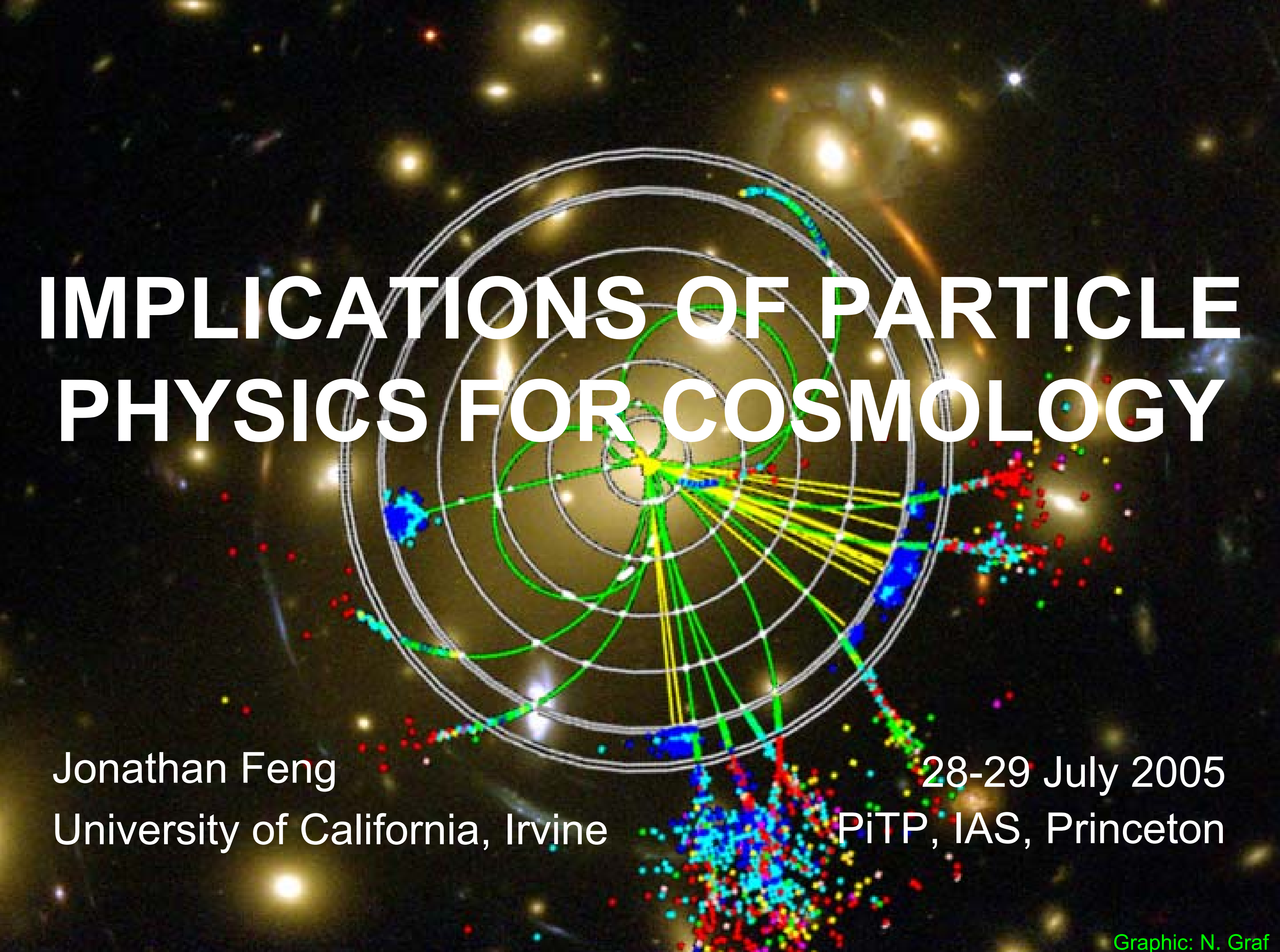

IMPLICATIONS OF PARTICLE PHYSICS FOR COSMOLOGY

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28-29 July 2005
PiTP, IAS, Princeton

Graphic: N. Graf

OUTLINE

LECTURE 1

The Universe Observed, WIMP Cosmology

LECTURE 2

WIMP Detection, WIMPs at Colliders

LECTURE 3

Gravitino Cosmology, SuperWIMPs at Colliders

GRAVITINO COSMOLOGY

- Let's consider a dark matter candidate with completely different, but equally rich, implications for particle physics and cosmology.

- There is one other class of particles with all the virtues of WIMPs: SuperWIMPs
  - Well-motivated stable particle
  - Present in "½" of parameter space
  - Naturally correct relic density

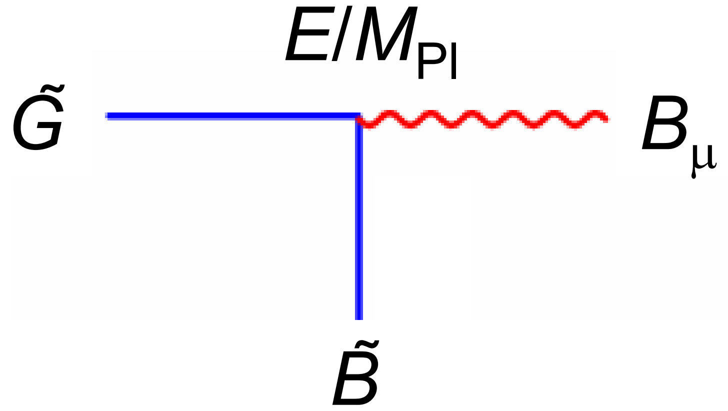
- …and more
  - Spectacular collider signals
  - There is already cosmological evidence for it (BBN, small scale structure, …)

The prototypical superWIMP is the gravitino (also axinos, quintessino, other similar candidates)

Gravitinos

- SUSY: graviton $G \rightarrow$ gravitino $\tilde{G}$
- Mass: expect ~ 100 GeV – 1 TeV (high-scale SUSY breaking)
- $\tilde{G}$ interactions: $$-\frac{i}{8M_{\rm Pl}}\bar{\tilde{G}}_\mu\left[\gamma^\nu,\gamma^\rho\right]\gamma^\mu\tilde{B}F_{\nu\rho}$$

Couplings grow with energy, but are typically extremely weak



GRAVITINOS: THE FIRST SUSY DM

Pagels, Primack (1982)
Weinberg (1982)
Krauss (1983)
Nanopoulos, Olive, Srednicki (1983)

Khlopov, Linde (1984)
Moroi, Murayama, Yamaguchi (1993)
Bolz, Buchmuller, Plumacher (1998)
…

- Original ideas: If the universe cools from $T \sim M_{\rm Pl}$, gravitinos decouple while relativistic, expect $n_{\tilde{G}} \sim n_{\rm eq}$.
- Stable:

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

(cf. neutrinos)

Pagels, Primack (1982)

- Unstable:

$$\tau_{\tilde{G}} \sim \frac{M_{\rm Pl}^2}{m_{\tilde{G}}^3} \sim 1 \text{ yr} \left[\frac{100 \text{ GeV}}{m_{\tilde{G}}}\right]^3$$

BBN → $m_{\tilde{G}}$ > 10-100 TeV

Weinberg (1982)

Both inconsistent with TeV mass range.

Gravitino Production: Reheating

- More modern view: gravitino density is diluted by inflation.

