Leptogenesis And Inflation\textsuperscript{a}

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In this talk, we studied the implication of the constraint on the reheating temperature coming from the gravitino problem on models of leptogenesis. We point out that in supersymmetric extensions of the standard model, all existing models of neutrino masses and leptogenesis, except the one with right-handed singlet neutrinos are ruled out for a large range of the gravitino mass.

Recent announcement of experimental indications\textsuperscript{1} for very small neutrino masses implies an extension of the standard model (SM) where the right-handed neutrinos and a mechanism to explain the smallness of the neutrino’s masses have to be included. In this talk, first, we review the different models of neutrino masses and leptogenesis. Secondly, we evaluate the effects of the SM gauge interaction on leptogenesis. Finally, we discuss the gravitino constraint on the reheating temperature and its implications for the neutrino masses and leptogenesis models.

1 Models of neutrino masses and leptogenesis

All the models of neutrino masses require existence of new heavy particles $H$ with a mass $M$ and lepton number violating interactions. At low energy this results in an effective dimension-5 operator $\mathcal{O} = h^2 \ell_L \ell_L \phi \phi$, where $\phi$ is the usual higgs doublet which gives masses to the quarks and charged leptons. $H$ could be a $SU(2)_L$ singlet or a triplet and it could be a fermion or a scalar, which gives four possible categories of models for neutrino masses. In the following, we briefly discuss the different classes of models:

Right handed neutrinos: The fermion content of the standard model is extended to include one right handed neutrinos ($N_{\alpha}$, $\alpha = 1, 2, 3$) per generation, which are singlets under the SM gauge group. The right handed neutrinos have Majorana masses and Yukawa couplings with other leptons. By

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the usual see-saw mechanism, the left-handed neutrinos get a small Majorana mass $M_\nu = -m_D D_R m_D$. The decay of $N_\alpha$ can generate the amount of lepton asymmetry of the universe if it satisfies the out-of-equilibrium condition,

$$\Gamma_{N_\alpha} \equiv \frac{h_i^{\alpha}}{8\pi} \frac{g_* T^2}{M_P l} \sqrt{g_*} T^2_a \approx H = 1.7 \sqrt{g_*} T^2_a$$

at $T = M_{N_\alpha}$, where $H$ is the Hubble constant, $g_*$ is the effective number of helicity states, $M_P$ is the Planck scale and $h_i^{\alpha}$, the Yukawa coupling of the neutrinos.

**Triplet higgs**: It is possible to extend the standard model to include $SU(2)_L$ triplet higgs scalar fields $(\xi_a \equiv (1, 3, -1), a = 1, 2$ two of them are required for $CP$ violation), whose relevant interactions are,

$$L = M_a \xi_a \phi + f_{ij} \xi_a \ell_i \ell_j + \mu \xi_a \phi \phi + h.c. \tag{1}$$

The triplet higgs acquires a very tiny $vev$, which gives a Majorana mass to the neutrinos. Lepton number violation comes from the decays of the triplet higgs, $\xi_a$. The one loop self-energy diagrams interfere with the tree level decays to give $CP$ violation. If $M_2 > M_1$ and $\xi_1$ decays away from thermal equilibrium, i.e., $\Gamma_1 < H$ at $T = M_1$, then a lepton asymmetry will be generated.

**Triplet Majorana fermions**: One can also extend the standard model to include a $SU(2)_L$ triplet fermions, whose large Majorana masses breaks lepton number. For all practical purposes they behave similar to those like the right-handed neutrinos and give neutrino masses through see-saw mechanism. Their decay can generate a lepton and hence baryon asymmetry of the universe.

**Radiative models**: It is possible to write down the effective dimension-5 operator with $SU(2)_L$ singlet field $(\chi_a \equiv (1, 1, -1), a = 1, 2$, two of these fields are required to get $CP$ violation) if there are at least two higgs doublets $(\phi_a, a = 1, 2)$. The neutrino masses originate from radiative diagrams and hence are naturally small. The relevant part of the Lagrangian for leptogenesis is given by

$$L = M_a \chi_\alpha \chi_a + f_{ij} \chi_\alpha \ell_i \ell_j + \mu \chi \phi_1 \phi_2 + h.c. \tag{2}$$

Among all the above four classes of models for neutrino masses, only models with a singlet right-handed neutrino does not have any standard model gauge interaction. In all the three other classes of models, the new particles whose interactions break lepton number, transform non-trivially under the standard model. We shall next study the consequences of the SM gauge interaction on leptogenesis.

