# Tree level soft leptogenesis in NMSSM

**Abhijit Kumar Saha**
PRL, Ahmedabad, India

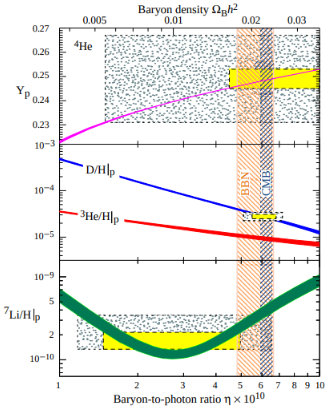
Conference: Anomalies 2020, IIT Hyderabad

# Baryogenesis

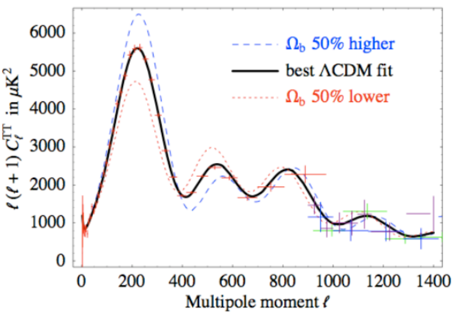
- We have not observed clusters of antimatter within the solar system.
- Baryon to photon ratio: $5.7 \times 10^{-10} \lesssim \eta \lesssim 6.7 \times 10^{-10}$.

K.A. Olive et al., Review of Particle Physics. Chin.Phys. C, 2014

Katherine Garrett and Gintaras Duda. 2011 Dark Matter: A Primer. Adv.Astron




(CMB temperature fluctuations)



# Condition for Baryogenesis

- Baryon number violation.
- C-symmetry and CP-symmetry violation.
- Interactions out of thermal equilibrium.

In SM, Sakharov's conditions are satisfied, the baryon asymmetry of the Universe could be created during the electroweak phase transition.

Unfortunately, it has been shown that the amount of CP violation coupled with the strength of a first order phase transition is not sufficient to create enough baryon asymmetry in the SM

# Different versions of leptogenesis scenario

## Non SUSY framework

- Leptogenesis in type I-II seesaw Davidson and Ibara Phys.Lett.B 535 (2002)
  R G Felipe etc. IJMPA 28 (2013)
- Resonant leptogenesis A Pilaftsis NPB 692 (2004)
- Leptogenesis from scalar decay etc. P Konar,.., AKS et al 2007.15608

## SUSY framework

- Affleck Dine Leptogenesis I. Affleck and M. Dine, Nucl. Phys. B 249, 361 (1985)
- Dirac leptogenesis B Thomas et al. 0712.4134
- Soft leptogenesis

# Soft leptogenesis in MSSM

. D'Ambrosio, G. F. Giudice, and M. Raidal, Phys. Lett. B (2003)

## The supersymmetric see-saw model

$$W = Y_{ij} L_i L_j H + \frac{1}{2} M_{ij} N_i N_j.$$

The supersymmetry-breaking terms:

$$-\mathcal{L}_{\rm soft} \;=\; \tilde{m}^2_{ij} \tilde{N}_i{}^\dagger N_j + A_{ij} Y_{ij} \tilde{N}_i \tilde{l}_j H + \frac{1}{2} B_{ij} M_{ij} \tilde{N}_i \tilde{N}_j + h.c. \qquad (1)$$

Soft: dimension full parameters.

Only one complex parameter when the relative phase between $A$ and $B$ is absorbed.

## Neutrino mass

$$\mathcal{L} = \frac{\partial^2 W}{\partial L \partial H} LH = YLHN, \text{ Neutrino mass: } m_\nu = \frac{m_D^\dagger m_D}{M_N}.$$

Mass matrix of $\tilde{N} - \tilde{N}^\dagger$ system:

$$\mathcal{M} = M \begin{pmatrix} 1 & \frac{B}{2M} \\ \frac{B}{2M} & 1 \end{pmatrix} \tag{2}$$

• Sneutrino and anti-sneutrino states mix in the mass matrix. Their mass eigenvectors

$$\tilde{N}^+ = \frac{1}{\sqrt{2}}\left(\tilde{N}e^{i\Phi/2} + \tilde{N}^\dagger e^{-i\Phi/2}\right) \tag{3}$$

$$\tilde{N}^- = \frac{-i}{\sqrt{2}}\left(\tilde{N}e^{i\Phi/2} - \tilde{N}^\dagger e^{-i\Phi/2}\right) \tag{4}$$

where $\Phi = \arg(BM)$ and the mass eigenvalues are

$$M_\pm^2 = M^2 + \tilde{m}^2 \pm |BM|. \tag{5}$$

• The system of $\tilde{N} - \tilde{N}^\dagger$ is analogous to the $K_0$–$\bar{K}_0$ or $B_0$–$\bar{B}_0$ system.

