Gravitational Particle Production and Leptogenesis

Yuber F. Perez-Gonzalez

Universidad Autónoma de Madrid

Instituto de Física Teórica UAM-CSIC

yuber.perez@uam.es

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October 10th, 2024

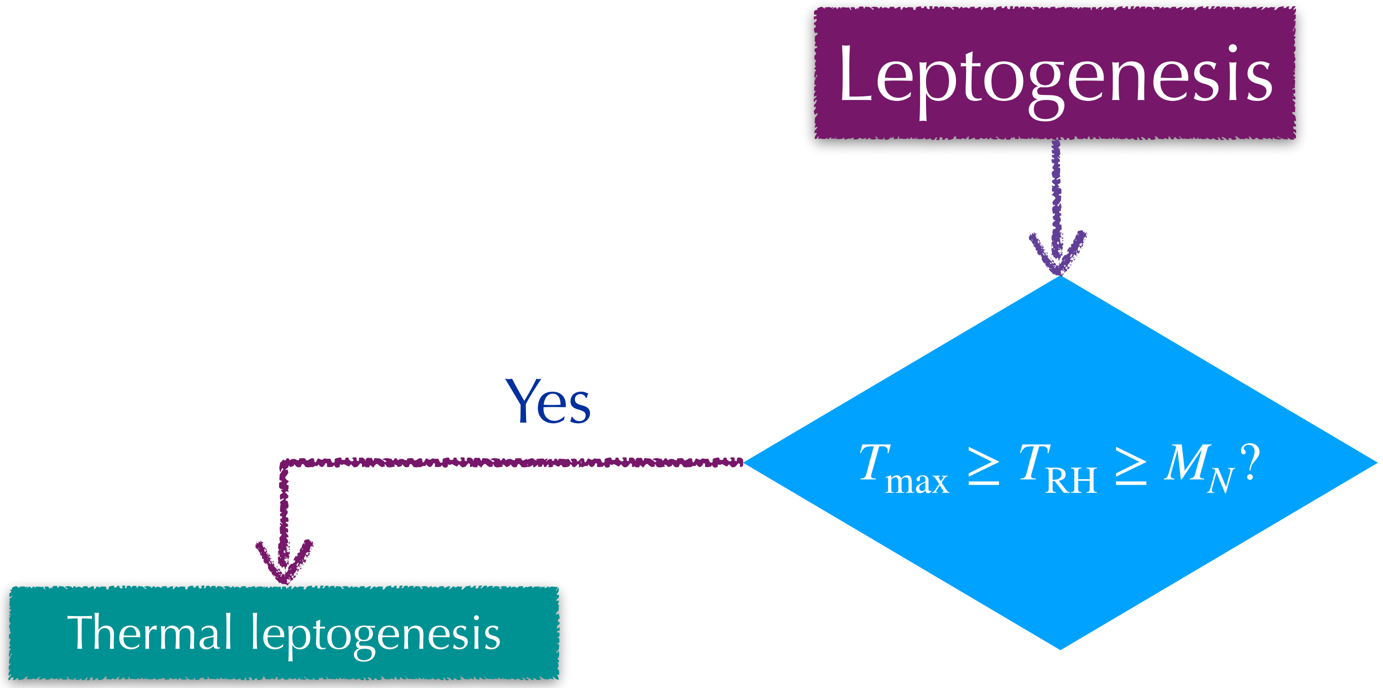
Leptogenesis

See Nuria and Rishav's talk

Leptogenesis

$T_{\rm max} \geq T_{\rm RH} \geq M_N?$

See Nuria and Rishav’s talk



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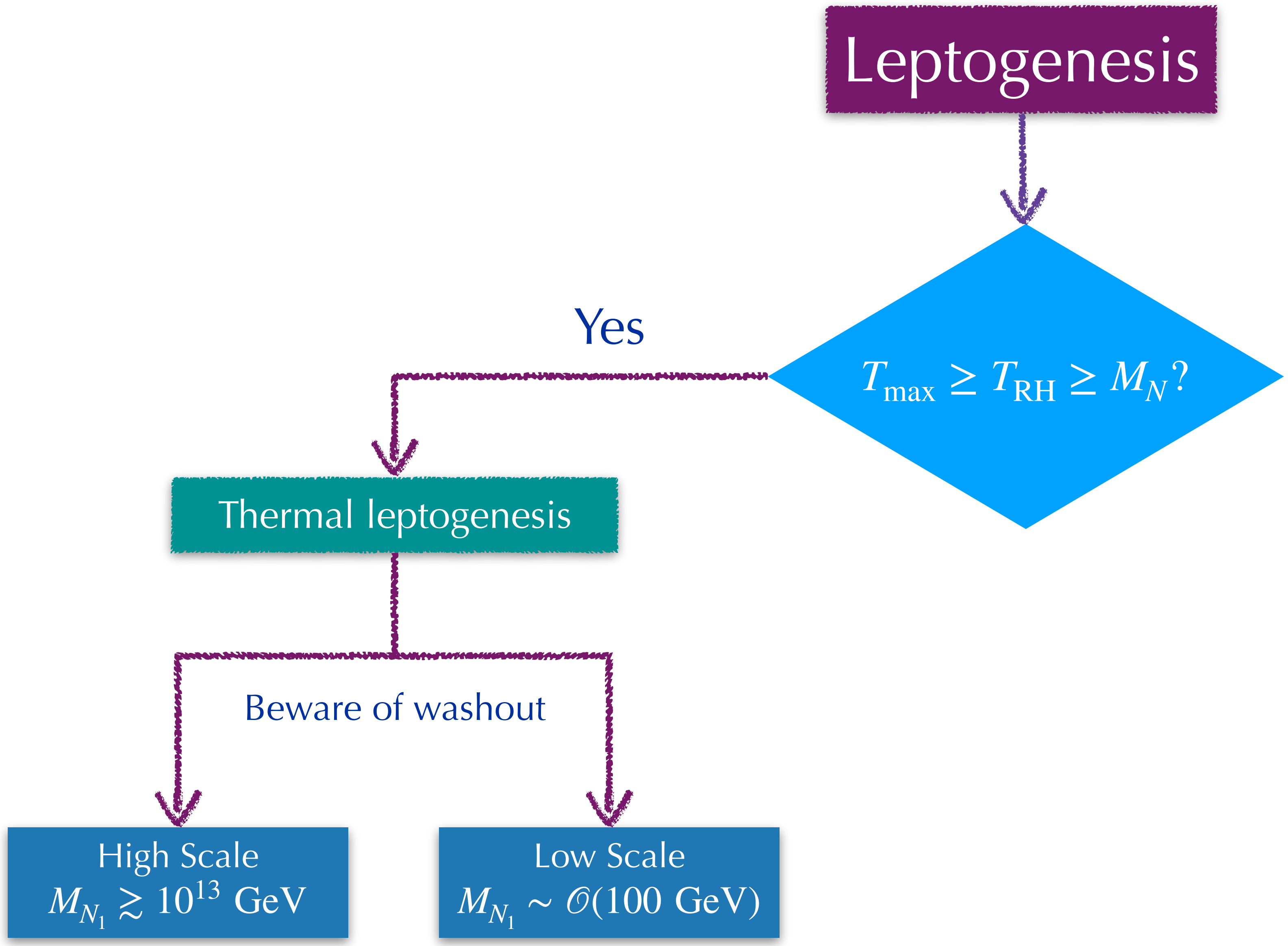

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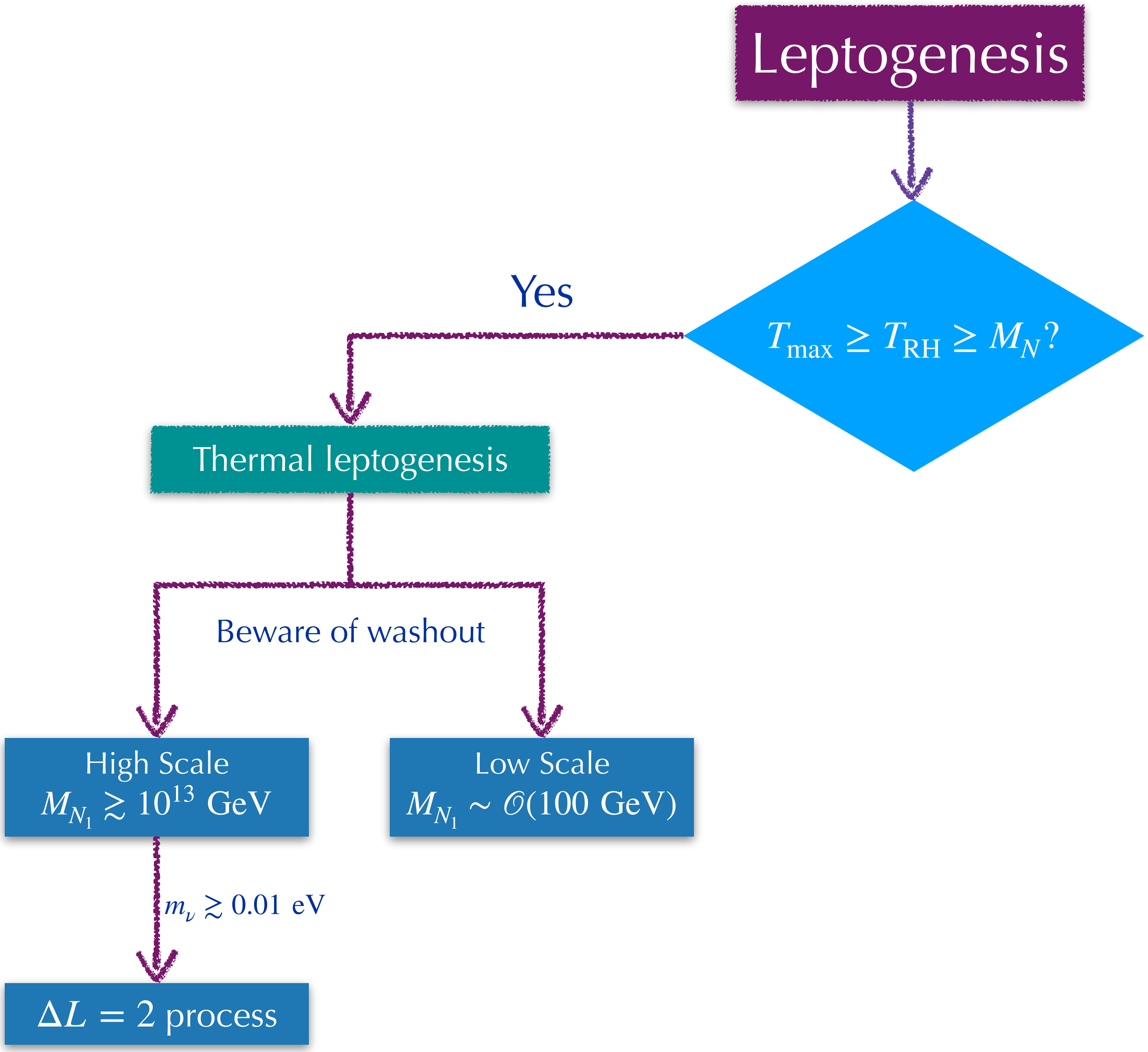

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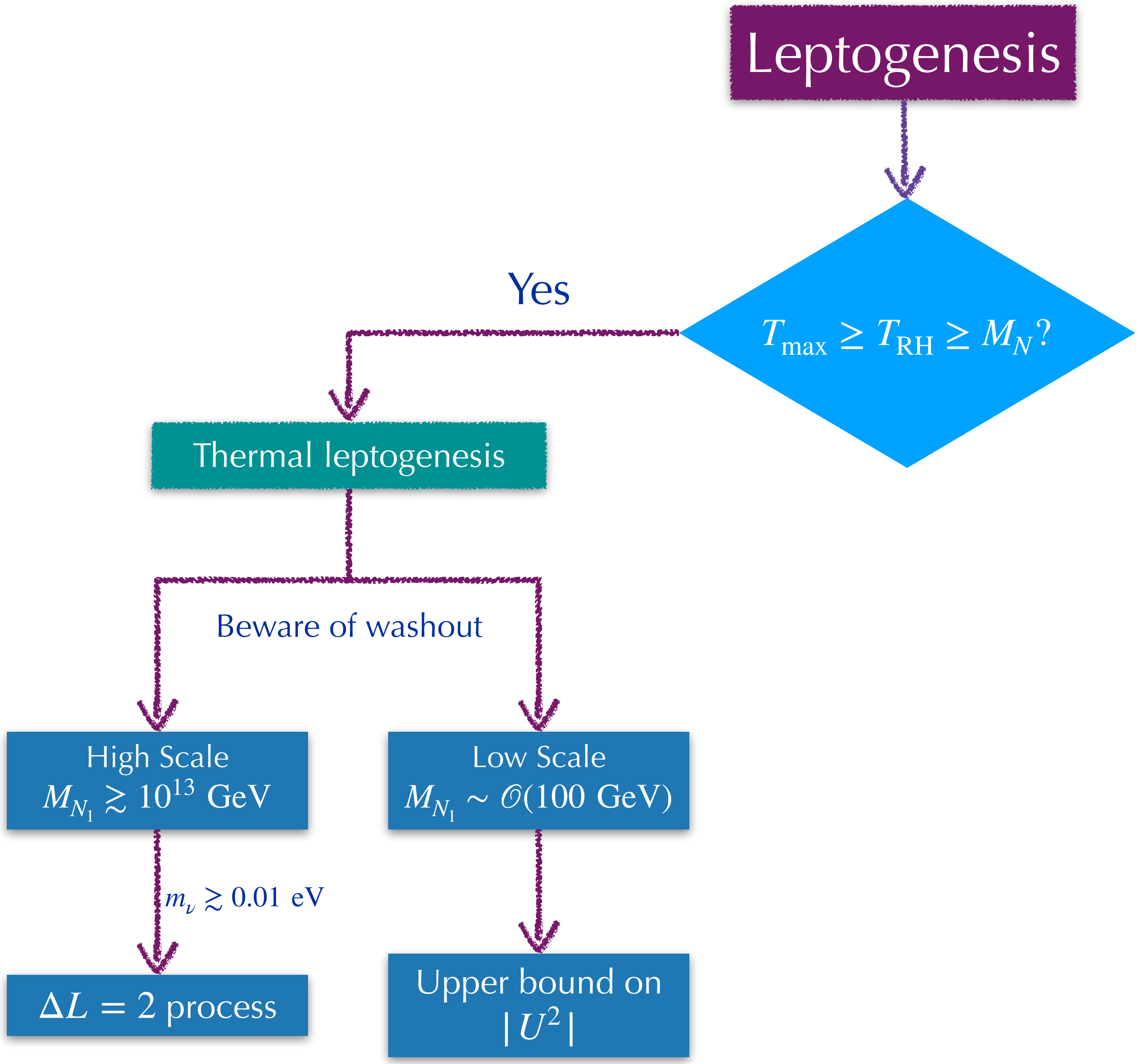

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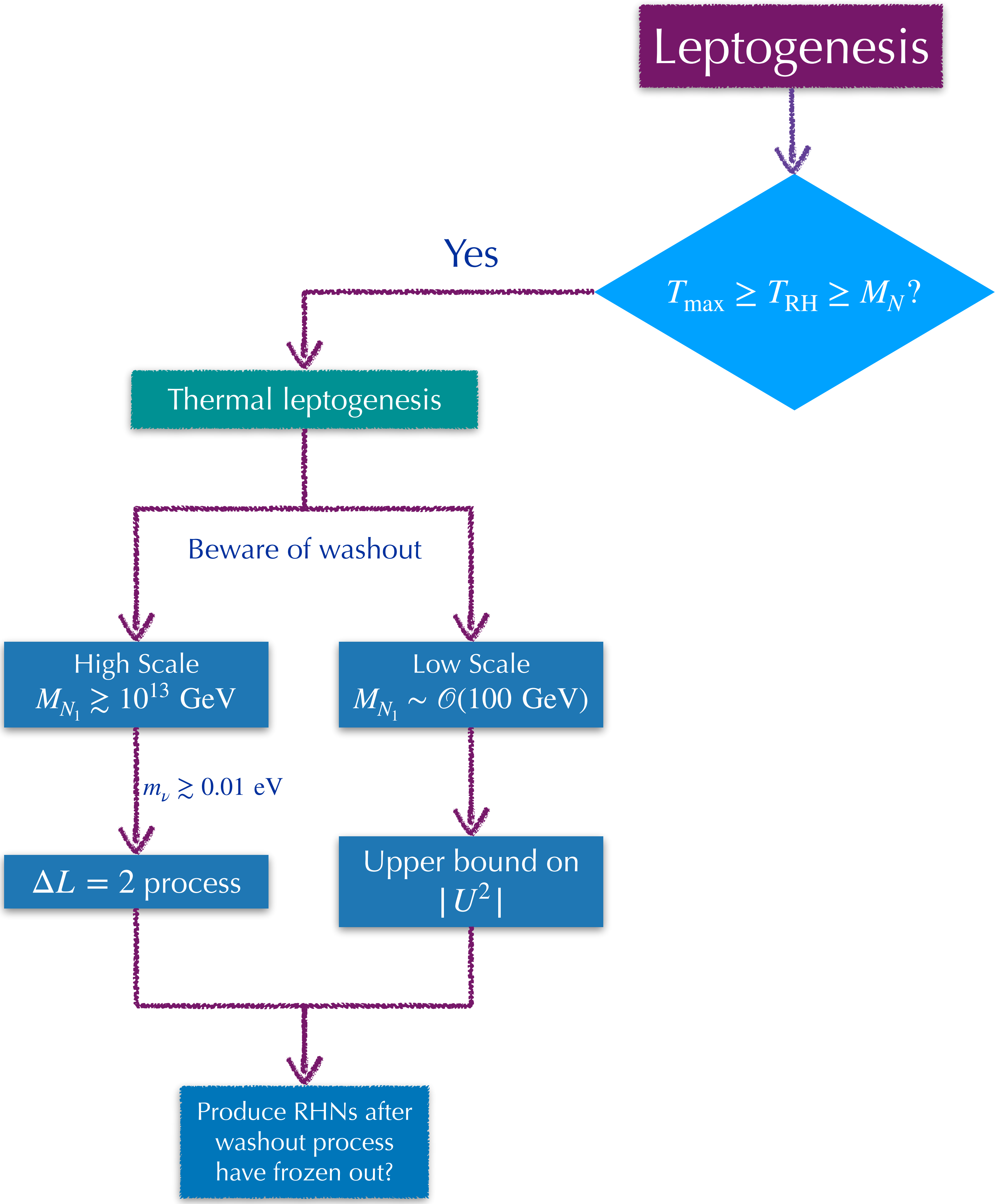

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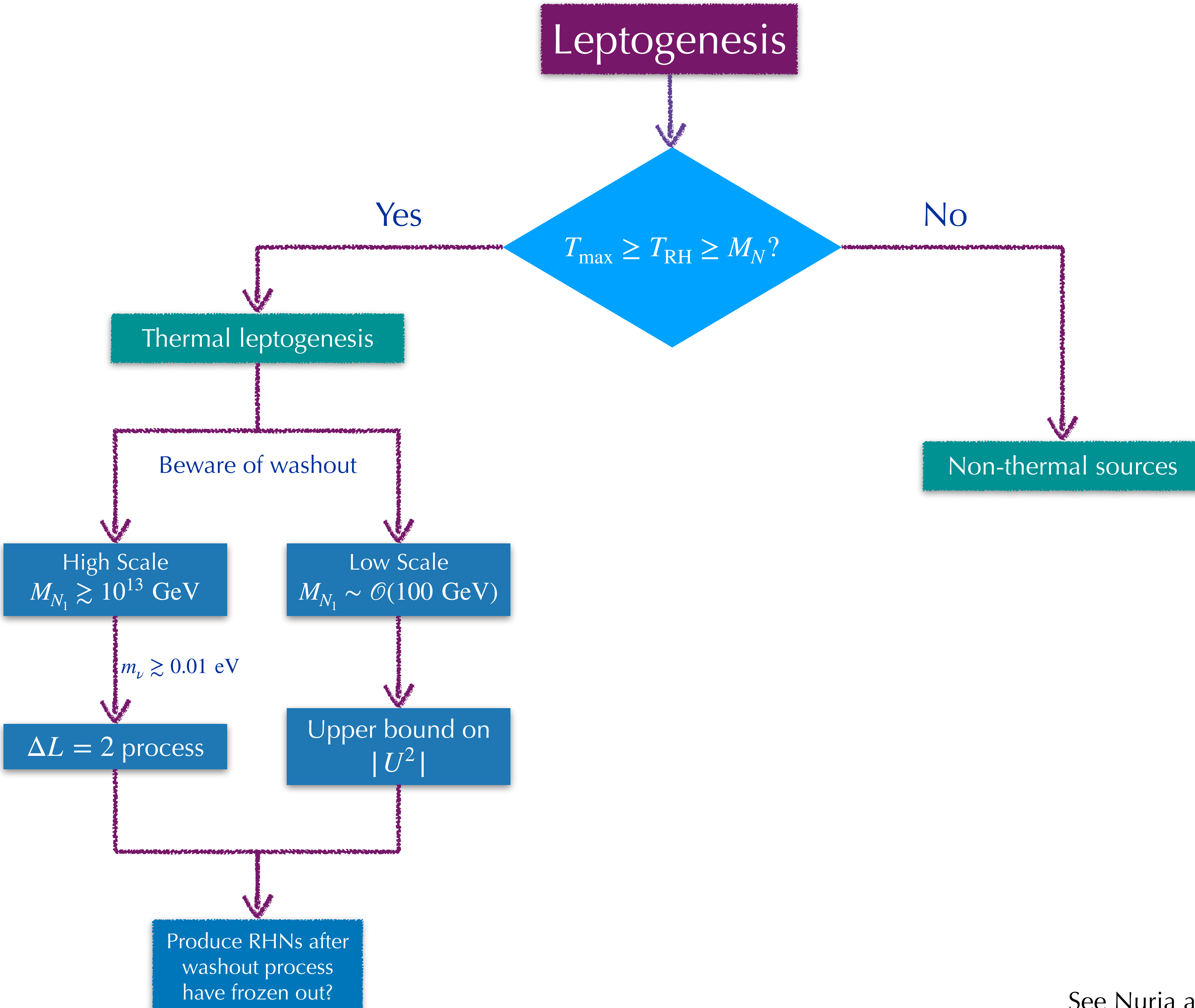

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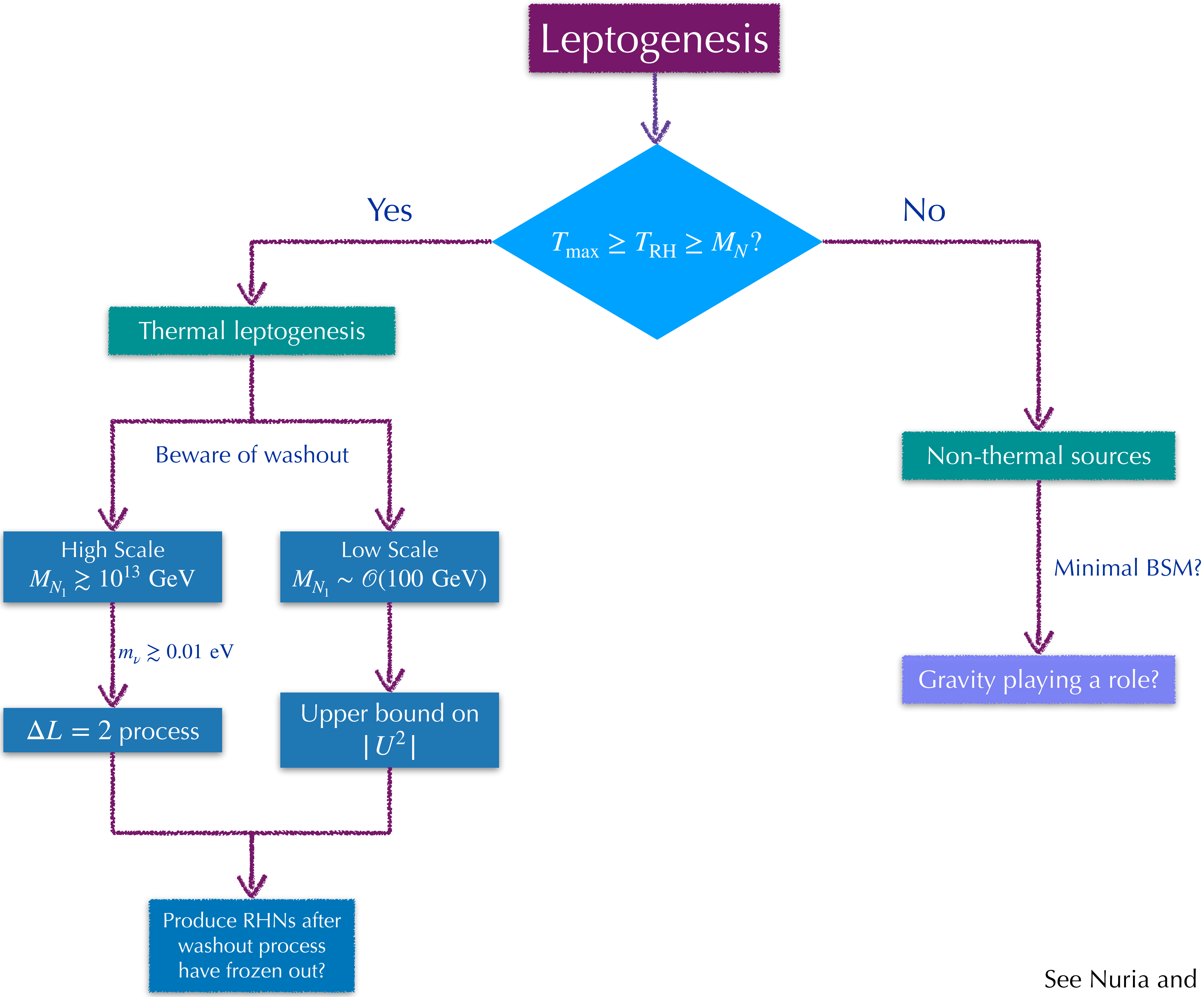

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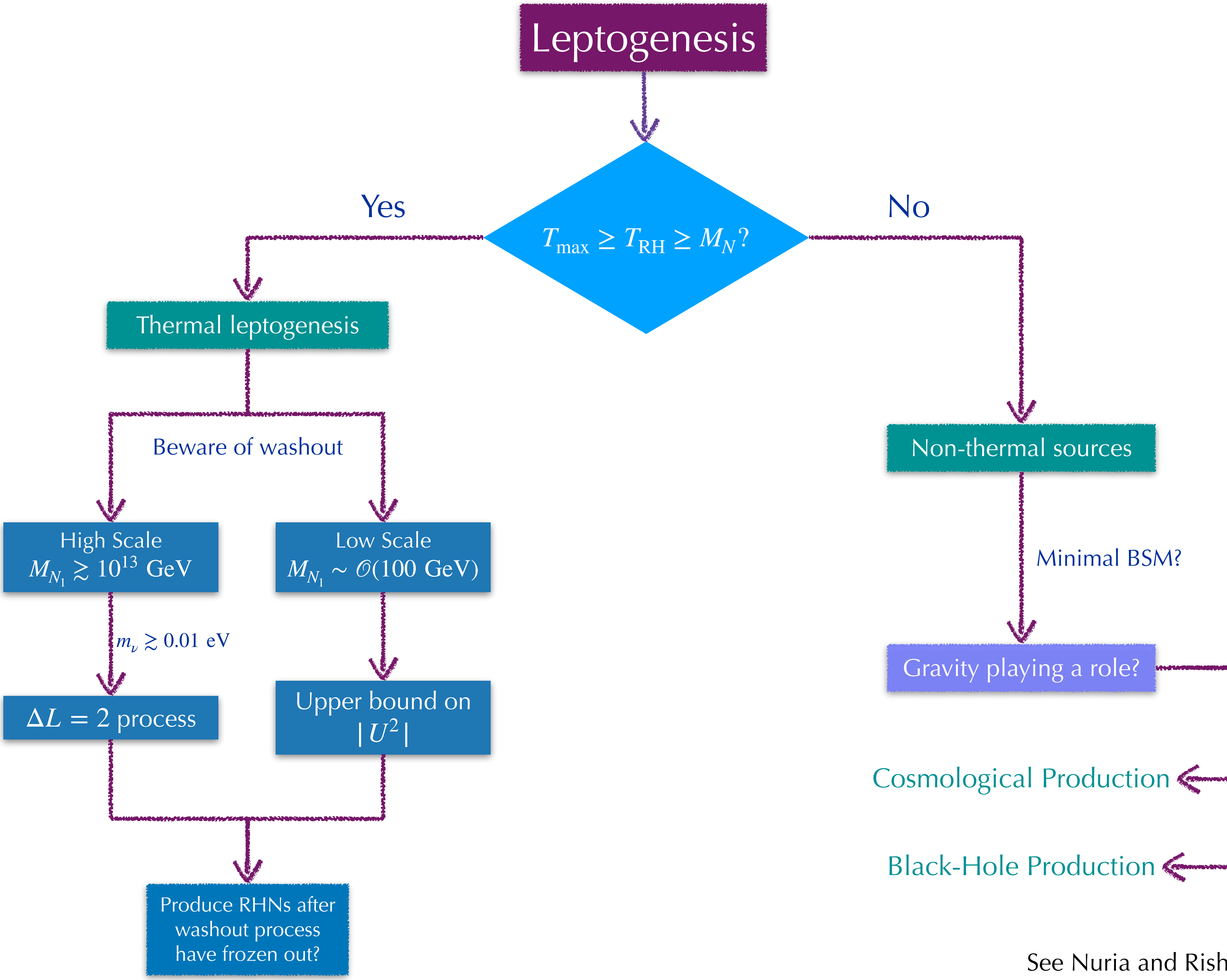

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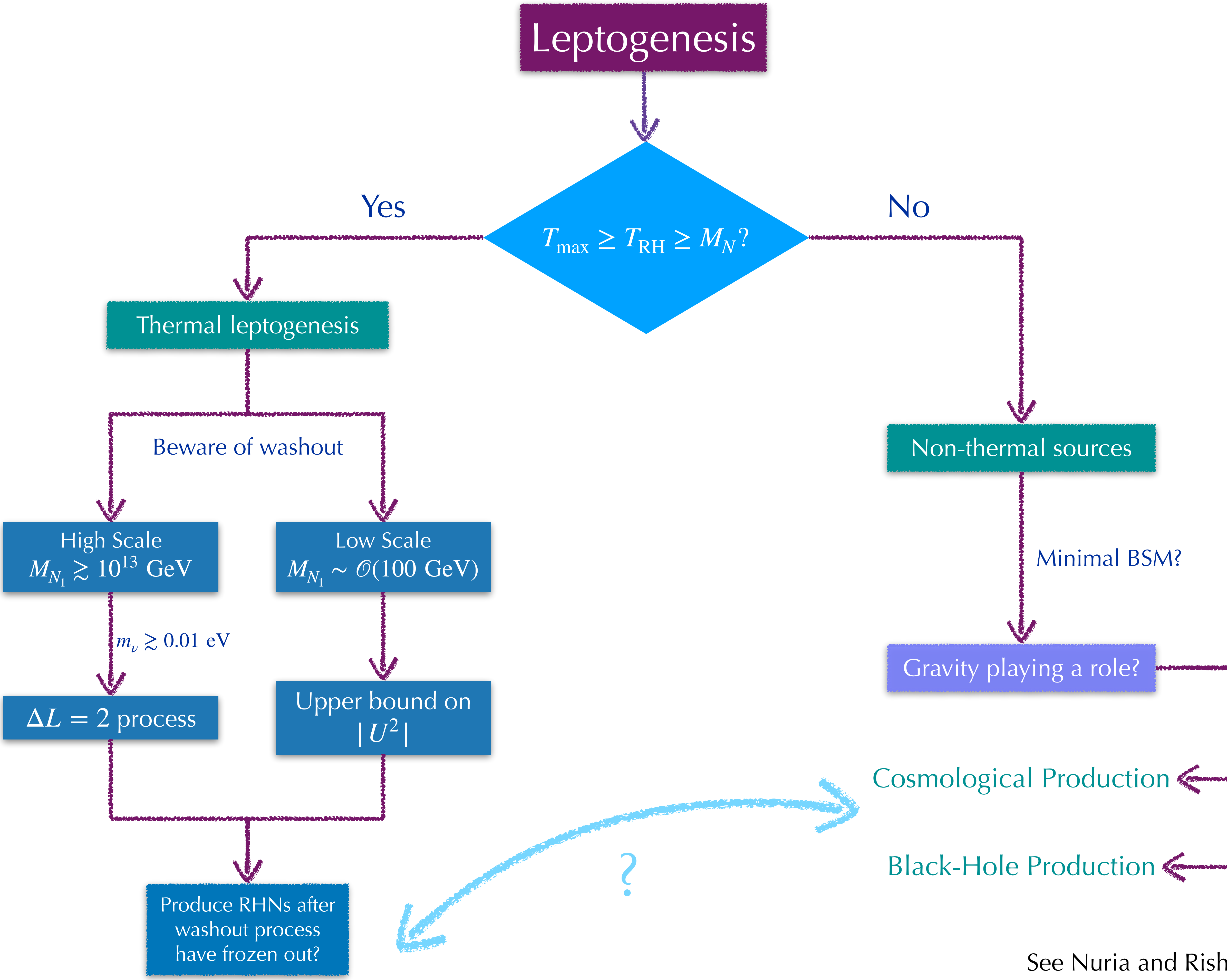


See Nuria and Rishav's talk

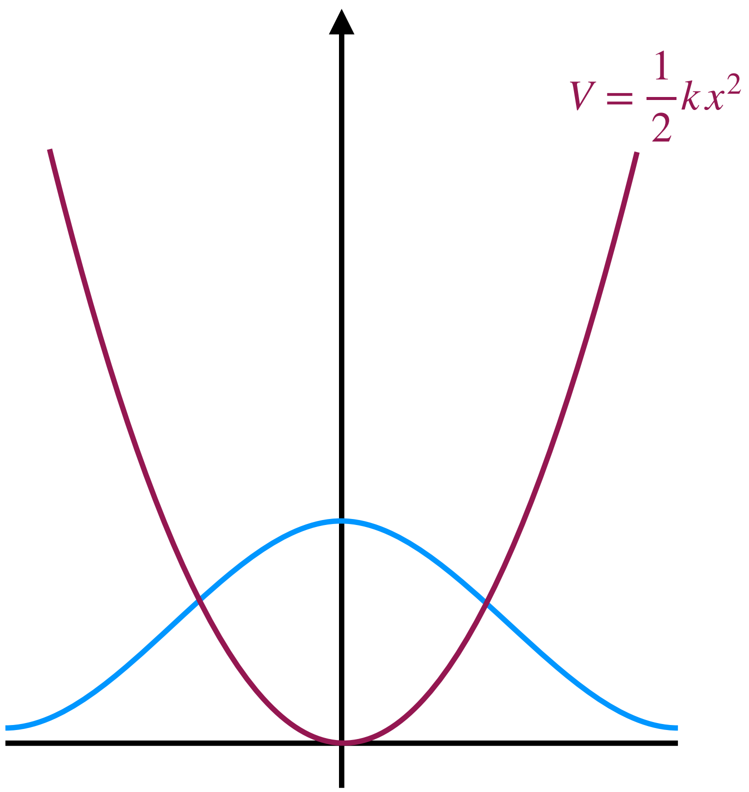
Generalities

Or how to create particles from the vacuum

See review of Kolb and Long, arXiv:2312.09042

Particle Creation in non-static Gravitational Backgrounds

A quantum mechanical analogy



Non-adiabatic (Diabatic) evolution

Particle Creation in non-static Gravitational Backgrounds

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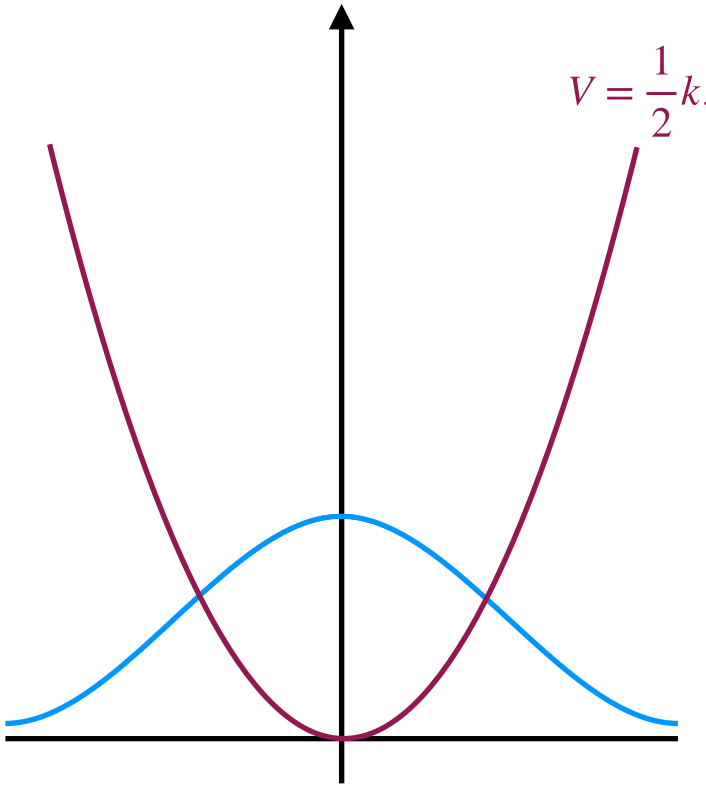

$$a_k |0\rangle = 0$$

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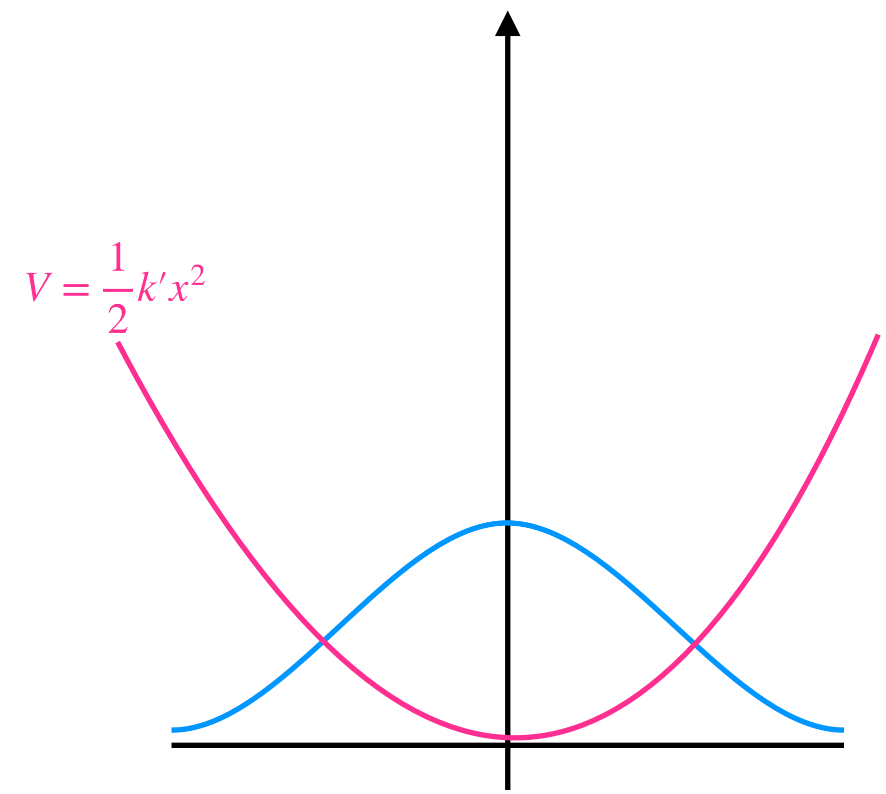

