PBHs and the matter-antimatter asymmetry

Focus week on Primordial black holes

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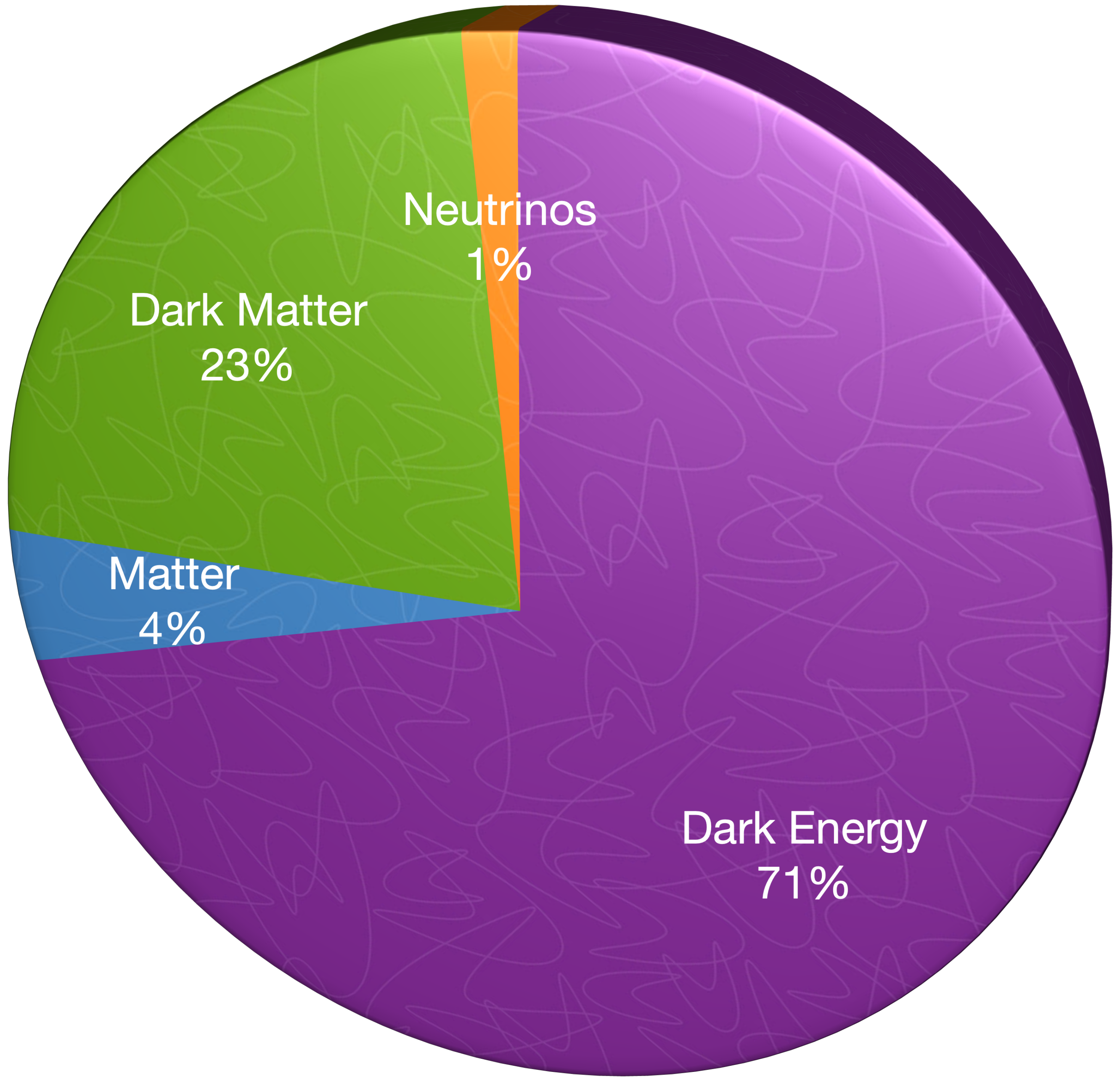
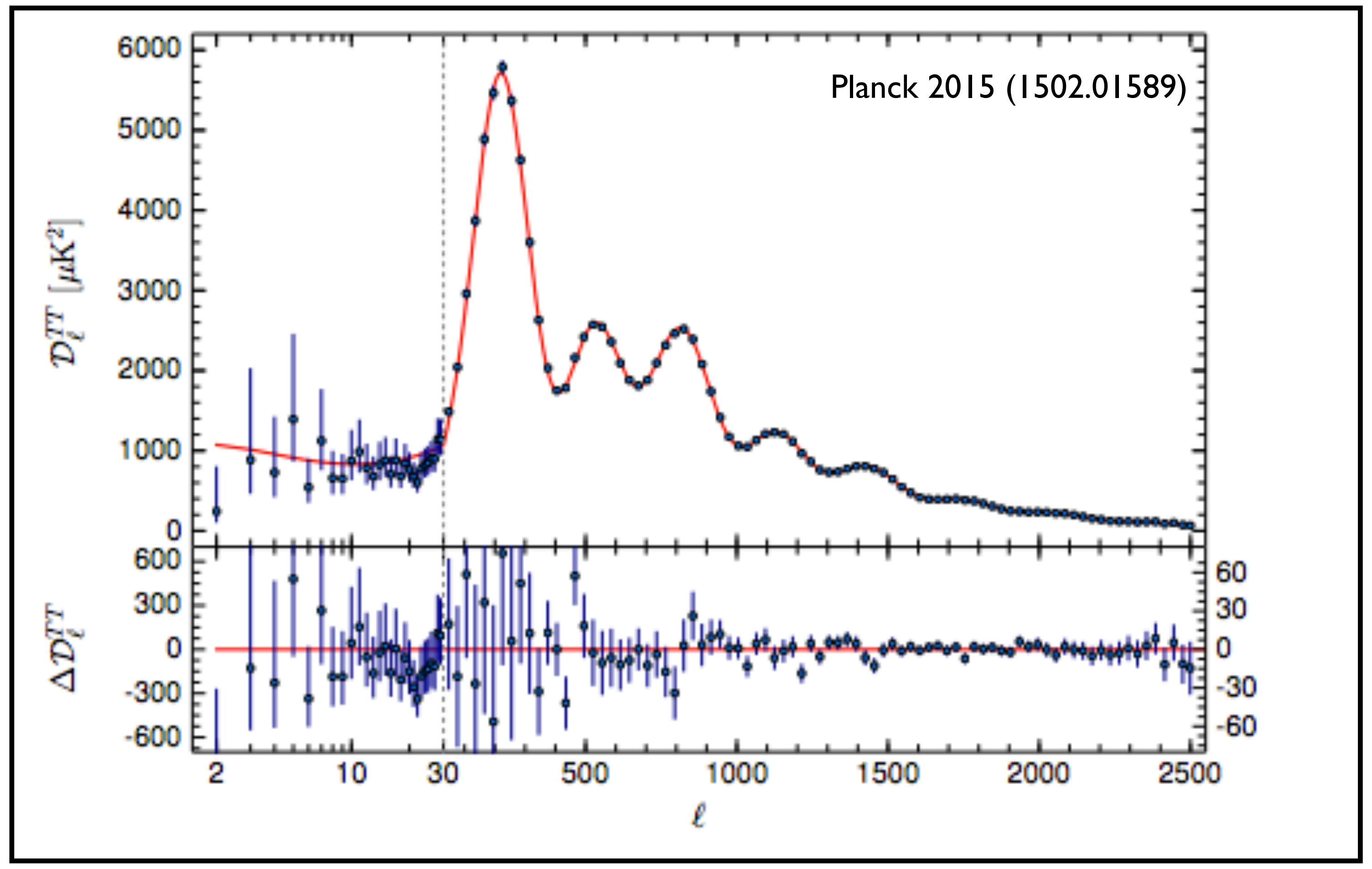
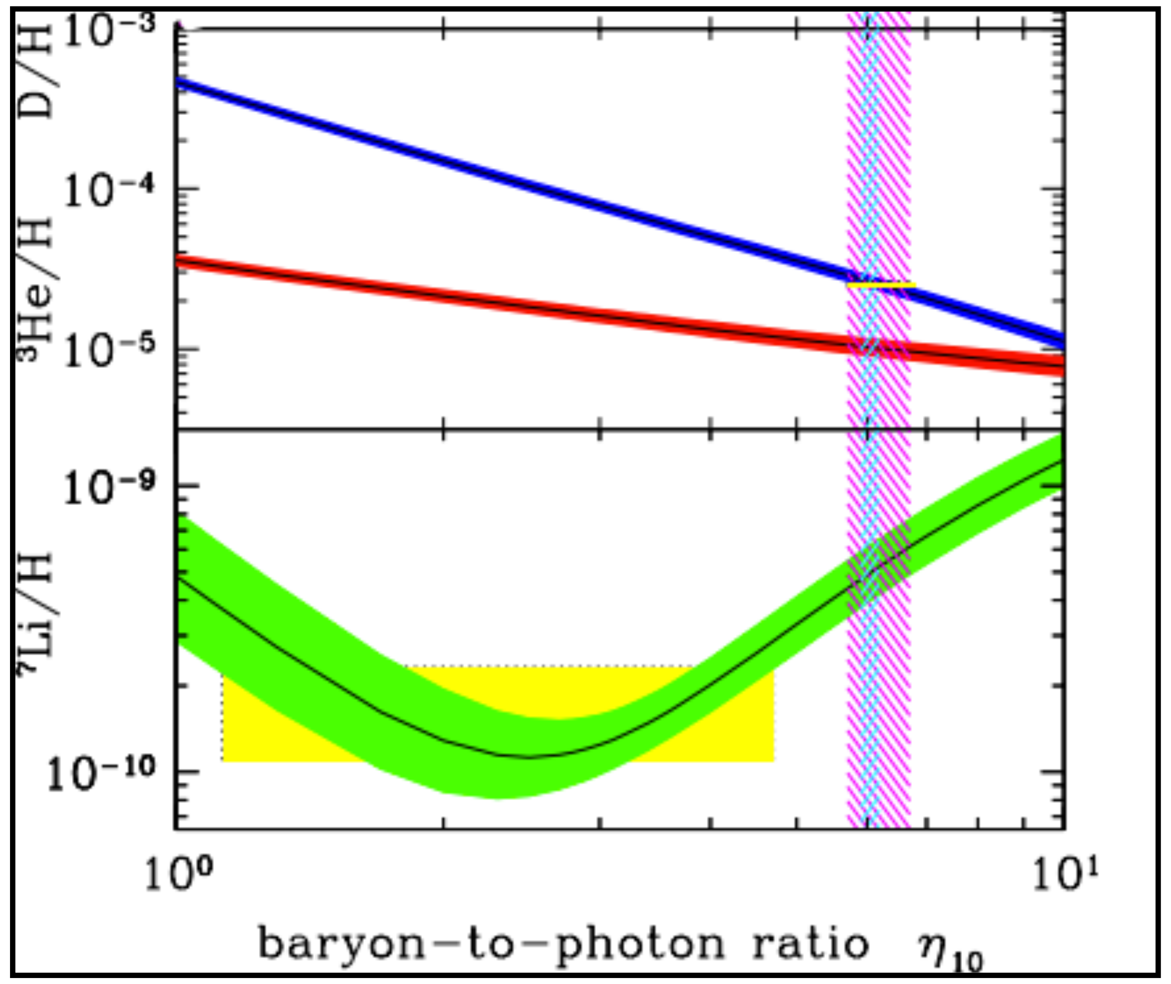
Matter-Antimatter Asymmetry





$$6.02 \times 10^{-10} \leq \eta_B \leq 6.18 \times 10^{-10}\ (95\%\mathrm{CL})$$

B. D. Fields et al., JCAP (2019).



$$5.8 \times 10^{-10} \leq \eta_B \leq 6.5 \times 10^{-10}\ (95\%\mathrm{CL})$$

Sakharov's Conditions

- ☑ Baryon number violation — Kuzmin, Rubakov & Shaposhnikov (1985)
- ☒ C & CP-violation — Gavela, Hernandez, Orloff & Pene (1994)
- ☒ Departure from thermal equilibrium — Kajantie, Laine, Rummukainen & Shaposhnikov (1996)

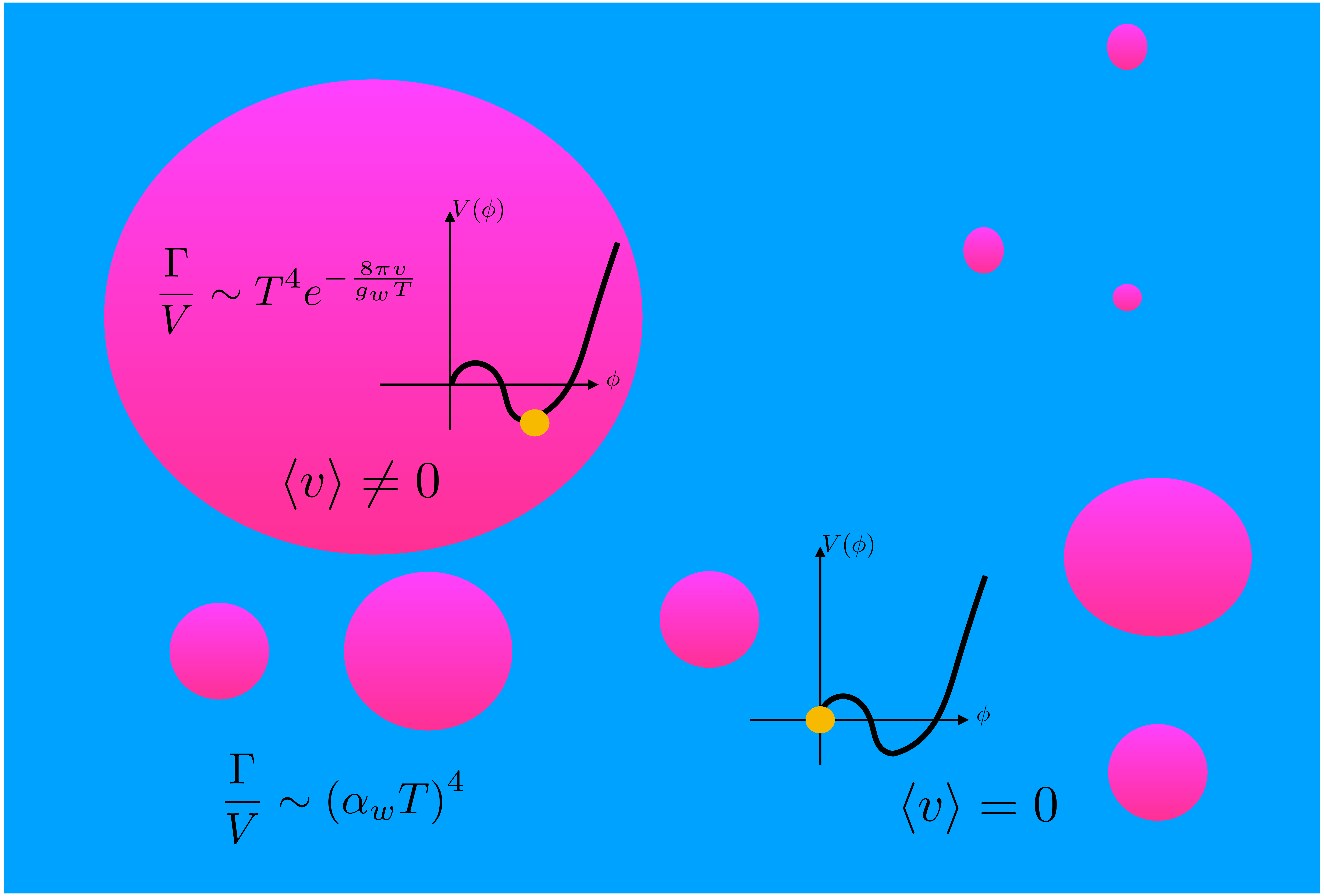
Popular Theories of Baryogenesis

Popular Theories of Baryogenesis

Electroweak Baryogenesis

- Strong first-order EW phase transition $\Longrightarrow$ modifications in the **Higgs sector**

Kuzmin, Rubakov & Shaposhnikov (1985)
Cohen, Kaplan & Nelson (1993)



Electroweak Baryogenesis

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- Fermion species reflected CP violating at Higgs bubble wall $\Longrightarrow$ **electric dipole moment**

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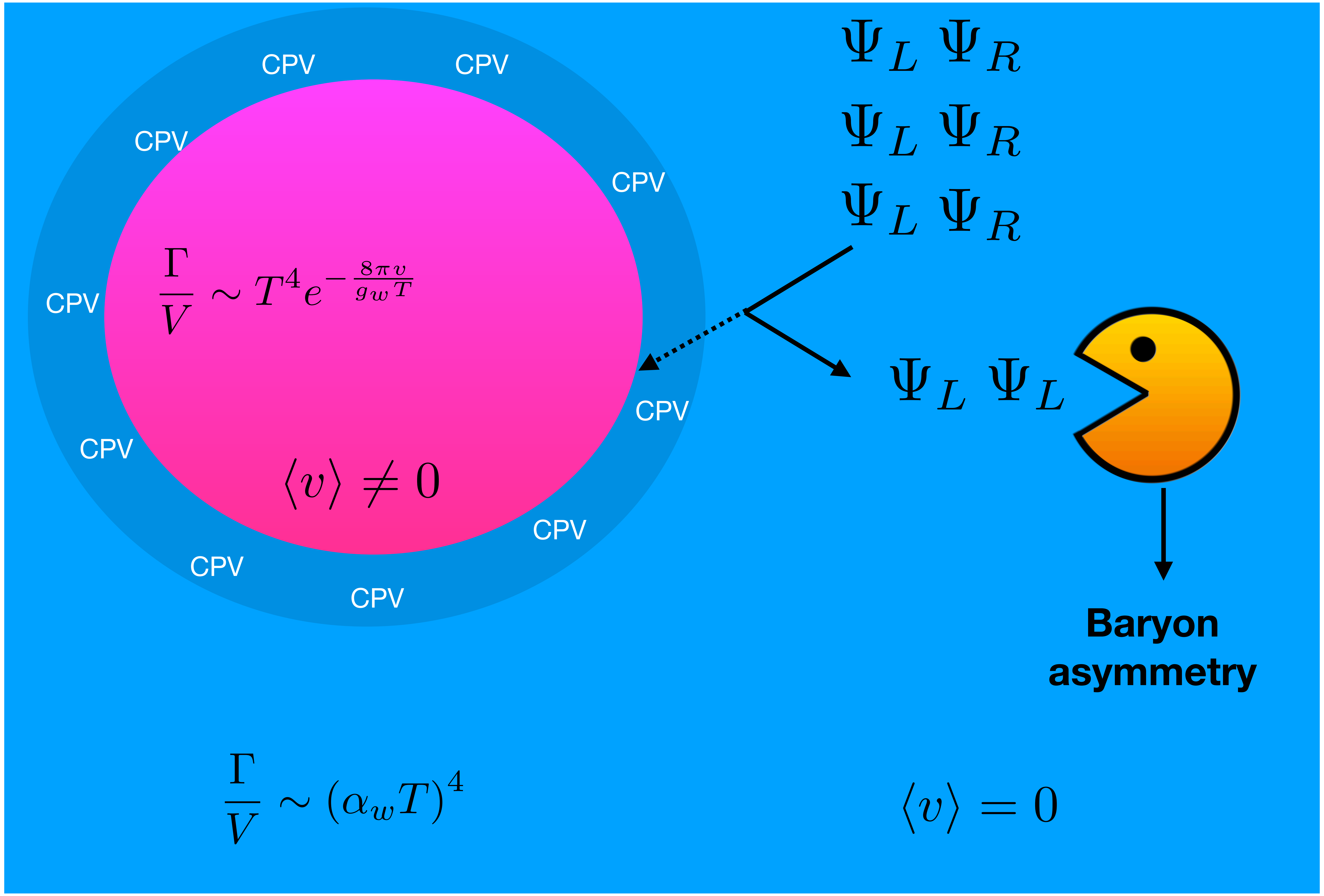

Electroweak Baryogenesis

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$$|d_e| < 4.1 \times 10^{-30}\,\mathrm{e}\cdot\mathrm{cm}$$

Roussy et al (2023)

$$|d_n| < 1.8 \times 10^{-26}\,\mathrm{e}\cdot\mathrm{cm}$$

PSI (2020)

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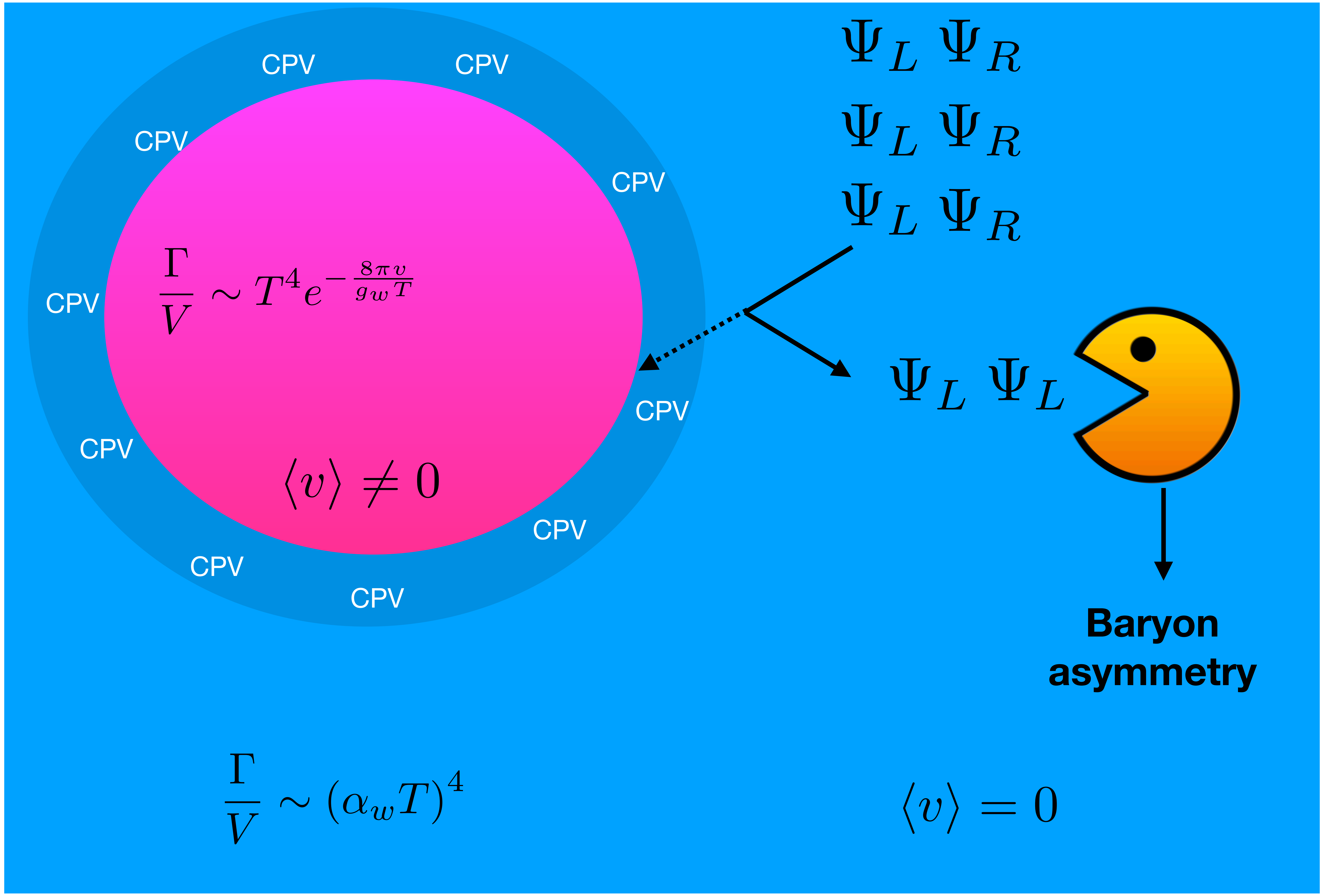

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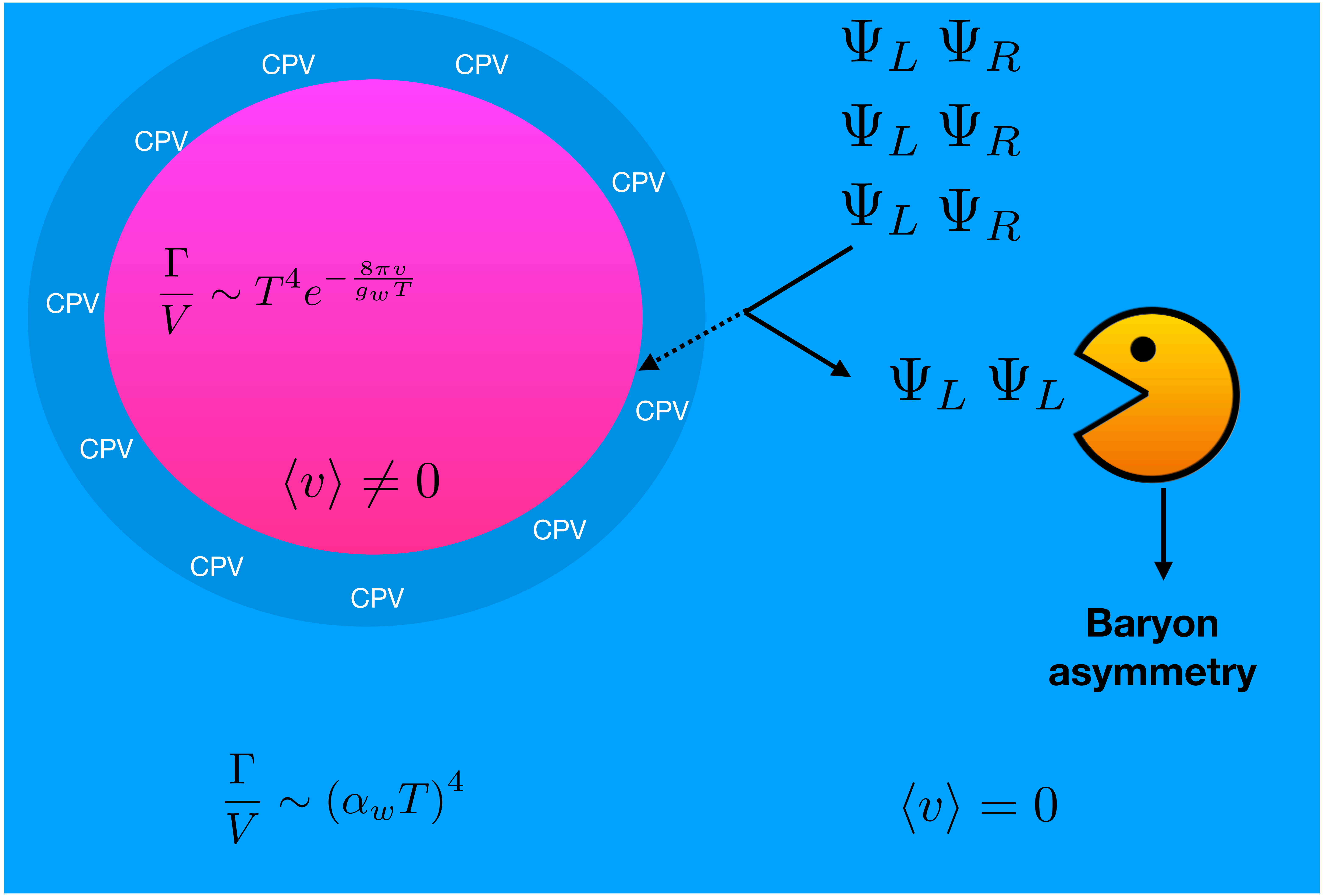
PSI (2020)

- Stringent EDM limits place many models under tight constraints such as MSSM & 2HDM

Kuzmin, Rubakov & Shaposhnikov (1985)
Cohen, Kaplan & Nelson (1993)



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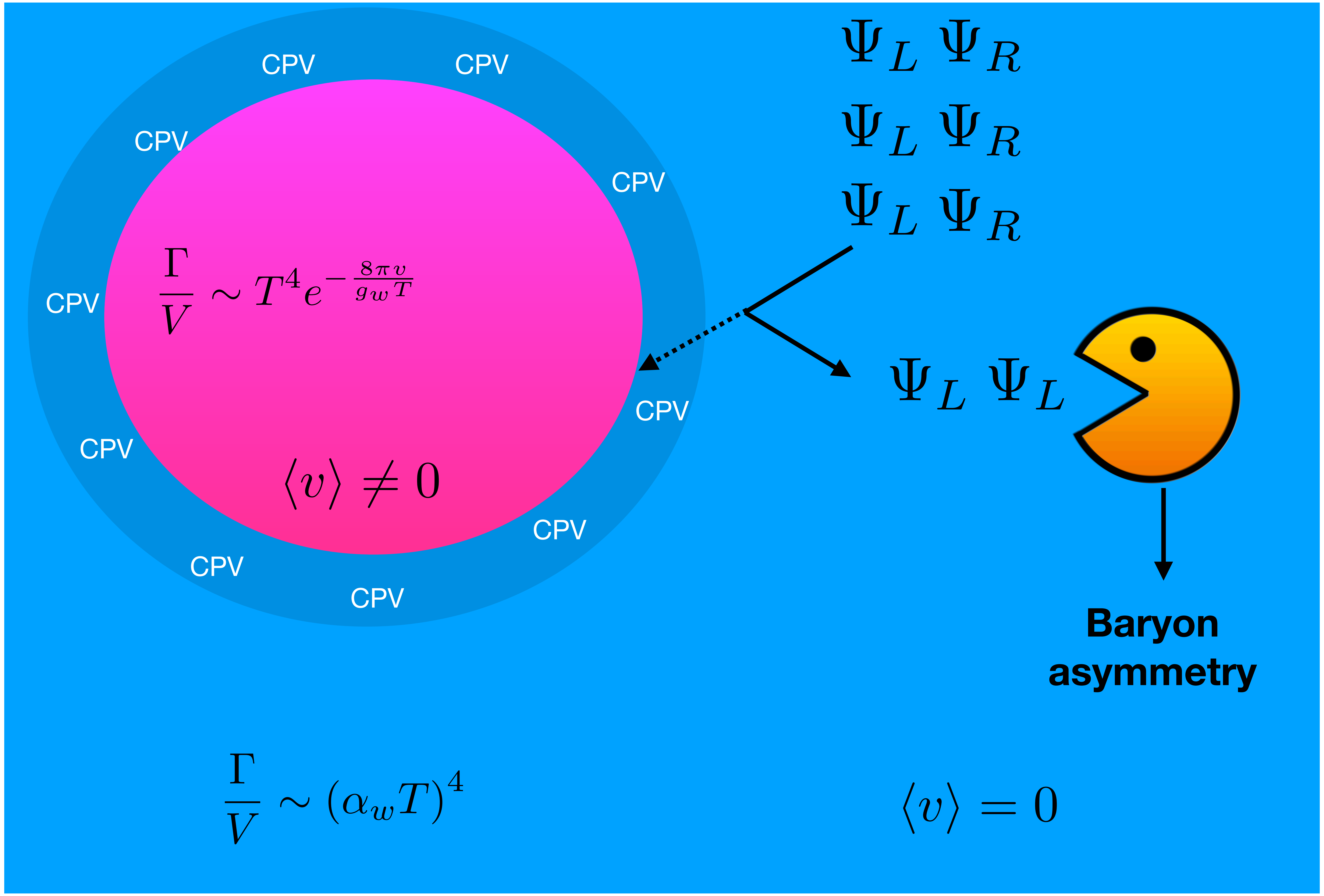
- **Time-varying Yukawa couplings:**

CKM varies during EWPT $\Longrightarrow$ Yukawa couplings $\mathcal{O}(1)$ at EW symmetric phase and evolve to values today at end of PT

Kuzmin, Rubakov & Shaposhnikov (1985)
Cohen, Kaplan & Nelson (1993)



Baldes, Bruggisser, Konstantin, Servant (2016)

Electroweak Baryogenesis

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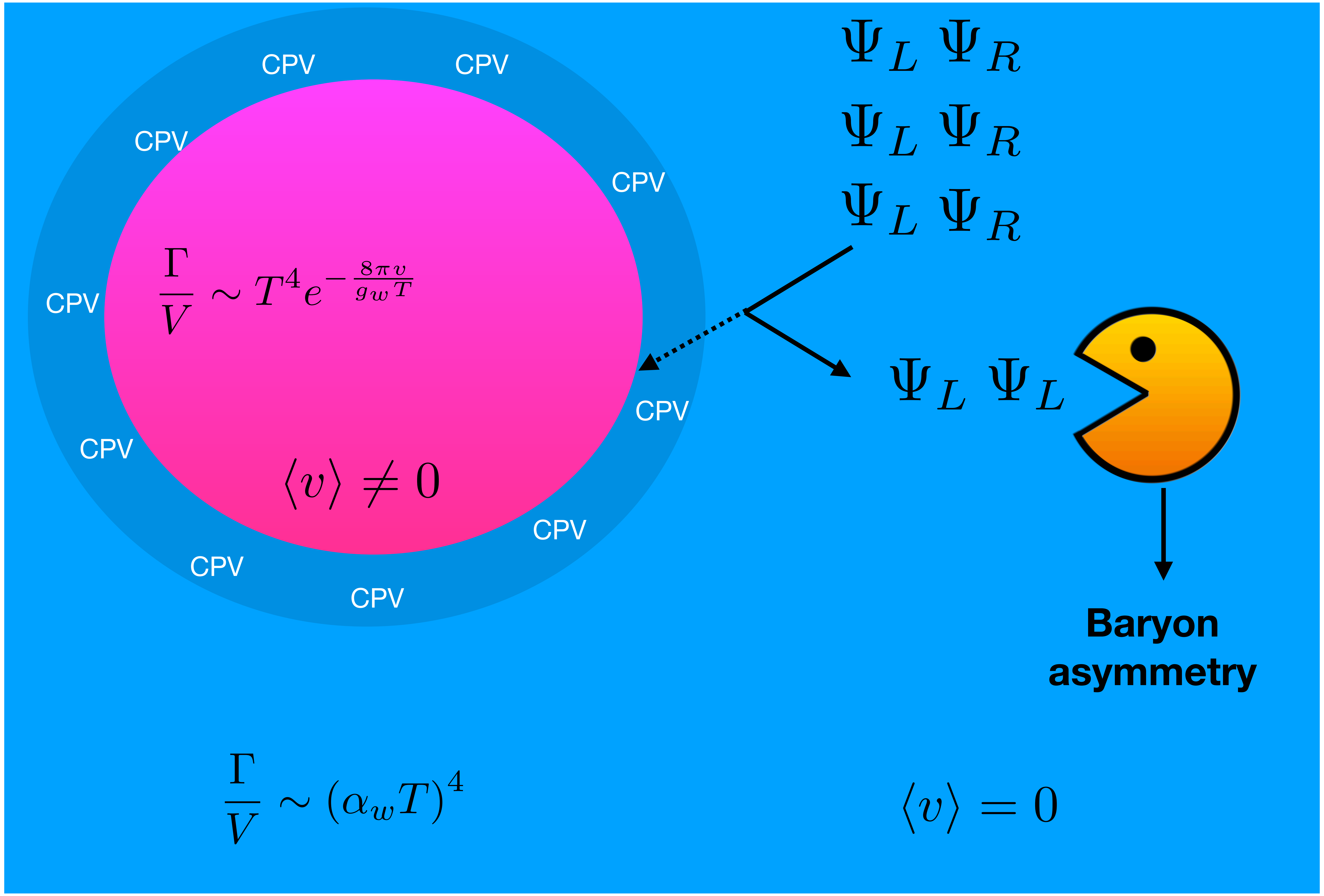
PSI (2020)

- **Composite Higgs:**

confining PT and EWPT linked. Yukawa couplings depend on mixing between elementary and composite fermion $\Longrightarrow$ vary during confining phase transition.

Kuzmin, Rubakov & Shaposhnikov (1985)
Cohen, Kaplan & Nelson (1993)



$$\frac{\Gamma}{V} \sim T^4 e^{-\frac{8\pi v}{g_w T}}$$

$$\langle v \rangle \neq 0$$

$$\frac{\Gamma}{V} \sim (\alpha_w T)^4$$

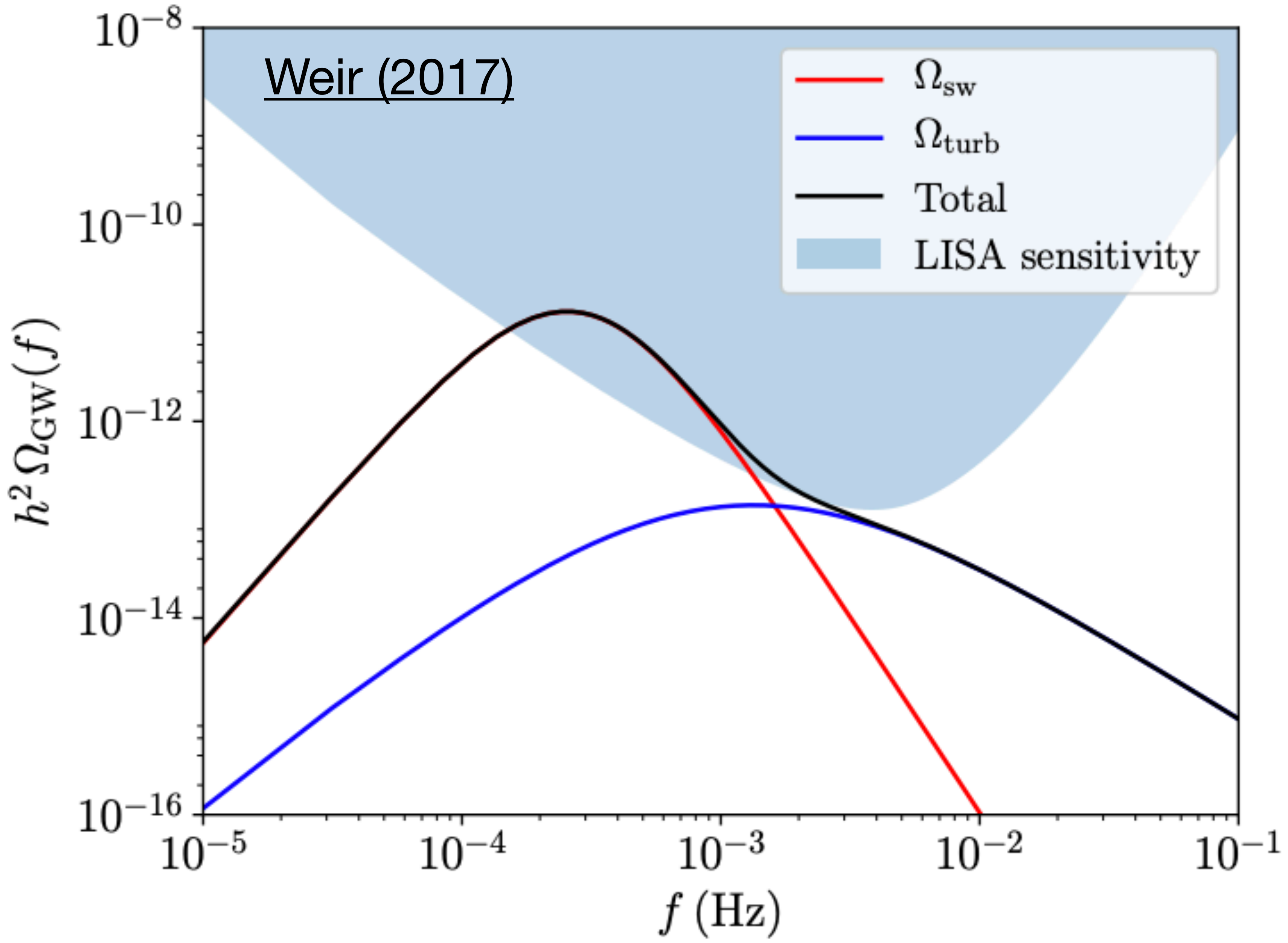
$$\langle v \rangle = 0$$

Bruggisser, von Harling, Matsedonskyi, Servant (2018)

Electroweak Baryogenesis

Gravitational waves are a prediction of many scenarios of electroweak baryogenesis & spectra depends on

- Strength of phase transition, phase transition duration, bubble wall velocity & nucleation temperature
- GWs sourced by collision of the walls, sound waves in plasma (post PT) & turbulence



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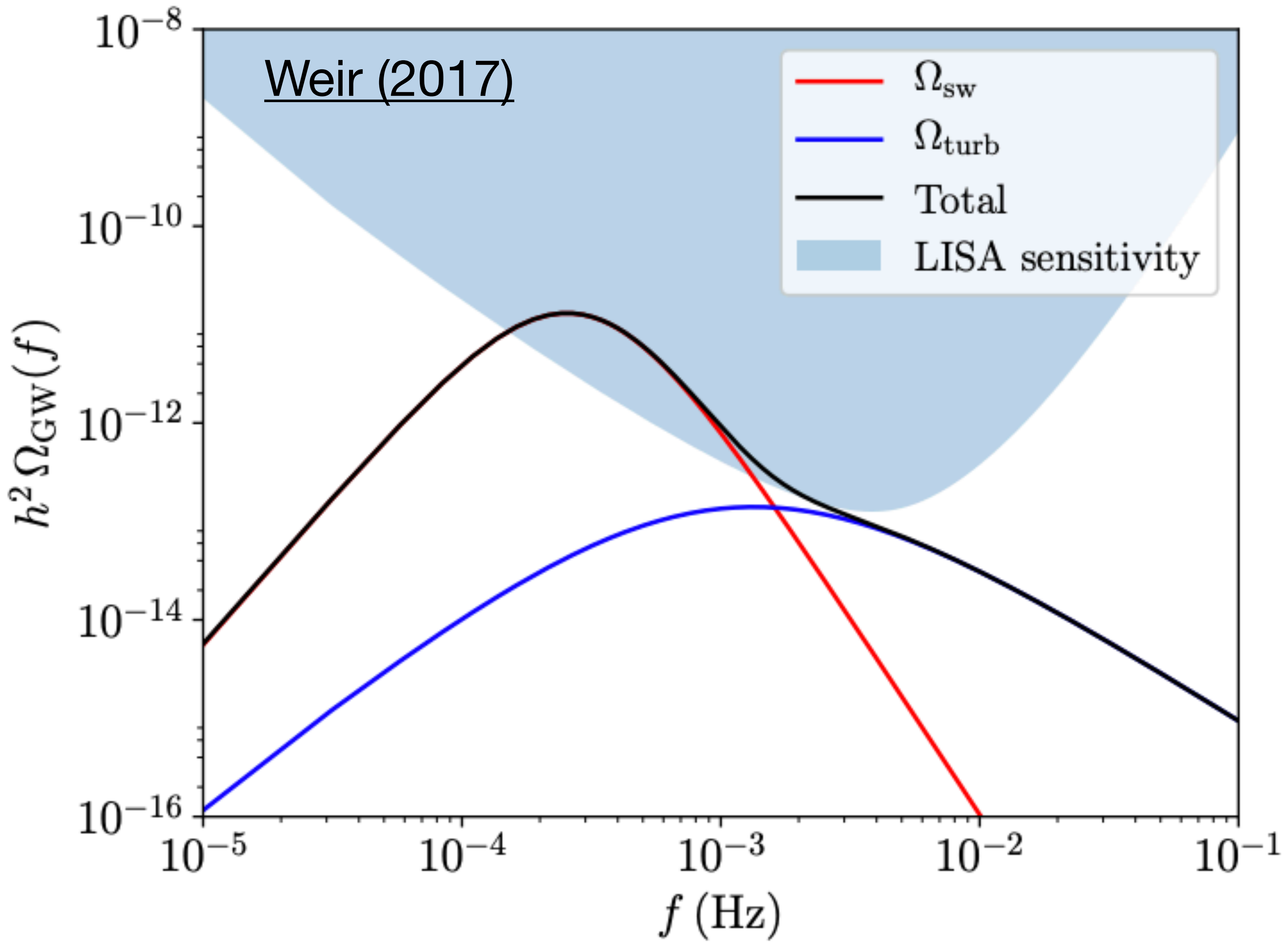
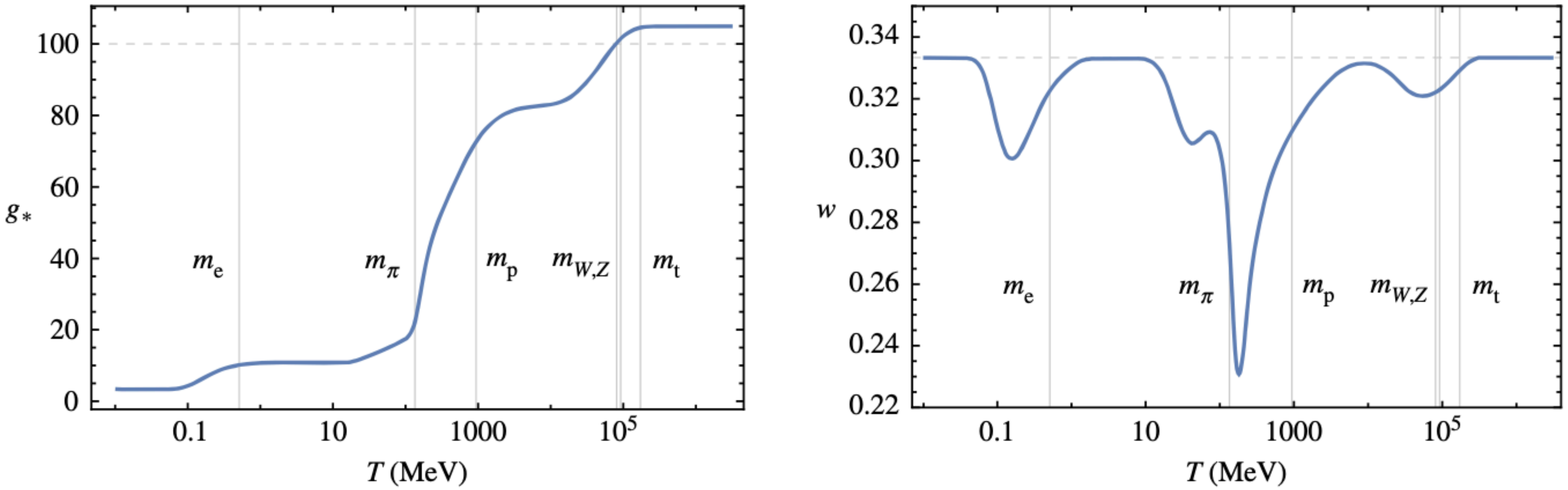


LISA will come online in 2030s & probe large range of cosmological phase transitions in terms of strength and temperature close to electroweak scales

Hot Spot Electroweak Baryogenesis

- **PBHs form during QCD phase transition** At QCD PT causes drop in speed of sound $\implies$ reduction in radiation pressure lowers critical curvature necessary for gravitational collapse (see talk by F. Kuhnel)

