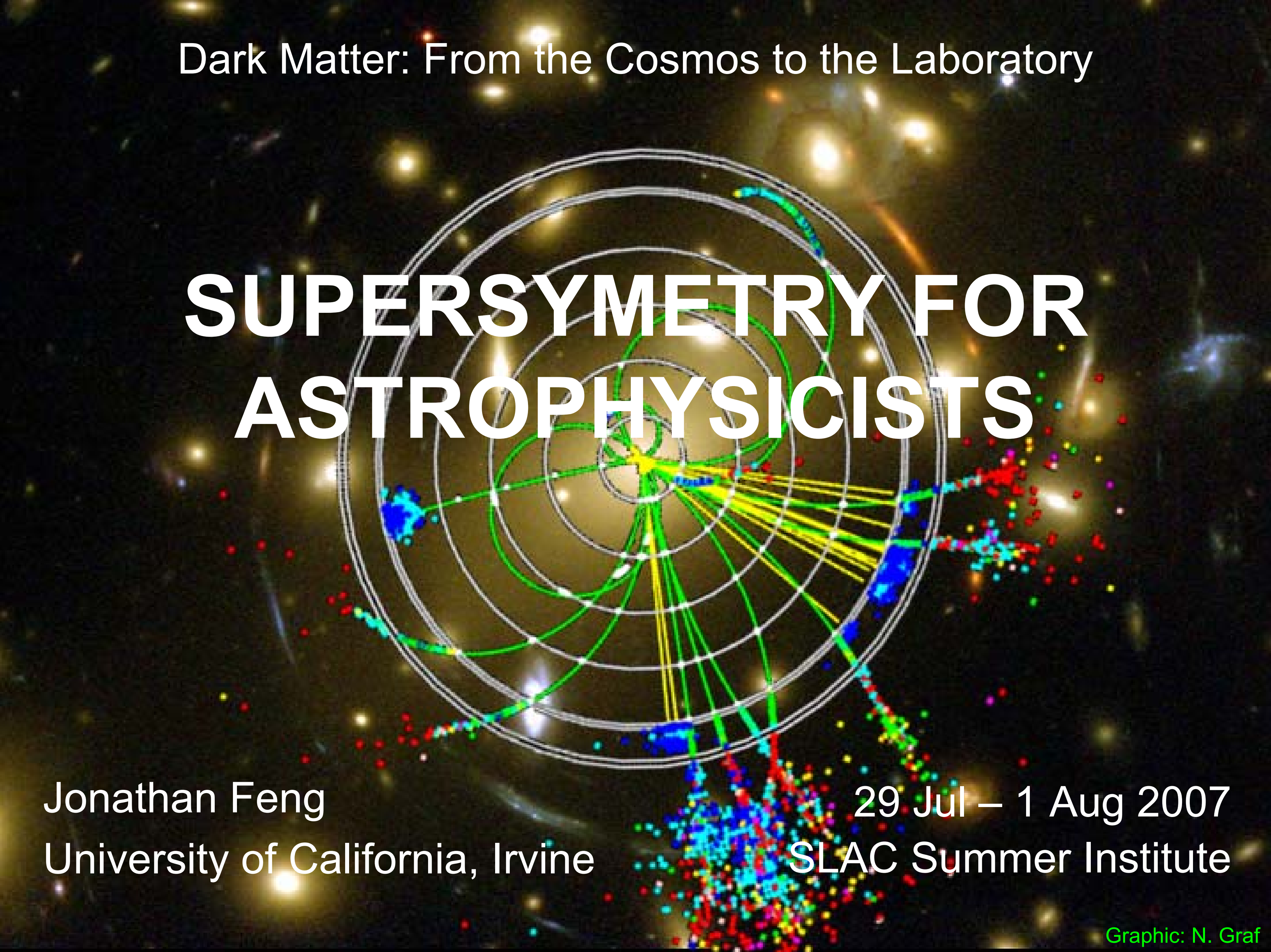
Dark Matter: From the Cosmos to the Laboratory



SUPERSYMETRY FOR ASTROPHYSICISTS

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SLAC Summer Institute

Graphic: N. Graf

POLLING DATA

I’m giving summer school lectures titled, “Supersymmetry for Astrophysicists.” What should I talk about?

- Astrophysicist #1: “Beats me. I couldn’t care less about supersymmetry. Maybe you can get out of it somehow.”
- Astrophysicist #2: “Dark matter, of course. Isn’t that the only motivation for supersymmetry?”

OUTLINE

LECTURE 1: SUSY ESSENTIALS

Standard Model; SUSY Motivations; LSP Stability and Candidates

LECTURE 2: NEUTRALINOS

Properties; Production; Direct Detection; Indirect Detection; Collider Signals

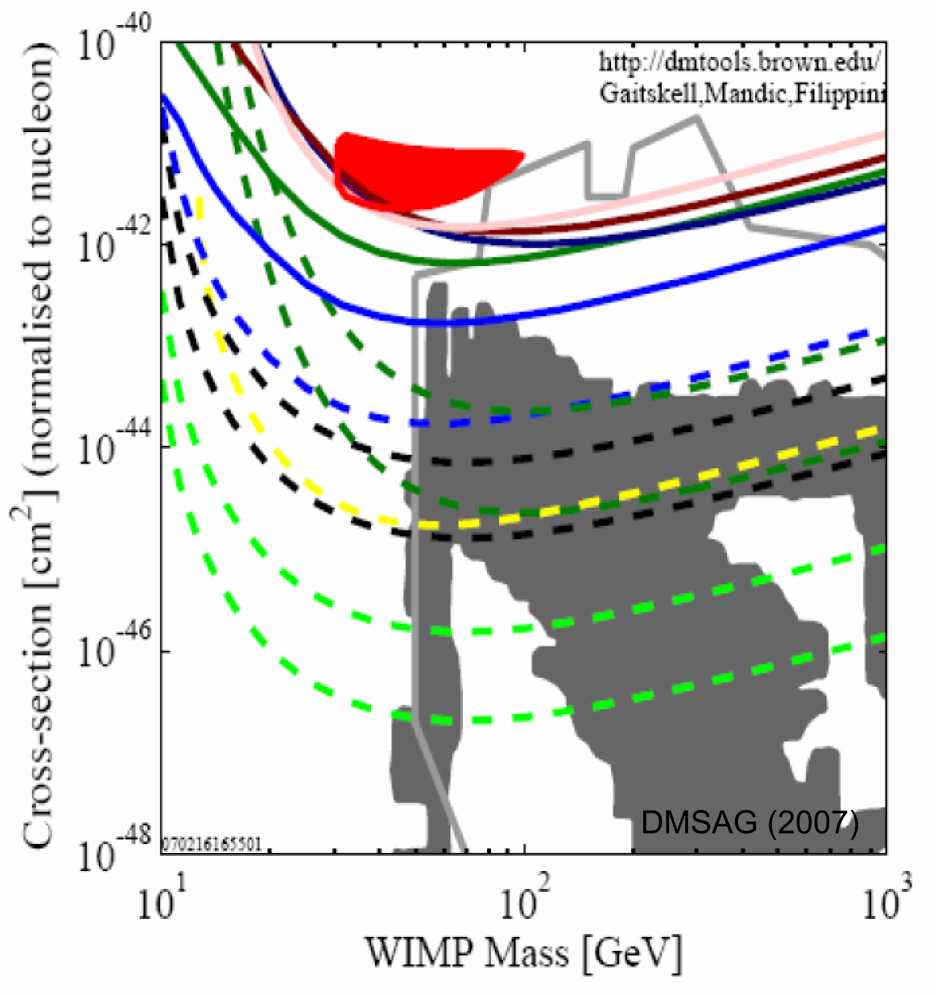
LECTURE 3: GRAVITINOS

Properties; Production; Astrophysical Detection; Collider Signals

SUSY ESSENTIALS

First discuss motivations for supersymmetry. Why?

- Supersymmetry is the best motivated framework for new particle physics
- Generic properties vs. special models (What do these shaded regions mean?)
- Direct implications for astrophysics



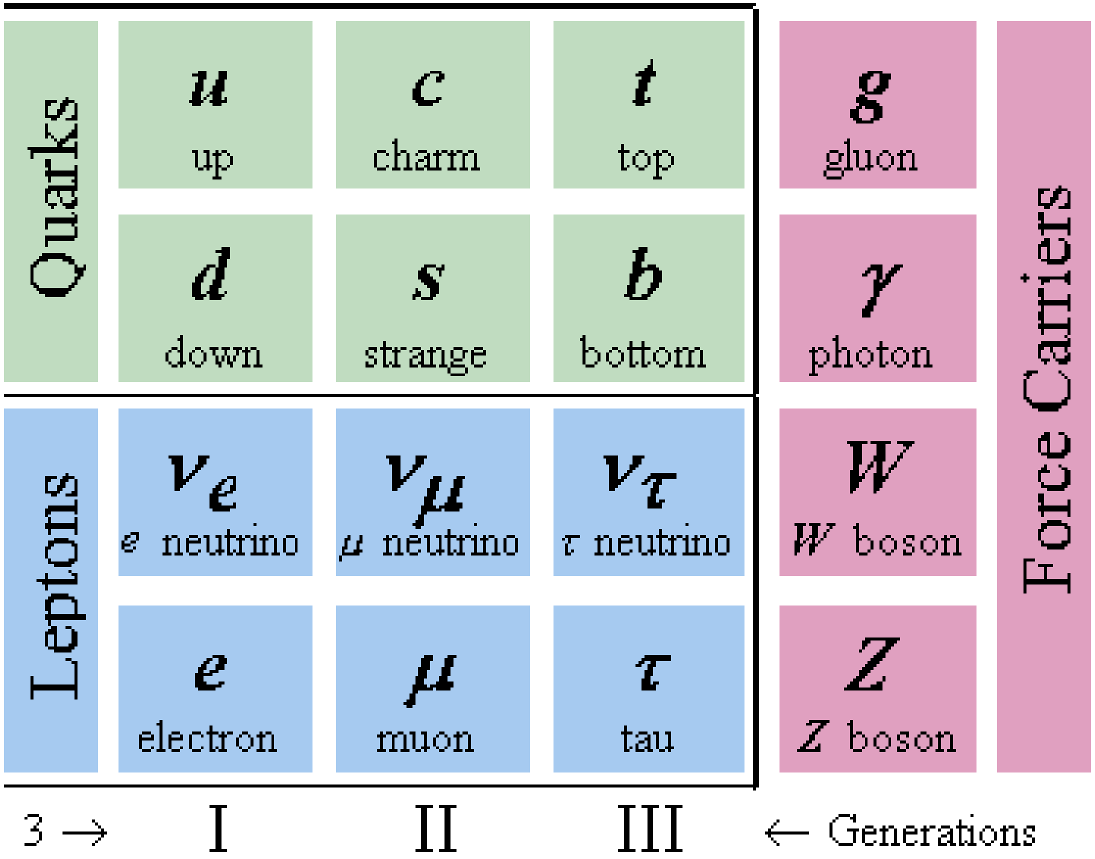
DMSAG (2007)

STANDARD MODEL

- Matter Particles
  - Quarks and leptons
  - Spin ½ fermions

- Force Particles
  - Photon (EM)
  - *W*, *Z* (weak)
  - Gluons (strong)
  - Spin 1 bosons

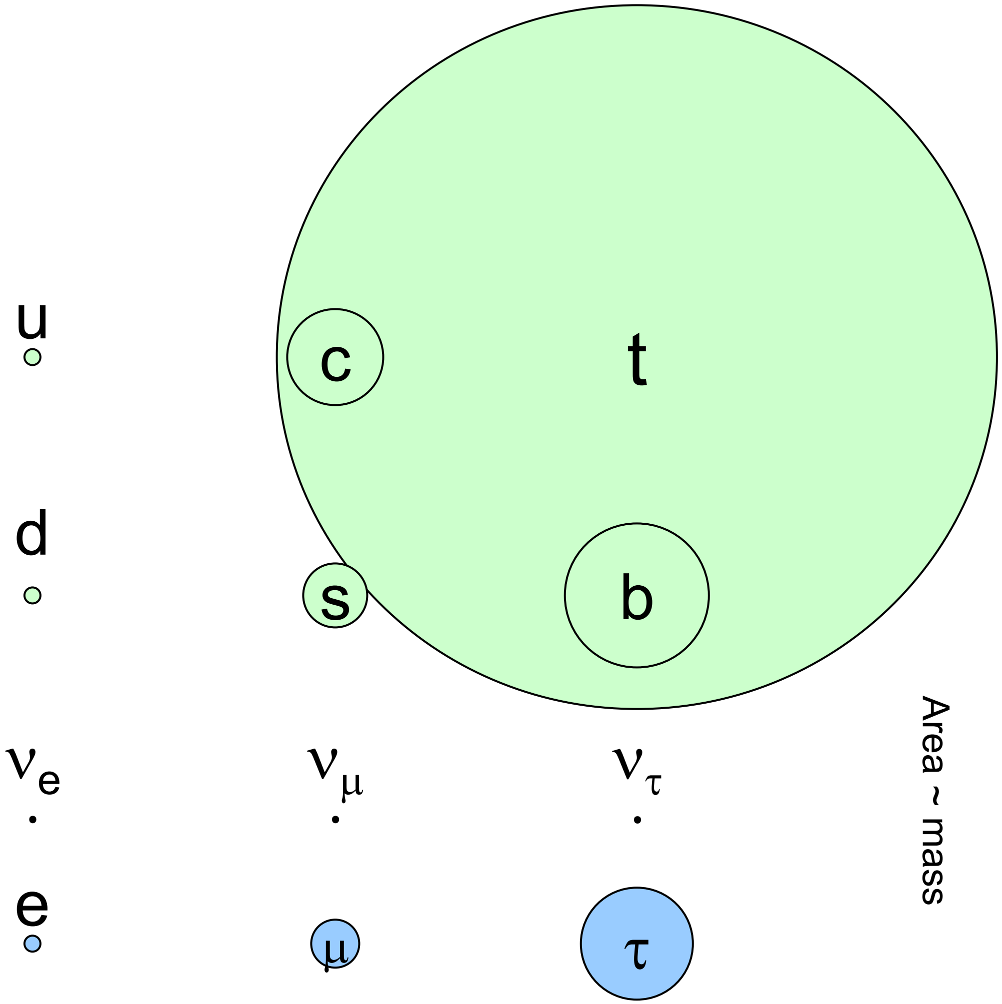
- Higgs Particle
  - Undiscovered
  - Spin 0 boson



Quarks	u up	c charm	t top	g gluon	Force Carriers
	d down	s strange	b bottom	γ photon	
Leptons	ν_e e neutrino	ν_μ μ neutrino	ν_τ τ neutrino	W W boson	
	e electron	μ muon	τ tau	Z Z boson	
3 →	I	II	III	← Generations	

Matter Particles

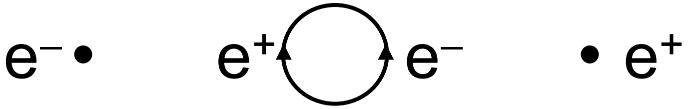
- Most of the unexplained parameters of the SM are here
- Interactions determined by unusual quantum numbers
- Masses span at least 11 orders of magnitude
  - Neutrinos ~ eV
  - Electron: 511 keV
  - Top quark: 171 GeV
- The top quark is heavy!

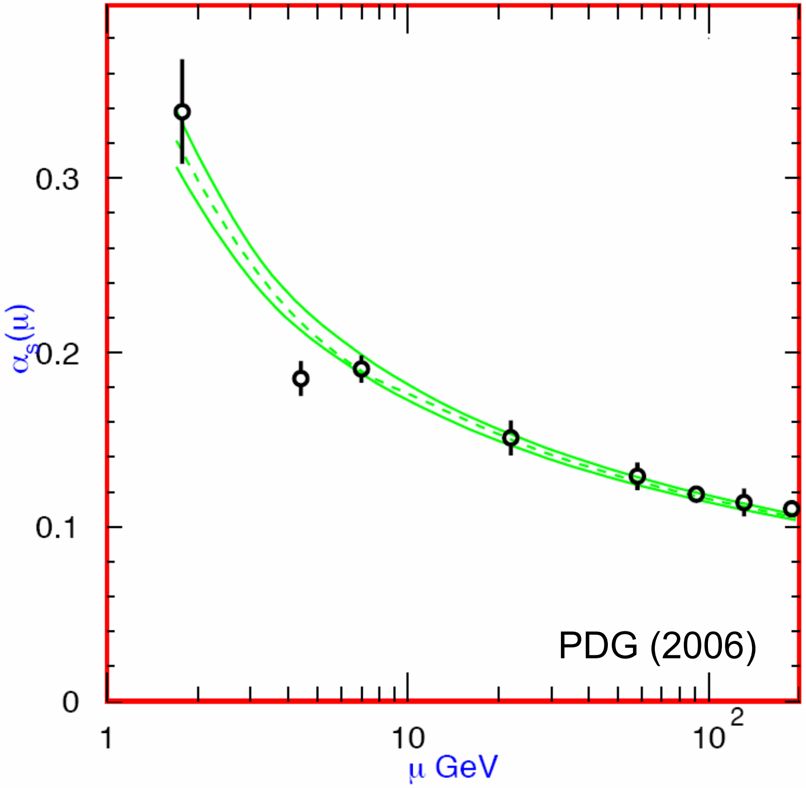


Force Particles

- Couplings $\alpha \equiv g^2/(4\pi)$ at m_Z
  - $\alpha_{EM} = 0.007818 \pm 0.000001$
  - $\alpha_{weak} = 0.03381 \pm 0.00002$
  - $\alpha_s = 0.118 \pm 0.002$
- At observable energies,

  $\alpha_{EM} < \alpha_{weak} < \alpha_s$
- Precisely measured
- Scale-dependent – the quantum vacuum has dielectric properties



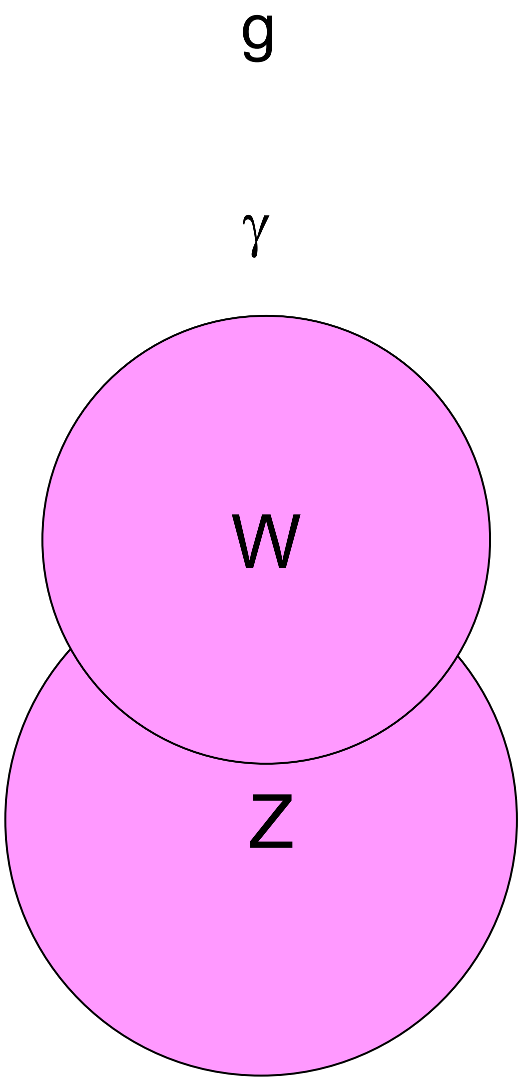


PDG (2006)

