

SO(10)-inspired leptogenesis predictions on low-energy neutrino parameters



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25 June 2026, PASCOS 2026, Sheffield

Based on the work with Pasquale Di Bari
arXiv:2507.06144; 2607.xxxxx

Experimental landscape: testing neutrino cosmology

Low-energy neutrino experiments

- **Oscillation parameters and mass ordering**
JUNO measures θ_{12} , Δm_{21}^2 , $\Delta m_{31/32}^2$ and tests the mass ordering; T2K/NOvA/SK constrain θ_{23} , δ and $|\Delta m_{31}^2|$, with DUNE/HK expected to improve δ , θ_{23} and ordering.
- **Absolute neutrino-mass scale**
KATRIN directly probes $m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$ and gives $m_\beta < 0.45$ eV at 90% C.L.; cosmology probes $\sum_i m_i$ close to the minimal-mass region, with model dependence.
- **Majorana nature**
 $0\nu\beta\beta$ searches test lepton-number violation and $m_{ee} = |\sum_i U_{ei}^2 m_i|$. Current KamLAND-Zen limits imply $m_{ee} \lesssim 28\text{--}122$ meV.

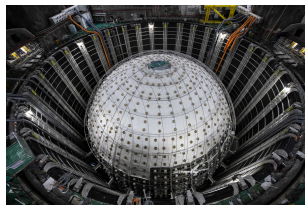
Relevant low-energy tests: m_1 , ordering, δ , θ_{23} , m_{ee}

NuFIT 6.1 input (NO):

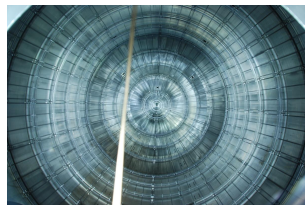
$\theta_{12} \simeq 33.7^\circ$, $\theta_{13} \simeq 8.6^\circ$, $\theta_{23} \simeq 43.3^\circ$ or 48.5° , $\delta \simeq 212^\circ$.

See also all nice talks in neutrino physics session for latest updates.

Refs.: NuFIT 6.1; KATRIN Collaboration, Science 388 (2025); KamLAND-Zen Collaboration, arXiv:2406.11438.



JUNO: precision reactor-neutrino oscillations



KATRIN: direct neutrino-mass measurement

Neutrinos and cosmology as BSM hints

- **Neutrino oscillations:** show that flavour and mass eigenstates do not coincide and neutrinos are massive.
- 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

Type-I See-saw mechanism

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

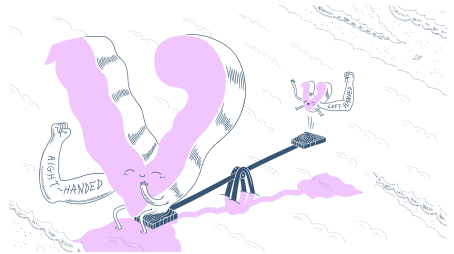
$$-\mathcal{L}_M = \overline{L}_L D_{m_L} L_R + \overline{\nu}_L m_D N_R + \frac{1}{2} \overline{N}_R^c D_M N_R + \text{h.c.}$$

- 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:

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



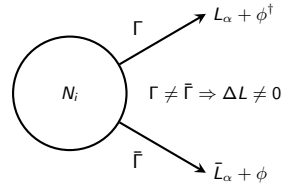
"Seesaw": heavy $N_i \Downarrow$ light m_ν

Leptogenesis: linking neutrinos and baryon asymmetry

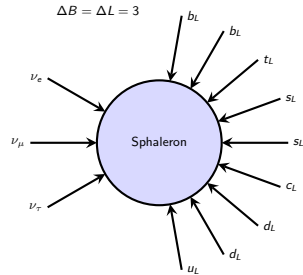
- Type-I seesaw predicts heavy Majorana RH neutrinos N_i and naturally generates small m_ν .
- In the early Universe, CP-violating and out-of-equilibrium decays of N_i generate a lepton asymmetry $L - \bar{L}$.
- Sphaleron processes partially convert this L asymmetry into a baryon asymmetry, while preserving $B - L$:

$$\eta_{B0} \equiv \frac{n_{B0} - n_{\bar{B}0}}{n_{\gamma 0}} = \frac{1}{f} N_B^f = \frac{a_{\text{sph}}}{f} N_{B-L}^f \simeq 6.1 \times 10^{-10}.$$

- Leptogenesis therefore links neutrino masses and the matter–antimatter asymmetry within a unified framework.



