SuperCDMS results and plans for SNOLAB

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The SuperCDMS Collaboration

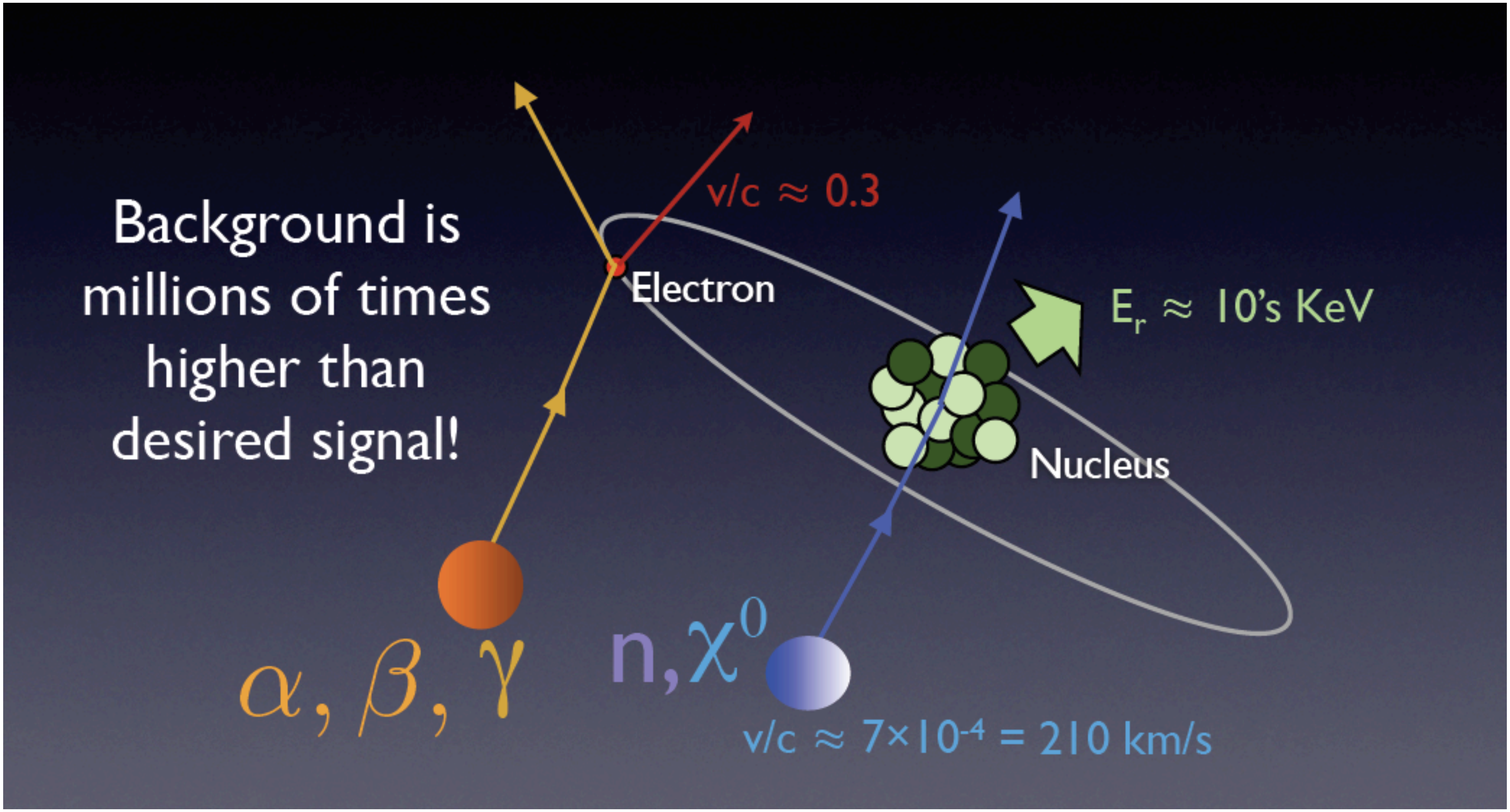
California Inst. of Tech. CNRS-LPN Durham University FNAL Mass. Inst. of Tech.

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. British Columbia

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

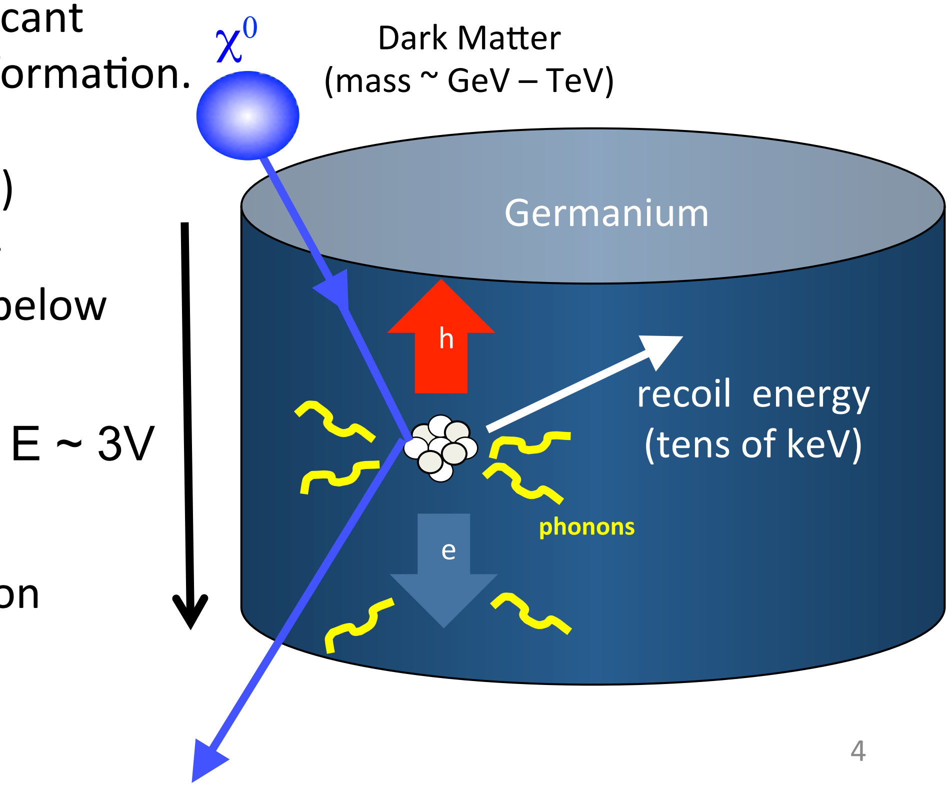
WIMP (χ^0) direct detection



Background is millions of times higher than desired signal!

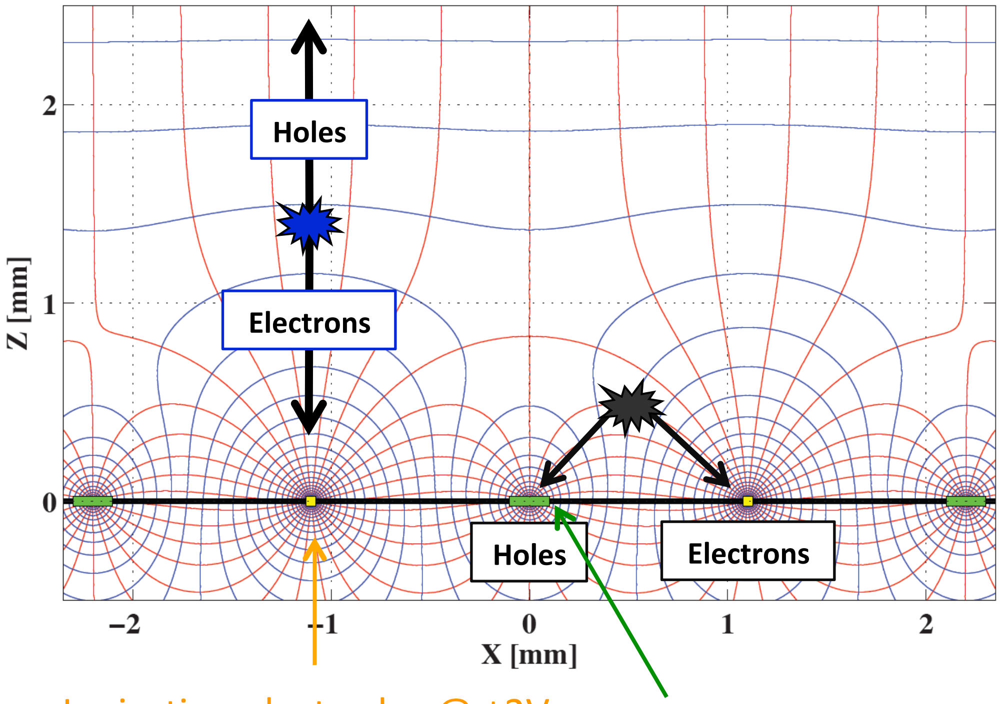
ZIP Detector Operation

- CDMS ‘ZIP’ detectors employ a robust and powerful discrimination technique:
  - Use both ionization and phonon readout to identify signal and background recoil events on an event-by-event basis
  - Most of the energy is determined by the phonon signals, which are not statistically limited and have good energy resolution to improve background rejection.
  - Reading out the phonons before significant thermalization gives event position information.
  - Requires Transition Edge Sensors (TESs) fabricated using semiconductor photo-lithographic techniques and operated below 100 mK.
  - Also measure signal in charge carriers: ionization = holes + electrons to give near-surface location information and identify event recoil type.



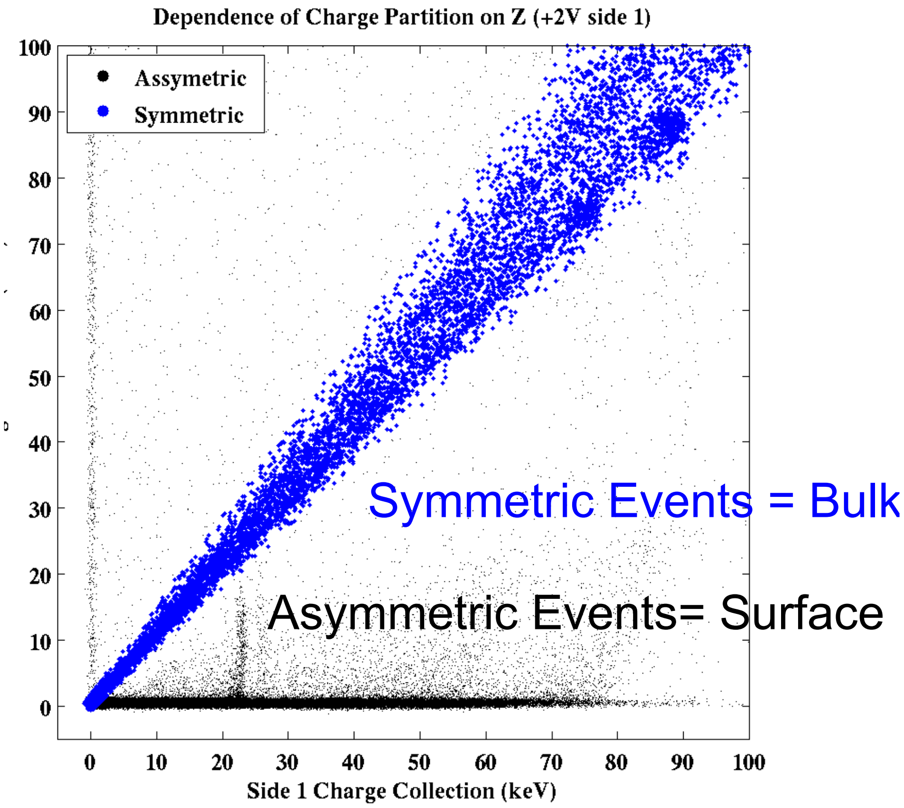
iZIP Charge signals reject near-surface events

- Define a fiducial volume :
  - Outer charge electrodes separately read out for radial information
  - Complex E-fields produced by interleaving electrodes encode near-surface position Information



