Impact of flavour coupling on SO(10)-inspired leptogenesis

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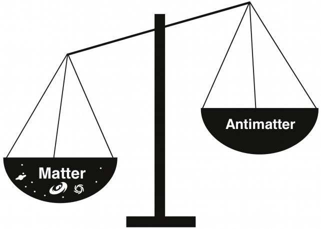
Overview

1. Introduction
2. Framework
3. Results
4. Final Remarks

Neutrinos and cosmology as BSM hints

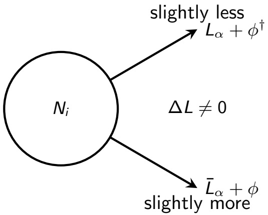
Neutrino flavour oscillations



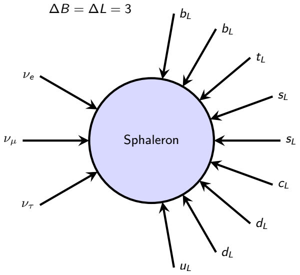
Matter–antimatter (baryon) asymmetry

- **Neutrino oscillations**: show that flavour and mass eigenstates are mixed $\Rightarrow$ 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 asymmetry coincides with the matter abundance.
- Both neutrino masses and the baryon asymmetry can be explained by **new physics above the electroweak scale**.

Leptogenesis: linking neutrinos and baryon asymmetry

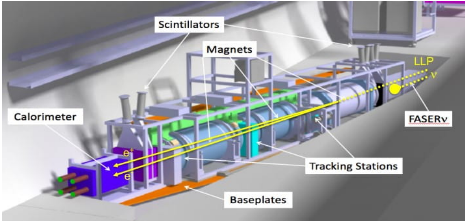


CP-violating N_i decays in the early Universe

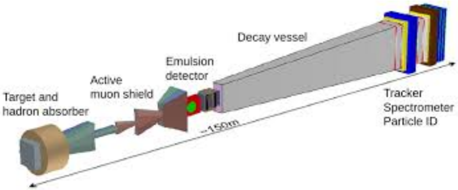


Sphalerons converting $B - L$ into B

- Type-I seesaw introduces heavy Majorana RH neutrinos N_i and naturally generates small m_ν.
- In the early Universe, out-of-equilibrium, CP-violating N_i decays produce a **lepton asymmetry**.
- Sphalerons process partially convert $B - L$ into a **baryon asymmetry**.
- **Leptogenesis** therefore links neutrino masses and the matter–antimatter asymmetry within a single framework.



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



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

- **High-scale leptogenesis:** typically $M_i \gtrsim 10^9$ GeV, 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).

Why SO(10)-inspired leptogenesis?

- **Top-down motivation:** SO(10) GUTs naturally unify one SM family in a single multiplet and accommodate RH neutrinos.
- **SO(10)-inspired** conditions relate the Dirac neutrino masses to up-quark masses and constrain the RH spectrum.
- This leads to a **predictive high-scale** scenario with N_2-dominated leptogenesis and sharp correlations between low-energy parameters: $(m_1, \theta_{23}, \delta, m_{ee})$.
- Our goal:
  - To include **flavour coupling** and **strong thermal** conditions in a full analytic treatment;
  - Quantify how the allowed parameter space for successful leptogenesis changes within an SO(10)-inspired model;
  - Highlight the resulting **testable predictions** for current and future experiments.

See-saw mechanism

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

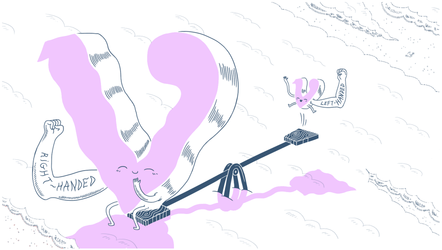
$$-\mathcal{L}_M = \overline{L_L} D_{m_L} L_R + \overline{\nu_L} m_D N_R + \frac{1}{2}\overline{N_R^c} D_M N_R + \text{h.c.}$$

- 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:

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



“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:

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

$0\nu\beta\beta$ **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.): $m_{ee} \lesssim 30\text{–}120 \ {\rm meV}$.

