SUSY dark matter, catalyzed BBN and heavy moduli decay with gravitino LSP and stau NLSP

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Introduction

- Combined observational data suggest that we need dark matter
- Standard big bang nucleosynthesis (BBN) very successful, however Lithium problems
- Catalyzed BBN can solve the problem. Consider a heavy unstable negatively charged particle X^- which can form Coulomb bound states together with Helium 4. Then the following reaction

$$(^4HeX^-) + D \rightarrow ^6 Li + X^- \tag{1}$$

can affect the primordial light element abundances substantially. The Lithium 6 observations can constrain the properties of X^-, and in particular its lifetime

We need candidates for dark matter and X^- particle

The model

- We work within mSUGRA model assuming

a) gravitino (LSP) is dark matter, and

b) stau (NLSP) is X^- particle

- The parameters of the model $(sign(\mu), tan\beta, m_0, m_{1/2}, A_0)$

- Gravitino mass $m_{3/2} = m_0$

- Neutralino and stau masses

$$\begin{aligned} m_\chi &\simeq 0.42 m_{1/2} & (2) \\ m_{\tilde{\tau}}^2 &\simeq m_0^2 + 0.15 m_{1/2}^2 & (3) \end{aligned}$$

In the limit $m_0 \ll m_{1/2}$, the stau mass $m_{\tilde{\tau}} \simeq 0.387 m_{1/2}$ and stau is lighter than neutralino

Basics of moduli fields

- Appear generically in higher dimensional theories $D > 4$ upon compactification down to 4d
- Scalar fields with a potential and a mass
- Parameterize the shape and size of the manifold used for $D \longrightarrow 4$
- Vevs typically of the order of M_p
- Gravitational interactions suppressed by Planck mass, $\sim 1/M_p$

Basics of moduli fields (Continued)

- Normally masses close to gravitino mass, $m_T \simeq 4\pi^2 m_{3/2}$ (bad for phenomenology and model building)

- BUT: with fine-tuning we can have heavy modulus and light gravitino

Analysis (general)

$$0.075 < \Omega_{cdm} h^2 = \Omega_{3/2} h^2 < 0.126 \qquad (4)$$

Introducing $Y \equiv n/s, s = h_{eff} 2\pi^2 T^3/45$, compute total $Y_{3/2} = Y_{3/2}^{TP} + Y_{3/2}^{NLSP} + Y_{3/2}^{modulus}$

$$\Omega_{3/2} h^2 = \frac{m_{3/2} s(T_0) Y_{3/2} h^2}{\rho_{cr}} = 2.75 \times 10^8 \left(\frac{m_{3/2}}{GeV} \right) Y_{3/2}(T_0) \qquad (5)$$

where we have used the values

$$\begin{aligned} T_0 &= 2.73K = 2.35 \times 10^{-13}\ GeV && (6) \\ h_{eff}(T_0) &= 3.91 && (7) \\ \rho_{cr}/h^2 &= 8.1 \times 10^{-47}\ GeV^4 && (8) \end{aligned}$$

Analysis (production from thermal bath)

Integrate Boltzmann eqn

$$\dot{n}_{3/2} + 3Hn_{3/2} = C(T) \tag{9}$$

where the collision term $C(T)$ is computed using thermal field theory

$$C(T) \sim T^6/M_p^2 \tag{10}$$

Using the yield $Y_{3/2}$ Boltzmann eqn becomes

$$\frac{dY}{dT} = \frac{C(T)}{Ts(T)H(T)} \tag{11}$$

and upon integration it gives

$$Y_{3/2}^{TP} = 1.1 \times 10^{-12} \left(\frac{T_R}{10^{10}\ GeV} \right) \tag{12}$$

Analysis (production from NLSP decay)

The second contribution comes from NLSP decay

$$\Omega_{3/2}^{NLSP} h^2 = \frac{m_{3/2}}{m_{NLSP}} \Omega_{NLSP} h^2 \tag{13}$$

with $\Omega_{NLSP} h^2$ the NLSP abundance had it did not decay into the gravitino, which for the stau is estimated to be

$$\Omega_{\tilde{\tau}} h^2 \simeq \left(\frac{m_{\tilde{\tau}}}{2\ TeV} \right)^2 \tag{14}$$

The decay width of stau to tau and gravitino is given by

$$\frac{1}{\tau_{\tilde{\tau}}} = \Gamma(\tilde{\tau} \rightarrow \tau + \psi_{3/2}) = \frac{1}{48\pi M_p^2} \frac{m_{\tilde{\tau}}^5}{m_{3/2}^2} \left(1 - \frac{m_{3/2}^2}{m_{\tilde{\tau}}^2} \right)^4 \tag{15}$$

