The unbearable lightness of being: CDMS versus XENON

Christopher McCabe

with Mads T. Frandsen, Felix Kahlhoefer, Subir Sarkar and Kai Schmidt-Hoberg

Ripples in the Cosmos, Durham – 22nd July 2013
Searches for (WIMP) dark matter

- Indirect detection
- Collider production
- Direct detection

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Direct detection

Flux of DM

Target nucleus

Detector

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Direct detection

Nucleus

DM

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Direct detection

- DAMA/LIBRA
- KIMS
- XMASS
- DEAP/CLEAN
- XENON
- ZEPLIN
- LUX
- PandaX
- DarkSide

Phonon/Heat

Ionization

CoGeNT

MAJORANA

CDMS

EDELWEISS

COUPP

PICASSO

CRESST-II

Scintillation

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Roadmap for this talk

• Summary of direct detection experimental results: focus on XENON10, XENON100 and CDMS-Si

• Compare CDMS-Si and XENON10/XENON100:
  1. under the standard theoretical assumptions
  2. beyond the standard theoretical assumptions
Latest results

XENON100: 1207.5988
Latest results: low mass region

- Focus on CDMS-Si, XENON10 and XENON100 in this talk
CDMS-Si

- 140 kg-days (July 2007-Sept 2008) with silicon detectors
- Previous CDMS results used germanium detectors

- Three events passed all cuts (0.7 expected)
- DM + background hypothesis preferred over known-background only hypothesis at 99.8% C.L.

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• S2/S1 discriminates between electronic and nuclear recoils

• Two events passed all cuts in 225-day run (1.0 ± 0.2 expected)
XENON10 (S2-only)

- XENON10 analysed 12-day run (from 2006) with S2-only:
  - Pro: Energy threshold of S2 is significantly lower than S1
  - Con: Lose electronic/nuclear recoil discrimination (23 events in the signal region)
XENON10 (S2-only) limit

- Published XENON10 limit in PRL paper:

- Our analysis did not agree:

Frandsen, Kahlhoefer, Sarkar, CM, Schmidt-Hoberg: 1304.6066
XENON10 (S2-only) limit

- Published XENON10 limit in PRL paper
- Erratum with corrected limit agrees with our analysis:

- Our analysis did not agree:
Summary of experimental results

- Small region of compatibility between CDMS-Si signal and XENON10 and XENON100 limits

Frandsen, Kahlhoefer, Sarkar, CM, Schmidt-Hoberg: 1304.6066
Confronting experiment with theory

- Rate for spin-independent scattering:

\[
\frac{dR}{dE_R} = \text{flux} \cdot \frac{d\sigma}{dE_R}
\]

where

\[
\text{flux} = \frac{\rho_X}{m_X} \int_{v_{\text{min}}} v f(v) \, d^3v,
\]

\[
\frac{d\sigma}{dE_R} = A^2 \frac{m_N \sigma_n}{2\mu_n^2 v^2}
\]

- \( v_{\text{min}} = \sqrt{\frac{m_N E_R}{2\mu_N}} \) : minimum DM speed for nucleus to recoil with energy

- Standard theoretical assumptions:
  1. ‘Standard Halo Model’
  2. Short range interaction
  3. Equal couplings to protons and neutrons
  4. Elastic scattering
Truncated Maxwell-Boltzmann velocity distribution (in Galactic frame):

\[ f(v) = \begin{cases} 
N_0 \exp \left( -\frac{v^2}{v_0^2} \right) & v < v_{\text{esc}} \\
0 & v > v_{\text{esc}} 
\end{cases} \]

- Canonical values are \( v_0 = 220 \text{ kms}^{-1} \) and \( v_{\text{esc}} = 544 \text{ kms}^{-1} \)
- Typical ranges are: \( 200 \text{ kms}^{-1} \lesssim v_0 \lesssim 250 \text{ kms}^{-1} \) and \( 498 \text{ kms}^{-1} \lesssim v_{\text{esc}} \lesssim 608 \text{ kms}^{-1} \)

McMillan, Binney: 0907.4685
RAVE survey: 0611671
Beyond the Standard Halo Model

1. Vary galactic parameters:
Beyond the Standard Halo Model

2. Introduce a ‘debris flow’:

- Modifying astrophysical-parameters does not improve agreement

Tidally stripped (from subhalos) component near the galactic centre

Lisanti, Spergel: 1105.4166
Kuhlen, Lisanti, Spergel: 1202.0007

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Mapping results to velocity integral

- Scattering rate depends on the ‘velocity integral’
- Changes in astrophysical parameters enter here

- CDMS-Si, XENON10 and XENON100 probe same ‘velocity integral’

- Cannot improve agreement by varying astrophysical parameters

\[
\frac{dR}{dE_R} \propto g(v_{\text{min}}) = \int_{v_{\text{min}}} \frac{f(v)}{v} d^3v
\]