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

Transformation of neutrino Dirac mass matrix between the flavour basis and the Yukawa basis

$$m_D = V_L^\dagger D_{m_D} U_R.$$

Minimal $SO(10)$-inspired model: SM particles + 3 RH neutrinos, with the eigenvalues in the Dirac mass matrix in terms of the up quark masses,

$$m_{D1} = \alpha_1 m_{up}, \quad m_{D2} = \alpha_2 m_{charm}, \quad m_{D3} = \alpha_3 m_{top},$$

under conditions:

$$i) I \leq V_L \leq V_{CKM} (\theta_{ij}^L \leq \theta_{ij}^{CKM}),$$
$$ii) \alpha_i = \mathcal{O}(0.1 - 10).$$

In this framework one finds (see details in later slides)

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

For SO(10)-inspired set up: Abud & Buccella, Int. J. Mod. Phys. A16 (2001) 609 [hep-ph/0006029];
Di Bari & Riotto, Phys. Lett. B671 (2009) 462 [arXiv:0809.2285].

Leptogenesis from RH-neutrino decays

- Out-of-equilibrium decays:

$$N_i \to L_\alpha + \phi^\dagger, \quad N_i \to \bar{l}_\alpha + \phi$$

- CP-violating interference (tree + loop) $\Rightarrow$ lepton asymmetry

$$\varepsilon_{i\alpha} \equiv \frac{\Gamma(N_i \to L_\alpha \phi^\dagger) - \Gamma(N_i \to \bar{L}_\alpha \phi)}{\Gamma(N_i \to L_\alpha \phi^\dagger) + \Gamma(N_i \to \bar{L}_\alpha \phi)} .$$

- Sphalerons partially convert $B - L$ into baryon asymmetry

$$\eta_B \equiv \frac{N_B}{N_\gamma} \simeq 0.0096 N_{B-L} \simeq \eta_B^{\mathrm{CMB}} \simeq 6.1 \times 10^{-10}.$$

η_B^{CMB} from Planck 2018 + BAO.

Flavour effects

Flavour effects in leptogenesis arise in two complementary ways:

- **Flavoured lepton effects:** different lepton flavours have different CP asymmetries and washout parameters, so that each flavour α contributes differently to the final $B-L$ asymmetry.
- **Spectator effects(This work!):** the Higgs field is not flavour-labelled. During the wash-out process, inverse decays with an unflavoured Higgs break the independence of different flavours and induce **flavour coupling** effects.

See e.g. Antusch et al. [arXiv:1003.5132], Blanchet et al. [arXiv:1112.4528] for full flavour treatment.

Analytic framework I: along the thermal history

$T \gg M_2 \qquad T \sim M_2 \quad 10^9 \ll T \ll 10^{12}\,\mathrm{GeV} \quad \longrightarrow T$

Without flavour coupling

- $T \gg M_2$: $N_{N_2} \simeq N_{N_2}^{\rm eq}$, $N_{\Delta_\alpha} = 0$.
- $T \sim M_2$: N_2 decays out of equilibrium and generates flavoured asymmetries:

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

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

$$D_i(z_i) \equiv \frac{\Gamma_i}{H\,z_i}, \quad W_i(z_i) = \frac{1}{4} K_i\,\mathcal{K}_1(z_i)\,z_i^3,$$

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

- $10^9 \ll T \ll 10^{12}\,\mathrm{GeV}$: flavoured regime: each N_{Δ_α} evolves independently; the asymmetry after the wash-out can be described in terms of a single-flavour efficiency $\kappa(K_{2\alpha})$.

With flavour coupling

- $T \gg M_2$: unflavoured regime, lepton doublets are coherent superpositions.
- $T \sim M_2$: τ breaks coherence into two-flavour regime ($\gamma \equiv e + \mu$, τ); inverse decay processes induce flavour coupling described by a matrix $C^{(2)}$:

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

- $10^9 \ll T \ll 10^{12}\,\mathrm{GeV}$: collect asymmetries into a vector $\mathbf{N}_\Delta^{(2)}$ and go to the *coupled basis*

$$\mathbf{N}_\Delta^{\prime(2)} = U^{(2)-1}\mathbf{N}_\Delta^{(2)},\, C_{\rm diag}^{(2)} = U^{(2)\,-1} C^{(2)} U^{(2)};$$

in this basis each component obeys again a single-flavour-like equation with the usual efficiency factor $\kappa(K)$.

