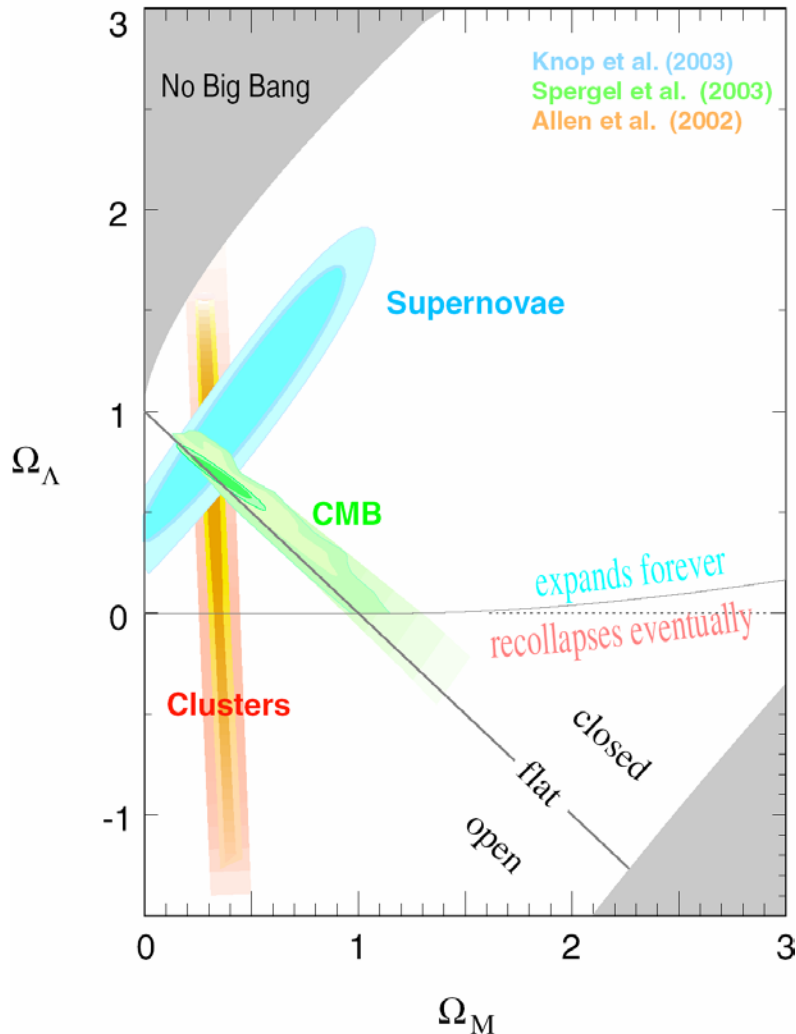


SuperWIMP Dark Matter

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UC Irvine

FNAL Theoretical Astrophysics Seminar
17 May 2004

Dark Matter



- Tremendous recent progress

- $\Omega_M = 0.27 \pm 0.04$
 $\Omega_\Lambda = 0.73 \pm 0.04$
[$\Omega_B = 0.044 \pm 0.004$]

- 3 measurements agree;
2 must be wrong to
change these conclusions

- On the other hand...

COSMOLOGY MARCHES ON



- We live in interesting times: we know how much there is, but we have no idea what it is
- Precise, unambiguous evidence for new particle physics

Dark Matter Candidates

- The Wild, Wild West of particle physics: axions, warm gravitinos, neutralinos, Kaluza-Klein particles, Q balls, wimpzillas, self-interacting particles, self-annihilating particles, fuzzy dark matter, superWIMPs...
- Masses and interaction cross sections span many orders of magnitude
- Consider neutralinos: a favorite because they have at least three virtues...

I. Well-motivated Stable Particle

Goldberg (1983)

Ellis et al. (1983)

- Required by supersymmetry, and so motivated by
 - electroweak symmetry breaking
 - force unification
 - heavy top quark
 - ...
- Stable
 - χ is typically the lightest supersymmetric particle (LSP), and so stable (in R-parity conserving supergravity)

II. Natural Relic Density

1) Initially, neutralinos χ are in thermal equilibrium:



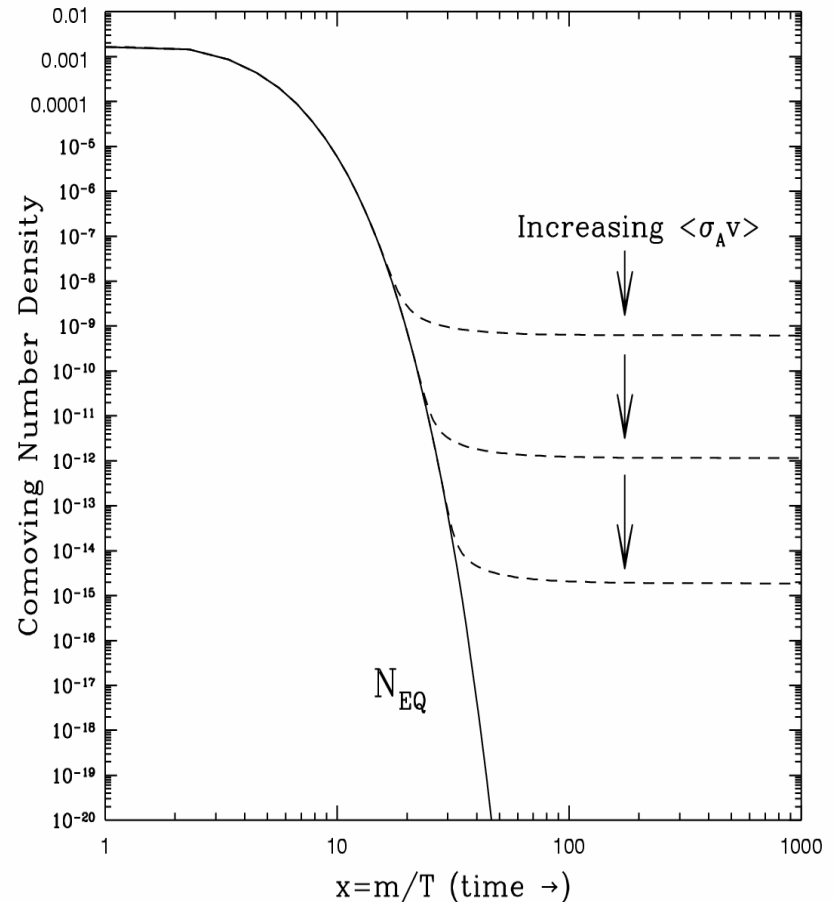
2) Universe cools:

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

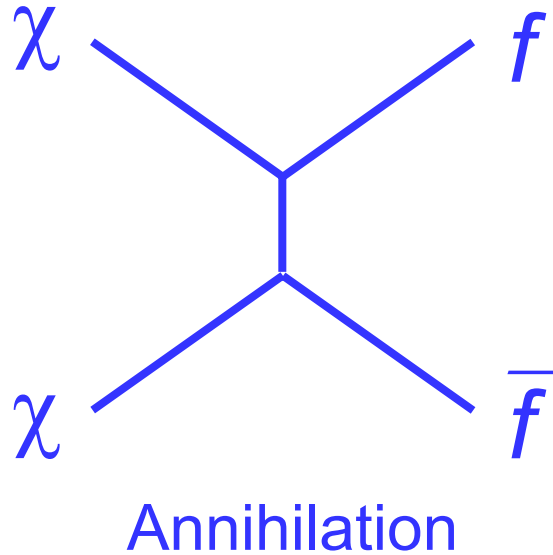
3) χ s “freeze out”:

$$N \sim \text{constant}$$

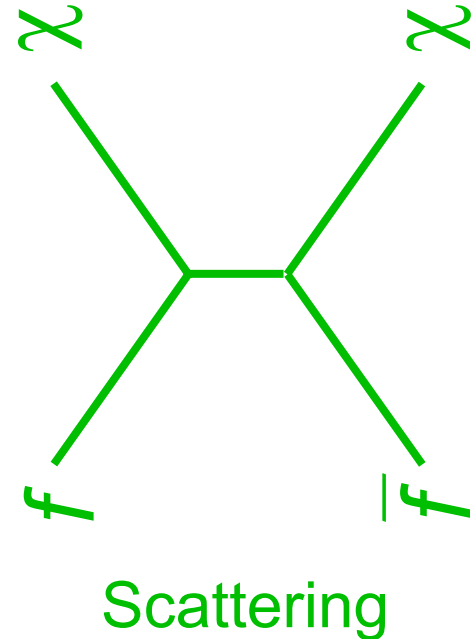
Freeze out determined by annihilation cross section:
for neutralinos, $\Omega_{DM} \sim 0.1$;
natural – no new scales!



