

# Implications of compressed SUSY with stop-mediated annihilation of dark matter

Stephen P. Martin

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Based on: `hep-ph/0703097`, `0707.2812`, and

“Diphoton decays of stoponium at the LHC”, preprint to appear.

## Executive Summary

Experimental results from LEP2, Tevatron, and WMAP put tension on the parameter space of minimal SUSY.

A possible resolution:

- “Compressed” SUSY: the spectrum of superpartner masses has a narrower range than is found in the most popular models.
- Dark matter with observed density explained by LSP (neutralino) pair annihilation to top quark-antiquark pairs.

This scenario has sharp implications for collider physics and dark matter detection.

## Cast of Important Characters:

$\tilde{t}_1, \tilde{t}_2$  top squarks (“stops”), spin 0.

$\tilde{N}_1$  lightest neutralino (LSP = dark matter), spin 1/2.

$\tilde{g}$  gluino, spin 1/2 superpartner of the gluon

$h$  lightest neutral Higgs boson

## LEP2 did not find a Higgs boson

If the Higgs sector is Standard Model-like, then LEP2 implies  $M_h \gtrsim 114$  GeV in most of SUSY parameter space.

A simplified form of the SUSY prediction is:

$$M_h^2 < m_Z^2 + \frac{3y_t^2}{4\pi^2} m_t^2 \ln \left( \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)$$

To evade discovery at LEP2, need large top-squark masses, naively:

$$\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \gtrsim 700 \text{ GeV.}$$

(Actually, top-squark mixing effects mitigate this somewhat.)

Meanwhile, the condition for Electroweak Symmetry Breaking is:

$$m_Z^2 = -2 \left( |\mu|^2 + m_{H_u}^2 \right) + \text{small corrections}$$

Here  $|\mu|^2$  is a SUSY-preserving Higgs squared mass,  
 $m_{H_u}^2$  is a SUSY-violating Higgs scalar squared mass.

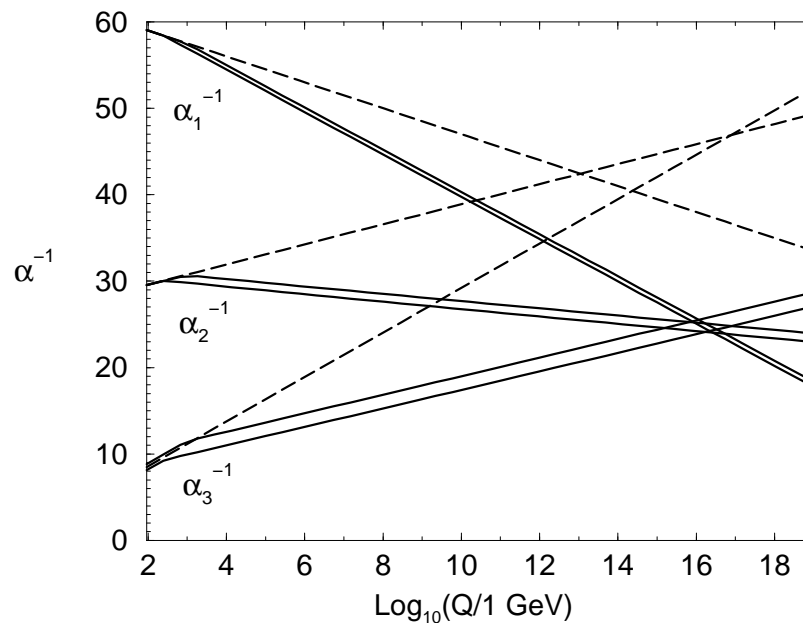
**The problem:** if  $-m_{H_u}^2$  is comparable to  $m_{\tilde{t}_1} m_{\tilde{t}_2} \approx (700 \text{ GeV})^2$ ,  
then required cancellation of order 1%. This may seem like an  
amazing coincidence.

However, the fine-tuning required is actually not quite so severe as often portrayed, for two reasons:

- The previous expression for  $M_h^2$  is too simplistic
- The relation between  $m_{H_u}^2$  and stop masses  $m_{\tilde{t}_1}, m_{\tilde{t}_2}$  is subtle

Why are  $m_{H_u}^2$  and  $m_{\tilde{t}_1}$  and  $m_{\tilde{t}_2}$  related at all?

This is a model-dependent assumption, motivated (but not required) by the apparent unification of gauge couplings:



This invites us to use renormalization group running to also evolve SUSY breaking masses down from the GUT scale.

The so-called mSUGRA model says:

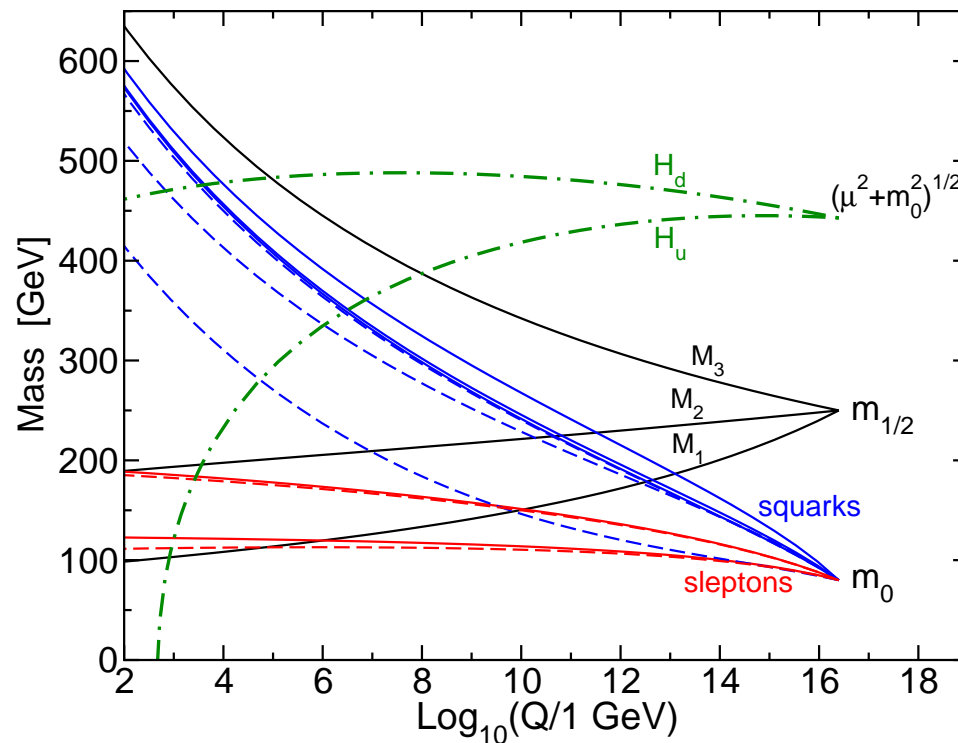
gluino, wino, bino masses unified:  $\hat{M}_3 = \hat{M}_2 = \hat{M}_1 = m_{1/2}$

all scalar masses unified:  $\hat{m}_\phi^2 = m_0^2$

Hats denote running couplings at the GUT scale.

