Status and Future Plans of the Cryogenic Dark Matter Search Experiment

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for the CDMS Collaboration

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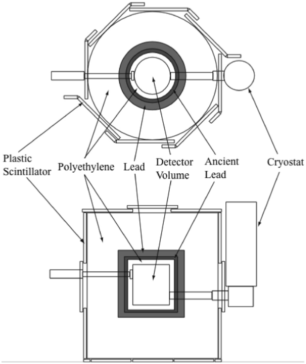
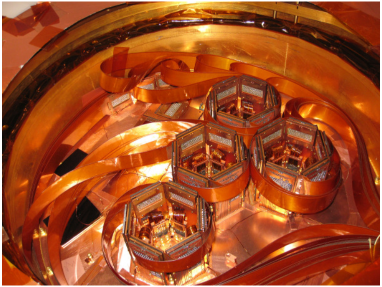
The Cryogenic Dark Matter Search Experiment

- Search for Dark Matter in the form of Weakly Interacting Massive Particles (WIMPs)
- Located in Soudan Mine, Minnesota, USA (2090 mwe)
- Ge & Si crystals cooled to $\approx$ 40 mK
- Passive Pb & polyethylene shielding

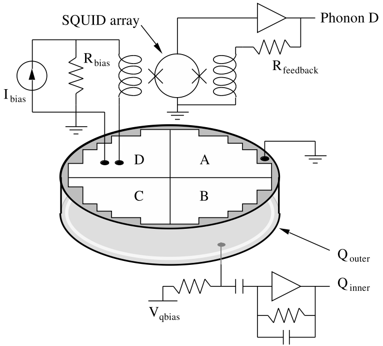


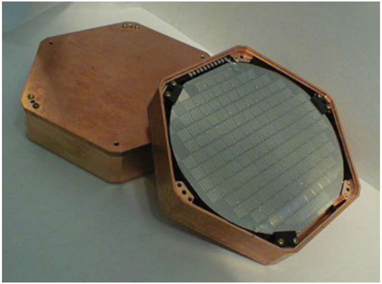


- Muon scintillator veto
- Collect phonon & ionisation signals for event-by-event discrimination

CDMS-II Detector: ZIP

- Z-sensitive Ionisation & Phonon detector (ZIP)
- 3″ diameter × 1 cm thick
- Mass:
  - 19 × 250 g (Ge)
  - 11 × 100 g (Si)



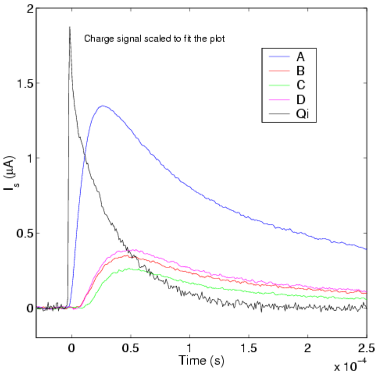


- 2 charge electrodes on one surface:
  - inner disc & outer ring
- 4 phonon sensors on opposite surface:
  - each covers one quadrant

Ionisation & Phonon Signals

Simultaneous measurement of charge-carriers (ionisation) and phonons generated by an event

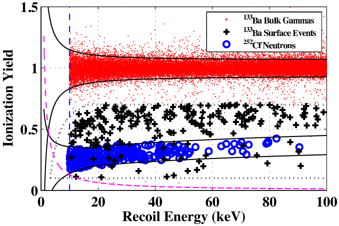
- Ionisation signal:
  - Fast: 1 μs rise- & 40 μs fall-times
  - Provides event time information
- Phonon signal:
  - Pulse shape depends on event position
- Recoil energy from ionisation & phonon signal amplitudes
- Event position reconstruction from timing and amplitude of phonon signals

