INTRODUCTION
TO
SUPERSYMMETRY

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THE PLAN

I. The Gauge Hierarchy

II. Guiding Principles

III. EWSB

IV. Models and Collider Signatures

V. Low Energy Probes

VI. Dark Matter

Haber, Introductory Low-energy SUSY, hep-ph/9306207
Bagger, Weak Scale Supersymmetry, hep-ph/9604232
Martin, A Supersymmetry Primer, hep-ph/9709356
Polonsky, *Supersymmetry and Related Phenomena*
⋮

I. SUSY AND THE GAUGE HIERARCHY

Symmetries of Nature:

	Exact	Broken
Gauge	$U(1)_{EM}$ $SU(3)_C$	$SU(2)_L \times U(1)_Y$
Global	B, L	L_e, L_μ, L_τ
Spacetime	P, J	SUSY

Supersymmetry is a new *class* of symmetry:

bosons $\leftrightarrow$ fermions

The Gauge Hierarchy Problem

Why are all the known particles so light?

We know 3 fundamental constants:

Special relativity: speed of light c
Quantum mechanics: Planck's constant h
General relativity: Newton's constant G

We can form one mass from these:

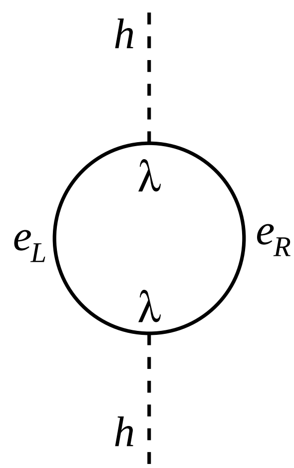
$$M_{\mathsf{Pl}} = \sqrt{\frac{hc}{G}} \approx 10^{19}\ \text{GeV}$$

Why is the weak scale $m_h, m_W, m_Z \ll M_{\mathsf{Pl}}$?

In the SM with a fundamental scalar Higgs boson, the weak scale is extremely unstable.

Large corrections to m_h appear in perturbation theory:

$$m_h^2 \;=\; (m_h^2)_0 \;+$$



$$(m_h^2)_0 \quad - \quad \frac{1}{16\pi^2}\lambda^2\Lambda^2 \;,$$

where Λ is some high energy cutoff.

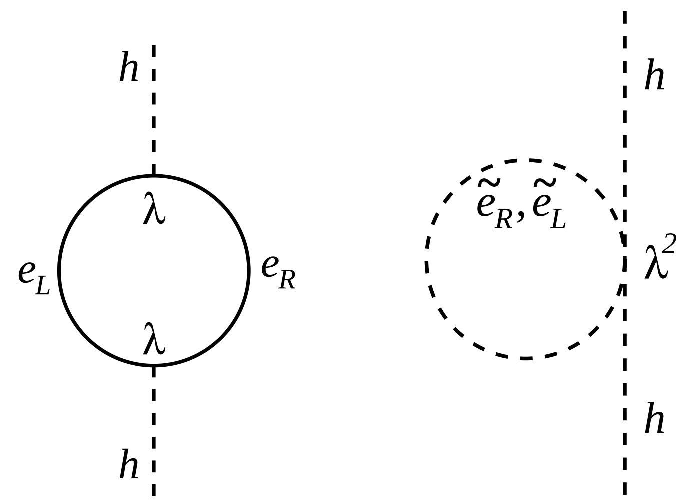
We know $m_h \sim \mathcal{O}(100\ \text{GeV})$.

$\Lambda \sim M_{\text{Pl}} \Rightarrow$ fine-tuning.

The supersymmetric solution

Introduce two partner particles: $\tilde{e}_L$, $\tilde{e}_R$, both complex scalar bosons, so $n_B = n_F$.

$$m_h^2 \ = \ (m_h^2)_0 \ + $$



$$(m_h^2)_0 \ + \ \underbrace{-\frac{1}{16\pi^2}\lambda^2\Lambda^2 \ + \ \frac{1}{16\pi^2}\lambda^2\Lambda^2} \ + \ \frac{1}{16\pi^2}\lambda^2(m_{\tilde{e}}^2 - m_e^2)\ln(\Lambda/m_h)$$

$\tilde{e}_{L,R}$ soften the self-energy divergence to a logarithm.

We must do this for every SM particle. Introduce

$$
\begin{array}{rlll}
\text{Squarks}: & \tilde{u}_{L,R} & \tilde{c}_{L,R} & \tilde{t}_{L,R} \\
 & \tilde{d}_{L,R} & \tilde{s}_{L,R} & \tilde{b}_{L,R} \\
\text{Sleptons}: & \tilde{\nu}_e & \tilde{\nu}_\mu & \tilde{\nu}_\tau \\
 & \tilde{e}_{L,R} & \tilde{\mu}_{L,R} & \tilde{\tau}_{L,R} \\
\text{Gauginos}: & \tilde{B} \quad \tilde{W}^{\pm} & \tilde{W}^0 & \tilde{g} \\
\text{Higgsinos}: & \tilde{H}_u \quad \tilde{H}_d & &
\end{array}
$$

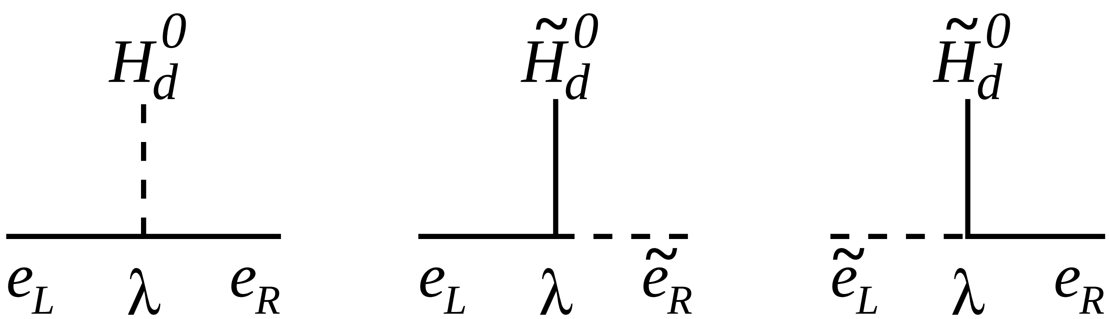
• If we add these fields, quadratic divergences cancel order by order.

• Scalar masses and many other (but not all) dimension 2 and 3 terms can be added without ruining this feature. These are *soft supersymmetry breaking* terms.

• (boson, fermion) $\rightarrow$ supermultiplets.
SUSY algebra: $\{Q, \bar{Q}\} = P$,
$[P, Q] = [P, \bar{Q}] = 0$.

Superpartner properties

• Dimensionless couplings: must be identical to those of partners. This property *defines* superpartners.



For example, a scalar with $Q = -1$ and $I = 0$, but with a non-negligible coupling to a Higgsino, is *not* $\tilde{e}_R^-$.

• Dimensionful couplings (masses): unknown, but presumably not too large. (See below.)

Superpartners cannot completely decouple.

An analogy

	Soap Bubble	SM
large parameter	length L height H	M_{GUT}
small parameter	$\Delta = L - H$	M_Z
symmetry explanation	O(3) rotational invariance	SUSY
symmetry breaking	gravity	M_{SUSY}
natural if:	gravity weak	M_{SUSY} small

Two Higgs doublets

Gauge anomalies must cancel.

In SM, e.g., Tr$Y^3 = 0$.

SUSY adds extra chiral fermions with $Y = -1$:

$$\begin{pmatrix} h^0 \\ h^- \end{pmatrix} \equiv \begin{pmatrix} h_d^0 \\ h_d^- \end{pmatrix} \Rightarrow \begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$$

To cancel the anomaly, add an extra Higgs doublet with $Y = 1$:

$$\begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix} \Rightarrow \begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$$

All SUSY models are (at least) two Higgs doublet models.

The General MSSM

Given these new fields, add all possible renormalizable, gauge-invariant interactions:

$$
\begin{aligned}
\mathcal{L} \;=\; & y^u_{ij}\widehat{H}_u\widehat{Q}_i\widehat{U}_j + y^d_{ij}\widehat{H}_d\widehat{Q}_i\widehat{D}_j + y^e_{ij}\widehat{H}_d\widehat{L}_i\widehat{E}_j \\
& +\mu\widehat{H}_u\widehat{H}_d \\
& +M_1\tilde{B}\tilde{B} + M_2\tilde{W}\tilde{W} + M_3\tilde{g}\tilde{g} \\
& +\sum_{f,ij} m^2_{ij}\tilde{f}^*_i\tilde{f}_j + m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 \\
& +A^u_{ij}h_u\tilde{q}_i\tilde{u}_j + A^d_{ij}h_d\tilde{q}_i\tilde{d}_j + A^e_{ij}h_d\tilde{l}_ie_j \\
& +Bh_uh_d \\
& +\lambda_{ijk}\widehat{L}_i\widehat{L}_j\widehat{E}_k + \lambda'_{ijk}\widehat{L}_i\widehat{Q}_j\widehat{D}_k + \lambda''_{ij}\widehat{U}_i\widehat{D}_j\widehat{D}_k \\
& +\mu'_i\widehat{H}_u\widehat{L}_i \\
& \rho_{ijk}\tilde{l}_i\tilde{l}_j\tilde{e}_k + \rho'_{ijk}\tilde{l}_i\tilde{q}_j\tilde{d}_k + \rho''_{ijk}\tilde{u}_i\tilde{u}_j\tilde{d}_k \\
& +B'_ih_u\tilde{l}_i \\
& +\text{gauge and other couplings}
\end{aligned}
$$

Here, $\widehat{A}\widehat{B} \equiv \psi_A\psi_B$, $\widehat{A}\widehat{B}\widehat{C} \equiv \phi_A\psi_B\psi_C + \psi_A\phi_B\psi_C + \psi_A\psi_B\phi_C$.

370 new parameters!

II. GUIDING PRINCIPLES

Proton Decay (dimension 4)

In generic SUSY, protons decay:

$$L-\text{violation}: \quad \hat{L}\hat{L}\hat{E}, \hat{L}\hat{Q}\hat{D}$$
$$B-\text{violation}: \quad \hat{U}\hat{D}\hat{D}$$

$$p = u\,(u_R d_R) \to u\,(\bar{\tilde{s}}_R) \to u\,(\bar{u}_L e^+) = \pi^0 e^+$$

Forbid this with R-parity: $R = (-1)^{3(B-L)+2S}$

SM particles have $R_p = 1$
SUSY particles have $R_p = -1$
Require $\prod R_p = 1$ at all vertices.

R_p conservation $\Rightarrow \lambda, \lambda', \lambda'', \mu', \rho, \rho', \rho'', B' = 0$.

Consequences:

• 370 $\rightarrow$ 107 new parameters.

• All superpartners decay to the lightest supersymmetric particle (LSP).

To a large extent, the properties of the LSP determine the signature of supersymmetry.

• LSP is stable (unless it finds another superpartner) — dark matter!

In many SUSY models, LSP = WIMP.

Note: R_p is overkill for proton decay, but required for dark matter.

Unification of gauge couplings

Matter unification: $Q, U, D, L, E, N \rightarrow \mathbf{16}$ of SO(10)

Gauge coupling constants RG evolve:

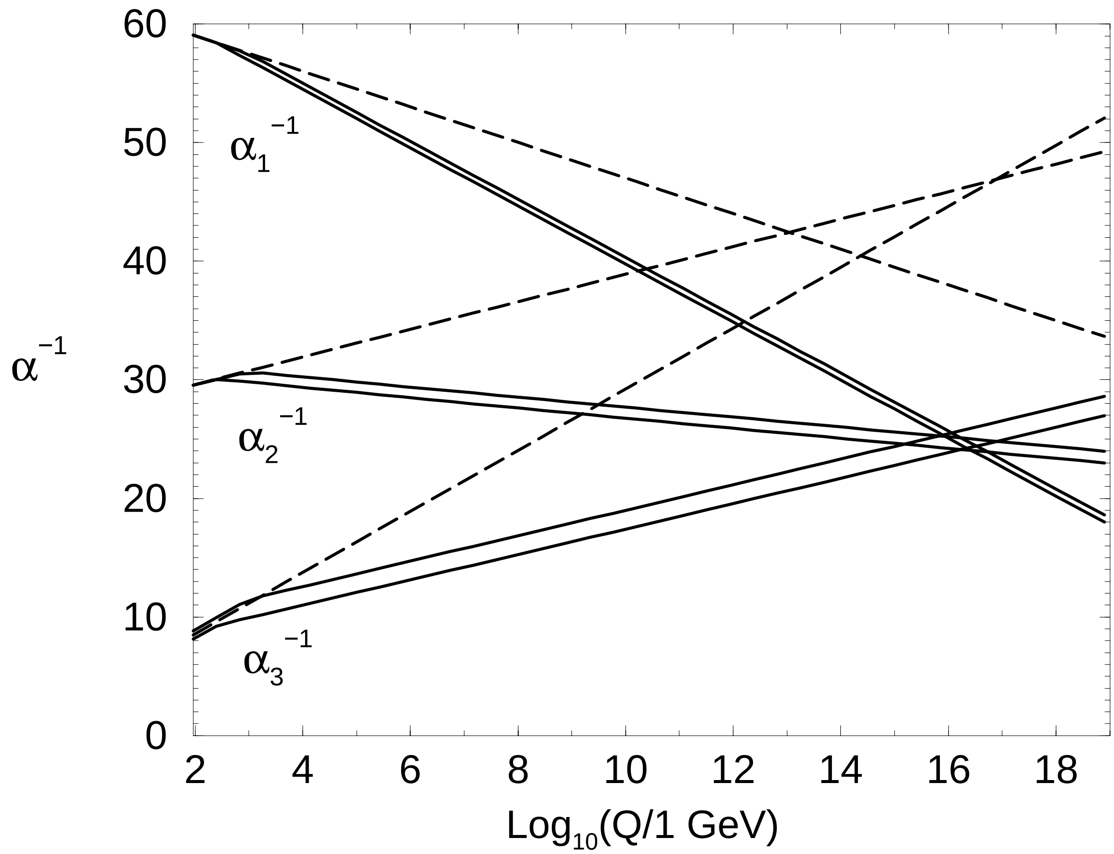
$$\frac{dg_i}{dt} = \frac{1}{16\pi^2} b_i g_i^3$$

where $t \equiv \ln(Q_0/Q)$ (so asymptotic freedom $\Rightarrow b_i > 0$).

$$\text{SM}: \qquad b_i = \left(-\tfrac{41}{10}, \tfrac{19}{6}, 7\right)$$

$$\text{MSSM}: \qquad b_i = \left(-\tfrac{33}{5}, -1, 3\right)$$

The introduction of many new superpartners modifies the RG evolution above the superpartner mass scale.



