

# Stop NLSP in the Gravitino Dark Matter Scenario

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Based on works with Lorenzo Diaz-Cruz, John Ellis and Keith Olive (JHEP05(2007)003)

# SUSY Dark Matter Hypothesis

- (Theoretical) problem in particle physics: gauge hierarchy problem.
- (Theoretical) problem in astrophysics: what is the dark matter.
- Supersymmetry provides solution to the gauge hierarchy problem through fermion-boson pair cancellations.
- Imposing  $R$ -parity conservation, the lightest supersymmetric particle (LSP) would be stable, if the LSP is neutral it could be candidate for Dark Matter.
- SUSY DM candidates: Neutralino, sneutrino, gravitino

# Properties of Dark Matter

- Massive - source of gravity.
- Dark (not black) - no charge, no color (or hidden?).
- (Very) stable - has relic density today.
- Its mass density is greater than the baryonic mass density. (About 4.7 times larger).

$$\Omega_{DM}^{(WMAP)} h^2 = 0.1045^{+0.0073}_{-0.0128}$$

- (Very) weakly interacting with ordinary matter - difficult to detect.
- Cold (or warm) - suggested by structure formation simulations.
- Usual assumption: Local density  $0.3 \text{ GeV/cm}^3$ , velocity 220-240 km/s.

# Testing SUSY DM Hypothesis

- All 3 (neutralino, sneutrino, gravitino) are viable candidates for CDM. (Given how little we know about CDM). Have to test each SUSY model against observational constraints.
- Laboratory constraints:
  - The Higgs mass bound:  $m_h \gtrsim 114.4 \text{ GeV}$ .
  - $\text{BR}(b \rightarrow s\gamma) = (3.54 \pm 0.41_{-0.23}^{+0.35}) \times 10^{-4}$ .
  - $\text{BR}(B_s \rightarrow \mu^+ \mu^-) < 2 \times 10^{-7}$  (Tevatron)
  - Chargino mass
  - Slepton and squark masses
  - Muon anomalous magnetic moment  $g_\mu - 2$  (?)

$$\text{Jegerlehner: } \delta a_\mu[\text{exp} - \text{theo}] = 278 \pm 91 \times 10^{-11}$$

# Testing SUSY DM Hypothesis (2)

- Cosmological constraints:
  - Relic density.  
Cannot exceed the observed value:  
 $(\Omega_{DM} h^2)_{\max} = 0.119$  (WMAP  $2\sigma$ ). The lower bound is not as stringent as the upper bound, in view of multiple DM possibilities.
  - Big Bang Nucleosynthesis (BBN).  
In some models there are some metastable particles that eventually decay to DM-particle. These metastable particles could affect the BBN prediction through their decays and charges.
  - Cosmic Microwave Background Radiation (CMBR).  
A very long-lived charged metastable particle could distort the CMBR black-body spectrum.

# Testing SUSY DM Hypothesis (3)

- For weakly interacting DM particle (WIMP):
  - Direct detection: detecting recoil from elastic scattering of DM with atoms in the detector.
  - Indirect detection: searching for high energy particles - products of relic DM annihilation.
- Very weakly interacting DM particle (SWIMP), unfortunately, is very difficult (if not impossible) to detect (other than from its gravitational interaction).

# Gravitino Dark Matter Scenario

- Stable gravitino LSP is a candidate for dark matter in supergravity models.
- Gravitino interacts very weakly, hence the Next Lightest Supersymmetric Particle (NLSP) - which has to decay to gravitino - 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. Signatures of this scenario come from the NLSP.

