Nonthermal $CP$ violation in soft leptogenesis

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Outline

Motivations

Soft leptogenesis (CP violation)

Phenomenological constraints

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Summary
We live in a matter(baryon)-dominated Universe

If we have the same amount of baryons and antibaryons in the early Universe, we will be left with \( n_B/s \sim n_{\bar{B}}/s \sim 10^{-19} \) when their annihilations freeze out. However BBN and CMB measurements *consistently* point to \( (n_B - n_{\bar{B}})/s \sim n_B/s \sim 10^{-10} \).
Neutrinos are massive
In the standard model, neutrinos are massless but they are not

(Talks by Everett, Coloma, Volkas)

Simplest solution is to introduce right-handed neutrinos \( N_i \)

\[ \implies \text{two possibilities:} \]

(i) \(-\mathcal{L} \supset (Y_{\alpha i})(\bar{\ell}_\alpha H)N_i + \frac{1}{2}M_i\bar{N}_i^cN_i + \text{H.c.}\)

(ii) \(-\mathcal{L} \supset (Y_{\alpha i})(\bar{\ell}_\alpha H)N_i + \text{H.c.}\) due to some symmetry e.g. lepton number

Virtues of (i) a.k.a. type-I seesaw

- Justify the lightness of neutrino masses: \( m_\nu \sim Y^2 \langle H \rangle^2 / M \)
- Baryogenesis through leptogenesis [Fukugita, Yanagida (1986)] (di Bari’s talk): \( M_1 \gtrsim 10^9 \text{ GeV} \) (true only for hierarchical spectrum \( M_1 \ll M_2 \ll M_3 \))
  
  [Davidson, Ibarra (2002)]

Neutrinos are massive & we still love SUSY

Some well-known virtues of supersymmetry (Tata’s talk)

- Gauge coupling unification
- Hierarchy between weak and GUT scales is stabilized
- With R-parity, we have dark matter candidates

So we supersymmetrize type-I seesaw

\[ W \supset \left( Y \right)_{\alpha i} (\hat{\ell}_{\alpha} \hat{H}_u) \hat{N}_i^c + \frac{1}{2} M_i \hat{N}_i^c \hat{N}_i^c \]

similar feature to the SM leptogenesis \( \epsilon \propto Y^2 \): \( M_1 \gtrsim 10^9 \text{ GeV} \)
Neutrinos are massive & we still love SUSY

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So we supersymmetrize type-I seesaw

\[ W \supset (Y)_{\alpha i}(\ell_{\alpha} \hat{H}_u)\hat{N}^c_i + \frac{1}{2} M_i \hat{N}^c_i \hat{N}^c_i \]

similar feature to the SM leptogenesis \[ \epsilon \propto Y^2 : M_1 \gtrsim 10^9 \text{ GeV} \]

\[ -\mathcal{L}_{\text{soft}} \supset \tilde{m}_{ij}^2 \tilde{N}_i^* \tilde{N}_j + \left[ (A)_{\alpha i} (\ell_{\alpha} H_u)\hat{N}^*_i + \frac{1}{2} B M_i \hat{N}_i \hat{N}_i + \text{H.c.} \right] \]

- \( (A)_{\alpha i} \rightarrow \) new sources of \( CP \) violation
- \( B \rightarrow \) mass splitting of sneutrinos within the same generation

New possibility: soft leptogenesis [D’Ambrosio et al. (2003); Grossman et al. (2003)]

\[ \epsilon \propto A/M : \text{cannot work for } M_1 \gtrsim 10^9 \text{ GeV could work for } M_1 \lesssim 10^9 \text{ GeV} \]

\[ \rightarrow \text{eases tension of gravitino overproduction } T_{RH} \lesssim 10^{6-9} \text{ GeV} \]
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Soft leptogenesis

Consider the lightest generation $i = 1$ and drop the index. Physics ‘decouples’ from heavier generations $i = 2, 3$.

