Moduli and Dark Matter Problem in the G_2-MSSM Scenario

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Motivation

The presence of moduli is generic in string theory compactification

- Cosmological moduli problem
  - Moduli fields should decay before BBN in order not to spoil the success of the standard big bang cosmology.
  - Moduli decay to gravitino, if not suppressed, is dangerous $\Longrightarrow m_{3/2} > 10^5$ GeV.
  - Moduli decay to stable neutralino LSP, the abundance should not overclose the universe $\Longrightarrow m_{3/2} > 10^6$ GeV
- In scenarios with wino LSP, thermal dark matter relic density is too small to be consistent with current data.
- Can both problems be solved in a consistent string-motivated beyond SM physics?
- Yes, the G_2-MSSM scenario probably provides a solution.

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Moduli in early universe

The dynamics of modular fields

$$\ddot{\Phi} + (3H + \Gamma_\phi)\dot{\Phi} + \frac{\partial V}{\partial \Phi} = 0$$

- After adequate inflation and reheating, when $H \gg m_\Phi$, modular fields are expected to be displaced by an amount of $\mathcal{O}(m_p)$ from their true minimum.
- When $H < m_\Phi$, moduli will start coherent oscillation and quickly dominate the energy density as pressureless matter
- May worry about the “overshooting problem” here, may be solved by other ideas.

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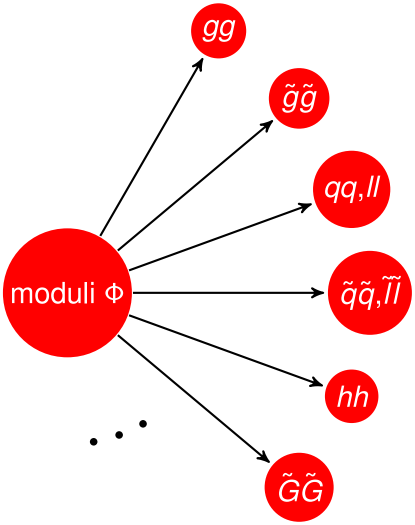
Moduli decay and BBN constraint



- gravitational interaction; decay width

$$\Gamma_\Phi = D_\Phi \frac{m_\Phi^3}{m_p^2}$$

- D_Φ is determined by all the possible couplings to light fields; generally less than one.
- Light moduli usually suffer from the constraint from BBN.
- KKLT, Large Volume Compactification

Moduli decay and generation of dark matter

The evolution of LSPs are given by the Boltmann equation

$$\dot{n}_{LSP} = -3Hn_{LSP} - \langle \sigma v \rangle \left[n_{LSP}^2 - n_{eq}^2 \right], \qquad (1)$$

where $\langle \sigma v \rangle$ is the thermally averaged cross-section, n_{LSP} is the number density, and n_{eq} is the number density of the species in chemical equilibrium.

- Moduli decay to LSPs with branching ratio B_{LSP}.
- Typical Reheat temperature $T_R \sim \sqrt{\Gamma_\Phi m_p} \sim MeV$
- LSP freeze-out temperature $T_f \sim \frac{1}{30} m_\chi \sim GeV$
- LSP $T_R \ll T_f$, so the produced LSPs is out of chemical equilibrium

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Brief review of G_2-MSSM scenario

Consider M-theory compacitification on singular G_2 manifold with no background flux

- Gauge fields on codim 4 ADE-like singularity
- Chiral matter fields on codim 7 conical singularities
- Assume MSSM can be realized by local engineering of singularities.
- Supersymmetry is broken by gaugino condensation in hidden sector
- The Planck scale mediation is generic
  - gaugino masses are suppressed relative to gravitino mass by the volume of hidden sector three cycles; Wino LSP is generic in the allowed parameter space.
  - generically unsequestered $\Longrightarrow$ scalar masses $\sim m_{3/2}$;
  - gravitino mass $m_{3/2} \sim 10 - 100$ TeV consistent with the light gaugino spectrum

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The modular fields of G_2 manifold $z_i = t_i + is_i$ can be stabilized by non-perturbative superpotential

