

13 -17 March 2023

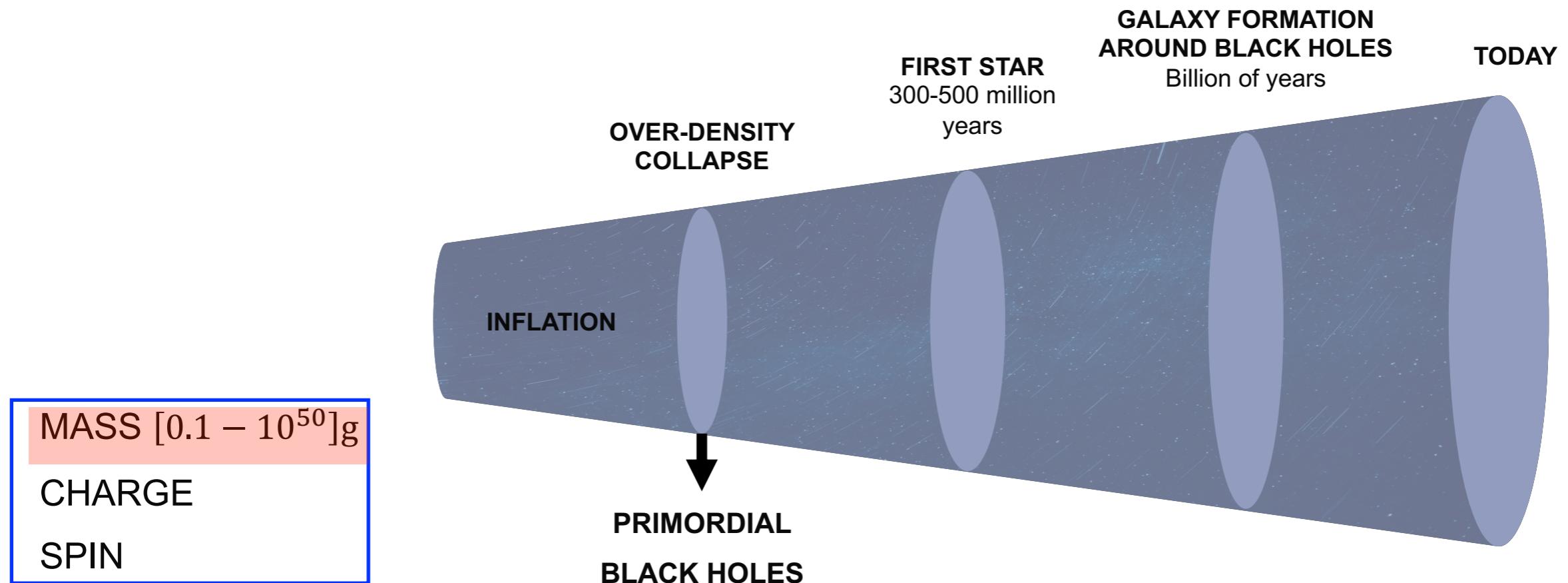
Light PBH limits from high scale leptogenesis

Ninetta Saviano

*Based on 2304.XXXX in collaboration with R. Calabrese, M. Chianese,
J. Gunn, G. Miele, S. Morisi*

Genesis of Primordial Black Holes

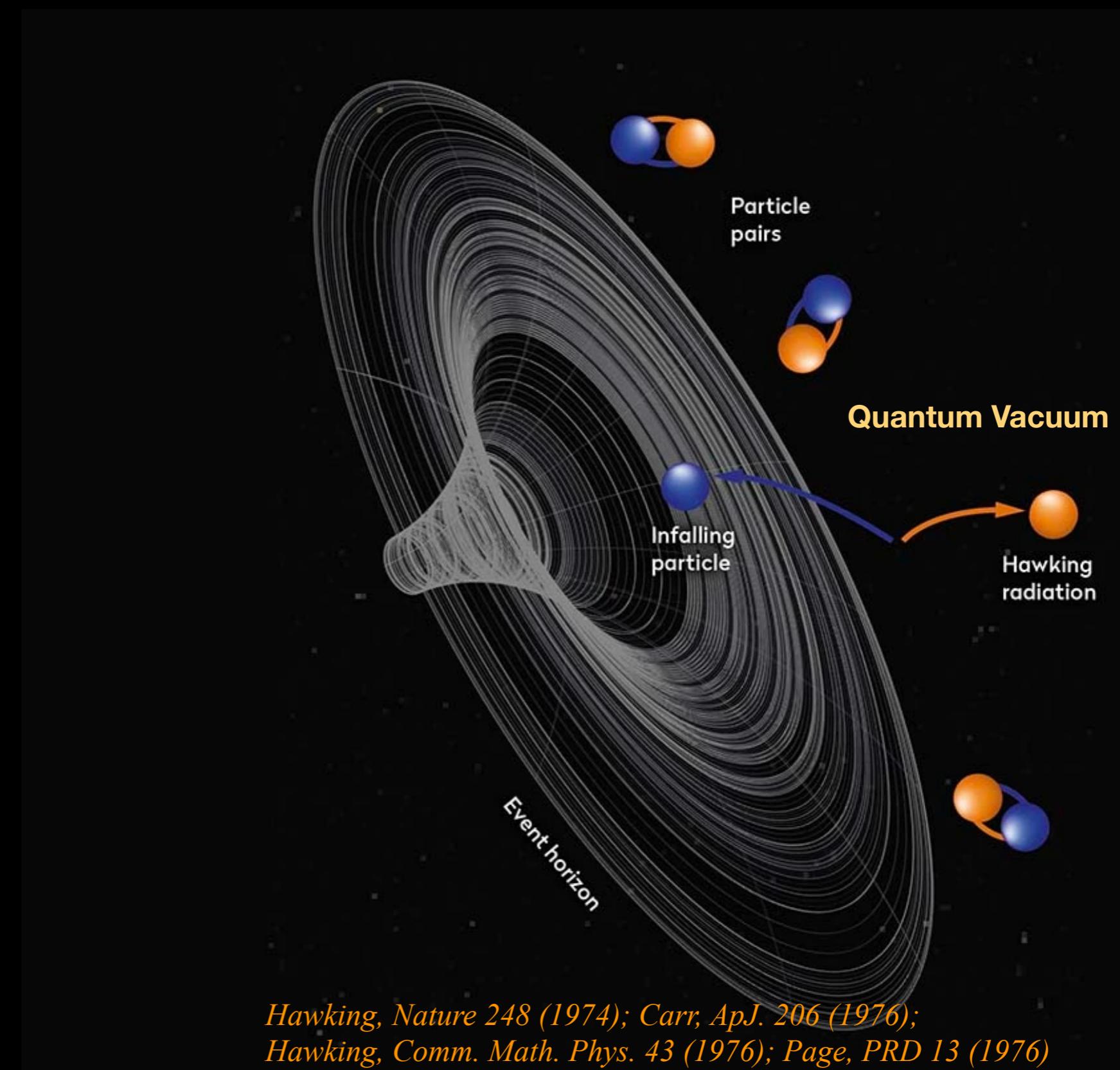
Primordial Black Holes: Black Holes generated at earlier than star formation times and therefore not of stellar origin.



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)

