Investigating Leptogenesis in a Modular A_4 Type-III Seesaw Framework with Fast Cosmic Expansion

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Collaboration

This work is done in collaboration with
Priya and B. C. Chauhan

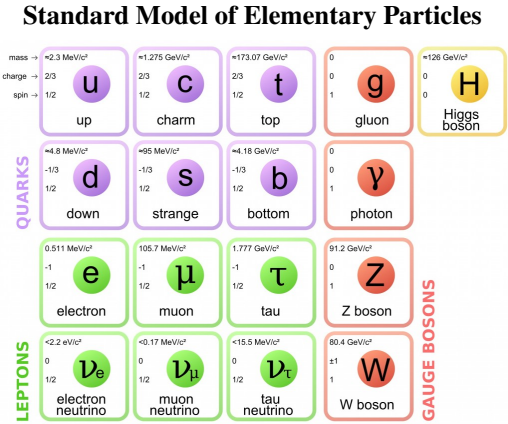
Outline of the Talk

1. Introduction to the Standard Model
2. Motivation for Physics Beyond the Standard Model
3. Neutrino Oscillation Data and Experimental Constraints
4. Non-Holomorphic Modular A_4 Type-III Seesaw Model
5. Neutrino Phenomenology and Thermal Leptogenesis in a Fast-Expanding Universe
6. Results and Conclusions

STANDARD MODEL OF PARTICLE PHYSICS

The Standard Model (SM) of particle physics describes

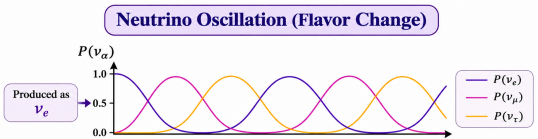
- Three of the four fundamental interactions in the universe: *electromagnetic, weak, and strong* excluding *gravitational interaction*
- Classifies all known *elementary* particles with **massless neutrinos.**



Two Big Mysteries Beyond the Standard Model

(1) Neutrino Mass

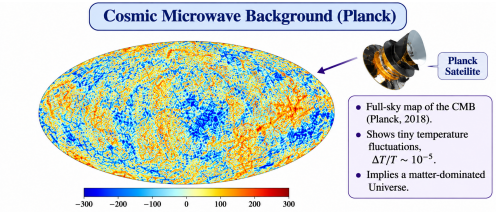
- In the Standard Model, neutrinos are massless ($m_\nu = 0$).
- Neutrino oscillation experiments show flavor change, implying **tiny, non-zero masses** ($m_\nu \neq 0$).



(2) Matter–Antimatter Asymmetry

- Observations (e.g., Planck) show that the Universe is filled with matter, with very little antimatter.
- Quantified by the **baryon-to-photon ratio**.

$$\eta_B \simeq 6.1 \times 10^{-10}$$



Symmetries Beyond the SM

The SM is based on continuous gauge symmetries described by the group $SU(3)_C \times SU(2)_L \times U(1)_Y$, which successfully explain the strong, weak, and electromagnetic interactions.

But, several open questions such as the origin of fermion mass, hierarchies, mixing patterns, and the matter–antimatter asymmetry cannot be fully addressed within the framework of these continuous symmetries alone.

This has motivated the introduction of discrete flavor symmetries.

Why Non-Holomorphic Modular A_4 Symmetry?

Older Discrete Flavor Models

- Use discrete flavour symmetries (e.g., A_4) with additional scalar fields called **flavons** ϕ_i.
- Require a flavon potential and specific vacuum alignments:

$$\langle \phi_i \rangle \neq 0$$

- Introduce many **free parameters** to reproduce lepton masses and mixing.