### 2 SM gauge interaction and leptogenesis

For simplicity, we shall consider a couple of generic heavy scalar $H_a, a = 1, 2$, which couples to the standard model gauge bosons through gauge interactions.
In a supersymmetric model, the corresponding superpartner will have similar
gauge interactions with the gauginos and hence will suffer from the same problem.
For the generation of a lepton asymmetry of the universe we assume that
the relevant part of the lagrangian is similar to that of eqn(1). The generated
CP asymmetry is given by $\eta$. We shall also assume that $M_1^h < M_2^h$, so that
first $M_2^h$ decays and then the decay of $M_1^h$ generates the lepton asymmetry of
the universe. The evolution of lepton number ($n_L = n_\ell - n_{\ell c}$) is given by the
Boltzmann equation:

$$
Dn_L = \eta \Gamma_H [n_H - n_H^e] - \left( \frac{n_L}{n_\gamma} \right) ^2 n_H^e \Gamma_H - 2n_\gamma n_L \langle \sigma_L | v \rangle ,
$$

(3)

where, the operator $D \equiv \left[ \frac{d}{dt} + 3H \right]$; $n_H^e$ is the equilibrium distribution of $H_1$
given by $n_H^e = \frac{T M_2^h}{2 \pi K_2(M_2) \Gamma}$; $\Gamma_H$ is the thermally-averaged decay rate of $H_1$;
$n_\gamma$ is the photon density and $\langle \sigma_L | v \rangle$ is the thermally-averaged lepton number
violating scattering cross section. The number density ($n_H$) of $H_1$ satisfies the
Boltzmann equation,

$$
Dn_H = -\Gamma_H [n_H - n_H^e] + (n_H^2 - n_H^e^2) \langle \sigma_H | v \rangle .
$$

(4)

The second term on the right is the lepton number conserving thermally-averaged
$H_1^\dagger + H_1 \rightarrow W_L + W_L$ scattering cross section of the heavy particles $H_1$. The details of the computation can be found in ref(3). Here, we shall summarize the main results.

For our analysis we shall thus assume, $\gamma \Gamma_H(M_2^h = T) \ll 1$ at $T \sim M_1^h$ and
thus $\eta < 10^{-5}$. Taking the $SU(2)_L$ gauge coupling constant to be given by the
GUT coupling constant at the GUT scale, the effects of the SM gauge scattering are presented in figure 1. So, for the allowed value of $\eta \leq 10^{-5}$ the lowest possible $H_1^h$ mass for the generation of enough lepton asymmetry of the universe becomes $M_1^h > O(10^{12})$ GeV.

3 Gravitino problem and leptogenesis

We have to keep in mind that leptogenesis can occur only after the end of
inflation. In supersymmetric theories, the thermal production of massive gravitinos restricts the beginning of the radiation-dominated era following inflation except when the gravitino is very light. After the inflation a large number of gravitinos are produced, which interact very weakly. The late decays of unstable gravitinos can then modify the abundances of light elements causing inconsistency with observation. In the other hand, stable gravitinos may over-close the universe. This imposes a upper bound on the reheating temperature $T_{RH}$.

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Figure 1: Lepton asymmetry of the universe for different masses of $H_1$, when effects of gauge interaction is included. $R$ is defined as $R = \frac{(n_L/s)_{with}}{(n_L/s)_{without}}$ with $H_1^+H_1 \rightarrow W_L+W_L$ and $f = f_{h_{ij}}^h$.

In the case of stable gravitinos, a limit on the $T_{RH}$ can be derived from the closure limit of the universe:

$$T_{RH} \leq 10^{10} \text{ GeV} \times \left( \frac{m_{3/2}}{100 \text{ GeV}} \right) \times \left( \frac{1 \text{ TeV}}{m_{\tilde{g}}(\mu)} \right)^2$$

with $m_{3/2}$ is the mass of the gravitino and $m_{\tilde{g}}(\mu)$ is the running mass of the gluino. Essentially, one gets the following constraints from primordial nucleosynthesis:

$$T_{RH} \leq 10^9 \text{ GeV} \quad m_{3/2} < 1 \text{ TeV} \quad (6)$$

$$T_{RH} \leq 10^{12} \text{ GeV} \quad 1 \text{ TeV} < m_{3/2} < 5 \text{ TeV} \quad (7)$$

So, even for the stable gravitino, when the bound on the reheating temperature is given by eqn(6), it will not be possible to generate enough lepton asymmetry in these scenarios, where the lepton number violating particle have got standard model gauge interactions.

In summary, we point out that all the supersymmetric models of neutrino masses, except for the one with singlet right handed neutrinos and left-right symmetric models, may not be able to generate enough lepton asymmetry of the universe consistently with the gravitino bound on the reheating temperature in inflationary universe.
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