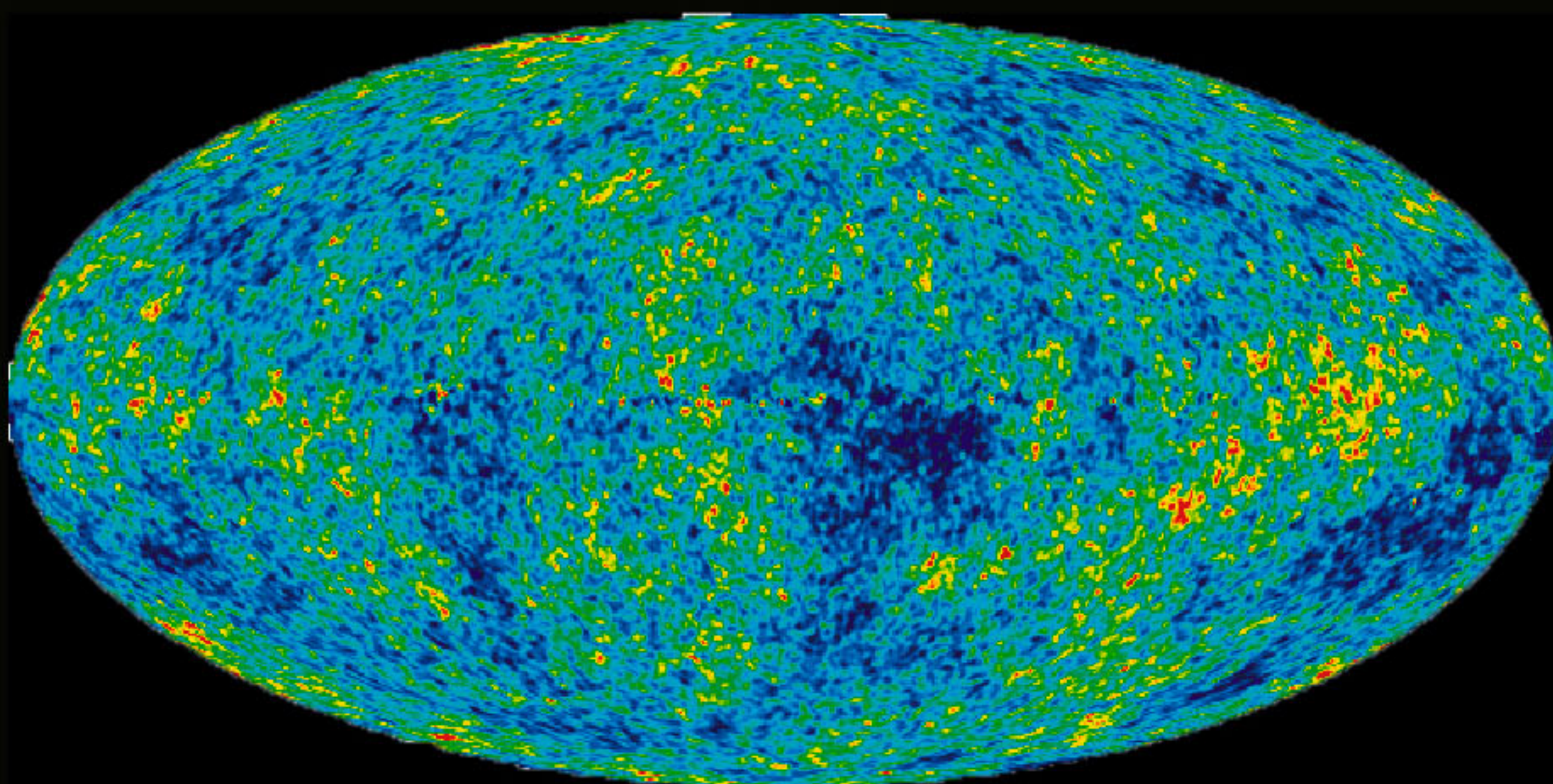
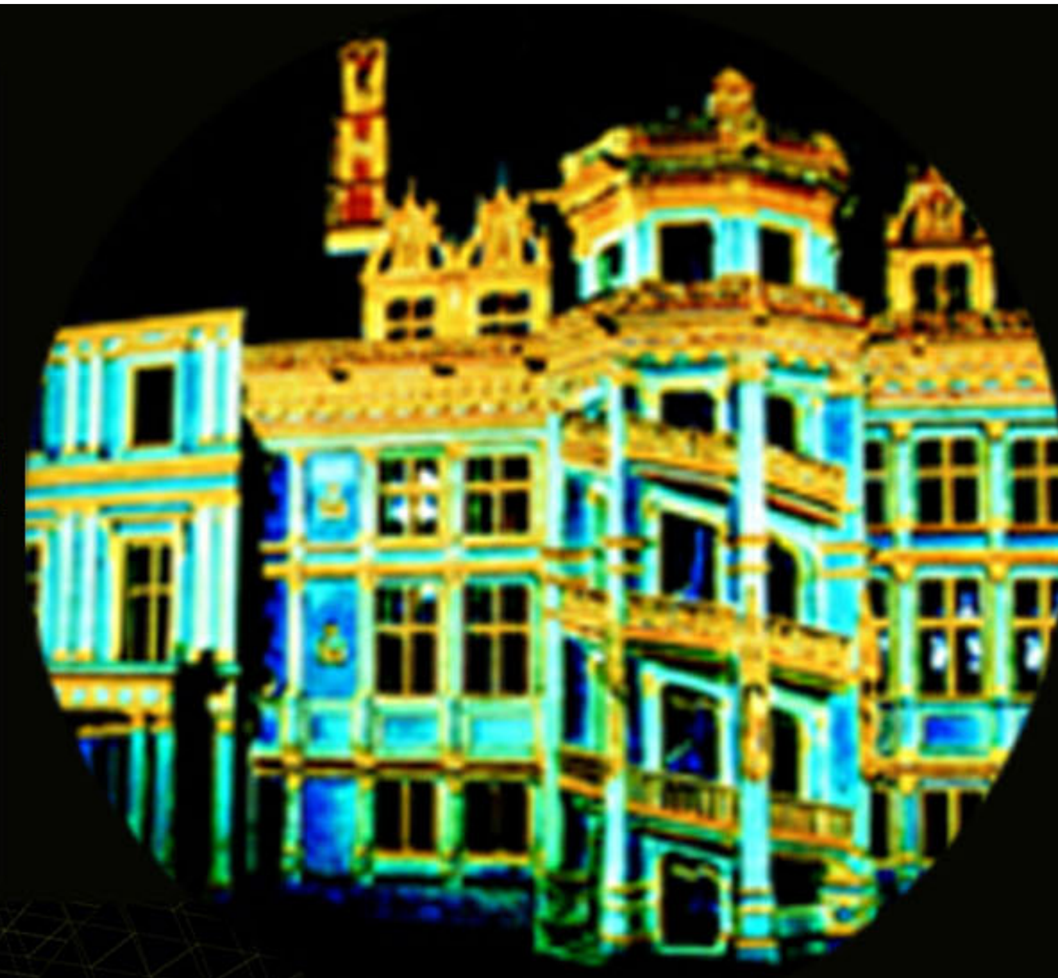
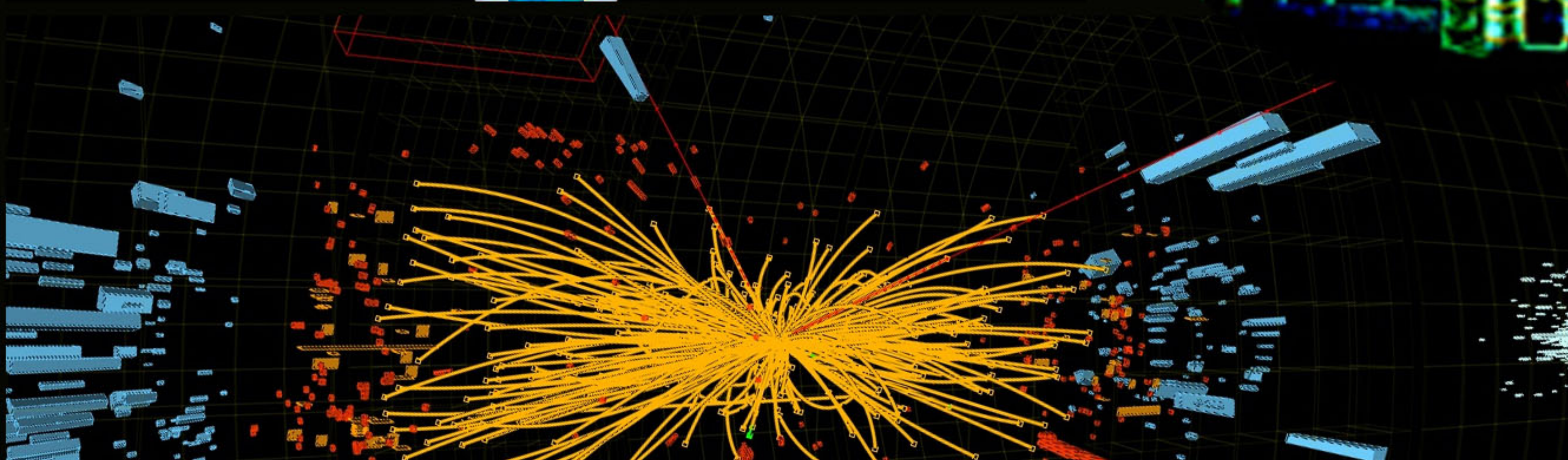
An overview of Leptogenesis

33rd Rencontres de Blois

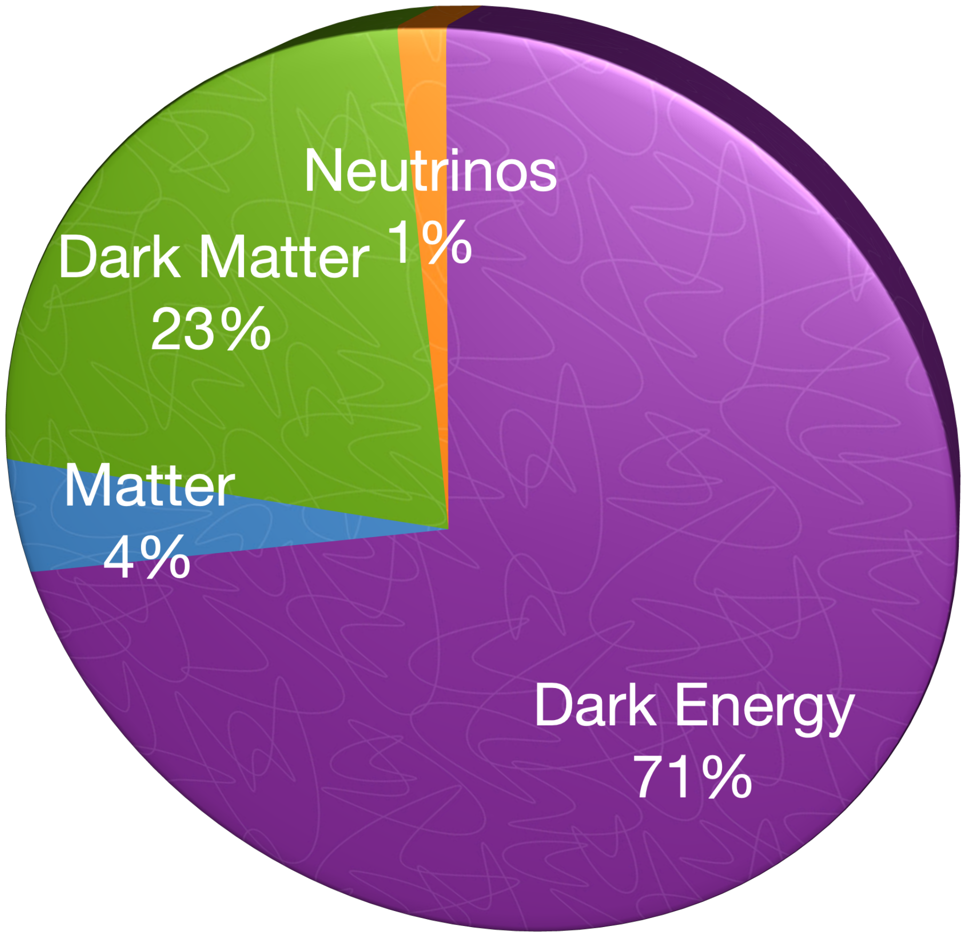
Jessica Turner, IPPP, Durham University







Universe's Energy Budget



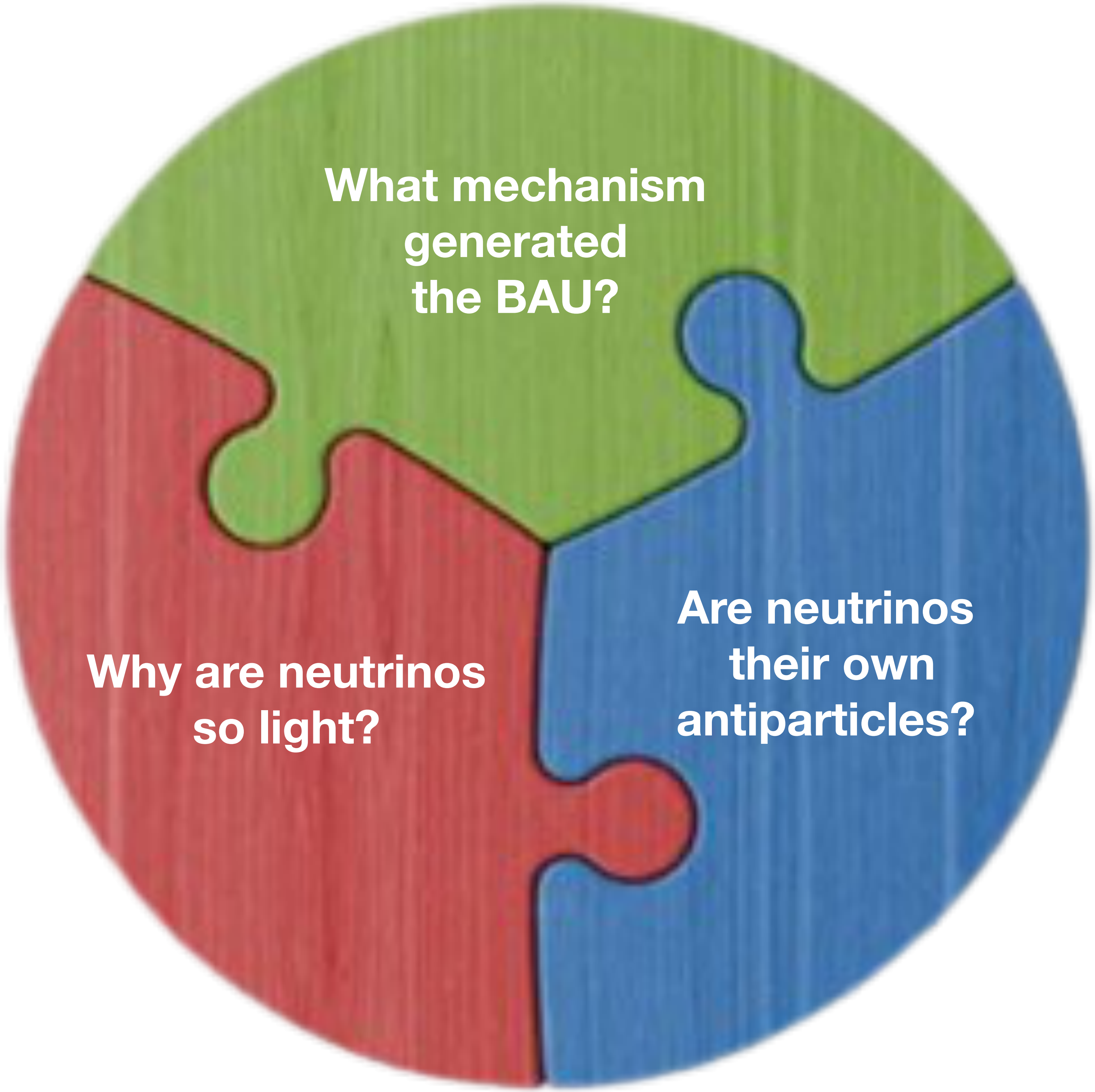
$$\eta_B = (6.02 - 6.18) \times 10^{-10}$$

