SuperWIMP Dark Matter

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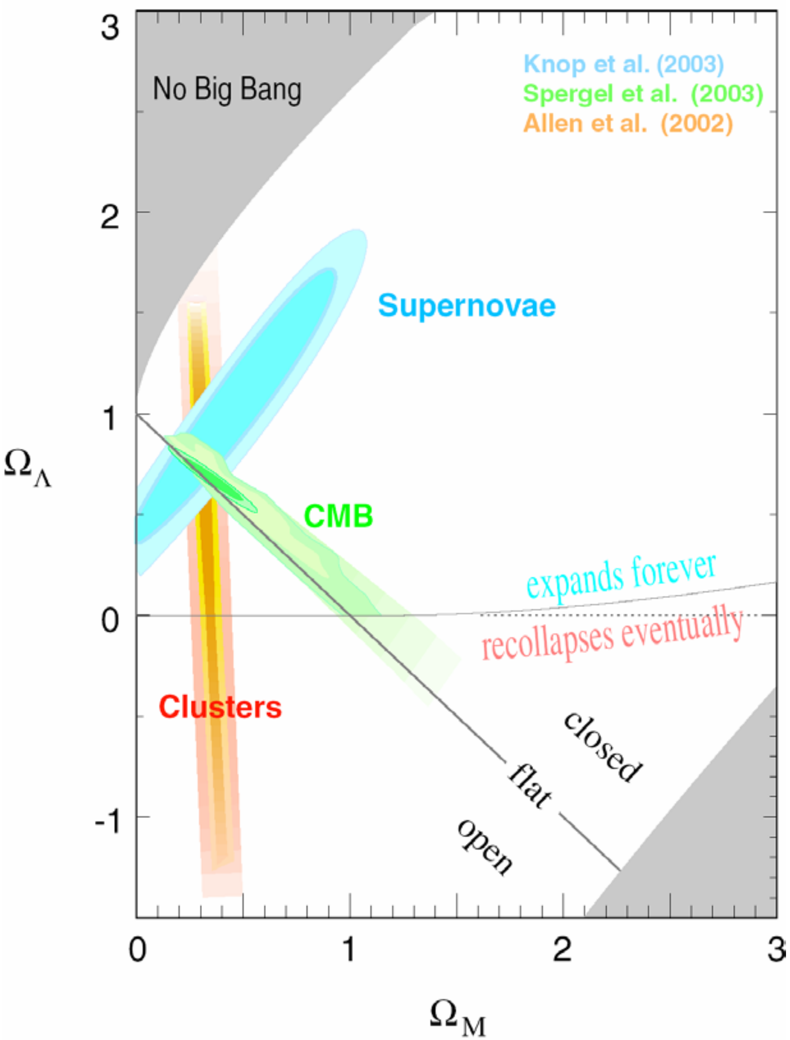
Based On…

- Feng, Rajaraman, Takayama, *Superweakly Interacting Massive Particles*, Phys. Rev. Lett., hep-ph/0302215
- Feng, Rajaraman, Takayama, *SuperWIMP Dark Matter Signals from the Early Universe*, Phys. Rev. D, hep-ph/0306024
- Feng, Rajaraman, Takayama, *Probing Gravitational Interactions of Elementary Particles*, Gen. Rel. Grav., hep-th/0405248
- Feng, Su, Takayama, *Gravitino Dark Matter from Slepton and Sneutrino Decays*, Phys. Rev. D, hep-ph/0404198
- Feng, Su, Takayama, *Supergravity with a Gravitino LSP*, Phys. Rev. D, hep-ph/0404231
- Feng, Smith, *Slepton Trapping at the Large Hadron and International Linear Colliders*, Phys. Rev. D, hep-ph/0409278

Dark Matter



- Tremendous recent progress:

  $\Omega_{DM} = 0.23 \pm 0.04$

- But…we have no idea what it is

- Precise, unambiguous evidence for new particle physics

SuperWIMPs – New DM Candidate

- Why should we care?

  We already have axions, warm gravitinos, neutralinos, Kaluza-Klein particles, Q balls, wimpzillas, branons, self-interacting particles, self-annihilating particles,…

- SuperWIMPs have all the virtues of neutralinos…

  Well-motivated stable particle

  Naturally obtains the correct relic density

- …and more

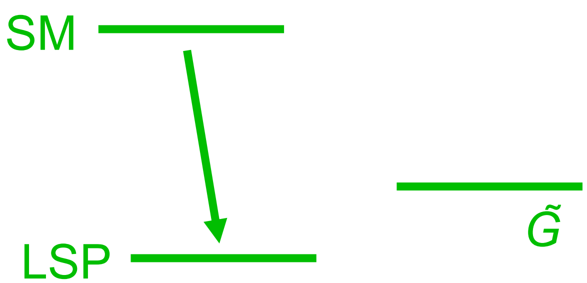
  Rich cosmology, spectacular collider signals

  There is already a signal

SuperWIMPs: The Basic Idea

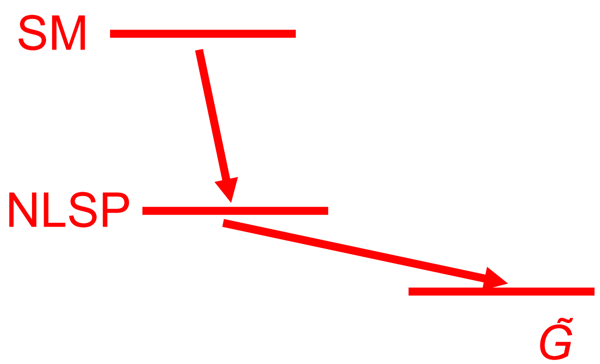
- Supergravity gravitinos: mass ~ M_W , couplings ~ M_W/M_*