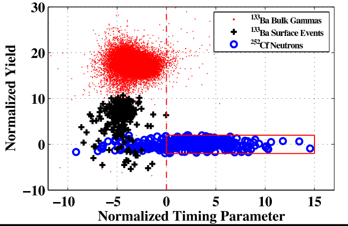


Electron-Nuclear Recoil Discrimination

Nuclear recoils generate less ionisation than electron recoils of the same deposited energy

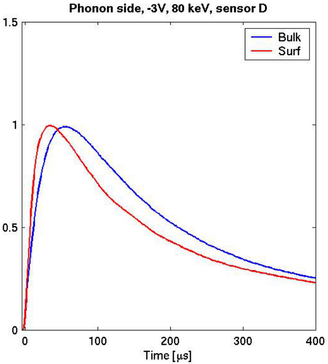
Therefore, ionisation-phonon recoil energy ratio is a discrimination parameter $\Longrightarrow$ Ionisation Yield

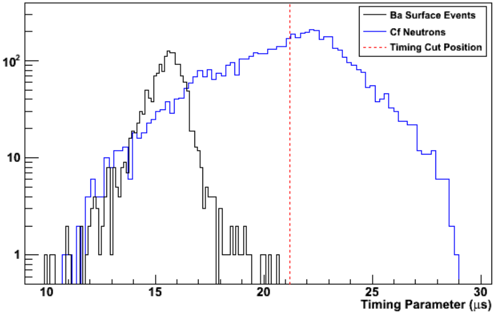




- γ-rays from ^{133}Ba source define electron recoil band
- neutrons from ^{252}Cf source define nuclear recoil band
- Bands are well separated down to 10 keV
- Surface electron-recoil events:
  - Incomplete charge collection
  - Reduced yield $\Longrightarrow$ background

Shape of phonon pulses indicates interaction depth

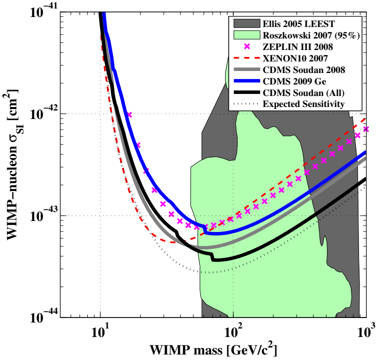




Surface events have faster rise time than bulk events, enabling definition of a timing cut

Results from Final Exposure of CDMS-II

- 612 kg-days exposure
- 2 candidate events:
  1. $E_R = 12.3$ keV, Tower 1, ZIP 5, 02:48 GMT 28 Oct 07
  2. $E_R = 15.5$ keV, Tower 3, ZIP 4, 19:41 GMT 5 Aug 07
- Expected irredicible backgrounds:
  - 0.8 ± 0.1 (stat) ± 0.2 (sys) misclassified surface electron recoils
  - ≈ 0.1 background neutrons from cosmic-rays & radioactivity
- 23% probability of observing 2 or more background events over this exposure time

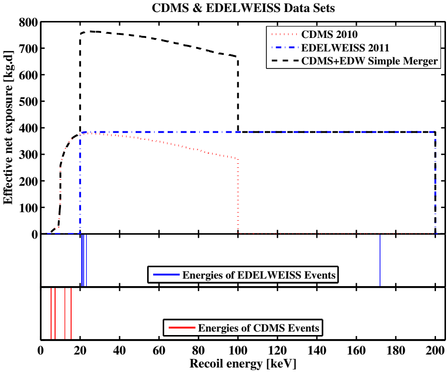


Z. Ahmed *et al.*, Science **327**, 1619 (2010)

- Cannot be interpreted as significant evidence for WIMP interactions, nor can either event be rejected as a WIMP
- In process of reanalysing results to reduce background estimates

CDMS-EDELWEISS Combined Limit

- EDELWEISS also uses cryogenic Ge detectors to search for WIMPs at Modane Underground Laboratory (4800 mwe)

