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:

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

Dilution from expansion

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

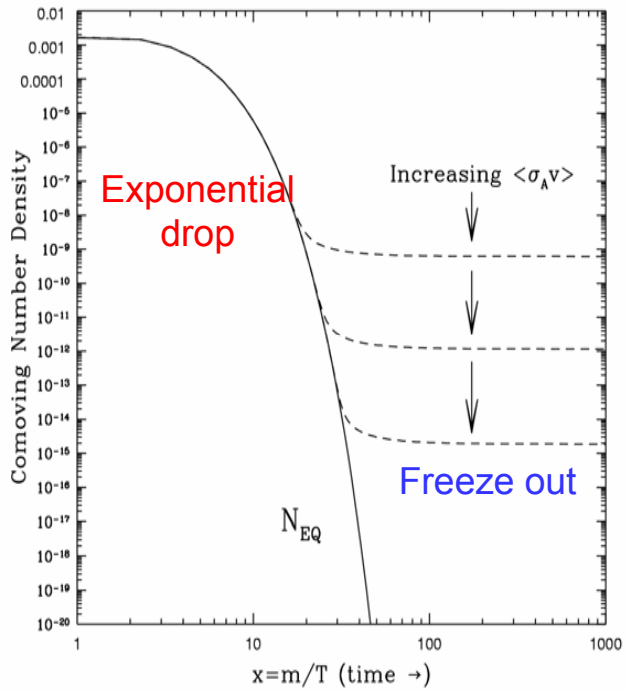
$f\bar{f} \to \chi\chi$

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

$$n_{\rm eq} \langle \sigma v \rangle \sim H$$

$(mT)^{3/2} e^{-m/T}$ $\quad$ $T^2/M_{\rm Pl}$

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

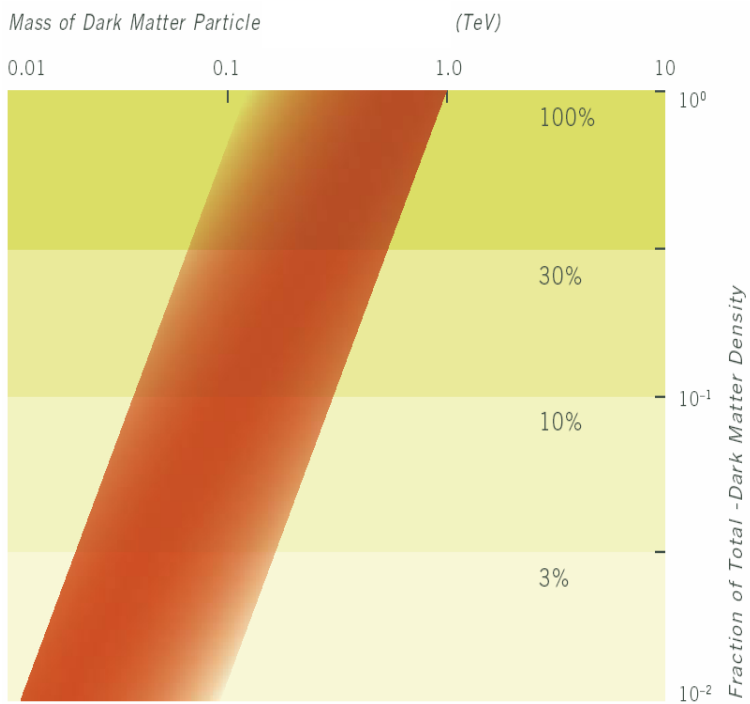


- The amount of dark matter left over is inversely proportional to the annihilation cross section:

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

- 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
$h \to v$	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
$Z \to F$	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:

$$c_{ij}\frac{Z^\dagger Z}{M_{\rm Pl}^2}\phi_i^*\phi_j \rightarrow \text{scalar masses}$$

