Measuring the spin of SUSY particles

SUSY:

- every SM fermion (spin 1/2) ↔ SUSY scalar (spin 0)
- every SM boson (spin 1 or 0) ↔ SUSY fermion (spin 1/2)

Want to check experimentally that (e.g.) $\tilde{e}_{L,R}$ are really spin 0 and $\widetilde{C}_{1,2}$ are really spin 1/2.

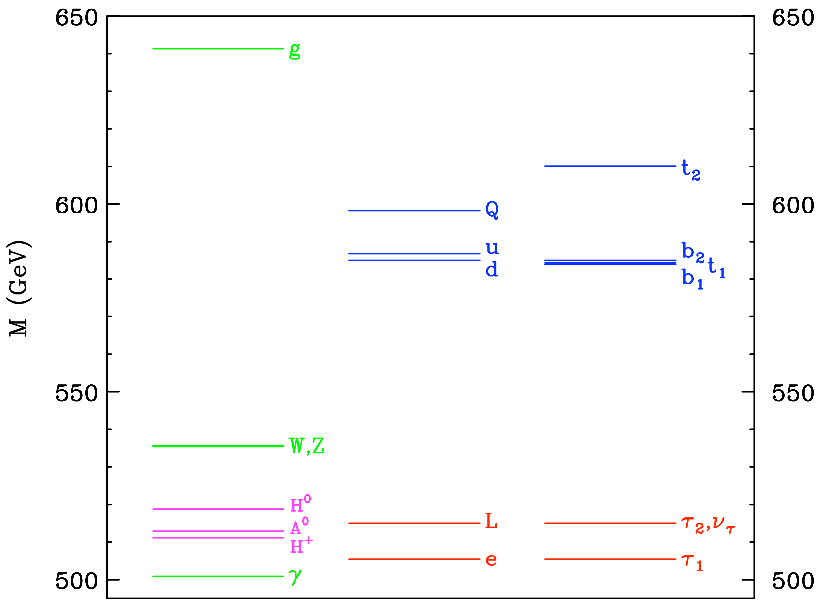
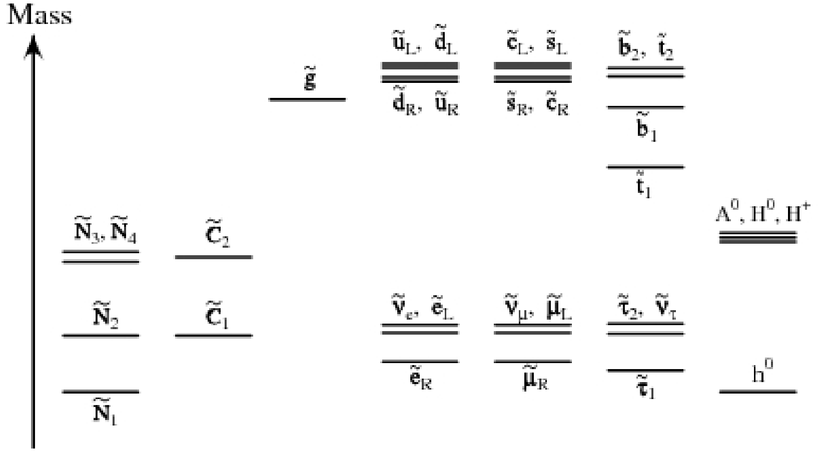


FIG. 1: *One-loop corrected mass spectrum of the first KK level in MUEDs for* $R^{-1} = 500$ *GeV,* $\Lambda R = 20$ *and* $m_h = 120$ *GeV.*

Model with a 500 GeV-size extra dimension could give a rather SUSY-like spectrum!



We could be fooled into thinking we discovered SUSY, when it is really extra dimensions!

EDim: “Kaluza-Klein excitations” (heavier copies) of SM particles: same spin as SM “partners”.

Measuring spin at an e^+e^- collider: threshold dependence of cross section. Consider direct production of slepton pairs; compare to direct production of KK lepton pairs.

Scalar pair production $f\bar{f} \to \gamma^*, Z^* \to \tilde{\ell}^+\tilde{\ell}^-$ (sleptons):

$$\sigma \propto \beta^3 \tag{1}$$

Fermion pair production $f\bar{f} \to \gamma^*, Z^* \to \ell_1^+\ell_1^-$ (KK leptons):

$$\sigma \propto \beta(3 - \beta^2) \tag{2}$$

where $\beta = p/E = \sqrt{1 - 4m^2/s}$ is the velocity of the produced particle.

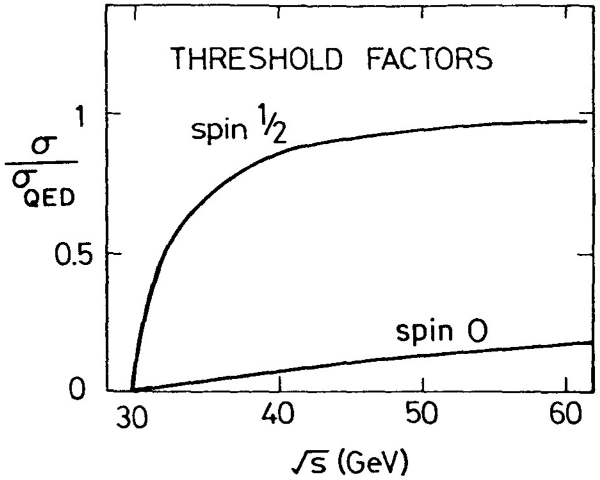


Fig. 4.7. Comparison of spin-0 and spin-$\frac{1}{2}$ particle pair production in e^+e^- collisions, for particles of mass m = 15 GeV.

Can do a threshold scan: scan the e^+e^- beam energy across $2m_{\tilde{\ell}}$ (measured from kinematic endpoint techniques!).

- Get the spin from β dependence of threshold.
- Also get very precise mass measurement.

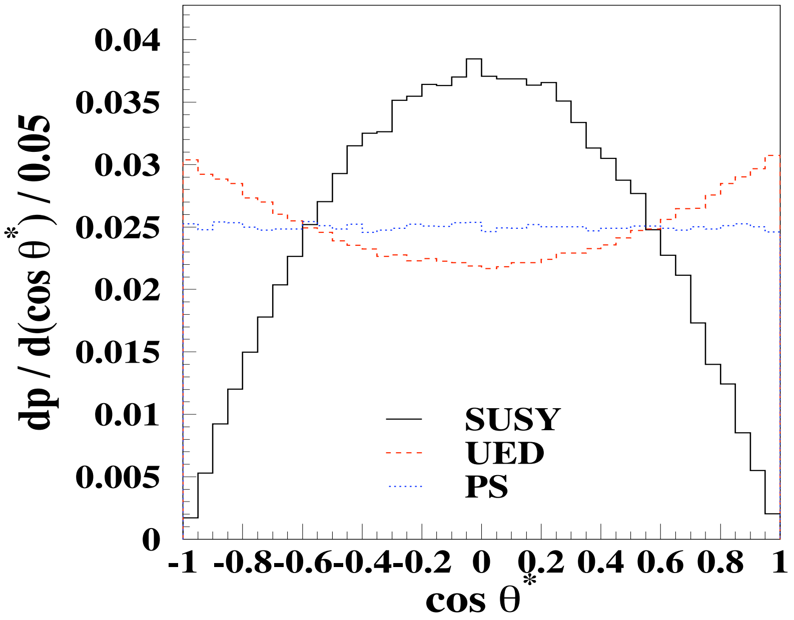
Another way to measure spin: angular distribution of pair production.
Consider direct production of slepton pairs; compare to direct production of KK lepton pairs.

