Modulus Decay at the MeV Scale: From Problem to Progress?

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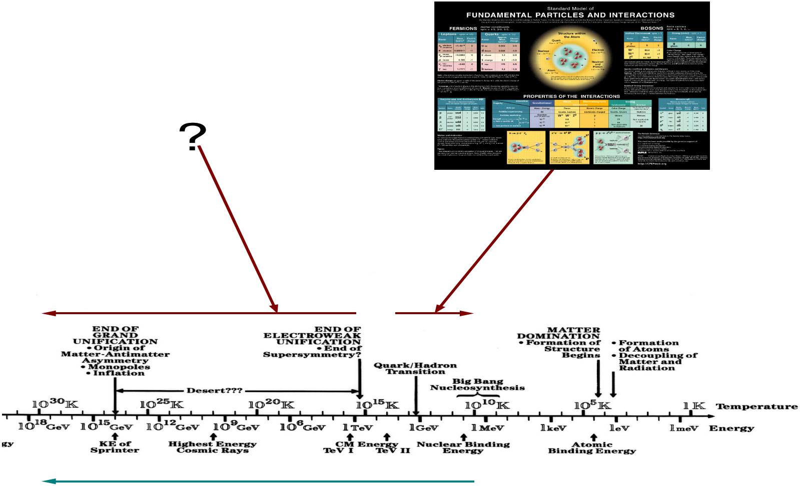
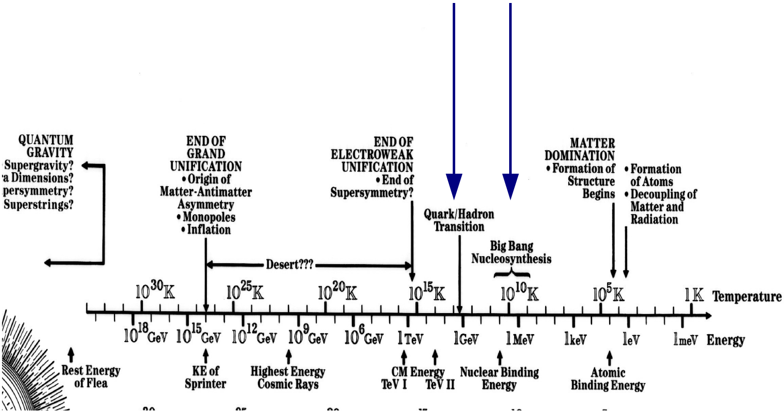


Radiation dominated?


QUANTUM GRAVITY
Supergravity?
a Dimensions?
persymmetry?
Superstrings?
END OF GRAND UNIFICATION
• Origin of Matter-Antimatter Asymmetry
• Monopoles
• Inflation
END OF ELECTROWEAK UNIFICATION
• End of Supersymmetry?
Quark/Hadron Transition
Big Bang Nucleosynthesis
MATTER DOMINATION
• Formation of Structure Begins
• Formation of Atoms
• Decoupling of Matter and Radiation
Desert???
10^{30}K
10^{25}K
10^{20}K
10^{15}K
10^{10}K
10^{5}K
1 K
Temperature
10^{18}GeV
10^{15}GeV
10^{12}GeV
10^{9}GeV
10^{6}GeV
1 TeV
1 GeV
1 MeV
1 keV
1 eV
1 meV
Energy
Rest Energy of Flea
KE of Sprinter
Highest Energy Cosmic Rays
CM Energy
TeV I
TeV II
Nuclear Binding Energy
Atomic Binding Energy

Mass: $\mathcal{O}(20)$ TeV - $\mathcal{O}(1000)$ TeV

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

In KKLT,

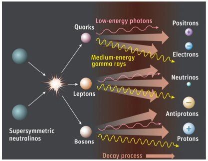
$$\begin{aligned} m_{3/2} &\simeq \frac{W_{\rm flux}}{(2\,{\rm Re}\,T)^{3/2}} \sim 30{\rm TeV}\ , \\ m_\sigma &\simeq F^{\bar{T}}_{,T} \simeq a\,{\rm Re}\,T\ m_{3/2} \sim 1000{\rm TeV}\ , \\ m_{\rm soft} &\simeq \frac{F_T}{{\rm Re}\,T} \sim \frac{m_{3/2}}{a\,{\rm ReT}}\ , \end{aligned}$$

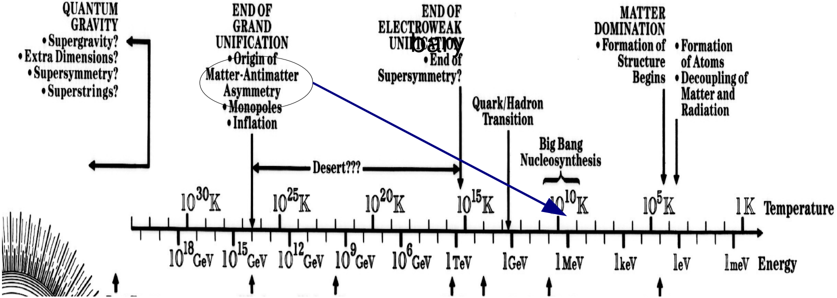
Effect through Decay

Decay very late: $T \sim 10$ MeV

Produces entropy, dilutes previously existing baryon asymmetry, thermally produced dark matter, etc.