Analytic framework II: N_1 wash-out and final asymmetry

$$T \lesssim M_2 \qquad 10^9 \gg T \gtrsim M_1 \qquad T \ll M_1 \qquad \longrightarrow T$$

Without flavour coupling

- $T \lesssim M_2$: after N_2 wash-out we have

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

- $10^9\,\mathrm{GeV} \gg T \gtrsim M_1$: three-flavour regime, e, μ, τ fully resolved; N_1 inverse decays wash out each flavour component:

$$\frac{dN_{\Delta_\alpha}}{dz_1} = -K_{1\alpha} W_1 N_{\Delta_\alpha},$$

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

- $T \ll M_1$: final leptonic $B-L$ asymmetry:

$$N_{B-L}^{\mathrm{lep,f}} = \sum_{\alpha=e,\mu,\tau} N_{\Delta_\alpha}^{(3),\mathrm{f}} \simeq \sum_\alpha \varepsilon_{2\alpha}\,\kappa(K_{2\alpha})\,e^{-\frac{3\pi}{8}K_{1\alpha}}.$$

With flavour coupling

- $T \lesssim M_2$: in the **coupled basis** (diagonal $C^{(2)}_{\mathrm{diag}}$) the N_2-generated asymmetries are

$$N_{\Delta_\alpha}^{\prime(2),\mathrm{f}} \simeq \varepsilon'_{2\alpha}\,\kappa(K'_{2\alpha}).$$

- $10^9\,\mathrm{GeV} \gg T \gtrsim M_1$: three-flavour regime with another coupling matrix $C^{(3)}$; define the coupled basis at $T \sim M_1$ by $\mathbf{N}_\Delta^{\prime(3)} = U^{(3)-1}\mathbf{N}_\Delta^{(3)}$, so that each component again has a single-flavour-like wash-out with effective parameters $K'_{1\alpha}$.
- $T \ll M_1$: each component in the coupled basis has similar analytic structure as on the left $\varepsilon'_{2\alpha}\,\kappa(K'_{2\alpha})\,e^{-\frac{3\pi}{8}K'_{1\alpha}}$. Rotating back to uncoupled basis, one obtains the asymmetry for physical flavour

$$N_{\Delta_\alpha}^{(3)\,\mathrm{f}} = U_{\alpha\beta}^{(3)}\,N_{\Delta_\beta}^{\prime(3)\,\mathrm{f}}.$$

Strong thermal leptogenesis

Idea and consideration

- Possible pre-existing $B-L$ asymmetry from some unknown very high-scale mechanism ($N_{B-L}^{\mathrm{p,i}}$).
- N_2 and N_1 inverse decays wash it out.
- The observed asymmetry comes entirely from the leptogenesis mechanism and becomes independent of the initial condition.
- The strong thermal condition can be expressed schematically by

$$N_{B-L}^{\mathrm{p,f}} + N_{B-L}^{\mathrm{lep,f}} \simeq N_{B-L}^{\mathrm{CMB}},$$

with

$$|N_{B-L}^{\mathrm{p,f}}| \ll |N_{B-L}^{\mathrm{lep,f}}|.$$

Implications

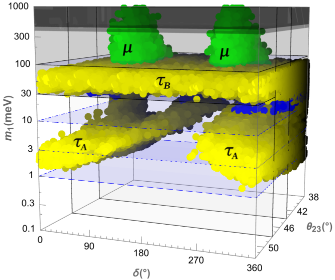
- In our work, this defines the subset of SO10INLEP within the full parameter space: more predictive ranges for $(m_1, \theta_{23}, \delta, m_{ee})$.

3D projection of hyper parameter space for SO10INLEP

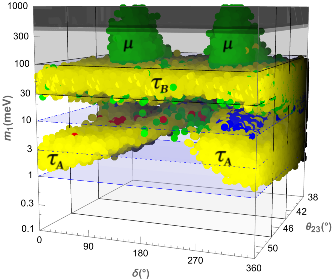
- The allowed parameter space in SO10INLEP given by the correct value of the final asymmetry, combined with the current experimental constraints within the 3σ range

$$\eta^{\mathrm{lep}}(m_1, U_{\mathrm{PMNS}}, V_L) \simeq \eta^{\mathrm{CMB}} \simeq 6.1 \times 10^{-10}$$

- This projection shows the SO10INLEP constraints for parameters $(m_1, \theta_{23}, \delta)$ that can be predicted experimentally but currently remain subject to significant uncertainty.
- The colour indicates the flavour that dominates the asymmetry (i.e. which N_{Δ_α} contributes most).



