SUSY AND COSMOLOGY

Jonathan Feng
UC Irvine

SLAC Summer Institute
5-6 August 2003

Target Audience

From the organizers:

“ graduate students, junior postdocs… ”

“ ¾ experimentalists, ¼ theorists… ”

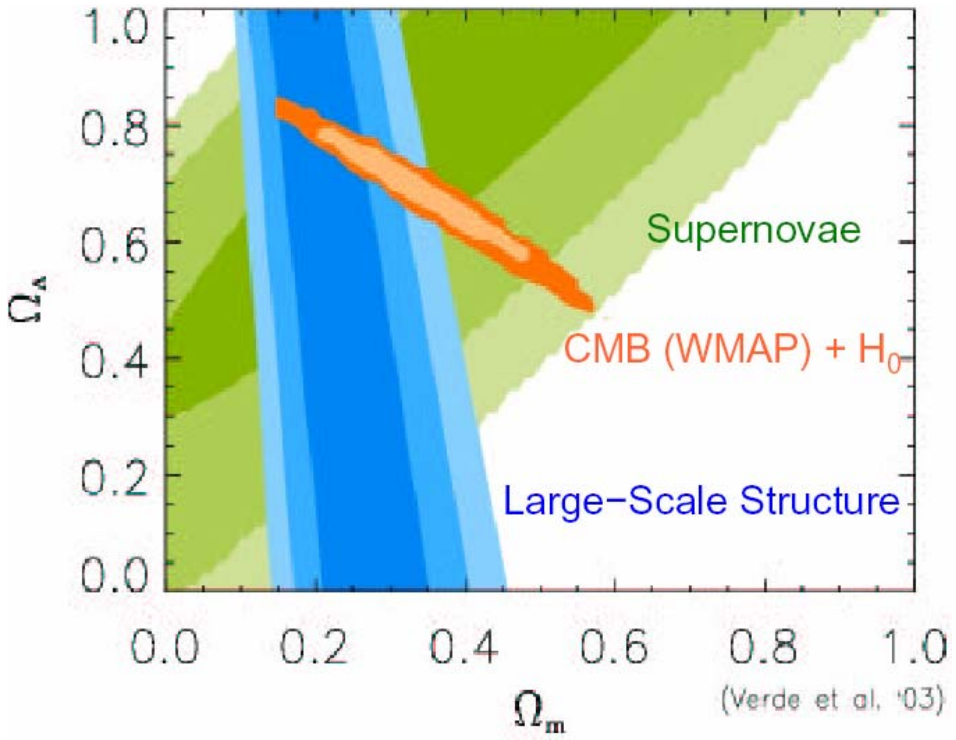
“ Students enjoy the lively discussion sections. ”

(What about the lecturers? Ominous!)

Why Cosmology?

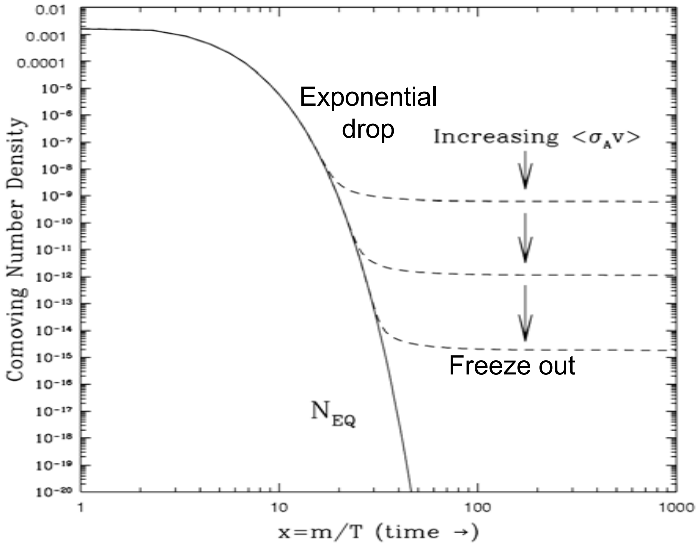
- "The standard model successfully explains all observed phenomena of fundamental particles to date."

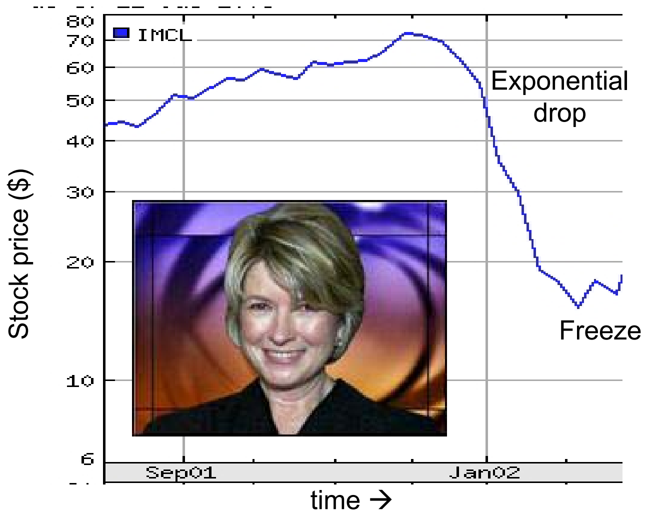
- No! The standard model is a great triumph, but it also fails at the most basic level.



- At present, cosmology and astroparticle physics provide the best evidence for new particle physics.

Why SUSY?
Cosmology and the Weak Scale





- Universe cools, leaves a residue of dark matter with $\Omega_{DM} \sim 0.1\ (\sigma_{Weak}/\sigma)$

- 13 Gyr later, Martha Stewart sells ImClone stock – the next day, stock plummets

Coincidence? Maybe, but worth investigating!

