SuperWIMP Dark Matter

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FNAL Theoretical Astrophysics Seminar
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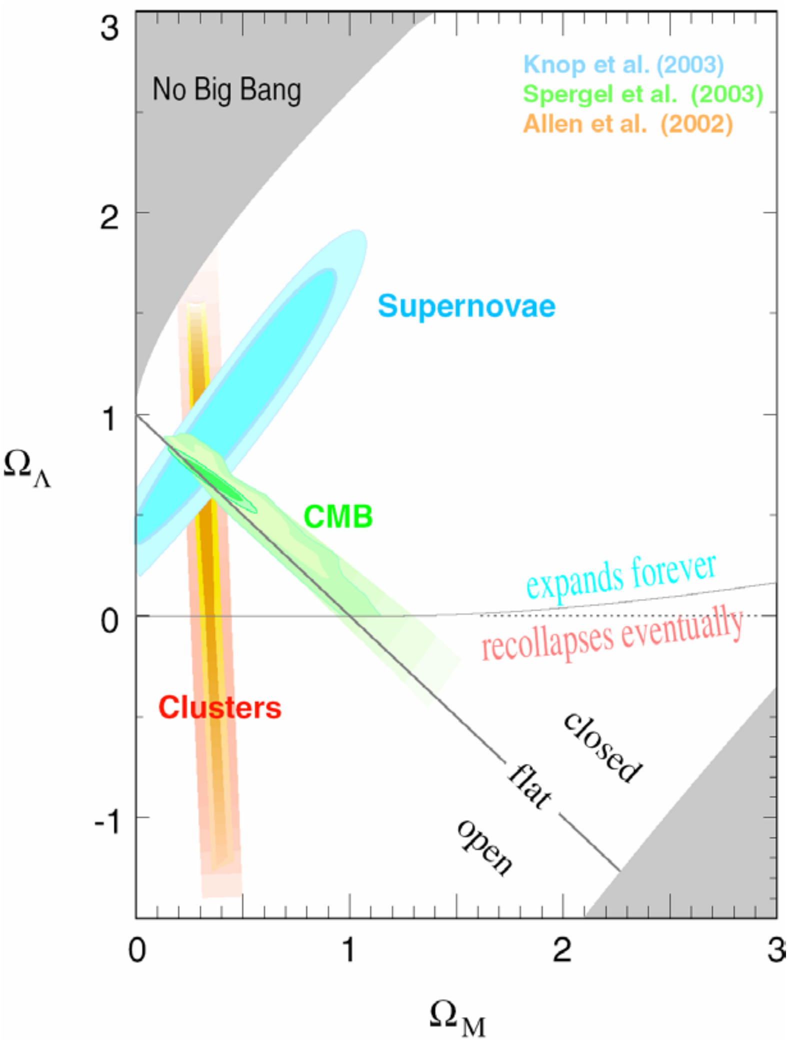
Dark Matter



- 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…

- 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:

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

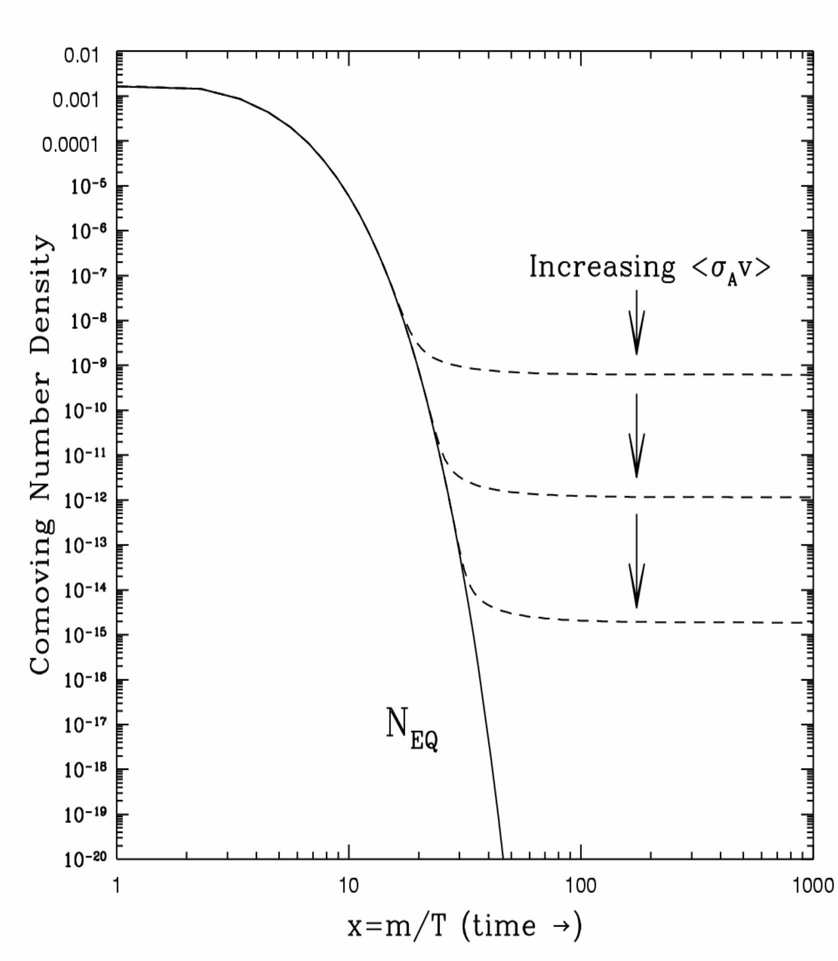
2) Universe cools:

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

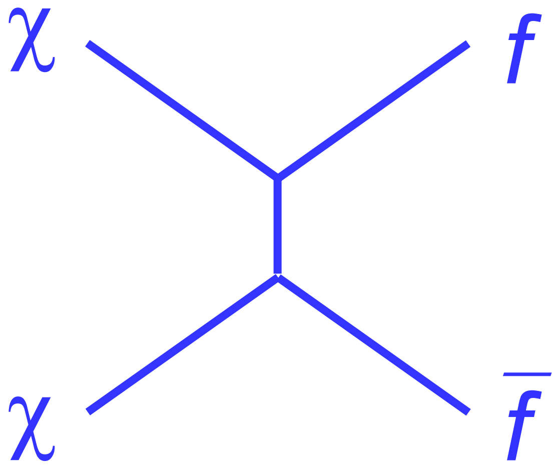
3) χs “freeze out”:

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

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

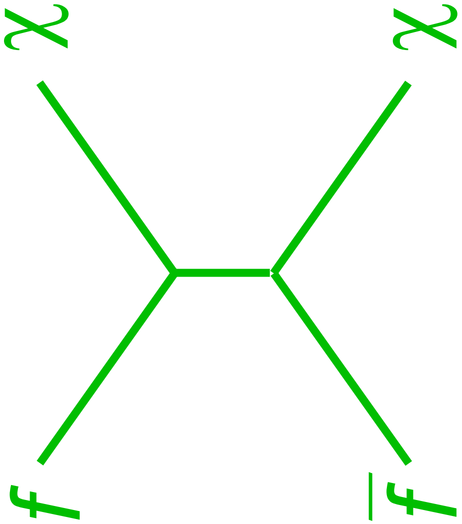


III. Detection Promising



Annihilation

Crossing → symmetry



Scattering

Correct relic density → efficient annihilation then

→ efficient annihilation now, efficient scattering now

No-Lose Theorem

Illustration: mSUGRA

- Well-motivated stable particle:

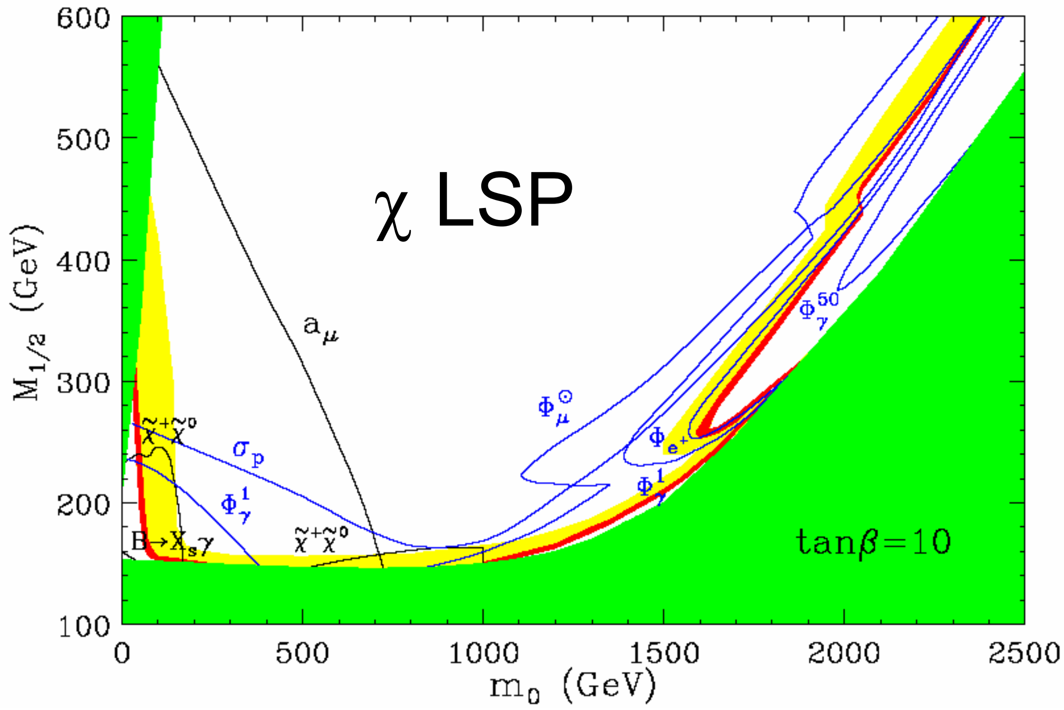
  χ LSP in unshaded region

- Natural relic density:

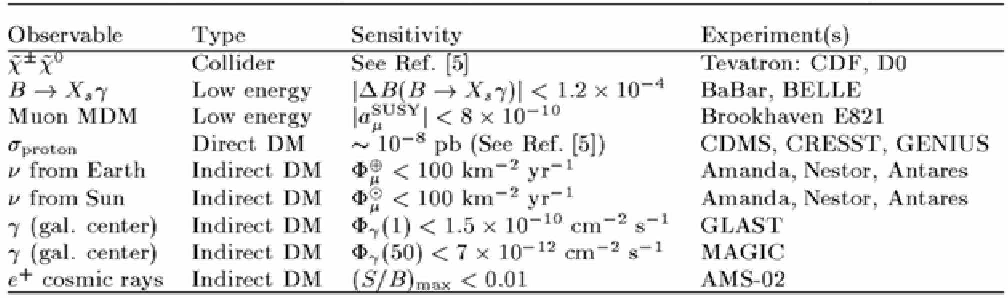
  $\Omega_\chi = 0.23 \pm 0.04$

  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
$B \to X_s\gamma$	Low energy	$\lvert\Delta B(B \to X_s\gamma)\rvert < 1.2 \times 10^{-4}$	BaBar, BELLE
Muon MDM	Low energy	$\lvert a_\mu^{\mathrm{SUSY}}\rvert < 8 \times 10^{-10}$	Brookhaven E821
σ_{proton}	Direct DM	$\sim 10^{-8}$ pb (See Ref. [5])	CDMS, CRESST, GENIUS
ν from Earth	Indirect DM	$\Phi_\mu^\oplus < 100\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$	Amanda, Nestor, Antares
ν from Sun	Indirect DM	$\Phi_\mu^\odot < 100\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$	Amanda, Nestor, Antares
γ (gal. center)	Indirect DM	$\Phi_\gamma(1) < 1.5 \times 10^{-10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	GLAST
γ (gal. center)	Indirect DM	$\Phi_\gamma(50) < 7 \times 10^{-12}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	MAGIC
e^+ cosmic rays	Indirect DM	$(S/B)_{\mathrm{max}} < 0.01$	AMS-02

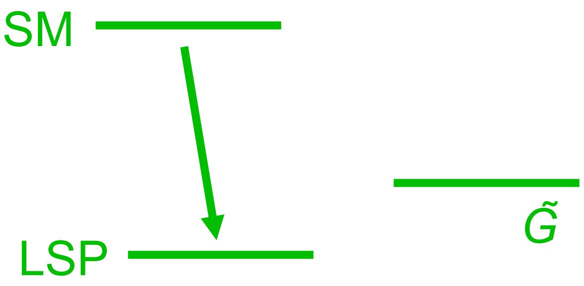
SuperWIMPs: The Basic Idea

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

- Supergravity requires gravitinos:

