# Neutrino Phenomenology in $A_4$ Modular Symmetry with Type-III Seesaw

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## Abstract

For neutrino phenomenology, we work in $A_4$ modular symmetry and $U(1)_{B-L}$ gauged symmetry with type-III seesaw mechanism. In type-III seesaw we add extra fermion triplet superfields to the Standard Model (SM). We show some interesting results of neutrinoless double beta decay mass parameter (NDBD) along with leptogenesis.

## Introduction

- SM has no right handed neutrino, and hence fails to explain mass of neutrinos. So we need to go beyond SM.
- If we work in discrete flavour symmetry group for extension in SM symmetry, we need to handle several flavon field alignments.
- We particularly incorporate $A_4$ modular symmetry, in which Yukawa couplings are function of a complex modulus $\tau$ and transforms in particular manner under this symmetry.
- Modulus $\tau$ is defined in the upper half of the complex plane and transforms under modular group in the following manner

$$\tau \to \frac{c\tau+d}{a\tau+b}$$

where $a, b, c, d$ are integers and $cb-da=1$.

## NDBD ($0\nu\beta\beta$)

Expression for neutrinoless double beta decay is given as,

$$\langle m_{ee}\rangle = \sum m_k |U_{ek}|^2 \qquad (1)$$

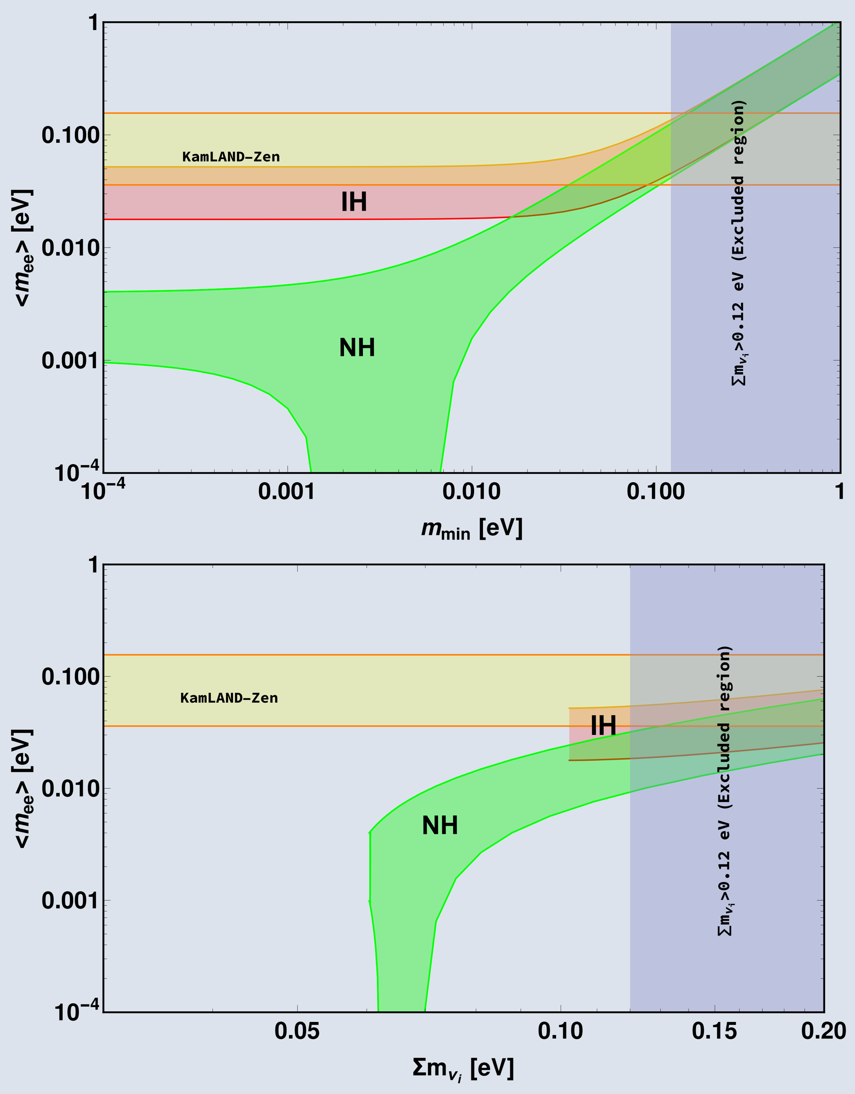



**Fig 2:** The green (red) band in both plots corresponds to the normal (inverted) mass hierarchy.

## Results

- With the help of Chi-square minimization technique, we derived best fit values of model parameters.
- We find a strong correlation between neutrino oscillation observable.
- The model engenders neutrinoless double beta decay mass parameter $\langle m_{ee}\rangle$ between 0.0039 and 0.0087, which assures the limit coming from KamLAND-Zen experiment.
- Baryon and lepton asymmetry of the universe is also explained in this model.