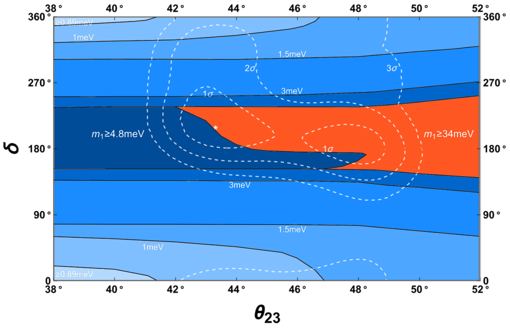
A1: Without flavour coupling



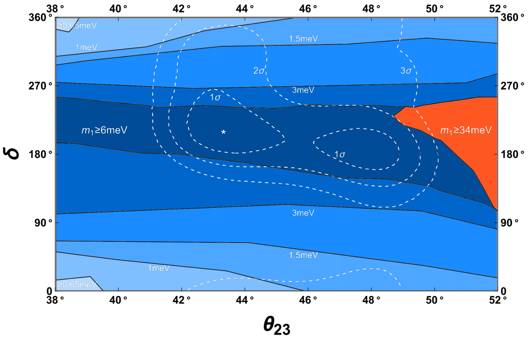
A2: With flavour coupling

Contour line for m_1 lower bound

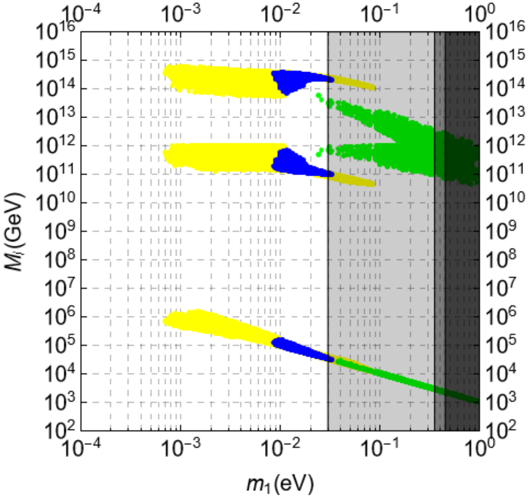
- This links the absolute neutrino mass scale with the neutrino mixing.
- The previously disfavoured second-octant region in (θ_{23}, δ) is now reopened thanks to flavour coupling effects.

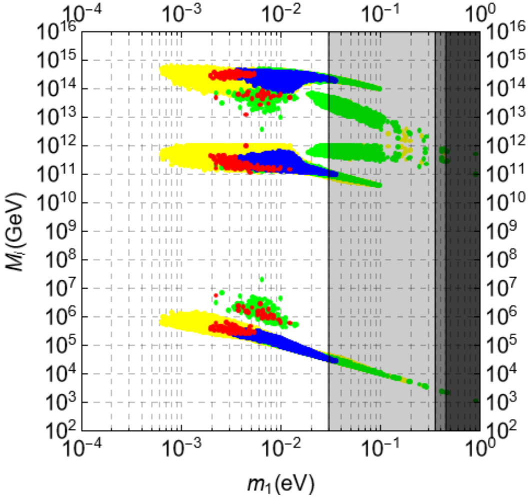


B1: Without flavour coupling



B2: With flavour coupling





C1: Without flavour coupling

C2: With flavour coupling

Final Remarks

Framework

- Non-SUSY SO(10)-inspired scenario with hierarchical RH neutrinos and N_2-dominated leptogenesis.
- Flavour-coupling effects from spectator processes are consistently included via flavour coupling matrices.
- Possible pre-existing $B - L$ asymmetries are washed out, realising strong thermal leptogenesis.

Impact of flavour coupling

- Modifies the distribution of the asymmetry among flavours.
- Relaxes the lower bound on the lightest neutrino mass from $m_1 \sim 1\,\mathrm{meV}$ to $m_1 \sim 0.65\,\mathrm{meV}$.
- Allows for new muon-dominated and electron-dominated solutions.

Cosmology / $0\nu\beta\beta$ / oscillations

- The preferred region $m_1 \sim \mathcal{O}(10)\,\mathrm{meV}$ is being probed by present and future cosmological bounds on $\sum m_\nu$.
- The predicted band in the (m_{ee}, m_1) plane partly overlaps with the sensitivity of upcoming ton-scale $0\nu\beta\beta$ experiments.
- The preference for the first octant and the correlated ranges of θ_{23} and δ will be tested by next-generation long-baseline experiments (DUNE, Hyper-K, ...).

Thank you!