Recent results from the SuperCDMS experiment and the status of SuperCDMS SNOLAB

Robert Calkins

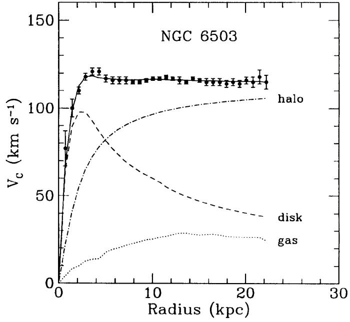
Southern Methodist University

October 19, 2015

Introduction

1. Dark Matter and WIMPs
2. SuperCDMS Soudan
   - The detectors
   - Performance
   - CDMSlite analysis
   - High threshold analysis
3. SuperCDMS SNOLAB project
   - Experiment design
   - Science goals
   - Estimated backgrounds
   - Projected sensitivity

Dark Matter in the Universe?

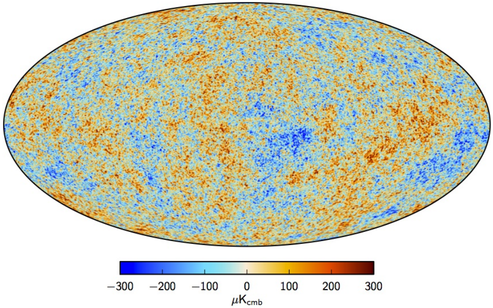


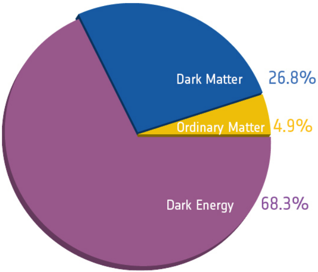
[1]

- Modern interest but a old problem, dates back to 1930s
- Oort noticed discrepancies with nearby star velocities
- Zwicky noted galactic velocities in the Coma Cluster are too large for the mass
- Rubin measured galactic rotation curves, going too fast

[1] Freese 2009

Composition of the Universe



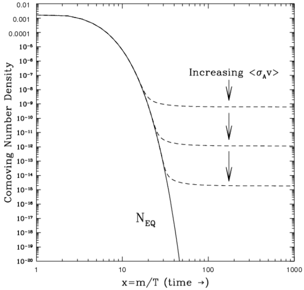


[2]

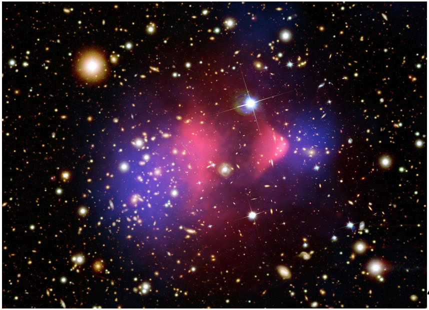
- We don't know much about the majority of the universe
- Assuming the SM is complete, we are 5% done
- Most of the matter is invisible according to cosmological data

[2] PLANCK 2015 - arXiv:1502:01582

The WIMP hypothesis



[3]


[4]

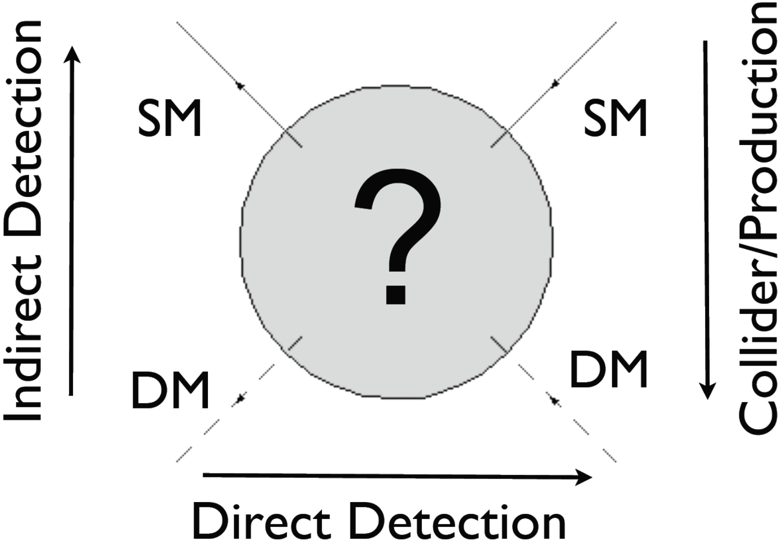
- WIMP - 'Weakly' Interacting Massive Particle
- A 100 GeV particle with weak couplings gives correct relic density - WIMP 'Miracle/Coincidence'

---

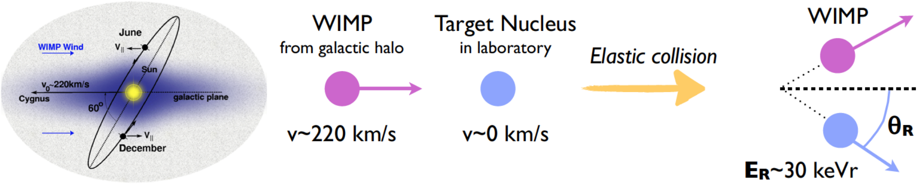
[3] arXiv:0901.4090 [hep-ph]