Hawking Evaporation



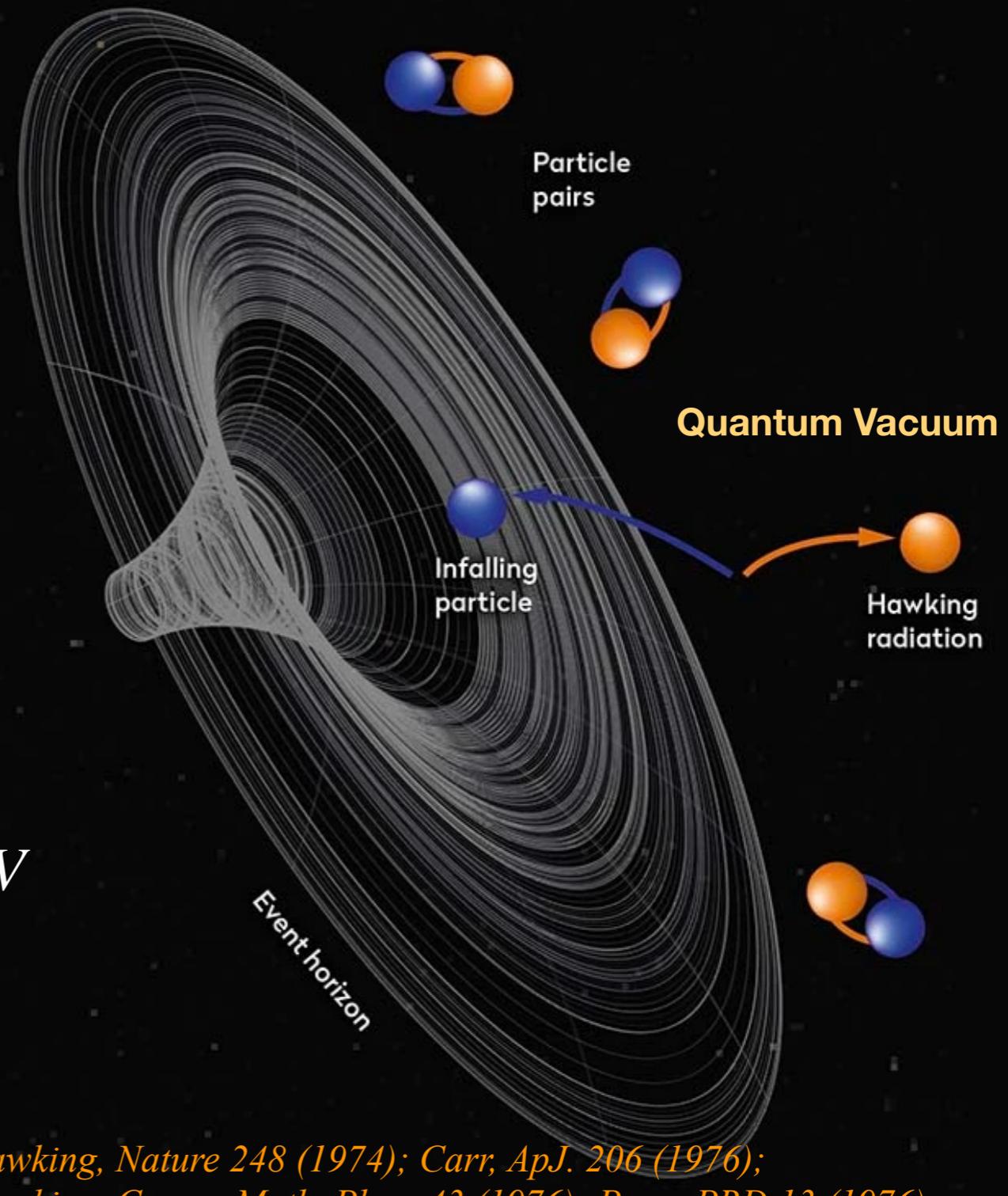
Hawking Evaporation

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 $< T_H$

For non-rotating and neutral PBH:

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



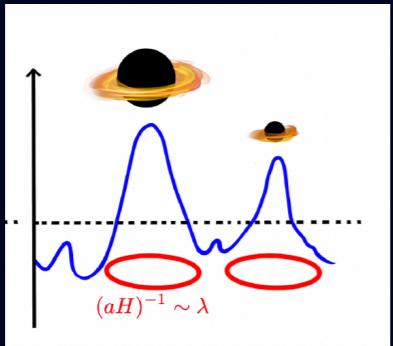
*Hawking, Nature 248 (1974); Carr, ApJ. 206 (1976);
Hawking, Comm. Math. Phys. 43 (1976); Page, PRD 13 (1976)*