Typical Yukawa structure

$$\mathcal{L}_Y \supset \frac{y_i}{\Lambda^{n_i}} L \phi_i H$$

Modular Symmetry

Replaces the set of flavons $\{\phi_i\}$ with a single **complex modulus**:

$$\tau = x + iy$$

Modular transformation

$$\tau' = \frac{a\tau + b}{c\tau + d},$$
$$ad - bc = 1.$$

$$\tau \in \mathbb{H}, \qquad \mathrm{Im}(\tau) > 0$$

(Upper half-plane)

Modular forms constrain the allowed lepton mass and mixing structures.

Our Choice: Non-Holomorphic A_4

- Traditional modular models often required **Supersymmetry (SUSY)**.
- We adopt the **non-holomorphic modular A_4** framework of **Qu and Ding**.
- Employs **polyharmonic Maaß forms**

$$\widehat{Y}^{(k)}(\tau, \bar{\tau}),$$

allowing a predictive framework **without invoking SUSY**.

Type-III Seesaw Framework and Fast Cosmic Expansion

Type-III seesaw neutrino masses and leptogenesis in a fast-expanding early Universe.

(1) Particle-Physics Framework

- Introduces three heavy fermion triplets Σ_i.
- Uses the **Type-III seesaw** mechanism to generate tiny neutrino masses.
- Provides the framework for CP violation and leptogenesis.

$$m_\nu \simeq -m_D M_\Sigma^{-1} m_D^T$$

(2) Cosmological Framework

- Considers a **fast-expanding early Universe**.
- Modifies the expansion rate during the leptogenesis epoch.
- Influences heavy fermion decays, washout processes and the evolution of the $B - L$ asymmetry.

$$H(T) > H_{\text{standard}}(T)$$

Particle Assignments and Yukawa Lagrangian

Field content and transformation properties under A_4 modular symmetry

	L	e_R	μ_R	τ_R	Σ_i	H
A_4	3	1	$1''$	$1'$	3	1
k_T	-2	0	4	4	-2	0

Yukawa Lagrangian

The Yukawa Lagrangian is given by:

Complete Yukawa Lagrangian

$$
\begin{aligned}
-\mathcal{L} = {} & \alpha\, \bar{L} H e_R Y_3^{(-2)} + \beta\, \bar{L} H \mu_R Y_3^{(2)} + \gamma\, \bar{L} H \tau_R Y_3^{(2)} \\
& + g_1 (\bar{L}\Sigma_i)\phi Y_1^{(-4)} + g_2 (\bar{L}\Sigma_i)_{\text{sym}} \phi Y_3^{(-4)} + g_2' (\bar{L}\Sigma_i)_{\text{asym}} \phi Y_3^{(-4)} \\
& + M_0\, \text{Tr}[\Sigma_i \Sigma_i] Y_1^{(-4)} + M_1\, \text{Tr}[\Sigma_i \Sigma_i] Y_3^{(-4)} + \text{H.c.}
\end{aligned}
$$

Neutrino and Charged-Lepton Mass Matrices

Dirac Neutrino Mass Matrix

$$M_D = v_\phi \begin{pmatrix} 2\frac{g_1}{3} Y_{31}^{(-4)} & \left(\frac{g_1'}{2} - \frac{g_1}{3}\right) Y_{33}^{(-4)} & -\left(\frac{g_1'}{2} + \frac{g_1}{3}\right) Y_{32}^{(-4)} \\ -\left(\frac{g_1'}{2} + \frac{g_1}{3}\right) Y_{33}^{(-4)} & 2\frac{g_1}{3} Y_{32}^{(-4)} & g_1 Y_1^{(-4)} + \left(\frac{g_1'}{2} - \frac{g_1}{3}\right) Y_{31}^{(-4)} \\ \left(\frac{g_1'}{2} - \frac{g_1}{3}\right) Y_{32}^{(-4)} & \left(\frac{g_1'}{2} + \frac{g_1}{3}\right) Y_{31}^{(-4)} & 2\frac{g_1}{3} Y_{33}^{(-4)} \end{pmatrix}$$

