Extended SO(10)-inspired Model and Leptogenesis

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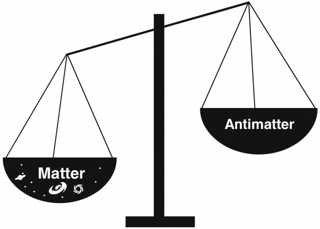
Overview

Neutrinos and cosmology as BSM hints

- **Neutrino oscillations**: show that flavour and mass eigenstates do not coincide $\Rightarrow$ neutrinos have non-zero masses.
- In the SM there is no renormalisable neutrino mass term $\Rightarrow$ need new degrees of freedom (e.g. right-handed neutrinos, seesaw).
- **Cosmology** (CMB, BBN, LSS): There is no evidence of primordial antimatter.
- Today, the relevant observable is the baryon asymmetry.
- Both neutrino masses and the baryon asymmetry can be explained by **new physics above the electroweak scale**.

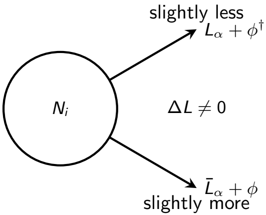
Neutrino flavour oscillations



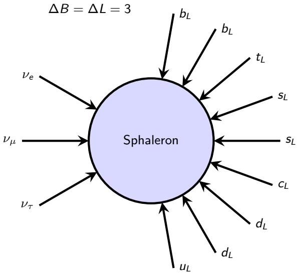
Matter–antimatter (baryon) asymmetry

Leptogenesis: linking neutrinos and baryon asymmetry

- Type-I seesaw introduces heavy Majorana RH neutrinos N_i and naturally generates small m_ν.
- In the early Universe, CP-violating and out-of-equilibrium decays of N_i generate a lepton asymmetry $L - \bar{L}$.
- Sphaleron processes partially convert this L asymmetry into a baryon asymmetry, while preserving $B - L$.
- Leptogenesis therefore links neutrino masses and the matter–antimatter asymmetry within a unified framework.



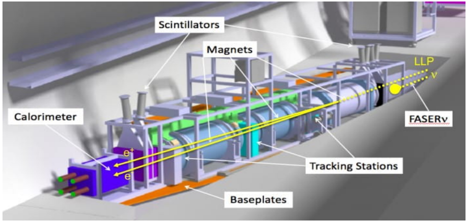
CP-violating N_i decays in the early Universe



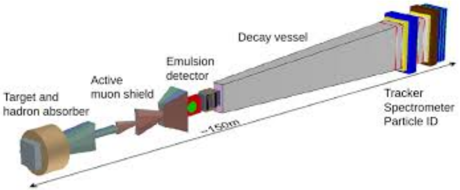
Sphalerons converting $B - L$ into B

Challenges and low-scale leptogenesis at colliders

- **High-scale leptogenesis:** $M_\nu \gg \mathrm{TeV}$, essentially impossible to test directly in the laboratory.
- **Low-scale leptogenesis:** resonant scenarios with GeV–TeV heavy neutral leptons can be probed at colliders and beam-dump experiments (LHC, FASER, SHiP, . . .).
- So far no evidence for new physics has been found; current searches place strong constraints on many low-scale baryogenesis scenarios (including resonant leptogenesis and electroweak baryogenesis).



LHC and forward detectors (e.g. FASER) searching for HNLs



SHiP: beam-dump experiment for long-lived particles and HNLs

Why SO(10)-inspired leptogenesis?

- **Top-down motivation:** SO(10) GUTs naturally unify one SM family into a single multiplet and accommodate RH neutrinos.
- **SO(10)-inspired conditions:** they relate the Dirac neutrino masses to the up-quark sector and strongly constrain the RH-neutrino spectrum.
- **Bottom-up approach:** constructing an EFT at low energy and requiring successful leptogenesis leads to predictive links with low-energy neutrino observables, such as m_1, $U_{\rm PMNS}$ and m_{ee}, which can be tested by ongoing and future experiments.
- **Our goal:**
  - extend the framework by relaxing non-essential constraints in model building, and explore a more generic N_2-leptogenesis scenario;
  - simultaneously include the leading physical effects in the asymmetry calculation and understand their impact;
  - ultimately construct a realistic model with an appropriate UV completion, capable of consistently addressing neutrino mixing, the matter–antimatter asymmetry, and possibly other open problems beyond the Standard Model, such as dark matter.

