New approach to neutrino masses and leptogenesis with Occam's razor

D. M. Barreiros[1†], F. R. Joaquim[1] and T. T. Yanagida[2,3]

[1]Departamento de Física and CFTP, Instituto Superior Técnico, Universidade de Lisboa, [2]Tsung-Dao Lee Institute, Shanghai Jiao Tong University, [3]Kavli IPMU (WPI), UTIAS, The University of Tokyo

†Presenter, e-mail: **debora.barreiros@tecnico.ulisboa.pt**

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Motivation

The **Standard Model** (SM) of particle physics describes electroweak interactions at low energies with remarkable precision but cannot provide an explanation for:

- **neutrino flavour oscillations** which imply nonvanishing neutrino masses and lepton mixing;
- the observed **Baryon Asymmetry of the Universe** (BAU).

These two limitations may be overcome by adding to the SM **two heavy right-handed (RH) neutrinos**, which:

- act as light-neutrino mass mediators at the classical level, via **type-I seesaw mechanism** and,
- Play a crucial role in generating the BAU via **leptogenesis**.

Occam's Razor approach

Consider the **most economical seesaw framework** with the **most economical texture zeros** in the lepton Yukawa and mass matrices of the model

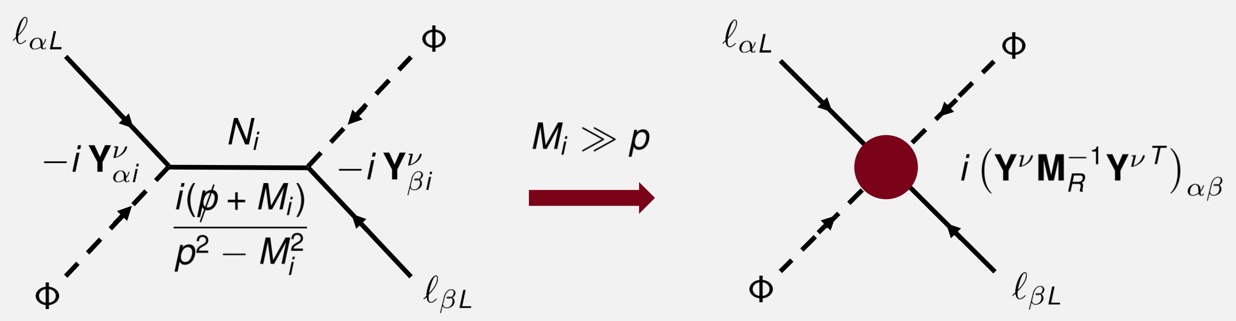
Previous studies [1] have shown that the two RH neutrino extension of the SM (2RHνSM) with maximally-restrictive texture-zero Yukawa and mass matrices **is not compatible with data** for a **normally-ordered** (NO) neutrino mass spectrum (currently preferred by data at 3σ [2]), when **the lepton mixing originates solely from the neutrino sector**. Also, the lightest RH neutrino mass required to generate the observed BAU via leptogenesis ($M_1 \sim 10^{14}$ GeV) is in **conflict with vanilla scenarios for axion dark matter** where the reheating temperature of the Universe is typically below 10^{12} GeV.

Can we get compatibility with NO and a lower leptogenesis scale by including two-flavour charged-lepton mixing in our model?

Minimal type-I seesaw mechanism

In the neutrino sector: $\mathcal{L}_\nu = -\overline{\ell_L}\mathbf{Y}_\nu^*\tilde{\Phi}\nu_R - \frac{1}{2}\overline{\nu_R}\mathbf{M}_R\nu_R^c + \text{H.c.}$

Type-I seesaw mechanism



After EWSB: $\mathbf{M}_\nu = -v^2\mathbf{Y}_\nu\mathbf{M}_R^{-1}\mathbf{Y}_\nu^T$ with $\mathbf{U}_\nu^T\mathbf{M}_\nu\mathbf{U}_\nu = \text{diag}(m_1, m_2, m_3)$

In the charged-lepton sector: $\mathcal{L}_\ell = -\overline{\ell_L}\mathbf{Y}_\ell\Phi\, e_R + \text{H.c.}$

After EWSB: $\mathbf{M}_\ell = v\mathbf{Y}_\ell$ with $\mathbf{U}_\ell^\dagger\mathbf{M}_\ell\mathbf{M}_\ell^\dagger\mathbf{U}_\ell = \text{diag}(m_e^2, m_\mu^2, m_\tau^2)$