[4] X-ray: NASA/CXC/CfA/ M.Markevitch et al.;Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;

Paths to discovery



Direct detection event rates



- Direct detection experiments rely on having a target material, wait for 220 km/s WIMP wind to blow
- Expect a local DM density of ≈0.4 GeV/cm^3
- Rate should modulate annually due to Earth's motion around Sun [5]

[5] DAMA/LIBRA claims to have seen this signal

Direct detection event rates

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_n m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R) dv$$

With:

$$E_R = \frac{\mu_N^2 v^2 (2 - cos\theta)}{m_N}$$ - recoil energy

$f(v)$ - normalized WIMP velocity distribution in detector frame

$$u_N = \frac{m_\chi m_N}{m_\chi + m_N}$$ - reduced mass

$$v_{min} = \sqrt{\frac{m_N E_R}{2\mu_N^2}}$$ - minimum velocity for recoil energy E_R

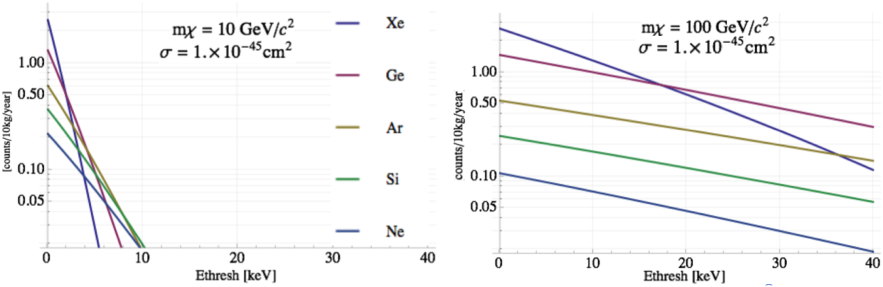
$$\frac{d\sigma_{WN}}{dE_R} = \frac{m_N}{2\mu_N^2 v^2}(\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R))$$

- Contributions for particle, nuclear and astro physics
- We expect just a few events every year from WIMPs

---

reference : arXiv:1002.1912 [astro-ph.CO]

Choice of target material

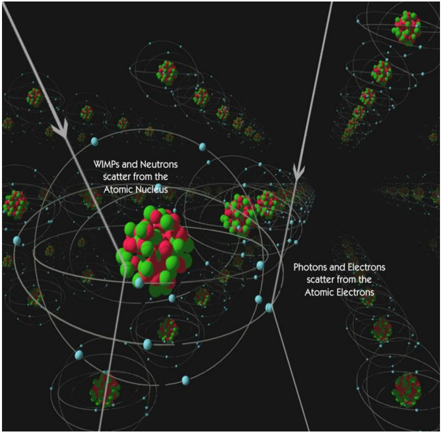


[6]

- Event rates depend on WIMP and target nuclei mass
- Thresholds matter a lot, especially for low masses!
- Spin-dependent interactions add a whole additional layer of complexity

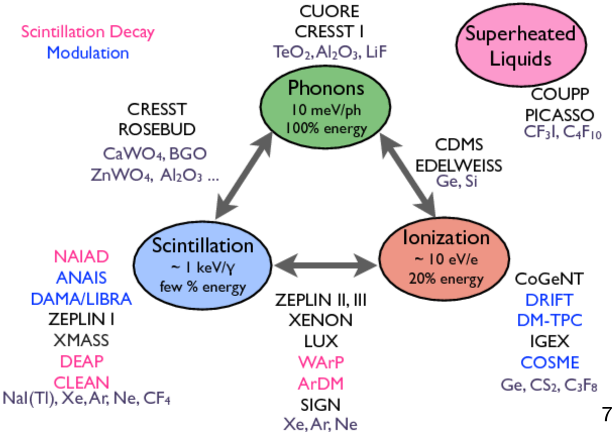
[6] arXiv:1308.0044 [astro-ph.IM]

WIMP-nucleus interactions



- Interactions come in two types
  1. Nuclear recoil (NR) - recoils against nucleus
  2. Electron recoil (ER) - recoils against surrounding electrons

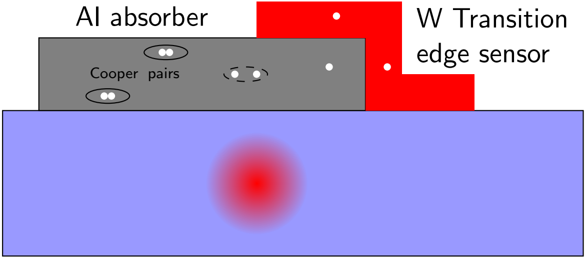
Overview of direct detection approaches

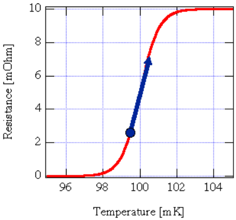


[7]

[7] arXiv:1203.2566 [physics.ins-det]