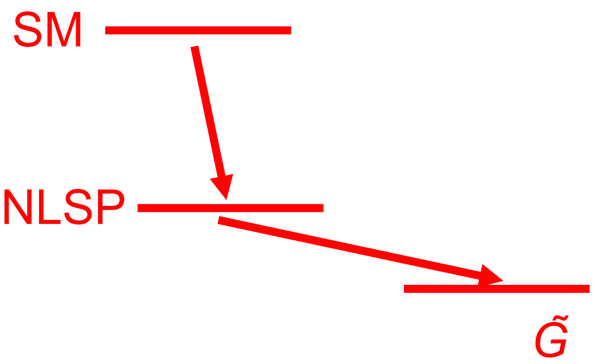
  mass ~ M_W , couplings ~ M_W/M_*

- $\tilde{G}$ not LSP

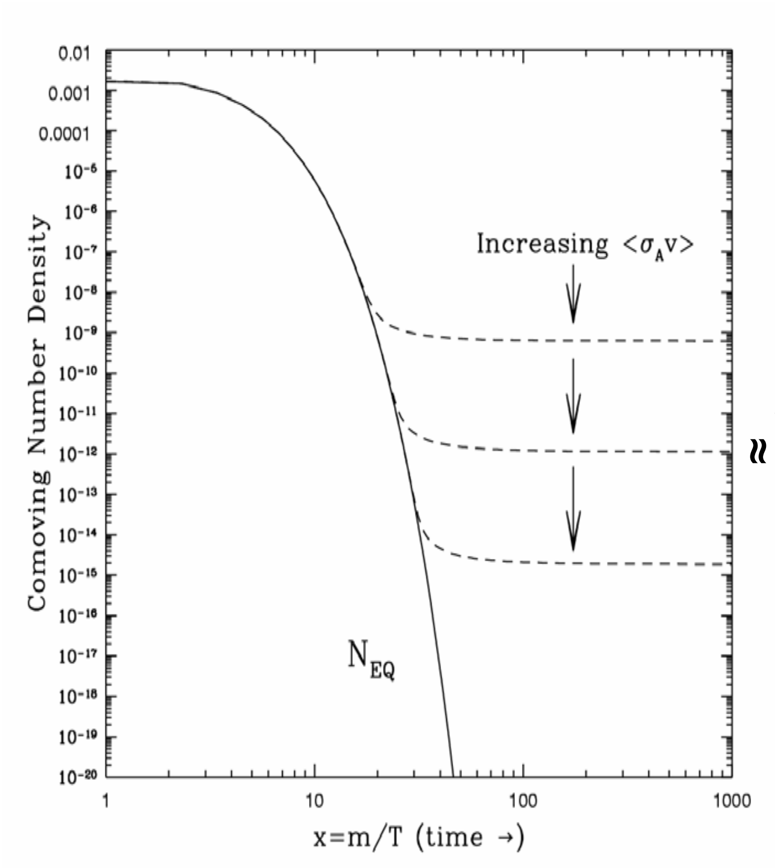


- No impact – assumption of most of literature

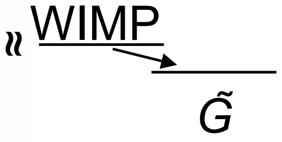
- $\tilde{G}$ LSP



- Qualitatively different cosmology



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



M_*^2/M_W^3 ~ 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

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

- DM if bound saturated, requires new scale

- Weak scale gravitinos diluted by inflation, regenerated in reheating

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

- 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: $m_{\tilde{G}}\,,\quad \Delta m = m_{\text{NLSP}} - m_{\tilde{G}}$

Decays to SuperWIMPs

- Lifetime

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

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

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

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

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

- Energy release

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

i = EM, had

ε_i = energy released in each decay

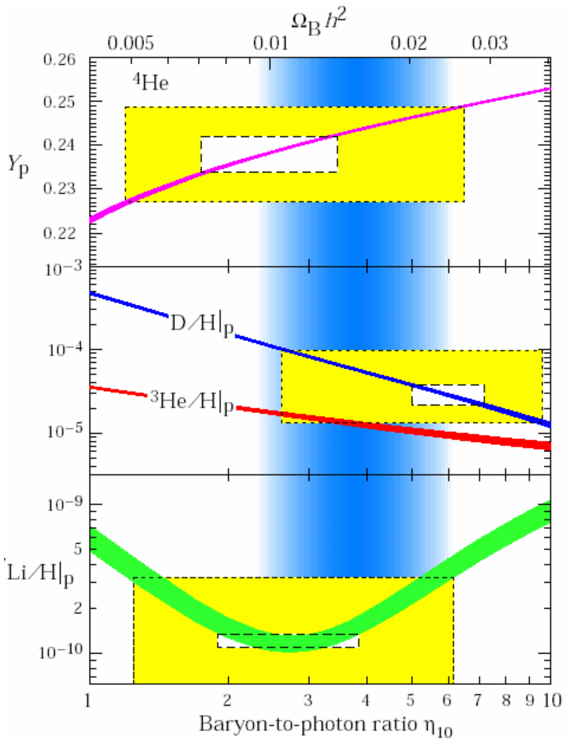
B_i = branching fraction

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

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

Big Bang Nucleosynthesis

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

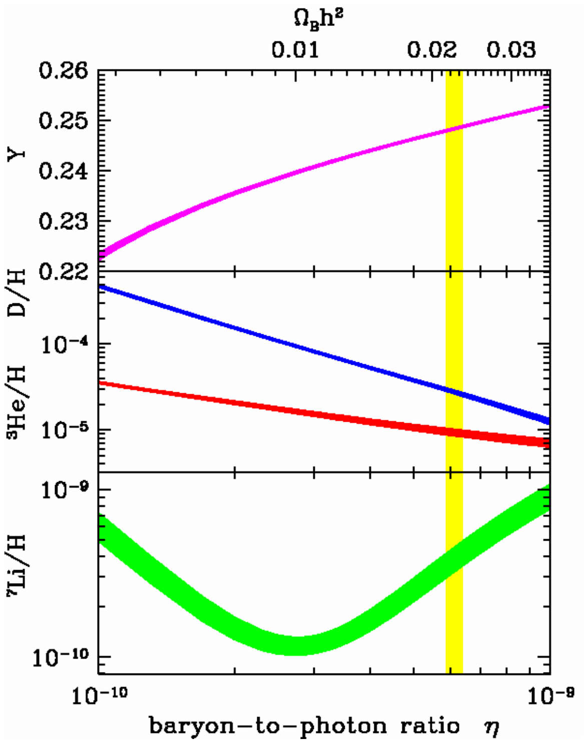


Fields, Sarkar, PDG (2002)

WMAP

$\eta_D = \eta_{CMB}$

^{7}Li low



Cyburt, Fields, Olive (2003)