Low-energy constraints

Effective neutrino mass matrices $\mathbf{M}_\nu$ generated from the most restrictive $\mathbf{Y}_\nu$ and $\mathbf{M}_R$ texture-zero matrices:

$$A:\begin{pmatrix}0&\times&\times\\ \cdot&\times&\times\\ \cdot&\cdot&\times\end{pmatrix}\; B:\begin{pmatrix}\times&0&\times\\ \cdot&\times&\times\\ \cdot&\cdot&\times\end{pmatrix}\; C:\begin{pmatrix}\times&\times&0\\ \cdot&\times&\times\\ \cdot&\cdot&\times\end{pmatrix}\; D:\begin{pmatrix}\times&\times&\times\\ \cdot&0&\times\\ \cdot&\cdot&\times\end{pmatrix}\; E:\begin{pmatrix}\times&\times&\times\\ \cdot&\times&0\\ \cdot&\cdot&\times\end{pmatrix}\; F:\begin{pmatrix}\times&\times&\times\\ \cdot&\times&\times\\ \cdot&\cdot&0\end{pmatrix}$$

which feature the condition $(\mathbf{M}_\nu)_{ij} = 0$, resulting in two low-energy constraints. For NO:

$$\frac{m_2}{m_3} = -\frac{(\mathbf{U}_\ell^*\mathbf{U}^*)_{i3}(\mathbf{U}_\ell^*\mathbf{U}^*)_{j3}}{(\mathbf{U}_\ell^*\mathbf{U}^*)_{i2}(\mathbf{U}_\ell^*\mathbf{U}^*)_{j2}}$$

$$\sqrt{\frac{\Delta m_{21}^2}{\Delta m_{31}^2}} = \left|\frac{(\mathbf{U}_\ell^*\mathbf{V}_\delta^*)_{i3}(\mathbf{U}_\ell^*\mathbf{V}_\delta^*)_{j3}}{(\mathbf{U}_\ell^*\mathbf{V}_\delta^*)_{i2}(\mathbf{U}_\ell^*\mathbf{V}_\delta^*)_{j2}}\right|$$

$$\alpha = -\arg\left[-\frac{(\mathbf{U}_\ell^*\mathbf{V}_\delta^*)_{i3}(\mathbf{U}_\ell^*\mathbf{V}_\delta^*)_{j3}}{(\mathbf{U}_\ell^*\mathbf{V}_\delta^*)_{i2}(\mathbf{U}_\ell^*\mathbf{V}_\delta^*)_{j2}}\right]$$

being the **lepton mixing matrix** in the standard parametrization given by:

$$\mathbf{U} = \mathbf{U}_\ell^\dagger\mathbf{U}_\nu = \underbrace{\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta}\\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}\\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}\end{pmatrix}}_{\mathbf{V}_\delta}\begin{pmatrix}1&0&0\\0&e^{i\alpha/2}&0\\0&0&1\end{pmatrix}$$

Most restrictive two-flavour mixing **charged-lepton mass matrices $\mathbf{M}_\ell$**:

$$\mathrm{L}_1^k:\begin{pmatrix}m_k&0&0\\0&0&\epsilon\\0&\epsilon&m\end{pmatrix}\quad \mathrm{L}_2^k:\begin{pmatrix}0&0&\epsilon\\0&m_k&0\\ \epsilon&0&m\end{pmatrix}\quad \mathrm{L}_3^k:\begin{pmatrix}0&\epsilon&0\\ \epsilon&m&0\\0&0&m_k\end{pmatrix}$$

which are diagonalized by a matrix $\mathbf{U}_\ell$ parametrized by a single angle:

$$\theta_\ell^k = \pm\frac{1}{2}\arctan\left(\frac{2\sqrt{m_i m_j}}{m_j - m_i}\right) \simeq \pm\sqrt{m_i/m_j} \text{ with } i \neq j \neq k = e, \mu, \tau \text{ and } m_j > m_i$$

δ, θ_{23} and $m_{\beta\beta}$ predictions

After verifying the compatibility of all possible combinations ($\mathbf{M}_\nu$, $\mathbf{M}_\ell$, θ_ℓ^k) = (A – F, $\mathrm{L}_{1,2,3}^k$, ±) with a NO neutrino mass spectrum, we conclude that the **best-fit case corresponds to (C, L_1^e ,+)**. This case selects the **second octant for θ_{23}** and predicts **$m_{\beta\beta} \in$ [1.2,3.8] meV**.