Fox, Liu & Weiner: 1011.1915

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Beyond short range interactions

- Standard assumption: DM scatters with a short range contact interaction – via a ‘heavy \( (m_{\text{med}} \gg 50 \text{ MeV}) \) mediator’

- Parameterise long-range interaction by:\n  \( q^2 = 2m_N E_R \) is the momentum transfer\n  \[
  \frac{d\sigma}{dE_R} \rightarrow \left( \frac{q^2}{q_{\text{ref}}^2} \right)^n \frac{d\sigma}{dE_R}
  \]

- Agreement does not improve: \( q \propto v_{\text{min}} \) for light DM
Beyond equal p and n couplings

• Assumed equal couplings to protons and neutrons

• More generally: \( \frac{d\sigma}{dE_R} \propto [Z + f_n/f_p(A - Z)]^2 \)

• If \( f_n/f_p < 0 \), get destructive interference

• Known mediators:
  - Photon
  - \( Z \)-boson
  - Higgs

\[
f_n/f_p = 0 \quad f_n/f_p = \frac{-1}{1 - 4\sin^2 \theta_W} \approx -13.2 \quad f_n/f_p \approx 1
\]

• DM mediated by new \( Z' \) could give other values

See Frandsen et al: 1107.2118 & 1204.3839
Beyond equal p and n couplings

- Assumed equal couplings to protons and neutrons
- More generally:
  \[ \frac{d\sigma}{dE_R} \propto [Z + f_n/f_p(A - Z)]^2 \]

- Xenon constraints can be significantly weaker
Beyond elastic scattering

- For inelastic scattering, can up-scatter ($\delta = m_2 - m_1 > 0$) or down-scatter ($\delta < 0$) to a different mass eigenstate.

- ‘Down-scattering’ enhances rate for light target nuclei.
Summary

- CDMS-Si detected 3 events:
  - DM + background hypothesis preferred at ~ 3σ C.L.
- Strong constraints from XENON10 and XENON100

- Attempts to alleviate tension:
  - Vary astrophysical parameters
  - Short range interaction
  - Distinct couplings to protons and neutrons
  - Inelastic scattering:
    - Up-scattering
    - Down-scattering
Backup slides – CDMS-Si signal
CDMS-Si background distribution

Tower 4, Detector 3

Note: these are the Normalized Distributions!
Limits for $f_n/f_p = -0.7$

Frandsen, Kahlhoefer, CM, Sarkar, Schmidt-Hoberg:1111.0292

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Signal at XENON100?

Hooper: 1306.1790
Backup slides – other signals
Event rate over time:

Modulation amplitude:

Bernabei et al: 1002.1028
CoGeNT (Ge) – unmodulated signal

‘Excess’: Dark matter? Background?

Aalseth et al:1106.0650

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CoGeNT – surface event cut

Cut events with large rise time

Pre-cut

Post-cut

Aalseth et al:1002.4703

Aalseth et al:1106.0650
CoGeNT – at TAUP (Sept. 2011)

Cut may not be efficient at low energies:

Is there any excess left if we remove another 70% of the events?
CoGeNT – modulated signal

Modulation preferred at $2.8\,\sigma$

Aalseth et al.:1106.0650

Modulation below $3\,\text{keV}_{ee}$

Surface events do not modulate
The observed signal and lead to a similar spectral distribution. In the context of the latter, the fit assigns roughly two likely maxima. The small statistical error of the two likelihood maxima. The expected total contributions from the backgrounds considered. Both these backgrounds are accounted for the expected total contributions from the backgrounds. The observed events in the energy spectrum, also the distribution in the light yield parameters.

**Four main backgrounds**

Gamma

Alpha and neutrons

WIMP

Pb recoil

**Events from 1 module (of 8):**

- Alpha and neutrons
- Gamma
- Pb

**Summary:**

- Four main backgrounds:
  - Gamma
  - Alpha and neutrons
  - WIMP
  - Pb recoil

**Table 4:**

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<th>M1</th>
<th>Pb recoils</th>
<th>neutron events</th>
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<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>7</td>
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**Figure:**

- Energy spectrum of the accepted events / keV
- Accepted events per module according to the choice of the acceptance region for each detector module which contains pre-defined Pb reference regions of all detector modules, but additionally highlighted are the acceptance region (orange), the background region (gray), and the expected WIMP signal (green).
CRESST-II: Pb recoils

- CRESST-II simulations (black line) indicate that the spectrum should be flat at low recoil energies.

- Simulations by Kuzniak et al. find that it rises.

...is there any excess left to explain?

Kuzniak, Boulay, Pollmann:1203.1576
Consistency of all experiments?

- No known model to bring all experiments into agreement