$a_k|0\rangle = 0$

Sudden change

Time

Non-adiabatic (Diabatic) evolution

Particle Creation in non-static Gravitational Backgrounds

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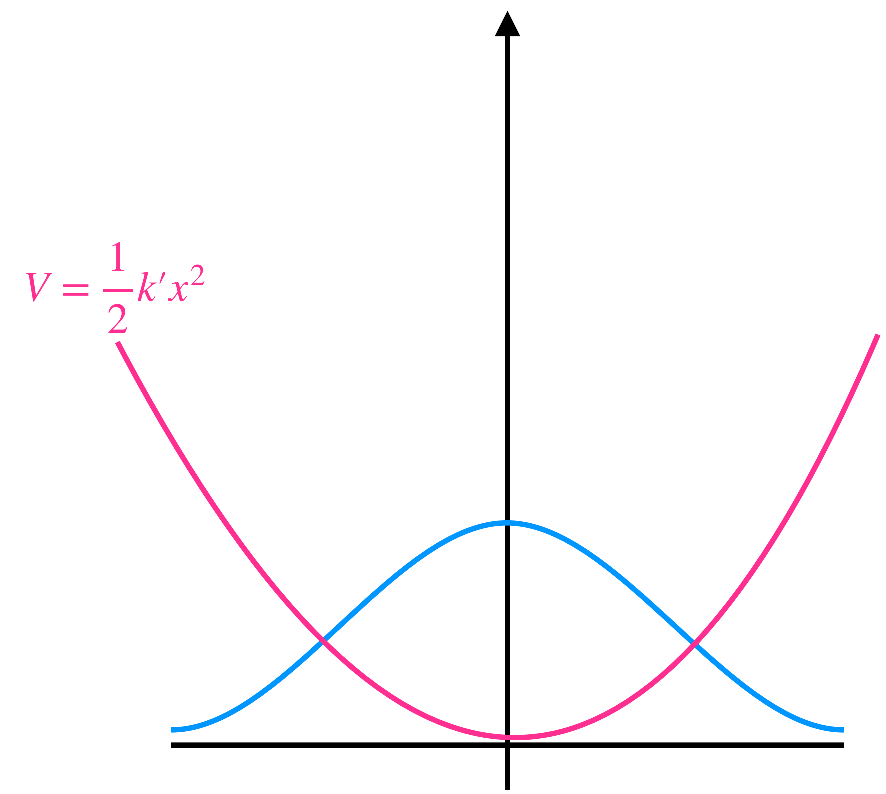

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$A_k |0\rangle \neq 0$

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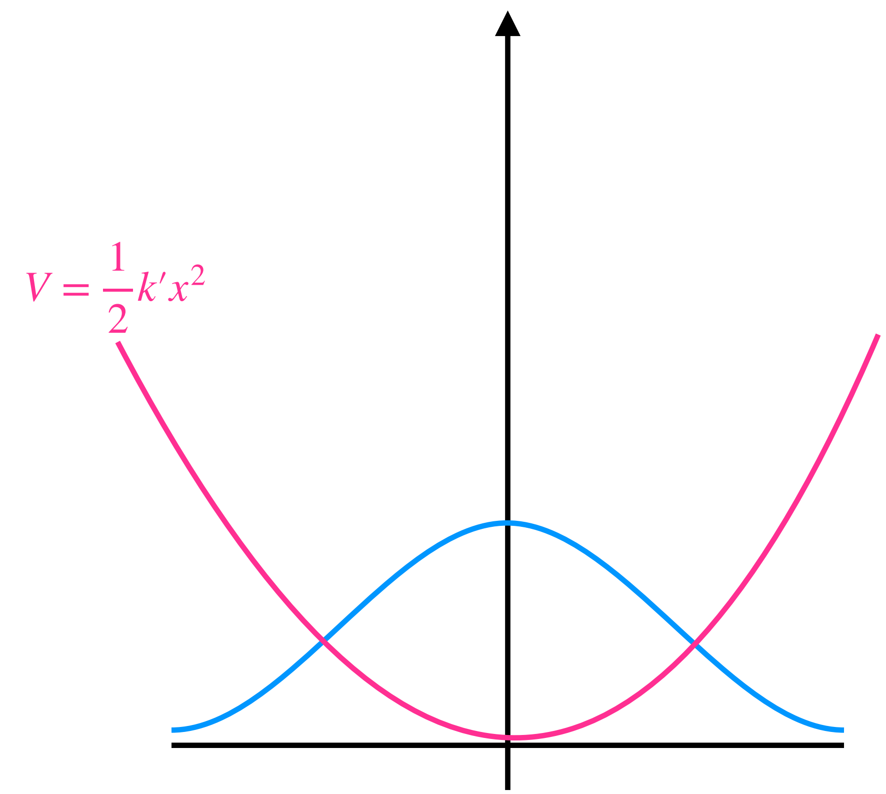
Excited state! → Particles



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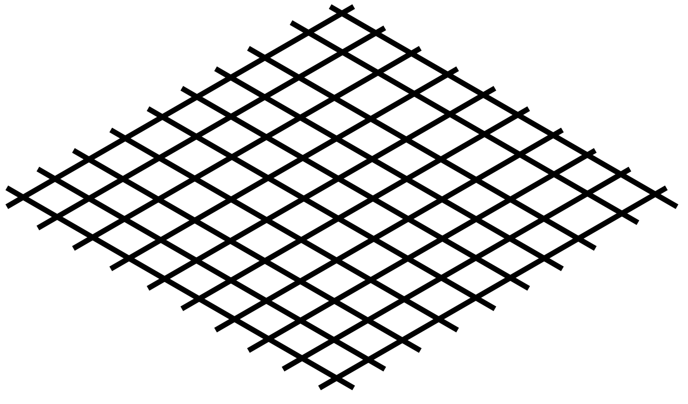
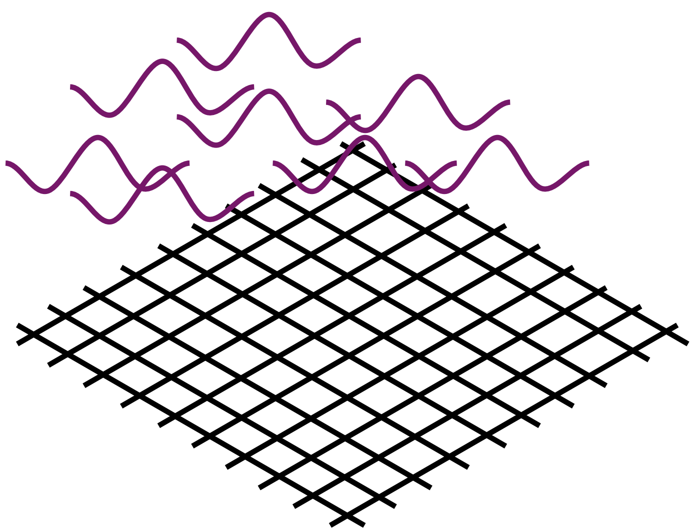


Static

Particle Creation in non-static Gravitational Backgrounds

$\Phi \propto a_k u_k + a_k^\dagger u_k^*$



${}_a\langle 0 | a_k^\dagger a_k | 0 \rangle_a = 0$

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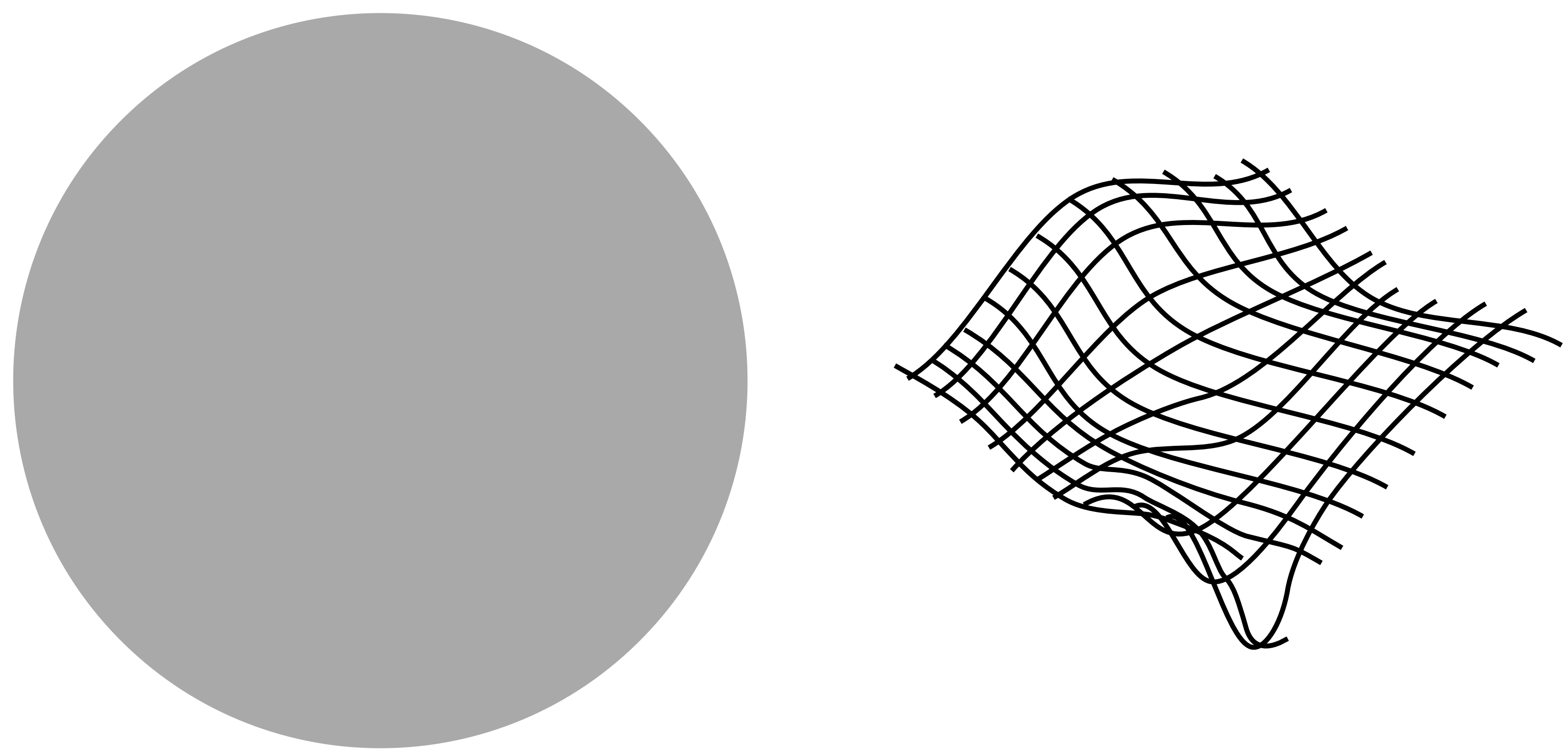


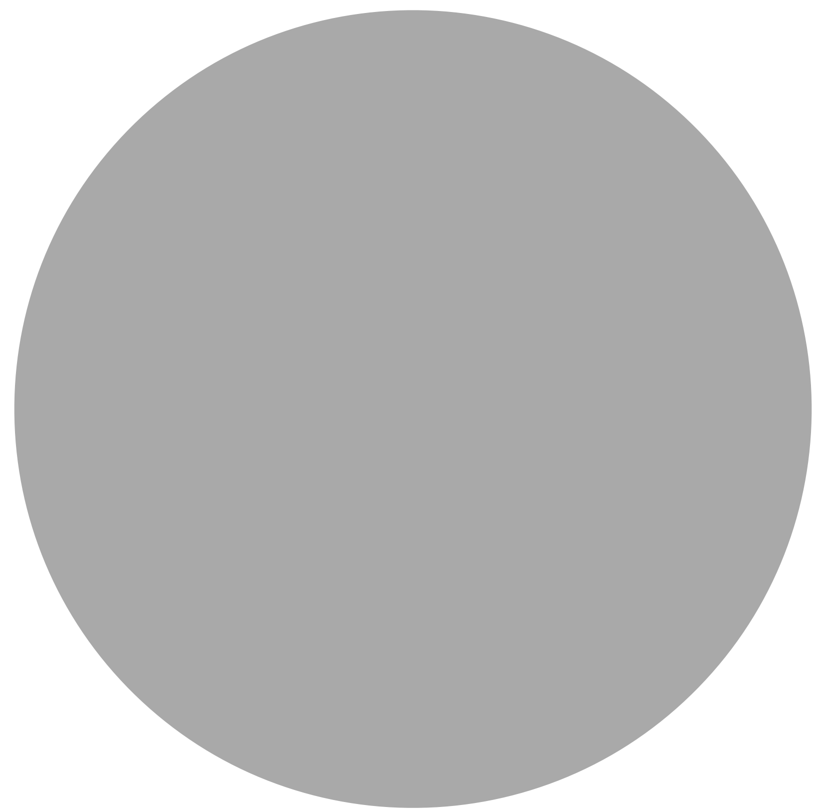
Static

Non-trivial
time dependence

Static

Time

Particle Creation in non-static Gravitational Backgrounds



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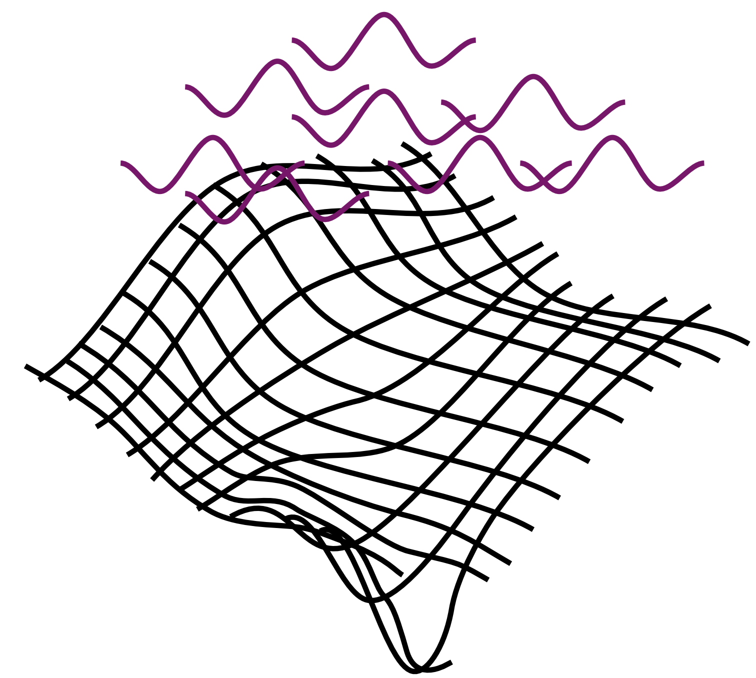

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Particle Creation in non-static Gravitational Backgrounds

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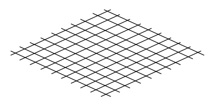
Cosmological GPP

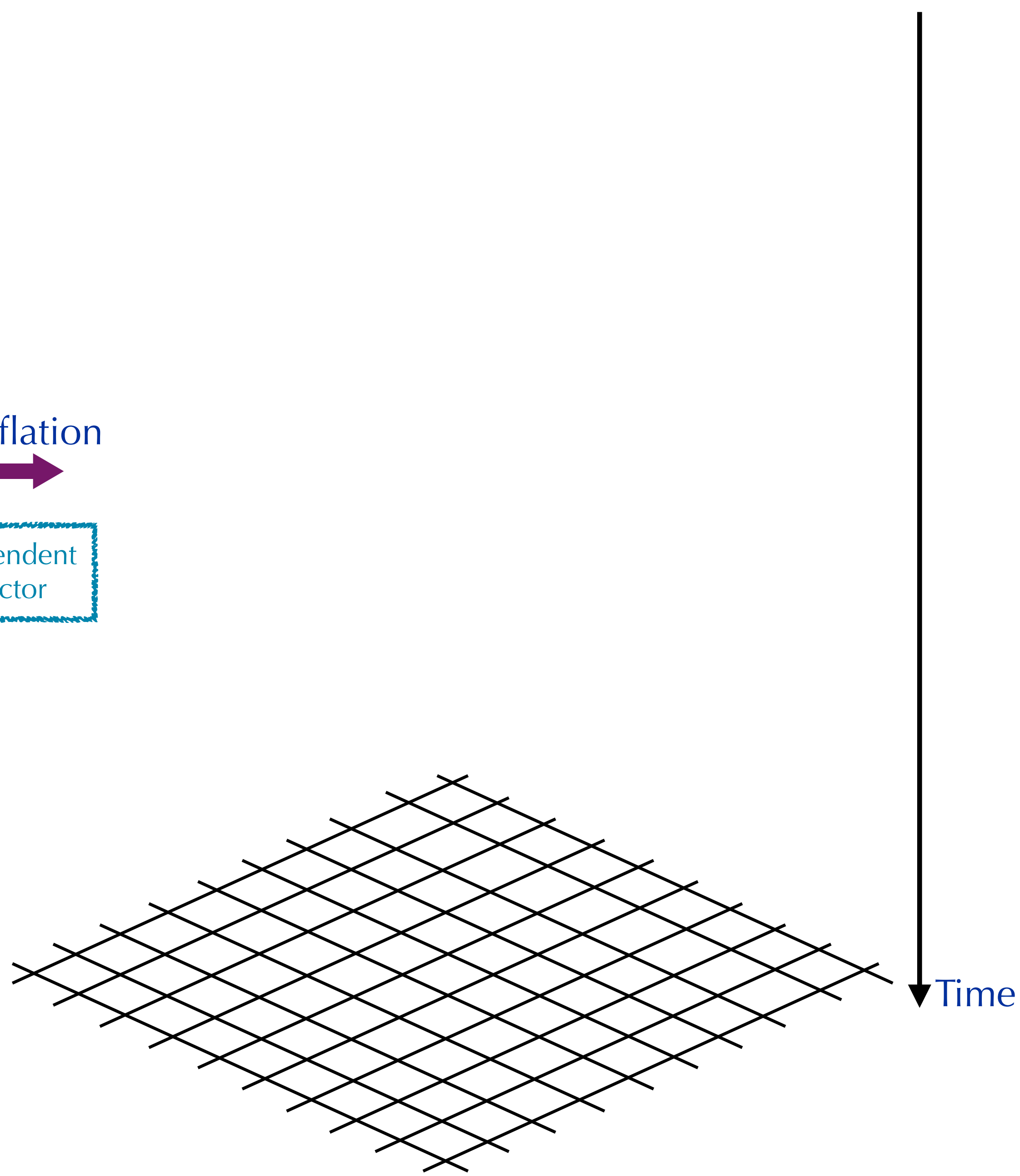


Particle Creation in non-static Gravitational Backgrounds

Cosmological GPP

End of inflation

Time dependent
scale factor



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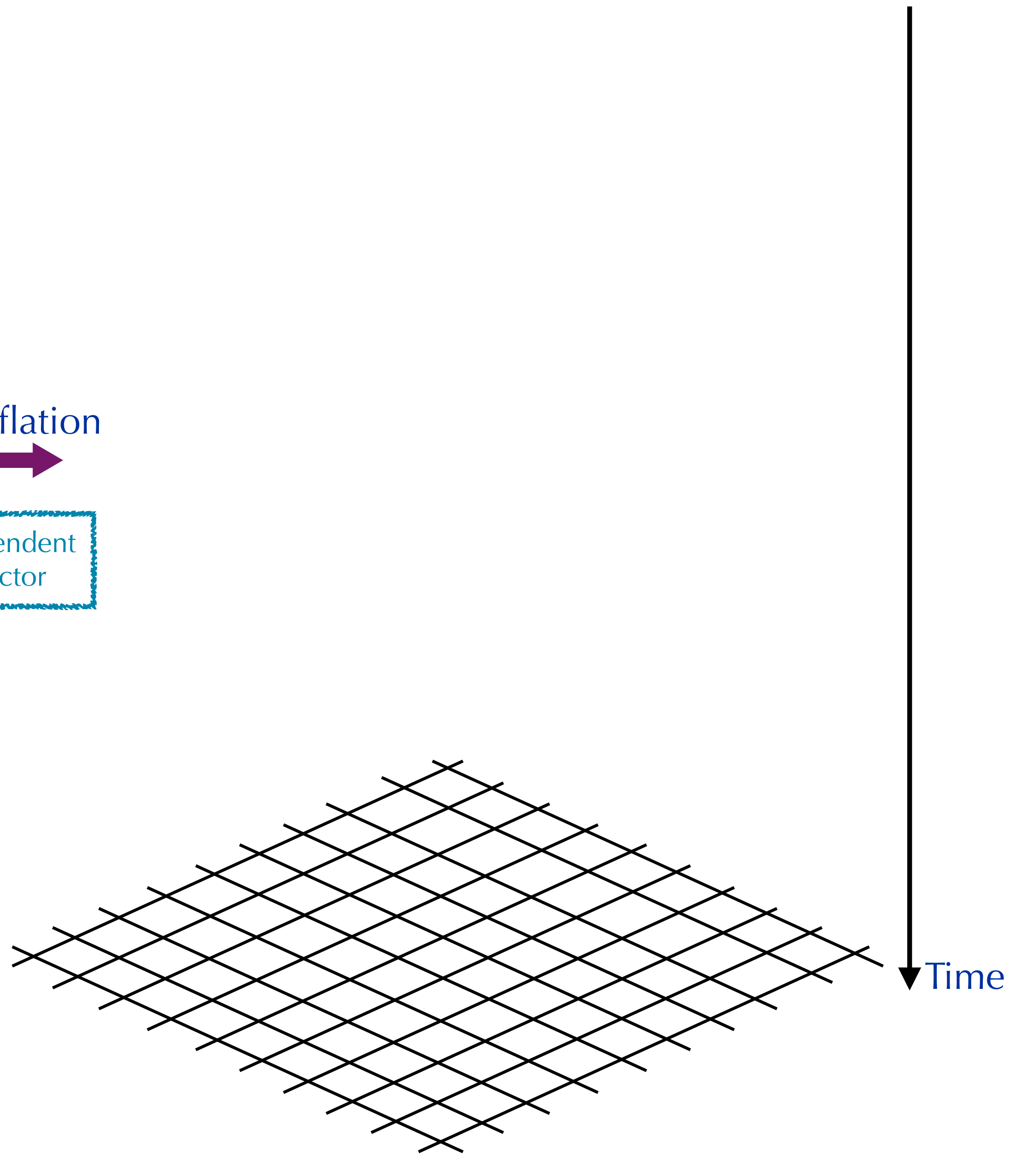
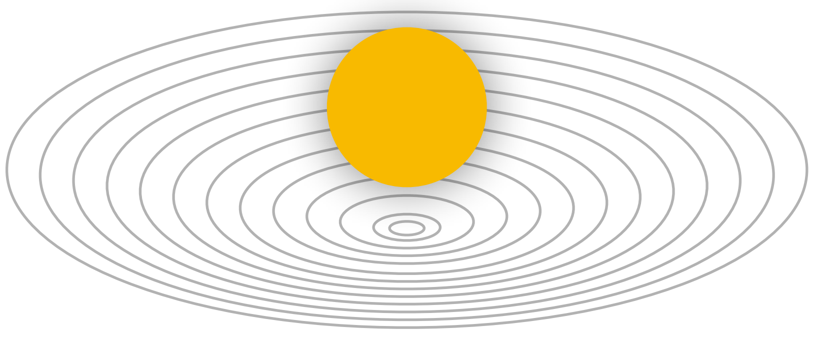


Black-Hole GPP



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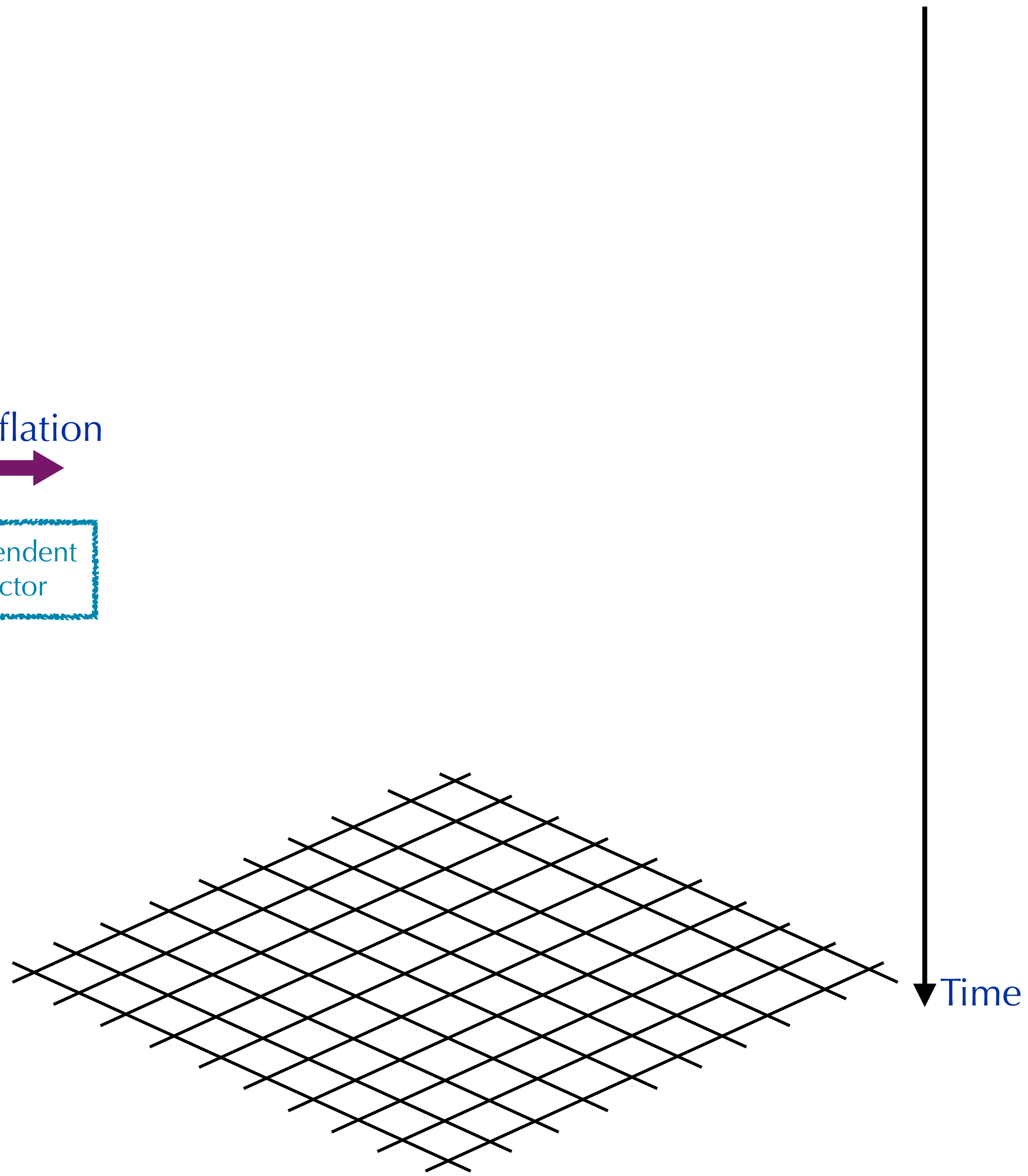
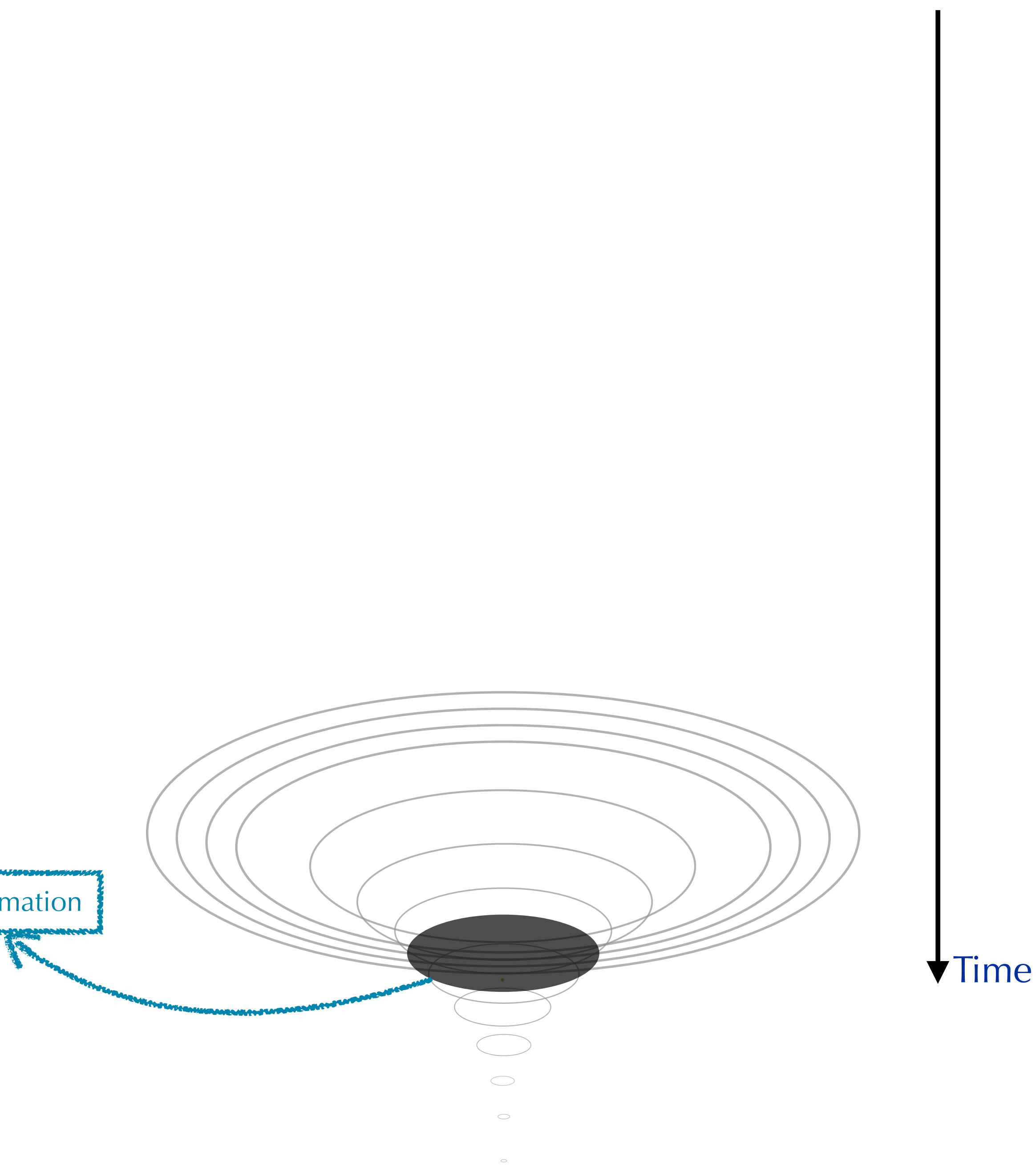


Black-Hole GPP

Horizon formation



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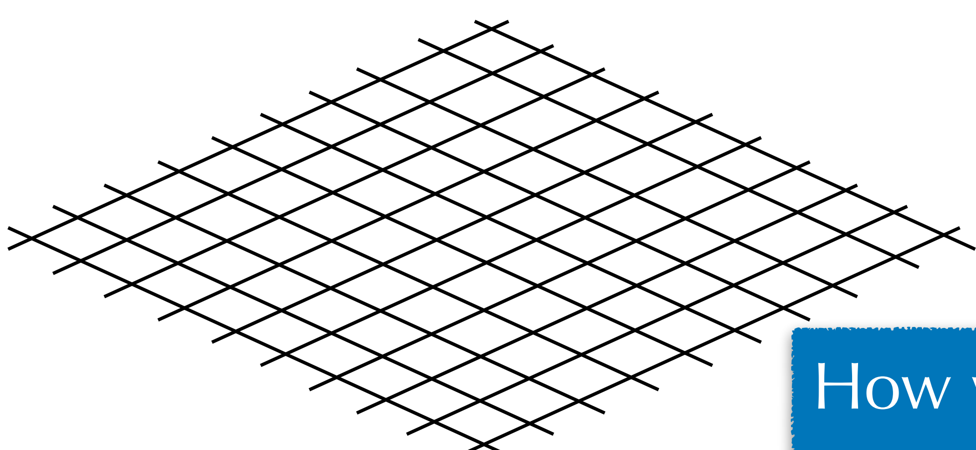

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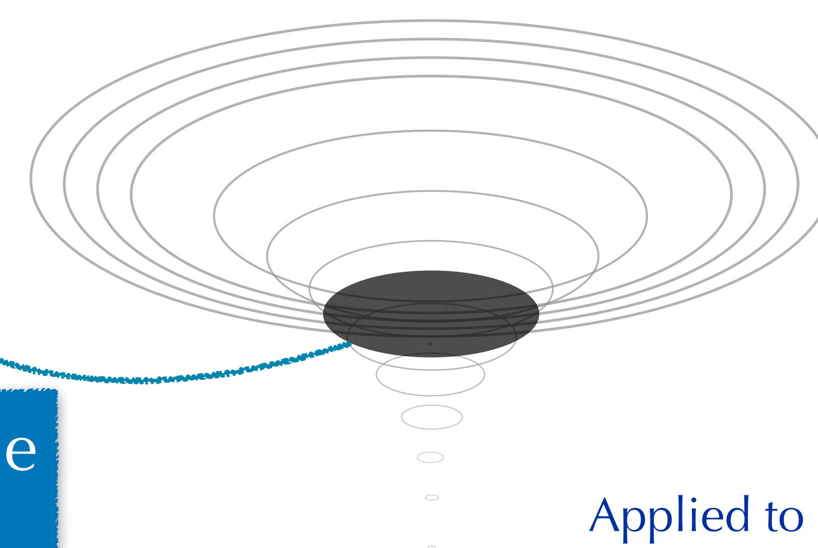

Time

Applied to Dark Matter production

How would this affect the generation of baryon asymmetry?