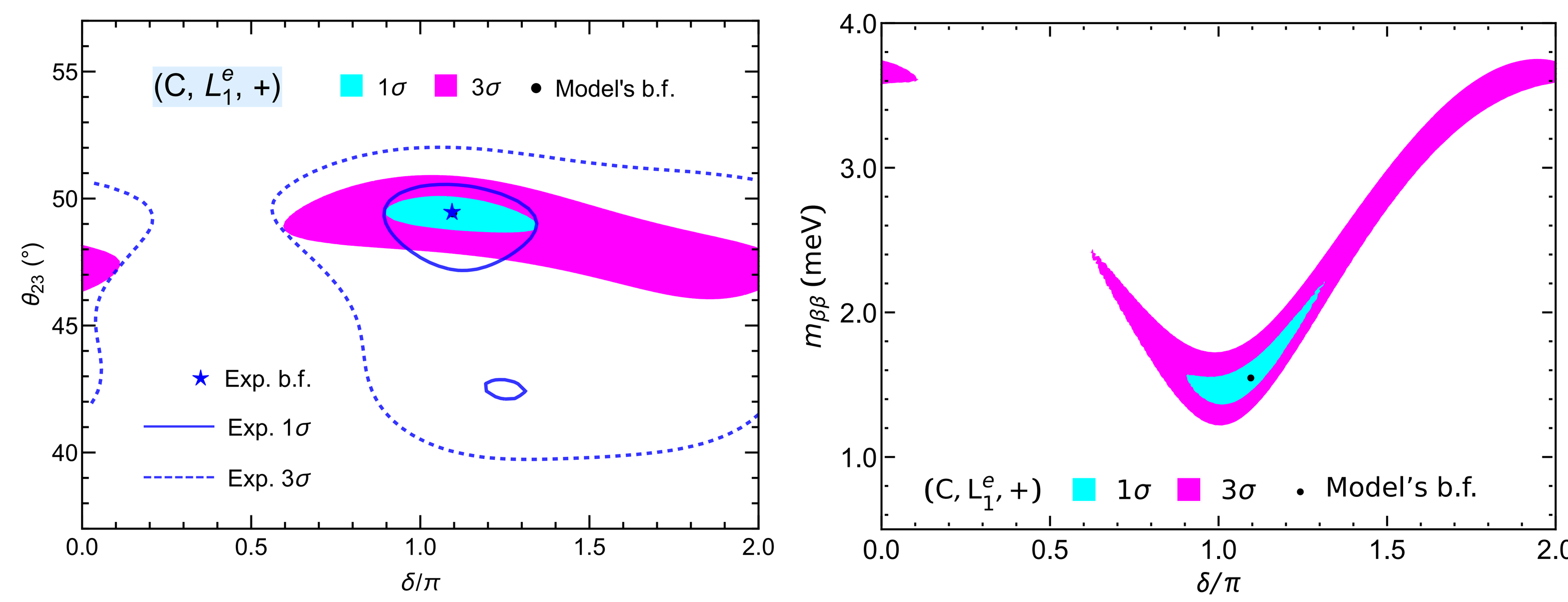
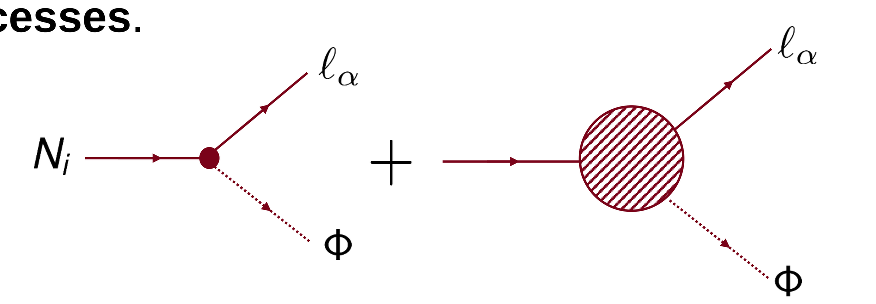


Fig. 1. 1σ and 3σ allowed regions (in cyan and magenta, respectively) in the (δ, θ_{23}) and (δ, $m_{\beta\beta}$) planes, for the $\mathbf{M}_\nu$ and $\mathbf{M}_\ell$ texture zero patterns, C and L_1^e, respectively, with $\theta_\ell^e \simeq +0.24$. For comparison, the lines delimiting the regions allowed by experimental data are also shown (solid and dashed for 1σ and 3σ, respectively).

