"Begin at the beginning and go on till you come to the end: then stop"

Lewis Carroll in "Alice in Wonderland"

6

Conclusion

In this chapter we have discussed about the over all conclusion drawn from the aforementioned works exhibited in the earlier chapters which primarily deal with the study of connecting neutrino masses with modern cosmology such as origin of dark matter, and the baryon asymmetry of the universe (BAU). To explain the neutrino mass, class of seesaw mechanisms have been implemented, specially the inverse seesaw, type II seesaw and TeV scale type I seesaw. We have studied the possibility of generating non-zero reactor angle and origin of dark matter within a single frame work. We also have explored a way to reproduce origin of non-zero reactor angle and BAU inside the same setting. Effective mass prediction for NDBD has also been addressed very briefly.

We summarize the notable conclusions drawn from the present study, chapter wise in Sections **6.1 6.2, 6.3, 6.4** respectively.

6.1 Chapter 2

In **chapter 2** an A_4 based IH neutrino mass model originating from both Inverse and type II seesaw have been studied. Here ISS is implemented as a leading order contribution to the light neutrino mass matrix yielding zero reactor mixing and $m_3 = 0$. Then the type II seesaw has been used in order to produce non-Zero reactor mixing angle, which later on produces $m_3 \neq 0$ keeping the hierarchy as inverted only. We have studied the possibility of having a common parameter space where both the Neutrino oscillation parameters in the 3σ range and DM relic abundance has a better reach. With a proper choice of Yukawa coupling(y), right handed neutrino (mediator particle) mass (m_ψ) , and complex scalar (potential DM candidate) mass (m_χ) the variation in relic abundance as a function of Yukawa coupling has been shown. For a choice of Yukawa coupling between 0.994 to 0.9964, m_{DM} around 50 GeV, the mediator mass needs to fall around 153 GeV to match the correct relic abundance. The same Yukawa coupling has got a key role in generating the Neutrino oscillation parameters as well. We have studied the prospect of producing non-zero θ_{13} by introducing a perturbation to the light neutrino mass matrix using type II seesaw within the A_4 model. We have also determined the strength of the type II seesaw term which is responsible for the generation of non-zero θ_{13} in the correct 3σ range. We have also checked whether the proposed model can project about neutrinoless double beta decay or not. In context to the presented model we have found a wide range of parameter space where one may have a better reach for both neutrino and dark matter sector as well.

6.2 Chapter 3

In **chapter 3** we have studied a TeV scale inverse seesaw model based on S_4 flavor symmetry which can naturally generate correct light neutrino masses with Tri-Bi-maximal type mixing at leading order. The model also predicts a neutrino mass sum rule that can further predict the value of the lightest neutrino mass, that can be tested at experiments like neutrinoless double beta decay. Since

TBM mixing has already been ruled out by the latest neutrino oscillation data, we consider two possible ways of generating non-zero θ_{13} which automatically take dark matter into account. The idea is based on the scotogenic mechanism of neutrino mass generation, where neutrino mass arises at one loop level with DM particles going inside the loop. We first give such a one loop correction to the leading order light neutrino mass matrix and numerically evaluate the model parameters from the requirement of satisfying the correct neutrino data. This however, disturbs the mass sum rule prediction of the original model. The dark matter candidate in such a case could either be a singlet neutral fermion or the neutral component of a scalar doublet, depending whichever is lighter. We also study the possibility of generating $\theta_{13} \neq 0$ by giving a correction to the charged lepton sector. Such a case is found to be more constrained from the requirement of satisfying the correct neutrino data. We find much narrower ranges of points in terms of light neutrino parameters which can bring the model predictions closer to the observed data. Consistency with light neutrino data also requires the right diagonalising matrix of charged lepton to have very small mixing angles. The DM candidate in this case is the neutral component of a scalar doublet.

We also study the predictions for neutrinoless double beta decay and found that the charged lepton correction case with inverted hierarchy is disfavored by the latest KamLAND-Zen data. The predictions for effective neutrino mass in this model is very specific and confined to a tiny region around a particular value of lightest neutrino mass. This is due to the neutrino mass sum rule which forces the lightest neutrino mass to remain within a very narrow range. We also find the allowed parameter space for scalar dark matter from the requirement of producing the correct neutrino data, ignoring the Higgs portal and gauge mediated annihilations. Such lepton portal annihilations are efficient for large Yukawa couplings or smaller mediator masses. Since the same Yukawa couplings and mediator mass go into the one loop correction for both neutrino and charged lepton mass matrix, the charged lepton correction is more favourable from lepton portal scalar DM point of view. As mentioned before, this is due to the fact that large Yukawa or small mediator mass will be able to generate sub-GeV corrections to charged lepton mass matrix more naturally than generating sub-eV corrections to light neutrino mass matrix. Also, the charged lepton correction case is much more predictive, as obvious from a much narrower region of allowed parameter space compared to the model with neutrino mass correction.