$$c_a\frac{Z}{M_{\rm Pl}}\lambda_a\lambda_a \rightarrow \text{gaugino masses}$$

$$c_{ijk}\frac{Z}{M_{\rm Pl}}\phi_i\phi_j\phi_k \rightarrow A \text{ terms}$$

$$c\frac{Z^\dagger Z}{M_{\rm Pl}^2}\phi_i\phi_j \rightarrow B \text{ term}$$

- The gravitino mass is

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

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

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

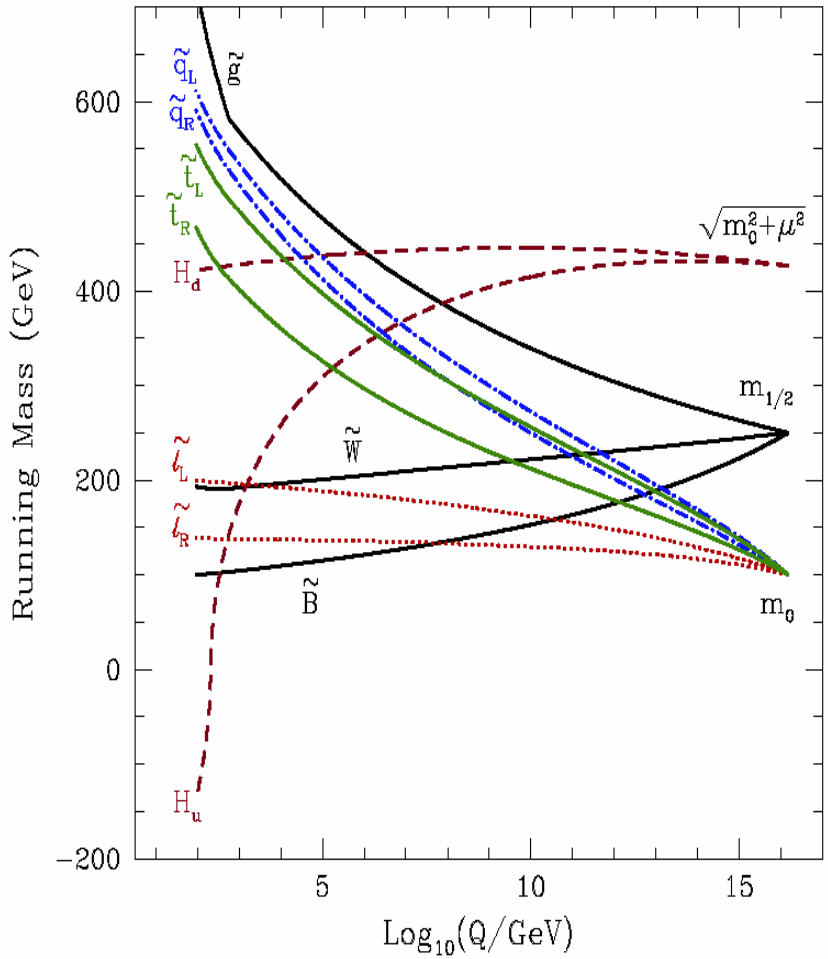
SUPERSYMMETRIC MODELS

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

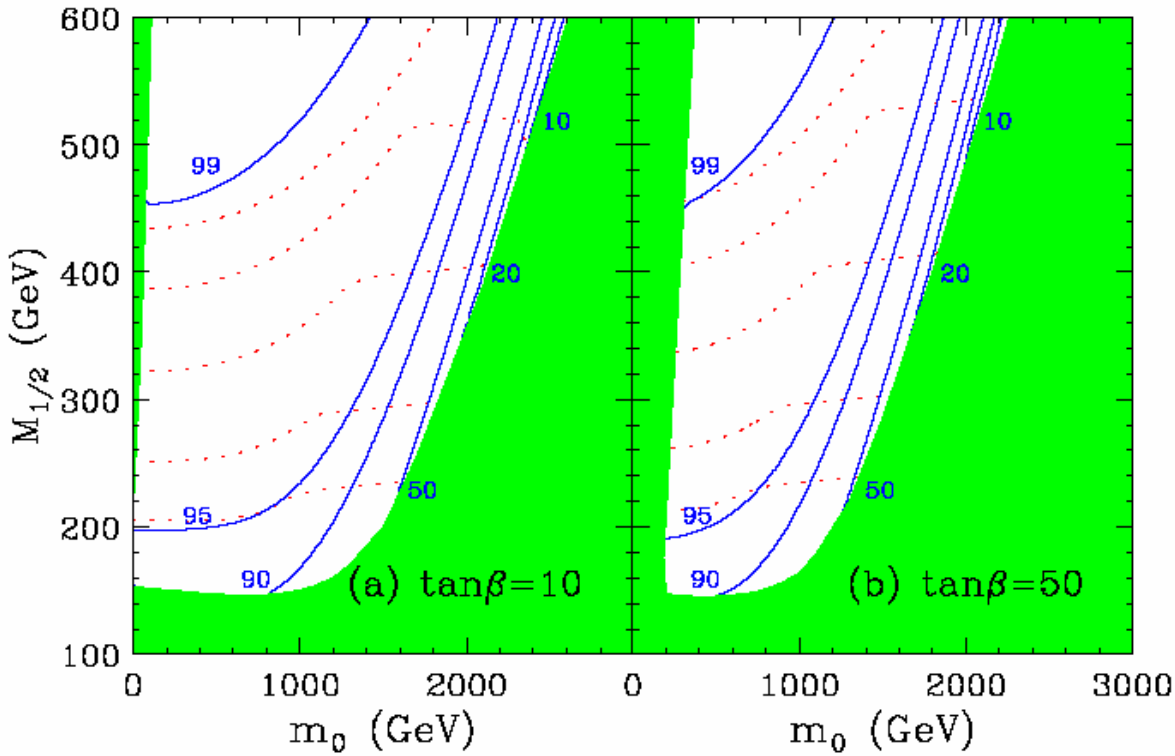
- Two choices
  - scan parameters model-independently
  - Choose models that embody many of the nice features discussed last time

AN EXAMPLE: MINIMAL SUPERGRAVITY

- Defined by 4+1 parameters
  - m_0: universal scalar mass
  - $M_{1/2}$: universal gaugino mass
  - A_0: universal trilinear scalar coupling
  - tanβ: 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

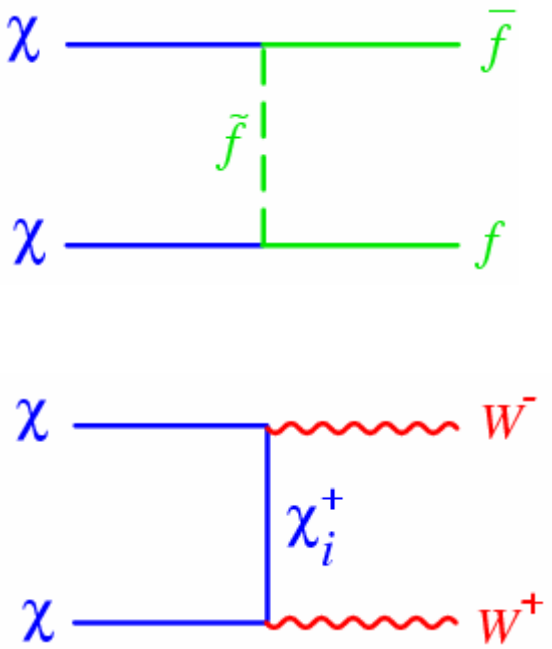
$$\chi = a_{\tilde{B}}\tilde{B} + a_{\tilde{W}}\tilde{W}^0 + a_{\tilde{H}_u}\tilde{H}_u^0 + a_{\tilde{H}_d}\tilde{H}_d^0$$

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:

