Search for light WIMPS with SuperCDMS and the impact of neutrino background

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The SuperCDMS experiment

21 institutions

http://cdms.berkeley.edu
The SuperCDMS Experiment

- Upgrade from CDMS II, in continuous operation since spring 2012 at Soudan Underground Laboratory
- 600g Germanium detectors measure ionization and non-equilibrium phonons
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- interleaved ionization and phonon sensors on both sides to reject surface events

phonon sensors (0V)
ionization electrodes (±2V)

75 mm
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• ionization guard rejects sidewall events
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- phonon channels reject sidewall events, provide 3D position estimators
- 15 detectors = 9 kg target mass
Low-mass Region (without SuperCDMS-LT)

What can we say about low-mass dark matter "hints"?

![Graph showing the WIMP-nucleon cross section versus WIMP mass with various experimental constraints and sensitivities. The graph highlights the Low-mass Region with SuperCDMS-LT excluded.](image-url)
Strategies for Light WIMP Searches

Lowering the energy threshold is the key for light WIMP searches

1. **CDMSLite**: Amplification of the signal to reduce the effective threshold (see P. Di Stefano’s talk)

2. **Low Threshold analysis**: Improve exposure and extend background ID to low energy

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Low Threshold analysis

Lowering the analysis thresholds down to the experiment’s trigger thresholds

- Use 7 detectors with lowest trigger thresholds (~1.6 keV - 5 keV)
- 577 kg-d of exposure (Oct. 2012 - July 2013)
- Blind analysis optimized for exclusion
Low Threshold analysis

\[ E_t = E_r + E_L \]
\[ E_r = E_t - \frac{1}{3eV} E_Q(E_t) \Delta V \]

• Since signal-to-noise is poor, fit mean ionization energy for nuclear recoils

• Systematic uncertainties propagated into final limit using a MCMC approach

• Most detectors consistent with or slightly below Lindhard

\[ V_b \]

Since signal-to-noise is poor, fit mean ionization energy for nuclear recoils

Systematic uncertainties propagated into final limit using a MCMC approach

Most detectors consistent with or slightly below Lindhard
Low Threshold analysis

210Pb “surface events”

- betas and 206Pb nuclei from 210Pb decay chain
- events are located on detector face and sidewall surfaces from 222Rn contamination

- 22.3 y: 210Pb
- 5.01 d: 210Bi
- 138.4 d: 210Po
- 100%: β 17.0 keV
- 20%: β 63.5 keV
- 100%: β 1161.5 keV
- 206Pb 103 keV
- 80%: conv. e 30.2 keV
- 14.3%: conv. e 42.5 keV
- 23.6%: γ 10.8 keV
- 4.3%: γ 46.5 keV
- 103 keV
- Copper housings
- 206Pb α 5.3 MeV
Low Threshold analysis

**210Pb “surface events”**

- betas and 206Pb nuclei from 210Pb decay chain
- events are located on detector face and sidewall surfaces from 222Rn contamination

**External gammas**

- from radioactivity in shielding and cryostat

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Low Threshold analysis

\[ ^{210}\text{Pb} \text{ “surface events”} \]

- betas and \(^{206}\text{Pb}\) nuclei from \(^{210}\text{Pb}\) decay chain
- events are located on detector face and sidewall \textit{surfaces} from \(^{222}\text{Rn}\) contamination

\[ ^{210}\text{Pb} \quad \begin{array}{c} 22.3 \text{ y} \quad 20\%: \beta 17.0 \text{ keV} \\ 5.01 \text{ d} \quad 80\%: \beta 63.5 \text{ keV} \\ 100\%: \beta 1161.5 \text{ keV} \end{array} \]

\[ ^{210}\text{Po} \quad \begin{array}{c} 138.4 \text{ d} \quad 100\%: \alpha 5.3 \text{ MeV} \end{array} \]

\[ ^{206}\text{Pb} \quad 103 \text{ keV} \]

\[ ^{210}\text{Bi} \quad 5.01 \text{ d} \]

\[ ^{138}\text{Bi} \quad 22.3 \text{ y} \]

\[ ^{206}\text{Bi} \quad 5.01 \text{ d} \]

\[ ^{222}\text{Rn} \quad \begin{array}{c} \text{alpha decay} \\ 210\%: \alpha 5.3 \text{ MeV} \end{array} \]

\[ ^{138}\text{Ba} \quad \begin{array}{c} \text{beta decay} \\ 100\%: \beta 5.3 \text{ MeV} \end{array} \]

External gammas

- from radioactivity in shielding and cryostat

\[ ^{210}\text{Pb} \quad \begin{array}{c} \text{internal radioactivity} \\ \end{array} \]

