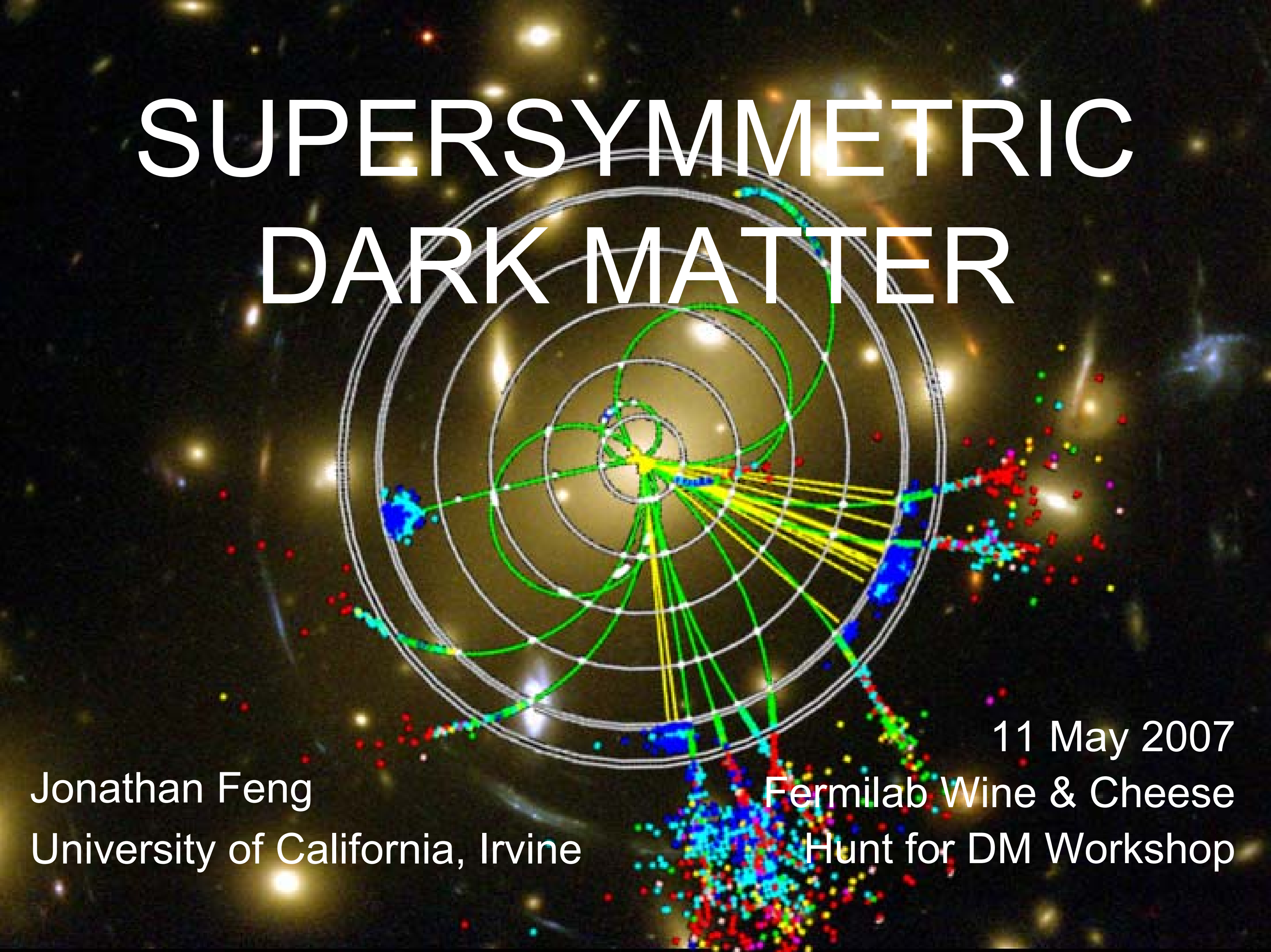


SUPERSYMMETRIC DARK MATTER

Jonathan Feng
University of California, Irvine

11 May 2007
Fermilab Wine & Cheese
Hunt for DM Workshop

Dark Matter

- $\Omega_{DM}h^2 = 0.105 \pm 0.004$ (WMAP, SDSS)
- Best evidence for new physics
  - Unambiguous
  - Intimately connected to central problems: electroweak symmetry breaking and structure formation
- Theory: many compelling and new possibilities
  - Not baryonic (≠ weakly-interacting)
  - Not hot (≠ cold)
  - Not short-lived (≠ stable)
- Experiment, observation: bright prospects
  - Astroparticle physics: direct and indirect detection
  - Cosmology: halo profiles, CMB, BBN, …
  - Particle physics: Tevatron, LHC

THE "WIMP MIRACLE"

(1) Assume a new (heavy) particle χ is initially in thermal equilibrium:

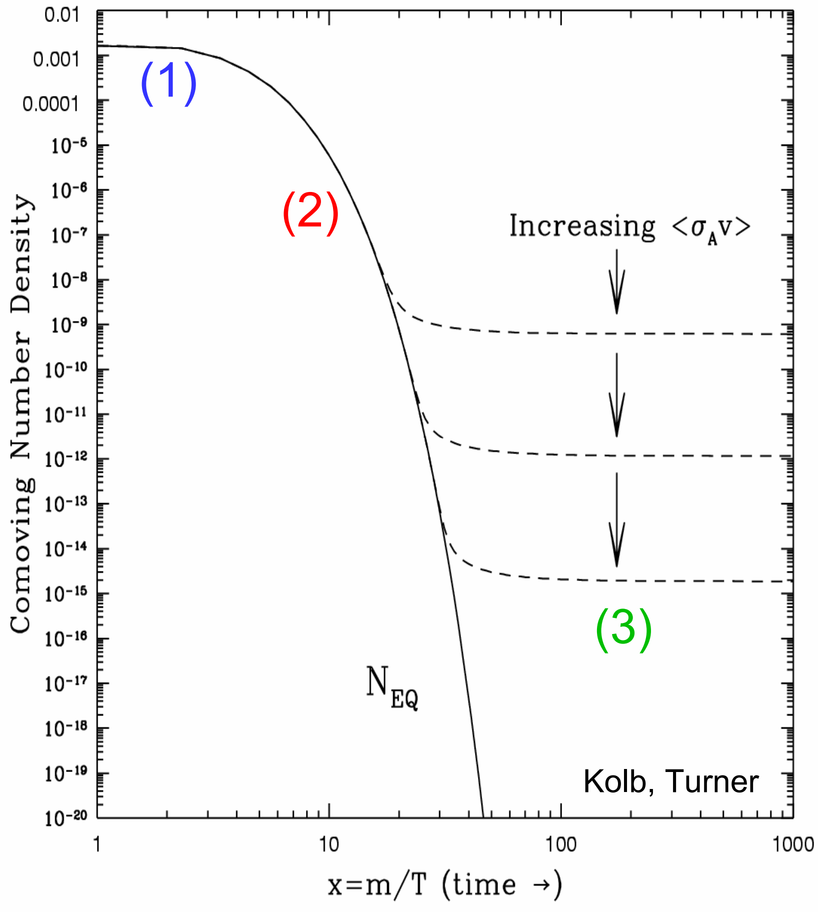
$$\chi\chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

$$\chi\chi \; \substack{\rightarrow \\ \not\leftarrow} \; \bar{f} f$$

(3) χs "freeze out":

$$\chi\chi \; \substack{\not\rightarrow \\ \not\leftarrow} \; \bar{f} f$$



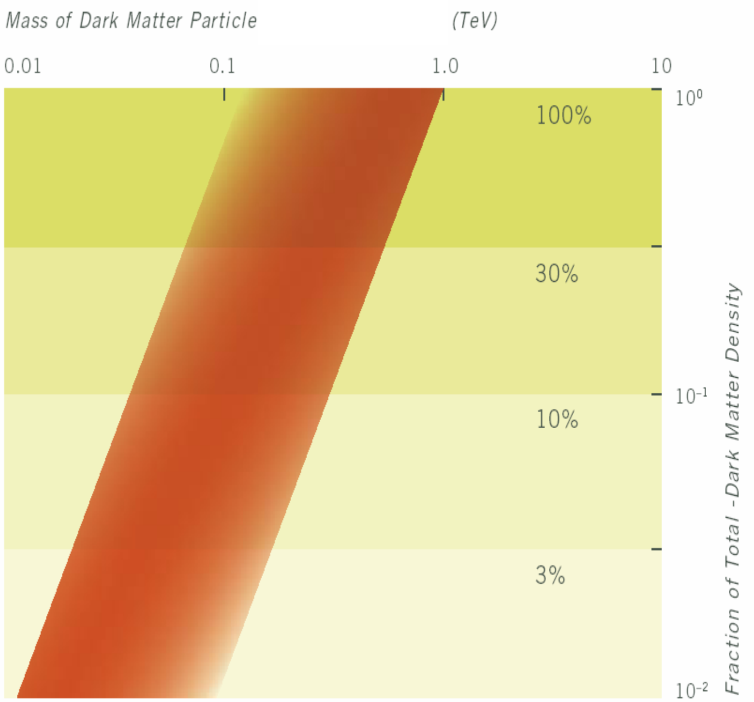
- The amount of dark matter left over is inversely proportional to the annihilation cross section:

$$\Omega_{DM} \sim \langle \sigma_A v \rangle^{-1}$$

- What is the constant of proportionality?

- Impose a natural relation:

$$\sigma_A = k\alpha^2/m^2 \text{ , so } \Omega_{DM} \sim m^2$$

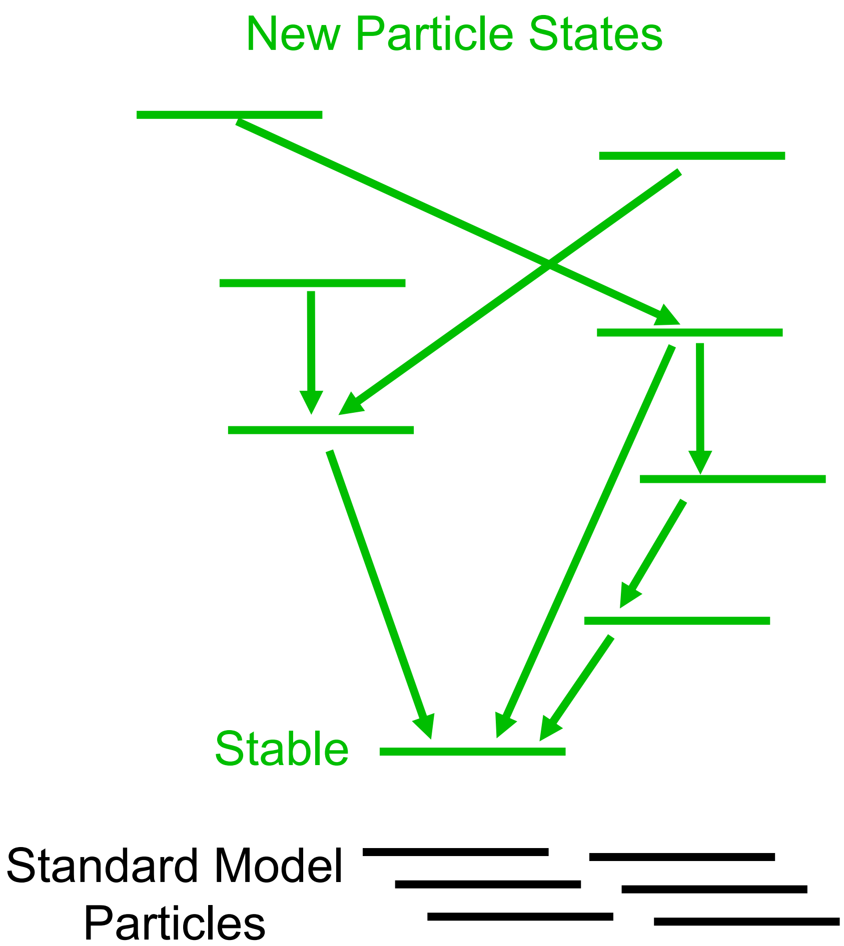


HEPAP LHC/ILC Subpanel (2006)
[band width from k = 0.5 – 2, S and P wave]

Remarkable "coincidence": $\Omega_{DM} \sim 0.1$ for $m \sim 0.1 – 1$ TeV
Cosmology alone tells us we should explore the weak scale

