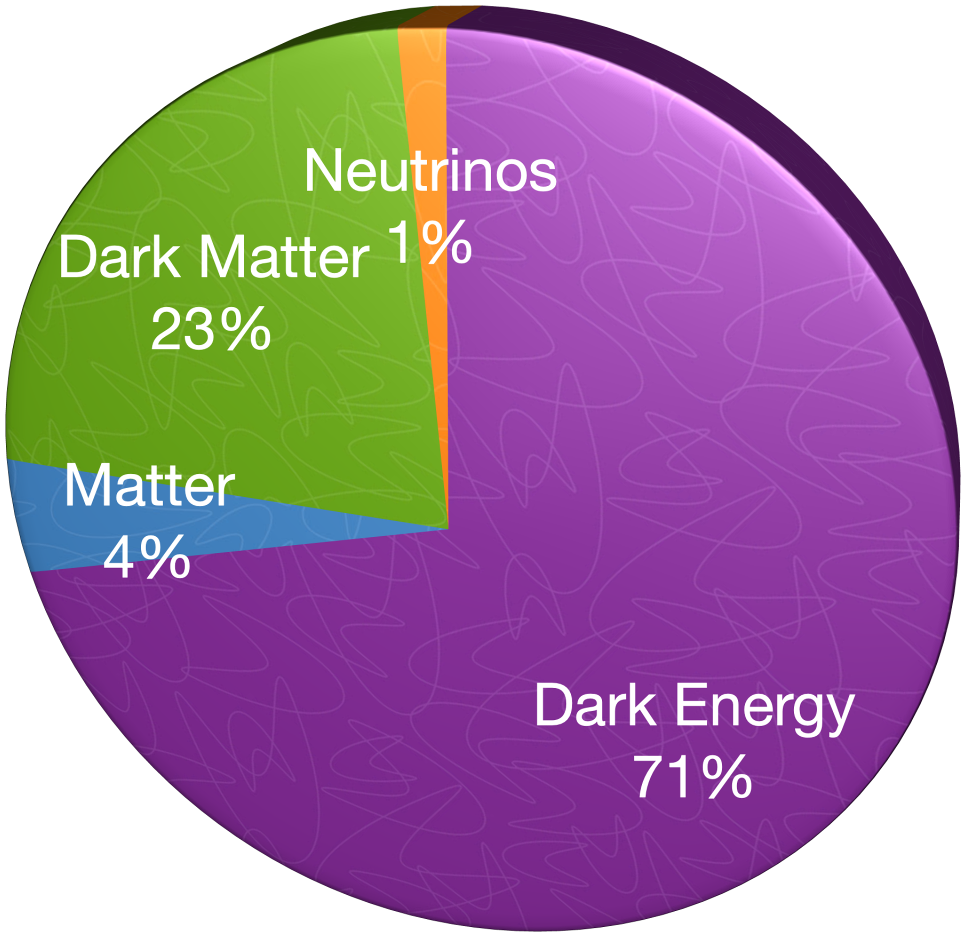
Leptogenesis

XIX International Workshop on Neutrino Telescopes

Jessica Turner, Durham University

Universe's Energy Budget



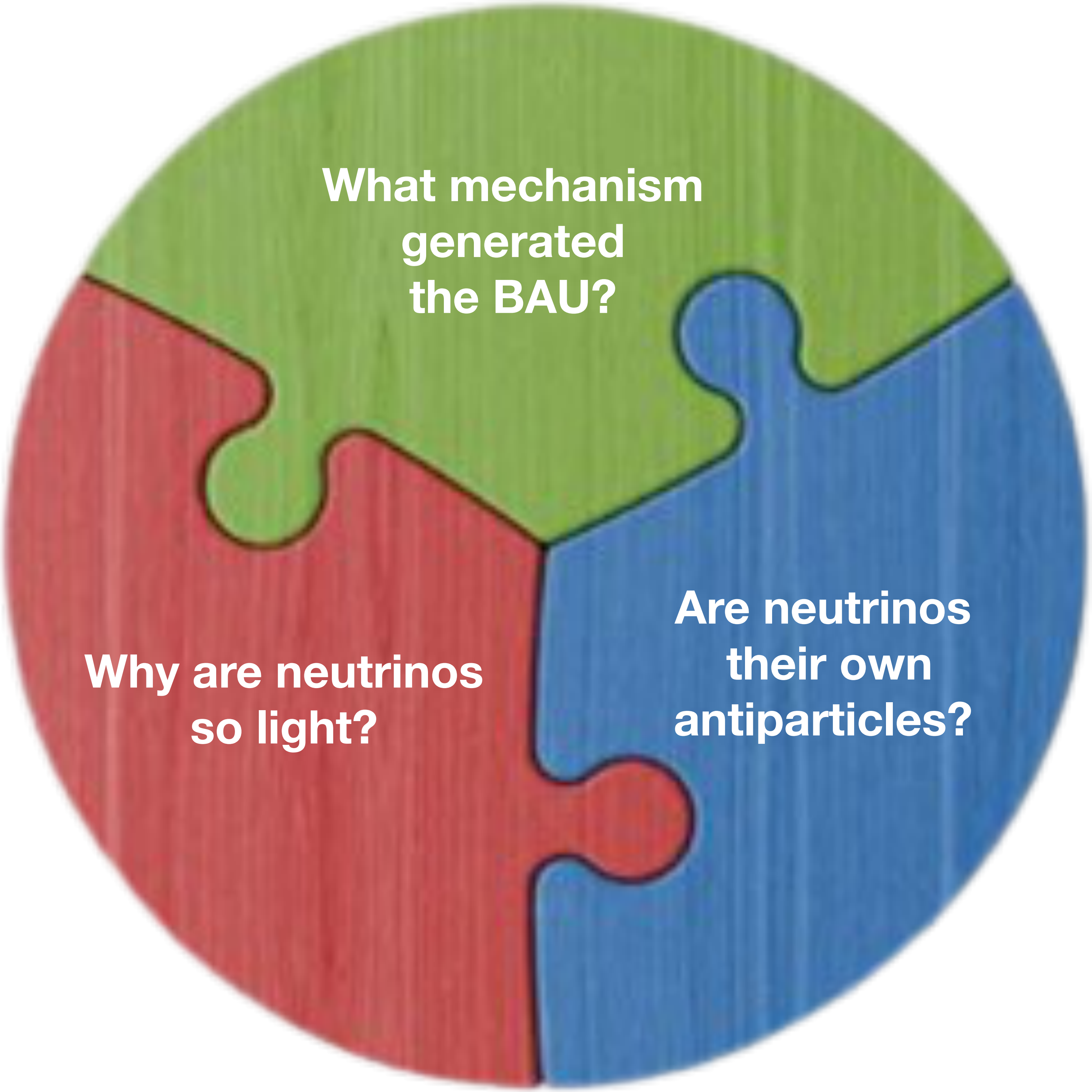
$$\eta_B = (6.02 - 6.18) \times 10^{-10}$$

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

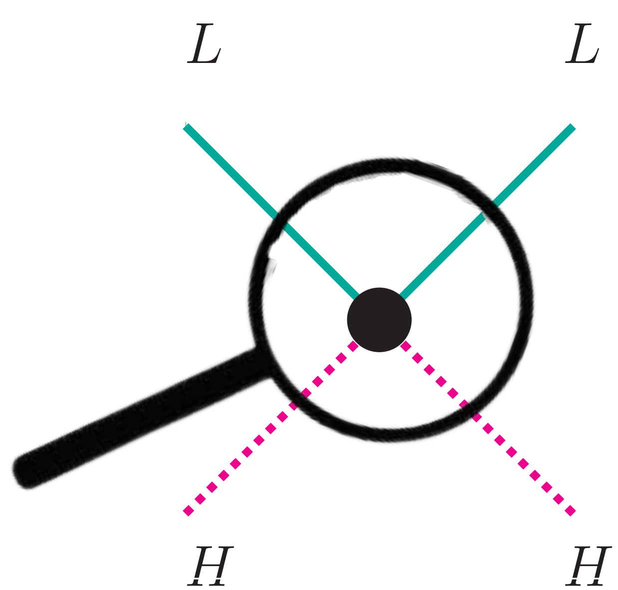


The Seesaw Mechanism

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

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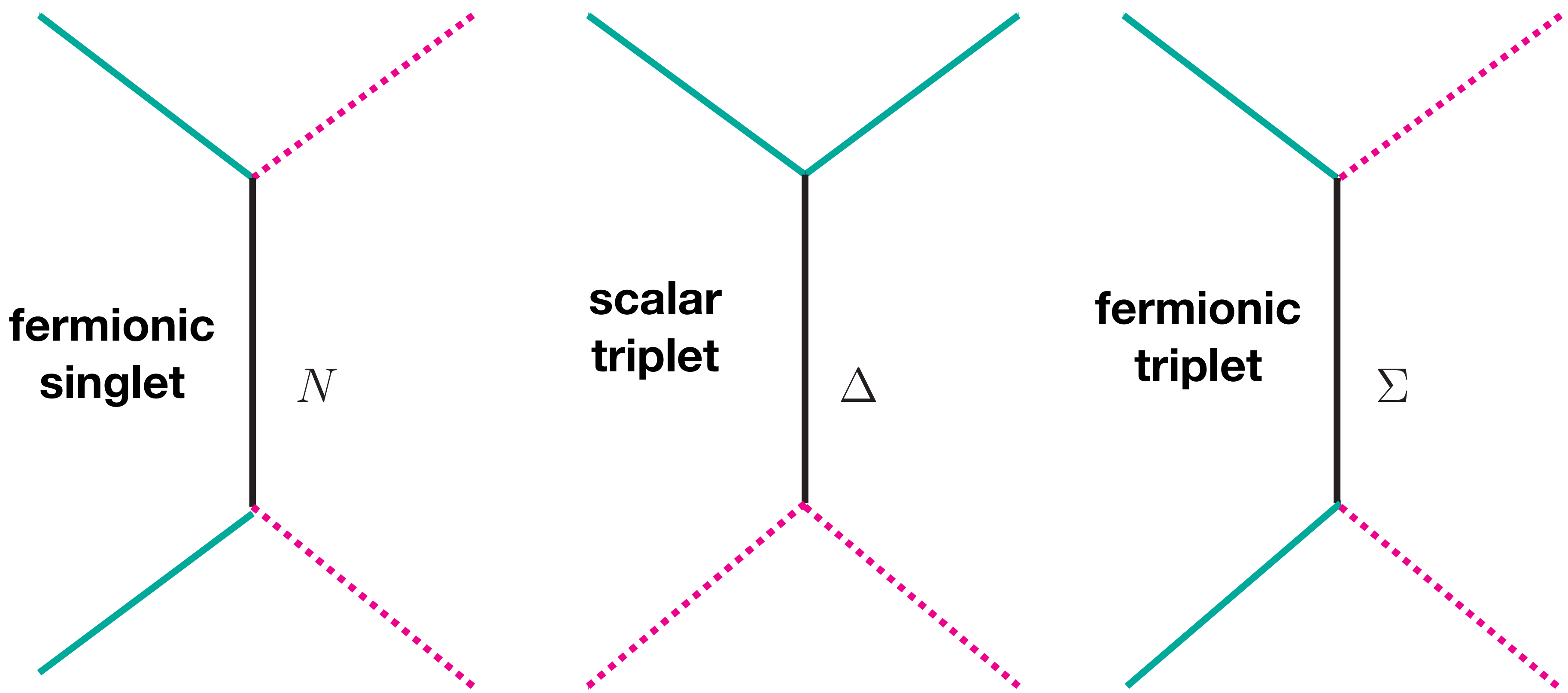

Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

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Ma, Roy, Senjanovic, Hambye

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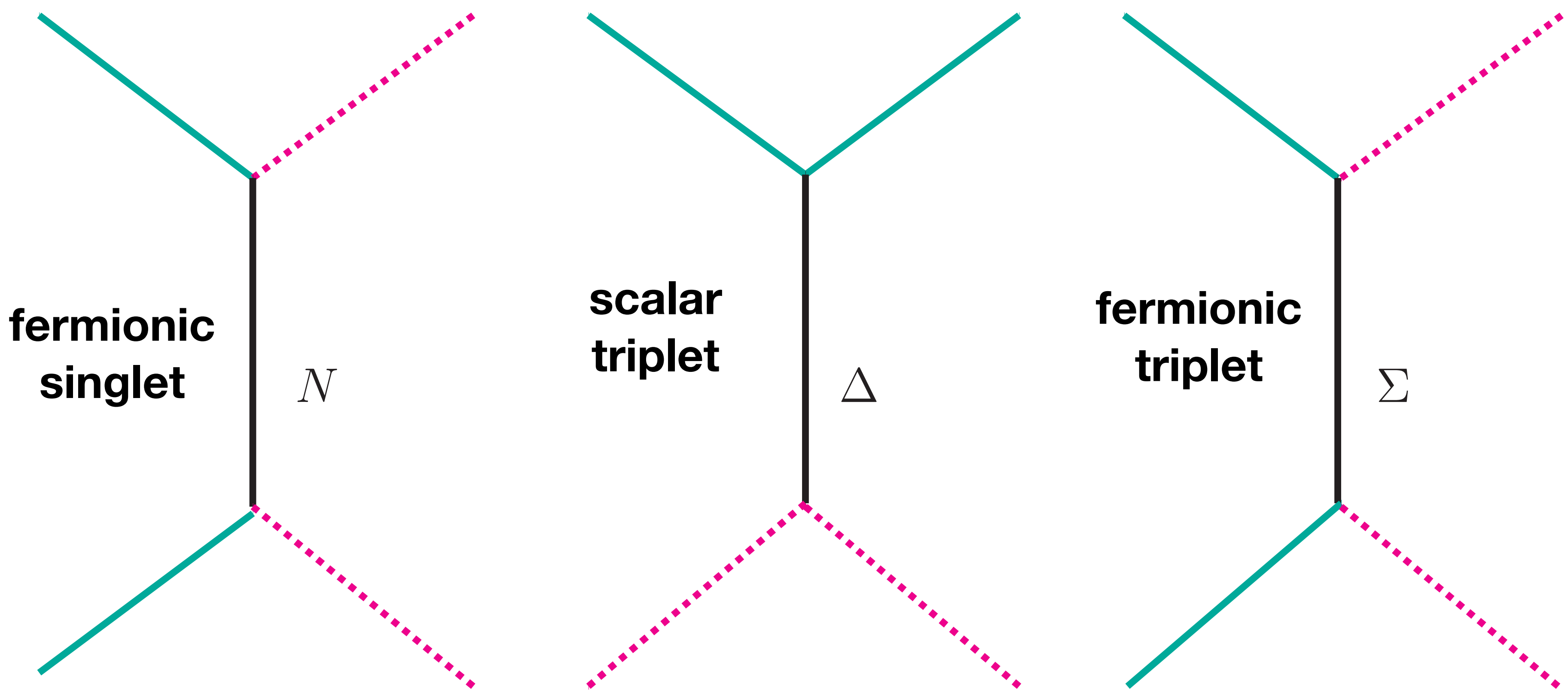
Type-I seesaw **Type-II seesaw** **Type-III seesaw**



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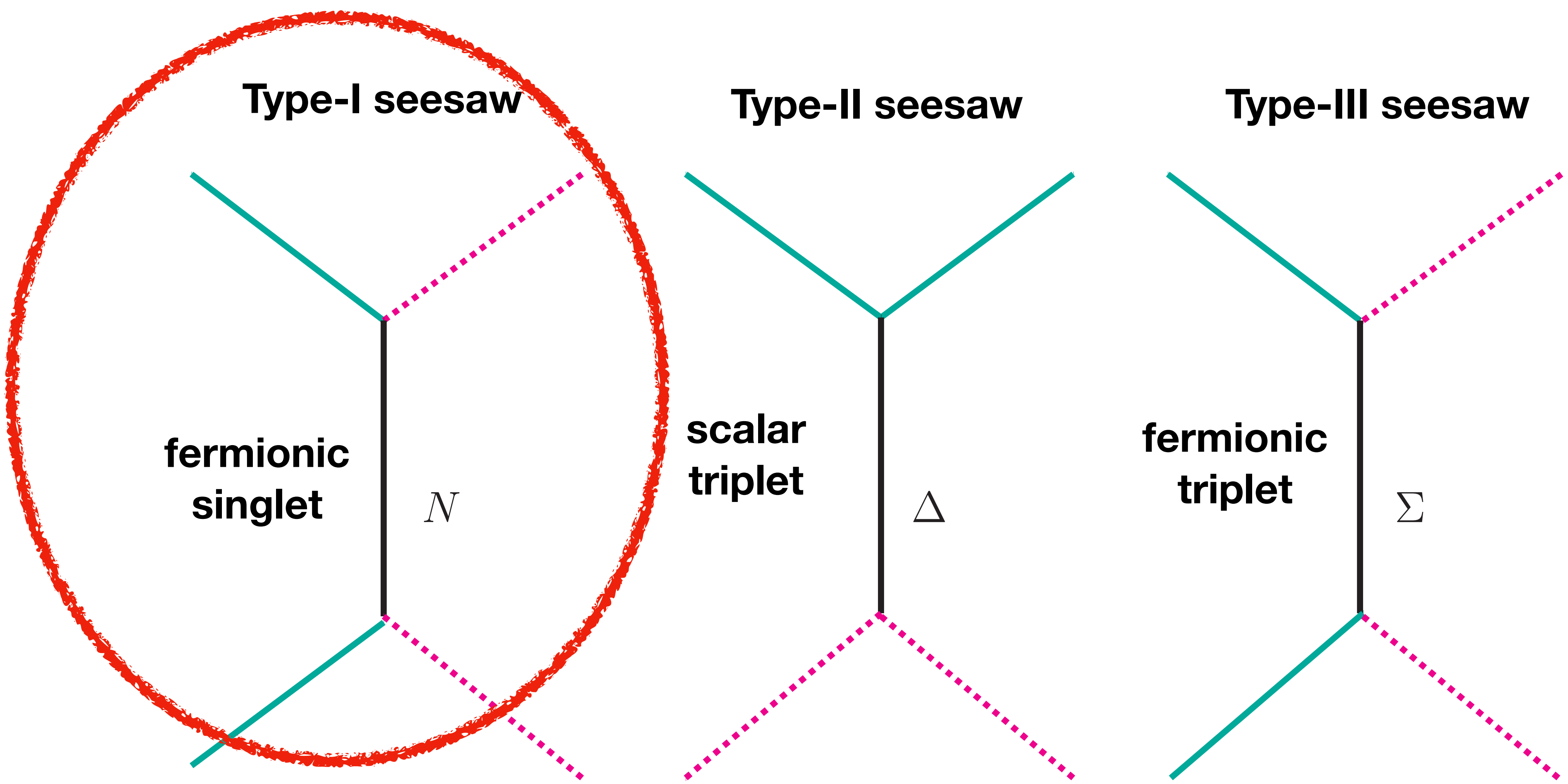

