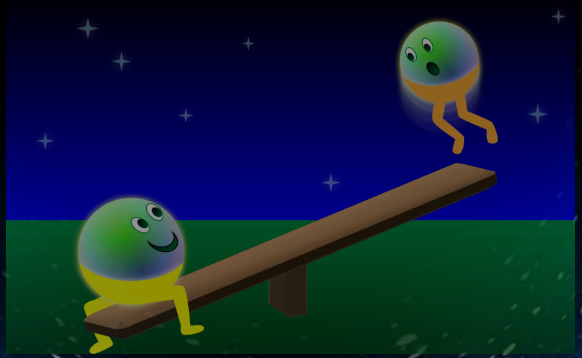
TAsP Meeting

18 -19 January 2024

The interplay between Primordial Black Holes and Leptogenesiss



Ninetta Saviano

INFN (NA)

Based on PRD 107.123537 and on 2311.13276 in collaboration with R. Calabrese,M. Chianese, J. Gunn, G. Miele, S. Morisi

INFN Istituto Nazionale di Fisica Nucleare

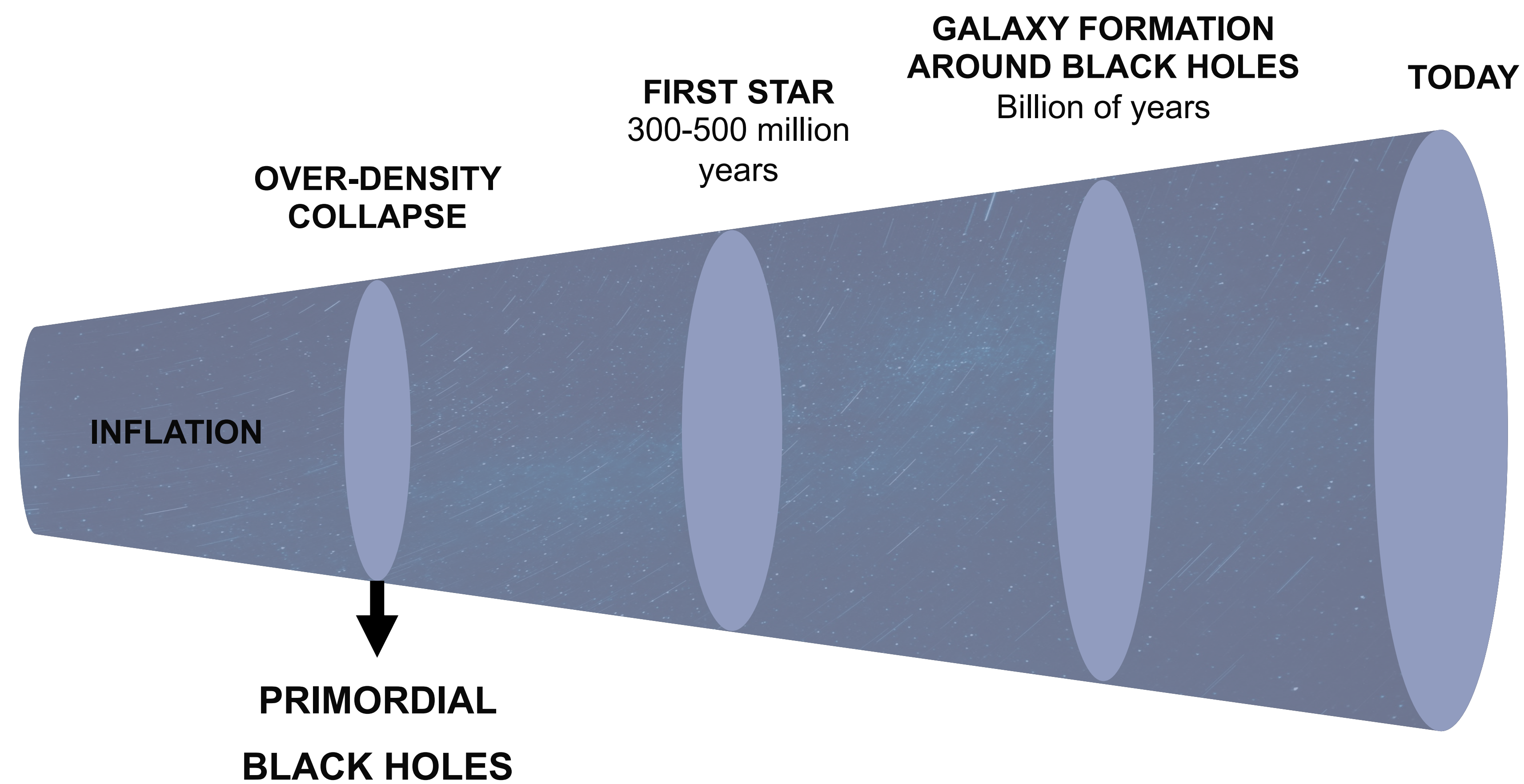
Genesis of Primordial Black Holes

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

MASS $[0.1 - 10^{50}]$g

CHARGE

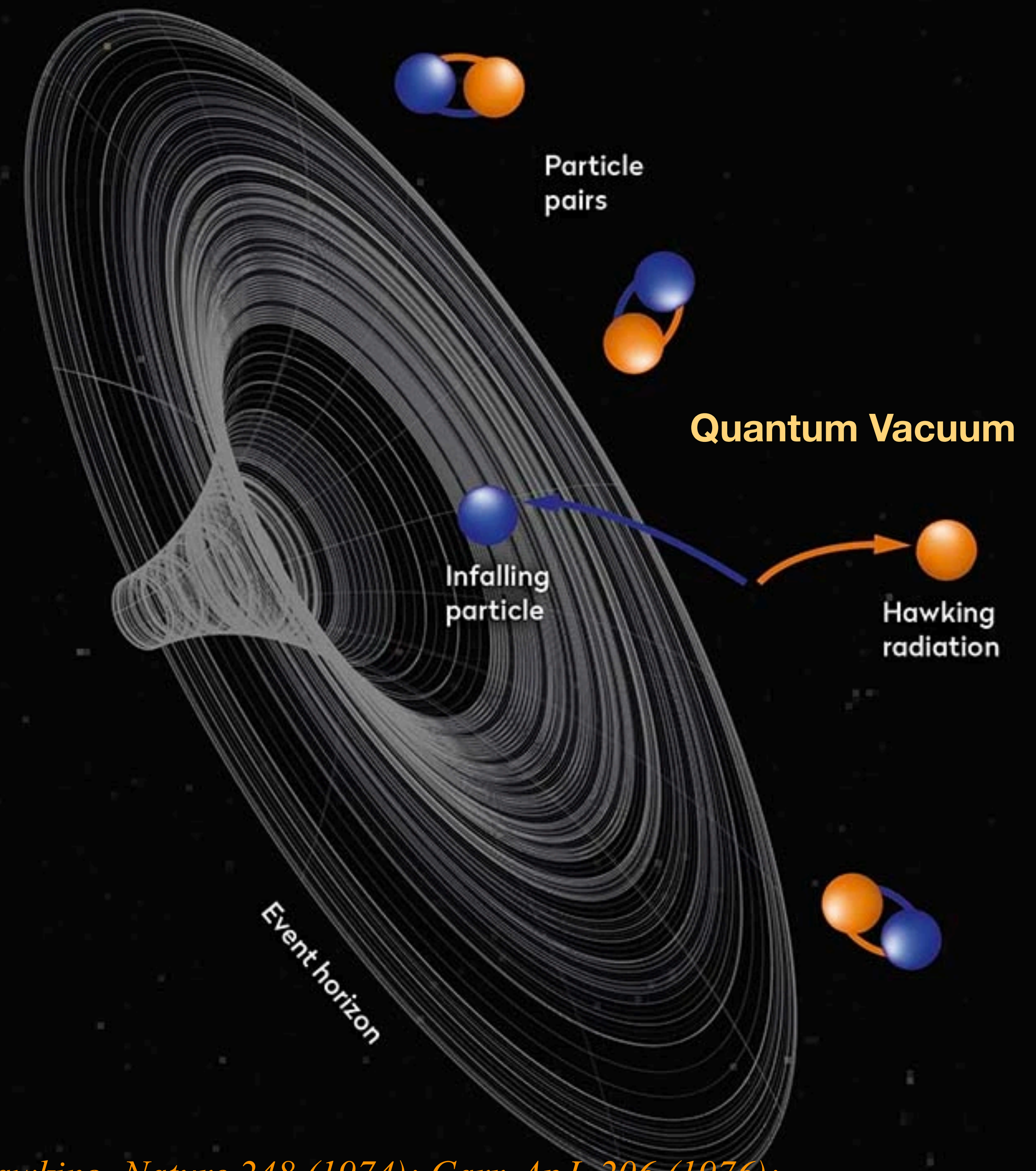
SPIN



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

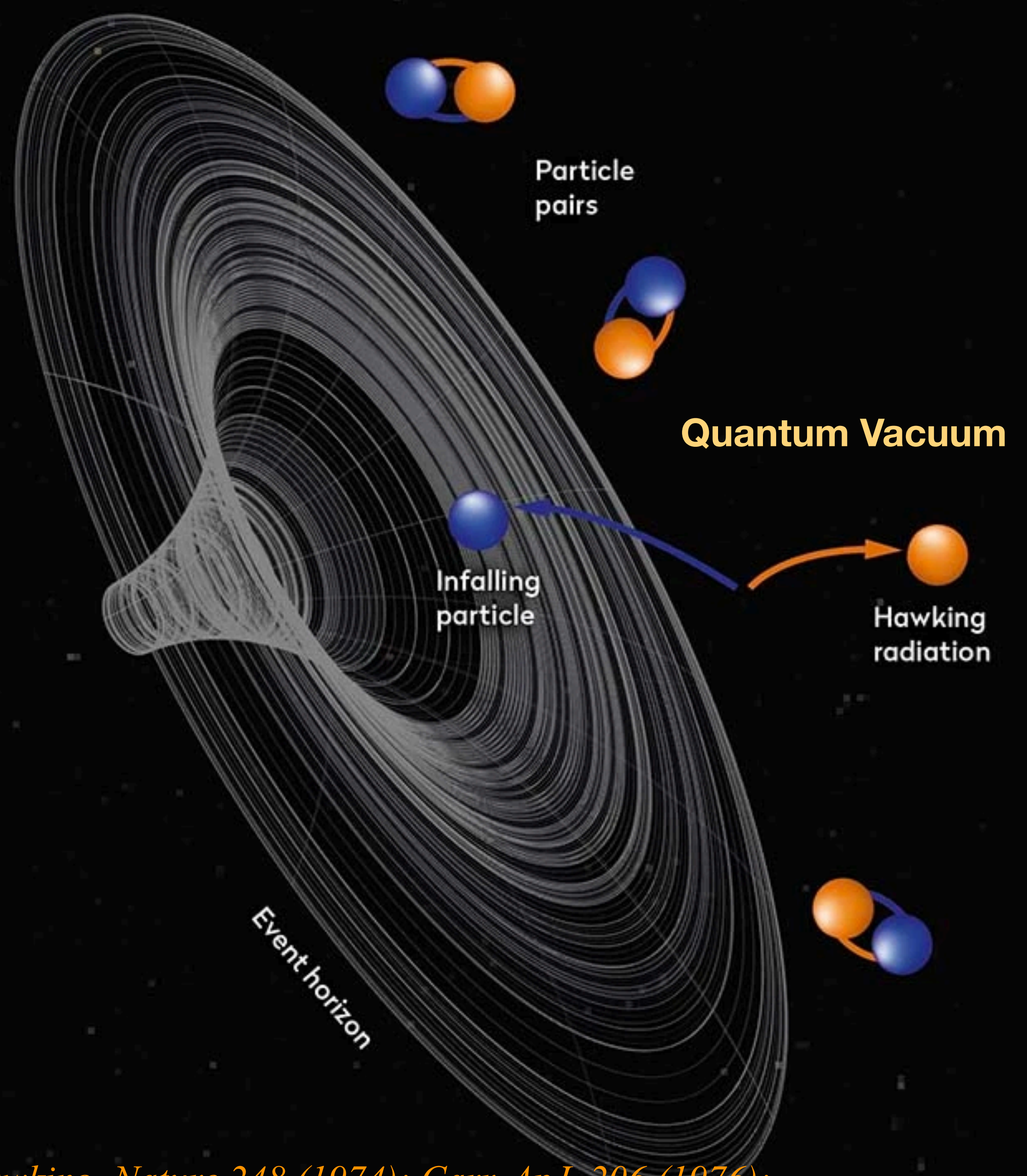


Hawking, Nature 248 (1974); Carr, ApJ. 206 (1976);
Hawking, Comm. Math. Phys. 43 (1976); Page, PRD 13 (1976)