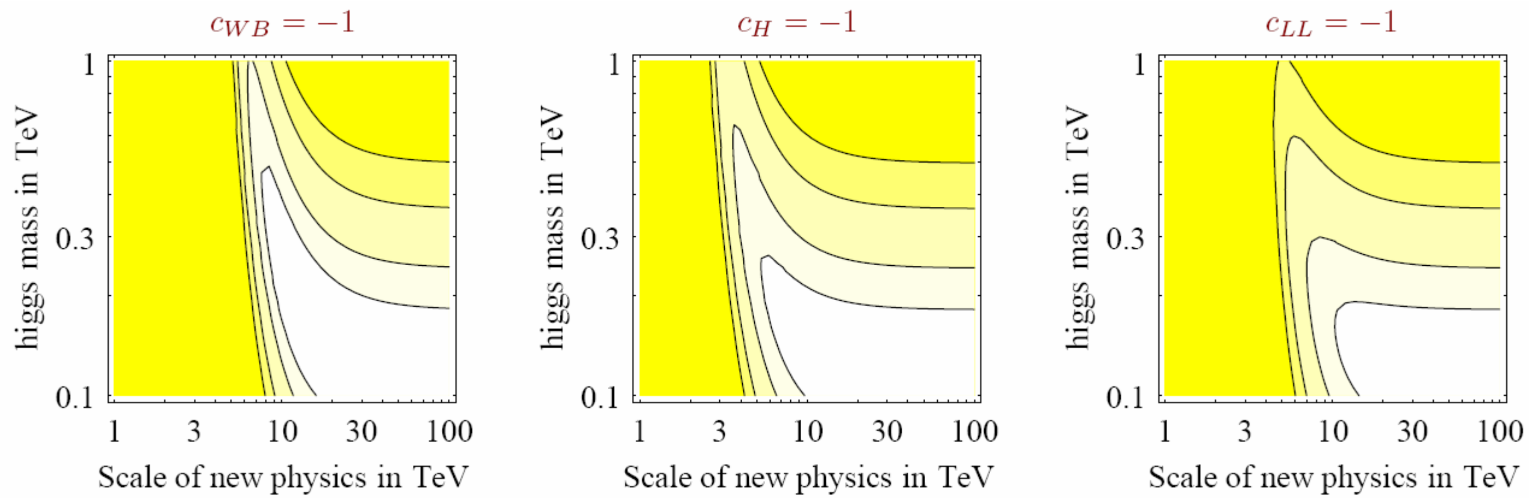
STABILITY

- This all assumes the WIMP is stable
- How natural is this?



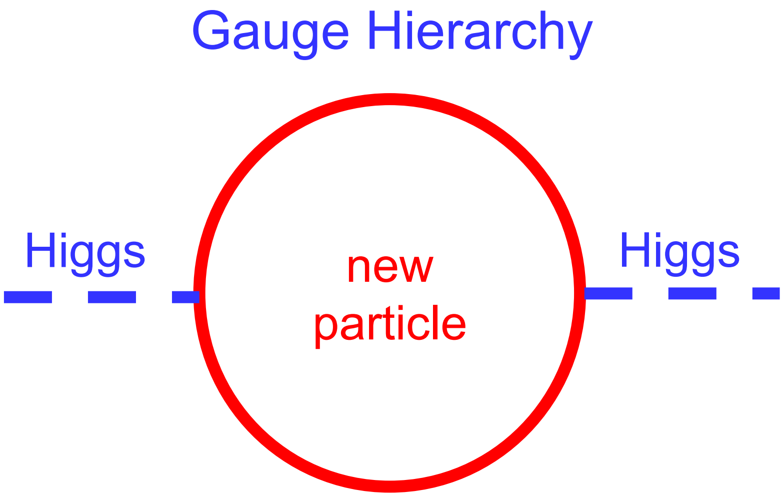
LEP

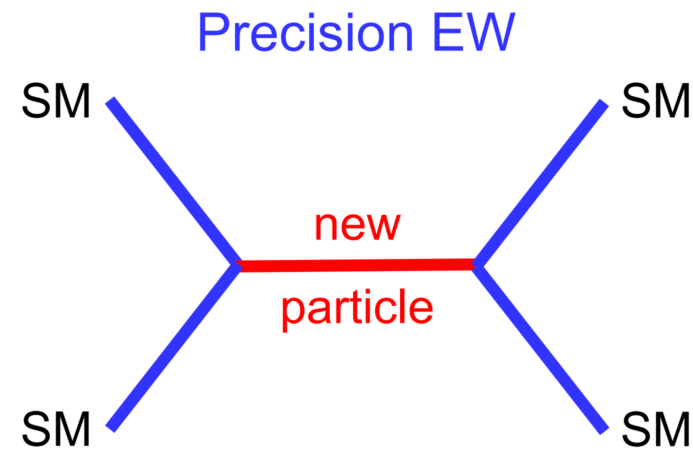
- Large Electron Positron Collider at CERN, 1989-2000
- LEP and SLC confirmed the standard model, stringently constrained effects of new particles
- Problem: Gauge hierarchy → new particles ~100 GeV
  LEP/SLC → new particles > 3 TeV
  (even considering only flavor-, CP-, B-, and L-conserving effects)



Barbieri, Strumia (2000)

LEP'S COSMOLOGICAL LEGACY





- Simple solution: impose a discrete parity, so all interactions require pairs of new particles. This also makes the lightest new particle stable.

Cheng, Low (2003); Wudka (2003)

- LEP's Cosmological Legacy:

LEP constraints ↔ Discrete symmetry ↔ Stability

- Dark matter is easier to explain than no dark matter
- The WIMP paradigm is more natural than ever before, leading to a proliferation of candidates

EXAMPLES

- Supersymmetry
  - R-parity
  - Neutralino DM

Goldberg (1983); Ellis et al. (1984)

- Universal Extra Dimensions
  - KK-parity
  - Kaluza-Klein DM

Appelquist, Cheng, Dobrescu (2000)

Servant, Tait (2002)

Cheng, Feng, Matchev (2002)

- Branes
  - Brane-parity
  - Branons DM

Cembranos, Dobado, Maroto (2003)

- …

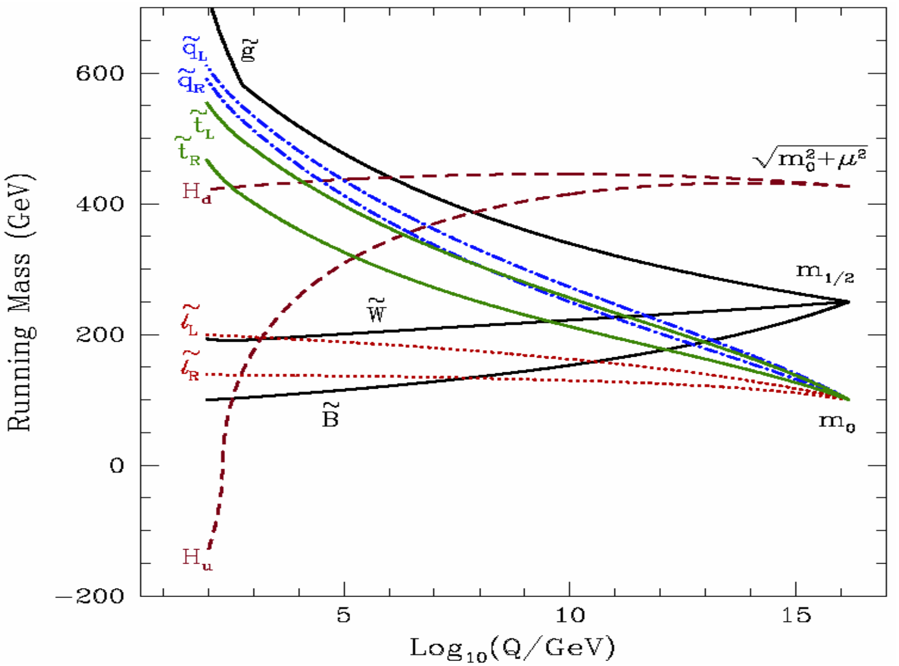
SUSY DM CANDIDATES

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	$\tilde{B}$ Bino	$\tilde{W}^0$ Wino	$\tilde{H}_u$ Higgsino	$\tilde{H}_d$ Higgsino	ν	
0			H_u	H_d	$\tilde{\nu}$ sneutrino	

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

NEUTRALINOS

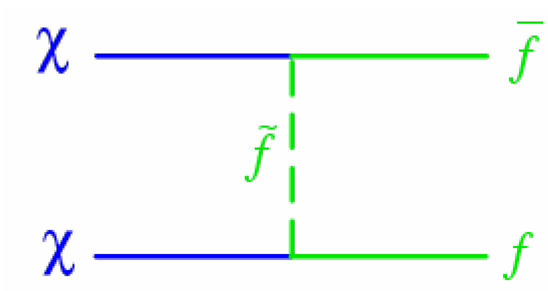
- The neutralino is the classic WIMP
  - ~ 50 GeV – 1 TeV
  - weakly-interacting
  - Naturally the lightest standard model superpartner in many models



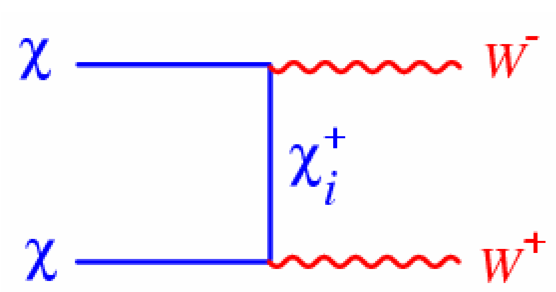
- So many SUSY models and parameters. Can we say anything interesting?

Neutralino Characteristics

- Neutralinos are sensitive to *many* processes. [→]
  But there are essentially two classes:



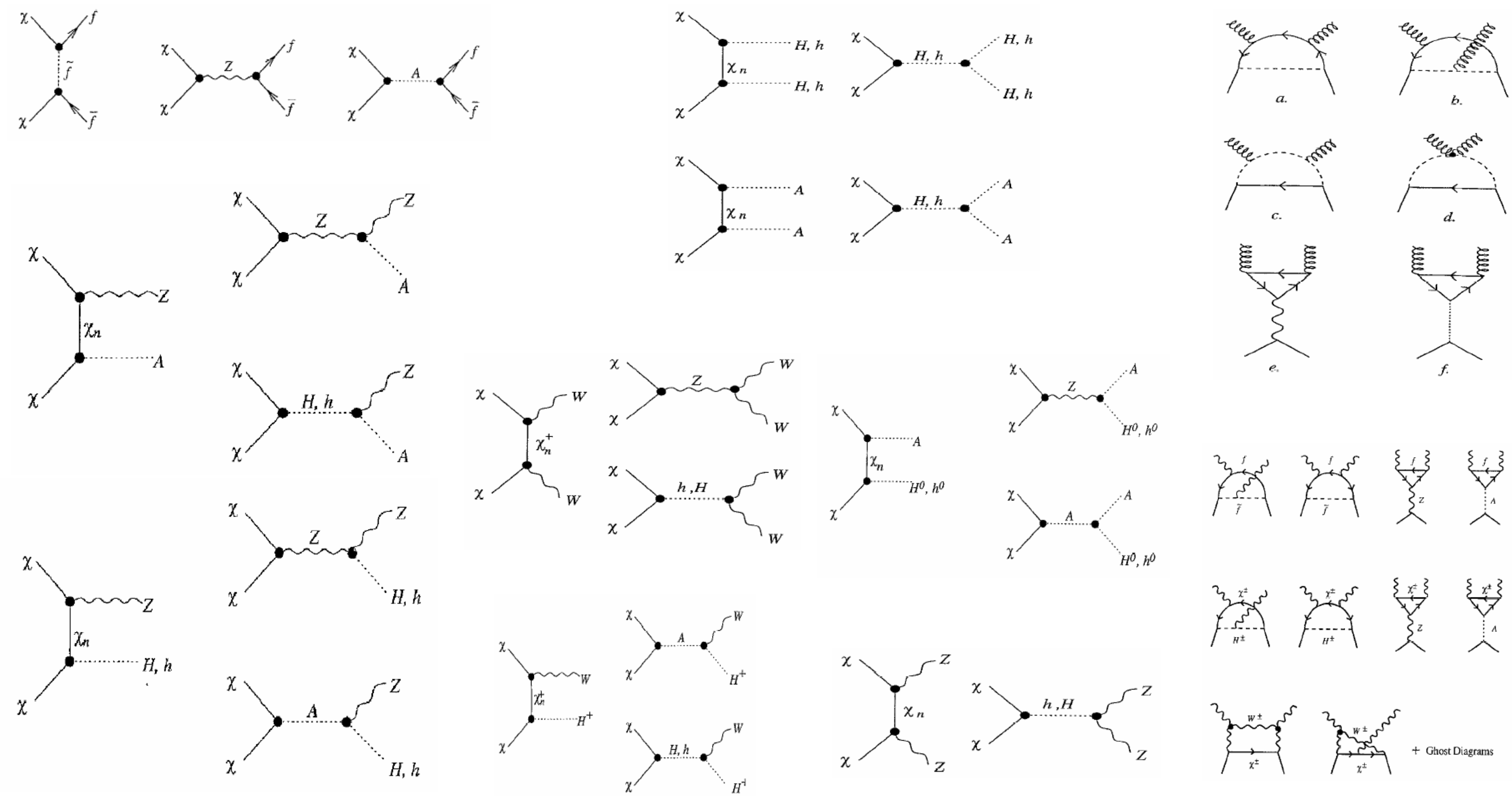
- Fermion diagrams
  χ are Majorana fermions:
  Pauli exclusion → $S = 0$
  L conservation → P wave suppression
  m_f / m_W suppression