Type-I See-saw mechanism

- Leptonic mass terms after EWSB
  ("flavour basis": diagonal m_ℓ and M):

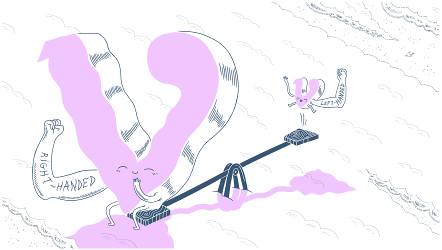
$$-\mathcal{L}_M = \overline{L_L} D_{m_L} L_R + \overline{\nu_L} m_D N_R + \frac{1}{2}\overline{N_R^c} D_M N_R + \text{h.c.}$$

- Light neutrinos from type-I see-saw:

$$m_\nu = -m_D D_M^{-1} m_D^T$$

- Where D_M is the diagonalized mass matrix for Heavy neutrinos N_i .
- Diagonalisation:

$$U^\dagger m_\nu U^* = -D_m, \quad U = U(\theta_{ij}, \delta, \rho, \sigma) \quad \text{(PMNS matrix)}.$$



"Seesaw": heavy N_i $\Downarrow$ light m_ν

Low energy neutrino parameters

Mixing angles and Dirac phase (NO., global fit, consistent with recent JUNO results):

$$\theta_{13} = 8.56^\circ \pm 0.11^\circ, \quad \theta_{12} = 33.68^{\circ}{}^{+0.73^\circ}_{-0.70^\circ},$$
$$\theta_{23} = 43.3^{\circ}{}^{+1.0^\circ}_{-0.8^\circ}, \quad \delta = -148^{\circ}{}^{+26^\circ}_{-41^\circ}.$$

Solar and atmospheric mass scales:

$$m_{\rm sol} \equiv \sqrt{m_2^2 - m_1^2} \simeq 8.65\ \mathrm{meV}, \qquad m_{\rm atm} \equiv \sqrt{m_3^2 - m_1^2} \simeq 50.1\ \mathrm{meV}.$$

$0\nu\beta\beta$ **effective neutrino mass:**

$$m_{ee} \equiv |(m_\nu)_{ee}| = \left| U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3 \right|.$$

Current $0\nu\beta\beta$ limit (KamLAND-Zen, 90% C.L.): $m_{ee} \lesssim 30\text{–}120\ \mathrm{meV}$.

Global fit: NuFIT 5.x (NO, SK+IceCube); $0\nu\beta\beta$: KamLAND-Zen (2024).
JUNO: JUNO collaboration (arXiv:2511.14593).

SO(10)-inspired model set-up

Bottom-up input at a common low-energy scale

$$m_D = V_L^\dagger D_{m_D} U_R, \quad D_{m_D} = \mathrm{diag}(m_{D1}, m_{D2}, m_{D3})$$

$$m_{D1} = \alpha_1 m_u, \quad m_{D2} = \alpha_2 m_c, \quad m_{D3} = \alpha_3 m_t$$

$$I \lesssim V_L \lesssim V_{\rm CKM} \; (\theta^L_{ij} \lesssim \theta^{\rm CKM}_{ij}), \quad \alpha_i = \mathcal{O}(0.1\text{–}10)$$

- The standard SO(10)-inspired hierarchy is

$$M_1 \ll 10^9\, GeV, \quad 10^9 \lesssim M_2 \lesssim 10^{12}\, GeV,$$
$$M_3 \gg 10^{12}\, GeV,$$

namely the usual window for N_2-leptogenesis.

P. Di Bari and A. Riotto, Phys. Lett. B671 (2009) 462 [arXiv:0809.2285],

P. Di Bari and M. Re Fiorentin, JHEP 10 (2017) 029 [arXiv:1705.01935].

Model realization

- SO(10)-type GUT relations motivate a **hierarchical** Dirac neutrino mass spectrum linked to the up-quark sector.
- V_L parametrises the **mismatch** between the flavour basis and the neutrino Yukawa basis.
- α_i encode model dependence from **GUT-scale** details, e.g. Higgs representations, Clebsch factors, running and thresholds.
- Inputs are specified at a common **low-energy scale** (typically $\mu_0 \sim m_Z$); RG running to the RH thresholds leaves room for additional UV structure, so this should be viewed as an **EFT** setup that may later be matched onto different fully specified top-down GUT models.