III. Detection Promising



Crossing
→
symmetry

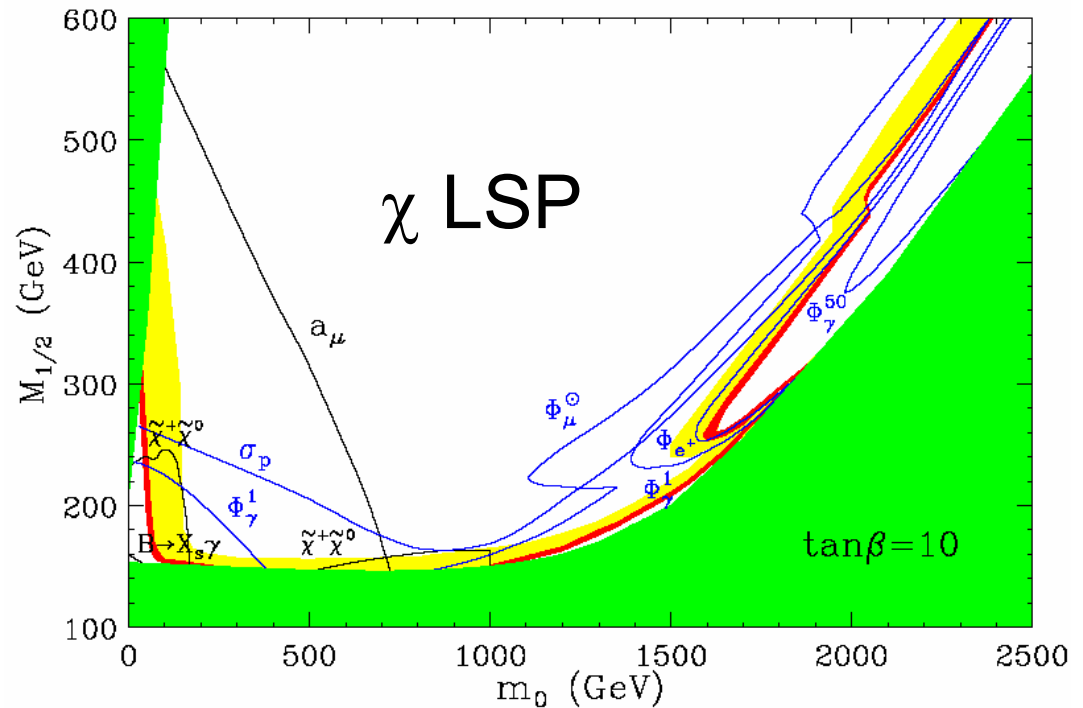


Correct relic density \rightarrow efficient annihilation then
 \rightarrow efficient annihilation now, efficient scattering now

No-Lose Theorem

Illustration: mSUGRA

- Well-motivated stable particle: χ LSP in unshaded region
- Natural relic density: $\Omega_\chi = 0.23 \pm 0.04$ in red region
- Detection promising: below contours



Feng, Matchev, Wilczek (2000)

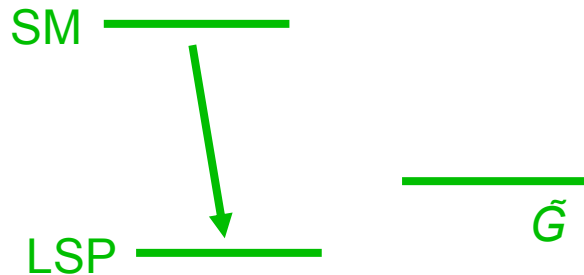
Observable	Type	Sensitivity	Experiment(s)
$\tilde{\chi}^\pm \tilde{\chi}^0$	Collider	See Ref. [5]	Tevatron: CDF, D0
$B \rightarrow X_s \gamma$	Low energy	$ \Delta B(B \rightarrow X_s \gamma) < 1.2 \times 10^{-4}$	BaBar, BELLE
Muon MDM	Low energy	$ a_\mu^{\text{SUSY}} < 8 \times 10^{-10}$	Brookhaven E821
σ_{proton}	Direct DM	$\sim 10^{-8}$ pb (See Ref. [5])	CDMS, CRESST, GENIUS
ν from Earth	Indirect DM	$\Phi_\mu^0 < 100 \text{ km}^{-2} \text{ yr}^{-1}$	Amanda, Nestor, Antares
ν from Sun	Indirect DM	$\Phi_\mu^0 < 100 \text{ km}^{-2} \text{ yr}^{-1}$	Amanda, Nestor, Antares
γ (gal. center)	Indirect DM	$\Phi_\gamma(1) < 1.5 \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$	GLAST
γ (gal. center)	Indirect DM	$\Phi_\gamma(50) < 7 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$	MAGIC
e^+ cosmic rays	Indirect DM	$(S/B)_{\text{max}} < 0.01$	AMS-02

SuperWIMPs: The Basic Idea

Feng, Rajaraman, **Takayama**, hep-ph/0302215, hep-ph/0306024, hep-ph/0307375
Feng, Su, **Takayama**, hep-ph/0404198, hep-ph/0404231

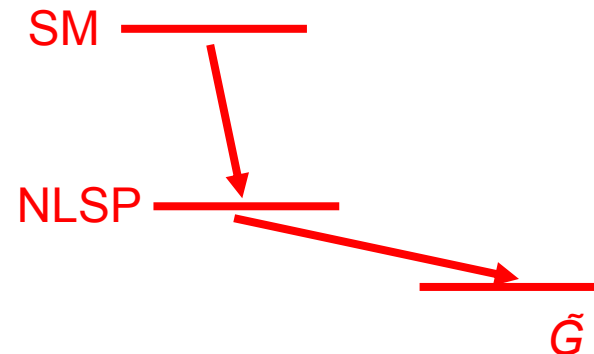
- Supergravity requires gravitinos:
mass $\sim M_W$, couplings $\sim M_W/M_*$

- \tilde{G} not LSP

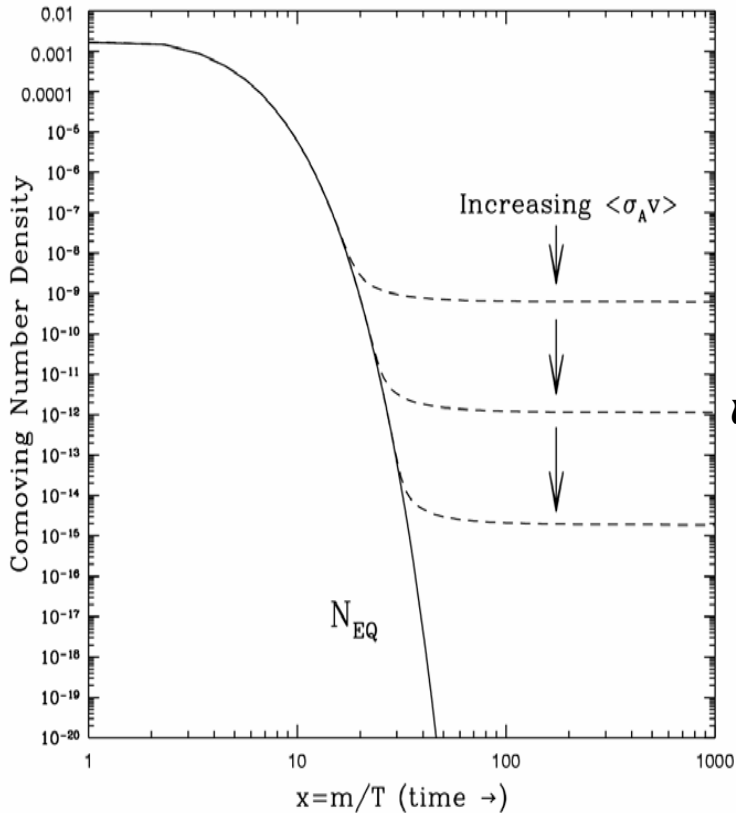


- No impact – assumption of most of literature

- \tilde{G} LSP



- Qualitatively different cosmology



- Assume gravitino is LSP. Early universe behaves as usual, WIMP freezes out with desired thermal relic density

$$\propto \frac{\text{WIMP}}{\tilde{G}} \quad M_*^2/M_W^3 \sim \text{year}$$

- A year passes...then all WIMPs decay to gravitinos

Gravitinos are dark matter now. They are superWIMPs – superweakly-interacting massive particles

