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Neutrino mass from neutrinophilic Higgs and leptogenesis

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In a class of two Higgs doublet model, where one Higgs doublet generates masses of quarks and charged leptons whereas the other Higgs doublet with a tiny vacuum expectation value(VEV) generates neutrino Dirac masses, smallness of neutrino masses might be understand as the consequence of the small second Higgs VEV. In this framework, thermal leptogenesis scenarios work well at low energy scale and have several advantages as follows. Under the assumption of hierarchical right-handed neutrino masses, the lightest right-handed neutrino can be as light as $\mathcal{O}(10^2)$ TeV. The required degeneracy for successful resonant leptogenesis also can be significantly reduced as small as $\mathcal{O}(10^4)$. Availability of low scale thermal leptogenesis provides a novel solution to gravitino problem in supergravity models.

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1 Introduction

Various experiments have confirmed that neutrinos have tiny masses. Smallness of the neutrino mass is one of the important questions in particle physics. Several approaches to address this question have been proposed. A new class of two Higgs doublet models (THDM) called "neutrinophilic Higgs doublet model", the vacuum expectation value (VEV) of the additional Higgs v_ν is of much smaller energy scale comparing to the SM Higgs doublet [1, 2, 3, 4, 5, 6], is also one of those candidates. Its various aspects such as phenomenology [7, 8, 9], vacuum structure [10], an extension to grand unification [11], astrophysical and cosmological implications [12, 13] have been intensively investigated. The idea of this class of models is that neutrino masses are much smaller than other fermion because those come from the different Higgs doublet with a smaller VEV, $v_\nu \ll v \simeq 246$ GeV. Masses of light neutrino are given by

$$m_{ij} = \sum_k \frac{y^\nu_{ik} v_\nu {y^\nu}^T_{kj} v_\nu}{M_k}, \tag{1}$$

with M_k being k-th right-handed Majorana neutrino mass. For $v_\nu \ll v$, neutrino masses can be small for relatively large neutrino Yukawa couplings y^ν and small right-handed neutrino masses M_k.

In modern cosmology and particle physics, one of important open problems is the origin of the baryon asymmetry in the Universe. Thermal leptogenesis [14] by heavy right-handed Majorana neutrinos for seesaw mechanism [15] is one of the most attractive scenarios for baryogenesis. The size of CP asymmetry in a right-handed neutrino decay is, roughly speaking, proportional to the mass of right-handed neutrino. For hierarchical mass spectrum of right-handed neutrino, the lightest right-handed neutrino mass must be larger than 10^8 GeV [16, 17].

Notice that neutrino Yukawa couplings in neutrinophilic Higgs doublet models do not need to be so small for lighter right-handed neutrinos. This fact has significant implication to leptogenesis. This opens new possibility of low scale thermal leptogenesis. Here, we will show that CP asymmetry is enhanced and thermal leptogenesis suitably works in multi-Higgs models with a neutrinophilic Higgs doublet [18].

The resonant leptogenesis scenario [19, 20] also has been known as a possibility of leptogenesis at low energy scale, say TeV scale, where the CP asymmetry is enhanced by a self energy of strongly degenerated right-handed neutrinos. However, we will show the masses of right-handed neutrinos can be reduced to 2 TeV and the required degeneracy becomes much milder as of order $\mathcal{O}(10^4)$ in the minimal neutrinophilic Higgs doublet model [21].

The realization of low scale thermal leptogenesis is attractive particularly in supersymmetric models, because of "gravitino problem" [22]. Hence, thermal leptogenesis at a low energy scale in a neutrinophilic Higgs doublet model offers a new solution to avoid gravitino problem [18, 23].

2 Minimal neutrinophilic THDM

Let us show the minimal neutrinophilic THDM model originally suggested by Ma [1]. In the model, one additional Higgs doublet Φ_ν, which gives only neutrino Dirac masses, besides the SM Higgs doublet Φ and a discrete Z_2-parity are introduced. Under the discrete symmetry, Yukawa interactions are given by

$$\mathcal{L}_{yukawa} = y^u \overline{Q}_L \Phi U_R + y^d \overline{Q}_L \tilde{\Phi} D_R + y^l \overline{L} \Phi E_R + y^\nu \overline{L} \Phi_\nu N + \frac{1}{2} M \overline{N^c} N + \text{h.c.} \tag{2}$$

where $\tilde{\Phi} = i\sigma_2 \Phi^*$, and we omit a generation index. Φ_ν only couples with a right-handed neutrino N by the Z_2-parity so that flavor changing neutral currents (FCNCs) are suppressed. The Higgs potential of the neutrinophilic THDM is given by

