SuperWIMP Dark Matter

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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
  - $\chi$ is typically the lightest supersymmetric particle (LSP), and so stable (in R-parity conserving supergravity)
II. Natural Relic Density

1) Initially, neutralinos $\chi$ are in thermal equilibrium:

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

2) Universe cools:

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

3) $\chi$'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

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

No-Lose Theorem
Illustration: mSUGRA

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

<table>
<thead>
<tr>
<th>Observable</th>
<th>Type</th>
<th>Sensitivity</th>
<th>Experiment(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^\pm \chi^0$</td>
<td>Collider</td>
<td>See Ref. [5]</td>
<td>Taeatron, CDF, D0</td>
</tr>
<tr>
<td>$B \to X,\gamma$</td>
<td>Low energy</td>
<td>$</td>
<td>\Delta B(B \to X,\gamma)</td>
</tr>
<tr>
<td>Muon MDM</td>
<td>Low energy</td>
<td>$</td>
<td>a_{\mu}^{\text{SM}} - a_\mu^\chi</td>
</tr>
<tr>
<td>$\sigma_{\text{DD}}$</td>
<td>Direct DM</td>
<td>$\sim 10^{-8}$ pb (See Ref [5])</td>
<td>CDMS, CRESST, GENIUS</td>
</tr>
<tr>
<td>$\nu$ from Earth</td>
<td>Indirect DM</td>
<td>$\phi_\nu &lt; 100$ km$^{-2}$ yr$^{-1}$</td>
<td>Amanda, Nestor, Aantes</td>
</tr>
<tr>
<td>$\nu$ from Sun</td>
<td>Indirect DM</td>
<td>$\phi_\nu &lt; 100$ km$^{-2}$ yr$^{-1}$</td>
<td>Amanda, Nestor, Aantes</td>
</tr>
<tr>
<td>$\gamma$ (gal center)</td>
<td>Indirect DM</td>
<td>$\phi_\gamma(1) &lt; 1.5 \times 10^{-10}$ cm$^{-2}$ s$^{-1}$</td>
<td>GLAST</td>
</tr>
<tr>
<td>$\gamma$ (gal center)</td>
<td>Indirect DM</td>
<td>$\phi_\gamma(500) &lt; 7 \times 10^{-12}$ cm$^{-2}$ s$^{-1}$</td>
<td>MAGIC</td>
</tr>
<tr>
<td>$e^+$ cosmic rays</td>
<td>Indirect DM</td>
<td>$S/B_{\text{ano}} &lt; 0.01$</td>
<td>AMS-02</td>
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</tbody>
</table>
SuperWIMPs: The Basic Idea


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

• $\tilde{G}$ not LSP
  
  ![Diagram]

  SM $\rightarrow$ LSP $\rightarrow$ $\tilde{G}$

• No impact – assumption of most of literature

• $\tilde{G}$ LSP

  ![Diagram]

  SM $\rightarrow$ NLSP $\rightarrow$ $\tilde{G}$

• Qualitatively different cosmology
• Assume gravitino is LSP. Early universe behaves as usual, WIMP freezes out with desired thermal relic density.

$\tilde{G}$

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)

  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

  \[ T_{RH} < 10^{10} \text{ GeV} \]

- 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
  \[ \tilde{\tau} \rightarrow \tilde{G} \tau, \quad \tilde{B} \rightarrow \tilde{G} \gamma \]
  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**

\[
\Gamma(\ell \rightarrow \ell \tilde{G}) = \frac{1}{48\pi M^2} \frac{m^5}{m_G^2} \left[ 1 - \frac{m_G^2}{m^2}\right]^4
\]

\[
\Gamma(\tilde{B} \rightarrow \gamma \tilde{G}) = \frac{\cos^2 \theta_W m_B^5}{48\pi M^2 m_G^2} \left[ 1 - \frac{m_G^2}{m^2}\right]^3 \left[ 1 + 3 \frac{m_G^2}{m_B^2}\right]
\]

In the limit \( \Delta m \ll m_G \),

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

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

- **Energy release**

\[
\zeta_i = \epsilon_i B_i Y_{NLSP}
\]

\( i = \text{EM, had} \)

\( \epsilon_i = \text{energy released in each decay} \)

\( B_i = \text{branching fraction} \)

\( Y_{NLSP} = n_{NLSP} / n_{BG} \)

\( \Omega_{\tilde{G}} = \Omega_{DM} \Rightarrow (m_{\tilde{G}}, \Delta m) \leftrightarrow (\tau, \zeta_i) \)
Big Bang Nucleosynthesis

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

\[ \eta_D = \eta_{\text{CMB}} \]

\[ ^7\text{Li} \text{ low} \]

Fields, Sarkar, PDG (2002)

BBN EM Constraints

- NLSP = WIMP $\rightarrow$ Energy release is dominantly EM

- EM energy quickly thermalized, so BBN constrains ($\tau$, $\zeta_{EM}$)

- BBN constraints weak for early decays: hard $\gamma$, $e^-$ 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)
  $\Delta m = 600$ 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)
Given $\eta_D = \eta_{CMB}$, $^7$Li is underabundant by factor of 3-4.

