# Discriminating Dirac and Majorana neutrino CP Phases in the light of thermal leptogenesis in type I+II seesaw models.

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**Abstract**

We study the effects of Dirac and Majorana CP phases in the origin of baryon asymmetry of the Universe through the mechanism of the leptogenesis. In this work we also try to connect neutrino CP phases, lightest neutrino mass and baryogenesis within the framework of a model where both type I and type II seesaw contribute to the neutrino mass. Type I seesaw mass matrix considered as a TBM type neutrino mass matrix which gives zero $\theta_{13}$ whereas type II seesaw acts as a correction to generate nonzero $\theta_{13}$. Considering type II seesaw mass matrix as a subleading and equally dominating compared to type I seesaw, we try to constrain all these experimentally undetermined neutrino parameters namely Dirac and Majorana CP phases and lightest neutrino mass from the requirement of producing correct baryon asymmetry of the Universe.

## Introduction

Neutrino oscillation experiments in the last few years have given substantial amount of evidence in favor of non-zero neutrino mass and mixing. More recently, neutrino oscillation experiments T2K [1], Double ChooZ [2], Daya-Bay [3] and RENO [4] have not only made the earlier predictions for neutrino parameters more precise, but also predicted non-zero value of the reactor mixing angle $\theta_{13}$. Before the discovery of non-zero $\theta_{13}$, the neutrino oscillation data were consistent with the so called TBM form of the neutrino mixing matrix which predicts the mixing angles as $\theta_{12} \simeq 35.3^o,\ \theta_{23} = 45^o$ and $\theta_{13} = 0$.

In the present work, we attempt to find a mechanism which can not only generate non-zero $\theta_{13}$ but can also shed some light on those parameters of the neutrino sector which are not yet accurately measured namely, the lightest neutrino mass, the leptonic Dirac CP phase and the majarona neutrino phases. Apart from incorporating the constraints from neutrino oscillation experiments, we also take the constraints from cosmology into account. Cosmology can constrain the the sum of absolute neutrino masses as $\sum_i |m_i| < 0.23$ eV. We can further constrain the neutrino parameters from cosmology if we assume leptonic sector origin of matter antimatter asymmetry of the Universe. The matter antimatter asymmetry or the baryon asymmetry of the Universe is measured in terms of baryon to photon ratio which according to the latest data available from Planck mission is given as

$$Y_B \simeq (6.065 \pm 0.090) \times 10^{-10} \tag{1}$$

## Numerical Methods

Here we consider the type I seesaw to give rise to TBM type neutrino mixing whereas the type II seesaw term acts like a deviation from TBM mixing in order to generate non-zero $\theta_{13}$. The TBM type neutrino mass matrix can be parametrized as

$$U_{TBM} == \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \tag{2}$$

It predicts the mixing angles as $\theta_{12} \simeq 35.3^o,\ \theta_{23} = 45^o$ and $\theta_{13} = 0$.

The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) leptonic mixing matrix is related to the diagonalizing matrices of neutrino and charged lepton mass matrices $U_\nu, U_l$ respectively, as

$$U_{\text{PMNS}} = U_l^\dagger U_\nu \tag{3}$$

The PMNS mixing matrix can be parametrized as

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\delta+i\beta} \end{pmatrix} \tag{4}$$

We write the neutrino mass matrix as

$$U_{\text{PMNS}} M_\nu^{\text{diag}} U_{\text{PMNS}}^T = M_\nu^{II} + U_{TBM} M_\nu^{I(\text{diag})} U_{TBM}^T \tag{5}$$

For normal hierarchy, the diagonal mass matrix of the light neutrinos can be written as $M_\nu^{\text{diag}} = \text{diag}(m_1, \sqrt{m_1^2 + \Delta m_{21}^2}, \sqrt{m_1^2 + \Delta m_{31}^2})$ whereas for inverted hierarchy it can be written as $M_\nu^{\text{diag}} = \text{diag}(\sqrt{m_3^2 + \Delta m_{23}^2 - \Delta m_{21}^2}, \sqrt{m_3^2 + \Delta m_{23}^2}, m_3)$.

