Leptogenesis and black holes in the primordial universe

Based on:
Calabrese et al, Phys.Rev.D 107 (2023) 12, 123537
Calabrese et al, arXiv 2311.13276

Jacob Gunn, University of Naples Federico II

Type-1 Seesaw & neutrino masses

The SM is extended by 3 singlet fermions

$$\mathcal{L}_N = -\frac{1}{2}\bar{N}^c \hat{M} N - Y\bar{\ell}\tilde{\Phi}N + h.c.$$

$$\begin{pmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{pmatrix}$$

$M_1 \ll M_{2,3}$

$M_1 \approx M_2 \ll M_3$

Left handed (SM) neutrinos supplemented by right handed Majorana partners (RHNs)

Majorana mass from $10^{-2} - 10^{16}$ GeV

Yukawa coupling to SM leptons and Higgs generates active neutrino masses

$$Y = \frac{1}{v_{EW}}\sqrt{\hat{M}} \cdot R \cdot \sqrt{\hat{m}_\nu} \cdot U^\dagger_{PMNS}$$

Casas-Ibarra parameterisation, we take $\Delta m^2{}_{sol} \ll \Delta m^2{}_{atm}$ → $R = R_{13}(\theta_{13} = x + iy)$

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Type-1 Seesaw & leptogenesis

Sakharov's conditions:

CP violation

Departure from equilibrium

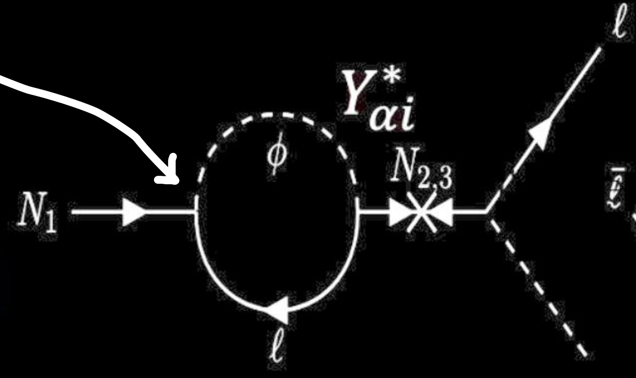
Baryon number violation

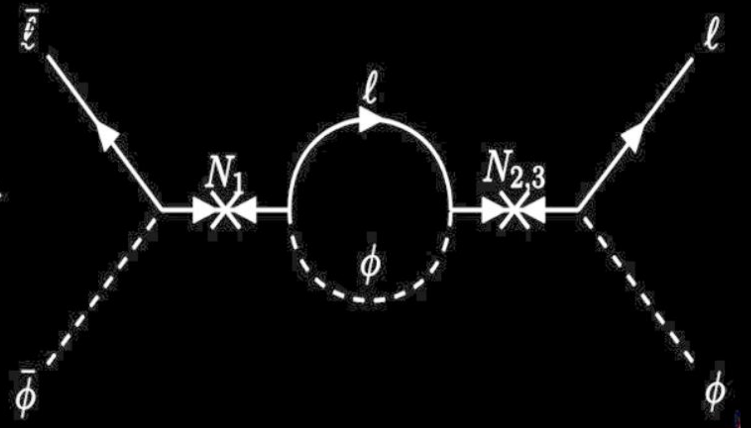
"Freeze-in" or "Freeze-out"

Depends on initial conditions

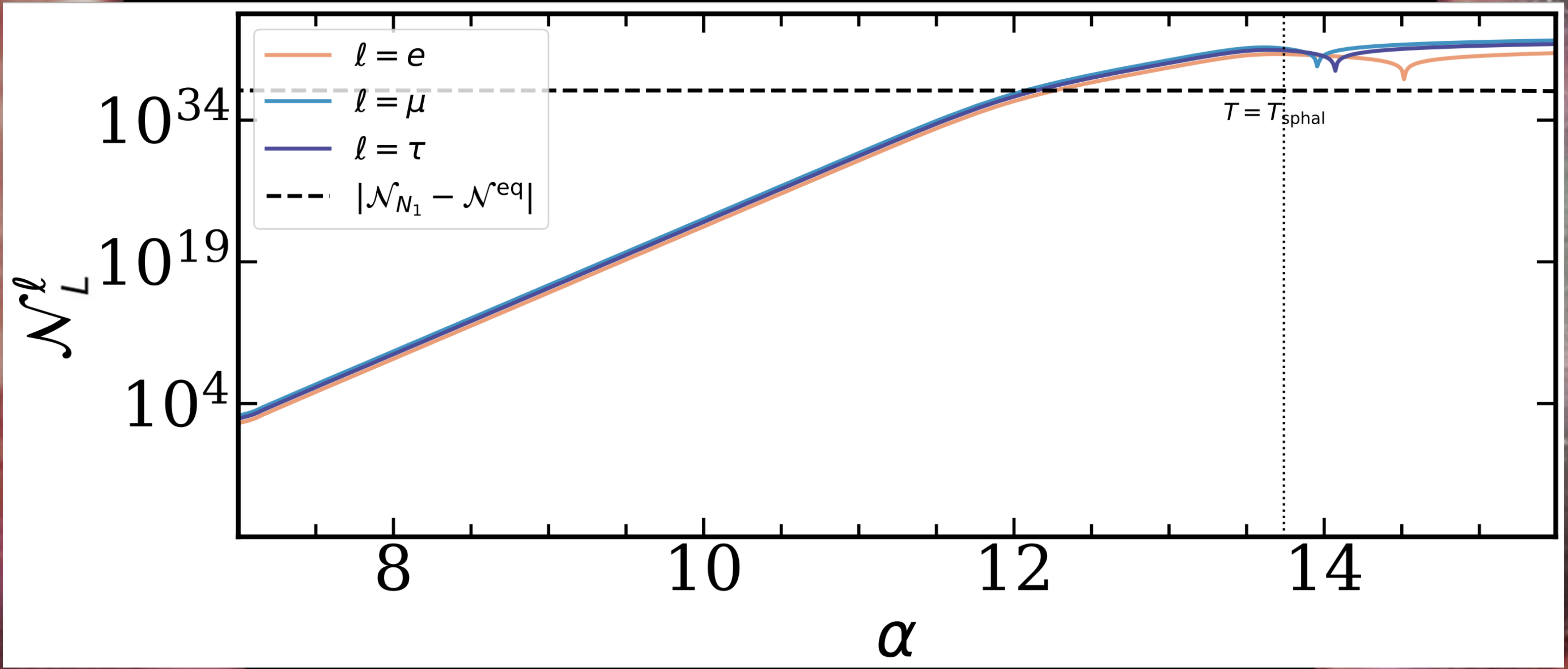
Exists in the SM at $T > T_{\text{sphal}} \approx 130\text{GeV}$

EW sphalerons violate B,L, conserve B-L.





Asymmetry generation



Models of leptogenesis

Low scale models

More easily accessible experimentally

Require some degeneracy

May freeze-in

Sensitive to flavour and thermal effects

Problem – all of these models are difficult to constrain

10^4GeV

10^{-2}GeV

10^9GeV

10^{16}GeV

Intermediate scale models

Difficult to probe with experiments

Some theoretical constraints

Not widely studied

High scale models

Very difficult to reach experimentally

No degeneracy required

Freeze-out at very early times

Insensitive to flavour effects

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$$y \to U^2\,,\; M_1$$

$10^4\,\mathrm{GeV}$

$10^{-2}\,\mathrm{GeV}$ — $10^9\,\mathrm{GeV}$ — $10^{16}\,\mathrm{GeV}$

Intermediate scale models

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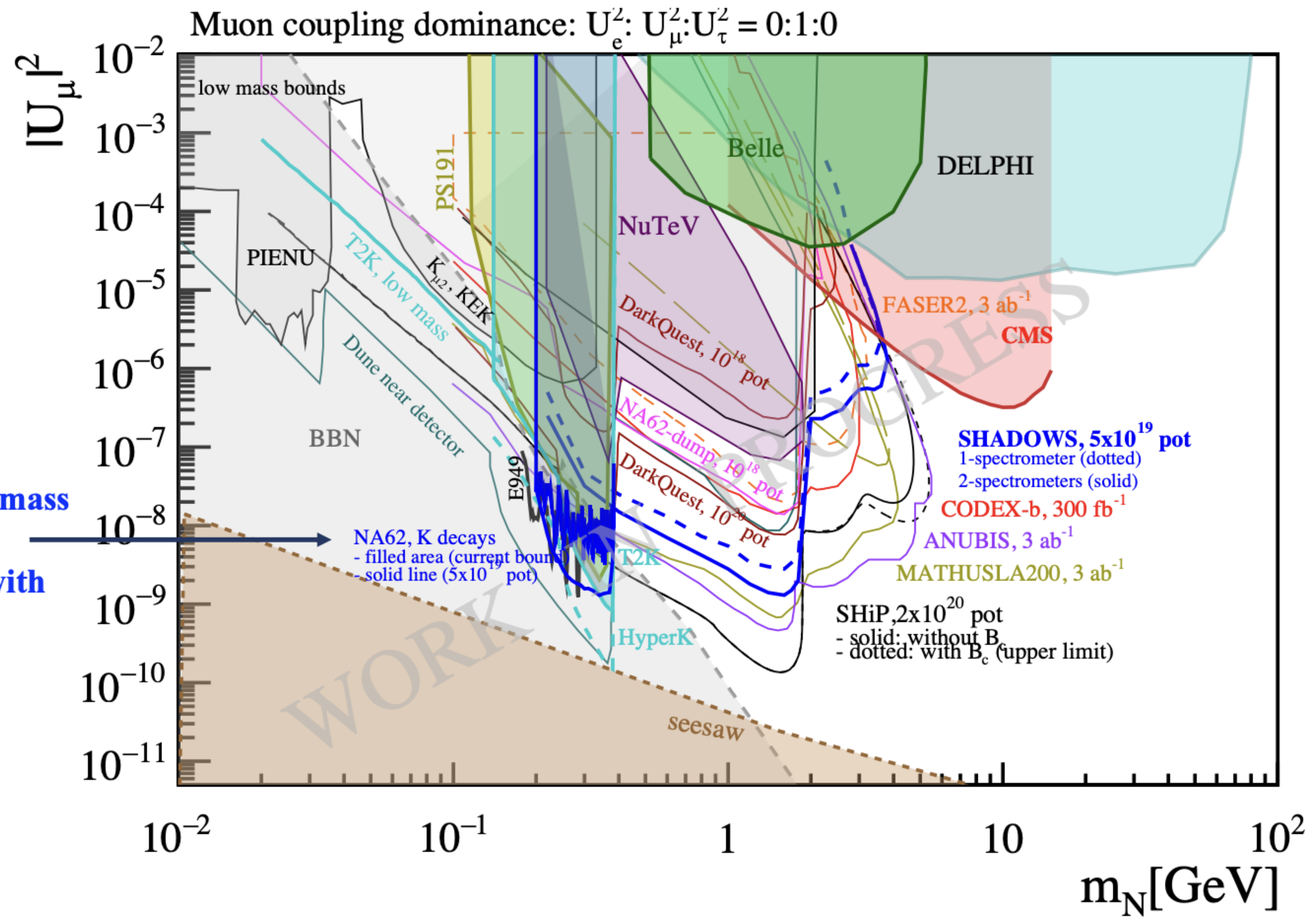
Current constraints



NA62 in K-mode covers the range below K-mass down to the seesaw limit. Strong complementarity with SHADOWS.

Lanfranchi 2022

Exploding PBHs?