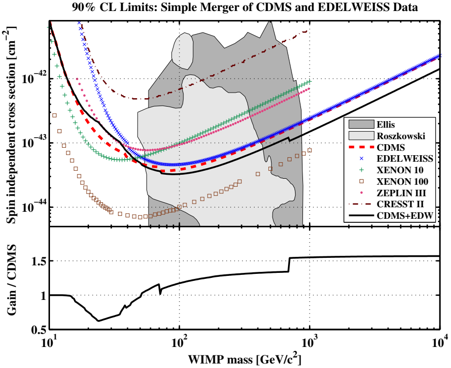


Z. Ahmed *et al.*, Phys. Rev. D **84**, 011102 (2011)

- Same target nucleus allows results to be combined without introducing additional model dependence
- Technology not identical: 400 g crystals & patterned electrodes
- CDMS data:
  - Threshold pushed down to 5 keV
  - 4 events observed
- EDELWEISS data:
  - Threshold set at 20 keV
  - 5 events observed

CDMS-EDELWEISS Combined Limit

- Sum exposure-weighted efficiencies
- Treat all events on equal footing regardless of experiment of origin
- Biggest improvement at high WIMP masses due to large eventless window between 23.2 & 172 keV
  - Up to a factor of ~ 1.6 for $M_\chi >\sim 50$ GeV
- Low energy events in EDELWEISS lead to degredation in limit for low mass WIMPs



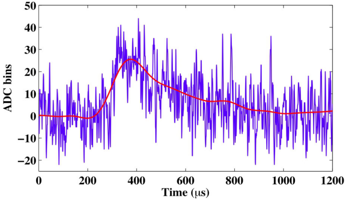
Z. Ahmed *et al.*, Phys. Rev. D **84**, 011102 (2011)

- Alternative procedures for combining data are explored, and could provide stronger constraints at certain masses

CDMS-II Low Energy Analysis

- Recent results from DAMA/LIBRA & CoGENT have been interpreted in terms of elastic scatters from a WIMP with mass $\sim$ 10 GeV and cross-section $\sim 10^{-40}$ cm^2
- Previous CDMS results not sensitive to such WIMPs since thresholds were $\sim$ 10 keV to maintain sufficient rejection of electron recoils

- Can lower threshold significantly at cost of higher backgrounds
- Repeat analysis with lower 2 keV threshold:
  - Use 8 Ge detectors with lowest thresholds
  - Results driven by best detector (Tower 1, ZIP 5)

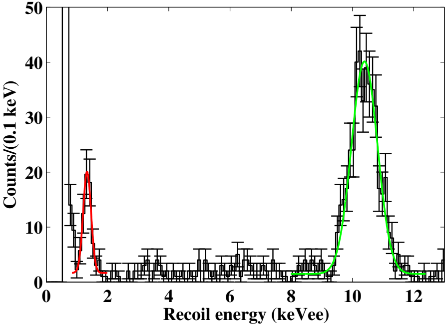


2 keVnr phonon pulse (Tower 1 ZIP 5)

Energy Calibration

- Ionisation energy scale initially calibrated with 356 keV line (^{133}Ba)
- Phonon energy calibrated by normalising phonon-based recoil energy for electron recoils to their mean ionisation energy
- From 1.3 and 10.4 keV lines, small rescaling ($\sim 4\%$) applied to ensure electron recoil energy scale was not underestimated

1.333 ± 0.025 keVee $\quad$ 10.39 ± 0.02 keVee



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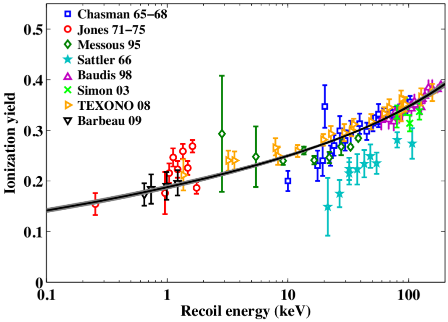
Please see S. Fallows APS talk