Internal activation lines

- L-shell capture from \(^{68,71}\text{Ge}, \quad {65}\text{Zn}, \quad {68}\text{Ga}\)

\[ ^{210}\text{Pb} \quad \begin{array}{c} \text{Copper housings} \end{array} \]

Copper housings

- \textit{surface events} from \(^{210}\text{Pb}\) decay chain
- L-shell capture from \(^{68,71}\text{Ge}, \quad {65}\text{Zn}, \quad {68}\text{Ga}\)
Low Threshold analysis

• Total phonon energy
• Ionization energy

Bulk electron recoils

![Graph showing total phonon energy vs. ionization energy with approximate signal region.]
Low Threshold analysis

- Total phonon energy
- Ionization energy
- Phonon « r-partition »

Bulk electron recoils

Low energy sidewall events
Low Threshold analysis

- Total phonon energy
- Ionization energy

- Phonon « r-partition »

- Phonon « z-partition »

Bulk electron recoils

Low energy sidewayl events

Low energy surface events

![Graphs and images showing energy distributions and event classifications]
Low Threshold analysis

**Background model:** pulse simulation

**Signal model:** $^{252}$Cf NR events reweighted to match 5, 7, 10, and 15 GeV WIMP

![Graphs showing ionization energy and total phonon energy distributions for different models and thresholds.](image)
Low Threshold analysis

- 1 BDT classifier per detector
- Each detector has a BDT cut that has to be optimized
- Set detector BDT cuts simultaneously to minimize expected 90% CL upper limit on WIMP nucleon cross section
- Final cut is the logical OR of all the BDT cuts optimized for WIMPs of 5, 7, 10, and 15 GeV

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Low Threshold analysis

**Quality**
- Remove periods of poor detector performance
- Remove misreconstructed and noisy pulses
- Measure efficiency with pulse Monte Carlo

**Thresholds**
- Trigger and analysis thresholds 1.6-5 keVnr
- Measure efficiency using $^{133}$Ba calibration data

**Preselection**
- Ionization consistent with nuclear recoils
- Ionization-based fiducialization
- Remove multiple-detector hits
- Remove events coincident with muon veto

**BDT**
- Optimized cut on energy and phonon position estimators
- Estimate BDT+preselection efficiency using fraction of 252Cf passing

Includes ~20% correction, from Geant4 simulation, for multiple scattering in single detector

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Low Threshold analysis

Passing data quality & ionization fiducialization cuts
Low Threshold analysis

11 events observed passing BDT (expected $6.2^{+1.1}_{-0.8}$)

95% CL contours for 5, 7, 10, 15 GeV WIMP
Low Threshold analysis

- Background consistent with expectations overall and on most individual detectors
- Shorted ionization guard on T5Z3 may have affected background model performance—*further study ongoing*
- Background model **accurate in full preselection region**
- Future 210-Pb calibration data to reduce systematics and enhance the sensitivity of the experiment

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Low Threshold analysis

set 90% CL upper limit with optimal interval method (no background subtraction)

band includes systematics from efficiency, energy scale, trigger efficiency

difference due to high-energy events on T5Z3

expected sensitivity

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Neutrino background

Based on:
- J. Billard, L. Strigari and E. Figueroa-Feliciano, PRD 89 (2014)
Neutrino interactions with Dark Matter experiment target material

**Ge target**

- WIMP signal: $m_\chi = 6 \text{ GeV}/c^2$, $\sigma_{\chi n} = 4.4 \times 10^{-45} \text{ cm}^2$
- Total CNS background
- Weak neutrino-electron

Event rate [(ton.year.keV)$^{-1}$]

- $1 \text{ keV threshold} \rightarrow 100 \text{ evt/ton/year}$
Neutrino background

**Neutrino interactions with Dark Matter experiment target material**

**Ge target**

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**Event rate [ton.year.k_eV]$^{-1}$**

1 keV threshold -> 100 evt/ton/year

Neutrino-electron background

negligible for Ge cryogenic detectors

BUT

problematic for Xe based detectors
Neutrino background

Neutrino interactions with Dark Matter experiment target material

**Ge target**

- **WIMP signal**: $m_\chi = 6$ GeV/c$^2$, $\sigma_{\chi n} = 4.4 \times 10^{-45}$ cm$^2$
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Event rate [(ton.year.keV)$^{-1}$]

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WIMP or 8B-neutrino??