Ionization electrodes @ ±2V

Phonon sensors @ 0V



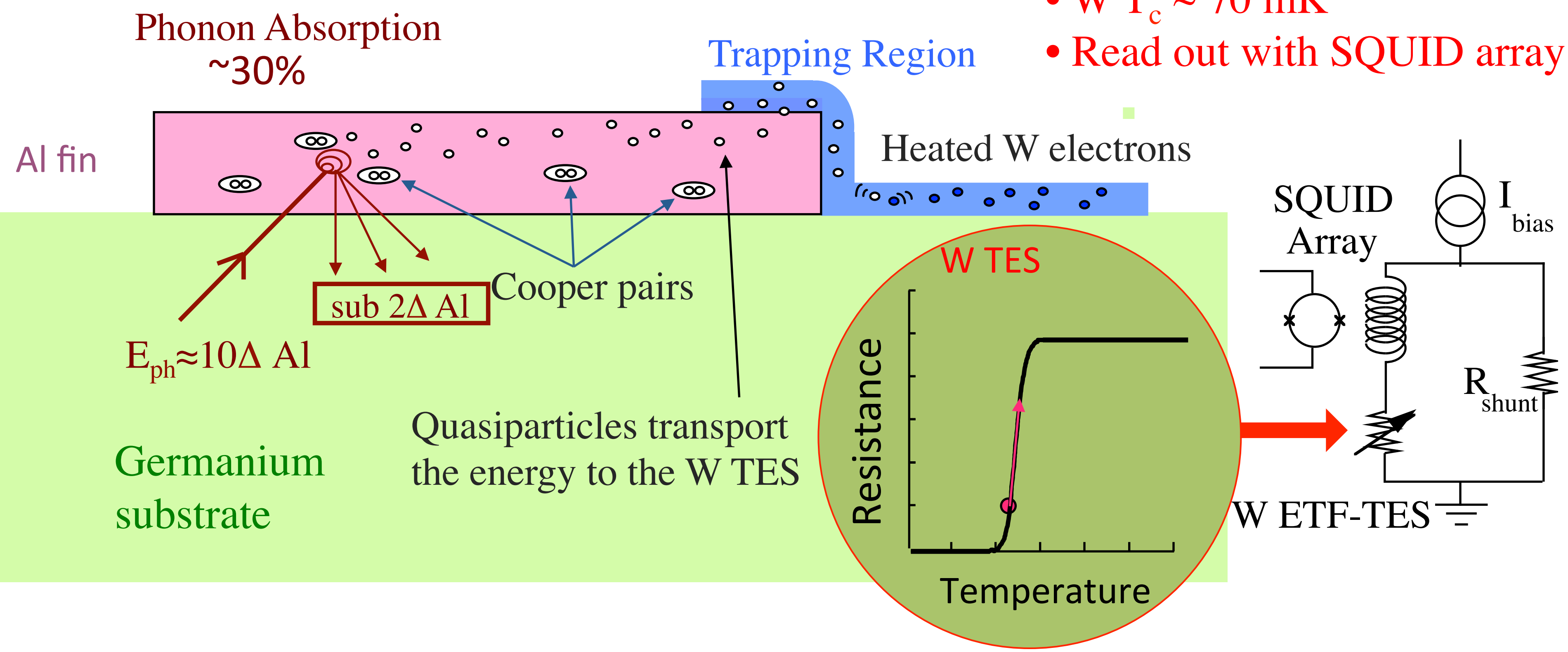
Symmetric Events = Bulk

Asymmetric Events= Surface

CDMS Phonon sensor operation

- Electron or Nuclear recoil event occurs in germanium substrate.
- Aluminum fins 300 nm thick absorb phonons arriving from substrate underneath.
- Fins connect to Tungsten transition edge sensors (W TESs).

- W T_c ~ 70 mK
- Read out with SQUID array



SuperCDMS ZIP background rejection

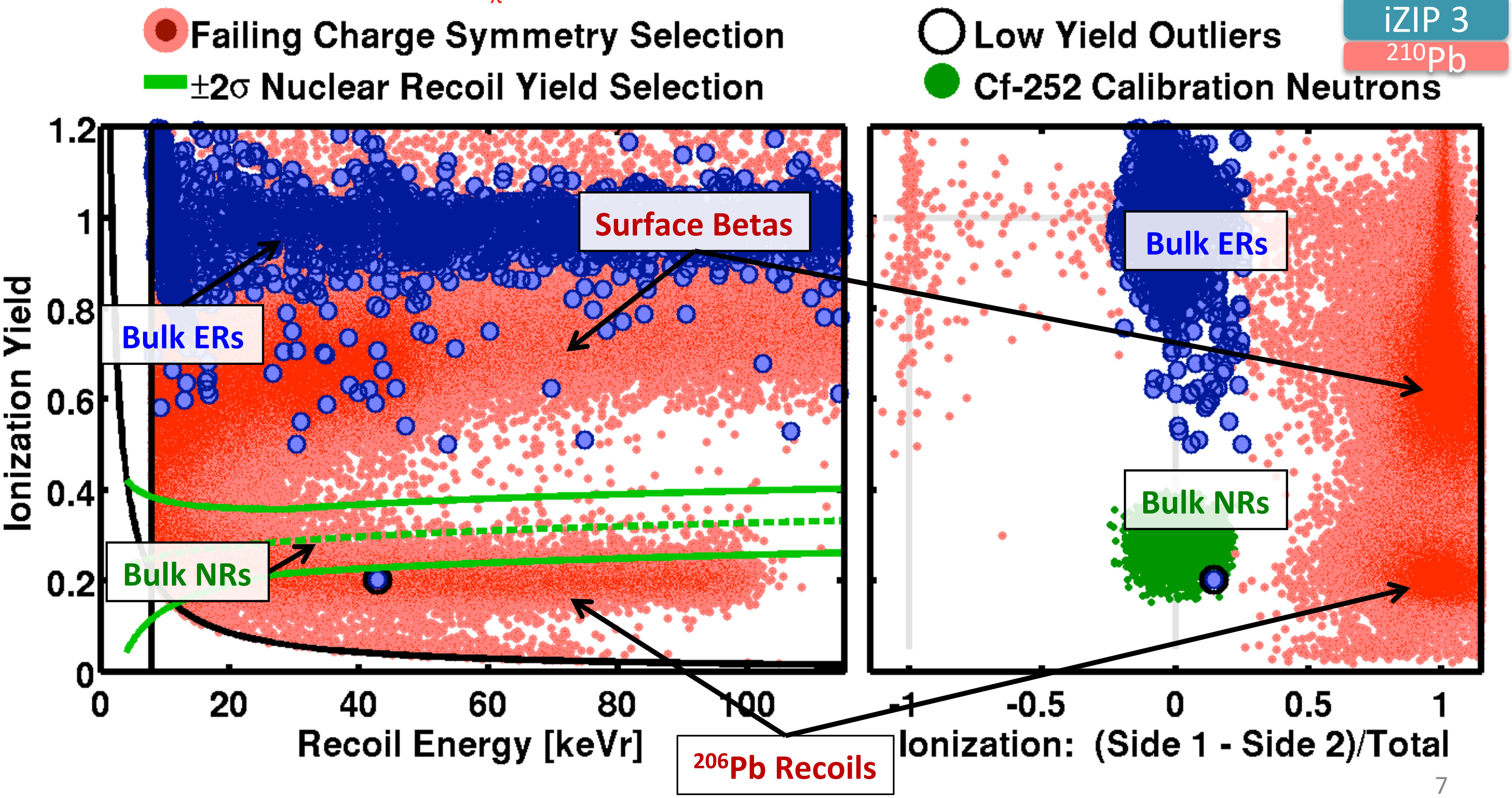
Surface-event Rn-daughter sources placed above and below 2 detectors (*in situ* @ Soudan)

50 live days → 0 of 132,968 surface events leaked into NR signal region (> 8keV)

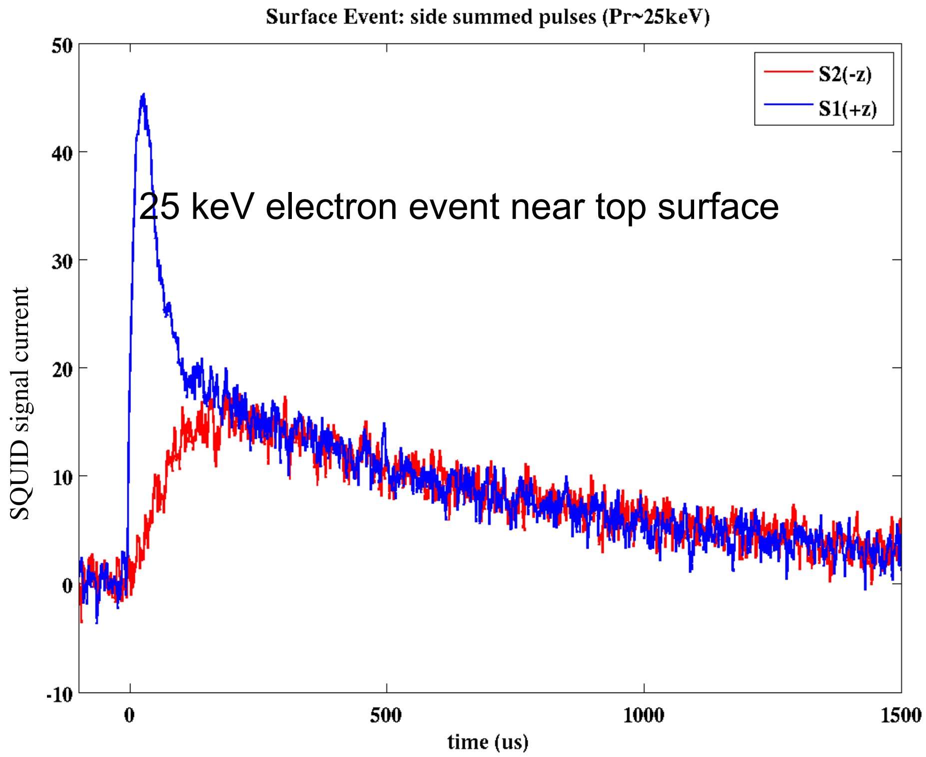
→ Good enough rejection for proposed SuperCDMS SNOLAB

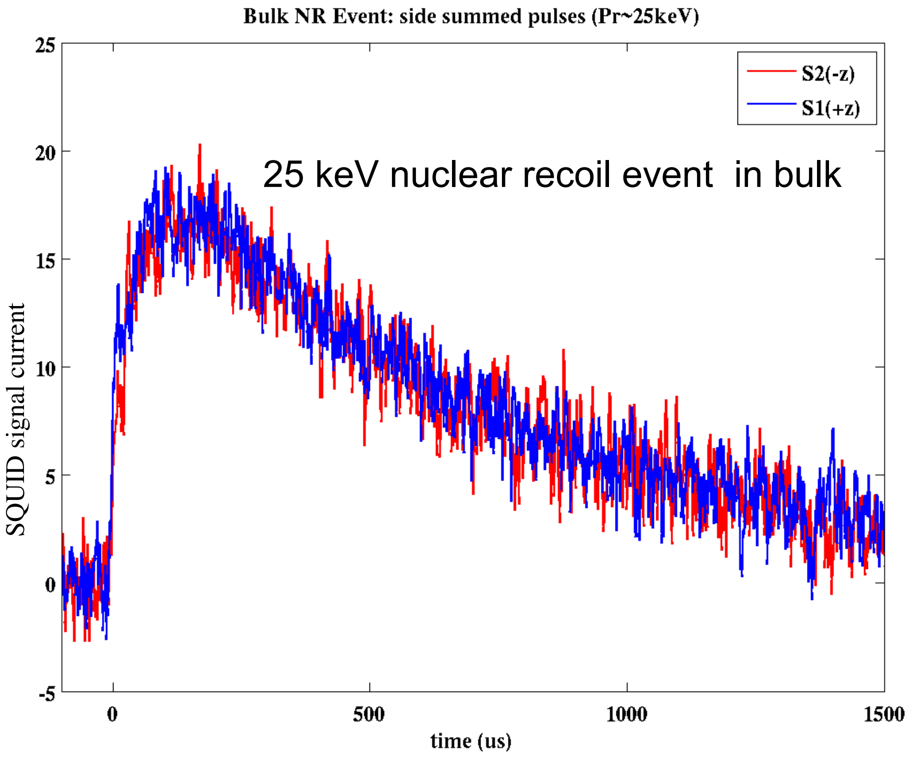
(100 kg, $\sigma_{\chi\text{-}N} < 8 \times 10^{-47}$ cm^2 for 60 GeV/c^2 WIMP)

^{210}Pb
iZIP 1
iZIP 2
iZIP 3
^{210}Pb



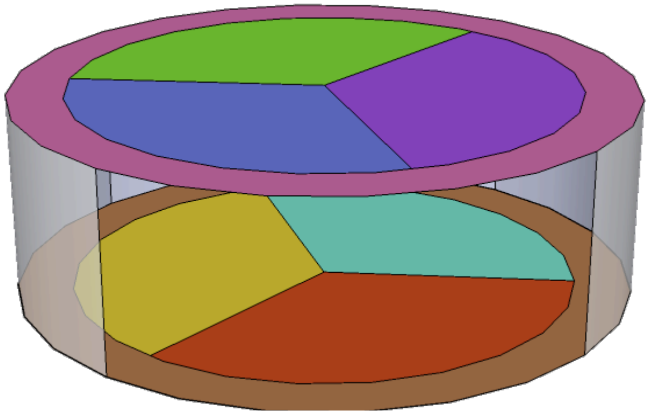
iZIP Phonon Pulse Shape Discrimination





Surface Electron *vs* Nuclear Recoil discrimination seen in operating iZIP detectors in both phonon pulse shape differences and energy partition in z-direction.