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The Seesaw Mechanism

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

After diagonalising the mass matrix

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

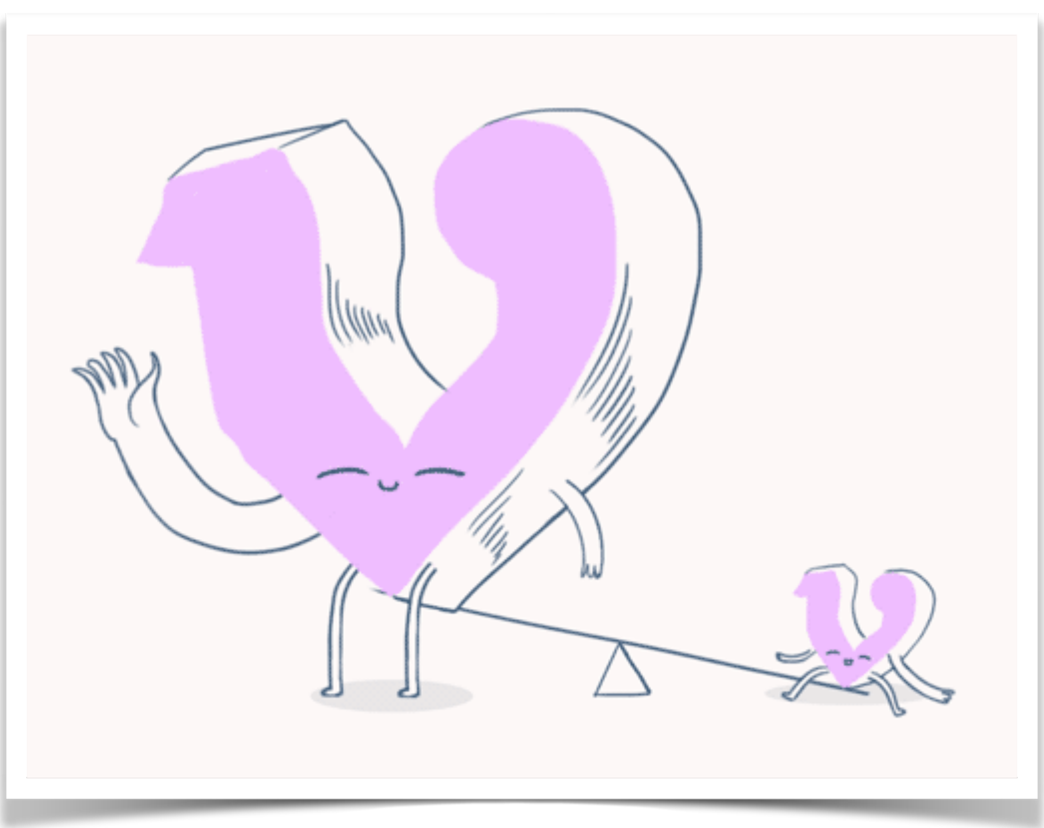

Image courtesy of Symmetry Magazine

Sakharov's Conditions

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

Mass RHN

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

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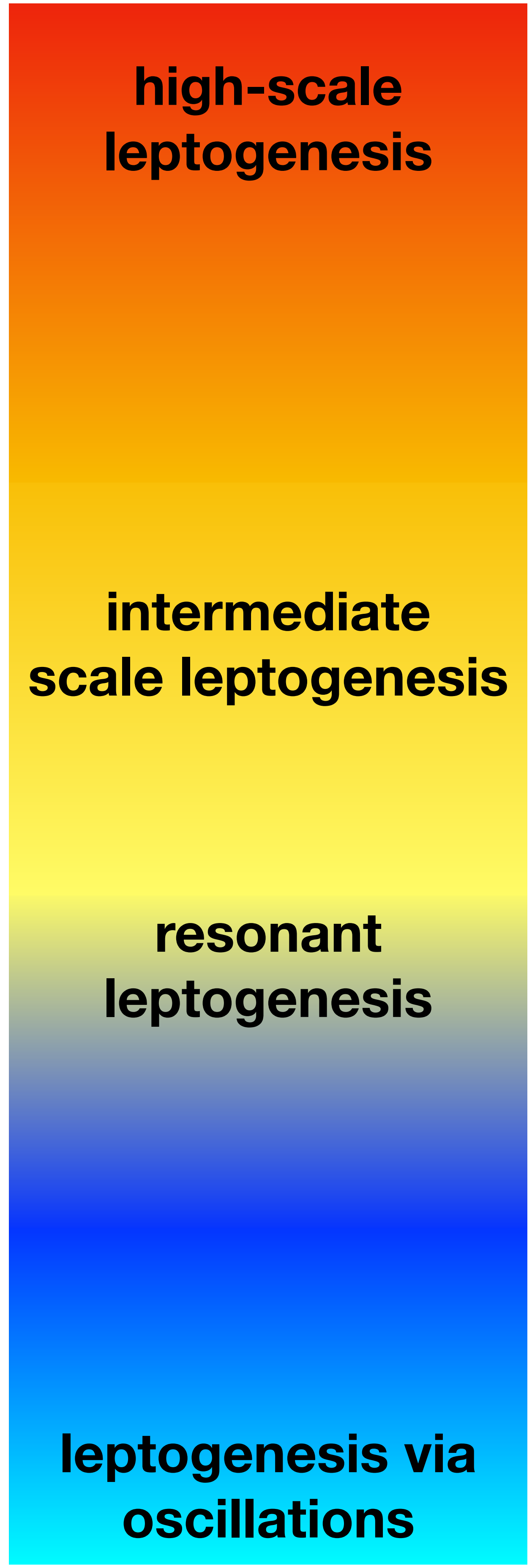

Leptogenesis: dynamical generation of lepton asymmetry. Electroweak sphaleron: lepton →baryon asymmetry

Need to Boltzmann equations which track the time evolution of the RHN and lepton asymmetry

Mass RHN

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high-scale leptogenesis

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Due to expansiveness of the field my references will not be exhaustive.

Apologises.

See this excellent and recent review: 2009.07294 by Bödeker & Buchmüller

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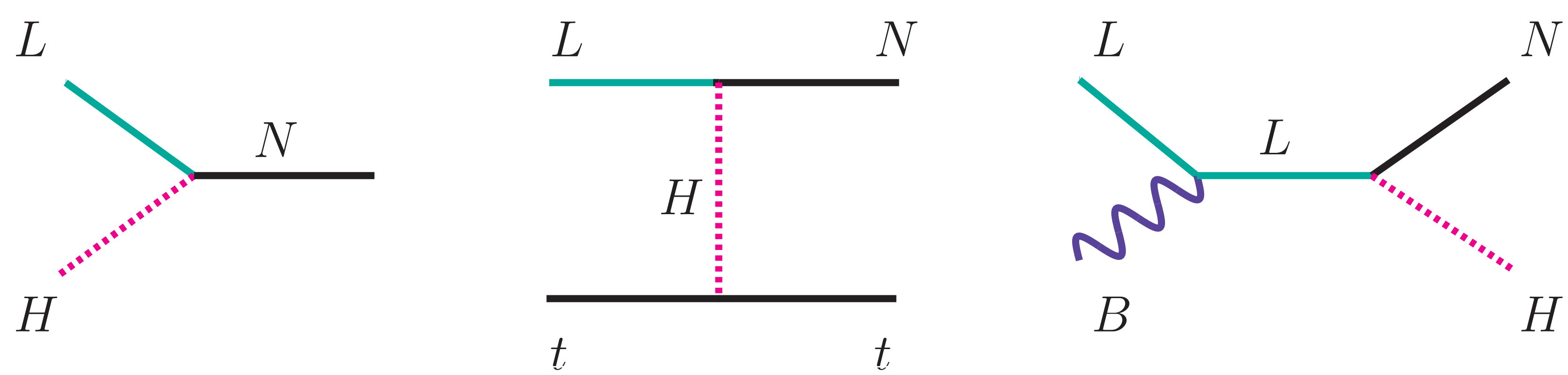
Leptogenesis via Oscillations

- 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 → 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)
Asaka, Eijima & Ishida *JHEP 1104 011*(2011)
Canetti, Drewes, Frossard & Shaposhnikov *Phys.Rev. D87 093006* (2013)
Abada, Arcadi, Domcke & Lucente *JCAP 1511 041* (2015)
Hernandez, Kekic, Lopez-Pavon, Racker, Salvado *JHEP 1608 157* (2016)
Ghiglieri & Laine *JHEP 1705 (2017) 132* (2017)
Bodeker & Schroder *JCAP 1905 010* (2019)

