Dark Matter and Baryonic Asymmetry in Beyond Standard Models

ABSTRACT

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Abstract

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This thesis addresses the two main questions that the Standard Model (SM) cannot address related to the early Universe. The first one is the viable model, which can have a credible dark matter candidate and explain the proper dark matter relic density. Second is the matter-antimatter asymmetry in the baryonic sector of the Universe, also known as baryonic asymmetry of Universe.

Despite SM's beautiful power of predictions and explanations of different phenomena in nature, there are relevant and crucial questions that are difficult to be answered in the SM framework of particle physics. This is the reason why particle physicists realize their work is away from done. Some of the questions are:

- Can SM provide a suitable dark matter candidate?
- Why is there more matter than anti-matter in the Universe (Baryonic asymmetry)?
- Why neutrinos are massive?

Besides there are other theoretical shortcomings in SM. Without going to the details of those, we mention here one such important problem. In SM, there is hierarchy problem in the context of Higgs mass. At

fermions present in the model.

Apart from Planck data constraint on relic abundance and LHC constraint on extra $U(1)$ gauge boson mass and its gauge coupling, we have taken into account the possible constraints coming from active, sterile neutrino masses and their mixing from different oscillation experiments, to find the allowed region in M_X (mass of extra $U(1)$ gauge boson) and m_ψ (mass of lightest dark matter candidate) plane. In the extra $U(1)$ gauge model considered by us, the neutrino oscillations constraints - particularly active-sterile neutrino mixing have led to the requirement of non-zero mixing θ between dark matter ψ_1 with the other heavy right handed Majorana fermion ψ_2. This has led to the consideration of both annihilation and co-annihilation channels for the dark matter. Also the oscillation data constrains the allowed region of θ and Δ (mass gap between two lightest dark matter candidates) . The allowed region in M_X and m_ψ plane is found to be reduced for co-annihilation channel with respect to no co-annihilation channel. Particularly the allowed region with co-annihilation channel is sensitive to θ value and for higher θ values with same Δ value there is lesser allowed region in the M_X and m_ψ plane.

The other important thing is that particularly with LHC constraint, in general there is some kind of lower bound on both M_X and m_ψ. As followed from our numerical analysis, after using the lower possible values corresponding to g_X M_X and m_ψ and using the tree level relationship for the mass of extra gauge boson, predicted by the model which connects $vevs$ of χ_1 and χ_2 (other scalars of the model) with mass of extra gauge boson M_X; we get an understanding and approxihigher than electroweak scale like Grand Unified Theory (GUT) scale or the Planck scale, where one expects new physics, where gravitational interactions could be unified along with other three interactions, such problem arises. At such high scale, very large quantum contributions to Higgs mass square is expected and this makes the mass huge in comparison to the new physics scale unless there is too much fine tuned cancellation between the bare mass and the quadratic radiative corrections. In the new theory of fundamental particles, one expects that the Higgs mass should be calculable without too much fine tuning. Many physicists think that supersymmetry could solve this problem. In supersymmetric extension of the Standard Model, there is natural cancellation of Higgs boson quadratic mass renormalization between bosonic and fermionic loops in the Feynman diagrams.

For addressing the dark matter problem in the beyond Standard Model scenario, we have considered a simple $U(1)$ extension to the SM, which presents an extra neutral gauge boson into the picture. All the charged lepton masses and active neutrino masses has been generated radiatively through the loop diagrams. There is a sterile neutrino also which can provide $3+1$ framework of neutrino mass matrix and then there is the possibility of active-sterile neutrino mixing. Besides, there are right-handed Majorana fermions present in the model - the lightest one among those, could be dark matter. In this thesis work, it has been shown that the extra gauge boson mass and dark matter mass are related with each other and the allowed region in the gauge boson mass and dark matter mass plane has been shown in different figures for different conditions on the lightest and next to lightest Majorana mation of the lower possible scale of extra $U(1)$ spontaneous symmetry breaking roughly of the order of 10 – 12 TeV. However, for higher values of M_X such specific conclusion is difficult to obtain because of multiple possible values of M_X, m_ψ and g_X in the allowed region.

In the extra $U(1)$ gauge extended model, while obtaining constraints on dark matter mass, we have considered zero $Z - X$ mixing at the tree level which implies the relationship of extra $U(1)$ charges as $n_1 = n_4$ (n_1 n_4, are the $U(1)_X$ charges corresponding to $(u, d)_L$ and $(\nu, e)_L$ respectively, and are discussed in detail in chapter 2 of the thesis). This consideration is important as then the model satisfies various phenomenological low energy constraints and as well as the the electroweak precision data. In this thesis work, it has also been shown that even if we consider higher order corrections to such tree level mixing, the changes are very insignificant and does not lead to any potential conflicts with experimental data. In future with the improvement on the constraint on extra $U(1)$ gauge boson mass and its gauge coupling from LHC experiments, the allowed region in M_X and m_ψ plane could be further reduced and the lower bounds on M_X and m_ψ could be further higher.