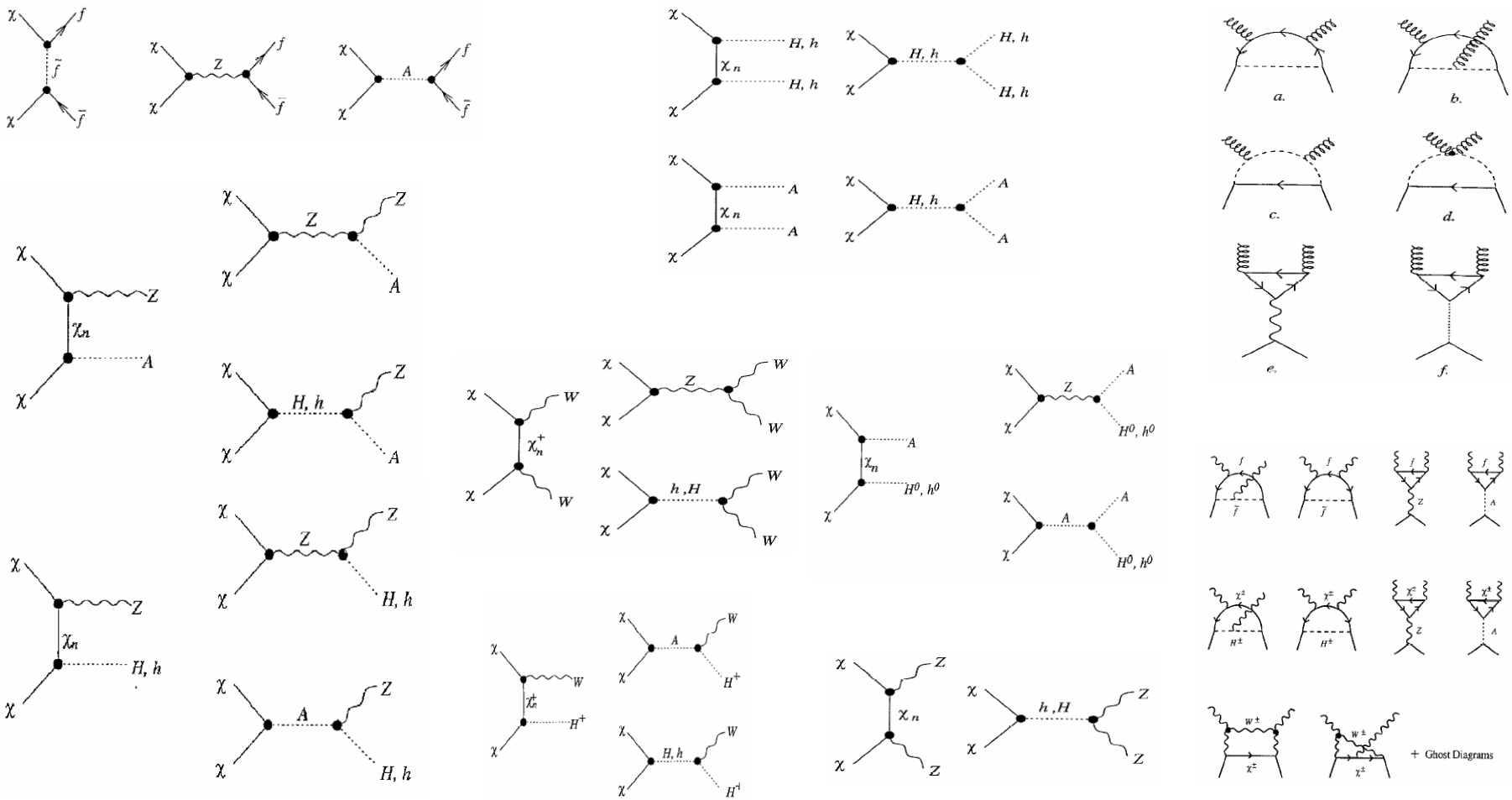


- Fermion diagrams
  χ are Majorana fermions:
  Pauli exclusion → $S = 0$
  L conservation → P wave suppression
  m_f/m_W suppression

- Gauge boson diagrams
  suppressed for χ ≈ 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

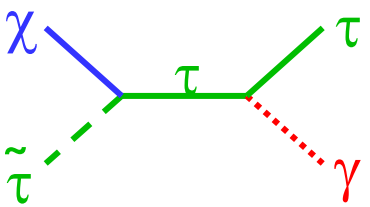
Typically get too much DM, but there are generic mechanisms for reducing it