Hawking Evaporation

Due to a mixture of quantum and general relativity effects, the PBH can emit particles in a "black body" like (**grey-body**) with a temperature T_{PBH}

Hawking radiation: emission of all elementary particles with mass < T_H



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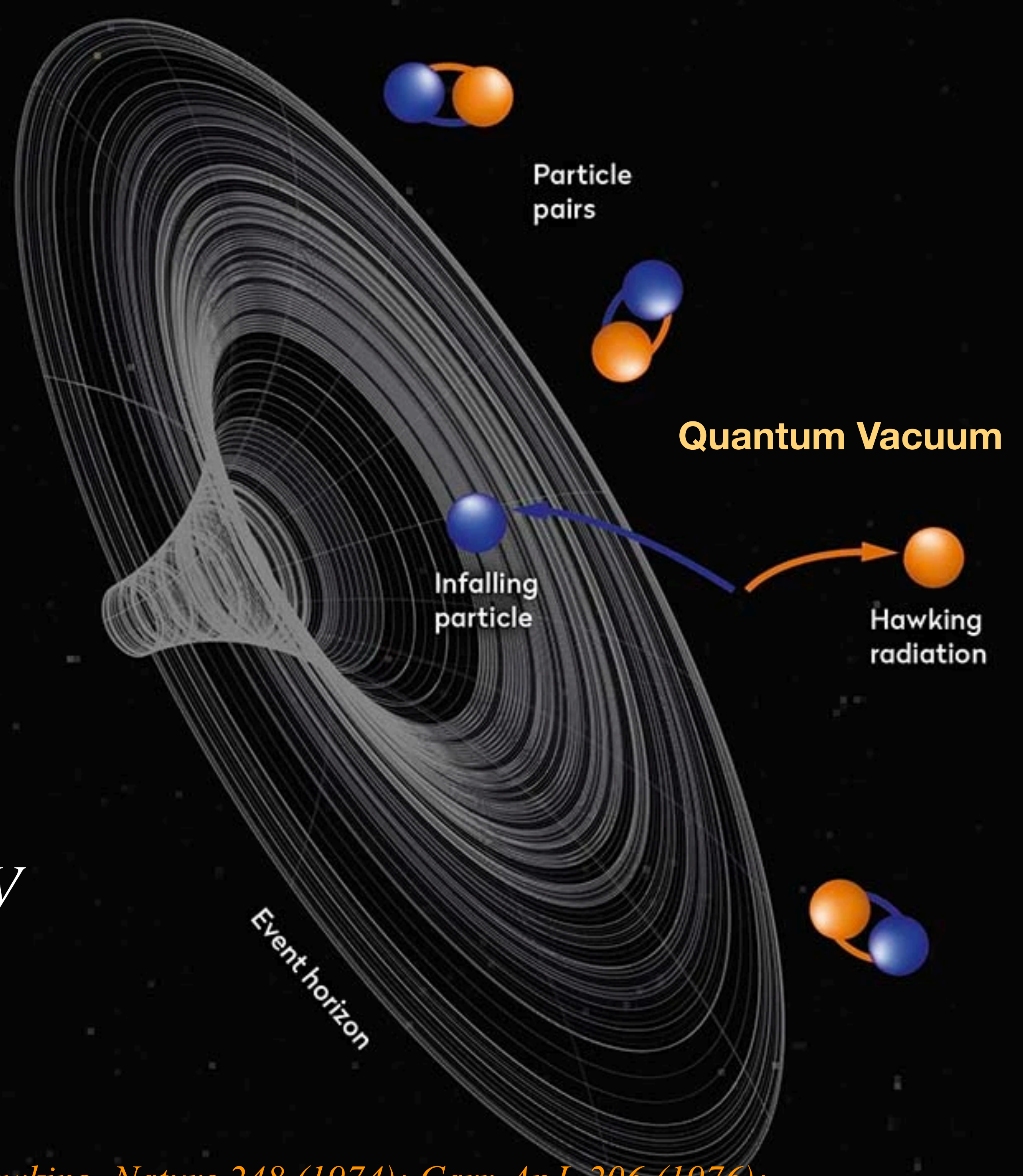
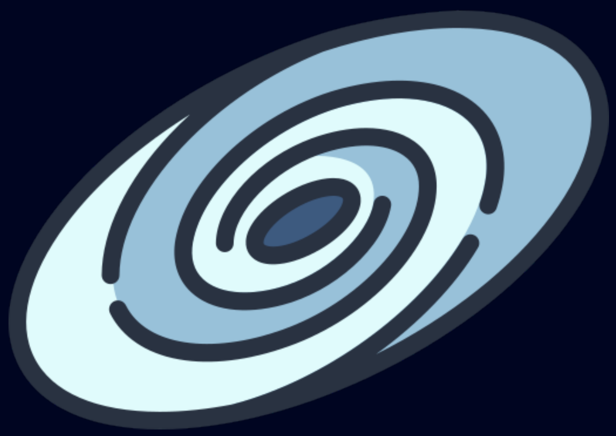


For non-rotating and neutral PBH:

$$T_{PBH} = \frac{\hbar c^3}{8\pi G k_B M_{pl}} \simeq 10.6 \left[\frac{10^{15} g}{M_{pl}}\right] MeV$$

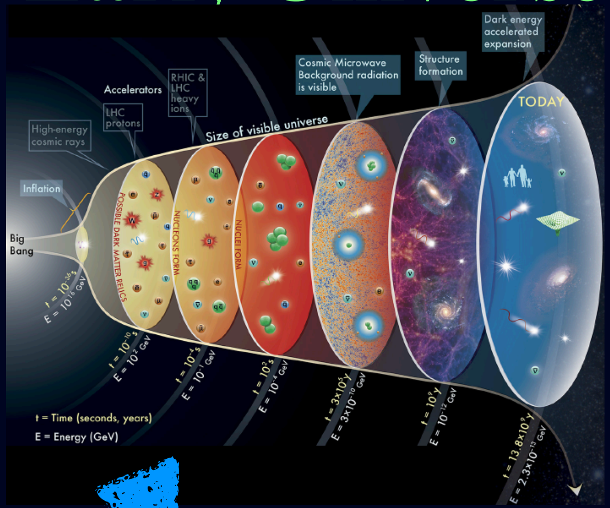
Hawking, Nature 248 (1974); Carr, ApJ. 206 (1976); Hawking, Comm. Math. Phys. 43 (1976); Page, PRD 13 (1976)

