SuperCDMS: Results for low-mass WIMPS

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“Hints” for low-mass WIMPs in direct detection experiments

Particle Physics models provide candidates for light DM

Among other possibilities:

- Supersymmetry neutralino in the NMSSM or sneutrino in extended models
- Asymmetric DM

Are these theoretical predictions within the reach of our detectors?

It is an appealing window of the DM parameter space that is essential to explore
The search for low-mass WIMPs is challenging

- The signal is expected at very low recoil energies
  
  Favours light targets
  Low-threshold searches

- Ge is relatively heavy so the threshold has to be just above the noise to be sensitive to 5 GeV WIMPs
  
  trigger threshold 1.6 keVnr

- Backgrounds are more difficult to discriminate (this is not a background-free search)
SuperCDMS at SOUDAN

Operational since March 2012

**iZIP**
interleaved Z-sensitive
Ionization & Phonon detectors

3” Diameter 2.5 cm Thick

Instrumented on both sides with 2 charge + 4 phonon sensors

Data for this analysis:

577 kg-days 
taken from March 2012 – July 2013 
using the 7 lowest threshold iZIPS

9.0 kg Ge (15 iZIPS x 600g)
iZIP discrimination of surface events

In the new iZIPS the ionization lines (±2V) are interleaved with phonon sensors (0V) on a ~1mm pitch

**Bulk events:**
charges \((e,h)\) drift to **both sides** of the crystal

**Surface events:**
charges \((e,h)\) drift to **only one side** of the crystal

Z-PARTITION:
The resulting **symmetry/asymmetry** on charge collection in sides 1 and 2
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**Sidewalls**
Surface events on the sides of the detector leave more energy in the outer sensors.

**Z-PARTITION:**
The resulting **symmetry/asymmetry** on charge collection in sides 1 and 2

**RADIAL PARTITION:**
division of energy between inner and outer sensors
The rejection of surface events with the new iZIPs using Z-partition has been demonstrated with data from exposure to betas from $^{210}\text{Pb}$ sources.

In ~800 live hours, no events leaked into the 8-115 keV signal region.

This could allow a background free search for 5 yr of operation in SuperCDMS @ SNOLAB (~100 kg).

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The low threshold analysis corresponds to smaller energies and some leakage is expected.
Background

- **Bulk electron recoils**
  
  Compton background
  1.3 keV activation line

- **Sidewall & surface events**
  
  Betas and x-rays from $^{210}$Pb, $^{210}$Bi,
  recoils from $^{206}$Pb, outer radial Comptons,
  ejected electrons from Compton scattering

- **Neutrons**
  (cosmogenic & radiogenic)

Rejection

Yield = Ionization/phonon helps discriminating NR from ER

Z-Partition and Radial partition define a fiducial volume

Use active and passive shielding.
Cut on multiple hits.
Simulation determines remaining irreducible rate
Analysis: Selection criteria and efficiencies

We carry out a blind analysis, with cuts set by examining only events that will never be accepted as WIMP candidates (multiple scatters, calibration events, and periods following high activation from $^{252}$Cf calibration).

**Data Quality:**
Reject periods with poor detector performance
Remove misreconstructed and noisy pulses
Measure efficiency with pulse MC

**Trigger and analysis threshold:**
Select periods with stable well-defined trigger threshold
Measure efficiency from $^{133}$Ba calibration data

**Preselection:**
Single-detector scatter
Remove events coincident with muon veto
Ionization fiducial volume
Ionization and phonon partitions consistent with NR

**Boosted Decision Tree:**
Optimised cut on the phonon fiducial volume and ionization yield at low energy
Efficiency estimated from fraction of $^{252}$Cf passing
Boosted Decision Tree (BDT)

Inputs (per detector)

![Graphs showing distributions of total phonon energy, ionization energy, phonon z-partition, and phonon r-partition for different WIMP models.]

Output

- Summed over detectors

10 GeV WIMP
\( \sigma = 6 \times 10^{-42} \text{ cm}^2 \)

Background: Modelled with simulated data on sidebands and calibration.

WIMP Signal: Modelled with NR data from \(^{252}\text{Cf}\), then rescaled for WIMPs with mass 5, 7, 10, 15 GeV
Unblinding: Before BDT cut

Events passing all the cuts prior to applying BDT

- Total phonon energy [keV]
- Ionization energy [keV]
- Lindhard nuclear-recoil energy [keVnr]

Approx NR band

Bulk comptons

Outer radial events

1.3 keV line
Unblinding: After BDT cut

11 candidates (6.2 +1.1 -0.8 expected)
Unblinding: After BDT cut

11 candidates (6.2 ±1.1 -0.8 expected)

The three highest energy events were all found in T5Z3, which was not functioning fully
Post-unblinding discussion

Events are high in quality. Only the lowest energy candidate looks like spurious noise.

