

Leptogenesis from $SU(5)$ GUT with \mathcal{T}_{13} Family Symmetry

Moinul Hossain Rahat

IFT, University of Florida

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Based on: MHR, Phys.Rev.D 103 (2021) 035011, arXiv:2008.04204 [hep-ph],

C.S. Fong, MHR, S. Saad, arXiv:2103.14691 [hep-ph]

- ▶ **Baryogenesis via Leptogenesis**
 - ▶ out of equilibrium decay of right-handed neutrinos explain baryon asymmetry of the universe
- ▶ **The Asymmetric Texture**
 - ▶ Yukawa texture based on $SU(5)$ GUT and \mathcal{T}_{13} family symmetry
- ▶ **Leptogenesis from the “asymmetric texture”**
 - ▶ thermal leptogenesis in both nonresonant and resonant regimes

Baryogenesis via Leptogenesis

Baryon Asymmetry:

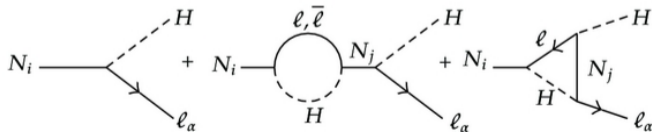
Net baryon to photon ratio of the universe from CMB data:

$$\eta_B = (N_B - N_{\bar{B}})/N_\gamma \simeq (6.12 \pm 0.04) \times 10^{-10}$$

Leptogenesis:

$$\bar{N} \leftrightarrow \ell + H^*, \quad \bar{N} \leftrightarrow \bar{\ell} + H$$

out of equilibrium decays **violate L , C and CP** ; $B - L$ conserving sphaleron processes convert L violation into B violation



Leptogenesis from the Asymmetric Texture

- ▶ $SU(5) \times \mathcal{T}_{13}$ model describes the GUT-scale mass ratios and mixing angles of **both quarks and leptons**
- ▶ **Single CP violating phase** in the seesaw sector generates both Dirac and Majorana CP violation
- ▶ Requires **four right-handed neutrinos** to generate viable light neutrino mass spectrum
- ▶ **Can the decay of these right handed neutrinos translate the CP violation into CP asymmetry?**

Asymmetric Texture and \mathcal{T}_{13} Family Symmetry

- ▶ Lepton mixing is **unlike** quark mixing!

$$\theta_{12} = 33.65^{\circ}{}_{-2.47^{\circ}}^{+2.38^{\circ}}, \quad \theta_{23} = 47.58^{\circ}{}_{-3.61^{\circ}}^{+3.66^{\circ}}, \quad \theta_{13} = 8.49^{\circ}{}_{-0.42^{\circ}}^{+0.40^{\circ}}$$

- ▶ **Large angles** from **Tribimaximal mixing** in the seesaw sector

$$\mathcal{U}_{TBM} \equiv \mathcal{R}(\theta_{12} = 35.3^{\circ}), \mathcal{R}(\theta_{23} = 45^{\circ}), \mathcal{R}(\theta_{13} = 0^{\circ})$$

and the small reactor angle from EW sector: '**Cabibbo haze**'

- ▶ The "**asymmetric texture**": minimal $SU(5)$ texture with a complex TBM mixing does the job! [MHR, Ramond, Xu PRD **98** (2018) 055030]
- ▶ The **asymmetric term** arises naturally from a \mathcal{T}_{13} **family symmetry** [Pérez, MHR, Ramond, Stuart, Xu PRD **100** (2019) 075008]

Seesaw Parameters for Leptogenesis

- ▶ Seesaw matrix in terms of Dirac Yukawa and Majorana mass matrix:

$$\mathcal{S} = v^2 Y^{(0)} \mathcal{M}^{-1} Y^{(0)T} = \mathcal{U}_{TBM}(\delta_{TBM}) \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}) \mathcal{U}_{TBM}(\delta_{TBM})^T$$

- ▶ Requires four right-handed neutrinos. \mathcal{T}_{13} determines nonzero entries in $Y^{(0)}$ (δ_{TBM}) and \mathcal{M} , expressed in terms of undetermined familon VEV (b_1, b_2, b_3) and a free parameter M
- ▶ Prediction: normal ordering of light neutrino masses:
 $|m_{\nu_1}| = 27.6, |m_{\nu_2}| = 28.9, |m_{\nu_3}| = 57.8 \text{ meV}$
- ▶ Cancellation of free parameters between $Y^{(0)}$ and \mathcal{M} implies the seesaw scale is unknown!
- ▶ Diagonalizing \mathcal{M} yields right-handed neutrino mass spectrum in terms of b_1, b_2, b_3 and M : masses could be degenerate!
- ▶ If leptogenesis is viable, can the undetermined parameters b_1, b_2, b_3 and M be constrained? Is the sign of δ_{TBM} resolved by the sign of baryon asymmetry?