$$\begin{aligned} V^{\text{THDM}} &= m_\Phi^2 \Phi^\dagger \Phi + m_{\Phi_\nu}^2 \Phi_\nu^\dagger \Phi_\nu - m_3^2 \left(\Phi^\dagger \Phi_\nu + \Phi_\nu^\dagger \Phi \right) + \tfrac{\lambda_1}{2} (\Phi^\dagger \Phi)^2 + \tfrac{\lambda_2}{2} (\Phi_\nu^\dagger \Phi_\nu)^2 \\ &\quad + \lambda_3 (\Phi^\dagger \Phi)(\Phi_\nu^\dagger \Phi_\nu) + \lambda_4 (\Phi^\dagger \Phi_\nu)(\Phi_\nu^\dagger \Phi) + \tfrac{\lambda_5}{2} \left[(\Phi^\dagger \Phi_\nu)^2 + (\Phi_\nu^\dagger \Phi)^2 \right]. \end{aligned} \tag{3}$$

The Z_2-symmetry is softly broken by m_3^2.

3 Leptogenesis in neutrinophilic THDM

We consider leptogenesis in the neutrinophilic THDM with the extra Higgs doublet Φ_ν described in Sec. 2. Under hierarchical right-handed neutrino mass spectrum, the CP asymmetry,

$$\varepsilon \simeq -\frac{3}{16\pi} 10^{-6} \left(\frac{0.1\text{GeV}}{v_\nu} \right)^2 \left(\frac{M_1}{100\text{GeV}} \right) \left(\frac{m_\nu}{0.05\text{eV}} \right) \sin\delta, \tag{4}$$

is significantly enhanced for a light right-handed neutrinos due to the tiny Higgs VEV, v_ν . On the other hand, one should notice that, for lower v_ν, the $\Delta L = 2$ lepton number violating washout processes become more significant.

All conditions for successful thermal leptogenesis is presented in Fig. 1. The horizontal axis is the VEV of neutrino Higgs v_ν and the vertical axis is the mass of the lightest right-handed neutrino, M_1. In the red brown region, the out of equilibrium decay of lightest right-handed neutrino is not possible. In turquoise region, $\Delta L = 2$ lepton number violating washout effect is too strong. The red and green line are contours of the CP asymmetry of $\varepsilon = 10^{-6}$ and 10^{-7}, respectively. Thus, in the parameter region above the line of $\varepsilon = 10^{-7}$, thermal leptogenesis easily works even with hierarchical masses of right-handed neutrinos.

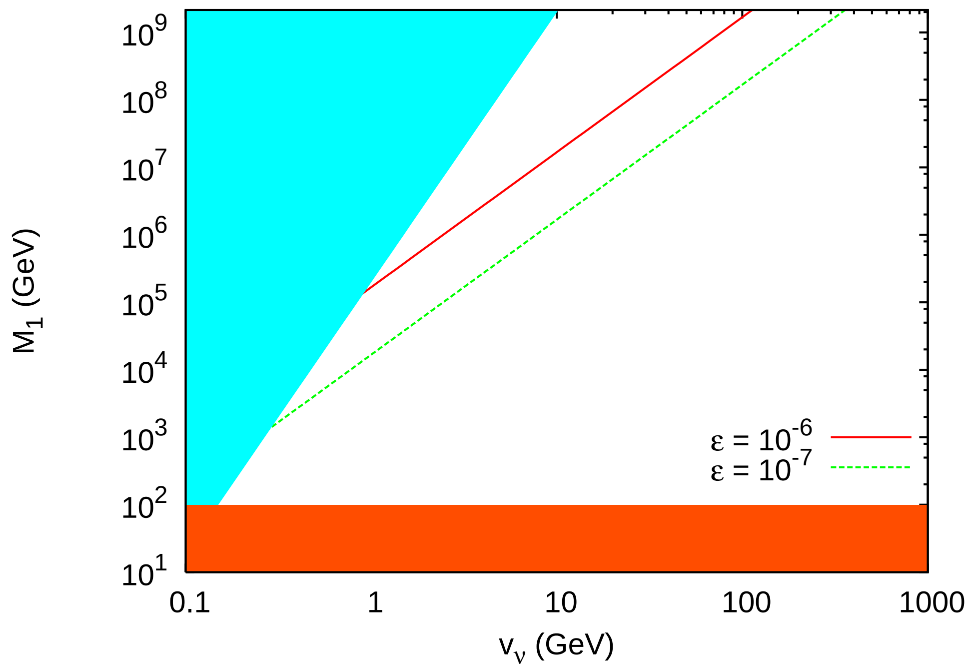

Figure 1: Available region for leptogenesis [18]. The horizontal axis is the VEV of neutrino Higgs v_ν and the vertical axis is the mass of the lightest right-handed neutrino M_1. In the red brown region, the lightest right-handed neutrino decay is kinematically forbidden. In turquoise region, $\Delta L = 2$ washout effect is too strong. The red and green line are contours of the CP asymmetry of $\varepsilon = 10^{-6}$ and 10^{-7}, respectively.