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

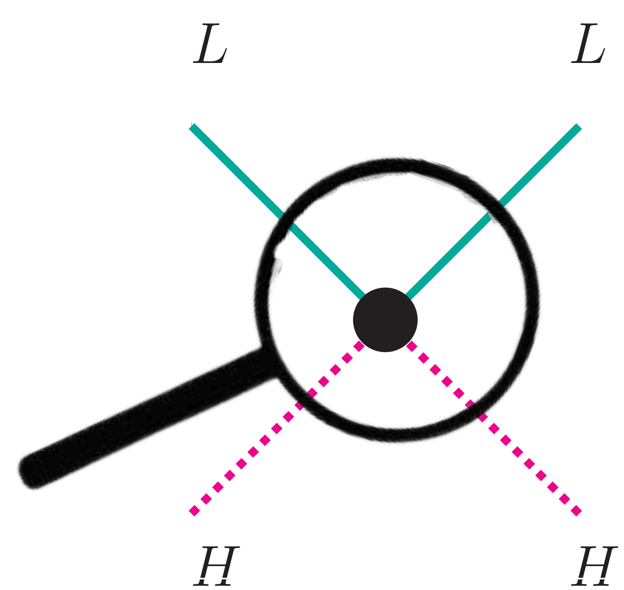


The Seesaw Mechanism

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

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

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



The Seesaw Mechanism

After SSB a Majorana mass is produced for the active neutrinos

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

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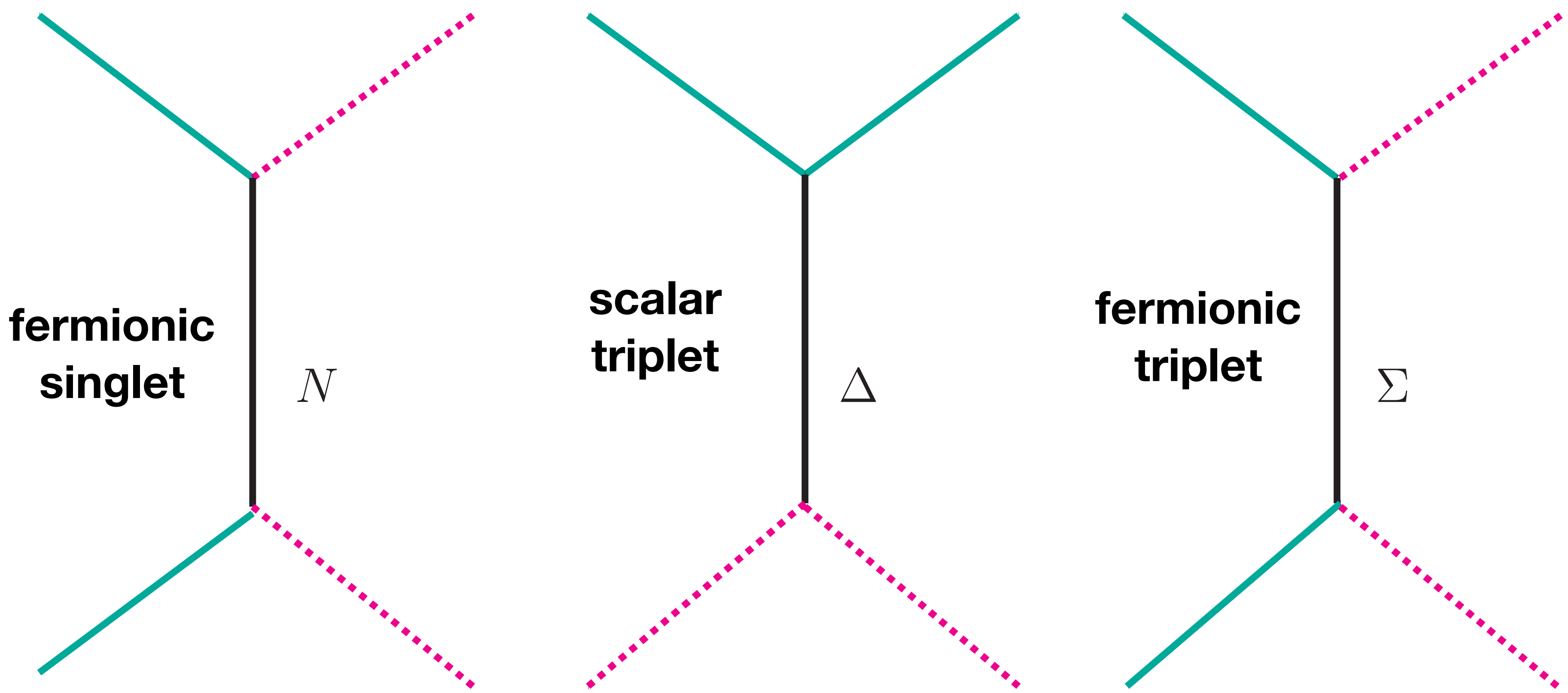

Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

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

Ma, Roy, Senjanovic, Hambye

The Seesaw Mechanism

After SSB a Majorana mass is produced for the active neutrinos

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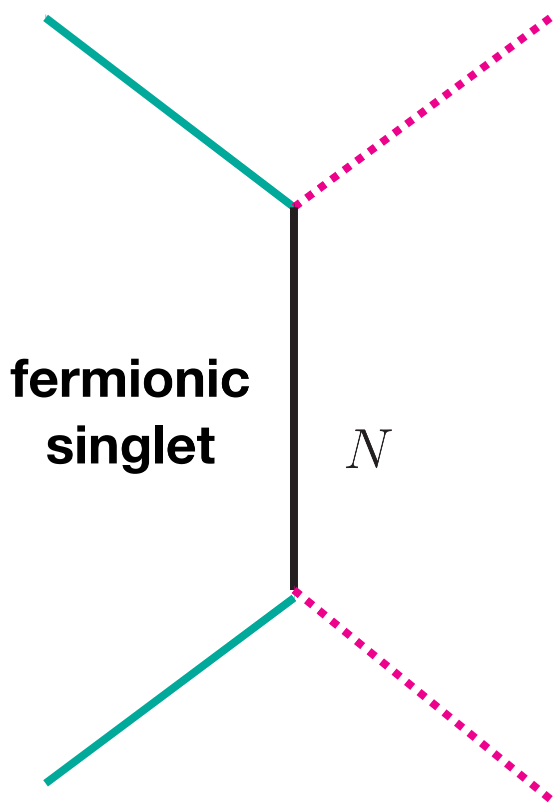
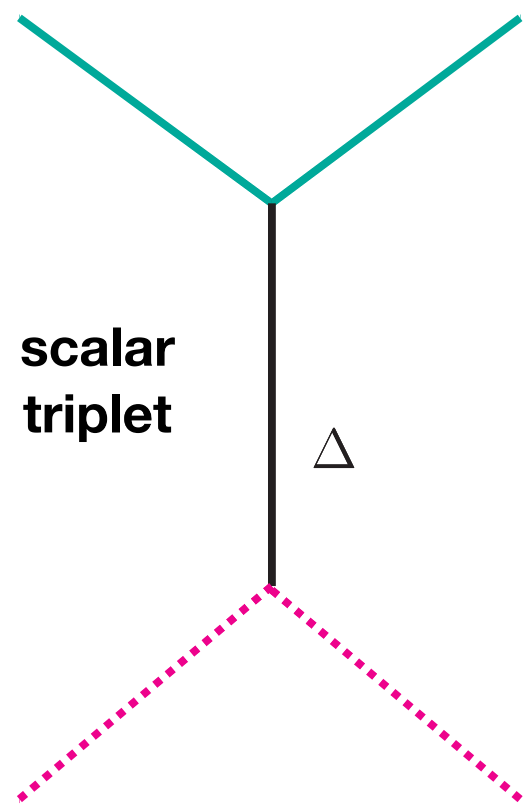
Type-I seesaw



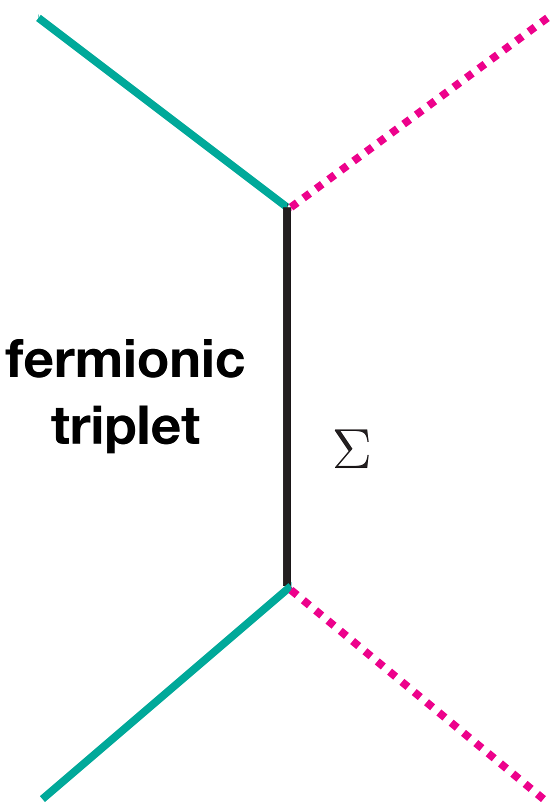
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