Cosmological Gravitational Particle Production (CGPP)

Based on arXiv:2404.06530

CGPP

Ford (1987),
Chung et al (1998, 1999)
Kuzmin & Tkachev (1998)
Ema et al (2015, 2016)
Herring, Boyanovsky, & Zentner (2020)
Ema, Nakayama, Tang (2018, 2019), …

CGPP

$\alpha-$attractor T-models: $V(\varphi) = \lambda M_P^4 \left| \sqrt{6} \tanh\left(\frac{\varphi}{\sqrt{6} M_P}\right) \right|^\kappa$

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$a_e \rightarrow$ End of inflation
$H_e \rightarrow$ Hubble at a_e

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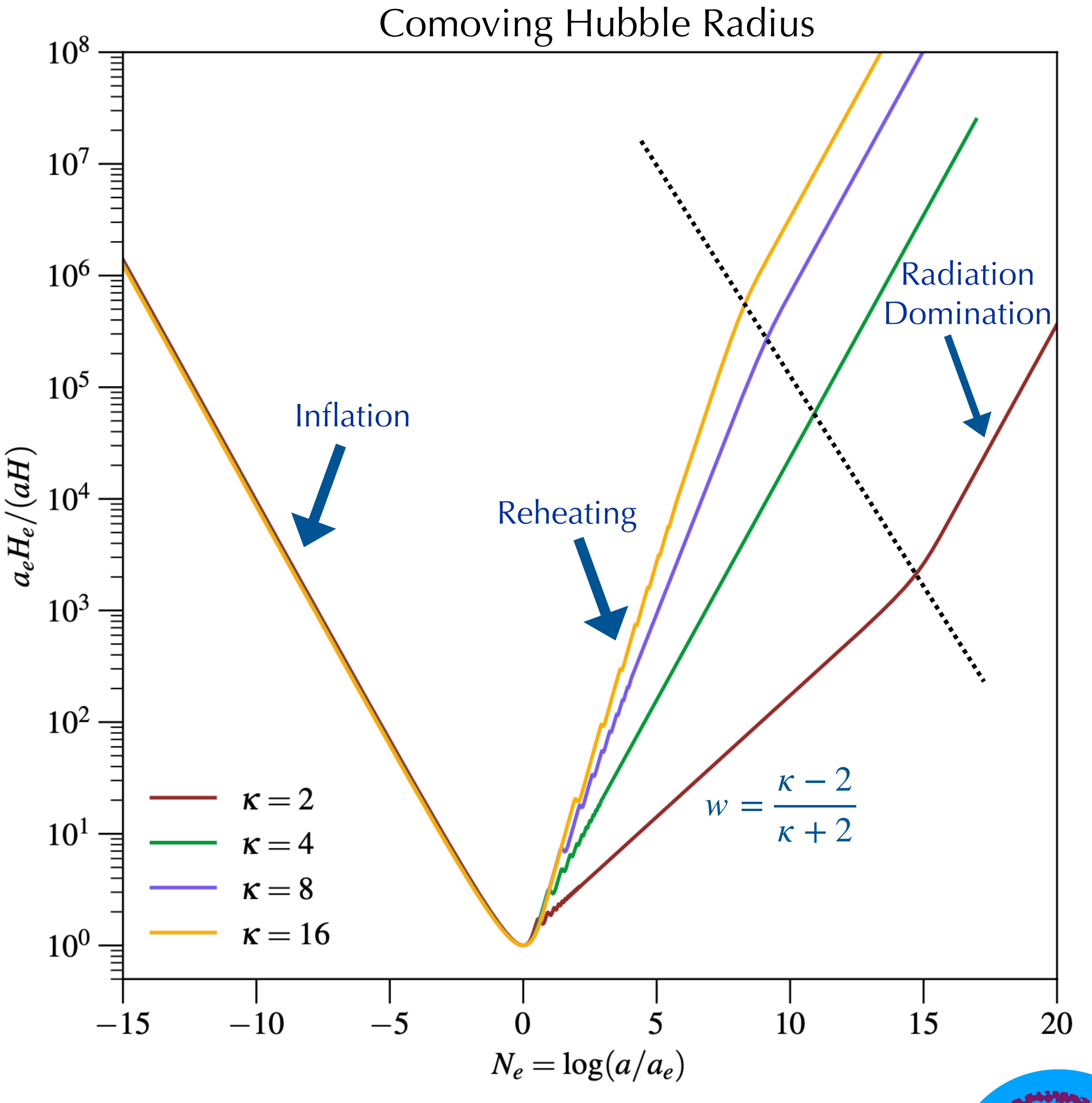

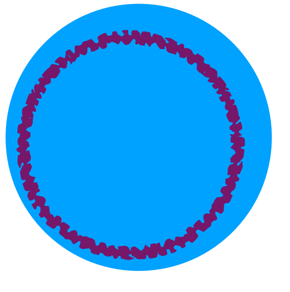

$\frac{1}{aH}$

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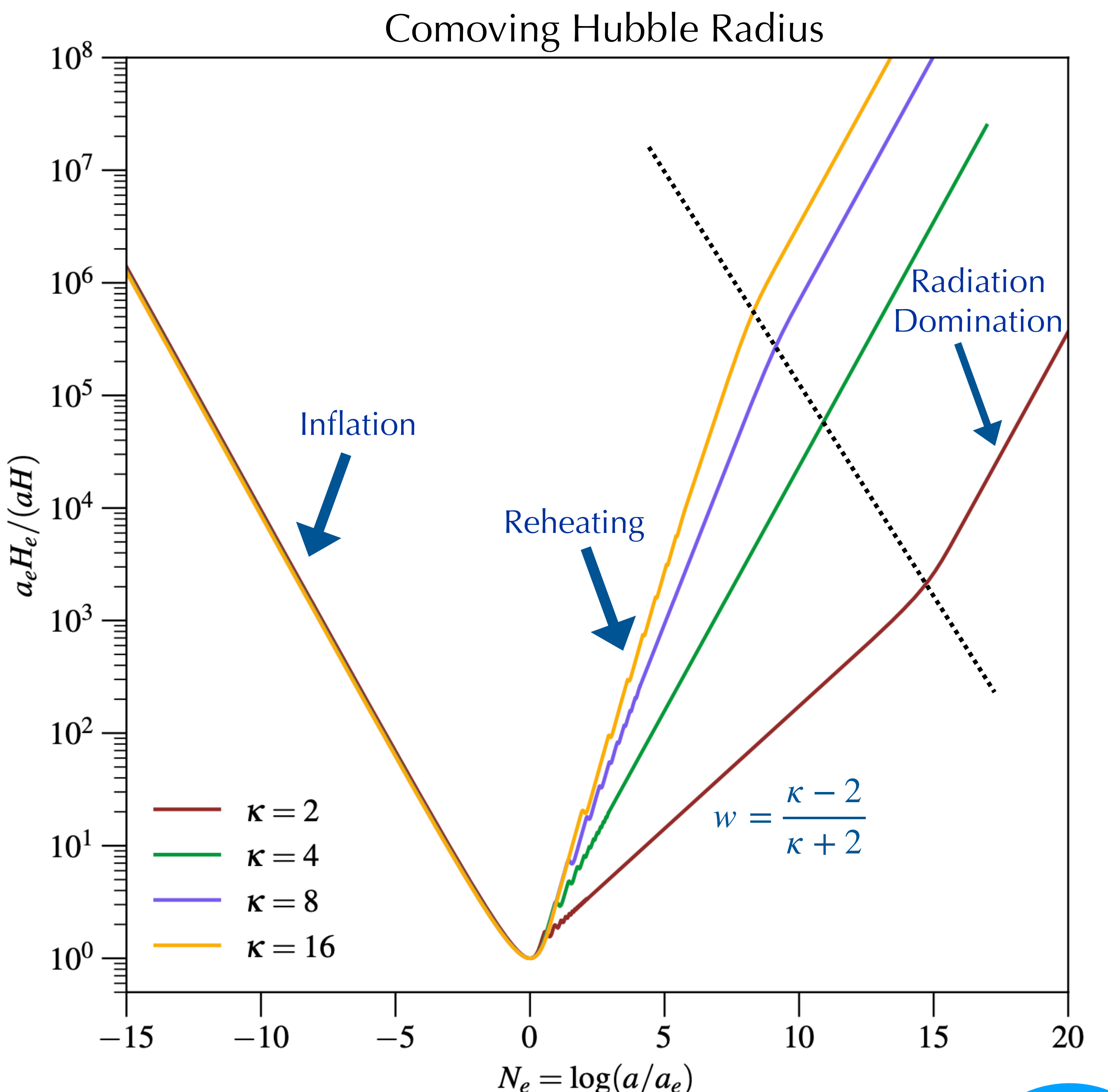
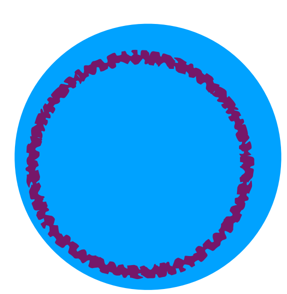
Let's add fields
on the background



Scalar $\phi'' - \nabla^2 \phi + a^2 m_{\rm eff}^2 \phi = 0$



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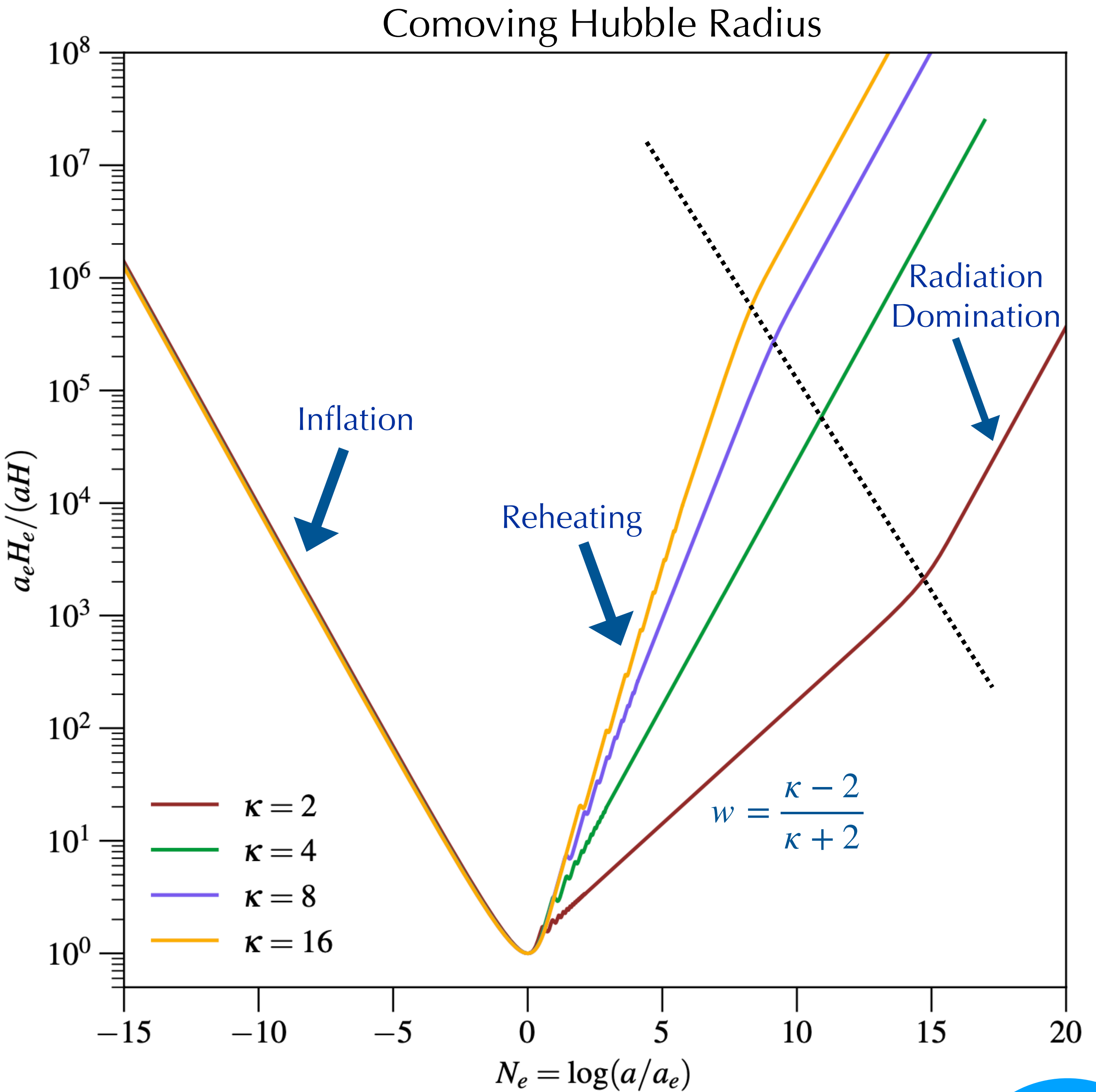
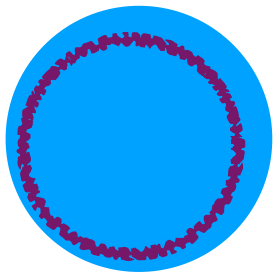


Let's add fields on the background

$$m_{\rm eff}^2 = m^2 + \left(\frac{1}{6} - \xi\right) R(\eta)$$

Scalar $\phi'' - \nabla^2\phi + a^2 m_{\rm eff}^2 \phi = 0$



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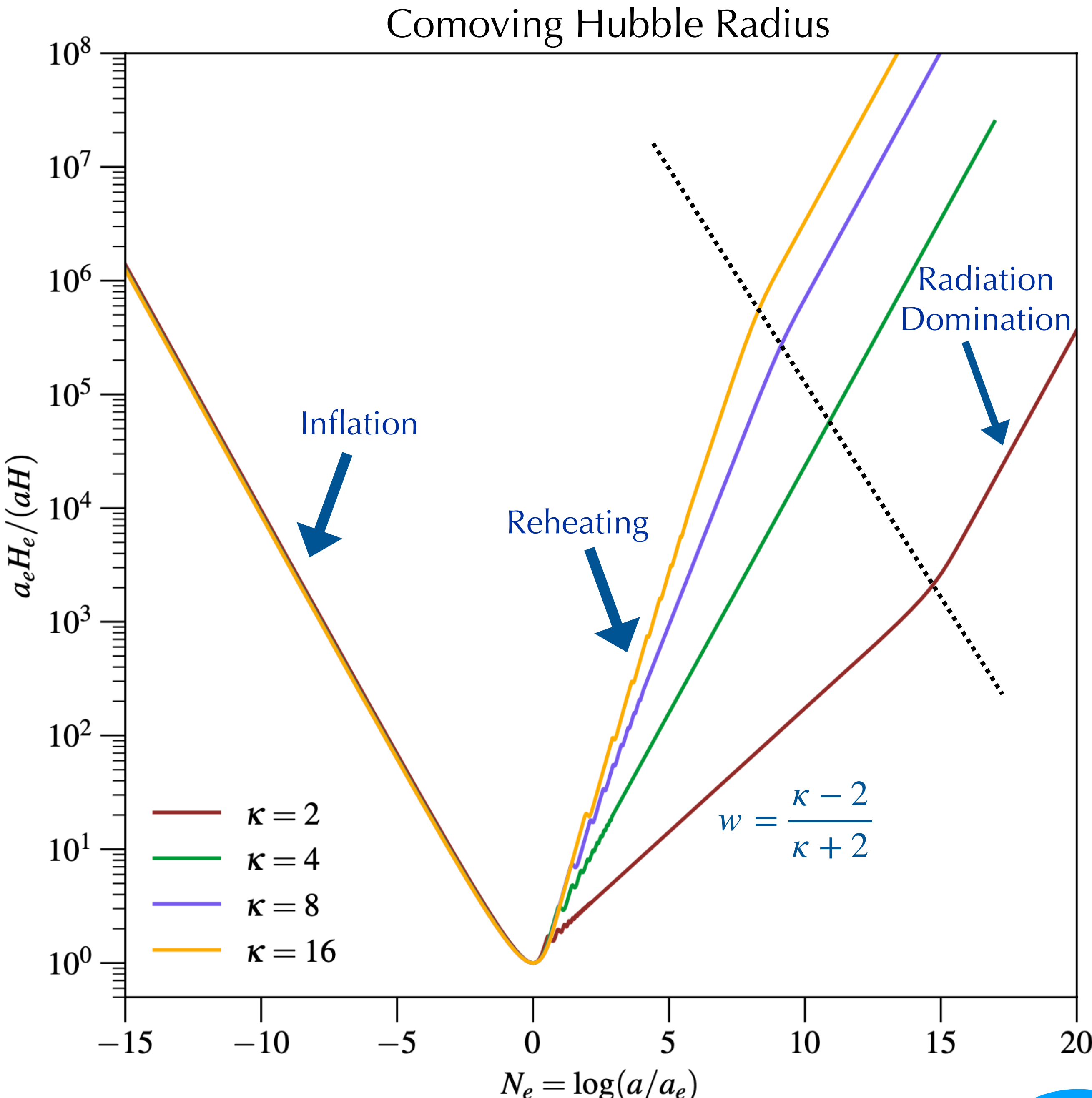

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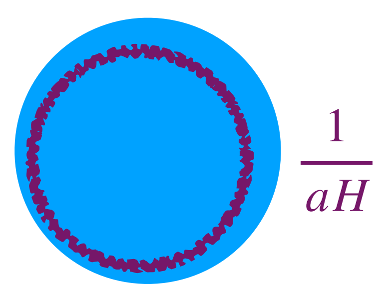
$$m_{\rm eff}^2 = m^2 + \left(\frac{1}{6} - \xi\right) R(\eta)$$

Scalar $\phi'' - \nabla^2\phi + a^2 m_{\rm eff}^2 \phi = 0$

$$\phi(\eta, \mathbf{x}) = \int \frac{d^3k}{(2\pi)^3} a_{\mathbf{k}} \chi_k(\eta) e^{i\mathbf{k}\cdot\mathbf{x}} + \mathrm{h.c.}$$

$$\chi_k''(\eta) + (k^2 + a^2 m_{\rm eff}^2)\chi_k(\eta) = 0$$

Modes obey a harmonic-oscillator-like equation with a time dependent frequency



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CGPP — 2

Lyth, Roberts (1998)
Kuzmin & Tkachev (1999);
Chung, Everett, Yoo, & Zhou (2011)
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…

CGPP — 2

Basis differ at different times

$$\chi_k^{\rm IN}(\eta) = \alpha_k\, \chi_k^{\rm OUT}(\eta) + \beta_k\, \chi_k^{\rm OUT*}(\eta)$$

$\alpha_k, \beta_k \to$ Bogoliubov coefficients

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Late time

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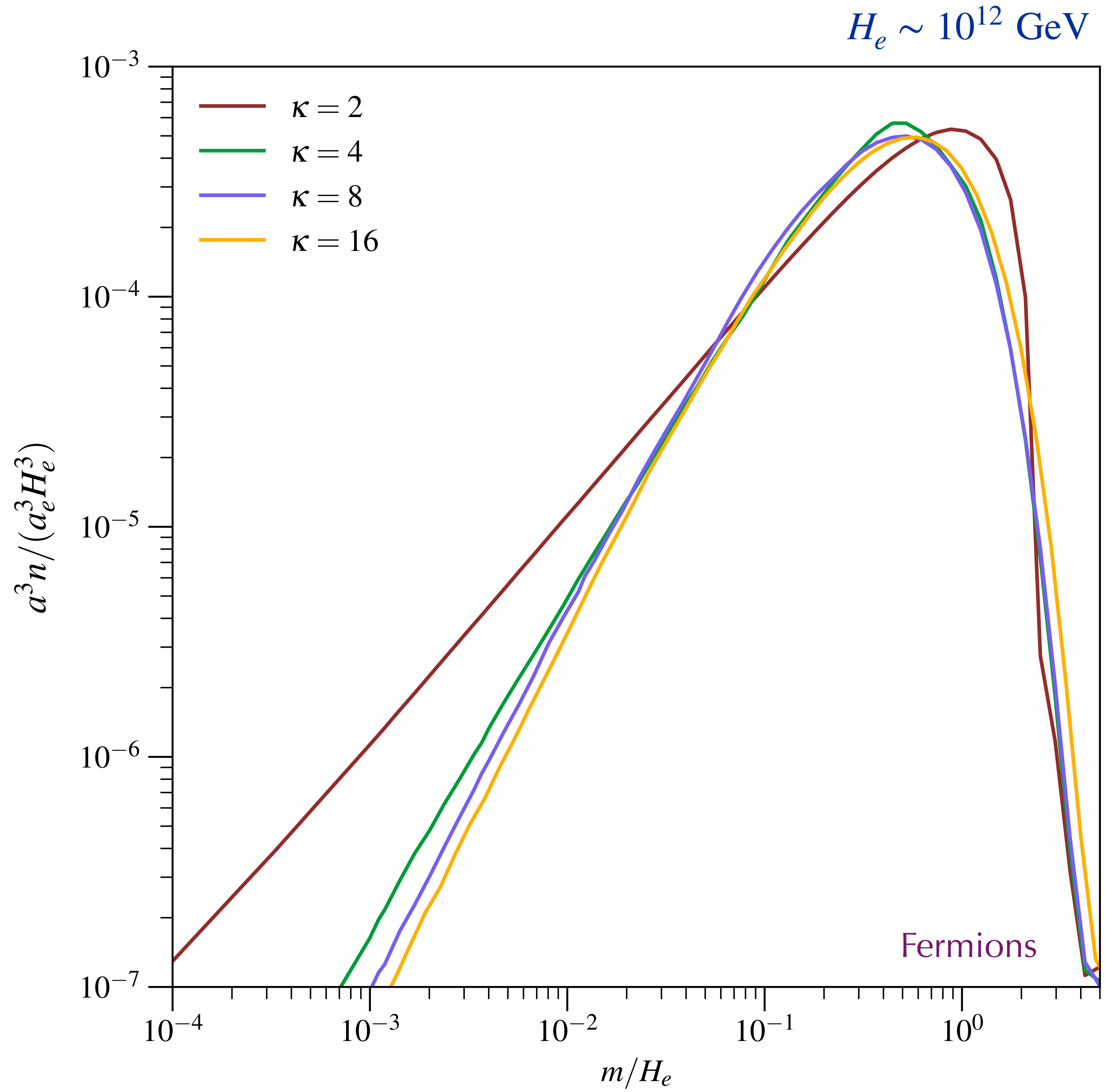
Number density from CGPP:

$$a^3 n = \frac{1}{V}{}_{\text{BD}}\langle 0 | N^{\text{OUT}} | 0 \rangle_{\text{BD}}$$

$$a^3 n = \int \frac{dk}{k} \frac{k^3}{2\pi^2} |\beta_k|^2$$



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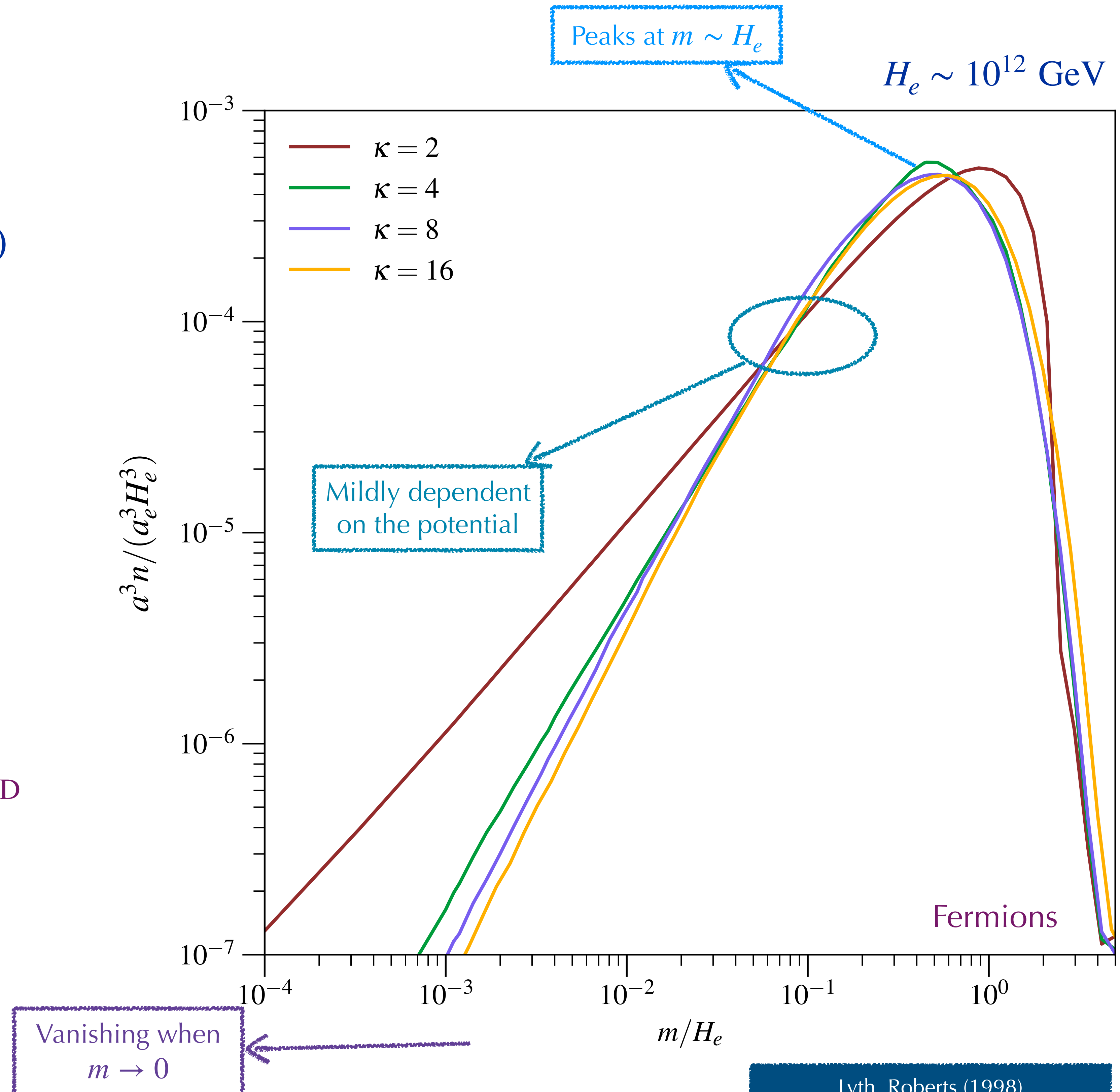

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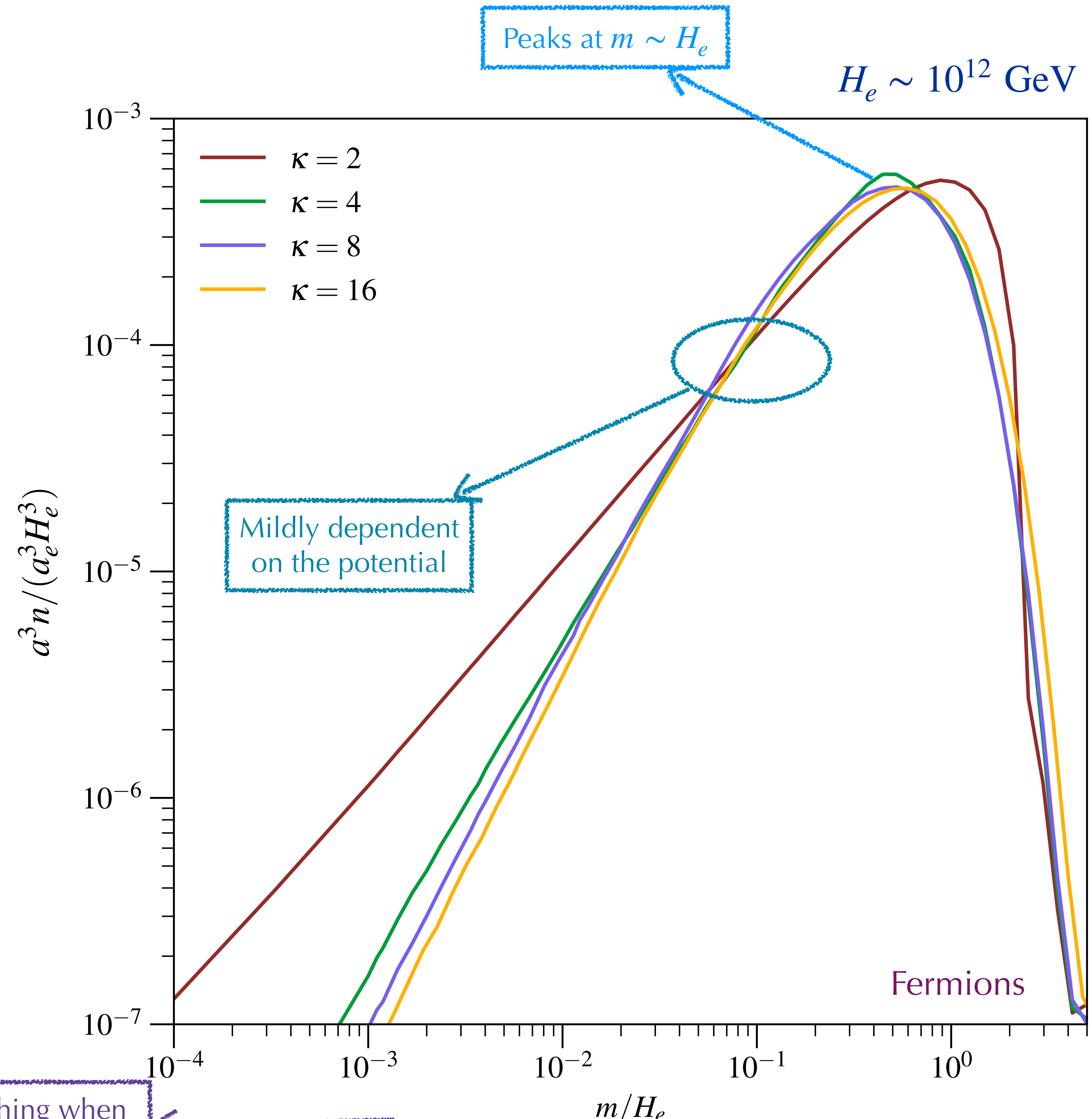

Vanishing when $m \rightarrow 0$

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The existence of this number density is unavoidable

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Non-thermal Baryon Asymmetry in $\alpha-$attractor T-models

Flores, YFPG, 2404.06530

Non-thermal Baryon Asymmetry in $\alpha-$attractor T-models

Are the RHNs from CGPP enough?

Assumption: CGPP ends before the decay of the particle produced

$\tau \gg t_{\rm CGPP}$

$X \to LH \quad X \to \bar{L}H$

Flores, YFPG, 2404.06530

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$$\frac{d(n_X a^3)}{dt} = -\Gamma_X n_X, \quad \frac{d(n_{\rm B-L} a^3)}{dt} = \epsilon_{\rm CP} \Gamma_X n_X$$

$$n_X = n_X^{\rm in} \left(\frac{a_{\rm in}}{a}\right)^3 \exp(-\Gamma_X t)$$

$$n_{\rm B-L} = \epsilon_{\rm CP}\, n_X^{\rm in} \left(\frac{a_{\rm in}}{a}\right)^3 (1 - \exp(-\Gamma_X t))$$

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Non-thermal Baryon Asymmetry in $\alpha-$attractor T-models

$t \propto a^{3(1+w_\varphi)/2}$

$T \propto a^{-3\kappa/(4(2+\kappa))}$

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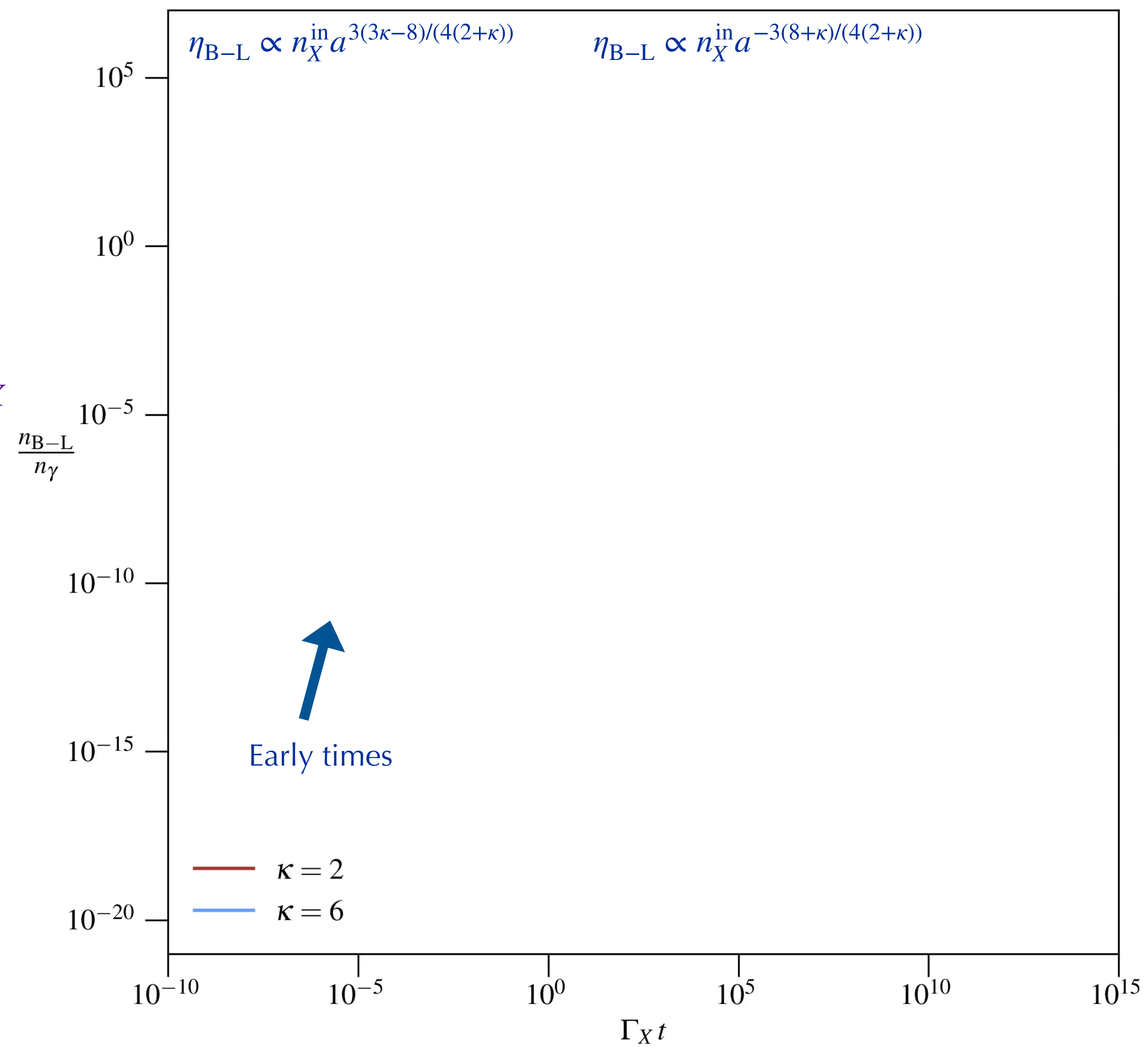

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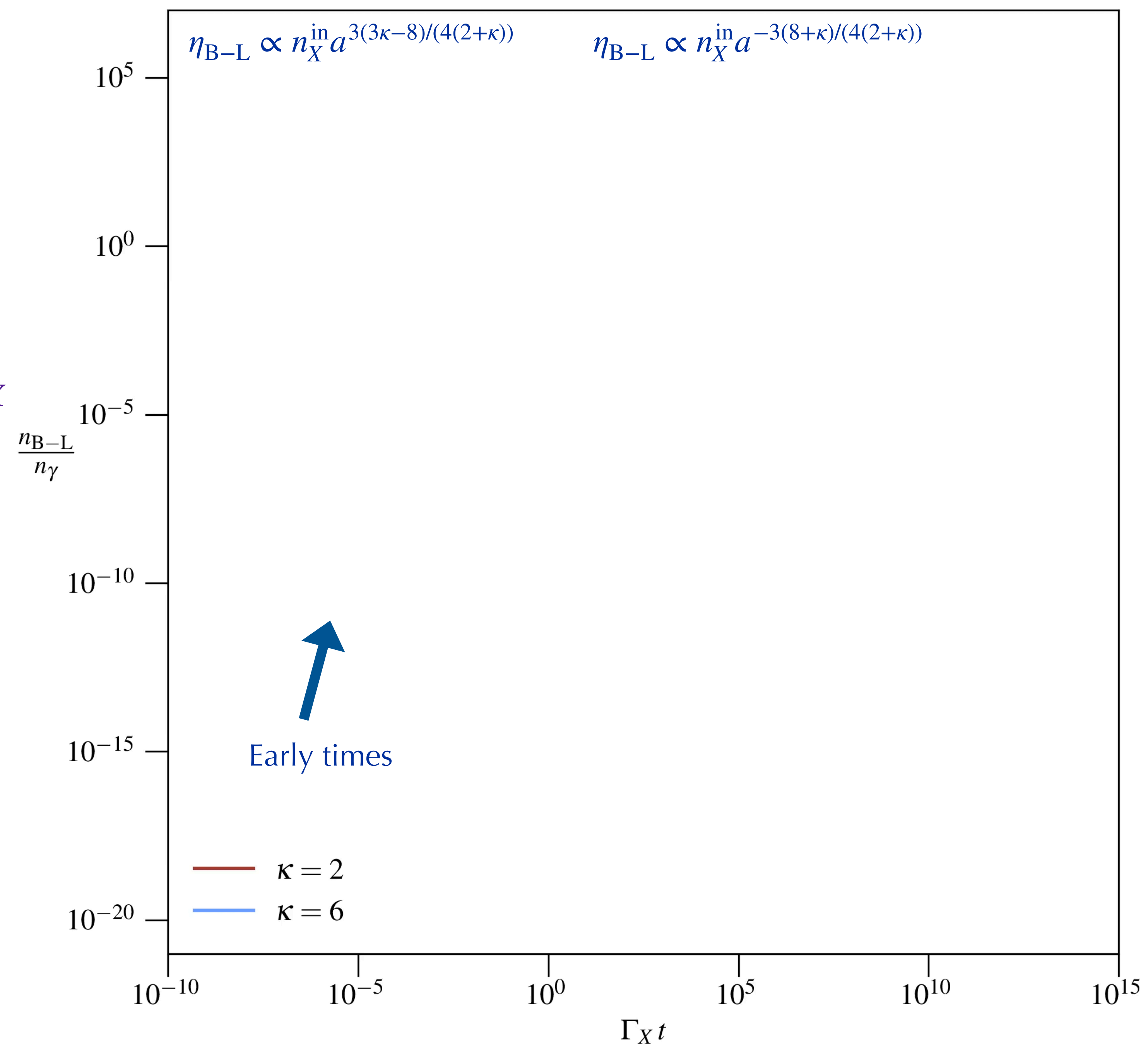
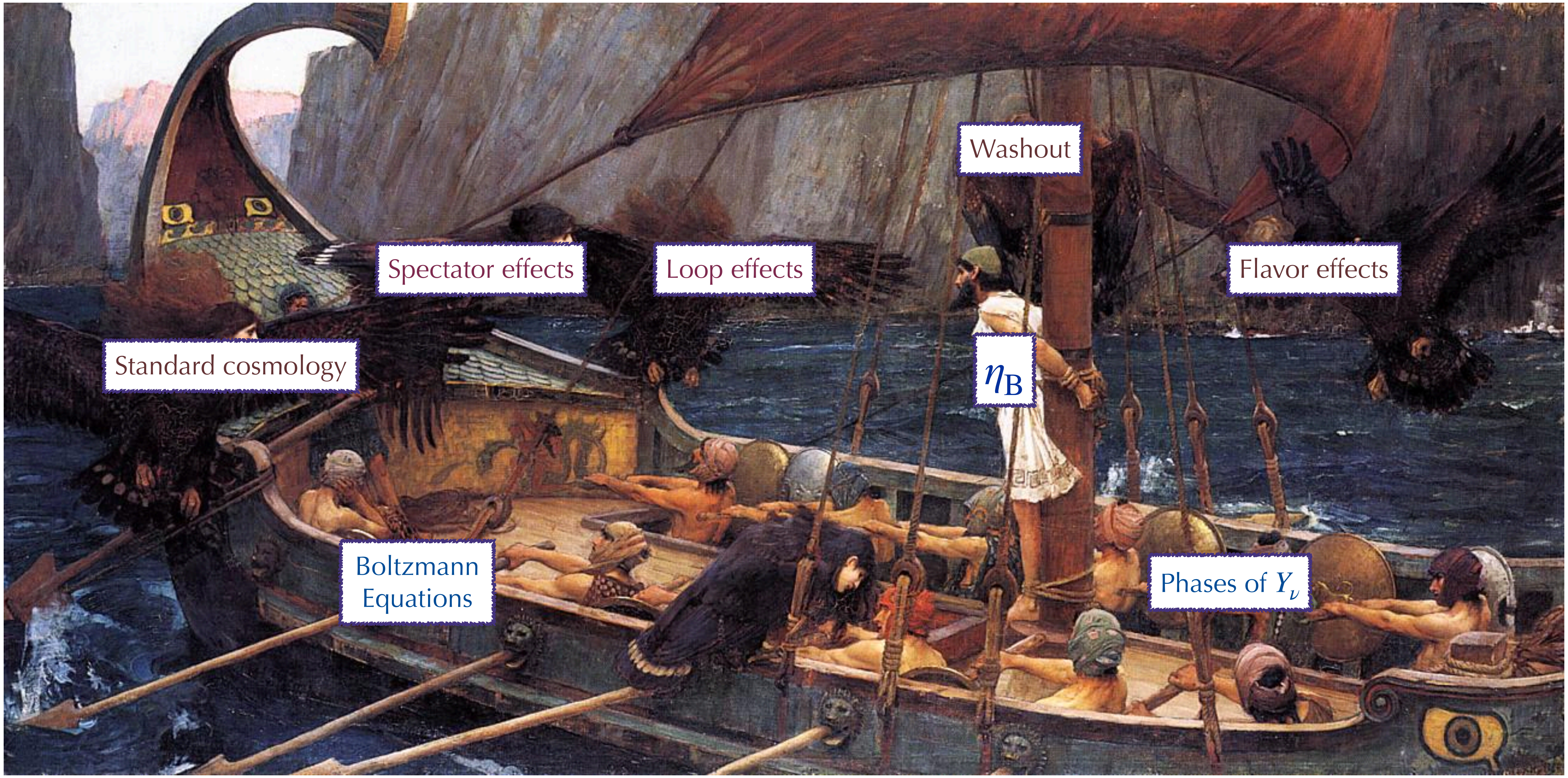


$\kappa \leq 8/3 \to$ large initial $n_X^{\rm in}$

Depends on the reheating of the Universe!