Black hole explosions?

QUANTUM gravitational effects are usually ignored in calculations of the formation and evolution of black holes. The justification for this is that the radius of curvature of space-time outside the event horizon is very large compared to the Planck length $(G\hbar/c^3)^{1/2} \approx 10^{-33}$ cm, the length scale on which quantum fluctuations of the metric are expected to be of order unity. This means that the energy density of particles created by the gravitational field is small compared to the space-time curvature. Even though quantum effects may be small locally, they may still, however, add up to produce a significant effect over the lifetime of the Universe $\approx 10^{17}$ s which is very long compared to the Planck time $\approx 10^{-43}$ s.

Stephen Hawking 1974, Nature

Black holes radiate all particles – finite lifetime

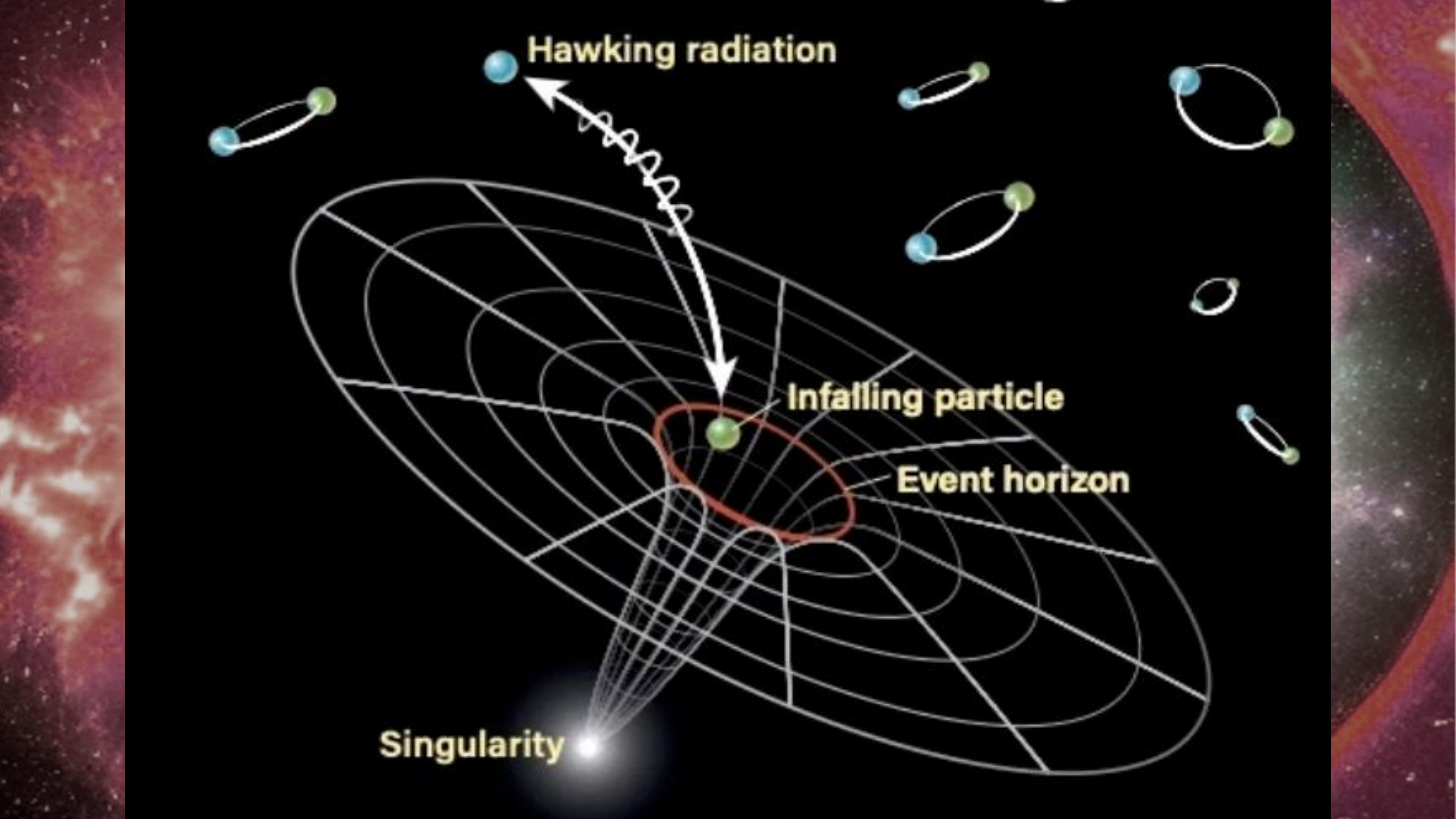
At the end of life, evaporation is extremely rapid

Essentially unobservable for stellar Black holes

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

Light (primordial) black holes evaporate extremely quickly

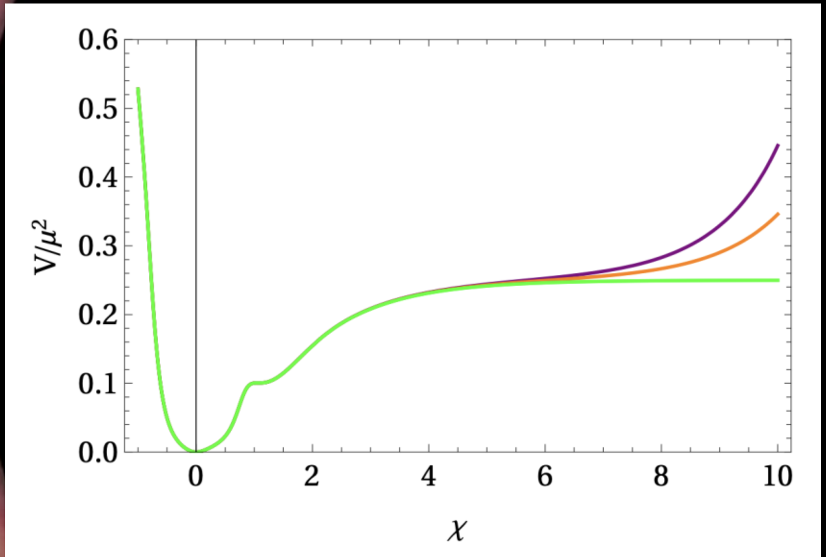
Even during leptogenesis!


Hawking radiation
Infalling particle
Event horizon
Singularity

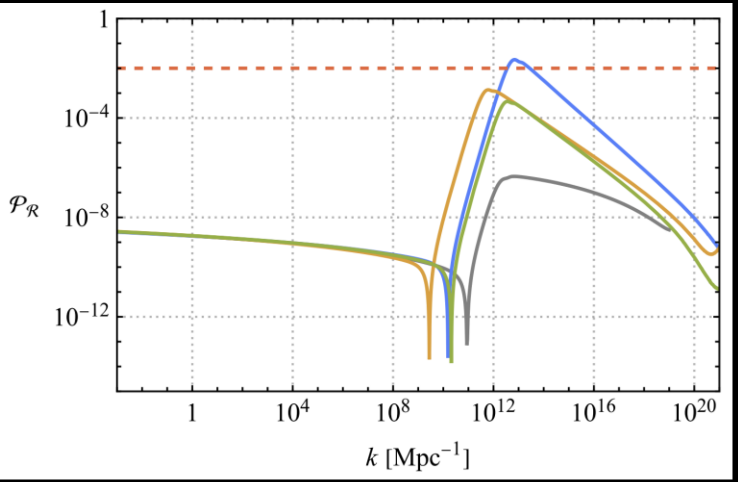
What are Primordial Black Holes?

Black Holes which form in the primordial universe!

Features in inflaton potentials



I. Dalianis, 2023



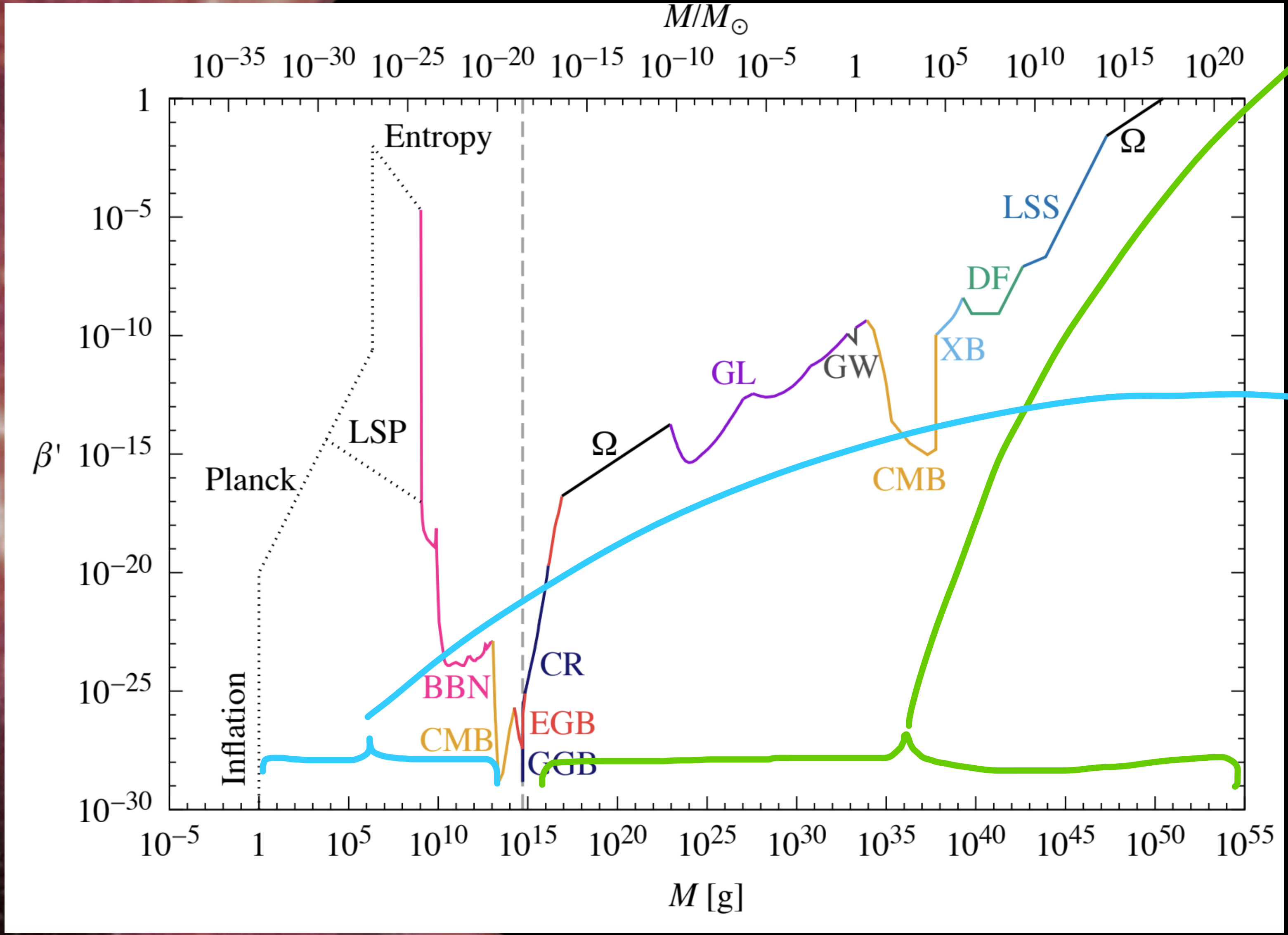
Gu, Shu, Yang, 2023

Enhancement of small scale power spectrum

Huge range of masses possible, more than 50 orders of magnitude!

