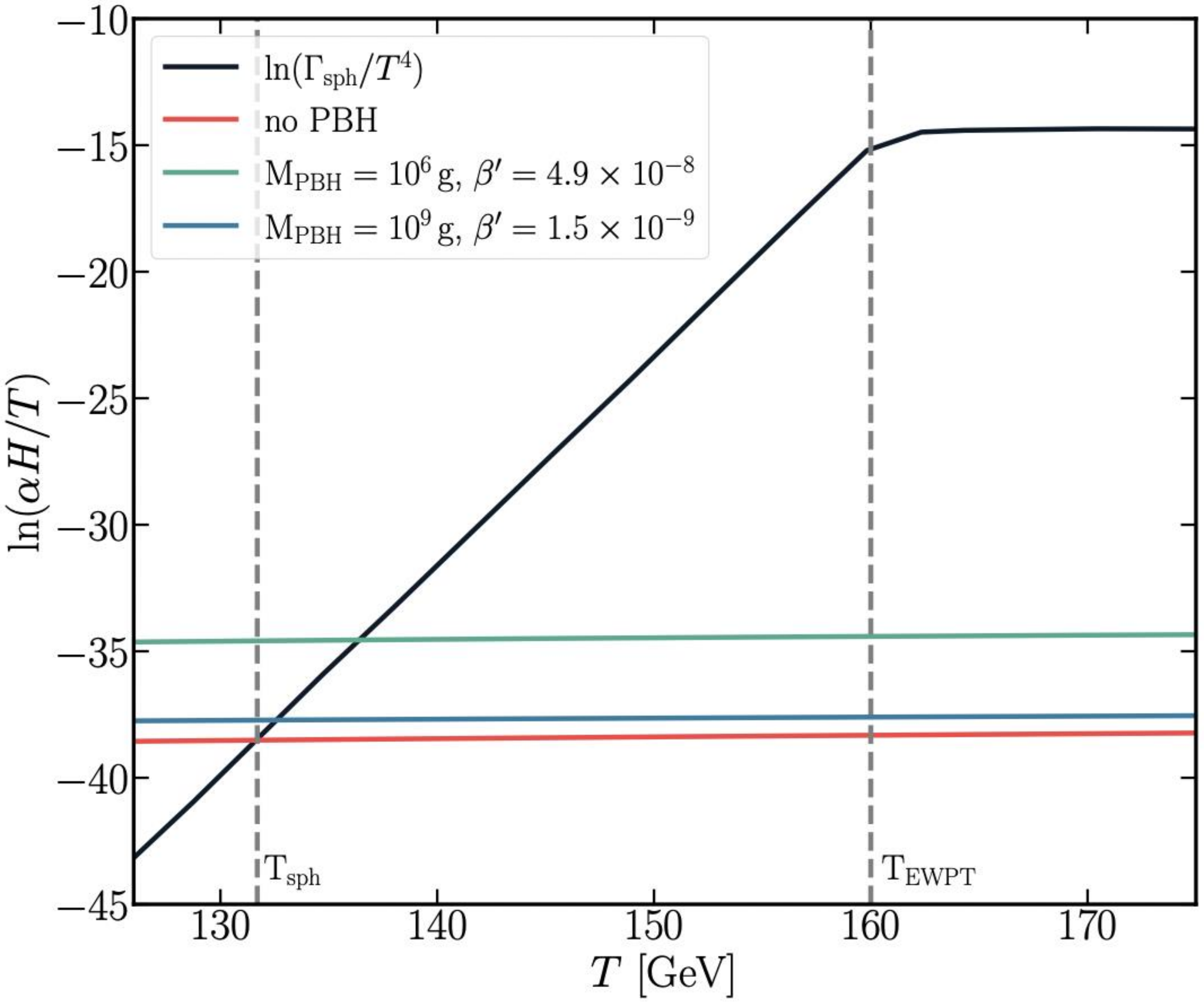


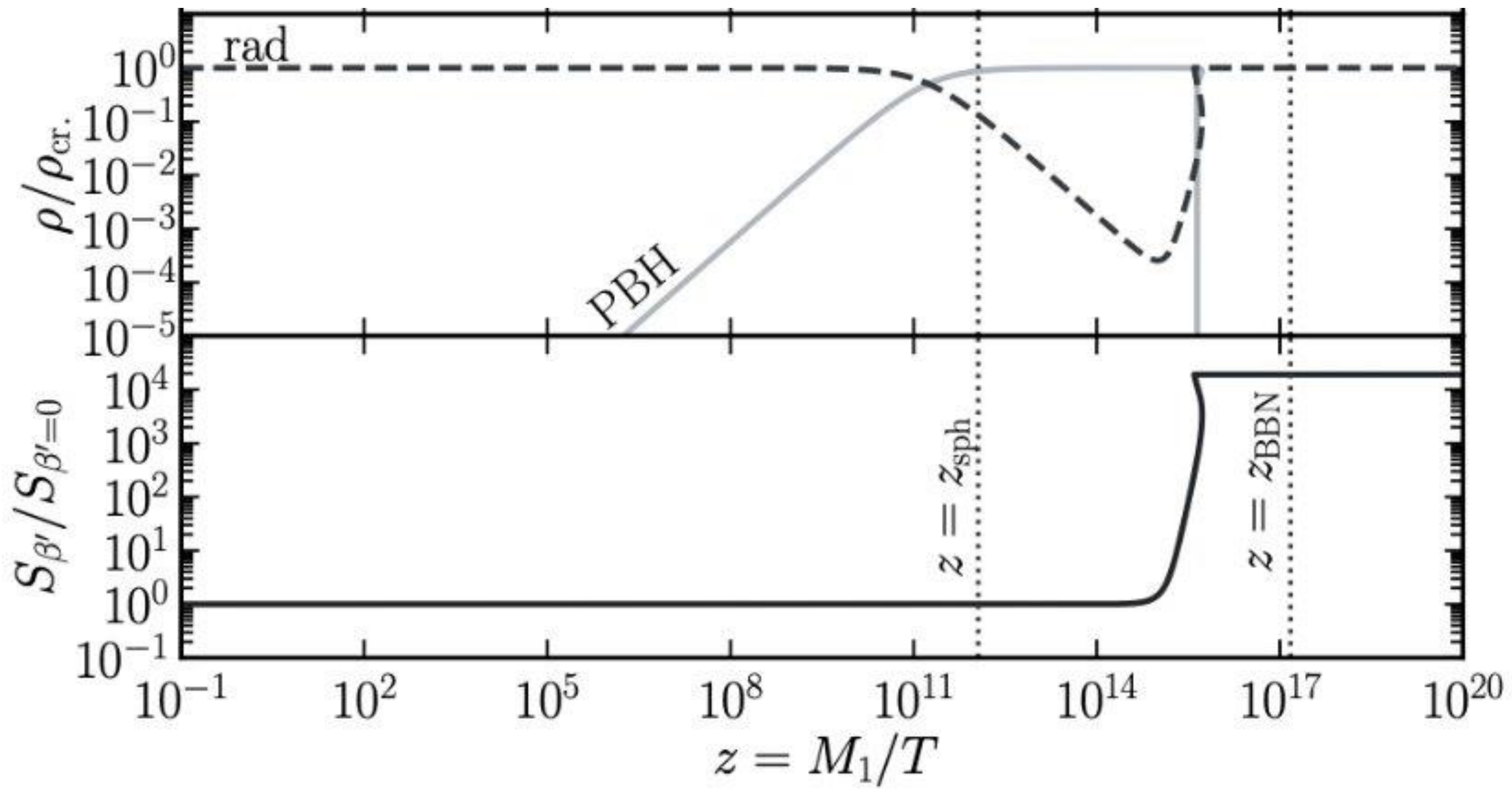
PBHs result in a hotter (earlier) freeze-out temperature

Relevant for low-scale models

Entropy Injection

$$Y_B \approx \eta \frac{\mathcal{N}_L}{\mathcal{S}}$$

$$\frac{\mathcal{S}_\beta}{\mathcal{S}_{\beta=0}}$$



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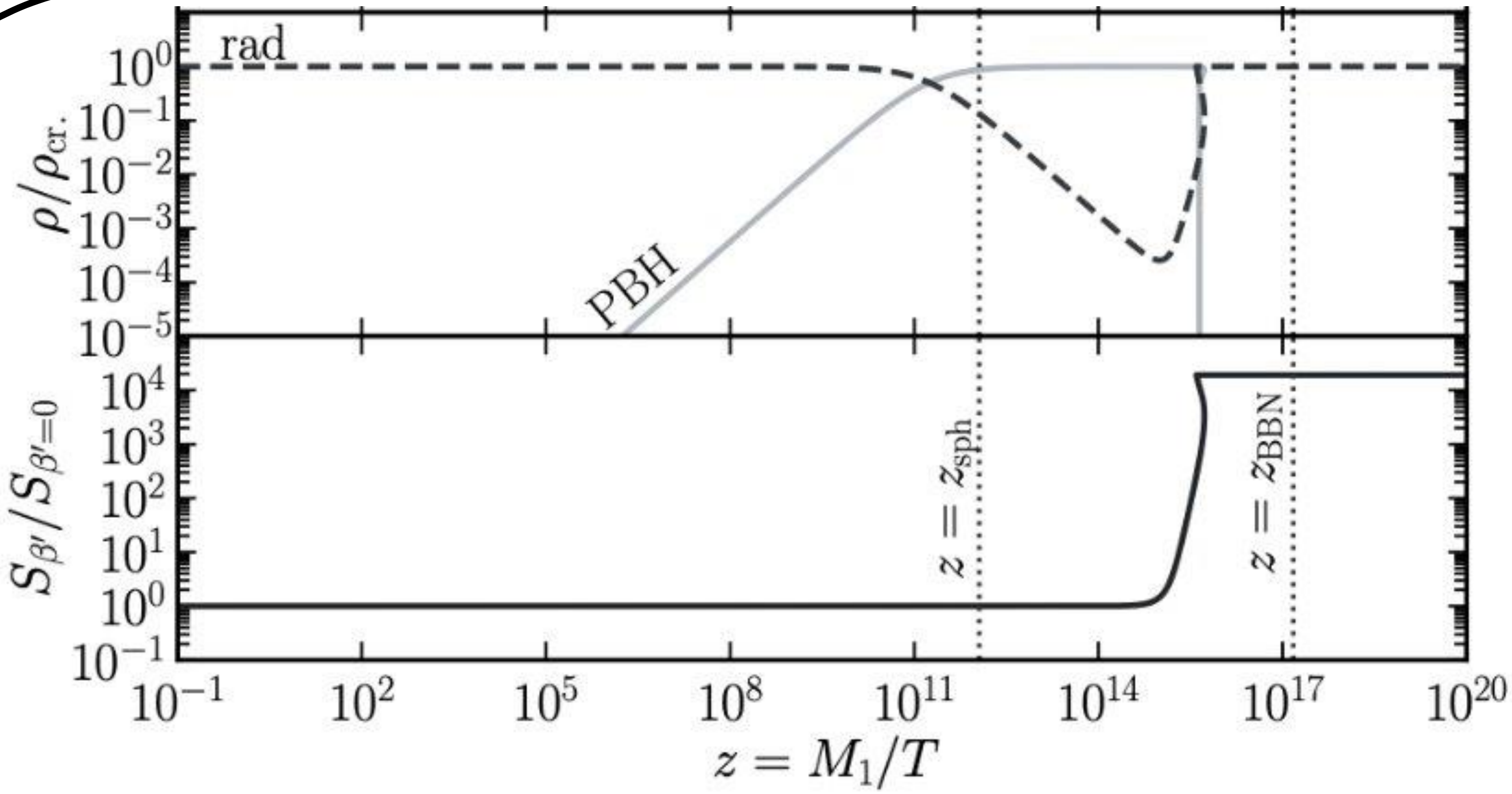

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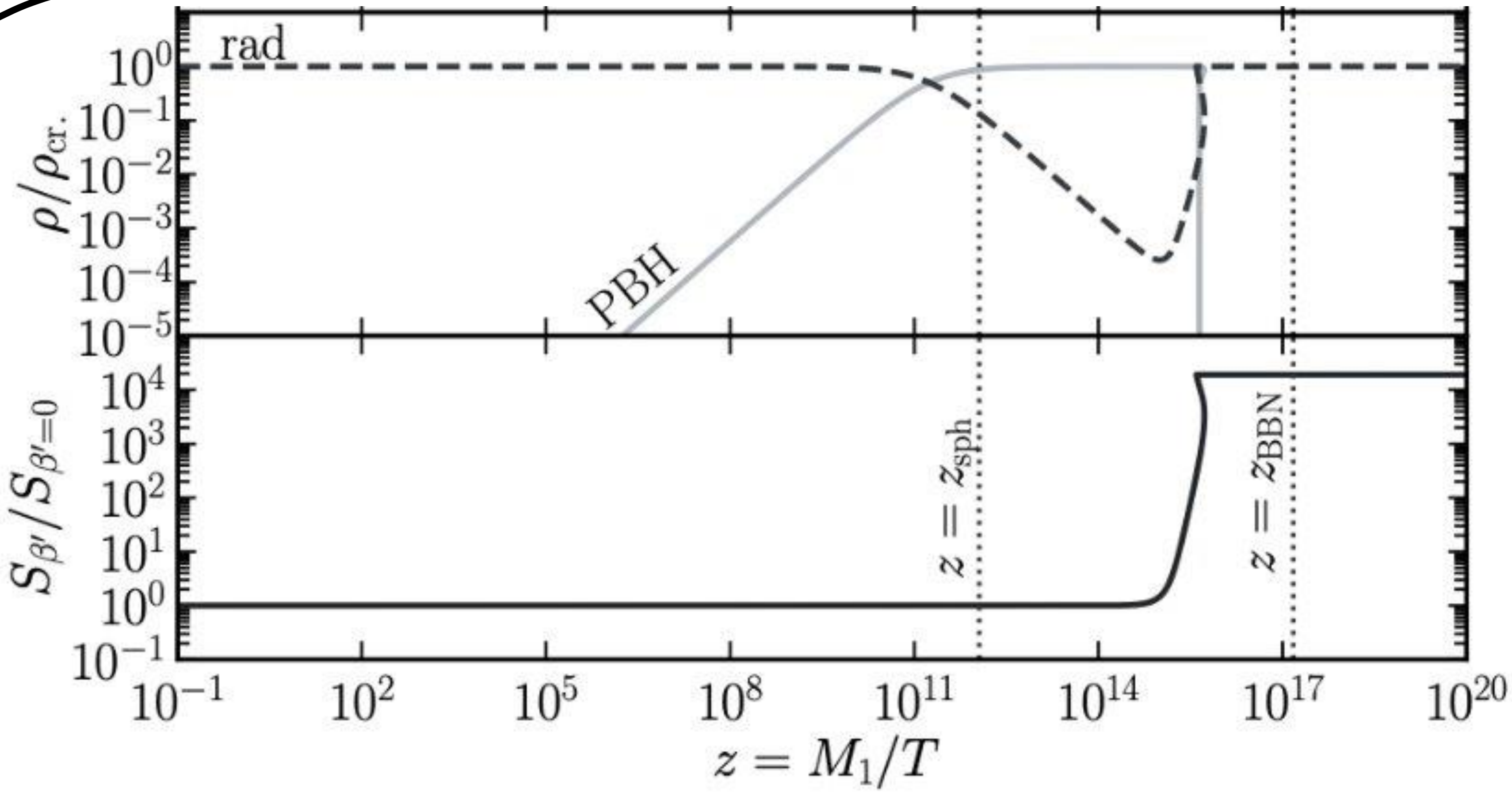

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Mutual exclusion!

