Thermal Leptogenesis below the Davidson-Ibarra bound in an extended NMSSM model

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- Ref. (1) J. Phys. G32: L65-L68, 2006, [hep-ph/0603043]
- Ref. (2) J. Phys. G 34, 741 (2007), [hep-ph/0611257]

Outline of the talk

1. Neutrinos: The physics beyond Standard Model
2. Canonical seesaw model and thermal leptogenesis
3. Davidson-Ibarra bound on lightest RH neutrino
4. Gravitino bound on reheating temperature
5. Extended seesaw model and neutrino masses
6. Leptogenesis in the extended seesaw model
7. Evading DI-bound in an extended seesaw model
8. Summary and Conclusions

Neutrinos: The physics beyond Standard Model

- Within the Standard Model the neutrinos are massless. However, the present evidence suggests that the physical left handed neutrinos are massive and hence they mix up.
- The present neutrino oscillation experiments give the best fit values of the mass scales:

$$\Delta m_{atm} \equiv \sqrt{|m_3^2 - m_2^2|} \simeq 0.05eV$$

$$\Delta m_{\circ} \equiv \sqrt{m_2^2 - m_1^2} \simeq 0.009eV$$

- The best fit values of the mixing angles are given by: $\theta_{12} = \theta_{\circ} \simeq 34^{\circ}, \;\; \theta_{23} = \theta_{atm} \simeq 45^{\circ}, \;\; \theta_{13} \leq 10^{\circ}.$

Canonical seesaw model and neutrino masses

- In the minimal extension of the SM with three RH neutrinos the Lagrangian is given by

$$
\begin{aligned}
\mathcal{L} &= \overline{\ell_{Li}} i\gamma^\mu D_\mu \ell_{Li} + \overline{\ell_{Ri}} i\gamma^\mu \partial_\mu \ell_{Ri} + \overline{N_{R\alpha}} i\gamma^\mu \partial_\mu N_{R\alpha} \\
&- \left(\frac{1}{2} \overline{(N_{R\alpha})^c} (M_R)_{\alpha\beta} N_{R\beta} + \overline{\ell_{Li}} \phi (Y_e)_{ij} \ell_{Rj} \right. \\
&+ \left. \overline{\ell_{Li}} \tilde{\phi} (Y_\nu)_{i\alpha} N_{R\alpha} + H.C. \right) ,
\end{aligned}
$$

- After electroweak symmetry breaking neutrino Dirac mass matrix is given by $m_D = vY_\nu$.

Canonical seesaw model continued...

$$-\mathcal{L}_{mass} = \frac{1}{2}\begin{pmatrix} \overline{\nu}_L & \overline{(N_R)^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} (\nu_L)^c \\ N_R \end{pmatrix},$$

- The neutrino mass matrix is then given by

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

- M_ν can be diagonalised to get the physical states

$$\begin{pmatrix} \mathbf{N_1} \\ \mathbf{N_2} \end{pmatrix}_{\mathbf{R}} = \begin{pmatrix} \mathbf{1} & -\frac{\mathbf{m_D}}{\mathbf{M_R}} \\ \frac{\mathbf{m_D}}{\mathbf{M_R}} & \mathbf{1} \end{pmatrix} \begin{pmatrix} (\nu_\mathbf{L})^\mathbf{c} \\ \mathbf{N_R} \end{pmatrix},$$

Canonical seesaw model continued...

$$\begin{pmatrix} \mathbf{N_1} \\ \mathbf{N_2} \end{pmatrix}_{\mathbf{L}} = \begin{pmatrix} \mathbf{1} & -\frac{\mathbf{m_D}}{\mathbf{M_R}} \\ \frac{\mathbf{m_D}}{\mathbf{M_R}} & \mathbf{1} \end{pmatrix} \begin{pmatrix} (\nu_{\mathbf{L}}) \\ (\mathbf{N_R})^{\mathbf{c}} \end{pmatrix},$$

- where N_1 and N_2 are self conjugate Majorana states with

$$\begin{aligned} N_1 &= N_{1L} + N_{1R} \\ &= (\nu_L + (\nu_L)^c) - \frac{m_D}{M_R} (N_R + (N_R)^c) = (N_1)^c \\ &= \nu - \left(\frac{m_D}{M_R} \right) N \simeq \nu \end{aligned}$$

