The Neutrino Mass Bound from Leptogenesis Revisited

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Based on 2411.09765 with B. Garbrecht

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Introduction

- Early 2000s: discovery of neutrino oscillations $\Rightarrow$ neutrinos have mass

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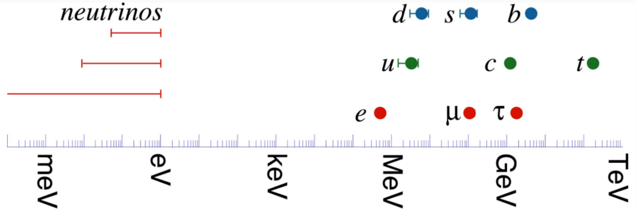

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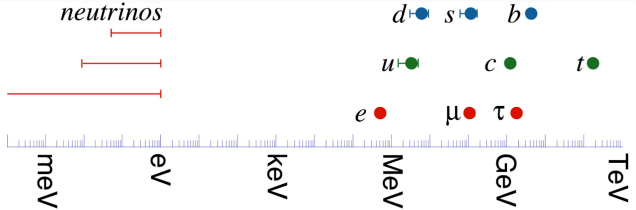

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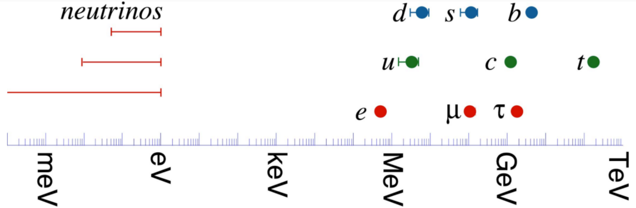
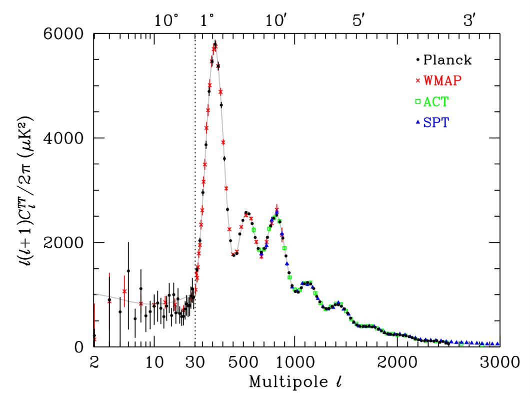
- Mass mechanism unknown, why so tiny?
- More matter than antimatter in the Universe, but CP-violation in the SM insufficient
- Leptogenesis as common explanation



Matter-Antimatter Asymmetry

- From CMB power spectrum and BBN predictions, know $\eta_B = n_B/n_\gamma = 6.104 \pm 0.058 \times 10^{-10}$



[PDG (2024)]

Matter-Antimatter Asymmetry

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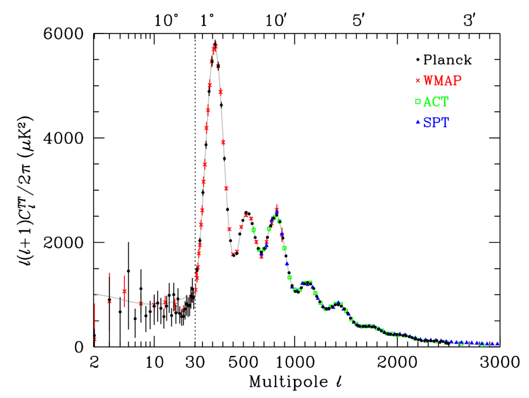
- No evidence for relevant antimatter density



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Seesaw Mechanism

Add Majorana fermions N_i coupling to ν and to ϕ:

$$\mathcal{L} \supset -\frac{1}{2} M_i \bar{N}_i N_i - Y_{ij} \bar{\ell}_i \tilde{\phi} N_j + h.c.$$

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After Electroweak Symmetry Breaking,
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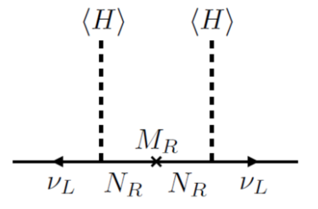
$$m_\nu = \frac{v^2}{2} Y M^{-1} Y^T.$$