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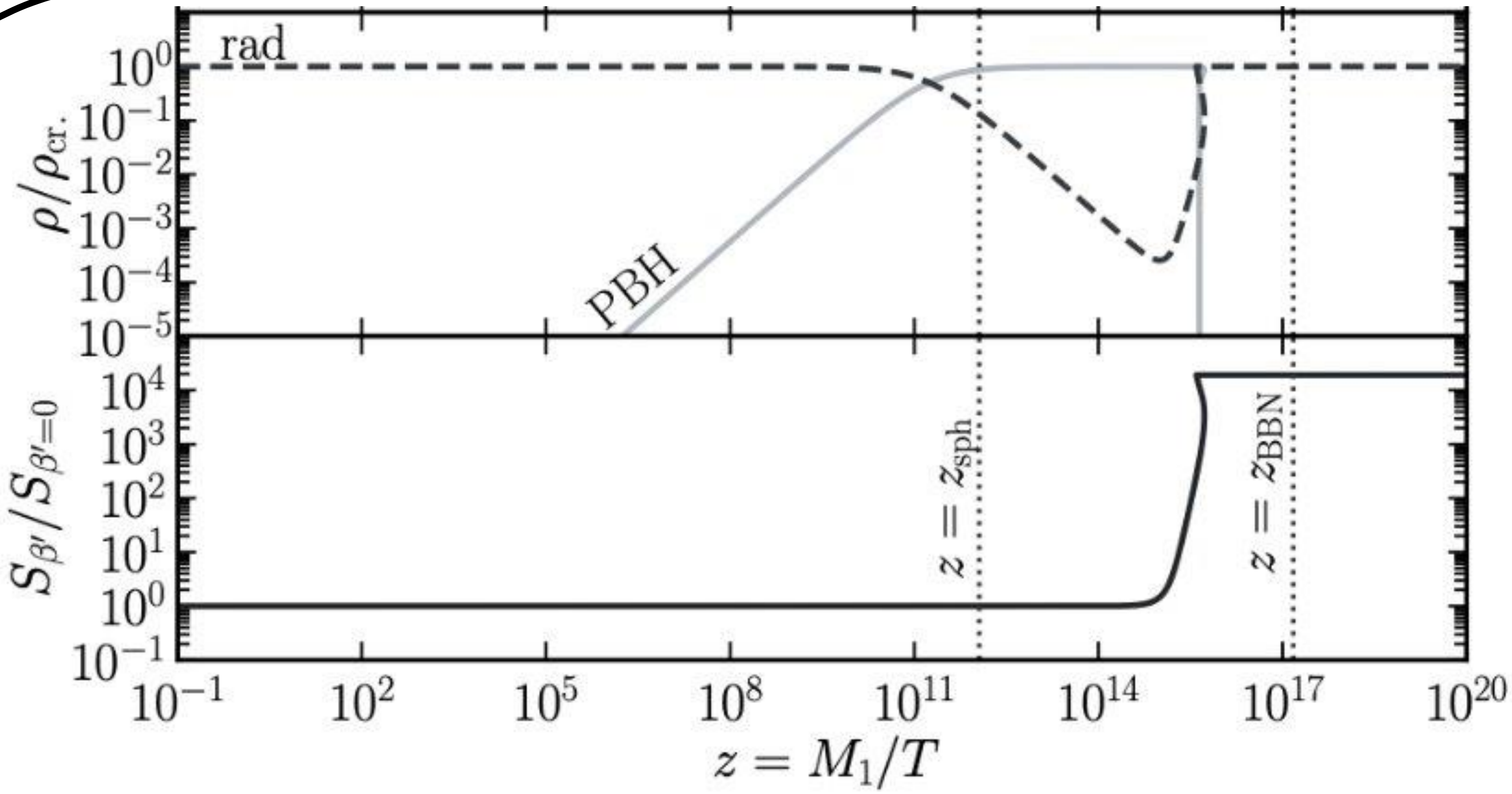
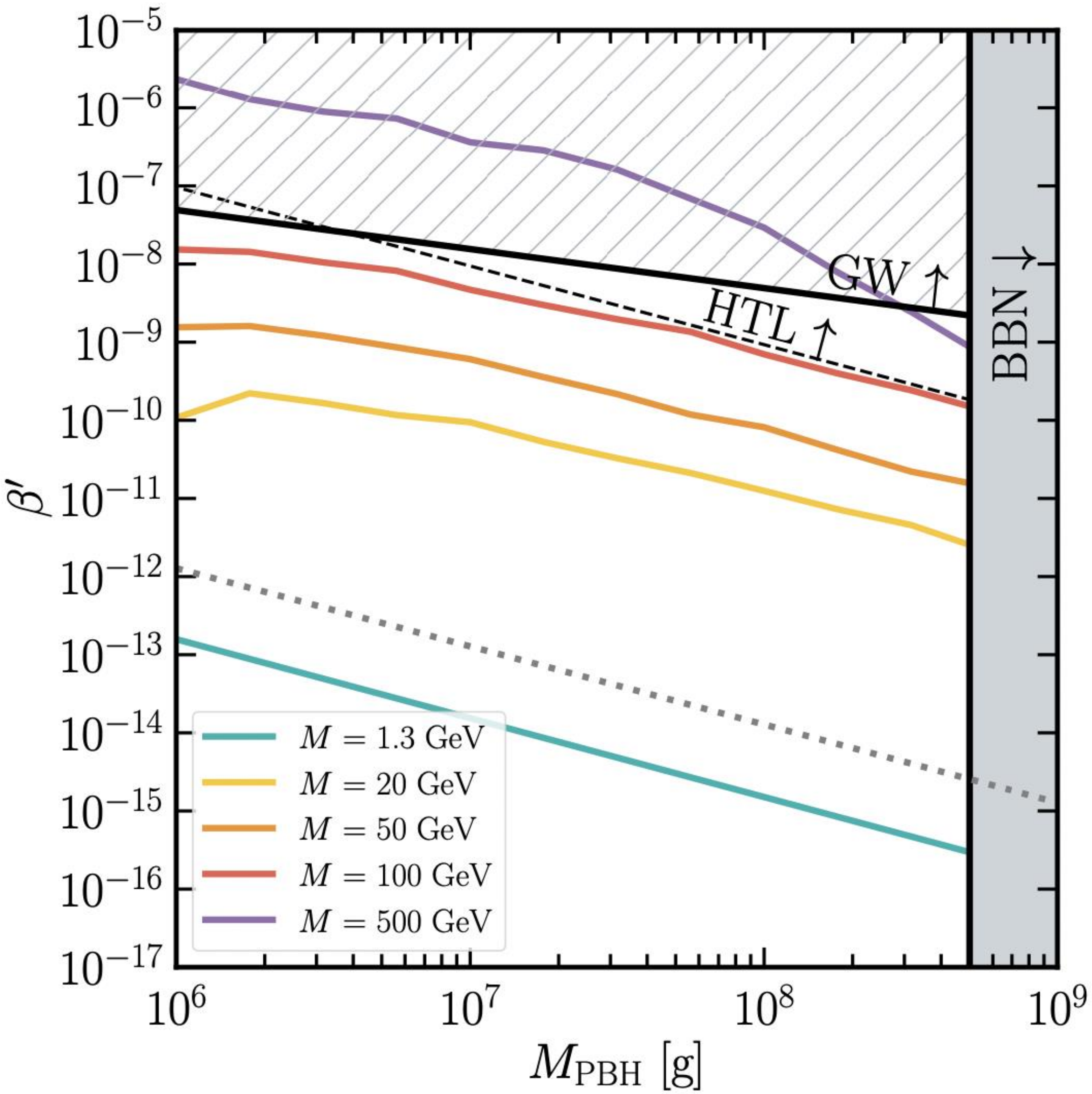
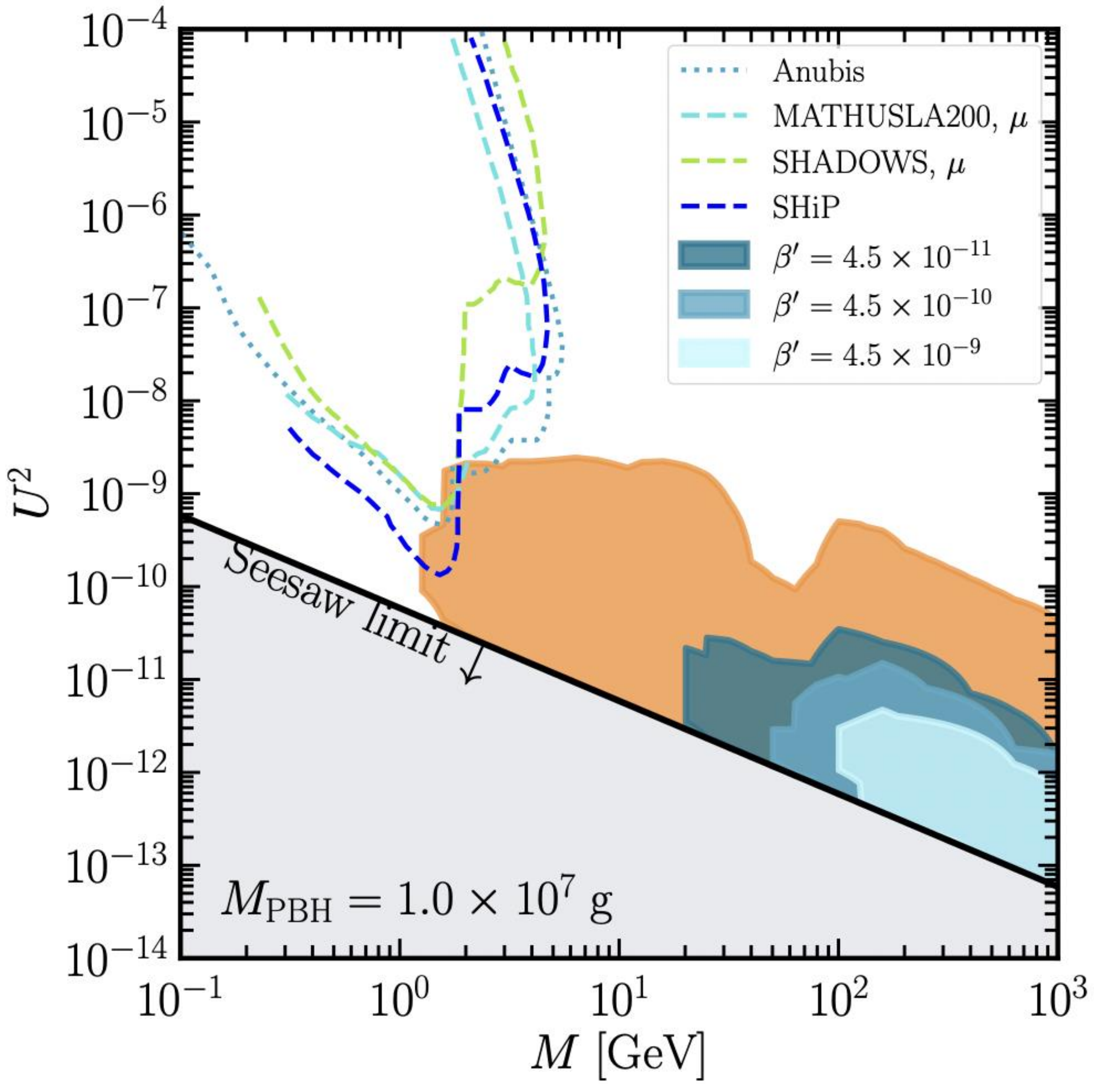


Mutual exclusion limits





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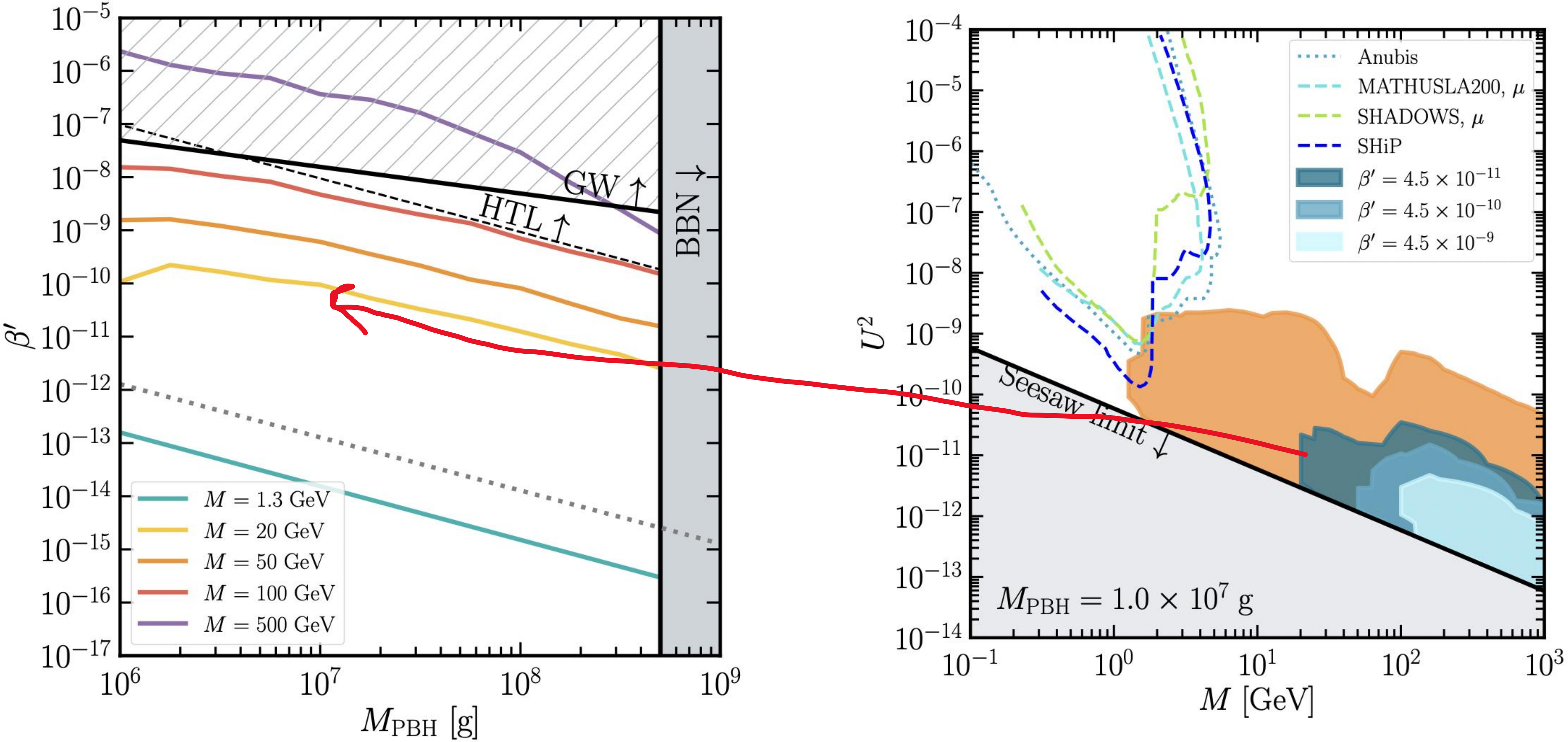