- ▶ Classical Boltzmann Equations for three regimes:
(i) $T \gg 10^{12}$ GeV: one flavor, (ii) $10^9 \ll T \ll 10^{12}$ GeV: two flavors, (iii) $T \ll 10^9$ GeV: three flavors
- ▶ One-flavor leptogenesis fails because of the flavor structure dictated by \mathcal{T}_{13}
- ▶ What about the transition regions? What if the mass scale is unknown? Density Matrix Equations
- ▶ 3×3 CP asymmetry matrix in flavor space with nonzero off-diagonal entries, accounts for flavor transitions
- ▶ $B - L$ asymmetries are calculated by solving coupled differential equations
- ▶ Final baryon asymmetry is proportional to the trace of the $B - L$ asymmetry matrix

- ▶ The simplest case $(b_1, b_2, b_3) \equiv b(1, 1, 1)$ yields zero CP asymmetry
- ▶ Set $(b_1, b_2, b_3) \equiv b(1, f, 1)$, define $M \equiv ab$
- ▶ For a fixed $f \neq 1$, right-handed neutrino masses are determined as a function of a in the **non-degenerate** regions
- ▶ **Required right-handed neutrino masses** for successful leptogenesis are $\mathcal{O}(10^{11-12})$ GeV
- ▶ **Is something special going on near the $M_3 - M_4$ degeneracy?**

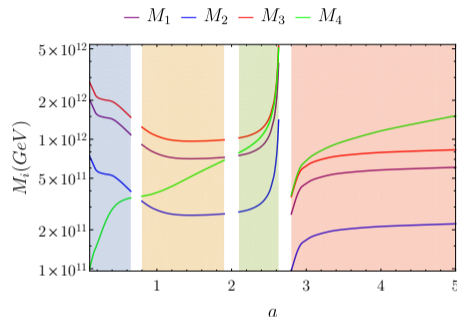


Figure: Right-handed neutrino mass spectrum required for successful leptogenesis setting $f = 2$. Shaded regions represent non-degenerate masses.

- ▶ The magnitude of δ_{TBM} is constrained, but **the sign remained undetermined**
- ▶ **Final $B - L$ asymmetry** is proportional to the diagonal CP asymmetries, which are proportional to $\sin \delta_{TBM}$
- ▶ $-85^\circ \leq \delta_{TBM} \leq -66^\circ$ yields **positive baryon asymmetry** in all four regions and picks the *correct* sign of the **Dirac \mathcal{CP} phase** $1.27\pi \leq \delta_{CP} \leq 1.35\pi$, compared to the 2021 PDG estimate $1.37 \pm 0.17\pi$

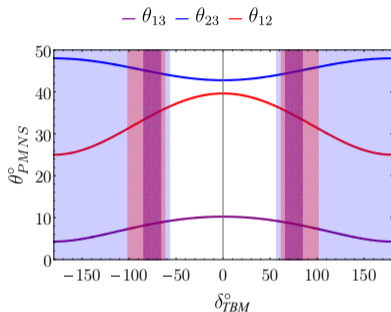


Figure: The asymmetric texture requires $66^\circ \leq |\delta_{TBM}| \leq 85^\circ$ to yield all PMNS angles within 3σ of their 2021 PDG estimate.

- ▶ **Exact degeneracy** yields zero CP asymmetry, but **quasi-degeneracy** can enhance the CP asymmetry to nearly $\mathcal{O}(1)$
- ▶ CP asymmetry is proportional to $\text{Re} \left[\left(Y_\nu^\dagger Y_\nu \right)_{ij} \right]$, which is nonzero **only for $N_3 - N_4$ quasi-degeneracy**
- ▶ Resonance condition $|M_3 - M_4| \simeq \frac{\Gamma_{3,4}}{2}$ fixes a in terms of b and f
- ▶ There is a **minimum b** below which the generated asymmetry is lower than the CMB value

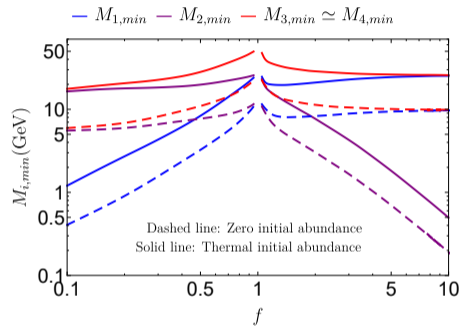


Figure: Minimum right-handed neutrino mass spectrum required for successful leptogenesis at $N_3 - N_4$ resonance.

- ▶ M_1 and M_2 are smaller than the resonant pair M_3, M_4
- ▶ There is a **maximum b** above which the generated asymmetry is **severely washed out** by lighter right handed neutrinos
- ▶ The upper bound **only occurs for $f \gtrsim 2$** below which the washout is not efficient
- ▶ There is a **discontinuity at $f \simeq 6.2$** due to change of sign of baryon asymmetry for **nontrivial flavor interactions**

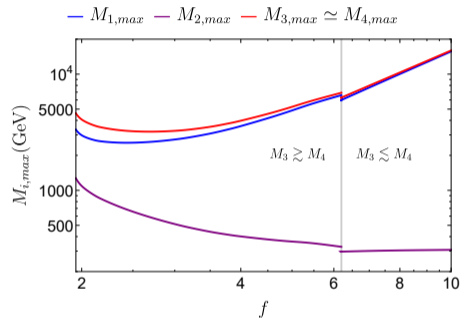
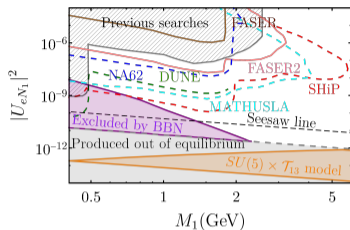
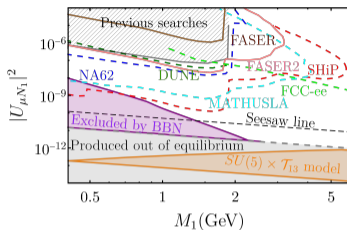


