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

Xubin Hu
Physics and Astronomy
University of Southampton

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Work with Pasquale Di Bari
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Experimental landscape: testing neutrino cosmology

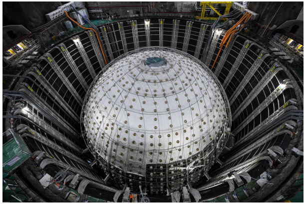
Low-energy neutrino expreiments

- **Oscillation parameters and mass ordering**
  JUNO measures θ_{12}, Δm^2_{21}, $\Delta m^2_{31/32}$ and tests the mass ordering; T2K/NOvA/SK constrain θ_{23}, δ and $|\Delta m^2_{31}|$, 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 $m_\beta < 0.45\ \mathrm{eV}$ 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 $m_{ee} \lesssim 28\text{–}122\ \mathrm{meV}$.

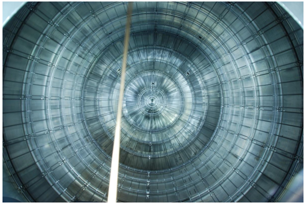
Relevant low-energy tests: $m_1,\ \mathrm{ordering},\ \delta,\ \theta_{23},\ m_{ee}$

NuFIT 6.1 input (NO):

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



JUNO: precision reactor-neutrino oscillations



KATRIN: direct neutrino-mass measurement

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.

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 ⇒ 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):

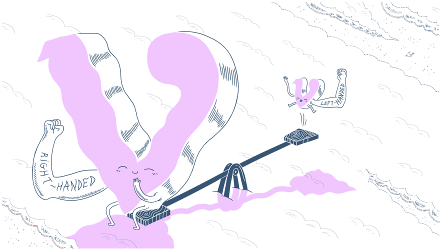
$$-\mathcal{L}_M = \overline{L_L} D_{m_L} L_R + \overline{\nu_L} m_D N_R + \frac{1}{2}\overline{N_R^c} D_M N_R + \text{h.c.}$$

- 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:

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



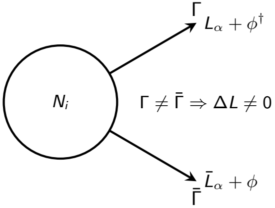
"Seesaw": heavy $N_i \Downarrow$ light m_ν

Leptogenesis: linking neutrinos and baryon asymmetry

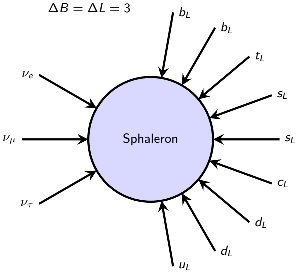
- Type-I seesaw predicts heavy Majorana RH neutrinos N_i and naturally generates small m_ν.
- In the early Universe, CP-violating and out-of-equilibrium decays of N_i generate a lepton asymmetry $L - \bar{L}$.
- Sphaleron processes partially convert this L asymmetry into a baryon asymmetry, while preserving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

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

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



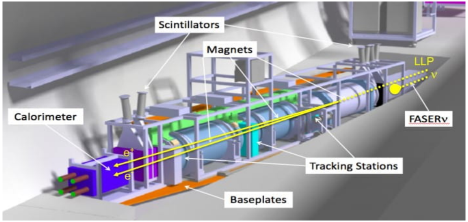
CP-violating N_i decays in the early Universe



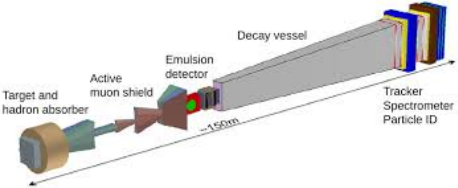
Sphalerons converting $B - L$ into B

Challenges and low-scale leptogenesis at colliders

- **High-scale leptogenesis:** $M_i \gg \mathrm{TeV}$, 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

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

Together with the lightest mass and effective neutrino mass,

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

they partially reconstruct the light-neutrino mass matrix

$$m_\nu = U^*_{\mathrm{PMNS}} D_m U^\dagger_{\mathrm{PMNS}}.$$

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

$$m_\nu \quad \Longrightarrow \quad m_D,\ M_i \quad \Longrightarrow \quad \eta_B.$$

SO(10)-inspired model

SO(10)-inspired setup

Decompose the Dirac neutrino mass matrix as

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

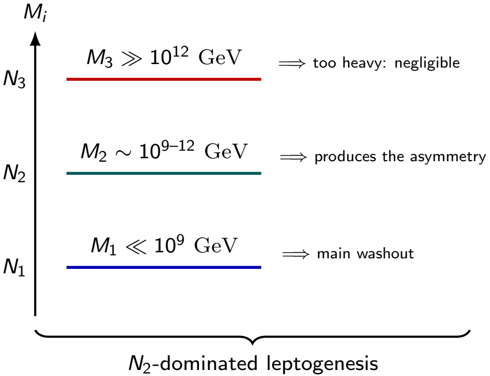
The SO(10)-inspired condition is

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

together with

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

Typical Mass Hierarchy



M_i

N_3 $M_3 \gg 10^{12}$ GeV $\Longrightarrow$ too heavy: negligible

N_2 $M_2 \sim 10^{9\text{–}12}$ GeV $\Longrightarrow$ produces the asymmetry

N_1 $M_1 \ll 10^{9}$ GeV $\Longrightarrow$ main washout

N_2-dominated leptogenesis

Refs.: Abud & Buccella, IJMPA 16 (2001) 609; Di Bari & Riotto, PLB 671 (2009) 462.