Due to the $B$ term, $\tilde{N}$ and $\tilde{N}^*$ mix to form mass eigenstates:

\[
\tilde{N}_+ = \frac{1}{\sqrt{2}}(\tilde{N} + \tilde{N}^*)
\]
\[
\tilde{N}_- = -\frac{i}{\sqrt{2}}(\tilde{N} - \tilde{N}^*)
\]

with $M_\pm^2 = M^2 + \tilde{m}^2 \pm BM \implies \text{small mass splitting}$
Soft leptogenesis

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For soft leptogenesis to proceed, the decays $\tilde{N}_\pm \rightarrow \tilde{\ell}_\alpha H_u$ (scalar) and $\tilde{N}_\pm \rightarrow \ell_\alpha \tilde{H}_u$ (fermionic) need to fulfill 3 well-known Sakharov’s conditions [Sakharov (1967)]:

(1) lepton number violation

(2) $C$- and $CP$- violation (our focus today)

(3) the decays are of the order of/slower than the expansion rate of the Universe
Soft leptogenesis: \textit{CP} violation

From interference between tree and one-loop diagrams ($i = \pm$)

\[\tilde{N}_i \xrightarrow{\quad H^b_u \quad} \tilde{N}_j \quad \text{and} \quad \tilde{N}_i \xrightarrow{\quad \tilde{H}^c_{u} \quad} \tilde{N}_j\]

[D’Ambrosio et al. (2003); Grossman et al. (2003)]

We should check if $\epsilon_{\text{scalar}} + \epsilon_{\text{fermion}} = 0$? (see however [CSF, Gonzalez-Garcia, and Nardi (2011)] when $\mu_{\text{scalar}} \neq \mu_{\text{fermion}}$)

[Grossman et al. (2004)]
Soft leptogenesis: \textit{CP} violation

From interference between tree and one-loop diagrams ($i = \pm$)

\[ \tilde{N}_i \overset{H_u^b}{\longrightarrow} + \tilde{N}_j \]
\[ \tilde{N}_i \overset{\tilde{\ell}_a}{\longrightarrow} \tilde{N}_j \]
\[ \tilde{N}_i \overset{\tilde{H}_{c,b}^c}{\longrightarrow} + \tilde{N}_j \]
\[ \tilde{N}_i \overset{\ell_a}{\longrightarrow} \tilde{N}_j \]

[\text{D'Ambrosio et al. (2003); Grossman et al. (2003)}] [\text{Grossman et al. (2004)}]

\textbf{We should check if} $\epsilon_{\text{scalar}} + \epsilon_{\text{fermion}} = 0$ ?

(see however [CSF, Gonzalez-Garcia, and Nardi (2011)] when $\mu_{\text{scalar}} \neq \mu_{\text{fermion}}$)
Soft leptogenesis: $CP$ violation from gaugino vertex

$\tilde{N}_i \rightarrow H_u \tilde{\lambda}_{1,2} \tilde{\ell} \ell^a \ell_{\alpha}$

$\tilde{H}^{c,b}_u \rightarrow H_u \tilde{\lambda}_{1,2} \ell \tilde{\ell}^a \ell_{\alpha}$

$\tilde{N}_i \rightarrow H_u \tilde{\lambda}_{1,2} \tilde{\ell} \ell^a \ell_{\alpha}$

$\tilde{H}^{c}_u \rightarrow H_u \tilde{\lambda}_{1,2} \ell \tilde{\ell}^a \ell_{\alpha}$

[Note: The diagram illustrates the process of leptogenesis through the exchange of gaugino vertices, leading to the production of neutrinos ($\tilde{N}_i$) and the violation of $CP$ symmetry.]

- [Grossman et al. (2004)]: $\epsilon^{T=0}_{\text{scalar}} + \epsilon^{T=0}_{\text{fermion}} \neq 0$
Soft leptogenesis: $CP$ violation from gaugino vertex

$\tilde{N}_i \rightarrow H_u \tilde{\lambda}_{1,2} \ell \ell^a_{\alpha} \tilde{N}_i \rightarrow H_u \tilde{\lambda}_{1,2} \ell \ell^a_{\alpha}$

