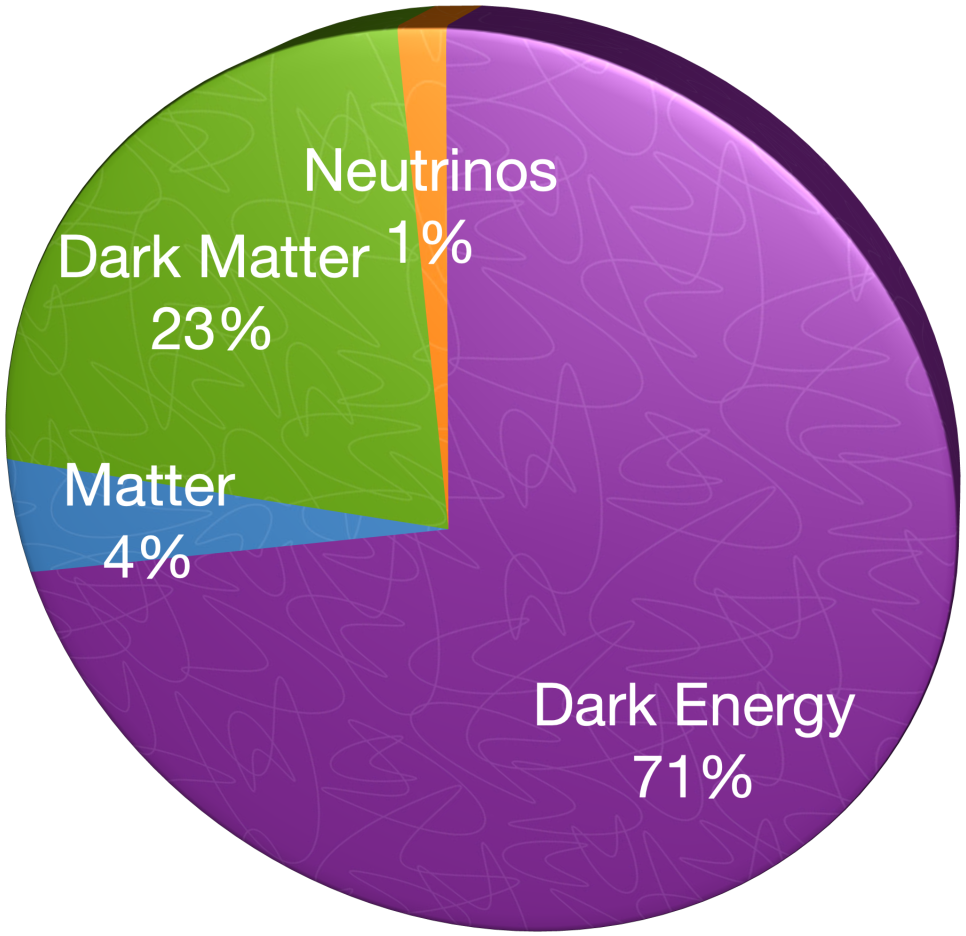
An overview of Leptogenesis

FPCapri 2022

Jessica Turner, IPPP, Durham University

12 June 2022

Universe's Energy Budget



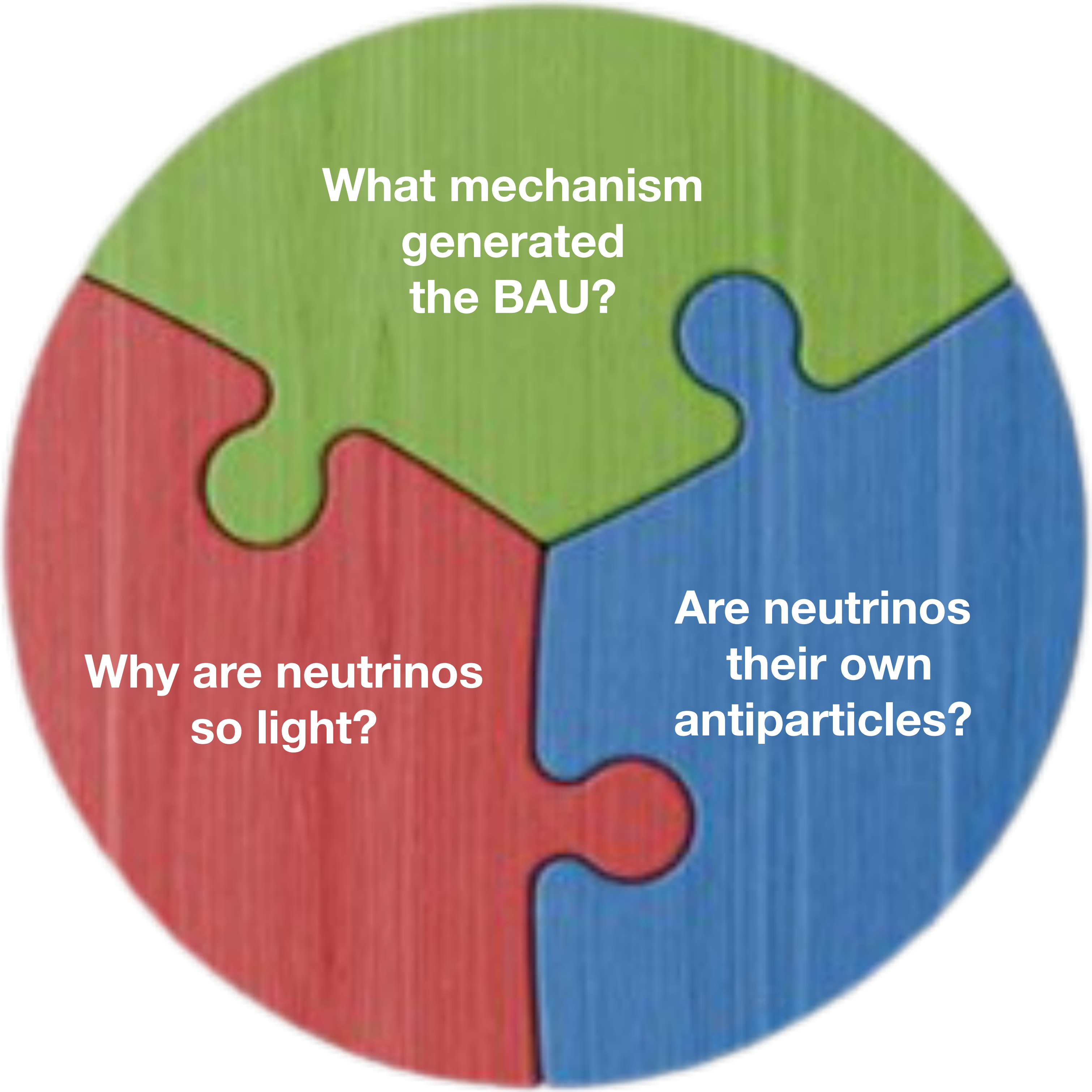
$$\eta_B = (6.02 - 6.18) \times 10^{-10}$$

Planck 1807.06209 (2018)

Sakharov's Conditions

- ☑ Baryon number violation — Kuzmin, Rubakov & Shaposhnikov *Phys.Lett.B 155* (1985)
- ☒ C & CP-violation — Gavela, Hernandez, Orloff & Pene *Mod.Phys.Lett. A9 795-810* (1994) Huet & Sather *Phys.Rev. D51 379-394* (1994)
- ☒ Departure from thermal equilibrium — Kajantie, Laine, Rummukainen & Shaposhnikov *Phys.Rev.Lett. 77 2887-2890* (1996)

Motivation for Leptogenesis

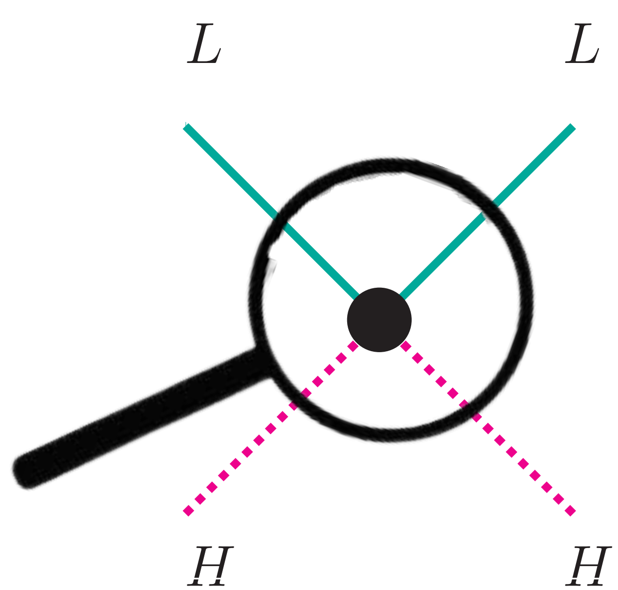


The Seesaw Mechanism

The Standard Model is an effective theory which contains non-renormalisable operators

Weinberg, *Phys.Rev.Lett. 43* (1979)

$$\mathcal{L} \supset -Y_{ij}\frac{L^i H L^j H}{2M} + \mathcal{O}\left(\frac{1}{M^2}\right) + \text{h.c}$$



The Seesaw Mechanism

After SSB a Majorana mass is produced for the active neutrinos

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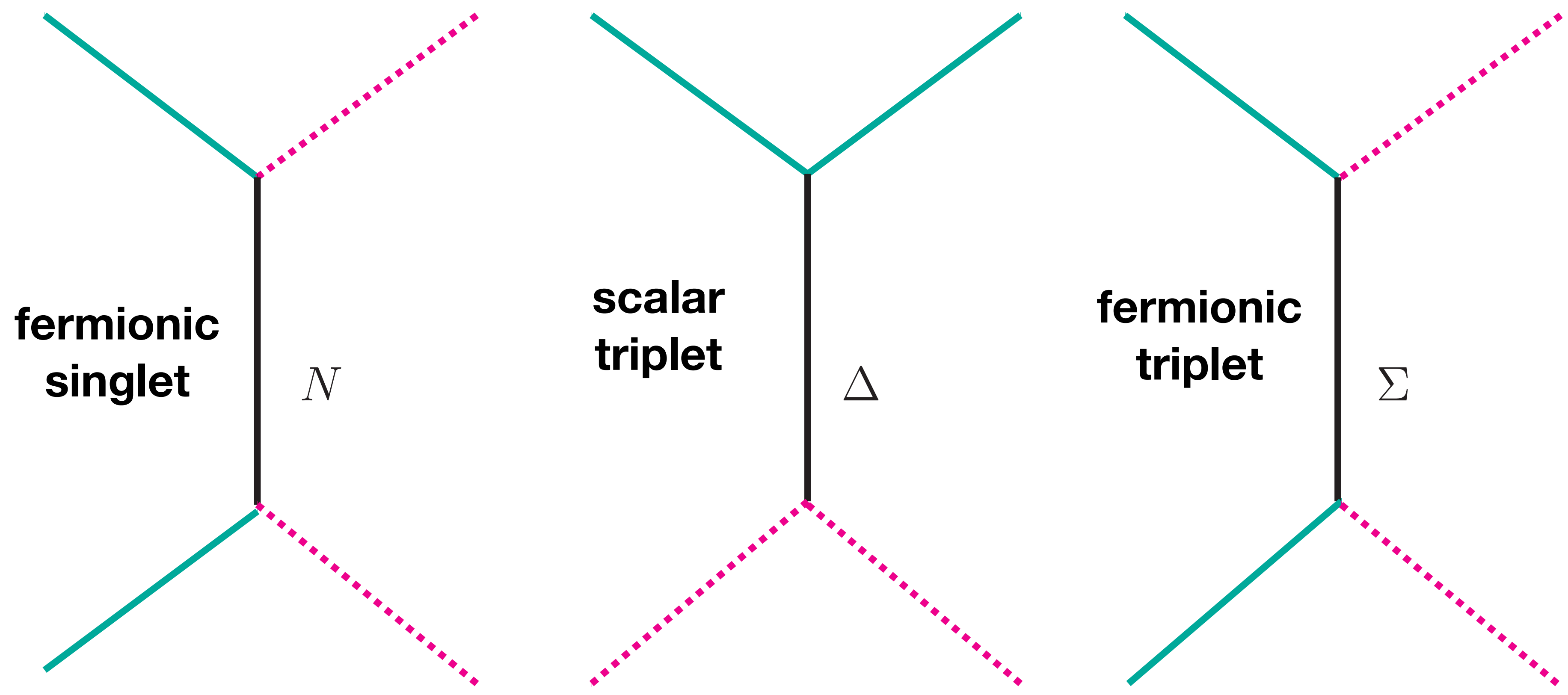

Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

Ma, Roy, Senjanovic, Hambye

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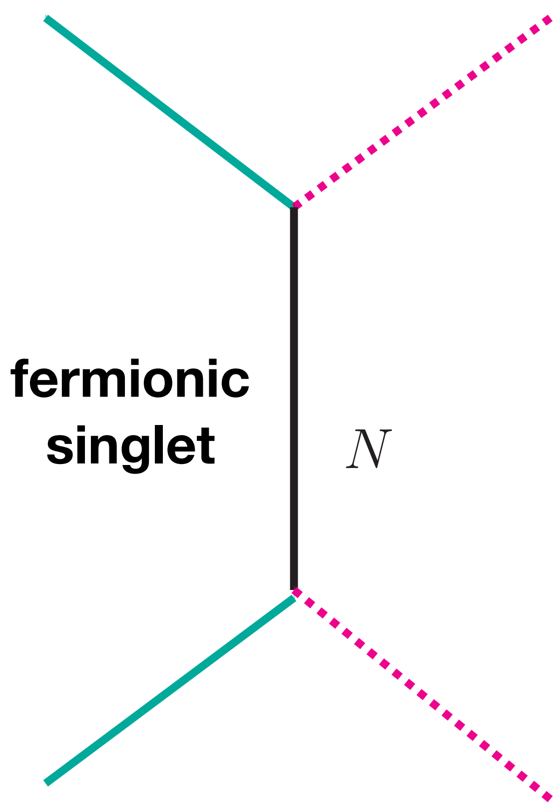
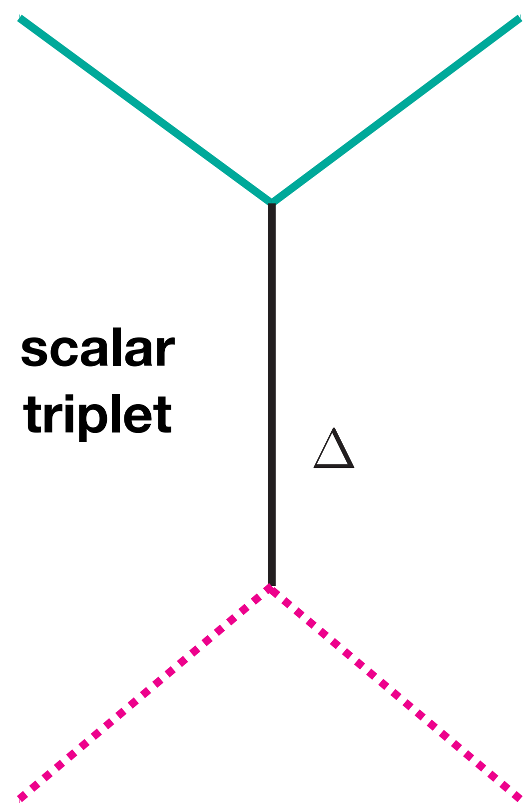
Type-I seesaw



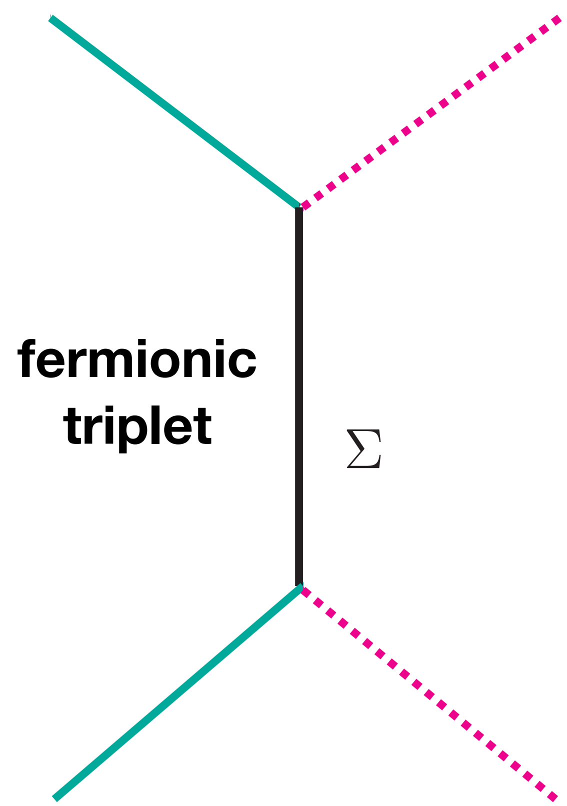
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

