Gravitino Dark Matter with Stop NLSP

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Dark Matter from Supersymmetry

- The big puzzle: what is the dark matter ?
- Hypothesis: dark matter is from particle physics beyond the Standard Model. Stable (or *meta*stable), neutral, and gravitationally interacting (massive) particle. Could only be weakly interacting with ordinary matter.
- Supersymmetry with R-parity conservation provides a candidate for dark matter when the LSP is neutral.
- SUSY DM candidates: neutralino, sneutrino, gravitino.

Gravitino as Dark Matter

- Stable gravitino LSP, being a superweakly interacting massive particle, is a suitable candidate for dark matter in supergravity models.
- Because of the very weak interaction of gravitino, the NLSP could be long lived, with typical life time $> O(1\,\mathrm{s})$ (for $m_{\mathrm{NLSP}} \lesssim 1$ TeV, $m_{\tilde{G}} \gtrsim 1$ GeV). Therefore there would be direct effect on BBN.
- The gravitino relic comes from two sources:
  - thermal production by reheating (proportional to T_R),
  - decays of the NLSP.

  $$\Omega_{\tilde{G}} = (m_{\tilde{G}}/m_{\mathrm{NLSP}})\Omega_{\mathrm{NLSP}} + \Omega_{\tilde{G}}^{\mathrm{th}}$$
- 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 one of the supersymmetric particles we want.
- Gravity mediated MSSM with universal soft masses:
  - 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 sfermion masses are non-universal at the input GUT scale.

The Case for Stau NLSP

- This is the most popular model due to the clear signals that should be found at colliders, given enough energy.
- Cascade decays of SUSY particles produce stau which is stable through the detector. The signature of the stau would be like slow muon: analyses through Time of Flight and energy loss. (Ellis, Raklev and Oye; Cakir, Cakir, Ellis and Kirca; Rajaraman and Smith; ...
- Storage idea (Feng and Smith): Being a charged particle, stau can be stopped, and then stored until it decays sometime later. Thus we can measure the lifetime, and 'confirm' the gravitino DM scenario.
- Additional BBN constraint from EM bound state effect. But might solve lithium problem for a range of parameter space (Pospelov).

The Case for Neutralino NLSP

- Signature at colliders would be similar to the neutralino LSP scenario, i.e. neutralino as missing energy. Except that now the neutralino relic density is not directly constrained by the WMAP. So can go to region of parameter space with greater neutralino relic density ($> \Omega_{\rm WMAP}$) $\rightarrow$ larger m_0 $\rightarrow$ different branching ratios for χ_2 decays (De Roeck etal hep-ph/0508198).
- Search for neutral metastable particle (CDF arXiv:0704.0760). Decay inside the detector - delayed photon. However this only works for relatively short lifetime: neutralino mass limit 101 GeV at 5 ns. If decay outside the detector - neutralino cannot be stopped.
- Possible scenario: SUSY is found at LHC resembling neutralino LSP scenario, but direct detection of Dark Matter yields none.

The Case for Sneutrino NLSP

- Signatures at colliders: Talk by Laura Covi (Covi and Kraml, hep-ph/0703130). Compared to neutralino - distinguishable.
- EM shower effect on BBN (Kanzaki etal.):
  - Although the high energy neutrino produced is neutral, it carries energy that eventually converted to radiation through scattering with background particles.
  - The 3 and 4 body decays of sneutrino produced charged leptons.