This model parameterization is simple, but not otherwise well-motivated.

Assuming unified gaugino and scalar masses near the GUT scale predicts a hierarchical mass spectrum at the TeV scale:



The fine tuning is mostly the gluino's fault.

Fine tuning of the electroweak scale is reduced if the pernicious influence of the gluino is suppressed. (G. Kane and S. King, hep-ph/9810374)

$$\begin{aligned} -m_{H_u}^2 &= 1.92\hat{M}_3^2 + 0.16\hat{M}_2\hat{M}_3 - 0.21\hat{M}_2^2 \\ &\quad - 0.63\hat{m}_{H_u}^2 + 0.36\hat{m}_{t_L}^2 + 0.28\hat{m}_{t_R}^2 \\ &\quad + \text{many terms with tiny coefficients} \end{aligned}$$

The hatted parameters on the right are at the GUT scale, result is at the TeV scale.

**If one takes a smaller gluino mass at the GUT scale, say  $\hat{M}_3/\hat{M}_2 \sim 1/3$ , then  $-m_{H_u}^2$  will be much smaller.**

As a result,  $|\mu|^2$  will be smaller also.

Are there reasonable models in which  $\hat{M}_3/\hat{M}_2$  is smaller?

**Answer: yes, too many to count.**

I'll review my favorite mechanism, which even works if there is really a GUT theory like  $SU(5)$  or  $SO(10)$ . But results below about dark matter don't depend crucially on this choice.

Usual assumption: the source of spontaneous SUSY breaking is a VEV

$$\langle F \rangle \neq 0$$

that is a singlet under the unified gauge group. This is implicit in the mSUGRA boundary condition.

But, more generally,  $F$  could transform as anything in the symmetric product of the adjoint rep of the unified gauge group with itself, as long as it is a Standard Model singlet.

For  $SU(5)$ :

$$(\mathbf{24} \times \mathbf{24})_S = \mathbf{1} + \mathbf{24} + \mathbf{75} + \mathbf{200}.$$

Suppose the  $F$  terms that break SUSY include both a singlet and an adjoint. Then at the GUT scale, one can parametrize:

$$\begin{aligned}\hat{M}_1 &= m_{1/2}(1 + C_{24}), \\ \hat{M}_2 &= m_{1/2}(1 + 3C_{24}), \\ \hat{M}_3 &= m_{1/2}(1 - 2C_{24}).\end{aligned}$$

The special case  $C_{24} = 0$  recovers the usual mSUGRA model.

In  $SU(5)$  GUT models, there is a superfield in the **24** (adjoint) representation anyway, used to break the group down to the Standard Model.

It is unnatural for the corresponding  $F$  field to not get a VEV, if the scalar component does.

To obtain  $\hat{M}_3/\hat{M}_2 \sim 1/3$ , one needs only  $C_{24} \sim 0.2$ .

$$\hat{M}_1 = m_{1/2}(1 + C_{24}),$$

$$\hat{M}_2 = m_{1/2}(1 + 3C_{24}),$$

$$\hat{M}_3 = m_{1/2}(1 - 2C_{24}).$$

In the following, I also assume a common scalar squared mass  $m_0^2$ .

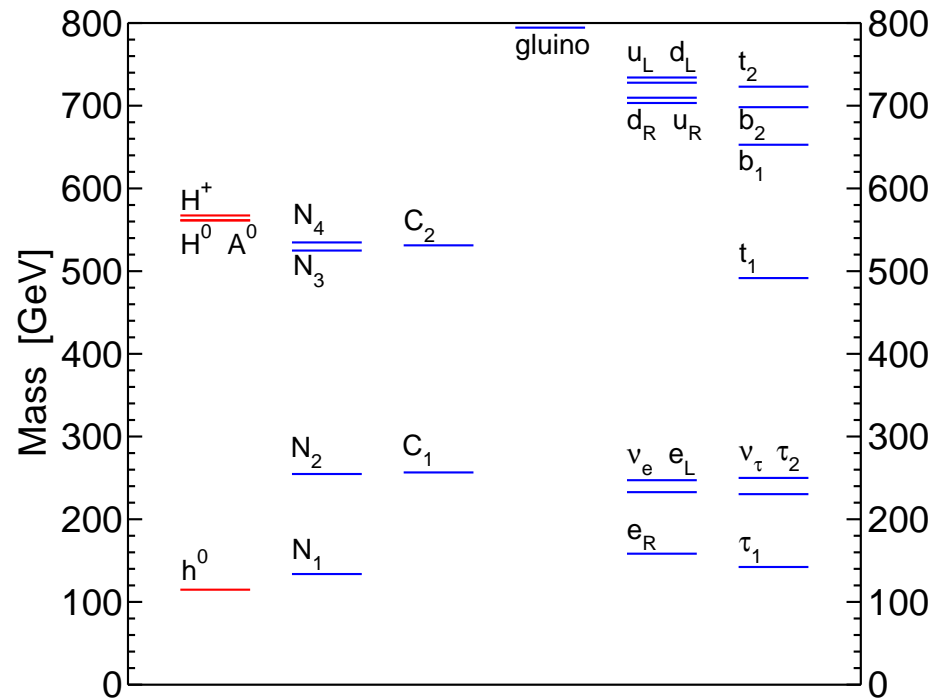
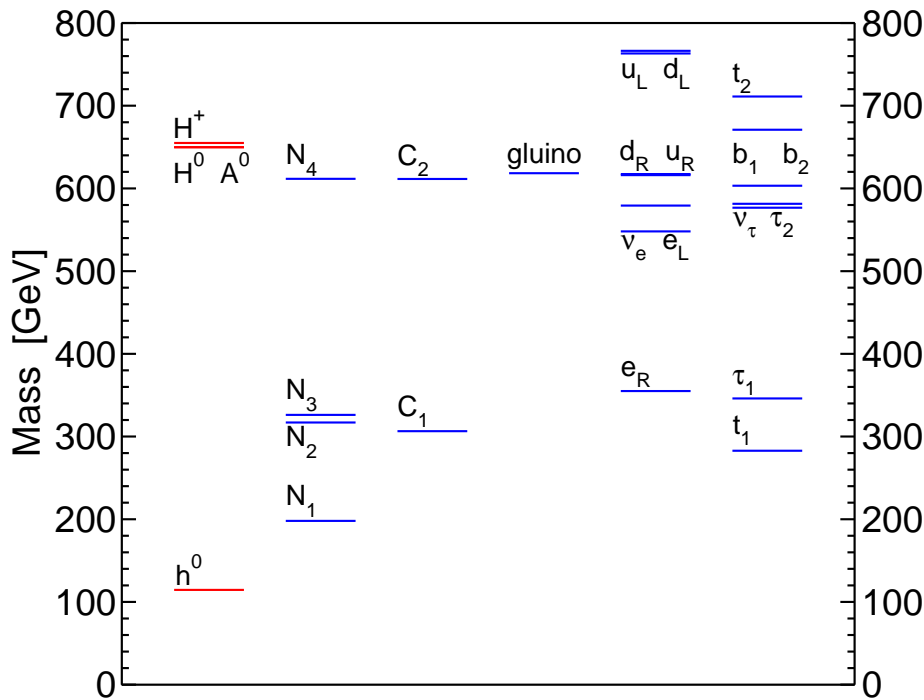
This is for simplicity and convenience; the main qualitative feature of interest is the relative suppression of the gluino mass, which then feeds less into squark masses.