- $\tilde{G}$ not LSP



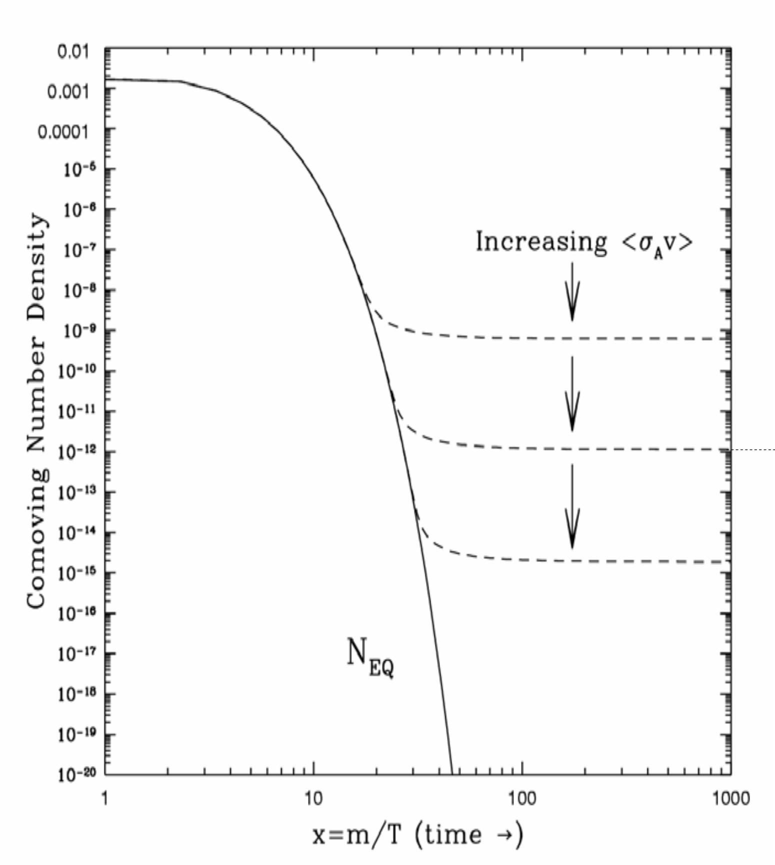
- Assumption of most of literature

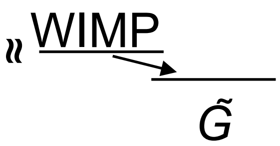
- $\tilde{G}$ LSP



- Completely different cosmology and phenomenology

- Assume $\tilde{G}$ LSP, WIMP NLSP
- WIMPs freeze out as usual





- But at $t \sim M_*^2/M_W^3 \sim$ month, WIMPs decay to gravitinos

Gravitinos are dark matter now: they are *superWIMPs*, superweakly interacting massive particles

SuperWIMP Virtues

- Well motivated stable particle. Present in
  - supersymmetry (supergravity with R-parity conservation)
  - Extra dimensions (universal extra dimensions with KK-parity conservation)

  Completely generic: present in "½" of parameter space

- Naturally obtains the correct relic density:

$$\Omega_{\tilde{G}} = (m_{\tilde{G}} / m_{\mathrm{NLSP}})\, \Omega_{\mathrm{NLSP}}$$

Other 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, fine-tuned 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, fine-tuned energy scale

SuperWIMP Signals

Typical expectations:

A) Signals too strong; scenario is completely excluded

B) Signals too weak; scenario is possible, but completely untestable

Can’t both be right – in fact both are wrong!

SuperWIMP Signals

- SuperWIMPs escape all conventional DM searches
- But late decays $\tilde{\tau} \rightarrow \tau \tilde{G}$, $\tilde{B} \rightarrow \gamma \tilde{G}$, …, have cosmological consequences
- Assuming $\Omega_{\tilde{G}} = \Omega_{DM}$, signals determined by 2 parameters:

$$m_{\tilde{G}} , \quad m_{NLSP}$$

Lifetime

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

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

Energy release

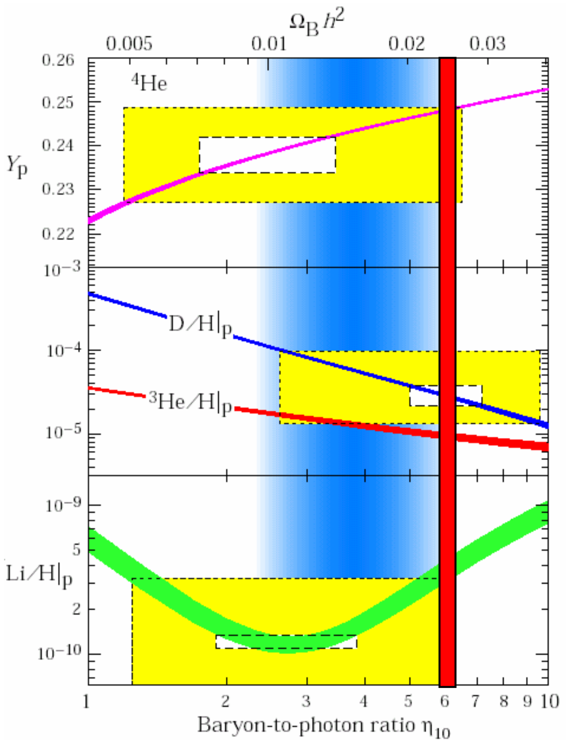
$$\zeta_i = \varepsilon_i B_i Y_{NLSP}$$

i = EM, had

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

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:

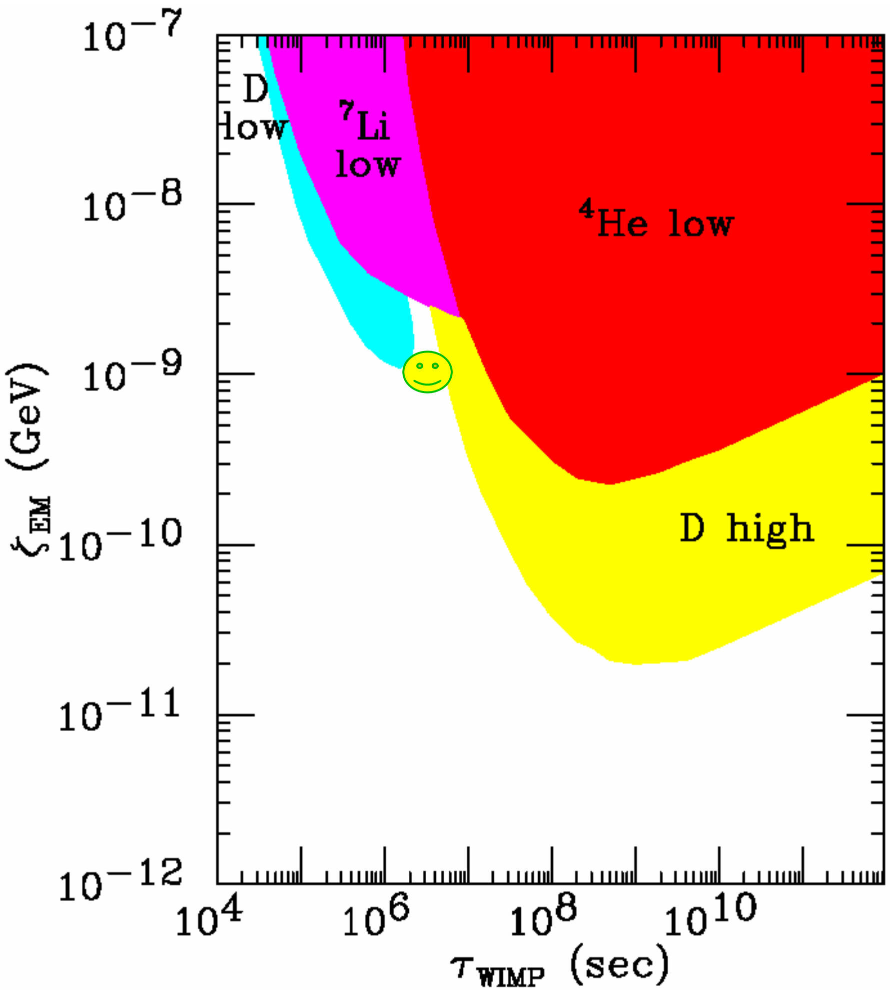
$$^7\mathrm{Li/H} = 1.5^{+0.9}_{-0.5} \times 10^{-10} \quad (95\%\ \mathrm{CL})\ [27]$$
$$^7\mathrm{Li/H} = 1.72^{+0.28}_{-0.22} \times 10^{-10} \quad (1\sigma + \mathrm{sys})\ [28]$$
$$^7\mathrm{Li/H} = 1.23^{+0.68}_{-0.32} \times 10^{-10} \quad (\mathrm{stat} + \mathrm{sys},\ 95\%\ \mathrm{CL})\ [29]$$

