

# Lepton Asymmetries and Their Evolution in E6SSM

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# Outline

- 1 The BAU problem and the Framework of leptogenesis
- 2 The E6SSM
- 3 Leptogenesis in the E6SSM
- 4 Result of lepton asymmetries
- 5 Flavoured Boltzmann Equations
- 6 Summary

# The Baryon Asymmetry of Universe

Matter is dominant over anti-matter in the present Universe

WMAP's result:

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.1 \pm 0.3) \times 10^{-10}$$

need to be explained.....

- Ingredients in Leptogenesis

- ▶ Majorana RH neutrino mass (violating  $L$ )  
+ Sphaleron process (violating  $B + L$ , conserving  $B - L$ )
- ▶ Complexity of Yukawa couplings
- ▶ Out-of-thermal processes

- The Lagrangian of SM + RH neutrinos

$$\mathcal{L} = \mathcal{L}_{SM} + h_{ik} \bar{N}_{Ri} \ell_{Lk} H - \frac{1}{2} M_{Nij} N_{Ri} N_{Rj} + h.c.$$

- Seesaw Mechanism

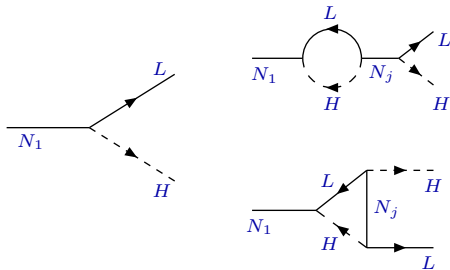
$$m_\nu = hh^T \frac{v^2}{M_R}$$

$M_R \sim 10^{14} \text{ GeV}$  to explain  $m_\nu \sim 10^{-1} \text{ eV}$  [Mohapatra. 1980]

# CP Asymmetry in Leptogenesis

- The Majorana nature of RH neutrino allows it to decay into both lepton and anti-lepton. The ratio is the same at tree level, but small differences arise at loop level [Yanagida. 86]

$$\epsilon_{i,\ell_k} \equiv \frac{\Gamma_{N_i \rightarrow \ell_k + H} - \Gamma_{N_i \rightarrow \bar{\ell}_k + H^*}}{\Gamma_{total}}$$



- We are interested in the asymmetry induced by the lightest RH neutrino  $\epsilon_1$ . In non-susy models,

$$\epsilon_{1,\ell_k} = -\frac{1}{8\pi} \sum_{j=2,3} \frac{\text{Im}[(h^\dagger h)_{1j} h_{1k}^\dagger h_{kj}]}{(h^\dagger h)_{11}} \left[ f_V \left( \frac{M_j^2}{M_1^2} \right) + f_S \left( \frac{M_j^2}{M_1^2} \right) \right]$$

where  $f_V(x) = \sqrt{x} \left[ -1 + (x+1) \ln \left( 1 + \frac{1}{x} \right) \right]$ ,  $f_S(x) = \frac{\sqrt{x}}{x-1}$ .

- In the case of  $M_1 \ll M_{2,3}$ , it can be written as

$$\epsilon_{1,\ell_k} = -\frac{1}{4\pi} \sum_{j=2,3} \frac{\text{Im}[(h^\dagger h)_{1j} h_{1k}^\dagger h_{kj}]}{(h^\dagger h)_{11}} \frac{M_1}{M_j}$$

# $E_6$ SSM

Exceptional Supersymmetric Standard Model ( $E_6$ SSM) [King, 06] is based on

$$SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_N,$$

a subgroup of  $E_6$ , where

$$\begin{aligned} E_6 &\rightarrow SO(10) \times U(1)_\chi, \\ SO(10) &\rightarrow SU(5) \times U(1)_\psi \end{aligned}$$

$$U(1)_N = \frac{1}{4}U(1)_\chi + \frac{\sqrt{15}}{4}U(1)_\psi$$

## Particle content of $E_6$ SSM

- 3 generations of the 27 fundamental representation of  $E_6$ .  $\Rightarrow$  anomalies cancelation.

$$Q_{Li} \quad L_{Li} \quad u_{Ri} \quad d_{Ri} \quad e_{Ri} \quad N_i \quad H_{1i} \quad H_{2i} \quad S_i \quad D_i \quad \bar{D}_i$$

with  $i$  the family index.