# The NLSP

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

- General MSSM: could be any supersymmetric particle we 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

$$\widetilde{M}_t^2 = \begin{pmatrix} M_{LL}^2 & M_{LR}^2 \\ M_{LR}^{2\dagger} & M_{RR}^2 \end{pmatrix}$$

$$M_{LL}^2 = M_{\tilde{t}_L}^2 + m_t^2 + \frac{1}{6} \cos 2\beta (4m_W^2 - m_Z^2)$$

$$M_{RR}^2 = M_{\tilde{t}_R}^2 + m_t^2 + \frac{2}{3} \cos 2\beta \sin^2 \theta_W m_Z^2$$

$$M_{LR}^2 = -m_t(A_t + \mu \cot \beta) \equiv -m_t X_t$$

Eigenvalues

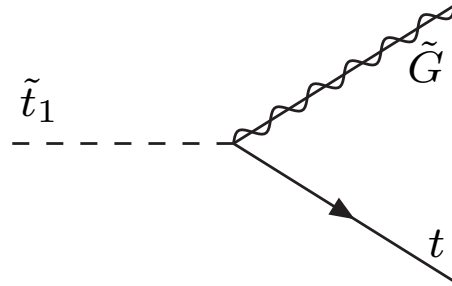
$$m_{\tilde{t}_{1,2}}^2 = m_t^2 + \frac{1}{2}(M_{\tilde{t}_L}^2 + M_{\tilde{t}_R}^2) + \frac{1}{4}m_Z^2 \cos 2\beta \mp \frac{\Delta}{2}$$

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

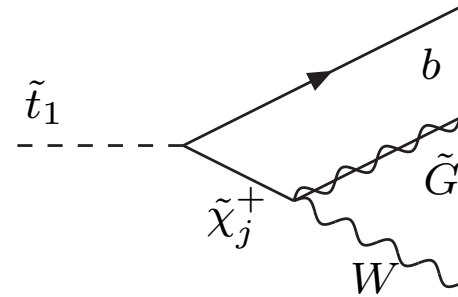
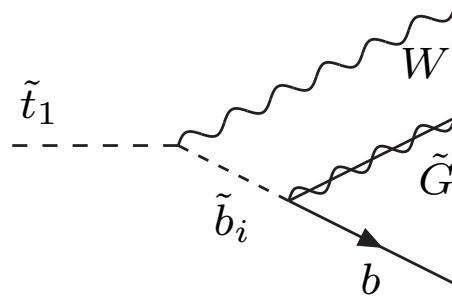
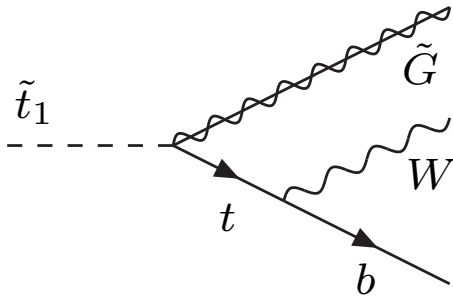
Light stop needs large  $A_0$ .

# Stop decay

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



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



# Stop decay

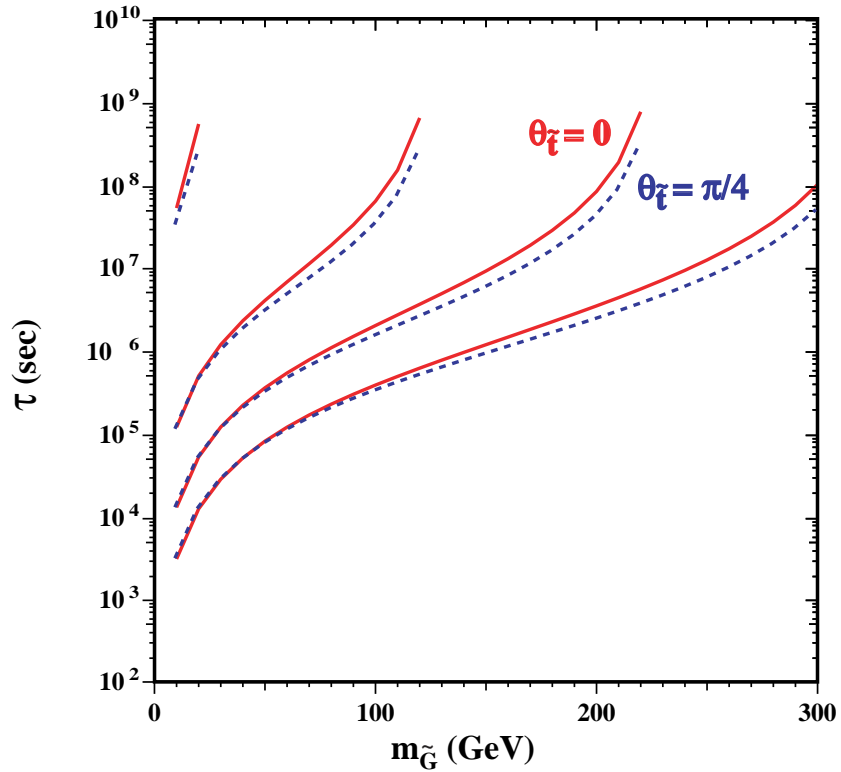
2-body:  $\tilde{t}_1 \rightarrow \tilde{G} + t$