The corresponding charged-lepton mass matrix is given as:

$$M_L = \begin{pmatrix} \alpha Y_{31}^{(-2)} & \alpha Y_{33}^{(-2)} & \alpha Y_{32}^{(-2)} \\ \beta Y_{32}^{(2)} & \beta Y_{31}^{(2)} & \beta Y_{33}^{(2)} \\ \gamma Y_{33}^{(2)} & \gamma Y_{32}^{(2)} & \gamma Y_{31}^{(2)} \end{pmatrix} \frac{v_H}{\sqrt{2}}$$

Heavy Majorana Neutrino Mass Matrix

The heavy Majorana neutrino mass matrix is given as:

$$M_\Sigma = \begin{pmatrix} M_0 Y_1^{(-4)} + 2M' Y_{31}^{(-4)} & -M' Y_{33}^{(-4)} & -M' Y_{32}^{(-4)} \\ -M' Y_{33}^{(-4)} & 2M' Y_{32}^{(-4)} & M_0 Y_1^{(-4)} - M' Y_{31}^{(-4)} \\ -M' Y_{32}^{(-4)} & M_0 Y_1^{(-4)} - M' Y_{31}^{(-4)} & 2M' Y_{33}^{(-4)} \end{pmatrix}$$

Neutrino Mass Diagonalization and PMNS Mixing

1. Heavy Majorana Mass Matrix

$$U_R^T M_\Sigma U_R = \mathrm{diag}(M_{\Sigma_1}, M_{\Sigma_2}, M_{\Sigma_3})$$

2. Type-III Seesaw Formula

$$\boxed{M_\nu = -M_D M_\Sigma^{-1} M_D^T}$$

3. Light Neutrino Mass Matrix

$$U_\nu^T M_\nu U_\nu = \mathrm{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$$

4. PMNS Mixing Matrix

$$\boxed{U_{\mathrm{PMNS}} = U_L^\dagger U_\nu}$$

The charged-lepton mass matrix is not diagonal in the flavour basis.

Chi-Square Test Formulation

$$\chi^2 = \sum_{i=1}^{7} \left(\frac{P_i - P_i^0}{\sigma_i} \right)^2$$

Model & Observables

P_i
Predicted value from the model.

P_i^0
Experimental value from NuFIT 6.1 data.

Uncertainty & Confidence

σ_i
Standard deviation or experimental error.

1σ
Confidence level associated with error bounds.

Best-Fit Values of Neutrino Observables

Numerical best-fit results from the phenomenological analysis

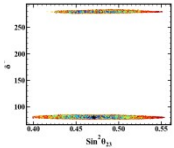
$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}	Δm^2_{solar}	Δm^2_{atm}	Σ_i [eV]
0.308	0.469	0.022	280.9	0.000076	0.00250	0.088

BEST-FIT RESULT

$$\chi^2_{min} = 0.016$$

Best-fit values of neutrino observables corresponding to the minimum chi-square.

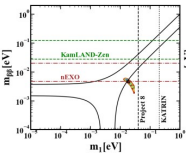
Predictions for Future Experiments



CP Phase and Atmospheric Mixing

The Dirac CP phase is predicted in the range $275° - 284°$, with a best-fit value of $280.9°$.

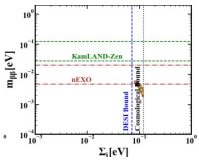
The atmospheric mixing angle is $\sin^2\theta_{23} = 0.469$, placing it in the **lower octant**.



Neutrino Mass Predictions

The effective Majorana mass $m_{\beta\beta}$ is relevant for future neutrinoless double-beta decay searches such as **nEXO**.

The effective electron-neutrino mass m_β can be tested by **KATRIN and Project 8**.



Sum of Neutrino Masses

The predicted sum of neutrino masses is

$$\sum_i m_i = 0.088\,\text{eV}.$$

This is below the Planck cosmological limit of $0.12\,\text{eV}$.

Benchmark Points and Lepton Asymmetry

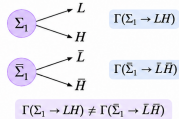
Evolution of the generated $B - L$ asymmetry for three benchmark points.

