ABSTRACT

The Standard Model(SM) is an entrenched model in particle physics which successfully explains the theory for fundamental particles and their interactions. It is considered as one of the most accurate models wherein the building blocks of the Universe are well described. Notwithstanding the immense popularity of SM, it has to face many drawbacks and anamolies. With the experimental evidence of neutrino masses and mixing obtained from various experiments, it is verified that neutrinos are massive. It is also believed that there must be some unknown matter and force which opposes the galaxies to drift apart. Such matter are termed as dark matter[69, 70], which is beyond the scope of SM. However, in the SM, we obtain explanation of three fundamental forces governing the Universe viz. electromagnetism, weak force and strong force. It is yet unable to incorporate the gravitational force, also why gravity is so weak compared to electroweak or nuclear forces. These discrepencies alongwith baryon asymmetry of the Universe, CP-violation, etc pushes the idea of extending the SM as it couldnot accomodate the same.

Neutrinos being very weakly interacting particles are thereby hard to be detected inspite of the fact that a trillion of them passes through our body every second. There exist three flavors of neutrinos namely; electron neutrino(ν_e), muon neutrino(ν_μ) and tau neutrino(ν_τ). The existence of neutrino mass was experimentally proven by the breakthrough discovery of neutrino oscillation by the Super-Kamiokande experiment in 1998. This discovery led to the conclusion that neutrino have finite mass though very tiny. The parameters successfully measured by the neutrino oscillation experiments[272, 273] are the three mixing angles: θ_{12}, θ_{23} and θ_{13} and the mass square differences of the neutrinos, i.e. $m_{12} - m_{22}$, $m_{22} - m_{32}$. The recent Neutrino experiments MINOS[274],RENO[275],T2K[54],Double-Chooz[56] have not only confirmed but also measured the neutrino oscillation parameters more accurately. However, there is yet no answer to the exact mass of each neutrinos[66], mass heirarchies and the CP violating parameter.

The need of beyond Standard Model frameworks have thus become popular in order to pull out the anamolies of SM. Some of these frameworks include the seesaw mechanism [7–11], radiative seesaw mechanism[12–14], neutrino two Higgs doublet model and many more. The seesaw mechanism is one such convincing framework wherein the neutrino mass can be generated. It predicts that the neutrinos have two type of handedness, i,e, left-handed neutrino and a hypothetical right-handed neutrino. The name seesaw itself hints on the fact that right-handed neutrino mass must be higher in order to achieve light left-handed neutrino mass. Furthermore, it also puts up a condition on the right-handed neutrinos, stating that if they existed then they would be their own anti-particle.

A significant tool in particle physics which helps in constraining the models and thereby explaining various phenomena is the discrete flavor symmetries. Some of the commonly used flavor symmetries in neutrino physics[276, 10, 97, 277, 238, 278] are A_n, S_4, Z_n, etc. These discrete symmetries are prefered over the continuous symmetry as it prevents the production of unwanted goldstone bosons. We thus realize the beyond SM models, in our case we mainly realize the scotogenic model(radiative seesaw) and the neutrino two Higgs doublet model(ν2HDM) with the help of A_4, Z_2, Z_4 and Z_8 symmetries[201, 238, 279]. Such realization opens up various window of possibility in determining the unsolved mysteries of the Universe. We can generate the light neutrino mass, explain the baryon asymmetry of the Universe, dark matter and many more other cosmological consequences. Thus, on analysing these phenomenas by the virtue of their experimental bounds, we can check the validity of our model. We briefly discuss some of the above mentioned phenomenas as follows:
Baryon asymmetry of the Universe is one such fascinating phenomenon which illustrates the imbalance in the matter and anti-matter content of the Universe[67, 68]. The idea of baryon asymmetry of the Universe also known as baryogenesis was proposed by Shakarov[77] who stated three necessary conditions: C and CP violation, baryon number violation and departure from equilibrium. It therefore, enhances the motivation to go beyond SM and

at the same time leads to various bounds on feasible outline of the evolution of the early Universe. Baryogenesis can be achieved via the process of lepton asymmetry which is termed as leptogenesis. This includes the decay of a heavy right-handed neutrino into a lepton doublet and a scalar doublet or into an anti-lepton and a CP conjugate scalar doublet. In most of the BSM frameworks, the mass of the right-handed neutrino required is much high scaling over $10^{14} - 10^{15}$ GeV. However, in the frameworks considered in this thesis, namely the scotogenic model and ν2HDM, the righ-handed neutrino mass can be lowered upto 10 TeV[68, 85], thus, producing low scale leptogenesis.

