WIMPs and superWIMPs

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SUGRA20
18 March 2003
Dark Matter

• The dawn (mid-morning?) of precision cosmology:

\[ \Omega_{\text{DM}} = 0.23 \pm 0.04 \]
\[ \Omega_{\text{total}} = 1.02 \pm 0.02 \]
\[ \Omega_{\text{baryon}} = 0.044 \pm 0.004 \]
\[ t_0 = 13.7 \pm 0.2 \text{ Gyr} \]

WMAP (2003)

• We live in interesting times:
  We know how much dark matter there is
  We have no idea what it is

• Our best evidence for new particle physics
WIMPs

- Weakly-interacting particles with weak-scale masses decouple with $\Omega_{DM} \sim 0.1$; this is remarkable [Cf. quarks with natural $\Omega_B \sim 10^{-11}$]

- Either
  - a devious coincidence,
  or
  - a strong, fundamental, and completely cosmological motivation for new physics at the electroweak scale

Jungman, Kamionkowski, Griest (1995)
SUSY WIMPs

- **Neutralinos:**
  - Depends on composition, but generally $\Omega_{\text{DM}} \sim 0.1$ in much of parameter space

- **Requirements:**
  - high supersymmetry breaking scale (supergravity)
  - $R$-parity conservation

Relic density regions (blue $0.1 < \Omega\chi h^2 < 0.3$) and gaugino-ness (%)

Feng, Matchev, Wilczek (2000)
SUSY WIMP Detection

Particle probes

Direct DM detection

Indirect DM detection

- Astrophysical and particle searches are promising: many possible DM signals before 2007

- This is generally true of WIMPs: undetectable $\rightarrow$ weak interactions $\rightarrow$ weak annihilation $\rightarrow$ too much relic density

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<table>
<thead>
<tr>
<th>Observable</th>
<th>Type</th>
<th>Sensitivity</th>
<th>Experiment(s)</th>
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</thead>
<tbody>
<tr>
<td>$\tilde{\chi}^0$</td>
<td>Collider</td>
<td>See Ref. [5]</td>
<td>Tevatron: CDF, D0</td>
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<tr>
<td>$B \rightarrow X_s \gamma$</td>
<td>Low energy</td>
<td>$</td>
<td>\Delta B(B \rightarrow X_s \gamma)</td>
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<tr>
<td>Muon MDM</td>
<td>Low energy</td>
<td>$</td>
<td>a_{\mu}^{\text{SUSY}}</td>
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<tr>
<td>$\sigma_{\text{proton}}$</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>$\Phi^0_\nu &lt; 100$ km$^{-2}$ yr$^{-1}$</td>
<td>Amanda, Nestor, Antares</td>
</tr>
<tr>
<td>$\nu$ from Sun</td>
<td>Indirect DM</td>
<td>$\Phi^0_\nu &lt; 100$ km$^{-2}$ yr$^{-1}$</td>
<td>Amanda, Nestor, Antares</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>$\Phi_\gamma(50) &lt; 7 \times 10^{-12}$ cm$^{-2}$ s$^{-1}$</td>
<td>MAGIC</td>
</tr>
<tr>
<td>$e^+$ cosmic rays</td>
<td>Indirect DM</td>
<td>$(S/B)_{\text{max}} &lt; 0.01$</td>
<td>AMS-02</td>
</tr>
</tbody>
</table>
superWIMPs

• Are neutralinos the only viable SUSY DM candidates?
  In SUGRA,
  \[ m_{3/2} \sim m_0 \sim M_{1/2} \sim \langle F \rangle / M_{Pl}, \]
  unknown \( O(1) \) coefficients determine ordering. Gravitino LSPs may be *cold* dark matter.

• If NLSP is a WIMP, the WIMP freezes out with the desired \( \Omega \), then decays much later via WIMP \( \rightarrow \) gravitino.

• Gravitino inherits the desired \( \Omega \), retains all WIMP virtues.

• **BUT:** Gravitino is superweakly-interacting, undetectable by *all* DM searches. Gravitino = *superWIMP* (also KK gravitons in UED,...)
superWIMP Lifetime

- The WIMP decay width depends only on the WIMP and gravitino masses.

- For $\Delta m \ll m$, $\tau \sim (\Delta m)^{-3}$ and is independent of the overall mass scale.

- For Bino NLSP, 

$$
\Gamma(\tilde{B} \rightarrow \tilde{G}\gamma) = \frac{\cos^2 \theta_W}{4\pi} \frac{m_{\tilde{B}}^5}{M_* M_G^2} \left[1 - \frac{m_G^2}{m_{\tilde{B}}^2}\right]^3 \left[1 + 3 \frac{m_G^2}{m_{\tilde{B}}^2}\right]
$$

$m_{\text{SWIMP}} = 0.1, 0.3, 1$ TeV (from below)

Feng, Rajaraman, Takayama (2003)
BBN

- Late decays may destroy BBN light element abundance predictions

- $\gamma$ typically quickly thermalize, BBN constrains total energy release $\zeta_X = \varepsilon_\gamma n_{SWIMP} / n_{BG}$

- Constraints are weak for early decays: universe is hot, $\gamma \gamma_{BG} \to e^+e^-$ suppresses spectrum at energies above nuclear thresholds

Cyburt, Ellis, Fields, Olive (2002)
CMB

- Late decays may also destroy black-body spectrum of CMB

- Again get weak constraints for early decays, when
  \[ e^- \gamma \rightarrow e^- \gamma \]
  \[ e^- X \rightarrow e^- X \gamma \]
  \[ e^- \gamma \rightarrow e^- \gamma \gamma \]
  are all effective

- superWIMP DM:
  \[ m_{\text{WIMP}}, m_{\text{SWIMP}} \rightarrow \tau, e^- \gamma \]
  \[ \Omega_{\text{SWIMP}} = \Omega_{\text{DM}} \rightarrow \text{abundance } Y_{\text{SWIMP}} \]
Diffuse Photon Flux

• For very late decays with small \( \Delta m \), photons do not interact

• Photons produced at earlier times have larger initial

\[ E_\gamma \sim \Delta m \]

but redshift by

\[ 1 + z \sim \tau^{2/3} \sim (\Delta m)^2 \]

and so are now softer

\( \Rightarrow \) stringent bounds on \( \Delta m < 10 \text{ GeV} \)

\( m_{\text{SWIMP}} = 1 \text{ TeV} \)

\( \Delta m = 10 \text{ GeV} \)

\( \Delta m = 1 \text{ GeV} \)

Feng, Rajaraman, Takayama (2003)
superWIMP Dark Matter

Weak-scale superWIMPs are viable CDM for natural parameters
Is it testable?

- BBN versus CMB baryometry is a powerful probe

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

but

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

Fields, Sarkar, PDG (2002)

Gravitino superWIMPs: predicted lifetime and abundance are in the range to resolve BBN tensions

Cyburt, Ellis, Fields, Olive (2002)

Feng, Rajaraman, Takayama (2003)
Conclusions

• DM guiding principles:
  – well-motivated particle physics
  – naturally correct $\Omega_{\text{DM}}$

• superWIMPs: gravitinos naturally obtain desired thermal relic density, preserve all WIMP virtues but are inaccessible to all conventional searches

• Bino NLSP: BBN, CMB signals

• Many other NLSP candidates to investigate
  Escape from the tyranny of neutralino dark matter!