Leptogenesis via Oscillations with 2 RHNs

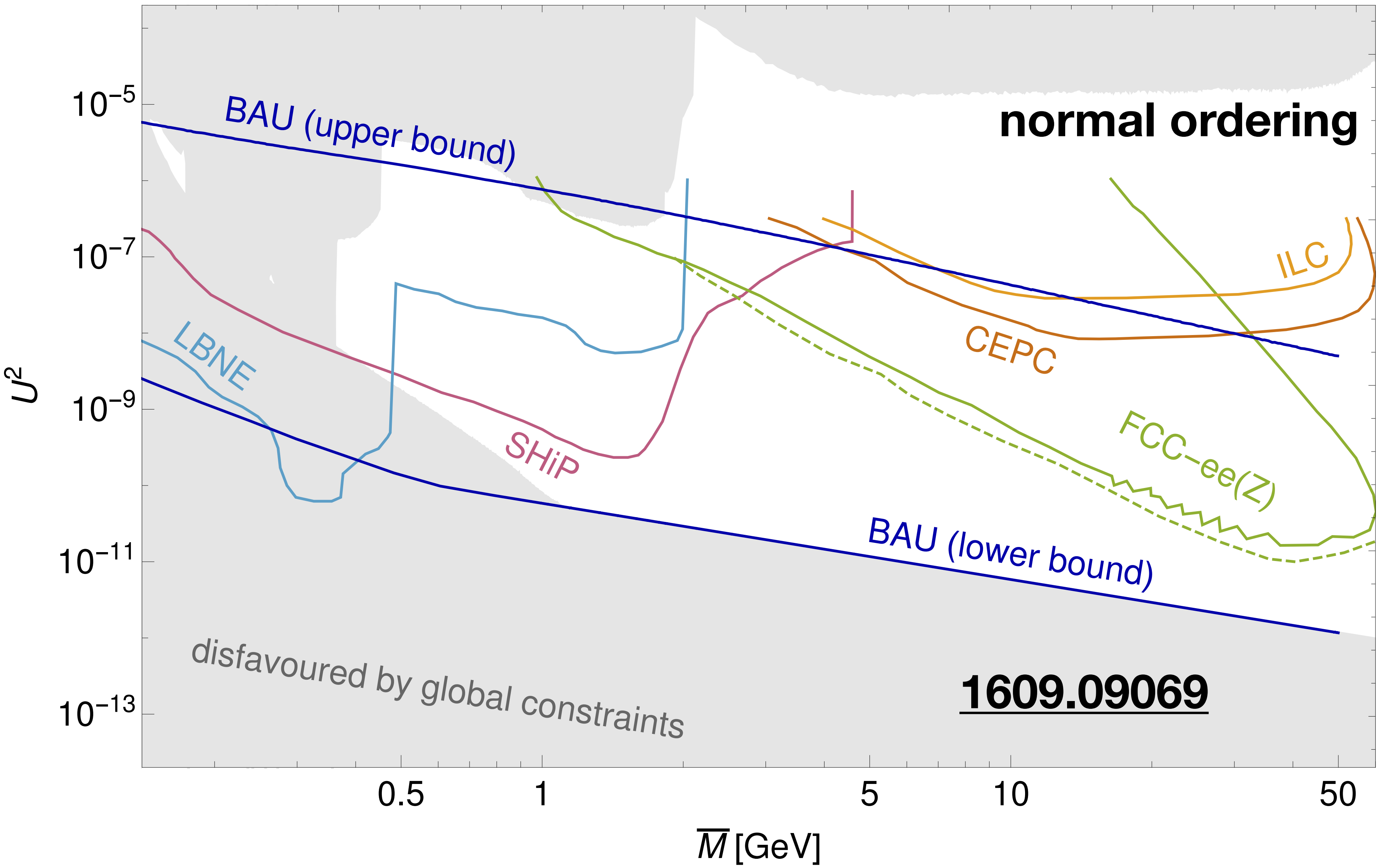
- GeV-scale RHNs → rich phenomenology

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

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

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

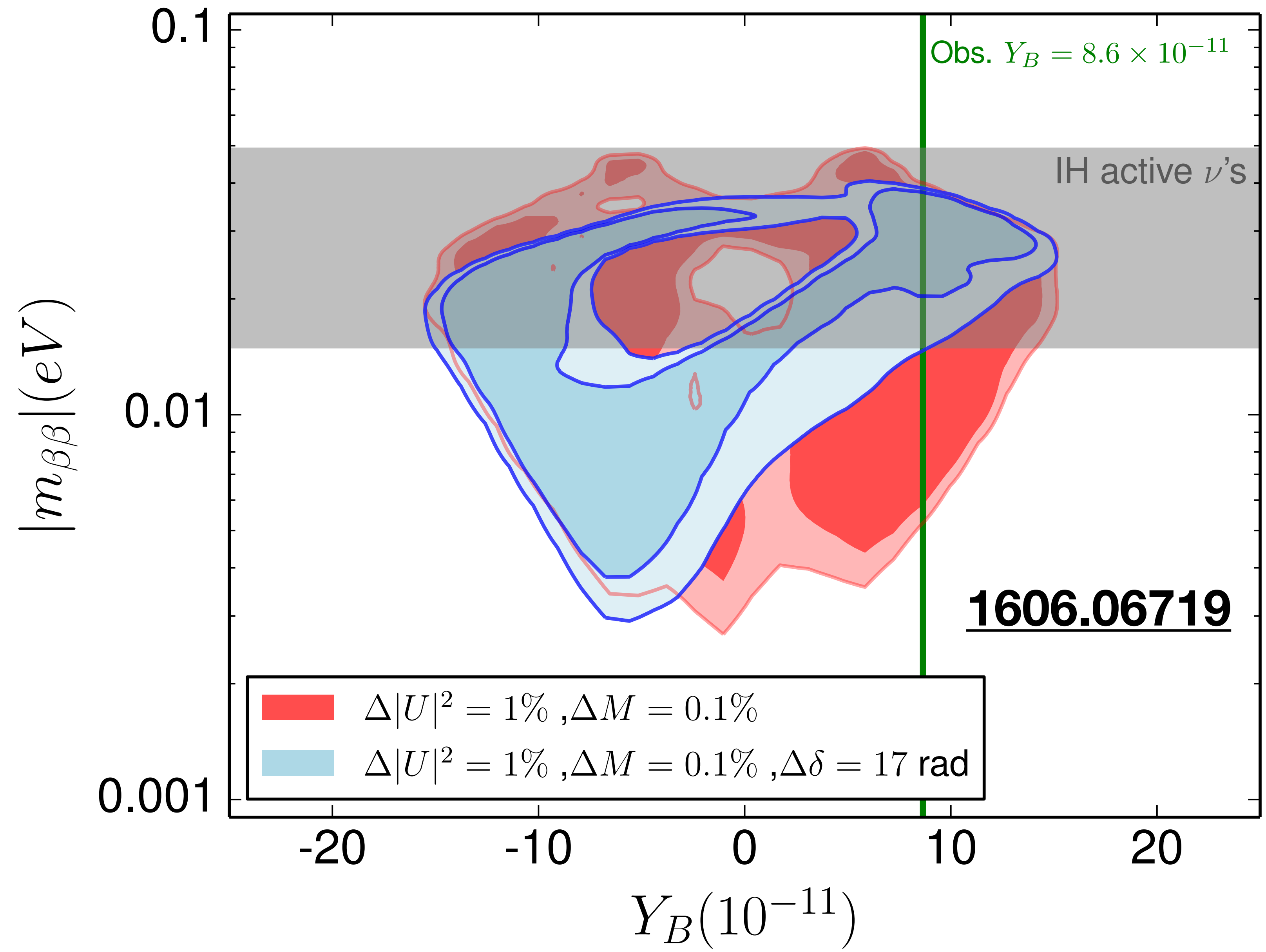
$$\nu_\alpha = U_{\alpha i}\nu_i + \Theta_{\alpha I} N_I^c \qquad |U|^2 = \sum_{\alpha I} |\Theta_{\alpha I}|^2 \qquad \overline{M} = \frac{M_1 + M_2}{2}$$



Drewes, Garbrecht, Gueter, Klaric *JHEP 1708 (2017)* 018

Leptogenesis via Oscillations with 2 RHNs

- leptogenesis requires* Majorana neutrinos so we should observe $\nu 0\beta\beta$ (see talks by Fantini, Ozaki, Arazi & Commaletto)



SHiP measurement

DUNE & HyperK measurement

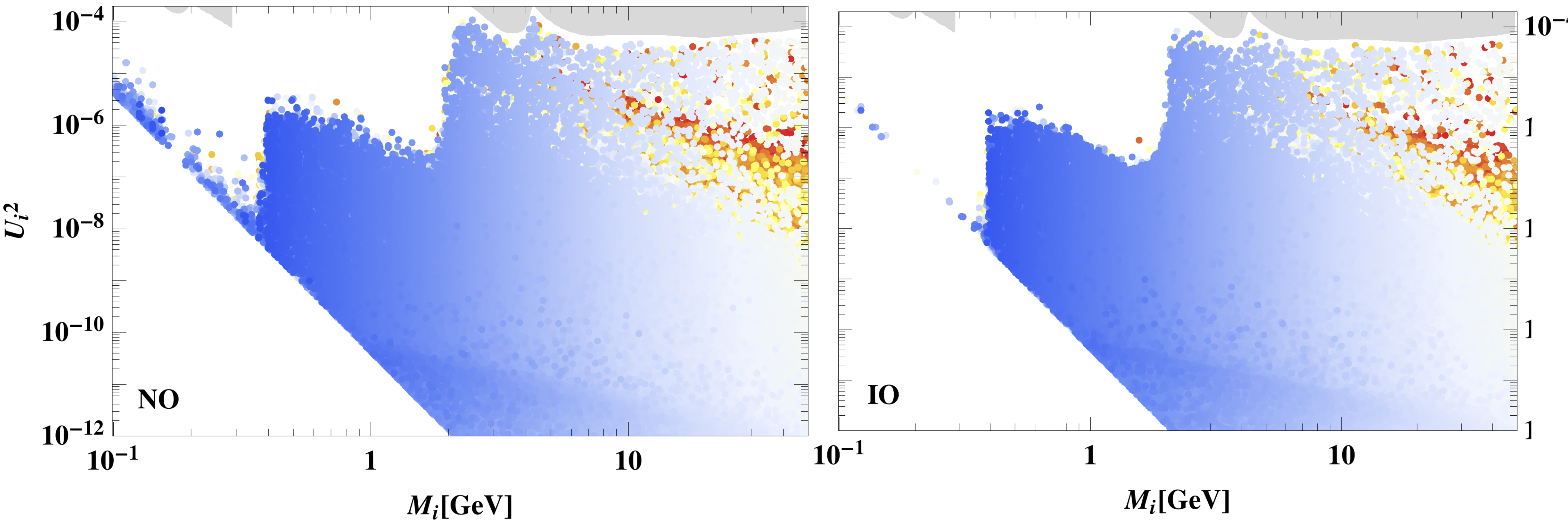
Hernandez, Kekic, Lopez-Pavon, Racker & Salvado *JHEP 1608 (2016) 157*

* with the exception of Dirac Leptogenesis: Dick, Lindner, Ratz, Wright (2000)

Leptogenesis via Oscillations with 3 RHNs

- 3 RHNs more viable parameter space $Y = \frac{1}{v} U \sqrt{m} R^T \sqrt{M}$

  6 masses, 6 angles, 6 phases (2 masses + 3 angles measured)



Abada, Arcadi, Domcke, Drewes, Klaric & Lucente *JHEP 1901 (2019) 164*

- Much of parameter space is viable. Blue (red) → higher (lower) fine tuning

$$f.t.(m_\nu) = \sqrt{\sum_{i=1}^{3} \left(\frac{m_i^{\text{loop}} - m_i^{\text{tree}}}{m_i^{\text{loop}}} \right)^2}$$

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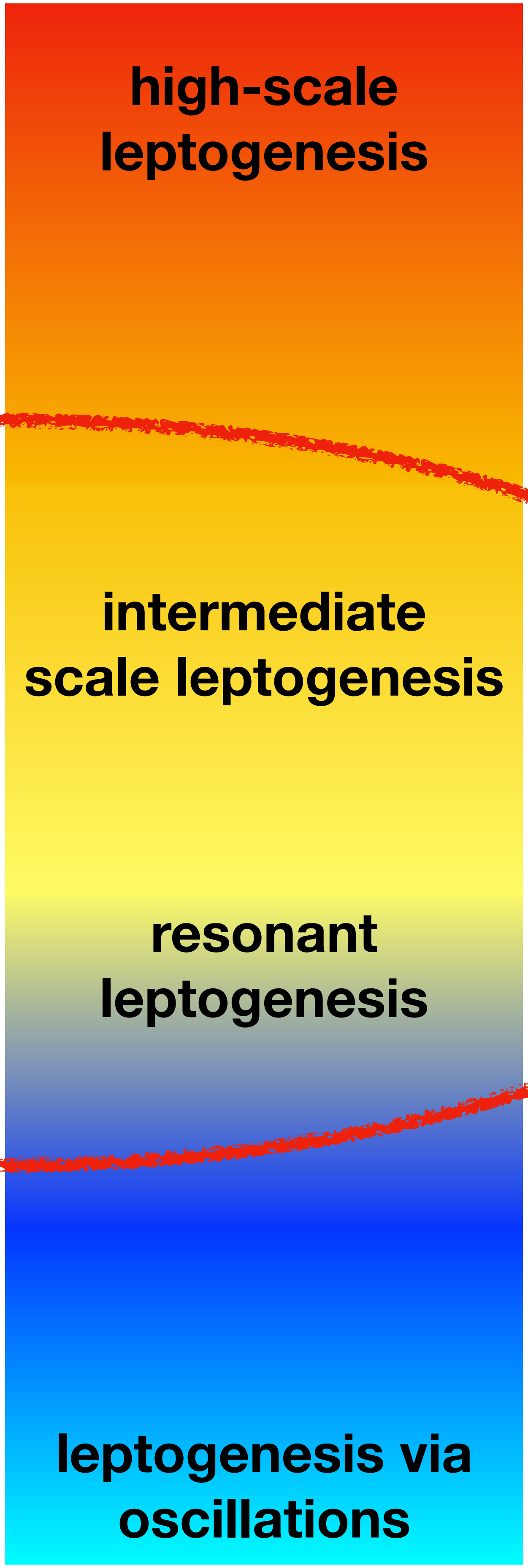
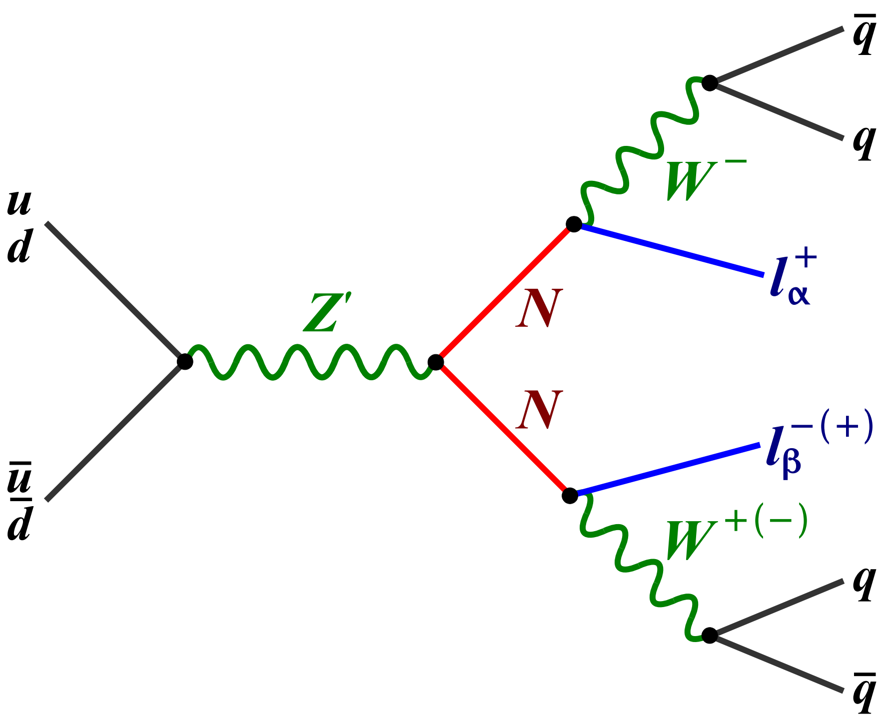