- But gravitinos regenerated in reheating. What happens?

$$\sigma_{\rm SM} n \sim T \gg H \sim \frac{T^2}{M_{\rm Pl}} \gg \sigma_{\tilde{G}} n \sim \frac{T^3}{M_{\rm Pl}^2}$$

SM interaction rate >> expansion rate >> $\tilde{G}$ interaction rate

- Thermal bath of SM particles: occasionally they interact to produce a gravitino: $f\, f \rightarrow f\, \tilde{G}$

Gravitino Production: Reheating

- The Boltzmann equation:

$$\frac{dn}{dt} = \underbrace{-3Hn}_{\text{Dilution from expansion}} - \langle \sigma v \rangle \left[\underbrace{\cancelto{0}{n^2}}_{f\tilde{G} \to f\bar{f}} - \underbrace{n_{\rm eq}^2}_{f\bar{f} \to f\tilde{G}} \right]$$

- Change variables:

$$t \to T \qquad n \to Y \equiv \frac{n}{s}$$

- New Boltzmann equation:

$$\frac{dY}{dT} = -\frac{\langle \sigma_{\tilde{G}} v \rangle}{HTs} n^2 \sim \langle \sigma_{\tilde{G}} v \rangle \frac{T^3 T^3}{T^2 T T^3}$$

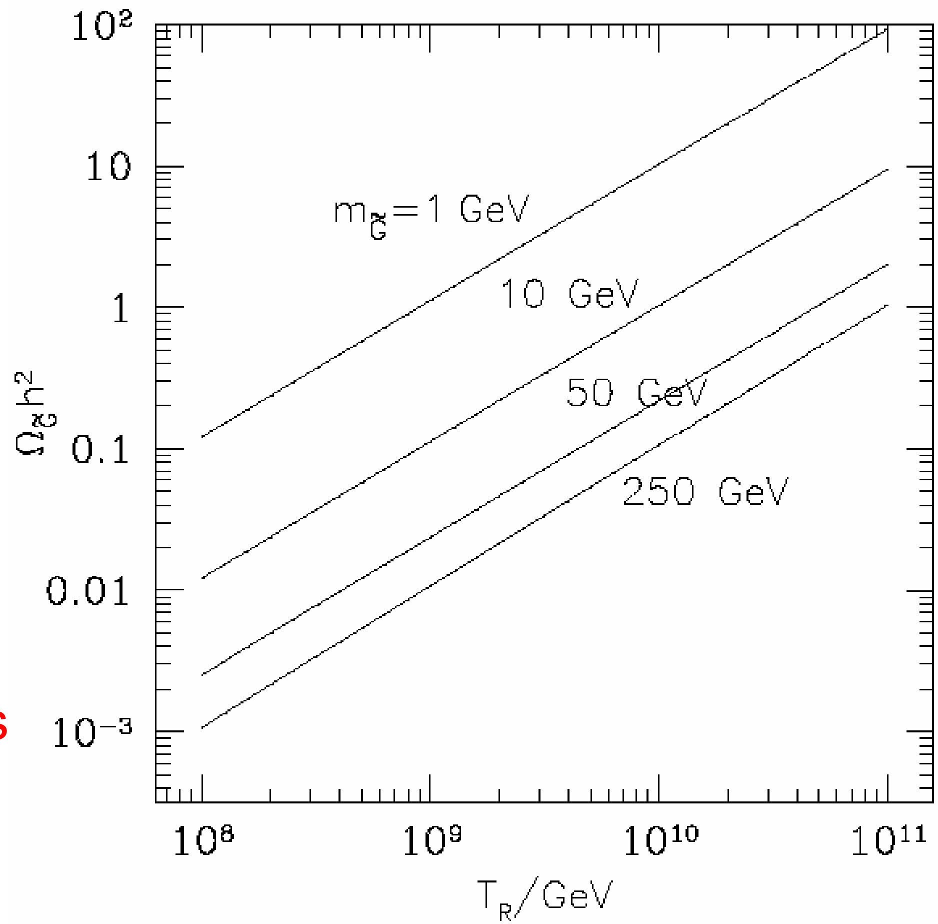
- Simple: *Y* ~ reheat temperature

Bounds on T_{RH}

- <σv> for important production processes:

	process i	$\lvert\mathcal{M}_i\rvert^2/\frac{g^2}{M^2}\left(1+\frac{m_{\tilde{g}}^2}{3m_{\tilde{G}}^2}\right)$
A	$g^a + g^b \to \tilde{g}^c + \tilde{G}$	$4(s+2t+2\frac{t^2}{s})\lvert f^{abc}\rvert^2$
B	$g^a + \tilde{g}^b \to g^c + \tilde{G}$	$-4(t+2s+2\frac{s^2}{t})\lvert f^{abc}\rvert^2$
C	$\tilde{q}_i + g^a \to q_j + \tilde{G}$	$2s\lvert T^a_{ji}\rvert^2$
D	$g^a + q_i \to \tilde{q}_j + \tilde{G}$	$-2t\lvert T^a_{ji}\rvert^2$
E	$\bar{\tilde{q}}_i + q_j \to g^a + \tilde{G}$	$-2t\lvert T^a_{ji}\rvert^2$
F	$\tilde{g}^a + \tilde{g}^b \to \tilde{g}^c + \tilde{G}$	$-8\frac{(s^2+st+t^2)^2}{st(s+t)}\lvert f^{abc}\rvert^2$
G	$q_i + \tilde{g}^a \to q_j + \tilde{G}$	$-4(s+\frac{s^2}{t})\lvert T^a_{ji}\rvert^2$
H	$\tilde{q}_i + \tilde{g}^a \to \tilde{q}_j + \tilde{G}$	$-2(t+2s+2\frac{s^2}{t})\lvert T^a_{ji}\rvert^2$
I	$q_i + \bar{q}_j \to \tilde{g}^a + \tilde{G}$	$-4(t+\frac{t^2}{s})\lvert T^a_{ji}\rvert^2$
J	$\tilde{q}_i + \bar{\tilde{q}}_j \to \tilde{g}^a + \tilde{G}$	$2(s+2t+2\frac{t^2}{s})\lvert T^a_{ji}\rvert^2$

- $T_{\text{RH}} < 10^8 - 10^{10}$ GeV; constrains inflation, leptogenesis
- $\tilde{G}$ DM if bound saturated (introduce new scale).

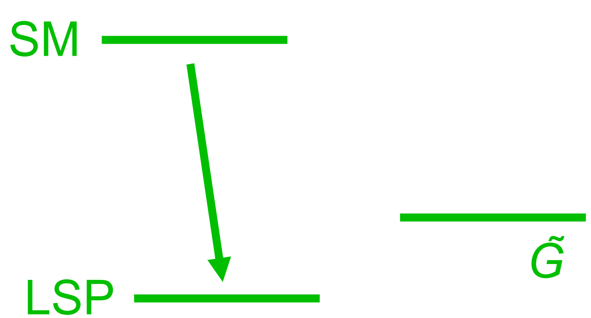


Bolz, Brandenburg, Buchmuller (2001)

Gravitino Production: Late Decay

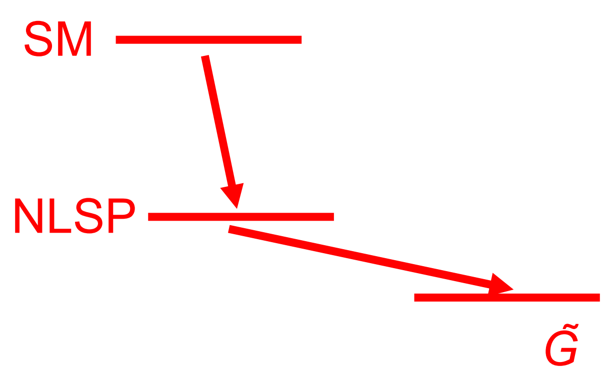
- What if gravitinos are diluted by inflation, and the universe reheats to low temperature?

