Dark Matter Theory and Searches

Pearl Sandick
University of Utah
DM Papers (inSPIRE)

Number of Papers


Number of Papers
DM Papers (inSPIRE)

First PHENO Symposium
DM Papers (inSPIRE)

Number of Papers


COBE
Cosmic Background Explorer

first PHENO
Symposium
DM Papers (inSPIRE)

Number of Papers

0 135 245 345 450 900 1350 1800

first results from DAMA & CDMS

first PHENO Symposium

COBE Cosmic Background Explorer
DM Papers (inSPIRE)

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Number of Papers

1800
1350
900
450
0

first PHENO Symposium

first results from DAMA & CDMS

WMAP
Wilkinson Microwave Anisotropy Probe

COBE
Cosmic Background Explorer


Number of Papers
DM Papers (inSPIRE)

Number of Papers


first results from DAMA & CDMS

first PHENO Symposium
Old Results in Dark Matter

Observations

• Galactic Rotation Curves
• Cluster Dynamics (incl. collisions)
• Velocity dispersions of galaxies - dark matter extends beyond the visible matter
• Weak Gravitational Lensing (distribution of dark matter)
• CMB (+ Type 1A SNe, plus BAO) all agree on LambdaCDM
• Structure Formation

Summary

• Some explanation is necessary for observed gravitational phenomena.
• It’s largely non-relativistic (cold).
• Its abundance is $\Omega_{DM} \approx 0.26$.
• It’s stable or very long-lived.
• It’s non-baryonic (BBN+CMB, structure).
• It’s neutral (heavy isotope abundances).
If dark matter is a particle:
If dark matter is a particle:

Indirect Detection

DM → SM

New Physics

DM → SM
If dark matter is a particle:

- **Indirect Detection**
  - DM
  - SM

- **Collider Searches**
  - DM
  - SM

**New Physics**
If dark matter is a particle:

- Indirect Detection
  - DM
  - SM
- New Physics
- Direct Detection
- Collider Searches
If dark matter is a particle:
If dark matter is a particle:

- Unambiguous evidence of the particle nature of dark matter
- Connection between terrestrially-observed DM and cosmological DM
- Confirm the theory of new physics and measure dark matter’s properties
Current Situation

• Abundance of experimental data!
  ▶ “We’re exploring dark matter with unprecedented and growing precision.” -Zhen Liu

• Theoretical approaches:

  Totally Data-Driven

  ⇔

  Totally Theory-Driven
Current Situation

• Abundance of experimental data!
  ▸ “We’re exploring dark matter with unprecedented and growing precision.” -Zhen Liu

• Theoretical approaches:
  
  Totally Data-Driven

  ⇕

  Hybrid / Simplified Models

  ⇕

  Totally Theory-Driven
Effective Theories

\[ \mathcal{L} = \mathcal{L}_{SM} + i \bar{X} \gamma^\mu \partial_\mu X - M_X \bar{X} X + \sum_q \sum_{i,j} \frac{G_{qij}}{\sqrt{2}} \left[ \bar{X} \Gamma_i X \right] [\bar{q} \Gamma^j_q q] \]

- Idea: Reduce DM-SM interaction to a contact interaction.
- Universe of possible interactions is small (can enumerate)
- Utility in evaluating complementarity of detection techniques (good)
- Range of validity (careful)
Fundamental Theory

Supersymmetry
Fundamental Theory

Supersymmetry
MSSM Non-Minimal Model
Fundamental Theory

Supersymmetry

MSSM       Non-Minimal Model

Gravity Mediation     Gauge Mediation       ...       EW-Scale Inputs
Fundamental Theory

Supersymmetry

MSSM

Gravity Mediation

Gauge Mediation

mSUGRA

CMSSM

Non-Minimal Model

EW-Scale Inputs

NUHM
Fundamental Theory

- Supersymmetry
  - MSSM
    - Gravity Mediation
      - mSUGRA
    - Gauge Mediation
      - CMSSM
      - NUHM
  - Non-Minimal Model
    - "...
    - EW-Scale Inputs
      - pMSSM
      - MSSMn (n=7,9,etc.)
      - Relevant Parameters Only
Fundamental Theory

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- MSSM

Relevant Parameters Only
SUSY Dark Matter

1. **What is predicted** within the SUSY framework?
   - specific realization or more general possibilities

2. **What are the data** really **telling us**?
   - Priors on model → different interpretations

3. **When will we know** for sure?
   - Direct Dark Matter Searches
SUSY Dark Matter

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\[
\tilde{\chi}_i = N_{i1} \tilde{B} + N_{i2} \tilde{W} + N_{i3} \tilde{H}_d + N_{i4} \tilde{H}_u
\]
Dimensionality