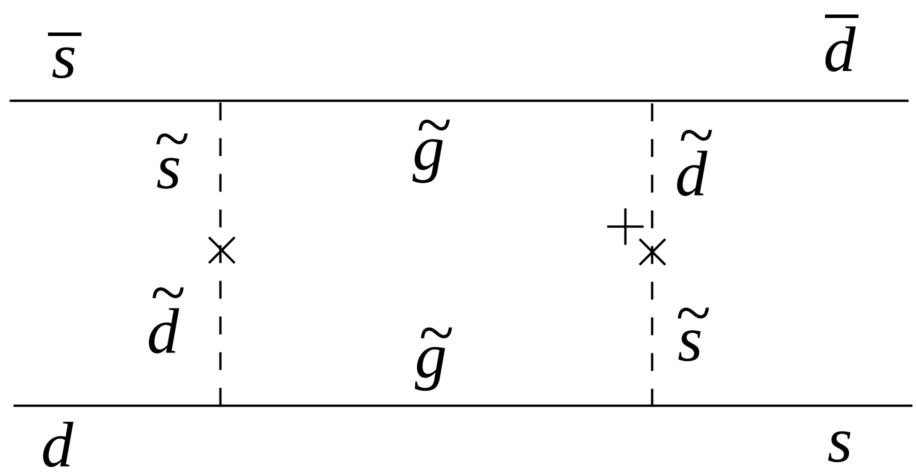
Martin (1997)

- No free parameters
- Requires α_i as measured at % level
- Coupling at unification: $\alpha_{\text{unif}}^{-1} \gtrsim 1$
- Scale of unification:

  $\mu_{\text{unif}} \gtrsim 10^{16}$ GeV [SuperK proton decay]

  $\mu_{\text{unif}} \lesssim 10^{18}$ GeV [Quantum gravity]

Flavor Constraints

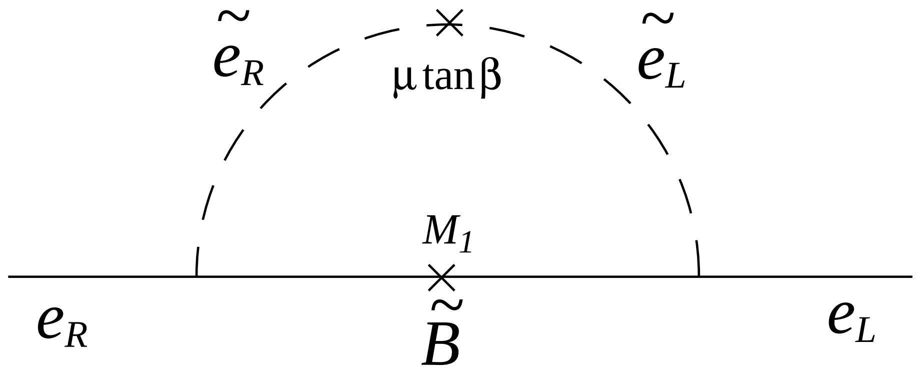


$$\Delta m_K \Rightarrow \left[\frac{10 \text{ TeV}}{m_{\tilde{q},\tilde{g}}}\right]^2 \left[\frac{\Delta m^2_{\tilde{q}_{12}}/m^2_{\tilde{q}}}{0.1}\right]^2 < 1$$

Requires squark degeneracy (super-GIM mechanism) or extremely heavy squarks.

Leptonic version: $\mu - e$ conversion, $\mu \to e\gamma$, etc.

CP Constraints



SUSY contribution to EDM$_e$. A photon attached to any charged internal line is implicit.

$$\text{EDM}_e \Rightarrow \left[\frac{2\ \text{TeV}}{m_{\tilde{e}}}\right]^2 \left[\frac{\mu M_1}{m_{\tilde{e}}^2}\right] \tan\beta \sin\phi_{CP} < 1$$

Requires heavy selectrons or $\phi_{CP} \ll 1$.

Note: flavor-conserving, so cannot be suppressed by degeneracy.

Hadronic version: EDM$_n$.

III. EWSB

How is electroweak symmetry broken in SUSY models?

The potential for the neutral Higgs bosons is

$$V = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2$$
$$-(BH_u^0 H_d^0 + \text{c.c.}) + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2$$

Two requirements for consistent EWSB:

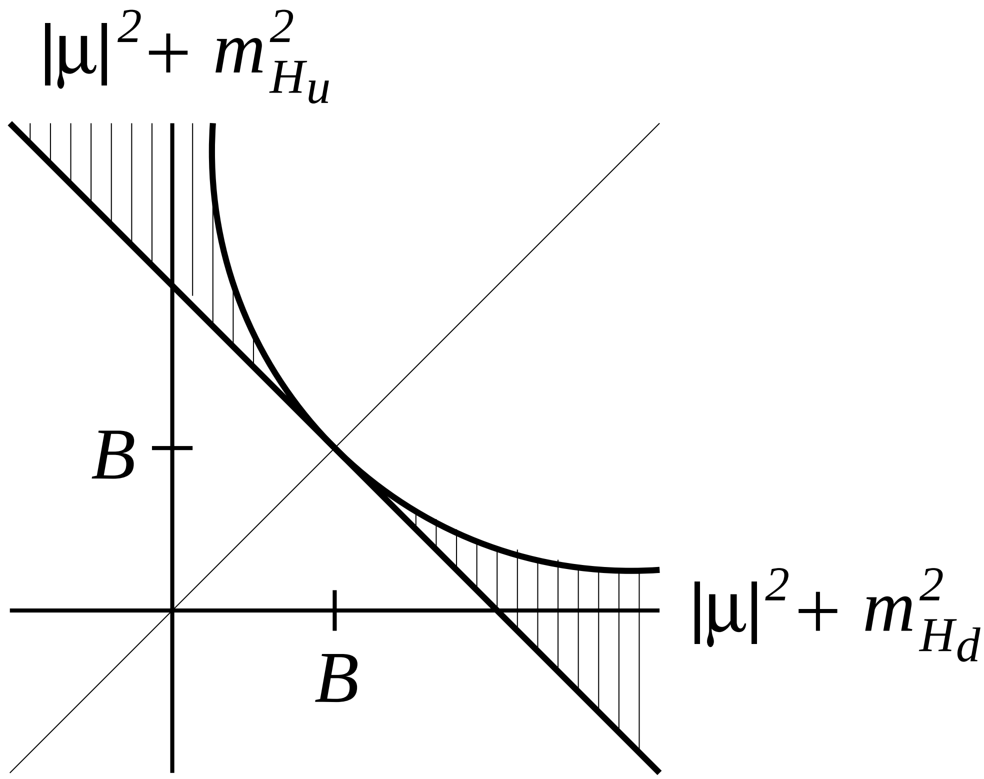
- Potential bounded from below:

$$(|\mu|^2 + m_{H_u}^2) + (|\mu|^2 + m_{H_d}^2) > 2B$$

- Origin is not a stable minimum:

$$\det m^2 = \begin{vmatrix} |\mu|^2 + m_{H_u}^2 & B \\ B & |\mu|^2 + m_{H_d}^2 \end{vmatrix} < 0$$

Consistent EWSB is found in the shaded region:



We can simply require that the parameters are in this region: typically (but not always), requires $m^2_{H_u} m^2_{H_d} < 0$.

But unbroken U(1)$_{\rm EM}$, SU(3) $\Rightarrow m^2 > 0$ for other scalars.

Also, in many models, $m^2_{H_u} = m^2_{H_d}$. This is unsatisfying.

Radiative EWSB

All parameters RG evolve, however. In detail, this is a complicated system of differential equations. But schematically, at 1-loop:

$$\begin{aligned}
\frac{dg}{dt} &\sim \frac{1}{16\pi^2} g^3 \\
\frac{dy}{dt} &\sim \frac{1}{16\pi^2} \left[g^2 y - y^3 \right] \\
\frac{dM}{dt} &\sim \frac{1}{16\pi^2} g^2 M \\
\frac{dA}{dt} &\sim \frac{1}{16\pi^2} \left[-g^2 M - y^2 A \right] \\
\frac{dm^2}{dt} &\sim \frac{1}{16\pi^2} \left[g^2 M^2 - y^2 A^2 - y^2 m^2 \right]
\end{aligned}$$

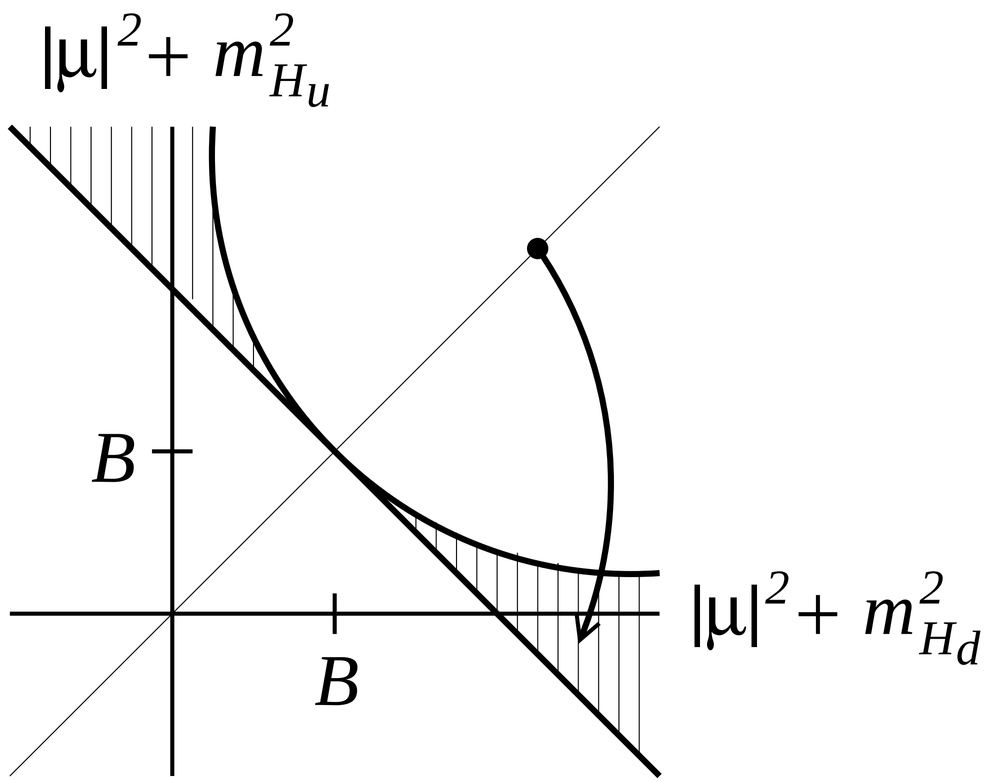
where $t \equiv \ln(Q_0/Q)$, and *positive* numerical coefficients have been neglected.

Gauge interactions raise m^2, Yukawa interactions lower m^2.