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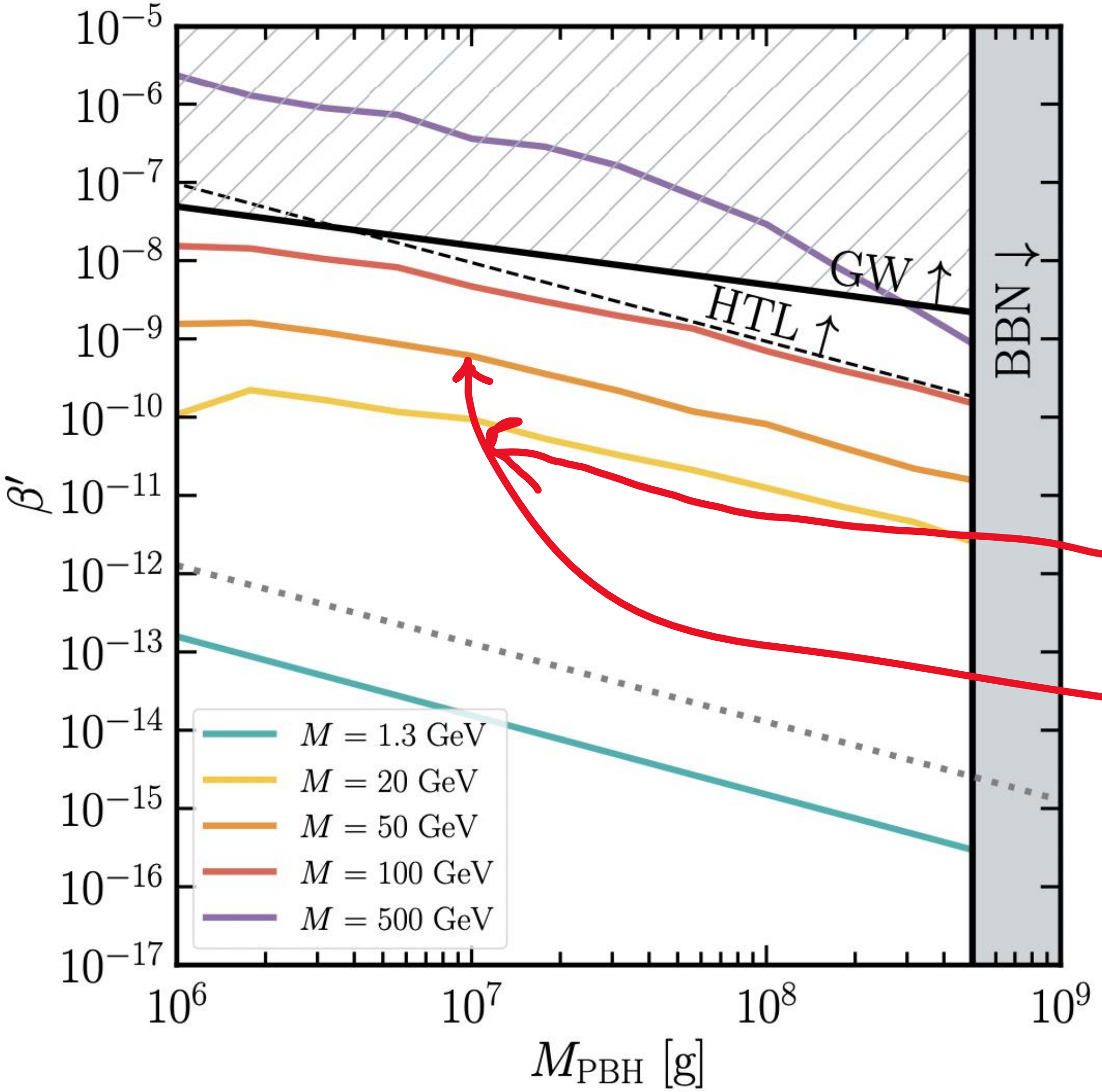
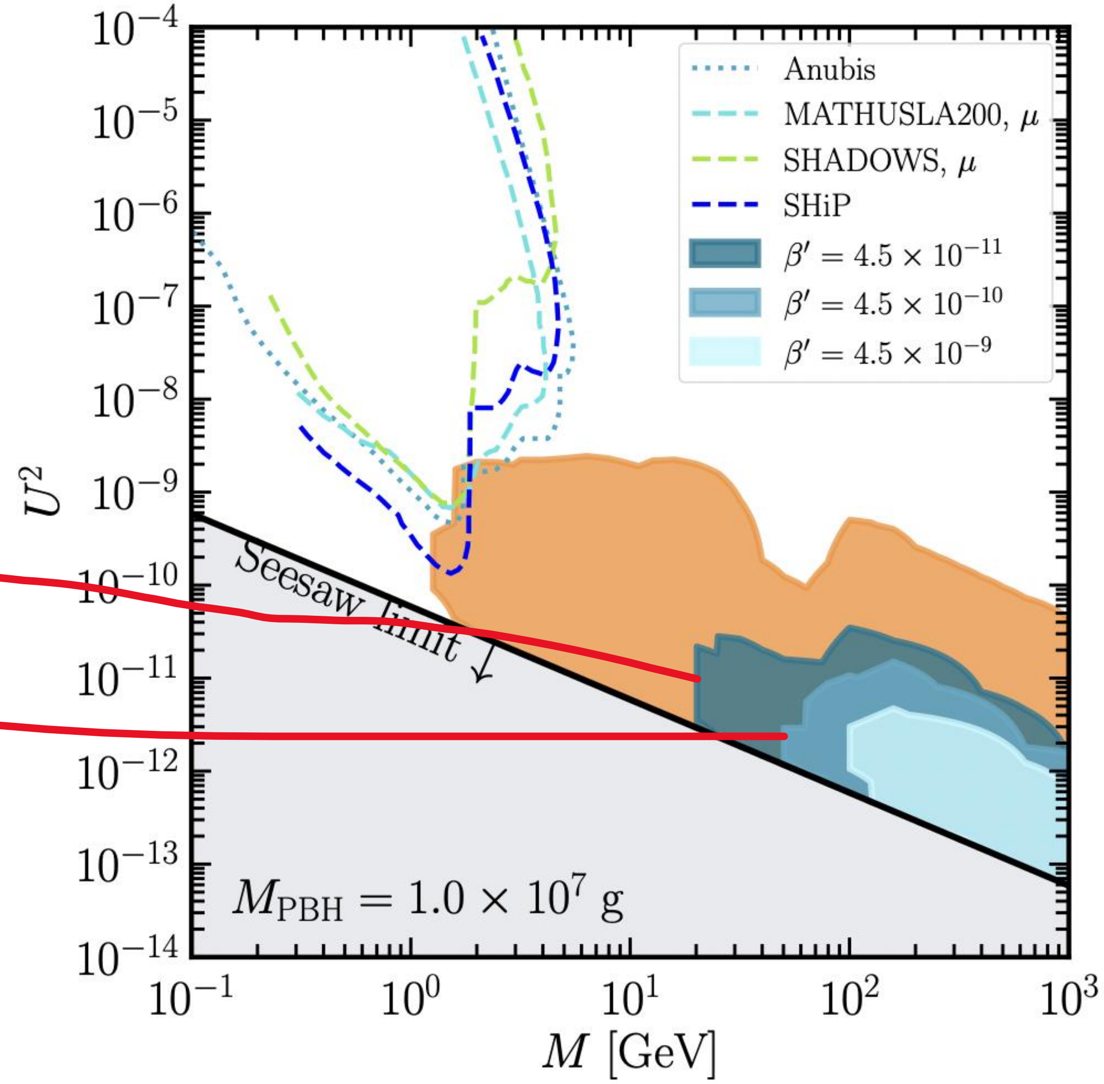
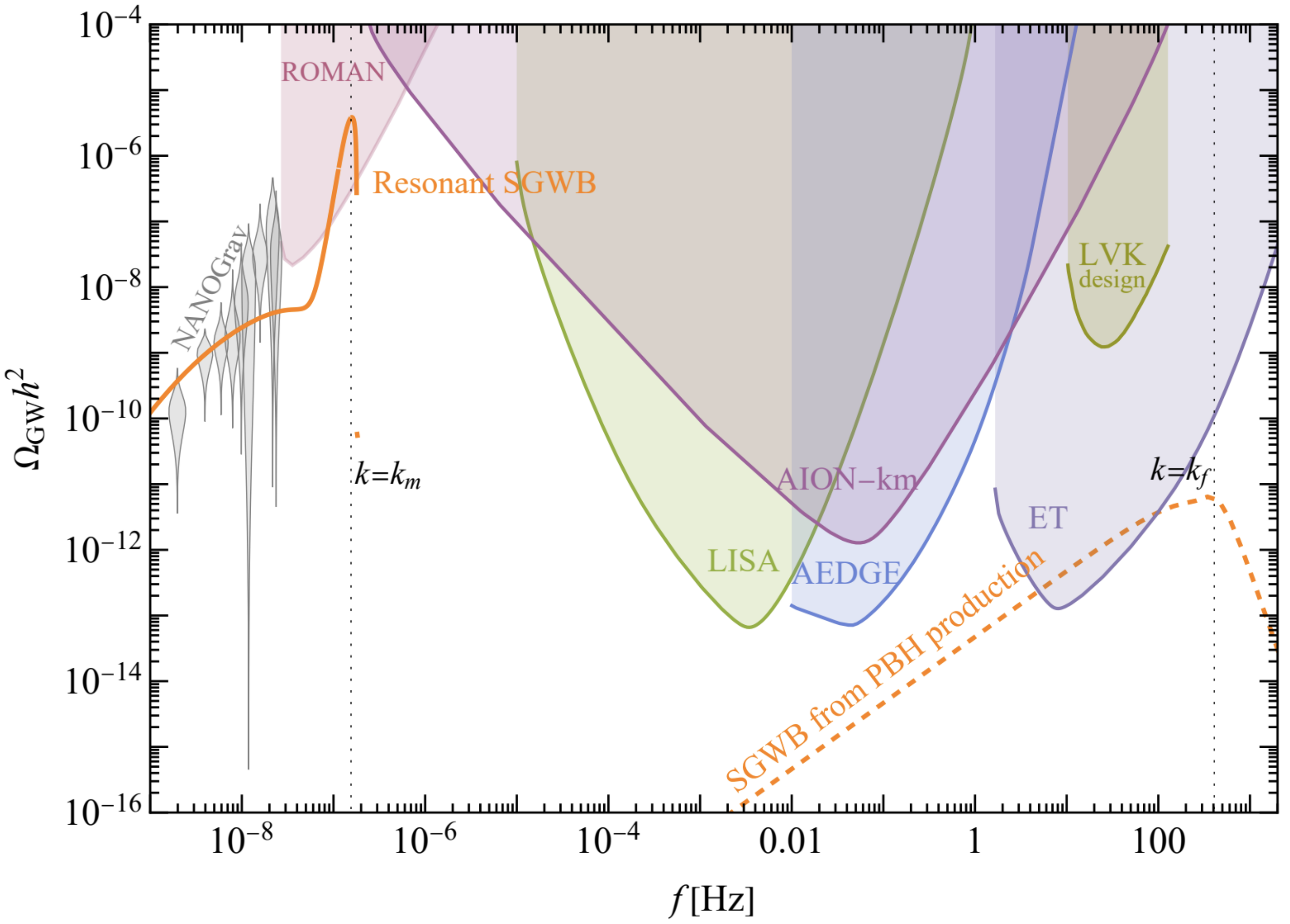


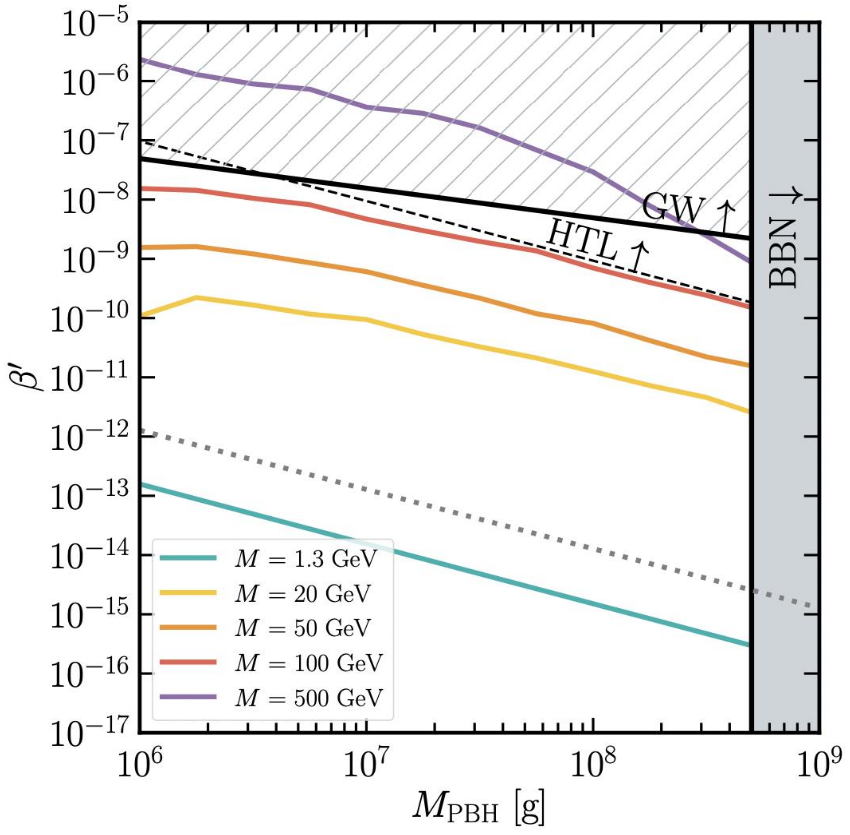


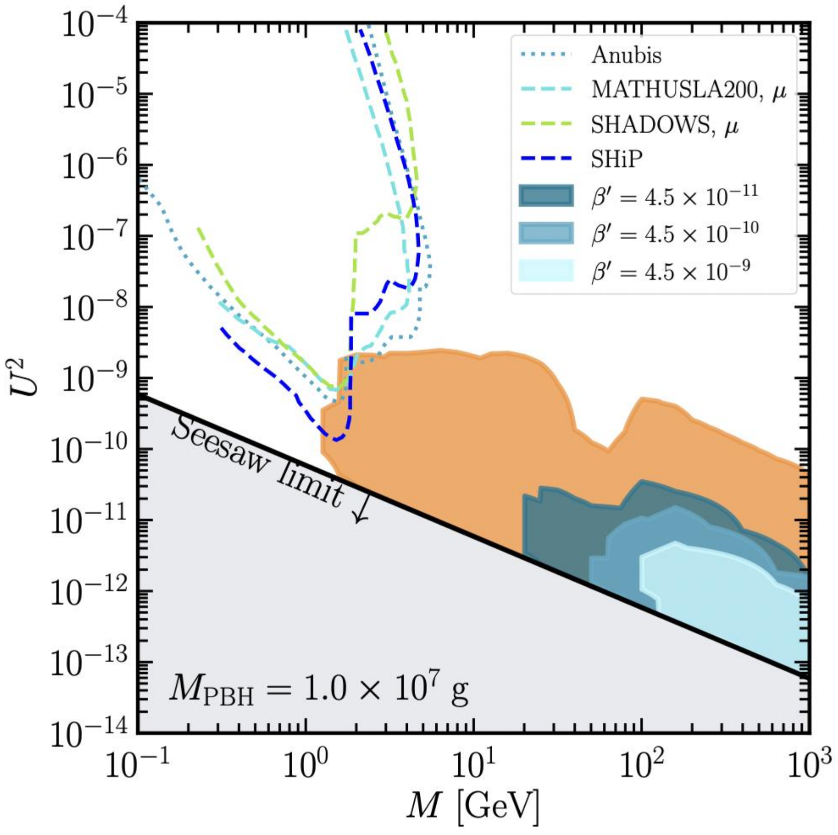
Hope on the Gravitational Wave horizon?



Bhaumik, Jain, Lewicki

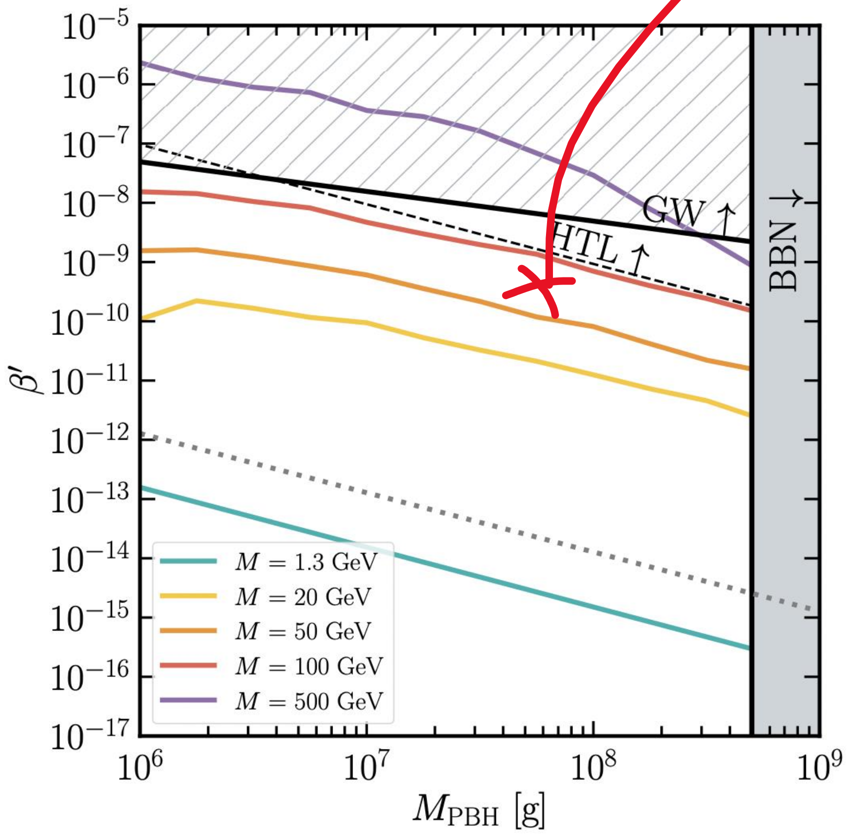
Interpretation

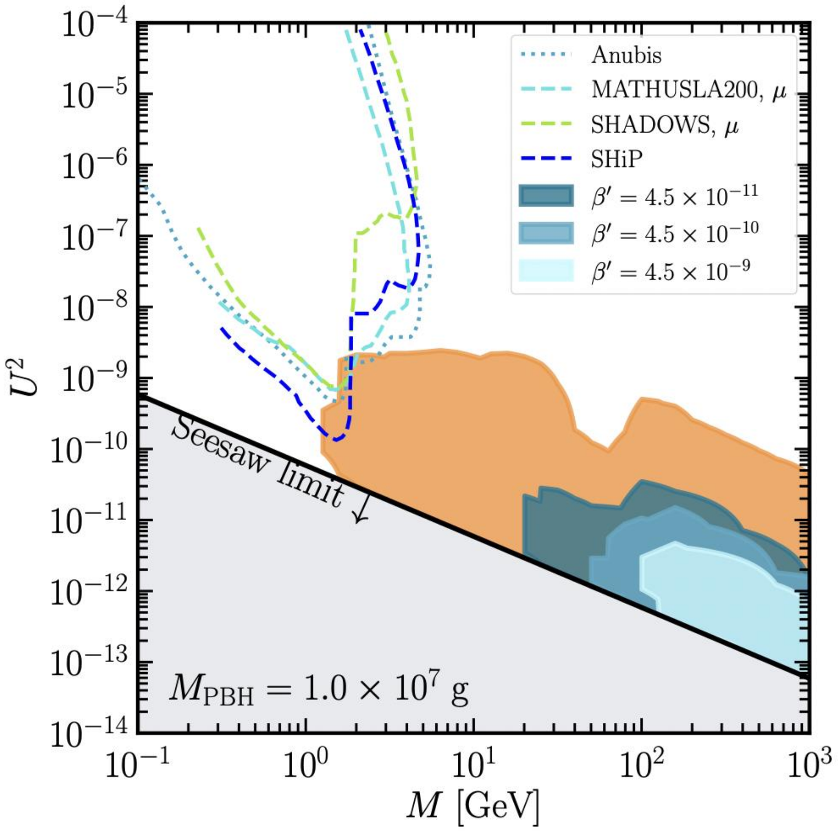




Interpretation

Detection? (GW observations)





