SUSY Dark Matter

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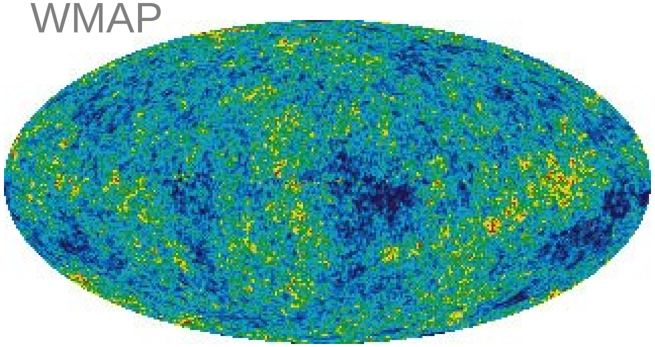
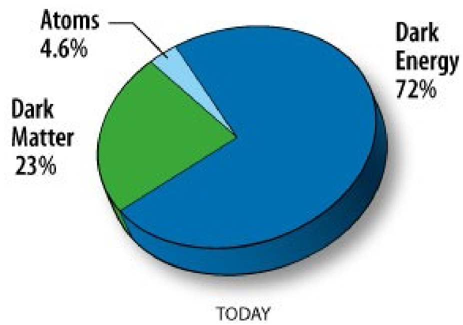
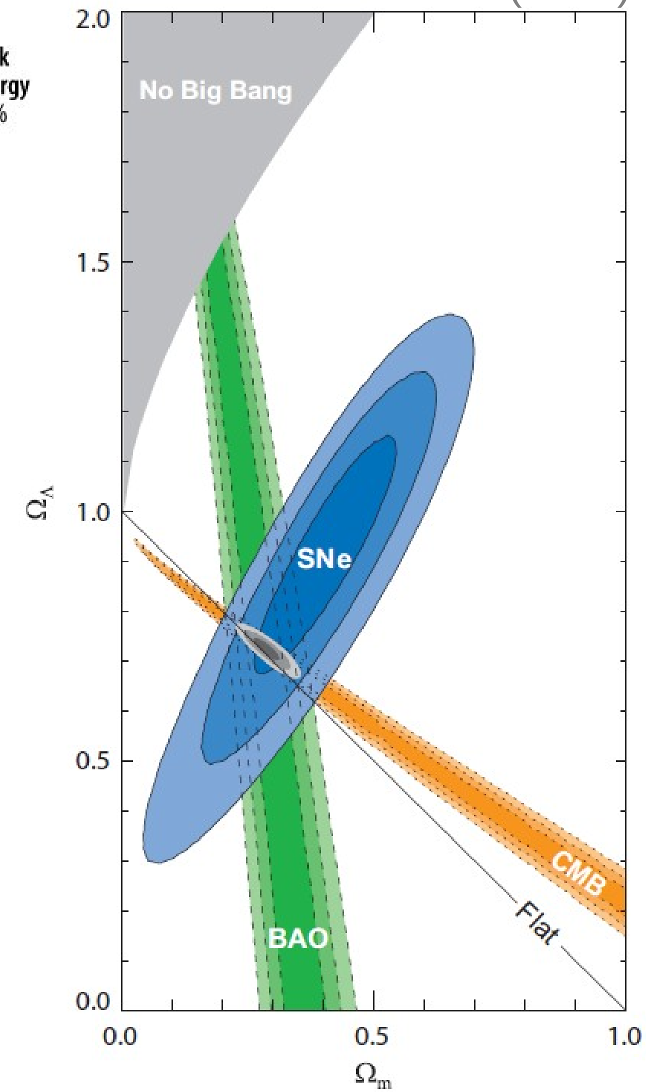
Dark Matter

WMAP





Kowalski *et al.* (2008)

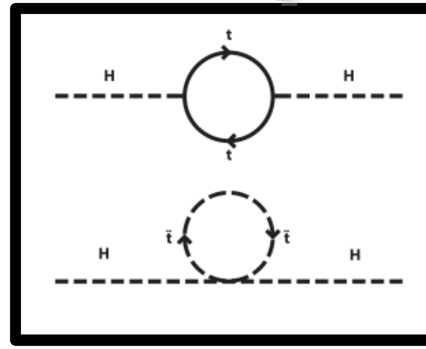


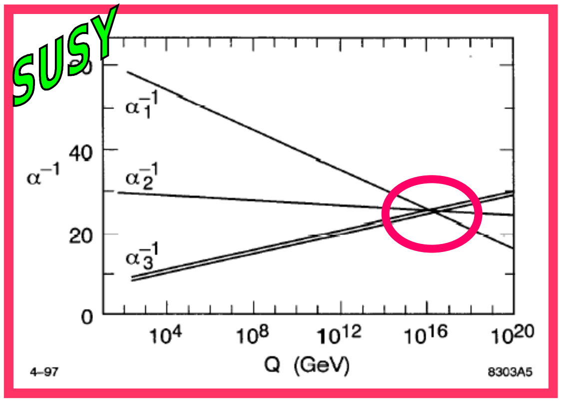
- $\Omega_{DM} = 0.233 \pm 0.0013$ Komatsu *et al.* (2009)
- It's non-baryonic (BBN+CMB, structure formation).
- It's stable or very long-lived.
- It's not charged (heavy isotope abundances).
- It's largely non-relativistic (cold).

85% of the matter density of the universe is unexplained by the Standard Model.

Why Supersymmetry?

Solves the Naturalness Problem



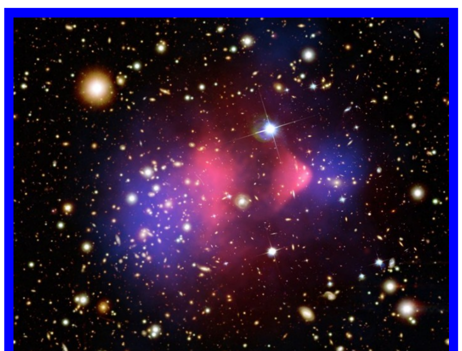


Gauge coupling unification (GUTs)

Predicts a light Higgs boson

MSSM:	105 GeV $\lesssim m_h \lesssim$ 135 GeV
LEP:	114.4 GeV $< m_h <$ 157 GeV

LEP Collaborations and Electroweak Working Group, August 2009



And yes, dark matter

(assuming R-Parity)

Particle Zoo

MSSM:

Minimal Supersymmetric Standard Model

Has the *minimal particle content* possible in a SUSY theory.

particle	sparticle	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_i$	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_i$	3	2	$\frac{1}{6}$
u_i^c	$\tilde{u}_i^c$	$\bar{3}$	1	$-\frac{2}{3}$
d_i^c	$\tilde{d}_i^c$	$\bar{3}$	1	$\frac{1}{3}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_i$	$\begin{pmatrix} \tilde{\nu} \\ \tilde{e} \end{pmatrix}_i$	1	2	$-\frac{1}{2}$
e_i^c	$\tilde{e}_i^c$	1	1	1
W	$\tilde{W}$	1	3	0
g	$\tilde{g}$	8	1	0
B	$\tilde{B}$	1	1	0
$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$	1	2	$\frac{1}{2}$
$\begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$	1	2	$-\frac{1}{2}$

Particle Zoo

Also

axion: *a*, spin 0

saxion: *s*, spin 0

axino: $\tilde{a}$, spin ½

graviton: *G*, spin 2

gravitino: $\tilde{G}$, spin 3/2

quarks and squarks

leptons and sleptons

W boson and wino

gluon and gluino

B boson and bino

Higgs bosons and higgsinos

particle	sparticle	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_i$	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_i$	3	2	$\frac{1}{6}$
u_i^c	$\tilde{u}_i^c$	$\bar{3}$	1	$-\frac{2}{3}$
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$\begin{pmatrix} \nu \\ e \end{pmatrix}_i$	$\begin{pmatrix} \tilde{\nu} \\ \tilde{e} \end{pmatrix}_i$	1	2	$-\frac{1}{2}$
e_i^c	$\tilde{e}_i^c$	1	1	1
W	$\tilde{W}$	1	3	0
g	$\tilde{g}$	8	1	0
B	$\tilde{B}$	1	[illegible]	0
$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$	1	2	$\frac{1}{2}$
$\begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$	1	2	$-\frac{1}{2}$

Neutralinos!