- $\tilde{G}$ not LSP



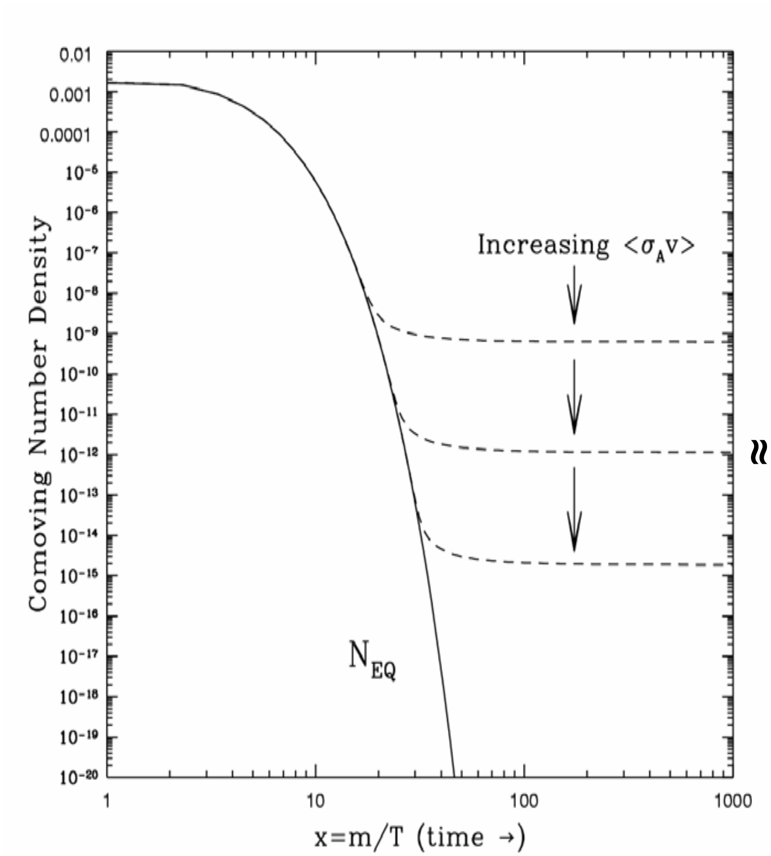
- No impact – implicit assumption of Lectures 1 and 2

- $\tilde{G}$ LSP



- A new source of gravitinos

SuperWIMPs



- Early universe behaves as usual, WIMP freezes out with desired thermal relic density
- A long time later…

$$\text{WIMP} \rightarrow \tilde{G} \qquad M_{Pl}^2/M_W^3 \sim \text{month}$$

all WIMPs decay to gravitinos

- Gravitinos inherit WIMP density, but are superweakly interacting – superWIMPs

Gravitino naturally have right relic density

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

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

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

Energy release

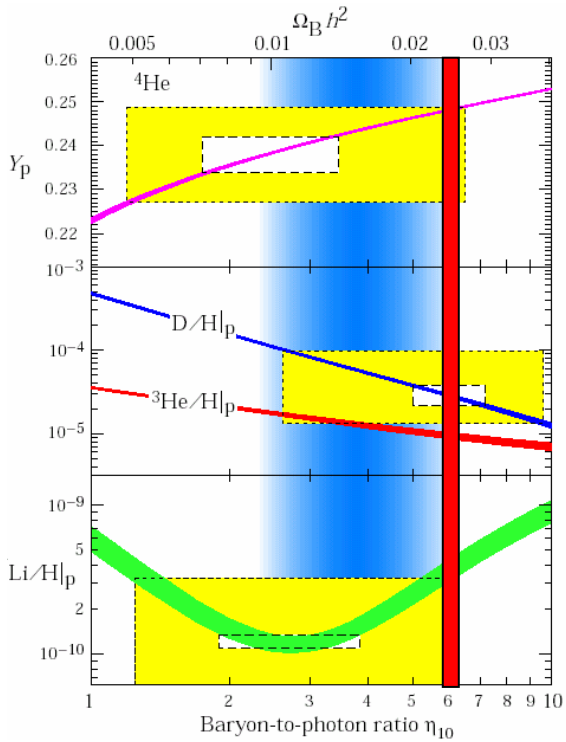
$$\zeta_i = \varepsilon_i\, B_i\, Y_{NLSP}$$

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:

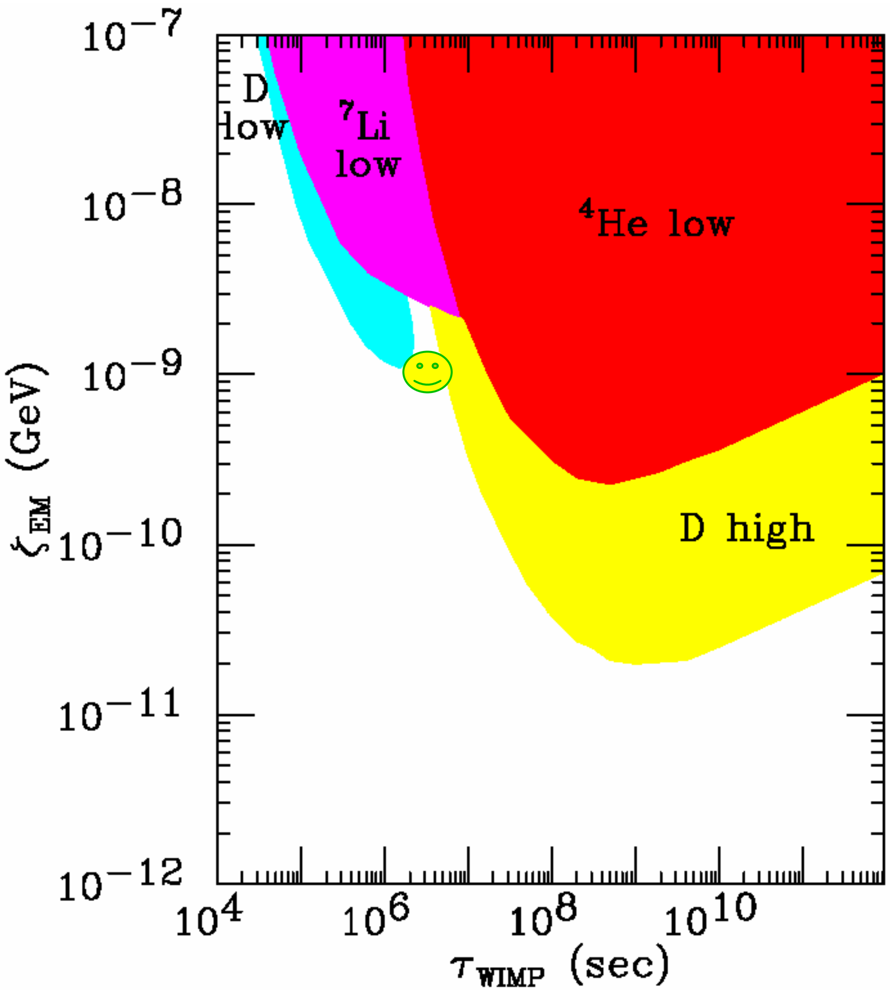
$$^7\mathrm{Li/H} = 1.5^{+0.9}_{-0.5} \times 10^{-10} \quad (95\%\ \mathrm{CL})\ [27]$$
$$^7\mathrm{Li/H} = 1.72^{+0.28}_{-0.22} \times 10^{-10} \quad (1\sigma + \mathrm{sys})\ [28]$$
$$^7\mathrm{Li/H} = 1.23^{+0.68}_{-0.32} \times 10^{-10} \quad (\mathrm{stat} + \mathrm{sys},\ 95\%\ \mathrm{CL})\ [29]$$

- ^{7}Li is now a 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)