Current big interest in PBHs

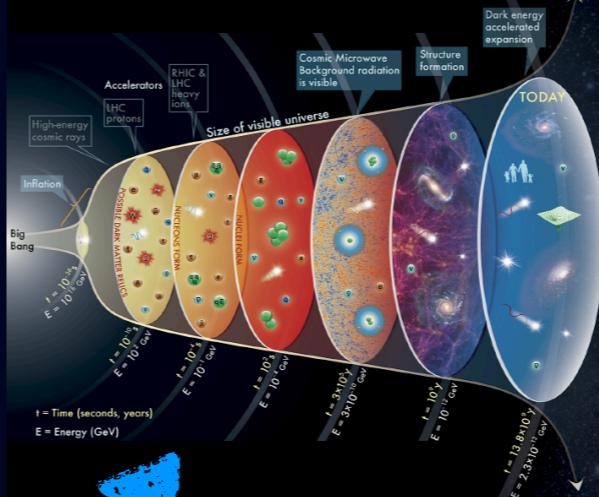


Current big interest in PBHs

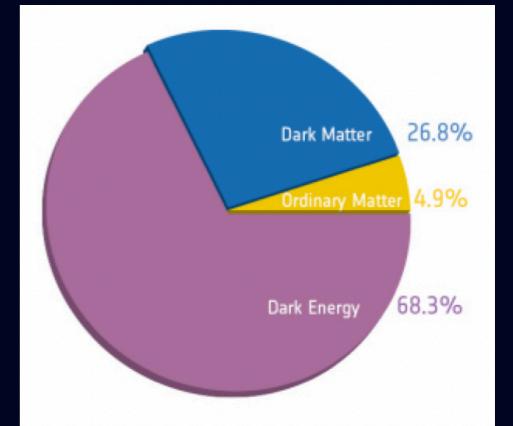
Formation mechanism



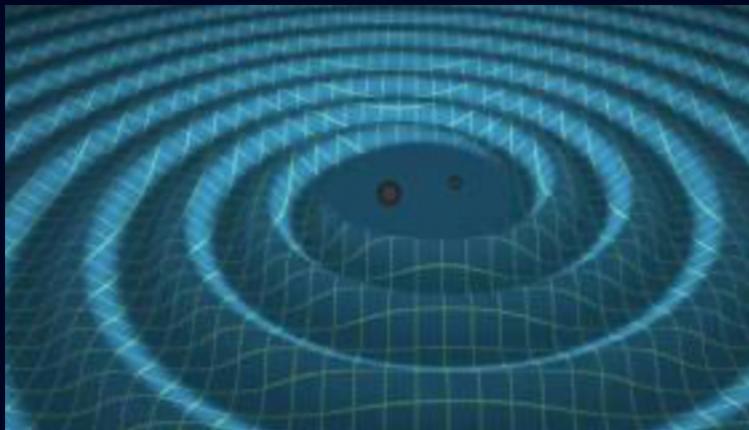
Early Universe



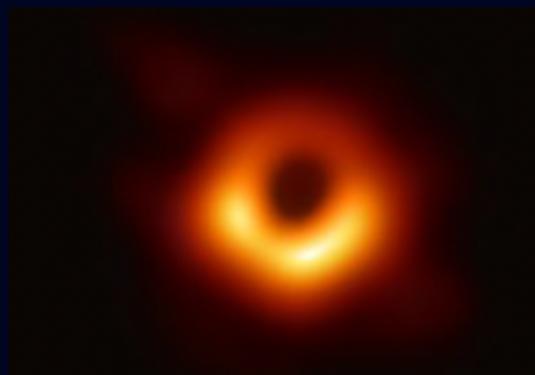
Dark Matter



Gravitational waves

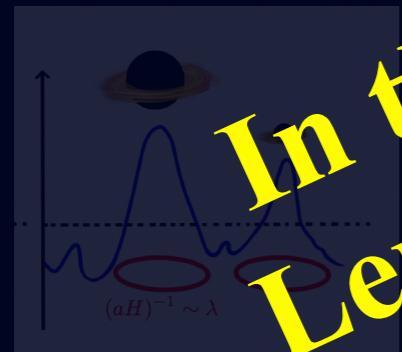


Astrophysical issues



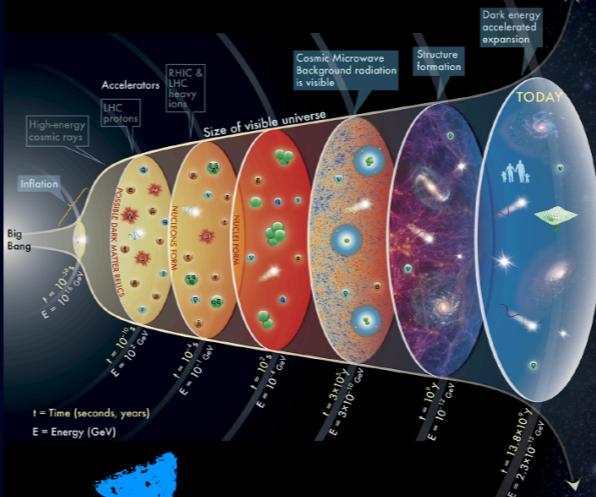
Current big interest in PBHs

Formation mechanism

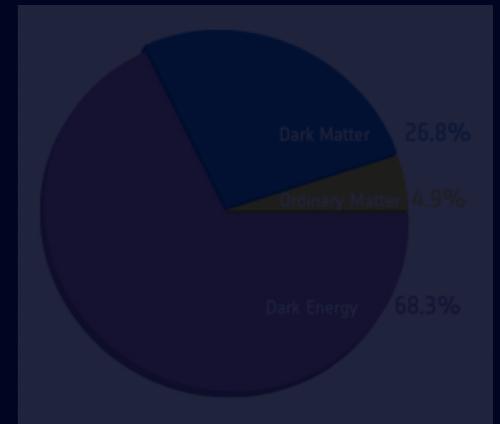


In this talk:
Leptogenesis

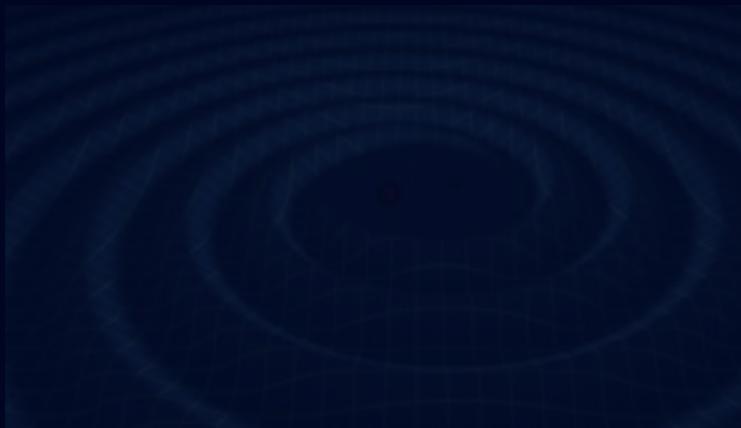
Early Universe



Dark Matter



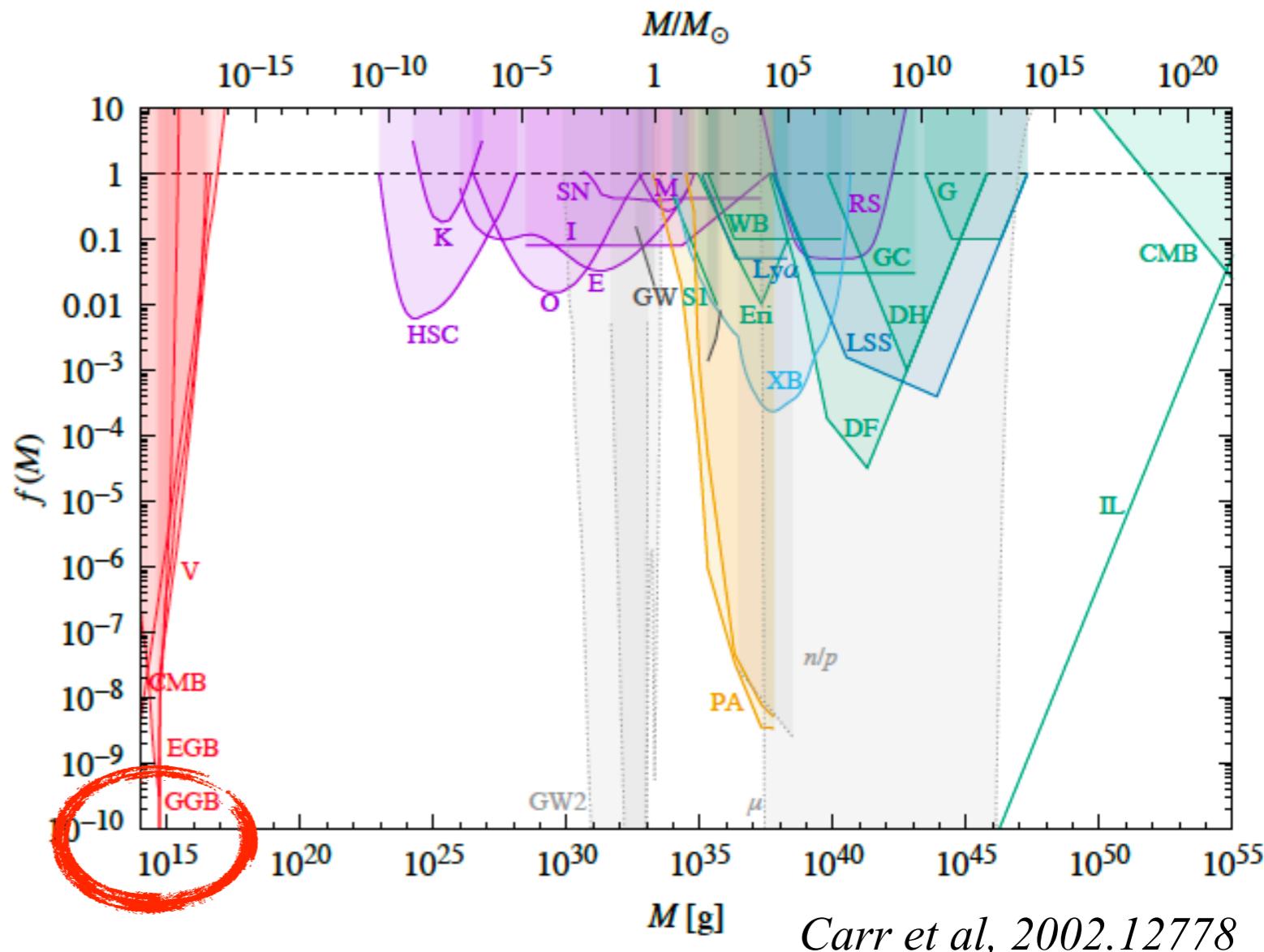
Gravitational waves



Astrophysical issues

Constraints on PBH abundance

Several observations strongly constrain the PBH abundance:

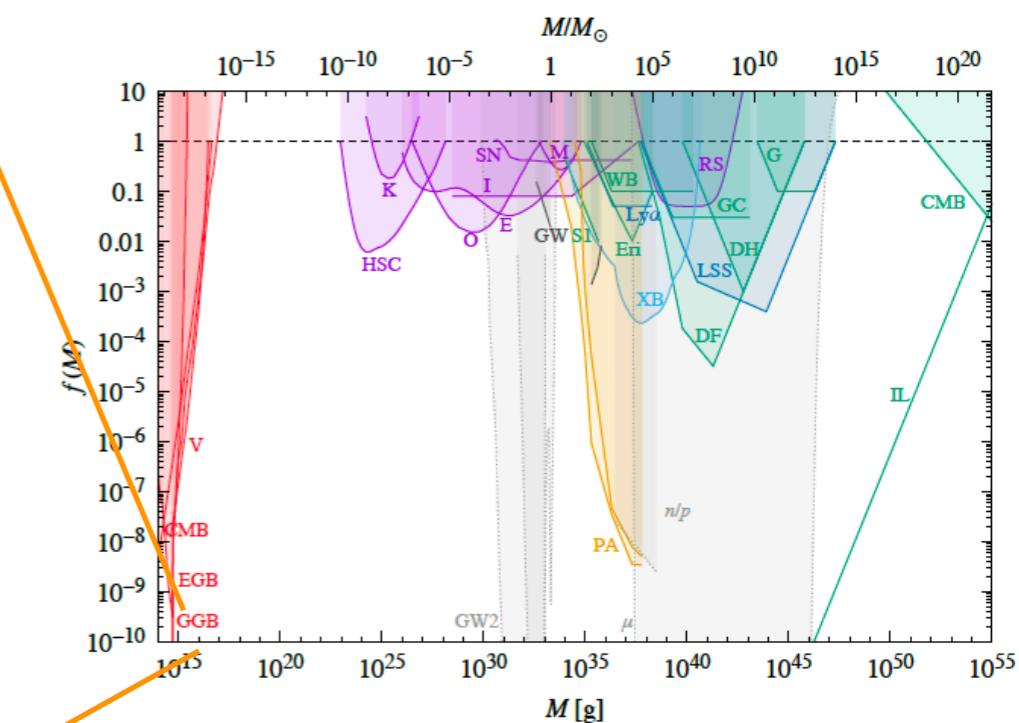
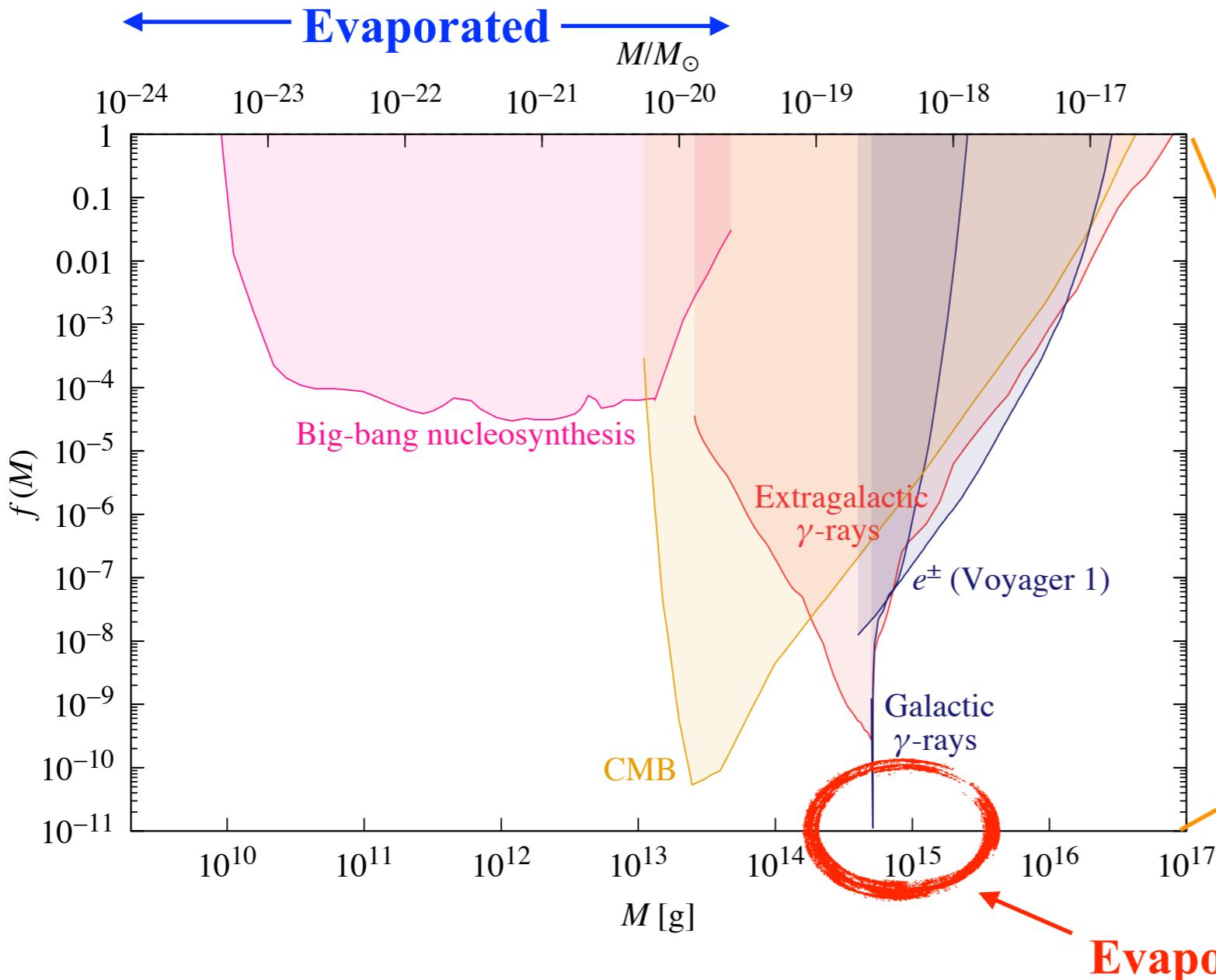