Now time for stop NLSP

Diaz-Cruz, Ellis, Olive and Santoso, JHEP **0705** (2007) 003

Stop NLSP

Stop mass matrix

$$\widetilde{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{LL} & M^2_{LR} \\ M^{2\,\dagger}_{LR} & M^2_{RR} \end{pmatrix}$$

$$\begin{aligned} M^2_{LL} &= M^2_{\tilde{t}_L} + m_t^2 + \tfrac{1}{6}\cos 2\beta\,(4m_W^2 - m_Z^2) \\ M^2_{RR} &= M^2_{\tilde{t}_R} + m_t^2 + \tfrac{2}{3}\cos 2\beta \sin^2\theta_W\, m_Z^2 \\ M^2_{LR} &= -m_t(A_t + \mu\ \cot\beta) \equiv -m_t X_t \end{aligned}$$

Eigenvalues

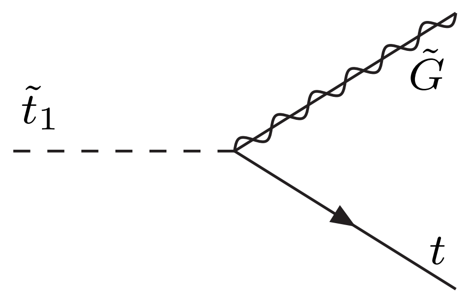
$$m^2_{\tilde{t}_{1,2}} = m_t^2 + \frac{1}{2}(M^2_{\tilde{t}_L} + M^2_{\tilde{t}_R}) + \frac{1}{4}m_Z^2\cos 2\beta \mp \frac{\Delta}{2}$$

$$\Delta^2 = \left(M^2_{\tilde{t}_L} - M^2_{\tilde{t}_R} + \frac{1}{6}\cos 2\beta(8m_W^2 - 5m_Z^2)\right)^2 + 4\,m_t^2|A_t + \mu\cot\beta|^2$$

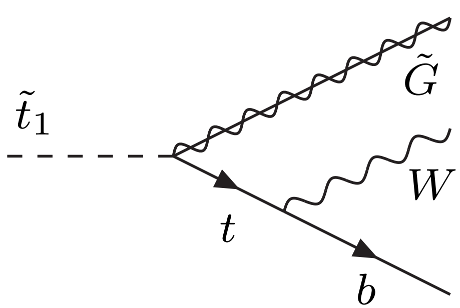
Light stop needs large A_0.

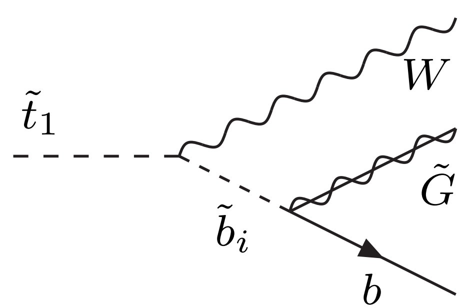
Stop decay

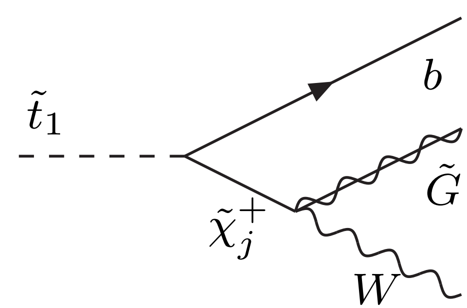
2-body: $\tilde{t}_1 \rightarrow \widetilde{G} + t$