SUSY Breaking (pheno.)

Don't observe boson-fermion degeneracy, so SUSY must be broken (How?)

Most general case (MSSM) has > 100 new parameters!

OR make some assumptions about SUSY breaking at a high scale, and evolve mass parameters down to low scale for observables

Explicitly add [soft] SUSY-breaking terms to the theory:

Masses for all gauginos and scalars

Couplings for scalar-scalar and scalar-scalar-scalar interactions

Example: CMSSM (Constrained MSSM)

Assume universality of soft SUSY-breaking parameters at M_{GUT}

$\Rightarrow$ Free Parameters: m_0, $m_{1/2}$, A_0, $\tan(\beta)$, sign(μ)

Constraints

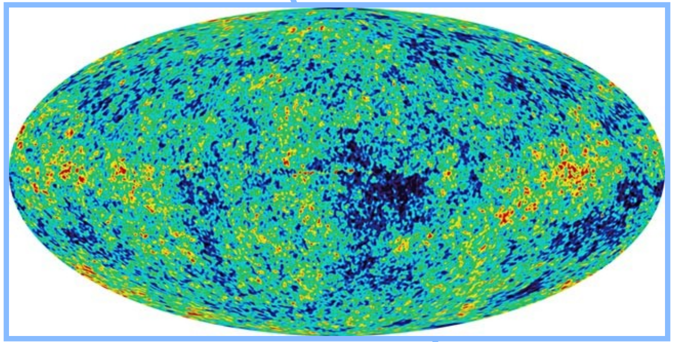
Apply constraints from colliders and cosmology:

$m_h > 114$ GeV
$m_{\chi^\pm} > 104$ GeV } LEP

BR($b \to s\,\gamma$) HFAG

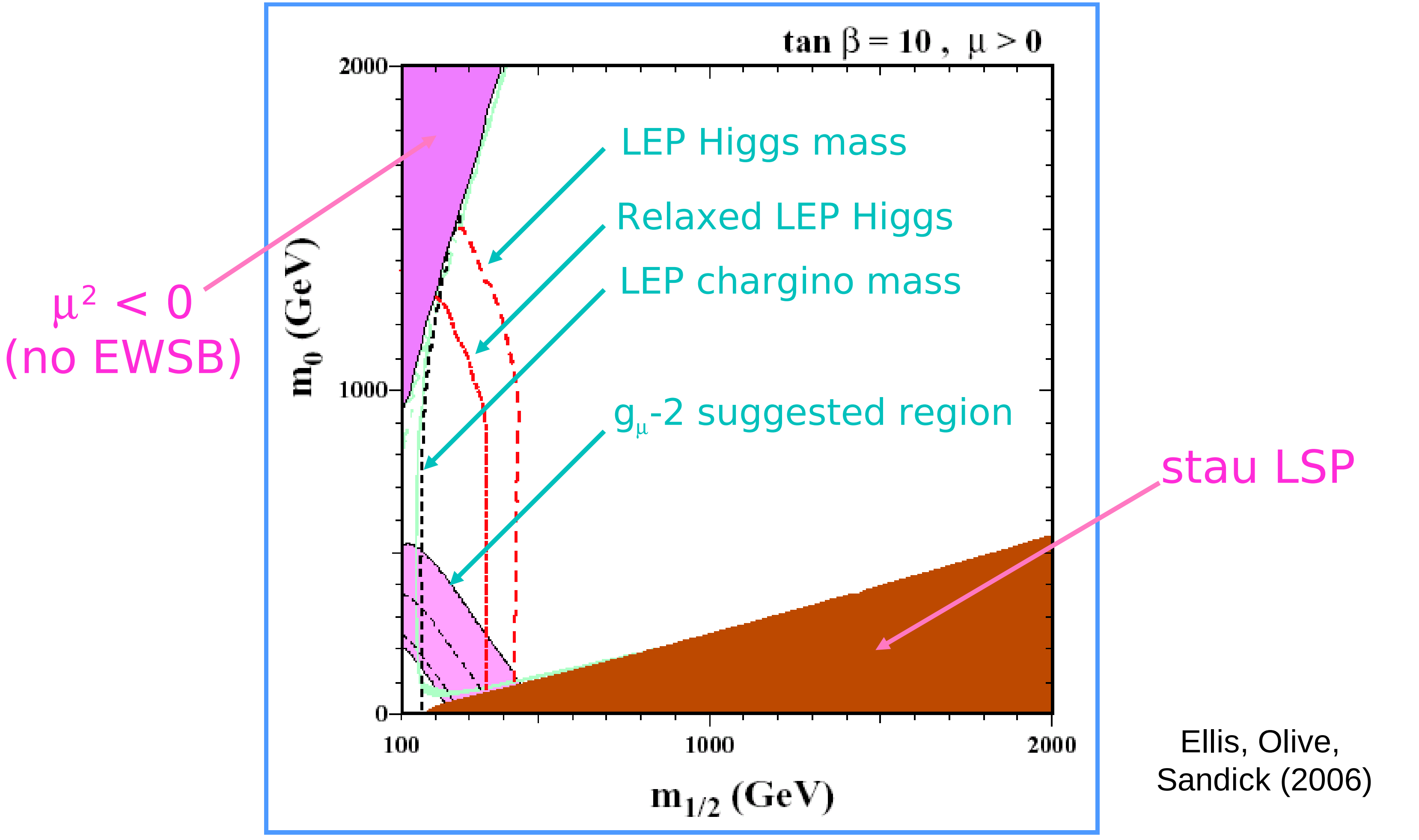
BR($B_s \to \mu^+\mu^-$) CDF

$(g_\mu - 2)/2$ g-2 collab.



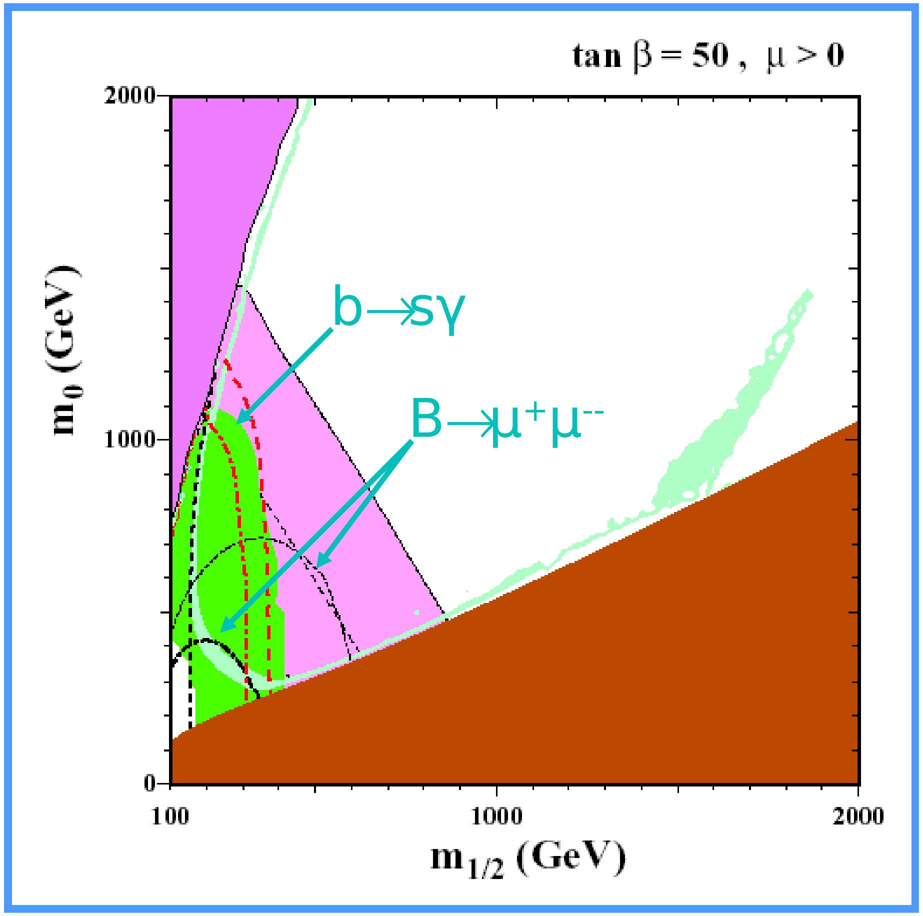
$0.09 \lesssim \Omega_\chi h^2 \lesssim 0.12$

