Baryogenesis through R-genesis

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Outline

Motivation

We live in a matter-antimatter asymmetric universe!

e.g. WMAP measurement [Dunkley et. al. (2008)]

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

Supersymmetry (SUSY) + type-I seesaw

- Hierarchy between weak and seesaw scale is stabilized
- Light active neutrino masses can be accommodated
- *Baryogenesis* can happen through leptogenesis
  $\Longrightarrow \; M \gtrsim 10^9\,\text{GeV} \;\Longrightarrow\; T_{RH} \gtrsim 10^9\,\text{GeV}$

Tension with upper bound on reheating temperature from overproducing gravitino
$\Longrightarrow \; T_{RH} \lesssim 10^9\,\text{GeV}$

Framework: SUSY + type-I seesaw + soft terms

SUSY + type-I seesaw: $W = W_{\text{MSSM}} + \frac{1}{2} M_{ij} \hat{N}_i^c \hat{N}_j^c + Y_{i\alpha} \hat{N}_i^c \hat{L}_\alpha \hat{H}_u$

SUSY is *broken* $\longrightarrow$ new sources of CP violations for leptogenesis

[Boubekeur (2002)], [Boubekeur et. al.(2002)]

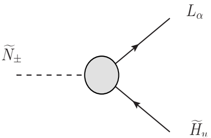
$$V_{soft} = AY_{i\alpha} \widetilde{N}_i \tilde{\ell}_\alpha H_u + \frac{1}{2} BM_{ij} \widetilde{N}_i \widetilde{N}_j + \frac{1}{2} m_{\widetilde{g}} \overline{\widetilde{\lambda}}_{\widetilde{g}} P_L \widetilde{\lambda}_{\widetilde{g}} + m^2_{\widetilde{\ell}_{\alpha\beta}} \widetilde{\ell}_\alpha \widetilde{\ell}_\beta + \ldots + \text{h.c.}$$

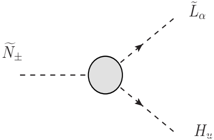
Soft Leptogenesis [Grossman et al.(2003)],[Grossman et al.(2004)],[D'Ambrosio et al.(2003)]

Minimal scenario: single generation of $\hat{N} \equiv \hat{N}_1$, $M \equiv M_{11}$, $Y_\alpha \equiv Y_{1\alpha}$ etc.

CP violating phases: $\phi_A = \arg(AB^*)$, $\phi_g = \frac{1}{2}\arg(Bm_{\widetilde{g}}^*)$

$\widetilde{N}$ and $\widetilde{N}^*$ mix to form mass eigenstates $\widetilde{N}_\pm$ with masses $M_\pm^2 = M^2 \pm |BM|$





$\epsilon^{s,f}(T) = \pm\bar{\epsilon}\,\Delta_{s,f}(T)$

At $T = 0$, $\epsilon^f(0) + \epsilon^s(0) = 0$

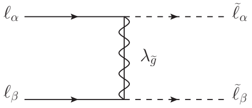
Thermal effects are fundamental to lift the cancellation!

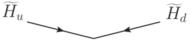
(Non)superequilibration

Superequilibration: equilibration between the chemical potentials of a particle and its superpartner i.e. $\boxed{\mu_\phi = \mu_{\tilde{\phi}}}$ [Chung et. al. (2009)]

- Soft gaugino masses $\Longrightarrow \Gamma_{\tilde{g}} \sim m_{\tilde{g}}^2/T$
- $W_H = \mu \hat{H}_u \hat{H}_d \Longrightarrow \Gamma_\mu \sim \mu^2/T$

$$(1)\mu_\ell = \mu_{\tilde{\ell}} + \mu_{\tilde{g}}, \quad (2)\mu_\ell = \mu_{\tilde{\ell}}$$





SE : $\Gamma_{\tilde{g},\mu}(T) > H(T) \Longrightarrow T \lesssim 5 \times 10^7 \left(\frac{m_{\tilde{g}},\, \mu}{500\,\text{GeV}}\right)^{2/3} \text{GeV} \equiv T_{seq}$

we have $\boxed{\mu_{\tilde{g}} = 0}$, $\boxed{\mu_{\widetilde{H}_u} + \mu_{\widetilde{H}_d} = 0}$

NSE : $\Gamma_{\tilde{g},\mu}(T) < H(T) \Longrightarrow T \gtrsim T_{seq}$

we can set $m_{\tilde{g}} = \mu = 0 \rightarrow \boxed{U(1)_R}$, $\boxed{U(1)_{PQ}}$