- Besides 27, extra fields with one generation  $\Rightarrow$  gauge unification

$$L_4, \bar{L}_4$$

# $E_6$ SSM

- $Z_2^H$  symmetry  $\Rightarrow$  suppress the proton decay and FCNC
  - ▶ Odd for all fields, except  $H_d \equiv H_{1,3}$ ,  $H_u \equiv H_{2,3}$  and  $S \equiv S_3$

$$\begin{aligned}
 W_{E_6SSM} \simeq & \lambda_i S(H_{1i}H_{2i}) + \kappa_i S(D_i\bar{D}_i) + f_{\alpha\beta}(H_d H_{2\alpha})S_\beta + \tilde{f}_{\alpha\beta}(H_{1\alpha}H_u)S_\beta \\
 & + h_{ij}^U(H_u Q_i)u_j^c + h_{ij}^D(H_d Q_i)d_j^c + h_{ij}^E(H_d L_i)e_j^c + h_{ij}^N(H_u L_i)N_j^c \\
 & + \frac{1}{2}M_{ij}N_i^c N_j^c + \mu'(L_4\bar{L}_4) + h_{4j}^E(H_d L_4)e_j^c + h_{4j}^N(H_u L_4)N_j^c
 \end{aligned}$$

$L_4$  has one lepton number.

- The breaking of  $Z_2^H$  gives extra terms in the superpotential:

$$W_N = \xi_{\alpha ij}(H_{2\alpha}L_i)N_j^c + \xi_{\alpha 4j}(H_{2\alpha}L_4)N_j^c$$

- ▶ Model I,  $D$  - diquark

$$W_1 = g_{ijk}^Q D_i (Q_j Q_k) + g_{ijk}^q \bar{D}_i d_j^c u_k^c$$

- ▶ Model II,  $D$  - leptoquark

$$W_2 = g_{kij}^N D_k d_i^c N_j^c + g_{kij}^E D_k u_i^c e_j^c + g_{ijk}^D (Q_i L_j) \bar{D}_k$$

- The superpotential of interactions of RH neutrinos can be rewritten with compact notations:

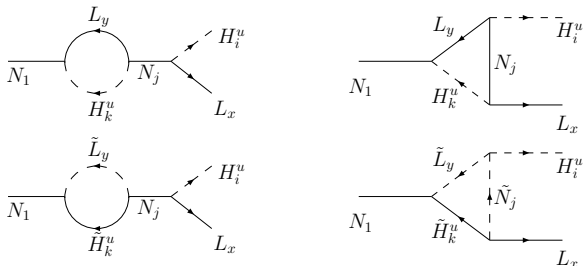
$$W_N = h_{kxj}^N (H_k^u L_x) N_j^c + g_{kij}^N D_k d_i^c N_j^c$$

where  $x = 1, 2, 3, 4$ ,  $k, i, j = 1, 2, 3$

# CP Asymmetry in $E_6SSM$ , $Z_2^H$ conserved case

- New contributions to  $N_1$  decay in the case of conserved  $Z_2^H$  :

$$N_1 \rightarrow L_x + H_k^u, \quad N_1 \rightarrow \tilde{L}_x + \tilde{H}_k^u, \quad \tilde{N}_1 \rightarrow \tilde{L}_x + \tilde{H}_k^u, \quad \tilde{N}_1 \rightarrow \tilde{L}_x + H_k^u$$



Here  $x, y = 1, 2, 3, 4$  and  $i, k = 3$ , representing the Higgs in the SM.

- $Z_2^H$  conserved case, distributed in  $L_x$  and ordinary leptons respectively

$$\varepsilon_{1, \ell_x}^3 \simeq -\frac{3}{8\pi} \sum_{j=2,3} \frac{\text{Im} \left[ (h^{N^\dagger} h^N)_{1j} h_{x1}^{N*} h_{xj}^N \right]}{(h^{N^\dagger} h^N)_{11}} \frac{M_1}{M_j}$$

## CP Asymmetry in $E_6SSM$ , $Z_2^H$ violating case (model I)

- In  $Z_2^H$  symmetry violating case (Model I), the 1st and 2nd generations of Higgs are considered ( $k = 1, 2, 3$ ).

$$N_1 \rightarrow L_x + H_k^u, \quad \tilde{N}_1 \rightarrow \tilde{L}_x + \tilde{H}_k^u, \quad \tilde{N}_1 \rightarrow \tilde{L}_x + \tilde{H}_k^u, \quad \tilde{N}_1 \rightarrow \tilde{L}_x + H_k^u$$

- Similarly, one-loop calculation gives CP asymmetries of different final states:

$$\begin{aligned} \varepsilon_{1, \ell_x}^k = \varepsilon_{1, \tilde{\ell}_x}^k = \varepsilon_{\tilde{1}, \ell_x}^k = \varepsilon_{\tilde{1}, \tilde{\ell}_x}^k = \frac{1}{8\pi A_1} \sum_{j=2,3} \text{Im} \left\{ 2 A_j h_{kx1}^{N*} h_{kxj}^N \frac{M_1}{M_j} \right. \\ \left. + \sum_{m,y} h_{my1}^{N*} h_{mxj}^N h_{kyj}^N h_{kx1}^{N*} \frac{M_1}{M_j} \right\} \end{aligned}$$

where  $A_j = \sum_{m,y} h_{my1}^{N*} h_{mxy}^N$  and  $x, y = 1, 2, 3, 4$ ,  $i, k = 1, 2, 3$ .