Constraints on PBHs

Carr, 2020



Still exist today

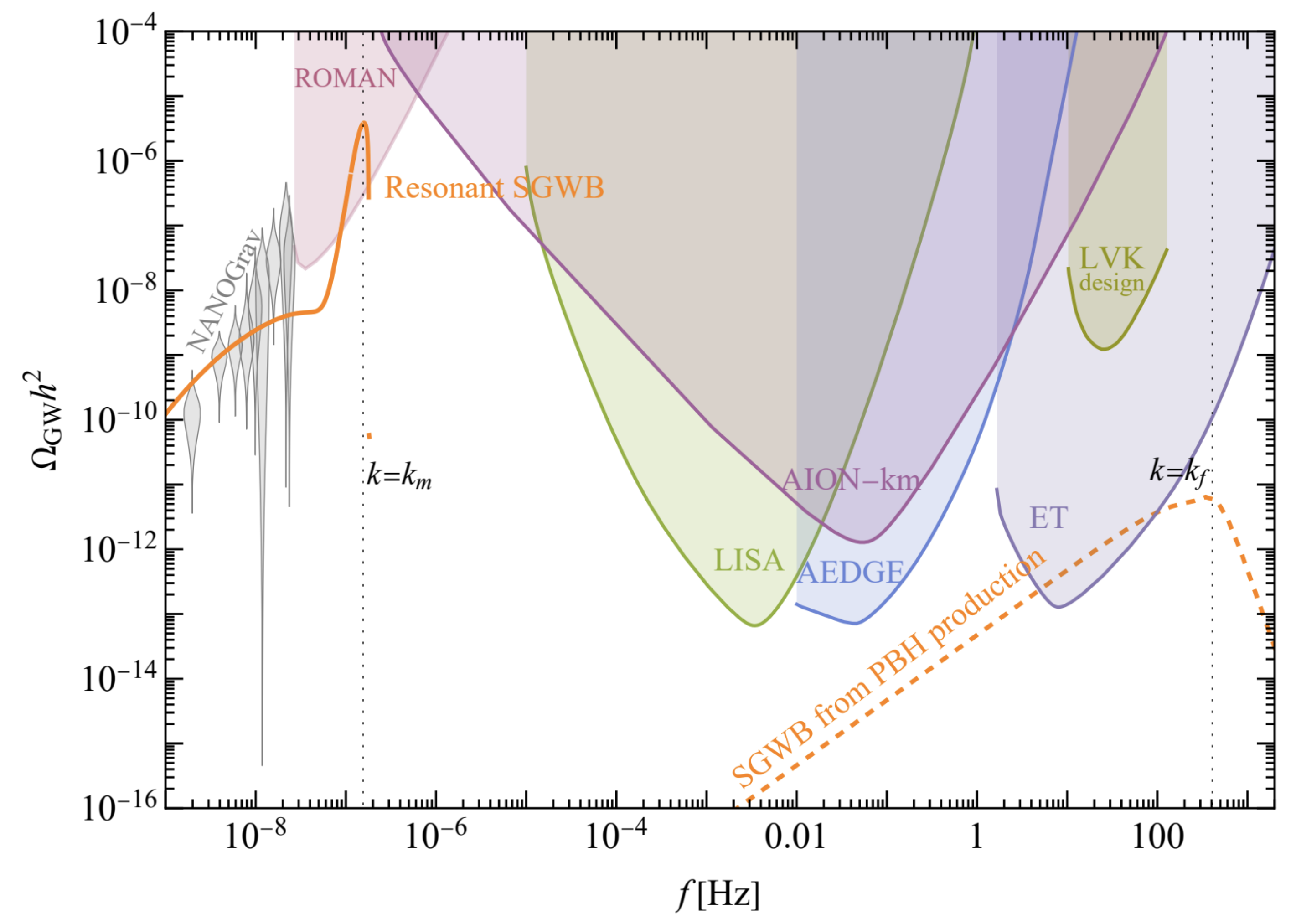
Subject to various observational constraints

Evaporated completely

Very difficult to constrain but increasingly subject to GW constraints

Hope on the Gravitational Wave Horizon?

Bhaumik, Jain, Lewicki



$M_{\rm PBH} \sim 10^8 {\rm g}$

PBHs in the early universe

$$M_{\rm PBH} < 10^9 \rm g$$

- Evaporate completely before BBN
- Inject high energy (boosted) particles
- Heat their surroundings
- May dominate the universe

PBHs in the early universe

$$M_{\rm PBH} < 10^9\,{\rm g}$$

- Evaporate completely before BBN
- Inject high energy (boosted) particles
  - How is leptogenesis affected?
  - Can leptogenesis survive?
  - Conclusions from experiments?
- Heat their surroundings
- May dominate the universe

How is leptogenesis affected?

- Domination of the energy budget of the universe
- Emission of RHNs
- Injection of entropy (entropy dilution)

PBH Domination

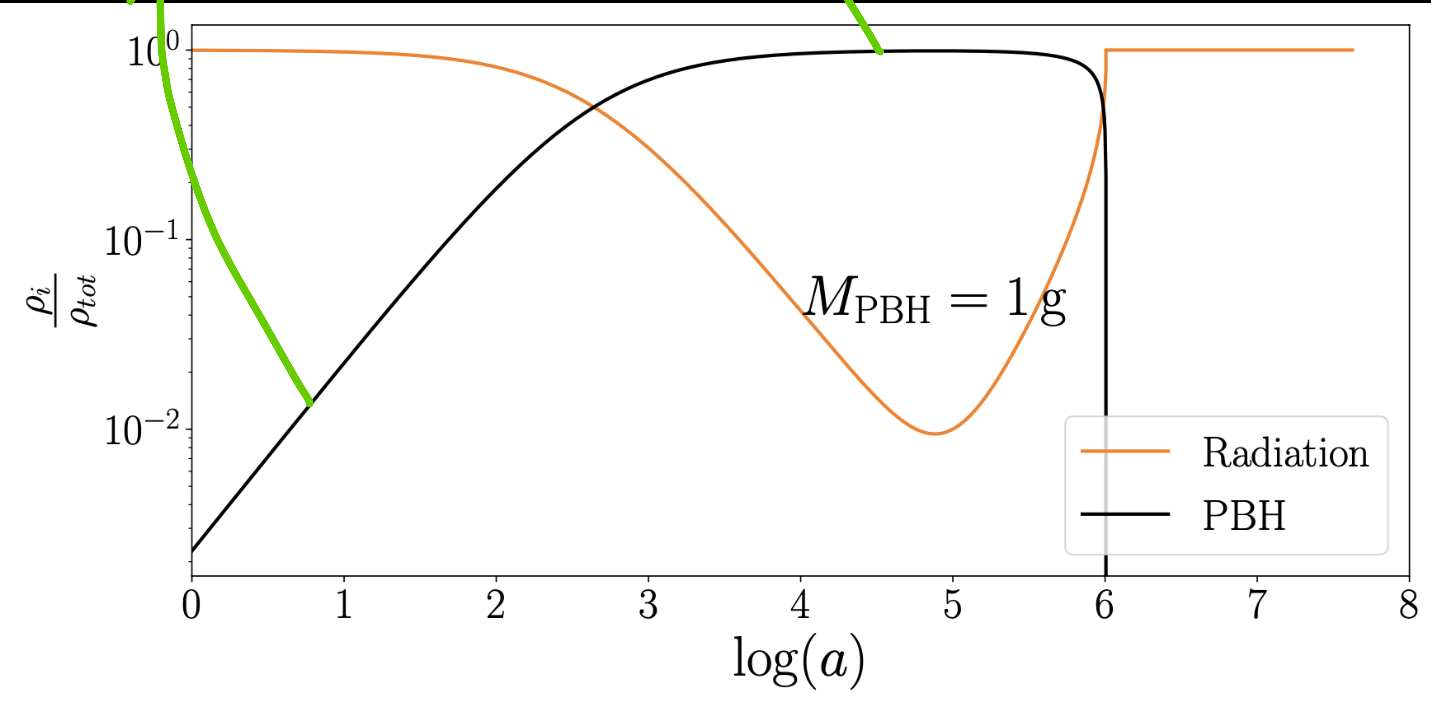
Expansion rate of the universe enhanced

Relative contribution of PBHs grows like matter

Especially important for low scale models

$$M_{N_1} \sim 10^2 \mathrm{GeV}$$

$$H(T_{\rm sphal}) = \Gamma_{\rm sphal}(T_{\rm sphal})/T_{\rm sphal}^3$$



Perez-Gonzalez, Turner

Production of RHNs

PBHs radiate all d.o.f lighter than their temperature

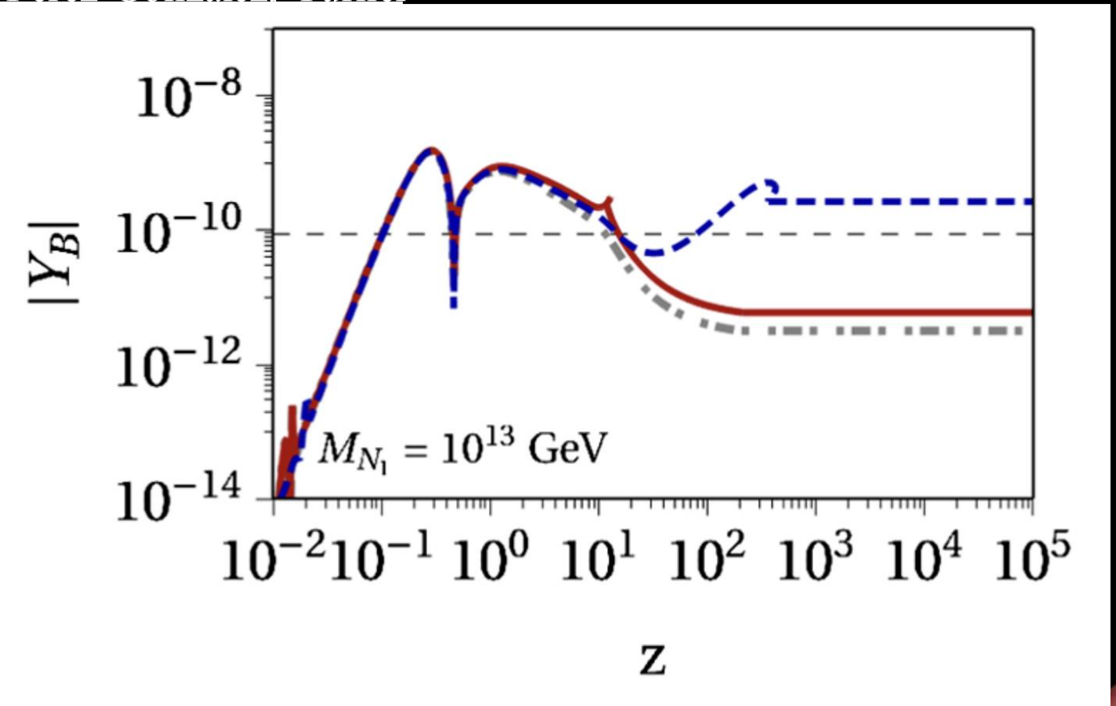
$$\frac{\mathrm{dM}_{\mathrm{PBH}}}{dt} \propto M_{\mathrm{PBH}}^{-2}$$