SuperWIMP Virtues

I. Well-motivated stable particle?

Yes – SuperWIMPs exist in same frameworks as WIMPs

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

Universal extra dimensions $B^1 \rightarrow G^1$

Appelquist, Cheng, Dobrescu (2001)

II. Natural relic density?

Yes – Inherited from WIMP freeze out, no new scales

III. Detection Promising?

No – Impossible to detect by conventional DM searches
(No-Lose Theorem loophole)

Yes – Qualitatively new signals

History

- 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

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

- DM if bound saturated, requires new scale

- Weak scale gravitinos diluted by inflation, regenerated in reheating

$$T_{\text{RH}} < 10^{10} \text{ GeV}$$

- DM if bound saturated, requires new scale

SuperWIMP Signals

- SuperWIMP couplings are suppressed by M_W/M_* , no signals in direct or indirect DM searches

- But this same suppression means that the decays

$$\tilde{\tau} \rightarrow \tilde{G} \tau, \tilde{B} \rightarrow \tilde{G} \gamma$$

are *very* late with possibly observable consequences

- Signals depend on
 - The NLSP
 - Two free parameters: $m_{\tilde{G}}, \Delta m = m_{\text{NLSP}} - m_{\tilde{G}}$

Decays to SuperWIMPs

- Lifetime

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

$$\Gamma(\tilde{B} \rightarrow \gamma\tilde{G}) = \frac{\cos^2 \theta_W}{48\pi M_*^2} \frac{m_{\tilde{B}}^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{B}}^2}\right]^3 \left[1 + 3\frac{m_{\tilde{G}}^2}{m_{\tilde{B}}^2}\right]$$

In the limit $\Delta m \ll m_{\tilde{G}}$,

$$\tau(\tilde{\ell} \rightarrow \ell\tilde{G}) \approx 3.6 \times 10^8 \text{ s} \left[\frac{100 \text{ GeV}}{\Delta m}\right]^4 \frac{m_{\tilde{G}}}{1 \text{ TeV}}$$

$$\tau(\tilde{B} \rightarrow \gamma\tilde{G}) \approx 2.3 \times 10^7 \text{ s} \left[\frac{100 \text{ GeV}}{\Delta m}\right]^3$$

- Energy release

$$\zeta_i = \varepsilon_i B_i Y_{\text{NLSP}}$$

$i = \text{EM, had}$

$\varepsilon_i = \text{energy released in each decay}$

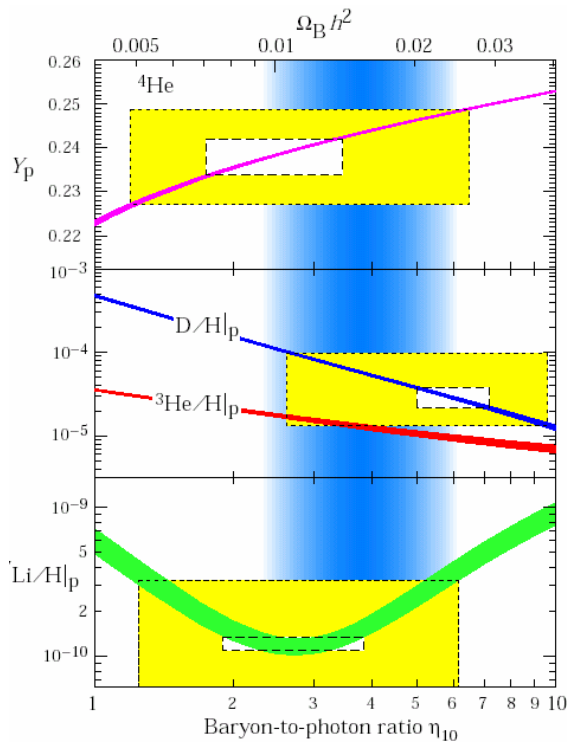
$B_i = \text{branching fraction}$

$$Y_{\text{NLSP}} = n_{\text{NLSP}} / n_{\gamma}^{\text{BG}}$$

$$\Omega_{\tilde{G}} = \Omega_{\text{DM}} \rightarrow (m_{\tilde{G}}, \Delta m) \leftrightarrow (\tau, \zeta_i)$$

Big Bang Nucleosynthesis

- Late decays occur after BBN and before CMB. This has consequences for light element abundances.

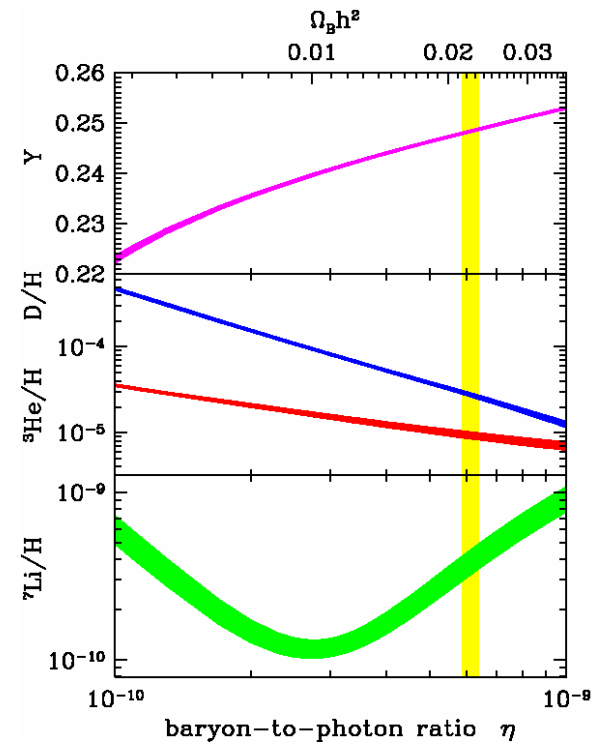


Fields, Sarkar, PDG (2002)



$$\eta_D = \eta_{\text{CMB}}$$

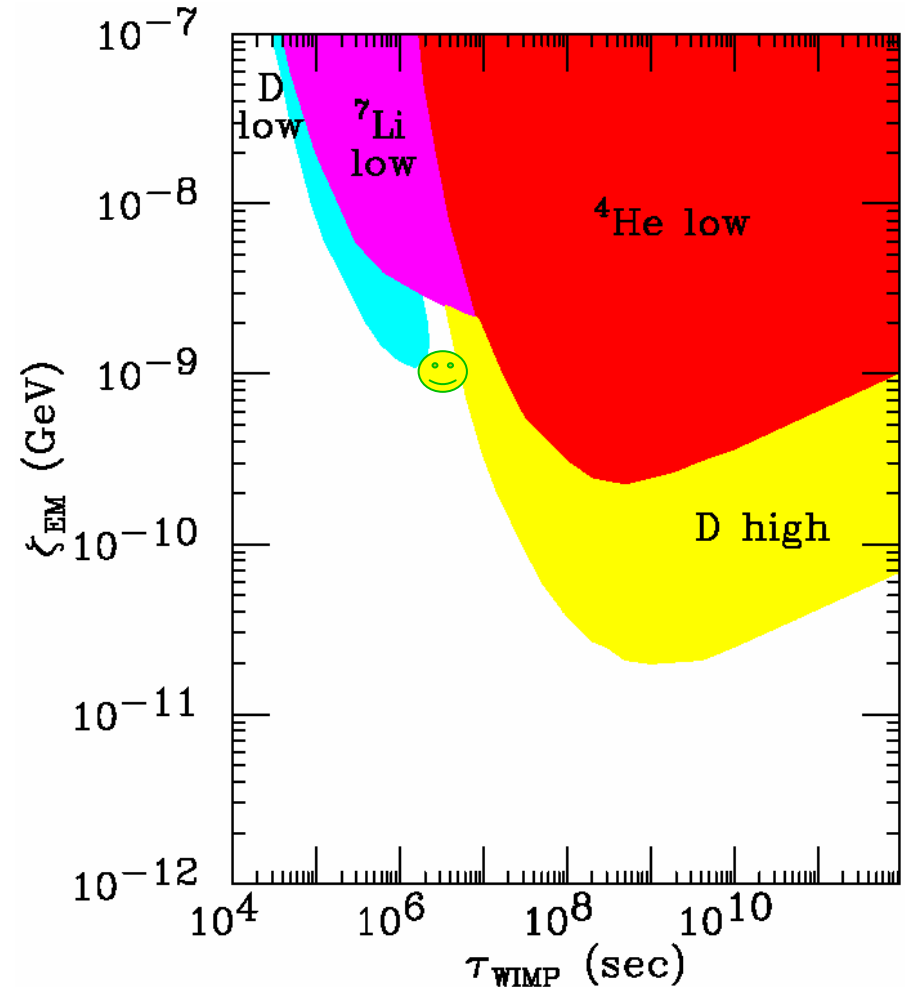
^7Li low



Cyburt, Fields, Olive (2003)