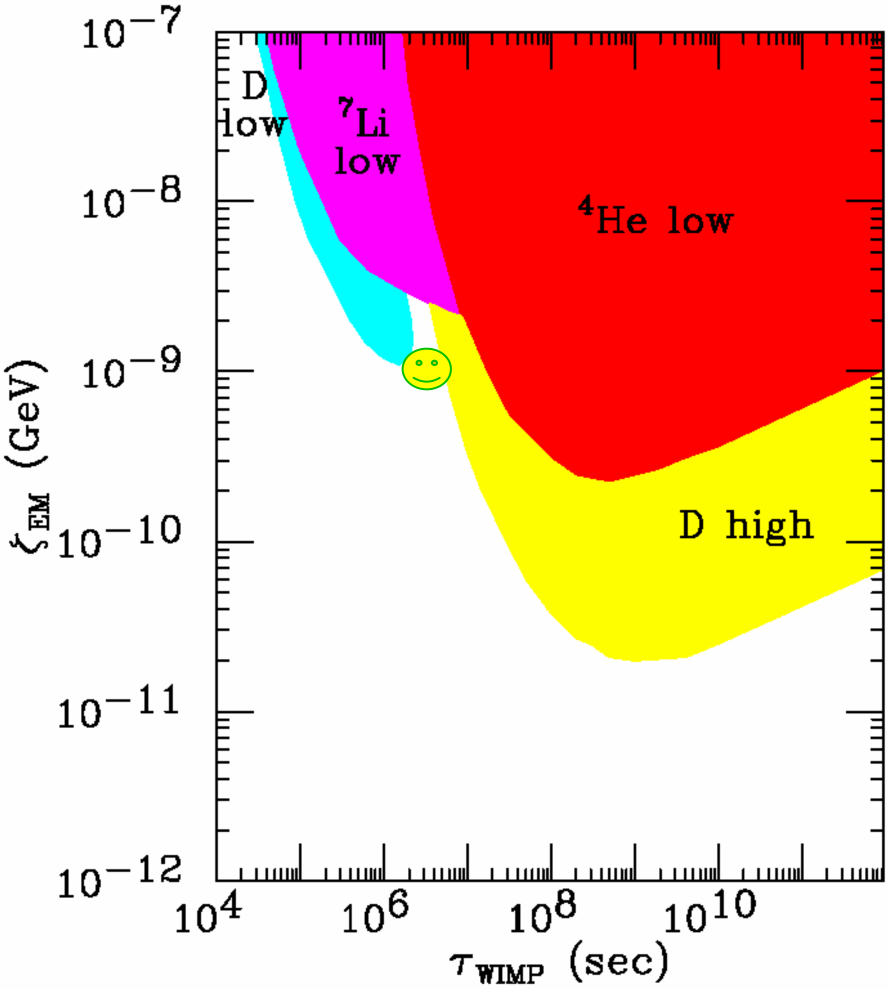
BBN EM Constraints

- NLSP = WIMP → 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}Li: ☺



Cyburt, Ellis, Fields, Olive (2002)

BBN EM Predictions

- Consider $\tilde{\tau} \rightarrow \tilde{G}\, \tau$ (others similar)

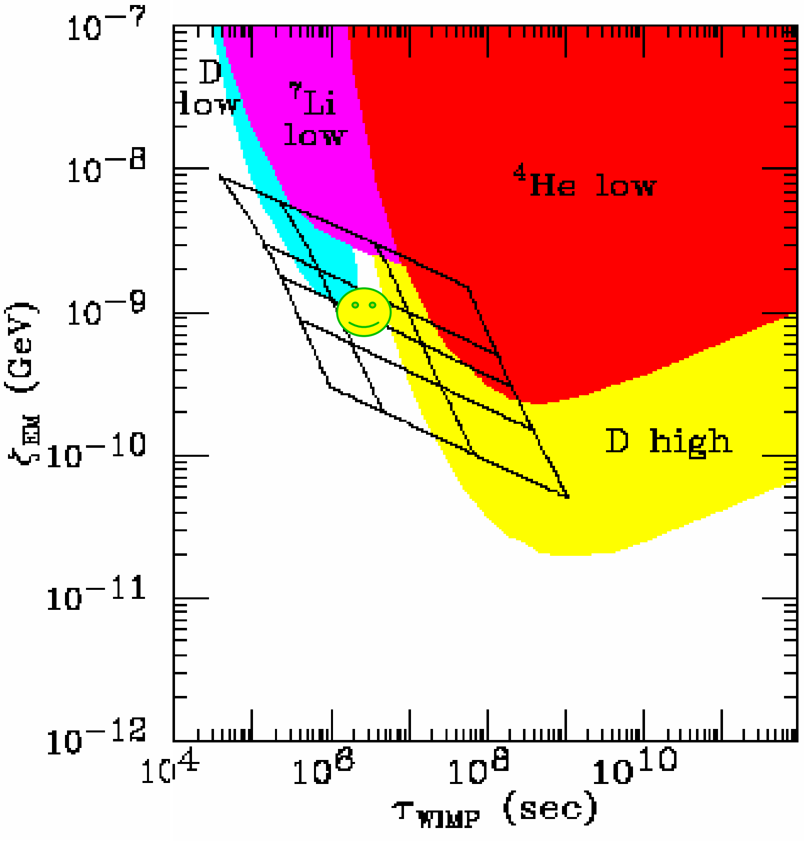
- Grid: Predictions for

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

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

- Some parameter space excluded, but much survives

- In fact, superWIMP DM naturally explains ^{7}Li !



Feng, Rajaraman, Takayama (2003)

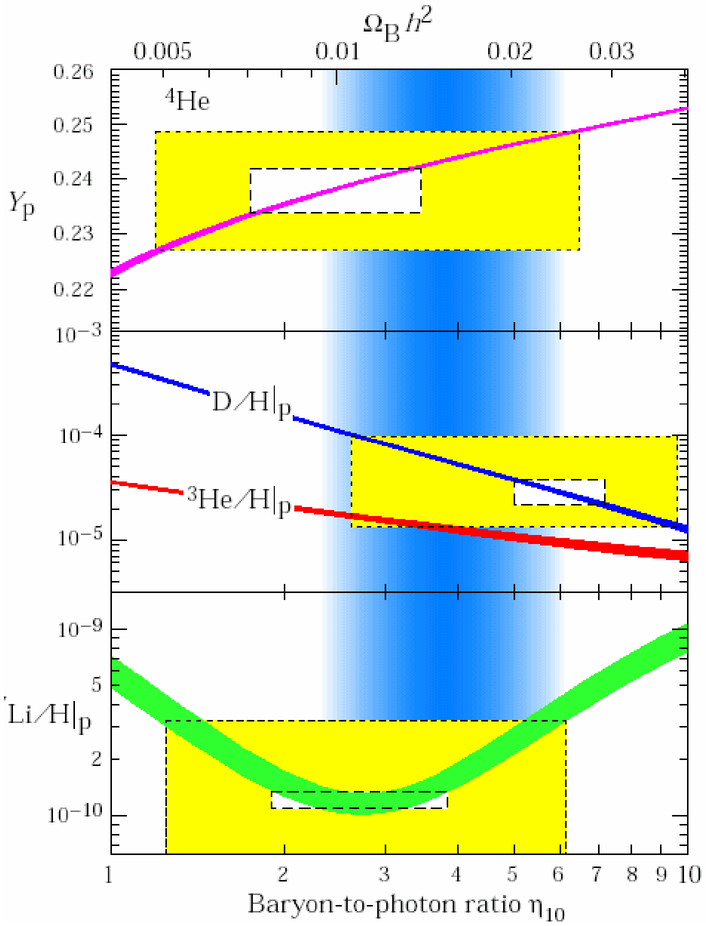
^{7}Li Anomaly

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

- Observations:

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

- 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:

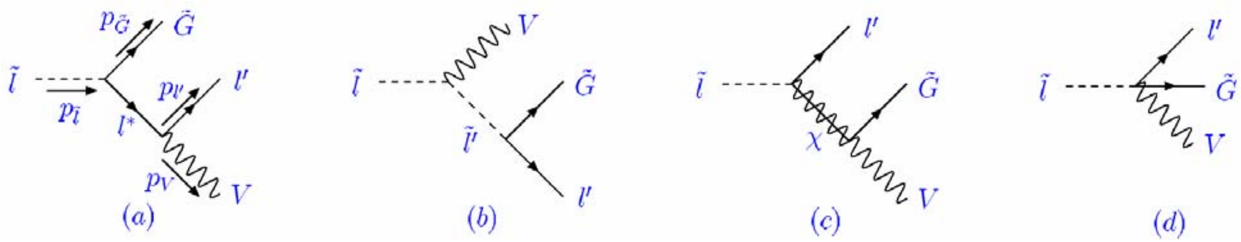
$$\begin{aligned}\tilde{l} &\to lZ\tilde{G}\ ,\ \nu W\tilde{G} \\ \tilde{\nu} &\to \nu Z\tilde{G}\ ,\ lW\tilde{G}\end{aligned}$$