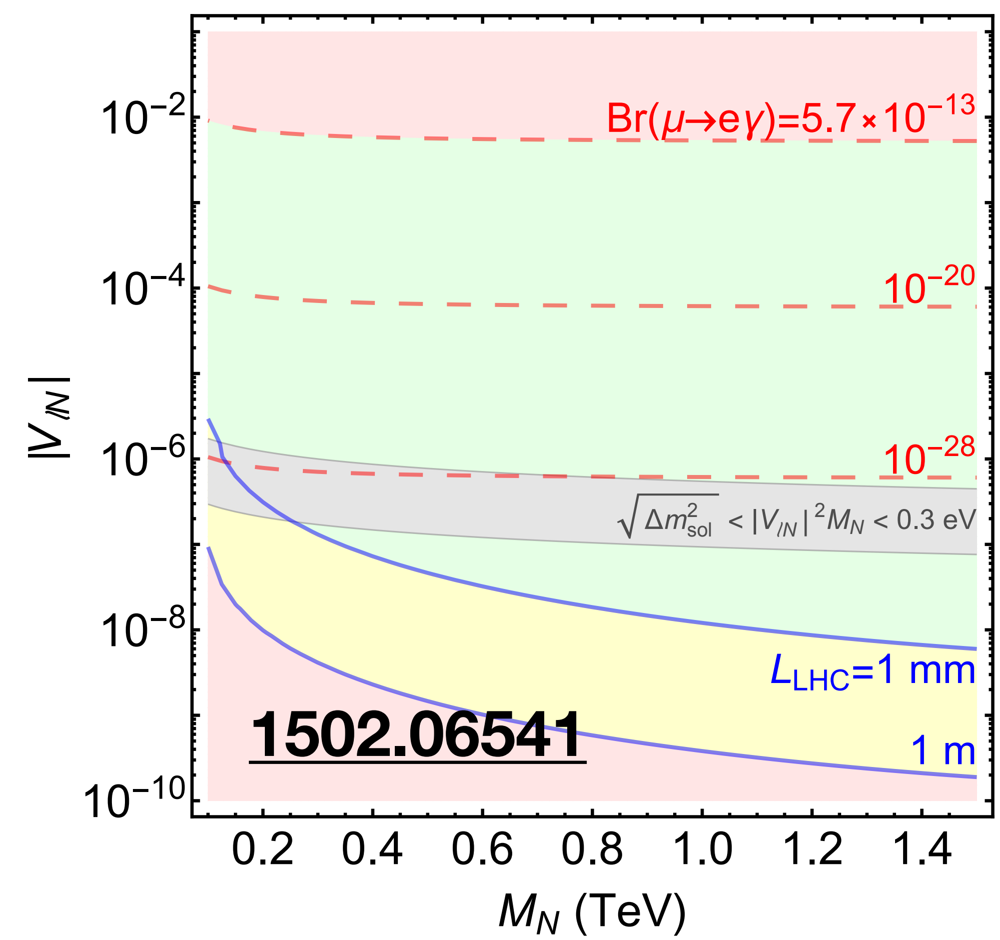
Resonant Leptogenesis

- 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)

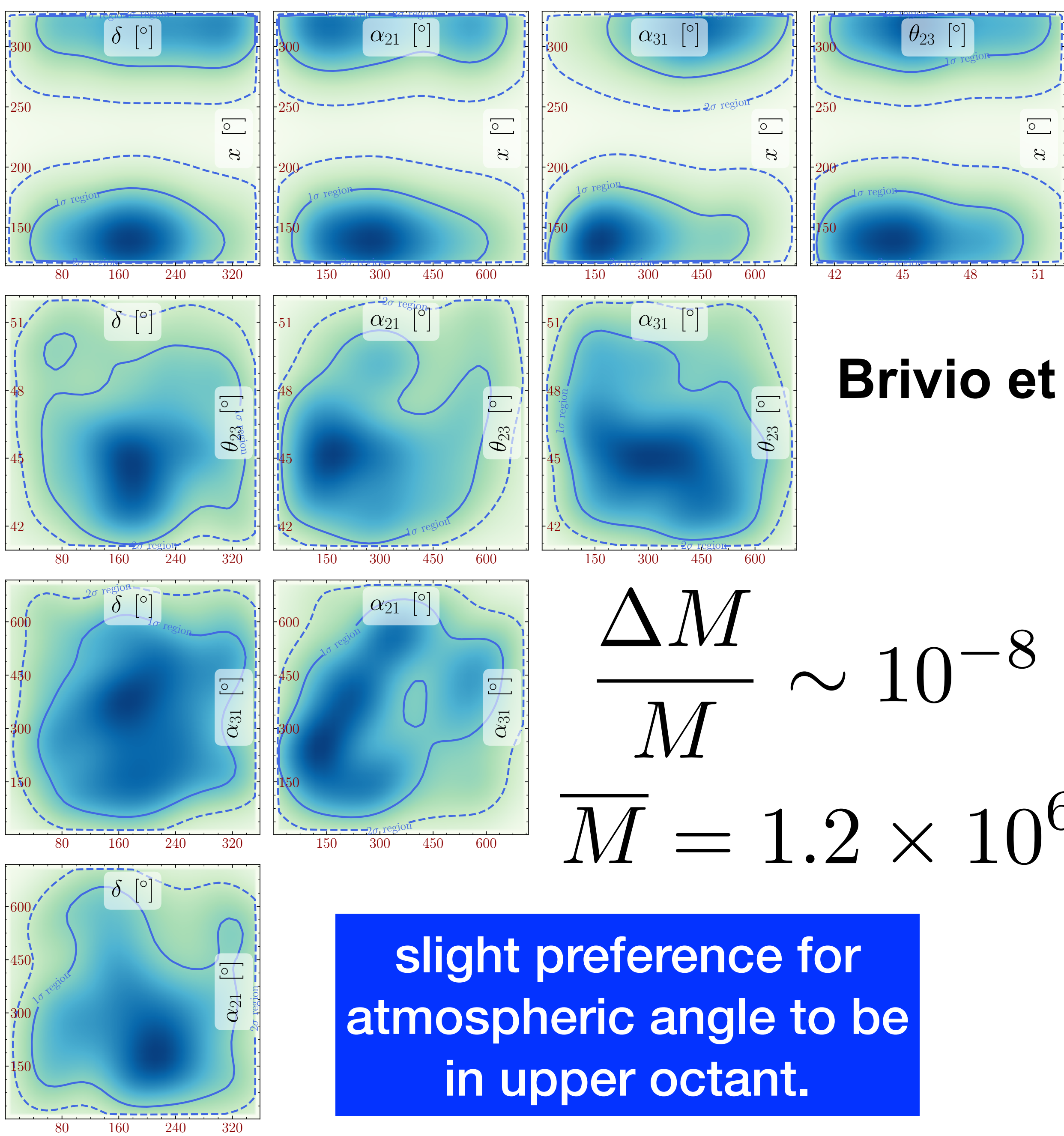
Deppisch, Dev, Pilaftsis, New J.Phys. 17 (2015) no.7, 075019

Resonant leptogenesis in the Neutrino Option

- Assume Higgs potential vanishes at 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

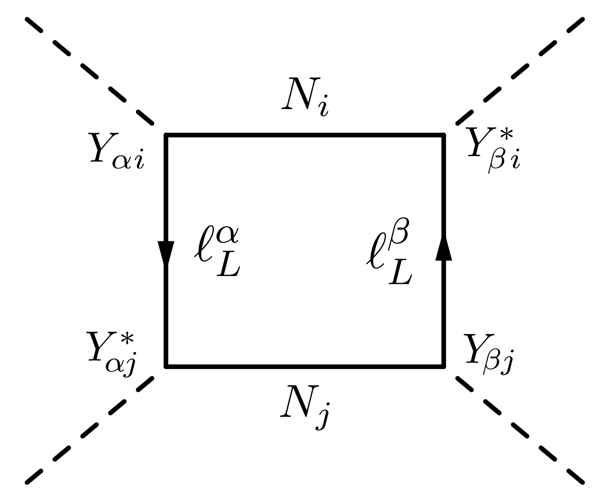


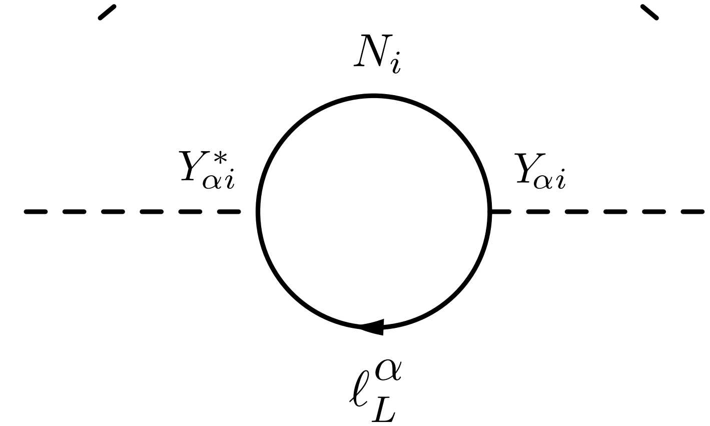
Brivio et al 2019

$$\frac{\Delta M}{M} \sim 10^{-8}$$

$$\overline{M} = 1.2 \times 10^{6}\ \mathrm{GeV}$$

slight preference for atmospheric angle to be in upper octant.