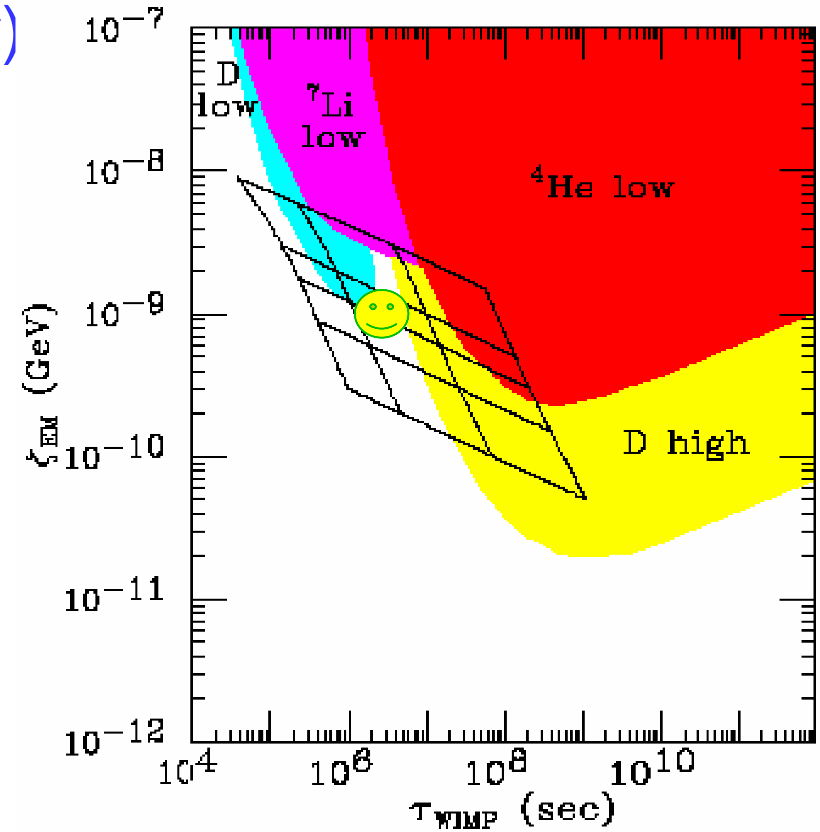
- Grid: Predictions for

  $m_{\tilde{G}}$ = 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)

- Neutralino NLSPs highly disfavored: hadrons from

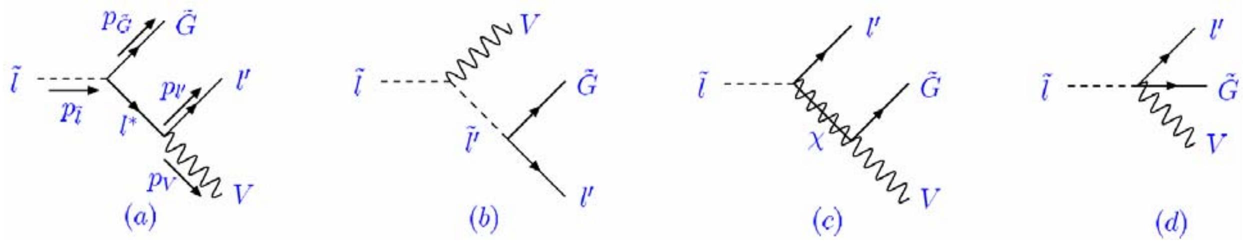
$$\chi \rightarrow Z\tilde{G},\ h\tilde{G}$$

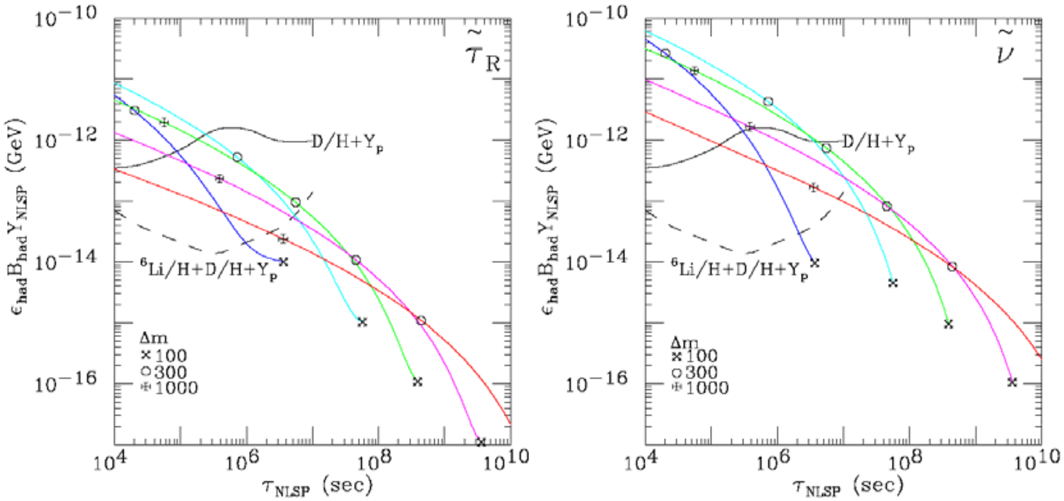
  destroy BBN. Possible ways out:
  - Kinematic suppression? No, $\Delta m < m_Z$ ➔ BBN EM violated.
  - Dynamical suppression? $\chi = \tilde{\gamma}$ ok, but unmotivated.

- For sleptons, cannot neglect subleading decays:

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

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":

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

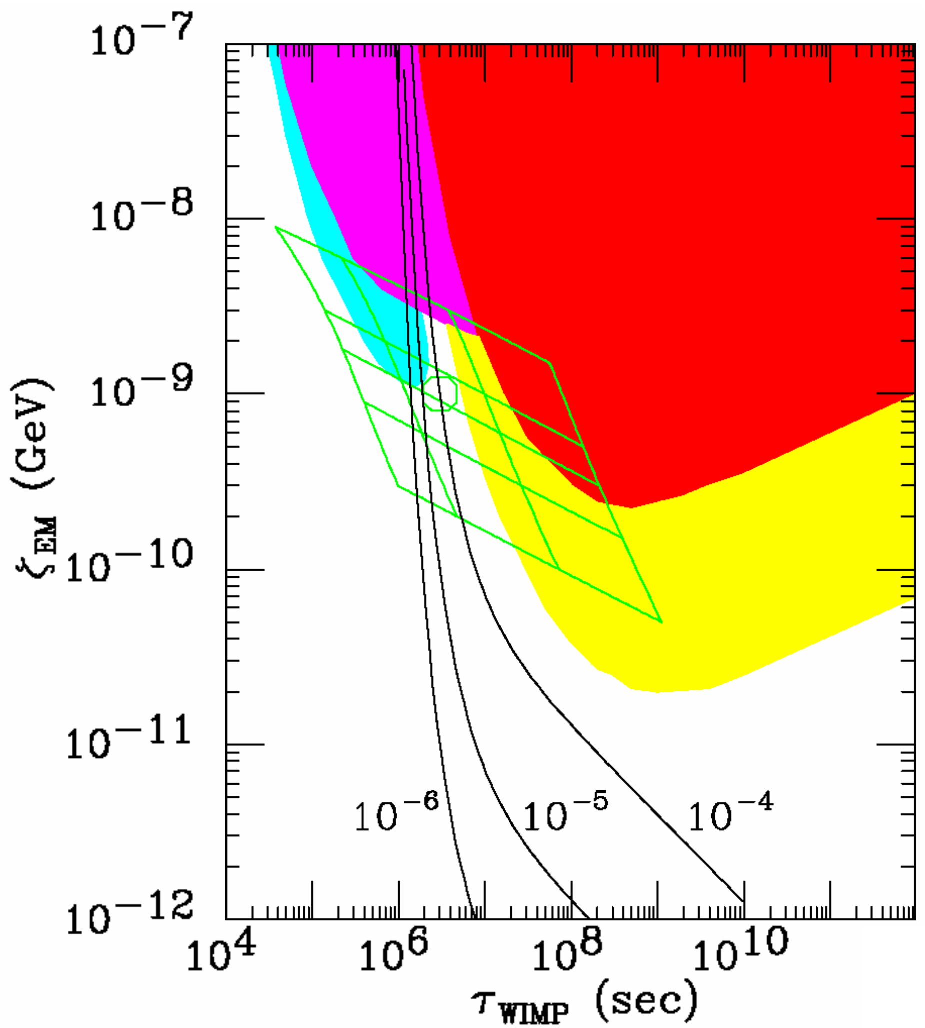
μ=0: Planckian spectrum

$\mu \neq 0$: 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)