For dark matter or for inflation, reheating and leptogenesis, we have to consider some theoretical models beyond SM. However, the $U(1)$ gauge extended Scotogenic model considered for dark matter may be considered as an effective theory at much lower than Planck scale, rather nearer to the electroweak scale as required by the type of annihilation cross-sections of the dark matter. On the other hand, for inflation, reheating and leptogenesis, we have considered Supergravity embedded NMSSM, which could be relevant at much above electroweak scale, rather nearer to Planck scale, where unification of gravitational interactions with other known fundamental interactions could be envisioned.

Next, we study inflation , reheating and leptogenesis in the super gravity embedded non minimal supersymmetric standard model in the Type-I Seesaw scenario of generating small neutrino mass. To get small active neutrino masses around eV scale, if one try to avoid too small Yukawa couplings of neutrinos, the seesaw mechanism with heavy right handed neutrinos is preferred. In the Non-minimal extension of Minimal Supersymmetric Standard Model (NMSSM), there are singlet heavy right handed neutrinos which could explain the light neutrino mass with not too small Yukawa couplings of neutrinos with scalars. The sneutrinos which are scalars and superpartner of these heavy right handed neutrinos, could play the role of inflation and then the slow roll condition of inflation potential could be addressed. There is another cosmological problem: the observed baryonic asymmetry of the universe over antibaryons. One suitable mechanism which could address this problem is baryogenesis via leptogenesis through sphaleron transition. In leptogenesis, the leptonic asymmetry could be created from the out of equilibrium decays of heavy right-handed neutrinos and sneutrinos. In general, for successful leptogenesis with heavy right handed neutrinos requires the mass of such heavy neutrinos to be above 10^9 GeV. However, after inflation, large number of massive gravitinos may be produced and their decays could modify the abundance of light elements as observed. To avoid this problem, is controlled by lightest Right handed neutrino with mass M_1 and after numerically solving Boltzmann equations and taking into account various scattering processes, it is found that it could be in the approximate range of 10^6 to 10^8 GeV. In getting the Starobinsky like potential from V_F potential with D-flat direction for inflation, two Yukawa couplings Y_{22} and Y_{33} are required to be of almost same order. Then from seesaw relations of heavy right handed neutrino, it is found that the lightest active neutrino mass should be mainly related with M_3, while the other light neutrino mass which is slightly heavier than the earlier one, should mainly depend on M_2. While the heaviest one among three light neutrino masses should depend mainly on M_1.

The soft susy breaking A and B parameters have played role in leptogenesis. Using the non-thermal condition in soft leptogenesis, the out of equilibrium condition and also using the upper bound on reheating temperature, the allowed region in A and M_1 plane has been found. Using resonance condition in soft leptogenesis as well as the condition on reheating temperature, the constraint on B parameter has been obtained. Constraining these soft parameters could give us some understanding of the hidden sector spontaneous symmetry breaking in Supergravity as well as could signify the low-energy phenomenology of Non-minimal Supersymmetric Standard model.

the reheating temperature is required to be within 10^6 to 10^9 GeV. This gravitino problem could be circumvented if one considers soft-leptogenesis in which soft supersymmerty breaking terms in the Lagrangian are considered. In presence of these terms, heavy sneutrino and anti-sneutrino in the same supermultiplet will mix. Leptogenesis could occur below 10^9 GeV in which the asymmetry is generated from the decay of two mixed eigenstates of sneutrino and anti-sneutrino and the gravitino problem could be avoided. Thus heavy right handed neutrinos and sneutrinos could play role in successful inflation, reheating, leptogenesis as well as in the formation of light neutrino mass. In this work, we try to correlate all these issues and find out what kind of conditions on various parameters including Yukawa couplings of heavy right handed neutrinos and soft supersymmetry breaking parameters, are required to be satisfied.

For inflation an appropriate choice of no-scale Kähler potential results in Starobinsky like inflation from the F-term potential where the inflation occurs along a sneutrino-Higgs D-flat direction and gives appropriately different cosmological parameters as observed.

In Type-I Seesaw framework of active neutrino masses, the heavier two right-handed neutrino fields have been considered for inflation. In keeping the amplitude consistent with observation, the approximate mass scale for the heaviest right handed neutrino with mass M_3 is obtained around 10^{13} GeV. As the decay of second heaviest Right handed neutrino with mass M_2 has been considered for reheating, the mass scale of it is expected to be below 10^9 GeV which is several order below M_3. The leptonic asymmetry and the leptogenesis mechanism