DARK MATTER IMPLICATIONS FOR LINEAR COLLIDERS

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MOTIVATIONS

- If superpartners can be produced,
  an LC is ideal

- What energy is required?
  Potential upper bounds on SUSY:
  Naturalness
  Dark matter

- Dark matter is the most phenomenological motivation for SUSY

K. Matchev and T. Moroi
Phys. Rev. Lett. 84 2322 (2000)
Phys. Rev. D 61 075005 (2000)

K. Matchev and F. Wilczek
Phys. Lett. B 482 388 (2000)
astro-ph/0008155

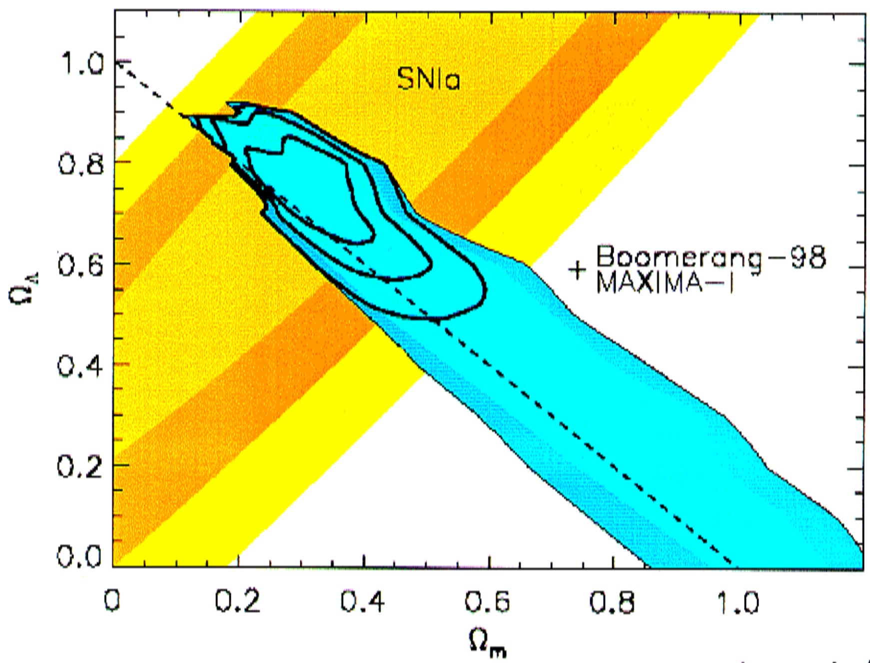
Modern evidence for DM:

- Clusters of galaxies $\Rightarrow 0.2 \lesssim \Omega_m \lesssim 0.4$

  Carlberg, Yee, Ellingson (1997)

- SN Ia luminosities

- CMB anisotropy



astro-ph/0007333

We are entering the era of precision Ω_m:

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

SUSY DARK MATTER

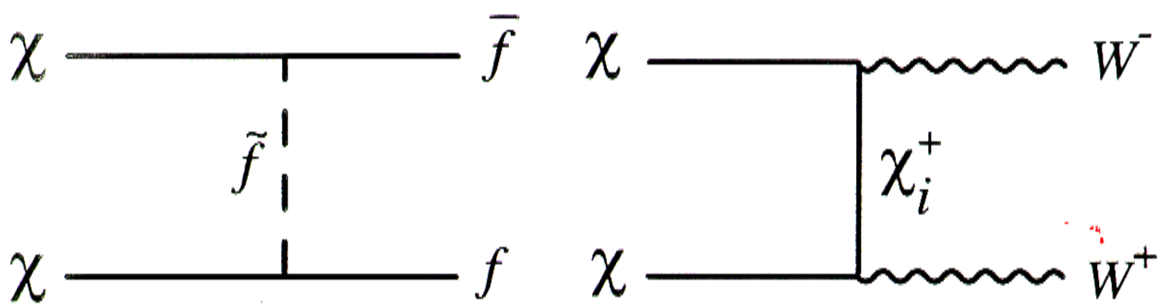
Goldberg (1983)
Ellis et al. (1983)

- Stable LSP assured by R-parity conservation

- Neutral, non-baryonic LSP is generic:

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

- Annihilation is through superpartner exchange



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

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

Arnowitt, Nath et al.
Ellis, Falk, Olive, et al.
Bottino et al.
Baer, Brhlik

Kane, Kolda, Roszkowski, Wells
⋮

DM properties rely on the full array of SUSY parameters:

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

$\vdots$

Many studies perform a random scan.

However, if supersymmetry exists, there are many additional considerations:

- Flavor problem
- CP problem
- Proton decay

$\vdots$

A Simple Example (mSUGRA)

At GUT scale, choose

- Universal scalar mass: m_0
- Universal gaugino mass: $M_{1/2}$
- Universal tri-linear coupling: A_0
- Ratio of Higgs vevs: $\tan\beta$
- Sign of supersymmetric Higgs mass: sign(μ)

All weak scale parameters determined by RGEs.

$|\mu|$ determined by EWSB.

Flavor problem solved by fiat (scalar degeneracy).

But (seemingly) all other problems remain.

