Dark Matter: Theory and Phenomenology

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What kind of particle?

What is the mass? What is the spin? What is the associated Model

Can it be observed at the Colliders? How about direct and Indirect detection experiments?

Do we have more components?

Is it thermal or non-thermal in nature?

Is there a correlation between the DM content and Baryon content? --- Coincidence problem
Now

Current Status

We have results from the LHC, Direct and Indirect detection experiments

→ What have we learnt? What is the current status of the DM explanations?

→ How much more do we expect in the near future at the 8 TeV LHC, Direct and Indirect detection?

Are we closing in?
Outline

(i) Thermal dark matter and SUSY

(ii) LHC status of SUSY

(iii) Models with larger annihilation cross-section ➔ Under-abundance: Motivated? Non-thermal DM?

(iv) Non-thermal DM and benefits

(v) 8 TeV LHC and DM

(vi) Conclusion
(i) Thermal Dark Matter

Production of thermal DM:

Non-relativistic

Thermal Models:
Hubble expansion dominates over the interaction rate:

$$\langle \sigma v \rangle = 3 \times 10^{-26} \frac{cm^3}{s}$$

freeze out: $$T_f \sim \frac{m_{DM}}{20}$$

Dark Matter content: $$\Omega_{DM} \sim \frac{1}{\langle \sigma v \rangle}$$

Assuming: $$\langle \sigma v \rangle_f \sim \frac{\alpha_{\chi}^2}{m_{\chi}^2}$$

$$\alpha_{\chi} \sim O(10^{-2})$$ with $$m_{\chi} \sim O(100)$$ GeV leads to the correct relic abundance
Suitable DM candidate: Weakly Interacting Massive Particle (WIMP)

Typical in physics beyond the SM (LSP, LKP, …)

Most Common: Neutralino (SUSY Models)

Neutralino is a mixture of Wino, Higgsino and Bino

% of various components of Neutralinos: Model details
(ii) LHC status

Begin with the simplest model: mSUGRA/CMSSM

Searches for new physics with Missing Energy

\[ \tilde{\chi}_1^0 \sim 0.4m_{1/2} \]

\[ a_\mu \text{ of muon, } Br(B_s \rightarrow \mu\mu), \text{ dark matter relic density, squark mass constraint + Higgs mass constraint} \]

Is there any parameter space left? First casualty in the SUSY family?
Recent Higgs search results from Atlas and CMS indicate that $m_h$ (if it is Higgs) $\sim 125$ GeV

- in the tight MSSM window: 115-135 GeV

$$m_{\tilde{q}} \text{ (1st gen.)} \sim m_{\tilde{g}} \geq 1.4\text{TeV}$$

For heavy $m_{\tilde{q}}$, $m_{\tilde{g}} \geq 1$ TeV

- $\tilde{t}_1$ produced from $\tilde{g}$, $m_{\tilde{t}_1} \geq 700$ GeV
- $\tilde{t}_1$ produced directly, $m_{\tilde{t}_1} \geq 550$ GeV (special case)

- $\tilde{e}/\tilde{\mu}$ between 85 and 195 GeV for a 20 GeV $\tilde{\chi}_1^0$ are excluded at 95% confidence
- $\tilde{\chi}_1^{\pm}$ masses between 110 and 340 GeV are excluded at 95% CL for a $\tilde{\chi}_1^0$ of 10 GeV for $\tilde{\chi}_1^{\pm}$ decaying into $e/\mu$
(iii) Higgsino Dark Matter

LHC constraints on first generation squark mass + Higgs mass:

Natural SUSY and dark matter [Baer, Barger, Huang, Mickelson, Mustafayev and Tata’12; Gogoladze, Nasir, Shafi’12, Hall, Pinner, Ruderman,’11; Papucchi, Ruderman, Weiler’11],

Higgs mass 125 GeV & Cosmological gravitino solution [Allahverdi, Dutta, Sinha’12]

→ Higgsino dark matter
   Higgsino dark matter has larger annihilation cross-section
   Typically > 3 x 10^{-26} cm^3/sec for sub-TeV mass

Thermal underproduction of sub-TeV Higgsino

• Unnatural SUSY: Wino DM - Larger annihilation cross-section
  Arkani-Hamid, Gupta, Kapla, Weiner, Zorawsky’12 (for smaller wino mass)
$\langle \sigma_{\text{ann}} v \rangle_o$ is constrained by Fermi constraint

Gamma-rays constraints: Dwarf spheroidals, Galactic center

Hooper, Kelso, Queiroz, arXiv:1209.3015

Problem of large DM annihilation cross-section:

Large Cross-section/under production is constrained
Need for Non-Thermal DM

Question: How to obtain the correct relic abundance? 
Non-thermal dark matter, additional DM candidate

- Two component DM: Strong CP problem solved by the Peccei-Quinn mechanism in a SUSY context
  In this case, dark matter may be consisting of two particles: Axion, Higgsino

  Baer, Kraml, Lessa, Sekmen, 2010
  Baer, Barger, Huang, Mickelson, Mustafayev and Tata, ’12

- Decay of heavy scalar field (Moduli/Visible sector scalar): Non-Thermal DM Many Interesting Prospects

  Moroi, Randall,’99, Allahverdi, Dutta, Sinha,’ 10,’11,’12
  Kane, Watson, et al, ’10, ‘11
Non-Thermal DM

Dark Matter from Moduli decay:

Moduli are heavy scalar fields that acquire mass after SUSY breaking and are gravitationally coupled to matter.

The moduli decay width:

\[ \Gamma_\tau = \frac{c}{2\pi} \frac{m_\tau^3}{M_p^2} \]

- start oscillating when \( H < m_\tau \)
- dominate the Universe before decaying and reheating it

\[ T_r \sim c^{1/2} \left( \frac{m_\tau}{100\text{TeV}} \right)^{3/2} \] (5 MeV)

\[ T_r \sim \text{MeV} : \text{not allowed by BBN} \]
Dark Matter from Moduli

Moduli decay produces dilution in the yield of the decay products

- The dilution factor even from a 100 TeV moduli is huge!

\[ Y_\tau = \frac{n_\tau}{s} = \frac{3T_r}{4m_\tau} \sim c^{1/2} \left( \frac{m_\tau}{100 \text{TeV}} \right)^{1/2} \quad (5 \times 10^{-8}) \]

Any previously produced DM abundance and baryon asymmetry are also diluted away

Interesting:

- baryon abundance \( \sim 10^{-10} \),
- dark matter abundance \( 10^{-11} \) (50 GeV DM particle)
The dark matter abundance from the moduli decay

\[ \frac{n_\chi}{s} = \min \left( \frac{n_\chi}{s}, \frac{T_f}{T_r}, Y_T \text{Br}_\chi \right) \]

entropy density

\[ \Omega = \frac{\rho}{\rho_c}, \rho = mn \]

Moduli Decay + DM annihilation: Larger annihilation cross-section

Moduli Decay to DM particles: Independent of Cross-section (unless it is very large)
Baryogenesis from moduli decay

Need to produce baryon asymmetry from moduli decay

\[ W_{\text{extra}} = \lambda_{i\alpha\beta} N_\beta u^c_i X_\alpha + \lambda'_{ij\alpha} d^c_i d^c_j \bar{X}_\alpha + M_\alpha X_\alpha \bar{X}_\alpha + \frac{M_\beta}{2} N_\beta N_\beta \]

\( N \) : SM singlet; \( X, \bar{X} \) : Color triplet, hypercharge \( + \frac{4}{3} \)

\( R = +1 \): \( N \) fermions and \( X \) scalars \( \Rightarrow \) \( R \) parity conserved

Baryogenesis:

From decays of \( X, \bar{X} \) (if \( M_\alpha > M_\beta \))

Or

decays of \( N \) (if \( M_\alpha < M_\beta \))

\[ \varepsilon_\alpha = \frac{1}{24\pi} \frac{\text{Im}[(\bar{\lambda}^\dagger \lambda)_{\alpha\beta}]^2}{(\bar{\lambda}^\dagger \lambda)_{\alpha\alpha}} [3F_s(x) + F_V(x)] \]

\( \lambda \sim O(1), \)

\( \varepsilon_\alpha \sim O(0.1) \)

(iv) Benefit of Non-Thermal DM

Coincidence Problem: *Cladogenesis* ➞ Both DM abundance and Baryon asymmetry are produced from the same source

DM abundance in this model:

\[
\frac{n_\chi}{s} = Y_\tau Br_\chi
\]

- \( Y_\tau \sim 10^{-7} - 10^{-9} \)
- \( Br_\chi \): branching ratio of moduli decay to \( \chi \)
- \( \varepsilon Br_N \sim 10^{-3} \) easy to satisfy for baryogenesis

\[
\frac{n_B}{s} = Y_\tau \varepsilon Br_N \quad : \quad \varepsilon Br_N \sim 10^{-3}
\]

\[
\frac{\Omega_b}{\Omega_\chi} = \frac{1}{m_\chi} \frac{\varepsilon BR_N}{BR_\chi}
\]

\[
5 \text{GeV} \leq m_\chi \leq 500 \text{GeV}
\]

\[
Br_\chi \geq 10^{-3} \quad \text{Lower limit from the branching ratio into gauginos}
\]

No annihilation cross-section involves

Annihilation of lightest neutralinos $\rightarrow$ SM particles

Annihilation diagrams: mostly non-colored particles, e.g., sleptons, staus, charginos, neutralinos, etc.