Current big interest in PBHs

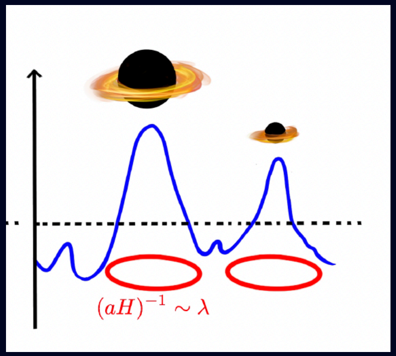


Current big interest in PBHs

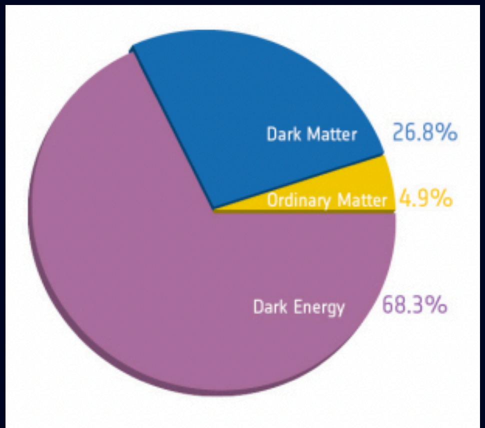
Early Universe

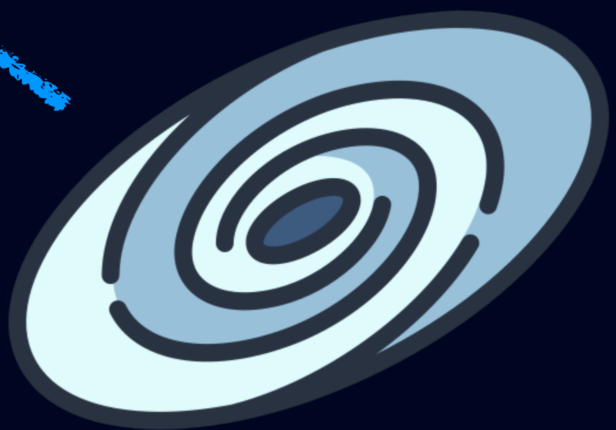


Formation mechanism

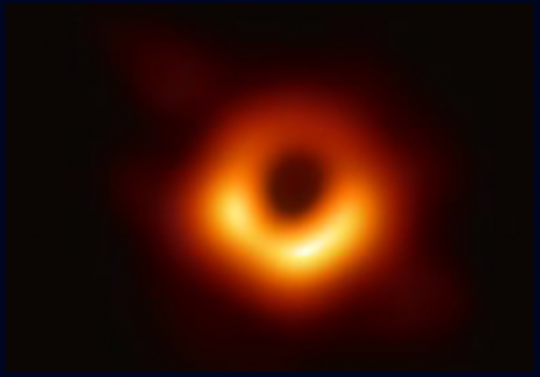


Dark Matter

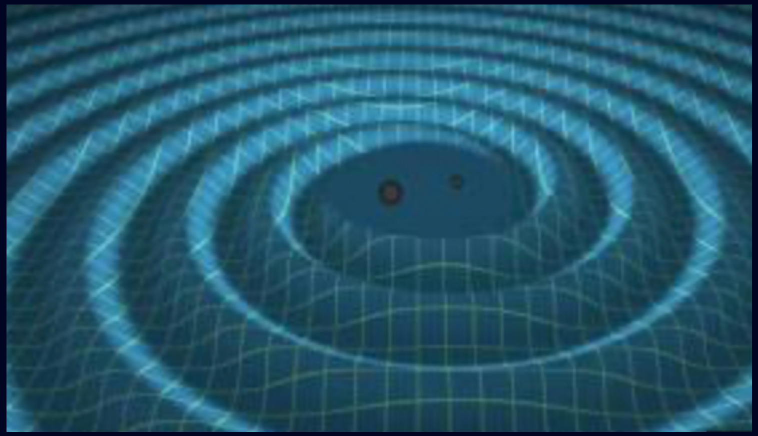




Astrophysical issues

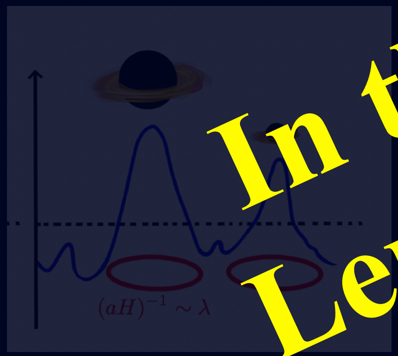


Gravitational waves



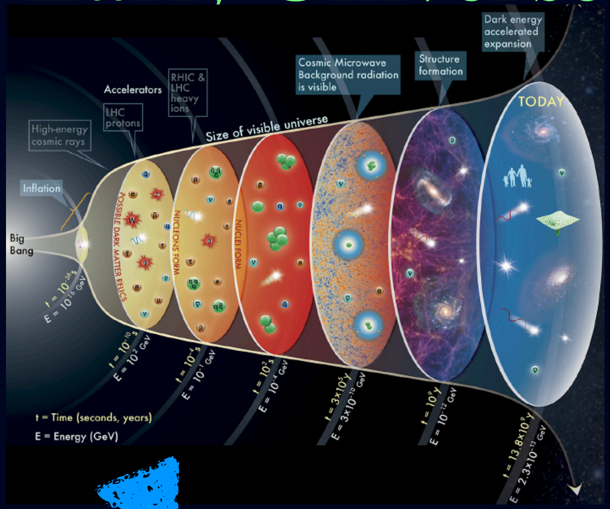
Current big interest in PBHs

Formation mechanism

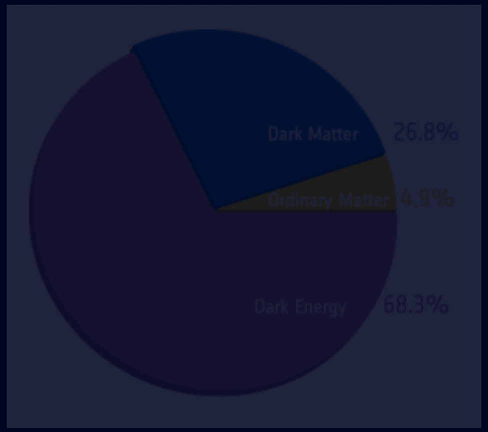


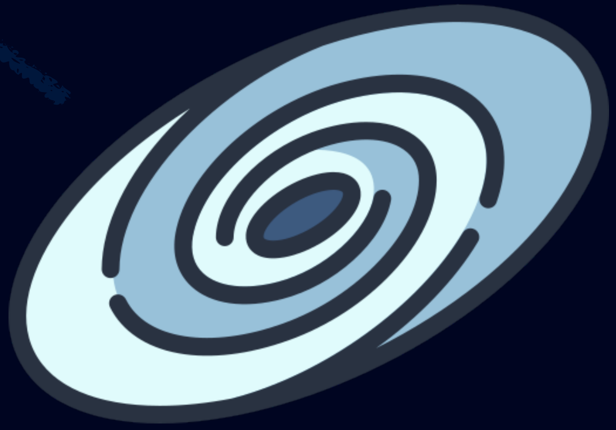
In this talk: Leptogenesis

Early Universe

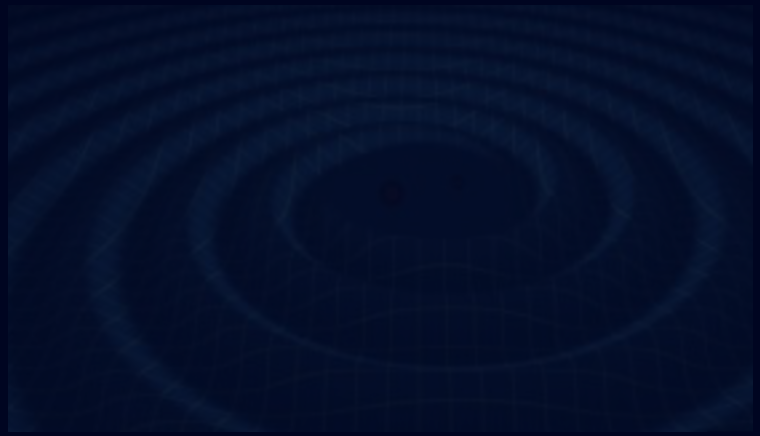


Dark Matter





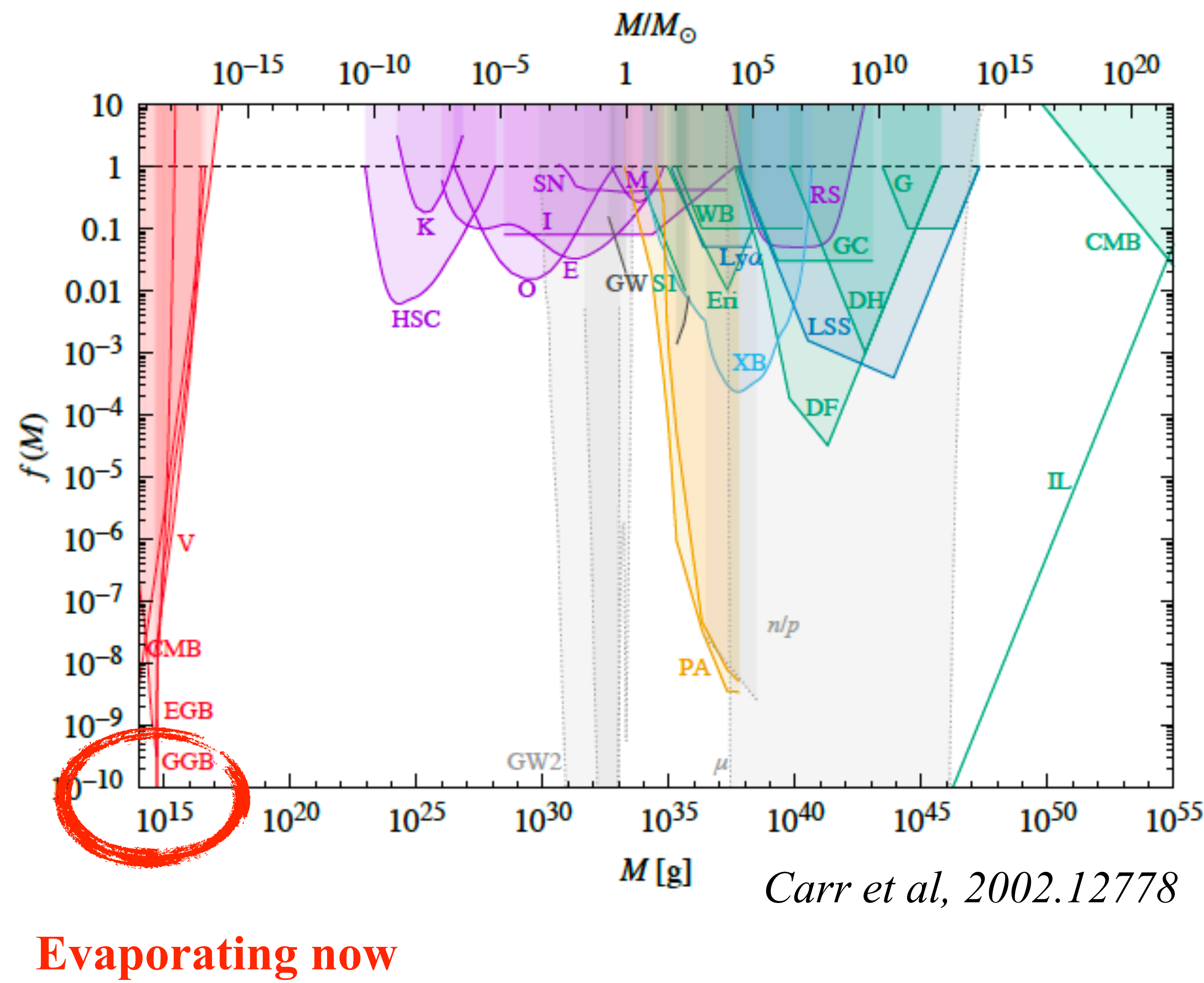
Gravitational waves



Astrophysical issues

Constraints on PBH abundance

Several observations strongly constrain the PBH abundance:



Carr et al, 2002.12778

$$f(M) \equiv \frac{\Omega_{\rm PBH}(M)}{\Omega_{\rm CDM}}$$

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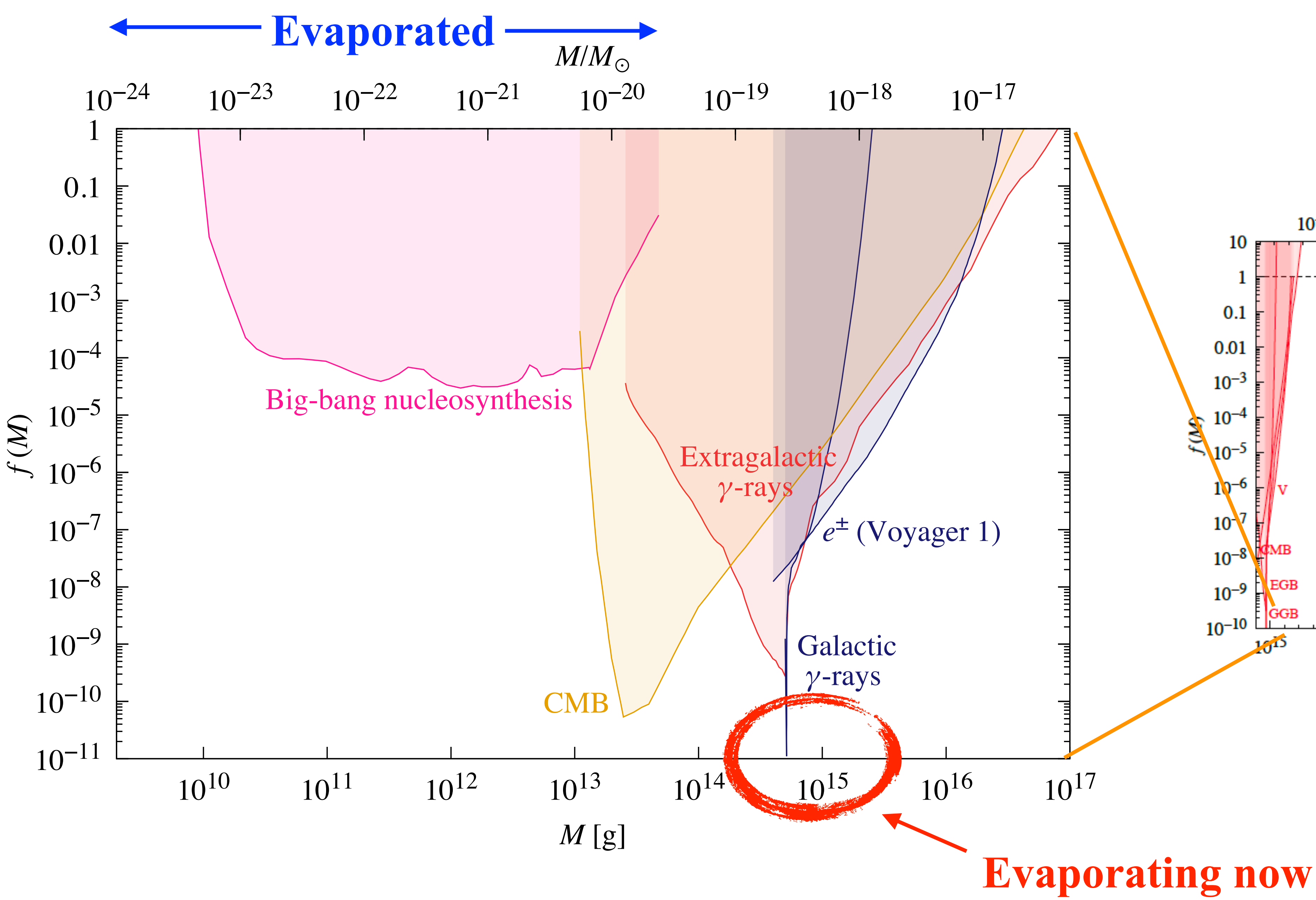