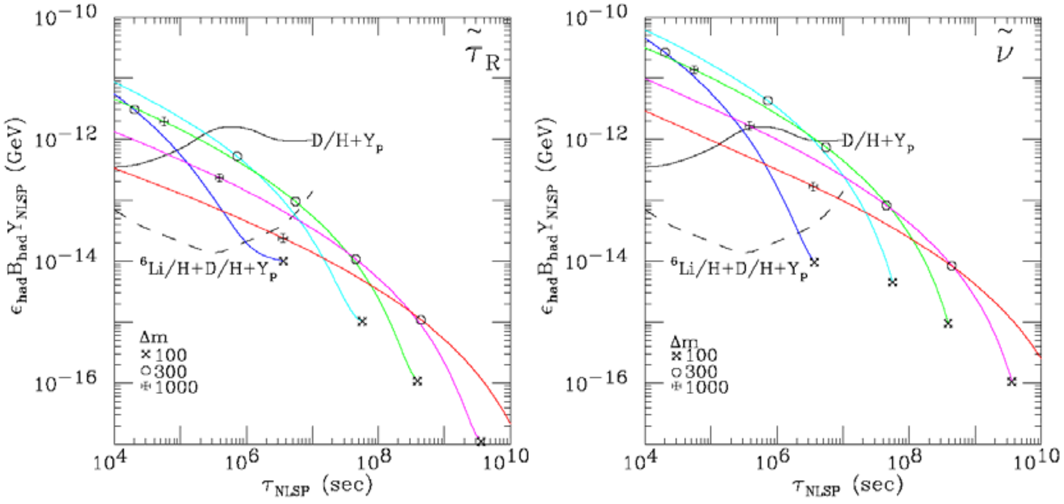
- In fact, for neutralinos, these aren't even subleading:

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

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

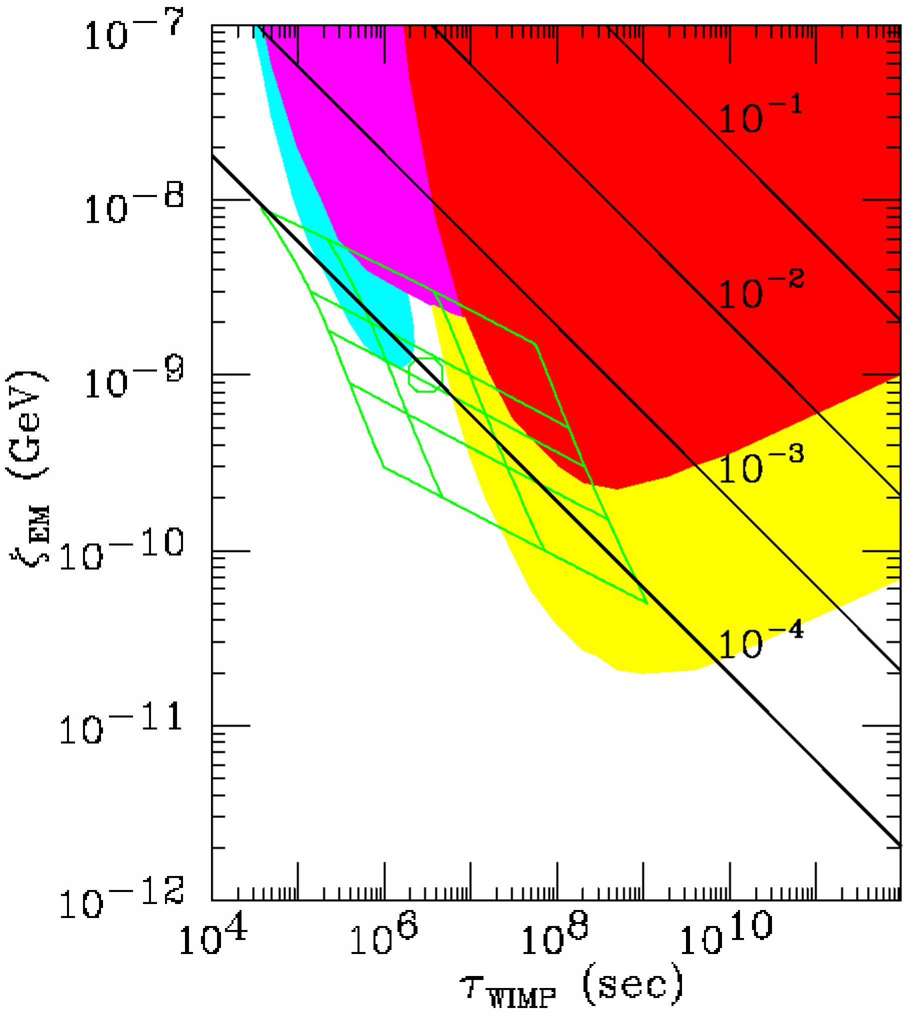
Kaplinghat, Turner (2001)

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

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

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

- BBN constraints → entropy constraint satisfied



Feng, Rajaraman, Takayama (2003)