Garcia-Bellido, Carr, Cleese



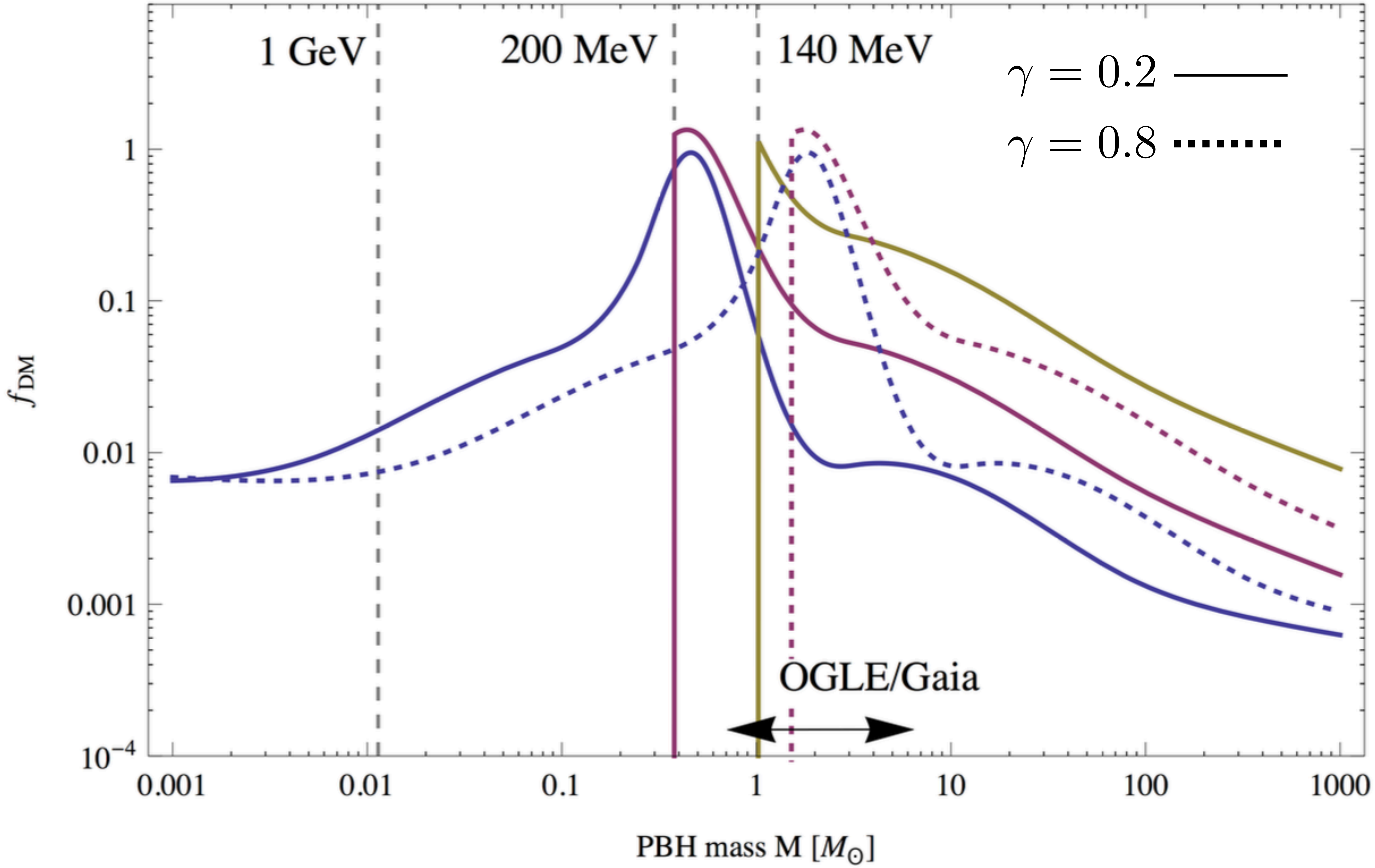
- Still need large curvature fluctuations. QCD axion acts as spectator field $\implies$ large curvature in rare regions of space

Harwick, Vennin, Byrnes, Torrado, Wands

Hot Spot Electroweak Baryogenesis

Garcia-Bellido, Carr, Cleese

- Leads to predictions of PBH mass distribution peaked at $M_\odot$

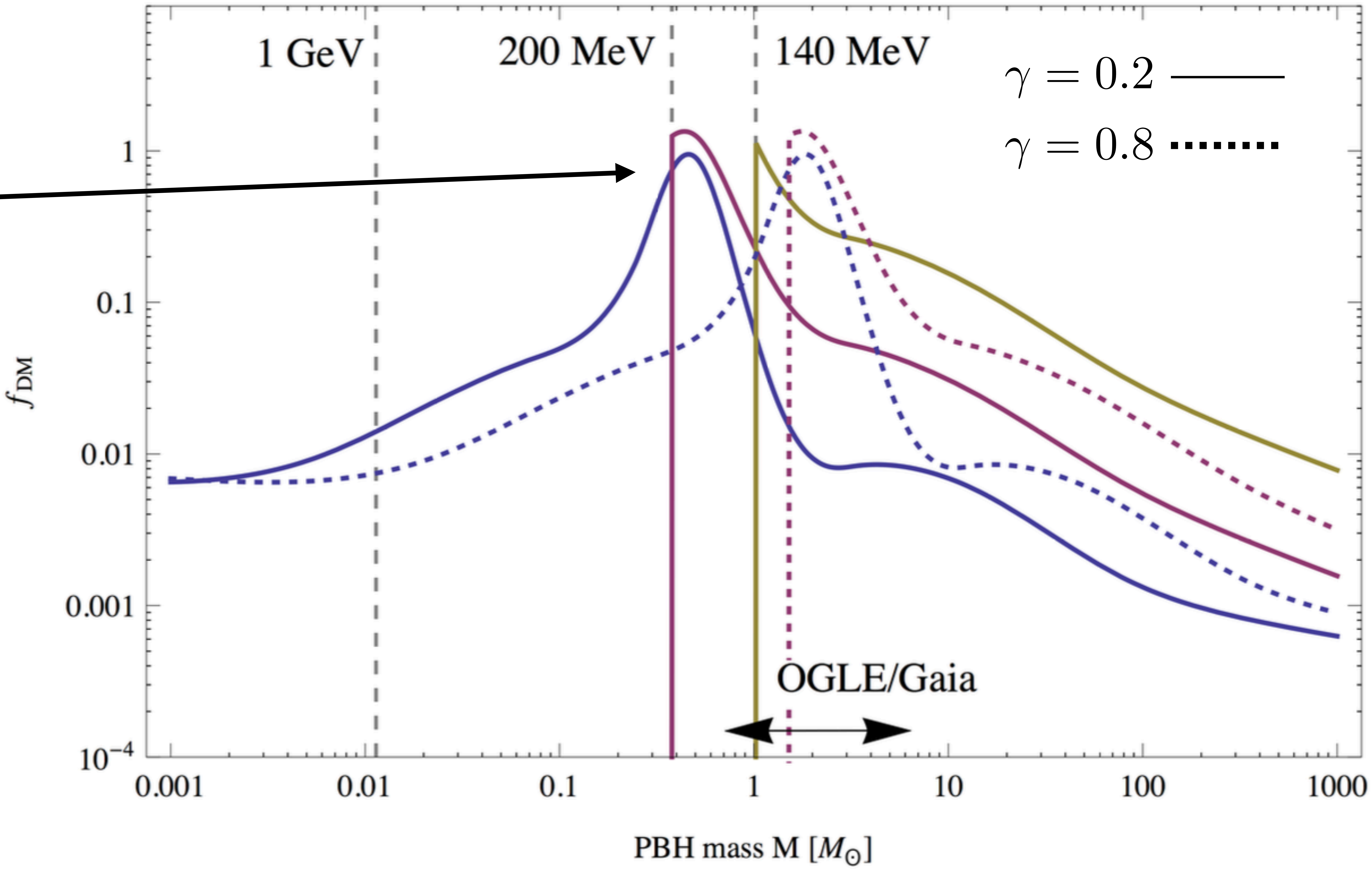


Hot Spot Electroweak Baryogenesis

Garcia-Bellido, Carr, Cleese

- Leads to predictions of PBH mass distribution peaked at $M_{\odot}$

Distributions peaks
Mass within horizon
at $T = \Lambda_{QCD}$

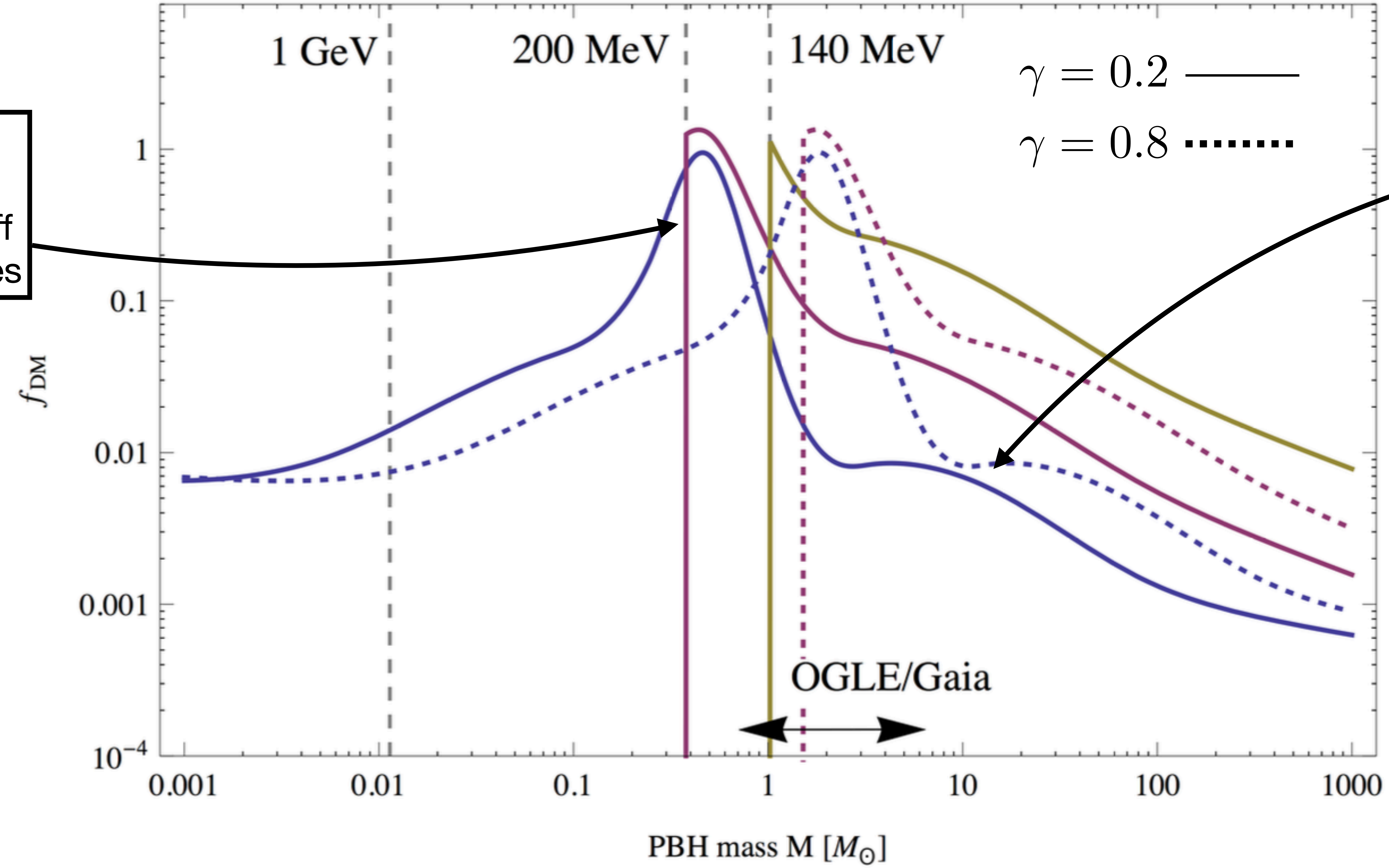


Hot Spot Electroweak Baryogenesis

Garcia-Bellido, Carr, Cleese

- Leads to predictions of PBH mass distribution

Once QCD Axion gains a mass PBH formation cut off At higher temperatures



π non-relativistic

Hot Spot Electroweak Baryogenesis

Garcia-Bellido, Carr, Cleese

- Formation of PBHs at QCD PT causes shockwave/jet of particles escaping PBH.
- Effective temperature around PBH larger than T_{EW}
- Jet of high energy particles travel through hot spot and generate BAU

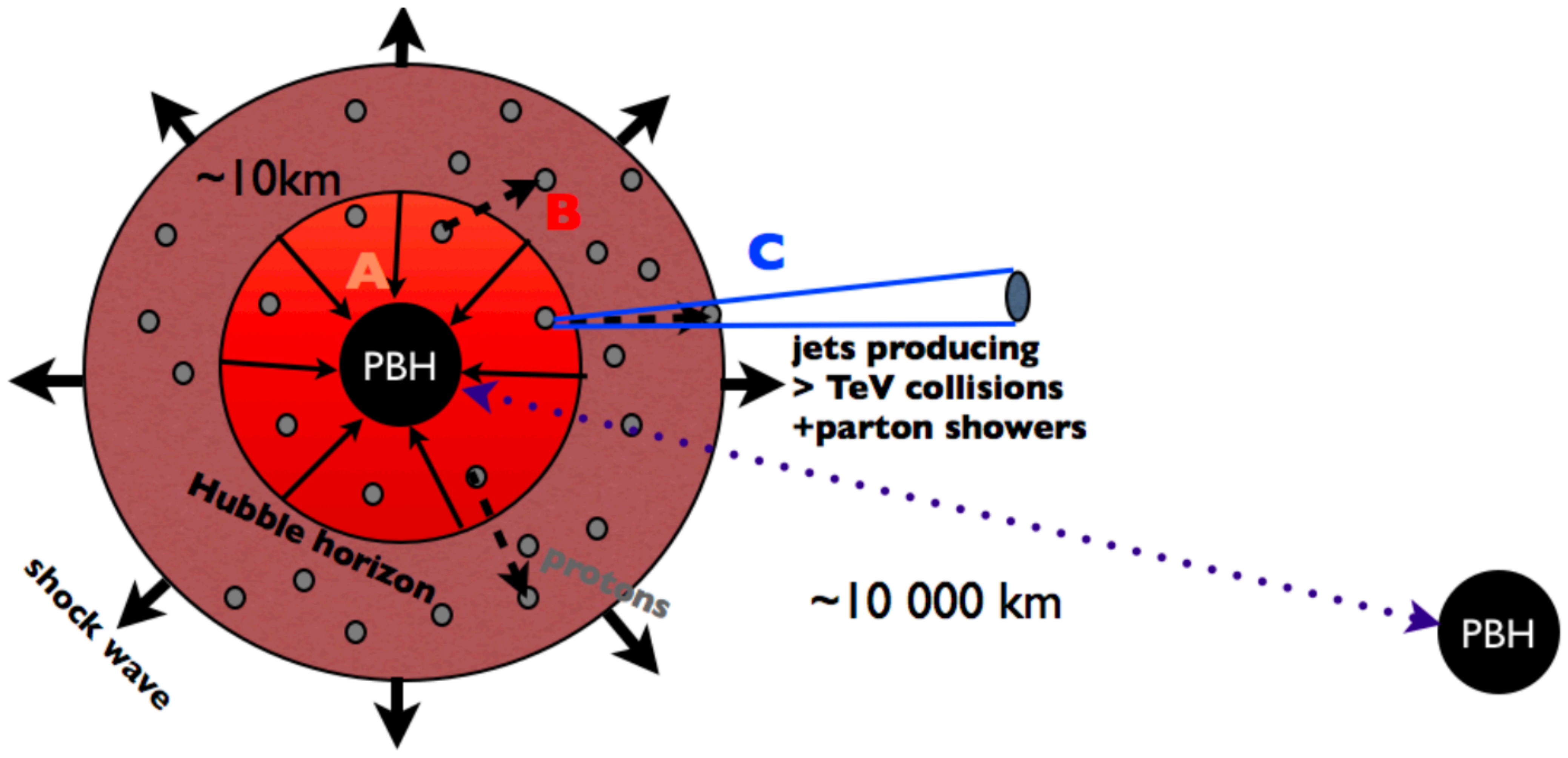


Image credit: Garcia-Bellido, Carr, Cleese

☑ Baryon number violation

$T > T_{EW}$ sphalerons unsuppressed in hotspot

☑ C & CP-violation

$$\delta_{\rm CP}(T) = 3 \times 10^{-5} \left(\frac{20.4\,\mathrm{GeV}}{T^{12}} \right)$$

Farrar & Shaposhnikov

☑ Departure from thermal equilibrium

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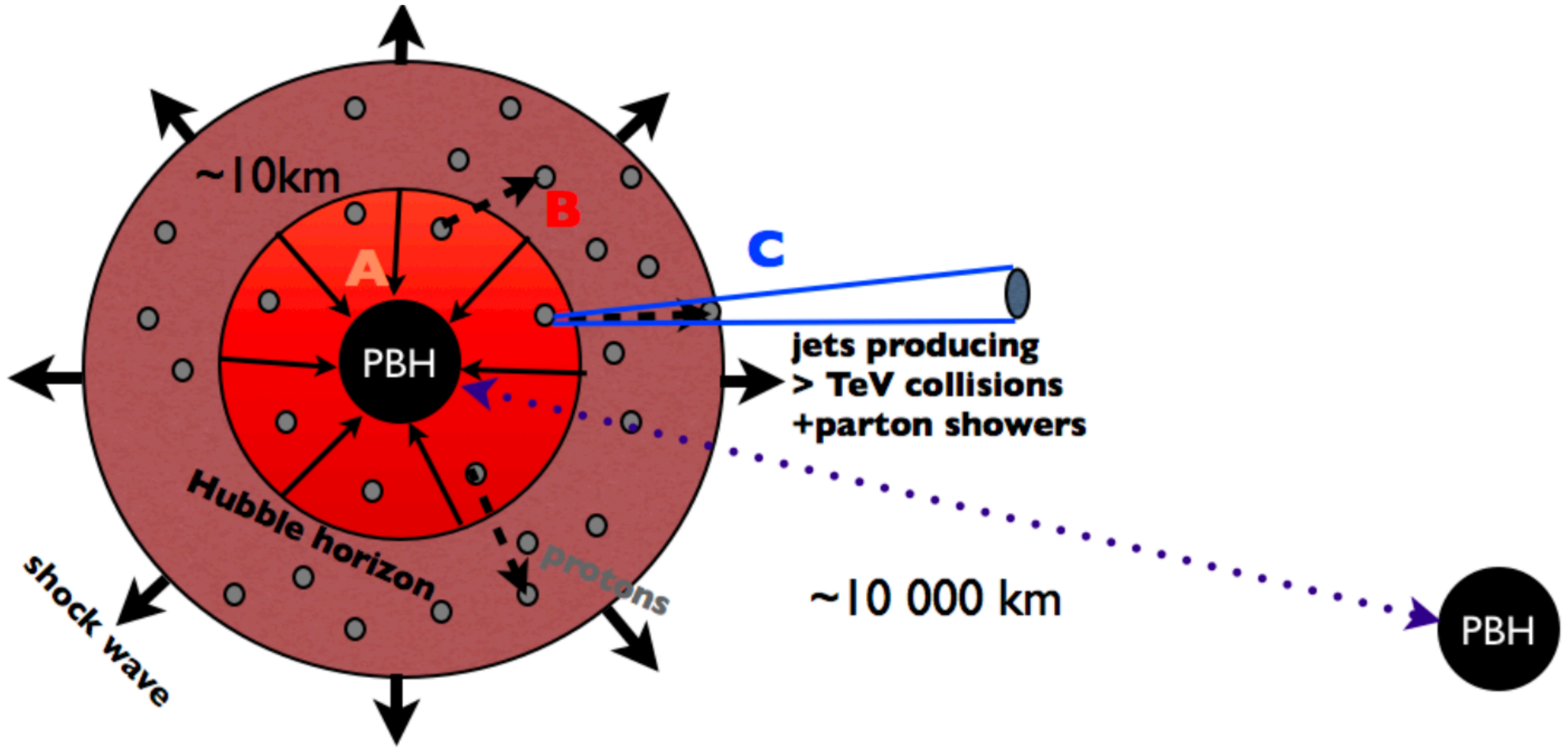

Image credit: Garcia-Bellido, Carr, Cleese

$$\eta_B \approx \frac{7 n_{\mathrm{par}}}{s} \times \Gamma_{\mathrm{sph}}\left(T_{\mathrm{eff}}\right) V_{\mathrm{H}} \Delta t \times \delta_{\mathrm{CP}}$$

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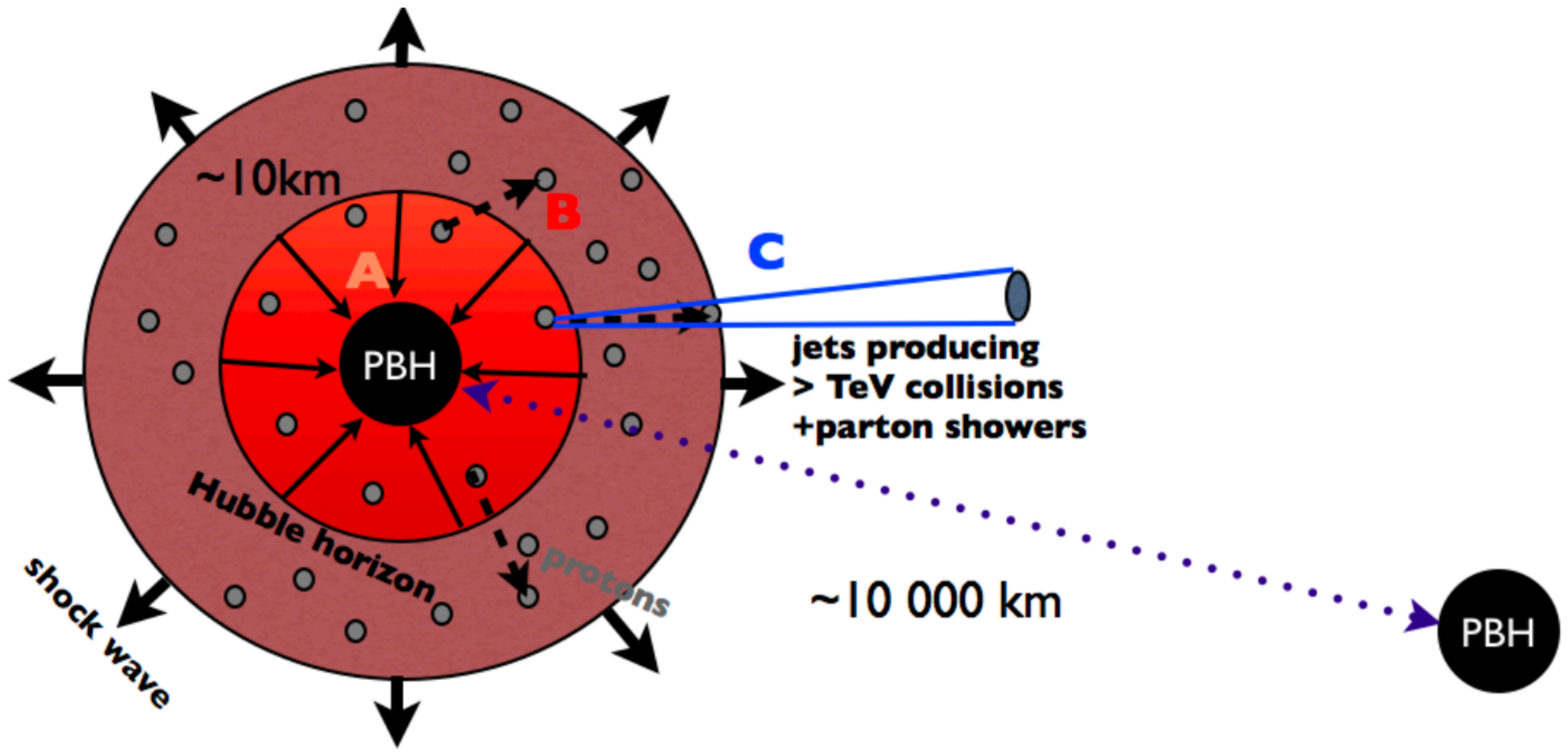

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Effective temperature of

Jet $\sim \mathrm{TeV} \implies \delta_{\rm CP} \sim \mathcal{O}(1)$

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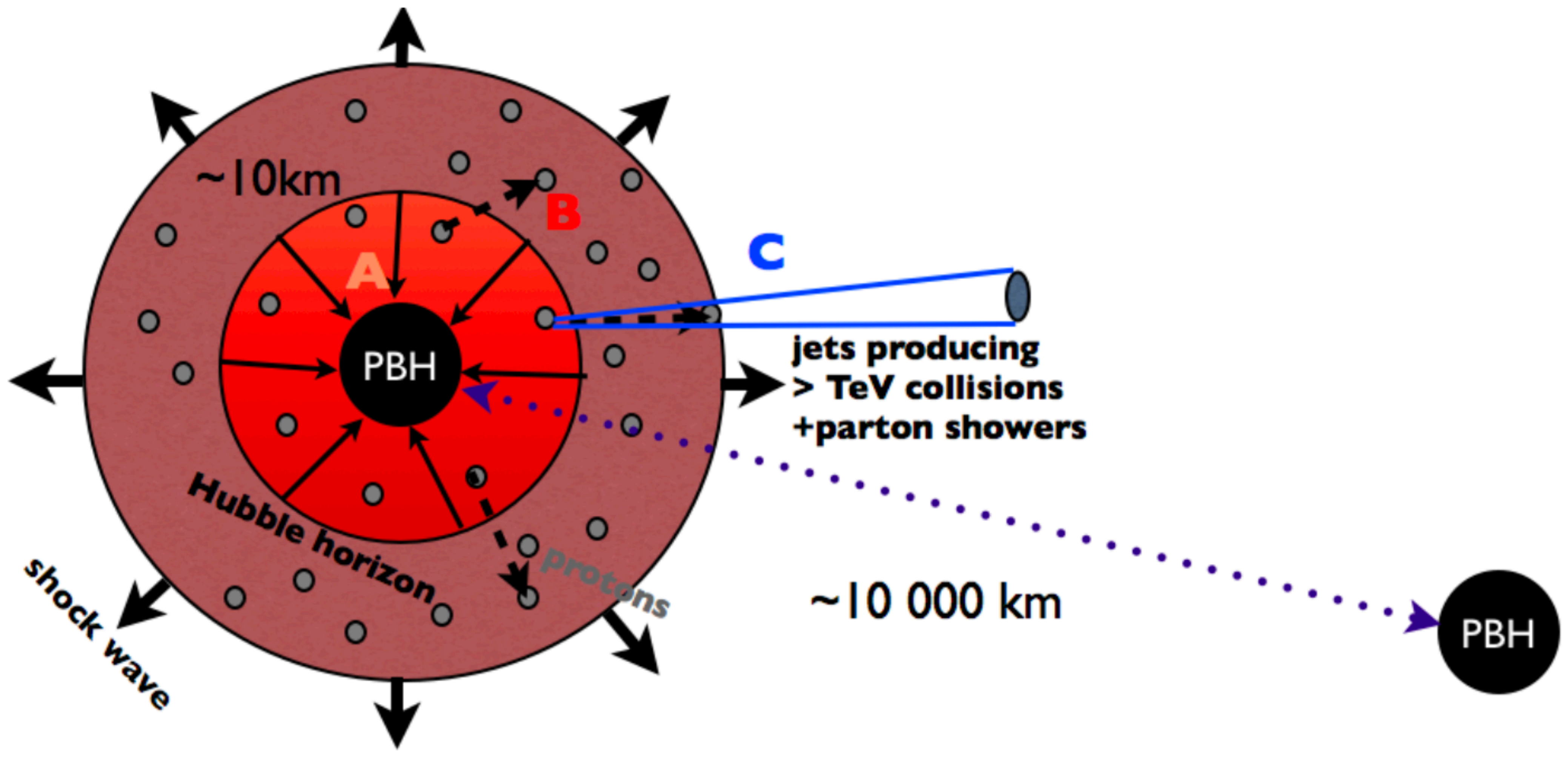

Image credit: Garcia-Bellido, Carr, Cleese

Duration of sphaleron process

$$\Delta t \propto \frac{1}{T_{\rm sph}}$$

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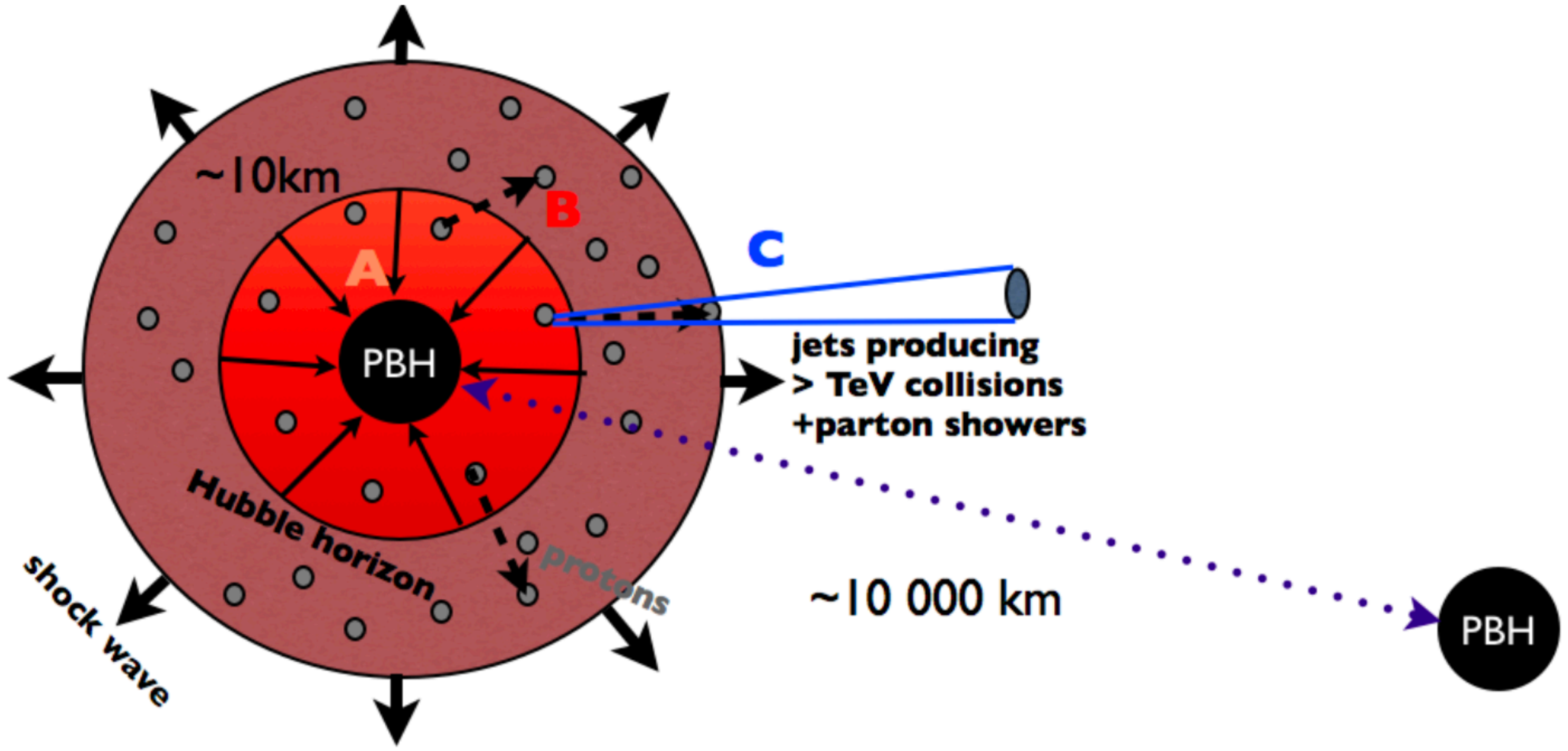

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$\Gamma_{\rm sph} \sim \alpha_{\rm W}^4 T_{\rm eff}^4$

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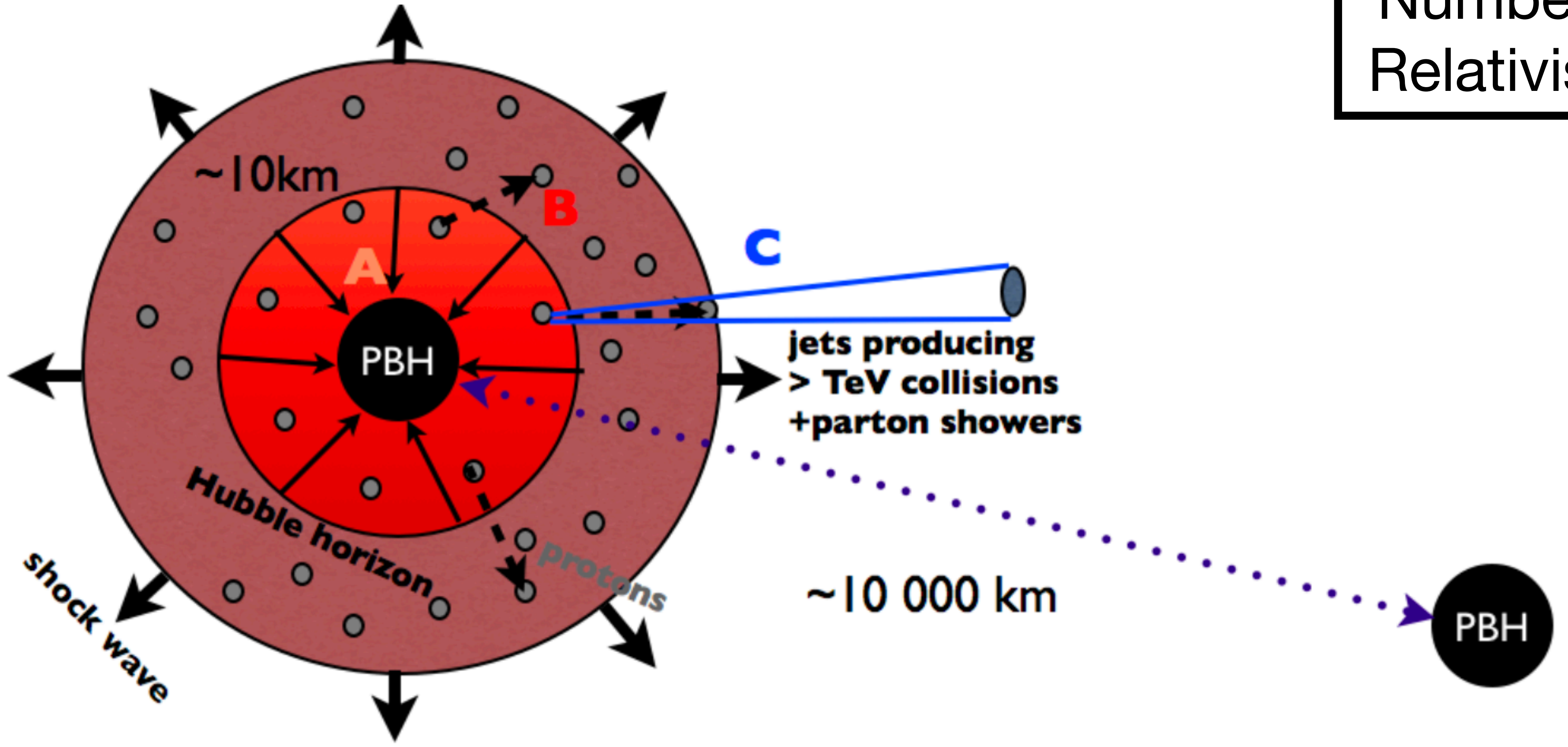

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Number density of Relativistic Partons

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Effective temperature of Jet $\sim \mathrm{TeV} \implies \delta_{\rm CP} \sim \mathcal{O}(1)$

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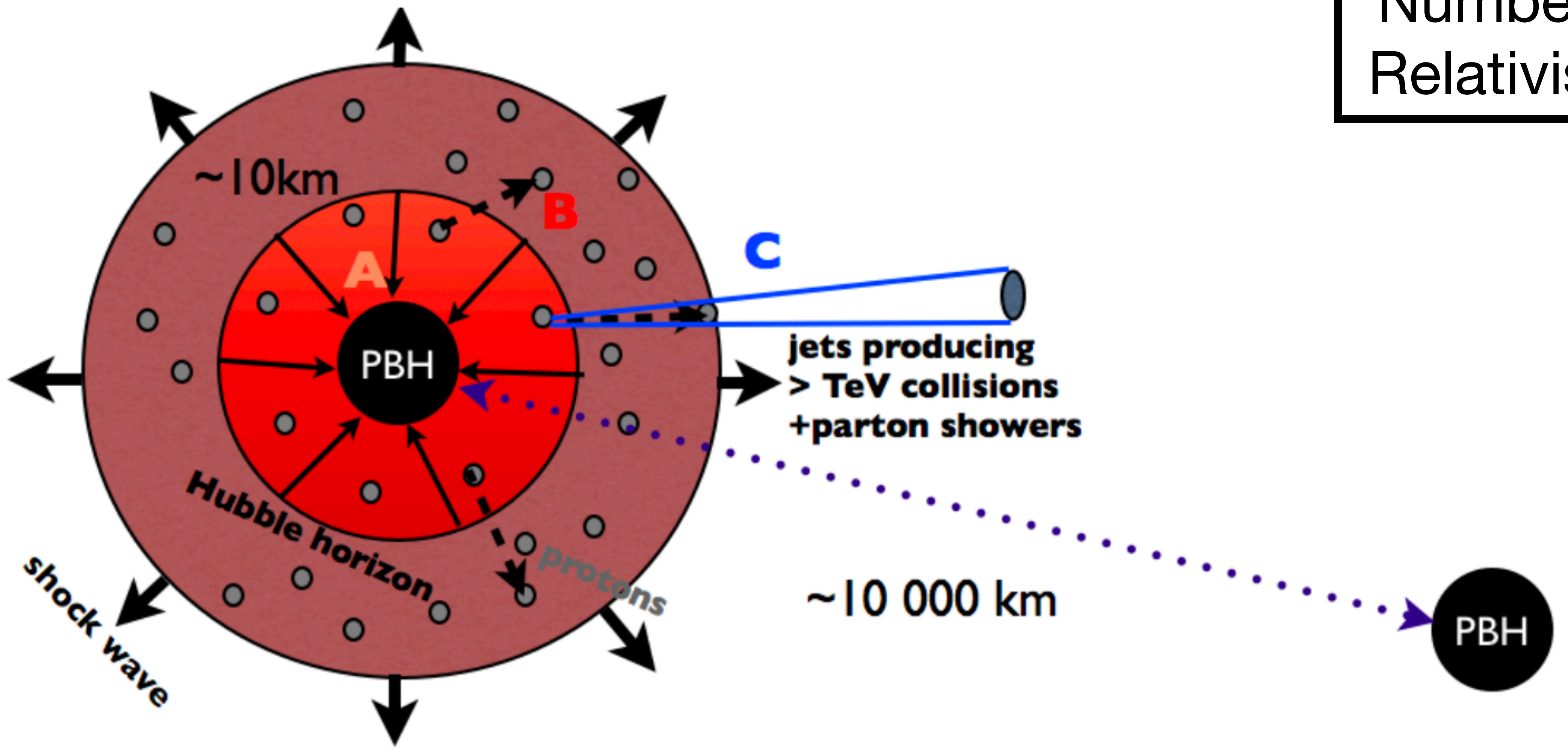

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$$\eta_B \approx \frac{7 n_{\rm par}}{s} \times \Gamma_{\rm sph}\left(T_{\rm eff}\right) V_{\rm H} \Delta t \times \delta_{\rm CP}$$

Entropy density of surrounding plasma
At much cooler temp

Effective temperature of
Jet $\sim \mathrm{TeV} \implies \delta_{\rm CP} \sim \mathcal{O}(1)$

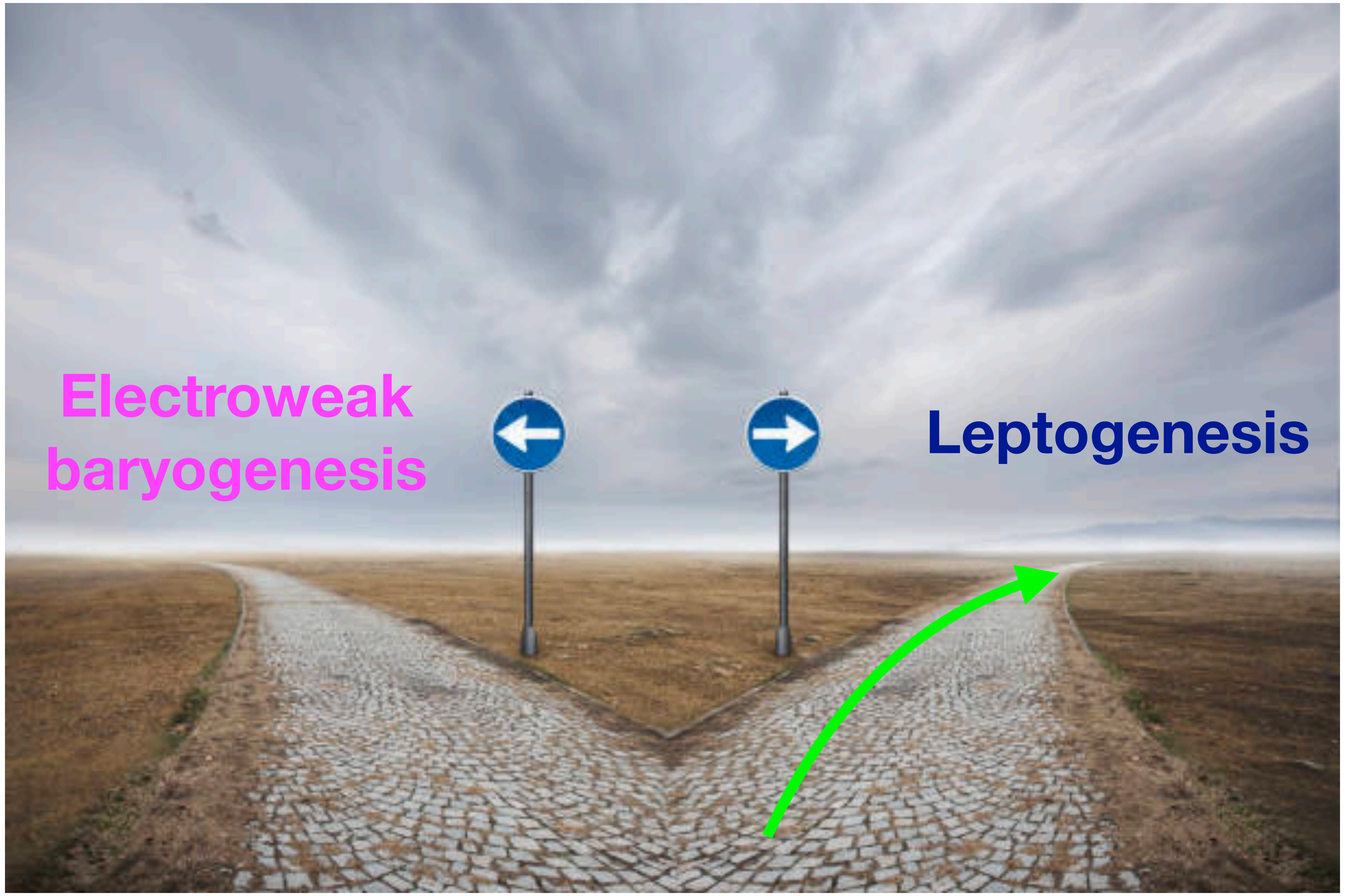
Hot Spot Electroweak Baryogenesis Summary

- If PBHs produce all of the DM then $\beta \sim 10^{-9}$. Locally around hotspot Baryon asymmetry $\sim \mathcal{O}(1)$ and observed η_B comes from rareness of PBHs

Qualitative differences from typical EWBG:

- BAU is created at QCD PT, for baryogenesis this is at a very low scale
- SM provides CP-violation, in fact (almost) no new physics required!
- More complex dynamics since surrounding plasma is in a confined phase
  Solving transport equations highly non-trivial
- First order phase transition not necessary
- See also more recent work by Flores, Kusenko, Pearce & White (2208.09789)