Type-II seesaw



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

Type-III seesaw

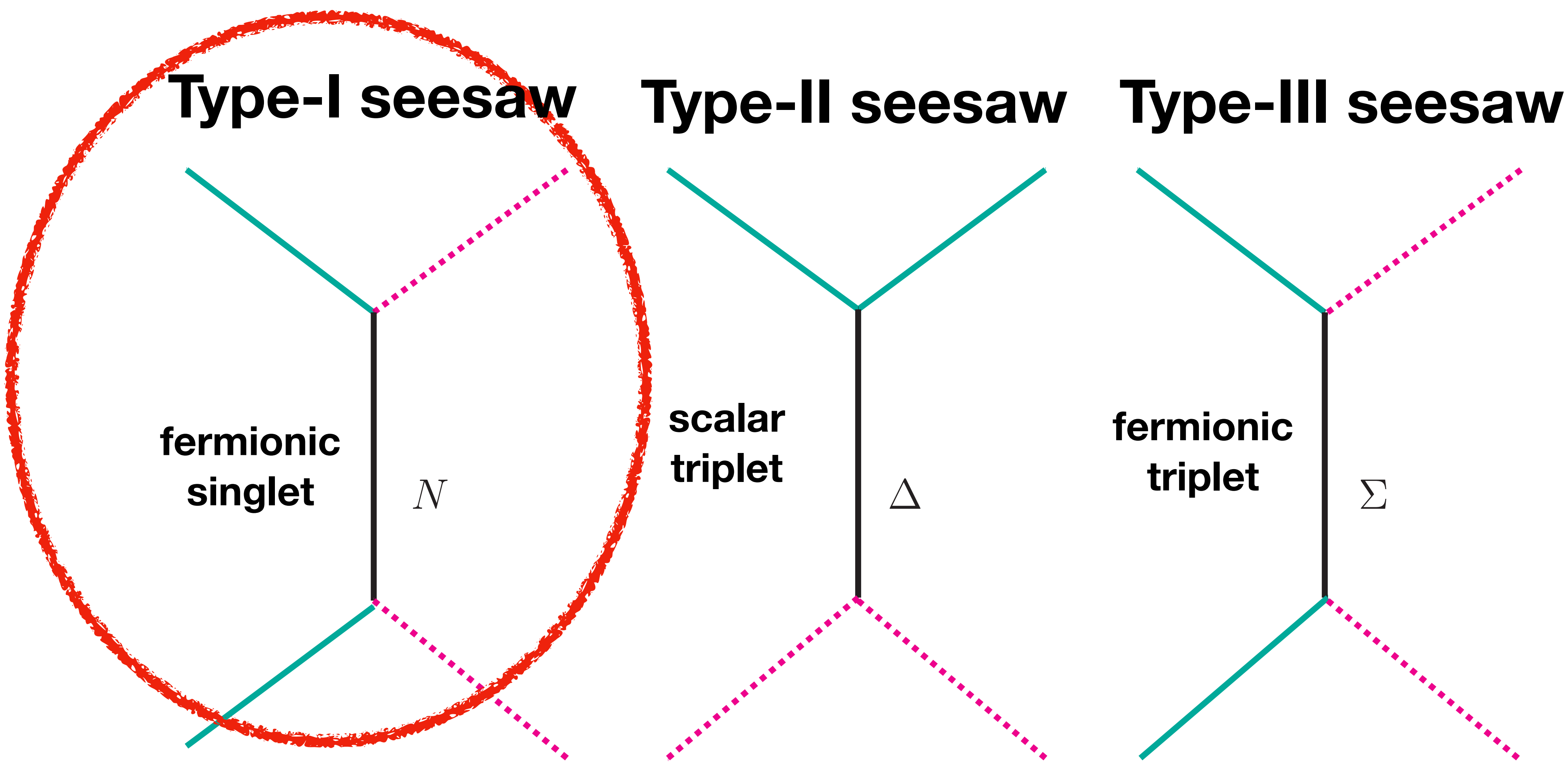


Ma, Roy, Senjanovic, Hambye

The Seesaw Mechanism

After SSB a Majorana mass is produced for the active neutrinos

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



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

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

Ma, Roy, Senjanovic, Hambye

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

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

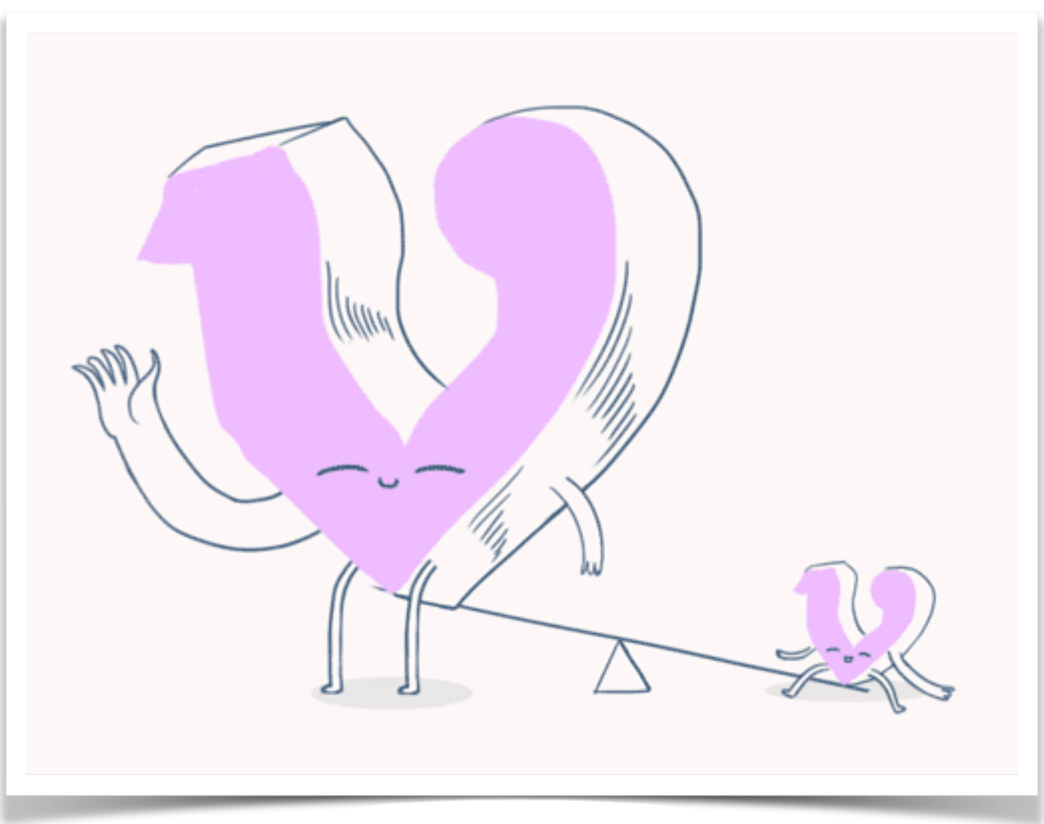
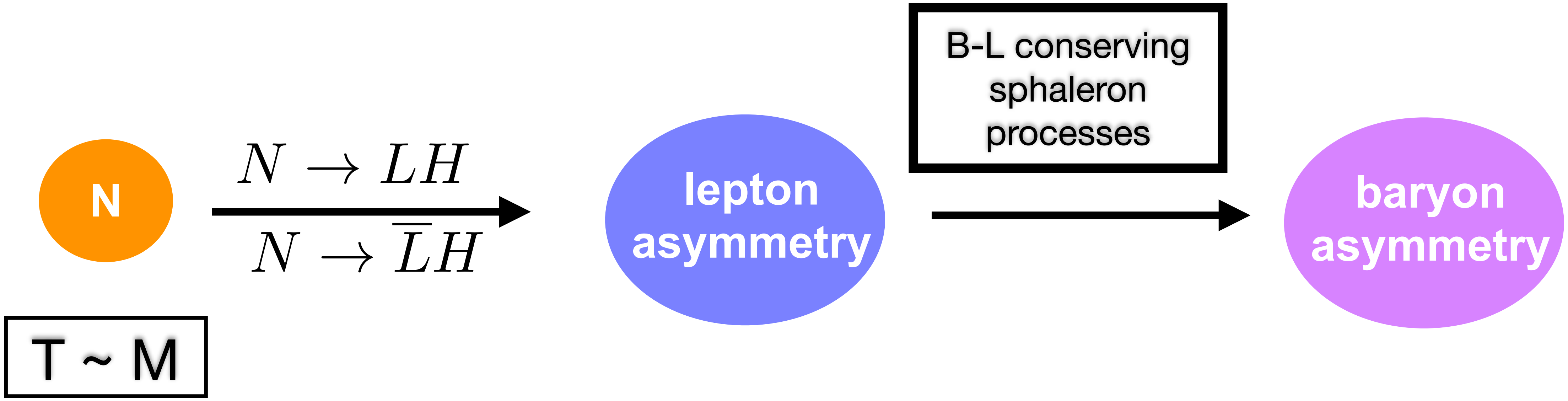


Image courtesy of Symmetry Magazine

Sakharov's Conditions

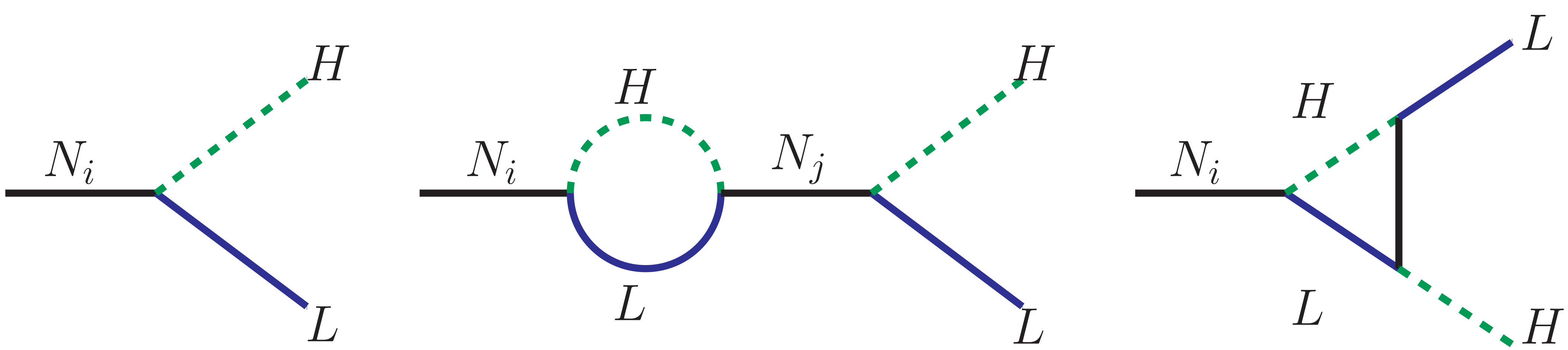
- ☑ Baryon number violation
- ☑ C & CP-violation
- ☑ Departure from thermal equilibrium

Thermal Leptogenesis



Decay asymmetry from interference between tree and loop level diagrams

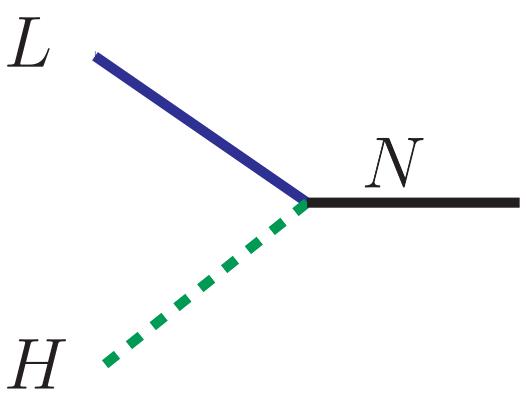
Covi, Roulet, Vissani



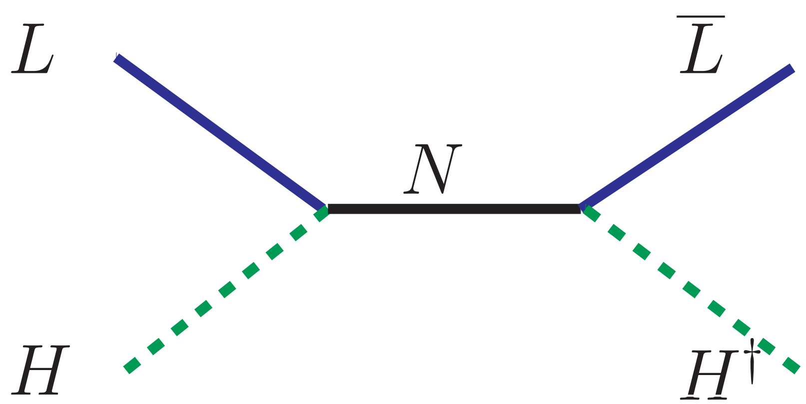
$$\epsilon_i = \frac{\Gamma_i - \overline{\Gamma_i}}{\Gamma_i + \overline{\Gamma_i}}$$

Thermal Leptogenesis

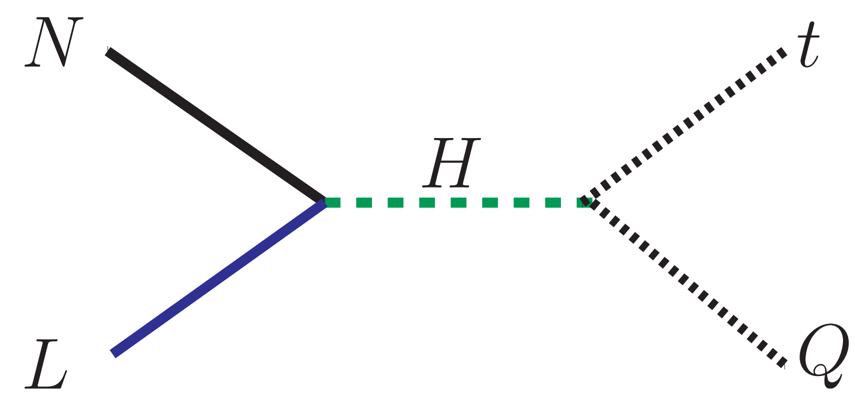
Washout and scattering processes



inverse Decays



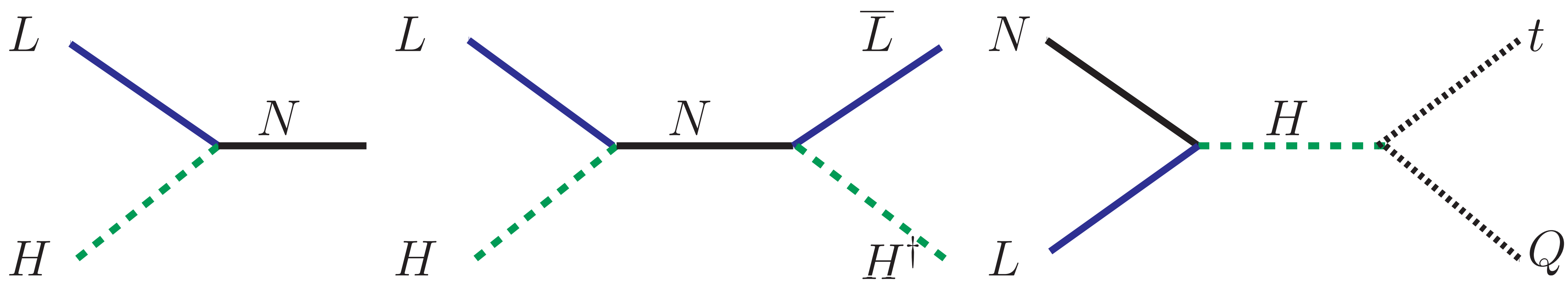
ΔL=2



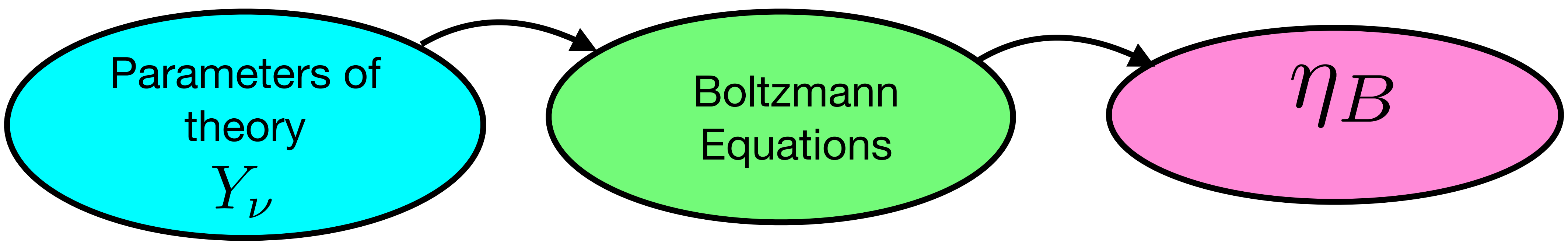
ΔL=1

Thermal Leptogenesis

Washout and scattering processes



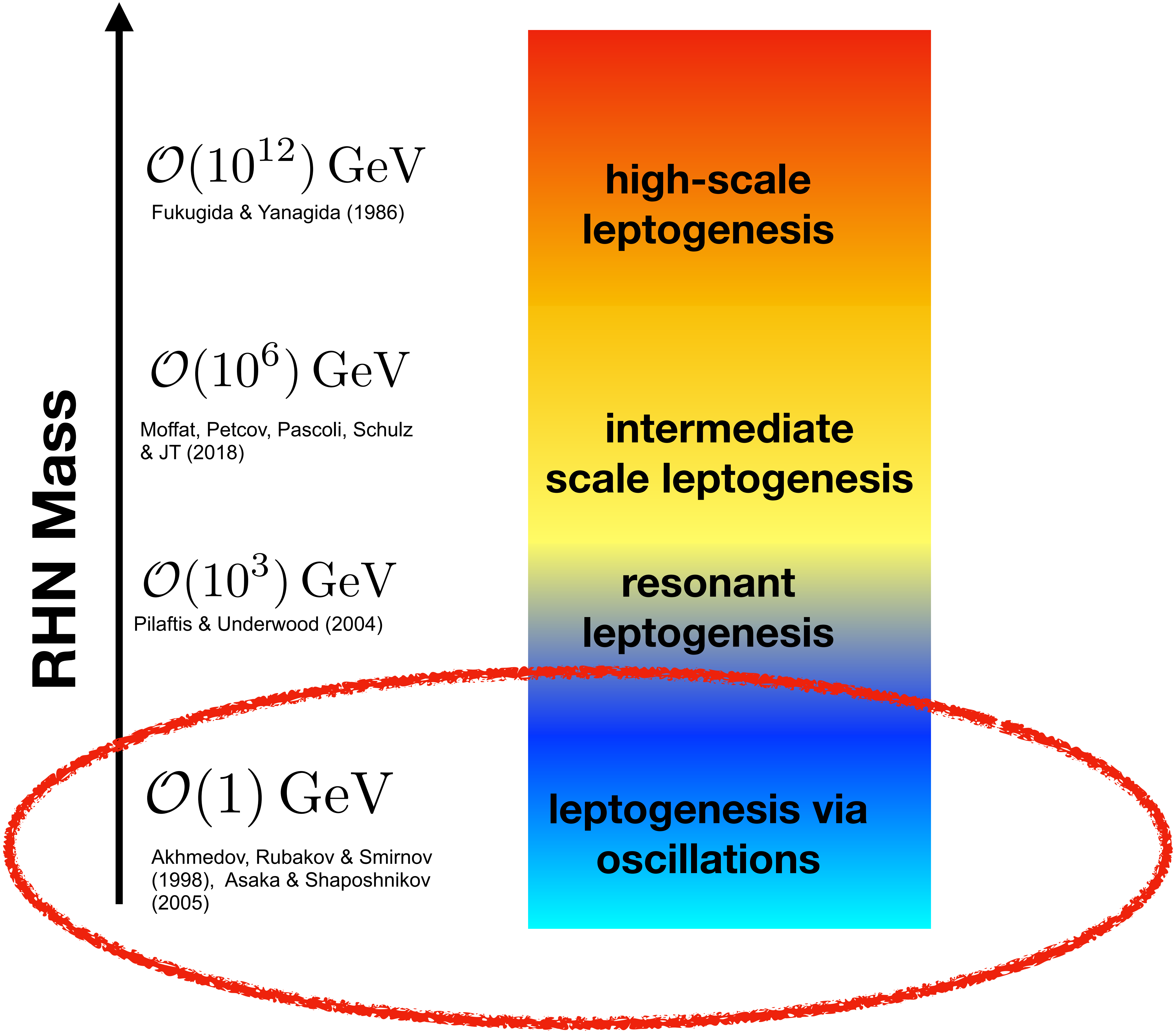
inverse Decays ΔL=2 ΔL=1



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

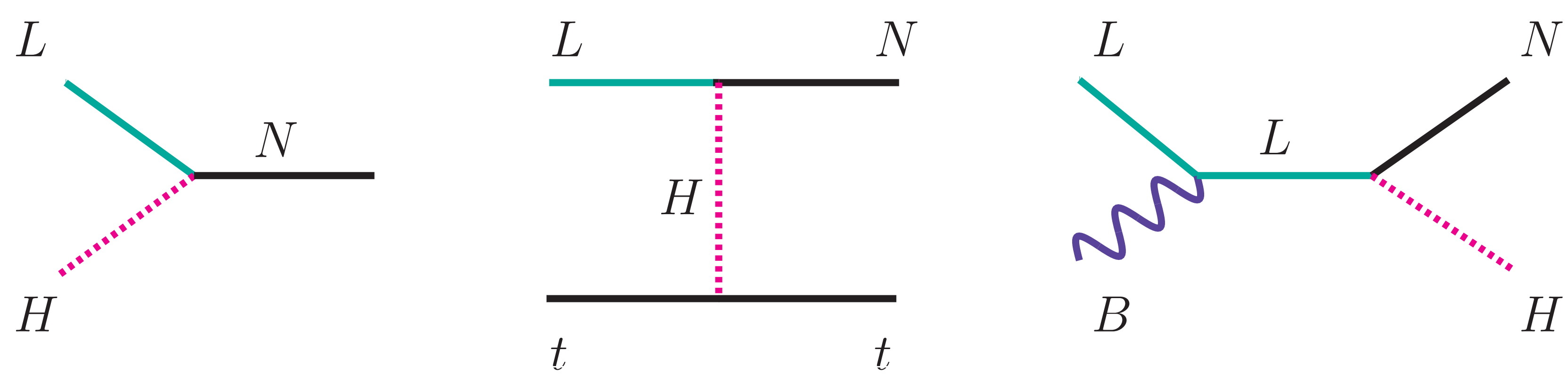
source **sink**

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


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

Leptogenesis via Oscillations

- highly degenerate RHNs produced via scattering at $T > T_{EW}$



- small Yukawa couplings → RHNs may not have equilibrated by the EWPT

- RHNs CP-violating oscillations & decays → source of lepton number and flavour asymmetry.