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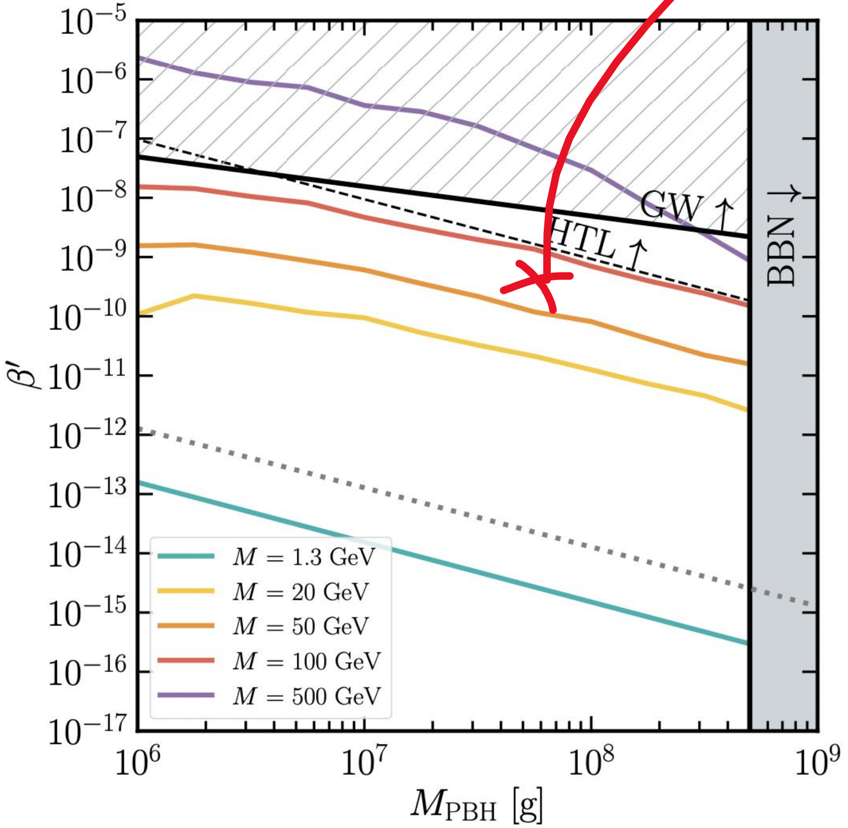
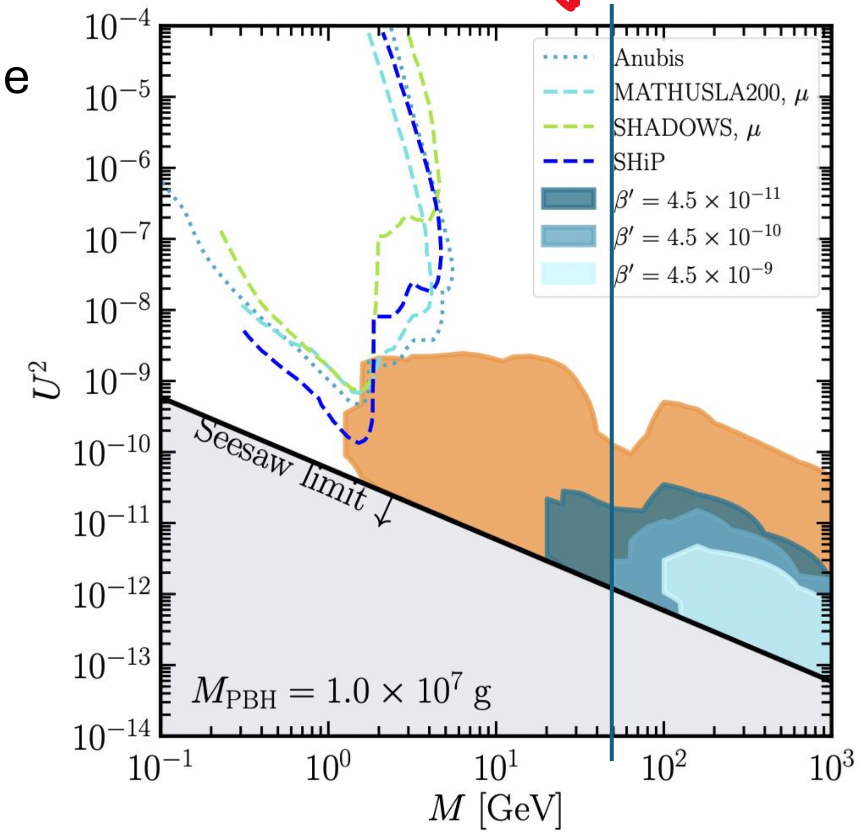


Information in the PBH space is translated into HNL searches



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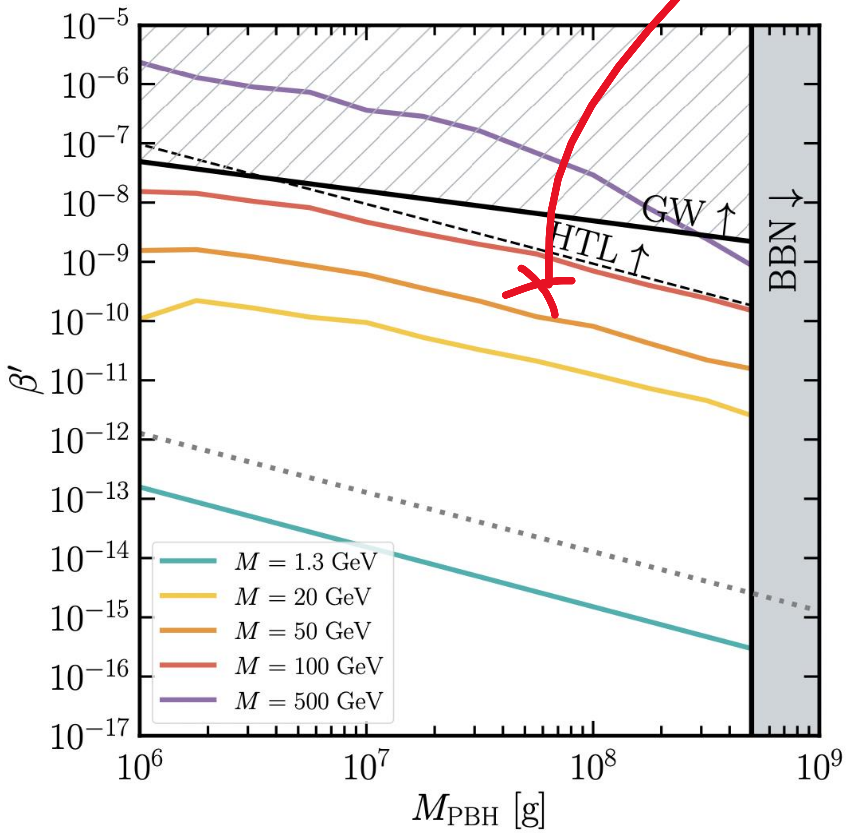

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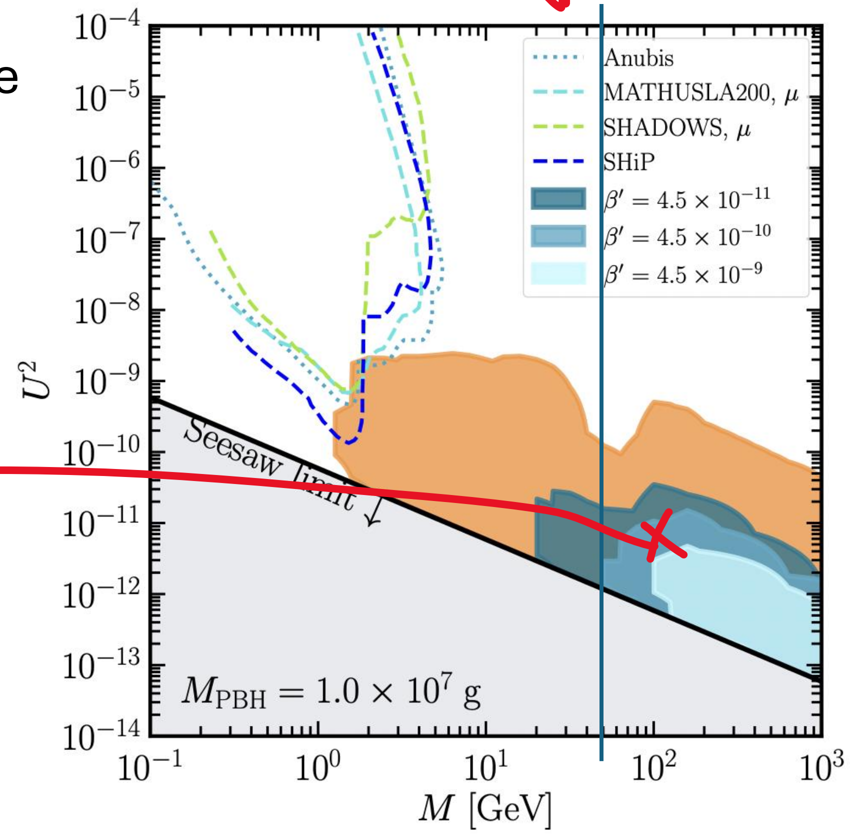

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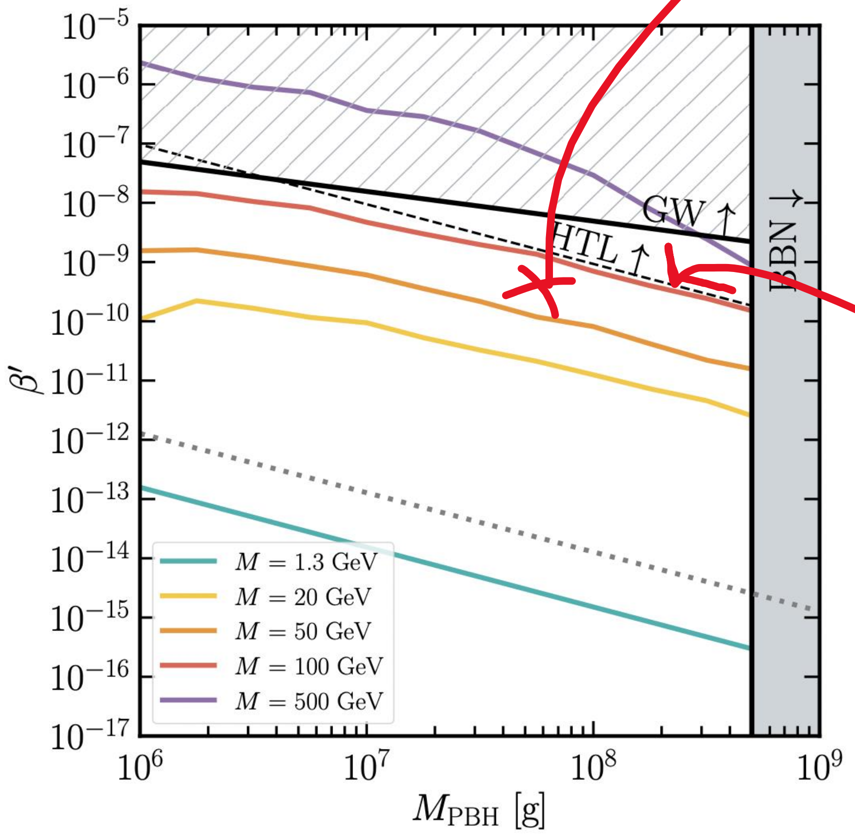
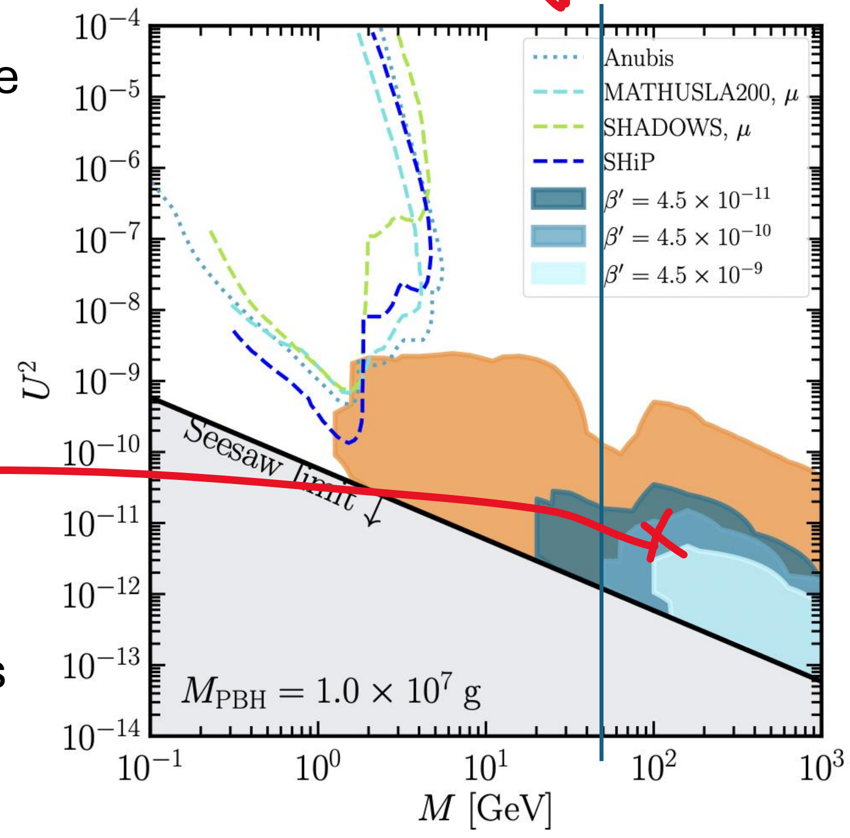