Electroweak Symmetry Breaking

The Higgs potential is entirely specified by SUSY parameters, gauge couplings.

$$
\begin{aligned}
\frac{1}{2} m_Z^2 &= \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - |\mu|^2 \\
&\approx -m_{H_u}^2 - |\mu|^2 \\
&= -0.02\, m_0^2 + 0.7 M_{1/2}^2 - |\mu|^2
\end{aligned}
$$

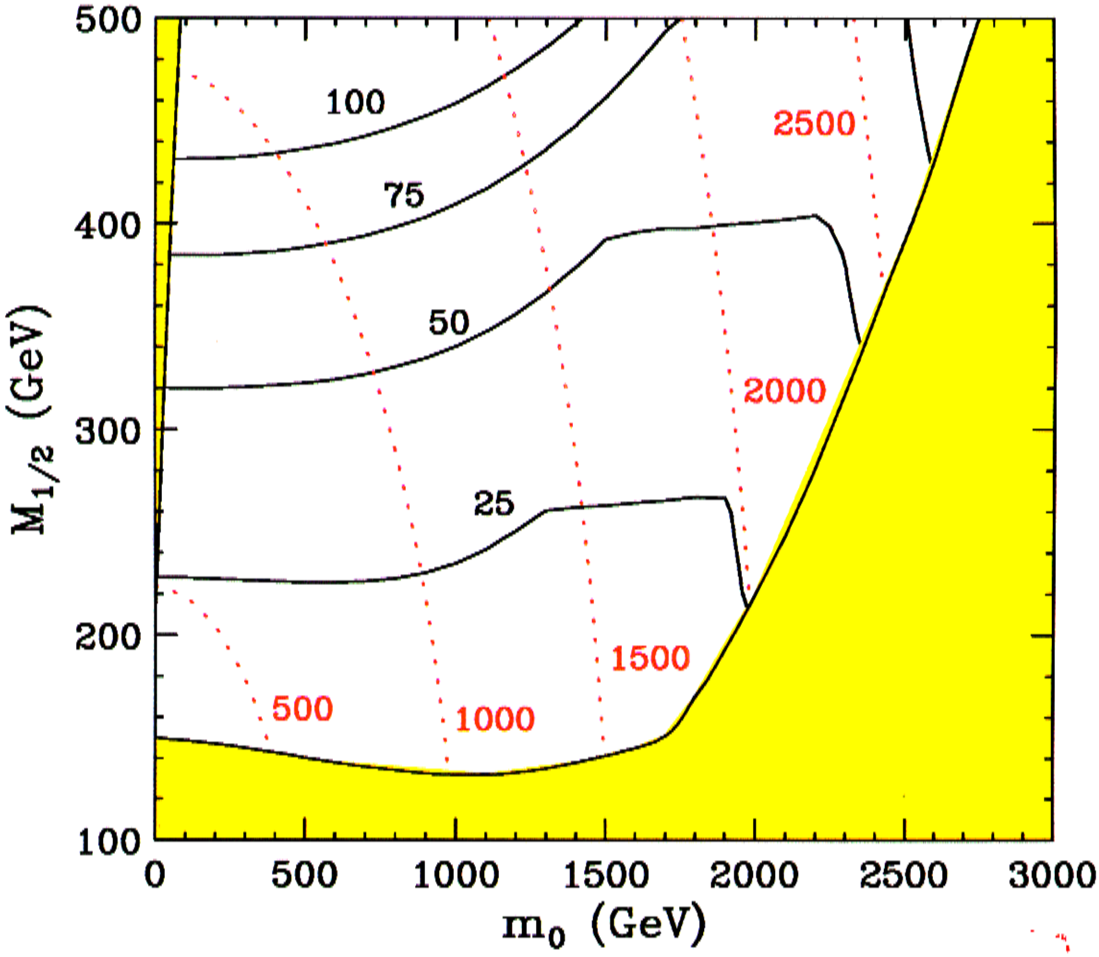
Alvarez-Gaume, Polchinski, Wise (1983)
Barbieri, Giudice (1988)

For $m_0 \sim$ few TeV, no large cancellations:

Large m_0 is natural

JF, Matchev, Moroi (1999)

Fine-tuning



JF, Matchev, Moroi (1999)

Black: contours of fine-tuning

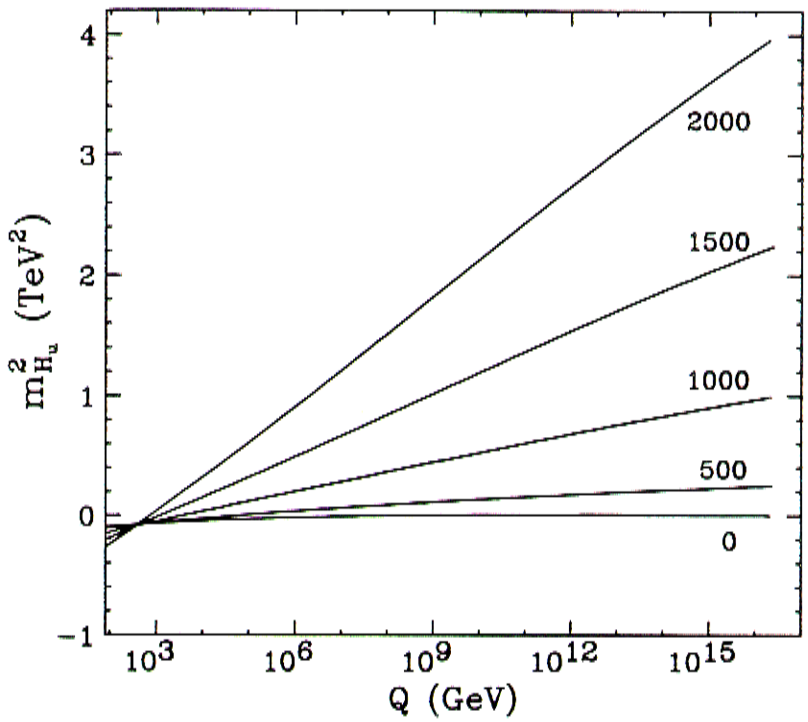
Red: contours of squark masses

Yellow: Excluded (charged LSP in upper left, LEP chargino bounds in bottom and right)