CMSSM



Ellis, Olive, Sandick (2006)

CMSSM



Ellis, Olive, Sandick (2006)

SUSY Dark Matter

- A neutral LSP is an excellent dark matter candidate!
- The lightest one may be stable (WIMP?) with $\Omega_\chi h^2 \approx \Omega_{DM} h^2$

Caveat: The lightest SUSY particle (LSP)
is stable if R-parity is conserved.

$$R = (-1)^{3B+L+2S} = \begin{cases} +1 \text{ for SM particles} \\ -1 \text{ for sparticles} \end{cases}$$

Why conserve R-parity?

•Stability of proton
•Neutron-antineutron oscillations
•Neutrino mass

Ad hoc?

•SO(10) GUTs
•B and L numbers become accidental symmetries of SUSY

SUSY DM Candidates

- A plethora of DM candidates:
  - neutralinos (favorite WIMPs)
    - H. Goldberg, Phys. Rev. Lett. 50, 1419 (1983); J. Ellis, J. Hagelin, D.V. Nanopoulos, K. Olive, and M. Srednicki, Nucl. Phys. B 238, 453 (1984), etc.
  - sneutrinos (also WIMPs)
    - T. Falk, K. A. Olive and M. Srednicki, Phys. Lett. B 339 (1994) 238; T. Asaka, K. Ishiwata, and T. Moroi, Phys. Rev. D 73, 051301 (2006); 75, 065001 (2007); F. Deppisch and A. Pilaftsis, J. High Energy Phys. 10 (2008) 080; J. McDonald, J. Cosmol. Astropart. Phys. 01 (2007) 001; H. S. Lee, K. T. Matchev, and S. Nasri, Phys. Rev. D 76, 041302 (2007); D. G. Cerdeno, C. Munoz, and O. Seto, Phys. Rev. D 79, 023510 (2009); D. G. Cerdeno and O. Seto, J. Cosmol. Astropart. Phys. 08 (2009) 032; etc.
  - gravitinos (SuperWIMPs)
    - J.L. Feng, A. Rajaraman and F. Takayama, Phys. Rev. Lett. 91, 011302 (2003) [hep-ph/0302215], Phys. Rev. D 68, 063504 (2003) [hep-ph/0306024]; J.R. Ellis, K.A. Olive, Y. Santoso and V.C. Spanos, Phys. Lett. B 588, 7 (2004) [hep-ph/0312262]; J.L. Feng, S.f. Su and F. Takayama, Phys. Rev. D 70, 063514 (2004) [hep-ph/0404198]; etc.
  - axinos (SuperWIMPs)
    - T. Goto and M. Yamaguchi, Phys. Lett. B 276, 103 (1992); L. Covi, H.B. Kim, J.E. Kim and L. Roszkowski, JHEP 0105, 033 (2001) [hep-ph/0101009]; L. Covi, L. Roszkowski, R. Ruiz de Austri and M. Small, JHEP 0406, 003 (2004) [hep-ph/0402240]; etc.

SuperWIMPs (E-WIMPs)

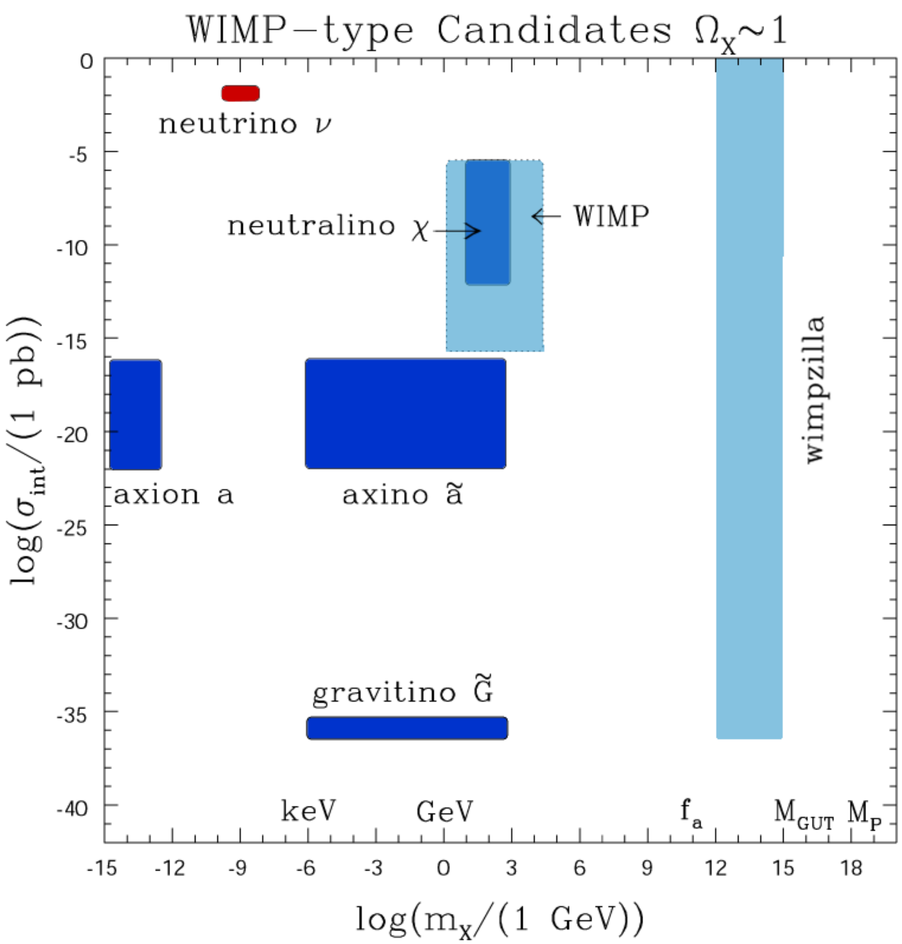
- Interaction scale with ordinary matter suppressed by large mass scale:
  - For gravitino, $m_P \approx 10^{19}$ GeV

    (gravitational interactions)
  - For axino, $f_a \approx 10^{11}$ GeV

    $\sigma \approx (m_W / f_a)^2\, \sigma_{weak}$

    $\approx 10^{-18}\, \sigma_{weak}$

    $\approx 10^{-20}$ pb



Choi & Roszkowski (2005)

Axinos

- Axion is a solution to the strong CP problem, i.e. Why does QCD conserve CP when CP violating operators are allowed?
  - Peccei-Quinn Mechanism: Promote CP-violating operator to a field by requiring new global (P-Q) symmetry
  - P-Q symmetry is spontaneously broken → Axion is Goldstone Boson ("pseudo" due to small mass from QCD vacuum effects)
  - SUSY: axion is in a chiral multiplet with axion + saxion, axino:

$$\Phi_a = (s + \mathrm{i}a)/\sqrt{2} + \vartheta \tilde{a} + (F \text{ term})$$

- Axion gets its mass from QCD effects: $m_a \simeq f_\pi m_\pi / f_{PQ}$
- SUSY breaking splits saxion/axino masses from tiny axion mass
  - $m_s \sim m_{SUSY}$ (not LSP)
  - $m_{\tilde{a}}$ unconstrained (could be LSP and DM)