BBN EM Constraints

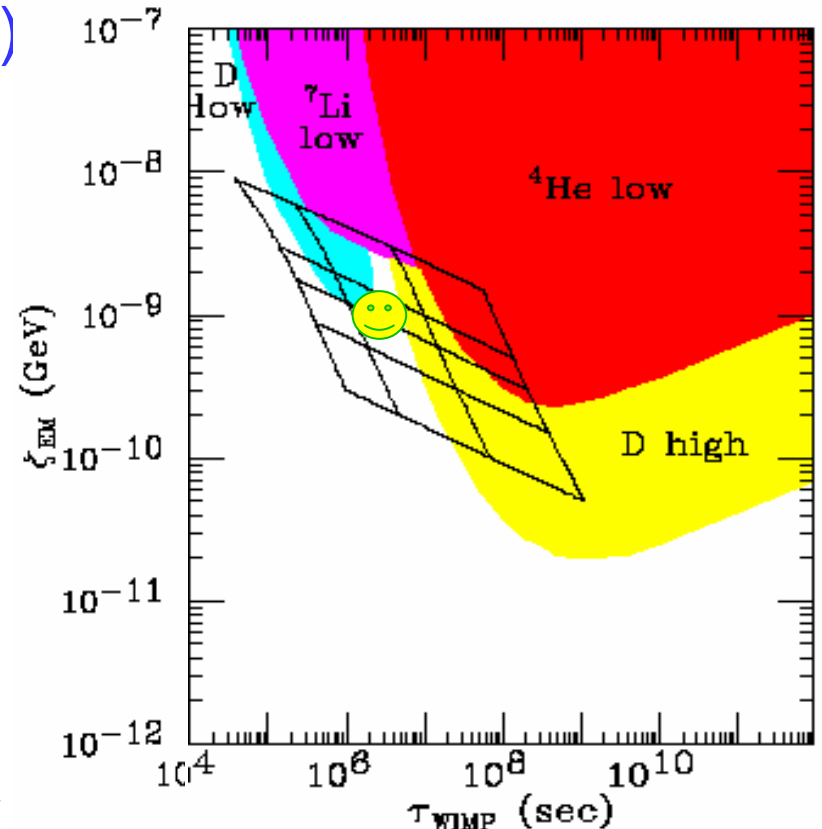
- NLSP = WIMP \rightarrow Energy release is dominantly EM
- EM energy quickly thermalized, so BBN constrains (τ, ζ_{EM})
- BBN constraints weak for early decays: hard γ , e^- thermalized in hot universe
- Best fit reduces ${}^7\text{Li}$: 😊



Cyburt, Ellis, Fields, Olive (2002)

BBN EM Predictions

- Consider $\tilde{\tau} \rightarrow \tilde{G} \tau$ (others similar)
- Grid: Predictions for
 $m_{\tilde{G}} = 100 \text{ GeV} - 3 \text{ TeV}$ (top to bottom)
 $\Delta m = 600 \text{ GeV} - 100 \text{ GeV}$ (left to right)
- Some parameter space excluded, but much survives
- In fact, superWIMP DM naturally explains ${}^7\text{Li}$!



Feng, Rajaraman, Takayama (2003)

${}^7\text{Li}$ Anomaly

- Given $\eta_D = \eta_{\text{CMB}}$, ${}^7\text{Li}$ is underabundant by factor of 3-4.

- Observations:

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

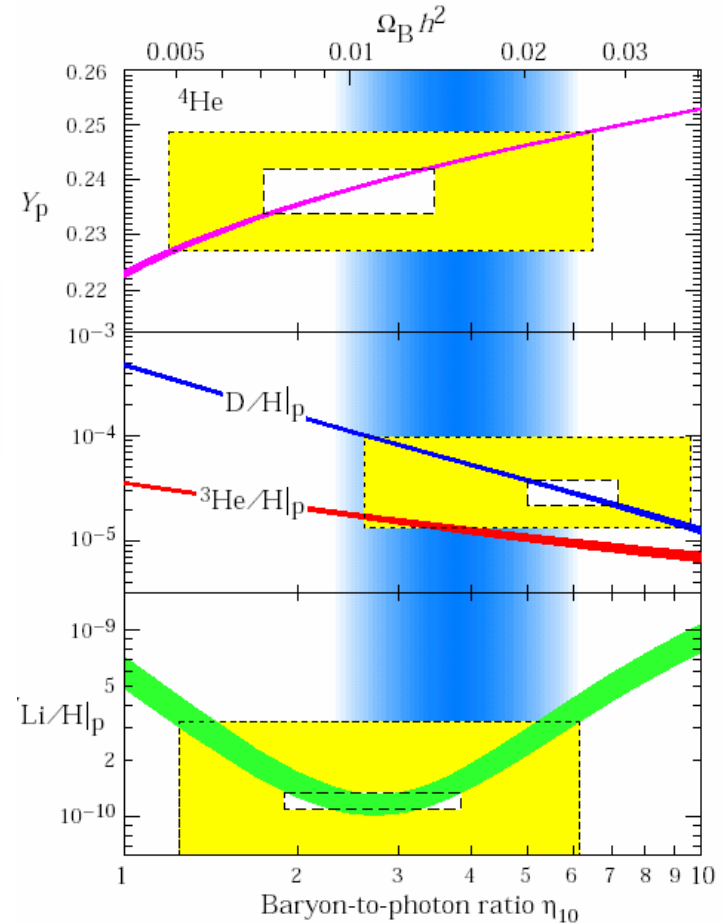
$${}^7\text{Li}/\text{H} = 1.72_{-0.22}^{+0.28} \times 10^{-10} \quad (1\sigma + \text{sys}) \quad [28]$$

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

- Possible explanations:

- Destruction in stellar cores (but no scatter?)
- Nuclear systematics (not likely)
- New physics

Cyburt, Fields, Olive (2003)



BBN Hadronic Constraints

- BBN constraints on *hadronic* energy release are severe for early decay times

Kawasaki, Kohri, Moroi (2004)

- Cannot neglect subleading hadronic decays:

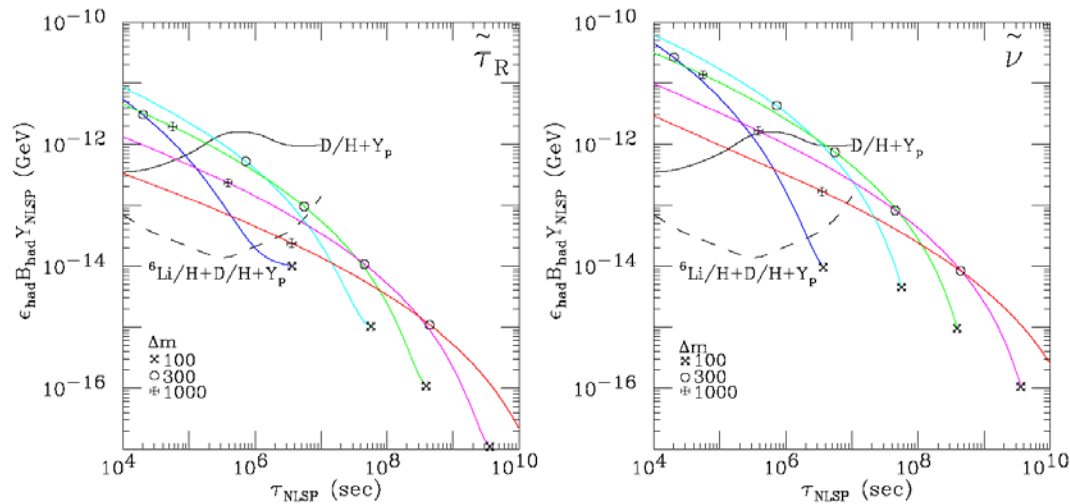
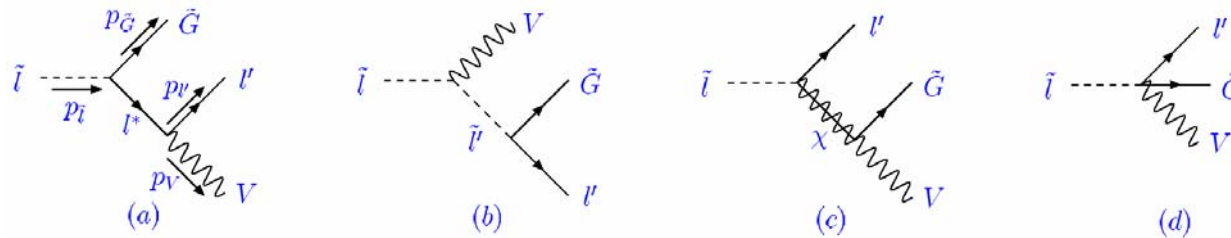
$$\begin{aligned}\tilde{l} &\rightarrow lZ\tilde{G}, \nu W\tilde{G} \\ \tilde{\nu} &\rightarrow \nu Z\tilde{G}, lW\tilde{G}\end{aligned}$$

- In fact, for neutralinos, these aren't even subleading:

$$\chi \rightarrow Z\tilde{G}, h\tilde{G}$$

This effectively eliminates \tilde{B} NLSP (photino still ok)

BBN Hadronic Predictions



Feng, Takayama, Su (2004)

Strong constraints on early decays

Entropy Production

- η_D and η_{CMB} measure same thing, but at different times

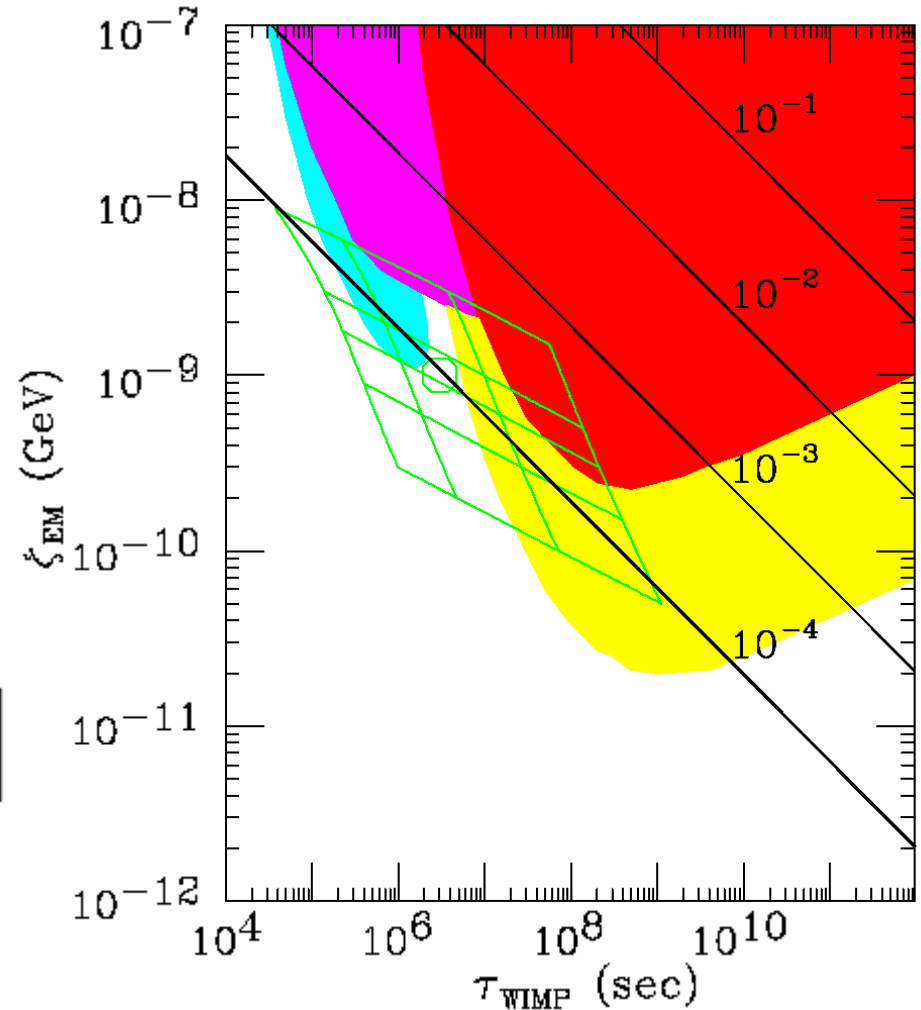
Kaplinghat, Turner (2001)

- $\eta_D = \eta_{\text{CMB}}$ constrains entropy production:

$$\frac{\eta_f}{\eta_i} = \frac{S_i}{S_f}$$

$$\frac{S_f}{S_i} = \exp \left[\zeta(3) \frac{45^{3/4}}{\pi^{11/4}} \frac{(g_*^\tau)^{1/4}}{g_{*s}^i} \frac{\varepsilon_{\text{EM}} n_{\text{WIMP}}^i}{n_\gamma^i} \sqrt{\frac{\tau}{M_{\text{Pl}}}} \right]$$

- BBN constraints \rightarrow entropy constraint satisfied



Feng, Rajaraman, Takayama (2003)

Cosmic Microwave Background

- Late decays may also distort the CMB spectrum

- For $10^5 \text{ s} < \tau < 10^7 \text{ s}$, get “ μ distortions”:

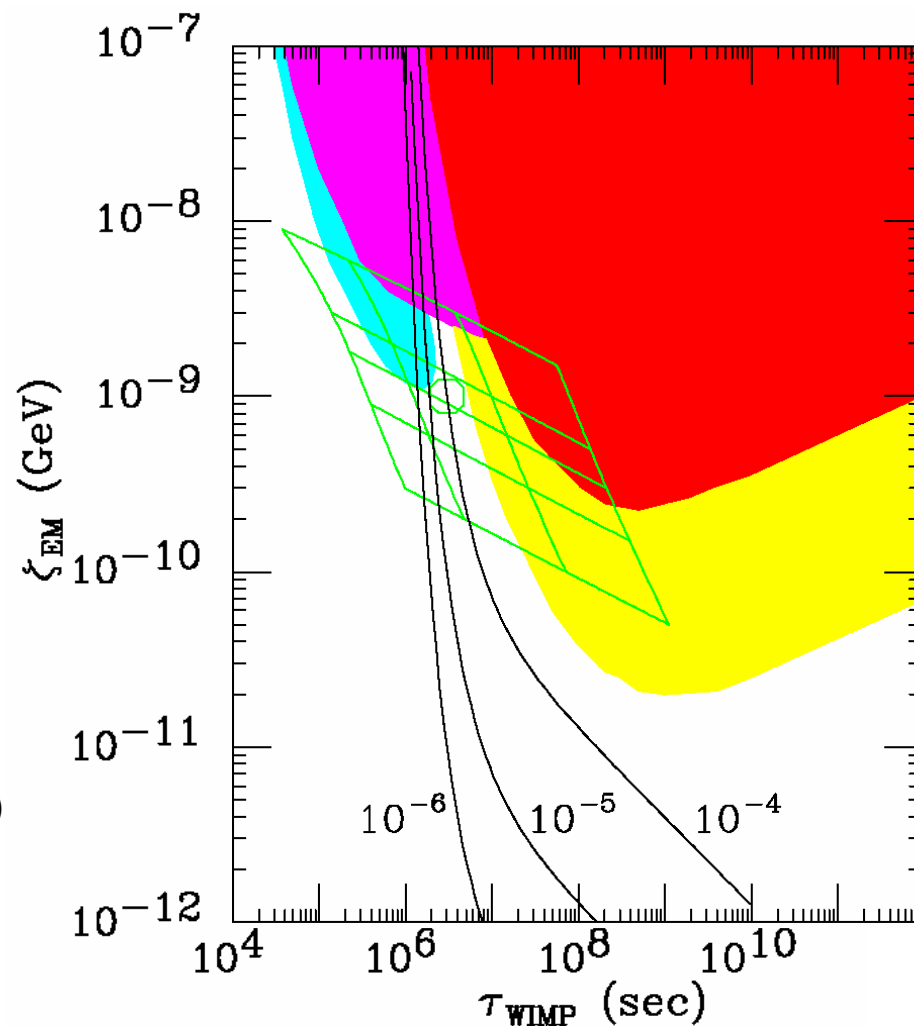
$$\frac{1}{e^{E/(kT)+\mu} - 1}$$

$\mu=0$: 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)