Anomalous Global Symmetries

$W = W_{\rm MSSM} + \frac{1}{2}M_{ij}\hat{N}_i^c\hat{N}_j^c + Y_{i\alpha}\hat{N}_i^c\hat{L}_\alpha\hat{H}_u,$ (Note: $\mu\hat{H}_u\hat{H}_d$)

$V_{soft} = AY_{i\alpha}\widetilde{N}_i\widetilde{\ell}_\alpha H_u + \frac{1}{2}BM_{ij}\widetilde{N}_i\widetilde{N}_j + \frac{1}{2}m_{\widetilde{g}}\overline{\widetilde{\lambda}}_{\widetilde{g}}P_L\widetilde{\lambda}_{\widetilde{g}} + m^2_{\widetilde{\ell}_{\alpha\beta}}\widetilde{\ell}_\alpha\widetilde{\ell}_\beta + \text{h.c.}$

- Without $\hat{N}_i^c$, MSSM has 4 global symmetries: $U(1)_B,\ U(1)_{L_\alpha}\ (\alpha = e, \mu, \tau)$
- Setting $m_{\widetilde{g}}, \mu \to 0$, MSSM gains 2 global symmetries: $U(1)_{PQ},\ U(1)_R$
- If some of the Yukawas are zeros, we gain some chiral symmetry: $U(1)_\chi$

In MSSM, B and L_α have $SU(2)$ mixed anomalies.
We can form 3 combinations $\Delta_\alpha \equiv B/3 - L_\alpha$ which are anomaly-free.

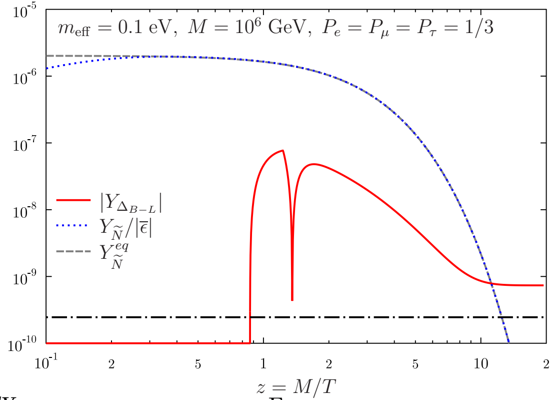
Both PQ and R have $SU(2)$ and $SU(3)$ mixed anomalies [Ibanez, Quevedo(1992)].
Let's define $R_2 \equiv R - 2PQ$, $R_3 \equiv R - 3PQ$ such that R_n only has $SU(n)$ anomaly.
We can form the following anomaly-free charges: $R_B \equiv \frac{2}{3}B + R_2$, $R_\chi \equiv \chi_{q_L} + \kappa_{q_L}R_3$
(Assigning L-handed supermultiplet $\chi_{q_L} = -1$, then $\kappa_{u_L^c} = \kappa_{d_L^c} = \frac{1}{2}\kappa_{Q_L} = \frac{1}{3}$.)

The interactions involving $\hat{N}_i^c$ violate $\Delta_\alpha, R_B, R_\chi$ *slowly*.

Superequilibration Regime

$T \lesssim T_{seq}$, 3 independent quantities: Y_{Δ_α}

$$Y_{\Delta_{B-L}} \equiv \sum_\alpha Y_{\Delta_\alpha}; \qquad m_{\rm eff} = \sum_\alpha \frac{|Y_\alpha|^2 v_u^2}{M}$$



$$\frac{dY_{\widetilde{N}}}{dz} = -\left(Y_{\widetilde{N}} - Y^{eq}_{\widetilde{N}}\right)\frac{<\Gamma_D>}{2Hz},$$

$$\frac{dY_{\Delta_\alpha}}{dz} = -\epsilon_\alpha(z)\left(Y_{\widetilde{N}} - Y^{eq}_{\widetilde{N}}\right)\frac{<\Gamma_D>}{2Hz} + \left(Y_{\Delta\ell_\alpha} + Y_{\Delta\widetilde{H}_u}\right)\frac{<\Gamma^\alpha_{ID}>}{Hz}$$

Non-superequilibration Regime: R-genesis[hep-ph/1012.1597]

Choose $T \gtrsim T_{seq}$ such that ($\phi \equiv \mu_\phi$)

- Only $\Gamma_{h_u}(T) < H(T) \to h_u = 0$ (e.g. $\tan\beta \sim 10$)
- $\Gamma_{\widetilde{g},\mu}(T) < H(T) \to m_{\widetilde{g}} = \mu = 0 \implies \boxed{\widetilde{g} \neq 0}, \boxed{\widetilde{H}_u + \widetilde{H}_d \neq 0}$

