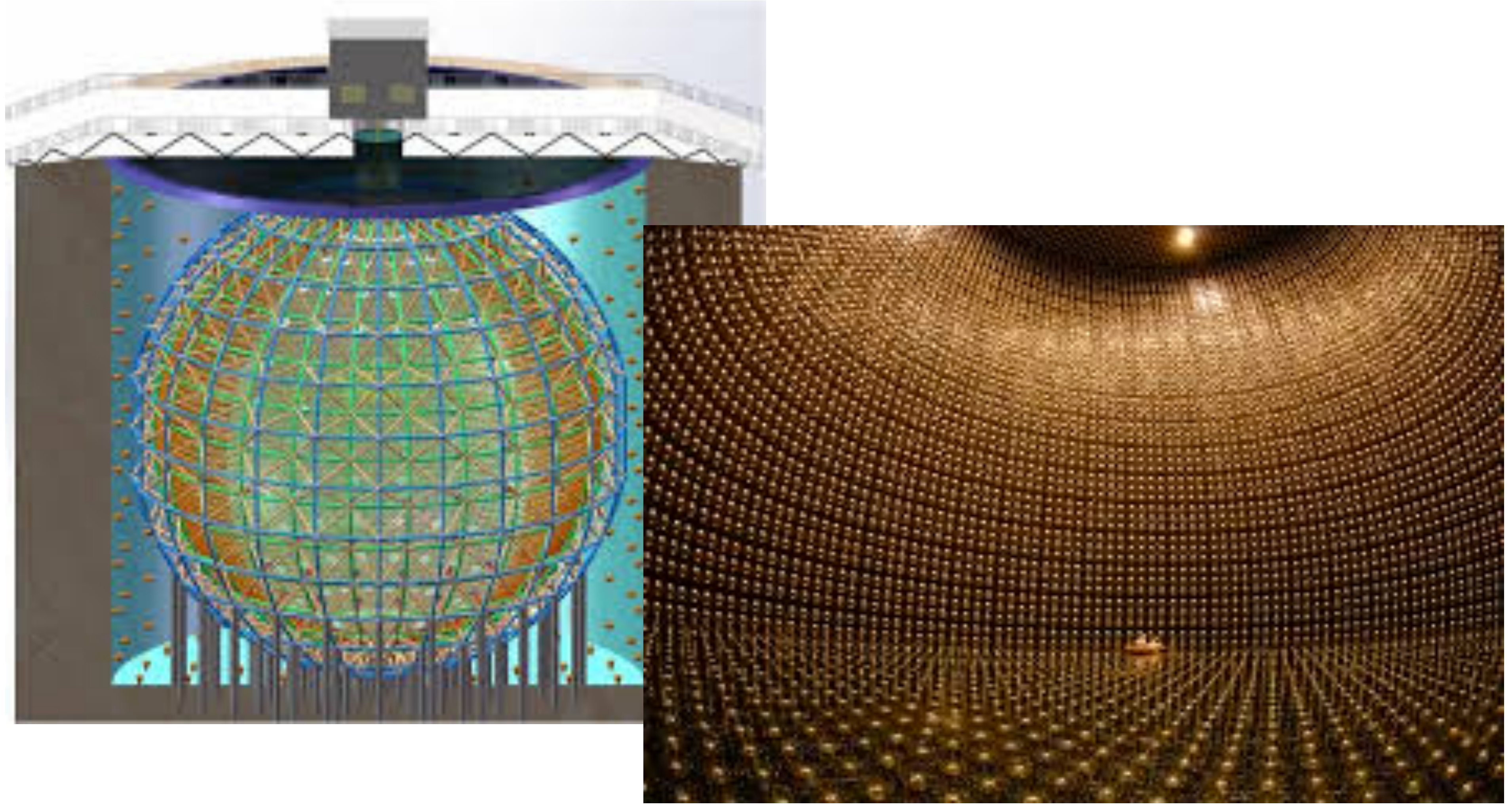
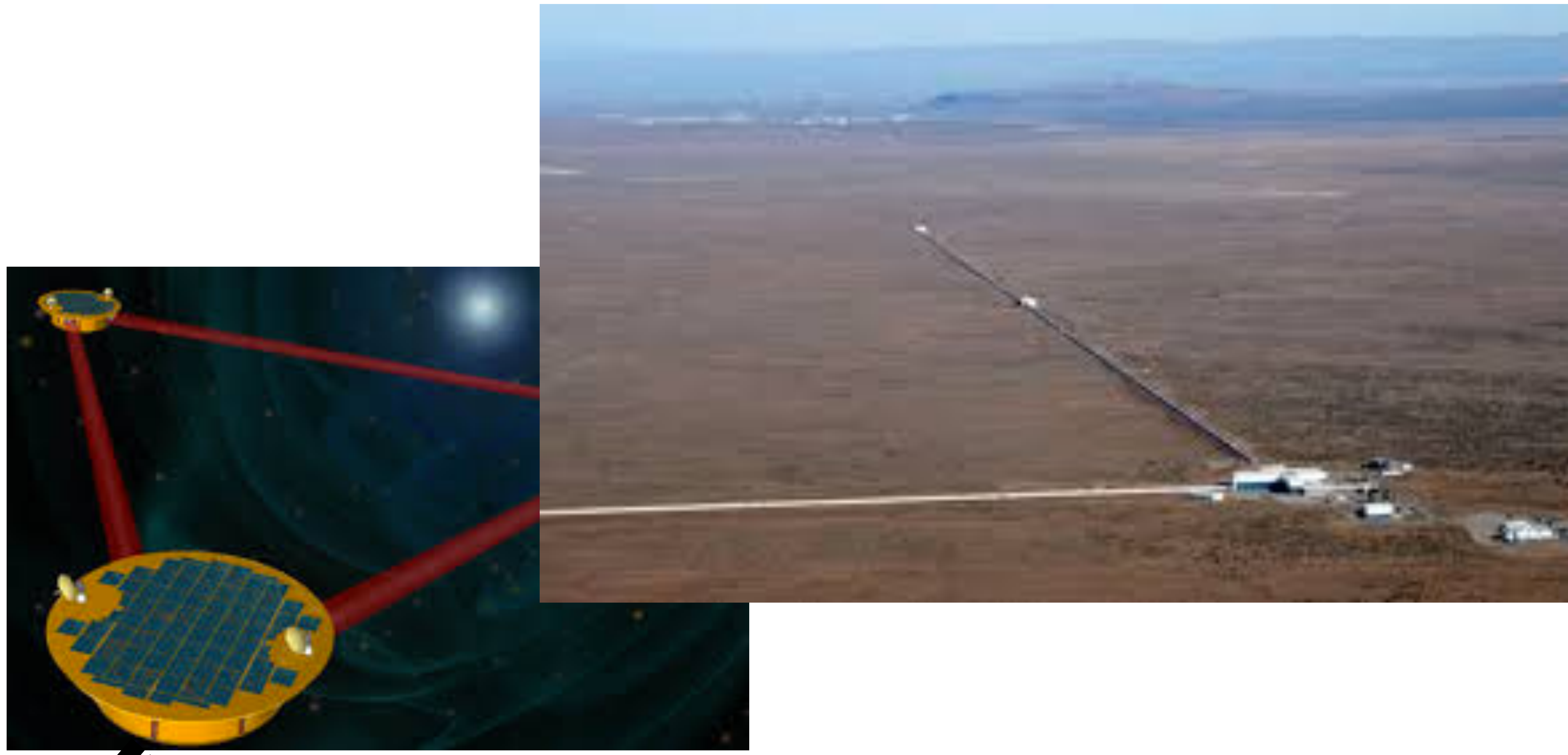
The complementarity between neutrino and gravitational wave data in exploring physics beyond the Standard Model

Jessica Turner

Institute of Particle Physics Phenomenology, Durham University

Dark Matter as a Portal to New Physics , 02 Feb 2021





What created more matter than anti-matter?

What is the nature of particles and forces at the GUT scale?

Neutrino Mixing

Reactor LBL

$P(\overline{\nu_e} \to \overline{\nu_e})$

SNO flux

$\frac{\phi_{CC}}{\phi_{NC}}$

Reactor SBL

$P(\overline{\nu_e} \to \overline{\nu_e})$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

LBL accelerator

$P(\nu_\mu \to \nu_\mu)$

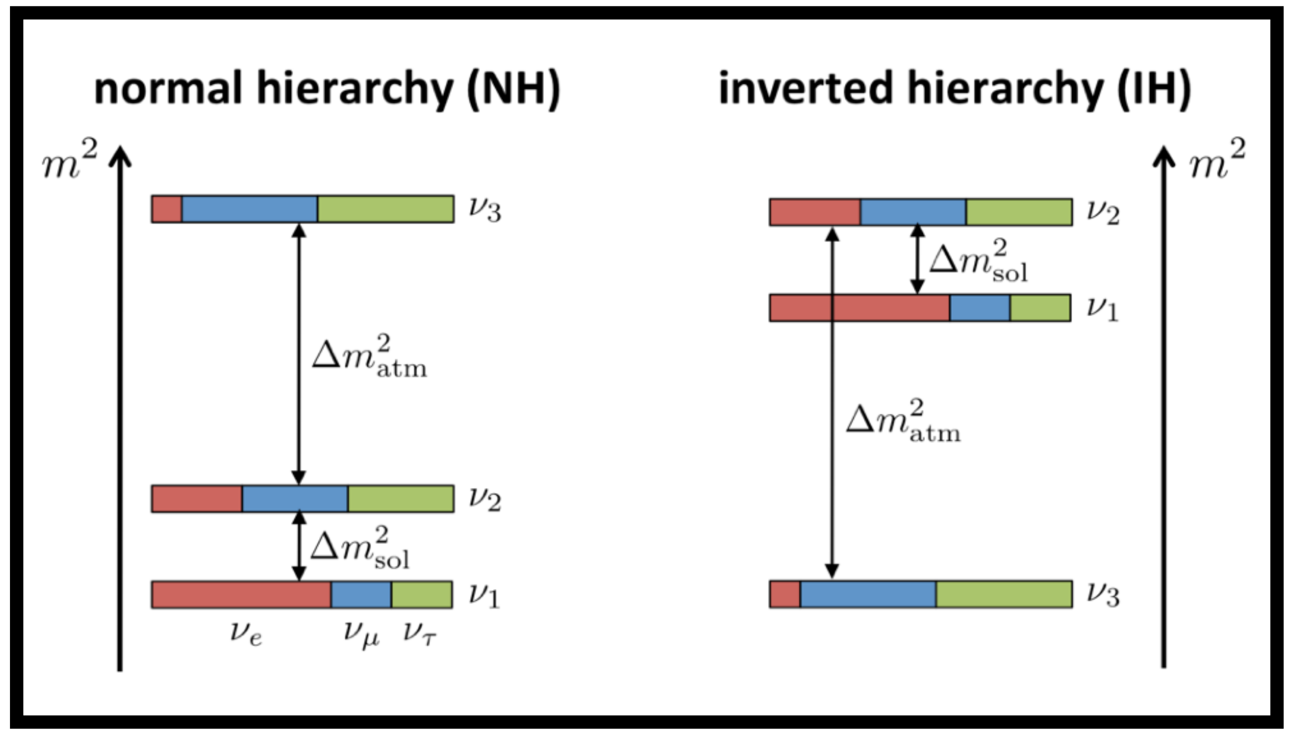
SK/Opera

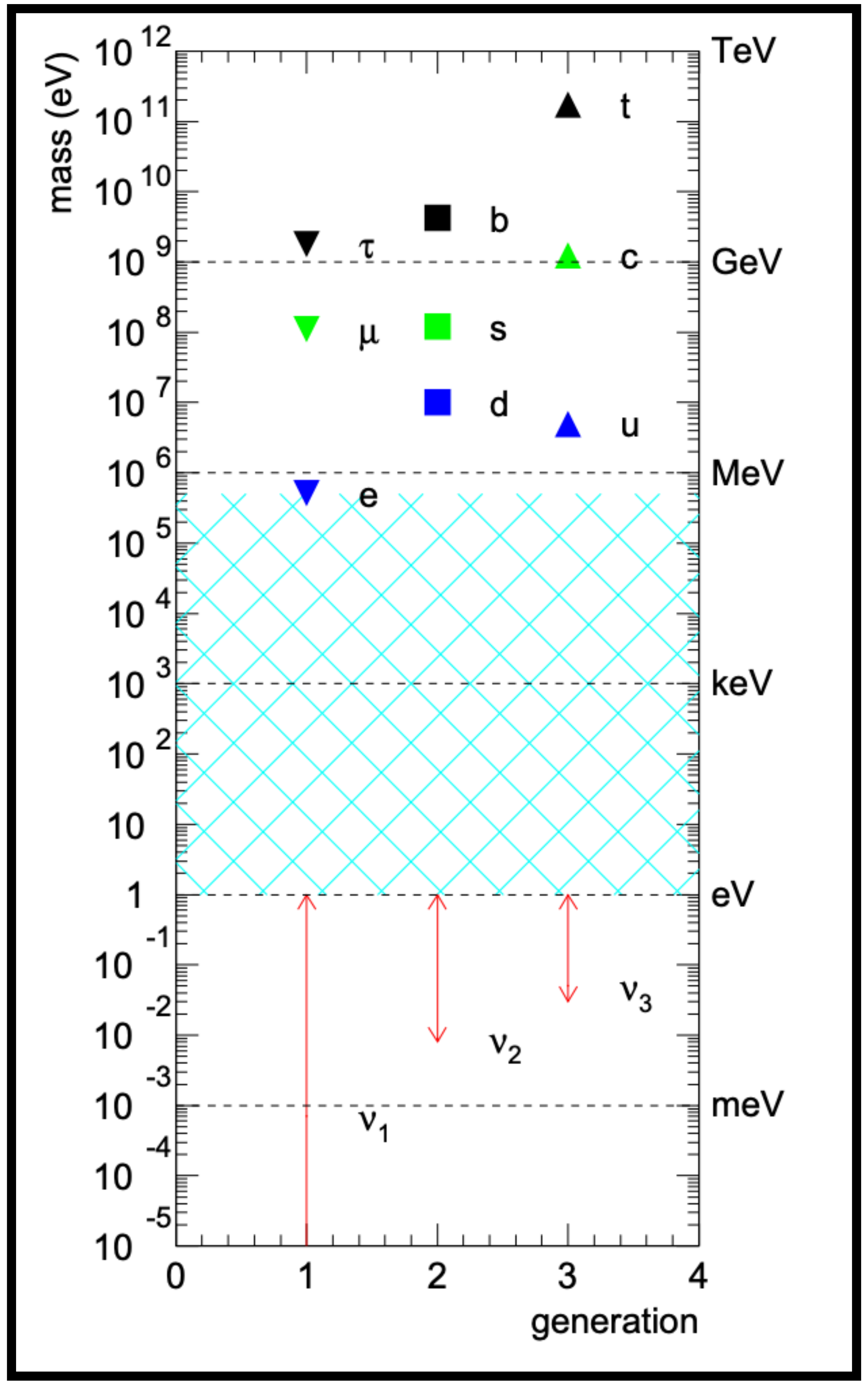
$P(\nu_\mu \to \nu_\tau)$

- Mass ordering?
- Precise LMM structure?
- CP-violation?
- Dirac or Majorana?
- Absolute mass scale?

$$\sum_{i=1}^{3} m_i \leq 0.2\,\mathrm{eV}$$ PDG

It is clear neutrinos much lighter than other known fermions





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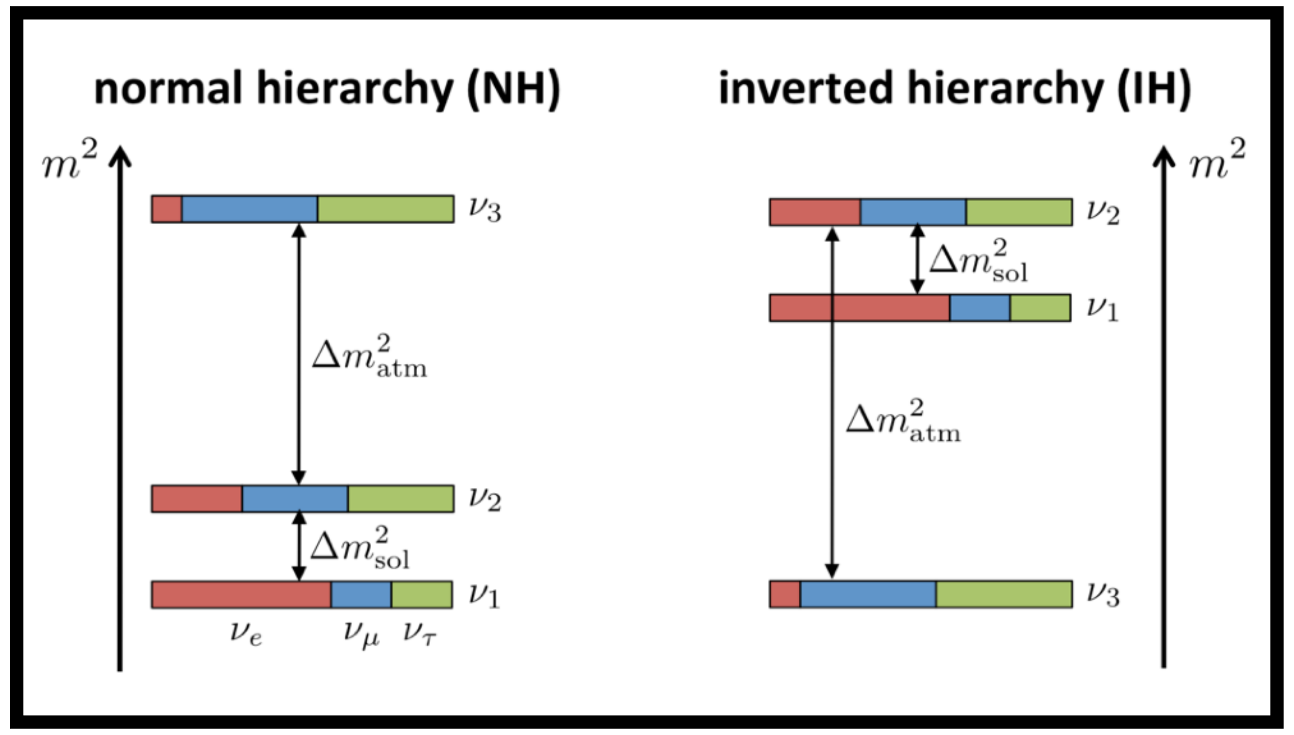
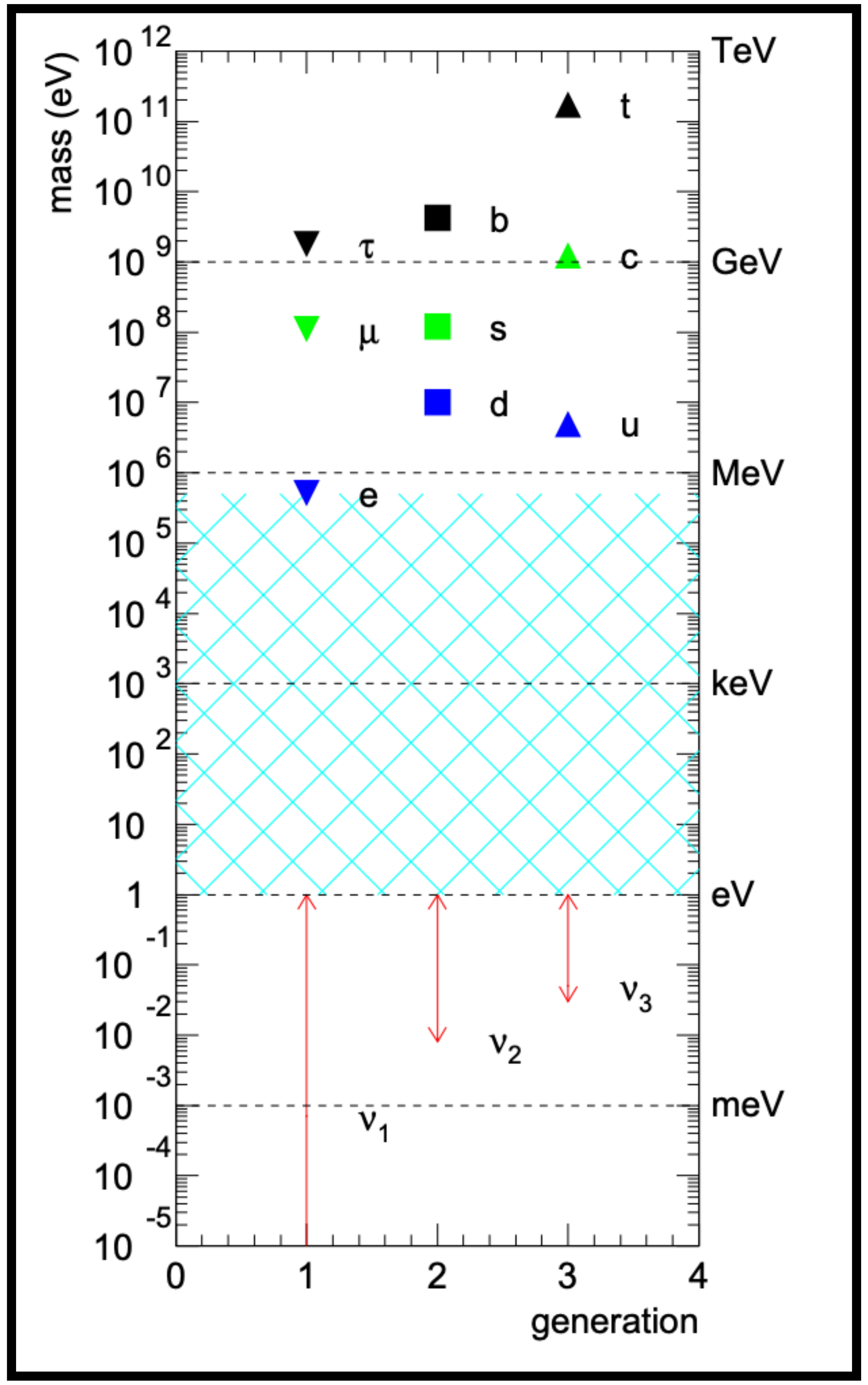




Lepton Number Violation and Majorana neutrinos

Simple to distinguish an electron from its antimatter counterpart →electric charge.

ν	$\overline{\nu}$
neutrino	**antineutrino**
L = + 1	**L = -1**

Neutrino electrically neutral → the anti-neutrino may be “indistinguishable” from neutrino

The nature of the neutrino is linked to lepton number.

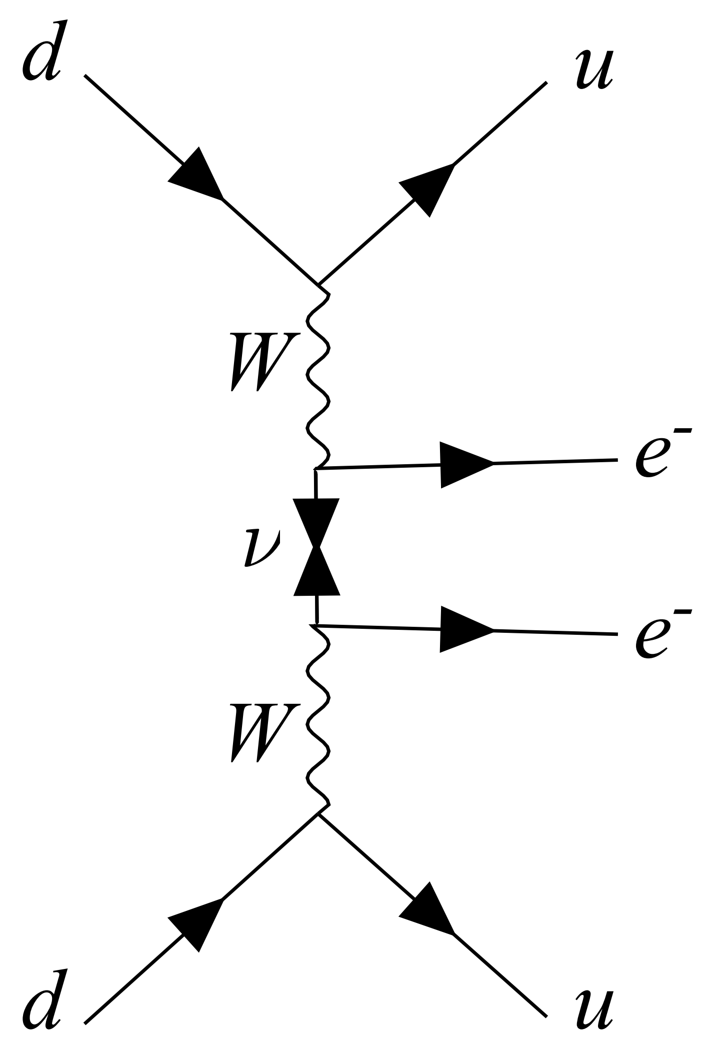
lepton number conserved → neutrino Dirac fermions

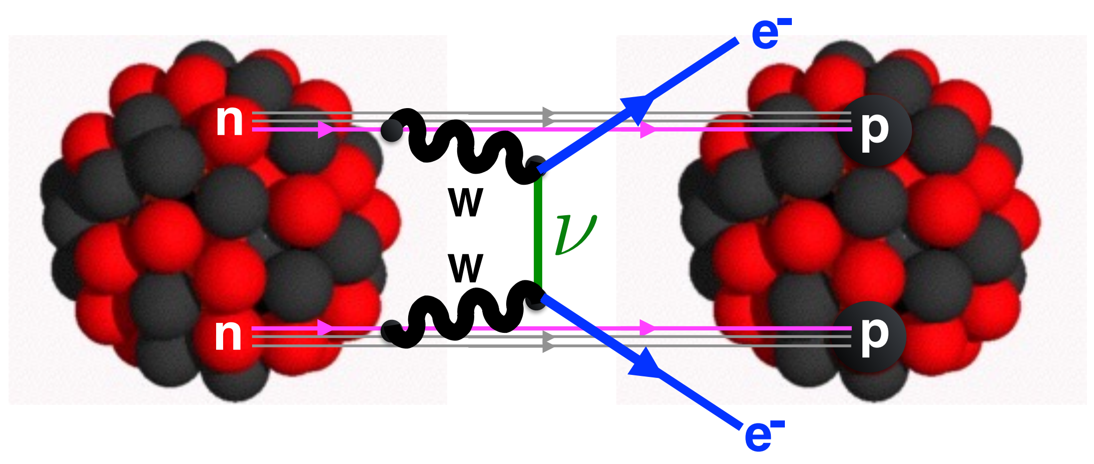
lepton number violated → neutrino Majorana fermions

Majorana condition $\nu = C\overline{\nu}^T$

Neutrinoless double beta decay

$$(A, Z) \to (A, Z+2) + 2e^-$$





massive neutrinos mediate this process.

