Low-Scale Leptogenesis beyond the Type-I Seesaw.

Kai Schmitz (INFN / University of Padua)

Based on:
1804.09660, 1812.04421, and 1905.12634.

In collaboration with:
Tommi Alanne, Vedran Brdar, Alexander Helmboldt, Thomas Hugle, Sho Iwamoto, and Moritz Platscher.

APEC Seminar | Kavli IPMU | Kashiwa, Japan | 17 July 2019

Outline

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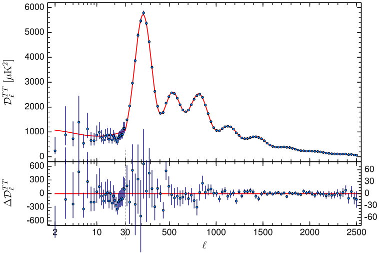
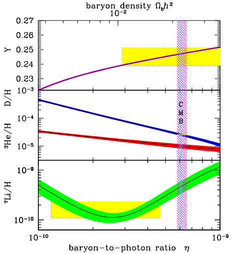
Baryogenesis via leptogenesis

[PLANCK '15]



[PDG '17]



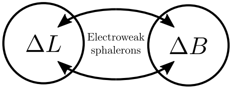
$$\eta_B = \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq \frac{n_b}{n_\gamma} \simeq 6.1 \times 10^{-10}$$

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]

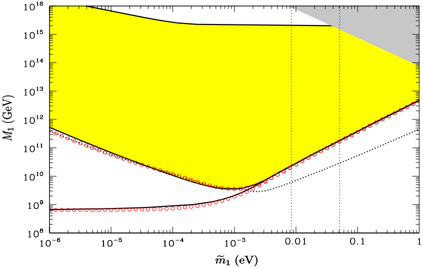


Leptogenesis at high energies

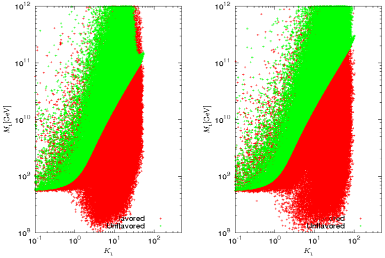
Standard thermal leptogenesis requires very heavy right-handed neutrinos (RHNs)

- 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)]

[Buchmuller, Di Bari, Plumacher, hep-ph/0401240]



[Blanchet, Di Bari, 0807.0743 [hep-ph]]



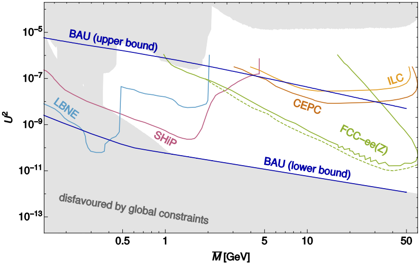
Davidson-Ibarra bound: *CP* asymmetry parameter suppressed by SM neutrino masses

$$\left|\varepsilon_1\right| \lesssim \frac{3}{16\pi}\,\frac{\left(m_3 - m_1\right) M_1}{v_{\mathrm{ew}}^2} \sim 10^{-6}\left(\frac{M_1}{10^{10}\,\mathrm{GeV}}\right)$$

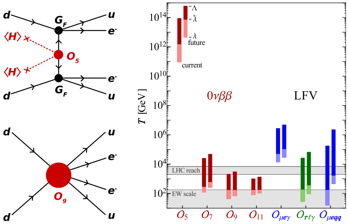
Leptogenesis at low energies

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

[Drewes, Garbrecht, Gueter, Klaric, 1609.09069 [hep-ph]]



[Deppisch, Harz, Huang, 1503.04825 [hep-ph]]



1. Directly search for RHNs with masses of $\mathcal{O}(1 \cdots 10)$ GeV in collider experiments.
2. Evidence for low-energy LNV / LFV would challenge high-scale leptogenesis.
3. Heavy RHNs contribute to the SM Higgs mass $\rightarrow$ EW naturalness problem.

This talk: A few ideas to lower the leptogenesis scale in beyond-type-I-seesaw scenarios.