The Plan

LECTURE 1

SUSY Essentials

Neutralino Cosmology
    Relic Density
    Detection

LECTURE 2

Gravitino Cosmology
    Relic Density
    Detection

Particle/Cosmo Synergy

SUSY Essentials

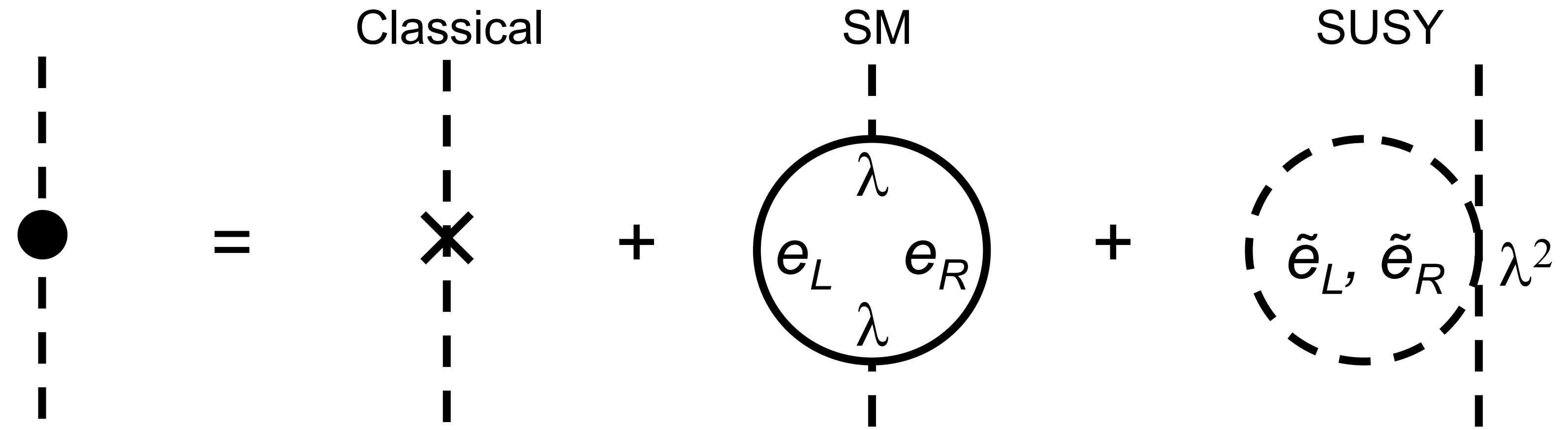
- Supersymmetry: a new spacetime symmetry

$$\{ P_\mu, L_i, K_i \} \rightarrow \{ P_\mu, L_i, K_i, Q_\alpha \}$$

- Q_α: bosons ↔ fermions. Each known particle requires a (new) superpartner.

- What does this have to do with the weak scale?
  The gauge hierarchy problem:
  Why is $m_h \sim 100$ GeV $\ll M_{\mathrm{Pl}} \sim 10^{19}$ GeV?

SUSY and the Gauge Hierarchy



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

$\tilde{e}_L$, $\tilde{e}_R$ soften divergence, remove unnaturalness

Requirements: $\lambda_{\tilde{e}} = \lambda_e$, $m_{\tilde{e}} \sim m_h$

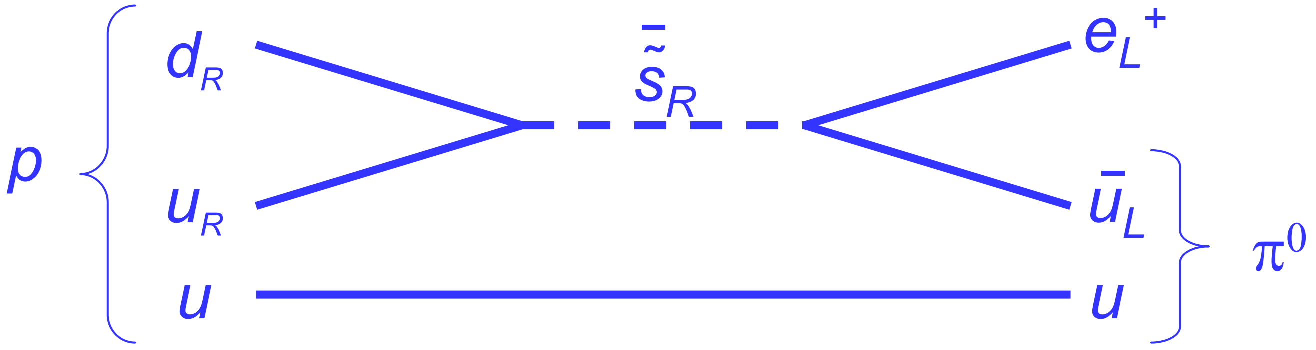
Neutral SUSY Spectrum

Spin	U(1) M_1	SU(2) M_2	Up-type μ	Down-type μ	$m_{\tilde{\nu}}$	$m_{3/2}$
2						G graviton
3/2						$\tilde{G}$ gravitino
1	B	W^0				
1/2	Bino			ggsino	ν	
0			H_u	H_d	$\tilde{\nu}$ sneutrino	

