Recent results in dark matter direct detection

or

The unbearable lightness of being

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August 20, 2013

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arXiv:1304.6066
How to detect dark matter?

We know it is out there...

If dark matter has non-gravitational couplings, then there are three different detection strategies:

- Indirect detection
- Direct detection
- Collider searches

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Dark matter particles from the Galactic halo that pass through the Earth will occasionally scatter off nuclei. The resulting recoil energy of the nucleus can be measured in dedicated low background detectors.
Direct detection experiments

• Different target nuclei...
• Can’t compare ‘directly’
• Complementarity useful
Experimental signatures

1. Exponentially falling energy spectrum

Typical recoil energies: 10 keV

But backgrounds...
Experimental signatures

1. Exponentially falling energy spectrum
2. Annual modulation of the signal
DAMA/LIBRA annual modulation

- Scintillation light in NaI detector
- Weak background rejection
- $8.9\sigma$ evidence for annual modulation in energy range of 2-6 keVee

What is it???
- Period and phase ($146 \pm 7$, June 2=152) consistent with DM interpretation, energy range looks ok...
- Modulating background? No known ‘non-dark matter’ explanation
- DarkIce...

Bernabei et al, 0804.2741, 1002.1028

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CoGeNT (Ge)

‘Excess’:
Dark matter? Background?

~ 2.8 $\sigma$ evidence for annual modulation

Current status?

Surface event cut may not be efficient at low energies:
Any signal left if you remove another 70%?

Aalseth et al: 1106.0650

$\sigma$ 1 1 1 1 1 1 1 1

$D_M = m_D \pm m_D$ $G = e^{-4V_{eV}}$ $m_c m_n$ $c_0$ $10^2$ $10^4$ $10^6$ $10^8$ $10^{10}$ $E_{keV}$

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CRESST-II (CaWO$_4$)

Angloher et al:1109.0702

Four main backgrounds

gamma

alpha and neutrons

Pb

Events from 1 module (of 8):

Light Yield

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

Energy [keV]

0 20 40 60 80 100 120 140

alpha

O

W

Pb

gamma

angular dependence

Pb recoil

WIMP signal

\gamma\text{ bck}

\alpha \text{ bck}

neutron bck

accepted events / keV

10 15 20 25 30 35 40

Energy [keV]
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
CDMS-II

• CDMS-II observed 3 events in data taken with their Si detectors compared to a background expectation of 0.7 events.

• At face value, this is not very impressive... The probability to have 3 or more events as a result of background fluctuations is about 5%.

• However, the distribution of the signal events is different from the shape of the expected background spectrum!
CDMS-II

- Background: Spectrum relatively flat in energy.
- Signal: All events close to the threshold (7 keV).

![Graph showing event rates vs. energy]

- Expected Dark Matter event rate for $\sigma_p = 2 \times 10^{-41} \text{ cm}^2$ and $m_\chi = 8.6 \text{ GeV}$
- Total expected background event rate

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CDMS-II

- The background+DM hypothesis is favoured over the background-only hypothesis with a probability of 99.6%.

![Graph showing event rates vs. energy](image)

- Expected Dark Matter event rate for $\sigma_p = 2 \times 10^{-41}$ cm$^2$ and $m_\chi = 8.6$ GeV

- Total expected background event rate

- Surface events

- Neutron events

- Pb events

- Observed events

- $E_R$ [keV]
• S2/S1 discriminates between electronic and nuclear recoils

• Two events passed all cuts in 225-day run (1.0 ± 0.2 expected)
Overall consistency?
The standard picture...

arXiv: 1304.4279
What are the uncertainties?

- (spin-independent) DM-nucleus scattering rate:

Additional experimental uncertainties:
- Efficiencies, energy resolution, backgrounds
- Translating measured energies into recoil energies
- In particular light dark matter challenging since close to detector thresholds...

\[
\frac{dR}{dE_R}(E_R, t) = M_{\text{tar}} \frac{\rho_X}{2 m_X \mu^2} \frac{(f_p Z + f_n (A - Z))^2}{f_n^2} \sigma_n F^2(E_R) \int d^3 \bar{v} \frac{f_{\text{local}}(\bar{v}, t)}{\bar{v}}
\]

\[= g(v_{\text{min}}, t)\]

Particle physics
Nuclear physics
astrophysics

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Example: XENON10 S2-only

• The outcome depends sensitively on the ionisation yield $Q_y$.

