RECENT PROGRESS IN SUSY DARK MATTER

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12 April 2006
Texas A&M
Mitchell Symposium

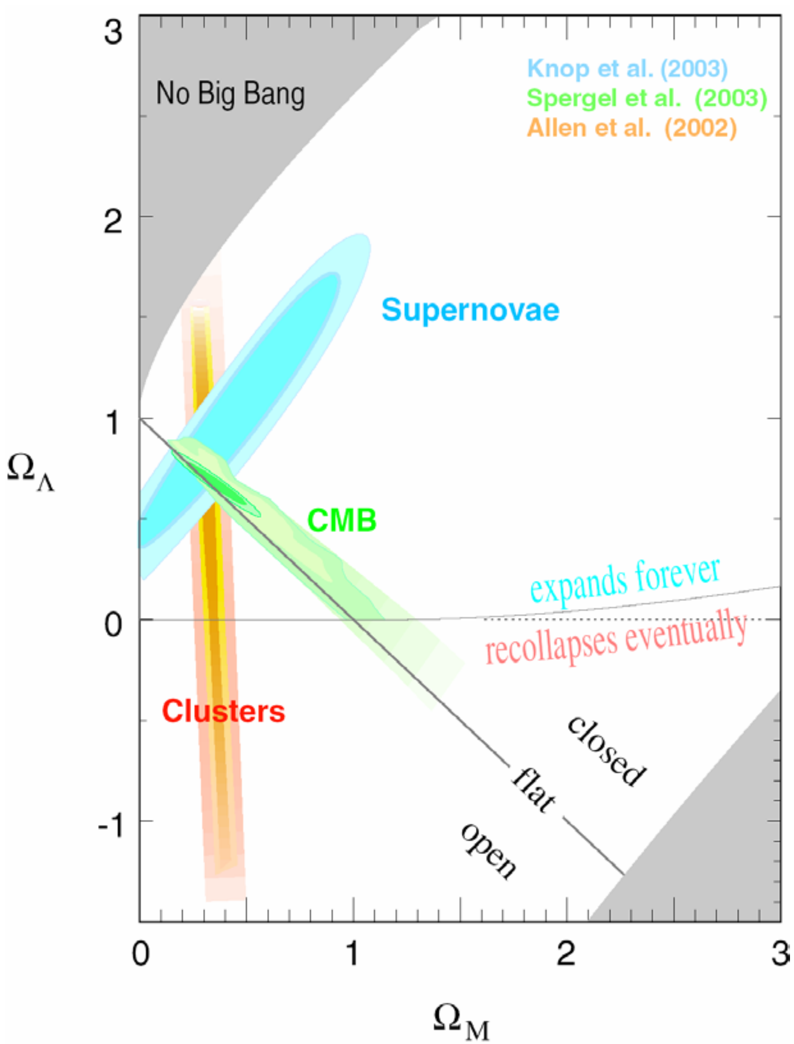
Graphic: N. Graf

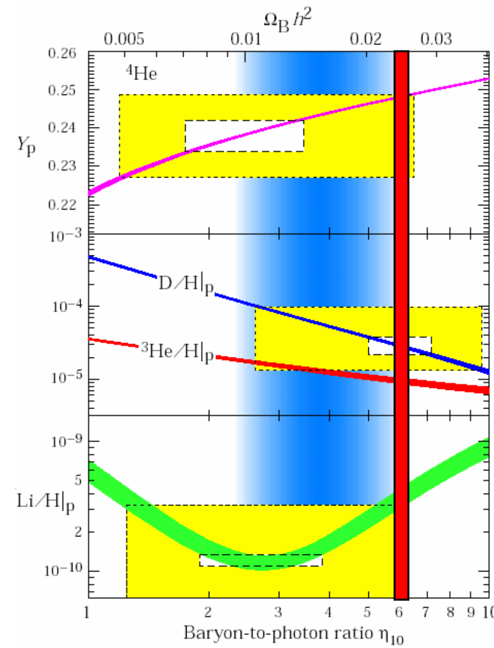
Supersymmetric dark matter has been around for over 2 decades.

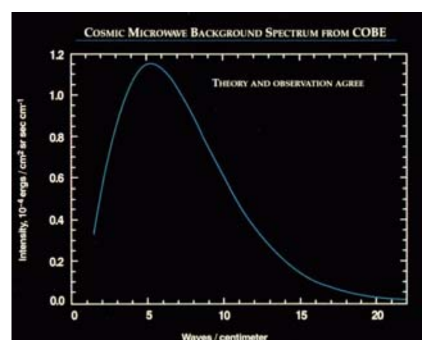
We still haven't found it.

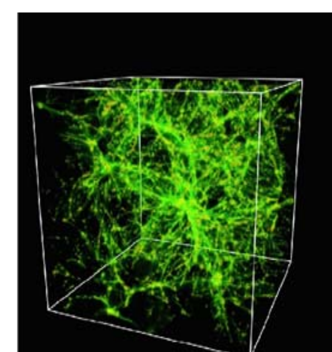
What possibly could be new?

In fact, the wealth of cosmological data has sharpened old proposals and also led to qualitatively new possibilities









In addition, the *anticipated* wealth of particle physics data has generated new approaches to old questions

- What particle forms dark matter?
- What is its mass?
- What is its spin?
- What are its other quantum numbers and interactions?
- Is dark matter composed of one particle species or many?
- How and when was it produced?
- Why does Ω_{DM} have the observed value?
- How is dark matter distributed now?
- What is its role in structure formation?
- Is it absolutely stable?

WIMP Dark Matter

The classic WIMP: neutralinos predicted by supersymmetry

Goldberg (1983), Ellis et al. (1983)

- Supersymmetry: For every known particle X, predicts a partner particle $\tilde{X}$. Stabilizes weak scale if masses are ~ 100 GeV.

- Neutralino $\chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}_u, \tilde{H}_d)$: neutral, weakly-interacting.

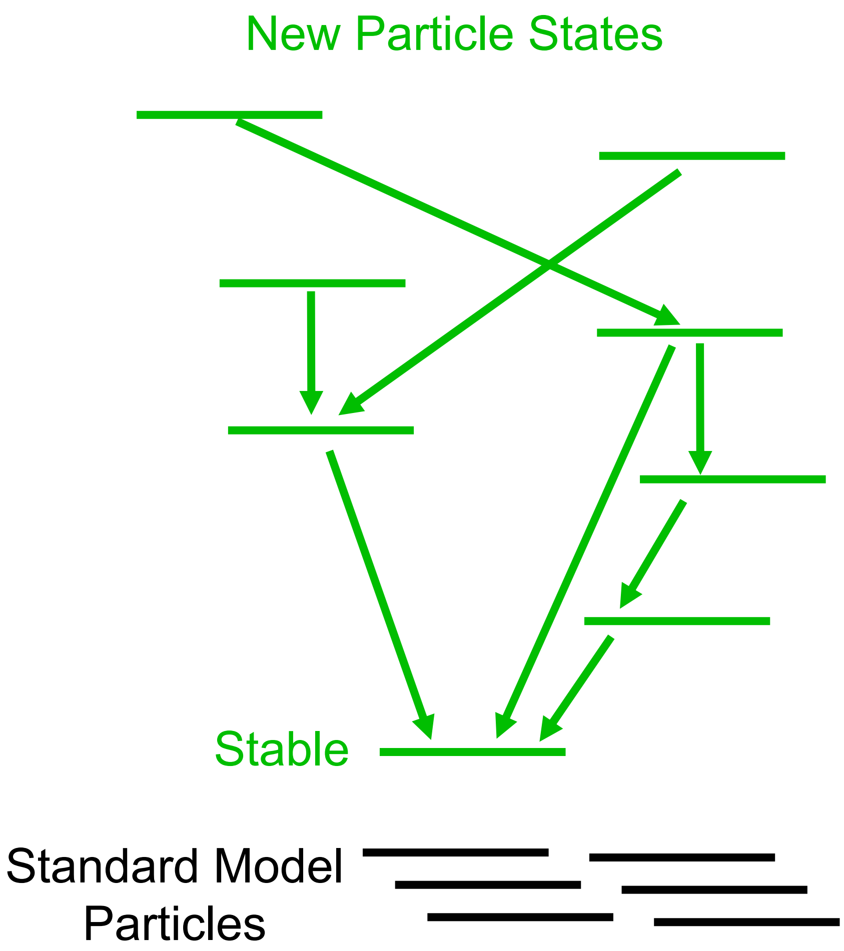
- In many models, χ is the lightest supersymmetric particle and stable. All the right properties for dark matter!