Type-II seesaw



Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

Type-III seesaw



Ma, Roy, Senjanovic, Hambye

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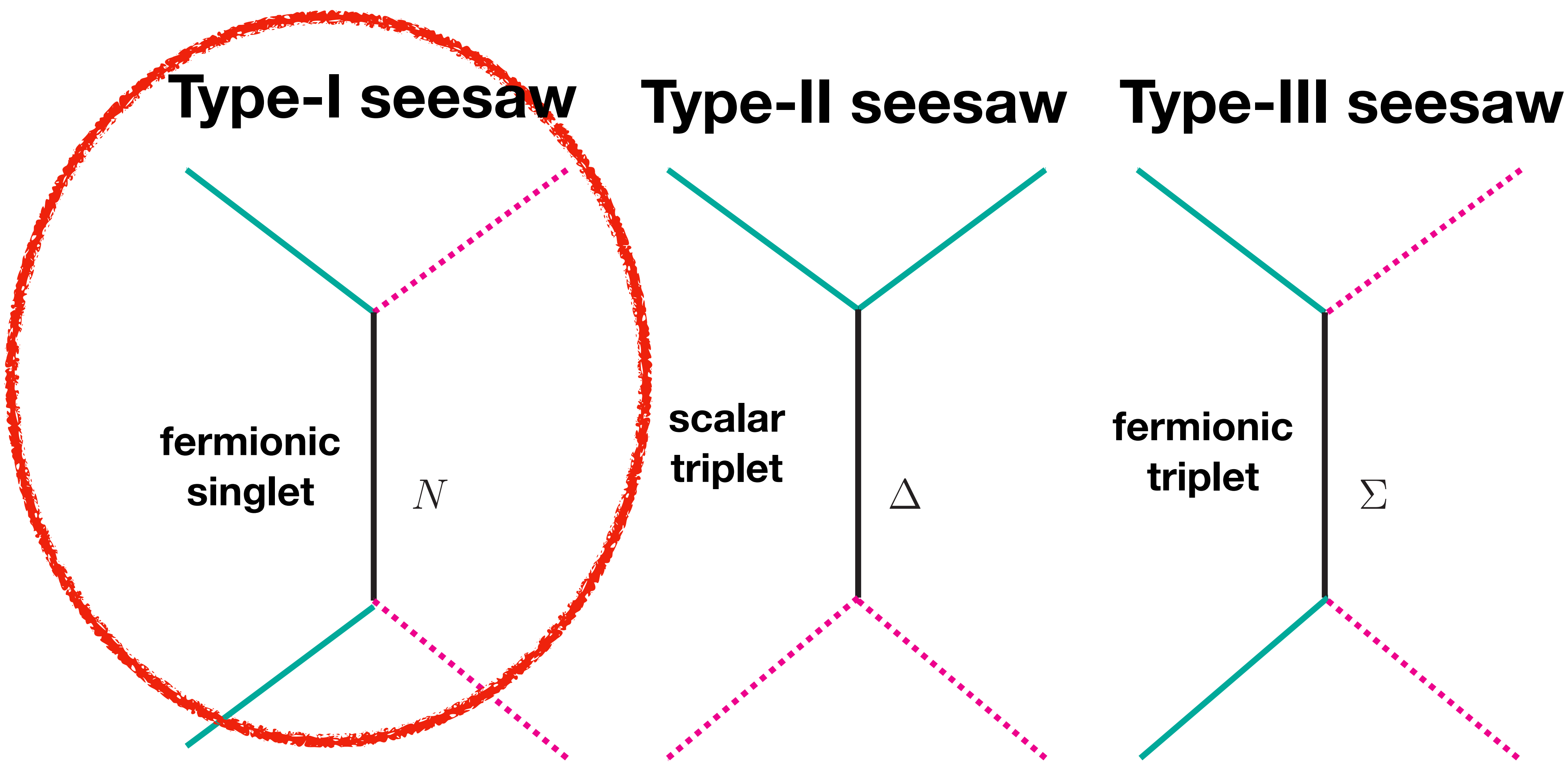

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The Seesaw Mechanism

$$\mathcal{L} \supset -\overline{L_\alpha} Y_{\alpha i} N_i \tilde{H} - \frac{1}{2}\overline{N_i^C} M_{N_i} N_i + \text{h.c.}$$

After diagonalising the mass matrix

$$m_\nu \approx \frac{m_D m_D^T}{M_N} = \frac{Y^2 v^2}{M_N}$$

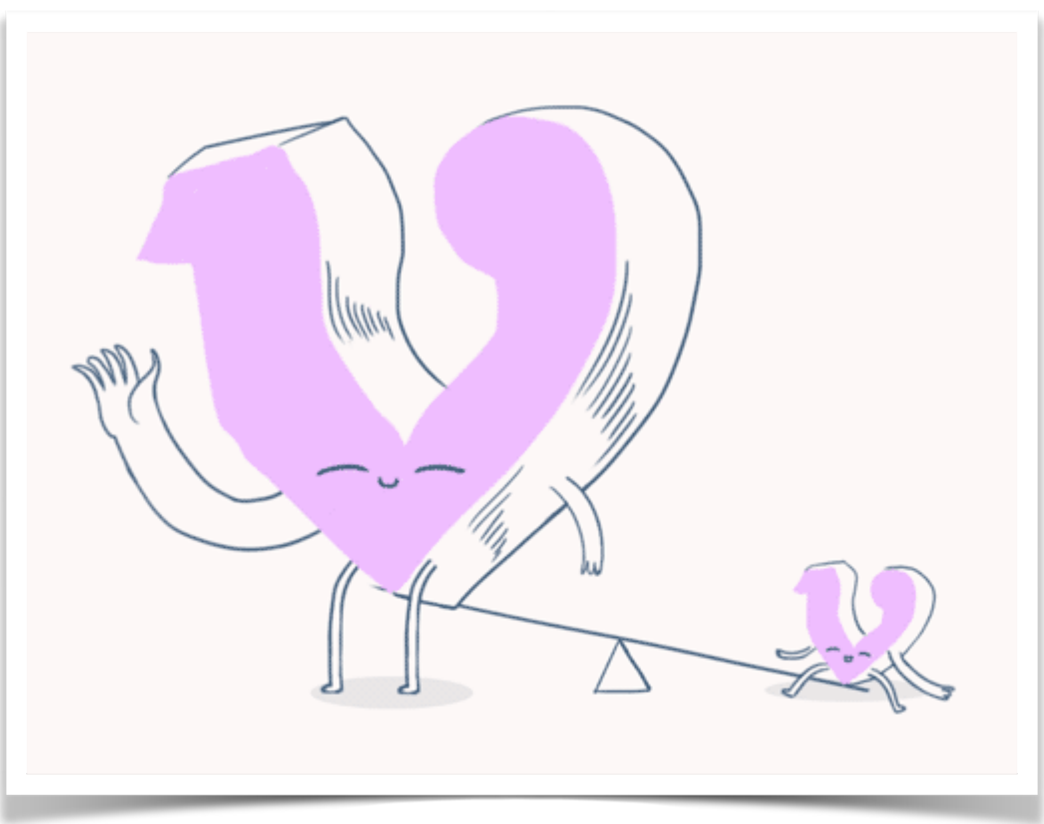

Image courtesy of Symmetry Magazine

Sakharov's Conditions

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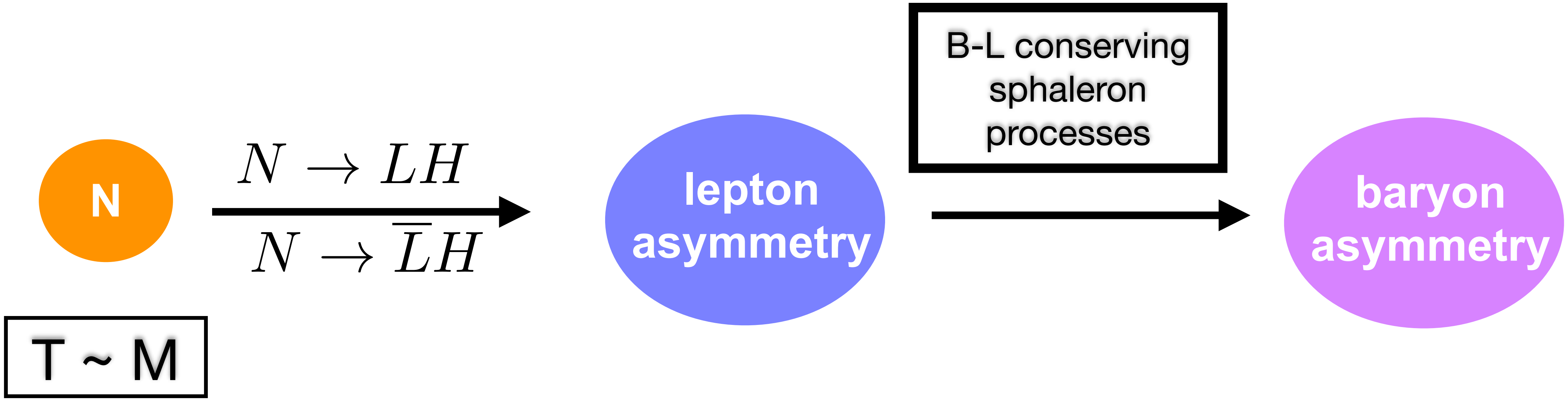
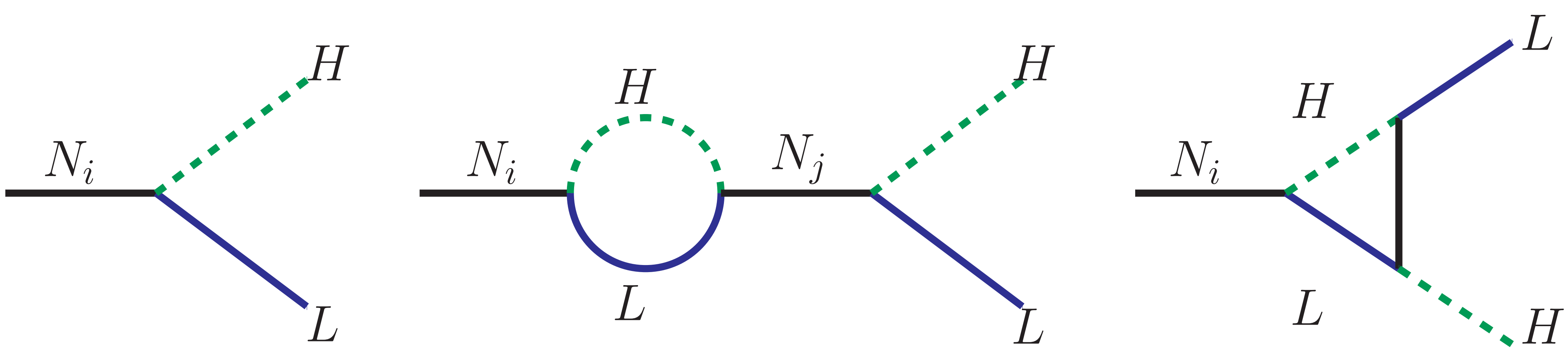
- ☑ C & CP-violation
- ☑ Departure from thermal equilibrium

Thermal Leptogenesis



Decay asymmetry from interference between tree and loop level diagrams

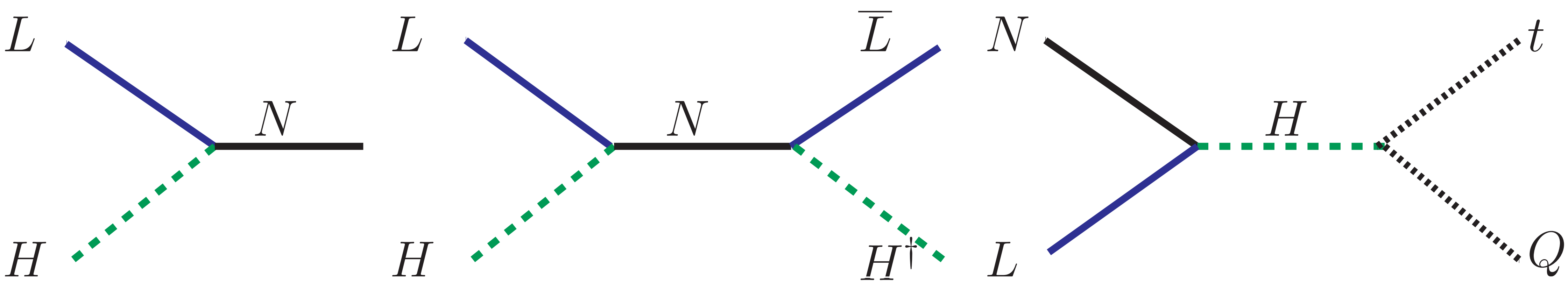
Covi, Roulet, Vissani



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

Thermal Leptogenesis

Washout and scattering processes



inverse Decays ΔL=2 ΔL=1

Thermal Leptogenesis

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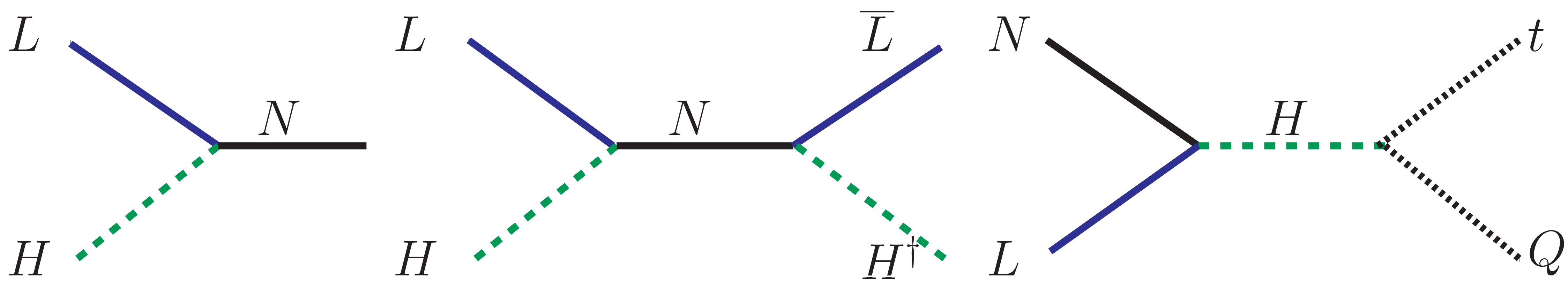

