Low-Scale Leptogenesis in Extended Neutrino Mass Models.

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Based on arXiv:1804.09660 [hep-ph] and work in progress.

In collaboration with: **Tommi Alanne** (Postdoc), **Thomas Hugle** (Ph.D. student), **Moritz Platscher** (Ph.D. student)

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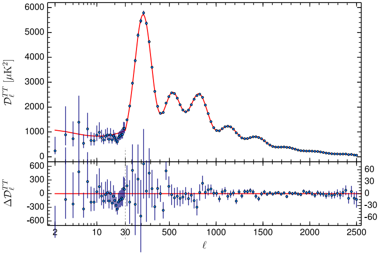
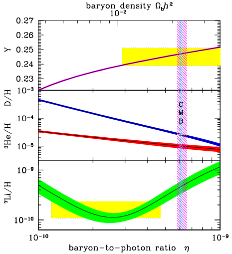
Baryogenesis via leptogenesis

[PLANCK '15]



[PDG '17]



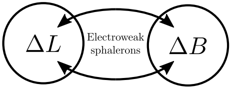
$$\eta_B = \frac{n_b - n_{\bar b}}{n_\gamma} \simeq \frac{n_b}{n_\gamma} \simeq 6.1 \times 10^{-10}$$

Problem: The *Baryon Asymmetry of the Universe* cannot be explained by Standard Model physics!

Sakharov conditions: [Sakharov '67]

1. *B* violation
2. *C* and *CP* violation
3. Departure from therm. equilibrium

Baryogenesis via leptogenesis: [Fukugita & Yanagida '86]



See Giorgio's talk!

The case for leptogenesis at a low energy scale

Observation: Standard thermal leptogenesis requires very heavy right-handed neutrinos.

- Vanilla leptogenesis: $M_1 \gtrsim \mathcal{O}\left(10^9\right)\,\mathrm{GeV}$ [Davidson & Ibarra '02] [Buchmüller et al. '02] [Giudice et al. '03]
- Plus flavor effects, etc.: $M_1 \gtrsim \mathcal{O}\left(10^8\right)\,\mathrm{GeV}$ [Blanchet & Di Bari '08] [See also Moffat et al. '18 (1804.05066)]

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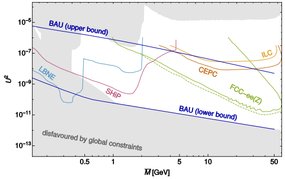
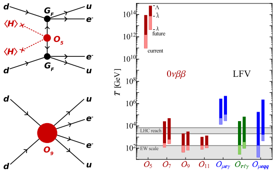
Goal: Try to find alternative scenarios that can be realized at a lower energy scale.

[Drewes, Garbrecht, Gueter, Klaric '16]



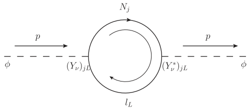
❶ Direct detection of RHNs

[Deppisch, Harz, Huang '15]



❷ Low-energy LNV / LFV

[Vissani '97] [Fig. from Bambhaniya et al. '16]



$$\delta\mu^2 \sim \frac{1}{4\pi^2}\,\mathrm{Tr}\left[Y_\nu^\dagger D_N^2 Y_\nu\right]$$

❸ EW naturalness

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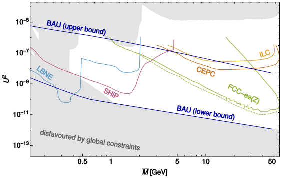

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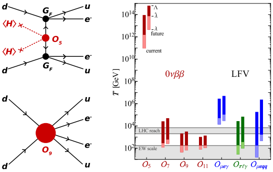

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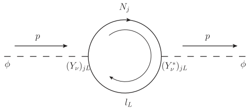

$$\delta\mu^2 \sim \frac{1}{4\pi^2}\,\mathrm{Tr}\left[Y_\nu^\dagger D_N^2 Y_\nu\right]$$

❸ EW naturalness

This talk: Two less conventional ideas to lower the energy scale of leptogenesis.