Popular Theories of Baryogenesis

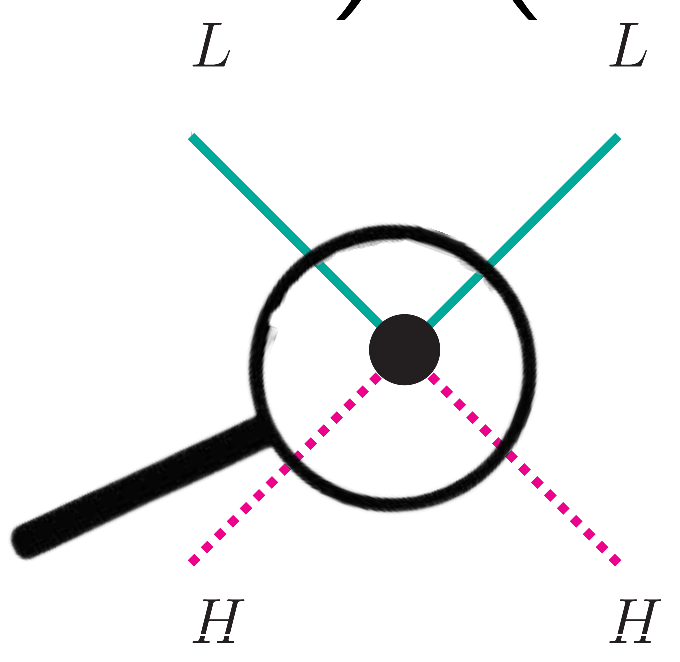


Leptogenesis

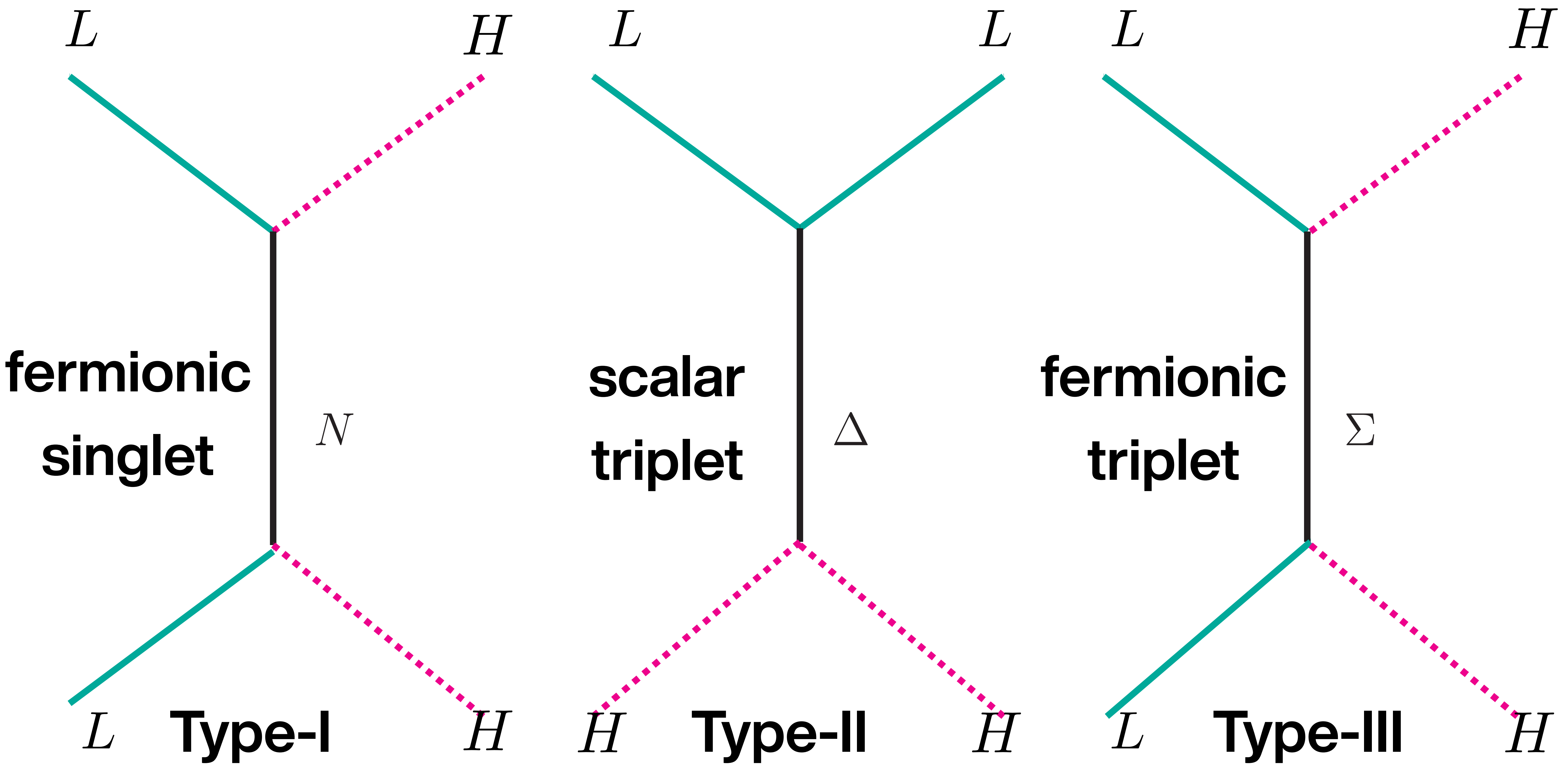
Fukugita & Yanagida (1986)

- Theory which simultaneously explains small neutrino masses and BAU

$$\mathcal{L}_5 = \frac{Y_\nu}{2M}\left(\overline{L^c}\tilde{H}^*\right)\left(\tilde{H}^\dagger L\right)$$



- Introduce lepton number violating operator & UV completion explanation of m_ν



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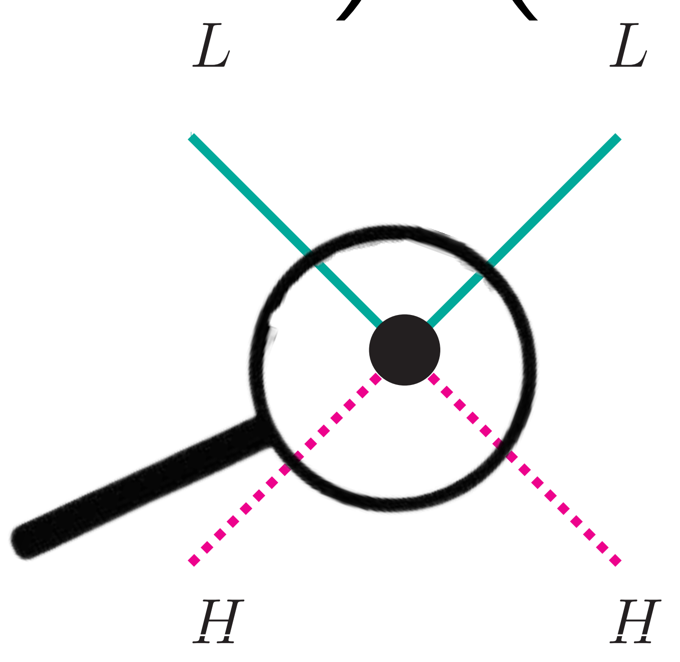

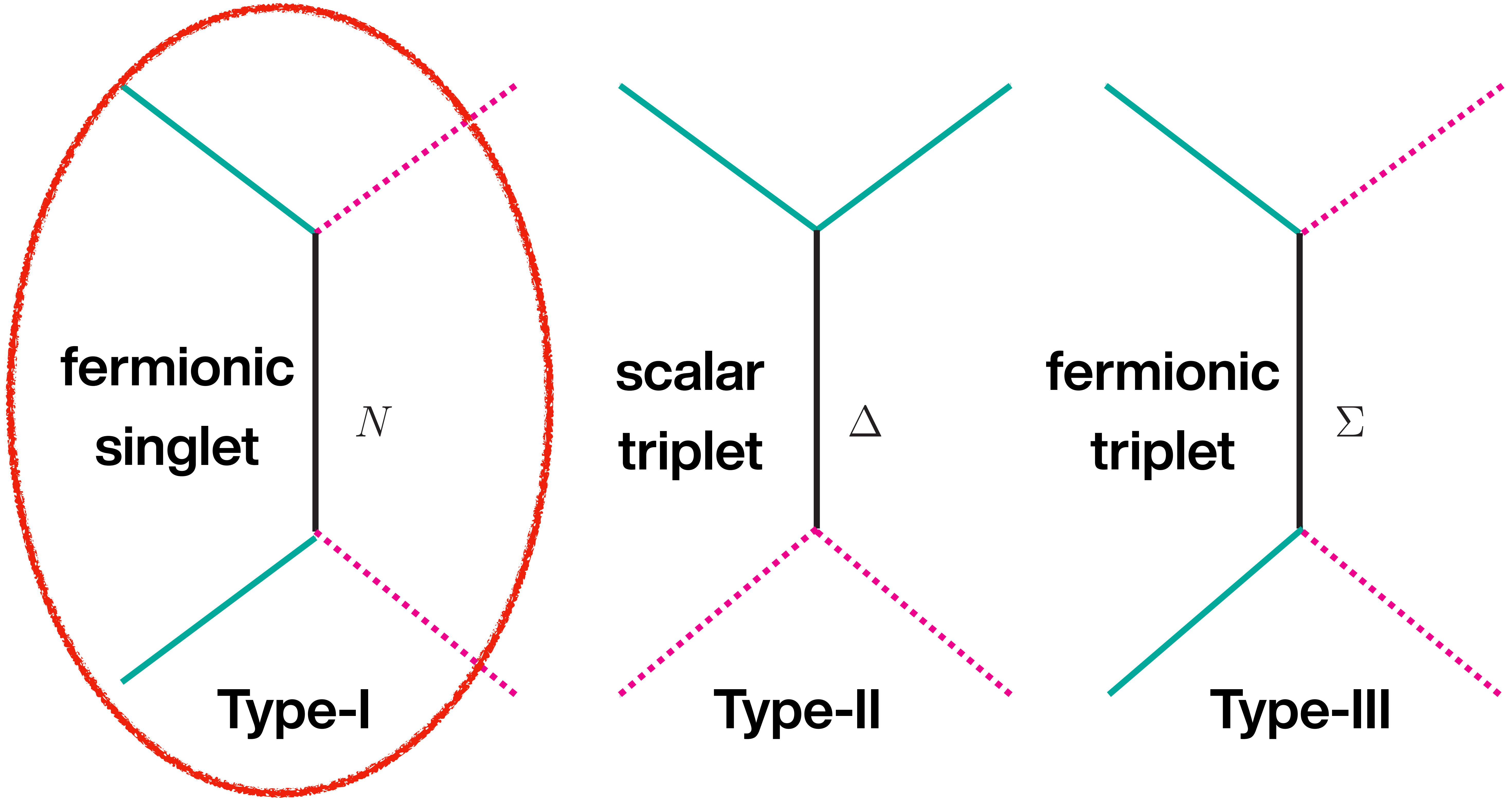

fermionic singlet

scalar triplet

fermionic triplet

Type-I

Type-II

Type-III

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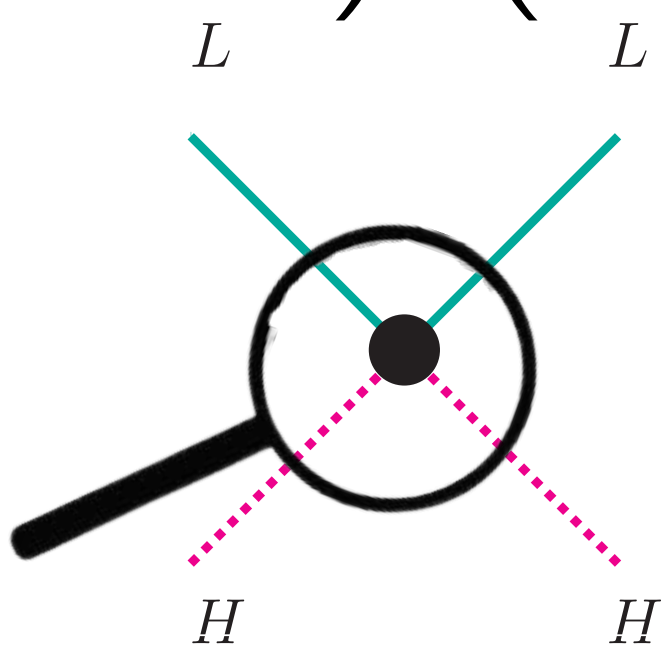

$$\mathcal{L} = Y_\nu \bar{L}\tilde{H}N - \frac{1}{2}M_N\overline{N^c}N$$

$$= -\frac{1}{2}\left(\bar{\nu}_L, \overline{N^c}\right)\begin{pmatrix} 0 & \frac{Y_\nu v}{\sqrt{2}} \\ \frac{Y_\nu v}{\sqrt{2}} & M_N \end{pmatrix}\begin{pmatrix} \nu_L^c \\ N \end{pmatrix}$$

$$m_\nu = \frac{Y_\nu^2 v^2}{2M_N} \sim 0.1\text{eV} \implies M_N \sim 10^{14}\,\text{GeV}$$

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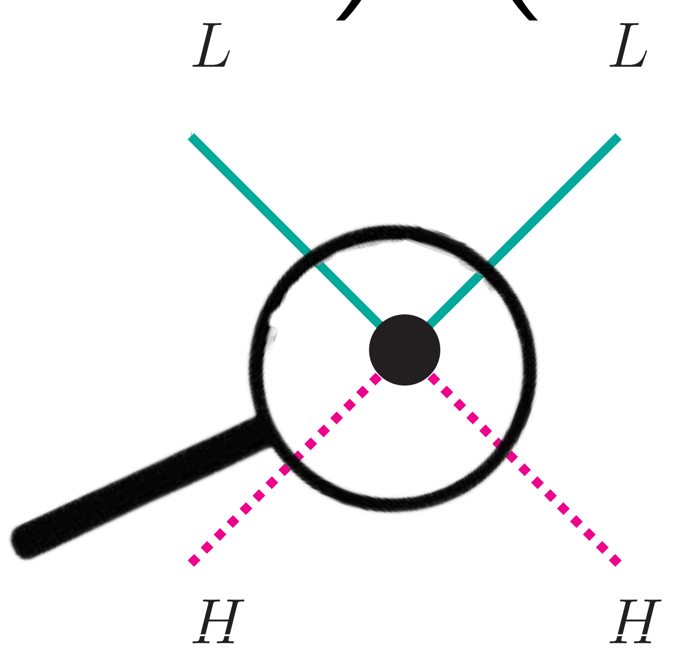

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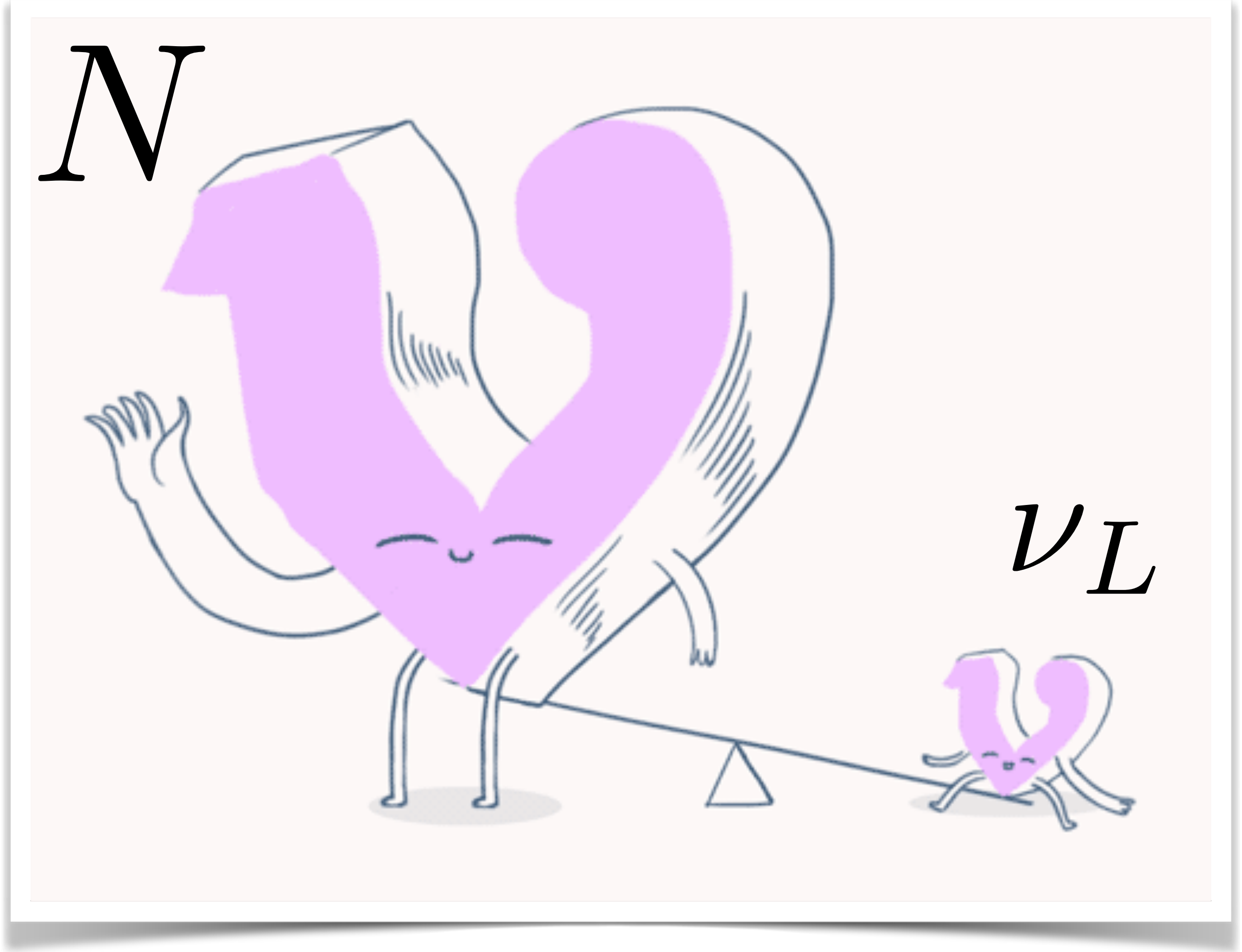

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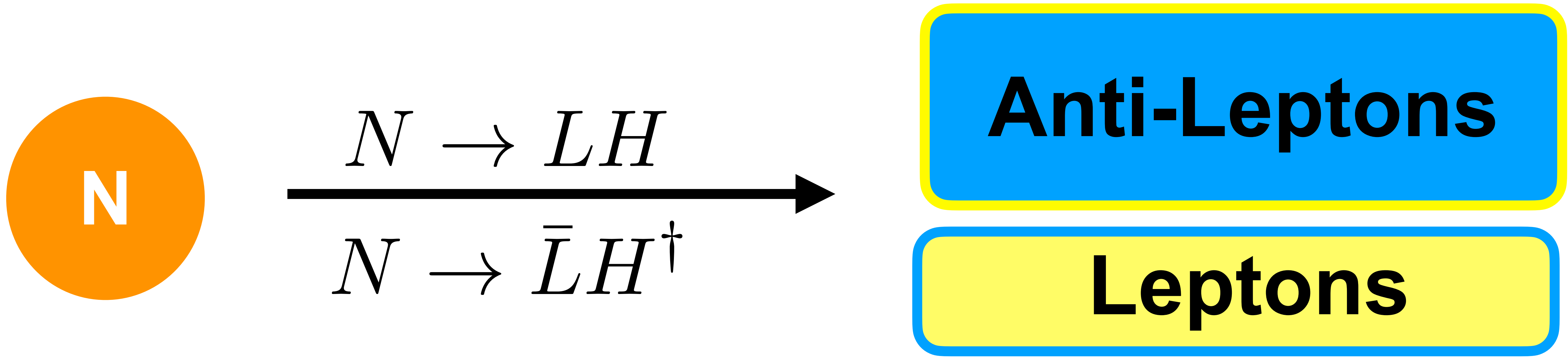


N

$N \to LH$

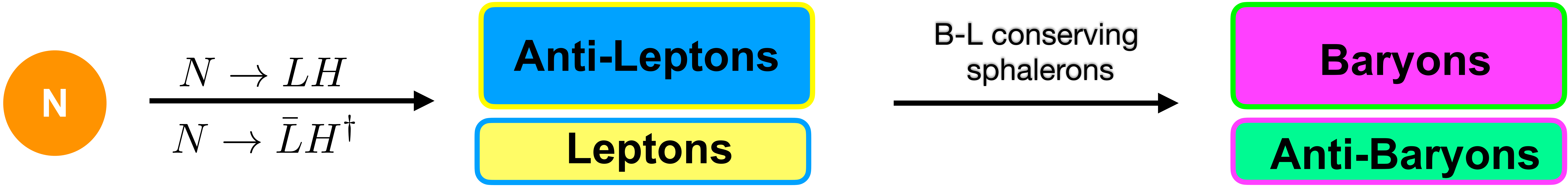
$N \to \bar{L}H^\dagger$

Anti-Leptons

Leptons

Leptogenesis

Fukugita & Yanagida (1986)



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Anti-Leptons

Leptons

B-L conserving sphalerons

Baryons

Anti-Baryons

Leptogenesis

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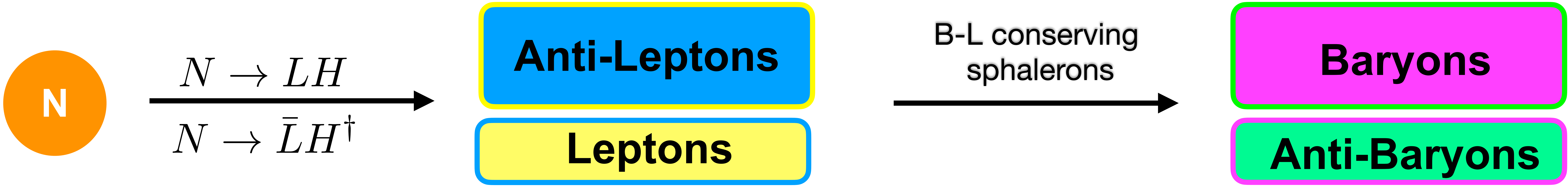

N

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Anti-Leptons

Leptons

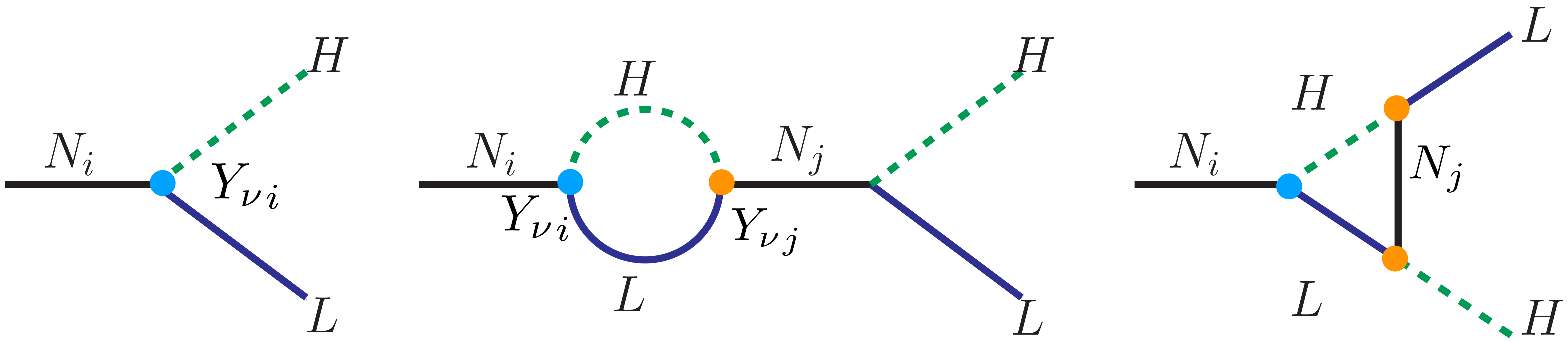
B-L conserving sphalerons

Baryons

Anti-Baryons

Decay asymmetry from interference between tree and loop level diagrams

Covi, Roulet, Vissani



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

Leptogenesis

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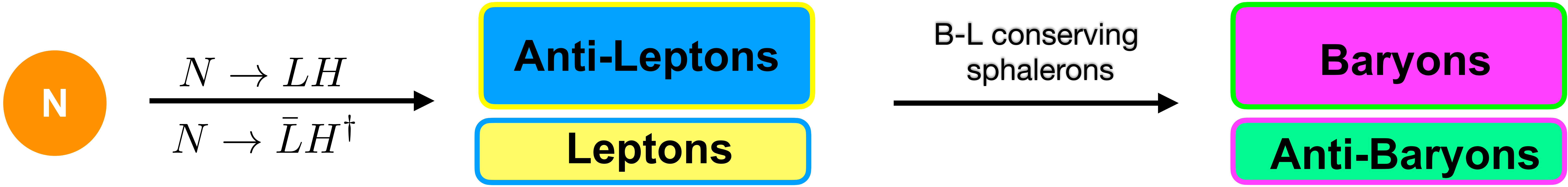

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Anti-Leptons

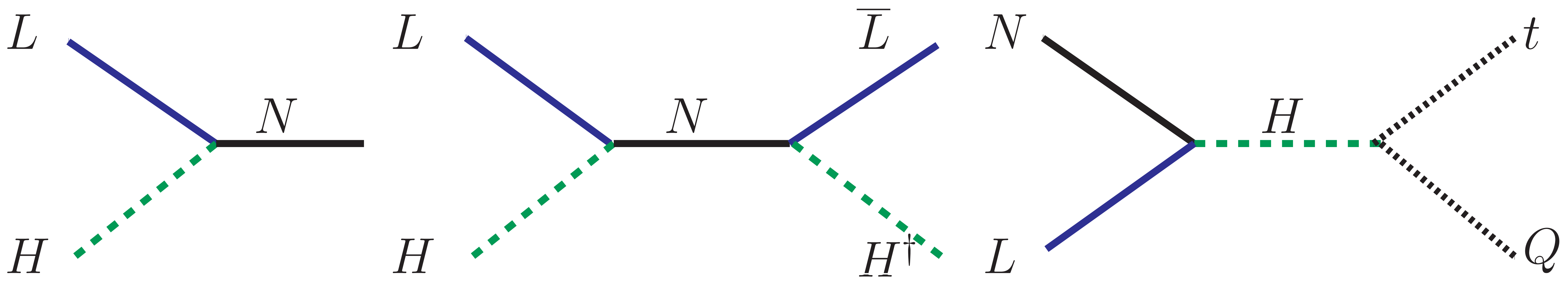
Leptons

B-L conserving sphalerons

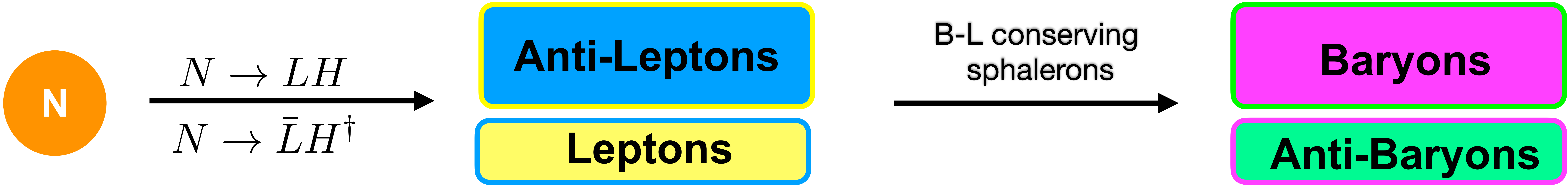
Baryons

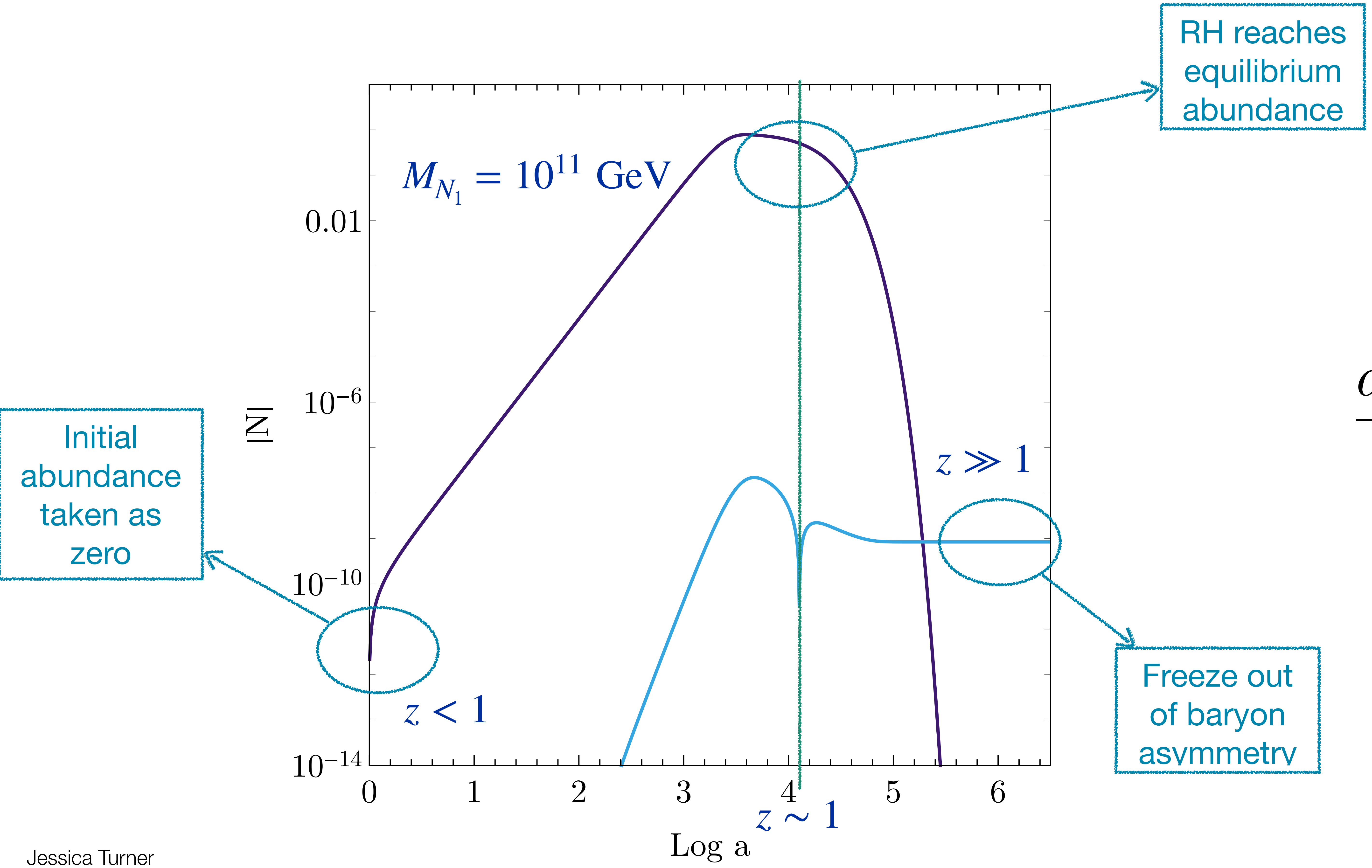
Anti-Baryons

Washout and scattering processes



Leptogenesis





RH reaches equilibrium abundance

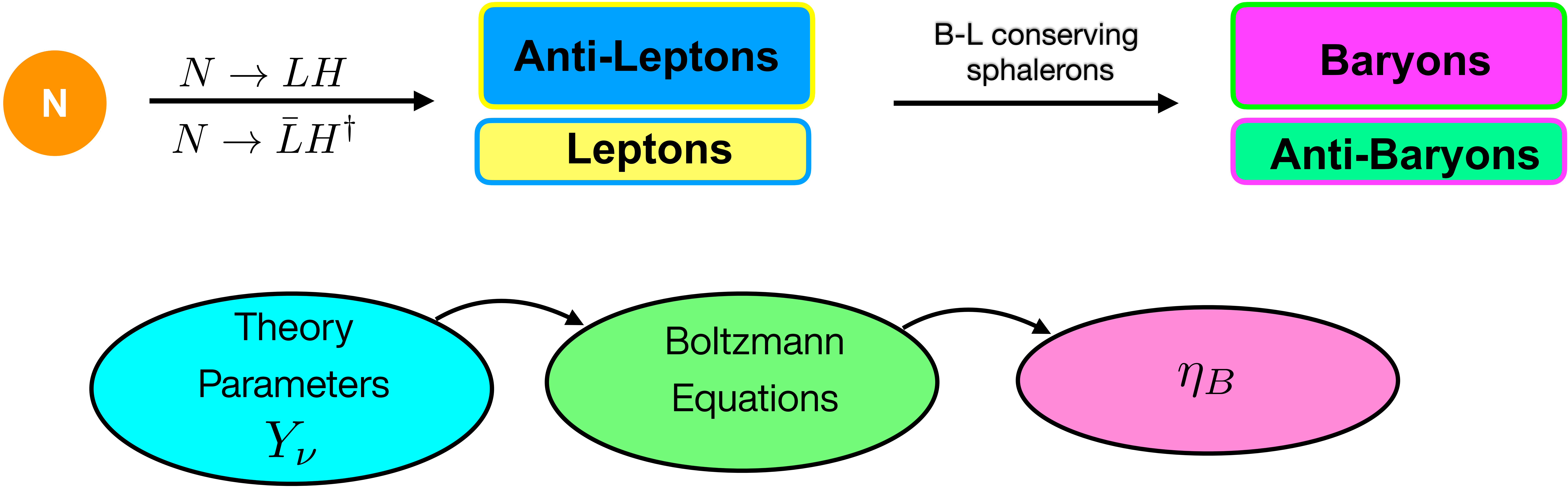
Initial abundance taken as zero

Freeze out of baryon asymmetry

$$\frac{dN_N}{dz} = -D(z)\left(N_N - N_N^{\rm eq}\right)$$

$$\frac{dN_{B-L}}{dz} = \underbrace{\epsilon D(z)\left(N_N - N_N^{\rm eq}\right)}_{\text{Source Term}} - \underbrace{W(z)N_{B-L}}_{\text{Sink Term}}$$

Leptogenesis



N

$N \to LH$

$N \to \bar{L}H^\dagger$

Anti-Leptons

Leptons

B-L conserving sphalerons

Baryons

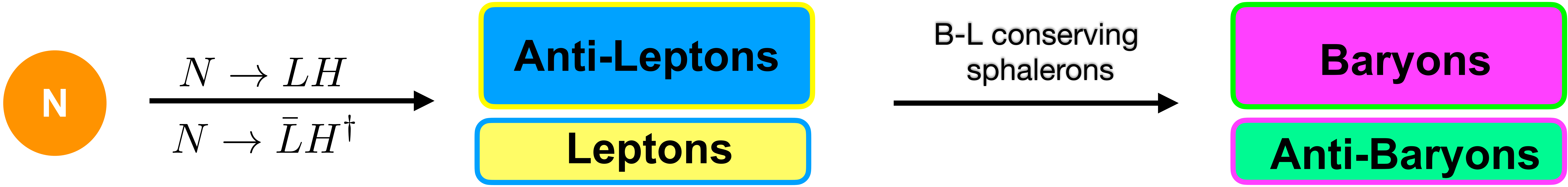
Anti-Baryons

Theory Parameters Y_ν

Boltzmann Equations

η_B

Leptogenesis



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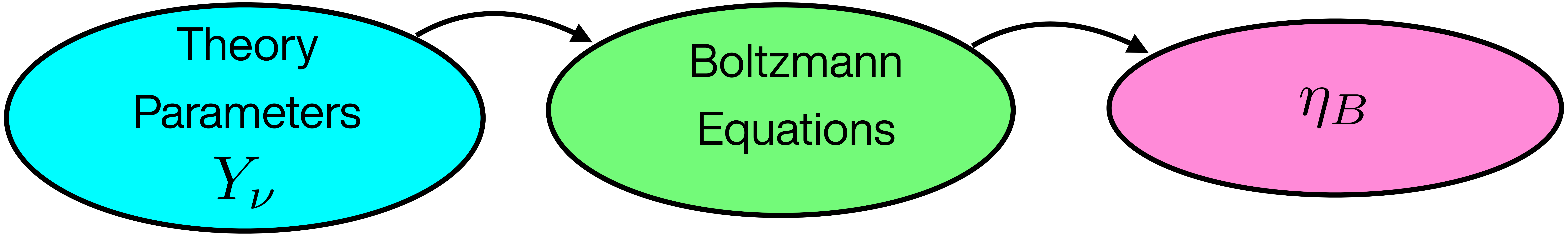

Theory Parameters Y_ν

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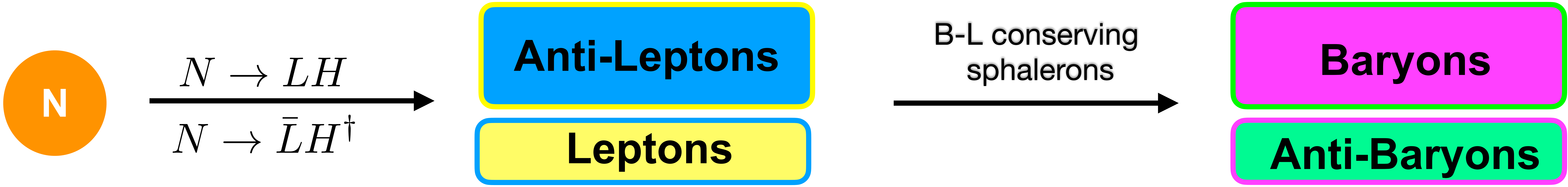
η_B

$$Y_\nu = \frac{1}{v} U_{\text{PMNS}} \sqrt{m} R^T \sqrt{M}$$

Leptogenesis



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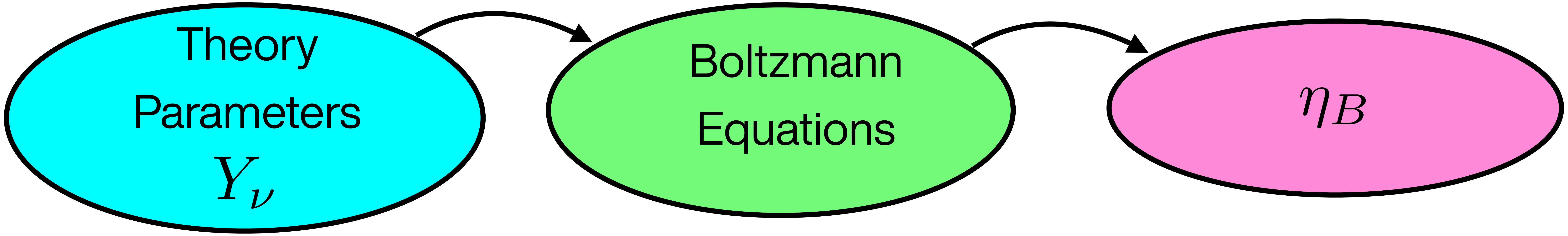

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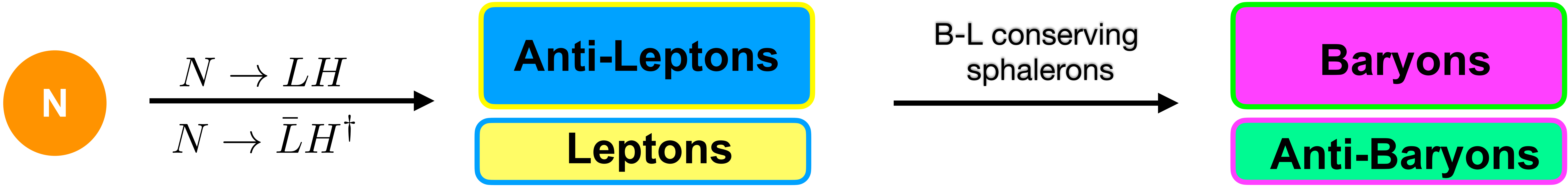
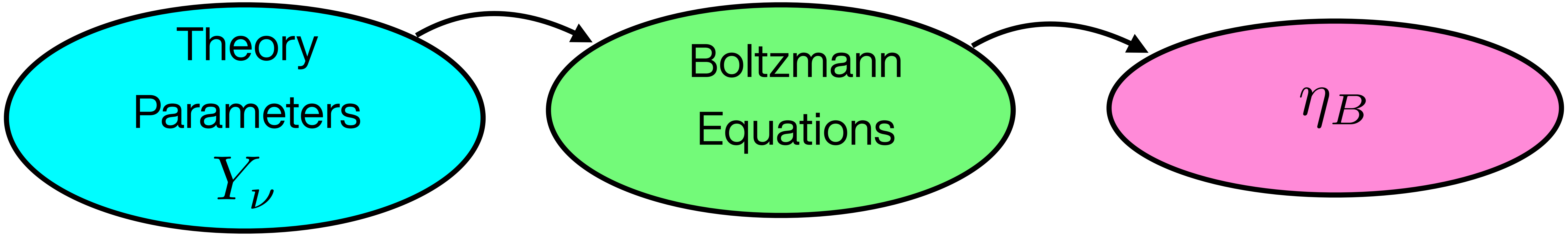
9 low-scale neutrino parameters

Leptogenesis

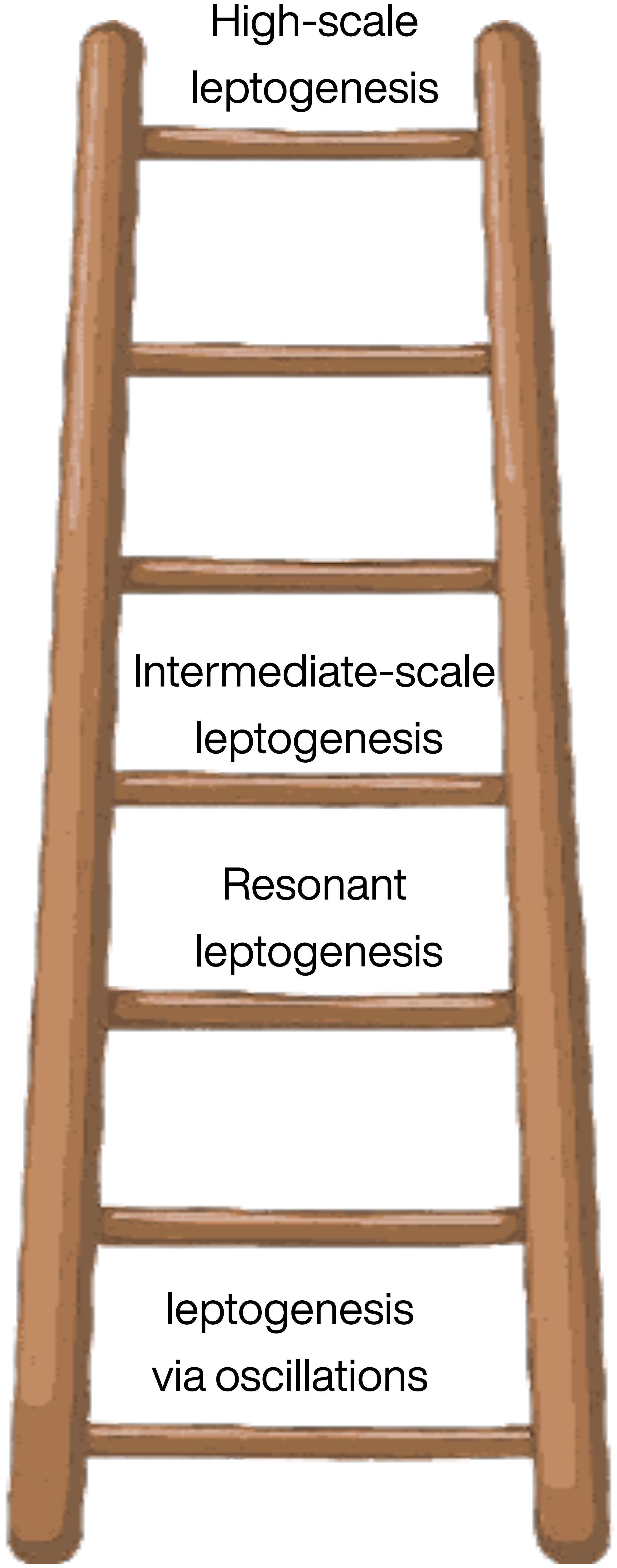




$$Y_\nu = \frac{1}{v} U_{\text{PMNS}} \sqrt{m} R^T \sqrt{M}$$

9 high-scale parameters

Mass RHN



$\mathcal{O}(10^{12})\ \mathrm{GeV}$

Fukugida & Yanagida

High-scale leptogenesis

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

Racker, Rius & Pena

Intermediate-scale leptogenesis

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

Pilaftis & Underwood

Resonant leptogenesis

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

Akhmedov, Rubakov & Smirnov

leptogenesis via oscillations

Mass RHN

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Fukugida & Yanagida

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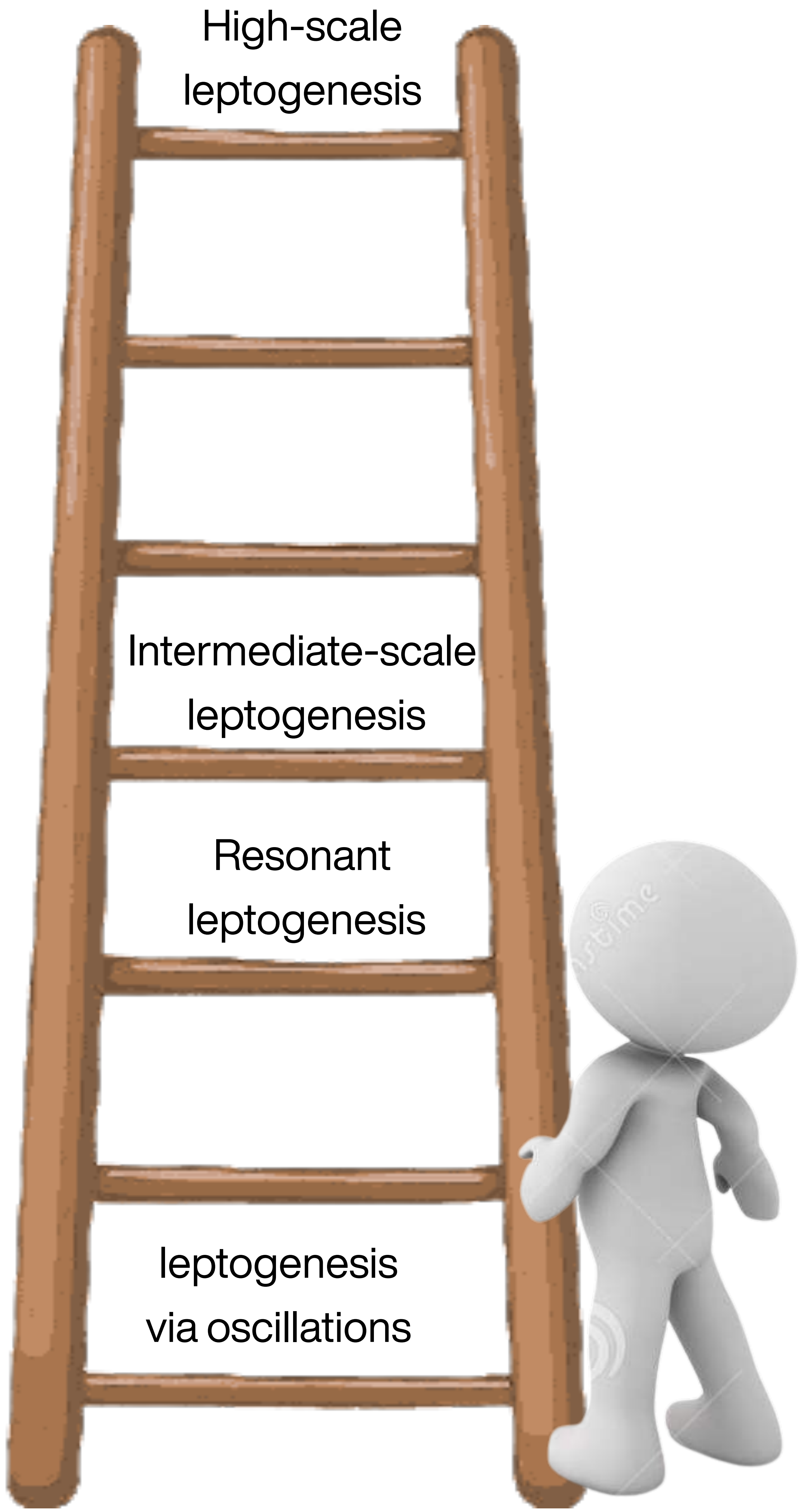