- [Grossman et al. (2004)]: $\epsilon^{T=0}_{\text{scalar}} + \epsilon^{T=0}_{\text{fermion}} \neq 0$
- [CSF, Gonzalez-Garcia (2009)]: $\epsilon^{T=0}_{\text{scalar}} + \epsilon^{T=0}_{\text{fermion}} = 0$, $\epsilon^{T\neq0}_{\text{scalar}} + \epsilon^{T\neq0}_{\text{fermion}} \neq 0$
Soft leptogenesis: \textit{CP} violation from gaugino vertex

\[ \tilde{N}_i \xrightarrow{H_u} \tilde{\lambda}_{1,2} \xrightarrow{\tilde{\ell}} \tilde{\ell}_a \]

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\[ \epsilon^{T=0}_{\text{scalar}} + \epsilon^{T=0}_{\text{fermion}} \neq 0 \]

\[ \epsilon^{T=0}_{\text{scalar}} + \epsilon^{T=0}_{\text{fermion}} = 0, \quad \epsilon^{T \neq 0}_{\text{scalar}} + \epsilon^{T \neq 0}_{\text{fermion}} \neq 0 \]

\[ \epsilon^{T=0}_{\text{scalar}} + \epsilon^{T=0}_{\text{fermion}} = \epsilon^{T \neq 0}_{\text{scalar}} + \epsilon^{T \neq 0}_{\text{fermion}} = 0 \]

It could actually still work in a narrow window \( 10^8 \text{ GeV} \lesssim T \lesssim 10^9 \text{ GeV} \) with \( m_{\tilde{\lambda}_{1,2}} \sim \text{TeV} \) when \( \mu_{\text{scalar}} \neq \mu_{\text{fermion}} \) [CSF, Gonzalez-Garcia, and Nardi (2011)] but we won’t consider it further.
Soft leptogenesis: $CP$ violation

- [Adhikari, Rangarajan (2002)] showed that at $T = 0$, if the baryon/lepton number is conserved to the ‘right’ of the cut, the total $CP$ asymmetry vanishes.
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- Apparently, it also holds for $T \neq 0$ (work in progress).
Soft leptogenesis: \textit{CP} violation

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- Apparently, it also holds for $T \neq 0$ (work in progress).

\[ \tilde{N}_i \tilde{\lambda}_{1,2} \tilde{\ell} \tilde{\ell}_\alpha \tilde{H}_{u,c,b} \]

\[ \tilde{N}_i \tilde{\lambda}_{1,2} \tilde{\ell} \tilde{\ell}_\alpha \tilde{H}_{u,c,b} \]

\[ \tilde{N}_\pm \tilde{\ell}_\beta \tilde{N}_\mp \tilde{\ell}_\alpha \tilde{H}_u \]

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Soft leptogenesis: \( CP \) violation from mixing

\[
\epsilon_{\pm \alpha} = \frac{1}{4\pi G_{\pm}(T)} Y_\alpha^2 \sum_\beta Y_\beta \frac{\text{Im}(A_\beta)}{M} \frac{4BM}{4B^2 + \Gamma^2_\mp} [c_F(T) - c_B(T)] r_B(T)
\]

\[
+ \frac{1}{4\pi G_{\pm}(T)} \frac{|A_\alpha|^2}{M^2} \sum_\beta Y_\beta \frac{\text{Im}(A_\beta)}{M} \frac{4BM}{4B^2 + \Gamma^2_\mp} r_B(T) c_B(T)
\]

where

\[
G_{\pm}(T) \equiv \left[ Y^2 + \sum_\alpha \left( \frac{|A_\alpha|^2}{M^2} \pm \frac{2Y_\alpha \text{Re}(A_\alpha)}{M} \right) \right] c_B(T) + Y^2 \left( 1 + \frac{\tilde{M}^2}{M^2} \pm \frac{B}{M} \right) c_F(T),
\]

\[
\Gamma_{\pm} = \frac{M}{8\pi} G_{\pm} \quad \text{and thermal factors } c_F(T), c_B(T), r_B(T) \rightarrow 1 \text{ as } T \rightarrow 0.
\]

With \( A_\alpha = AY_\alpha \) (original papers), the ‘thermal’ (first) term always dominates and due to additional suppression by \( Y_\alpha \), \( B \ll M_{\text{SUSY}} \) is needed to resonantly enhance the CP violation.
Soft leptogenesis: \( CP \) violation from mixing

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With \( A_{\alpha} = AY_{\alpha} \) (original papers), the ‘thermal’ (first) term always dominates and due to additional suppression by \( Y_{\alpha}, B \ll M_{\text{SUSY}} \) is needed to resonantly enhance the CP violation.