Occurs rapidly at the end of the PBH life

$$aH\frac{d\mathcal{N}_{B-L}}{da} = \epsilon[(\mathcal{N}_{N_1}^{\mathrm{TH}} - \mathcal{N}_{N_1}^{\mathrm{eq}})\Gamma_{N_1}^{T} + \mathcal{N}_{N_1}^{\mathrm{BH}}\Gamma_{N_1}^{\mathrm{BH}}] + \left(\frac{1}{2}\Gamma_{N_1}^{T}\mathcal{N}_{N_1}^{\mathrm{eq}} + \gamma\right)\frac{\mathcal{N}_{B-L}}{\mathcal{N}_{\ell}^{\mathrm{eq}}},$$

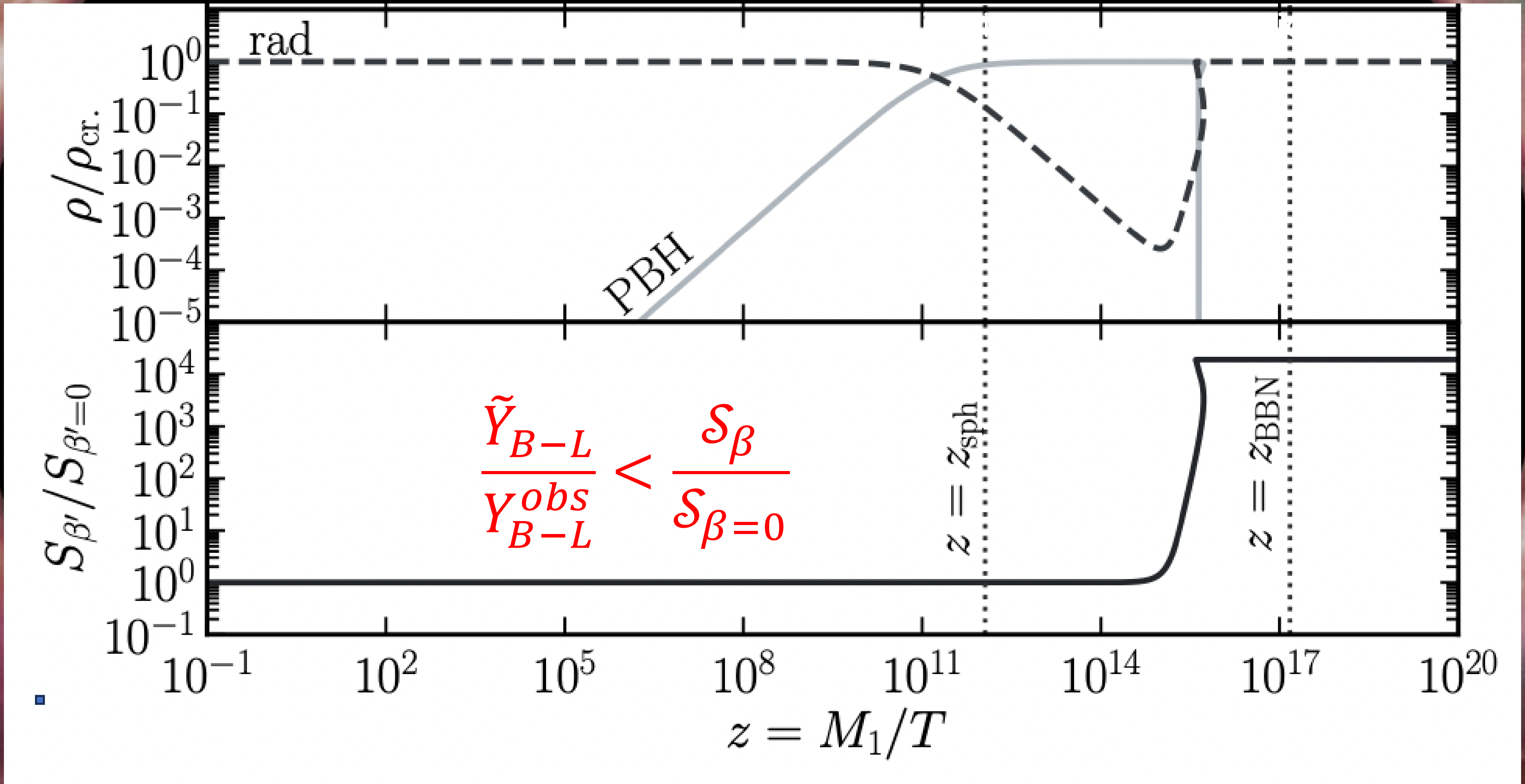
New source term for asymmetry

Perez-Gonzalez, Turner

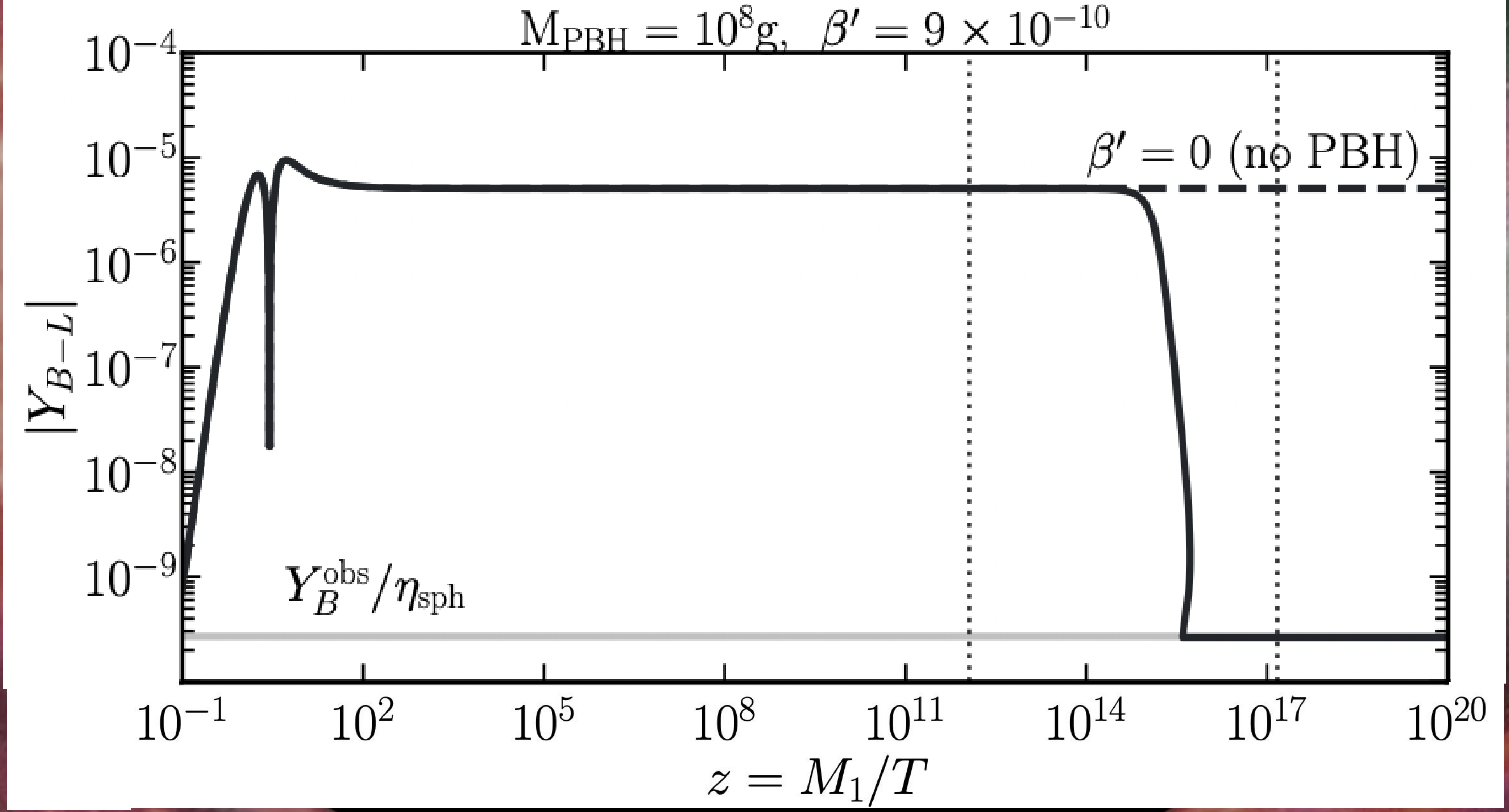


Entropy dilution

$$Y_{B-L} \equiv \frac{\mathcal{N}_{B-L}}{\mathcal{S}} \qquad \mathcal{S}_{\beta}/\mathcal{S}_{\beta=0}(\beta, M_{PBH})$$

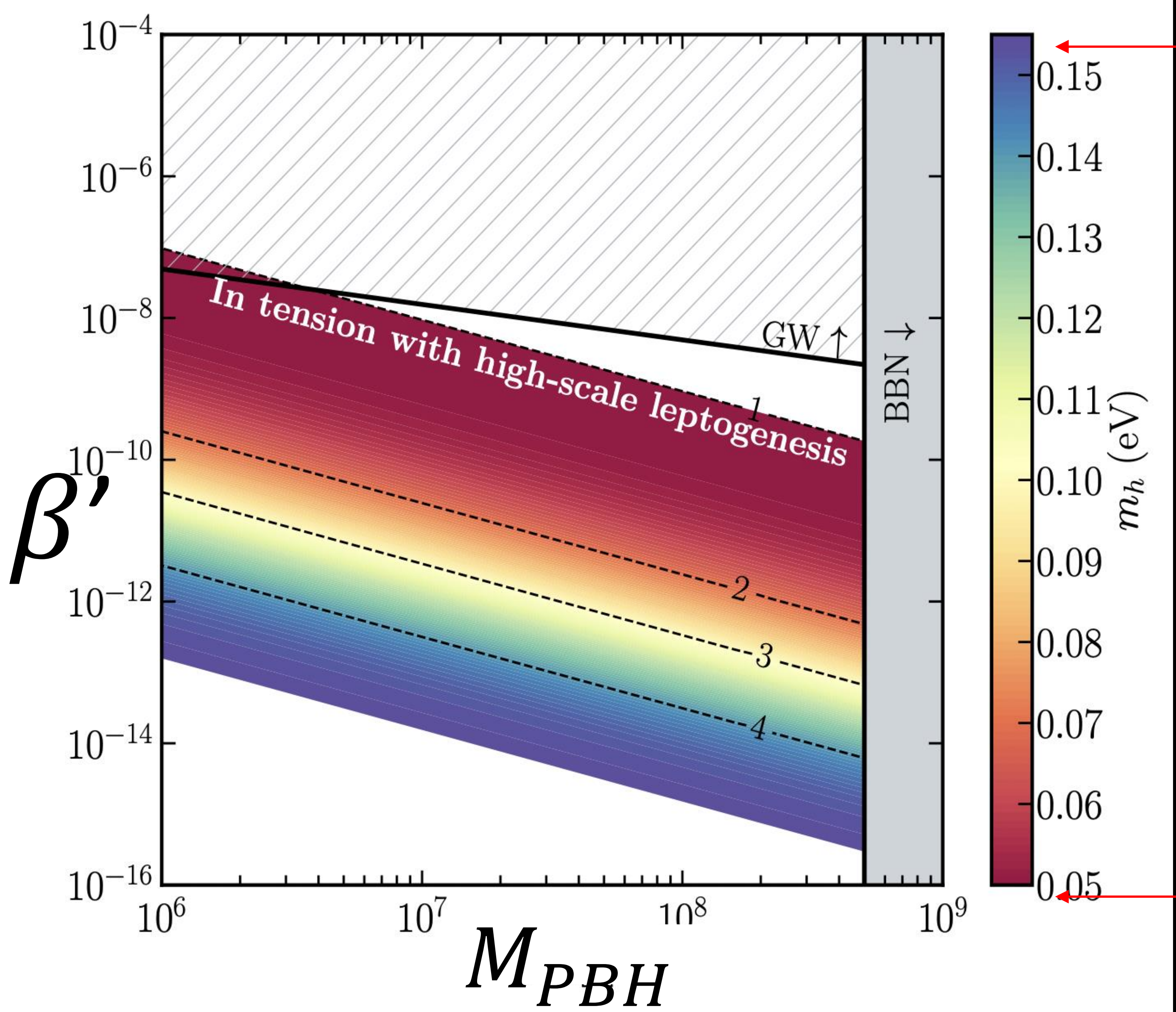


Dilution of asymmetry



PBHs can exclude leptogenesis (and vice versa)

Calabrese et al.