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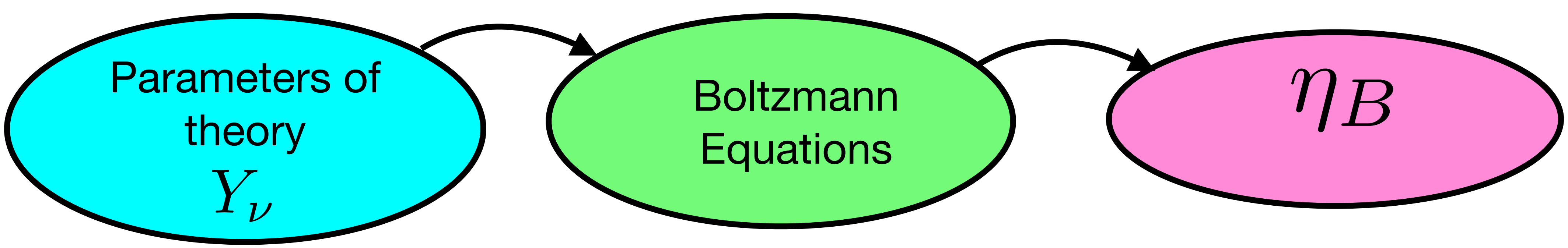
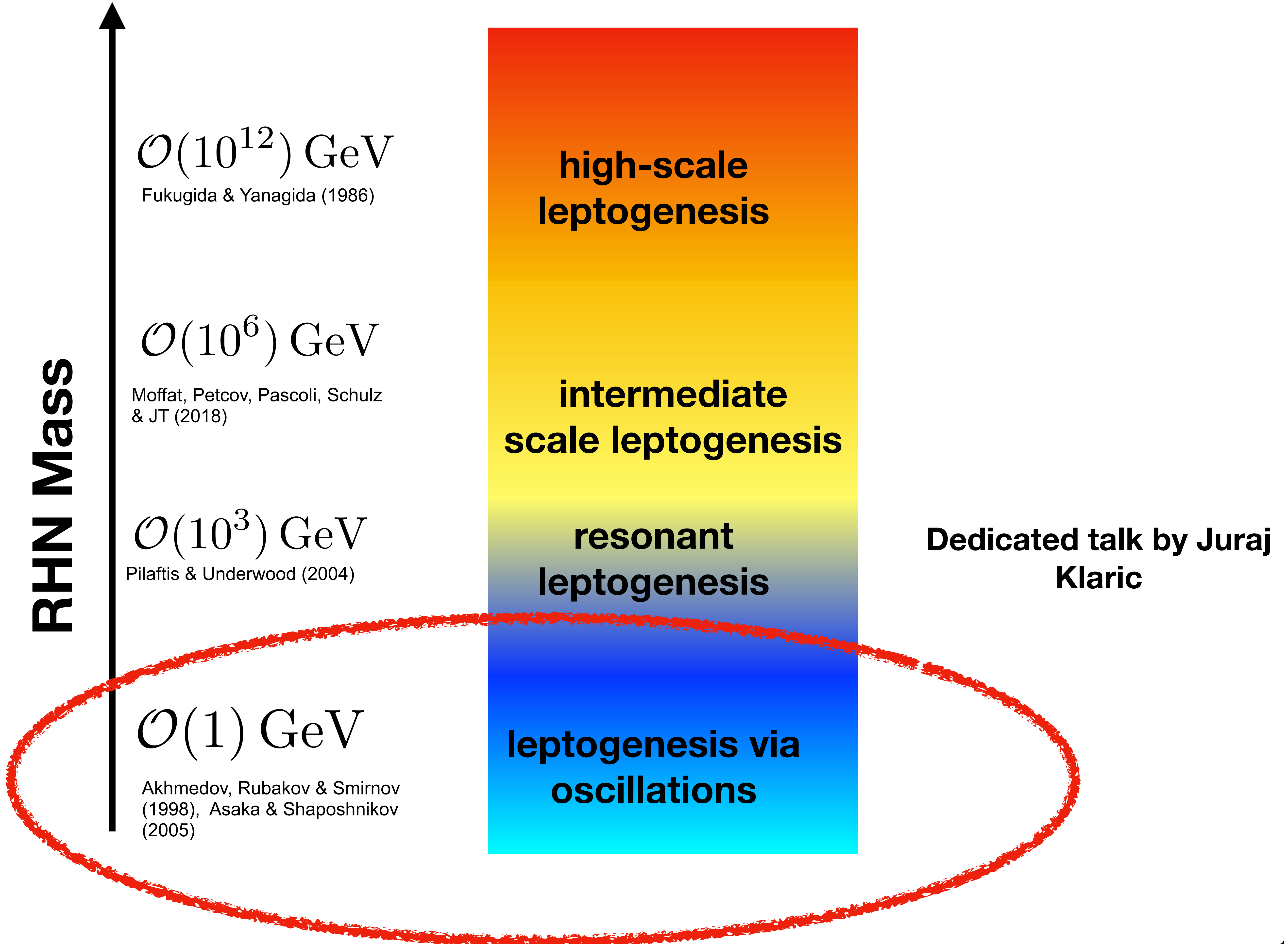
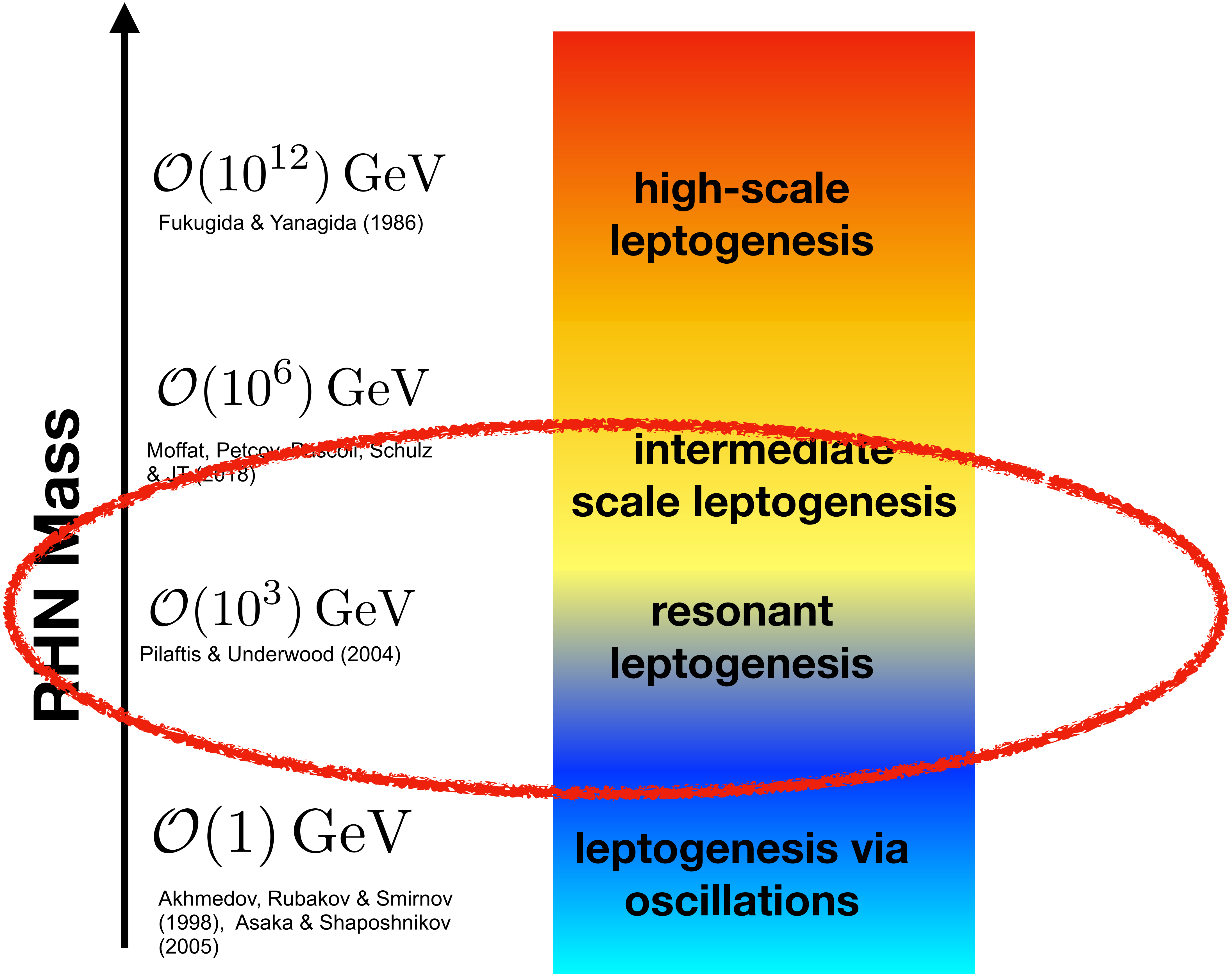


$$\frac{dn_{N_i}}{dz} = -\,D_i(n_{N_i} - n_{N_i}^{\rm eq}),$$

source **sink**

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


RHN Mass
$\mathcal{O}(10^{12})$ GeV
Fukugida & Yanagida (1986)
$\mathcal{O}(10^{6})$ GeV
Moffat, Petcov, Pascoli, Schulz & JT (2018)
$\mathcal{O}(10^{3})$ GeV
Pilaftis & Underwood (2004)
$\mathcal{O}(1)$ GeV
Akhmedov, Rubakov & Smirnov (1998), Asaka & Shaposhnikov (2005)
high-scale leptogenesis
intermediate scale leptogenesis
resonant leptogenesis
leptogenesis via oscillations
Dedicated talk by Juraj Klaric



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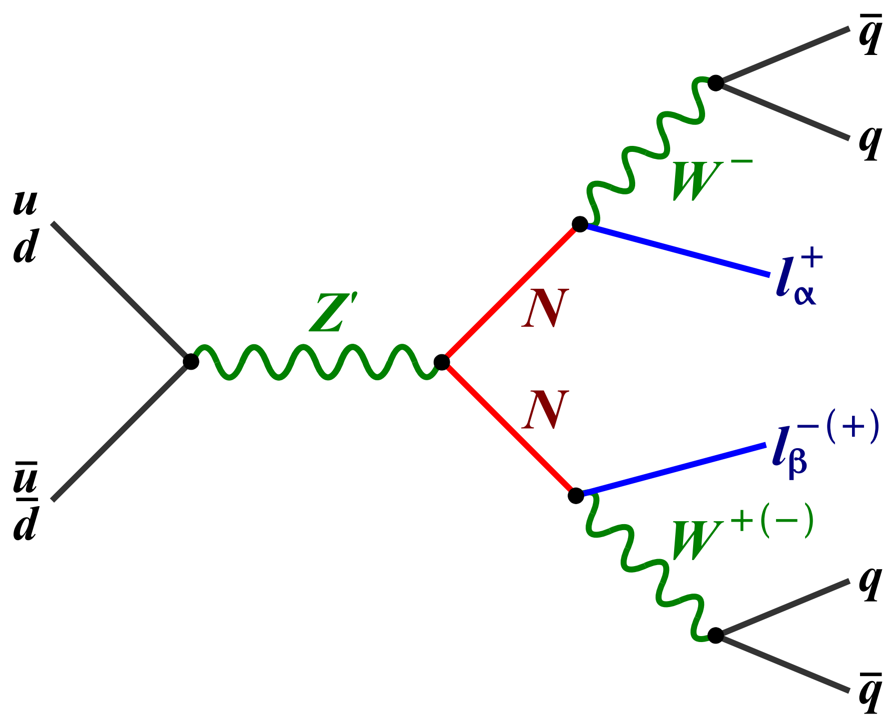
leptogenesis via oscillations

Resonant Leptogenesis

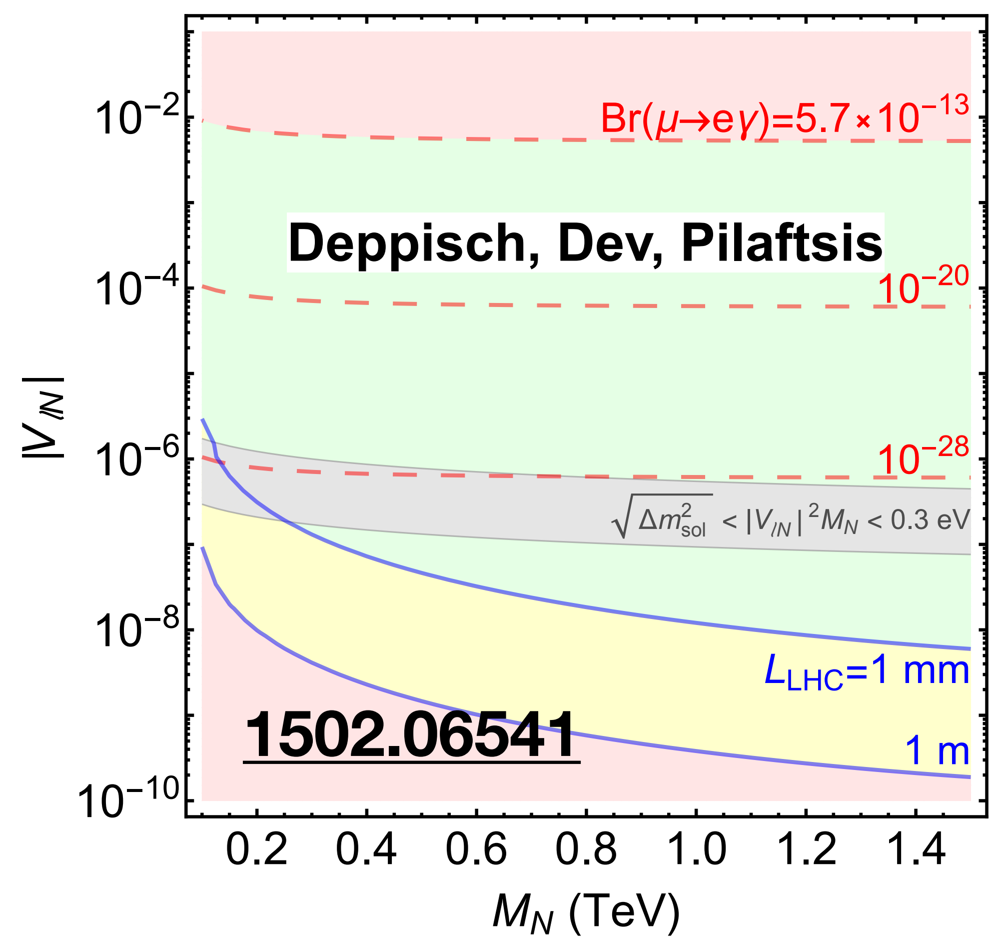
- Regime where RHNs decay width similar to their mass differences. Mass range ~ TeV

Pilaftis & Underwood (2004)
Abada, Aissaoui, Losada (2005)

- RHN masses explained by additional $U(1)_{B-L}$ symmetry and can be sufficiently long-lived → displaced-vertex signature searched for at LHC, MATHUSLA or SHiP.



LNV, LFV at colliders
talk by Stefan Antusch



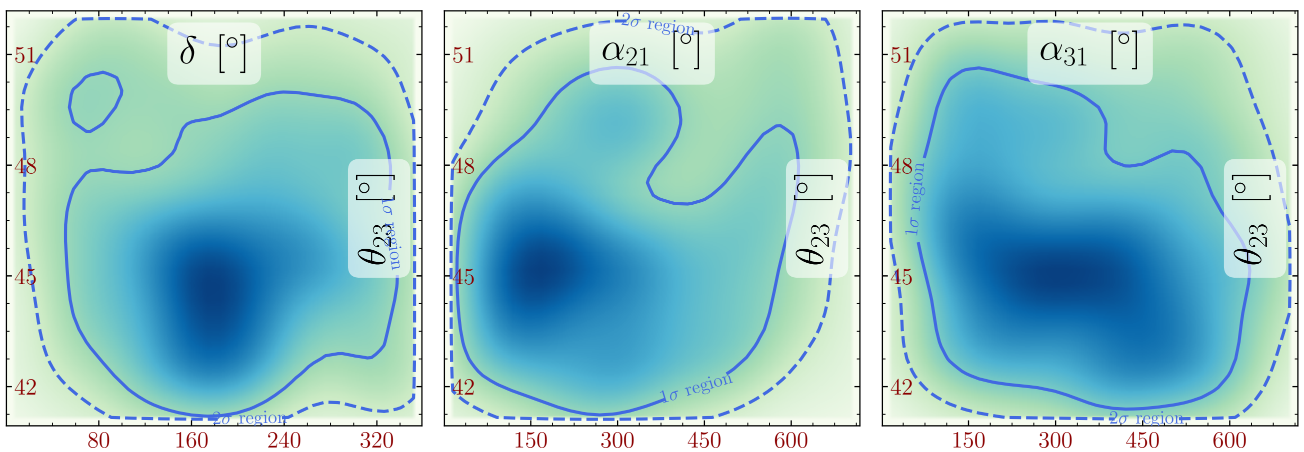
Resonant leptogenesis in the Neutrino Option