The result is a “compressed” SUSY spectrum, with a smaller ratio of the masses of the heaviest SUSY particle and the LSP:

Comparison of Compressed SUSY and mSUGRA, for models with Higgs mass  $m_h$  just above LEP2 bound, and heaviest squarks in the 700-800 GeV range:

Compressed SUSY  $\hat{M}_3/\hat{M}_2 = 1/3$

mSUGRA  $\hat{M}_3/\hat{M}_2 = 1$

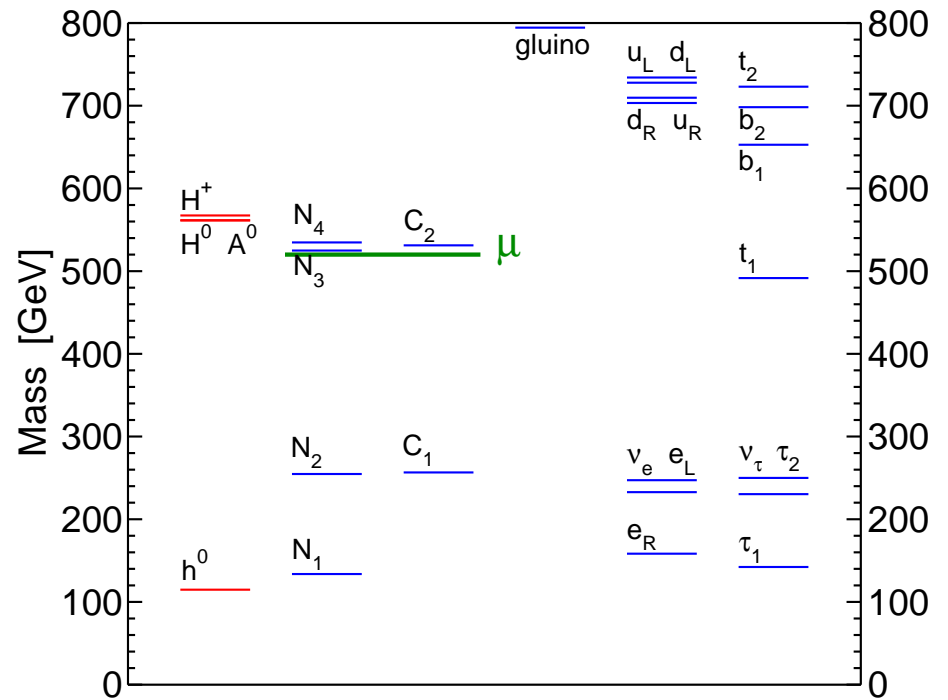
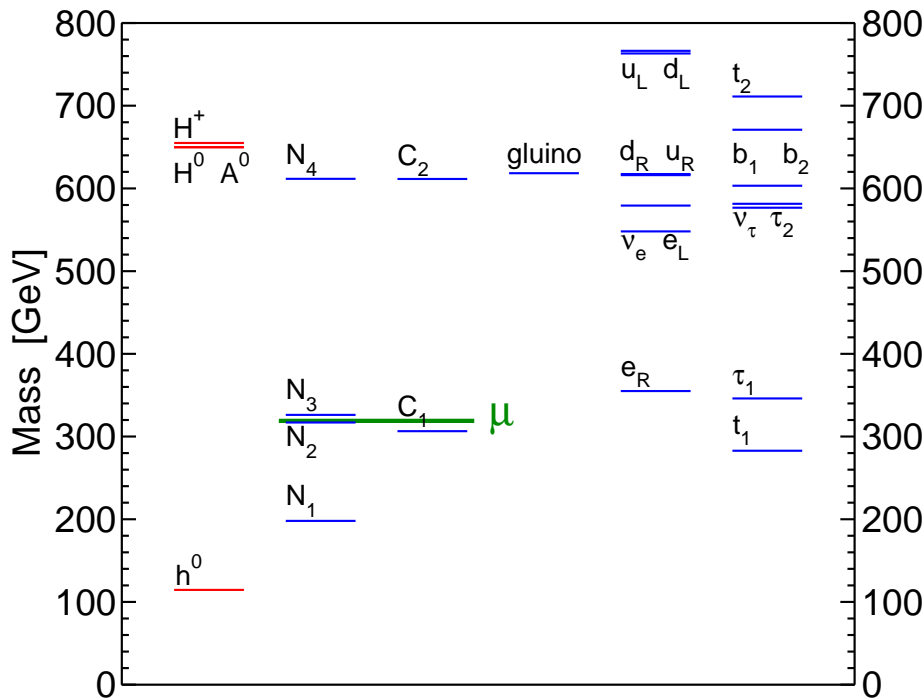


Note  $|\mu|^2$  lower in Compressed SUSY; less cancellation needed.