Evaporating now

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

Constraints on PBH abundance

Several observations strongly constrain the PBH abundance:

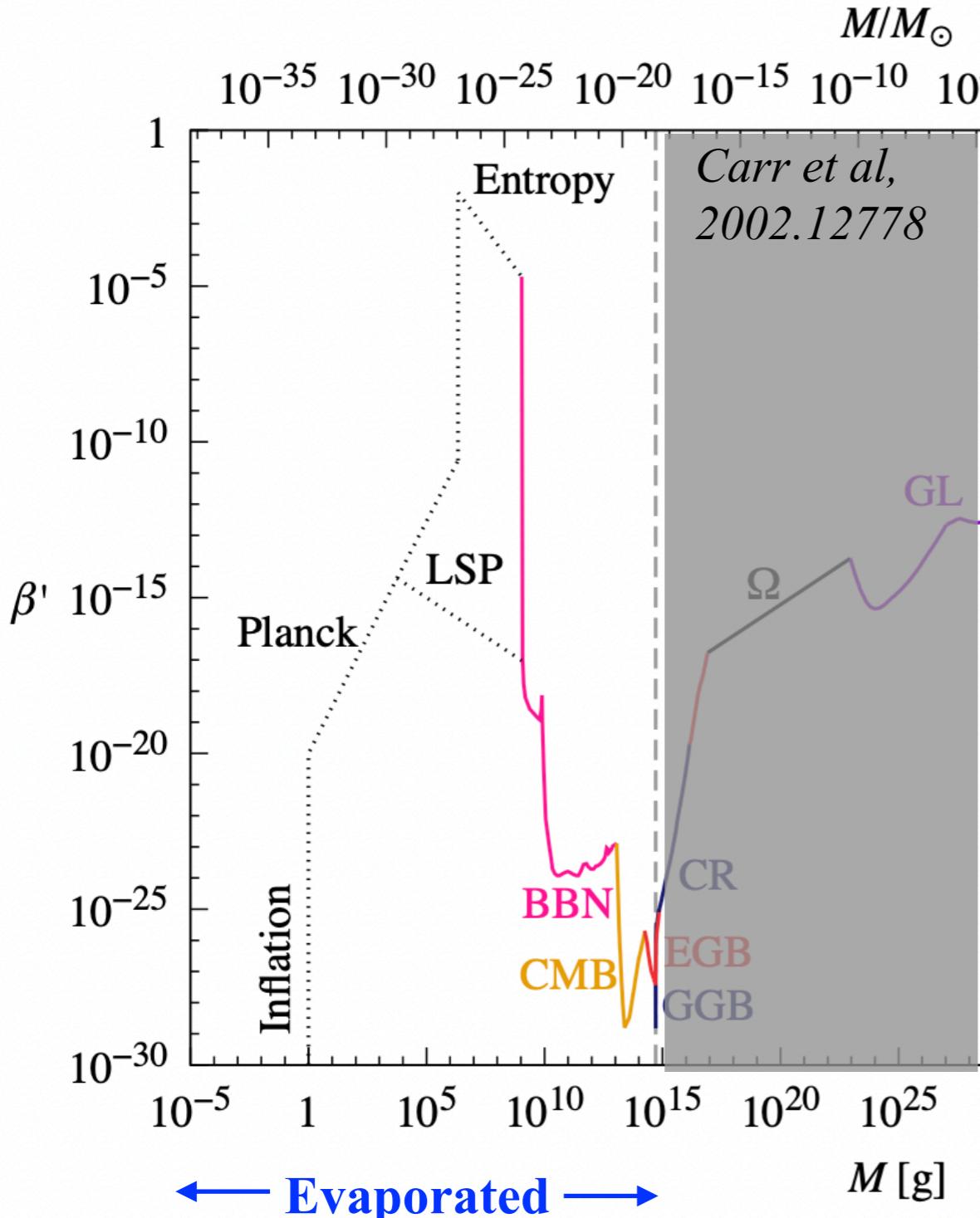


Carr et al, 2002.12778

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

Constraints on PBH abundance

Combined constraints on $\beta(M)$ for a monochromatic PBH mass function



$$\beta \equiv \frac{\rho_{\text{BH}}(T_0)}{\rho_R(T_0)} = \frac{n_0 M_{\text{BH}0}}{\rho_R(T_0)}$$