- Ionisation yield measured for nuclear recoils from ^{252}Cf source

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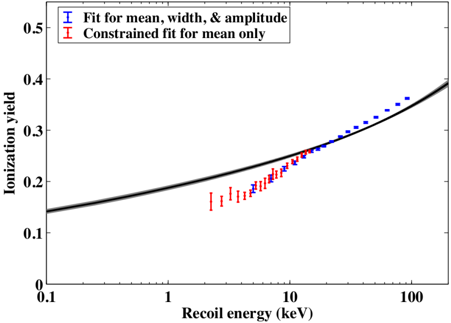
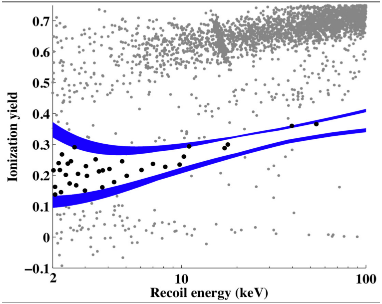


- Ionisation yield measured for nuclear recoils from ^{252}Cf source
  - Measured to $\sim$ 4 keV, power-law extrapolation to lower energies
  - Conservative when compared with literature

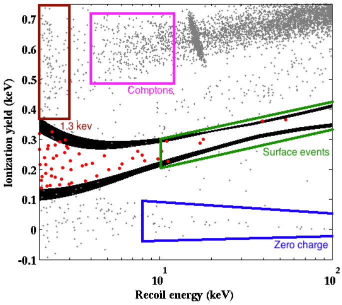
Nuclear Recoil Definition

- Ionisation energy within $(+1.25,-0.5)\sigma$ of mean from ^{252}Cf calibration
- Maximise sensitivity while limiting leakage from electron recoils & zero-charge events



Nuclear Recoil Definition

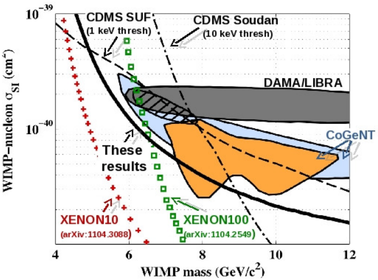
- Ionisation energy within $(+1.25,-0.5)\sigma$ of mean from ^{252}Cf calibration
- Maximise sensitivity while limiting leakage from electron recoils & zero-charge events
- Events in nuclear recoil band can be identified as possible background
- Zero-charge events have ionisation signals consistent with noise
  - Charge carriers collected on cylindrical wall
  - At $E_R < 10$ keV, phonon-based reconstruction unreliable



- Signal-to-noise too low at $E_R < 5$ keV to reject surface events with phonon timing
- At $E_R < 5$ keV ionisation-based discrimination breaks down
- 1.3 keV line leaks above 2 keV threshold as recoil energy estimate assumes ionisation signal is consistent with nuclear recoil

90% Confidence Upper Limits

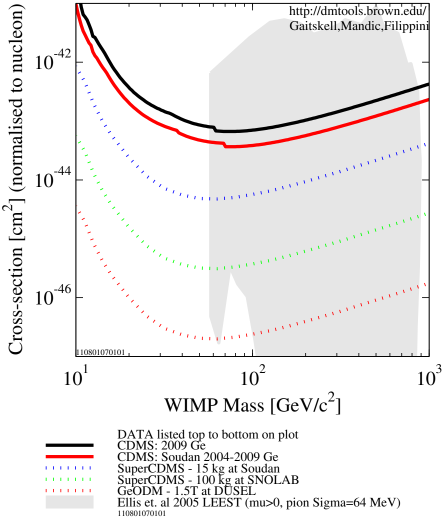
- Can extrapolate observed spectra for each potential background to lower energies to estimate leakage, but systematic errors are potentially large and difficult to quantify
- Therefore, be conservative and assume all candidates are WIMPs
- No background subtraction
- For spin-independent, elastic scattering, 90% confidence level limits incompatible with DAMA/LIBRA & CoGENT excess