Neutralinos: $\{\chi \equiv \chi_1, \chi_2, \chi_3, \chi_4\}$

R-parity and Stable LSPs

- One slight problem: proton decay



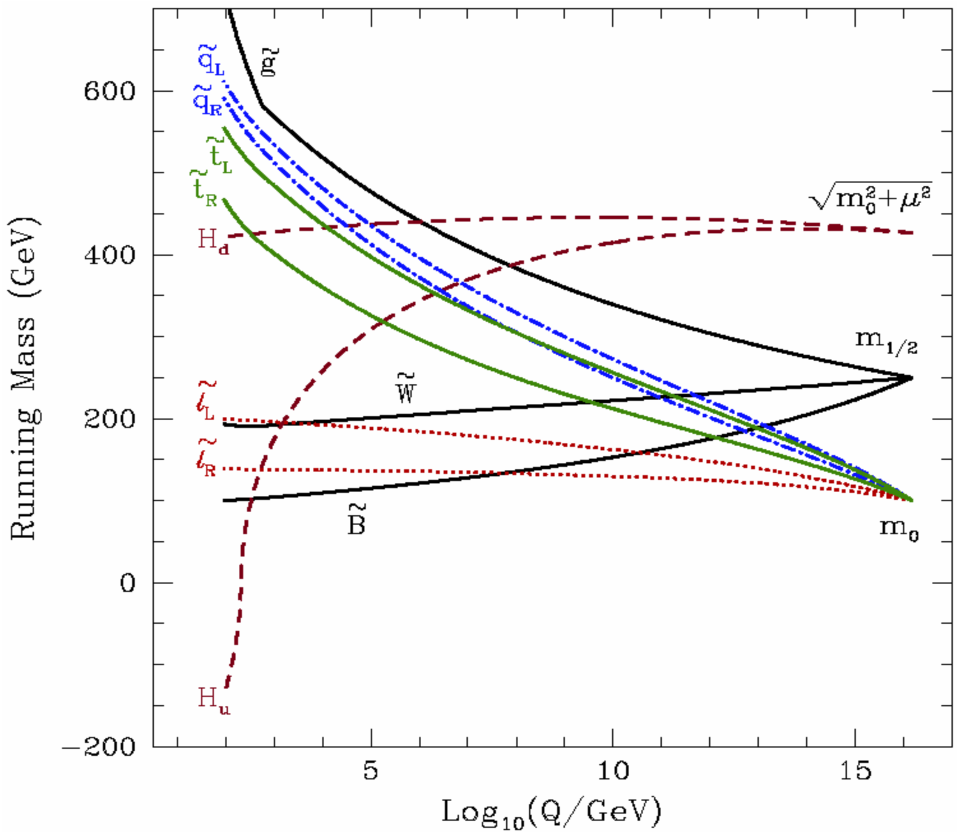
- Forbid this with R-parity conservation: $R_p = (-1)^{3(B-L)+2S}$
  - SM particles have $R_p = 1$, SUSY particles have $R_p = -1$
  - Require $\Pi\, R_p = 1$ at all vertices
- Consequence: the lightest SUSY particle (LSP) is stable!

Models

- We expect the weak-scale theory to be derived from a high-energy fundamental theory by RGEs.

- Gauge couplings increase masses;

  Yukawa couplings decrease masses



Olive (2003)

End result: “typical” LSPs: χ , $\tilde{\tau}_R$

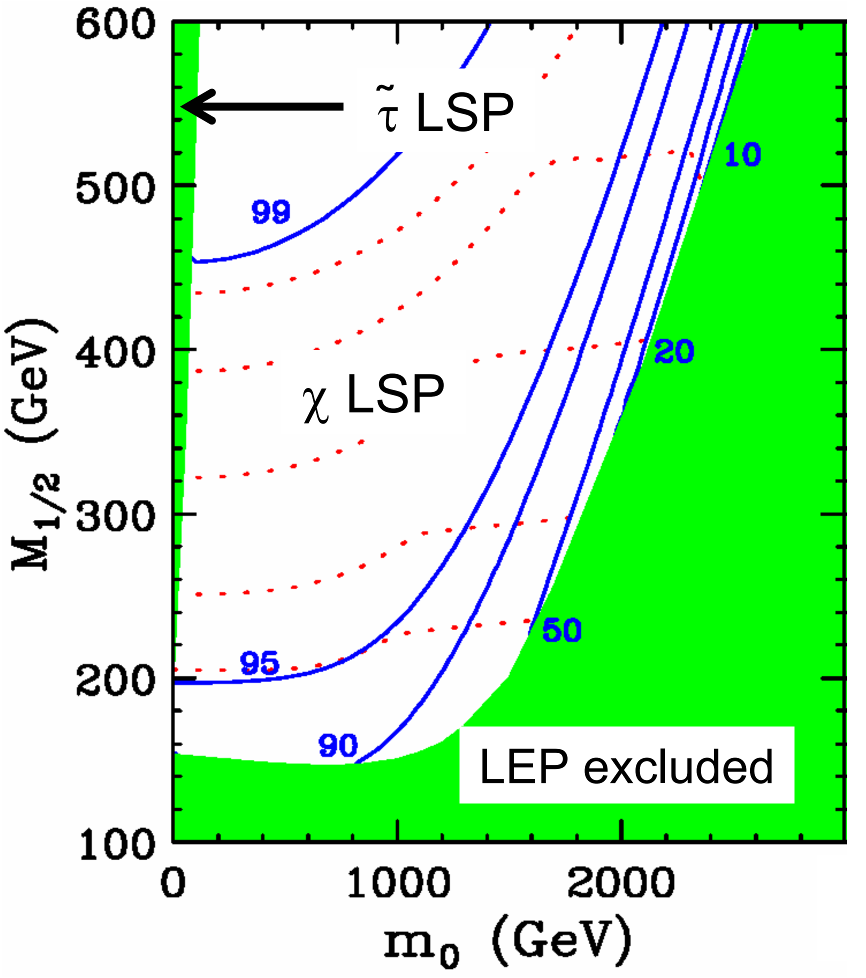
Minimal Supergravity

- The canonical SUSY model is mSUGRA, specified by only 5 parameters (actually 6 – see Lecture 2):

  $\{ m_0, M_{1/2}, A_0, \tan\beta, \mathrm{sgn}(\mu) \}$

- It exhibits virtually all dark matter possibilities (if one looks hard enough!)