- ^{7}Li is now a serious problem

Jedamzik (2004)

BBN EM Constraints

- NLSP = WIMP → Energy release is dominantly EM (even mesons decay first)
- 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)

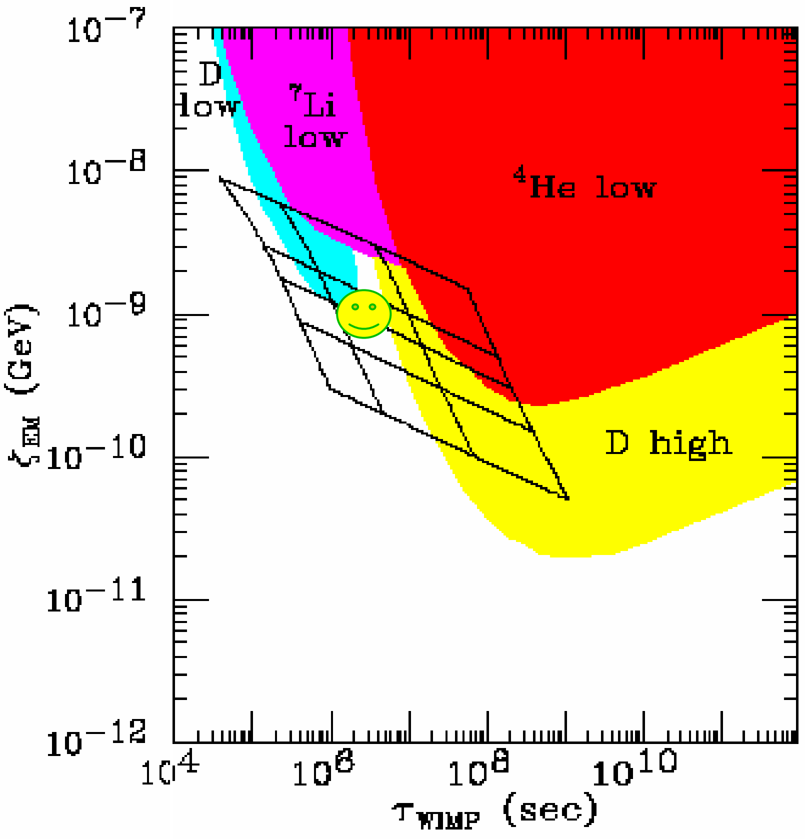
- Grid: Predictions for

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

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

- Some parameter space excluded, but much survives

- SuperWIMP DM naturally explains ^{7}Li !



Feng, Rajaraman, Takayama (2003)

BBN Hadronic Constraints

- BBN constraints on hadronic energy release are severe.

Dimopoulos, Esmailzadeh, Hall, Starkman (1988)
Reno, Seckel (1988)

Jedamzik (2004)
Kawasaki, Kohri, Moroi (2004)

- For neutralino NLSPs, hadrons from

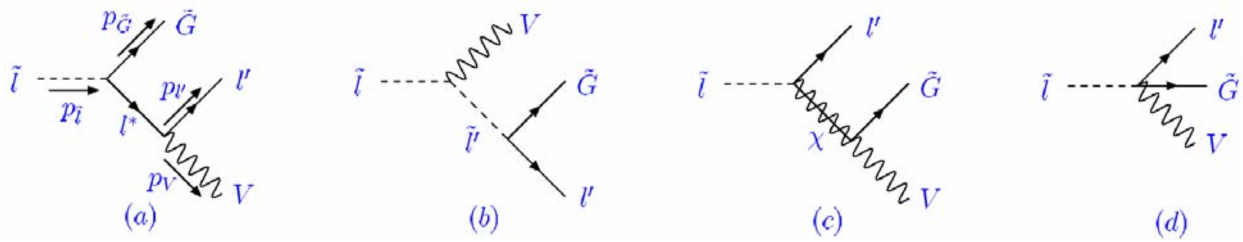
$$\chi \to Z\tilde{G},\ h\tilde{G}$$

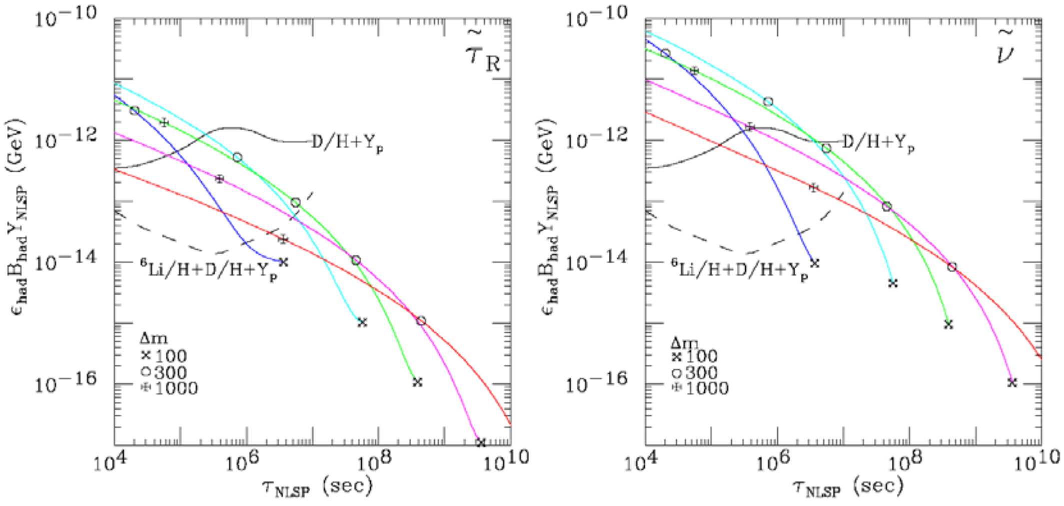
destroy BBN. Possible ways out:
  - Kinematic suppression? No, $\Delta m < m_Z$ ➔ BBN EM violated.
  - Dynamical suppression? $\chi = \tilde{\gamma}$ ok, but unmotivated.