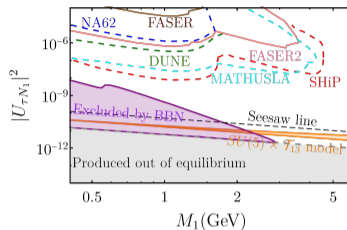
Figure: Maximum right-handed neutrino mass spectrum required for successful leptogenesis at $N_3 - N_4$ resonance.



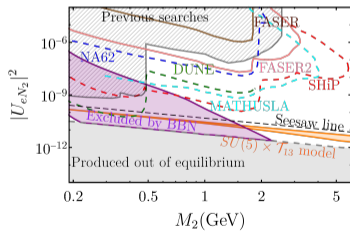
(a) $0.1 < f < 1$



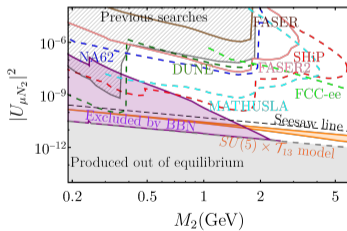
(b) $0.1 < f < 1$



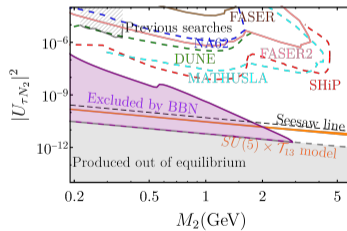
(c) $0.1 < f < 1$



(d) $1 < f < 10$



(e) $1 < f < 10$



(f) $1 < f < 10$

Key Findings

- ▶ Nontrivial relation between seesaw familon VEVs generate light neutrino masses and lepton mixings **without fixing the seesaw scale!**

Nonresonant Leptogenesis

- ▶ **No unflavored leptogenesis**, flavored leptogenesis requires right-handed neutrino masses $\mathcal{O}(10^{11-12})$ GeV
- ▶ TBM phase δ_{TBM} must be **negative**, yields positive baryon asymmetry and **Dirac CP phase consistent with global fits**

Resonant Leptogenesis

- ▶ **Nontrivial upper bound** on right-handed neutrino mass because of washout by lighter neutrinos
- ▶ **Minimum right-handed neutrino mass** $\mathcal{O}(1)$ GeV, mixing parameters **close to the sensitivity of DUNE**

Backup Slides

Hunting the 'Minimal' Texture

What is the 'minimal' Yukawa texture that

- ▶ reproduces the GUT-scale mass relations, the CKM mixing angles, and
- ▶ generates *enough* 'Cabibbo haze' for the reactor angle?

The Asymmetric Texture arXiv:1805.10684

$$Y^{(\frac{2}{3})} \sim \text{diag} (\lambda^8, \lambda^4, 1),$$

$$Y^{(-\frac{1}{3})} \sim \begin{pmatrix} bd\lambda^4 & a\lambda^3 & b\lambda^3 \\ a\lambda^3 & c\lambda^2 & g\lambda^2 \\ d\lambda & g\lambda^2 & 1 \end{pmatrix}, \quad Y^{(-1)} \sim \begin{pmatrix} bd\lambda^4 & a\lambda^3 & d\lambda \\ a\lambda^3 & -3c\lambda^2 & g\lambda^2 \\ b\lambda^3 & g\lambda^2 & 1 \end{pmatrix}$$

$$\mathcal{U}_{\text{Seesaw}} = \text{diag} (1, 1, e^{i\delta}) \mathcal{U}_{\text{TBM}}$$

$$a = c = \frac{1}{3}, \quad g = A, \quad b = A\sqrt{\rho^2 + \eta^2}, \quad d = \frac{2a}{g} = \frac{2}{3A}, \quad \cos \delta = 0.2$$

TBM Mixing with a Phase

$$\mathcal{U}_{PMNS} = \mathcal{U}^{(-1)\dagger} \mathcal{U}_{TBM}(\delta)$$
$$\mathcal{U}_{TBM}(\delta) = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{e^{i\delta}}{\sqrt{6}} & -\frac{e^{i\delta}}{\sqrt{3}} & \frac{e^{i\delta}}{\sqrt{2}} \end{pmatrix}$$

With **real TBM** mixing $\delta = 0$,

$$|\sin \theta_{13}| = \frac{1}{\sqrt{2}} \left| \mathcal{U}_{21}^{(-1)} + \mathcal{U}_{31}^{(-1)} \right|$$

$$\theta_{13} \simeq 10.59^\circ \text{ (2.26}^\circ \text{ above PDG)}, \quad \theta_{12} \simeq 39.81^\circ \text{ (6.16}^\circ \text{ above PDG)},$$