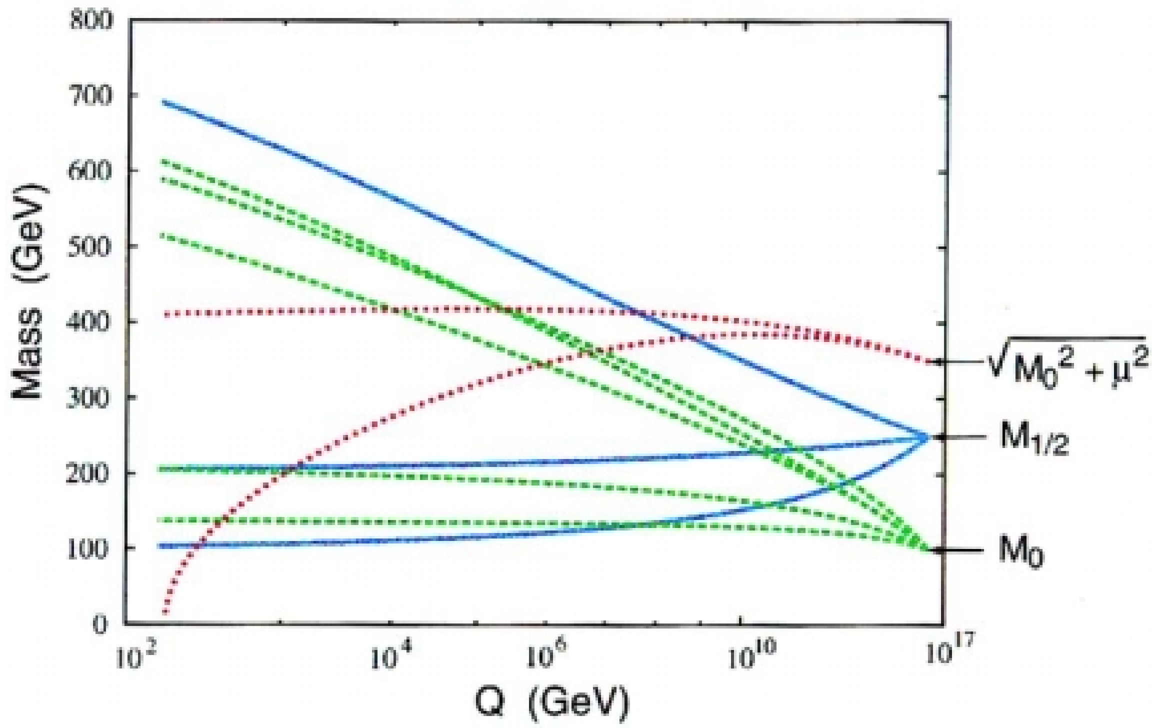
Recall

$$\mathcal{L} \supset y^u_{ij}\widehat{H}_u\widehat{Q}_i\widehat{U}_j + y^d_{ij}\widehat{H}_d\widehat{Q}_i\widehat{D}_j + y^e_{ij}\widehat{H}_d\widehat{L}_i\widehat{E}_j$$

Top Yukawa coupling enters RGE for H_u but not for H_d. The heavy top quark drives $m^2_{H_u}$ negative.



Example RG trajectories:



Squarks/sleptons (green), gauginos (blue), Higgses (red)

This does not explain why the top quark is heavy. However, given this experimental fact, EWSB is generic.

Note that logarithmic running of $m_{H_u}^2$ *does not* explain the gauge hierarchy in the way α_s evolution explains Λ_{QCD}.

We need EW symmetry to break, but also to give the correct m_Z. Let

$$\tan\beta \equiv \frac{\langle H_u^0\rangle}{\langle H_d^0\rangle}$$

Then

$$\begin{aligned}\frac{1}{2}m_Z^2 &= \frac{m_{H_d}^2 - m_{H_u}^2\tan^2\beta}{\tan^2\beta - 1} - |\mu|^2 \\ 2B &= (m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2)\sin 2\beta\end{aligned}$$

We lack a quantitative theory for μ.

To enforce EWSB:

- Soft terms given at some (high) scale
- Weak scale values determined by RGEs
- $\tan\beta$ a free parameter
- μ (and B) determined by relations above

m_Z fixed by hand, but large $|\mu| \Rightarrow$ fine-tuning. This is the starting point for all discussions of naturalness.

Naturalness

How heavy can superpartners be?

Clearly subjective, but there are interesting *qualitative* conclusions.

Prescription:

- Choose a model framework, with some fundamental parameters a_i.

- Define sensitivity coefficients

$$c_i \equiv \left| \frac{\partial \ln m_Z^2}{\partial \ln a_i} \right|$$

- Require an upper bound on $c = \max\{c_i\}$.

Ellis, Enqvist, Nanopoulos, Zwirner (1986)
Barbieri, Giudice (1988)

Superheavy SUSY

Drees (1986)
Dimopoulos, Giudice (1995)
Pomarol, Tommasini (1995)

Recall

$$\frac{dm^2}{dt} \sim \frac{1}{16\pi^2}\left[g^2M^2 - y^2A^2 - y^2m^2\right]$$

For the H_u and H_d RGEs, squark/slepton masses enter proportional to Yukawa couplings.

Suggests the following spectrum:

Heavy: $\tilde{u}_{L,R}, \tilde{d}_{L,R}, \tilde{e}_{L,R}, \tilde{\nu}_e \ldots$

Light: $\tilde{t}_{L,R}$, $\tilde{b}_L$, all gauginos, Higgsinos

Superheavy 1st two generation squarks/sleptons ease flavor, CP problems.

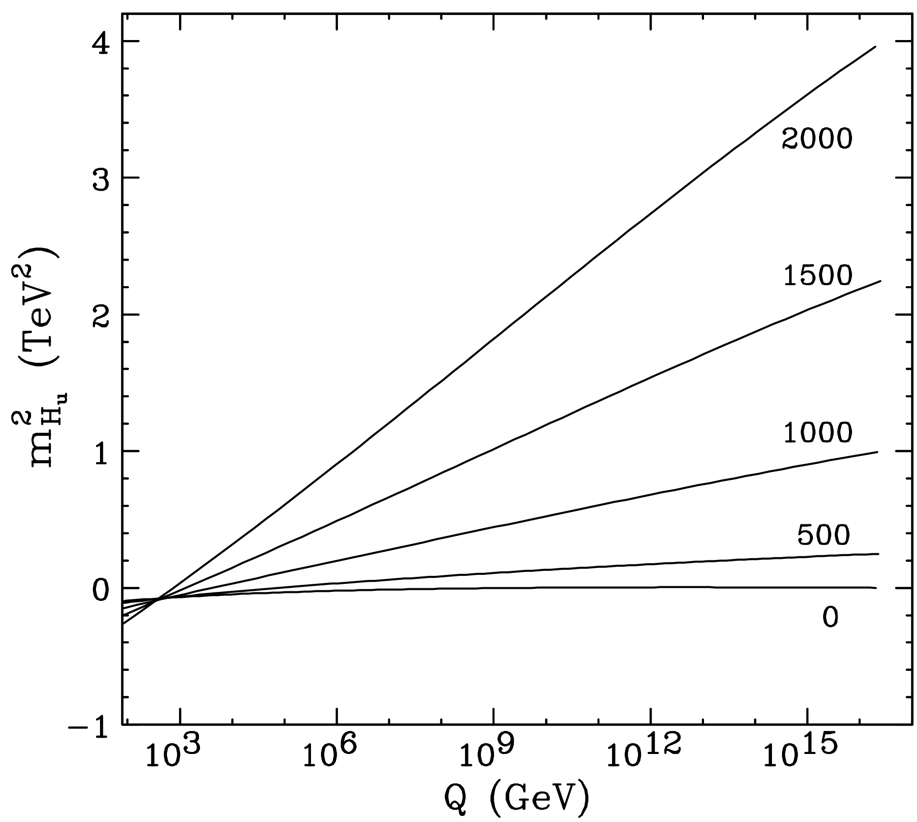
Focus Point SUSY

JF, Matchev, Moroi (1999)

In simple models,

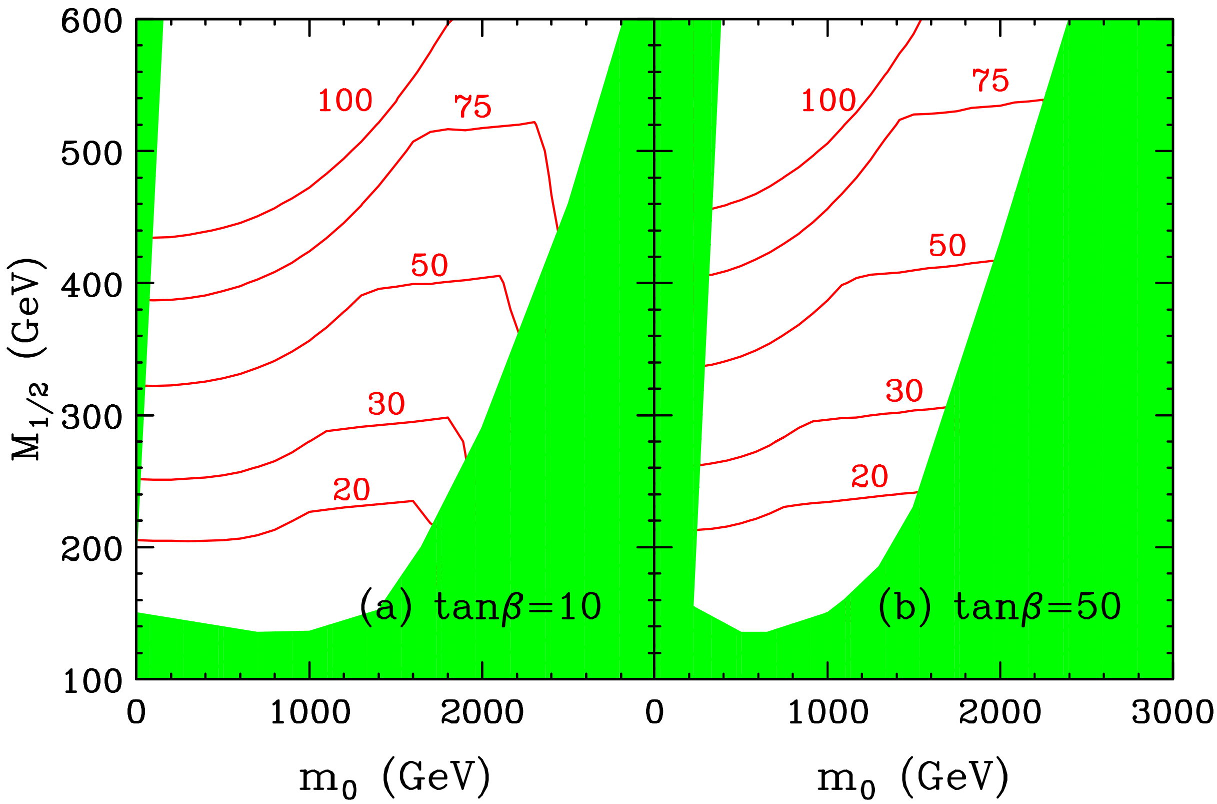
$m_t = 175 \pm 5$ GeV $\Rightarrow$ RG focus point at M_{Weak}

For example, in "minimal supergravity," a model with universal scalar mass m_0:



RG trajectories in mSUGRA for various m_0, $\tan\beta = 10$.

EWSB is highly insensitive to m_0 at high scales.



Contours of "fine-tuning" c in mSUGRA.

Heavy: $\tilde{t}_{L,R}$, $\tilde{b}_{L,R}$, $\tilde{u}_{L,R}, \tilde{d}_{L,R}, \tilde{e}_{L,R}, \ldots$

Light: All gauginos, Higgsinos

Again, all flavor, CP problems alleviated.

To date, however, there are no proposals for naturally heavy gauginos or Higgsinos.

Scalar Higgs bosons

The Higgs sector contains (at least) 8 real scalar degrees of freedom:

$$H_u, H_d \to G^{\pm}, G^0, H^{\pm}, h, H, A$$

Masses:

$$m_A^2 = \frac{B}{\sin\beta\cos\beta} \qquad m_{H^\pm}^2 = m_A^2 + m_W^2$$

$$m_{h,H}^2 = \frac{1}{2}\Big[m_A^2 + m_Z^2 \pm\sqrt{(m_A^2 + m_Z^2)^2 - 4m_Z^2 m_Z^2 \cos^2 2\beta}\Big]$$

A, $H^{\pm}$, H^0 may become arbitrarily heavy. But

$$m_h < |\cos 2\beta| m_Z$$

However, there are large radiative corrections:

$$\Delta m_h^2 = \frac{3}{4\pi^2} v^2 y_t^4 \sin^4\beta \ln(m_{\tilde{t}_1} m_{\tilde{t}_2}/m_t^2)$$

Haber, Hempfling (1991)
Okada, Yamaguchi, Yanagida (1991)
Ellis, Ridolfi, Zwirner (1991)

In the end, $m_h \lesssim 130$ GeV for $m_{\tilde{t}} \lesssim 1$ TeV.