Excluded:
Stau LSP

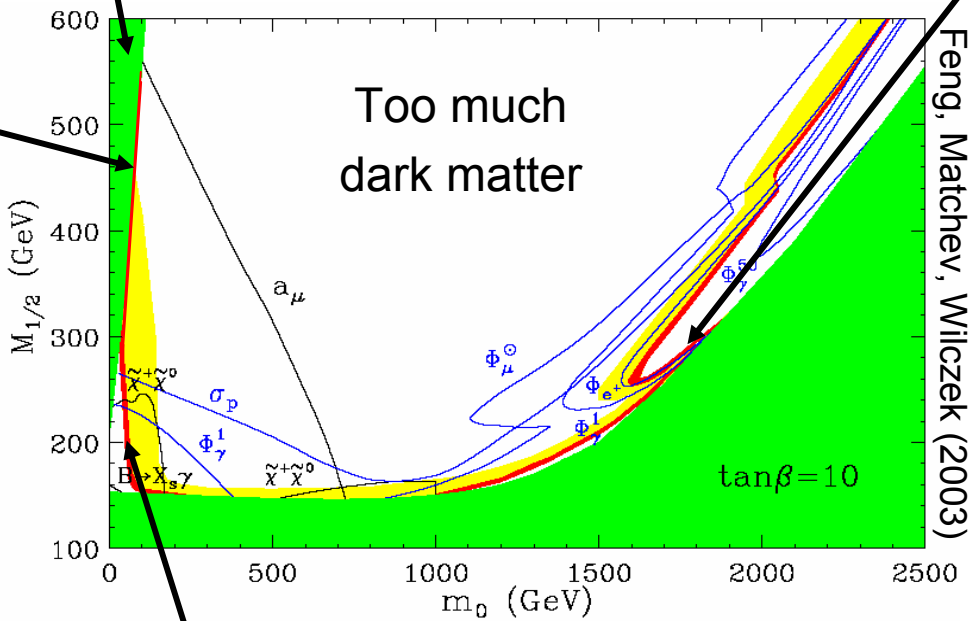
Yellow: pre-WMAP
Red: post-WMAP

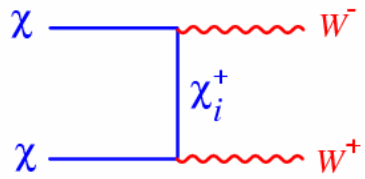
Focus point region

Co-annihilation region



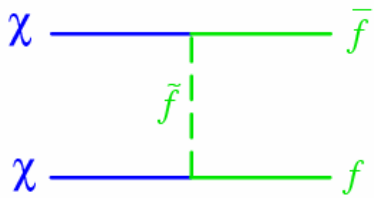
Degenerate χ and stau





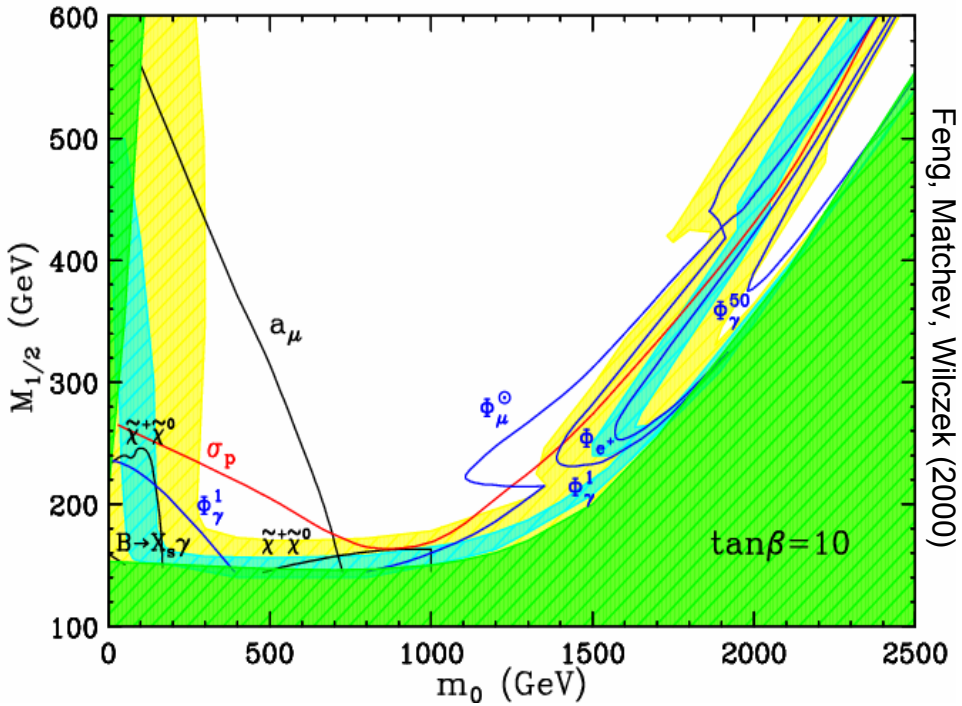
Mixed Neutralinos

Bulk region



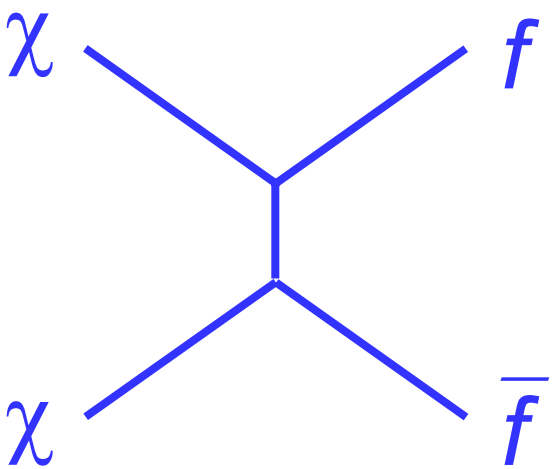
Light sfermions

Implications for Detection



Many diverse experiments are promising in the cosmologically preferred regions

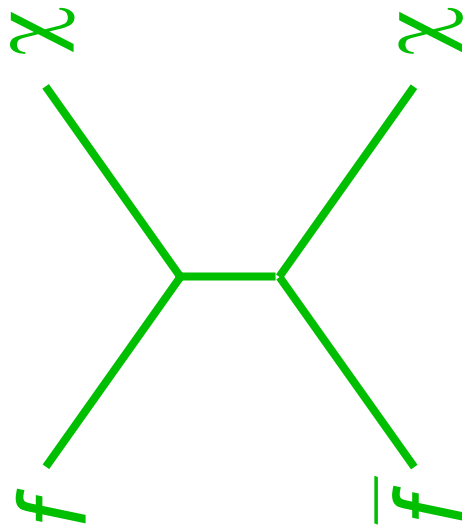
WIMP DETECTION



Annihilation

Crossing

symmetry



Scattering

Correct relic density → Efficient annihilation then

→ Efficient annihilation now (indirect detection)

→ Efficient scattering now (direct detection)

DIRECT DETECTION

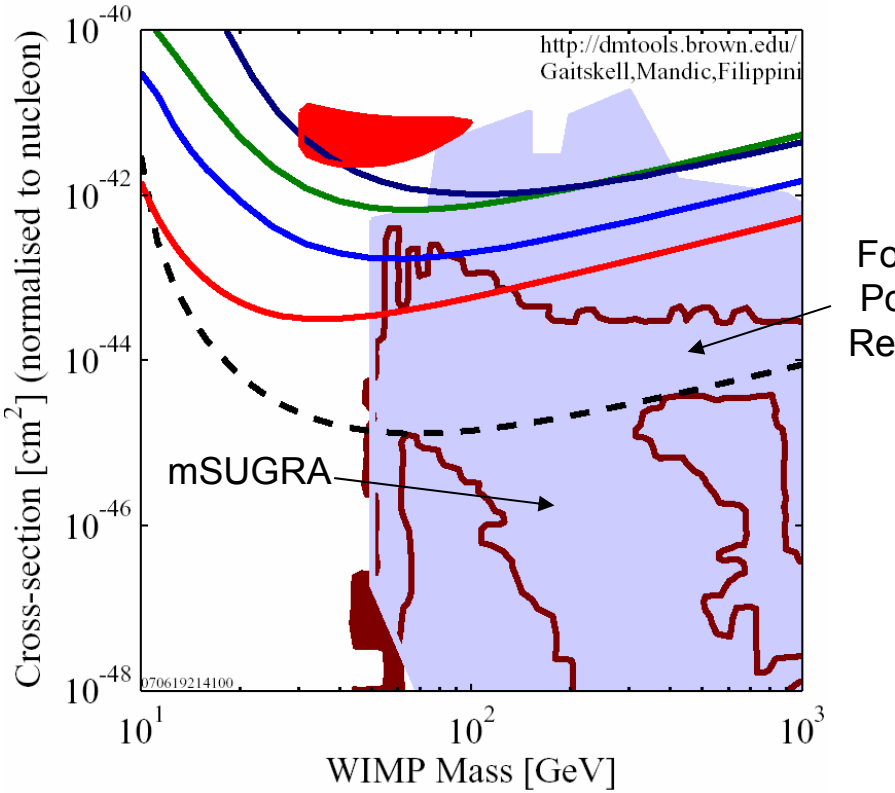
- WIMP essentials:

  $v \sim 10^{-3}\ c$

  Kinetic energy ~ 100 keV

  Local density ~ 1 / liter

- Detected by recoils off ultra-sensitive underground detectors



Indirect Detection

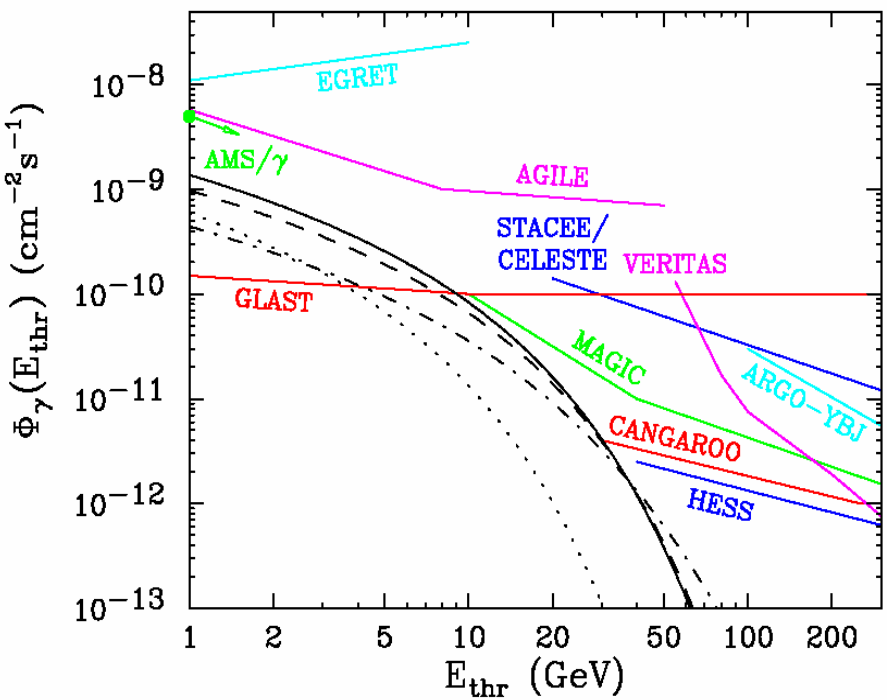
Dark Matter Fill-in-the-Blank!

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

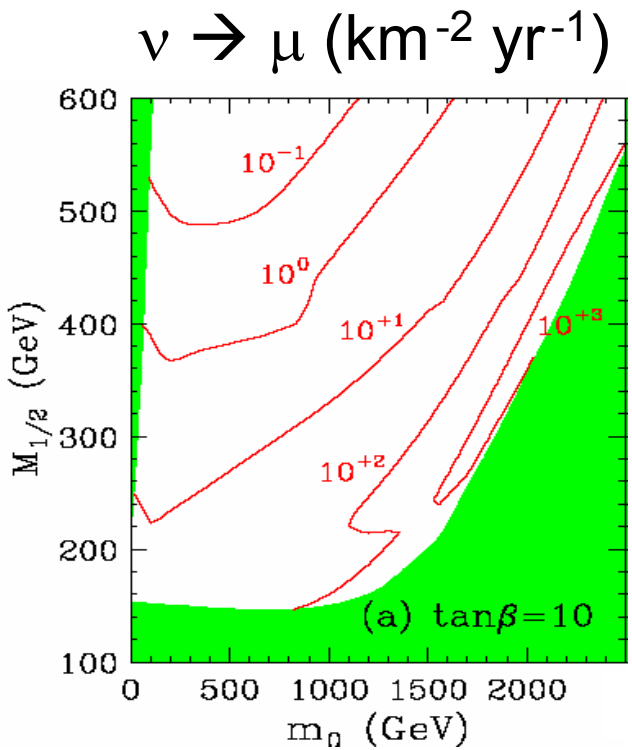


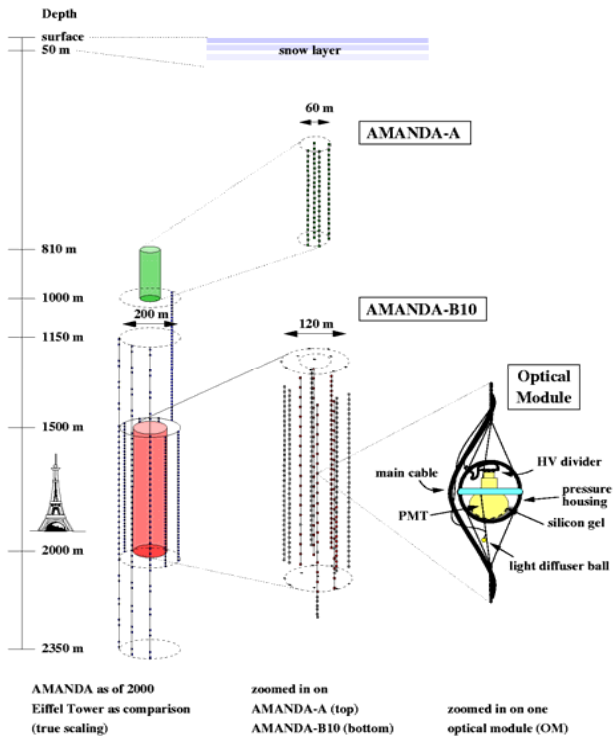
Typically $\chi\chi \not\to \gamma\gamma$,