Scalar pair production $f\bar{f} \to \gamma^*, Z^* \to \tilde{\ell}^+\tilde{\ell}^-$ (sleptons):

$$\frac{d\sigma}{d\cos\theta} \propto 1 - \cos^2\theta \qquad (3)$$

Fermion pair production $f\bar{f} \to \gamma^*, Z^* \to \ell_1^+\ell_1^-$ (KK leptons):

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \left(\frac{E^2 - M^2}{E^2 + M^2}\right)\cos^2\theta \qquad (4)$$



from hep-ph/0511115

Also for comparison a pure "phase space" (uniform distribution) is shown: $d\sigma/d\cos\theta =$ constant.

- Particles decay, $\tilde{\ell}^+\tilde{\ell}^- \to \ell^+ \tilde{N}_1 \ell^- \tilde{N}_1$ or $\ell_1^+\ell_1^- \to \ell^+\gamma_1\ell^-\gamma_1$

In e^+e^- this is not a problem: can still reconstruct $\tilde{\ell}^+\tilde{\ell}^-$ directions (with "background" from wrong reconstruction)

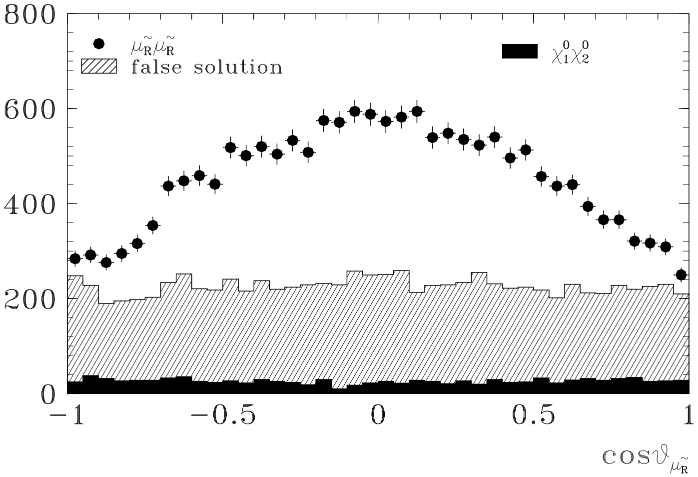
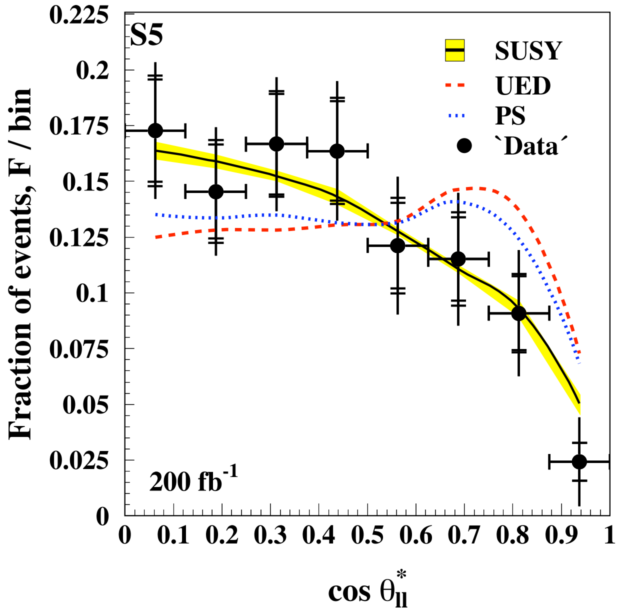


Figure 3.2.3: *Angular distribution of smuons (two entries per event) in the reaction* $e_R^- e_L^+ \to \tilde{\mu}_R\tilde{\mu}_R \to \mu^-\tilde{\chi}_1^0\,\mu^+\tilde{\chi}_1^0$. *The hatched histogram represents the false solution.*

from Tesla TDR, hep-ph/0106315

- At LHC, more difficult: CM frame is boosted longitudinally

Measure instead the lepton polar angle in the $\ell^+\ell^-$ CM frame



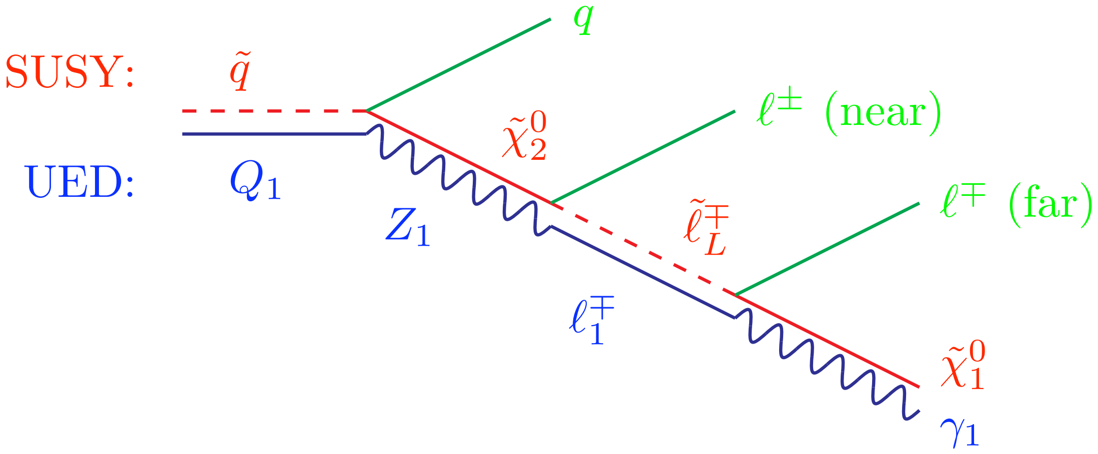
from hep-ph/0511115

Still has some sensitivity

Need to select events with direct slepton pair production.