Information in the PBH space is translated into HNL searches

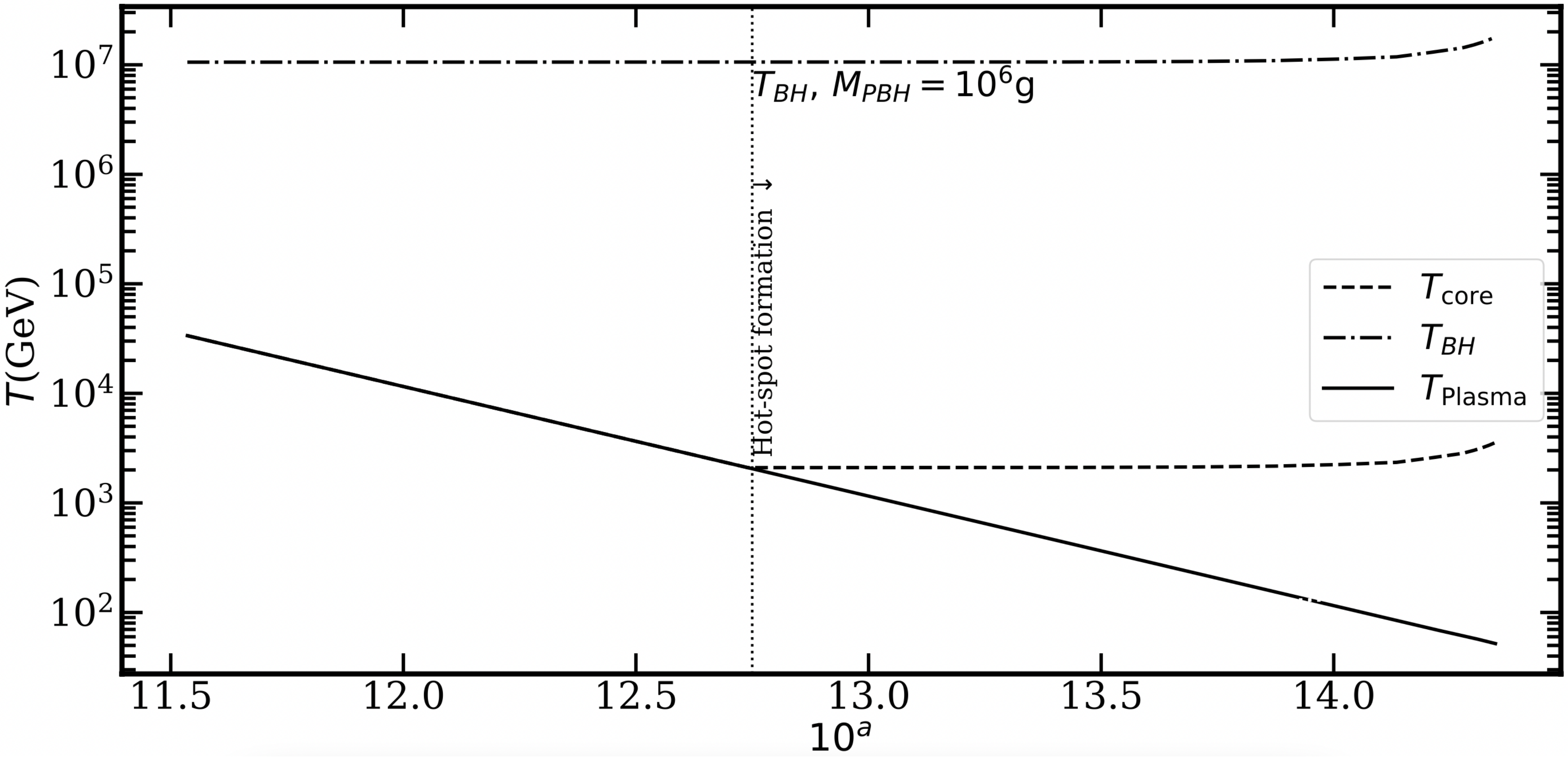
Detection? (HNL search)

Information in leptogenesis parameter space is translated into PBH constraints



PBH Hot-spots formation

Hawking radiation deposits energy at particular r



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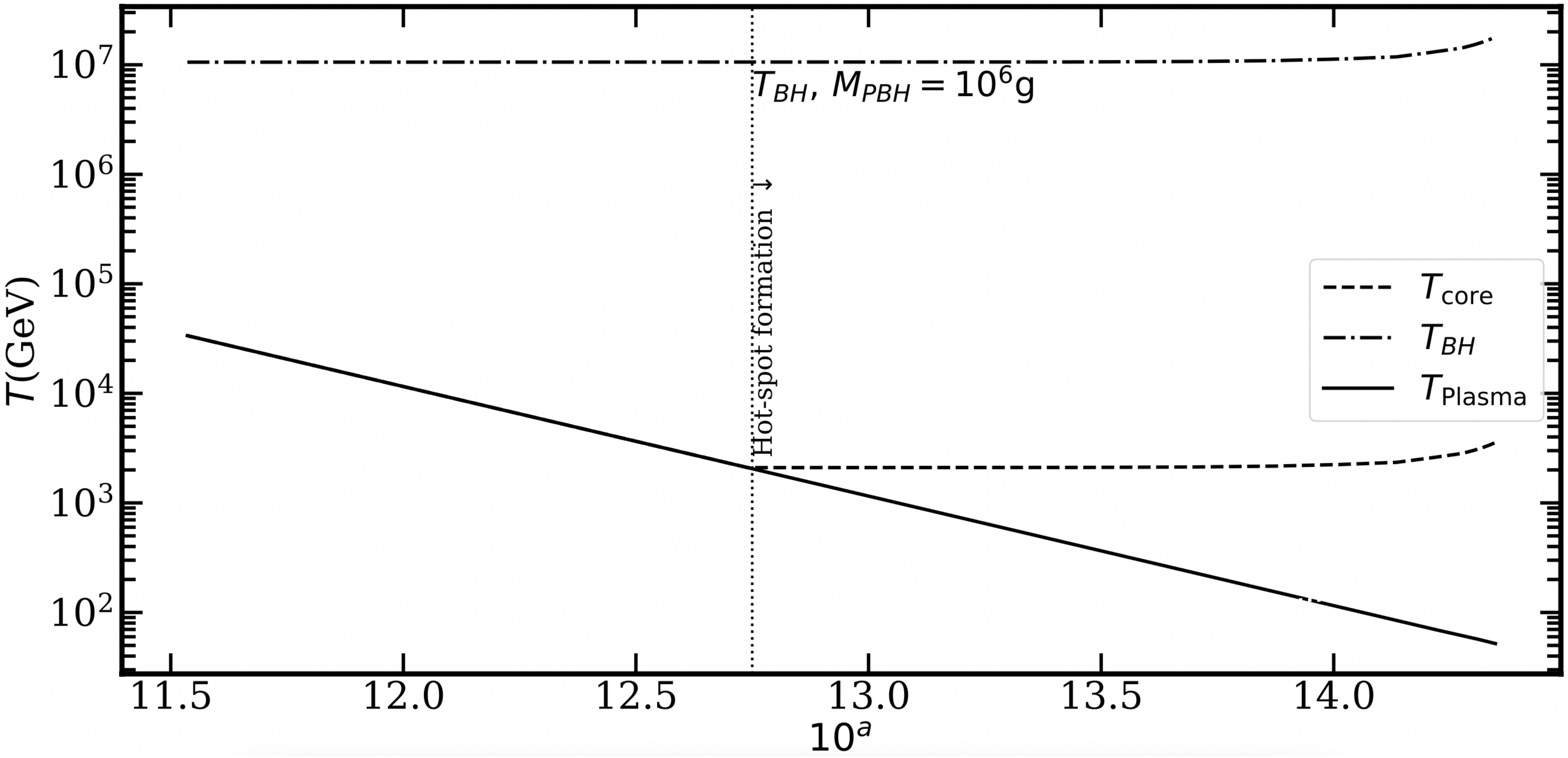
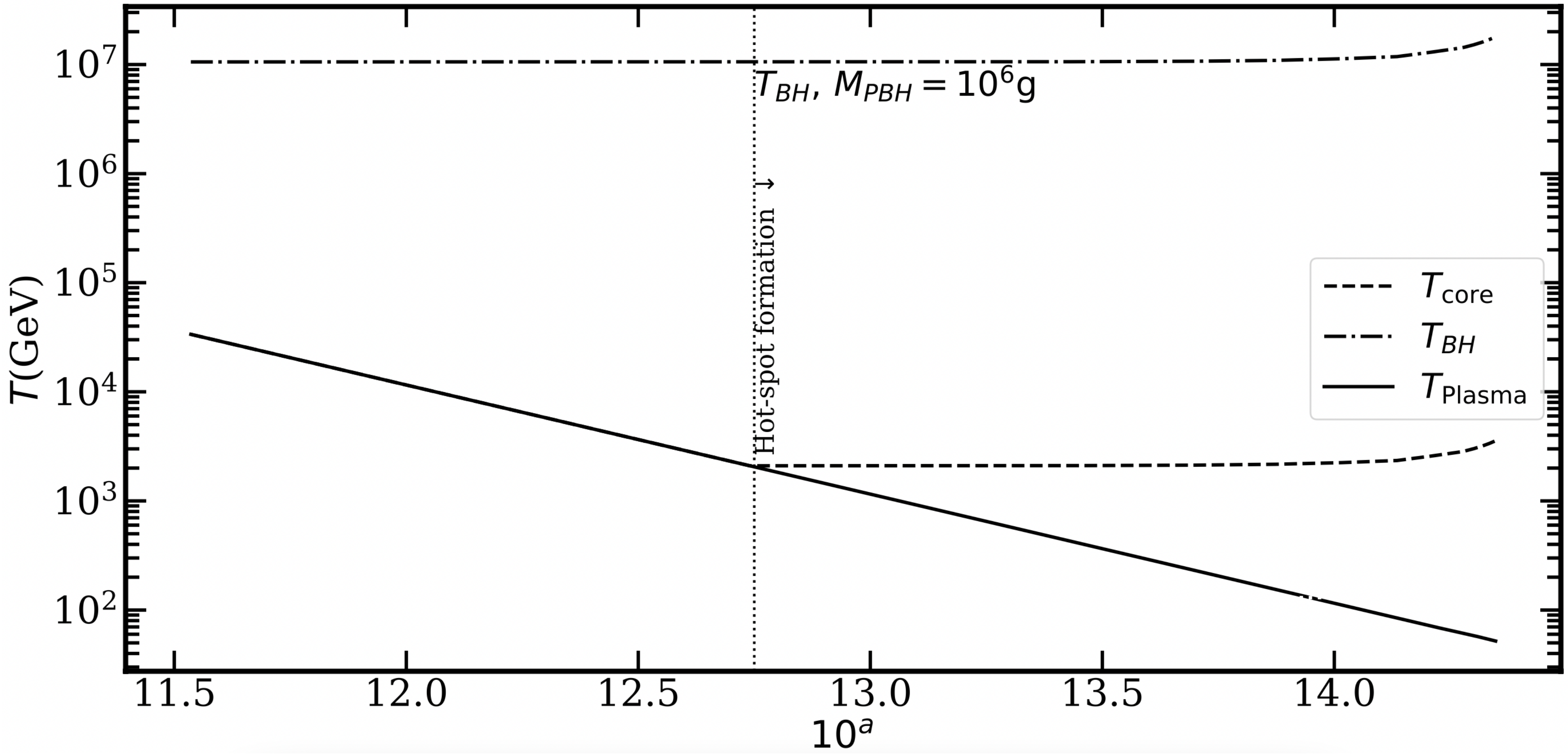
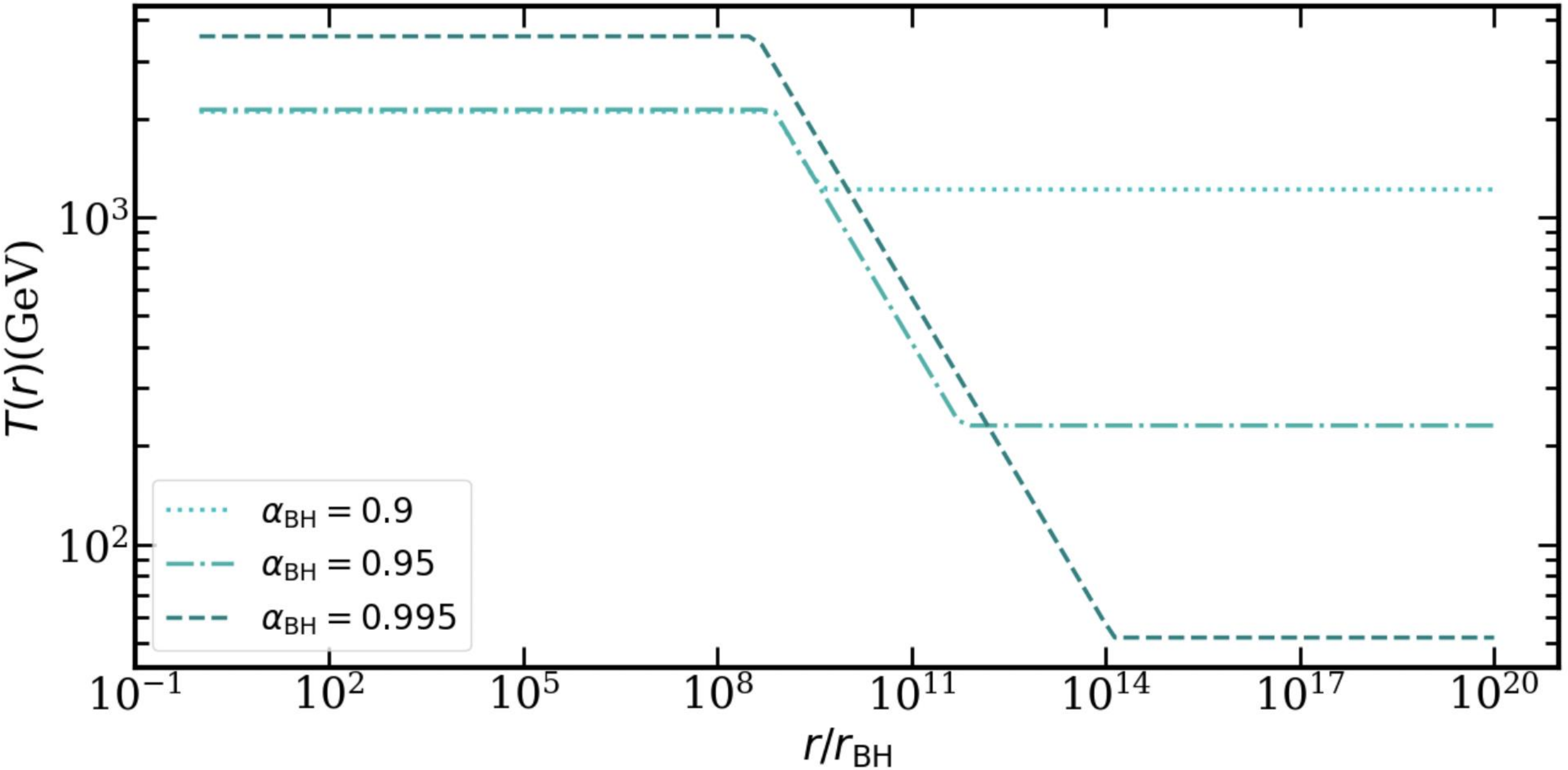


PBH Hot-spots formation

Hawking radiation deposits energy at particular r → Deposited energy diffuses by random-walk → Local temperature diverges



PBH Hot-spot profiles



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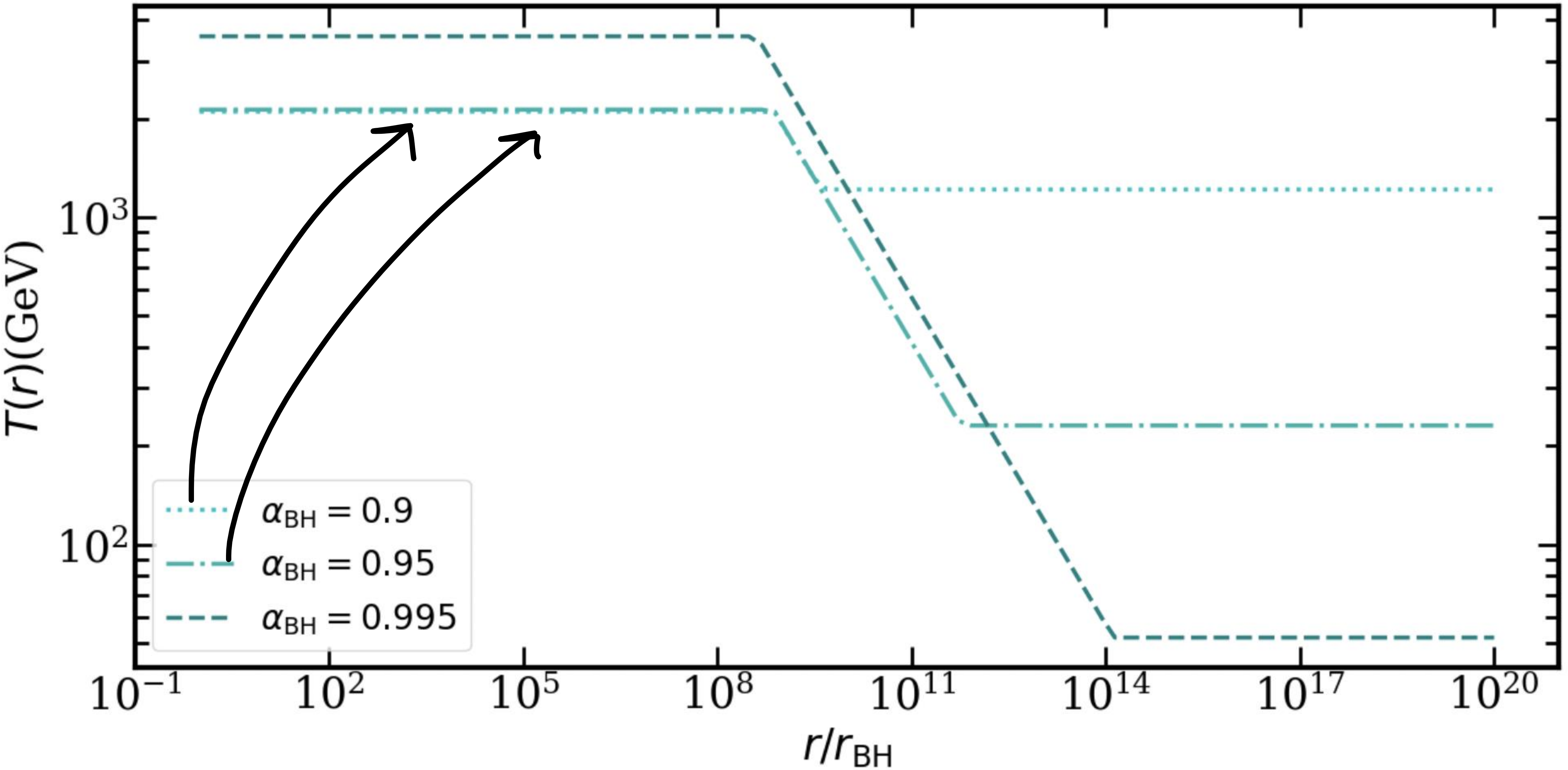