Why this framework?

GUT-motivated predictivity

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

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

  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**

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

2. **N_1 era: final flavour filtering**

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

$$N^f_{B-L} = \sum_\alpha N^f_{\Delta_\alpha}, \qquad \eta_B^{\rm lep} \simeq 0.0096\, N^f_{B-L} \simeq \eta_B^{\rm obs}.$$

Key ingredients

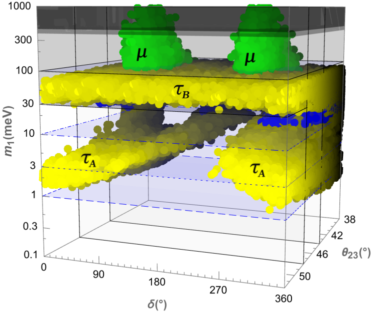
- $\varepsilon_{2\alpha}$: CP asymmetry
- $W_{i\alpha}$: washout
- $C^{(2,3)}_{\alpha\beta}$: flavour coupling
- N_1: final flavour filter

Other potential relevant

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

3D projection of the allowed parameter space

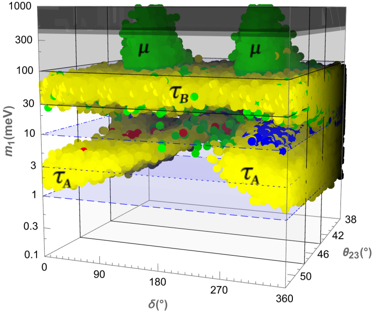
$$\eta_B^{\mathrm{lep}}(m_1, U_{\mathrm{PMNS}}; V_L \simeq I; \alpha_2 = 5) \simeq \eta_B^{\mathrm{obs}}$$



Without flavour coupling

$\Longrightarrow$

including flavour coupling



With flavour coupling

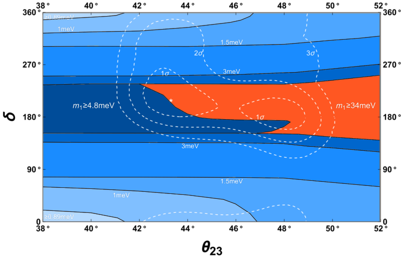
🟡 tauonic 🟢 muonic 🔴 electronic 🔵 strong thermal

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

[†] See previous JUNO talk by Xianguo Lu.

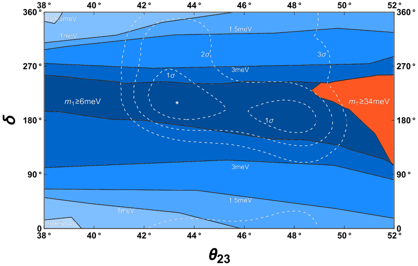
Flavour coupling: reshaping the prediction

- 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 $m_1 > 34\,\mathrm{meV}$, while cosmology demands $m_1 \lesssim 30\,\mathrm{meV}$.
- 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.



$\Longrightarrow$

including flavour coupling

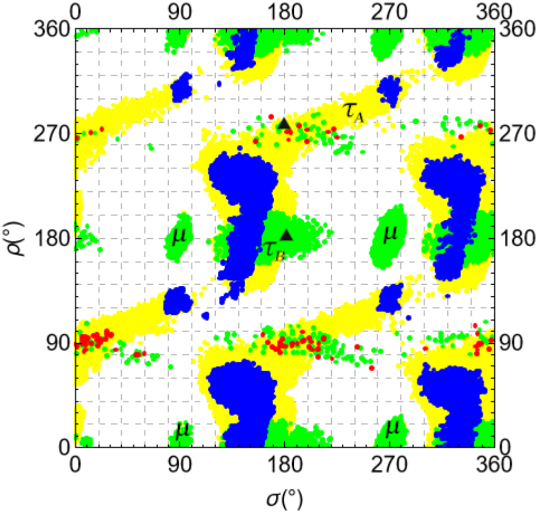


† Contours correspond to experimental constraints from NuFIT 6.1 (NO).

Probing Majorana phases indirectly

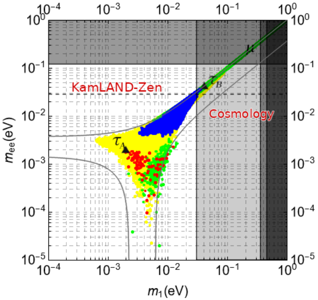
- Majorana phases (ρ, σ) are not directly accessible in current neutrino experiments.
- In the seesaw reconstruction, they enter the leptogenesis asymmetry and washout.
- Successful leptogenesis selects non-trivial islands in the (ρ, σ) plane.

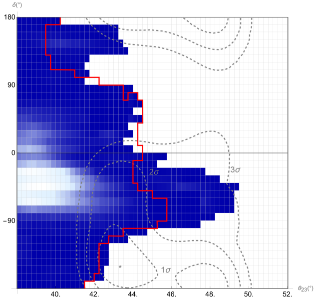
An indirect window on parameters beyond direct experimental access.



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

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

Further predicts:

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

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

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!