- LSP is "usually" χ



SUSY Essentials: Summary

- SUSY predicts many new particles at the weak scale
- Proton decay → LSP is stable
- Dark matter candidates: gravitino, sneutrino, neutralino
- High energy models → neutralino

Neutralino Cosmology
Thermal Relic Density

- The Boltzmann equation:

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[n^2 - n_{\rm eq}^2 \right]$$

Dilution from expansion

$\chi\chi \to f\bar{f}$

$f\bar{f} \to \chi\chi$

- Change variables:

$$t \to x \equiv \frac{m}{T} \qquad n \to Y \equiv \frac{n}{s}$$

- New Boltzmann equation:

$$\frac{x}{Y_{\rm eq}} \frac{dY}{dx} = -\frac{n_{\rm eq} \langle \sigma v \rangle}{H} \left[\frac{Y^2}{Y_{\rm eq}^2} - 1 \right]$$

- $Y \approx Y_{\rm eq}$ until interaction rate drops below expansion rate

Freeze Out

$$\underset{\overset{\uparrow}{(mT)^{3/2}e^{-m/T}}}{n_{\rm eq}}\langle\sigma v\rangle \sim \underset{\overset{\uparrow}{T^2/M_{\rm Pl}}}{H}$$

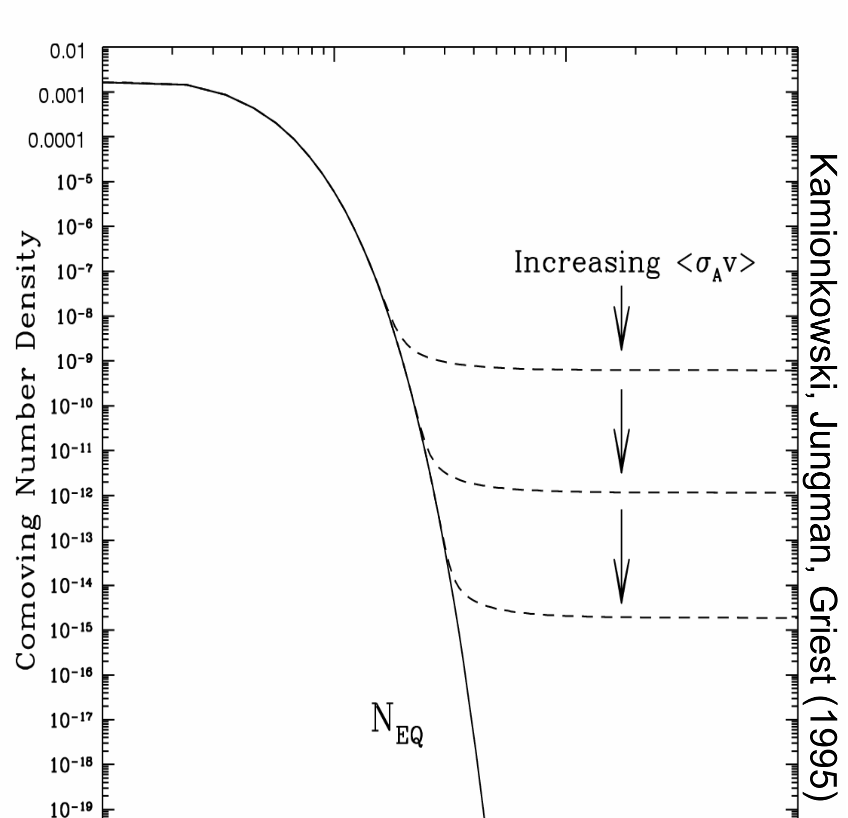
$$\frac{m}{T} \sim \ln\left[\langle\sigma v\rangle m M_{\rm Pl}\left(\frac{m}{T}\right)^{1/2}\right] \to 25$$

A little more work (see Kolb and Turner) shows:

$$\Omega h^2 = m s Y_\infty \sim \frac{10^{-10}\ \mathrm{GeV}^{-2}}{\langle\sigma v\rangle}$$

But $\langle\sigma v\rangle \sim \frac{\alpha^2}{m_W^2} 0.1 \sim 10^{-9}\ \mathrm{GeV}$

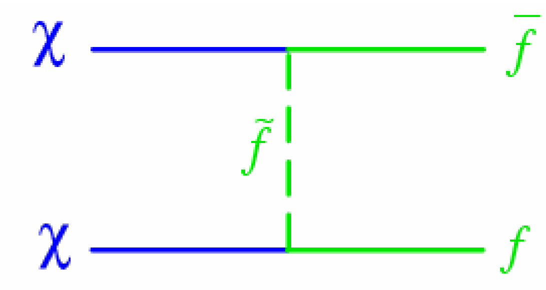
We naturally find $\Omega h^2 \sim 0.1$!



Kamionkowski, Jungman, Griest (1995)

$\chi\chi$ Annihilation

- In more detail: Pandora's box! Neutralino annihilation is sensitive to *many* processes. Two classes:



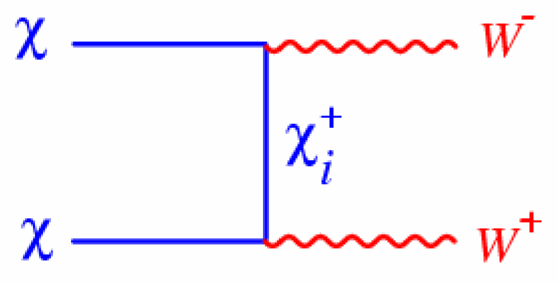
- Fermion diagrams

  χ are Majorana fermions:

  Pauli → $S = 0$

  L cons → P wave suppression

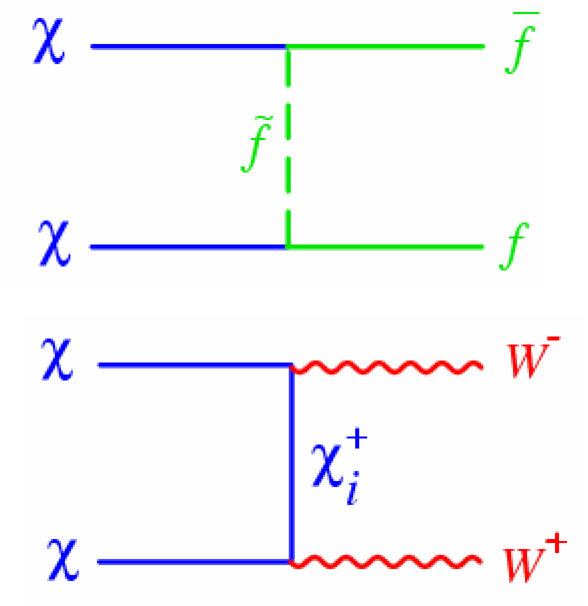
Goldberg (1983)
Ellis, Hagelin, Nanopoulos, Srednicki (1983)



- Gauge boson diagrams vanish for χ = pure Bino.