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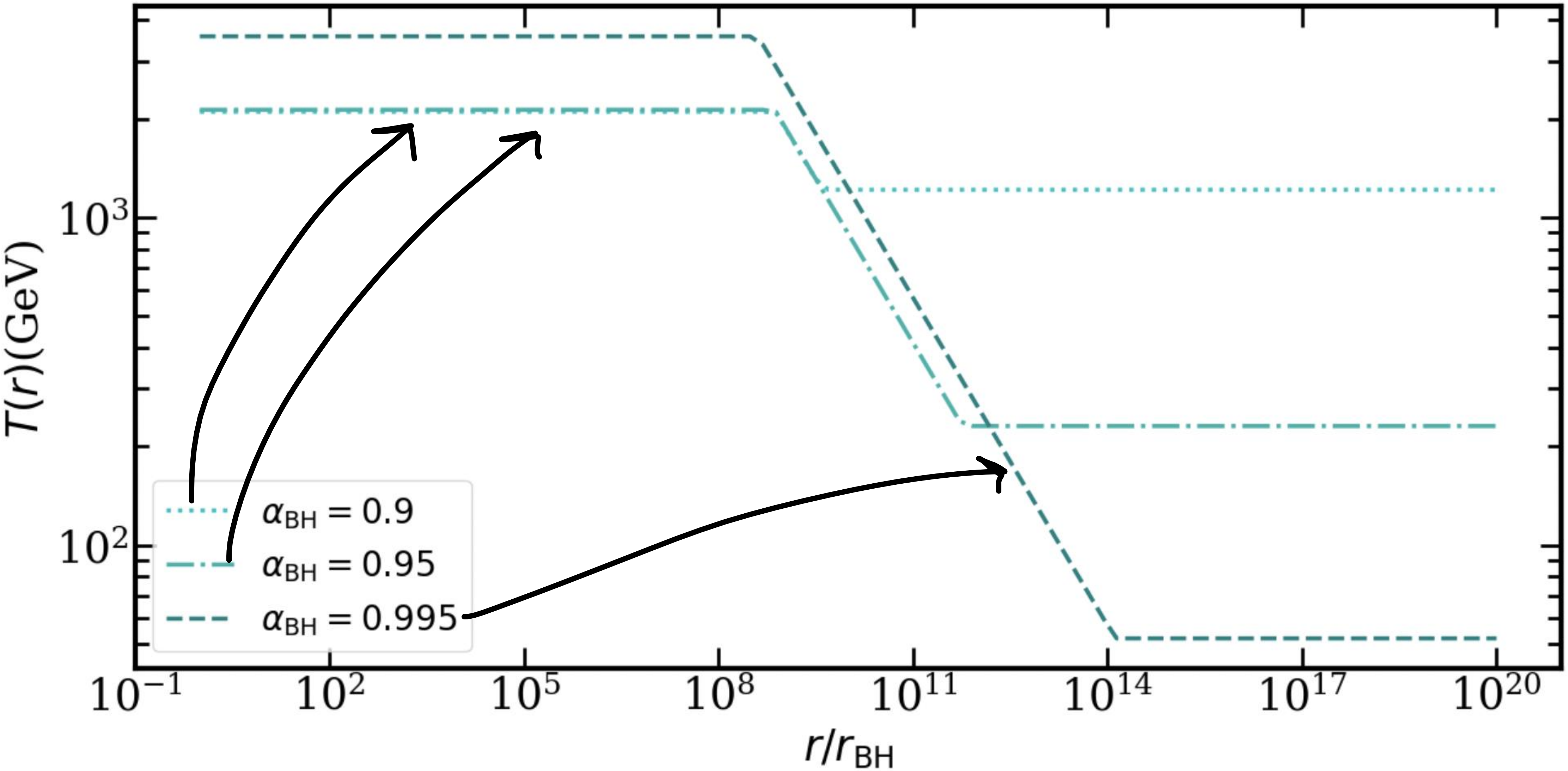

Can Hawking Radiation escape Hot-spots?

$$\lambda(T(r)) = \frac{1}{\Gamma_X(T(r))}$$

$$\Gamma_X(r) = \Gamma_S(r) + \Gamma_D(r)$$

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$$P(\lambda) \equiv \frac{1}{2}$$

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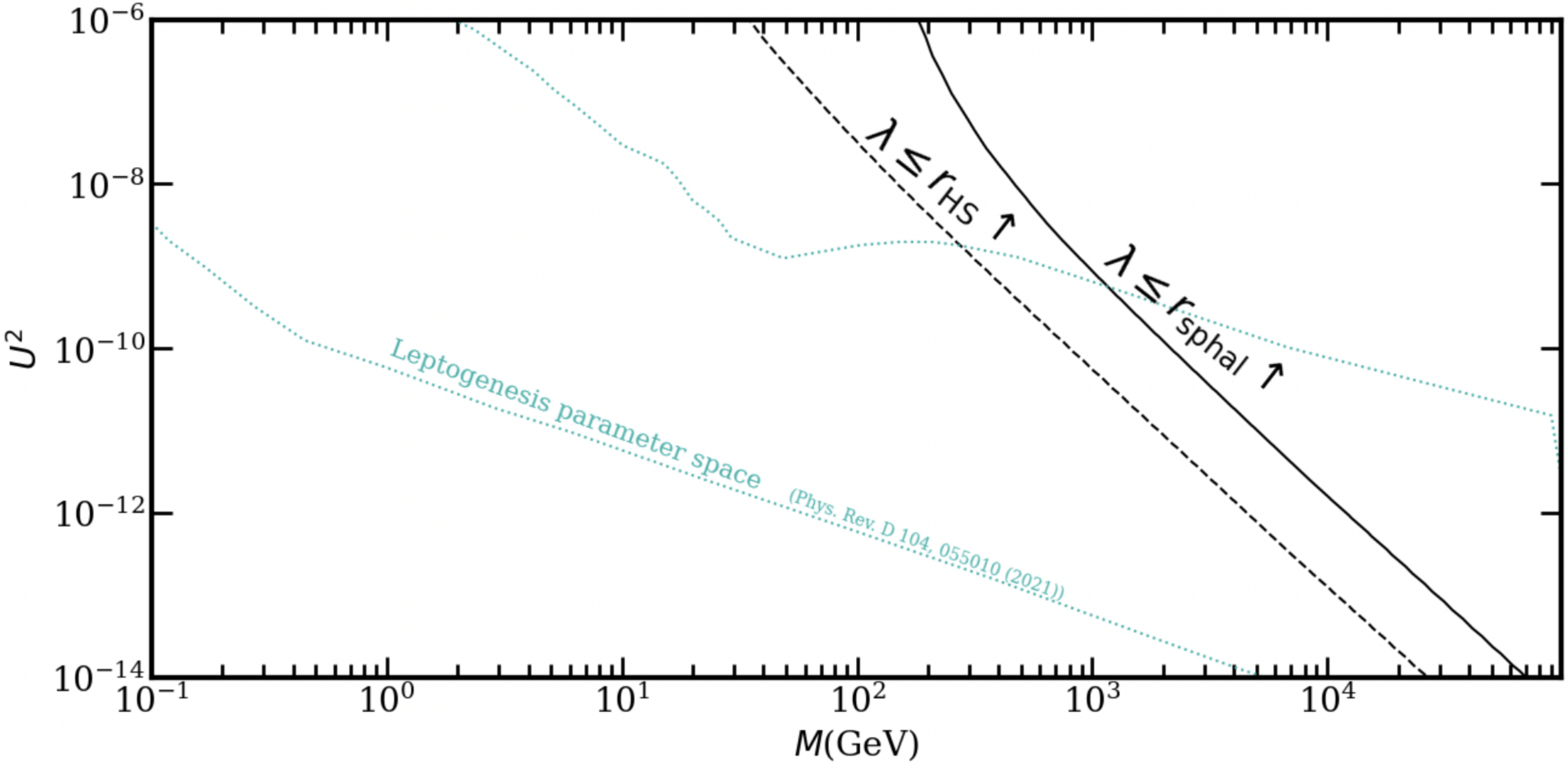

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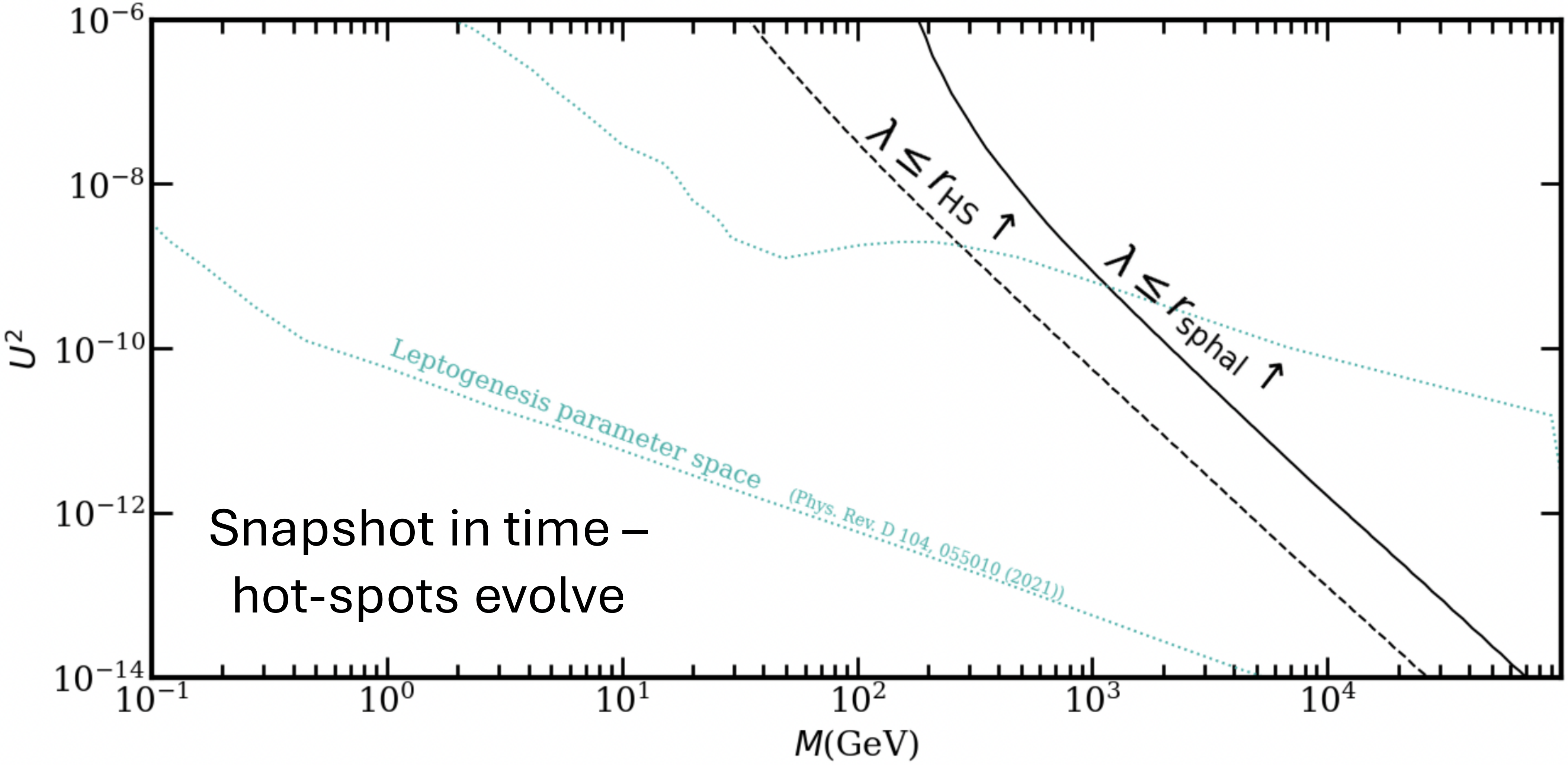

Can Hawking Radiation escape Hot-spots?

$$\mathcal{N}_X^{\mathrm{escape}} = \int_{\alpha_{\mathrm{form}}}^{\alpha_{\mathrm{evap}}} \frac{\log(10)}{H} P(r_{\mathrm{HS}}) \Gamma_{\mathrm{PBH}\to\mathrm{X}} \mathrm{d}\alpha$$

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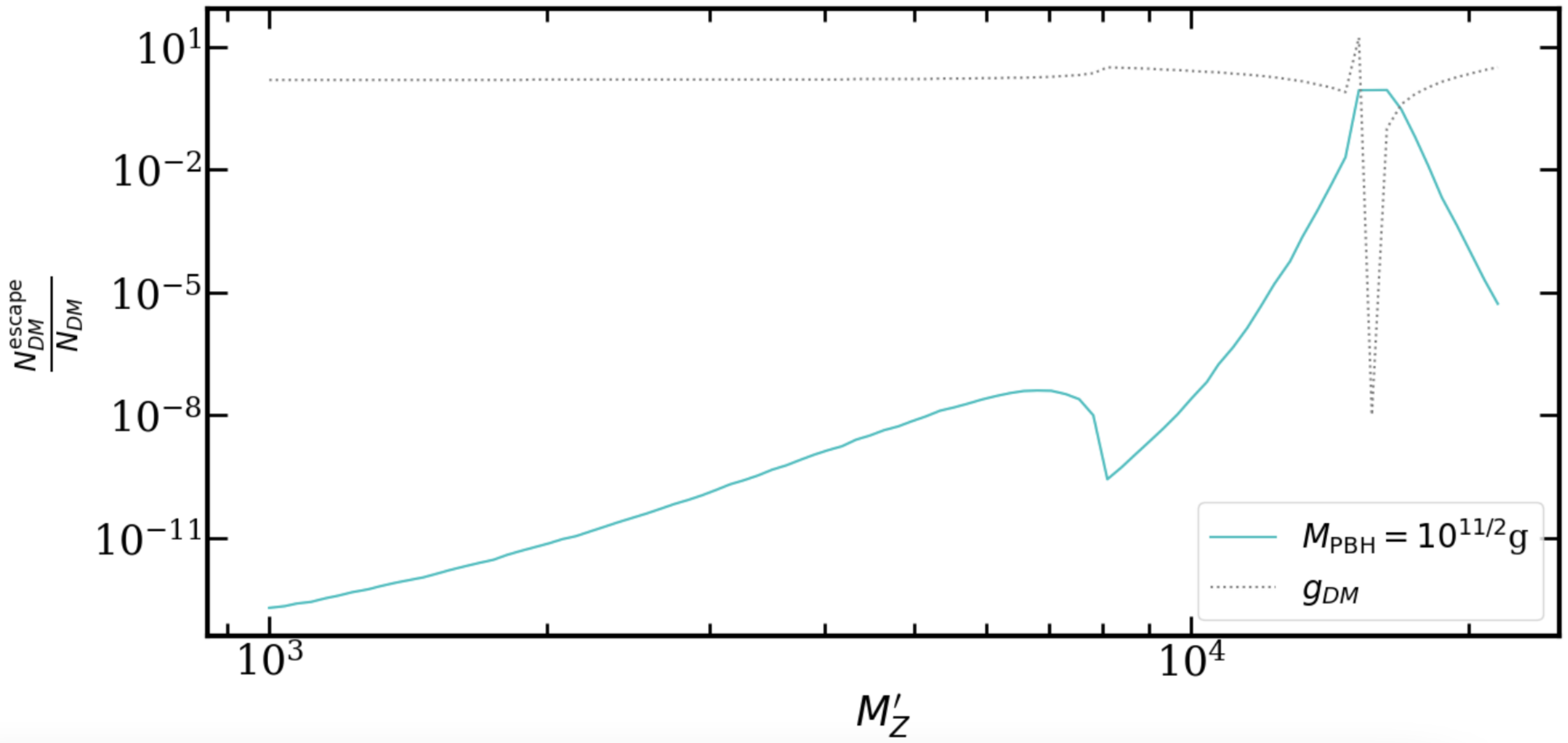
Integrate over lifetime of Hot-Spot