4 Resonant leptogenesis in neutrinophilic THDM

Next, let us consider resonant leptogenesis in the neutrinophilic THDM. When two right-handed neutrinos are degenerate, the CP asymmetry is approximately given by [19, 20]

$$\varepsilon_i \simeq \frac{\mathrm{Im}\,(y^{\nu\dagger} y^\nu)^2_{ij}}{(y^{\nu\dagger} y^\nu)_{ii}\,(y^{\nu\dagger} y^\nu)_{jj}} \frac{\widetilde{m}_j M_j}{8\pi v^2} \frac{M_i M_j}{M_i^2 - M_j^2}, \tag{5}$$

$$\widetilde{m}_i \equiv \frac{(y^{\nu\dagger} y^\nu)_{ii} v^2}{M_i}, \tag{6}$$

where the last factor expresses mass degeneracy of two right-handed neutrinos. For $M_1 < M_2$, here we define

$$d_N \equiv \frac{M_1 M_2}{M_2^2 - M_1^2}, \tag{7}$$

to parameterize the degree of degeneracy. In neutrinophilic Higgs model, v in Eq. (5) is replaced with $v_\nu \ll v$. Thus, from Eqs. (5) and (7), one can easily find a large enough CP asymmetry can be obtained for smaller d_N. Figure 2 shows that the minimum degeneracy d_N significantly reduces for larger y^ν, equivalently smaller v_ν.

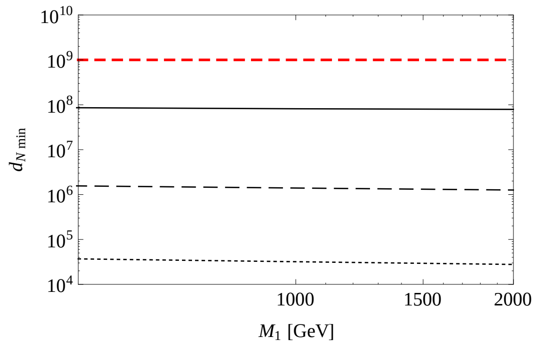

Figure 2: Required $d_{N\rm min}$ for $K_1 = 10^{-2}$ and its M_1 dependence. The solid, dashed and dotted lines correspond to $y_\nu = 10^{-6}, 10^{-5}$, and 10^{-4}, respectively. The red-thick-dashed line shows d_N for the standard resonant leptogenesis [21].

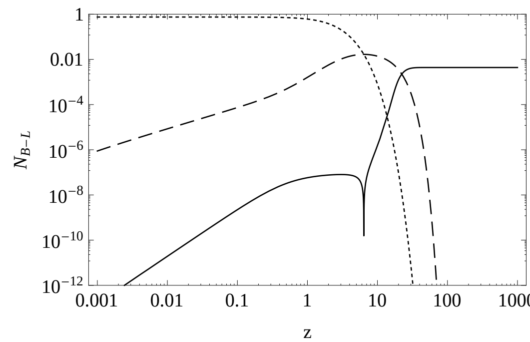

Figure 3: Time evolution of $B-L$ asymmetry N_{B-L} with $\varepsilon_1 = -1$, $M_1 = 2\,\mathrm{TeV}$, $y_\nu = 10^{-4}$, and $K_1 = 10^{-2}$ is shown by the solid line. For information, the dashed and dotted lines correspond to N_1 and N_2 abundance are also drawn [21].

Another consequence on resonant leptogenesis in neutrinophilic Higgs models is the enhancement of $\Delta L = 1$ washout effect. As mentioned above, small v_ν corresponds to large y^ν. Such large Yukawa couplings bring N_2 in thermal equilibrium. This means that N_2 is relatively abundant when N_1 decays, as seen in Fig. 3. As the results, the $\Delta L = 1$ washout effect by the scattering between light lepton and N_2 tends to be large. In order to suppress this $\Delta L = 1$ washout, in other words to reduce relative abundance of N_2 to N_1 after N_1 decay, we need to delay N_1 decay time, which corresponds to a small decay parameter

$$K_1 = \frac{\Gamma_{N_1}}{H(T = M_1)}, \tag{8}$$

with Γ_{N_1} being the decay width of N_1.