Flores, YFPG, 2404.06530

Intermezzo. Universal LeptogeneSiS Equation Solver (ULYSSES)



A Granelli, K Moffat, YFPG,
H Schulz and J Turner,
arXiv: 2007.09150
arXiv:2301.05722

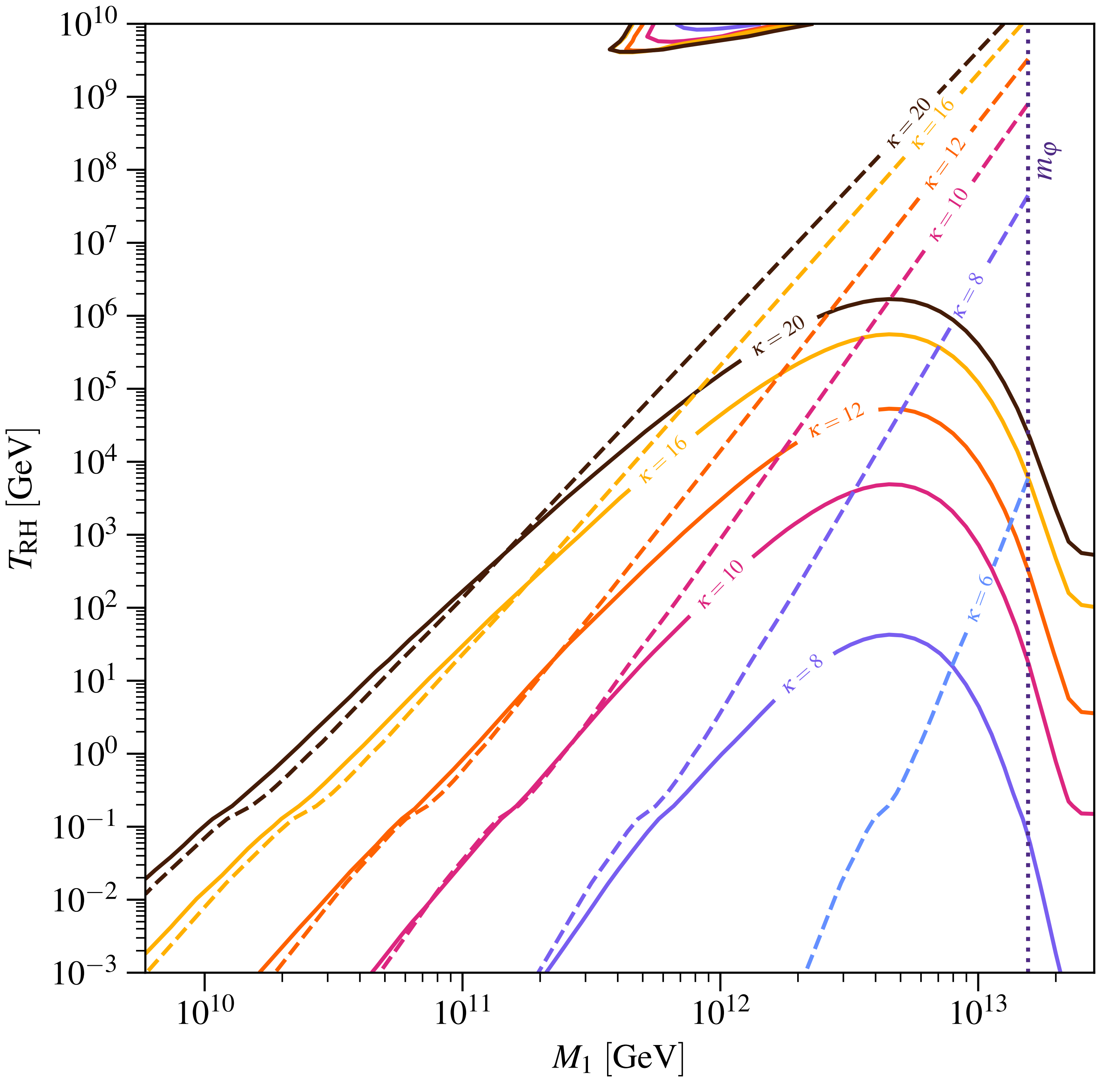
- Leptogenesis via decays and resonant leptogenesis
- ARS Leptogenesis
- Easy parallelization
- Rapid evaluation
- Multidimensional scan of the parameter space

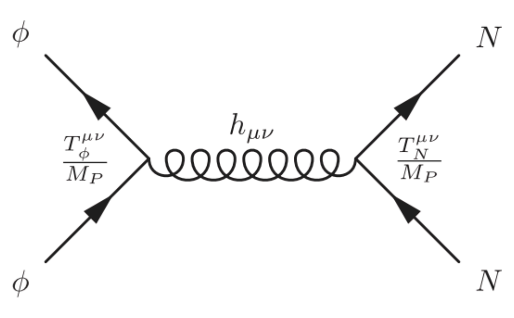
CGPP and Leptogenesis

Flores, YFPG, 2404.06530

Saturating Casas-Ibarra bound on ϵ_{CP}

Casas, Ibarra, 2001





Dashed lines: Perturbative approach from Co, Mambrini, Olive, 2205.01689

See also: Hashiba, Yokoyama 1905.12423

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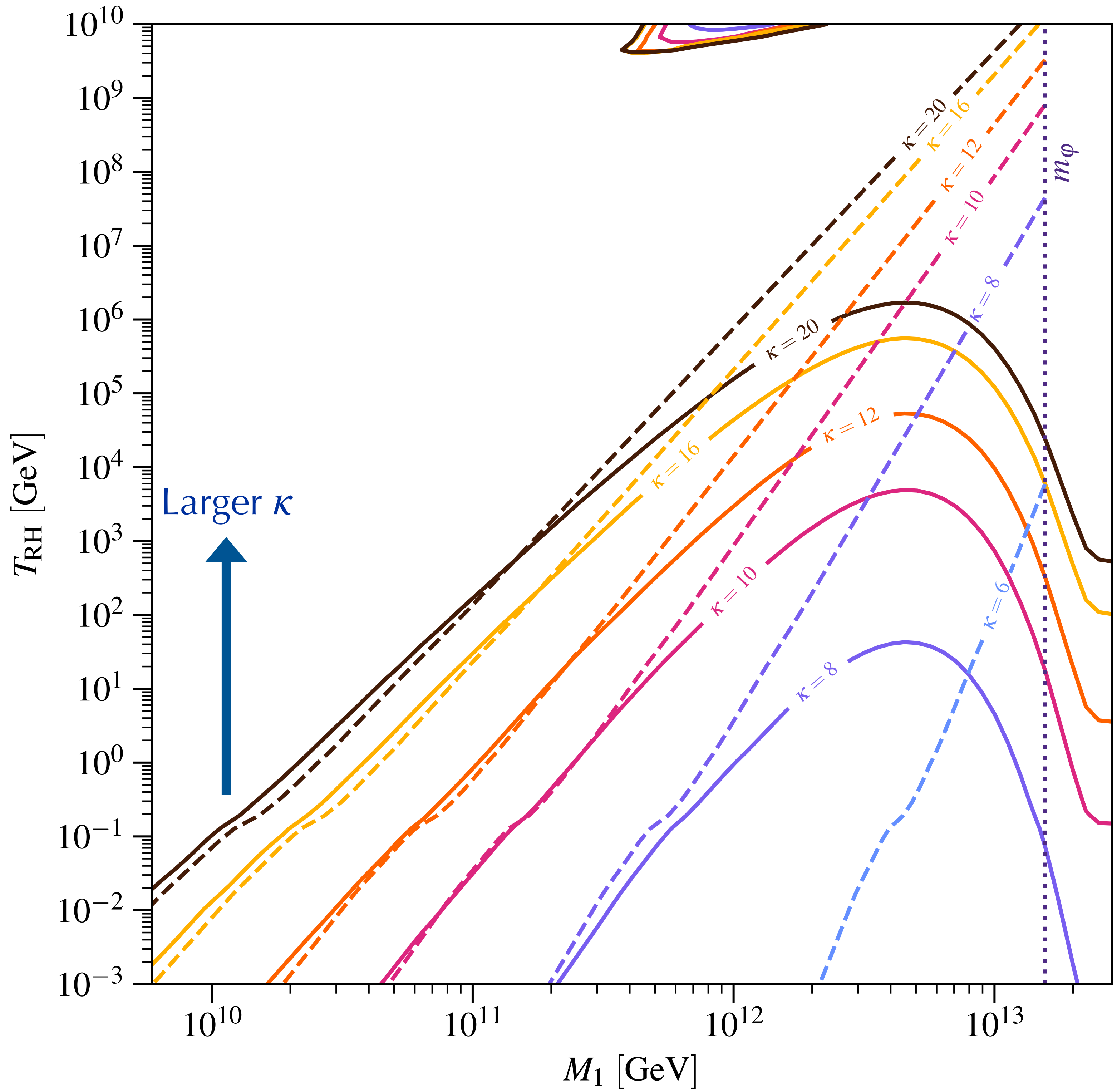

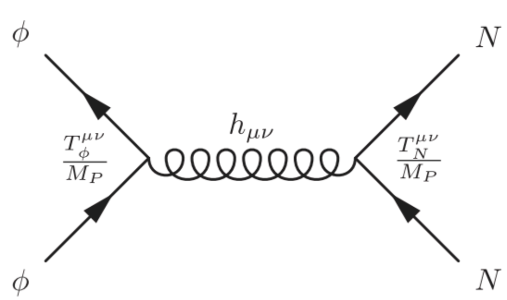

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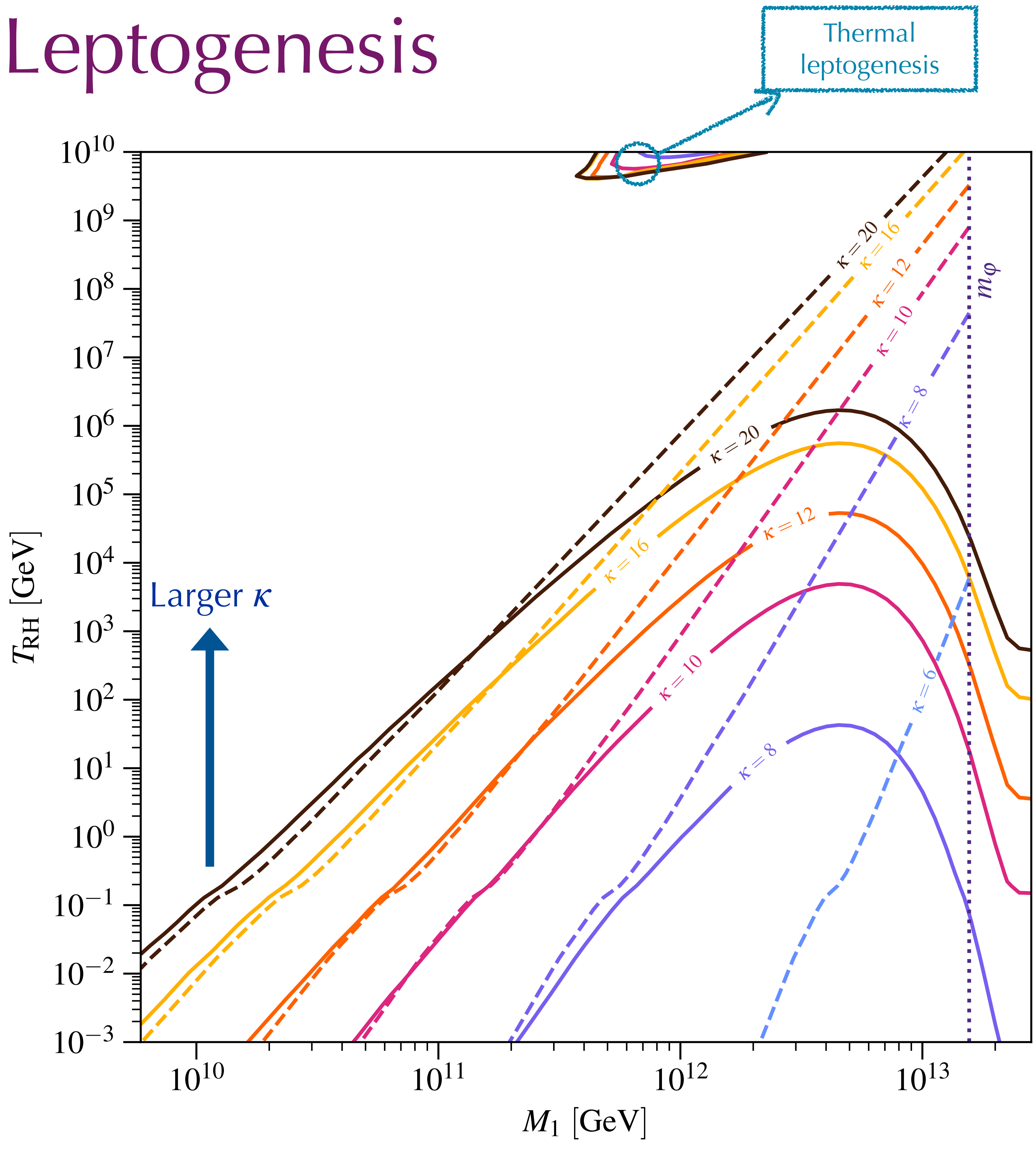

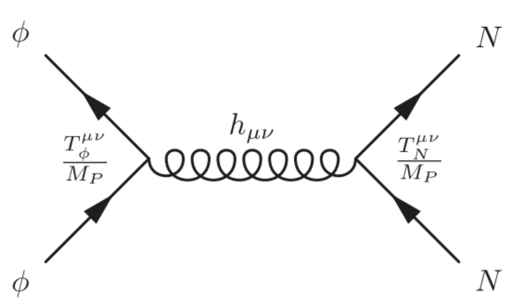

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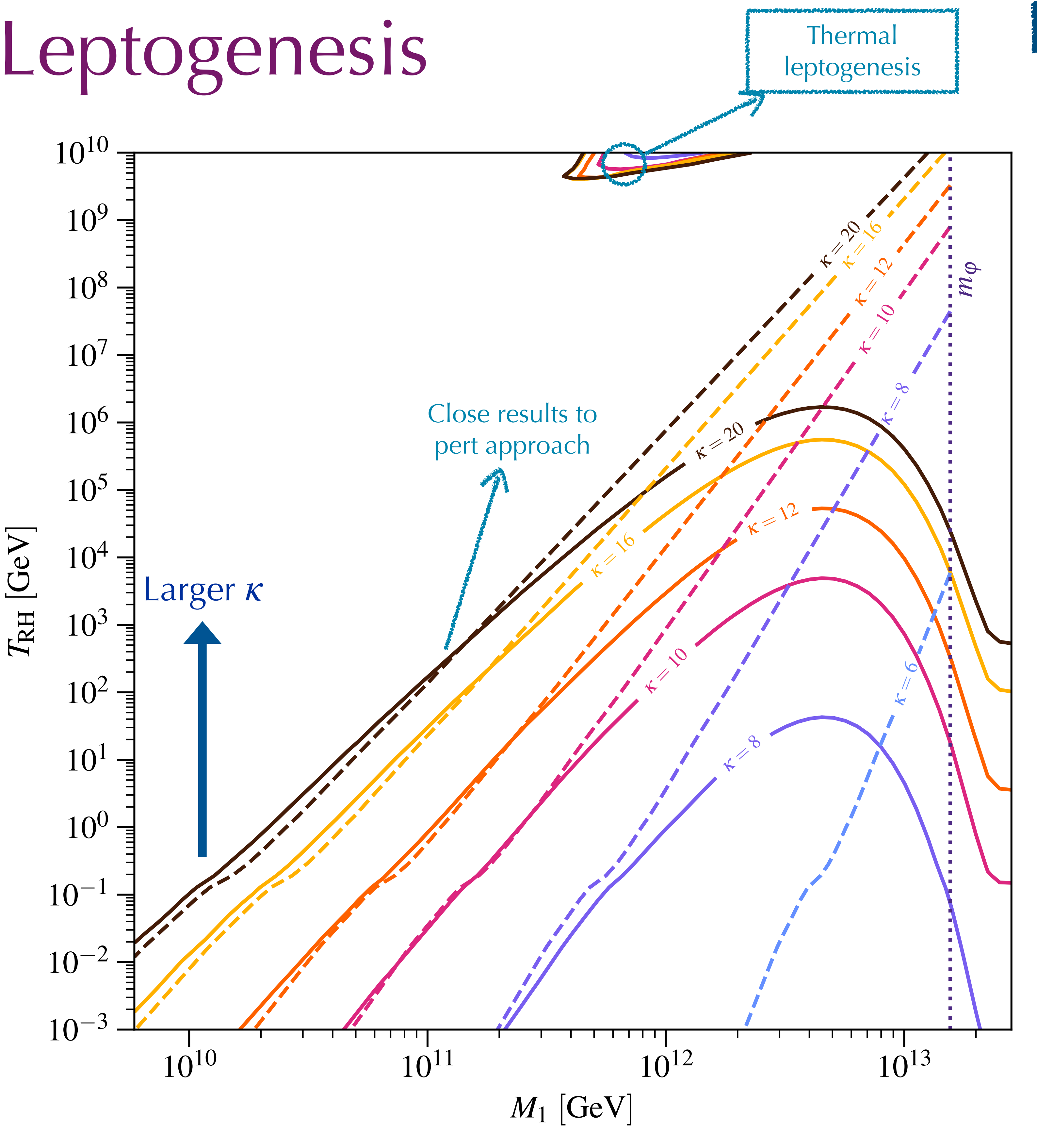

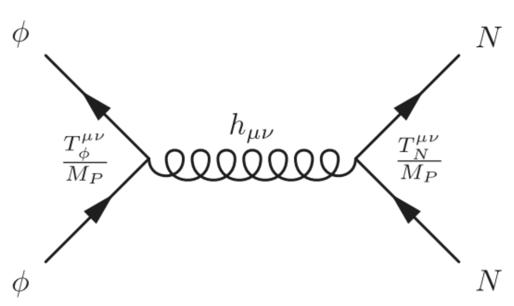

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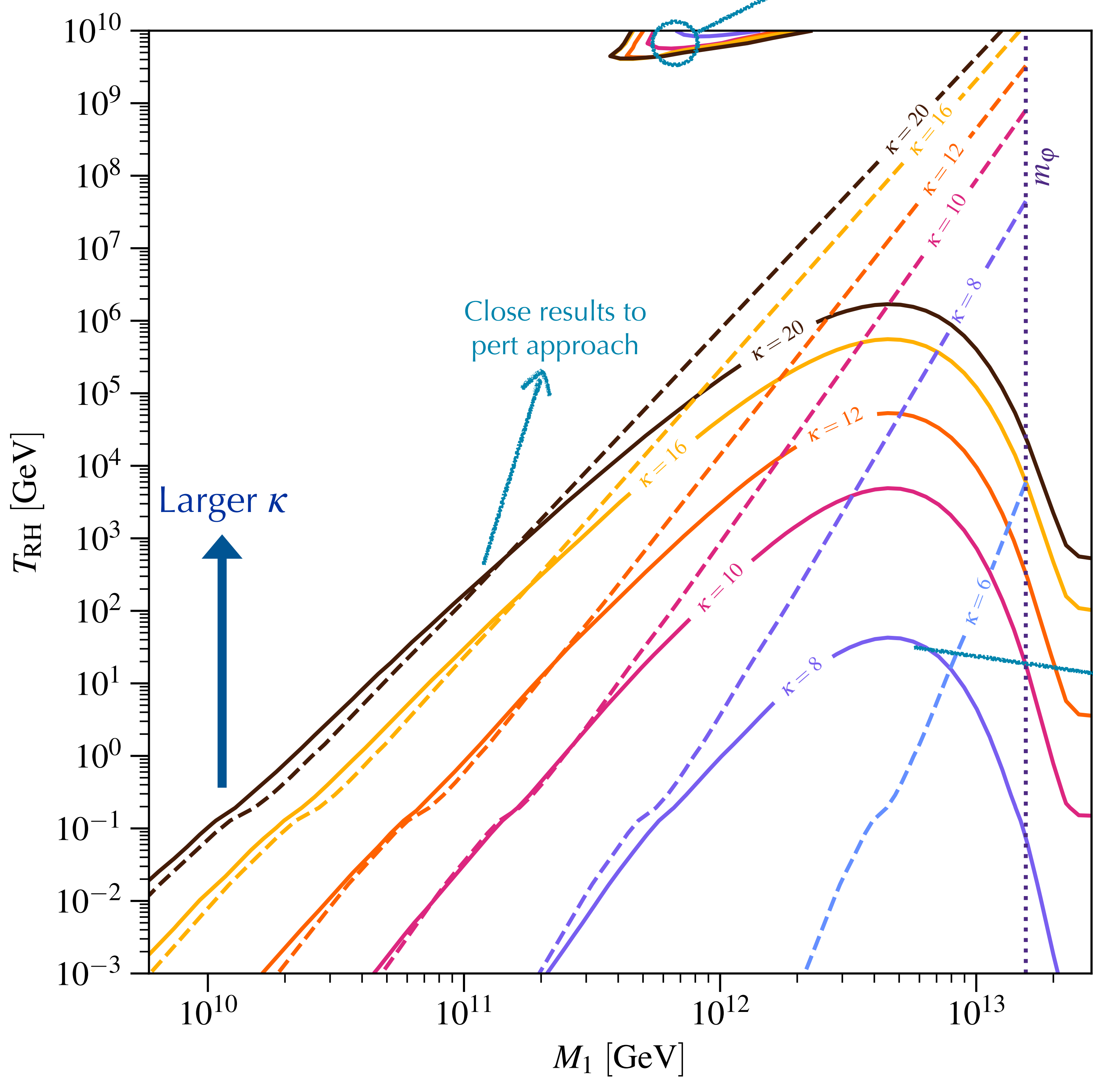

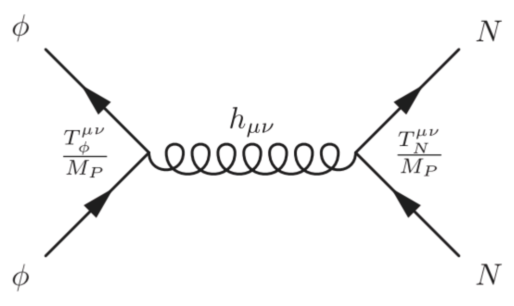

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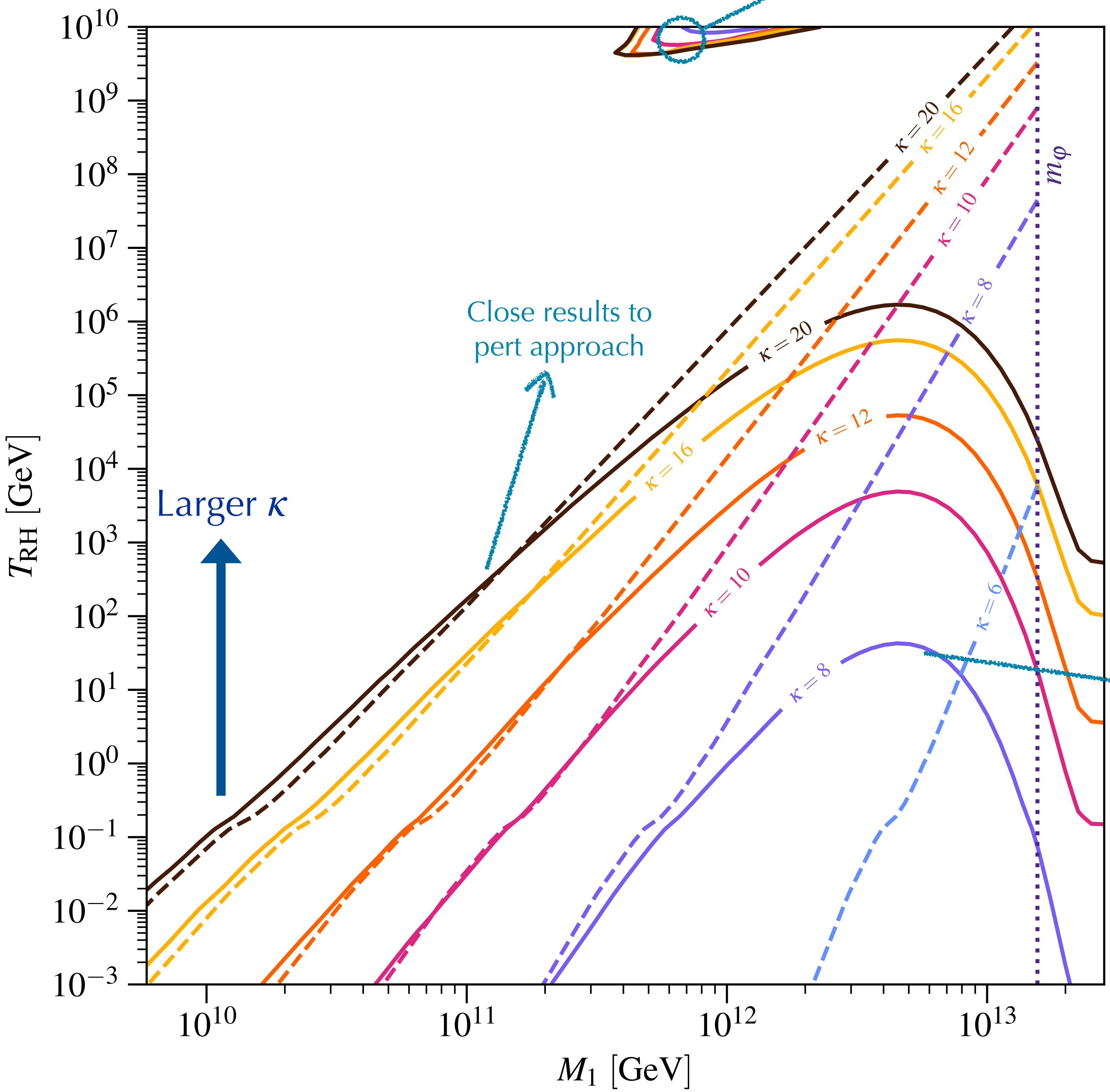
Thermal leptogenesis

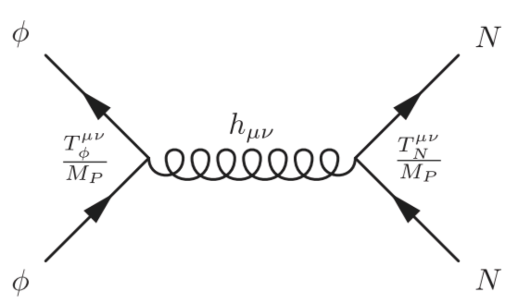


Close results to pert approach

Larger κ

Exponential suppression of CGPP

Lower k-modes ($k \ll H_e$) are not captured by the Boltzmann approach



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Kaneta, Lee, Oda, 2206.10929

Primordial Black Holes

Based on arXiv: 2010.03565,
2203.08823,
2312.06768, 2409.02173

Primordial Black Holes

Lighter Black Holes → Large densities

$$M_{\rm BH,i} \sim \frac{t}{G} \sim 10^{15}\ {\rm g} \left(\frac{t}{10^{-23}\ {\rm s}}\right)$$

Carr et al. 2002.12778

Zeldovich, Novikov '66, Hawking '71

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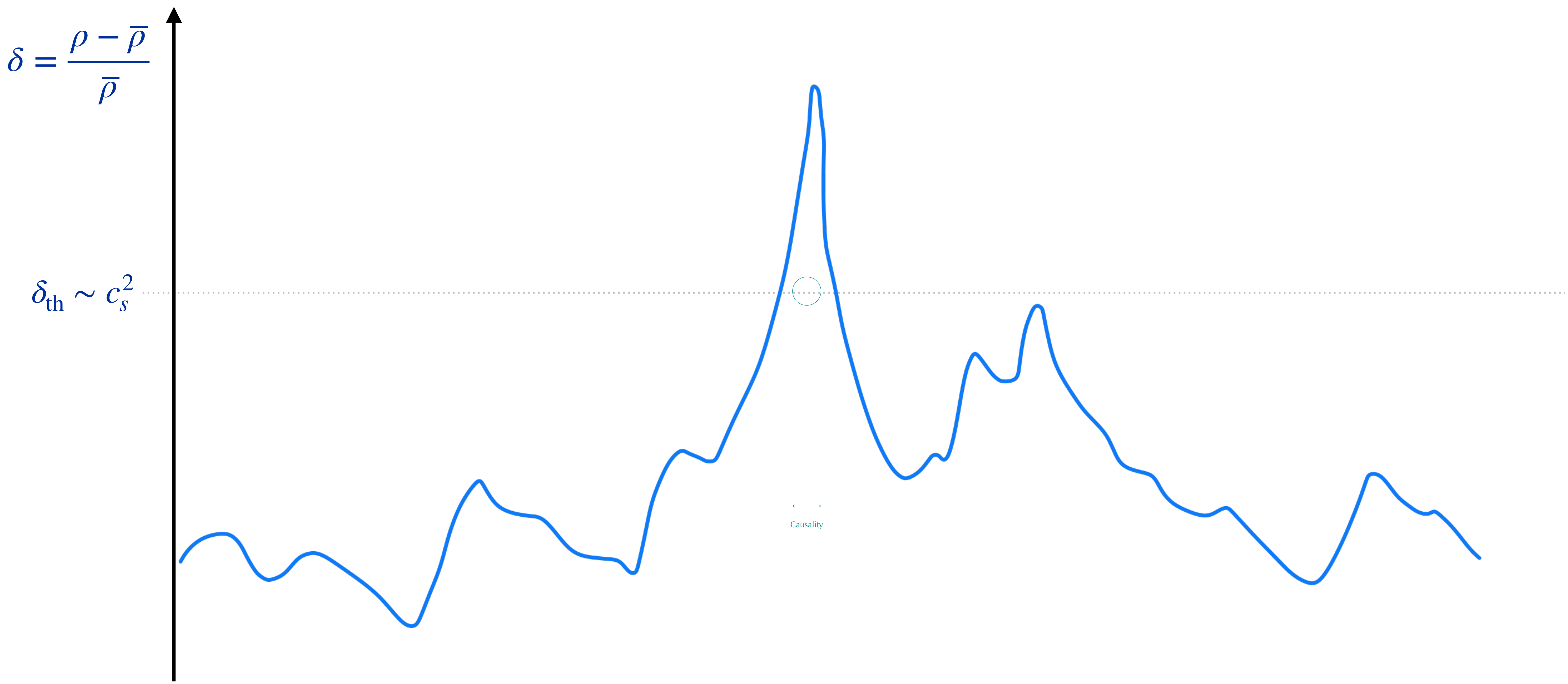
- Collapse of density fluctuations



Inspired on Villanueva-Domingo, Mena, Palomares-Ruiz 2103.12087

Carr et al. 2002.12778

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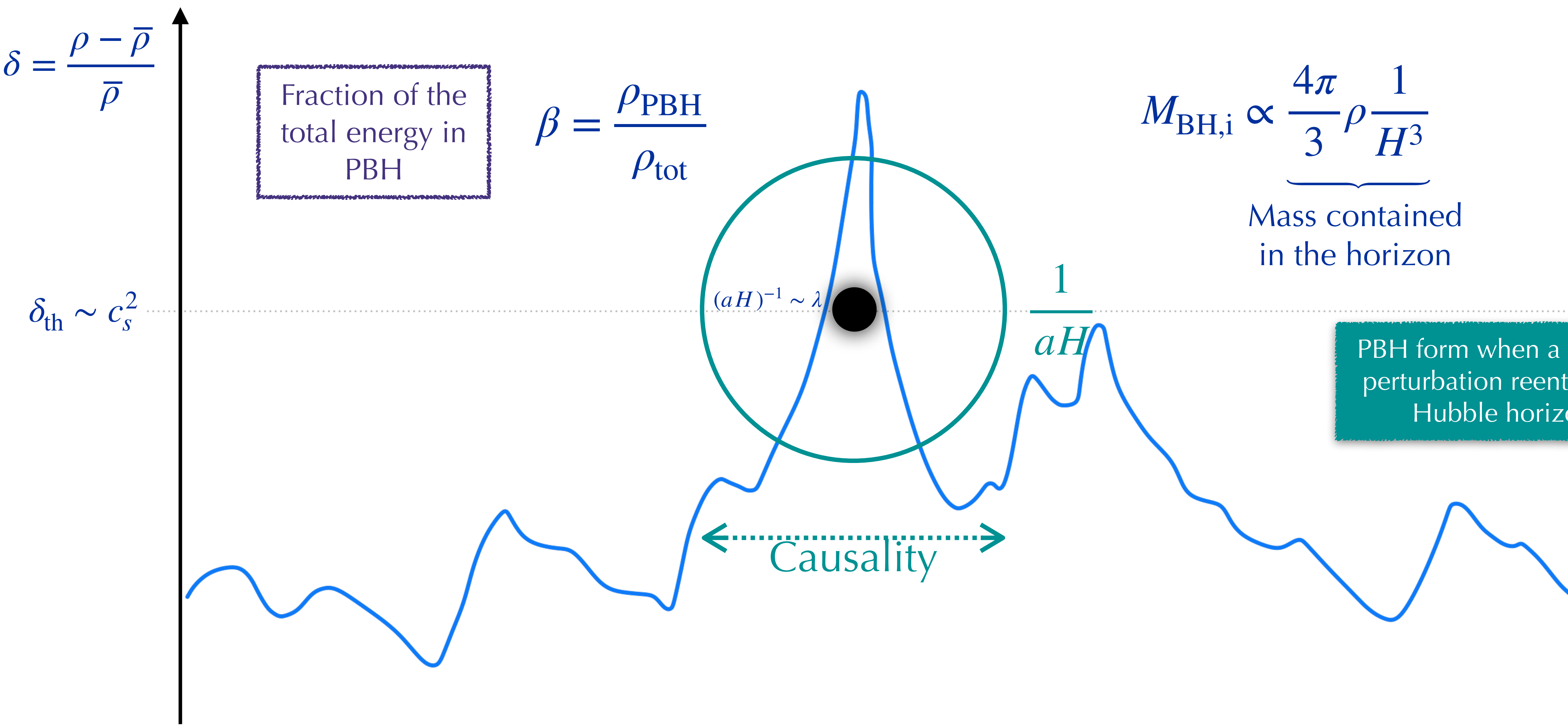
$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}$$