GRAVITINOS AT COLLIDERS

- Each SUSY event may produce 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)
…

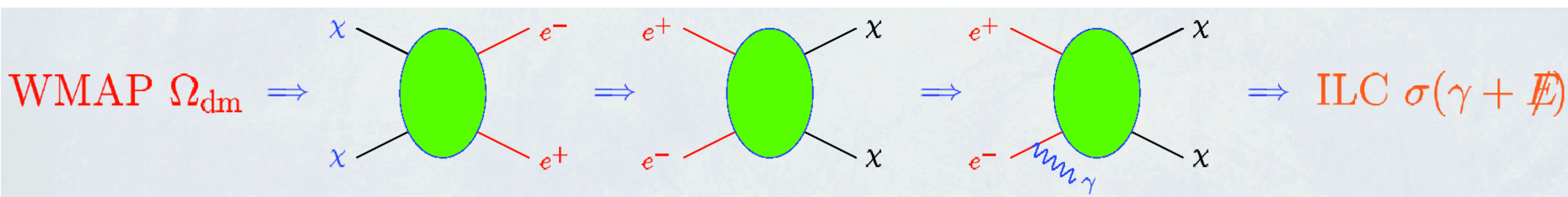
Guaranteed Rates from Cosmology

- Cosmology implies model-independent guaranteed rates for collider signals

- WIMPs

Birkedal, Matchev, Perelstein (2004)

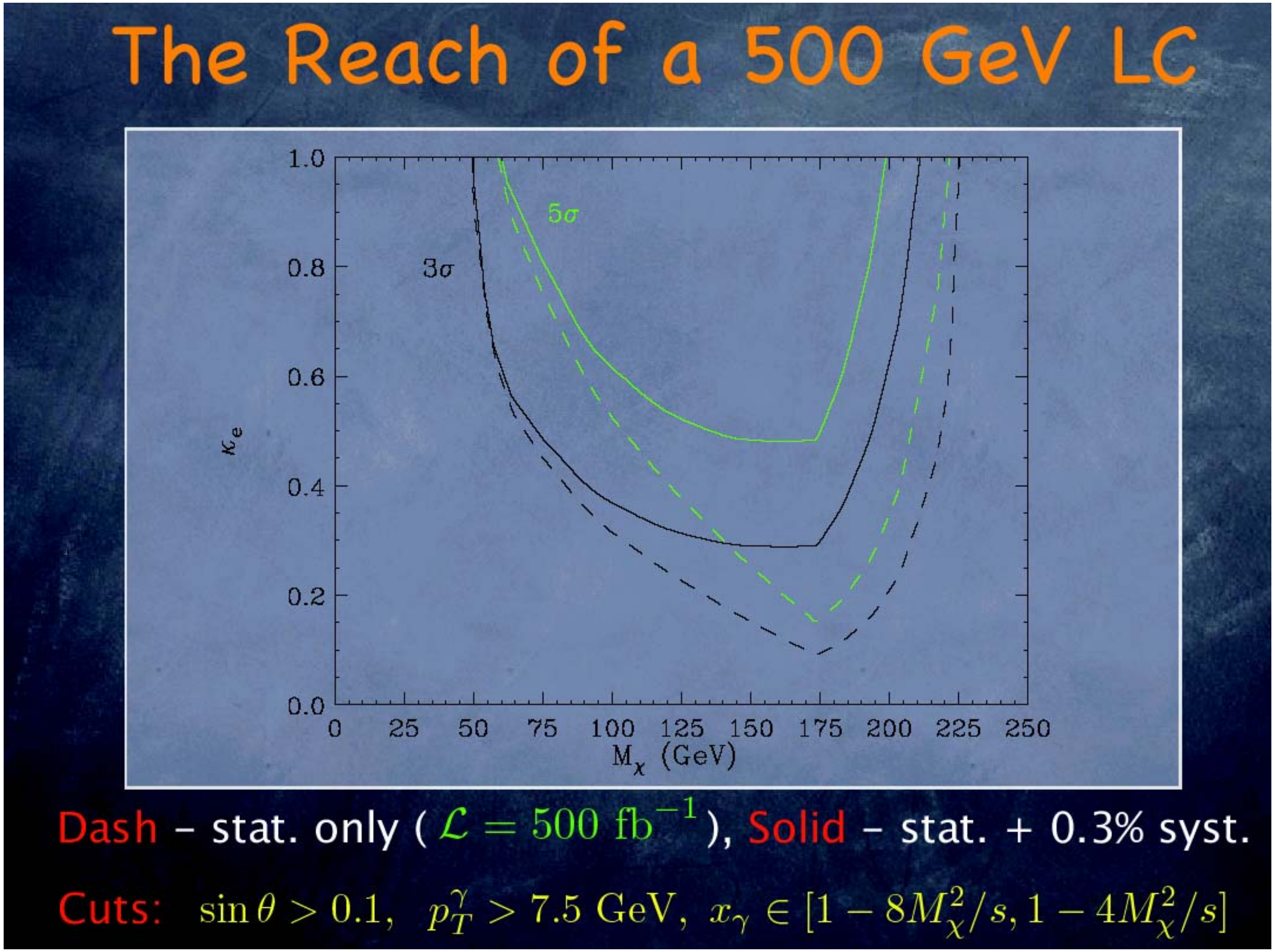
Pair production invisible → radiate jet or photon



$$\sigma(ij \to X\bar{X}; \hat{s}) = \frac{\eta_{ij} v_X^2 (2S_X+1)^2}{4(2S_i+1)(2S_j+1)} \sigma(X\bar{X} \to ij; \hat{s}) = \frac{\eta_{ij}(2S_X+1)^2}{4(2S_i+1)(2S_j+1)} \kappa_{ij} \sigma_{\rm an} v_X^{2n+1}$$