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

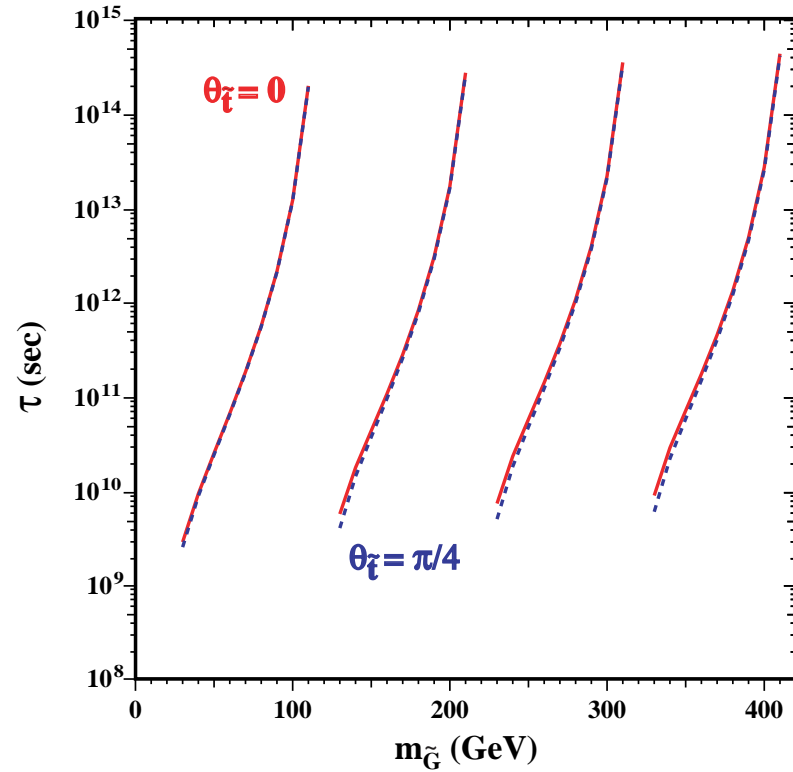
3-body:  $\tilde{t}_1 \rightarrow \tilde{G} + W + b$

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

# Stop lifetime



2-body



3-body

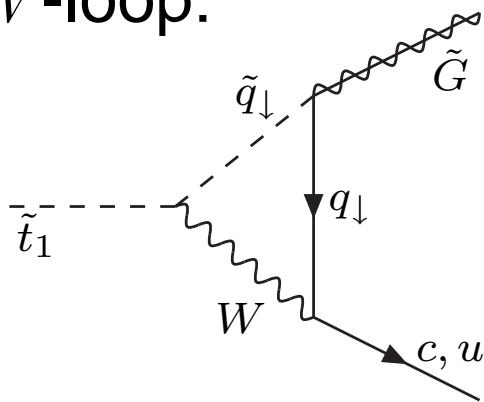
# Small Mass Gap Case

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

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

- W-loop:



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

- 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:

$$\Lambda_{\tilde{T}}^+ \equiv \tilde{t}_1 u d \text{ (lightest sbaryon)}$$

$$\Sigma_{\tilde{T}}^{+,+,0} \equiv \tilde{t}_1 (uu, ud, dd) \text{ (decay strongly)}$$

$$\Xi_{\tilde{T}}^{+,0} \equiv \tilde{t}_1 s(u, d) \text{ (semileptonically } \tau \lesssim 10^{-2} \text{ s)}$$

- Light mesinos:

$$\tilde{T}^0 \equiv \tilde{t}_1 \bar{u} \text{ (lightest mesino)}$$

$$\tilde{T}^+ \equiv \tilde{t}_1 \bar{d} \text{ (lifetime } \tau \simeq 1.2 \text{ s)}$$

$$\tilde{T}_s \equiv \tilde{t}_1 \bar{s} \text{ (} \tau \simeq 2 \times 10^{-6} \text{ s)}$$

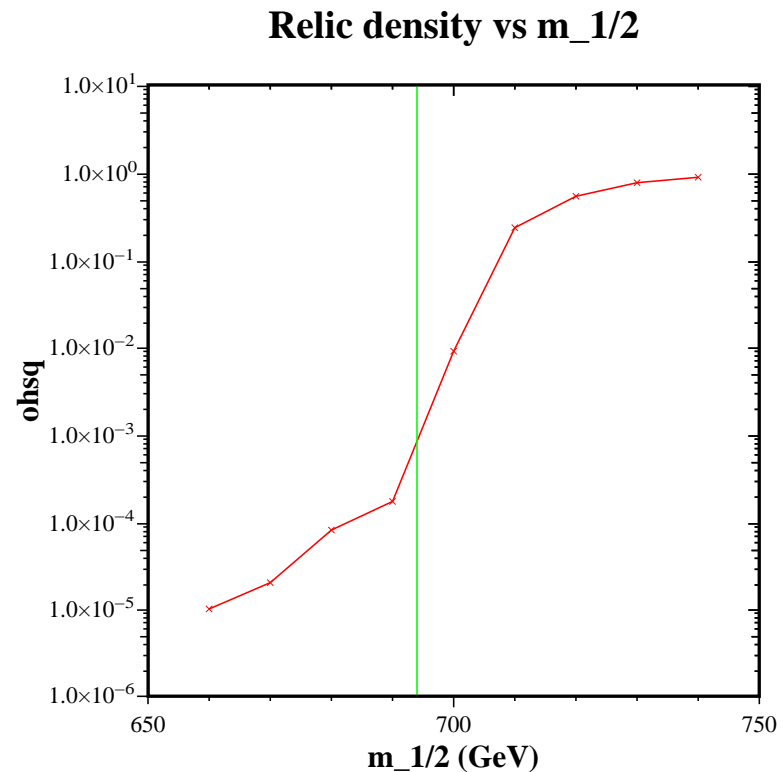
There is also antistop that would hadronize into the corresponding antisbaryons and antimesinos.

# Stop Search at Colliders

- Stop and/or 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 hadrons (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 the clear signal would be below the production rate.
- 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  $\Omega_{\tilde{t}_1} h^2 \lesssim 10^{-4}$
- Coannihilation with neutralino does actually increase the stop relic density.