Akhmedov, Rubakov & Smirnov *Phys.Rev.Lett. 81 1359-1362* (1998)
Asaka & Shaposhnikov *Phys.Lett. B620 17-26* (2005)

Leptogenesis via Oscillations with 2 RHNs

- GeV-scale RHNs → rich phenomenology

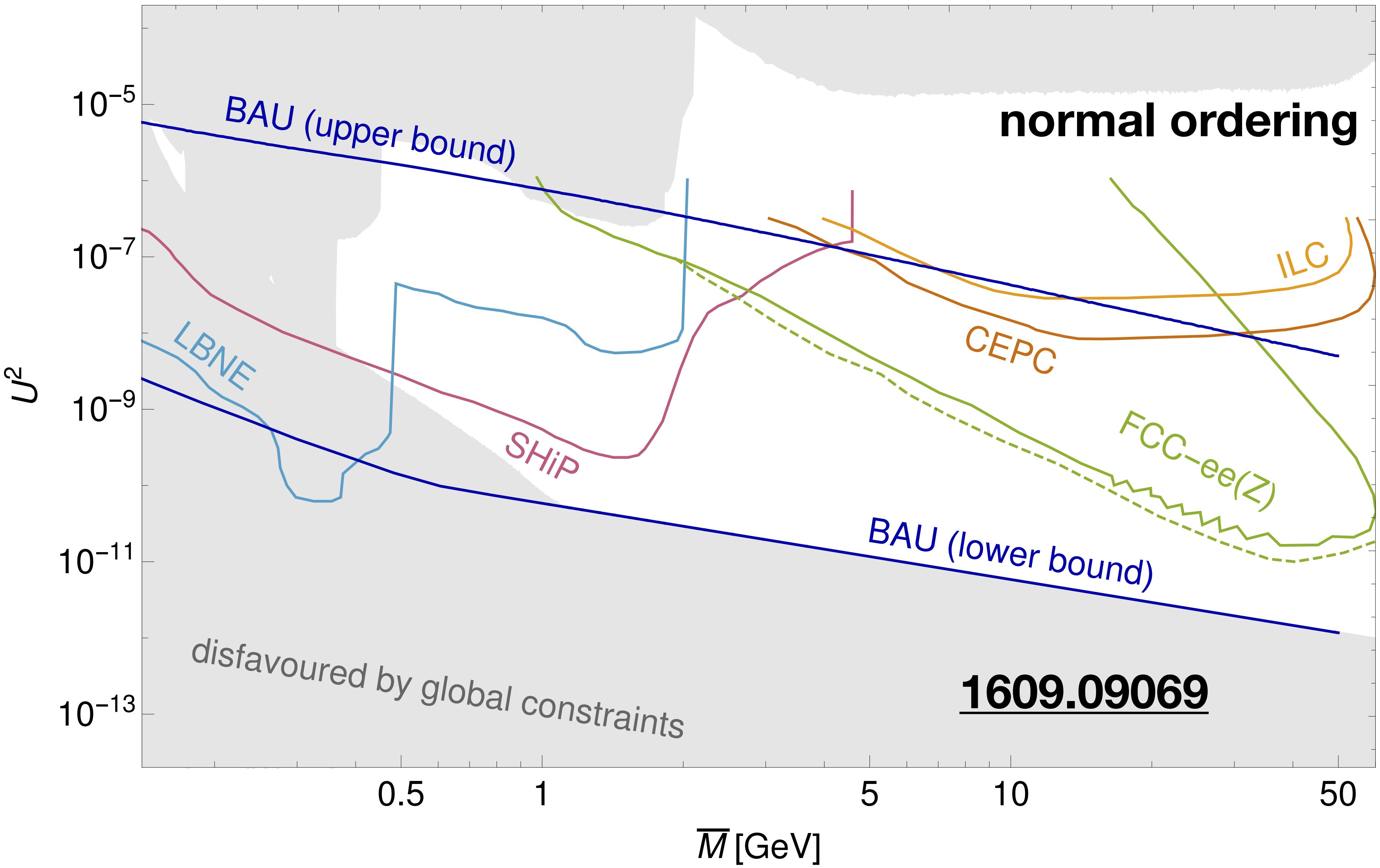
$$Y = \frac{1}{v} U \sqrt{m} R^T \sqrt{M}$$

4 masses, 4 angles, 3 phases (2 masses + 3 angles + 1 phase measured)

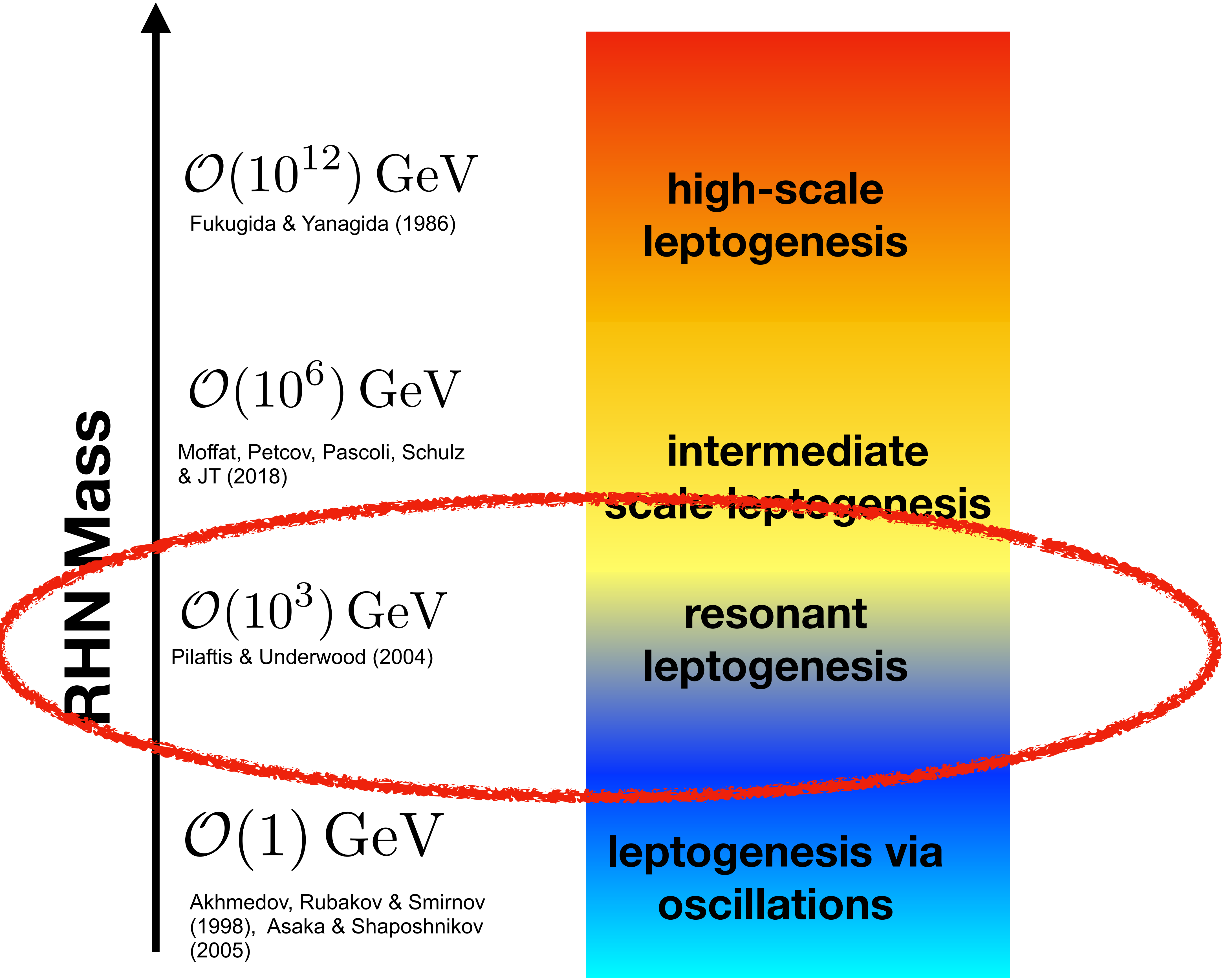
(2 masses + 3 angles + 1 phase from oscillation data $\Longrightarrow$ 5 free parameters

Casas & Ibarra, *Nucl.Phys. B618 (2001) 171-204*

$$\nu_\alpha = U_{\alpha i}\nu_i + \Theta_{\alpha I} N_I^c \qquad |U|^2 = \sum_{\alpha I} |\Theta_{\alpha I}|^2 \qquad \overline{M} = \frac{M_1 + M_2}{2}$$



Drewes, Garbrecht, Gueter, Klaric *JHEP 1708 (2017)* 018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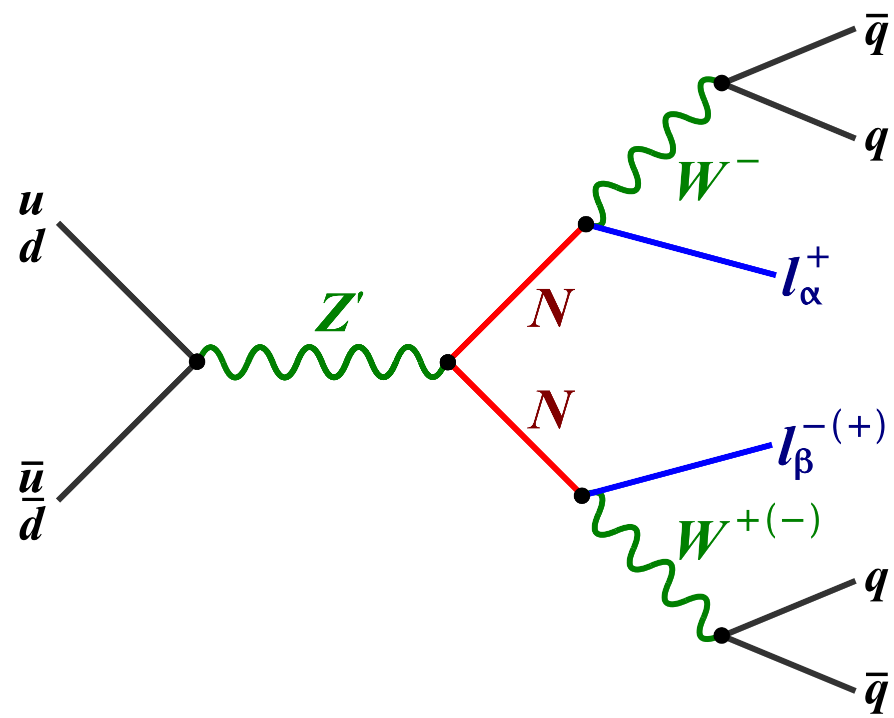
high-scale leptogenesis
intermediate scale leptogenesis
resonant leptogenesis
leptogenesis via oscillations

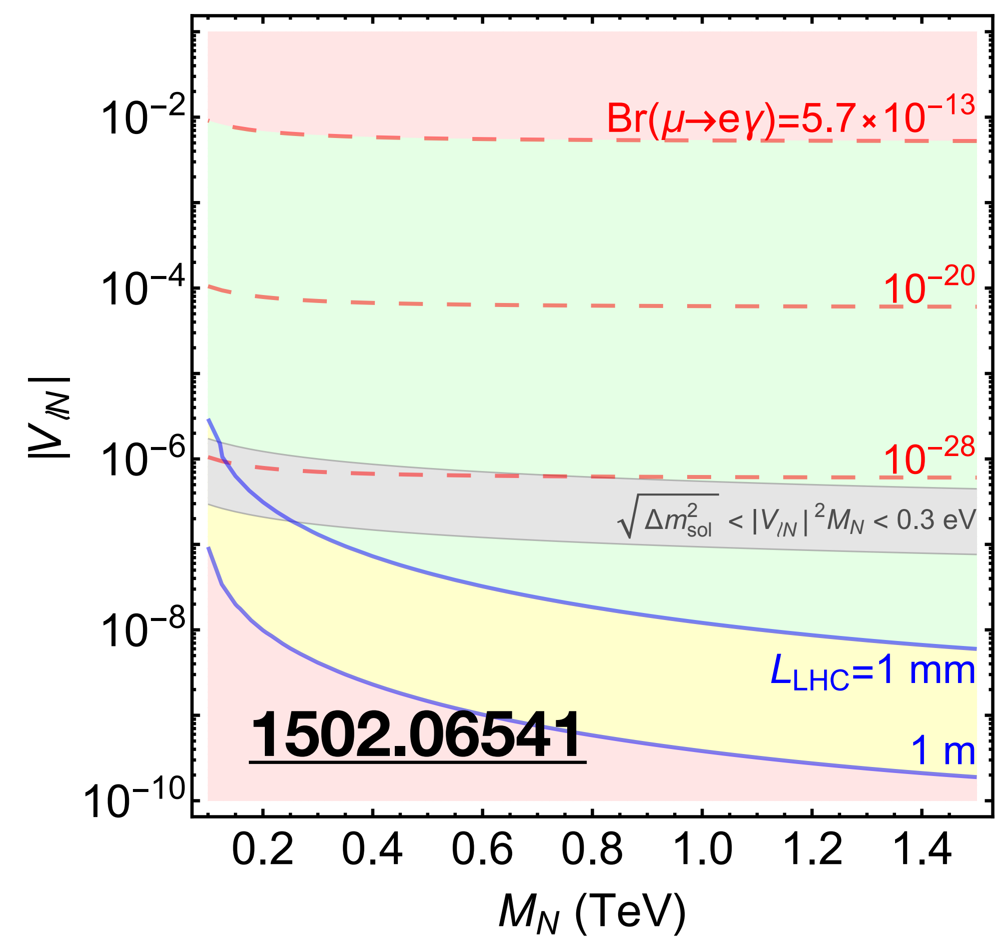
Resonant Leptogenesis

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

Pilaftis & Underwood *Nucl.Phys. B692 303-345*(2004) Abada, Aissaoui, Losada *Nucl.Phys. B728 55-66* (2005)
Garny, Kartavtsev & Hohenegger Annals Phys. 328 (2013) 26-63,
Dev, Millington, Pilaftsis, Teresi Nucl.Phys. B886 (2014) 569-664

- 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.