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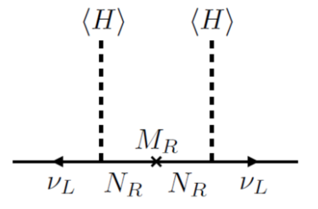

Diagonalized by PMNS matrix:

$$D_\nu = \text{diag}(m_1, m_2, m_3) = U^T m_\nu U$$

Seesaw Parameters

Casas and Ibarra introduced a parametrization of Seesaw parameters:

$$Y = \frac{\sqrt{2}}{v} U \sqrt{D_\nu} R \sqrt{M},$$

with R a complex 3×3 orthogonal matrix.

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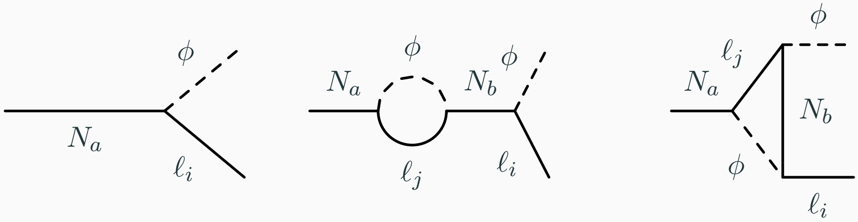

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Mechanism for producing a matter-antimatter asymmetry must satisfy three Sakharov conditions:

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- CP-violation $\Rightarrow$ Majorana fermion decay

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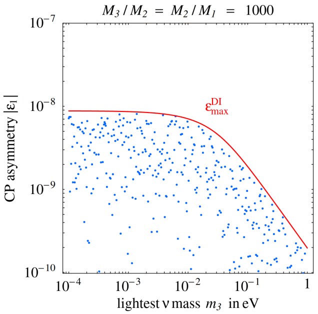
Davidson-Ibarra Bound

In unflavored leptogenesis with hierarchical RHNs, N_1 decay dominant source of asymmetry. Upper bound for the decay asymmetry of the lightest RHN [Davidson, Ibarra (2002)]

$$\varepsilon_1 \lesssim 10^{-6} \frac{M_1}{10^{10}\,\text{GeV}} \frac{m_{\text{atm}}}{m_1 + m_3}.$$

Unflavored
leptogenesis insensitive to PMNS parameters.



[Hambye et. al. (2004)]

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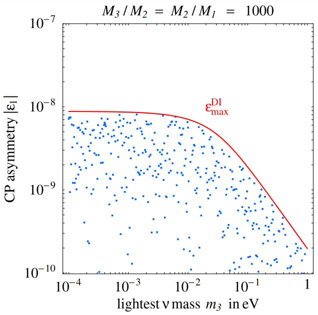

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leptogenesis insensitive to PMNS parameters. Implies

$$M_1 \gtrsim 10^{8-9}\text{GeV},$$

for thermal leptogenesis.

Flavored Leptogenesis

Unflavored leptogenesis from kinetic equations

$$\begin{aligned}\frac{dY_{N_i}}{dz} &= -\, C_{N_i}(Y_{N_i} - Y_{N_i}^{\mathsf{eq}}),\\ \frac{dY_\ell}{dz} &= -\, \varepsilon_i C_{N_i}(Y_{N_i} - Y_{N_i}^{\mathsf{eq}}) - W Y_\ell.\end{aligned}$$

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$\varepsilon_{\alpha i}$ in principle unbounded, but DI-bound still holds in absence of resonant enhancement.

Low-Scale Leptogenesis

- At high temperatures, RHNs relativistic

$$\frac{d}{dz} f_{h,ij} \approx (M_i^2 - M_j^2) f_{h,ij} - \{\Gamma_h, f\}_{ij} + \dots$$