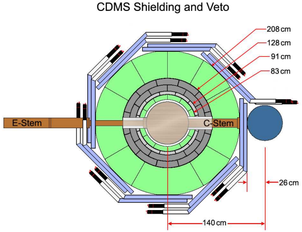
Phonons and TES

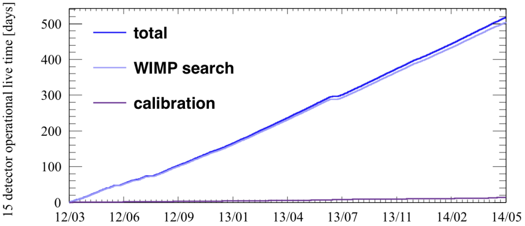




- Phonons are an quantum of vibration
- Transition Edge Sensor is held at critical temperature $\rightarrow$ large changes in R

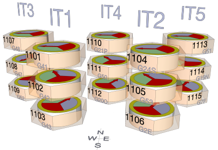
SuperCDMS Soudan

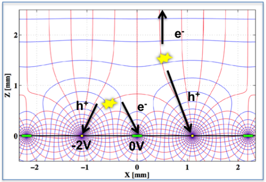


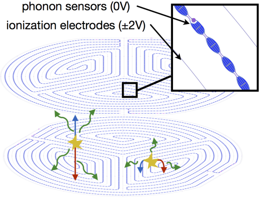


- Located in Soudan Underground Lab, $\approx \frac{1}{2}$ mile underground with 2090 M.W.E. of overburden
- Utilizes the shielding and cryostat from CDMS-II experiment
- Started exposure in March 2012 and finished main exposure in May 2014
- Currently doing dedicated studies and disassembling

interleaved Z-sensitive Ionization and Phonon (iZIP) Detectors

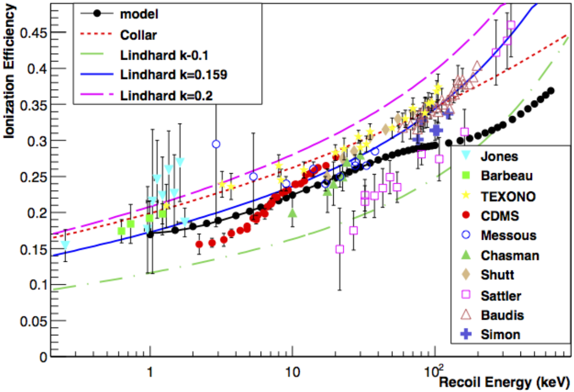






- Detector array :15 Ge iZIP detectors (0.6 kg each) held at 50 mK
- 4 phonon and 2 charge channels on each detector face
- Phonon channels are grounded, charge channels are biased at $\pm$ 2 V
- Field configuration causes events near surface to have charge collection localized to one side

Nuclear recoils in crystals

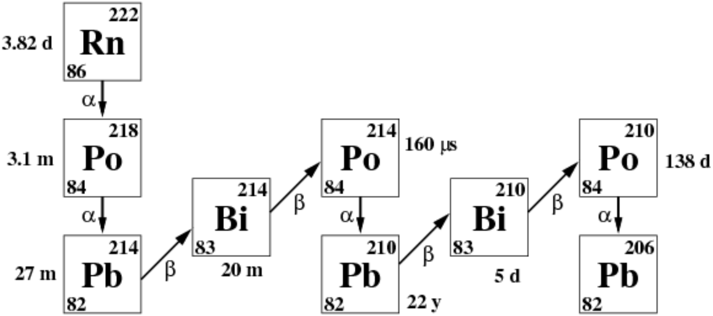


[8]

- Nuclear recoils have only a fraction of their energy in ionization
- Can be reasonably modeled using Lindhard model

[8] arXiv:1304.6773 [physics.ins-det]

Rn and ^{210}Pb

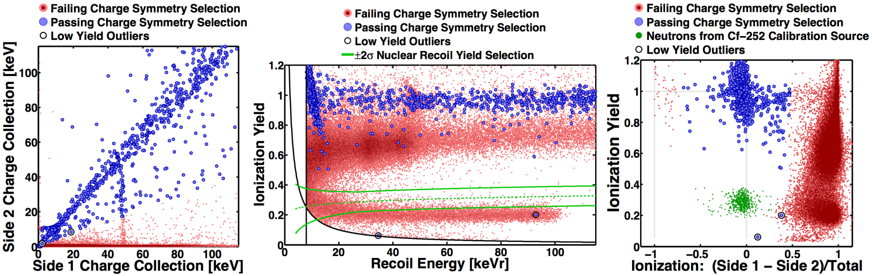


[9]

- Rn is common in atmosphere, produced by U/Th chain
- Pb/Po atoms can 'plate-out' onto surfaces
- ^{210}Pb has a 22y half life > lifetime of experiment
- Contamination becomes a source of gammas, betas and ^{206}Pb nuclei

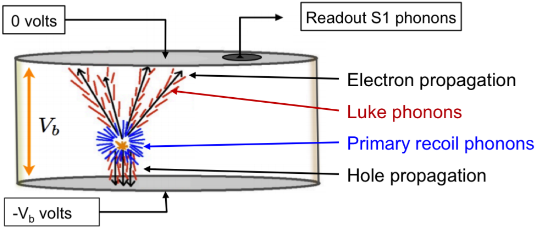
[9] figure from arXiv:1101.0126 [nucl-ex]