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





AMANDA in the Antarctic Ice

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

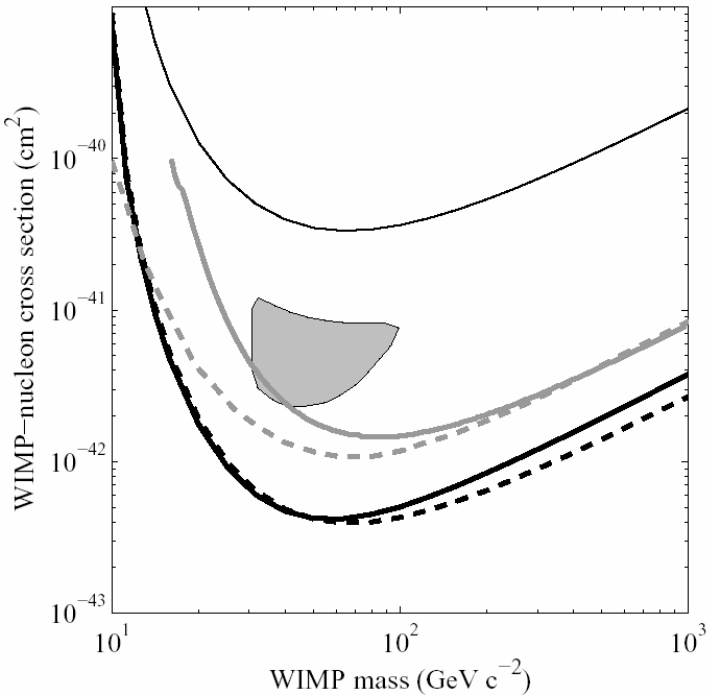
Indirect dark matter searches

Tevatron at Fermilab

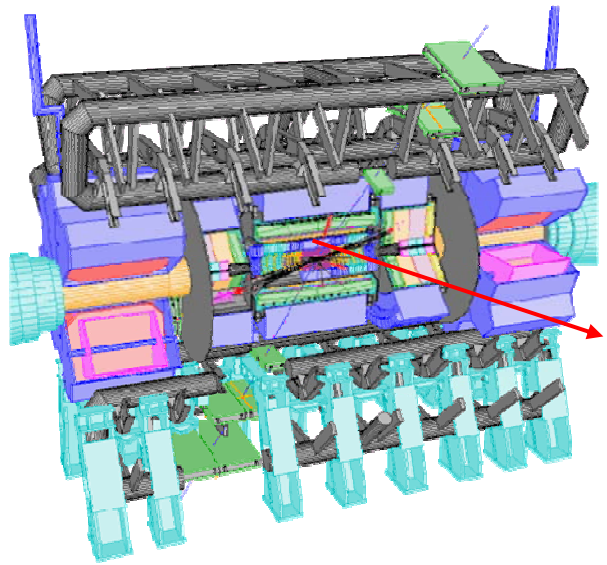
Large Hadron Collider at CERN

What then?

- Cosmo/astro can't discover SUSY

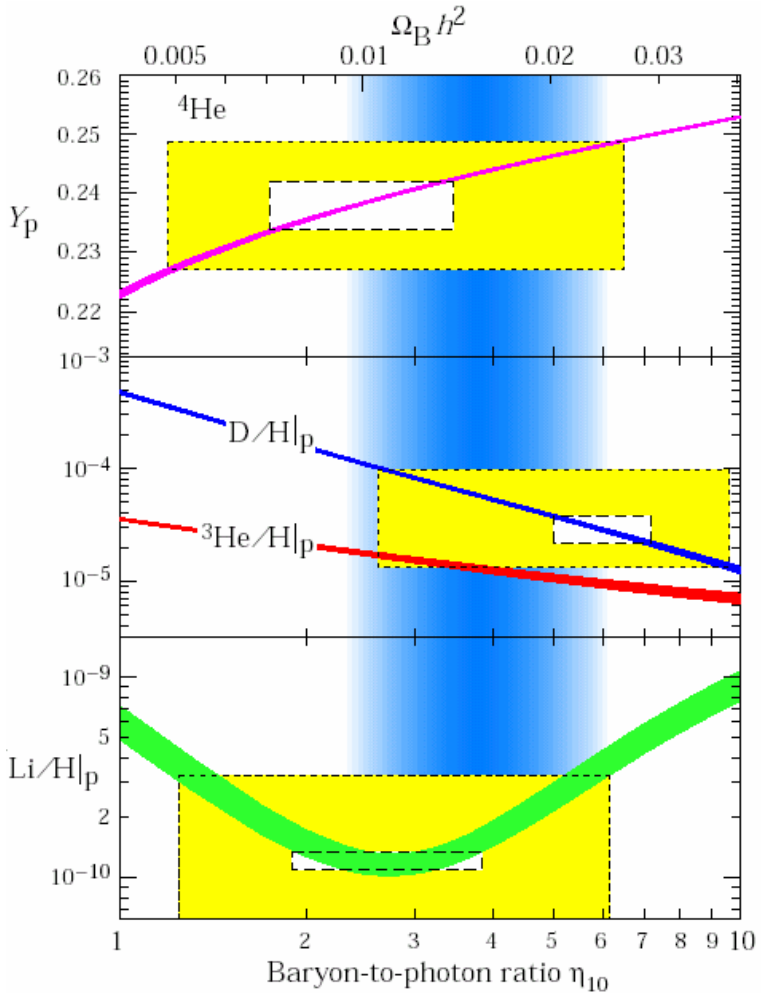


- Particle colliders can't discover DM



Lifetime > 10^{-7} s → 10^{17} s ?

THE EXAMPLE OF BBN

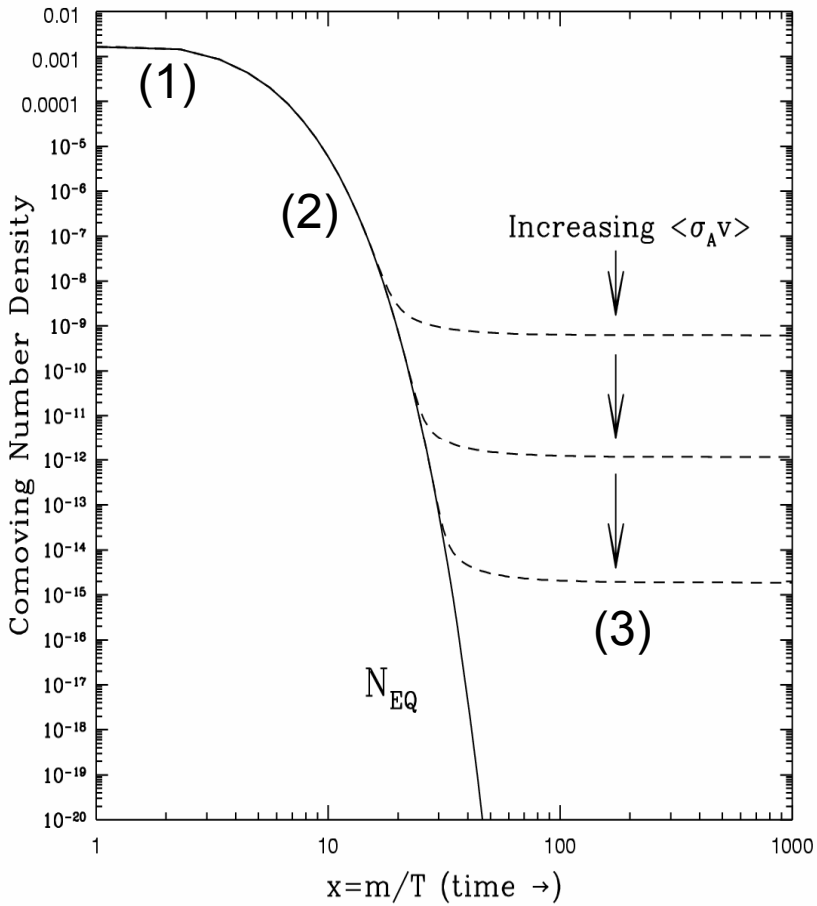


- Nuclear physics → light element abundance predictions
- Compare to light element abundance observations
- Agreement → we understand the universe back to