Deppisch, Dev & Pilaftsis *New J.Phys. 17 no.7, 075019* (2015)
Helo, Kovalenko & Hirsch *Phys.Rev. D89 073005* (2014)
Gago, Hernández, Jones-Pérez, Losada & Briceño *Nucl.Part.Phys.Proc. 273-275 2693-2695* (2016)
Antusch, Cazzato & Fischer *JHEP 1612 007* (2016)

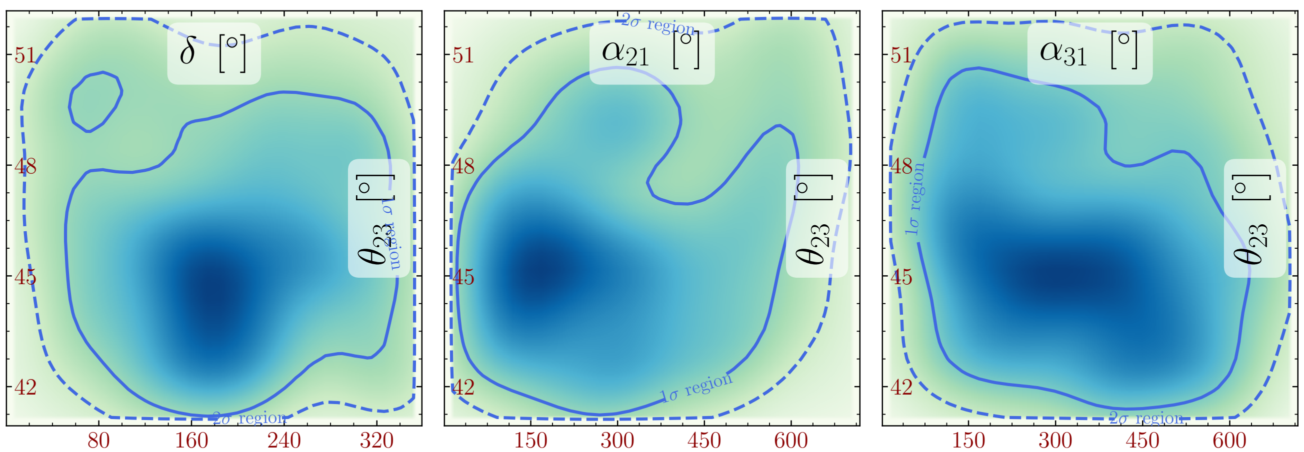
Deppisch, Dev, Pilaftsis, New J.Phys. 17 (2015) no.7, 075019

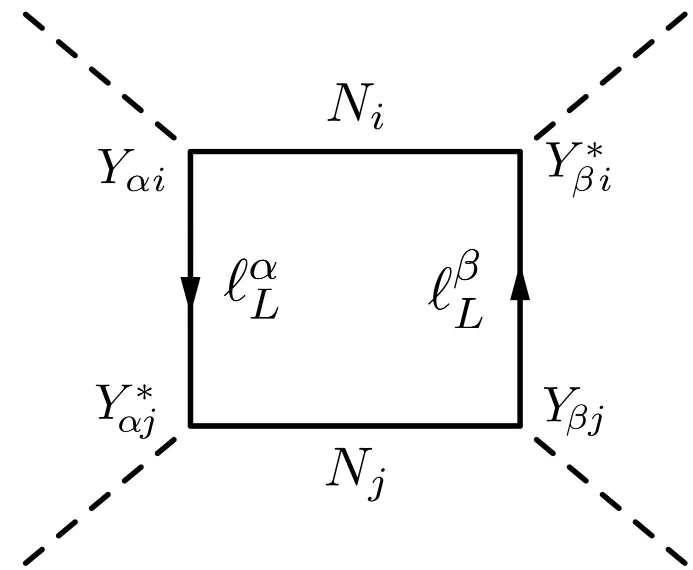
Resonant leptogenesis in the Neutrino Option

- Assume scale invariance about M
- Integrate out TeV scale RHN and RG evolve: Higgs potential produced for M ~ 10^3 TeV

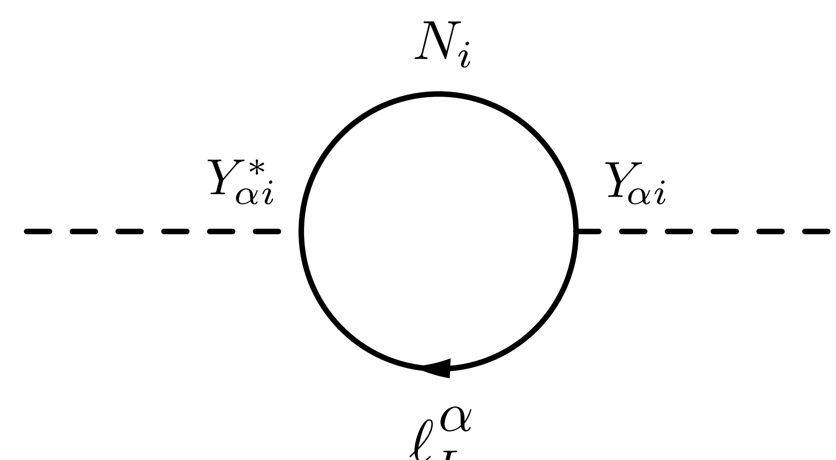
Brdar, Hemboldt, Iwamoto, Schmitz *Phys.Rev. D100 075029* (2019)
Brivio, Moffat, Pascoli, Petcov, Turner *JHEP 1910 059* (2019)

Normal Ordering





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

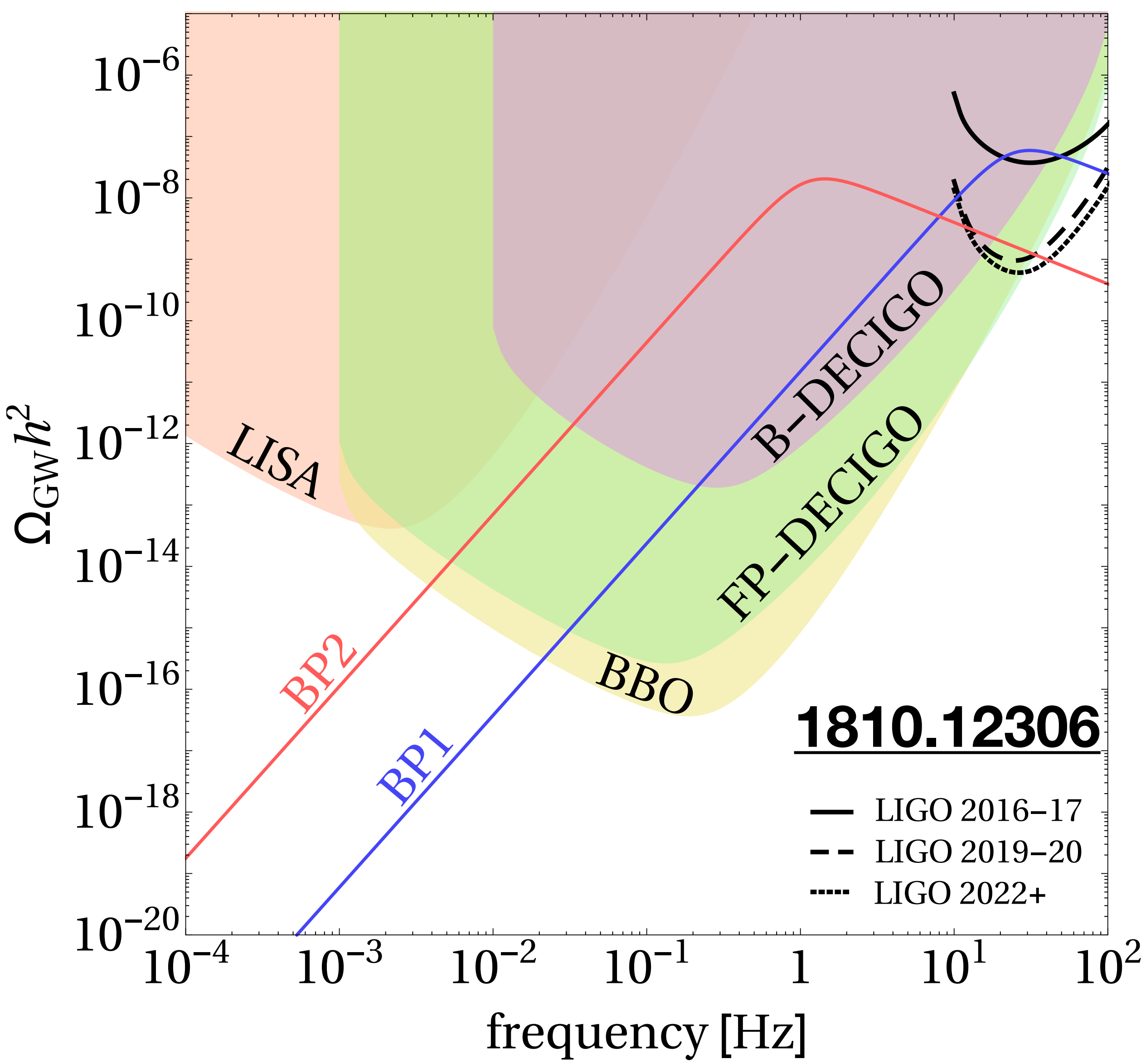


slight preference for $\theta_{23} < 45^\circ$ and $\delta \sim 180^\circ$

Scale invariance broken at quantum level

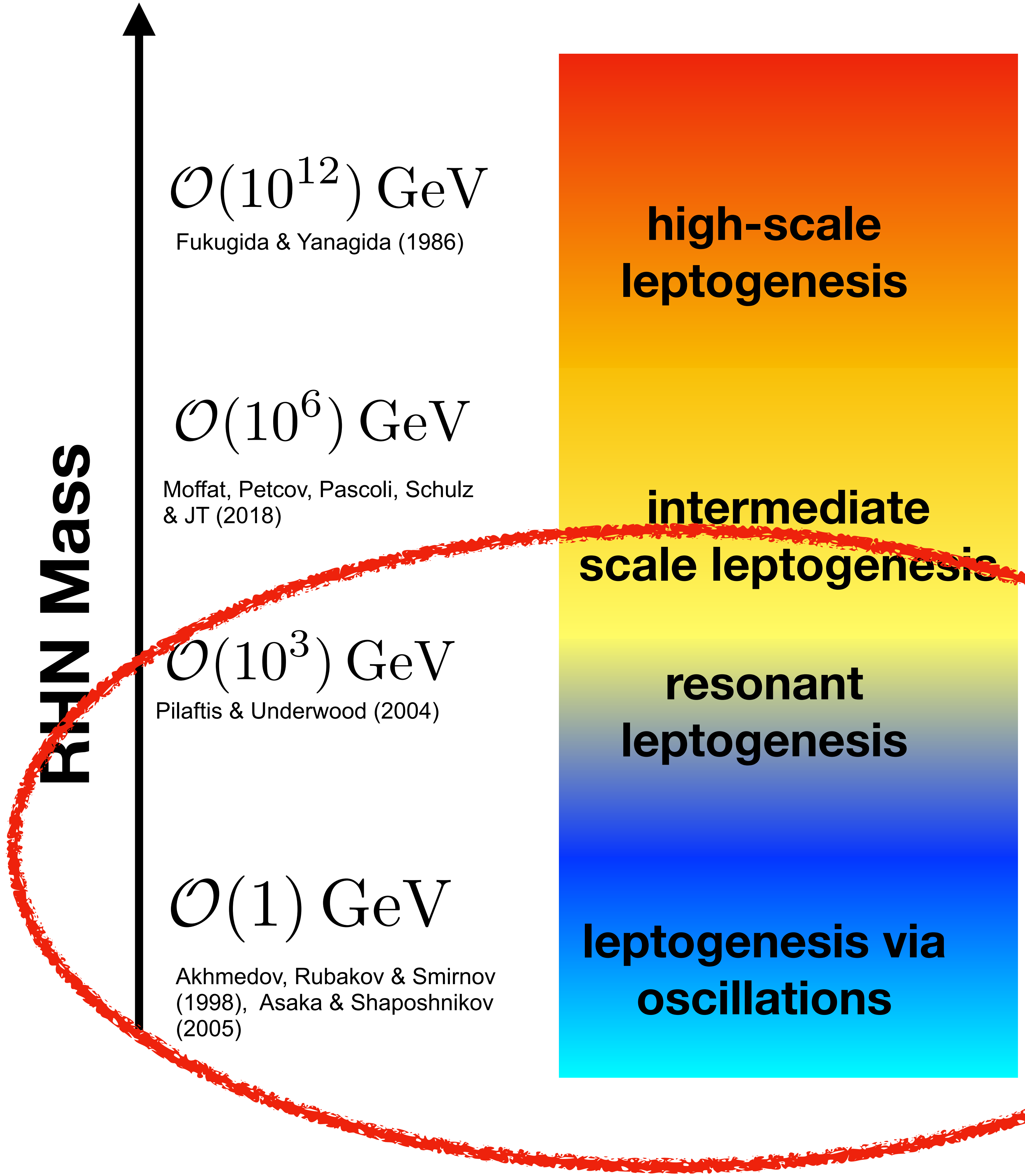
Resonant leptogenesis in the Neutrino Option

