SUPERSYMMETRIC DARK MATTER

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Fermilab Wine & Cheese Hunt for DM Workshop
Dark Matter

- $\Omega_{DM} h^2 = 0.105 \pm 0.004$ (WMAP, SDSS)

- Best evidence for new physics
  - Unambiguous
  - Intimately connected to central problems:
    electroweak symmetry breaking and structure formation

- Theory: many compelling and new possibilities
  - Not baryonic (≠ weakly-interacting)
  - Not hot (≠ cold)
  - Not short-lived (≠ stable)

- Experiment, observation: bright prospects
  - Astroparticle physics: direct and indirect detection
  - Cosmology: halo profiles, CMB, BBN, …
  - Particle physics: Tevatron, LHC
THE “WIMP MIRACLE”

(1) Assume a new (heavy) particle $\chi$ is initially in thermal equilibrium:

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

(2) Universe cools:

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

(3) $\chi$’s “freeze out”:

$$\chi \chi \not\leftrightarrow f \bar{f}$$
• The amount of dark matter left over is inversely proportional to the annihilation cross section:
\[ \Omega_{DM} \sim <\sigma_A v>^{-1} \]

• What is the constant of proportionality?

• Impose a natural relation:
\[ \sigma_A = k\alpha^2/m^2 \], so \( \Omega_{DM} \sim m^2 \)

Remarkable “coincidence”: \( \Omega_{DM} \sim 0.1 \) for \( m \sim 0.1 – 1 \) TeV
Cosmology alone tells us we should explore the weak scale
STABILITY

• This all assumes the WIMP is stable

• How natural is this?

New Particle States

Standard Model Particles

Stable
LEP

- Large Electron Positron Collider at CERN, 1989-2000

- LEP and SLC confirmed the standard model, stringently constrained effects of new particles

- Problem: Gauge hierarchy → new particles ~100 GeV
  LEP/SLC → new particles > 3 TeV
  (even considering only flavor-, CP-, B-, and L-conserving effects)
LEP’S COSMOLOGICAL LEGACY

- Simple solution: impose a discrete parity, so all interactions require pairs of new particles. This also makes the lightest new particle stable.

  Cheng, Low (2003); Wudka (2003)

- LEP’s Cosmological Legacy:

  LEP constraints ↔ Discrete symmetry ↔ Stability

- Dark matter is easier to explain than no dark matter

- The WIMP paradigm is more natural than ever before, leading to a proliferation of candidates
EXAMPLES

• Supersymmetry
  – R-parity
  – Neutralino DM

  Goldberg (1983); Ellis et al. (1984)

• Universal Extra Dimensions
  – KK-parity
  – Kaluza-Klein DM

  Appelquist, Cheng, Dobrescu (2000)
  Servant, Tait (2002)
  Cheng, Feng, Matchev (2002)

• Branes
  – Brane-parity
  – Branons DM

  Cembranos, Dobado, Maroto (2003)

• ...

11 May 07  Feng  8
### SUSY DM CANDIDATES

<table>
<thead>
<tr>
<th>Spin</th>
<th>$U(1)$</th>
<th>$SU(2)$</th>
<th>Up-type</th>
<th>Down-type</th>
<th>$m_\nu$</th>
<th>$m_{3/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$M_1$</td>
<td>$M_2$</td>
<td>$\mu$</td>
<td>$\mu$</td>
<td></td>
<td>$G$</td>
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<tr>
<td>3/2</td>
<td></td>
<td>Neutralinos: ${\chi \equiv \chi_1, \chi_2, \chi_3, \chi_4}$</td>
<td></td>
<td></td>
<td></td>
<td>$\tilde{G}$ gravitino</td>
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<tr>
<td>1</td>
<td>$B$</td>
<td>$W^0$</td>
<td>$\mu$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/2</td>
<td>$\tilde{B}$ Bino</td>
<td>$\tilde{W}^0$ Wino</td>
<td>$\tilde{H}_u$ Higgsino</td>
<td>$\tilde{H}_d$ Higgsino</td>
<td>$\nu$</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td>$H_u$</td>
<td>$H_d$</td>
<td>$\tilde{\nu}$ sneutrino</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- $\nu$ stands for neutrino.
- $\tilde{G}$ gravitino indicates the gravitino with half integer spin.
- $\tilde{G}$ graviton indicates the graviton with integer spin.
- $m_{3/2}$ refers to the mass of the gravitino or graviton with spin $3/2$.
- $m_\nu$ refers to the mass of the neutrino.