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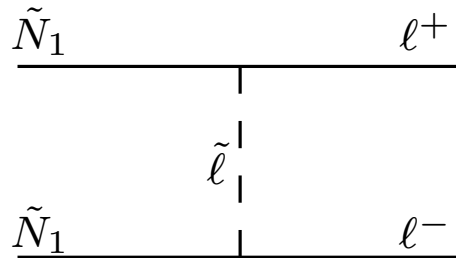
Note  $|\mu|^2$  lower in Compressed SUSY; less cancellation needed.

Now let's switch gears and consider the constraint from dark matter.

WMAP and other experiments have measured  $\Omega_{\text{DM}}h^2 \approx 0.11$

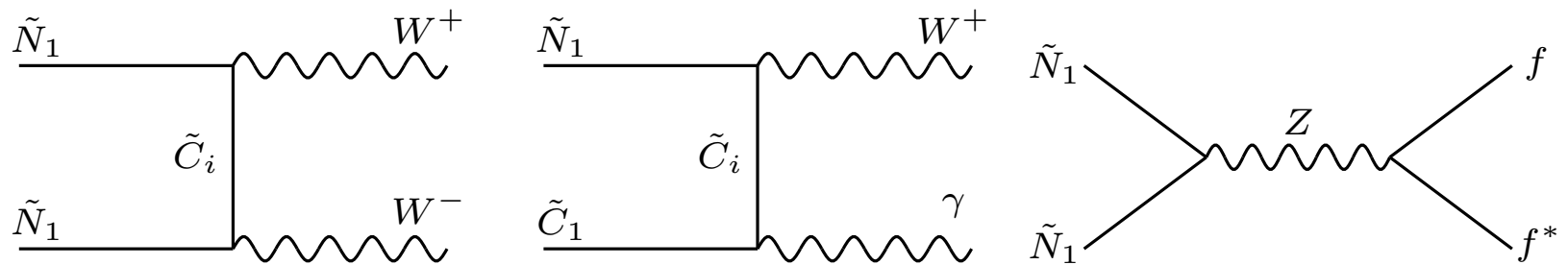
In much of the remaining SUSY parameter space,  $\Omega_{\text{DM}}h^2$  comes out too large. A mechanism for efficient annihilation of LSPs in the early universe is needed. The exceptions are usually classified qualitatively in 4 main categories:

**1) “Bulk region”: LSPs annihilate through slepton exchange.**



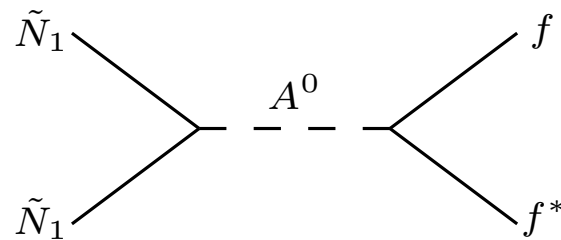
In mSUGRA, it is tough to accommodate this and LEP2 bounds at the same time.

2) “Focus point/Small  $\mu$ ”: LSPs have enough higgsino content to annihilate or coannihilate to/through weak bosons



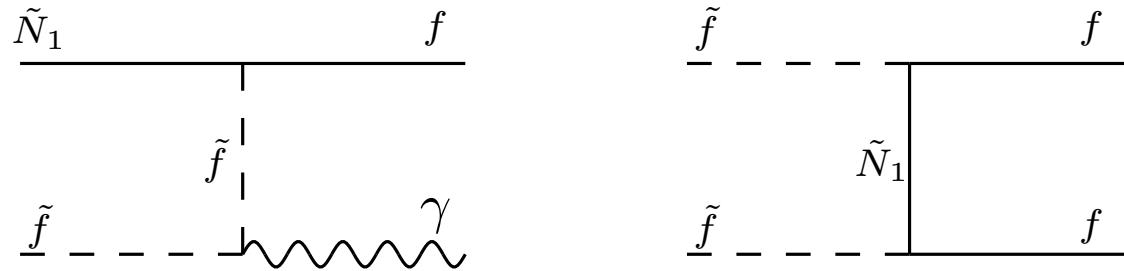
Need to tune  $\mu$  just right.

3) “Higgs resonance (funnel)”: LSPs annihilate by  $s$  channel pseudoscalar Higgs exchange



Need LSP mass to be close to  $m_{A^0}/2$ , usually large  $\tan \beta$ .

**4) “Co-annihilation region”:** LSPs co-annihilate with sleptons (or top squarks) in thermal equilibrium

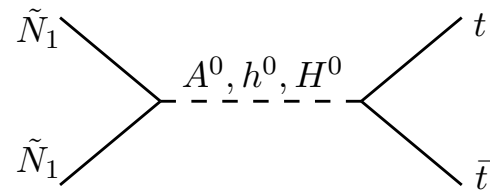
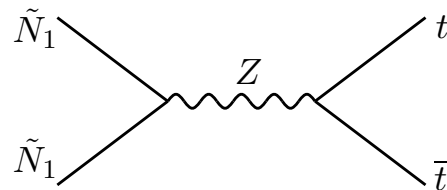
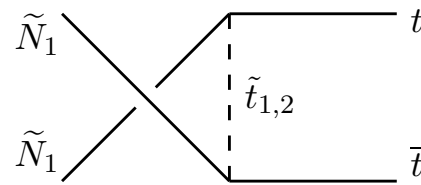
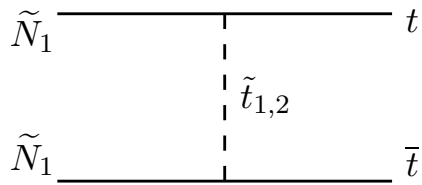


Need a small sfermion-LSP mass difference, tuned just right.

In Compressed Supersymmetry, I claim another scenario becomes natural, because the LSP is naturally heavier than the top quark, and the top squark is the next-lightest superpartner. . .