First idea: Leptogenesis in the scotogenic model [Ma '06]

"Dark" equivalent of the type-I seesaw mechanism

- Again introduce $N_{i=1,2,\ldots}$, but replace SM Higgs doublet H by "dark" scalar doublet η
- Impose exact $\mathbb{Z}_2$ symmetry: $[N_i] = [\eta] = -1$, whereas $[\mathrm{SM}] = +1$

$$L \supset -h_{\alpha i}\, \ell_\alpha\, \tilde{\eta}\, N_i + \frac{1}{2} M_i\, N_i\, N_i + \mathrm{h.c.}$$

$$V = -\mu^2 |H|^2 + m_\eta^2 |\eta|^2 + \frac{\lambda_1}{2}|H|^4 + \frac{\lambda_2}{2}|\eta|^4 + \lambda_3 |H|^2|\eta|^2 + \lambda_4 |H^\dagger \eta|^2 + \lambda_5\, \mathrm{Re}\left\{(H^\dagger \eta)^2\right\}$$

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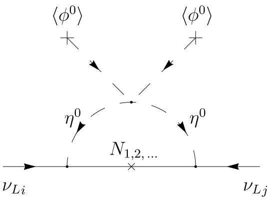
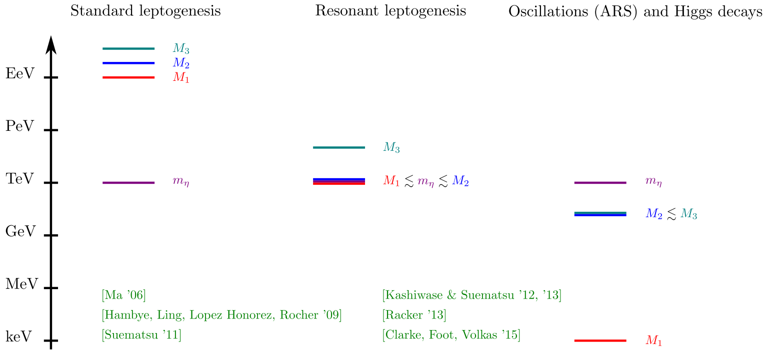


[Fig. from Merle & Platscher '15]

Neutrino masses, dark matter, and leptogenesis in one go!

- $\langle\eta\rangle \equiv 0$, no Dirac mass, neutrino masses at one loop
- Lightest $\mathbb{Z}_2$-odd state = viable DM candidate
- LNV by RHN Majorana masses / scalar λ_5 interaction

Possible avenues towards low-scale leptogenesis



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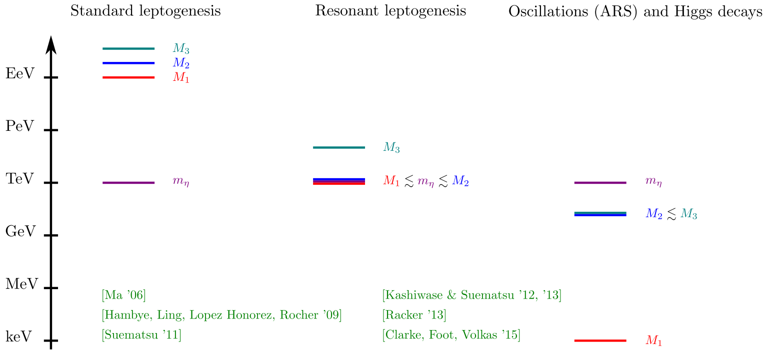


Our work: Standard thermal leptogenesis without any degeneracy in the mass spectrum

- N_1 DM suffers from large Yukawa couplings $\rightarrow$ LFV, washout. Therefore, η DM.
- Analytical + numerical study of both 2 and 3 RHNs (incl. Boltzmann equations).
- Restrict to parameters that manage to reproduce the neutrino oscillation data.

Key parameter relations (1)

Active-neutrino mass matrix $\mathcal{M}_\nu$

$$\left(\mathcal{M}_\nu\right)_{\alpha\beta} = \sum_i \left(\frac{\lambda_5}{2\pi^2}\,\frac{1}{\xi_i} \times h_{\alpha i}^* h_{\beta i}^* \frac{v_{\rm ew}^2}{M_i}\right)$$

- Extra suppression by small λ_5 values allows for larger Yukawas couplings $h_{\alpha i}$.