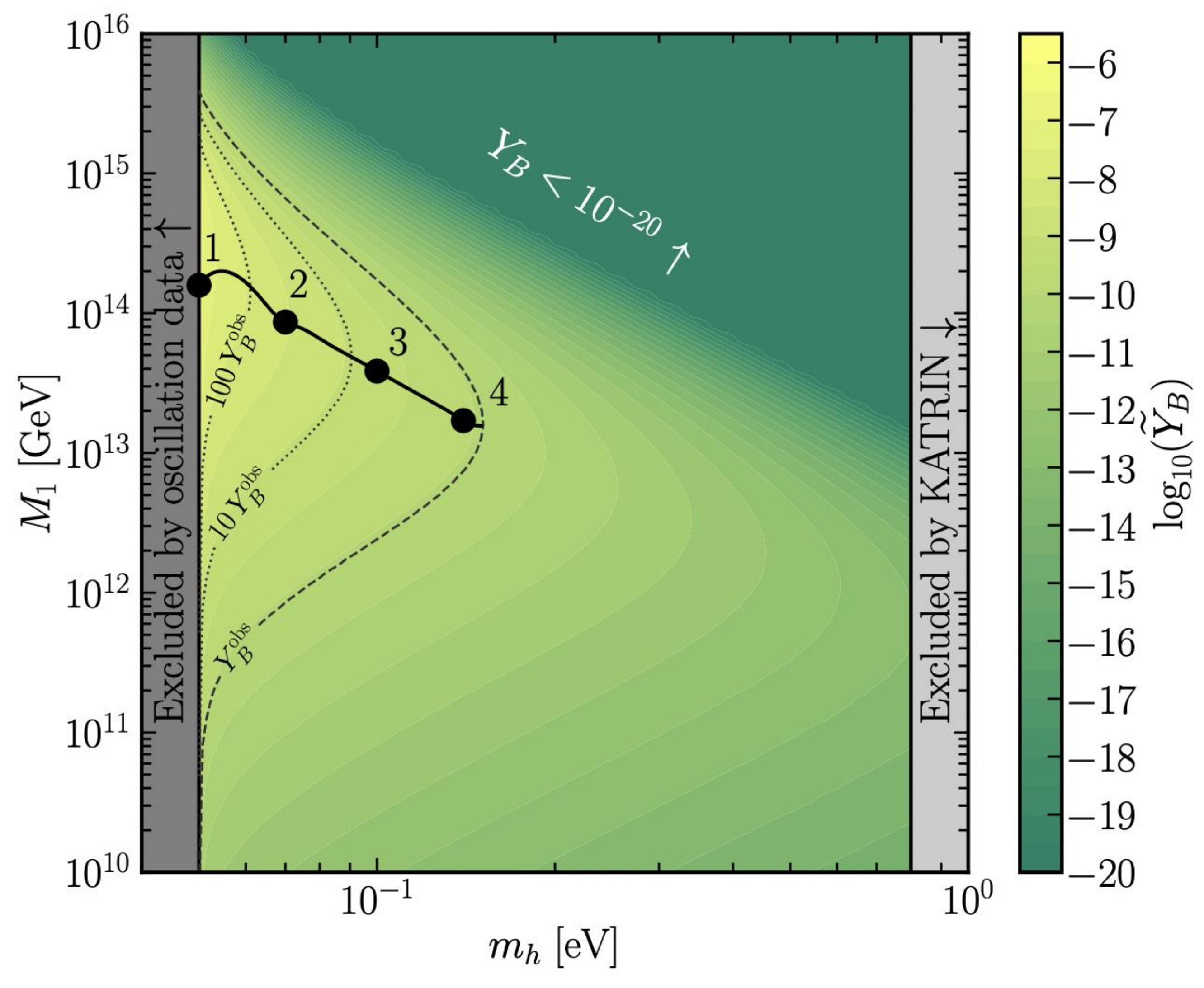


Upper bound for leptogenesis

The mutual exclusion limits become more severe with heavier active neutrino masses

Oscillation data lower bound

The maximum asymmetry



$$\begin{pmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{pmatrix}$$

$$M_1 \ll M_{2,3}$$

Casas-Ibarra parameterisation,

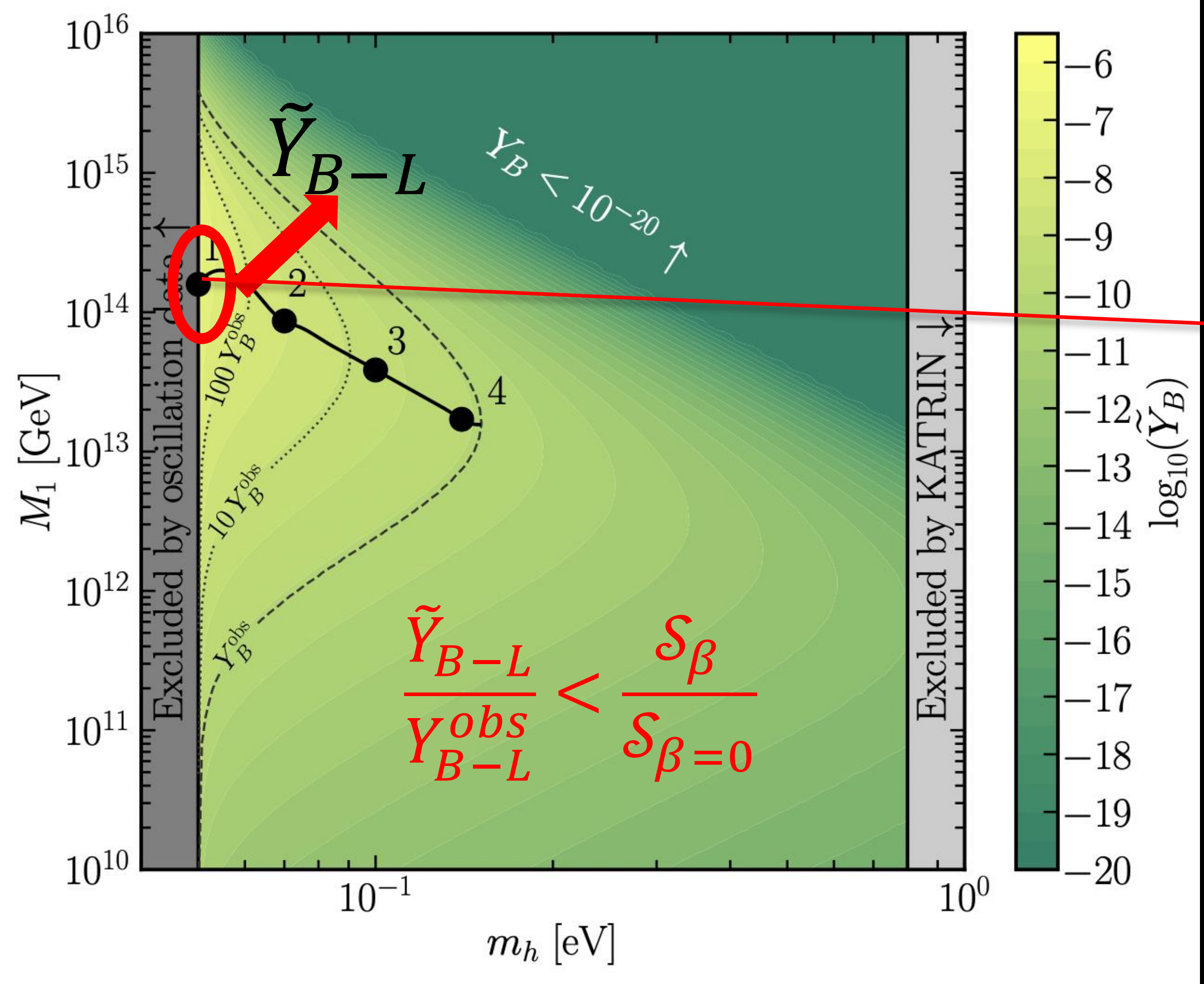
we take $\Delta m^2{}_{sol} \ll \Delta m^2{}_{atm}$