A simple extension: relaxing the V_L constraint

Motivation and goal

- Enlarge the class of viable N_2-leptogenesis solutions while preserving the genuinely SO(10)-inspired core of the framework.
- A more generic set-up reduces model-building bias and fine tuning, and can be matched onto a wider class of UV completions.

What should be kept?

$$m_{Di} = \alpha_i m_{u_i}^{\text{quark}}, \qquad \alpha_i = \mathcal{O}(0.1\text{–}10)$$

- The hierarchical Dirac pattern linked to the up-quark sector is the core GUT-motivated ingredient.
- Relaxing the α_i range would weaken the connection to the quark sector and move away from the SO(10)-inspired framework.

What is relaxed, and why?

$$I \lesssim V_L \lesssim V_{\text{CKM}} \qquad \Longrightarrow \qquad V_L \text{ more general}$$

- We relax, or even remove, the CKM-like bound on V_L.
- In practice, this means allowing larger left-handed mismatch angles θ_{ij}^L instead of restricting V_L to a small-angle region.
- The CKM-like bound on V_L is a useful simplifying assumption, but not the essential SO(10)-inspired ingredient.
- Relaxing V_L therefore gives the simplest and most natural extension, with more UV freedom and less model dependence.

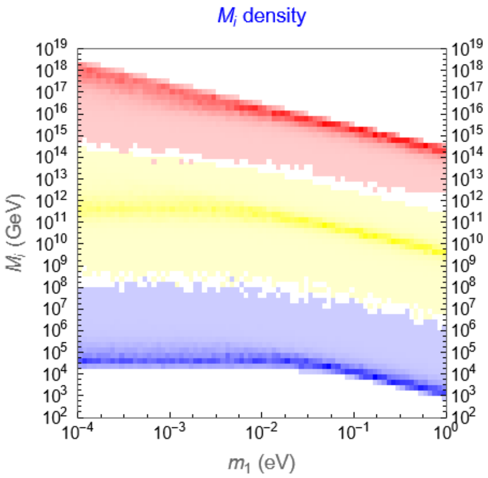
The most common case: hierarchical RHN mass spectrum

Analytic expressions

$$M_1 \simeq \frac{\alpha_1^2 m_u^2}{|(\tilde{m}_\nu)_{11}|}, \qquad M_2 \simeq \frac{\alpha_2^2 m_c^2}{m_1 m_2 m_3} \frac{|(\tilde{m}_\nu)_{11}|}{|(\tilde{m}_\nu^{-1})_{33}|},$$

$$M_3 \simeq \alpha_3^2 m_t^2 \, |(\tilde{m}_\nu^{-1})_{33}|, \qquad \tilde{m}_\nu = V_L \, m_\nu \, V_L^T .$$

- The analytic expressions work well for generic inputs $\{m_1, U, V_L\}$, and agree well with the numerical results.
- The plot shows that the hierarchy mass spectrum is still the most common case in the extended SO(10)-inspired model.
- Furthermore, the masses are concentrated in relatively narrow bands, corresponding to the darker regions in the plot.

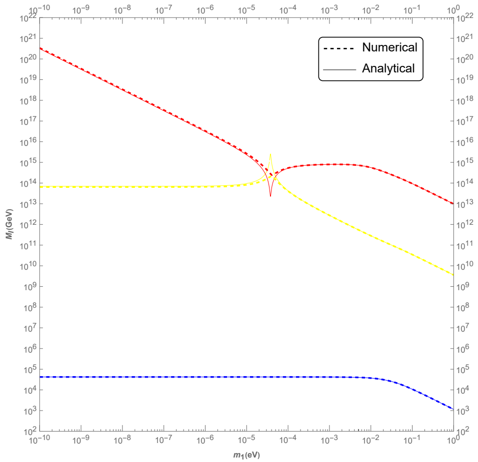


A Monte-Carlo scan of the RH neutrino mass spectrum with free V_L, for a benchmark choice $\alpha_i = \{1, 5, 5\}$.