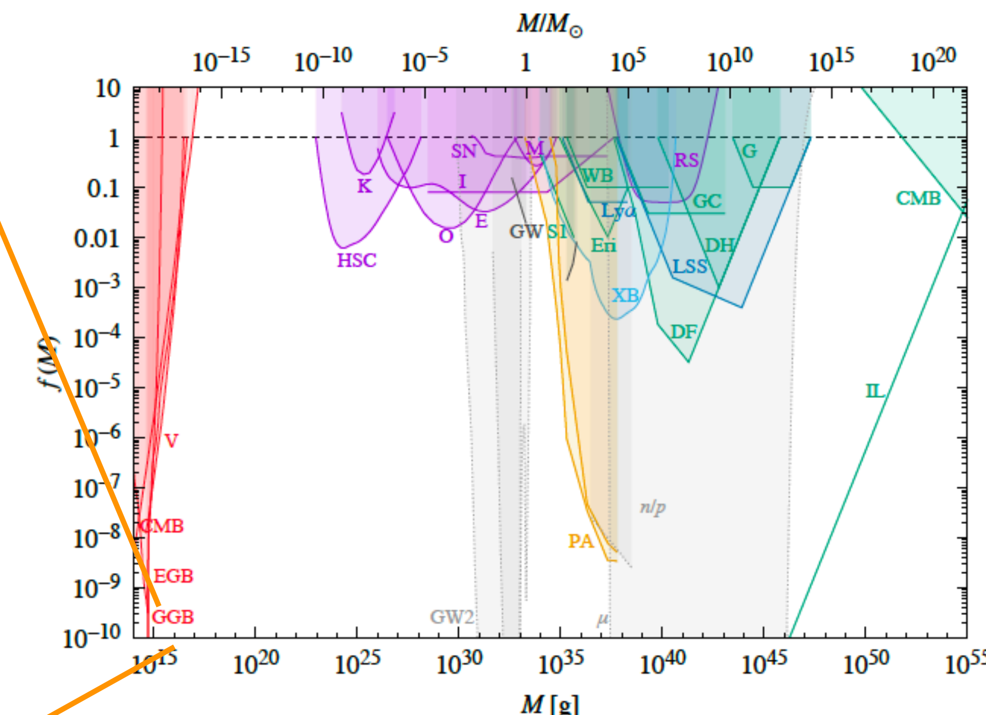

Carr et al, 2002.12778

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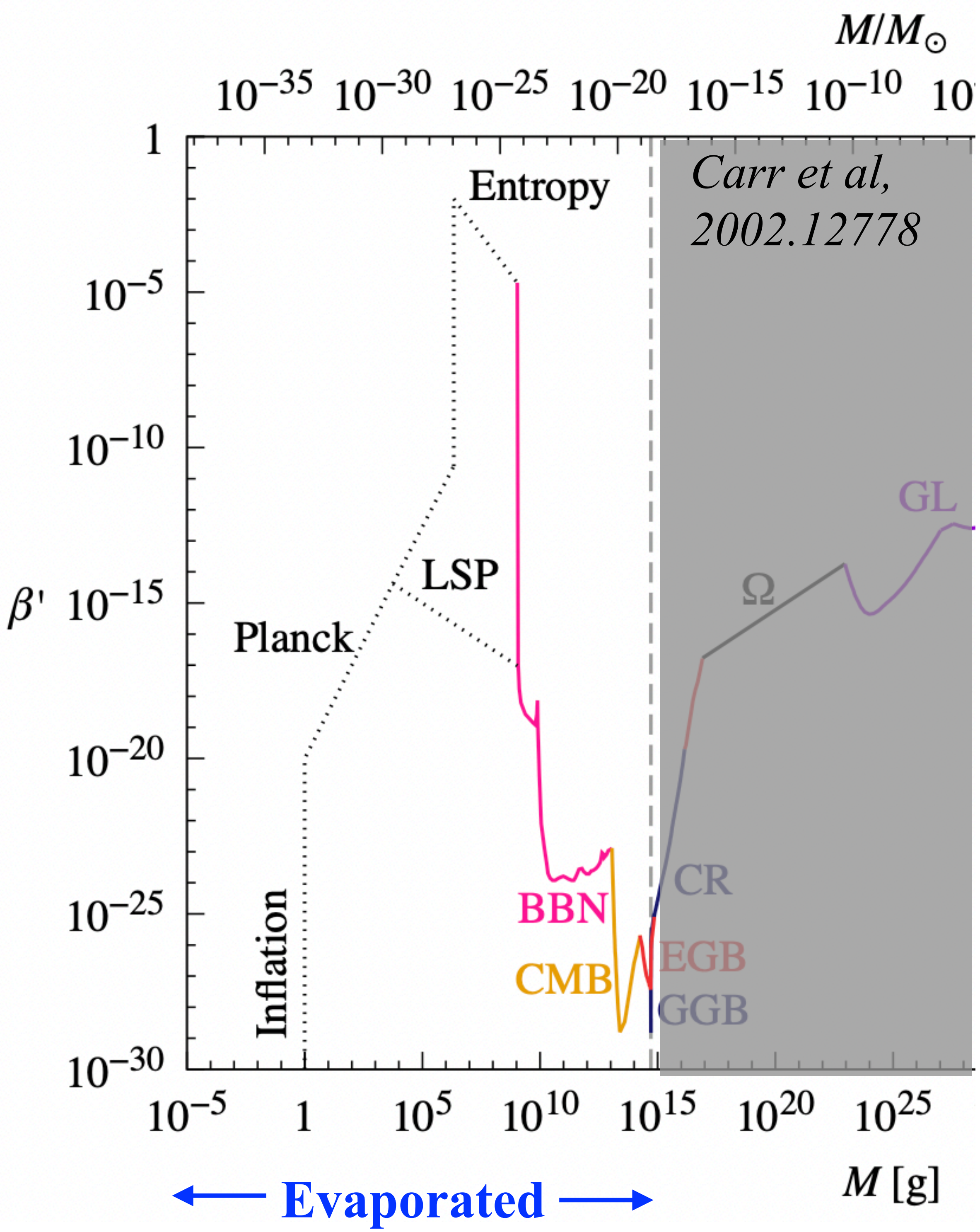
Constraints on PBH abundance

Combined constraints on β(M) for a monochromatic PBH mass function



$$\beta \equiv \frac{\rho_{\rm BH}(T_0)}{\rho_R(T_0)} = \frac{n_0 M_{\rm BH0}}{\rho_R(T_0)}$$

$$\beta'(M) \equiv \gamma^{1/2} \left(\frac{g_{*i}}{106.75}\right)^{-1/4} \left(\frac{h}{0.67}\right)^{-2} \beta(M)$$

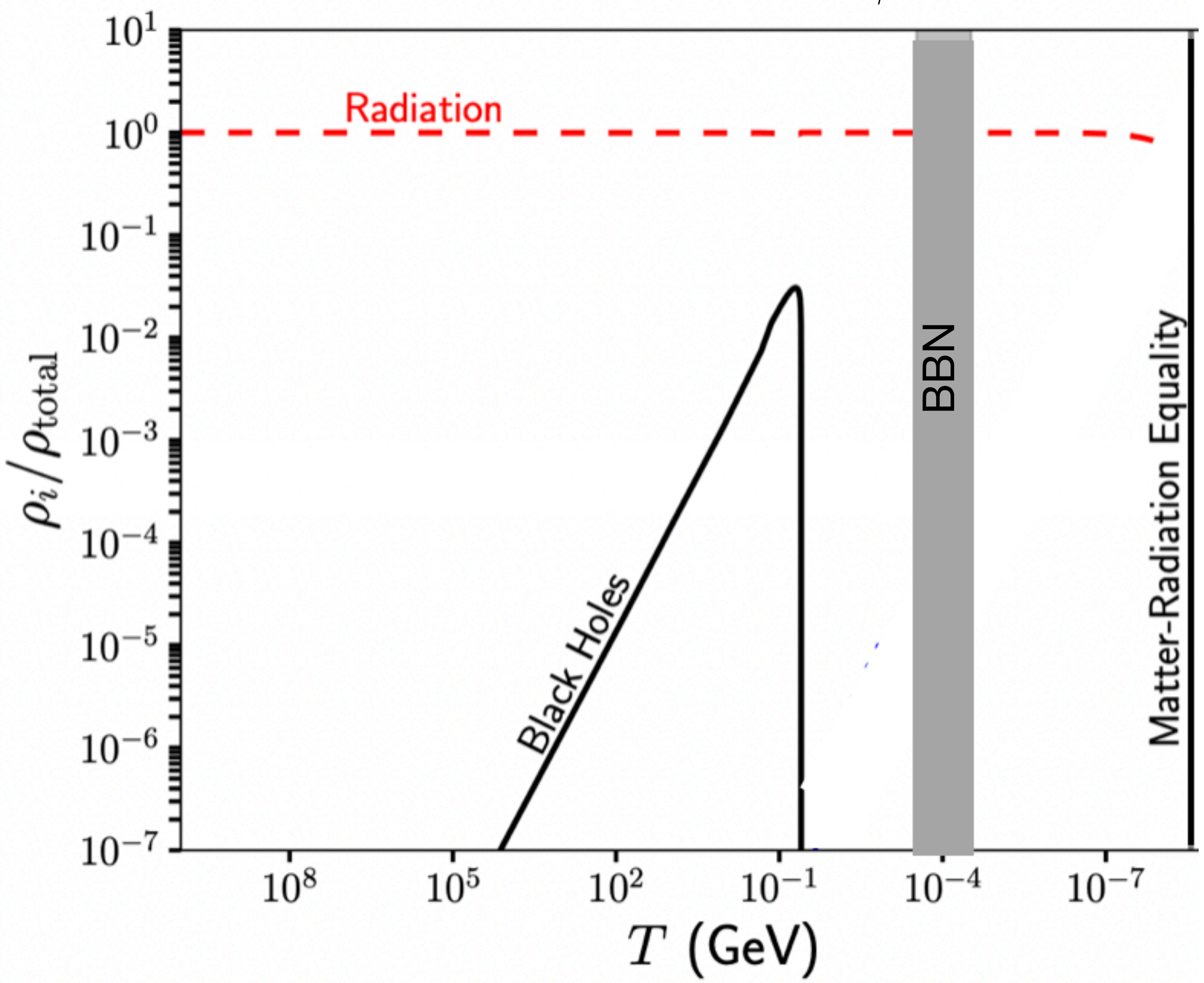
dimensionless gravitational collapse parameter

$$f(M) \equiv \frac{\Omega_{\rm PBH}(M)}{\Omega_{\rm CDM}} \approx 3.79\,\Omega_{\rm PBH}(M) = 3.81 \times 10^8 \beta'(M) \left(\frac{M}{M_\odot}\right)^{-1/2}$$

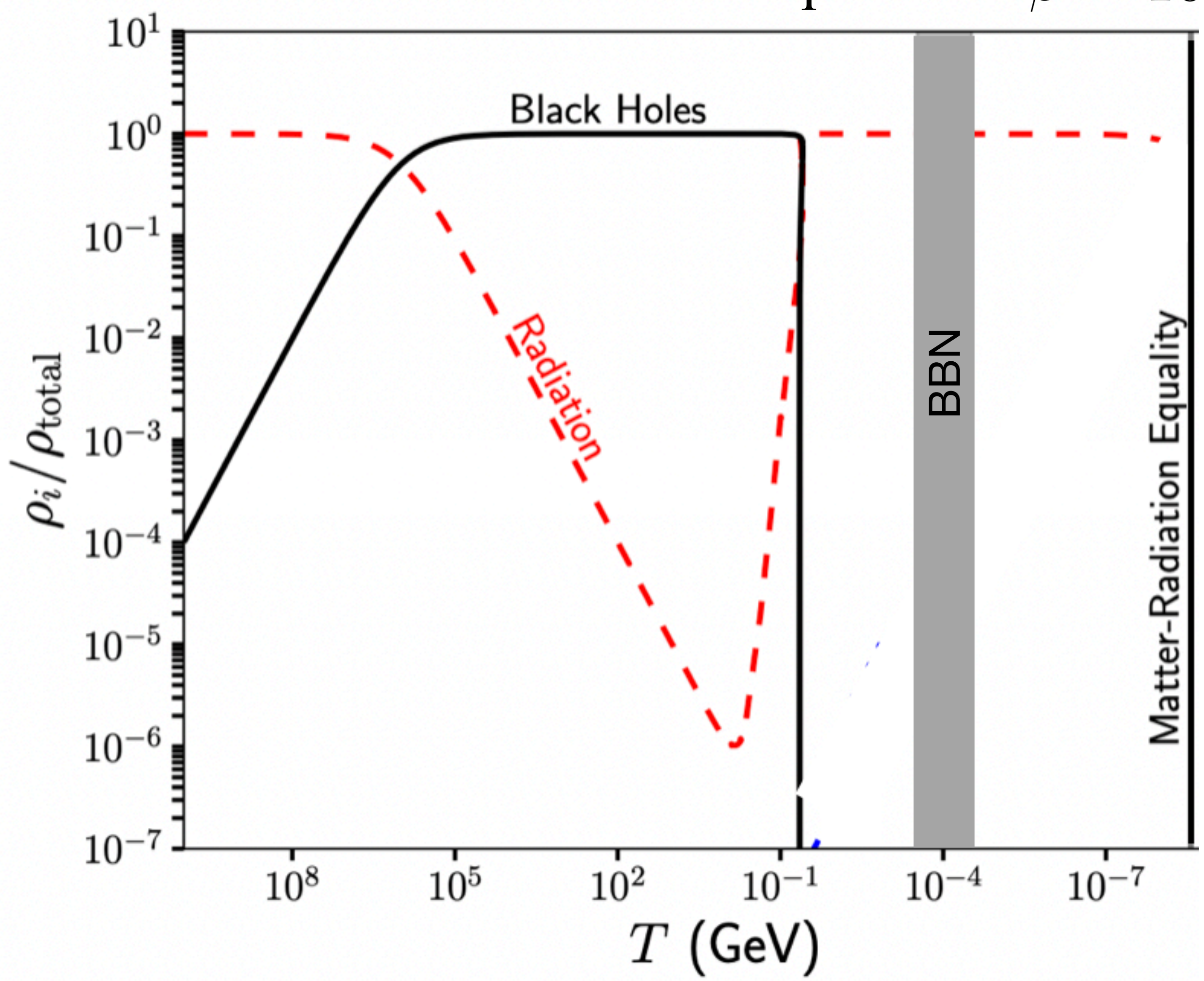
Non-standard cosmology PBH induced

Depending on the value of β (β') the PBHs could eventually dominate the evolution of the universe before their evaporation