Focus Point SUSY

JF, Matchev, Moroi (1999)

This may be understood from RGEs:



$M_{1/2} = 200$ GeV, $A_0 = 0$, $\tan\beta = 10$, $m_t = 174$ GeV, and several values of m_0 (shown, in GeV).

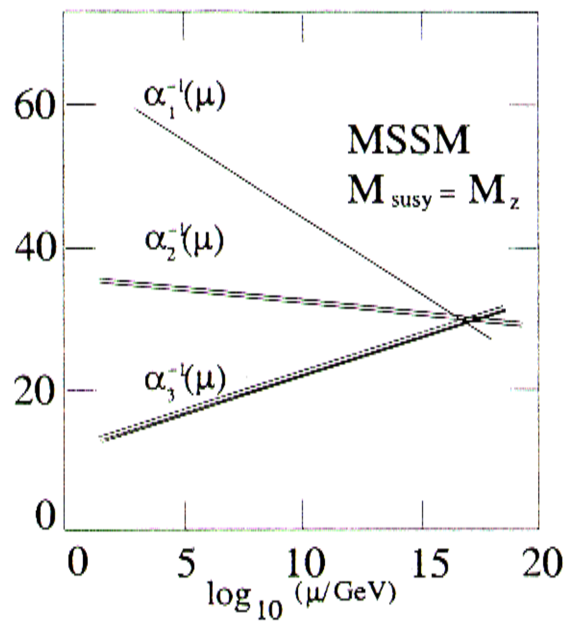
The focus scale is determined by the top Yukawa. Remarkably,

$$\left.\begin{array}{l}\text{Any } \tan\beta \gtrsim 5 \\ m_t \approx 174 \text{ GeV}\end{array}\right\} \Rightarrow Q_{FP} \sim m_W$$

Requires only $m^2_{H_u} \approx \frac{1}{2}(m^2_{Q_3} + m^2_{U_3})$.

Analogy

Consider a rather well-known focus point:



Gauge coupling unification

- No free parameters
- Requires α_i as measured at % level
- May be coincidence, but supported by multiplet unification

Focus Point SUSY

- No free parameters
- Requires m_t as measured at % level
- May be coincidence, but supported by SUSY flavor problem, CP problem, etc.

Implications

- Preferred: $m_0 \gtrsim 1$ TeV, not $m_0 \lesssim 1$ TeV.

- Naturally explains EDMs, τ_{proton}, etc.

- All scalars may be a challenge for colliders.

- All charginos, neutralinos are still within LC reach.

$\vdots$

... On to dark matter!

COMMON LORE

Recall

$$\frac{1}{2}m_Z^2 = -0.02\, m_0^2 + 0.7 M_{1/2}^2 - |\mu|^2$$
$$= -0.02\, m_0^2 + 4.4 M_1^2 - |\mu|^2$$

The conventional wisdom:

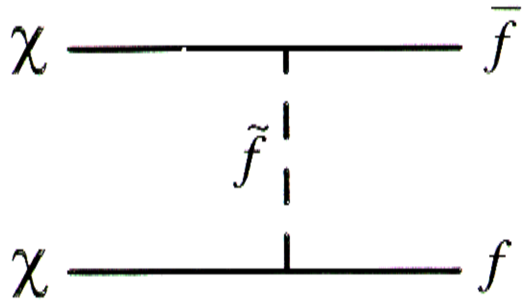
$$\text{naturalness} \Rightarrow m_0, M_{1/2}, |\mu| \lesssim \text{ TeV}$$

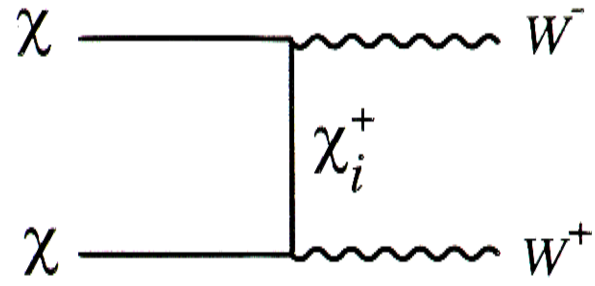
Then

- $|\mu|$ is much larger than M_1, and

$$\text{DM is Bino-like} : \chi \approx \tilde{B}$$

- Annihilation occurs through $\tilde{f}$ exchange only.