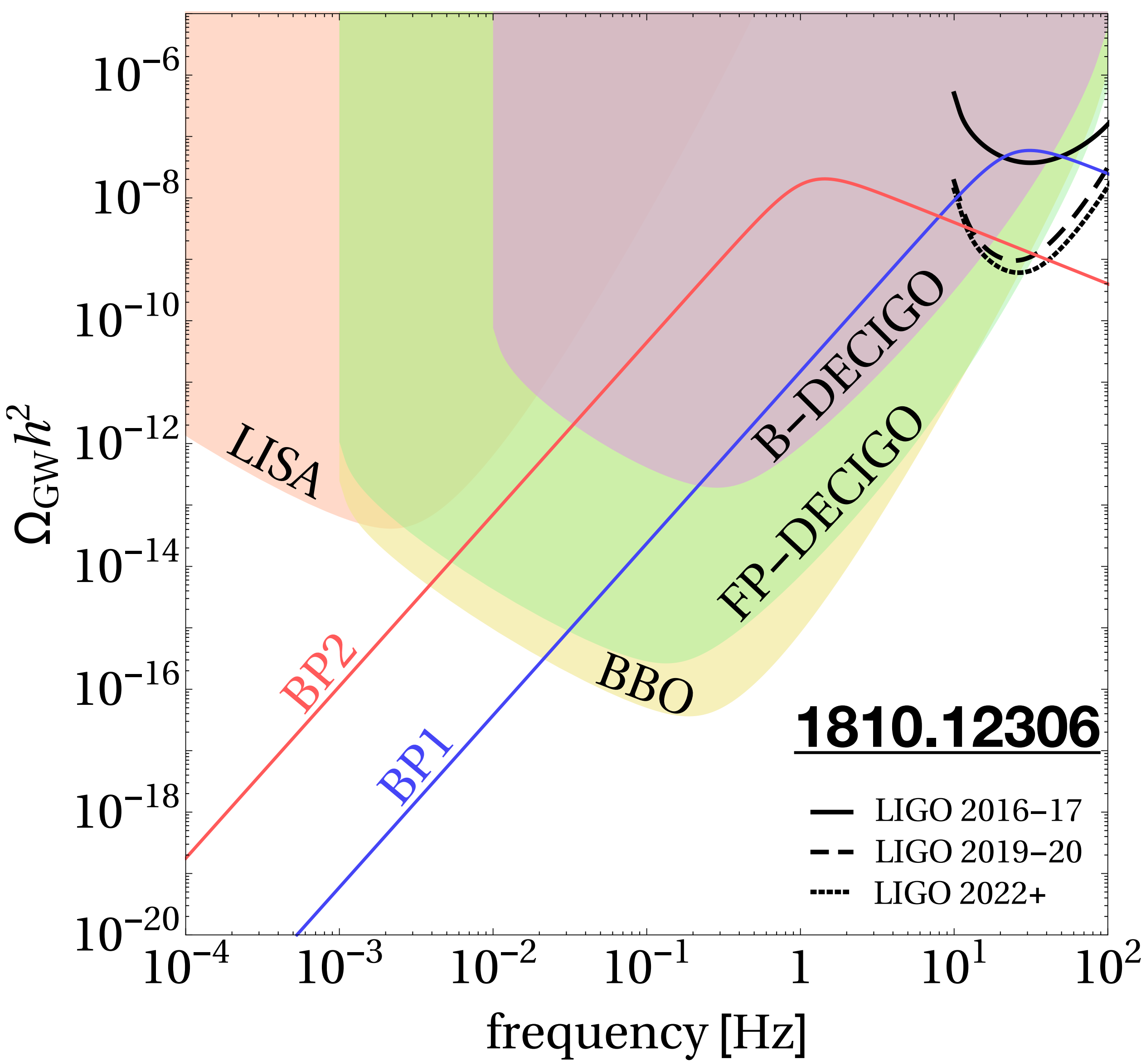




Scale invariance broken at quantum level

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

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leptogenesis via oscillations

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

These are in fact the same mechanism (i.e. we can use the same Boltzmann equations) see **Klaric, Shaposhnikov & Timiryasov 2008.13771**

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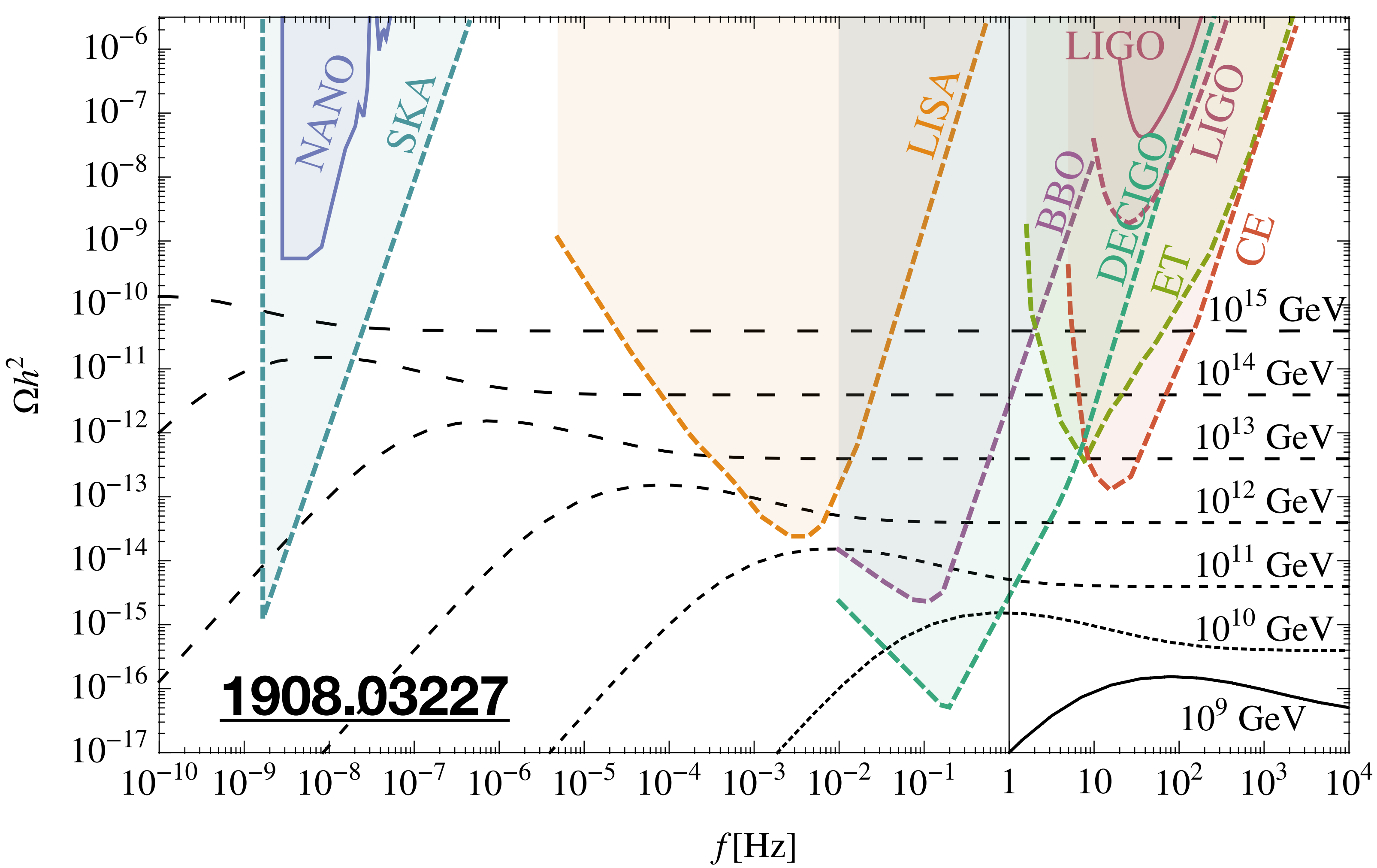
Difficult to test as RHNs very heavy however gravitational waves offer an additional telescope on high-scale leptogenesis

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



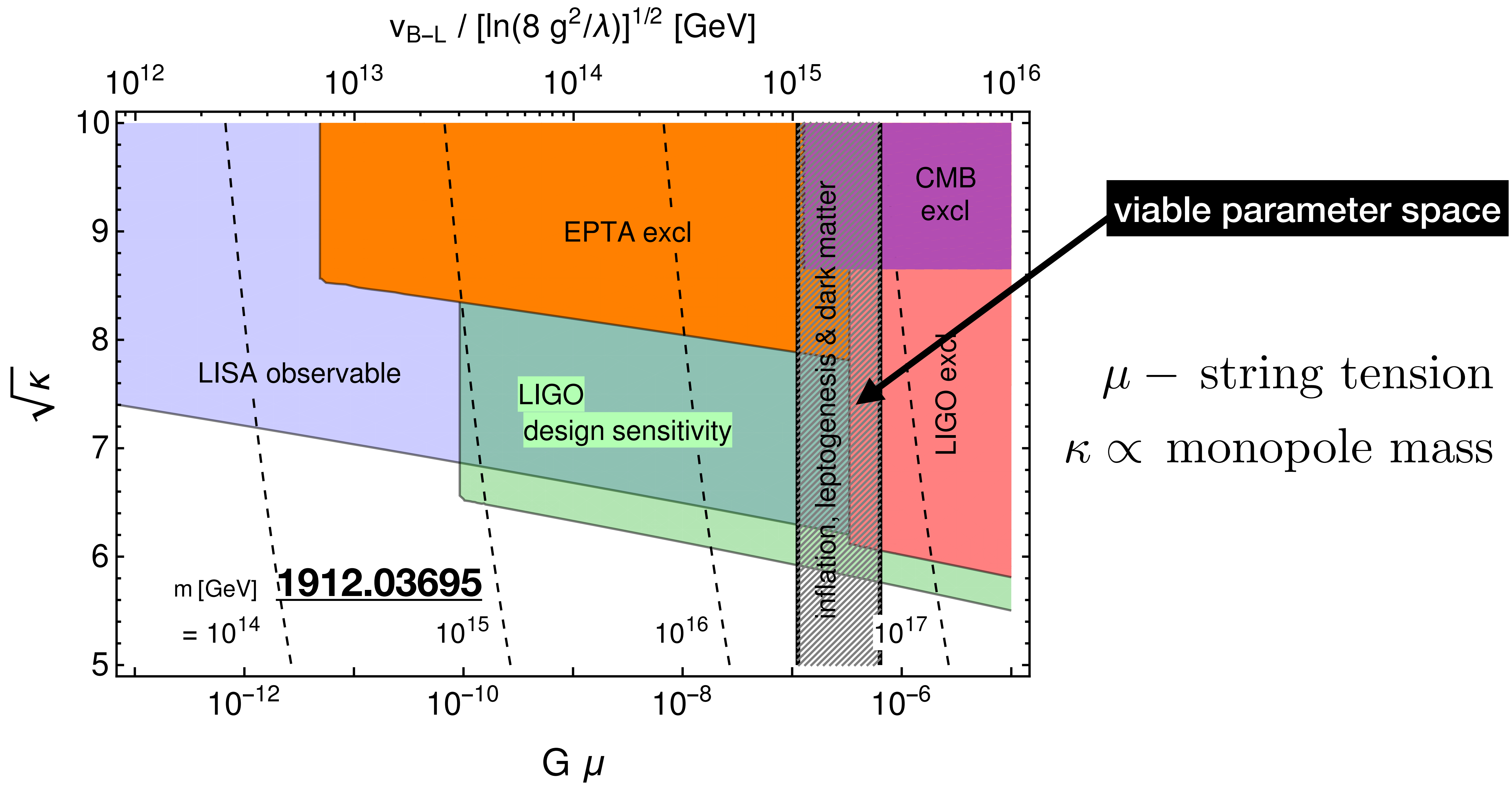
Dror, Hiramatsu, Kohri , Murayama & White *Phys.Rev.Lett. 124 (2020) no.4, 041804*