- Gauge boson diagrams
  suppressed for $\chi \approx$ Bino

Bottom line: annihilation is typically suppressed, $\Omega_{DM}h^2$ is typically high

Contributions to Neutralino WIMP Annihilation

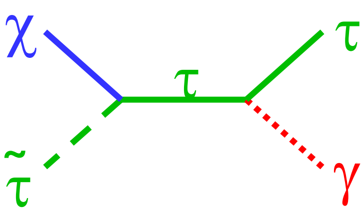


Jungman, Kamionkowski, Griest (1995)

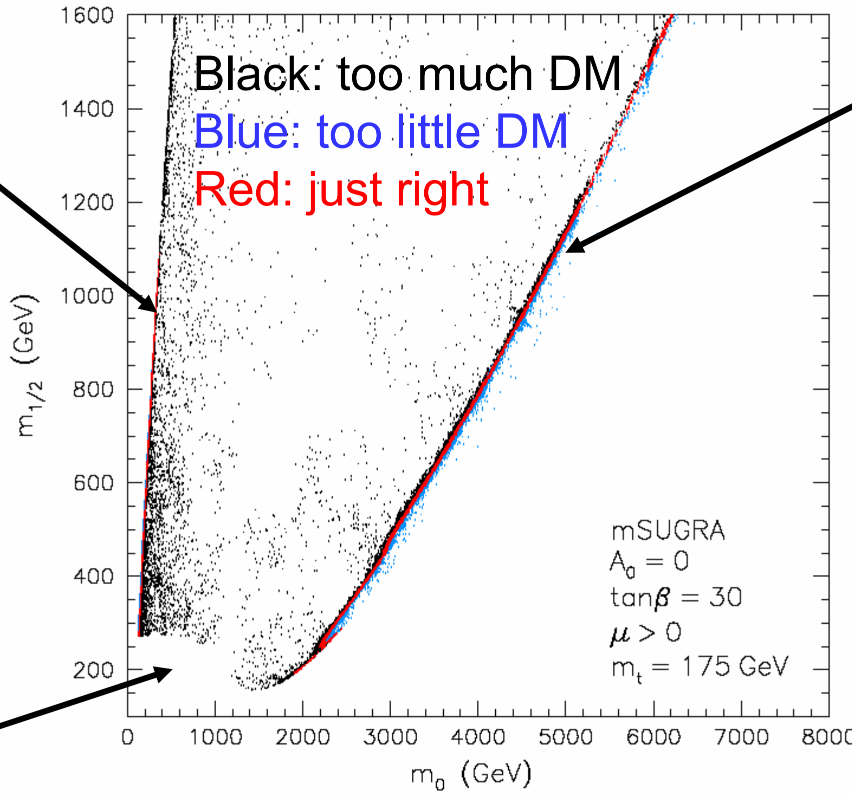
Cosmologically Preferred Supersymmetry

$\Omega_{DM}h^2$ excludes many possibilities, favors certain models

Co-annihilation region

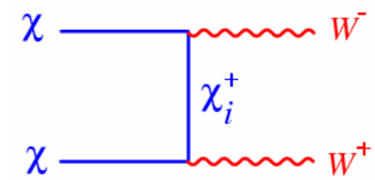


Degenerate χ and stau



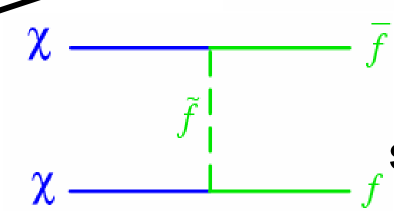
Baltz, Gondolo (2004)

Focus point region



Mixed Neutralinos

Bulk region

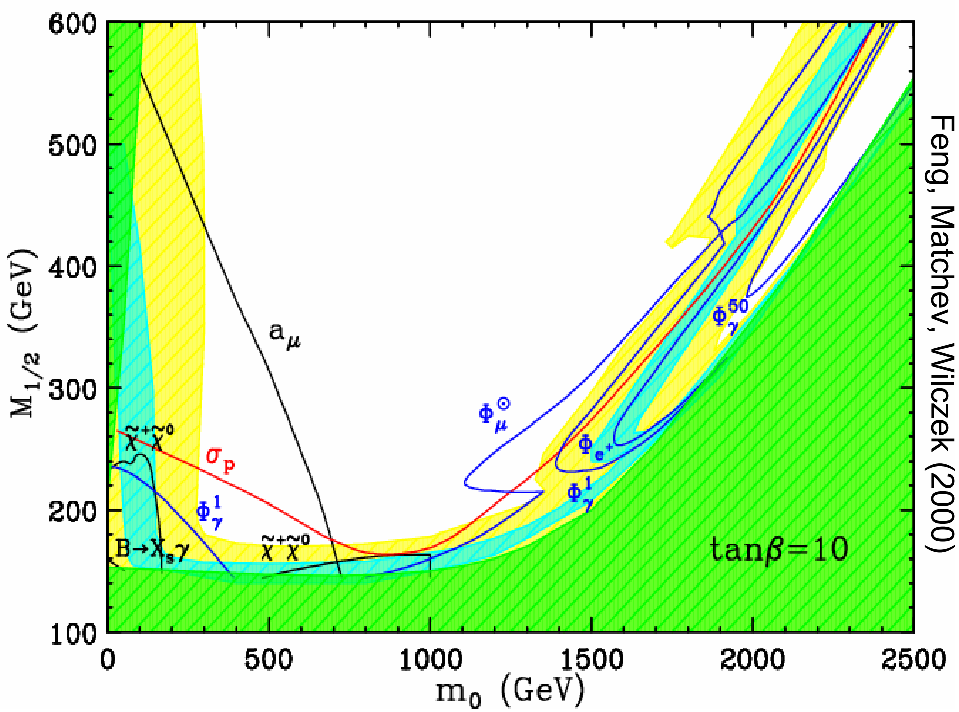


Light sfermions

A funnel region,
Stop co-annihilation

Balazs, Carena, Wagner (2004)

Implications for Detection



Feng, Matchev, Wilczek (2000)

Many diverse experiments are promising
More than one required, even in the same category, to establish/explore signals

The View from 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 $\theta \approx 15°$ 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 ... start date and expect ... ts constructed in stag ... es for details.

Experi	E_γ Range
EGRE	0.02–30
STAC	20–300
CELE	20–300
ARGC	100–2,000
MAGI	
AGILE [93]	
HESS [94]	
AMS/γ [95	
CANGARO	
VERITAS [	
GLAST [98	

Discovery prospects "before the LHC"

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	$E_{e^+}^{\rm max}$	$\frac{dN}{dE}(50)$	$\frac{dN}{dE}(100)$
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

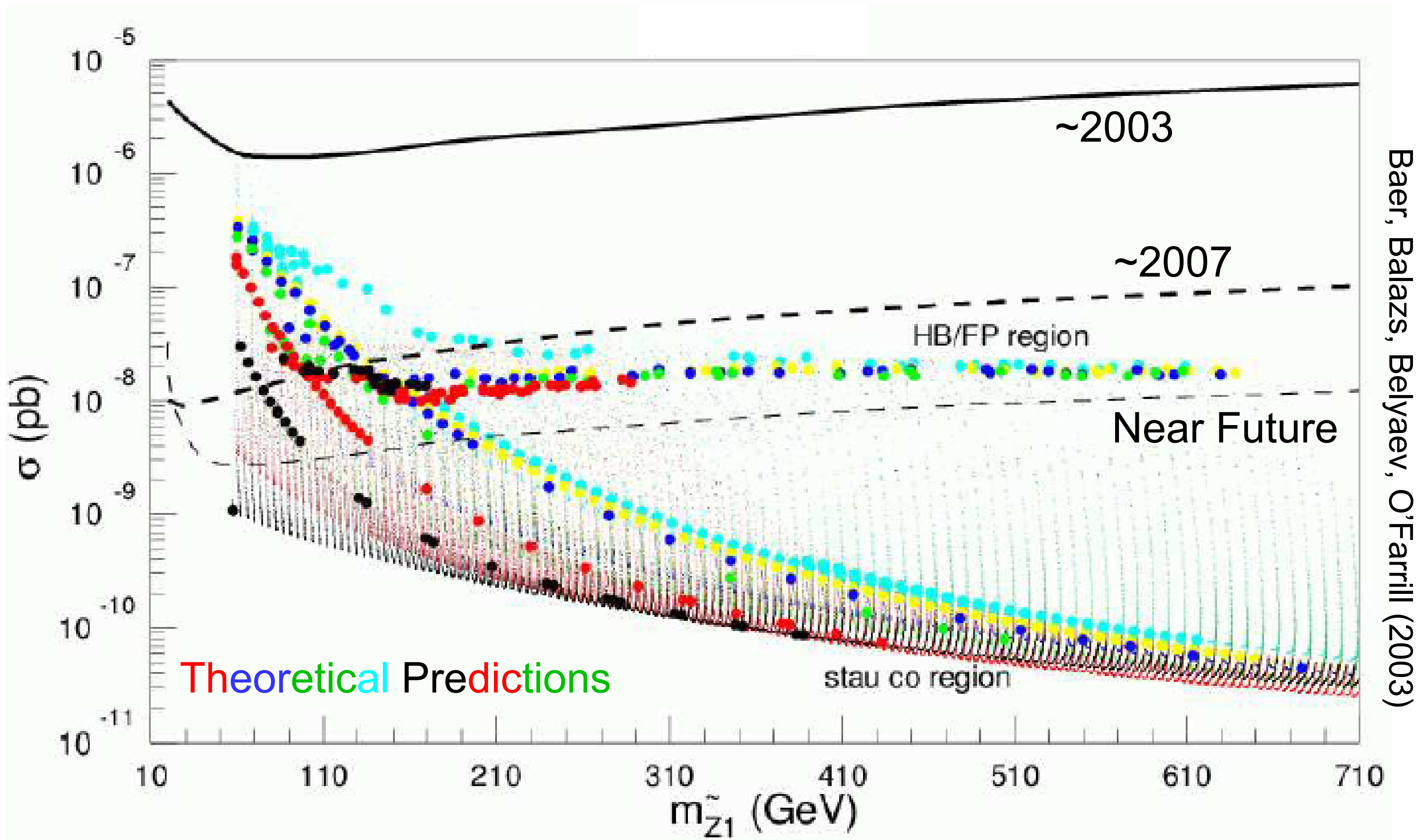
A Note on Direct Detection

- Details are model-dependent, but there are general lessons to abstract from these considerations. For example:

- Direct detection
  SUSY flavor, CP problems suggest that sleptons and squarks are heavy
  $\Omega_{DM}h^2 \rightarrow$ mixed (Bino-Higgsino, focus point) neutralinos