  T ~ 1 MeV

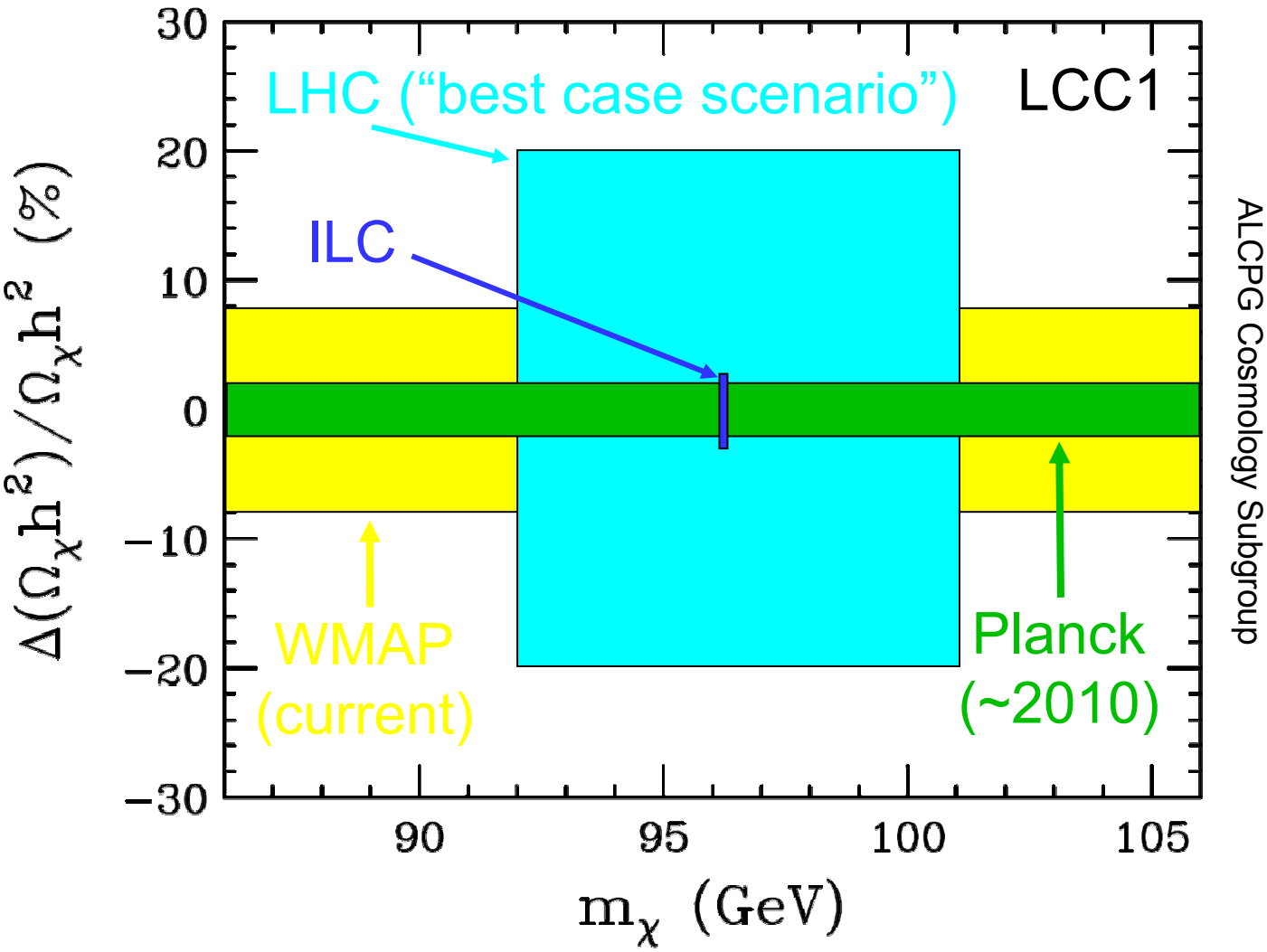
  t ~ 1 sec

DARK MATTER ANALOGUE



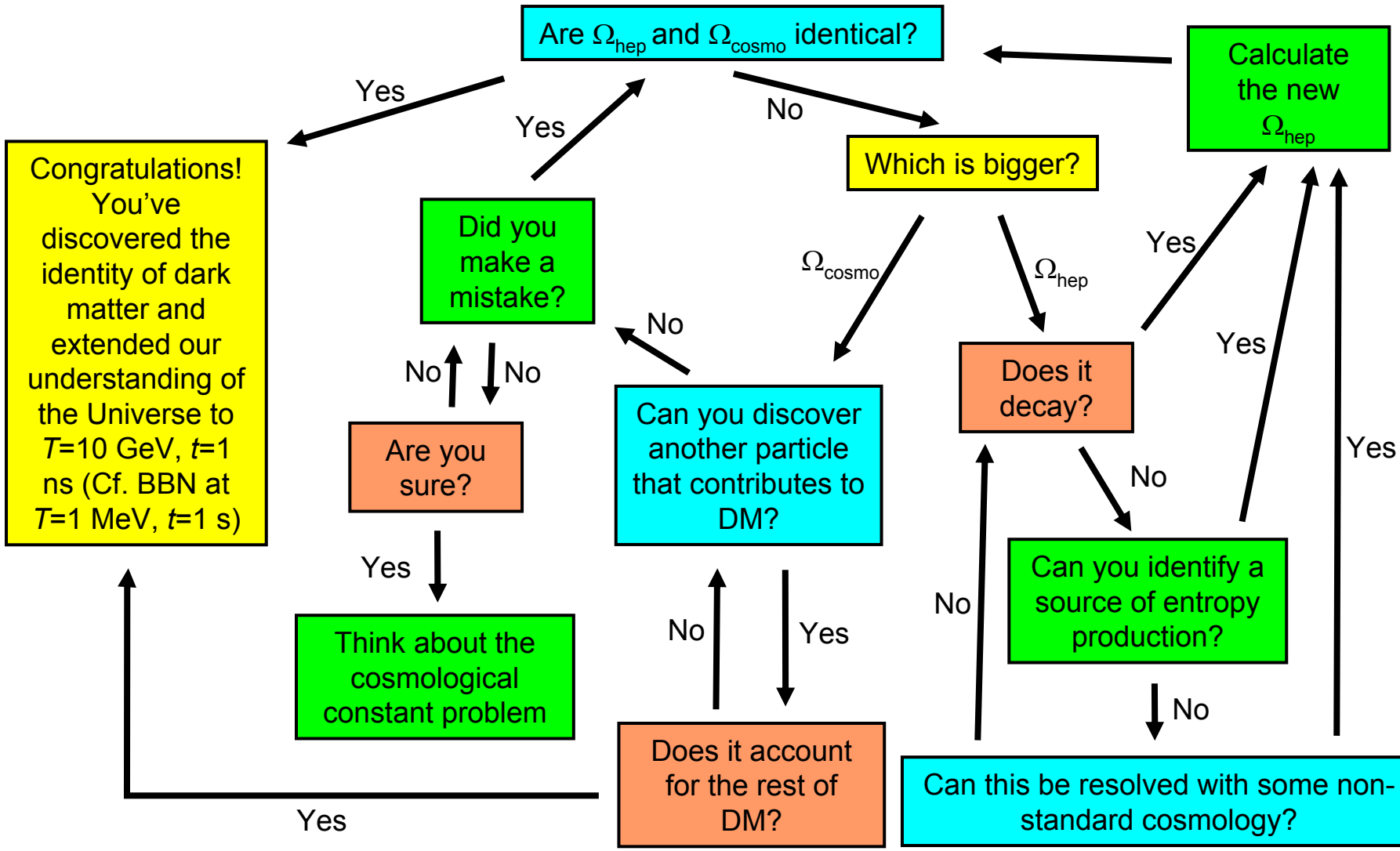
- Particle physics → dark matter abundance prediction
- Compare to dark matter abundance observation
- How well can we do?

RELIC DENSITY DETERMINATIONS