STABILITY

- DM must be stable

- Problems
  ↕
  Discrete symmetry
  ↕
  Stability

- In many theories, dark matter is easier to explain than no dark matter



Cosmological Implications

(1) Initially, neutralinos are in thermal equilibrium:

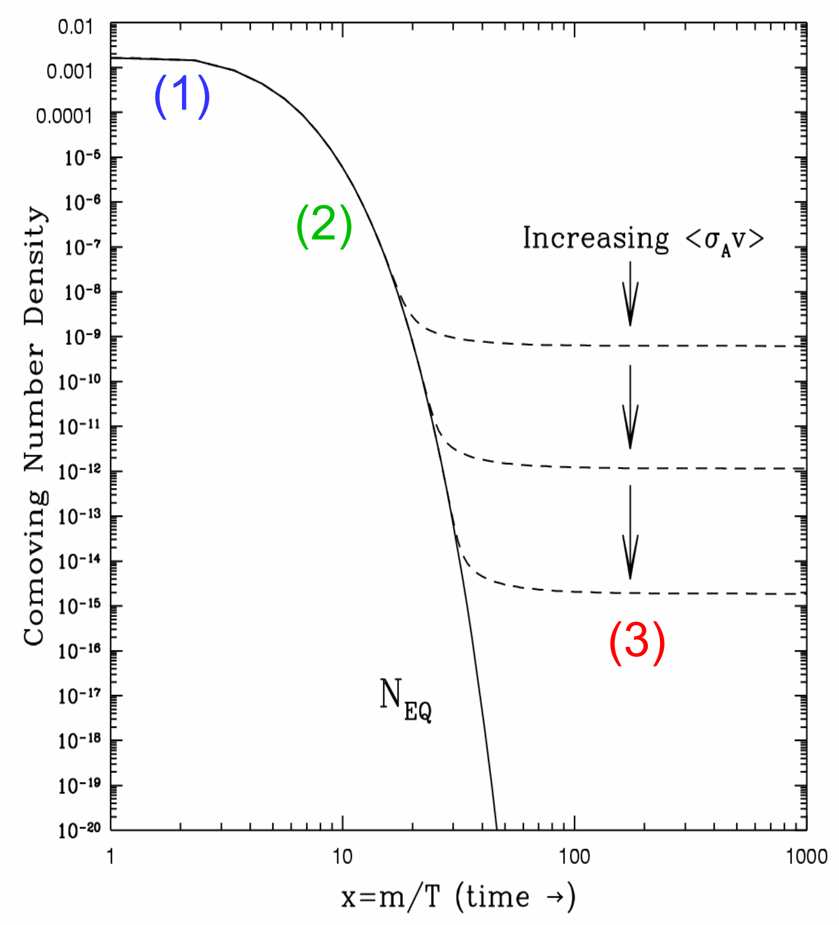
$$\chi\chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

$$N = N_{EQ} \sim e^{-m/T}$$

(3) χs "freeze out":

$$N \sim \text{const}$$



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

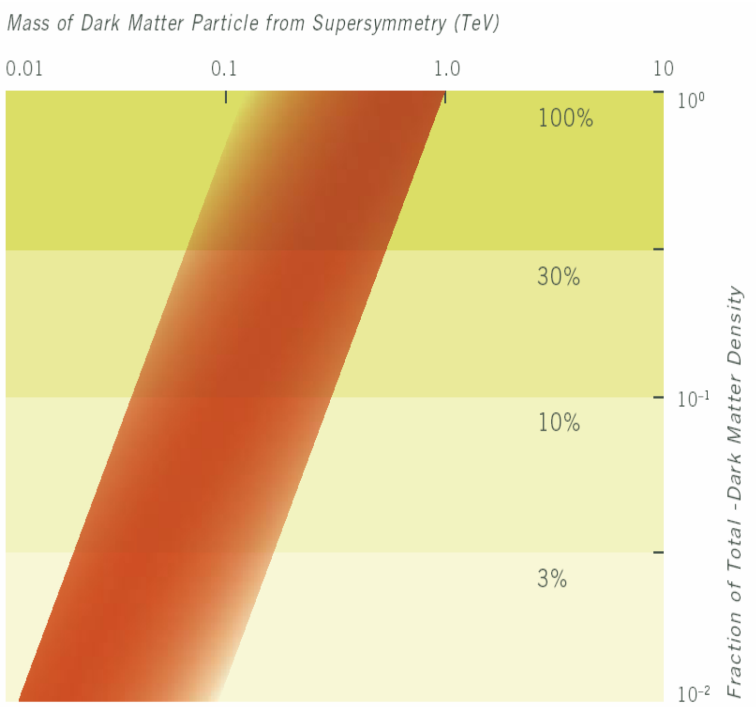
$$\Omega_{DM} \sim \langle\sigma_A v\rangle^{-1}$$

Scherrer, Turner (1985)

- What's 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 (2005)

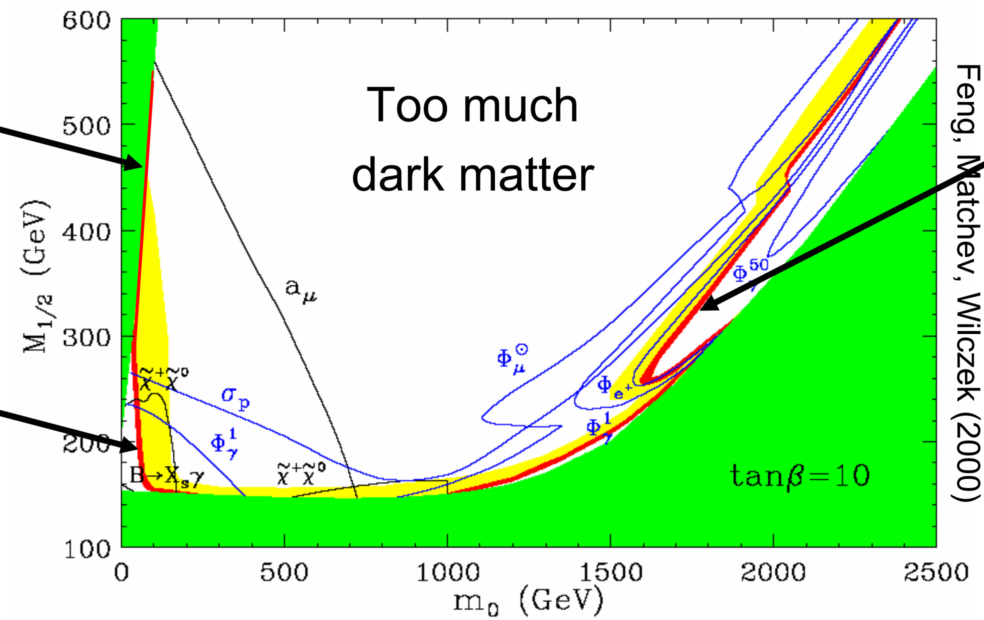
[k = 0.5 – 2]

Remarkable "coincidence": ~100 GeV mass particles are naturally produced in the right quantity to be dark matter

Ω_{DM} = 23% ± 4% stringently constrains SUSY models

Co-annihilation region

Bulk region



Focus point region

Yellow: before 2003

Red: after 2003

Cosmology excludes many possibilities, favors certain regions

IDENTIFYING NEUTRALINOS

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

Direct dark matter searches

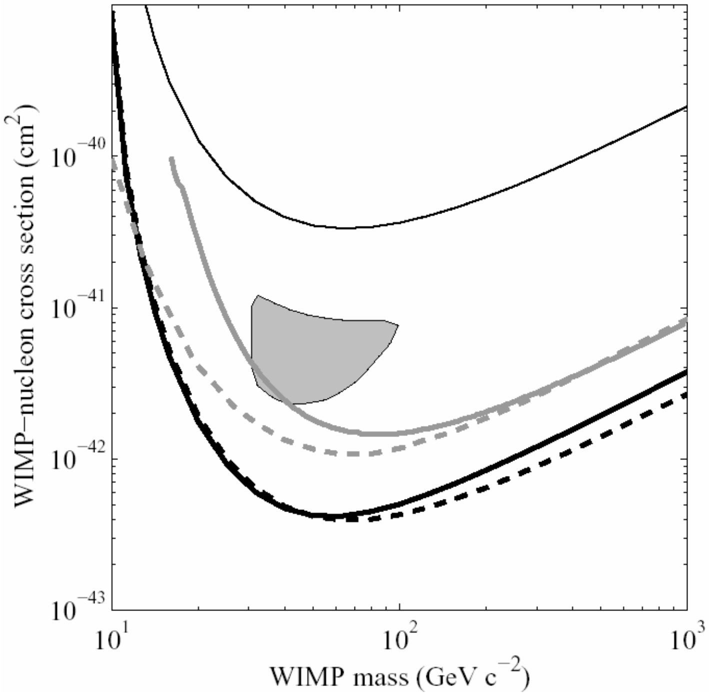
Indirect dark matter searches

Tevatron at Fermilab

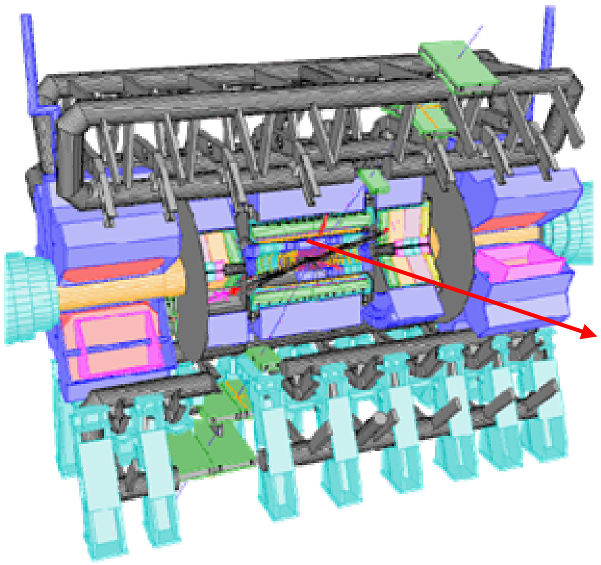
Large Hadron Collider at CERN (2007)

What then?