**Additional Elements:**
- $\tilde{\nu}$ indicates a sneutrino.
- $\tilde{B}$ indicates a Bino.
- $\tilde{W}^0$ indicates a Wino.
- $\tilde{H}_u$, $\tilde{H}_d$ indicate Higgsinos.
NEUTRALINOS

- The neutralino is the classic WIMP
  - $\sim 50$ GeV – 1 TeV
  - weakly-interacting
  - Naturally the lightest standard model superpartner in many models

- So many SUSY models and parameters. Can we say anything interesting?
Neutralino Characteristics

• Neutralinos are sensitive to many processes. [→]

But there are essentially two classes:

- Fermion diagrams
  - $\chi$ are Majorana fermions:
    - Pauli exclusion $\rightarrow S = 0$
    - $L$ conservation $\rightarrow P$ wave suppression
      - $m_f/m_W$ suppression

- Gauge boson diagrams
  - Suppressed for $\chi \approx \text{Bino}$

Bottom line: annihilation is typically suppressed, $\Omega_{DM}h^2$ is typically high
Contributions to Neutralino WIMP Annihilation

Jungman, Kamionkowski, Griest (1995)
Cosmologically Preferred Supersymmetry

$\Omega_{DM} h^2$ excludes many possibilities, favors certain models

**Co-annihilation region**

**Degenerate $\chi$ and stau**

**Bulk region**

**Light sfermions**

**Focus point region**

**Mixed Neutralinos**

**A funnel region, Stop co-annihilation**

Implications for Detection

Many diverse experiments are promising
More than one required, even in the same category, to establish/explore signals
The View from 2000

TABLE I. Current and planned neutrino experiments. We list each experiment’s (expected) start date, physical dimensions (or approximate effective area), muon threshold energy $E_{\mu}^{\text{thr}}$ in GeV, and 90% CL flux limits for the Earth $\Phi_{\mu}^\oplus$ and Sun $\Phi_{\mu}^-\oplus$ in km$^{-2}$ yr$^{-1}$ for half-cone angle $\theta \approx 15^\circ$ when available.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Date</th>
<th>Dimensions</th>
<th>$E_{\mu}^{\text{thr}}$</th>
<th>$\Phi_{\mu}^\oplus$</th>
<th>$\Phi_{\mu}^-\oplus$</th>
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<tr>
<td>Baikal [65]</td>
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<tr>
<td>Kamiokande [66]</td>
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<td>Super-Kamiokande [68]</td>
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<td>Baikal NT-96 [69]</td>
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<td>AMANDA B-10 [70]</td>
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<td>IceCube [71]</td>
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</tbody>
</table>

* 2 GeV for Sun

TABLE II. Some of the current and planned $\gamma$-ray detector experiments, with sensitivity to photons in GeV. We list each experiment’s expected start date and energy range. Note: upper limits at $90\%$ CL. For details of experiments constructed in stages, see references for details.

<table>
<thead>
<tr>
<th>$E_\gamma$ Range</th>
<th>Experiment</th>
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<tbody>
<tr>
<td>0.02–30</td>
<td>EGRET</td>
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<tr>
<td>20–300</td>
<td>HEG</td>
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<tr>
<td>20–300</td>
<td>HEG</td>
</tr>
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<td>100–2000</td>
<td>HEG</td>
</tr>
<tr>
<td></td>
<td>AGILE [93]</td>
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<td></td>
<td>HESS [94]</td>
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<td></td>
<td>AMS/$\gamma$ [95]</td>
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<td></td>
<td>CANGARO</td>
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<td></td>
<td>VERITAS [96]</td>
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<td></td>
<td>GLAST [97]</td>
</tr>
</tbody>
</table>