# Cosmology - BBN

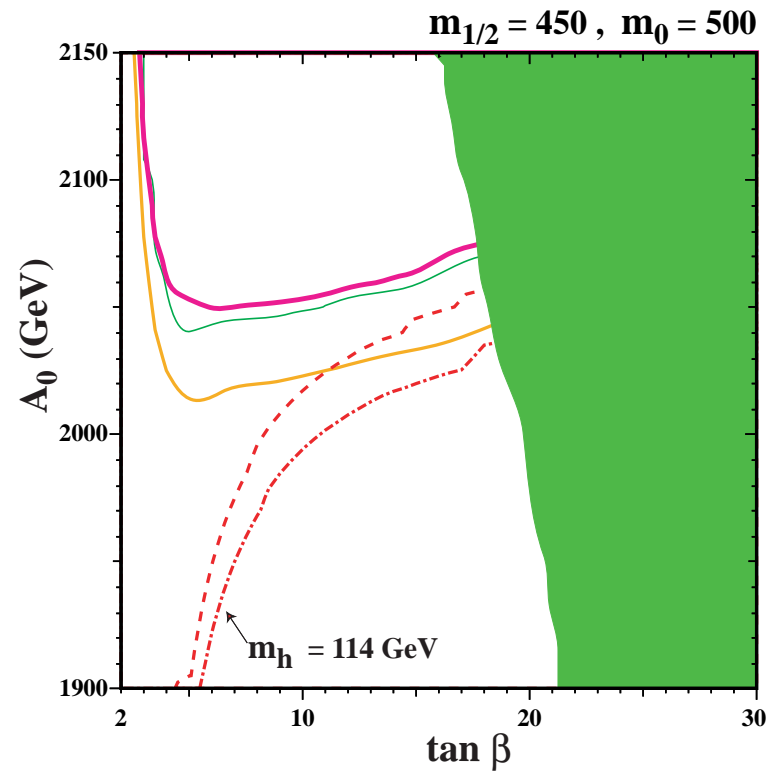
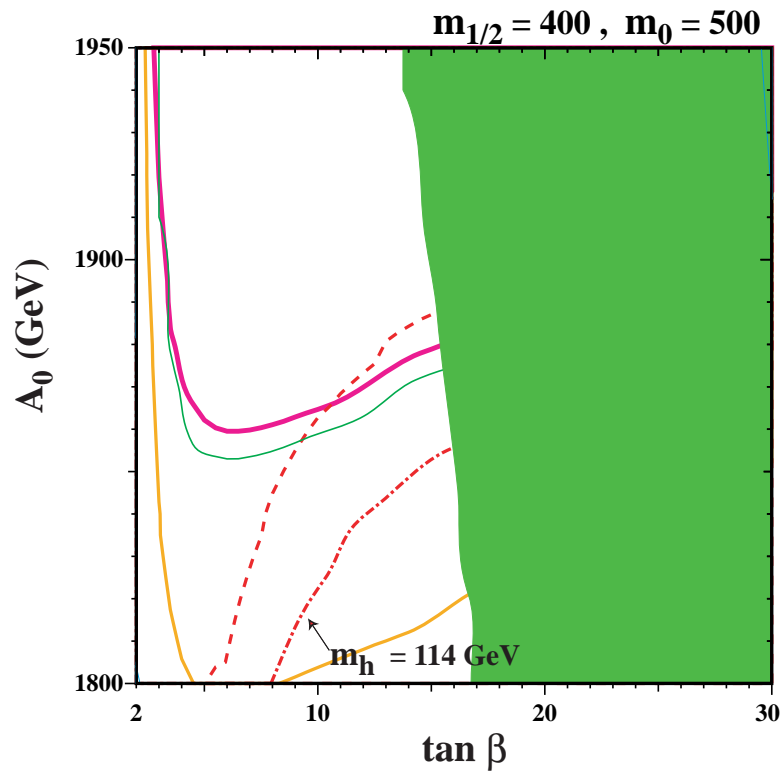
## Effects of Metastable Particle on BBN:

- 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  $\alpha_{BG}$ )
- 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  $\Lambda_{\tilde{T}}^{\pm}$  and  $\tilde{T}^0$  left. Because of the mass difference,  $\tilde{T}^0$  is more abundance than  $\Lambda_{\tilde{T}}^{\pm}$  by  $\sim O(10)$ . Further suppression of  $\Lambda_{\tilde{T}}^{-}$  by: (1) pairing and subsequent annihilation of  $\Lambda_{\tilde{T}}^{+}$  and  $\Lambda_{\tilde{T}}^{-}$ ; and (2) quark exchange with ordinary hadrons (proton and neutron) into  $\tilde{T}^0$ . With only the neutral mesino (and harmless  $\Lambda_{\tilde{T}}^{+}$ ) around, we do not need to worry about bound state catalytic effect.
- Small relic density (before decay) 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 ( $\gtrsim 10^8$  s).