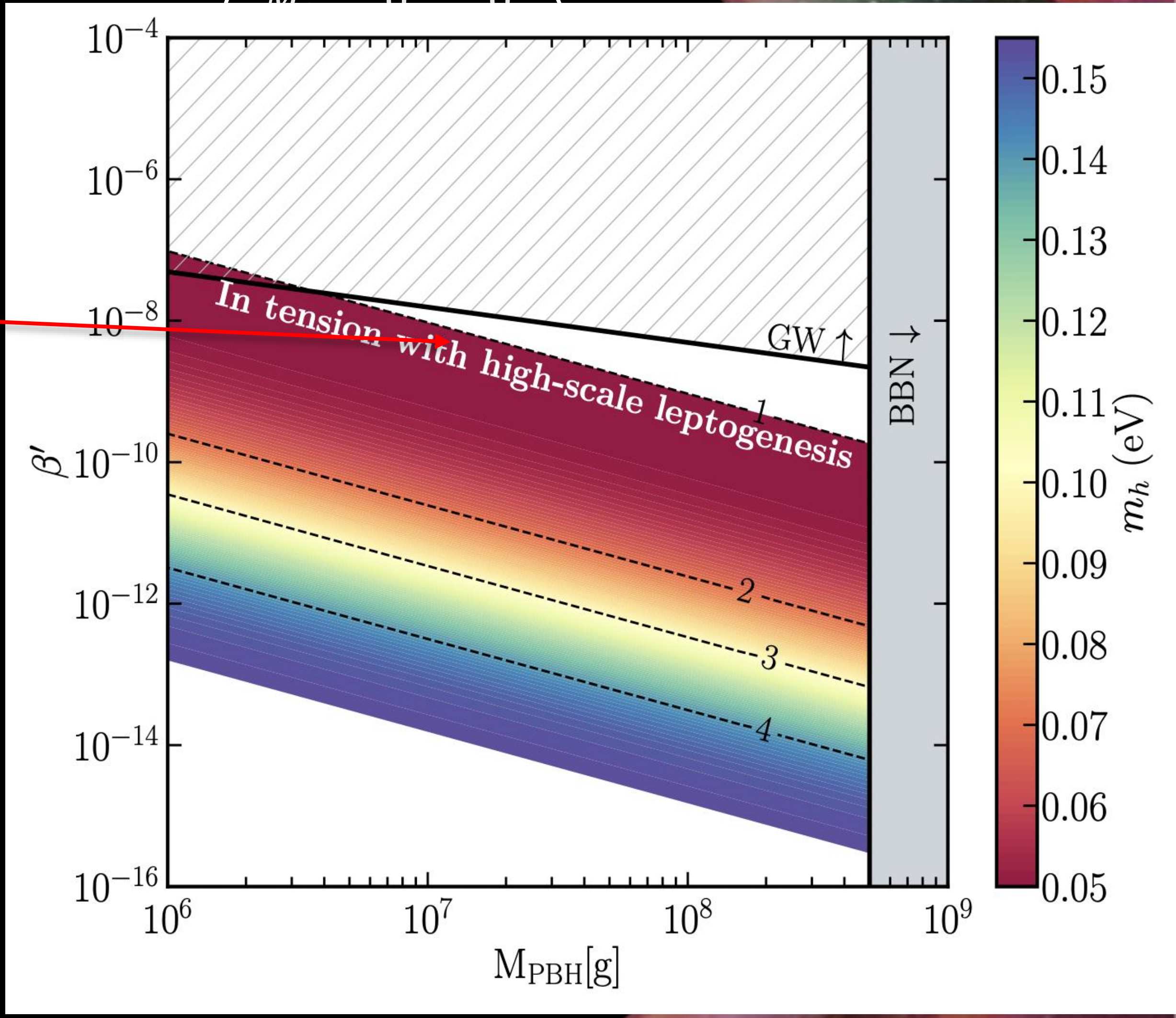
$$R = R_{13}(\theta_{13} = x + iy)$$

$$\{M_1, m_h, x, y\}$$

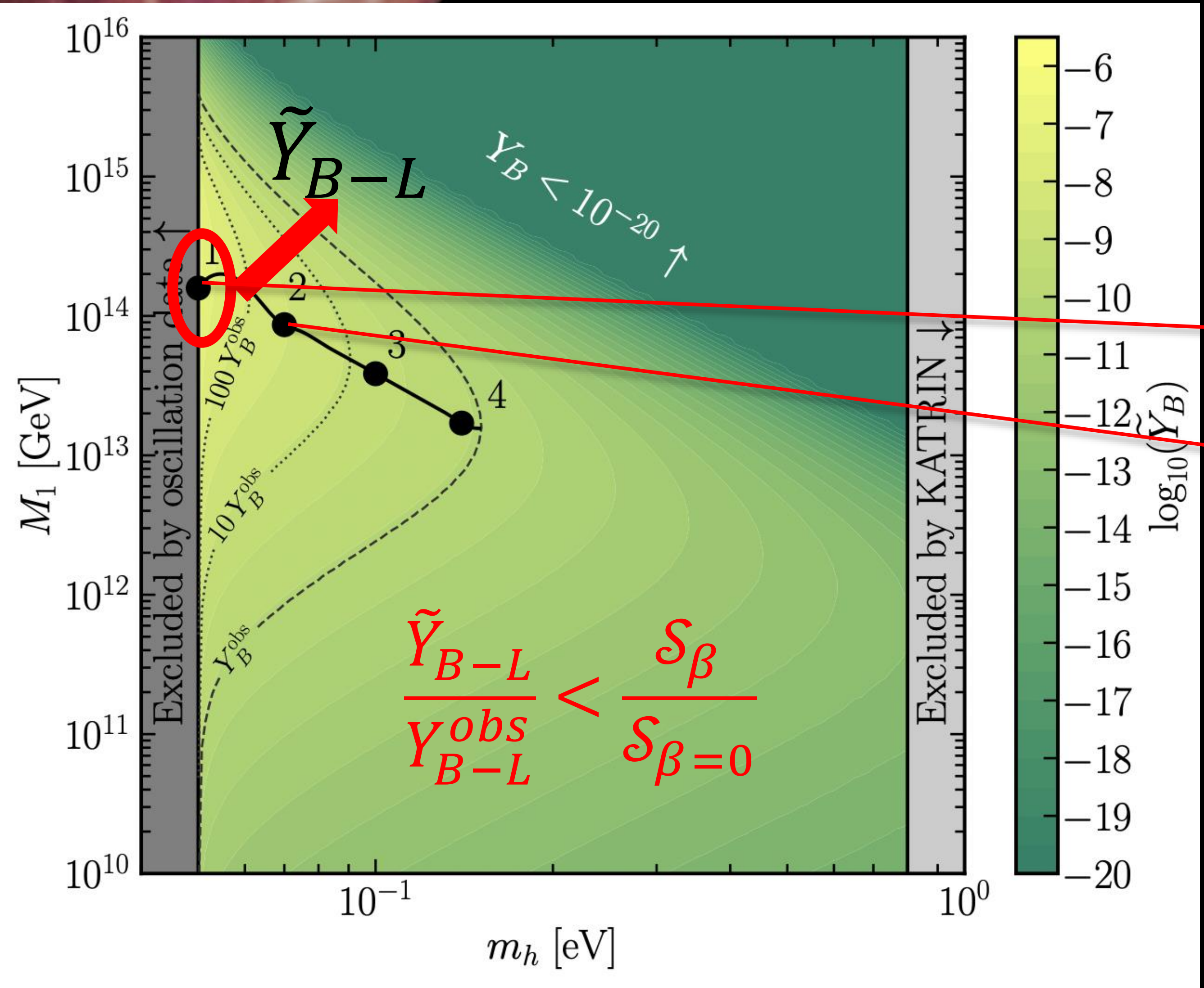
Leptogenesis parameter space is 4 - dimensional