- For sleptons, cannot neglect subleading decays:

$$\tilde{l} \to lZ\tilde{G}\ ,\ \nu W\tilde{G} \qquad \tilde{\nu} \to \nu Z\tilde{G}\ ,\ lW\tilde{G}$$

BBN Hadronic Predictions





Feng, Su, Takayama (2004)

Despite B_{had} ~ 10^{-5} – 10^{-3}, hadronic constraints are leading for τ ~ 10^{5} – 10^{6}, must be included

Cosmic Microwave Background

- Late decays may also distort the CMB spectrum

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

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

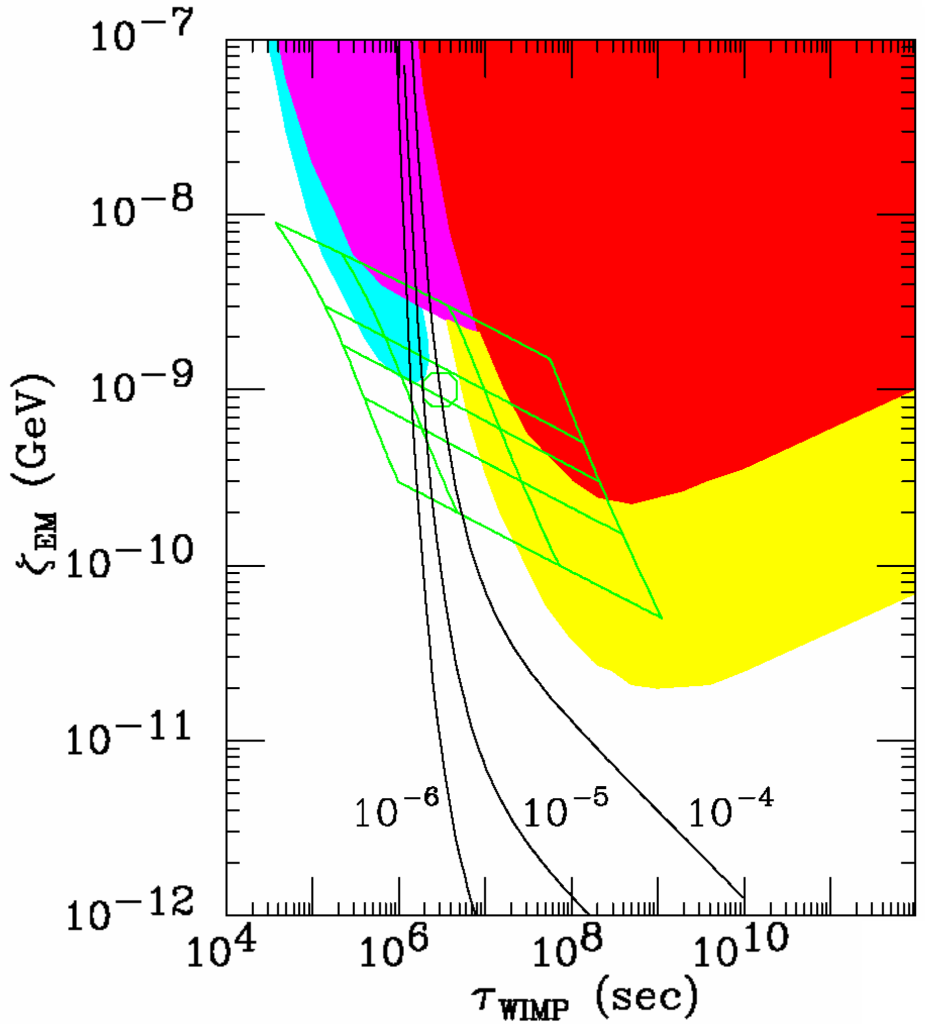
μ=0: Planckian spectrum

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

Hu, Silk (1993)

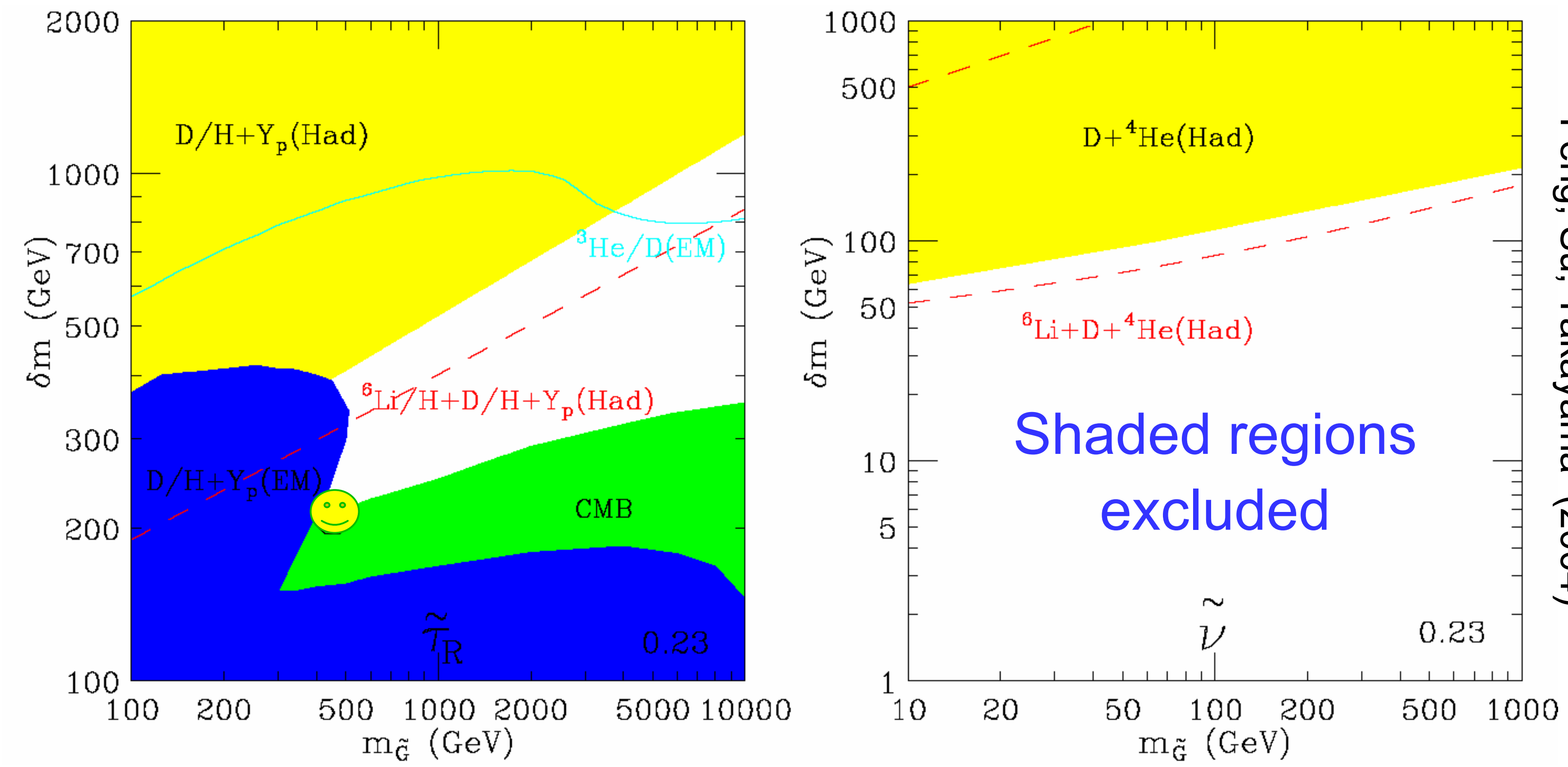
- Current bound: $|\mu| < 9 \times 10^{-5}$

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



Feng, Rajaraman, Takayama (2003)

SUSY Spectrum ($\Omega_{\tilde{G}} = \Omega_{DM}$)



Feng, Su, Takayama (2004)