• The energy dependence of $Q_y$ is very difficult to measure and completely unknown below 3 keV.

Bezrukov, FK, Lindner
arXiv:1011.3990

arXiv:1304.1427
XENON10 (S2-only) limit

- Published XENON10 limit in PRL paper:

- Our analysis did not agree:

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XENON10: PRL, 1104.3088

XENON100: 1304.6066

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XENON10 (S2-only) limit

- Published XENON10 limit in PRL paper
- Erratum with corrected limit agrees with our analysis:
  - Our analysis did not agree:

![Graph showing XENON10, XENON100, CDMS-Si limits](image)

XENON10: PRL, 1104.3088

1304.6066
XENON10 (S2-only) limit

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- Our analysis did not agree:

Note impact of $Q_y$ on bound

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Astrophysical uncertainties: The velocity integral

SHM: Maxwell-Boltzmann velocity distribution

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

\( v_c = 220 \text{ km/s}, \) \( v_{\text{esc}} = 544 \text{ km/s} \)

\[ v_{\text{min}} = \sqrt{\frac{m_A E_R}{2\mu^2}}, \quad \mu = \frac{m_\chi m_A}{m_\chi + m_A} \]
Astrophysical uncertainties: The velocity integral

SHM: Maxwell-Boltzmann velocity distribution

Change parameters in SHM

Consider different halo models
Measuring the velocity integral

- In principle, we can use dark matter direct detection experiments to infer $g(v_{\text{min}})$ by converting recoil spectra into “$v_{\text{min}}$-space”

\[
\frac{dR}{dE_R} = \frac{\rho \sigma_n}{2 m_\chi \mu^2_{n\chi}} A^2 F^2(E_R) g(v_{\text{min}})
\]

\[
g(v_{\text{min}}) = \frac{2 m_\chi \mu^2_{n\chi}}{\rho \sigma_n} \frac{1}{A^2 F^2(E_R)} \frac{dR}{dE_R}
\]

Fox, Liu, Weiner (2010)
An example

- CoGeNT and CRESST-II probe different regions of $v_{\text{min}}$-space
- A consistent description of these two experiments is possible!
- What about other experiments?

1111.0292
Constraining the velocity integral

Experimental null results allow to constrain the velocity integral.

No consistent description possible!

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How about CDMS-II Si?
How about CDMS-II Si?

- XENON10, XENON100 and CDMS-II Si probe essentially the same region of $\nu_{\text{min}}$-space.
- Therefore, it will not be possible to improve the consistency of these experiments by varying astrophysical parameters.
Possible solutions

• To reduce the tension between XENON10/100 and CDMS-Si, we need to modify particle physics in order to suppress scattering for heavy targets.
  • Exothermic dark matter: In collision, dark matter particles make a transition from a metastable heavier to a lighter state and release a small amount of energy (about 50 keV).
Exothermic dark matter

Exothermic Dark Matter
($\delta = -50$ keV)

$\sigma_n$ [cm$^2$]

$m_\chi$ [GeV]
Possible solutions

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• Exothermic dark matter: In collision, dark matter particles make a transition from a metastable heavier to a lighter state and release a small amount of energy (about 50 keV).

• Isospin-dependent couplings: Partial destructive interference between protons and neutrons suppresses targets with large ratio A/Z.
Isospin-dependent couplings

- No excessive fine-tuning necessary.
Conclusions

• The 3 events in CDMS-II Si point towards low-mass DM.
• The XENON10/100 experiments do not exclude the entire parameter region favoured by CDMS-II, even for the standard case of elastic spin-independent scattering.
• The remaining tension between these experiments is independent of astrophysical uncertainties.
• The tension is reduced if scattering of DM on heavy targets is suppressed, e.g. if DM couplings are isospin-dependent.
• No overall consistent picture emerging from dark matter direct detection experiments – but exciting hints in low mass region!
• Wait for XENON100 low threshold analysis and LUX...