In the case with \( A_{\alpha} \sim M_{\text{SUSY}} \) [CSF et al. (2010)], we have new possibilities:

- \( |A_{\alpha}|/M \ll Y_{\alpha}: \) ‘thermal’ (first) term dominates
- \( |A_{\alpha}|/M \gg Y_{\alpha}: \) ‘nonthermal’ (second) term dominates
- \( |A_{\alpha}|/M \sim Y_{\alpha}: \) both terms contributes

No resonant enhancement required: \( B \sim M_{\text{SUSY}} \)
Soft leptogenesis: $CP$ violation from mixing

$B=1$ TeV, $\arg(A_\alpha)=-\pi/2$, $\tan\beta=10$

\[ Y_{\Delta B}(\infty) \equiv \frac{n_B - n_{\bar{B}}}{s}|_{\text{current}}, \quad K \equiv \frac{\Gamma_{\pm}}{H(T=M)} \]

with $H(T)$ the Hubble expansion rate and $M = 5 \times 10^7$ GeV.

- **Red dotted**: $|A_\alpha|/M \ll Y_\alpha$
- **Blue dashed**: $|A_\alpha|/M \gg Y_\alpha$
- **Purple solid**: $|A_\alpha|/M \sim Y_\alpha$

On the left of blue dashed or purple solid vertical lines, $|A_\alpha| < 5$ TeV.
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Constraints from electric dipole moment (EDM) of charged leptons and for charged lepton flavor violating (CLFV) processes for $A_\alpha = AY_\alpha$ scenario are weak [Kashti (2005)].

How about for generic $A_\alpha \sim M_{SUSY}$?
Soft leptogenesis: Phenomenological constraints

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How about for generic $A_\alpha \sim M_{\text{SUSY}}$?

- EDM of electron

\[ |d_e| \approx \frac{e m_e \tan \beta}{16\pi M_{\text{SUSY}}} \left| \frac{Y_\alpha}{M^2} \right| (|A_\alpha| + B Y_\alpha) \]

Out-of-equilibrium decay condition $\Gamma_\pm \lesssim H(T = M)$ gives

\[ |d_e| \lesssim 5 \times 10^{-38} \left( \frac{\tan \beta}{10} \right) \left( \frac{10^7 \text{ GeV}}{M} \right)^{3/2} \left( \frac{1 \text{ TeV}}{M_{\text{SUSY}}} \right) e\text{ cm} \]

Current experimental bound: $|d_e|_{\text{exp}} < 8.7 \times 10^{-29} e\text{ cm}$ [Baron et al. (2014)]

For muon and tau ($m_e \rightarrow m_\mu,\tau$), experimental constraints much weaker:

$|d_\mu|_{\text{exp}} < 1.9 \times 10^{-19} e\text{ cm}$ [Bennett et al. (2009)]

$|d_\tau|_{\text{exp}} < 5.1 \times 10^{-17} e\text{ cm}$ [Inami et al. (2003)]
Soft leptogenesis: Phenomenological constraints

- **CLFV processes**

\[
(m^2_{\tilde{\ell}})_{\alpha\beta} \approx -\frac{1}{8\pi^2} A_{\alpha}^* A_{\beta} \ln \left(\frac{M_{\text{GUT}}}{M}\right), \quad \text{BR}(\ell_\alpha \to \ell_\beta \gamma) \approx \frac{\alpha^3}{G_F^2} \frac{|(m^2_{\tilde{\ell}})_{\alpha\beta}|^2}{M_{\text{SUSY}}^8} \tan^2 \beta
\]

with \(\text{BR}(\mu \to 3e) \sim 6.6 \times 10^{-3} \text{BR}(\mu \to e\gamma)\) and \(\mu - e\) conversion in \(^{27}\)\(^{13}\)Al nucleus \(R_{\mu e} \sim 2.5 \times 10^{-3} \text{BR}(\mu \to e\gamma)\)