Another method for LHC: look at a decay chain

Example:
- $\widetilde{q} \rightarrow q\widetilde{N}_2 \rightarrow q\ell^{\pm}\widetilde{\ell}^{\mp} \rightarrow q\ell^{+}\ell^{-}\widetilde{N}_1$ in SUSY
- $q_1 \rightarrow qZ_1 \rightarrow q\ell^{\pm}\ell_1^{\mp} \rightarrow q\ell^{+}\ell^{-}\gamma_1$ in EDim



Form $M_{q\ell}$ invariant mass dist'n with first (near) lepton
Shape depends on spin of intermediate particle:
- $\widetilde{N}_2$ in SUSY – spin 1/2
- Z_1 in EDim – spin 1

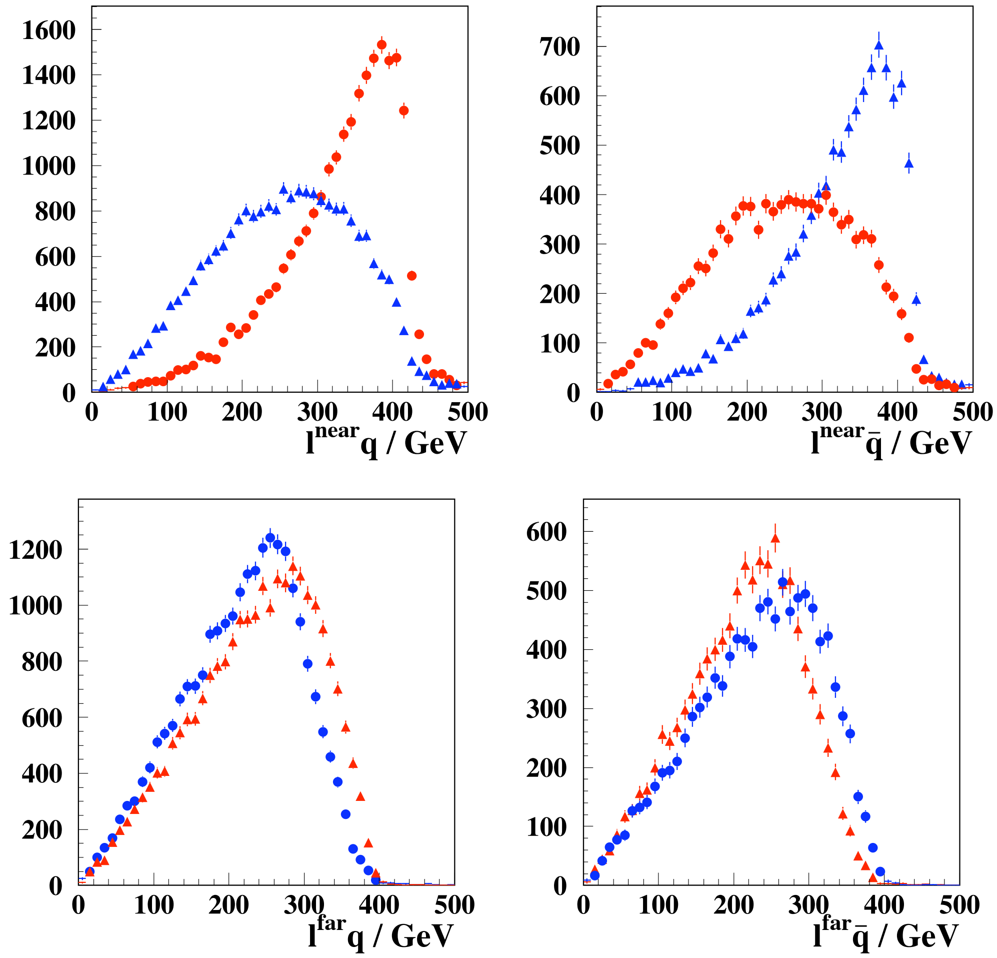
But: hard to distinguish the first (near) lepton from the second (far) lepton.
Tends to wash out spin correlations.

Idea: use a charge asymmetry between $q\ell^+$ and $q\ell^-$

How does this work?

$\widetilde{N}_2$ typically mostly $\widetilde{W}^0$: couples to LH fermions / RH antifermions

Helicity conservation causes an $M_{\ell q}$ difference between ℓ^+ and ℓ^-:



ℓ^- ℓ^+

from hep-ph/0405052

Summing over $\tilde{q} + \tilde{q}^*$ would wash this out again EXCEPT:

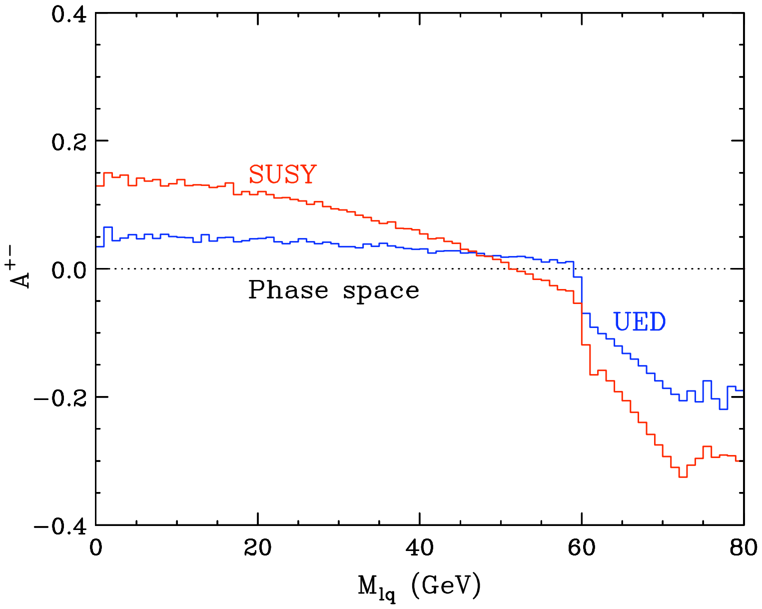
LHC is a pp collider: more q than $\bar{q}$ in PDFs.

Make a lepton charge asymmetry:

$$A^{+-} = \frac{s^+ - s^-}{s^+ + s^-}, \qquad s^\pm = \frac{d\sigma}{d(M_{\ell^\pm q})} \tag{5}$$

- For SUSY there's a dependence of the charge asymmetry on $M_{\ell q}$.

- For the Extra Dimension model there's also a dependence (because Z_1 couples differently to LH and RH fermions) but different from that of SUSY (because Z_1 is spin 1, not spin 1/2).

