On Gaugino Contributions to Soft Leptogenesis

The Role of Thermal and Flavor Effects

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Outline

1. Introduction
2. Soft Leptogenesis
   - The Lagrangian and CP Phases
   - CP Asymmetries from Field Theoretical Approach
   - CP Asymmetries from Quantum Mechanical Approach
   - Results
3. Conclusion

Introduction: Leptogenesis

GOAL: To explain the baryon asymmetry Y_B
e.g. WMAP measurement [Dunkley et. al. (2008)]

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} = 8.78 \pm 0.24 \times 10^{-11}$$

Recipe [Shakarov(1967)] for leptogenesis [Fukugita,Yanagida(1986)]

- Out of thermal equilibrium decays of heavy particles $X \to L, \overline{L}$ ($\Gamma_X \lesssim H$)
- CP asymmetries from phases of the X-'Yukawa couplings'
- $\Delta L \neq 0$ processes $\to L$ asymmetry $\to$ partially converted to B asymmetry through spharelon interactions at high $T \gtrsim T_c (\sim 100$ GeV)

Types of leptogenesis

- Type-I: X Fermion singlet
- Type-II: X Scalar SU(2) triplets
- Type-III: X Fermion SU(2) triplets
- or hybrid model
  $\to$ can be supersymmetrized in a straightforward way

Introduction: Soft Leptogenesis

- **Soft supersymmetry(SUSY)-breaking bilinear B and trilinear A terms** provide the CP-violating phase and the mass splitting between $\widetilde{N}$ and $\widetilde{N}^*$ [Grossman et. al.(2003)],[D'Ambrosio et. al.(2003)]
  $\longrightarrow$ Only 1 generation $\widetilde{N}$ is needed
  $\longrightarrow$ Successful for $M \sim 10^{5-8}$ GeV (avoids overproduction of gravitinos)
  $\longrightarrow$ Unconventional small $B \lesssim \mathcal{O}(10^{-3})$ TeV
  $\longrightarrow$ Fermionic and scalar CP asymmetries cancel at $T = 0$, need Thermal Effect

- New source of CP-violation from **gaugino soft SUSY-breaking masses** m_2 [Grossman et. al.(2004)]
  $\longrightarrow$ $B \sim \mathcal{O}$ (TeV)
  $\longrightarrow$ Thermal Effect not required (we showed that this is not correct)

The Lagrangian and CP Phases

The Type-I SUSY Seesaw model could be described by the superpotential:

$$W = \frac{1}{2} M_{ij} N_i N_j + Y_{ij} \epsilon_{\alpha\beta} N_i L_j^\alpha H^\beta$$

The **soft SUSY-breaking terms**:

$$\mathcal{L}_{soft} = -\left(A_{ij} Y_{ij} \epsilon_{\alpha\beta} \widetilde{N}_i \tilde{\ell}_j^\alpha h^\beta + \frac{1}{2} B_{ij} M_{ij} \widetilde{N}_i \widetilde{N}_j + \frac{1}{2} m_2 \overline{\widetilde{\lambda}}_2^a P_L \tilde{\lambda}_2^a + \text{h.c.} \right)$$

The $\tilde{N}$ and $\tilde{N}^*$ mix with the mass eigenstates

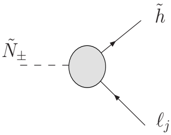
$$\widetilde{N}_{+i} = \frac{1}{\sqrt{2}} (e^{i\Phi/2} \widetilde{N}_i + e^{-i\Phi/2} \widetilde{N}_i^*), \qquad \widetilde{N}_{-i} = \frac{-i}{\sqrt{2}} (e^{i\Phi/2} \widetilde{N}_i - e^{-i\Phi/2} \widetilde{N}_i^*)$$

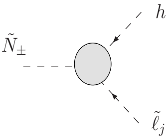
where $\Phi \equiv \arg(BM)$ and with mass eigenvalues $M_{ii\pm}^2 = M_{ii}^2 \pm |B_{ii} M_{ii}|$.

For simplicity, we assume single generation of $\tilde{N}_\pm$ and universal trilinear couplings A $\Rightarrow$ 2 independent physical CP violating phases:

$$\phi_A = \arg(AB^*), \qquad \phi_g = \frac{1}{2} \arg(B m_2^*)$$

CP Asymmetries from Field Theoretical Approach





$$c_f(T) = (1 - x_\ell - x_{\tilde{h}})\lambda(1, x_\ell, x_{\tilde{h}}) \left[1 - f_\ell^{eq}\right] \left[1 - f_{\tilde{h}}^{eq}\right]$$