Davidson-Ibarra bound on ε_1

$$\left|\varepsilon_1\right| \lesssim \frac{2\pi^2}{\lambda_5}\,\xi_{2/3} \times \frac{3}{16\pi}\,\frac{\left(m_3 - m_1\right) M_1}{v_{\rm ew}^2}$$

- As a consequence, small λ_5 values result in a larger *CP* asymmetry parameter ε_1.

Decay parameter $K_1 = \Gamma_{N_1}/H\left(T = M_1\right)$ and decay rate Γ_{N_1}

$$\left(1 - a_\eta\right)^{-2}\Gamma_{N_1} = \frac{1}{8\pi}\left(h^\dagger h\right)_{11} M_1 = \frac{2\pi^2}{\lambda_5}\,\xi_1 \times \frac{1}{8\pi}\,\frac{\widetilde{m}_1 M_1^2}{v_{\rm ew}^2}$$

- But at the same time, small λ_5 values also easily lead to a stronger washout.

Key parameter relations (2)

The effective mass parameter $\widetilde{m}_1$ is bounded from below: $\widetilde{m}_1 \geq m_{\rm lightest}$

$$\widetilde{m}_1 \quad \gtrsim \quad \sqrt{\Delta m^2_{\rm sol}}\ (\rm 2RHN + NO)\,, \quad \sqrt{\Delta m^2_{\rm atm}}\ (\rm 2RHN + IO)\,, \quad m_1\ (\rm 3RHN)$$

- For 2 RHNs: $K_1 \gtrsim 10$ → strong-washout regime → no gain in η_B, despite $\lambda_5 \ll 1$.

Larger parametric freedom for 3 RHNs: Enlarge ε_1 by small λ_5, control K_1 by small m_1

$$K_1 = K_1^{\rm opt} \sim \mathcal{O}(1)\,, \quad \varepsilon_1 = \varepsilon_1^{\rm max} \qquad \Rightarrow \qquad m_1 \sim 8 \times 10^{-3} \left(\lambda_5/0.1\right) \rm meV$$

- RHNs must decay out of equilibrium → $\left(h^\dagger h\right)_{11}$ must remain small → tiny mass m_1.

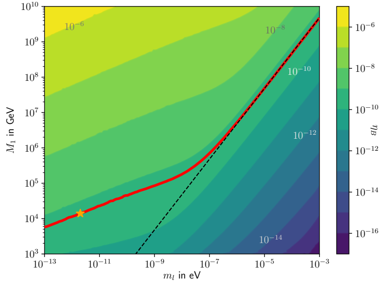
Washout because of $\Delta L = 2$ scattering processes: $\ell\eta \leftrightarrow \bar{\ell}\eta^*$, $\ell\ell \leftrightarrow \eta^*\eta^*$

$$\frac{\Gamma_{\Delta L=2}}{H} \propto \lambda_5^{-2}\, v_{\rm ew}^{-4}\, \overline{m}_\xi^2\, T\, M_{\rm Pl}$$

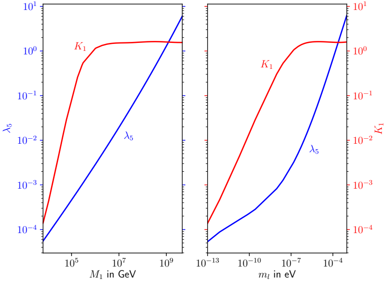
- Becomes relevant at small λ_5 values, $\lambda_5 \lesssim \mathcal{O}\left(10^{-2}\right)$ → Solve Boltzmann equations!

Scan of parameter space

Contours of η_B in the m_1–M_1 plane



K_1 and λ_5 as functions of M_1 and m_1



Main results:

- If $\Delta L = 2$ washout is negligible, analytical and numerical results agree very well.
- If not, M_1 and m_1 can still be lowered by $K_1 \ll 1$. RHNs then decay at very late times.
- This is possible as long as leptogenesis occurs before sphaleron freeze-out.