# Lepton Asymmetry in Constrained Sequential Dominance of See-saw model

- In the basis where RH neutrino mass matrix is diagonal and LH neutrinos in ew eigenstates.

$$M_N = \begin{pmatrix} M_A & 0 & 0 \\ 0 & M_B & 0 \\ 0 & 0 & M_C \end{pmatrix} \quad h^N = \begin{pmatrix} A_1 & B_1 & C_1 \\ A_2 & B_2 & C_2 \\ A_3 & B_3 & C_3 \end{pmatrix}$$

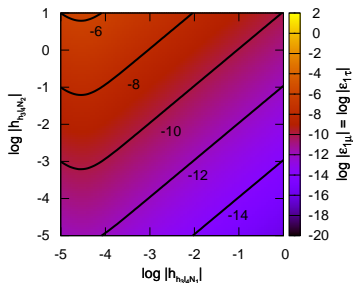
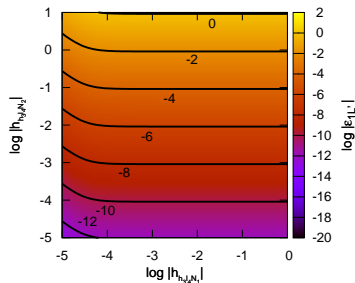
- It is natural to assume  $\frac{|A_i A_j|}{M_A} \gg \frac{|B_i B_j|}{M_B} \gg \frac{|C_i C_j|}{M_C}$ , in the case of strong-hierarchy of RH neutrino masses. And  $|A_1| \ll |A_{2,3}|$
- The LH neutrino masses from see-saw model:

$$m_3 \simeq \frac{(|A_2|^2 + |A_3|^2)v^2}{M_A}, \quad m_2 \simeq \frac{|B_1|^2 v^2}{s_{12}^2 M_B}, \quad m_1 \simeq \mathcal{O}\left(\frac{|C|^2 v^2}{M_C}\right)$$

where  $v$  is the vev of Higgs potential, and  $s_{12} \equiv \sin \theta_{12} \sim \sqrt{1/3}$

- For  $m_1 \ll m_2 \ll m_3$ , LH neutrino masses can be determined:  $m_1 \sim 0$ ,  $m_2 \simeq 8.7 \times 10^{-3} eV$ ,  $m_3 \simeq 4.9 \times 10^{-2} eV$ . Then Yukawa couplings depend on RH neutrino mass  $M_{A,B}$ .

# Lepton Asymmetry with $L_4$



- Lepton asymmetries versus leptoquark couplings in  $E_6SSM Z_2$  conserved case
- We take  $M_1 = 10^6 GeV$ , and  $M_2 = 10M_1$ .
- Lepton asymmetries are expected to be  $\sim 10^{-4} - 10^{-6}$ , to generate right amount of baryon asymmetry.

# Boltzman Equations in SM+N

The evolution of flavoured lepton asymmetries is described by a set of Boltzmann Equations.

$$\frac{dY_{N_1}}{dz} = \frac{-z}{sH(M_1)} (\gamma_D + \gamma_{S,\Delta L=1,2}) \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right),$$
$$\frac{dY_{\Delta\alpha}}{dz} = \frac{-z}{sH(M_1)} \left[ \epsilon_\alpha (\gamma_D + \gamma_{S,\Delta L=1}) \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) - \left( \frac{\gamma_D^\alpha}{2} + \gamma_{W,\Delta L=1,2}^\alpha \right) \frac{\sum_\beta A_{\alpha\beta} Y_{\Delta\beta}}{Y_\ell^{eq}} \right].$$

- $Y_{\Delta\alpha} \equiv Y_{B/3} - Y_{L_\alpha}$  and  $Y_{N_1}$  are the density of  $B - L_\alpha$  and  $N_1$  respectively.
- $\gamma_D$ ,  $\gamma_{S,\Delta L=1,2}$ ,  $\gamma_{W,\Delta L=1,2}$  are the thermally averaged reaction density for RH neutrino decay,  $\Delta L = 1, 2$  scatterings and wash-out processes.
- $z \equiv M_1/T$  is a dimensionless parameter.
- Matrix  $A_{\alpha\beta}$  is the transition matrix between leptonic flavours.