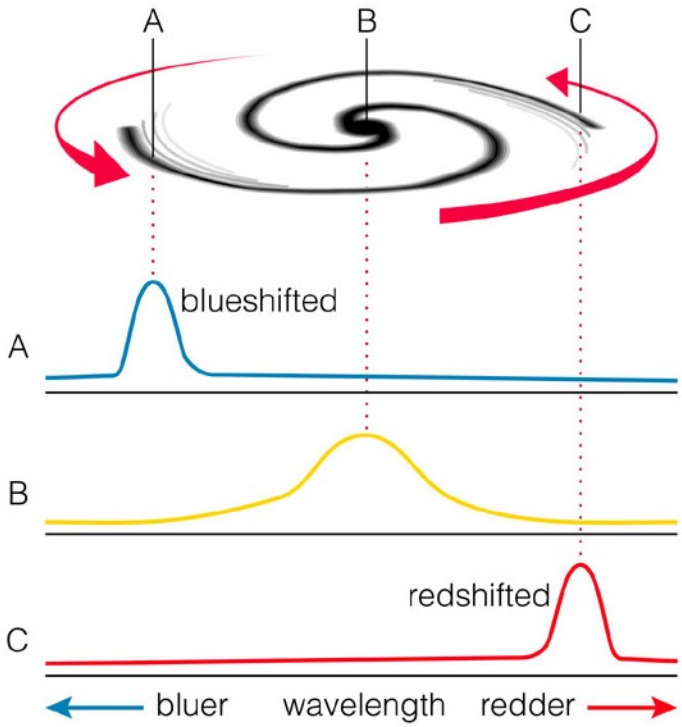


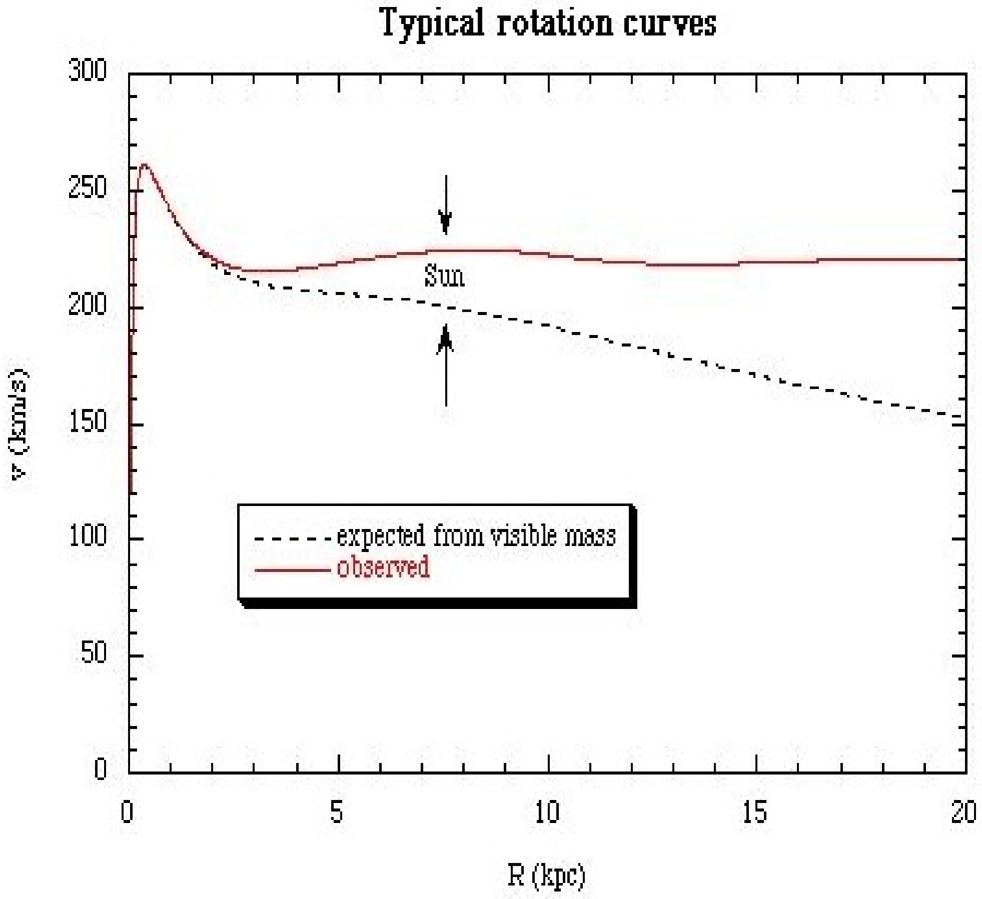
from hep-ph/0509246

Dark Matter

How do we know about dark matter?
→ Purely through its gravitational effects.

“Weigh the stars” by their gravitational effects:

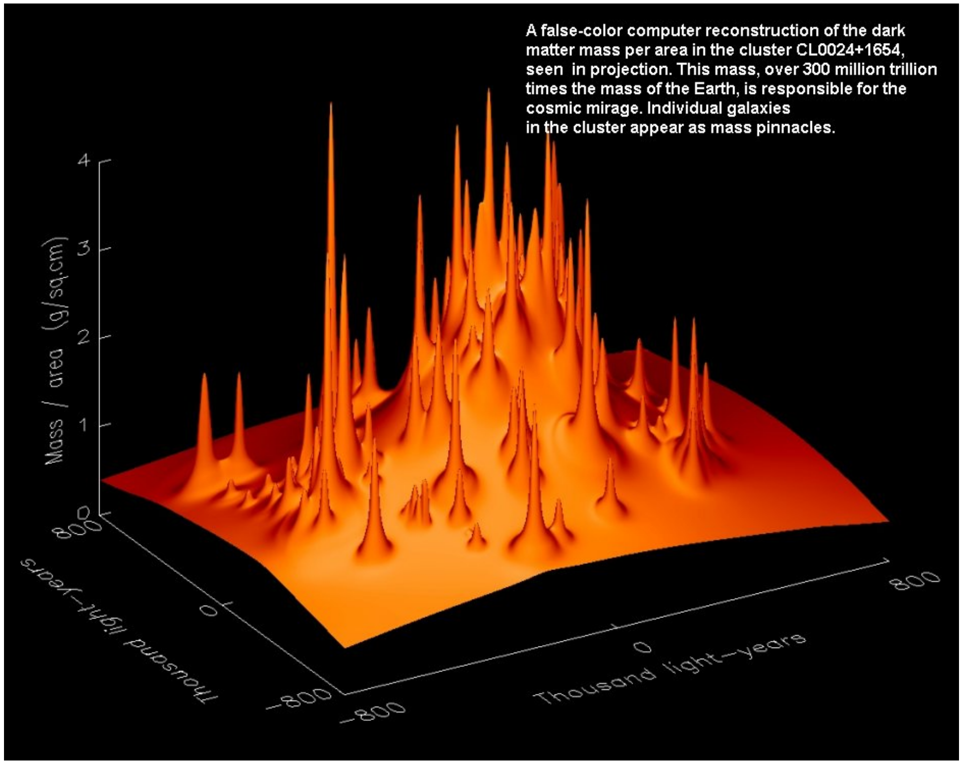




More matter in our galaxy than what we see in stars, gas, dust, etc

On a larger scale, bending of light by matter lets us reconstruct the distribution of mass in galaxy clusters.