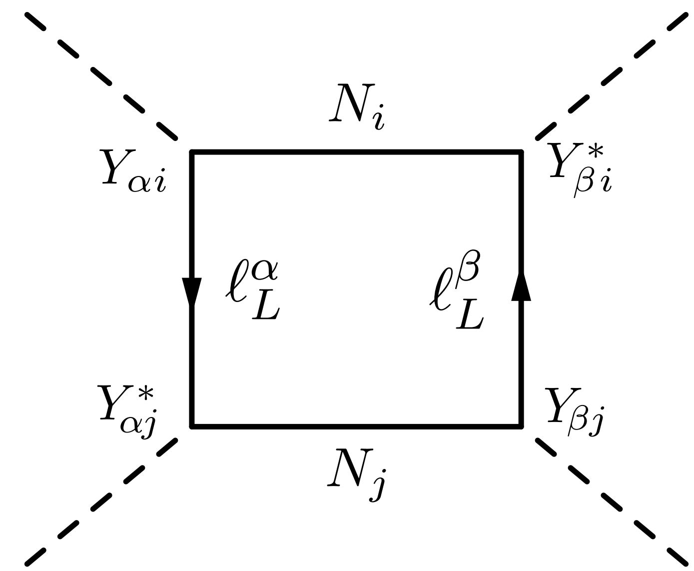
- Assume scale invariance above M_N
- Integrate out TeV scale RHN and RG evolve: Higgs potential produced for $M_N \sim 1000\,\mathrm{TeV}$

Brdar, Hemboldt, Iwamoto, Schmitz

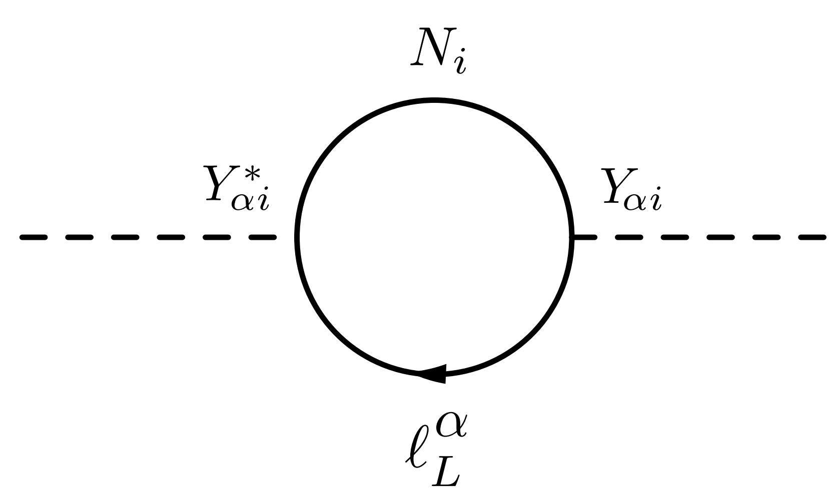
Brivio, Moffat, Pascoli, Petcov, Turner

Normal Ordering





$$\frac{\Delta M}{M} \sim 10^{-8} \qquad \overline{M} = 1.2 \times 10^6\,\mathrm{GeV}$$

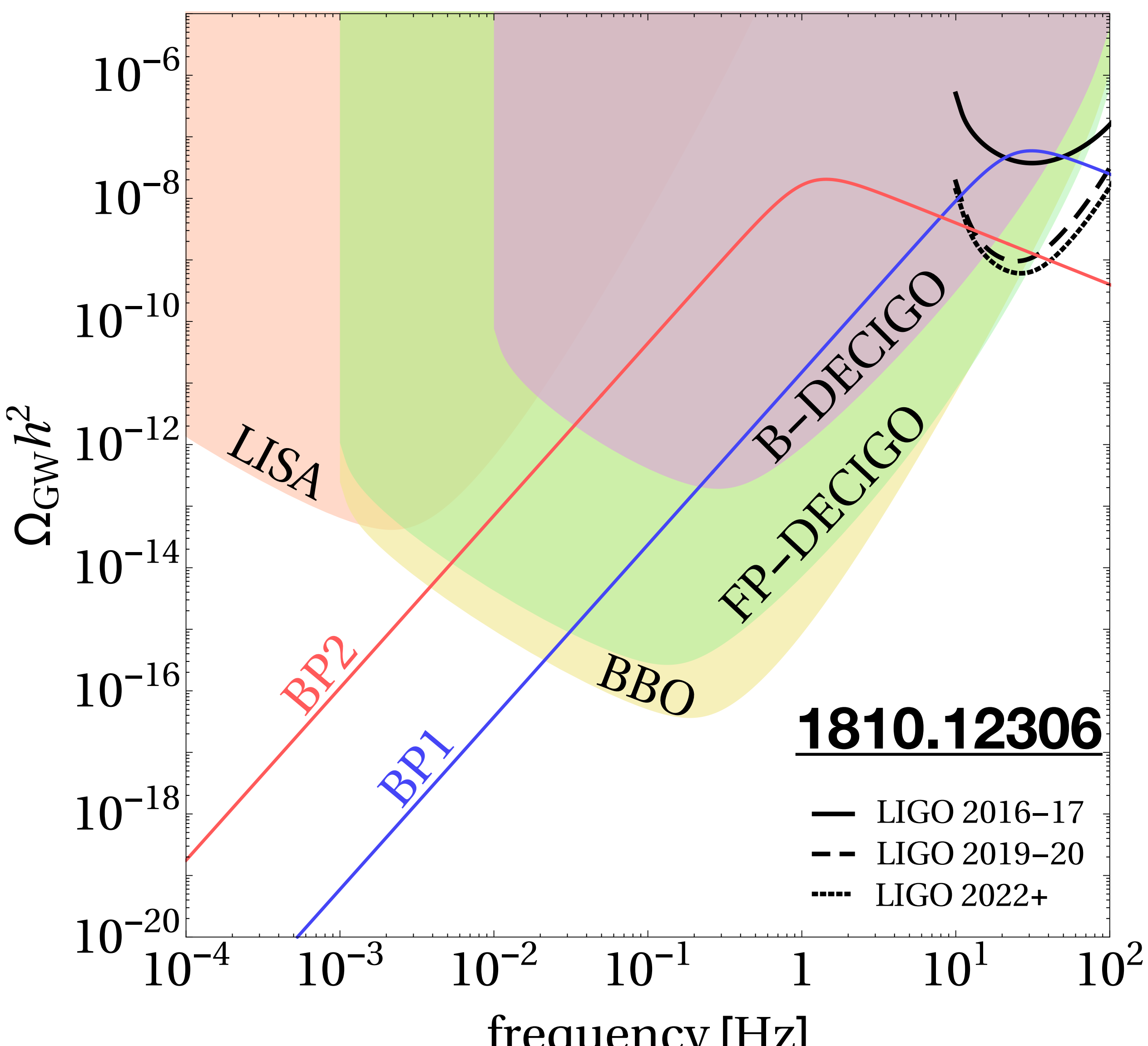


slight preference for $\theta_{23} < 45^\circ$ and $\delta \sim 180^\circ$

Scale invariance broken at quantum level

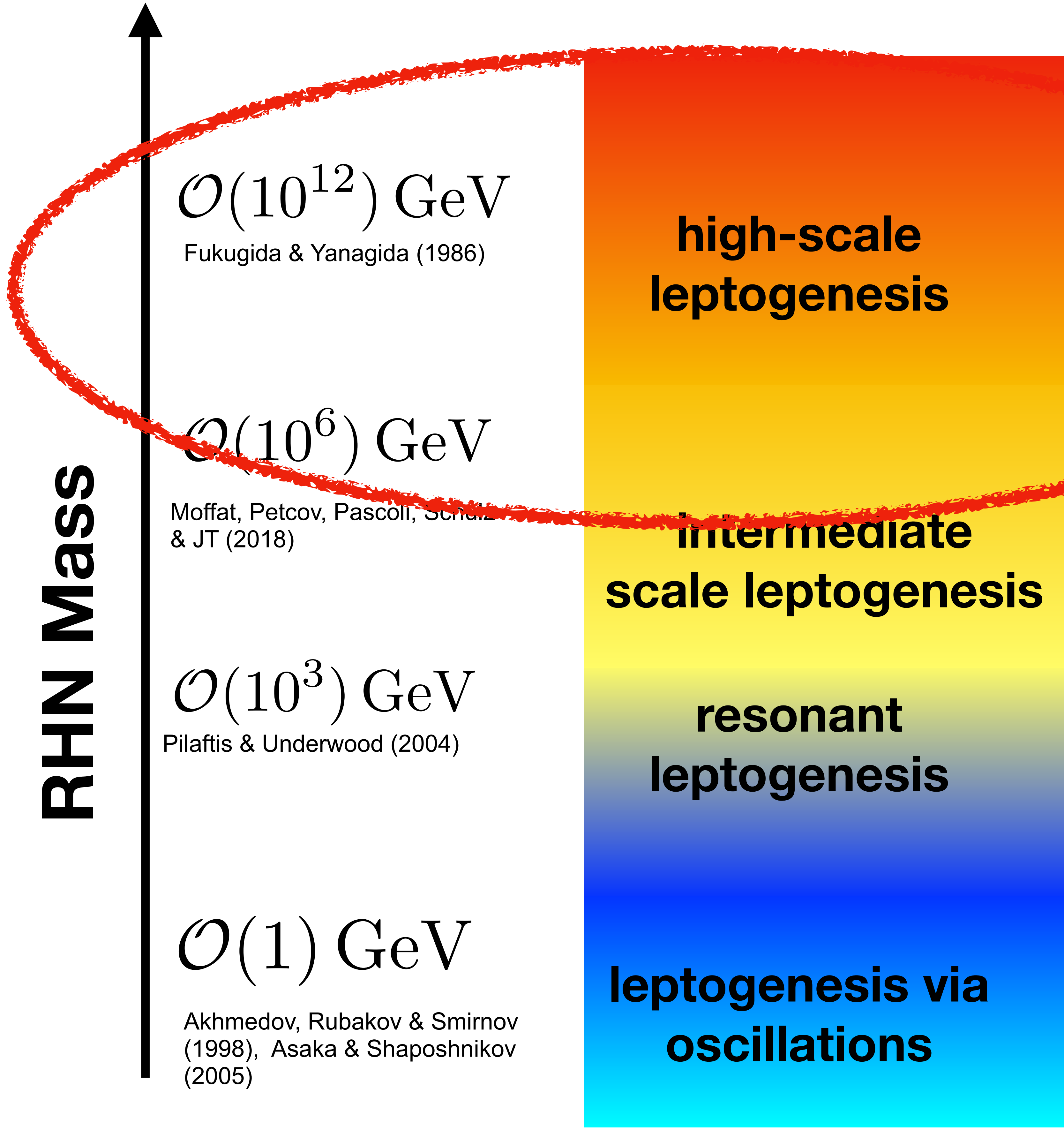
Resonant leptogenesis in the Neutrino Option

- UV-completion of Neutrino Option (**Brdar**, Emonds, Helmboldt, Lindner) minimal renormalisable model based on classical scale invariance
- New scalar breaks scale-invariance → generates mass for RHNs and strong first order phase transition

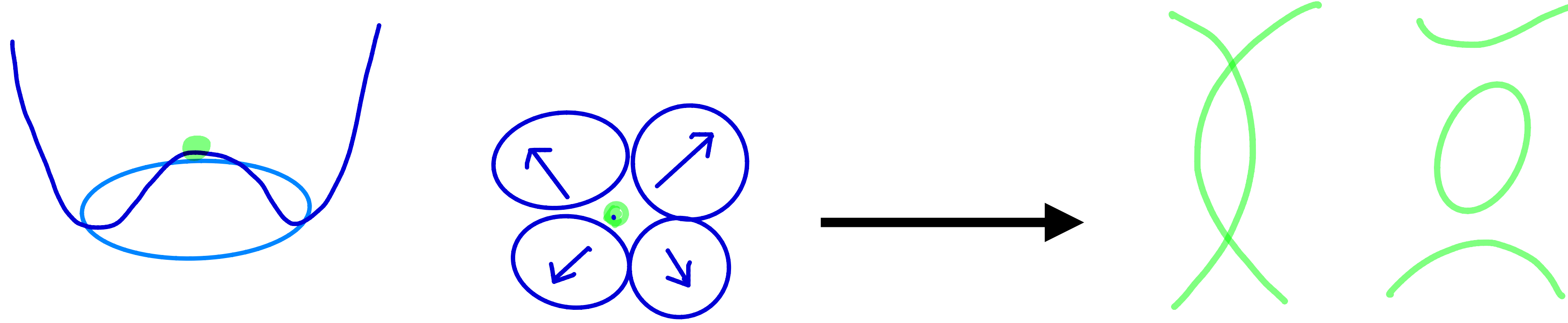


Brdar, Helmboldt, Kubo (2018)

See also "Probing the seesaw scale with gravitational waves" Okada & Seto



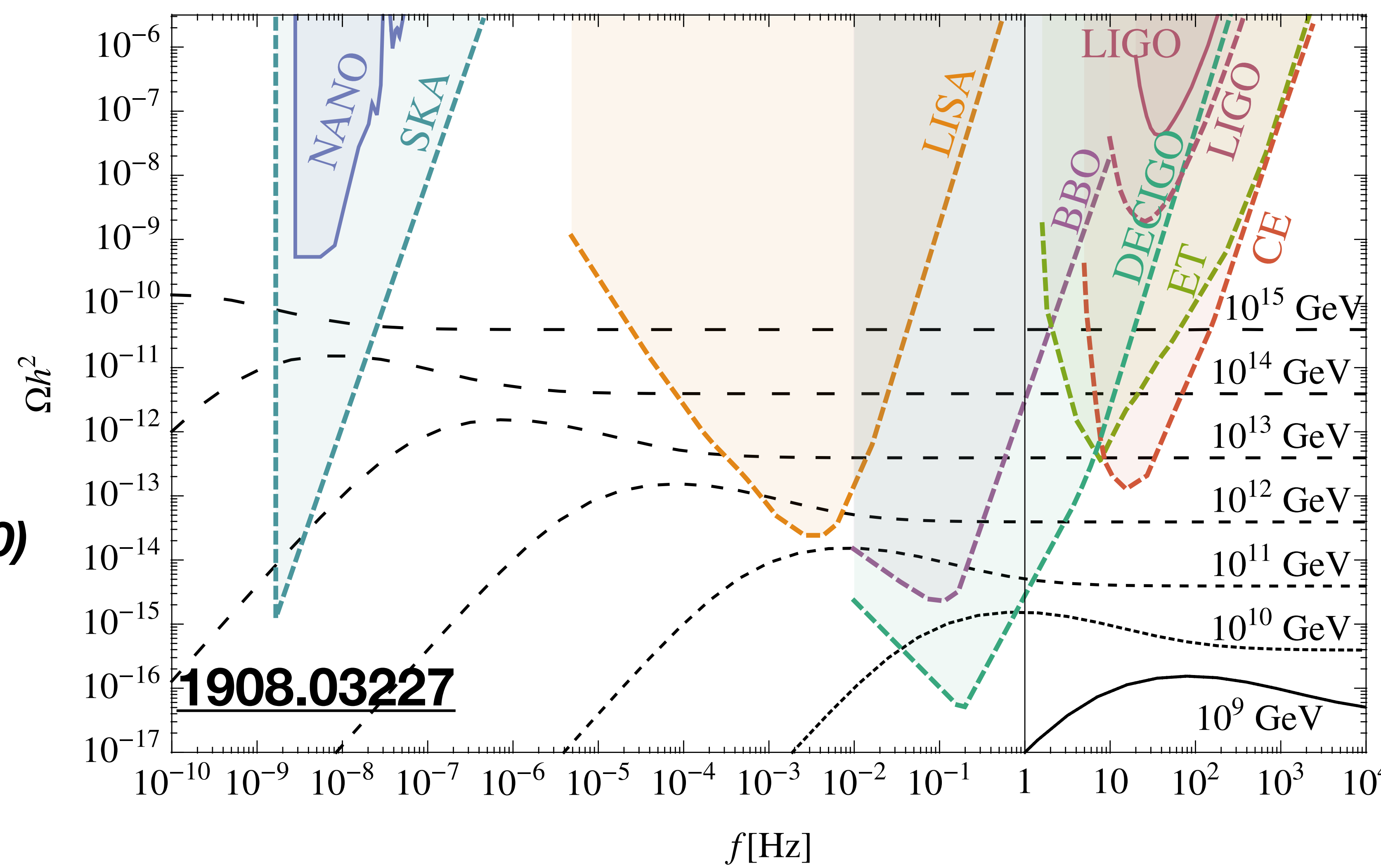
Difficult to test, however gravitational waves offer an additional telescope on high-scale leptogenesis



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

- Highlighted that GWs from cosmic string network generic prediction of seesaw mechanism