Canonical seesaw model continued...

$$
\begin{aligned}
N_2 &= N_{2L} + N_{2R} \\
&= (N_R + (N_R)^c) + \frac{m_D}{M_R}(\nu_L + (\nu_L)^c) = (N_2)^c \\
&= N + \left(\frac{m_D}{M_R}\right)\nu \simeq N
\end{aligned}
$$

with mass eigenvalues

$$
\mathbf{M_1 \equiv m_\nu \simeq -\frac{m_D^2}{M_R}} \quad \text{and} \quad \mathbf{M_2 \equiv M_N \simeq M_R}.
$$

m_ν is now see-saw suppressed and tiny.

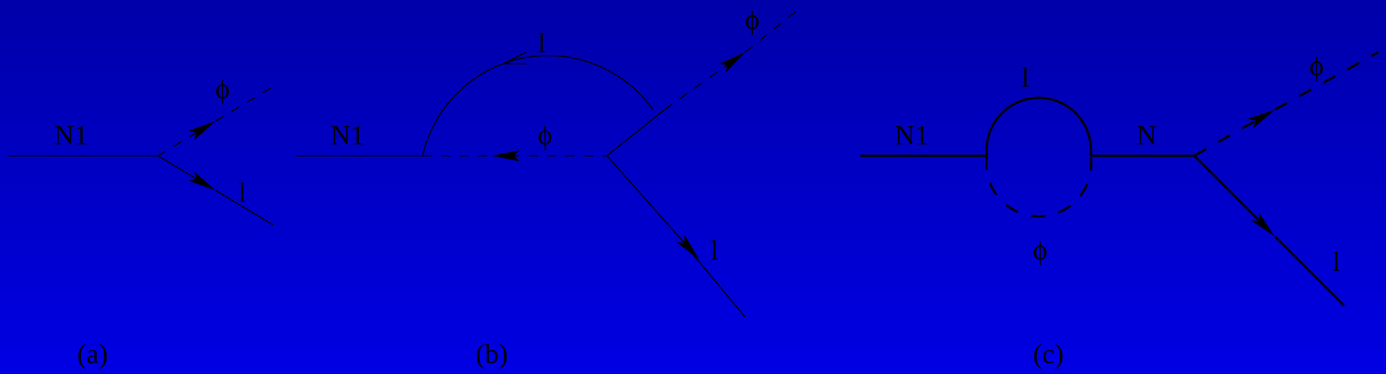
ν's are the observed light physical neutrinos.

Canonical leptogenesis and DI-bound on M_{N_1}

- The L-asymmetry arises from the decay of $N = \frac{1}{\sqrt{2}}(N_R + N_R^c)$

$$N \rightarrow \begin{cases} \bar{\ell}\phi \\ \ell\phi^\dagger \end{cases} \qquad \Delta L = 2$$

- The CP asymmetry arises from the interference of tree, one loop radiative correction and self-energy correction diagrams as follows:



Canonical leptogenesis and DI-bound on M_{N_1}

- Assuming a normal hierarchy in the right handed neutrino sector the CP asymmetry is given by

$$\epsilon_1 = \frac{\Gamma_i - \bar{\Gamma}_i}{\Gamma_i + \bar{\Gamma}_i} = \frac{3M_{N_1}}{16\pi v^2} \frac{\sum_{i,j} Im\left[(h^\dagger)_{1i}(m_\nu)_{ij}(h^*)_{j1}\right]}{(h^\dagger h)_{11}}$$

$$\epsilon^I_{1,max} = \frac{3M_{N_1}}{16\pi v^2}\sqrt{\Delta m^2_{atm}}$$

- From the observed B-asymmetry we can get a lower bound on the mass of N_1 to be

$$M_{N_1} \geq 3\times 10^9 GeV \left(\frac{n_B/n_\gamma}{6.1\times 10^{-10}}\right)\left(\frac{4\times 10^{-3}}{Y_{N_1}\delta}\right)\left(\frac{0.05eV}{\sqrt{\Delta m^2_{atm}}}\right)$$

- The DI-bound remain unchanged even if the underlying theory of matter is supersymmetric.
- It is believed that the Universe has gone through a period of inflation and then reheated to a maximum temperature $T_{reh} = 10^{6-9}$ GeV.
- This implies that the thermal production of right handed neutrinos with mass scale $> O(10^9)$ GeV is very much unlikely and hence thermal leptogenesis is impossible.
- We solve this problem by adding an extra singlet to the canonical seesaw model.