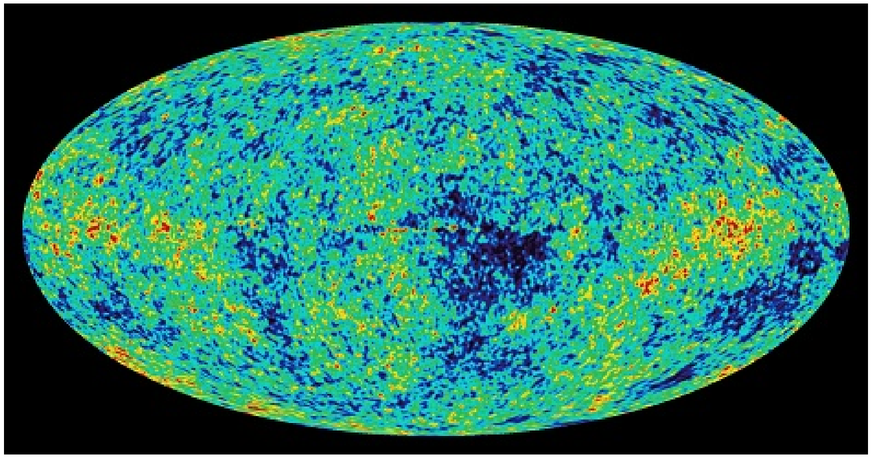
Gravitational lensing of background galaxies by foreground cluster: reconstruct mass distribution of cluster

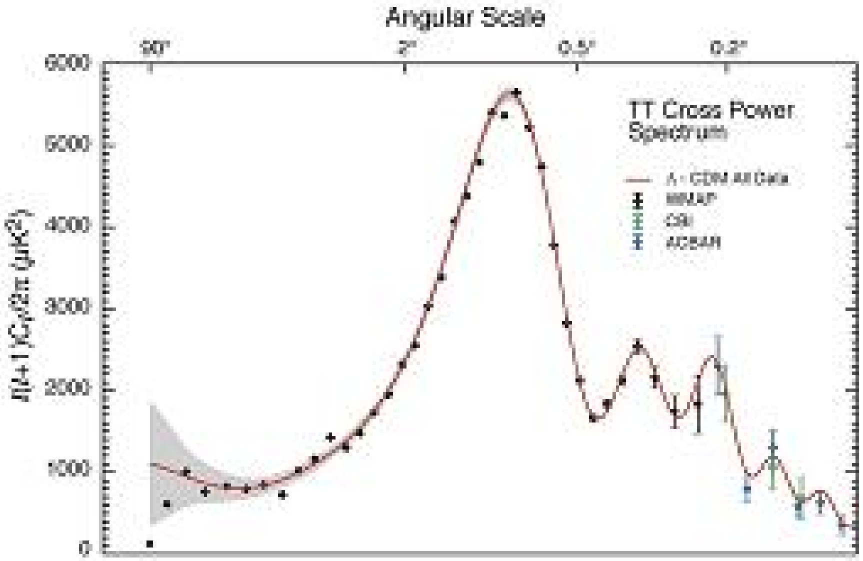


A false-color computer reconstruction of the dark matter mass per area in the cluster CL0024+1654, seen in projection. This mass, over 300 million trillion times the mass of the Earth, is responsible for the cosmic mirage. Individual galaxies in the cluster appear as mass pinnacles.

Again, much more mass than we see in stars, gas, dust, etc in the cluster

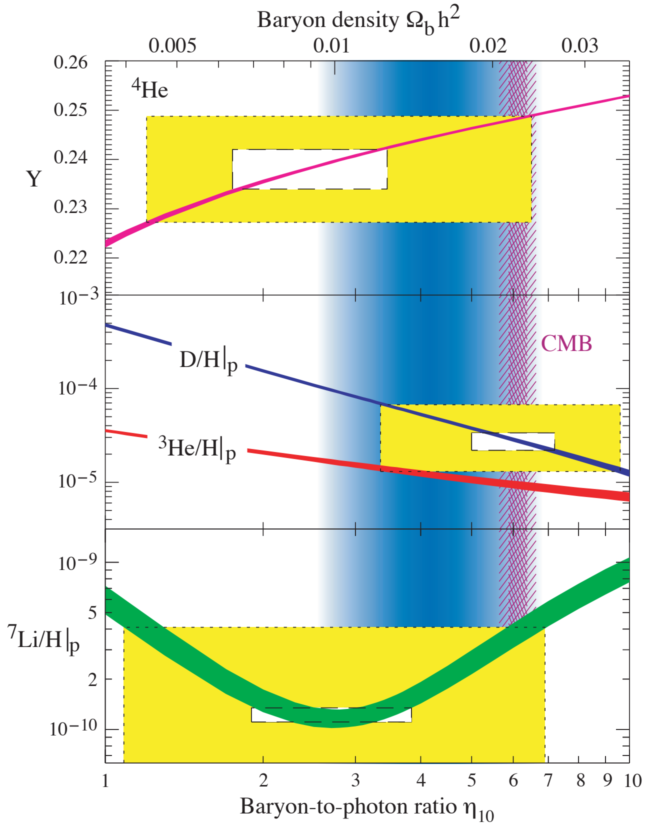
- Temperature fluctuations in the Cosmic Microwave Background





Measure total matter density and baryon density separately!

Consistent with big bang nucleosynthesis →



- Baryons 4%
- Nonbaryonic dark matter 23%

  known to ±10% precision!
- Dark energy 73%

Thermal production of dark matter

Early universe:

DM particles in thermal equilibrium with ordinary SM particles.

Pair production ↔ pair annihilation in balance.

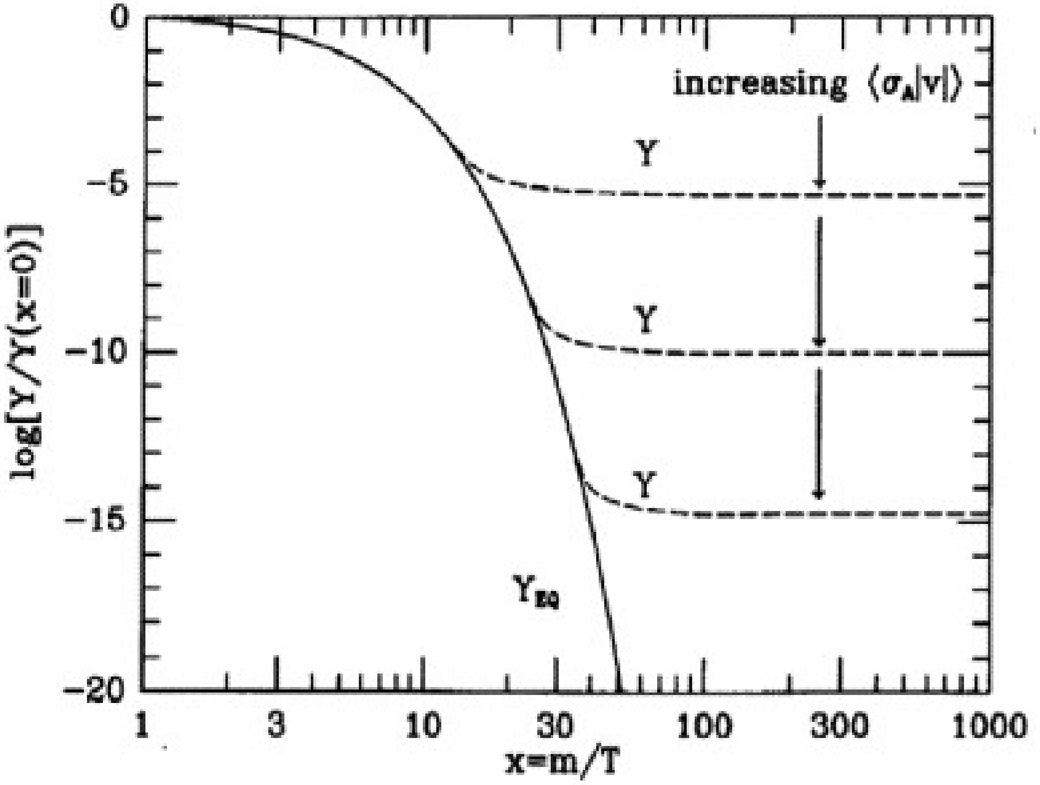
Universe cools and expands...