In the limit in which $m_{3/2} \ll m_{\tilde{\tau}}$ the stau lifetime is simplified as follows

$$\tau_{\tilde{\tau}} = 6.1 \times 10^3 \ sec \left(\frac{m_{3/2}}{100 \ GeV} \right)^2 \left(\frac{1000 \ GeV}{m_{\tilde{\tau}}} \right)^5 \qquad (16)$$

Catalyzed BBN works when stau lifetime ranges within the interval

$$10^3 \ sec < \tau_{\tilde{\tau}} \leq 5 \times 10^3 \ sec \qquad (17)$$

Using that $m_{3/2} = m_0$, $m_{\tilde{\tau}} = 0.387 m_{1/2}$ we find the bounds

$$426 \left(\frac{m_0}{GeV} \right)^{2/5} \ GeV \leq m_{1/2} < 588 \left(\frac{m_0}{GeV} \right)^{2/5} \ GeV \qquad (18)$$

E.g. if $m_0 = 100$ GeV then $2.69 \ TeV \leq m_{1/2} < 3.71 \ TeV$

Analysis (production from modulus decay)

The last contribution comes from heavy modulus decay

$$Y_{3/2}^{modulus} = \frac{3}{2}\frac{\Gamma_{3/2}}{\Gamma_{tot}}\frac{T_R}{m_X} \tag{19}$$

where

$$\Gamma_{tot} \equiv \Gamma(X \to all) = \frac{3}{16\pi}\frac{m_X^3}{M_p^2} \tag{20}$$

and

$$\Gamma_{3/2} = \frac{1}{288\pi}\frac{m_X^3}{M_p^2} \tag{21}$$

in the limit in which $m_X \gg m_{3/2}$. Therefore the branching ratio

$$Br(X \to \psi_{3/2}\psi_{3/2}) = \frac{\Gamma_{3/2}}{\Gamma_{tot}} = \frac{1}{54} \sim 0.01 \tag{22}$$

$$T_R = \left(\frac{90}{\pi^2 g_*(T_R)}\right)^{1/4} \sqrt{\Gamma_{tot} M_p} \tag{23}$$

or

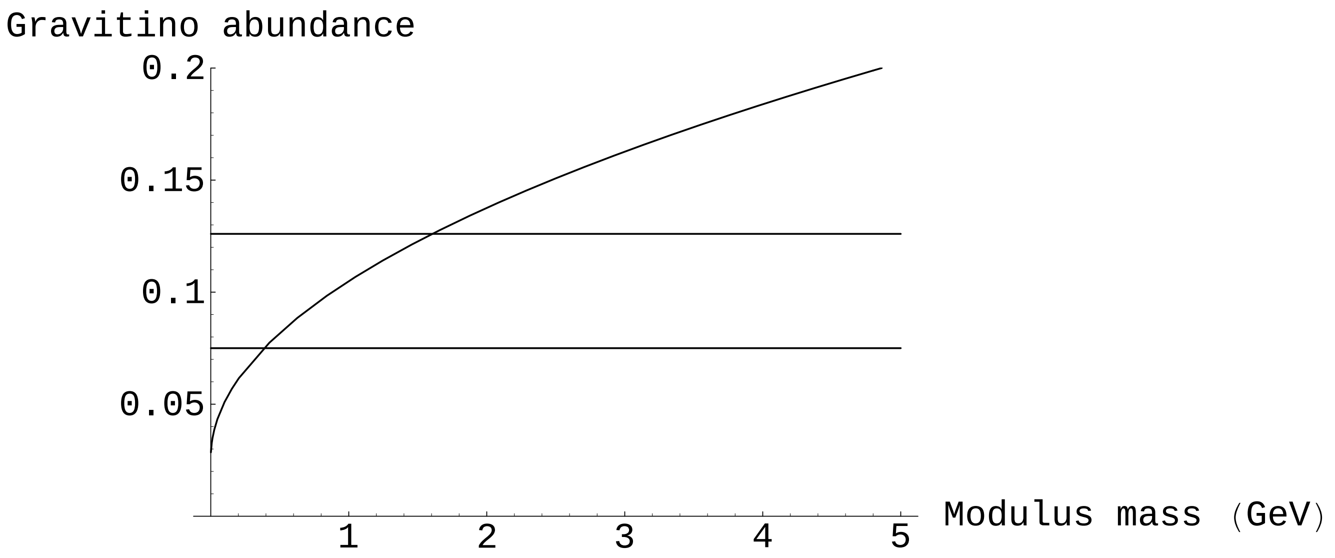
$$T_R = 4.9 \times 10^{-3} \left(\frac{10}{g_*(T_R)}\right)^{1/4} \left(\frac{m_X}{10^5\ GeV}\right)^{3/2}\ GeV \tag{24}$$