16 chemical potentials: $Q,\ \ell_\alpha,\ u_i,\ d_i,\ e_\alpha,\ \widetilde{H}_{u,d},\ \widetilde{g}$

11 constraints: 8 from Yukawas, 2 from QCD and EW sphalerons, 1 from neutrality

$\implies$ 5 independent quantities: e.g. $\ell_\alpha, \widetilde{H}_u, \widetilde{g}$

We choose the 5 anomaly-free *'quasi-conserved'* charges: $\Delta_\alpha,\ R_B,\ R_\chi$

We can relate them through $\boxed{Y_{\Delta_{\psi_a}} = A_{ab} Y_{\Delta_b}}$

where $Y_{\Delta_a} = \{Y_{\Delta_\alpha}, Y_{\Delta R_B}, Y_{\Delta_{R_\chi}}\}$ and $Y_{\Delta_{\psi_a}} = \{Y_{\Delta \ell_\alpha}, Y_{\Delta \widetilde{g}}, Y_{\Delta \widetilde{H}_u}\}$

Notice that $\mu_\phi \neq \mu_{\widetilde{\phi}}$ and scalar and fermionic asymmetries will be washed out differently due to different statistics!

Could non-superequilibration effects dominate over thermal effects?

R-genesis: Simplified Boltzmann Equations

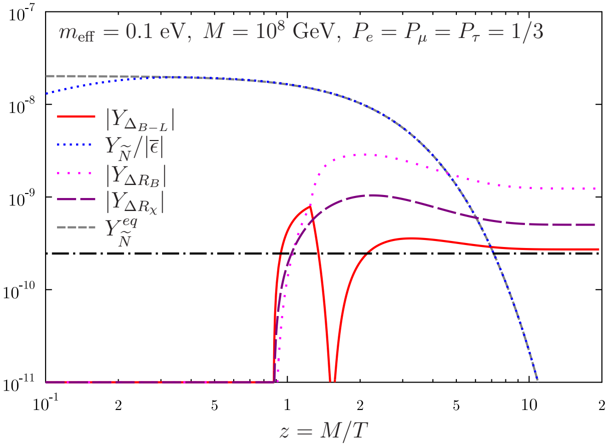
$$\frac{dY_{\widetilde{N}}}{dz} = -\left(Y_{\widetilde{N}} - Y_{\widetilde{N}}^{eq}\right)\frac{<\Gamma_D>}{2Hz}$$

$$\frac{dY_{\Delta\alpha}}{dz} = -\epsilon_\alpha(z)\left(Y_{\widetilde{N}} - Y_{\widetilde{N}}^{eq}\right)\frac{<\Gamma_D>}{2Hz} + \left(Y_{\Delta\ell_\alpha} + Y_{\Delta\widetilde{H}_u} + Y_{\Delta\widetilde{g}}\right)\frac{<\Gamma_{ID}^\alpha>}{Hz}$$

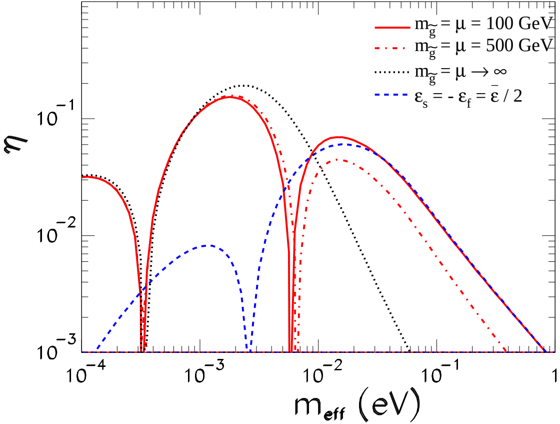
$$\frac{dY_{\Delta R_B}}{dz} = \epsilon^s(z)\left(Y_{\widetilde{N}} - Y_{\widetilde{N}}^{eq}\right)\frac{<\Gamma_D>}{Hz} - \sum_\alpha\left(Y_{\Delta\ell_\alpha} + Y_{\Delta\widetilde{H}_u} + \mathcal{Y}_{\Delta\widetilde{g}}\right)\frac{<\Gamma_{ID}^\alpha>}{Hz}$$
$$-Y_{\Delta\widetilde{g}}\frac{<\Gamma_{ID}>}{2Hz} - Y_{\Delta\widetilde{g}}\frac{<\Gamma_{\widetilde{g}}^{\rm eff}>}{Hz}$$