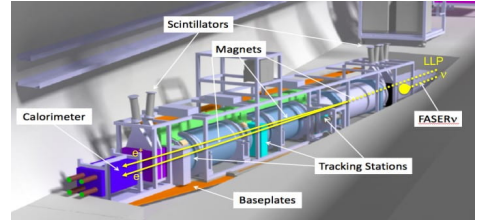
CP-violating N_i decays in the early Universe



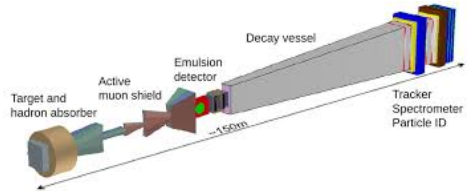
Sphalerons converting $B - L$ into B

Challenges and low-scale leptogenesis at colliders

- **High-scale leptogenesis:** $M_i \gg \text{TeV}$, essentially impossible to test directly by producing the heavy RH neutrinos.
- **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

From observables to a predictive framework

Low-energy neutrino data

Oscillation experiments determine

$$\Delta m_{21}^2, \quad |\Delta m_{31}^2|, \quad \theta_{12}, \quad \theta_{13}, \quad \theta_{23}, \quad \delta.$$

Together with the lightest mass and effective neutrino mass,

$$m_1, \quad m_{ee},$$

they partially reconstruct the light-neutrino mass matrix

$$m_\nu = U_{\text{PMNS}}^* D_m U_{\text{PMNS}}^\dagger.$$

The question

Can we test high-scale leptogenesis with these low-energy parameters?

High-scale leptogenesis

The baryon asymmetry depends on heavy RHN quantities:

$$M_i, \quad K_{i\alpha}, \quad \varepsilon_{i\alpha},$$

which cannot be determined by low-energy data alone.

A predictive framework requires a link

$$m_\nu \implies m_D, M_i \implies \eta_B.$$

SO(10)-inspired model

SO(10)-inspired setup

Decompose the Dirac neutrino mass matrix as

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

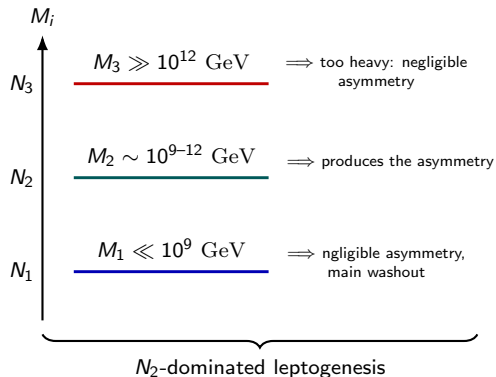
The SO(10)-inspired condition is

$$\begin{aligned} m_{D1} &= \alpha_1 m_u, \\ m_{D2} &= \alpha_2 m_c, & \alpha_i &= \mathcal{O}(0.1-10), \\ m_{D3} &= \alpha_3 m_t, \end{aligned}$$

together with

$$I \lesssim V_L \lesssim V_{\text{CKM}}.$$

Typical Mass Hierarchy



Why this framework?

GUT-motivated predictivity

- SO(10) naturally accommodates one RH neutrino per SM family.
- The GUT-motivated relation

$$m_D \sim m_{\text{up}}^{\text{quark}}$$

reduces the freedom of the seesaw.

- The up-quark hierarchy maps into a hierarchical RH-neutrino spectrum, leading naturally to an N_2 -dominated scenario.
- This makes high-scale leptogenesis predictive rather than completely arbitrary.