$$\kappa_{ij} = \sigma(X\bar{X} \to ij; \hat{s})/\sigma_{\rm tot}$$

WIMP guaranteed rates not promising

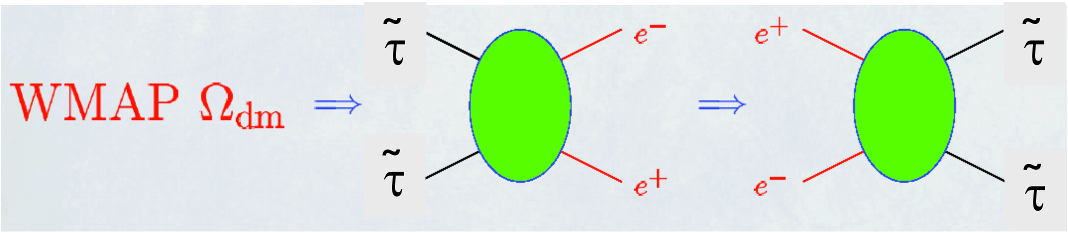


Guaranteed Rates from Cosmology

- SuperWIMPs

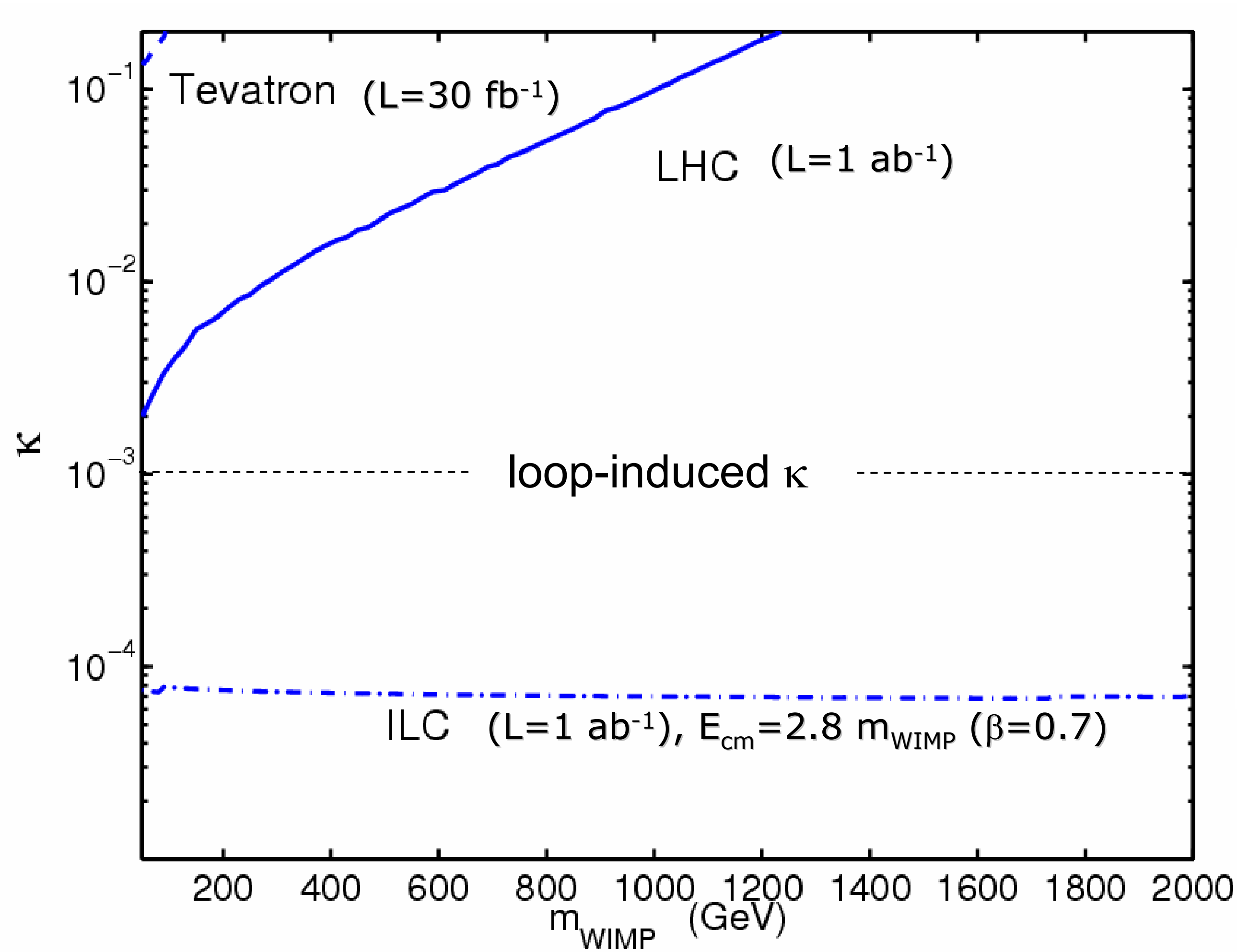
Feng, Su, Takayama (2004)

Stau pair production visible and spectacular!



LHC sensitive to many annihilation channels: u, d, s, c, b

SuperWIMP guaranteed rates much more promising



10 event discovery contours:
P-wave, $S_X=0$
$m_{SWIMP}/m_{WIMP}=0.6$

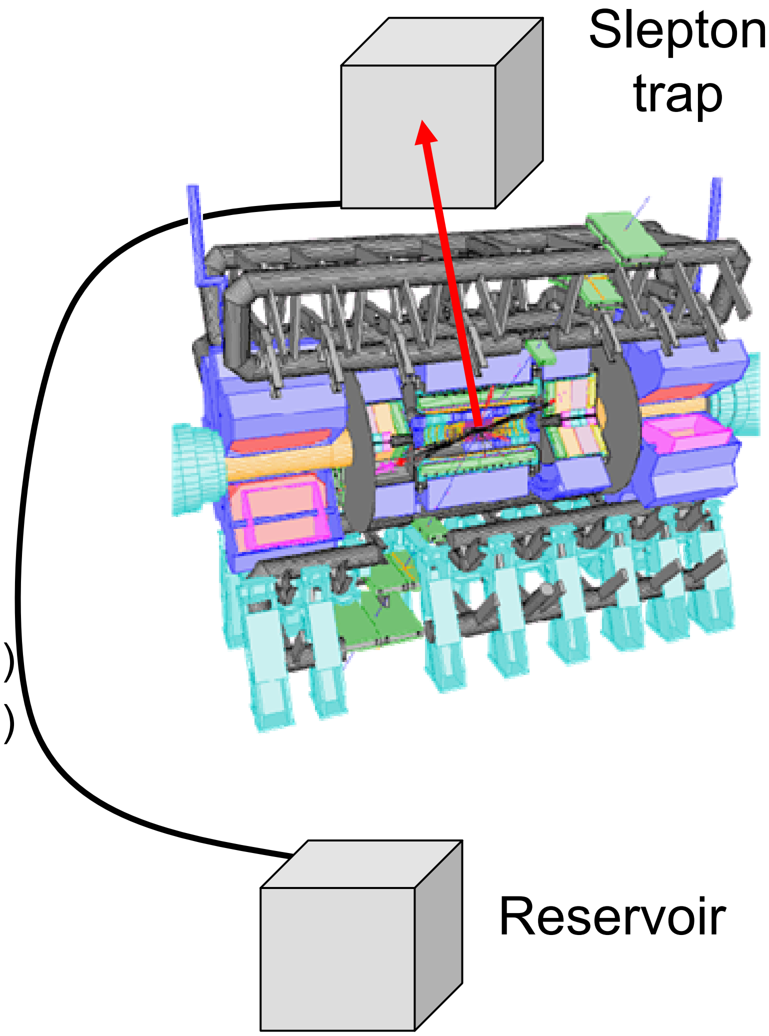
Scale as
$(2\ S_X+1)^{-2}$ and
$(m_{SWIMP}/m_{WIMP})^{-1}$

Slepton Trapping

- Cosmological constraints ➔
  - Charged slepton NLSP
  - τ_{NLSP} < year
- Sleptons can be trapped and moved to a quiet environment to study their decays

Feng, Smith (2004)
Nojiri et al. (2004)