Recap

Virtues	Constraints
EW stability (naturalness)	Proton decay
Coupling unification	Flavor violation
Dark matter	CP violation
Radiative EWSB	

The field of SUSY model building is essentially the attempt to elegantly satisfy these constraints without sacrificing these virtues.

IV. MODELS AND SIGNATURES

Previously, we listed the many soft SUSY breaking parameters and noted some generic constraints, virtues.

How are they related? Need models for specific predictions, collider searches.

Let's consider three model frameworks with drastically different experimental consequences:

- Gravity-mediated SUSY breaking
- Gauge-mediated SUSY breaking
- Anomaly-mediated SUSY breaking

General features

EWSB in the Standard Model:

EWSB Sector $h \to \langle v \rangle$	Mediating Interactions h, q, l	Observable Sector q, l

EWSB parametrized by $\langle v \rangle$.
Mediating interactions (Yukawa couplings) $\Rightarrow$ signatures.

"Hidden Sector" SUSY breaking:

SUSY Breaking Sector $Z \to \langle F \rangle$	Mediating Interactions Z, Q, L	Observable Sector Q, L

SUSY breaking parametrized by $\langle F \rangle$ ($[m]^2$).
Mediation mechanism $\Rightarrow$ signatures.

Gravity mediation

Minimal option: supergravity (string theory)

Non-renormalizable terms suppressed by $M_{\mathrm{Pl}} \to$ soft terms when $Z \to \langle F \rangle$:

$$
\begin{aligned}
c_{ij}\frac{Z^\dagger Z}{M_{\mathrm{Pl}}^2}\phi_i^*\phi_j &\to \text{ scalar masses} \\
c_a\frac{Z}{M_{\mathrm{Pl}}}\lambda_a\lambda_a &\to \text{ gaugino masses} \\
c_{ijk}\frac{Z}{M_{\mathrm{Pl}}}\phi_i\phi_j\phi_k &\to A \text{ terms} \\
c\frac{Z^\dagger Z}{M_{\mathrm{Pl}}^2}\phi_i\phi_j &\to B \text{ term}
\end{aligned}
$$

• Gravitino $\tilde{G}$ properties from (complicated!) $\mathcal{L}_{\mathrm{SUGRA}}$:

$$
\begin{aligned}
m_{\tilde{G}} &\sim \frac{F}{M_{\mathrm{Pl}}} \\
\mathcal{L} &\supset \frac{1}{F}\left[m_{\tilde{f}}^2\bar{f}\tilde{f} + \frac{m_\lambda}{4\sqrt{2}}\bar{\lambda}\sigma^{\mu\nu}F_{\mu\nu}\right]\tilde{G}
\end{aligned}
$$

All soft terms are $\sim F/M_{\mathsf{Pl}}$:

$$F \sim M_{\mathsf{Weak}} M_{\mathsf{Pl}} \sim (10^{10}\ \mathsf{GeV})^2$$

"High-scale supersymmetry breaking"

If we can generate this intermediate scale in the hidden sector, then we have (finally!) explained the gauge hierarchy.

Example: gaugino condensation, with $F \sim \Lambda^3/M_{\mathsf{Pl}}$ and $\Lambda \sim 10^{13}$ GeV.

<u>What's the LSP?</u>

$m_{\tilde{G}} \sim F/M_{\mathsf{Pl}} \sim M_{\mathsf{Weak}}$

Gravitino LSP $\Rightarrow$ NLSP decays after BBN.

So typically assume LSP is a SM superpartner.

Minimal Supergravity (mSUGRA)

Arnowitt, Chamseddine, Nath (1981)
Barbieri, Ferrara, Savoy (1982)
Hall, Lykken, Weinberg (1983)

Defined by

$$
\begin{aligned}
m_0 &: \text{ Universal scalar mass} \\
M_{1/2} &: \text{ Gaugino mass unification (GUT)} \\
A_0 &: \text{ Universal } A \text{ term} \\
\tan\beta &: \text{ Input parameter} \\
\text{sign}(\mu) &: \ |\mu| \text{ determined by EWSB}
\end{aligned}
$$

SUSY flavor problem “solved” by m_0.

Gauginos: $\frac{d}{dt}\left(M_i/g_i^2\right) = 0$ at one-loop, so

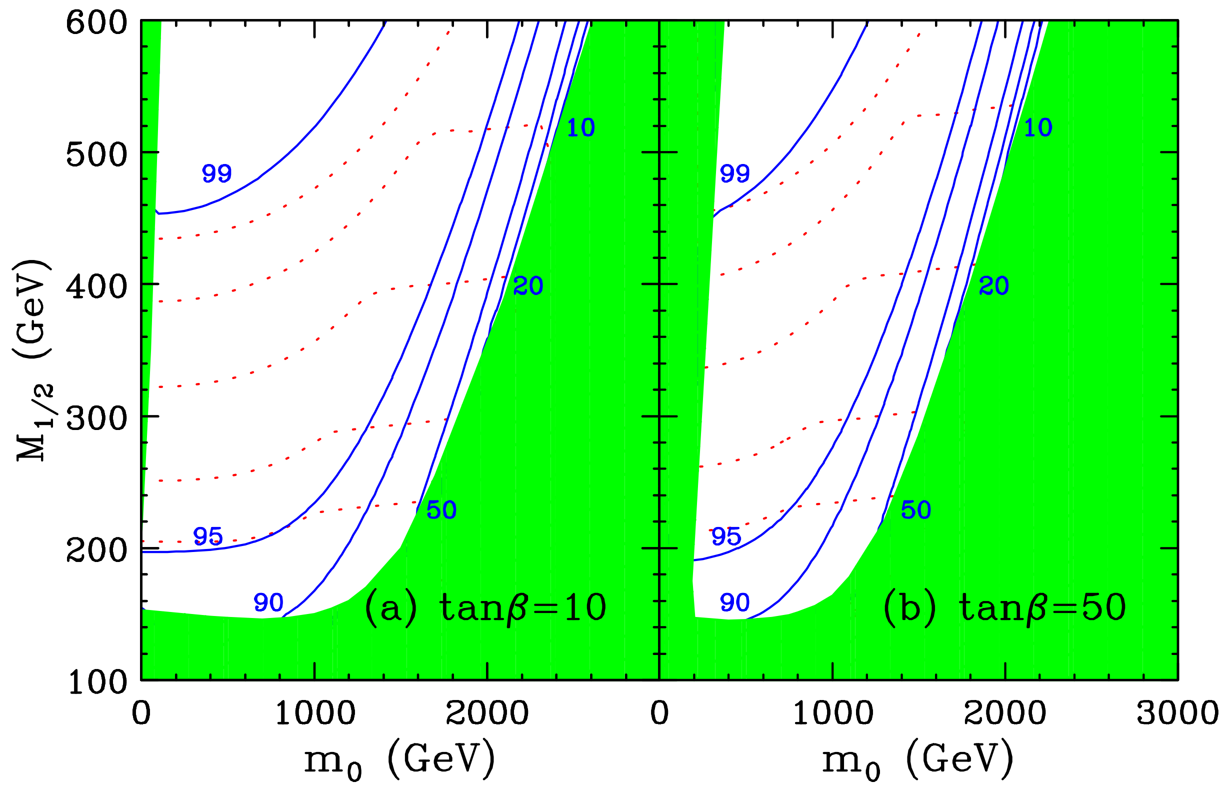
$$M_1 : M_2 : M_3 \simeq g_1^2 : g_2^2 : g_3^2 \simeq 1 : 2 : 7$$

Higgsinos: mass $|\mu|$.

LSP candidates:

- $\tilde{l}_R$ (more precisely, $\tilde{\tau}_R$)

- $\tilde{B}$, $\tilde{H}_u^0$, $\tilde{H}_d^0$ (more precisely, χ, the lightest neutralino, a mixture of these)



Bino fraction of χ LSP in mSUGRA with $A_0 = 0$, $\mu > 0$. Left shaded region has $\tilde{\tau}$ LSP. Remaining shaded region excluded by LEP chargino search.

JF, Matchev, Wilczek (2000)

$\tilde{\tau}$ LSP: Disfavored by rare isotope searches.

χ LSP: Neutral, weakly interacting:

- $\not{E}_{(T)}$ signature at colliders

(and excellent dark matter candidate!)

A (somewhat) random assortment of possible signals:

Tevatron:

$$p\bar{p} \to \tilde{W}^{+}\tilde{W}^{0} \to W\chi Z\chi \to l\nu l\bar{l}\chi\chi$$

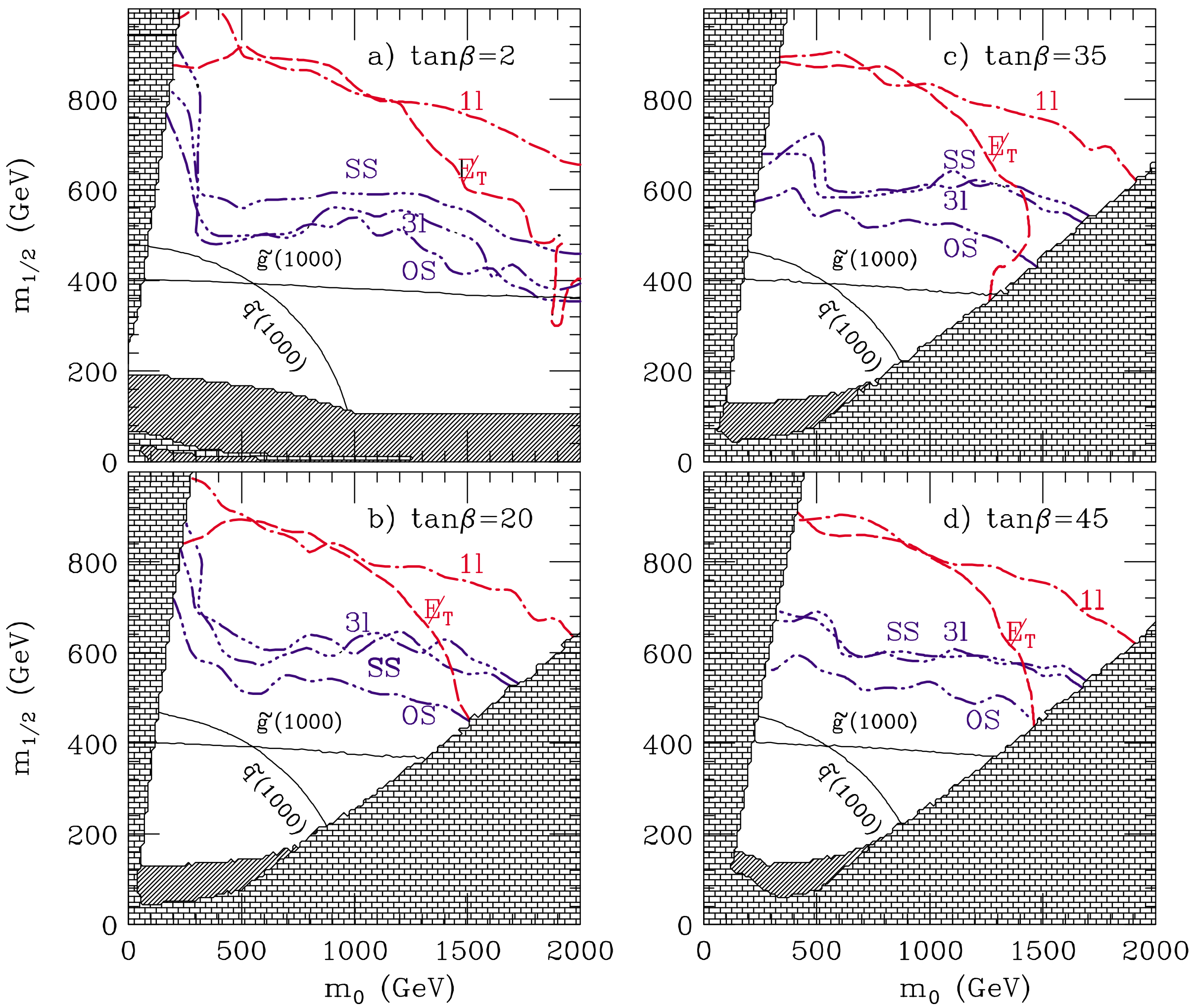
LHC:

$$pp \to \tilde{q}\tilde{g}, \tilde{g}\tilde{g}, \tilde{q}\tilde{q}$$

Linear Collider:

$$e^{+}e^{-} \to \tilde{W}^{+}\tilde{W}^{-}, \tilde{l}^{*}\tilde{l}$$

LHC Reach



Baer, Chen, Drees, Paige, Tata (1999)

LHC reach is well beyond the 1 TeV scale in mSUGRA.