Neutrino-cosmology testability

Low-energy neutrino data become indirect tests of high-scale leptogenesis.

Predicted / constrained observables

- mass ordering
- lightest mass m_1 and absolute scale
- Majorana phases (ρ, σ)
- θ_{23} octant and Dirac phase δ

Here “SO(10)-inspired” is used as a predictive EFT structure, not as a fully specified UV-complete GUT model.

Asymmetry in N_2 -dominated leptogenesis

1. N_2 era: production and flavoured washout

$$\frac{dN_{\Delta\alpha}}{dz_2} \simeq \underbrace{\varepsilon_{2\alpha} D_2}_{\text{CP source from } N_2} - \underbrace{W_{2\alpha} \sum_{\beta} C_{\alpha\beta}^{(2)} N_{\Delta\beta}}_{\text{flavoured washout + flavour coupling}}$$

2. N_1 era: final flavour filtering

$$\frac{dN_{\Delta\alpha}}{dz_1} \simeq - \underbrace{W_{1\alpha} \sum_{\beta} C_{\alpha\beta}^{(3)} N_{\Delta\beta}}_{\text{final washout mainly from } N_1}$$

$$N_{B-L}^f = \sum_{\alpha} N_{\Delta\alpha}^f, \quad \eta_B^{\text{lep}} \simeq 0.0096 N_{B-L}^f \simeq \eta_B^{\text{obs}}.$$

Key ingredients

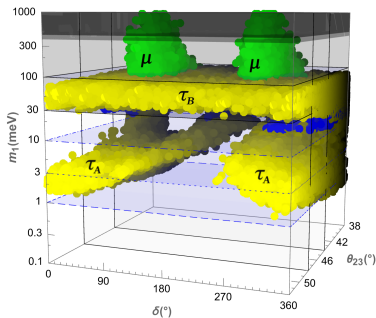
- $\varepsilon_{2\alpha}$: CP asymmetry
- $W_{i\alpha}$: washout
- $C_{\alpha\beta}^{(2,3)}$: flavour coupling
- N_1 : final flavour filter

Other potential relevant

- density matrix
- RG running
- thermal corrections
- kinematic effects
- initial conditions

3D projection of the allowed parameter space

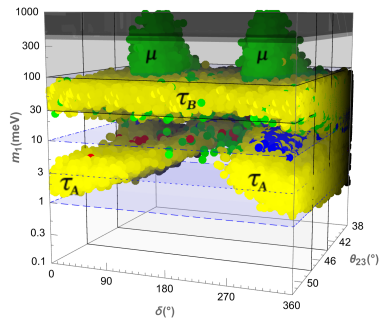
$$\eta_B^{\text{lep}}(m_1, U_{\text{PMNS}}; V_L \simeq I; \alpha_2 = 5) \simeq \eta_B^{\text{obs}}$$



Without flavour coupling



including flavour
coupling



With flavour coupling

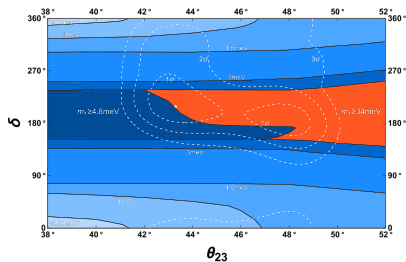
● tauonic ● muonic ● electronic ● strong thermal

Normal ordering is predicted, which is now favoured by the most recent JUNO data at 2.3σ .[†]

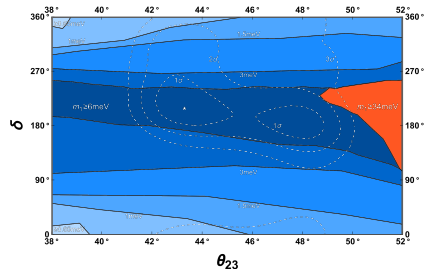
[†] See previous JUNO talk by Xianguo Lu.