Cosmic Microwave Background

- Late decays may also distort the CMB spectrum

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

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

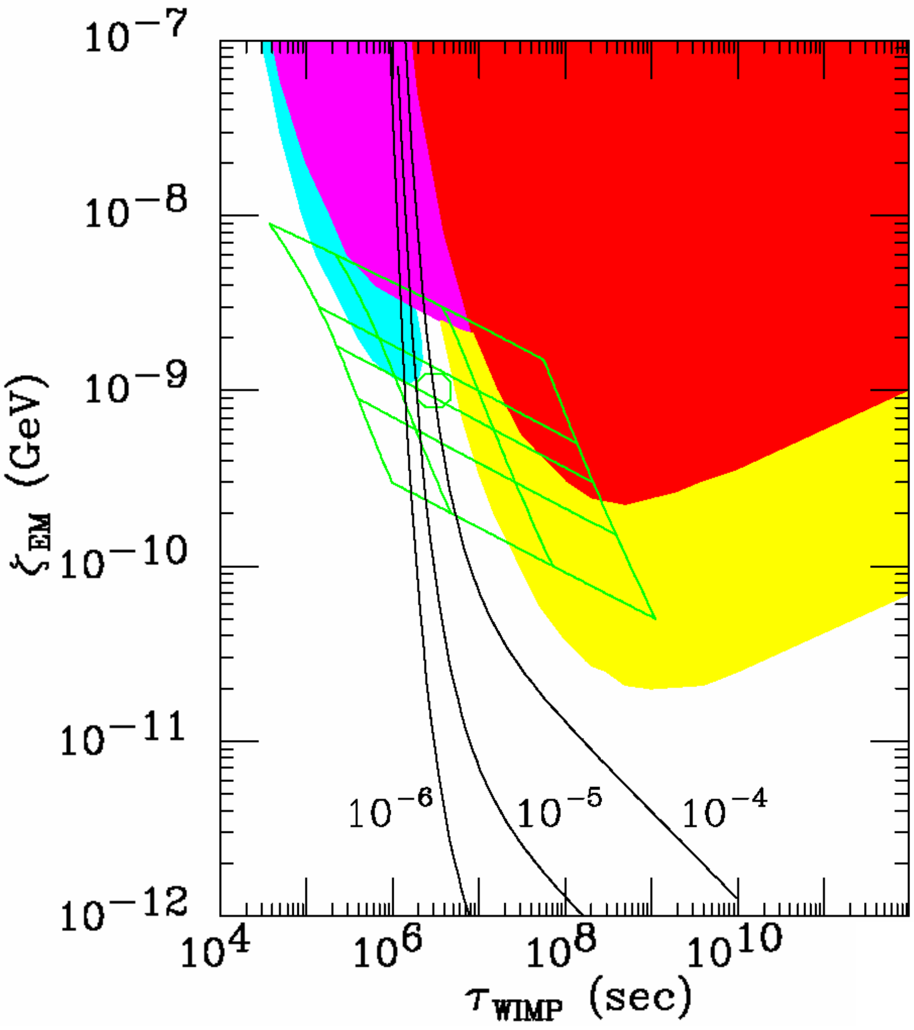
$\mu=0$: Planckian spectrum

$\mu\neq0$: Bose-Einstein spectrum

Hu, Silk (1993)

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

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



Feng, Rajaraman, Takayama (2003)

SuperWIMPs in Extra Dimensions

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

Appelquist, Cheng, Dobrescu (2000)

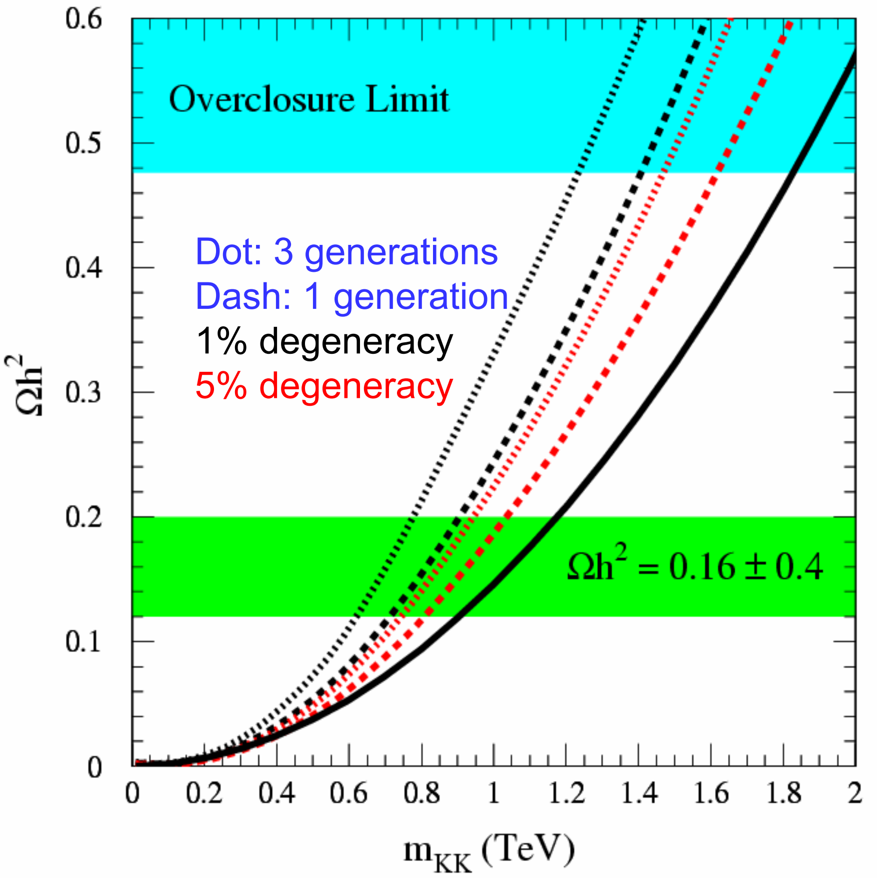
- SUSY → UED:
  Superpartners → KK partners
  R-parity → KK-parity
  LSP → LKP
  $\tilde{B}$ dark matter → B^1 dark matter

- 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)
…



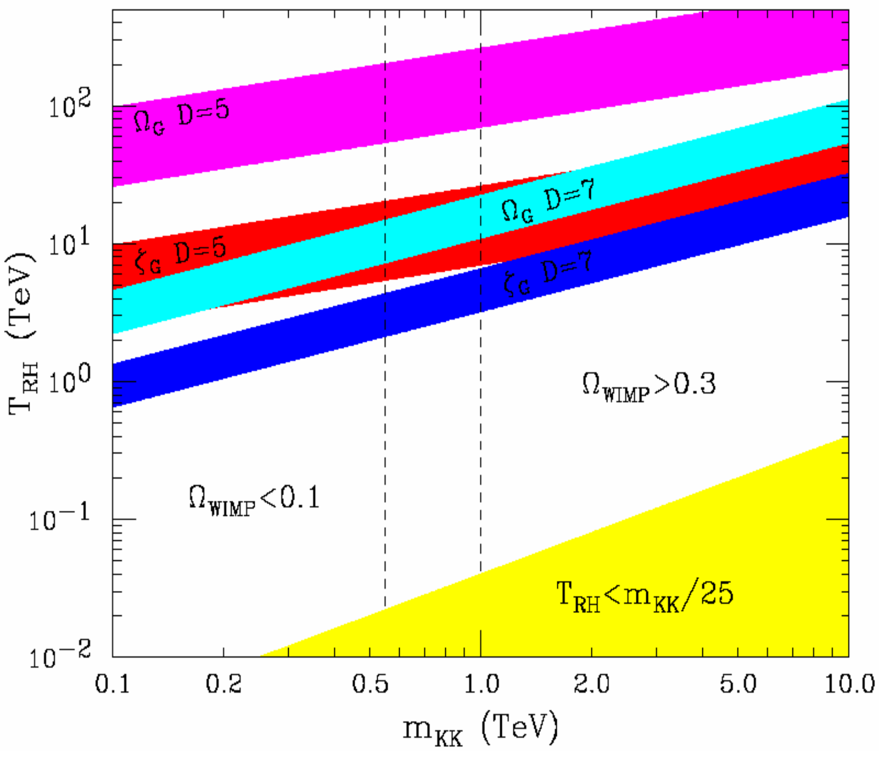
Servant, Tait (2002)

SuperWIMPs in Extra Dimensions

- SuperWIMP: $\tilde{G} \rightarrow G^1$
- O(1) modifications, except: tower of KK gravitons → reheating is *extremely* efficient
- T_{RH} < 1 - 10 TeV

(Cf. SUSY $T_{RH} < 10^{10}$ GeV)

