Low-Energy Analyses of Data from SuperCDMS at Soudan

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Motivation for Light WIMPs

Important to better constrain existing and future anomalies
Motivation for Light WIMPs

Wide-open parameter space…
Remain agnostic!

\[
\text{WIMP\textunderscore nucleon cross section [cm}^2]\]

\[
\text{WIMP\textunderscore nucleon cross section [pb]}
\]

WIMP Mass [GeV/c^2]

\[
\text{7Be Neutrinos}
\]
\[
\text{8B Neutrinos}
\]

\[
\text{Atmospheric and DSNB Neutrinos}
\]

\[
\text{Billard, et al. arXiv:1307.5458}
\]
SuperCDMS Overview

- Upgrade to CDMS II experiment
- Ge detectors measure both ionization and phonons

0.6 kg Ge crystals
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- Detectors operate at 50 mK in $^3$He/$^4$He dilution fridge
- Continuous operation from spring 2012 to July 2014
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- 15 detectors x 0.6 kg = 9 kg target mass
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- Continuous operation from spring 2012 to July 2014
- 15 detectors x 0.6 kg = 9 kg target mass
- Active and passive shielding surround detectors
iZIP Detectors

Charge/Phonon sensors

WIMP

E field
iZIP Detectors

Charge/Phonon sensors

prompt phonons

e- e-
h+

Charge/Phonon sensors

E field
iZIP Detectors

Prompt phonons

Phonon energy = $E_{\text{recoil}} + E_{\text{Luke}}$

Charge/Phonon sensors

Charge/Phonon sensors

$h^+$

$e^-$

$E$ field
Position Sensitivity

phonon channels

ionization channels

75 mm
Probing Lighter WIMPs

![Graph showing WIMP scattering rate vs. recoil energy](image)

- **5 GeV WIMP**
- **10 GeV WIMP**
- **20 GeV WIMP**
Probing Lighter WIMPs

lower “effective” threshold

![Graph showing WIMP scattering rates vs. recoil energy for different WIMP masses (5 GeV, 10 GeV, 20 GeV). The graph displays a logarithmic scale for both WIMP scattering rates and recoil energy, with lines for each mass indicating the expected scattering rates at various energy levels.]
Probing Lighter WIMPs

reduce “effective” background

graph showing WIMP scatters / kg / d in Ge vs recoil energy [keV]

- 5 GeV WIMP
- 10 GeV WIMP
- 20 GeV WIMP
Two Approaches

1.) Improve exposure and background ID: Low-energy analysis of SuperCDMS data
Low-energy Analysis

- Use 7 detectors with lowest trigger thresholds (~1.6 keV - 5 keV)
- 577 kg-d of exposure (Oct. 2012 - July 2013)
- **Background discrimination still possible near threshold!!**
- **Blind** analysis optimized for exclusion
Dominant Backgrounds at Low Energy

$^{210}$Pb “surface events”

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

$^{210}$Pb
- 22.3 y $^\beta$ 17.0 keV
- 16%: $^\beta$ 63.5 keV
- 5.01 d $^{210}$Bi
- 100%: $^\beta$ 1161.5 keV
- 138.4 d $^{210}$Po
- 100%: $^\alpha$ 5.3 MeV

$^{206}$Pb
- 22.3 y $^\beta$ 17.0 keV
- 16%: $^\beta$ 63.5 keV
- 5.01 d $^{210}$Bi
- 100%: $^\beta$ 1161.5 keV
- 138.4 d $^{210}$Po
- 100%: $^\alpha$ 5.3 MeV

External gammas

- from radioactivity in shielding and cryostat

$^{206}$Pb
- 103 keV

$^{210}$Pb
- 22.3 y $^\beta$ 17.0 keV
- 16%: $^\beta$ 63.5 keV
- 5.01 d $^{210}$Bi
- 100%: $^\beta$ 1161.5 keV
- 138.4 d $^{210}$Po
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Internal activation lines