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







Stop decay

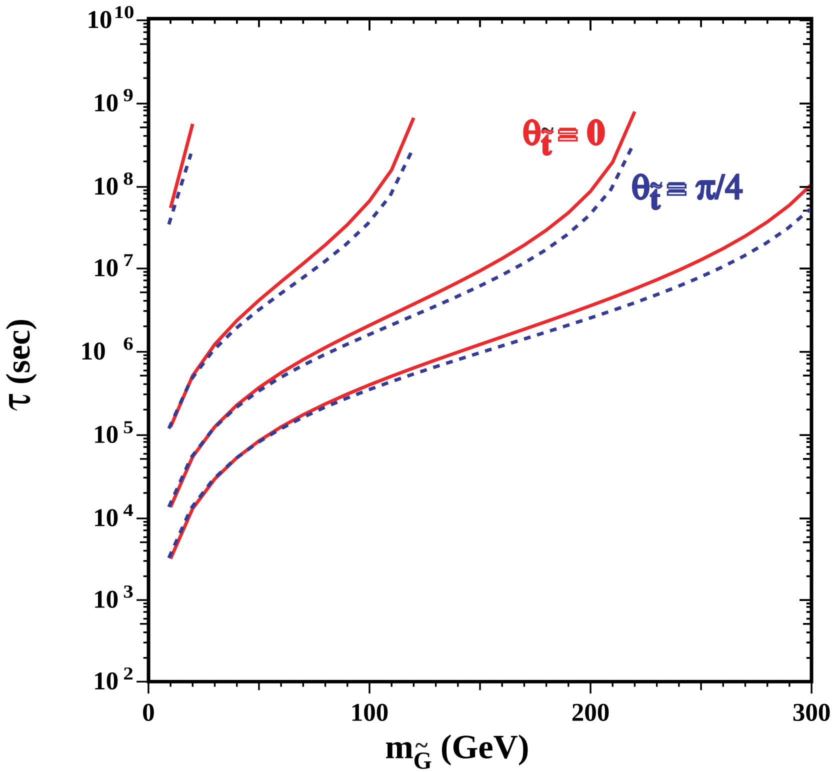
2-body: $\tilde{t}_1 \to \widetilde{G} + t$

$$\begin{aligned}\Gamma &= \frac{1}{48\pi}\frac{1}{M_{\rm Pl}^2 m_{\widetilde{G}}^2 m_{\tilde{t}_1}^3}\left[\left(m_{\tilde{t}_1}^2 - m_{\widetilde{G}}^2 - m_t^2\right) + 4\,\sin\theta_{\tilde{t}}\,\cos\theta_{\tilde{t}}\,m_t\,m_{\widetilde{G}}\right] \\ &\times \left[(m_{\tilde{t}_1}^2 + m_{\widetilde{G}}^2 - m_t^2)^2 - 4m_{\tilde{t}_1}^2 m_{\widetilde{G}}^2\right] \\ &\times \left[(m_{\tilde{t}_1}^2 + m_t^2 - m_{\widetilde{G}}^2)^2 - 4m_{\tilde{t}_1}^2 m_t^2\right]^{1/2}\end{aligned}$$

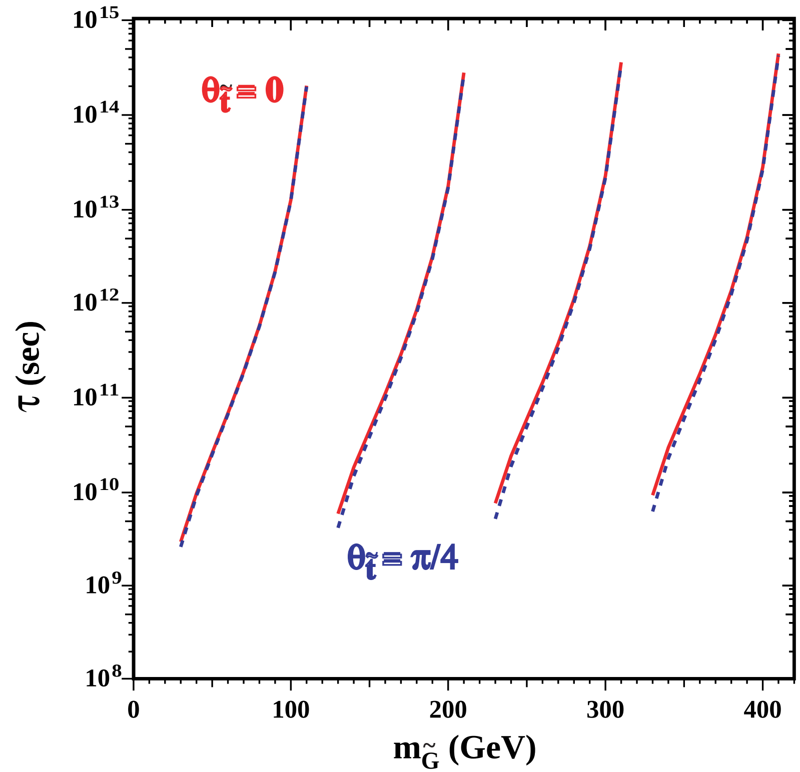
3-body: $\tilde{t}_1 \to \widetilde{G} + W + b$