Dror, Hiramatsu, Kohri, Murayama & White *(2020)*

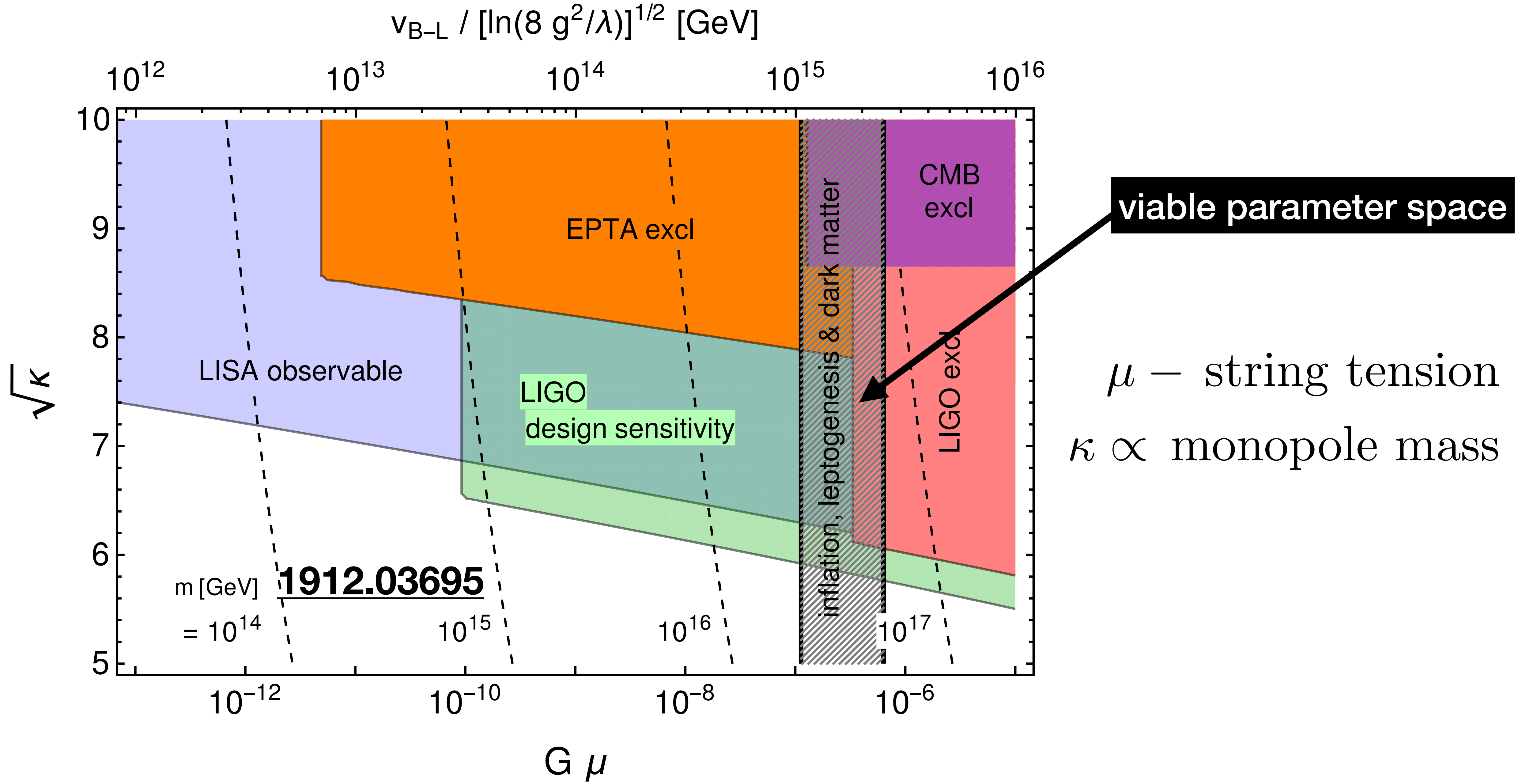


Thermal leptogenesis

- $U(1)_{\mathrm{B-L}}$ used to explain inflation, leptogenesis and neutralino (DM).

monopoles   cosmic strings

$$SO(10) \longrightarrow G_{SM} \times U(1)_{B-L} \longrightarrow G_{SM}$$

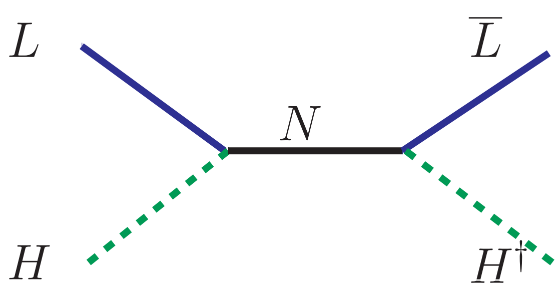


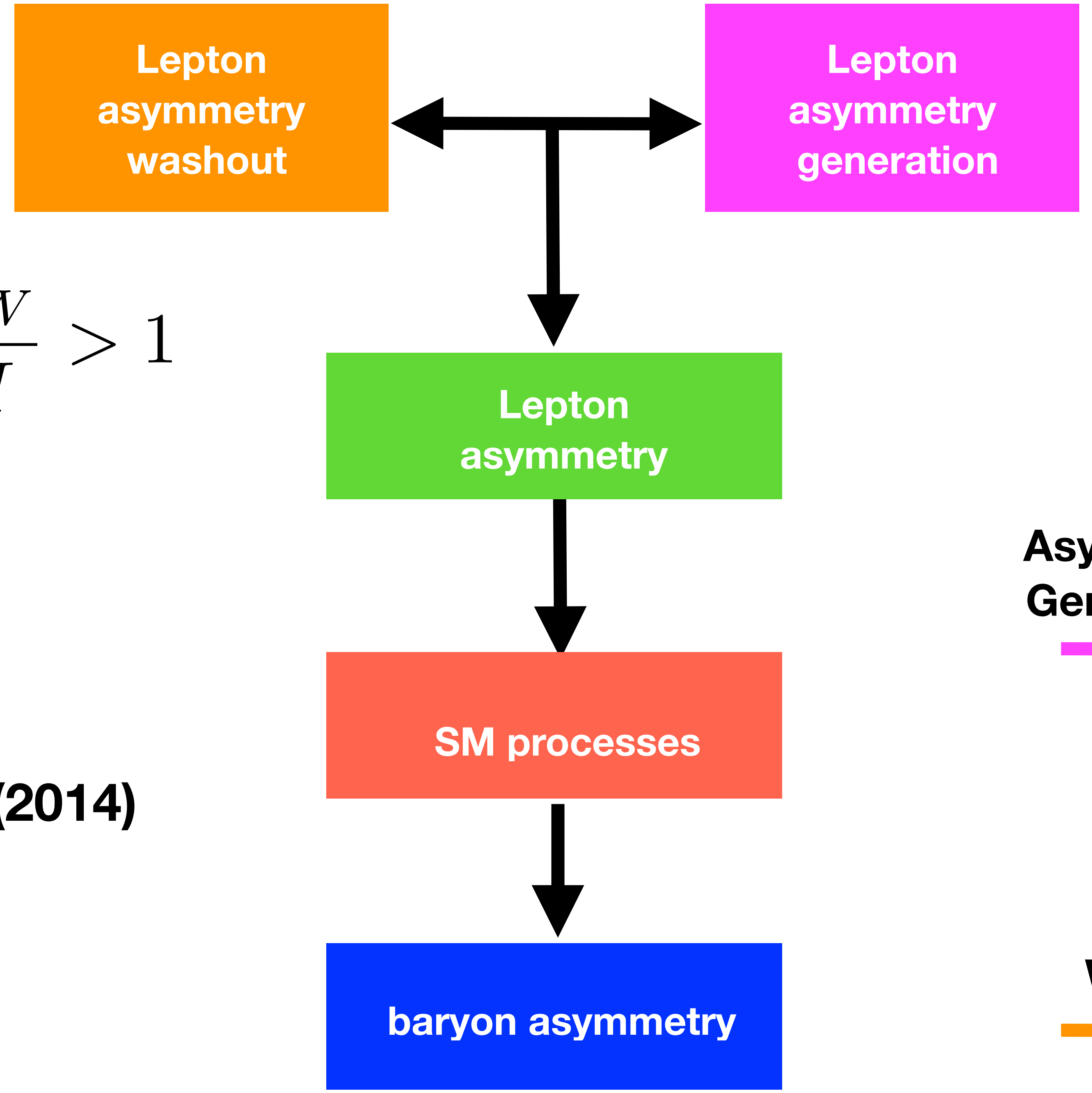
μ – string tension

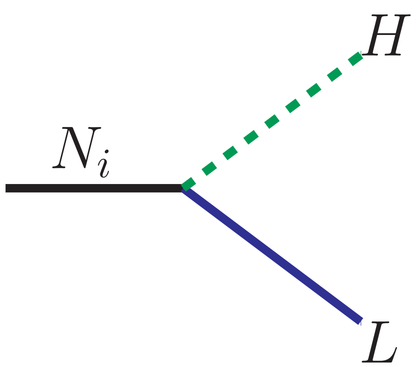
$\kappa \propto$ monopole mass

Buchmuller, Domcke, Murayama & Schmitz (2019)

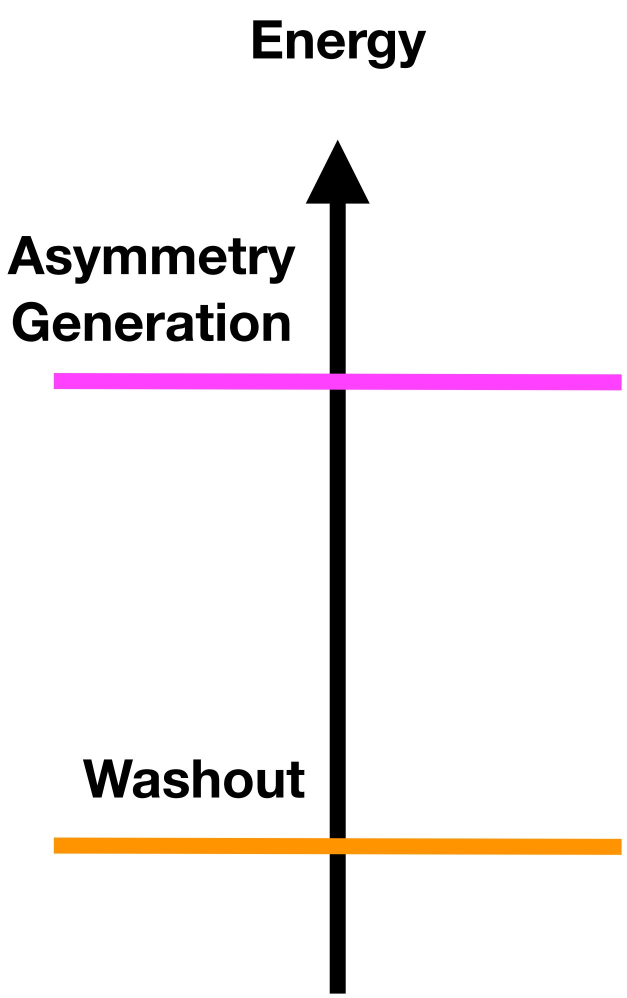
Falsifiability of High-Scale Leptogenesis







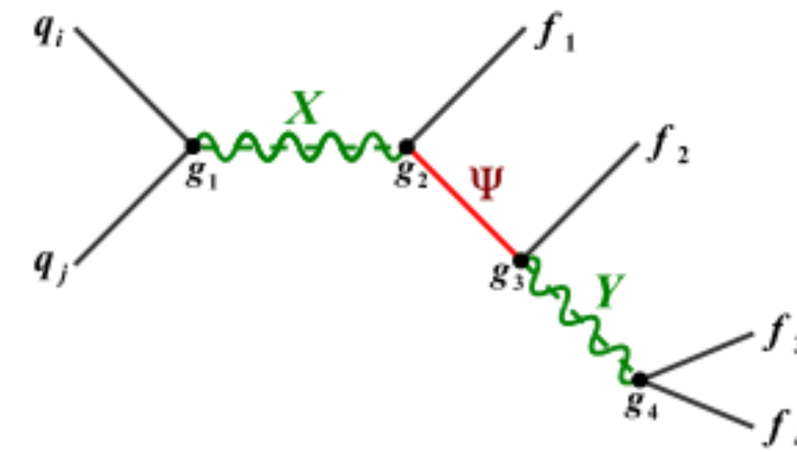
$$\frac{\Gamma_W}{H} > 1$$



Harz, Deppisch, Hirsch (2014)

If washout processes are large they may be searched for and could possibly falsify leptogenesis

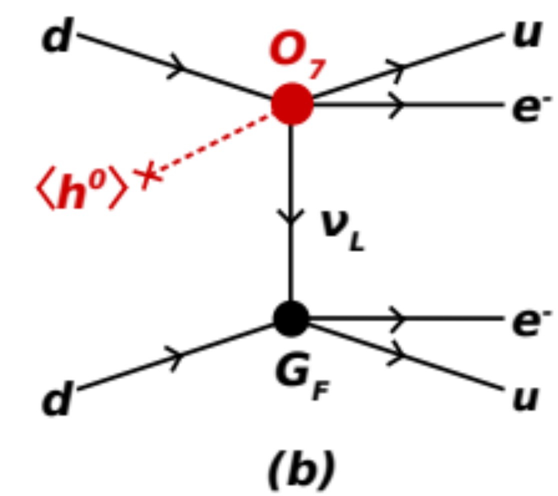
- Observation of LNV (TeV) washout processes at the LHC would falsify high-scale leptogenesis



Deppisch & Harz (2014)
Deppisch, Graf, Harz, Huang (2017)

- Observation of NDBD with new physics from > dim-5 operators would falsify high-scale leptogenesis

- Caveats:
  1. NDBD only probes electron flavour so including flavour effects can evade this
  2. Dark $\mathrm{U}(1)$ symmetry



- Nonetheless, if one observes LNV at the TeV scale $\Longrightarrow$ high-scale leptogenesis can be falsified.

Thermal leptogenesis and primordial black holes

- BH merger observed via GWs.
- Primordial BHs could have formed in early Universe:
  $0.1 \leq M_{\mathrm{PBH}}\ (g) \leq 10^9$
- 2010.03565, **Yuber Perez-Gonzalez** & JT

PBHs in a nutshell

- Lighter PBHs have shorter lives
- PBH temperature inverse proportional mass

$$T_{\mathrm{PBH}} \approx 1.06\,\mathrm{GeV}\left(\frac{10^{13}\ \mathrm{g}}{M_{\mathrm{PBH}}}\right) \qquad \frac{dM_{\mathrm{PBH}}}{dt} = -\varepsilon\left(M_{\mathrm{PBH}}\right)\frac{M_P^4}{M_{\mathrm{PBH}}^2}$$

- PBHs produce particles indiscriminately $T_{\mathrm{PBH}} \gtrsim M$
- Assume PBH dominated EU & monochromatic mass spectrum

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RHN from thermal plasma

RHN from PBH evaporation

$$aH\frac{dn_{N_1}}{da} = -\left(n_{N_1} - n_{N_1}^{\rm eq}\right)\Gamma_{N_1}^T + n_{N_1}^{\rm BH}$$