- 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



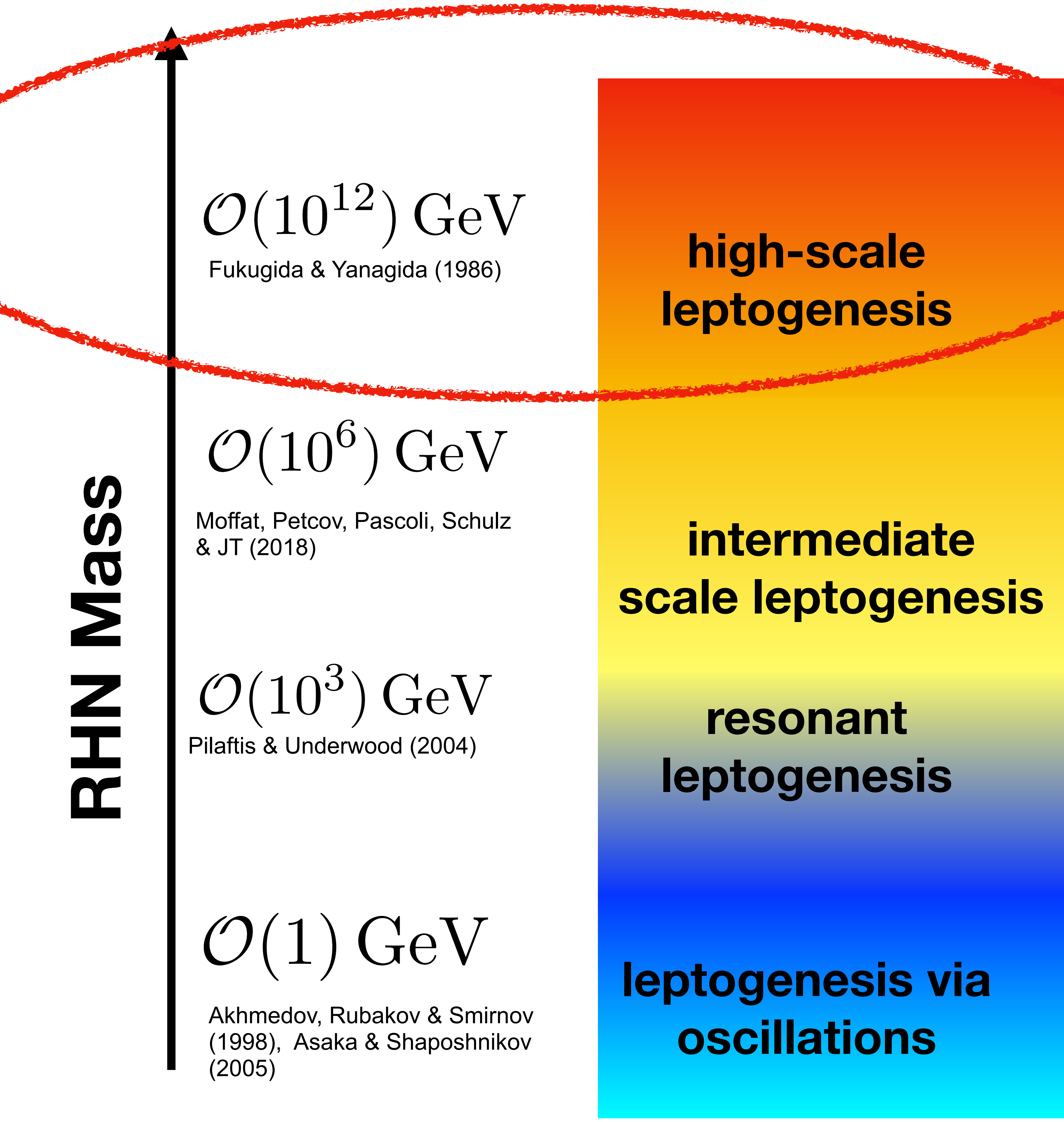
Brdar, Emonds, Helmboldt, Lindner *Phys.Rev. D99 (2019) no.5, 055014*

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



We reviewed results in **low-scale** and **resonant leptogenesis.**

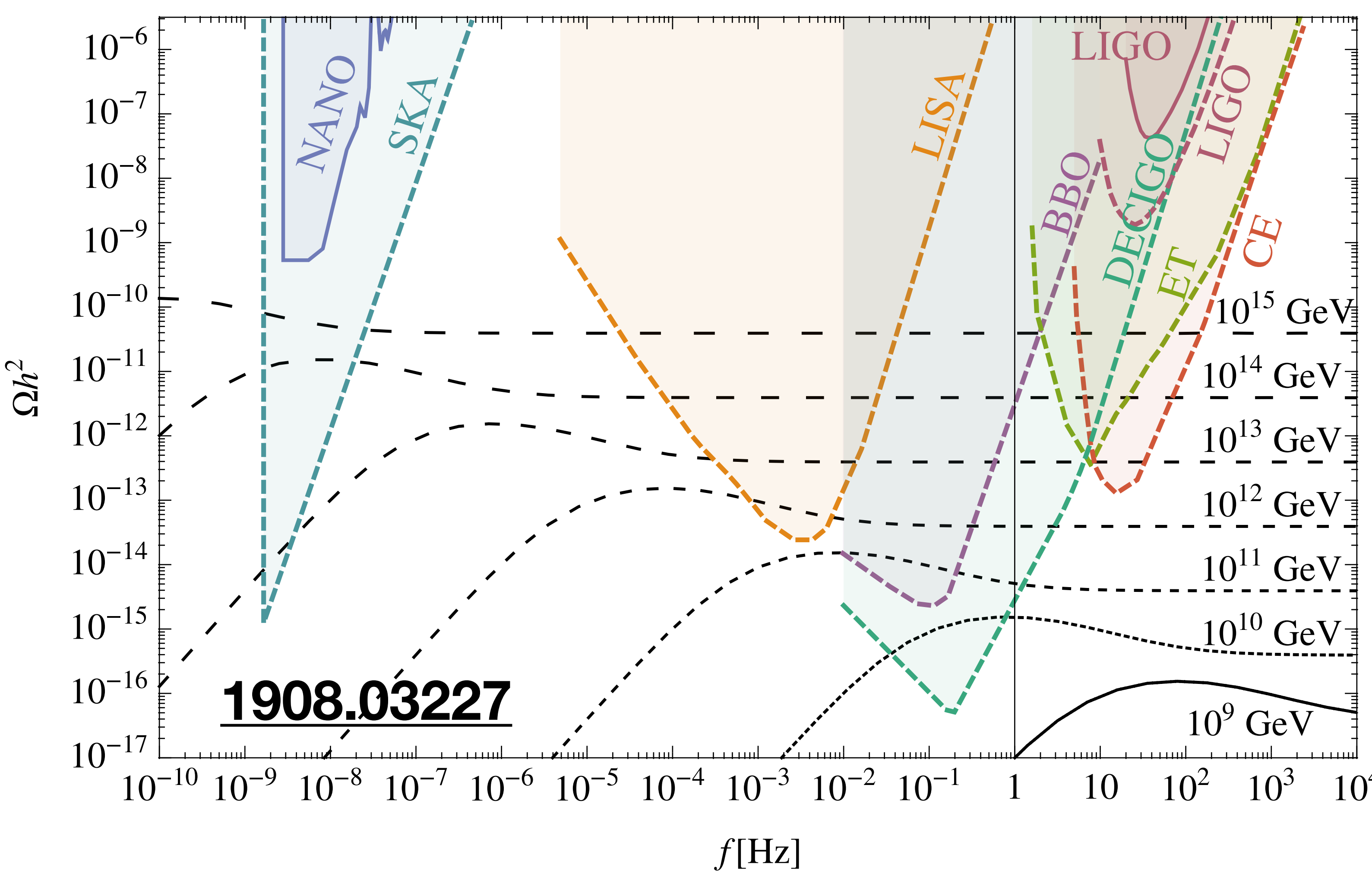
These are the same mechanism see **Klaric et al <u>2008.13771</u>**



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

Thermal leptogenesis

- Lepton asymmetry produced by detailed balance between CP-violating decays of heavy (>10^6 GeV) RHNs and washout processes
- Highlighted by Dror et al that GWs from cosmic string network generic prediction of seesaw mechanism



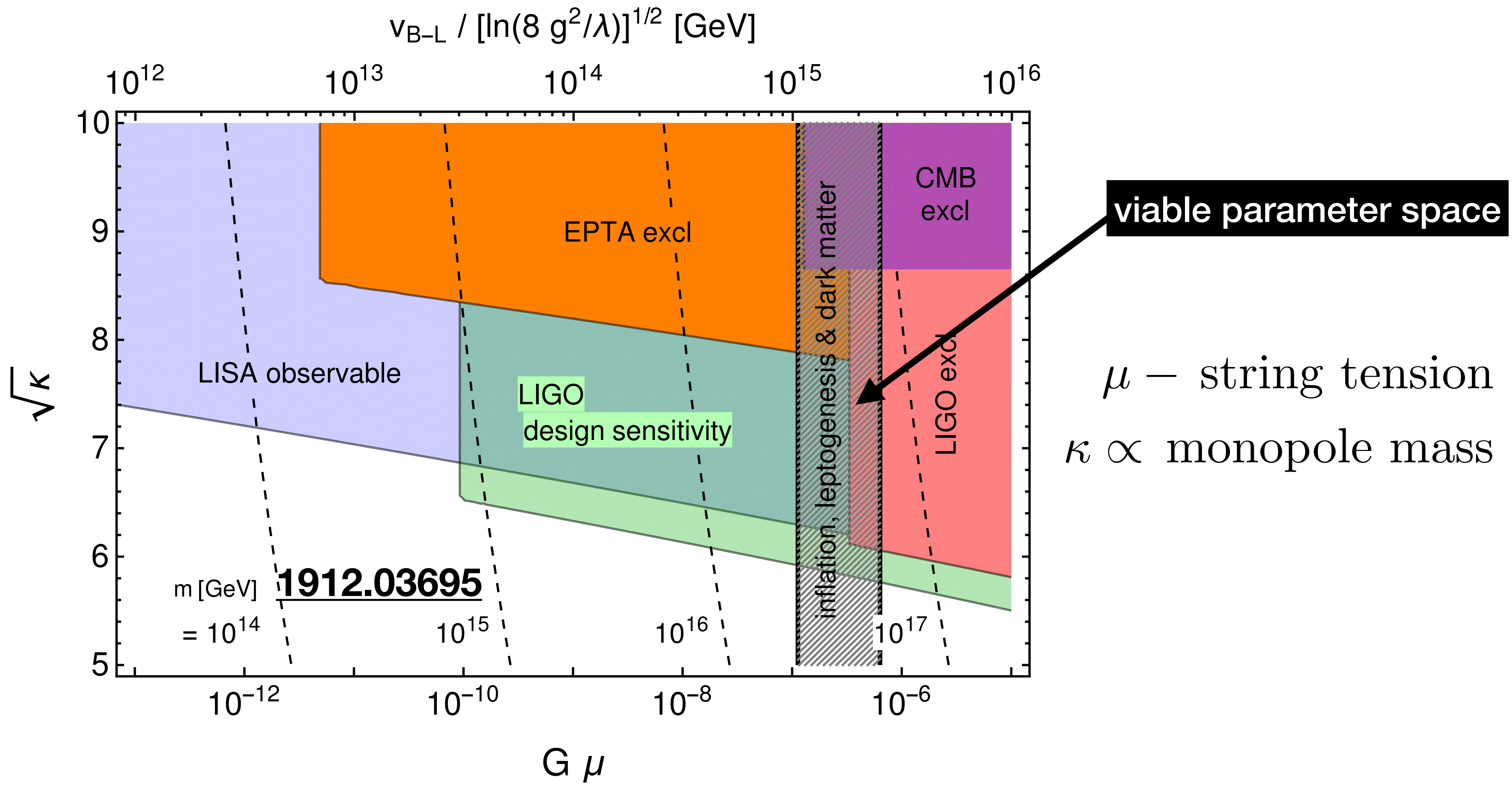
Dror, Hiramatsu, Kohri , Murayama & White *Phys.Rev.Lett. 124 (2020) no.4, 041804*

Thermal leptogenesis

- U(1)B-L used to explain inflation, leptogenesis and neutralino (DM).

monopoles — cosmic strings

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

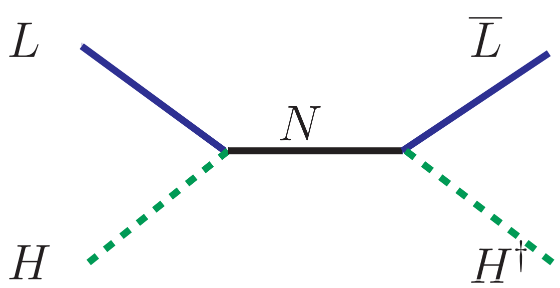


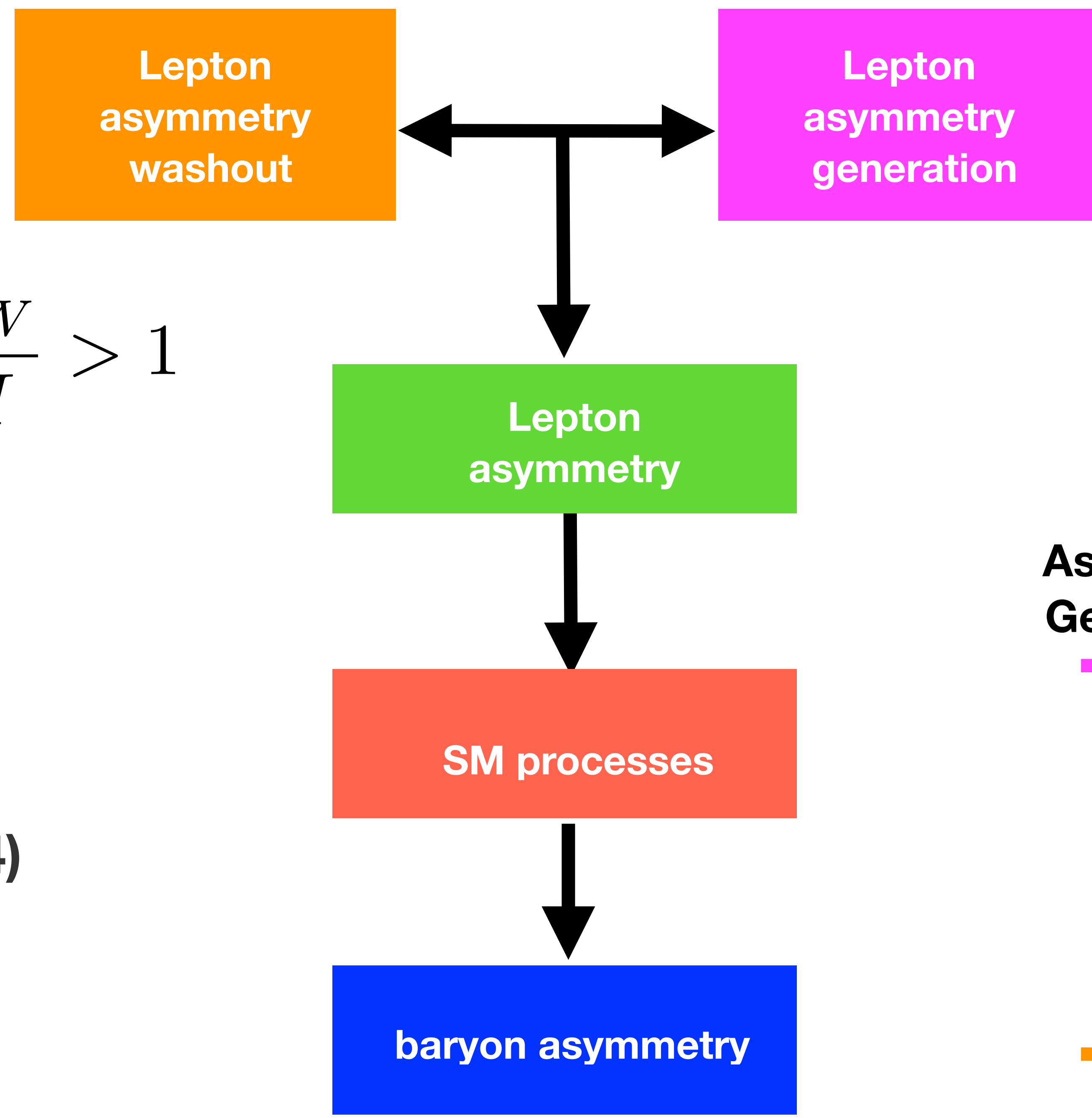
μ — string tension

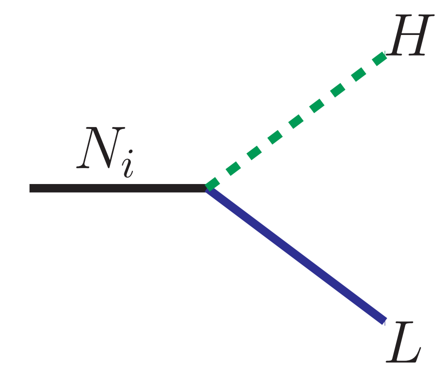
$\kappa \propto$ monopole mass

Buchmuller, Domcke, Murayama & Schmitz *Phys.Lett. B809 (2020) 135764*

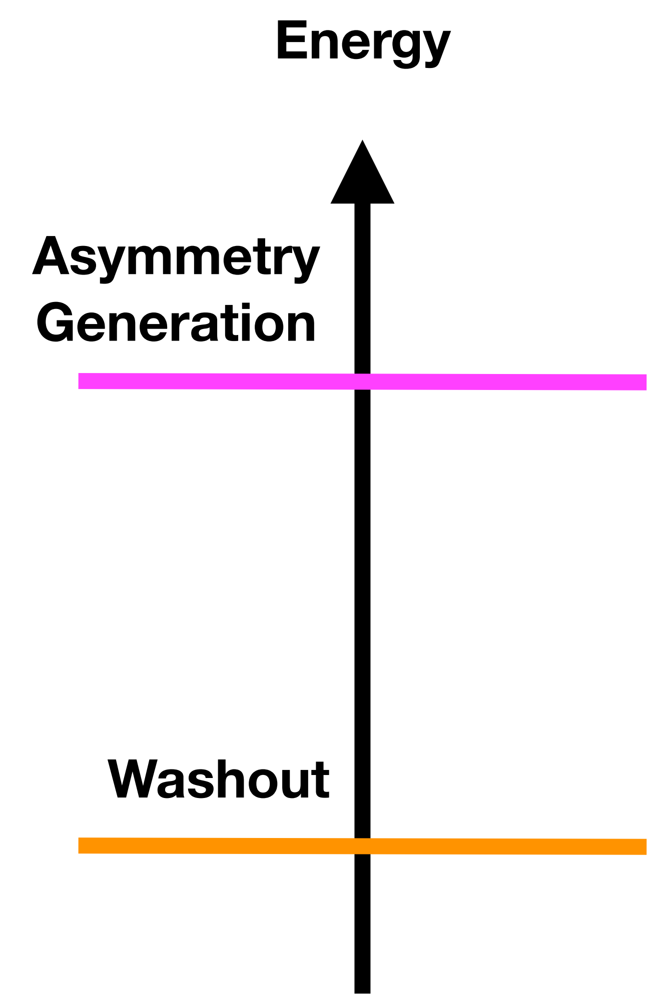
Falsifiability of High-Scale Leptogenesis