Leptogenesis predictions

A lepton asymmetry is dynamically generated via the **CP-violating out-of-equilibrium decay** of the heavy neutrinos N_1 and N_2 added to the SM, and later transformed into a baryon asymmetry via **(B-L)-conserving sphaleron processes**.



In the **two-flavoured regime** where only electron and muon Yukawa interactions are out of equilibrium (for $10^9 \lesssim M_1$, $M_2 \lesssim 10^{12}$ GeV), the baryon-to-photon ratio is approximately given by [3]:

$$\eta_B \simeq -9.6\times10^{-3}(-\kappa_1^\tau\epsilon_1^\tau - \kappa_1^\gamma\epsilon_1^\gamma)$$

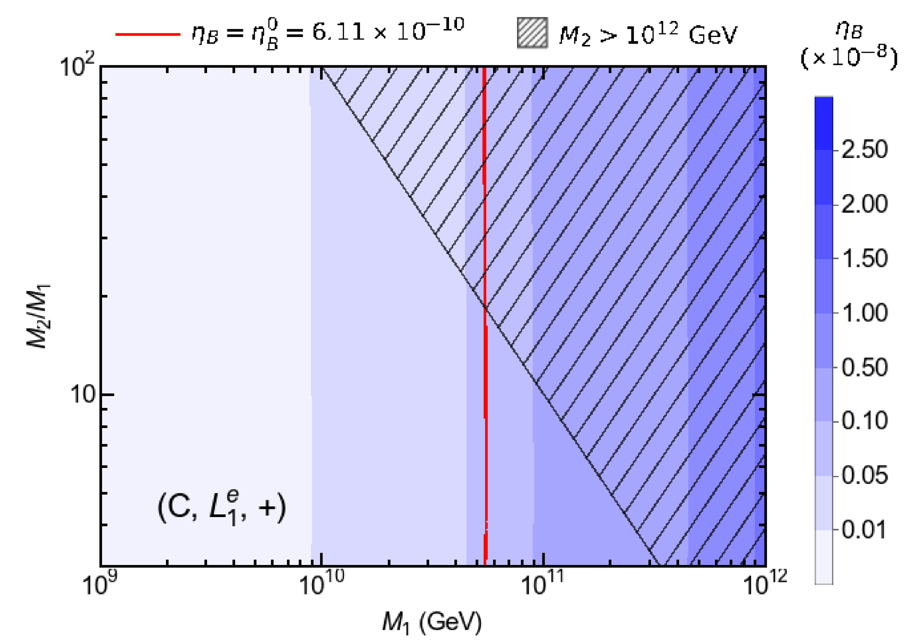
In the specific case of (C,L_1^e,+), the obtained **CP asymmetries** read:

$$\epsilon_1^\gamma = \epsilon_1^\mu \simeq \frac{3M_1\sqrt{\Delta m_{31}^2}\,s_\delta s_{13}s_{23}c_{23}}{16\pi v^2 r_\nu \tan\theta_{12}},\quad \epsilon_1^\tau \simeq \frac{3M_1\sqrt{\Delta m_{31}^2}\,s_\delta s_{13}(s_{13}c_{23}^2 - r_\nu s_{12}c_{12}s_{23}c_{23})}{16\pi v^2(r_\nu^2 s_{12}^2 + s_{13}^2)}$$

and the **efficiency factors** are $\kappa_1^\tau \simeq 1.7\times10^{-1}$ and $\kappa_1^\gamma \simeq 5.6\times10^{-3}$.

The **observed BAU is obtained for $M_1 \sim 5.5\times10^{10}$ GeV**, being consistent with axion dark matter.

Fig. 2. η_B contour regions in the (M_1,M_2/M_1) plane, taking the low-energy parameters that best fit the combination (C, L_1^e, +). The blue-scale contour regions represent the obtained η_B values, while the red contour line corresponds to the observed value η_B^0 [4]. In the hatched region, M_2 is out of the mass interval for the flavored leptogenesis regime ($M_2 \gtrsim 3\,M_1$).



Conclusions

- New Occam's razor scenario for texture–zero Yukawa and mass matrices with ($\mathbf{M}_\nu$,$\mathbf{M}_\ell$, θ_ℓ^e) = (C,L_1^e,+) is **compatible with NO**, and **predicts θ_{23} belonging to the second octant**.
- Lightest RH neutrino mass required for leptogenesis to work is substantially **lowered to 5.5 × 10^{10} GeV** (comparing with previous works where only mixing in the neutrino sector was considered [1]).

References

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