Number density of particle in equilibrium:

$$Y_\ell^{eq} = \frac{45}{\pi^4 g_*}, \quad Y_{N_1}^{eq} = \frac{45}{2\pi^4 g_*} z^2 K_2(z).$$

where  $K_2(z)$  is the modified Bessel function.

# Why Flavoured Boltzmann Equations?

## Processes involved in generating Lepton/Baryon Asymmetries.

- $SU(2)$  electro-weak instanton process (left-handed leptons  $\leftrightarrow$  left-handed quarks)
  - $SU(3)$  QCD instanton process (left-handed quarks  $\leftrightarrow$  right-handed quarks)
  - Yukawa interactions ( $\ell_i \leftrightarrow H + e_j$ )
- 
- The Yukawa interactions in thermal equilibrium (if  $\gamma > H(z)$ ) for some lepton flavours e.g.  $\tau$ , at some temperature, whereas some may not e.g.  $e$
  - The ratio of particles in equilibrium can be calculated from the chemical potential relation of these processes, represented in the flavour transition matrix in Boltzmann Equations  $A_{\alpha\beta}$

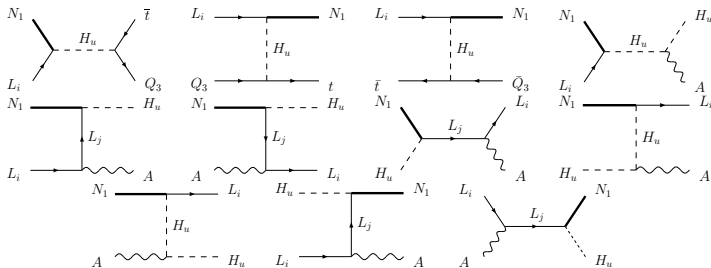
# Wash-out Processes

The lepton asymmetries generated by RH neutrino decay and simultaneously (partially, we hope) washed-out by inversed decays and scatterings.

- $\Delta L = 2$  scatterings  $LH \rightarrow \bar{L}\bar{H}$  and  $LL \rightarrow \bar{H}\bar{H}$



- $\Delta L = 1$  scatterings with top quark  $N_1 L \rightarrow Q_3 \bar{t}$  and  $LQ_3 \rightarrow N_1 t$ ,  $Lt \rightarrow N_1 Q_3$   
with gauge bosons:  $N_1 \bar{L} \rightarrow HA$ ,  $LH \rightarrow N_1 A$ ,  $\bar{L}A \rightarrow N_1 H$



# Numerical result of Boltzmann equations without scattering terms<sup>1</sup>

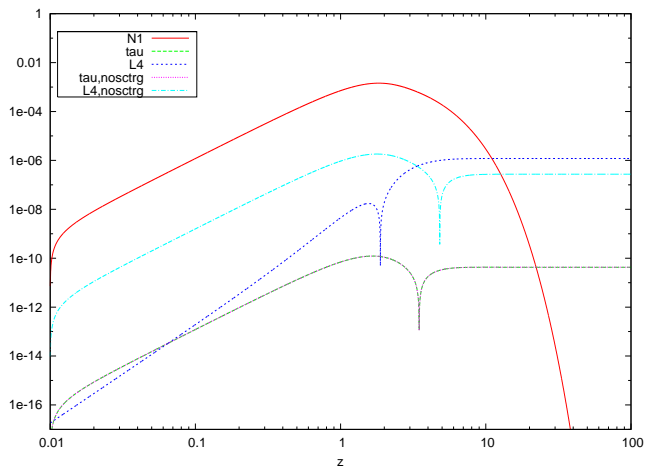


Figure: Evolution of  $N_1$ ,  $\tau$  and  $L_4$ , when  $h_{41} = 10^5$ ,  $h_{42} = 1$

<sup>1</sup>work in progress with Stefan Antusch, Steve King, David Miller, and Roman Nevzorov

# Summary

- Leptogenesis provides an elegant explanation to BAU.
- $E_6SSM$
- New contribution of  $CP$  asymmetry from  $E_6SSM$
- Result in the Sequential Dominance scenario
- Lepton Asymmetries can be enhanced drastically.
- Boltzmann equations is going to be solved for Baryon asymmetry.

## To complete Boltzmann Equations

- 1 The transition matrix  $A_{\alpha\beta}$  with  $L_4$ .
- 2 Numerical result.