TABLE III. Recent and planned $e^+$ detector experiments. We list each experiment’s (expected) start date, duration, geometrical acceptance in cm$^2$ sr, maximal $E_{e^+}$ sensitivity in GeV, and (expected) total number of $e^+$ detected per GeV at $E_{e^+} = 50$ and 100 GeV.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Date</th>
<th>Duration</th>
<th>Acceptance</th>
<th>$E_{e^+}^{\text{max}}$</th>
<th>$\frac{dN}{dE}$ (50)</th>
<th>$\frac{dN}{dE}$ (100)</th>
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<td>HEAT94/95 [114]</td>
<td>Balloon</td>
<td>1994/95</td>
<td>29/26 hr</td>
<td>495</td>
<td>50</td>
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<td>CAPRICE94/98 [115]</td>
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<td>18/21 hr</td>
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<td>10/30</td>
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<td>PAMELA [116]</td>
<td>Satellite</td>
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<td>3 yr</td>
<td>20</td>
<td>200</td>
<td>7</td>
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<td>AMS-02 [117]</td>
<td>Space station</td>
<td>2003-6</td>
<td>3 yr</td>
<td>6500</td>
<td>1000</td>
<td>2300</td>
<td>250</td>
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</table>

Discovered prospects “before the LHC”
A Note on Direct Detection

• Details are model-dependent, but there are general lessons to abstract from these considerations. For example:

• Direct detection
  SUSY flavor, CP problems suggest that sleptons and squarks are heavy
  $\Omega_{DM}h^2 \rightarrow$ mixed (Bino-Higgsino, focus point) neutralinos

• This conclusion
  – holds for a wide variety of models (mSUGRA, general focus point SUSY, gaugino-mediated, more minimal SUSY, 2-1 models, split SUSY, ...), constrains models that are not even cosmologically motivated
  – leads to concrete predictions
Direct Detection

$10^{-8}$ pb ($10^{-44}$ cm$^2$) is an extremely significant goal for direct detection
Future Direct Detection
NEUTRALINO PROSPECTS

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
What then?

• Cosmo/astro can’t discover SUSY

• Particle colliders can’t discover DM

Lifetime > $10^{-7}$ s $\rightarrow$ $10^{17}$ s ?
THE EXAMPLE OF BBN

- Nuclear physics $\rightarrow$ light element abundance predictions

- Compare to light element abundance observations

- Agreement $\rightarrow$ we understand the universe back to
  \[ T \sim 1 \text{ MeV} \]
  \[ t \sim 1 \text{ sec} \]
DARK MATTER ANALOGUE

• Particle physics $\rightarrow$ dark matter abundance prediction

• Compare to dark matter abundance observation

• How well can we do?
RELIC DENSITY DETERMINATIONS

% level comparison of predicted $\Omega_{\text{hep}}$ with observed $\Omega_{\text{cosmo}}$

11 May 07
IDENTIFYING DARK MATTER

Congratulations! You’ve discovered the identity of dark matter and extended our understanding of the Universe to \( T=10 \) GeV, \( t=1 \) ns (Cf. BBN at \( T=1 \) MeV, \( t=1 \) s)

Are \( \Omega_{\text{hep}} \) and \( \Omega_{\text{cosmo}} \) identical?

Yes

No

Did you make a mistake?

Yes

No

Which is bigger?

\( \Omega_{\text{cosmo}} \)

\( \Omega_{\text{hep}} \)

Calculate the new \( \Omega_{\text{hep}} \)

Can you discover another particle that contributes to DM?

Yes

No

Can you identify a source of entropy production?

Yes

No

Can this be resolved with some non-standard cosmology?

Yes

No

Does it decay?

Yes

No

Does it account for the rest of DM?

Yes

No

Think about the cosmological constant problem

Yes

No

Are you sure?

Yes

No

Can you discover another particle that contributes to DM?