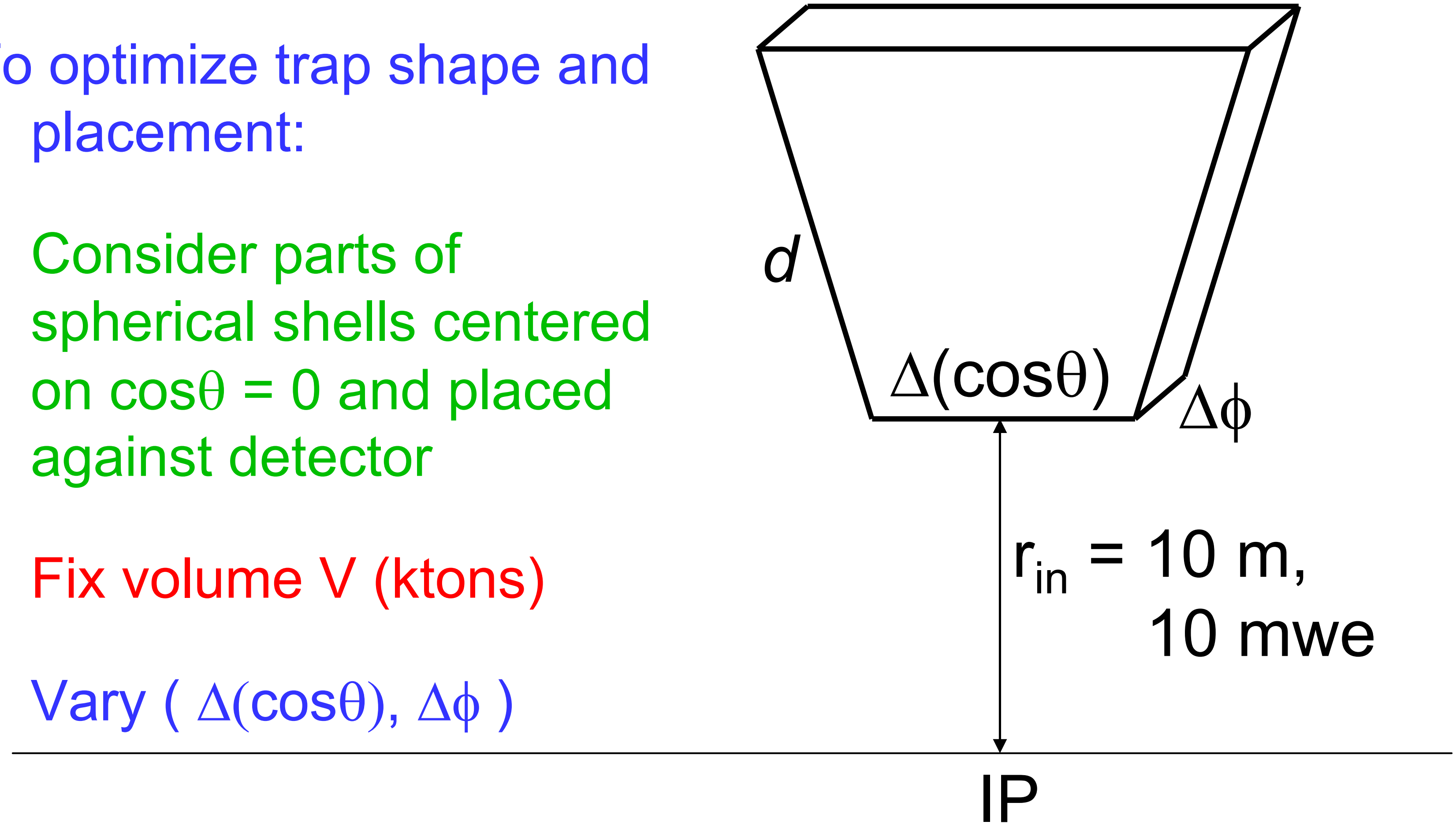
- Crucial question: how many can be trapped by a reasonably sized trap in a reasonable time?



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 ($\Delta(\cos\theta)$, $\Delta\phi$)

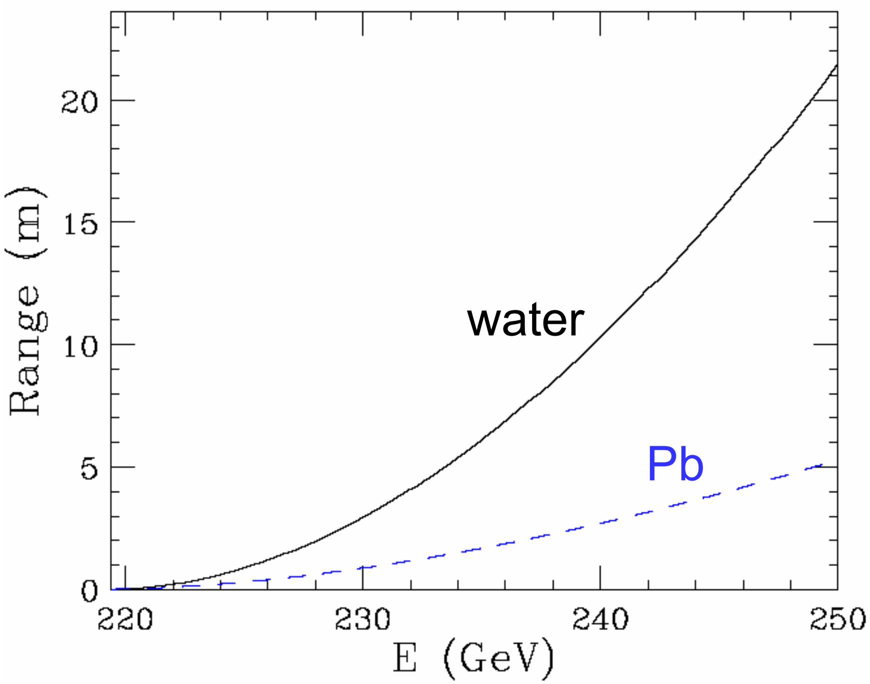


Slepton Range

- Ionization energy loss described by Bethe-Bloch equation:

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

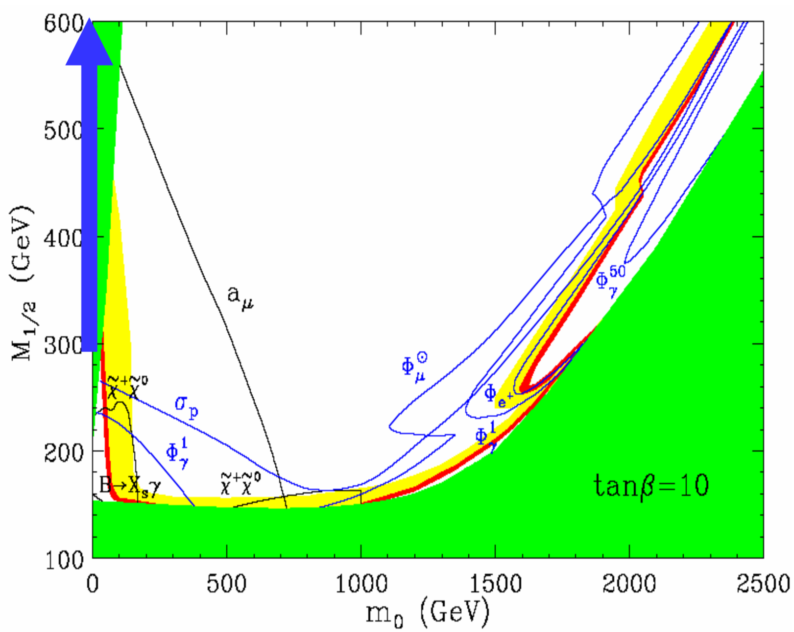
- Use "continuous slowing down approximation" down to $\beta = 0.05$