Axino Dark Matter

- If the axino is the LSP, expect

see Baer *et al.* (2010) and references therein

$$\Omega_{a\tilde{a}}h^2 = \Omega_{\tilde{a}}^{NTP}h^2 + \Omega_{\tilde{a}}^{TP}h^2 + \Omega_a h^2$$

non-thermally produced axinos from neutralino NLSP decay

$$\widetilde{Z}_1 \to \tilde{a}\gamma$$

$$\Omega_{\tilde{a}}^{NTP} = \frac{m_{\tilde{a}}}{m_{\widetilde{Z}_1}}\Omega_{\widetilde{Z}_1}h^2$$

thermally produced axinos from radiation off MSSM scattering processes

$$\Omega_{\tilde{a}}^{TP} = h^2 \simeq 5.5 g_s^6 \ln\left(\frac{1.211}{g_s}\right)\left(\frac{10^{11}\ \mathrm{GeV}}{f_a/N}\right)^2\left(\frac{m_{\tilde{a}}}{0.1\ \mathrm{GeV}}\right)\left(\frac{T_R}{10^4\ \mathrm{GeV}}\right)$$

axions from vacuum mis-algnment mechanism

$$\Omega_a h^2 \simeq \frac{1}{4}\left(\frac{f_a/N}{10^{12}\ \mathrm{GeV}}\right)^{7/6}\theta_i^2$$

- TP axinos are CDM for $m_{\tilde{a}} \gtrsim 0.1\ \mathrm{MeV}$

Axino Dark Matter

- Unfortunately, no direct or indirect WIMP detection signals are expected for stable axino dark matter.
- If R-parity is broken, decaying axinos may be responsible for anomalous CR positron excess measured by PAMELA.
  - Depending on R-parity breaking model, radiative or leptonic decay channels may be preferred. i.e. $\tilde{a} \to \gamma \nu_i$ or $\tilde{a} \to e^+ e^- \nu_i$
- Collider signatures are possible, but depend on NLSP:
  - Charged NLSP would be easy to see, but would need to carefully study its decays to determine what the LSP is. Decays would likely happen outside the detector (need to trap staus).
  - Neutral NLSP would be harder to see, and could itself be dark matter. Mass and couplings compatible?

see, for example, Covi *et al.* (2001), Covi & Kim (2009)

Gravitino Dark Matter

- Like axino, both thermal and non-thermal production mechanisms
  - NTP: $$\Omega_{\tilde{G}}^{\mathrm{NTP}} h^2 = \frac{m_{\tilde{G}}}{m_{\mathrm{NLSP}}} \Omega_{\mathrm{NLSP}} h^2$$
    - Late decays of NLSP can lead to entropy overproduction and hot dark matter, so $m_{NLSP} > 500$ GeV
    - $\Omega_G h^2 \sim 0.1$ for 1 GeV < m_G < 700 GeV (Steffen, 2006)
  - TP: $$\Omega_{\tilde{G}}^{\mathrm{TP}} h^2 \simeq 0.2 \left(\frac{T_{\mathrm{R}}}{10^{10}\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_{\tilde{G}}}\right)\left(\frac{m_{\tilde{g}}(\mu)}{1\,\mathrm{TeV}}\right)^2$$
    - $T_R << T_{eq}$ to avoid overproduction of gravitinos (“Gravitino Problem”)
    - For natural ranges of gluino and gravitino masses, one can have TP $\Omega_G h^2 \sim 0.1$ at T_R as high as $10^{9\text{-}10}$ GeV (Bolz *et al.* 1998, 2001).
- NLSP decays produce energetic SM particles, could spoil BBN light element abundances

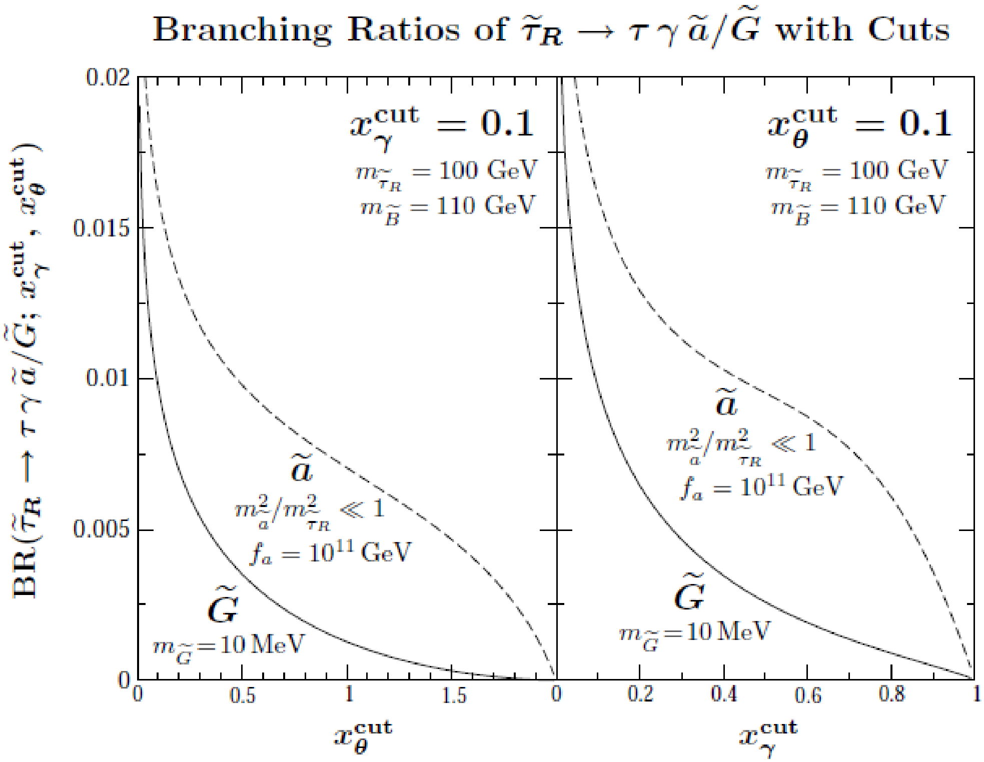
Gravitino Mass

- Gravitino mass depends on how SUSY breaking is communicated to the observable sector:
  - Gravity (modulus) mediated ~~SUSY~~: **maybe LSP**
    - $m_{3/2} \approx 100$ GeV − few TeV
  - Anomaly mediated ~~SUSY~~: **not LSP**
    - $m_{3/2} \approx 10$ TeV – 100 TeV
  - Gauge mediated ~~SUSY~~: **probably LSP**
    - $m_{3/2} \approx 10$ eV – 1 GeV
  - Gaugino mediated ~~SUSY~~: **maybe LSP**
    - $m_{3/2} \approx 10$ GeV – TeV

Gravitino vs. Axino

Can we tell them apart?

Maybe! If long-lived staus are accumulated and observed (i.e. at the LHC), we might be able to determine if CDM is axino or gravitino based on stau decay event distributions.