Fraction of the total energy in PBH

$$\beta = \frac{\rho_{\rm PBH}}{\rho_{\rm tot}}$$

$$M_{\rm BH,i} \propto \underbrace{\frac{4\pi}{3}\rho\frac{1}{H^3}}_{\text{Mass contained in the horizon}}$$



PBH form when a density perturbation reenters the Hubble horizon

Inspired on Villanueva-Domingo, Mena, Palomares-Ruiz 2103.12087

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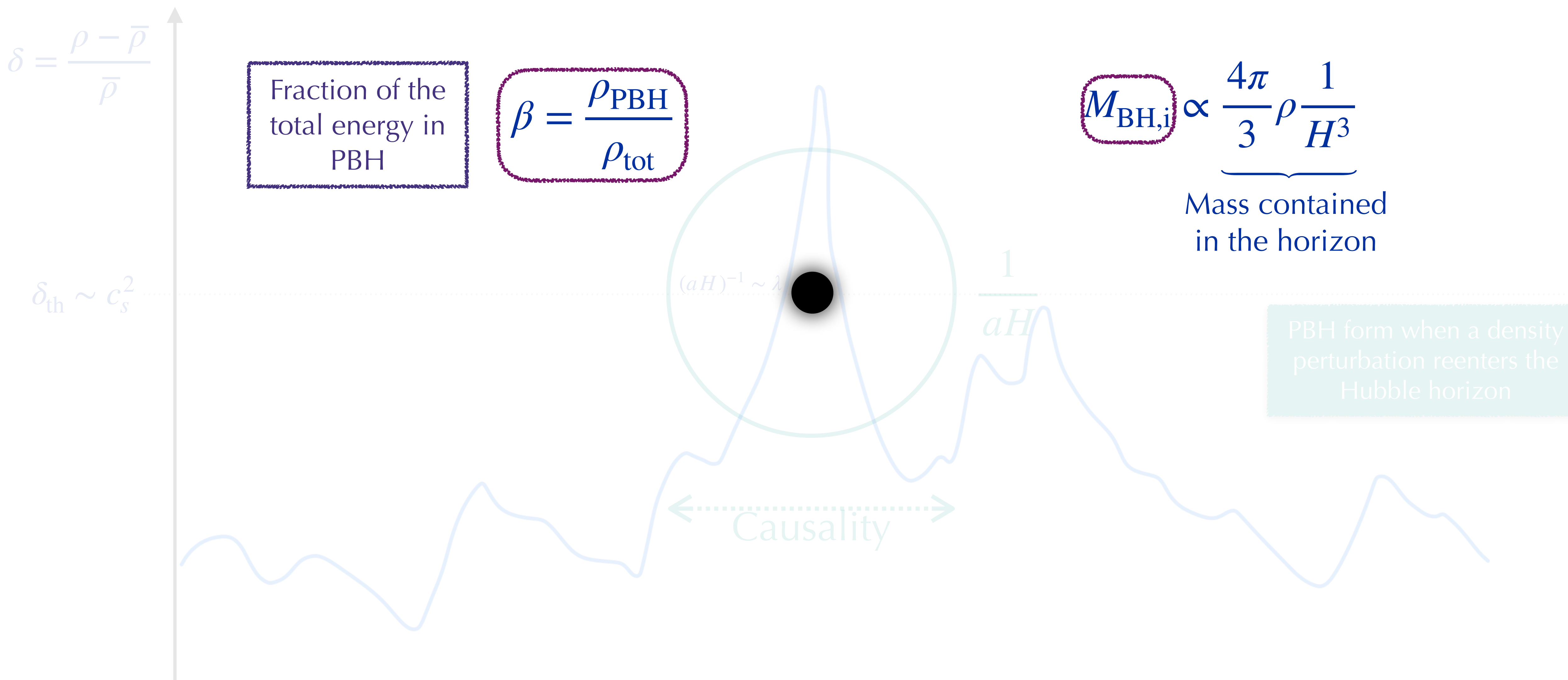


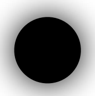
Assume a monochromatic mass distribution

$M_{\mathrm{BH},i}\,,\ \beta$

All PBHs with the same mass

Carr et al. 2002.12778

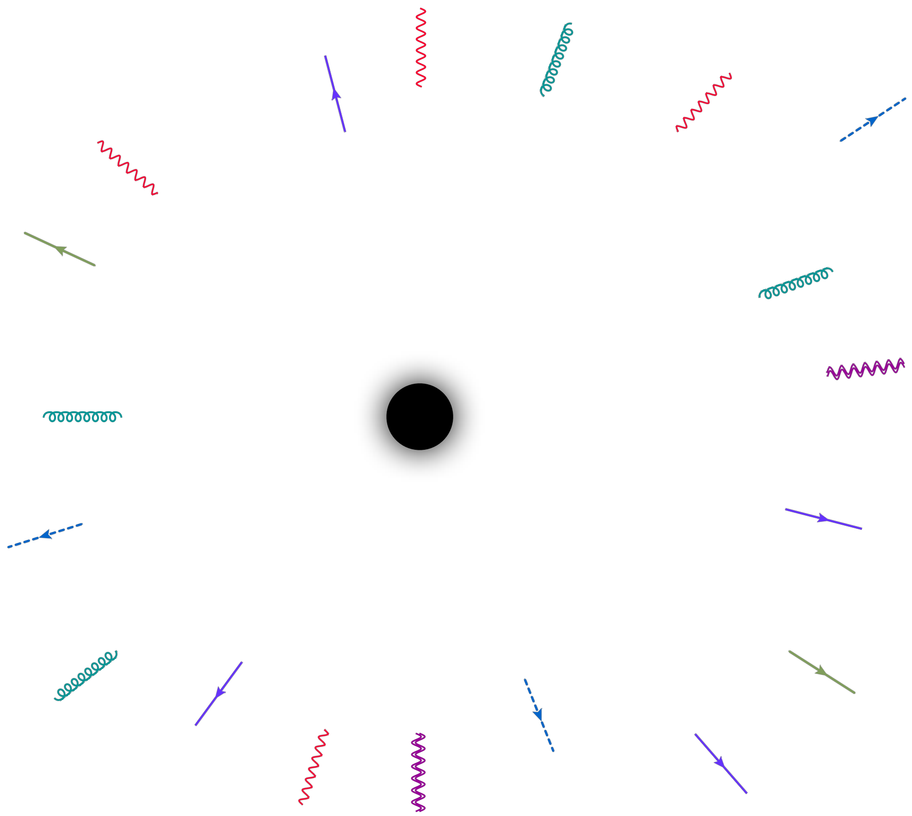
Zeldovich, Novikov '66, Hawking '71



Hawking — Nature, 248 (1974) 30. Commun. Math. Phys., 43, 199

Evaporation — Schwarzschild BHs

Described by $M_{\rm BH}$

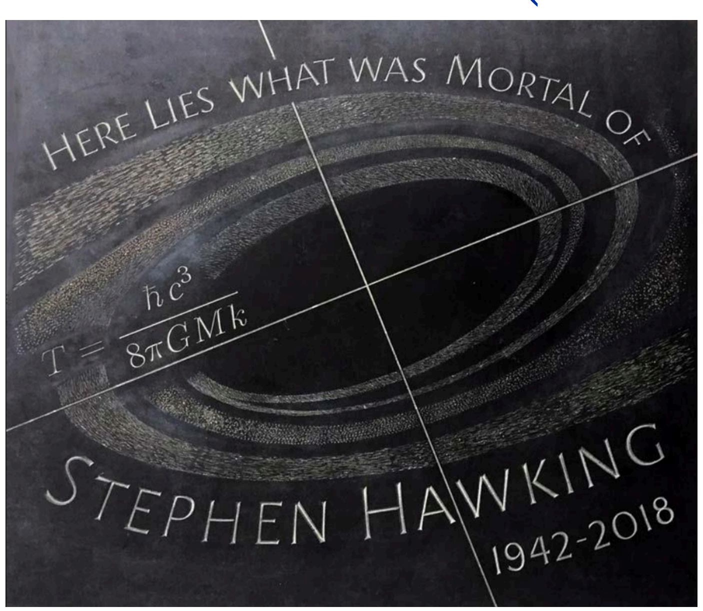


$$\frac{d^2N_i}{d\omega\, dt} = \frac{g_i}{2\pi^2}\frac{{}_{s_i}\Gamma(M,\omega,\mu_i)}{\exp[\omega/T]-(-1)^{2s_i}}$$

Hawking Instantaneous Spectrum

BH Temperature

$$T = \frac{\hbar c^3}{8\pi G M k} \sim 1\ \text{GeV}\left(\frac{10^{13}\ \text{g}}{M}\right)$$



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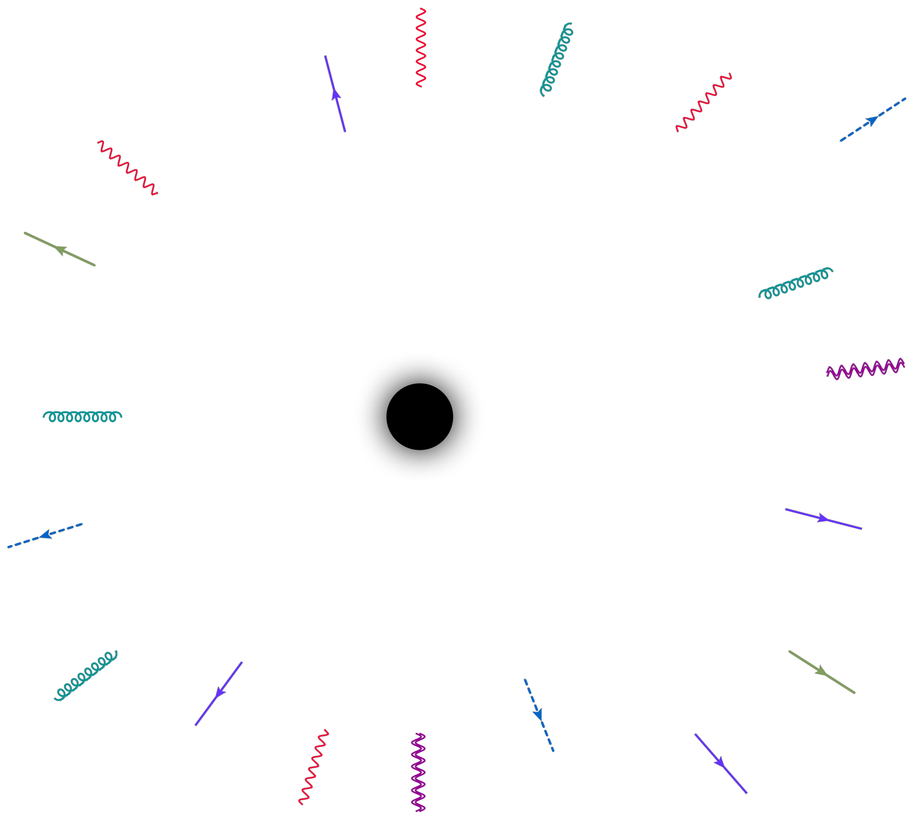

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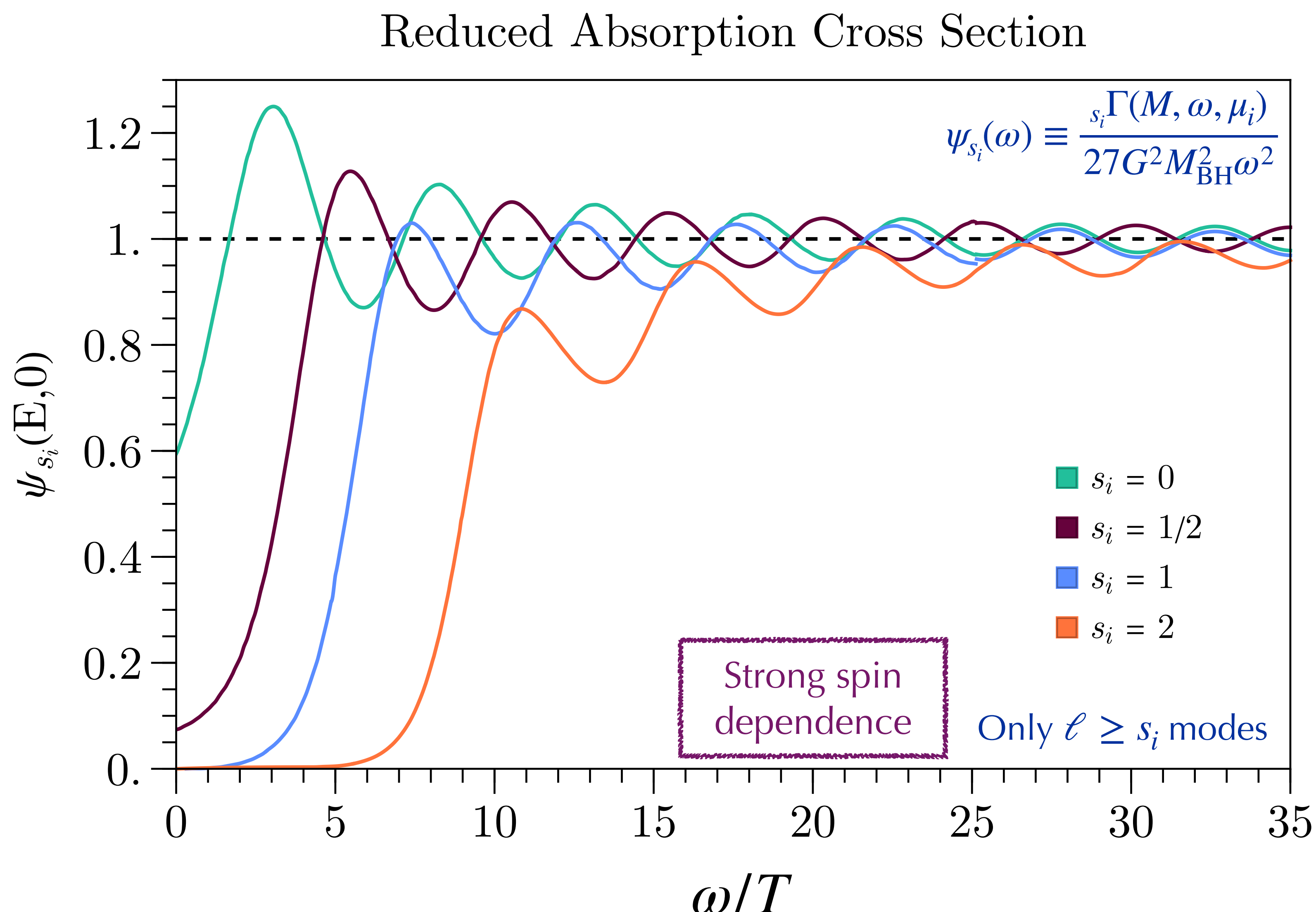
Hawking Instantaneous Spectrum

Absorption probability



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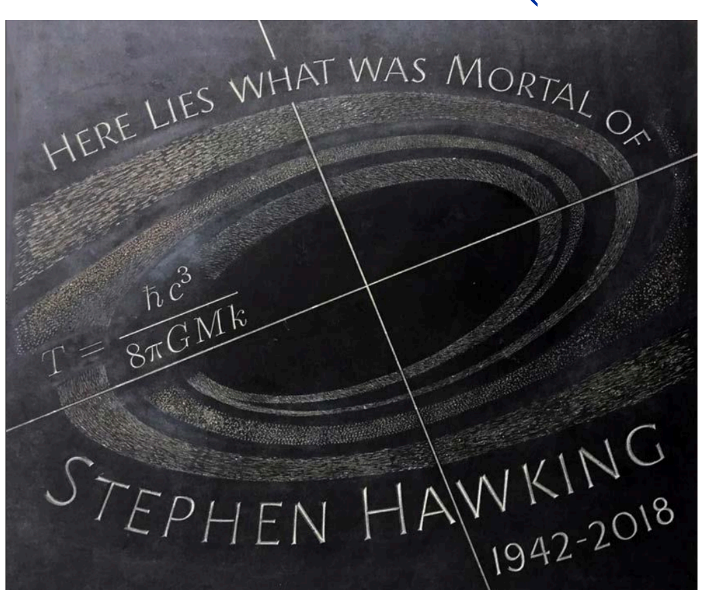
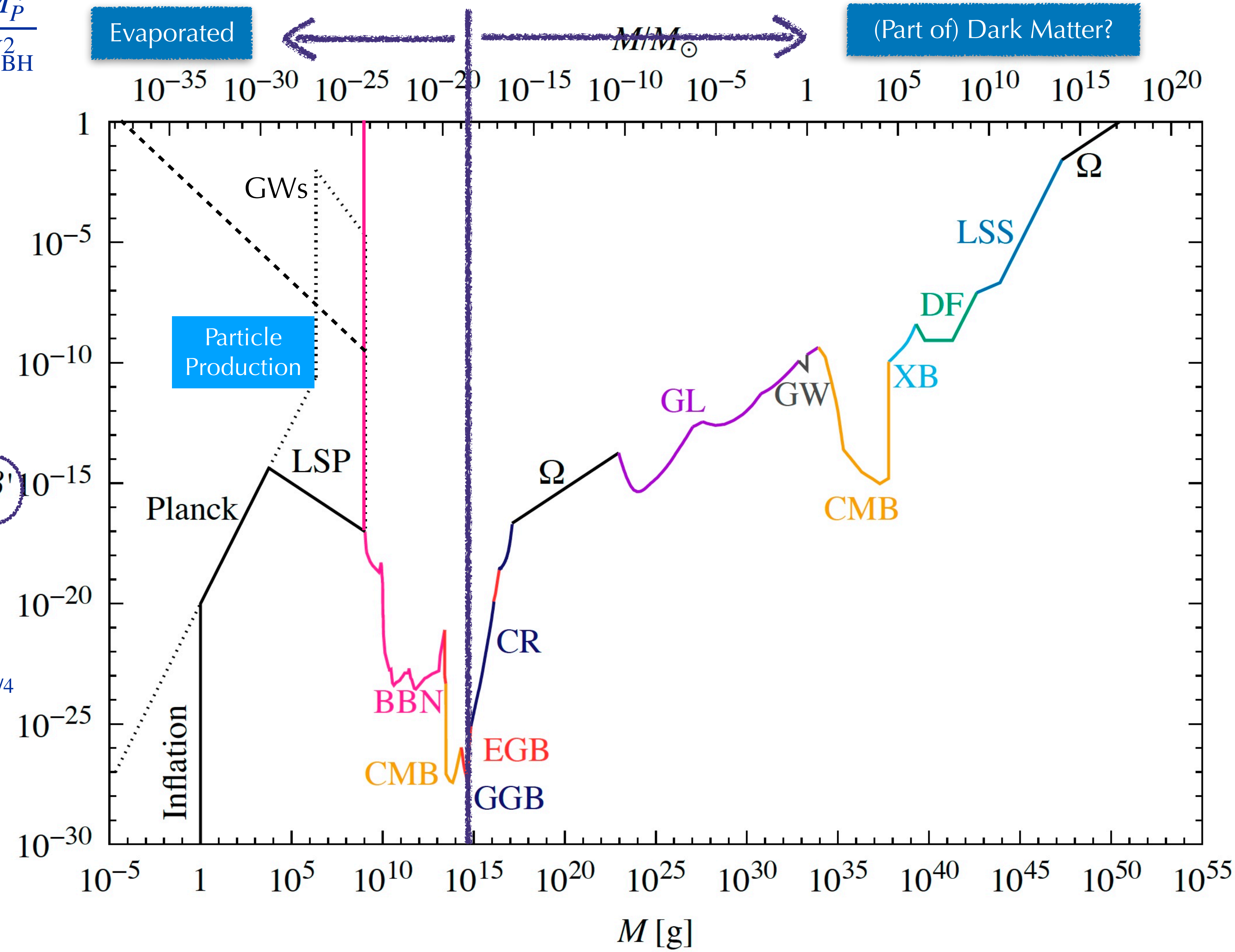


Hawking — Nature, 248 (1974) 30. Commun. Math. Phys., 43, 199

$$\frac{dM_{BH}}{dt} = -\underbrace{\varepsilon(M_{BH})}_{\text{Evaporation function}} \frac{M_P^4}{M_{BH}^2}$$



Reduced β

$$\beta' = \beta\gamma^{1/2}\left(\frac{g_{*f}}{106.75}\right)^{1/4}$$

Gravitational collapse factor

$M_{in}(\tau = \text{age of the Universe}) \approx 5 \times 10^{14}$ g

Carr, Kohri, Sendouda, Yokoyama, 2002.12778

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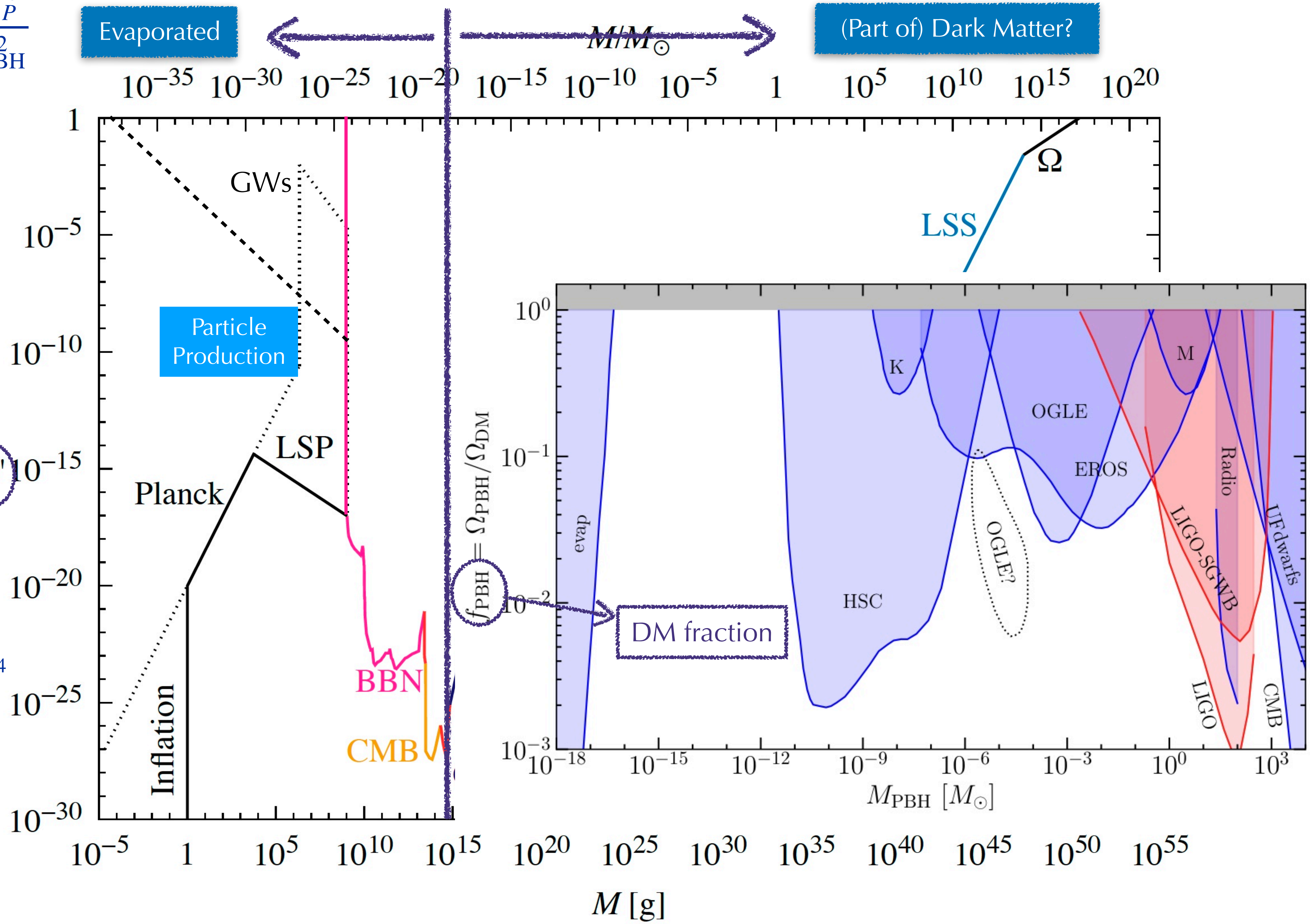

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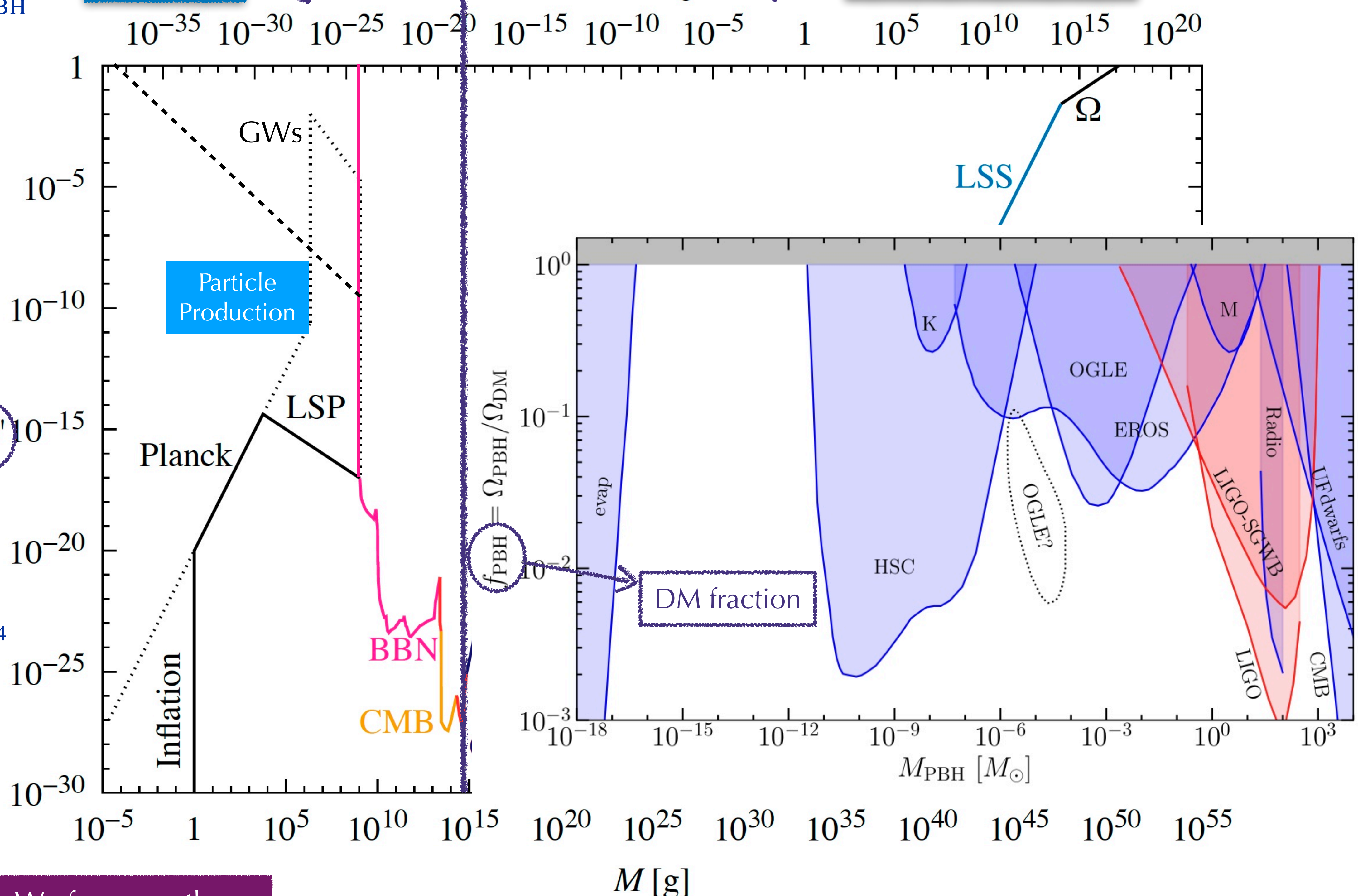
Carr, Kohri, Sendouda, Yokoyama, 2002.12778

B. Kavanagh
10.5281/zenodo.3538999

$$\frac{dM_{\rm BH}}{dt} = -\underbrace{\varepsilon(M_{\rm BH})}_{\text{Evaporation function}} \frac{M_P^4}{M_{\rm BH}^2}$$

Evaporated ⟵ $M/M_\odot$ ⟶ (Part of) Dark Matter?



β' → Reduced β

$f_{\rm PBH}$ → DM fraction

$$\beta' = \beta\,\gamma^{1/2}\left(\frac{g_{*f}}{106.75}\right)^{1/4}$$

γ: Gravitational collapse factor

We focus on the region $M_{\rm BH,i} \leq 10^9$ g

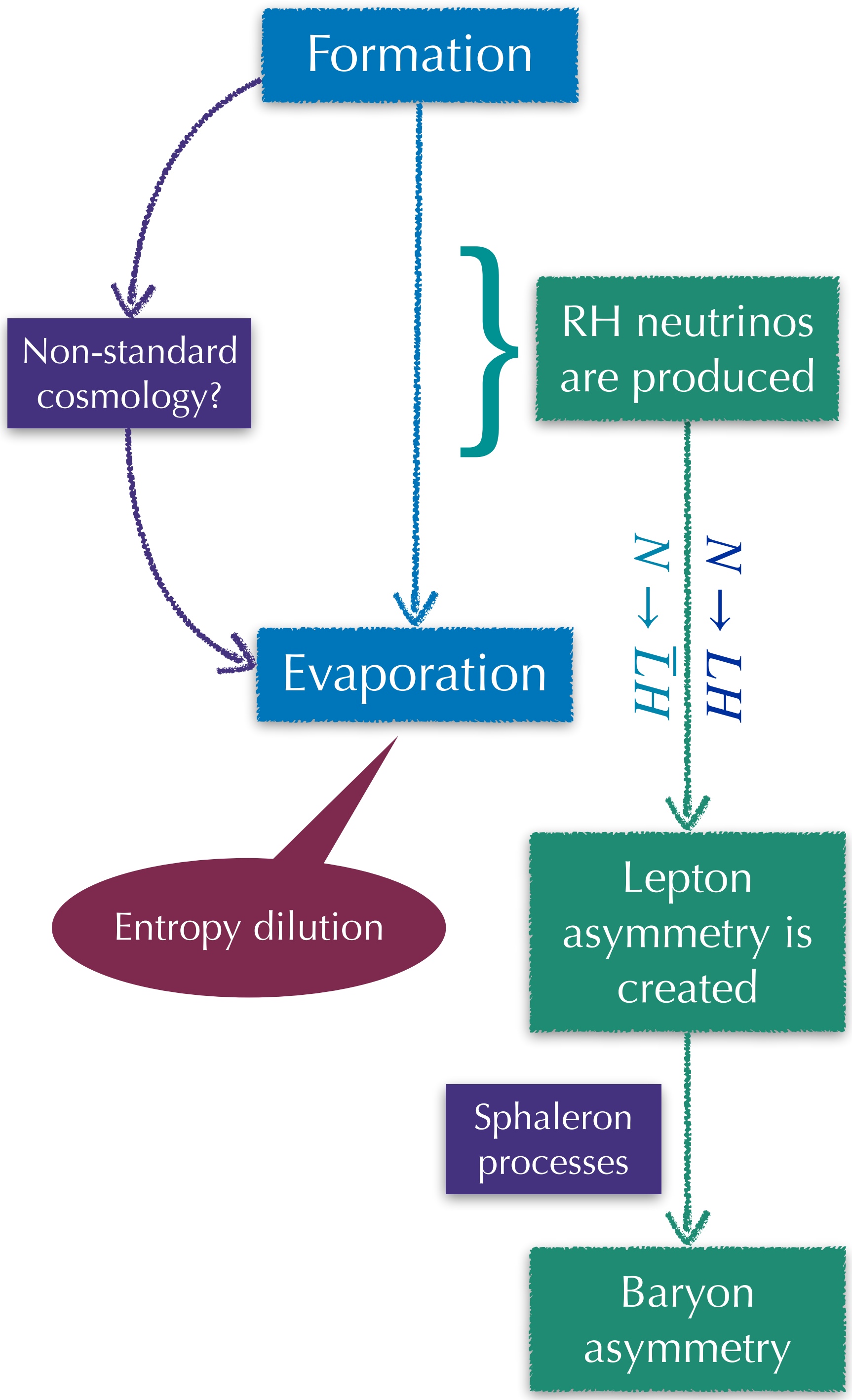
$M_{\rm in}(\tau = \text{age of the Universe}) \approx 5\times 10^{14}$ g

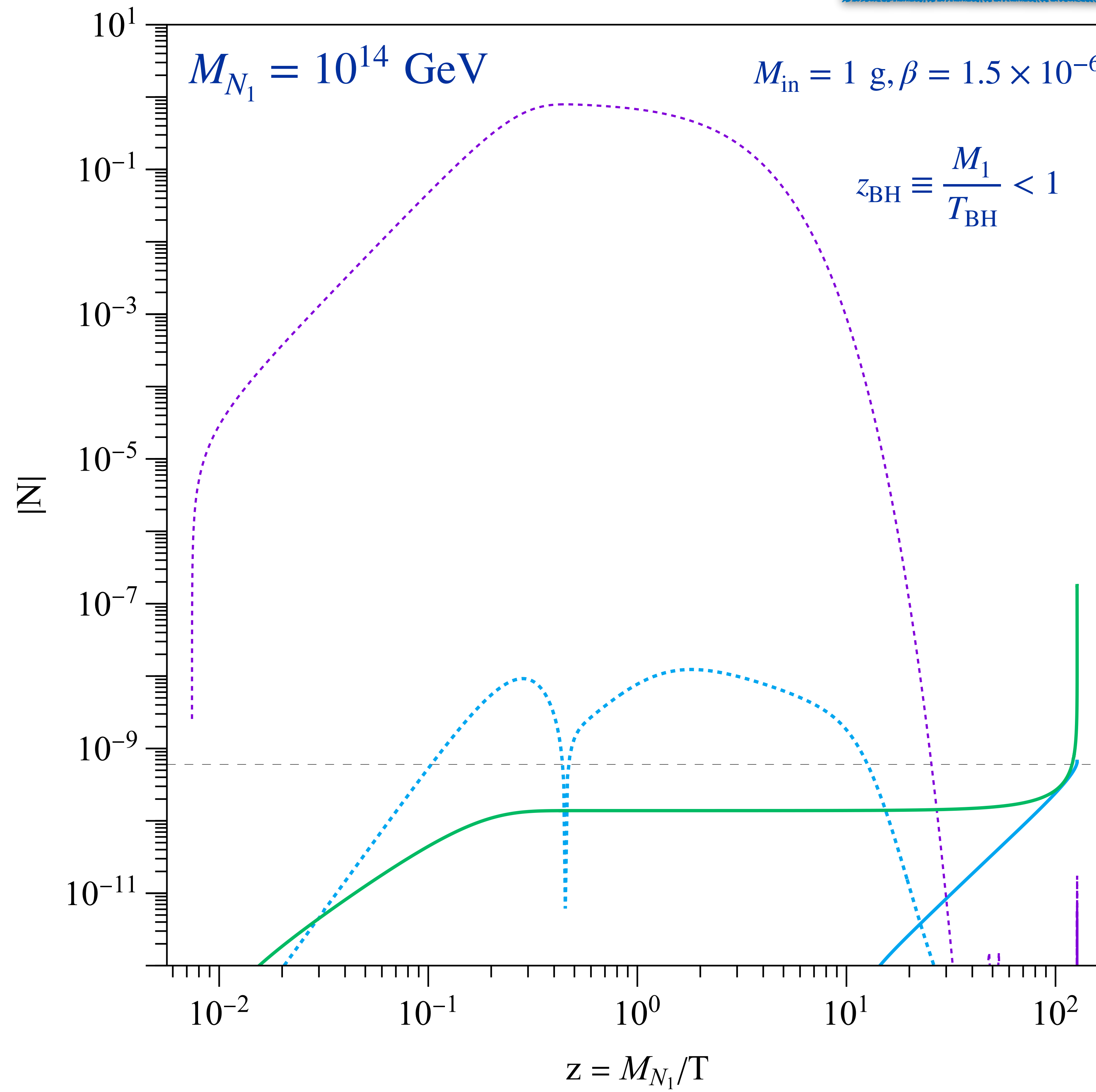
B. Kavanagh 10.5281/zenodo.3538999

Carr, Kohri, Sendouda, Yokoyama, 2002.12778

PBH + Leptogenesis

How to save HSL? → Produce RHNs after washout process have frozen out?





