Baryogenesis and Late-Decaying Moduli

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Introduction

String moduli play interesting roles in cosmology and particle phenomenology

1. A modulus of mass $\sim$ 1000 TeV
2. Gravitational coupling to matter $\Gamma_T = \frac{c}{2\pi} \frac{m_\sigma^3}{M_P^2}$

$\Rightarrow$

$$T_{\text{reheat}} \sim \sqrt{\Gamma_T M_P} \sim 200\text{MeV}$$

Affects dark matter physics, baryon asymmetry, etc.

arXiv:0904.3773 [hep-ph]

The most well-studied moduli stabilization models have such moduli...

In KKLT,

$$\begin{aligned} m_{3/2} &\simeq \frac{W_{\rm flux}}{(2\,{\rm Re}\,T)^{3/2}} \sim 30{\rm TeV}\ , \\ m_\sigma &\simeq F^{\bar{T}}_{,T} \simeq a\,{\rm Re}\,T\ m_{3/2} \sim 1000{\rm TeV}\ , \\ m_{\rm soft} &\simeq \frac{F_T}{{\rm Re}\,T} \sim \frac{m_{3/2}}{a\,{\rm ReT}}\ , \end{aligned}$$

Standard processes of baryogenesis may be affected by late production of entropy...

Dilution roughly $(T_{\mathrm{EW}}/T_{\mathrm{reheat}})^3 \sim 10^7$

Baryogenesis is a challenge at low temperatures...

May invoke Affleck-Dine baryogenesis scenarios

Or consider operators like $W \supset \frac{\lambda}{M_P}\sigma\, u^c d^c d^c$ hep-ph/9507453, hep-ph/9506274

Result in constraints on modulus sector

We will consider MSSM extension, leaving modulus sector unconstrained.

The Model

Basic idea:

1. Modulus decays, produces MSSM + extra matter (X) non-thermally
2. Extra matter X has baryon violating couplings to MSSM
3. Decay violates CP

Sakharov conditions are satisfied.

Estimates:

Net baryon asymmetry

$$6 \times 10^{-10} = \eta = \frac{n_B - n_{\overline{B}}}{n_\gamma} \sim \epsilon\, Y_X$$

$$\text{Yield } Y_X = 2 Y_T (\mathrm{Br})_X = \frac{3}{2} \frac{T_r}{m_T} (\mathrm{Br})_X \sim 10^{-7} (\mathrm{Br})_X$$

$$(\mathrm{Br})_X \sim 0.1$$

$$\Rightarrow \text{ Need } \epsilon \sim 10^{-3}$$

Typically, $\epsilon \sim \frac{\lambda^4}{\mathrm{Tr}\lambda^2}$

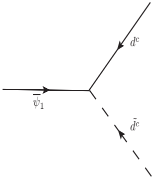
Yukawas $\mathcal{O}(0.1)$

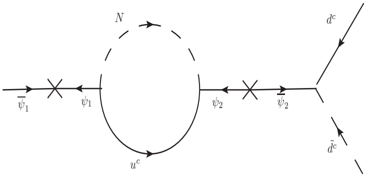
MSSM extension:

Two flavors of $X = (3, 1, 4/3)$, $\overline{X} = (\overline{3}, 1, -4/3)$
Singlet N hep-ph/0612357, arXiv:0908.2998

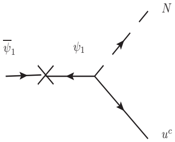
$$\begin{aligned} W_{extra} &= \lambda_{i\alpha} N u_i^c X_\alpha + \lambda'_{ij\alpha} d_i^c d_j^c \overline{X}_\alpha \\ &+ \frac{M_N}{2} NN + M_{X,(\alpha)} X_\alpha \overline{X}_\alpha \ . \end{aligned} \quad (1)$$

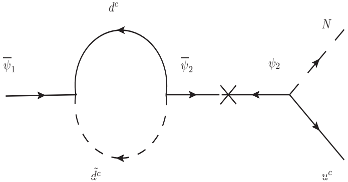
$M \sim 500$ GeV. Can be obtained by the Giudice-Masiero mechanism if the modulus has non-zero F-term.


d^c
$\overline{\psi}_1$
$\tilde{d}^c$


N
d^c
$\overline{\psi}_1$
ψ_1
ψ_2
$\overline{\psi}_2$
$\tilde{d}^c$
u^c

$$\Delta B = +2/3$$


$\overline{\psi}_1$
ψ_1
N
u^c


d^c
$\overline{\psi}_1$
$\overline{\psi}_2$
ψ_2
N
$\tilde{d}^c$
u^c

$$\Delta B = -1/3$$

$\bar{\psi}_1 \to d_i^{c*}\tilde{d}_j^{c*}$ and $\bar{\psi}_1 \to \tilde{N}u_k^c,\ N\tilde{u}_i^c$

$$\epsilon_1 = \frac{1}{8\pi}\,\frac{\sum_{i,j,k}\mathrm{Im}\left(\lambda_{k1}^*\lambda_{k2}\lambda_{ij1}'^*\lambda_{ij2}'\right)}{\sum_{i,j}\lambda_{ij1}'^*\lambda_{ij1}' + \sum_k \lambda_{k1}^*\lambda_{k1}}\,\mathcal{F}_S\left(\frac{M_2^2}{M_1^2}\right)$$

where, for $M_2 - M_1 > \Gamma_{\bar{\psi}_1}$, we have

$$\mathcal{F}_S(x) = \frac{2\sqrt{x}}{x-1}.$$

Same asymmetry from ψ_1 and ψ_1^* decays since $\bar{\psi}_1$ and ψ_1^c form a four-component fermion with hypercharge quantum number $-4/3$.