Brandenburg *et al*. (2005)

"WIMP Miracle"

1. New (heavy) particle χ in thermal equilibrium:

$\chi\,\chi \rightleftarrows f\,\bar{f}$

Expansion and annihilation compete to determine the number density:

$$\boxed{\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma v_{rel} \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]}$$

and cools:

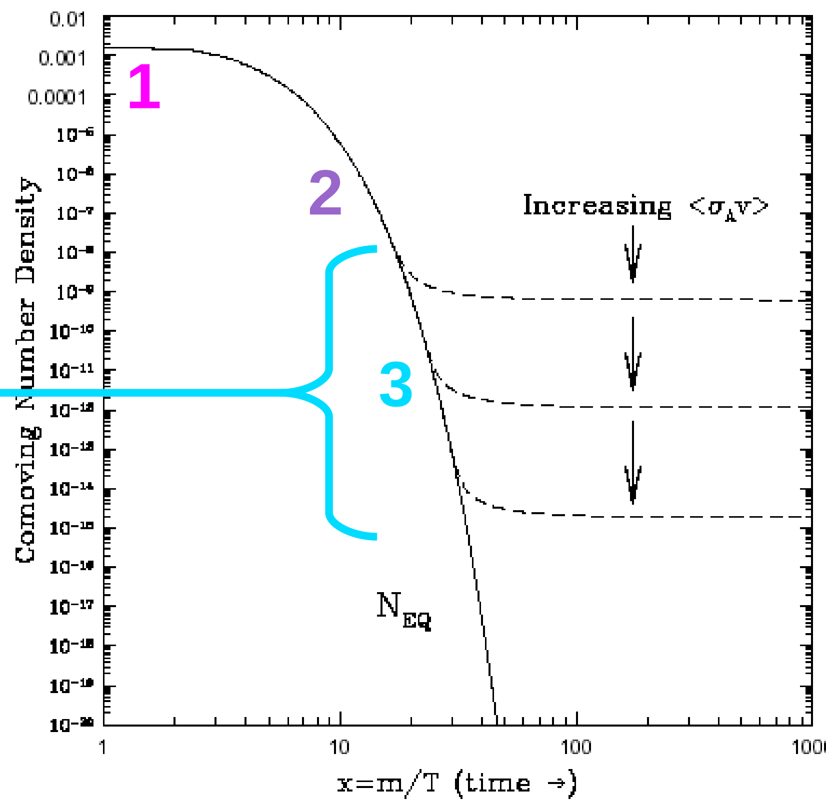
$\chi\,\chi \rightleftarrows f\,\bar{f}$

Stable matter with GeV-TeV mass and weak-scale interaction strength yield

3. χ's "freeze out"

$\Omega h^2 \approx 0.1$

$\chi\,\chi \rightleftarrows f\,\bar{f}$



Jungman, Kamionkowski and Griest, PR 1996

Sneutrinos

- L-handed neutrinos have L-handed sneutrino superpartners in the MSSM
  - Large coupling to Z boson leads to low relic abundance and larger-than-observed scattering rates with nuclei. Falk, Olive & Srednicki (1994)
  - Low mass window closed by limits from invisible Z decay at LEP. LEPEWWG (2003)
- R-handed neutrinos can be added to the SM to explain the origin of neutrino masses, so expect R-handed sneutrino partners.
  - L-R mixed sneutrinos have reduced coupling to Z, but a significant L-R mixing is only possible in very particular SUSY-breaking scenarios.
    - Sweet spot: Need the right mixing to generate the annihilation rate that leads to the dark matter abundance today, but that much mixing may imply too large a scattering rate with nuclei. [Bélanger's talk]
  - Pure R-handed sneutrinos could be CDM, but can't be thermal relics because their coupling to ordinary matter is very small. These ARE viable DM candidates in SUSY models with extended gauge or Higgs sectors (and therefore additional matter interactions). Arina & Fornengo (2007), Asaka, Ishiwata & Moroi (2007), Cerdeno & Seto (2009), etc.

Sneutrino Dark Matter

- Example: MSSM + gauged $U(1)_{B-L}$ Allahverdi *et al*. (2007, 2009)
  - DM could be R-sneutrino if $U(1)_{B-L}$ is broken at ~TeV scale.
- Example: MSSM + singlet superfield S for μ problem + singlet superfield N for R-(s)neutrino states Cerdeno & Seto (2009)
  - DM is pure R-sneutrino with couplings to MSSM fields, so it has the properties of a thermally-produced WIMP.
- Example: MSSM + 6 complex sneutrino fields (12 mixed L/R sneutrino mass eigenstates) March-Russell, McCabe & McCullough (2009)
  - DM could be lightest sneutrino, or combination of long-lived sneutrinos

Take-home message:

Sneutrino DM must be substantially R-handed to suppress coupling to Z, so generally arises in extended versions of the MSSM.

Properties of sneutrino depend on the MSSM extension – many possibilities.

Neutralinos

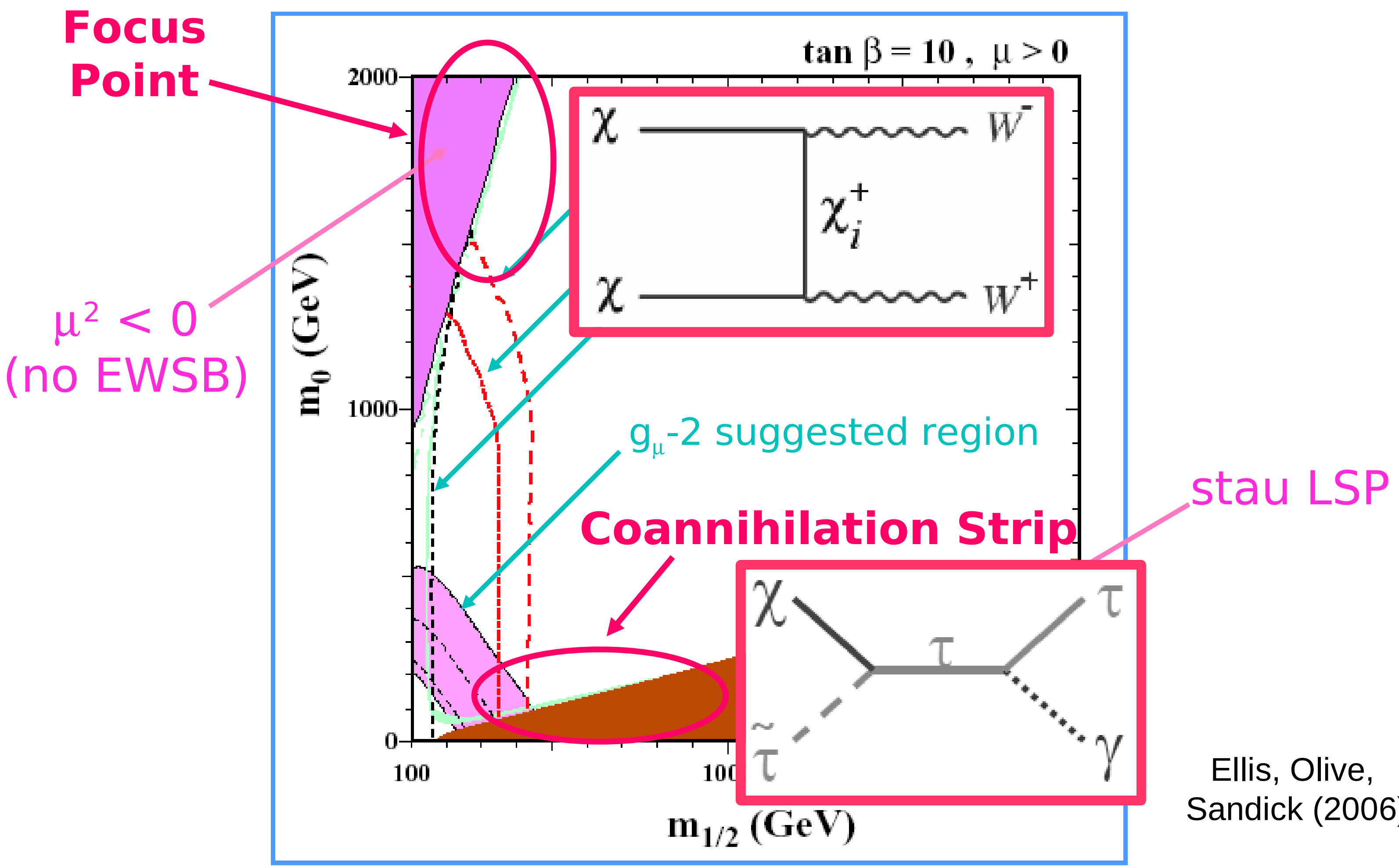
- The LSP is a neutralino in much of parameter space of even most-constrained SUSY models.
- The lightest one may be a stable WIMP with $\Omega_\chi h^2 \approx \Omega_{DM} h^2$

