Gravitino Dark Matter in with Coloured (Stop) NLSP

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Gravitino Dark Matter Scenario

- Stable gravitino LSP is a suitable candidate for dark matter in supergravity models.
- Gravitino interacts very weakly, hence the Next Lightest Supersymmetric Particle (NLSP) could be long lived.
- The gravitino relic comes from two sources:
  - thermal production by reheating (depends on $T_R$),
  - decays of the NLSP.
- The metastable NLSP in this scenario would typically decay after $O(1 \text{ s})$ (for $m_{\text{NLSP}} \lesssim 1 \text{ TeV}$, $m_{\tilde{G}} \gtrsim 1 \text{ GeV}$). Therefore there would be direct effect on BBN.
- It would be difficult to detect gravitino directly. Signatures come from the NLSP.
The NLSP

What is the NLSP in the MSSM? (With Gravitino as LSP)

- General MSSM: could be any supersymmetric particle you want.
- CMSSM: stau, neutralino, stop.
- NUHM: stau, neutralino, stop, selectron, sneutrino, (sup/scharm).

Note: sbottom is usually heavier than stau due to the RGE, unless the masses are non-universal at the input GUT scale.
Stop NLSP

Stop mass matrix

\[
\widetilde{M}_t^2 = \begin{pmatrix}
M^2_{LL} & M^2_{LR} \\
M^2_{LR} & M^2_{RR}
\end{pmatrix}
\]

\[
M^2_{LL} = M^2_{tL} + m_t^2 + \frac{1}{6} \cos 2\beta (4m^2_W - m^2_Z)
\]

\[
M^2_{RR} = M^2_{tR} + m_t^2 + \frac{2}{3} \cos 2\beta \sin^2 \theta_W m^2_Z
\]

\[
M^2_{LR} = -m_t(A_t + \mu \cot \beta) \equiv -m_tX_t
\]

Eigenvalues

\[
m^2_{t1,2} = m_t^2 + \frac{1}{2}(M^2_{tL} + M^2_{tR}) + \frac{1}{4}m^2_Z \cos 2\beta \mp \frac{\Delta}{2}
\]

\[
\Delta^2 = \left(M^2_{tL} - M^2_{tR} + \frac{1}{6} \cos 2\beta (8m^2_W - 5m^2_Z)\right)^2 + 4m_t^2|A_t + \mu \cot \beta|^2
\]

Light stop needs large \(A_0\).
Stop decay

2-body: \( \tilde{t}_1 \rightarrow \tilde{G} + t \)

3-body: \( \tilde{t}_1 \rightarrow \tilde{G} + W + b \)

4-body: \( \tilde{t}_1 \rightarrow \tilde{G} + b + (\bar{q}q, \ell\nu) \)
Stop decay

2-body: $\tilde{t}_1 \rightarrow \tilde{G} + t$

$$\Gamma = \frac{1}{48\pi} \frac{1}{M_{Pl}^2 m_{\tilde{G}}^2 m_{\tilde{t}_1}^3} \left[ \left( m_{\tilde{t}_1}^2 - m_{\tilde{G}}^2 - m_t^2 \right) + 4 \sin \theta_{\tilde{t}} \cos \theta_{\tilde{t}} m_t m_{\tilde{G}} \right]$$

$$\times \left[ (m_{\tilde{t}_1}^2 + m_{\tilde{G}}^2 - m_t^2)^2 - 4m_{\tilde{t}_1}^2 m_{\tilde{G}}^2 \right]$$

$$\times \left[ (m_{\tilde{t}_1}^2 + m_t^2 - m_{\tilde{G}}^2)^2 - 4m_{\tilde{t}_1}^2 m_t^2 \right]^{1/2}$$

3-body: $\tilde{t}_1 \rightarrow \tilde{G} + W + b$

$$\Gamma_{3\text{-body}} \approx 10^{-23} \text{GeV}^{-6} s^{-1} (\Delta m) \left( (\Delta m)^2 - m_W^2 \right)^{5/2}$$

4-body: $\tilde{t}_1 \rightarrow \tilde{G} + b + (\bar{q}q, \ell\nu)$

$$\Gamma_{4\text{-body}} \approx 10^{-30} \text{GeV}^{-8} s^{-1} (\Delta m)^3 \left( (\Delta m)^2 - m_b^2 \right)^{5/2}$$
Stop lifetime

2-body

3-body
Stop Hadronization

Long lived stop would hadronize:

- **Light sbaryons:**
  \[ \Lambda^+_T \equiv \tilde{t}_1 ud \text{ (lightest sbaryon)} \]
  \[ \Sigma^{++,+}_T, 0 \equiv \tilde{t}_1 (uu, ud, dd) \text{ (decay strongly)} \]
  \[ \Xi^{+,0}_T \equiv \tilde{t}_1 s(u, d) \text{ (semileptonically } \tau \lesssim 10^{-2} \text{ s)} \]

- **Light mesinos:**
  \[ \widetilde{T}^0 \equiv \tilde{t}_1 \bar{u} \text{ (lightest mesino)} \]
  \[ \widetilde{T}^+ \equiv \tilde{t}_1 \bar{d} \text{ (lifetime } \tau \simeq 1.2 \text{ s)} \]
  \[ \widetilde{T}_s \equiv \tilde{t}_1 \bar{s} \text{ (} \tau \simeq 2 \times 10^{-6} \text{ s)} \]

There is also antistop that would hadronize into the corresponding antisbaryons and antimesinos.
Stop Search at Colliders

Stop and antistop could be pair produced at colliders, provided there is enough energy, and (assuming metastable) they would hadronize before passing the detector.