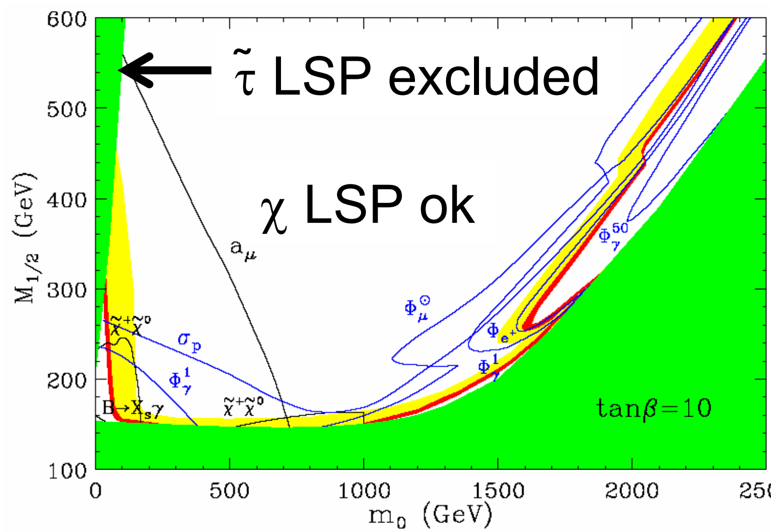
[If $\Omega_{\tilde{G}} = (m_{\tilde{G}} / m_{NLSP})\, \Omega_{NLSP}$, high masses excluded]

Model Implications

- 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

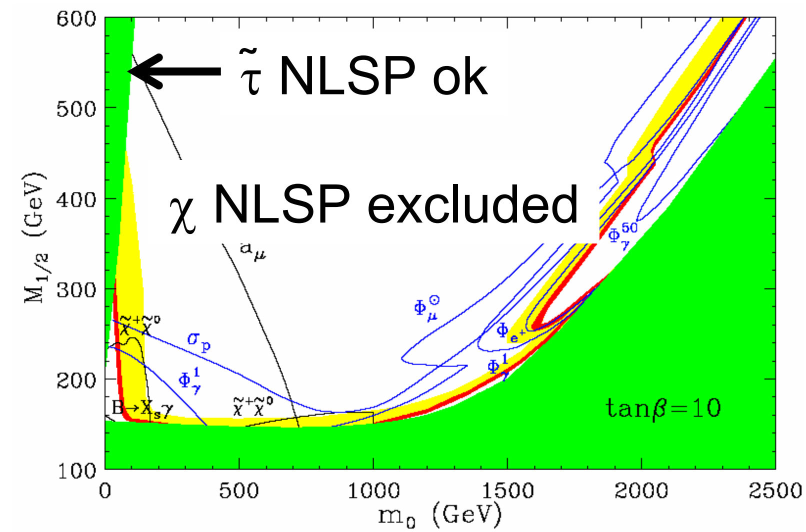
$\Omega_{LSP} > 0.23$ excluded



Feng, Matchev, Wilczek (2000)

$\tilde{G}$ LSP

$\Omega_{NLSP} > 0.23$ ok



Collider Physics

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

Current bound (LEP): $m_{\tilde{l}} > 99$ GeV

Tevatron Run II reach: $m_{\tilde{l}} \sim 180$ GeV for 10 fb^{-1}

LHC reach: $m_{\tilde{l}} \sim 700$ GeV for 100 fb^{-1}

Drees, Tata (1990)
Goity, Kossler, Sher (1993)
Feng, Moroi (1996)

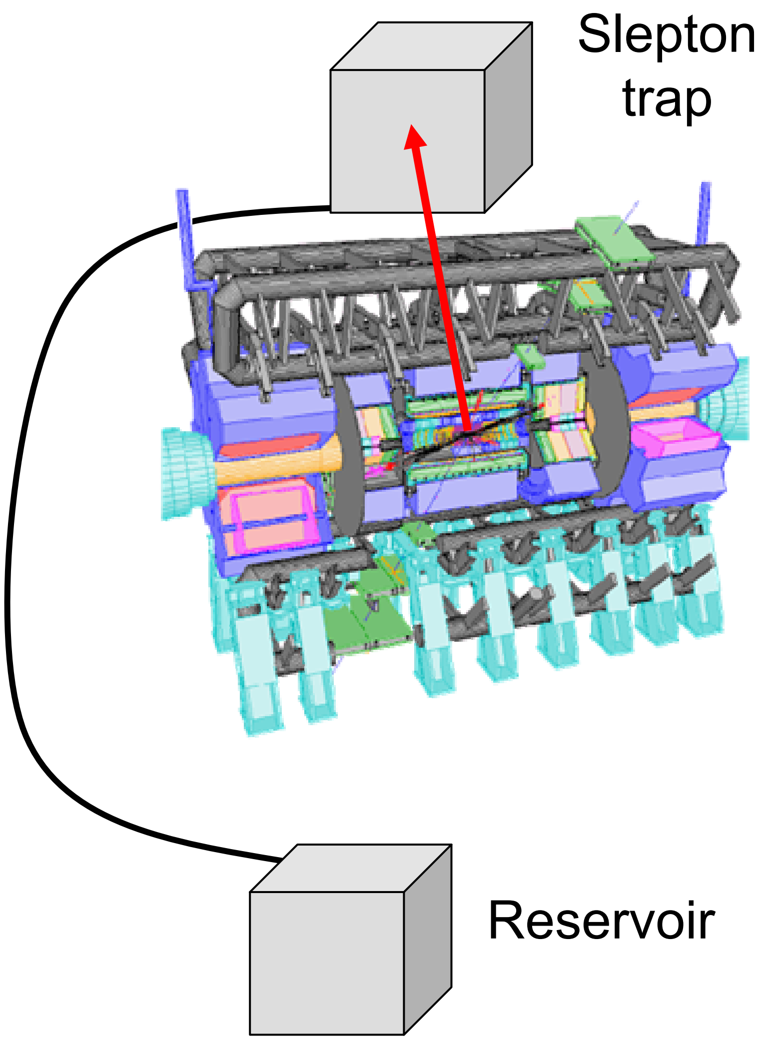
Hoffman, Stuart et al. (1997)
Acosta (2002)
…