NDBD gives important information on the properties of neutrinos as it probes lepton number violation.

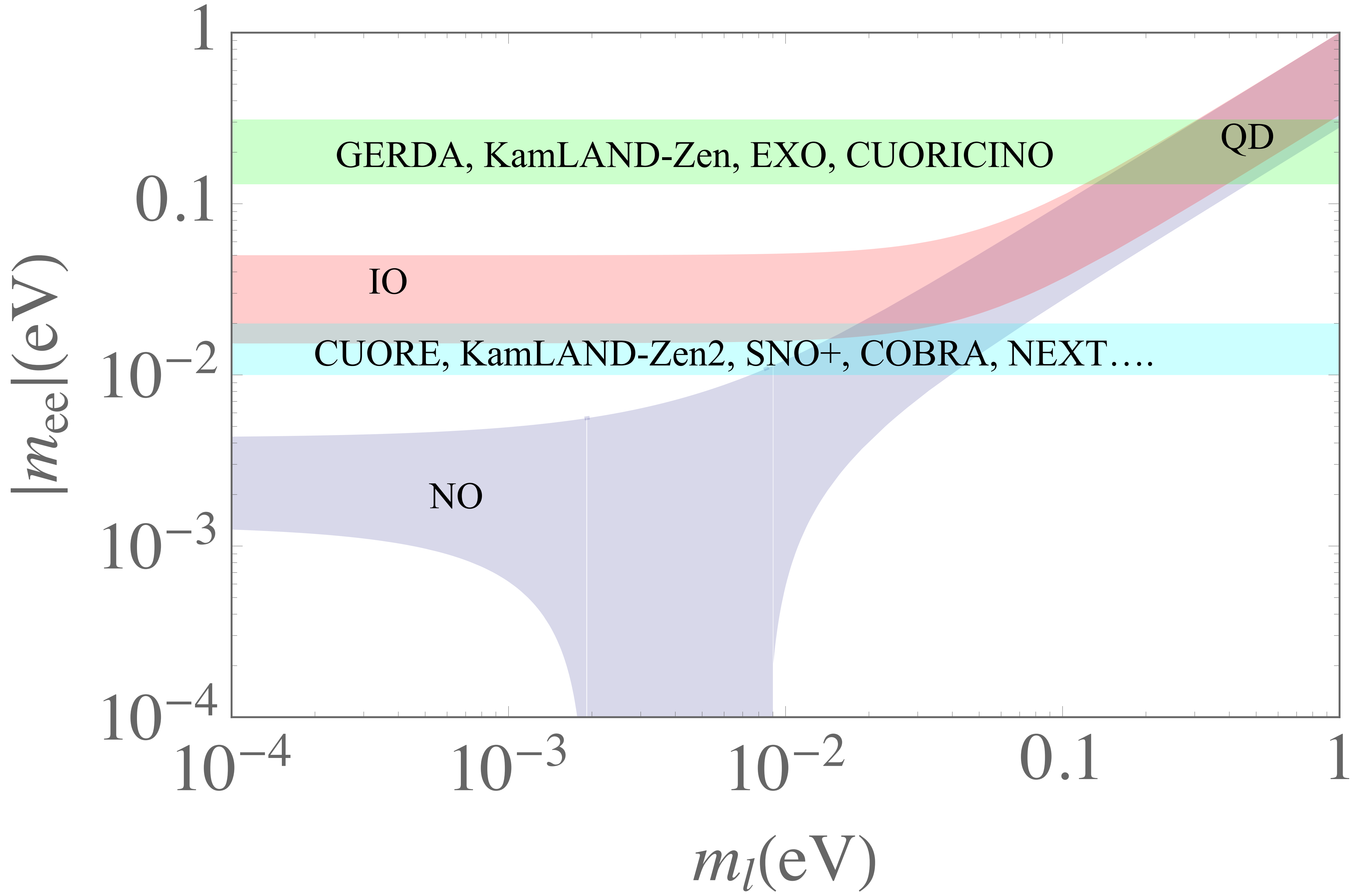
Offer important information on masses and possibly CP-violation

Neutrinoless double beta decay

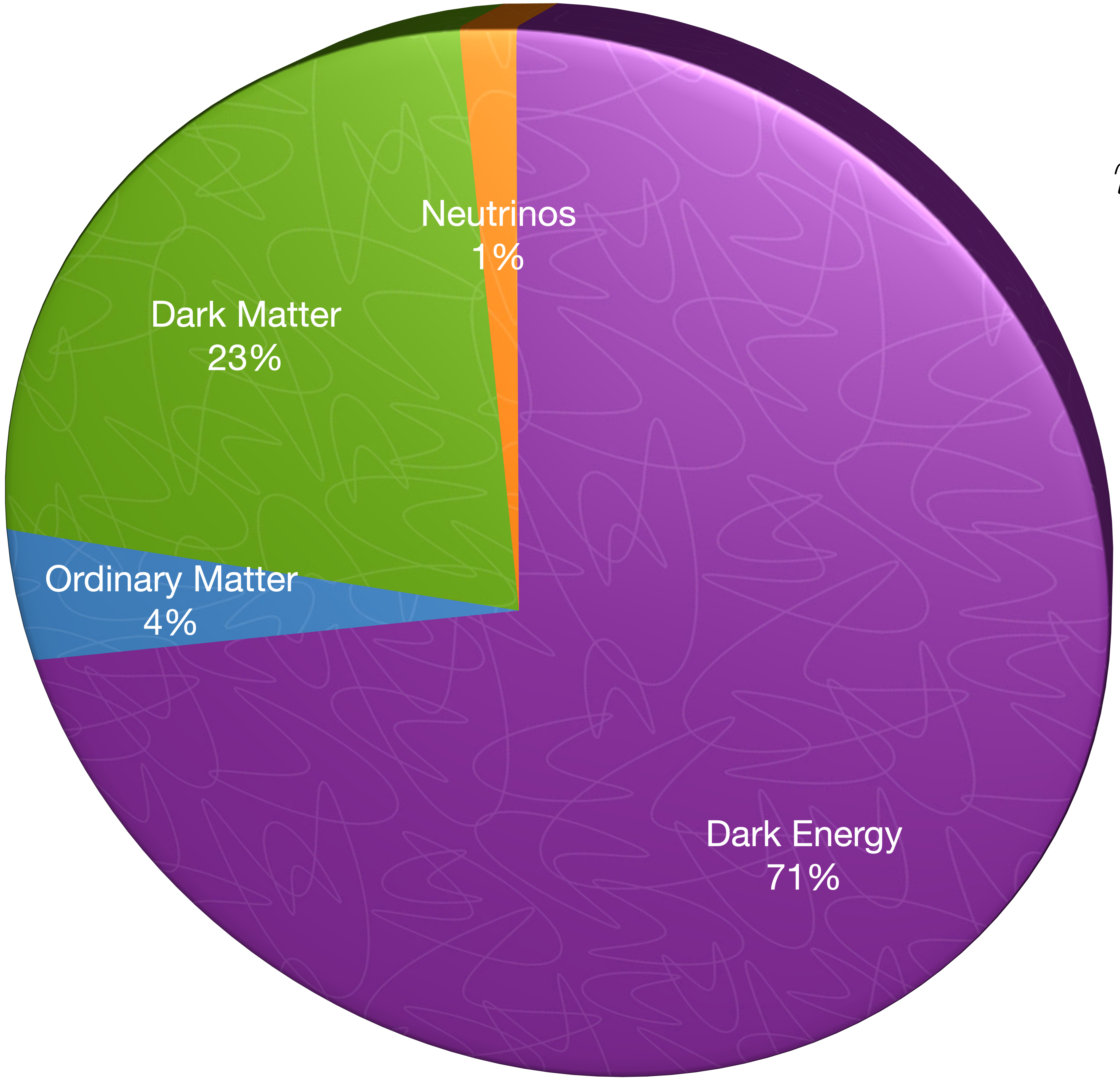
Decay rate $\Gamma_{1/2} \sim |m_{ee}|^2 M_{\rm nucl}^2$

effective majorana mass

$$|m_{ee}| = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 e^{2i(\alpha_{31}-\alpha_{21})} m_2 + s_{13}^2 e^{-2i(\delta+\alpha_{21})} m_3 \right|$$



Neutrino masses and the matter anti-matter asymmetry



$$\eta = \frac{n_B}{n_\gamma} \sim 6 \times 10^{-10}$$

Sakharov’s Conditions

Baryon and Lepton Number Violation

Kuzmin, Rubakov and Shaposhnikov

Insufficient CP-violation

Gavela, Hernandez, Orloff, Pene; Huet and Sather

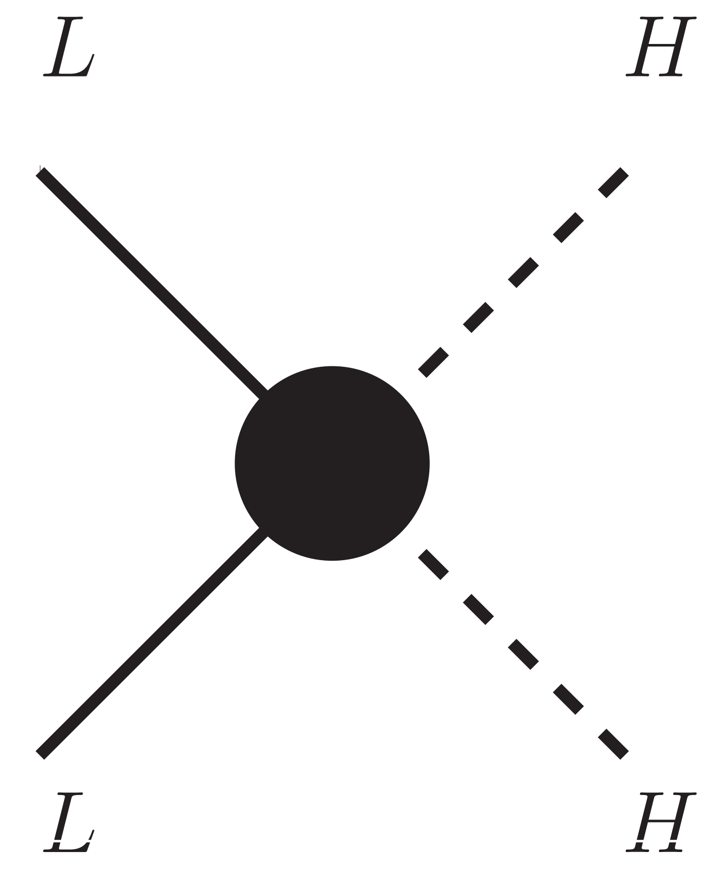
No departure from thermal equilibrium

Kajantie, Laine, Rummukainen, Shaposhnikov

* assumes CPT conserved

- SU2L invariant term mass term for neutrinos

$$-\mathcal{L}_{d=5} = \lambda \frac{L.HL.H}{M}$$



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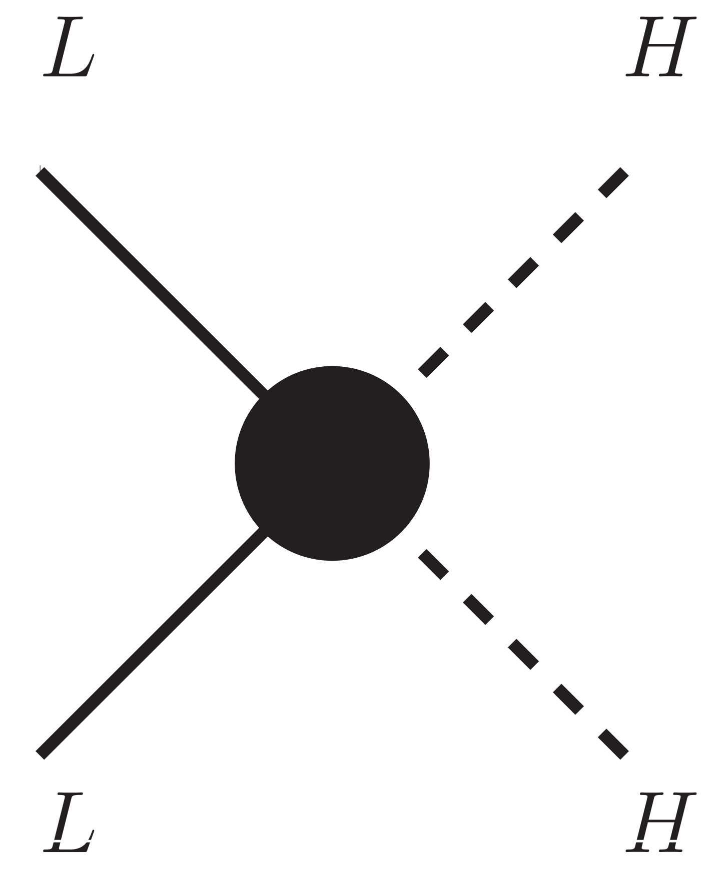

- How can we ultraviolet complete this operator at tree-level?

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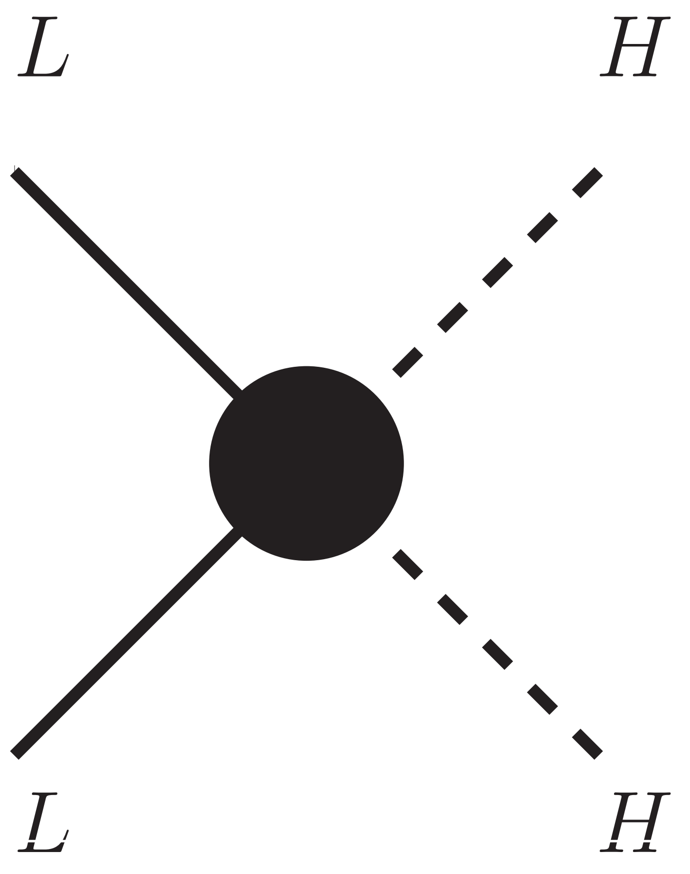

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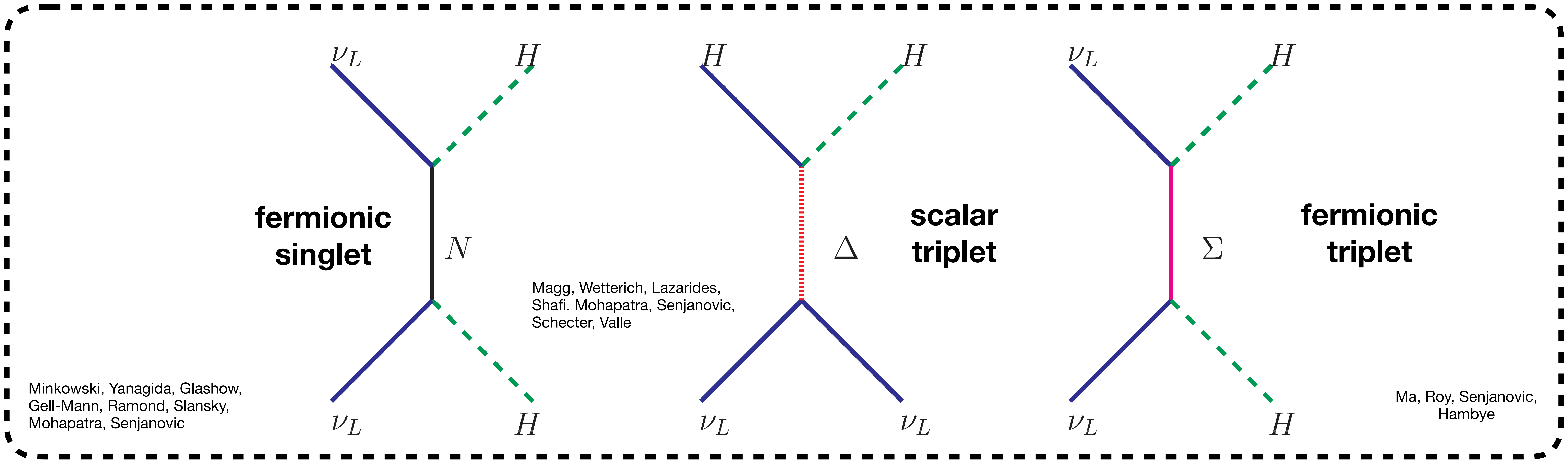
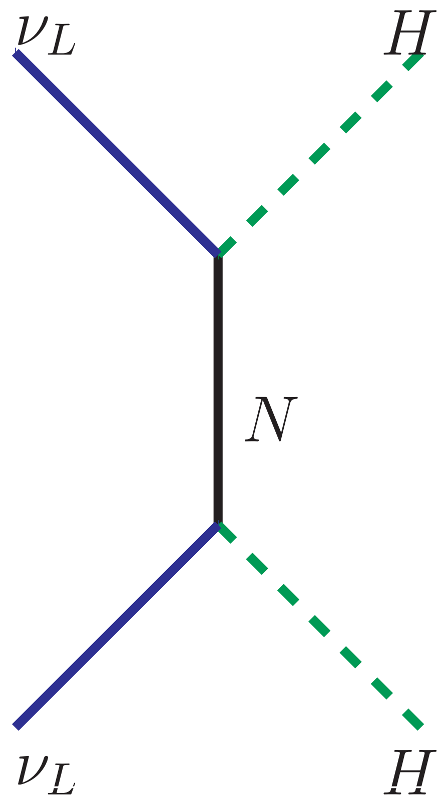
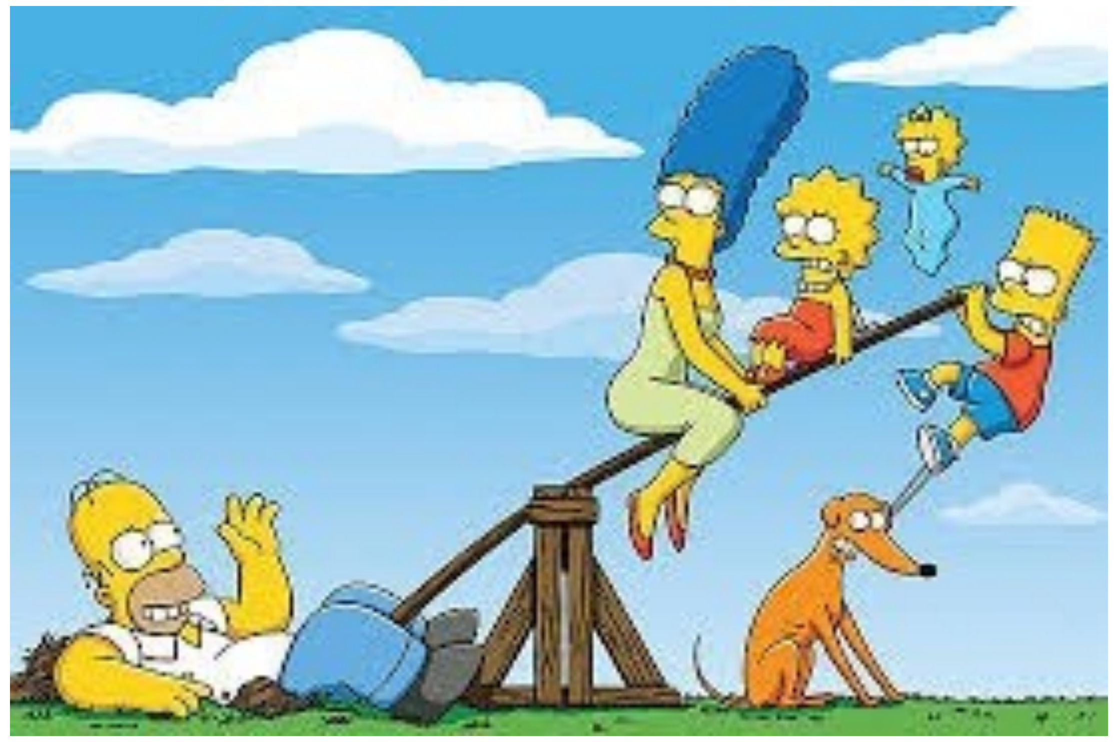


- Type-I seesaw mechanism





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

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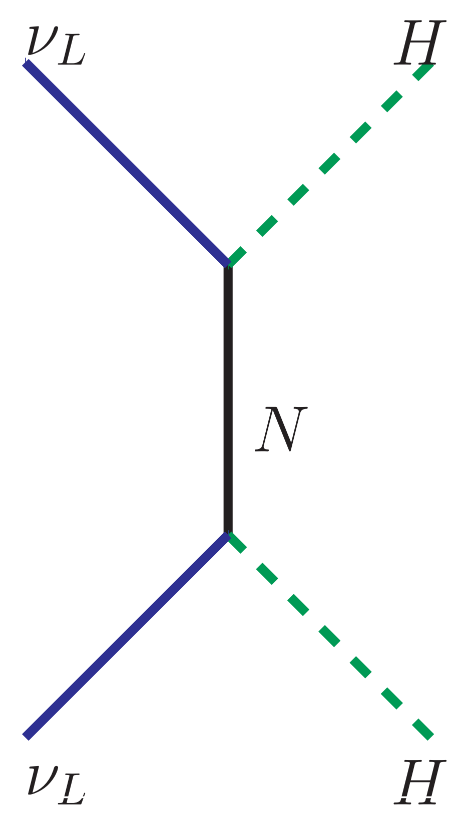

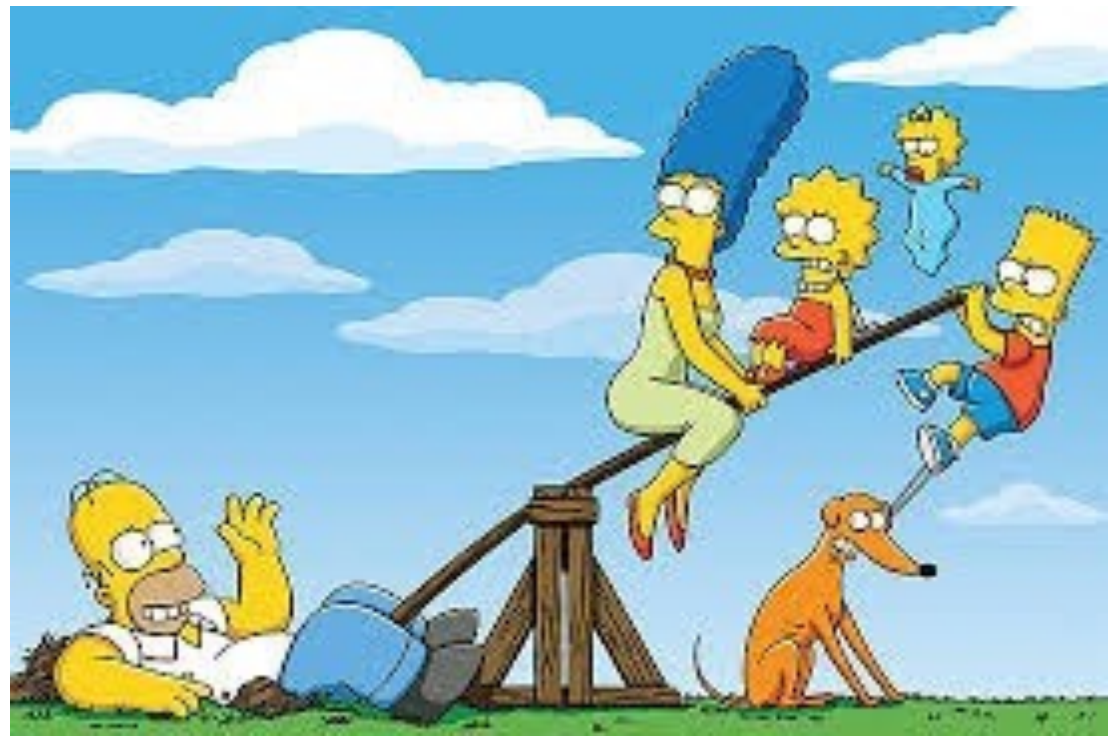

$$\mathcal{L} = Y_\nu \overline{L}\tilde{\Phi} N - \frac{1}{2} M_N \overline{N^c} N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$$m_D = Y_\nu v$$