See also: Baumann (2003), Fujita et al (2014), Profumo et al (2017), Baldes etal (2020), Datta et al (2021), Barman et al (2022)…

YFPG, Turner 2010.03565
Bernal, Fong, YFPG, Turner 2203.08823

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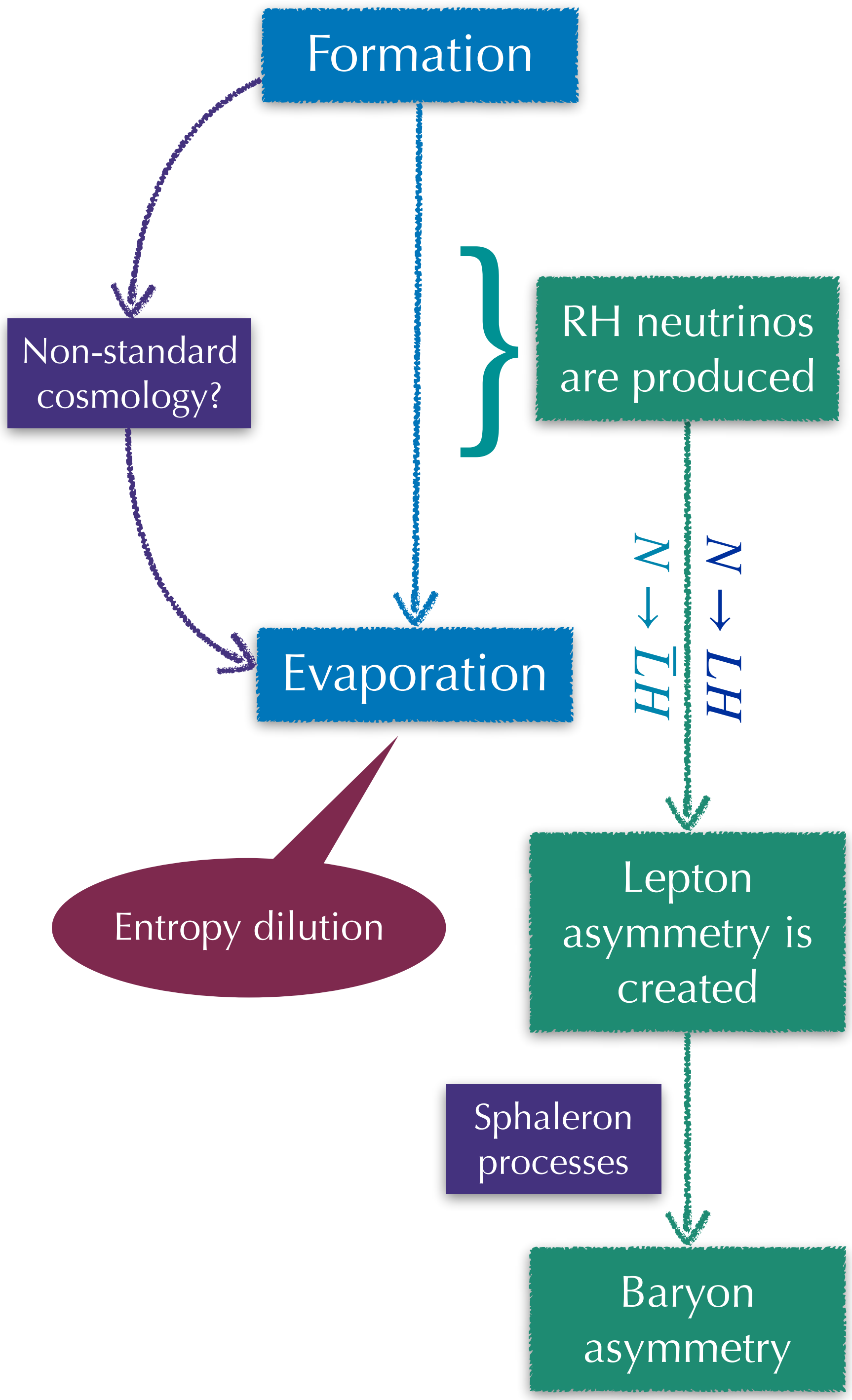

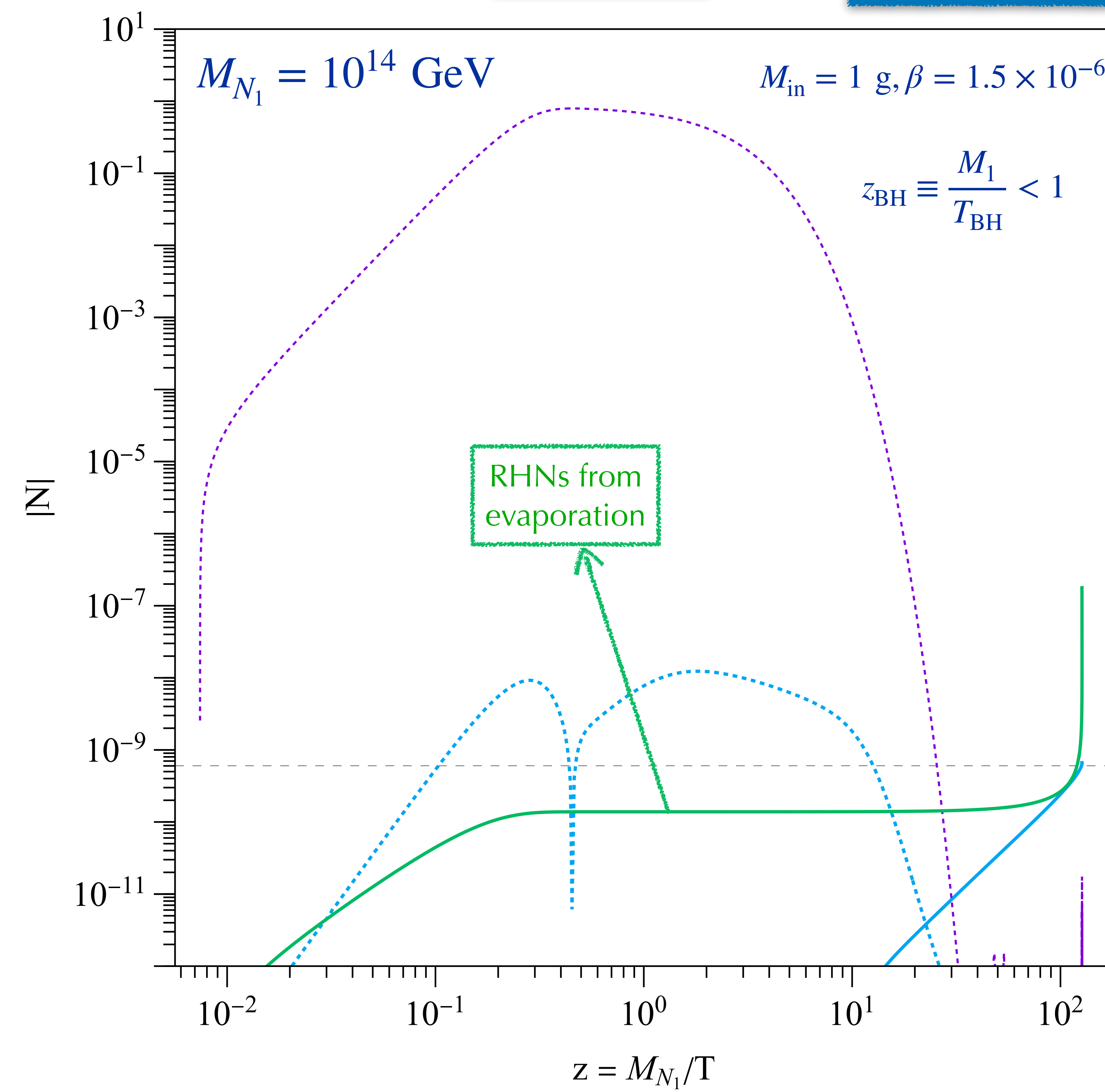

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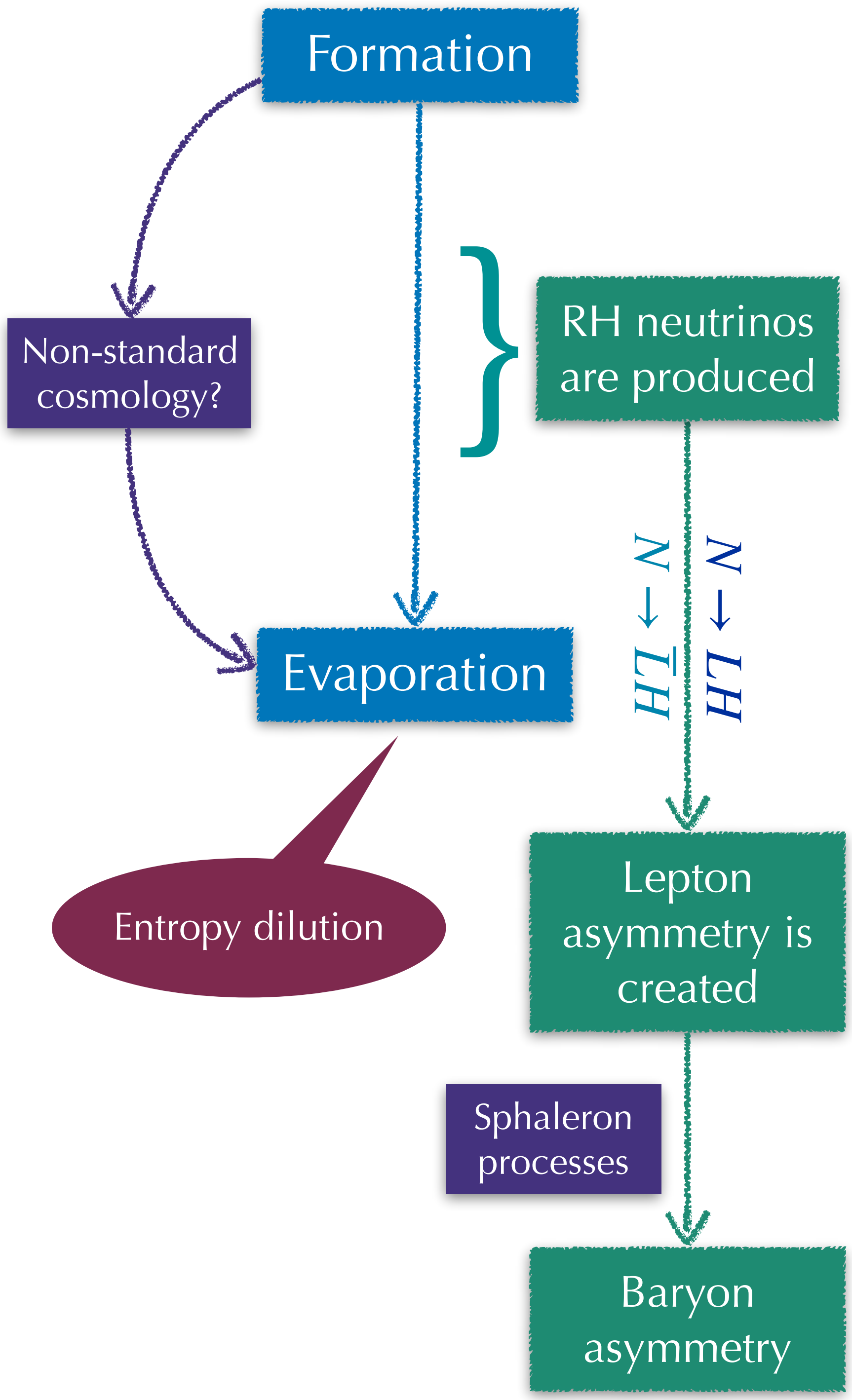

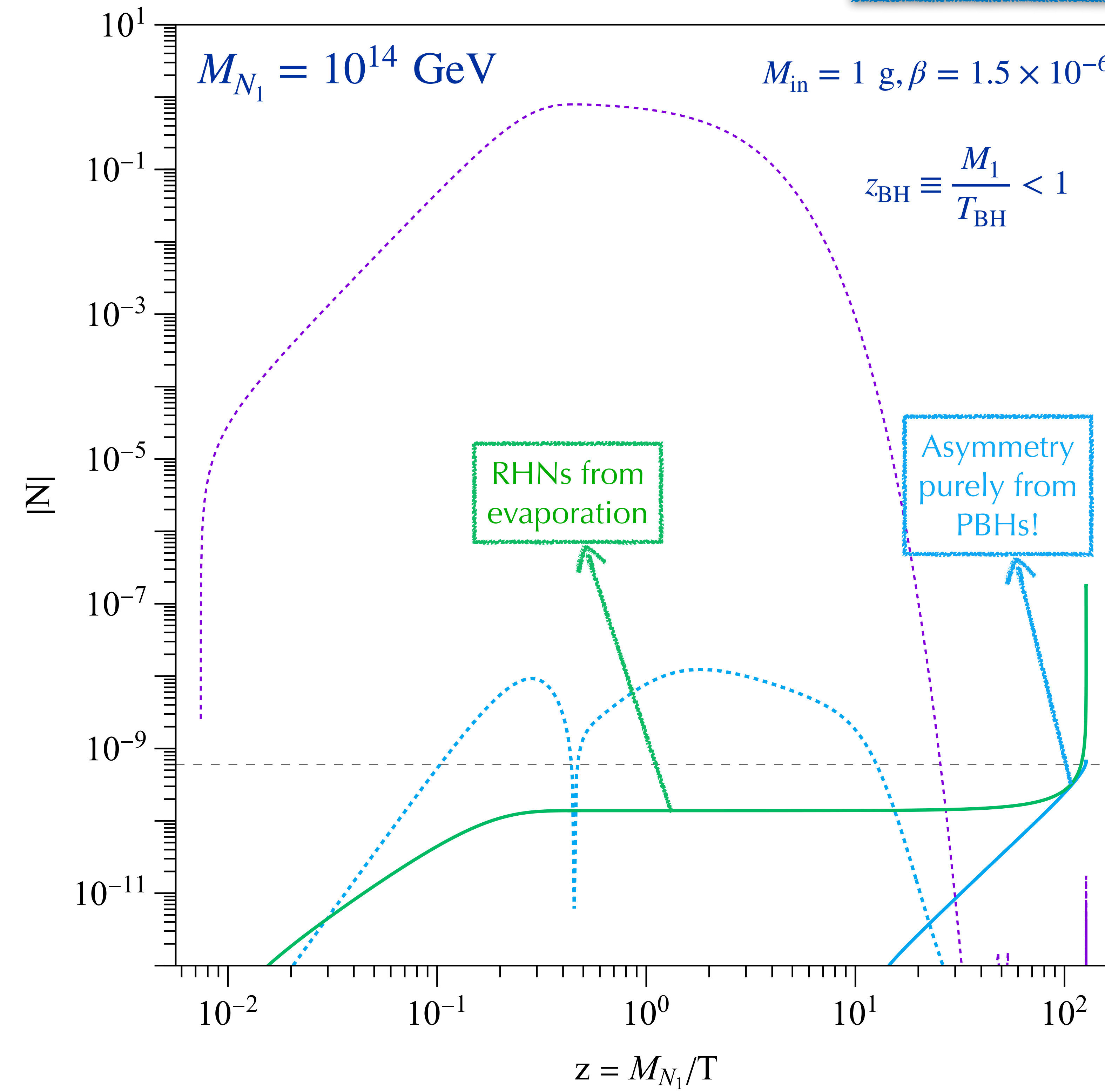

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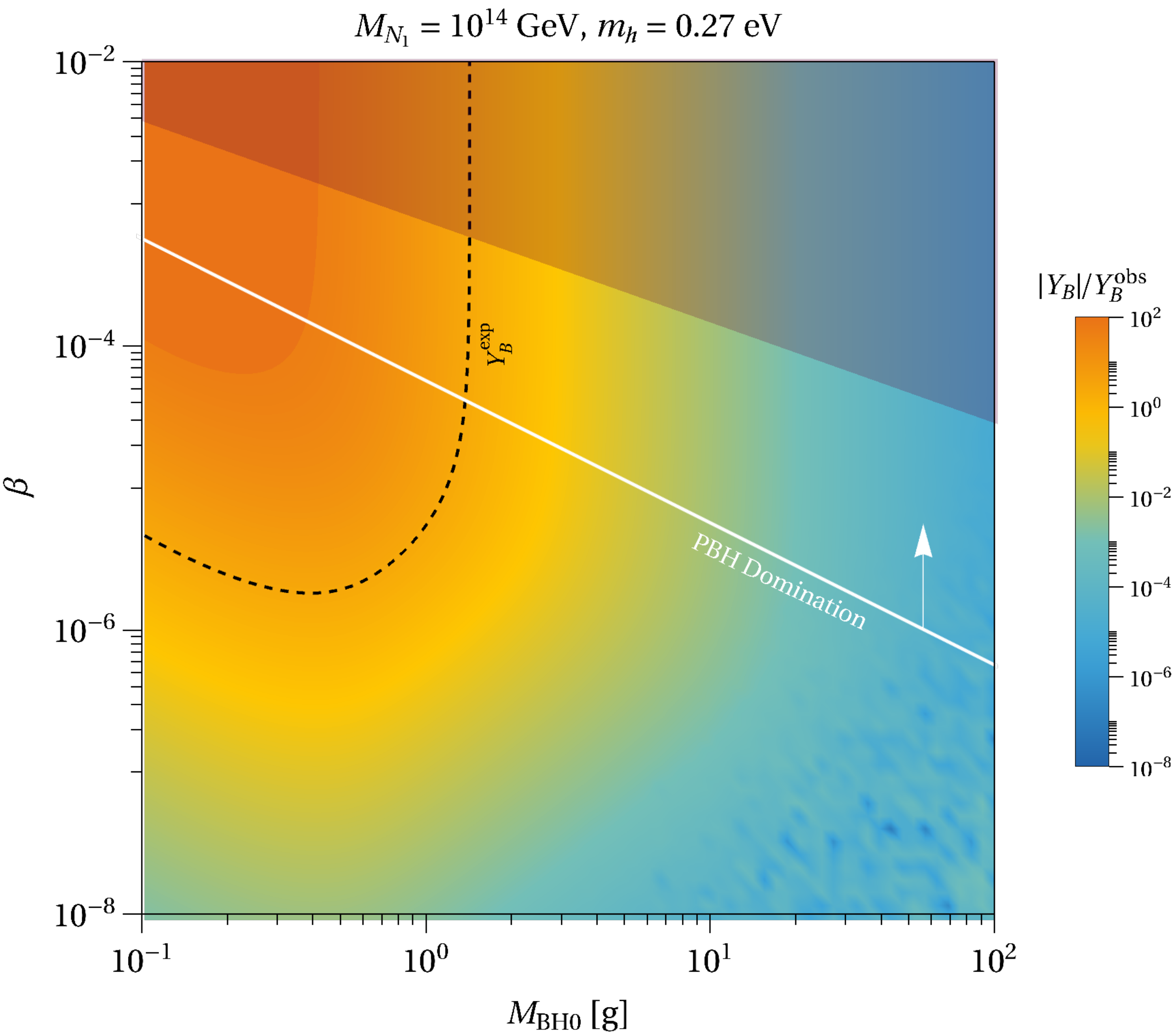
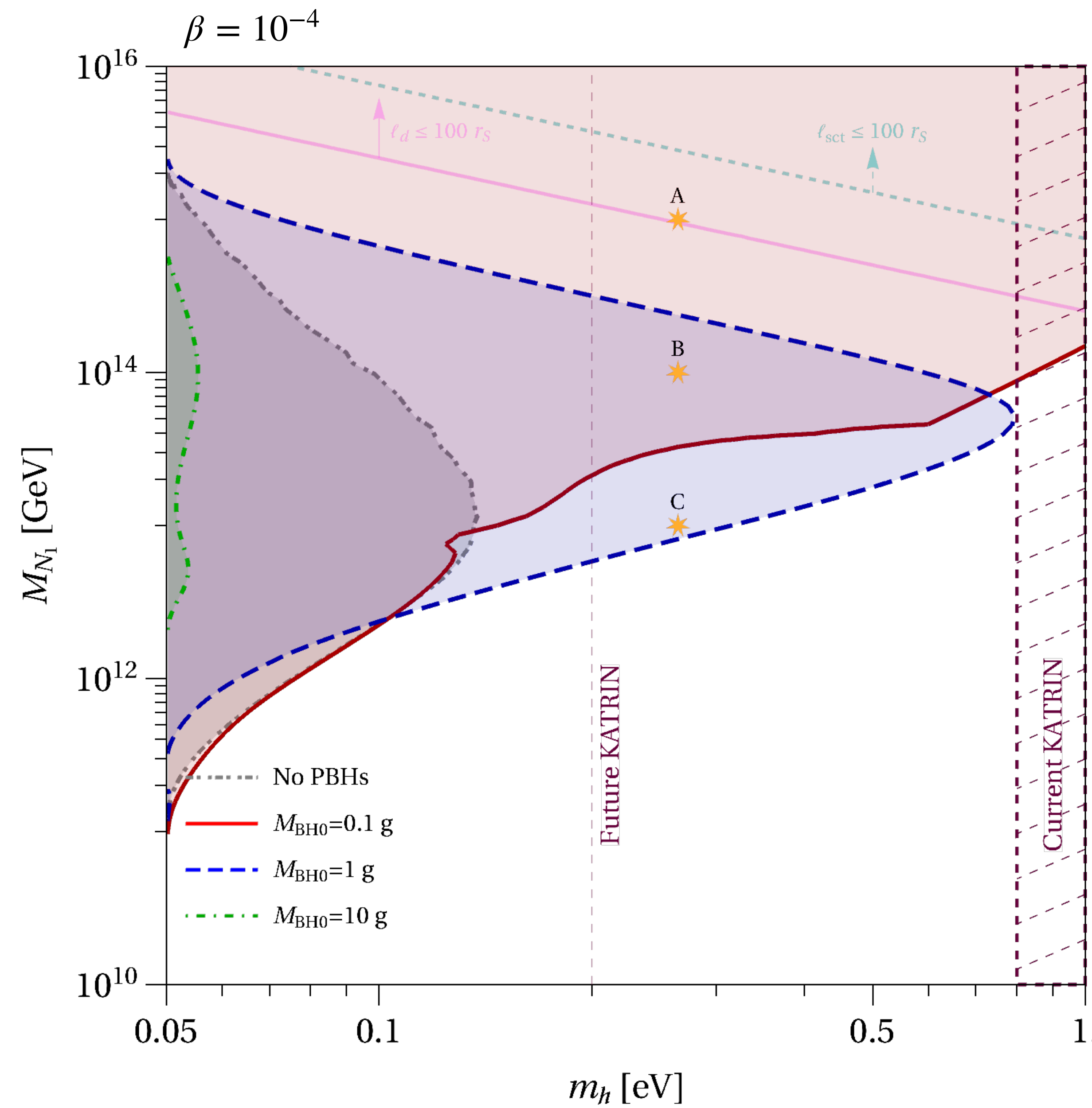
YFPG, Turner 2010.03565
Bernal, Fong, YFPG, Turner 2203.08823

Rescuing HSL

Colored Regions with $|Y_B| \gtrsim Y_B^{obs}$





m_h = Heaviest neutrino mass

PBHs allow for viable HS leptogenesis for heavier active neutrinos

Maximizing over Yukawa parameters

*Up to perturbativity

Bernal, Fong, YFPG, Turner 2203.08823

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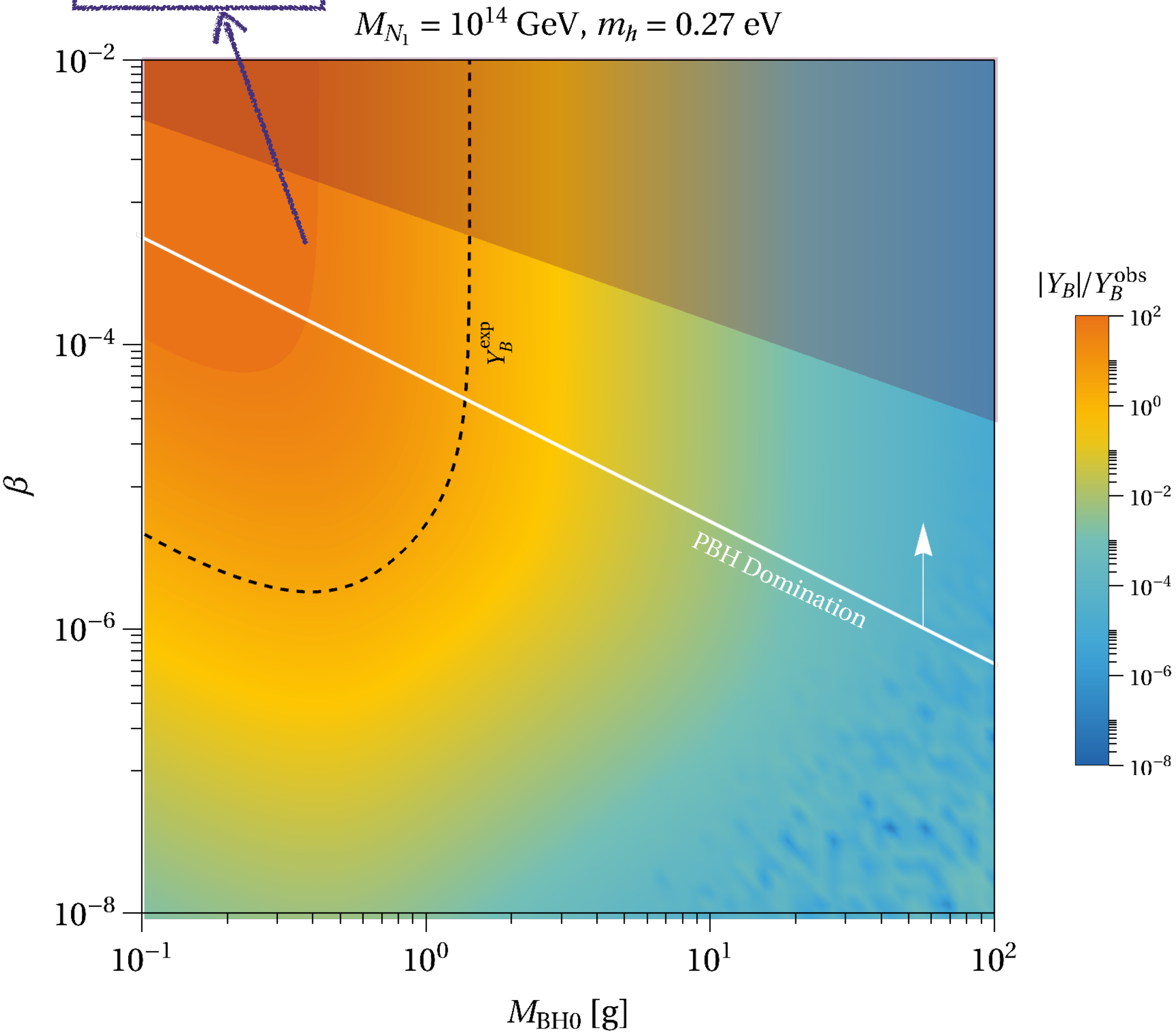
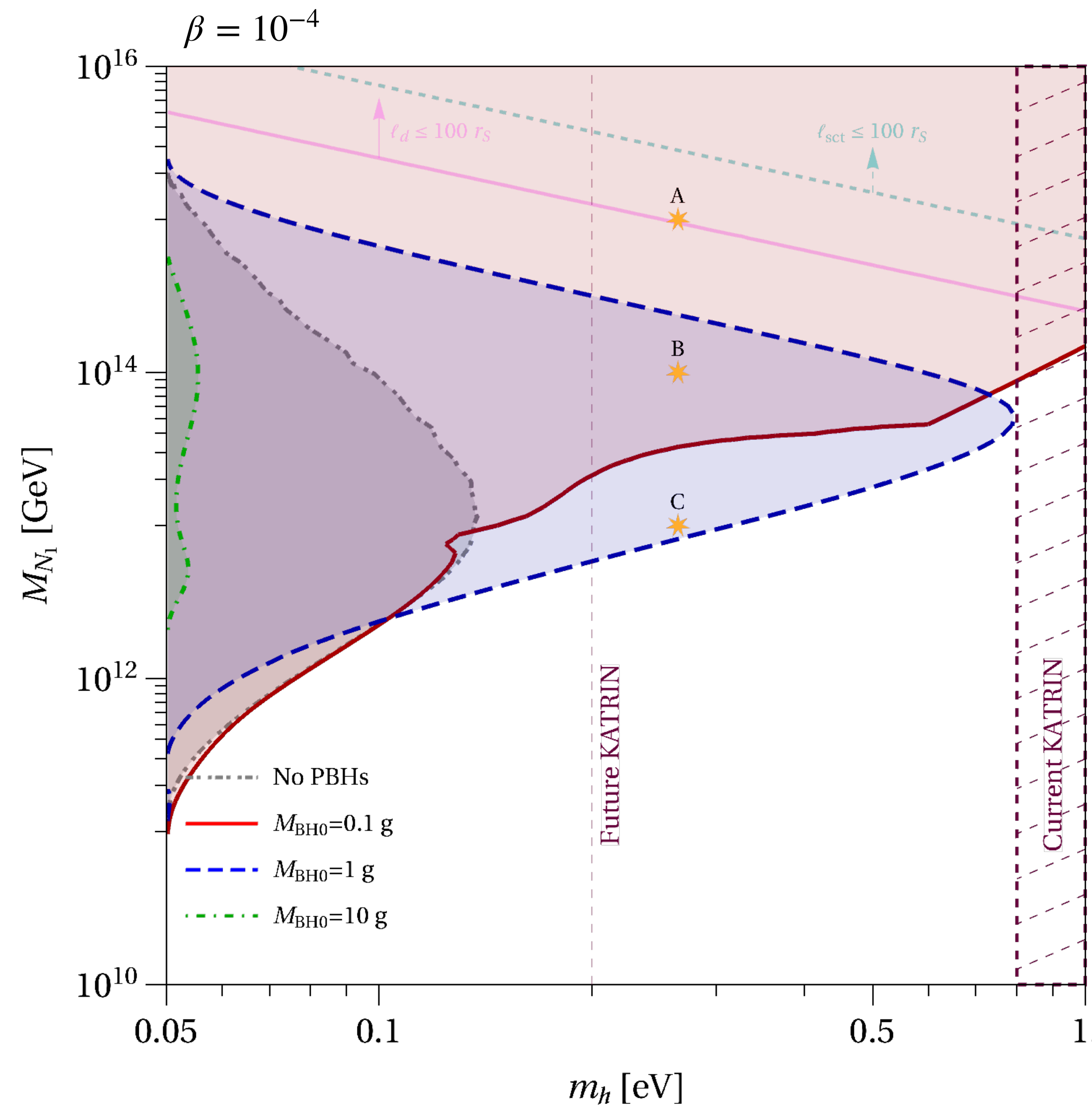
$\mathcal{O}(10^6)$ enhancement





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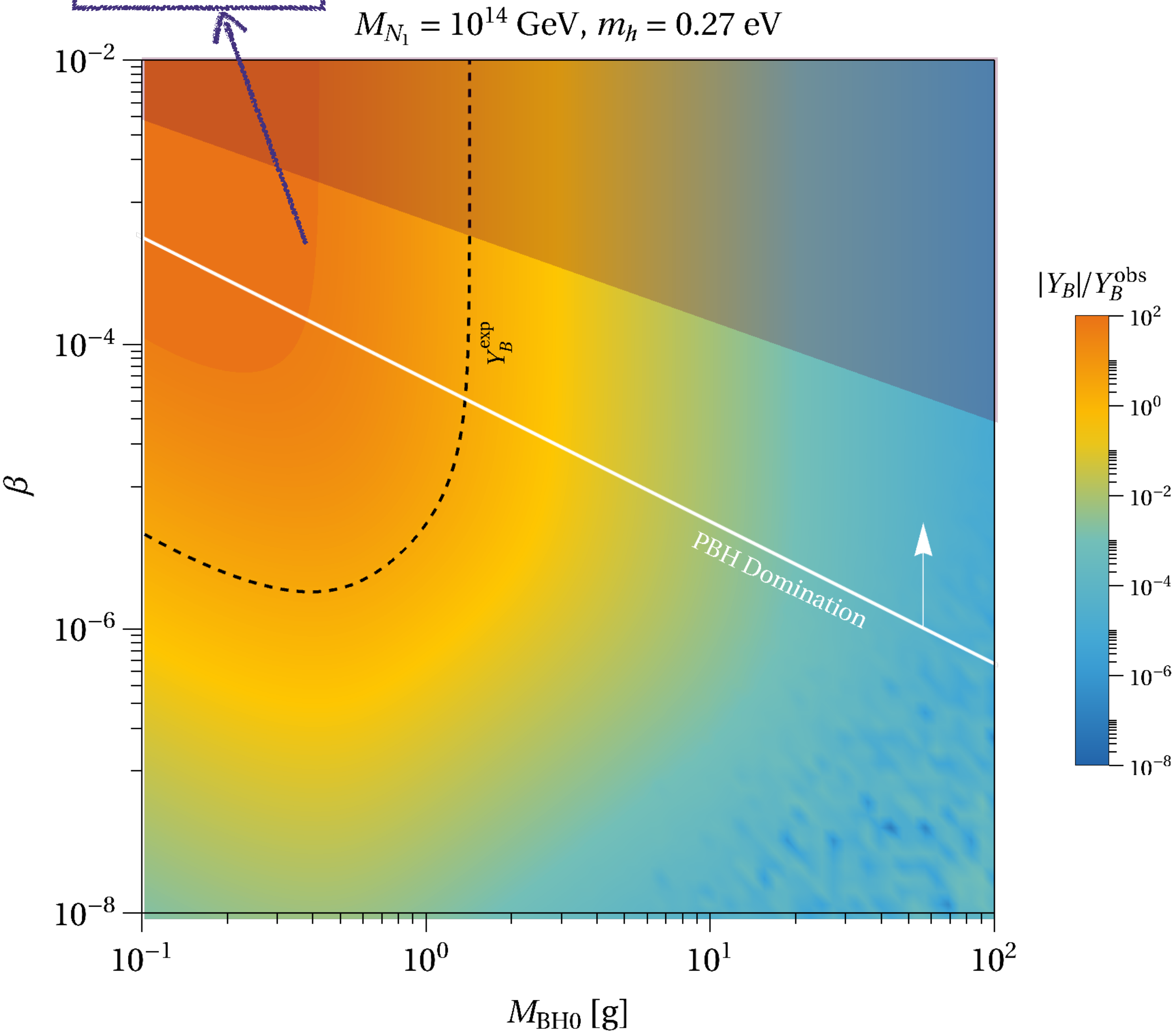