Discrimination



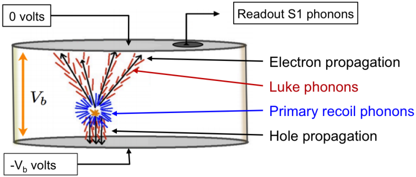
- Two of the detectors are faced with a ^{210}Pb implanted Si wafer as a calibration source for ^{206}Pb nuclei and low-energy betas
- Yield is still a powerful discriminant but can be combined with charge asymmetry to improve rejection of surface events
- Set an upper limit of 1.3×10^{-5} for surface event rejection power in the nuclear recoil signal region

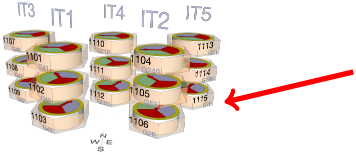
HV Biasing



- Phonons are created from charges passing through a crystal through Luke-Neganov effect
- The contribution to total phonon energy goes as $N_{e/h}eV_b$: proportional to bias voltage V_b
- High bias voltage allows us to measure small amount of charges through phonon signal (CDMSlite mode)
- Trade-off: no separate measurement of primary phonon signal, sacrifices ER/NR discrimination

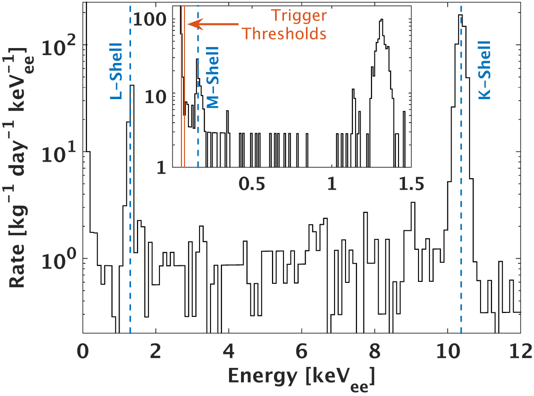
CDMSlite : Introduction





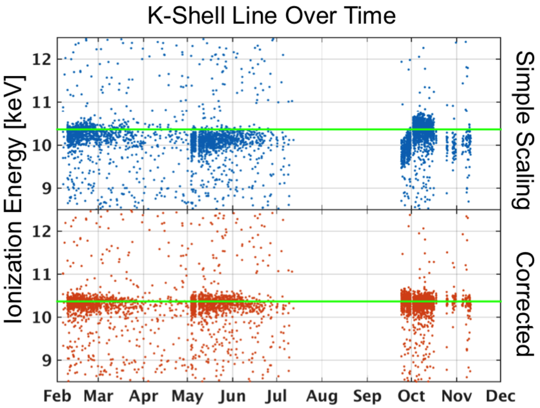
- Low Ionization Threshold Experiment (Lite) - using T5Z2
- Uses L-N amplification to measure small charge signals using phonons
- Two physics runs, separated by cryogenic maintenance
- Run 1 results published in PRL 112, 04130 in 2013
  1. $V_b = 69$ V bias
  2. 6.5 kg-d exposure
- Run 2 ran Feb-Nov 2014, results shown at TAUP2015
  1. $V_b = 70$ V bias
  2. Utilizes one detector, 70.10 kg-d exposure
  3. Divided into two sub periods due to cryo maintenance

CDMSlite : Energy Scale Calibration



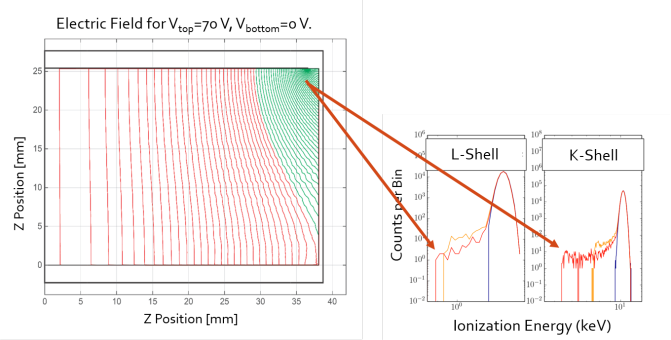
- Ge has some low energy activation lines = calibration source
- Activation comes from periodic ^{252}Cf calibration

CDMSlite : Energy Scale Stability



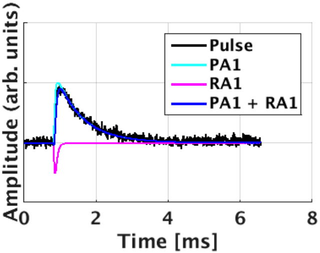
- Many things (temperature, HV fluctuations, ect..) can affect energy scale
- Tracking the peak allows us to correct for it

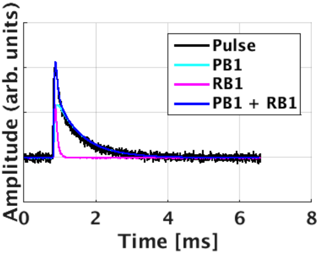
CDMSlite : Fiducial Volume

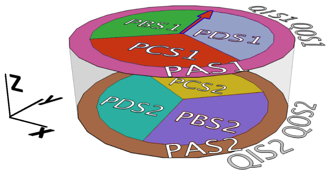


- Detector is housed in a grounded Cu housing
- Not all portions see full bias potential → low energy tails in peaks
- Betas, alphas and many gammas will propagate this region
- Bottom line : We want to cut away the sidewall portions