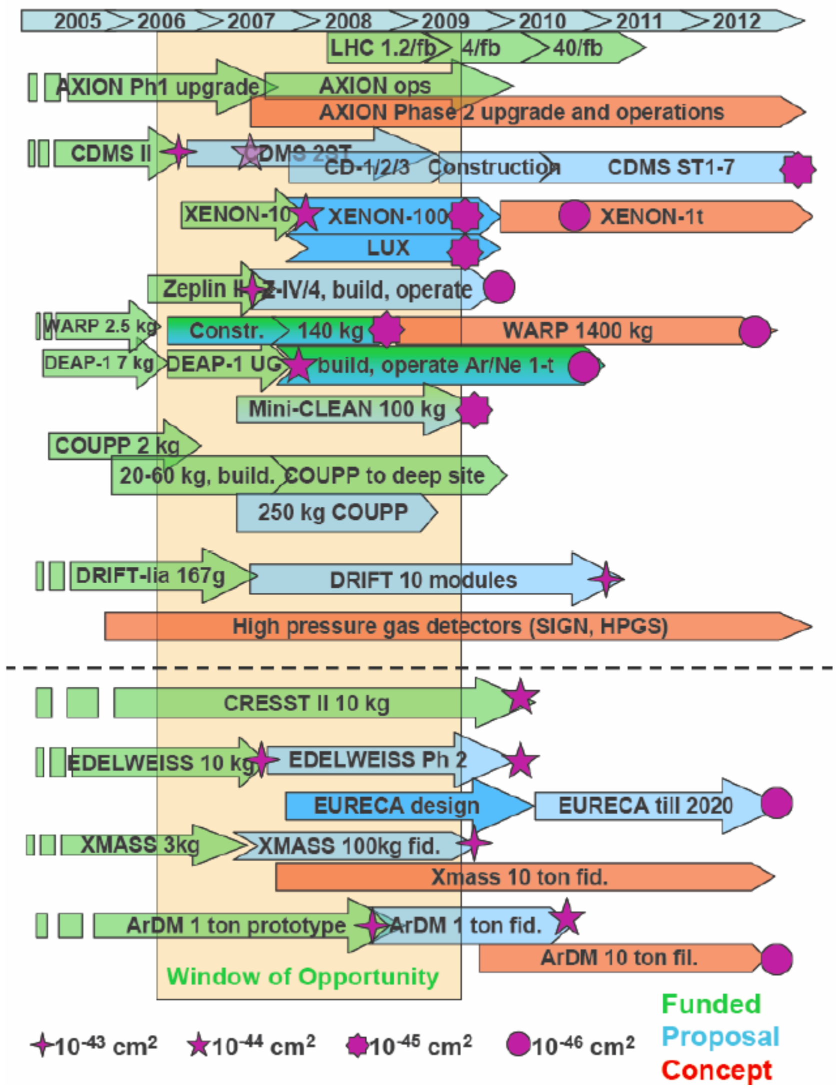
- This conclusion
  - holds for a wide variety of models (mSUGRA, general focus point SUSY, gaugino-mediated, more minimal SUSY, 2-1 models, split SUSY,…), constrains models that are not even cosmologically motivated
  - leads to concrete predictions

Direct Detection



10^{-8} pb (10^{-44} cm^2) is an extremely significant goal for direct detection

Future Direct Detection



HEPAP/AAAC DMSAG Subpanel (2007)

NEUTRALINO PROSPECTS

If neutralinos contribute significantly to dark matter, we are likely to see signals before the end of the decade:

Direct dark matter searches

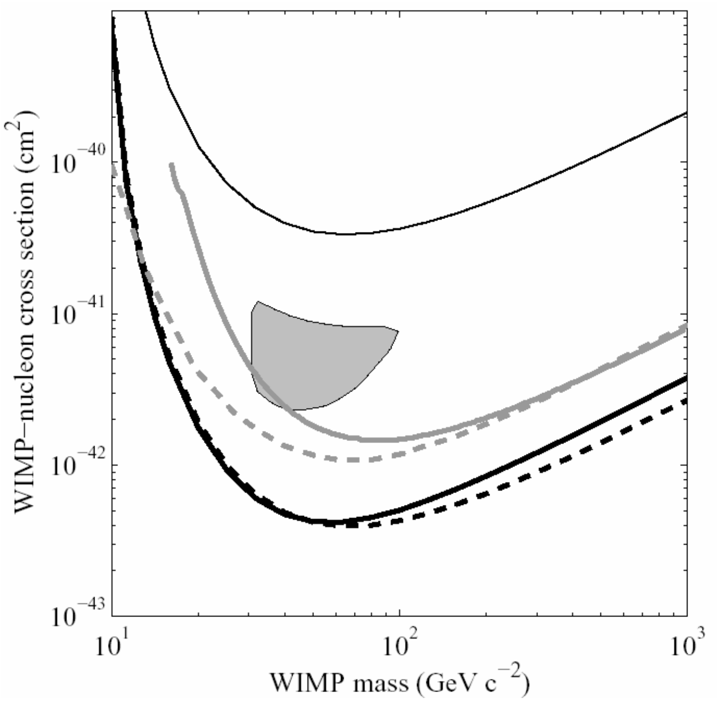
Indirect dark matter searches

Tevatron at Fermilab

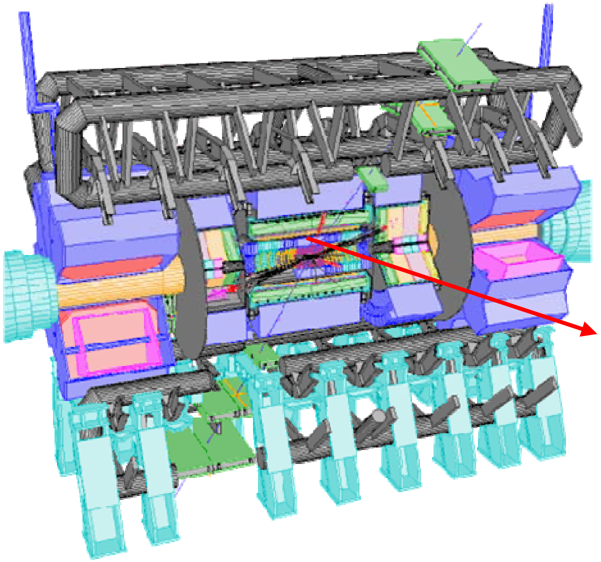
Large Hadron Collider at CERN

What then?

- Cosmo/astro can't discover SUSY

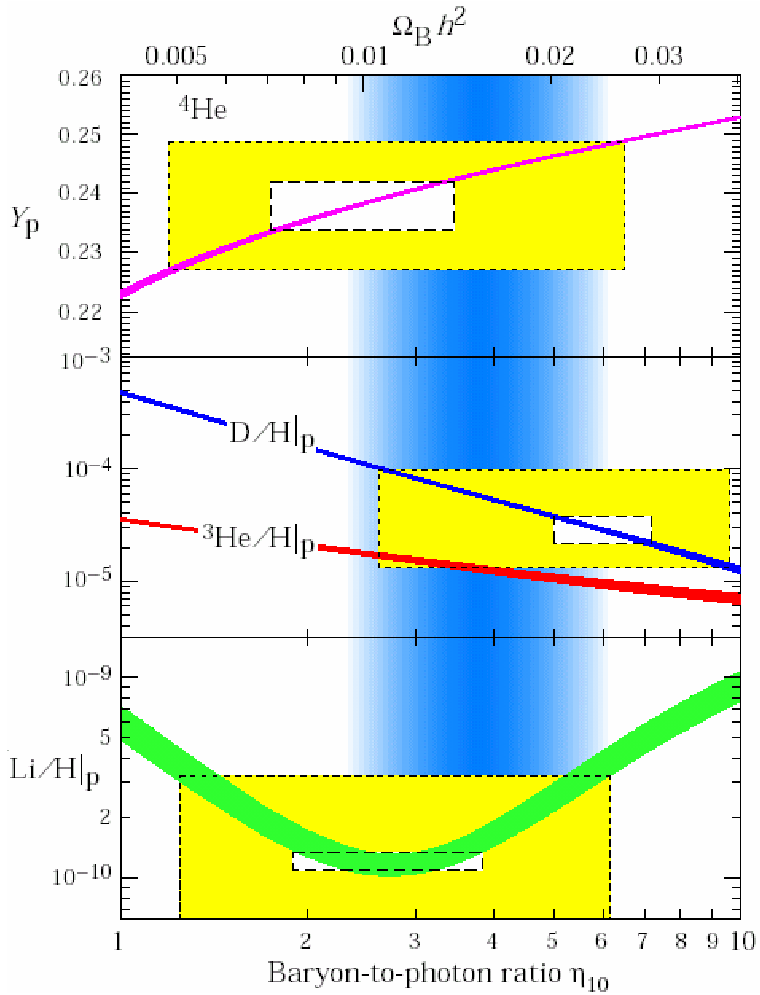


- Particle colliders can't discover DM



Lifetime > 10^{-7} s → 10^{17} s ?

THE EXAMPLE OF BBN

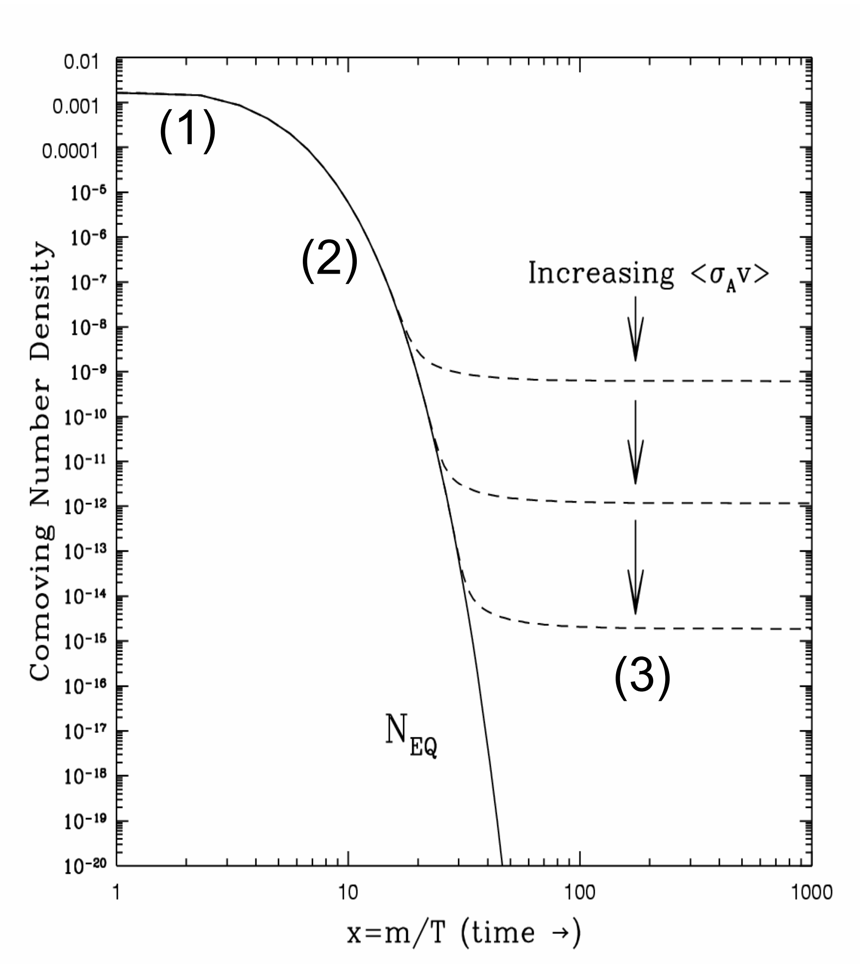


- Nuclear physics → light element abundance predictions
- Compare to light element abundance observations
- Agreement → we understand the universe back to