$$\boxed{\chi = \alpha\tilde{B} + \beta\tilde{W}^3 + \gamma\tilde{H}_1 + \delta\tilde{H}_2}$$

$$(\tilde{W}^3, \tilde{B}, \tilde{H}_1^0, \tilde{H}_2^0)\begin{pmatrix} M_2 & 0 & \frac{-g_2 v_1}{\sqrt{2}} & \frac{g_2 v_2}{\sqrt{2}} \\ 0 & M_1 & \frac{g_1 v_1}{\sqrt{2}} & \frac{-g_1 v_2}{\sqrt{2}} \\ \frac{-g_2 v_1}{\sqrt{2}} & \frac{g_1 v_1}{\sqrt{2}} & 0 & -\mu \\ \frac{g_2 v_2}{\sqrt{2}} & \frac{-g_1 v_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix}\begin{pmatrix} \tilde{W}^3 \\ \tilde{B} \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

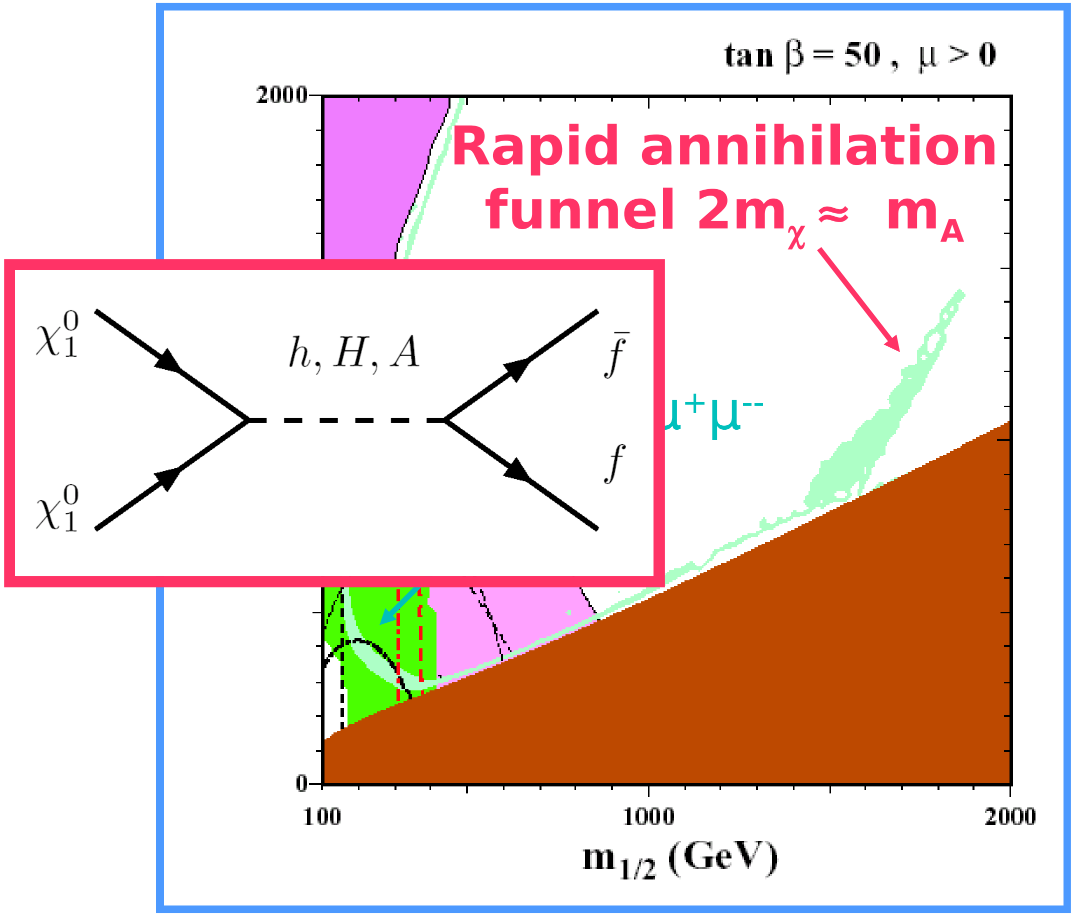
Properties of neutralino LSP depend on its composition.

CMSSM



Ellis, Olive, Sandick (2006)

CMSSM

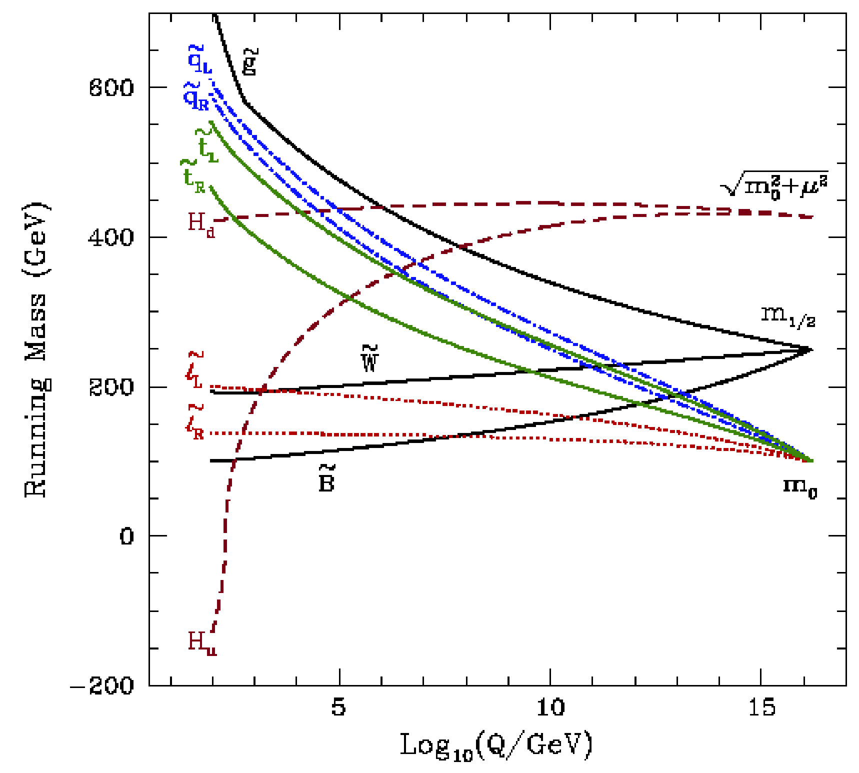


Ellis, Olive, Sandick (2006)

Departures from CMSSM

- More general patterns of SUSY breaking:
  - NU scalar masses m_0
    - NU Higgs masses?
  - NU gaugino masses $M_{1/2}$
  - NU trilinear couplings A_0
- Extended particle content
  - NMSSM
  - nMSSM
  - UMSSM
  - etc.