Thermal Leptogenesis

- The baryon asymmetry is generated through *CP*-violating, out-of-equilibrium decays of the lightest heavy fermion triplet, Σ_1.
- Assume a hierarchical spectrum $M_{\Sigma_1} < M_{\Sigma_2} < M_{\Sigma_3}$.
- The *CP* asymmetry arises from interference between tree-level and one-loop decay amplitudes.

$$\epsilon_{\Sigma_1} = \frac{\Gamma(\Sigma_1 \to LH) - \Gamma(\bar{\Sigma}_1 \to \bar{L}\bar{H})}{\Gamma(\Sigma_1 \to LH) + \Gamma(\bar{\Sigma}_1 \to \bar{L}\bar{H})}.$$

- In this model, the complex modulus τ fixes the *CP*-violating phases; there are no additional arbitrary *CP* phases.



Benchmark points

BP	M_{Σ_1}	ϵ_{CP}
BP1	2.60×10^{13} GeV	-4.5×10^{-4}
BP2	3.35×10^{13} GeV	-8.4×10^{-3}
BP3	1.46×10^{13} GeV	1.44×10^{-6}

Evolution of Y_{B-L} with $z = M_{\Sigma_1}/T$.

Evolution of Y_{B-L} with $z = M_{\Sigma_1}/T$.

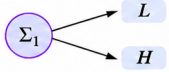
Benchmark Points

BP	χ^2_{min}	M_{Σ_1} (GeV)	ϵ_{CP}
BP1	0.016	2.60×10^{13}	-4.5×10^{-4}
BP2	14.99	3.35×10^{13}	-8.4×10^{-3}
BP3	29.99	1.46×10^{13}	1.44×10^{-6}

The three benchmark points have different CP-asymmetry parameters, resulting in different final $B - L$ asymmetries.

Creating Matter via Thermal Leptogenesis

- Assume a hierarchical spectrum $M_{\Sigma_1} \ll M_{\Sigma_2}, M_{\Sigma_3}$.
- The lightest triplet Σ_1 decays out of equilibrium into leptons and Higgs:



- A *CP* asymmetry arises from the interference between tree-level and one-loop decays:

$$\varepsilon_{\Sigma_1} = \frac{\Gamma(\Sigma_1 \to LH) - \Gamma(\bar{\Sigma}_1 \to \bar{L}\bar{H})}{\Gamma(\Sigma_1 \to LH) + \Gamma(\bar{\Sigma}_1 \to \bar{L}\bar{H})}$$

- The complex modulus τ is the single source of *CP* violation.
- We consider three benchmark points (BP1, BP2, BP3) with $M_{\Sigma_1} \sim 10^{13}$ GeV.

BP	χ^2_{min}	M_{Σ_1} (GeV)	ε_{CP}
BP1	0.016	2.60×10^{13}	-4.5×10^{-4}
BP2	14.99	3.35×10^{13}	-8.4×10^{-3}
BP3	29.99	1.46×10^{13}	1.44×10^{-6}

The Washout Problem in Standard Cosmology

- The evolution is described by the coupled Boltzmann equations:

$$sHz\frac{dY_\Sigma}{dz} = -\gamma_D\left(\frac{Y_\Sigma}{Y_\Sigma^{\text{eq}}} - 1\right) - 2\gamma_A\left(\frac{Y_\Sigma^2}{(Y_\Sigma^{\text{eq}})^2} - 1\right),$$

$$sHz\frac{dY_{B-L}}{dz} = -\gamma_D\varepsilon_\Sigma\left(\frac{Y_\Sigma}{Y_\Sigma^{\text{eq}}} - 1\right) - \frac{Y_{B-L}}{Y_l^{\text{eq}}}\left(\frac{\gamma_D}{2} + \gamma_2^{\text{sub}}\right),$$

- For Type-III triplets (with $SU(2)_L$ gauge charges), the generated asymmetry is strongly washed out by two competing processes:

Inverse decays (D): $LH \to \Sigma_1,\ \bar{L}\bar{H} \to \bar{\Sigma}_1$

Gauge annihiliations (A): $\Sigma_1\Sigma_1 \to W^+W^-$ (and ZZ)

- In the standard radiation-dominated Universe, these back-reactions efficiently erase the produced lepton asymmetry, leaving too little matter behind.