  T ~ 1 MeV

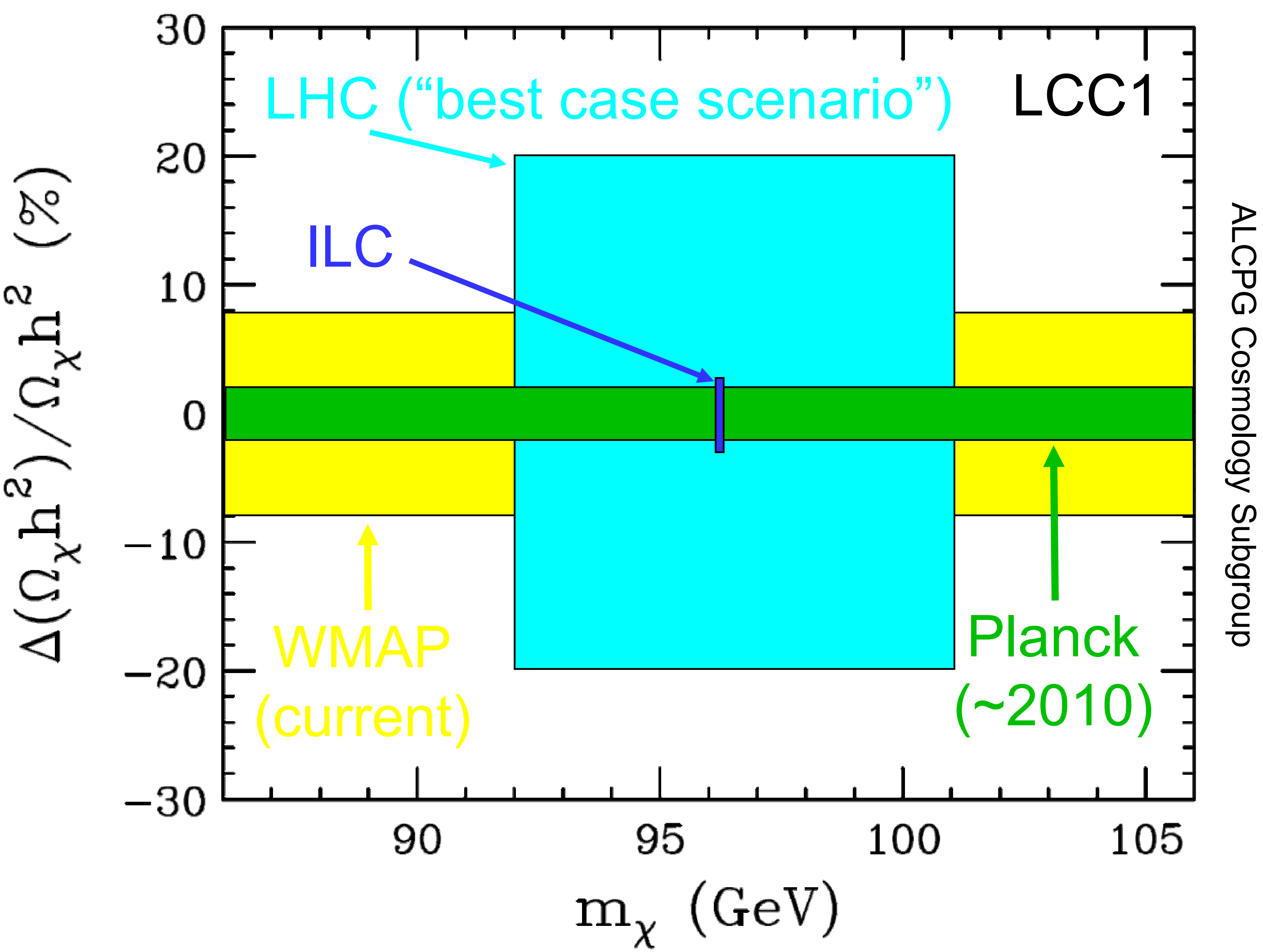
  t ~ 1 sec

DARK MATTER ANALOGUE



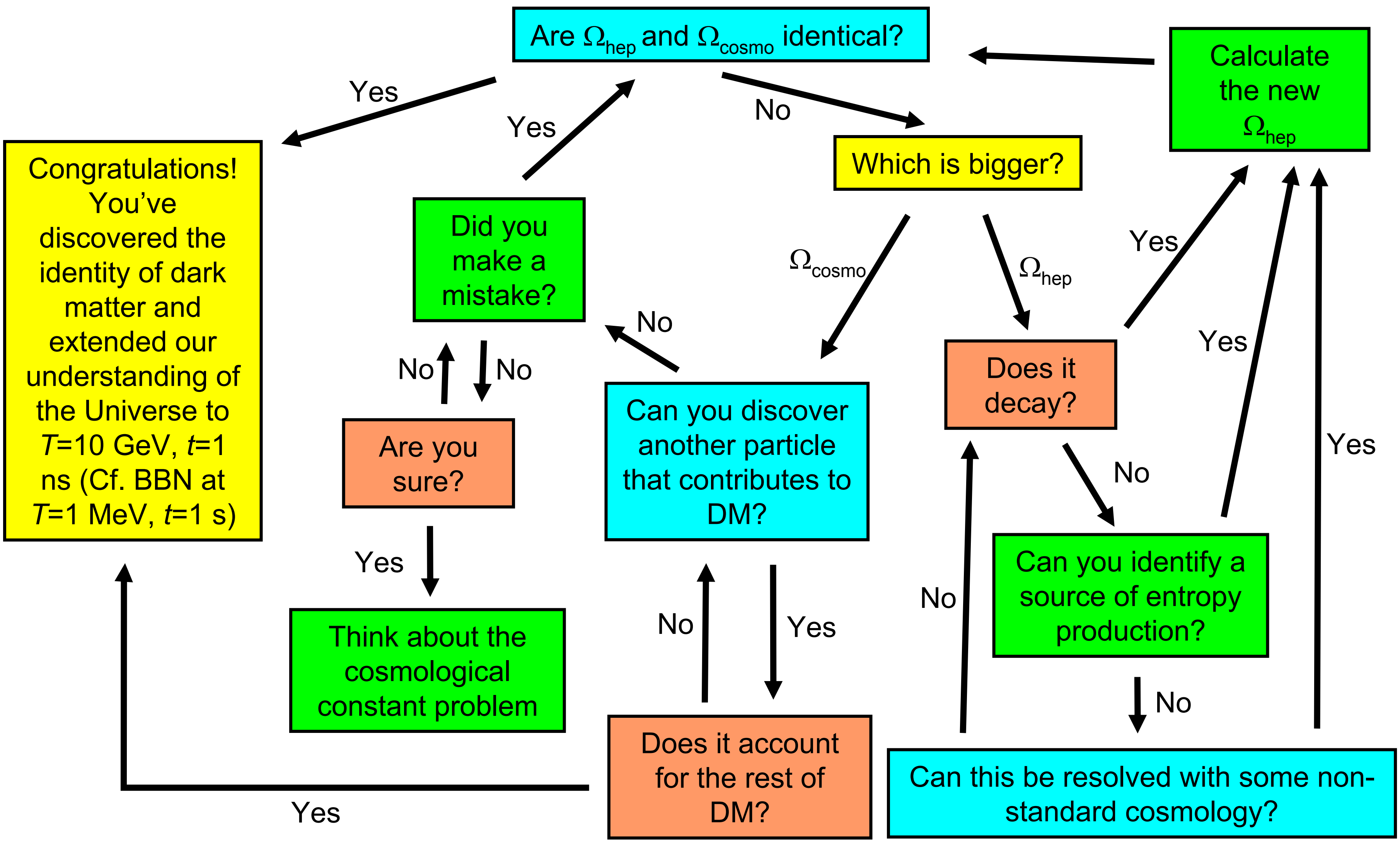
- Particle physics → dark matter abundance prediction
- Compare to dark matter abundance observation
- How well can we do?

RELIC DENSITY DETERMINATIONS

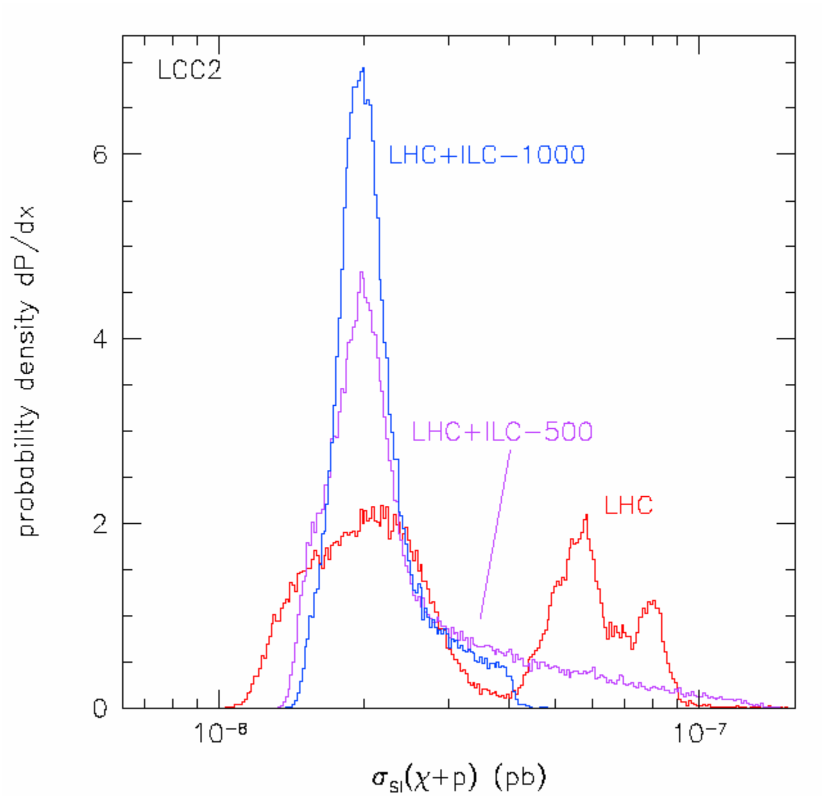


% level comparison of predicted Ω_{hep} with observed Ω_{cosmo}

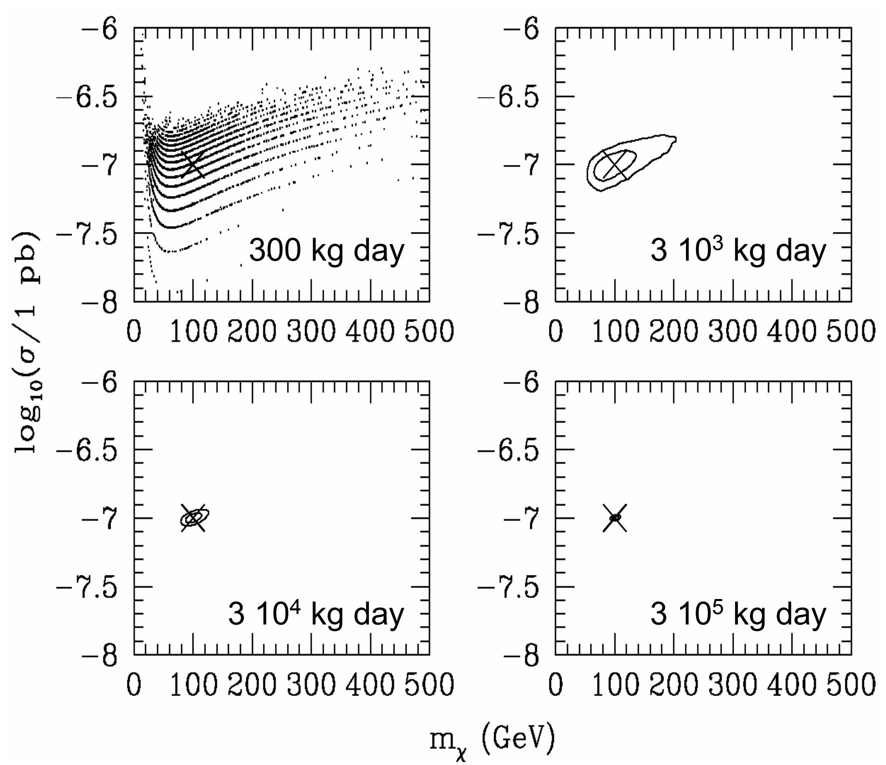
IDENTIFYING DARK MATTER



DIRECT DETECTION IMPLICATIONS



Baltz, Battaglia, Peskin, Wizansky (2006)



Green (2007)

Comparison tells us about local dark matter density and velocity profiles

INDIRECT DETECTION IMPLICATIONS

$$\frac{d\Phi_\gamma}{d\Omega dE} = \sum_i \underbrace{\frac{dN_\gamma^i}{dE}\sigma_i v \frac{1}{4\pi m_\chi^2}}_{\text{Particle Physics}} \underbrace{\int_\psi \rho^2 dl}_{\text{Astro-Physics}}$$

Gamma ray fluxes factorize

COLLIDERS ELIMINATE PARTICLE PHYSICS UNCERTAINTIES, ALLOW ONE TO PROBE ASTROPHYSICAL DISTRIBUTIONS

TAKING STOCK

- Neutralinos (and all WIMPs) are
  - Weakly-interacting
  - Cold
  - Stable

- Is this true of all DM candidates?

  No!

- Is this true of all SUSY candidates?

