Development of a New Paradigm for Direct Dark Matter Detection

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(working with Dr. Kamyshkov)
Dark Matter Recap

• Evidence:
  – Galactic Rotation Curves
  – Gravitational Lensing
  – Cosmic Microwave Background
  – Collisions of galactic clusters
  – And more...
Dark Matter Recap

- Characteristics
  - Conclusively observed only indirectly by gravitational interaction with baryonic matter
  - Outnumbers baryonic matter 5 to 1
  - Important component of structure formation
  - Composed of WIMPs (weakly interacting massive particles)
  - But we don’t actually know what it is
Mirror Matter

MSSM

Supersymmetry

NMSSM

R-parity violating

Q-balls

Graviscite DM

mSUGRA

pMSSM

R-parity conserving

Dirac DM

Hidden Sector DM

Self-Interacting DM

Techni-baryons

Light Force Carriers

Dark Photon

Asymmetric DM

Warm DM

Warm DM

Sterile Neutrinos

Axion DM

QCD Axions

Axion-like Particles

Little Higgs

Extra Dimensions

Warped Extra Dimensions

UED DM

6d

5d

RS DM

Tait, Snowmass 2013
Detection Categories

• Indirect Detection
  – Interactions with standard model particles through annihilations and decays

• Accelerators
  – Search for energy and momentum violation
  – No luck yet

• Direct Detection
  – Our field
Existing Direct Detection Approach

• Dark matter is a single type of particle (LSP neutralino) which is heavy (~100 GeV/c^2) and not self-interacting
• Possibility of weak interaction with baryonic matter through unknown forces (assumed)
• Unknown parameters: M_{DM} and cross-section
• Method used:
  – Look for small recoil energy with small cross-section (large M_T)
  – Rule out background or electronic noise (atmospheric, solar, reactor, and geo neutrinos; neutrons)
  – Build detector with optimal material (M_T = M_{DM})
Present and Future of Direct DM Search

No limits established for $M_{\text{DM}} < 6 \text{ GeV}$
The Supersymmetric Dream

• No positive results in expected supersymmetric mass range from direct detection experiments

• No positive results from LHC

• Searching for heavier masses at smaller cross sections is expensive due to large detector mass

• Regardless, many research collaborations still pursue supersymmetry and are well-funded for large detectors
Experiments Claiming DM Detection

- The results say to look for the low-mass WIMP
- These experiments have low mass target nuclei and low thresholds
Dark Matter Search Results Using the Silicon Detectors of CDMS II


(CDMS Collaboration)

We report results of a search for Weakly Interacting Massive Particles (WIMPs) with the silicon detectors of the CDMS II experiment. A blind analysis of 140.2 kg-days of data revealed three WIMP-candidate events with an expected total background of 0.7 events. The probability that the known backgrounds would produce three or more events in the signal region is 5.4%. A profile likelihood ratio test of the three events that includes the measured recoil energies gives a 0.19% probability for the known-background-only hypothesis when tested against the alternative WIMP+background hypothesis. The highest likelihood occurs for a WIMP mass of 8.6 GeV/c² and WIMP-nucleon cross section of $(1.9\times10^{-41}$ cm².

Why low masses are not detectable?

\[ E_{\text{max}} = E_{\text{kin}} \cdot \frac{4M_T M_{DM}}{(M_T + M_{DM})^2} \]

For \( v_{DM} \) 250 km/s

- CDMS-Si 7 keV
- DAMA-Na 2 keV

Yuri Kamyshkov
Example Recoil Distribution

- Probability
- Recoil Energy

Threshold

\( E_{\text{max}} \)

Undetectable
Example Recoil Distribution

• For a WIMP mass of 8.5 GeV/c² and $v_{DM} = 200$ km/s, $E_{kin} = 1.89$ keV
• For a detector made of germanium ($A = 72$), $E_{max} = .81648$ keV in this case
• For a detector made of silicon ($A = 28$), $E_{max} = 1.395$ keV
• This is a 70.9% increase in $E_{max}$
Example Recoil Distribution

Probability

Recoil Energy

$E_{\text{max, Ge}}$

$E_{\text{max, Si}}$
Our Research

• There is no alternative paradigm to SUSY direct dark matter detection
• The concept of mirror matter (co-developed with Z. Berezhiani) includes:
  – Multiple species of atoms and nuclei with similar interactions as ordinary matter (self-interacting)
  – Abundances: 25% mirror hydrogen, 74% mirror helium, 1% mirror metals by mass
  – Resides in gas clouds similar to baryonic clouds in galaxy where it thermalizes because of self-interaction
  – Interacts with ordinary matter through a weak, unknown force beyond the standard model
  – Average local density of dark matter is .48 GeV/cm³
  – Nobody but us pursuing these ideas, as far as we know
Components of our Model