SuperWIMP scenario requires T_{RH} > 40 GeV



Feng, Rajaraman, Takayama (2003)

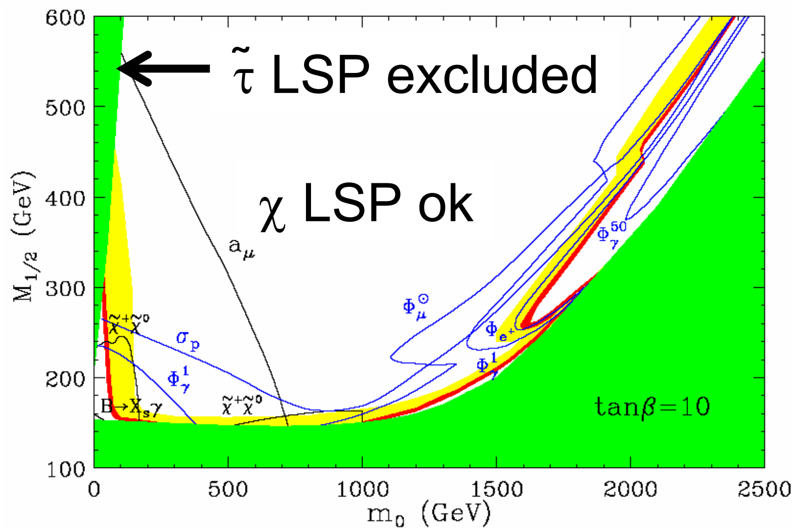
Implications for Particle Physics

- We've been missing half of parameter space.
  For example, mSUGRA should have 6 parameters:
  $\{ m_0, M_{1/2}, A_0, \tan\beta, \mathrm{sgn}(\mu)\,, m_{3/2} \}$

$\tilde{G}$ not LSP

$\Omega_{LSP} > 0.23$ excluded

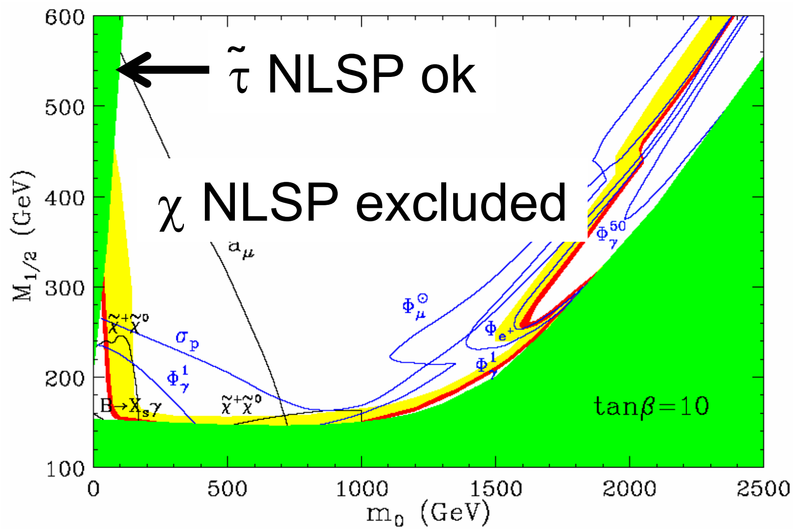
$\tilde{\tau}$ LSP excluded



$\tilde{G}$ LSP

$\Omega_{NLSP} > 0.23$ ok

$\tilde{\tau}$ LSP ok



Implications for SUSY Spectrum

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

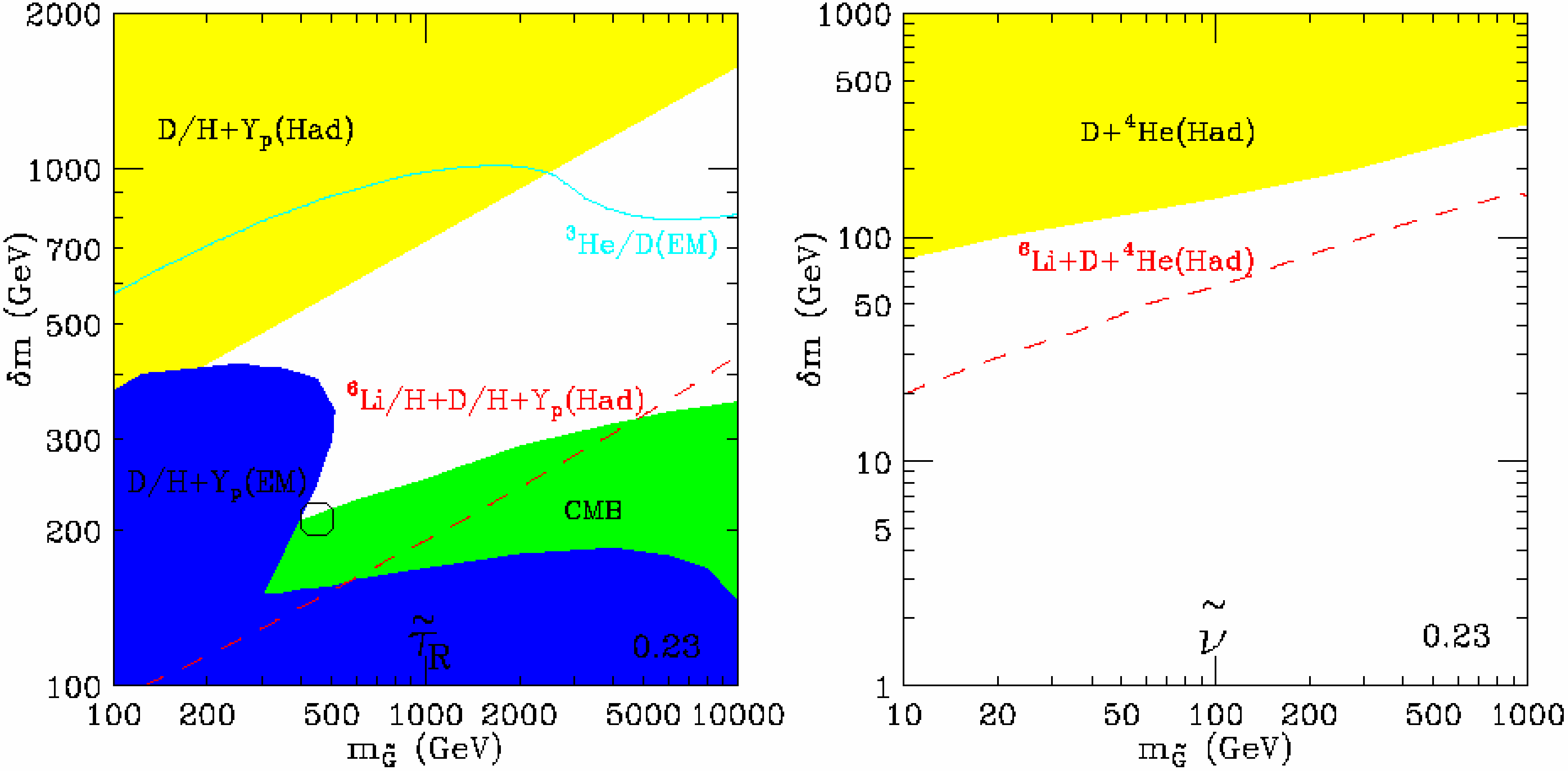
  It depends…constraints bound $n_{\tilde{G}} = \Omega_{\tilde{G}} / m_{\tilde{G}}$

