Low-Scale Leptogenesis in Extended Neutrino Mass Models.

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Baryogenesis via leptogenesis

Sakharov conditions: [Sakharov '67]

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

Baryogenesis via leptogenesis: [Fukugita & Yanagida '86]

Problem: The Baryon Asymmetry of the Universe cannot be explained by Standard Model physics!
The case for leptogenesis at a low energy scale

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

- Vanilla leptogenesis: $M_1 \gtrsim \mathcal{O}(10^9) \text{ GeV}$ [Davidson & Ibarra '02] [Buchmüller et al. '02] [Giudice et al. '03]
- Plus flavor effects, etc.: $M_1 \gtrsim \mathcal{O}(10^8) \text{ GeV}$ [Blanchet & Di Bari '08] [See also Moffat et al. '18 (1804.05066)]
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2. Low-energy LNV/LFV
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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 $\eta$
- Impose exact $\mathbb{Z}_2$ symmetry: $[N_i] = [\eta] = -1$, whereas $[\text{SM}] = +1$

\[
L \supset -h_{\alpha i} \ell_{\alpha} \tilde{\eta} N_i + \frac{1}{2} M_i N_i N_i + \text{h.c.}
\]
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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 \Re \{ (H^\dagger \eta)^2 \}
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\]

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 $\lambda_5$ interaction

[Fig. from Merle & Platscher ’15]
### Possible avenues towards low-scale leptogenesis

<table>
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<tr>
<th>Energy Scale</th>
<th>Standard leptogenesis</th>
<th>Resonant leptogenesis</th>
<th>Oscillations (ARS) and Higgs decays</th>
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<tr>
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<tr>
<td>PeV</td>
<td>$M_2$</td>
<td>$M_1 \lesssim m_\eta \lesssim M_2$</td>
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<td>MeV</td>
<td>[Ma '06]</td>
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<td>[Hambye, Ling, Lopez Honorez, Rocher '09]</td>
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<td>keV</td>
<td>[Suematsu '11]</td>
<td>[Clarke, Foot, Volkas '15]</td>
<td>$M_1$</td>
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</table>
Our work: Standard thermal leptogenesis without any degeneracy in the mass spectrum

- $N_1$ DM suffers from large Yukawa couplings $\rightarrow$ LFV, washout. Therefore, $\eta$ 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 $\mathcal{M}_\nu$

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

- Extra suppression by small $\lambda_5$ values allows for larger Yukawas couplings $h_{\alpha i}$.

Davidson-Ibarra bound on $\varepsilon_1$

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

- As a consequence, small $\lambda_5$ values result in a larger CP asymmetry parameter $\varepsilon_1$.

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

$$(1 - a_\eta)^{-2} \Gamma_{N_1} = \frac{1}{8\pi} (h^\dagger h)_{11} M_1 = \frac{2\pi^2}{\lambda_5} \frac{\xi_1}{8\pi} \frac{\tilde{m}_1 M_1^2}{v_{\text{ew}}^2}$$

- But at the same time, small $\lambda_5$ values also easily lead to a stronger washout.
Key parameter relations (2)

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

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

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

Larger parametric freedom for 3 RHNs: Enlarge $\varepsilon_1$ by small $\lambda_5$, control $K_1$ by small $m_1$

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

- RHNs must decay out of equilibrium $\rightarrow (h^+ h)_{11}$ must remain small $\rightarrow$ tiny mass $m_1$.

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

$$\frac{\Gamma_{\Delta L=2}}{H} \propto \lambda_5^{-2} v_{\text{ew}}^{-4} m_\xi^2 T M_{\text{Pl}}$$

- Becomes relevant at small $\lambda_5$ values, $\lambda_5 \ll \mathcal{O}(10^{-2}) \rightarrow$ Solve Boltzmann equations!
Scan of parameter space

Contours of $\eta_B$ in the $m_1-M_1$ plane

$K_1$ and $\lambda_5$ 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 $K_1 \ll 1$. RHNe then decay at very late times.
- This is possible as long as leptogenesis occurs before sphaleron freeze-out.

Absolute lower bounds: \[ m_1 \gtrsim \mathcal{O}(10^{-12}) \text{ eV}, \quad M_1 \gtrsim \mathcal{O}(10) \text{ TeV} \]
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 $N_j \rightarrow S N_i$ decays.
- UV origin: Multiple breaking of $B-L$? Composite Higgs models? ... [Alanne, Meroni, Tuominen '17]

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Additional CP-violating diagrams

- $\alpha_{ij}$ 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 → N_2 → ℓH.
- Respective deviations from thermal equilibrium: N_{N_2} - N_{N_2}^{eq} ∼ N_{N_1} - N_{N_1}^{eq}

Working parameter examples for: M_1 ∼ 10 · · · 100 GeV, M_2 ∼ 1 · · · 10 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.
   - $M_1 \gtrsim 10\text{ TeV}$, $m_1 \gtrsim 10^{-12}\text{ eV}$ $\rightarrow$ 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 $\mathcal{CP}$ diagrams
   - Successful examples with $M_1 \sim 10 \cdots 100\text{ GeV}$ and $M_2 \sim 1 \cdots 10\text{ TeV}$.
   - Promising scenario. Stay tuned for further progress.
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Thank you for your attention!