In gravity mediation, non-renormalizable M_{Pl}^{-1} interactions $\rightarrow$ soft terms:

- Efficient — these terms are there!
- No predictive power

Three options:

- Extract phenomenological predictions from string theory

- Consider viable/attractive possibilities

  mSUGRA
  Superheavy SUSY
  Focus point SUSY
  ⋮

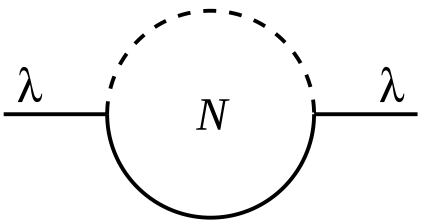
- Suppress these gravity contributions, find other sources for soft terms

  Gauge mediation
  Anomaly mediation
  ⋮

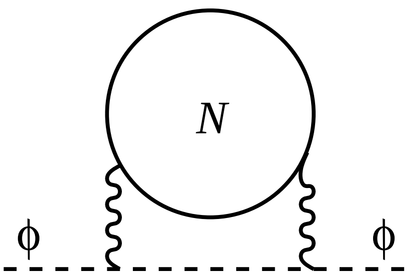
Gauge mediation

Dine, Nelson, Shirman (1993)
Dimopoulos, Dine, Raby, Thomas (1996)

Add N "messenger fields" with mass M_{mess} and SUSY breaking vev F that couple to SM gauge fields:



$$M_\lambda \sim N \frac{g^2}{16\pi^2} \frac{F}{M_{\text{mess}}}$$



$$m_\phi^2 \sim N \left[\frac{g^2}{16\pi^2}\right]^2 \left[\frac{F}{M_{\text{mess}}}\right]^2$$

Choose $M_{\text{mess}} \ll M_{\text{Pl}}$:

• $\frac{F}{M_{\text{mess}}} \gg \frac{F}{M_{\text{Pl}}}$, gravity mediated contributions neglgible. (Assume one F.)

• Scalar masses determined by gauge quantum numbers: solves SUSY flavor problem!

"Low-scale supersymmetry breaking"

If $F \sim M_{\text{mess}}^2$, then $\sqrt{F} \sim M_{\text{mess}} \sim 10^4$ GeV. But 10^4 GeV $\lesssim M_{\text{mess}} \lesssim 10^{14}$ GeV possible.

What's the LSP?

$\tilde{G}$ LSP: $m_{\tilde{G}} \sim \frac{F}{M_{\text{Pl}}} \ll M_{\text{Weak}}$

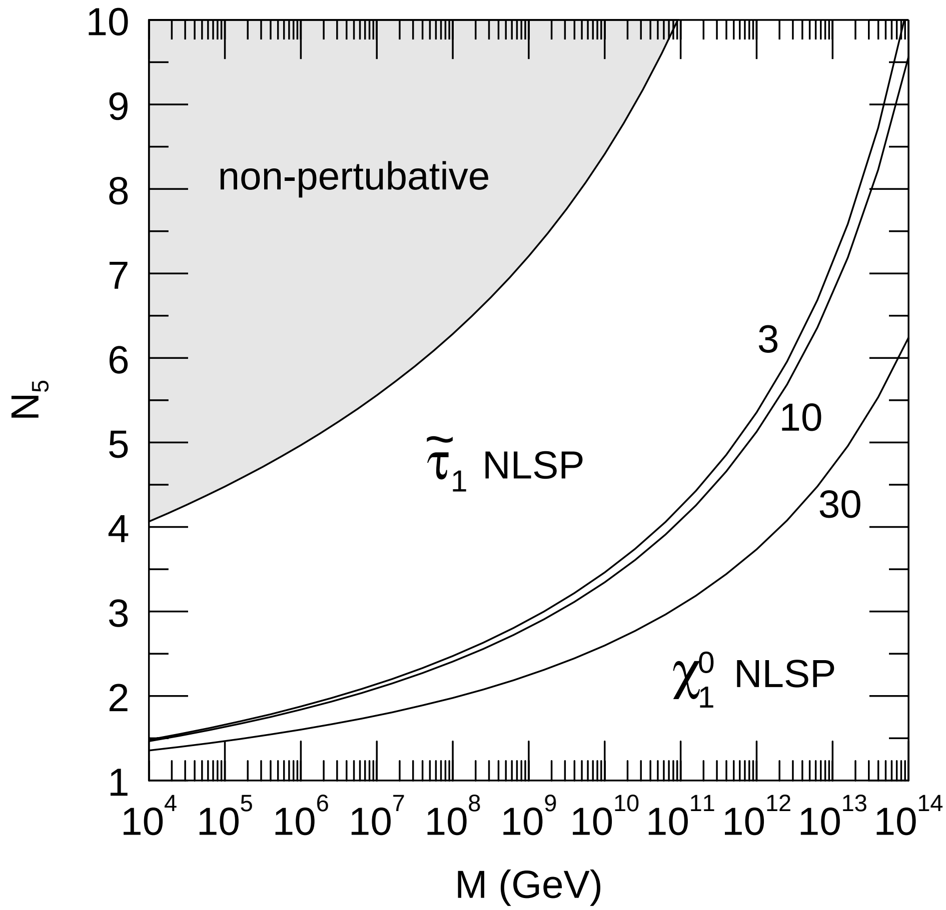
What's the NLSP?

$M_i \propto g_i^2 \Rightarrow M_1 : M_2 : M_3 = 1 : 2 : 7$ — same as mSUGRA for a completely different reason.

But now $M_\lambda, m_\phi^2 \propto N \Rightarrow \frac{m_\chi}{m_{\tilde{\tau}}} \propto \sqrt{N}$.

NLSP is unstable, so both $\tilde{\tau}$ and χ are possible.

$$L \simeq 10 \text{ km} \times \langle \beta\gamma \rangle \left[\frac{\sqrt{F}}{10^7 \text{ GeV}} \right]^4 \left[\frac{100 \text{ GeV}}{m_{\text{NLSP}}} \right]^5$$



NLSP in GMSB for various $\tan \beta$.

JF, Moroi (1997)

Signatures

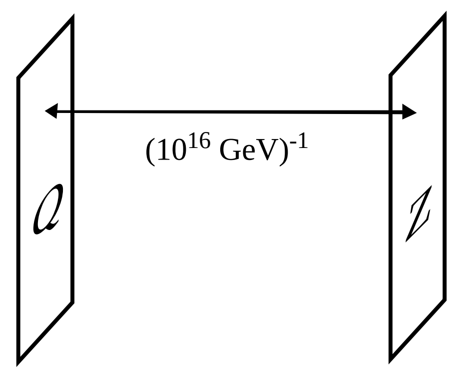
Decay Length	χ	$\tilde{\tau}$
Macroscopic	$\not{E}_{(T)}$	High $\frac{dE}{dx}$
Microscopic	Photons	Leptons

Anomaly mediation

Randall, Sundrum (1998)
Giudice, Luty, Murayama, Rattazzi (1998)

Gravity-mediated scalar masses, $c_{ij}\frac{F^\dagger F}{M_{\text{Pl}}^2}\phi_i^*\phi_j$, cannot be forbidden by 4D symmetries.

Suppress them by geometrical separation in extra dimensions:



Assume observable Q fields are on one brane, "sequestered sector" Z fields are on another, and gravity propagates in the bulk.

However, the conformal anomaly generates loop-suppressed soft SUSY breaking. These contributions are always present, but usually sub-dominant.

The anomaly-mediated contributions:

$$
\begin{aligned}
M_i &= -b_i g_i^2 \frac{M_{\mathsf{aux}}}{16\pi^2} \qquad b_i = (-\tfrac{33}{5}, -1, 3) \\
(m^2)_i^j &= \frac{1}{2} (\dot{\gamma})_i^j \left[\frac{M_{\mathsf{aux}}}{16\pi^2}\right]^2
\end{aligned}
$$

$$
\begin{aligned}
\gamma_{H_u} &= -3\mathrm{Tr}(\boldsymbol{Y_u}^\dagger \boldsymbol{Y_u}) + \tfrac{3}{2} g_2^2 + \tfrac{3}{10} g_1^2 \\
\boldsymbol{\gamma_Q} &= -\boldsymbol{Y_u}^\dagger \boldsymbol{Y_u} - \boldsymbol{Y_d}^\dagger \boldsymbol{Y_d} + \tfrac{8}{3} g_3^2 + \tfrac{3}{2} g_2^2 + \tfrac{1}{30} g_1^2 \\
&\vdots
\end{aligned}
$$

Almost flavor-blind!

$$
m^2 \sim -y\dot{y} + g\dot{g} \sim \sum_a b_a g_a^4 \qquad (y \approx 0)
$$

Unfortunately, $\tilde{l}_L$, $\tilde{l}_R$ are tachyonic.

Many models fix this — a phenomenologically interesting feature is the gaugino mass relation, however.

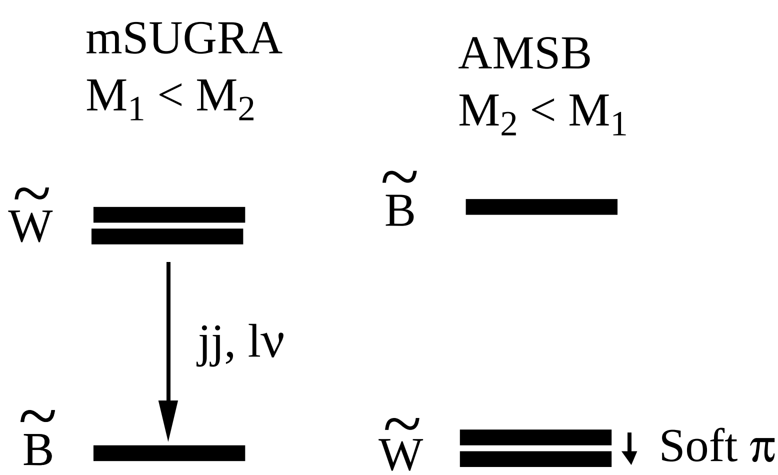
Wino LSPs

Without mixing, gaugino/Higgsino masses are

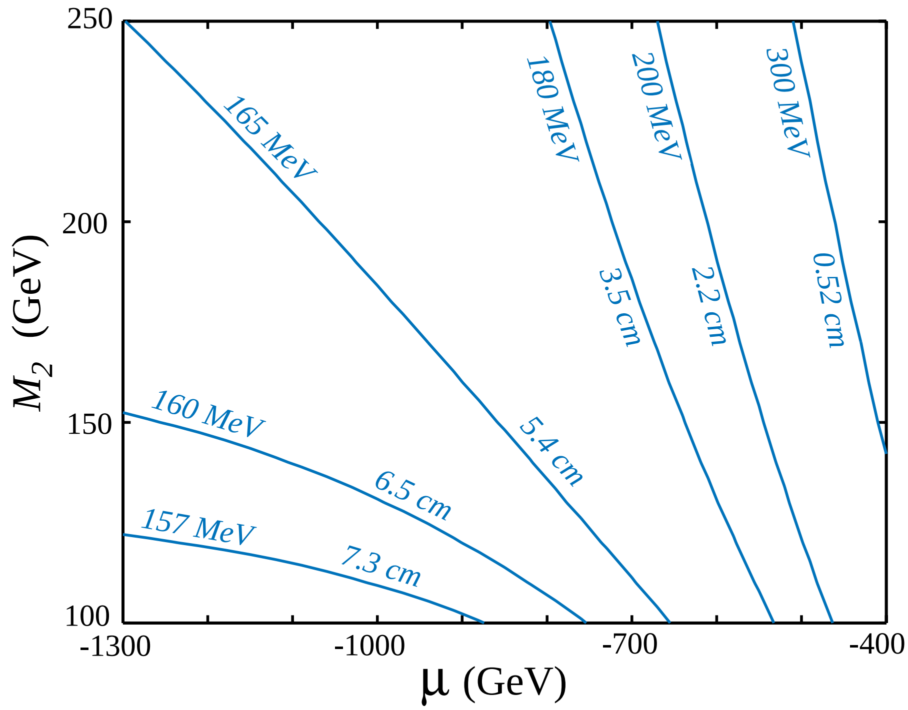
$$M_1 : \quad \tilde{B}$$
$$M_2 : \quad \tilde{W}^0 \ , \tilde{W}^\pm$$
$$|\mu| : \quad \tilde{H}_u^0 \pm \tilde{H}_d^0 \ , \ \tilde{H}^\pm$$

In mSUGRA, $M_1 : M_2 : M_3 = 1 : 2 : 7$

In mAMSB, $M_1 : M_2 : M_3 = 3 : 1 : -8$



In mAMSB, the (N)LSPs are a triplet of Winos.
(Not specific to AMSB.)



Contours of $\Delta M \equiv m_{\tilde{W}^\pm} - m_{\tilde{W}^0}$ and decay length $c\tau$.

Winos are highly degenerate

- $\Delta M = M_{\tilde{W}^\pm} - M_{\tilde{W}^0} \sim 150$ MeV – 1 GeV
- $\tilde{W}^\pm \to \pi^\pm \tilde{W}^0$ has decay length $c\tau \sim \mathcal{O}(\text{cm})$.