- Cosmo/astro can't identify SUSY

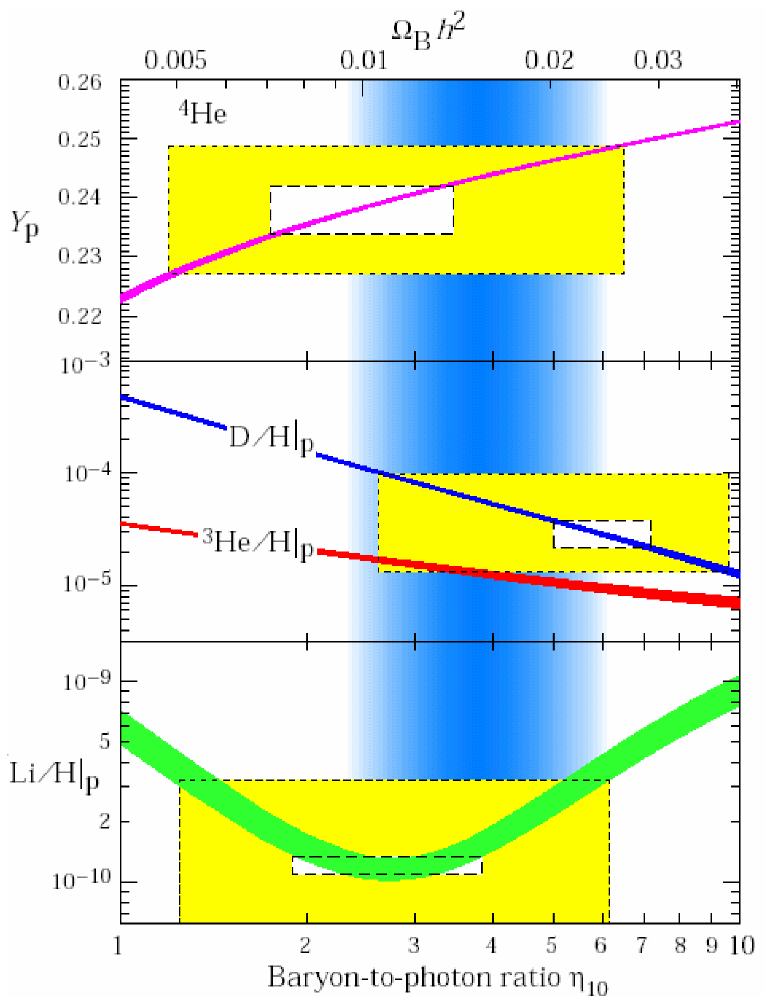


- Particle colliders can't identify DM



Lifetime > 10^{-7} s → 10^{17} s ?

THE EXAMPLE OF BBN

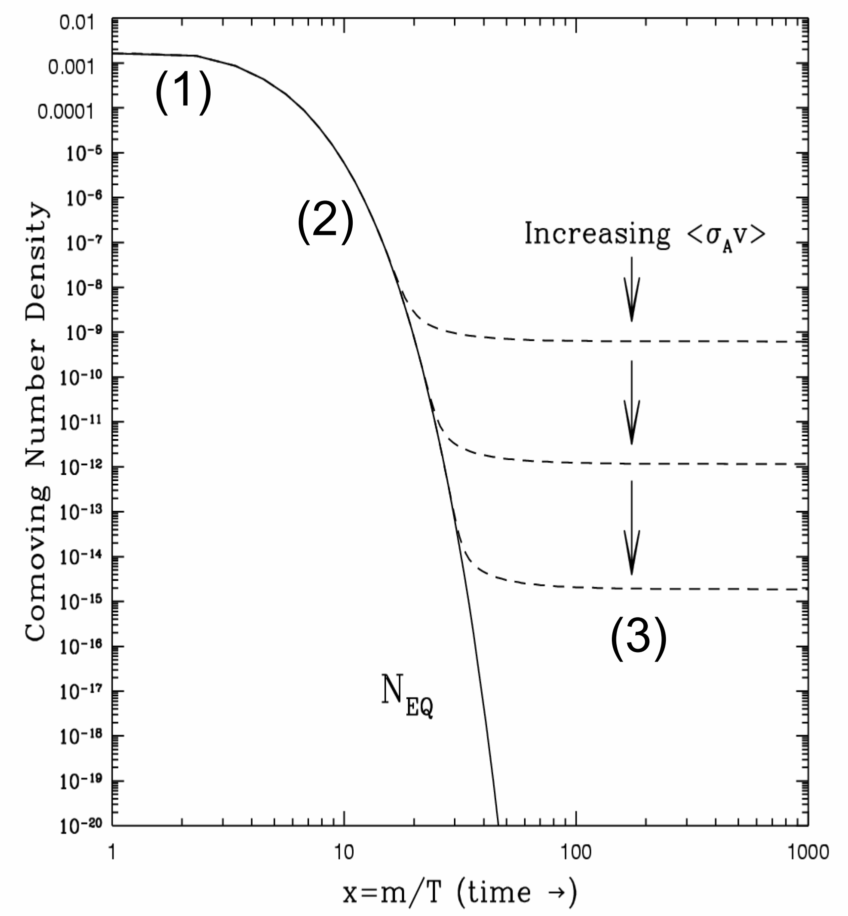


- Nuclear physics → light element abundance predictions
- Compare to light element abundance observations
- Agreement → we understand the universe back to