In the limit of unbroken supersymmetry, we get exactly the same asymmetry from the decay of scalars $X_1,\ \bar{X}_1$ and their antiparticles $X_1^*,\ \bar{X}_1^*$. In the presence of supersymmetry breaking the asymmetries from fermion and scalar decays will be similar provided that $m_{1,2} \sim M_{1,2}$

Similarly, the decay of the scalar and fermionic components of $X_2, \bar{X}_2$ will result in an asymmetry ϵ_2, with $1 \leftrightarrow 2$.

$$\eta_B = 7.04 \times 10^{-6}\ \frac{1}{8\pi}\ \frac{M_1 M_2}{M_2^2 - M_1^2}\ \sum_{i,j,k} \mathrm{Im}\left(\lambda_{k1}^* \lambda_{k2} \lambda_{ij1}'^* \lambda_{ij2}'\right)$$
$$\times \left[\frac{\mathrm{Br}_1}{\sum_{i,j} \lambda_{ij1}'^* \lambda_{ij1}' + \sum_k \lambda_{k1}^* \lambda_{k1}} + \frac{\mathrm{Br}_2}{\sum_{i,j} \lambda_{ij2}'^* \lambda_{ij2}' + \sum_k \lambda_{k2}^* \lambda_{k2}}\right] .$$

Want: $4 \times 10^{-10} \leq \eta_B \leq 7 \times 10^{-10}$.

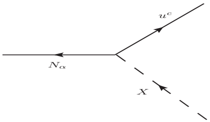
Assume similar couplings to all flavors of (s)quarks where $|\lambda_{i1}| \sim |\lambda_{i2}| \gg |\lambda_{ij1}'| \sim |\lambda_{ij2}'|$ ($1 \leq i, j \leq 3$), and *CP*-violating phases of $\mathcal{O}(1)$ in λ and λ'.

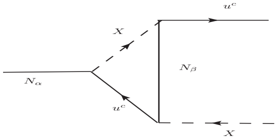
$$|\lambda_{i1}| \sim |\lambda_{i2}| \sim 1 \ \ , \ \ |\lambda_{ij1}'| \sim |\lambda_{ij2}'| \sim 0.04.$$

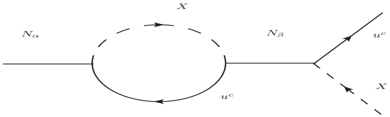
Can consider variations of the model

Single flavor of X, two flavors of singlets N

$$\begin{aligned} W_{extra} &= \lambda_{i\alpha} N_\alpha u_i^c X + \lambda'_{ij} d_i^c d_j^c \overline{X} \\ &+ \frac{M_{N_{\alpha\beta}}}{2} N_\alpha N_\beta + M_X X \overline{X} \end{aligned} \tag{2}$$


u^c
N_α
X


u^c
X
N_β
N_α
u^c
X


X
N_α
N_β
u^c
X
u^c

$$\epsilon_\alpha = \frac{\sum_{i,j,\beta} \mathrm{Im}\left(\lambda_{i\alpha}\lambda^*_{i\beta}\lambda^*_{j\beta}\lambda_{j\alpha}\right)}{24\pi \sum_i \lambda^*_{i\alpha}\lambda_{i\alpha}} \left[\mathcal{F}_S\left(\frac{M_\beta^2}{M_\alpha^2}\right) + \mathcal{F}_V\left(\frac{M_\beta^2}{M_\alpha^2}\right)\right]$$

where

$$\mathcal{F}_S(x) = \frac{2\sqrt{x}}{x-1} \ , \ \mathcal{F}_V = \sqrt{x}\,\ln\left(1+\frac{1}{x}\right)$$

Choose λs, can get required BAU

Other variations: singlets replaced by iso-doublet color triplet fields $Y, \overline{Y}$ with charges $\mp 5/3$.

$$\begin{aligned} W_{extra} &= \lambda_{i\alpha} Y Q_i X_\alpha + \lambda'_{ij\alpha} d_i^c d_j^c \overline{X}_\alpha \\ &+ M_Y Y \overline{Y} + M_{X,(\alpha)} X_\alpha \overline{X}_\alpha \end{aligned} \tag{3}$$

No parity-violating terms in the superpotential, the LSP is absolutely stable.

Dark matter is produced non-thermally. Annihilation cross-section must be enhanced.

The enhancement factor is given by $(T_f/T_r) \sim 50$, where $T_f \sim 10$ GeV is the freeze-out temperature of the LSP, and $T_r \sim 200$ MeV is the reheat temperature.

Conclusion

String moduli play interesting roles in cosmology and particle phenomenology

We looked at non-thermal production of baryon asymmetry

Constructed a model which satisfies the Sakharov conditions.

Stable LSP dark matter