Slepton Trapping

- Cosmological constraints ➔
  - Slepton NLSP
  - τ_{NLSP} < year

- Sleptons can be trapped and moved to a quiet environment to study their decays

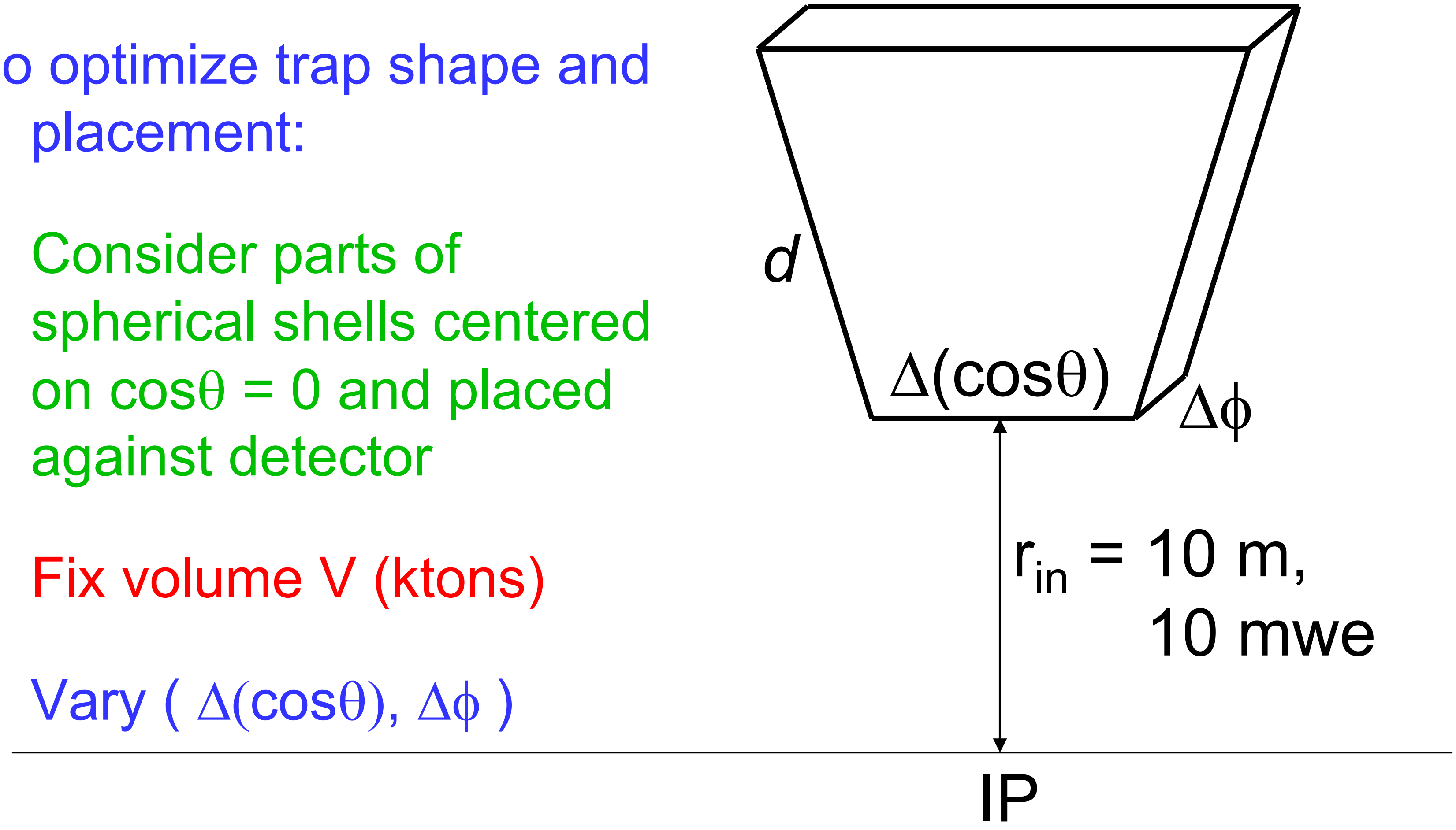
- Crucial question: how many can be trapped by a reasonably sized trap in a reasonable time?



Trap Optimization

To optimize trap shape and placement:

- Consider parts of spherical shells centered on $\cos\theta = 0$ and placed against detector
- Fix volume V (ktons)
- Vary ($\Delta(\cos\theta)$, $\Delta\phi$)

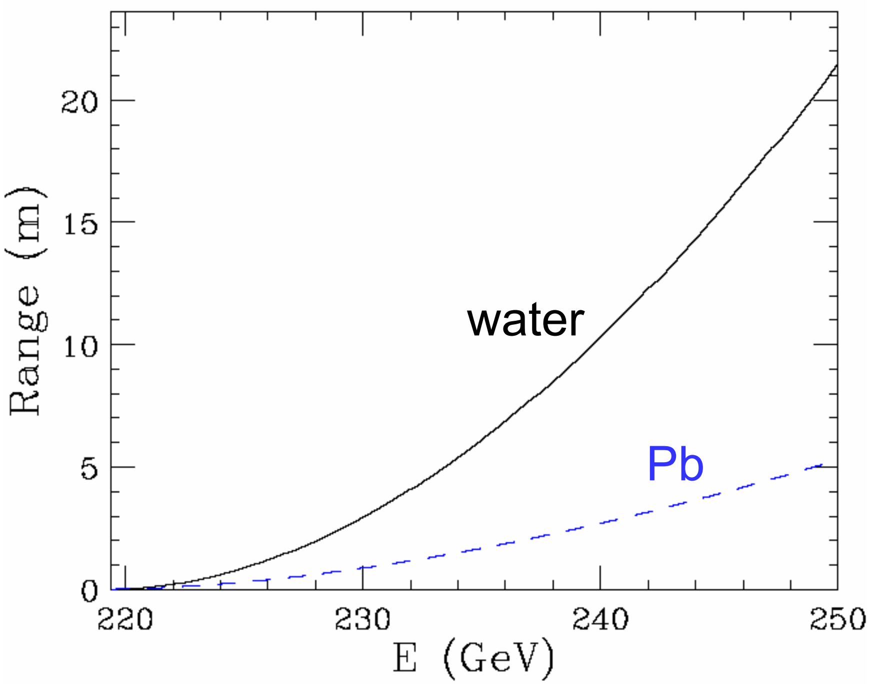


Slepton Range

- Ionization energy loss described by Bethe-Bloch equation:

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

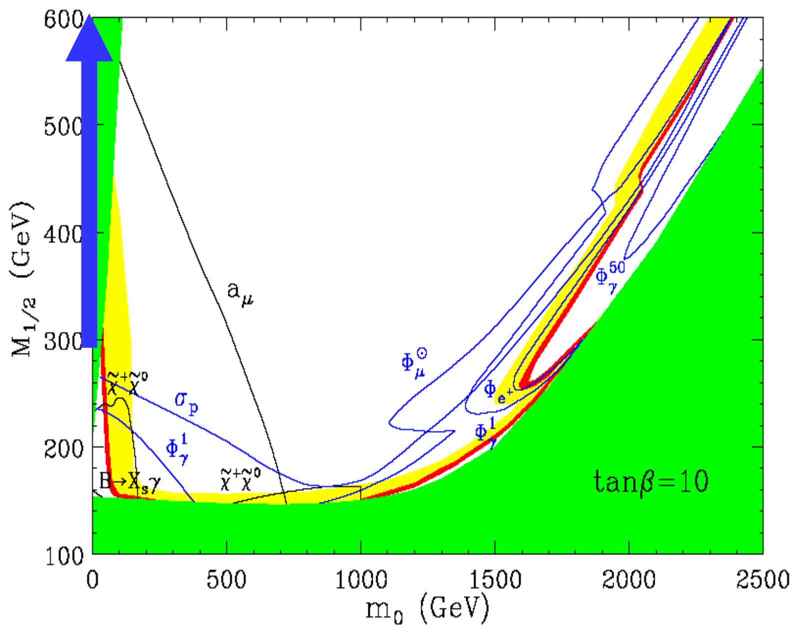
- Use "continuous slowing down approximation" down to $\beta = 0.05$