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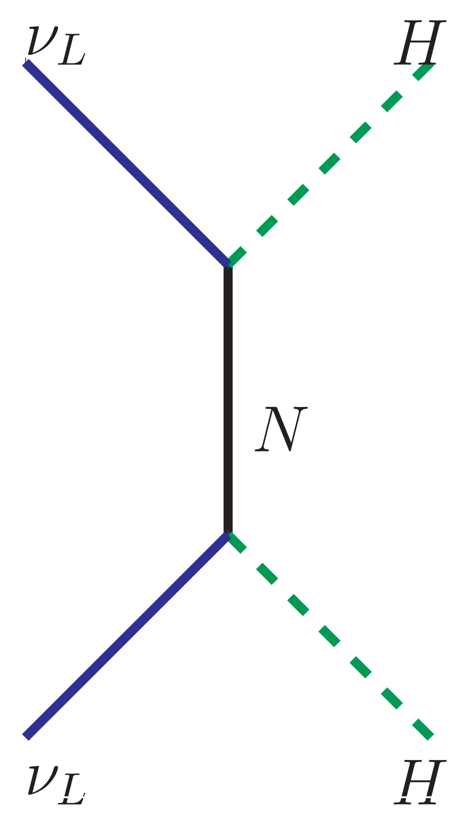
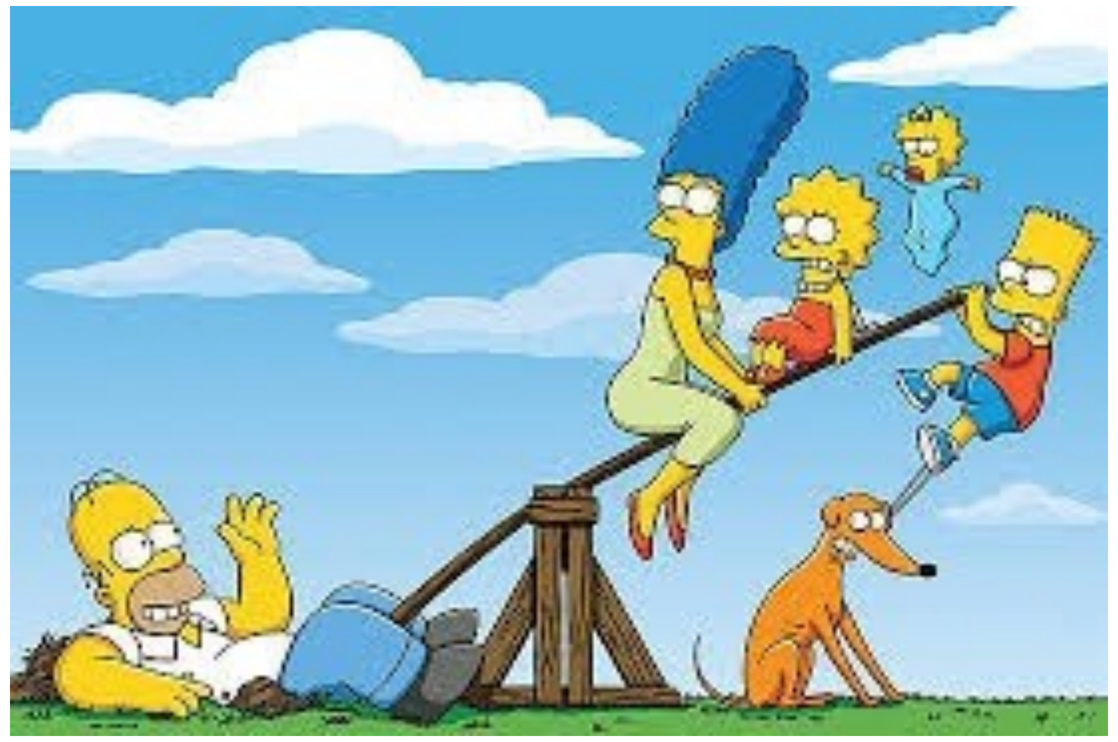




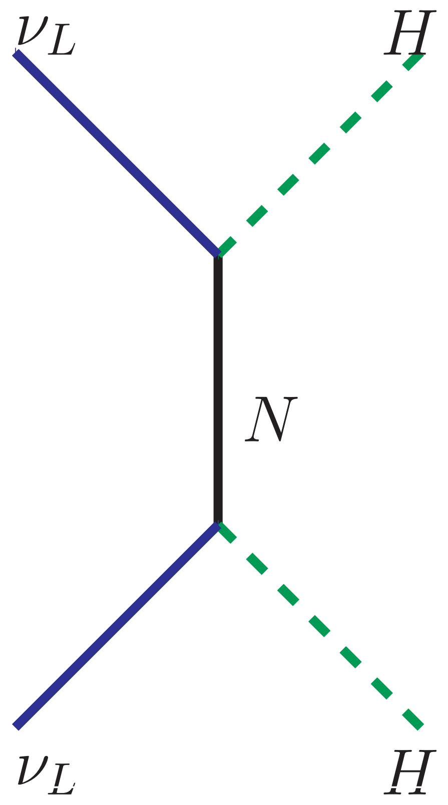
$$\mathcal{L} = Y_\nu \overline{L} \tilde{\Phi} N - \frac{1}{2} M_N \overline{N^c} N$$

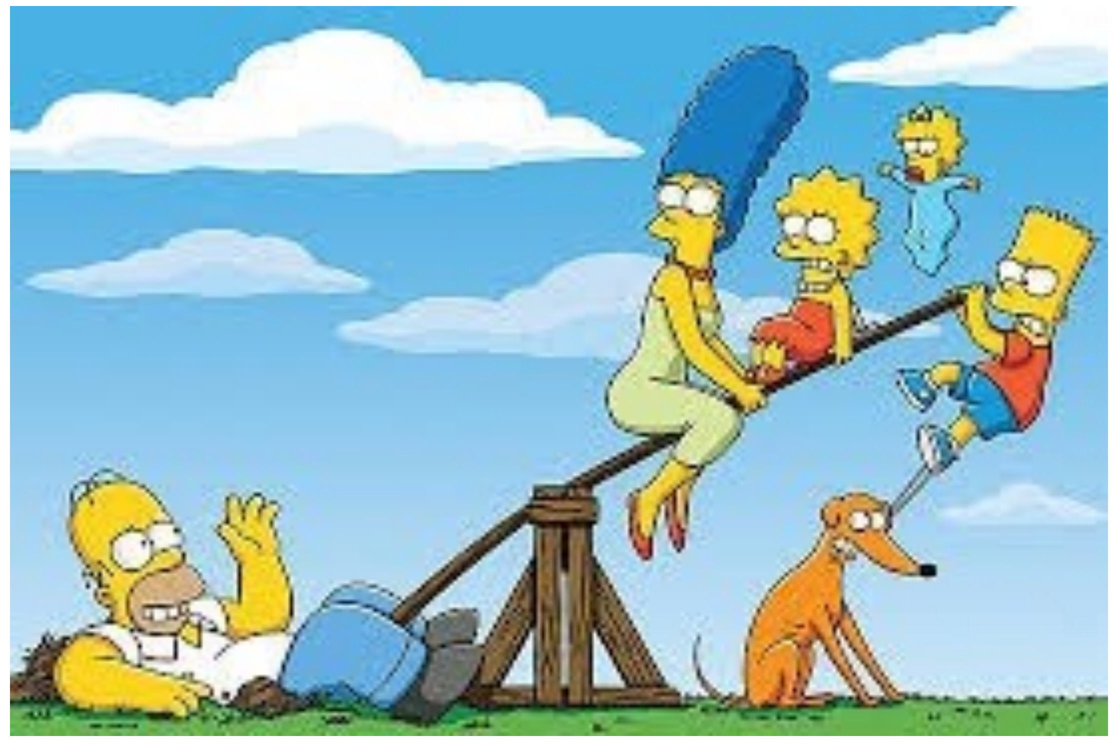
$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \longrightarrow m_\nu = \frac{Y_\nu^2 v^2}{M_N} \sim 0.1\,\mathrm{eV}$$

find eigenvalues of mass matrix

$$m_D = Y_\nu v$$

- Type-I seesaw mechanism





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

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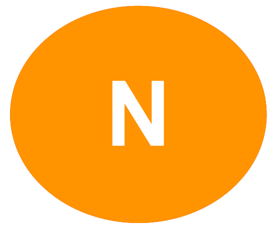
Seesaw mechanism qualitatively satisfies Sakharov's conditions!

Thermal leptogenesis

Fukugida, Yanagida



Thermal leptogenesis

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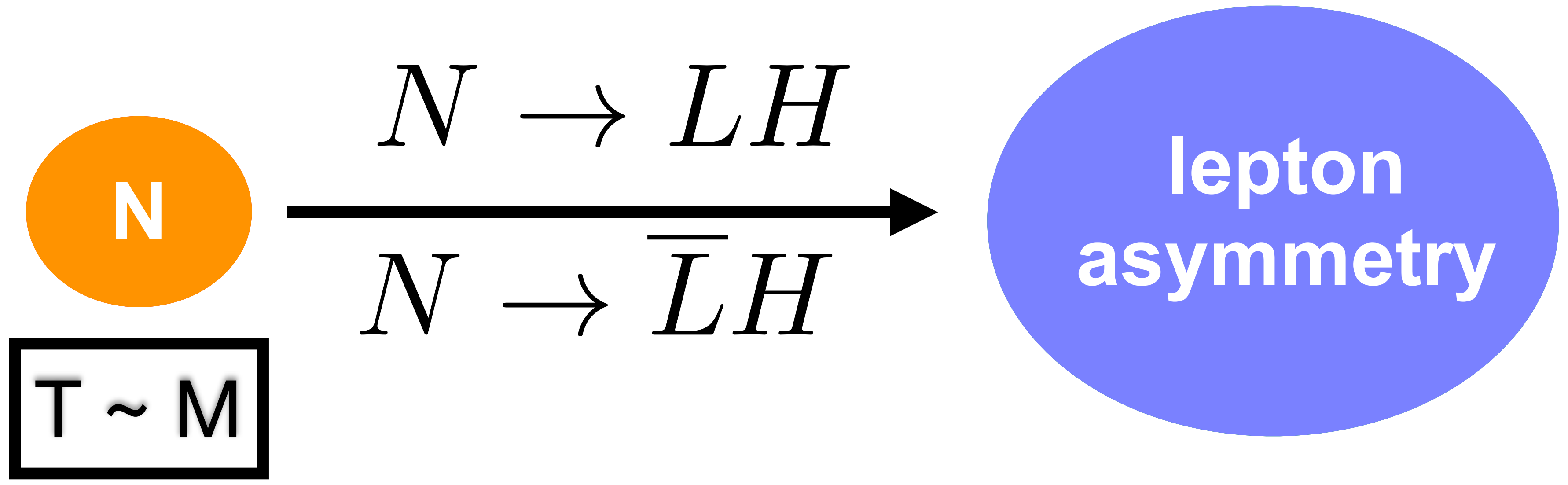

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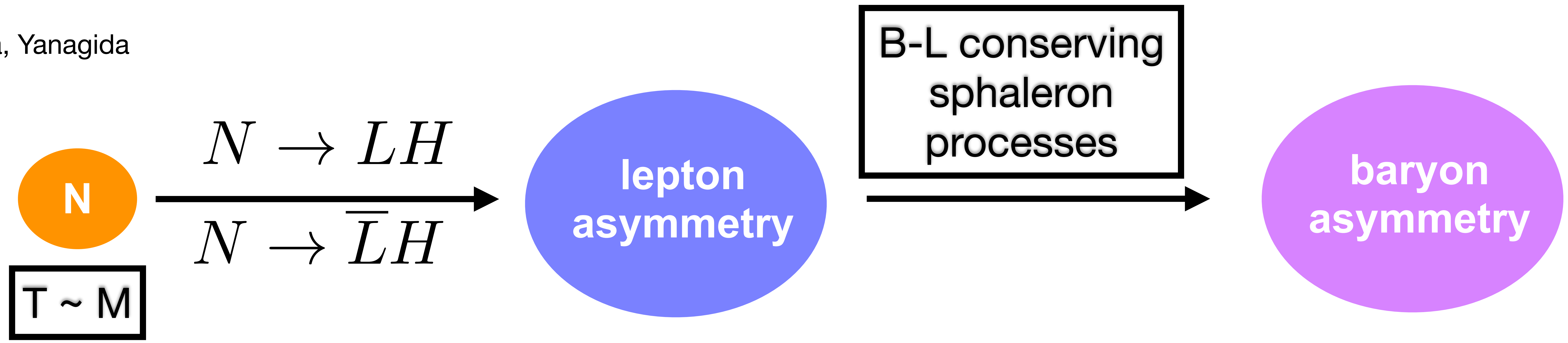

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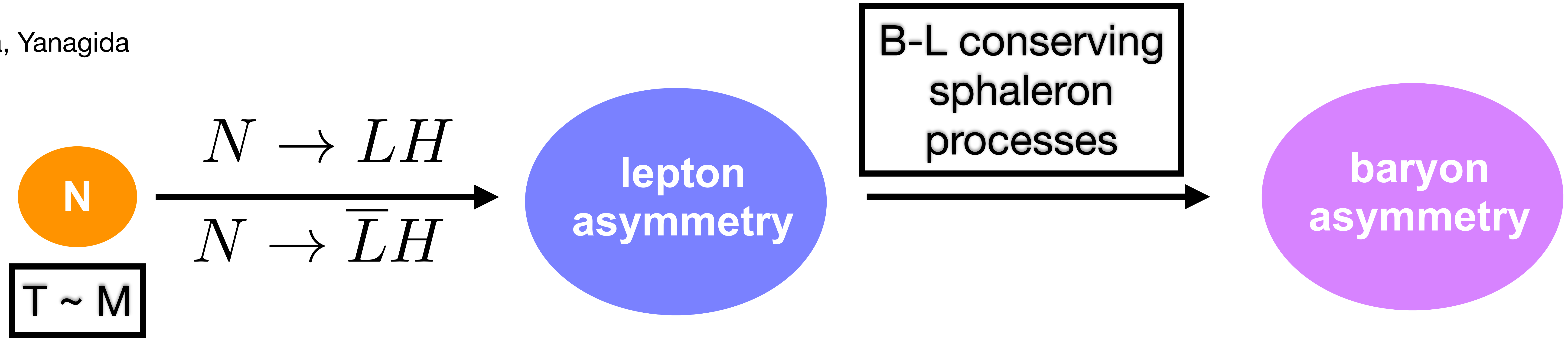
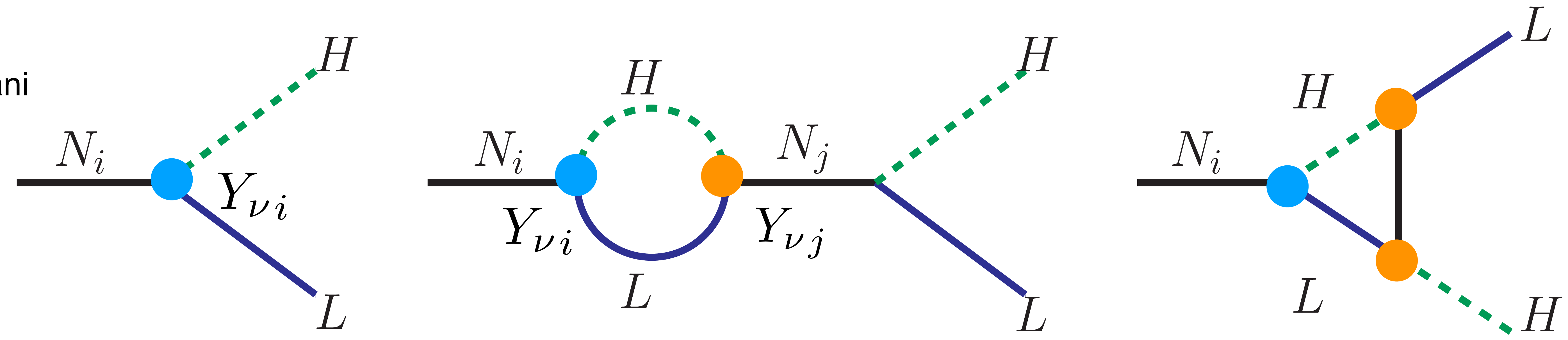


Decay asymmetry from interference between tree and loop level diagrams

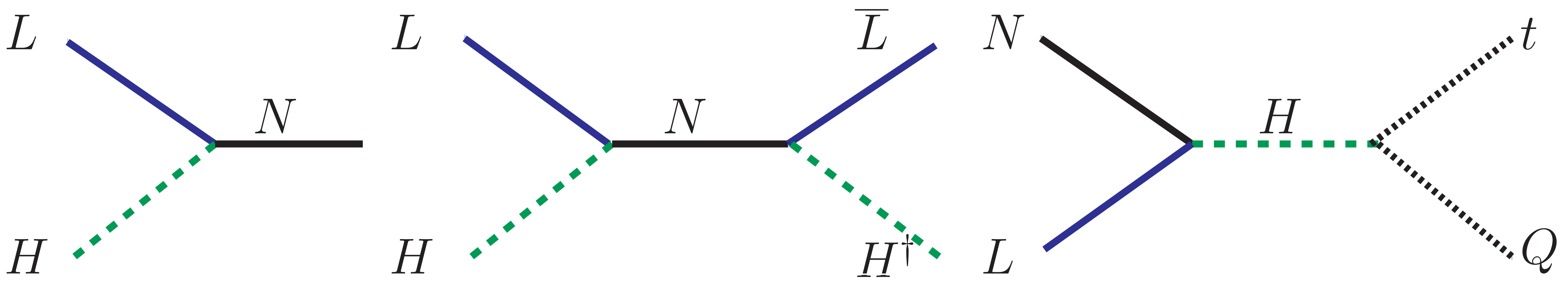
Covi, Roulet, Vissani



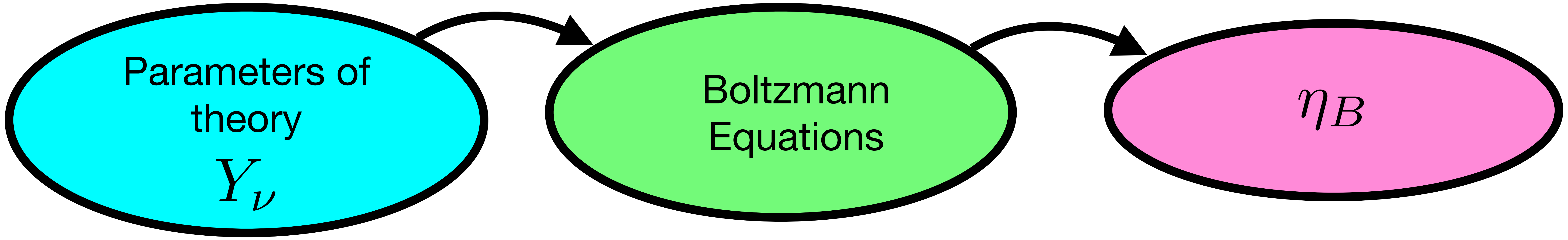
$$\epsilon_i = \frac{\Gamma_i - \overline{\Gamma}_i}{\Gamma_i + \overline{\Gamma}_i}$$

Thermal leptogenesis

Washout and scattering processes



inverse Decays ΔL=2 ΔL=1

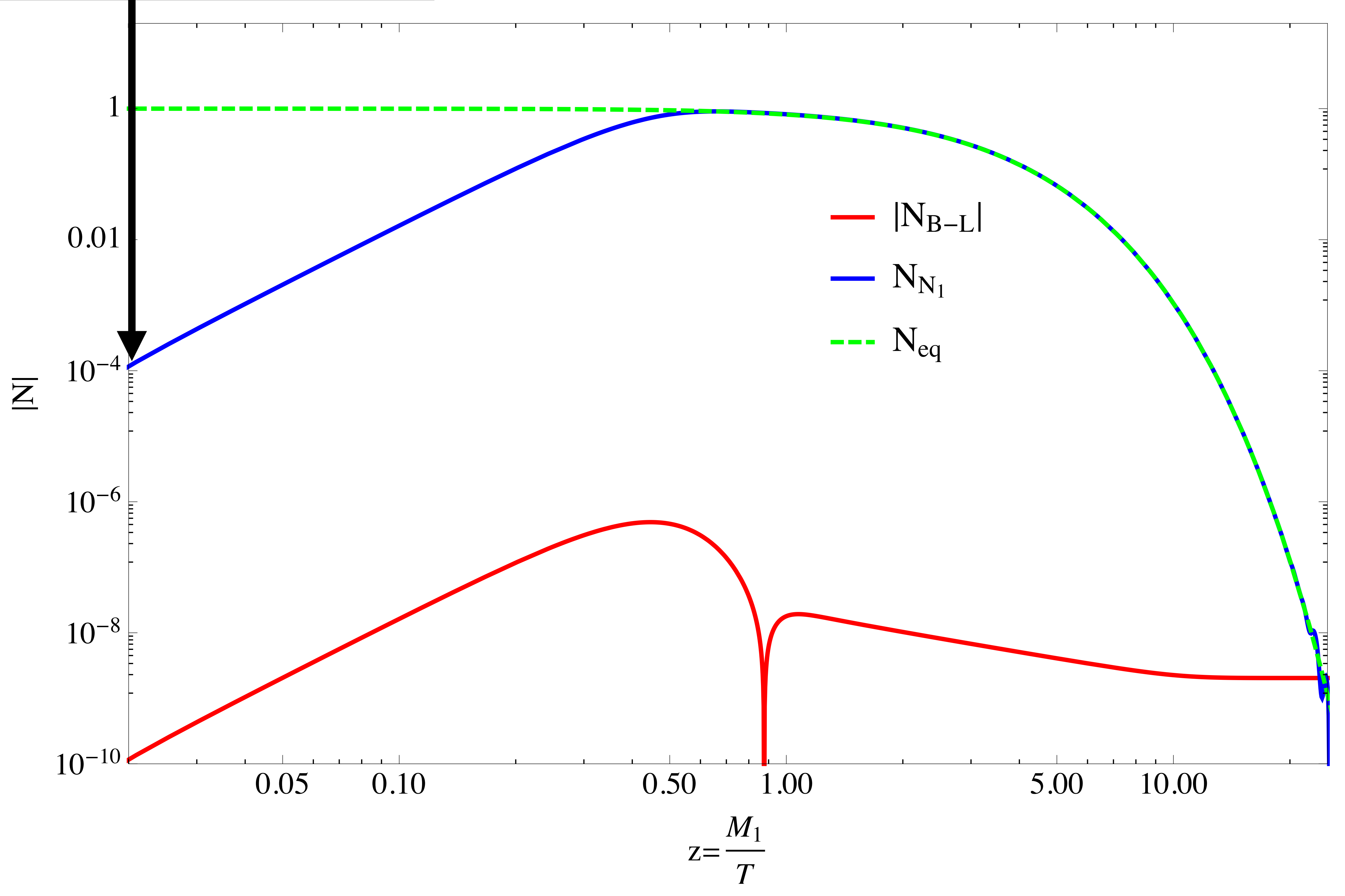


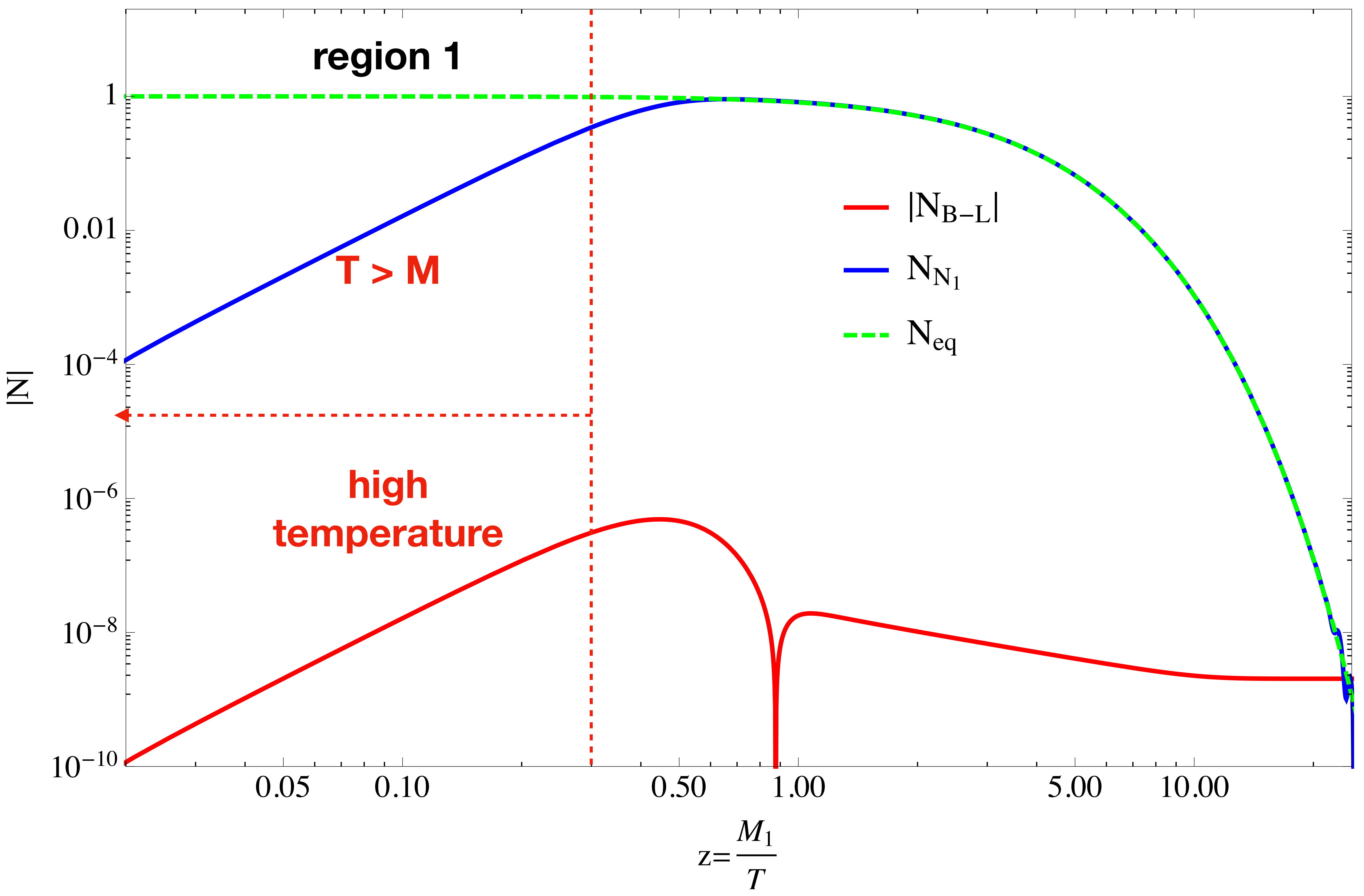
$$\frac{dn_{N_i}}{dz} = - D_i(n_{N_i} - n^{\rm eq}_{N_i}),$$