CDMSlite : Fast and slow Pulse shapes

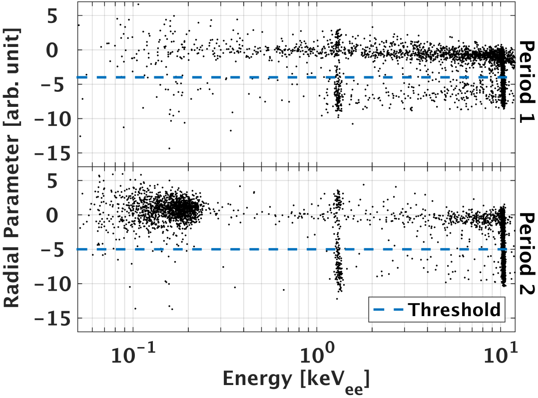






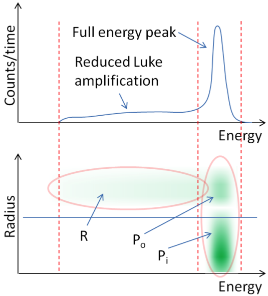
- Reconstructed using a two-template optimal filtering algorithm
- Fast template gives information about position, slow template contains information about energy

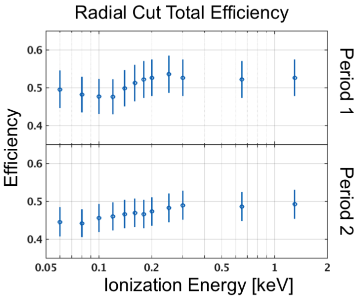
CDMSlite : Radial Cut



- A new background appeared in second portion of run
- Higher values indicate higher radius, keep events below lines

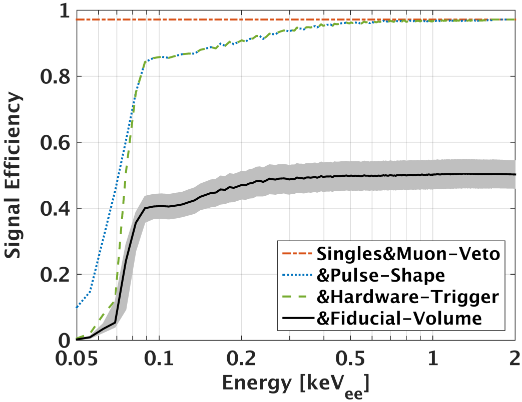
CDMSlite : Radial Cut Efficiency





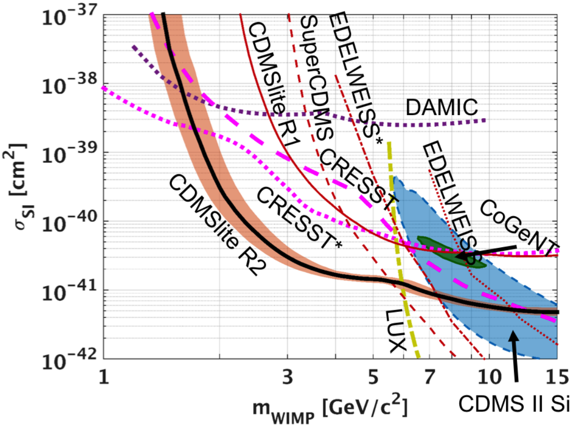
- Activation events appear uniformly throughout detector, can be used for calibration
- Half-lives of activation peaks are known $\rightarrow$ can estimate non-peak tails assuming decay $+$ constant background

CDMSlite : Overall efficiency



- Veto events with activity in other iZIPs or muon panels
- Biggest hit comes from fiducialization

CDMSlite : Results



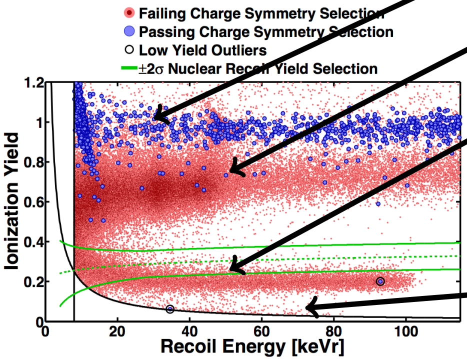
- Rely on Lindhard to convert to keV$_{nr}$ scale
- Limits set using Yellin optimal interval method [10]

[10] arXiv:physics/0203002

High mass WIMP search : Introduction

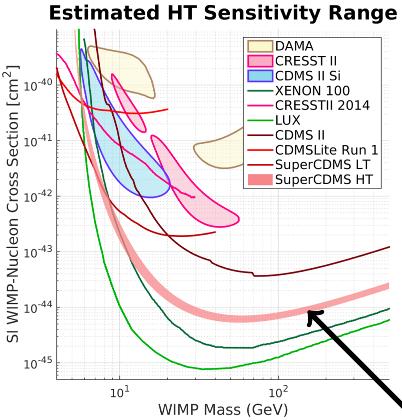
- Search uses data collected from Feb 2012 - May 2014
- Utilizes majority of the detector array excluding CDMSlite detector
- Collected about 2500 kg-days of raw exposure
- Heavy masses $\rightarrow$ more energy, thresholds don't matter as much
- Downside, lower number density $\rightarrow$ fiducial volumes and exposures are critical
- Background rejection is very good at high energies, also makes modeling difficult