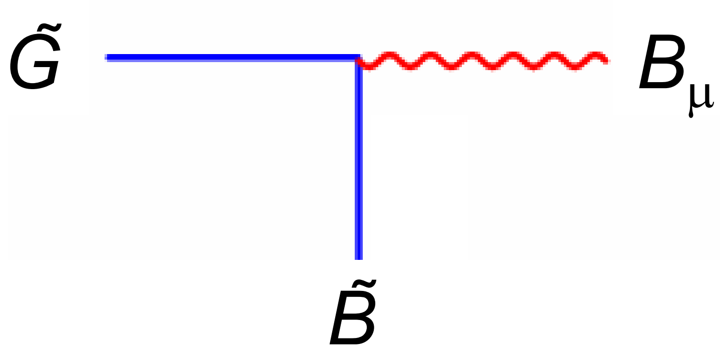
  No!

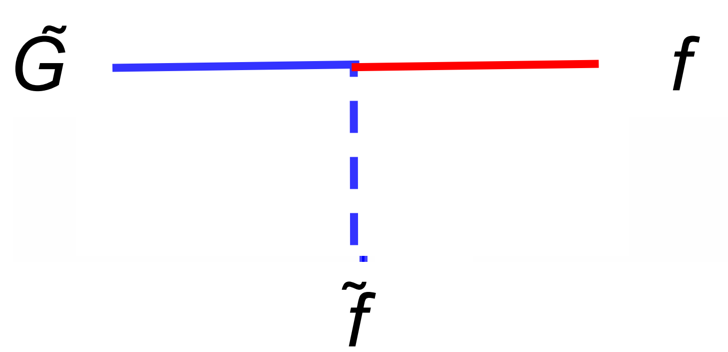
- Is this true of all SUSY candidates motivated by the "WIMP miracle"?

  No!

GRAVITINOS

- SUSY: graviton G → graviton $\tilde{G}$
- Gravitino properties
  - Spin 3/2
  - Mass: eV → 100 TeV
  - Interactions are superweak (weaker than weak)





Production Mechanisms

- Gravitinos are the original SUSY dark matter

Pagels, Primack (1982)
Weinberg (1982)
Krauss (1983)
Nanopoulos, Olive, Srednicki (1983)

Khlopov, Linde (1984)
Moroi, Murayama, Yamaguchi (1993)
Bolz, Buchmuller, Plumacher (1998)
Baltz, Murayama (2001)
…

Classic ideas:

- Gravitinos have thermal relic density

$$\Omega_{\tilde{G}} < 1 \Rightarrow m_{\tilde{G}} < 1 \text{ keV}$$

- For DM, require a new, energy scale (and entropy production)

- Weak scale gravitinos diluted by inflation, regenerated in reheating

$$\Omega_{\tilde{G}} < 1 \rightarrow T_{RH} < 10^{10} \text{ GeV}$$

- For DM, require a new, energy scale

VIRTUES AND DRAWBACKS

- Are these acceptable scenarios?
- Strictly speaking, yes – the only required DM interactions are gravitational (much weaker than weak)
- But they are not very testable, and they aren't motivated by the "WIMP miracle," which strongly prefers weak interactions

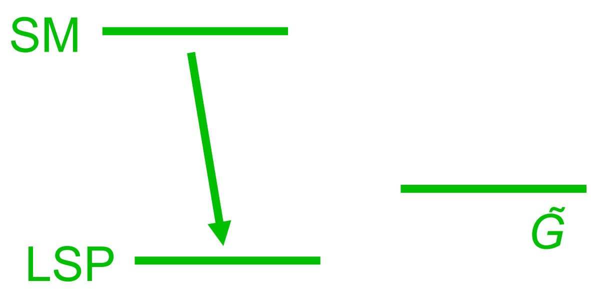
Can we fix these drawbacks?

SUPERWIMPS: BASIC IDEA

Feng, Rajaraman, Takayama (2003)

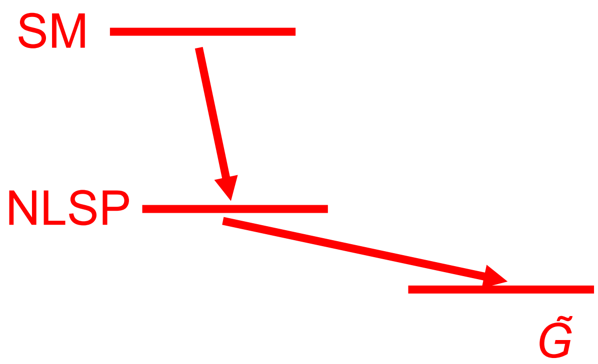
Gravitino mass ~ 100 GeV, couplings ~ M_W/M_{Pl} ~ 10^{-16}

- $\tilde{G}$ not LSP



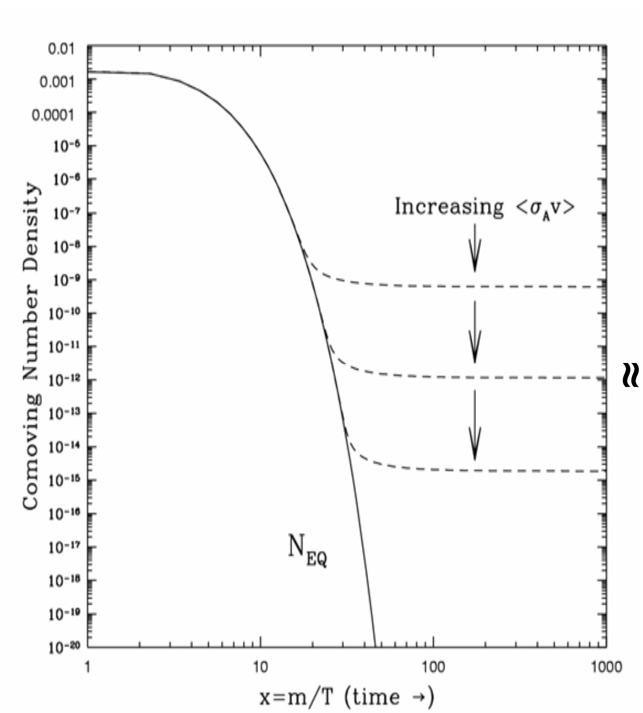
- Assumption of most of literature

- $\tilde{G}$ LSP

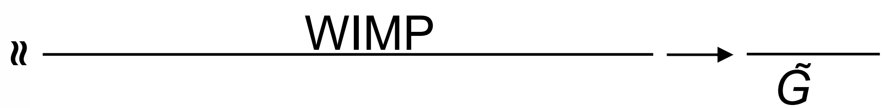


- Completely different cosmology and particle physics

SUPERWIMP RELICS



- Suppose gravitinos $\tilde{G}$ are the LSP
- WIMPs freeze out as usual



- But then all WIMPs decay to gravitinos after

  M_{Pl}^2/M_W^3 ~ hours to month

Gravitinos naturally inherit the right density, but interact only gravitationally – they are superWIMPs (also axinos, KK gravitons, quintessinos, etc.)

Feng, Rajaraman, Takayama (2003); Bi, Li, Zhang (2003); Ellis, Olive, Santoso, Spanos (2003); Wang, Yang (2004); Feng, Su, Takayama (2004); Buchmuller, Hamaguchi, Ratz, Yanagida (2004); Roszkowski, Ruiz de Austri, Choi (2004); Brandeburg, Covi, Hamaguchi, Roszkowski, Steffen (2005); …

SuperWIMP Detection

- SuperWIMPs evade all direct, indirect dark matter searches.

news@nature.com All the news you need

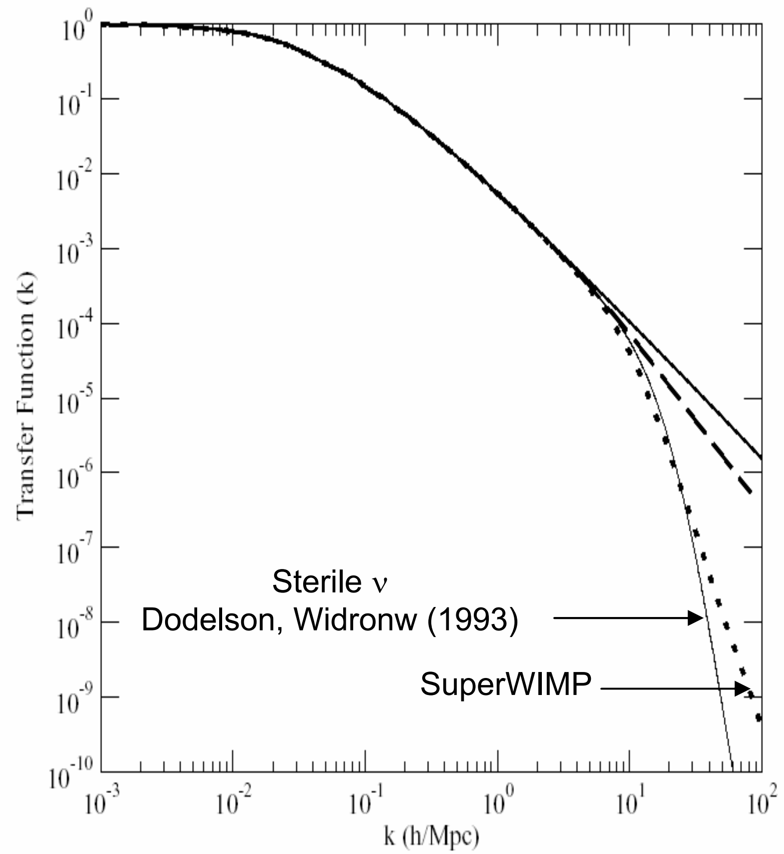
"Dark Matter may be Undetectable"

- But cosmology is complementary: Superweak interactions → very late decays to gravitinos → observable consequences.

- Signals
  - Small scale structure
  - Big Bang nucleosynthesis
  - CMB μ distortions

SMALL SCALE STRUCTURE

- SuperWIMPs are produced in late decays with large velocity (0.1c – c)
- Suppresses small scale structure, as determined by λ_{FS}, Q
- Warm DM with cold DM pedigree
- SUSY does not predict only CDM; small scale structure constrains SUSY

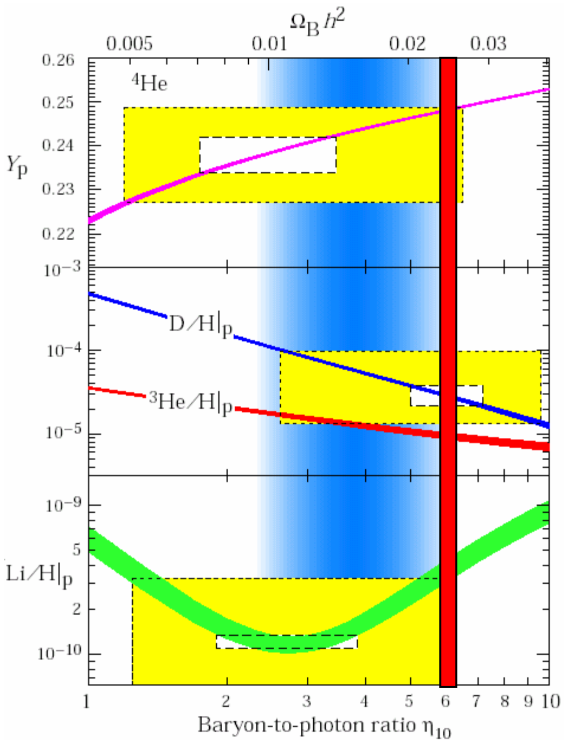


Kaplinghat (2005)

Dalcanton, Hogan (2000)
Lin, Huang, Zhang, Brandenberger (2001)
Sigurdson, Kamionkowski (2003)
Profumo, Sigurdson, Ullio, Kamionkowski (2004)
Kaplinghat (2005)
Cembranos, Feng, Rajaraman, Takayama (2005)
Strigari, Kaplinghat, Bullock (2006)
Bringmann, Borzumati, Ullio (2006)

BIG BANG NUCLEOSYNTHESIS

Late decays may modify light element abundances



Fields, Sarkar, PDG (2002)

After WMAP

- $\eta_D = \eta_{CMB}$
- Independent ^{7}Li measurements are all low by factor of 3:

$$^7\mathrm{Li/H} = 1.5^{+0.9}_{-0.5} \times 10^{-10} \quad (95\%\ \mathrm{CL})\ [27]$$
$$^7\mathrm{Li/H} = 1.72^{+0.28}_{-0.22} \times 10^{-10} \quad (1\sigma + \mathrm{sys})\ [28]$$
$$^7\mathrm{Li/H} = 1.23^{+0.68}_{-0.32} \times 10^{-10} \quad (\mathrm{stat} + \mathrm{sys},\ 95\%\ \mathrm{CL})\ [29]$$