- For most of the detectors there is good agreement with predicted background.
Post-unblinding discussion

Events are high in quality. Only the lowest energy candidate looks like spurious noise.

- For most of the detectors there is good agreement with predicted background.

- However, T5Z3 observes the 3 highest-energy events. (Poisson p-value is 0.04%)

T5Z3 has a shorted ionization guard. This may have affected the background model performance. Additional studies are ongoing.
New limit for low-mass WIMPs

90% C.L. optimal interval method (no background subtraction)

systematics (efficiency, energy scale, trigger efficiency)


Difference with expectation due to events in T5Z3
Conclusions

- First result using the background rejection capability of SuperCDMS
  7 iZIPs analysed (threshold 1.6 keV$_{nr}$)
  Exposure: 577 kg day
  $\sigma^S > 1.2 \times 10^{-6}$ pb at 8 GeV
  New limit for WIMPs with masses in the range 4 - 6 GeV
  (below 4 GeV CDMSlite dominates)

- CoGeNT interpretation of WIMP signal disfavoured in model-independent way
  CDMS-II (Si) disfavoured assuming standard WIMP interactions and for the standard halo model.

- High threshold analysis of SuperCDMS ongoing
  SuperCDMS Soudan detectors are a vast improvement over CDMS II
- SuperCDMS-SNOLAB (with ~100 kg Ge and ~10 kg Si) will extend the sensitivity by over an order of magnitude with an excellent coverage of the light mass window.
The SuperCDMS collaboration

California Inst. of Tech., CNRS-LPN, FNAL, Mass. Inst. of Tech., NIST Inst. of Tech.,
PNNL, Queen's University, SLAC, Southern Methodist U., Santa Clara University,
South Dakota SM&T, Stanford University, Texas A&M University, U. Autónoma de Madrid,
Extra material & Backup slides
Maximum Likelihood fit for CDMS II (Ge) Limit derived from singles data

Using a background model derived from detector simulations and calibration data.

No significant evidence for Nuclear Recoils in the data

The resulting limit is approximately **5 times stronger** than previous analysis without background subtraction

arXiv:1410.1003
Limit without T5Z3

The limit extracted without T5Z3 only differs for $m > 10$ GeV and is approx. a factor 2 better.
11 candidates that pass all the cuts

<table>
<thead>
<tr>
<th>Detector</th>
<th>Candidate energies [keV$_{nr}$]</th>
<th>Expected background</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1Z1</td>
<td>—</td>
<td>0.03$^{+0.01}_{-0.01}$</td>
</tr>
<tr>
<td>T2Z1</td>
<td>1.7, 1.8</td>
<td>1.4$^{+0.2}_{-0.2}$</td>
</tr>
<tr>
<td>T2Z2</td>
<td>1.9, 2.7</td>
<td>1.8$^{+0.4}_{-0.3}$</td>
</tr>
<tr>
<td>T4Z2</td>
<td>—</td>
<td>0.04$^{+0.02}_{-0.02}$</td>
</tr>
<tr>
<td>T4Z3</td>
<td>—</td>
<td>1.7$^{+0.4}_{-0.3}$</td>
</tr>
<tr>
<td>T5Z2</td>
<td>5.8, 1.9, 3.0, 2.3</td>
<td>1.1$^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>T5Z3</td>
<td>7.8, 9.4, 7.0</td>
<td>0.13$^{+0.06}_{-0.04}$</td>
</tr>
</tbody>
</table>
Efficiencies by Detector

Efficiencies

Lindhard nuclear-recoil energy [keVnr]

Efficiency

Total phonon energy [keV]
Measurement of the recoil energy

Ionization for nuclear recoils, measured from $^{252}$Cf data:

Detector: T2Z2

Total phonon energy = $E_{\text{total}} = E_{\text{Luke}} + E_{\text{recoil}}$

$E_{\text{total}}$ is measured with phonons

NR equivalent energy = $E_{\text{total}} - E_{\text{Luke NR}}$

$E_{\text{Luke NR}}$ estimated from mean NR ionization, varies with $E_{\text{total}}$
SuperCDMS Soudan
CDMSlite – Amplification of the Luke-Neganov phonons