Bulk Region

- Where can we get the correct Ωh^2? Various regions. In the “bulk region,” $\chi \approx$ pure Bino.



$\Omega_{DM} < 0.3$ → lower bound on $\langle \sigma v \rangle$

→ sfermion mass < 200 GeV

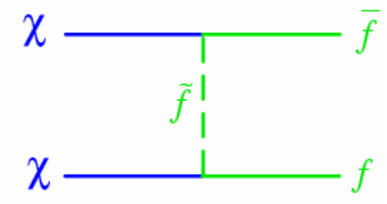
→ χ mass < 200 GeV!

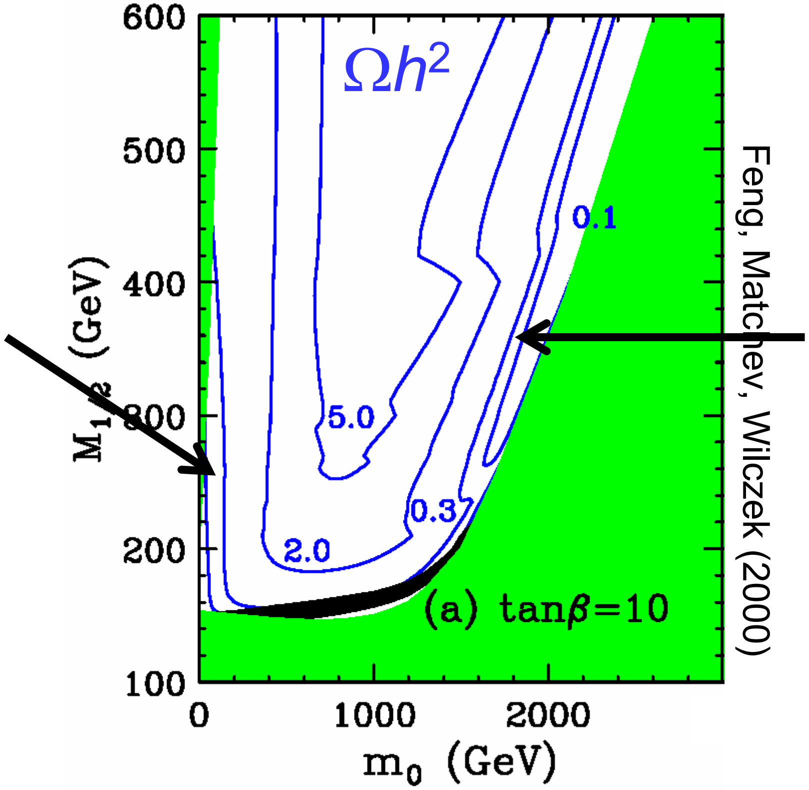
→ Cosmology (seemingly) guarantees light SUSY !

Focus Point Region

- Unfortunately, this assumes $\chi \approx$ pure Bino. This is not necessarily true, even in simple models like mSUGRA.

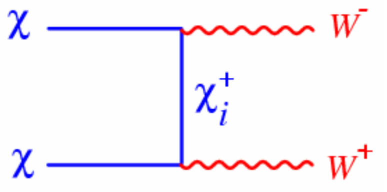
Bulk region
$\chi \approx$ pure Bino
$m\chi < 200$ GeV





Feng, Matchev, Wilczek (2000)

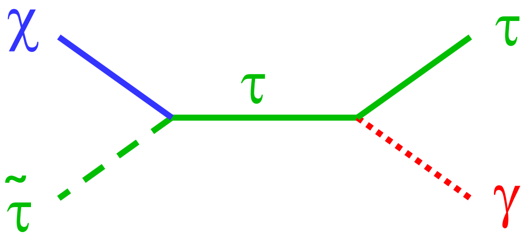
Focus point region
$\chi \approx$ Bino-Higgsino
$m\chi <$ few TeV



- Nevertheless, Ωh^2 very constraining! (Often too much χ DM.)

Co-annihilation Region

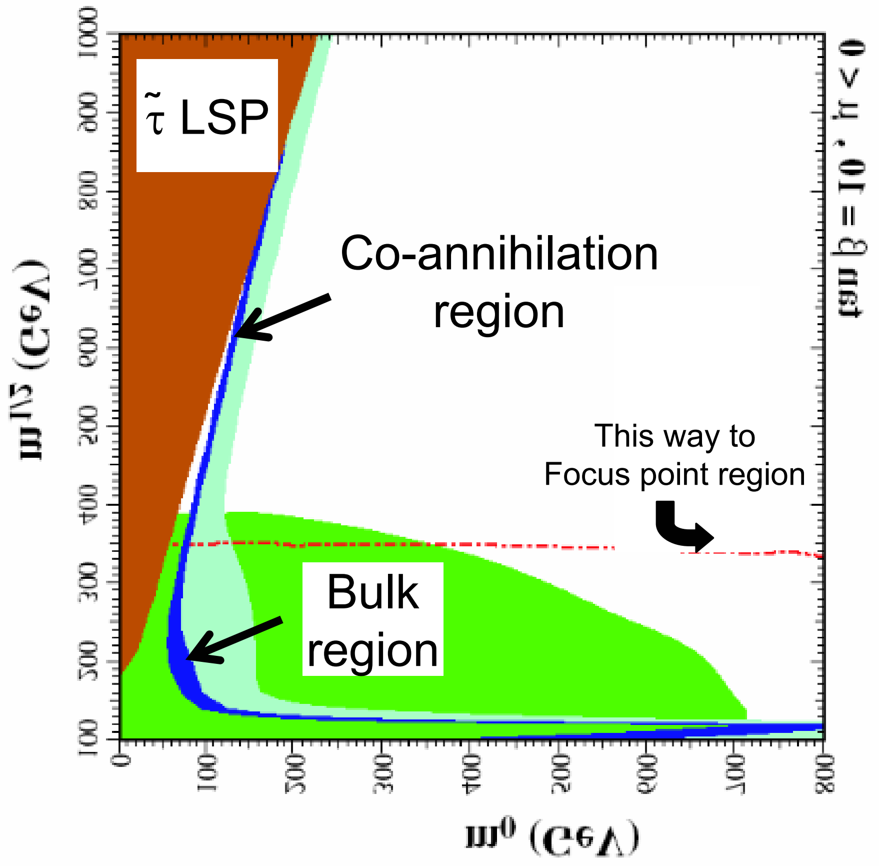
- If other superpartners are nearly degenerate with the χ LSP, they can help it annihilate