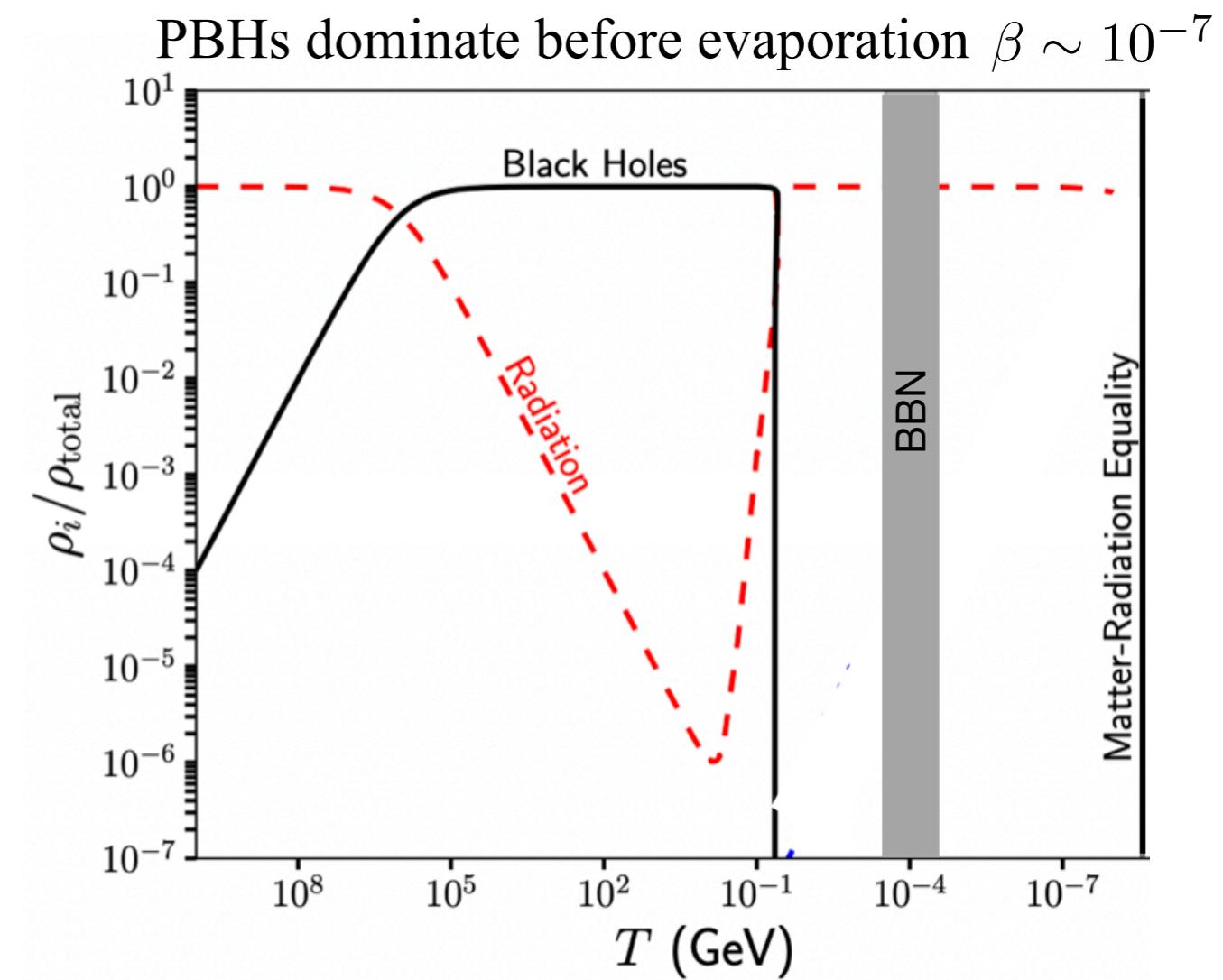
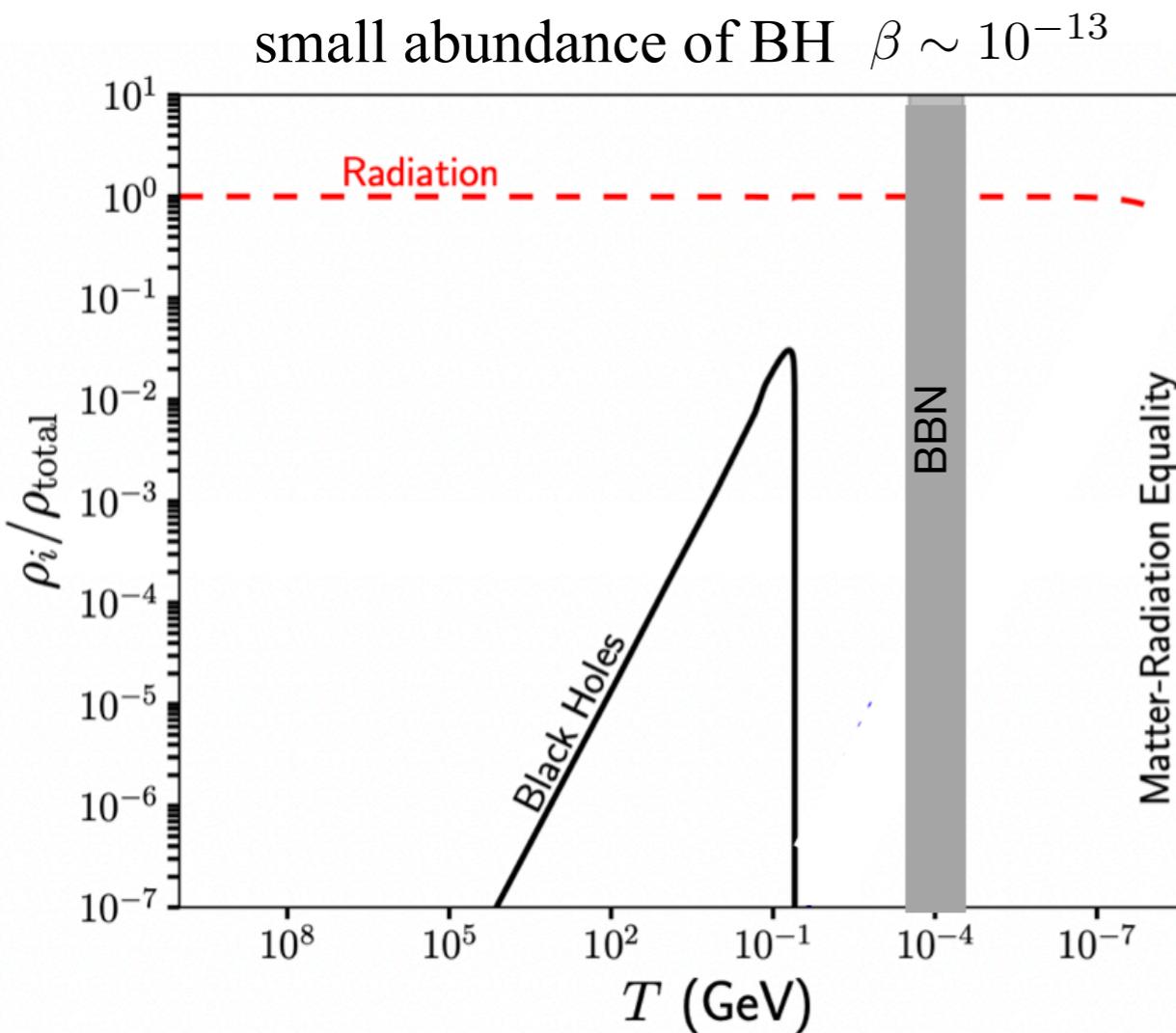
$$\beta'(M) \equiv \gamma^{1/2} \left(\frac{g_{*i}}{106.75} \right)^{-1/4} \left(\frac{h}{0.67} \right)^{-2} \beta(M)$$

dimensionless
gravitational collapse
parameter

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

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



Adapted from Hooper et al, 1905.01301

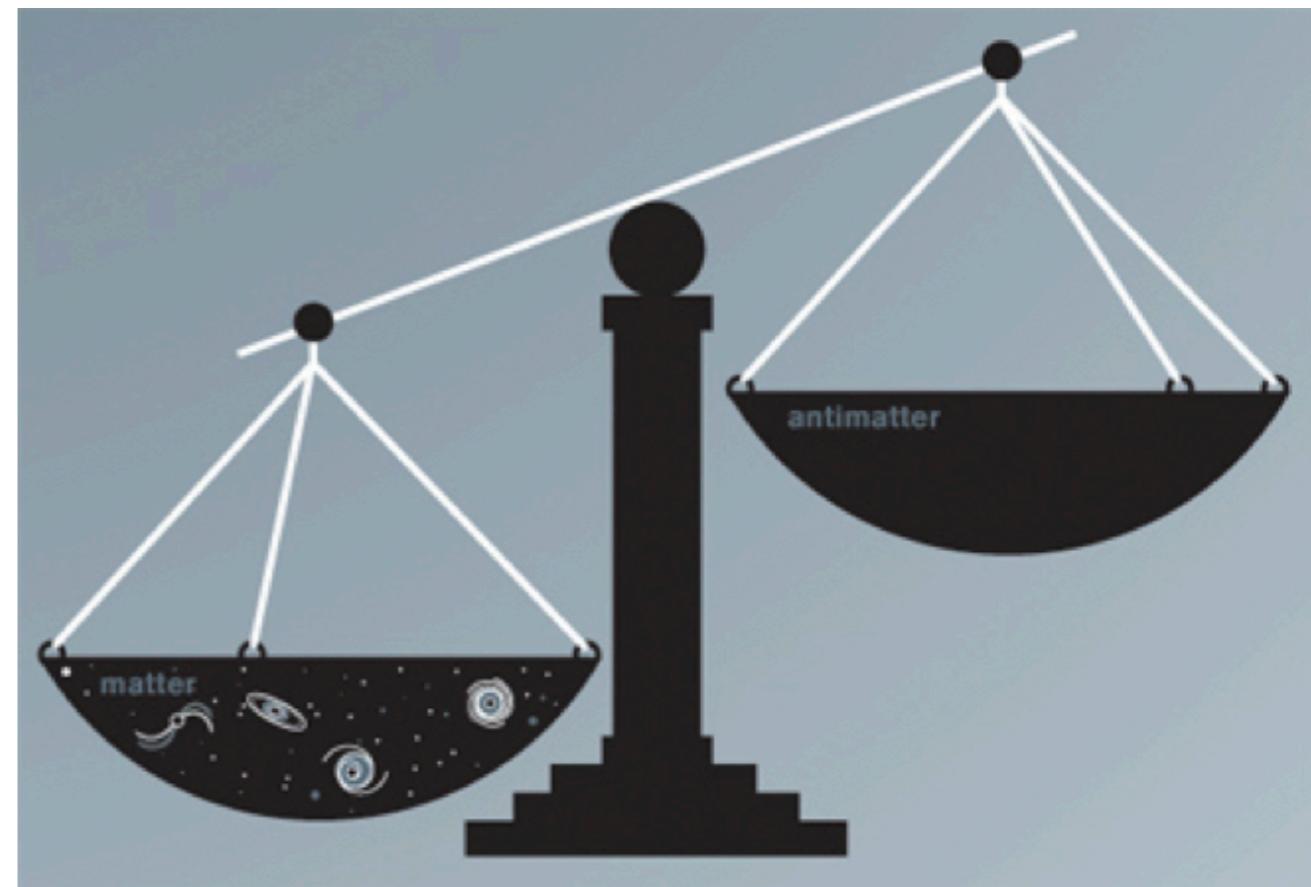
Baryogenesis

Baryon asymmetry of the Universe:

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

Planck Collaboration

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



Sakharov conditions to dynamically generate a baryon asymmetry

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

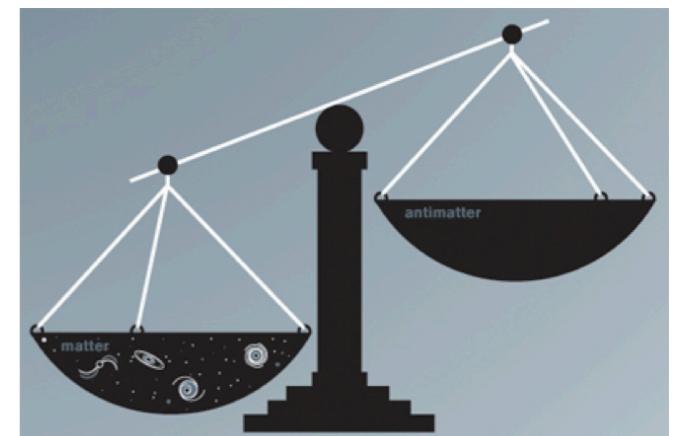
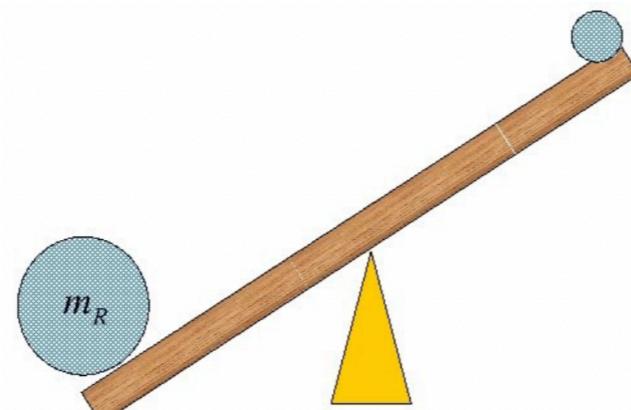
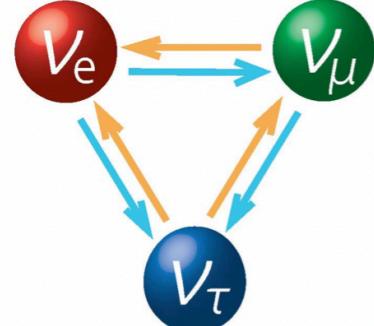
These ingredients are all present in the Standard Model. However, no SM mechanism generating a large enough baryon asymmetry has been found.

Leptogenesis

Simple and elegant explanation of the cosmological matter-antimatter asymmetry

- Naturally satisfies the Sakharov conditions
 - L violation due to the Majorana nature of heavy RH neutrinos.
 $L \rightarrow B$ 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**

$\mathcal{O}(1 \text{ GeV})$

$\mathcal{O}(10^3 \text{ GeV})$

$\mathcal{O}(10^6 \text{ GeV})$

$\mathcal{O}(10^{12} \text{ GeV})$ M_{RH}

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)...

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

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

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)...

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

Leptogenesis Landscape

**Leptogenesis
via oscillations**

**Resonant
Leptogenesis**

**Intermediate-scale
Leptogenesis**

**High-scale
Leptogenesis**

$O(1 \text{ GeV})$

$O(10^3 \text{ GeV})$

$O(10^6 \text{ GeV})$

$O(10^{12} \text{ GeV})$ $\mathbf{M_{RH}}$

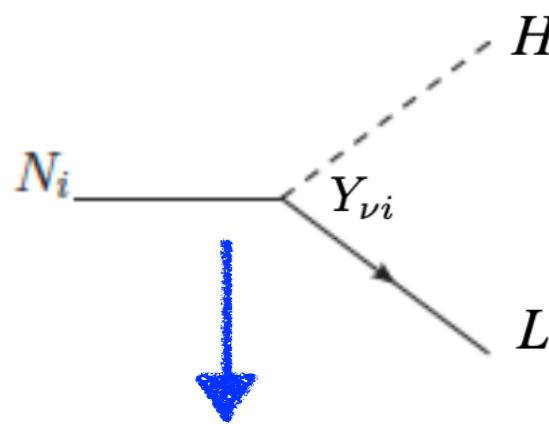
Akhmedov, Rubakov & Smirnov
Phys.Rev.Lett. 81 1359-1362 (1998)
Asaka & Shaposhnikov *Phys.Lett.*
B620 17-26 (2005) Asaka, Eijima &
Ishida *JHEP* 1104 011(2011)...

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

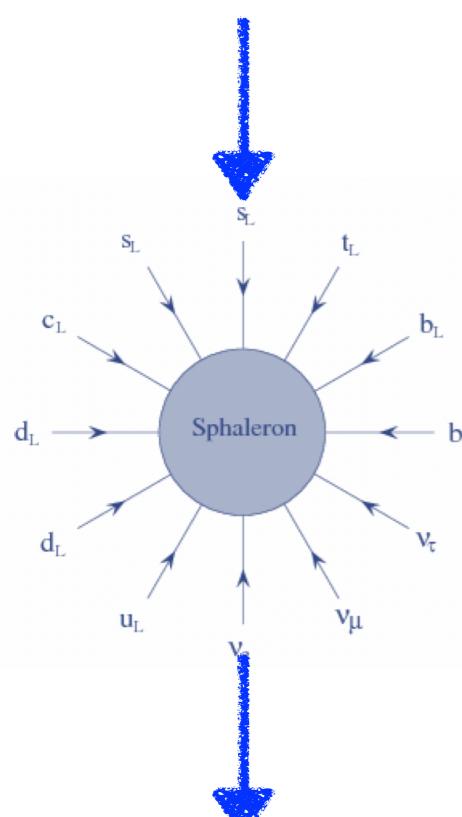
Racker, Rius & Pena JCAP 1207
030 (2013) *Moffat, Petcov, Pascoli,*
Schulz & Turner Phys.Rev. D98
no.1, 015036 (2018) ...

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)...

Basic steps of Leptogenesis



Lepton asymmetry

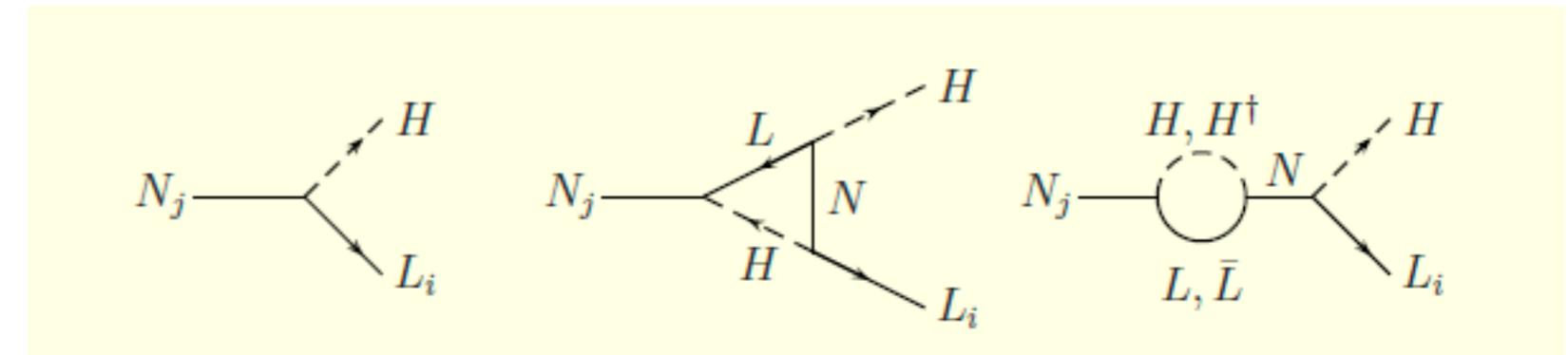


Baryon asymmetry

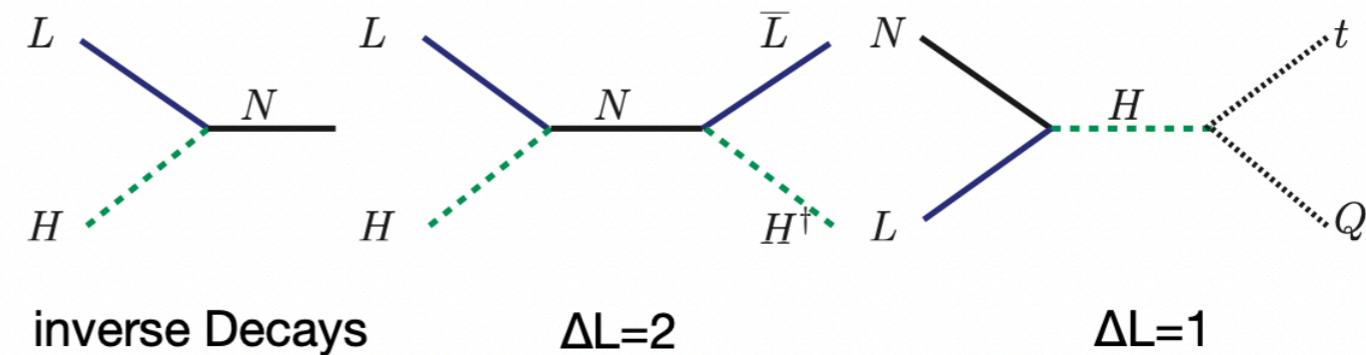
$$N \rightarrow LH / N \rightarrow \bar{L}H$$