High-scale leptogenesis

Intermediate-scale leptogenesis

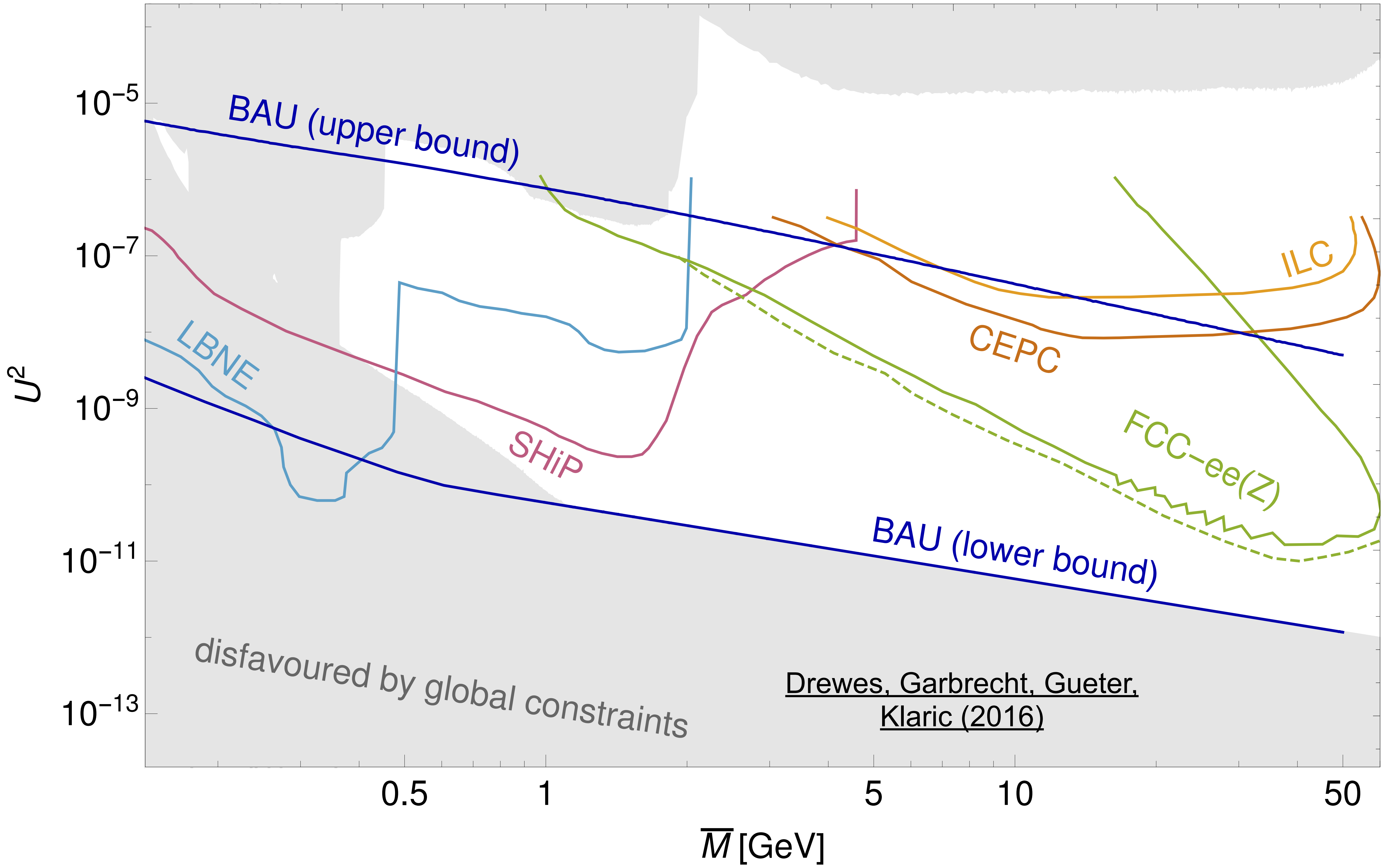
Resonant leptogenesis

leptogenesis via oscillations

- Testable searches for LNV, $\nu 0\beta\beta$, beam dump & oscillation experiments

$$\nu_\alpha = U_{\alpha i}\nu_i + \Theta_{\alpha I} N_I^c$$

$$|U|^2 = \sum_{\alpha I} |\Theta_{\alpha I}|^2 \qquad \overline{M} = \frac{M_1 + M_2}{2}$$



Drewes, Garbrecht, Gueter, Klaric (2016)

Mass RHN

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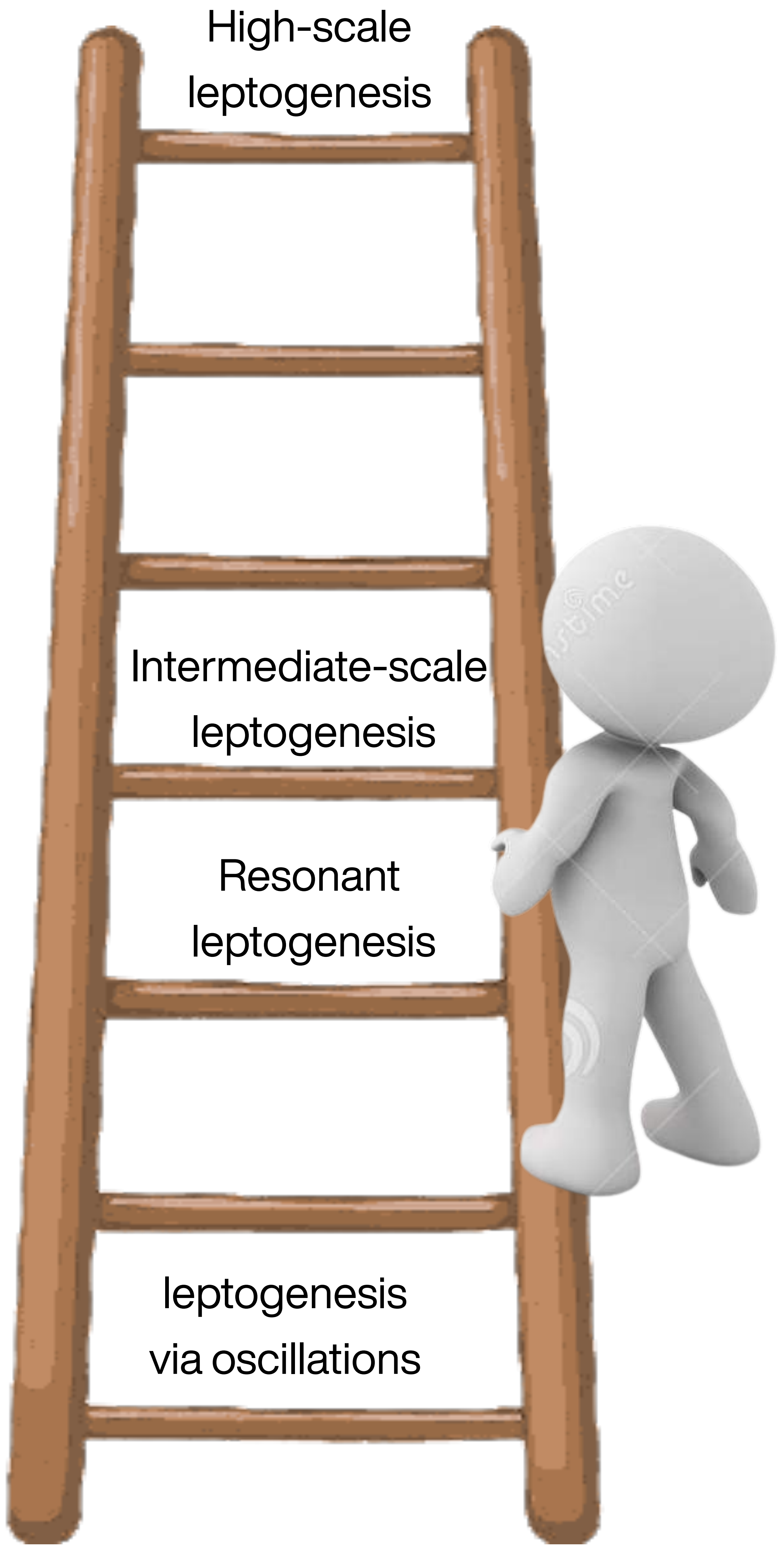


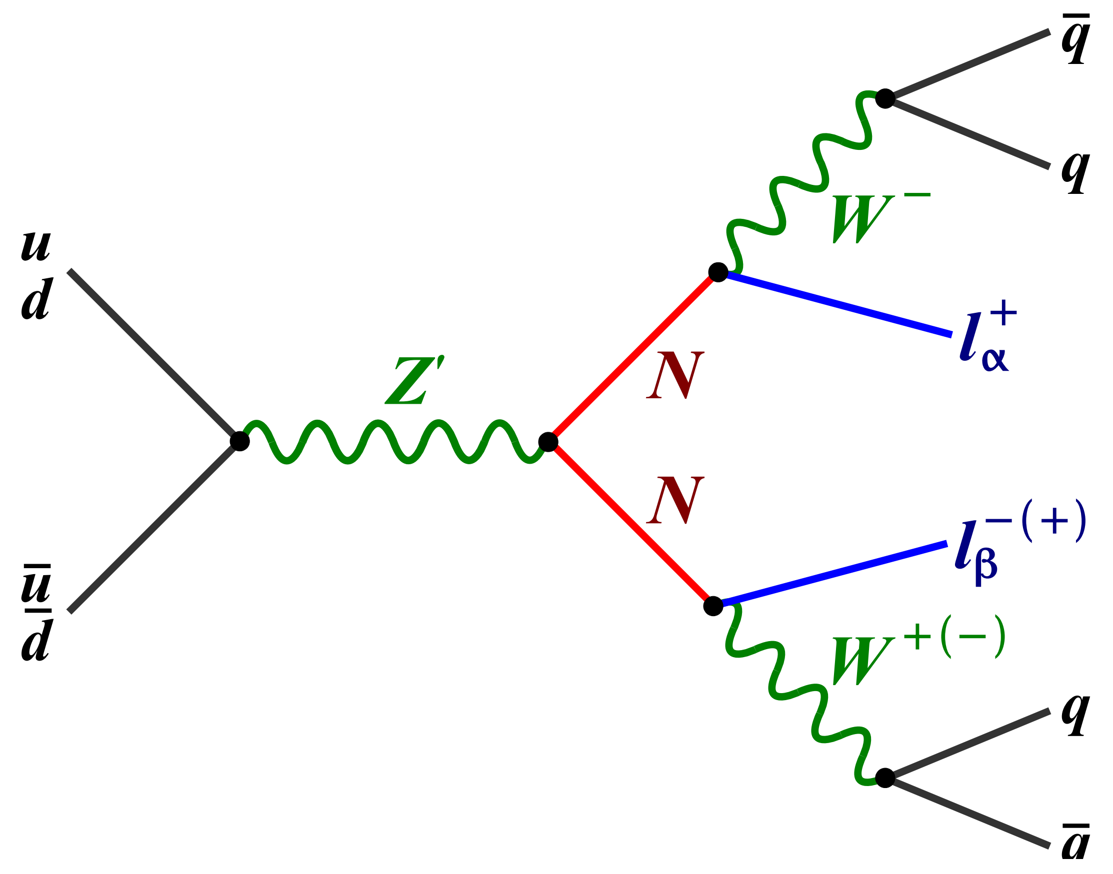
High-scale leptogenesis

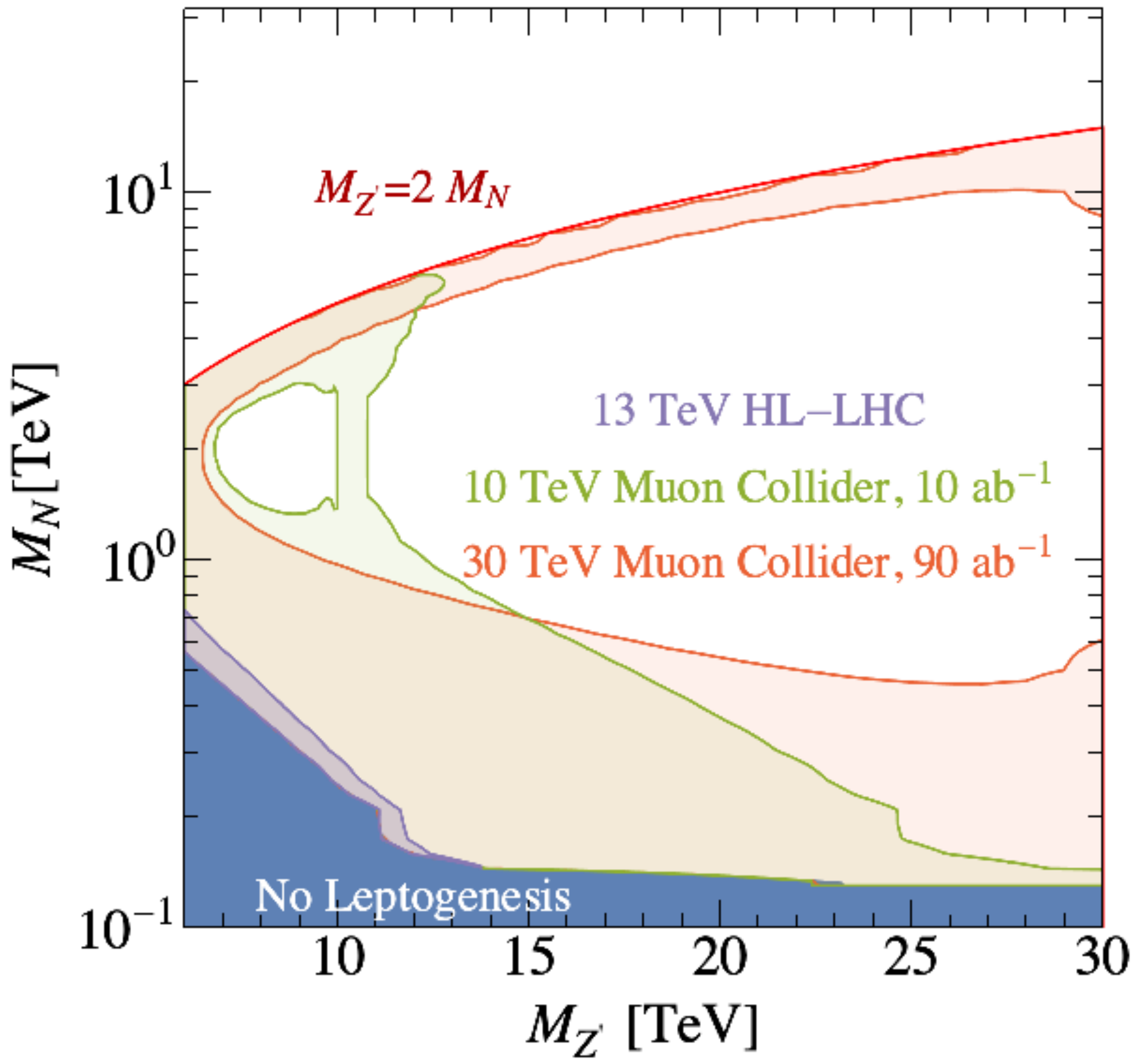
Intermediate-scale leptogenesis

Resonant leptogenesis

leptogenesis via oscillations

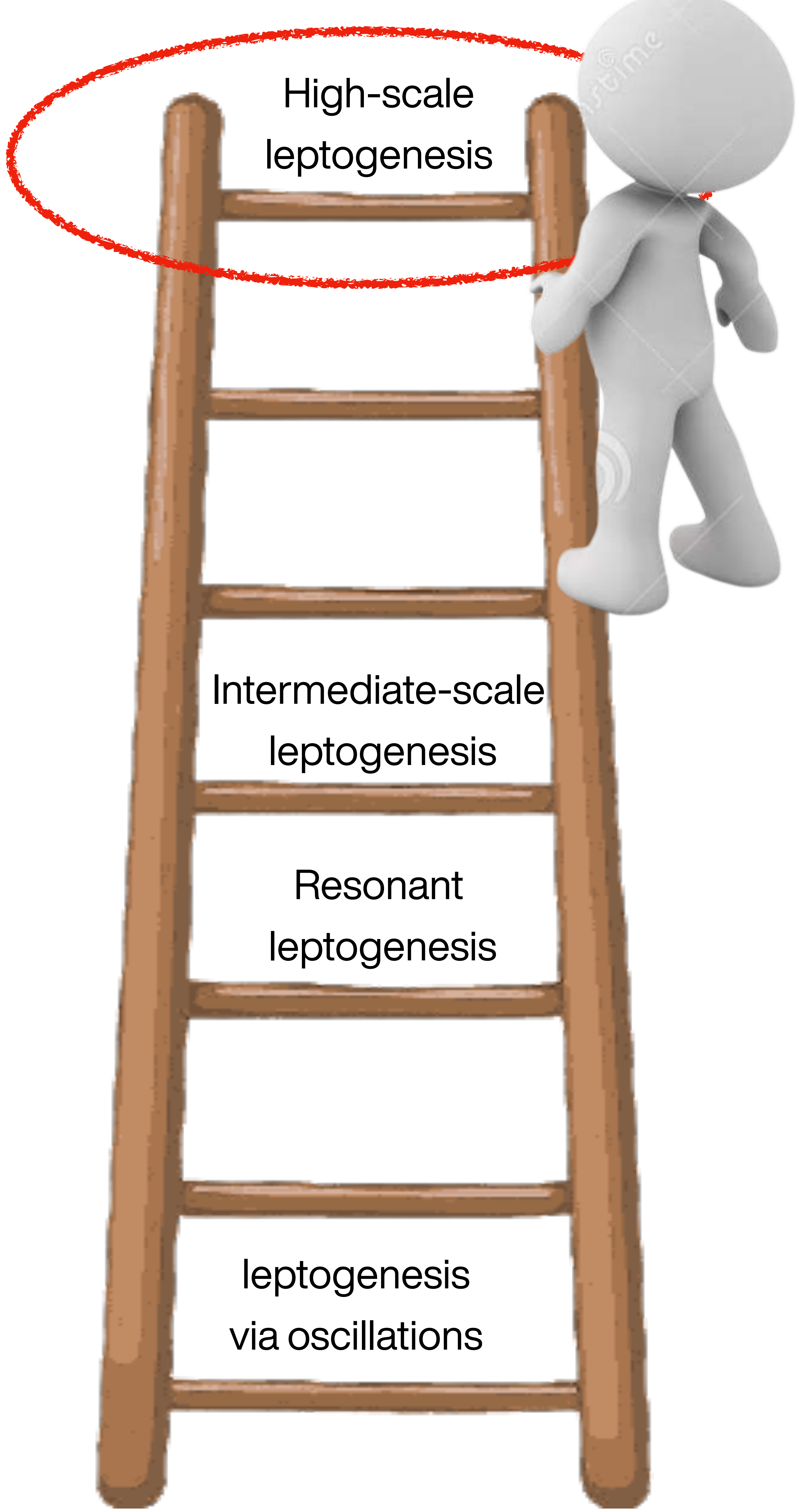
- Only testable at colliders if Z' present
- Can induce the EW scale





Liu, Xie and Yi (2021)

Mass RHN



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Intermediate-scale leptogenesis

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

Pilaftis & Underwood

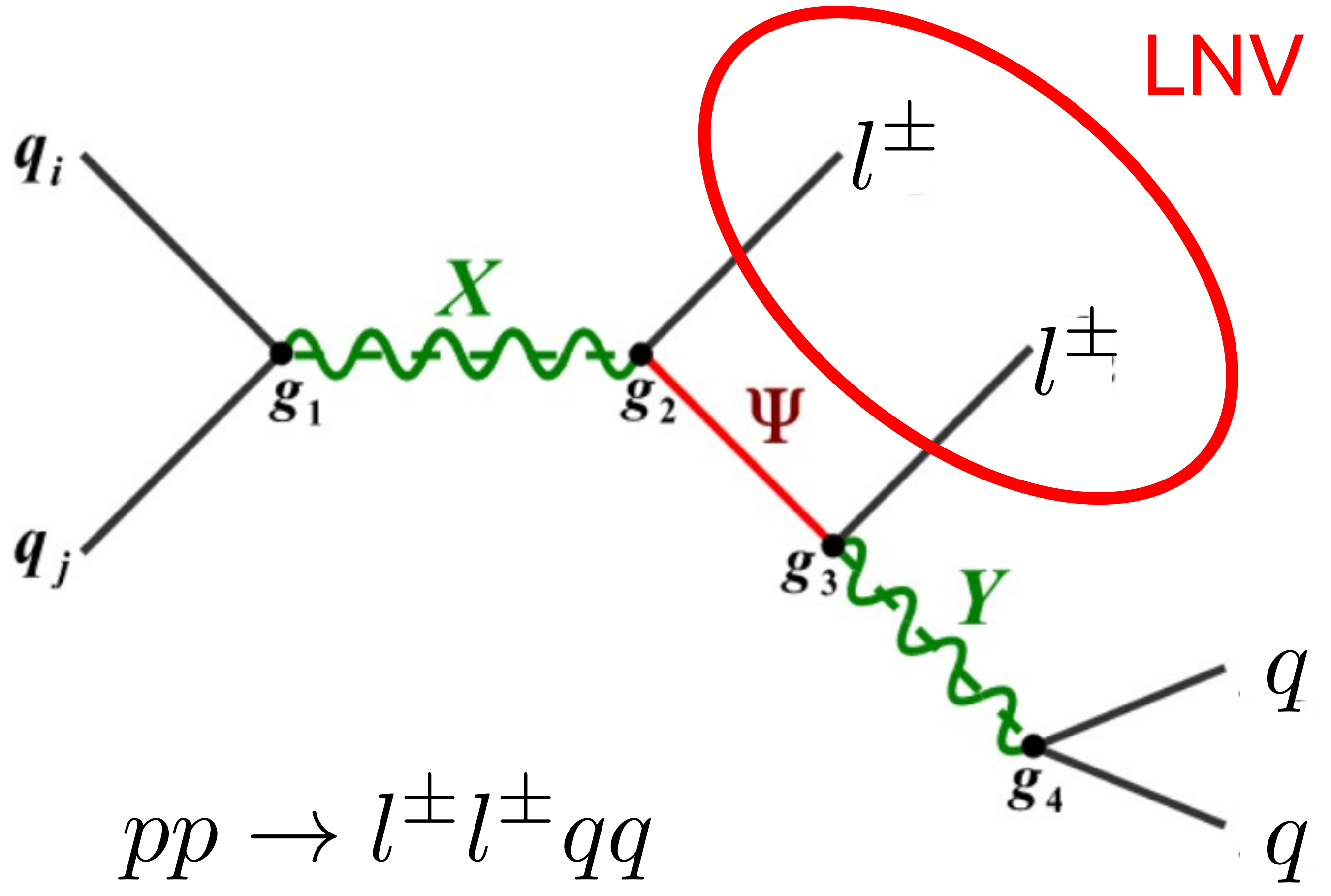
Resonant leptogenesis

$\mathcal{O}(1)$ GeV

Akhmedov, Rubakov & Smirnov

leptogenesis via oscillations

- Impossible to fully test
- Arguably "natural" scale of RHN
- Predicted within many GUTs
- Falsifiable through observation of LNV at colliders



$$pp \to l^{\pm} l^{\pm} qq$$

Deppisch & Harz (2014)

PBH Leptogenesis

Perez-Gonzalez & JT (2020)

- Assume population of Schwarzschild PBHs with monochromatic mass spectrum form after inflation & RHN exists and their decays can lead to a baryon asymmetry
- $T_{PBH} \sim M_N$ athermal production of RHNs from Hawking evaporation & thermal production

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

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B-L asymmetry

From thermal RHNs decays

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B-L asymmetry
From thermal RHNs decays

B-L asymmetry
From PBH RHNs decays

$$\Gamma_{N_1}^{\mathrm{BH}}\left(z_{\mathrm{BH}}\right) \qquad z_{\mathrm{BH}} = \frac{M_N}{T_{BH}}$$

PBH Leptogenesis

Perez-Gonzalez & JT (2020)

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Usual washout from thermal bath

$$aH\frac{dn^{\mathrm{B-L}}}{da} = \epsilon_1\left[\left(n_{N_1}^{\mathrm{TH}} - n_{N_1}^{\mathrm{eq}}\right)\Gamma_{N_1}^{T} + n_{N_1}^{\mathrm{BH}}\Gamma_{N_1}^{\mathrm{BH}}\right] - W_1 n^{\mathrm{B-L}}$$

B-L asymmetry
From PBH RHNs decays

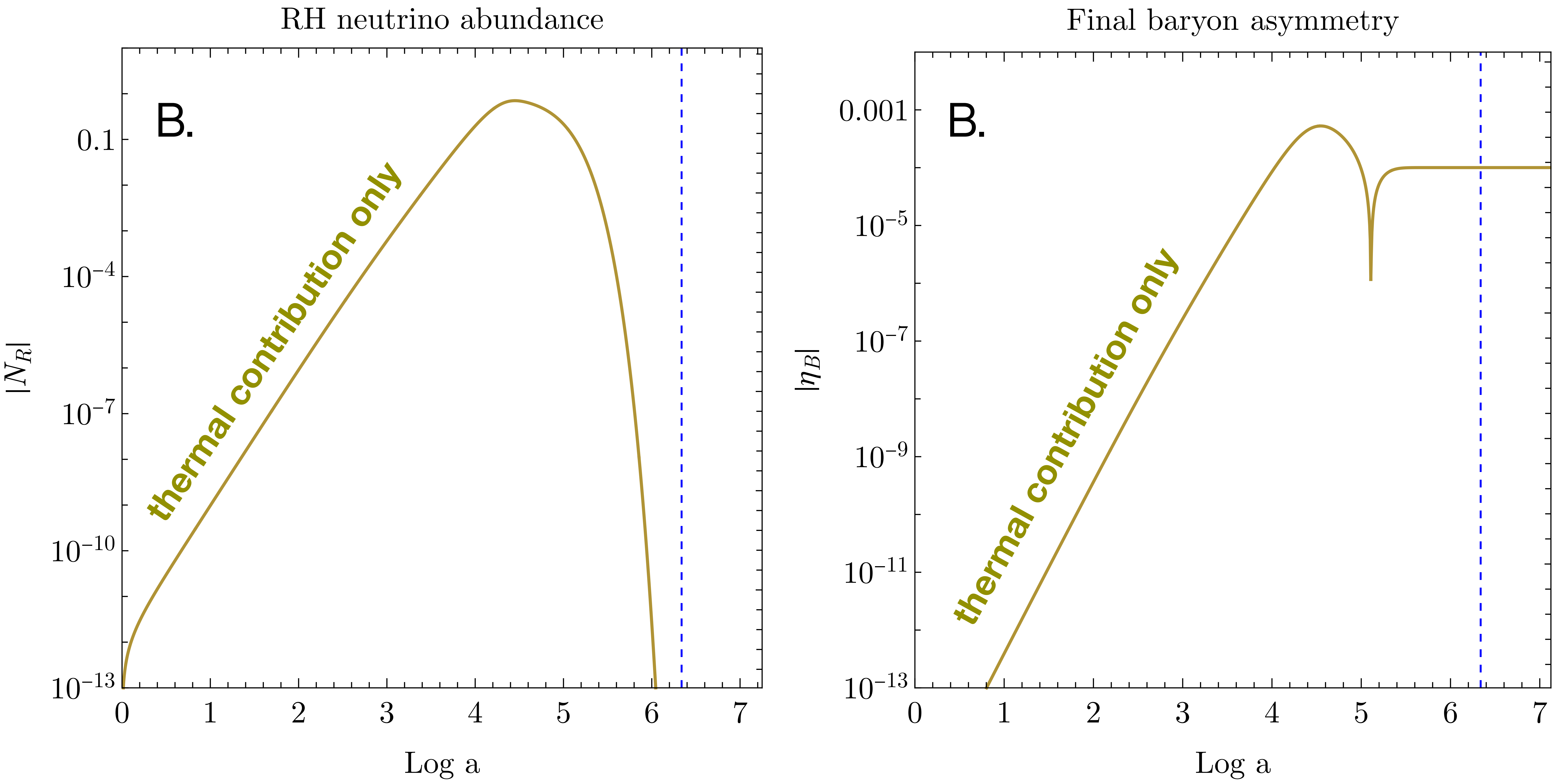
B-L asymmetry
From thermal RHNs decays

$$\Gamma_{N_1}^{\mathrm{BH}}\left(z_{\mathrm{BH}}\right)$$

A. PBH evaporate **before/during** RHNs are thermally produced from plasma → PBH evaporation creates an initial condition → erased by fast interactions

B. PBH evaporation happens **shortly after** thermal leptogenesis

$$M_i = 1.7\,\mathrm{g} \quad \beta_i = 10^{-3} \quad M_N = 10^{11}\,\mathrm{GeV}$$



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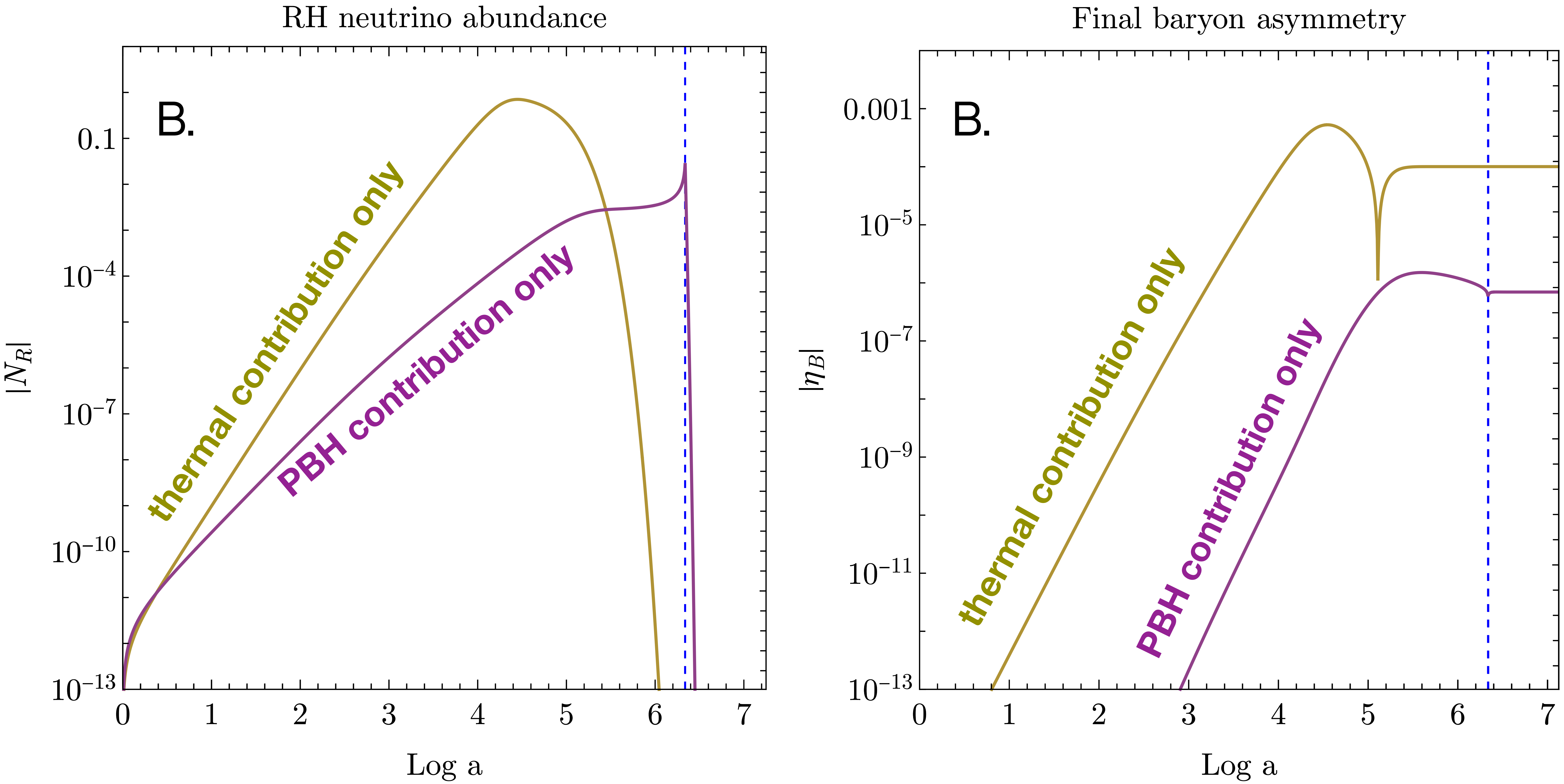

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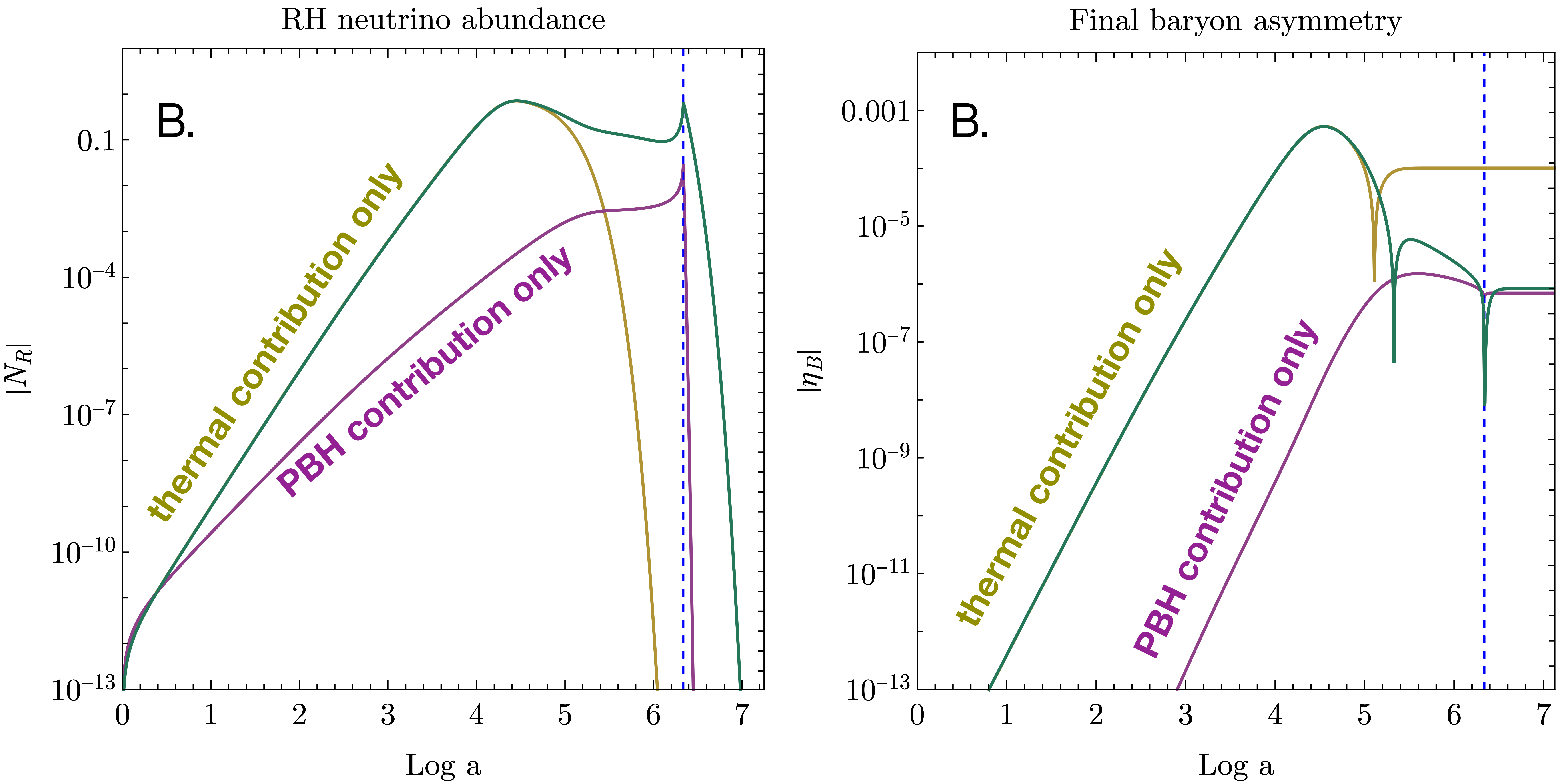
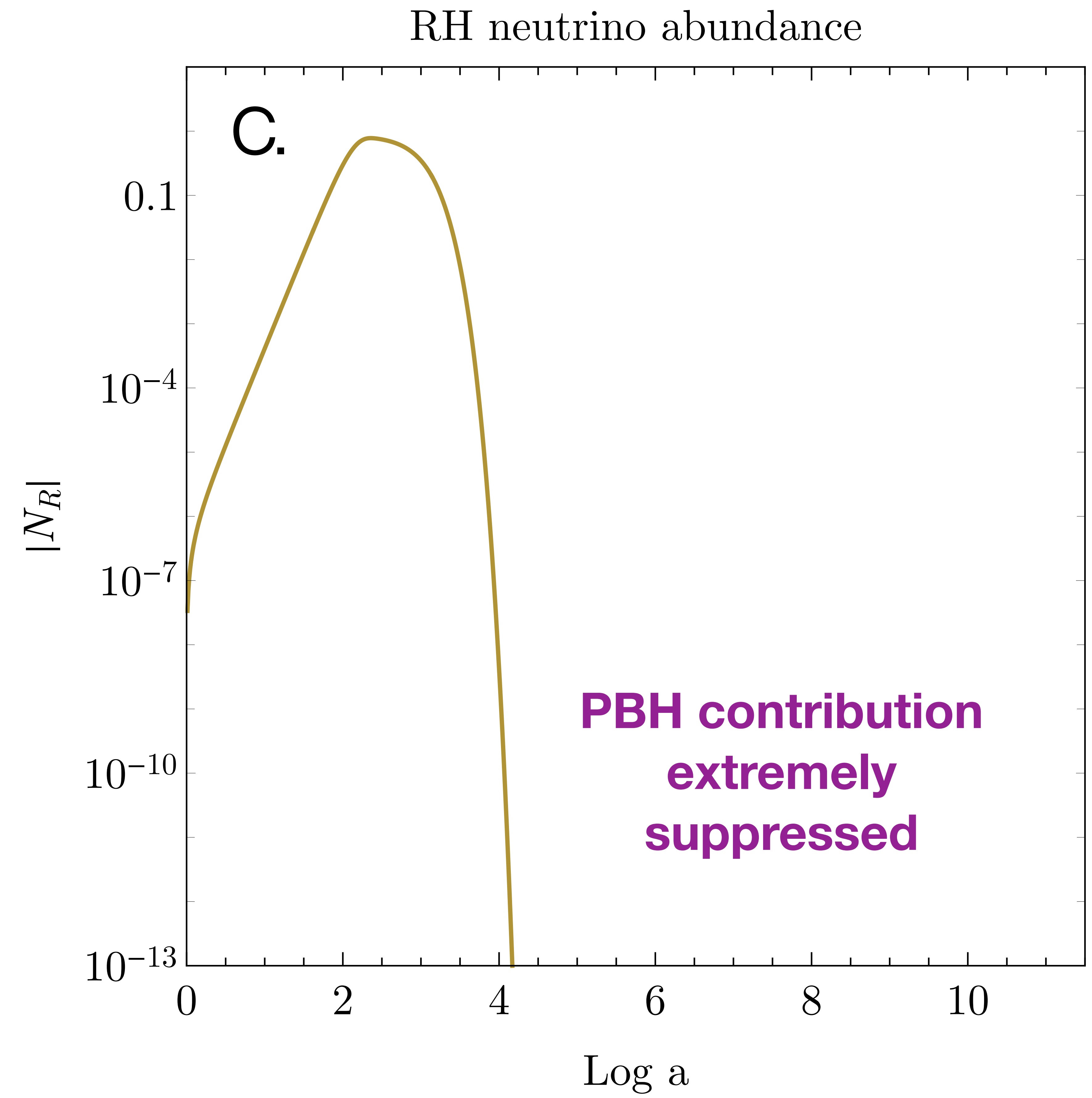
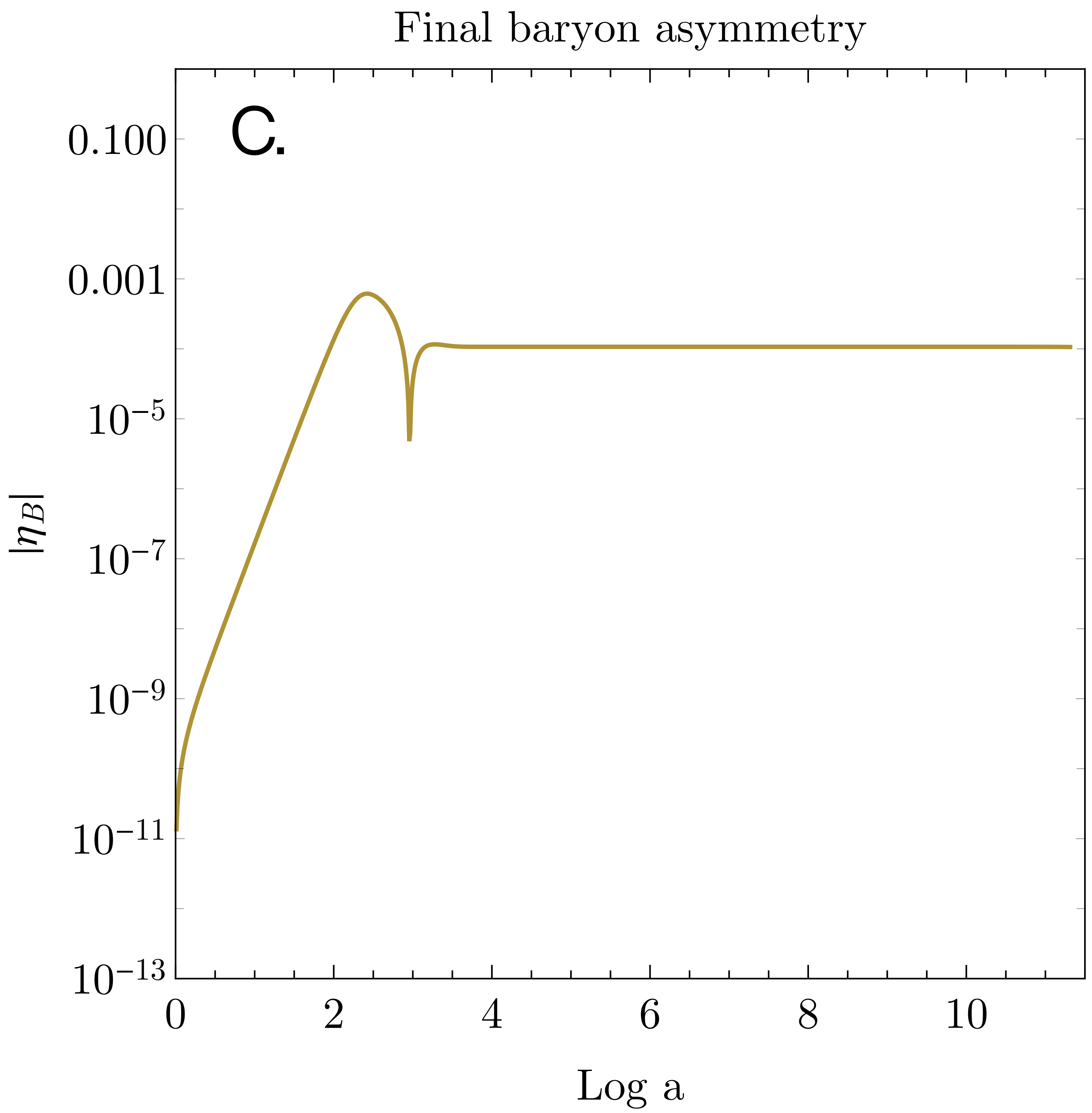


C. PBH evaporation occurs much **after** thermal leptogenesis era

$$M_i = 10^4\,\mathrm{g} \quad \beta_i = 10^{-3} \quad M_N = 10^{11}\,\mathrm{GeV}$$