Thermal leptogenesis

- U(1)B-L used to explain inflation, leptogenesis and neutrino (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*

Thermal leptogenesis and primordial black holes

- Primordial BHs could have formed in the EU due to large density perturbations.
- If RHNs exist, PBHs would have produced them. In 2010.03565, Yuber Perez-Gonzalez & I study this interplay

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

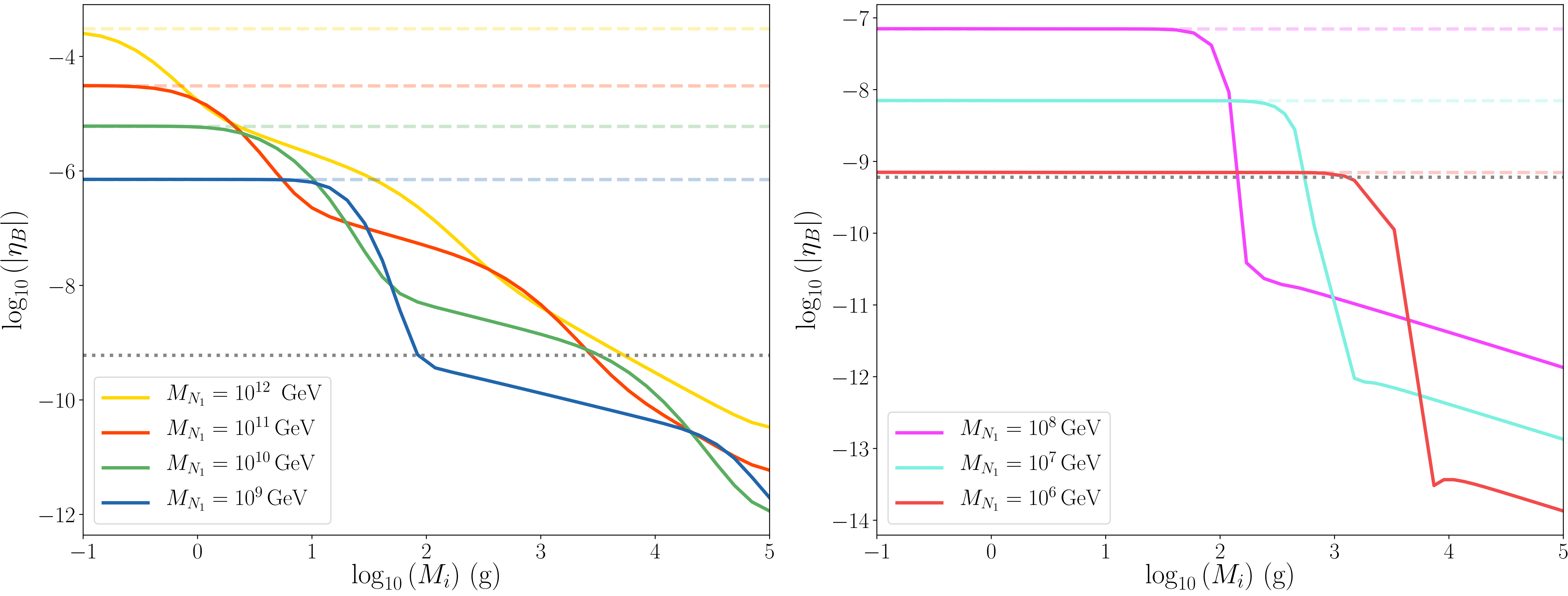
$$aH\frac{dn_{\alpha\beta}^{\mathrm{B-L}}}{da} = \epsilon_{\alpha\beta}^{(1)}\left[(n_{N_1}^{\mathrm{TH}} - n_{N_1}^{\mathrm{eq}})\Gamma_{N_1}^{T} + n_{N_1}^{\mathrm{BH}}\Gamma_{N_1}^{\mathrm{BH}}\right] + \mathcal{W}_{\alpha\beta}$$

B-L asymmetry from thermal leptogenesis

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

Also requires us to solve Friedmann equations for evolution of comoving energy density radiation and PBHs

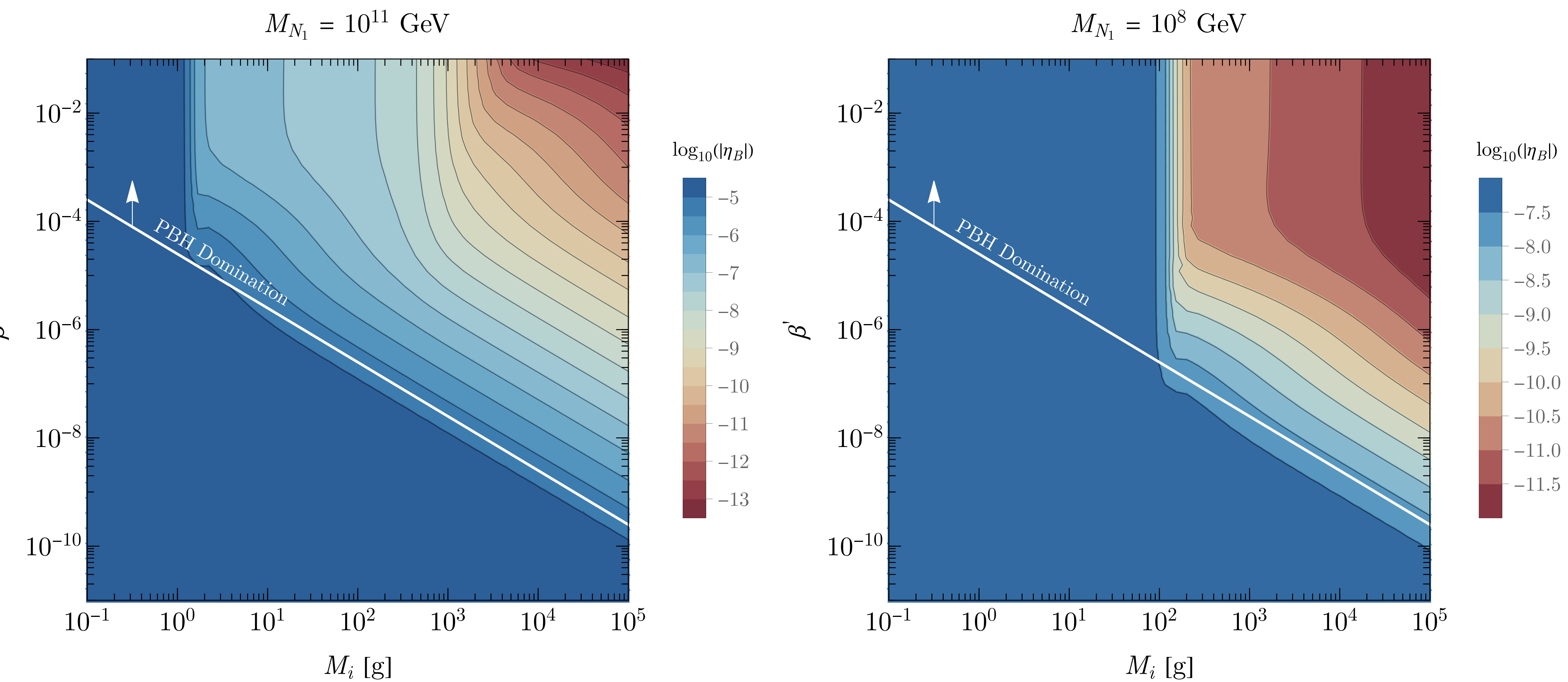
Thermal leptogenesis and primordial black holes