Flavour coupling: reshaping the prediction

- The colour map gives the minimum lightest-neutrino mass required for successful leptogenesis at each point in the (δ, θ_{23}) plane.
- Without flavour coupling, much of the preferred region is effectively lost: successful leptogenesis requires $m_1 > 34 \text{ meV}$, while cosmology demands $m_1 \lesssim 30 \text{ meV}$.
- With flavour coupling, this tension is largely removed: viable solutions extend over both octants, including a sizeable second-octant window.
- Flavour coupling therefore shifts the low-energy prediction in the direction favoured by current data.



⇒
including flavour
coupling

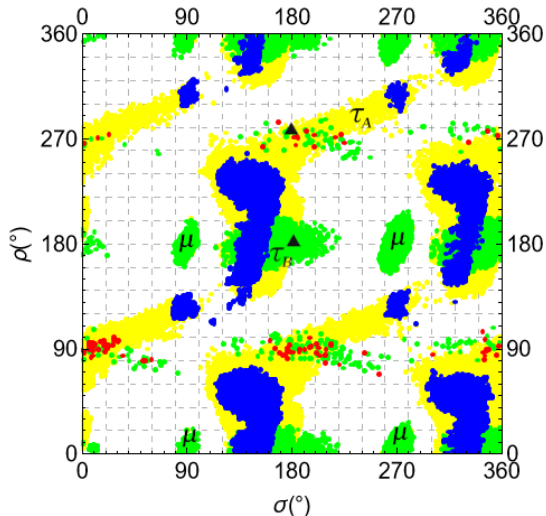


[†] Dashed contours correspond to experimental constraints from NuFIT 6.1 (NO).

Probing Majorana phases indirectly

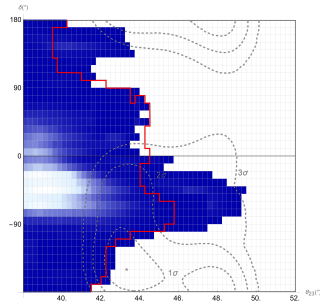
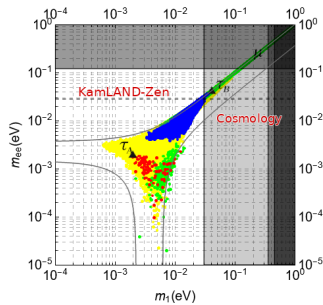
- Majorana phases (ρ, σ) are not directly accessible in current neutrino experiments.
- In the seesaw reconstruction, they enter the leptogenesis asymmetry and washout.
- Successful leptogenesis selects non-trivial islands in the (ρ, σ) plane.

An indirect window on parameters beyond direct experimental access.



Absolute mass scale and strong thermal leptogenesis

- SO(10)-inspired leptogenesis predicts a lower bound for the effective neutrino mass $m_{ee} \gtrsim 10^{-5} \text{eV}$.
- The strong thermal region begins near the experimental “corner” where cosmology and $0\nu\beta\beta$ searches meet.
- Next-generation experiments including KamLAND-Zen upgrades and LEGEND-1000[†] can start testing this region. [†]See previous LEGEND talk by Alex Biondi.



Strong thermal leptogenesis requires

$$N_{B-L}^{\text{pre},f} \ll N_{B-L}^{\text{lep},f}.$$

Further predicts:

$$10 \text{ meV} \lesssim m_1 \lesssim 30 \text{ meV},$$

$$\theta_{23} < 45^\circ, \quad -90^\circ \lesssim \delta \lesssim 0^\circ.$$

Conclusions

- SO(10)-inspired type-I see-saw links low-energy neutrino data to high-scale N_2 -dominated leptogenesis.
- Normal ordering is a robust prediction of this framework, and is now favoured by the newest JUNO data.
- Flavour coupling reshapes the prediction, opening viable regions in the (δ, θ_{23}) plane that are favoured by current data.
- The strong thermal condition gives sharper targets for m_1 , m_{ee} , δ and θ_{23} , making the scenario testable by future oscillation, $0\nu\beta\beta$ and cosmological data.

Thank you for your attention!