- Requires (very roughly)

  $$\Delta m < T \sim m_\chi/25$$

- In co-annihilation region, m_χ < 500 GeV

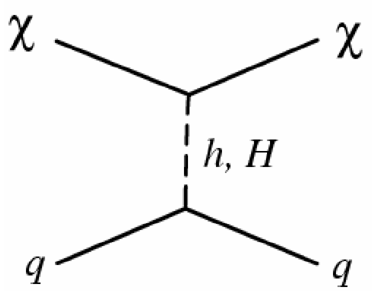


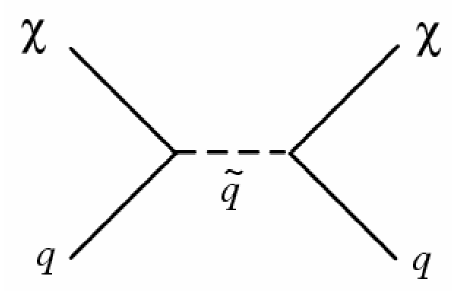
Ellis, Olive, Santoso, Spanos (2003)

Light blue: pre-WMAP
Dark blue: post-WMAP

Neutralino Cosmology
Dark Matter Detection

- Direct detection depends on χN scattering





- Indirect detection depends on $\chi\chi$ annihilation

$\chi\chi \rightarrow \gamma$ in galactic center
$\chi\chi \rightarrow e^+$ in halo

or both

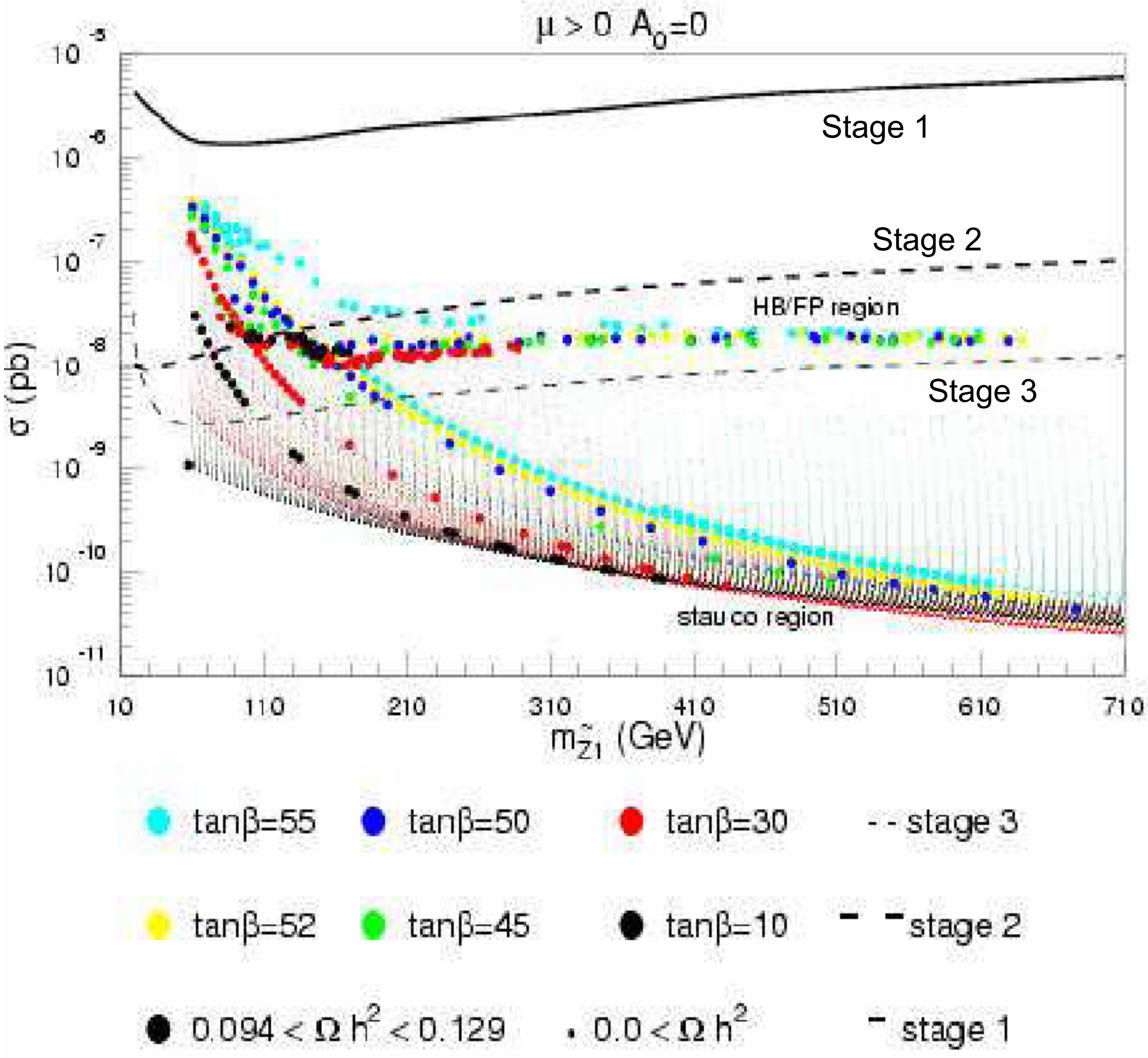
$\chi\chi \rightarrow \nu$ in centers of the Sun and Earth