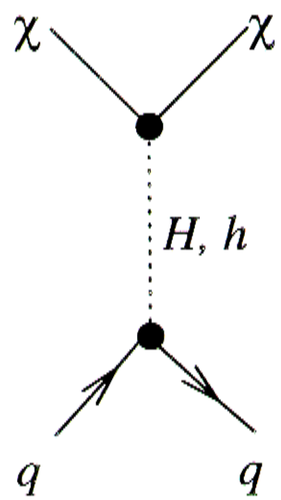


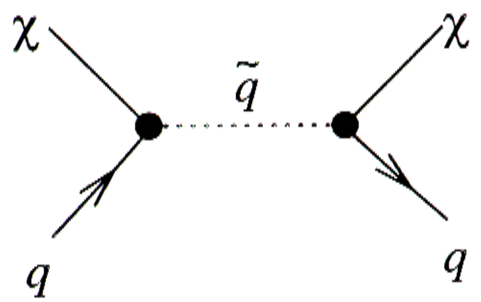
$\Omega_\chi h^2 \lesssim 0.3 \Rightarrow m_{\tilde{f}} \lesssim 200$ GeV.

Neutralino LSP $\Rightarrow m_\chi \lesssim 200$ GeV, all super-partners must be light.

Cosmology $\Rightarrow$ upper bounds.

- Direct detection relies on $q\tilde{B} \to \tilde{q} \to q\tilde{B}$ only.





Large $m_0 \Rightarrow$ low detection rates.

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

But $\tilde{B}$ annihilation products are soft: for example,

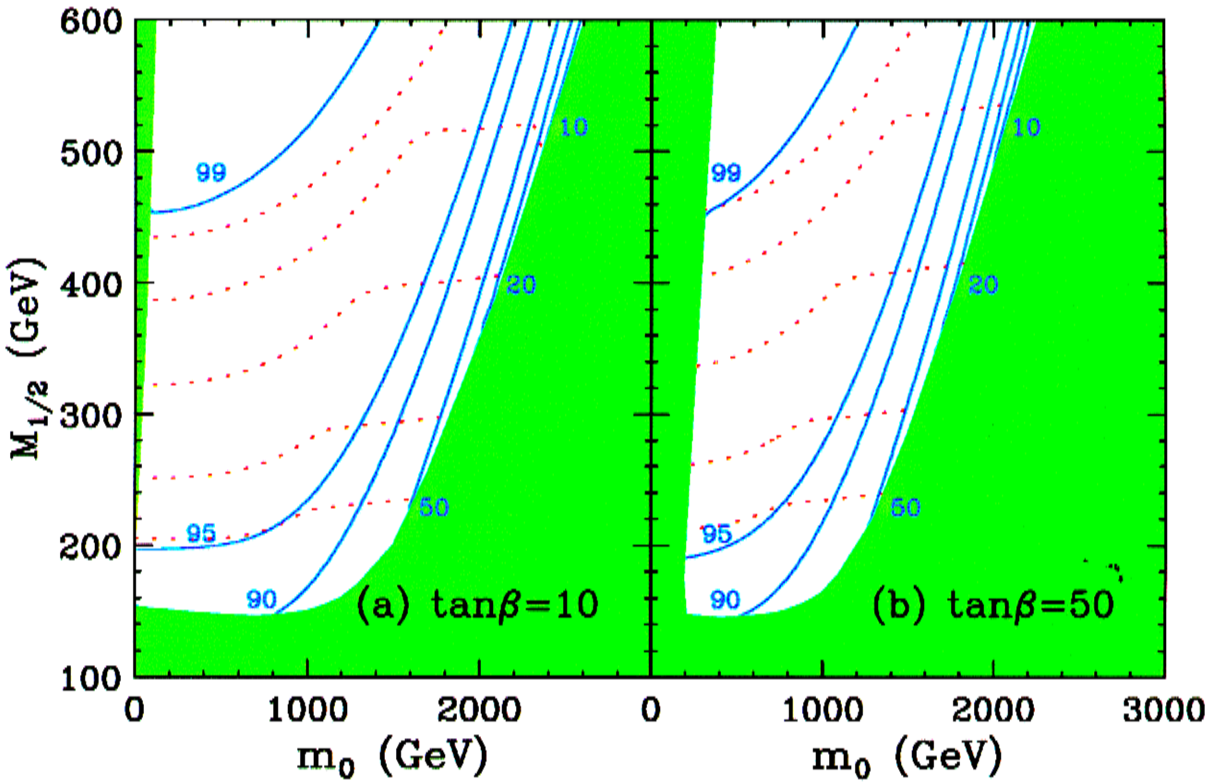
$$\tilde{B}\tilde{B} \to b\bar{b} \to ce\bar{\nu}\bar{c}e^{+}\nu$$

Rates for all experiments are hopelessly small.