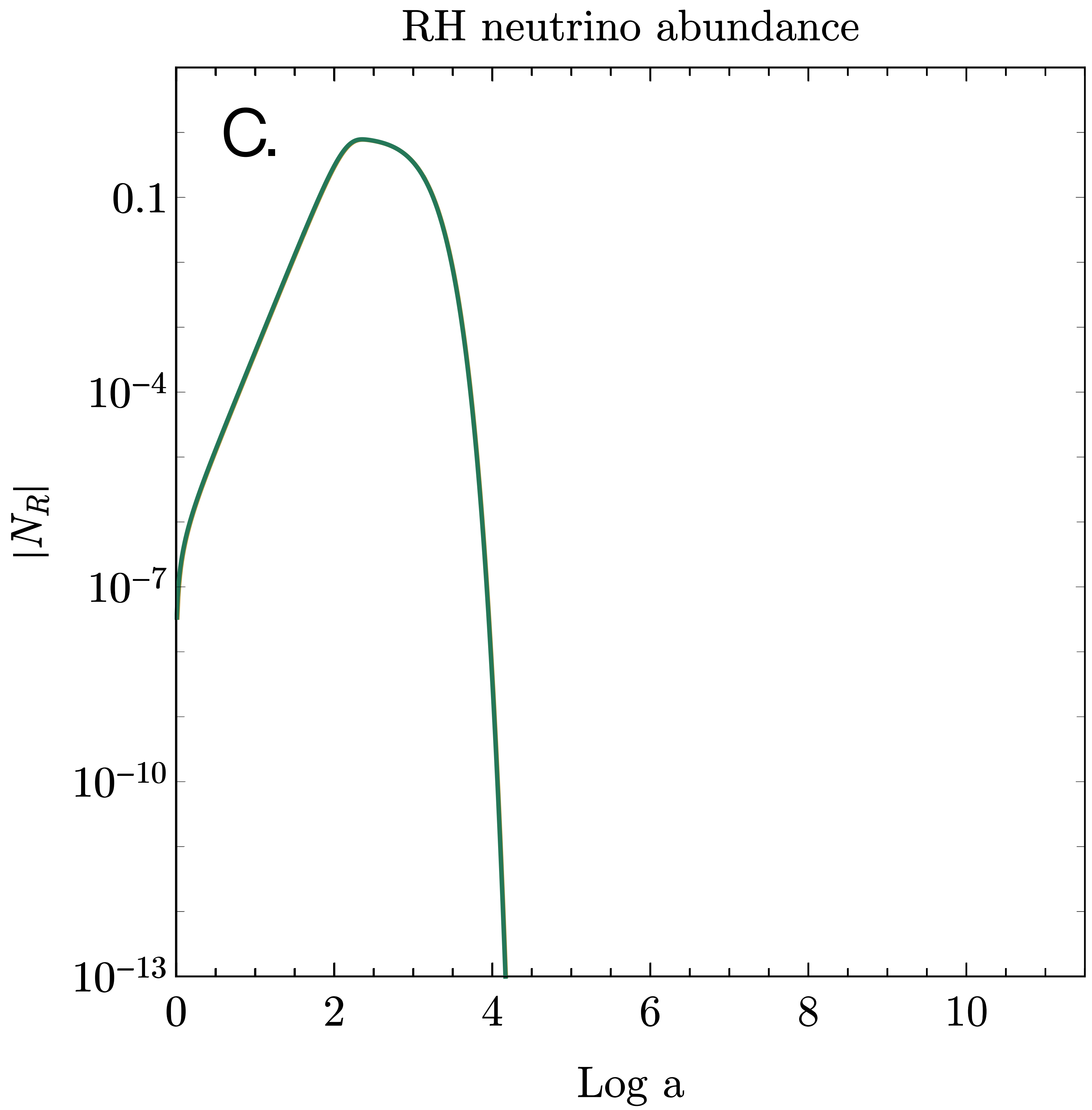

RH neutrino abundance

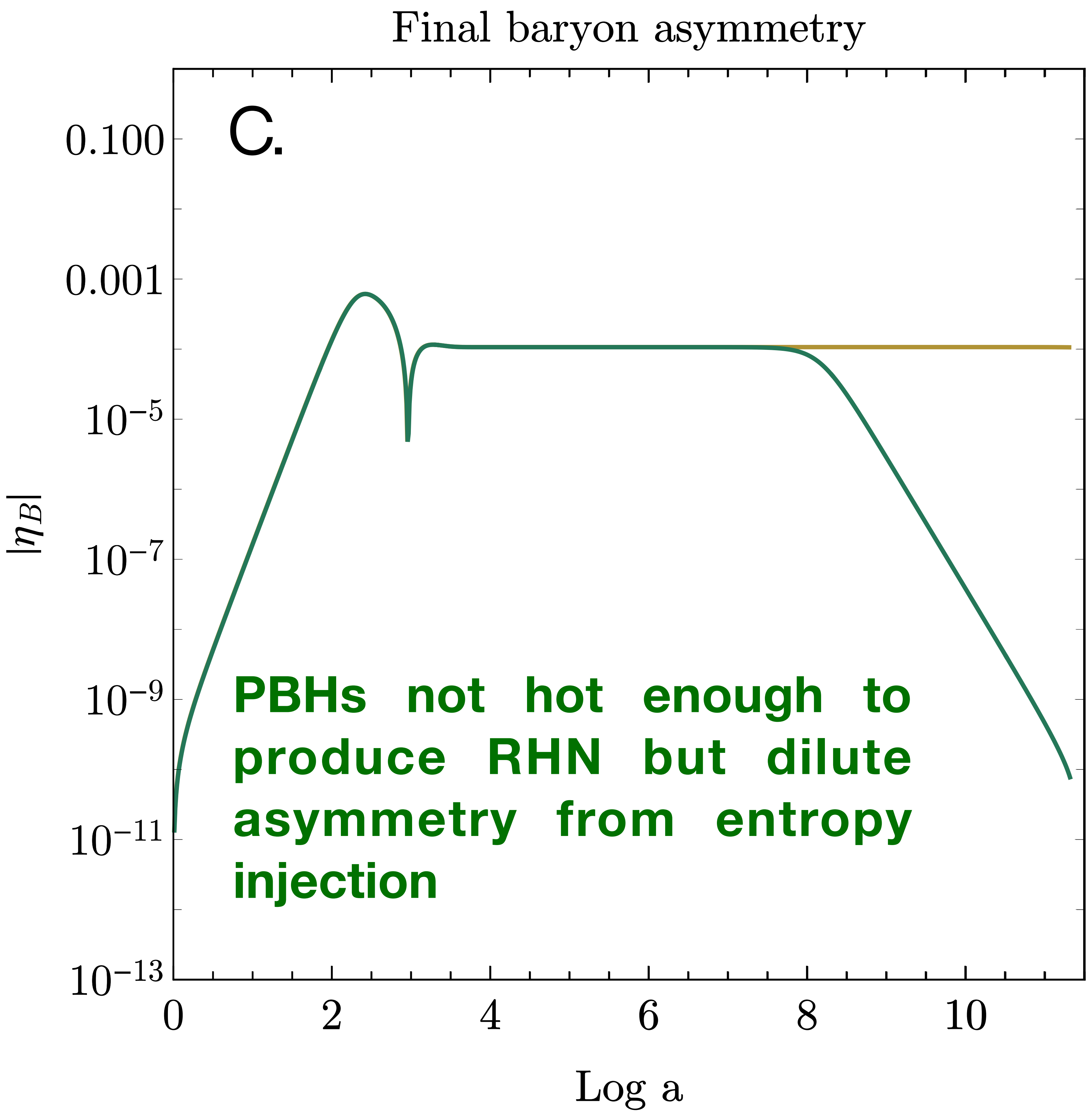
PBH contribution extremely suppressed


Final baryon asymmetry

C. PBH evaporation occurs **after** thermal leptogenesis era

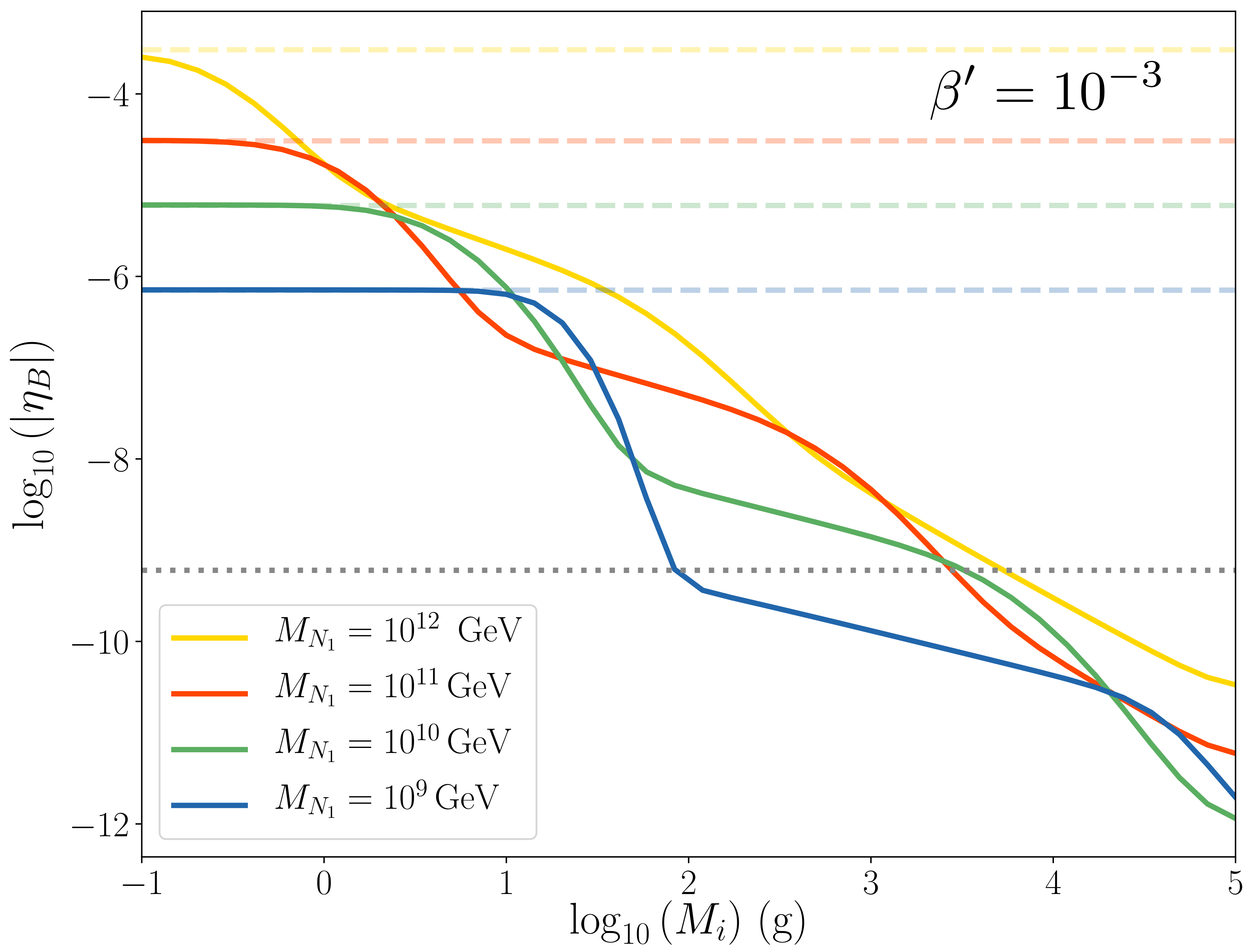
$$M_i = 10^4\,\mathrm{g} \quad \beta_i = 10^{-3} \quad M_N = 10^{11}\,\mathrm{GeV}$$

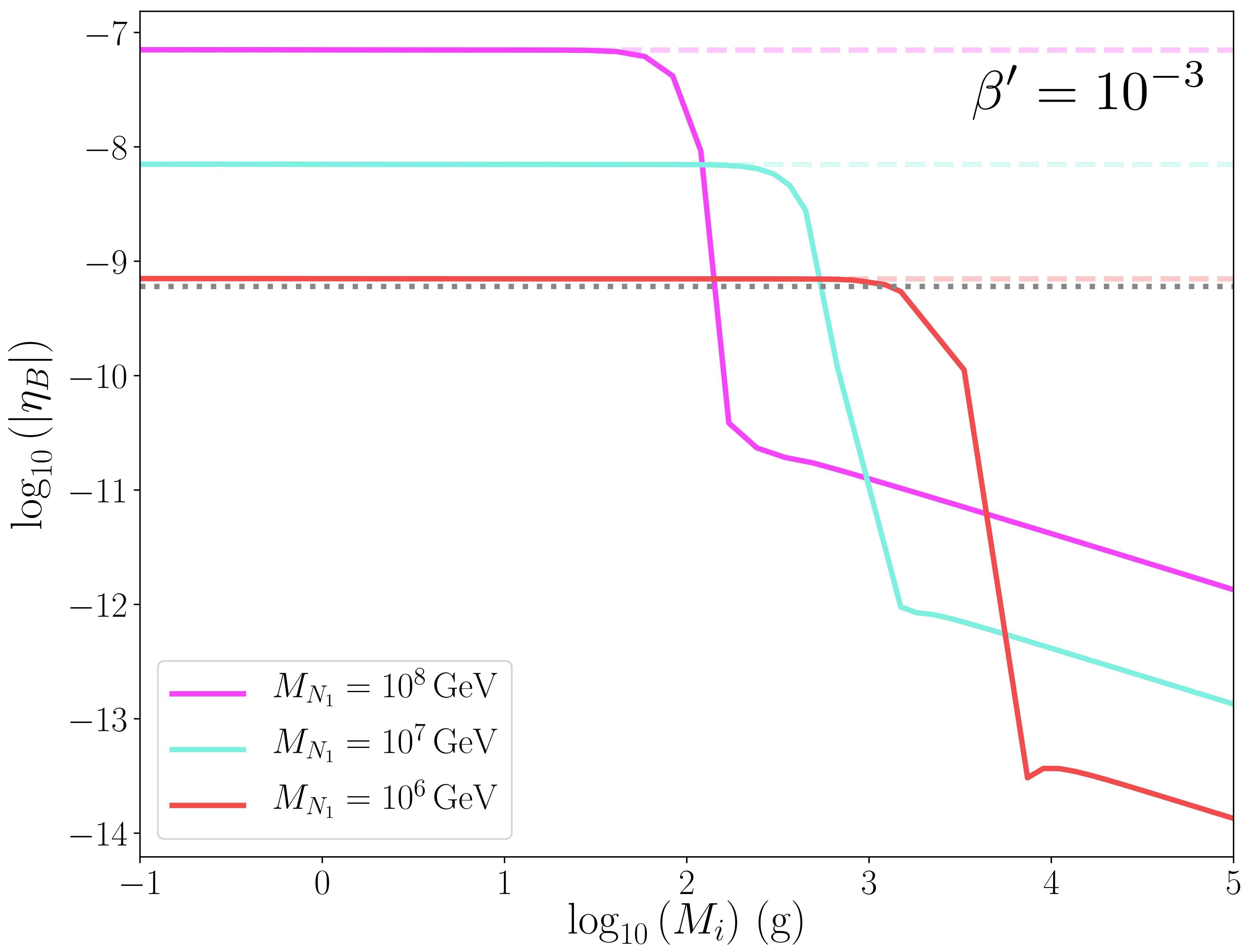




PBHs not hot enough to produce RHN but dilute asymmetry from entropy injection

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

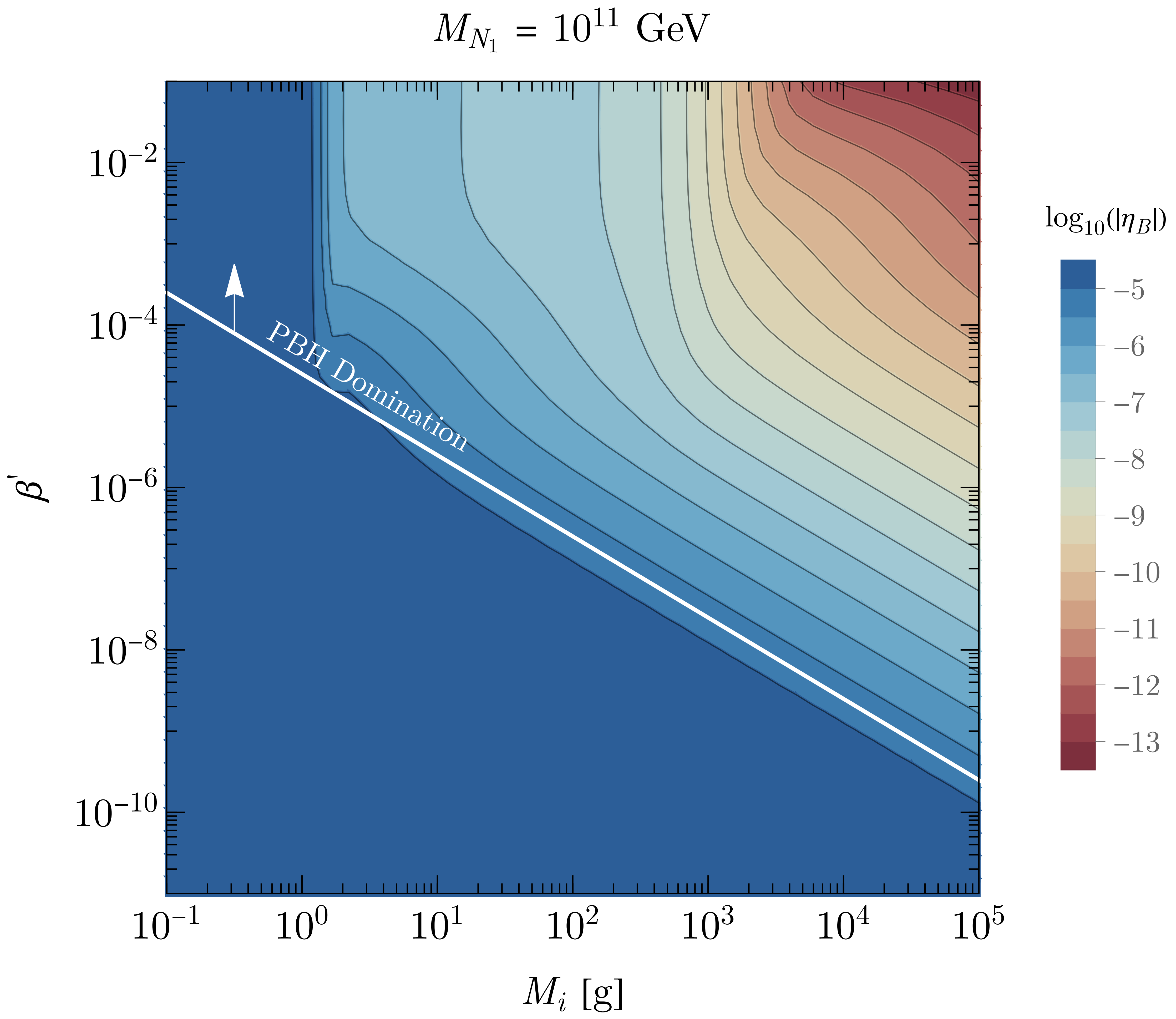


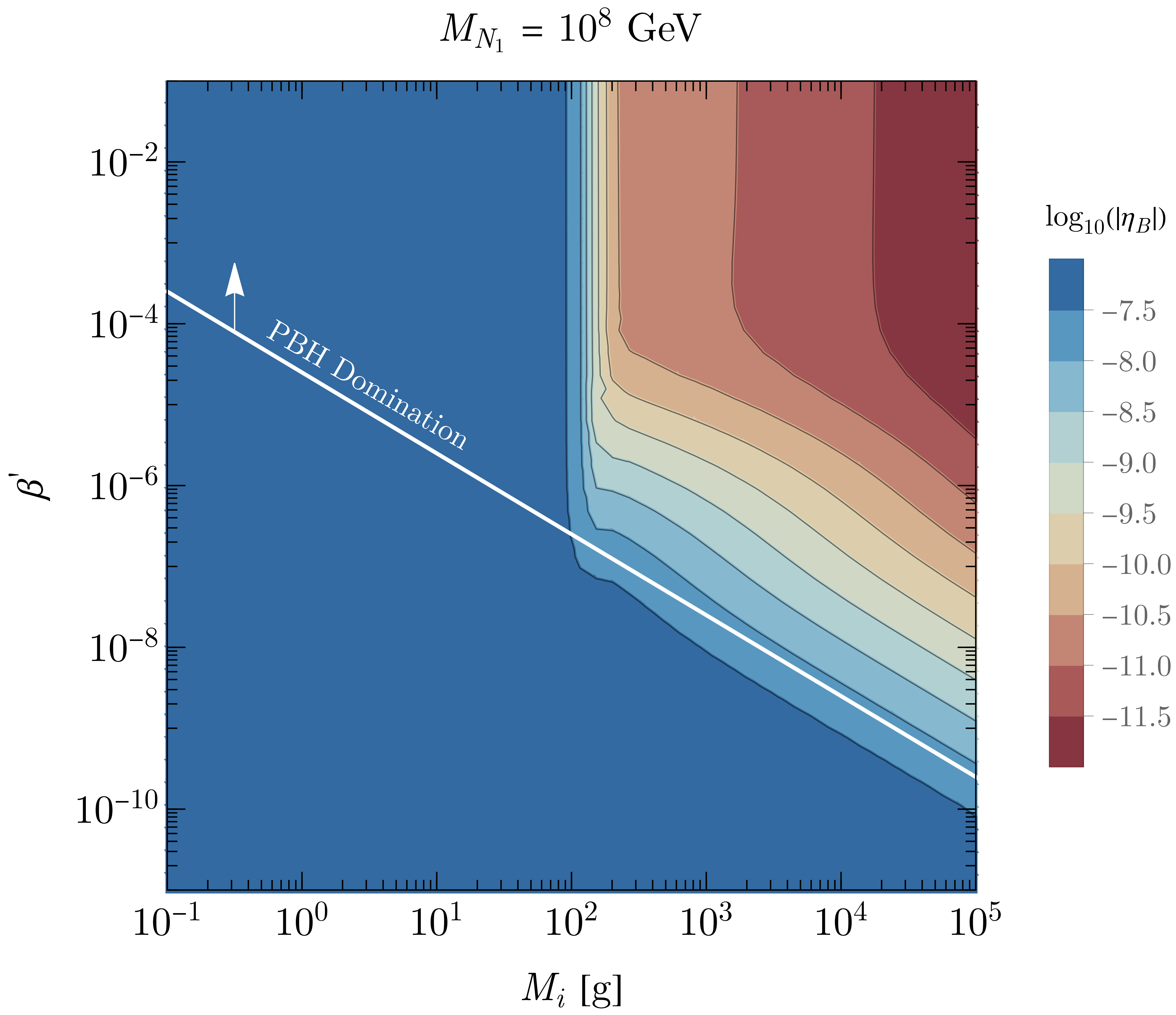


Chose Yukawa matrix for maximal baryon asymmetry

Dilution from heavy PBHs is generic feature

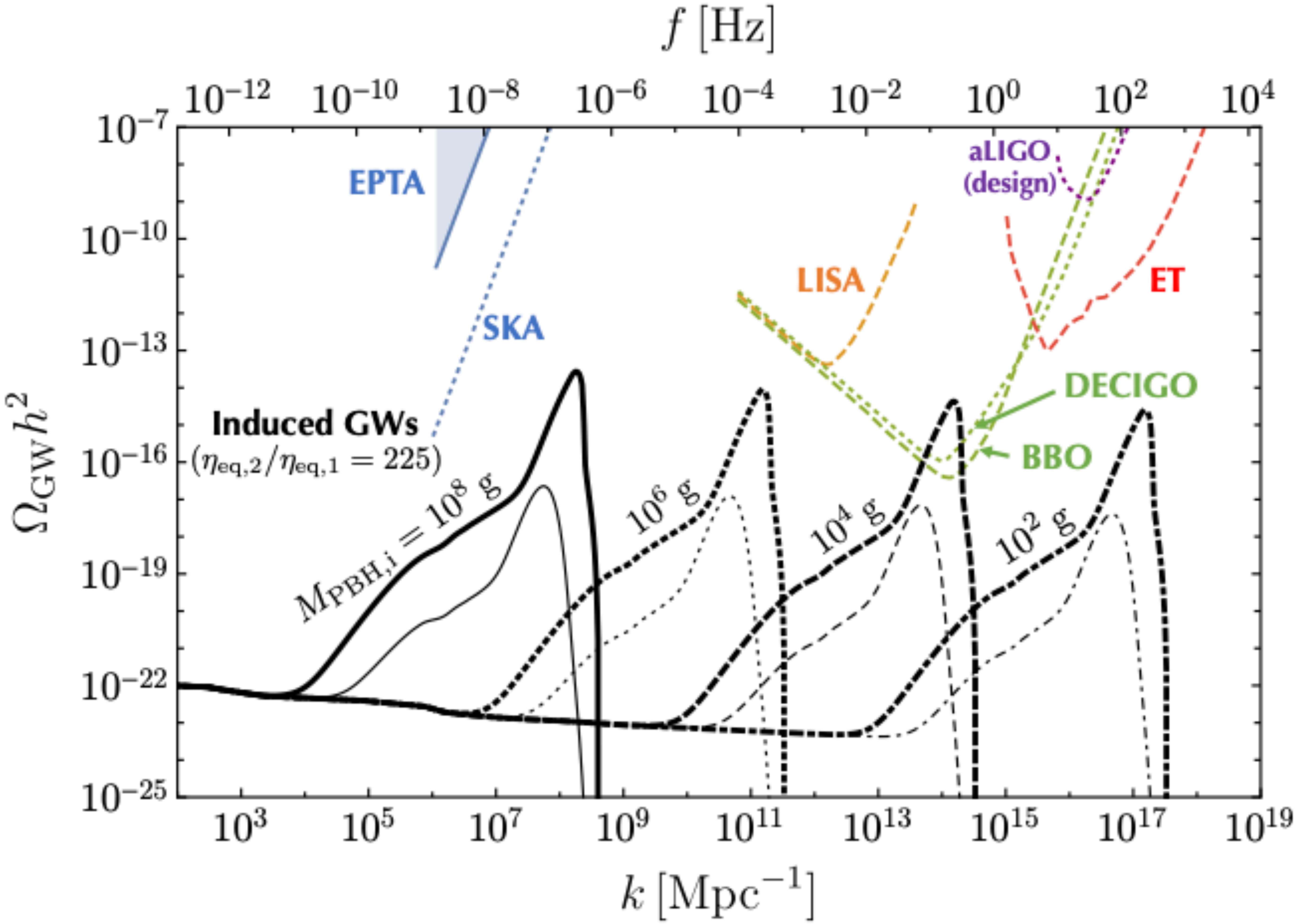
$$\beta' = \beta\,\gamma^{1/2}\left(\frac{g_{*f}}{106.75}\right)^{1/4}$$





Detection of PBHs in mass range $\gtrsim$ 1 kg would place thermal leptogenesis under serious tension.

PBHs can produce gravitational waves from their sudden evaporation
“poltergeist mechanism”



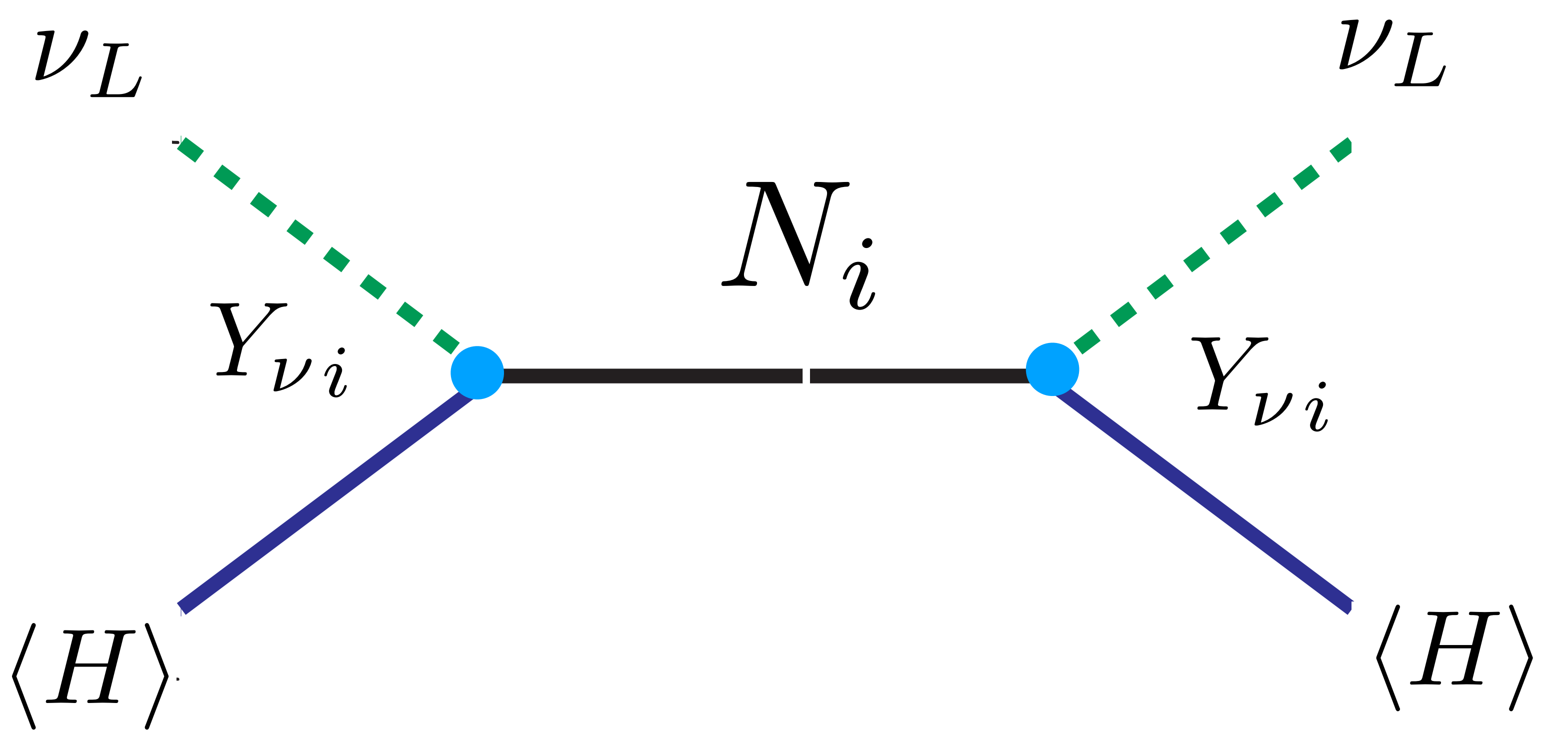
Inomata, Kohri, Nakama, Terada (2019)

Inomata, Kawasaki, Mukaida, Terada, Yanagida (2020)

Detection of such GWs could place tension on high scale leptogenesis

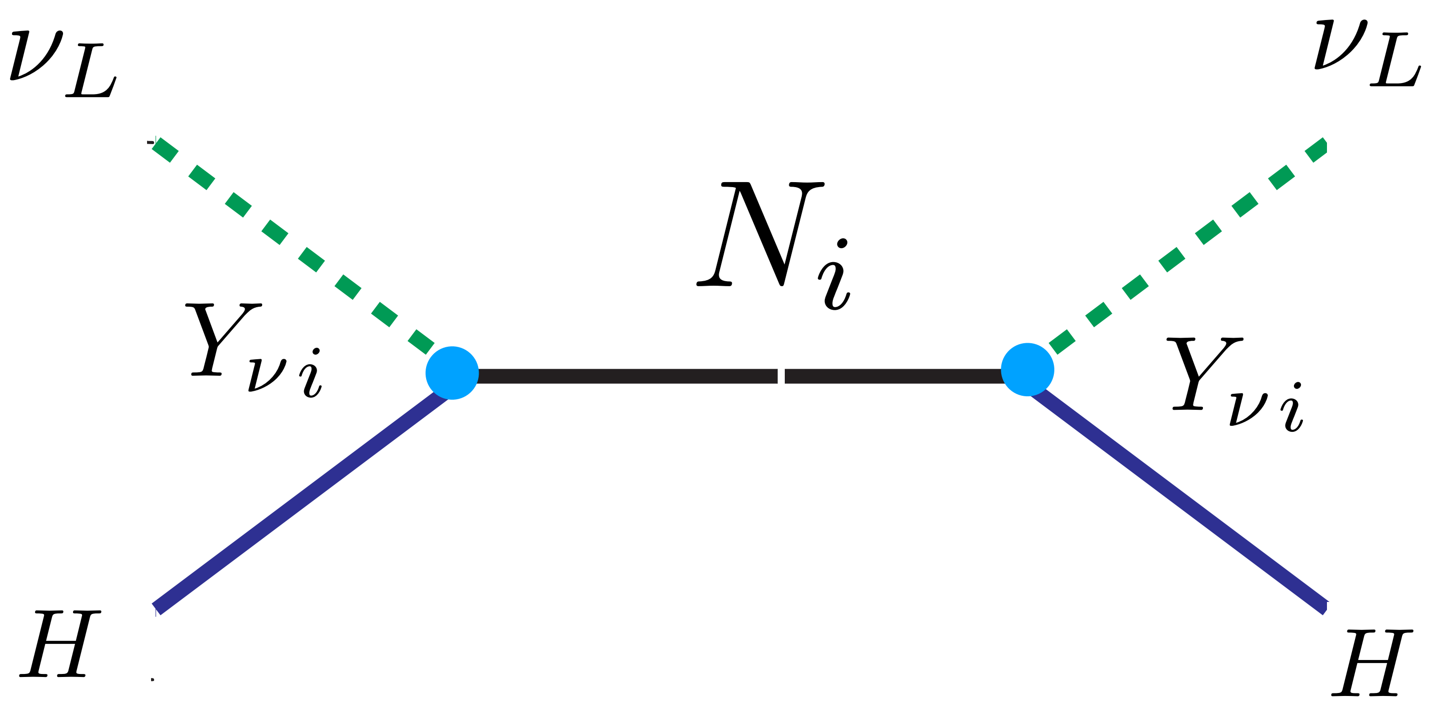
- Considered $10^6 \lesssim M_N\,(\mathrm{GeV}) \lesssim 10^{12}$
- What about $M_N > 10^{12}\,\mathrm{GeV}$?
- Some tension at this scale since $\Delta L = 2$ washout strong

Bernal, Fong, Perez-Gonzalez, JT



Light neutrino masses

$$m_{\nu i} \propto \frac{Y^2 v^2}{M_N}$$



$\Delta L = 2$ washout

$$\sigma_{\Delta L=2} \propto \frac{Y^4}{M_N^2} = \frac{m_{\nu i}^2}{v^4}$$

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Bernal, Fong, Perez-Gonzalez, JT

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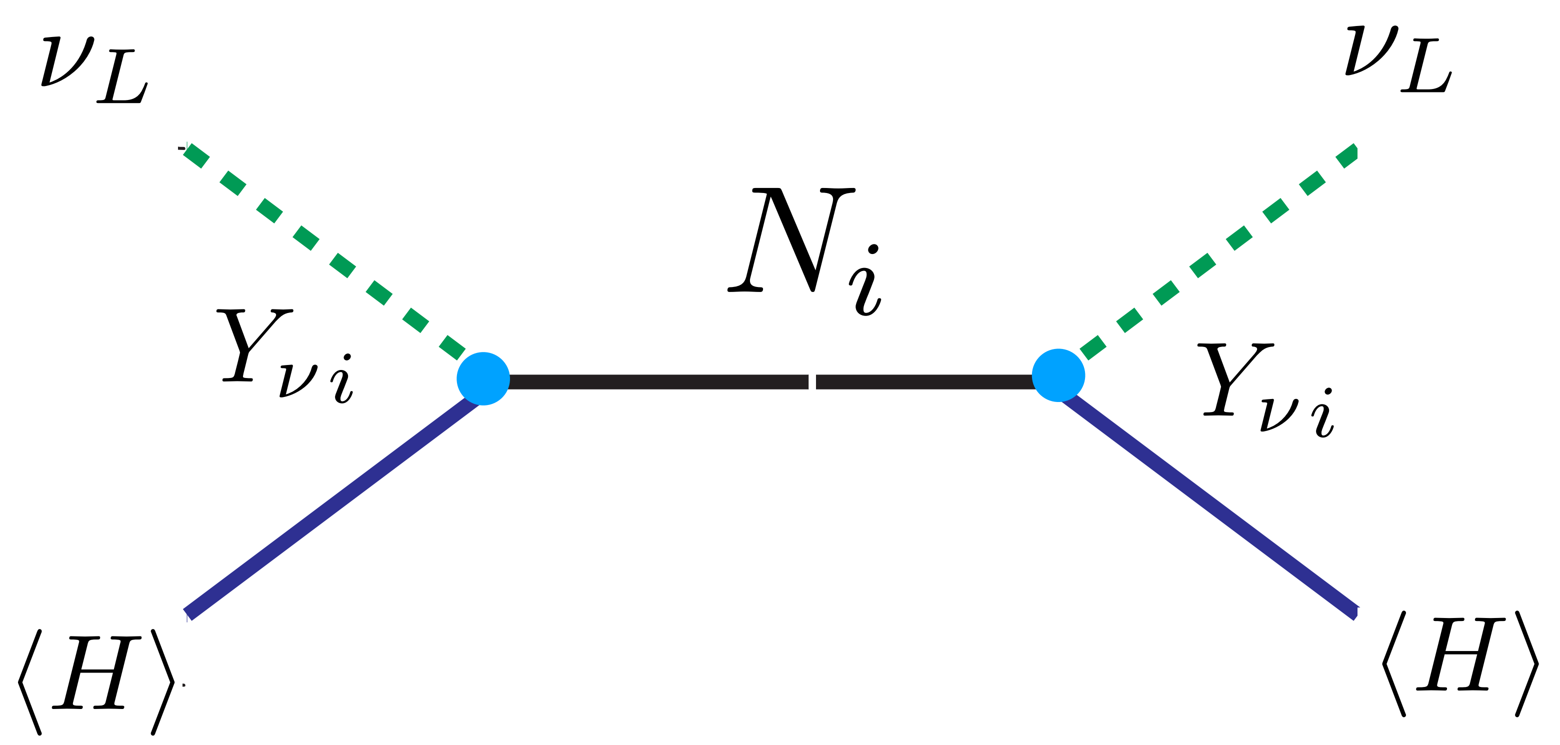
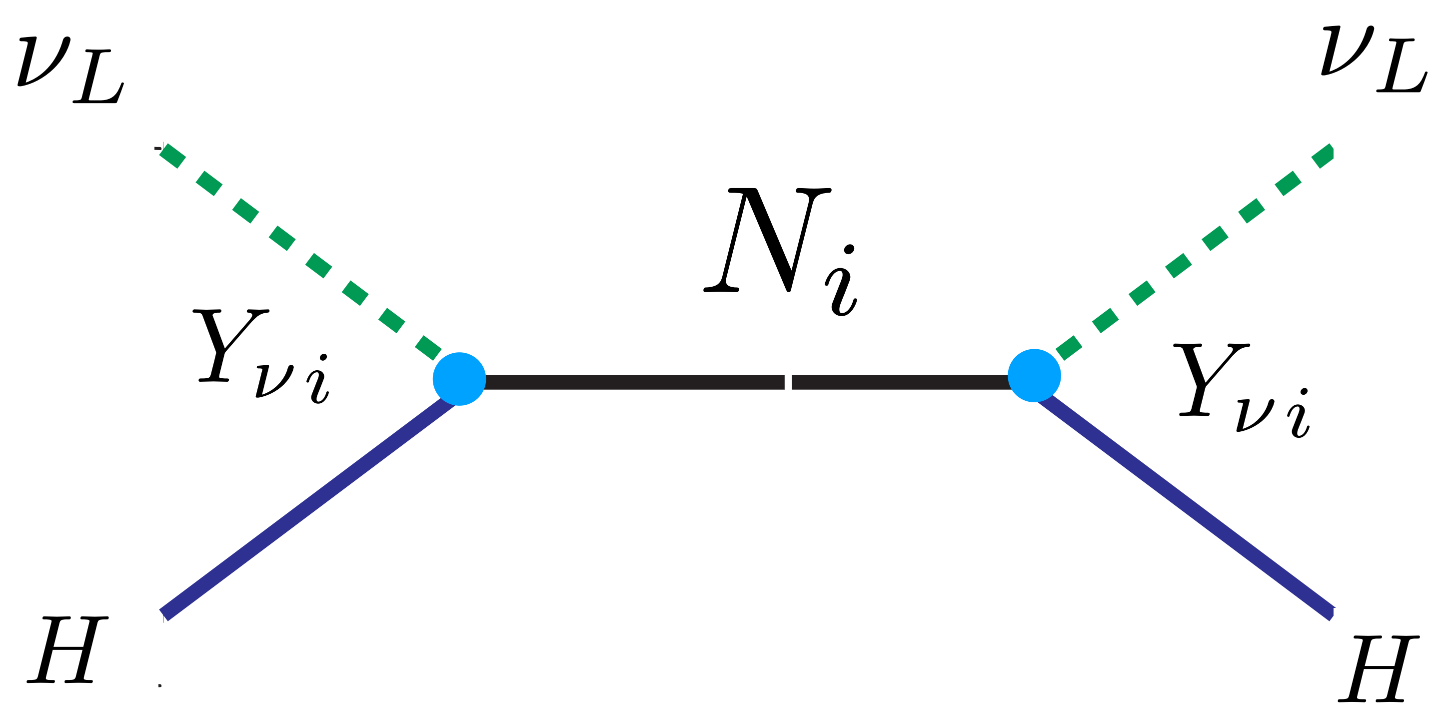




To ensure $\Delta L = 2$ washout effects are not too strong requires

$$m_{\nu 1}^2 + m_{\nu 2}^2 + m_{\nu 3}^2 \lesssim (0.15\,\mathrm{eV})^2$$

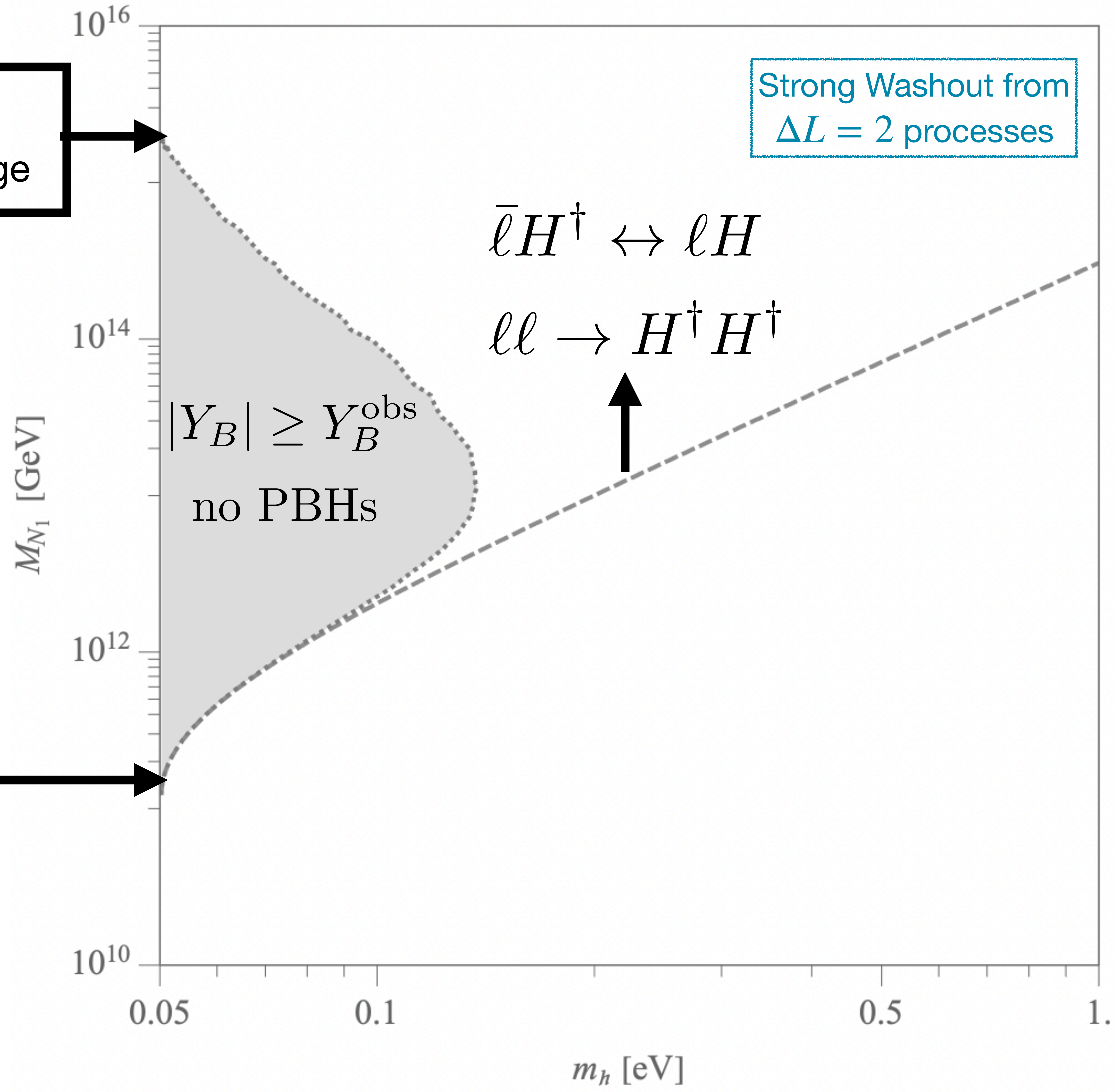
Bernal, Fong, Perez-Gonzalez, JT

$\sigma_{\Delta L=2}$

Washout too large

Y_ν

Too small



Bernal, Fong, Perez-Gonzalez, JT

$\sigma_{\Delta L=2}$

Washout too large

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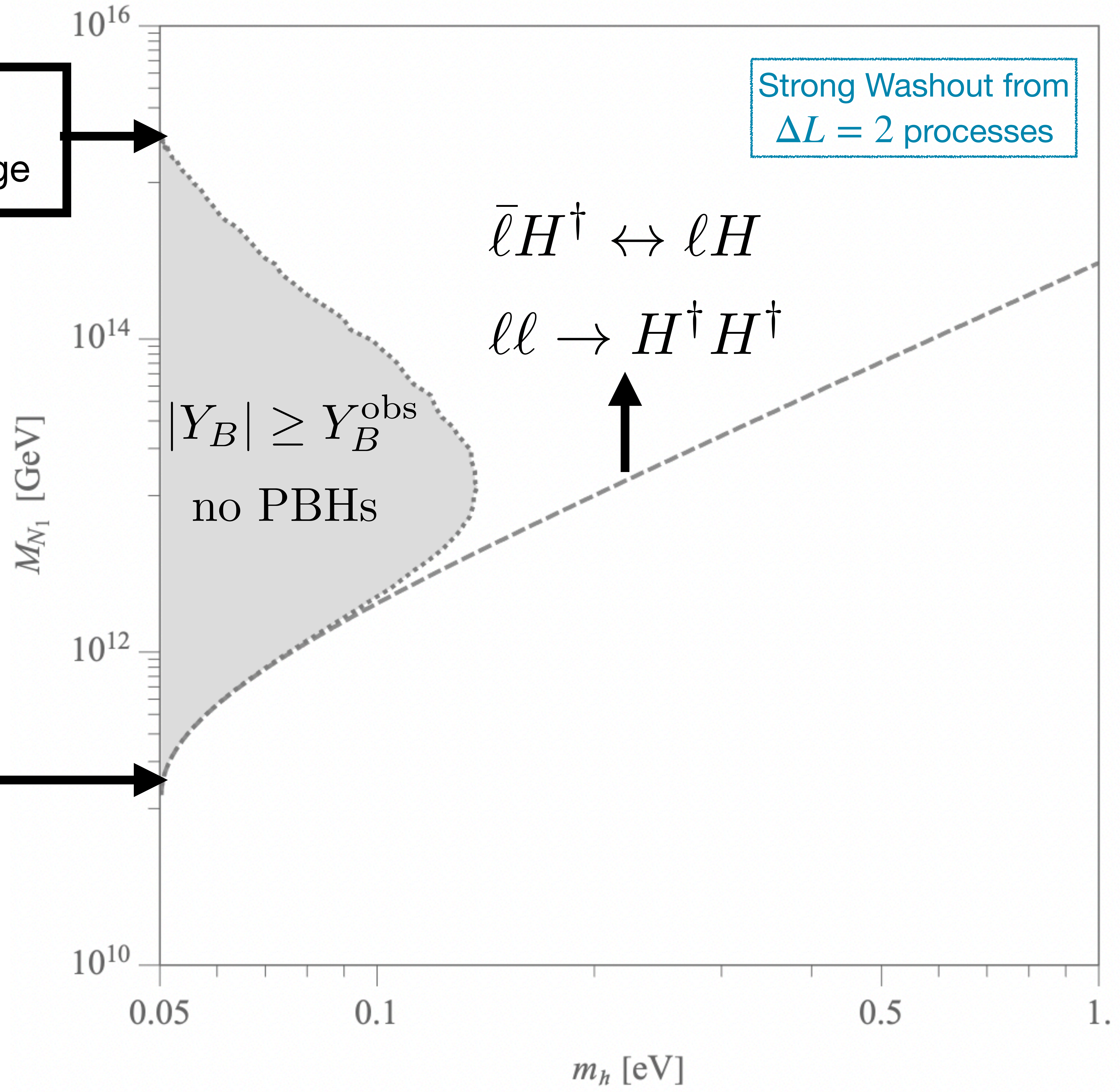
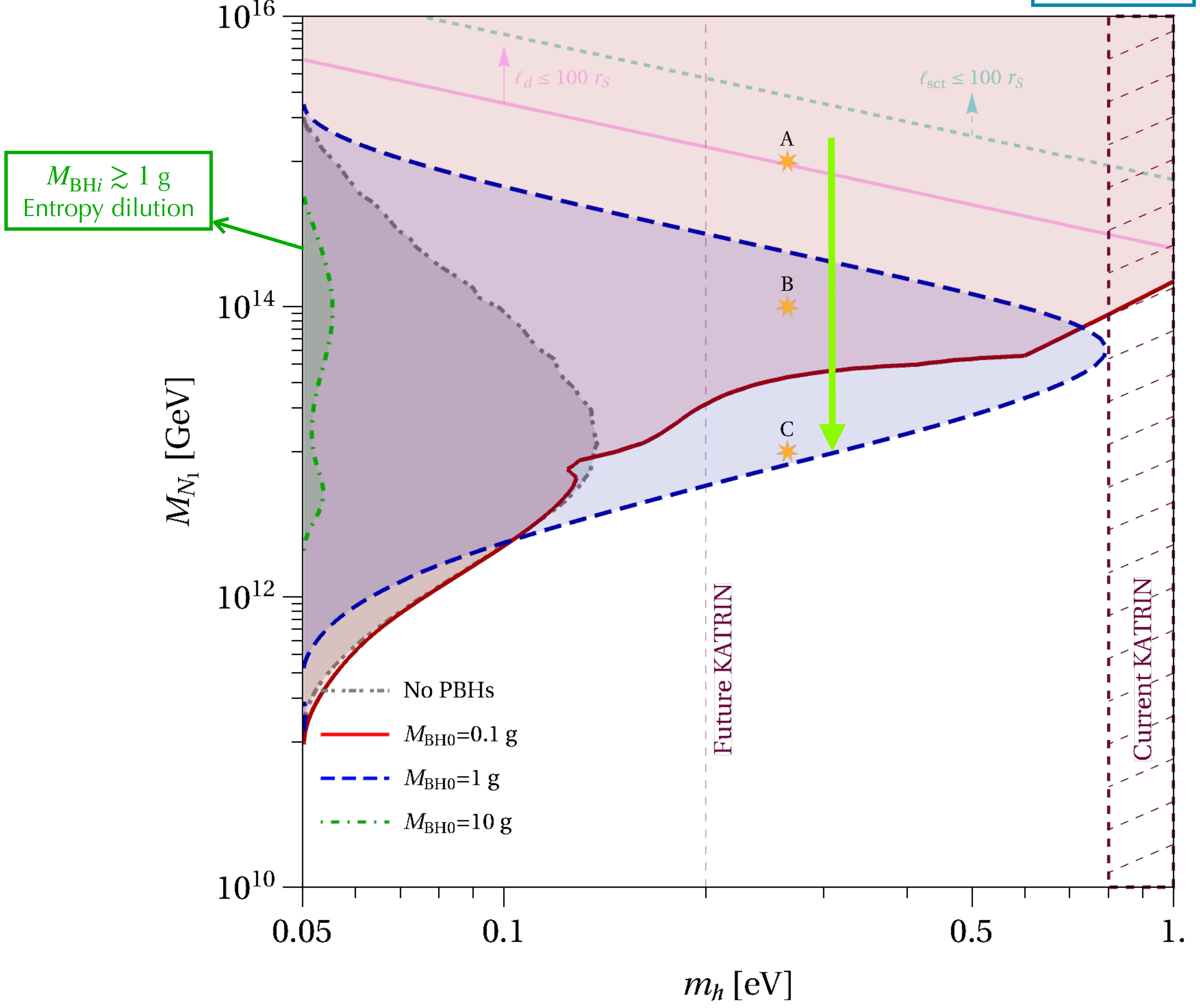