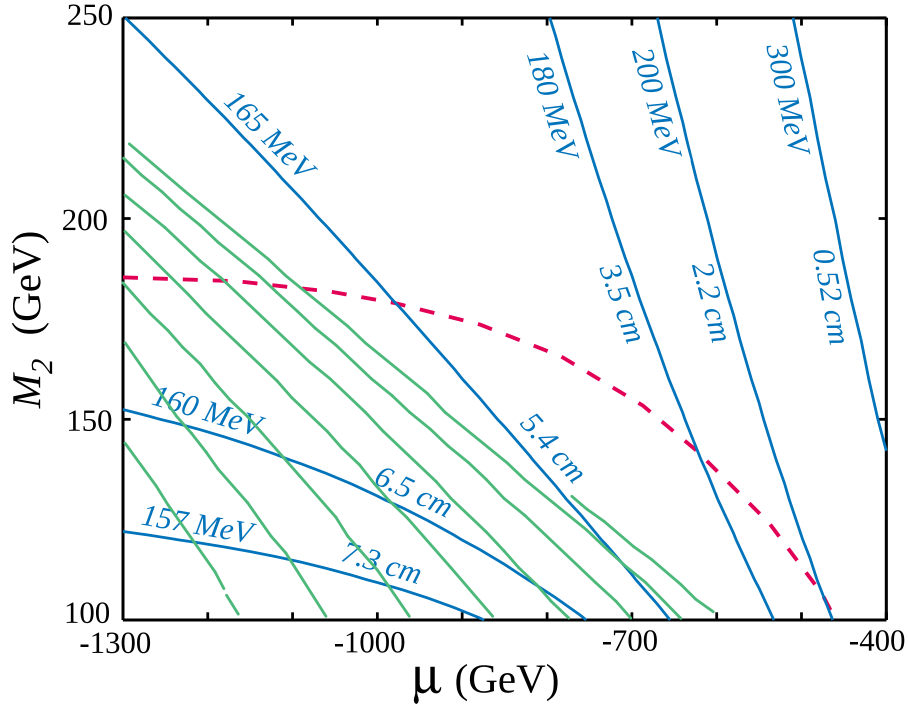
Chen, Drees, Gunion (1996)
Thomas, Wells (1998)

Mesoscopic decay length! Charged Winos decay

- before muon chambers
- to soft decay products

$\tilde{W}^\pm\tilde{W}^\mp$, $\tilde{W}^\pm\tilde{W}^0$ events escape all conventional triggers.

Try $p\bar{p} \to \tilde{W}^{\pm}\tilde{W}^{\mp,0}j$ at Tevatron. Jet provides trigger, $\tilde{W}^{\pm}$ is seen as a disappearing track.



Allowed parameter range.

5 event contour for Tevatron with $\mathcal{L} = 2\ \text{fb}^{-1}$.

JF, Moroi, Randall, Strassler, Su (1999)

Recap

SUSY breaking models and the SUSY flavor and CP problems motivate a wide variety of signals:

LSP	$c\tau_{\text{NLSP}}$	Signal
$\tilde{B}, \tilde{H}^0_{u,d}$	Microscopic	$\not{E}_{(T)}$
$\tilde{G}$	Macroscopic Microscopic	$\not{E}_{(T)}$, $\frac{dE}{dx}$ γ, τ
$\tilde{W}$	Mesoscopic	Disappearing tracks

Colliders test SUSY, and SUSY tests colliders.

V. LOW ENERGY PROBES

High precision probes

- Indirect, more ambiguous

- Many probes

  Rare μ, K, B decays
  Electric dipole moments
  Magnetic dipole moments
  $\vdots$

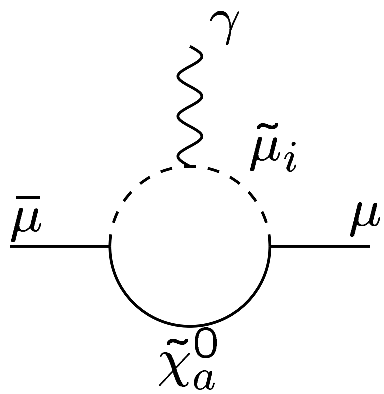
Often proportional to down-type Yukawas:

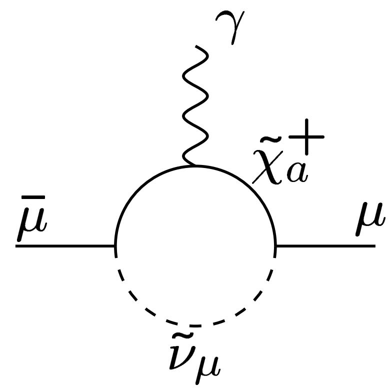
$$\begin{aligned} m_b &= y_b v_d \\ y_b &= \frac{g m_b}{\sqrt{2} m_W \cos\beta} \approx \frac{g m_b}{\sqrt{2} m_W} \tan\beta \end{aligned}$$

They become especially effective at "large $\tan\beta$."

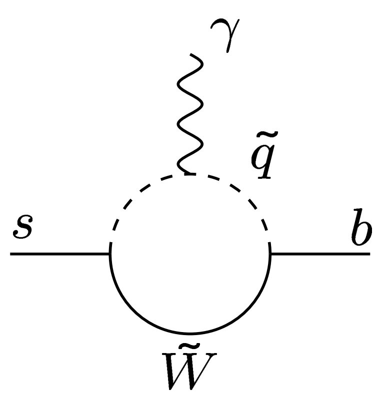
Examples:

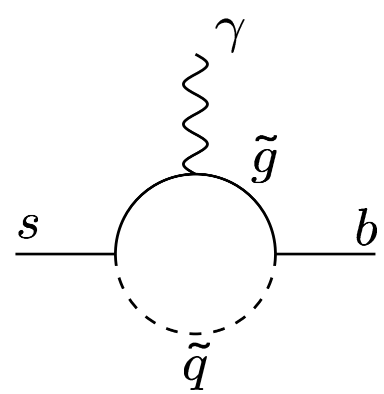
Contributions to a_μ from supersymmetry:





Contributions to $b \to s\gamma$ from supersymmetry:

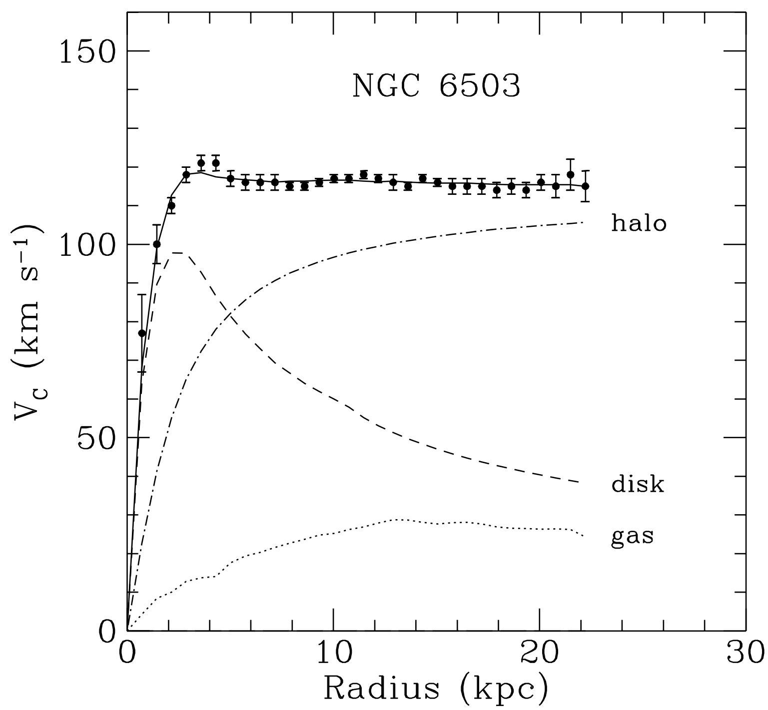




VI. DARK MATTER

"The standard model is a very successful theoretical framework that describes all confirmed observations to date."

No! Evidence on "small" scales: spiral galaxies



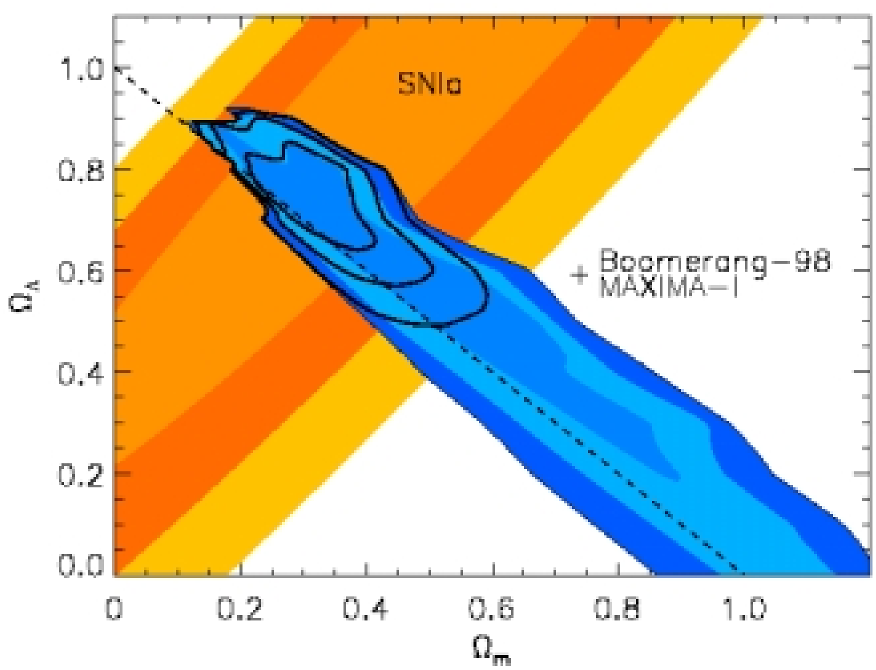
Begeman, Broeils, Sanders (1991)

$$\frac{Mv^2}{r} = \frac{GMM_{\text{tot}}}{r^2} \Rightarrow v \sim r^{-1/2}$$

Large scale:

- SN Ia luminosities
- CMB anisotropy
- Clusters of galaxies $\Rightarrow \Omega_m = 0.19 \pm 0.06$

Carlberg, Yee, Ellingson (1997)



Boomerang, Maxima, SN Collabs, astro-ph/0007333

The dawn of precision cosmology:

$$0.1 \lesssim \Omega_m h^2 \lesssim 0.3 \qquad [h \approx 0.65]$$

$$[\text{and } \Omega_\Lambda \approx 0.7]$$

DM Requirements

- Stable

  Lifetime $\gtrsim 10$ Gyr

- Non-baryonic

  BBN $\Rightarrow \Omega_B h^2 \approx 0.02 \quad [\Omega_{\rm lum} \approx 0.005]$

- Neutral

- Cold

  Non-relativistic for structure formation

- Yield correct density

No plausible candidates in the SM.

$[m_\nu \sim 10^{-1}$ eV $\Rightarrow \Omega_\nu \sim 0.001]$

Neutralino Dark Matter

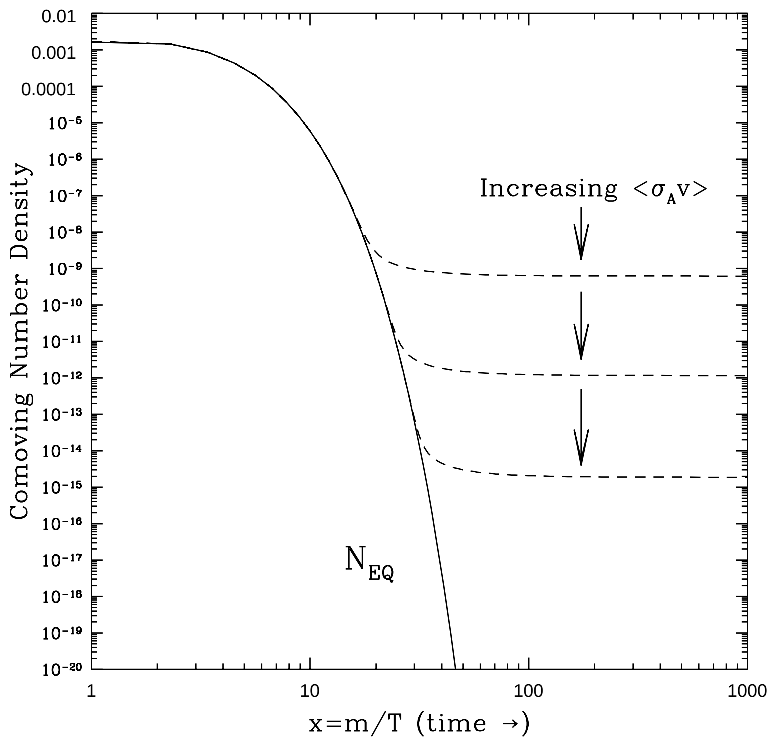
In supergravity, as we've seen, the LSP is often the lightest neutralino

$$\chi \in \{\tilde{B}, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0\}$$

This LSP is

- Stable (given R_P conservation)
- Non-baryonic
- Neutral
- Cold

• χ annihilates to correct thermal relic density



$$\Omega_m \sim \frac{10^{-10}\ \text{GeV}^{-2}}{\langle \sigma_A v \rangle}$$

For supersymmetric DM,

$$\langle \sigma_A v \rangle \sim \frac{\alpha^2}{m_W^2} 0.1 \sim 10^{-9\pm1}\ \text{GeV}^{-2} \Rightarrow \Omega_\chi \sim 10^{-1\pm1}$$

Particle physics considerations alone guarantee an excellent cold dark matter candidate.