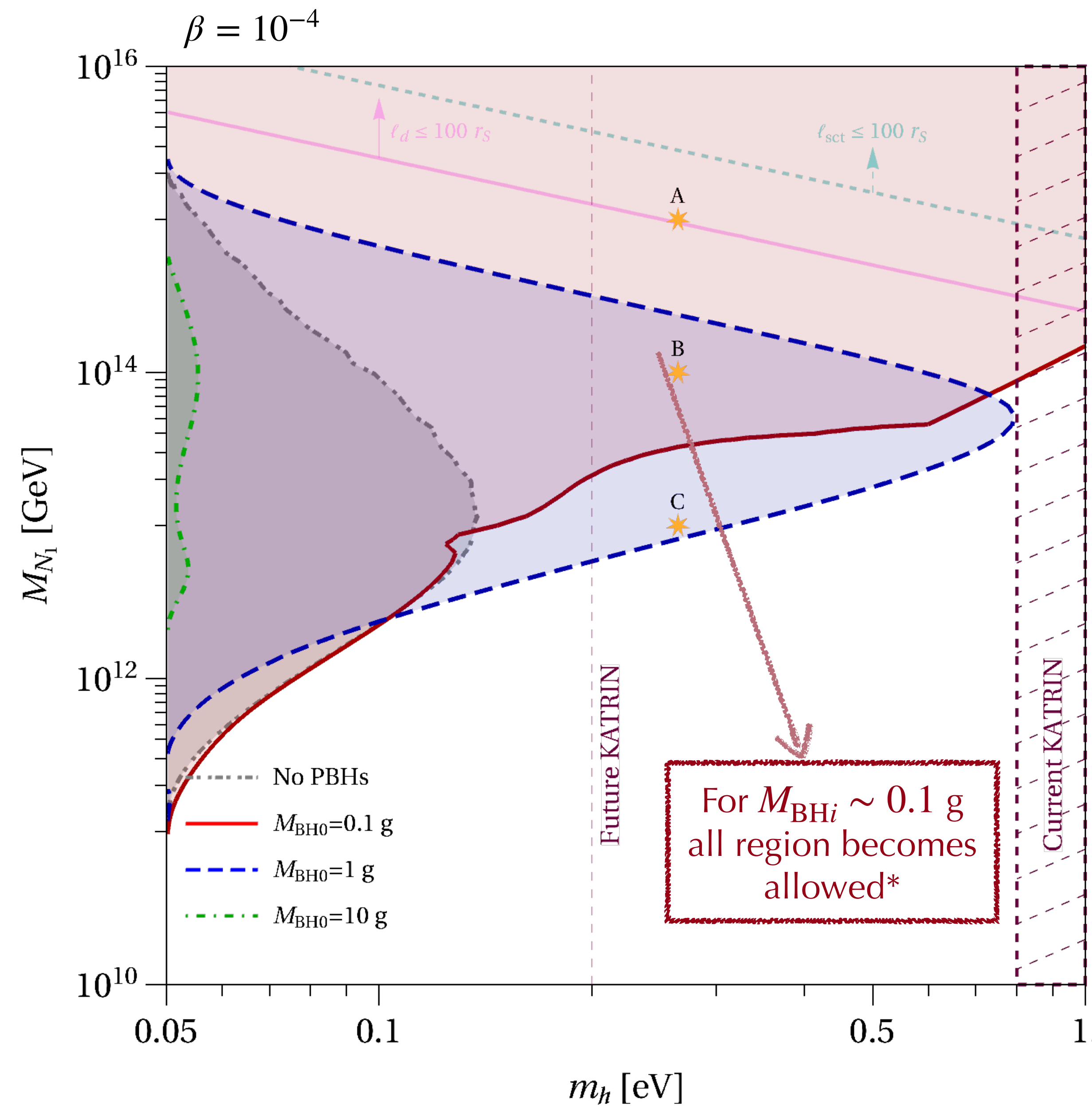

For $M_{BHi} \sim 0.1$ g all region becomes allowed*

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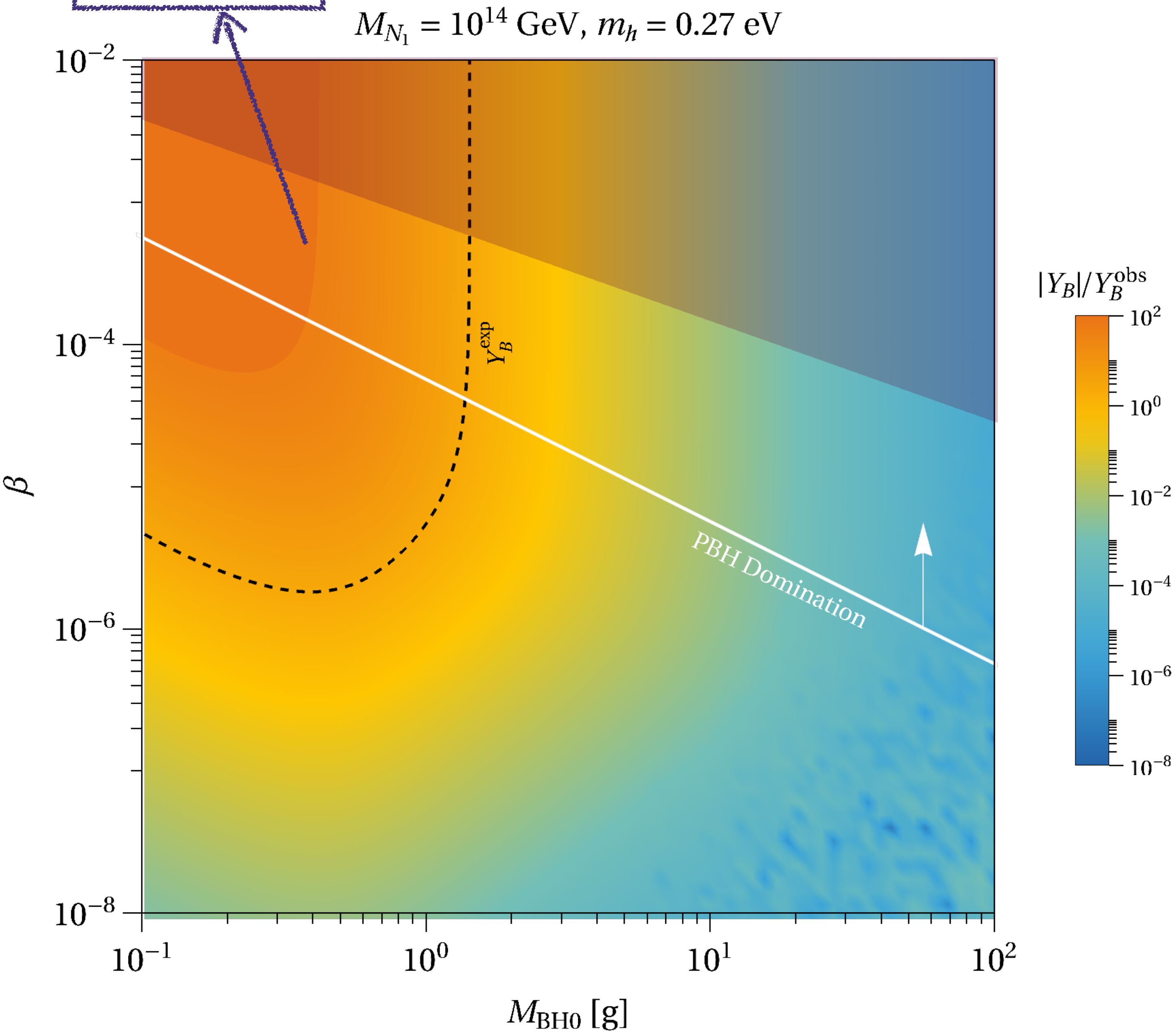
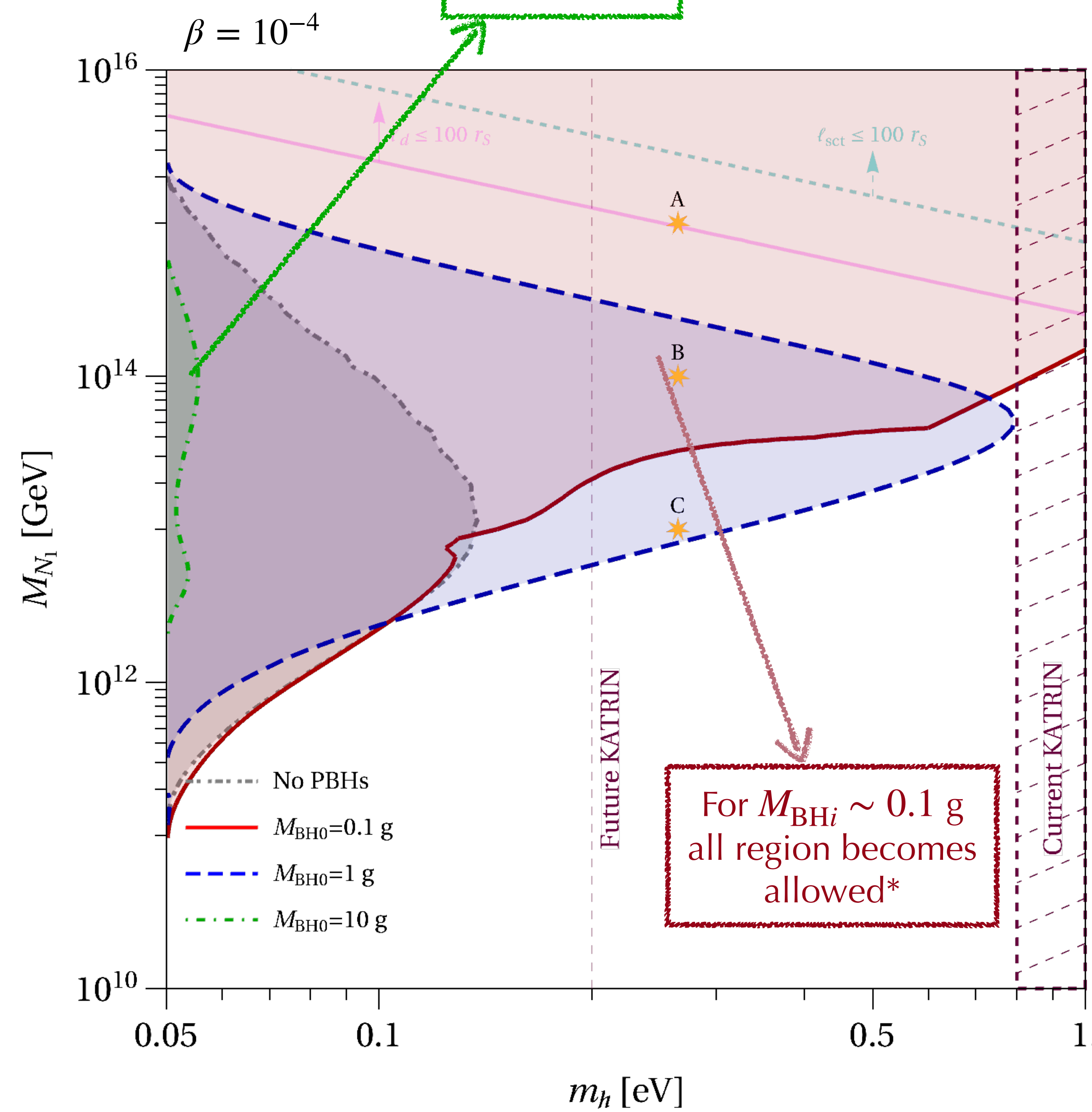


Colored Regions with $|Y_B| \gtrsim Y_B^{\rm obs}$

$M_{{\rm BH}i} \gtrsim 1$ g Entropy dilution



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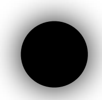
Bernal, Fong, YFPG, Turner 2203.08823

PBH Hot Spots

Gunn, Heurtier, YFPG, Turner. 2409.02173



He, Kohri, Mukaida, Yamada
2210.06238, 2407.15926

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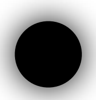
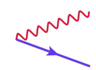
Gunn, Heurtier, YFPG, Turner. 2409.02173



Thermalization
via LPM



He, Kohri, Mukaida, Yamada
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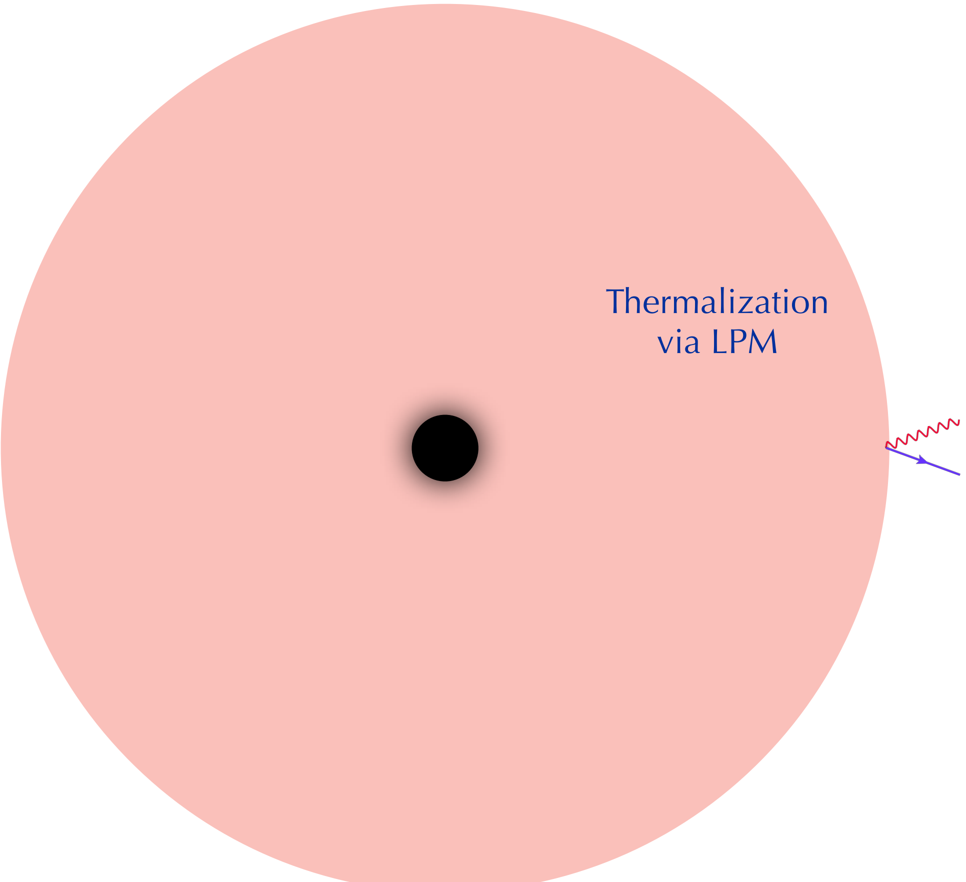

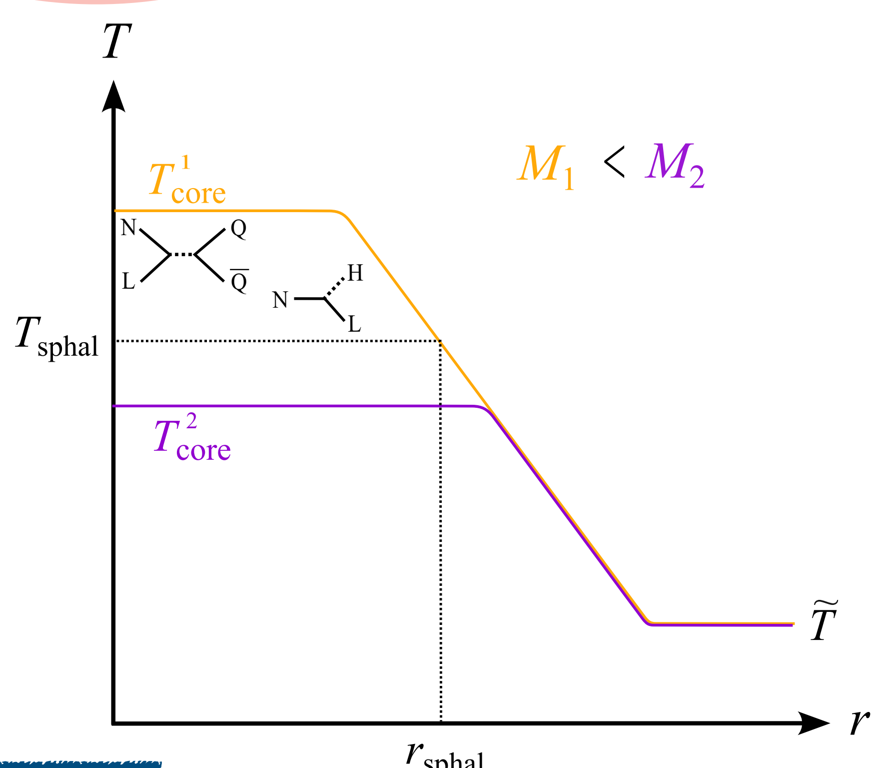

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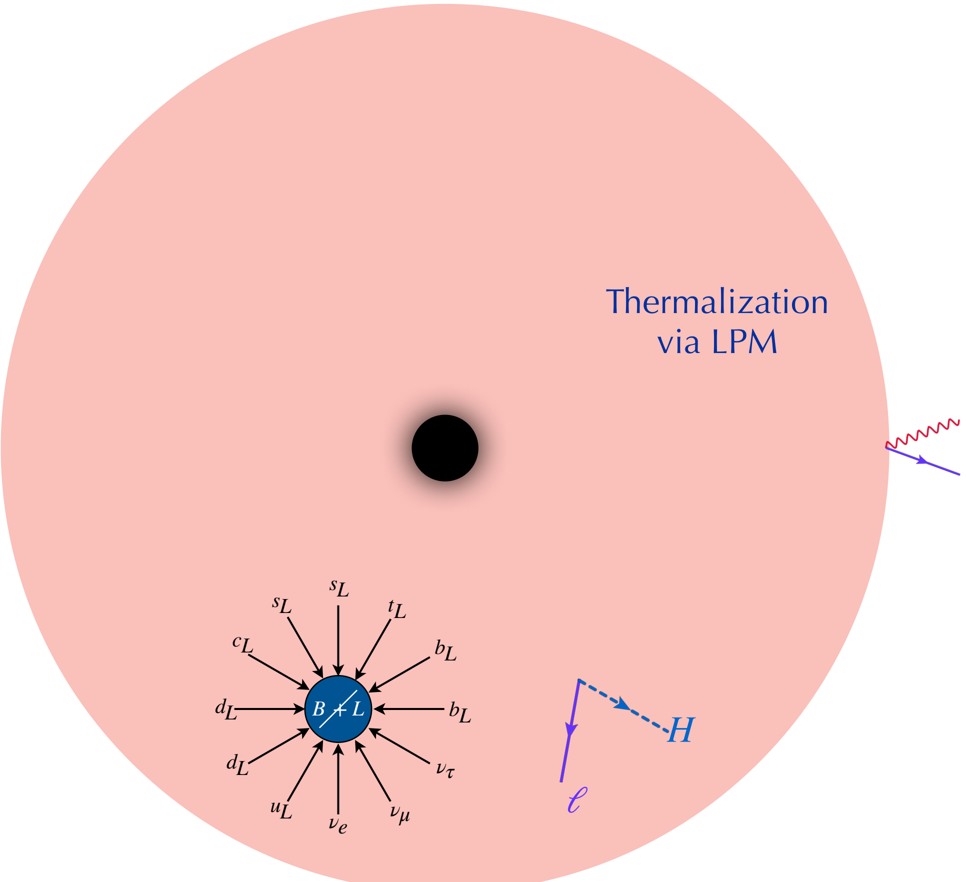
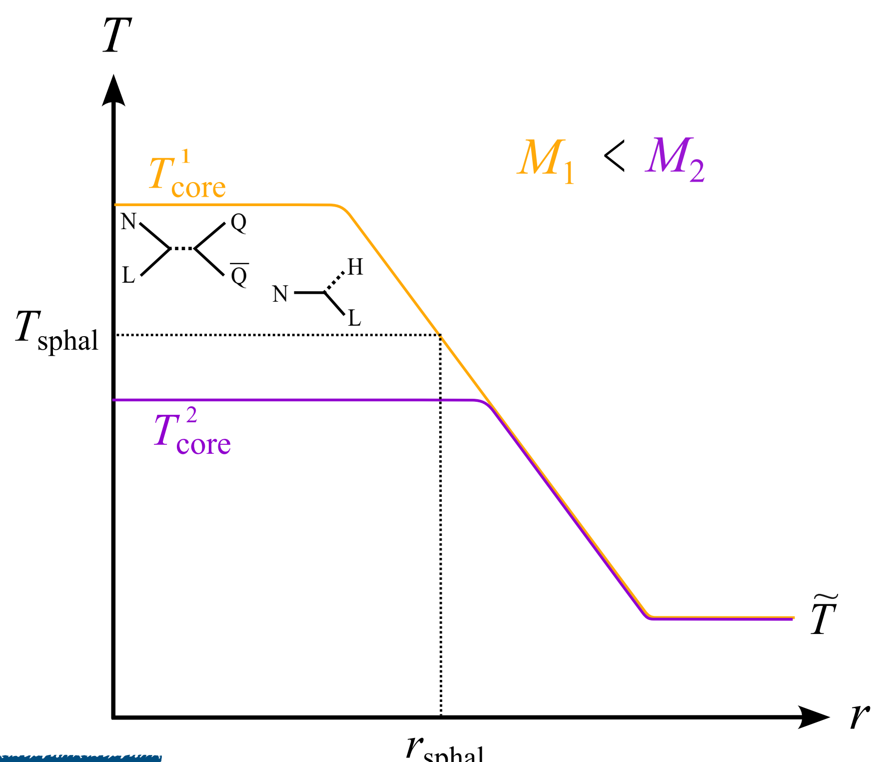
PBH Hot Spots

Gunn, Heurtier, YFPG, Turner. 2409.02173

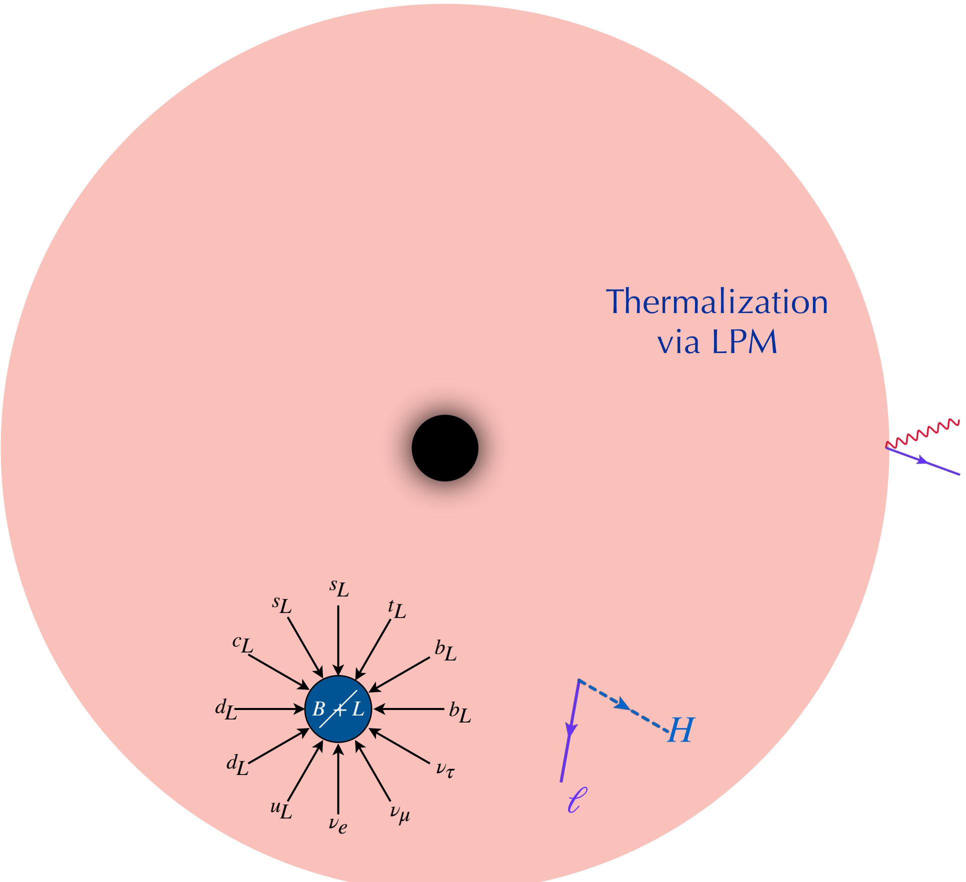


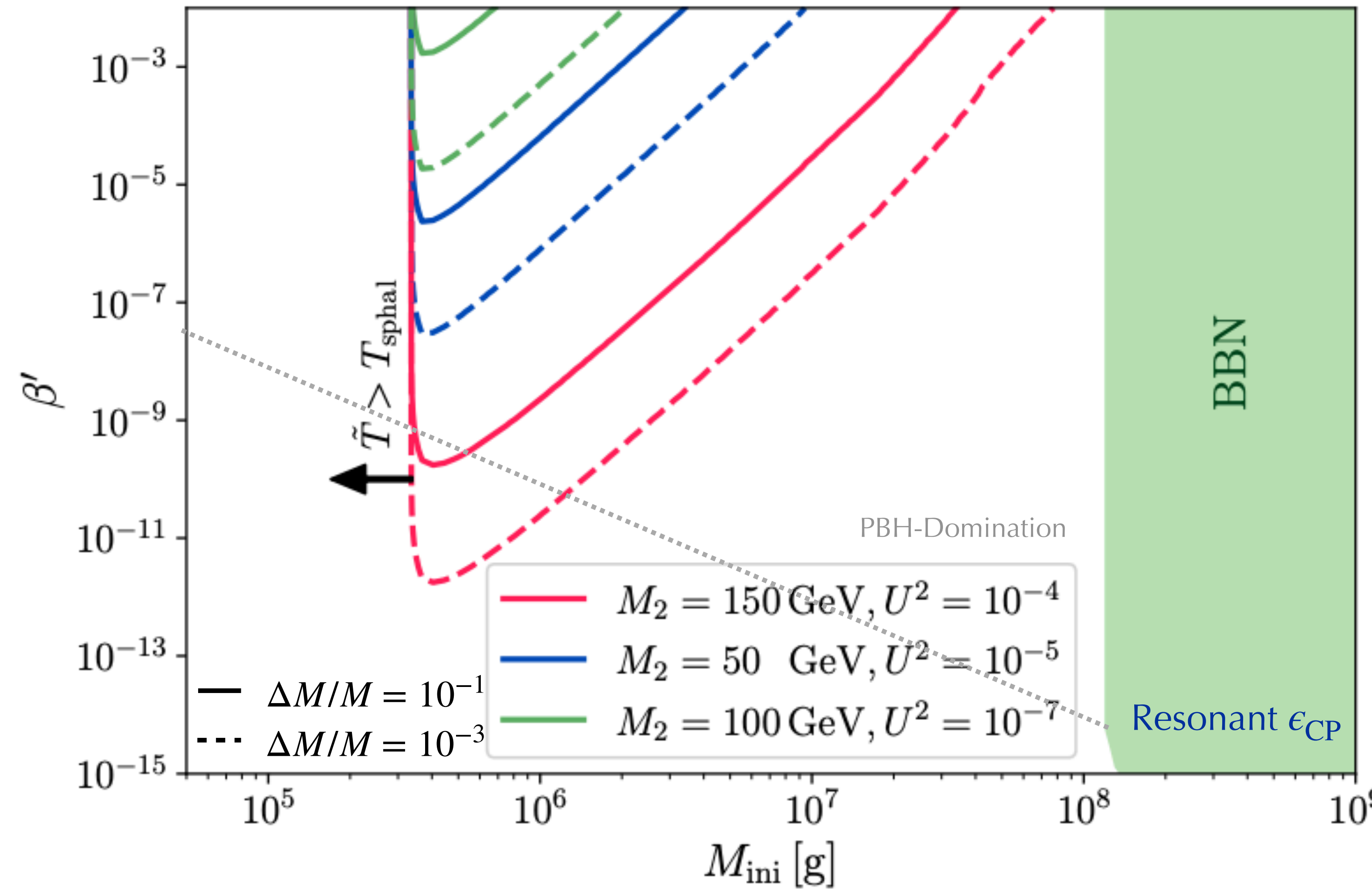


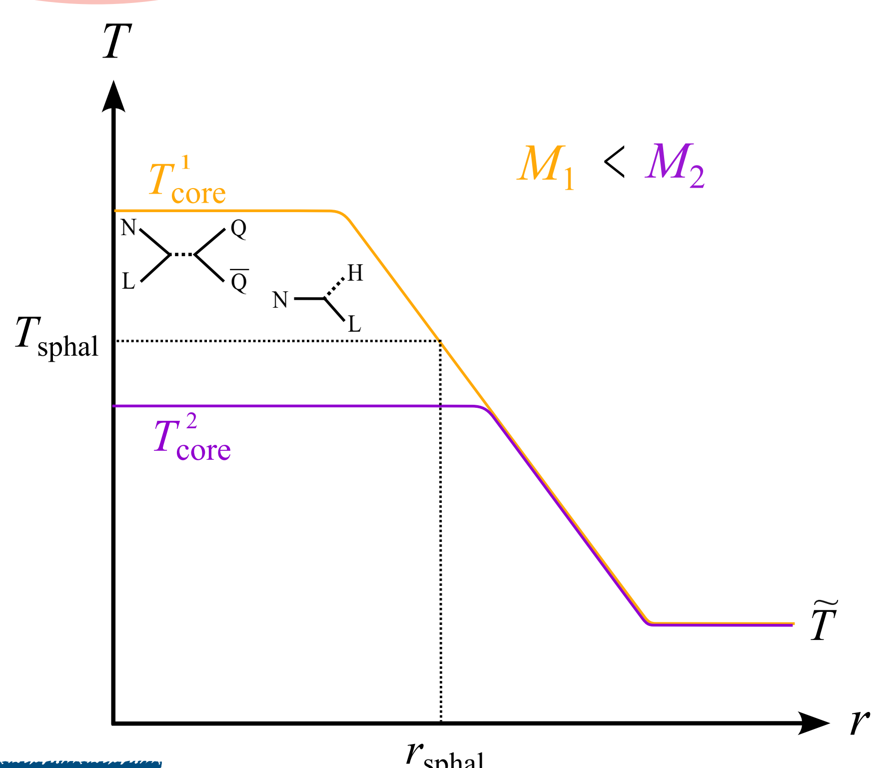
He, Kohri, Mukaida, Yamada
2210.06238, 2407.15926

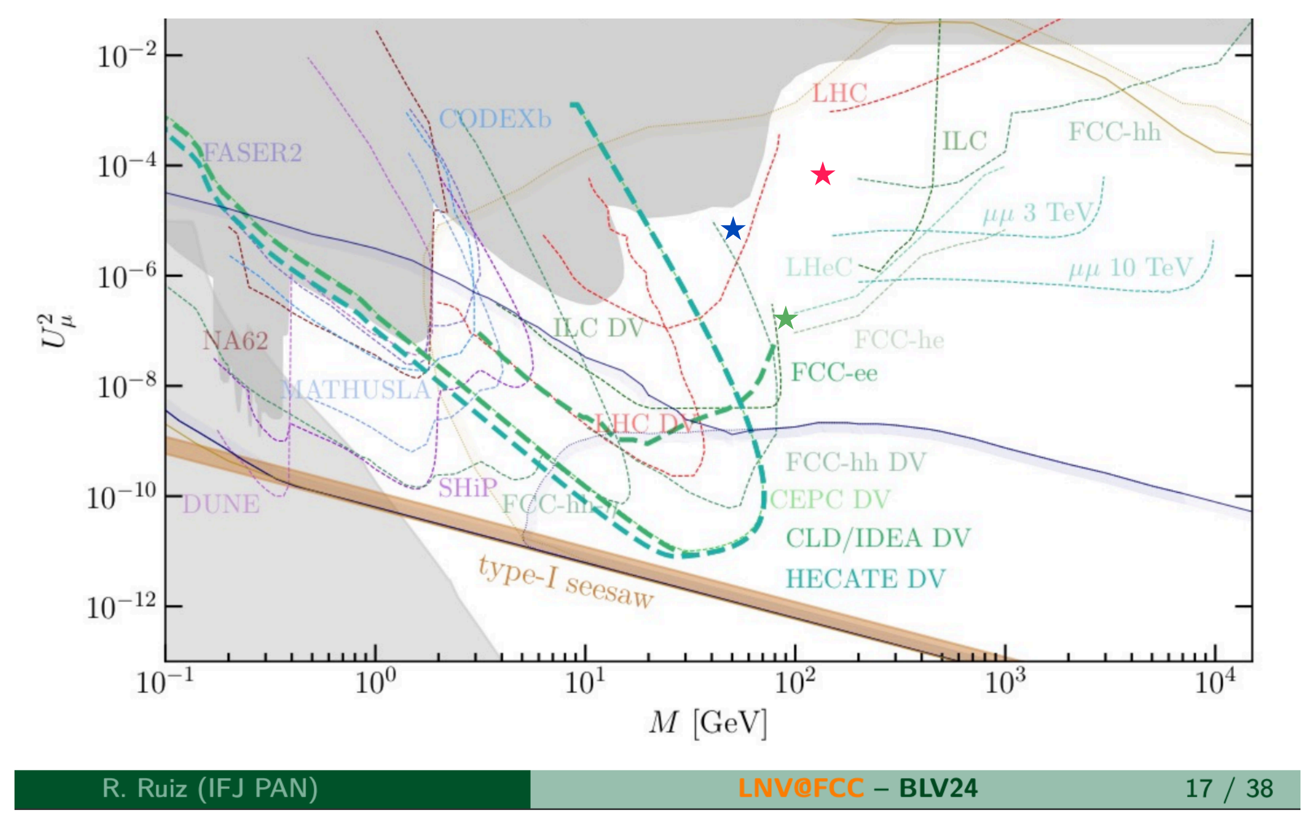
PBH Hot Spots

Gunn, Heurtier, YFPG, Turner. 2409.02173









He, Kohri, Mukaida, Yamada 2210.06238, 2407.15926

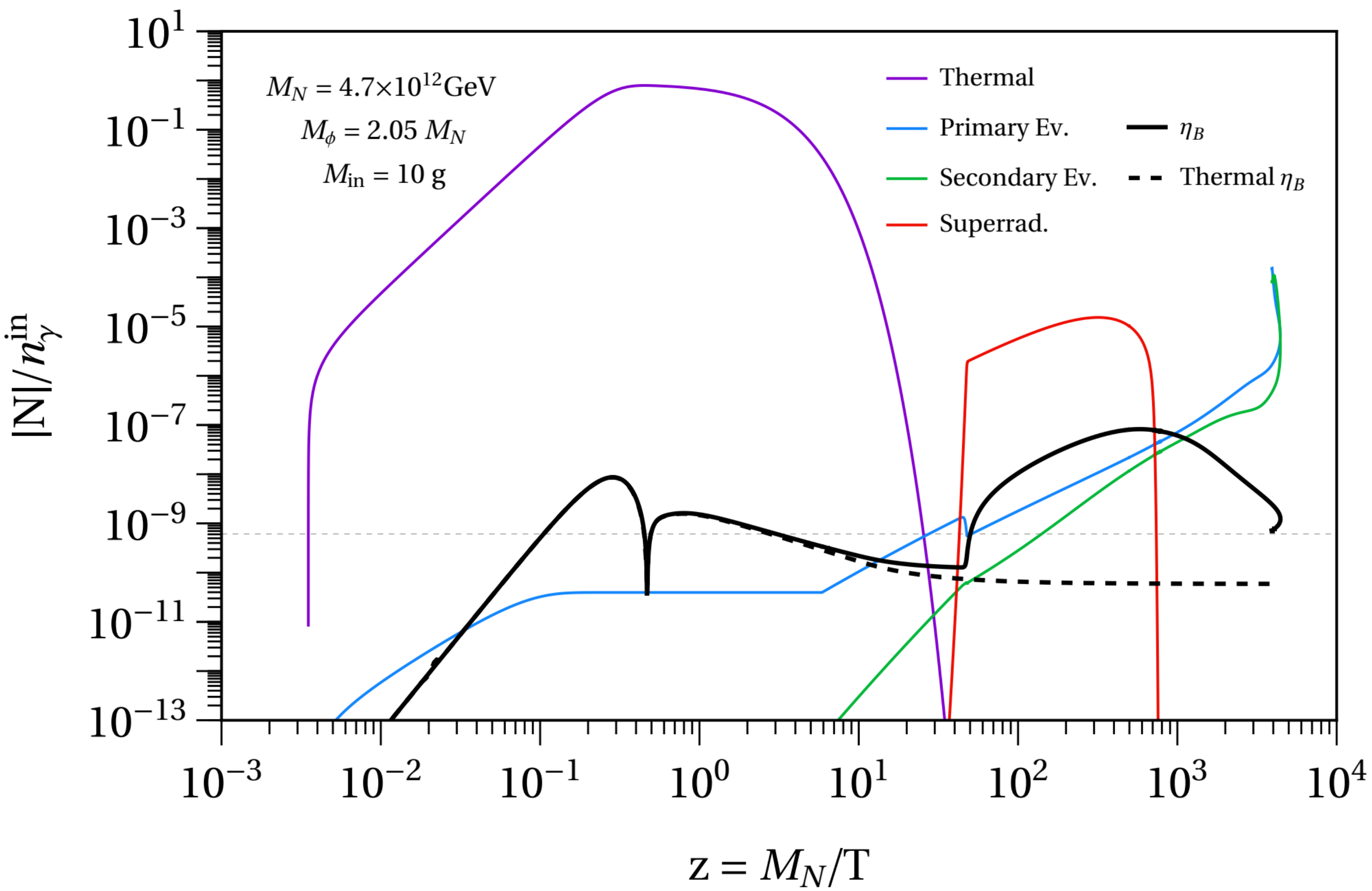
More "Baroque" Models

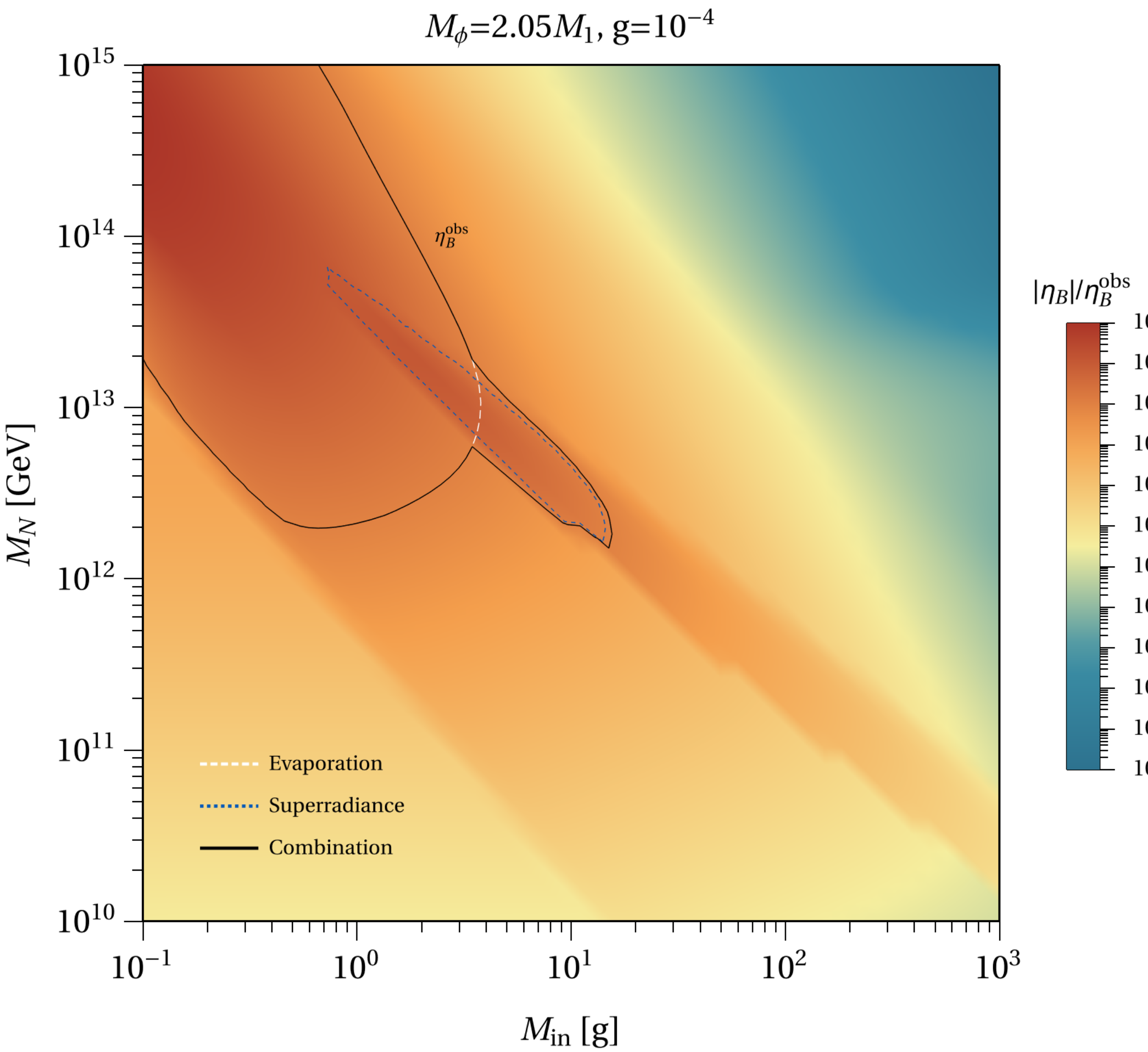
Dark sectors containing scalar dofs

$\phi \to NN$

New possible phenomena → Superradiant enhancement?