**MEG:** \(\text{BR}(\mu \to e\gamma)_{\text{exp}} < 5.7 \times 10^{-13}\) [Adam et al. (2013)]

\[
|A_{\mu}^* A_e| \lesssim 5 \times 10^3 \text{ GeV}^2 \left(\frac{M_{\text{SUSY}}}{1 \text{ TeV}}\right)^4 \left(\frac{10}{\tan \beta}\right)
\]

**BABAR:** \(\text{BR}(\tau \to e\gamma)_{\text{exp}} < 3.3 \times 10^{-8}, \text{BR}(\tau \to \mu\gamma)_{\text{exp}} < 4.4 \times 10^{-8}\) [Aubert et al. (2010)]

\[
|A_\tau^* A_e| \approx |A_\tau^* A_\mu| \lesssim 1 \times 10^6 \text{ GeV}^2 \left(\frac{M_{\text{SUSY}}}{1 \text{ TeV}}\right)^4 \left(\frac{10}{\tan \beta}\right)
\]

Projected sensitivities: \(\text{BR}(\mu \to 3e) \sim 10^{-15-16}\) [Mu3e, Blondel et al. (2013)] and \(R_{\mu e} \sim 10^{-17}\) [Mu2e, Abrams et al. (2012)]

Close to sensitivities of present and future experiments!
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Consider soft leptogenesis with generic $A_\alpha \sim M_{\text{SUSY}}$

- Works for $M \lesssim 10^9$ GeV, reduce/avoid tension with gravitino overproduction
- ‘Nonthermal’ CP violation is possible $\implies$ enhanced CP violation
- No extra suppression from $Y_\alpha$ $\implies$ enhanced CP violation
- No resonant enhancement required, allows natural $B \sim M_{\text{SUSY}}$
- Contributions to EDM of electron negligible
- Contributions to charged LFV interactions close to sensitivities of present and future experiments

Thank you for your attention!
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Soft leptogenesis: CP violation

There are 3 physical CP phases: \( \Phi_\alpha \equiv \text{arg}(A_\alpha Y^*_\alpha B^*) \rightarrow \) can be assigned to \( A_\alpha \).

\[
\varepsilon^{S,V}_{\pm \alpha} \equiv \frac{\gamma(\bar{N}_\pm \rightarrow a_\alpha) - \gamma(\bar{N}_\pm \rightarrow \bar{a}_\alpha)}{\sum_{a_\beta;\beta} \left[ \gamma(\bar{N}_\pm \rightarrow a_\beta) + \gamma(\bar{N}_\pm \rightarrow \bar{a}_\beta) \right]}, \quad a_\alpha = \{ \ell_\alpha \tilde{H}_u, \tilde{\ell}_\alpha H_u \}.
\]
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\[ \sum_{\alpha} \left[ \epsilon^{S,(a)}_{\pm\alpha} + \epsilon^{S,(b)}_{\pm\alpha} + \epsilon^{S,(c)}_{\pm\alpha} \right] = 0 \]
(extra) Soft leptogenesis: \(CP\) violation

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\[\epsilon_{s,v}^{\pm,\alpha} \equiv \frac{\gamma(\tilde{N}_\pm \rightarrow a_\alpha) - \gamma(\tilde{N}_\pm \rightarrow \bar{a}_\alpha)}{\sum_{a_\beta;\beta} \left[ \gamma(\tilde{N}_\pm \rightarrow a_\beta) + \gamma(\tilde{N}_\pm \rightarrow \bar{a}_\beta) \right]}, \quad a_\alpha = \{\ell_\alpha \tilde{H}_u, \tilde{\ell}_\alpha H_u\}\]

\[\sum_\alpha \left[ \epsilon_{s,(a)}^{\pm,\alpha} + \epsilon_{s,(b)}^{\pm,\alpha} + \epsilon_{s,(c)}^{\pm,\alpha} \right] = 0\]

\[\text{Enhancement from small mass splitting: } \epsilon_{s}^{\pm,\alpha} \propto \frac{M}{B} \gg \epsilon_{v}^{\pm,\alpha}\]