χ Dark Matter: Direct Detection

- Spin-independent scattering most promising for SUSY

- Theorists: χq scattering
- Expts: χ nucleus scattering
- Meet in middle: χp scattering

Stage 1: CDMS, EDELWEISS, ZEPLIN1, DAMA
Stage 2: CDMS2, EDELWEISS2, ZEPLIN2, CRESST2
Stage 3: GENIUS, ZEPLIN4, CRYOARRAY



Baer, Balazs, Belyaev, O'Farrill (2003)

Indirect Detection Experiments

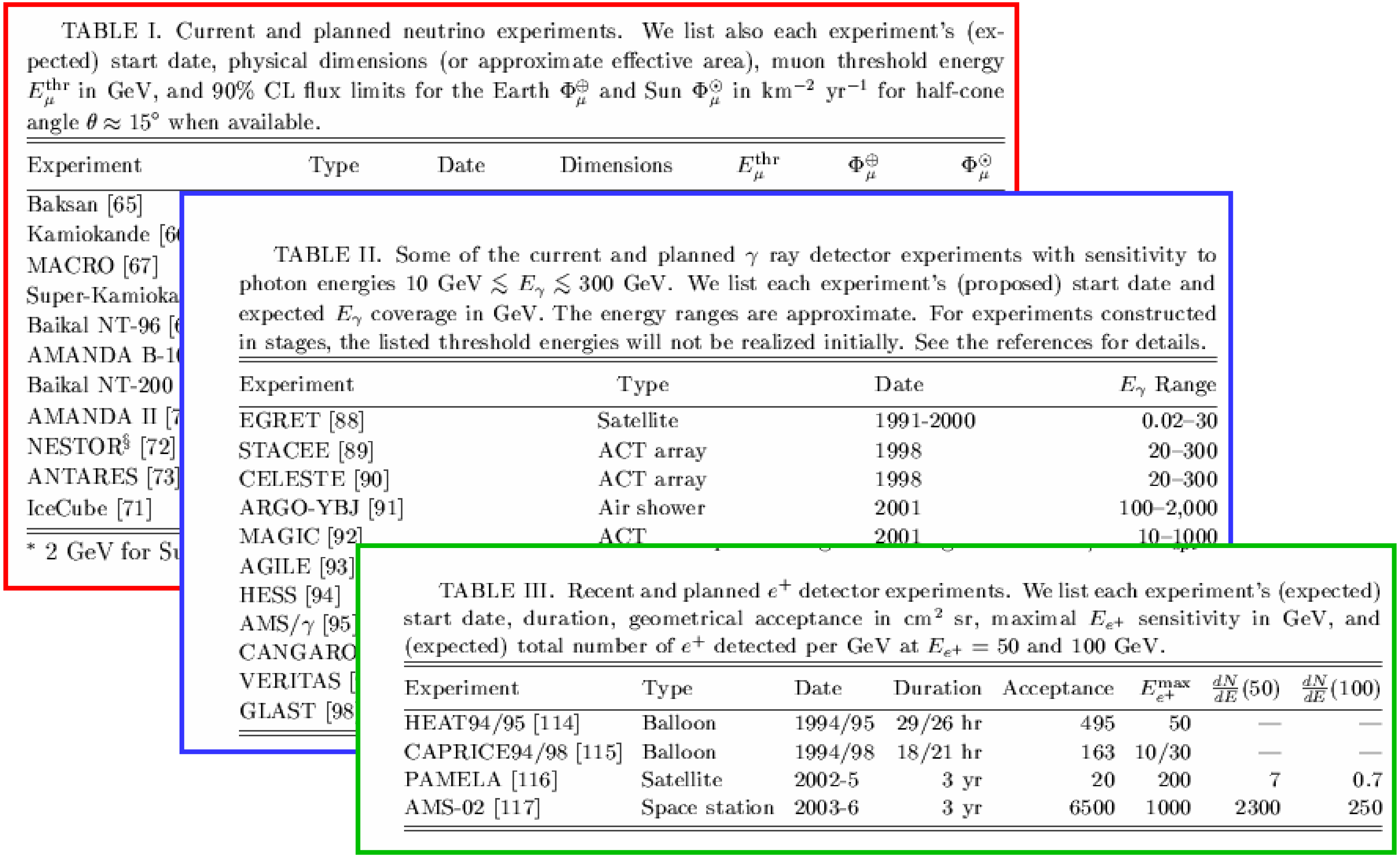


TABLE I. Current and planned neutrino experiments. We list also each experiment's (expected) start date, physical dimensions (or approximate effective area), muon threshold energy $E_\mu^{\rm thr}$ in GeV, and 90% CL flux limits for the Earth $\Phi_\mu^\oplus$ and Sun $\Phi_\mu^\odot$ in km^{-2} yr^{-1}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

Experiment	Type	Date	Dimensions	$E_\mu^{\rm thr}$	$\Phi_\mu^\oplus$	$\Phi_\mu^\odot$
Baksan [65]						
Kamiokande [6						
MACRO [67]						
Super-Kamioka						
Baikal NT-96 [						
AMANDA B-1						
Baikal NT-200						
AMANDA II [7						
NESTOR§ [72]						
ANTARES [73]						
IceCube [71]						