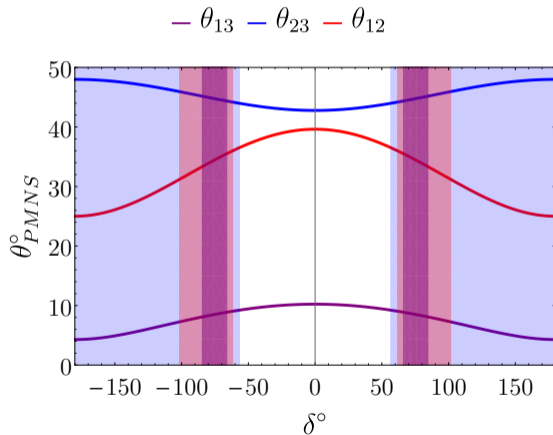
$$\theta_{23} \simeq 42.67^\circ \text{ (2.90}^\circ \text{ below PDG)}$$

With **complex TBM** mixing,

$$|\sin \theta_{13}| = \frac{1}{\sqrt{2}} \left| \mathcal{U}_{21}^{(-1)} + e^{i\delta} \mathcal{U}_{31}^{(-1)} \right|$$

TBM Mixing with a Phase

One phase to rule them all: $66^\circ < |\delta| < 85^\circ$ brings all three angles within 3σ of PDG 2020 value



Suppose $SU(5)$ matter fields $F \sim \bar{\mathbf{5}}$ and $T \sim \mathbf{10}$ are triplets of some discrete family symmetry group, G_f .

F and T must be different triplets of G_f

- ▶ $Y^{(-1/3)}$ and $Y^{(-1)}$ comes from $F \otimes T = (\bar{\mathbf{5}}, \mathbf{r}) \otimes (\mathbf{10}, \mathbf{s})$
- ▶ $3 \times 3 \Rightarrow$ either symmetric or antisymmetric
We need a group with at least two different triplets!
- ▶ Candidates: S_4 (order 24), $\Delta(27)$ (order 27), T_{13} (order 39)

$\mathbf{s} \otimes \mathbf{s}$ must distinguish diagonal from off-diagonal

- ▶ $Y^{(2/3)}$ comes from $T \otimes T = (\mathbf{10}, \mathbf{s}) \otimes (\mathbf{10}, \mathbf{s})$

Only T_{13} survives!

Generating the Asymmetric Term

$$Y^{(-\frac{1}{3})} \leftarrow FTH\bar{5}\varphi^{(-\frac{1}{3})}$$

$$\begin{pmatrix} F_1 \\ F_2 \\ F_3 \end{pmatrix}_{\mathfrak{3}_1} \otimes \begin{pmatrix} T_1 \\ T_3 \\ T_2 \end{pmatrix}_{\mathfrak{3}_2} = \begin{pmatrix} F_3T_2 \\ F_1T_1 \\ F_2T_3 \end{pmatrix}_{\mathfrak{3}_1} \oplus \begin{pmatrix} F_3T_1 \\ F_1T_3 \\ F_2T_2 \end{pmatrix}_{\bar{\mathfrak{3}}_2} \oplus \begin{pmatrix} F_3T_3 \\ F_1T_2 \\ F_2T_1 \end{pmatrix}_{\mathfrak{3}_2}$$

T_{13} can dial *individual* matrix elements!

$$Y^{(\frac{2}{3})} \leftarrow TTH\bar{5}\varphi^{(\frac{2}{3})}$$

$$\begin{pmatrix} T_1 \\ T_3 \\ T_2 \end{pmatrix}_{\mathfrak{3}_2} \otimes \begin{pmatrix} T_1 \\ T_3 \\ T_2 \end{pmatrix}_{\mathfrak{3}_2} = \begin{pmatrix} T_3T_3 \\ T_2T_2 \\ T_1T_1 \end{pmatrix}_{\bar{\mathfrak{3}}_1} \oplus \begin{pmatrix} T_3T_2 \\ T_2T_1 \\ T_1T_3 \end{pmatrix}_{\bar{\mathfrak{3}}_2} \oplus \begin{pmatrix} T_2T_3 \\ T_1T_2 \\ T_3T_1 \end{pmatrix}_{\bar{\mathfrak{3}}_2}$$

Diagonals are distinguished from off-diagonals!

Lepton Sector of the $SU(5) \times \mathcal{T}_{13} \times \mathcal{Z}_{12}$ Model

arXiv:2001.04019

	F	\bar{N}	\bar{N}_4	\bar{H}_5	Λ	φ_A	φ_B	φ_v
$SU(5)$	$\bar{\mathbf{5}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{5}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
\mathcal{T}_{13}	$\mathbf{3}_1$	$\mathbf{3}_2$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}_1$	$\bar{\mathbf{3}}_2$	$\mathbf{3}_2$	$\bar{\mathbf{3}}_1$
\mathcal{Z}_{12}	ω	ω^3	$\mathbf{1}$	ω^9	ω^2	ω^{11}	ω^6	ω^2

Table: Transformation properties of matter, Higgs, messenger and familon fields in the seesaw sector. Here $\omega^{12} = 1$. The \mathcal{Z}_{12} ‘shaping’ symmetry prevents unwanted tree-level operators.