  T ~ 1 MeV

  t ~ 1 sec

DARK MATTER ANALOGUE

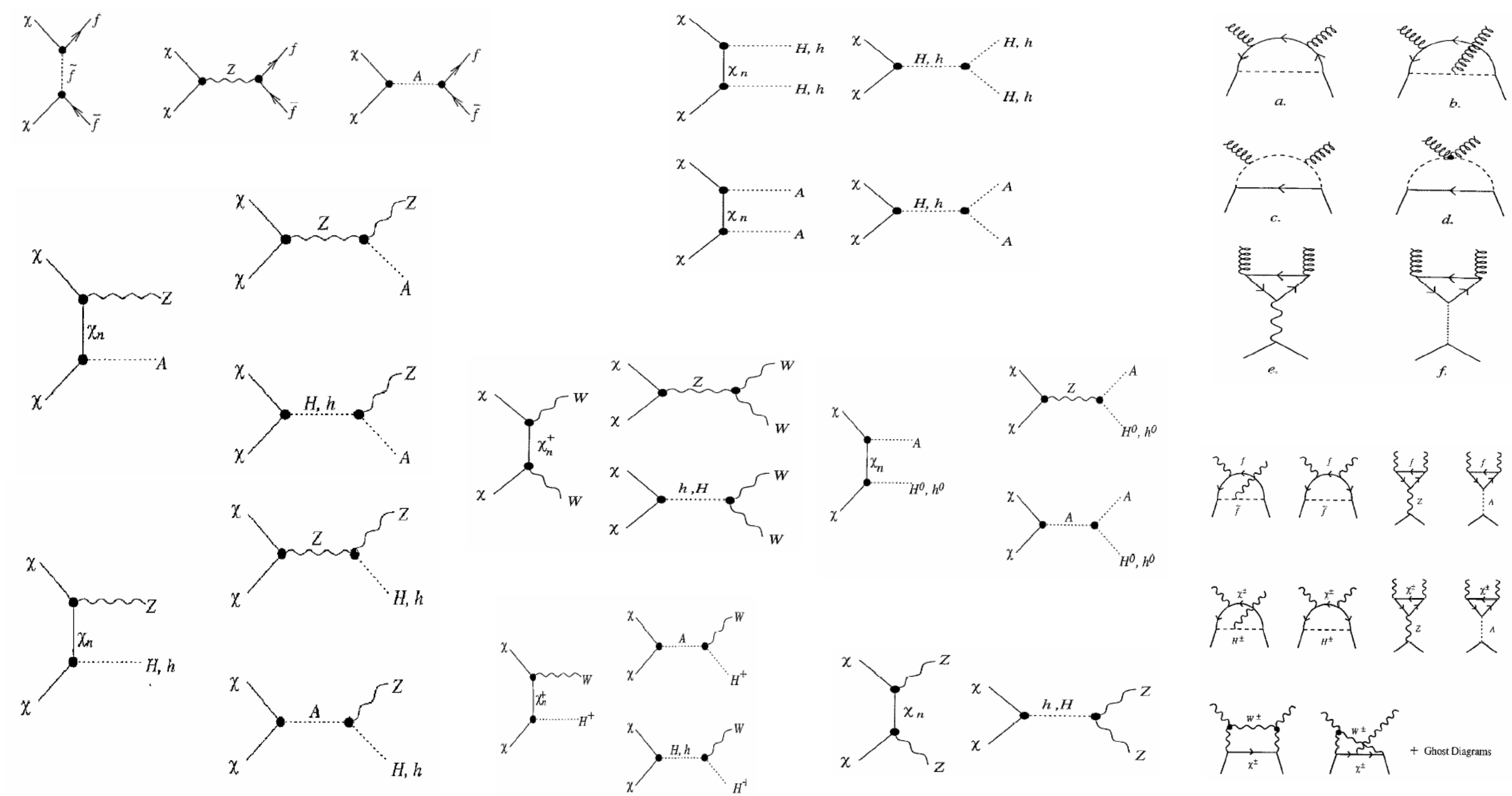


- Particle physics → dark matter abundance prediction

- Compare to dark matter abundance observation

- How well can we do?

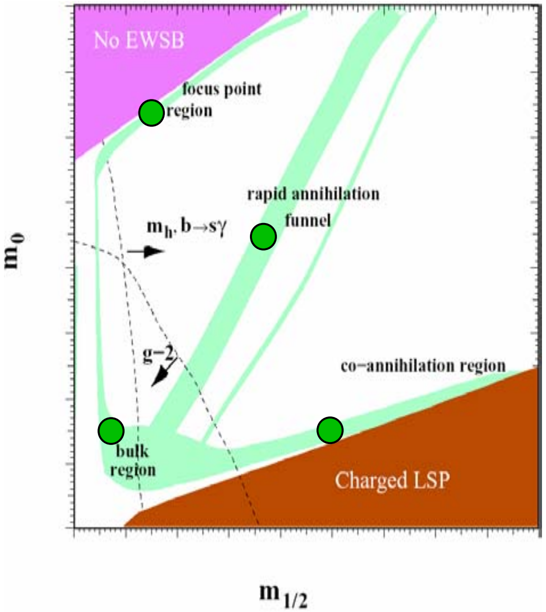
Contributions to Neutralino WIMP Annihilation



An Approach (ALCPG Cosmology Group)

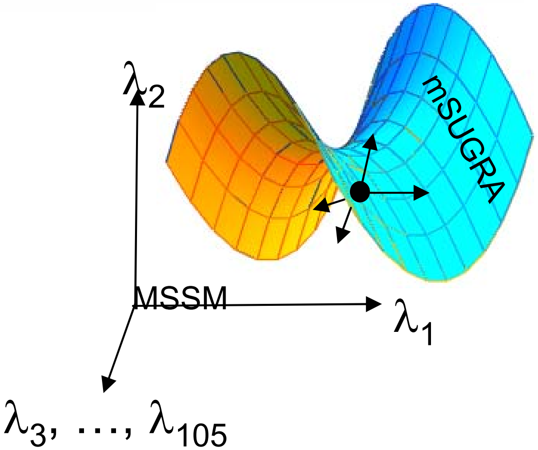
Choose a representative model

- Bulk region (Baltz, Battaglia, Peskin, Wizansky)
- Focus point region (Alexander, Birkedal, Ecklund, Matchev; Moroi, Shimizu, Yotsuyanagi;…)
- Co-annihilation region (Arnowitt, Dutta, Kamon, Khotilovich, Toback; Nauenberg; …)
- Funnel region (Allanach, Belanger, Boudjema, Pukhov; …)



- Relax model-dependent assumptions and determine parameters

- Identify cosmological, astroparticle implications

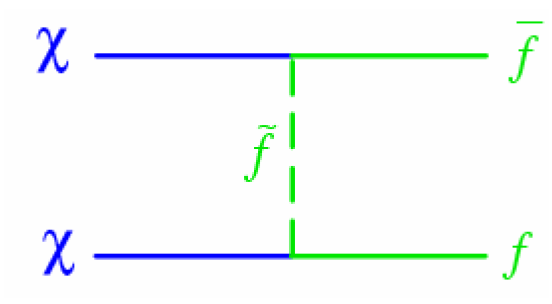


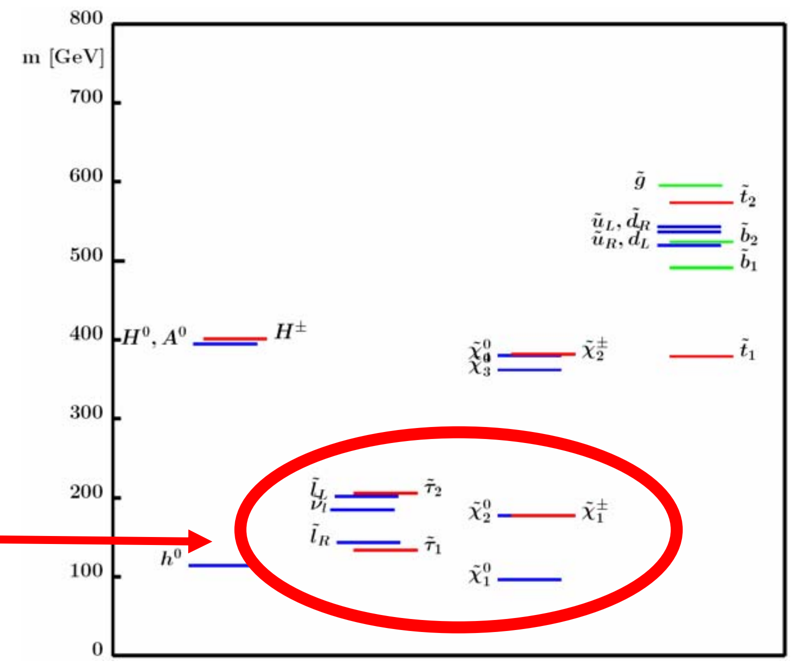
An example in the bulk region: LCC1 (SPS1a)

ALCPG Cosmology Subgroup

$m_0, M_{1/2}, A_0, \tan\beta$ = 100, 250, -100, 10 [$\mu>0$, $m_{3/2}>m_{LSP}$]

- Correct relic density through χ annihilation with light sfermions:

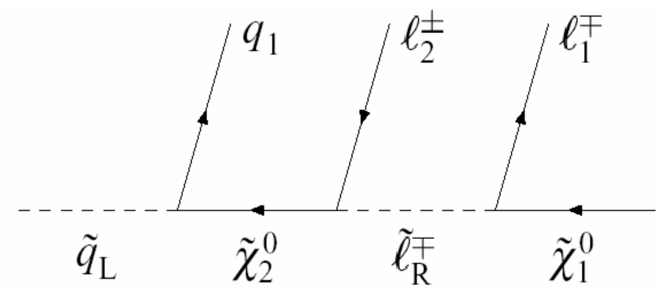




- Representative of SUSY with relatively light $\chi, \tilde{l}$

PRECISION MASSES

- LHC produces strongly-interacting superpartners, which cascade decay



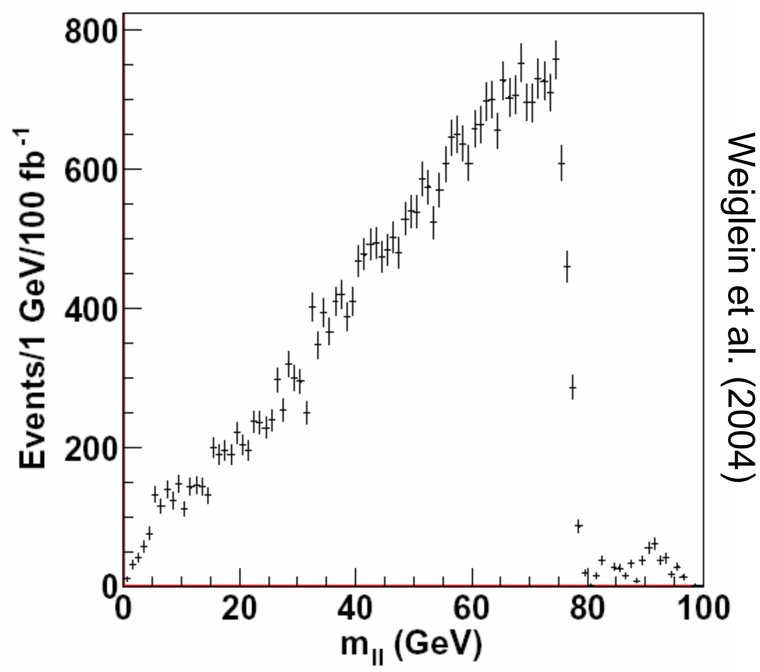
$$\left(m^2_{ll}\right)^{\rm edge} = \frac{\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R}\right)\left(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{l}_R}}$$

$$\left(m^2_{qll}\right)^{\rm edge} = \frac{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2}\right)\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{\chi}^0_2}}$$

$$\left(m^2_{ql}\right)^{\rm edge}_{\rm min} = \frac{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2}\right)\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R}\right)}{m^2_{\tilde{\chi}^0_2}}$$

$$\left(m^2_{ql}\right)^{\rm edge}_{\rm max} = \frac{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2}\right)\left(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{l}_R}}$$