**An alternative: Pair annihilation of LSPs to top quarks, mediated by top squark exchange.**

Diagrams leading to  $\tilde{N}_1 \tilde{N}_1 \rightarrow t \bar{t}$  :



To get  $\Omega_{\text{DM}} h^2$  into the WMAP allowed range, need roughly:

$$m_t < m_{\tilde{N}_1} \lesssim m_t + 100 \text{ GeV},$$

$$m_{\tilde{N}_1} + 25 \text{ GeV} \lesssim m_{\tilde{t}_1} \lesssim m_{\tilde{N}_1} + 100 \text{ GeV}.$$

In Compressed Supersymmetry, the  $\tilde{t}_1$  exchange can naturally dominate.

(The  $Z$  exchange diagram interferes destructively.)

In the following, I consider models with  $m_0$  and  $\hat{M}_1$  variable, with

$$C_{24} \neq 0, \quad \tan \beta = 10, \quad \mu > 0.$$

Imposed Higgs mass constraint (noting significant theoretical uncertainties):

$$M_h > 113 \text{ GeV}.$$

Also, I assume

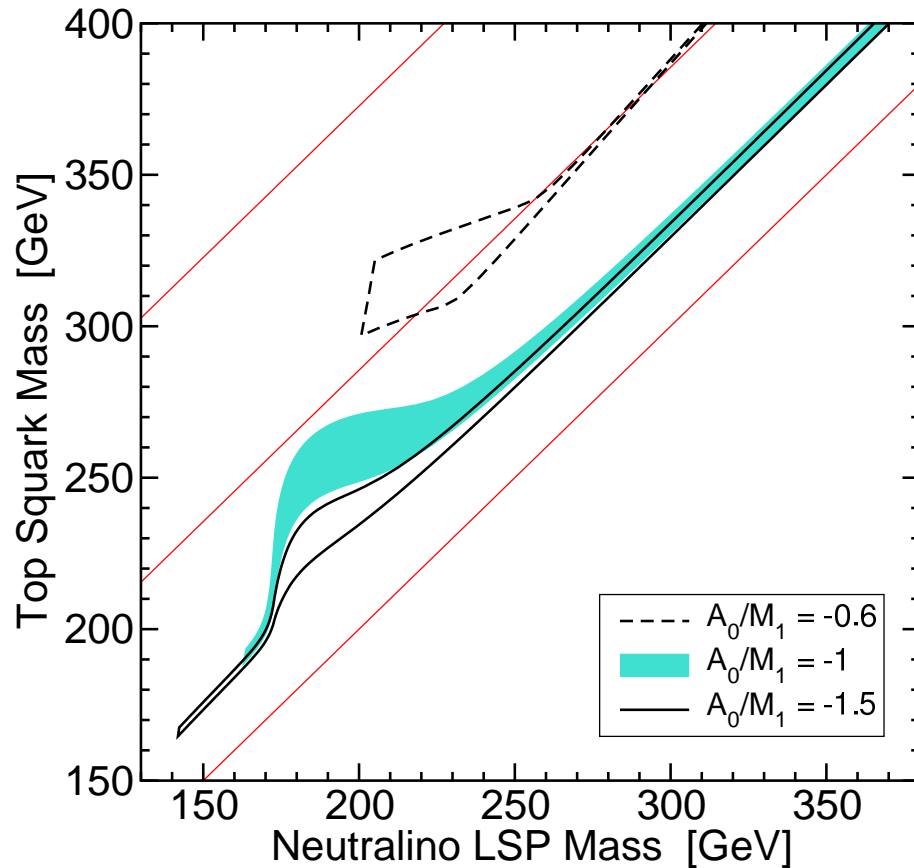
$$M_t = 172.7 \text{ GeV}.$$

Finally, I impose the rather conservative constraint on dark matter:

$$0.09 < \Omega_{\text{DM}} h^2 < 0.13$$

computed using `micrOMEGAS` (Belanger, Boudjema, Pukhov, Semenov).

Allowed regions in the  $m_{\tilde{t}_1}, m_{\tilde{N}_1}$  plane for  $C_{24} = 0.21$ :



In the bulge regions,  
 $\tilde{N}_1 \tilde{N}_1 \rightarrow t\bar{t}$  is mediated mostly  
 by  $\tilde{t}_1$  exchange.

Below upper red line,  $\tilde{t}_1 \rightarrow t\tilde{N}_1$   
 is forbidden.

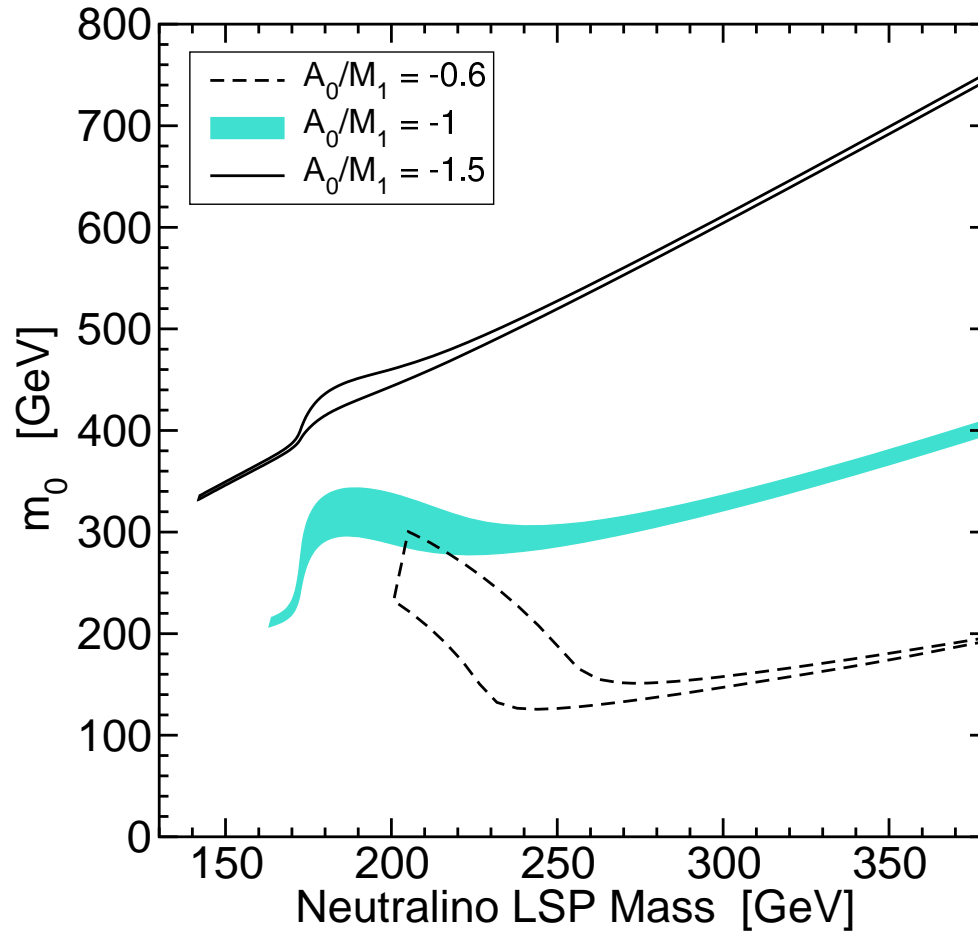
Below middle red line,  
 $\tilde{t}_1 \rightarrow Wb\tilde{N}_1$  is also forbidden.