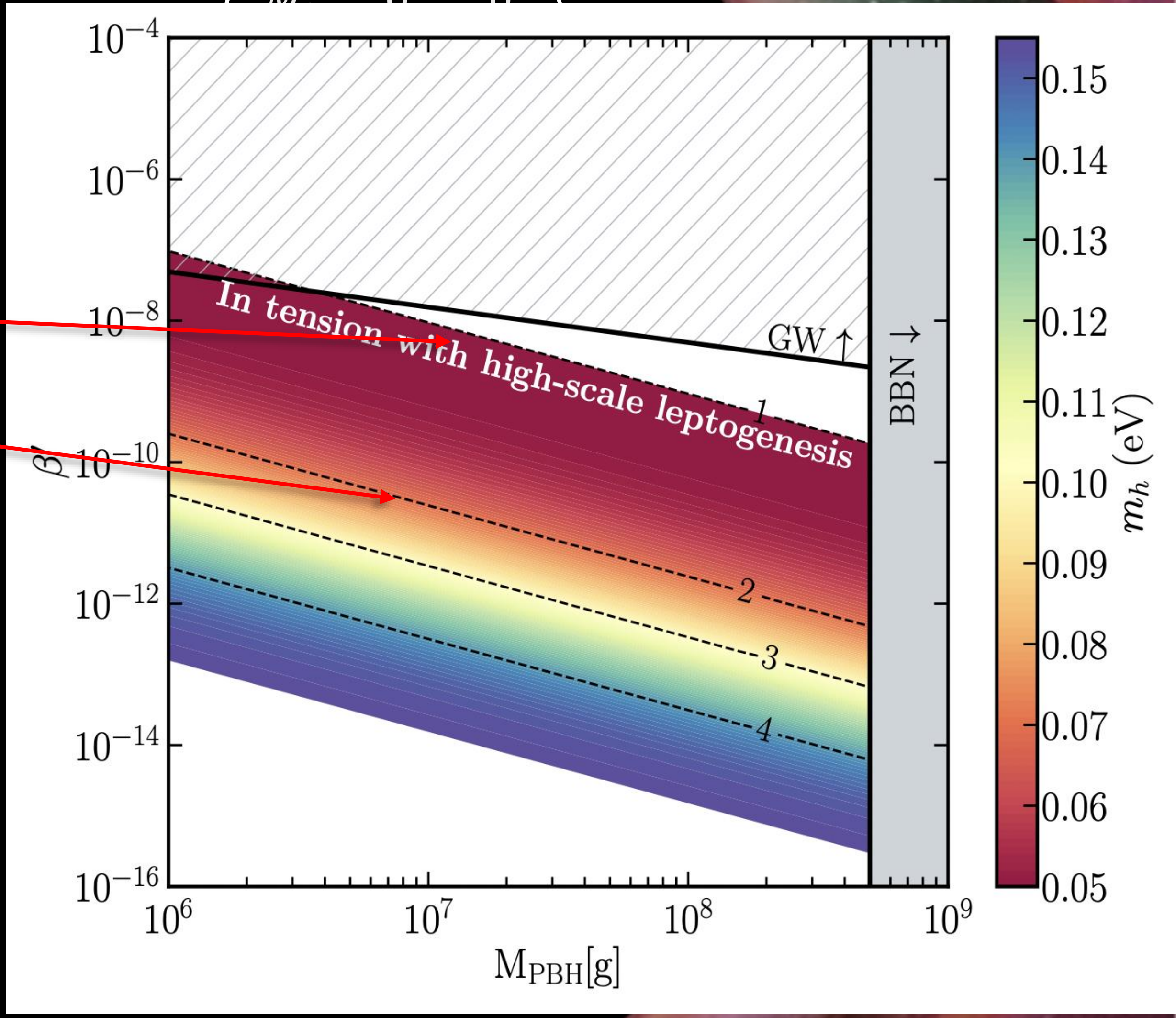
The maximum asymmetry



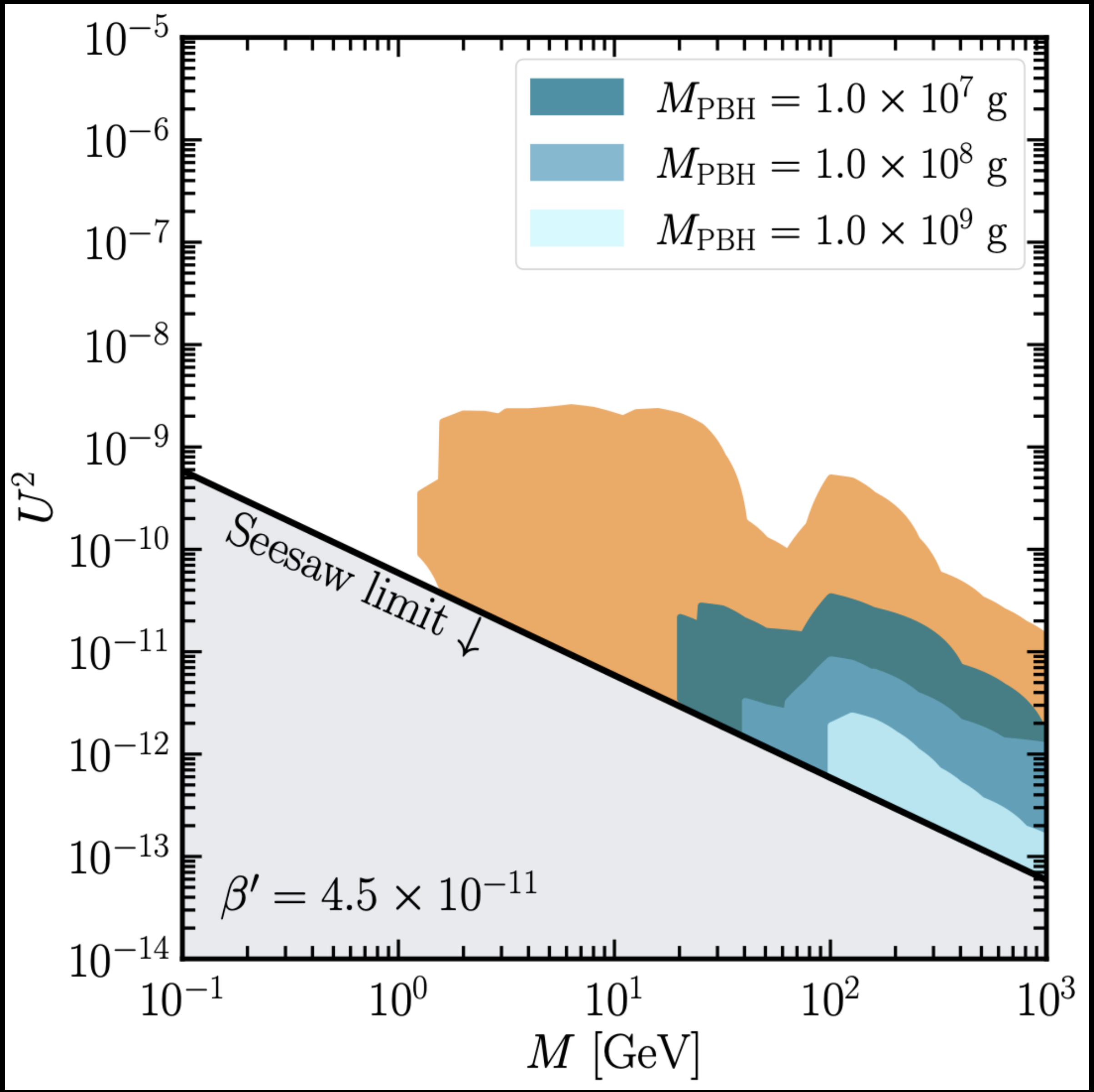


The maximum asymmetry



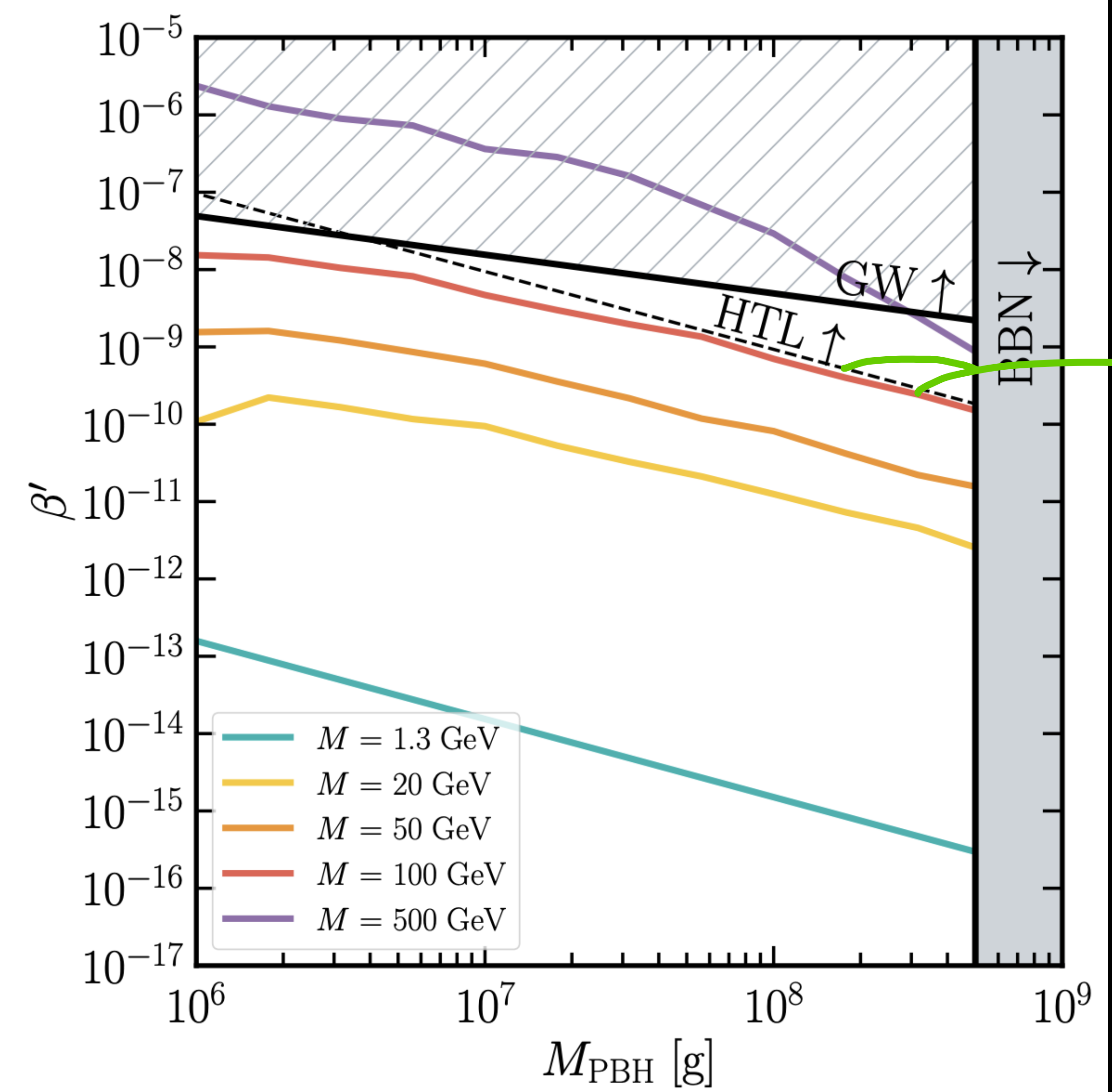


Low scale leptogenesis



Low scale leptogenesis

Calabrese et al.



In this case the limits depend on the heavy neutrino mass scale rather than the active one

Here we compare the constraints from high and low scale leptogenesis.

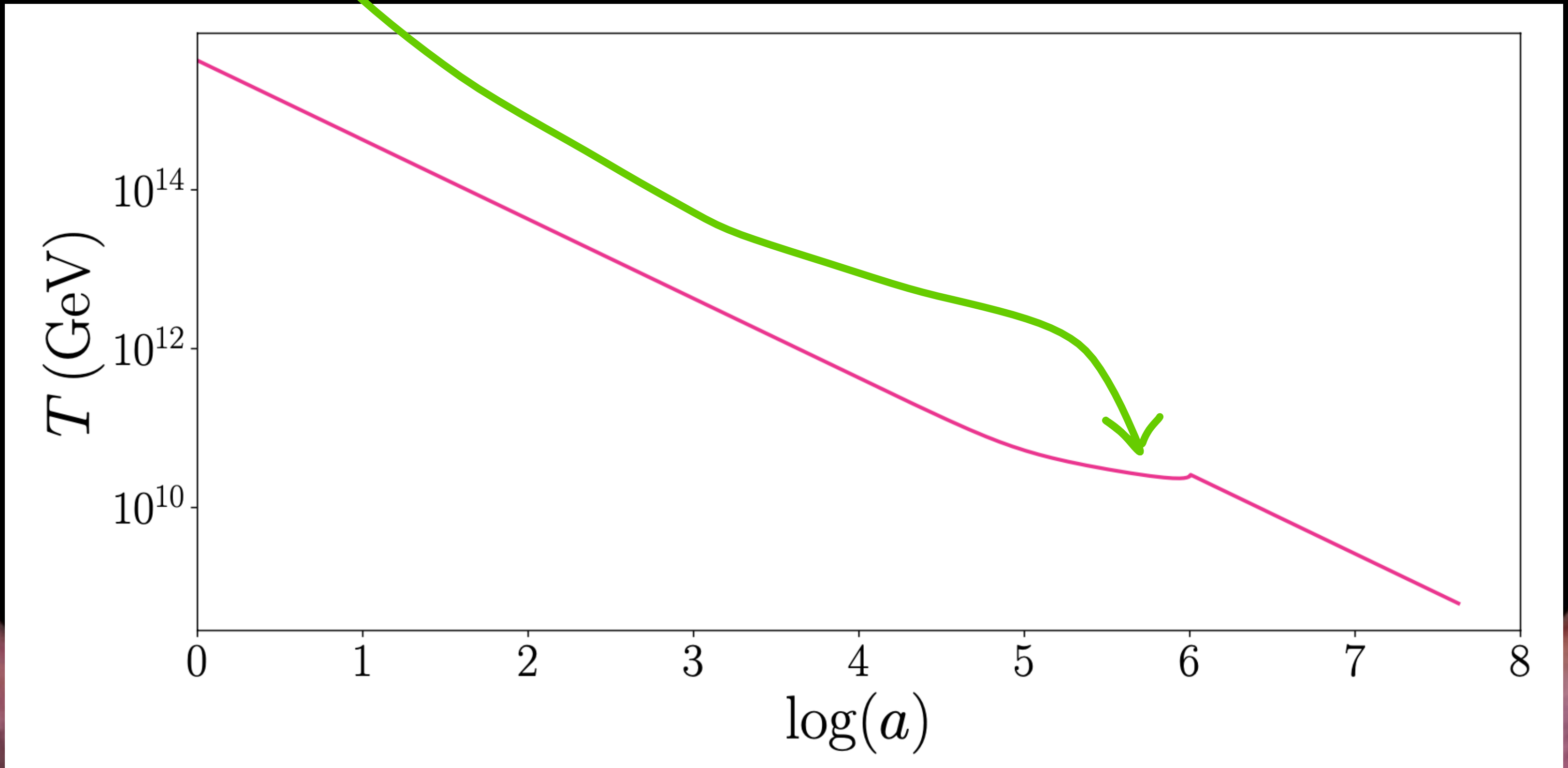
Similar arguments will hold for intermediate scale models too

Hot-spots

Evaporation of PBHs heats the universe

Most analyses assume this heating is homogeneous throughout the universe

This is a strong assumption

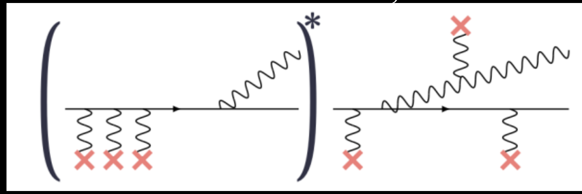


Perez-Gonzalez, Turner

Hot-spots

PBHs do not evaporate in a vacuum!