- dS minimum obtained by F-term uplifting with meson field ϕ in the hidden sector
- For an explicit example, consider two hidden sectors with non-Abelian gauge theories $SU(P)$ and $SU(Q)$.
- The moduli Kähler potential and superpotential

$$\begin{aligned} K/m_p^2 &= -3\ln(4\pi^{1/3}V_7) + \bar{\phi}\phi \\ W/m_p^3 &= C_1\, P\, \phi^{-(2/P)}\, e^{ib_1 f_1} + C_2\, Q\, e^{ib_2 f_2}; \end{aligned}$$

  - Volume of G_2 manifold $V_7 = \prod_{i=1}^{N} s_i^{a_i}$ with $\sum_{i=1}^{N} a_i = \frac{7}{3}$, roughly $a_i \sim \frac{1}{N}$
  - β function coefficient $b_1 = \frac{2\pi}{P}$, $b_2 = \frac{2\pi}{Q}$,
  - Gauge kinetic functions $f_1 = f_2 = f_{\rm hid} = \sum_{i=1}^{N} N_i z_i$
- The particular solution: $Q - P = 3$, $V_{\mathcal{Q}_{\rm hid}} \sim \frac{P_{\rm eff} Q}{6\pi}$, $P_{\rm eff} \sim 80$

Moduli Masses

The mass matrix for the canonical normalized modular fields $\delta s_i'$ and $\delta\phi$

$$M_{\alpha\beta} = \left(\begin{array}{c|c} M_{ij} = (a_i a_j)^{1/2} K_1 + \delta_{ij} K_2 & M_{i\phi} = a_i^{1/2} K_3 \\ \hline M_{\phi j} = a_i^{1/2} K_3 & M_{\phi\phi} = K_4 \end{array} \right) m_{3/2}^2$$

where K_i are functions of $V_{\mathcal{Q}_{hid}}$ and Q.

$$\begin{aligned} K_1 &= \frac{16}{9261} \left(\frac{Q}{Q-3} \right)^2 P_{\text{eff}}^4 \\ K_2 &= \frac{22}{3} - \frac{8}{9\phi_0^2} - 2\phi_0^2 - (1 + \frac{2}{3\phi_0^2}) \frac{36}{P_{\text{eff}}} \\ K_3 &= \sqrt{\frac{2}{3}} \left(\frac{16}{1323} \right) \left(\frac{Q}{Q-3} \right)^2 \frac{P_{\text{eff}}^3}{\phi_0} \\ K_4 &= \frac{32}{567} \left(\frac{Q}{Q-3} \right)^4 \frac{P_{\text{eff}}^4}{\phi_0^2} \end{aligned}$$

Moduli Masses

- The mass matrix can be diagonalized analytically
- $N-1$ light eigenstates X_i with mass $K_2^{1/2} m_{3/2}$, one heavy eigenstate with mass $(\frac{7}{3}K_1 + K_2)^{1/2} m_{3/2}$
- The heavy modulus corresponds to volume of three-cycle

$$X_N = \sqrt{\frac{3}{7}} \sum_{k=1}^{N} \sqrt{a_k}\, \delta s'_k$$

where $\delta s'_i = \sqrt{\frac{3a_i}{2s_i^2}}\, \delta s_i$.

- The meson field ϕ has almost no mixing with other moduli, but the mass of meson is affected significantly.
- Moduli masses

$$m_{X_i}, m_\phi \lesssim 2m_{3/2}, \quad m_{X_N} \sim 600 m_{3/2}$$

Moduli couplings

The coupling of moduli to MSSM fields can be obtained by expanding the effective $N = 1$ supergravity lagrangian