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

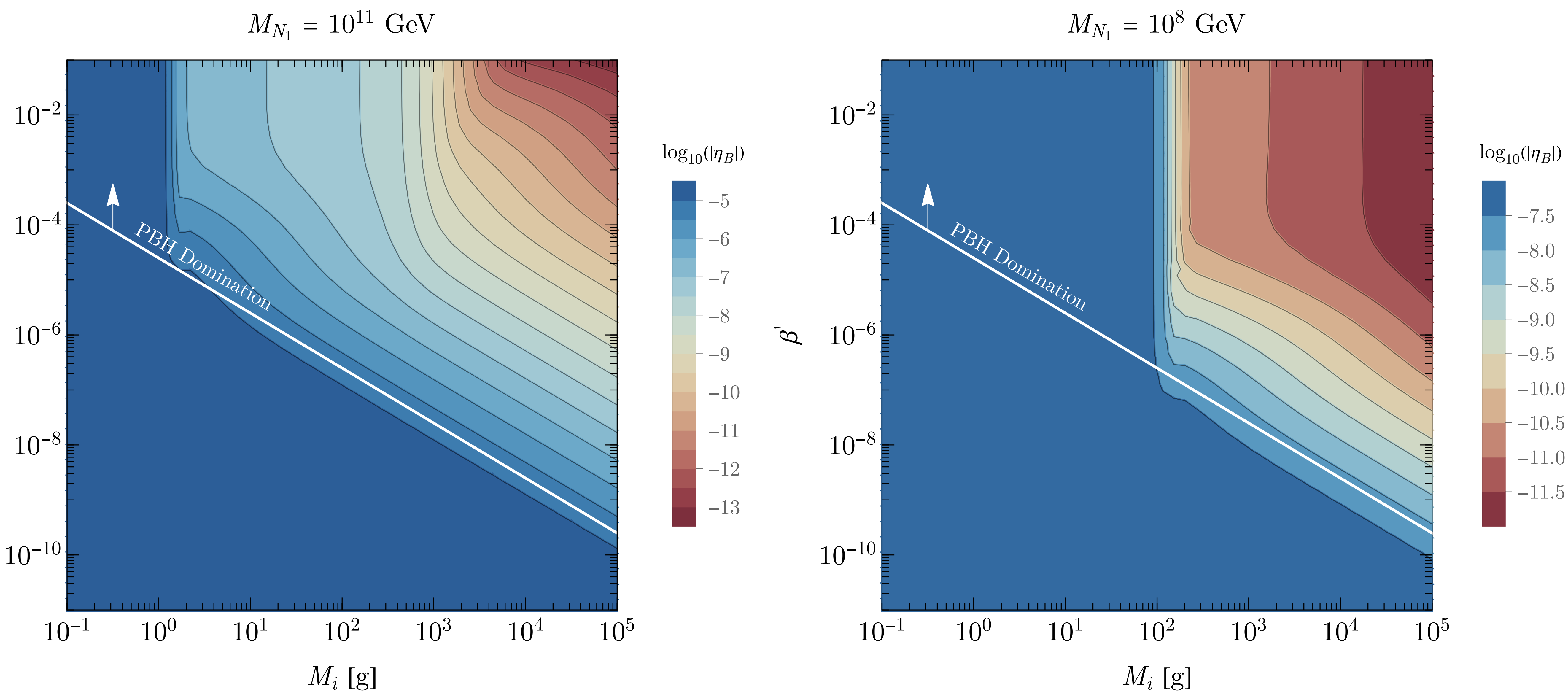
Chose Yukawa matrix for maximal baryon asymmetry

Thermal leptogenesis and primordial black holes



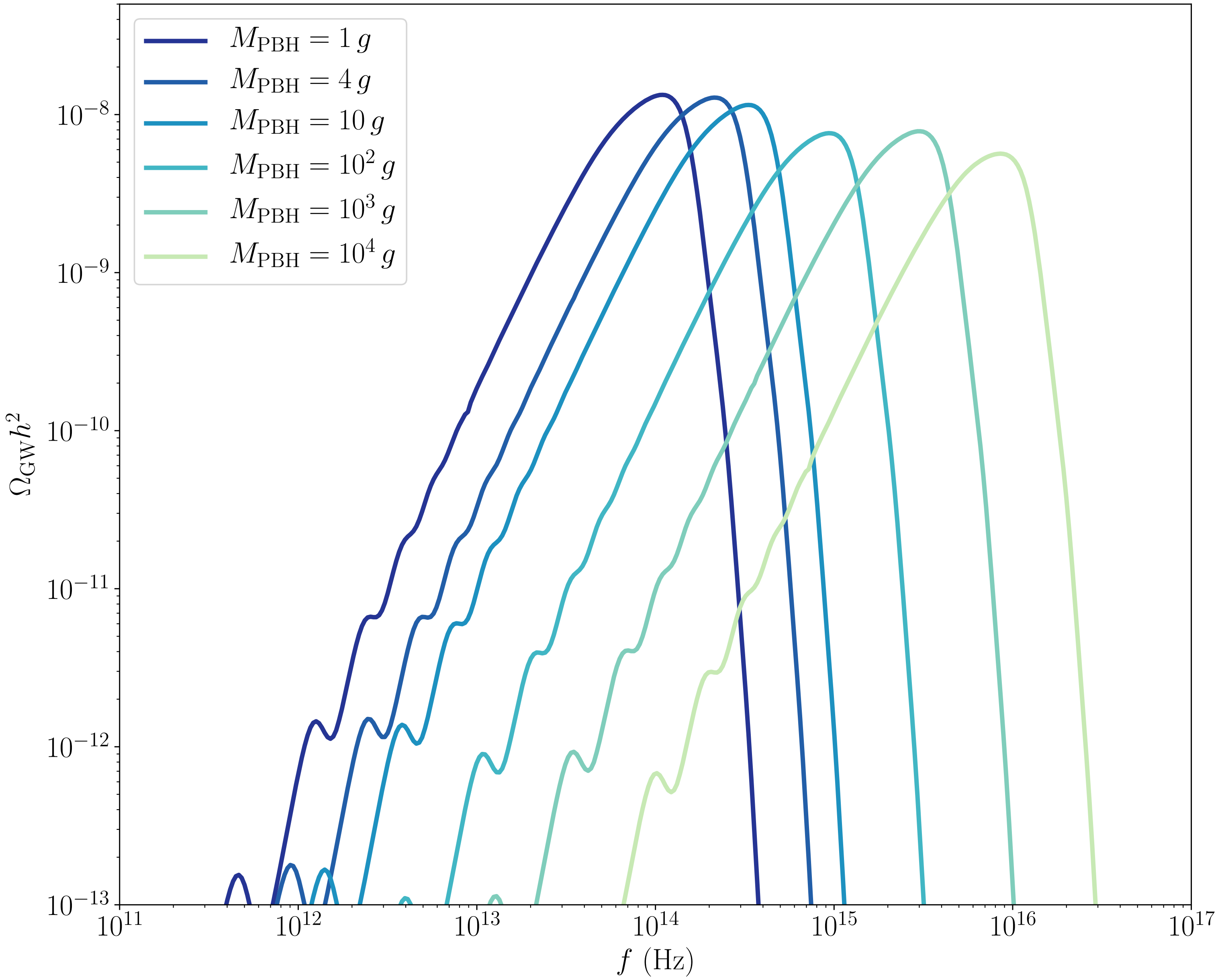
Dilution effect present as long as there is PBH domination

Thermal leptogenesis and primordial black holes



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

Thermal leptogenesis and primordial black holes

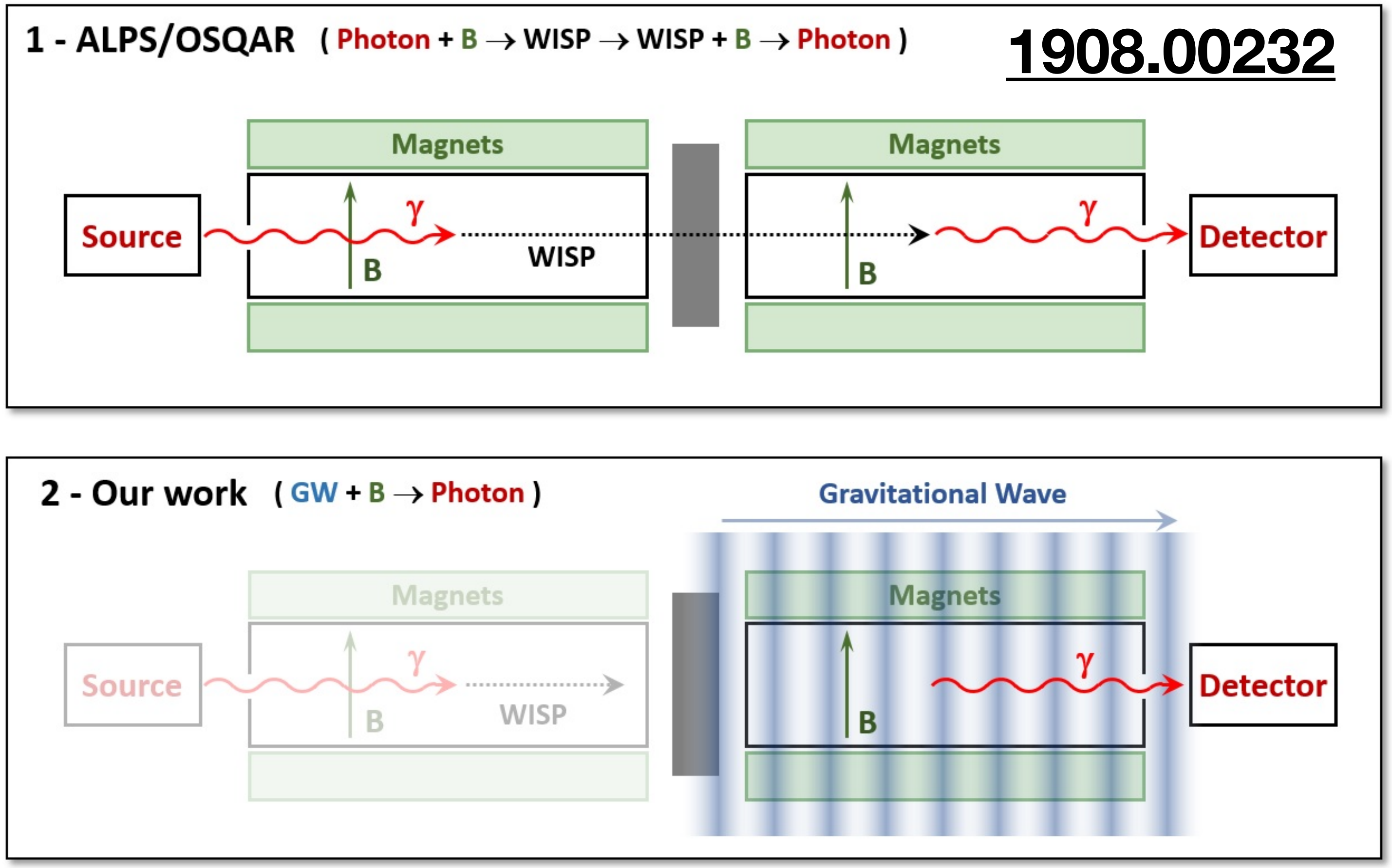


PBHs also copious produce gravitons which constitute a stochastic GW background in the ultrahigh frequency regime

Thermal leptogenesis and primordial black holes

- Next generation of experiments looking for WISP DM (axions and hidden sector photons) can detect **THz** GW produced by PBHs via graviton-photon conversion

Ejlli, Ejlli, Cruise, Pisano, Grote Eur.Phys.J. C79 (2019) no.12, 1032



- Detection of such GWs would place thermal leptogenesis under serious tension

ULYSSES: Universal LeptogeneSiS Equation Solver

- Thermal and resonant leptogenesis
- Easy parallelisation
- rapid evaluation
- python package

In collaboration with Granelli, Perez-Gonzalez, Moffat & Schulz. Happy for people to add their own plugins

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


Thank you for your attention!