SuperWIMPs in Extra Dimensions

- Universal Extra Dimensions: all fields propagate in TeV^{-1} size extra dimensions

Appelquist, Cheng, Dobrescu (2000)

- SUSY \rightarrow UED:
 Superpartners \rightarrow KK partners
 R-parity \rightarrow KK-parity
 LSP \rightarrow LKP
 \tilde{B} dark matter $\rightarrow B^1$ dark matter

- B^1 thermal relic density

Servant, Tait (2002)

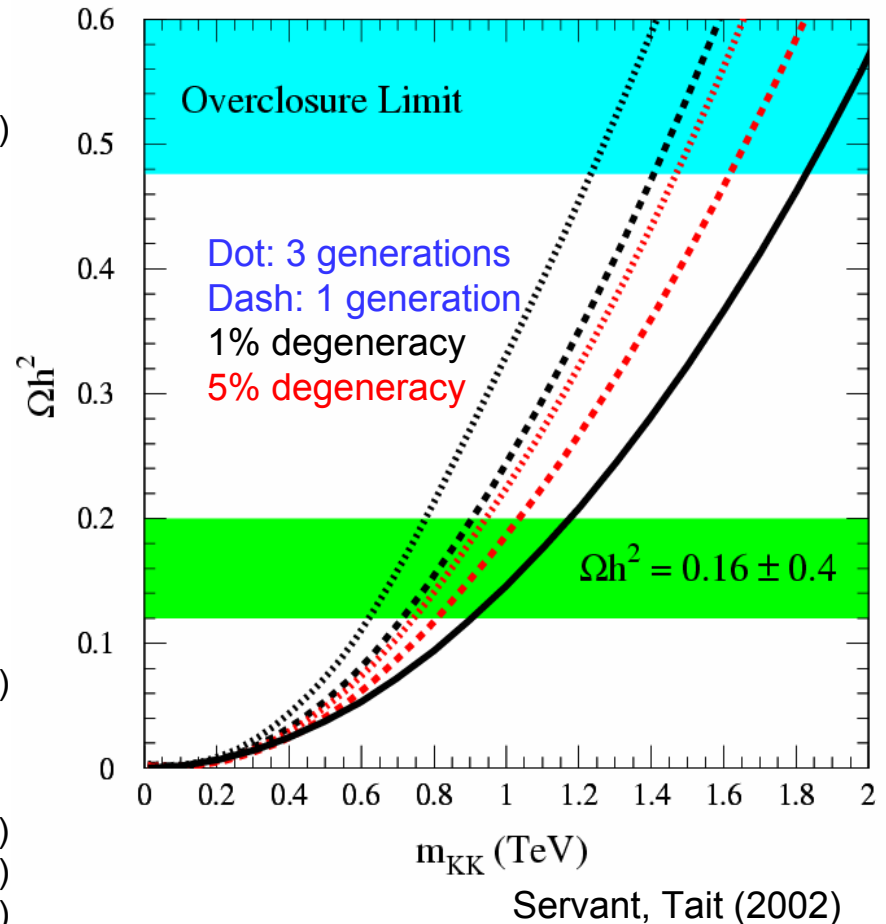
- B^1 direct and indirect detection

Cheng, Feng, Matchev (2002) Hooper, Kribs (2002)

Servant, Tait (2002) Majumdar (2002)

Bertone, Servant, Sigl (2002)

...

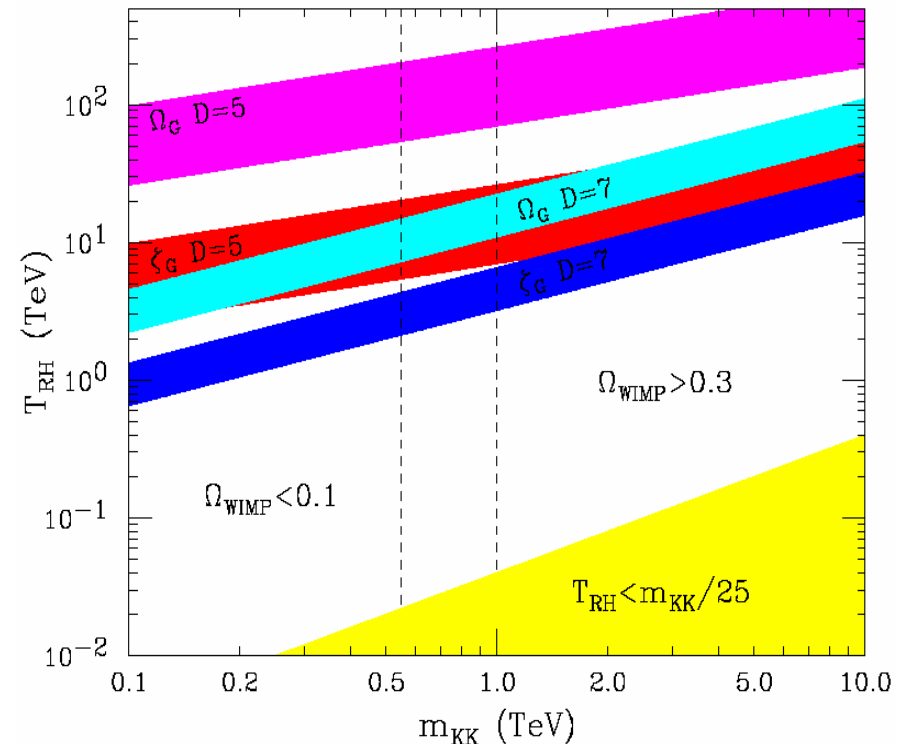


SuperWIMPs in Extra Dimensions

- SuperWIMP: $\tilde{G} \rightarrow G^1$
- $O(1)$ modifications, except: tower of KK gravitons \rightarrow reheating is *extremely* efficient

- $T_{RH} < 1 - 10 \text{ TeV}$
(Cf. SUSY $T_{RH} < 10^{10} \text{ GeV}$)

SuperWIMP scenario
requires $T_{RH} > 40 \text{ GeV}$



Feng, Rajaraman, Takayama (2003)

Implications for Particle Physics

- We've been missing half of parameter space.
For example, mSUGRA should have **6** parameters:

$$\{ m_0, M_{1/2}, A_0, \tan\beta, \text{sgn}(\mu), m_{3/2} \}$$

\tilde{G} not LSP

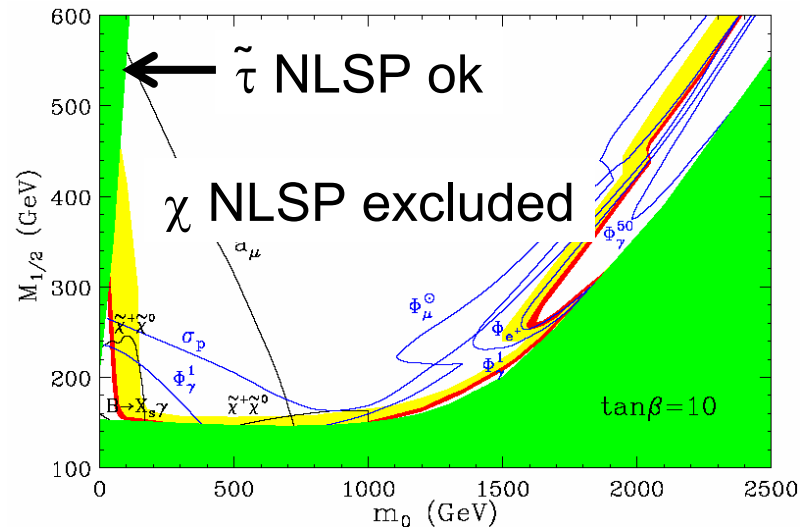
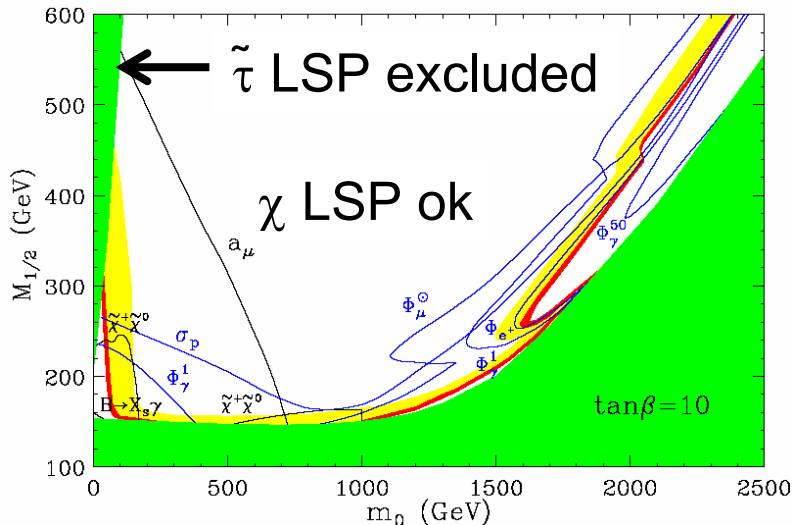
$\Omega_{\text{LSP}} > 0.23$ excluded