- L-shell capture from $^{68,71}$Ge, $^{65}$Zn, $^{68}$Ga

Copper housings
Dominant Backgrounds at Low Energy

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Copper housings

Detectors
Discriminators

ionization yield + total phonon energy

phonon “r-partition”

phonon “z-partition”

Bulk electron recoils

Low energy sidewall events

Low energy surface events

external gammas
approx. signal region
simulation

ionization energy [keV]

phonon energy [keV]

sidewall event

surface event

side-summed phonons

outer phonon channels
Boosted Decision Tree

**Background model:** pulse simulation

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

**Construction:** 1 BDT per detector

**Optimization:** set cuts simultaneously to minimize expected 90% CL upper limit on WIMP-nucleon cross section

$10$ GeV WIMP

$\sigma = 6 \times 10^{-42} \text{ cm}^2$
Boosted Decision Tree

**BDT inputs**

- **Background model:** pulse simulation
- **Signal model:** $^{252}\text{Cf}$ NR events reweighted to match 5, 7, 10, and 15 GeV WIMP

**BDT outputs**

- **Construction:** 1 BDT per detector
- **Optimization:** set cuts simultaneously to minimize expected 90% CL upper limit on WIMP-nucleon cross section.
Unblinding: After BDT

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

95% CL contours for 5, 7, 10, 15 GeV WIMP
set 90% CL upper limit with optimal interval method (no background subtraction)

band includes systematics from efficiency, energy scale, trigger efficiency

this work

expected sensitivity

difference due to high-energy events on T5Z3

arXiv:1402.7137
Post-Unblinding Follow Up

- Background model **accurate in full preselection region**

- Shorted ionization guard on T5Z3 may have affected background model performance (p-value is 0.04%)  

- Now calibrating detector response to sidewall events with sidewall $^{210}$Pb source
Two Approaches

1.) Improve exposure and background ID: **Low-energy analysis of SuperCDMS data**

2.) Lower energy threshold: **CDMSlite**
CDMSlite: “low ionization threshold experiment”

\[ E_{\text{total}} = E_{\text{recoil}} + E_{\text{luke}} \]
\[ = E_{\text{recoil}} + \frac{1}{3 \text{eV}} E_{\text{q}} \Delta V \]

- Measure charge with phonons, and increase voltage to amplify signal
- Lose background discrimination, but achieve lower ionization energy threshold
CDMSlite: Run 1

- Acquired 6 kg-d of exposure on detector with best combination of breakdown voltage and threshold
- Ionization energy calibration with EC lines at 1.3 keVee and 10.4 keVee
- Operated stably at 69V or 24x amplification (only 12x due to electronics limitations)
- 860 eVnr => 170 eVee threshold
- **Must assume NR energy scale**

![Recoil energy spectrum of WIMP-search events, after application of event-selection cuts. Inset: Low-energy sp](image)
CDMSlite: Run 1 Results
### CDMSlite: Run 2 Outlook

<table>
<thead>
<tr>
<th></th>
<th>Run 2</th>
<th>Run 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>raw exposure</strong></td>
<td>4 months</td>
<td>15 days</td>
</tr>
<tr>
<td><strong>baseline noise</strong></td>
<td>8.3 eVee</td>
<td>13.3 eVee</td>
</tr>
<tr>
<td><strong>resolution @ 1.3 eVee</strong></td>
<td>30 eVee</td>
<td>50 eVee</td>
</tr>
<tr>
<td><strong>threshold</strong></td>
<td>80 eVee (preliminary)</td>
<td>170 eVee</td>
</tr>
<tr>
<td><strong>background discrimination</strong></td>
<td>reject sidewall surface events</td>
<td>none</td>
</tr>
</tbody>
</table>

**Backgrounds for low-threshold analysis also affect CDMSlite**

CDMSlite can also use radial phonon info to reject backgrounds!
Conclusion

• Limits from low-energy analysis and CDMSlite significantly constrain low-mass anomalies