Force Particles

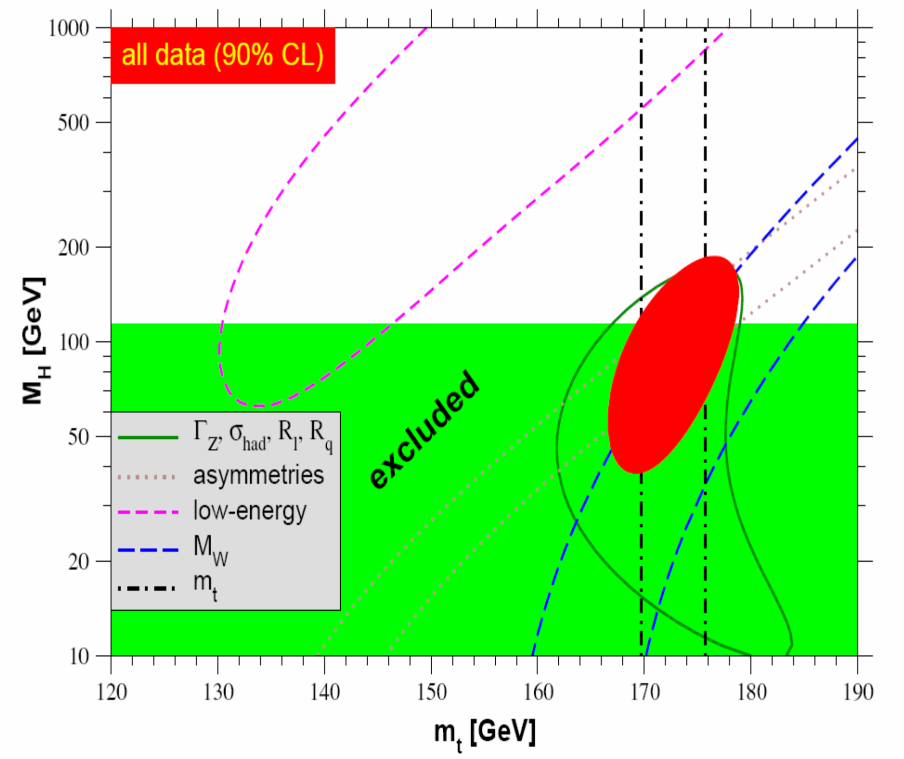
- Masses
  - $m_\gamma = 0$: U(1) conserved
  - $m_g = 0$: SU(3) conserved
  - $m_W = 80$ GeV: SU(2) broken
  - $m_Z = 91$ GeV: SU(2) broken

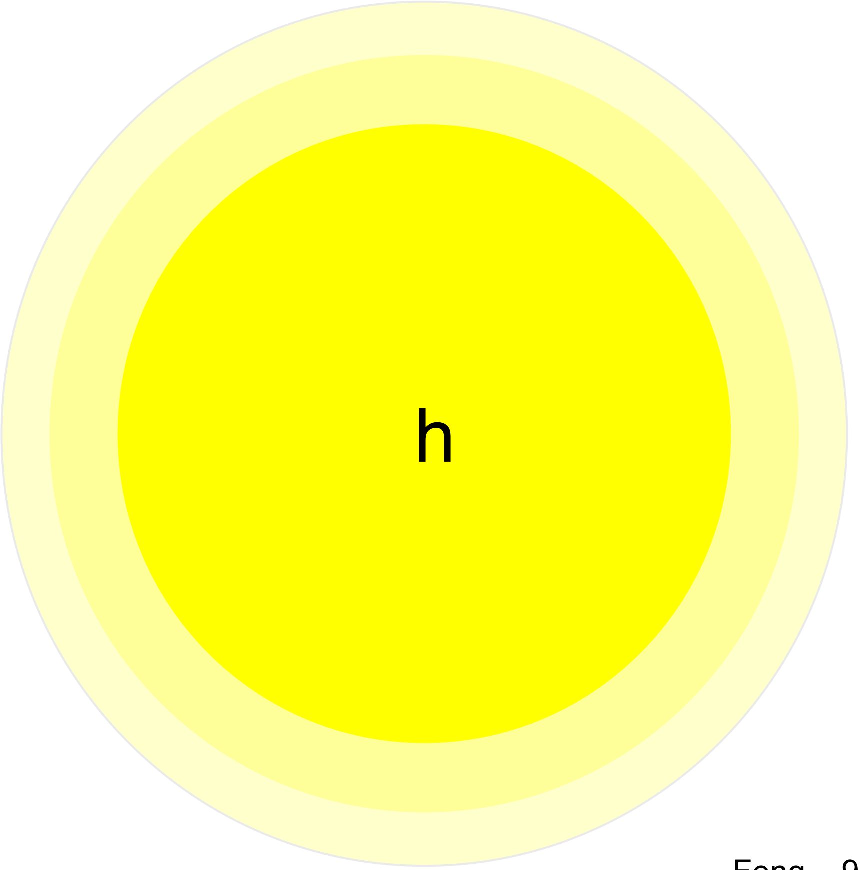
- SU(2) is broken, the others aren't



Higgs Particle

- Mass
  - Direct searches: $m_h > 115$ GeV
  - Indirect constraints from precision data: 40 GeV $< m_h <$ 200 GeV





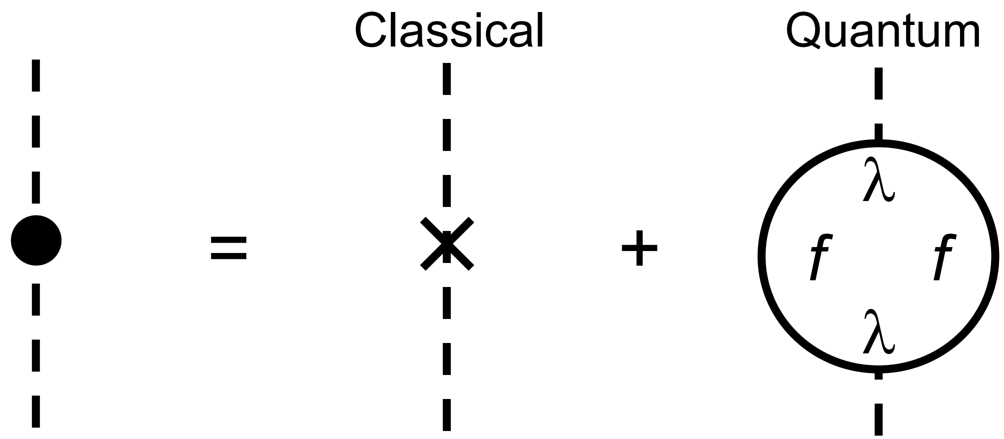
NATURALNESS

- We know 3 fundamental constants
  - Special relativity: speed of light c
  - Quantum mechanics: Planck's constant h
  - General relativity: Newton's constant G
- From these we can form the Planck mass

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

- Why are m_h, m_W, m_Z, … << M_{Pl}?

Gauge Hierarchy Problem



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

In the SM, m_h is naturally ~ Λ, the largest energy scale

m_h ~ 100 GeV, Λ ~ 10^{19} GeV → cancellation of 1 part in 10^{34}

SUPERSYMMETRY

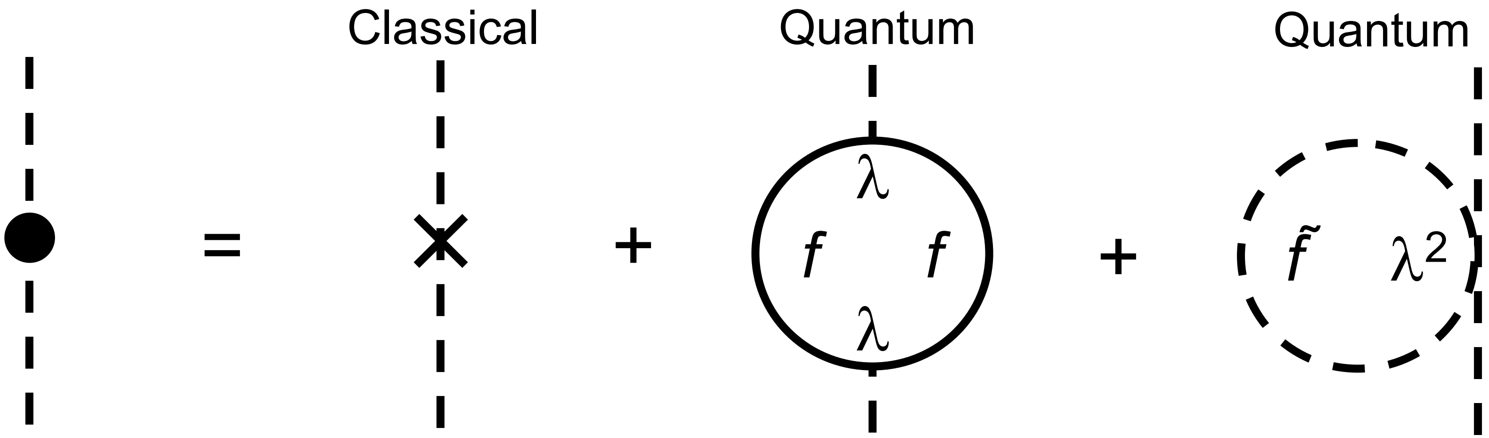
SYMMETRIES OF NATURE	Exact	Broken
Gauge	$U(1)_{EM,}$ $SU(3)_c$	$SU(2) \times U(1)_Y$
Global	B, L	L_e , L_μ , L_τ
Spacetime	Rotations, Boosts, Translations	SUSY

Supersymmetry is a qualitatively new class of symmetry

Superpartners

- Translations: particle P at x → particle P at x’
- SUSY: particle P at x → particle P̃ at x, where
  - P and P̃ differ in spin by ½: fermions ↔ bosons
  - P and P̃ are identical in all other ways (mass, couplings)
- New particles
  - Superpartners of matter particles: Spin 0 bosons, add “s” (selectron, sneutrinos, squark, …)
  - Superpartners of force particles: Spin ½ fermions, add “ino” (photino, Wino, …)
  - Superpartners of Higgs particles: Spin ½ fermions, “Higgsinos”

SUSY AND NATURALNESS



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

Dependence on Λ is softened to a logarithm

SUSY solves the gauge hierarchy problem, even if broken, provided superpartner masses are ~ 100 GeV

Higgs Doubling

- SUSY requires 2 Higgs doublets to cancel anomalies and to give mass to both up- and down-type particles

- E.g., anomaly cancelation requires $\Sigma Y^3 = 0$, where Y is hypercharge and the sum is over fermions. This holds in the SM

- SUSY adds an extra fermion 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 we add another Higgs doublet with Y = +1:

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

SUSY PARAMETERS

SUSY breaking introduces many unknown parameters. These are

- Masses for sleptons and squarks: $m^2_{\tilde{f}\,ij}$
- Masses for gauginos: M_1 , M_2 , M_3
- Trilinear scalar couplings (similar to Yukawa couplings): A^f_{ij}
- Mass for the 2 Higgsinos: $\mu \tilde{H}_u \tilde{H}_d$
- Masses for the 2 neutral Higgs bosons: $B H_u H_d + m^2_{Hu} |H_u|^2 + m^2_{Hd} |H_d|^2$
- The 2 neutral Higgs bosons both contribute to electroweak symmetry breaking:

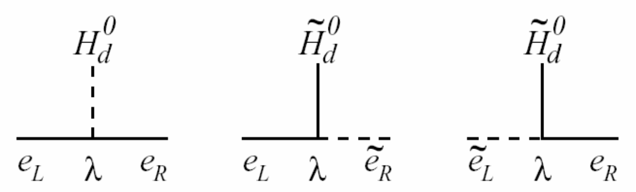
$$v^2 = (174 \text{ GeV})^2 \rightarrow v_u^2 + v_d^2 = (174 \text{ GeV})^2$$

The extra degree of freedom is called $\tan\beta = v_u/v_d$

TAKING STOCK

- SUSY is a single symmetry, which implies many new particles

- Many new parameters, but
  - Dimensionless couplings are fixed (no “hard” breaking)

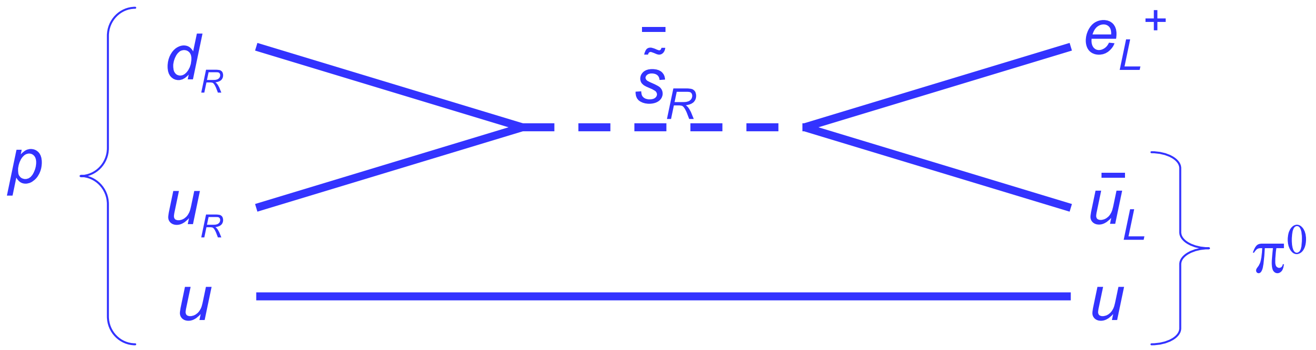


  - Dimensionful parameters are allowed (soft breaking), but should be ~ 100 GeV
  - Even the dimensionful parameters cannot be arbitrary

Analogy	Soap Bubble	SM
Large Parameter	Length L Height H	M_{Pl}
Small Parameter	L - H	m_h
Symmetry explanation	Rotational invariance	SUSY
Symmetry breaking	Gravity	M_{SUSY}
Natural if	Gravity weak	M_{SUSY} small

R-PARITY AND STABLE SUPERPARTNERS

- One 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 $R_p = -1$
  - – Requires 2 superpartners in each interaction

- Consequence: the lightest SUSY particle (LSP) is stable and cosmologically significant. What is the LSP?

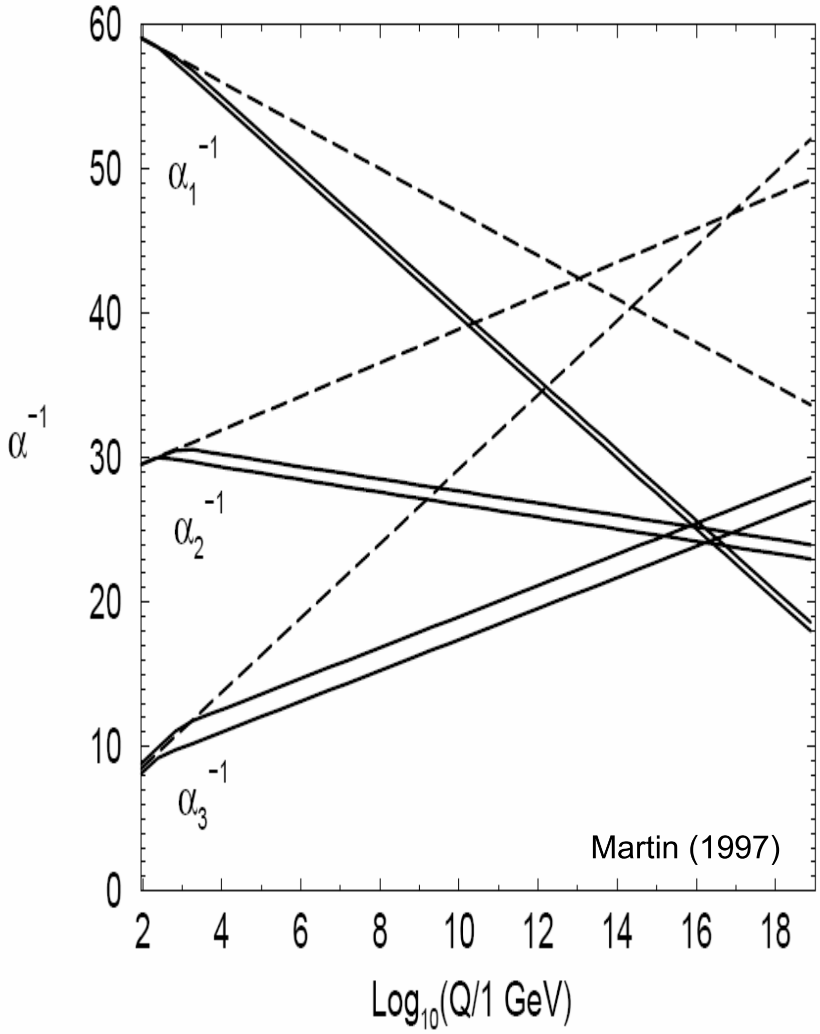
Neutral SUSY Particles

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

FORCE UNIFICATION

- Can the 3 forces be unified, e.g., SU(3) x SU(2) x U(1) → SO(10)?
- Superpartners modify the scale dependence of couplings
- With TeV superpartners, 3 couplings meet at a point!
  - No free parameters
  - % level "coincidence"
  - Coupling at unification: $\alpha^{-1} > 1$
  - Scale of unification
    - $Q > 10^{16}$ GeV (proton decay)
    - $Q < 10^{19}$ GeV (quantum gravity)
- SUSY explains $\alpha_{EM} < \alpha_{weak} < \alpha_s$
- Gaugino mass unification implies $M_1:M_2:M_3 \approx \alpha_1:\alpha_2:\alpha_3 \approx$ 1:2:7, the Bino is the lightest gaugino