THE TRUTH

$$\frac{1}{2}m_Z^2 = -0.02\, m_0^2 + 4.4 M_1^2 - |\mu|^2$$

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

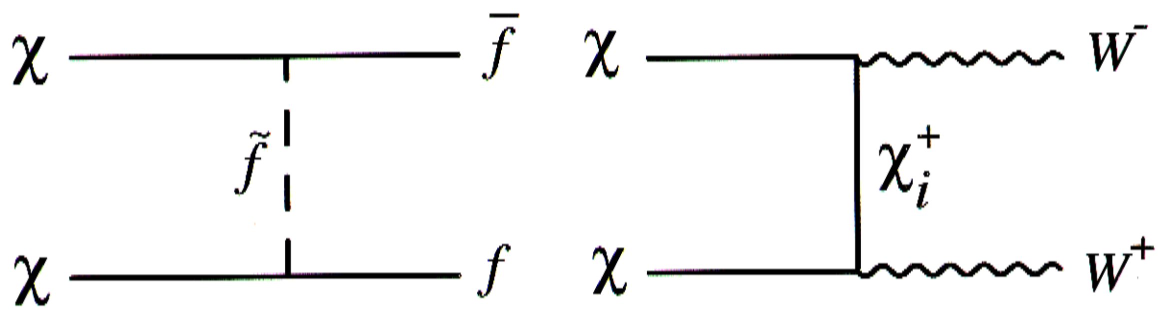


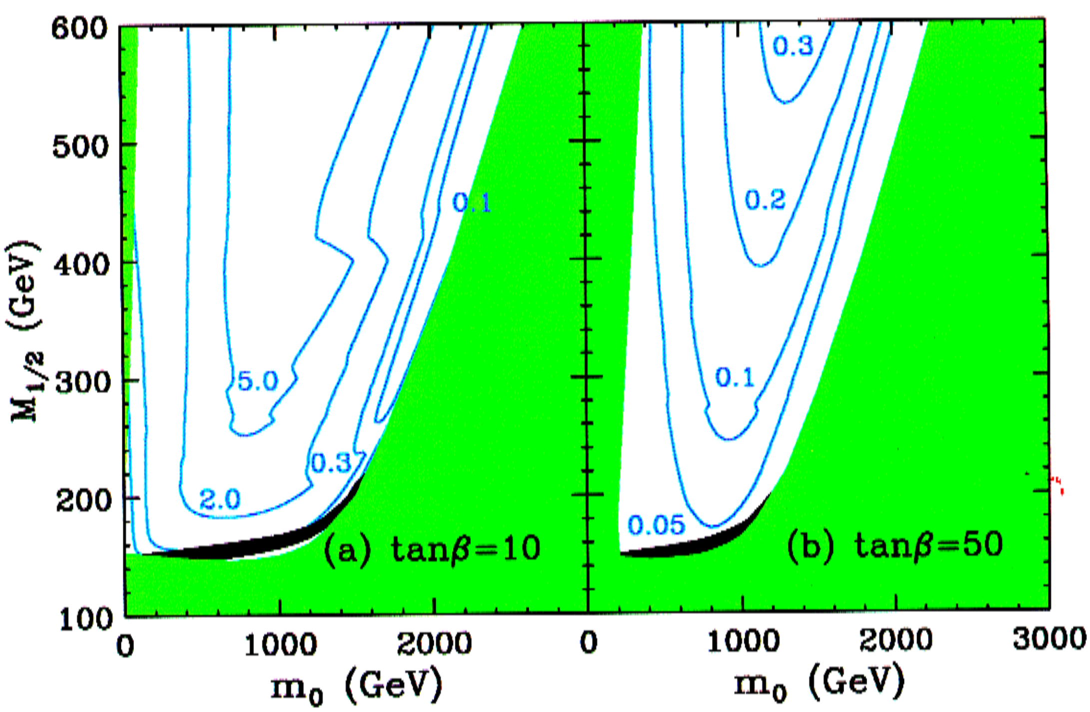
Contours of gaugino-ness $R_\chi \equiv |a_{\tilde{B}}|^2 + |a_{\tilde{W}}|^2$ in percent.

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

Relic density

Annihilation occurs through χ_i^+ also



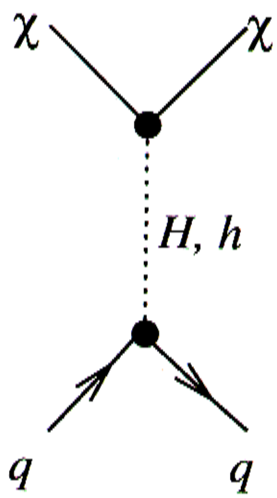


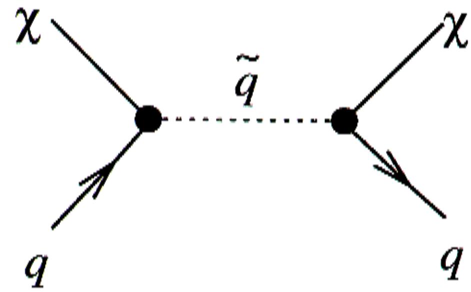
Contours of $\Omega_\chi h^2$.

JF, Matchev, Wilczek (2000)