Extended NMSSM model and neutrino masses

- We start with the NMSSM model, which includes a singlet superfield χ in addition to the usual particles of the Minimal Supersymmetric Standard Model (MSSM).
- To implement the seesaw mechanism, we also include three right-handed neutrinos $N_i,\ i = 1, 2, 3$.
- We include another singlet superfield S and impose a $Z_2 \times Z_2'$ discrete symmetry. Under Z_2, the lepton superfields L_i, l_i^c, N_i, S are odd, whereas the Higgs superfields $\phi_{1,2}, \chi$ are even. This corresponds to having an exactly conserved lepton number $(-1)^L$, or the usual $R-$parity of the MSSM.
- Under Z_2', S is odd and all others are even, but Z_2' is allowed to be broken softly.

Extended NMSSM model and neutrino masses

- The most general superpotential invariant under $Z_2 \times Z_2'$ is then given by

$$W = h^e_{ij} L_i l^c_j \phi_1 + h_{ij} L_i N_j \phi_2 + \mu \phi_1 \phi_2 + M_{ij} N_i N_j + M_\chi \chi \chi + \alpha \chi \chi \chi + \beta \chi \phi_1 \phi_2 + f_N \chi N_i N_j + M_S S S + f_S \chi S S.$$

- We now break Z_2' softly and the only possible such term is

$$W_s = d_i N_i S,$$

Extended NMSSM model and neutrino masses

- This allows S to mix with N_i to form a 7×7 mass matrix in the basis $[L_i \;\; N_i \;\; S]$, i.e.

$$\mathcal{M} = \begin{pmatrix} \mathbf{0} & m_D & 0 \\ m_D & M_N & d \\ 0 & d & M_S \end{pmatrix}$$

- For small $d_i/(M_i - M_S)$ as well as the usual seesaw assumption the heavy states are given by

$$\begin{aligned} M_{S'} &\simeq M_S - \sum_i \frac{d_i^2}{M_i - M_S} \simeq M_S \\ M_{N_i'} &\simeq M_i + \frac{d^2}{M_i - M_S} \simeq M_N \end{aligned}$$

Extended NMSSM model and neutrino masses

- The light neutrino mass matrix is then given by

$$(m_\nu)_{ij} \simeq -\sum_k (m_D)_{ik} \left(M_k + \frac{d_k^2}{M_k - M_S} \right)^{-1} (m_D)_{kj}$$

- In this model, the addition of S allows the choice $M_S < M_1$ since for small d/M_N, M_S is not constrained by the low energy neutrino oscillation data.
- The out-of-equilibrium decay of S can occur much below the mass scale of right handed neutrino and hence can produce the required lepton asymmetry even if the rehating temperature is 10^{6-9} GeV.