BBN EM PREDICTIONS

- Consider $\tilde{\tau} \rightarrow \tilde{G}\, \tau$

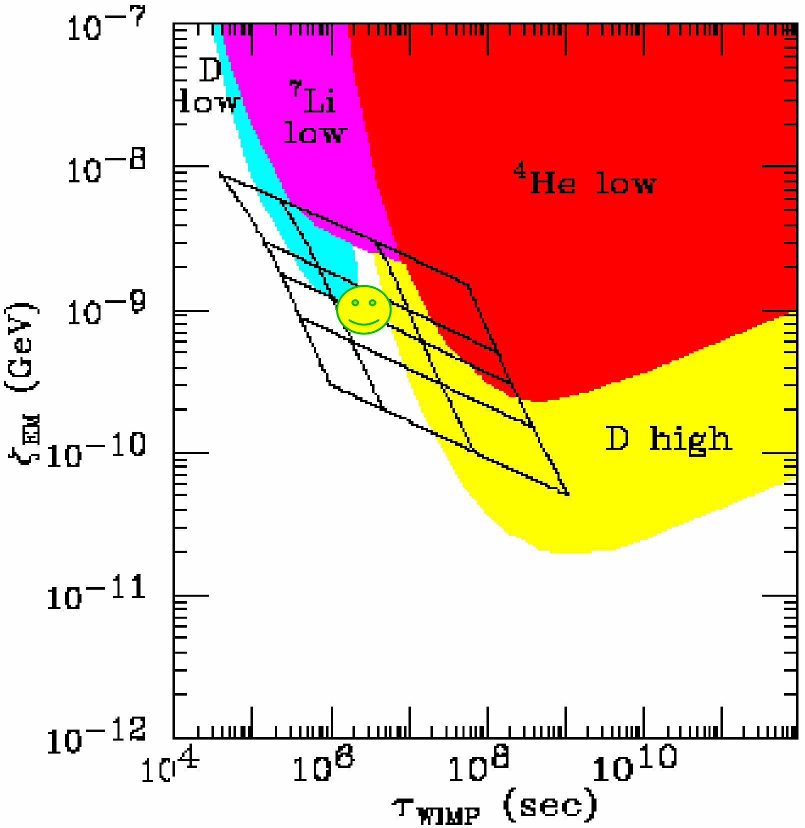
- Grid: Predictions for

  $m_{\tilde{G}}$ = 100 GeV – 3 TeV (top to bottom)

  Δm = 600 GeV – 100 GeV (left to right)

- Some parameter space excluded, but much survives

- SuperWIMP DM naturally explains ^{7}Li !



Feng, Rajaraman, Takayama (2003)

BBN RECENT DEVELOPMENTS

- Much recent progress, results depend sensitively on what particle decays to gravitino.

- Hadronic decays are important
  - constrain $\chi \rightarrow Z\,\tilde{G} \rightarrow q\,q\,\tilde{G}$
  - Slepton, sneutrino decays ok

Kawasaki, Kohri, Moroi (2004); Jedamzik (2004); Feng, Su, Takayama (2004);
Jedamzik, Choi, Roszkowski, Ruiz de Austri (2005)

- Charged particles catalyze BBN: $^4\mathrm{He}\,X^- + d \rightarrow {}^6\mathrm{Li} + X^-$
  - Constrain $\tilde{\tau} \rightarrow \tilde{G}\,\tau$ to lifetimes < 10^4 seconds
  - Neutralino, sneutrino decays ok

Pospelov (2006); Kaplinghat, Rajaraman (2006); Kohri, Takayama (2006);
Cyburt, Ellis, Fields, Olive, Spanos (2006); Hamaguchi, Hatsuda, Kamimura, Kino, Yanagida (2007);
Bird, Koopmans, Pospelov (2007); Takayama (2007)

SUPERWIMPS AT COLLIDERS

- Each SUSY event may produce 2 metastable sleptons

  Spectacular signature: slow, highly-ionizing charged tracks

Current bound (LEP): $m_{\tilde{l}} > 99$ GeV

Tevatron reach: $m_{\tilde{l}} \sim 180$ GeV for 10 fb^{-1} (now?)

LHC reach: $m_{\tilde{l}} \sim 700$ GeV for 100 fb^{-1}

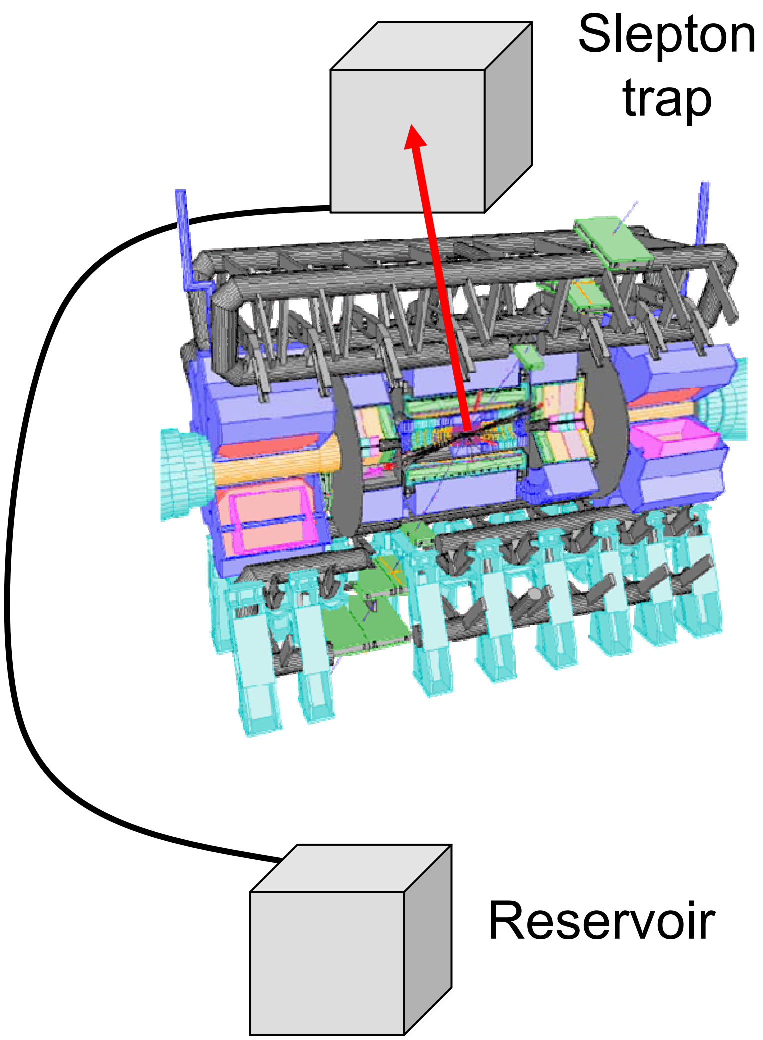
Drees, Tata (1990)
Goity, Kossler, Sher (1993)
Feng, Moroi (1996)

Hoffman, Stuart et al. (1997)
Acosta (2002)
…

Slepton Trapping

- Sleptons can be trapped and moved to a quiet environment to study their decays
- Crucial question: how many can be trapped by a reasonably sized trap in a reasonable time?

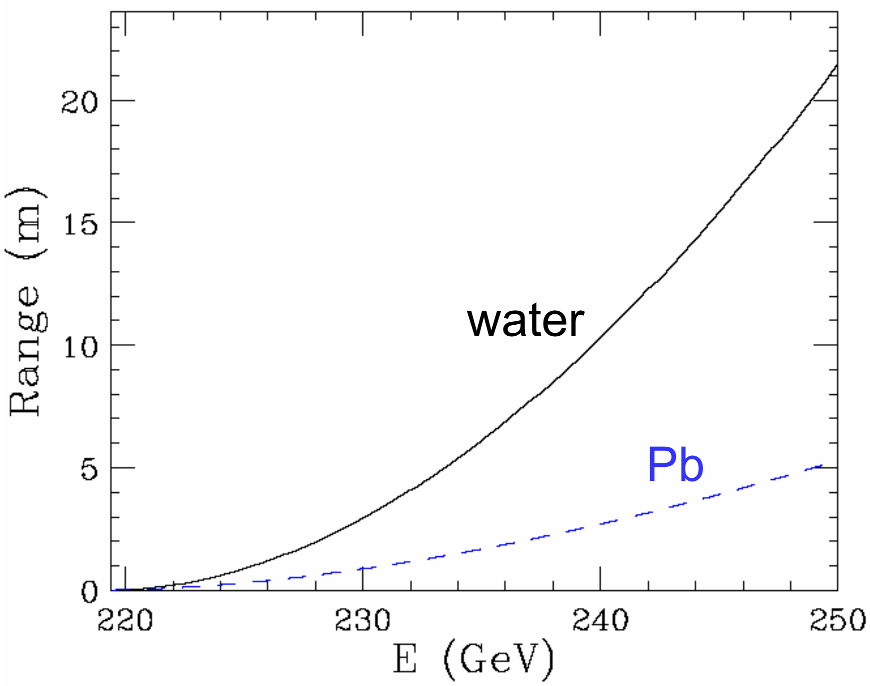
Feng, Smith (2004)
Hamaguchi, Kuno, Nakawa, Nojiri (2004)
De Roeck et al. (2005)



Slepton Range

- Ionization energy loss described by Bethe-Bloch equation:

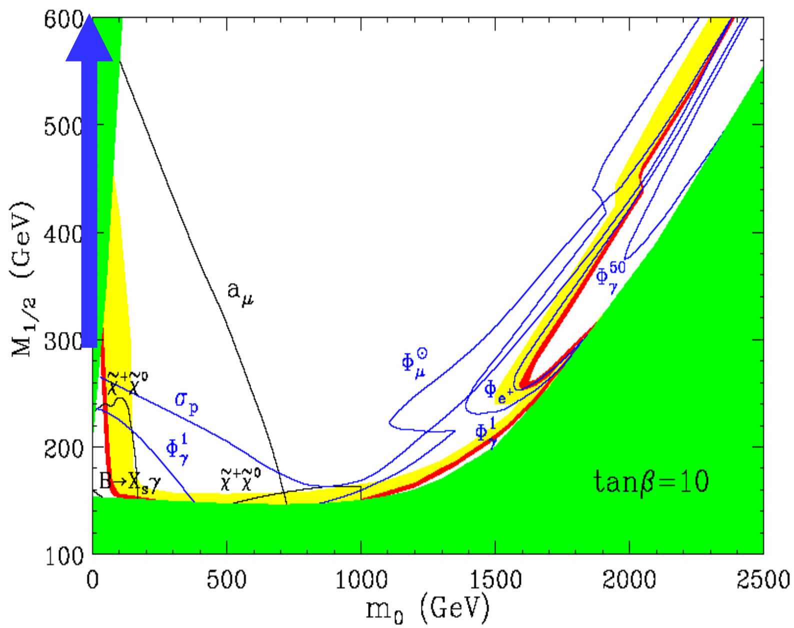
$$\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \left(\frac{2m_e c^2 \beta^2 \gamma^2}{I \sqrt{1 + \frac{2m_e \gamma}{M} + \frac{m_e^2}{M^2}}} \right) - \beta^2 - \frac{\delta}{2} \right]$$