source **sink**

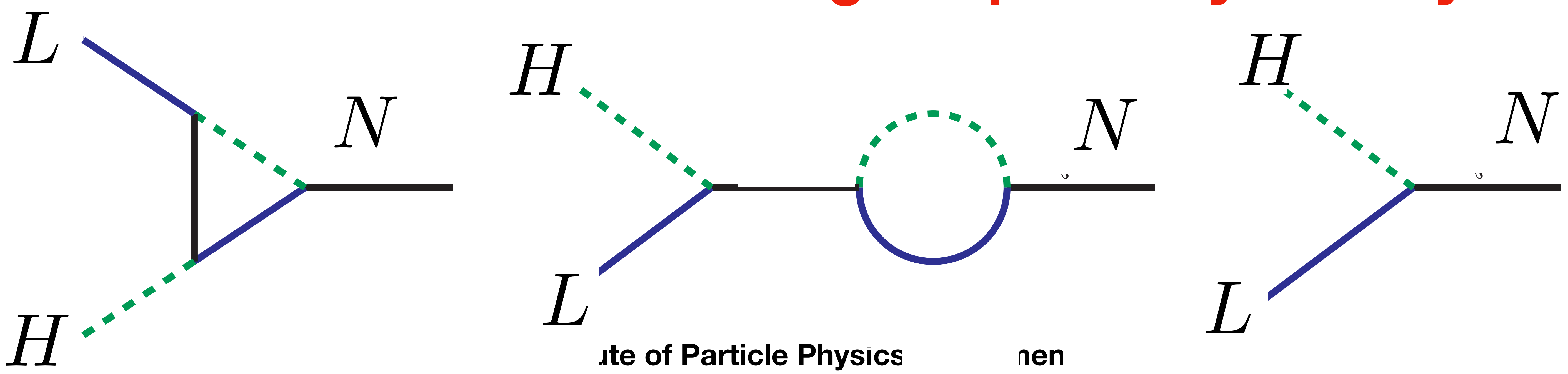
$$\frac{dn_{B-L}}{dz} = \sum_{i=1}^{3} \left(\epsilon^{(i)} D_i (n_{N_i} - n^{\rm eq}_{N_i}) - W_i n_{B-L} \right).$$

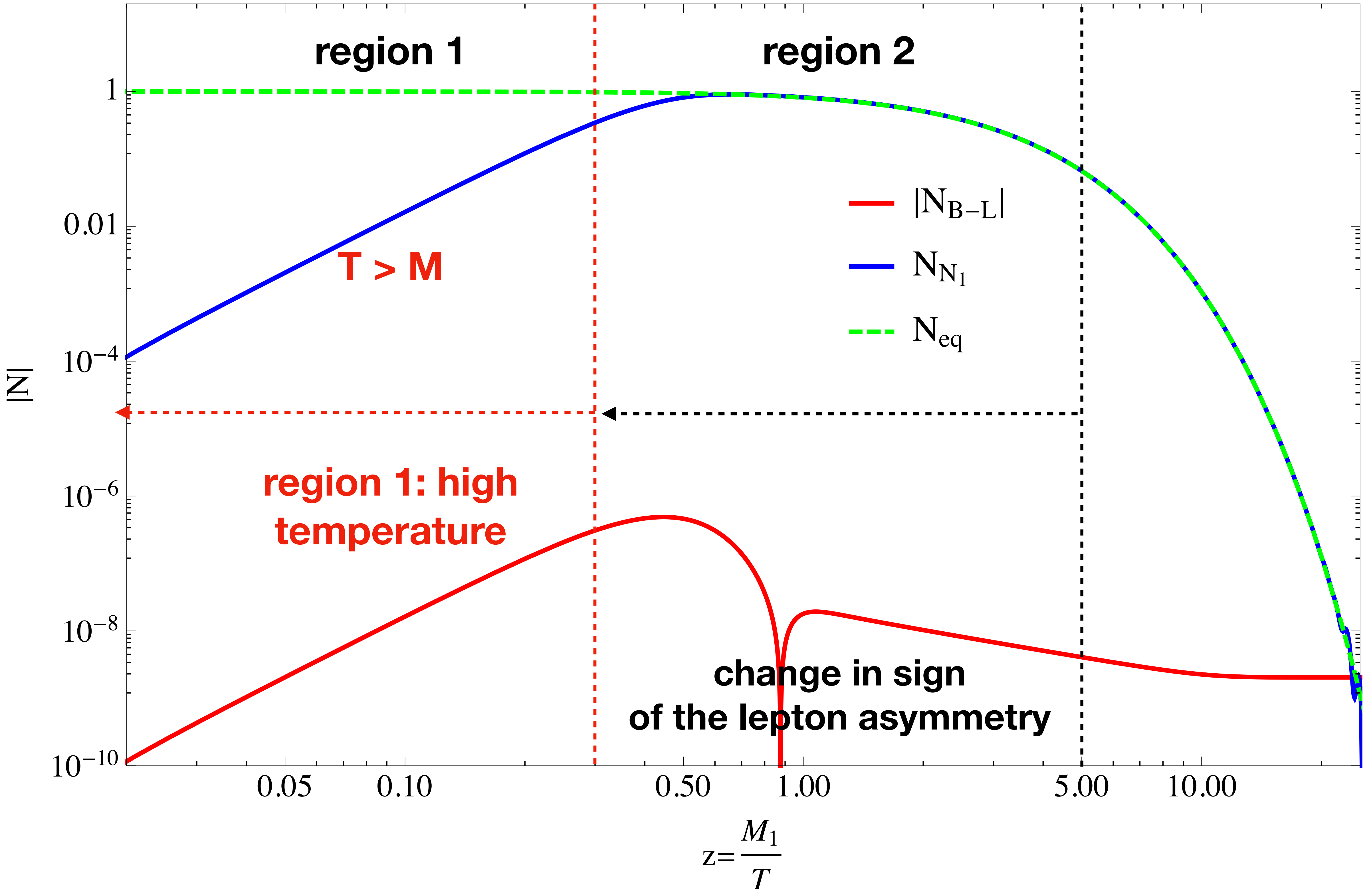
assume zero initial abundance of RHNs

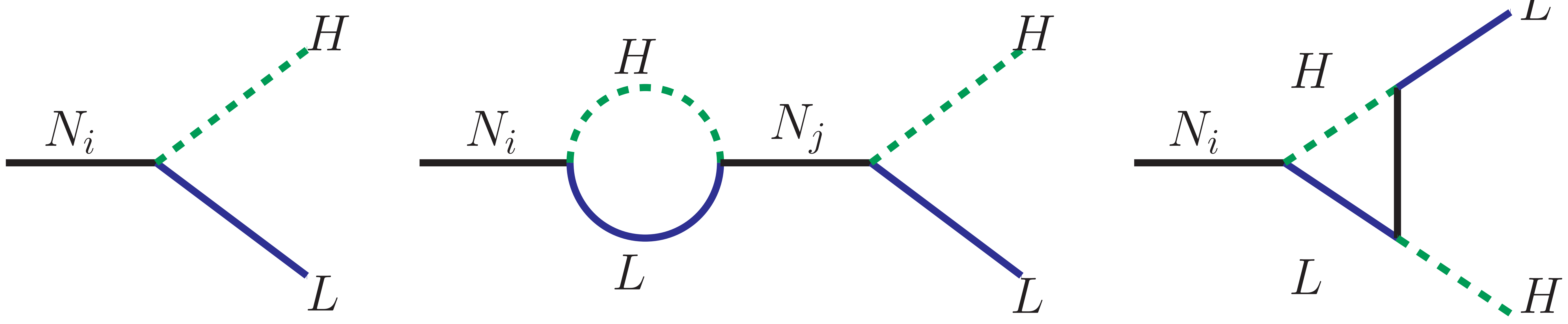


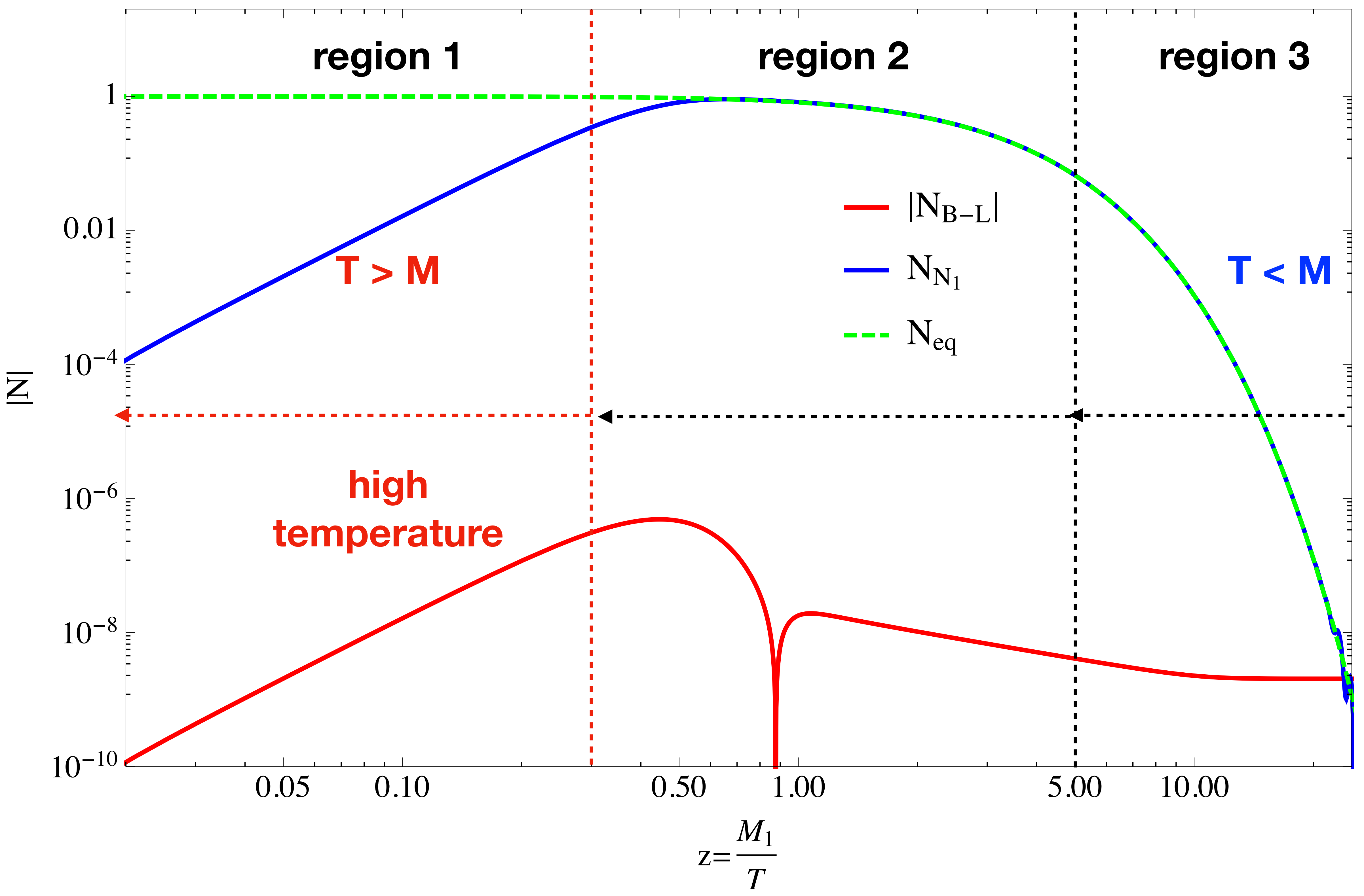


<u>Region 1</u>: leptons and Higgs have enough energy to inverse decay creating a lepton asymmetry




region 1
region 2
1
0.01
10^{-4}
10^{-6}
10^{-8}
10^{-10}
|N|
T > M
region 1: high temperature
change in sign of the lepton asymmetry
$|N_{B-L}|$
N_{N_1}
N_{eq}
0.05
0.10
0.50
1.00
5.00
10.00
$z=\frac{M_1}{T}$


N_i
H
L
N_i
H
L
N_j
H
L
N_i
H
L
L
H



<u>Region 3:</u> At T < M, RHN abundance is depleted. Lepton asymmetry freezes out.

Parameter Space

Casas, Ibarra

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

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low-energy scale: 3 phases, 3 mixing angles and 3 masses constrained by neutrino experiments

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low-energy scale: 3 phases, 3 mixing angles and 3 masses constrained by neutrino experiments

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low-energy scale: 3 phases, 3 mixing angles and 3 masses constrained by neutrino experiments

high-energy scale: 3 phases, 3 mixing angles and 3 masses

Without any symmetry constraints 18 parameters in total.

Primordial Black holes induced leptogenesis

Work in collaboration with **Yuber Perez Gonzalez**: 2010.03565

Astrophysical BHs require $M > 3M_\odot$

Carr et al, 0912.5297

For smaller BH mass (between Planck and solar mass scale) require large perturbations in the early Universe : **bubble collision, collapse of density perturbations…**

$r_S \sim \lambda_C \longrightarrow$ PBHs evaporate by emitting particles

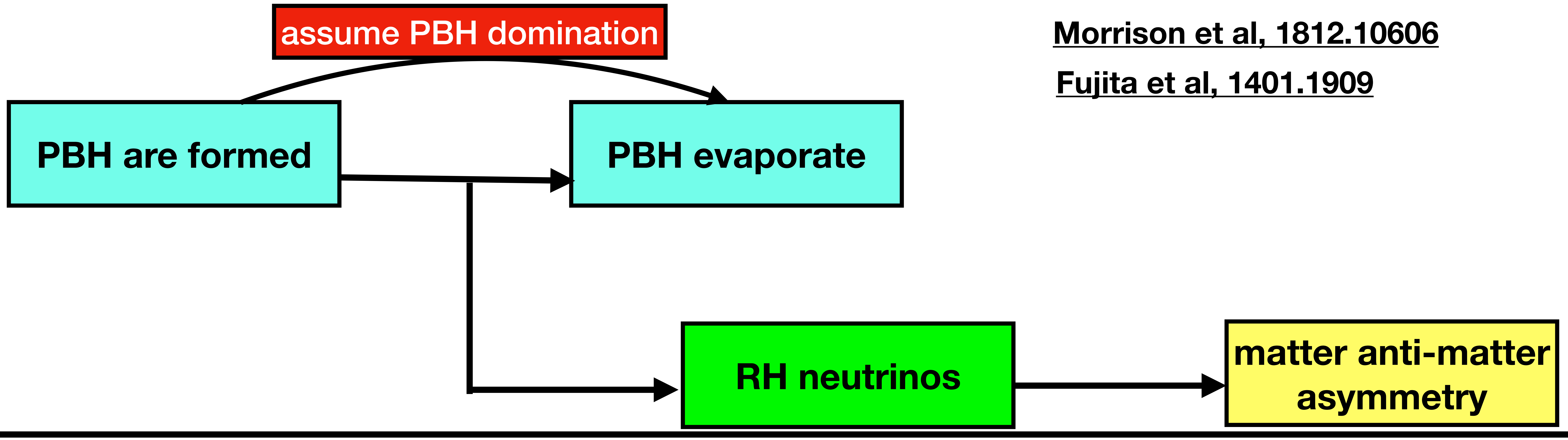
Hawking, 1975

$$\dot{M} = -\sum_j \frac{g_j}{2\pi^2} \int_0^\infty \frac{\sigma_{\rm abs}^{s_j}(M,p)\, p^2}{\exp[E_j(p)/T_{\rm BH}] - (-1)^{2s_j}}\, p\, dp$$

$$T_{\rm BH} = \frac{1}{8\pi G M} \approx 1.06 \left(\frac{10^{13}\ {\rm g}}{M}\right)\ {\rm GeV}\,.$$

PBHs are totally indiscriminate in their particle production: just need T_{BH} to be close to particle mass

Primordial Black holes induced leptogenesis



Morrison et al, 1812.10606

Fujita et al, 1401.1909

$$z_{\mathrm{BH}} = \frac{M_N}{T_{\mathrm{BH}}}$$

contribution to RHN population from thermal plasma

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

contribution to RHN population from PBH evaporation

lepton asymmetry production from RHN decays and inverse decays

Washout effects only sensitive to neutrino parameters

$$aH\frac{dn^{\mathrm{B-L}}_{\alpha\beta}}{da} = \epsilon^{(1)}_{\alpha\beta}\left[(n_{N_1} - n_{N_1}^{\mathrm{eq}})\Gamma^T_{N_1} + n_{\mathrm{BH}}\widetilde{\Gamma}^{\mathrm{BH}}_{N_1}\right] + \mathcal{W}_{\alpha\beta}$$

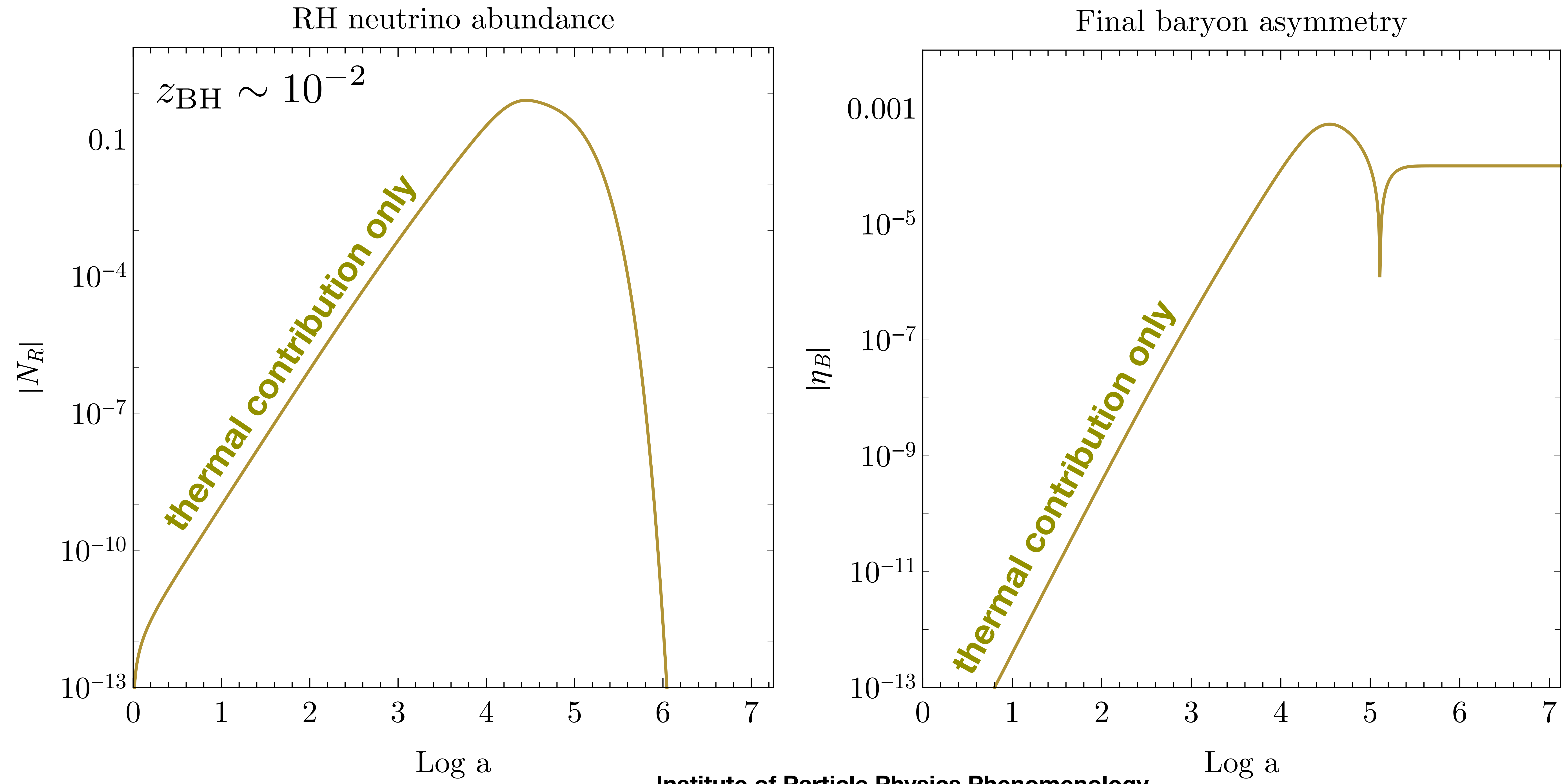
thermal averaged decay of RHN from PBH evaporation (function of z_{BH})

Primordial Black holes induced leptogenesis

A. PBH evaporate **before** RH are thermally produced from plasma → PBH evaporation creates an initial condition which gets erased by fast interactions in the plasma

B. PBH evaporation happens **during** thermal leptogenesis

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



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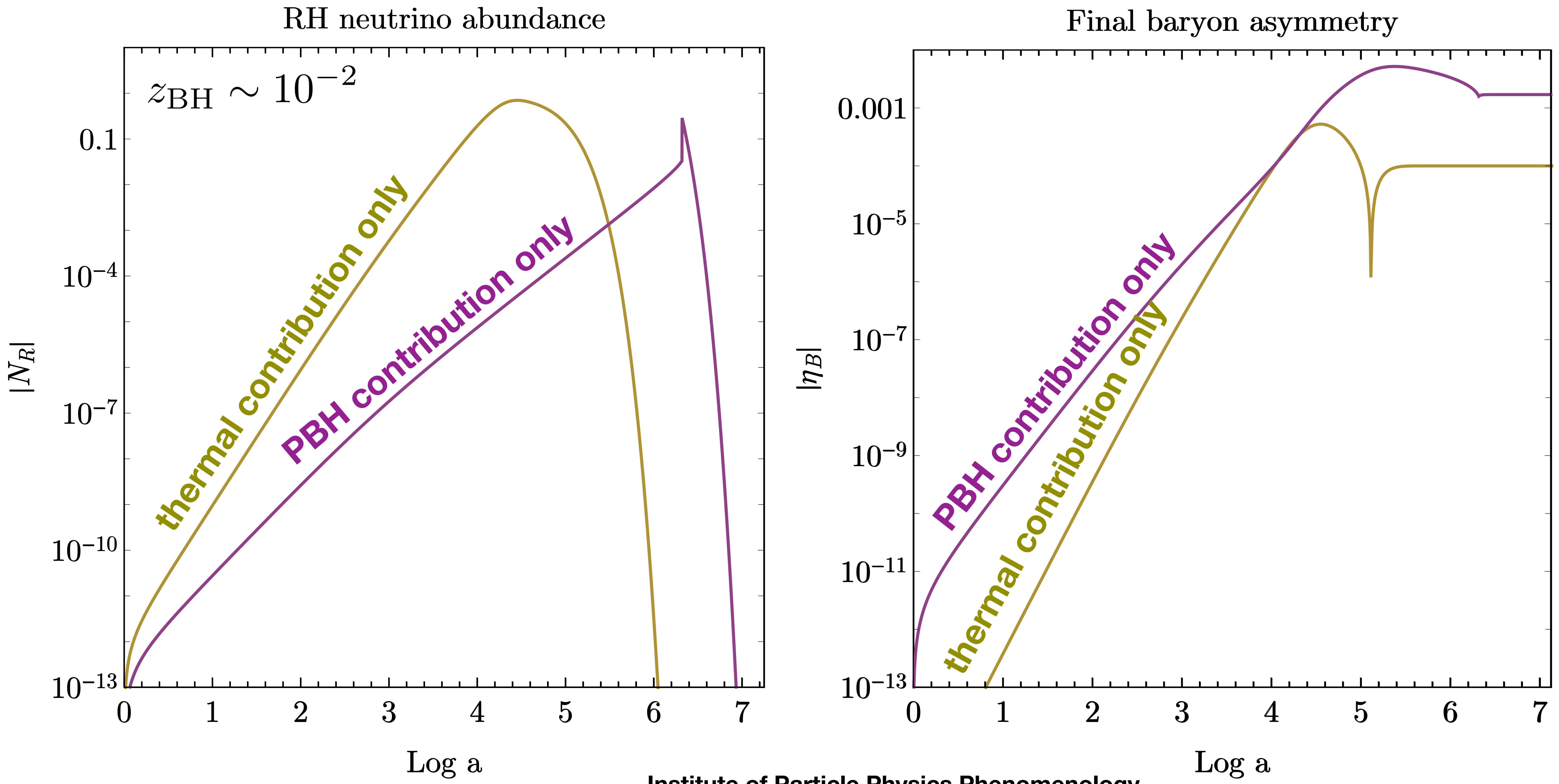