High mass WIMP search : Sources of Backgrounds



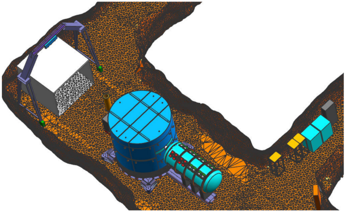
- Bulk gammas - modeled with ^{133}Ba gamma calibration data
- Betas - modeled from ^{210}Pb source and Ba data
- ^{210}Pb induced surface events - rates can be measured through alphas, modeling based on controlled sources (calibration plates, test facilities)
- Zero charge - originate from gammas interactions in regions with weak E-field at high radius, traditionally removed through ionization threshold

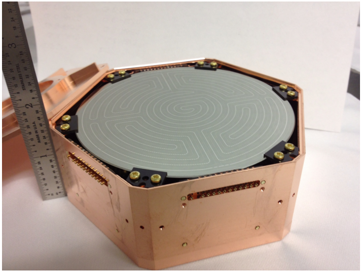
High mass WIMP search : Projected Sensitivity



- Analysis will focus on a subset of our best detectors
- Several techniques being pursued such as aBDT, cut-and-count and profile likelihood
- Assumptions used to derive sensitivity estimate
    1. 60-65% fiducial volume
    2. 95% data quality efficiency
    3. Phonon thresholds as measured for the individual detectors
    4. 11-14 detectors used
- Limits will be improved by an order of magnitude over CDMS-II analysis

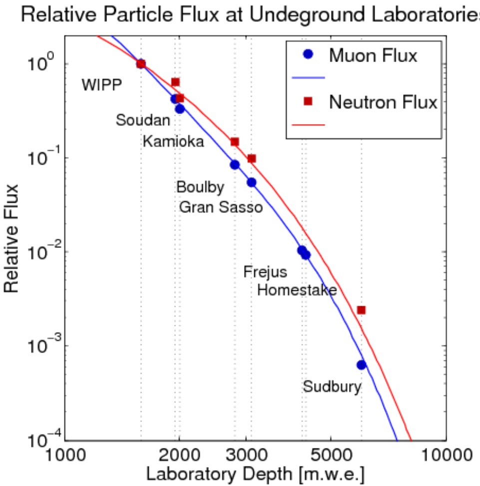
SuperCDMS SNOLAB : Introduction





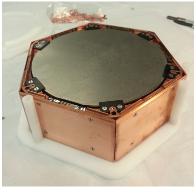
- One of three G-2 experiment selected to go forward
- SuperCDMS SNOLAB, whole new experiment at Creighton Mine, Sudbury, Canada
- SNOLAB : $\approx$ 2 km underground; 6010 mwe of shielding from cosmics; entire lab is class 2000 cleanroom
- Space at SNOLAB is reserved in ladder labs

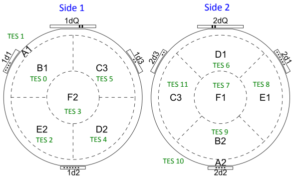
SuperCDMS SNOLAB : Overburden

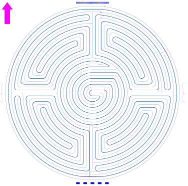


- For comparison : Soudan is .7 km underground
- Muons can induce neutrons from surrounding rock and materials
- Materials can become activated by cosmic rays
  1. Ge $\rightarrow$ ^{71}Ge
  2. Cu $\rightarrow$ ^{60}Co
  3. H $\rightarrow$ ^{3}H
- Going three times deeper buys orders of magnitude reduction

SuperCDMS SNOLAB : iZIP Detectors

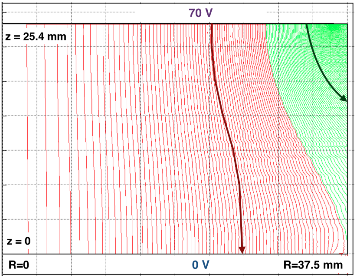


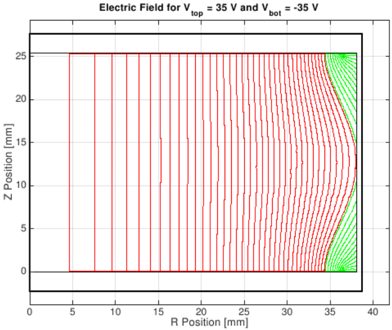




- Crystal dimensions : 33 mm thick, 100 mm diameter
- Two target materials : Ge (1.39 kg/detector) and Si (0.6 kg/detector)
- 6 phonon channels and 2 charge channels on each detector face (interleaved like in SuperCDMS Soudan detectors)