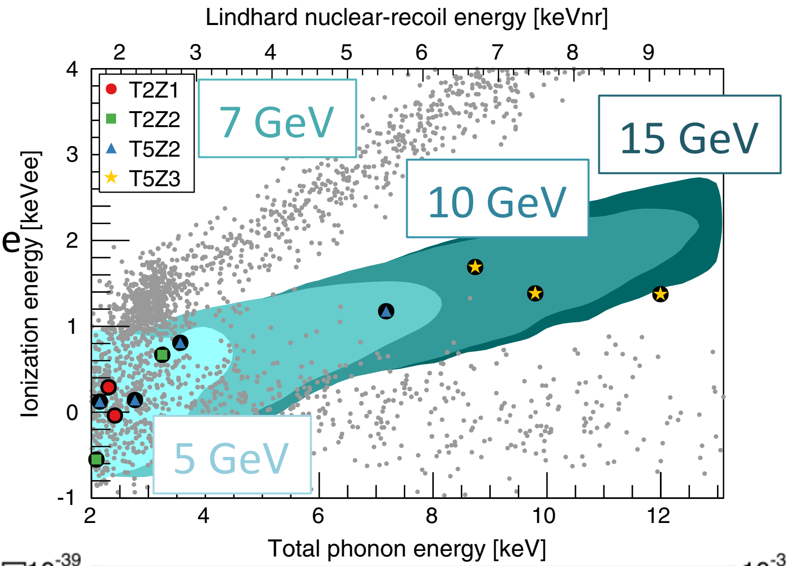
SuperCDMS Soudan iZIP Phonon sensor layout

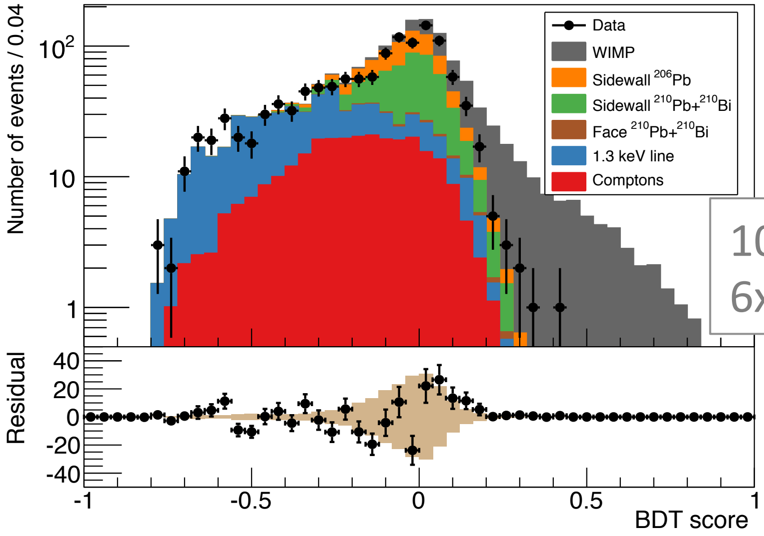


SuperCDMS Soudan — iZIPs

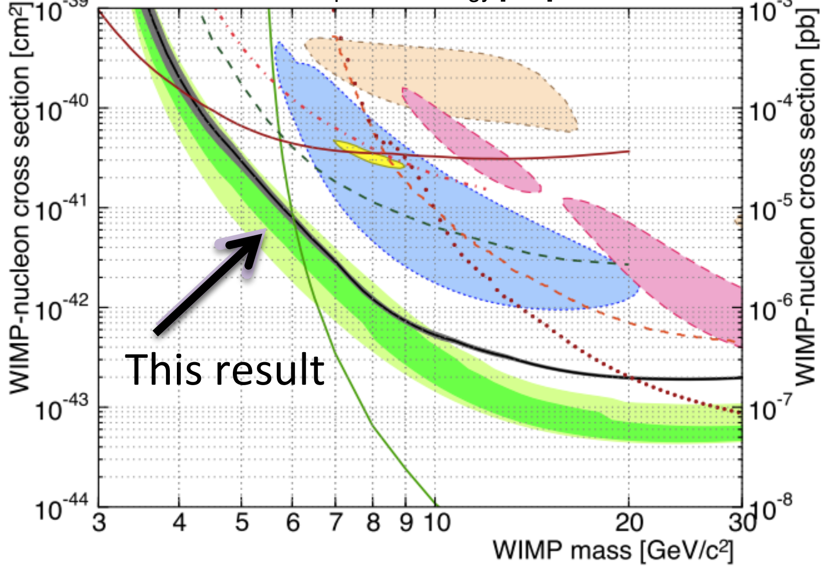
Ionization and phonon signals give electron recoil *vs* nuclear recoil discrimination.

- Used 7 Ge detectors with lowest noise for this low-mass WIMP search (others used to reject multiple scatters)
  - → Disagreement with expected WIMP sensitivity above 20 GeV WIMP mass due to high energy events from damaged detector (T5Z3)
  - → Tension with prior CDMS II Silicon result
- Boosted Decision Tree trained with a background model
  - → Significant sources include Pb-210, Ge L-capture, gammas from K, U, Th contamination.





10 GeV
6×10^{-42} cm^2



This result

A. Anderson et al., *Phys. Rev. Lett.* **112**, 241302 (2014). `ArXiv: 1402.7137`

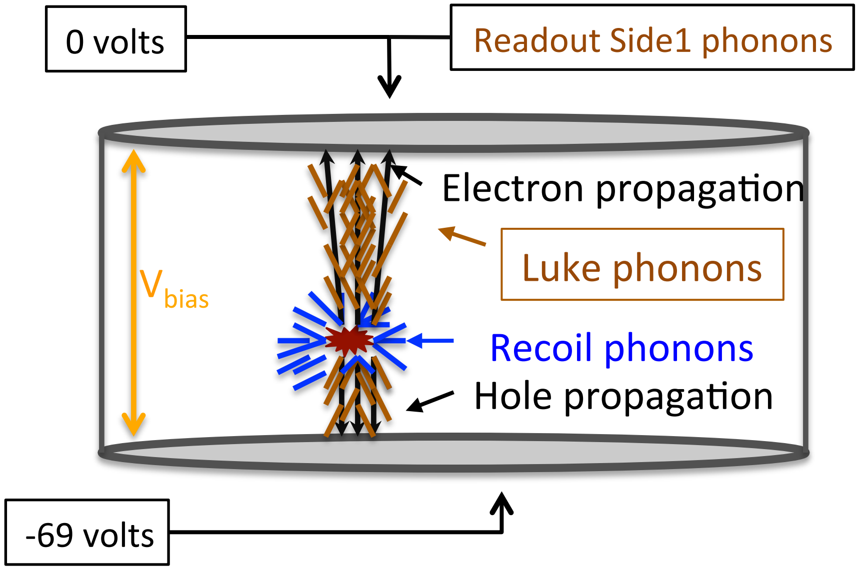
SuperCDMS Soudan — CDMSlite

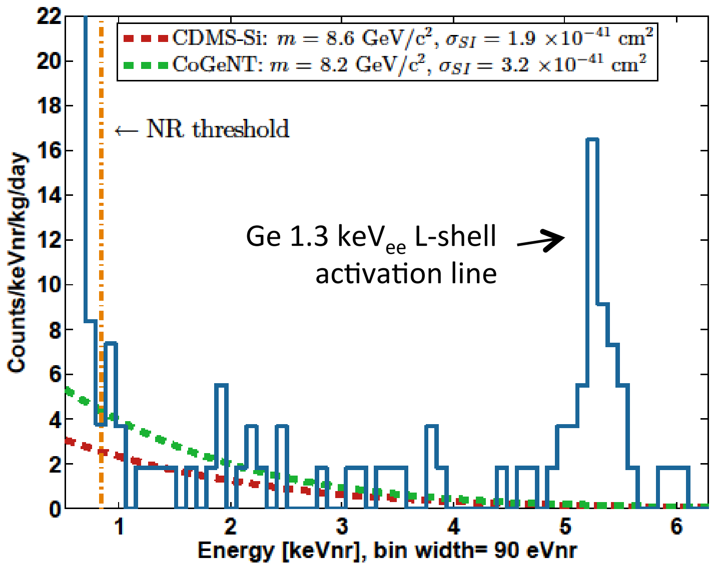
Luke-amplified ionization-energy measurement

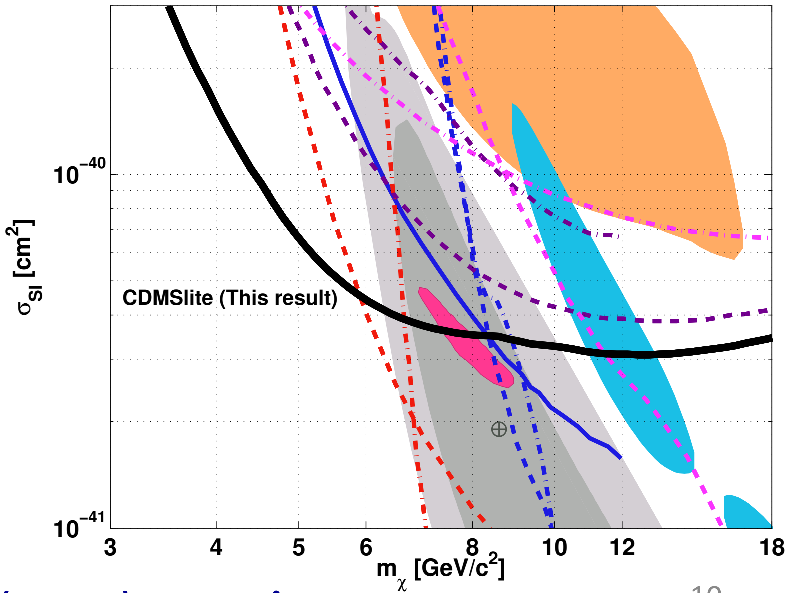
- 24x amplification of ionization energy via phonons
  - → 10x lower threshold for ERs
  - → ≈ equal noise performance

***vs.* normal ±2V mode**

- No event-by-event ER-NR discrimination
  - → But near perfect signal efficiency
- Fall 2012 search for light WIMPs
  - → Single-detector 10-day exposure (5.9 kg-days)
  - → Observed rate → 1.2±0.2 events /keV_{nr} /kg-d