$$\begin{aligned}
 \mathcal{L}_{ss} &\supset y_A F \Lambda \bar{H}_5 + y'_A \bar{N} \bar{\Lambda} \varphi_A + y_B \bar{N} \bar{N} \varphi_B + M_\Lambda \bar{\Lambda} \Lambda + y'_v \bar{N}_4 \bar{\Lambda} \varphi_v + M \bar{N}_4 \bar{N}_4 \\
 &\supset \frac{1}{M_\Lambda} y_A y'_A F \bar{N} \bar{H}_5 \varphi_A + \frac{1}{M_\Lambda} y_A y'_v F \bar{N}_4 \bar{H}_5 \varphi_v + y_B \bar{N} \bar{N} \varphi_B + M \bar{N}_4 \bar{N}_4.
 \end{aligned}$$

- ▶ Vacuum Expectation Value (VEV) of the familons:

$$y_{\mathcal{A}} y'_{\mathcal{A}} \langle \varphi_{\mathcal{A}} \rangle = \frac{M_{\Lambda}}{v} \sqrt{m_{\nu} b_1 b_2 b_3} (-b_2^{-1} e^{i\delta}, b_1^{-1}, b_3^{-1}),$$

$$y_{\mathcal{B}} \langle \varphi_{\mathcal{B}} \rangle = (b_1, b_2, b_3),$$

$$y_{\mathcal{A}} y'_v \langle \varphi_v \rangle = \frac{M_{\Lambda}}{v} \sqrt{M m'_v} (2, -1, e^{i\delta}),$$

- ▶ Majorana matrix from $y_{\mathcal{B}} \bar{N} \bar{N} \varphi_{\mathcal{B}} + M \bar{N}_4 \bar{N}_4$:

$$\mathcal{M} \equiv \begin{pmatrix} 0 & b_2 & b_3 & 0 \\ b_2 & 0 & b_1 & 0 \\ b_3 & b_1 & 0 & 0 \\ 0 & 0 & 0 & M \end{pmatrix}$$

Familon Structure (contd.)

- ▶ Vacuum Expectation Value (VEV) of the familons:

$$y_{\mathcal{A}} y'_{\mathcal{A}} \langle \varphi_{\mathcal{A}} \rangle = \frac{M_{\Lambda}}{v} \sqrt{m_{\nu} b_1 b_2 b_3} (-b_2^{-1} e^{i\delta}, b_1^{-1}, b_3^{-1}),$$

$$y_{\mathcal{B}} \langle \varphi_{\mathcal{B}} \rangle = (b_1, b_2, b_3),$$

$$y_{\mathcal{A}} y'_v \langle \varphi_v \rangle = \frac{M_{\Lambda}}{v} \sqrt{M m'_v} (2, -1, e^{i\delta}),$$

- ▶ Yukawa matrix from $\frac{1}{M_{\Lambda}} y_{\mathcal{A}} y'_{\mathcal{A}} F \bar{N} \bar{H}_5 \varphi_{\mathcal{A}} + \frac{1}{M_{\Lambda}} y_{\mathcal{A}} y'_v F \bar{N}_4 \bar{H}_5 \varphi_v$:

$$Y^{(0)} \equiv \frac{\sqrt{b_1 b_2 b_3 m_{\nu}}}{v} \begin{pmatrix} 0 & b_3^{-1} & 0 & 2\sqrt{\frac{M m'_v}{b_1 b_2 b_3 m_{\nu}}} \\ b_1^{-1} & 0 & 0 & -\sqrt{\frac{M m'_v}{b_1 b_2 b_3 m_{\nu}}} \\ 0 & 0 & -e^{i\delta} b_2^{-1} & e^{i\delta} \sqrt{\frac{M m'_v}{b_1 b_2 b_3 m_{\nu}}} \end{pmatrix}$$

- ▶ $\sum_i |m_{\nu_i}| = 114.3 \text{ meV}$ compared to Planck: $\sum_i |m_{\nu_i}| < 120 \text{ meV}$ [arXiv:1807.06209].
- ▶ Combining data from Euclid and LSST to DESI and WFIRST, the error bound on $\sum_i |m_{\nu_i}|$ will be constrained to $8 - 11 \text{ meV}$.
- ▶ Normal ordering is preferred above 3σ by Super-K, T2K and NOvA [arXiv:1710.09126].
- ▶ DUNE and Hyper-K will resolve the correct mass ordering beyond 5σ in $5 - 7 \text{ yrs}$ [arXiv:1807.10334, 1805.04163].

Neutrinoless Double Beta Decay

- ▶ Dirac \mathcal{CP} Jarlskog-Greenberg Invariant, $|\mathcal{J}| = 0.028$
- ▶ Majorana Invariants, $|\mathcal{I}_1| = 0.106$, $|\mathcal{I}_2| = 0.011$

Prediction for $0\nu\beta\beta$

$$|m_{\beta\beta}| = 13.02 \text{ or } 25.21 \text{ meV}$$

compared to $|m_{\beta\beta}| \leq 61 - 165 \text{ meV}$ by [KamLAND-Zen](#) [arXiv:1605.02889]

- ▶ Our predictions are expected to be tested in several next generation experiments [J.Phys.Conf.Ser. 1390 (2019) 1, 012048]:

Experiment	Sensitivity (meV)	Experiment	Sensitivity (meV)
LEGEND	11 - 28	SNO+-II	20 - 70
nEXO	8 - 22	AMoRE-II	15 - 30
CUPID	6 - 17	PandaX-III	20 - 55