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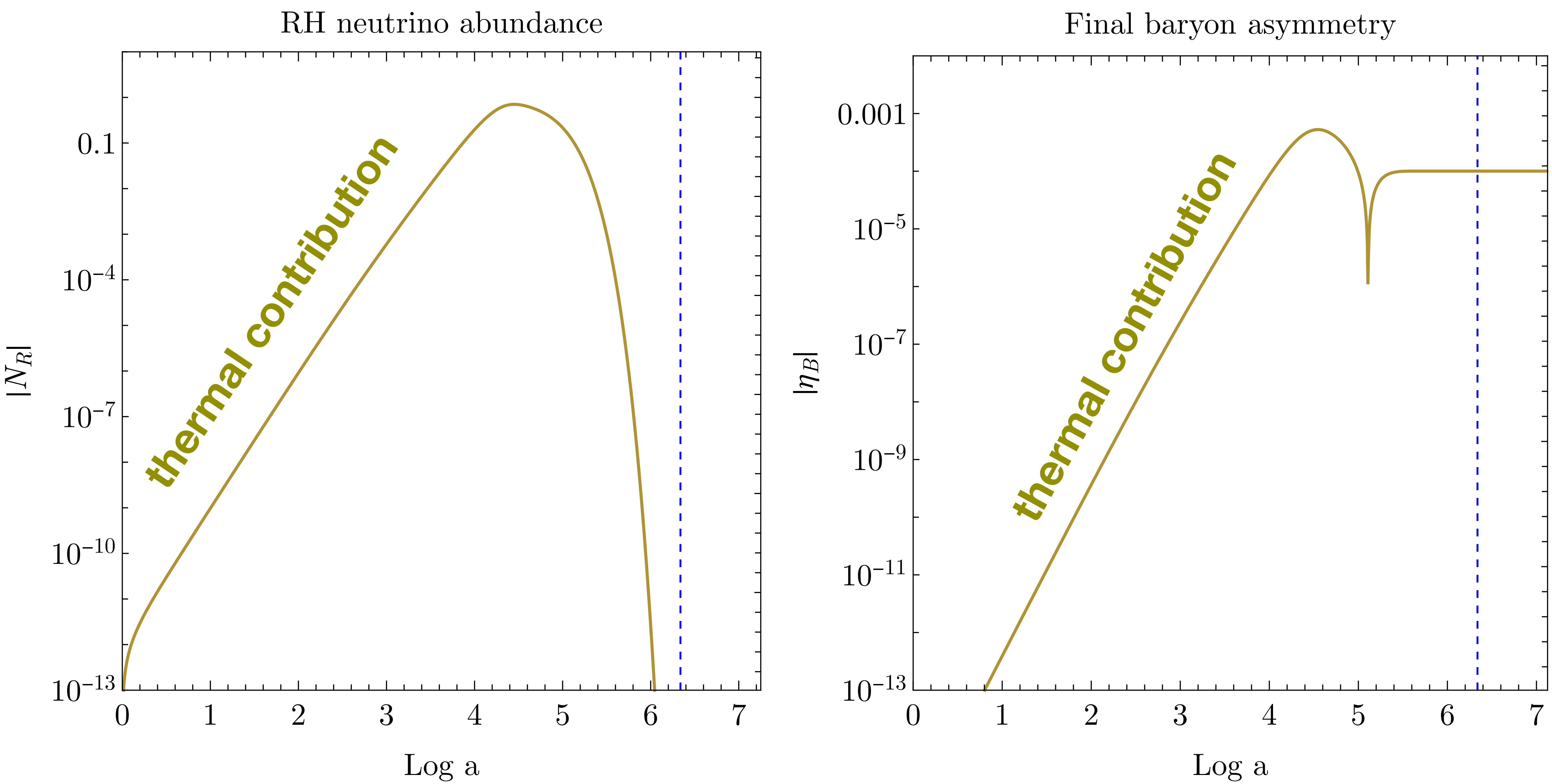
$$aH\frac{dn_{\alpha\beta}^{\rm B-L}}{da} = \epsilon_{\alpha\beta}^{(1)}\left[\left(n_{N_1}^{\rm TH} - n_{N_1}^{\rm eq}\right)\Gamma_{N_1}^{T} + n_{N_1}^{\rm BH}\Gamma_{N_1}^{\rm BH}\right] - W n_{\alpha\beta}$$

B-L from thermal leptogenesis

B-L asymmetry PBH leptogenesis Hawking radiation

A. PBH evaporate **during/shortly after** RHNs thermally produced → PBHs creates initial condition which gets erased by fast interactions in the plasma

$$M_i = 1.7 \text{ g} \quad \beta' = 10^{-3} \quad M_N = 10^{11} \text{GeV}$$



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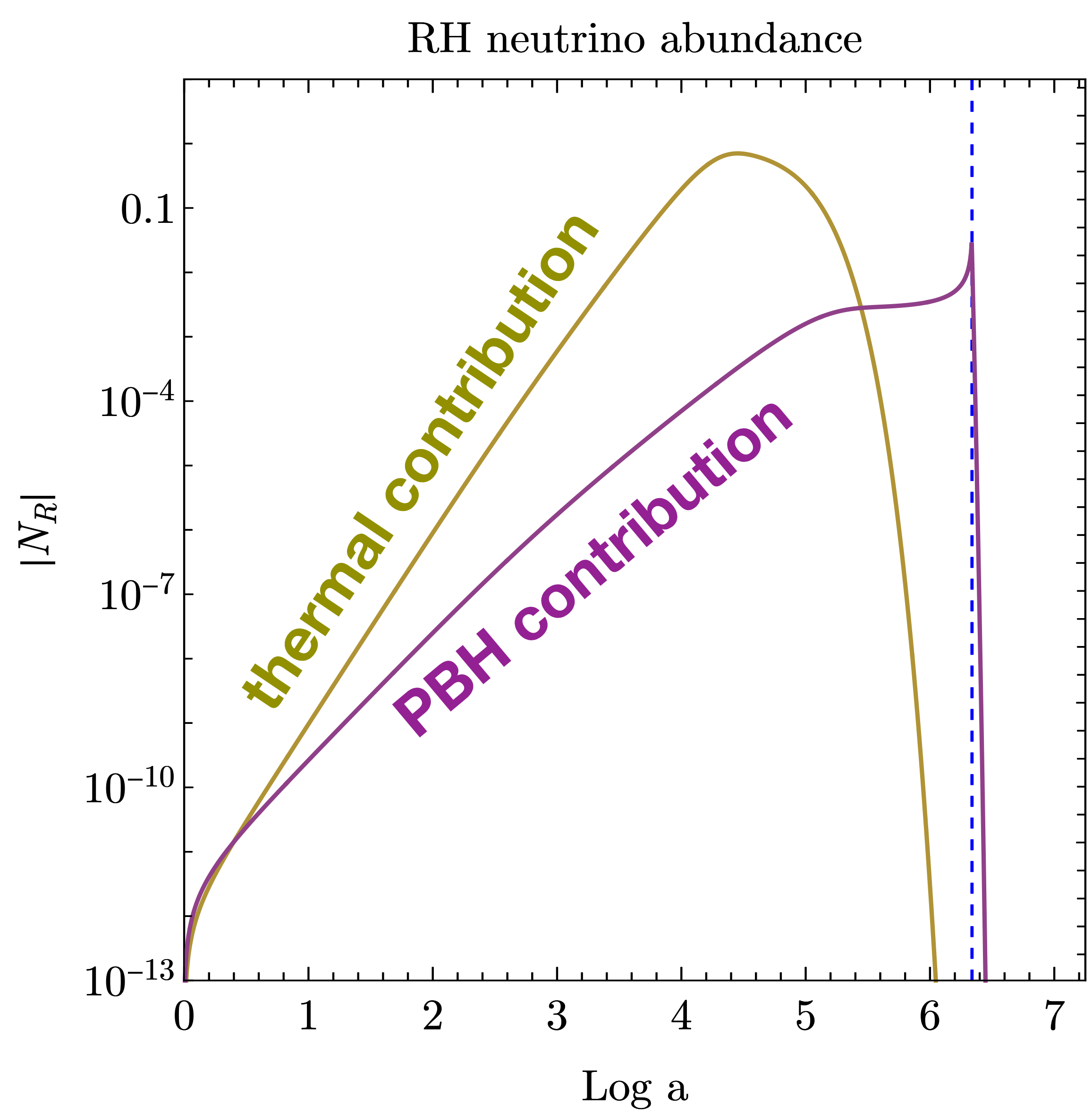