Crossing-level spectrum: a rare M_2–M_3 near-degeneracy

Key features

- In Monte-Carlo scans, only about 1 in 5000 points exhibit the so-called crossing-level (CL) spectrum characterised by
$$M_1 \ll 10^9\,\mathrm{GeV}, \quad 10^{12}\,\mathrm{GeV} < M_2 \lesssim M_3.$$
- A subset of CL is called quasi-degenerate (QD), defined by $\frac{M_3}{M_2} \lesssim 2$.
- A necessary condition for CL/QD solutions is $\frac{\alpha_2}{\alpha_3} \gtrsim 0.02$.
- Within the SO(10)-inspired range $0.1 < \alpha_i < 10$, even in the near-degenerate limit one typically finds $\frac{M_3}{M_2} \gtrsim 1.5$, still far from full degeneracy.



A benchmark example of a M_2–M_3 crossing-level: fixing U and V_L, and varying m_1.

Compact spectrum: an extremely fine-tuned limit

Key features

$$10^9\,\mathrm{GeV} \ll M_1 \simeq M_2 \simeq M_3, \quad \frac{M_{i+1}}{M_i} \lesssim 10.$$

- In SO(10)-inspired models, the RHN mass hierarchy is naturally enhanced by the strong hierarchy of quark masses.
- However, it is still theoretically possible to obtain a so-called compact spectrum (CS) with the following condition

$$(\tilde{m}_\nu^{-1})_{23} \simeq 0, \quad (\tilde{m}_\nu^{-1})_{33} \simeq 0.$$

- For suitable choices of $\{\alpha_i\}$, the compact spectrum can be pushed further towards the fully-degenerate limit,

$$|1 - \frac{M_3}{M_1}| < 10^{-3}.$$

Why is it highly fine-tuned?

- The simultaneous suppression of two matrix elements implies strong cancellations among the input parameters, and requires extremely high numerical precision, typically below 10^{-30}.
- Even tiny shifts in a single parameter (e.g. $\Delta\theta = 10^{-3}\theta$) can spoil the degeneracy.
- This is, therefore, an isolated solution class that requires extremely fine tuning rather than a generic region accessible to random Monte-Carlo scans.
- Furthermore, compact-spectrum solutions exist only in a restricted small mixing angle region of V_L.

$$\theta^L_{12} \lesssim 10^\circ, \qquad \theta^L_{13} \lesssim 5^\circ, \qquad \theta^L_{23} \lesssim 2^\circ$$

N_2–Leptogenesis

Ingredients for a realistic leptogenesis calculation

Leading effects

- **Flavour effects:** flavour regimes, flavour-dependent washouts, flavour coupling, density-matrix treatment.

Sub-leading effects

- **Running effects:** RG evolution, threshold matching, partial UV completion.
- **Finite-temperature/radiative effects:** loop corrections, thermal masses, quantum-statistical factors.
- **Kinematic/spectral effects:** RH mass spectrum, overlap of N_i epochs, departure from sequential N_2 leptogenesis, possible resonant limit.
- **Other sub-leading effects:** scatterings, momentum dependence, reheating/initial conditions.

N_2 production and washout

- $T \gg M_2$: $N_{N_2} \simeq N_{N_2}^{\rm eq}$ and $N_{\Delta_\alpha} = 0$.
- $T \sim M_2$: N_2 decays out of equilibrium and generates flavoured asymmetries; tau-Yukawa interactions break coherence and lead to the two-flavour regime ($\gamma \equiv e + \mu, \tau$):

$$\frac{dN_{N_2}}{dz_2} = -D_2\,(N_{N_2} - N_{N_2}^{\rm eq}),$$

$$\frac{dN_{\Delta_\alpha}^{(2)}}{dz_2} = \varepsilon_{2\alpha}\,D_2(N_{N_2} - N_{N_2}^{\rm eq}) - P_{2\alpha}^0\,W_2 \sum_\beta C_{\alpha\beta}^{(2)}\,N_{\Delta_\beta}^{(2)}.$$

$$\varepsilon_{i\alpha} \equiv \frac{\Gamma(N_i \to L_\alpha \phi^\dagger) - \Gamma(N_i \to \bar{L}_\alpha \phi)}{\Gamma(N_i \to L_\alpha \phi^\dagger) + \Gamma(N_i \to \bar{L}_\alpha \phi)}, \quad D_i(z_i) \equiv \frac{\Gamma_i}{H\,z_i}, \quad W_i(z_i) = \frac{1}{4}\,K_i\,\mathcal{K}_1(z_i)\,z_i^3,$$

$$K_i \equiv \sum_\beta K_{i\beta}, \quad K_{i\alpha} \equiv \frac{\Gamma_{i\alpha} + \bar{\Gamma}_{i\alpha}}{H(T = M_i)}, \quad P_{i\alpha}^0 = \frac{K_{i\alpha}}{K_i}.$$