Build new mechanisms of late-time baryon production, non-thermal dark matter. Changes dark matter annihilation cross-section, candidate.

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10^{12}GeV
10^{9}GeV
10^{6}GeV
1 TeV
1 GeV
1 MeV
1 keV
1 eV
1 meV
Energy

String moduli can affect early cosmology in dramatic ways

- Role through decay
  (*i*) Matter - anti matter asymmetry (main focus of this talk)
  arXiv:1005.2804 [PRD] (R. Allahverdi, B. Dutta, KS),
  arXiv:1008.0148 [PRD] (B. Dutta, KS)
  (*ii*) Remarkably, string moduli offer ways to connect dark matter physics and baryogenesis
  Work near completion
  (*iii*) Dark matter physics
  arXiv:0904.3773 [PRD] (B. Dutta, L. Leblond, KS)
  Many authors here
- Low-scale inflation: Effect on supersymmetry breaking?
  arXiv:0912.2324 [PRD] (R. Allahverdi, B. Dutta, KS)

Baryogenesis: A Classic Problem

- We see matter around us and not antimatter
- Cosmology teaches us that their abundances are equal in the early universe
- $\Rightarrow$ Intervening phase of Baryogenesis

$$\frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 6 \times 10^{-10}$$

- Sakharov (1968): (*i*) Violate baryon number B symmetry, (*ii*) Violate C and CP, (*iii*) Depart from thermal equilibrium
- Standard Model has all three but not enough

Lots of ways to do this

- Electroweak Baryogenesis
- Leptogenesis
- Affleck-Dine Baryogenesis

Need a mechanism that survives dilution from late-time modulus decay...

Outline

1. Examine initial conditions for Affleck-Dine baryogenesis
2. Propose late-time baryogenesis mechanism
3. Address baryon-dark matter coincidence problem

Affleck-Dine Baryogenesis

- Flat directions common in supersymmetric theories
- Finite energy density breaks SUSY $\rightarrow$ induces a SUSY breaking mass along ϕ. If this Hubble-induced mass is tachyonic, the field acquires a large vev during inflation.
- It starts to oscillate when the Hubble constant becomes smaller than the effective mass $V(\phi)'' \sim m_{3/2}$. The energy of the oscillations corresponds to a condensate of non-relativistic particles.
- Store baryon number in a condensate. After oscillations set in, a net baryon asymmetry may be produced depending on the magnitude of baryon number-violating terms in $V(\phi)$

$H_u L$: flat direction ϕ is given by

$$H_u = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ \phi\end{pmatrix}, \quad L = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi\\ 0\end{pmatrix}$$

MSSM flat directions are lifted by non-renormalizable terms in the superpotential

$$W = \frac{\lambda}{n M_P^{n-3}}\phi^n$$

$$\begin{aligned} V(\phi) &= (c_H H^2 + m_{\rm soft}^2)|\phi|^2 + \left(\frac{(A + a_H H)\lambda\phi^n}{n M_P^{n-3}} + \text{h.c.}\right) \\ &+ |\lambda|^2 \frac{|\phi|^{2n-2}}{M_P^{2n-6}} \end{aligned}$$

- For $H \gg m_{\rm soft}$, $c_H < 0$,

$$|\phi| \sim \left(\frac{\sqrt{-c} H M_P^{n-3}}{(n-1)\lambda} \right)^{\frac{1}{n-2}}$$

- n discrete vacua in the phase of ϕ, field settles into one of them.
- When $H \sim m_{\rm soft}$, ϕ oscillates around the new minimum $\phi = 0$
- Soft A-term becomes important and the field obtains a motion in the angular direction to settle into a new phase
- Baryon asymmetry

$$\frac{n_B}{n_\gamma} \sim 10^{-10} \left(\frac{T_{r,\rm inflaton}}{10^9\,\rm GeV} \right) \left(\frac{M_P}{m_{3/2}} \right)^{\frac{n-4}{n-2}}$$

Initial condition problem: is $c_H < 0$?