DM particle abundance drops as annihilation outpaces pair production.

Annihilation continues until DM particle density becomes so low that DM particles cannot find each other.

→ "freeze-out" of DM relic density:

determined by annihilation cross section.



What is the dark matter?

SUSY with exact R-parity has a natural dark matter candidate:
electrically neutral, stable LSP!
(There are other non-SUSY possibilities, but I won't talk about them here.)

Within SUSY, there are a few candidates:

- lightest sneutrino?
- lightest neutralino?
- gravitino?

- Sneutrino LSP:

Easy enough to find parameters to give correct relic abundance.
However, sneutrinos scatter off ordinary matter via Z exchange:
same gauge coupling as ordinary neutrinos
→ use this to do direct search (more later)
Scattering cross section quite large – sneutrino dark matter now ruled out.

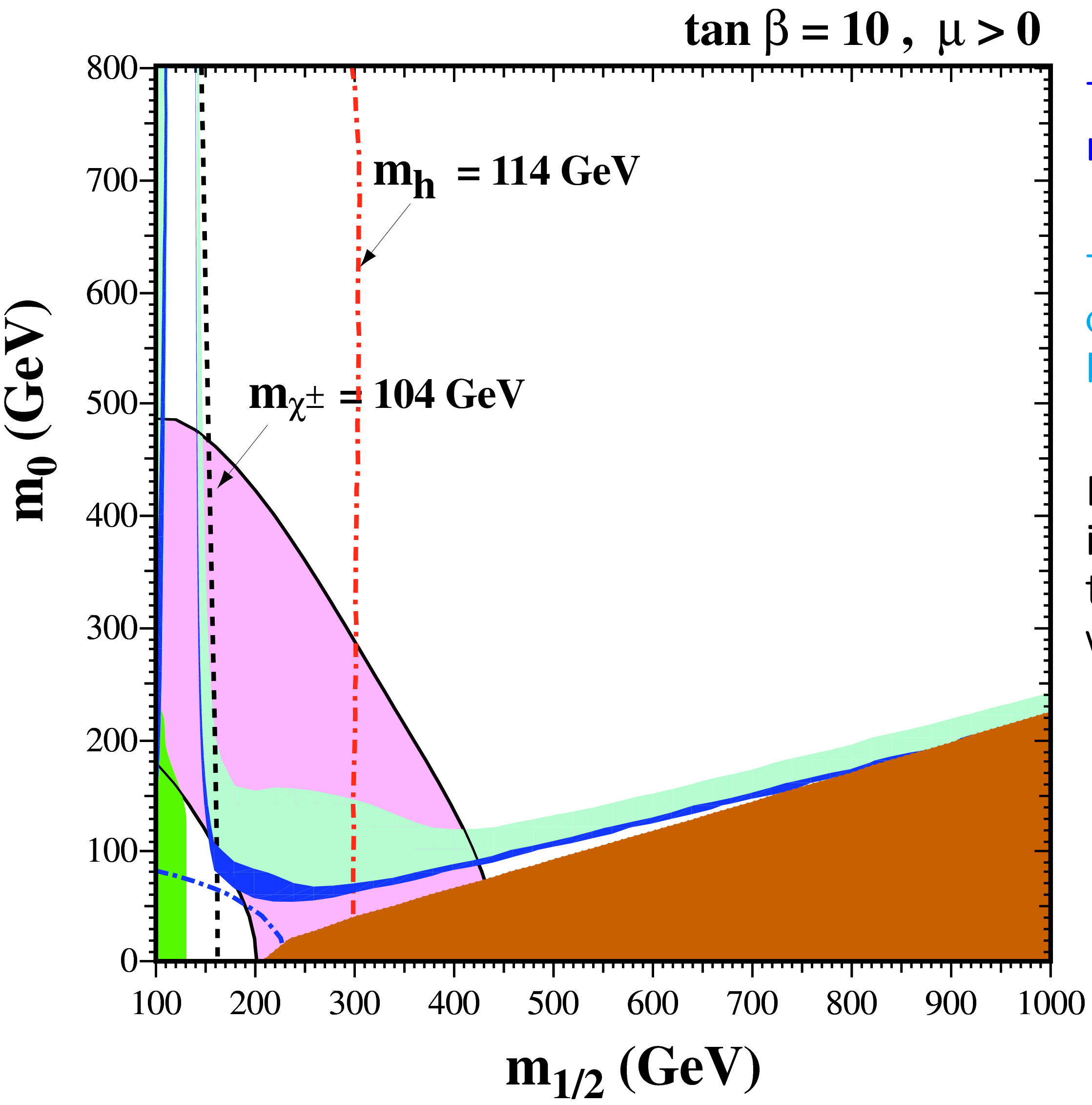
- Neutralino LSP: the favoured possibility.

How do we get the appropriate (measured) relic abundance?
Need a neutralino with the right combination of mass and annihilation cross section.

Many ways $\widetilde{N}_1$ can annihilate:
multiple regions of parameter space that give the right relic abundance.

Neutralino annihilation

mSUGRA is general enough to illustrate most of the possibilities



Thin blue area gives correct relic abundance

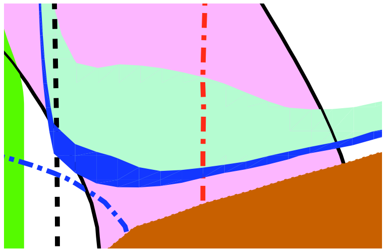
Thicker cyan region: from older, lower-precision cosmological measurements

Brown triangle at the bottom is where $\widetilde{\tau}_1$ becomes lighter than $\widetilde{N}_1$: excluded because DM would be electrically charged.

- Below the allowed region, relic abundance is too small.
- Above the allowed region, relic abundance is too large.

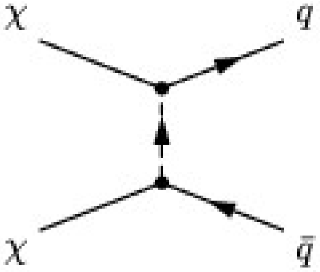
Trick is getting large enough annihilation cross section.

The "bulk region"



- $\widetilde{N}_1$ is mostly bino, and relatively light
- Sfermions are relatively light

Main annihilation process is $\widetilde{N}_1\widetilde{N}_1 \to f\bar{f}$ through a t-channel sfermion



A complication:
Because they are Majorana particles, $\widetilde{N}_1\widetilde{N}_1$ can come together only in certain (antisymmetric) ways: [Bruce's homework problem!]

