SuperWIMP Dark Matter

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Based On…


• Feng, Rajaraman, Takayama, Probing Gravitational Interactions of Elementary Particles, Gen. Rel. Grav., hep-th/0405248


• Feng, Smith, Slepton Trapping at the Large Hadron and International Linear Colliders, 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 $\sim M_W$, couplings $\sim M_W/M_*$

- $G_-$ not LSP

- Assumption of most of literature

- $G_-$ LSP

- Completely different cosmology and phenomenology
• Assume $G_\text{-} \text{LSP}$, WIMP NLSP

• WIMPs freeze out as usual

• But at $t \sim M_*^2/M_W^3 \sim \text{year}$, 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 “_” of parameter space

• Naturally obtains the correct relic density:
  \[ \Omega_{G_\text{nl}} = \left( \frac{m_{G_\text{nl}}}{m_{NLSP}} \right) \Omega_{NLSP} \]
Other Mechanisms

• 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

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

• For DM, require a new, fine-tuned energy scale

• Weak scale gravitinos diluted by inflation, regenerated in reheating

  \[ \Omega_{G^{-}} < 1 \Rightarrow T_{RH} < 10^{10} \text{ GeV} \]

• For DM, require a new, fine-tuned energy scale
SuperWIMP Signals

Most likely possibilities:

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 $\tau_\ldots \tau G_\ldots, B_\ldots \gamma G_\ldots, \ldots$, have cosmological consequences

• Assuming $\Omega_{G_\ldots} = \Omega_{DM}$, signals determined by 2 parameters:

$$m_{G_\ldots}, \ m_{NLSP}$$

**Lifetime**

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

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

**Energy release**

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

i = EM, had

$$Y_{NLSP} = n_{NLSP} / n_{BG}$$
Big Bang Nucleosynthesis

Late decays may modify light element abundances

After WMAP

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

\[
\frac{^7\text{Li}}{\text{H}} = 1.5^{+0.9}_{-0.5} \times 10^{-10} \quad (95\% \text{ CL}) \quad [27]
\]

\[
\frac{^7\text{Li}}{\text{H}} = 1.72^{+0.28}_{-0.22} \times 10^{-10} \quad (1\sigma + \text{sys}) \quad [28]
\]

\[
\frac{^7\text{Li}}{\text{H}} = 1.23^{+0.68}_{-0.32} \times 10^{-10} \quad (\text{stat + sys, 95\% CL}) \quad [29]
\]

- $^7\text{Li}$ is now a serious problem

Fields, Sarkar, PDG (2002)  
Jedamzik (2004)
BBN EM Constraints

- NLSP = WIMP $\rightarrow$ Energy release is dominantly EM (even mesons decay first)

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

- 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 $\tau_\tau G_\tau$ (others similar)

• Grid: Predictions for
  $m_{G_\tau} = 100$ 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 Hadronic Constraints

- BBN constraints on hadronic energy release are severe.
  - Dimopoulos, Esmailzadeh, Hall, Starkman (1988)
  - Reno, Seckel (1988)

- For neutralino NLSPs, hadrons from
  \[ \chi \rightarrow Z\tilde{G}, h\tilde{G} \]
  destroy BBN. Possible ways out:
  - Kinematic suppression? No, \( \Delta m < m_Z \) \( \Rightarrow \) BBN EM violated.
  - Dynamical suppression? \( \chi = \gamma \) ok, but unmotivated.

- For sleptons, cannot neglect subleading decays:
  \[ \tilde{l} \rightarrow lZ\tilde{G}, \nu W\tilde{G} \quad \tilde{\nu} \rightarrow \nu Z\tilde{G}, lW\tilde{G} \]
BBN Hadronic Predictions

Despite $B_{\text{had}} \sim 10^{-5} – 10^{-3}$, hadronic constraints are leading for $\tau \sim 10^5 – 10^6$, must be included
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
  $\mu \neq 0$: 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 ($\Omega_{G_{-}} = \Omega_{DM}$)

[ If $\Omega_{G_{-}} = (m_{G_{-}}/m_{NLSP}) \Omega_{NLSP}$, 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, \text{sgn}(\mu) , m_{3/2} \}

G_ not LSP
\Omega_{\text{LSP}} > 0.23 excluded

\chi \text { LSP ok}
\tau_ \text { LSP excluded}

G_ LSP
\Omega_{\text{NLSP}} > 0.23 ok

\chi \text { NLSP excluded}
\tau_ \text { NLSP ok}
Collider Physics

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

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

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

  LHC reach: $m_{l_}\sim 700$ 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
  - $\tau_{NLSP} < \text{year}$

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

$r_{in} = 10 \text{ m}, 10 \text{ mwe}$

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

- Ionization energy loss described by Bethe-Bloch equation:

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

- Use “continuous slowing down approximation” down to \( \beta = 0.05 \)

\[ m_{\tilde{l}_-} = 219 \text{ GeV} \]
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
International Linear Collider

\[ m_{\tilde{\tau}_R} = 219.3 \text{ GeV} \text{ NLSP only} \]

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

\[ 10^3 \text{ trapped sleptons} \]
ILC

\[
\begin{align*}
m_\chi &= 242.9 \text{ GeV} \\
m_{\tilde{e}_R}, m_{\tilde{\mu}_R} &= 227.2 \text{ GeV} \\
m_{\tilde{\tau}_R} &= 219.3 \text{ GeV}
\end{align*}
\]

\{ m_{\text{SUGRA}} \}

\{ \text{NLSP only} \}

Other nearby superpartners \(\rightarrow\) no need to tune \(E_{\text{beam}}\)
What we learn from slepton decays

• Recall:

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

• Measurement of \( \Gamma \rightarrow m_{G_-} \)
  \( \rightarrow \Omega_{G_-} \). SuperWIMP contribution to dark matter
  \( \rightarrow F \). Supersymmetry breaking scale
  \( \rightarrow \) BBN in the lab

• Measurement of \( \Gamma \) and \( E_{\ell} \rightarrow m_{G_-} \) and \( M_\ast \)
  \( \rightarrow \) 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
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
SuperWIMPs – a new class of particle dark matter with completely novel implications