Strategy: Induce tachyonic masses along chiral superfields during inflation. Avoid tachyons in the final spectrum.

arXiv:1008.0148 [PRD] (B. Dutta, KS)

$D = 4,\ N = 1$ supergravity

$D = 4$, $N = 1$ supergravity

$$V = e^K \left(K^{i\bar{j}} D_i W D_{\bar{j}} \overline{W} - 3|W|^2 \right)$$

Kahler potential and superpotential

$$\boxed{\mathrm{K} = \widehat{K}(T_i, \overline{T}_i) + \widetilde{K}_{\alpha\overline{\beta}}(T_i, \overline{T}_i)\overline{\phi}^{\alpha}\phi^{\beta} + \dots}$$

$$\boxed{\mathrm{W} = \widehat{W} + \frac{1}{6} Y_{\alpha\beta\gamma}\phi^{\alpha\beta\gamma} \ .}$$

Normalize ϕ: $\phi_{\text{normalized}} = \widetilde{K}^{1/2}\phi$

Scalar masses

$$m_{\rm soft}^2 = m_{3/2}^2 + V_0 - F^i F^{\bar{j}} \partial_i \partial_{\bar{j}} \ln \widetilde{K} \ .$$

V_0 is the potential along the modulus, given by

$$V_0 = F^i F^{\bar{j}} \widehat{K}_{i\bar{j}} - 3 m_{3/2}^2 + V_D$$

where $F^i = e^{\widehat{K}/2} D_{\bar{j}} \widehat{K}^{i\bar{j}}$ and $m_{3/2}^2 = e^{\widehat{K}} |W|^2$.

hep-ph/9308271, hep-th/9303040

Inflation due to modulus σ

$$c_H = \frac{m^2}{H^2} \sim 1 - \widehat{K}^{\sigma\overline{\sigma}} \partial_\sigma \partial_{\overline{\sigma}} \ln \widetilde{K} + \frac{V_D}{V_0} \widehat{K}^{\sigma\overline{\sigma}} \partial_\sigma \partial_{\overline{\sigma}} \ln \widetilde{K} \ .$$

$$c_H \sim 1 - \widehat{K}^{\sigma\overline{\sigma}} \partial_\sigma \partial_{\overline{\sigma}} \ln \widetilde{K} \ .$$

$$\widehat{K} = -2 \ln \mathcal{V}$$

What about $\widetilde{K}$?

Say something based on holomorphy of W

hep-th/0609180, hep-th/0610129

$$W = \widehat{W} + \frac{1}{6} Y_{\alpha\beta\gamma}\phi^{\alpha\beta\gamma} \; .$$

$$\widehat{Y}_{\alpha\beta\gamma}(\tau_s, \mathcal{U}) = e^{\widehat{K}/2} \frac{Y_{\alpha\beta\gamma}(\mathcal{U})}{\left(\widetilde{K}_\alpha \widetilde{K}_\beta \widetilde{K}_\gamma\right)^{\frac{1}{2}}}$$

Should only depend on local geometric data τ_s and complex structure moduli $\mathcal{U}$, but not the overall volume $\Rightarrow$

$$\ln \widetilde{K} = \frac{1}{3}\widehat{K} + \ln k(\tau_s, \mathcal{U}) \; ,$$

$$c_H \sim 1 - \widehat{K}^{\sigma\overline{\sigma}} \partial_\sigma \partial_{\overline{\sigma}} \ln \widetilde{K} \ . \qquad \ln \widetilde{K} = \tfrac{1}{3} \widehat{K} + \ln k(\tau_s, \mathcal{U}) \ ,$$

- Energy density is dominated by a modulus that is not a local modulus of the visible sector

$$c_H = \frac{2}{3} \ .$$

- Energy density is dominated by a local modulus

$$c_H = \frac{2}{3} - \widehat{K}^{T_s \overline{T_s}} \partial_{T_s} \partial_{\overline{T_s}} \ln k(\tau_s, \mathcal{U}) \ .$$

Extricate local condition from global:

$$\partial_{T_s}\partial_{\overline{T_s}} \ln\, k(\tau_s, \mathcal{U}) > 0\ .$$

What can you say about $k(\tau_s, \mathcal{U})$? Not much...