- $T \ll M_2$: after the N_2 washout, the surviving asymmetry can be described by the efficiency factor $\kappa(K_{2\alpha})$, schematically as

$$N_{\Delta_\alpha}^{(2),\rm f} \simeq U_{\alpha\beta}^{(2)} \varepsilon_{2\beta}\,\kappa(K_{2\beta}).$$

$T \gg M_2$

$T \sim M_2 \sim 10^{11}$ GeV

$T \sim 10^9$ GeV

N_1 washout and the final asymmetry

- $M_1 \lesssim T \ll 10^9\,\mathrm{GeV}$: muon-Yukawa interactions break the e–μ coherence, leading to the three-flavour regime; N_1 inverse decays wash out each flavour component:

$$\frac{dN^{(3)}_{\Delta_\alpha}}{dz_1} = -P^0_{1\alpha} W_1 \sum_\beta C^{(0)}_{\alpha\beta} N^{(3)}_{\Delta_\beta}.$$

- $T \ll M_1$: at the end of the N_1 washout, each flavour asymmetry can be written schematically as

$$N^{(3),\mathrm{f}}_{\Delta_\alpha} \simeq U^{(3)}_{\alpha\beta} N^{(2),\mathrm{f}}_{\Delta_\beta} \exp\left[-\frac{3\pi}{8} K_{1\beta}\right].$$

  Summing over flavours, we obtain the final $B-L$ asymmetry:

$$N^{\mathrm{lep,f}}_{B-L} = \sum_{\alpha=e,\mu,\tau} N^{(3),\mathrm{f}}_{\Delta_\alpha}.$$

- Sphaleron processes partially convert this $B-L$ asymmetry into the baryon asymmetry measured today:

$$\eta_B \equiv \frac{N_B}{N_\gamma} \simeq 0.0096 N_{B-L} \simeq \eta_B^{\mathrm{CMB}} \simeq 6.1 \times 10^{-10}. \qquad \text{(Planck 2018 + BAO)}$$

$T \sim 10^{5\div 6}\,\mathrm{GeV}$

$T \ll M_1$

Today

Leptogenesis in extended SO(10)-inspired setup

Hierarchy Spectrum

- Standard N_2-dominated leptogenesis works well: N_3 is too heavy to contribute significantly, N_2 generates the asymmetry, and N_1 provides the dominant washout.
- Removing the CKM-like bound on V_L relaxes the lower bound on m_1 from $0.65\,\mathrm{meV}$ to $0.08\,\mathrm{meV}$.
- Strong thermal leptogenesis can still be realised in a small subset of solutions, so a possible pre-existing asymmetry generated above the seesaw scale can be washed out.
- Normal ordering is strongly favoured, while inverted ordering is under severe pressure from absolute neutrino-mass constraints.

Crossing-level Spectrum *(Preliminary)*

- Standard N_2-leptogenesis is no longer sufficient; one must instead consider a combined $N_2 + N_3$ scenario.
- The final asymmetry is reduced to 60%–80% of the N_2-dominated result.
- Flavour effects are partially suppressed, since the system enters the unflavoured regime once $M_2 \gtrsim 10^{12}\,\mathrm{GeV}$.

Compact Spectrum

- Standard N_2-leptogenesis completely loses its validity; a more involved treatment including kinematic effects is required.
- In the fully-degenerate limit, the final asymmetry can be strongly suppressed and may even be completely washed out.

Final remarks

Summary

- We studied an extended SO(10)-inspired framework, where the SO(10)-inspired character comes from the GUT-motivated Dirac neutrino hierarchy linked to the up-quark sector.
- Within this framework, we explored all three possible classes of RH-neutrino mass spectra: the generic hierarchical case, the rare crossing-level case, and the highly fine-tuned compact limit.
- The hierarchical spectrum remains the dominant outcome, while the other two correspond to rare or highly tuned corners of parameter space.
- Therefore, the usual N_2-leptogenesis scenario turns out to be more generic and robust than naively expected.

Thank you!