$\tilde{\tau}$ LSP excluded

\tilde{G} LSP

$\Omega_{\text{NLSP}} > 0.23$ ok

$\tilde{\tau}$ LSP ok



Implications for SUSY Spectrum

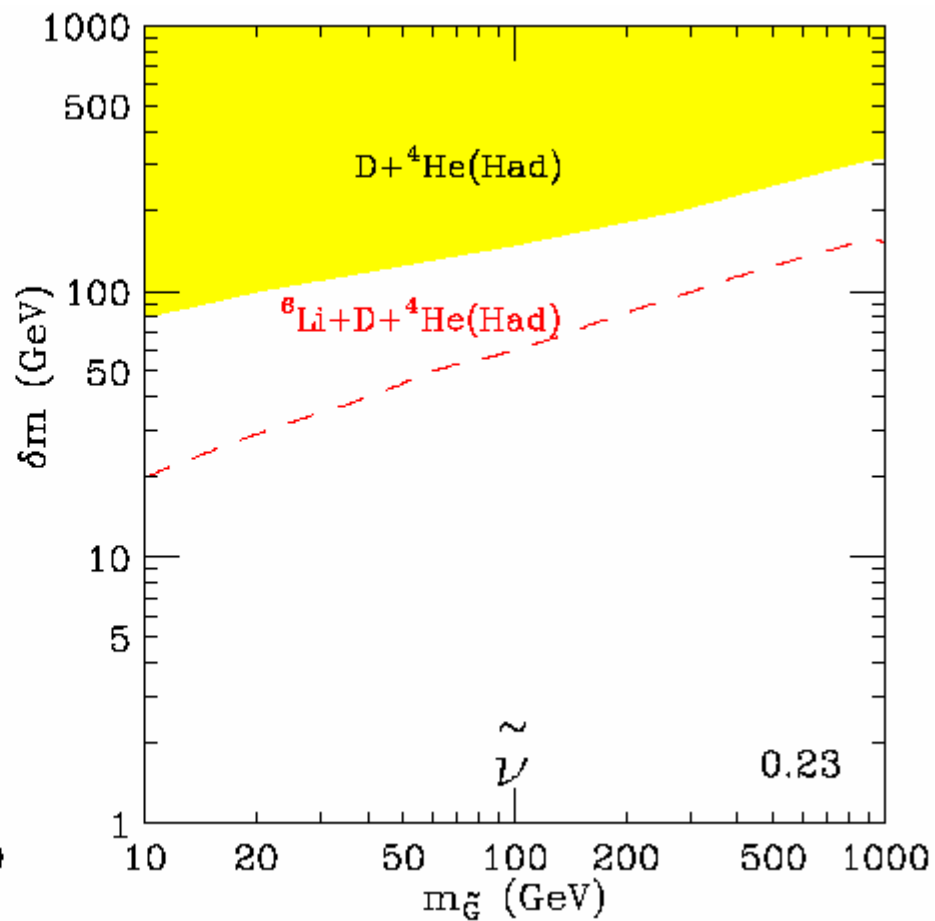
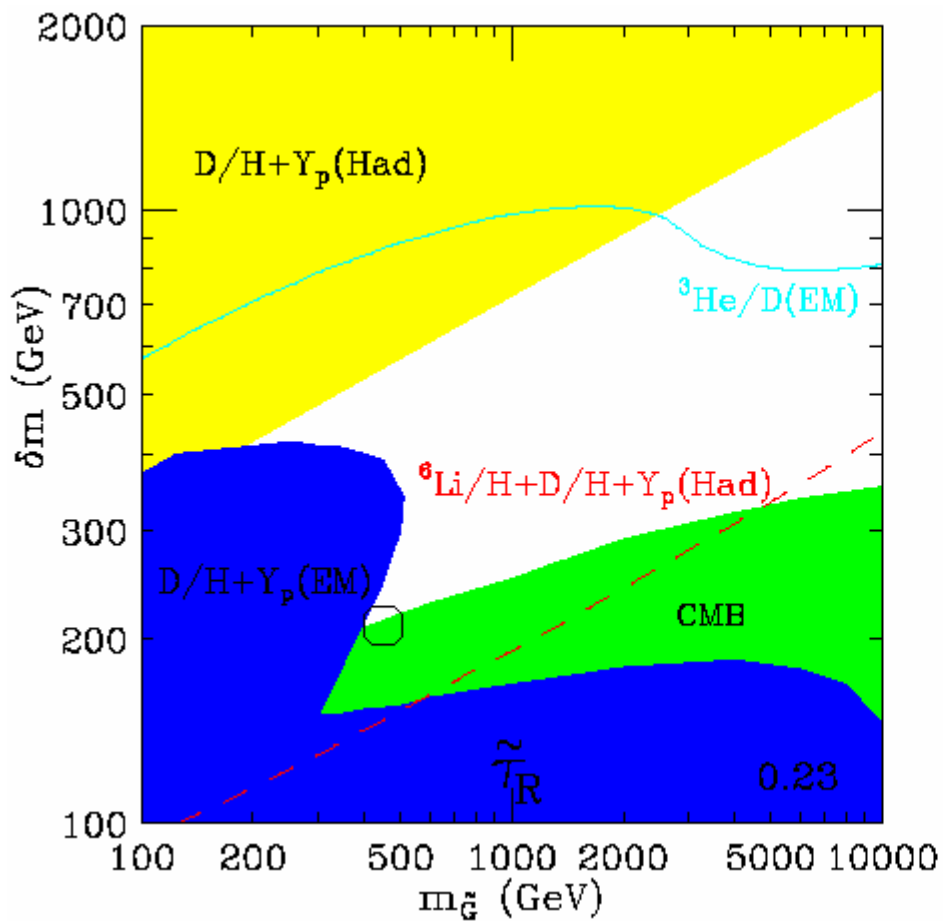
- What are the allowed superpartner masses in the superWIMP scenario?