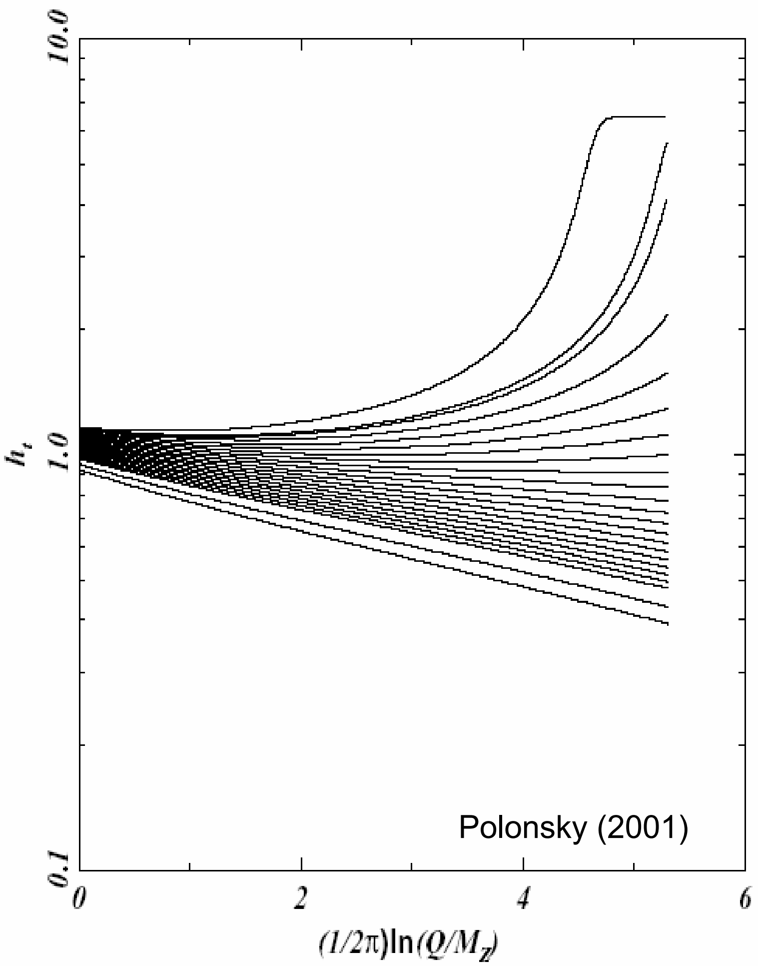
TOP QUARK MASS

- Force unification suggests we can extrapolate to very high energy scales

- All parameters (masses, couplings) have scale dependence

- The top quark Yukawa coupling has a quasi-fixed point near its measured value

- SUSY “explains” heavy top



Polonsky (2001)

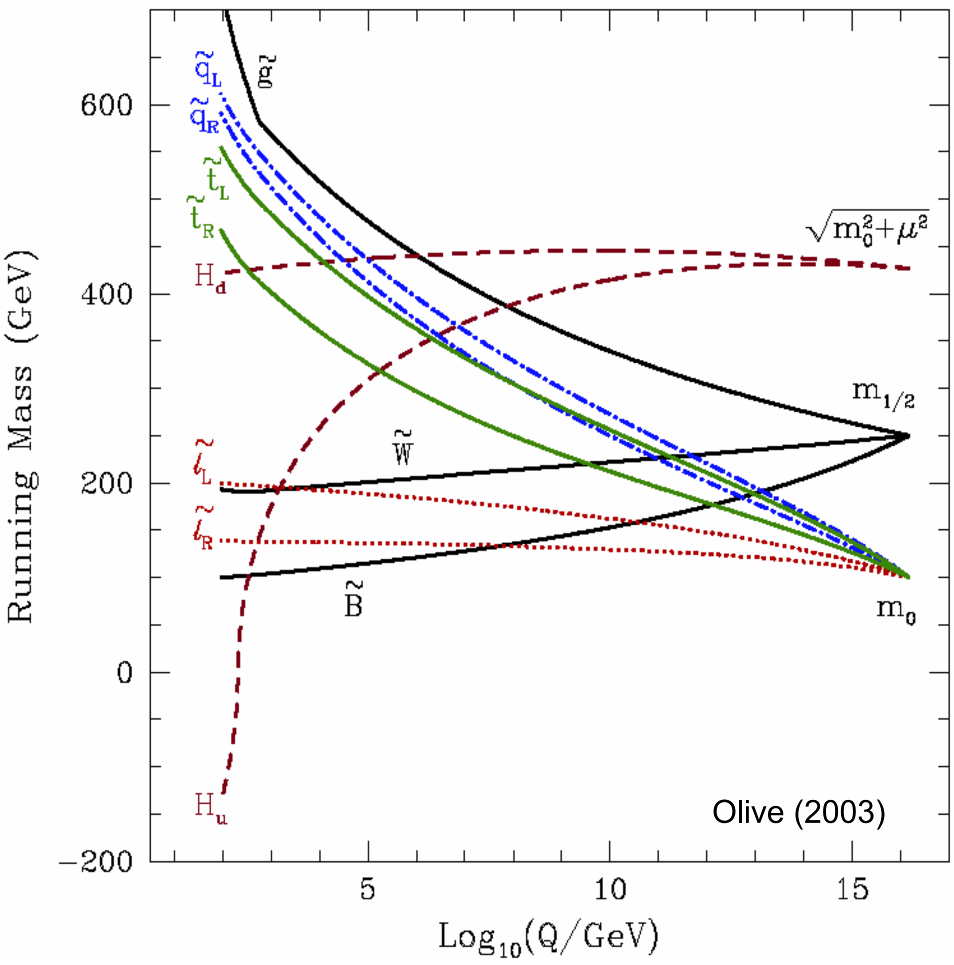
SCALAR MASSES

- How do scalar masses change with scale?

- Gauge couplings increase masses; Yukawa couplings decrease masses

- H_u has large top quark Yukawa, but no compensating strong interaction

- H_u is the lightest scalar. In fact, it's typically tachyonic!



Olive (2003)

ELECTROWEAK SYMMETRY BREAKING

- The Higgs boson potential is

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

- Minimizing this, one finds (for moderate/large tanβ)

$$\frac{1}{2}m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - |\mu|^2 \approx -m_{H_u}^2 - |\mu|^2$$

- EWSB requires $m_{Hu}^2 < 0$

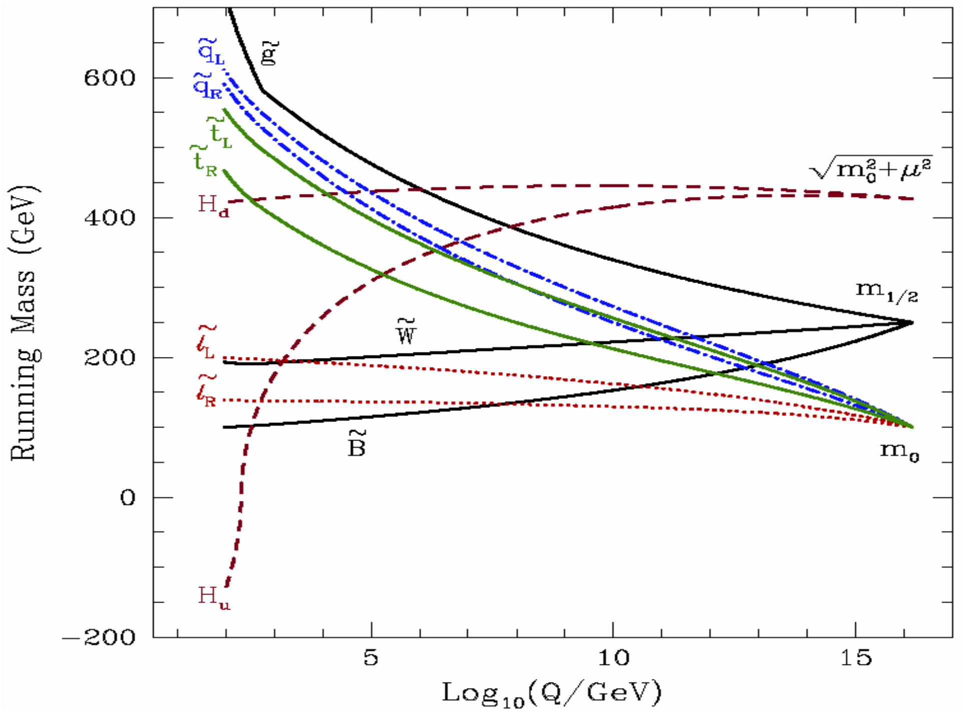
SUSY explains why SU(2) is broken and SU(3) and U(1) aren't

SNEUTRINOS AND HIGGSINOS

- Lightest physical scalars are typically the right-handed sleptons

- Sneutrinos
  - have SU(2) interactions, and so are typically heavier
  - Disfavored as LSPs by direct searches

- EWSB also fixes Higgsino mass μ



$$\frac{1}{2}m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - |\mu|^2$$

LECTURE 1 SUMMARY

- The Standard Model is incomplete

- SUSY provides elegant solutions
  - Naturalness
  - Force unification
  - Electroweak symmetry breaking

- Proton decay → R-parity, stable LSP

- Natural LSPs: neutralino (Bino/Higgsino), gravitino

OUTLINE

LECTURE 1: SUSY ESSENTIALS

The Standard Model; Motivations; Key Features

LECTURE 2: NEUTRALINOS

Properties; Production; Direct Detection; Indirect Detection; Collider Signals

LECTURE 3: GRAVITINOS

Properties; Production; Astrophysical Detection; Collider Signals

LAST TIME

- SUSY provides elegant solutions to SM problems
  - Naturalness
  - Force unification
  - Electroweak symmetry breaking

- SUSY predicts a new partner particle for every known particle (+ extra Higgs doublet)

- Proton decay → R-parity, lightest superpartner is stable, potentially significant dark matter

Thermal Relic Abundance

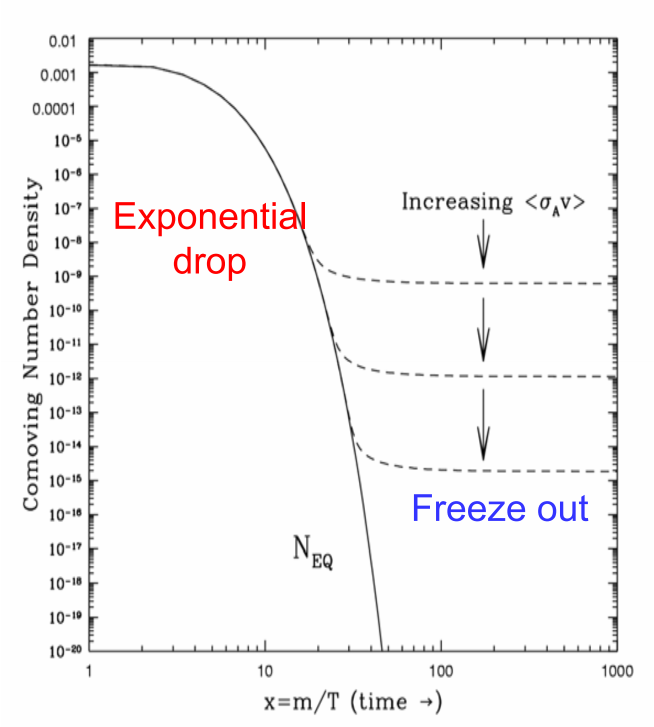
- The Boltzmann equation:

$$\frac{dn}{dt} = -\underset{\uparrow \atop \text{Dilution from expansion}}{3Hn} - \langle\sigma v\rangle\left[\underset{\uparrow \atop \chi\chi \to f\bar{f}}{n^2} - \underset{\nwarrow \atop f\bar{f} \to \chi\chi}{n_{\rm eq}^2}\right]$$

- $n \approx n_{eq}$ until interaction rate drops below expansion rate:

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

- The universe expands *slowly* ! Mass *m* particles freeze out at *T* ~ *m*/25



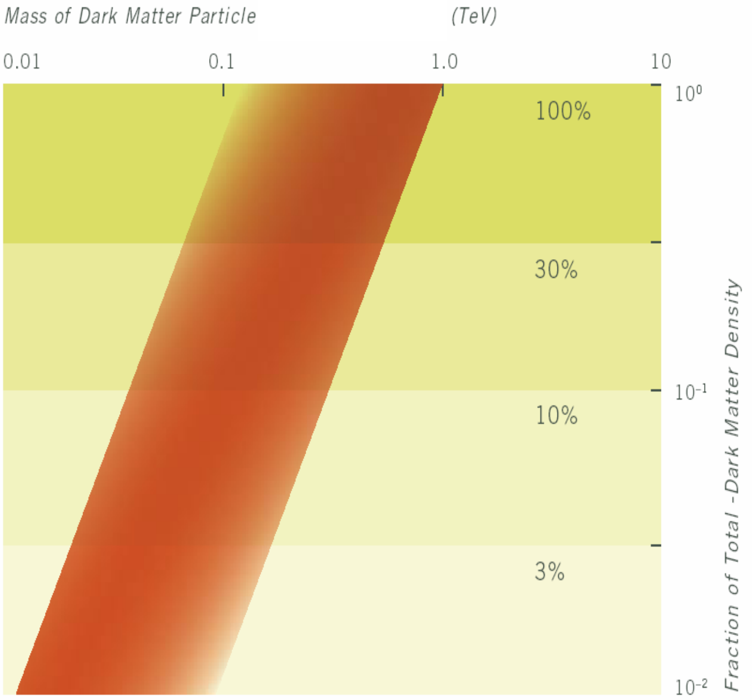
- The amount of dark matter left over is inversely proportional to the annihilation cross section:

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

- 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 ~ 0.1 – 1 TeV,
The mass range predicted for superpartners

SUPERSYMMETRY BREAKING

- How are superpartner masses generated?

- EWSB in the standard model:

EWSB Sector	Mediating Interactions	Observable Sector
h → v	h, q, l	q, l

EWSB parameterized by v. Mediating interactions (Yukawa couplings) → observable spectrum

- Hidden sector SUSY Breaking:

SUSY Breaking Sector	Mediating Interactions	Observable Sector
Z → F	Z, $\tilde{q}$, $\tilde{l}$	$\tilde{q}$, $\tilde{l}$

SUSY breaking parameterized by F (dimension 2). Mediation mechanism → observable spectrum

GRAVITY-MEDIATED SUSY BREAKING

- There are M_{Pl}-suppressed interactions. Minimal assumption: use these as the mediating interactions:

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

- The gravitino mass is

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

- For $F \sim (10^{10}\ \mathrm{GeV})^2$, when $Z \rightarrow F$, the gravitino and all superpartner masses are ~ 100 GeV

- Assume that the gravitino is not the LSP for this lecture

SUPERSYMMETRIC MODELS

- To get further, determine relic densities, detection rates, etc., we must specify the SUSY parameters

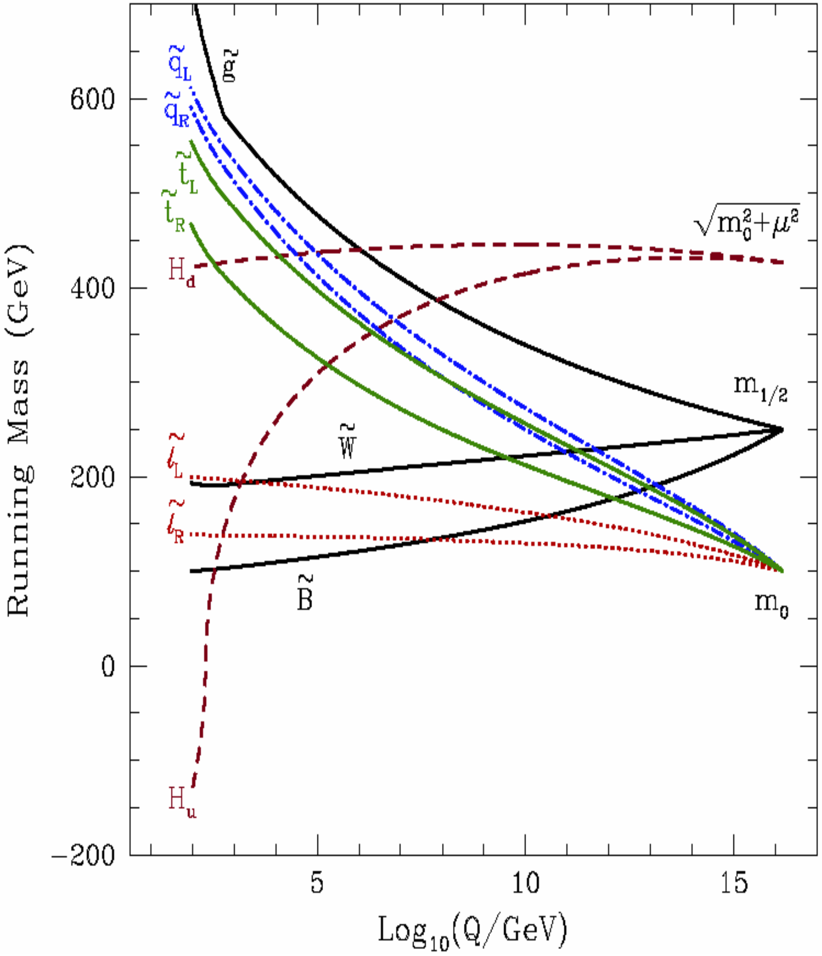
- Two choices
  - scan parameters model-independently
  - Choose models that embody many of the nice features discussed last time

AN EXAMPLE: MINIMAL SUPERGRAVITY

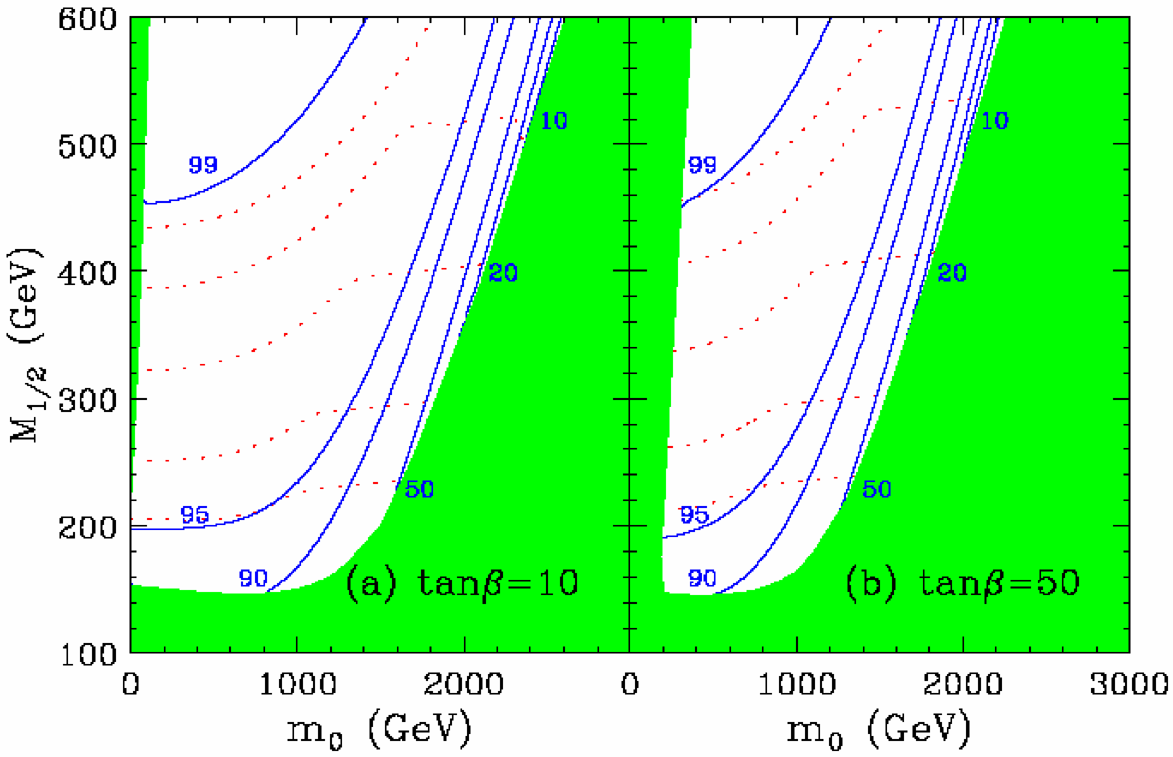
- Defined by 4+1 parameters
  - m_0: universal scalar mass
  - $M_{½}$: universal gaugino mass
  - A_0: universal trilinear scalar coupling
  - $\tan\beta$: ratio of Higgs vevs
  - sign(μ): $|\mu|$ determined by EWSB