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

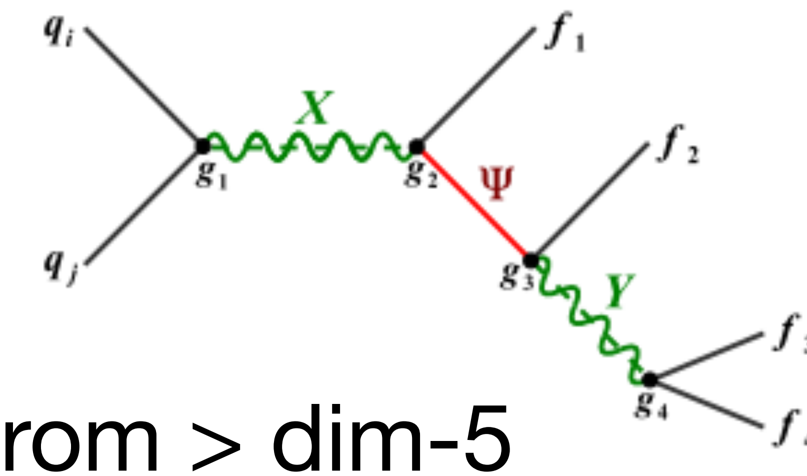


Harz, Deppisch, Hirsch
Phys.Rev.Lett. **112 (2014)**

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

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

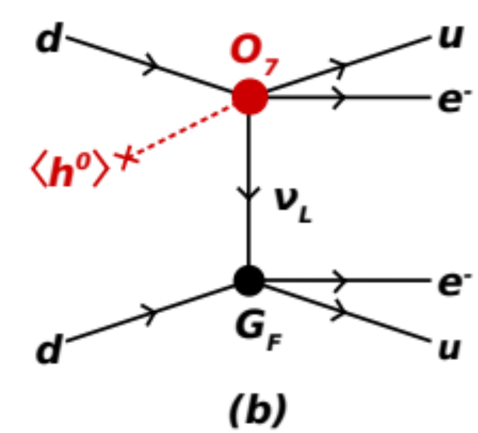
Deppisch & Harz (2014)



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. See 2106.10838 for details

Thermal leptogenesis and primordial black holes

- Primordial BHs could have formed in EU (for formation talk see **Y. Goutennaire**)
- If RHNs exist, PBHs would have produced them. In 2010.03565, Yuber Perez-Gonzalez & I studied this interplay

Morrison, Profumo & Yu *JCAP 1905 (2019) 005*
Fujita, Kawasaki, Harigaya & Matsuda Phys.Rev. D89 (2014) no.10, 103501

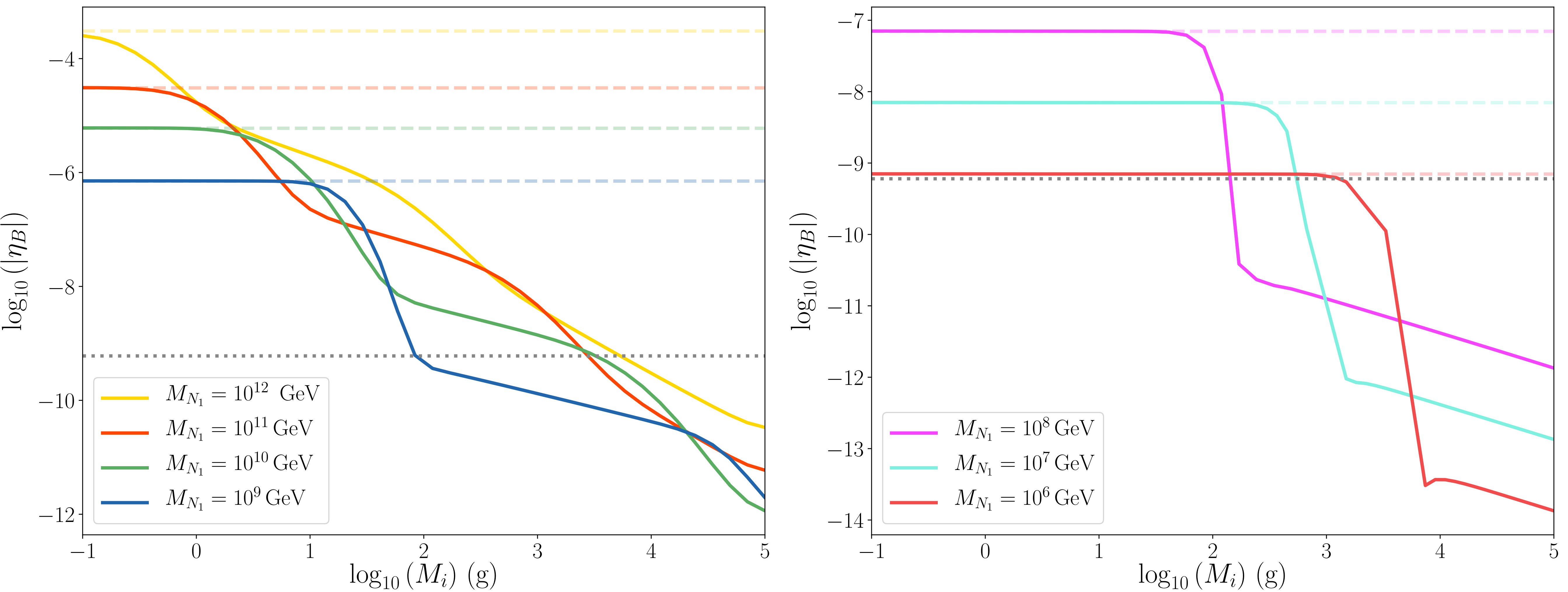
$$aH\frac{dn_{\alpha\beta}^{\rm B-L}}{da} = \epsilon_{\alpha\beta}^{(1)}\left[(n_{N_1}^{\rm TH} - n_{N_1}^{\rm eq})\Gamma_{N_1}^{T} + n_{N_1}^{\rm BH}\Gamma_{N_1}^{\rm BH}\right] + \mathcal{W}_{\alpha\beta}$$

B-L asymmetry from thermal leptogenesis

B-L asymmetry produced from RHN produced from PBH Hawking radiation

Requires solving Friedmann equations for evolution of comoving energy density radiation and PBHs

Thermal leptogenesis and primordial black holes



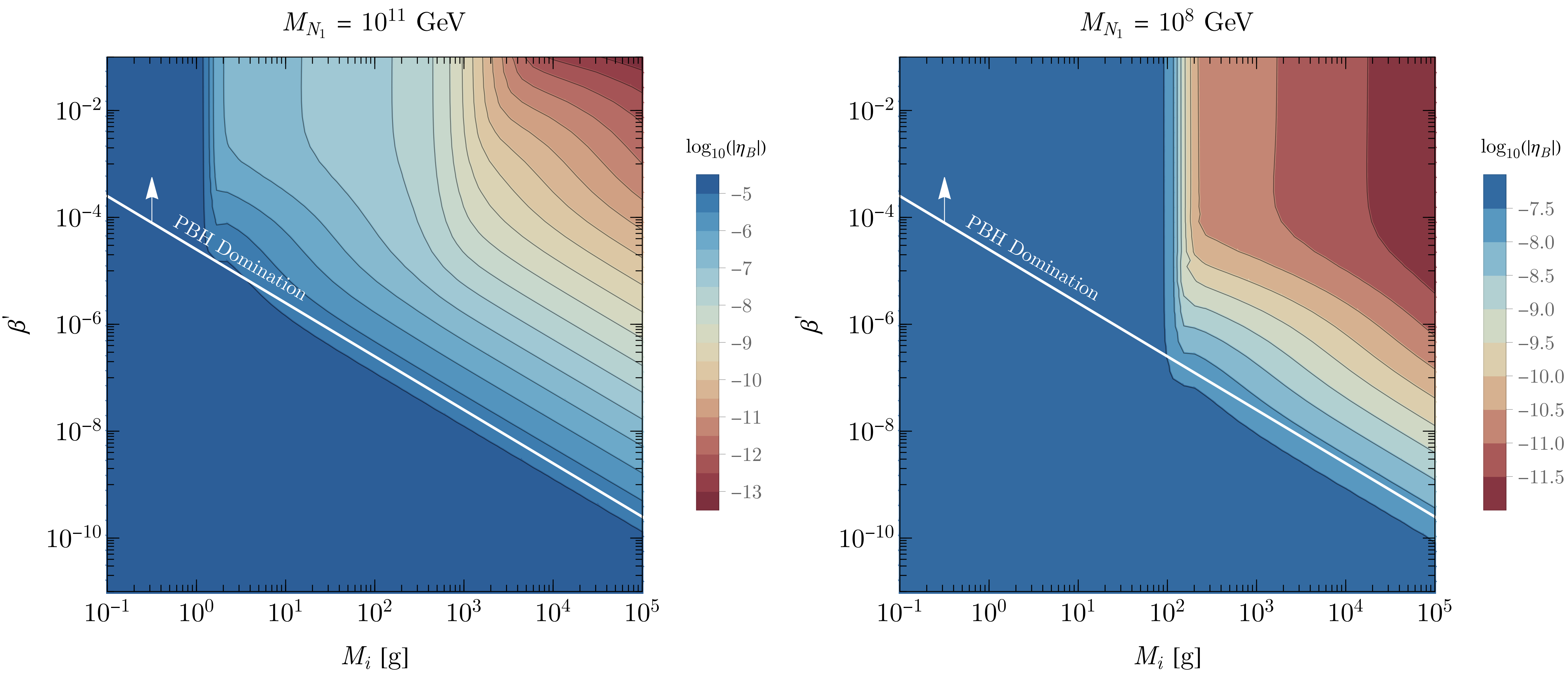
$$\beta' = 10^{-3}$$

Chose Yukawa matrix for maximal baryon asymmetry

Lines indicates upper bound

Thermal leptogenesis and primordial black holes

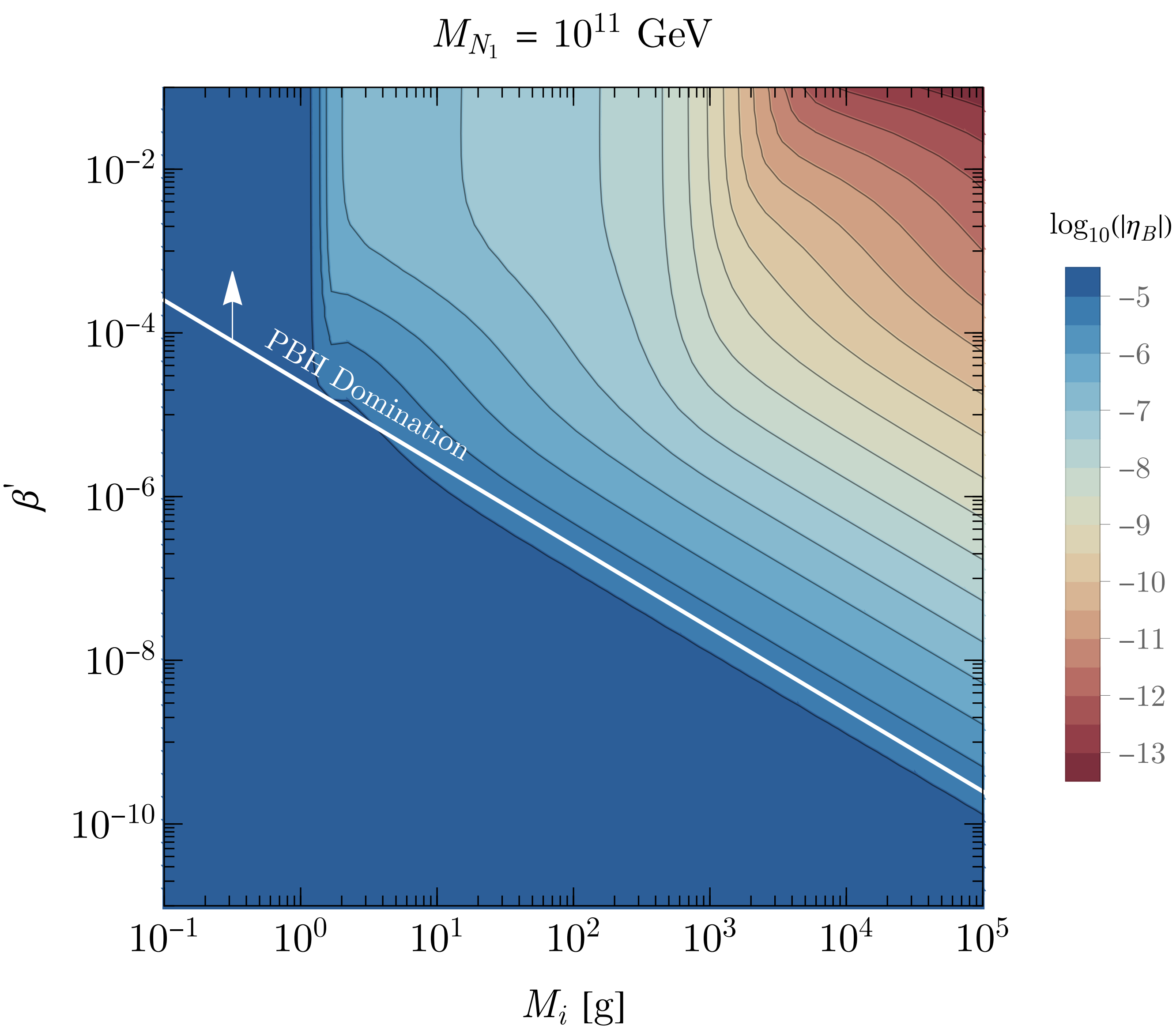
Dilution effect present as long as there is PBH domination