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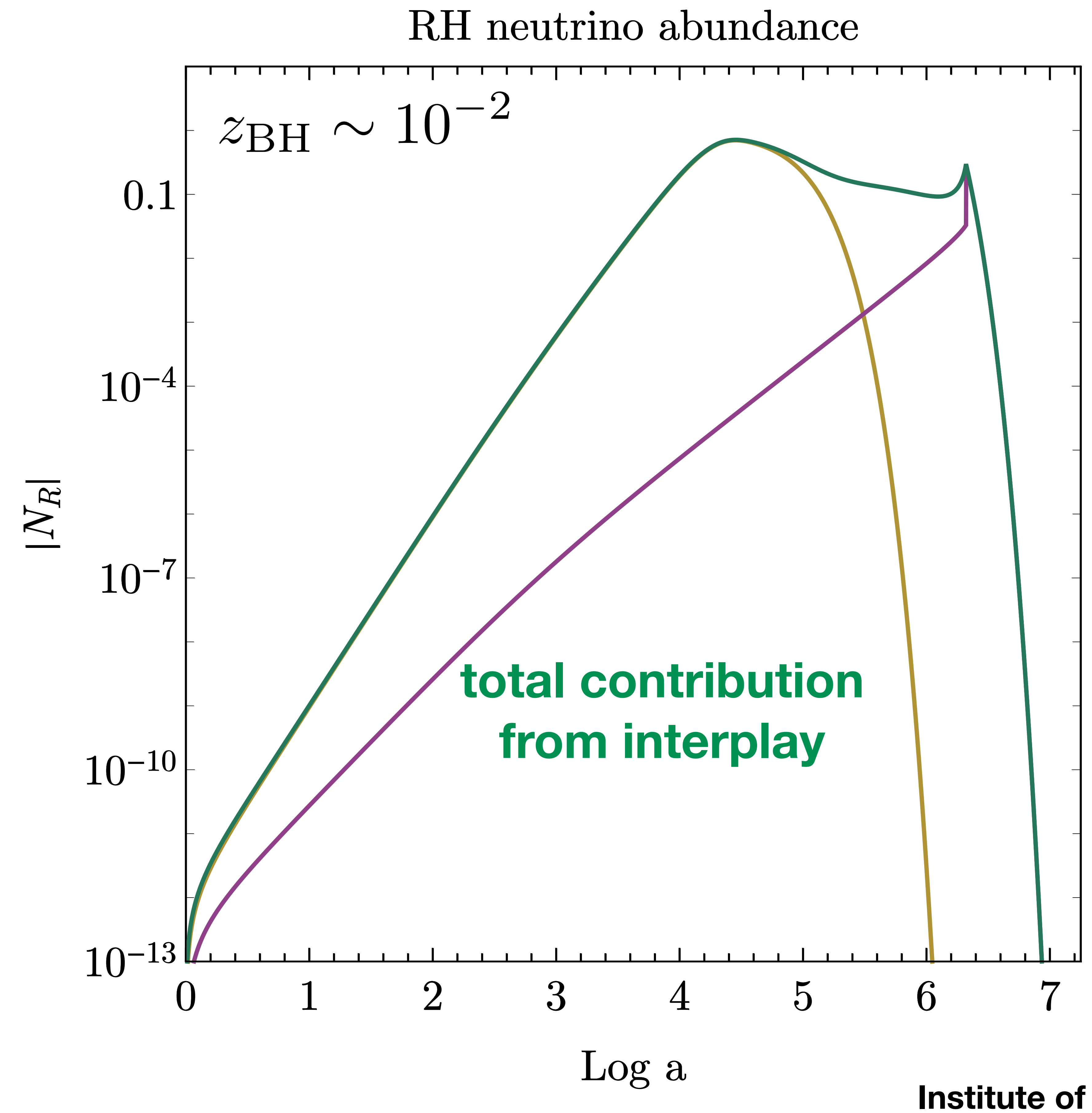
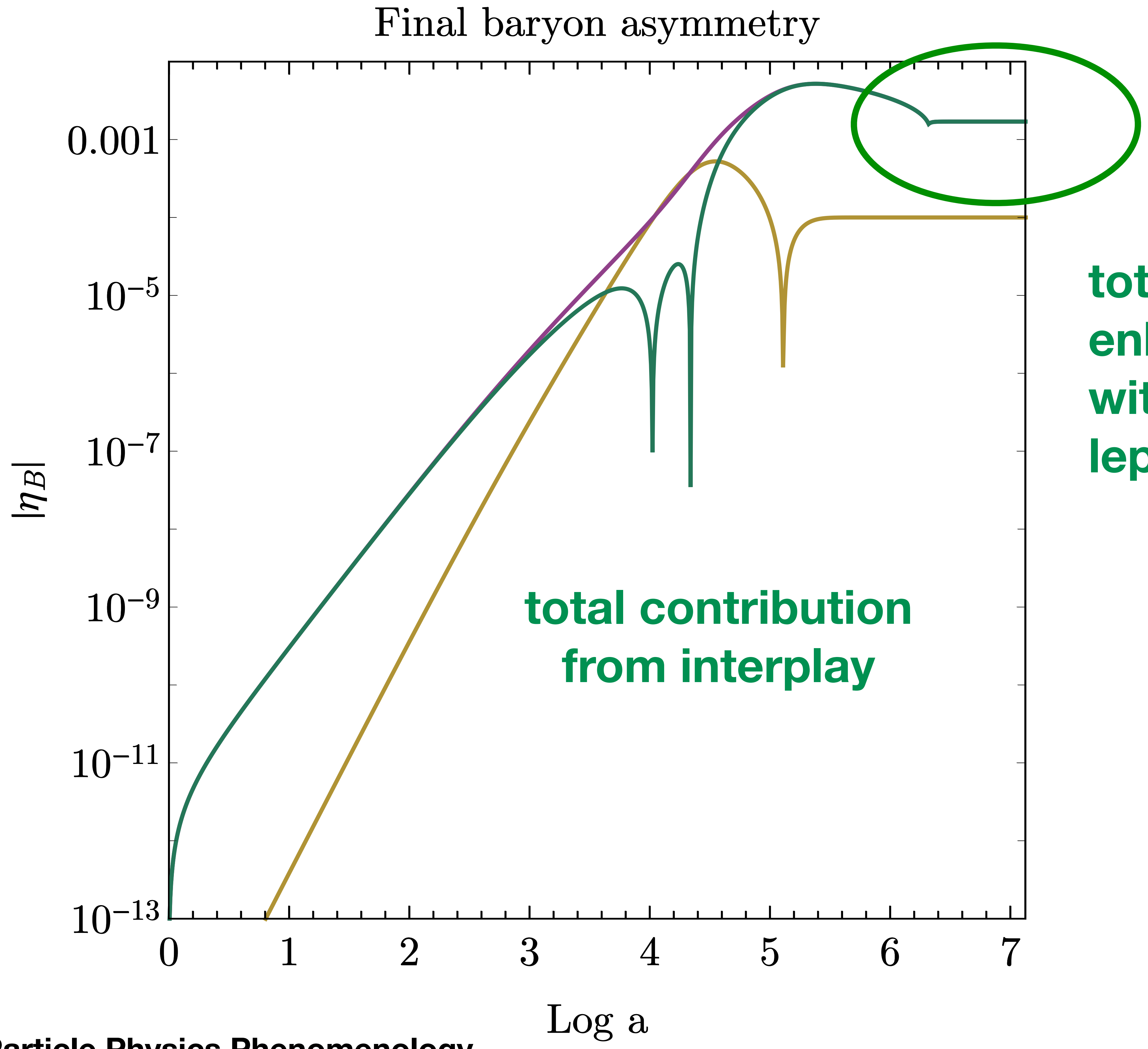


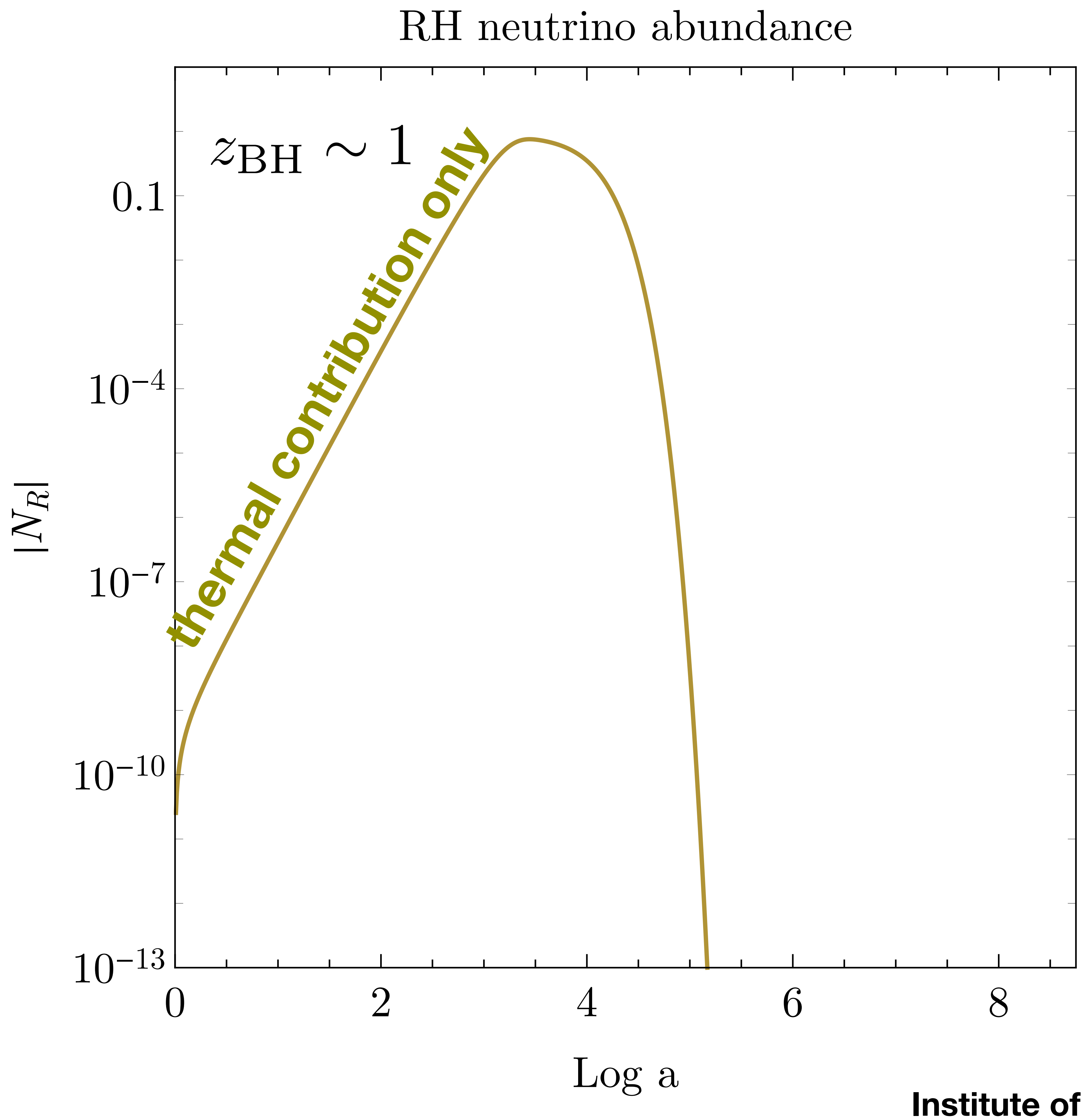


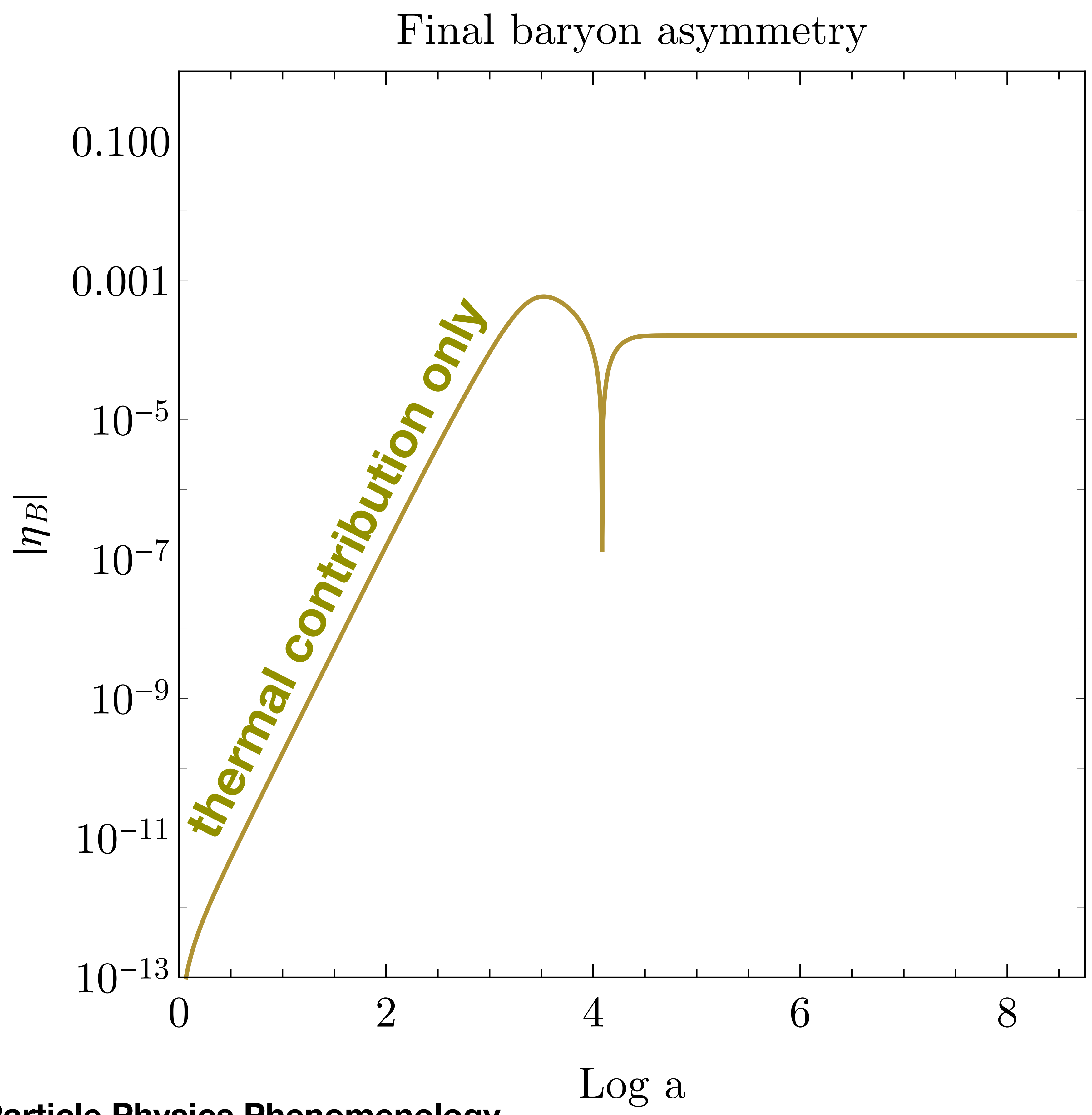
total contribution enhanced compared with thermal leptogenesis alone

Primordial Black holes induced leptogenesis

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

$$M_i = 10^2\,\text{g} \quad \beta_i = 10^{-3} \quad M_N = 10^{11}\,\text{GeV}$$





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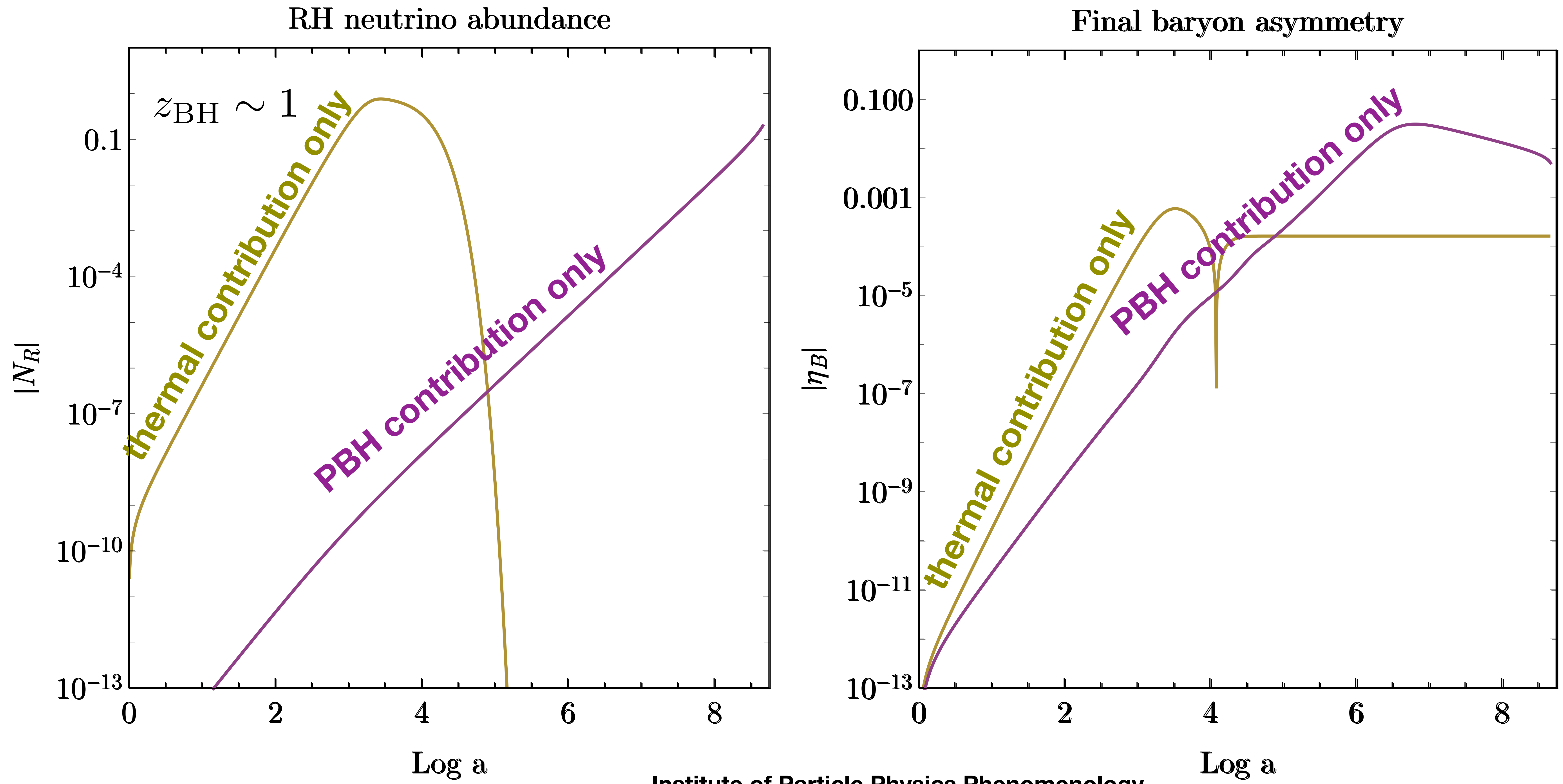

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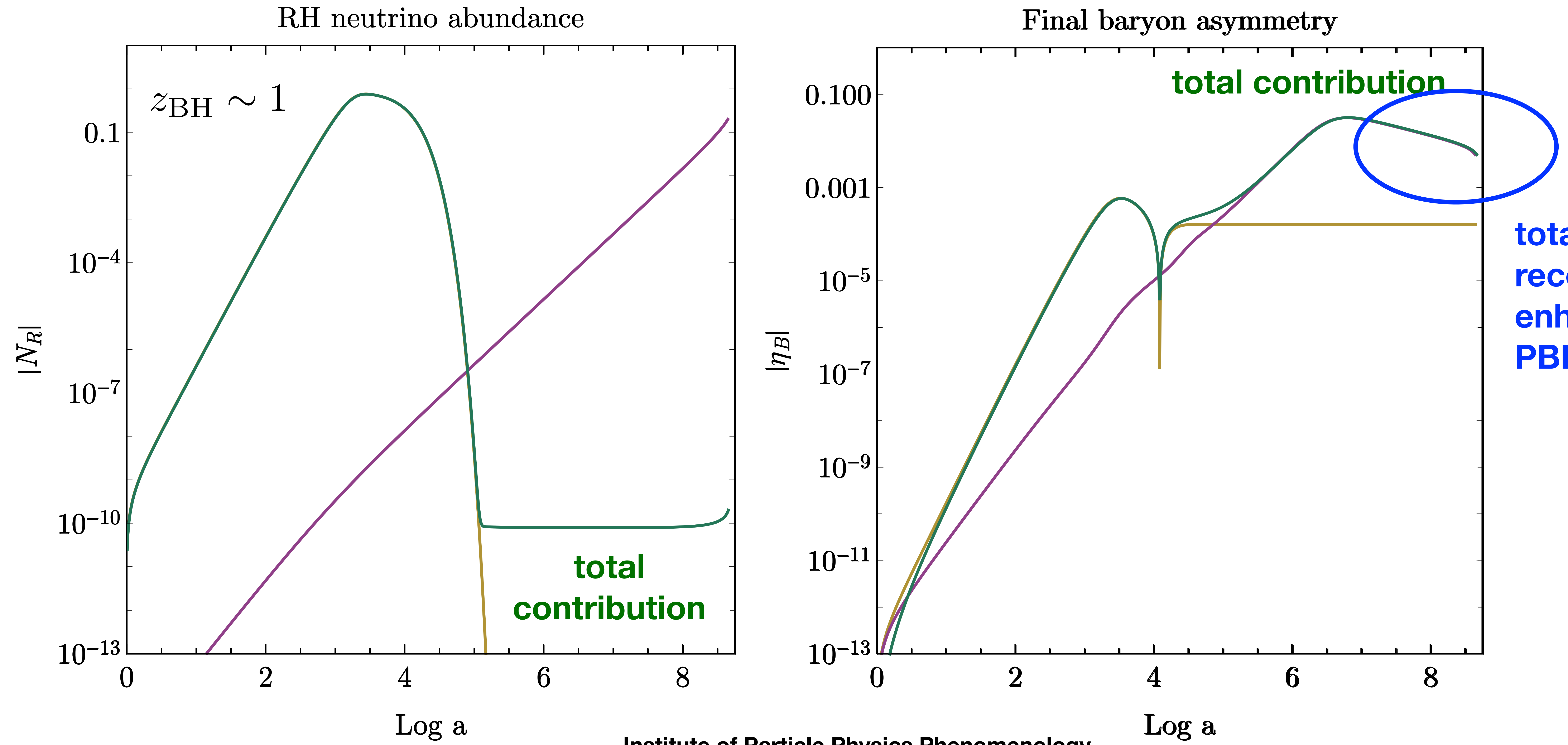


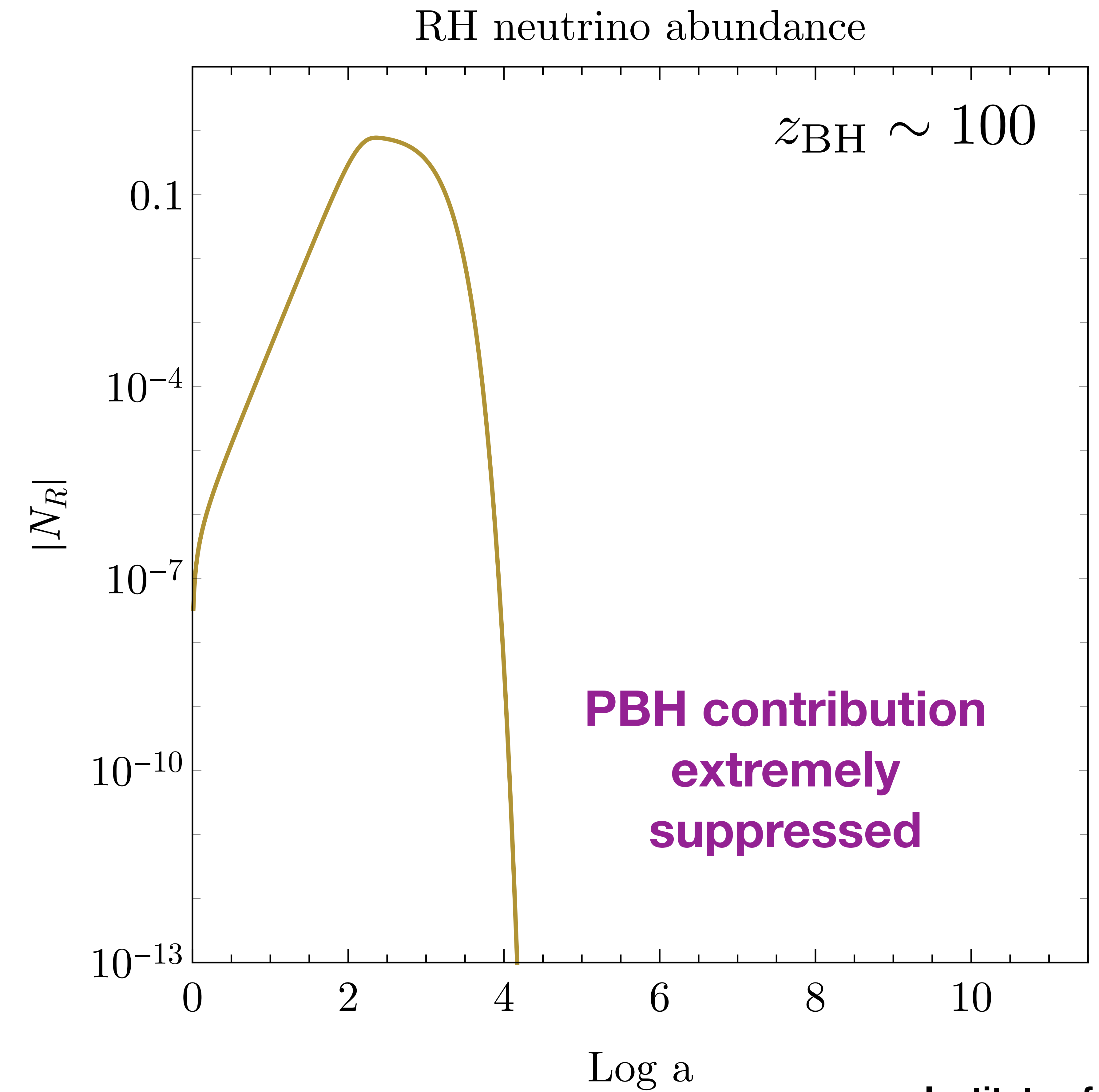
total contribution receives significant enhancement from PBH evaporation