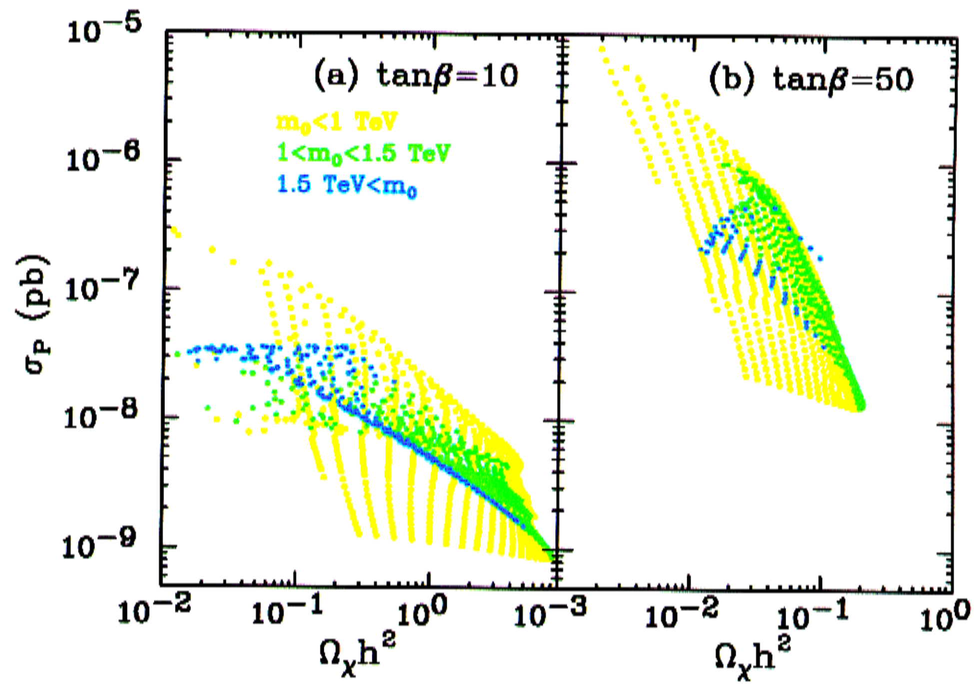
No stringent upper bounds from cosmology.

Direct Detection





For gaugino-Higgsino DM, Higgs diagram also contributes. Detection rates may be large, even for large m_0.



JF, Matchev, Wilczek (2000)

Indirect Detection: Neutrinos

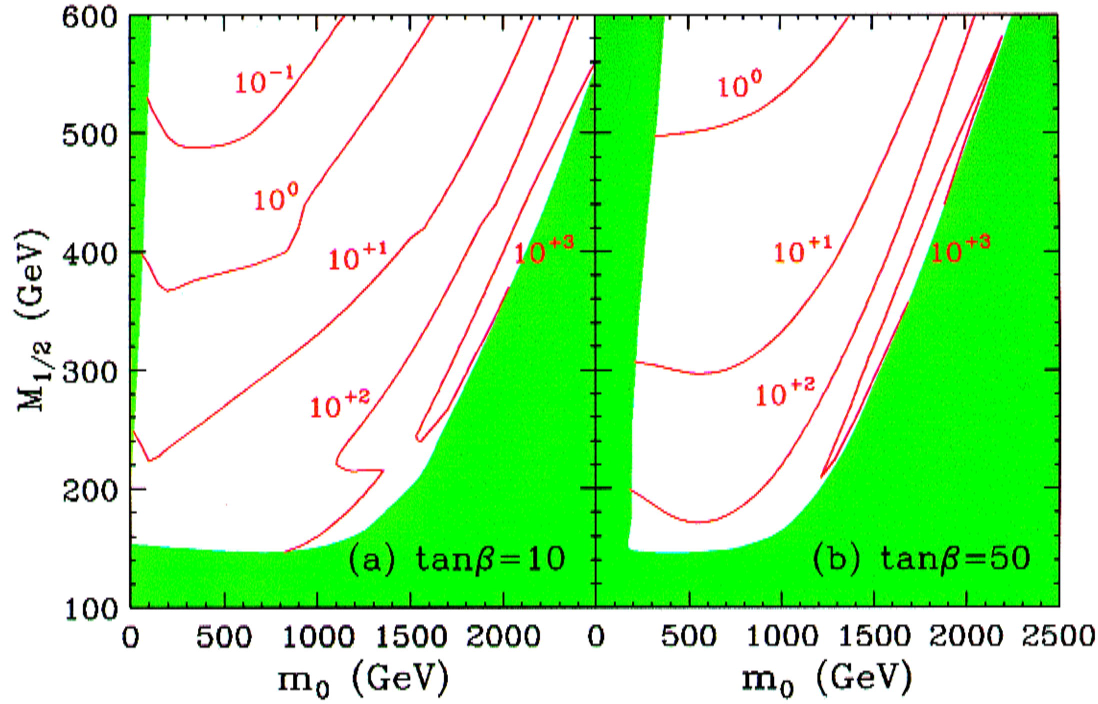
Neutralinos accumulate at the center of the Earth/Sun.

Neutrinos from annihilation may reach Earth's surface, convert to muons.

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

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

$\chi\chi \to WW$ followed by $W \to \ell\nu$ is the best source of energetic neutrinos. This requires gaugino-Higgsino DM.



Muon flux from χ annihilation in the Sun in km^{-2} yr^{-1}.

JF, Matchev, Wilczek (2000)

TABLE I. Current and planned neutrino experiments. We list also each experiment's (expected) start date, physical dimensions (or approximate effective area), muon threshold energy $E_\mu^{\rm thr}$ in GeV, and 90% CL flux limits for the Earth $\Phi_\mu^{\oplus}$ and Sun $\Phi_\mu^{\odot}$ in km^{-2} yr^{-1} for half-cone angle $\theta \approx 15^\circ$ when available.