- moduli X_j coupling to gauge bosons
  $\mathcal{L}_{X_j gg} = \frac{1}{4\, f_{sm}} \sum_{i=1}^{N} N_i^{sm} \frac{2\langle s_i \rangle}{\sqrt{3a_i}} U_{ij}\, X_j F^a_{\mu\nu} F^{a\mu\nu}$
- Generically, couplings to gauginos and gauge bosons are
  $g_{X_j gg} \sim \frac{N_i^{sm}}{N_i} \sqrt{a_i} \sim \frac{1}{\sqrt{N}}$
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- moduli coupling to squarks and sleptons can be derived from $\int d^4\theta \tilde{K}_\alpha Q^*_\alpha Q_\alpha, \Longrightarrow \mathcal{L} \sim m^2_{\tilde{f}} \partial_{s_i} \log(\tilde{K}_\alpha) \sqrt{\frac{2s_i^2}{a_i}} U_{ij} X_j \tilde{f}^*_\alpha \tilde{f}_\alpha$
- $g_{X_j \tilde{f}\tilde{f}} \sim \frac{2\langle s_i \rangle}{\sqrt{3a_i}} \partial_{s_i} \log(\tilde{K}_\alpha) \sim \frac{\xi_{i,\alpha}}{\sqrt{a_i}} \sim \sqrt{N}$.
- moduli couplings to higgs fields are similar to squark and sleptons. However, for heavy modulus, there is an enhancement in the coupling to higgs fields through $\int d^4\theta Z(s_i) H_d H_u$.

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Moduli decay widths

Summary of the result

- Light moduli and meson decay to LSP and SM particles with branching ratios of the same order.
- Heavy modulus decay dominantly to higgs fields
- The decay width is enhanced by a factor $\sim N$
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Total decay width

- Typical decay widths and reheating temperatures
  - $\Gamma_{X_i}^{-1} \sim 10^{-3}$ s, $T_R(X_i) \sim 30$ MeV
  - $\Gamma_{\phi}^{-1} \sim 10^{-5}$ s, $T_R(\phi) \sim 100$ MeV
  - $\Gamma_{X_N}^{-1} \sim 10^{-10}$ s, $T_R(X_N) \sim 40$ GeV
- As universe expands, oscillating modular fields undergo sequential decays, reheat the universe to higher temperature.
- The entropy produced from light moduli dilute the LSP and gravitino produced at early time.
- $(N-1)$ light modular fields provides sufficient dilution, but the neutralino abundance will be regenerated.

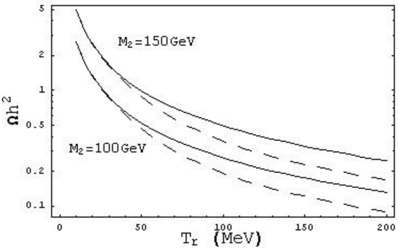
Dark matter relic density

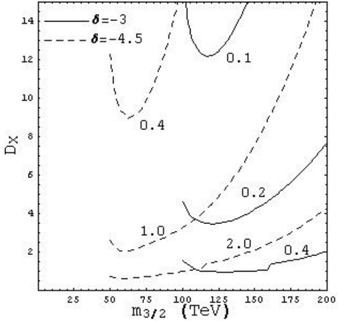
- LSP from X_i decay is too abundant $\Longrightarrow$ quick annihilation to fixed point value
- For Wino LSP, the LSP relic density now

$$
\begin{aligned}
\Omega_{LSP}^{X_i} &= \frac{m_{LSP} Y_{LSP}^c}{\rho_c / s_0} \\
&= \frac{1}{\rho_c / s_0} \left(\frac{45}{2\pi \sqrt{10 g_*} \sigma_0} \right) \left(\frac{m_{LSP}^3}{m_p T_r^{X_i}} \right) \\
&\sim \frac{m_{LSP}^{3/2}}{D_{X_i}^{1/2}} \left(\frac{m_{LSP}}{m_{3/2}} \right)^{3/2}
\end{aligned}
$$

moduli decay and reheating

- LSP relic density is generically less than one in the range of phenomenological interesting region; light gauginos and heavy gravitino (several tens of TeV)
  e.g. Take $m_{LSP} = 100$ GeV, $\left(\frac{m_{LSP}}{m_{3/2}}\right) = 10^{-3}$, $\Omega_{LSP}^{X_i} \sim 0.2$
- larger moduli-matter coupling and large hierarchy between gaugino masses and gravitino mass are preferred to get close to the correct relic density





Conclusion

- In G_2-MSSM scenario, the moduli-matter coupling is enhanced; Moduli could decay well before BBN.
- The moduli decay to LSP is unsuppressed. But the reheating temperature of moduli is high enough such that the LSPs abundance generated is within the right order of magnitude of the observed dark matter relic density.
- This way of generating dark matter can also work in other string-motivated models with Wino LSP and suppressed gaugino mass. It would be interesting to find some explicit constructions.