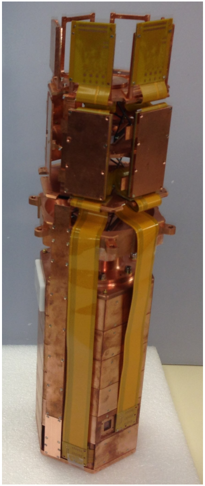
SuperCDMS SNOLAB : HV Biasing

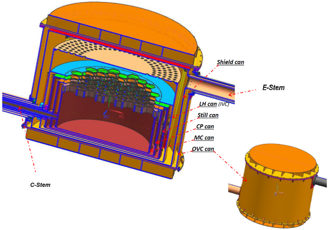


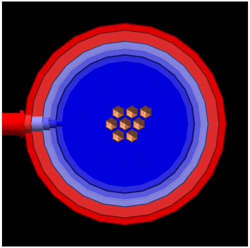


- Larger crystals will allow for increase from 70V to 100V
- Exploring double sided bias mode to improve fiducial volume
- Expected trigger threshold for SNOLAB: 70 eVt (total phonon energy); at 100 V bias this corresponds to single electron-hole pairs

SuperCDMS SNOLAB : Towers and Payload

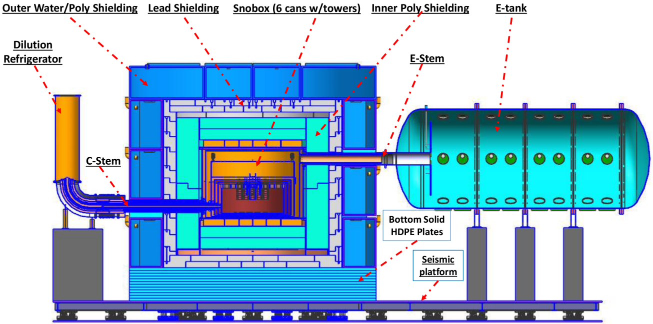






- Baseline design consists of 8 towers
- One tower will be entirely HV biased, with a mix of Ge and Si detectors
- One tower will consist of Si detectors
- Optimization of exact payload is still on-going

SuperCDMS SNOLAB : Shielding Design



- Similar to Soudan design, water tanks instead of poly in outer layers
- Lead shielding will consist of two layers, outer lead and an inner ancient Pb liner
- Inner poly maybe replaced with an active neutron veto in a future upgrade after initial deployment

SuperCDMS SNOLAB : Science Goals

- Mix of Ge/Si and HV/iZIP gives four WIMP search configurations
  1. Ge iZIP - 36 detectors, 50 kg
  2. Si iZIP - 6 detectors, 4.1 kg
  3. Ge HV - 4 detectors, 5.6 kg
  4. Si HV - 2 detectors, 1.4 kg
- HV detectors provide sensitivity to lowest masses while iZIP detectors cover above $\approx$5 GeV/c^2
- Different targets let us study non-standard interactions
- Can search for axions and lightly ionizing particles
- Expect to observe coherent scattering of ^{8}B solar neutrinos
- Cryostat will allow for future payload upgrades

SuperCDMS SNOLAB : Background Sources

- Same sources as Soudan HT analysis will also be present at SuperCDMS SNOLAB
- Neutrons are a dominant background for high mass WIMP searches, electron recoils dominate low mass search
- Lack of background discrimination in HV detectors means we need to get low energy background rates down during construction
- The lower background means that new background sources become important like ^3H

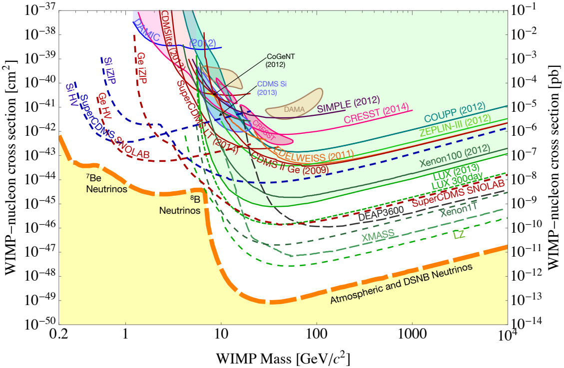
SuperCDMS SNOLAB : Expected Background Rates

Material	^{238}U	^{232}Th	^{40}K	Reference
Polyethylene	0.03 mBq/kg	0.02 mBq/kg	0.1 mBq/kg	DEAP
Copper	0.07 mBq/kg	0.02 mBq/kg	0.04 mBq/kg	XENON100
Lead	0.66 mBq/kg	0.5 mBq/kg	7.0 mBq/kg	XENON100
Detector and Housing surfaces		^{206}Pb: 25 nBq/cm^2		SuperCDMS Soudan

Type	Soudan Calculated Singles Rate events/keVr/kg/yr	SNOLAB Assumed Singles Rate events/keVr/kg/yr
Cosmogenic Neutrons	1.5×10^{-4}	2.8×10^{-5}
Radiogenic Neutrons	8×10^{-4}	2.5×10^{-5}
Bulk Gammas	1.1×10^{3}	2.2
Top/bottom Surface β	1.2	1.2
Radial Surface β	114	4.4
Top/Bottom Surface ^{206}Pb	0.18	0.18
Radial Surface ^{206}Pb	23	1
Cosmogenic Activation (^{3}H)	-	16.4 (Ge), 93.3 (Si)

- Backgrounds are simulated using a GEANT4 based framework
- Contamination rates are taken from literature
- Gamma rate is driven by contamination in Cu cryostat

SuperCDMS SNOLAB : Projected Reach



- SuperCDMS SNOLAB will be leading the way at for low mass WIMPS using HV biased detectors
- Standard detectors will give sensitivity to intermediate mass range; expect to reach neutrino floor around 10 GeV/c^2

Conclusion/Summary

- Dark matter is one of the big open puzzles in physics
- CDMSlite results are currently the most sensitive in the 2-5 GeV range
- We have collected $\approx$ 2500 kg-days of raw exposure with SuperCDMS Soudan for the high mass WIMP search
- Aim is to have a high mass result at beginning of 2016
- As Soudan operations shut down, focus turns to SuperCDMS SNOLAB project
- SuperCDMS SNOLAB will have superior sensitivity to low mass WIMPs
- Agency review process ongoing; CD-1 in a few weeks
- We hope to start collecting data in a few years at SNOLAB!