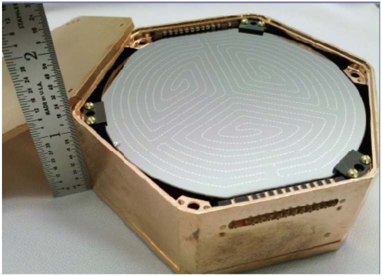
Z. Ahmed *et al.*, Phys. Rev. Lett. **106**, 131302 (2011)
D. S. Akerib *et al.*, Phys. Rev. D **82**, 122004 (2010)

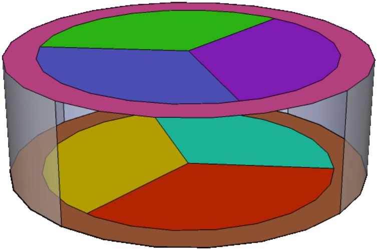
CDMS-II $\Longrightarrow$ SuperCDMS $\Longrightarrow$ GEODM

1. CDMS-II @ Soudan
   - $3''\phi \times 1$ cm $\rightarrow$ 250 g/det
   - Target mass 4 kg
   - $\sim$ 2 years $\rightarrow$ 612 kg-days
2. SuperCDMS Soudan
   - $3''\phi \times 1''$ $\rightarrow$ 600 g/det
   - Target mass 15 kg
   - 2 years $\rightarrow\sim$ 8000 kg-days
3. SuperCDMS SNOLAB
   - 100 mm $\phi\times$ 33.3 mm $\rightarrow$ 1.37 kg/det
   - Target mass 100 kg
   - 3 years $\rightarrow\sim$ 100000 kg-days
4. Ge-Observatory for Dark Matter (GEODM) @ SNOLAB/DUSEL
   - $6''\phi \times 2''$ $\rightarrow$ 5 kg/det
   - Target mass 1.5 T
   - 4 years $\rightarrow\sim$ 1500000 kg-days



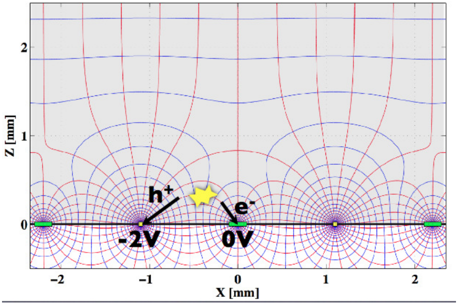
SuperCDMS Soudan Detector: iZIP

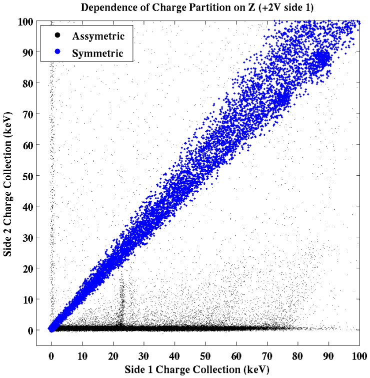




- interleaved Z-sensitive Ionisation & Phonon detector (iZIP)
- New detector design to improve surface event rejection efficiency
- Larger 3″ diameter, 1″ thick, 600 g crystals
- 8 phonon sensors, 4 on each side, provides new information on interaction depth
- Increased phonon sensor surface coverage improves collection efficiency and signal-to-noise ratio
- Better timing resolution from outer phonon sensor ring, which also breaks degeneracies in position reconstruction

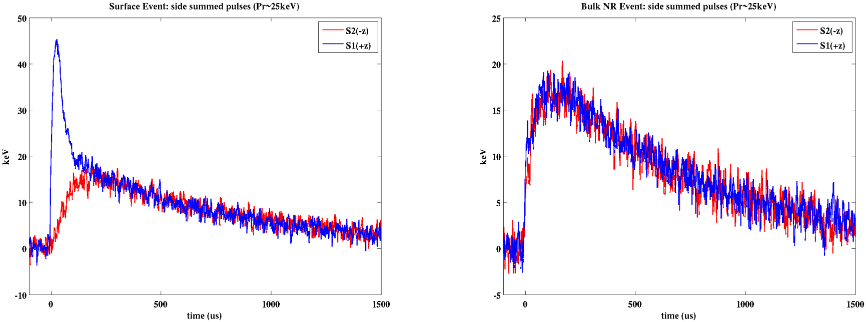
- Two ionisation electrodes on each surface: central disc & outer ring