Yamada, Mukhaida, Kohri



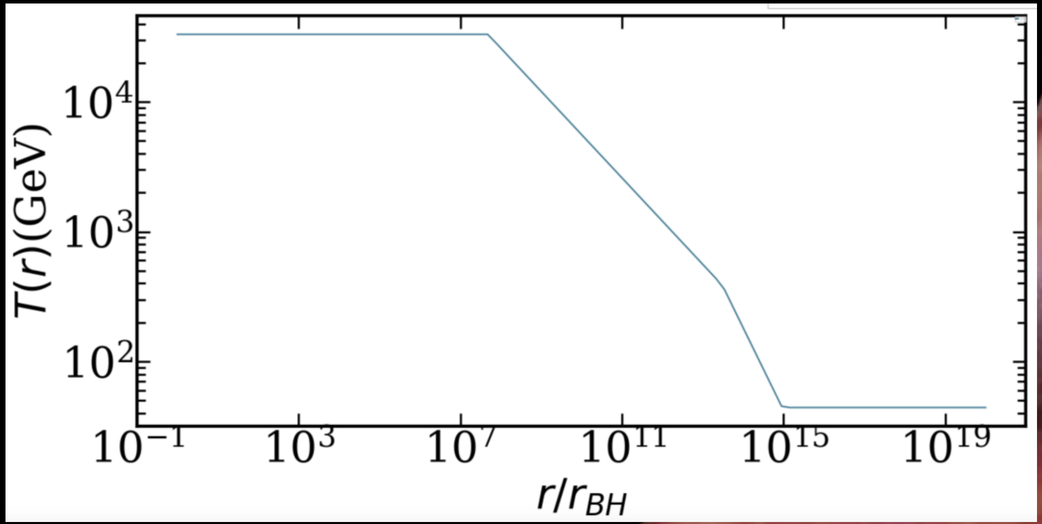
Hawking radiation interacts with the plasma

LPM suppressed collinear emission of soft gauge bosons is dominant

Energy is deposited close to the BH

Initially quasi-static, explosive at late times

Plasma around the BH heats up locally



Particle processes in a hot-spot

$$\lambda_S^X = \sum_{\text{all } Y,Z} \frac{1}{n_Y \sigma_{XY\leftrightarrow Z} v_{Mol}}$$

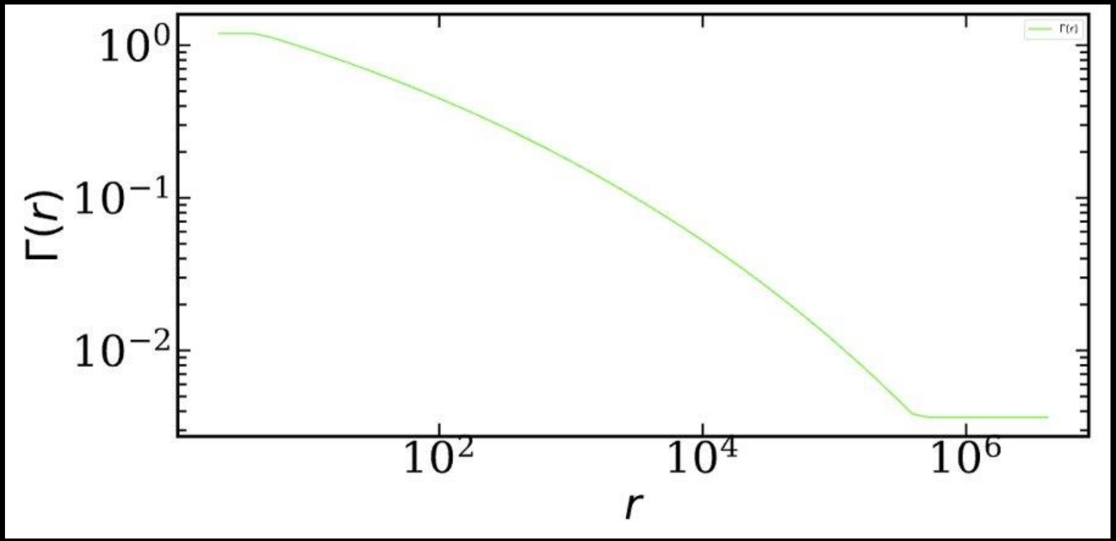
Functions of temperature → Functions of radius → ?

$$\Gamma_{N_i} = \frac{M_{N_i}(Y^\dagger Y)_{ii}}{8\pi} \Lambda(1, a_H, a_L)(1 - a_H + a_L)\theta(1 - a_H - a_L)$$

Very mild function of temperature and essentially unaffected

Escaping hot-spots

$$P(r) = 1 - e^{-\int_0^r \Gamma(r')\mathrm{d}r'}$$



Can a BSM particle escape the hot-spot?

Crucial for calculating observables

Particles which were massless when produced may gain mass simply by escaping

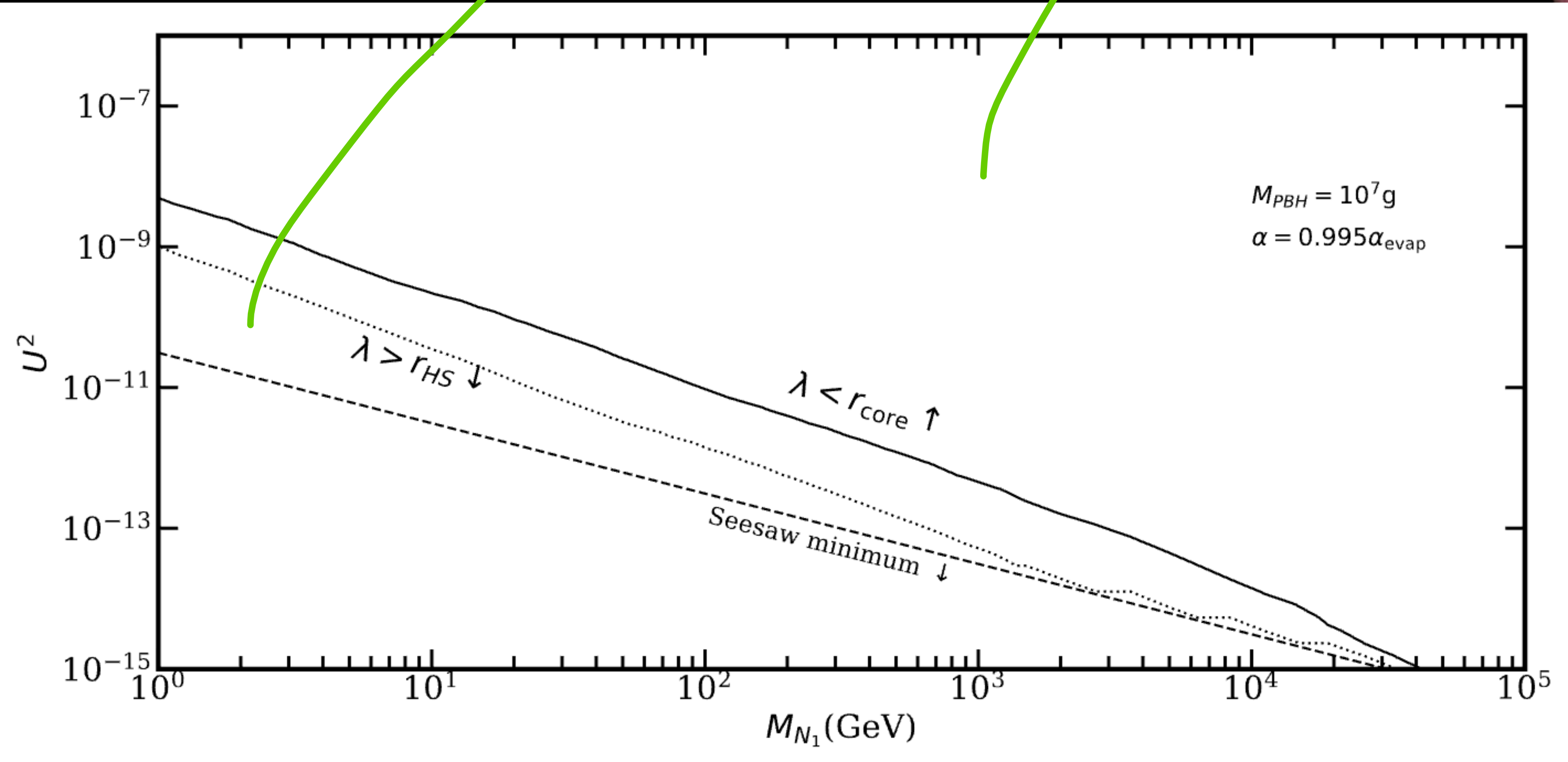
Which particle processes are possible depends on distance travelled

Preliminary results

Whether a particle may escape depends on its parameters

Only the lightest most weakly interacting particles escape

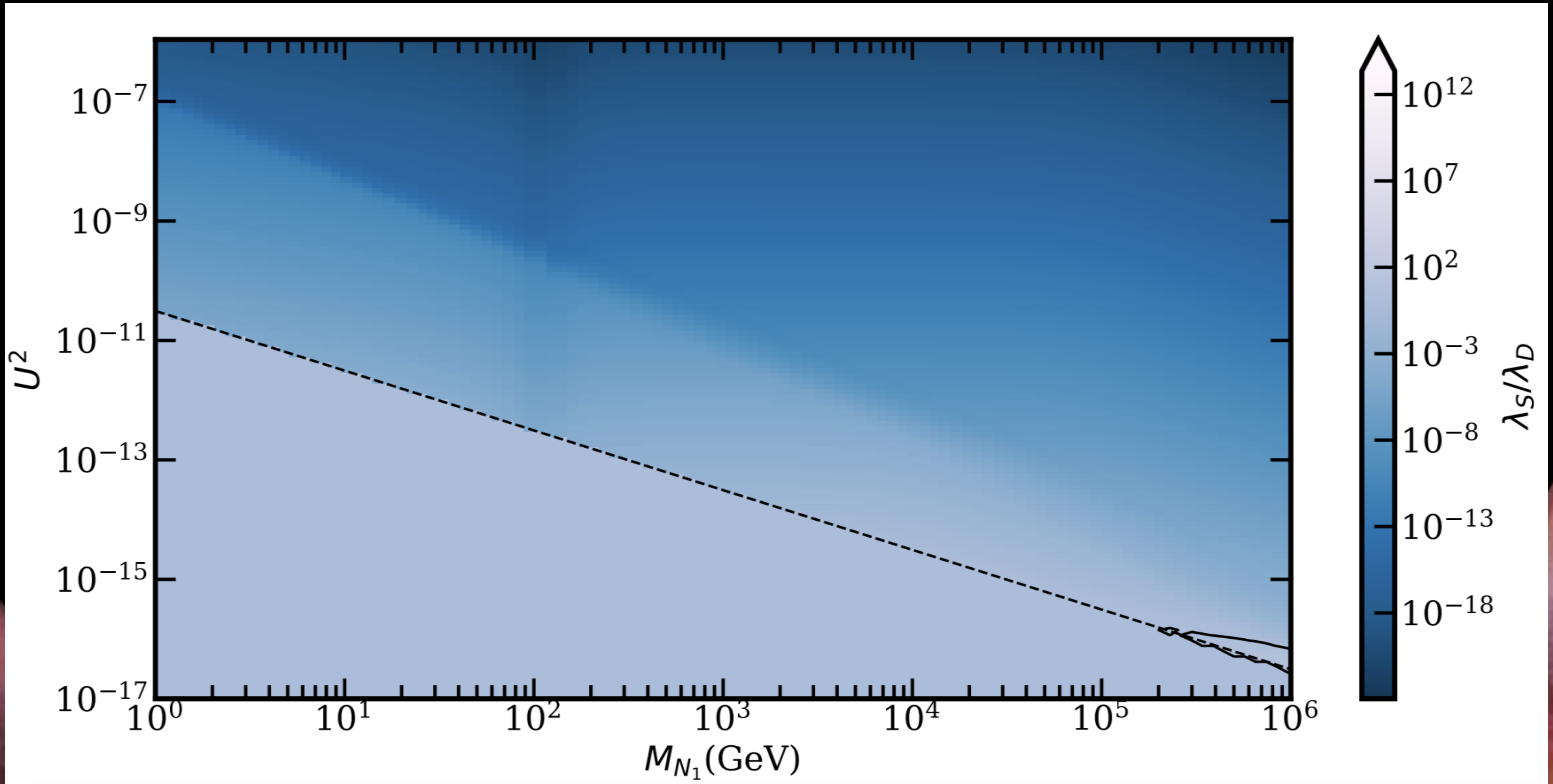
Most scatter close to the PBH



Preliminary results

Scattering with the plasma is strongly enhanced

Constraining for models involving decay of Hawking radiation



Conclusions

PBHs and leptogenesis are both interesting and well motivated new physics

Both are difficult to probe directly, but future experiments offer hope

We have shown that future discoveries in either parameter space can constrain the other

Locally heated regions around PBHs alter the dynamics of particle processes involving Hawking radiation