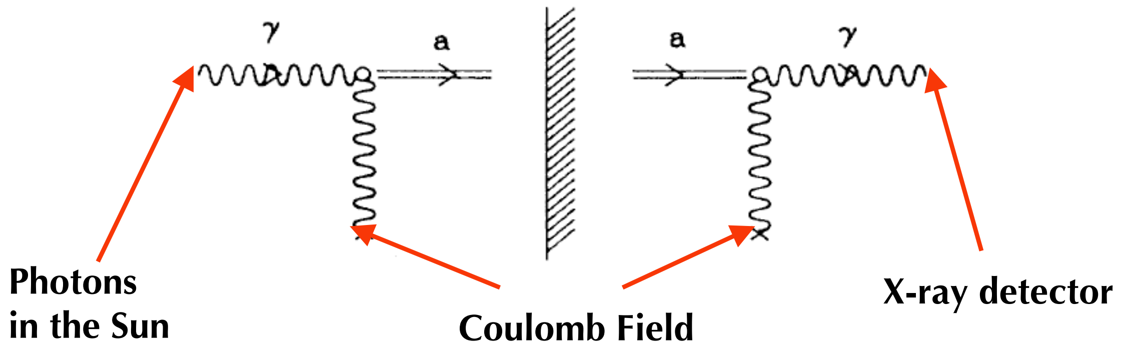




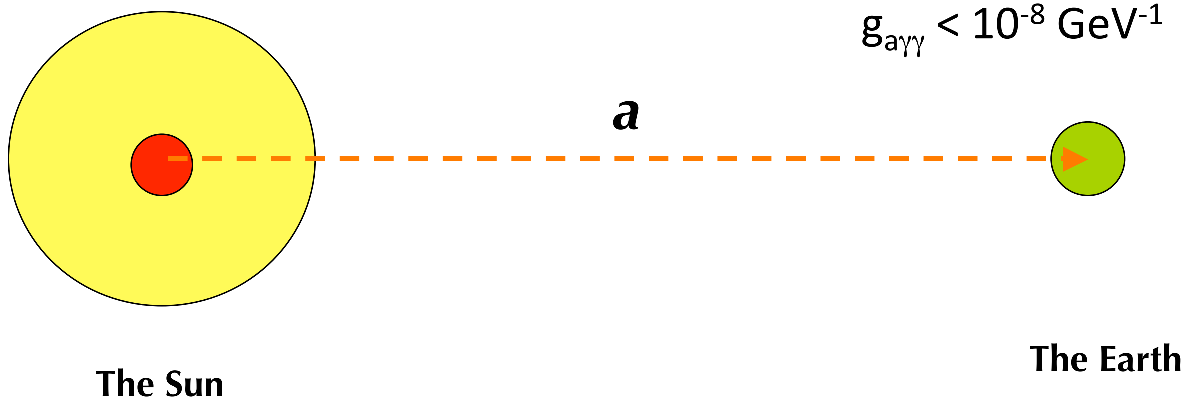


D. Bauer et al., *Phys. Rev. Lett.* **112**, 041302 (2014). `ArXiv: 1309.3259`

Axions – Solar Detection

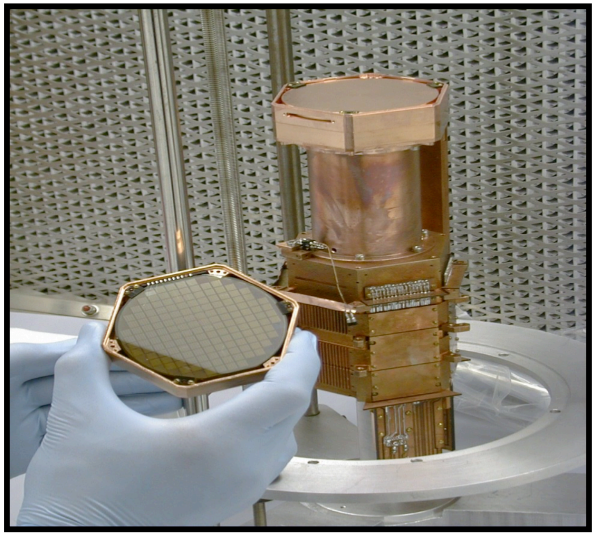


Primakov conversion to photons,
$g_{a\gamma\gamma} < 10^{-8}$ GeV^{-1}



- Events are Electron recoil events, in presence of background, CDMS II used information on the Sun’s location and coherent scattering.
- See J.H Yoo et al., *Phys. Rev. Lett.* **103**, 141802 (2009). `ArXiv: 0902.4693`

CDMS II Crystals & Bragg Scattering



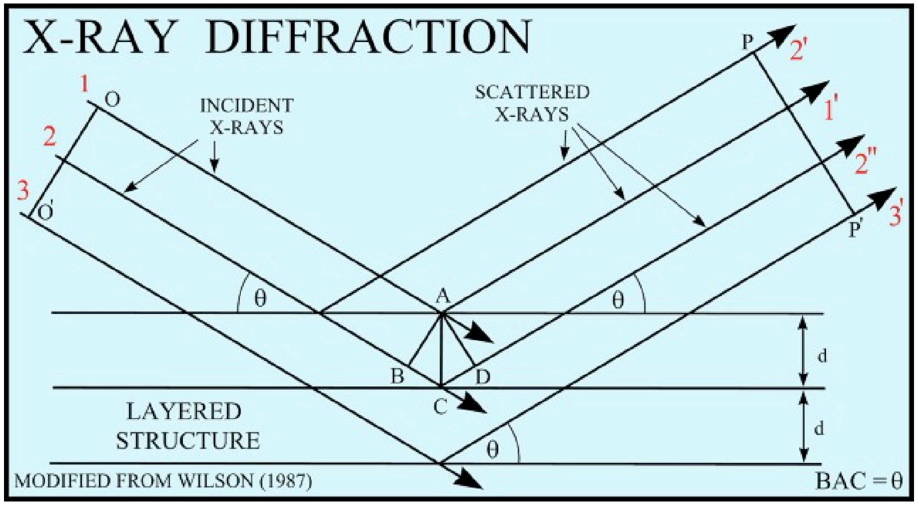
Coherent scattering of an axion in a crystal

$$R(E) = \int 2c\frac{d^3q}{q^2}\cdot\frac{d\Phi}{dE}\cdot[\frac{g^2_{a\gamma\gamma}}{16\pi^2}|F(\vec{q})|^2\sin^2(2\theta)]$$

$$F(\vec{q}) = k^2\int d^3x\;\phi(\vec{x})e^{i\vec{q}\cdot\vec{x}}$$

$$\phi(\vec{x}) = \sum_i \phi_i(\vec{x}) = \sum_i \frac{Ze}{4\pi|\vec{x}-\vec{x}_i|}e^{-\frac{|\vec{x}-\vec{x}_i|}{r}} = \sum_G n_G e^{i\vec{G}\cdot\vec{x}}$$

Bragg condition



MODIFIED FROM WILSON (1987)

BRAGG LAW

$$2d(\sin\theta) = \lambda_o$$

where:

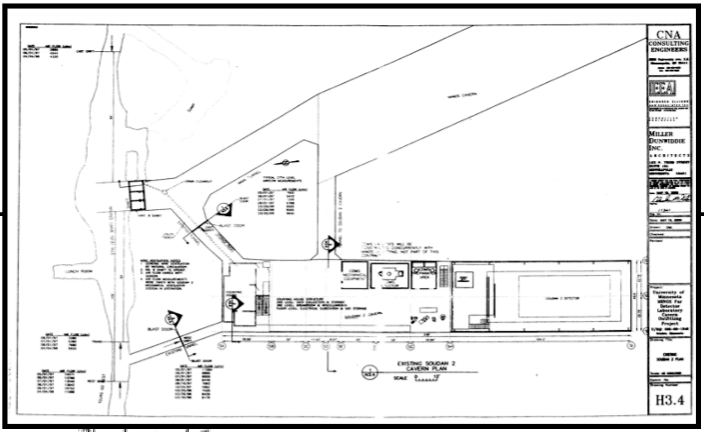
d = lattice interplanar spacing of the crystal
θ = x-ray incidence angle (Bragg angle)
λ = wavelength of the characteristic x-rays

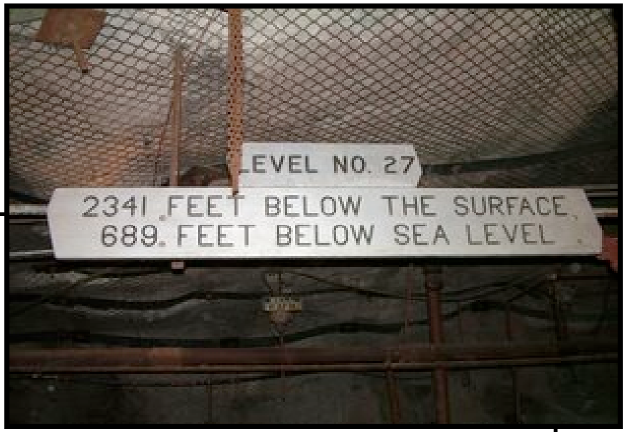
$$E_a = \hbar c\frac{|\vec{G}|^2}{2\hat{u}\cdot\vec{G}}$$

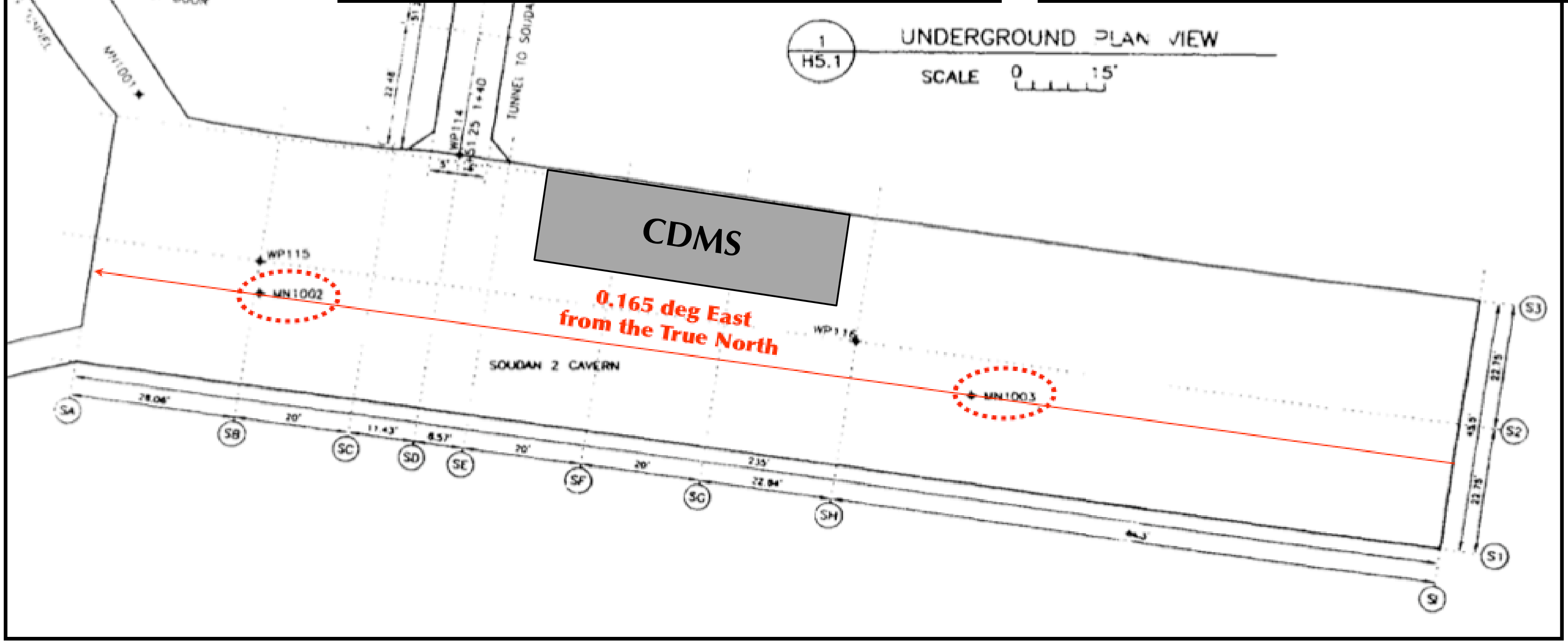
CDMS II – Soudan Laboratory

- Amazing collaboration among the CDMS, NuMI/MINOS and old mine crews
- FNAL Alignment Group measured the geodesic north in the Soudan mine (1999)