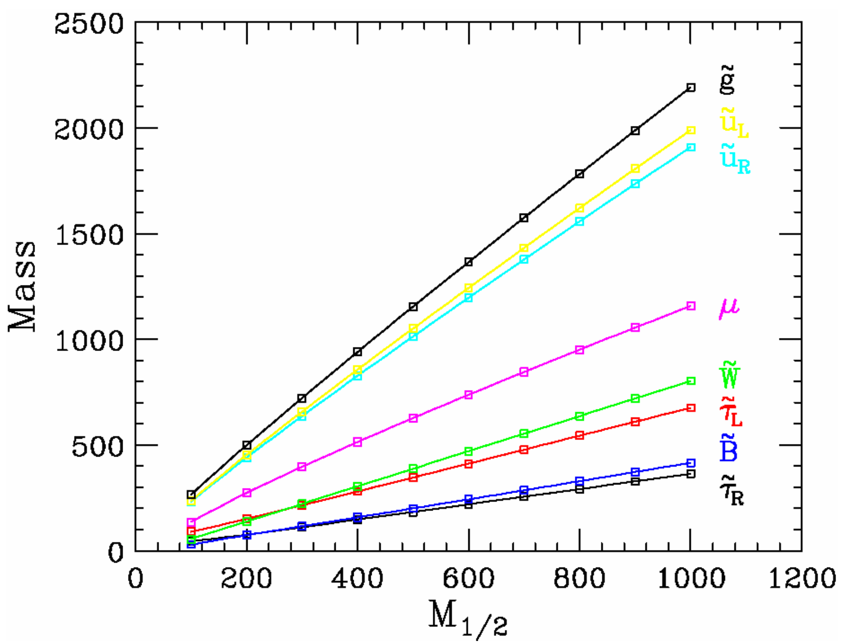


$m_{\tilde{l}}$ = 219 GeV

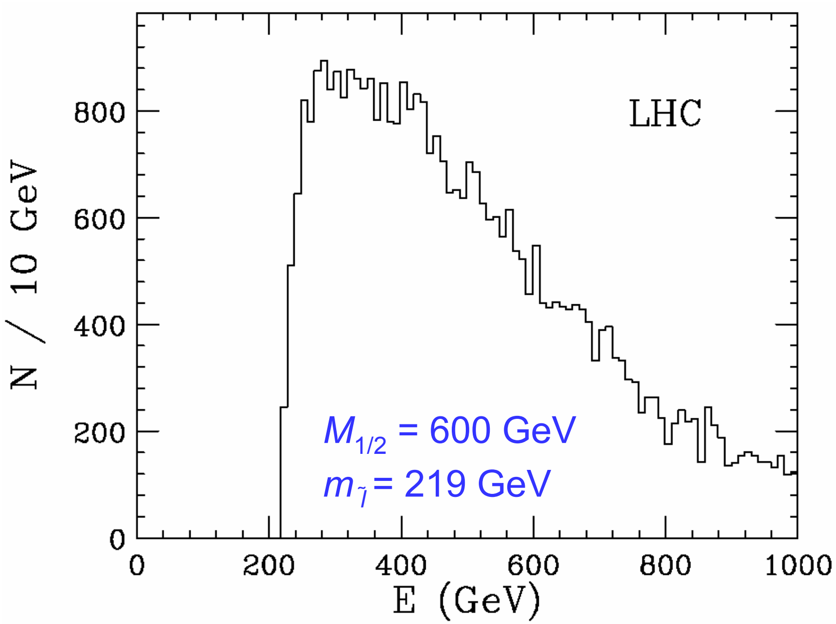
Model Framework

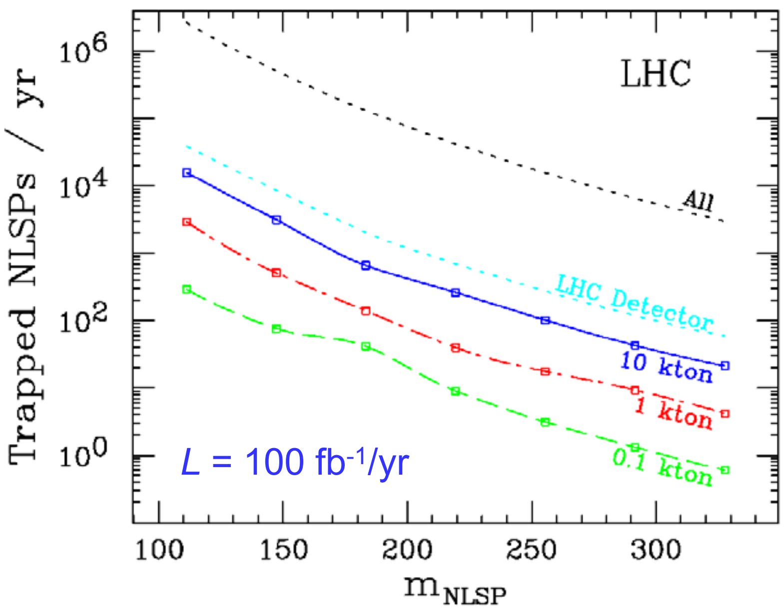
- Results depend heavily on the entire SUSY spectrum
- Consider mSUGRA with $m_0 = A_0 = 0$, $\tan\beta = 10$, $\mu > 0$
  $M_{1/2}$ = 300, 400,…, 900 GeV





Large Hadron Collider



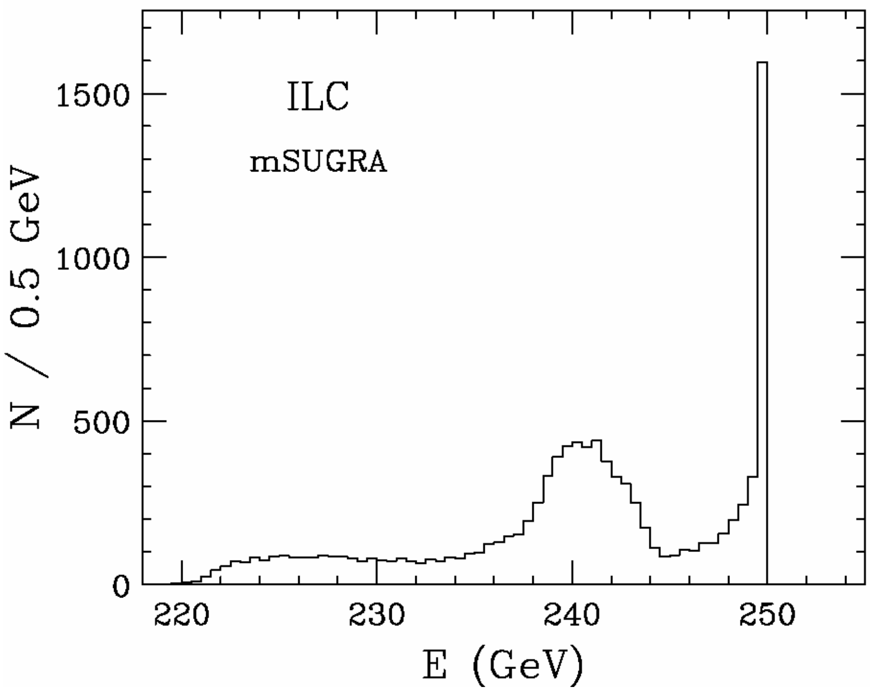


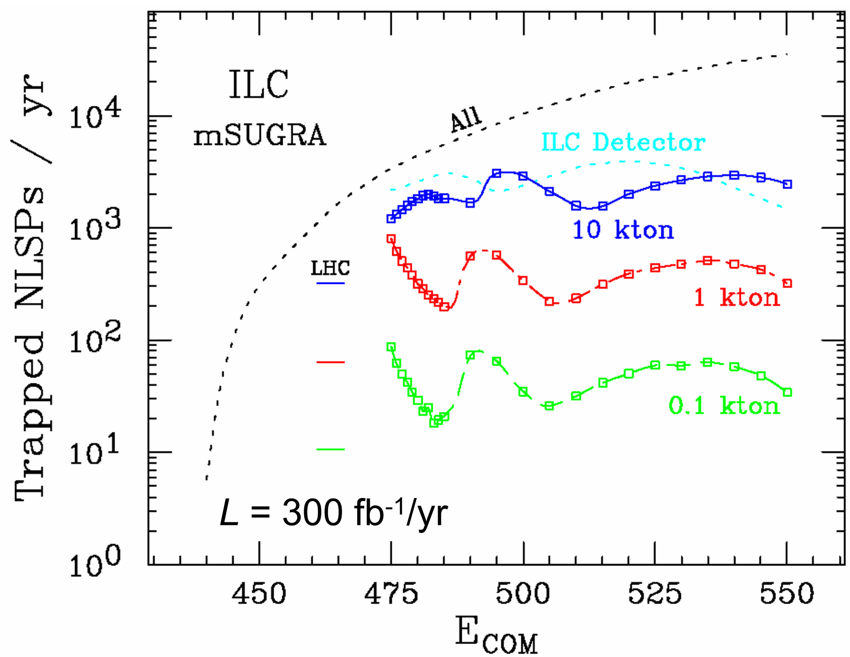
Of the sleptons produced, $O(1)$% are caught in 10 kton trap

10 to 10^4 trapped sleptons in 10 kton trap (1 m thick)

International Linear Collider

m_χ	242.9 GeV	mSUGRA
$m_{\tilde{e}_R}, m_{\tilde{\mu}_R}$	227.2 GeV	mSUGRA
$m_{\tilde{\tau}_R}$	219.3 GeV	} NLSP only; mSUGRA





Sleptons are slow, most can be caught in 10 kton trap

Factor of ~10 improvement over LHC

Measuring $m_{\tilde{G}}$ and M_*

- Decay width to $\tilde{G}$:

$$\Gamma(\tilde{\ell} \to \ell \tilde{G}) = \frac{1}{48\pi M_*^2} \frac{m_{\tilde{\ell}}^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\ell}}^2}\right]^4$$

- Measurement of Γ → $m_{\tilde{G}}$
  - → $\Omega_{\tilde{G}}$. SuperWIMP contribution to dark matter
  - → *F*. Supersymmetry breaking scale, dark energy
  - → Early universe (BBN, CMB) in the lab
- Measurement of Γ *and* E_l → $m_{\tilde{G}}$ *and* M_*
  - → Precise test of supergravity: gravitino is graviton partner
  - → Measurement of G_{Newton} on fundamental particle scale
  - → Probes gravitational interaction in particle experiment

Hamaguchi et al. (2004); Takayama et al. (2004)

ARE WIMPS STABLE?

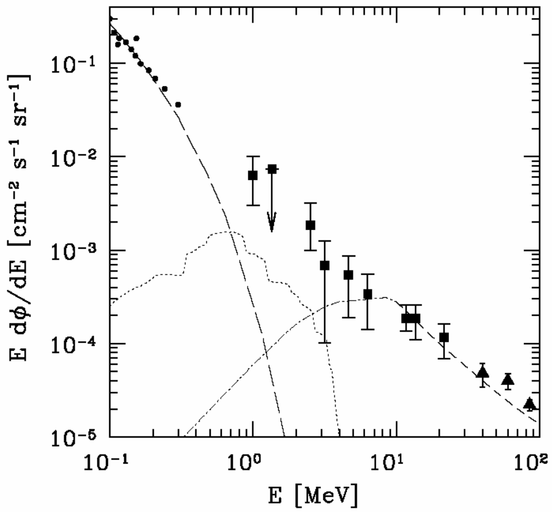
- Not necessarily. In fact, they can be decaying now:

$$\chi \rightarrow \gamma \tilde{G}$$

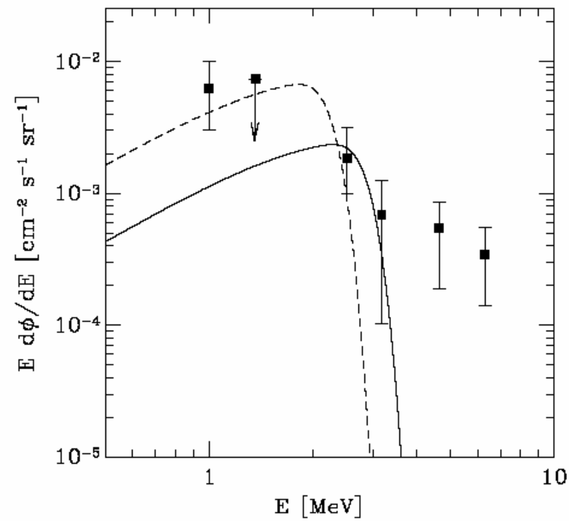
- Signals in the diffuse photon flux, completely determined by 1 parameter:

$$\tau \simeq \frac{3\pi}{b\cos^2\theta_W}\frac{M_P^2}{(\Delta m)^3} \simeq \frac{4.7\times 10^{22}\ \mathrm{s}}{b}\left[\frac{\mathrm{MeV}}{\Delta m}\right]^3$$

Observations and Background



SUSY Signal



Cembranos, Feng, Strigari (2007)

CONCLUSIONS

- Weak-scale DM has never been more motivated
  - Cosmological legacy of LEP: stability of a new particle is common feature of viable particle models
- SUSY provides many well-motivated, and qualitatively different, candidates
  - WIMPs and superWIMPs
  - Cold and warm
  - Stable and metastable
- If anything mentioned here is correct, life will be very interesting in the coming years