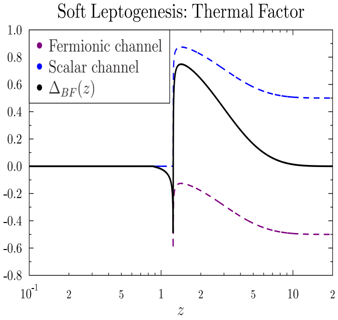
$$c_s(T) = \lambda(1, x_h, x_{\tilde{\ell}}) \left[1 + f_h^{eq}\right] \left[1 + f_{\tilde{\ell}}^{eq}\right]$$

The CP Asymmetry: $\epsilon_k = \epsilon^s_{+k} + \epsilon^s_{-k} + \epsilon^f_{+k} + \epsilon^f_{-k}$

$$\epsilon^{s,f}_{\pm k} = \frac{\left(|\hat{\mathcal{A}}_\pm^{s_k, f_k}|^2 - |\overline{\hat{\mathcal{A}}_\pm^{\bar{s}_k, \bar{f}_k}}|^2\right) c_\pm^{s_k, f_k} / M_\pm}{\sum_{i=\pm, a_k, k} \left(|\hat{\mathcal{A}}_i^{a_k}|^2 + |\overline{\hat{\mathcal{A}}_i^{\bar{a}_k}}|^2\right) c_i^{a_k} / M_i}$$

Thermal Factor:

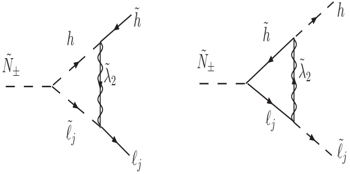
$$\Delta_{BF}(z) = \frac{c_s(z) - c_f(z)}{c_s(z) + c_f(z)}, \quad z = \frac{m_N}{T}$$



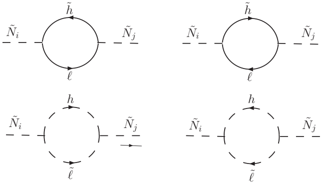
Using effective field-theoretical approach for unstable particles [Pilaftsis, 1997], the decay amplitude $\hat{\mathcal{A}}_i^{a_k}$ of the unstable external state $\widetilde{N}_i$ into a final state a_k is

$$\hat{\mathcal{A}}_{\pm}^{a_k} = \left(A_{\pm}^{a_k} + i\mathcal{V}_{\pm}^{a_k\,\text{abs}}(p^2)\right) - \left(A_{\mp}^{a_k} + i\mathcal{V}_{\mp}^{a_k\,\text{abs}}(p^2)\right) \frac{i\Sigma_{\mp\pm}^{\text{abs}}}{M_{\pm}^2 - M_{\mp}^2 + i\Sigma_{\mp\mp}^{\text{abs}}}$$

Vertex corrections



Self energies



[Grossman et. al.(2004)]

[Grossman et. al.(2003)],[D'Ambrosio et. al.(2003)]

CP Asymmetries

- Mixing

$$\epsilon_k^S(T) = -K_k^0 \frac{|A|}{M} \sin(\phi_A) \frac{4B\Gamma}{4B^2+\Gamma^2} \Delta_{BF}(T)$$

- Decay

$$\epsilon_k^V(T) = -\frac{3K_k^0 \alpha_2}{4} \frac{m_2}{M} \ln \frac{m_2^2}{m_2^2+M^2} \left[\frac{|A|}{M} \sin(\phi_A + 2\phi_g) - \frac{B}{M} \sin(2\phi_g) \right] \Delta_{BF}(T)$$

- Interference of Mixing and Decay

$$\epsilon_k^I(T) = \frac{3K_k^0 \alpha_2}{2} \frac{m_2}{M} \frac{|A|}{M} \ln \frac{m_2^2}{m_2^2+M^2} \sin(\phi_A) \cos(2\phi_g) \frac{\Gamma^2}{4B^2+\Gamma^2} \Delta_{BF}(T)$$

ALL cancel at $T=0$

CP Asymmetries from Quantum Mechanical Approach

In order to check the dependence on formalism and initial bases, we re-calculate the CP asymmetries based on an effective (non-hermitic) Hamiltonian (similar to $K^0 - \bar{K}^0$ mixing) as was used in [D'Ambrosio et. al.(2003)],[Grossman et. al.(2003)],[Grossman et. al.(2004)]

$$H = \begin{pmatrix} M & \frac{B}{2} \\ \frac{B}{2} & M \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma & \frac{\Gamma A^*}{M} \\ \frac{\Gamma A}{M} & \Gamma \end{pmatrix}.$$

We define the basis

$$\begin{aligned} \tilde{N}_1 &= \left(a\tilde{N} + b\tilde{N}^*\right), \\ \tilde{N}_2 &= e^{i\beta}\left(b\tilde{N} - a\tilde{N}^*\right). \end{aligned}$$