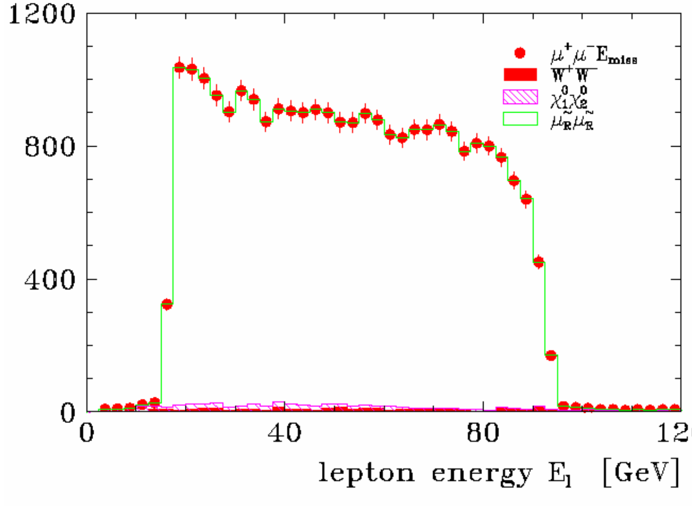
$$\begin{aligned}\left(m^2_{qll}\right)^{\rm thres} = {} & [(m^2_{\tilde{q}_L} + m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1}) \\ & -(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})\sqrt{(m^2_{\tilde{\chi}^0_2} + m^2_{\tilde{l}_R})^2(m^2_{\tilde{l}_R} + m^2_{\tilde{\chi}^0_1})^2 - 16 m^2_{\tilde{\chi}^0_2} m^4_{\tilde{l}_R} m^2_{\tilde{\chi}^0_1}} \\ & +2m^2_{\tilde{l}_R}(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1})]/(4m^2_{\tilde{l}_R} m^2_{\tilde{\chi}^0_2})\end{aligned}$$



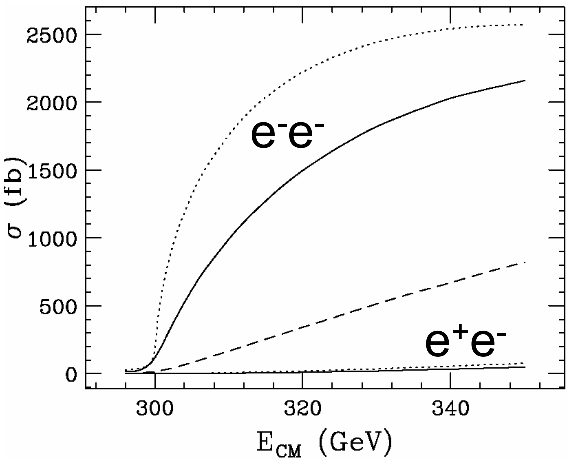
Weiglein et al. (2004)

PRECISION MASSES

- ILC: Exploit all properties
  - kinematic endpoints
  - threshold scans
  - e^- beam polarization
  - e^-e^- option



Martyn et al. (2004)

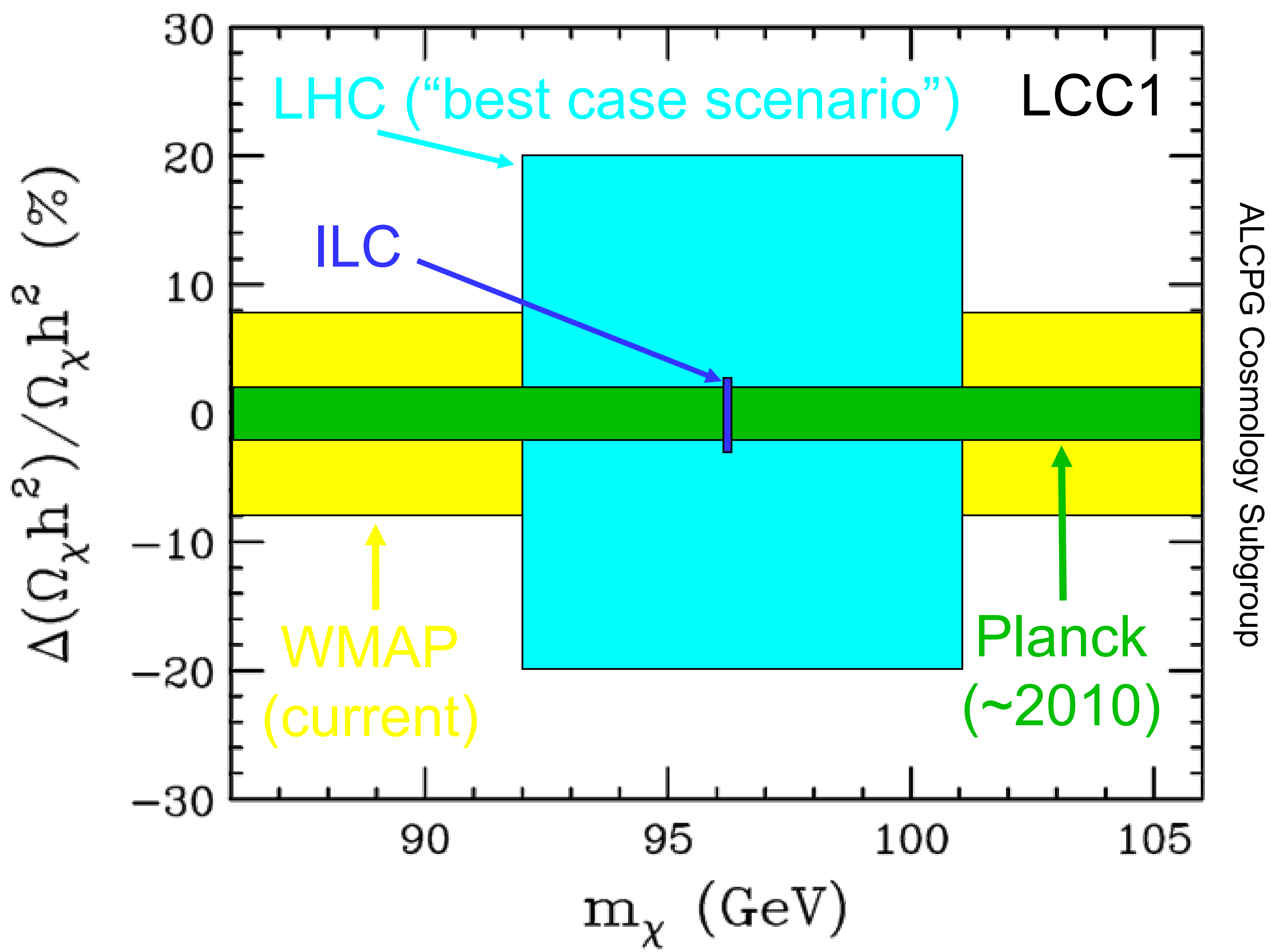


Feng, Peskin (2001)

	m [GeV]	Δm [GeV]	Comments
$\tilde{\chi}_1^\pm$	176.4	0.55	simulation threshold scan , 100 fb^{-1}
$\tilde{\chi}_2^\pm$	378.2	3	estimate $\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$, spectra $\tilde{\chi}_2^\pm \to Z\tilde{\chi}_1^\pm, W\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$	96.1	0.05	combination of all methods
$\tilde{\chi}_2^0$	176.8	1.2	simulation threshold scan $\tilde{\chi}_2^0\tilde{\chi}_2^0$, 100 fb^{-1}
$\tilde{\chi}_3^0$	358.8	3 – 5	spectra $\tilde{\chi}_3^0 \to Z\tilde{\chi}_{1,2}^0$, $\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_3^0\tilde{\chi}_4^0$, 750 GeV, > 1000 fb^{-1}
$\tilde{\chi}_4^0$	377.8	3 – 5	spectra $\tilde{\chi}_4^0 \to W\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0\tilde{\chi}_4^0, \tilde{\chi}_3^0\tilde{\chi}_4^0$, 750 GeV, > 1000 fb^{-1}
$\tilde{e}_R$	143.0	0.05	e^-e^- threshold scan, 10 fb^{-1}
$\tilde{e}_L$	202.1	0.2	e^-e^- threshold scan 20 fb^{-1}
$\tilde{\nu}_e$	186.0	1.2	simulation energy spectrum, 500 GeV, 500 fb^{-1}
$\tilde{\mu}_R$	143.0	0.2	simulation energy spectrum, 400 GeV, 200 fb^{-1}
$\tilde{\mu}_L$	202.1	0.5	estimate threshold scan, 100 fb^{-1} [36]
$\tilde{\tau}_1$	133.2	0.3	simulation energy spectra, 400 GeV, 200 fb^{-1}
$\tilde{\tau}_2$	206.1	1.1	estimate threshold scan, 60 fb^{-1} [36]
$\tilde{t}_1$	379.1	2	estimate b-jet spectrum, $m_{min}()$, 1TeV, 1000 fb^{-1}