Kahler potential data hard to calculate...

$$k(\tau) = k_0 + k_1 \tau^p + \ldots\ .$$

Inflation due to hidden sector scalar field ξ

- Planck suppressed operators mixing the visible and inflationary sectors in the Kahler potential induce negative masses by gravity mediation along flat directions if the dimensionless coupling is chosen appropriately.
- The contribution to soft masses from the hidden matter sector in the final stabilized vacuum at the end of inflation should be negligible.
- The inflationary dynamics should be compatible with moduli stabilization.

$$K = \widehat{K}(T_i) + K_{\text{hidden}}(\xi) + \widetilde{K}(T_i,\xi)\overline{\phi}\phi$$

$$\widetilde{K}(T_i,\xi) = \frac{1}{\mathcal{V}^{2/3}}(1+\gamma\,\overline{\xi}\xi)$$

$$W = \widehat{W}(T_i) + W_{\text{hidden}}(\xi)\,.$$

If the F-term for ξ dominates during inflation, we obtain for $\xi \ll 1$

$$c_H \sim 1-\gamma\ .$$

$$\boxed{c_H \sim 1 - \gamma}$$

For $\gamma > 1$, it is possible to obtain a negative induced mass during inflation.

$$m^2 \sim m_{3/2}^2 - \gamma \left| F^\xi \right|^2 \sim m_{3/2}^2 (1 - 3\gamma)$$

This leads to tachyons for $\gamma > 1$. To avoid tachyons and couplings that give rise to the flavor problem, the final supersymmetry breaking should not be matter dominated but sourced by another (sequestered) sector.

$$W(T) = W_{\text{flux}} + Ae^{-aT} + Be^{-bT}$$

$$V = e^{\widehat{K}} V(\xi) + V(T) + \mathcal{O}(\xi/M_p)$$

Take ξ as a pseudo-modulus. Supersymmetry preserving vacuum at $\xi = \xi_{\text{susy}}$. For $\xi \ll \xi_{\text{susy}}$, flat potential $\rightarrow$ inflation $\rightarrow$ rolls out to ξ_{susy}.

Try SQCD

$$\begin{aligned} W(\xi) &= hq_i\xi^i_j\tilde{q}^j - h\mu^2\xi^i_i \\ W_{np} &= N(h^{N_f}\Lambda_m^{-(N_f-3N)}\det\xi)^{1/N} \\ K(\xi) &= \xi^\dagger\xi + \tilde{q}^\dagger\tilde{q} + q^\dagger q \end{aligned}$$

$$V \sim \frac{1}{(T+\overline{T})^3}\mu^4 \ln(|\xi|^2) + V(T)$$

$$H \sim F^\xi \sim \mu^2, \;\; F^\xi \gg F^T \;\Rightarrow$$

$$H \sim \mu^2 \gg m_{3/2}$$

For $\gamma > 1$, the field ξ induces tachyonic masses along visible sector flat directions. Inflation ends with ξ rolling out to $\xi_{\rm susy}$, restoring supersymmetry.

Baryogenesis after modulus decay

Late-time Baryogenesis

Challenges:

- Sphaleron transitions are exponentially suppressed, thus rendering scenarios like electroweak baryogenesis and leptogenesis inapplicable.
- Baryon asymmetry by the direct decay of moduli, through *CP* and baryon number violating couplings to baryons.

$$W \supset \lambda T u^c d^c d^c / M_{\mathrm{P}}$$

Since $u^c d^c d^c$ is odd under R-parity, the Lightest Supersymmetric Particle (LSP) will be unstable unless $\langle T \rangle = 0$ at the minimum.

Strategy

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.

Cosmological history of modulus

Equation of motion of a scalar field with gravitational strength decay rate in a FRW background:

$$\ddot{\tau} + (3H + \Gamma_\tau)\dot{\tau} + V' = 0$$

$$\Gamma_\tau = \frac{c}{2\pi}\frac{m_\tau^3}{\Lambda^2}$$

- After inflation, the initial field vev is $\tau = \tau_{in}$
- For $H > m_\tau$, the friction term dominates, field frozen at $\tau = \tau_{in}$. Universe radiation dominated
- Oscillations start at temperature $T \sim \Gamma_\tau$. Matter dominated universe. Energy of τ dominates until it decays

Calculate reheat temperature

- At reheat, the lifetime of the modulus (Γ_τ^{-1}) is equal to the expansion rate at the time of reheating $t = \frac{2}{3H}$.
- Right after reheating the universe becomes radiation dominated with $H = \sqrt{\frac{\pi^2 g_*}{90}} \frac{T_r^2}{M_p}$

Combine, get

$$\begin{aligned} T_r &\approx \left(\frac{10.75}{g_*}\right)^{1/4} \sqrt{\Gamma_\tau M_p} \\ &= c^{1/2} \left(\frac{10.75}{g_*}\right)^{1/4} \left(\frac{m_\tau}{100\,\mathrm{TeV}}\right)^{3/2} \left(\frac{M_p}{\Lambda}\right) 5\,\mathrm{MeV}. \end{aligned}$$