• We also choose $\Phi = 0$ for simplicity. $A$ is the only complex parameter.

• Evolution of $\tilde{N} - \tilde{N}^\dagger$ is determined (in the non-relativistic limit) by the Hamiltonian:

$$\mathcal{H} = \mathcal{M} - \frac{i\Gamma}{2} \tag{6}$$

• Lagrangian of our interest:

$$\mathcal{L} = \tilde{N}\Big(Y_i \bar{\tilde{H}} l_L^i + M Y_i^* \tilde{l}_i^* H^* + A Y_i \tilde{l}_i H\Big) + h.c. \tag{7}$$

where, at leading order in the soft terms $\left(\frac{A^2}{M^2}, \frac{B^2}{M^2} \ll 1\right)$,

$$\mathcal{M} = M \begin{pmatrix} 1 & \frac{B}{2M} \\ \frac{B}{2M} & 1 \end{pmatrix} \quad \text{and} \quad \Gamma = \Gamma_0 \begin{pmatrix} 1 & \frac{A^*}{M} \\ \frac{A}{M} & 1 \end{pmatrix} \tag{8}$$

• Hamiltonian eigenstates are different from mass eigenstates and not CP conserving since $A$ is complex since $\left|\frac{q}{p}\right| = \sqrt{\frac{\mathcal{M}_{12}^* - \Gamma_{12}^*}{\mathcal{M}_{12} - \Gamma_{12}}} \neq 1.$

# Time evolution of $\tilde{N} - \tilde{N}^\dagger$ fields

- Schrodinger equation:

$$i\frac{\partial \Psi}{\partial t} = \mathcal{H}\Psi, \tag{9}$$

where $\Psi = \begin{pmatrix} \tilde{N} \\ \tilde{N}^\dagger \end{pmatrix}$. Solving this one gets,

$$\tilde{N}(t) = g_+(t)\tilde{N}(0) + \frac{q}{p}g_-(t)\tilde{N}^\dagger(0), \tag{10}$$

$$\tilde{N}^\dagger(t) = \frac{p}{q}g_-(t)\tilde{N}(0) + g_+(t)\tilde{N}(0), \tag{11}$$

where,

$$g_+(t) = e^{-iMt}e^{-\Gamma t/2}\cos(\Delta M t/2) \tag{12}$$

$$g_-(t) = ie^{-iMt}e^{-\Gamma t/2}\sin(\Delta M t/2), \tag{13}$$

with $\Delta M = M_+ - M_- = |B|$.

- Lepton asymmetry:

$$\epsilon = \frac{\Gamma(\tilde{N}(t) \to f) + \Gamma(\tilde{N}(t)^\dagger \to f) - \Gamma(\tilde{N}(t) \to \bar{f}) - \Gamma(\tilde{N}(t)^\dagger \to \bar{f})}{\Gamma(\tilde{N}(t) \to f) + \Gamma(\tilde{N}(t)^\dagger \to f) + \Gamma(\tilde{N}(t) \to \bar{f}) + \Gamma(\tilde{N}(t)^\dagger \to \bar{f})} \quad (14)$$

$$\epsilon = \frac{1}{2}\left(\left|\frac{q}{p}\right|^2 - \left|\frac{p}{q}\right|^2\right)\left(\frac{c_F - c_B}{c_F + c_B}\right)\frac{\int_0^\infty dt|g_-|^2}{\int_0^\infty dt(|g_+|^2 + |g_-|^2)} \quad (15)$$

$$= \frac{\Gamma B}{\Gamma^2 + B^2}\frac{\mathrm{Im}A}{M}\Delta_{BF}, \quad (16)$$

where $\Delta_{BF} = \frac{c_B - c_F}{c_B + c_f}$, $\left|\frac{q}{p}\right| = \left|\frac{p}{q}\right|$ for real $A$.

# Important points to note

Remember Yukawa coupling $Y$ is real. Only one RH neutrino is sufficient. However,

- $B \neq 0$ leads to $\epsilon = 0$.
- Real $A$ leads to $\epsilon = 0$.
- $c_B = c_F$ leads to $\epsilon = 0$.

Thermal mass corrections to the final state particles could generate non zero assymmetry.

**Final comments**

MSSM extended by RH neutrinos require thermal field theory for having non zero $\epsilon$ from $\tilde{N}$ decay at tree level.

# Our motivation and NMSSM

- Is it still possible to achieve observed lepton assymetry at tree level from sneutrino decay without thermal mass corrections!
- Study of soft leptogenesis in NMSSM.