Kerr PBHs





$\beta' = 10^{-4}$

$a_\star = 0.999$

Ghoshal, YFPG, Turner. 2312.06768

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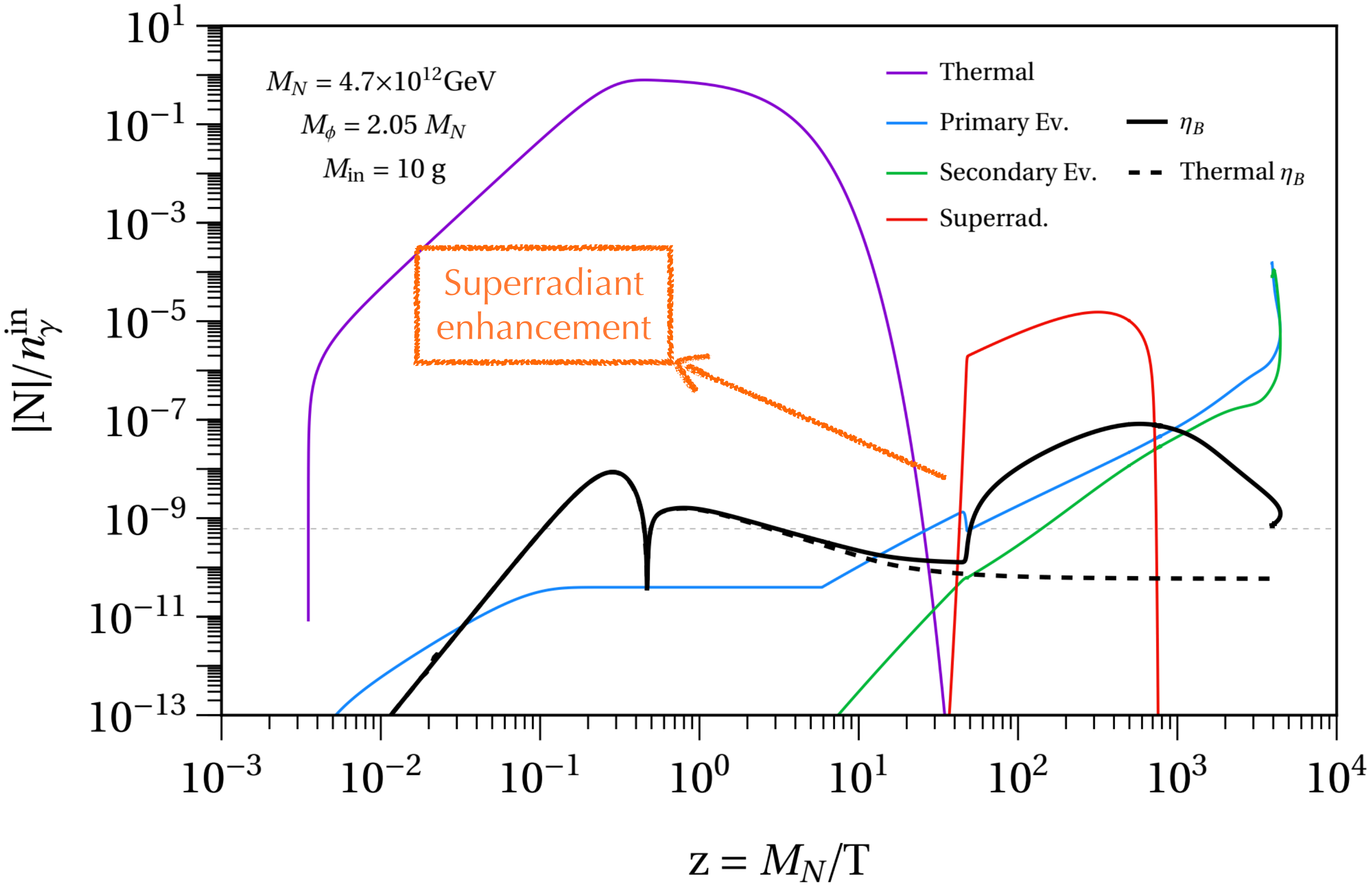

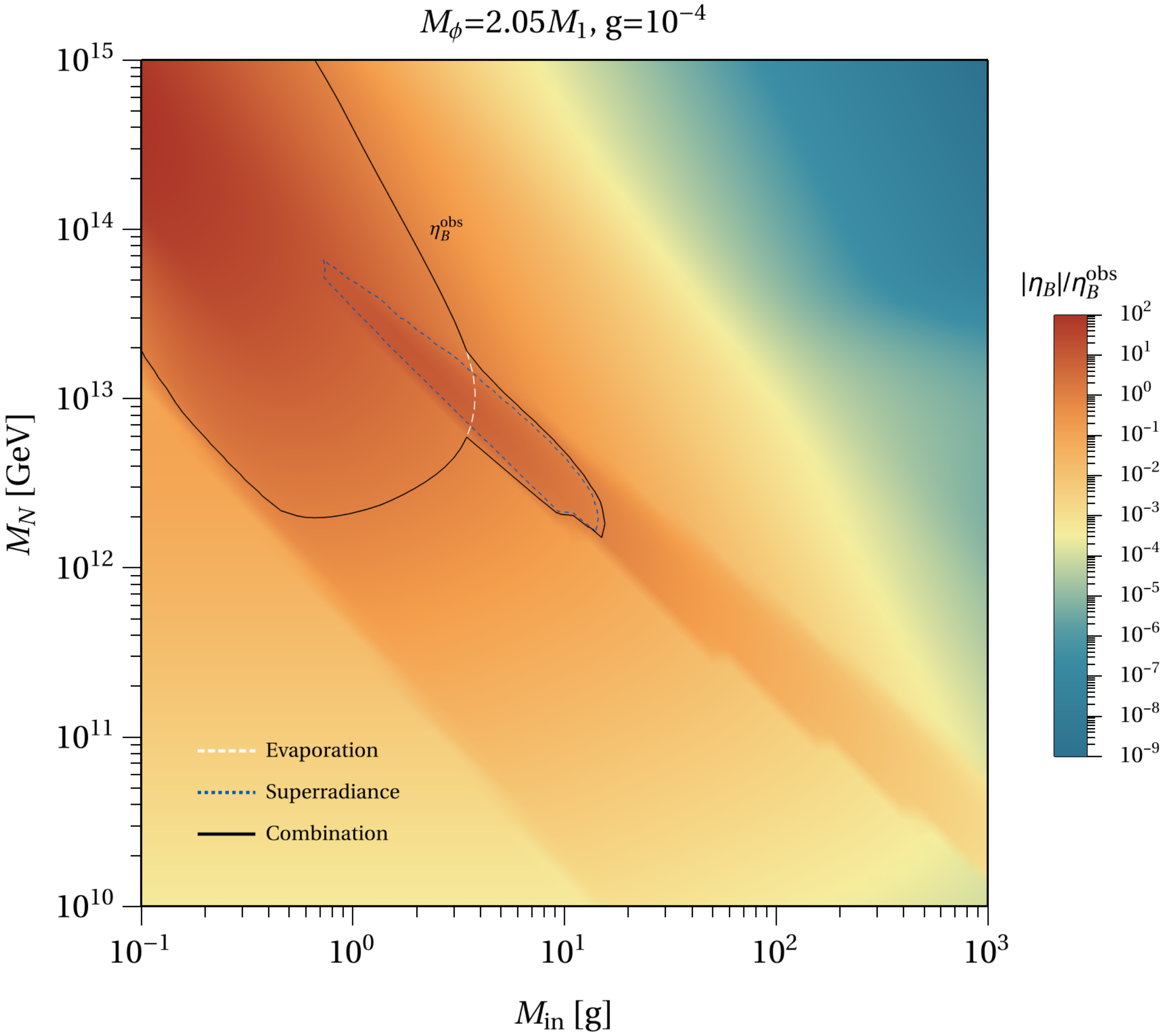

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Ghoshal, YFPG, Turner. 2312.06768

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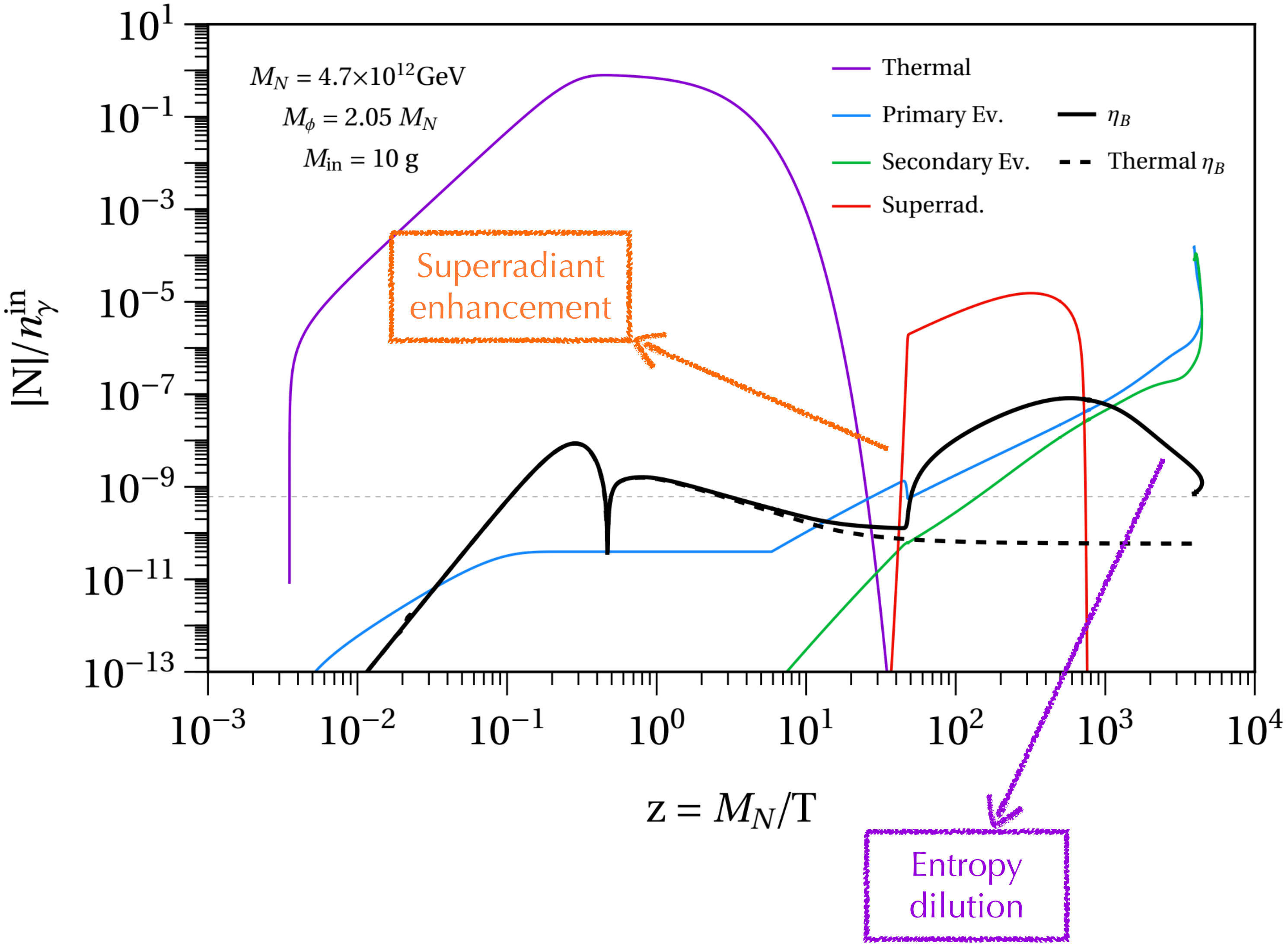

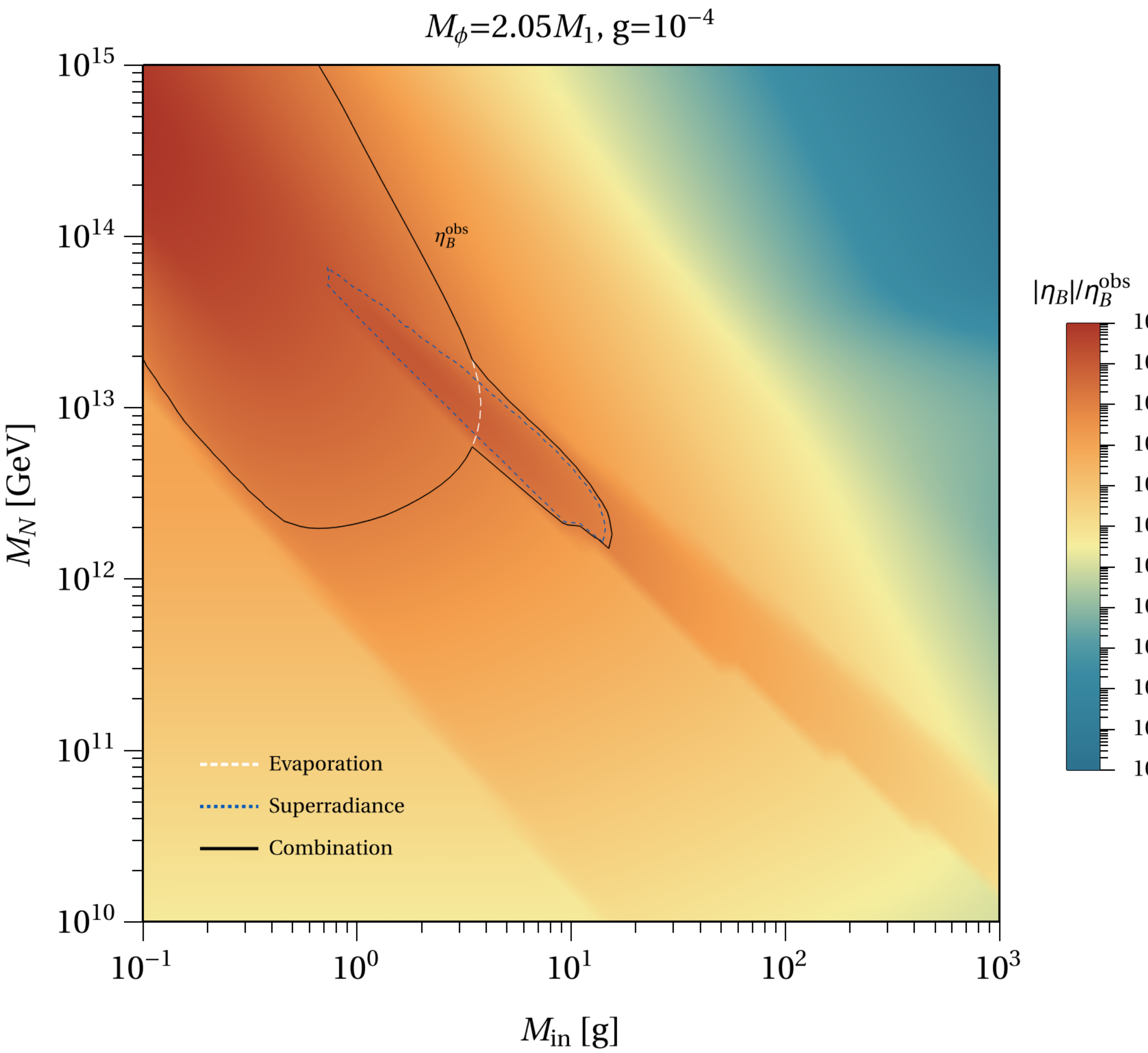

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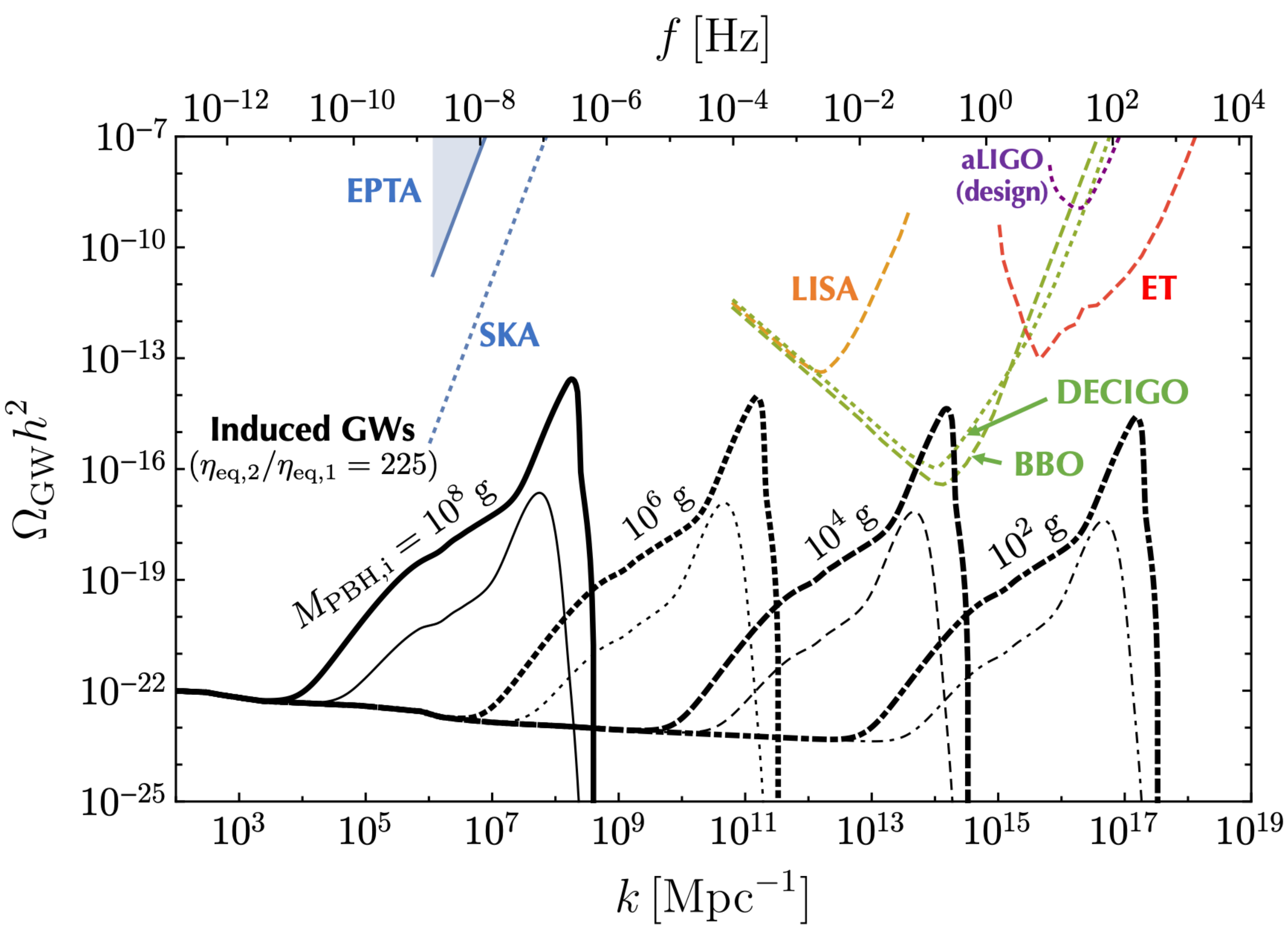
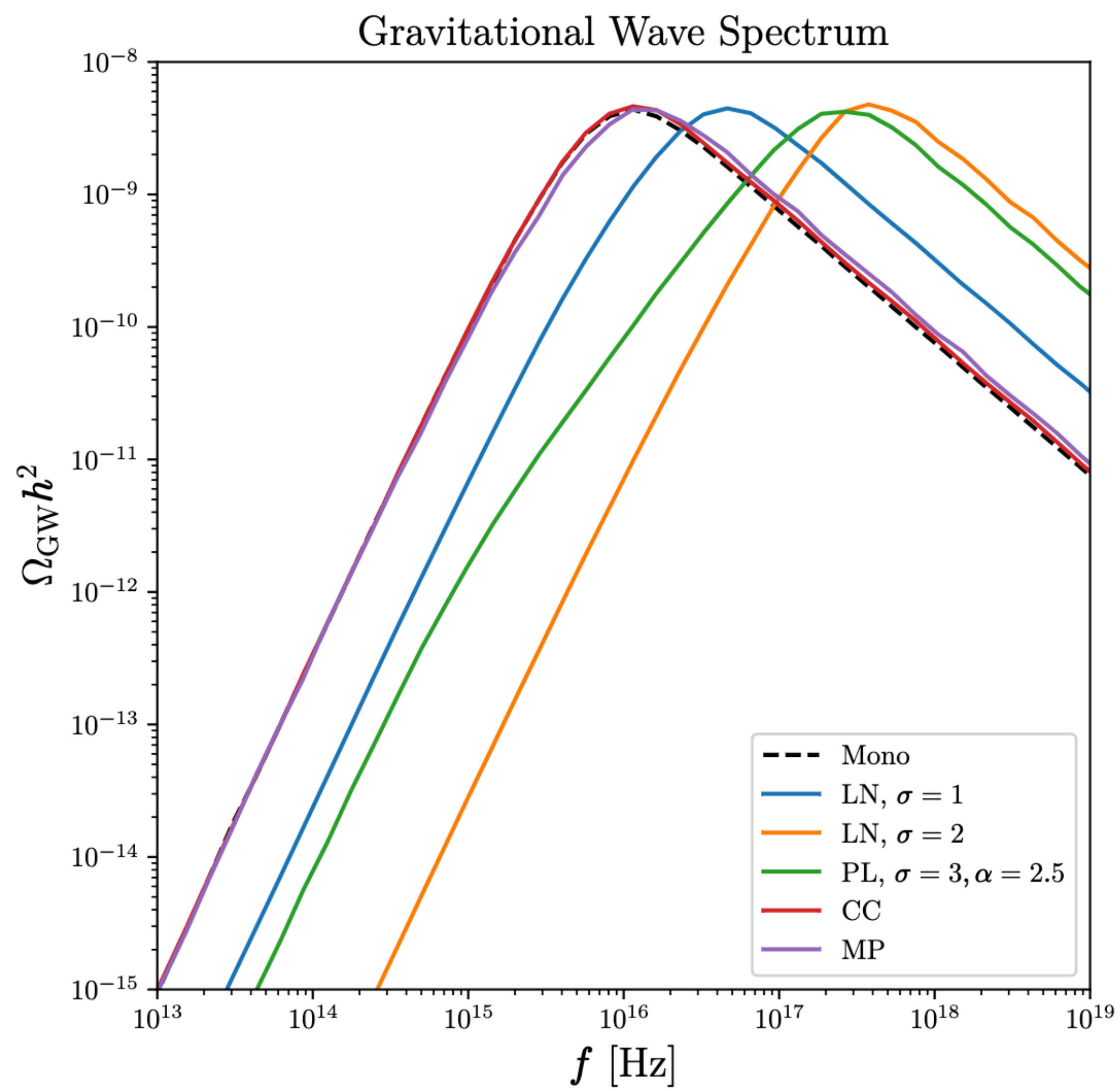
Ghoshal, YFPG, Turner. 2312.06768

Constraining these scenarios?





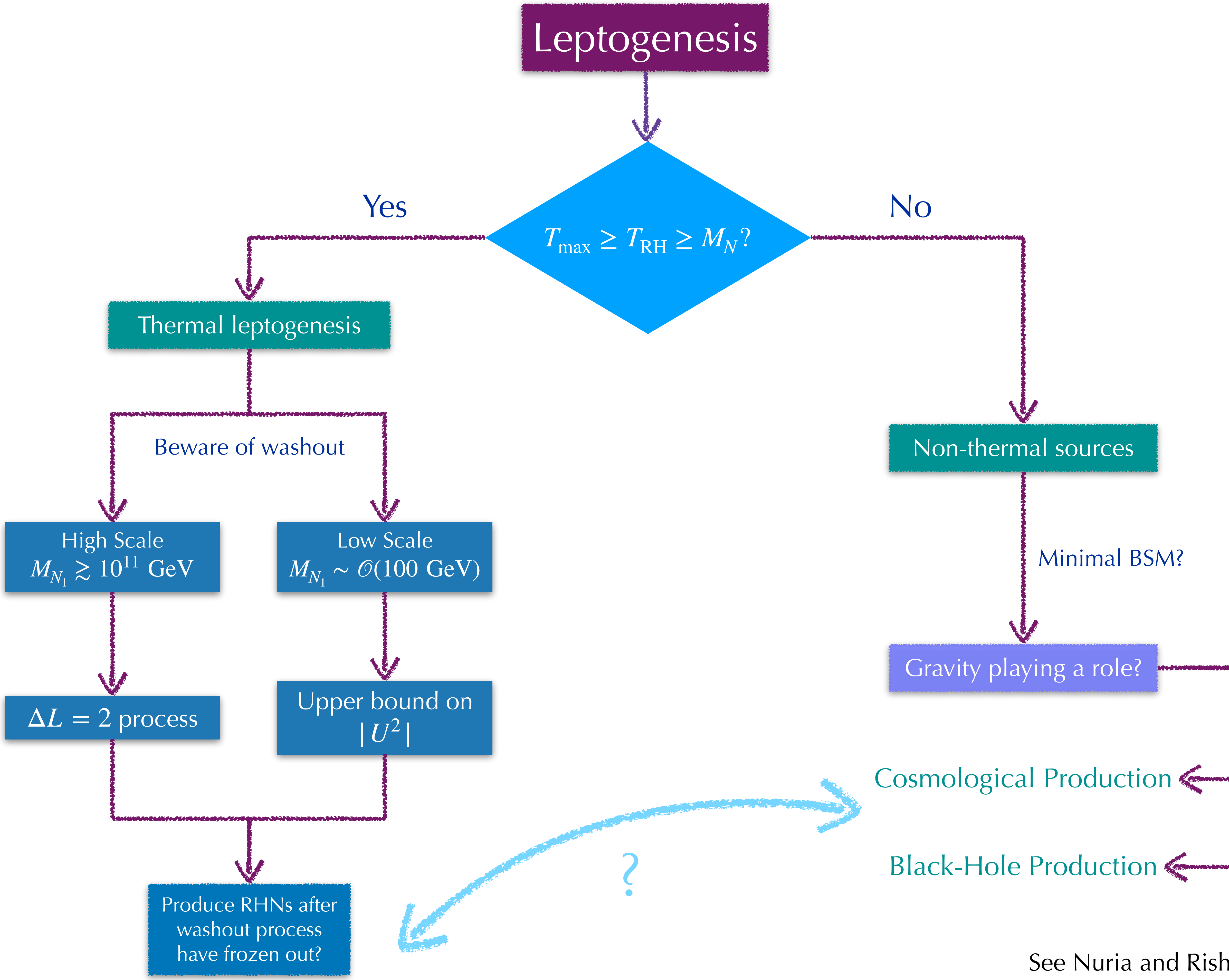
Cheek, Heurtier, YFPG, Turner, 2212.03878

GWs are induced after the sudden transition from a matter to radiation dominated U

Imprints of a PBH-dominated era in GWs

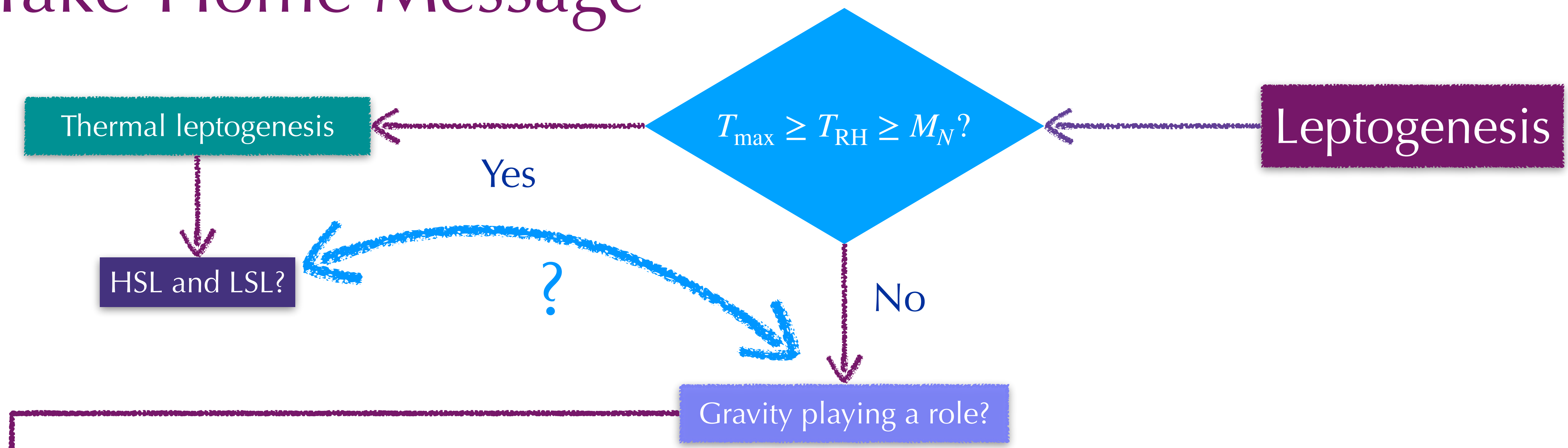
Inomata et al, 2003.10455, 2205.06260

Datta et al(2020), Das et al (2021), Barman et al (2022), Borah et al (2023), …



See Nuria and Rishav's talk

Take-Home Message

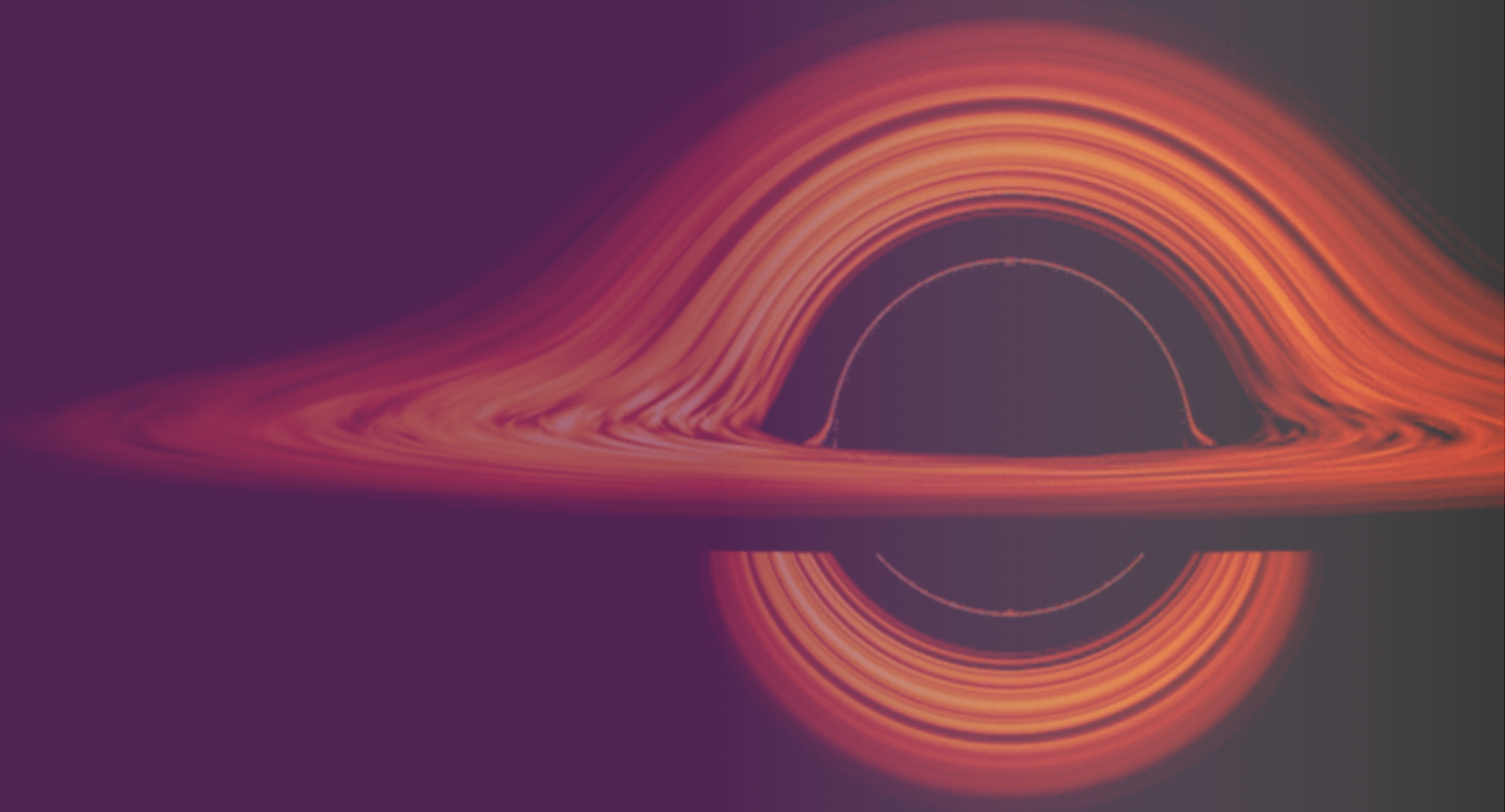


Cosmological Production

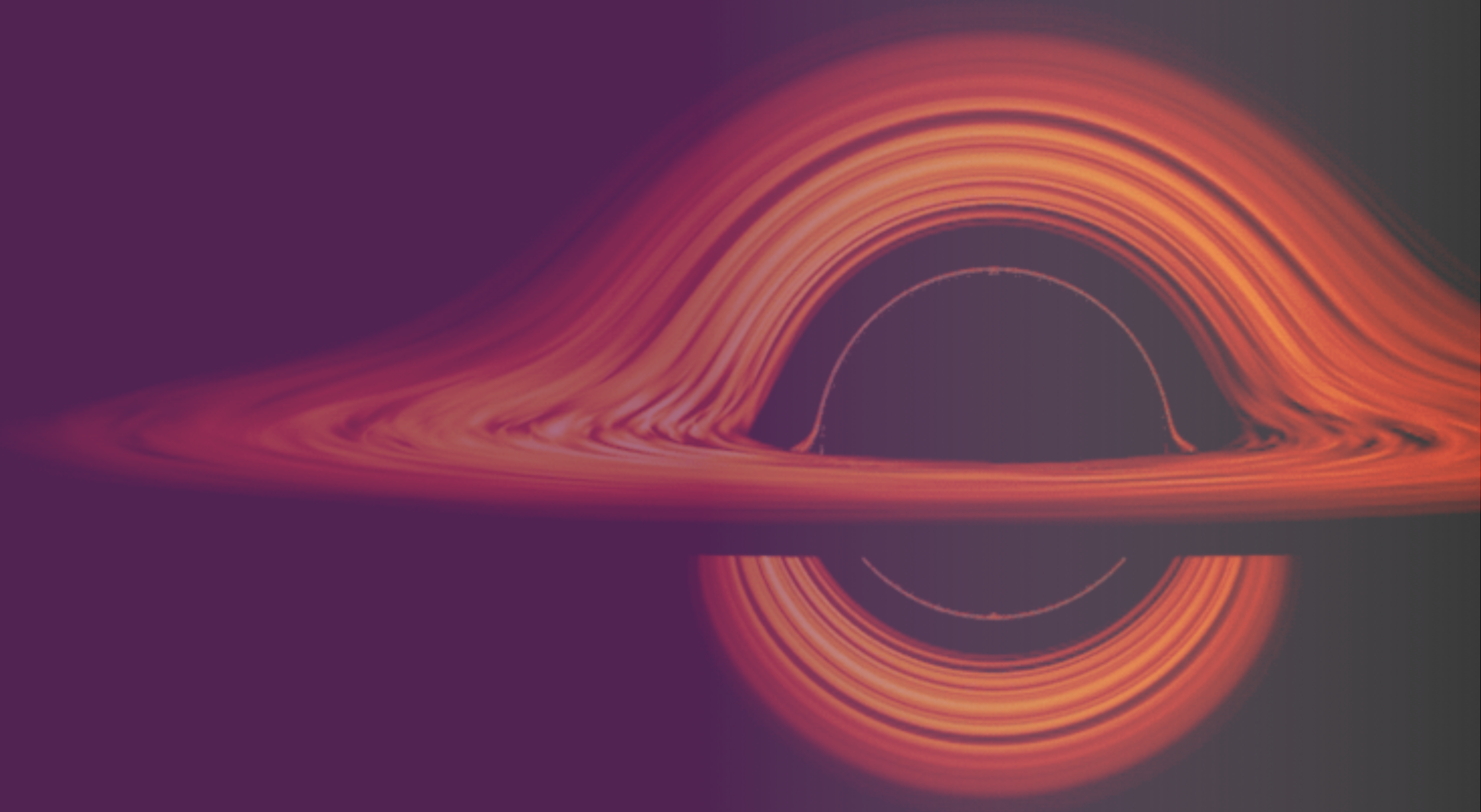
- Unavoidable number density → If it produces RHNs it could generate the observed lepton asymmetry for low reheating temperatures
- Non trivial dependence with the inflaton potential

Black-Hole Production

- RHNs produced via Hawking evaporation allow for HS leptogenesis
- For LS-resonant leptogenesis, hot-spots around PBHs can allow for the production of baryon asymmetry
- ARS leptogenesis → additional effects? Granelli, Shuve, YFPG, Turner, 241X.XXXXX



Thanks!



Thanks!