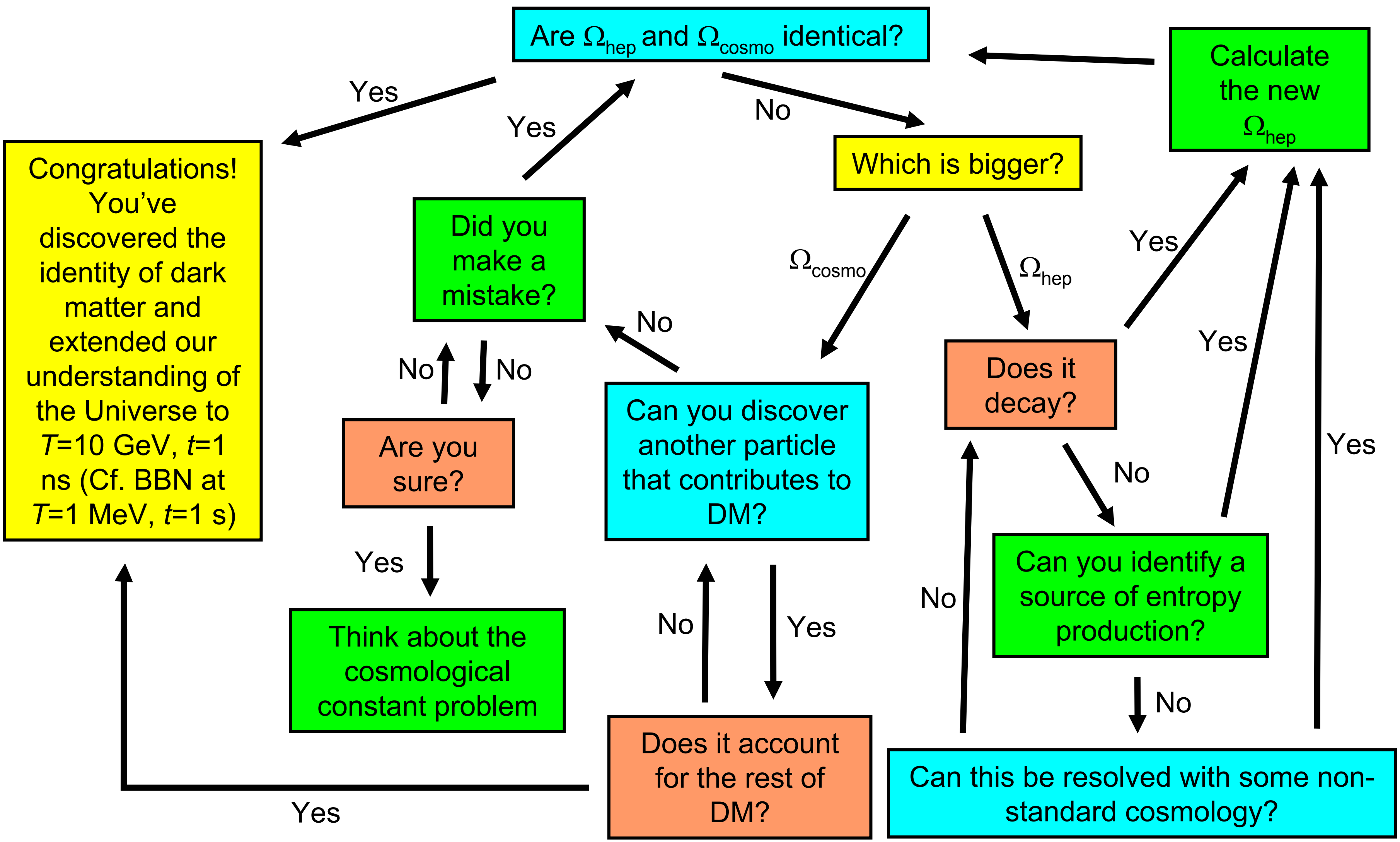
- Must also verify insensitivity to all other parameters

RELIC DENSITY DETERMINATIONS



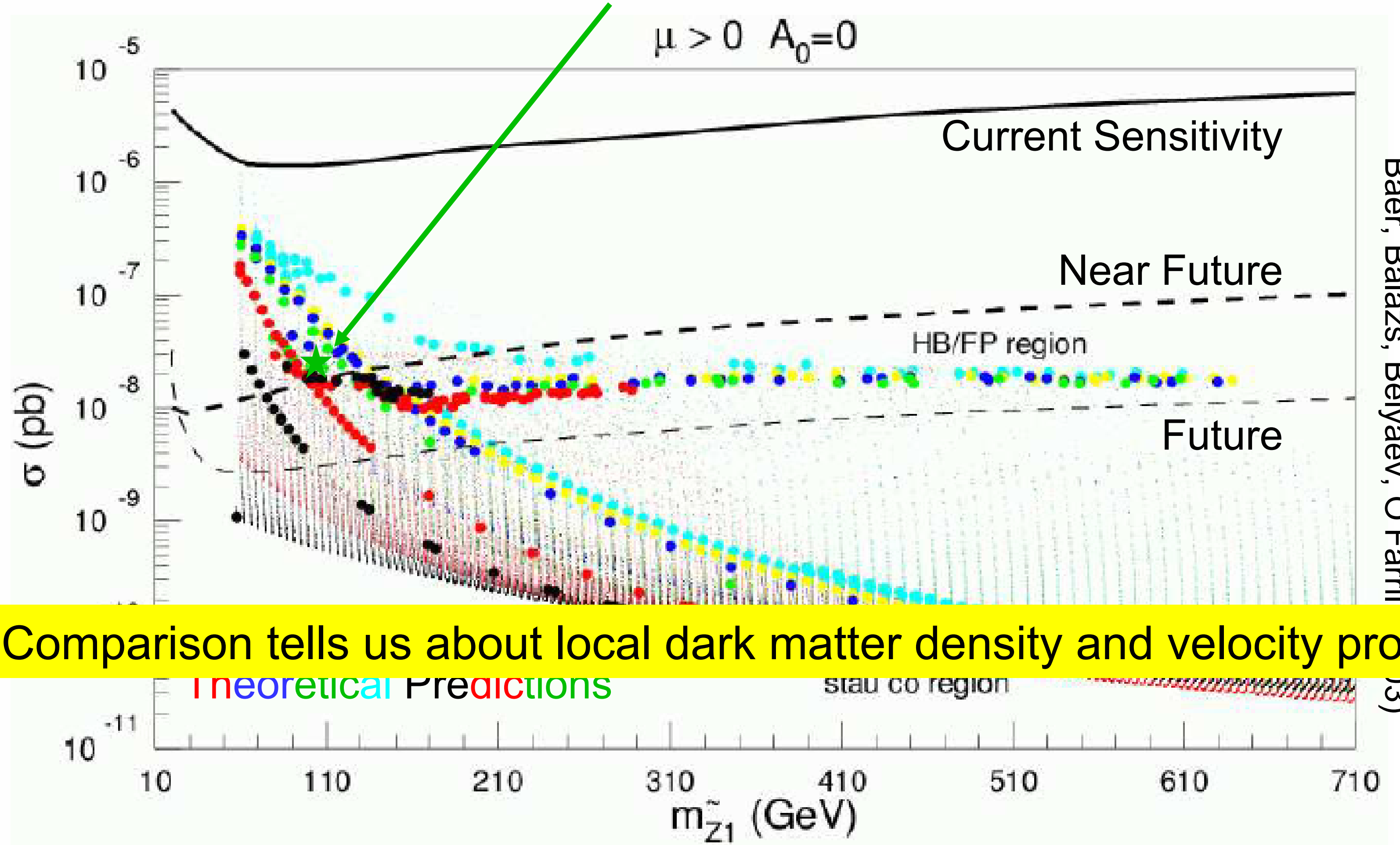
% level comparison of predicted Ω_{hep} with observed Ω_{cosmo}