Yes

No

Think about the cosmological constant problem
DIRECT DETECTION IMPLICATIONS

Comparison tells us about local dark matter density and velocity profiles

Baltz, Battaglia, Peskin, Wizansky (2006)

Green (2007)
INDIRECT DETECTION IMPLICATIONS

\[ \frac{d\Phi_\gamma}{d\Omega dE} = \sum_i \frac{dN^i_\gamma}{dE} \sigma_i v \frac{1}{4\pi m^2_\chi} \int_\psi \rho^2 dl \]

Gamma ray fluxes factorize

Particle Physics  Astro-Physics

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

• Neutralinos (and all WIMPs) are
  – Weakly-interacting
  – Cold
  – Stable

• Is this true of all DM candidates?  
  No!

• Is this true of all SUSY candidates?  
  No!

• Is this true of all SUSY candidates motivated by the  
  “WIMP miracle”?  
  No!
GRAVITINOS

- SUSY: graviton $G \rightarrow$ graviton $\tilde{G}$
- Gravitino properties
  - Spin 3/2
  - Mass: eV $\rightarrow$ 100 TeV
  - Interactions are superweak (weaker than weak)
Production Mechanisms

- Gravitinos are the original SUSY dark matter
  Pagels, Primack (1982)
  Weinberg (1982)
  Krauss (1983)
  Nanopoulos, Olive, Srednicki (1983)
  Moroi, Murayama, Yamaguchi (1993)
  Bolz, Buchmüller, Plumacher (1998)
  Baltz, Murayama (2001)
  ...

Classic ideas:

- Gravitinos have thermal relic density
  \[ \Omega_{\tilde{G}} < 1 \Rightarrow m_{\tilde{G}} < 1 \text{ keV} \]

- For DM, require a new, energy scale (and entropy production)

- 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
VIRTUES AND DRAWBACKS

• Are these acceptable scenarios?

• Strictly speaking, yes – the only required DM interactions are gravitational (much weaker than weak)

• But they are not very testable, and they aren’t motivated by the “WIMP miracle,” which strongly prefers weak interactions

Can we fix these drawbacks?
SUPERWIMPS: BASIC IDEA

Feng, Rajaraman, Takayama (2003)

Gravitino mass $\sim 100$ GeV, couplings $\sim M_W/M_{Pl} \sim 10^{-16}$

- $\tilde{G}$ not LSP

- Assumption of most of literature

- $\tilde{G}$ LSP

- Completely different cosmology and particle physics
SUPERWIMP RELICS

- Suppose gravitinos $\tilde{G}$ are the LSP
- WIMPs freeze out as usual
- But then all WIMPs decay to gravitinos after $M_{Pl}^2/M_W^3 \sim$ hours to month

Gravitinos naturally inherit the right density, but interact only gravitationally – they are superWIMPs (also axinos, KK gravitons, quintessinos, etc.)

Feng, Rajaraman, Takayama (2003); Bi, Li, Zhang (2003); Ellis, Olive, Santoso, Spanos (2003); Wang, Yang (2004); Feng, Su, Takayama (2004); Buchmuller, Hamaguchi, Ratz, Yanagida (2004); Roszkowski, Ruiz de Austri, Choi (2004); Brandenburg, Covi, Hamaguchi, Roszkowski, Steffen (2005); …
SuperWIMP Detection

• SuperWIMPs evade all direct, indirect dark matter searches.

“Dark Matter may be Undetectable”

• But cosmology is complementary: Superweak interactions $\rightarrow$ very late decays to gravitinos $\rightarrow$ observable consequences.

• Signals
  – Small scale structure
  – Big Bang nucleosynthesis
  – CMB $\mu$ distortions
SMALL SCALE STRUCTURE

- SuperWIMPs are produced in late decays with large velocity (0.1c – c)
- Suppresses small scale structure, as determined by $\lambda_{FS}$, $Q$
- Warm DM with cold DM pedigree
- SUSY does not predict only CDM; small scale structure constrains SUSY

Dalcanton, Hogan (2000)
Lin, Huang, Zhang, Brandenberger (2001)
Sigurdson, Kamionkowski (2003)
Profumo, Sigurdson, Ullio, Kamionkowski (2004)
Kaplinghat (2005)
Cembranos, Feng, Rajaraman, Takayama (2005)
Strigari, Kaplinghat, Bullock (2006)
Bringmann, Borzumati, Ullio (2006)
BIG BANG NUCLEOSYNTHESIS