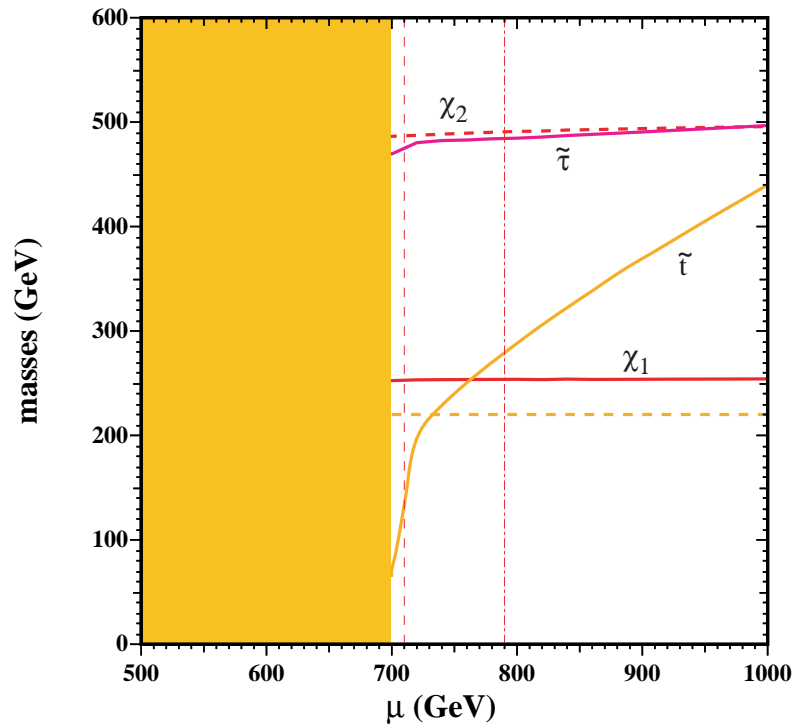
# CMSSM



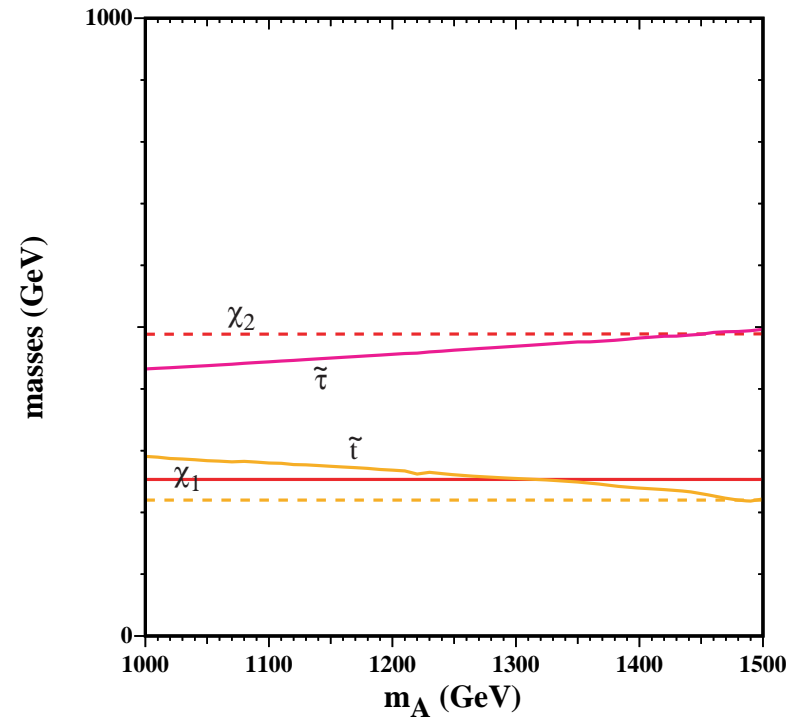
CMSSM free parameters:  $m_{1/2}, m_0, \tan \beta, A_0, \text{sign}(\mu)$