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

Stop lifetime



2-body



3-body

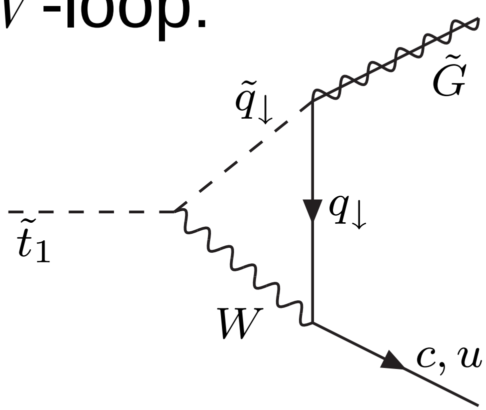
Small Mass Gap Case

When $\Delta m \equiv m_{\tilde{t}_1} - m_{\tilde{G}} < m_W$ the 2- and 3-body decays above are not available.

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

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

- W-loop:



Suppressed by large $m_{\tilde{q}_\downarrow}$ and V_{CKM}.

- Stop lifetime could be longer than the age of the Universes ($O(10^{17}\text{s})$).

Stop Hadronization

Long lived stop would hadronize:

- Light sbaryons:
  $\Lambda^+_{\widetilde{T}} \equiv \tilde{t}_1 ud$ (lightest sbaryon)
  $\Sigma^{++,+,0}_{\widetilde{T}} \equiv \tilde{t}_1(uu, ud, dd)$ (decay strongly)
  $\Xi^{+,0}_{\widetilde{T}} \equiv \tilde{t}_1 s(u, d)$ (semileptonically $\tau \lesssim 10^{-2}$ s)
- Light mesinos:
  $\widetilde{T}^0 \equiv \tilde{t}_1 \bar{u}$ (lightest mesino)
  $\widetilde{T}^+ \equiv \tilde{t}_1 \bar{d}$ (lifetime $\tau \simeq 1.2$ s)
  $\widetilde{T}_s \equiv \tilde{t}_1 \bar{s}$ ($\tau \simeq 2 \times 10^{-6}$ s)

There is also antistop that would hadronize into the corresponding antisbaryons and antimesinos.