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

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 $T > T_{\text{sph}}$: B - L conserved

Our model: HS Thermal Leptogenesis

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

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

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

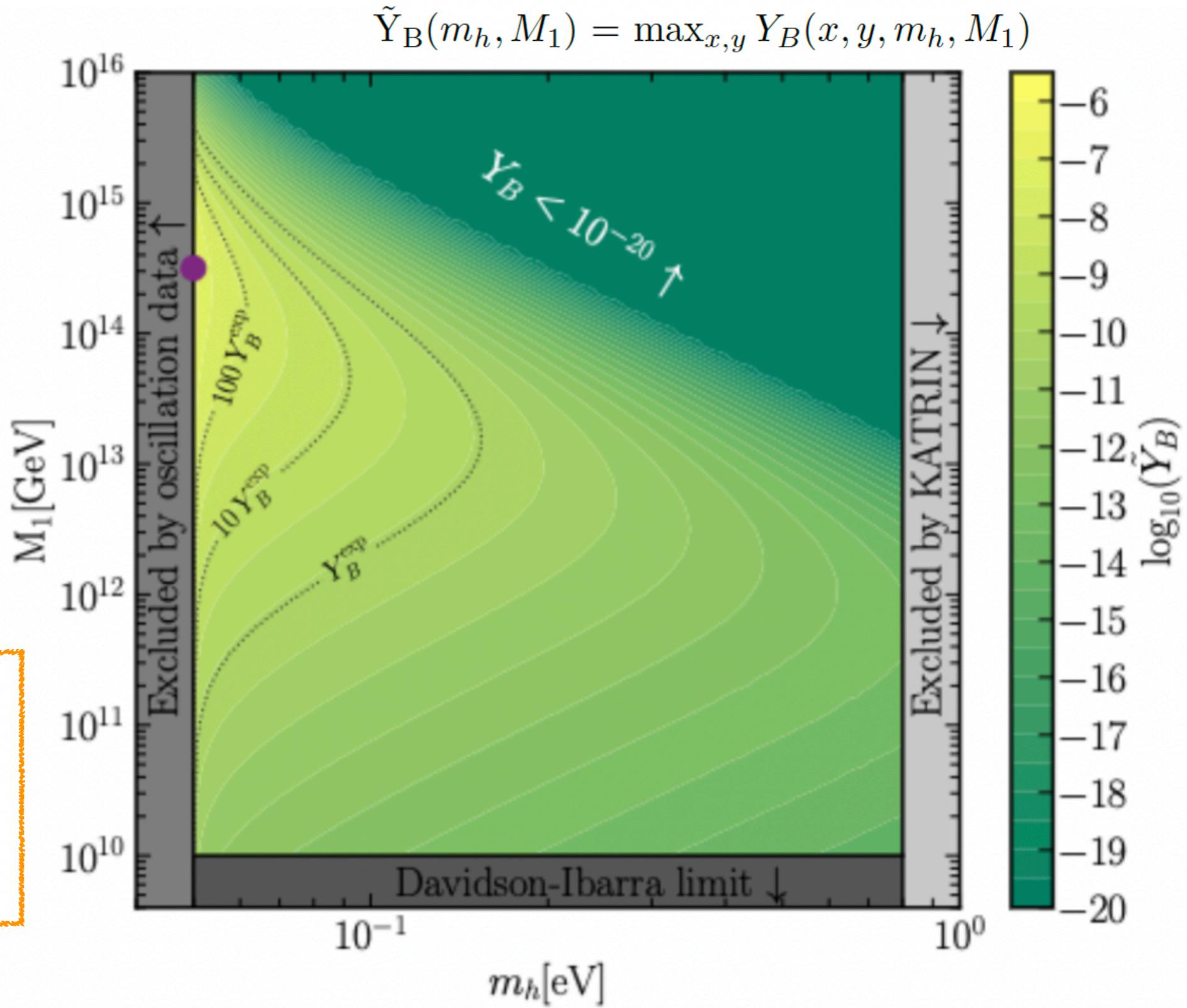
- High Scale $[10^{10} \leq M_1 \leq 10^{16}] \text{GeV}$
- Thermal leptogenesis era: $z = M_1/T \sim O(1)$ in which L=2 scatterings are relevant
- Hierarchical heavy neutrino spectrum $M_1 \ll M_{2,3}$
- Neglect the decays of $N_{2,3}$
- $m_1 = m_2$ since $\Delta m_{\text{sun}}^2 \ll \Delta m_{\text{atm}}^2$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

$$\begin{aligned} \frac{dY_{N_1}}{dz} &= -D_1(Y_{N_1} - Y_{N_1}^{eq}), \\ \frac{dY_{\Delta L}}{dz} &= \overset{\text{Decay}}{\epsilon_1 D_1(Y_{N_1} - Y_{N_1}^{eq})} - \overset{\text{Washout}}{W_1 Y_{\Delta L}} \end{aligned}$$

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

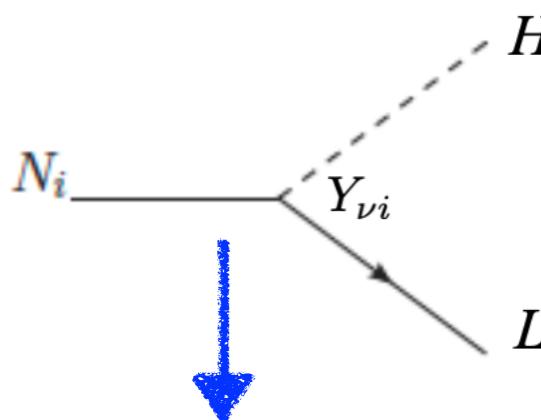
*For a detailed treatment see Hambye et al,
Nuclear Physics B 695 (2004) 169–191*

Parameter space of thermal leptogenesis

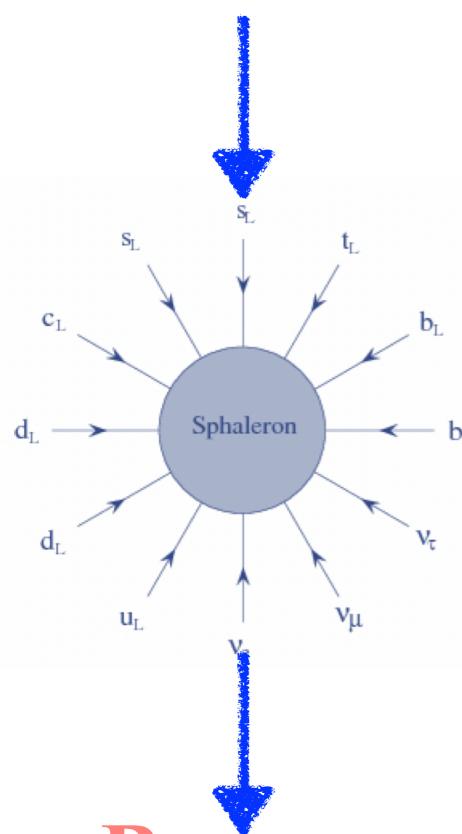


$0 < x < \pi$
 $0.14 < y < \pi$
 $\sqrt{m_{\text{atm}}^2} < m_h < 0.8 \text{ eV}$
 $10^{10} \text{ GeV} < M_1 < 10^{16} \text{ GeV}$