Below lowest red line,  $\tilde{t}_1$  is LSP.

Regions are cut off on the left by the  $M_h$  constraint.

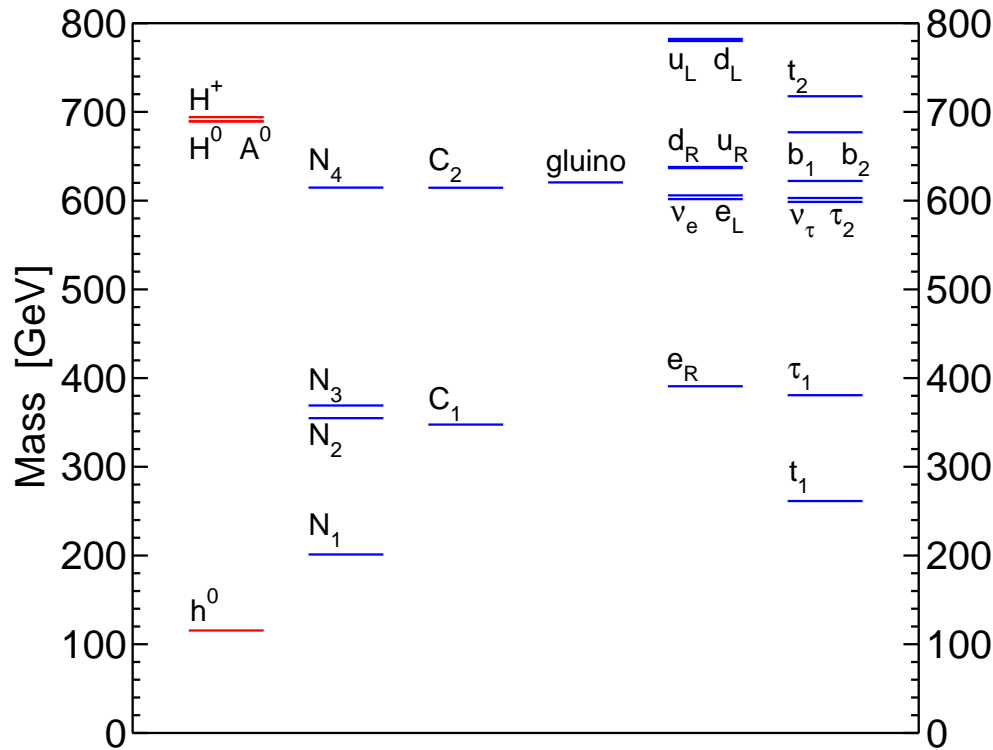
Thin regions on either side of the bulge obtain correct dark matter density by  
 co-annihilation with top-squark .

Common GUT-scale scalar mass  $m_0$  for the same models:



In these models, **all** soft SUSY-breaking mass parameters are less than  $\hat{M}_1, \hat{M}_2$ .  
Beating the LEP Higgs constraint (almost) forces  $m_{\tilde{N}_1}$  to be larger than  $m_t$ .

This scenario for SUSY dark matter has distinctive implications for colliders.



Important decays for hadron colliders:

$$\tilde{t}_1 \rightarrow c\tilde{N}_1 \quad (100\%)$$

$$\tilde{g} \rightarrow \begin{cases} t\tilde{t}_1^* & (\sim 50\%) \\ \bar{t}\tilde{t}_1 & (\sim 50\%) \end{cases}$$

$$\tilde{q}_L \rightarrow \begin{cases} q\tilde{g} & (\sim 78\%) \\ q'\tilde{C}_2 & (\sim 11\%) \end{cases}$$

$$\tilde{q}_R \rightarrow q\tilde{N}_1 \quad (\sim 90\%)$$

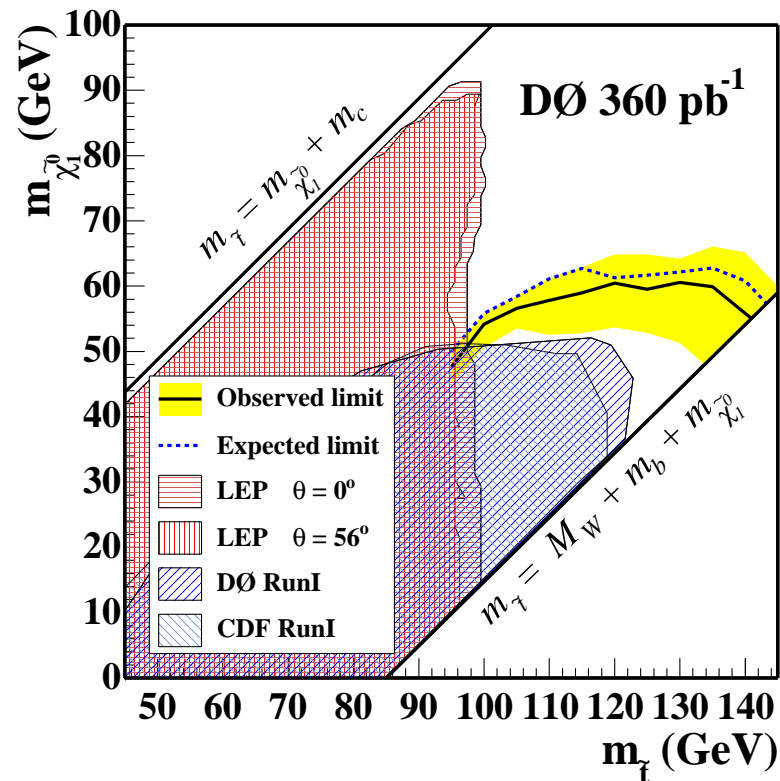
More generally,  $\tilde{t}_1$  cannot decay to  $t\tilde{N}_1$  in this scenario.