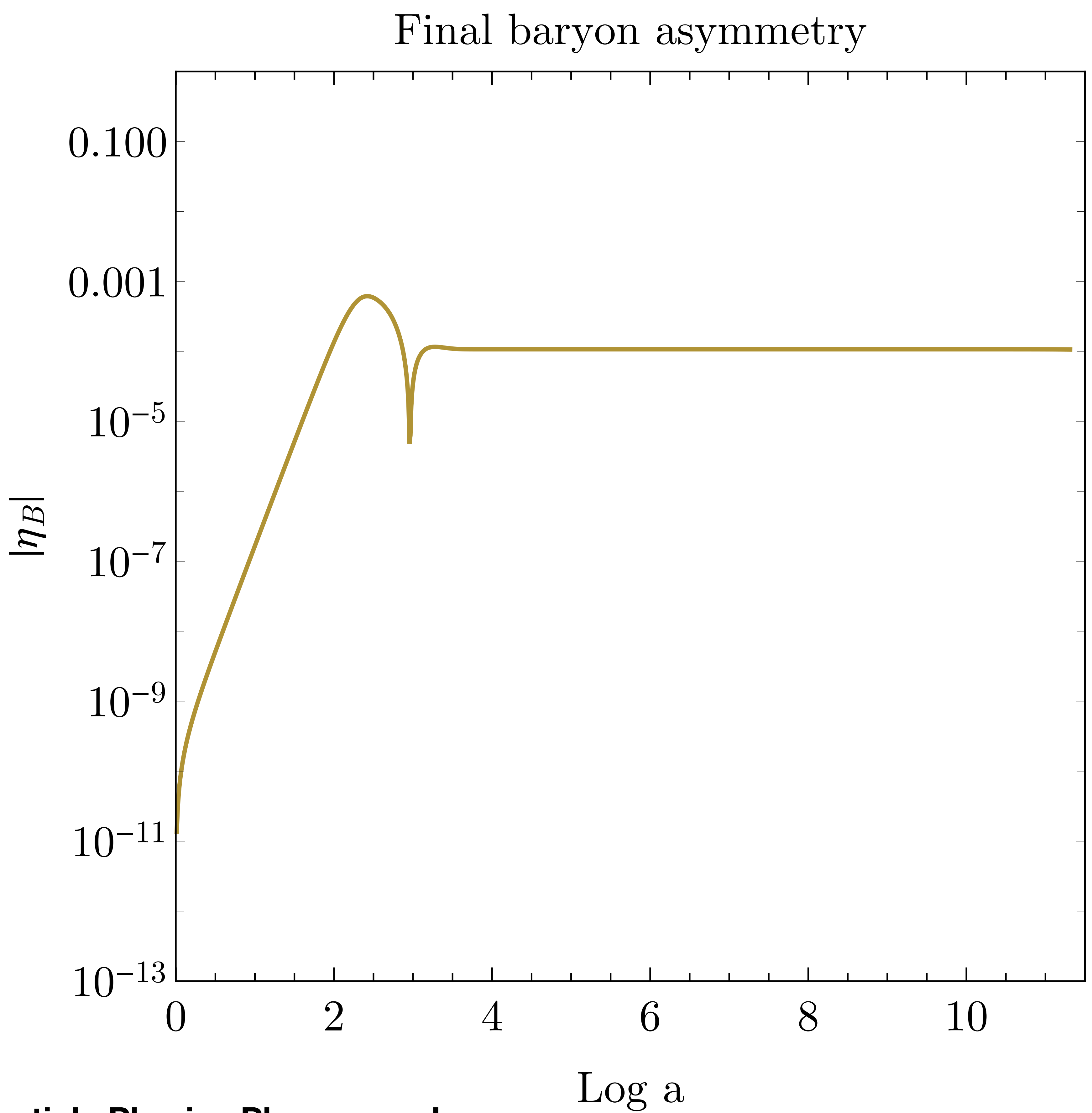
Primordial Black holes induced leptogenesis

D. PBH evaporation occurs **way after** thermal leptogenesis era

z_{BH} large → RHN emission suppressed

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





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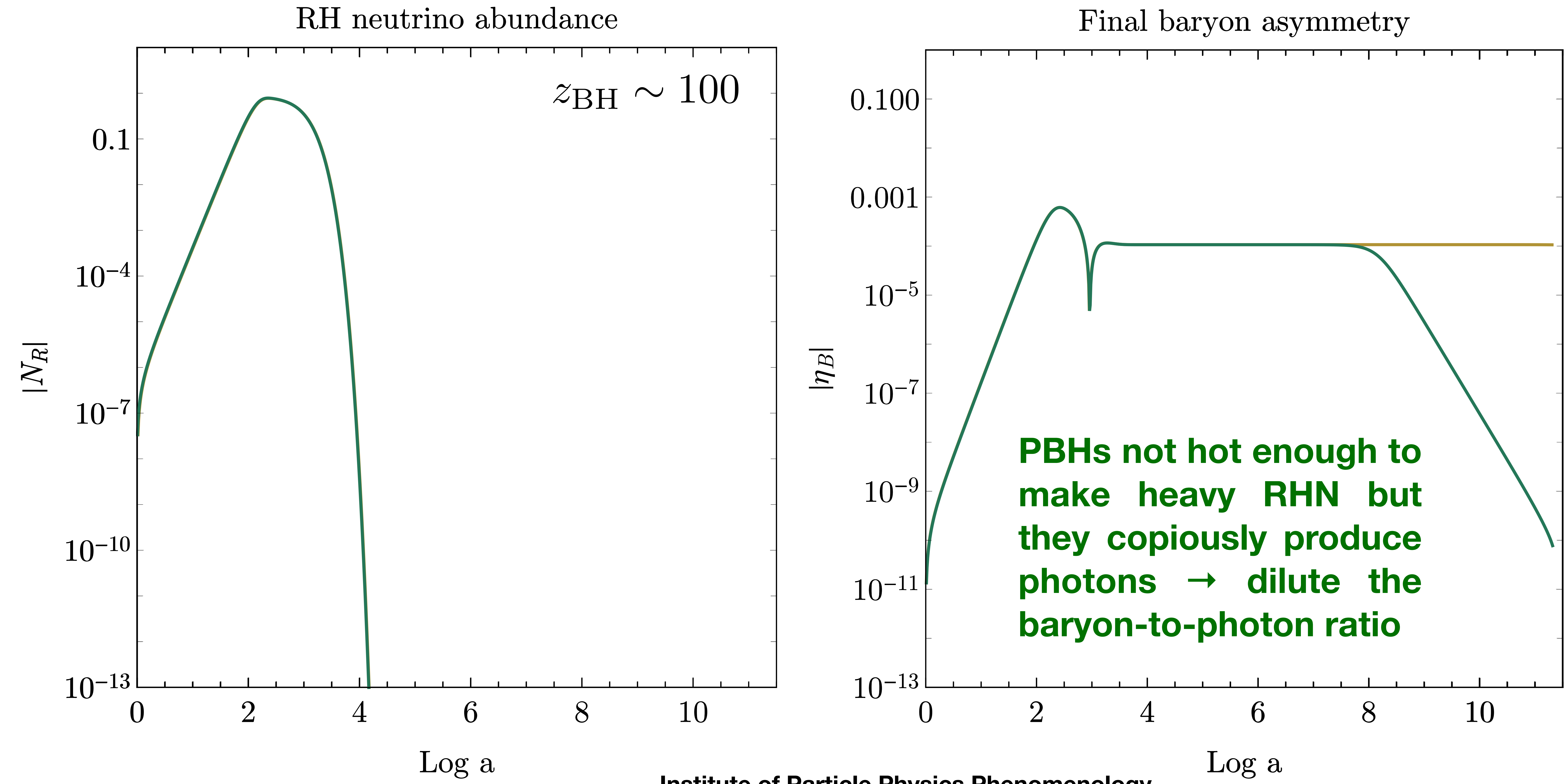
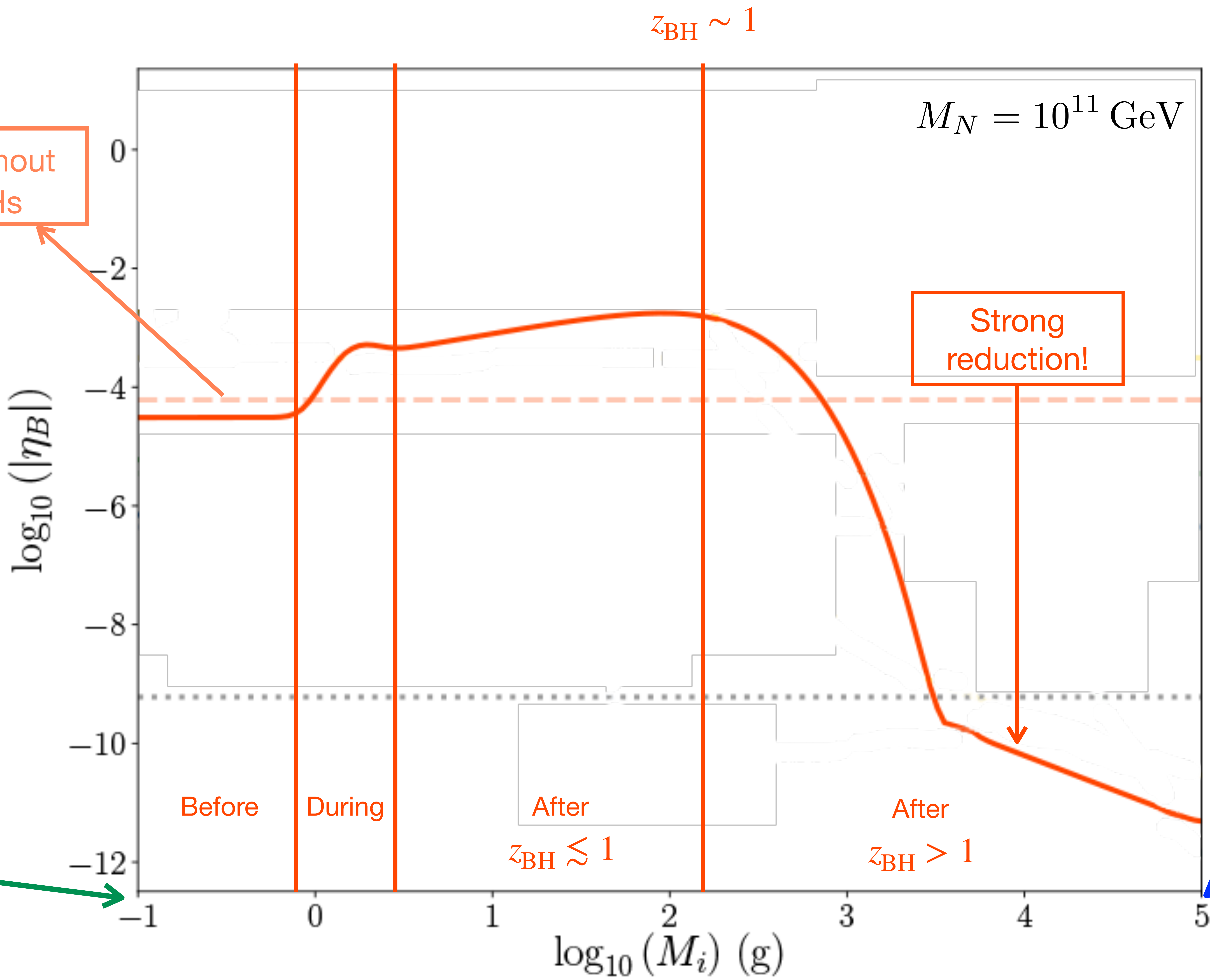
z_{BH} large → RHN emission suppressed

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



Primordial Black holes induced leptogenesis

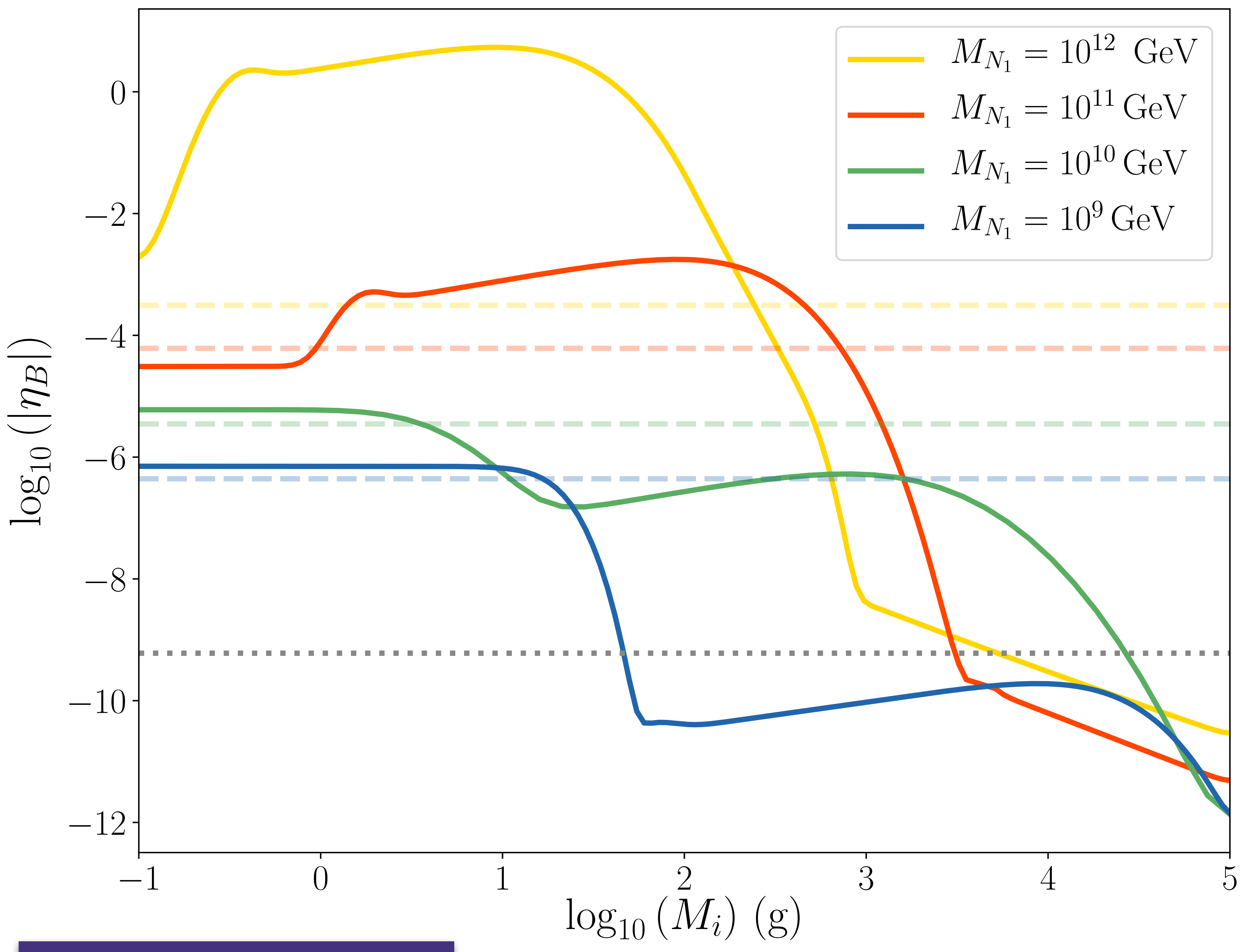


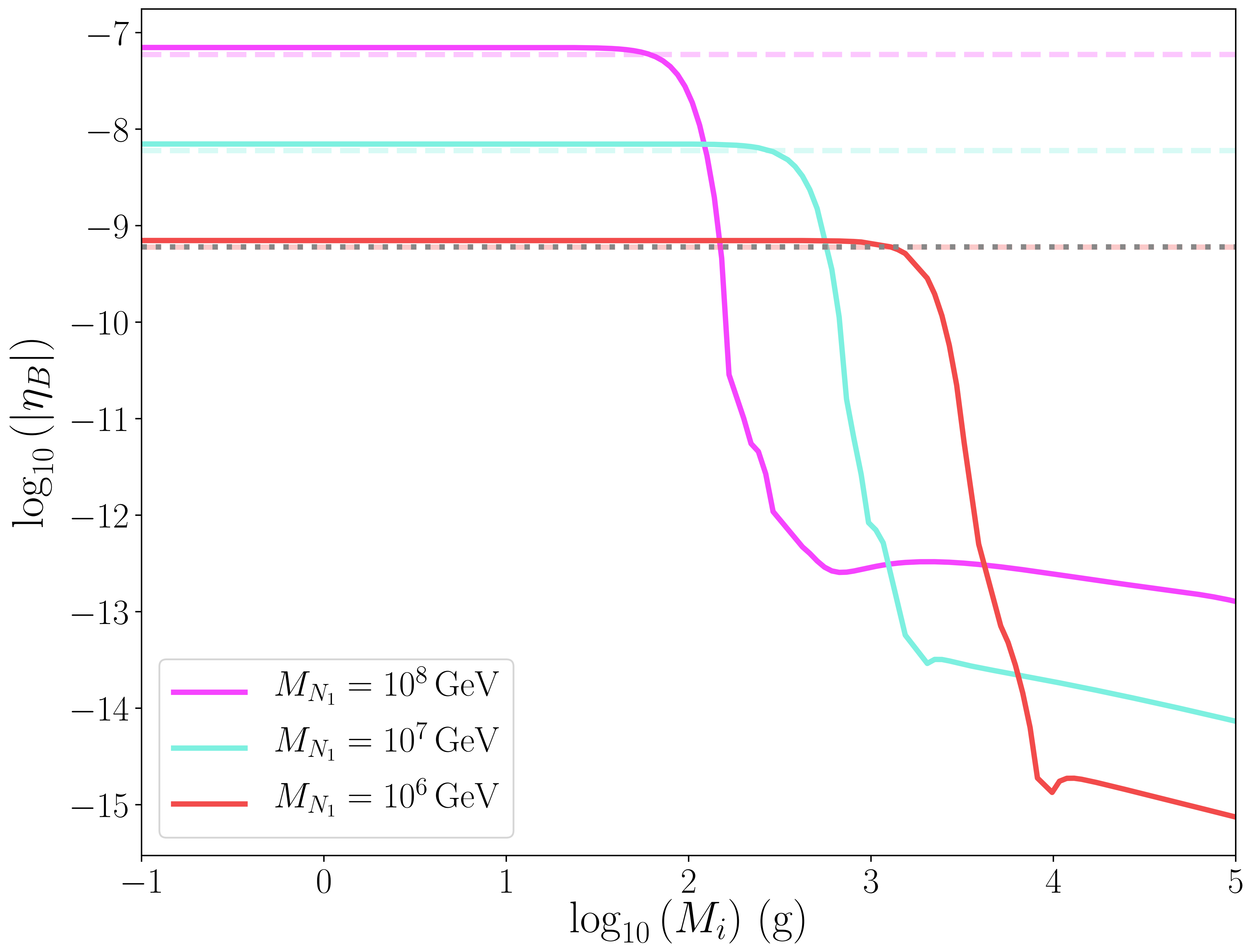
Lower range →from inflation: any PBH formed before end of inflation negligible density

upper range → need SM sphalerons to be active

2004.04740
2004.14773

Primordial Black holes induced leptogenesis





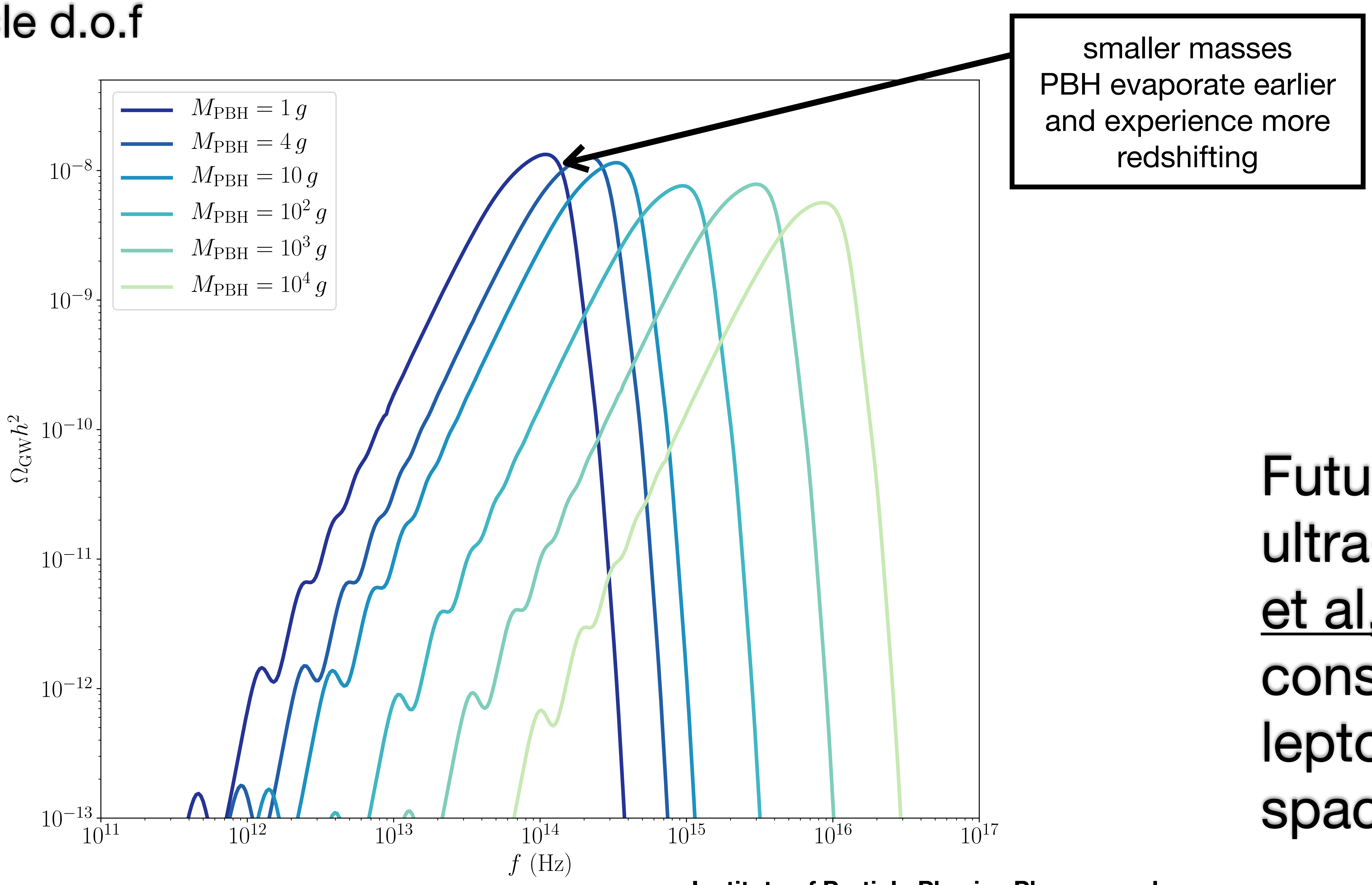
Enhancement or depletion depends on the RH neutrino mass