Leptogenesis & PBH



Lepton asymmetry



Baryon asymmetry

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

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

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*

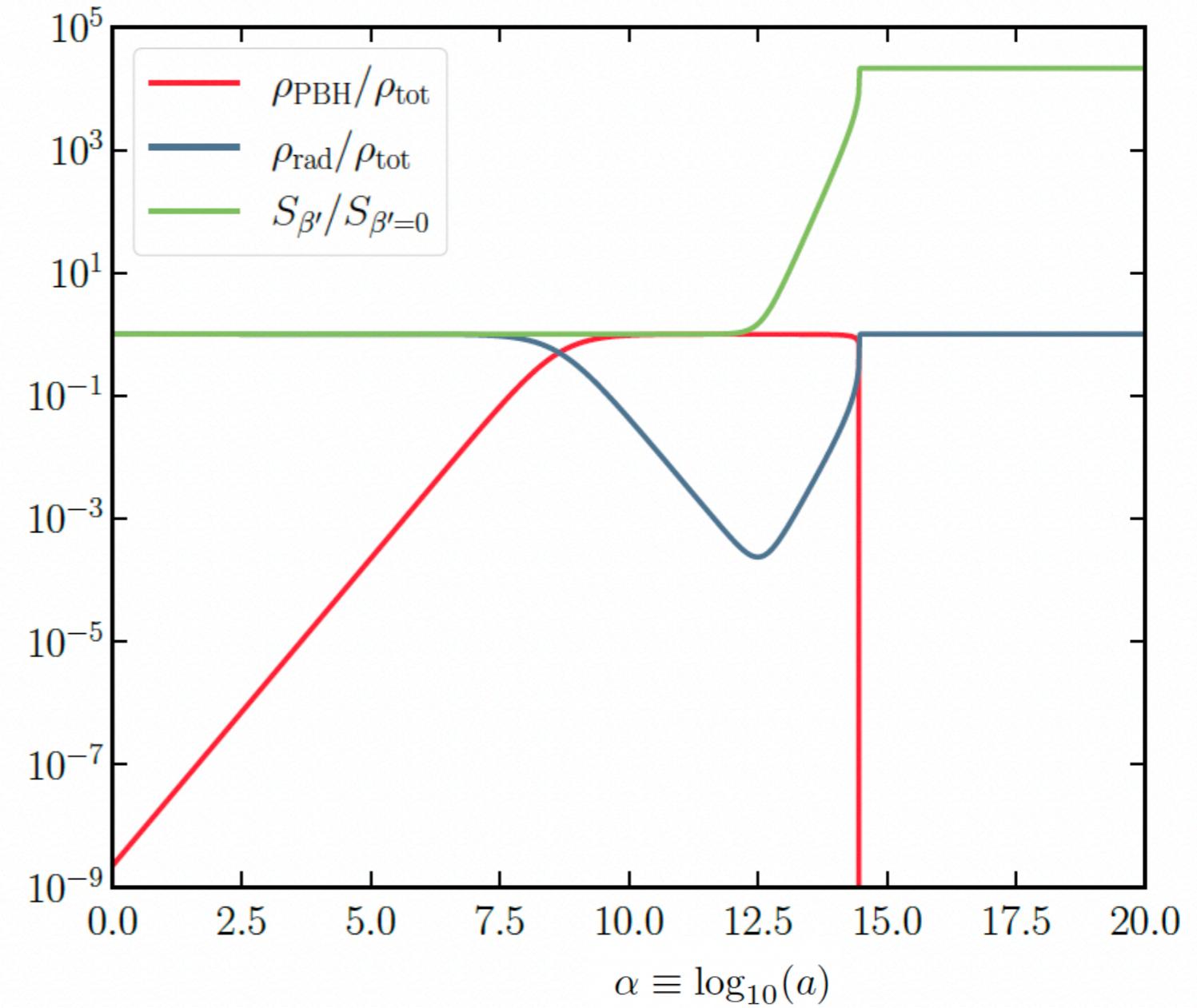
- Entropy injection in the primordial plasma (reheating)

*Studied for $10^5 g < M_{PBH} < 10^9 g$ in this work
 $10^{-15} < \beta' < 0.1$*

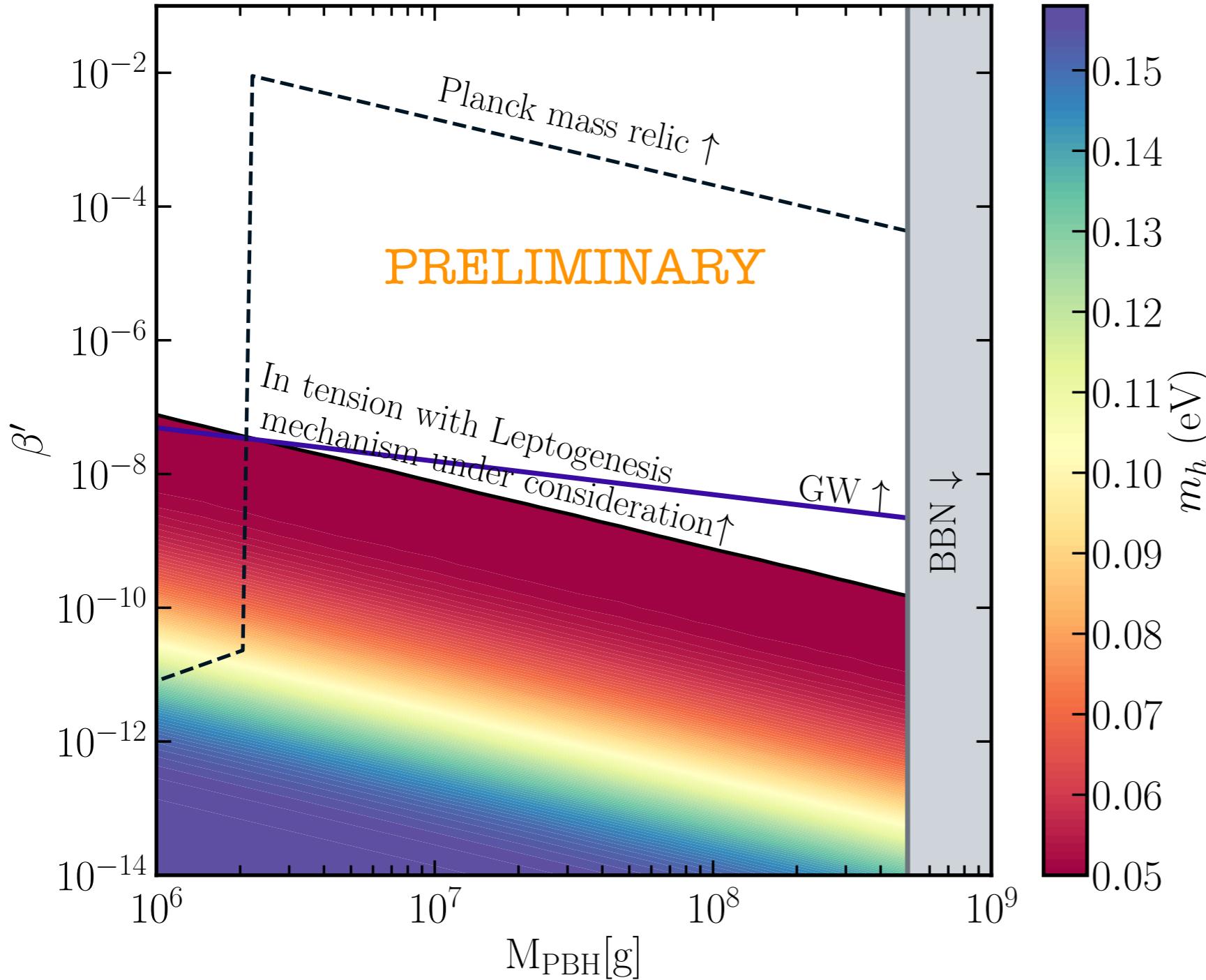
Entropy injection by PBH

PBH by evaporating injects standard model particles in the thermal plasma \rightarrow entropy increasing

$$\frac{dS}{d\alpha} = -\frac{f_{\text{SM}}}{TH} \frac{d \ln M_{\text{PBH}}}{d\alpha} \varrho_{\text{PBH}}$$



PBH Constraints by leptogenesis



GW constraints on the PBH dominated early universe:

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

NEHOP

NEW HORIZONS IN PRIMORDIAL BLACK HOLE PHYSICS

Naples, Italy
June 19th to June 21st 2023

Scientific Committee

Andrew Cheek, Astrocent, NCAC
Marco Chianese, UniNA Federico II
Lucien Heurtier, IPPP, Durham University
Stefano Morisi, UniNA Federico II (Chair)
Ninetta Saviano, INFN Napoli
Jessica Turner, IPPP, Durham University (Chair)

Local Organising Committee

Antonio Cerbone, UniNA Federico II
Marco Chianese, UniNA Federico II
Alessandro Corridore, UniNA Federico II
Stefano Morisi, UniNA Federico II
Ninetta Saviano, INFN Napoli

<https://conference.ippp.dur.ac.uk/event/1130/>



UNIVERSITÀ DEGLI STUDI DI NAPOLI
FEDERICO II



Istituto Nazionale di Fisica Nucleare



The background of the image is a deep navy blue, representing the void of space. A massive, luminous nebula dominates the center, its swirling patterns of light transitioning from bright cyan to deep teal. A single, intensely bright white star sits at the heart of the nebula, casting a soft glow. Numerous smaller, white stars are scattered throughout the dark expanse.

Thank you