$$M_R = M_D^T (M_\nu^I)^{-1} M_D \tag{6}$$

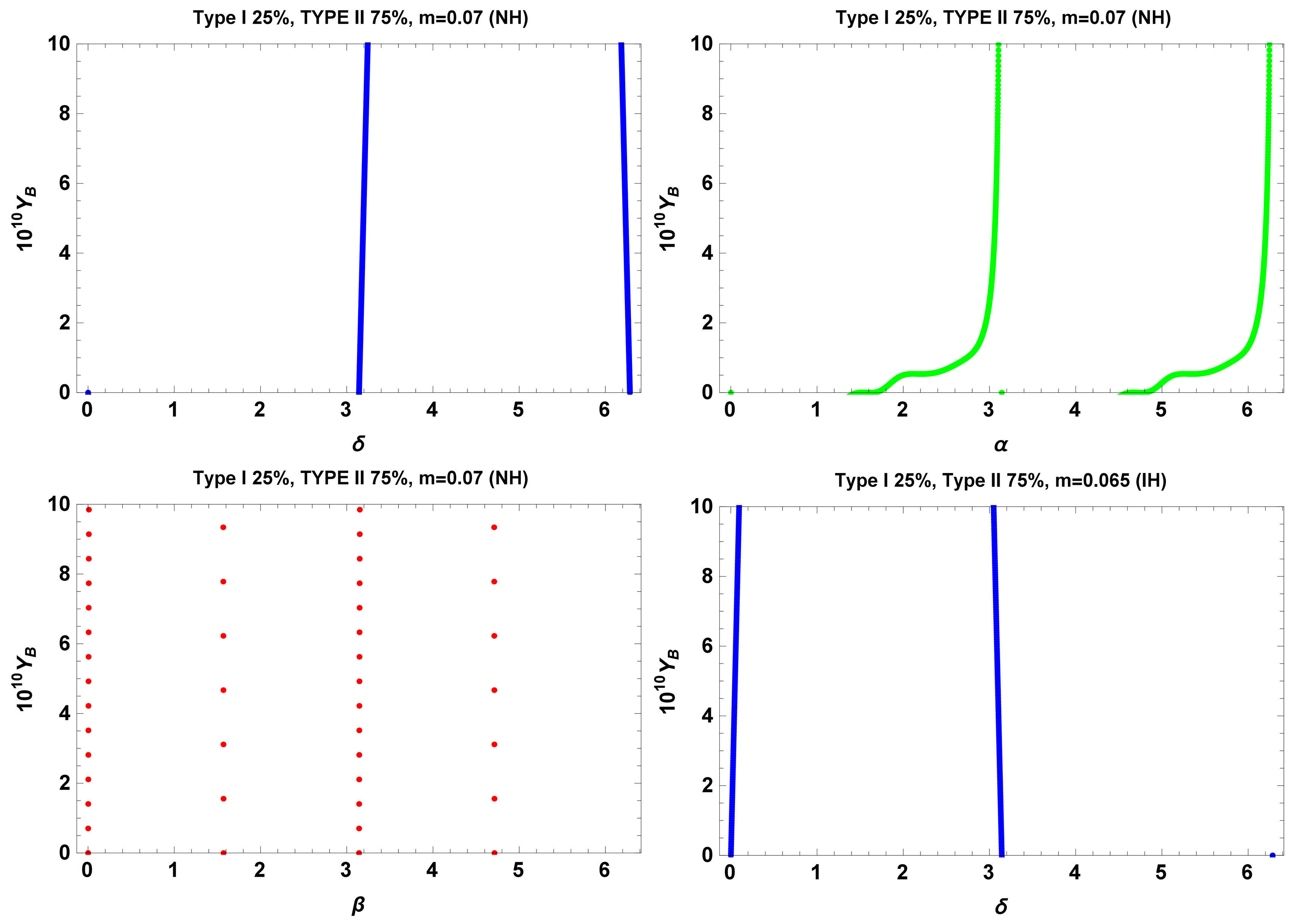
We consider a diagonal type Dirac neutrino mass matrix which can be parametrized as