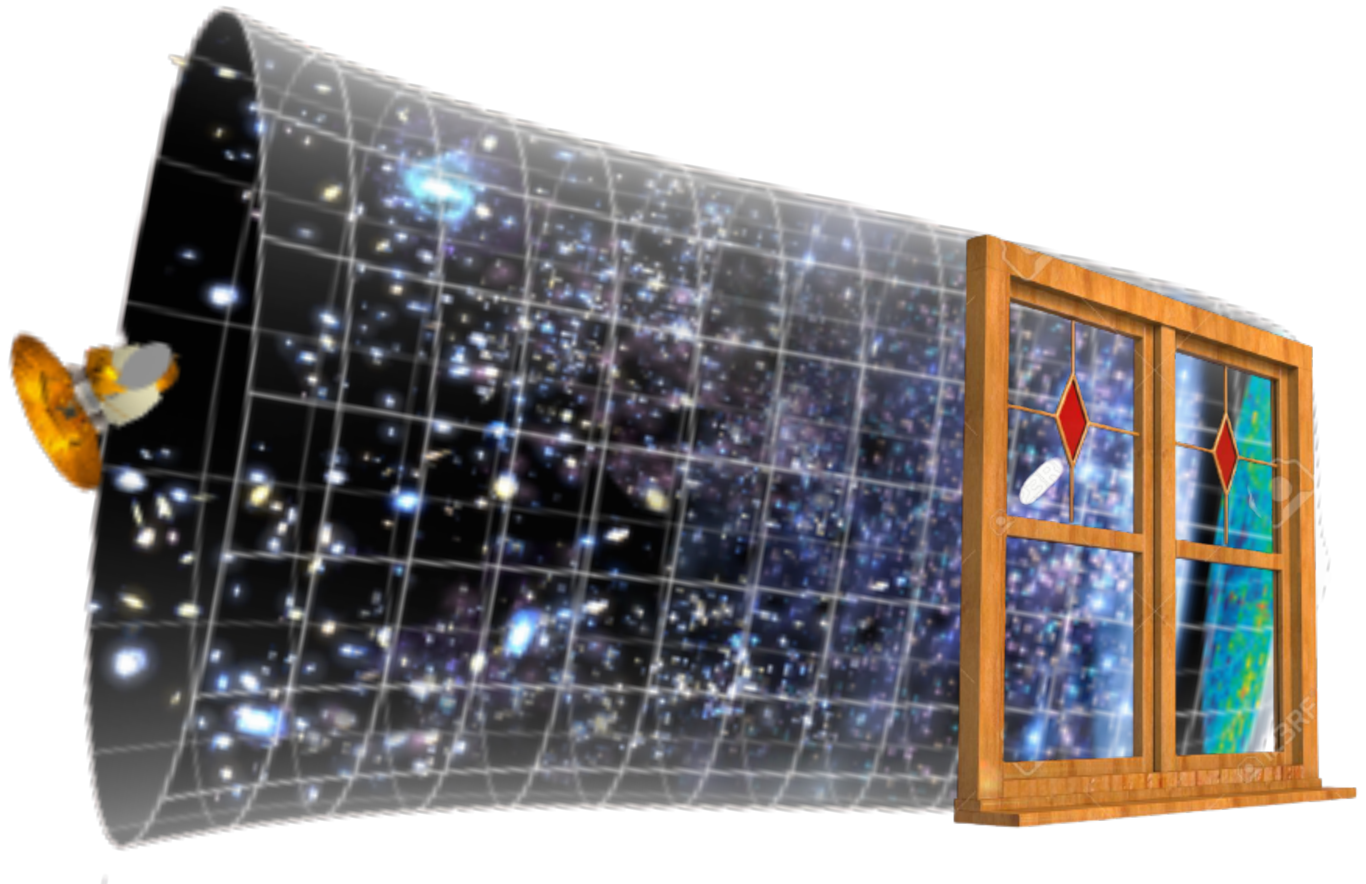
Only reduction of the baryon-to-photon ratio

Primordial Black holes induced leptogenesis

For RHN masses 1000 GeV or less, proving there was a existed a PBH dominated Universe would place leptogenesis under **serious tension**

PBHs are the epitome of democratic: they produce gravitons as well as all other particle d.o.f



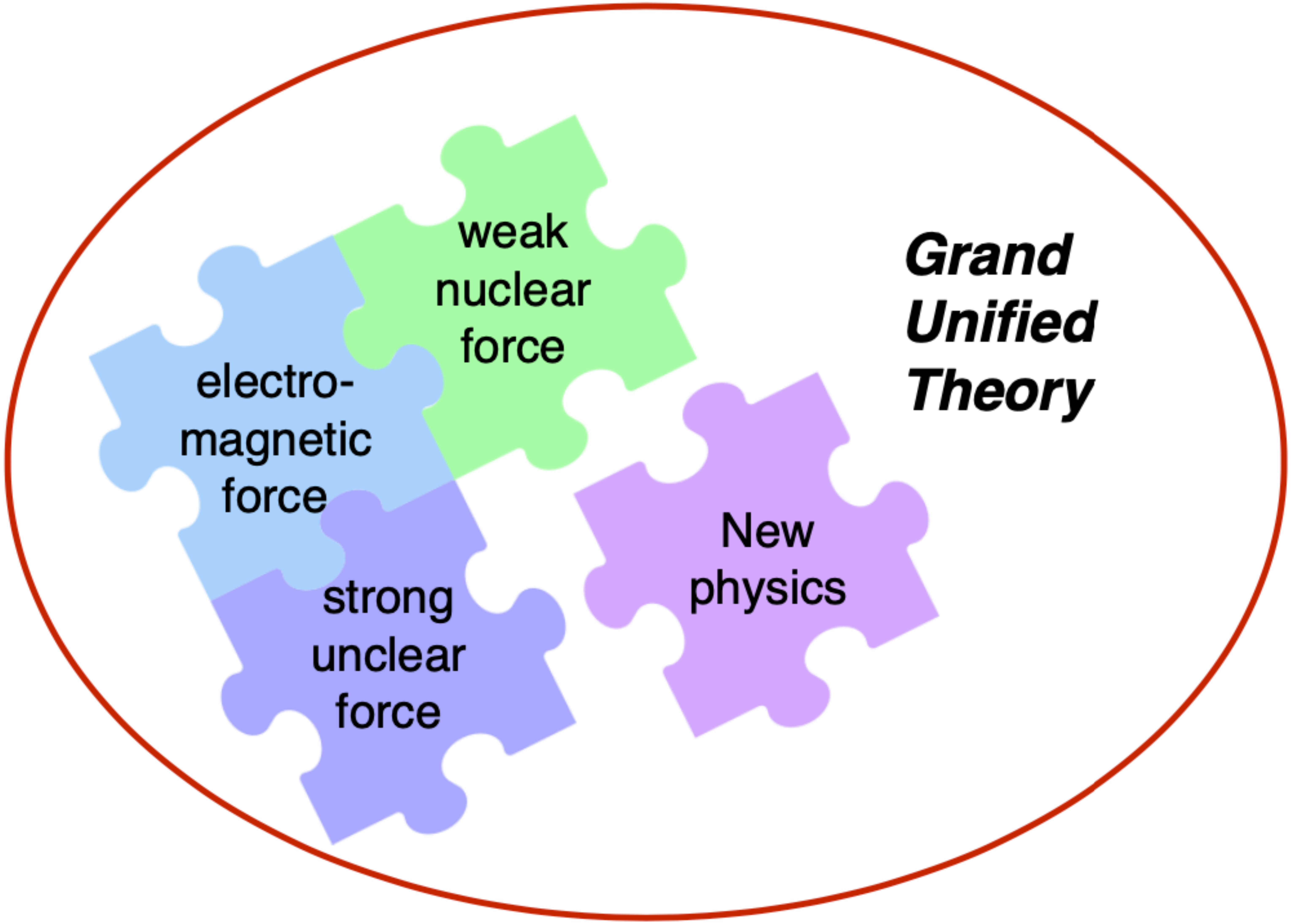


Future measurement of ultra-high GWs (see e.g Ito et al, 1903.04843) can constrain thermal leptogenesis parameter space

Half time Summary

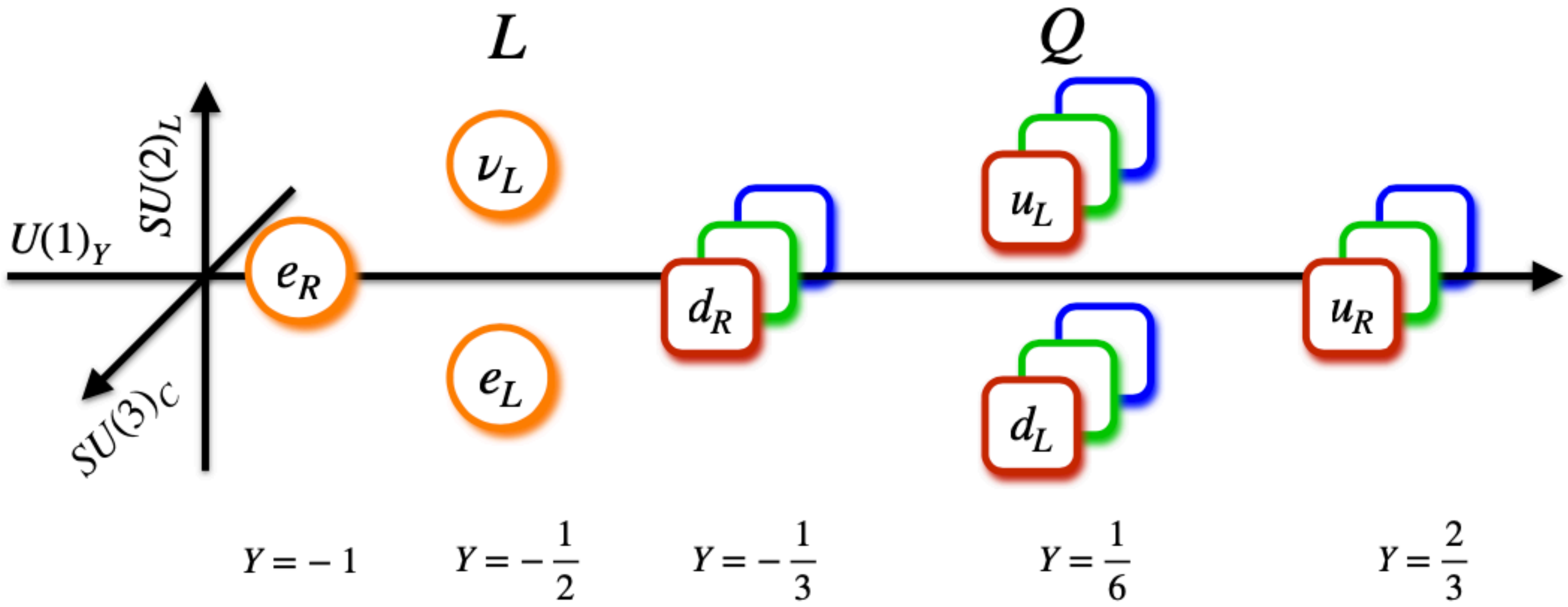
- Leptogenesis is one of the leading explanations of the matter anti-matter asymmetry. Added bonus is that light neutrino masses are also explained.
- It is entirely feasible the Universe underwent some non-standard cosmology such as PBH domination
- Due to the democratic nature of PBH, all particle degrees of freedoms are produced if the PBH is sufficiently hot.
- Non-trivial interplay between leptogenesis era and PBH evaporation. In some regions of the PS there is significant enhancement while in the low mass right-handed neutrino regime, heavier PBHs produce a giant entropy dump which dilutes the matter anti-matter asymmetry.
- While thermal leptogenesis is a very scale mechanism and therefore difficult to test, future probes of ultrahigh frequency GWs could falsify the intermediate scale leptogenesis.

The role of GUTs



The role of GUTs

GUTs can explain apparent arbitrariness of fermion masses and mixing



Thanks to
Ye-Ling Zhou for figure

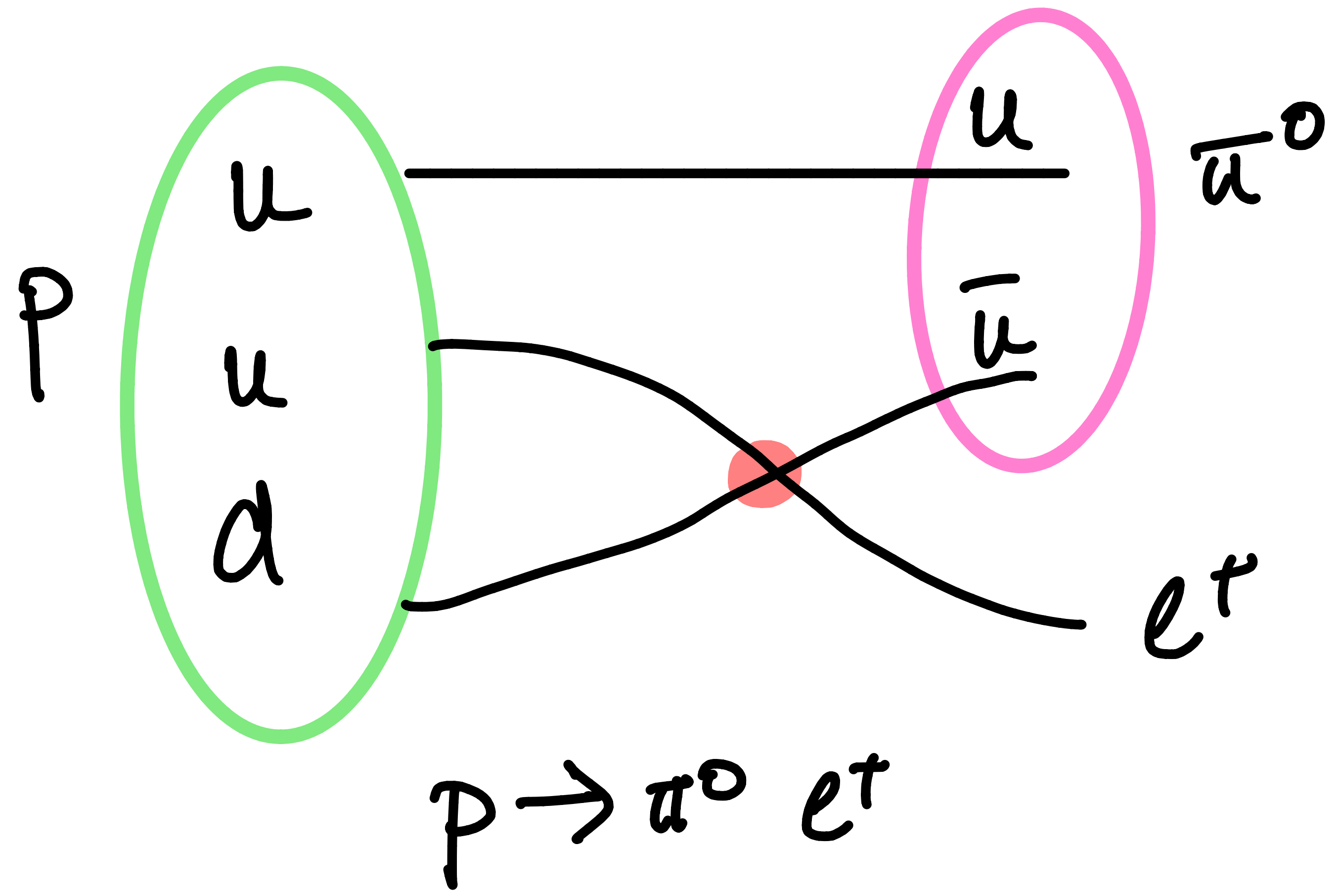
GUT prediction 1: proton decay

Proton decay from GUTs

GUTs unify leptons and quarks into common multiplets and as GUTs broken to SM gauge group, heavy gauge boson integrated out → BNV interactions i.e. proton decay

$$\frac{\epsilon_{\alpha\beta}}{\Lambda_1^2}\left[(\overline{u_R^c}\gamma^\mu Q_\alpha)(\overline{d_R^c}\gamma_\mu L_\beta) + (\overline{u_R^c}\gamma^\mu Q_\alpha)(\overline{e_R^c}\gamma_\mu Q_\beta)\right] + \frac{\epsilon_{\alpha\beta}}{\Lambda_2^2}\left[(\overline{d_R^c}\gamma^\mu Q_\alpha)(\overline{u_R^c}\gamma_\mu L_\beta) + (\overline{d_R^c}\gamma^\mu Q_\alpha)(\overline{\nu_R^c}\gamma_\mu Q_\beta)\right],$$

$\min[\Lambda_1, \Lambda_2]$ gives dominant PD



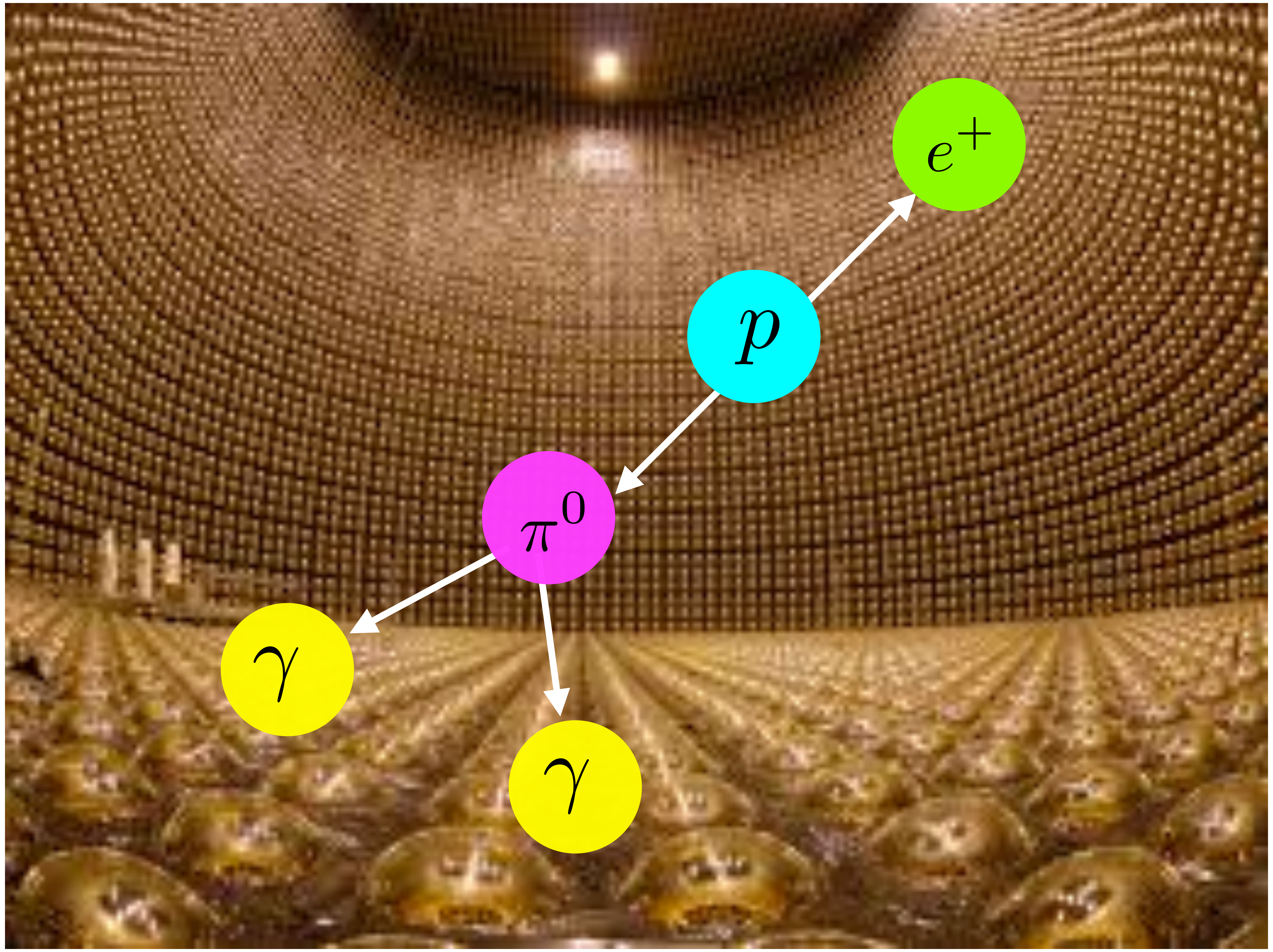
$$\tau_{\pi^0 e^+} > 1.6 \times 10^{34} \text{ years} \longrightarrow \begin{array}{l}\Lambda_1 > 6.7 \times 10^{15} \text{ GeV} \\ \Lambda_2 > 3.9 \times 10^{15} \text{ GeV}\end{array}$$

SK (1610.03597)

Limits (or even finding!) proton decay

The next generation of neutrino oscillation experiments are big vats of stuff sitting around for a long time (forgive me experimentalists ……)

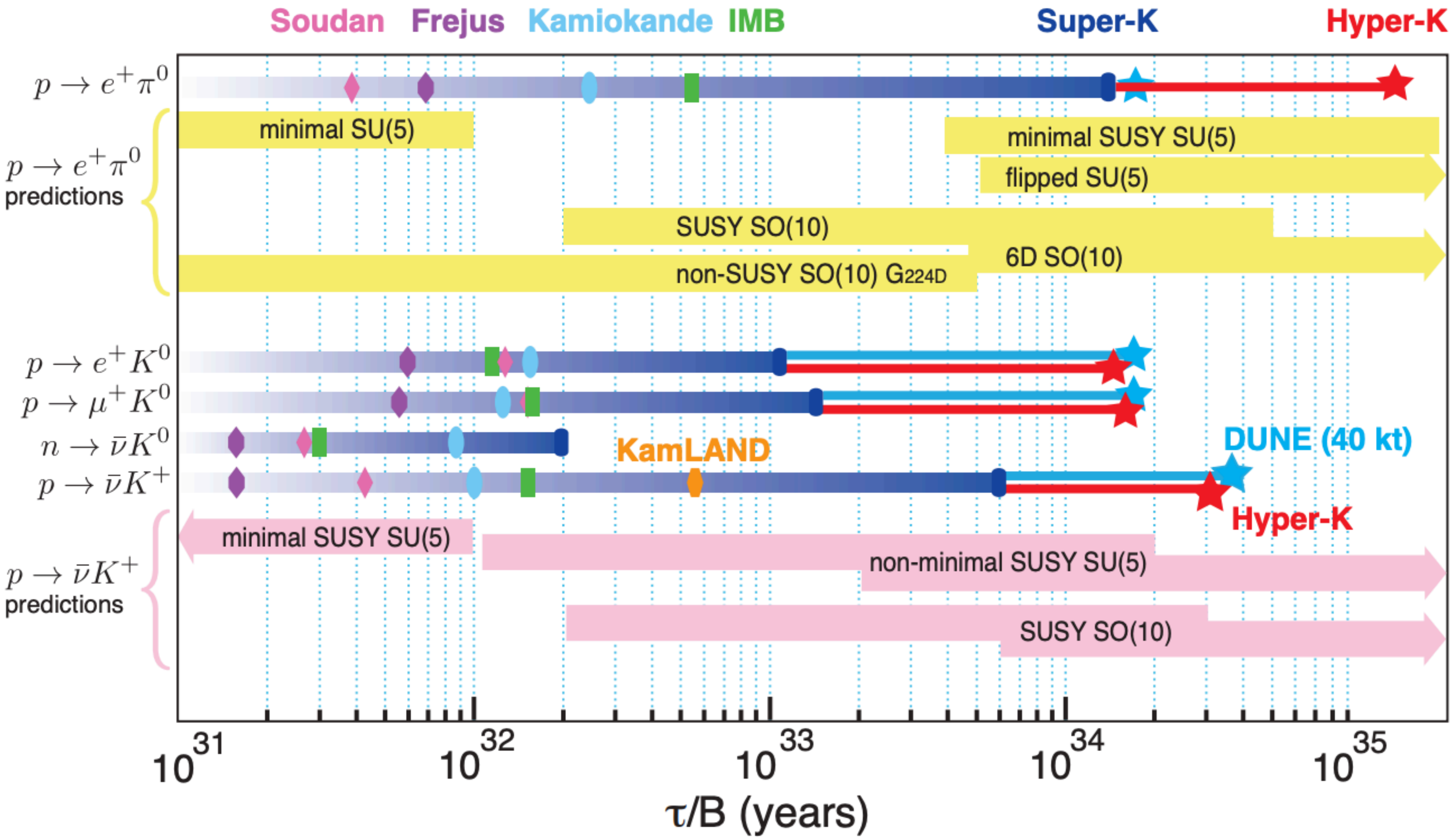
Super-Kamiokande and JUNO ~ 20 kiloton $\Longrightarrow$ 10^{33} protons



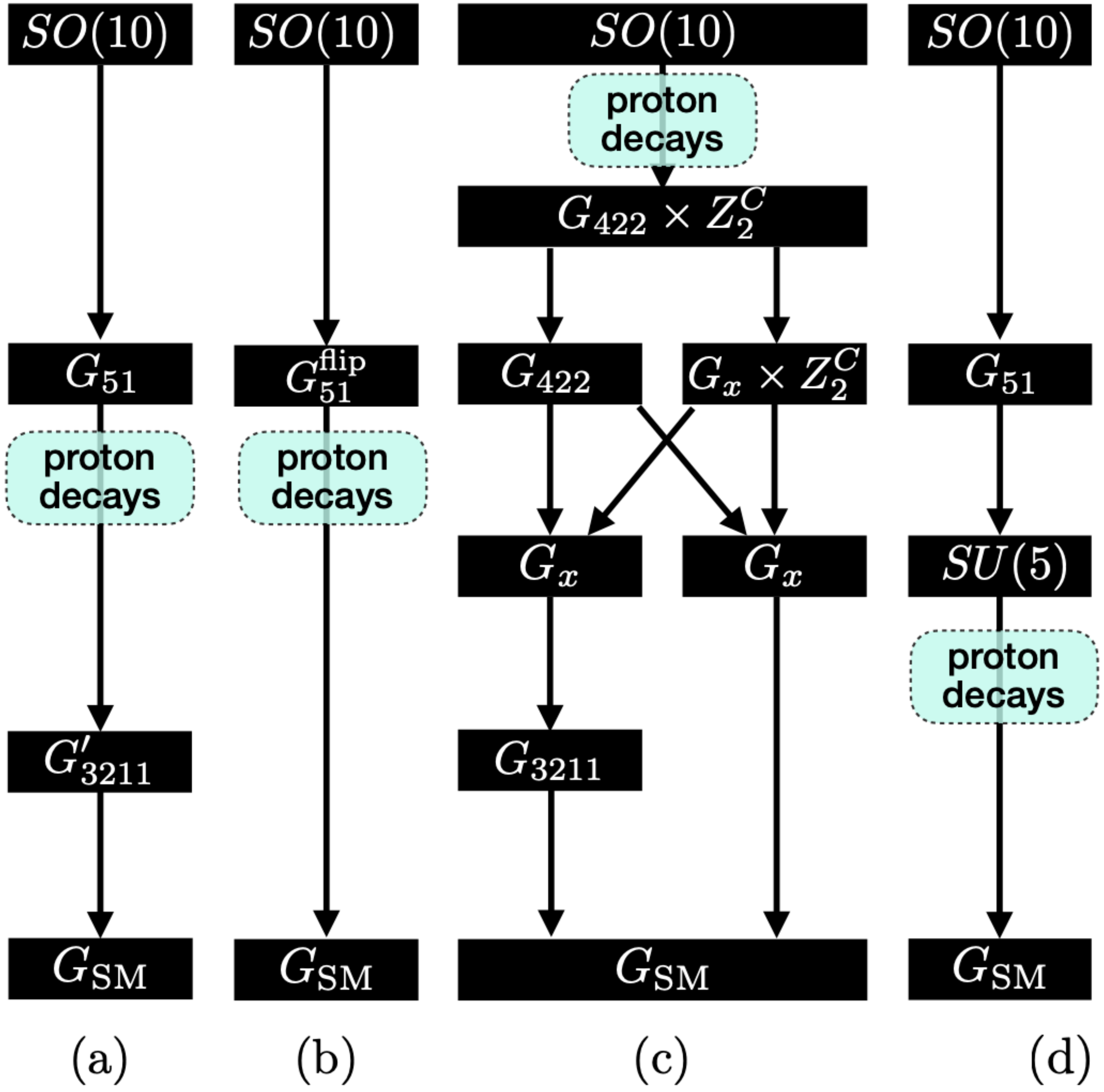
Nucleon decay limits

1.6×10^{34} years

1.5×10^{35} years



proton decay in SO(10)



2005.13549 in collaboration with **Stephen King, Silvia Pascoli, and Ye-Ling Zhou** use PD and GWs to examine viable SO(10) GUT breaking chains.