- Includes naturalness, force unification, radiative EWSB

- LSP candidates: Slepton, neutralino

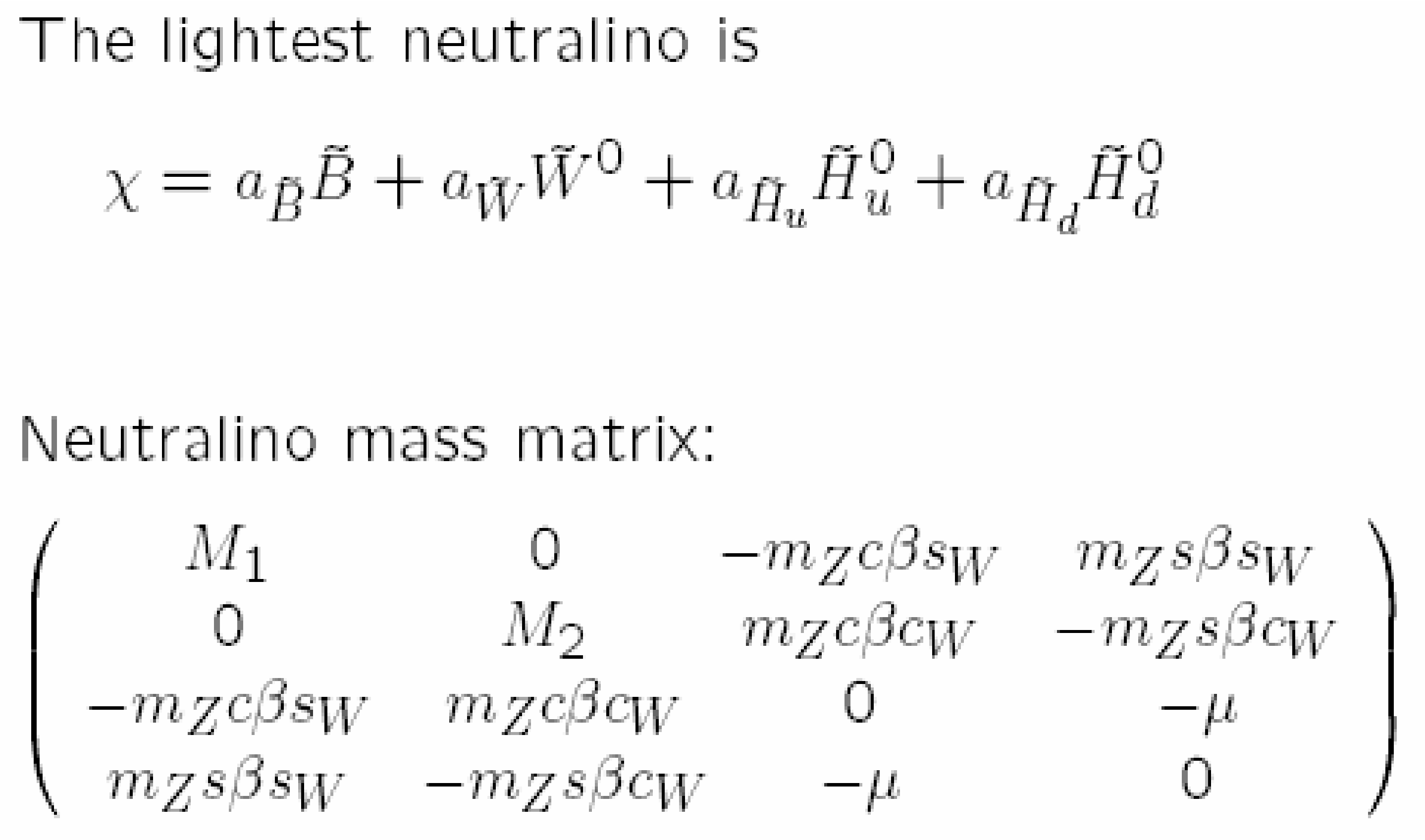


mSUGRA LSP



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.

NEUTRALINOS



The lightest neutralino is

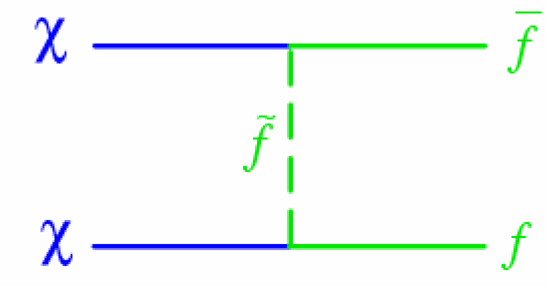
$$\chi = a_{\tilde{B}} \tilde{B} + a_{\tilde{W}} \tilde{W}^0 + a_{\tilde{H}_u} \tilde{H}_u^0 + a_{\tilde{H}_d} \tilde{H}_d^0$$

Neutralino mass matrix:

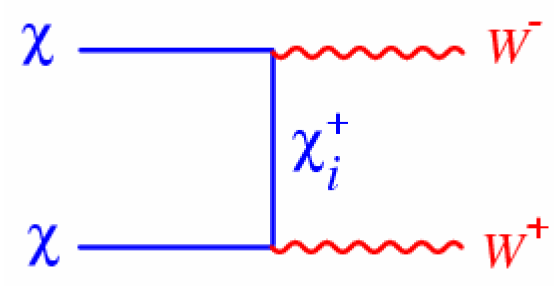
$$\begin{pmatrix} M_1 & 0 & -m_Z c\beta s_W & m_Z s\beta s_W \\ 0 & M_2 & m_Z c\beta c_W & -m_Z s\beta c_W \\ -m_Z c\beta s_W & m_Z c\beta c_W & 0 & -\mu \\ m_Z s\beta s_W & -m_Z s\beta c_W & -\mu & 0 \end{pmatrix}$$

RELIC DENSITY

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



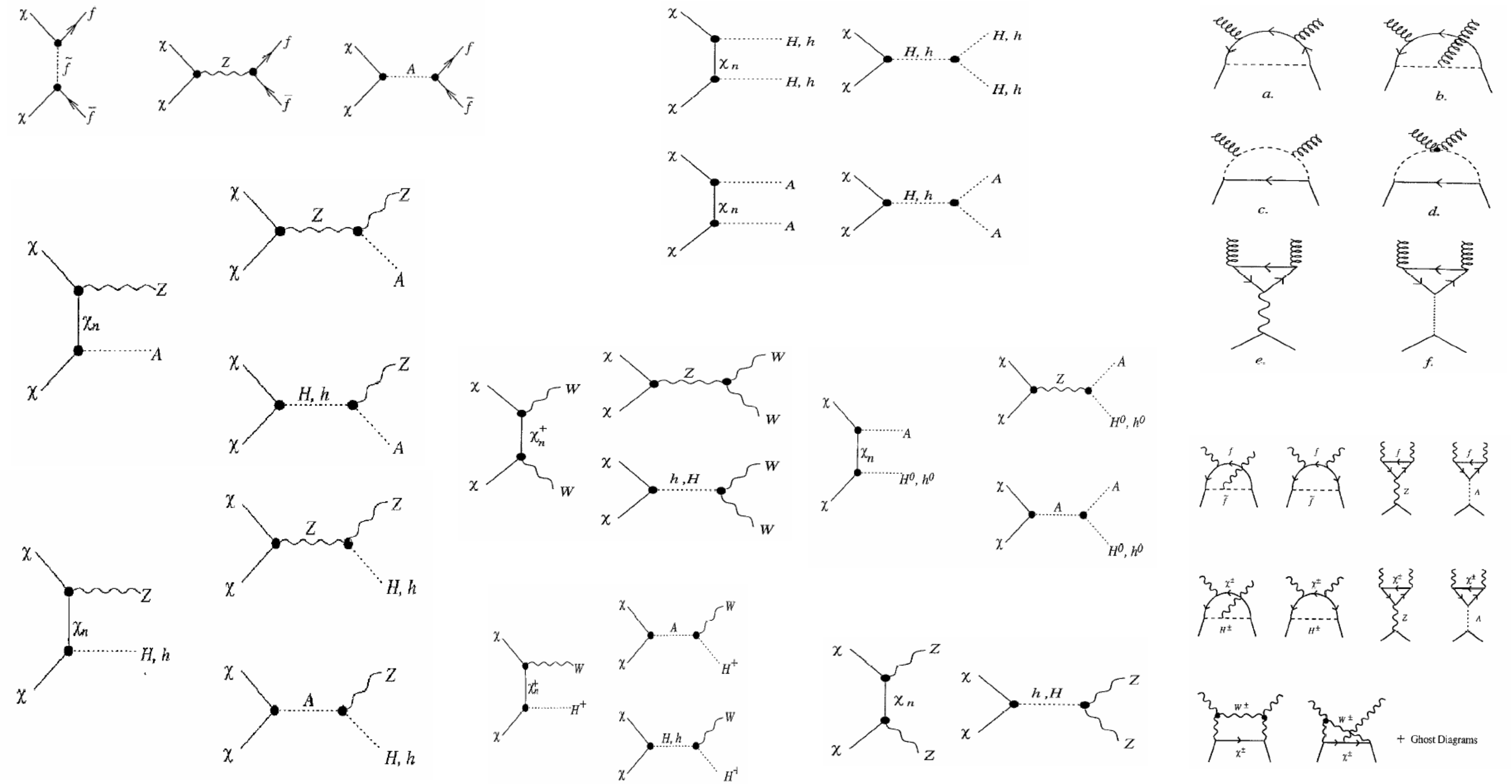
- Fermion diagrams
  χ are Majorana fermions:
  Pauli exclusion → $S = 0$
  L conservation → P wave suppression
  m_f / m_W suppression



- 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 SUSY

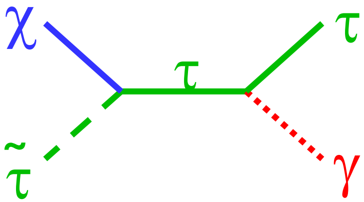
Typically get too much DM, but there are generic mechanisms for reducing it

Excluded:
Stau LSP

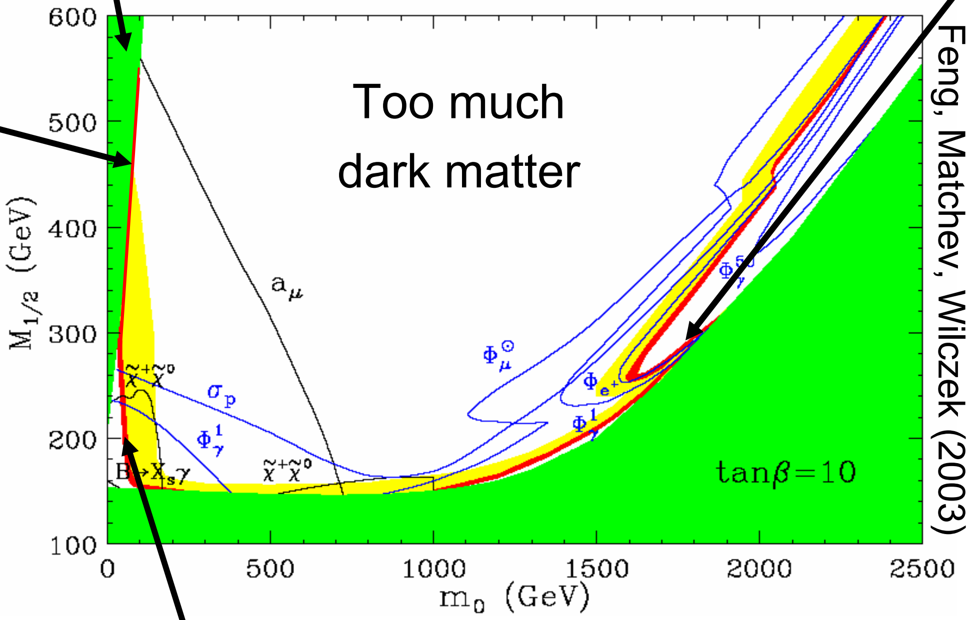
Yellow: pre-WMAP
Red: post-WMAP

Focus point
region

Co-annihilation
region

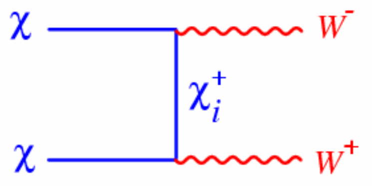


Degenerate
χ and stau



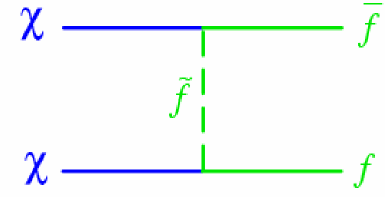
Too much
dark matter

Feng, Matchev, Wilczek (2003)



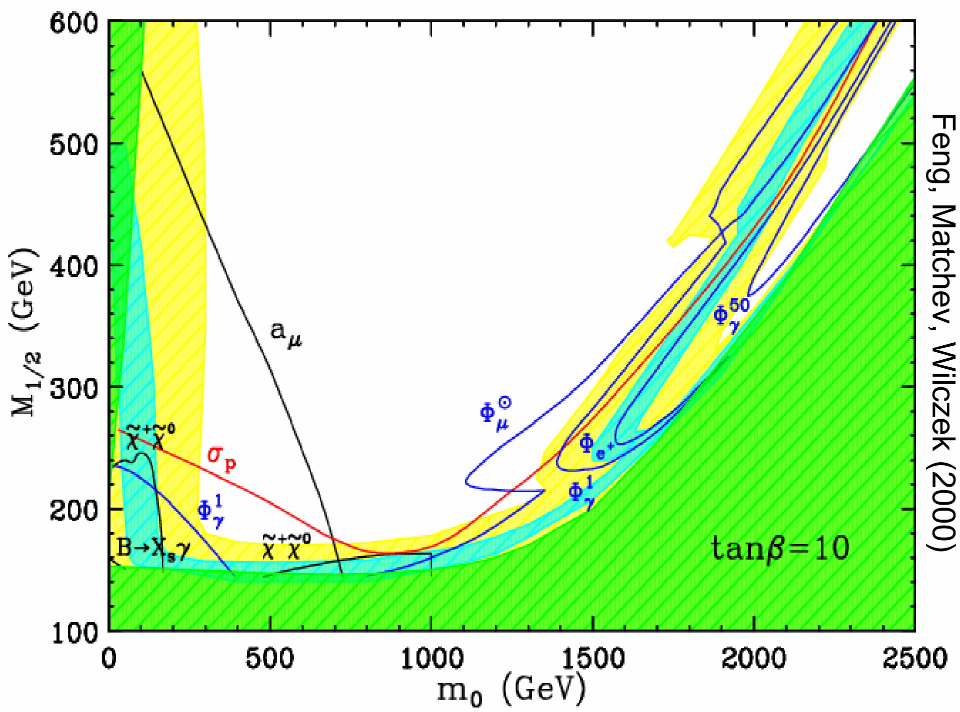
Mixed
Neutralinos

Bulk
region



Light sfermions

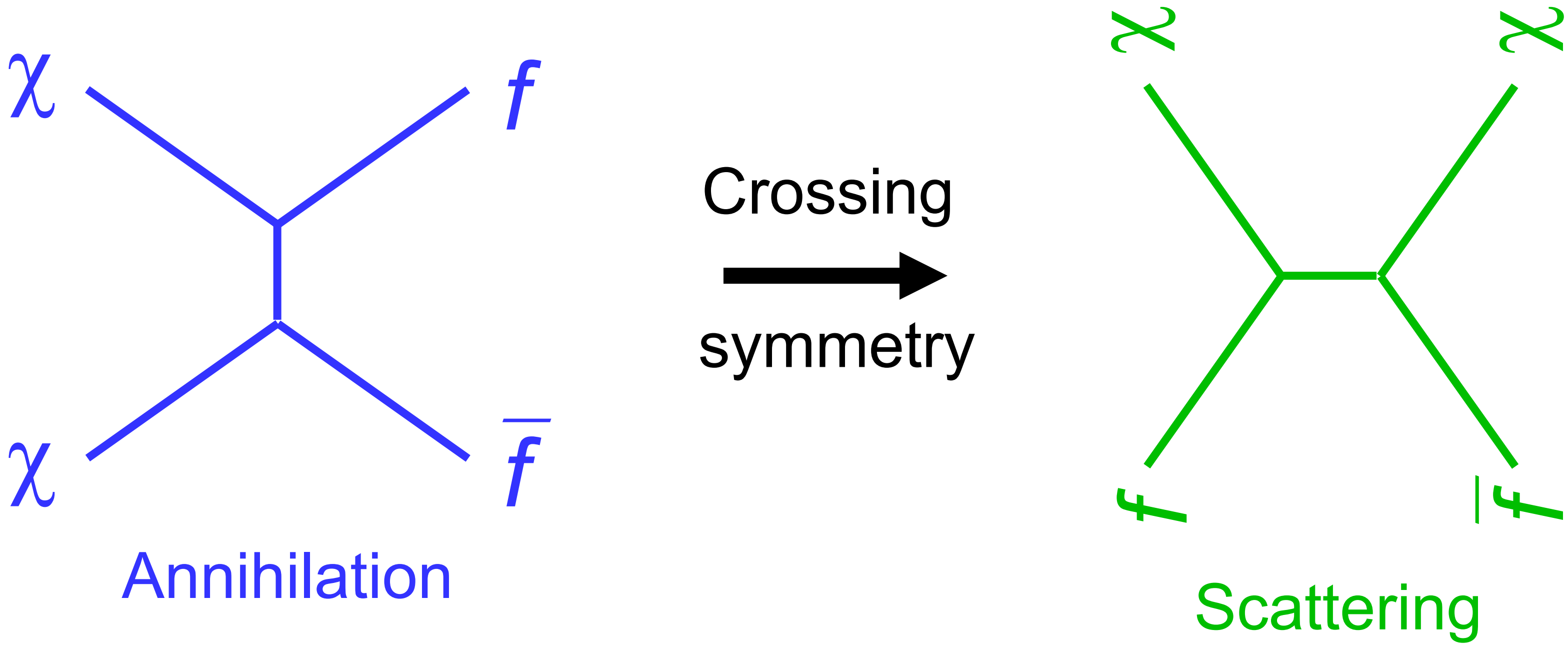
Implications for Detection



Feng, Matchev, Wilczek (2000)

Many diverse experiments are promising in the cosmologically preferred regions

WIMP DETECTION



Correct relic density → Efficient annihilation then

→ Efficient annihilation now (indirect detection)

→ Efficient scattering now (direct detection)