There would be neutral as well as charged shadrons (both sbaryons and mesinos), and there could be quark exchange with background nucleons that convert stop mesinos into stop sbaryons: \[ \tilde{T} + (p, n) \rightarrow (\Lambda_{\tilde{T}}, \Sigma_{\tilde{T}}) + n\pi. \] Thus we estimate about 1/16 of the produced stop-antistop pairs yield clear signal.

Looking for ‘slow muon’ and stop production cross section, one can set the metastable stop mass lower limit. From Tevatron Run II: \( m_{\tilde{t}} > 220 \text{ GeV} \) (CDF - Phillips).
Cosmology - Relic Density

- Due to the strong interaction nature, stop decouple later compared to neutralino of same mass. Stop relic is much smaller than typical neutralino relic density. For the models we consider $\Omega_i h^2 \lesssim 10^{-4}$

- Coannihilation with neutralino does actually increase the stop relic density.

![Graph showing relic density vs m_1/2](image-url)
Effects of Metastable Particle on BBN:

- **Photodissociation**: EM showers from the decay can destroy light elements formed by BBN. There would be related processes involving the products.

- **Hadronic showers**:
  - hadron injection - change $n/p$ ratio,
  - hadrodissoociation (especially $\alpha_{\text{BG}}$)

- **Catalytic bound state effect**: If negatively charged, the metastable particle can form bound state with nuclei, lowering the Coulomb barrier for certain nucleosynthesis processes and introducing photonless final state for radiative capture reactions (Pospelov hep-ph/0605215).
Cosmology - BBN - stop

After hadronization only $\Lambda_{T}^{\pm}$ and $\tilde{T}^{0}$ left. Because of the mass difference, $\tilde{T}^{0}$ is more abundance than $\Lambda_{T}^{\pm}$ by $\sim O(10)$. Further suppression of $\Lambda_{T}^{-}$ by: (1) pairing and subsequent annihilation of $\Lambda_{T}^{\pm}$ and $\Lambda_{T}^{-}$; and (2) quark exchange with ordinary hadrons (proton and neutron) into $\tilde{T}^{0}$. With only the neutral mesino (and harmless $\Lambda_{T}^{\pm}$) around, we do not need to worry about bound state catalytic effect.

Small relic density (before decay) and long lifetime alleviate hadronic shower constraint.

Smallness of relic density also suppresses the EM showers effect. However might still be constrained if the lifetime is too long.
CMSSM free parameters: $m_{1/2}, m_0, \tan \beta, A_0, \text{sign}(\mu)$
NUHM free parameters: $m_{1/2}$, $m_0$, $\tan \beta$, $A_0$, $\mu$, $m_A$
SUSY Spectrum (Partial)

\[ M_3 = 1333 \text{ GeV} \]
\[ \ldots \ldots \]
\[ m_{\chi_1^+} = 489 \text{ GeV} \]
\[ m_{\chi_2^0} = 488 \text{ GeV} \]
\[ m_{\tilde{\tau}_1} = 482 \text{ GeV} \]
\[ m_{\chi_1^0} = 253 \text{ GeV} \]
\[ m_{\tilde{t}_1} = 240 \text{ GeV} \]

Note that \( \chi_1^0 \rightarrow \tilde{t}_1 + t \) is kinematically not allowed.

Another benchmark point for LHC?
Neutralino could be only slightly heavier than stop. Results in neutralino long lifetime, and neutralino-stop coexistence.

\[ \Omega_{\chi} \simeq \frac{1}{3} \Omega_{\tilde{t}_1} \simeq 0.25 \Omega_{NLSP} \]

Neutralino could decay
- directly to gravitino,
- or to stop (which then decay to gravitino - Cascade decay).

Effects on BBN are coming from
- stop decay,
- neutralino decay,
- late-produced-stop decay.
Stop NLSP with gravitino dark matter scenario is phenomenologically very interesting.

Stop would naturally have low relic density (before decay) due to its strong interaction. Thus, would be possible to satisfy the BBN constraint.

Metastable stop hadronize. At the time of BBN practically only the lightest neutral mesino left. No EM bound state with nuclei.

This scenario is not feasible in the CMSSM, in particular because of the combined constraints from the stop mass and the Higgs mass bounds. In the NUHM this scenario is still possible. It would be interesting to see for other supersymmetric models.
The signal of this scenario could most likely come from the colliders.

For more detail see:
Diaz-Cruz, Ellis, Olive, YS, JHEP05(2007)003