$$\frac{dY_{\Delta R_\chi}}{dz} = \left[\epsilon^s(z) - \epsilon^f(z)\right]\left(Y_{\widetilde{N}} - Y_{\widetilde{N}}^{eq}\right)\frac{<\Gamma_D>}{6Hz} - Y_{\Delta\widetilde{g}}\frac{<\Gamma_{ID}>}{6Hz}$$
$$-\frac{1}{3}Y_{\Delta\widetilde{g}}\frac{<\Gamma_{\widetilde{g}}^{\rm eff}>}{Hz} + \frac{1}{3}\left(Y_{\Delta\widetilde{H}_u} + Y_{\Delta\widetilde{H}_d}\right)\frac{<\Gamma_{\widetilde{H}_u}^{\rm eff}>}{Hz}$$

R-genesis: Evolutions



R-genesis: Dominance over Thermal Effects and Enhancement



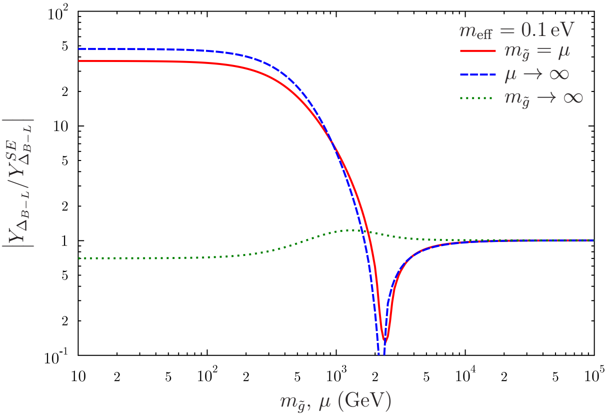
$$\eta \equiv \left| \frac{\sum_\alpha Y_{\Delta_\alpha}}{\bar{\epsilon}\, Y^{eq}_{\widetilde{N}}(T \gg M)} \right|$$

In the strong washout regime, soft leptogenesis could proceed without thermal effects!

Conclusions

- If *SUSY* is realized in nature, **soft leptogenesis** is a good candidate and it is successful for $M \lesssim 10^9$ GeV which relaxes/avoids gravitino problem.
- Leading order fermionic & scalar CP asymmetries always cancel at $T = 0$.
- For $T \gtrsim 10^7$ GeV $\implies$ baryogenesis proceeds through **R-genesis**
  i) Could proceed without thermal effect in strong washout regime
  ii) Could enhance efficiency up to $\mathcal{O}(50)$ compared to superequilibration scenario
- For $T \lesssim 10^7$ GeV $\implies$ thermal soft leptogenesis which requires thermal effects

Thank you for your attention!



[hep-ph/1012.1597]

Efficiency could be enhanced up to $\mathcal{O}(40)$ for $m_{\rm eff} = 0.1\,{\rm eV}$ and $m_{\tilde g} = \mu \lesssim 300\,{\rm GeV}$

A matrix in Non-superequilibration Regime

$$A = \frac{1}{9 \times 827466} \begin{pmatrix} -788776 & 38690 & 38690 & -56295 & 41931 \\ 38690 & -788776 & 38690 & -56295 & 41931 \\ 38690 & 38690 & -788776 & -56295 & 41931 \\ 41913 & 41913 & 41913 & 124281 & 12798 \\ -102411 & -102411 & -102411 & 108108 & -335907 \end{pmatrix}.$$

B, L, PQ and R charge assignments

		$\tilde{g}$	Q	u^c	d^c	ℓ	e^c	$\tilde{H}_d$	$\tilde{H}_u$	N^c
B		0	$\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	0	0	0	0
L		0	0	0	0	1	-1	0	0	0
PQ		0	0	-2	1	-1	2	-1	2	0
R	f	1	-1	-3	1	-1	1	-1	3	-1
	b	2	0	-2	2	0	2	0	4	0

R_2 and R_3 charge assignments

		$\tilde{g}$	Q	u^c	d^c	ℓ	e^c	$\tilde{H}_d$	$\tilde{H}_u$	N^c
R_2	f	1	-1	1	-1	1	-3	1	-1	-1
	b	2	0	2	0	2	-2	2	0	0
R_3	f	1	-1	3	-2	2	-5	2	-3	-1
	b	2	0	4	-1	3	-4	3	-2	0
R_B	f	1	$-\frac{7}{9}$	$\frac{7}{9}$	$-\frac{11}{9}$	1	-3	1	-1	-1
	b	2	$\frac{2}{9}$	$\frac{16}{9}$	$-\frac{2}{9}$	2	-2	2	0	0