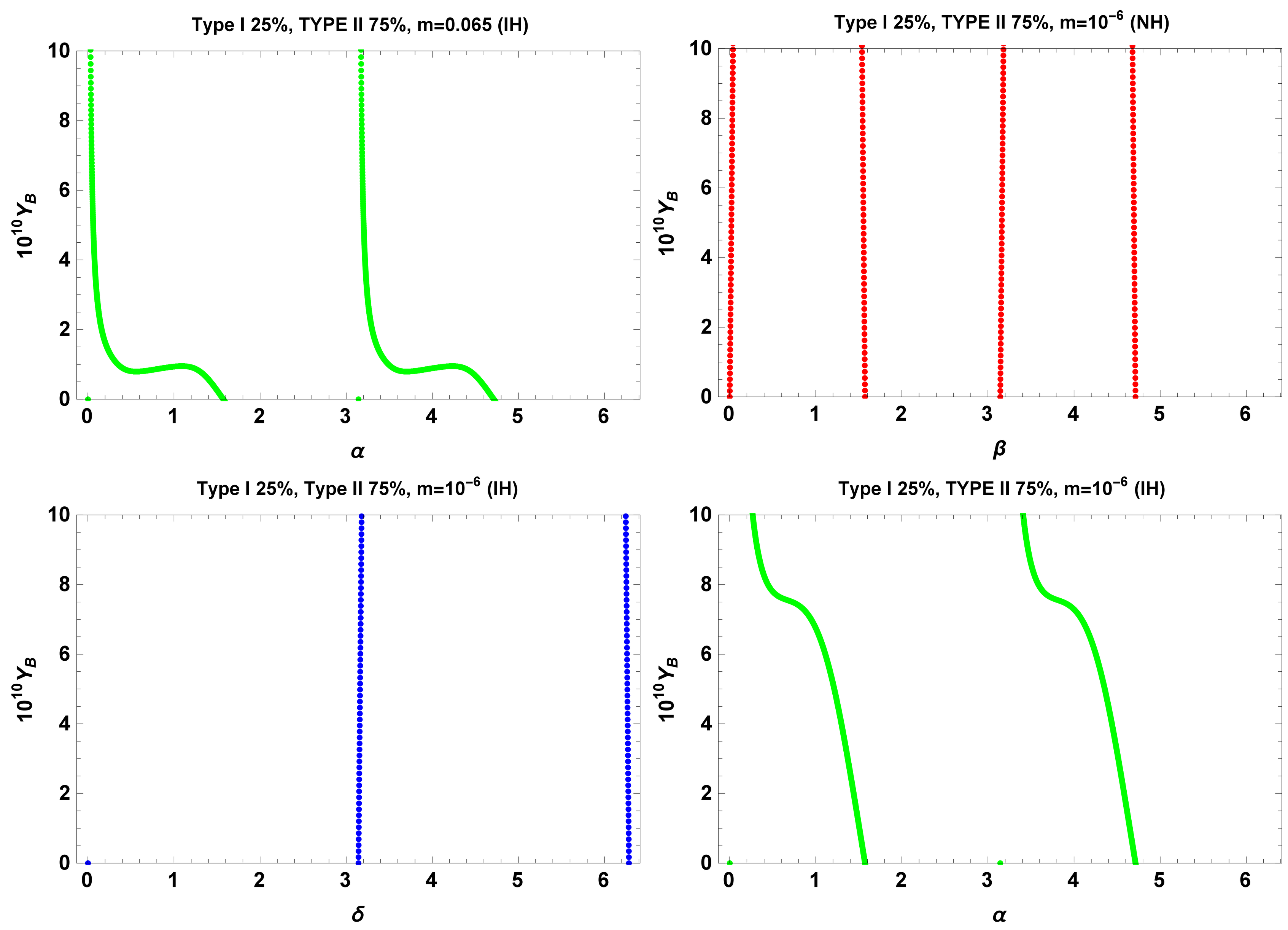
$$M_D = \begin{pmatrix} \lambda^m & 0 & 0 \\ 0 & \lambda^n & 0 \\ 0 & 0 & 1 \end{pmatrix} m_f \tag{7}$$

where $\lambda = 0.22$ is the standard Wolfenstein parameter and $(m, n)$ are positive integers. We fix $m_f = 82.43$ GeV and change the integers $(m, n)$ in order to keep the lightest right handed neutrino mass $M_1$ in the appropriate flavor regime

## Results

We have studied the possibility of generating non-zero reactor mixing angle as well as non-trivial leptonic CP phases (both Dirac and Majorana) through the combination of type I and type II seesaw mechanisms. We consider three different scenarios where type I seesaw contributions to neutrino mass are $25\%, 50\%$ and $75\%$ respectively. We also consider both inverted and normal hierarchical neutrino mass spectrum as well as two different types of lightest neutrino mass in order to show the effect of hierarchy. In our first case we consider $\alpha = 0, \beta = 0$ and try to see the dependence of Dirac CP phase with the baryon asymmetry of the Universe. Similarly we further consider $\delta = 0, \beta = 0$ and $\delta = 0, \alpha = 0$ to study the effects of Majorana phases on baryon asymmery of the Universe. We observe the correct baryon asymmetry for Dirac CP phase in all the cases except the NH with lightest neutrino mass $m = 10^{-6}$ eV. In case of Majorana Phase $(\alpha)$ we observe the correct baryon asymmetry for NH cases and IH with $m = 0.065$ eV. We observe the correct baryon symmetry only for NH mass spectrum in case of Majarona phase $(\beta)$




## Conclusions

- The variation of baryon asymmetry with Dirac CP phase is found to be very sharp in NH with $m = 0.07$ eV for $25\%$ Type I contribution.
- We have not observed the correct baryon asymmetry for Dirac CP phase in case of NH with $75\%$ Type I contribution. IH with other lightest neutrino masses with $25\%$ contribution of Type I seesaw gives very good result.
- We do not observe correct baryon asymmetry in case of $\alpha$ with NH $m = 10^{-6}$ eV for all contribution of Type I seesaw.
- In case of Majorana phase $\beta$ we observe the baryon asymmetry only for NH cases.
- Thus assuming thermal leptogenesis as the only source of baryon asymmetry of the Universe , we can discriminate different possible values of Dirac and Majorana CP phases.

## Forthcoming Research

It will be interesting to constrain Dirac and Majorana CP phases further by computing other observables like neutrinoless double beta decay lifetime by taking contribution from multiple seesaw mechanism .

## References

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