Latitude : 47.815°N
Longitude : -92.237°E
Altitude : -210m





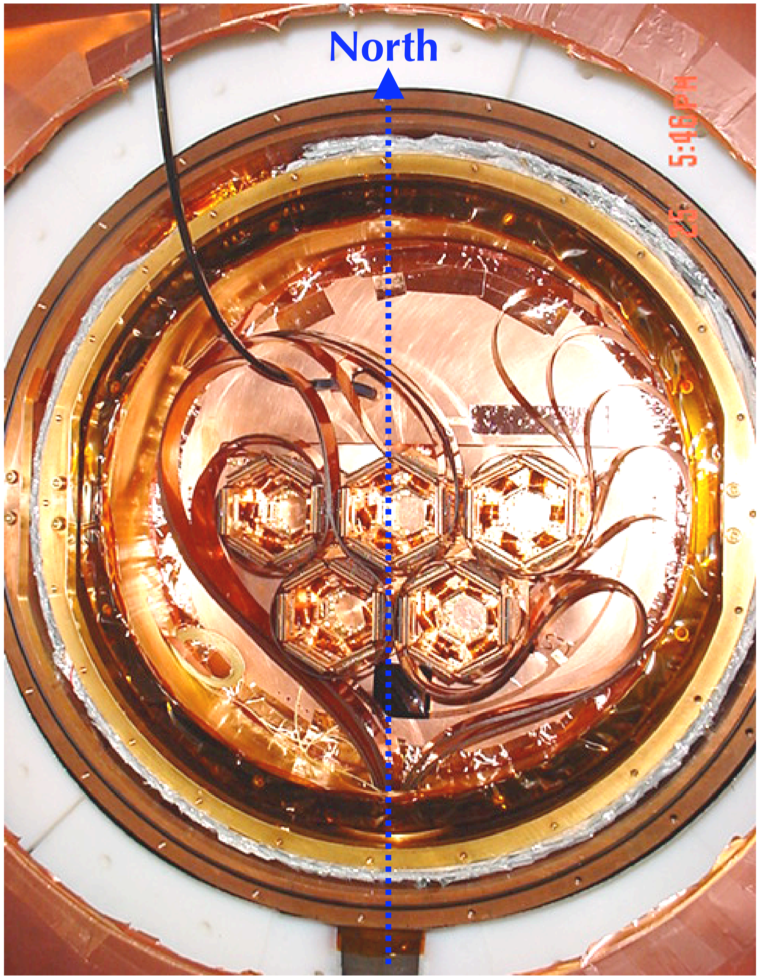


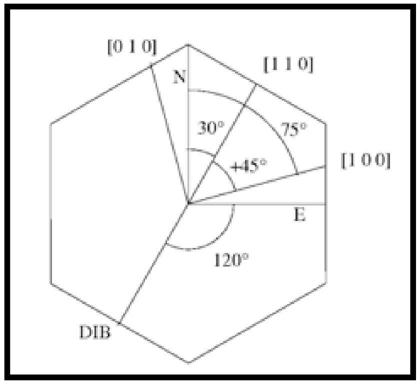
CDMS

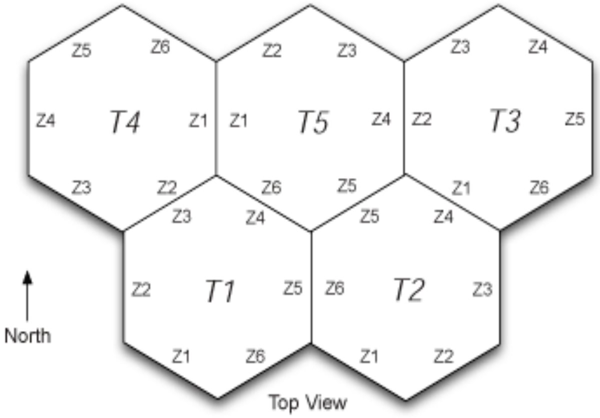
0.165 deg East
from the True North

CDMS II – Crystal orientation

- **Germanium crystal structure : Face-Centered-Cubic (*fcc*)**
- **Overall error in the direction measurement : 3 degree**

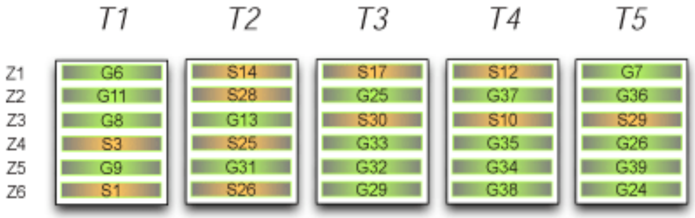






Top View

The following shows detector stack placement:



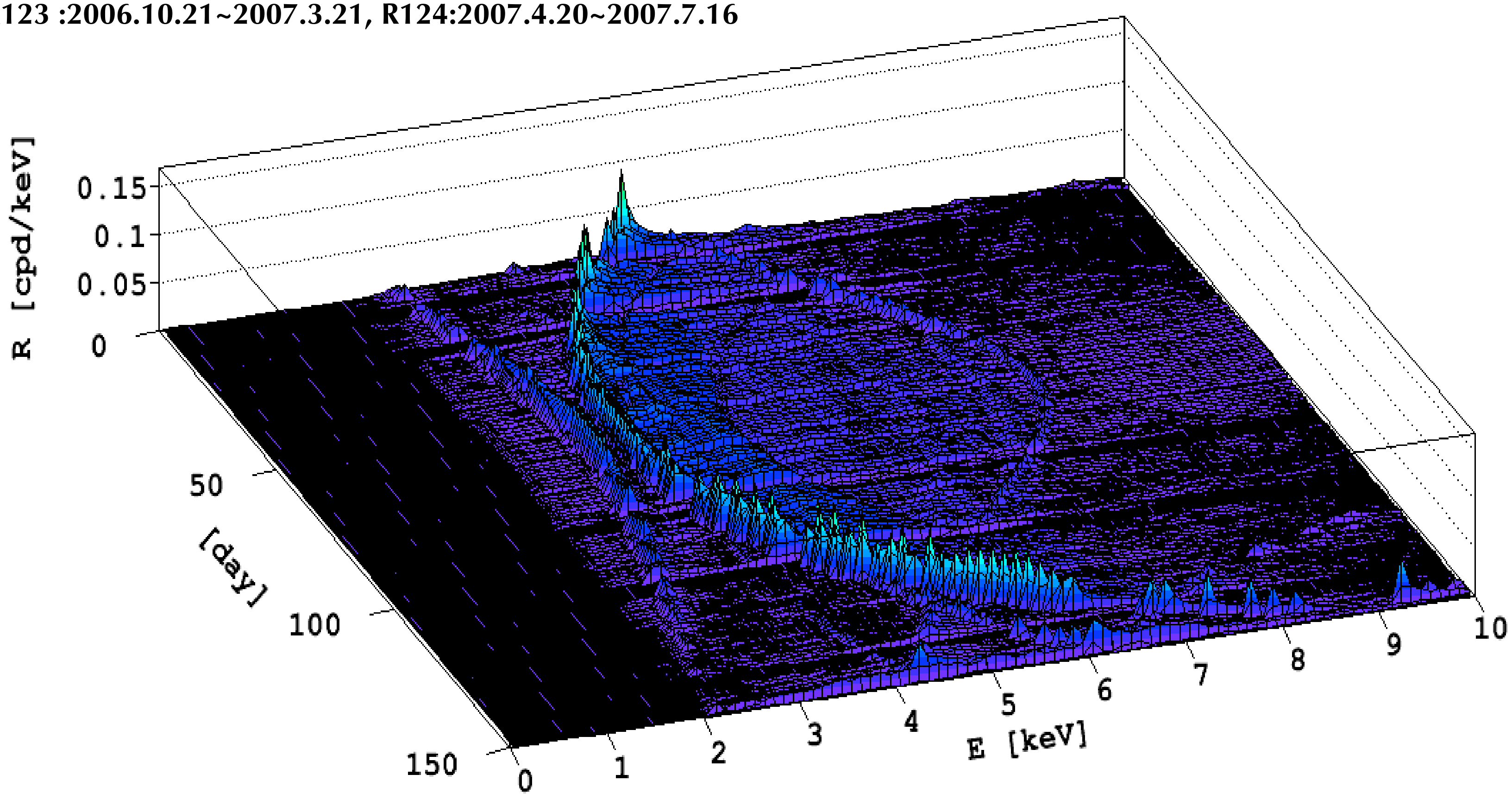
	T1	T2	T3	T4	T5
Z1	G6	S14	S17	S12	G7
Z2	G11	S28	G25	G37	G36
Z3	G8	G13	S30	S10	S29
Z4	S3	S25	G33	G35	G26
Z5	G9	G31	G32	G34	G39
Z6	S1	S26	G29	G38	G24

Side View

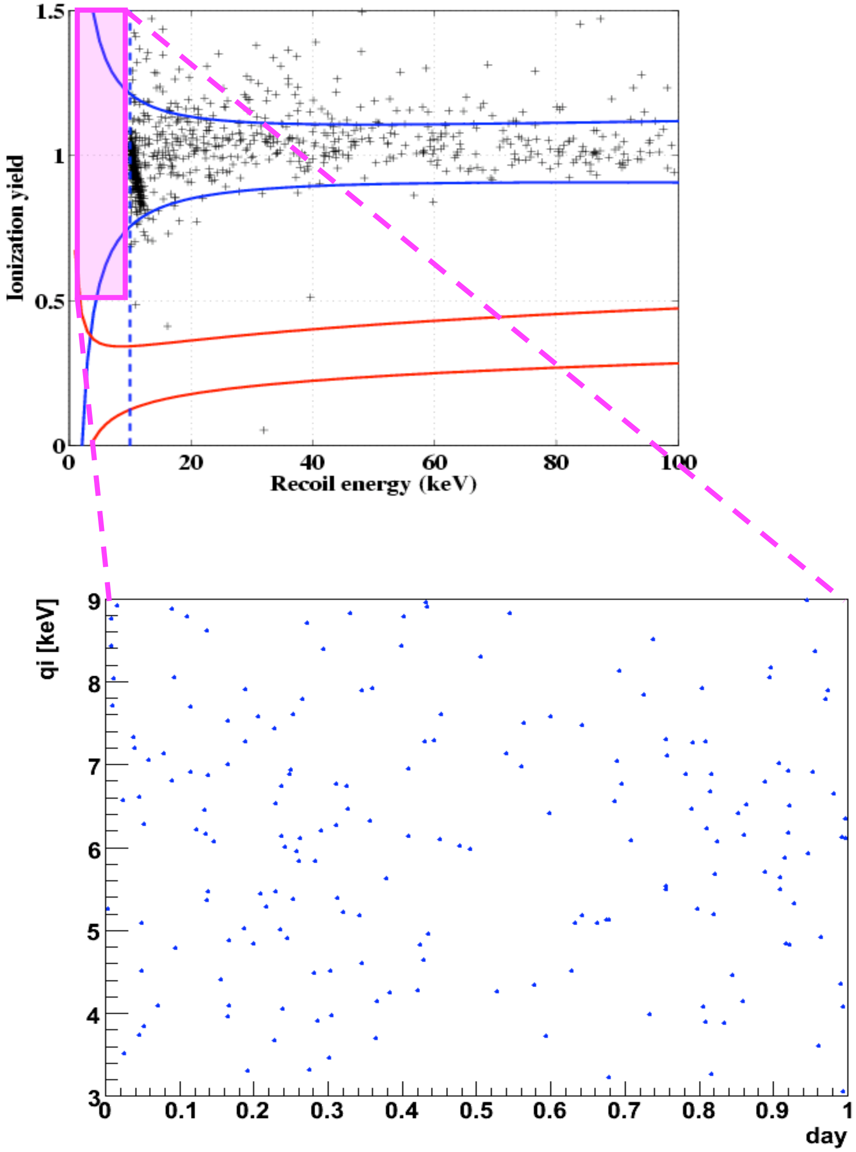
Model the Solar Axion event rate

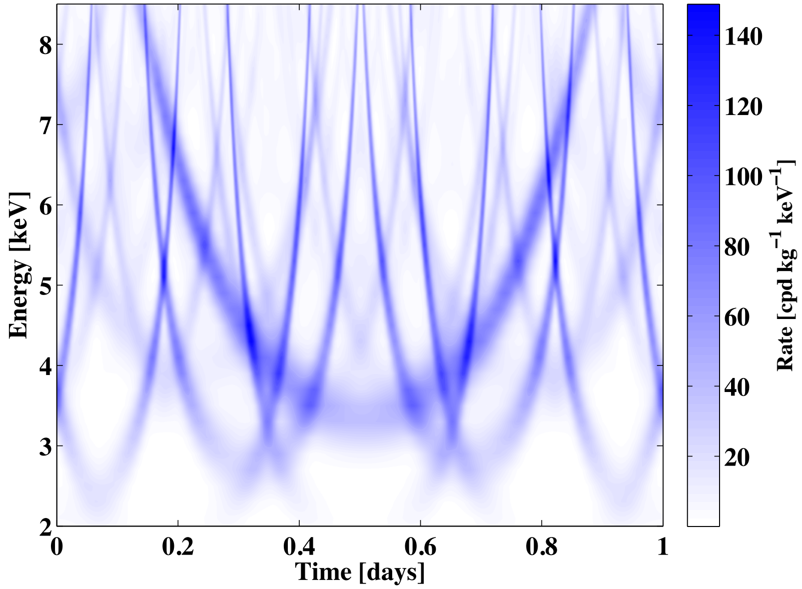
- **Seasonal variation of the solar flux**
- **The height of the Sun changes in seasons**
- **Detector energy resolutions**
- **Systematic uncertainty of the detector direction**
- **Detector livetime information**