Mass basis: $(a, b, \beta) = (\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, -\frac{\pi}{2})$
Weak basis: $(a, b, \beta) = (1, 0, \pi)$

The eigenstates $\widetilde{N}_1$ and $\widetilde{N}_2$ evolve with

$$\left|\tilde{N}_{1,2}(t)\right\rangle = \frac{1}{2}\left\{\left[e_L(t)+e_H(t)\pm C_0\left(e_L(t)-e_H(t)\right)\right]\left|\tilde{N}_{1,2}\right\rangle + e^{\mp i(\beta)}C_{1,2}\left(e_L(t)-e_H(t)\right)\left|\tilde{N}_{2,1}\right\rangle\right\} \ ,$$

where

$$C_0 = ab\left(\frac{p}{q}+\frac{q}{p}\right), \quad C_1 = b^2\frac{p}{q}-a^2\frac{q}{p}, \quad C_2 = b^2\frac{q}{p}-a^2\frac{p}{q}, \quad e_{H,L}(t) \equiv e^{-i(M_{H,L}-\frac{i}{2}\Gamma_{H,L})t}$$

$$\frac{q}{p} = -1-\frac{\Gamma|A|}{BM}\sin\left(\phi_A\right)-\frac{\Gamma^2|A|^2}{M^2B^2}\cos^2\left(\phi_A\right)-\frac{i}{2}\frac{\Gamma^2|A|^2}{M^2B^2}\sin\left(2\phi_A\right)$$

Total time integrated CP asymmetry:

$$\epsilon_k^{QM} = \frac{\int_0^\infty dt \sum_{i=1,2,a_k}\Gamma(\widetilde{N}_i(t)\to a_k)-\Gamma(\widetilde{N}_i(t)\to \bar{a}_k)}{\int_0^\infty dt \sum_{i=1,2,a_k,k}\Gamma(\widetilde{N}_i(t)\to a_k)+\Gamma(\widetilde{N}_i(t)\to \bar{a}_k)}$$

For initial $\widetilde{N}, \widetilde{N}^\dagger$ states

$$\epsilon_k^{R,QMw}(T) = -K_k^0 \frac{|A|}{M} \sin(\phi_A) \frac{B\Gamma}{B^2+\Gamma^2} \Delta_{BF}(T)$$

$$\epsilon_k^{NR,QMw}(T) = -\frac{3K_k^0\alpha_2}{4} \frac{m_2}{M} \ln \frac{m_2^2}{m_2^2+M^2} \left[\frac{|A|}{M} \sin(\phi_A)\cos(2\phi_g) + \frac{B}{2M} \sin(2\phi_g) \right] \Delta_{BF}(T)$$

$$\epsilon_k^{I,QMw}(T) = \frac{3K_k^0\alpha_2}{4} \frac{m_2}{M} \frac{|A|}{M} \ln \frac{m_2^2}{m_2^2+M^2} \sin(\phi_A) \cos(2\phi_g) \frac{\Gamma^2}{B^2+\Gamma^2} \Delta_{BF}(T)$$

For initial $\widetilde{N}_\pm$ states

$$\epsilon_k^{R,QMm}(T) = K_k^0 \frac{|A|}{M} \sin(\phi_A) \frac{B\Gamma}{B^2+\Gamma^2} \Delta_{BF}(T)$$

$$\epsilon_k^{NR,QMm}(T) = -\frac{3K_k^0\alpha_2}{4} \frac{m_2}{M} \ln \frac{m_2^2}{m_2^2+M^2} \left[\frac{|A|}{M} \sin(\phi_A)\cos(2\phi_g) + \frac{B}{2M} \sin(2\phi_g) \right] \Delta_{BF}(T)$$

$$\epsilon_k^{I,QMm}(T) = -\frac{3K_k^0\alpha_2}{4} \frac{m_2}{M} \frac{|A|}{M} \ln \frac{m_2^2}{m_2^2+M^2} \sin(\phi_A) \cos(2\phi_g) \frac{\Gamma^2}{B^2+\Gamma^2} \Delta_{BF}(T)$$