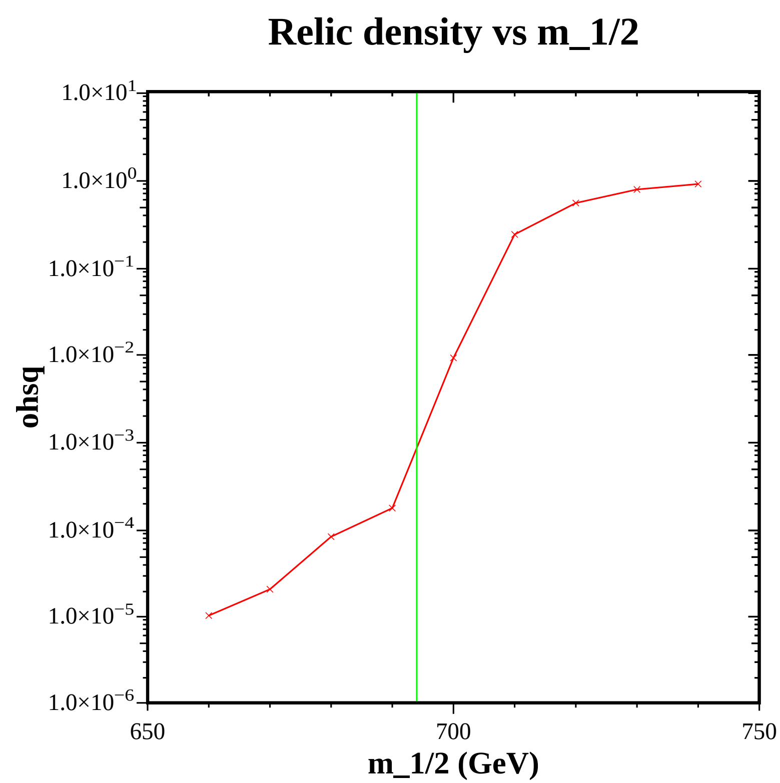
Stop Search at Colliders

- 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: $\widetilde{T} + (p, n) \to (\Lambda_{\tilde{T}}, \Sigma_{\tilde{T}}) + n\pi$. 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: $m_{\tilde{t}} > 220$ GeV (CDF - Phillips - Talk at DPF2006).

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 $\Omega_{\tilde{t}_1} h^2 \lesssim 10^{-4}$

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



Cosmology - BBN

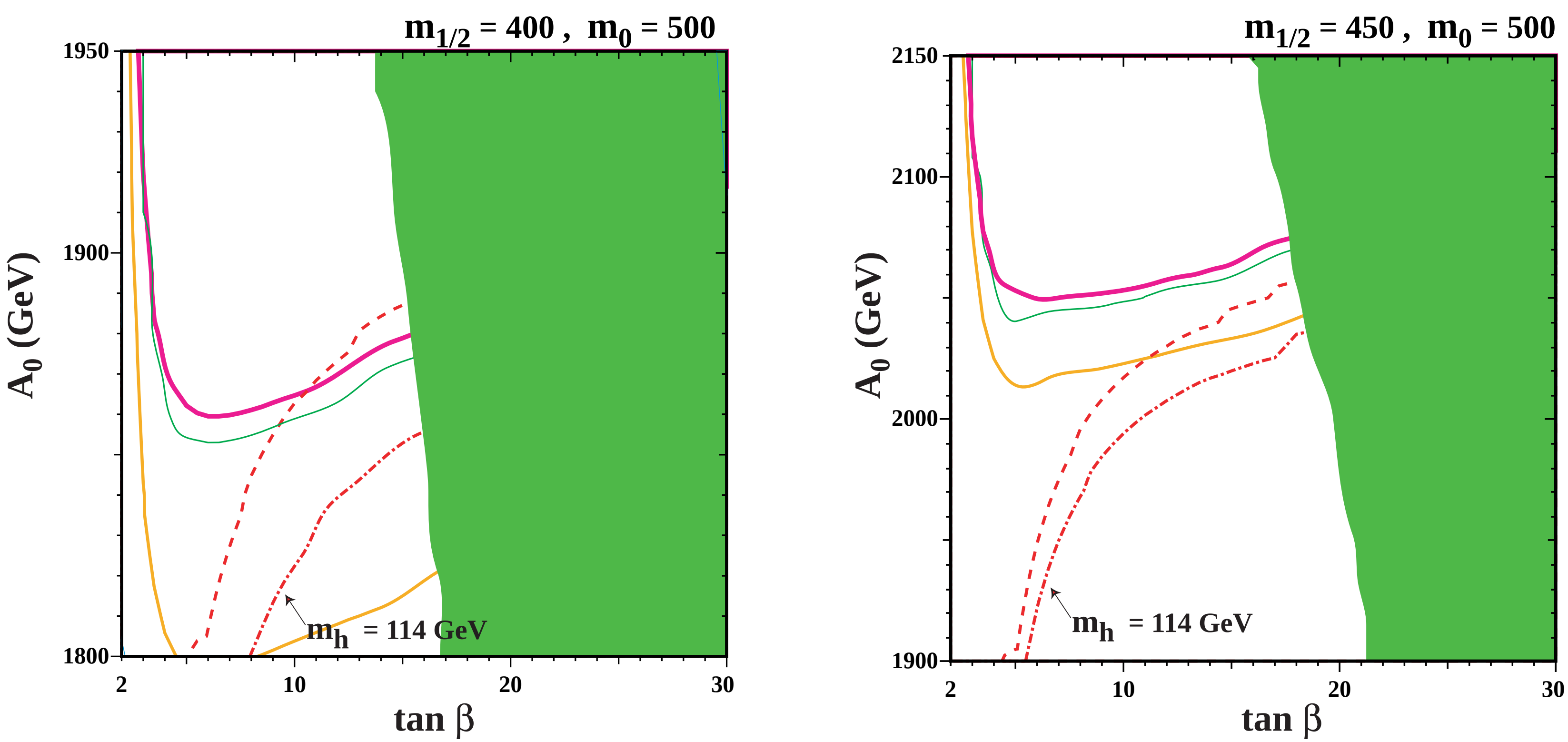
Effects of Metastable Particle on BBN:

- 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,
  - hadrodissociation (especially α_{BG})
- Catalytic bound state effect: If negatively charged, the metastable particle can form bound state with nuclei, lowering the Coulomb barrier for certain nucleosynthesis procesess and introducing photonless final state for radiative capture reactions (Pospelov hep-ph/0605215).

Cosmology - BBN - stop

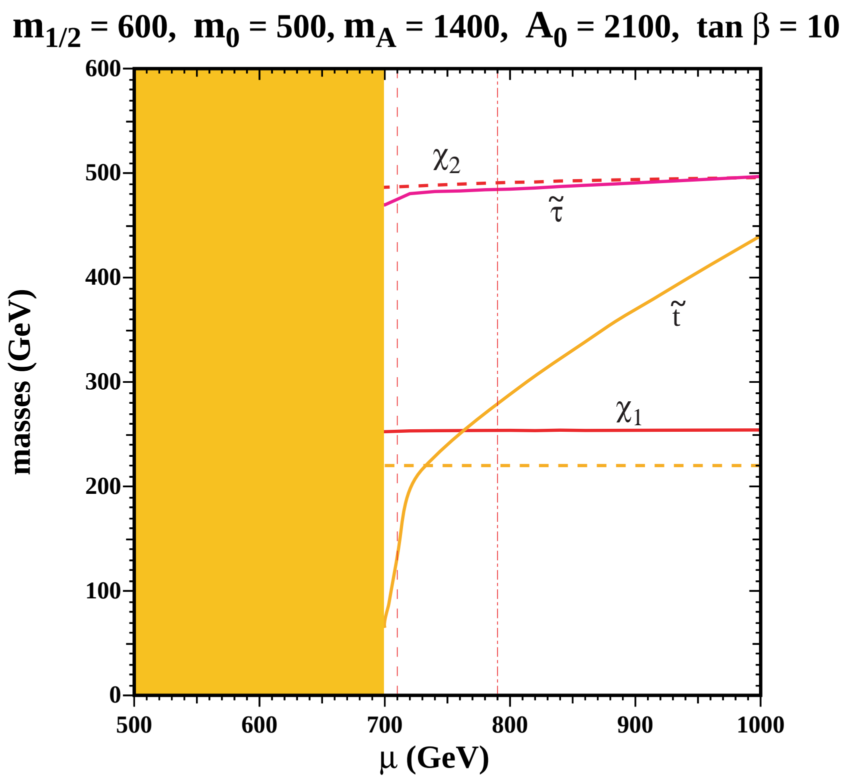
- After hadronization only $\Lambda^{\pm}_{\widetilde{T}}$ and $\widetilde{T}^0$ left. Because of the mass difference, $\widetilde{T}^0$ is more abundance than $\Lambda^{\pm}_{\widetilde{T}}$ by $\sim O(10)$. Further suppression of $\Lambda^{-}_{\widetilde{T}}$ by: $^{(1)}$ pairing and subsequent annihilation of $\Lambda^{+}_{\widetilde{T}}$ and $\Lambda^{-}_{\widetilde{T}}$; and $^{(2)}$ quark exchange with ordinary hadrons (proton and neutron) into $\widetilde{T}^0$. With only the neutral mesino (and harmless $\Lambda^{+}_{\widetilde{T}}$) around, we do not need to worry about bound state catalytic effect.
- Small relic density (before decay) and long lifetime aleviate hadronic shower constraint.
- Smallness of relic density also suppresses the EM showers effect. However might still be constrained if the lifetime is too long.