small abundance of BH $\beta \sim 10^{-13}$



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



Adapted from Hooper et al, 1905.01301

Baryogenesis

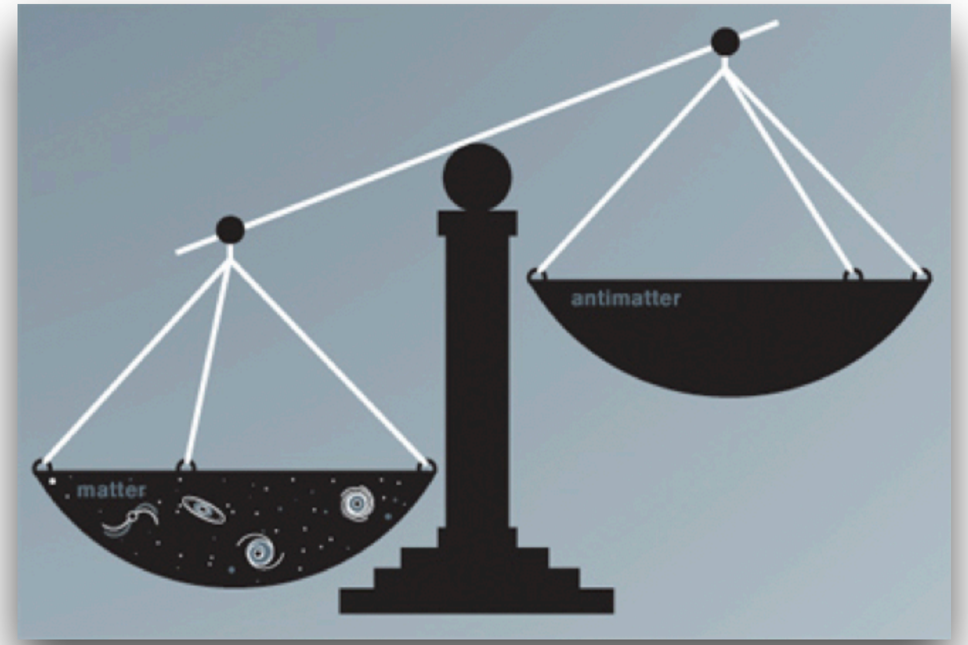
Baryon asymmetry of the Universe

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

Planck Collaboration

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

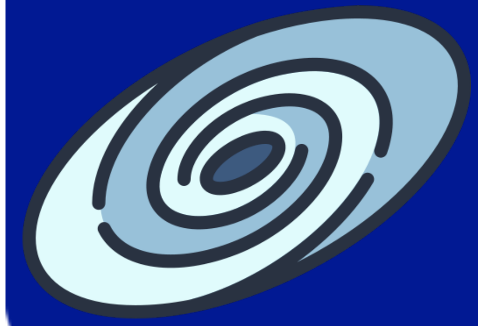
Inferred independently by BBN and CMB data



Sakharov conditions to dynamically generate a baryon asymmetry

1. **Baryon number violation**
2. **C and CP violation**
3. **Out of equilibrium dynamics**

These ingredients are all present in the SM. However, no SM mechanism generating a large enough baryon asymmetry has been found.



The democratic feature of PBHs can also lead to observed matter antimatter asymmetry.
This idea was already explored in the seminal papers of Hawking and Carr where heavy, new particles, produced from PBH evaporation, could decay violating CP and baryon number.

Leptogenesis

Simple and elegant explanation of the cosmological matter-antimatter asy

- Naturally satisfies the Sakharov conditions

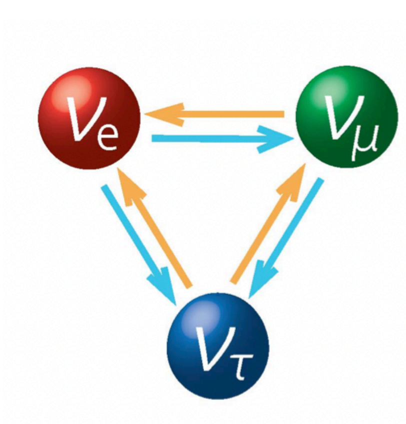
☑ L violation due to the Majorana nature of heavy RH neutrinos.
L → B through sphaleron interactions.

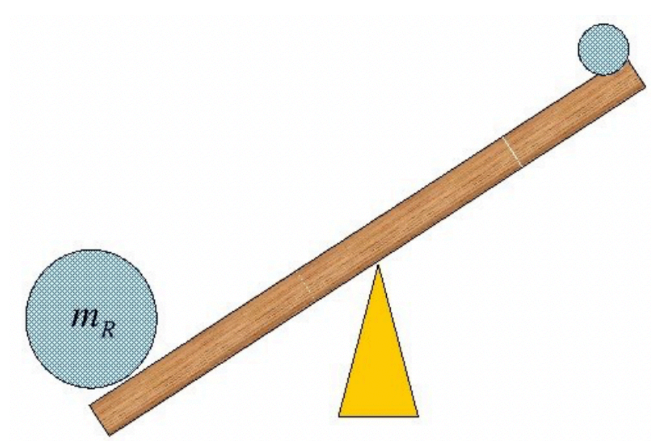
☑ New source of CP violation in the leptonic sector (through complex Dirac Yukawa couplings and/or PMNS CP phases).

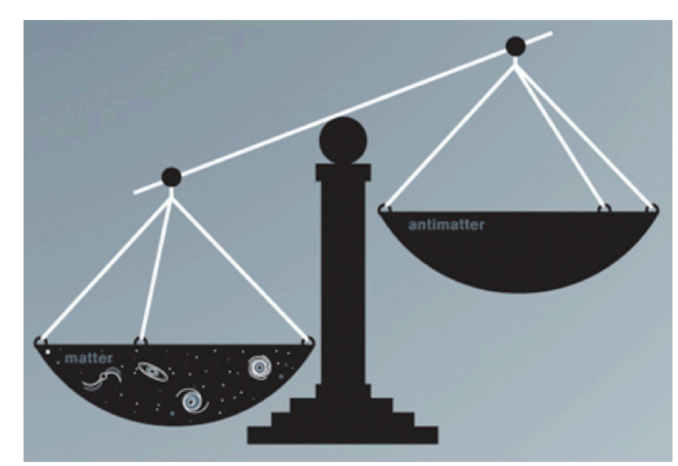
☑ Departure from thermal equilibrium when $\Gamma_N < H$.

- Provides a common link between neutrino mass and baryon asymmetry

A cosmological consequence of the seesaw mechanism







[Fukugita, Yanagida '86]

Leptogenesis Landscape

Leptogenesis via oscillations	Resonant Leptogenesis	Intermediate-scale Leptogenesis	High-scale Leptogenesis

→ M_{RH}

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

Pilaftis & Underwood Nucl.Phys. B692 303-345 (2004) Abada, Aissaoui, Losada Nucl.Phys. B728 55-66 (2005)….

Fukugida & Yanagida Phys.Lett. B17 45-47 (1986) Buchmuller, Di Bari & Plumacher New J.Phys. 6 105 (2004) Barbieri, Creminelli, Strumia & Tetradis Nucl.Phys. B575 61-77 (2000)…

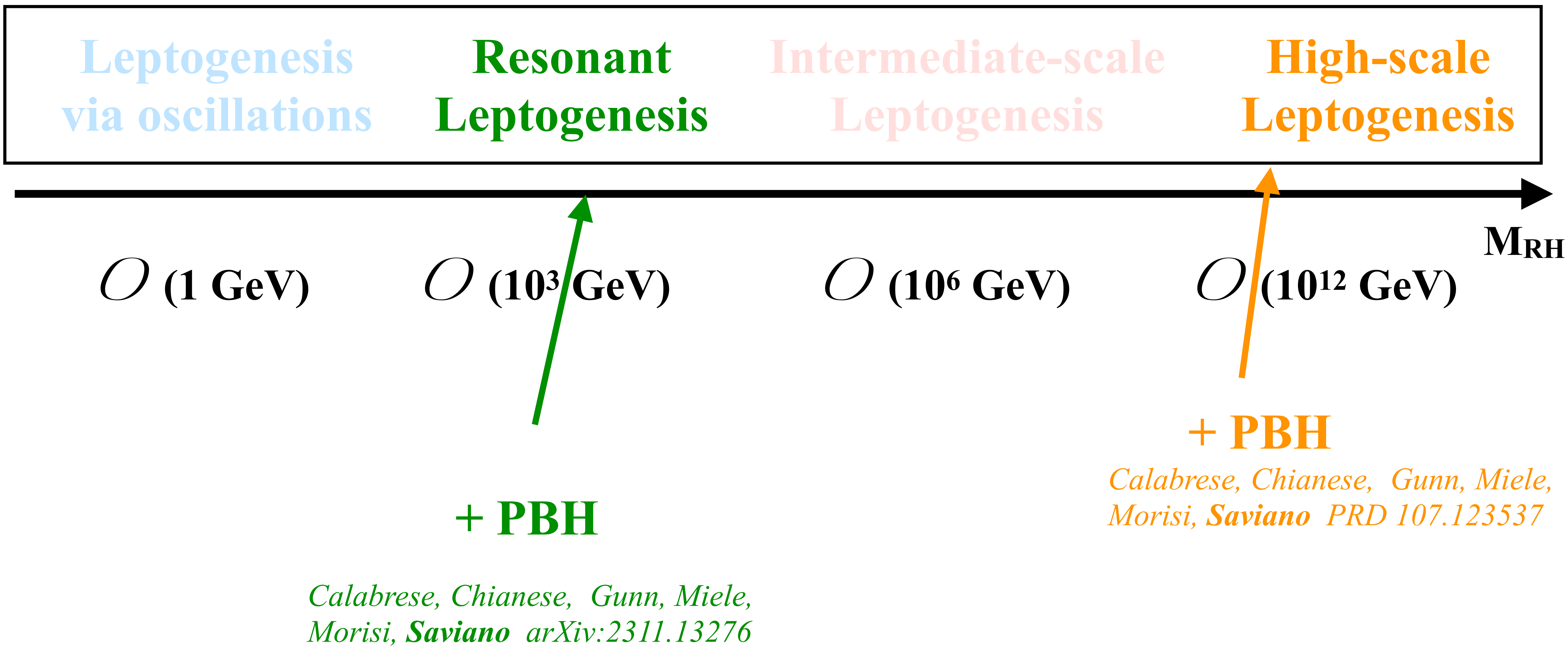
Akhmedov, Rubakov & Smirnov Phys.Rev.Lett. 81 1359-1362 (1998) Asaka & Shaposhnikov Phys.Lett. B620 17-26 (2005) Asaka, Eijima & Ishida JHEP 1104 011(2011)…

Racker, Rius & Pena JCAP 1207 030 (2013) Moffat, Petcov, Pascoli, Schulz & Turner Phys.Rev. D98 no.1, 015036 (2018) …

Incomplete list…

Interesting reviews: W. Buchmuller et al. hep-ph/0401240; Sheng Fong et al. 1301.3062; Davidson et al. 0802.2962;

Leptogenesis Landscape



Leptogenesis Landscape

Leptogenesis via oscillations	Resonant Leptogenesis	Intermediate-scale Leptogenesis	High-scale Leptogenesis
$\mathcal{O}$ (1 GeV)	$\mathcal{O}$ (10^3 GeV)	$\mathcal{O}$ (10^6 GeV)	$\mathcal{O}$ (10^{12} GeV)

M_{RH}

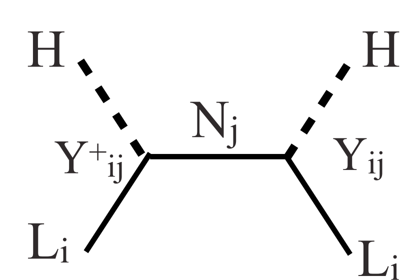
+ PBH

*Calabrese, Chianese, Gunn, Miele, Morisi, **Saviano** PRD 107.123537*

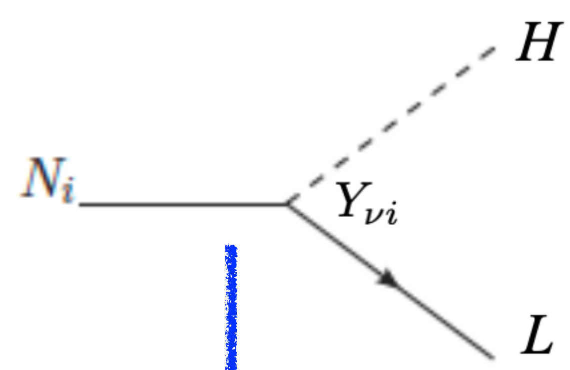
+ PBH

*Calabrese, Chianese, Gunn, Miele, Morisi, **Saviano** arXiv:2311.13276*

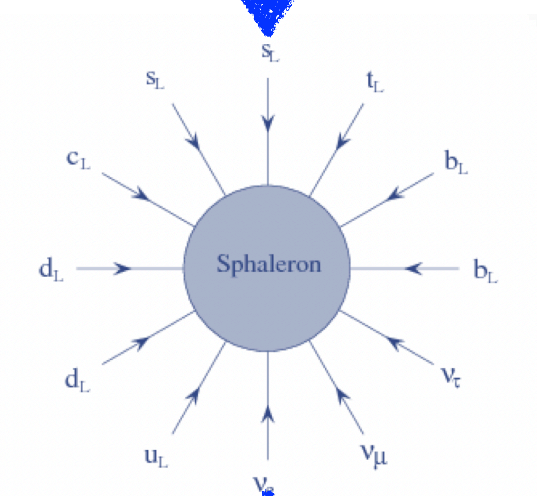
High-scale: based on type-I seesaw mechanism, hierarchical heavy Majorana RH neutrinos Nj, M1 ≪ M2 ≪ M3 with seesaw scale M ≥ 10^{12} GeV.