(Mostly) Known
• Detector mass, density, dimensions, and runtime
• Amount of events detected
• Combined motion of Earth
  – Revolution, local standard of rest, peculiar solar system motion
• Galactic escape velocity
• Average density of dark matter

Provided by model
• WIMP composition
• WIMP masses
• Local density and temperature of fast DM
• Relative speed of DM
  – Jets, debris sheets, rotation velocity, rotation angle

Unknown
• Cross-sections
• Interacting force
Characteristics:

- Mirror gas cloud temperature of 20 MK (parameter)
- Cloud is moving with velocity $\vec{V}$ (parameter) relative to solar system
- Velocity of solar system + Earth \( (\bar{V}_S = 230 \pm 30 \text{ km/s}) \)
# Feasibility of Cloud Types

<table>
<thead>
<tr>
<th>Component</th>
<th>Fractional Volume</th>
<th>Scale Height (pc)</th>
<th>Temperature (K)</th>
<th>Density (atoms/cm³)</th>
<th>State of Hydrogen</th>
<th>Primary Observational Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular clouds</td>
<td>&lt; 1%</td>
<td>80</td>
<td>10—20</td>
<td>10²—10⁶</td>
<td>molecular</td>
<td>Radio and infrared molecular emission and absorption lines</td>
</tr>
<tr>
<td>Cold Neutral Medium (CNM)</td>
<td>1—5%</td>
<td>100—300</td>
<td>50—100</td>
<td>20—50</td>
<td>neutral atomic</td>
<td>H I 21 cm line absorption</td>
</tr>
<tr>
<td>Warm Neutral Medium (WNM)</td>
<td>10—20%</td>
<td>300—400</td>
<td>6000—10000</td>
<td>0.2—0.5</td>
<td>neutral atomic</td>
<td>H I 21 cm line emission</td>
</tr>
<tr>
<td>Warm Ionized Medium (WIM)</td>
<td>20—50%</td>
<td>1000</td>
<td>8000</td>
<td>0.2—0.5</td>
<td>ionized</td>
<td>Hα emission and pulsar dispersion</td>
</tr>
<tr>
<td>H II regions</td>
<td>&lt; 1%</td>
<td>70</td>
<td>8000</td>
<td>10²—10⁴</td>
<td>ionized</td>
<td>Hα emission and pulsar dispersion</td>
</tr>
<tr>
<td>Coronal gas Hot Ionized Medium (HIM)</td>
<td>30—70%</td>
<td>1000—3000</td>
<td>10⁶—10⁷</td>
<td>10⁻⁴—10⁻²</td>
<td>ionized (metals also highly ionized)</td>
<td>X-ray emission; absorption lines of highly ionized metals, primarily in the ultraviolet</td>
</tr>
</tbody>
</table>

Wikipedia, “Interstellar Medium”  
K. Ferriere
Usual Velocity Distribution Models of DM

B. J. Kavanagh et al., arXiv:1308.6868v2
Interaction Overview

• Now that we have velocity...

\# WIMP interactions = Flux \cdot P \cdot \text{runtime} \cdot \text{Detector Area}

• Where integrated flux:

\[
\text{Flux} = n_{DM} \cdot \int_{0}^{v_{\text{esc}}} f(v) \cdot v \, dv = n_{DM} \cdot \bar{v}
\]

• And \( P = \text{Probability of detection} \):

\[
P = \sigma \cdot L \cdot n_T \quad \left( \sigma = \sigma_{NN'} \cdot A_{DM}^2 \cdot A_T^2 \right)
\]

\( \sigma = \text{WIMP-nucleus cross section} \quad \left( \sigma_{NN'} \text{ is parameter} \right) \)

\( L = \text{Detector length} \)

\( n_T = \text{Detector number density} \)
Interaction Overview

• We still must account for recoil spectrum and detector threshold:

• Check if recoil energy above threshold based on kinematics and scattering angle:

\[ E_{\text{recoil,lab}} = E_{\text{kin}} \cdot r \cdot \frac{1 - \cos(\theta_{\text{cms}})}{2} \]

Where \( E_{\text{kin}} \) is the kinetic energy of the DM particle and the kinematic factor \( r \):

\[ r = 4 \cdot \frac{m_{\text{DM}} \cdot m_{\text{Detec}}}{(m_{\text{DM}} \cdot m_{\text{Detec}})^2} \]
Research Direction

• Within the mirror matter paradigm, we created a model of composition and velocity distribution of dark matter
• Our next step is to explain all positive and negative experimental observations for dark matter within the new paradigm
• Will it be possible to find parameters such as temperature, velocity, and cross-section that will explain these experiments’ results?