The spectrum is relatively heavy; the compression is upwards to make  $M_h$  heavy, so weakly-interacting superpartners are hard to see at hadron colliders.

## The target is here!

In this scenario, superpartners are too heavy to give much hope at the Tevatron.  
One can look for the top squark  $\tilde{t}_1$  by:

$$p\bar{p} \rightarrow \tilde{t}_1\tilde{t}_1^* \rightarrow c\bar{c}\tilde{N}_1\tilde{N}_1 \rightarrow c\bar{c} + \cancel{E}_T$$



Usual Tevatron signals for SUSY, trileptons, like-sign dileptons, jets +  $\cancel{E}_T$ , all seem to be very hard or impossible. Not enough events.

## LHC discovery signal

If  $\tilde{t}_1 \rightarrow c\tilde{N}_1$ , gluino pair production leads to:

$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow \begin{cases} t\bar{t}\tilde{t}_1\tilde{t}_1^* \rightarrow t\bar{t}c\bar{c} + \cancel{E}_T & (50\%) \\ tt\tilde{t}_1^*\tilde{t}_1^* \rightarrow tt\bar{c}\bar{c} + \cancel{E}_T & (25\%) \\ \bar{t}\bar{t}\tilde{t}_1\tilde{t}_1 \rightarrow \bar{t}\bar{t}cc + \cancel{E}_T & (25\%) \end{cases}$$

Kraml and Raklev (2005) used like-charge leptonic decay modes for both top quarks. Both discovery and mass measurements are possible up to a gluino mass of about 900 GeV.

Most SUSY events at LHC will go through the gluino. (So add softer, light-flavor, jets from squark decays.)

## LHC discovery signals (continued)

On the other hand, if  $\tilde{t}_1 \rightarrow Wb\tilde{N}_1$ ,

$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow \begin{cases} t\bar{t}\tilde{t}_1\tilde{t}_1^* \rightarrow t\bar{t}b\bar{b}\ell^+\ell'^- + \cancel{E}_T & (50\%) \\ tt\tilde{t}_1^*\tilde{t}_1^* \rightarrow tt\bar{b}\bar{b}\ell^-\ell'^- + \cancel{E}_T & (25\%) \\ \bar{t}\bar{t}\tilde{t}_1\tilde{t}_1 \rightarrow \bar{t}\bar{t}bb\ell^+\ell'^+ + \cancel{E}_T & (25\%) \end{cases}$$

So 4 potential  $b$  tags, plus like sign dileptons, plus large  $\cancel{E}_T$ .

This tends to occur if  $\hat{A}_t$  is smaller.

## A distinctive possibility: Stoponium?

Because the stop is long-lived, it can form bound states, including stoponium  $\eta_{\tilde{t}_1}$ .

At the LHC, the most promising channel for stoponium is:

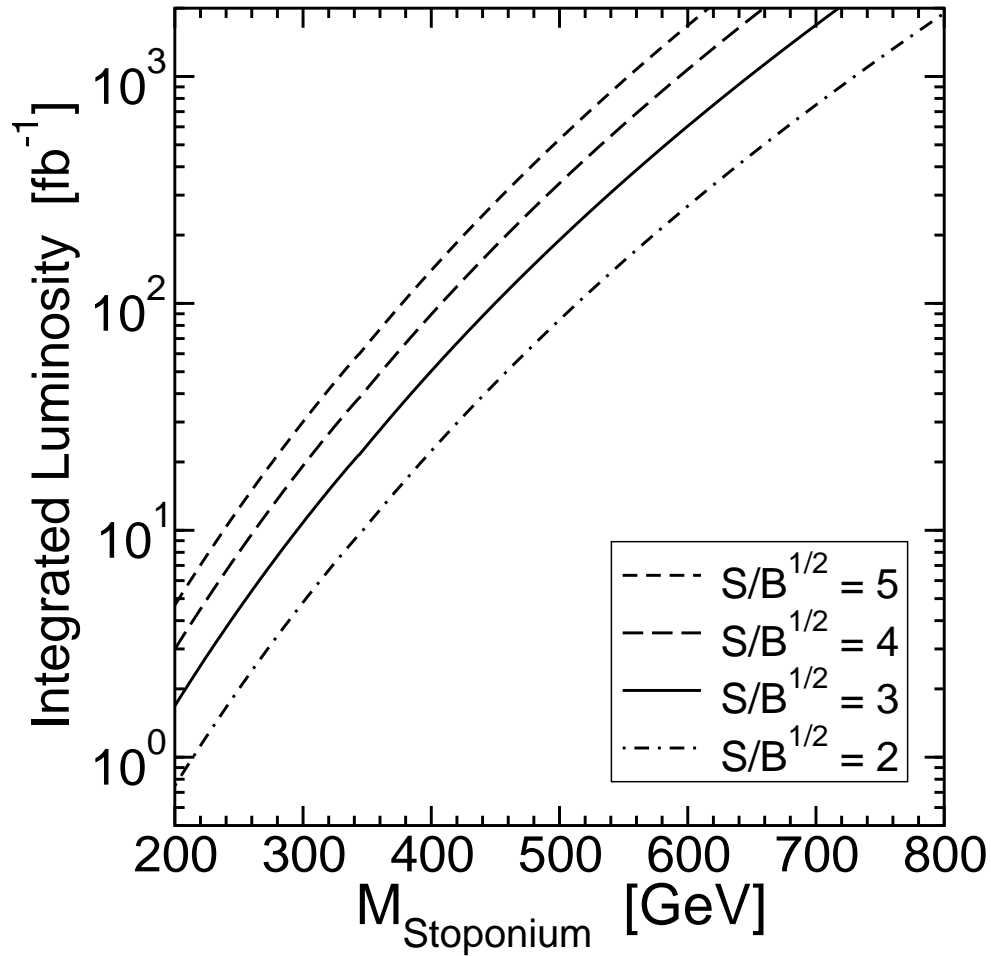
$$pp \rightarrow \eta_{\tilde{t}_1} \rightarrow \gamma\gamma$$

(Studied by Drees and Nojiri, 1993.)