**Observations:**

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

**Possible explanations:**
- Destruction in stellar cores (but no scatter?)
- Nuclear systematics (not likely)
- New physics
BBN Hadronic Constraints

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

  Kawasaki, Kohri, Moroi (2004)

• Cannot neglect subleading hadronic decays:

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

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

• 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

- $\eta_D$ and $\eta_{CMB}$ measure same thing, but at different times
  
  Kaplinghat, Turner (2001)

- $\eta_D = \eta_{CMB}$ constrains entropy production:
  
  $\frac{\eta_f}{\eta_i} = \frac{S_i}{S_f}$

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

- 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 "$\mu$ 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 $\rightarrow$ 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
  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

- $T_{RH} < 1 - 10$ 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:
  \[
  \{ m_0, M_{1/2}, A_0, \tan\beta, \text{sgn}(\mu), m_{3/2} \}
  \]

\(\tilde{\chi}\) not LSP
\(\Omega_{\text{LSP}} > 0.23\) excluded
\(\tilde{\tau}\) LSP excluded

\(\tilde{\chi}\) LSP ok

\(\tilde{\gamma}\) LSP ok

\(\tilde{\gamma}\) not LSP
\(\Omega_{\text{LSP}} > 0.23\) excluded
\(\tilde{\tau}\) LSP excluded

\(\tilde{\chi}\) NLSP excluded

\(\tilde{\gamma}\) NLSP excluded

\(\tilde{\gamma}\) LSP
\(\Omega_{\text{NLSP}} > 0.23\) ok
\(\tilde{\tau}\) LSP ok
Implications for SUSY Spectrum

• What are the allowed superpartner masses in the super-WIMP scenario?
  It depends...constraints bound $n_{\tilde{G}} = \Omega_{\tilde{G}} / m_{\tilde{G}}$

• If $\Omega_{\tilde{G}} = \Omega_{DM}$, $n_{\tilde{G}} \sim m^{-1}_{\tilde{G}}$, low masses excluded

• If $\Omega_{\tilde{G}} = (m_{\tilde{G}} / m_{NLSP}) \Omega_{NLSP}^{th}$, $n_{\tilde{G}} \sim m_{\tilde{G}}$, high masses excluded
\[ \Omega_{\tilde{G}} = \Omega_{DM} \]

Shaded regions excluded

Feng, Takayama, Su (2004)
\[ \Omega_{\tilde{G}} = \left( \frac{m_{\tilde{G}}}{m_{NLSP}} \right) \Omega_{NLSP}^{th} \]

Shaded regions excluded

Feng, Takayama, Su (2004)
Implications for Colliders

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

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

- Tevatron Run II reach: $\sim 150$ GeV

- LHC reach: $\sim 700$ GeV in 1 year
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 \(\sim 100\) in 100 m\(^3\) we

- At LC, can tune beam energy to produce slow sleptons
Implications for Colliders

• Recall:

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

• Measurement of \( \Gamma \rightarrow m_{\tilde{G}} \)
  \( \rightarrow \Omega_{\tilde{G}} \). SuperWIMP contribution to dark matter
  \( \rightarrow F \). Supersymmetry breaking scale, vacuum energy
  \( \rightarrow \) BBN in the lab

• Measurement of \( \Gamma \) and \( E_\ell \rightarrow m_{\tilde{G}} \) and Planck mass \( M_* \)
  \( \rightarrow \) Precise test of supergravity: gravitino is graviton partner
  \( \rightarrow \) Measurement of \( G_{\text{Newton}} \) on fundamental particle scale
  \( \rightarrow \) 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
Summary

SuperWIMPs – a new class of particle dark matter

<table>
<thead>
<tr>
<th></th>
<th>WIMPs</th>
<th>superWIMPs</th>
</tr>
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<tbody>
<tr>
<td>Well-motivated stable particle?</td>
<td>Yes</td>
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<tr>
<td>Natural relic density?</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Detection promising?</td>
<td>Yes</td>
<td>Yes (already seen?)</td>
</tr>
<tr>
<td>Years studied</td>
<td>20</td>
<td>1</td>
</tr>
</tbody>
</table>