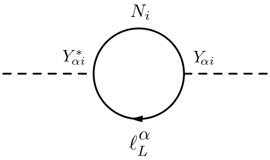
Outline

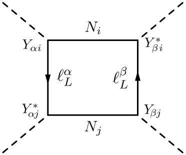
Radiative corrections to the Higgs potential

[Vissani, hep-ph/9709409]
[Clarke, Foot, Volkas, 1502.01352 [hep-ph]]

$$\mathscr{L}_{\rm seesaw} \supset -y_{I\alpha}\, N_I\, \ell_\alpha\, \tilde{H} + \frac{1}{2} M_I\, N_I\, N_I\,, \quad V_{\rm Higgs} = \mu^2\, |H|^2 + \lambda\, |H|^4$$

RHN loop diagrams contribute to the parameters in the Higgs potential





$$\Delta\mu^2 \sim \frac{1}{16\pi^2}\, |y|^2\, M_I^2$$

$$\Delta\lambda \sim \frac{1}{16\pi^2}\, |y|^4$$

Radiative corrections to the Higgs potential

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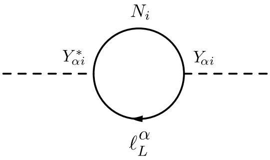

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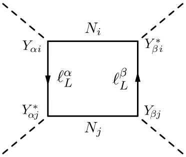

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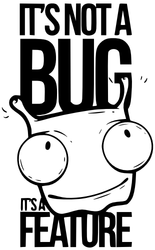
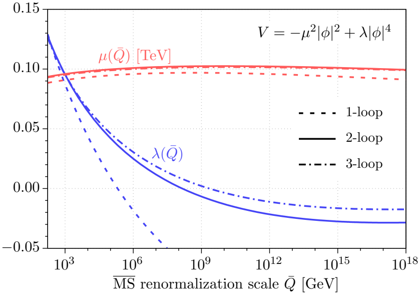


Philosophy of the "neutrino option": [Brivio, Trott, 1703.10924 [hep-ph], 1809.03450 [hep-ph]]

- Assume the Higgs sector respects classical scale invariance at high energies, $\mu \to 0$.
- Mass term soley induced by RHN threshold corrections at the RHN decoupling scale.
- New physics expected to be located at energies $E \gtrsim M_I$; no new physics at $\mathscr{O}(\text{TeV})$.

EFT matching at the RHN mass threshold



Running of parameters in the SM Higgs potential based on n-loop RG equations and $n-1$-loop threshold corrections:

$$\mu \sim 101\,\text{GeV} \quad @ \quad \bar{Q} \sim 10^6 \cdots 10^7\,\text{GeV}$$

Match UV theory (including RHNs) onto SMEFT (without RHNs) at mass threshold

$$V_{\text{UV}} = \lambda\,|H|^4$$

$$\rightarrow \quad V_{\text{SMEFT}} = \Delta\mu^2\,|H|^2 + (\lambda + \Delta\lambda)\,|H|^4$$

Type-I seesaw as the common origin of neutrino mass, BAU, and the EW scale

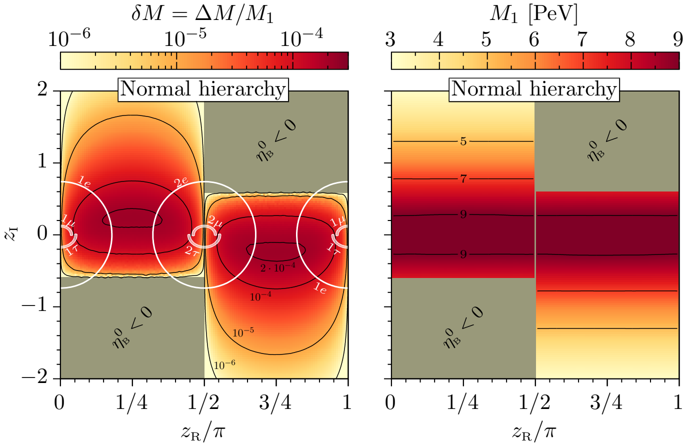
[Brdar, Helmboldt, Iwamoto, **KS**, 1905.12634 [hep-ph]] [See also Brivio, Moffat, Pascoli, Petcov, Turner, 1905.12642 [hep-ph]]

$$y_{I\alpha} = \frac{\mathrm{i}}{v/\sqrt{2}}\, M_I^{1/2} R_{Ii}\, m_i^{1/2} (U^\dagger)_{i\alpha}\,, \qquad \sum_{I,\alpha} \frac{C\,\varepsilon_{I\alpha}}{z_\alpha K_\alpha^{\text{eff}}} = \eta_B^{\text{obs}}\,, \qquad \frac{\text{Tr}\left[yy^\dagger\right]}{16\pi^2} M_1^2 = \mu_0^2\,.$$

- Use Casas–Ibarra parametrization and simultaneously solve conditions for η_B and μ.
- Vary experimental input values within $3\,\sigma$, scan over remaining free parameters.