Taking into account the Majorana nature of the neutrinos, neutrinoless double beta decay($0\nu\beta\beta$) is one of the most promising processes[114, 113]. It is a lepton number violating process which if observed will prove the Majorana nature of the neutrinos. Extending the picture from the SM to Grand Unified Theories (GUTs), quarks and leptons live together in multiplets, and hence both B and L are not expected to be conserved quantities. The combination of B-L, which is conserved in the SM both at the classical and quantum level, often plays an important role in GUTs, and is broken at some stage. $0\nu\beta\beta$ would also violate the B-L quantity which would further have significant implications in the theories which are trying to explain the matter anti-matter asymmetry of the Universe. It being a radioactive decay transforms a nuclie of atomic number Z to its isobar with atomic number Z+2, thereby violating the lepton number.

Dark matter being the hot topic of discussion in cosmology, is said to occupy 27% of the present Universe on the basis of latest data from Planck satellite. The presence of Dark matter in the Universe is a manifestation of the discrepancy between the luminous mass and the gravitaional mass. In order to measure the gravitational mass of the galaxy, or of a cluster of galaxy, one needs to study the motion of the galaxy and incorporating the graviattional calculations we can estimate the gravitational mass required to keep a system bound. Among the evidences for existence of DM galaxy cluster observations by Fritz Zwicky[88], observations of galaxy rotation curves in 1970[90], gravitational lensing[89] and the most latest cosmology data obtained from Planck satellite[91] are the most prominent ones. Although, the nature of DM is not yet confirmed, by the knowledge of its cosmological and gravitational evidences, it can be categorised on the basis of its production, particle nature of its constituents and mass of DM particles. Considering the possible production, it is classified as Thermal Dark Matter and Non-Thermal Dark Matter. We have tried to incorporate various possible candidate of dark matter in our work and checked its validity with the recent Planck data bounds, X-ray observation and Lyman-α constraints[252, 280].

Based on these motivations, we have constructed various models and have done an extensive analysis on its viability. The thesis is thus constructed in context with the various ideas and phenomenas that we have discussed above. An outline of my thesis is as follows:

Chapter 1 includes the introduction part, wherein we have briefly addressed the origin and history of the neutrinos, followed by the experimental and theoretical evidences. Further, we focus on the motivations of the beyond SM frameworks which is a consequence of the drawbacks of the SM. An adequate explanation on the various BSM phenomena is mentioned followed by discrete flavor symmetries which are used in constructing BSM models in our work.

In Chapter 2, we introduce the minimal scotogenic model to explore the intermediate dark matter mass region and at the same time generate the small neutrino mass. We look forward to produce BAU as well, which further restricts the N_1 decay due to the choice of the dark matter mass in our work. Thus, we continue with N_2 leptogenesis which opens up possibility to study production of thermal and non-thermal DM and baryon asymmetry of the Universe within the same framework. We also incorporate latest bounds from KamLAND-Zen experiment for $0\nu\beta\beta$ and upper bounds on lepton flavor violating processes by MEG collaboration.

In Chapter 3, we mainly discuss the realization of the minimal scotogenic model by discrete flavor symmetries $A_4 \otimes Z_4$. By proper choice of vacuum expectation value(vev), we generate three one zero Yukawa coupling matrices. Out of the three cases of the Yukawa coupling matrix, we carry out our analysis for only one of them as the other two turns out to be $\mu - \tau$ symmetric. We study phenomenas such as $0\nu\beta\beta$, baryon asymmetry of the Universe, dark matter within this model. From the results obtained, we can conclude that our model is a viable one.

Chapter 4 includes a detailed study of an extension of ν2HDM by a dark sector. In this model, we link the neutrino phenomenology, cosmology and dark matter with the virtue of a decay parameter. We also introduce flavor symmetry in this framework so as to constrain the Yukawa couplings which play a crucial role in the calculation of decay parameter. Incorporating bounds from recent Planck data, we check the consistency of relic abundance produced in our model. It can be summarized from various aspects carried out in our work that the dark matter candidate is of FIMP type.

In Chapter 5, we show our final work, which is an extension of the ν2HDM by a gauge singlet(S). This newly added particle is a sterile fermion which is considered as a probable dark matter candidate in our work. We also illustrate plots depicting the active-sterile mixing and try to evaluate the allowed parameter space considering bounds from X-ray observation and Lyman-α. Furthermore, we check the allowed mass range of dark matter which can successfully produce the observed relic abundance. The values of decay rate obtained in our work is also very negligible, thereby, validating the dark matter candidate. In addition to dark matter phenomenology, we have also carried out analysis for BAU and $0\nu\beta\beta$.

The last chapter of the thesis, i.e. Chapter 6 is the conclusion section. It includes the summary of various crucial and significant results and conclusion we have obtained from the works we have done.