DIRECT DETECTION

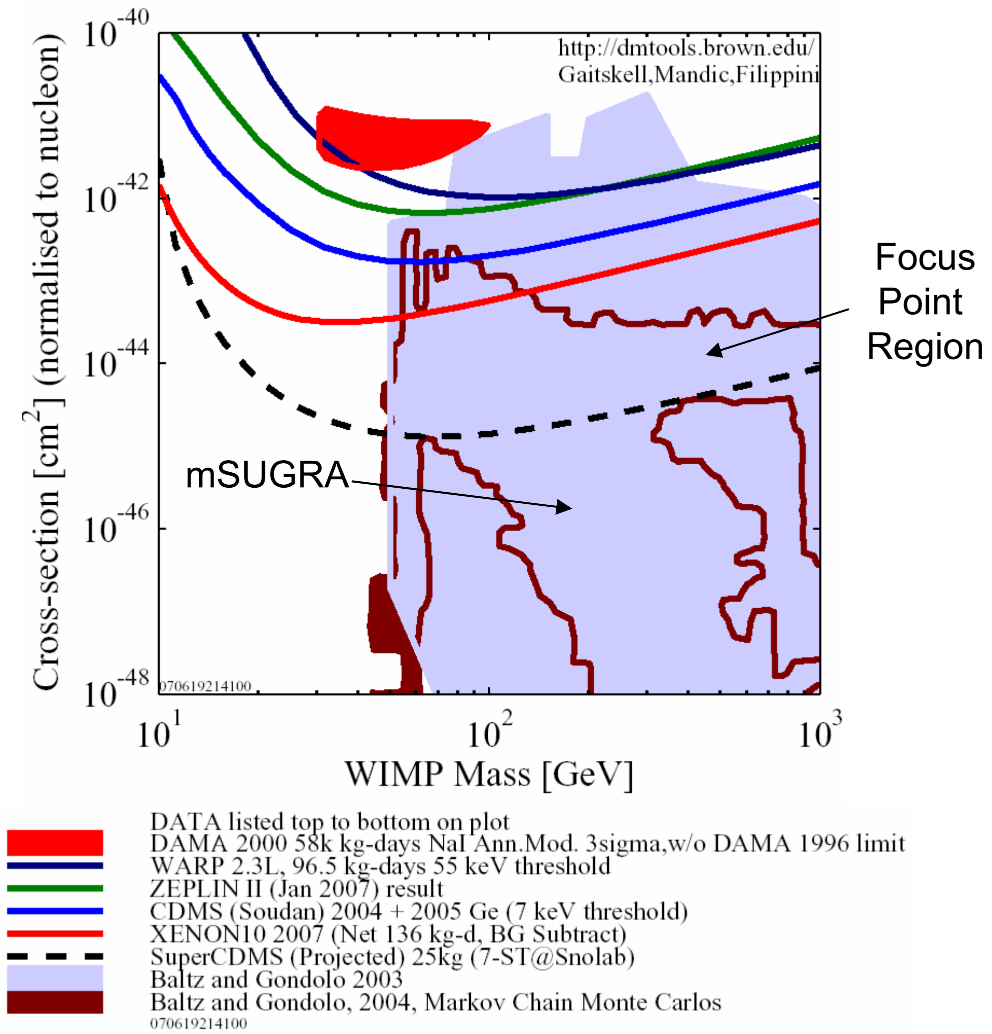
- WIMP essentials:

  v ~ 10^{-3} c

  Kinetic energy ~ 100 keV

  Local density ~ 1 / liter

- Detected by recoils off ultra-sensitive underground detectors



Indirect Detection

Dark Matter Fill-in-the-Blank!

Dark matter annihilates in ____________________ to
a place

____________ , which are detected by ________________ .
particles an experiment

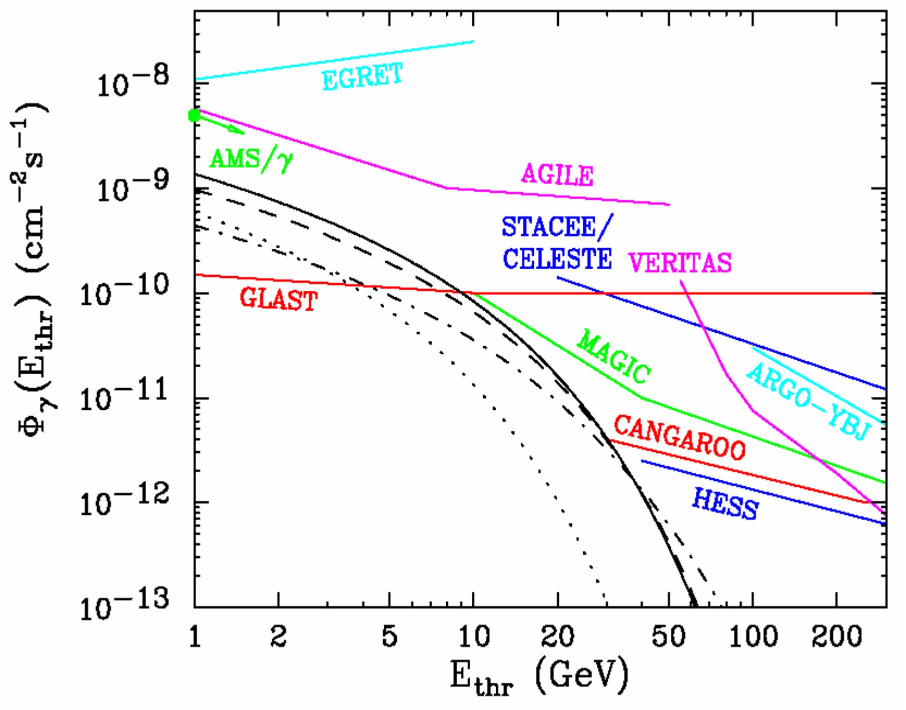
Dark Matter annihilates in __the galactic center__ to

a place

__photons__ , which are detected by __HESS, GLAST, …__ .

some particles

an experiment



Typically $\chi\chi \not\to \gamma\gamma$,

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

Dark Matter annihilates in the center of the Sun to

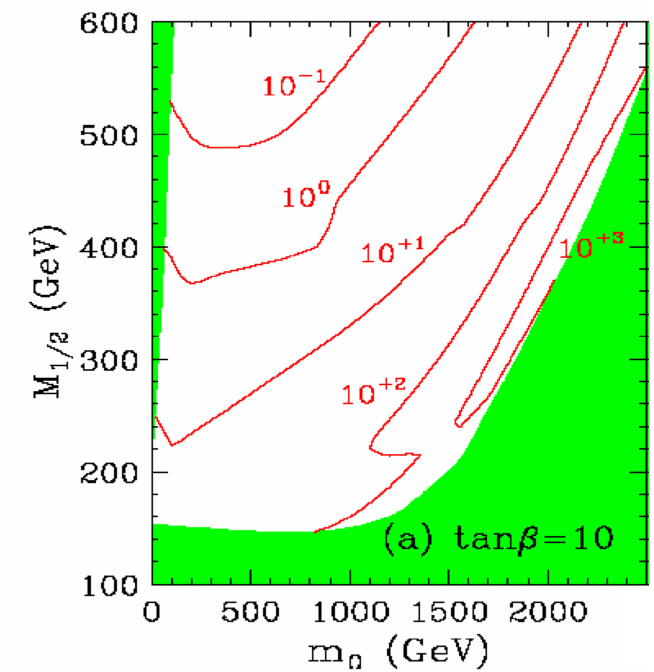
a place

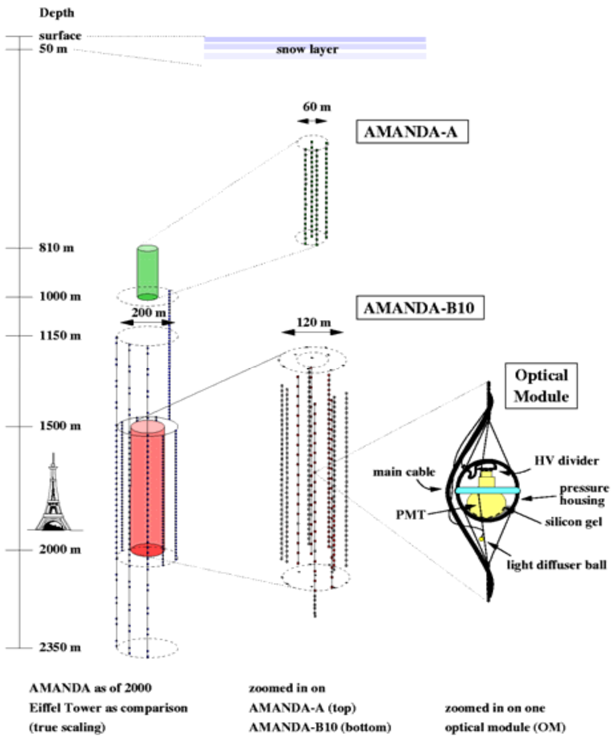
neutrinos , which are detected by AMANDA, IceCube .

some particles

an experiment

$\nu \rightarrow \mu$ (km^{-2} yr^{-1})

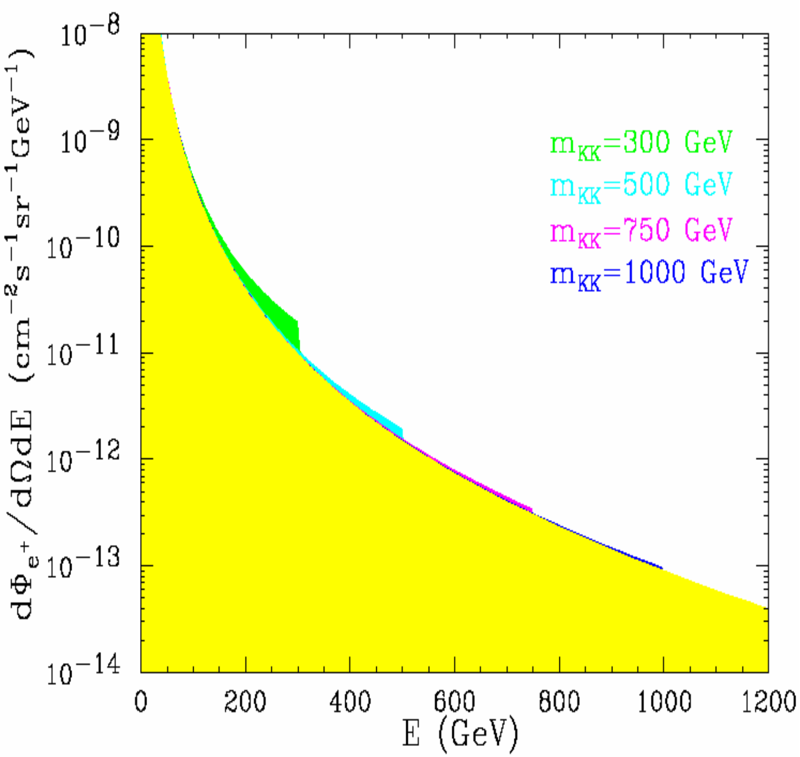


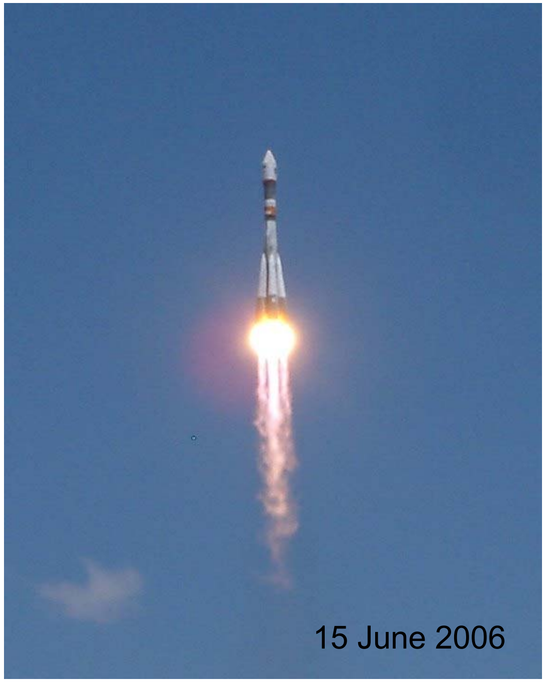


AMANDA in the Antarctic Ice

Dark Matter annihilates in ______the halo_______ to
a place

__positrons___ , which are detected by ___PAMELA___.
some particles an experiment




15 June 2006

NEUTRALINO PROSPECTS

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

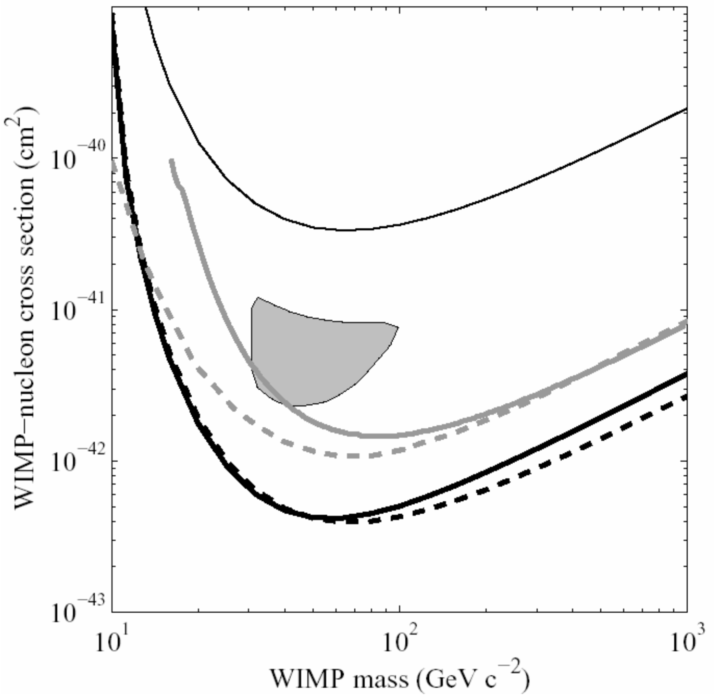
Direct dark matter searches
Indirect dark matter searches

Tevatron at Fermilab

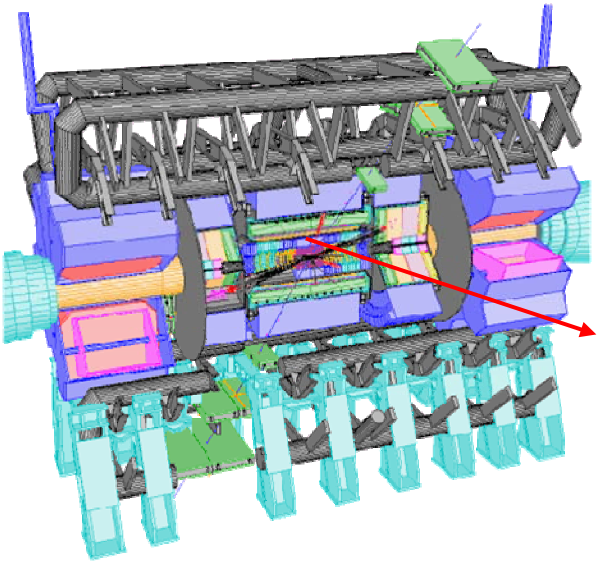
Large Hadron Collider at CERN

What then?

- Cosmo/astro can't discover SUSY

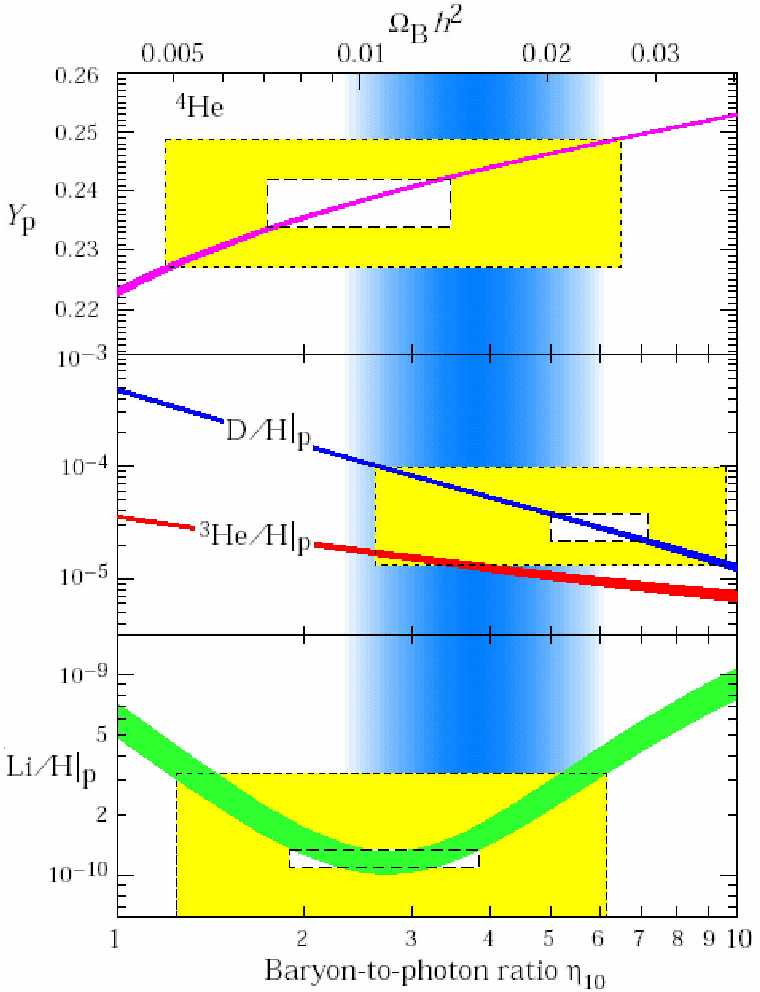


- Particle colliders can't discover DM



Lifetime > 10^{-7} s → 10^{17} s ?