Experiment	Type	Date	Dimensions	$E_\mu^{\rm thr}$	$\Phi_\mu^{\oplus}$	$\Phi_\mu^{\odot}$
Baksan [64]	Underground	1978	$17 \times 17 \times 11$ m^3	1	6.6×10^3	7.6×10^3
Kamiokande [65]	Underground	1983	~ 150 m^2	3	10×10^3	17×10^3
MACRO [66]	Underground	1989	$12 \times 77 \times 9$ m^3	1.5*	3.2×10^3	6.5×10^3
Super-Kamiokande [67]	Underground	1996	~ 1200 m^2	1.6	1.9×10^3	5.0×10^3
Baikal NT-96 [68]	Underwater	1996	~ 1000 m^2	10	15×10^3	
AMANDA B-10 [69]	Under-ice	1997	~ 1000 m^2 †	~ 25	44×10^3 †	
Baikal NT-200 [68]	Underwater	1998	~ 2000 m^2	~ 10		
AMANDA II [70]	Under-ice	2000	$\sim 3 \times 10^4$ m^2	~ 50		
NESTOR§ [71]	Underwater	2000	$\sim 10^4$ m^2 ‡	few		
ANTARES [72]	Underwater	2003	$\sim 2 \times 10^4$ m^2 ‡	$\sim$ 5–10		
IceCube [70]	Under-ice	2003-8	$\sim 10^6$ m^2			

* 2 GeV for Sun. † Hard spectrum, $m_\chi = 100$ GeV. § One tower. ‡ $E_\mu \sim 100$ GeV.

Indirect Detection: γ, e^+

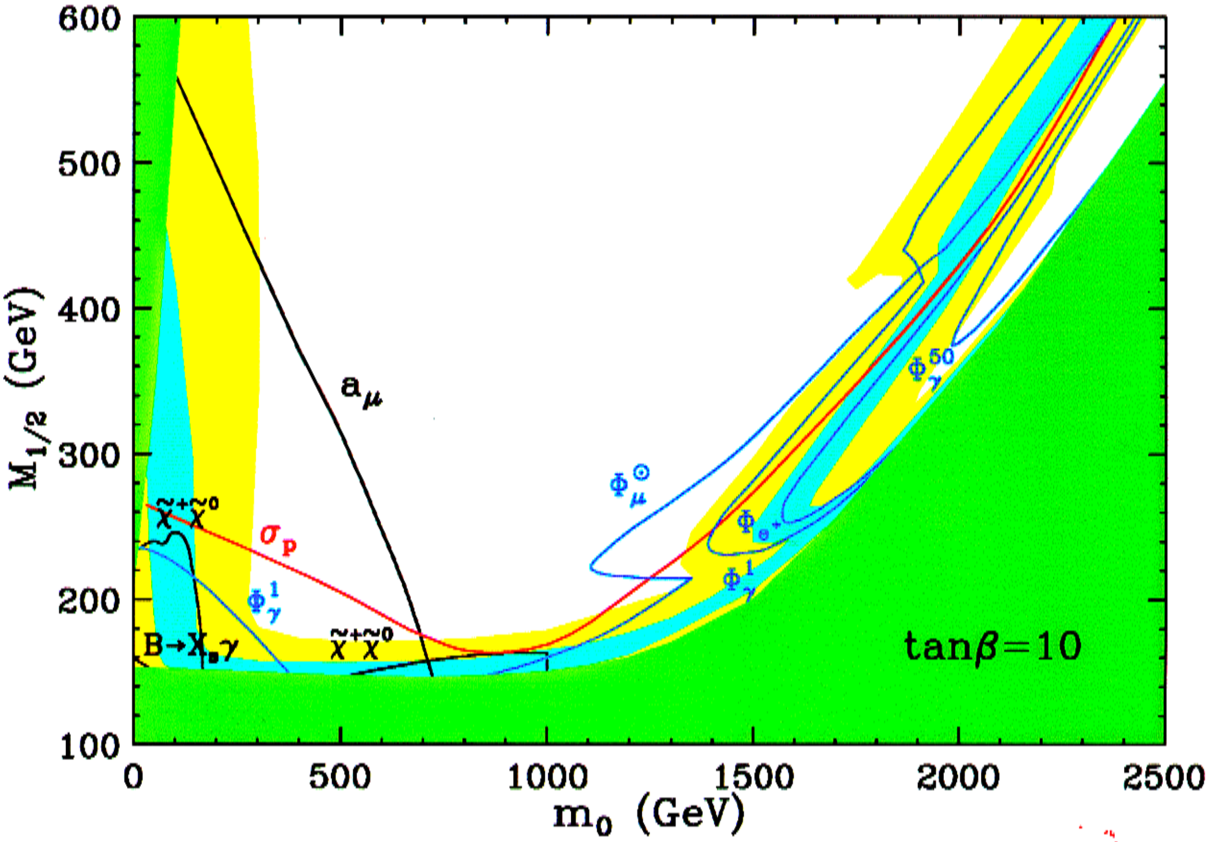
Gaugino-Higgsino mixture also enhances

- Photons from galactic center
  (Large uncertainties from halo profile)
  MAGIC, HESS, CANGAROO,
  VERITAS, GLAST, . . .