ALL cancel at $T = 0$

Flavored Boltzmann Equations for Soft Leptogenesis

At $T < (1+\tan^2\beta)\times 10^9$ GeV where e,ν,τ-interactions are in equilibrium

$$sHz\frac{dY_N}{dz} = -\left(\frac{Y_N}{Y_N^{eq}}-1\right)\left(\gamma_N + \gamma_{\text{top scat.}}\right)$$

$$sHz\frac{dY_{\widetilde{N}\text{tot}}}{dz} = -\left(\frac{Y_{\widetilde{N}\text{tot}}}{Y_{\widetilde{N}}^{eq}}-2\right)\left(\gamma_{\widetilde{N}} + \gamma'_{\text{top scat.}}\right)$$

$$sHz\frac{dY_{\Delta_k}}{dz} = -K_k^0\left\{\epsilon(T)\left(\frac{Y_{\widetilde{N}\text{tot}}}{Y_{\widetilde{N}}^{eq}}-2\right)\gamma_{\widetilde{N}} - \sum_j A_{kj}\frac{Y_{\Delta_j}}{2Y_c^{eq}}\left(\gamma_{\widetilde{N}} + \gamma''_{\text{top scat.}} + \frac{Y_{\widetilde{N}\text{tot}}}{Y_{\widetilde{N}}^{eq}}\gamma'''_{\text{top scat.}} + \frac{Y_N}{Y_N^{eq}}\gamma''''_{\text{top scat.}}\right)\right\}$$

$\Delta_k = B/3 - L_{\text{tot},k}$ and $K_k^0 = \frac{|Y_{1k}|^2}{\sum_m |Y_{1m}|^2}$

$$A = \begin{pmatrix} -\frac{93}{110} & \frac{6}{55} & \frac{6}{55} \\ \frac{3}{40} & -\frac{19}{30} & \frac{1}{30} \\ \frac{3}{40} & \frac{1}{30} & -\frac{19}{30} \end{pmatrix}$$

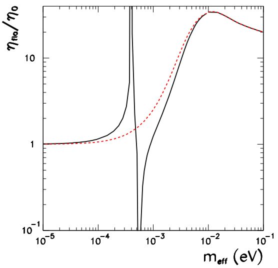
[Antusch et. al.(2006)]

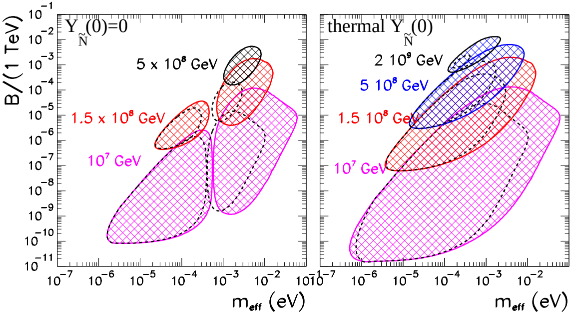
$$Y_B = \frac{8}{23}\sum_k Y_{\Delta_k}(z\to\infty)$$ [Harvey, Turner(1990)]

Results: Flavor Effect

Regions of $|Y_B| \geq 8.54 \times 10^{-11}$ (Unflavored: dotted boundaries)
$K_1^0 = K_2^0 = K_3^0 = 1/3$, $\tan\beta = 30$, $|\mathrm{Im}A| = 1$ TeV

$$m_{\rm eff} = \frac{(YY^\dagger)_{11}\, v_u^2}{M}, \qquad Y_{\Delta_k} = -2\eta_k K_k^0 \bar{\epsilon} Y_N^{eq}(T \gg M)$$

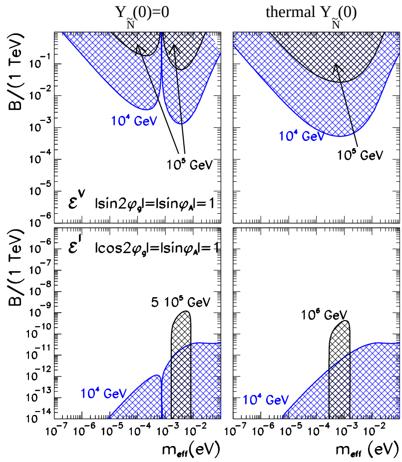




[C. S. F., M. C. Gonzalez-Garcia(2008)]

Mixing, small B

Results: Regions of Succcessful Baryogenesis



Regions of $|Y_B| \geq 8.54 \times 10^{-11}$
$K_1^0 = K_2^0 = K_3^0 = 1/3$, $\tan\beta = 30$,
$|\mathrm{Im}A| = 1$ TeV, $m_2 = 1$ TeV

Decay, $B \sim \mathcal{O}$(TeV)

Interference, small B

[C. S. F., M. C. Gonzalez-Garcia(2009)]

Conclusion

- Soft leptogenesis is successful for $\boxed{M \sim 10^{5-8}\ \text{GeV}}$ (avoids overproduction of gravitinos)
- Contributions of SU(2) gauginos λ_2^a to the CP asymmetries $\longrightarrow$ $\boxed{B \sim m_{susy}}$
- **Thermal Effect** is required for nonzero CP asymmetries in all scenarios
- In this mass ranges, **Flavor Effect** must be accounted for $\longrightarrow$ enhances Y_B up to $\mathcal{O}(30)$

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