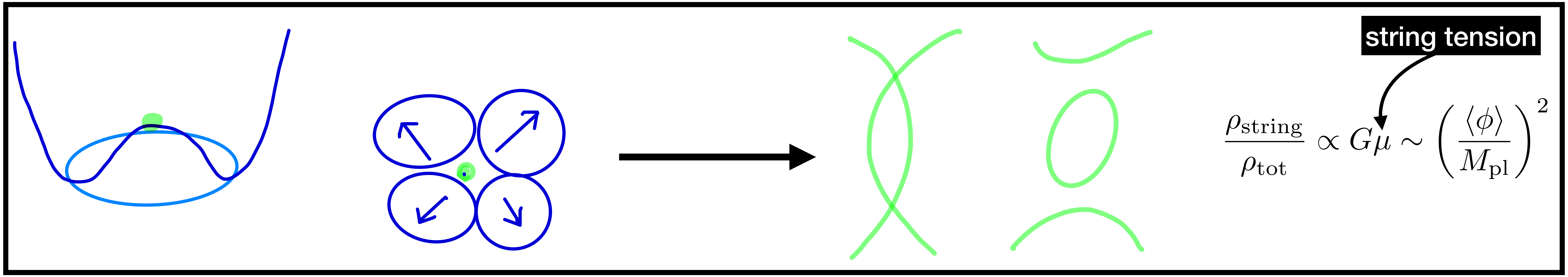
$$G_x = G_{3221} \,\text{or}\, G_{421}$$

GUT prediction 2: cosmic strings

topological defects in GUTs

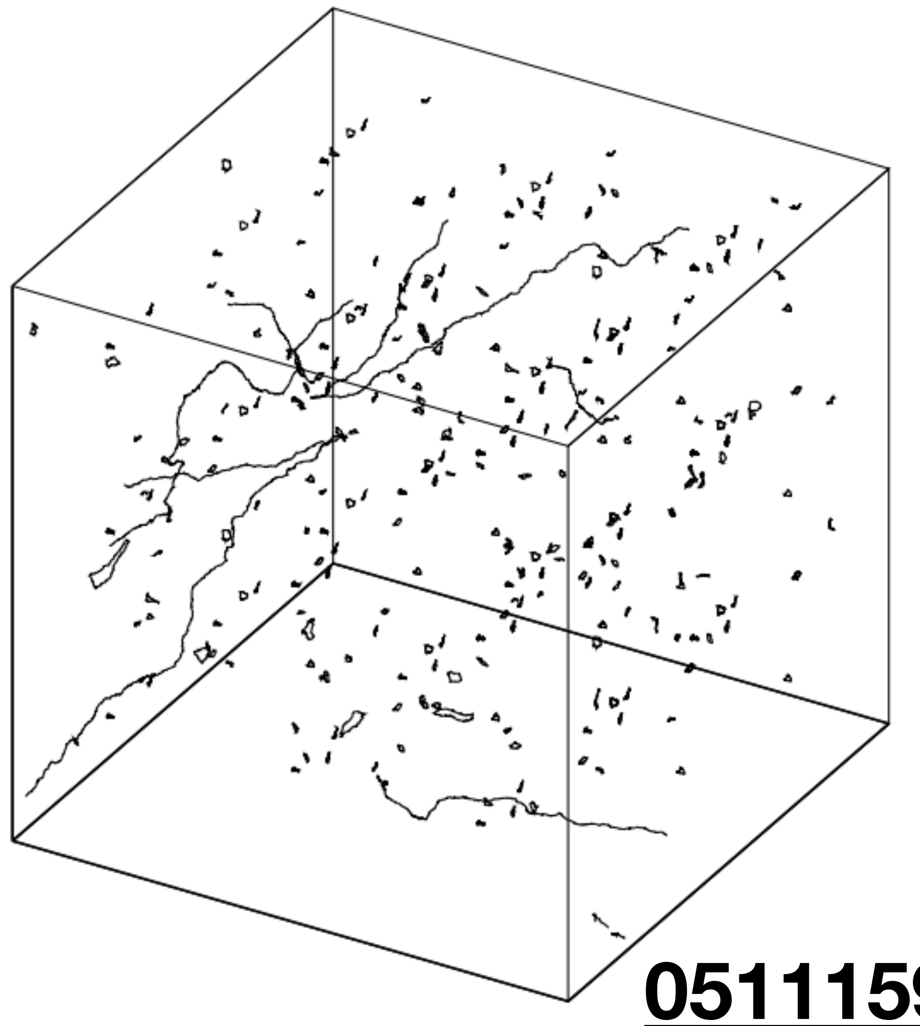
Kibble, Nielsen-Ole

Cosmic strings induced via U(1) symmetry breaking are ubiquitously as GUT breaks to SM gauge group.



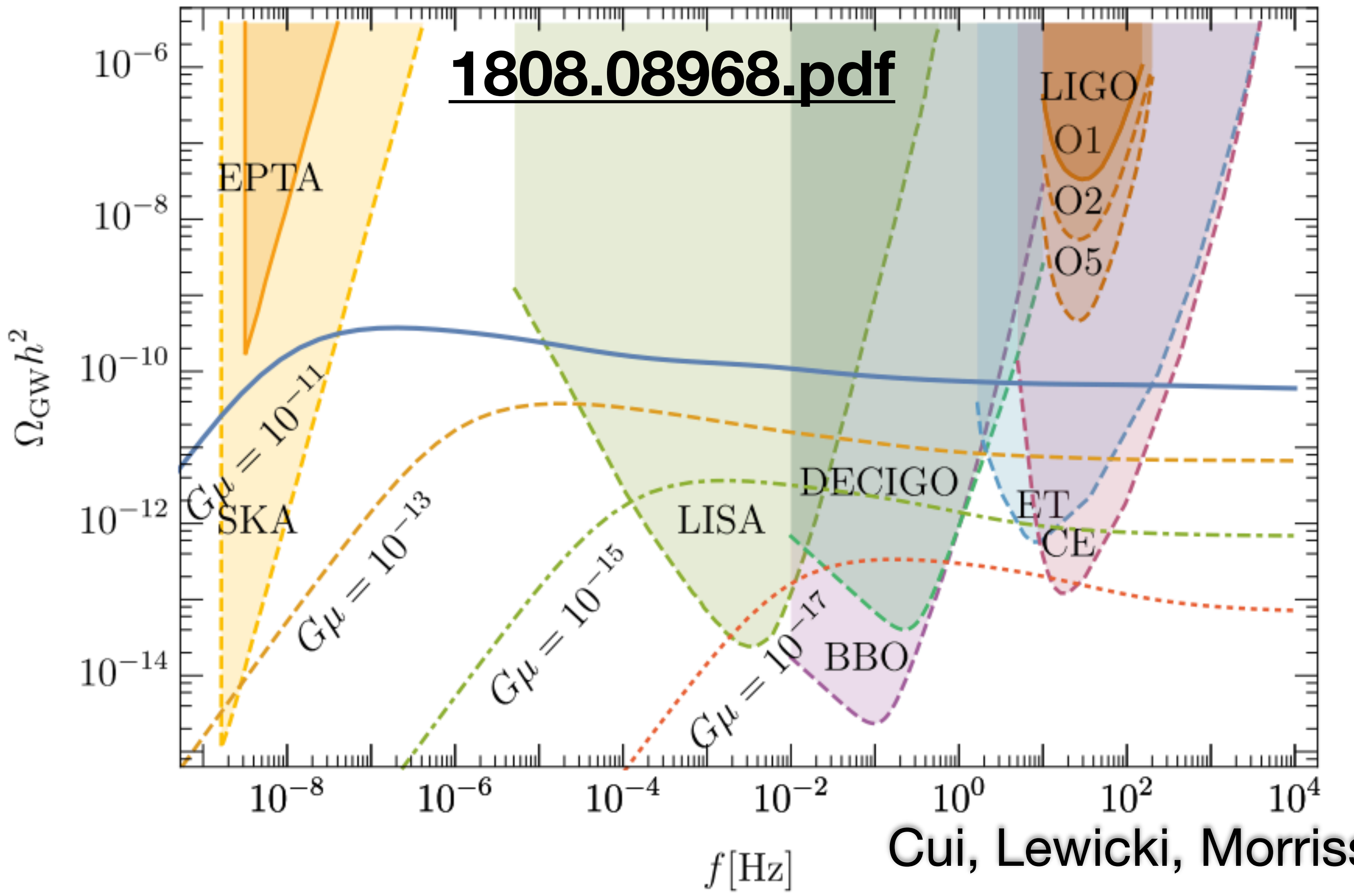
$$\frac{\rho_{\text{string}}}{\rho_{\text{tot}}} \propto G\mu \sim \left(\frac{\langle \phi \rangle}{M_{\text{pl}}}\right)^2$$

Strings intersect to form loops and cusps. Loop loss energy / decay via gravitational radiation



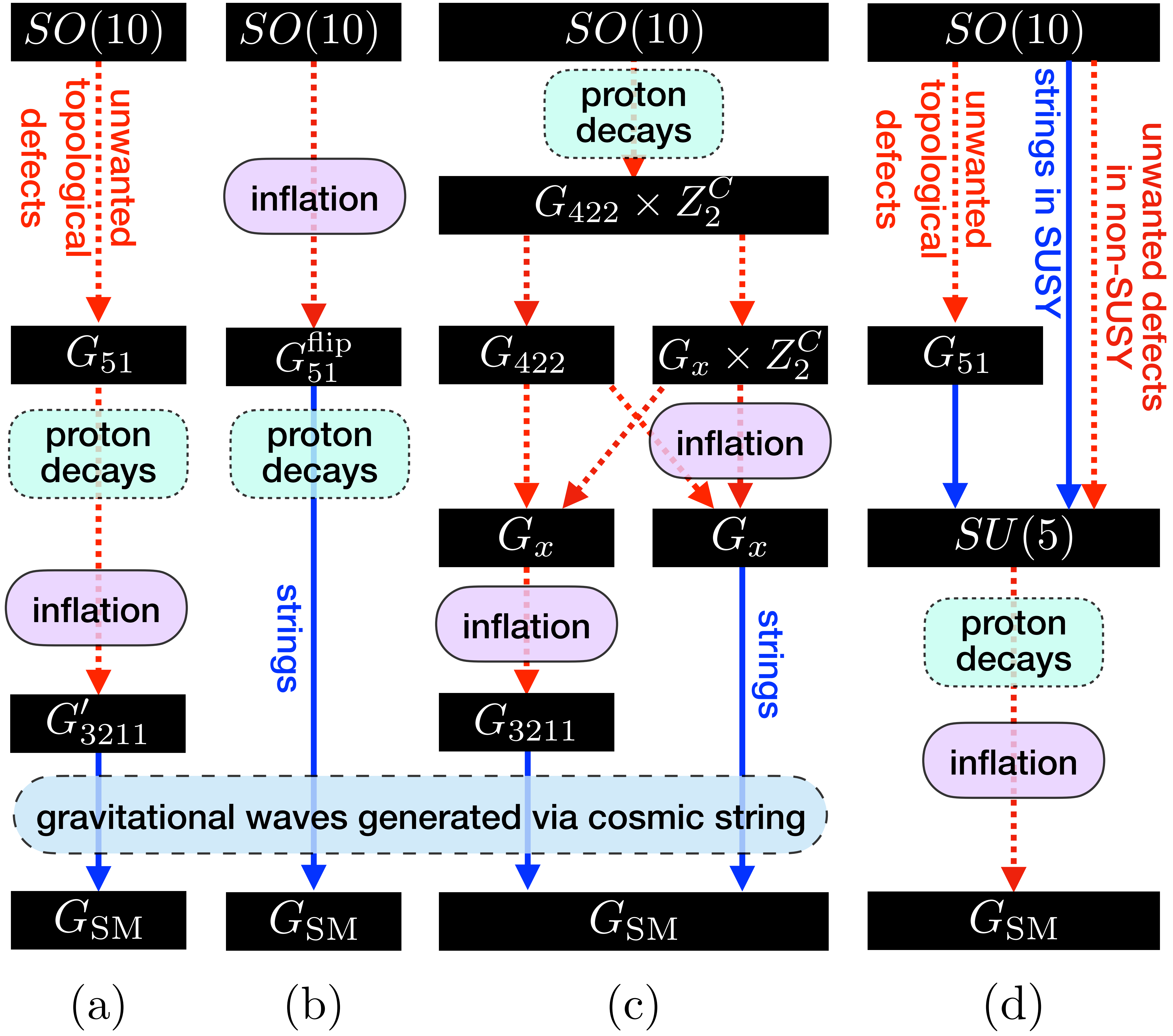
0511159.pdf

Number of simulations based on velocity-dependent one scale model Bennett, Blanco-Pillado, Bouchet, Martins, Olum, Ringeval, Sakellariadou, Shlaer, Shellard, Vanchurin, Vilenkin ……



Cui, Lewicki, Morrissey and Wells

topological defects in SO(10)



Complete study of topological defects in GUTs 0308134

monopoles and domains walls are unwanted topological defects

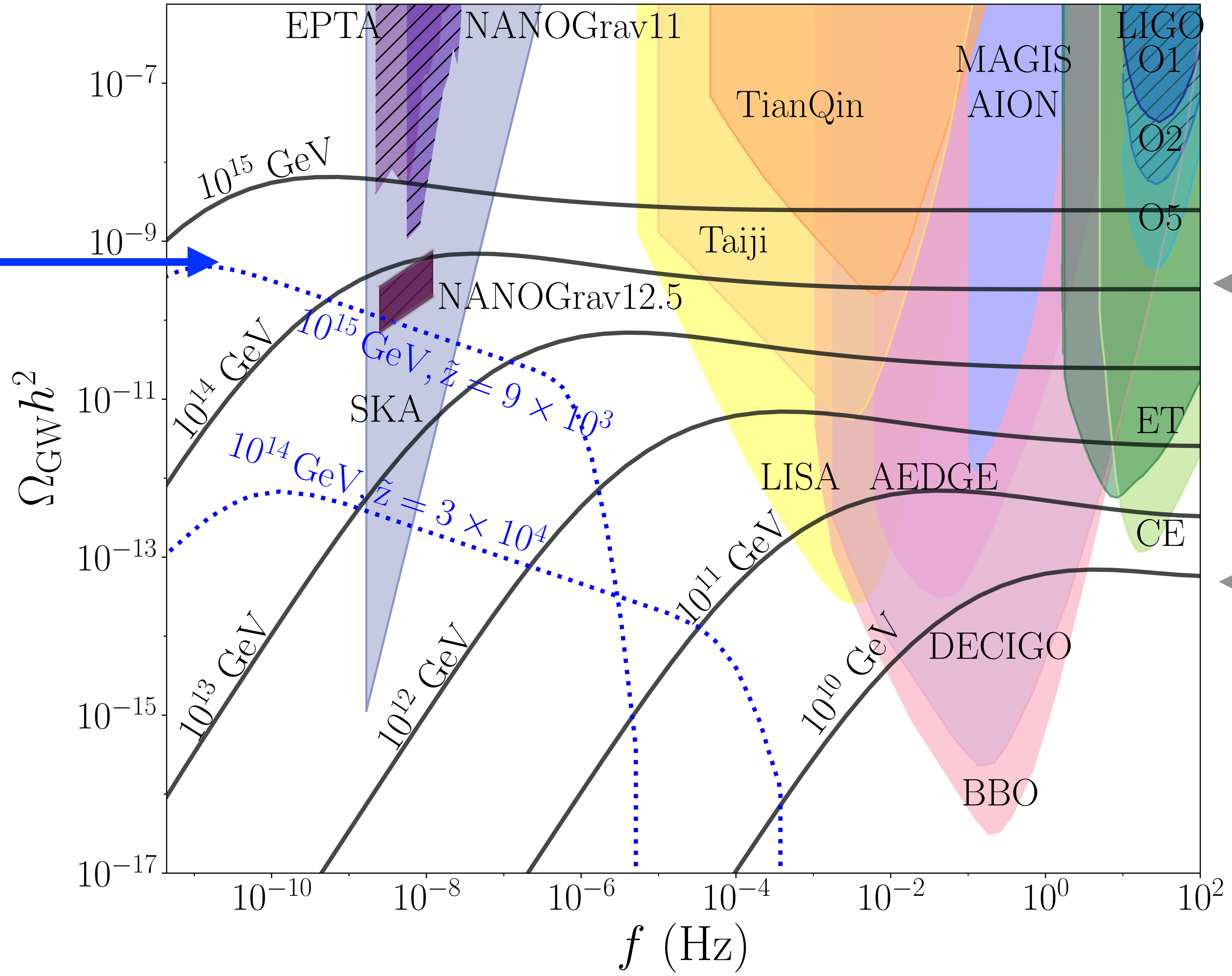
$$G_x = G_{3221} \text{ or } G_{421}$$

To remove unwanted defects we introduce a period of inflation

Inflationary period

- Inflation occurs **before** string formation → string network will produce its normal "scaling" solution → **GW signal has its usual flat form**.
- Inflation occurs **after** string formation → string network will be exponentially diluted and **no GW signal**
- Inflation occurs **during** string formation → diluted string network → **GW spectrum has broken power law behaviour** (Cui, Lewicki, Morrissey) 1912.08832

Diluted by inflation



$\Lambda_{\rm cs} = 10^{14}$ GeV

$G\mu = 0.7 \times 10^{-10}$

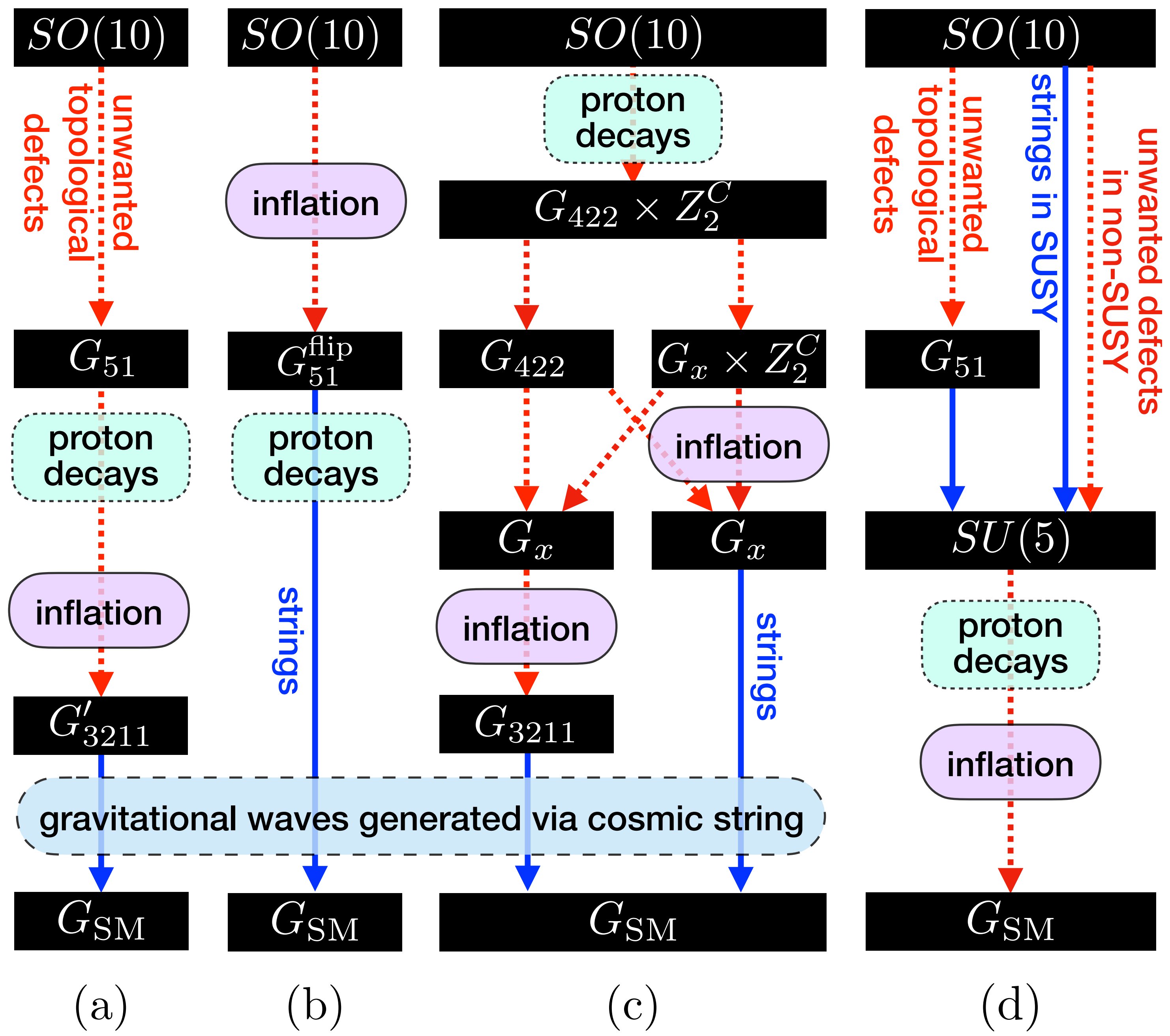
$\Lambda_{\rm cs} = 10^{10}$ GeV

$G\mu = 0.7 \times 10^{-18}$

$$\Lambda_{\rm cs} \equiv \sqrt{\mu}$$

Neutrino and GW data as a complementary window

- Type (a) via SU(5) x U(1) predicts $\Lambda_{pd} > \Lambda_{cs}$
- Type (b) via flipped SU(5) x U(1) predicts $\Lambda_{pd} \sim \Lambda_{cs}$
- Type (c) via flipped SU(4) x SU(2)$_L$ x SU(2)$_R$ predicts $\Lambda_{pd} > \Lambda_{cs}$
- Type (d) via SU(5) no GWs predicted



<table>
<tr><td colspan="2" rowspan="2">Observables</td><td>Proton decays</td></tr>
<tr><td>$p \to \pi^0 e^+$ observed ⇒ non-SUSY contribution indicated</td></tr>
<tr><td rowspan="2">GWs</td><td>Observed</td><td>• types (a) and (c) favoured
• types (b) and (d) excluded</td></tr>
<tr><td>Marginal</td><td>• types (a) and (c) favoured
• type (d) excluded
• type (b) allowed if $p \to K^+\bar{\nu}$ not observed and $\Lambda_{pd} \sim \Lambda_{cs}$</td></tr>
</table>

$$\Lambda_{\rm inf} \lesssim 10^{16}\ \mathrm{GeV}$$ Planck (1806.06211)

$$\Lambda_{\rm pd} \gtrsim 10^{15}\ \mathrm{GeV}$$ SK (1610.03597)

$$\Lambda_{\rm cs} \overset{?}{\sim} 10^{14}\ \mathrm{GeV}$$ NANOGrav (2009.04496)

Summary

- Proton decay is a smoking gun of GUTs and the next generation of neutrino oscillation experiments will probe the ultrahigh GUT scale determination of the proton lifetime.

- Topological defects are prodigiously produced during GUT symmetry breaking. The undesirable kind are monopoles and domain walls which, if existent, must have been inflated away. As defects cosmic strings are “well behaved” and can generate GW.

- Presence/absence and nature of cosmic strings is determined by the inflationary scale.

- Study the interplay of these three scales allows us to determine the viability of various types of breaking chains, with recent result from NANOGrav there is a preference for type (a)

- We are entering an exciting era where new observations of GWs from the heavens and proton decay experiments from under the Earth can provide complementary windows to reveal the details of the unification of matter and forces at the highest energies.


Thank you!

Green and Liddle, 9903484
Zel'dovich et al, 1977
MacGibbon, 1987
Barrow et al, 1992
Carr et al, 1994