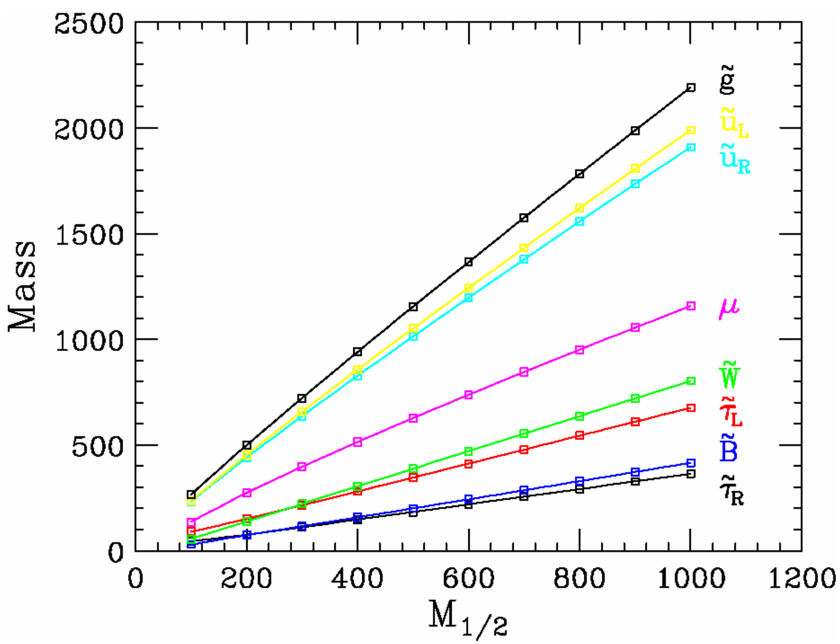


$m_{\tilde{l}}$ = 219 GeV

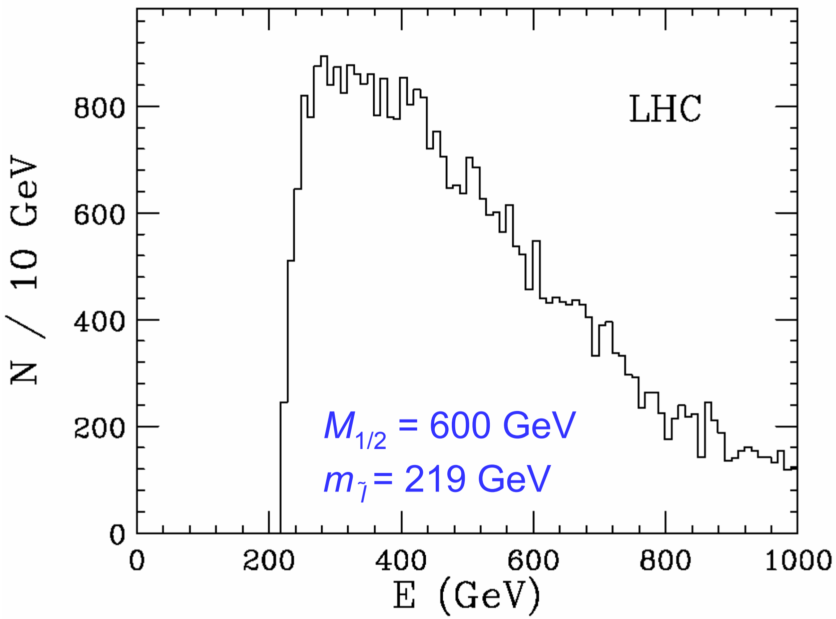
Model Framework

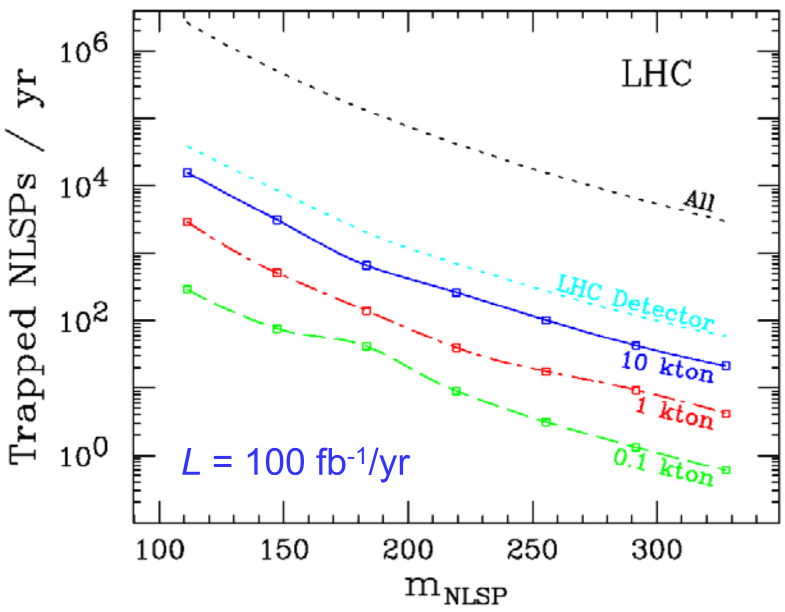
- Results depend heavily on the entire SUSY spectrum
- Consider mSUGRA with $m_0 = A_0 = 0$, $\tan\beta$ = 10, $\mu > 0$
  $M_{1/2}$ = 300, 400,…, 900 GeV





Large Hadron Collider



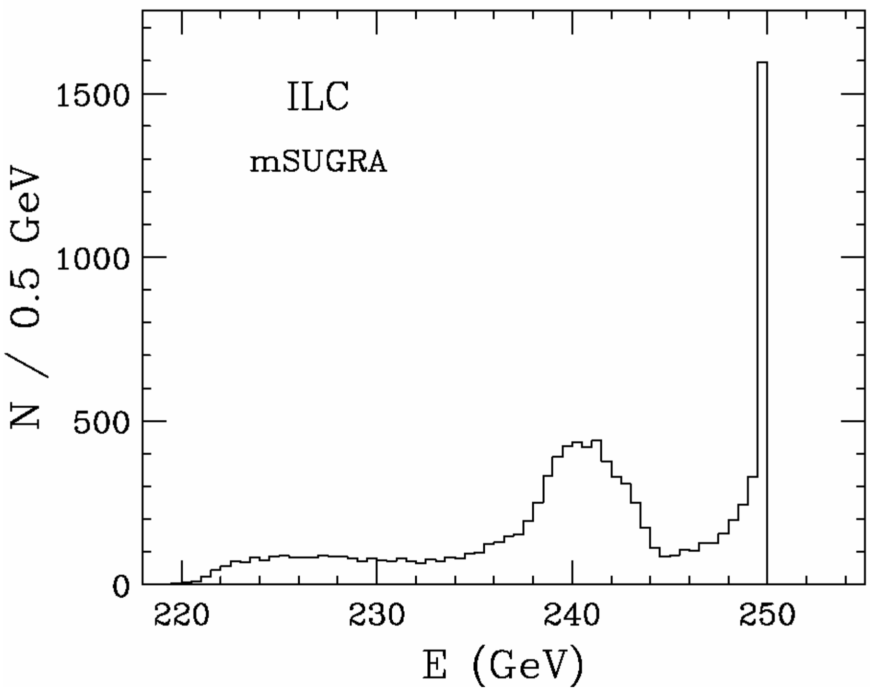


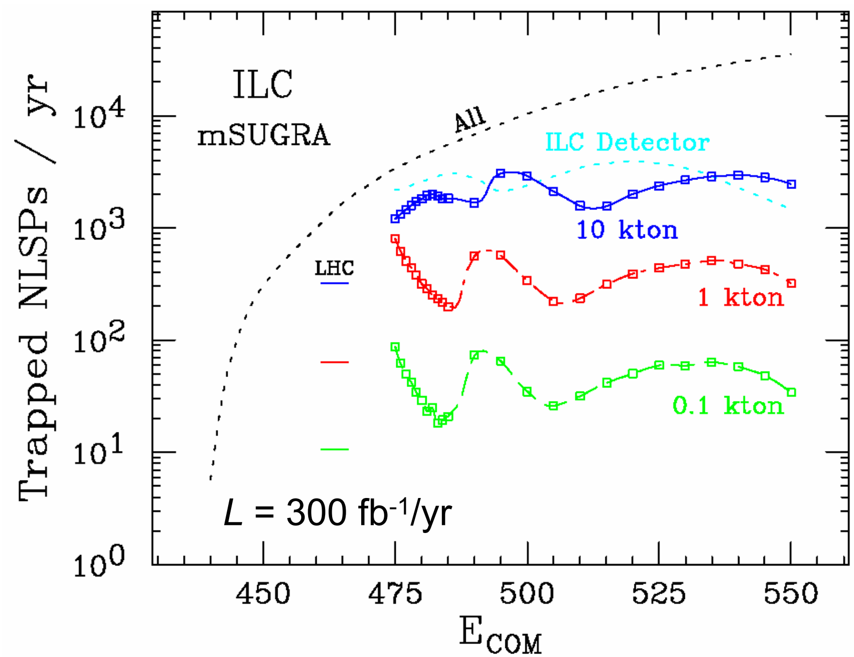
Of the sleptons produced, $O(1)$% are caught in 10 kton trap

10 to 10^4 trapped sleptons in 10 kton trap (1 m thick)

International Linear Collider

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





Sleptons are slow, most can be caught in 10 kton trap

Factor of ~10 improvement over LHC

What we learn from slepton decays

- Gravitational decays are simple:

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

- 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

LECTURE 3 SUMMARY

- There are two classes of DM candidates that naturally give the correct relic density: WIMPs and SuperWIMPs

- SuperWIMPs have spectacular, but completely different implications for cosmology, colliders

- If any of this is right, there will be a rich program of cosmology at colliders

- Is any of this right? We'll see – soon !