• First science results from SuperCDMS iZIP detectors

• Major improvements to CDMSlite performance and analysis will significantly improve future sensitivity

• Better simulations and sidewall event calibration will improve understanding of systematics at low energies

• 2.5 years of data from SuperCDMS at Soudan: more limits soon!
Acknowledgments

*Emeritus Professor at U.C. Santa Barbara
Backup
Cut Optimization

- 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
Calibration and Energy Scale

\[ E_t = E_r + E_L \]

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

- Since signal-to-noise is poor, fit mean ionization energy for nuclear recoils
- Systematic uncertainties propagated into final limit
- Most detectors consistent with or slightly below Lindhard

252Cf calibration data

\[ V_b \]

Charge model for T2Z2

\[ E_r = E_t - \frac{1}{3\text{eV}} E_Q(E_t)\Delta V \]
Efficiencies by Detector

Lindhard nuclear-recoil energy [keVnr]

Efficiency

Total phonon energy [keV]

T1Z1
T2Z1
T2Z2
T4Z2
T4Z3
T5Z2
T5Z3
Detector Pulse Simulation

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

\[
\begin{array}{|c|c|}
\hline
\text{background type} & \text{template source} \\
\hline
^{210}\text{WIMP-search data} & (\sim 40-100 \text{ keV}) \\
\hline
\text{External gammas} & ^{133}\text{ (\sim 100 \text{ keV})} \\
\hline
\text{L-shell lines} & \text{K-shell decays} \\
(\sim 1 \text{ keVee}) & (\sim 10 \text{ keVee}) \\
\hline
\end{array}
\]
Electric Field in T5Z3

Electric Field & Potential for $Q_{in} = +/- 2 \, V$ and $Q_{out} = 2 / 0$

outer event can look like inner!
BDT Distributions

5 GeV

- Data
- WIMP
- Sidewall $^{206}$Pb
- Sidewall $^{210}$Pb+$^{210}$Bi
- Face $^{210}$Pb+$^{210}$Bi
- 1.3 keV line
- Comptons

p-value = 0.21

10 GeV

- Data
- WIMP
- Sidewall $^{206}$Pb
- Sidewall $^{210}$Pb+$^{210}$Bi
- Face $^{210}$Pb+$^{210}$Bi
- 1.3 keV line
- Comptons

p-value = 0.26

7 GeV

- Data
- WIMP
- Sidewall $^{206}$Pb
- Sidewall $^{210}$Pb+$^{210}$Bi
- Face $^{210}$Pb+$^{210}$Bi
- 1.3 keV line
- Comptons

p-value = 0.14

15 GeV

- Data
- WIMP
- Sidewall $^{206}$Pb
- Sidewall $^{210}$Pb+$^{210}$Bi
- Face $^{210}$Pb+$^{210}$Bi
- 1.3 keV line
- Comptons

p-value = 0.08
BDT Input Distributions
CDMSlite: Effect of Nuclear Recoil Energy Scale

![Graph showing nuclear recoil energy scale effects.]

- The results of the CDMSlite project are shown, focusing on the effect of nuclear recoil energy scale.
- Various models, including Collar and Lindhard, are compared and analyzed for their impact on the derived limits.
- The systematic uncertainty in yield does not significantly affect the derived limits.
- The analysis threshold corresponds to 0.75 keV, which improves the sensitivity to light WIMPs.
- The substantial reduction in background levels allows for more detailed analysis and improved constraints on WIMP properties.
- The iZIP detectors are fabricated in the Minnesota Department of Natural Resources, contributing to the research.

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**Reference:**

Selection Criteria and Efficiencies

**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
Follow-Up Studies

- Validation and refinement of background models on unblinded data
- Investigating full detector simulation as replacement for pulse simulation
- Calibrate detector response to sidewall events with sidewall $^{210}\text{Pb}$ source
- Use calibration to validate modeling of detectors with shorted channels (e.g. T5Z3)
- Follow-up likelihood analysis to incorporate improved simulations