Absolute lower bounds: $m_1 \gtrsim \mathcal{O}\left(10^{-12}\right)\,\mathrm{eV}\,, \quad M_1 \gtrsim \mathcal{O}\left(10\right)\,\mathrm{TeV}$

Second idea: Scalar-extended RHN mass sector

Extend the RHN sector by an additional scalar gauge singlet S

- Introduce additional RHN Yukawa couplings that lead to fast $N_j \to S\, N_i$ decays.
- UV origin: Multiple breaking of $B-L$? Composite Higgs models? ... [Alanne, Meroni, Tuominen '17]

$$L \supset -h_{\alpha i}\,\ell_\alpha\,\tilde{H}\,N_i + \frac{1}{2}M_i\,N_i\,N_i + \frac{1}{2}\alpha_{ij}\,S\,N_i\,N_j + \mathrm{h.c.}$$

$$V = m_H^2|H|^2 + \frac{\lambda}{2}|H|^4 + \frac{1}{2}m_S^2\,S^2 + \mu\,S\,|H|^2 + \cdots$$

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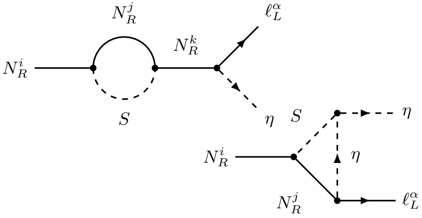
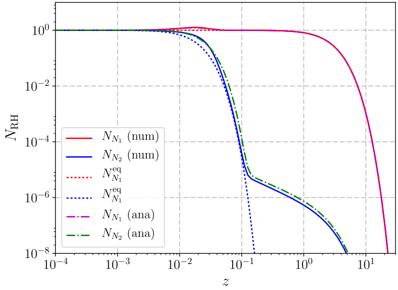


Additional *CP*-violating diagrams

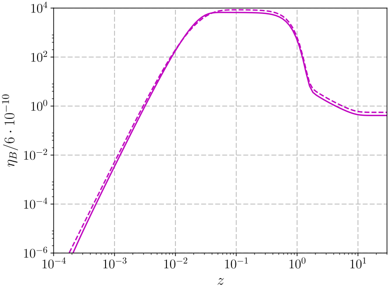
- α_{ij} not diagonal in RHN mass basis.
- Trilinear portal coupling to the Higgs.
- Realize N_2-dominated leptogenesis!

Preliminary results

Comoving RHN number densities



η_B as a function of $z = M_2/T$



Main results:

- N_2-dominated leptogenesis is boosted by additional contributions to ε_2.
- Washout by inverse N_1 decays is less severe because of $S\,N_1 \rightarrow N_2 \rightarrow \ell H$.
- Respective deviations from thermal equilibrium: $N_{N_2} - N_{N_2}^{\rm eq} \sim N_{N_1} - N_{N_1}^{\rm eq}$

Working parameter examples for: $M_1 \sim 10 \cdots 100\,\mathrm{GeV}\,, \quad M_2 \sim 1 \cdots 10\,\mathrm{TeV}$

Conclusions

This talk: Two less conventional ideas for leptogenesis at a low energy scale.

1. Leptogenesis in the scotogenic neutrino mass model
   - Extra suppression of the active-neutrino mass matrix by $\lambda_5 \rightarrow$ larger Yukawas.
   - $M_1 \gtrsim 10\,\mathrm{TeV}$, $m_1 \gtrsim 10^{-12}\,\mathrm{eV} \rightarrow$ can be tested by KATRIN / PROJECT 8, etc.
   - Next step: Include flavor effects, kinematic effects because of $m_\eta \neq 0$, etc.

2. Scalar-singlet-assisted leptogenesis
   - Additional Yukawa interactions in the RHN sector $\rightarrow$ additional $\not{CP}$ diagrams
   - Successful examples with $M_1 \sim 10 \cdots 100\,\mathrm{GeV}$ and $M_2 \sim 1 \cdots 10\,\mathrm{TeV}$.
   - Promising scenario. Stay tuned for further progress.

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Thank you for your attention!