Important quantity:

$$Y_\tau = \frac{n_\tau}{s} \sim \frac{3}{4}\frac{T_\mathrm{r}}{m_\tau}$$

$$= \left(\frac{m_\tau}{100\,\mathrm{TeV}}\right)^{1/2} \left(\frac{M_p}{\Lambda}\right) \times 5c^{1/2}\,10^{-8}$$

Estimates for baryogenesis

Net baryon asymmetry

$$10^{-10} \sim \eta = \frac{n_B - n_{\overline{B}}}{s} = \epsilon \frac{n_X}{s}$$

$$\frac{n_X}{s} = 2\frac{n_\tau}{s}(\mathrm{Br})_X = \frac{3}{2}\frac{T_r}{m_\tau}(\mathrm{Br})_X$$

$$10^{-10} = \epsilon \frac{3}{2}\frac{T_r}{m_\tau}(\mathrm{Br})_X$$

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

$$\frac{T_r}{m_\tau} \sim 10^{-7} - 10^{-8}$$

$$\Rightarrow \text{ Need } \epsilon \sim 10^{-1}$$

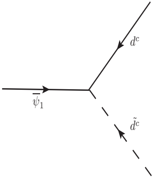
Typically, $\epsilon \sim \frac{1}{8\pi}\frac{\lambda^4}{\mathrm{Tr}\lambda^2}$

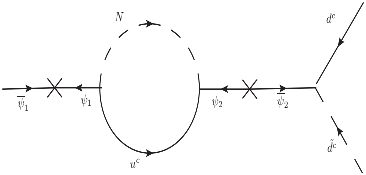
The Model

Two flavors of $X = (3, 1, 4/3)$, $\overline{X} = (\overline{3}, 1, -4/3)$
Singlet N
arXiv:1005.2804 [PRD] (R. Allahverdi, B. Dutta, KS)

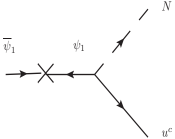
$$W_{extra} = \lambda_{i\alpha} N u_i^c X_\alpha + \lambda'_{ij\alpha} d_i^c d_j^c \overline{X}_\alpha + \frac{M_N}{2} NN + M_{X,(\alpha)} X_\alpha \overline{X}_\alpha \, . \qquad (1)$$

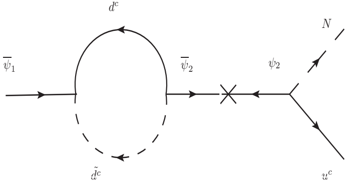
- $M \sim 500$ GeV. Can be obtained by the Giudice-Masiero mechanism if the modulus has non-zero F-term.
- $R-$parity conserving model $\rightarrow \mathrm{X} = (\mathrm{X}_{+1}, \psi_{-1})$ $N = (\tilde{N}_{-1}, N_{+1})$


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

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

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

Total asymmetry from $\bar{\psi}_1$ and $\bar{\psi}_1^*$ decays:

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

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 $1 \leftrightarrow 2$.

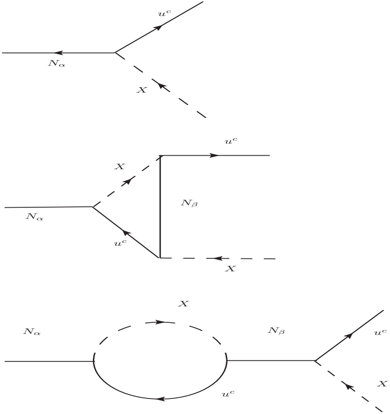
$$\eta = 10^{-7} \frac{1}{8\pi} \frac{M_1 M_2}{M_2^2 - M_1^2} \sum_{i,j,k} \mathrm{Im}\left(\lambda^*_{k1}\lambda_{k2}\lambda'^*_{ij1}\lambda'_{ij2}\right)$$
$$\times \left[\frac{\mathrm{Br}_1}{\sum_{i,j}\lambda'^*_{ij1}\lambda'_{ij1} + \sum_k \lambda^*_{k1}\lambda_{k1}} + \frac{\mathrm{Br}_2}{\sum_{i,j}\lambda'^*_{ij2}\lambda'_{ij2} + \sum_k \lambda^*_{k2}\lambda_{k2}}\right].$$

For $|\lambda_{i1}| \sim |\lambda_{i2}| \sim |\lambda'_{ij1}| \sim |\lambda'_{ij2}|$ and *CP* violating phases of $\mathcal{O}(1)$ in λ and λ', we need couplings $\sim \mathcal{O}(0.1 - 1)$ to generate the correct asymmetry.