Thermal leptogenesis in the extended NMSSM model

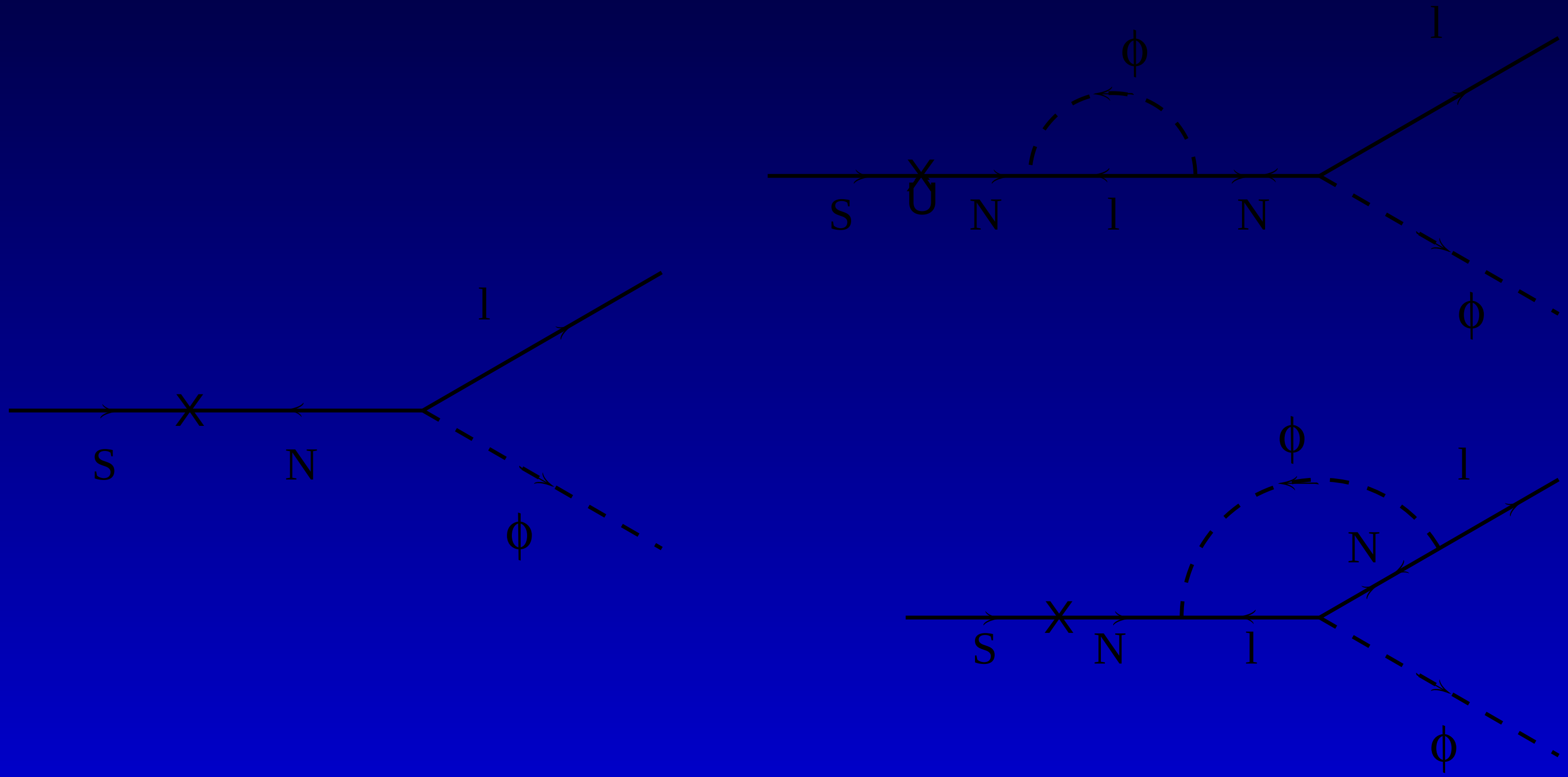


Figure 1: Tree-level and one-loop (self-energy and vertex) diagrams for S decay, which interfere to generate a lepton asymmetry.

Thermal leptogenesis in the extended NMSSM model

$$\Gamma_D^S = \frac{1}{8\pi v^2} M_S \sum_i \left[\tilde{m}_i M_i (d_i/M_i)^2\right]$$
$$\simeq \frac{1}{8\pi v^2} M_S \tilde{m}_3 M_3 (d_3/M_3)^2$$

- where $\tilde{m}_i = \frac{(m_D^\dagger m_D)_{ii}}{M_i}$
- The CP asymmetry is given by

$$\epsilon_S = \frac{\Gamma_i - \bar{\Gamma}_i}{\Gamma_i + \bar{\Gamma}_i} \simeq -\frac{3}{8\pi v^2}\left(\frac{M_S}{M_2}\right)\frac{Im[(m_D^\dagger m_D)_{12}]^2}{(m_D^\dagger m_D)_{11}}$$

- The suppression factor is thus given by

$$\eta = \left(\frac{d_3^2}{M_3 M_S}\right)\left(\frac{\tilde{m}_3}{\tilde{m}_1}\right) \equiv \kappa \left(\frac{\tilde{m}_3}{\tilde{m}_1}\right)$$