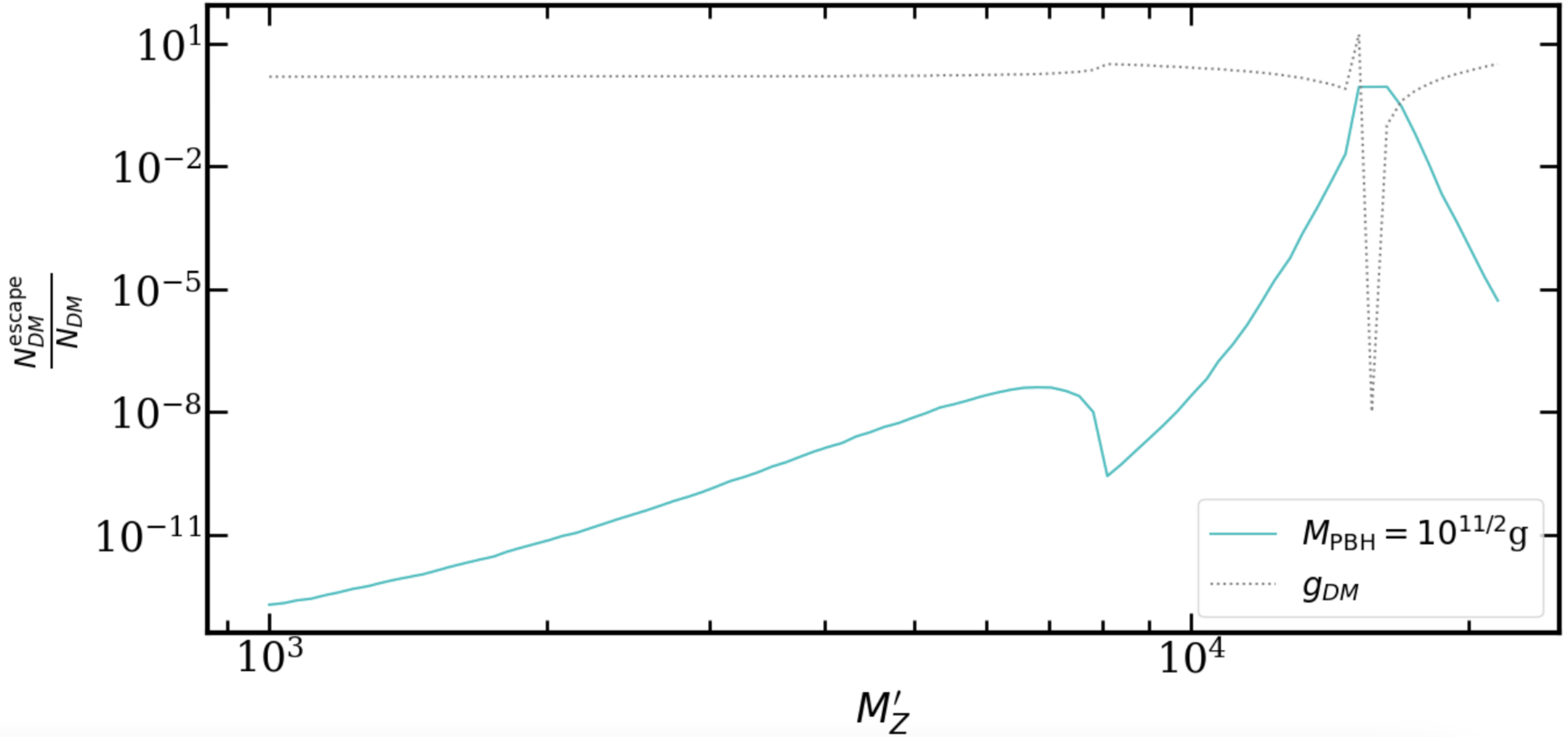
Rate of production of X by PBH

Can Hawking Radiation escape Hot-Spots



Can Hawking Radiation escape Hot-Spots

DM in this region is largely absorbed by the hot-spot and should not contribute to relic density



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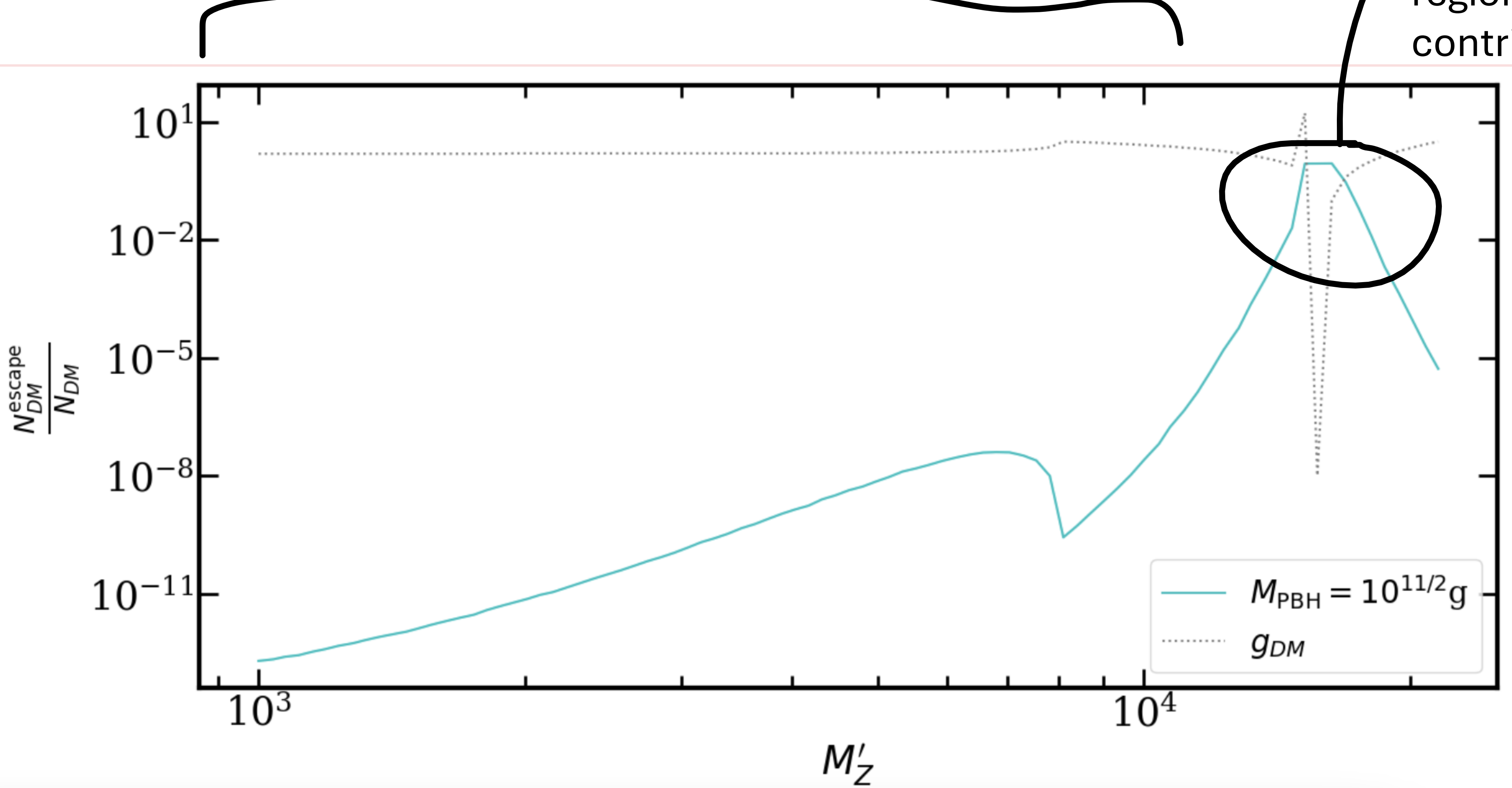
Almost all DM in this region escapes and contributes



Outlook

Where are PBHs incompatible with alternative mechanisms of baryogenesis (type-2 seesaw, GUT baryogenesis)

Does the standard treatment of entropy injection need modification in the presence of hot-spots?

How do hot-spots cool after PBH evaporation?

Is Hawking radiation ever able to equilibriate across the entire universe?

Type-1 Seesaw Mechanism – Neutrino Mass

$$\mathcal{L}_{\text{seesaw}} = \frac{1}{2}\bar{N}_i^c \hat{M}_{ij} N_j - Y_{\ell i} \bar{L}_\ell \tilde{\phi} N_i + \text{h.c.},$$

SM is extended by at least two gauge singlet Right Handed Neutrinos (RHNs)

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EWSB $\quad m_D \ll M_N$

$$m_\nu \approx -v_{\rm EW}^2 Y M_N^{-1} Y^T$$

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Provides mechanism of neutrino mass generation

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$$\mathcal{L}_{\rm seesaw} = \frac{1}{2}\bar{N}_i^c \hat{M}_{ij} N_j - Y_{\ell i}\bar{L}_\ell \tilde{\phi} N_i + \text{h.c.},$$

EWSB $\quad m_D \ll M_N$

$$m_\nu \approx -v_{\rm EW}^2 Y M_N^{-1} Y^T$$

SM is extended by at least two gauge singlet Right Handed Neutrinos (RHNs)

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Fits neutrino mass splitting and mixing data

$$\Delta m^2_{\rm sol} = m_m^2 - m_l^2$$
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free parameter

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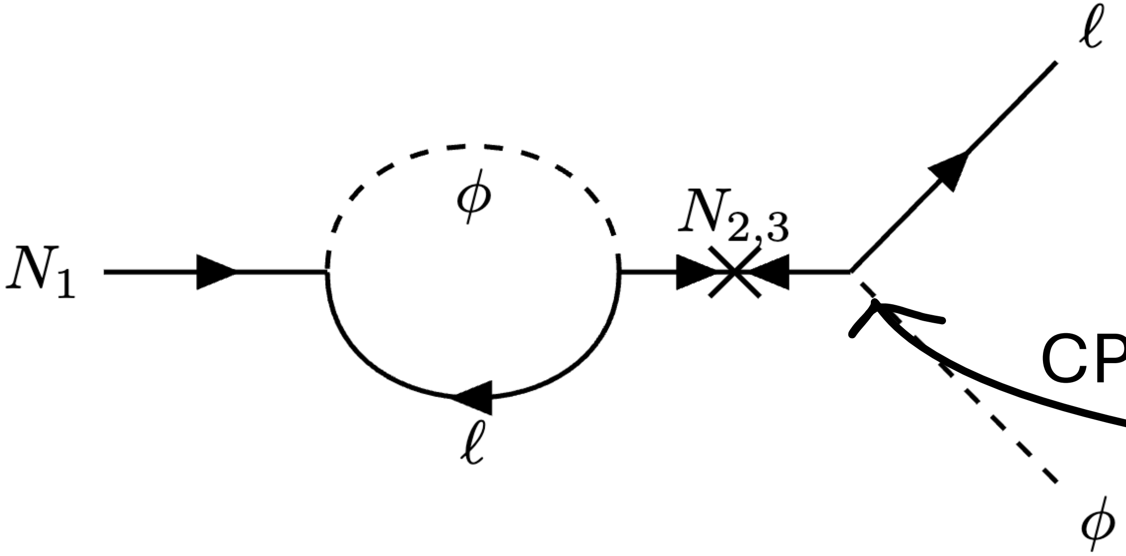

CP Violation

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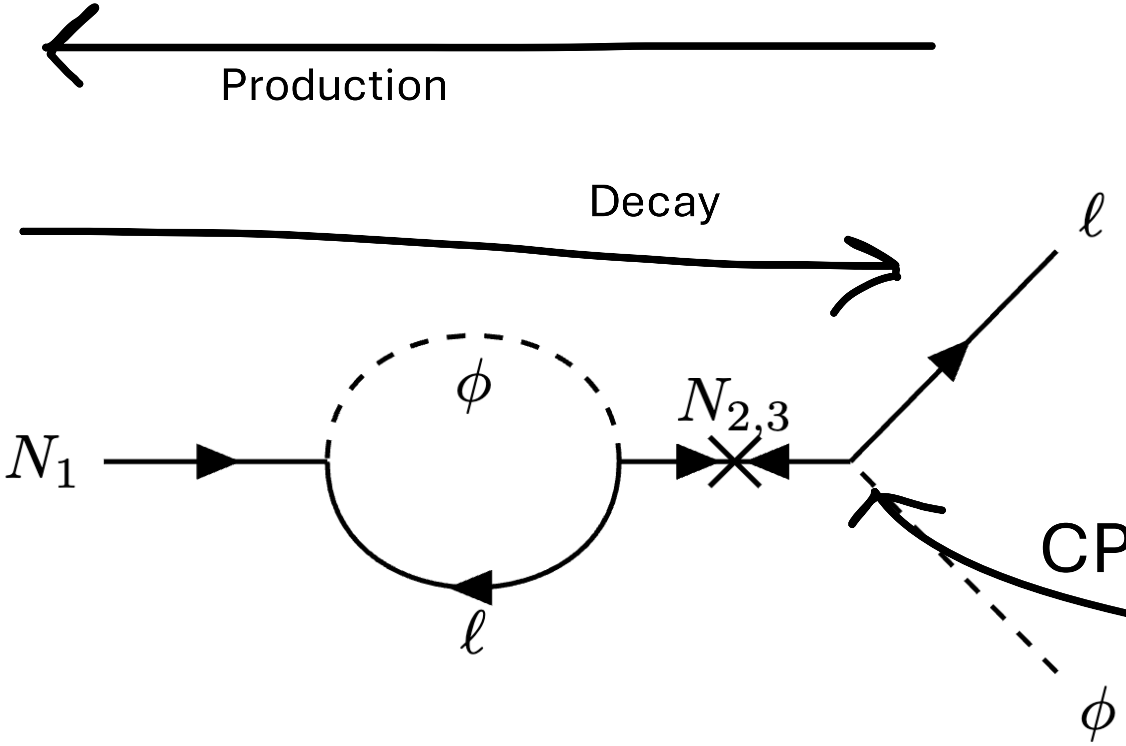

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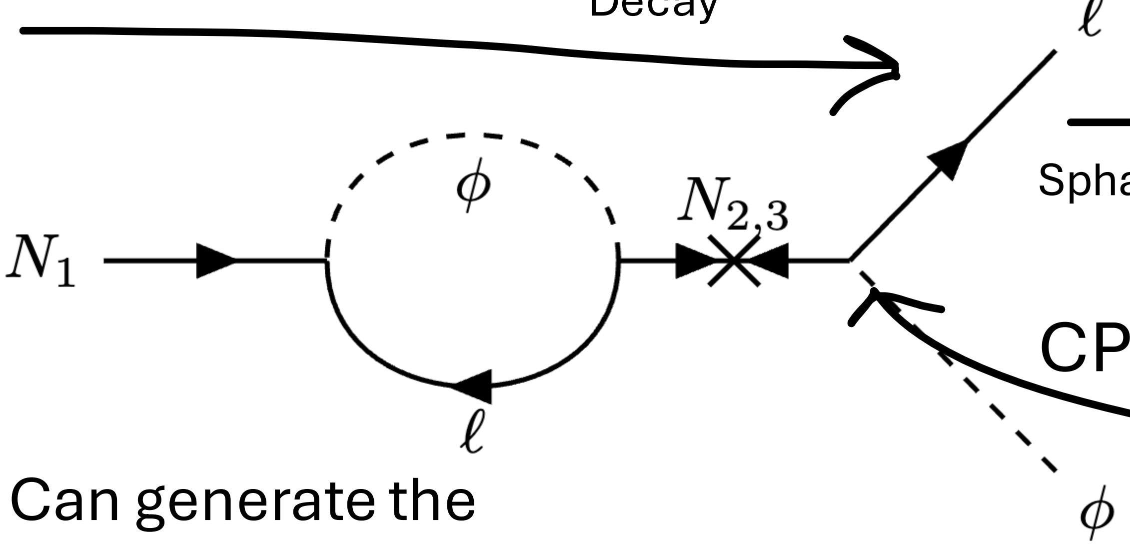
Production

Decay



Sphalerons

$$Y_B \approx \eta \frac{\mathcal{N}_L}{\mathcal{S}}$$

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CP Violation

$$z_{23} = x + i\,y$$

Can generate the Baryon asymmetry!