To generate lepton asymmetry by N_1 decay before the sphaleron process ceases at $T_{\rm sph} \simeq 100$ GeV, the mass of N_1 has to be somewhat heavier than $\mathcal{O}(100)$ GeV. Fig. 3 shows the evolution of the lepton asymmetry for $M_1 = 2$ TeV. In this case, the generation of the lepton asymmetry is completed at around $z = M_1/T \simeq 20$ and in time for the sphaleron transfer of the lepton asymmetry into the baryon asymmetry.

5 Leptogenesis in a supersymmetric neutrinophilic model

Construction of a supersymmetric model with Φ_ν is straightforward [18, 23]. By repeating the same analysis for leptogenesis in the previous section, we can find the availability of thermal leptogenesis and its results are summarized in Fig. 4. A sufficient CP violation $\varepsilon = \mathcal{O}(10^{-6})$ can be realized for $v_\nu = \mathcal{O}(1)$ GeV in the hierarchical right-handed neutrino with M_1 of $\mathcal{O}(10^5 - 10^6)$ GeV. This implies that the reheating temperature after inflation T_R of $\mathcal{O}(10^6)$ GeV is high enough to produce right-handed neutrinos by thermal scatterings. Thus, this class of model with $v_\nu = \mathcal{O}(1)$ GeV is a solution to compatible with thermal leptogenesis in gravity mediated supersymmetry breaking with unstable gravitino.

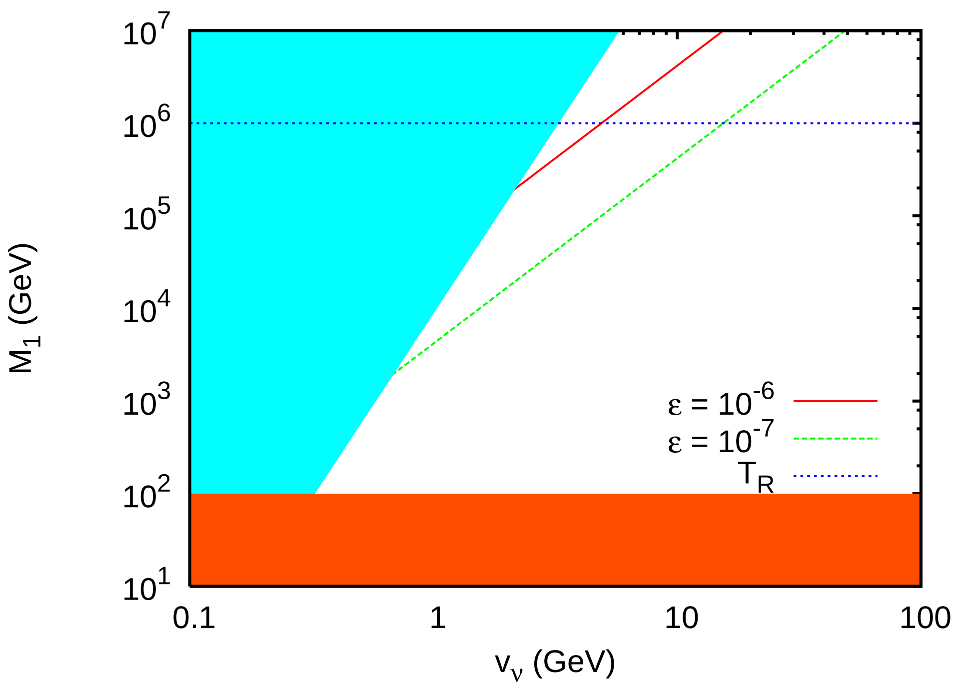

Figure 4: Available region for leptogenesis in a supersymmetric neutrinophilic model [23]. The blue dashed line denotes a reference value for the upper bound [24] of reheating temperature after inflation T_R.

6 Conclusion

We have examined the possibility of thermal leptogenesis in neutrinophilic Higgs doublet models. We have found the available parameter region of thermal leptogenesis where its washout effect is avoided as keeping the CP asymmetry large enough.

We have shown the resonant leptogenesis works by a few TeV mass right-handed neutrino in the neutrinophilic THDM, with the mass degeneracy being of the order of only $\mathcal{O}(10^4)$.

In a supersymmetric neutrinophilic Higgs doublet model, we have pointed out that thermal leptogenesis in supergravity works well at low energy by a light right-handed neutrino with the mass of $\mathcal{O}(10^5)$ GeV. Hence the scenario is free from gravitino problem.

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