**Prompt Phonons**

**Luke Phonons**

\[ E_Q = N_{eh} \varepsilon = \text{Ionisation energy} \]

\[ \varepsilon = 3 \text{ eV (in Ge)} = (e-h) \text{ pair creation mean energy} \]

\[ E_{\text{recoil}} = E. \text{ of prompt phonons} \]

\[ E_{\text{Luke}} = V \varepsilon N_{eh} \]

\[ P_{\text{tot}} = E_{\text{recoil}} + E_{\text{Luke}} \]

If the bias voltage is increased, the work done in drifting charge carriers, \( E_{\text{Luke}} \), increases.

The signal is amplified, allowing a substantial reduction in energy threshold and a better energy resolution.

The phonon instrumentation thus measures the ionization energy (no signal is used from the ionization channels) \( \rightarrow \) No Yield-based discrimination of electron and nuclear recoils.
CDMSlite – data taking

- Data were taken in three periods in 2012
  - with $^{133}$Ba calibration data interspersed throughout

- There were two neutron exposures ($^{252}$Cf)
  - to determine energy scale and monitor stability
  - August 22, and August 31

- One iZIP was used, IT5Z2 – 0.6 kg
  - Selected for its low trigger threshold and low leakage current
  - Signal gain at operating voltage of 69 V was 24

\[
E_T = E_r \times \left(1 + \frac{eV_b}{\varepsilon_\gamma}\right)
\]

Average excitation energy per charge pair \(\varepsilon_\gamma = 3\) eV.

- Raw exposure is 15 live days, 9.6 kg days
  - Optimized based on a flat extrapolation of known electron recoil backgrounds in the 2-7 keV window
Event selection criteria

- Not coincident with signals in the muon veto
- Single detector energy depositions
- Not consistent with high frequency noise ("glitches")
- Not consistent with low frequency noise (microphonics)

Time periods selected with low leakage and where the gain could be well calibrated

Exposure = 10.3 live days = 6.3 kg day

The spectrum shows features at 10.36 keV and 1.3 keV due to K- and L- shell electron captures in $^{71}\text{Ge}$. The energy resolution of the 1.3 keV line is 43 eV (1σ).
CDMSlite – Spectrum of nuclear recoils

\[ E_{nr} = E_{ee} \frac{(1 + e^{V_b}/\varepsilon_{\gamma})}{(1 + e^{V_b}/\varepsilon_{\gamma}Y(E_{nr}))} \]

The yield is not measured: use theoretical (Lindhard) model

A number of experiments have measured nuclear recoils in germanium over the relevant energy range.
CDMSlite – Results

This analysis limits new WIMP parameter space for low masses and rules out portions of CDMS II and CoGeNT contours.

The choice of a different model for the yield affects the reconstruction of the nuclear recoil energy and thus the interpretation as a limit on the WIMP-nucleon cross-section.
Resulting experimental situation for low-energy WIMPs
iZIP discrimination of surface events

In the new iZIPs the ionization lines (±2V) are interleaved with phonon sensors (0V) on a ~1mm pitch

Bulk events:

charges (e,h) drift to **both sides** of the crystal

Surface events:

charges (e,h) drift to **only one side** of the crystal

The resulting symmetry/asymmetry in charge collection is an extremely effective discriminant for surface events
iZIP calibration

~900 live hours in T3Z1 with a $^{210}$Pb source on side 1

71,525 electrons
16,258 $^{206}$Pb recoils

No events leaking into the signal region (8-115 keV)

For 300 kg yr (200 kg Ge SNOLAB) the estimated leakage is < 0.6 events 90% cl
CDMS II

4.6 kg Ge (19 x 240 g)
1.2 kg Si (11 x 106 g)

3” Diameter
1 cm Thick

2 charge + 4 phonon

SuperCDMS Soudan

9.0 kg Ge (15 x 600 g)

3” Diameter
2.5 cm Thick

2 charge + 2 charge
4 phonon + 4 phonon
The rejection of surface events with the new iZIPs using Z-partition has been demonstrated with data from exposure to betas from $^{210}\text{Pb}$ sources.

In ~800 live hours, no events leaked into the 8-115 keV signal region.

This could allow a background free search for 5 yr of operation in SuperCDMS @ SNOLAB (~100 kg).

Leakage < $1.7 \times 10^{-5}$

The low threshold analysis corresponds to smaller energies and some leakage is expected.

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