Basic steps of Leptogenesis



Lepton asymmetry

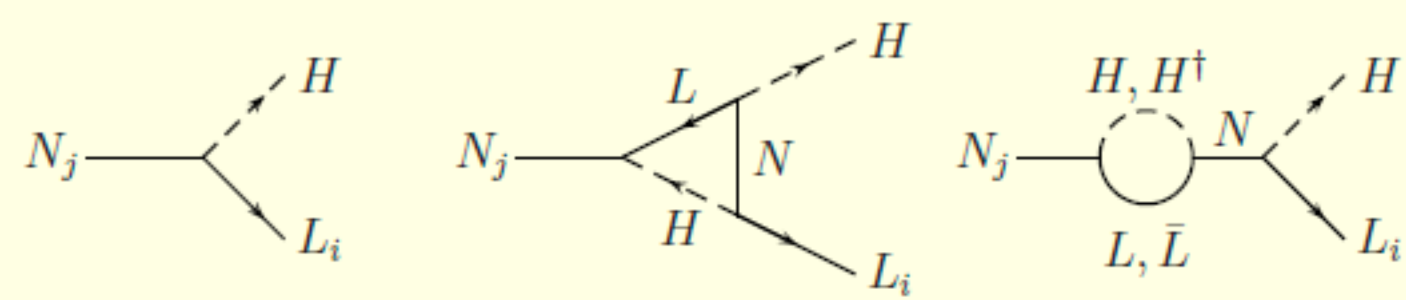


Baryon asymmetry

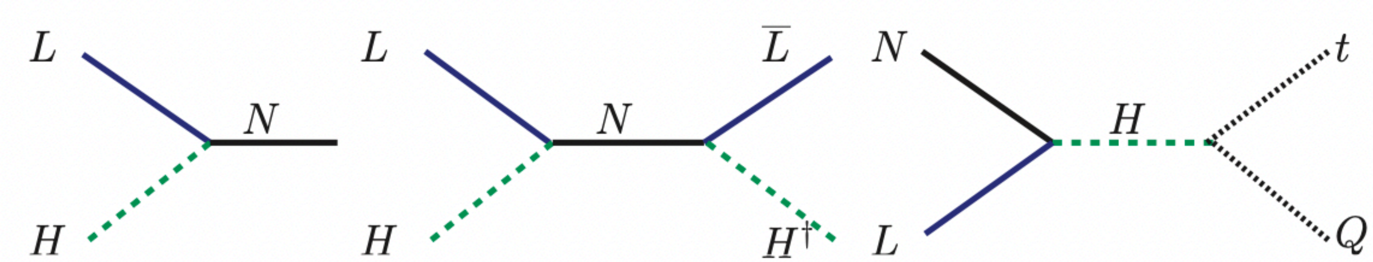
$$N \to LH / N \to \bar{L}H$$

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

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



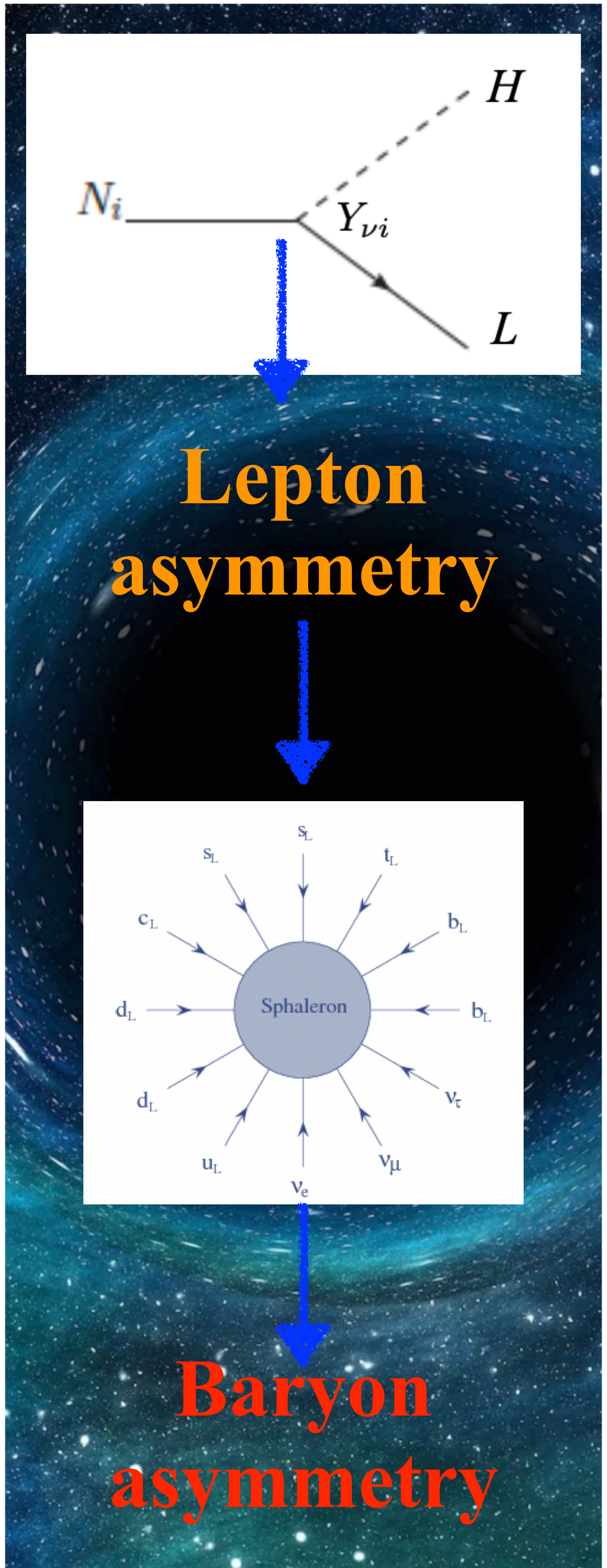
Partial washout of the asymmetry due to inverse decay and scatterings:



inverse Decays
ΔL=2
ΔL=1

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

Leptogenesis & PBH



PBH can affect the leptogenesis in different ways depending on the mass M_{PBH} and abundance (β')

In particular we can have:

- an additional (non-thermal) source for the HRN

$$aH\frac{dn_{N_1}}{da} = -(n_{N_1} - n_{N_1}^{\text{eq}})\Gamma_{N_1}^{T} + n_{\text{BH}}\widetilde{\Gamma}_{N_1}^{\text{BH}},$$

contribution from thermal plasma

contribution to RHN population from PBH evaporation

Studied for $M_{PBH} < 10^5$g in Perez-Gonzalez & Turner 2010.03565; Bernal et al. 2203.08823

- Entropy injection in the primordial plasma (reheating)

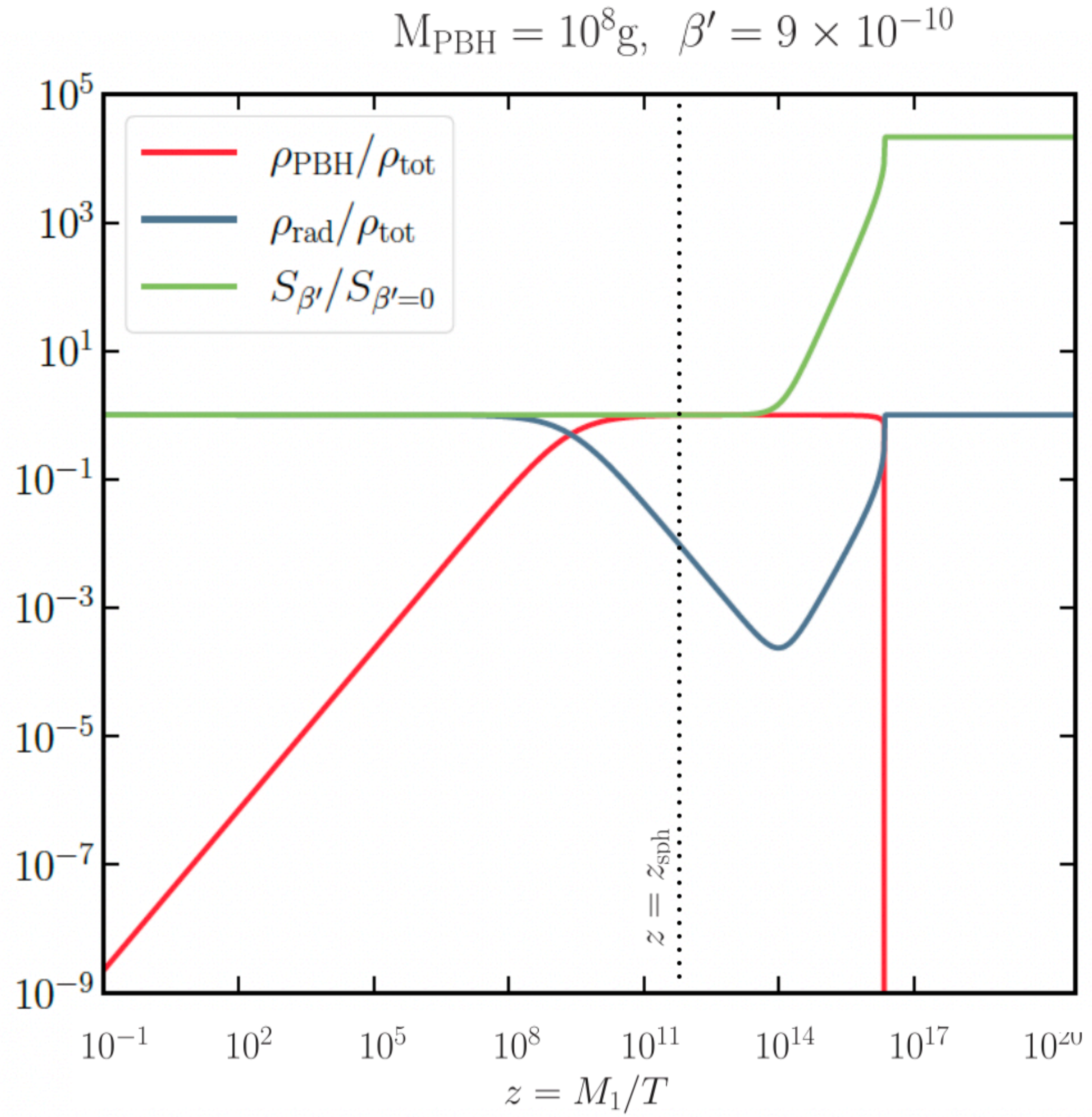
Studied for 10^5 g < MPBH < 10^9g in this work