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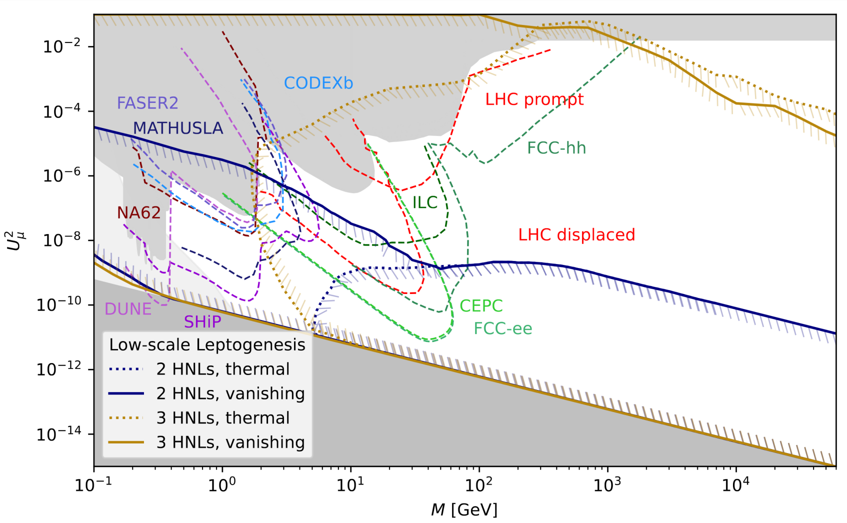
- Lepton number violating processes suppressed, but obtain flavored asymmetries in left-handed leptons
- At low temperatures, LNV processes unsuppressed and flavor dependent $\Rightarrow L$ asymmetry
- Asymmetry $\sim T^2/(M_j^2 - M_i^2)$ instead of $M_i M_j/(M_j^2 - M_i^2)$, no fine-tuning required

Seesaw Parameters



[Abdullahi et. al. (2022)]

Neutrino Mass Window from Leptogensis

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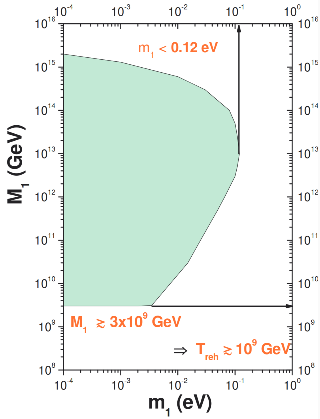

[Blanchet, Di Bari (2012)]

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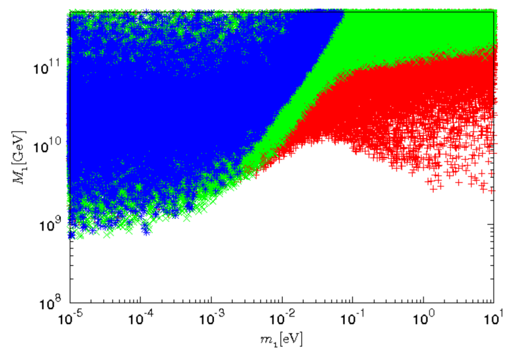
Can be evaded in flavored cases:



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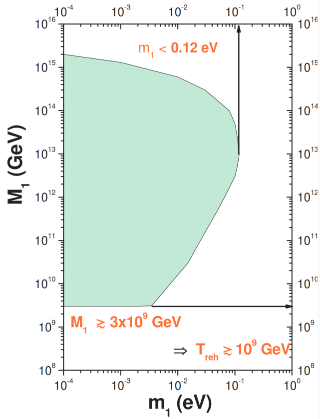

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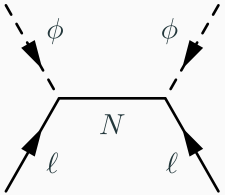

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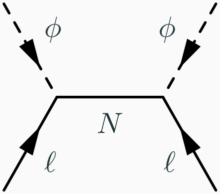
$$W_{\Delta L=2} \sim \frac{M_1}{z^2} \sum_i m_i^2,$$



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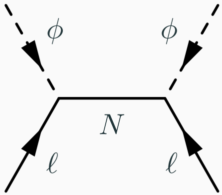

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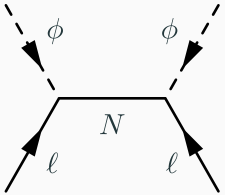

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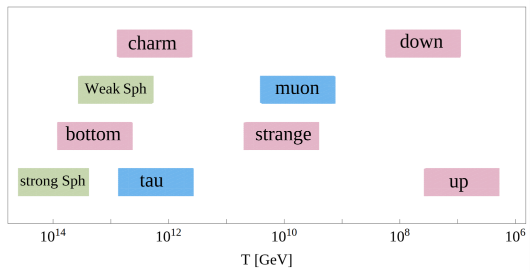
However, N_1 couples to linear combination of flavors $\ell_{||}$, interactions with $N_{2,3}$ have additional phases. New rate

$$W_{\Delta L=2} \sim \frac{K^2 M_1}{z^2},$$

with K the washout parameter.