IDENTIFYING DARK MATTER



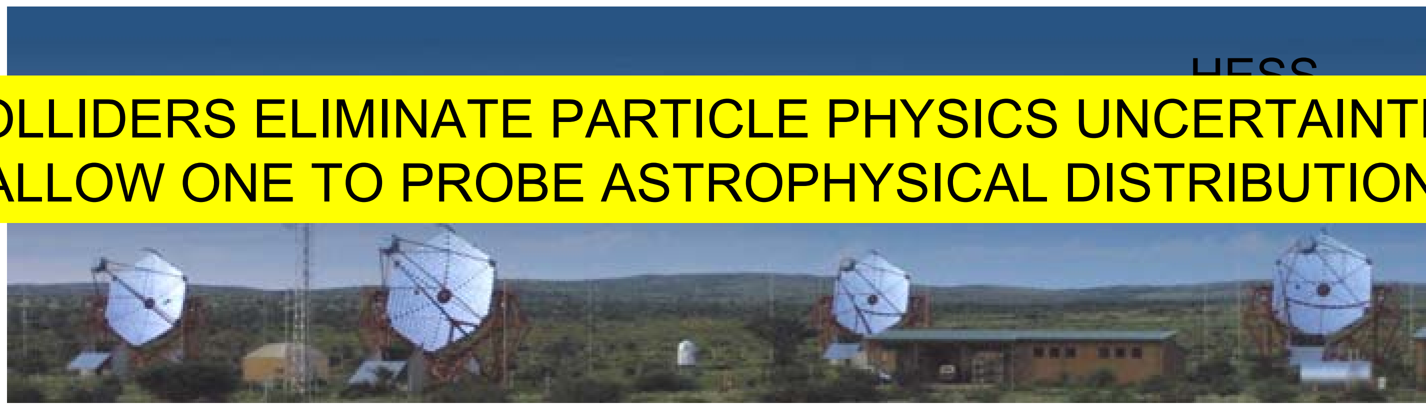
DIRECT DETECTION IMPLICATIONS

LHC + ILC → $\Delta m < 1$ GeV, $\Delta\sigma/\sigma < 10\%$



Comparison tells us about local dark matter density and velocity profiles

INDIRECT DETECTION IMPLICATIONS



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

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

Very sensitive to halo profiles near the galactic center

SuperWIMP Dark Matter

- Must DM have weak force interactions?
- Strictly speaking, no – the only required DM interactions are gravitational (much weaker than weak).
- But the relic density “coincidence” strongly prefers weak interactions.

Is there an exception to this rule?

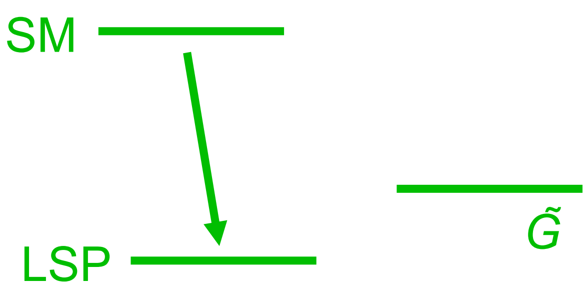
SuperWIMPs: The Basic Idea

Feng, Rajaraman, Takayama (2003)

- Consider gravitinos (also axinos,…):

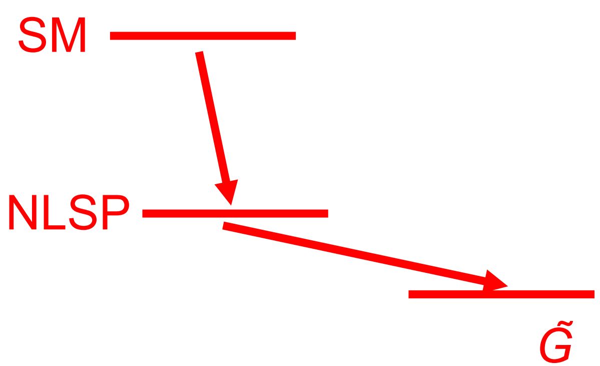
  spin 3/2, mass ~ M_W , couplings ~ M_W/M_*

- $\tilde{G}$ not LSP



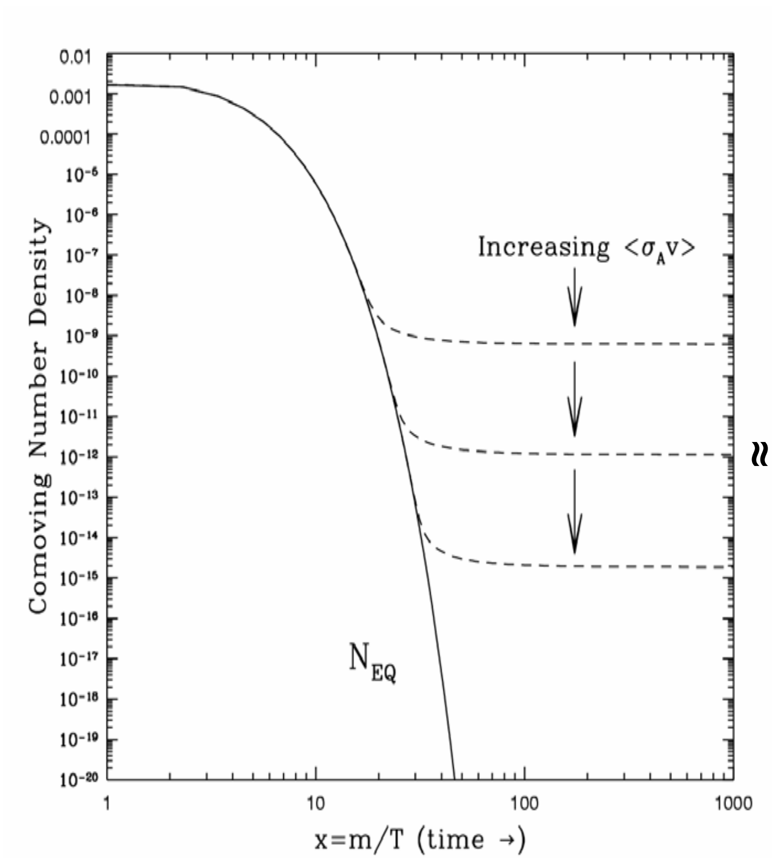
- Assumption of most of literature

- $\tilde{G}$ LSP

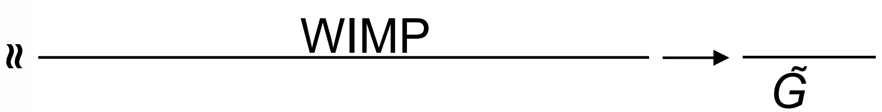


- Completely different cosmology and particle physics

- Suppose $\tilde{G}$ is the lightest superpartner



- WIMPs freeze out as usual



- But then all WIMPs decay to gravitinos after

M_{Pl}^2/M_W^3 ~ a month

Gravitinos naturally inherit the right density, but interact only gravitationally – they are “superWIMPs”

Other 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)
…

Old ideas:

- Gravitinos have thermal relic density

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

- For DM, require a new energy scale

- 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

SuperWIMP Detection

SuperWIMPs evade all particle dark matter searches.

news@nature.com All the news you need

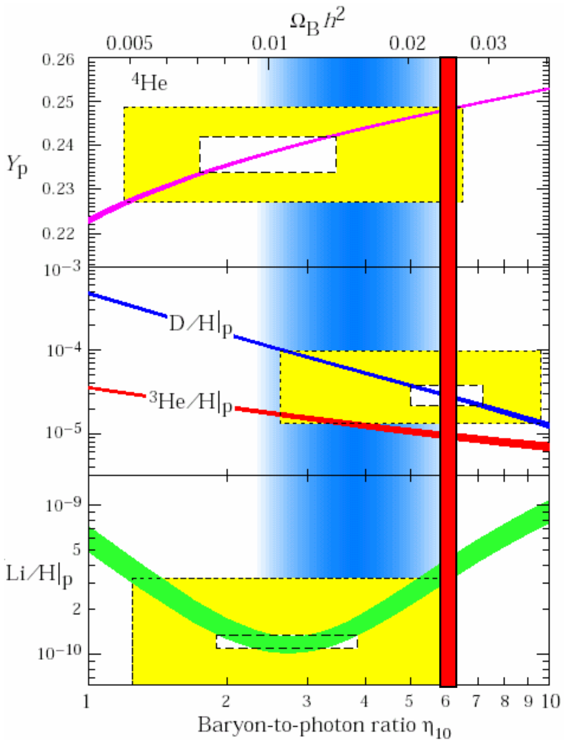
"Dark Matter may be Undetectable"

But cosmology is complementary: Superweak interactions → very late decays $\tilde{l} \rightarrow \tilde{G}\, l$ → observable consequences. In fact, must check that these do not exclude this scenario: BBN, CMB, structure formation.