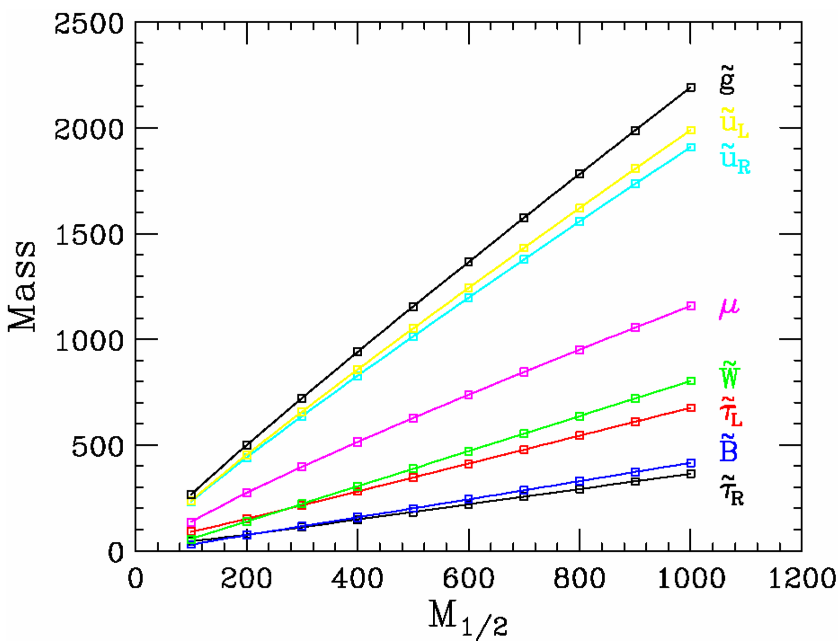


$m_{\tilde{l}} = 219$ GeV

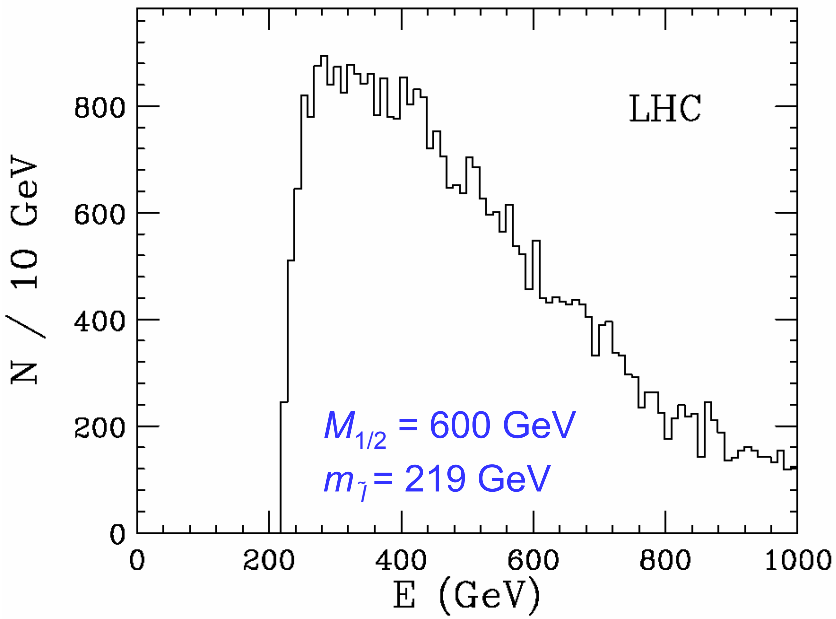
Model Framework

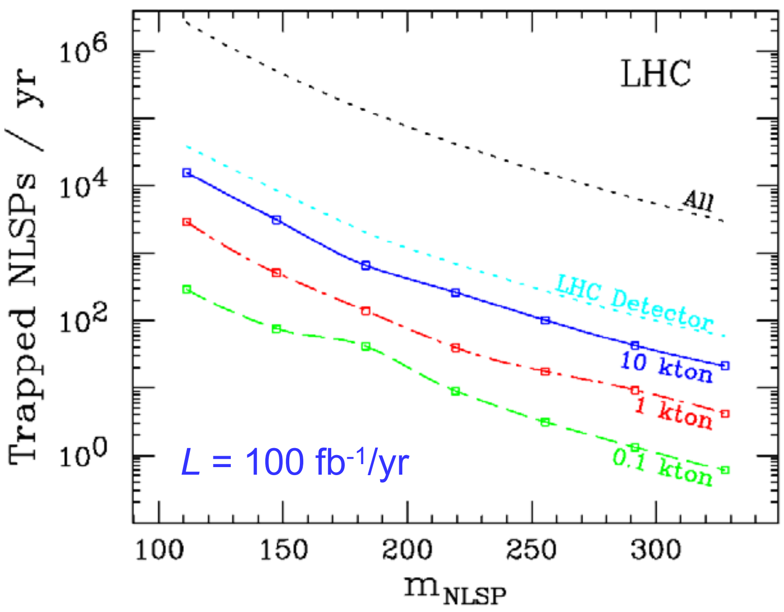
- Results depend heavily on the entire SUSY spectrum
- Consider mSUGRA with $m_0 = A_0 = 0$, $\tan\beta = 10$, $\mu > 0$
  $M_{1/2}$ = 300, 400,…, 900 GeV