Variations

Single flavor of X, two flavors of singlets N

$$W_{extra} = \lambda_{i\alpha} N_\alpha u_i^c X + \lambda'_{ij} d_i^c d_j^c \overline{X} + \frac{M_{N_{\alpha\beta}}}{2} N_\alpha N_\beta + M_X X\overline{X} \quad (2)$$


u^c
N_α
X
u^c
X
N_β
N_α
u^c
X
X
N_α
N_β
u^c
u^c
X

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

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 $\mp 5/3$.

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

Comments on Phenomenology

Stable LSP dark matter

$(X, \bar{X})$ pair produced at LHC $\rightarrow$ cascade decays into LSP neutralino via squarks, heavier neutralinos, charginos and sleptons $\rightarrow$ final states contain multi jets plus multi leptons and missing energy $\rightarrow$ $M_{\rm eff}$ of four highest E_T jets and missing energy gives mass scale of X.

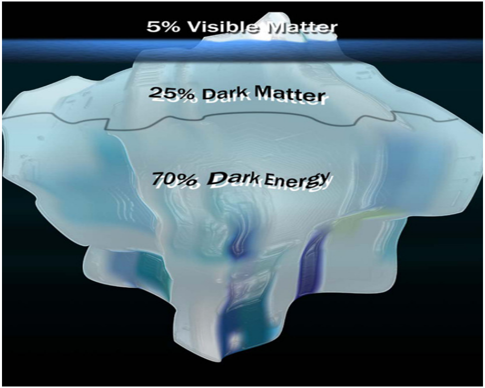
$\mathrm{n} - \bar{\mathrm{n}}$ oscillations

$$G = \frac{\lambda_1^2 \lambda_{12}'^2}{M_X^4 M_N} (u^c d^c s^c)^2$$

Oscillation time $t = 1/(2.5 \times 10^{-5}\, G) < 0.86 \times 10^8$ sec $\Rightarrow$ G < $3 \times 10^{-28}\ \mathrm{GeV}^{-5}$

Using this bound, for $M_X \sim M_N \sim 1$ TeV, we find $(\lambda_1\ \lambda_{12}') < 10^{-4}$

Non-thermal Approach to the Dark Matter - Baryon Coincidence Problem



Why is $\Omega_{\rm baryon} \sim \Omega_{\rm darkmatter}$?

Common origin from modulus decay near 1 MeV gives a natural answer...

Y_τ naturally small

$$Y_\tau = \frac{n_\tau}{s} \sim \frac{3\,T_r}{4\,m_\tau} \sim 10^{-7} - 10^{-8}$$

$$\frac{n_{\rm b} - n_{\bar{\rm b}}}{s} \sim 10^{-10}\,,$$

$$\frac{n_{\rm b} - n_{\bar{\rm b}}}{s} = Y_\tau\,\epsilon\,({\rm Br})_N$$

Count degrees of freedom $\rightarrow$ $({\rm Br})_N \sim 1\% - 10\%$

ϵ is loop-suppressed

Baryogenesis occurs naturally in non-thermal scenarios...

Strategy

- LSP and N both produced from modulus τ decay
- Physics of annihilation is particular to the dark sector. Makes sense to render annihilation irrelevant $\rightarrow$ use Y_τ
- Number densties n_χ and $n_{\rm b}$ related by simple branching fractions
- In the absence of symmetries, branching fractions similar

$$
\begin{aligned}
\frac{d\rho_\tau}{dt} &= -3H\rho_\tau - \Gamma_\tau \rho_\tau \ , \\
\frac{d\rho_R}{dt} &= -4H\rho_R + (m_\tau - N_{LSP} m_\chi)\Gamma_\tau n_\tau + \langle \sigma v \rangle 2m_\chi \left[n_\chi^2 - \left(n_\chi^{eq}\right)^2 \right] \ , \\
\frac{dn_\chi}{dt} &= -3Hn_\chi + N_{LSP}\Gamma_\tau n_\chi - \langle \sigma v \rangle \left[n_\chi^2 - \left(n_\chi^{eq}\right)^2 \right]
\end{aligned}
$$

- Modulus decays when $H \sim \Gamma_\tau$. Initial condition: modulus dominates energy density at the freeze-out of χ.
- χ is non-relativistic at the time of freeze-out (with $n_\chi^{eq} = g_* \left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T}$) and reaches equilibrium before reheating occurs.