THE EXAMPLE OF BBN

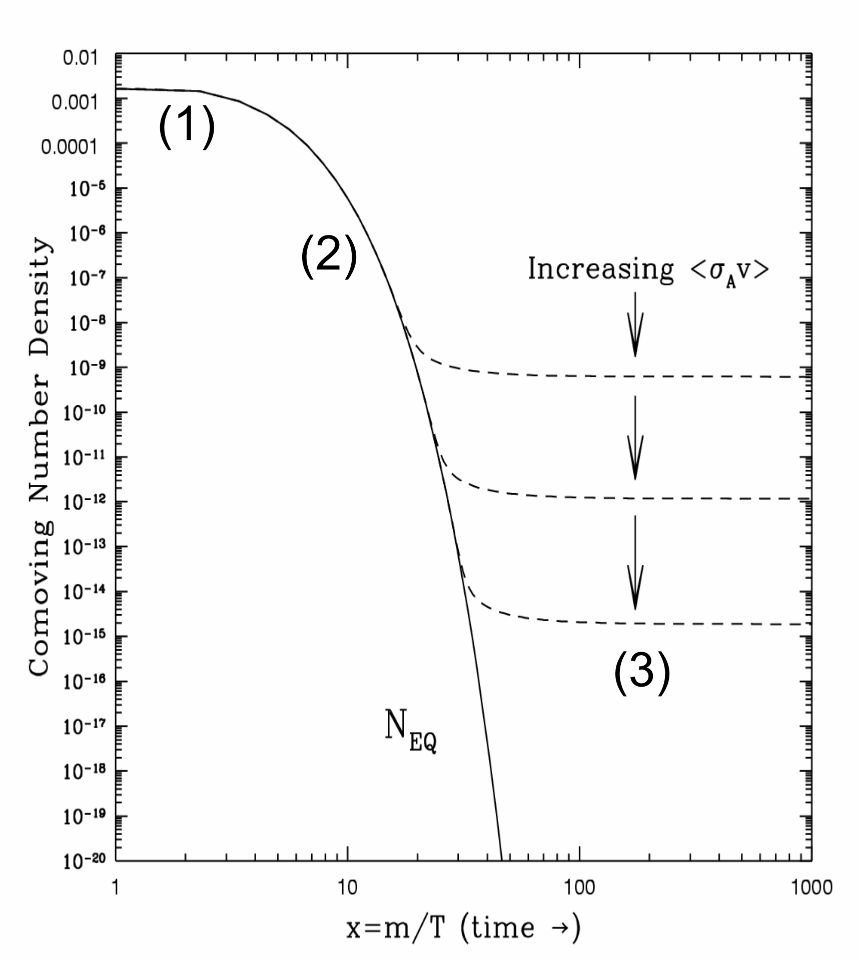


- Nuclear physics → light element abundance predictions
- Compare to light element abundance observations
- Agreement → we understand the universe back to

T ~ 1 MeV

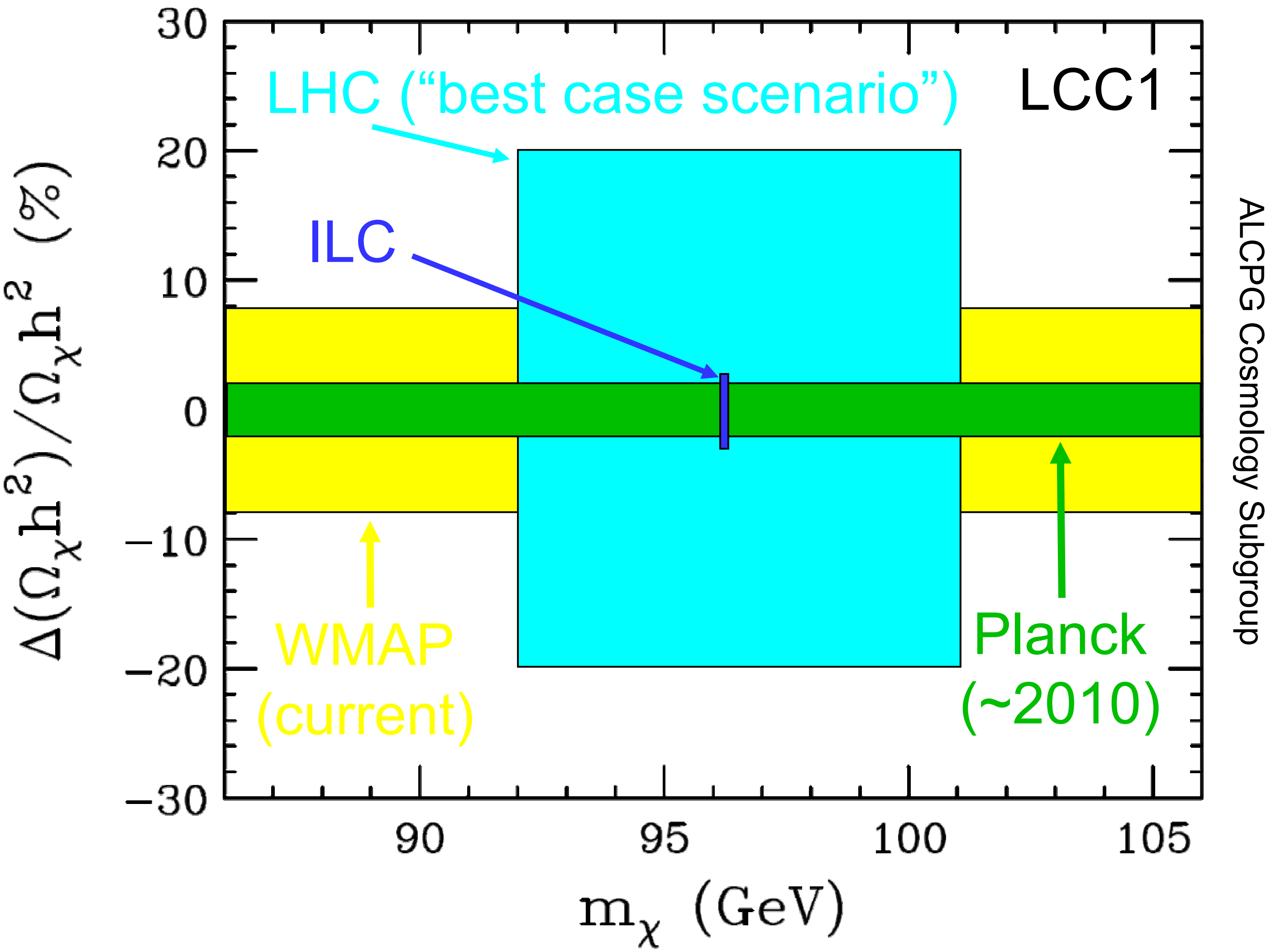
t ~ 1 sec

DARK MATTER ANALOGUE



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

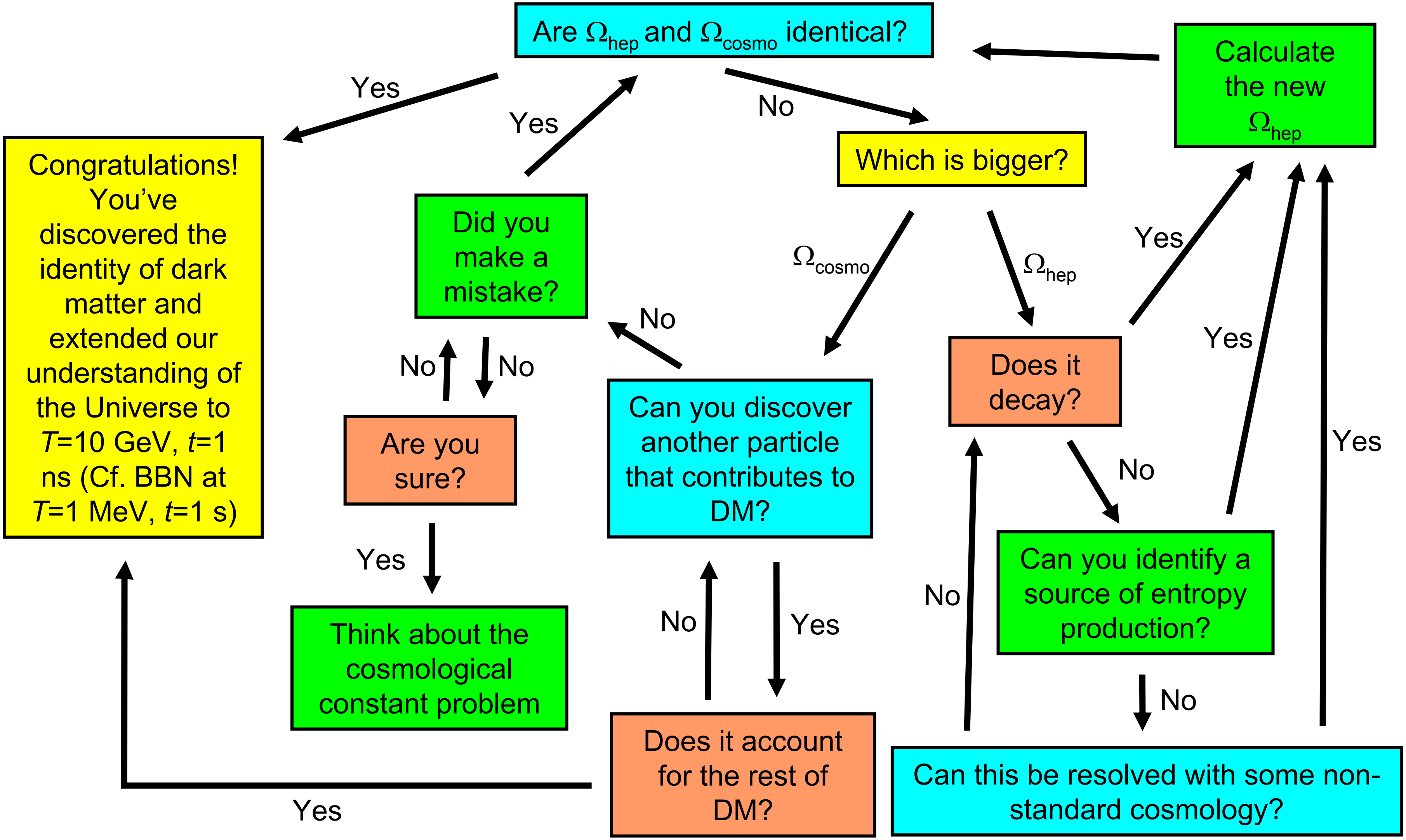
RELIC DENSITY DETERMINATIONS



ALCPG Cosmology Subgroup

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

IDENTIFYING DARK MATTER



Are Ω_{hep} and Ω_{cosmo} identical?

Calculate the new Ω_{hep}

Congratulations! You've discovered the identity of dark matter and extended our understanding of the Universe to T=10 GeV, t=1 ns (Cf. BBN at T=1 MeV, t=1 s)

Which is bigger?

Did you make a mistake?

Are you sure?

Can you discover another particle that contributes to DM?

Does it decay?

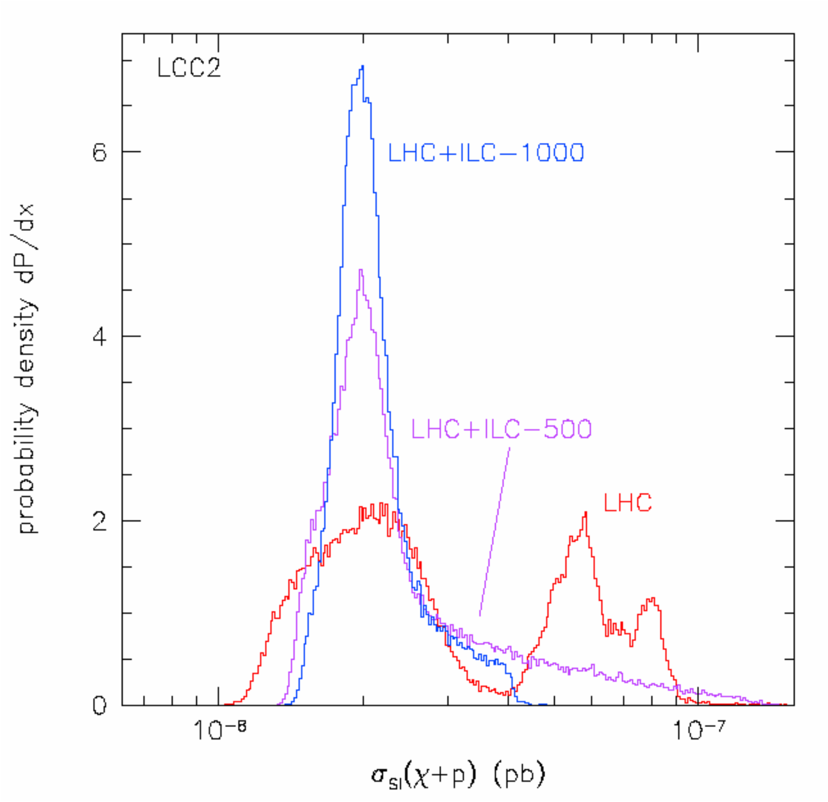
Think about the cosmological constant problem

Can you identify a source of entropy production?

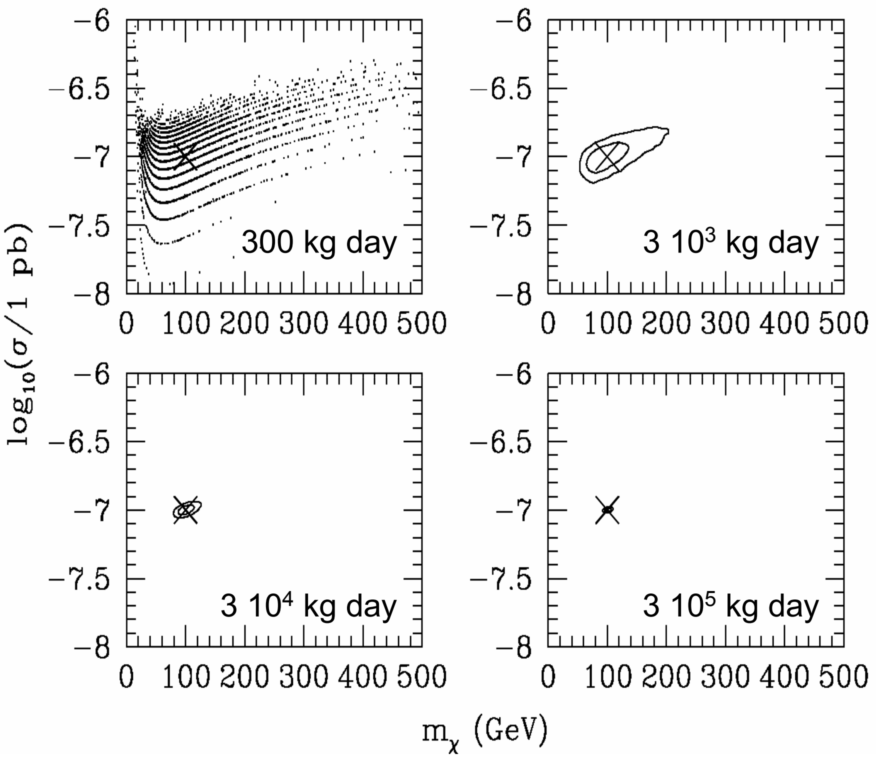
Does it account for the rest of DM?

Can this be resolved with some non-standard cosmology?

DIRECT DETECTION IMPLICATIONS



Baltz, Battaglia, Peskin, Wizansky (2006)



Green (2007)

Comparison tells us about local dark matter density and velocity profiles

INDIRECT DETECTION IMPLICATIONS

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

Gamma ray fluxes factorize

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

LECTURE 2 SUMMARY

- Neutralinos emerge as excellent dark matter candidates in many supersymmetric models
- Promising prospects for direct detection, indirect detection, and colliders
- At the same time, great progress requires synergy: comparisons may lead to discovery of the identity of dark matter, require the existence of another component, tell us about the distribution of dark matter in the galaxy, structure formation

OUTLINE

LECTURE 1: SUSY ESSENTIALS

Standard Model; SUSY Motivations; LSP Stability and Candidates

LECTURE 2: NEUTRALINOS

Properties; Production; Direct Detection; Indirect Detection; Collider Signals

LECTURE 3: GRAVITINOS

Properties; Production; Astrophysical Detection; Collider Signals

GRAVITINO COSMOLOGY

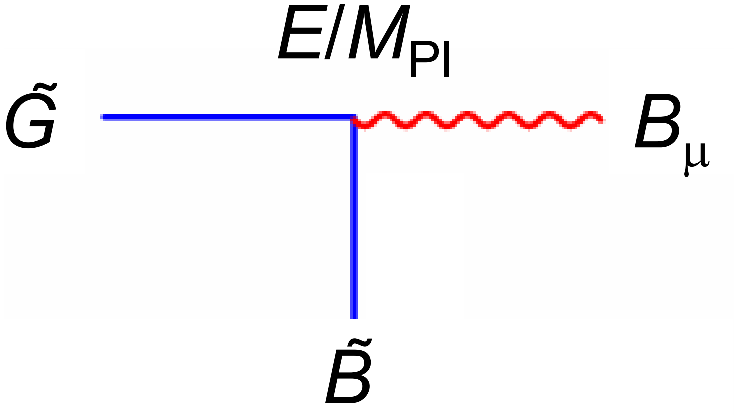
- Neutralinos (and all WIMPs) are cold and weakly-interacting. Is this a universal prediction of SUSY DM?
- No! Here, we'll consider the gravitino, a SUSY dark matter candidate with completely different, but equally rich, implications for particle physics and cosmology
- In some cases, the gravitino has identical motivations to neutralinos, preserving even the WIMP relic abundance "coincidence"

Gravitinos

- SUSY: graviton G → gravitino $\tilde{G}$
- Mass: in gravity-mediated SUSY breaking, expect ~ 100 GeV – 1 TeV
- $\tilde{G}$ interactions couple particles to their superpartners

$$-\frac{i}{8M_{\rm Pl}}\bar{\tilde{G}}_\mu\left[\gamma^\nu,\gamma^\rho\right]\gamma^\mu\tilde{B}F_{\nu\rho}$$

Couplings grow with energy, but are typically extremely weak



Gravitino Production 1: Thermal

- Gravitinos are the original SUSY DM. First ideas: If the universe cools from $T \sim M_{Pl}$, gravitinos decouple while relativistic, expect $n_{\tilde{G}} \sim n_{eq}$.

- Stable:

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

(cf. neutrinos). (Current constraints → too hot.)

Pagels, Primack (1982)

- Unstable:

$$\tau_{\tilde{G}} \sim \frac{M_{\rm Pl}^2}{m_{\tilde{G}}^3} \sim 1 \text{ yr} \left[\frac{100 \text{ GeV}}{m_{\tilde{G}}} \right]^3$$

Decay before BBN → $m_{\tilde{G}} > 10\text{-}100$ TeV

Weinberg (1982)

Both inconsistent with TeV mass range

Gravitino Production 2: Reheating

- More modern view: gravitino density is diluted by inflation.