6.3 Chapter 4

In **chapter 4** we have studied an extension of the standard model by discrete flavour symmetry $A_4 \times Z_3 \times Z_2$ that can simultaneously explain the correct neutrino oscillation data and the observed baryon asymmetry of the Universe. Considering a TeV scale type I seesaw we adopt the mechanism of resonant leptogenesis to generate a lepton asymmetry through out of equilibrium CP violating decay of right handed neutrinos which later gets converted into the required baryon asymmetry through electroweak sphalerons. The field content and its transformation under the flavour symmetry are chosen in such a way that the leading order right handed neutrino mass matrix has a trivial structure giving a degenerate spectrum. The tiny splitting between the right handed neutrino masses (required for resonant leptogenesis) arises through higher dimension mass terms, naturally suppressing the splitting. Due to the trivial structure of the right handed neutrino mass matrix, the leptonic mixing arises through the non-trivial structure of the Dirac neutrino mass matrix within a type I seesaw framework. This automatically leads to a $\mu - \tau$ symmetry breaking light neutrino mass matrix due to the existence of anti-symmetric terms arising from product of two triplet representations of A_4. Although such terms vanish for right handed neutrino mass matrix due to the Majorana nature, they do not vanish in general for Dirac neutrino mass matrix. Within a minimal setup, we then compare the $\mu - \tau$ symmetry breaking light neutrino mass matrix with the one constructed from light neutrino parameters and find the model parameters, while fixing the right handed neutrino mass at 5 TeV. Since there are only four independent complex parameters of the model that can be evaluated comparing four mass matrix elements, it gives rise to two constraints due to the existence of six independent complex elements of a light neutrino mass matrix which is complex symmetric if the light neutrinos are of Majorana type. These two constraints severely restrict the allowed parameter space to a narrow range, which we evaluate numerically by doing a random scan of ten million neutrino data points in the allowed 3σ range, for both normal and inverted hierarchical patterns of light neutrino masses. Among the unknown light neutrino parameters namely, the lightest neutrino mass, one Dirac and two Majorana CP phases, we get some interesting restrictions on some of these parameters from the requirement of satisfying the correct neutrino data within the model framework. After finding the model and neutrino parameters consistent with the basic setup, we then feed the allowed parameters to the resonant leptogenesis formulas and calculate the baryon asymmetry of the Universe. We find that both the normal and inverted hierarchical scenarios can satisfy the Planck 2015 bound on baryon asymmetry $\eta_B = 6.04 \pm 0.08 \times 10^{-10}$. We however get more allowed points for the inverted hierarchical scenario compared to the normal one. Finally, we also briefly outline the $\mu - \tau$ symmetric limit of the model taking the approximation of vanishing anti-symmetric triplet product term and a possible way to generate non zero θ_{13} in that scenario. We however, do not perform any separate numerical calculation in this limiting scenario. We find it interesting that, just by trying to generate leptonic mixing through a non-trivial Dirac neutrino mass term automatically leads to broken $\mu - \tau$ symmetry, automatically generating non-zero θ_{13}. This is in fact a more economical way to generate the correct neutrino oscillation data than taking the usual route of generating $\mu - \tau$ symmetric mass matrix at leading order followed by some next to leading order corrections responsible for generating $\theta_{13} \neq 0$ which was the usual procedure adopted after the discovery of non-zero θ_{13} in 2012. It is also interesting that the model can naturally generate the tiny mass splitting between right handed neutrinos and generate the required baryon asymmetry through the mechanism of resonant leptogenesis.

6.4 Chapter 5

In **chapter 5** we have studied an S_4 based ISS model which is accompanied by the type II seesaw as a perturbation to the leading order ISS mass, from the need of bringing non vanishing reactor angle into account. The entire study has been performed from a different aspect; by extracting the Yukawa coupling (y) from the light neutrino mass matrix and varying it from and to a certain range, in order to check the parameter space of the Yukawa coupling strength and the global fit neutrino parameters. For NH mass pattern it is seen that only the lower bound of the mass squared splittings can give a solution for the model parameters $a,\ b$ who further give rise to the other oscillation parameters in correct 3σ range for the chosen range of Yukawa coupling (y). For the same Yukawa coupling range the model prediction is more sensitive to IH mass pattern, as we obtain the oscillation parameters in agreement with experiments, while scanning the mass squared splittings from the lower bound of the 3σ bound to the best fit central value. Thus, we can conclude that a broader region of parameter space exists in case of IH. From the type II seesaw term we have the type II strength w which is responsible for the generation of non-zero θ_{13} in the correct 3σ range. We have also studied the effective mass prediction for the contribution of NDBD. However, for both hierarchy pattern we get the effective mass within GERDA limit. The variation of Yukawa coupling makes a better plot for a detailed study of the neutrino parameters.

6.5 Future Prospects

The class of models discussed in the present study apart the exhibited result do also have strong predictions. The models under discussion can be further studied to explore some untouched portion of neutrino mixing theory such as possible mass sum rules in each model. Below we present some of the future plans.

- We can explore viable DM phenomenology, by considering several decay channels which we have not considered here. We can further explore the models for a detailed study of Baryogenesis via leptogenesis.

- The above discussed TeV scale seesaw scenario can also have some other interesting implications in collider as well as rare decay experiments like lepton flavour violation. Also, such a TeV scale seesaw scenario can play a non-trivial role in restoring the electroweak vacuum stability.

- We can explore the possibility of leptogenesis in the TeV scale ISS models presented here, by considering a non-degenerate M structure and utilizing the complex solutions for the model parameters, considering them as sources of CP violation.