Very light PBHs can produce heavy RHNs after the $\sigma_{\Delta L=2}$ OOE

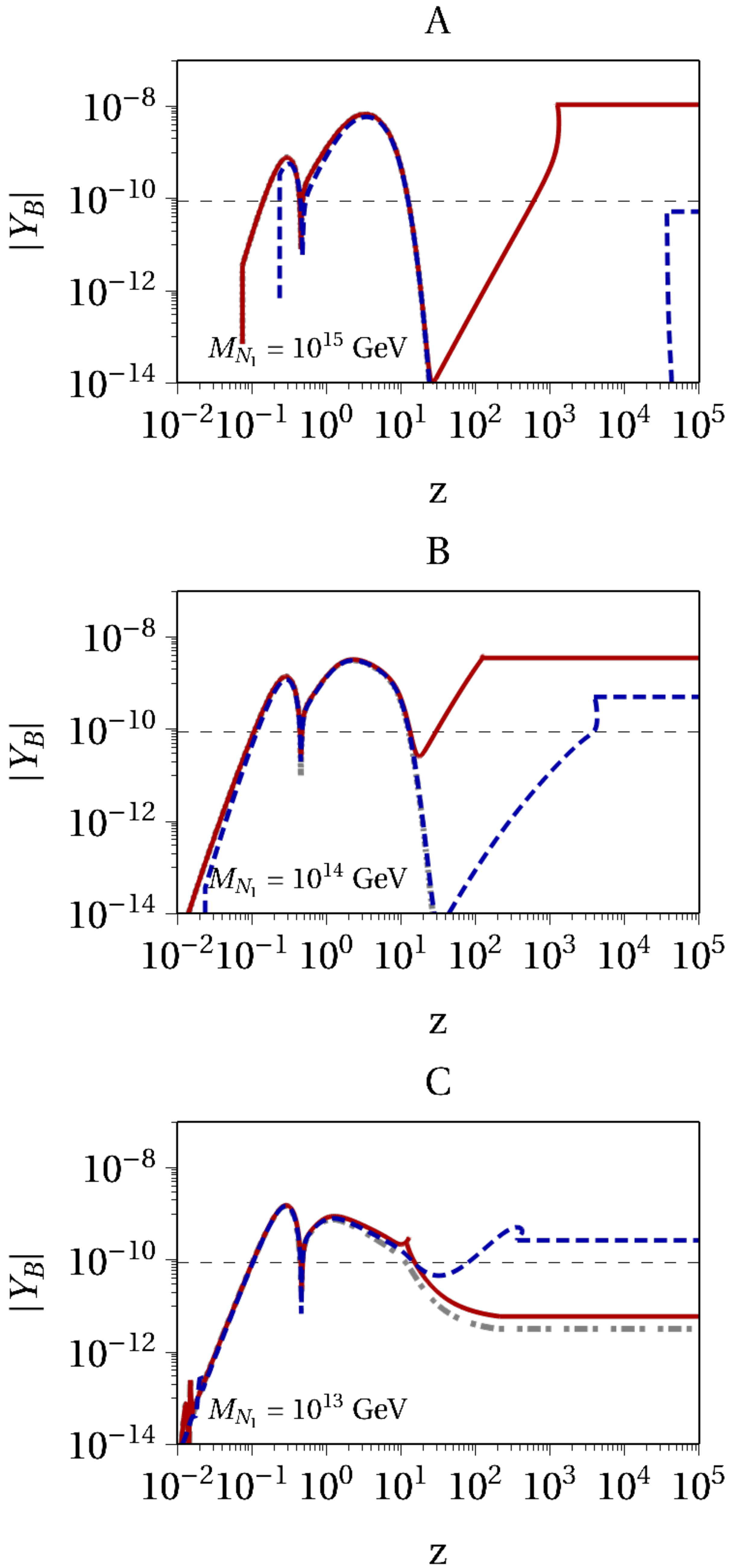
$$T \lesssim 4 \left(\frac{0.1\text{eV}}{m_\nu}\right)^2 \times 10^{12}\text{GeV}$$

Bernal, Fong, Perez-Gonzalez, JT

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



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

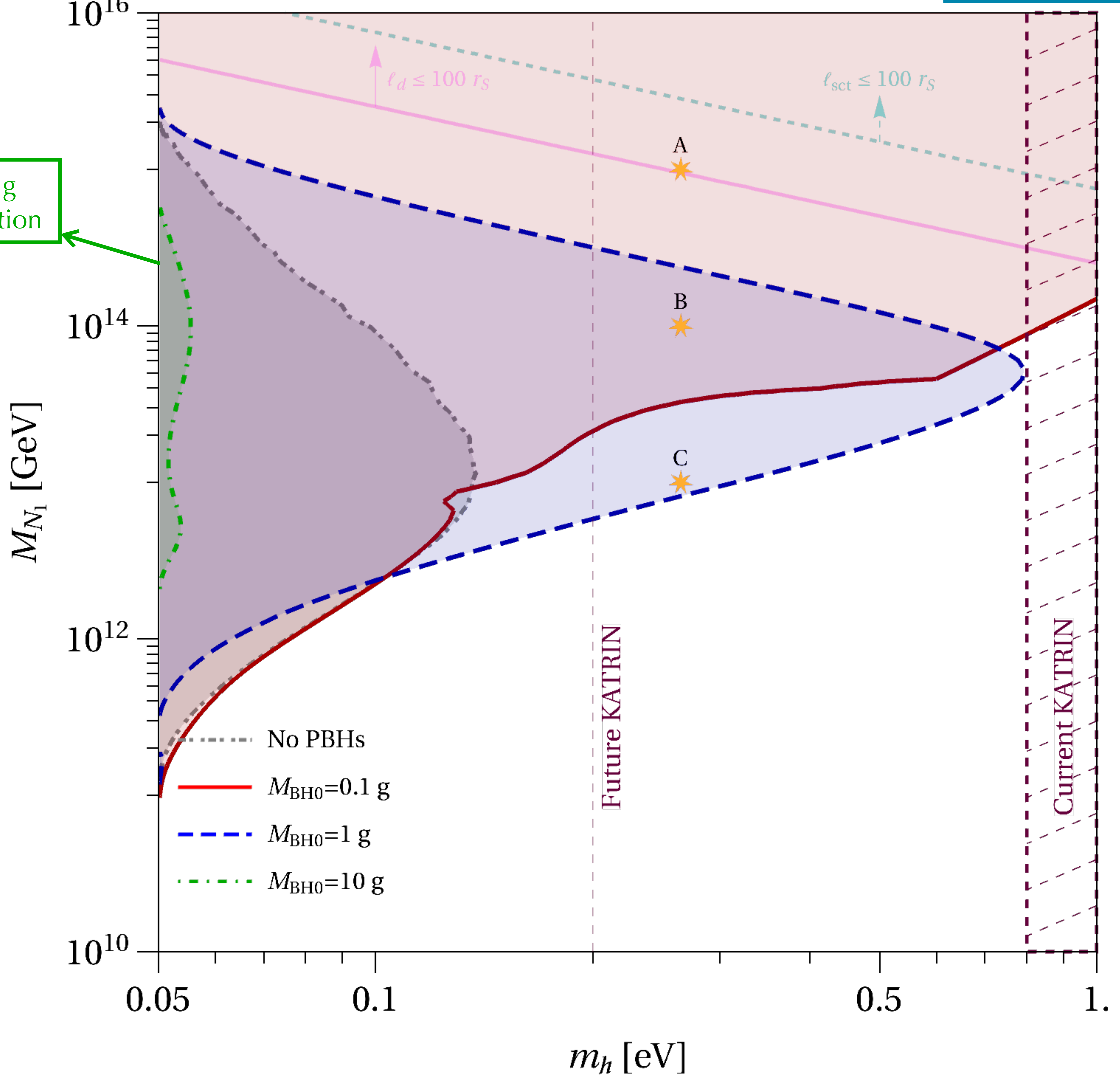


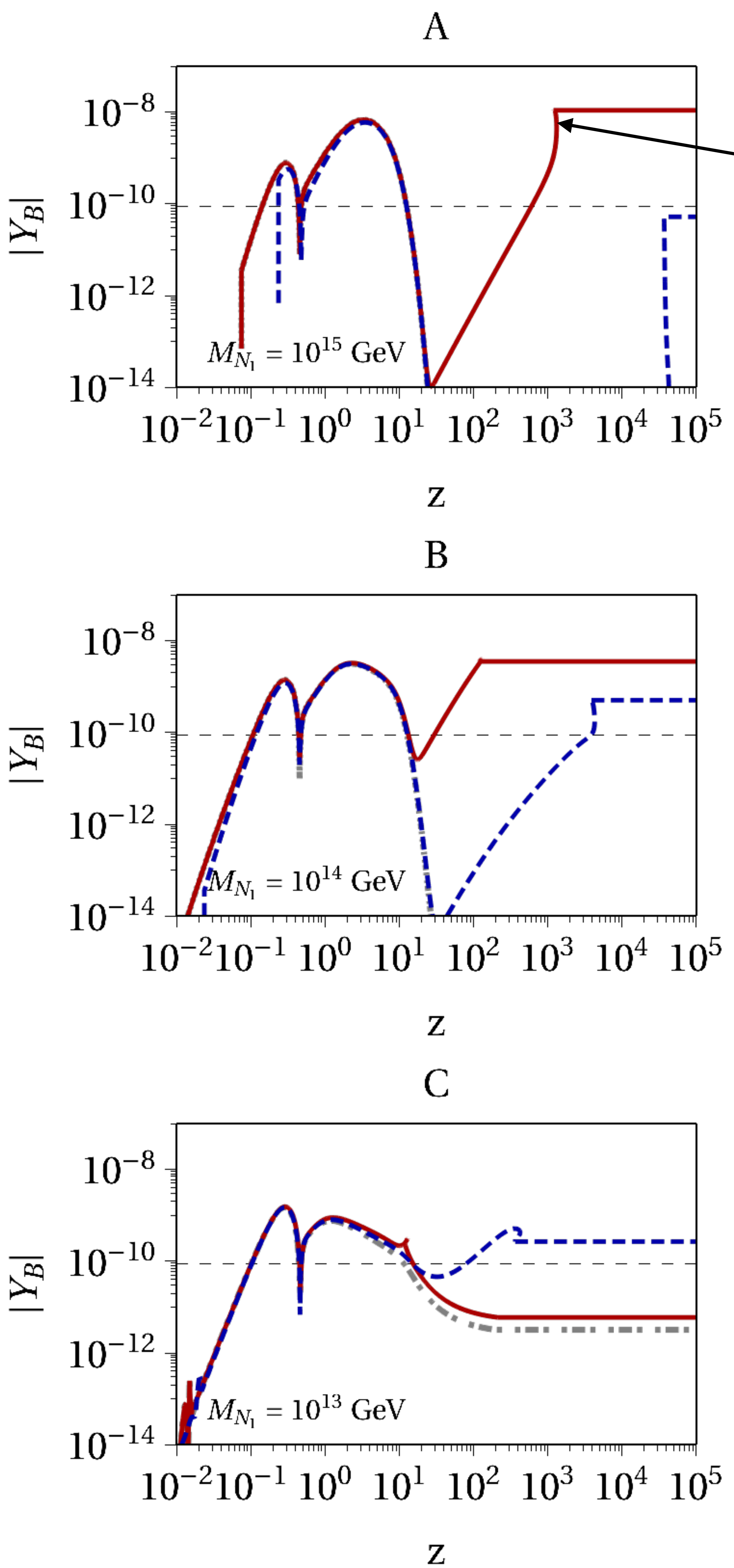
RHN
Getting lighter

Bernal, Fong, Perez-Gonzalez, JT

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

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



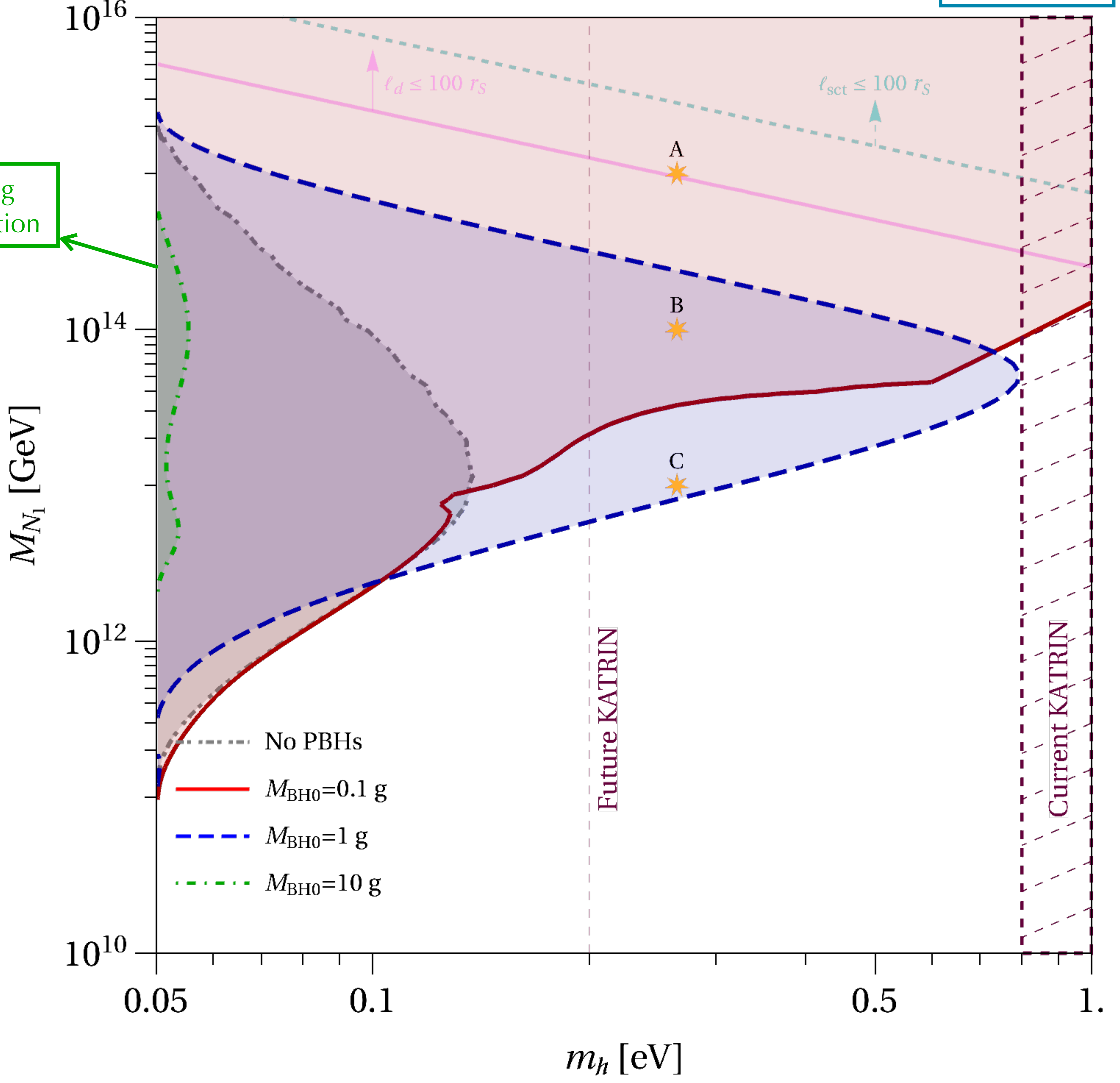


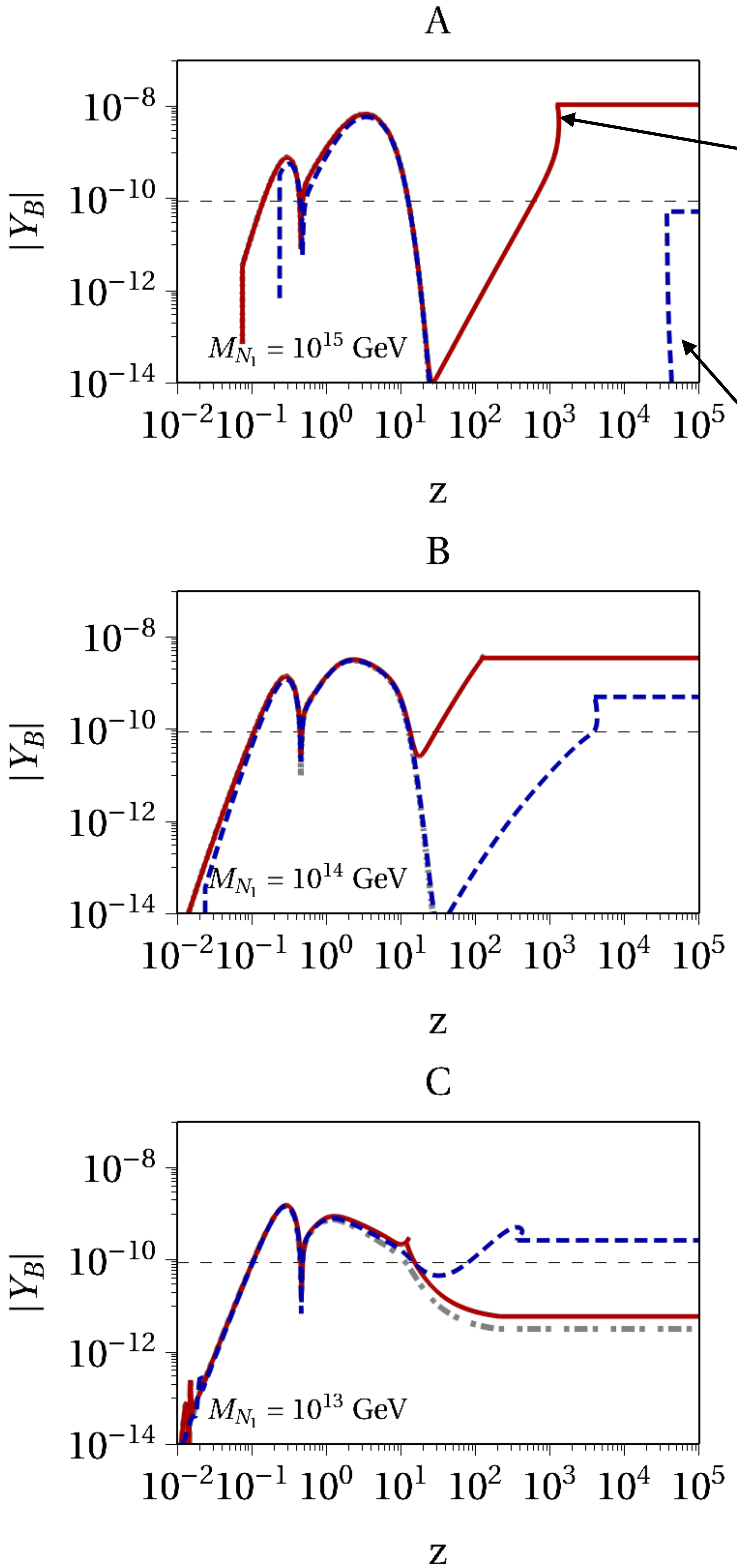
Lighter PBH produces heavy RHN **after** $\Delta L = 2$ washout switched off

Bernal, Fong, Perez-Gonzalez, JT

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

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





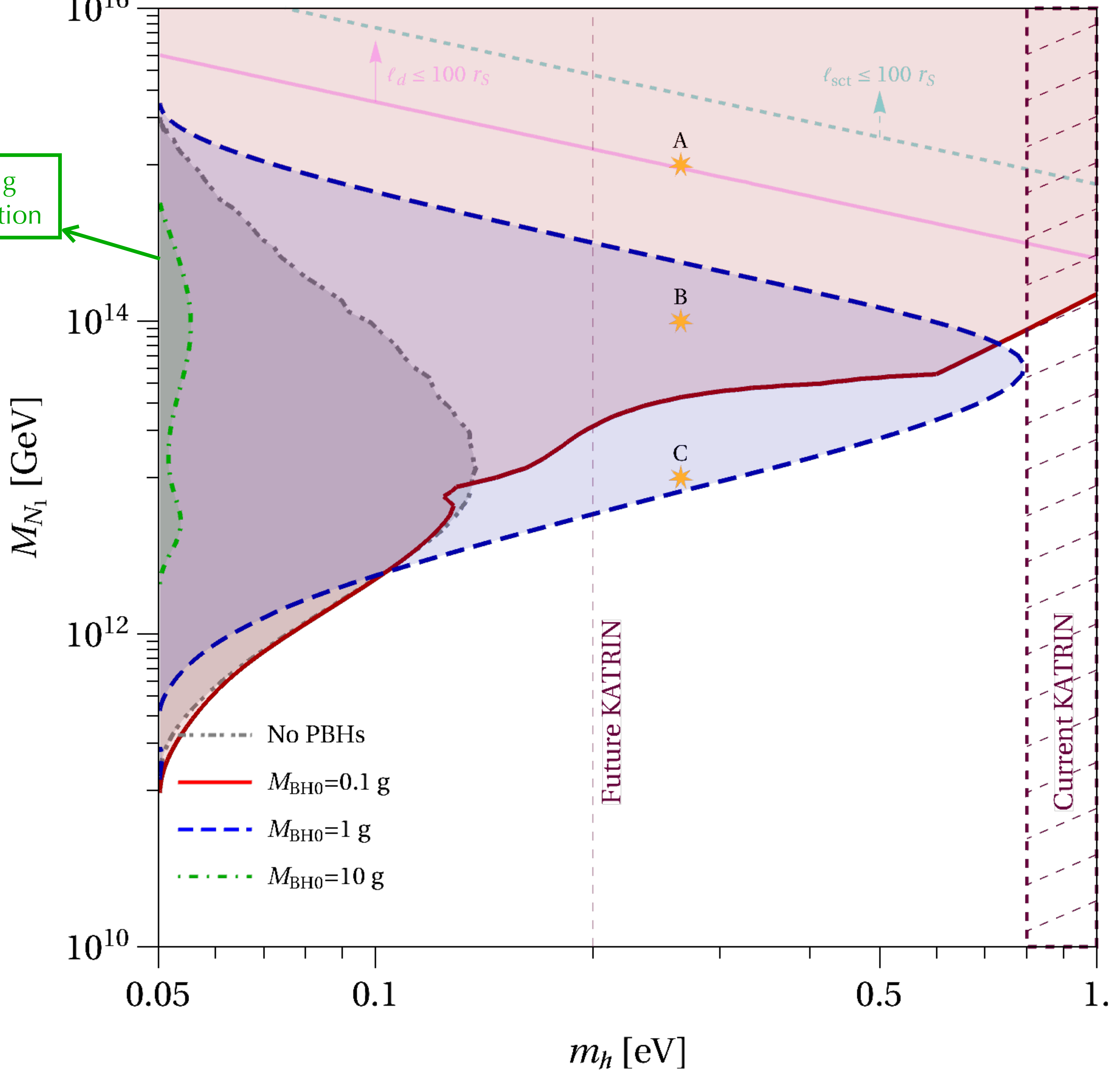
Lighter PBH produces heavy RHN **after** $\Delta L = 2$ washout switched off

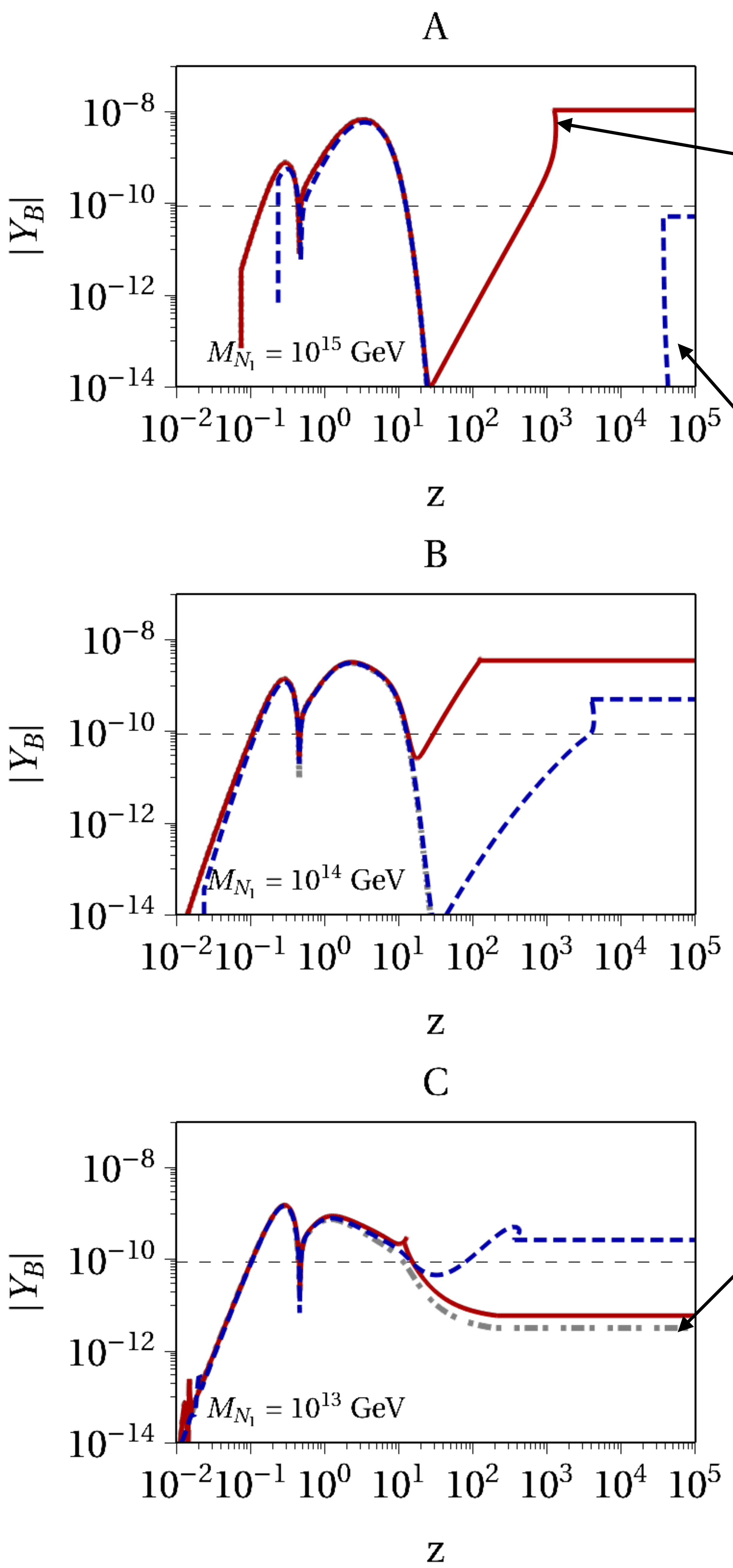
Slightly heavier PBH evaporates later & not as efficient at producing very heavy RHNs

Bernal, Fong, Perez-Gonzalez, JT

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

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



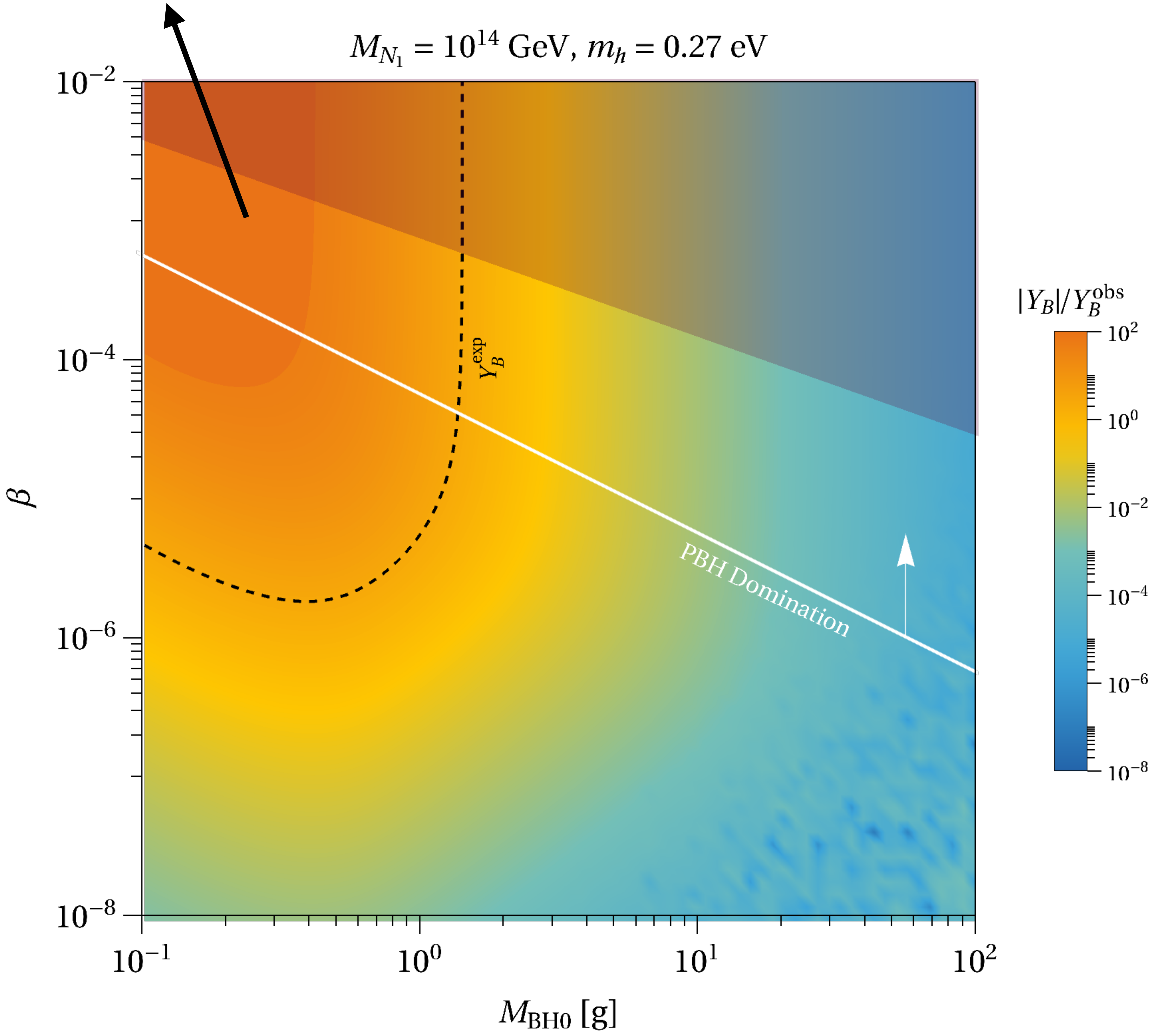


Lighter PBH produces heavy RHN **after** $\Delta L = 2$ washout switched off

Slightly heavier PBH evaporates later & not as efficient at producing very heavy RHNs

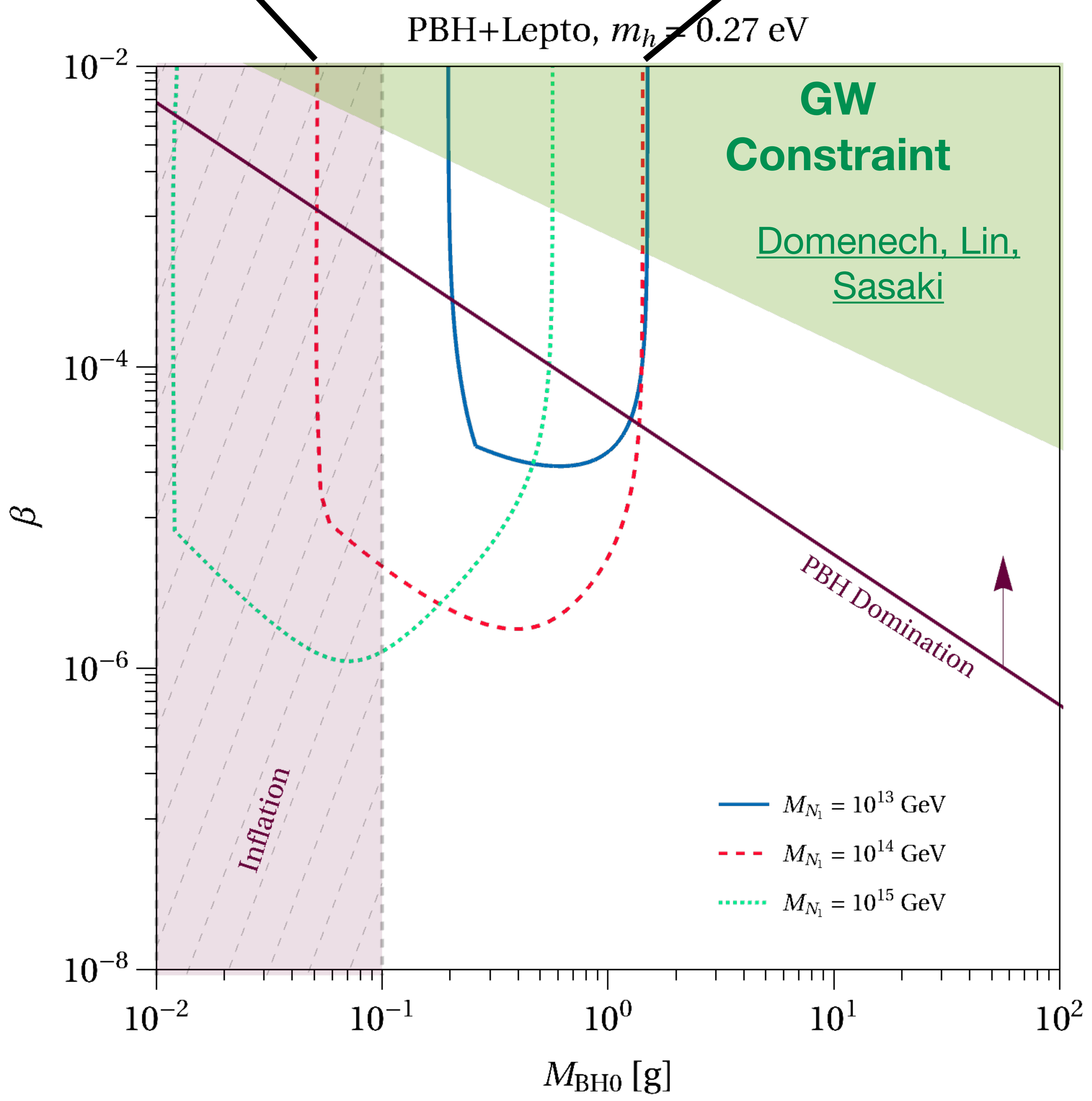
Lighter PBH evaporates Before thermal Leptogenesis era and no Effect observed

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



PBHs
Evaporate earlier
$\sigma_{\Delta L=2} > H$

PBHs
Entropy dump
exceeds
RHN production



Thoughts for the future

Monochromatic approximation *too* approximated?

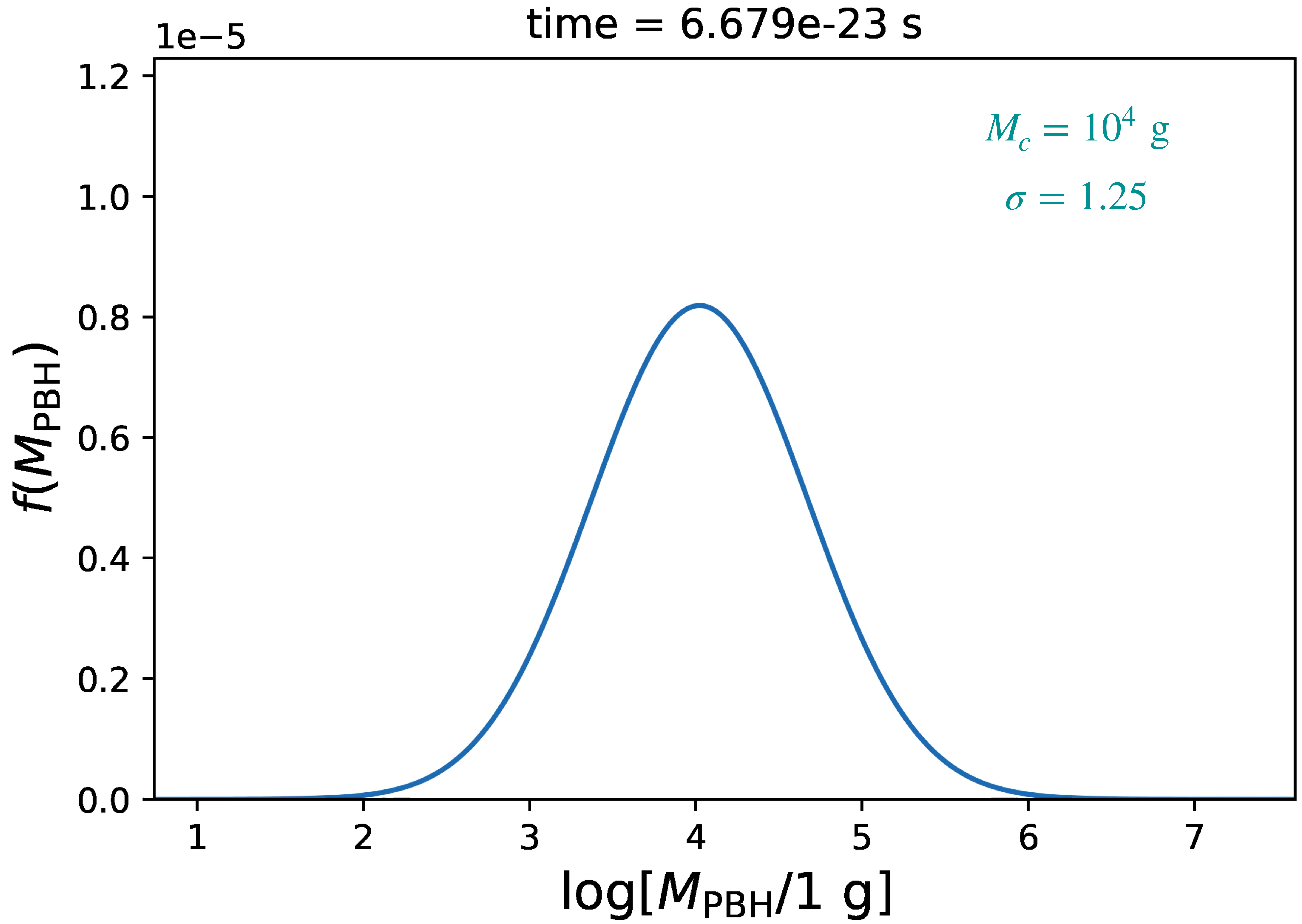
Connection with different formation mechanisms?

Having PBHs with different masses could have a distinct impact on the previous results

$$n_{\rm PBH} = \int dM f(M) \qquad f(M) = \frac{n_{\rm BH}}{\sqrt{2\pi}\sigma M} \exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$

Log-normal distribution

Dolgov, 93
Green, 2016
Kannike, 2017



Thanks to Yuber
For the nice animation

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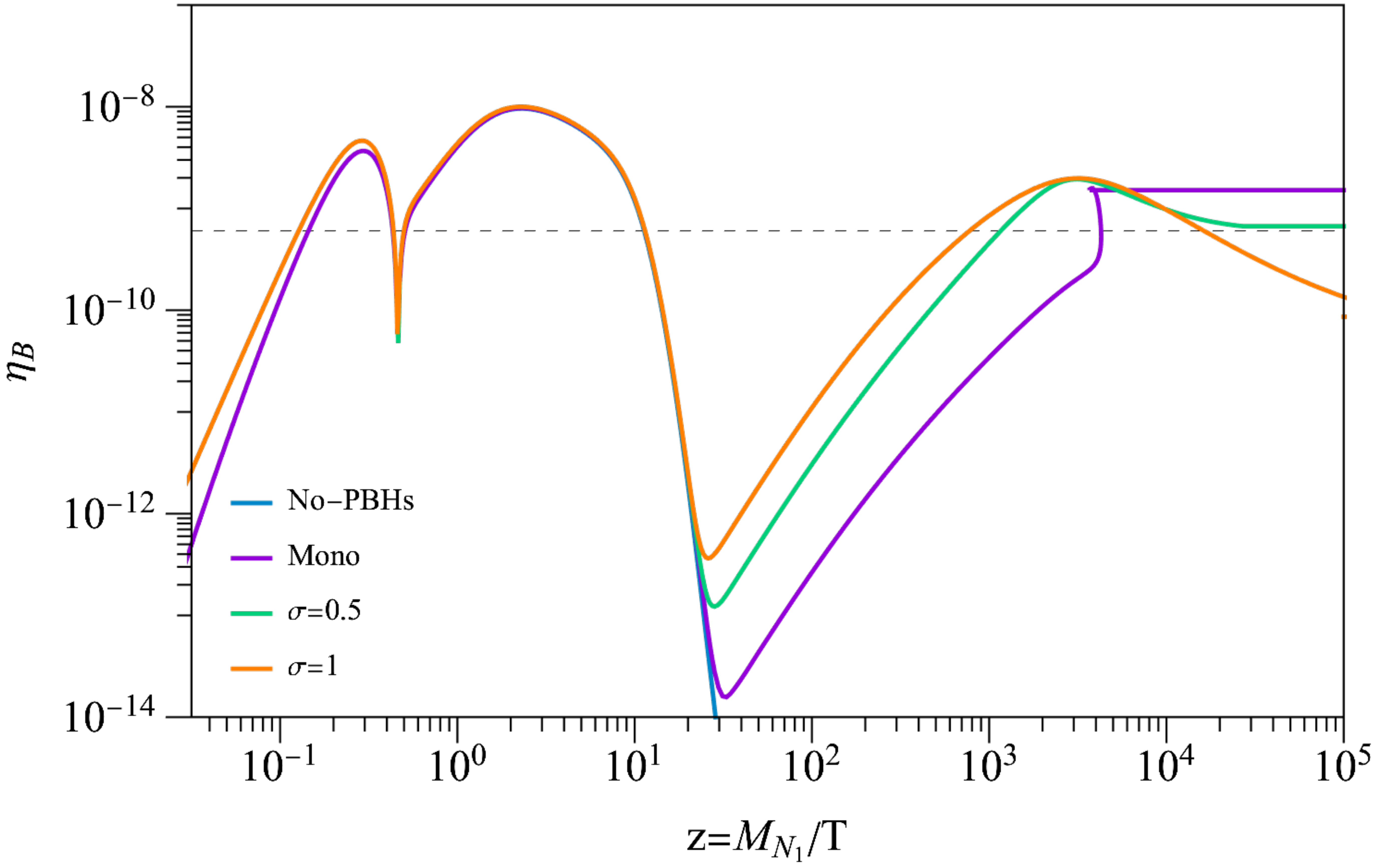


PBH Leptogenesis Summary

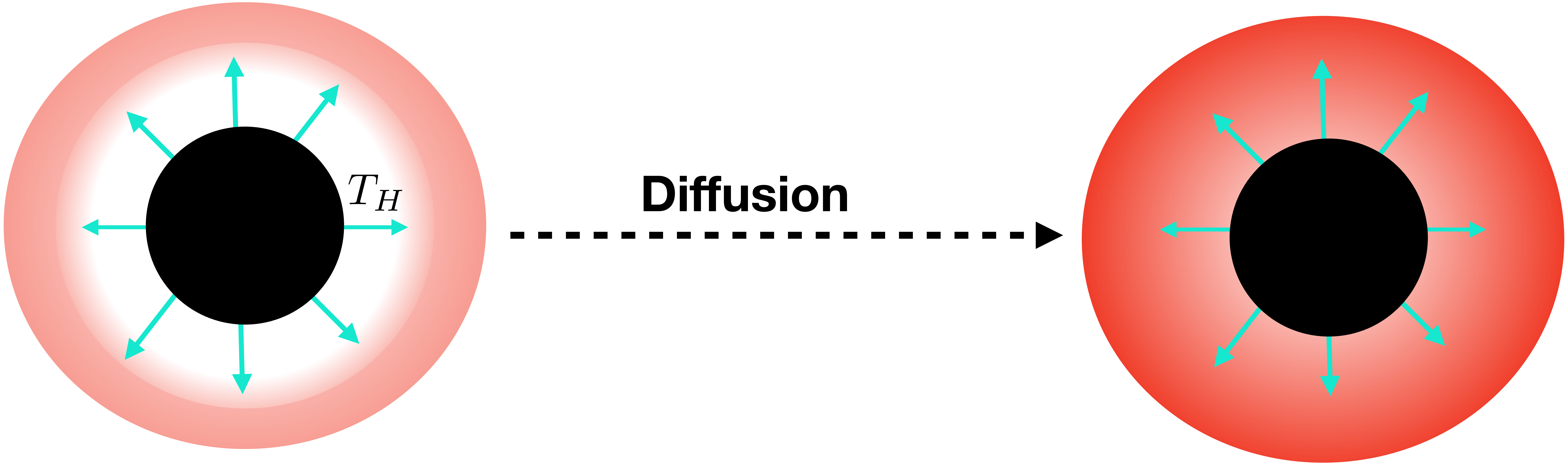
- **Leptogenesis** aims to simultaneously explain **light neutrino masses** and the **observed BAU** so typically the heavy degrees of freedom will couple to the thermal plasma

- PBHs of kg scale and beyond are **inefficient at producing a lepton asymmetry** But **deliver large entropy dumps** placing tension on the leptogenesis PS

- Very light PBHs $\lesssim 1\,\mathrm{g}$ can open up some of the parameter space for high-scale leptogenesis as production of RHNs via Hawking radiation is efficient after washout processes are out of equilibrium

Thoughts for the future

- Recent detailed studies on “hot spots” around PBHs Hook et al (2109.00039) and He, Kohri, Mukaida & Yamada (2210.06238)



- How do temperature inhomogeneities in thermal plasma created by PBHs affect cosmological observables? Work with **Yuber Perez Gonzalez, Jacob Gunn & Lucien Heurtier**

Thoughts for the future

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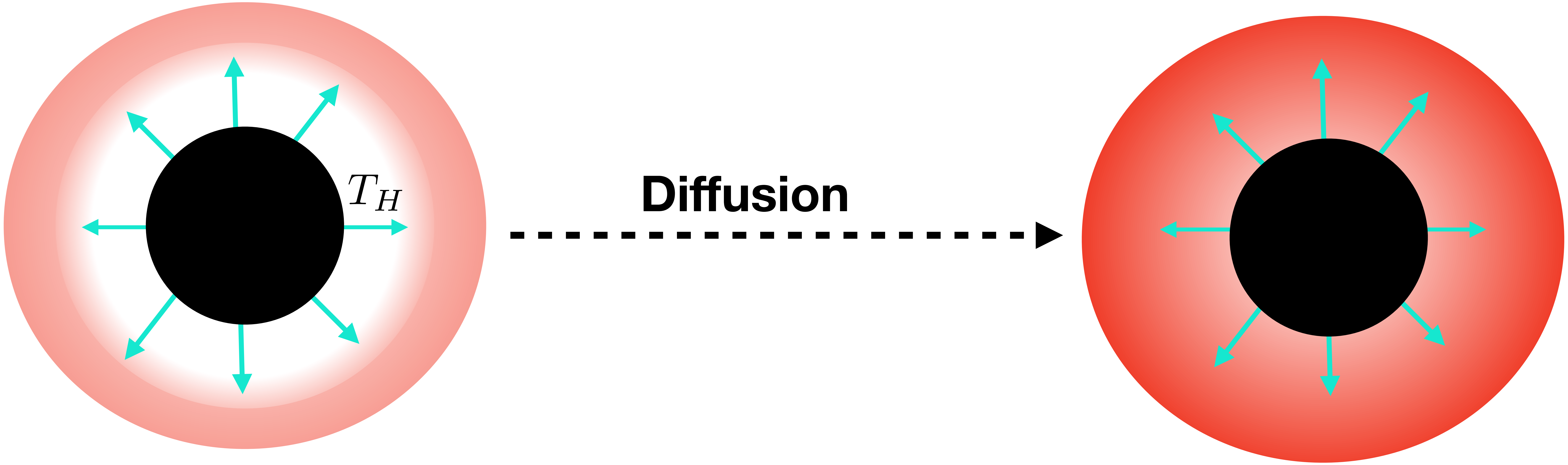

- If RHNs exist, PBHs would produce them. Do the RHNs escape the hot spot?