Thermal leptogenesis in the extended NMSSM model

- In this model S is produced through the decay of χ. Once the S particles are produced they decay through the lepton number violating channel:

$$S \rightarrow \begin{cases} \bar{\ell}\phi \\ \ell\phi^{\dagger} \end{cases} \qquad \Delta L = 2$$

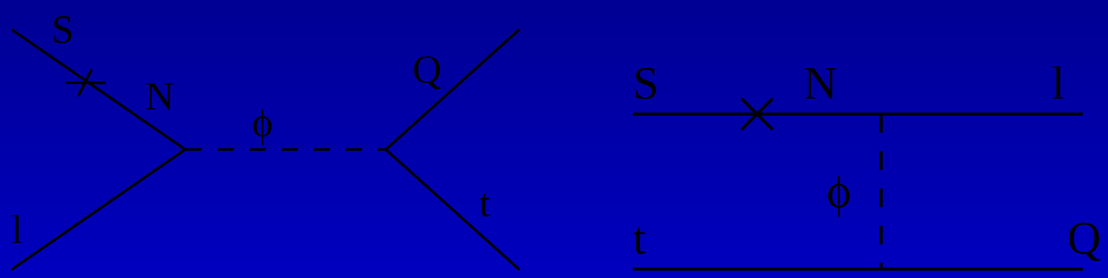


Figure 2: $\Delta L = \pm 1$ processes which deplete the number density of S. These processes also deplete the net lepton number density produced through the decay channel.

Thermal leptogenesis in the extended NMSSM model

- The required Boltzmann equations are given as

$$\frac{dY_S}{dz} = -\left(Y_S - Y_S^{eq}\right)\left[\frac{\Gamma_D^S}{zH(z)} + \frac{\Gamma_s^S}{zH(z)}\right]$$

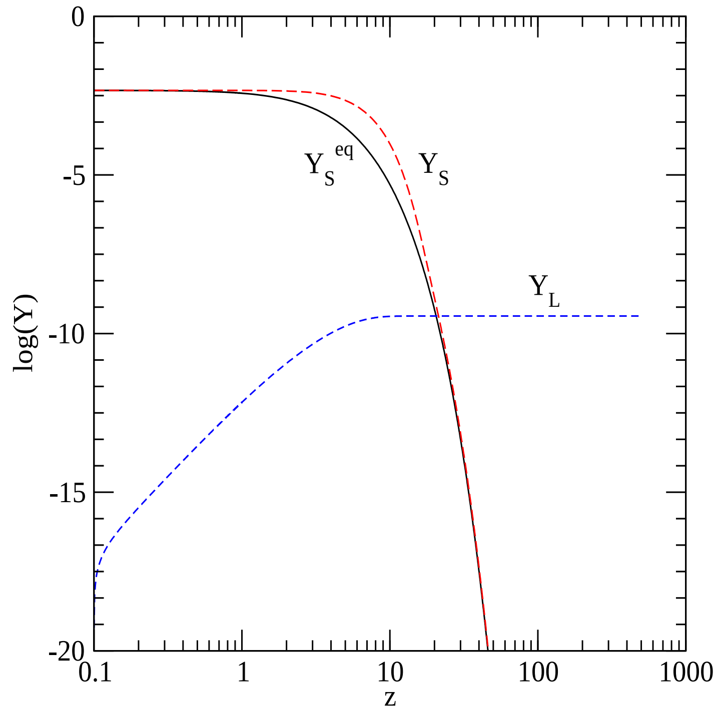
  and

$$\frac{dY_L}{dz} = \epsilon_S \frac{\Gamma_D^S}{zH(z)}\left(Y_S - Y_S^{eq}\right) - \frac{\Gamma_W^\ell}{zH(z)} Y_L$$