Large Hadron Collider



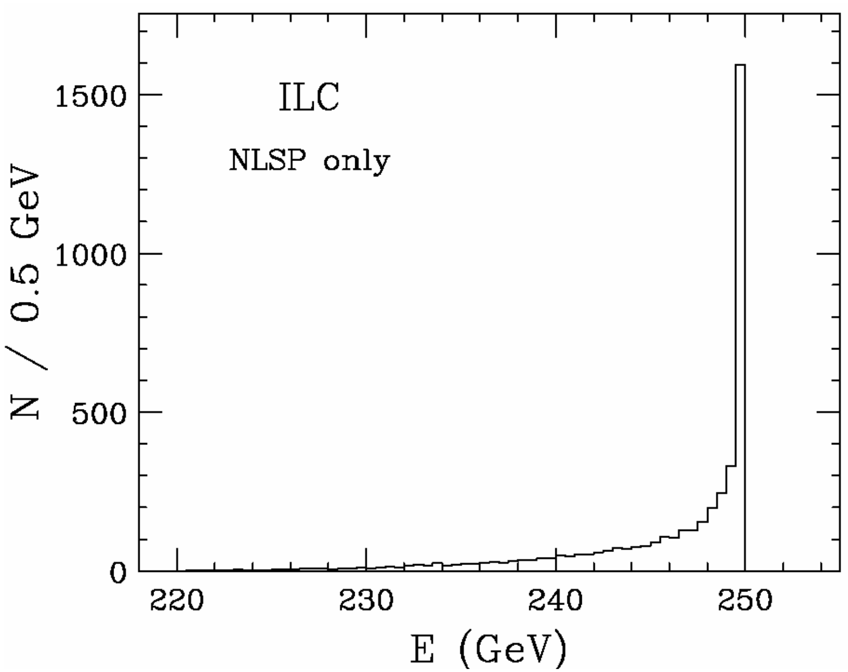


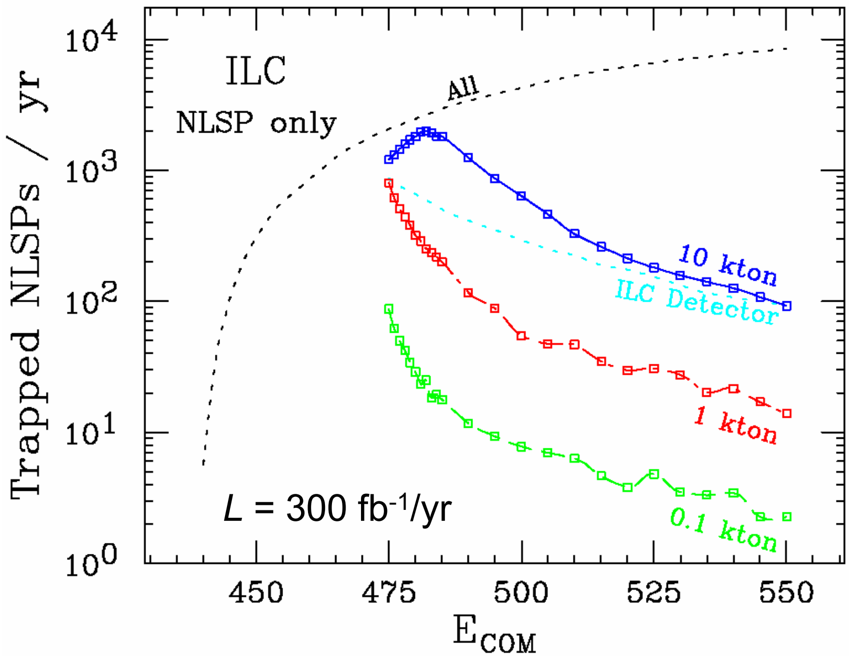
Of the sleptons produced, $O(1)$% are caught in 10 kton trap

10 to 10^4 trapped sleptons in 10 kton trap

International Linear Collider

$m_{\tilde{\tau}_R}$ 219.3 GeV } NLSP only



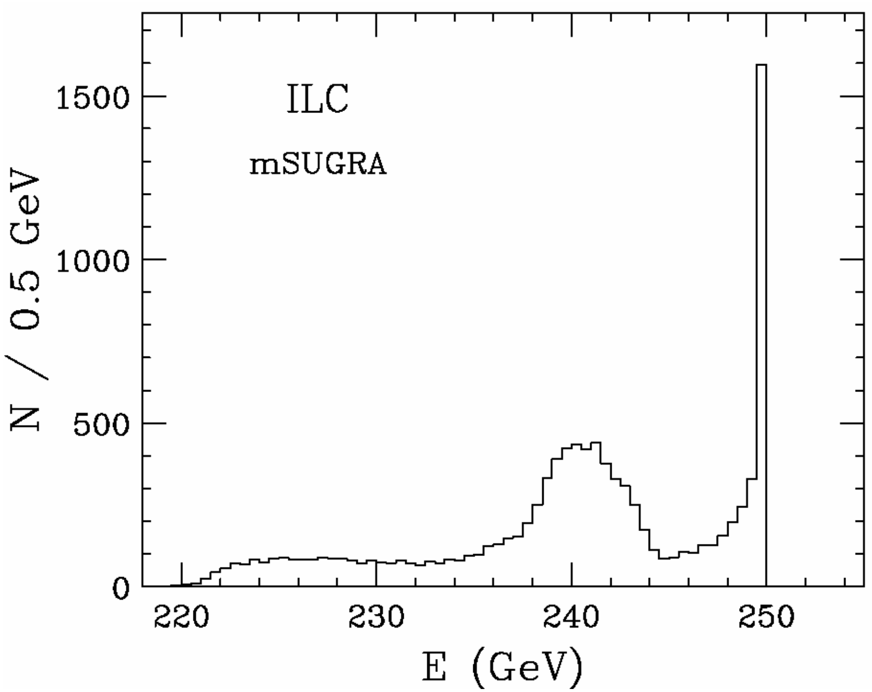


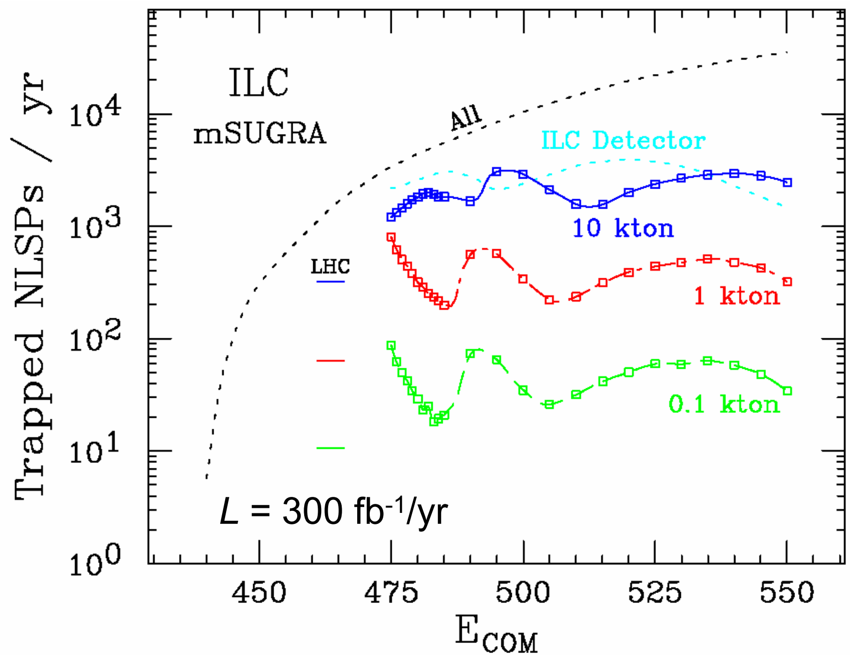
By tuning the beam energy, 75% are caught in 10 kton trap

10^3 trapped sleptons

ILC

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





Other nearby superpartners → no need to tune E_{beam}

What we learn from slepton decays

- 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
  - → BBN in the lab

- Measurement of Γ *and* E_l → $m_{\tilde{G}}$ *and* M_*
  - → Precise test of supergravity: gravitino is graviton partner
  - → Measurement of G_{Newton} on fundamental particle scale
  - → Probes gravitational interaction in particle experiment

Recent Related Work

- SuperWIMPs in universal extra dimensions
  - Feng, Rajaraman, Takayama, hep-ph/0307375
- Motivations from leptogenesis
  - Fujii, Ibe, Yanagida, hep-ph/0310142
- Impact on structure formation
  - Sigurdson, Kamionkowski, astro-ph/0311486
- Analysis in mSUGRA
  - Ellis, Olive, Santoso, Spanos, hep-ph/0312062
  - Wang, Yang, hep-ph/0405186
  - Roszkowski, de Austri, hep-ph/0408227
- Collider gravitino studies
  - Buchmuller, Hamaguchi, Ratz, Yanagida, hep-ph/0402179
  - Hamaguchi, Kuno, Nakaya, Nojiri, hep-ph/0409248

Summary

	WIMPs	superWIMPs
Well-motivated stable particle?	Yes	Yes
Naturally correct relic density?	Yes	Yes
Detection promising?	Yes	Yes ^{7}Li signal

SuperWIMPs – a new class of particle dark matter with novel implications