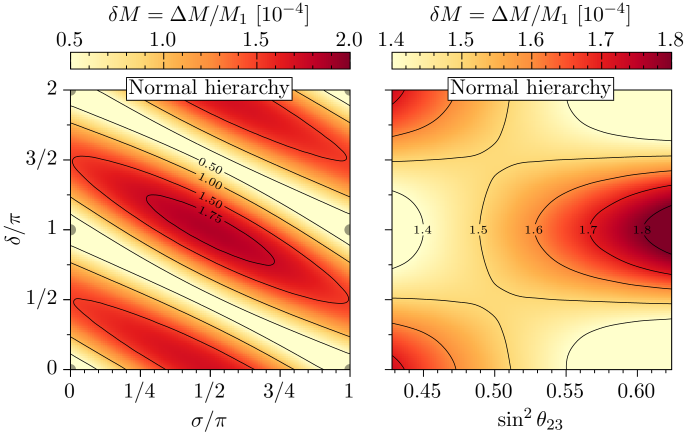
Resonant leptogenesis

$$\varepsilon_{I\alpha}^{(s)} = \sum_{J\neq I} \left\{ \frac{\Im\left[y_{I\alpha} y_{J\alpha}^{*} \left(yy^{\dagger}\right)_{IJ}\right]}{\left(yy^{\dagger}\right)_{II}\left(yy^{\dagger}\right)_{JJ}} + \frac{M_I}{M_J} \frac{\Im\left[y_{I\alpha} y_{J\alpha}^{*} \left(yy^{\dagger}\right)_{JI}\right]}{\left(yy^{\dagger}\right)_{II}\left(yy^{\dagger}\right)_{JJ}} \right\} \frac{M_I^2 - M_J^2}{\left(M_I^2 - M_J^2\right)^2 + R_{IJ}}$$



Leptogenesis from low-energy *CP* violation

Set all high-energy phases to zero $\rightarrow$ PMNS matrix *U* only source of *CP* violation



Outline

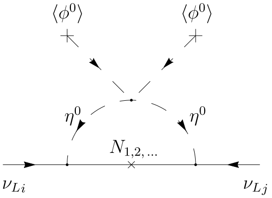
Ernest Ma's scotogenic model of neutrino masses [Ma '06]

"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 $[\mathrm{SM}] = +1$

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

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

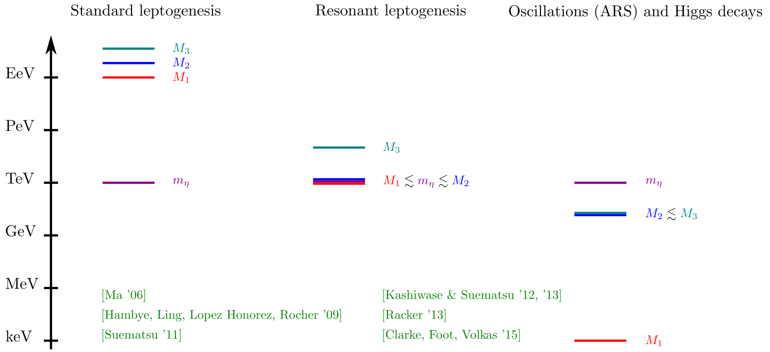


[Fig. from Merle & Platscher '15]

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



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 $\mathcal{M}_\nu$

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

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

Davidson-Ibarra bound on ε_1

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

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

Decay parameter $K_1 = \Gamma_{N_1}/H(T = M_1)$ 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: $\widetilde{m}_1 \geq m_{\text{lightest}}$

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

- 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

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

- 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: $\ell\eta \leftrightarrow \bar{\ell}\eta^*$, $\ell\ell \leftrightarrow \eta^*\eta^*$

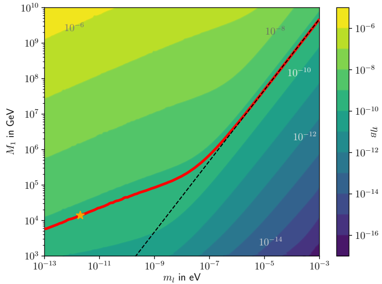
$$\frac{\Gamma_{\Delta L=2}}{H} \propto \lambda_5^{-2}\, v_{\text{ew}}^{-4}\, \overline{m}_\xi^2\, T\, M_{\text{Pl}}$$