Seesaw Parameters

- Define $\beta = \sqrt{\frac{a}{11.5f}}$. Dirac and Majorana matrices:

$$Y^{(0)} = \frac{\sqrt{bfm_\nu}}{v} \begin{pmatrix} 0 & 1 & 0 & 2\beta \\ 1 & 0 & 0 & -\beta \\ 0 & 0 & -f^{-1}e^{i\delta} & \beta e^{i\delta} \end{pmatrix}, \quad \mathcal{M} = b \begin{pmatrix} 0 & f & 1 & 0 \\ f & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & a \end{pmatrix}$$

- Takagi factorization: $\mathcal{M} = U_m \mathcal{D}_m U_m^T$

$$M_1 = bf, M_2 = \frac{b}{2} \left(\sqrt{f^2 + 8} - f \right), M_3 = \frac{b}{2} \left(\sqrt{f^2 + 8} + f \right), M_4 = ab$$

$$U_m = \begin{pmatrix} -\frac{i}{\sqrt{2}} & \frac{-i}{2} \sqrt{1 - \frac{f}{\sqrt{f^2+8}}} & \frac{1}{2} \sqrt{1 + \frac{f}{\sqrt{f^2+8}}} & 0 \\ \frac{i}{\sqrt{2}} & \frac{-i}{2} \sqrt{1 - \frac{f}{\sqrt{f^2+8}}} & \frac{1}{2} \sqrt{1 + \frac{f}{\sqrt{f^2+8}}} & 0 \\ 0 & \frac{i}{\sqrt{2}} \sqrt{1 + \frac{f}{\sqrt{f^2+8}}} & \frac{1}{\sqrt{2}} \sqrt{1 - \frac{f}{\sqrt{f^2+8}}} & 0 \end{pmatrix}$$

Viability of Leptogenesis

- ▶ Neutrino Yukawa matrix $Y_\nu = \mathcal{U}^{(-1)} Y^{(0)} \mathcal{U}_m^*$

$$Y_\nu^\dagger Y_\nu = \frac{b f m_\nu}{v^2} \times \begin{pmatrix} 1 & 0 & 0 & \frac{3i\beta}{\sqrt{2}} \\ * & \frac{1}{2} \left(1 - \frac{f^3 - f - \sqrt{f^2 + 8}}{f^2 \sqrt{f^2 + 8}} \right) & -\frac{i\sqrt{2}(f^2 - 1)}{f^2 \sqrt{f^2 + 8}} & -\frac{i\beta}{2f} \left(f \sqrt{1 - \frac{f}{\sqrt{f^2 + 8}}} + \sqrt{2 + \frac{2f}{\sqrt{f^2 + 8}}} \right) \\ * & * & \frac{1}{2} \left(1 + \frac{f^3 - f + \sqrt{f^2 + 8}}{f^2 \sqrt{f^2 + 8}} \right) & \frac{\beta}{2f} \left(f \sqrt{1 + \frac{f}{\sqrt{f^2 + 8}}} - \sqrt{2 - \frac{2f}{\sqrt{f^2 + 8}}} \right) \\ * & * & * & 6\beta^2 \end{pmatrix}$$

- ▶ **Unflavored** leptogenesis is **ruled out**

$$\varepsilon_i \equiv \frac{\Gamma_i - \bar{\Gamma}_i}{\Gamma_i + \bar{\Gamma}_i} = \frac{1}{8\pi} \sum_{j \neq i} \frac{\text{Im} \left[\left((Y_\nu^\dagger Y_\nu)_{ij} \right)^2 \right]}{(Y_\nu^\dagger Y_\nu)_{ii}} \xi \left(\frac{M_j^2}{M_i^2} \right)$$

Unflavored Leptogenesis

- ▶ Structure of $Y^{(0)}$ and $\mathcal{M} = \mathcal{U}_m \mathcal{D}_m \mathcal{U}_m^T$ determined by \mathcal{T}_{13}
- ▶ Change basis to *weak* basis: $Y^{(0)} \rightarrow Y_\nu = \mathcal{U}^{(-1)} Y^{(0)} \mathcal{U}_m^*$
- ▶ Charged-lepton flavors can be neglected for $T \gg 10^{12}$ GeV. **Unflavored** CP asymmetry depends on

$$\text{Im} \left[(Y_\nu^\dagger Y_\nu)^2 \right] = \text{Im} \left[\left(\mathcal{U}_m^T Y^{(0)\dagger} Y^{(0)} \mathcal{U}_m^* \right)^2 \right]$$

- ▶ $Y^{(0)} = \text{diag}(1, 1, e^{i\delta}) Y_{real}^{(0)}$ implies $Y^{(0)\dagger} Y^{(0)}$ is real
- ▶ **Real, symmetric** \mathcal{M} implies $\mathcal{U}_m = \mathcal{U}_{m,real} \mathcal{P}$ where \mathcal{P} is a diagonal phase matrix with entries ± 1 or $\pm i$
- ▶ $\text{Im} \left[(Y_\nu^\dagger Y_\nu)^2 \right] = \text{Im} \left[(\mathcal{P}^T \text{Real} \mathcal{P}^*)^2 \right]$ vanishes, **unflavored leptogenesis fails!**