The Fast-Expanding Universe with a Scalar Field

- Introduce a real scalar field ϕ whose energy density redshifts faster than radiation:

$$\rho_\phi \propto \alpha^{-(4+n)} \qquad (n > 0)$$

- The Hubble expansion rate is enhanced above a transition temperature T_r:

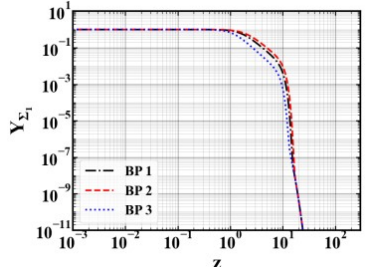
$$H(T) = \begin{cases} H_{\text{FE}}(T) = H_{\text{RD}}(T)\left[1 + \left(\dfrac{T}{T_r}\right)^n\right], & T > T_r, \\ H_{\text{RD}}(T), & T \le T_r, \end{cases}$$

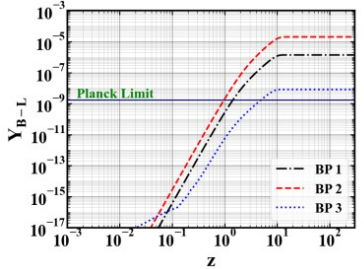
- The scalar energy quickly dilutes, and the Universe returns to the standard radiation-dominated phase before BBN.

Benchmark Points and Thermal Evolution

Benchmark Point	χ^2_{min}	M_{Σ_1} (GeV)	ϵ_{CP}
BP1	0.016	2.60×10^{13}	-4.5×10^{-4}
BP2	14.99	3.35×10^{13}	-8.4×10^{-3}
BP3	29.99	1.46×10^{13}	1.44×10^{-6}

Evolution of the heavy fermion abundance Y_{Σ_1} (left) and the $B - L$ asymmetry Y_{B-L} (right) as a function of $z = M_{\Sigma_1}/T$ for the fast-expanding cosmology with $n = 2$. The results are shown for the three benchmark points BP1, BP2, and BP3. The equilibrium abundance $Y_{\Sigma_1}^{\text{eq}}$ is shown by the dotted black curve in the left panel, while the horizontal line in the right panel indicates the observed value of the baryon asymmetry.





Conclusions

1. Model Construction

We construct a non-supersymmetric modular A_4 Type-III seesaw model with an additional **real scalar field** ϕ.

2. Neutrino Phenomenology

The model successfully fits the NuFIT 6.1 neutrino data in the Normal Hierarchy (NH), with

$$\chi^2_{\text{min}} = 0.016, \qquad \sin^2\theta_{23} = 0.469, \qquad \delta_{\text{CP}} \simeq 281^\circ$$

predicting the atmospheric mixing angle in the **lower octant**.

3. Thermal Leptogenesis in a Fast-Expanding Universe

The additional scalar field drives a fast-expanding early Universe for $n = 1$ and $n = 2$, weakening the washout processes and allowing the generated $B - L$ asymmetry to survive.

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Thank You!

Ongoing Research Directions

We are actively pursuing research in the following areas:

- **Modular Symmetries**
  Exploring modular flavour symmetries and their applications in particle physics.
- **Gravitational-Wave Phenomenology**
  Investigating possible gravitational-wave signatures associated with early-Universe physics.
- **Particle Physics Model Building**
  Developing theoretical frameworks beyond the Standard Model to address open questions in particle physics.

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