- Dark matter freeze-out occurs when the annihilation rate is equal to the rate of expansion

$$\Gamma_\chi = n_\chi^{eq}(T_f) \langle \sigma v \rangle = H(T_f) \ .$$

- $T_f \sim m_\chi/20 \sim 1$ GeV
- Entropy production during reheat with $T_r \sim 1$ MeV dilutes the initial density of dark matter by a factor of $T_r^3/T_f^3 \sim 10^{-9}$.
- Number density of non-thermally produced dark matter $\rightarrow$ if dark matter overproduced by modulus it annihilates back into radiation $\Rightarrow$ Maximal density of dark matter is

$$n_\chi^{eq}(T_r) \sim \frac{3H(T_r)}{2\langle \sigma v \rangle} \sim \frac{3\Gamma_\tau}{2\langle \sigma v \rangle}$$

$$\Rightarrow \; Y_\chi(T) \equiv \frac{n_\chi}{s(T)} \; = \sqrt{\frac{45}{8\pi^2 g_*}} \frac{1}{M_p T_r \langle \sigma v \rangle}$$

- For small N_{LSP},

$$Y_\chi(T) \equiv \frac{n_\chi}{s(T)} \; = \; B_{\tau \to \chi} Y_\tau$$

Therefore,

$$Y_\chi(T_r) = \min \left(\mathrm{Br}_\chi \mathrm{Y}_\tau \;\; , \;\; \sqrt{\frac{45}{8\pi^2 \mathrm{g}_*}} \frac{1}{\mathrm{M_p T_r} \langle \sigma \mathrm{v} \rangle} \right) \; .$$

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Consider $\mathrm{Br}_\chi \sim 10^{-3}$, $Y_\tau \sim 10^{-7} - 10^{-9}$ $\Rightarrow$ for annihilation to be important, need very large annihilation cross-section

$$\frac{\Omega_b}{\Omega_{DM}} \sim \frac{1}{5} = \frac{m_b}{m_\chi} \times \frac{Y_b}{Y_\chi}$$

$$= \quad \frac{m_b}{m_\chi} \times \frac{\epsilon \, \mathrm{Br}_N}{\mathrm{Br}_\chi}$$

We know that for $Y_\tau \sim 10^{-8}$

$$\epsilon \sim 0.1, \mathrm{Br}_N \sim 0.1$$

Therefore

$$m_b \sim 50\mathrm{GeV} \;\; \mathrm{for} \;\; \mathrm{Br}_\chi \sim 10^{-3}$$

Decay modes of the modulus

Consider Kahler moduli in type IIB string theory

- The gauginos and gauge bosons couple through the gauge kinetic function. We consider a scenario in which the visible sector is constructed on D7 branes wrapping a cycle Σ, with gauge coupling given by $1/g^2 = V(\Sigma)$, where $V(\Sigma) = \mathrm{Re}\, T = \tau$ is the volume of Σ in string units.
- Visible sector fermions and scalars couple to the modulus through the Kahler potential and soft terms.

Normalize moduli:

$$(\tau)_i \; = \; \sum_j \; C_{ij} \, (\tau_n)_j$$

where the C_{ij} are eigenvectors of the matrix $K^{-1} \, \partial^2 V$.

Decays to Gauge Bosons

$$\begin{aligned}\mathcal{L}_{\tau gg} &= (\mathrm{Re}f)\left(-\frac{1}{4}\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}\right) \\ &= \frac{-1}{4M_{\mathrm{P}}}\langle \mathrm{Re}f\rangle \langle \sum_j \partial_{\tau_i}\mathrm{Re}f\rangle\, C_{ij}(\tau_n)_j \mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}\end{aligned}$$

For simplicity, assume that τ_i is predominantly aligned along a single normalized eigenstate τ_n, with a coefficient C_i.

$$\Gamma_{T_i \to \mathrm{gauge}} = \frac{N_g}{128\pi}\,\frac{1}{\langle\tau\rangle^2}\,C_i^2\,\frac{m_{T_i}^3}{M_{\mathrm{P}}^2}$$

where $N_g = 12$ is the number of gauge bosons.

Decays to Gauginos

$$\mathcal{L}_{\tau_i\lambda\lambda} = \mathrm{Re} f\left(-\frac{1}{2}\bar{\lambda}\mathcal{D}\lambda\right) + \frac{1}{4} F^i\,\partial_i f^*\bar{\lambda}_R\lambda_R + \mathrm{h.c.}$$

$$\mathcal{L}_{T_i\lambda\lambda} \supset \frac{1}{4M_\mathrm{P}}\sum_p\left(\left\langle\partial_p F^i\right\rangle\, T_p + \left\langle\partial_{\bar{p}} F^i\right\rangle\, \bar{T}_p\right)\bar{\lambda}_R\lambda_R + \mathrm{h.c.}$$

$$T_p = C_p (T_n)_p$$

$$\Gamma_{T_i\to\tilde{g}\tilde{g}} = \sum_p \frac{N_g}{128\pi}\, C_p^2\,\left\langle\partial_p F^i\right\rangle^2 \frac{m_{T_i}^3}{M_\mathrm{P}^2}$$

$$\Gamma_{T_i^*\to\tilde{g}\tilde{g}} = \sum_p \frac{N_g}{128\pi}\, C_p^2\,\left\langle\partial_{\bar{p}} F^i\right\rangle^2 \frac{m_{T_i}^3}{M_\mathrm{P}^2}$$