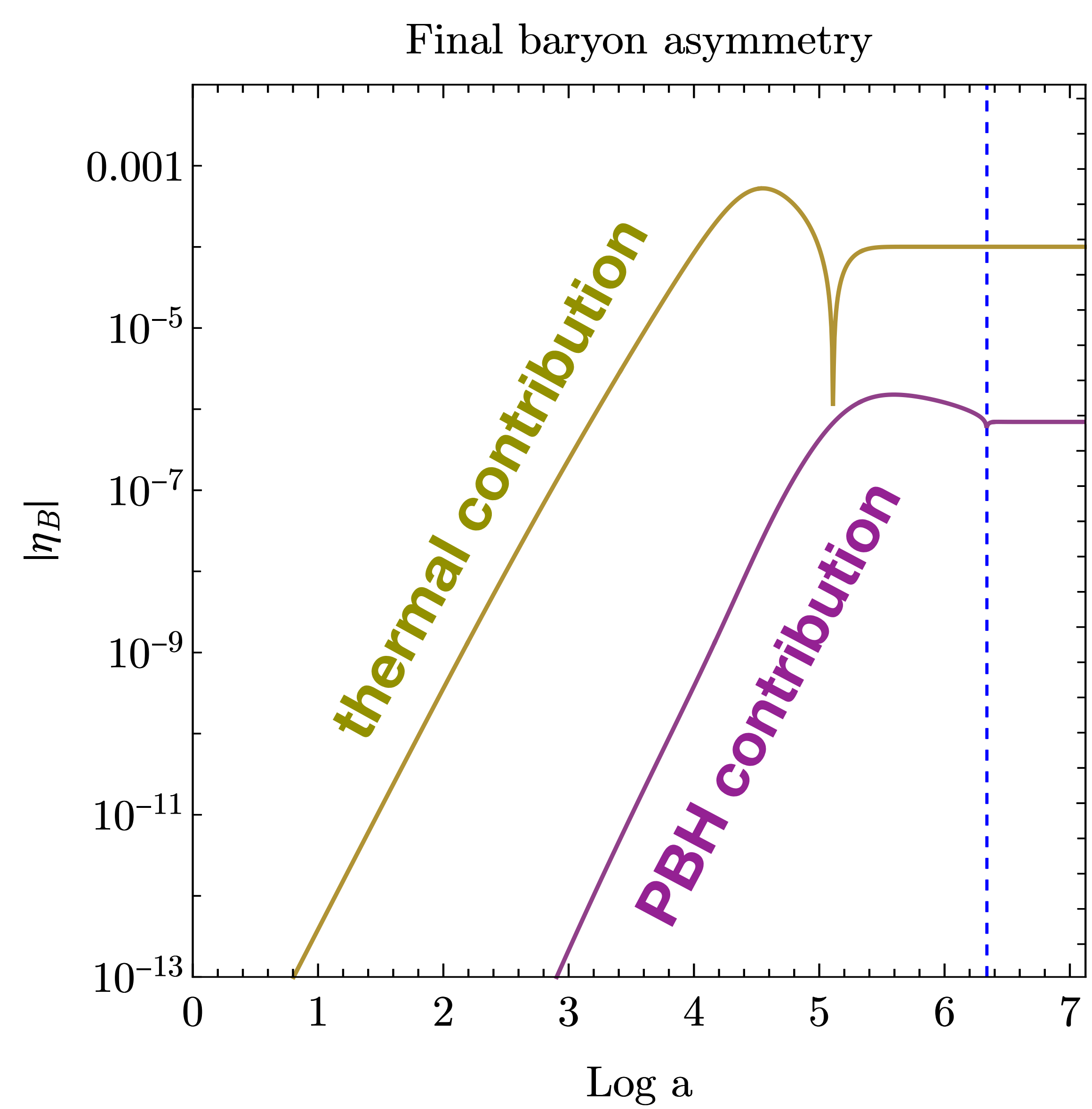

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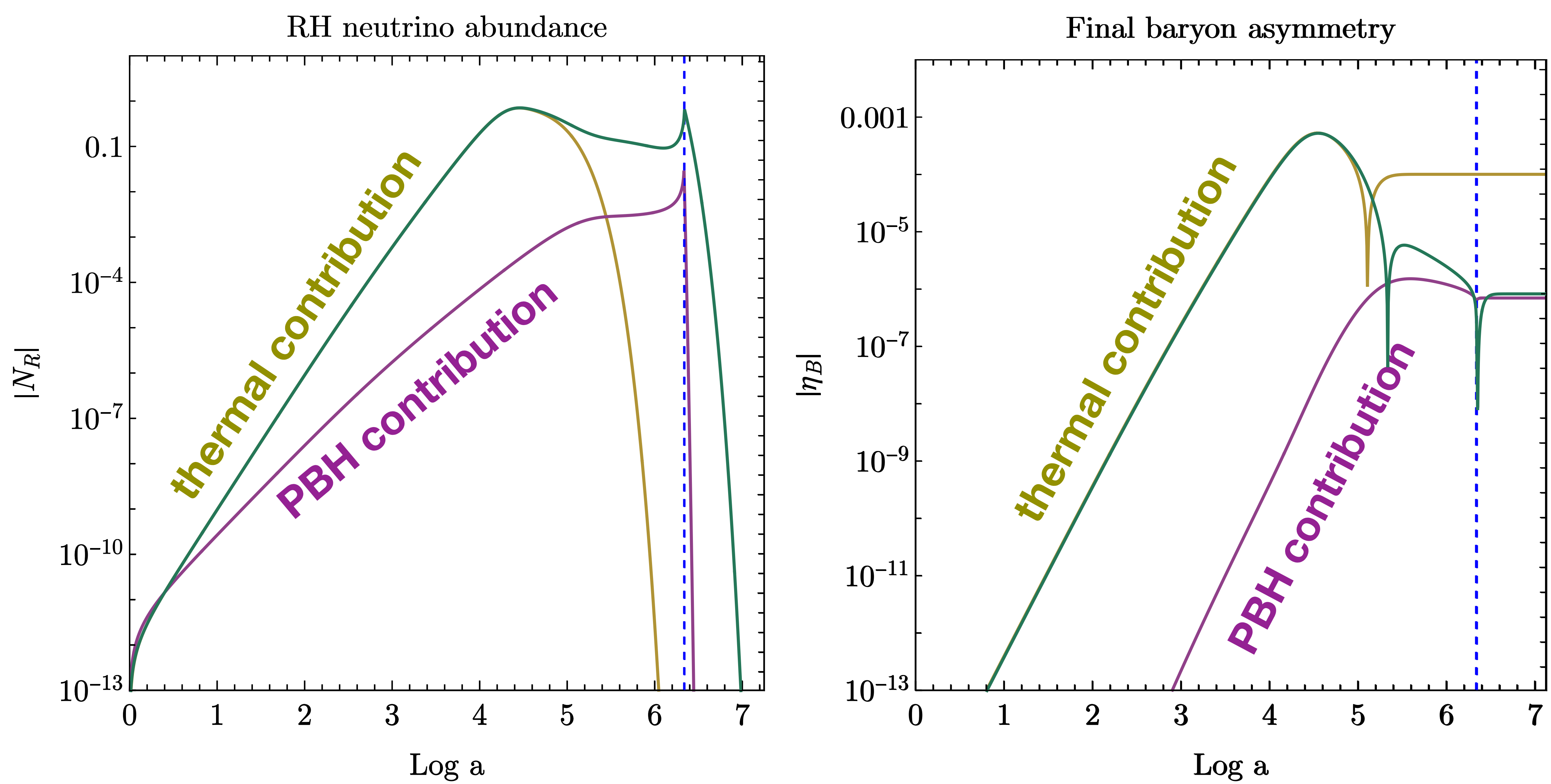
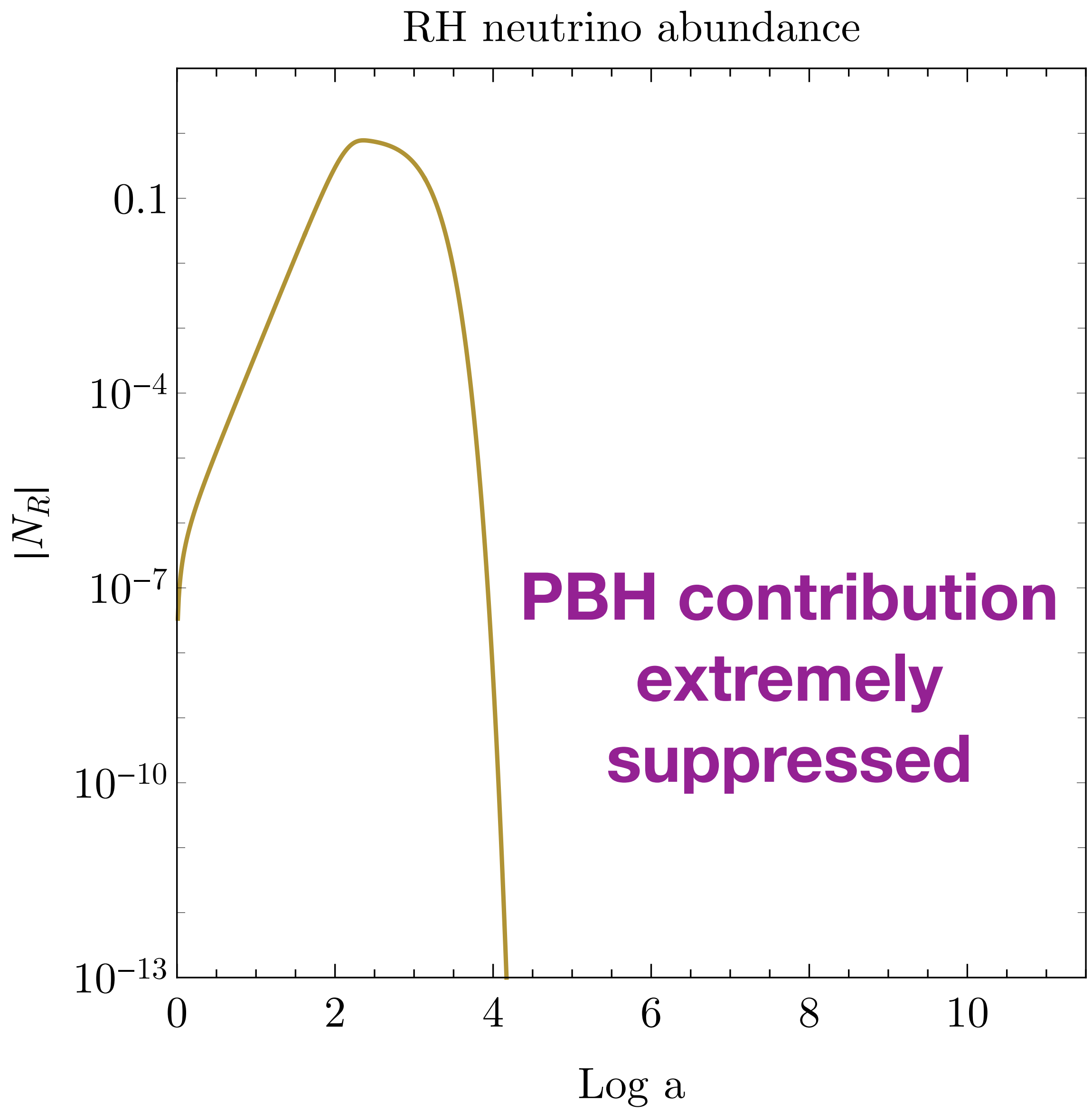
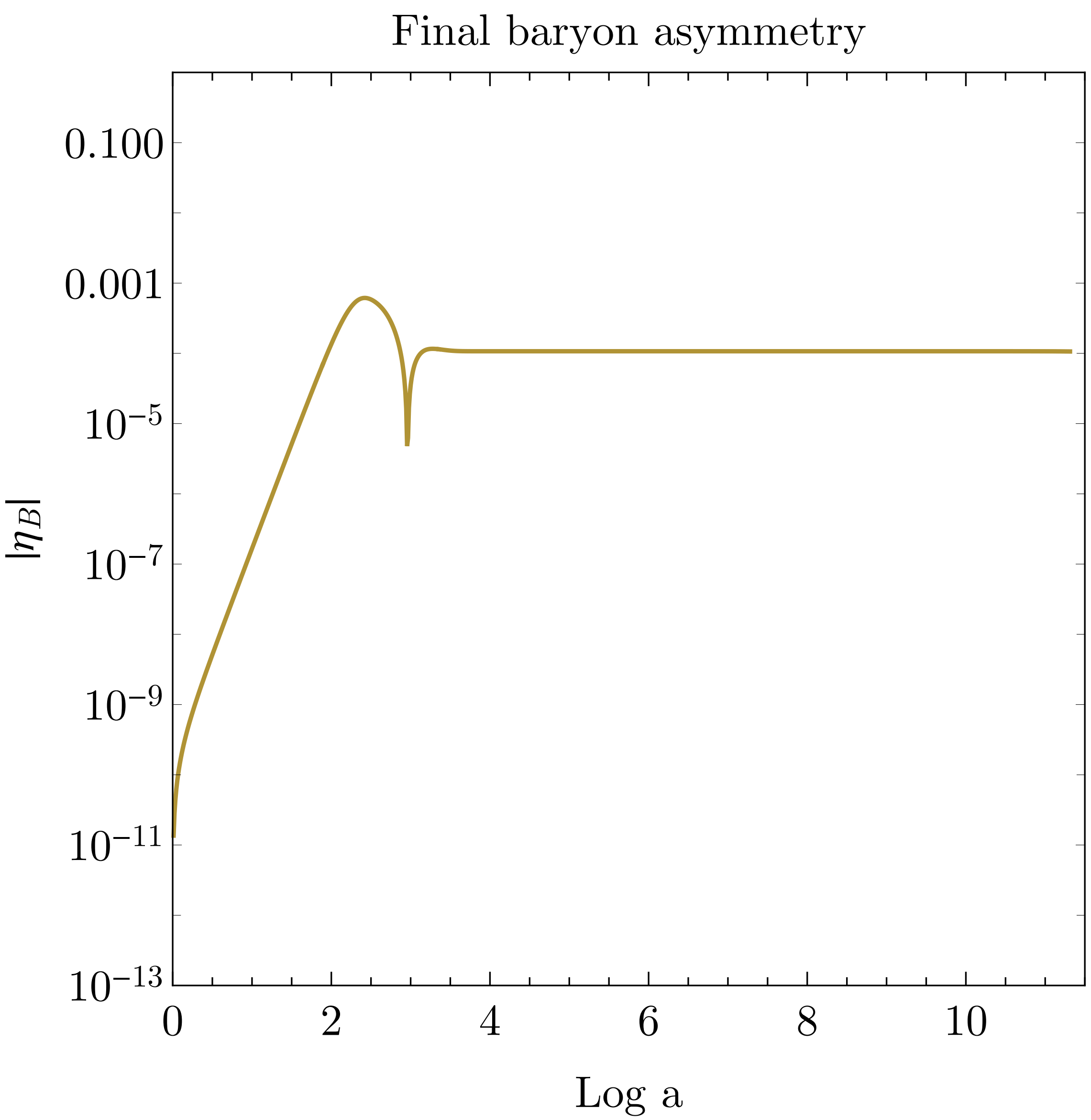


D. PBH evaporation occurs **way after** thermal leptogenesis era

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





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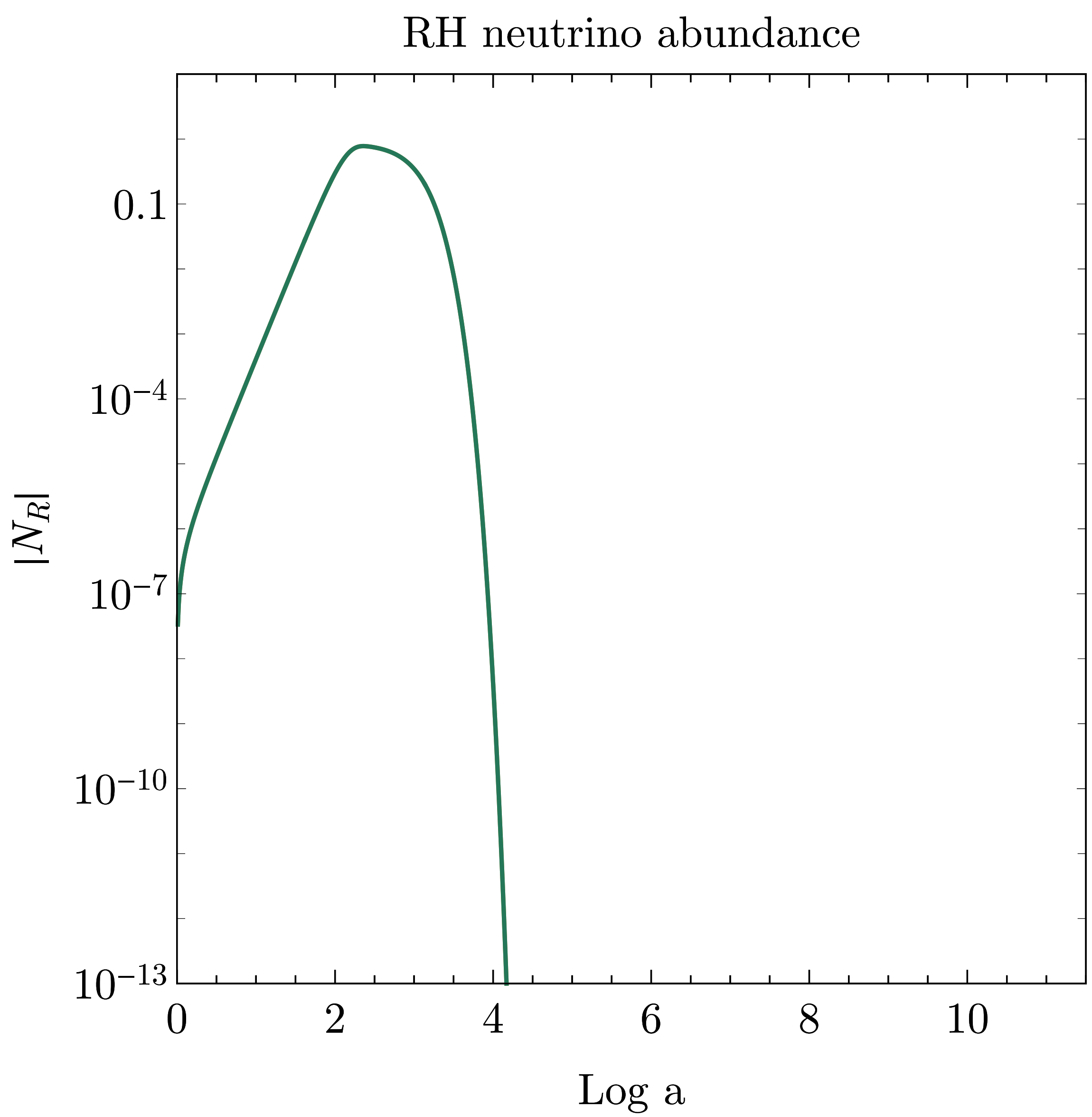
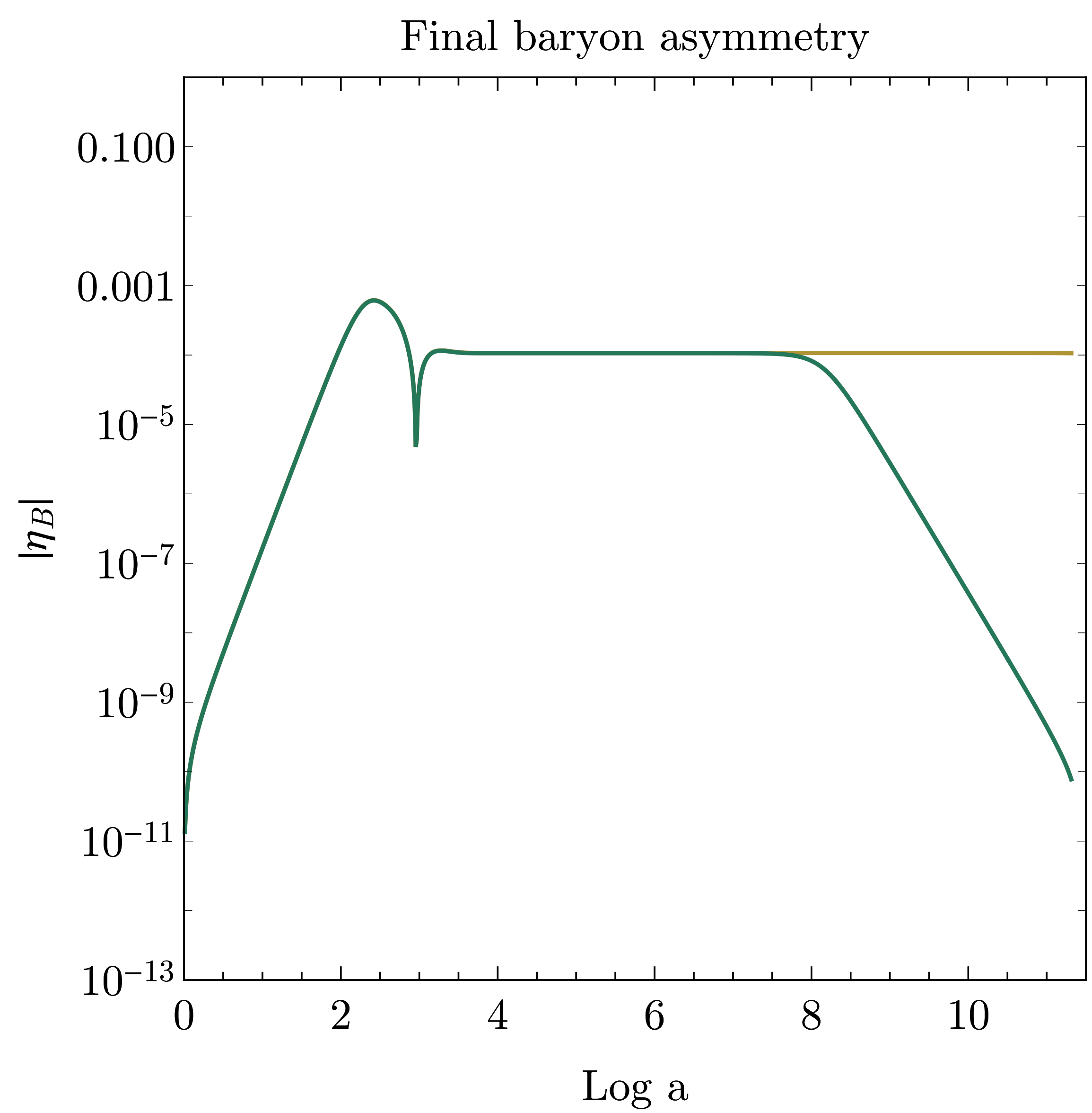
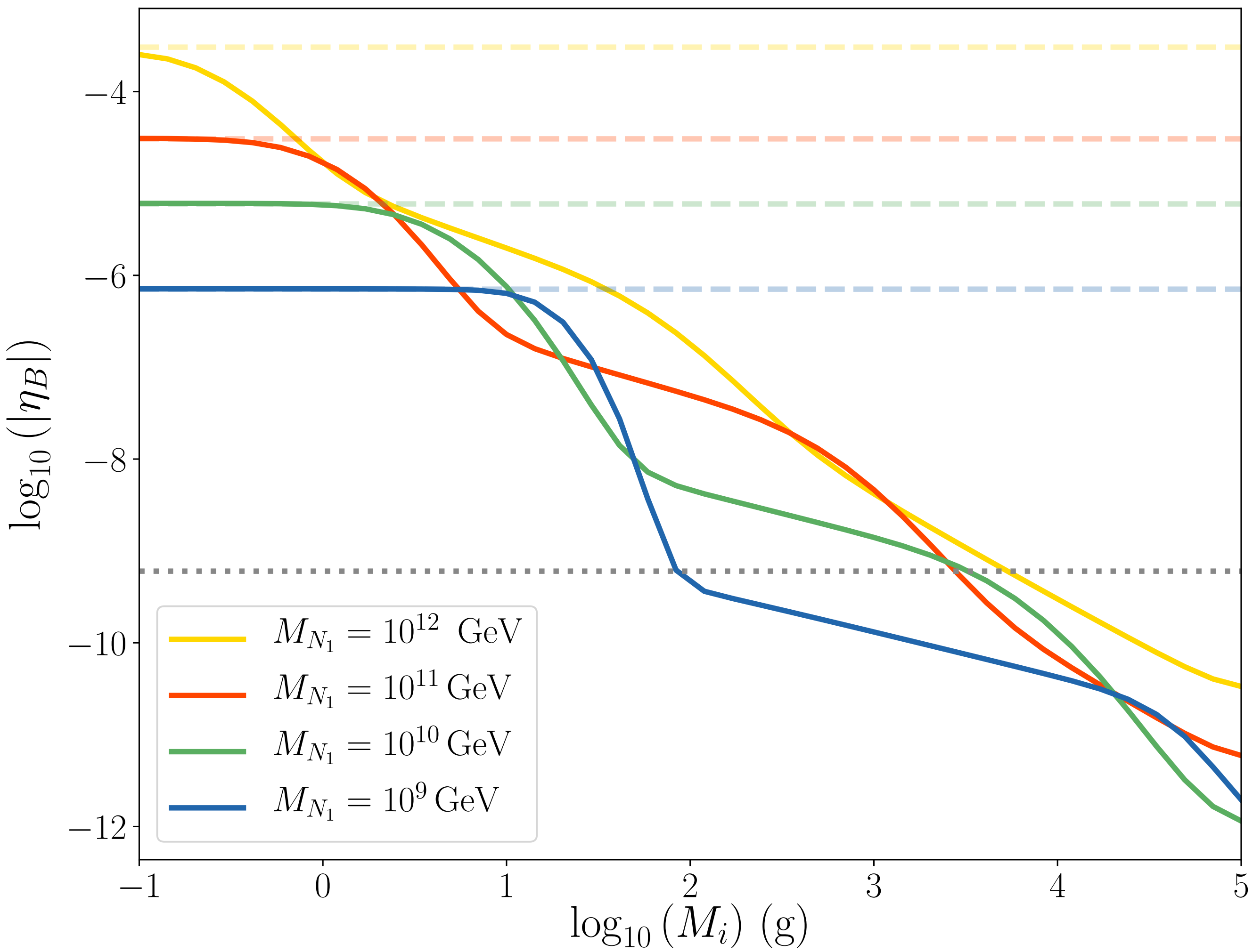
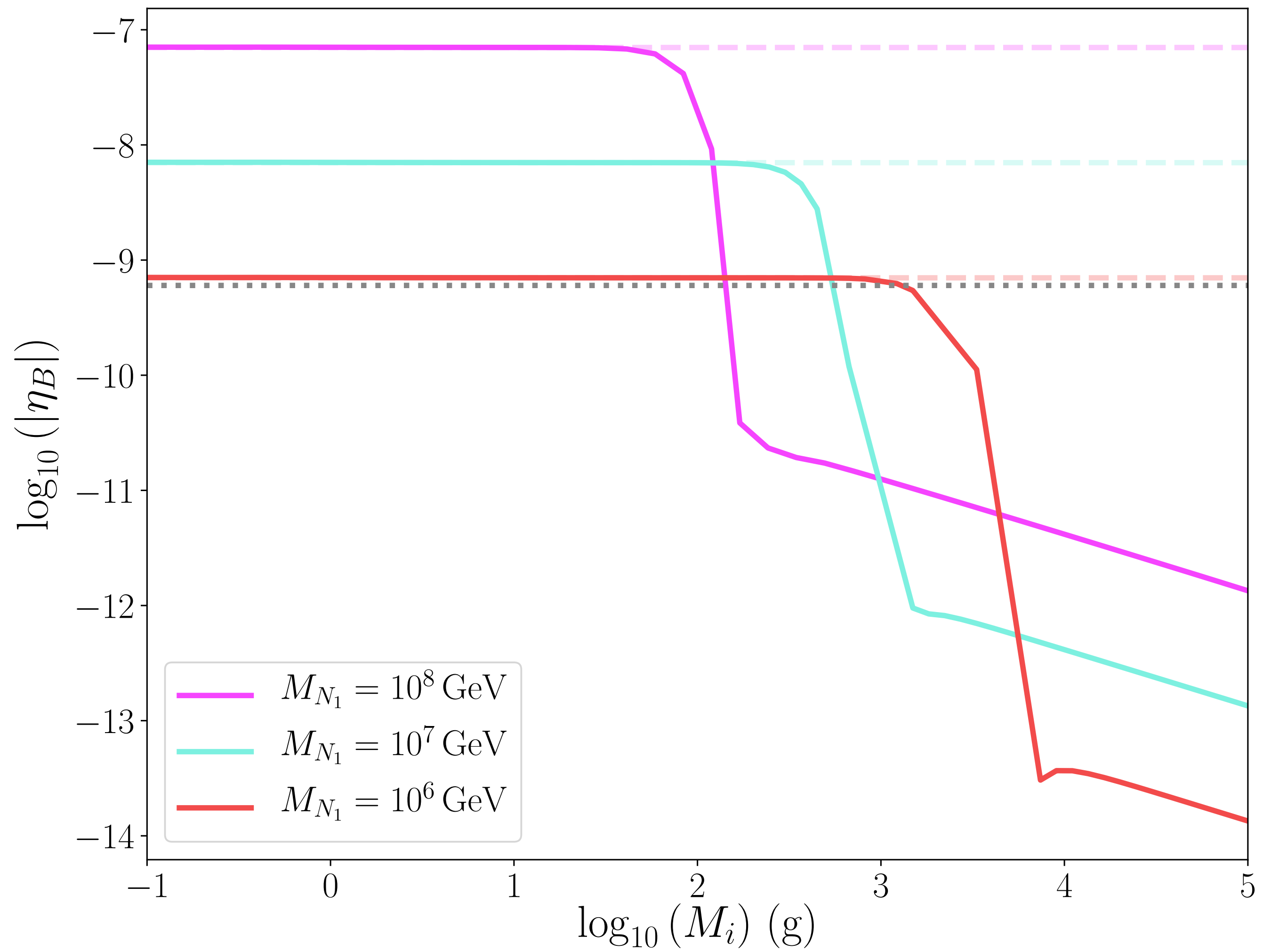