- Interleaved electrodes, so surface events show up on one detector side only

Surface Event Rejection: Phonon Signals

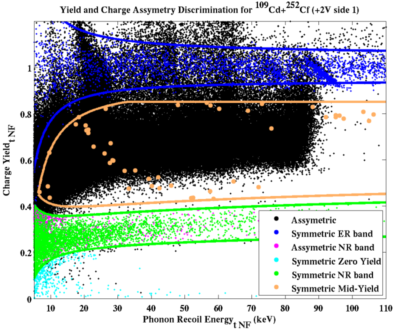


Two phonon-based discrimination parameters:

- Pulse shape differences as with ZIPs
- Side asymmetry provides new surface event rejection parameter

iZIP Performance

Preliminary

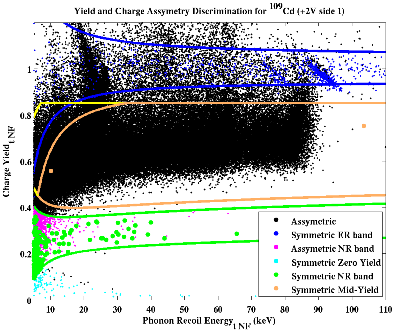


Electron recoils (^{133}Ba γ-rays)
Surface events (^{109}Cd β-particles)
Nuclear recoils (^{252}Cf neutrons & 7 evt/h background at surface test facility)

- Electron & nuclear recoils well-separated above $\approx$ 6 keV

iZIP Performance

Preliminary

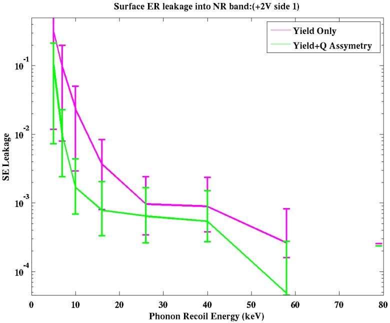


Electron recoils (^{133}Ba γ-rays)

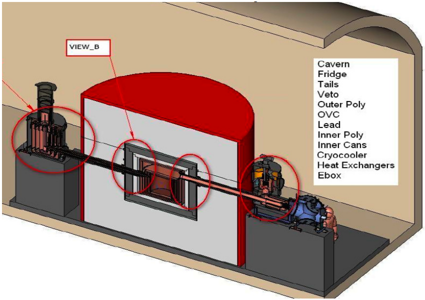
Surface events (^{109}Cd β-particles)

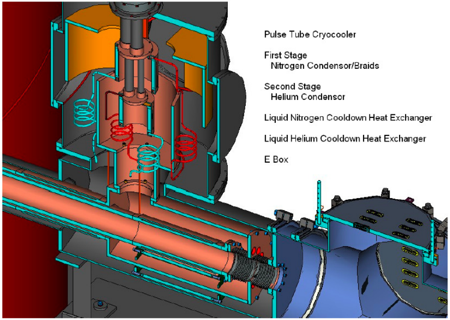
Nuclear recoils (7 evt/h background at surface test facility)

- Electron & nuclear recoils well-separated above $\approx$ 6 keV
- Yield-only discrimination begins to fail at 10 keV



SuperCDMS SNOLAB





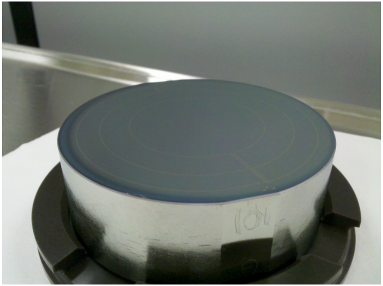
- Target mass 100 kg
- SNOLAB provides deeper facility ($>$ 4000 mwe) than Soudan
- New fridge and shield design work in progress at Fermilab
- Deploy crystals of iZIP detector technology