Decay to Visible Sector Fermions and Scalars

$$K \supset \widetilde{K}(\tau)\bar{\phi}\phi \tag{4}$$

$$\Gamma \sim \left\langle \widetilde{K} \right\rangle^{-1} \left\langle \partial_\tau \widetilde{K} \right\rangle^2 \frac{m_{\text{soft}}^2}{m_\tau^2} \sim \frac{m_{\text{soft}}^2}{m_\tau^2} \tag{5}$$

Suppressed

Typically unsuppressed two-body decays of τ to Higgs

$$K \supset \widetilde{K}(\tau)\bar{\phi}\phi + Z(\tau)\, H_u H_d$$

$$\Gamma \sim \frac{1}{8\pi}\, C_i^2\, \frac{1}{\tilde{K}}\, (\partial_i Z)^2\, \frac{m_{T_i}^3}{M_{\mathrm{P}}^2}$$

There is no branching to a fermionic LSP through this channel.

Decay to Gravitino

$$\mathcal{L} = \frac{1}{4}\epsilon^{k\ell mn}\left(G_{,T_i}\partial_k T - G_{,T_i^*}\partial_k T^*\right)\bar{\psi}_\ell\bar{\sigma}_m\psi_n - \frac{1}{2}e^{G/2}\left(G_{,T_i}T + G_{,T_i^*}T_i^*\right)\left[\psi_m\sigma^{mn}\psi_n + \bar{\psi}_m\bar{\sigma}^{mn}\bar{\psi}_n\right],$$

where $G = K + \log|W|^2$ is the Kahler function. The decay width to helicity $\pm 1/2$ components is given by

$$\Gamma_{T_i\to\mathrm{gravitino}} \sim \frac{1}{288\pi}\left(|G_{T_i}|^2 K^{-1}_{T_i\bar{T}_i}\right)\frac{m_T^2}{m_{3/2}^2}\frac{m_{T_i}^3}{M_{\mathrm{P}}^2}$$

Branching Conditions

Case 1:

The modulus decays mainly to Higgs bosons. For a fermionic LSP, this channel produces small branching fraction to dark matter.

$$\frac{\langle \tau_i \rangle}{\tilde{K}} (\partial_\tau Z) \ \sim \ 10 - 30$$

Low reheat:

$$\frac{1}{\langle \tau \rangle} C_i \sim 0.1$$

Case 2:

Decays gauge bosons, Higgs.

Gaugino and gravitino channel are suppressed.

$$\begin{aligned}
\text{Low reheat} \quad \frac{1}{\langle\tau\rangle} C_i &\sim 1 \\
\text{Gaugino suppression} \quad \sum_p \frac{C_p(\partial_p F^{T_i})}{m_{T_i}} &\sim 10^{-1} - 10^{-2} \\
\text{Gaugino suppression} \quad \sum_p \frac{C_p(\partial_{\bar{p}} F^{T_i})}{m_{T_i}} &\sim 10^{-1} - 10^{-2} \\
\text{Gravitino suppression} \quad \frac{m_{T_i}}{m_{3/2}} |G_{T_i}| K_{T_i \bar{T}_i}^{-1/2} &\sim 0.1
\end{aligned}$$

Conditions on branching to LSP can be made even milder for $Y_\tau \sim 10^{-9}$

Can happen if the overall constant c in the decay width $\Gamma_\tau = \frac{c}{2\pi}\frac{m_\tau^3}{M_p^2}$ of the modulus takes on extremely small values

Physically: a compactification with large volume $\mathcal{V}$, and a number of local geometric moduli that are decoupled in the Kahler metric by powers of $1/\mathcal{V}$. In that case, going to the eigenbasis ϕ_i of $K^{-1}\partial^2 V$, one obtains

$$\tau_i \,=\, \mathcal{O}(\mathcal{V}^{p_i})\,\phi_i \,+\, \sum_{j\neq i}\mathcal{O}(\mathcal{V}^{p_j})\,\phi_j \ , \tag{6}$$

with $p_j < p_i$.

Conclusion

- Interesting physics near the MeV scale
- Baryogenesis is a challenge, but very natural methods exist
- Coincidence problem becomes simpler to address. Reason: Y_τ is small, and remarkably close to the observed abundance of baryons and dark matter. Y_τ is small because moduli interact gravitationally (that's also why they decay late).
- Don't throw away a small number you got for free!