R123 :2006.10.21~2007.3.21, R124:2007.4.20~2007.7.16



CDMS II – single bulk electron recoils





Unbinned Likelihood Fit

$$R(E,t,d) = \lambda A(E,t,d) + B(E,d),$$

$$\lambda = [g_{a\gamma\gamma} / (10^{-8}\mathrm{GeV}^{-1})]^2$$

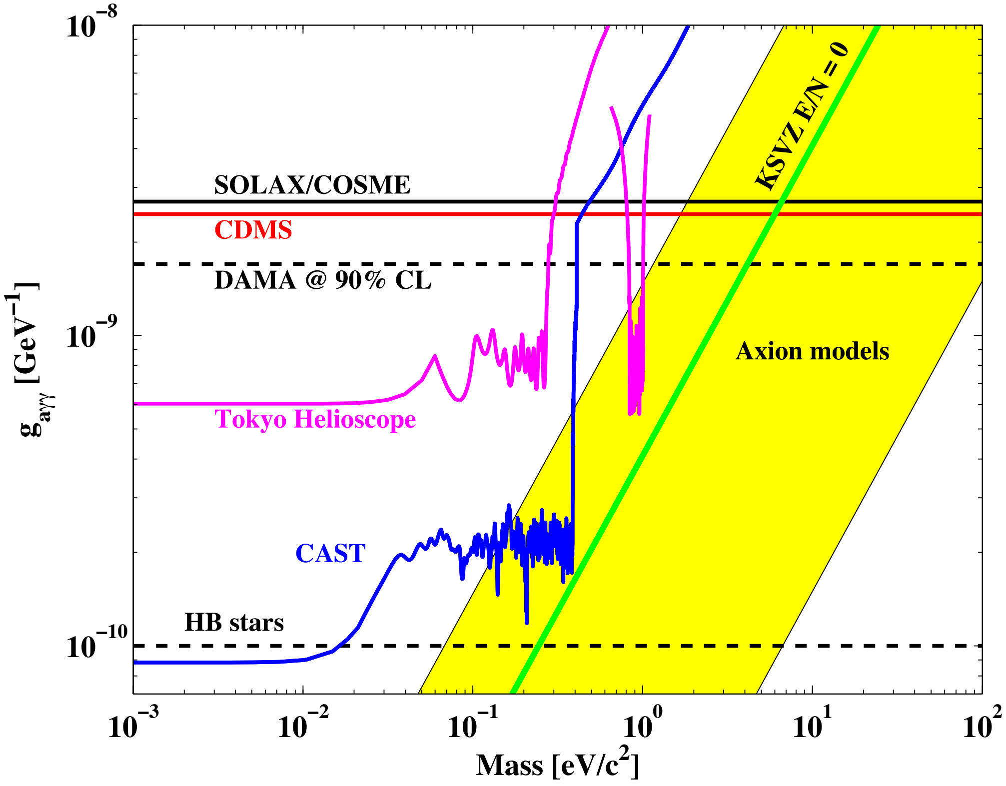
$$B(E,d) = \varepsilon(E,d)[\alpha(d) + \beta(d)E + \gamma(d)/E]$$

$$R_T = \sum_d \int dEdtR(E,t,d;\lambda,\alpha(d),\beta(d),\gamma(d))$$

$$\log(L) = -R_T + \sum_i \log(R(E_i,t_i,d_i))$$

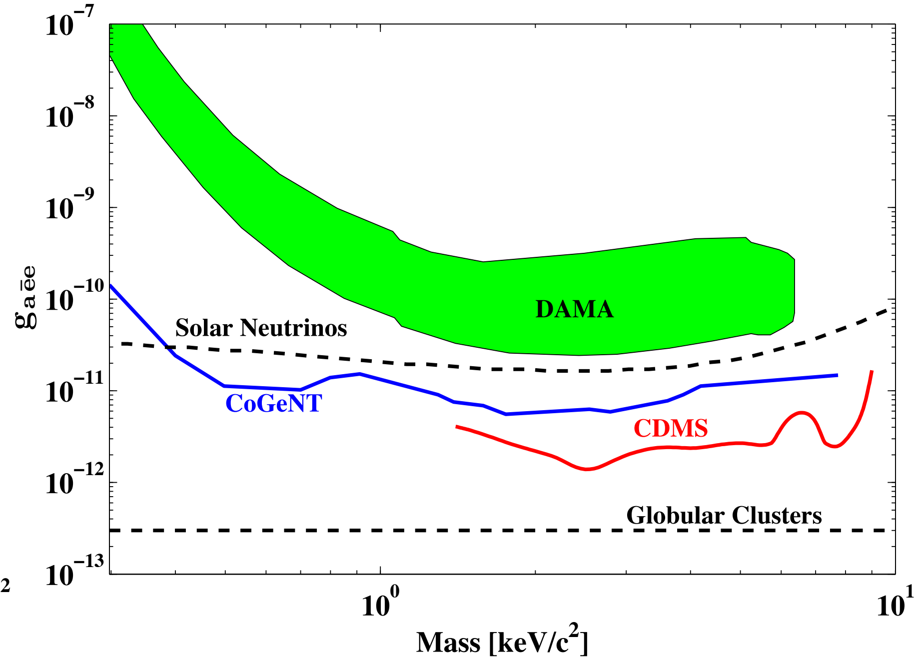
CDMS II – Axion limits

Solar Axion search, $g_{a\gamma\gamma} < 2.4 \times 10^{-9}$ GeV^{-1}



Axio-electric coupling strength from

Galactic axion search, $g_{a\bar{e}e} < 1.4 \times 10^{-12}$ GeV^{-1}



443 kg-days of Ge exposure, 1.5 counts/day/kg/keV for [2.0-8.5] keV$_{ee}$.

SuperCDMS – SNOLAB

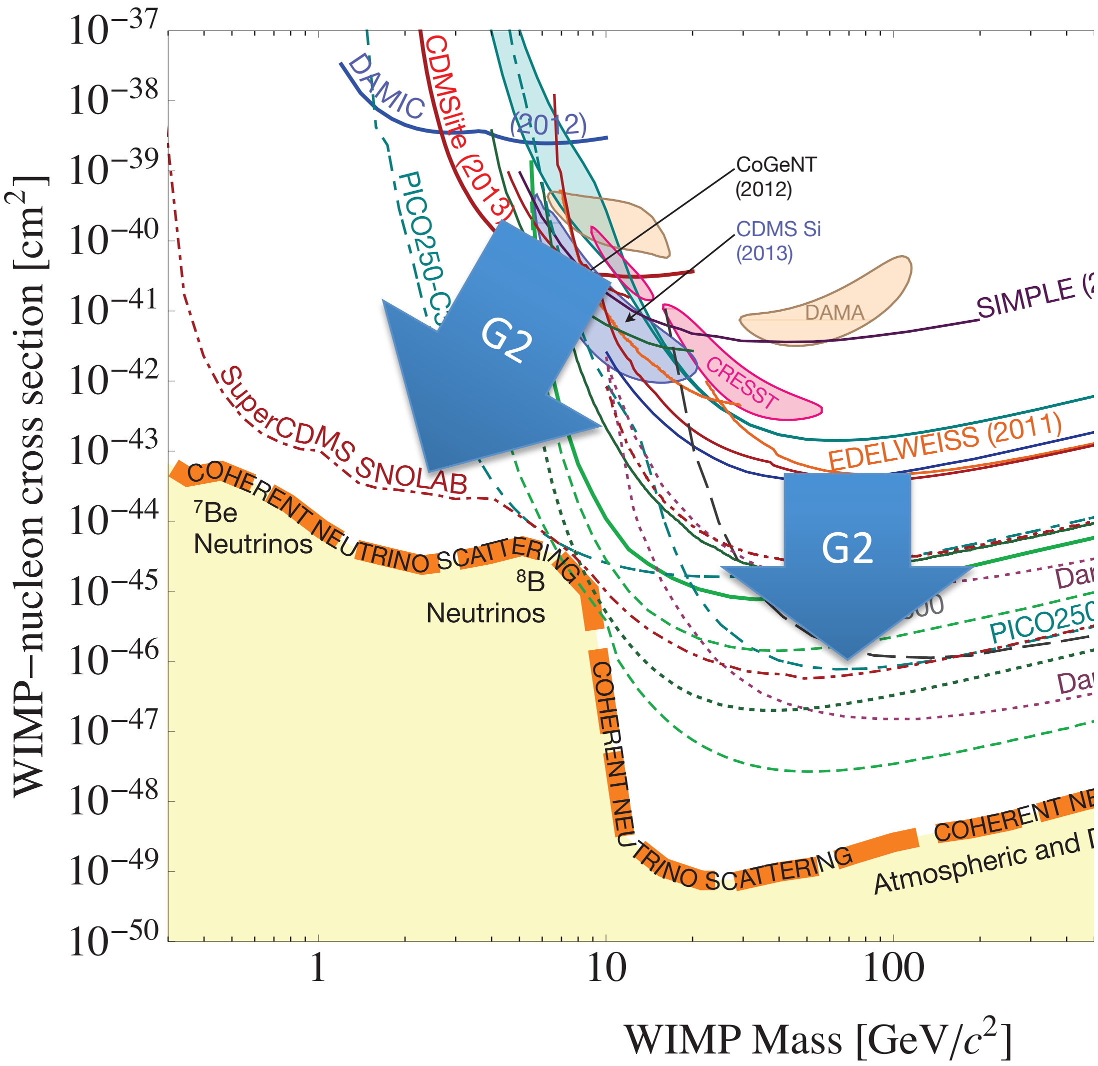
A Generation-2 Dark Matter search at deeper site focused on low-mass WIMPs