# NUHM

$m_{1/2} = 600$ ,  $m_0 = 500$ ,  $m_A = 1400$ ,  $A_0 = 2100$ ,  $\tan \beta = 10$



$m_{1/2} = 600$ ,  $m_0 = 500$ ,  $\mu = 750$ ,  $A_0 = 2100$ ,  $\tan \beta = 10$



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.

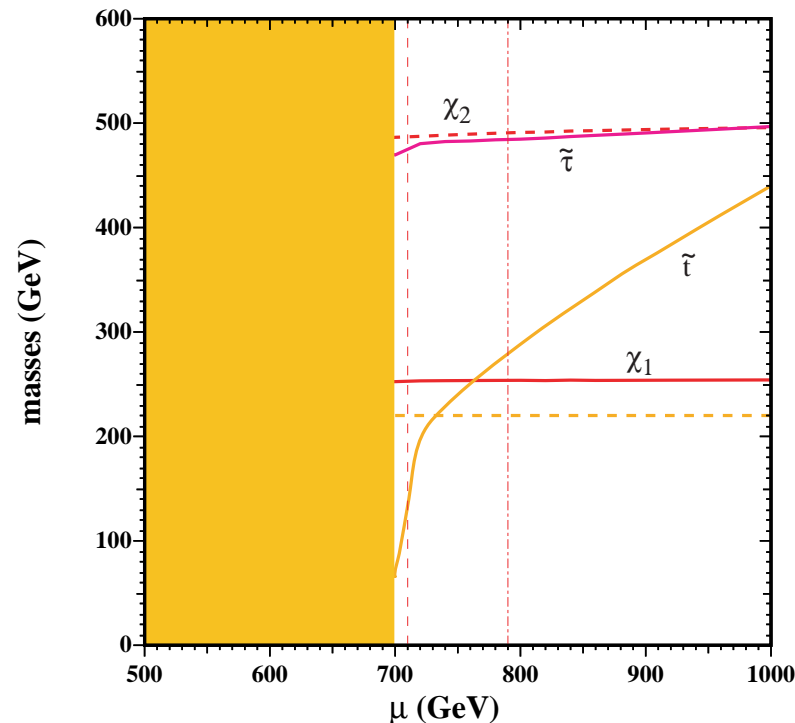
# SUSY Spectrum (Partial)

$$\begin{aligned}M_3 &= 1333 \text{ GeV} \\ \dots & \dots \\ m_{\chi_1^+} &= 489 \text{ GeV} \\ m_{\chi_2^0} &= 488 \text{ GeV} \\ m_{\tilde{\tau}_1} &= 482 \text{ GeV} \\ m_{\chi_1^0} &= 253 \text{ GeV} \\ m_{\tilde{t}_1} &= 240 \text{ GeV}\end{aligned}$$

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

# Future/Newer Limit

$m_{1/2} = 600$ ,  $m_0 = 500$ ,  $m_A = 1400$ ,  $A_0 = 2100$ ,  $\tan \beta = 10$



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

# Beyond NUHM

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

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

$$\begin{aligned} \frac{dm_{\tilde{t}_R}^2}{dt} = & \frac{1}{8\pi^2} \left( -\frac{16}{3} g_3^2 M_3^2 - \frac{16}{9} g_1^2 M_1^2 \right. \\ & \left. + 2h_t^2 (m_{\tilde{Q}_{3L}}^2 + m_{\tilde{t}_R}^2 + m_2^2 + A_t^2) - \frac{8}{3} S \right) \end{aligned}$$

$\hat{M}_3/\hat{M}_1 \lesssim 1/3$  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.