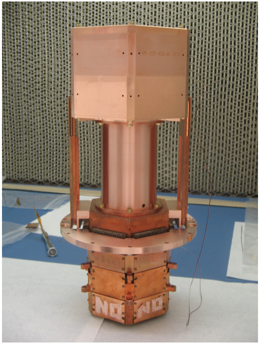
Scaling to 100–1000 kg

- iZIP technology appears to meet requirements for larger target masses
- Scaling difficult: $\sim 170\ 3''\phi \times 1''$ crystals for 100 kg target mass
- A number of factors make this expensive:
  - Increased manpower: fabrication and testing are labour intensive
  - Increased heat load: additional wiring to room temperature and Field Effect Transistors (FETs) on 4 K stage (5 mW/FET)
  - Increased cold hardware & warm electronics
- Can alleviate these problems through a number of R & D directions we are currently pursuing, to simplify the technology and hence reduce the cost:
  - Multiplexing to reduce number of signal wires to room temperature
  - Alternative SQUID-based ionisation readout
  - Increase the size of individual detectors

100 mm Diameter Germanium Crystals

- Up to 100 mm diameter detector-grade Ge crystals can be grown
- Purchased 2 crystals from Umicore, 33.3 mm thick and of mass 1.37 kg

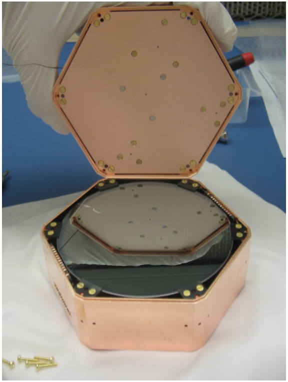




- Fabricated at SLAC & Stanford, and tested at Minnesota
- New hardware to enable standard 3″ readout

Ionisation Measurements

- Ionisation electrodes patterned as four concentric rings
- ^{241}Am source above each electrode



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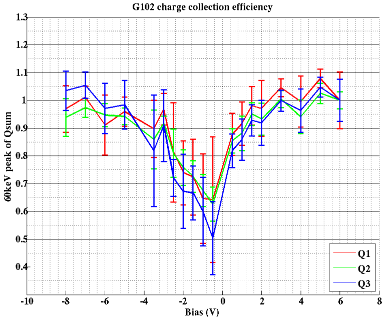

- Charge collection efficiency:
  - Bias voltage varied across detector
  - Gaussian fit to summed charge spectra from all four channels
  - Mean of peak used as a measure of charge collection efficiency
  - Scaling past measurements on 1 cm thick crystals, a bias voltage of 1.7 V required to achieve complete charge collection
- These crystals have necessary charge collection efficiency to be operated as dark matter detectors

To be presented at LTD14 on Thursday & to appear in J. Low Temp. Phys.

Summary

- CDMS-II has completed operation
  - See 2 candidate events, but cannot claim nor reject these as possible WIMPs
  - Reanalysis in progress to reduce background estimates
  - New result published combining CDMS & EDELWEISS data
  - Recent reanalysis with lower 2 keV threshold incompatable with an interpretation of DAMA/LIBRA & CoGENT in terms of spin-independent elastic scatters of low-mass WIMPs
- iZIP technology allows for better rejection of surface events:
  - Essential for scaling to larger target masses
  - 15 kg of 3″ diameter, 1″ thick Ge iZIP detectors to be installed at Soudan in Autumn 2011 forming SuperCDMS Soudan
- Ionisation tests conducted on larger 100 mm diameter, 33.3 mm thick Ge crystal:
  - Crystals have necessary charge collection efficiency to be operated as dark matter detectors
  - New mask designed with interleaved electrodes to investigate surface event rejection