This would give a **precision** measurement of the stop mass, in the form of a very narrow mass peak! The experimental width is dominated by electromagnetic calorimeter energy resolution.

In Compressed SUSY, I find that stoponium may indeed be a viable signal, although it will require high luminosity:

Integrated luminosity needed for stoponium signal:

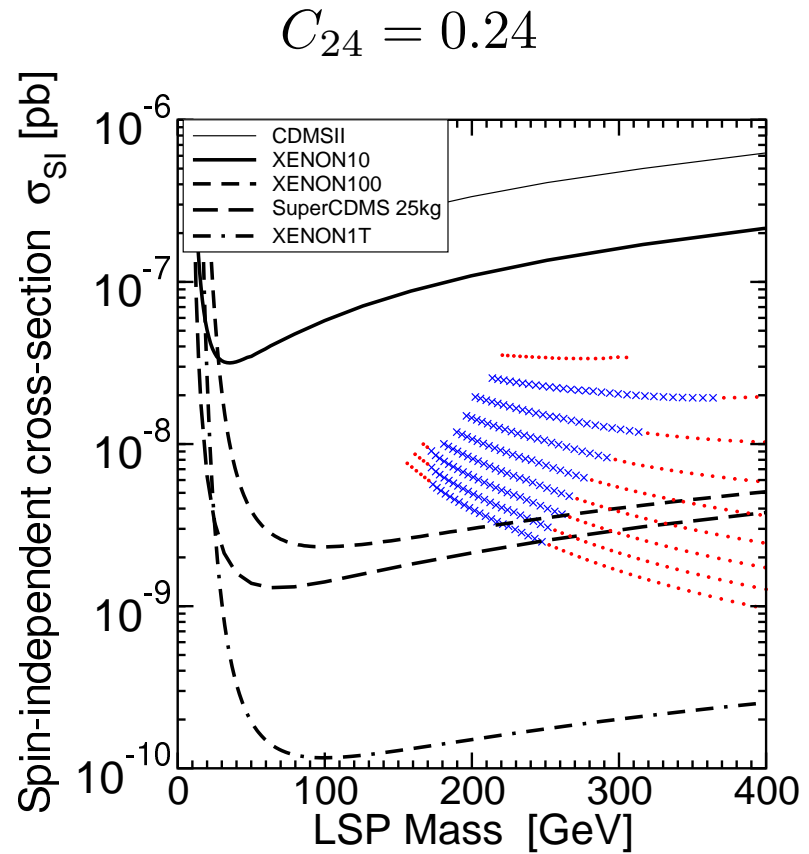
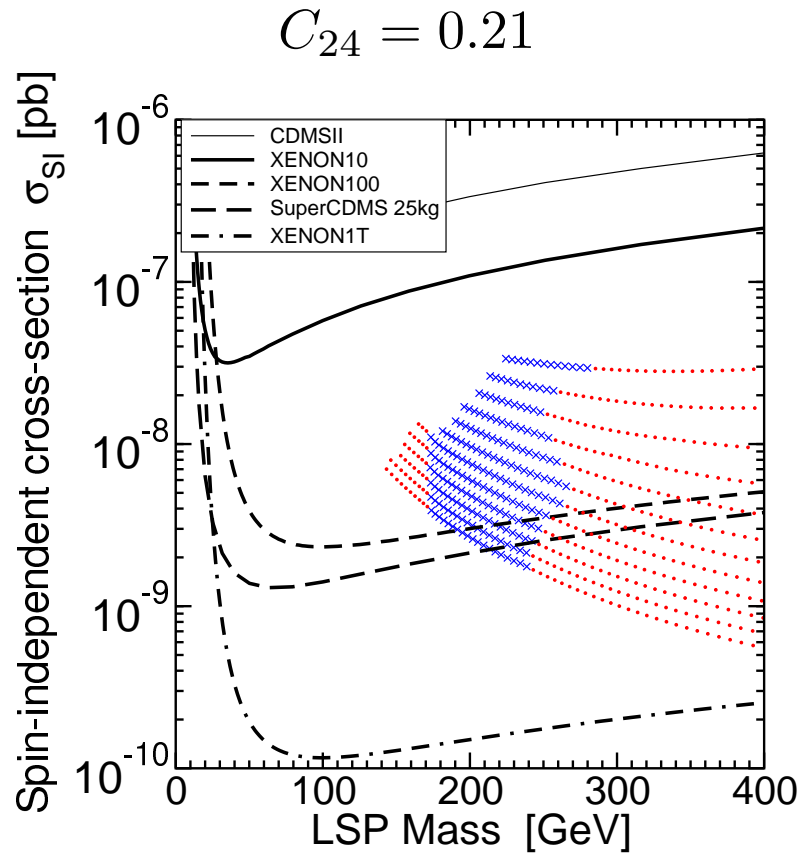


This optimistically assumes that  $\eta_{\tilde{t}} \rightarrow gg$  dominates.  
Recall  $100 \text{ fb}^{-1} = 1$  high luminosity year.

I also find robust predictions for the direct detection of dark matter, thanks to the limited range of LSP masses and mixings.

Neutralinos scatter off of heavy nuclei in low-background laboratory detectors. A standard figure of merit is the LSP-proton spin-independent cross-section.

In the following, I compare present experimental results (CDMSII, XENON10) and future projected sensitivities (XENON100, SuperCDMS 25kg at SNOLAB, and XENON1T) to the predictions of Compressed Supersymmetry.



Blue X's = “bulge” annihilation-to-top models,

Red dots = stop co-annihilation models

Present experiments do not constrain the scenario.

Future experiments should provide a definitive test.

## Outlook

- Non-universal gaugino masses at the GUT scale with  $\hat{M}_3/\hat{M}_2 \lesssim 1/3$  alleviate the fine-tuning problem of minimal SUSY, leading to a compressed mass spectrum
- A distinctive scenario for dark matter:  $\tilde{N}_1\tilde{N}_1 \rightarrow t\bar{t}$  through  $\tilde{t}_1$  exchange dominates
- Discovery is impossible at the past LEP2 collider, guaranteed at the imminent LHC (but some sleptons decouple, and Higgsinos and Winos will be tough)
- In this scenario, a much higher beam energy for a future ILC may be preferable. We'll know better after the LHC.
- Direct dark matter detection prospects are very promising.