Spectator Effects

Spectator fields are fields not coupling directly to the RHNs



[Garbrecht, Schwaller (2014)]

Spectator Effects

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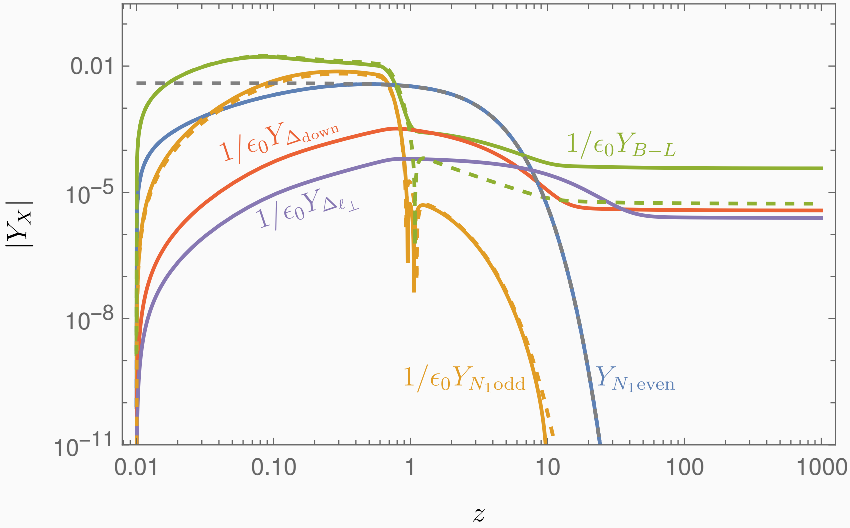
Adding equilibrated top-quark Yukawa interactions gives

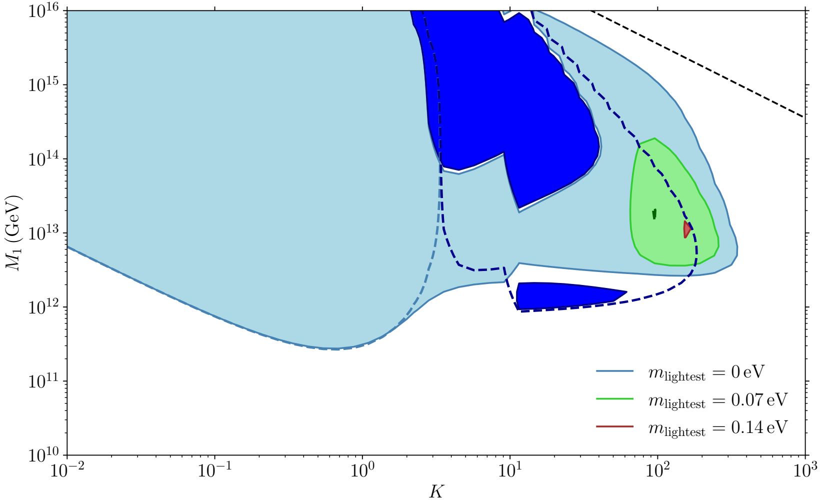
$$\left.\begin{aligned}&\mu_{Q_3} - \mu_{tR} + \mu_H = 0\\ &\mu_{Q_3} + 2\mu_{tR} - \mu_{\ell_{\|}} + 2\mu_H = 0\\ &2\mu_{Q_3} + \mu_{tR} = 0\end{aligned}\right\} \Rightarrow Y_{\ell_{\|}} = -\frac{1}{2}Y_{\Delta_{\|}}, Y_H = -\frac{1}{3}Y_{\Delta_{\|}}.$$

Boltzmann Equations

$M_1 = 10^{13}\,\text{GeV},\ K = 100$



Parameter Scan



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- So far consistent with constraints on neutrino masses and RHN searches
- Significant improvement in computations in recent years $\Rightarrow$ clearer picture

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