## Model Framework

- For symmetry extension we have used $A_4$ modular symmetry and $U(1)_{B-L}$ gauge symmetry.
- Since we work with type -III seesaw, we have taken extra hyperchargeless fermion triplet. The particle content of our model is given below,

| Fields | $E^c_{1R}$ | $E^c_{2R}$ | $E^c_{3R}$ | $L$ | $\Sigma^c_R$ | $H_{u,d}$ | $\rho$ |
|---|---|---|---|---|---|---|---|
| $SU(2)_L$ | 1 | 1 | 1 | 2 | 3 | 2 | 1 |
| $U(1)_Y$ | 1 | 1 | 1 | $-\frac{1}{2}$ | 0 | $\frac{1}{2}, -\frac{1}{2}$ | 0 |
| $U(1)_{B-L}$ | 1 | 1 | 1 | $-1$ | 1 | 0 | $-2$ |
| $A_4$ | 1 | $1'$ | $1''$ | $1, 1'', 1'$ | 3 | 1 | 1 |
| $k_I$ | 0 | 0 | 0 | 0 | $-2$ | 0 | 2 |

$$\mathrm{M}_D = v_u \begin{bmatrix} \alpha_1 & 0 & 0 \\ 0 & \alpha_2 & 0 \\ 0 & 0 & \alpha_3 \end{bmatrix} \begin{bmatrix} y_1 & y_3 & y_2 \\ y_2 & y_1 & y_3 \\ y_3 & y_2 & y_1 \end{bmatrix},$$

$$\mathrm{M}_R = \frac{v_\rho}{\Lambda\sqrt{2}} \left(\frac{M'_\Sigma}{2}\right) \left( \frac{\beta_\Sigma}{3} \begin{bmatrix} 2y_1 & -y_3 & -y_2 \\ -y_3 & 2y_2 & -y_1 \\ -y_2 & -y_1 & 2y_3 \end{bmatrix} + \gamma_\Sigma \begin{bmatrix} 0 & y_3 & -y_2 \\ -y_3 & 0 & y_1 \\ y_2 & -y_1 & 0 \end{bmatrix} \right).$$

- Active neutrino mass matrix is given by, $\mathrm{m}_\nu = -M_D M_R^{-1} M_D^T$ .