$10^{-15} < \beta' < 0.1$

Entropy injection by PBH

PBH by evaporating injects standard model particles in the thermal plasma —> entropy increasing

$$\frac{\mathrm{d}\mathcal{S}}{\mathrm{d}\alpha} = -\frac{f_{\rm SM}}{T(\alpha)}\frac{\mathrm{d}\ln M_{\rm PBH}}{\mathrm{d}\alpha}\,\varrho_{\rm PBH}$$



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Our model: HS Thermal Leptogenesis

Type I seesaw: $\mathcal{L} = i\overline{N}_i \partial N_i - Y_{\alpha i}\overline{L}_\alpha N_i \tilde{\phi} - \frac{1}{2}\overline{N^c}_i \hat{M}_{ij} N_j + h.c.\,,$ → $m_\nu \simeq -v^2 Y \frac{1}{M} Y^T$

Casas-Ibarra parametrization for the Yukawa couplings: $Y = \frac{1}{v_{EW}} \sqrt{\hat{M}} \cdot R \cdot \sqrt{\hat{m}_\nu} \cdot U^\dagger_{PMNS}$

R complex orthogonal matrix satisfying $R^T R = RR^T = 1$

For a detailed treatment see Hambye et al, Nuclear Physics B 695 (2004) 169–191

- High Scale $[10^{10} \leq M_1 \leq 10^{16}]$GeV
- Thermal letogenesis era: $z = M_1/T \sim O(1)$ in which L=2 scatterings are relevant
- Hierarchical heavy neutrino spectrum $M_1 << M_{2,3}$
- Neglect the decays of $N_{2,3}$
- $m_1 = m_2$ since $\Delta m^2_{\rm sun} \ll \Delta m^2_{\rm atm}$ → the only phase in R is $z_{13} = x + i\,y$
- Boltzmann equations:

$$\frac{dY_{N_1}}{dz} = -D_1(Y_{N_1} - Y^{eq}_{N_1}),$$
$$\frac{dY_{\Delta L}}{dz} = \epsilon_1 D_1(Y_{N_1} - Y^{eq}_{N_1}) - W_1 Y_{\Delta L}$$

Decay

Washout

The CP asymmetry parameter ε_1 can be expressed in terms of only four parameters $\{x, y, m_h, M_1\}$

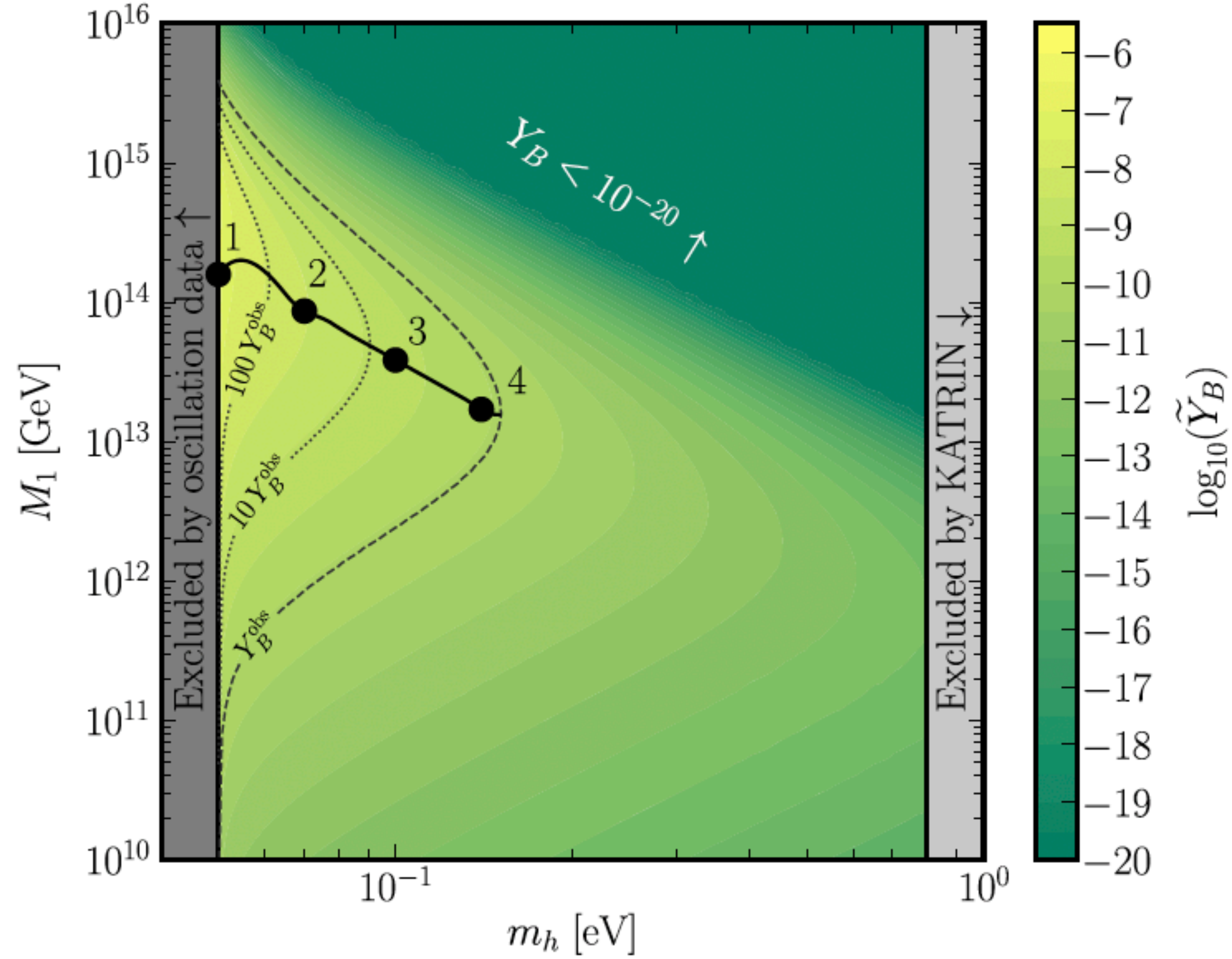
Parameter space of thermal leptogenis

Parameters that 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}

$$0 < x < \pi$$
$$0.14 < y < \pi$$
$$\sqrt{m^2_{\rm atm}} < m_h < 0.8\text{eV}$$
$$10^{10}\text{GeV} < M_1 < 10^{16}\text{GeV}$$

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



Dashed line: parameters for which $\tilde{Y}_B$ matches the observed value

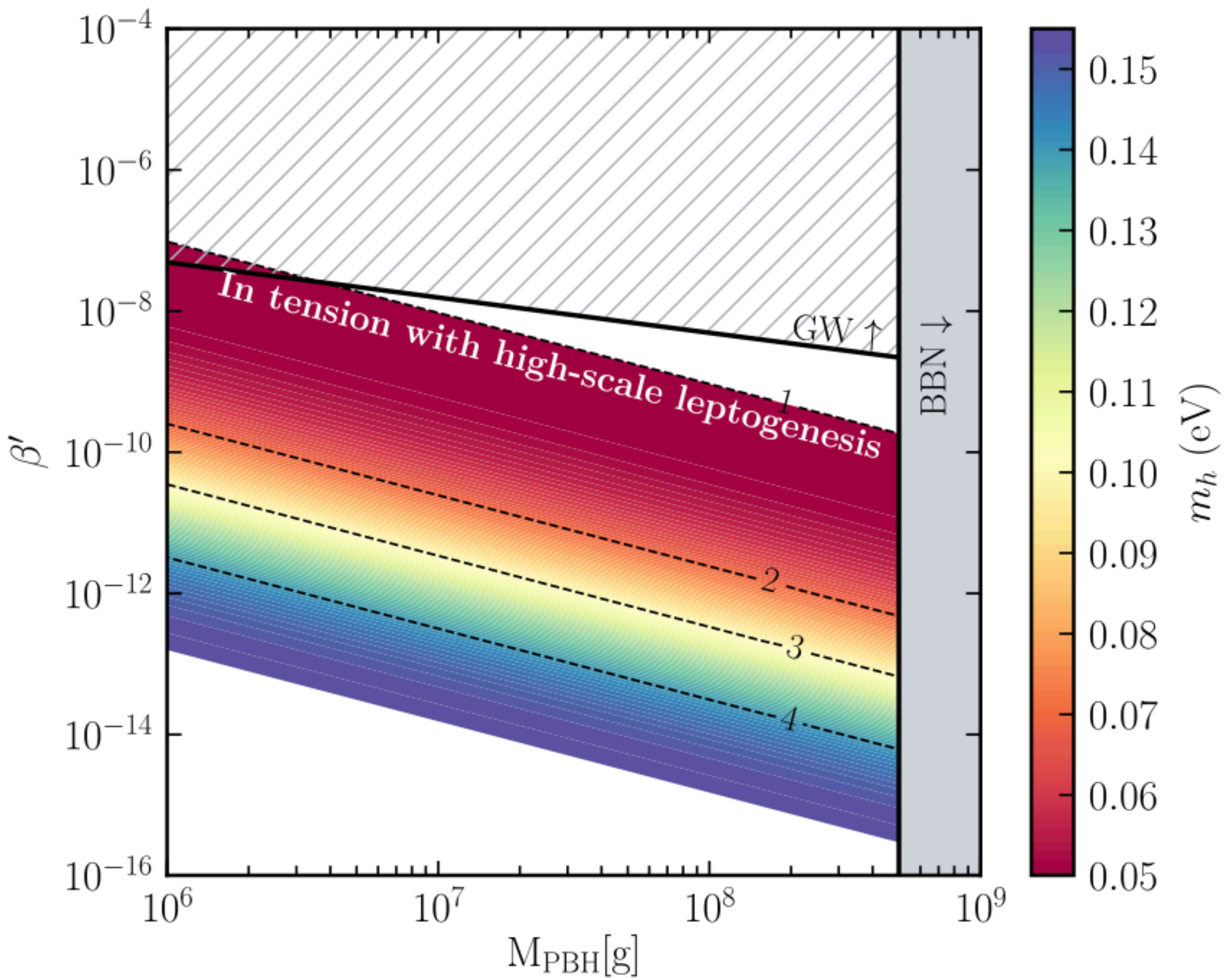
Dotted lines: increasing values for the ratio $\tilde{Y}_B / Y_B^{obs}$

Solid line: relation between m_h and M_1 that maximises the baryon asymmetry Y_B.

*Calabrese, Chianese, Gunn, Miele, Morisi, **Saviano** PRD 107.123537*

PBH Constraints by leptogenesis

Mutual exclusion limits between high scale leptognesis and light PBH



GW constraints on the PBH dominated early universe:

Papanikolaou et al. 2010.11573; Dome`nech et al., 2012.08151

The different colors correspond to the upper bounds obtained assuming different masses m_h for the heaviest active neutrino —> **Strong interplay between the PBH and active neutrino parameter space**

*Calabrese, Chianese, Gunn, Miele, Morisi, **Saviano** PRD 107.123537*

Conclusions

- *We investigate the impact of the nonstandard cosmology driven by the presence and the evaporation of light PBH on the production of the baryon asymmetry of the Universe through high-scale leptogenesis.*

- *The evaporation of PBHs is associated with a injection of entropy and reheating of the Universe. When this occurs after the sphaleron freeze-out the baryon asymmetry is diluted.*

- *We first explore the four-dimensional parameter space of* ***high-scale*** *leptogenesis in its minimal version demonstrating the existence of a finite, maximum achievable asymmetry* Y_B^{max}

- *If the entropy injection from PBH' evaporation is large enough, even does* Y_B^{max} *not reproduce the observed asymmetry, ruling out high-scale leptogenesis as the baryogenesis mechanism.*