Leptogenesis – High Scale Models

$$\begin{pmatrix} M_{N_1} & 0 & 0 \\ 0 & M_{N_2} & 0 \\ 0 & 0 & M_{N_3} \end{pmatrix}$$

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Davidson-Ibarra limit

Far out of the reach of direct detection

Dynamics at very high scales

Fewer relevant degrees of freedom

Mass hierarchy can be arbitrary

Free parameters

Low scale

M Common RHN mass

$\frac{\Delta M_{ij}}{M}$ Mass splitting ratio

x

y Real and imaginary parts of mixing angle

m_h Mass of heaviest active neutrino

Free parameters

Low scale

M	Common RHN mass
$\frac{\Delta M_{ij}}{M}$	Mass splitting ratio
x, y	Real and imaginary parts of mixing angle
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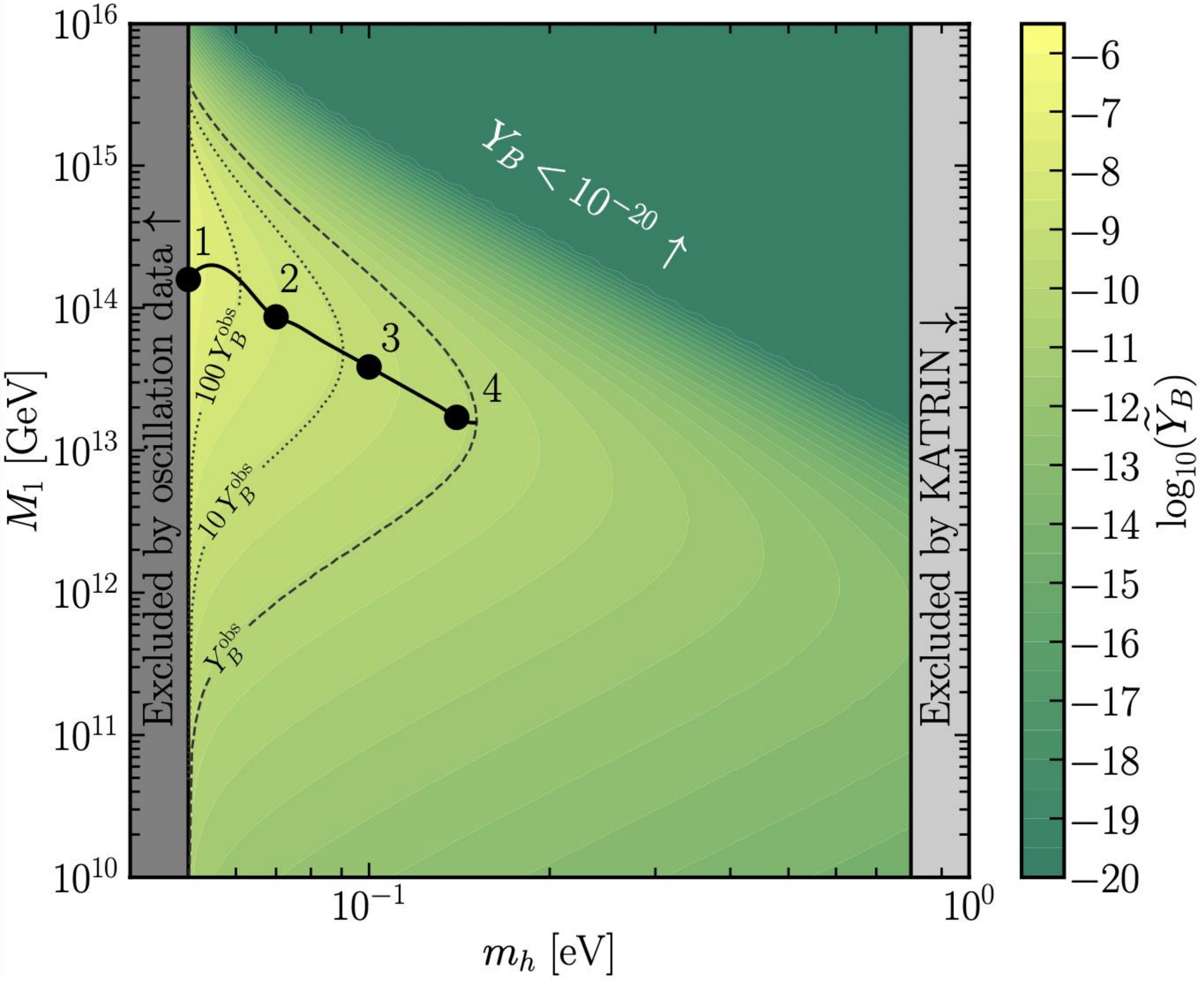
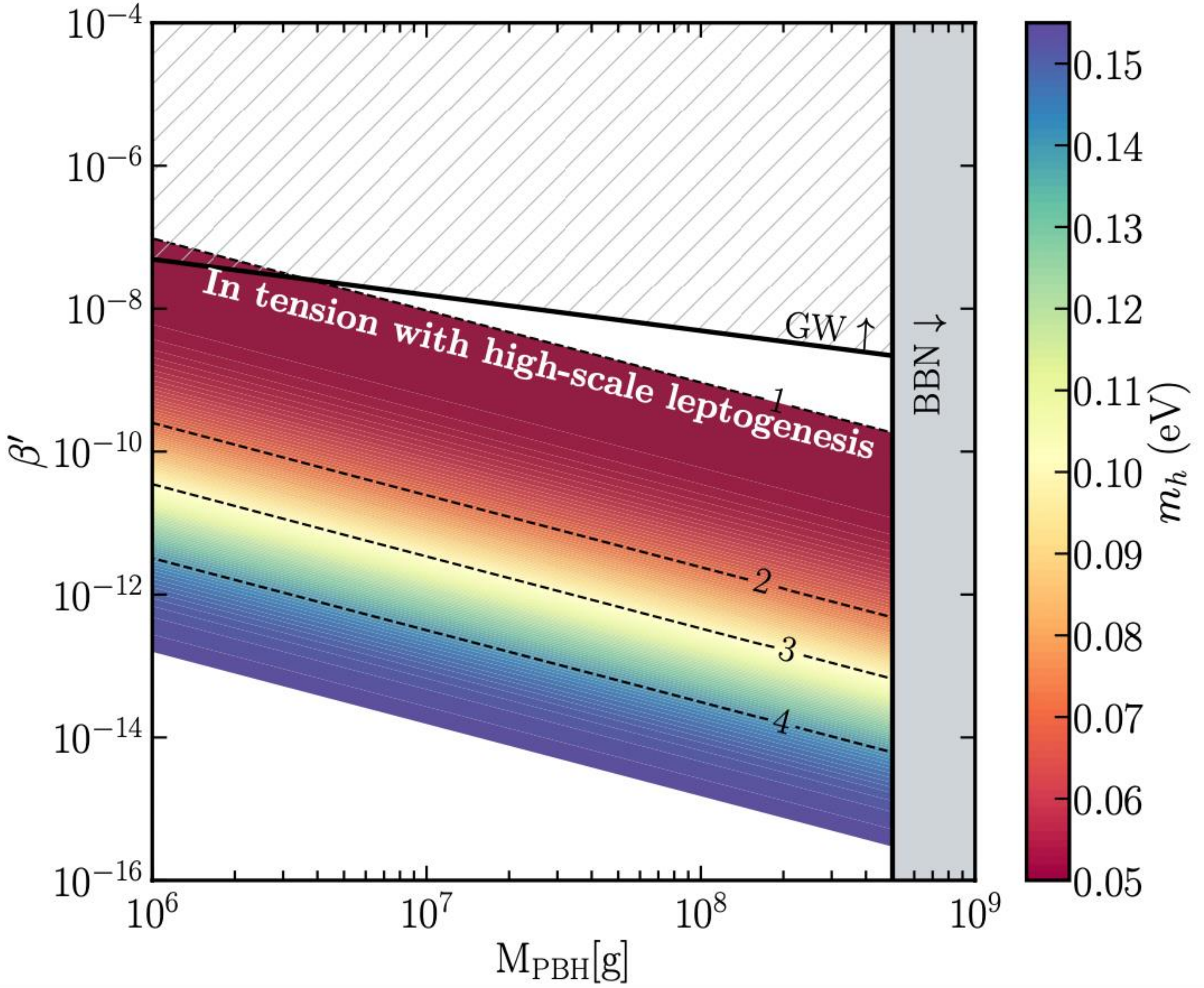
High scale

M_{N_1}	RHN mass
x, y	Real and imaginary parts of mixing angle
m_h	Mass of heaviest active neutrino

Mutual exclusion limits – High scale



High scale



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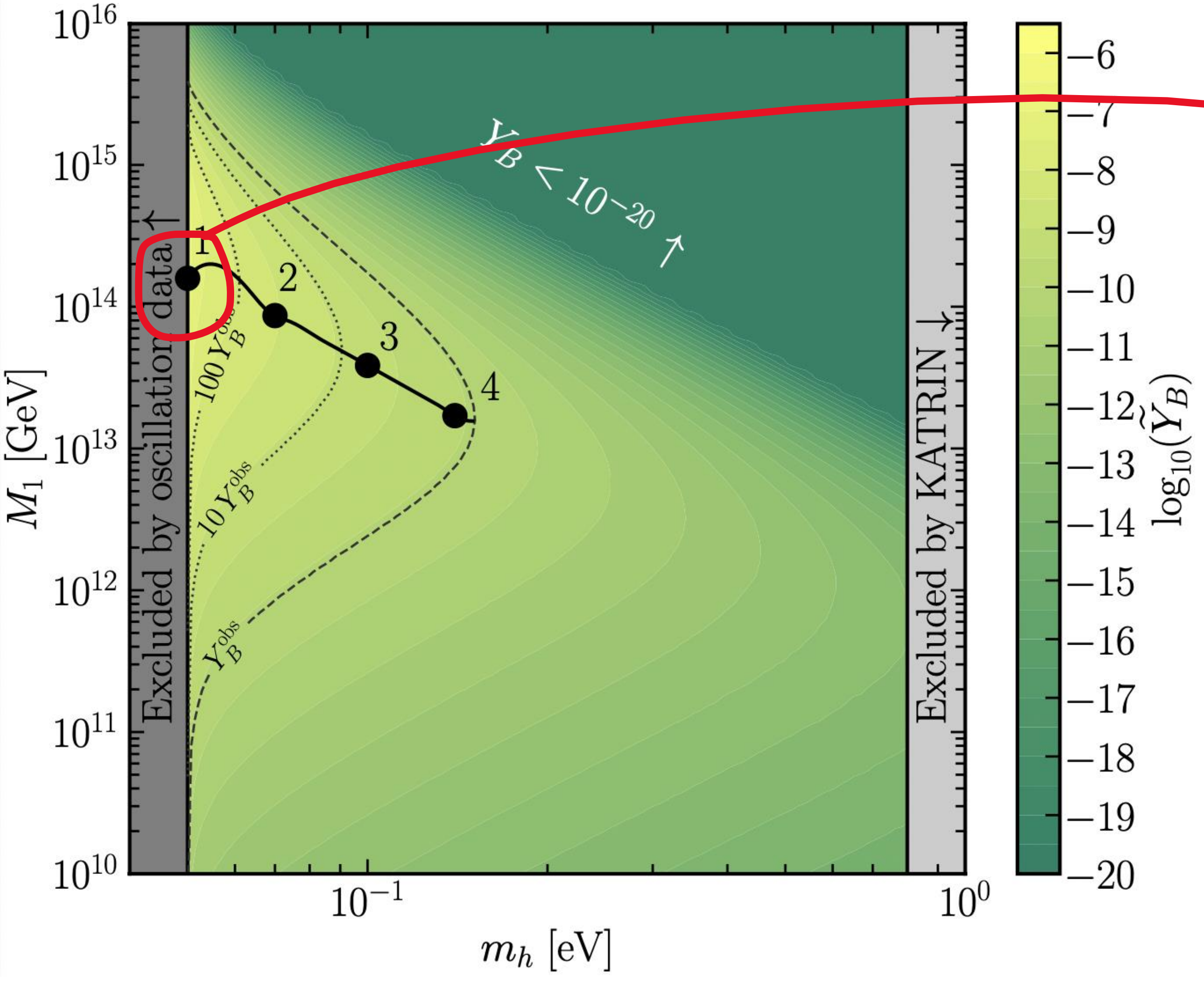
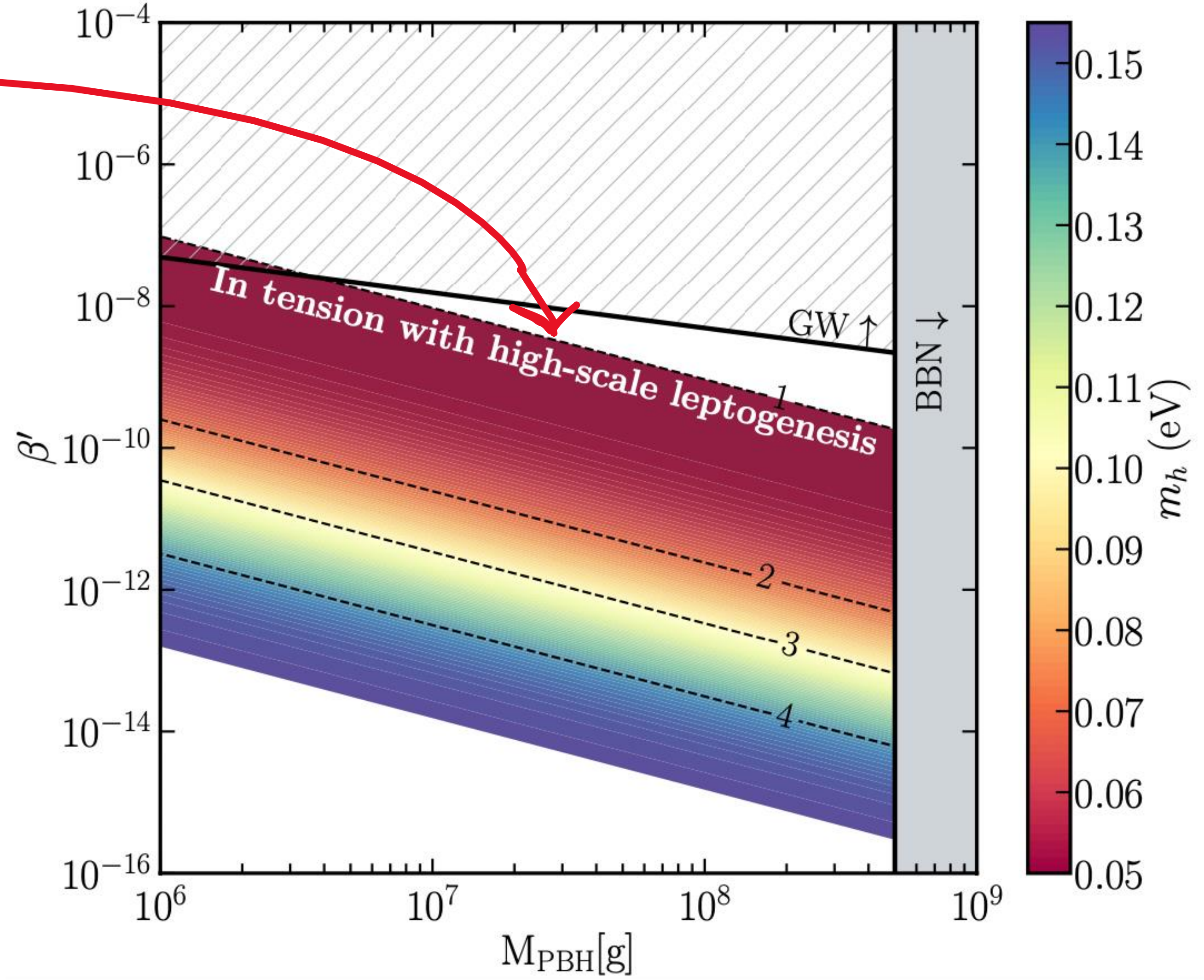


High scale



Mutual exclusion limits – High scale

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