Thermal leptogenesis and primordial black holes

$\beta' = 10^{-3}$



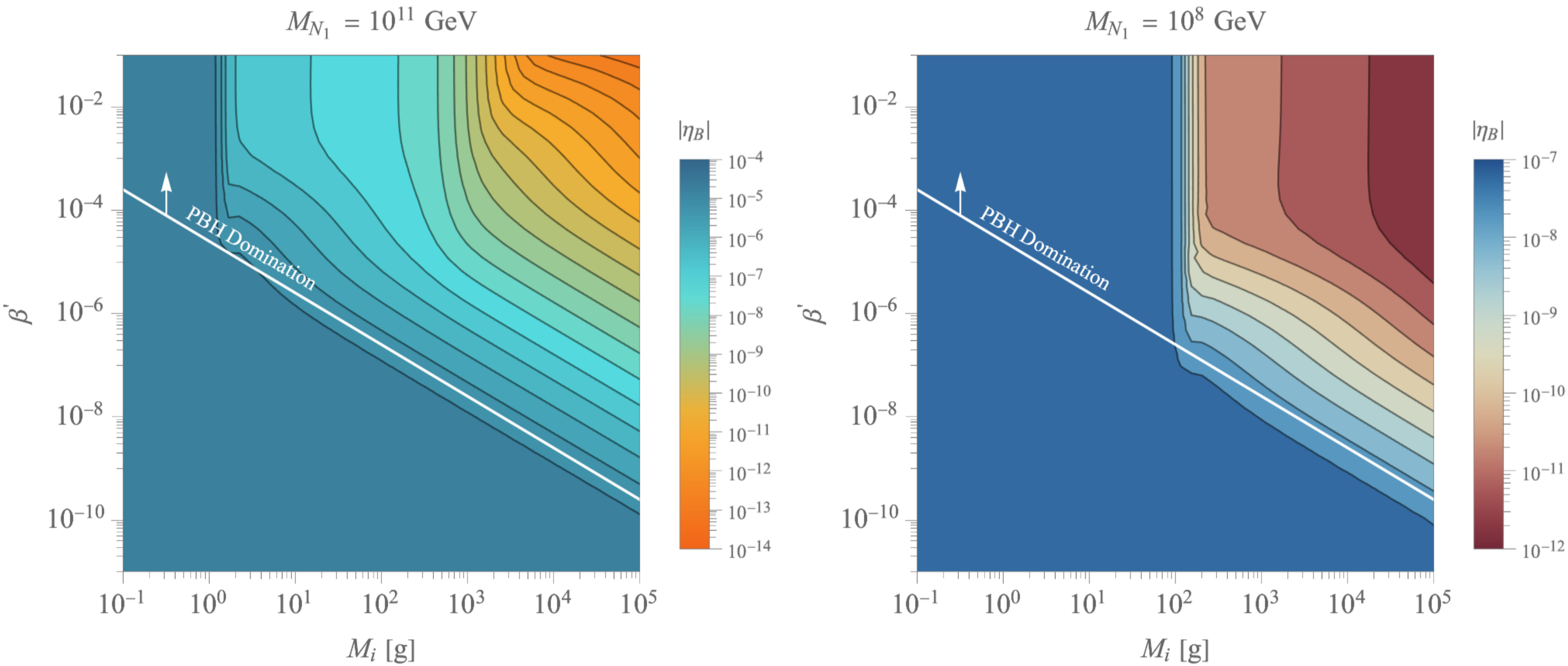


Chose Yukawa matrix for maximal baryon asymmetry

Lines indicates upper bound

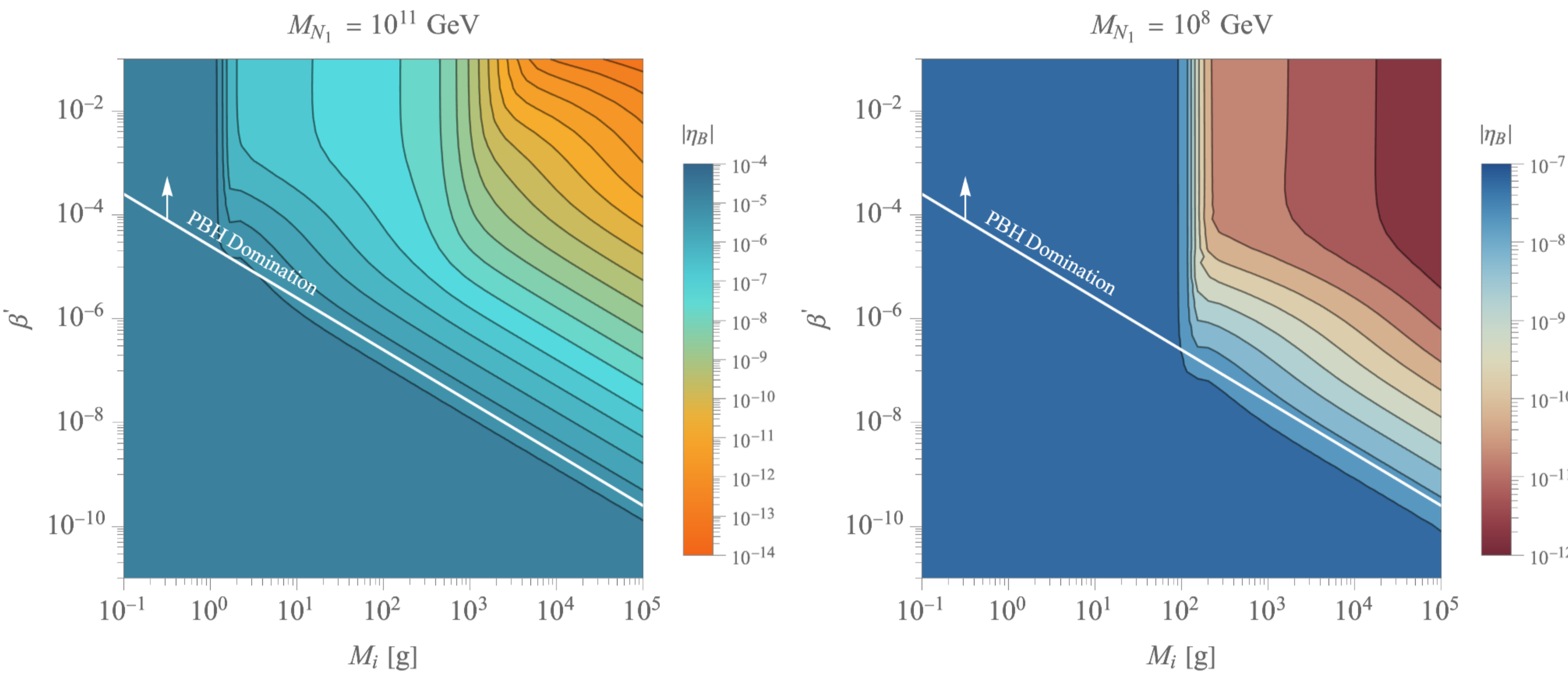
Thermal leptogenesis and primordial black holes

Dilution effect present as long as there is PBH domination



Thermal leptogenesis and primordial black holes

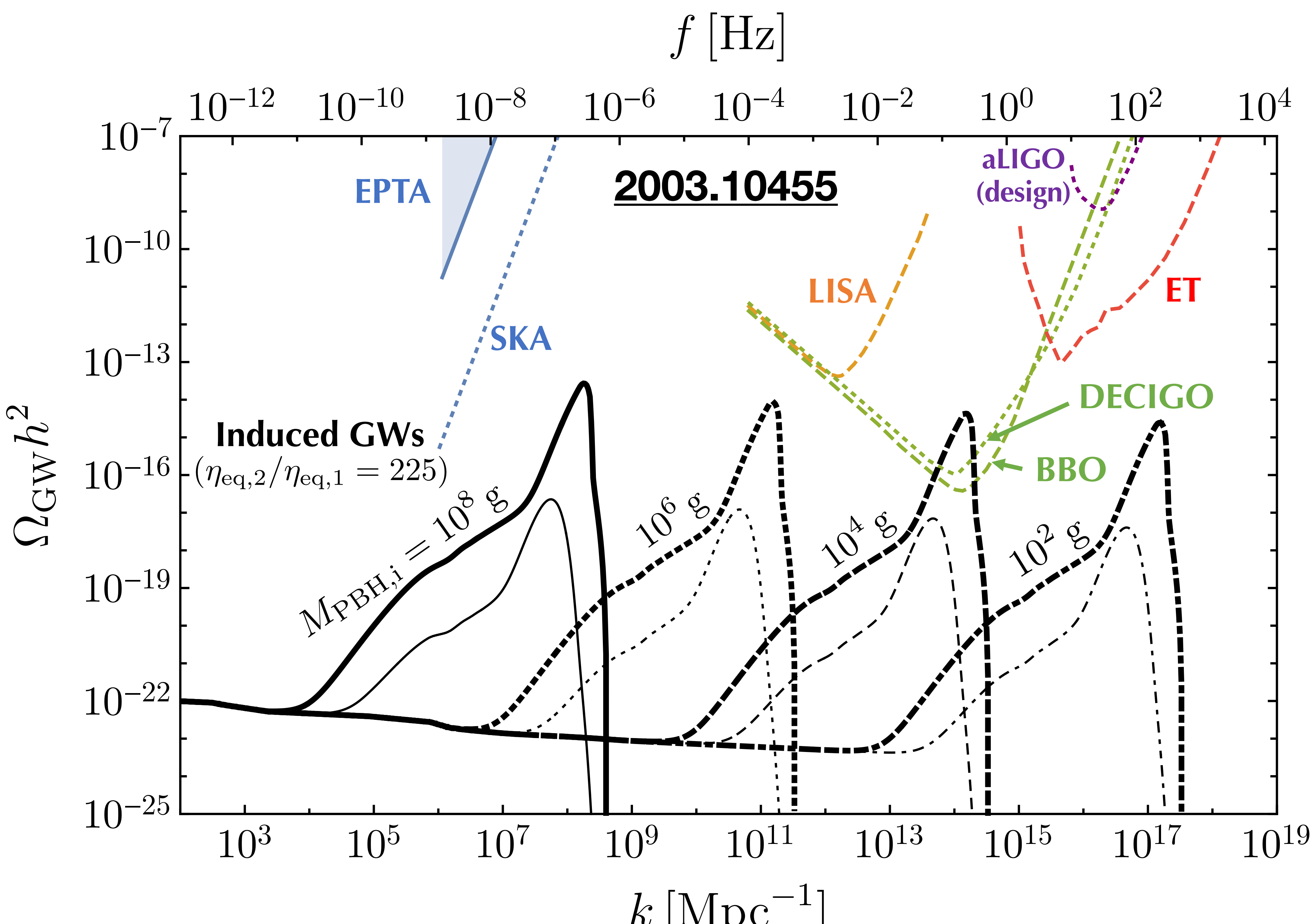
Detection of PBHs in mass range > 0.1 kg would place thermal leptogenesis under serious tension.



When PBHs evaporate ⟹ sudden transition

Matter to radiation domination ⟹ gravitational potential

opscillates ⟹ SGWB generated



"Poltergeist Mechanism"

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

Summary

- Leptogenesis is a plausible explanation for the smallness of neutrino masses and the observed matter anti-matter asymmetry

- In the type-I seesaw framework for leptogenesis, the mass of the RHN can range from GeV - 10^{13} GeV scale.

- Low-scale (and some regions of resonant) leptogenesis can be probed by a broad range of present and future experimental facilities (see Juraj's talk)

- Gravitational waves are a complementary probe of intermediate and high-scale leptogenesis and LNV & LFV searches will be key.