T_R is determined entirely by the modulus mass.
From BBN there is a lower bound on the reheating temperature

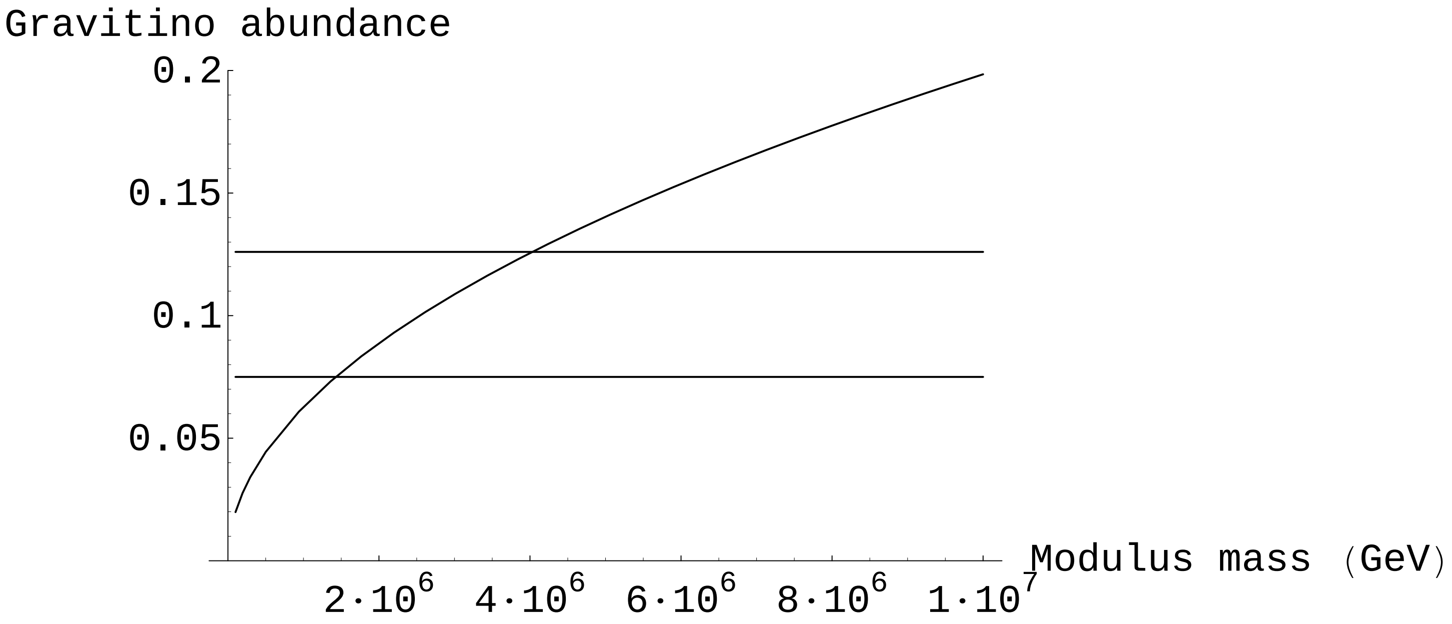
$$T_R \geq 7\ MeV \tag{25}$$

which in turn induces a lower bound on modulus mass

$$m_X \geq 1.5 \times 10^5\ GeV \tag{26}$$



Gravitino total abundance versus m_X for $m_0 = 100$ GeV and $m_{1/2} = 2.69$ TeV. The strip shows the cold dark matter constraint



Same as figure 1, but for $m_{3/2} = 0.1$ GeV and $m_{1/2} = 234$ GeV

Conclusions

- SUSY dark matter in mSUGRA model
- Gravitino (LSP) is dark matter and stau (NLSP) catalyzes BBN
- Compute total gravitino abundance and impose the dark mater constraint, $\Omega_{3/2}h^2 \simeq 0.1$
- All gravitino production mechanisms (thermal bath, stau decay, modulus decay)
- Plot gravitino abundance versus modulus mass for given gravitino and stau masses
- The allowed modulus mass is lower than the lower bound, $m_X \geq 1.5 \times 10^5$ GeV
- The scenario must be ruled out, unless gravitino is light (possibly gauge mediated SUSY breaking?)

Thank you