How to produce these non-colored particles at the LHC?

1. Cascade decays of squarks and gluinos
2. Via stop squark @ 8 TeV LHC
3. Vector Boson fusion @ 8 TeV LHC
1. Via Cascade decays at the LHC

Colored particles are produced and they decay finally into the weakly interacting stable particle

The signal:

jets + leptons + t’s + W’s + Z’s + H’s + missing $E_T$
DM at the LHC

Ambitious Goal:
Final states → Masses → Model Parameters → Calculate dark matter density

\[ \widetilde{Q} \rightarrow q + l + \tilde{\chi}_1^0 \quad \widetilde{L} \rightarrow l + \tilde{\chi}_1^0 \]

\[ \tilde{\chi}_{2,3,4}^0 \rightarrow Z, h, \bar{t}l + \tilde{\chi}_1^0 \] etc.

Problem 1:
Identifying one side is very tricky!

We may not be able to solve for masses of all the sparticles in a model

Problem 2:
Not all the sparticles appear in cascade decays

⇒ Solving for the MSSM: Very difficult
Determining Dark Matter Content

**mSUGRA**

\[ \Omega h^2 = 0.23 \pm 0.13. \]

\[ L = 10 \text{ fb}^{-1} \]

\[ 50 \text{ fb}^{-1} \]

**Non Universal Higgs Model**

\[ 100 \text{ fb}^{-1} \]

**Mirage Mediation Model**

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass (GeV)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tilde{t} )</td>
<td>690</td>
<td>± 6</td>
</tr>
<tr>
<td>( \tilde{b} )</td>
<td>1002</td>
<td>± 126</td>
</tr>
<tr>
<td>( \tilde{\tau} )</td>
<td>717</td>
<td>± 10</td>
</tr>
<tr>
<td>( \tilde{q} )</td>
<td>1133</td>
<td>−132, +167</td>
</tr>
</tbody>
</table>

\[ \Omega h^2 = 0.23 \pm 0.13. \]

Determine DM content at 14 TeV LHC with high luminosity

\( \mathcal{L} \) (fb) | \( m_{1/2} \) (GeV) | \( m_{h} \) (GeV) | \( m_{h} \) (GeV) | \( A_{0} \) (GeV) | \( \tan \beta \) | \( \mu \) (GeV) | \( \Omega_{\chi_{1}^{0}} h^2 \) |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>500 ± 3</td>
<td>727 ± 10</td>
<td>366 ± 26</td>
<td>3 ± 34</td>
<td>30.5 ± 3.8</td>
<td>321 ± 25</td>
<td>0.004 ± 0.017</td>
</tr>
<tr>
<td>1000</td>
<td>500 ± 9</td>
<td>727 ± 13</td>
<td>367 ± 57</td>
<td>0 ± 73</td>
<td>30.5 ± 4.5</td>
<td>331 ± 46</td>
<td>0.088 ± 0.072</td>
</tr>
<tr>
<td>Syst.</td>
<td>±10</td>
<td>±15</td>
<td>±56</td>
<td>±66</td>
<td>±4.5</td>
<td>±48</td>
<td>±0.175</td>
</tr>
</tbody>
</table>
2. DM via Stop at 8 TeV LHC

LHC Stop pair productions up to \( \sim 600\) GeV @ 8 TeV LHC
Utilize Stop decay modes to search charginos, sleptons, neutralinos

Ex. 1 \( \tilde{\chi}_1^0 \) is mostly bino and \( \tilde{\chi}_2^0 \) is wino

\[ \tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0 \]

Stop can identified via fully hadronic or 1 lepton plus multijet final states

Ex. 2 \( \chi_{1,2}^0 \) are mostly Higgsino

Topness variable to identify stops

Ex. 3 \( \chi_1^0 \) is mostly Bino-Higgsino
Correct relic density

For lighter sleptons

\[
\begin{align*}
\tilde{t}_1 & \rightarrow t + \tilde{\chi}_2^0 \rightarrow t + l + \bar{\ell}^* \rightarrow t + l + \bar{\ell} + \tilde{\chi}_1^0, \\
\tilde{t}_1 & \rightarrow b + \tilde{\chi}_1^\pm \rightarrow t + \nu + \bar{\ell} \rightarrow t + l + \nu + \tilde{\chi}_1^0 \\
\tilde{t}_1 & \rightarrow t + \tilde{\chi}_1^0
\end{align*}
\]