Thoughts for the future

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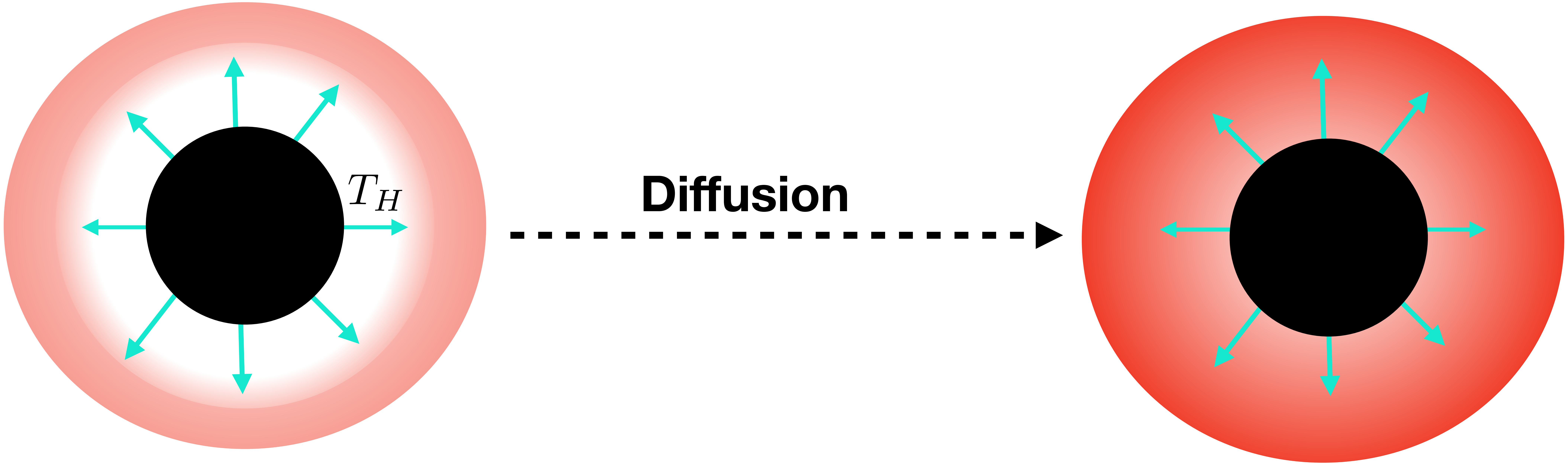
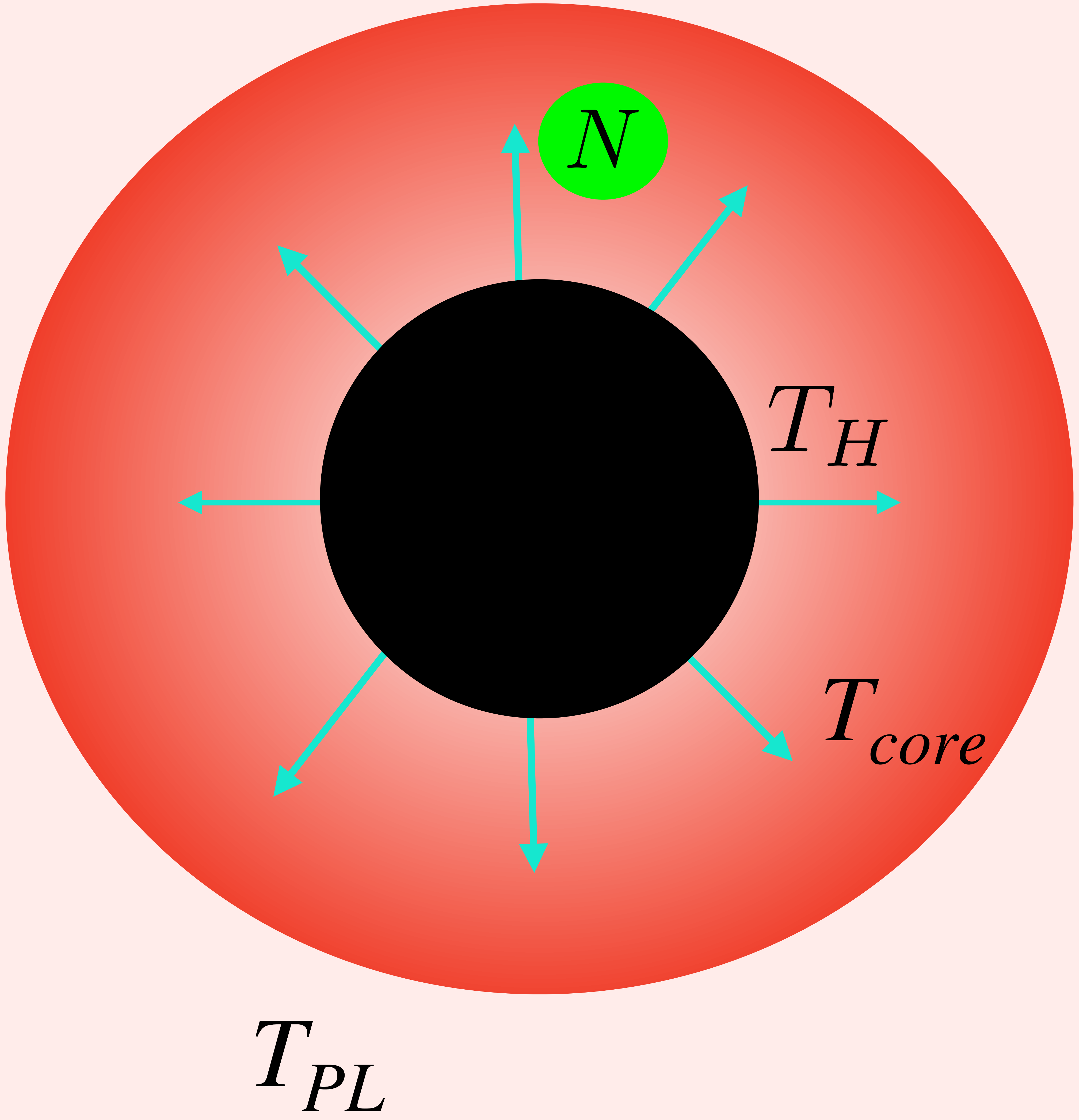


- If RHNs exist, PBHs would produce them. Do the RHNs escape the hot spot?
- Understand hot spot time evolution and $\langle \gamma_{\rm scattering} \rangle_{\rm T_H, T_{core}}$ and $\langle \gamma_{decay} \rangle$

Does RHN escape the hot spot?



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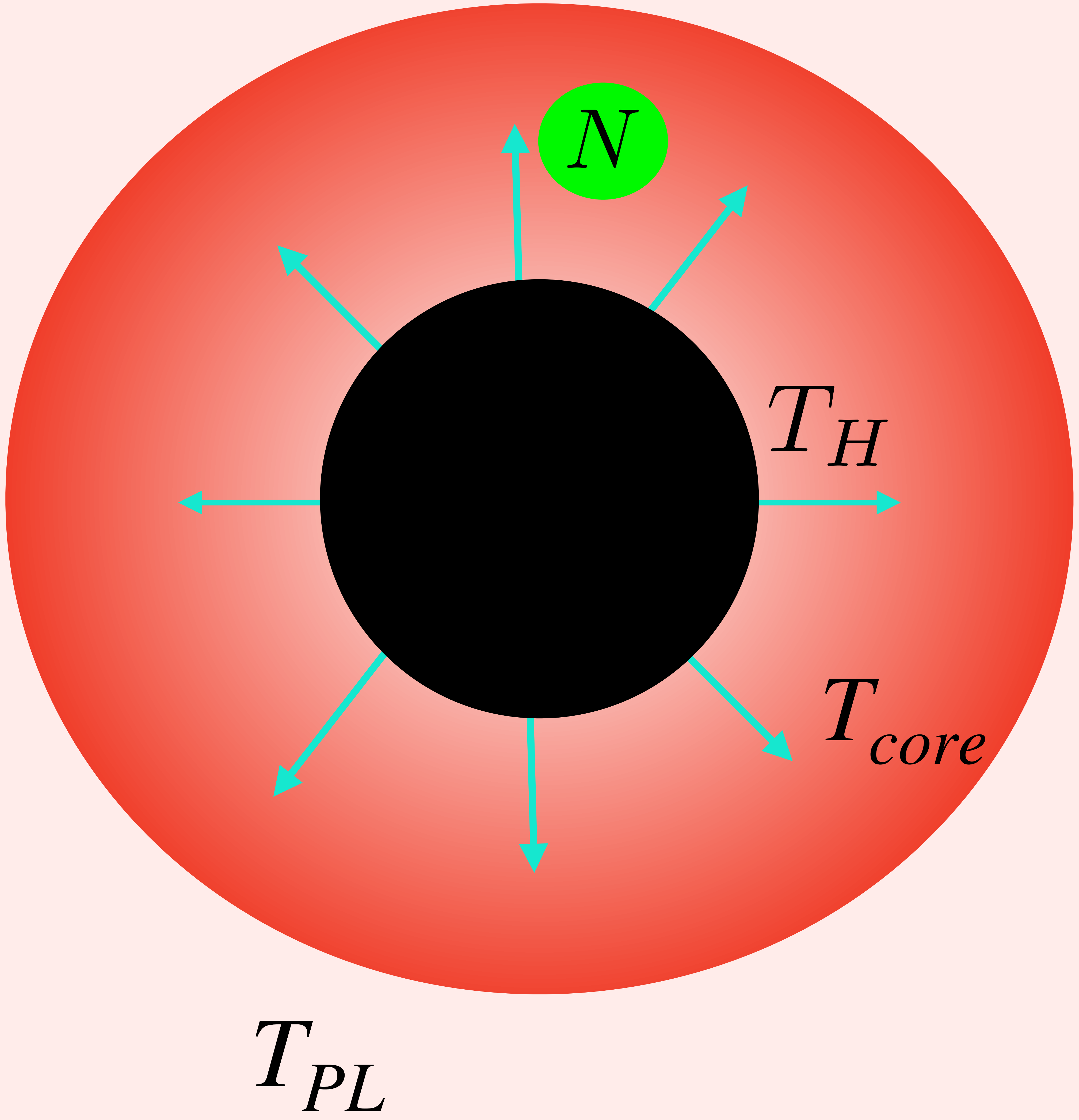

RHN emitted by PBH evaporation is boosted $\gamma = T_H/M_N$ & its decay is time dilated

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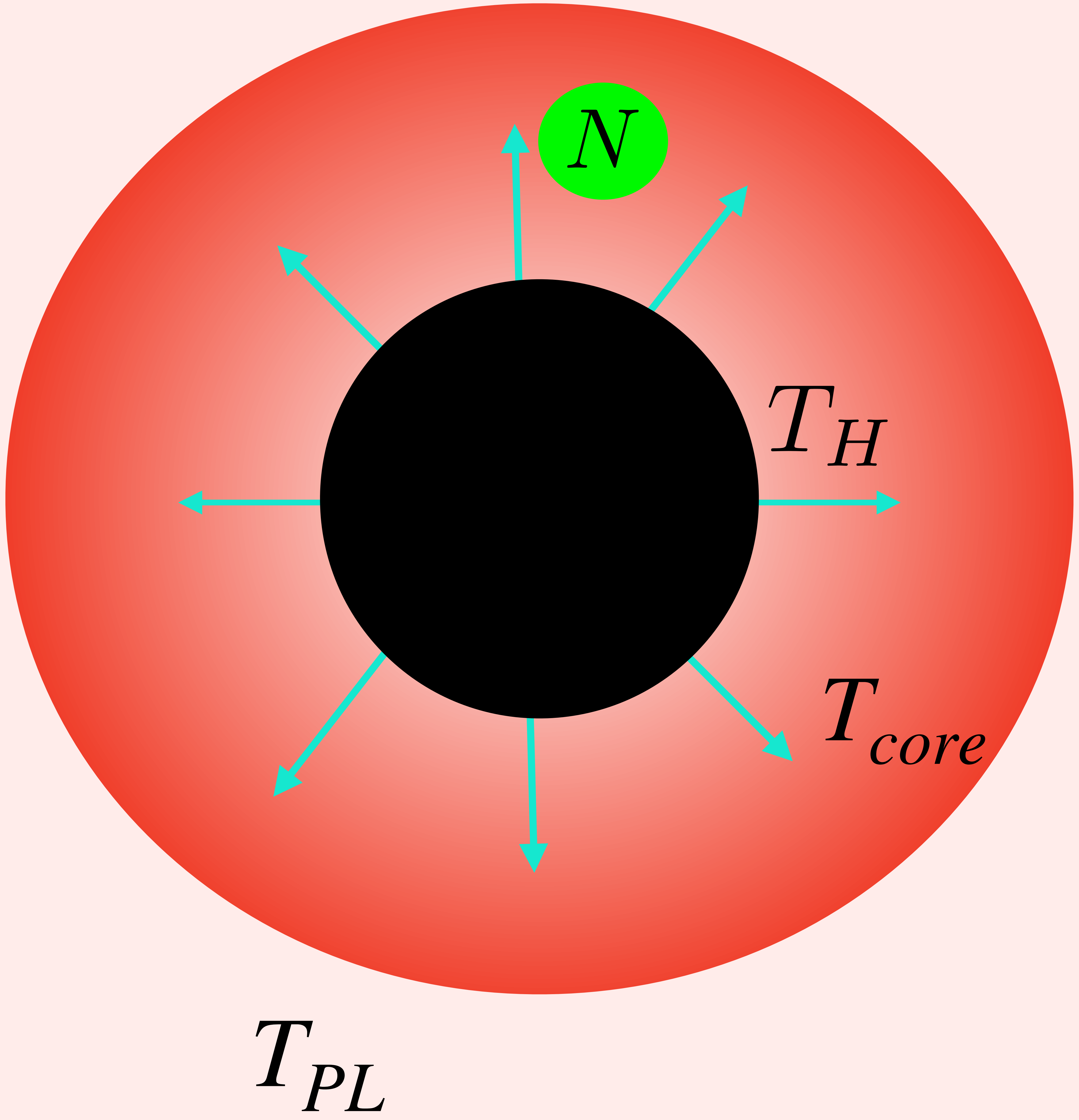

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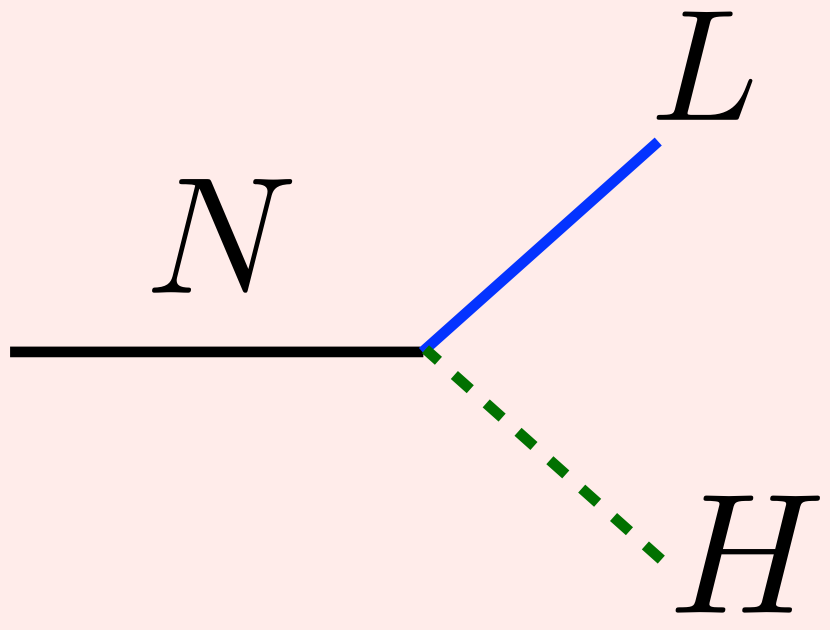
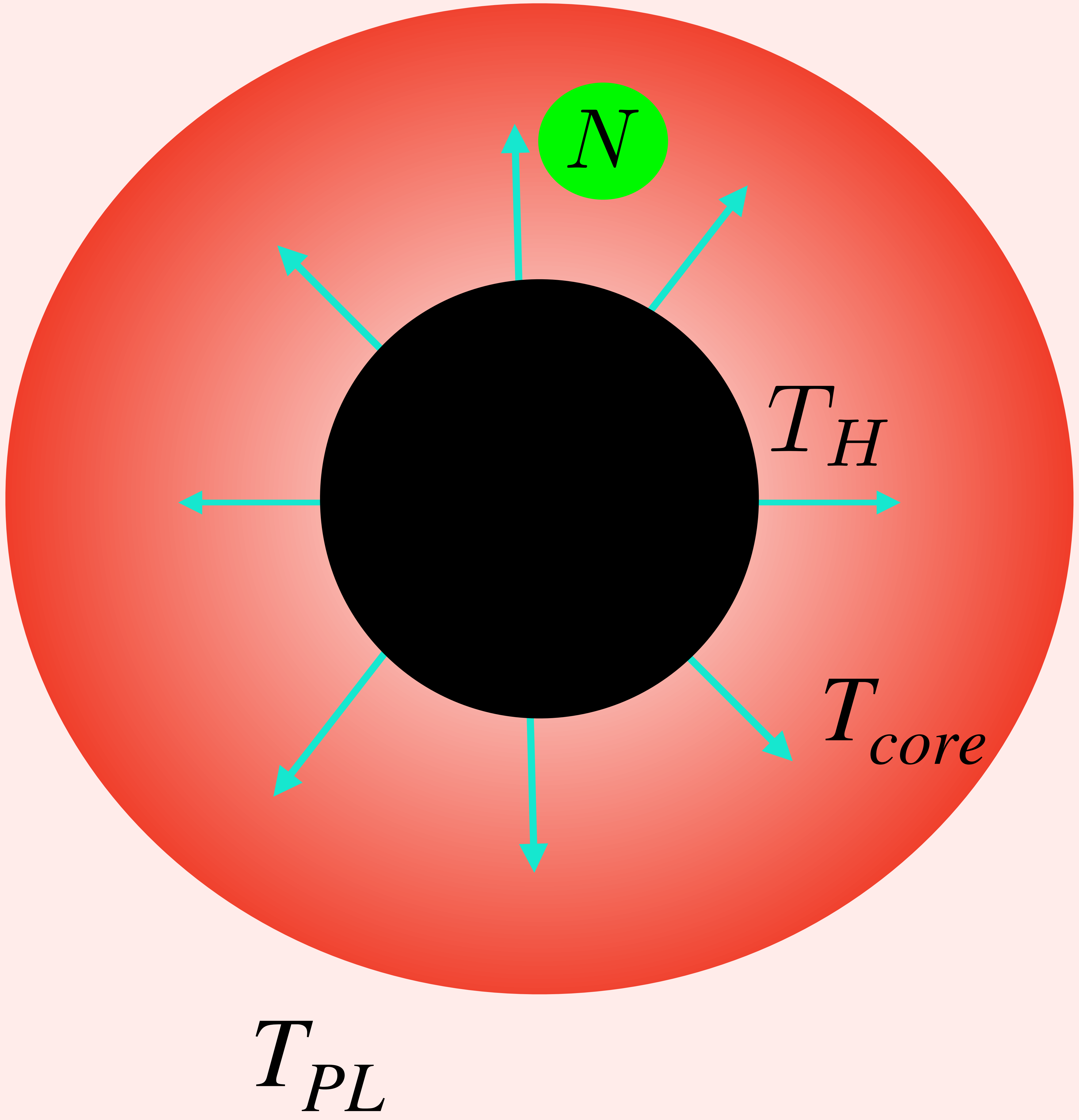


$$\Gamma \left\langle \frac{1}{\gamma} \right\rangle$$

Does RHN escape the hot spot?



But this RHN has to travel
through the hot spot
and can scatter
and possibly thermalise

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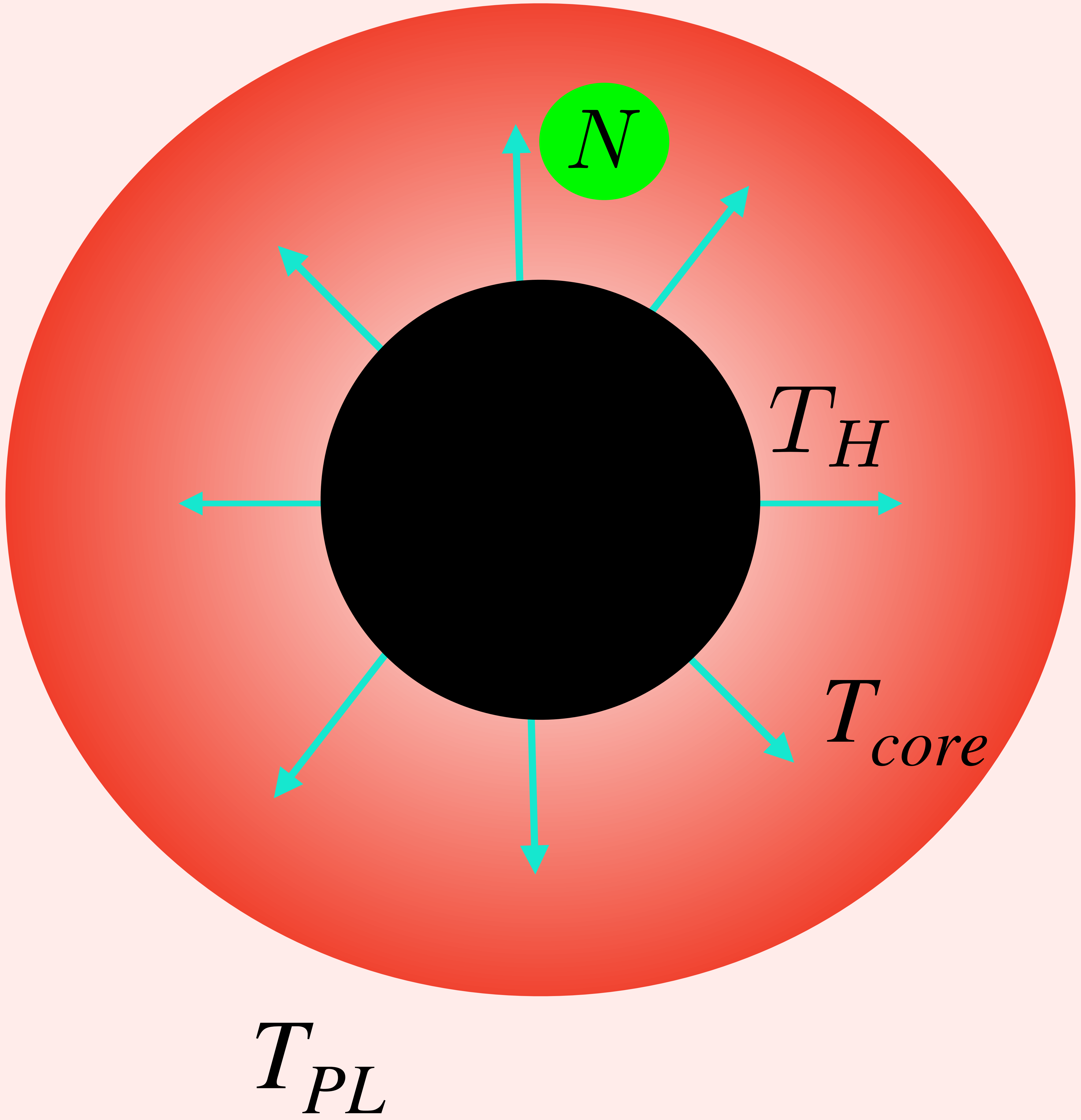

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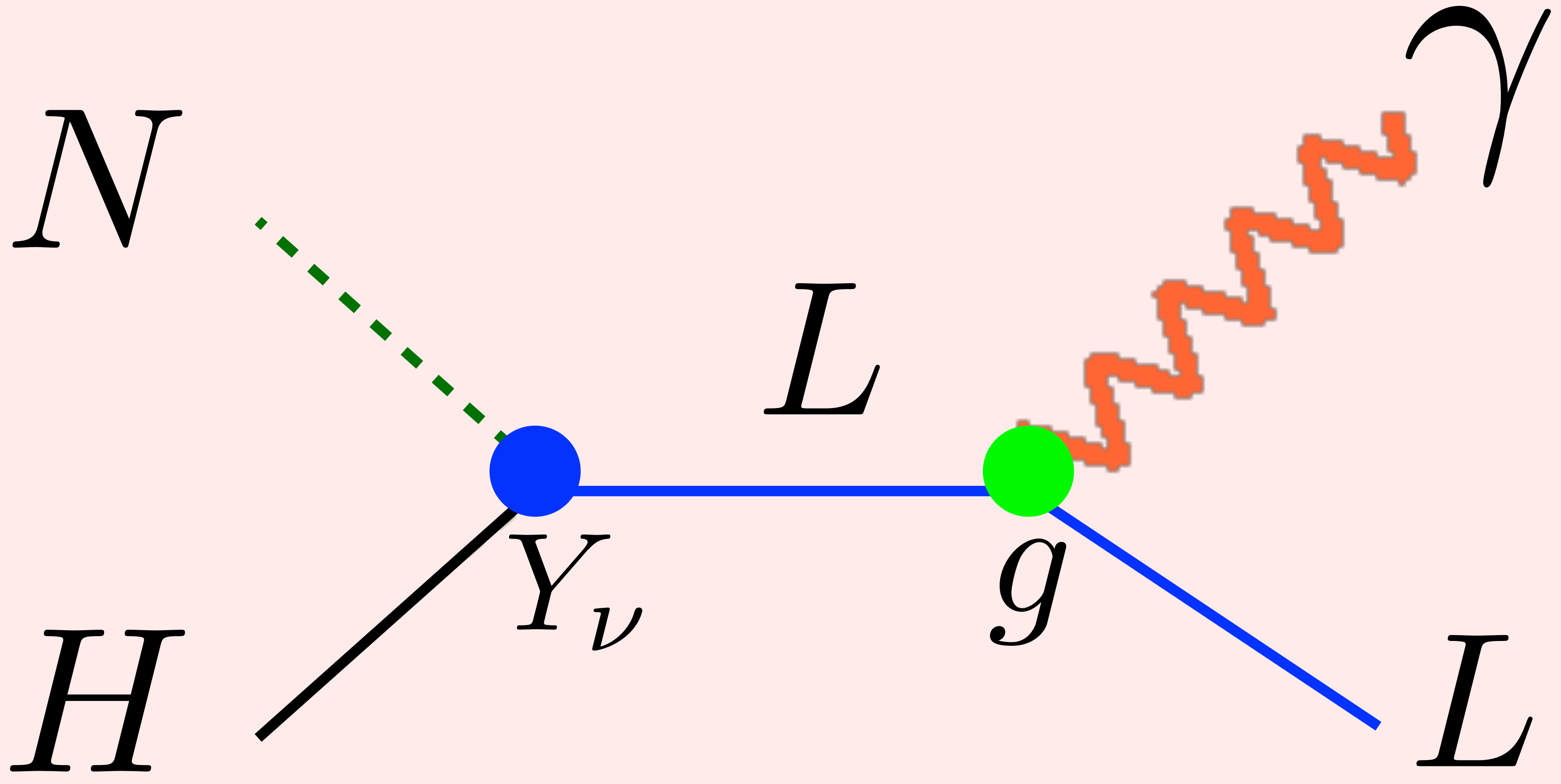

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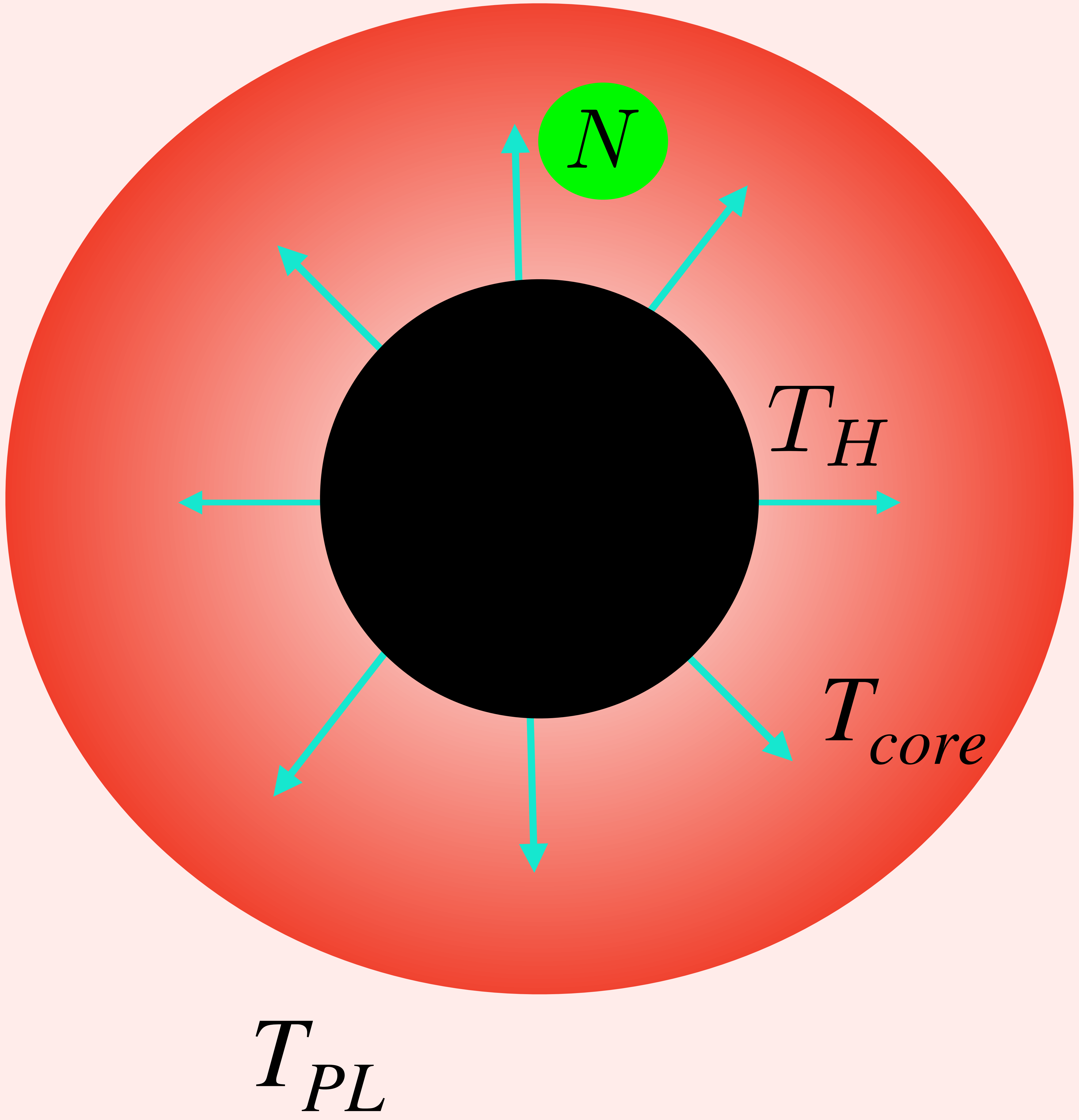

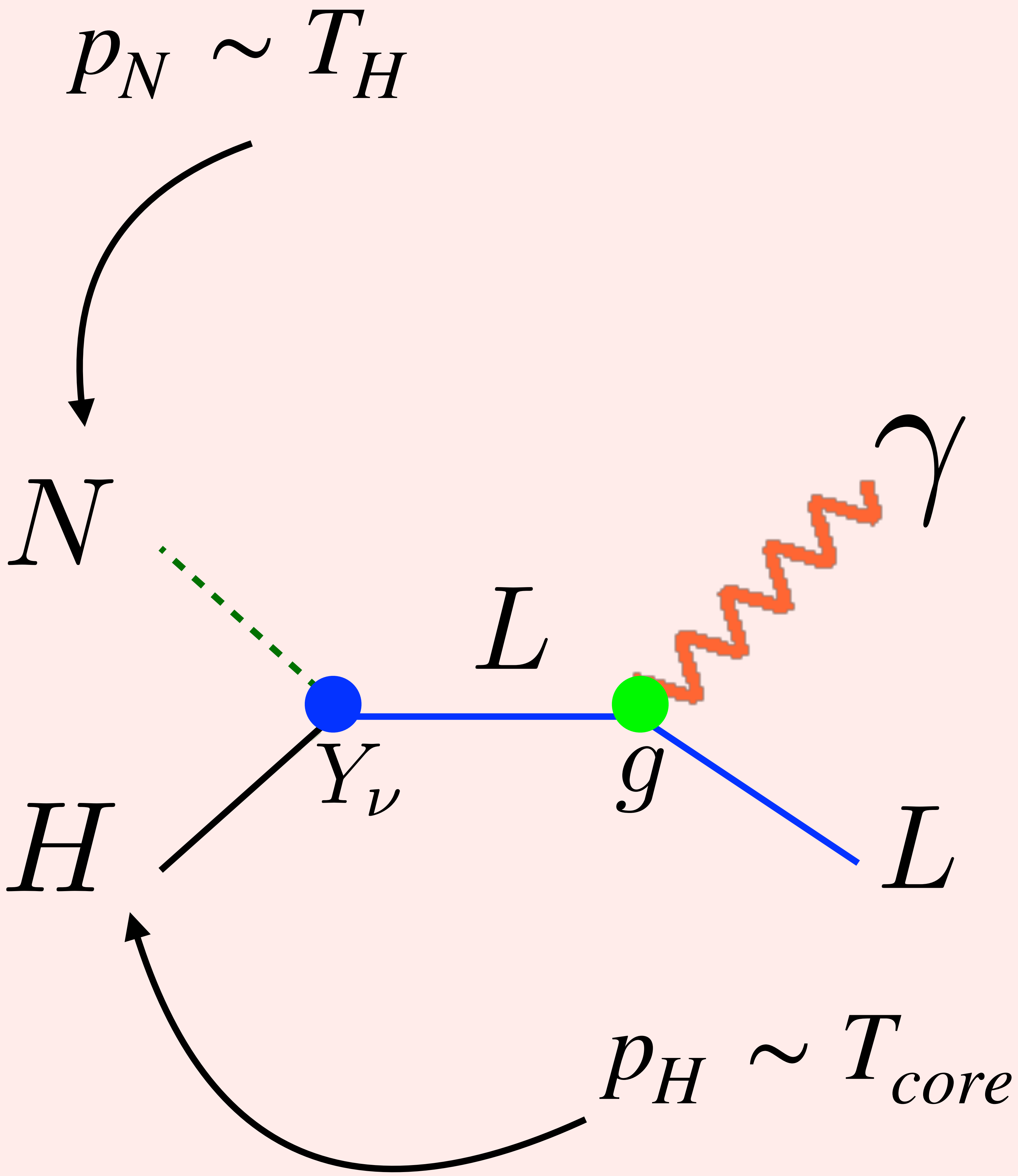

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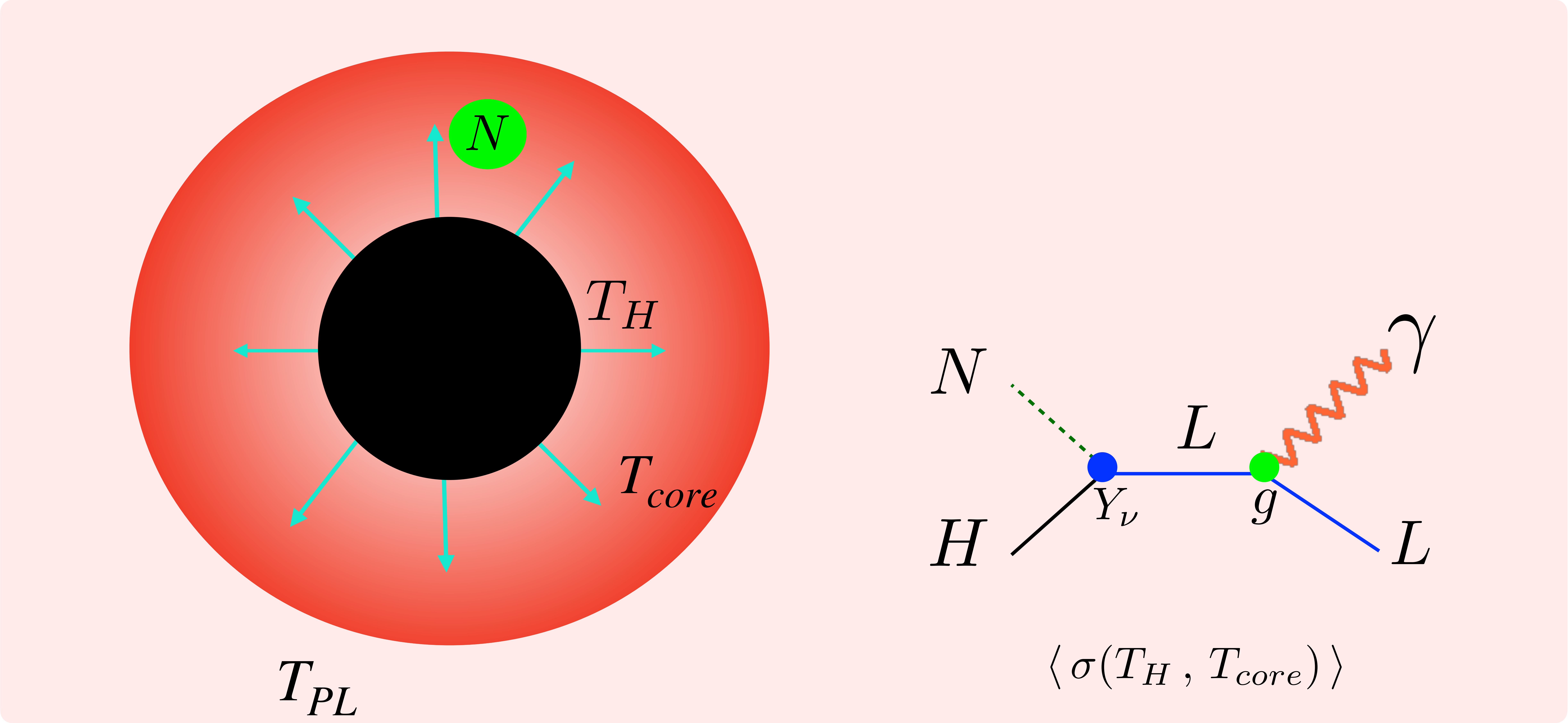
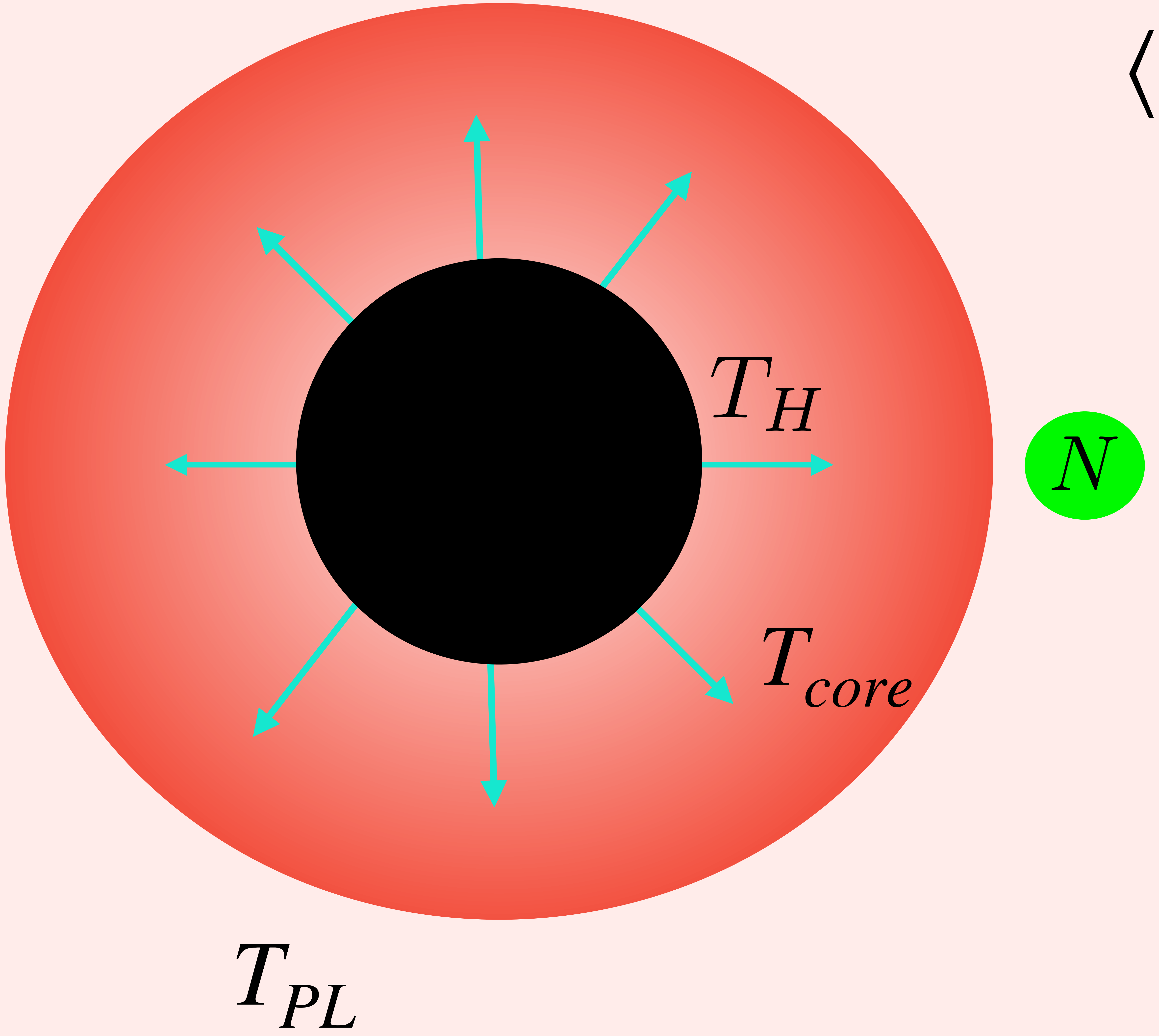


Considered scenario $T_H > T_{PL} > T_{EW}$ & RHN escapes core of the hot spot



$$\langle \gamma_{decay} \rangle \gg \langle \gamma_{\rm scattering} \rangle_{\rm T_H, T_{core}}$$