Improve energy resolution x10

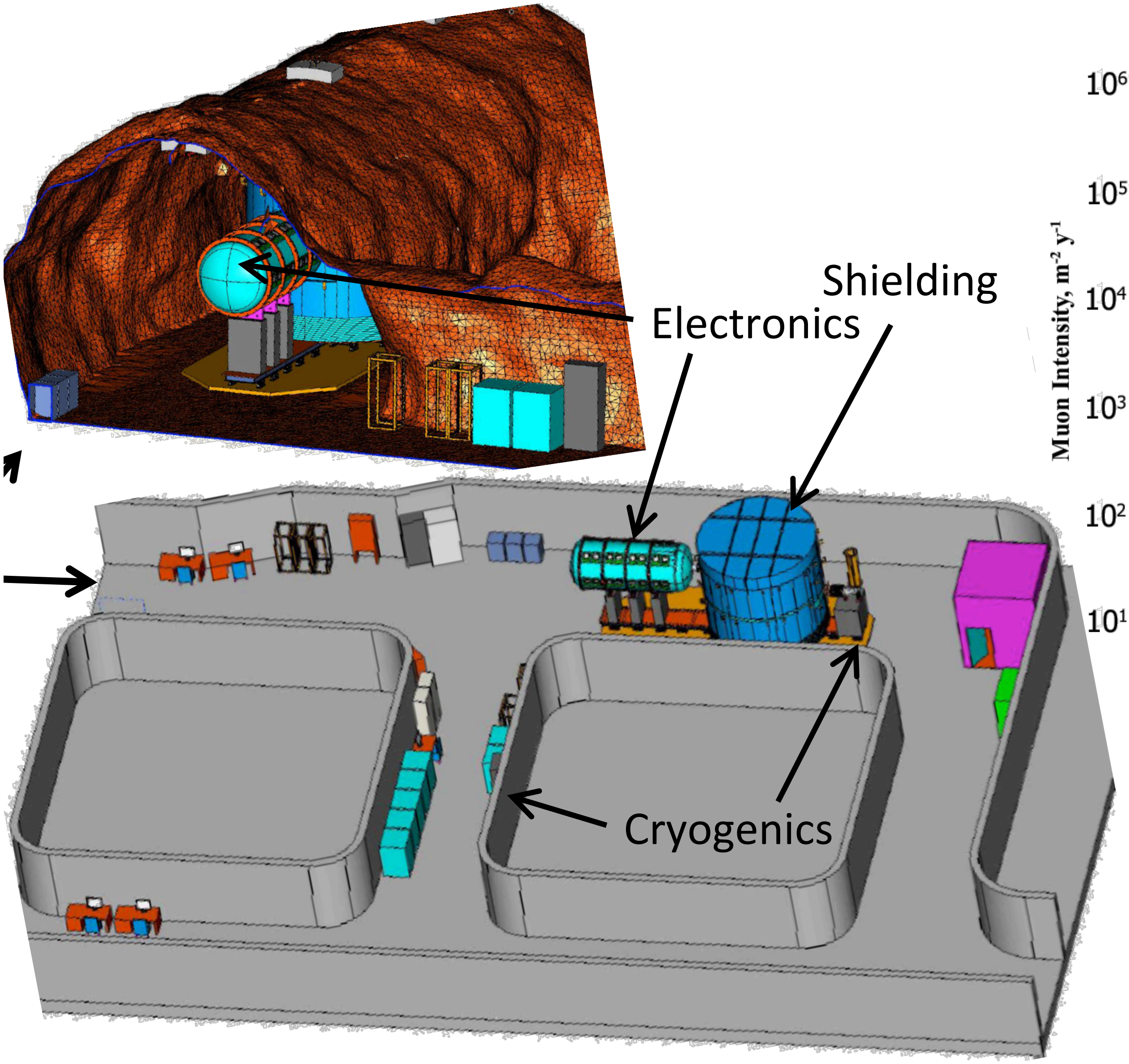
- New electronics (HEMTs, SQUIDs)
- Lower temperatures
- Detector design

Reduce backgrounds x200

- Material selection (Copper etc.)
- Reduce cosmogenic activation (Ge)
- New cleaning procedure (Copper)
- Reduce radon plate out.



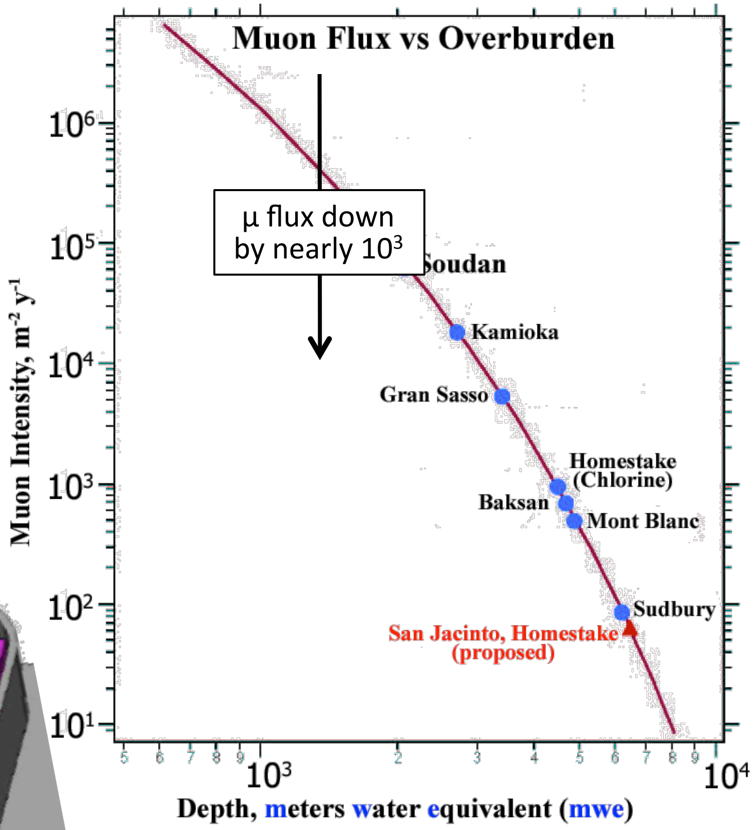
SuperCDMS SNOLAB ladder lab



Shielding

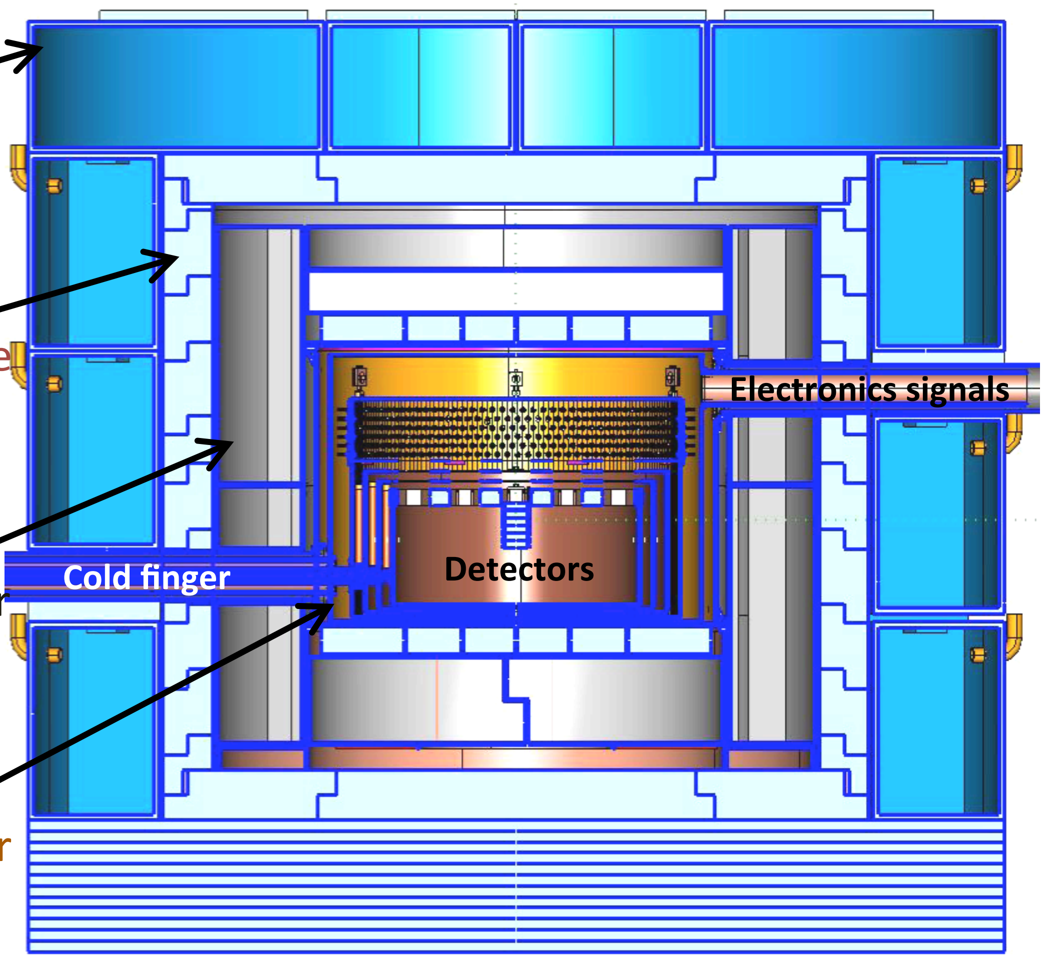
Electronics

Cryogenics



μ flux down by nearly 10^3

SuperCDMS SNOLAB shielding



Outer shielding (neutrons & gammas):
→ 40 cm polyethylene

Inner passive shielding (gammas):
→ 23 cm lead with radon purge

Active shielding (neutrons):
→ 40 cm doped scintillator

Nested cryostat (gammas):
→1/2–3/8” low-activity copper

Assumed bulk contaminant levels no lower than measured by other experiments for easily available radiopure materials

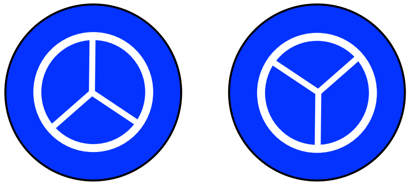
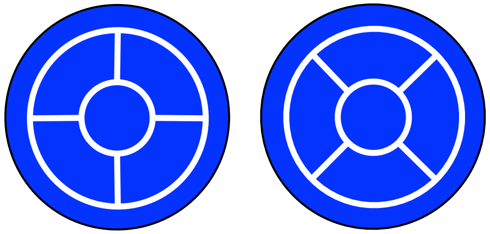
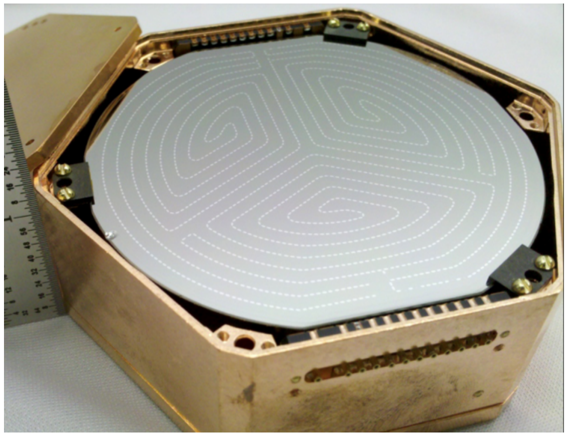
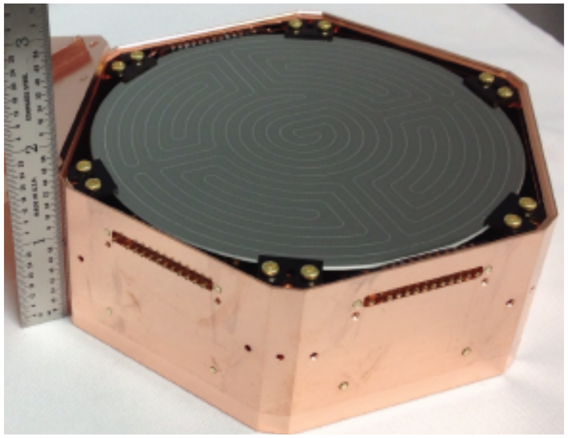
Detector advances for SuperCDMS SNOLAB

Larger 50 kg target mass:
- More & larger iZIPs
- Cryostat large enough for 400 kg
- **Si & Ge crystals**
- Start with 6 towers of iZIPs, and 1 tower in CDMSlite configuration (CDMS – HV)

Lower background:
- New facility at deeper site
- Cleaner materials selection
- Upgrade to active neutron veto in future

Improved signal readout:
- Phonons → new SQUID arrays
- Ionization → switch to HEMTs
- Improved tower design

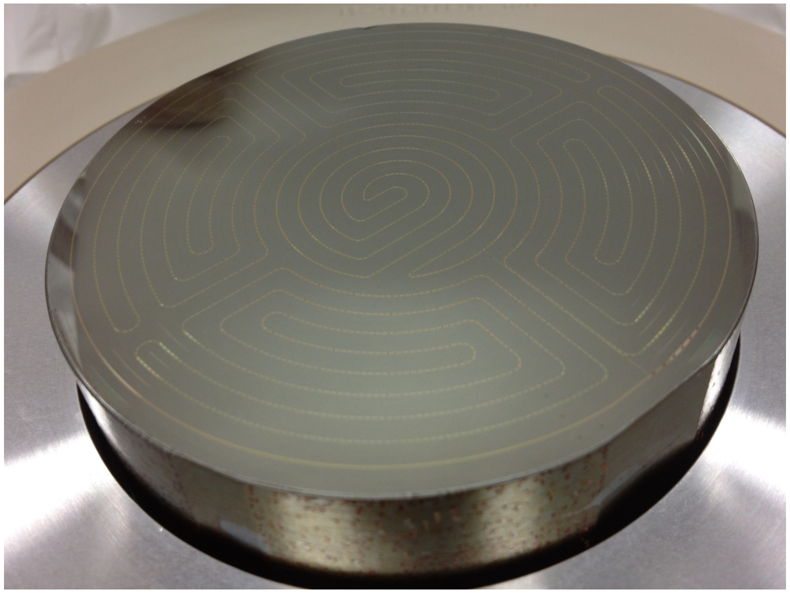
Improved resolution:
- $\sigma_{phonon} \propto T_c^3 \rightarrow$ lower operating temp
- 42 eV demonstrated (>4x better)
- Improved cryogenics could give
  >100x improvement!