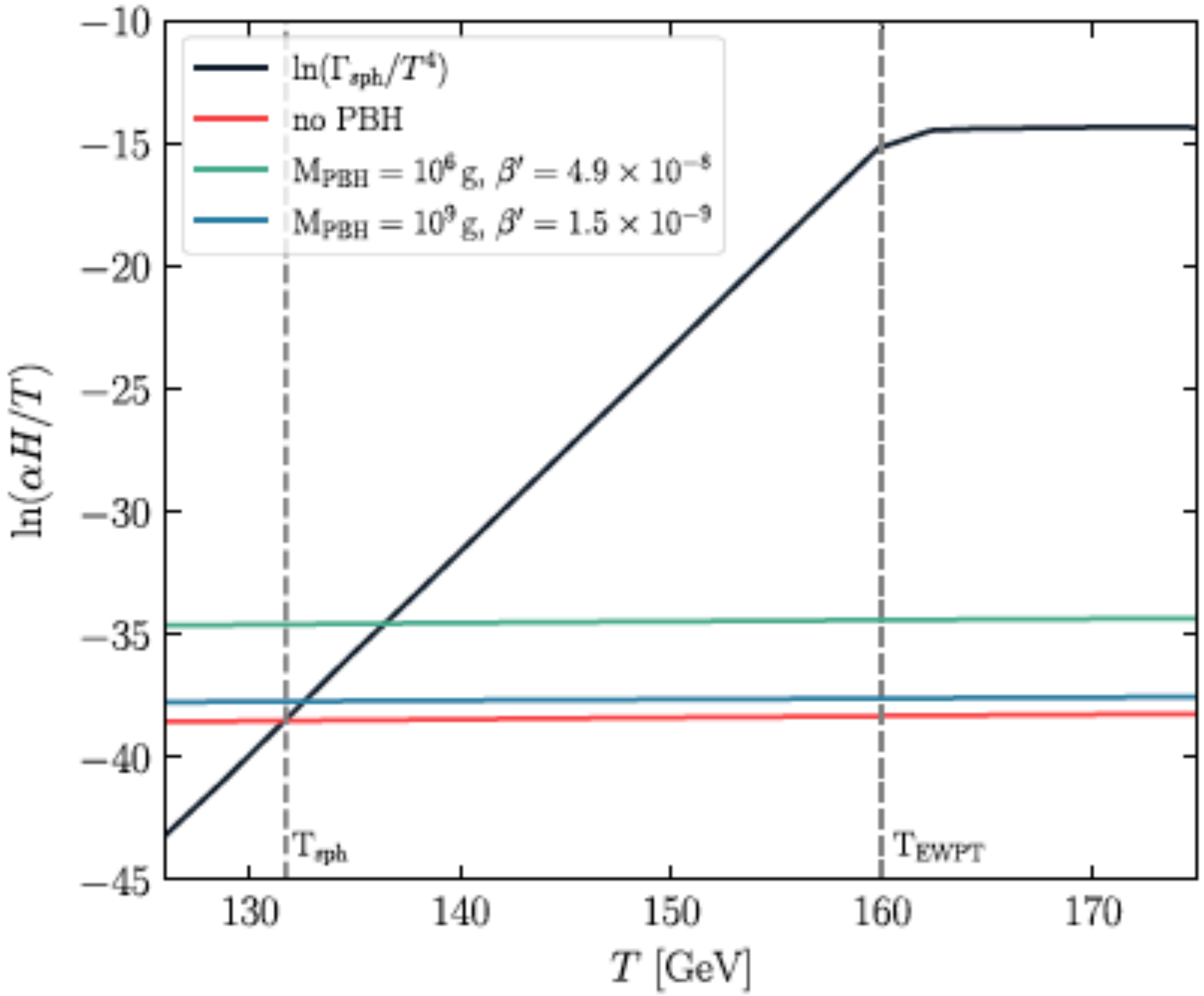
- *For an entropy increase greater than around four orders of magnitude, the minimal model for high-scale leptogenesis is insufficient to account for the baryon asymmetry of the Universe. This corresponds to a PBH population with masses from* 10^6 *to* 10^9 *grams with an initial abundance* $\beta^0 \gtrsim 10^{-9}$

- *Similar investigation of sub-TeV* ***resonant*** *leptogenesis, where the observed baryon asymmetry is achieved through the interactions of (at least) two almost-degenerate Right-Handed Neutrinos with mass from 1 GeV to few TeVs*

First edition last year in Naples

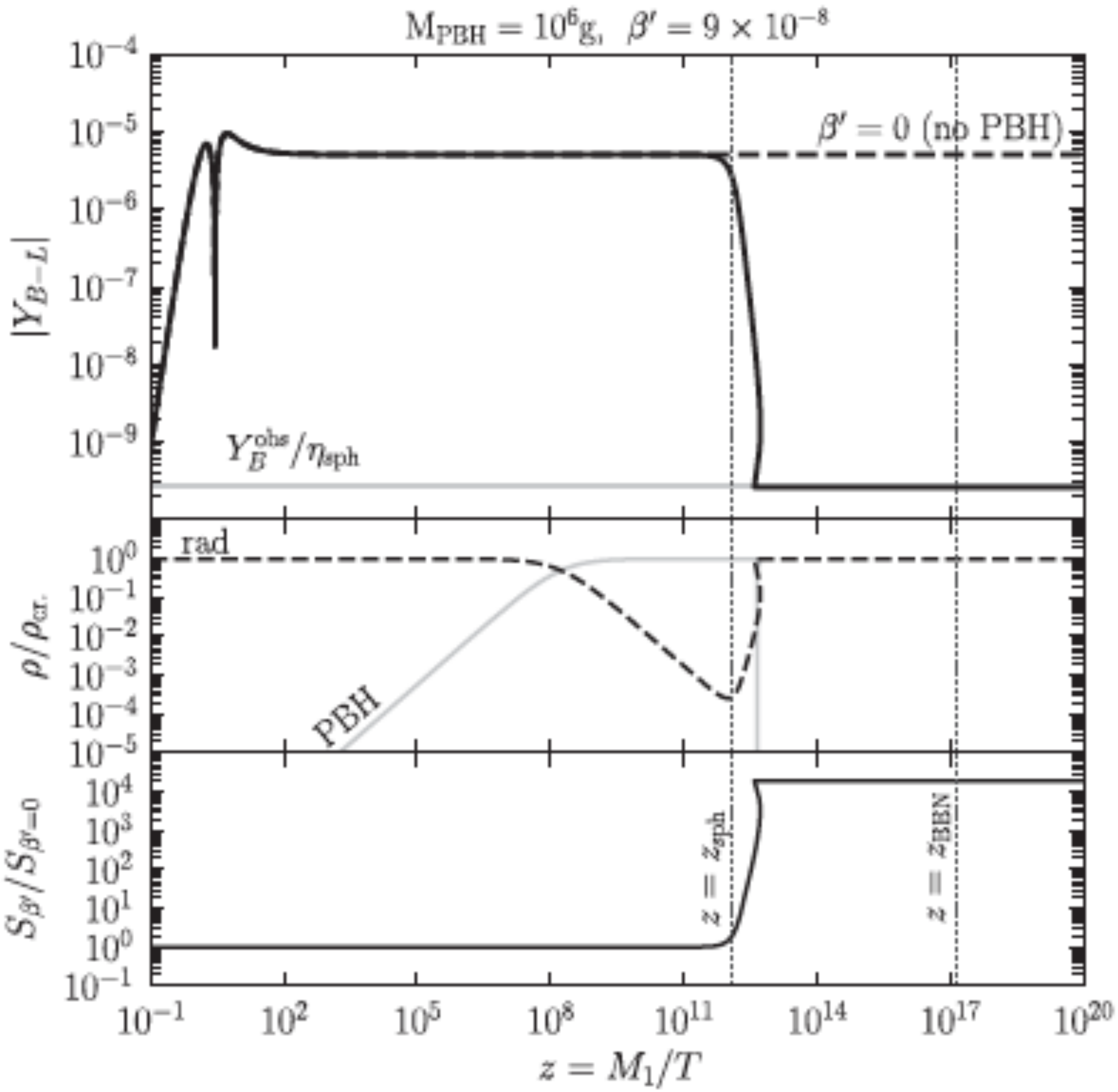

Thank you

The sphaleron rate

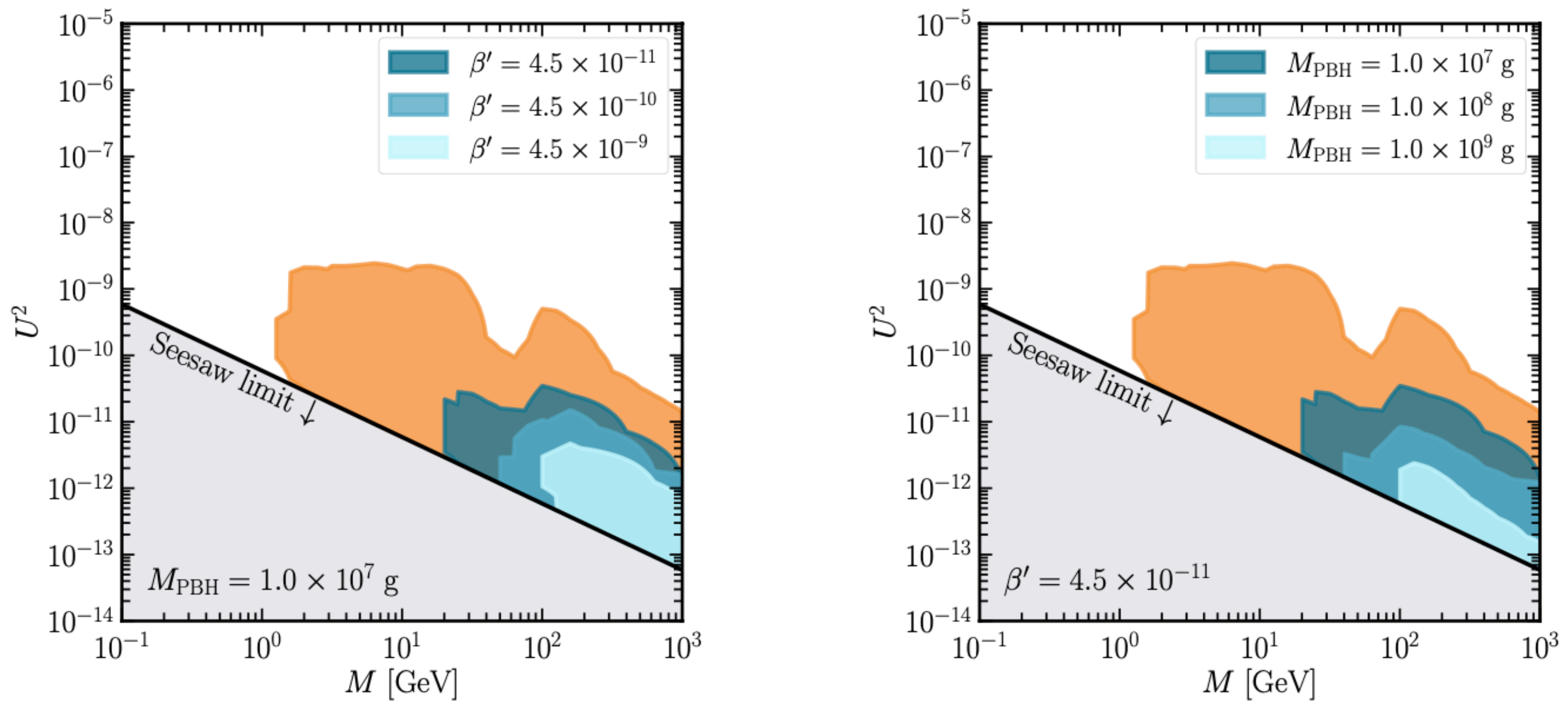


The colored lines show the Hubble rate for different scenarios with and without the presence of PBHs. The crossing between Γ_{sph} and H defines the temperature T_{sph} at which the sphaleron processes freeze-out. We find $T_{sph} < T_{EWPT}$ in the whole parameter space analyzed.

The yield Y_{B-L} with and without the presence of PBHs



Parameter space of resonant leptogenesis



Rhe RHNs parameter space providing successful leptogenesis is modified due to the presence of PBHs and their evaporation, for different PBHs abundance (left panel) and different PBHs mass (right panel).

The effect of PBHs is to shrink the allowed region for the RHNs parameters towards higher masses M and smaller mixing parameters U2. Indeed, the entropy injection from PBHs evaporation reduces the final yield YB of baryon asymmetry and tightens the allowed range for the parameters M and y in a non-linear way, due to the non-trivial effects on the sphaleron freeze-out and the Hubble rate.

PBH Constraints by resonant leptogenesis

Constraints on the PBHs abundance as a function of the PBHs for different RHNs mass scales. These constraints delineate the regions of PBHs parameter space which are incompatible with sub-Tev resonant leptogenesis at different mass scales M. The smaller the RHNs mass scale, the stronger the constraints on β′.

The potential laboratory detection of Right-Handed Neutrinos in the mass range from 1 to ~100 GeV would allowed us to place very competitive constraints on the abundance of Primordial Black Holes