\{m_{1/2}, m_0, A_0, \tan \beta, \text{sign}(\mu)\}
Dimensionality

- **MSSM25**
- **pMSSM**
- **NUHM2**
- **NUHM1**
- **CMSSM**
- **mSUGRA**
  \[ \{m_{1/2}, m_0, A_0, \text{sign}(\mu)\} \]
Dimensionality

MSSM25 → 25-D
pMSSM → 17-D
NUHM2 → 6-D
NUHM1 → 5-D
CMSSM → 4-D
mSUGRA → 3-D

mSUGRA
\{m_{1/2}, m_0, A_0, \text{sign} (\mu)\}

Polonyi mSUGRA

A_0 = (3 - \sqrt{3}) m_{3/2} \rightarrow \{m_{1/2}, m_0, \text{sign} (\mu)\}
Polonyi mSUGRA

\[ \frac{A_0}{m_0} = 3 - \sqrt{3}, \quad \mu > 0 \]

Ellis, Luo, Olive, Sandick (2013)
Polonyi mSUGRA

$A_0/m_0 = 3 - \sqrt{3}, \mu > 0$

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$\Omega_\chi > \Omega_{CDM}$

Ellis, Luo, Olive, Sandick (2013)
Polonyi mSUGRA

\[ \Omega \chi > \Omega_{\text{CDM}} \]

Increase dimensionality?

Ellis, Luo, Olive, Sandick (2013)
Universality Scale

• Input universality scale, $M_{\text{in}}$, assumed to be $M_{\text{GUT}}$

• Could be larger: “superGUT”

• SUSY breaking and mediation characterized by Planck or string scale

Polonsky & Pomarol (1994)
For recent analyses, see Ellis, Mustafayev, & Olive (2010, 2011)

• Could be smaller: “subGUT/GUTless”, “Mirage”, or “TGM”

Ellis, Olive, & Sandick (2006, 2007, 2008);
Ellis, Luo, Olive, & Sandick (2013)

Choi et al. (2004, 2005),
Kachru et al. (2003),
and others

Monaco et al. (2011)

• Lowest dynamical scale in the Polonyi/hidden sector where SUSY is broken, or scale of interactions that transmit breaking to observable sector
Dark Matter Abundance

1. neutralino LSP becomes Higgsino-like at low $M_{\text{in}}$

2. $m_A$ decreases with $M_{\text{in}}$ → appearance of rapid annihilation funnel

$(m_{1/2}, m_0) = (1.5 \text{ TeV}, 1.5 \text{ TeV})$
sub-GUT mSUGRA

\[ \frac{A_0}{m_0} = 3 - \sqrt{3}, \ \mu > 0, \ M_{\text{in}} = 10^{10} \text{ GeV} \]

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Ellis, Luo, Olive, Sandick (2013)
To Higher Dimensions…

• There are still viable, few-parameter models motivated by high-scale physics.

• Strength: one of these models might actually describe our Universe!

• Strength: understand how observables change in the parameter space!

• Weakness: may be missing important model classes

• Higher dimensional models more fully explore the possible combinations of observables (if sampling of the model space is adequate!).
pMSSM

Cahill-Rowley et al. (2013)

The figure shows a plot of $R \cdot \sigma_{SI}$ (pb) versus $m(\tilde{\chi}_1^0)$ (GeV). The plot includes data points that are excluded by XENON1T, survive direct detection (DD), survive indirect detection (ID), survive both DD and ID, and those that are excluded by DD but not ID.
Data-Driven SUSY

2. What are the data telling us?
   - Investigate parameter space near current constraints.
   - Dramatically different answers, depending on assumptions!

What we really know about sparticles: sleptons, charginos, and 3rd gen. squarks heavier than \( \sim 100 \) GeV, 1st/2nd gen. squarks heavier than \( \sim 1.1 \) TeV, gluino heavier than \( \sim 1 \) TeV

Other constraints: Higgs \( \sim 126 \) GeV, dark matter, rare B decays, electric dipole moments, anomalous magnetic moments

Simple model: bino-like LSP and light sleptons (everything else heavy)

- \( m_{\tilde{\chi}_1}, \ m_{\tilde{l}_1}, \ m_{\tilde{l}_2}, \ \alpha, \ \varphi \)

Fukushima, Kelso, Kumar, Sandick, & Yamamoto (in prep.)
Light Smuons Scenario ($M_1 \neq M_2$)

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Light Sleptons \((M_1 \neq M_2)\)

- Light \(\tilde{\mu}\): Possible to obey dipole moment constraints (or explain \(\Delta \alpha\)), and have thermal dark matter (for small range of \(\varphi\))

- Light \(\tilde{\tau}\): Relic abundance is the only constraint (see also Pierce, et al.; Hagiwara et al., 2013)