* 2 GeV for Su

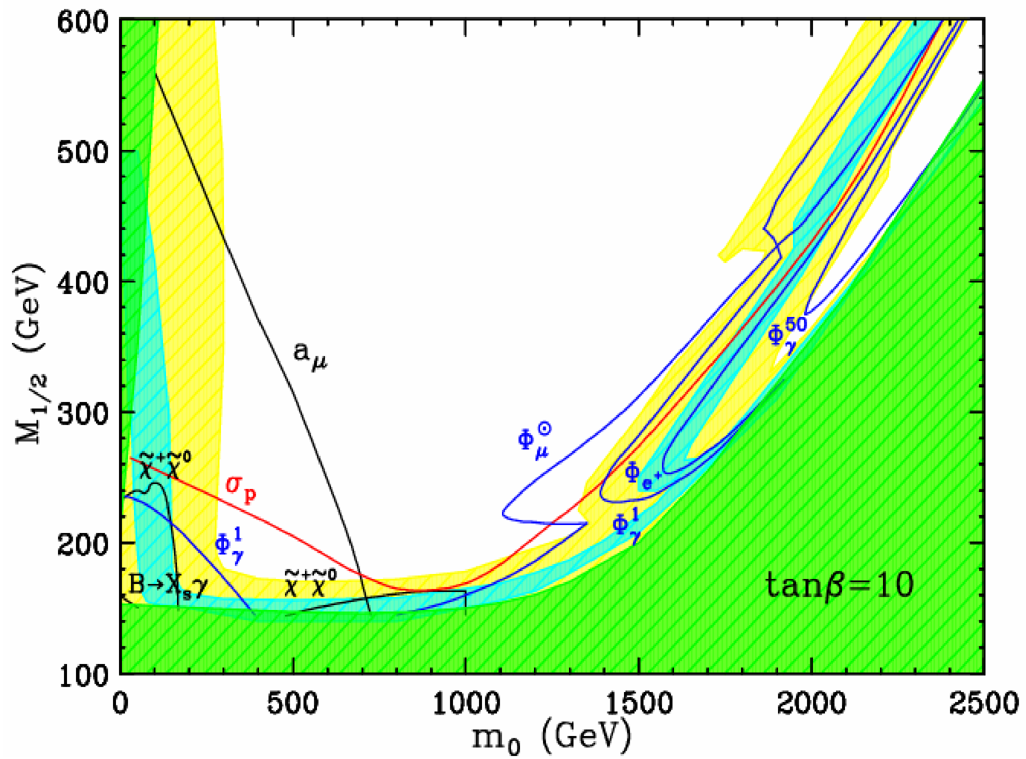
TABLE II. Some of the current and planned γ ray detector experiments with sensitivity to photon energies 10 GeV $\lesssim E_\gamma \lesssim$ 300 GeV. We list each experiment's (proposed) start date and expected E_γ coverage in GeV. The energy ranges are approximate. For experiments constructed in stages, the listed threshold energies will not be realized initially. See the references for details.

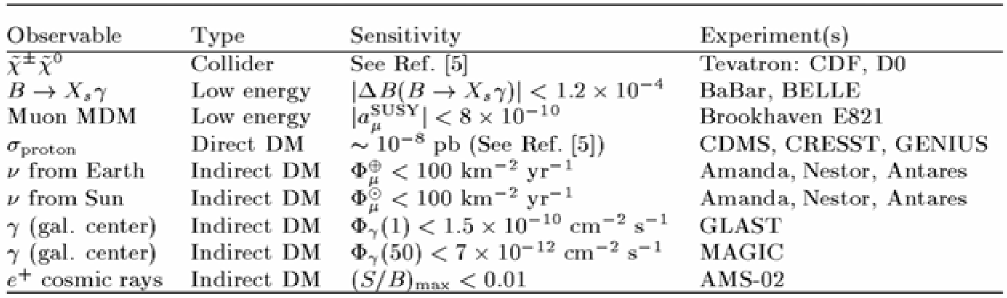
Experiment	Type	Date	E_γ Range
EGRET [88]	Satellite	1991-2000	0.02–30
STACEE [89]	ACT array	1998	20–300
CELESTE [90]	ACT array	1998	20–300
ARGO-YBJ [91]	Air shower	2001	100–2,000
MAGIC [92]	ACT	2001	10–1000
AGILE [93]			
HESS [94]			
AMS/γ [95			
CANGARO			
VERITAS [			
GLAST [98			

TABLE III. Recent and planned e^+ detector experiments. We list each experiment's (expected) start date, duration, geometrical acceptance in cm^2 sr, maximal E_{e^+} sensitivity in GeV, and (expected) total number of e^+ detected per GeV at E_{e^+} = 50 and 100 GeV.

Experiment	Type	Date	Duration	Acceptance	$E_{e^+}^{\max}$	$\frac{dN}{dE}(50)$	$\frac{dN}{dE}(100)$
HEAT94/95 [114]	Balloon	1994/95	29/26 hr	495	50	—	—
CAPRICE94/98 [115]	Balloon	1994/98	18/21 hr	163	10/30	—	—
PAMELA [116]	Satellite	2002-5	3 yr	20	200	7	0.7
AMS-02 [117]	Space station	2003-6	3 yr	6500	1000	2300	250

Dark Matter Detection





Observable	Type	Sensitivity	Experiment(s)
$\tilde{\chi}^\pm\tilde{\chi}^0$	Collider	See Ref. [5]	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	$\lvert a_\mu^{\text{SUSY}}\rvert < 8 \times 10^{-10}$	Brookhaven E821
σ_{proton}	Direct DM	$\sim 10^{-8}$ pb (See Ref. [5])	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	$\Phi_\gamma(50) < 7 \times 10^{-12}$ cm^{-2} s^{-1}	MAGIC
e^+ cosmic rays	Indirect DM	$(S/B)_{\text{max}} < 0.01$	AMS-02

Discovery prospects before LHC

Particle probes

Direct DM detection

Indirect DM detection

Correct relic density → detection promising! (Both require large χ-matter couplings)

Detection methods complementary

Neutralino Cosmology: Summary

- Neutralinos: excellent dark matter candidates
- Cosmology provides no useful upper bounds on SUSY masses, but Ω_{DM} is highly constraining
- Detection not yet constraining, but prospects promising
- Particle/cosmo searches complementary (see Lecture 2)