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

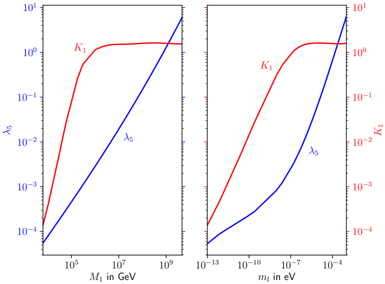
Scan of parameter space

[Hugle, Platscher, **KS**, 1804.09660 [hep-ph]]

Contours of η_B in the m_1–M_1 plane



K_1 and λ_5 as functions of M_1 and m_1



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

Outline

Type-I seesaw + a real scalar singlet

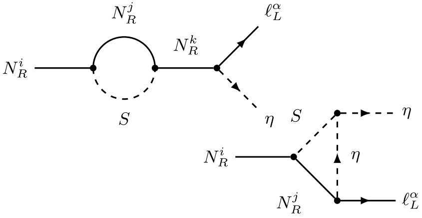
[Aristizabal Sierra, Tortola, Valle, Vicente, 1405.4706 [hep-ph]]
[Le Dall, Ritz, 1408.2498 [hep-ph]]

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]

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

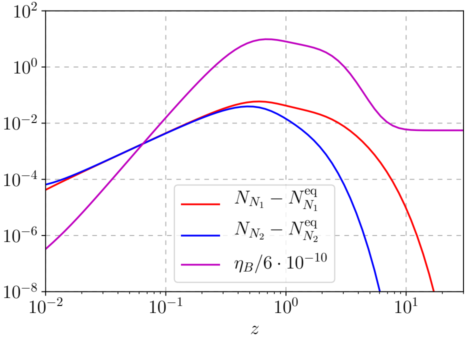
$$V = m_H^2|H|^2 + \frac{\lambda}{2}|H|^4 + \frac{1}{2}m_S^2\,S^2 + \mu\,S\,|H|^2 + \cdots$$



Additional *CP*-violating diagrams

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

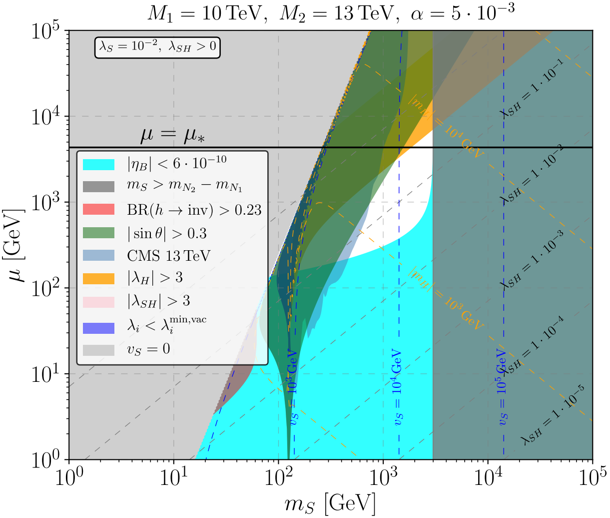
Time evolution of the baryon asymmetry [Alanne, Hugle, Platscher, **KS**, 1812.04421 [hep-ph]]



- N_2-dominated leptogenesis is boosted by additional contributions to ε_2.
- Washout by inverse N_1 decays is less severe because of $S\,N_1 \to N_2 \to \ell H$.
- 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: $M_1 \sim 0.1 \cdots 1\,\mathrm{TeV}\,, \quad M_2 \sim 1 \cdots 10\,\mathrm{TeV}$

Scan of parameter space



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Conclusions

This talk: Low-scale leptogenesis in three beyond-type-I-seesaw scenarios.

1. Leptogenesis + the neutrino option
   - Assume classically scale-invariant boundary conditions in the SM Higgs sector.
   - Successful resonant leptogenesis for a RHN mass splitting $\delta M \lesssim 10^{-4}$.
2. Leptogenesis + Ernest Ma's scotogenic 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.
3. Leptogenesis + the real-scalar-singlet extension of the Standard Model
   - Additional Yukawa interactions in the RHN sector $\rightarrow$ additional $\not{CP}$ diagrams.
   - Successful examples with $M_1 \sim 0.1 \cdots 1\,\mathrm{TeV}$ and $M_2 \sim 1 \cdots 10\,\mathrm{TeV}$.

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Thank you for your attention!