DM properties depend on several parameters.

The lightest neutralino is

$$\chi = a_{\tilde{B}}\tilde{B} + a_{\tilde{W}}\tilde{W}^0 + a_{\tilde{H}_u}\tilde{H}_u^0 + a_{\tilde{H}_d}\tilde{H}_d^0$$

Neutralino mass matrix:

$$\begin{pmatrix} M_1 & 0 & -m_Z c\beta s_W & m_Z s\beta s_W \\ 0 & M_2 & m_Z c\beta c_W & -m_Z s\beta c_W \\ -m_Z c\beta s_W & m_Z c\beta c_W & 0 & -\mu \\ m_Z s\beta s_W & -m_Z s\beta c_W & -\mu & 0 \end{pmatrix}$$

Without mixing, gaugino/Higgsino masses are

$$\begin{aligned} M_1 &: \quad \tilde{B} \\ M_2 &: \quad \tilde{W}^0 \\ |\mu| &: \quad \tilde{H}_u^0 \pm \tilde{H}_d^0 \end{aligned}$$

Lightest depends on relative ordering.

Interactions with matter rely on the full array of SUSY parameters:

- Gaugino masses: M_1, M_2, M_3
- Scalar masses: $\boldsymbol{m_Q^2, m_U^2, m_D^2, m_L^2, m_E^2}$
- SUSY Higgs mass: μ
- Ratio of Higgs vevs: $\tan\beta$

$\vdots$

Two approaches:

- Conduct model-independent scans.

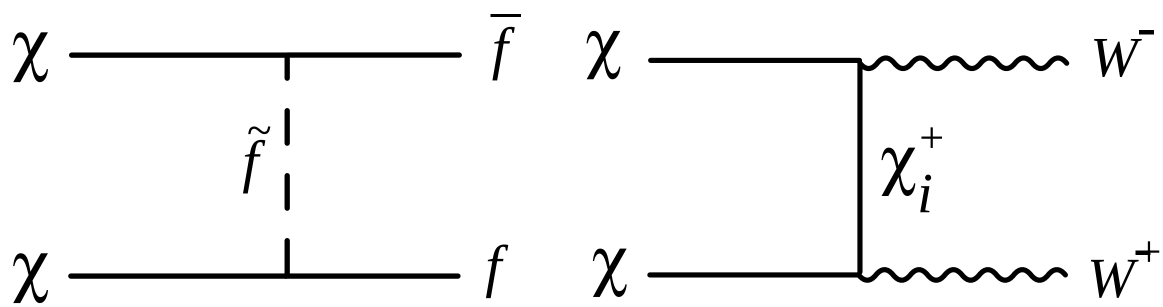
Jungman, Kamionkowski, Griest (1995)
Bergstrom, Ullio, Buckley (1997)
Baltz, Gondolo (2001)
$\vdots$

- Consider simple models.

Drees, Nojiri (1993)
Nath, Arnowitt (1994)
Baer, Brhlik (1996)
Bottino, Donato, Fornengo, Scopel (2000)
Battaglia, De Roeck, Ellis, Gianotti, Matchev, Olive, Pape, Wilson (2001)
$\vdots$

Relic density

Annihilation occurs through many channels:



If $\chi \approx \tilde{B}$, 2nd diagram vanishes. Then

Upper bound on $\Omega_\chi h^2$
$\Rightarrow$ Lower bound on annihilation rate
$\Rightarrow$ Upper bound on $m_{\tilde{f}}$

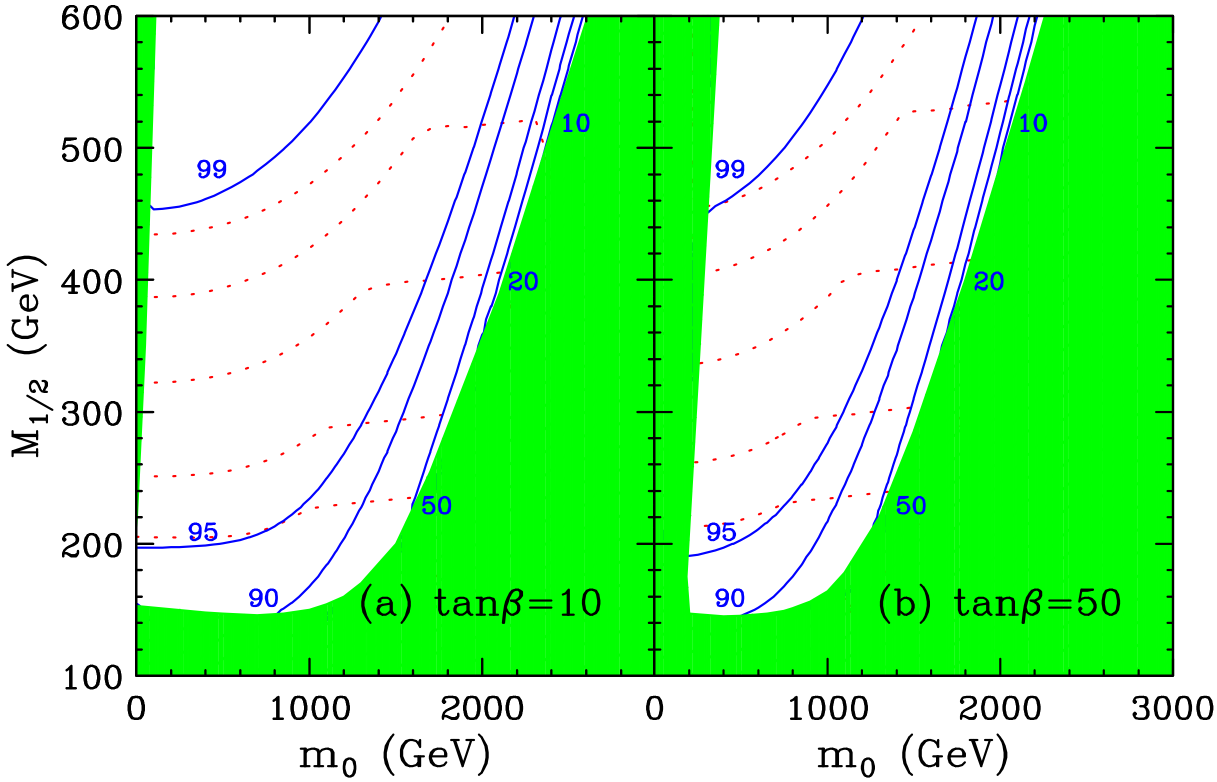
Neutralino LSP $\Rightarrow$ upper bound on gaugino masses also, and so cosmology $\Rightarrow$ upper bounds on all superpartners.

However, if χ has some Higgsino component, this argument fails.

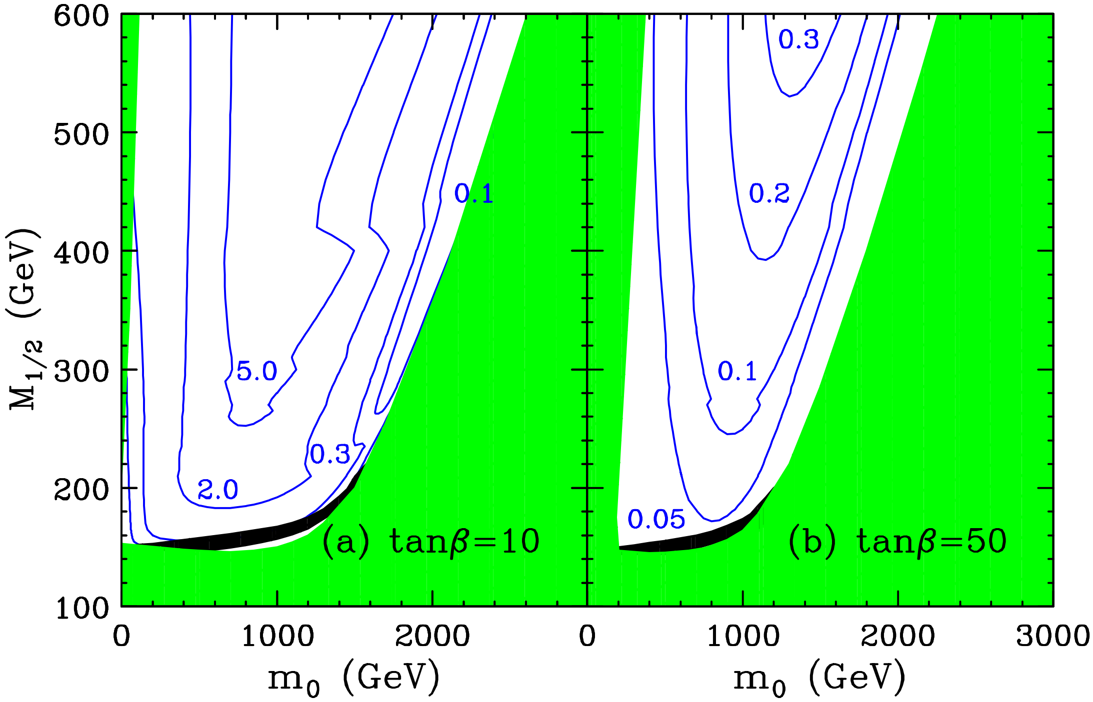
An illustration: mSUGRA

$$\frac{1}{2}m_Z^2 \;=\; -0.04\,m_0^2 + 8.8M_1^2 - |\mu|^2$$

Large $m_0 \Rightarrow |\mu| \sim M_1$, χ is a gaugino-Higgsino mixture.



Contours of gaugino-ness $R_\chi \equiv |a_{\tilde{B}}|^2 + |a_{\tilde{W}}|^2$ in percent.



Contours of $\Omega_\chi h^2$.

JF, Matchev, Wilczek (2000)

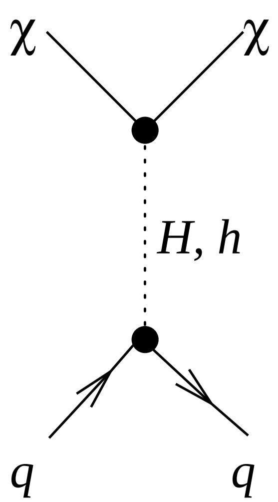
Note: Even $R_\chi \approx 90\%$ radically alters previous conclusions.

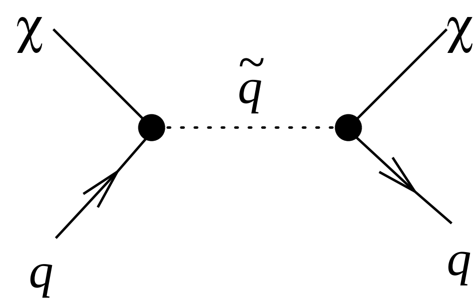
No stringent upper bounds from cosmology (especially for large $\tan\beta$).