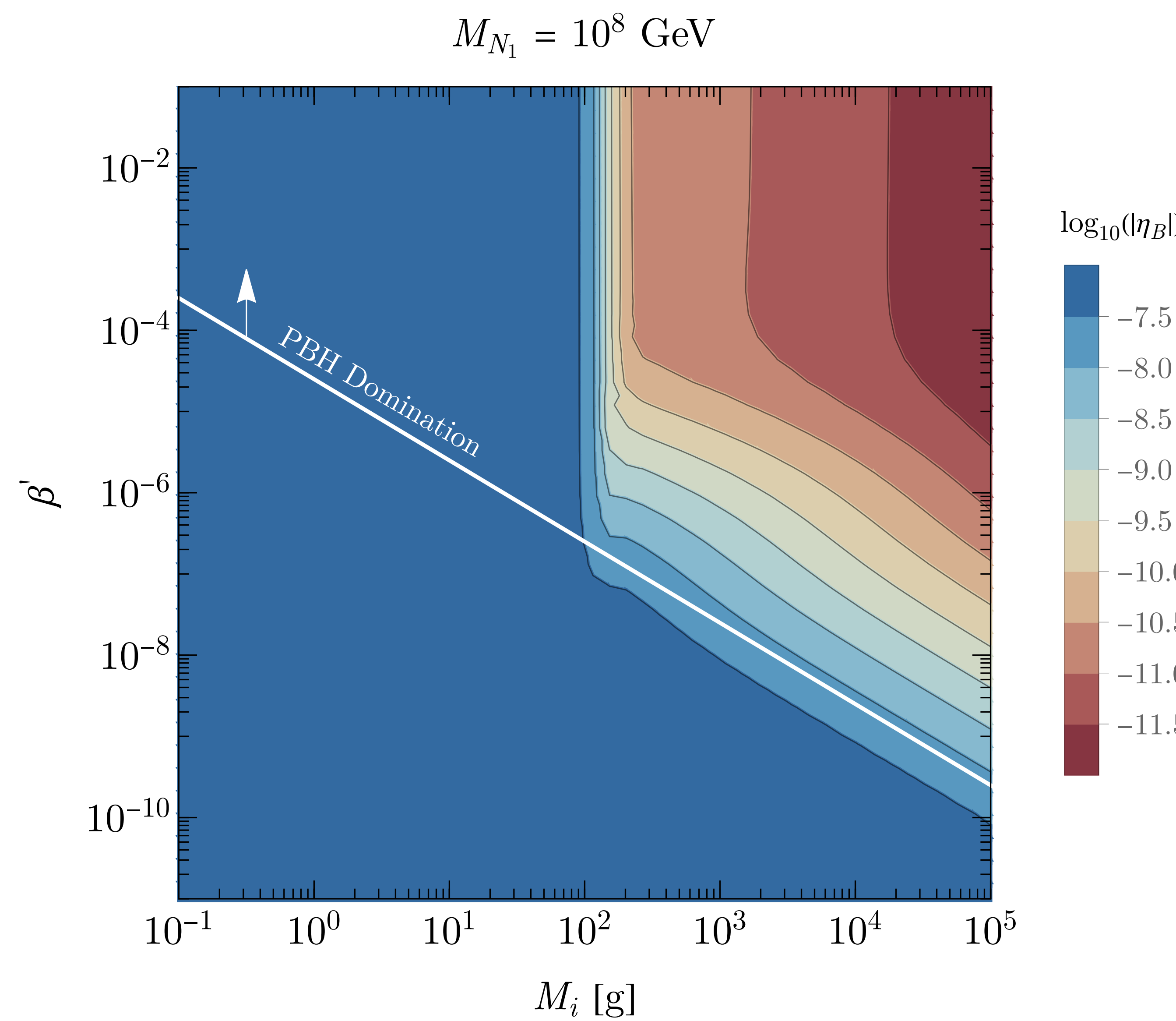


Perez-Gonzalez & JT
***Phys.Rev.D* 104 (2021) 10**

Thermal leptogenesis and primordial black holes

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

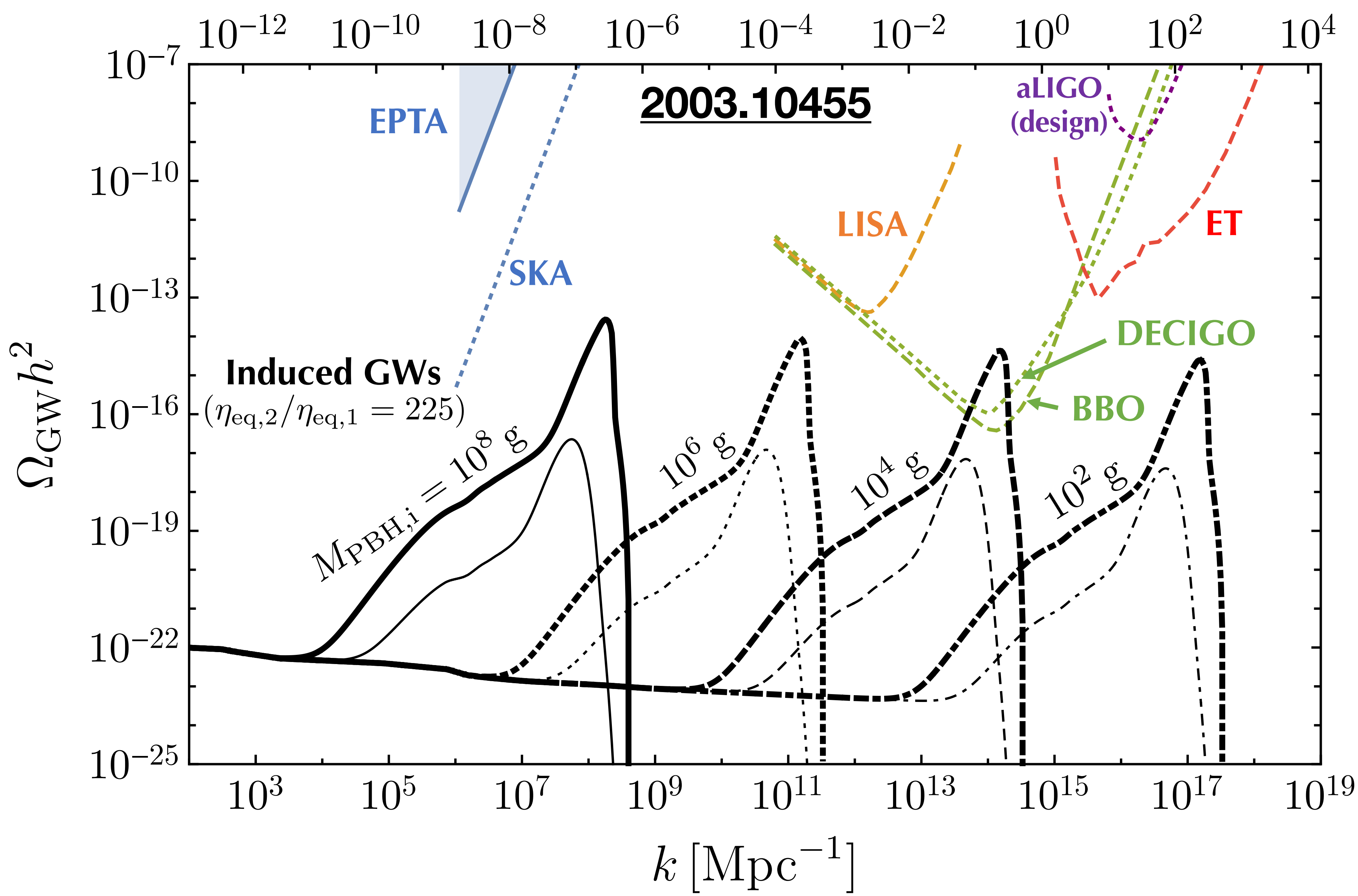




Perez-Gonzalez & JT *Phys.Rev.D* 104 (2021) 10

Thermal leptogenesis and primordial black holes

PBHs create scalar perturbations which generate SGWB via the "poltergeist" effect



Inomata, Kawasaki, Mukaida, Terada, Yanagida, *Phys.Rev.D* 101 (2020) 12

ULYSSES: Universal LeptogeneSiS Equation Solver

- Thermal & resonant with standard & non-standard cosmology
- This summer: evolution of full phase space + quantum statistics & leptogenesis via oscillations (in collaboration with B. Shuve)
- Looking for collaborators!

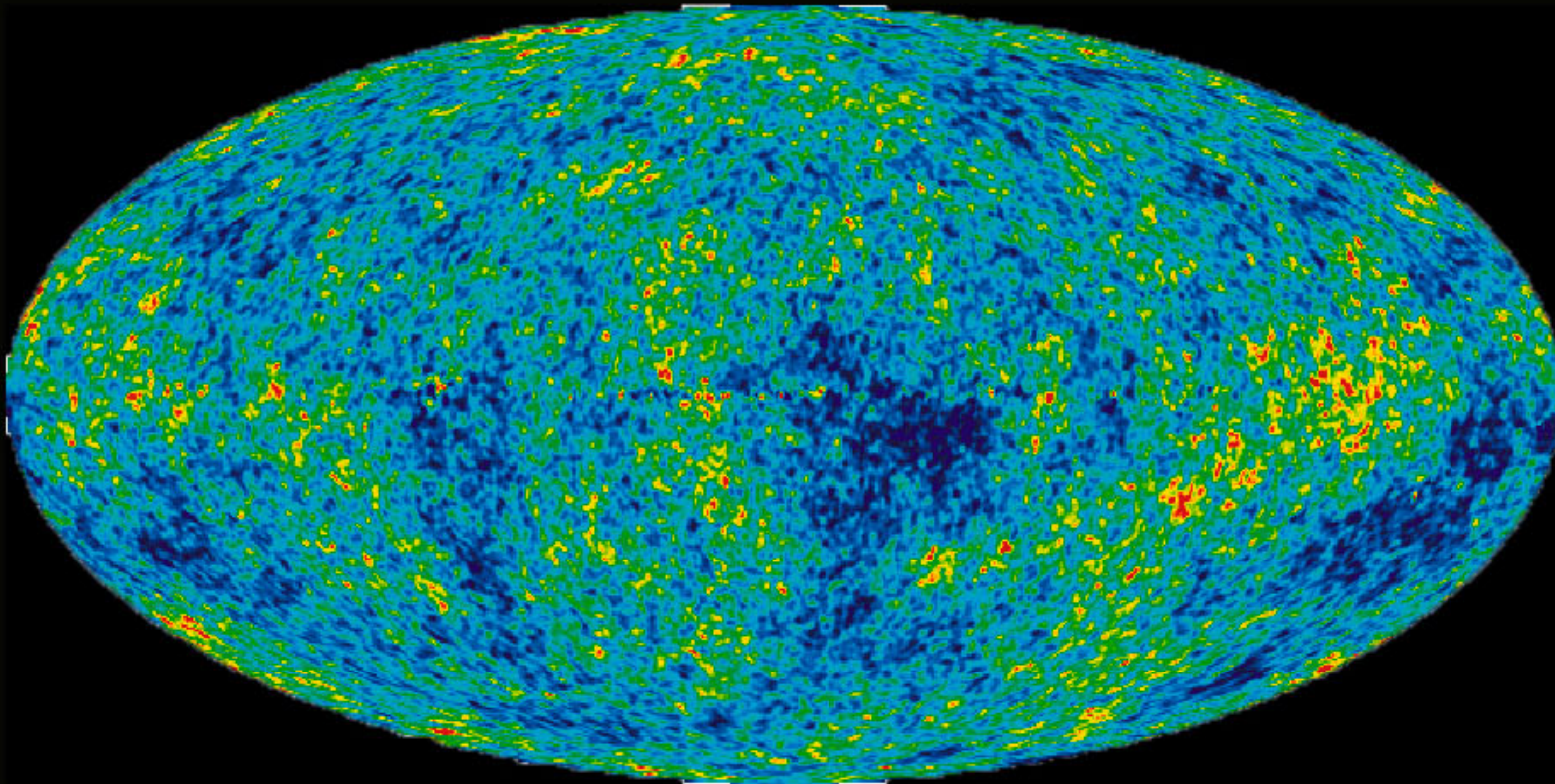
Summary

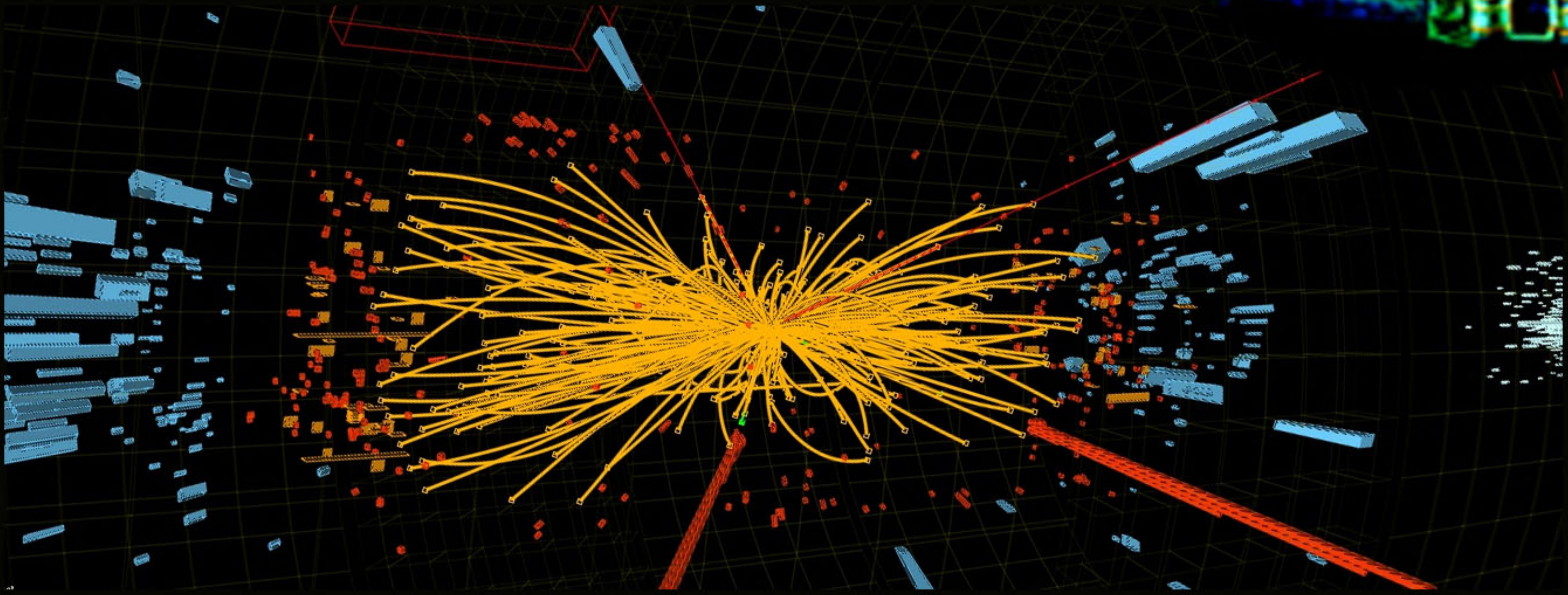
- Leptogenesis is a plausible explanation for the smallness of neutrino masses and the observed matter anti-matter asymmetry

- In the type-I seesaw framework for leptogenesis, the mass of the RHN can range from MeV - 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.

- Gravitational waves are a complementary probe of intermediate and high-scale leptogenesis





Merci!