- ^{1}S$_0$:

Initial state has zero orbital angular momentum and zero net spin.
– When $\widetilde{N}_1\widetilde{N}_1$ are at rest, can only get this state.
Need to produce a SM fermion-antifermion pair in same ^{1}S$_0$ state.

- If SM fermion is massless: Can only produce $f_L\bar{f}_L$ or $f_R\bar{f}_R$

E.g., left-handed electron and right-handed positron.
Back-to-back: net spin is 1! Need to flip a helicity in order to get ^{1}S$_0$ state.
But: massless fermion → can never flip the helicity. Cross section is zero!

- If SM fermions is not massless:

– Can produce $f_L\bar{f}_L$ or $f_R\bar{f}_R$ and then flip one of the spins, at the cost of a factor of m_f in the amplitude.
– Can produce $f_L\bar{f}_R$ or $f_R\bar{f}_L$ directly, again at the cost of a factor of m_f in the amplitude.
The cross section is suppressed by a $m_f^2/m_{\widetilde{N}_1}^2$ factor.

- ^{3}P$_0$, ^{3}P$_1$:

Initial state has one unit of orbital angular momentum and one unit of spin.

– Can get this state only when $\widetilde{N}_1\widetilde{N}_1$ have nonzero relative velocity.

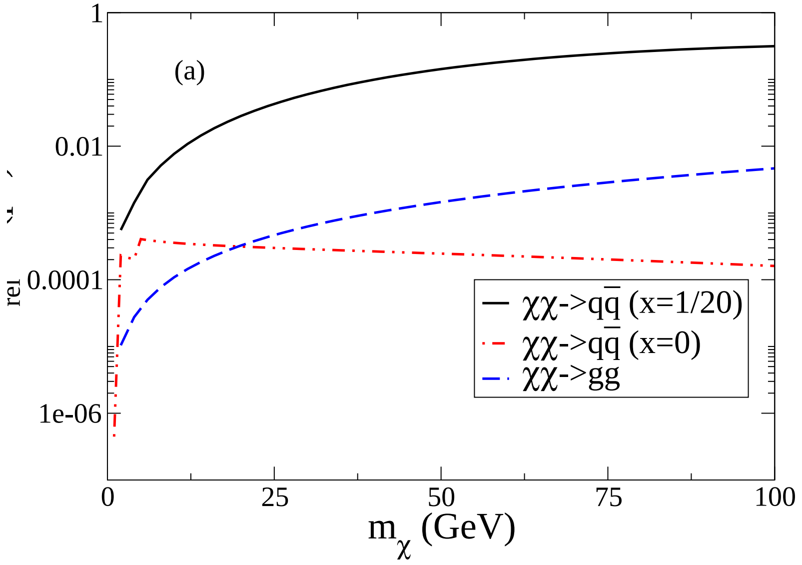
Can produce a SM fermion-antifermion pair in same ^{3}P$_1$ state without a helicity flip: cross section not suppressed by SM fermion mass!

- In the early universe, $\widetilde{N}_1\widetilde{N}_1$ relative velocity is small, but not tiny.

  – ^{3}P$_1$ wave annihilation can often dominate cross section.

- At the present day, the $\widetilde{N}_1\widetilde{N}_1$ relative velocity is $v \sim 10^{-3}c$: very small.

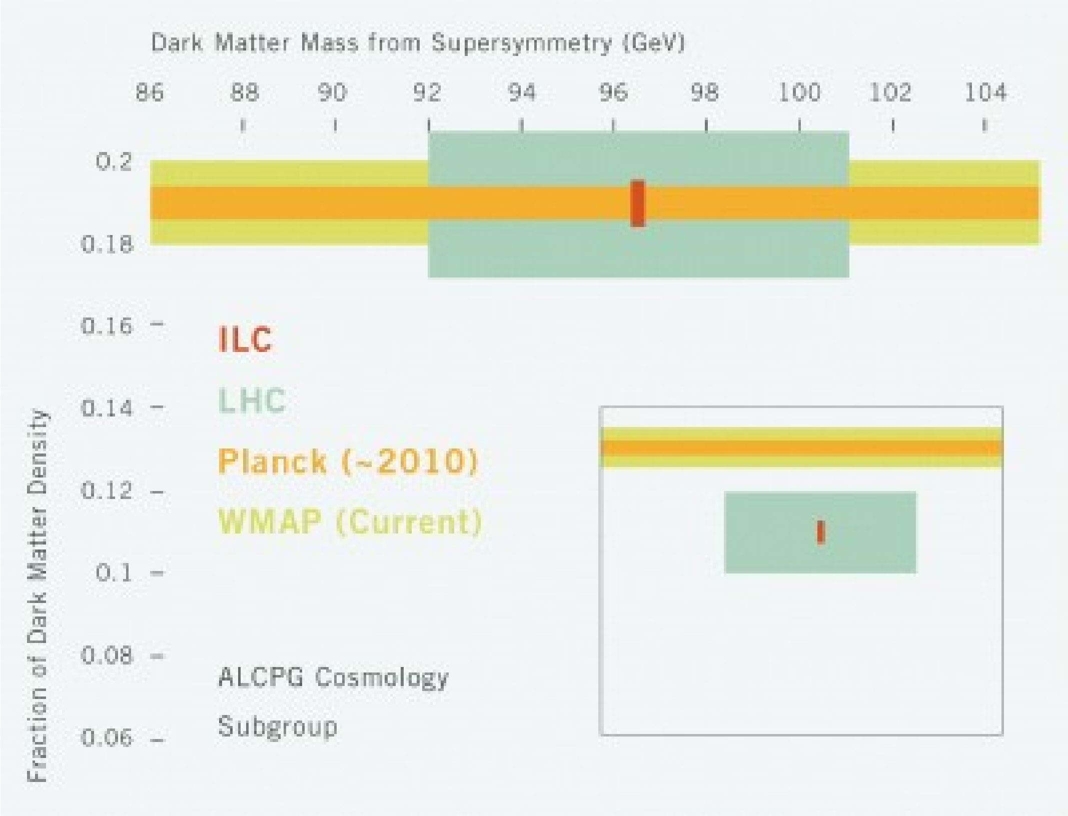
  – Neutralino annihilation in the galactic halo is controlled by the ^{1}S$_0$ wave only.



$\chi\chi \to q\bar{q}$ in early universe

$\chi\chi \to q\bar{q}$ in halo today

Testing it: "cosmology at colliders"



← The cartoon version

If we can measure the masses and couplings that go into the $\widetilde{N}_1\widetilde{N}_1$ annihilation cross section, we can predict the DM abundance.

Then we can check if our collider physics accounts for the cosmologically observed DM.