- But gravitinos regenerated in reheating. What happens?

$$\sigma_{\mathrm{SM}} n \sim T \gg H \sim \frac{T^2}{M_{\mathrm{Pl}}} \gg \sigma_{\tilde{G}} n \sim \frac{T^3}{M_{\mathrm{Pl}}^2}$$

SM interaction rate >> expansion rate >> $\tilde{G}$ interaction rate

- Thermal bath of SM particles and superpartners: occasionally they produce a gravitino: $f\, f \to f\, \tilde{G}$

Gravitino Production 2: Reheating

- The Boltzmann equation:

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[\cancelto{0}{n^2} - n_{\text{eq}}^2 \right]$$

Dilution from expansion

$f\,\tilde{G} \rightarrow f\,\bar{f}$

$f\,\bar{f} \rightarrow f\,\tilde{G}$

- Change variables:

$$t \rightarrow T \qquad n \rightarrow Y \equiv \frac{n}{s}$$

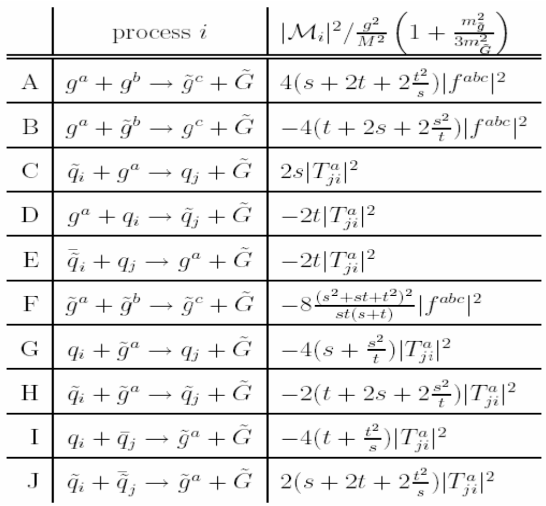
- New Boltzmann equation:

$$\frac{dY}{dT} = -\frac{\langle \sigma_{\tilde{G}} v \rangle}{HTs} n^2 \sim \langle \sigma_{\tilde{G}} v \rangle \frac{T^3 T^3}{T^2 T T^3}$$

- Simple: *Y* ~ reheat temperature

Bounds on T_{RH}

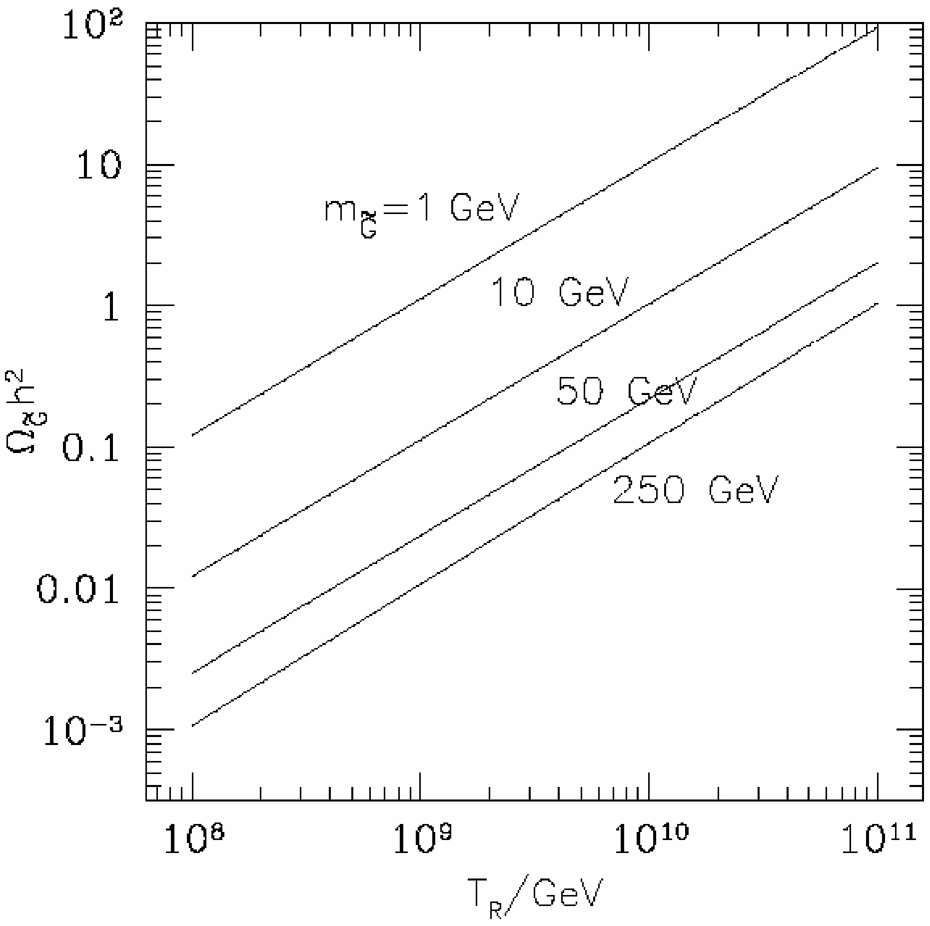
- <σ*v*> for important production processes:



	process i	$\lvert\mathcal{M}_i\rvert^2/\frac{g^2}{M^2}\left(1+\frac{m_{\tilde{g}}^2}{3m_{\tilde{G}}^2}\right)$
A	$g^a + g^b \longrightarrow \tilde{g}^c + \tilde{G}$	$4(s + 2t + 2\frac{t^2}{s})\lvert f^{abc}\rvert^2$
B	$g^a + \tilde{g}^b \longrightarrow g^c + \tilde{G}$	$-4(t + 2s + 2\frac{s^2}{t})\lvert f^{abc}\rvert^2$
C	$\tilde{q}_i + g^a \longrightarrow q_j + \tilde{G}$	$2s\lvert T^a_{ji}\rvert^2$
D	$g^a + q_i \longrightarrow \tilde{q}_j + \tilde{G}$	$-2t\lvert T^a_{ji}\rvert^2$
E	$\bar{\tilde{q}}_i + q_j \longrightarrow g^a + \tilde{G}$	$-2t\lvert T^a_{ji}\rvert^2$
F	$\tilde{g}^a + \tilde{g}^b \longrightarrow \tilde{g}^c + \tilde{G}$	$-8\frac{(s^2+st+t^2)^2}{st(s+t)}\lvert f^{abc}\rvert^2$
G	$q_i + \tilde{g}^a \longrightarrow q_j + \tilde{G}$	$-4(s + \frac{s^2}{t})\lvert T^a_{ji}\rvert^2$
H	$\tilde{q}_i + \tilde{g}^a \longrightarrow \tilde{q}_j + \tilde{G}$	$-2(t + 2s + 2\frac{s^2}{t})\lvert T^a_{ji}\rvert^2$
I	$q_i + \bar{q}_j \longrightarrow \tilde{g}^a + \tilde{G}$	$-4(t + \frac{t^2}{s})\lvert T^a_{ji}\rvert^2$
J	$\tilde{q}_i + \bar{\tilde{q}}_j \longrightarrow \tilde{g}^a + \tilde{G}$	$2(s + 2t + 2\frac{t^2}{s})\lvert T^a_{ji}\rvert^2$

- $T_{RH} < 10^8 – 10^{10}$ GeV; constrains inflation

- $\tilde{G}$ can be DM if bound saturated

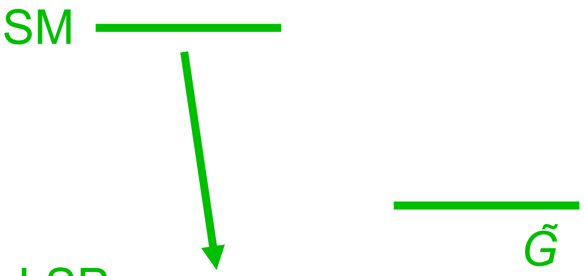


Bolz, Brandenburg, Buchmuller (2001)

Gravitino Production 3: Late Decay

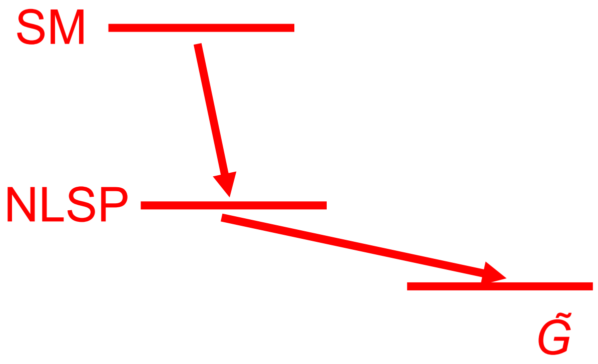
- What if gravitinos are diluted by inflation, and the universe reheats to low temperature?

- $\tilde{G}$ not LSP



- No impact – assumption of Lectures 1 and 2

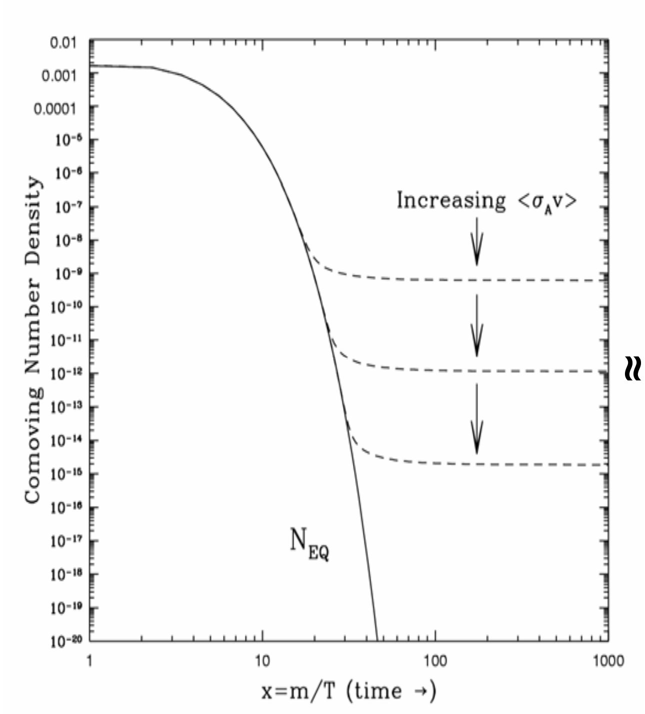
- $\tilde{G}$ LSP



- A new source of gravitinos

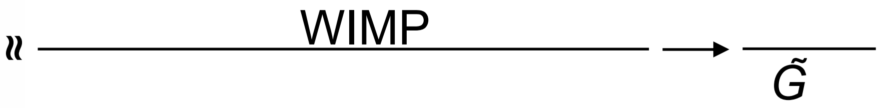
Feng, Rajaraman, Takayama (2003)

Gravitino Production 3: Late Decay



- 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 from WIMPs, but interact only gravitationally – they are superWIMPs

SuperWIMP Detection

- SuperWIMPs evade all direct, indirect dark matter searches

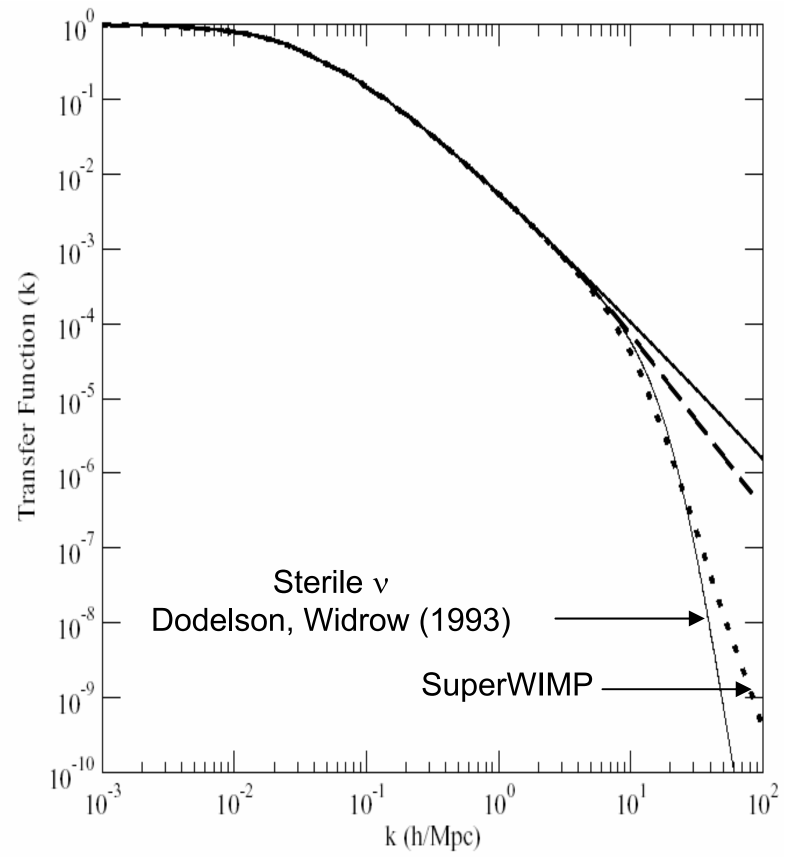
- But cosmology is complementary: Superweak interactions → very late decays to gravitinos → observable consequences

- 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

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)



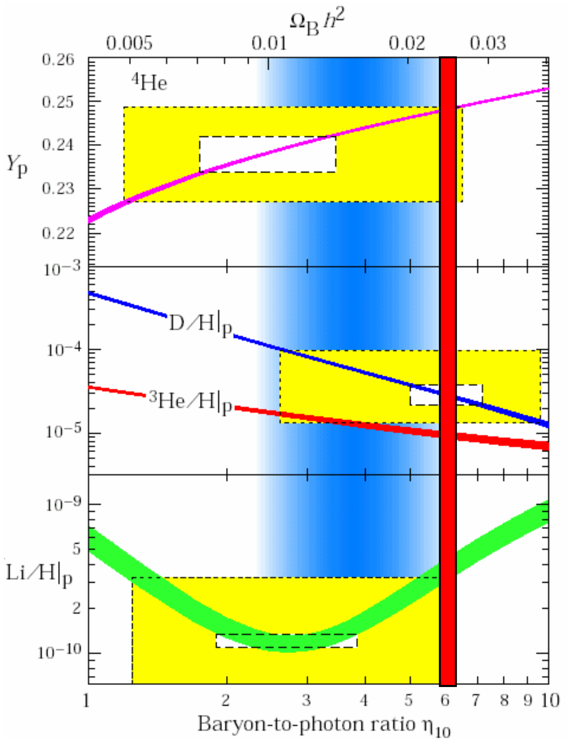
Sterile ν
Dodelson, Widrow (1993)

SuperWIMP

Kaplinghat (2005)

BIG BANG NUCLEOSYNTHESIS

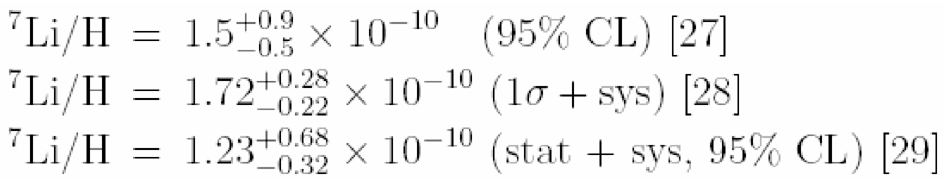
Late decays may modify light element abundances



Fields, Sarkar, PDG (2002)

After WMAP

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



$$^7\mathrm{Li/H} = 1.5^{+0.9}_{-0.5} \times 10^{-10} \quad (95\%\ \mathrm{CL})\ [27]$$

$$^7\mathrm{Li/H} = 1.72^{+0.28}_{-0.22} \times 10^{-10}\ (1\sigma + \mathrm{sys})\ [28]$$

$$^7\mathrm{Li/H} = 1.23^{+0.68}_{-0.32} \times 10^{-10}\ (\mathrm{stat} + \mathrm{sys},\ 95\%\ \mathrm{CL})\ [29]$$

BBN EM PREDICTIONS

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

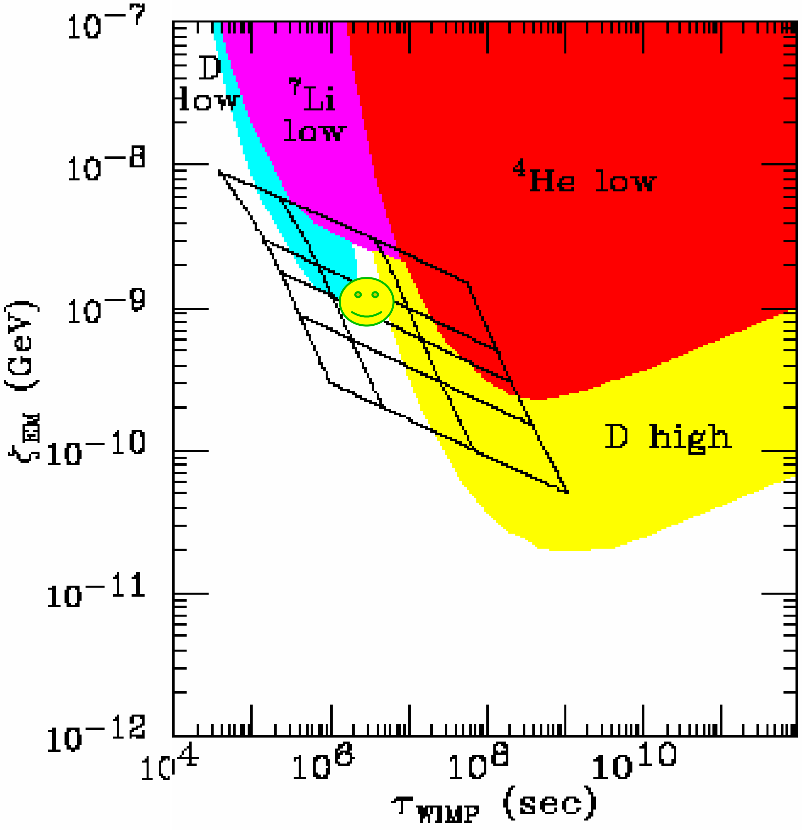
- Grid: Predictions for

  $m_{\tilde{G}}$ = 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 !



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 $< 10^4$ s, or maybe 10^6 s ok
  - 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); Jedamzik (2007)

Cosmic Microwave Background

- Late decays may also distort the CMB spectrum

- For 10^5 s < τ < 10^7 s, get "μ distortions":

$$\frac{1}{e^{E/(kT)+\mu} - 1}$$

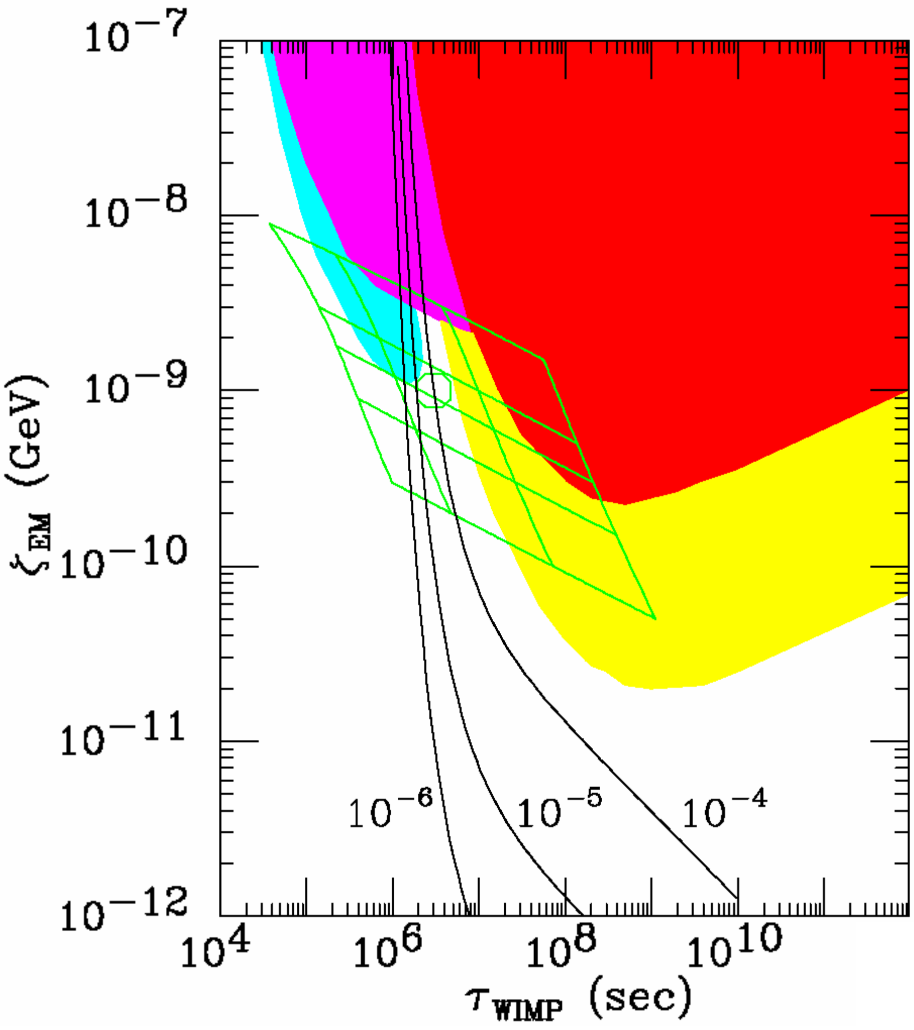
$\mu=0$: Planckian spectrum

$\mu\neq0$: Bose-Einstein spectrum

Hu, Silk (1993)

- Current bound: $|\mu| < 9 \times 10^{-5}$

Future (DIMES): $|\mu| \sim 2 \times 10^{-6}$



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)

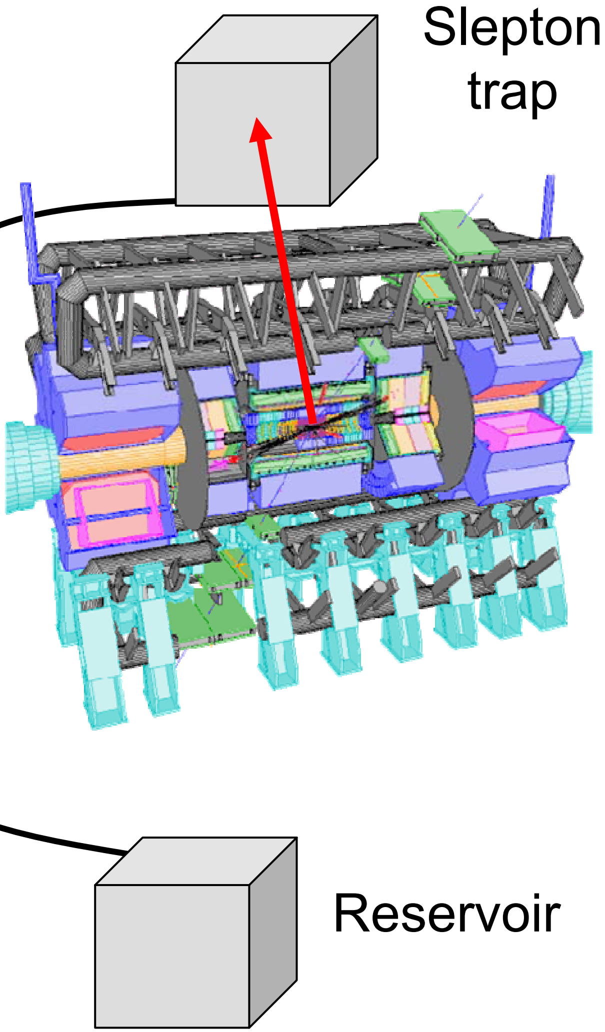
Hoffman, Stuart et al. (1997)
Acosta (2002)
…

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?