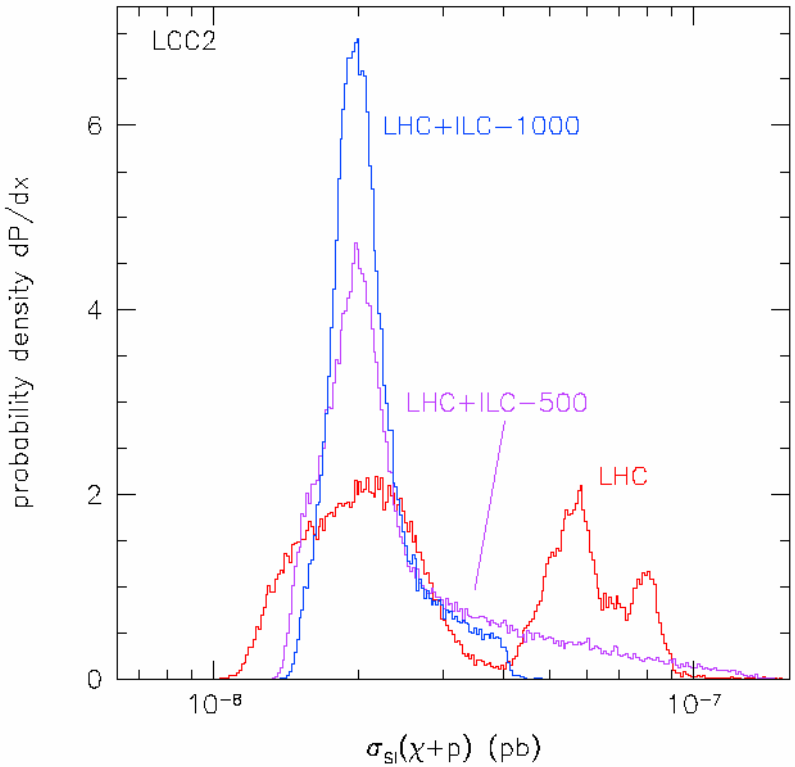


% level comparison of predicted Ω_{hep} with observed Ω_{cosmo}

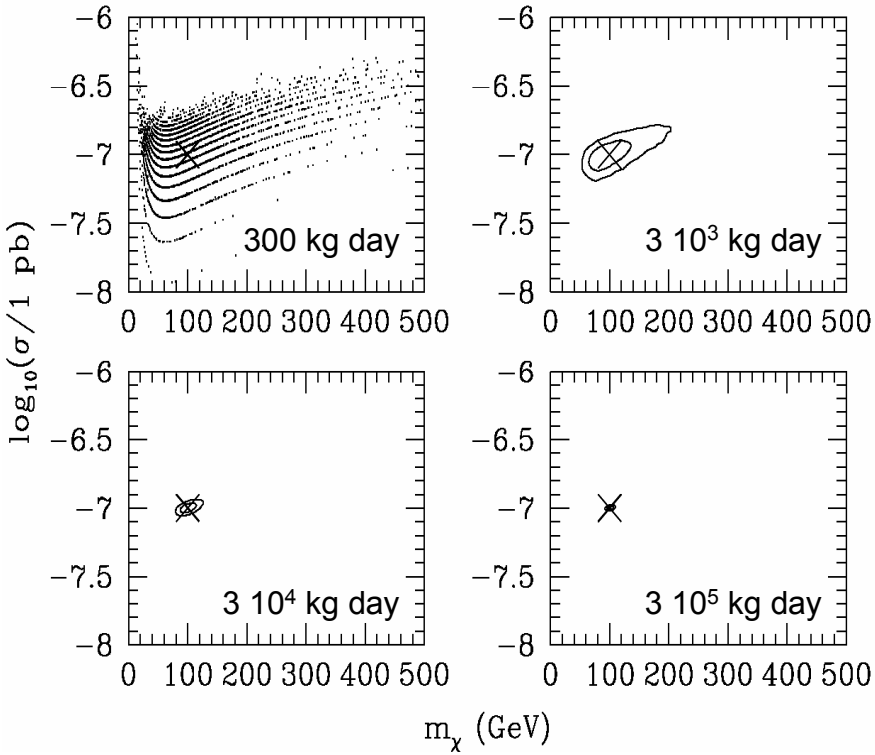
IDENTIFYING DARK MATTER



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

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