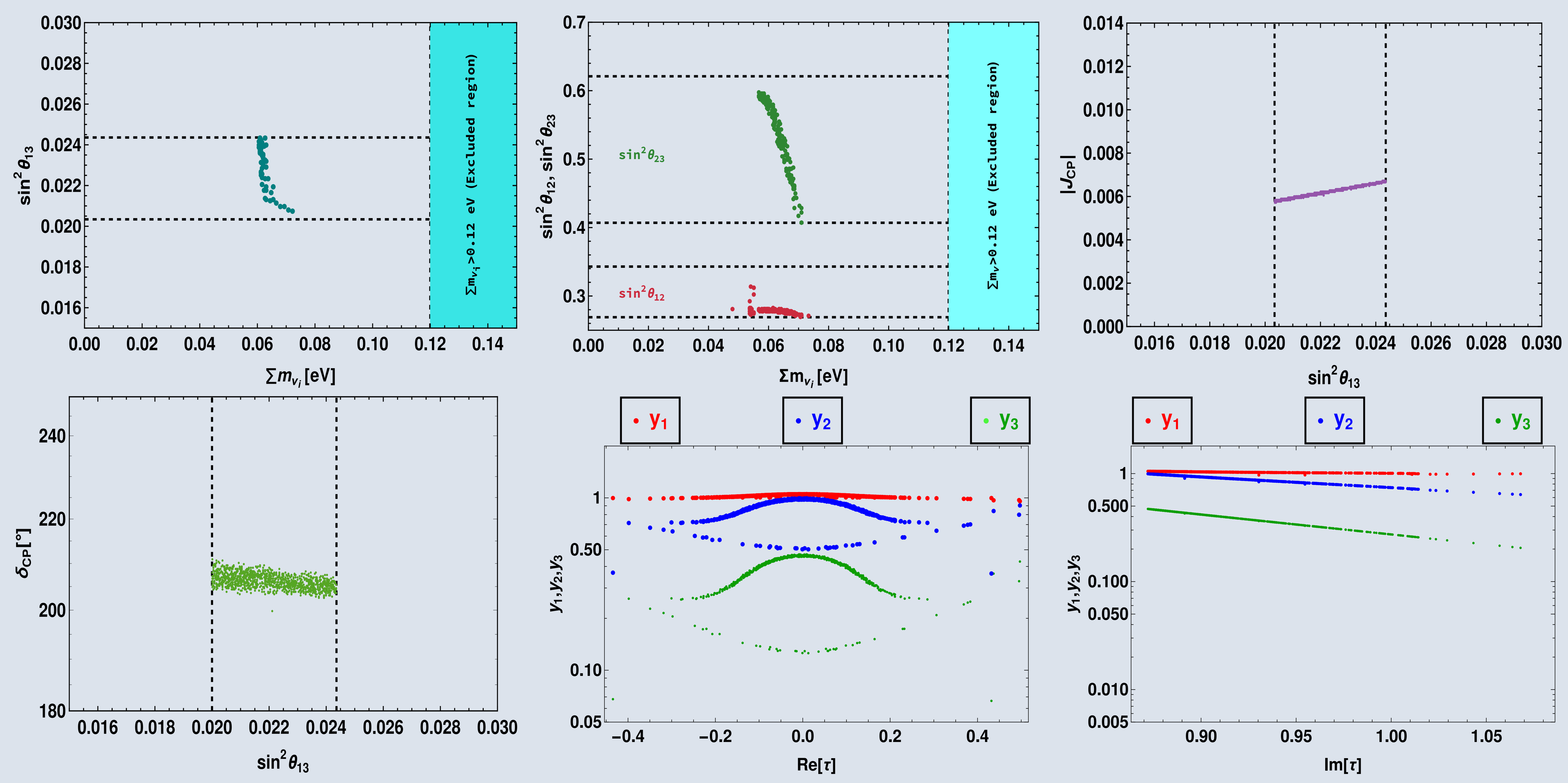


**Fig 1:** Some important plots from our model regarding oscillation parameters and Yukawa couplings.

## Leptogenesis

The CP violating parameter is defined as,

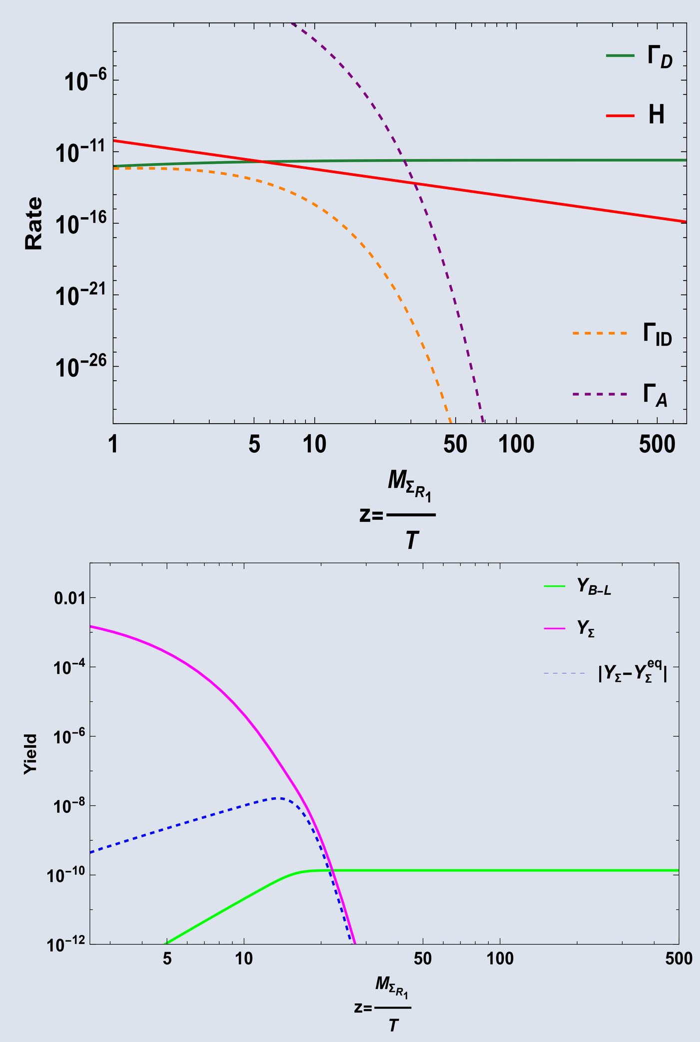
$$\epsilon_{CP} = -\sum_j \frac{3}{2} \frac{M_{\Sigma_{R_i}}}{M_{\Sigma_{R_j}}} \frac{\Gamma_{\Sigma_{R_i}}}{M_{\Sigma_{R_j}}} \left(\frac{V_j - 2S_j}{3}\right) \frac{\mathrm{Im}(\tilde{Y}_\Sigma \tilde{Y}_\Sigma^\dagger)_{ij}}{(\tilde{Y}_\Sigma \tilde{Y}_\Sigma^\dagger)_{ii} (\tilde{Y}_\Sigma \tilde{Y}_\Sigma^\dagger)_{jj}}.$$

**Boltzmann Equation :**

We use Boltzmann equation to plot number densuty in terms of yield.

$$\frac{dY_\Sigma}{dz} = -\frac{z}{sH(M_\Sigma)} \left[ \left(\frac{Y_\Sigma}{Y_\Sigma^{\rm eq}} - 1\right)\gamma_D + \left(\left(\frac{Y_\Sigma}{Y_\Sigma^{\rm eq}}\right)^2 - 1\right)\gamma_A \right],$$

$$\frac{dY_{B-L}}{dz} = -\frac{z}{sH(M_\Sigma)} \left[ \frac{Y_{B-L}}{Y_\ell^{\rm eq}}\gamma_D - \epsilon_{CP}\left(\frac{Y_\Sigma}{Y_\Sigma^{\rm eq}} - 1\right)\frac{\gamma_D}{2} \right].$$



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## References

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