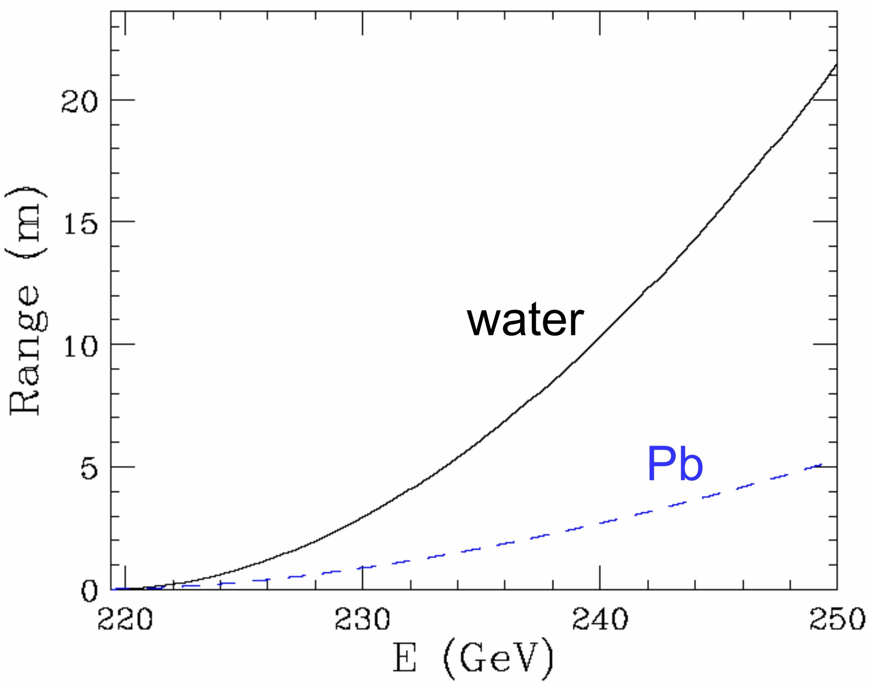
Feng, Smith (2004)
Hamaguchi, Kuno, Nakawa, Nojiri (2004)
De Roeck et al. (2005)



Slepton Range

- Ionization energy loss described by Bethe-Bloch equation:

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

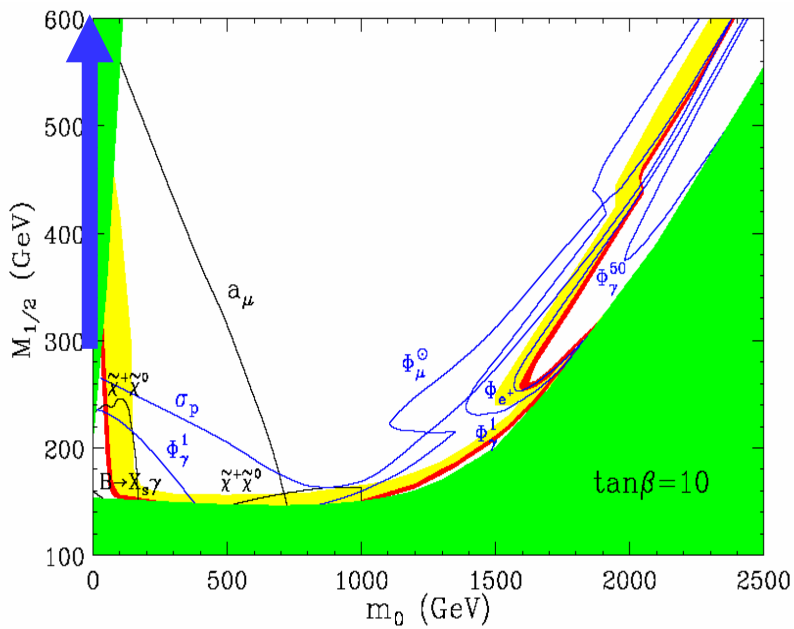


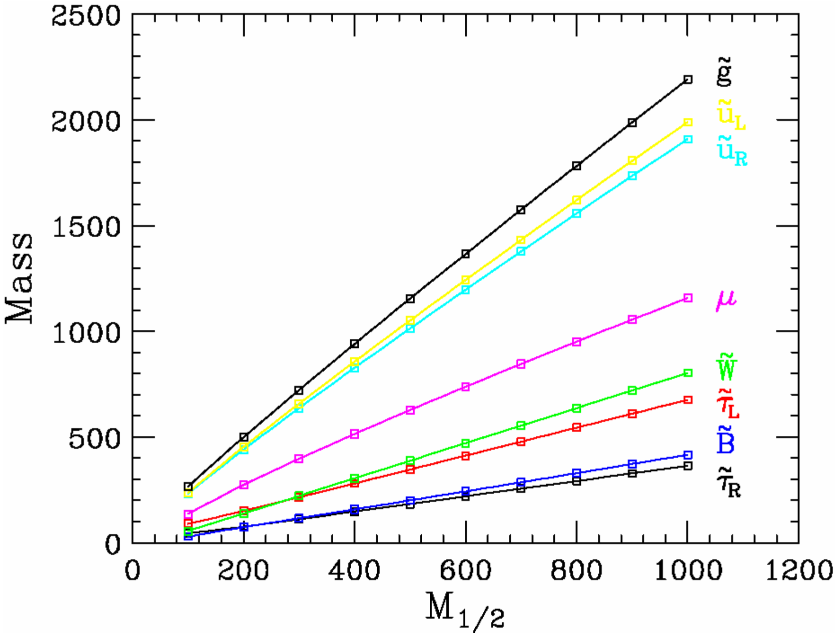
$m_{\tilde{l}}$ = 219 GeV

Model Framework

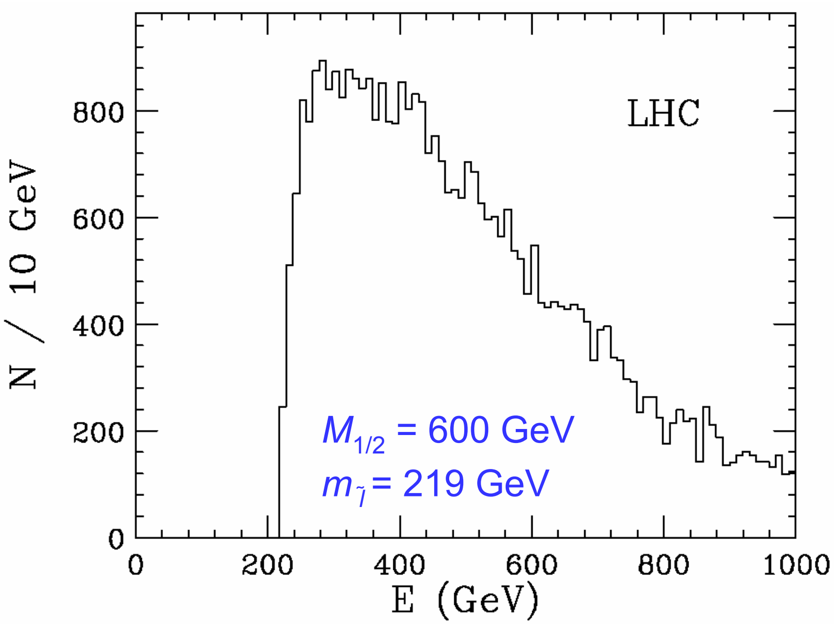
- Results depend heavily on the entire SUSY spectrum
- Consider mSUGRA with $m_0 = A_0 = 0$, $\tan\beta = 10$, $\mu > 0$

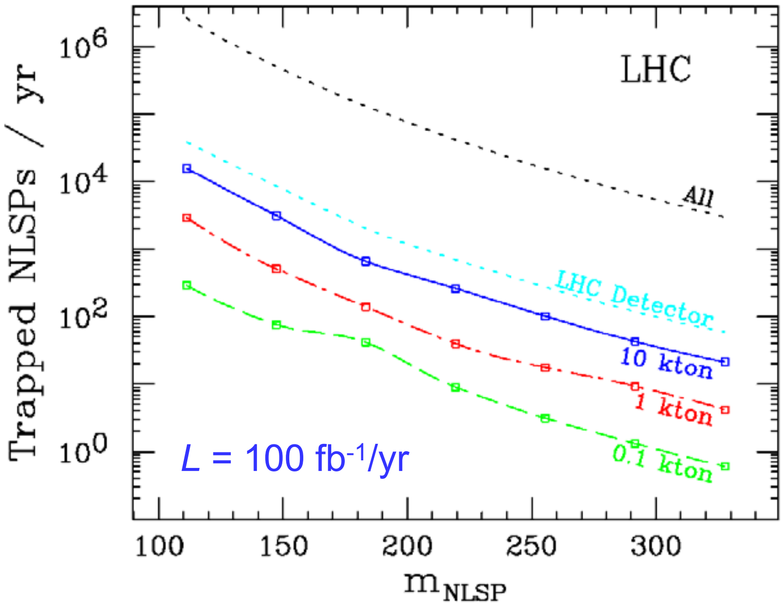
  $M_{1/2}$ = 300, 400,…, 900 GeV





Large Hadron Collider



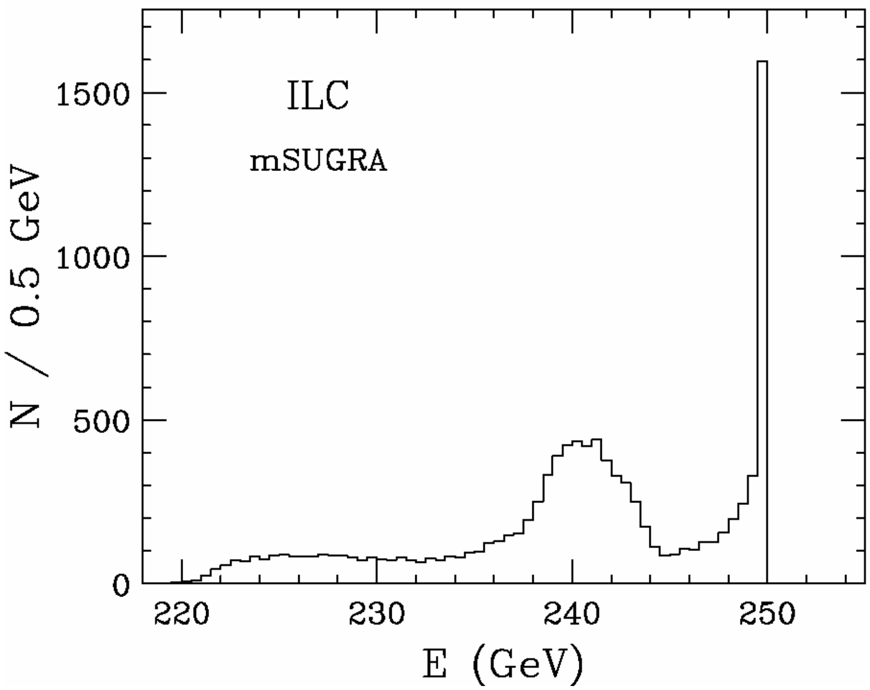


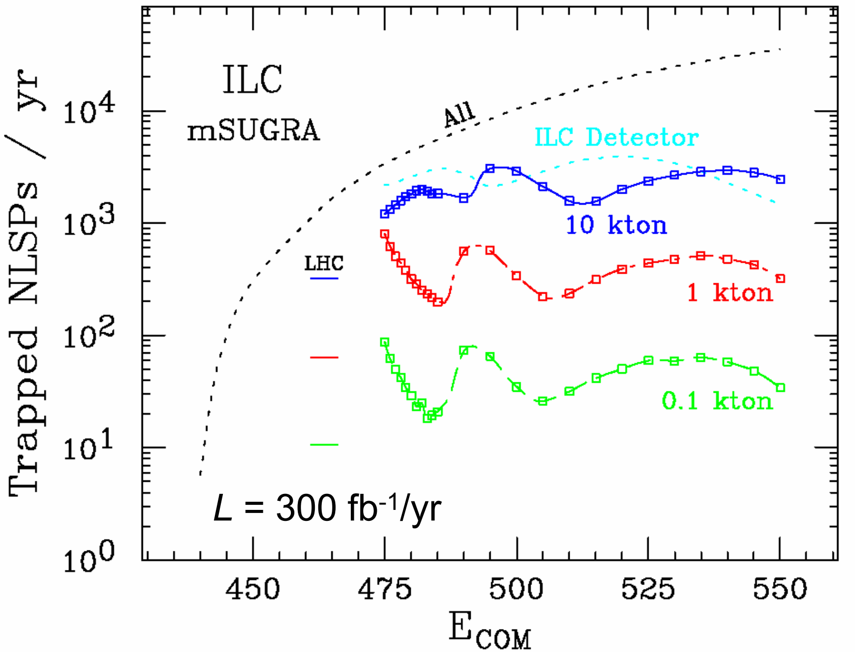
Assume 1 m thick shell of water (10 kton)

Sleptons trapped: ~1%, or 10 to 10^4 sleptons

International Linear Collider

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





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

Factor of ~10 improvement over LHC

IMPLICATIONS FROM DECAYS TO GRAVITINOS

$$\tau(\tilde{l} \to l\tilde{G}) = \frac{6}{G_N} \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^5} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^2}\right]^{-4}$$

- Measurement of τ , $m_{\tilde{l}}$ and E_l → $m_{\tilde{G}}$ and G_N
  - Probes gravity in a particle physics experiment!
  - Measurement of G_N on fundamental particle scale
  - Precise test of supergravity: gravitino is graviton partner
  - Determines $\Omega_{\tilde{G}}$: SuperWIMP contribution to dark matter
  - Determines F : supersymmetry breaking scale, contribution of SUSY breaking to dark energy, cosmological constant

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

ARE WIMPS STABLE?

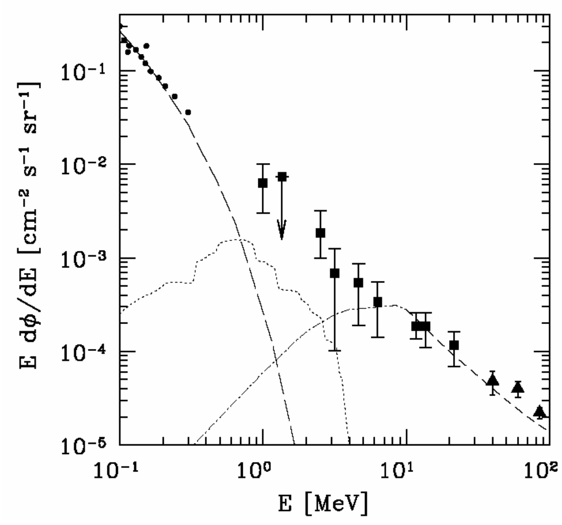
- Not necessarily. In fact, they can be decaying now:

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

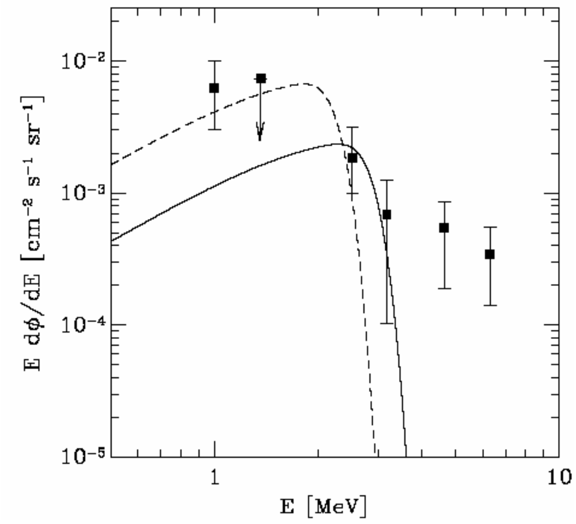
- Signals in the diffuse photon flux, completely determined by 1 parameter:

$$\tau \simeq \frac{3\pi}{b\cos^2\theta_W}\frac{M_P^2}{(\Delta m)^3} \simeq \frac{4.7\times10^{22}\ \mathrm{s}}{b}\left[\frac{\mathrm{MeV}}{\Delta m}\right]^3$$

Observations and Background



SUSY Signal



Cembranos, Feng, Strigari (2007)

LECTURE 3 SUMMARY

- Gravitinos are excellent SUSY dark matter candidates
- Many new astrophysical implications for small scale structure, BBN, CMB, colliders
- If dark matter is at the weak scale, we are likely to make great progress in identifying it in the coming years

RECENT BOOKS