**Why NMSSM?**

MSSM is plagued by the so-called $\mu$ problem which asks the question why the scale of the supersymmetry preserving $\mu$ term should be of the same order as the soft supersymmetry breaking terms, which are of the order of TeV.

$$\boxed{\mu \text{ term: } W_{\rm MSSM} = \mu H_u H_d,\ \mu \sim \mathcal{O}(1 \text{ TeV})}$$

$$\boxed{W_{\rm NMSSM} = \kappa S H_u H_d,\ \mu \sim \kappa \langle S \rangle}$$

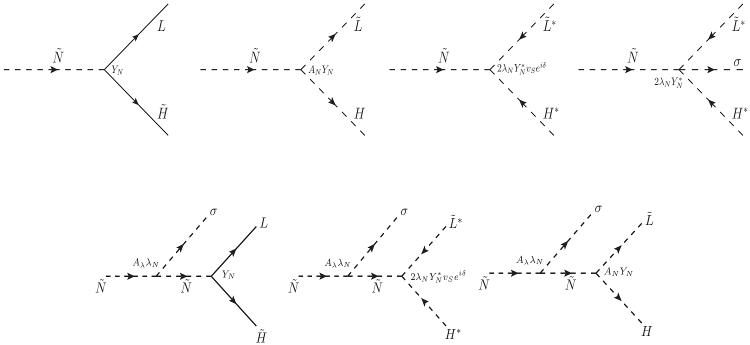
# NMSSM extended by a RH neutrino superfield

Superpotential: $W \supset Y_N \hat{L}\hat{H}\hat{N} + \lambda_N \hat{S}\hat{N}\hat{N} + \frac{\kappa}{3}\hat{S}^3$. Scalar partner $\langle S \rangle \sim v_s e^{i\delta}$.

Interactions:

$$\mathcal{L}_{\rm int} = \tilde{N}\left(Y_N \tilde{H} L + 2\lambda_N Y_N^* v_S e^{i\delta} H^* \tilde{L}^* + 2\lambda_N Y_N^* \sigma H^* \tilde{L}^* + A_N Y_N H \tilde{L}\right) + \sigma\left(\lambda_N N N + A_\lambda \lambda_N \tilde{N}\tilde{N}\right) + h.c., \quad (17)$$

where $\sigma = S - \langle S \rangle$.

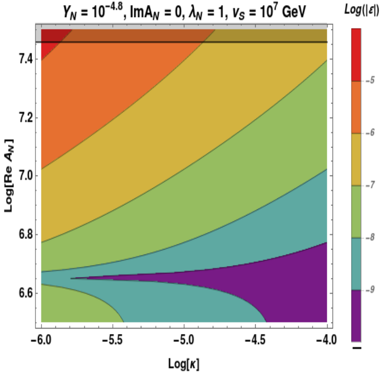


# Lepton Asymmetry

Expression of asymmetry parameter:

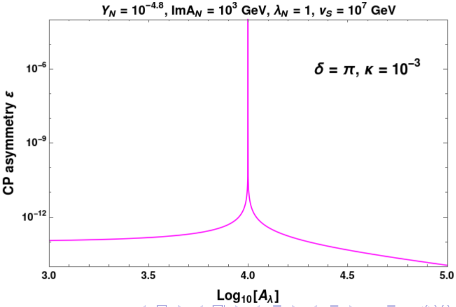
$$\varepsilon \simeq \frac{1}{2\pi}\left(\frac{\alpha}{2+\alpha}\right) \times \frac{Y_N^2\left[A_\lambda \mathrm{Im}A_N + \kappa v_S\{\cos(3\delta)\mathrm{Im}A_N + \sin(3\delta)\mathrm{Re}A_N\}\right]}{A_\lambda^2 + \kappa^2 v_S^2 + 2A_\lambda \kappa v_S \cos(3\delta)}.$$

Small $\delta$ case:




Large $\delta$ case:

$$\varepsilon\big|_{\delta=\pi} = \frac{1}{2\pi}\left(\frac{\alpha+\beta}{2+\alpha+\beta}\right)\frac{Y_N^2\,\mathrm{Im}A_N}{|A_\lambda - \kappa v_S|}.$$



# Conclusion

- Soft leptogenesis mechanism can yield non zero asymmetry even with single RH neutrino superfield and real Yukawa couplings.
- In MSSM, this requires one of the soft parameters complex and also thermal mass correction of the final state particles.
- In NMSSM we have shown,
  - Without thermal mass correction $\varepsilon$ could be non zero.
  - Complex nature of soft SUSY breaking parameter is not essential.
  - The phase of the additional scalar field $S$ turns out to be striking.

# Thank you