negligible for Ge cryogenic detectors
BUT
problematic for Xe based detectors

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Neutrino background

**WIMP discovery potential:**  
(J. Billard, F. Mayet and D. Santos PRD 2012)

- 90% probability to get a 3 sigma or more WIMP discovery significance
- Computed using a profile likelihood ratio test statistic (16% syst. on flux normalization)
- 8B neutrinos mimic almost perfectly a 6 GeV WIMP

![Graph showing WIMP discovery limits and significance](image)

Saturation regime:
2 orders of magnitude

Discrimination:
High stats
Neutrino background

WIMP–nucleon cross section [cm²]

WIMP Mass [GeV/c²]

CDMS II Ge (2009)
ZEPLIN-III (2012)
COUPP (2012)
EDELWEISS (2011)
CRESST
SIMPLE (2012)
CDMS Si (2013)
DAMA

COHERENT NEUTRINO SCATTERING

7Be Neutrinos
8B Neutrinos
Atmospheric and DSNB Neutrinos

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Neutrino background

- First detection of CNS!
- Solar neutrino physics
  (J. Billard et al., arXiv:1409.0050)

WIMP mass [GeV/c^2]

WIMP–neucleon cross section [cm^2]

WIMP–neucleon cross section [pb]

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Conclusions

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Conclusions

CDMSLite

R. Agnese et al., PRL 2014 (1)

(See P. Di Stefano's talk)
Conclusions

SuperCDMS LT analysis
R. Agnese et al., PRL 2014 (2)
(See P. Di Stefano’s talk)

CDMSLite
R. Agnese et al., PRL 2014 (1)

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Conclusions

CDMSLite

R. Agnese et al., PRL 2014 (1)

SuperCDMS LT analysis

R. Agnese et al., PRL 2014 (2)

Neutrino floor:
J. Billard et al., PRD 2014

Atmospheric and DSNB Neutrinos
Backup
Detector Pulse Simulation

Q-outer events

<table>
<thead>
<tr>
<th>background type</th>
<th>template source</th>
</tr>
</thead>
<tbody>
<tr>
<td>210</td>
<td>WIMP-search data (~40-100 keV)</td>
</tr>
<tr>
<td>External gammas</td>
<td>133</td>
</tr>
<tr>
<td>(~100 keV)</td>
<td></td>
</tr>
<tr>
<td>L-shell lines</td>
<td>K-shell decays (~10 keVee)</td>
</tr>
<tr>
<td>(~1 keVee)</td>
<td></td>
</tr>
</tbody>
</table>

High-E events as templates for low-E events: preserves pulse shape info

High-energy “templates” + noise from random triggers = fake pulse
Neutrino background

The neutrino flux at an Earth based detector:

Geo neutrinos are negligible
Neutrino background

The neutrino flux at an Earth based detector:

Solar neutrinos

Geo neutrinos are negligible

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Neutrino background

The neutrino flux at an Earth based detector:

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CNO neutrinos
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Neutrino background

The neutrino flux at an Earth based detector:

Solar neutrinos
CNO neutrinos
DSNB neutrinos
Geo neutrinos are negligible
Neutrino background

The neutrino flux at an Earth based detector:

![Graph showing neutrino fluxes](image)

- Solar neutrinos
- CNO neutrinos
- DSNB neutrinos
- Atm. neutrinos

Geo neutrinos are negligible
Neutrino background

*Neutrino interactions with Dark Matter experiment target material*

- Coherent neutrino scattering (CNS):

\[
\frac{d\sigma(E_{\nu}, E_r)}{dE_r} = \frac{G_f^2 Q_w^2 m_N}{4\pi} \left( 1 - \frac{m_N E_r}{2E_{\nu}^2} \right) F^2(E_r)
\]

- \(\sigma\): Cross Section
- \(E_r\): Recoil Energy
- \(E_\nu\): Neutrino Energy
- \(G_f\): Fermi Constant
- \(Q_w\): Weak Charge ~ A
- \(m_N\): Atomic Mass

**Neutral current**

No flavor-specific terms!!!
Same rate for \(\nu_e\), \(\nu_\mu\), and \(\nu_\tau\)

**Ultimate background to direct detection**
Neutrino background

Neutrino interactions with Dark Matter experiment target material

- Coherent neutrino scattering (CNS): Depending on the Energy threshold, the CNS background can be very high!

- 1 keV threshold -> 100 evt/ton/year on Ge detector
Target complementarity

How to bypass this neutrino-induced saturation of the sensitivity?

1. Diminution of the systematic errors will lower the saturation regime

2. Add directional information! Solar neutrinos and WIMPs have 2 very different angular distributions (P. Grothaus et al, PRD 90 (2014)), 2D and 1D directionality (J. Billard, arXiv:1411.5946)


4. Target complementarity: combining data from several experiments.