$\left.\begin{array}{l}\text{NMSSM}\\ \text{nMSSM}\\ \text{UMSSM}\end{array}\right\}$ extra singlet superfield



Departures from CMSSM

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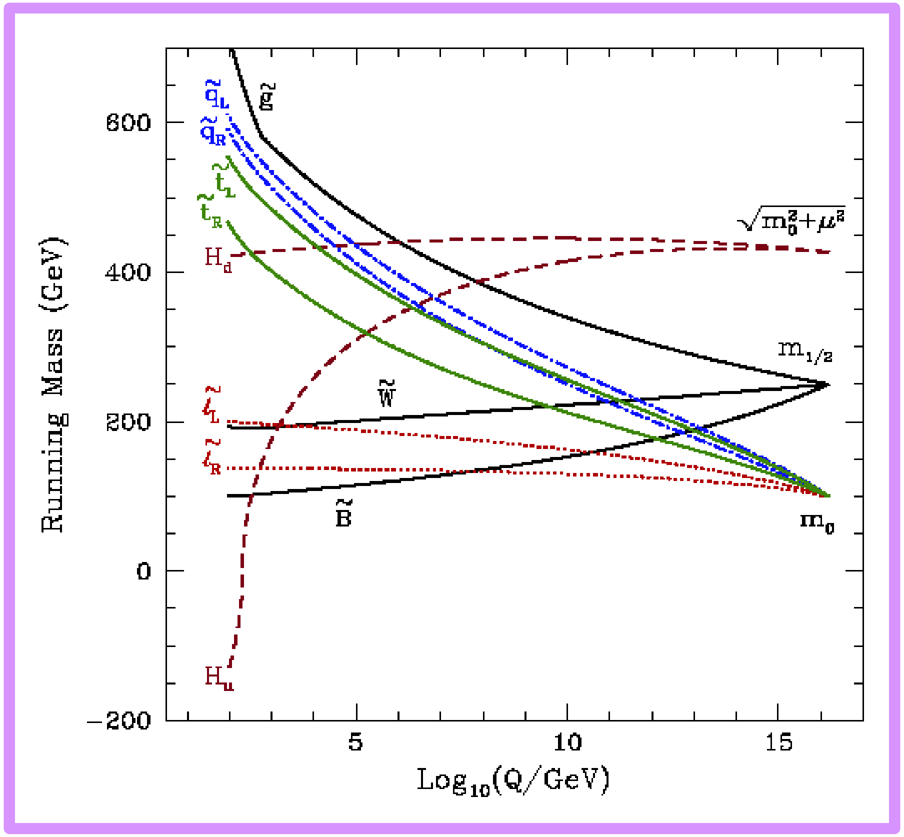
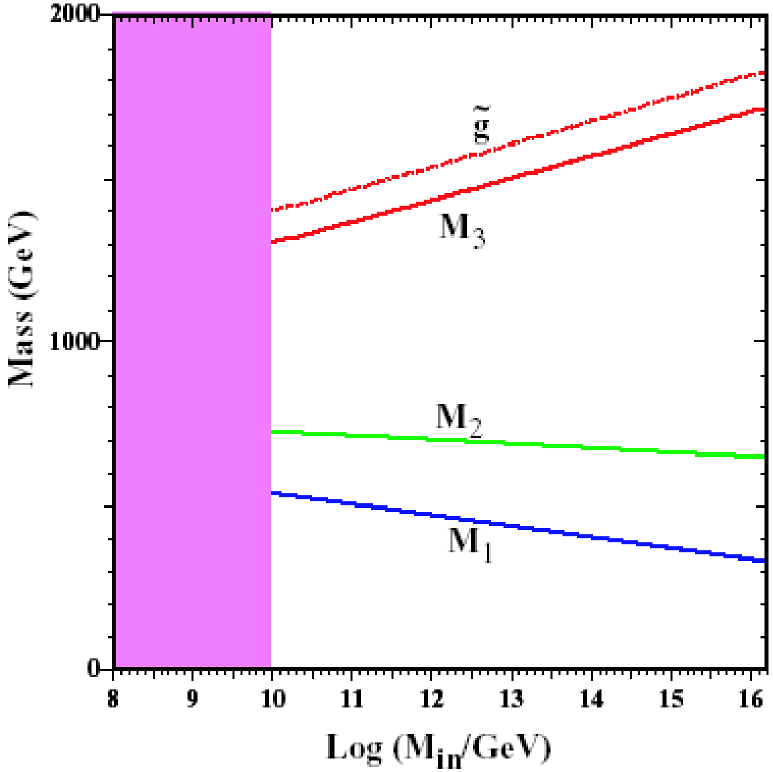
  - etc.