Measure SUSY masses/couplings, calculate $\widetilde{N}_1$ relic abundance from thermal production + freeze-out

Different possibilities:

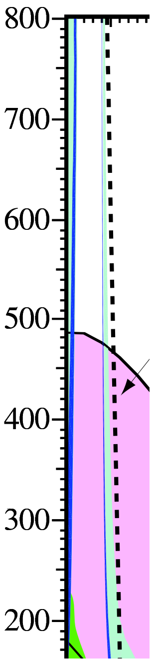
- Prediction is spot-on: we understand the universe all the way back to DM freeze-out!
- Prediction is too low: there must be another species of DM or another source of $\widetilde{N}_1$ production that we don't yet know about!
- Prediction is too high: maybe $\widetilde{N}_1$ is only metastable: decayed into something lighter (e.g., gravitino?) which is the true DM!

What must we measure to test the “bulk region” at colliders?

Need to measure:
- $\widetilde{N}_1$ mass: number density ↔ mass density; annihilation kinematics
- $\widetilde{N}_1$ composition: couplings to fermion-sfermion
- Squark and slepton masses: t-channel exchange in annihilation diagram
- Squark and slepton L-R mixings: $\widetilde{N}_1$-sfermion-fermion couplings

With these measurements in hand, we can also predict:
- Neutralino-nucleon scattering cross section
- Present-day ($v \simeq 0$) annihilation cross section and branching fractions

→ use indirect detection of DM
(gamma rays from DM annihilation in galactic centre; neutrinos from DM annihilation inside the sun – more later)
and direct detection of DM
(scattering of DM off detectors on earth – again more later)
to test our understanding of the particle properties of the DM
and to learn about the density profile of the galactic halo (astrophysics!).



The “focus point” (a.k.a. “hyperbolic branch”) region

- Large m_0: sfermions are very heavy
- μ parameter becomes small in this region: $\widetilde{N}_1$ is mixed bino-Higgsino

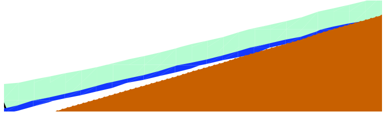
$\widetilde{N}_1\widetilde{N}_1$ can annihilate through a t-channel chargino into W^+W^- (they are typically heavy enough in this region).

Get efficient annihilation – relic abundance can be small enough to agree with cosmology

Collider issues:
- Squarks, gluinos, sleptons can be very heavy in this region
  – difficult for LHC?
- Higgsinos relatively light

Need to measure:
- $\widetilde{N}_1$ mass: number density ↔ mass density; annihilation kinematics
- $\widetilde{N}_1$ composition: couplings to $W\widetilde{C}$
- $\widetilde{C}_{1,2}$ masses and composition: t-channel exchange in annihilation diagram
- $\widetilde{N}_1$ couplings to Z, Higgses for neutralino-nucleon scattering calculation

The "stau coannihilation" region



- $\widetilde{\tau}_1$ is the lightest slepton, due to $\widetilde{\tau}_L$-$\widetilde{\tau}_R$ mixing
- $\widetilde{N}_1$ is only slightly lighter than $\widetilde{\tau}_1$

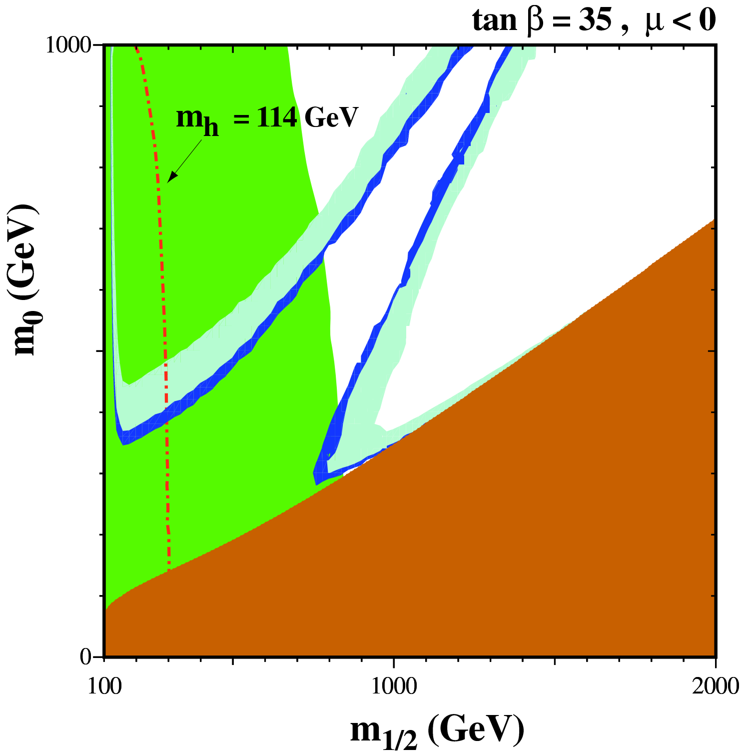
→ In the early universe, $\widetilde{N}_1$ and $\widetilde{\tau}_1$ freeze out together: an appreciable density of both species is present at the time of LSP annihilation.

Get "coannihilation" diagrams: $\widetilde{\tau}_1 \widetilde{N}_1 \to \tau\gamma(\tau Z, \tau h^0, \nu_\tau W)$ via s-channel τ
No helicity suppression as for $\widetilde{N}_1 \widetilde{N}_1 \to f\bar{f}$: efficient annihilation
Eventually the remaining $\widetilde{\tau}_1$s decay to $\tau \widetilde{N}_1$.

Collider issues:
- Small(-ish) $\widetilde{\tau}_1$-$\widetilde{N}_1$ mass splitting (like 5 or 10 GeV):
  decay $\widetilde{\tau}_1 \to \widetilde{N}_1$ gives a soft τ.

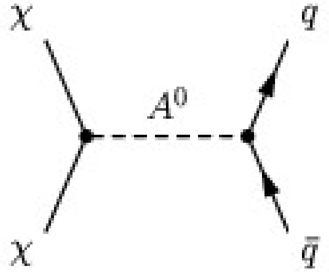
Need to measure:
- $\widetilde{N}_1$-$\widetilde{\tau}_1$ mass splitting with high precision
  – annihilation cross section is very sensitive to this.
- $\widetilde{N}_1$ mass: number density ↔ mass density; annihilation kinematics
- $\widetilde{N}_1$ composition and $\widetilde{\tau}_1$ L-R mixing: $\widetilde{N}_1$-$\widetilde{\tau}_1$-τ coupling

Yet another possibility at large(-ish) tan β:



Called the "A^0 funnel" region .

$m_{A^0} \simeq 2m_{\widetilde{N}_1}$ so $\widetilde{N}_1\widetilde{N}_1 \to A^0 \to XX$ is close to resonance.



Annihilation cross section becomes very large
$\to$ relic abundance becomes very small.

Need to measure:

- Mass and decay width of A^0 with high precision
  – annihilation cross section is very sensitive to this.
- $\widetilde{N}_1$ mass: number density ↔ mass density; annihilation kinematics
- $\widetilde{N}_1$ composition: coupling to A^0