Fukushima, Kelso, Kumar, Sandick, & Yamamoto (in prep.)
Light Slepton: \( \boldsymbol{M_1 \neq M_2} \)

- If \( M_1 = M_2 \), dipole moments vanish, but too much dark matter.
- Light \( \tilde{e} \): Angles must be tuned to \( \alpha \lesssim 10^{-3} \) and \( \phi \lesssim 10^{-6} \), but relic abundance is too large.
- Light \( \tilde{\mu} \): Possible to obey dipole moment constraints (or explain \( \Delta a \)), and have thermal dark matter (for small range of \( \phi \)).
- Light \( \tilde{\tau} \): Relic abundance is the only constraint (see also Pierce, et al.; Hagiwara et al., 2013).

Viable scenarios with bino-like dark matter and light smuons/staus.

Fukushima, Kelso, Kumar, Sandick, & Yamamoto (in prep.)
3. When will we know for sure?
Future Prospects

• Timeline for discovery/exclusion?

Akerib et al. (LUX Collaboration), 2013
Future Prospects

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Akerib et al. (LUX Collaboration), 2013
Future Prospects

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Could answer within a low-dimensional model (not general), or within the MSSM (not conclusive).
Future Prospects

• Timeline for discovery/exclusion?

Could answer within a low-dimensional model (not general), or within the MSSM (not conclusive).

Simplified models can help you construct a definite, model-independent answer.
Resonance Models

- **Neutralino:** \( \tilde{\chi}_1^0 = \alpha \tilde{B} + \beta \tilde{W}^0 + \gamma \tilde{H}_d^0 + \delta \tilde{H}_u^0 \)

- **s-channel resonance annihilations** occur when \( 2m_{\tilde{\chi}_1^0} \approx m_{A,H,h,Z} \)

- As \( (\sigma_{\text{ann.}v}) \) increases, \( \Omega_{\tilde{\chi}_1^0} \) decreases
  - If \( \Omega_{\tilde{\chi}_1^0} \) too large, increase Higgsino content: \( \mu \)

- **Scattering with quarks** is governed by \( M_1, \mu, m_A, \tan \beta \)

- Relevant parameters:
  \[ \{ M_1, \mu, m_A, \tan \beta, M_0, A_0 \} \]
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If DM abundance is achieved through a resonance, how small could $\sigma_{SI}$ possibly be?

Hooper, Kelso, Sandick, & Xue, PRD 2013

- Relic Abundance: $\mu$
- Higgs mass: $A_0$
- Free parameters: $(m_0, M_1, m_A, \tan\beta)$

<table>
<thead>
<tr>
<th>$A_0/m_0$</th>
<th>$\Omega_{\chi h^2}$</th>
<th>$m_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.5</td>
<td>125</td>
</tr>
<tr>
<td>1.5</td>
<td>0.5</td>
<td>125</td>
</tr>
<tr>
<td>2.0</td>
<td>0.5</td>
<td>125</td>
</tr>
</tbody>
</table>

- in units of $10^{-11}$ pb
- all detectable on ~decade timescale
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If Nature is MSSM–like, and neutralino dark matter at a resonance makes up all the dark matter in the Universe, then direct detection experiments are pushing the resonance to be more and more exact.

![Graph showing variations of $\sigma_{SI}$ with $M_1$ and $m_A$ for different values of $\tan\beta$.](image)
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At this rate of progress, direct detection experiments will be able to close the $A/H/h$ funnel regions in just over a decade!
Summary

- Finite distinct ways to observe dark matter:
  - Abundance, Annihilation Today, Decay Today, Production at Colliders, Direct Detection
- A spectrum of theoretical approaches to particle dark matter
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Extra Slides
Looking Forward

• Direct dark matter searches - towards the neutrino background! and directional searches!
• Indirect dark matter searches
  • Fermi, HAWK, VERITAS, AMS-02, GAPS, CTA GAMMA-400…
• LHC - SUSY/DM discovery potential at 14 TeV
• 100 TeV Hadron Collider
• Linear Collider - ILC at 500 GeV, CLIC at 3 TeV
sub-GUT mSUGRA

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sub-GUT mSUGRA

At large $\tan \beta$,

$$\text{BR}(B_s \rightarrow \mu^+ \mu^-) \sim \tan \beta^6$$

$$A_0 \left\{ \begin{array}{ll}
\text{large enough: } m_H \approx 126 \text{ GeV} \\
\text{small enough: } \frac{\text{BR}(B_s \rightarrow \mu^+ \mu^-)}{\text{BR}(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}}} \times 10 \leq 1.5 \text{ SM value}
\end{array} \right.$$
sub-GUT mSUGRA

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Polonyi Model seems to be the sweet spot!