Dutta, Kamon, Wang, Wu, In prep

2 jets + 2 leptons (OSSF-OSDF) + missing energy

\[ \rightarrow \text{Existence and type of DM particle, hard to calculate the DM content} \]

[Yang Bai, Cheng, Gallichio, Gu, 1203.4813; Han, Katz, Krohn, Reece, 1205.5808; Plehn, Spannowsky, Takeuchi, 1205.2696; Kaplan, Rehermann, Stolarski, 1205.5816; Dutta, Kamon, Kolev, Sinha, Wang, 1207.1893]

Grasser, Shelton, 2012
2. DM via Stop at 8 TeV LHC

Bino-Higgsino dark matter

Dilepton end-point after OSSF-OSDF including background

\[ m_{\chi_1^0} \approx 110 \text{GeV} \]
\[ m_{\chi_2^0} - m_{\chi_1^0} \approx 65 \text{GeV} \]

⇒ Correct dark matter content

Dutta, Kamon, Wang, Wu, In prep

\[ 5\sigma \ (s/\sqrt{s+B}) : \text{for lightest stop mass } \sim 600 \text{ GeV at } 30 \text{ fb}^{-1} \]
3. DM at the LHC Via VBF

Direct probes of charginos, neutralinos and sleptons

Two high $E_T$ forward jets in opposite hemispheres with large dijet invariant mass

Dutta, Gurrola, John, Kamon, Sheldon, Sinha, arXiv:1210.0964
Signal: \( \geq 2j + 2\mu, \ 2\tau + \text{miss. energy} \)

2 jets each with \( p_T > 50 \text{ GeV} \), leading \( p_T > 75 \text{ GeV} \)

\[ |\Delta\eta(j_1,j_2)| > 4.2, \ \eta_{j1}\eta_{j2} < 0, \ M_{j1j2} > 650 \text{ GeV} \]

\[ m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} = 180\text{GeV}, \ \sqrt{s} = 8 \text{ TeV}, \text{ Luminosity: 25 fb}^{-1} \]

(a) Signal: \( \geq 2j + 2\mu + \text{ missing energy} \)  
(b) Signal: \( \geq 2j + 2\tau + \text{ missing energy} \)

<table>
<thead>
<tr>
<th>VBF cuts</th>
<th>Signal</th>
<th>Z+jets</th>
<th>W+jets</th>
<th>WW</th>
<th>WZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_T &gt; 75 )</td>
<td>4.61</td>
<td>10.9</td>
<td>3.70 \times 10^3</td>
<td>0.97 \times 10^3</td>
<td>19.0</td>
</tr>
<tr>
<td>( \mu^\pm \mu^\pm ) ( (S/\sqrt{B}) )</td>
<td>0.87</td>
<td>0</td>
<td>0</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>( \mu^\pm \mu^\pm ) ( (S/\sqrt{B}) )</td>
<td>0.96</td>
<td>0.15</td>
<td>0</td>
<td>0.09</td>
<td>0.14</td>
</tr>
<tr>
<td>( (S/\sqrt{B}) )</td>
<td>4.33</td>
<td>0.27</td>
<td>5.29 \times 10^2</td>
<td>17.6</td>
<td>3.45</td>
</tr>
</tbody>
</table>

2.4\( \sigma \): \( m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} = 180\text{GeV} \)

\( \Rightarrow \) Can answer many questions:
- Is there coannihilation?
- What kind of Neutralino?
- Mass difference between neutralinos?

2.7\( \sigma \) \( (s/\sqrt{(s+B)}) \): \( m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} = 260\text{GeV} \)

VBF analysis for both 8 TeV and 14 TeV are important!
Conclusion

• Understanding the origin of DM requires a connection between the particle physics and cosmology
• Models with larger annihilation cross-sections seem to have preference.
• Non-thermal scenarios can accommodate both over and under abundance scenarios and can accommodate baryon abundance

Annihilation diagrams: mostly non-colored particles, e.g., sleptons, staus, charginos, neutralinos, etc.
  [not much constraints on their masses]
  ➔ Investigate sleptons, charginos, neutralinos etc. at the LHC
• Via Vector Boson Fusion
• Stop decay