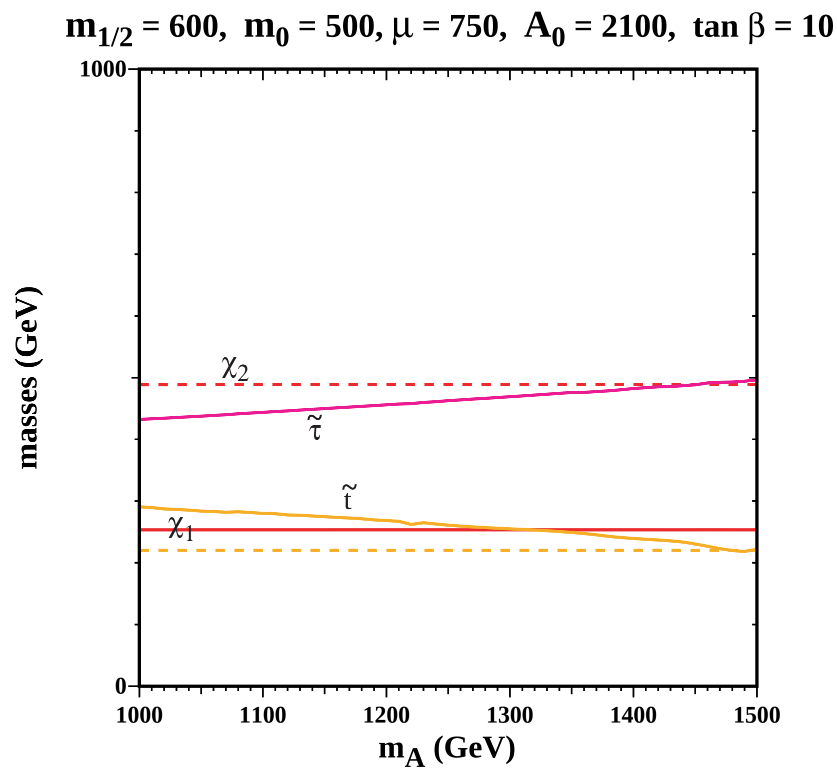
CMSSM



CMSSM free parameters: $m_{1/2},\ m_0,\ \tan\beta,\ A_0,\ \mathrm{sign}(\mu)$

NUHM





NUHM free parameters: $m_{1/2},\ m_0,\ \tan\beta,\ A_0,\ \mu, m_A$

Metastable Neutralino NNSP

- Neutralino could be only slightly heavier than stop. Results in neutralino long lifetime, and neutralino-stop coexistence.

$$\Omega_\chi \simeq \frac{1}{3}\,\Omega_{\tilde{t}_1} \simeq 0.25\,\Omega_{NLSP}$$