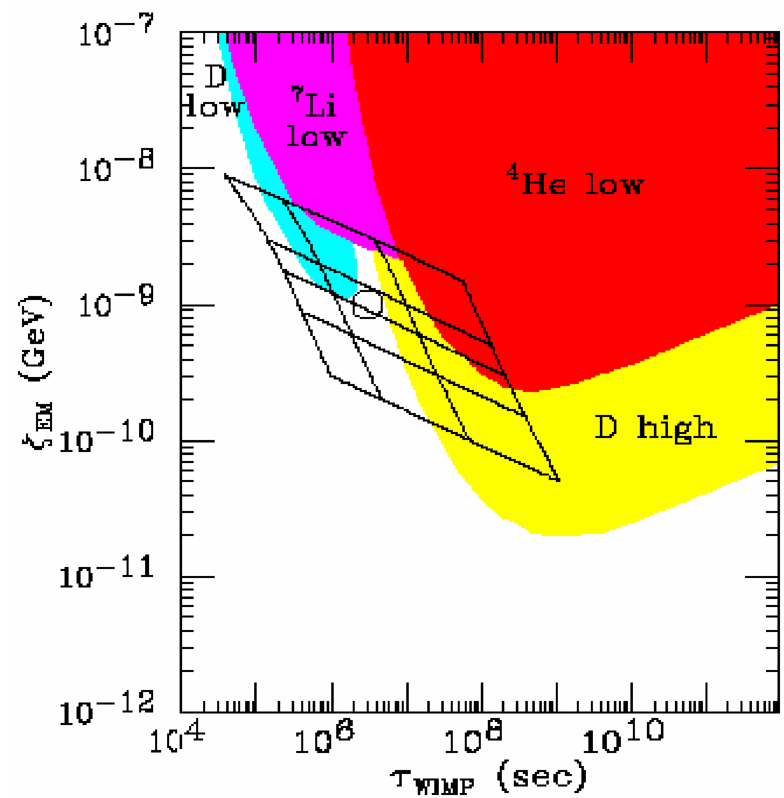
Big Bang Nucleosynthesis

Late decays may modify light element abundances

Cyburt, Ellis, Fields, Olive (2002)



Fields, Sarkar, PDG (2002)



Feng, Rajaraman, Takayama (2003)

Some SUSY parameter space excluded, much ok

Ellis, Olive, Vangioni (2005); Choi, Jedamzik, Roszkowski, Ruiz de Austri (2005)

Cosmic Microwave Background

- Late decays may also distort the CMB spectrum
- For 10^5 s < τ < 10^7 s, get "μ distortions":

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

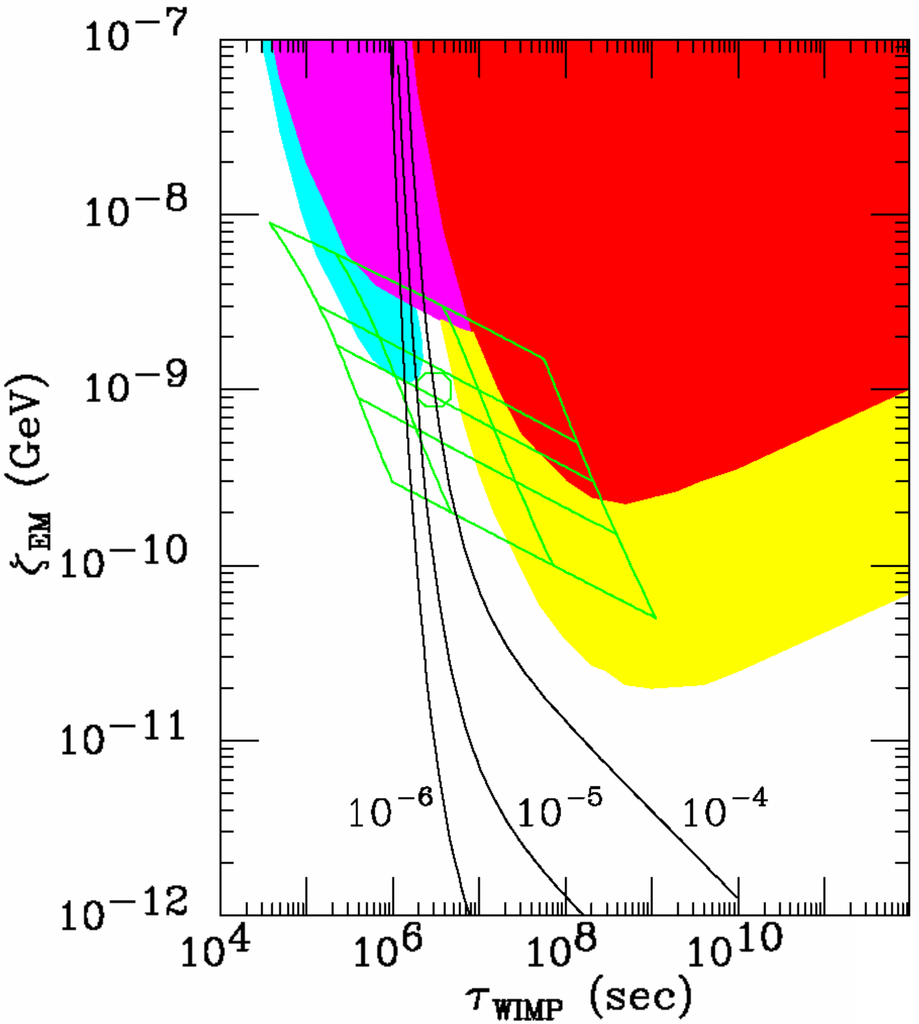
μ=0: Planckian spectrum

$\mu \neq$0: Bose-Einstein spectrum

Hu, Silk (1993)

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

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

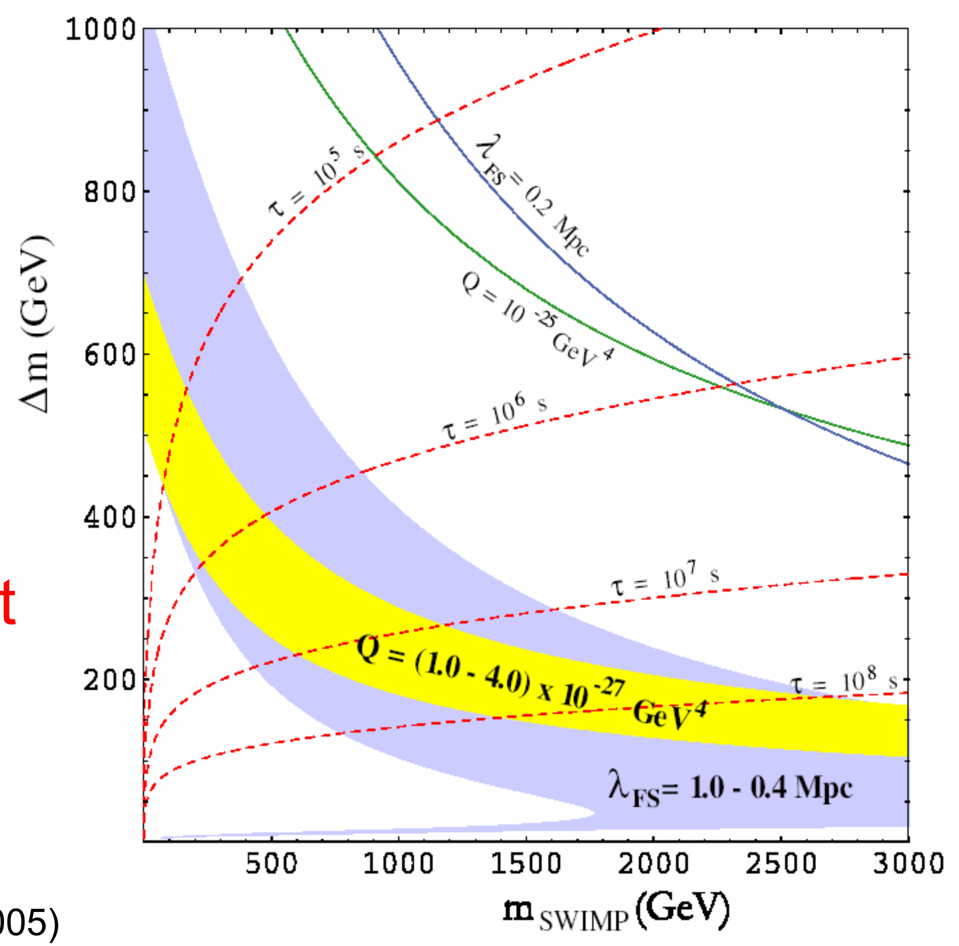


Feng, Rajaraman, Takayama (2003)

Structure Formation

Cold dark matter (WIMPs) seeds structure formation. Simulations may indicate more central mass than observed – cold dark matter may be too cold.

SuperWIMPs are produced at t ~ month with large velocity (v ~ 0.1c – c): warm dark matter



Kaplinghat (2005)
Cembranos, Feng, Rajaraman, Takayama (2005)

CONCLUSIONS

Dark matter: extraordinary progress, but many open questions

Neutralino WIMPs: synergy of dark matter detection experiments, colliders

Gravitino SuperWIMPs: qualitatively different implications for conventional detection, BBN, CMB, structure formation, colliders

Both cosmology and particle physics → new particles at 100 GeV: bright prospects!