[MHR PRD 103 (2021) 035011]

► Density Matrix Equations

$$\begin{aligned} \frac{dN_{N_i}}{dz} &= -(D_i + S_i)(N_{N_i} - N_{N_i}^{eq}) \\ \frac{dN_{\alpha\beta}}{dz} &= \sum_i \varepsilon_{\alpha\beta}^{(i)} D_i (N_{N_i} - N_{N_i}^{eq}) - \frac{1}{2} \sum_i W_i \{P^{0(i)}, N\}_{\alpha\beta} \\ &\quad - \frac{\text{Im}(\Lambda_\tau)}{Hz} \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, N \right] \right]_{\alpha\beta} \\ &\quad - \frac{\text{Im}(\Lambda_\mu)}{Hz} \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, N \right] \right]_{\alpha\beta} \end{aligned}$$

- Final value of the $B - L$ asymmetry: $N_{B-L}^f \equiv \sum_{\alpha=e,\mu,\tau} N_{\alpha\alpha}^f$
- Baryon asymmetry $\eta_B \simeq 1.28 \times 10^{-2} N_{B-L}^f$ to be compared with $\eta_B^{CMB} = (6.12 \pm 0.04) \times 10^{-10}$

The Simplest Case

- ▶ All seesaw parameters are described in terms of the familon VEV $\langle \varphi_B \rangle \equiv (b_1, b_2, b_3)$ and mass parameter M
- ▶ The simplest case $(b_1, b_2, b_3) \equiv b(1, 1, 1)$ fails
- ▶ Degeneracy in the mass spectrum

$$M_1 = M_2 = b, \quad M_3 = 2b, \quad M_4 = M \equiv ab$$

- ▶ CP asymmetries

$$\varepsilon^{(1)} = -\varepsilon^{(2)}, \quad \varepsilon^{(3)} = \varepsilon^{(4)} = 0$$

- ▶ Final $B - L$ asymmetry

$$N_{B-L}^f \propto \sum_i \varepsilon^{(i)} \times \text{Rate of Number density}$$

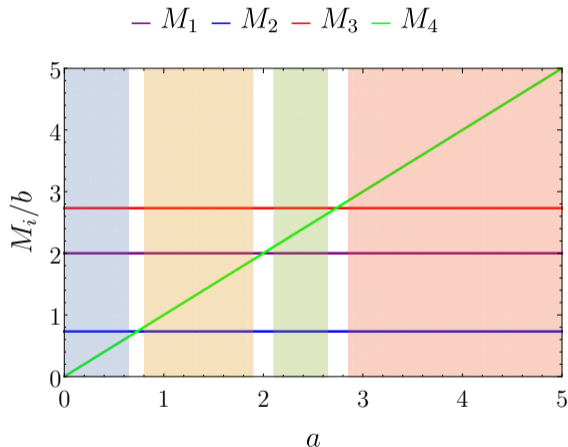
A Simpler Case

- ▶ Set $(b_1, b_2, b_3) \equiv b(1, f, 1)$, define $M \equiv ab$
- ▶ $f \neq 1$ breaks degeneracy in the mass spectrum

$$M_1 = bf, M_2 = \frac{1}{2} \left(\sqrt{f^2 + 8} - f \right)$$

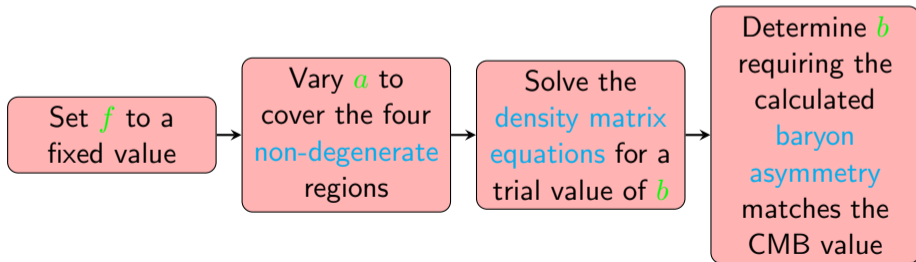
$$M_4 = ab, M_3 = \frac{1}{2} \left(\sqrt{f^2 + 8} + f \right)$$

- ▶ **Non-hierarchical mass spectrum:**
asymmetry generated by heavier neutrinos are not entirely washed out

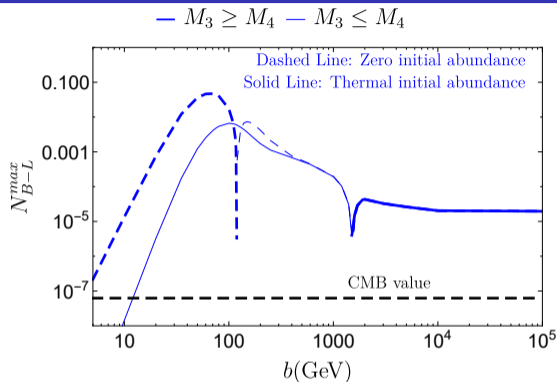


Constraining Model Parameters from Leptogenesis

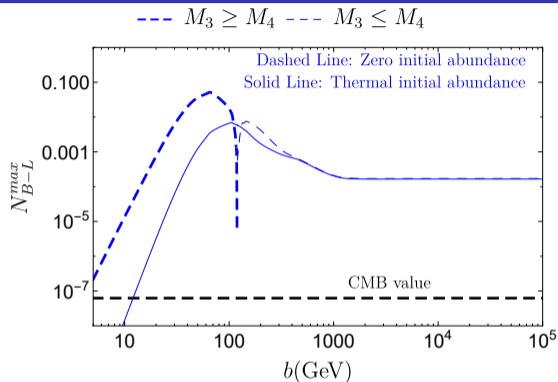
- ▶ Three undetermined parameters: a , b and f
- ▶ b is the overall mass scale, $f \neq 1$ lifts the degeneracy between M_1 and M_2 , a determines how heavy M_4 is w.r.t. others