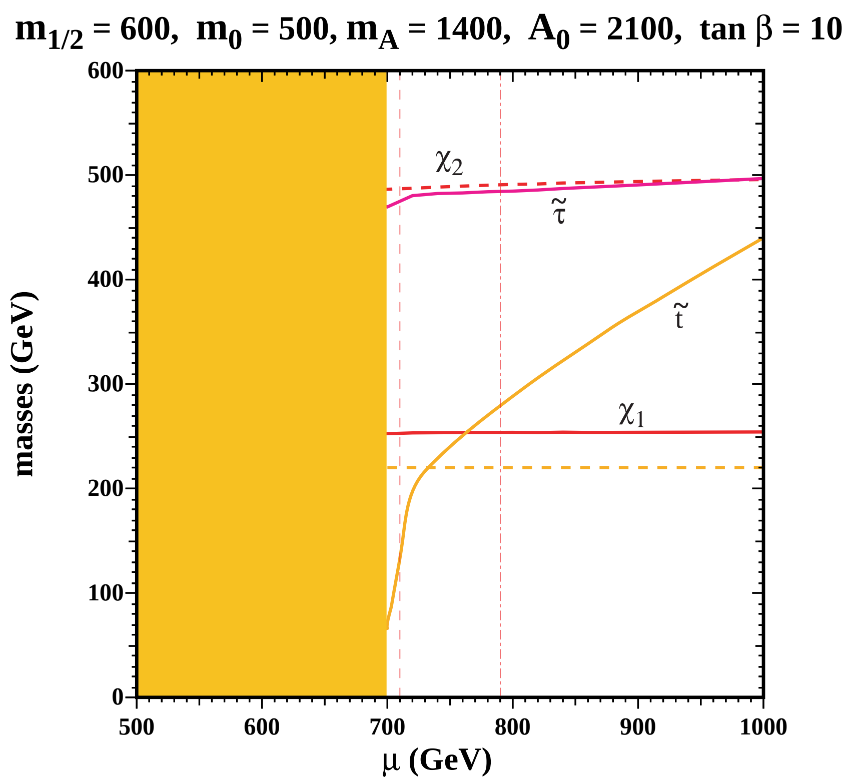
- Neutralino could decay
  - directly to gravitino,
  - or to stop (which then decay to gravitino - Cascade decay).
- Effects on BBN are coming from
  - stop decay,
  - neutralino decay,
  - late-produced-stop decay.

SUSY Spectrum

$$
\begin{aligned}
M_3 &= 1333\,\mathrm{GeV} \\
\text{(squarks at } &\sim 1\,\mathrm{TeV}) \\
\cdots & \quad \cdots \\
m_{\chi_1^+} &= 489\,\mathrm{GeV} \\
m_{\chi_2^0} &= 488\,\mathrm{GeV} \\
m_{\tilde{\tau}_1} &= 482\,\mathrm{GeV} \\
m_{\chi_1^0} &= 253\,\mathrm{GeV} \\
m_{\tilde{t}_1} &= 240\,\mathrm{GeV}
\end{aligned}
$$

Note that $\chi_1^0 \to \tilde{t}_1 + t$ is kinematically not allowed. So could have both missing energy AND slow muon at colliders. Another benchmark point for LHC?

Future/Newer Limit



Nachtman - Talk at Fermilab - CDF Run II preliminary limit for metastable stop: $m_{\tilde{t}} > 250$ GeV - almost exclude NUHM.

Beyond NUHM

Martin (arXiv:hep-ph/0703097) - Compressed Supersymmetry :

- SUSY little hierarchy problem: EWSB require cancellation between $|\mu|^2$ and $m^2_{H_u}$. The biggest contribution to $m^2_{H_u}$ comes from M_3.
- Light gluino mass $\rightarrow$ light stop.

$$\frac{dm^2_{\tilde{t}_R}}{dt} = \frac{1}{8\pi^2}(-\frac{16}{3}g_3^2 M_3^2 - \frac{16}{9}g_1^2 M_1^2 \\ +2h_t^2(m^2_{\tilde{Q}_{3L}} + m^2_{\tilde{t}_R} + m_2^2 + A_t^2) - \frac{8}{3}S)$$

$\hat{M}_3/\hat{M}_1 \lesssim 1/3$ to get stop lighter than stau.

- Can still add modest A_0 to get stop NLSP (through seesaw).

Conclusion

- 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 (barely) possible.
- Nonuniversal gaugino model with light gluino should revive the possibility. It would be interesting to see for other supersymmetric models.