Late decays may modify light element abundances

After WMAP

- $\eta_D = \eta_{CMB}$
- Independent $^7$Li measurements are all low by factor of 3:

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

Fields, Sarkar, PDG (2002)
BBN EM PREDICTIONS

- Consider $\tilde{\tau} \rightarrow \tilde{G} \tau$

- Grid: Predictions for $m_{\tilde{G}} = 100$ GeV – 3 TeV (top to bottom) $\Delta m = 600$ GeV – 100 GeV (left to right)

- Some parameter space excluded, but much survives

- SuperWIMP DM naturally explains $^7$Li!
BBN RECENT DEVELOPMENTS

• Much recent progress, results depend sensitively on what particle decays to gravitino.

• Hadronic decays are important
  – constrain $\chi \rightarrow Z \tilde{G} \rightarrow q q \tilde{G}$
  – Slepton, sneutrino decays ok

  Kawasaki, Kohri, Moroi (2004); Jedamzik (2004); Feng, Su, Takayama (2004);
  Jedamzik, Choi, Roszkowski, Ruiz de Austri (2005)

• Charged particles catalyze BBN: $^4\text{He} X^- + d \rightarrow ^6\text{Li} + X^-$
  – Constrain $\tilde{\tau} \rightarrow \tilde{G} \tau$ to lifetimes $< 10^4$ seconds
  – Neutralino, sneutrino decays ok

  Pospelov (2006); Kaplinghat, Rajaraman (2006); Kohri, Takayama (2006);
  Cyburt, Ellis, Fields, Olive, Spanos (2006); Hamaguchi, Hatsuda, Kamimura, Kino, Yanagida (2007);
  Bird, Koopmans, Pospelov (2007); Takayama (2007)
SUPERWIMPS AT COLLIDERS

• Each SUSY event may produce 2 metastable sleptons
Spectacular signature: slow, highly-ionizing charged tracks

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

Tevatron reach: $m_{\tilde{\gamma}} \sim 180$ GeV for 10 fb$^{-1}$ (now?)

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

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

Hoffman, Stuart et al. (1997)  
Acosta (2002)  
...
Slepton Trapping

• 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?

Feng, Smith (2004)
De Roeck et al. (2005)
Slepton Range

- Ionization energy loss described by Bethe-Bloch equation:

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

\[m_\gamma = 219 \text{ GeV}\]
Model Framework

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

\[ m_\chi \quad 242.9 \text{ GeV} \]
\[ m_{\tilde{e}_R}, m_{\tilde{\mu}_R} \quad 227.2 \text{ GeV} \]
\[ m_{\tilde{\tau}_R} \quad 219.3 \text{ GeV} \quad \text{NLSP only} \]
\{ mSUGRA \}

Sleptons are slow, most can be caught in 10 kton trap
Factor of \( \sim 10 \) improvement over LHC
Measuring $m_{\tilde{G}}$ and $M_*$

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

- Measurement of $\Gamma \rightarrow m_{\tilde{G}}$
  → $\Omega_{\tilde{G}}$. SuperWIMP contribution to dark matter
  → $F$. Supersymmetry breaking scale, dark energy
  → Early universe (BBN, CMB) in the lab

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

Hamaguchi et al. (2004); Takayama et al. (2004)
ARE WIMPS STABLE?

• Not necessarily. In fact, they can be decaying now:
  \[ \chi \rightarrow \gamma \tilde{G} \]

• Signals in the diffuse photon flux, completely determined by 1 parameter:
  \[
  \tau \approx \frac{3\pi}{b\cos^2\theta_W} \left(\frac{M_p^2}{(\Delta m)^3}\right) \approx \frac{4.7 \times 10^{22}}{b} \left[\frac{\text{MeV}}{\Delta m}\right]^3
  \]
CONCLUSIONS

• Weak-scale DM has never been more motivated
  – Cosmological legacy of LEP: stability of a new particle is common feature of viable particle models

• SUSY provides many well-motivated, and qualitatively different, candidates
  – WIMPs and superWIMPs
  – Cold and warm
  – Stable and metastable

• If anything mentioned here is correct, life will be very interesting in the coming years