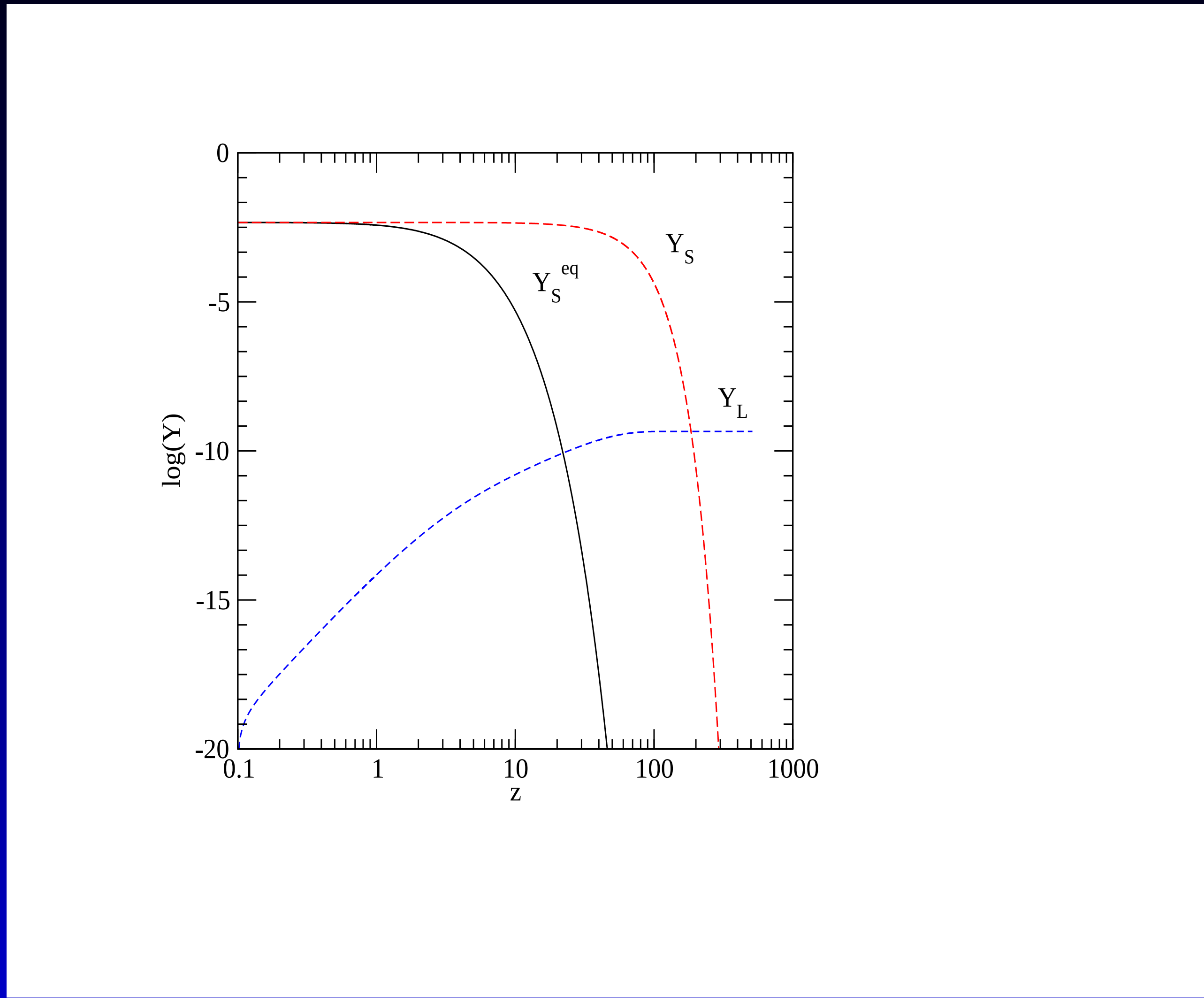
  where $z = M_S/T$, Γ_D^S, Γ_s^S and Γ_W^ℓ simultaneously represent the decay, scattering and wash out rates that takepart in establishing a net lepton asymmetry in a thermal plasma.

- We solve the above Boltzmann equations with the initial conditions:

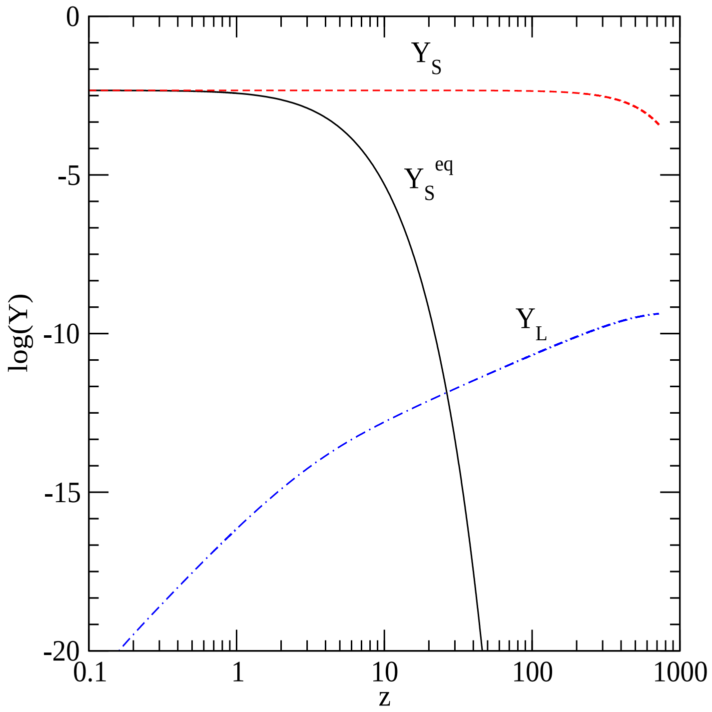
$$Y_S = Y_S^{eq} \quad \text{and} \quad Y_L = 0 \quad \text{at} \quad z \rightarrow 0\,. \tag{1}$$



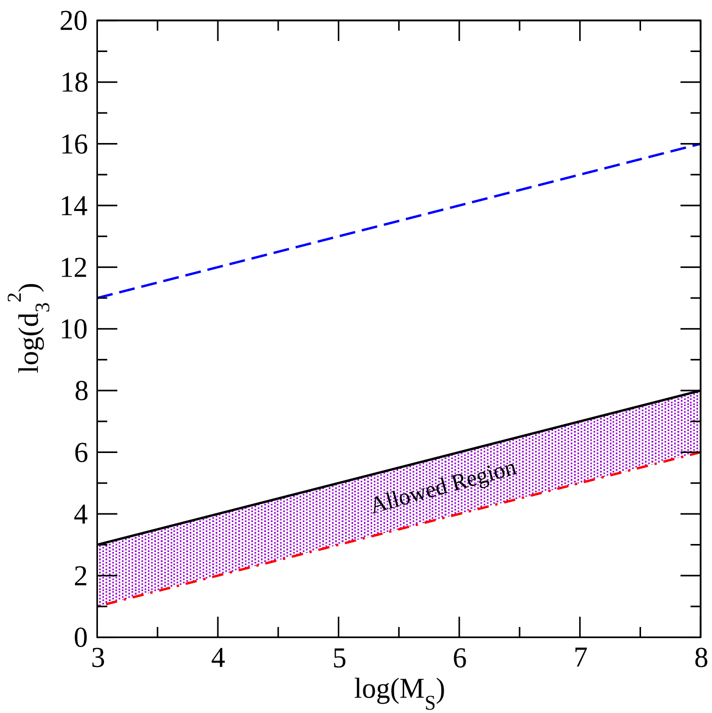
The evolution of S is shown against z with $M_S = 10^8$ GeV, $M_1 = 10^9$ GeV, $M_3 = 10^{10}$ GeV and $d_3 = 10^8$ GeV and the CP asymmetry parameter is $\epsilon_S = 10^{-7}$.



The evolution of S is shown against z with $M_S = 10^8$ GeV, $M_1 = 10^9$ GeV, $M_3 = 10^{10}$ GeV and $d_3 = 10^7$ GeV and the CP asymmetry parameter is $\epsilon_S = 10^{-7}$.



The evolution of S is shown against z with $M_S = 10^8$ GeV, $M_1 = 10^9$ GeV, $M_3 = 10^{10}$ GeV and $d_3 = 10^6$ GeV and the CP asymmetry parameter is $\epsilon_S = 10^{-7}$.



The allowed values of M_S are shown in the plane of d_3^2 versus M_S.

Summary and conclusions

- By adding a singlet field in the extended NMSSM model the scale of leptogenesis can be reduced up to 10^3 GeV which is not possible in canonical leptogenesis models with three RH neutrinos.
- The singlet is copiously produced from the decay of a scalar which doesn't takepart in building the lepton asymmetry.
- This generic mechanism is applicable to any supersymmetric model to achieve a low scale leptogenesis.

Thank You