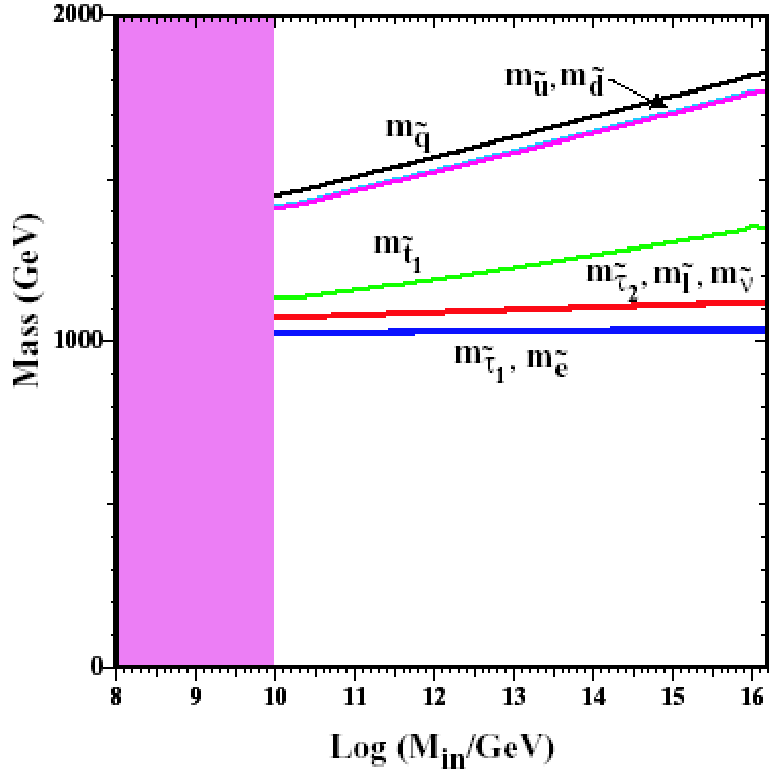
extra singlet superfield



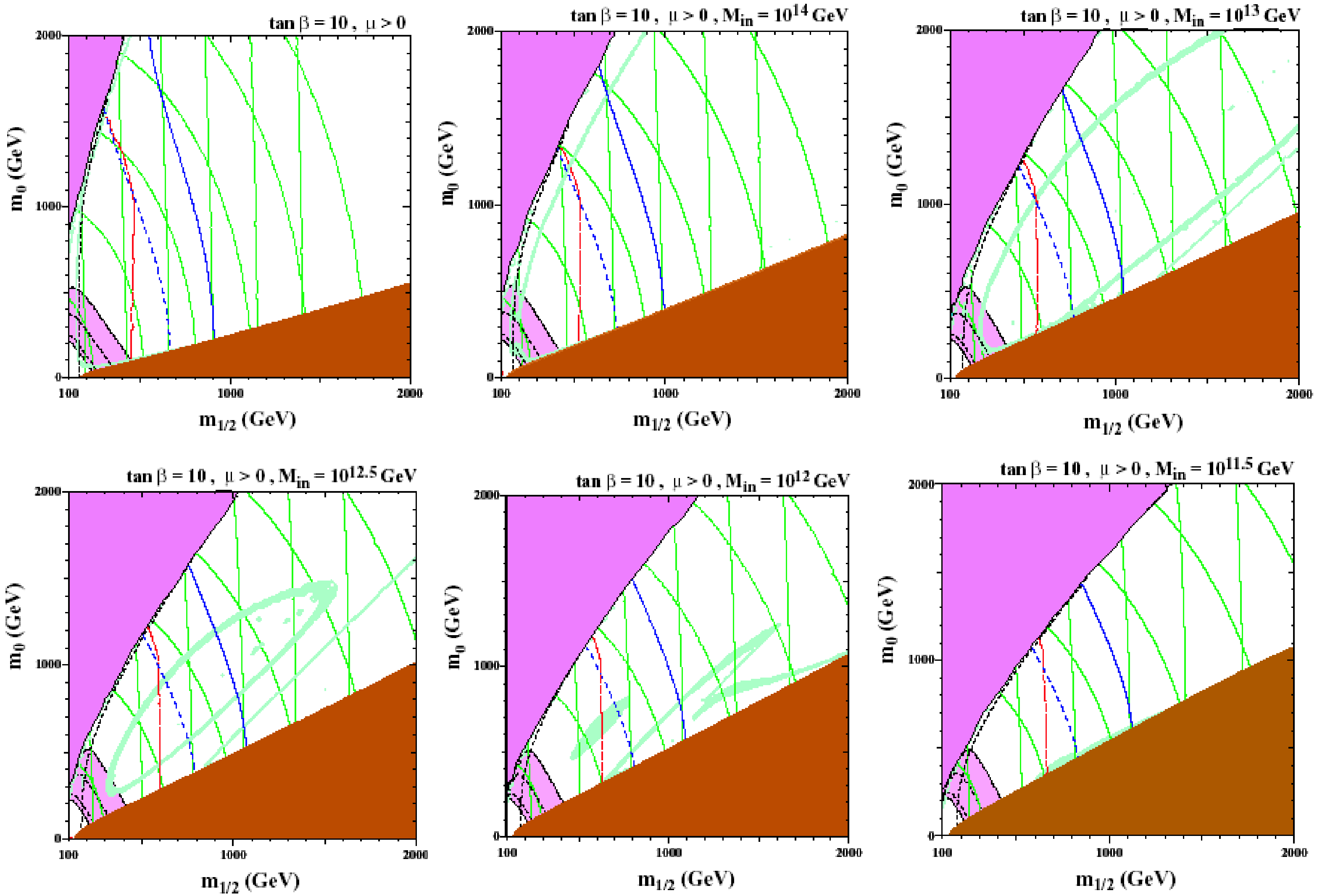
GUT-less SUSY

- What if SUSY-breaking appears below the GUT scale?
  - Universality of soft breaking parameters below M_{GUT}





GUT-less SUSY



Pearl Sandick, UT Austin

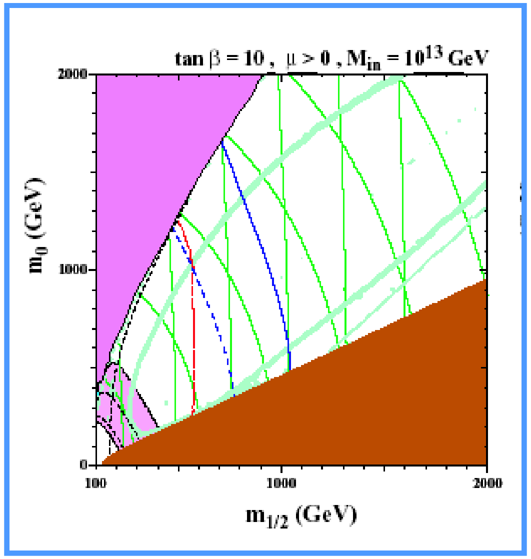
Linear Collider Prospects

$$e^+e^- \rightarrow \begin{cases} \boxed{\tilde{\chi}_1^0 \tilde{\chi}_1^0} \\ \boxed{\tilde{\chi}_1^0 \tilde{\chi}_2^0} \\ \boxed{\begin{matrix} \tilde{\chi}_1^+ \tilde{\chi}_1^- \\ \tilde{l}^+ \tilde{l}^- \end{matrix}} \end{cases}$$

Escape detector [see talk by Bartels]

Inferred from decay?

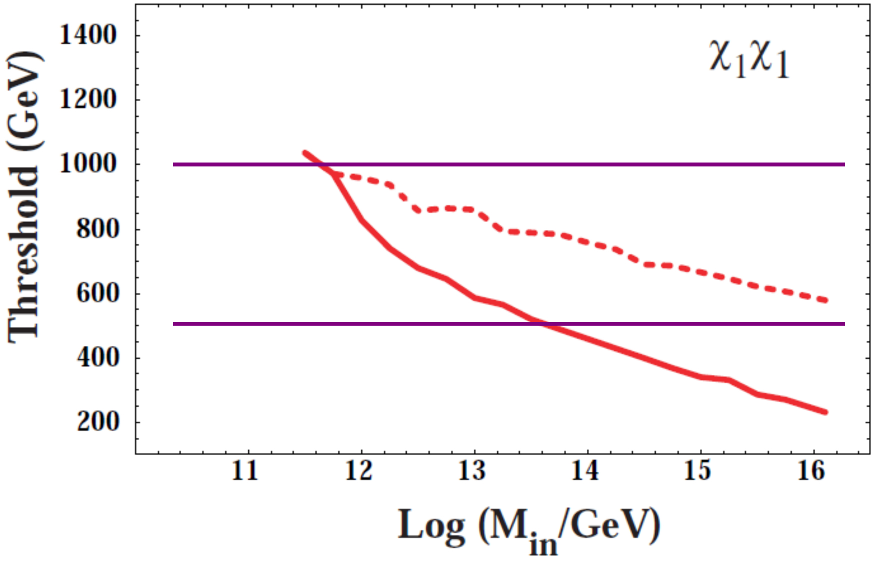
Charged sparticles easily discerned

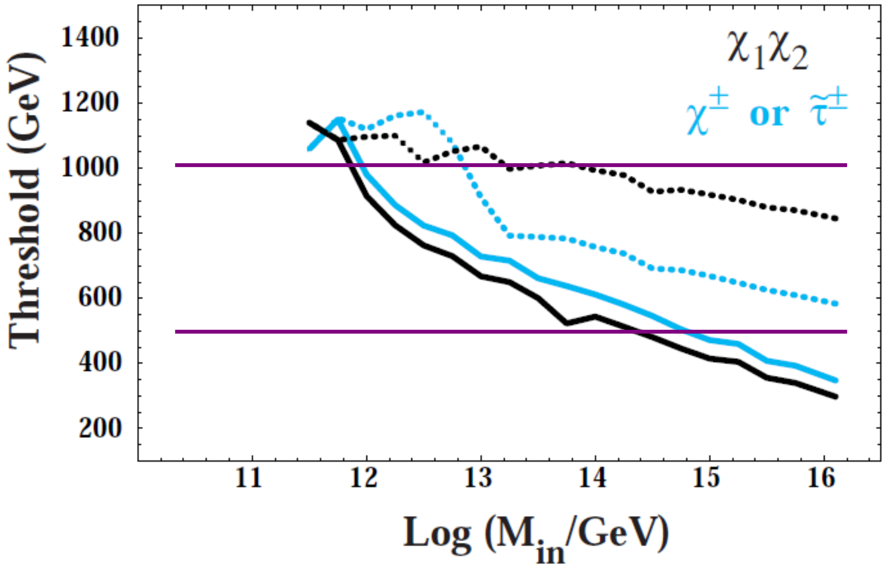


- **If LHC discovers**, what is the LC threshold to ***guarantee*** sparticle production?
- **If LHC excludes**, what is min. CM energy at which production ***may still occur***?

Note: Assume Ωh2 WMAP compatible!

LC (1 fb^{-1} @ LHC)





Example: If the LHC makes a discovery with 1 fb^{-1} of data, for most M_{in} a 1 TeV LC would suffice to guarantee follow-up measurements of at least some sparticles.

Closing Remarks

- Supersymmetry is an attractive theory in which there are several possible dark matter candidates.
  - SuperWIMPs: Axino and Gravitino
  - WIMPs: Sneutrino and Neutralino
- Dark matter phenomenology depends on many assumptions about SUSY breaking, but some general conclusions can be drawn (especially for MSSM neutralino dark matter).
- We hope for agreement among many experiments and techniques (direct detection, indirect detection, and collider searches) to give us a consistent picture of dark matter and its properties.