- Positrons in upper atmosphere, space
  PAMELA, AMS

Comparison

Compilation of all pre-LHC experiments



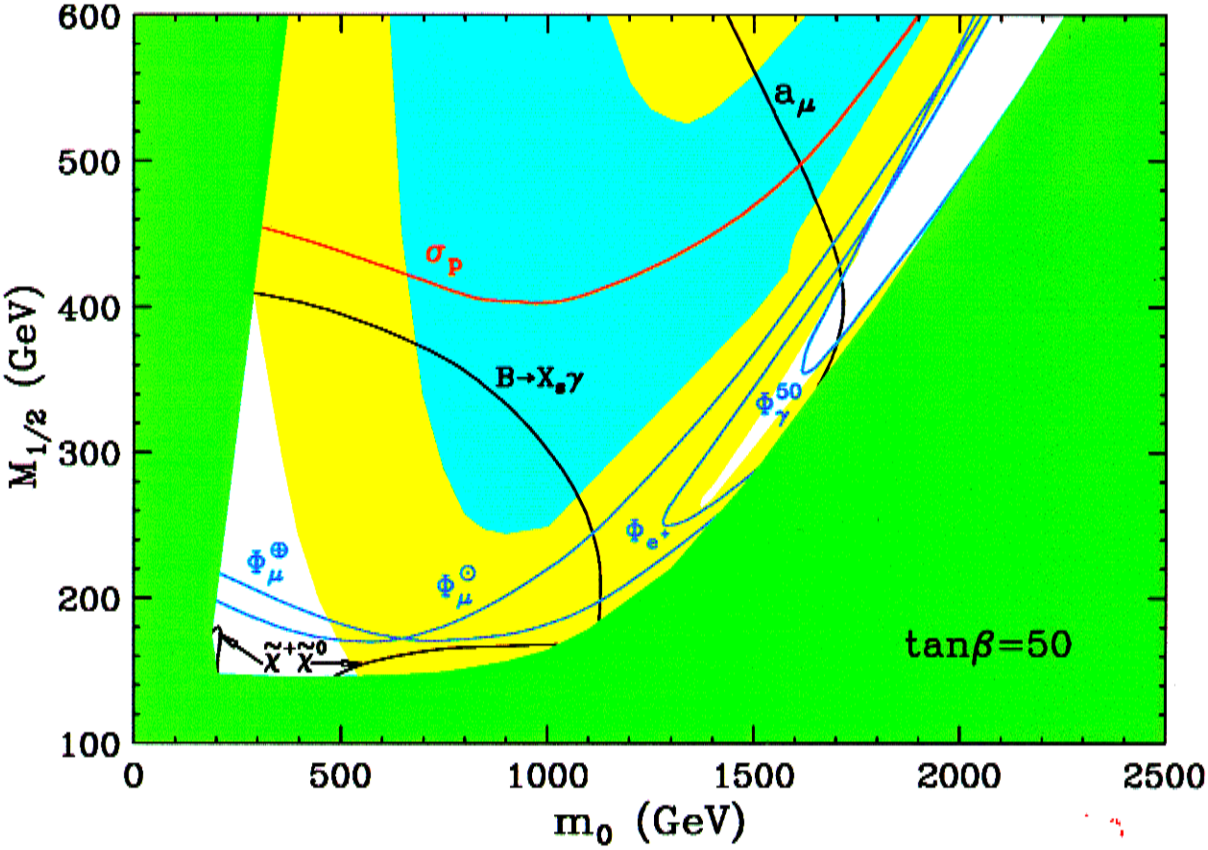
JF, Matchev, Wilczek (2000)

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

The entire cosmologically attractive parameter space within reach of a 500 GeV LC will be probed before the LHC.

TABLE IV. Constraints on supersymmetric models used in Figs. 18 and 19. We also list experiments likely to reach these sensitivities before 2006.

Observable	Type	Bound	Experiment(s)
$\tilde{\chi}^+\tilde{\chi}^-$	Collider	$m_{\tilde{\chi}}^{\pm} > 100$ GeV	LEP: ALEPH, DELPHI, L3, OPAL
$\tilde{\chi}^\pm\tilde{\chi}^0$	Collider	See Refs. [118,121,123]	Tevatron: CDF, D0
$B \to X_s\gamma$	Low energy	$\lvert\Delta B(B \to X_s\gamma)\rvert < 1.2 \times 10^{-4}$	BaBar, BELLE
Muon MDM	Low energy	$\lvert a_\mu^{\mathrm{SUSY}}\rvert < 8 \times 10^{-10}$	Brookhaven E821
σ_{proton}	Direct DM	Equation (19)	CDMS, CRESST, GENIUS
ν from Earth	Indirect DM	$\Phi_\mu^{\oplus} < 100$ km^{-2} yr^{-1}	AMANDA, NESTOR, ANTARES
ν from Sun	Indirect DM	$\Phi_\mu^{\odot} < 100$ km^{-2} yr^{-1}	AMANDA, NESTOR, ANTARES
γ (gal. center)	Indirect DM	$\Phi_\gamma(1) < 1.5 \times 10^{-10}$ cm^{-2} s^{-1}	GLAST
γ (gal. center)	Indirect DM	$\Phi_\gamma(50) < 3 \times 10^{-12}$ cm^{-2} s^{-1}	HESS, CANGAROO III
e^+ cosmic rays	Indirect DM	$(S/B)_{\mathrm{max}} < 0.01$	AMS-02



JF, Matchev, Wilczek (2000)

CONCLUSIONS

- Cosmology provides no useful bounds on sparticle masses

- In simple scenarios, focusing and low energy constraints $\Rightarrow$ we should consider $m_0 \gtrsim 1$ TeV

- Ongoing dark matter searches are promising, highly complementary to other supersymmetry searches

- In mSUGRA,
SUSY at 500 GeV LC $\Rightarrow$ SUSY *before* LHC

- Beyond mSUGRA? Quite robust — work in progress