[11]

...and we hope to do even better!

[11] Zero Gravity: The Lighter Side of Science; Detecting the Dark; Michael Lucibella Feb 2014

The SuperCDMS Collaboration - 2015

California Inst. of Tech. | CNRS-LPN* | Durham University | FNAL | NIST*

Northwestern | PNNL | Queen's University | SLAC | Southern Methodist U.

Santa Clara University | South Dakota SM&T | Stanford University | Texas A&M University | U. British Columbia

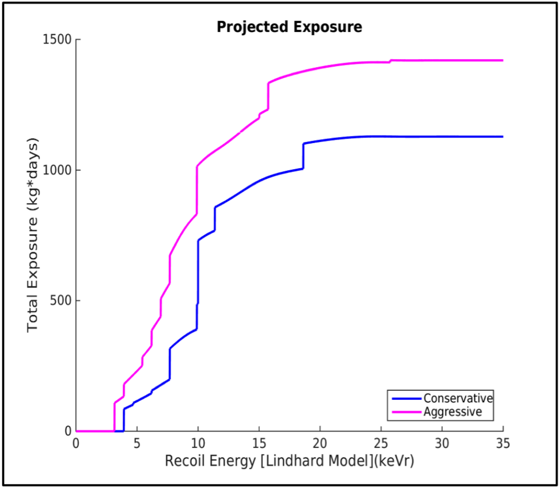
U. California, Berkeley | U. Colorado Denver | U. Evansville | U. Florida | U. Minnesota | U. South Dakota

* Associate members

Backup

Backup slides

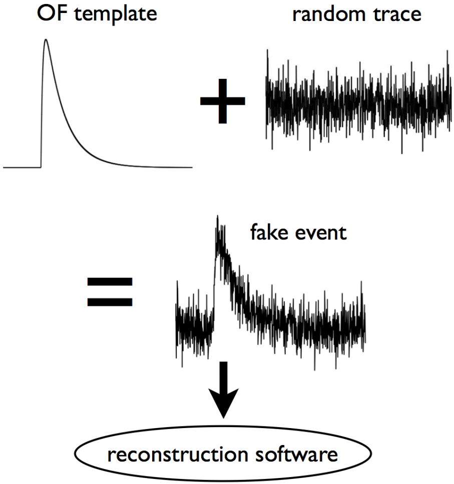
Projected exposure for Soudan HT analysis



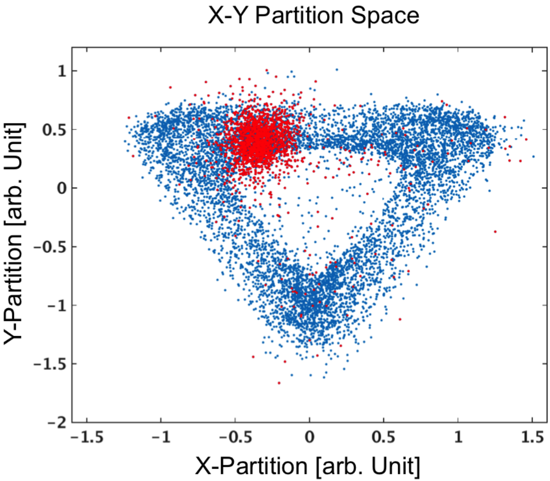
Projected Reach - 5 years exposure details

- 80% duty cycle
- Ge iZIP : 200 kg-y
- Si iZIP : 15 kg-y
- Ge HV : 22 kg-y
- Si HV : 5 kg-y

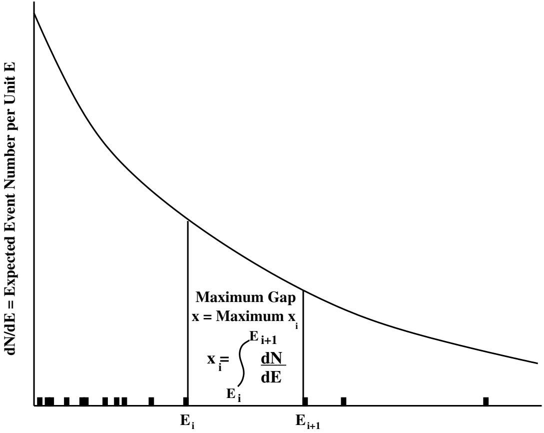
Pulse Simulation



CDMSlite unexpected background



Yellin Optimal Interval



Conceptually similar to the optimal gap method except that it allows for 1 event to fall into region. Assumes all events are signal.