Upper Bound on Right-Handed Neutrino Mass



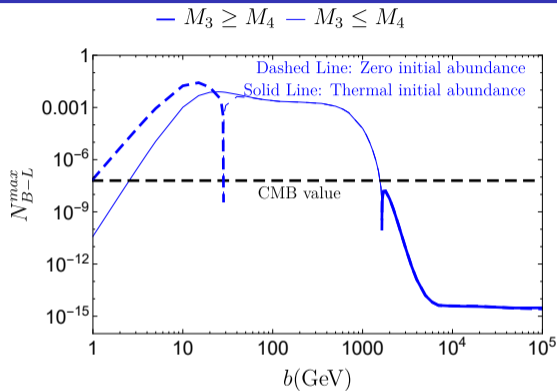
(a) $f = 0.1$



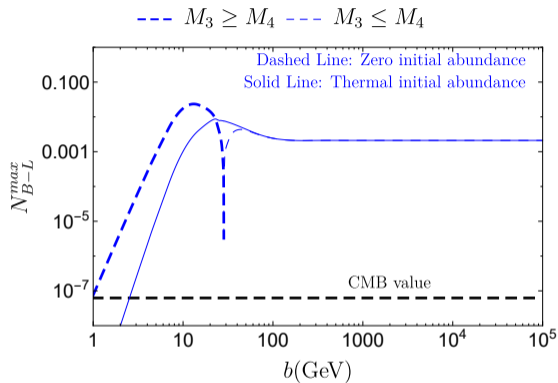
(b) $f = 0.1$, without N_1 washout

Figure: Maximum $B - L$ asymmetry at the resonance $M_3 \simeq M_4$ for (a) $f = 0.1$ and (b) $f = 0.1$ without considering N_1 washout. For large b , the $B - L$ asymmetry saturates at a value higher than the CMB value in case (a) and (b), thus indicating that there is no upper limit on b . N_1 washout decreases the final asymmetry by only a factor of 10, and is not very efficient.

Upper Bound on Right-Handed Neutrino Mass



(a) $f = 10$



(b) $f = 10$, without N_2 washout

Figure: Maximum $B - L$ asymmetry at the resonance $M_3 \simeq M_4$ for (a) $f = 10$, and (b) $f = 10$ without considering N_2 washout. For large b , the $B - L$ asymmetry saturates below the CMB value for large b , thus setting an upper limit above which successful resonant leptogenesis is not feasible. If the N_2 washout is disregarded, the final asymmetry is $\mathcal{O}(10^{12})$ times large, as shown in case (b), thus

Washout Factors

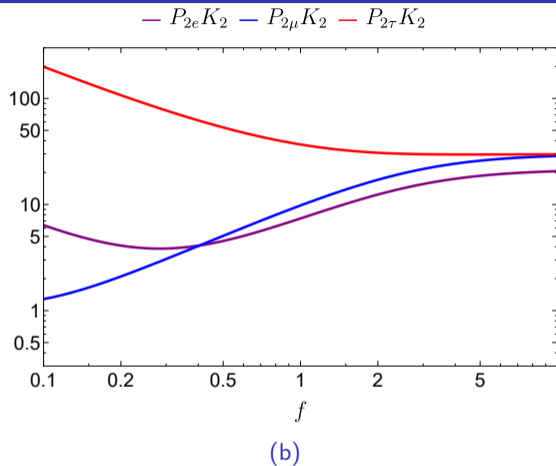
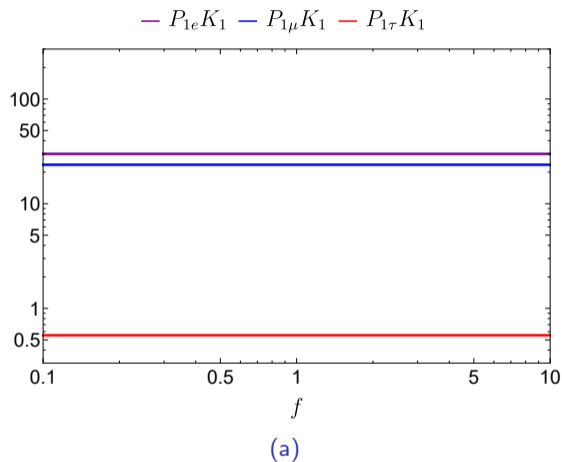


Figure: Decay parameter times branching ratio as a function of f at resonance. The asymmetry generated by N_3 and N_4 at resonance is partially washed out by N_1 and N_2 , and is proportional to $e^{-P_{i\alpha}K_i}$.