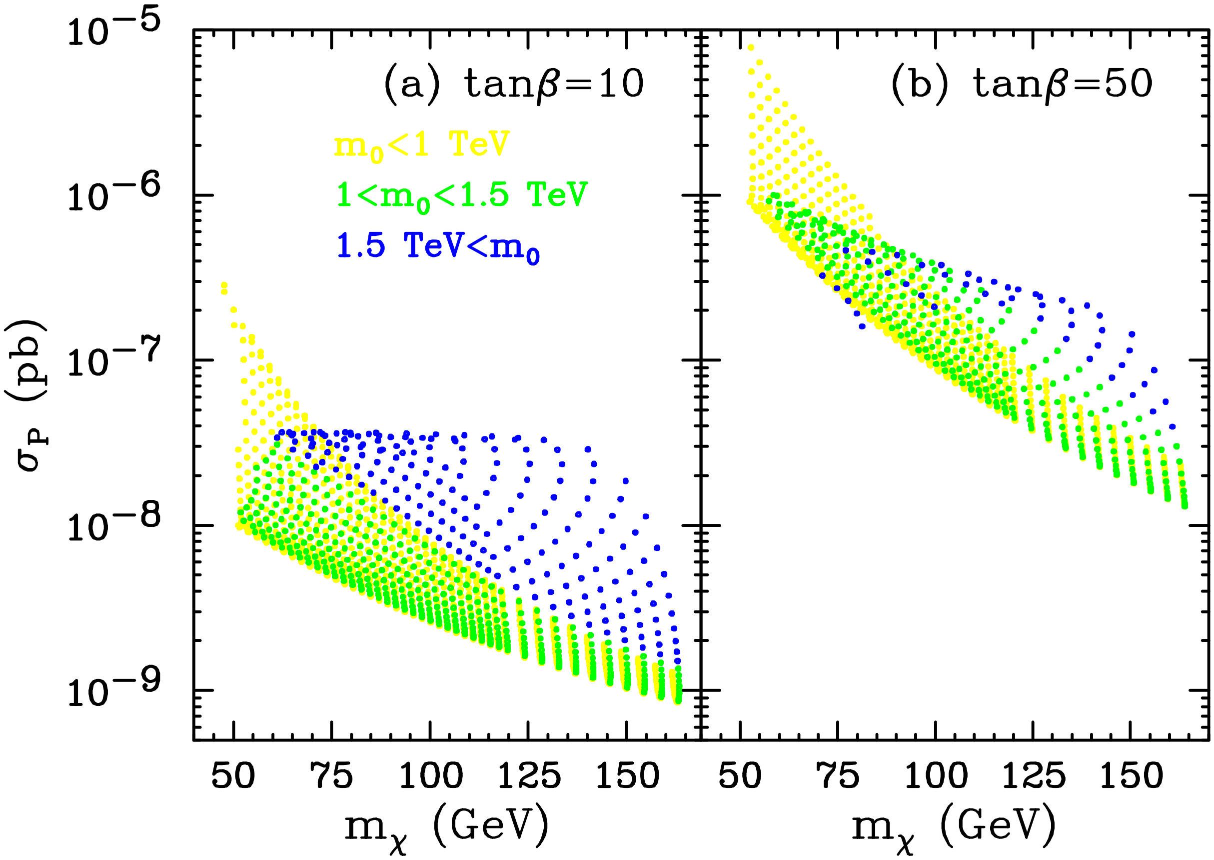
Direct detection

Searches for dark matter are often searches for SUSY.

• DM may be detected by looking for rare recoils from DM scattering off nucleons in detectors.







DAMA signal: 10^{-6} pb $\lesssim \sigma_P \lesssim 10^{-5}$ pb and 30 GeV $\lesssim m_\chi \lesssim$ 200 GeV (3σ CL).

For large $\tan\beta$, DAMA and CDMS are already approaching the necessary sensitivities. Experiments are very promising.

Indirect detection

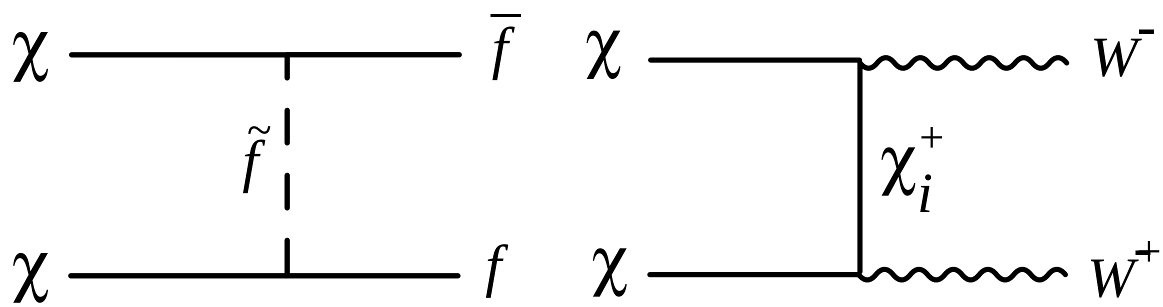
Indirect detection looks for DM annihilation products from the center of the Sun, Earth, galaxy.

For example: neutrinos from neutralino annihilation in the center of the Sun reach Earth's surface, convert to muons.

Possible signals in underground/underwater/under-ice experiments.

$$\left.\begin{array}{l}\sigma(\nu_\mu \to \mu) \sim E_\nu \\ \text{Muon range} \sim E_\nu\end{array}\right. \Rightarrow \text{Rate} \sim E_\nu^2$$

Requires energetic annihilation products.



For $\chi \approx \tilde{B}$, annihilation products are soft: for example,

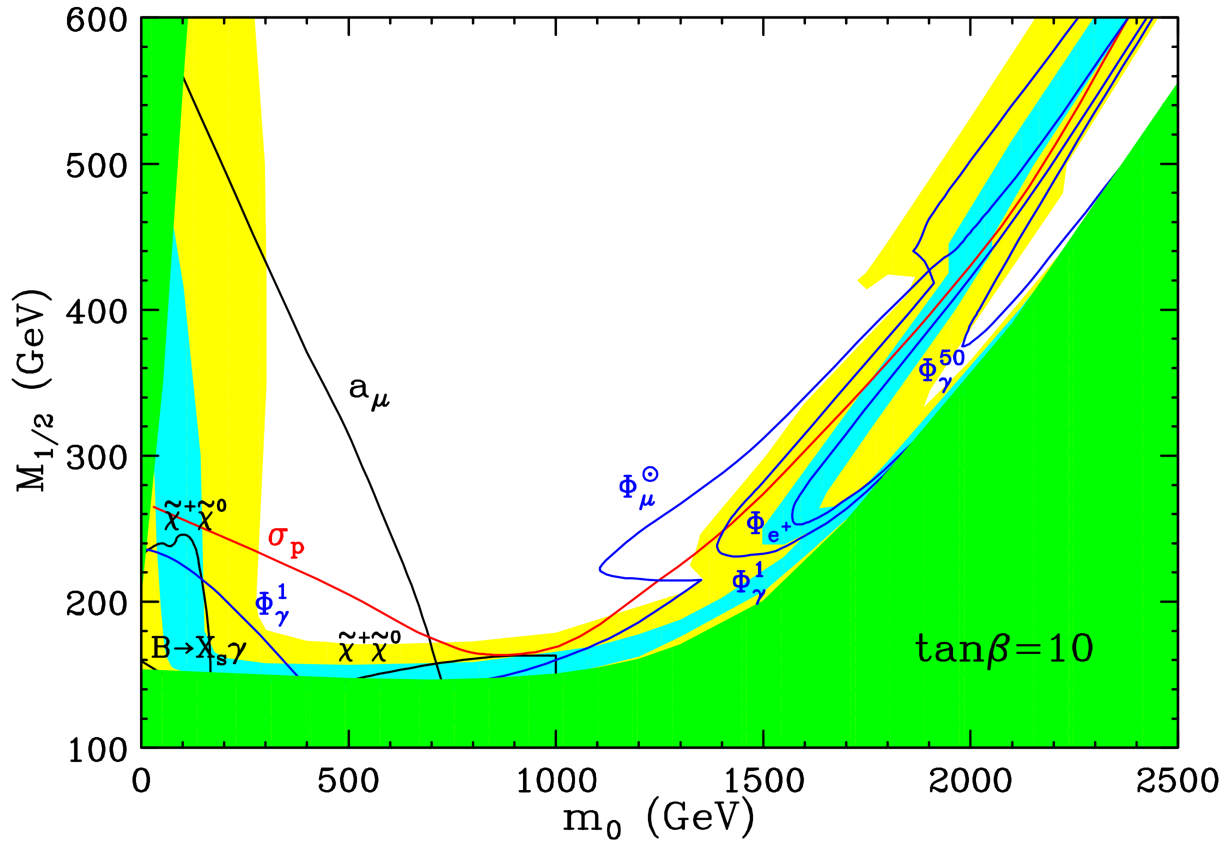
$$\tilde{B}\tilde{B} \to b\bar{b} \to ce\bar{\nu}\bar{c}e^{+}\nu$$

Hopelessly small rates for indirect detection.

However, for gaugino-Higgsino DM, $\chi\chi \to WW$ followed by $W \to \ell\nu$ is an excellent source of energetic neutrinos.

The Future

A compilation of all pre-LHC SUSY searches

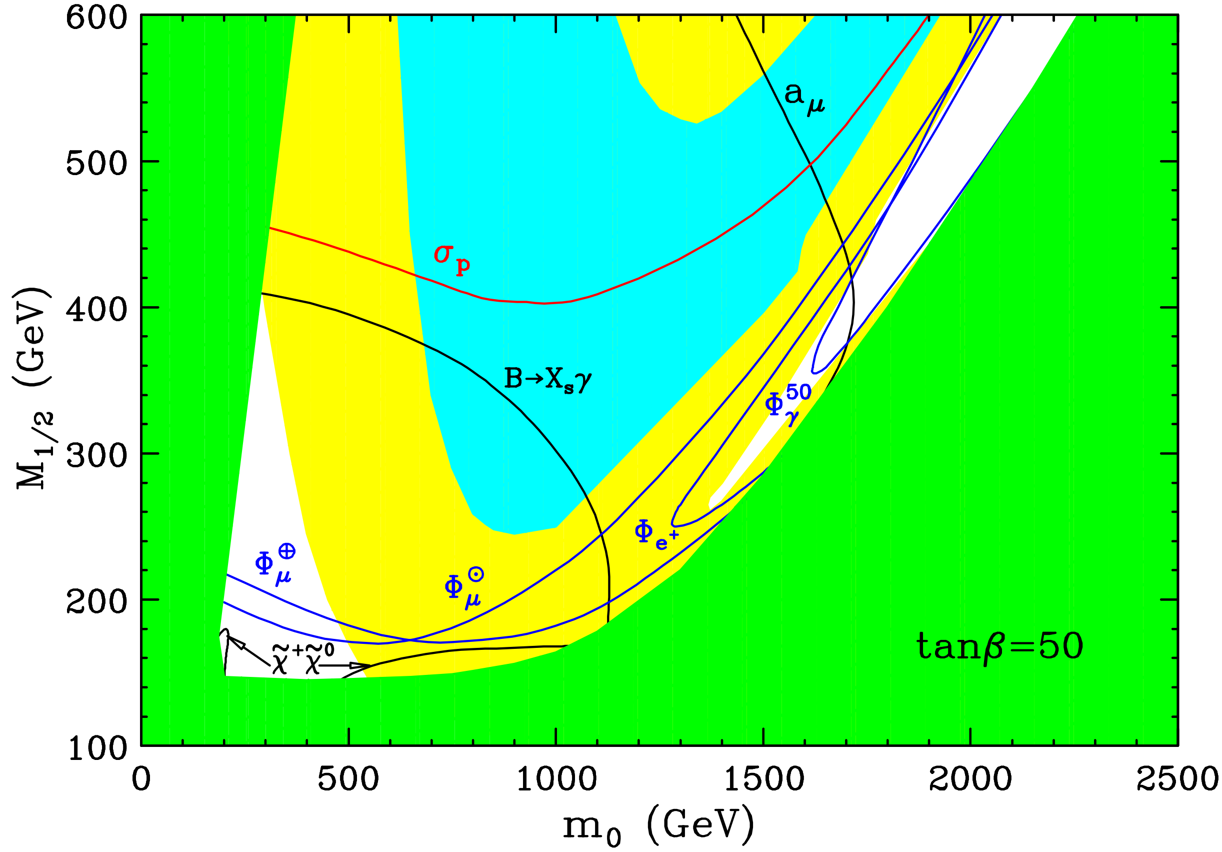


JF, Matchev, Wilczek (2000)

Dark matter searches are complementary to traditional collider and precision searches.

When combined, the entire cosmologically attractive parameter space will be explored before the LHC begins operation ($\sim$ 2006).

Large tan β:



Sensitivities assumed and experiments likely to reach these sensitivities before 2006.

Observable	Bound	Experiment(s)
$\tilde{\chi}^+\tilde{\chi}^-$	$m_{\tilde{\chi}}^{\pm} > 103$ GeV	LEP: ADLO
$\tilde{\chi}^{\pm}\tilde{\chi}^0$	See Ref.	Tevatron: CDF, D0
$B \to X_s\gamma$	$\lvert\Delta B(B \to X_s\gamma)\rvert < 1.2 \cdot 10^{-4}$	BaBar, BELLE
a_μ	$\lvert a_\mu^{\mathrm{SUSY}}\rvert < 8 \cdot 10^{-10}$	BNL E821
σ_{p}	See Ref.	CDMS, CRESST
ν from Sun	$\Phi_\mu^{\odot} < 100$ km^{-2} yr^{-1}	AMANDA
γ (gal. center)	$\Phi_\gamma^1 < 1.5 \cdot 10^{-10}$ cm^{-2} s^{-1}	GLAST
γ (gal. center)	$\Phi_\gamma^{50} < 7 \cdot 10^{-12}$ cm^{-2} s^{-1}	MAGIC
e^+ cosmic rays	Φ_{e^+}: $(S/B)_{\mathrm{max}} < 0.01$	AMS-02

CONCLUSIONS

• Weak-scale SUSY is an elegant mechanism for stabilizing the gauge hierarchy.

• Many models with a wide variety of implications.

• Nevertheless, SUSY looks unlikely to escape the LHC, and before that there are plenty of opportunities:

High energy colliders

High precision experiments

Dark matter searches