- If $\Omega_{\tilde{G}} = \Omega_{\mathrm{DM}}$, $n_{\tilde{G}} \sim m_{\tilde{G}}^{-1}$, low masses excluded

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

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

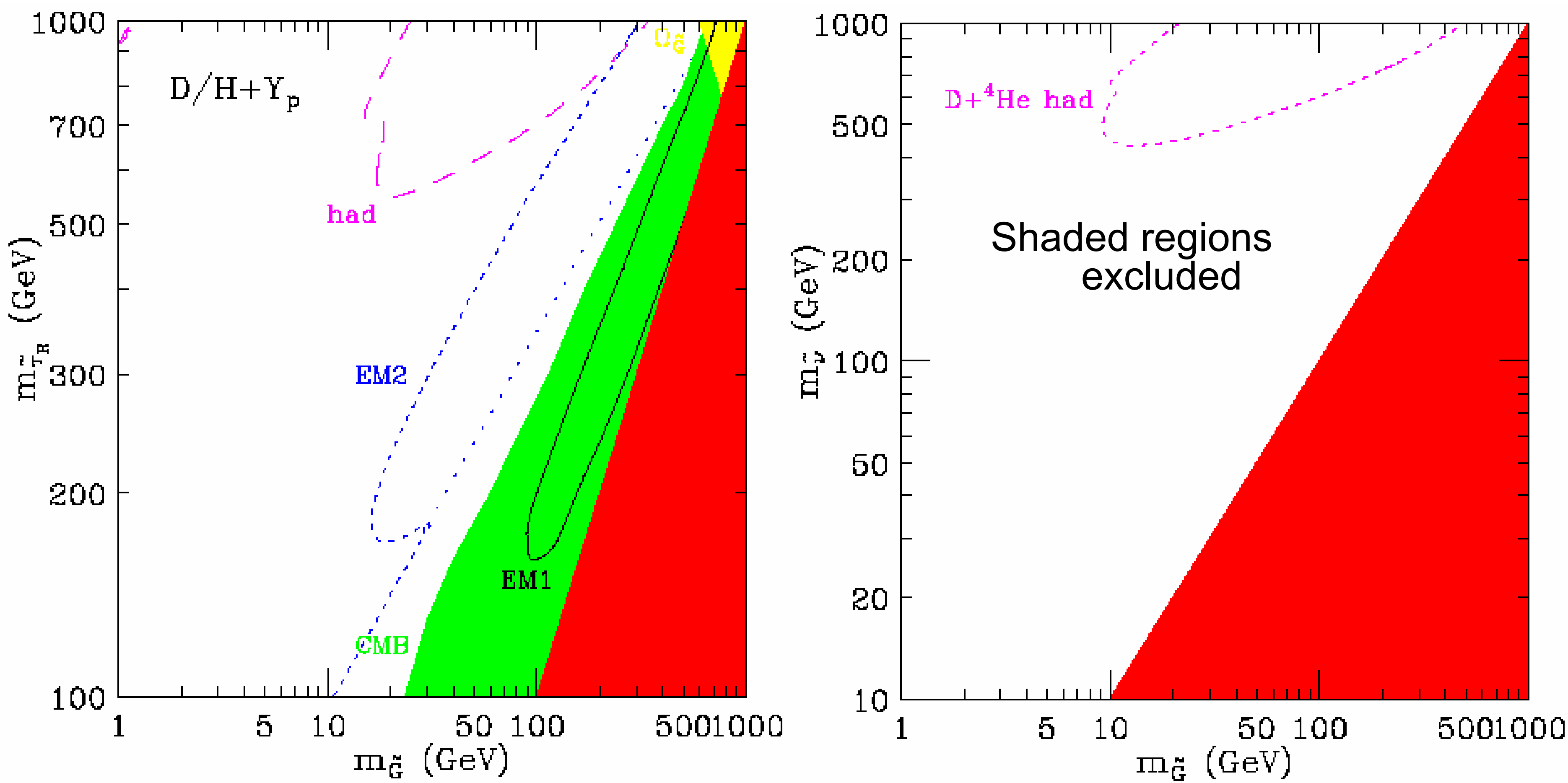
Shaded regions excluded



Feng, Takayama, Su (2004)

$\Omega_{\tilde{G}} = (m_{\tilde{G}} / m_{NLSP})\, \Omega^{th}_{NLSP}$

Shaded regions excluded



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): $m_{\tilde{l}} > 99$ GeV

- Tevatron Run II reach: ~ 150 GeV

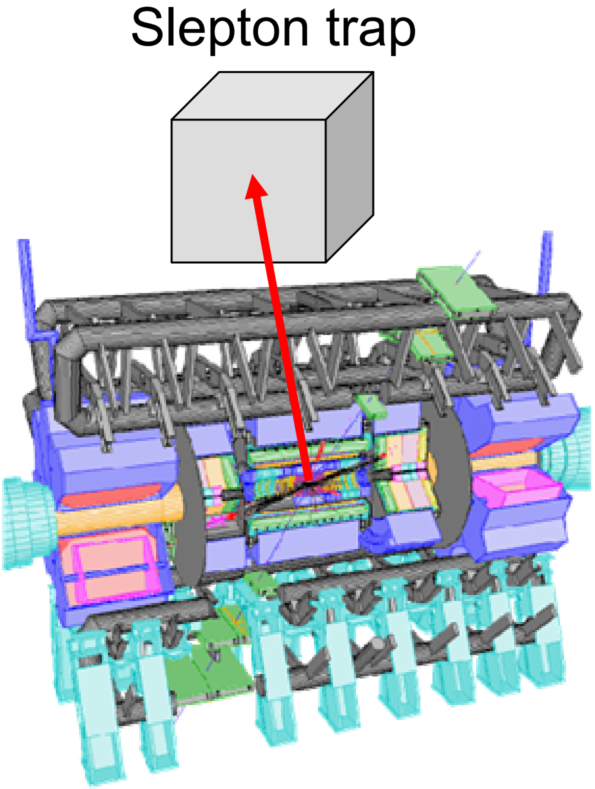
Feng, Moroi (1996)
Hoffman, Stuart et al. (1997)

- LHC reach: ~ 700 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, ~10^6 sleptons possible, can catch ~100 in 100 m^3we
- At LC, can tune beam energy to produce slow sleptons



Implications for Colliders

- Recall:

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

- Measurement of Γ → $m_{\tilde{G}}$
  - → $\Omega_{\tilde{G}}$. SuperWIMP contribution to dark matter
  - → *F*. Supersymmetry breaking scale, vacuum energy
  - → BBN in the lab

- Measurement of Γ and E_l → $m_{\tilde{G}}$ *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