It depends...constraints bound $n_{\tilde{G}} = \Omega_{\tilde{G}} / m_{\tilde{G}}$

- If $\Omega_{\tilde{G}} = \Omega_{\text{DM}}$, $n_{\tilde{G}} \sim m_{\tilde{G}}^{-1}$, low masses excluded
- If $\Omega_{\tilde{G}} = (m_{\tilde{G}} / m_{\text{NLSP}}) \Omega_{\text{NLSP}}^{\text{th}}$, $n_{\tilde{G}} \sim m_{\tilde{G}}$, high masses excluded

$$\Omega_{\tilde{G}} = \Omega_{\text{DM}}$$

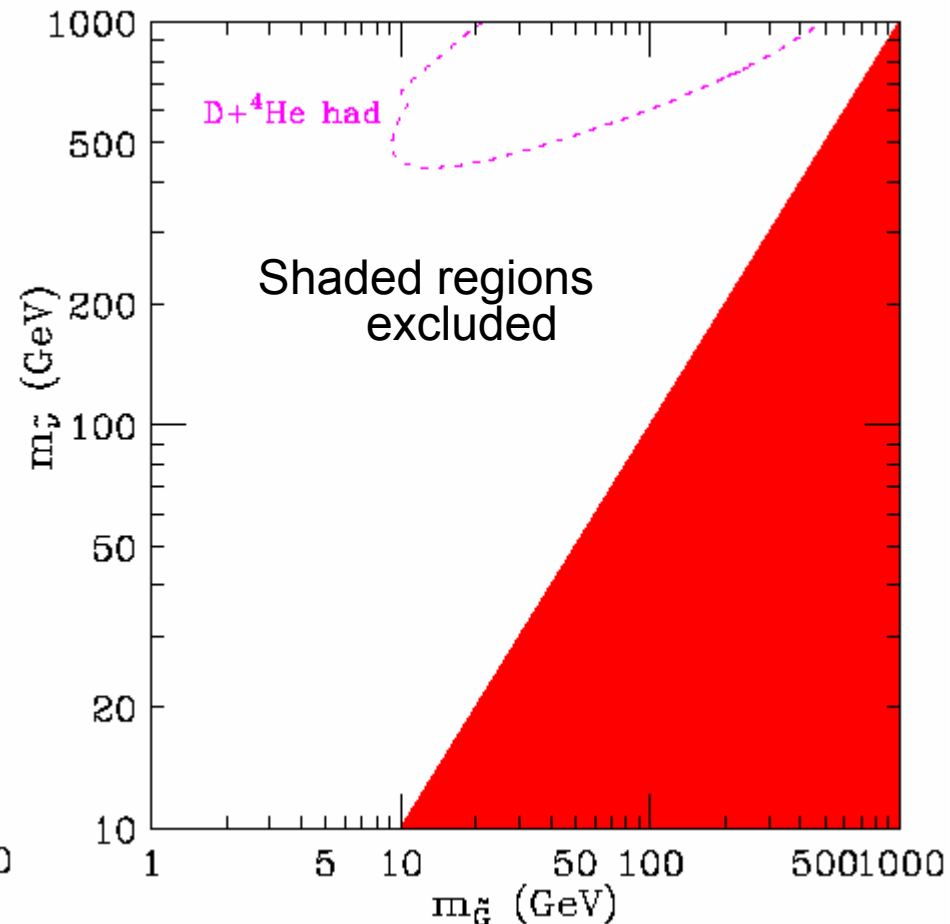
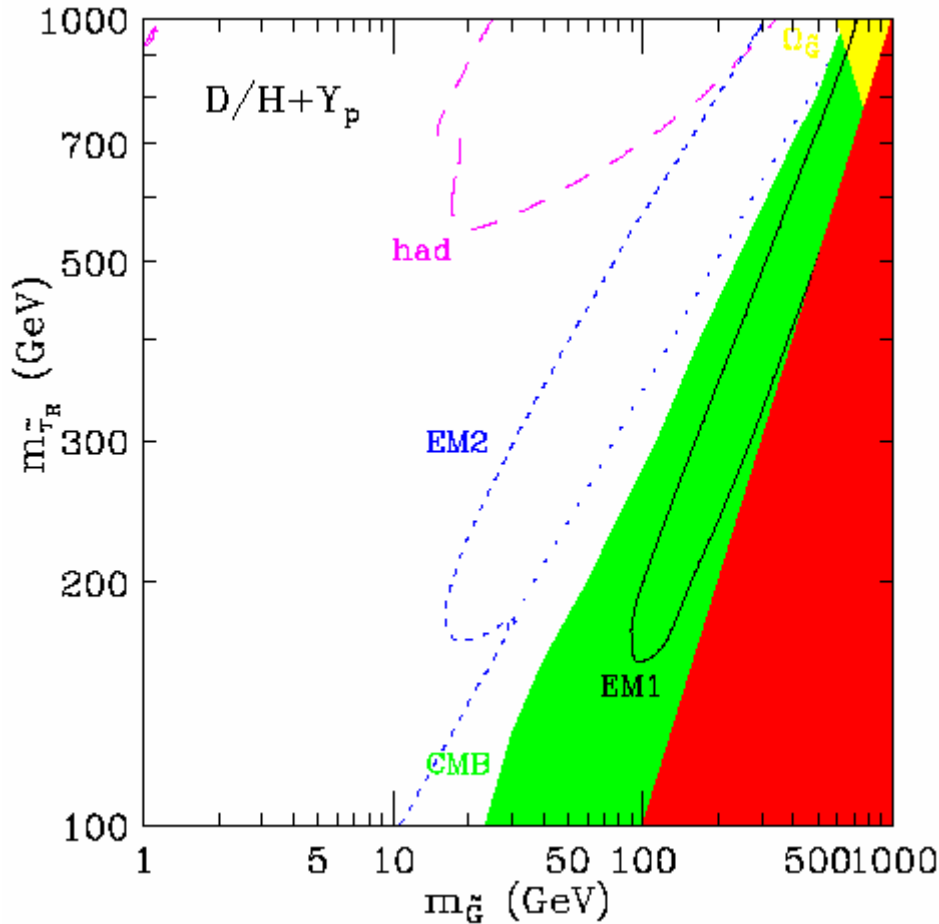
Shaded regions excluded



Feng, Takayama, Su (2004)

$$\Omega_{\tilde{G}} = (m_{\tilde{G}} / m_{\text{NLSP}}) \Omega_{\text{NLSP}}^{\text{th}}$$

Shaded regions excluded



Feng, Takayama, Su (2004)

Implications for Colliders

Feng, Su, Takayama (2004)

- Each SUSY event produces 2 metastable sleptons
Signature: highly-ionizing charged tracks

- Current bound (LEP): $m_{\tilde{\tau}} > 99 \text{ GeV}$

- Tevatron Run II reach: $\sim 150 \text{ GeV}$

Feng, Moroi (1996)

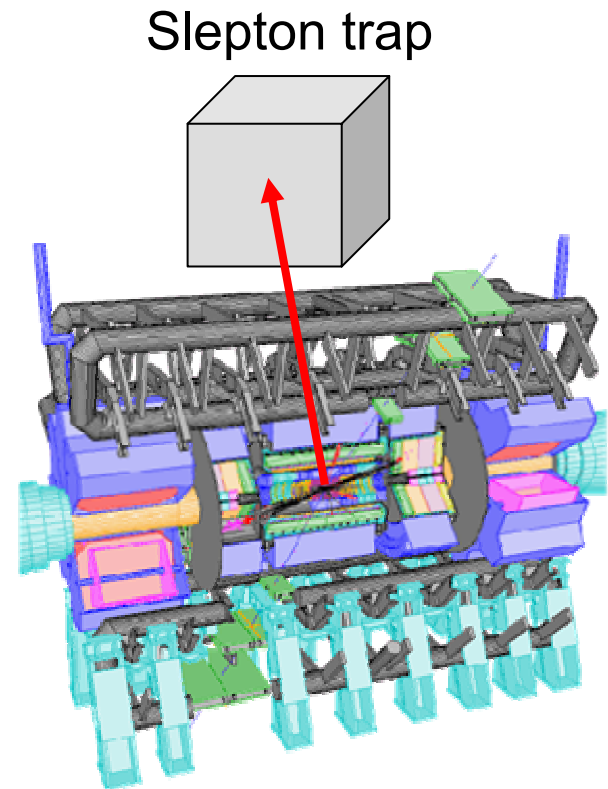
Hoffman, Stuart et al. (1997)

- LHC reach: $\sim 700 \text{ GeV}$ in 1 year

Acosta (2002)

Implications for Colliders

- May even be able to trap sleptons, move to a quiet environment to observe decays
- At LHC, $\sim 10^6$ sleptons possible, can catch ~ 100 in 100 m^3 we
- At LC, can tune beam energy to produce slow sleptons



Implications for Colliders

- Recall:

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

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

Related Recent Work

- Analysis in particular models
 - mSUGRA (Ellis, Olive, Santoso, Spanos, hep-ph/0312062)
- Astrophysics
 - Structure formation (Sigurdson, Kamionkowski, astro-ph/0311486)
- Collider physics
 - Gravitino studies (Buchmuller, Hamaguchi, Ratz, Yanagida, hep-ph/0402179, hep-ph/0403203)

Summary

SuperWIMPs – a new class of particle dark matter

	WIMPs	superWIMPs
Well-motivated stable particle?	Yes	Yes
Natural relic density?	Yes	Yes
Detection promising?	Yes	Yes (already seen?)
Years studied	20	1