SuperCDMS Soudan	**SuperCDMS SNOLAB**
2.5 cm thick 3”diameter 600 g Ge	3.3 cm thick 4”diameter 1.4 kg Ge / 615 g Si
2 ionization + 2 ionization 4 phonon + 4 phonon	2 ionization + 2 ionization 6 phonon + 6 phonon
	
5 towers of 3 iZIPs each	6 towers of 6 iZIPs each
	

SNOLAB iZIP 100 mm Detector

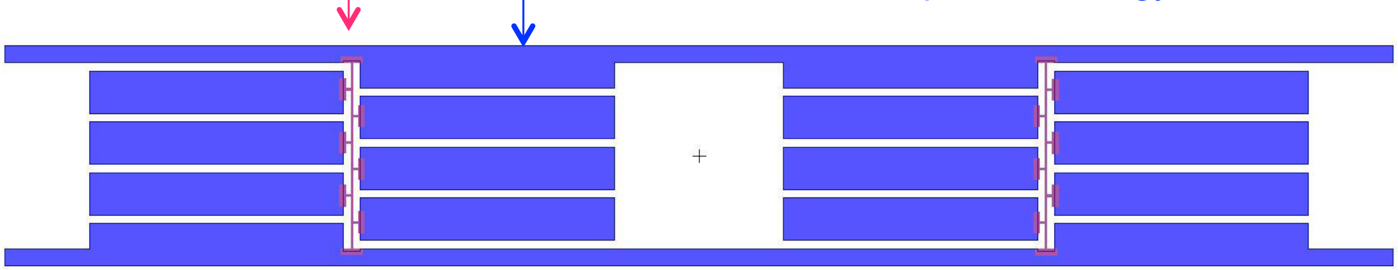
Side 1

Side 2

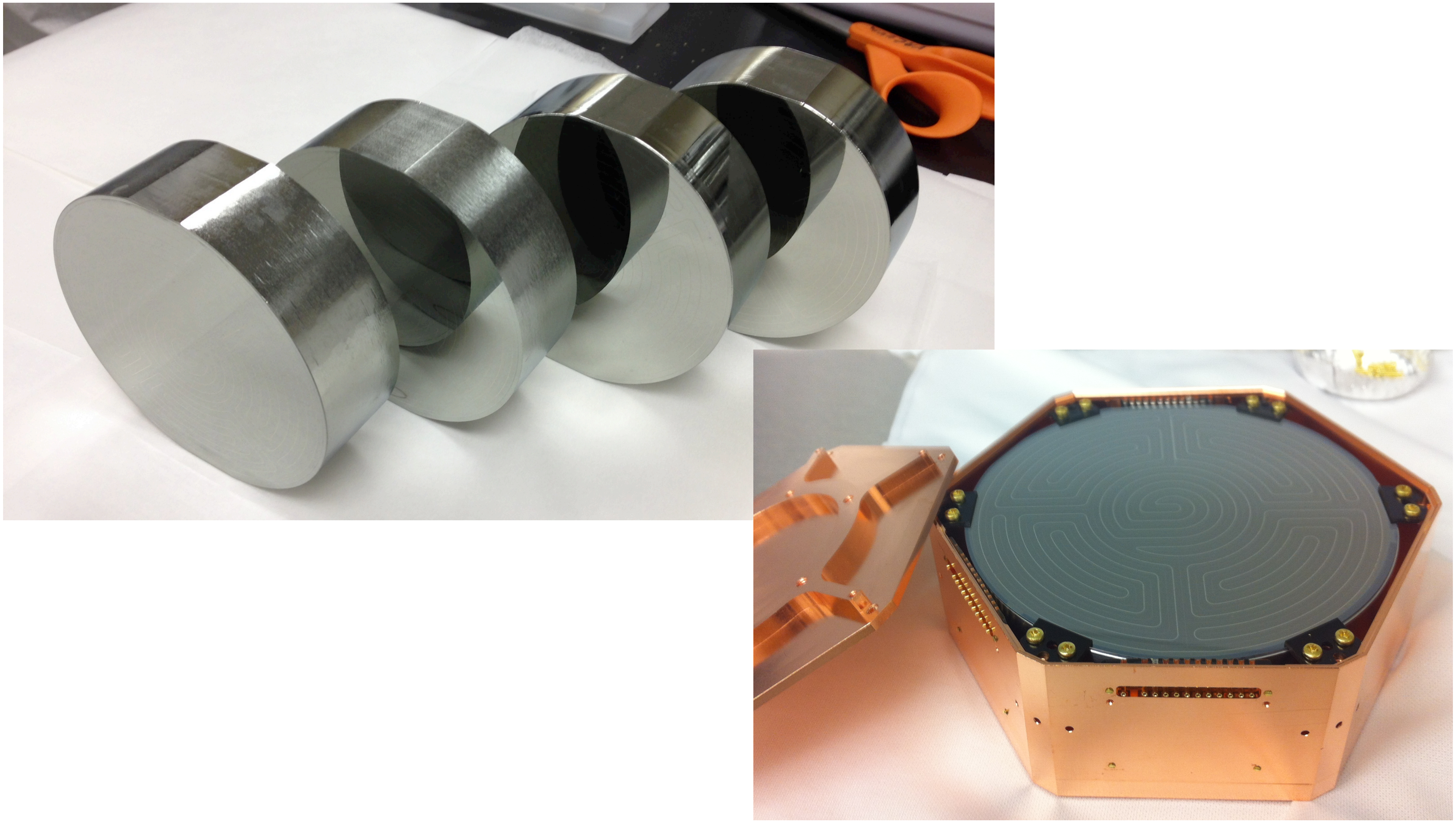


260 microns wide phonon sensor ribbon

One of 1000 tungsten Transition Edge Sensors (W TESs)
connected to aluminum phonon energy collection fins



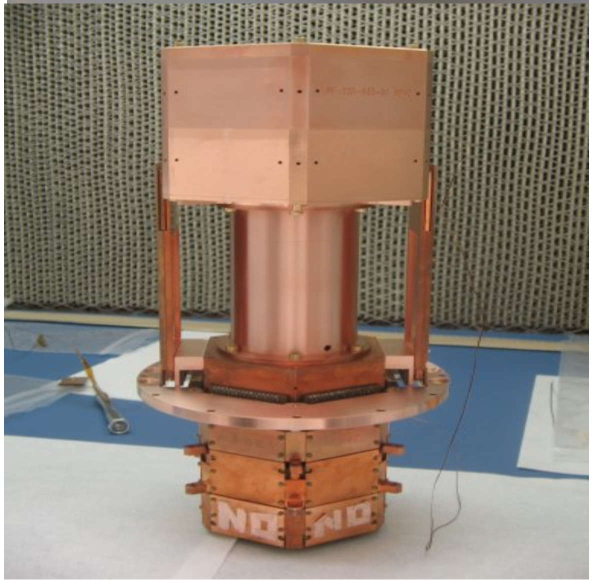
SNOLAB 100 mm x 33.3 mm Ge iZIPs



- Demonstrated fabrication of detectors at sufficient throughput.

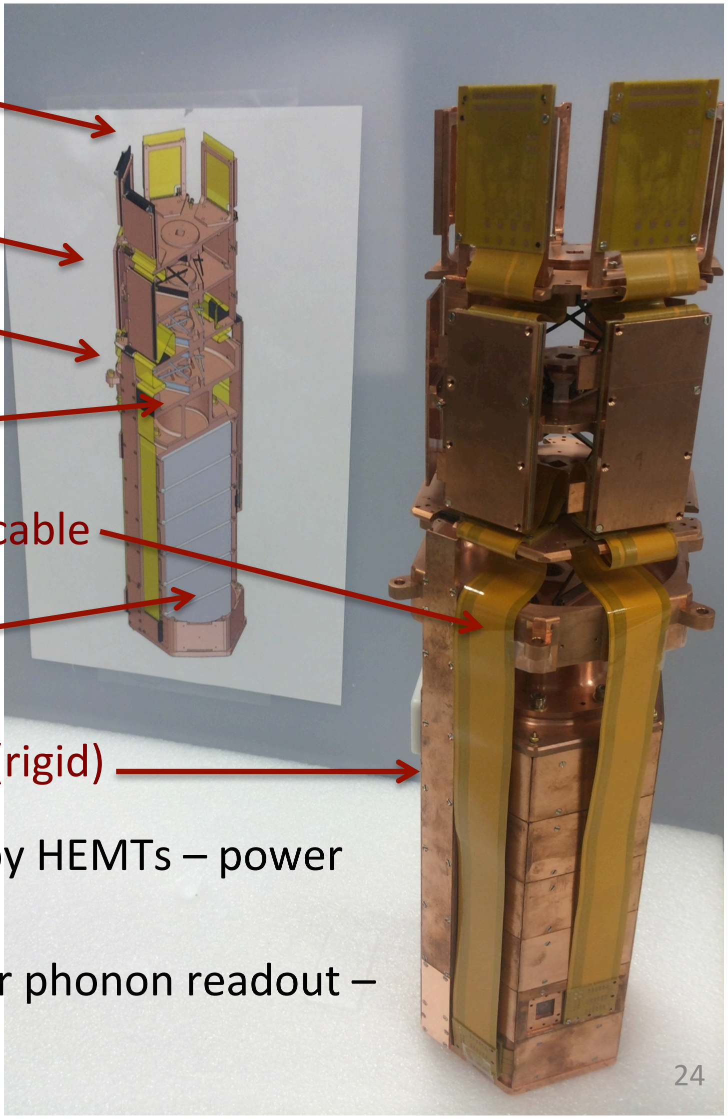
Detector Towers for SNOLAB

100 mm Ge detector in a copper housing



Integrated to CDMS II tower hardware.

- New SNOLAB Detector Tower



HEMT card

SQUIDs

Cold Plate

Mixing chamber

Phonon vertical cable

Detectors

Ionization cable (rigid)

  - FETs replaced by HEMTs – power dissipation
  - New SQUIDs for phonon readout – signal/noise

Conclusions

- DOE G2 downselect approved SuperCDMS SNOLAB at 50 kg scale
  - CDMS upgraded technology, site depth, materials screening, shielding, and (possible) active neutron veto:

    → 5 years of operation with 0.2 total expected background for WIMP masses > ~10 GeV/c^2

- Low backgrounds, improved resolution, upgraded electronics:

  → unique discovery potential for WIMP masses 1–10 GeV/c^2

  → opportunity to repeat axion searches with lower background and more exposure.

- CDMS-HV tower with high-gain, low-noise operation:

  → CDMSlite Run 2 at Soudan analysis in progress, more exposure, lower noise,

  → extremely low thresholds for world leading light-WIMP sensitivity from 0.3–5 GeV/c^2

  → extend axion search to lower masses.

Extra Slides