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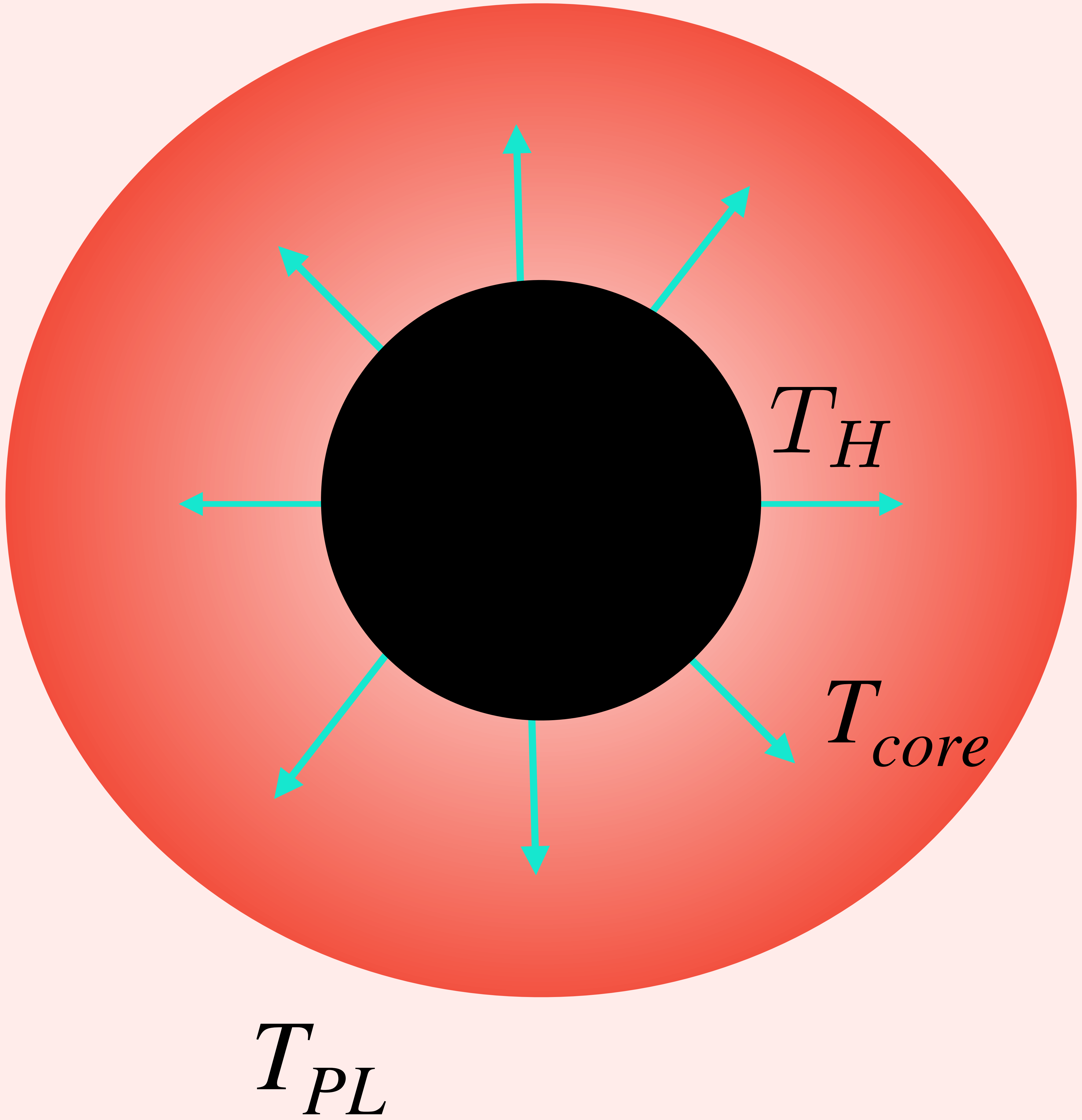

$$\langle \gamma_{decay} \rangle \gg \langle \gamma_{\rm scattering} \rangle_{\rm T_H, T_{core}}$$

$N \rightarrow$ **Lepton Asymmetry**

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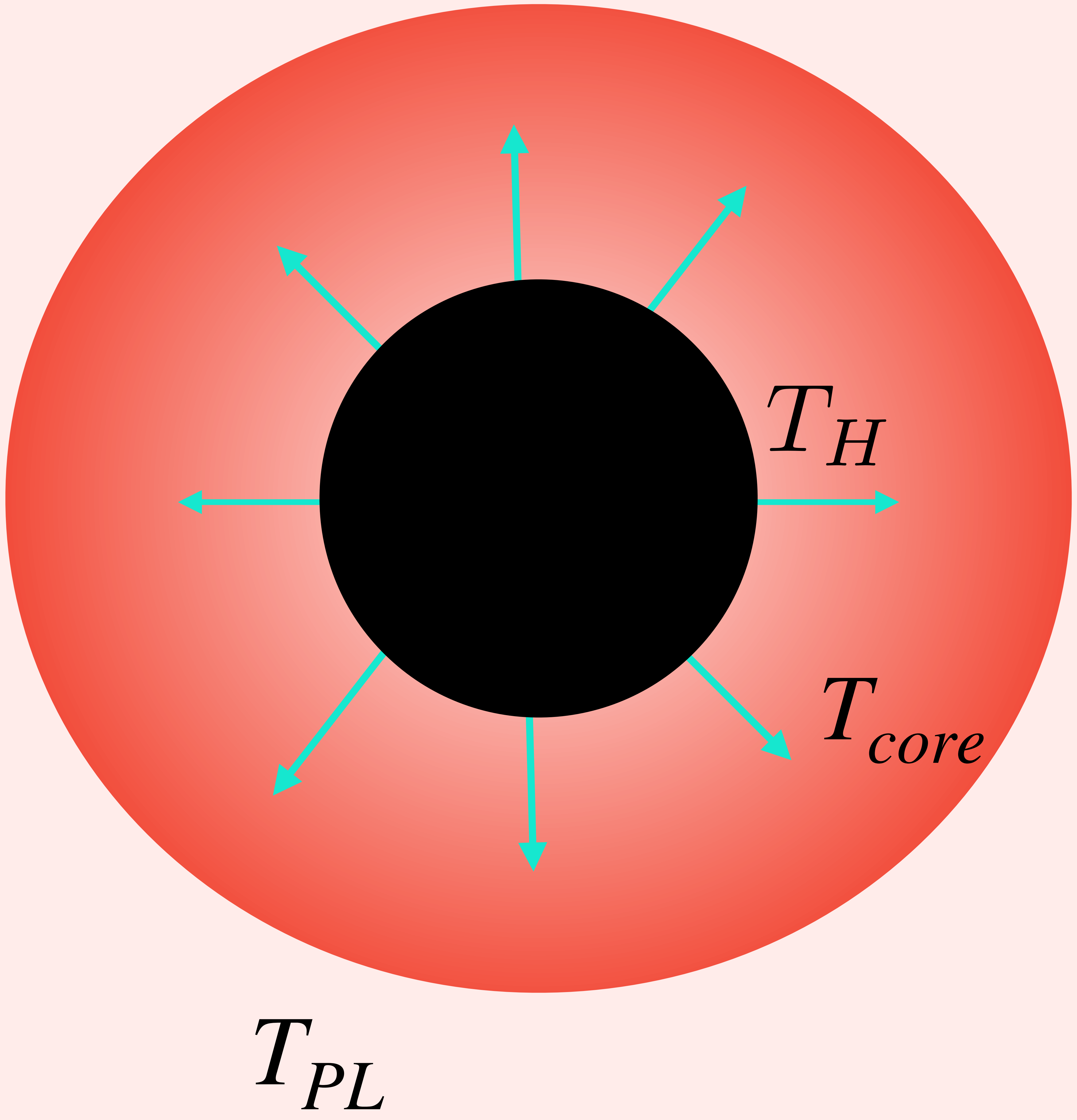
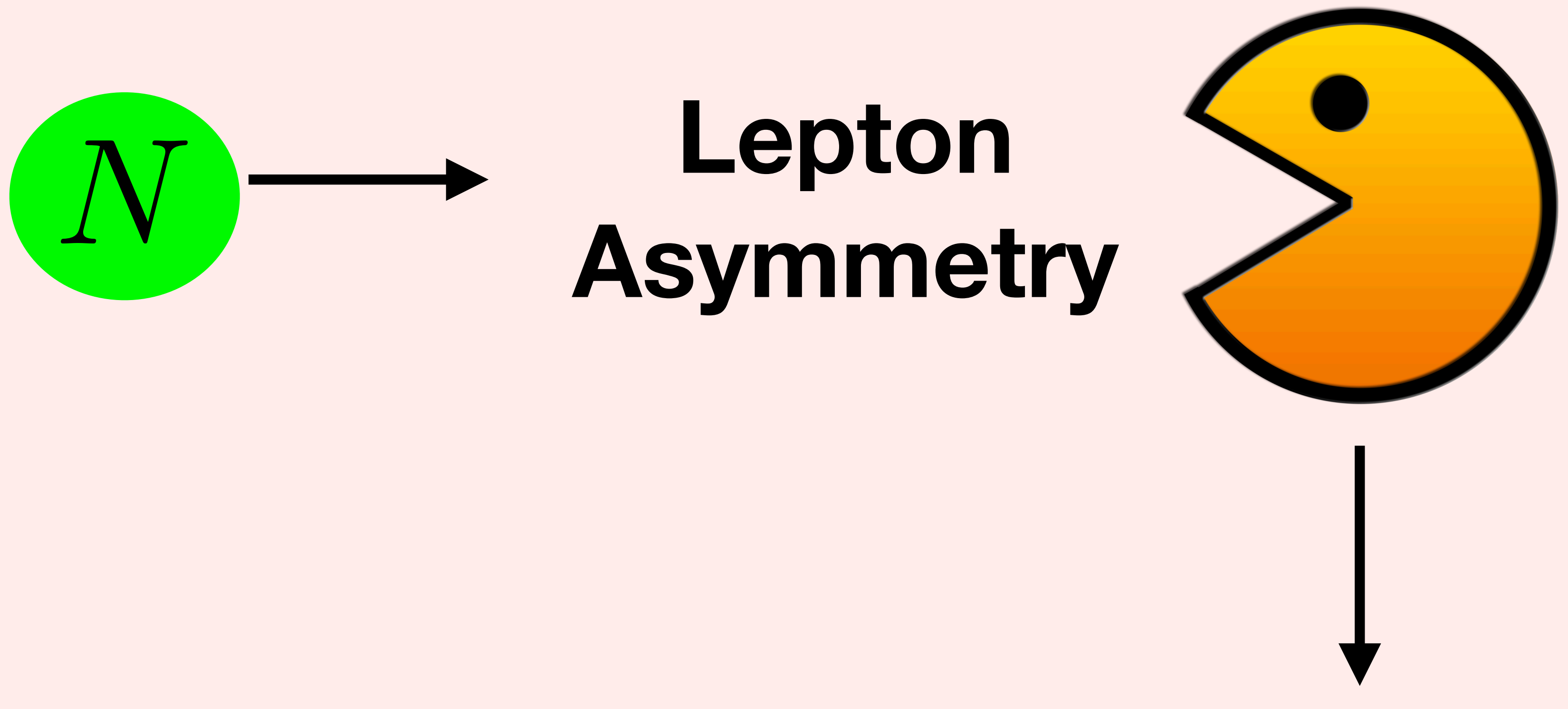
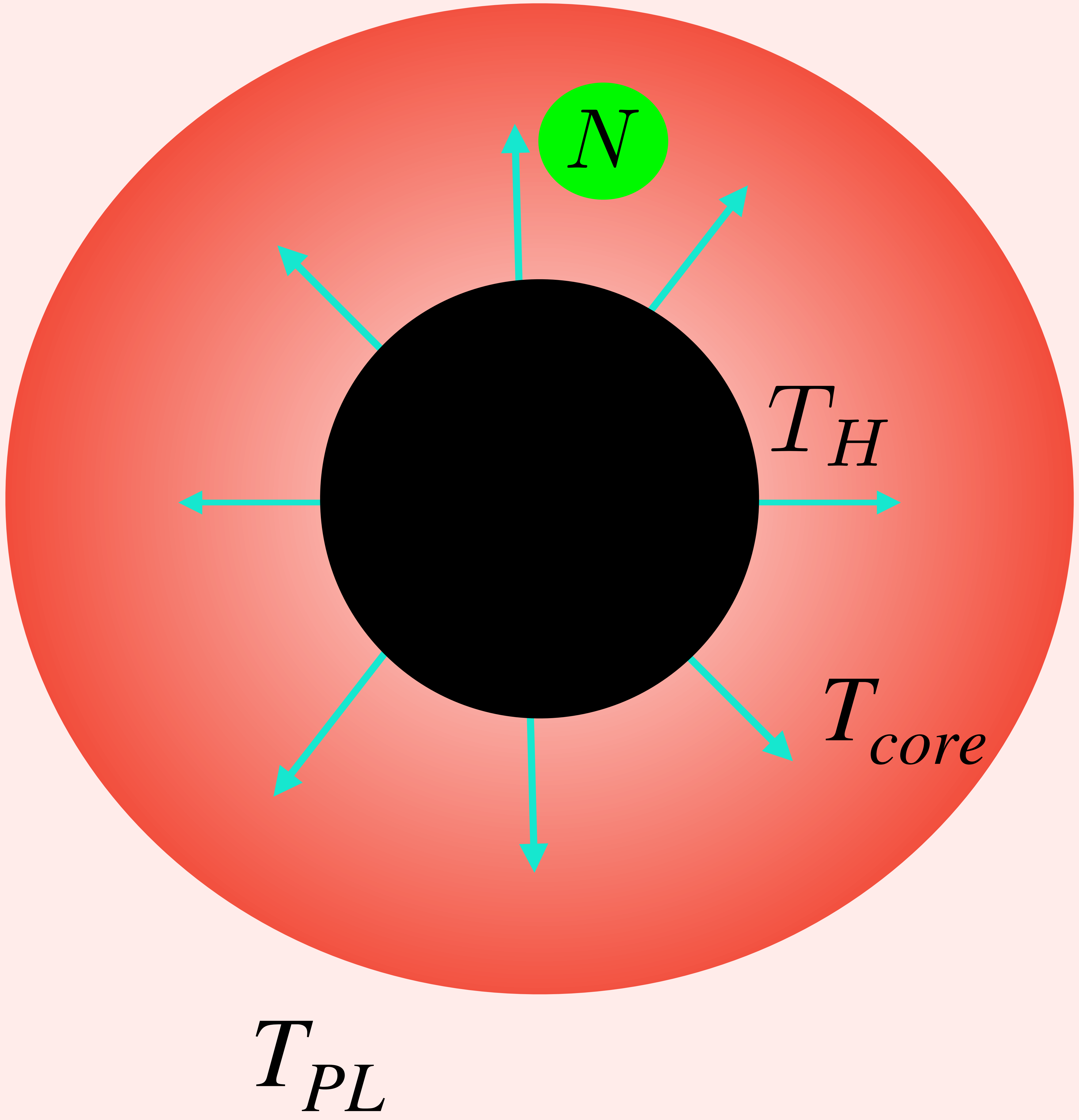




Lepton Asymmetry

Baryon Asymmetry

Considered scenario $T_H > T_{EW} > T_{PL}$ & RHN escapes core of the hot spot



$$\langle \gamma_{decay} \rangle \gg \langle \gamma_{\mathrm{scattering}} \rangle_{\mathrm{T_H,T_{core}}}$$

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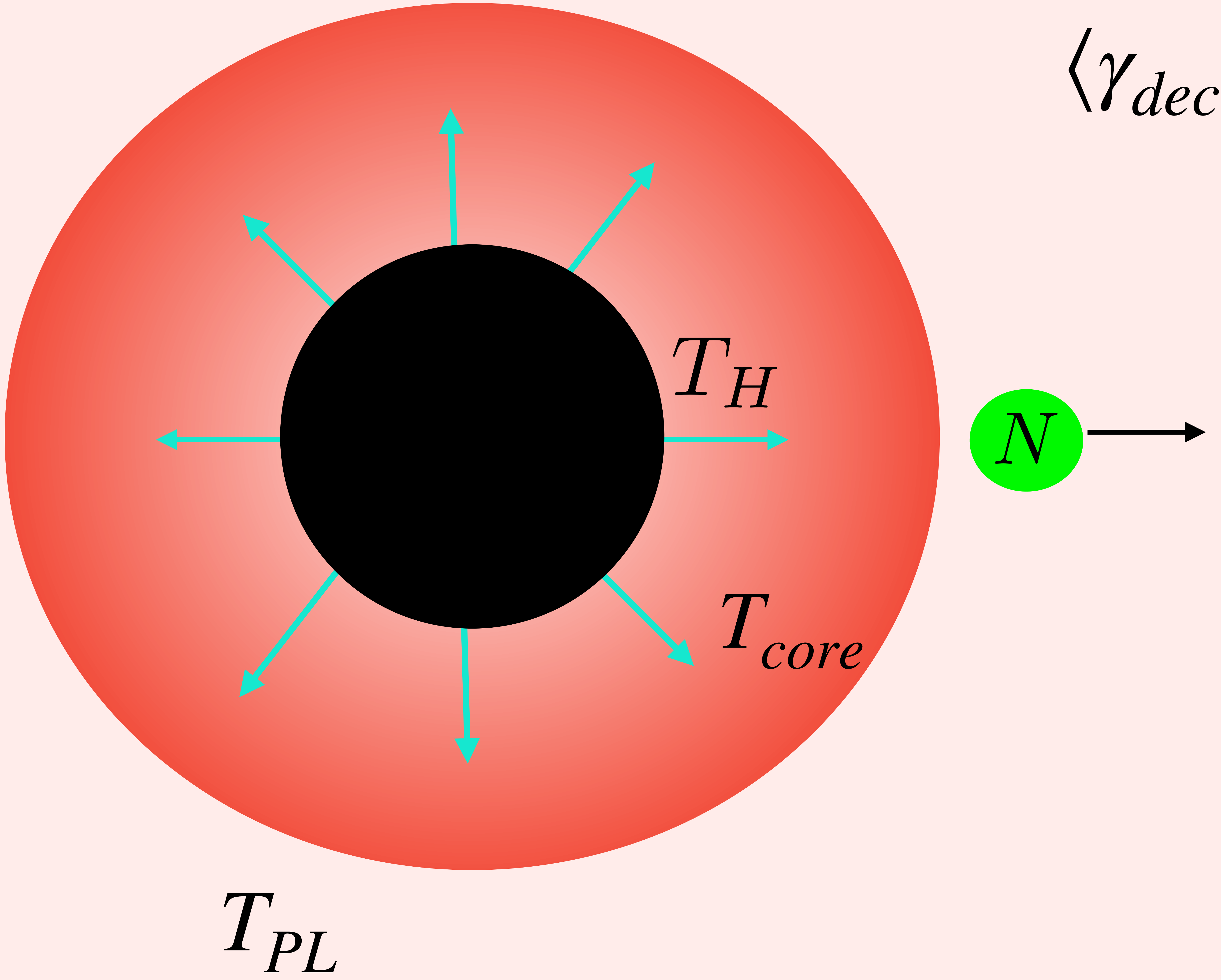

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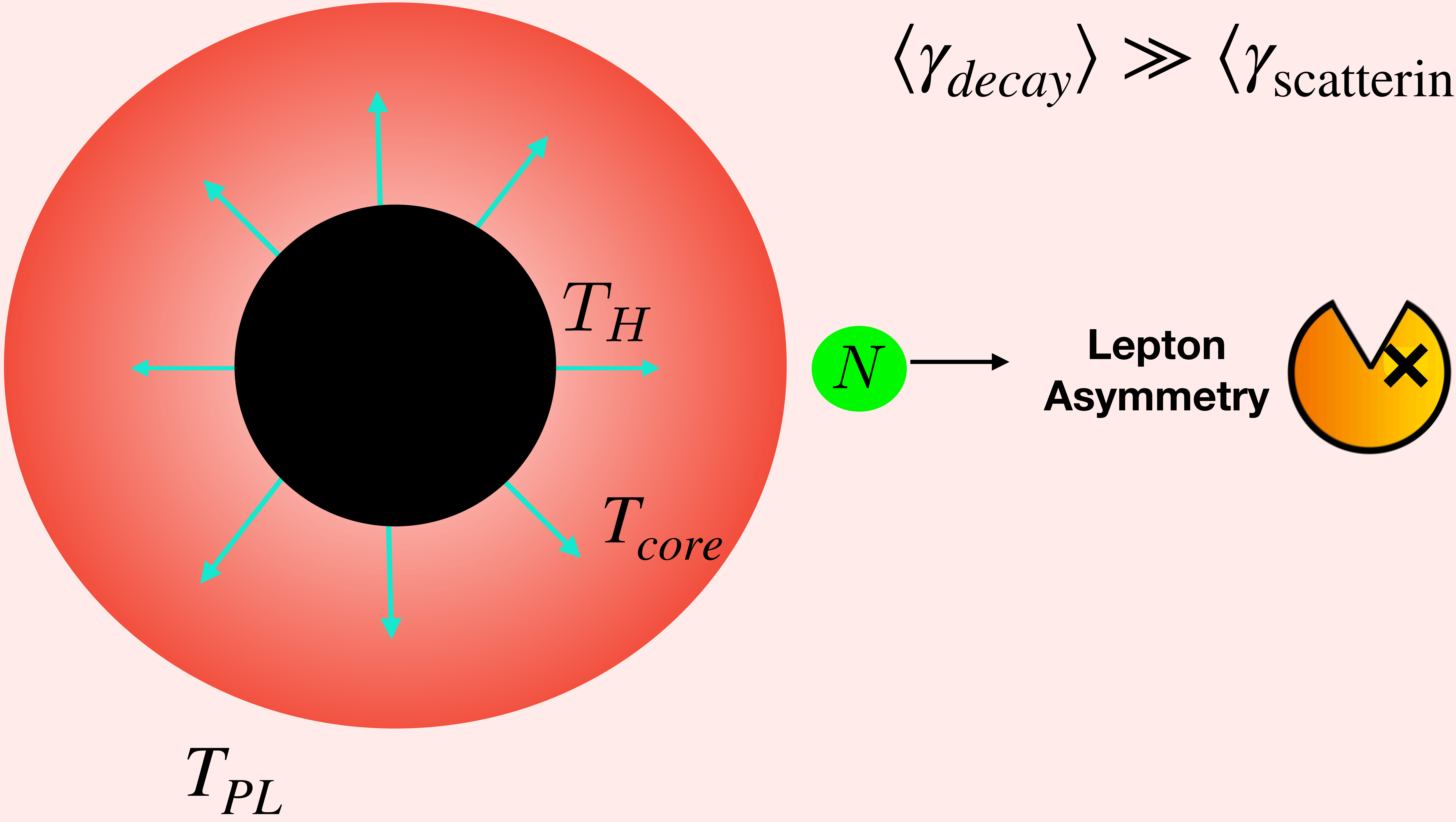

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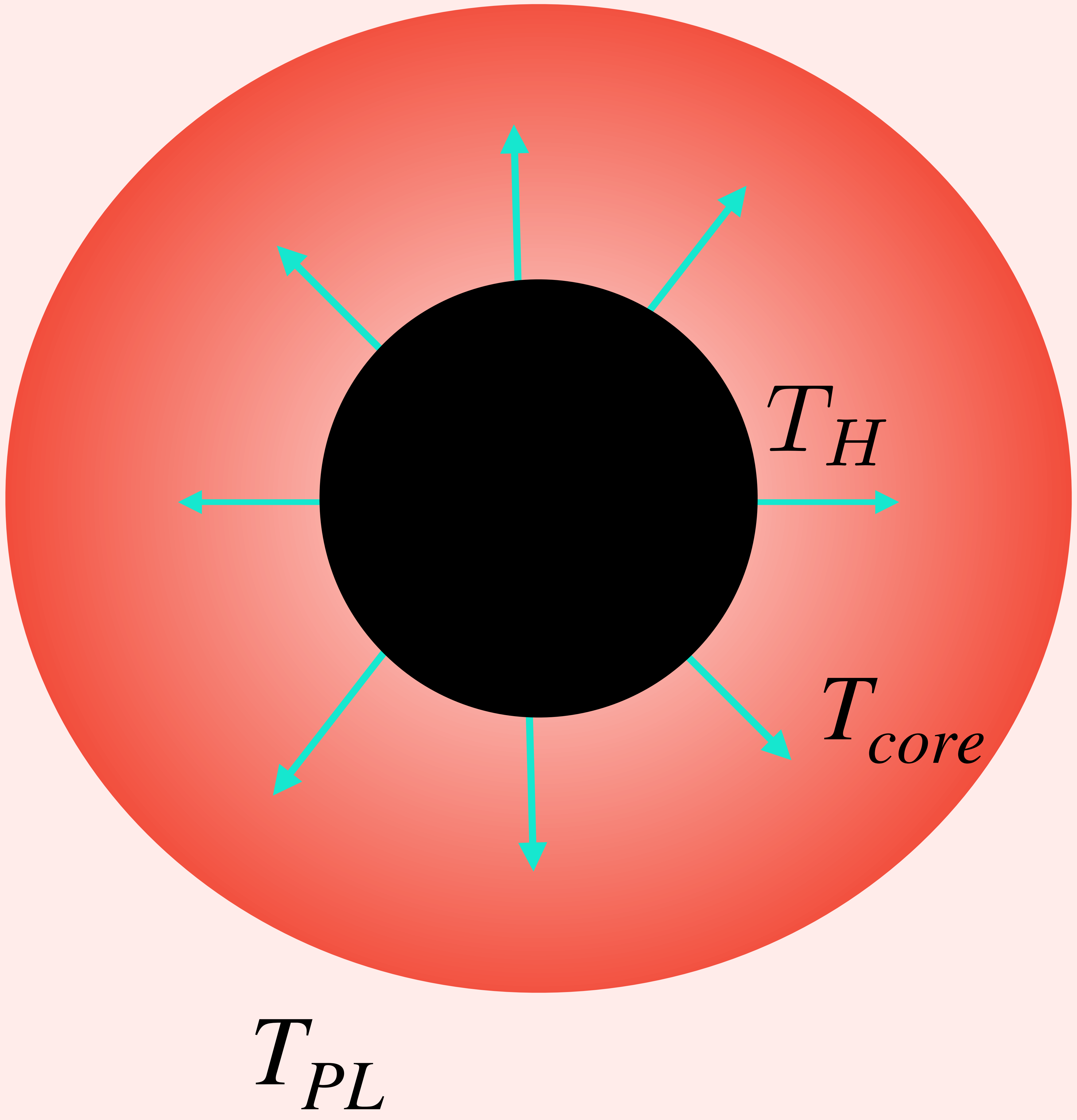


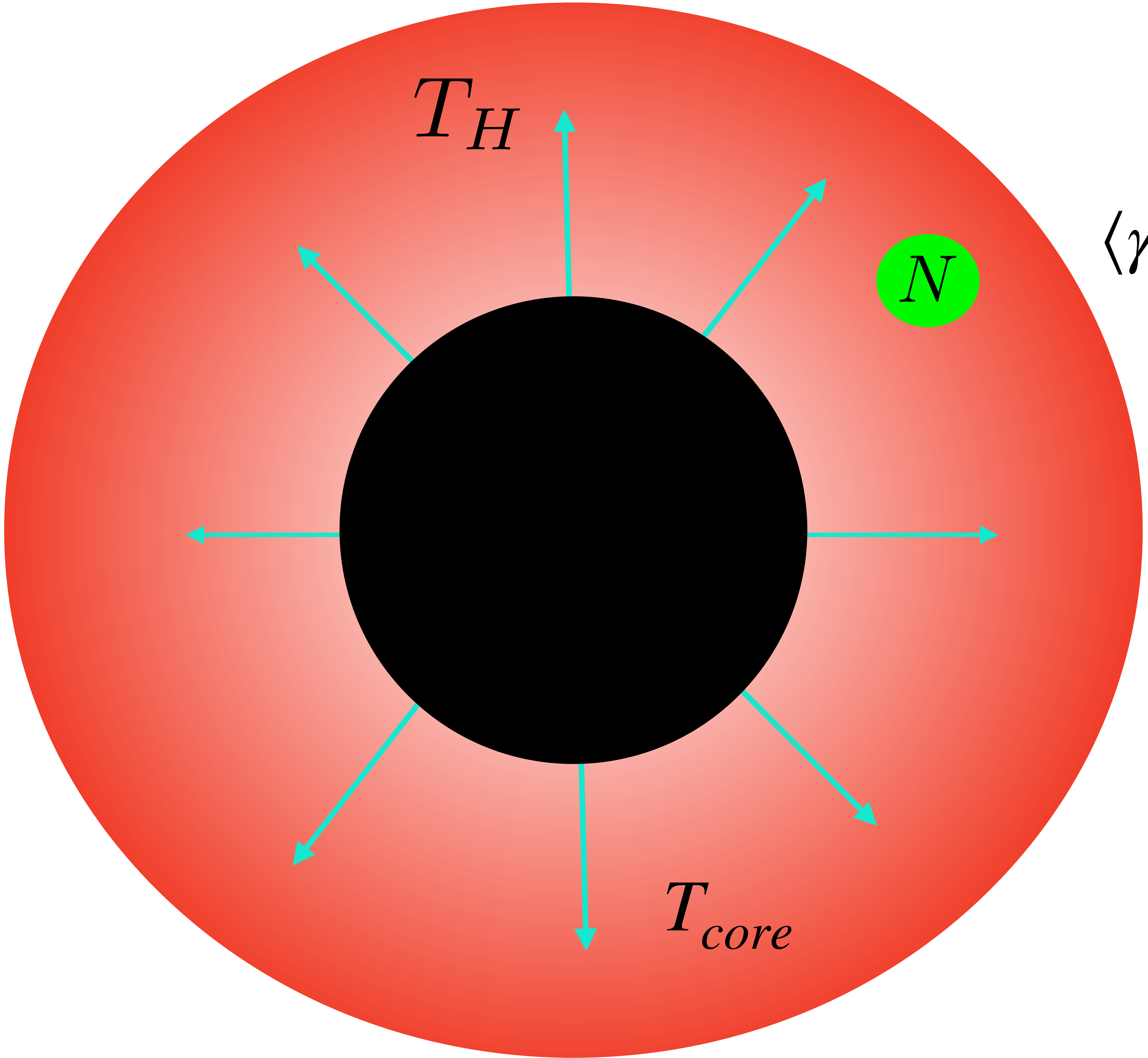
$$\langle \gamma_{decay} \rangle \gg \langle \gamma_{\mathrm{scattering}} \rangle_{\mathrm{T_H,T_{core}}}$$

Primordial lepton asymmetry

Seeded by RHN

& this can be constrained

Scenario where RHN **does not escape hot spot** $\Longrightarrow$ **no asymmetry**



$$\langle \gamma_{\text{scattering}} \rangle_{\text{T}_\text{H},\text{T}_\text{core}} \ll \langle \gamma_{\text{decay}} \rangle$$

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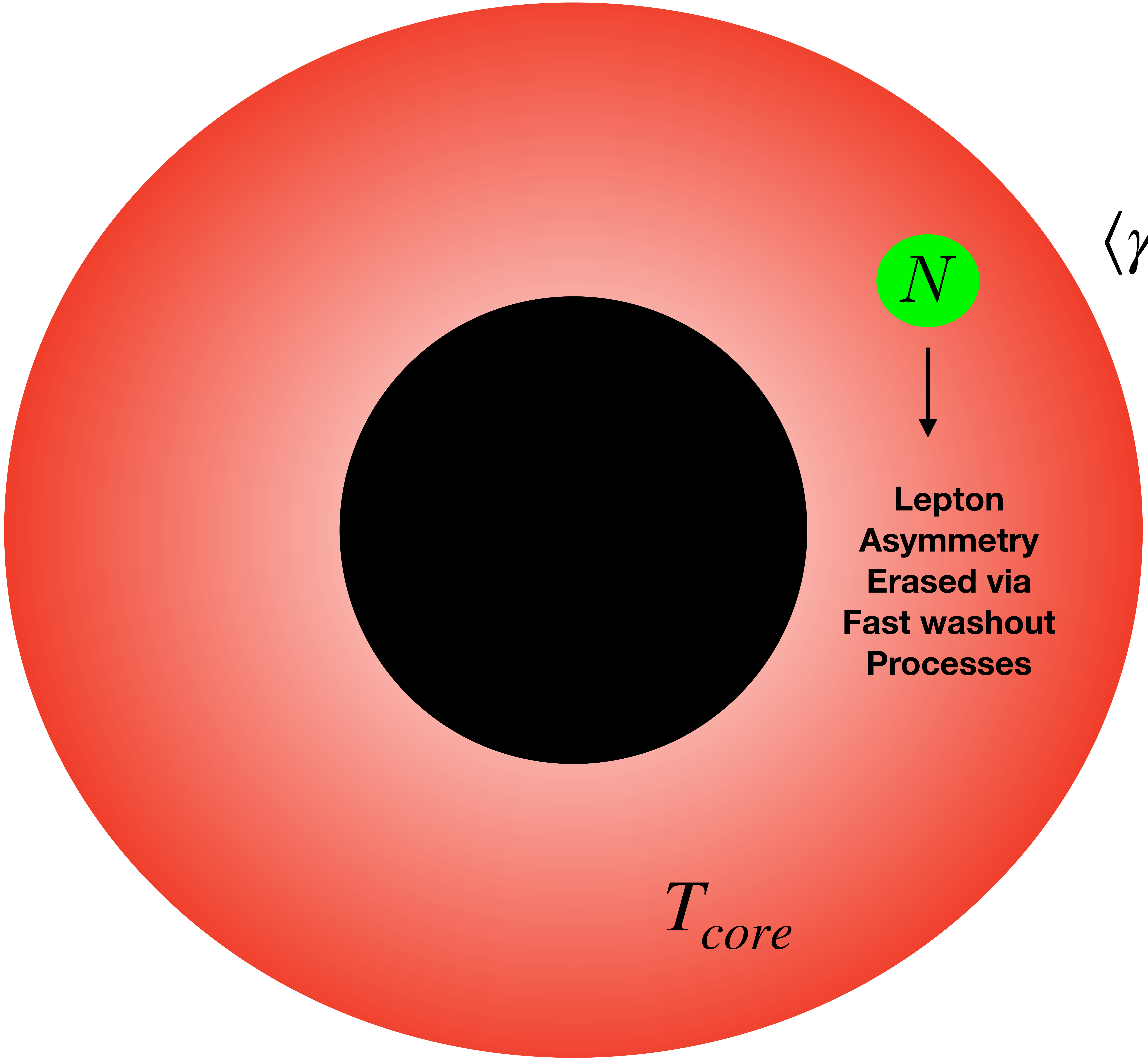
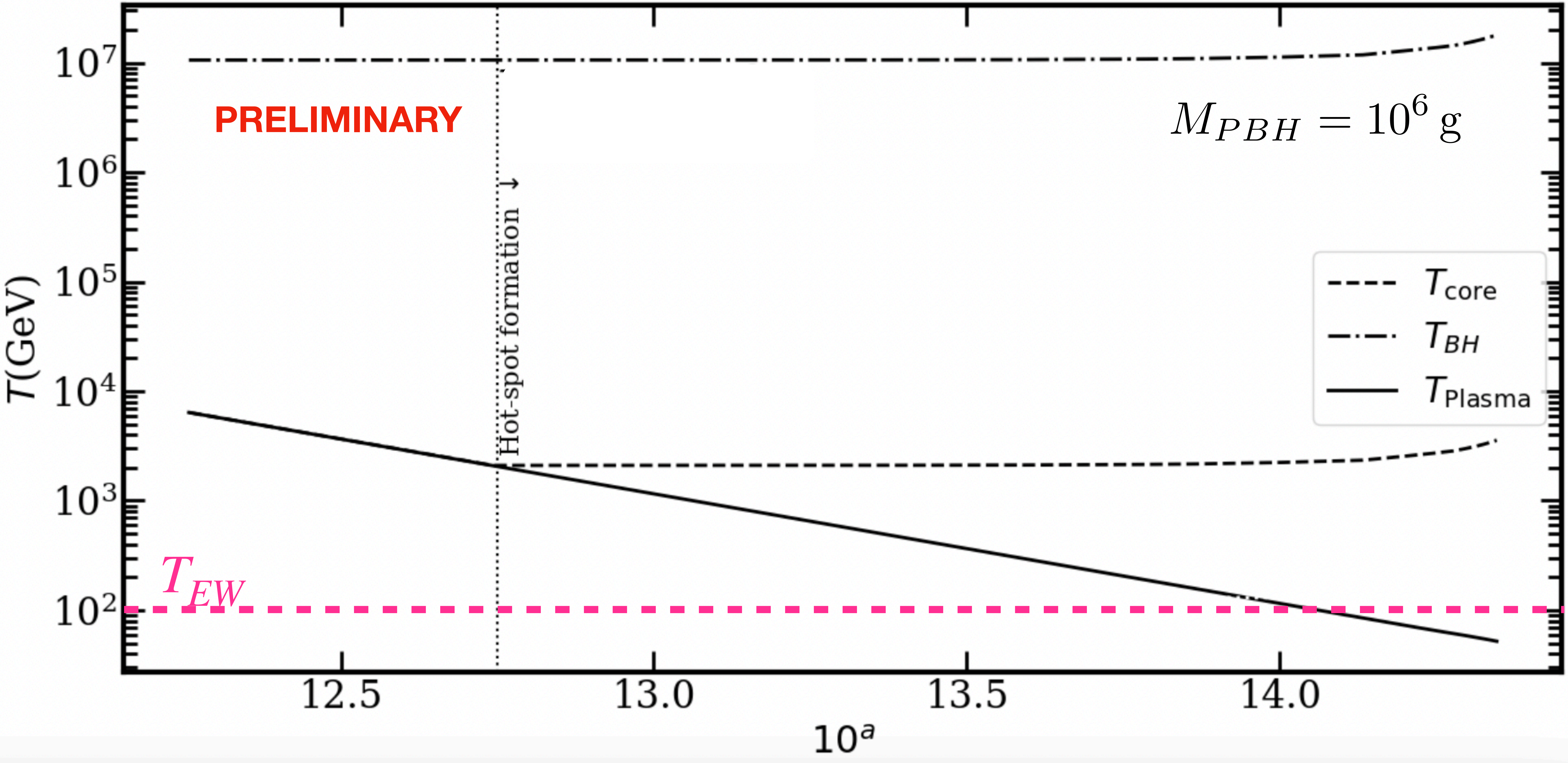
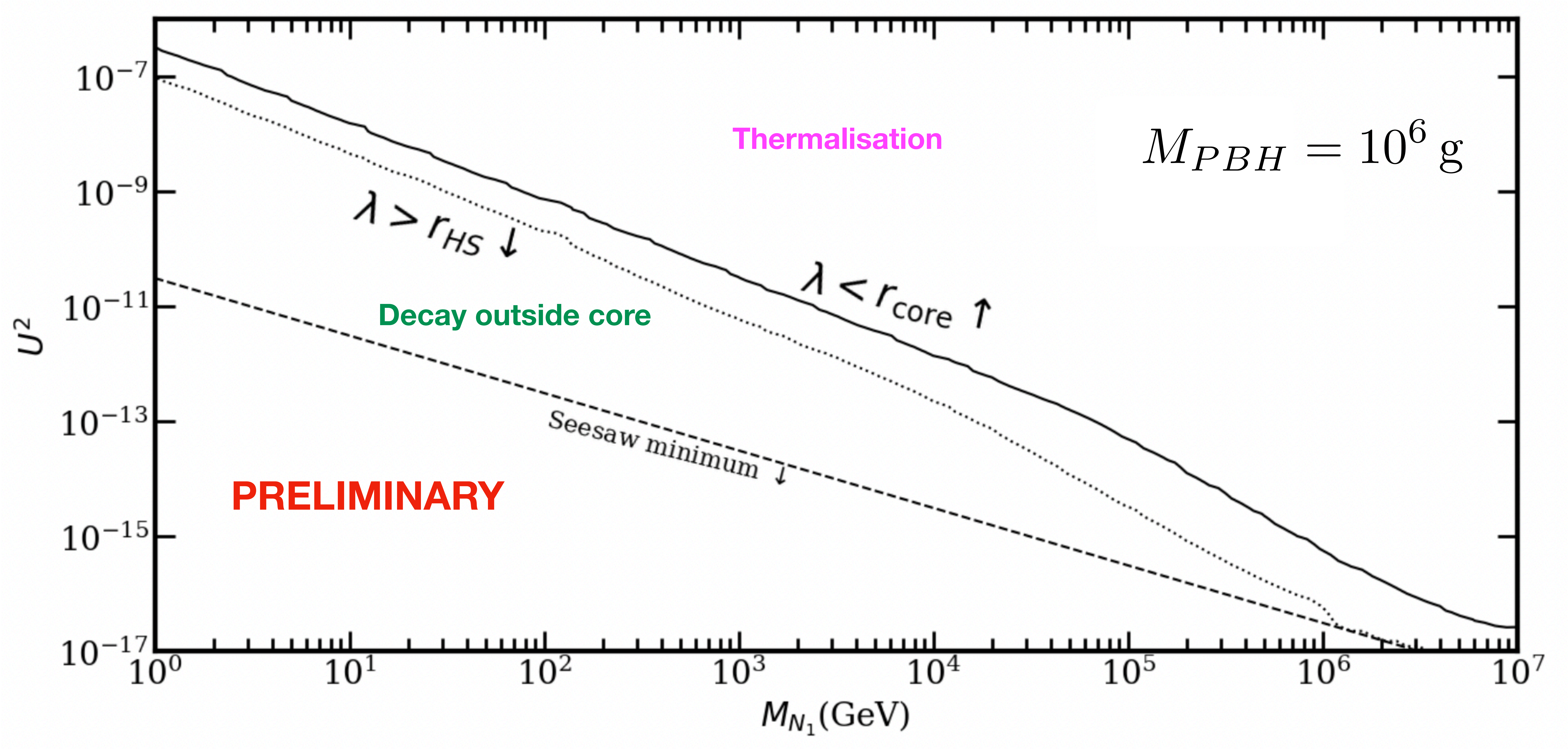


$$\langle \gamma_{\text{scattering}} \rangle_{\text{T}_\text{H},\text{T}_\text{core}} \ll \langle \gamma_{\text{decay}} \rangle$$

Temperature of the core being larger or smaller than T_{EW} does not matter since fast scatterings would washout any lepton asymmetry


PRELIMINARY
$M_{PBH} = 10^6\,\mathrm{g}$
T_{core}
T_{BH}
T_{Plasma}
T_{EW}
Hot-spot formation →
$T(\mathrm{GeV})$
10^2
10^3
10^4
10^5
10^6
10^7
12.5
13.0
13.5
14.0
10^a



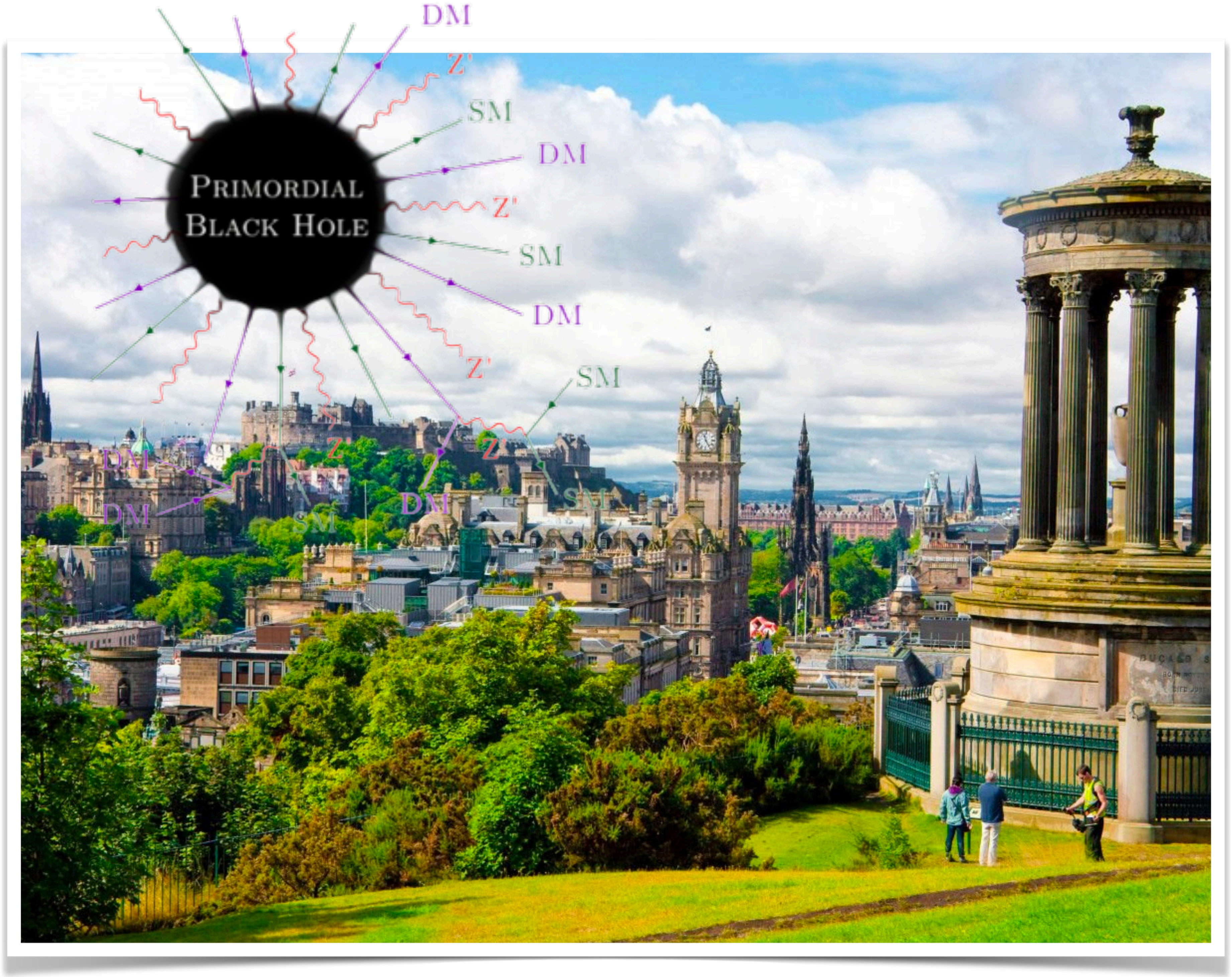
- If RHNs decay outside hotspot when sphalerons are switched off. RHNs would create Primordial lepton asymmetry which can be constrained
- This is interesting as GeV scale RHNs are in the testable regime

Conclusions

- PBH evaporation is a unique testbed for high energy physics and can have drastic implications for theories of baryogenesis

- PBH evaporation affects baryogenesis by **modifying the expansion rate of the universe**, providing non-thermal **source of particles** & **large entropy injections**. We find that light PBHs can place significant tension on leptogenesis but enlarge the parameter space for very high scale leptogenesis

- There are some interesting features of hot spots phenomenology are emerging, stay tuned!



New Horizons in Primordial Black Hole Physics

17-19 June 2024

National Gallery, Edinburgh

Please come and enjoy!

Thanks to Florian for the photo

Thank you for listening