# Cryogenic detectors for dark matter experiments

Ryan Smith

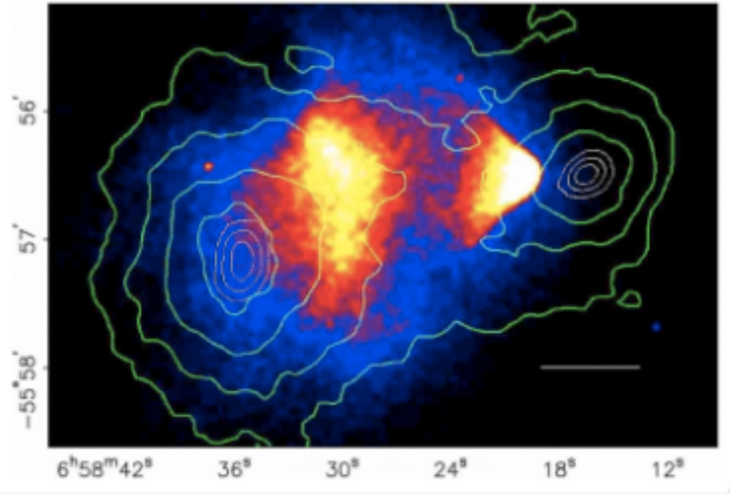
May 2, 2018

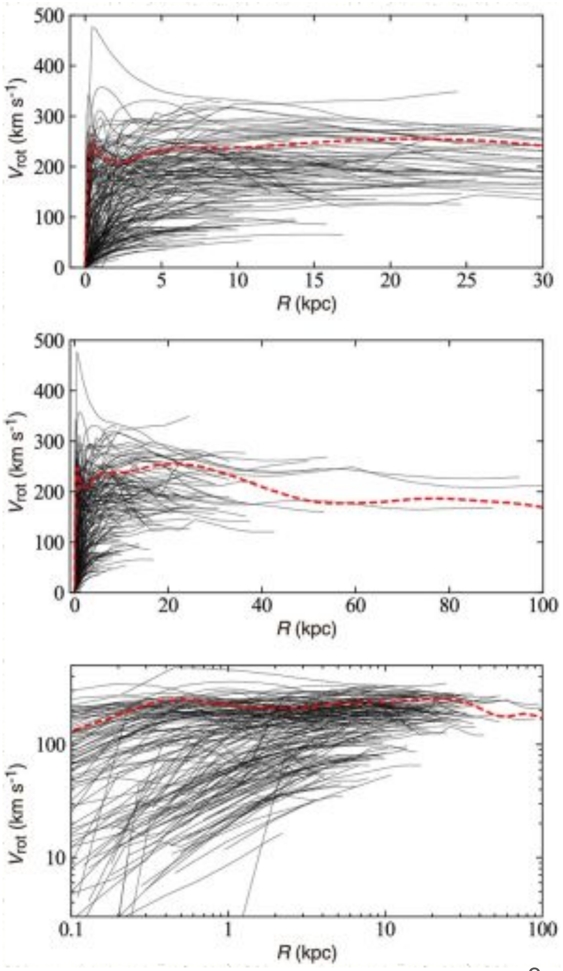
# Outline

- Dark matter / WIMP direct detection
- Cryogenic detectors (bolometers)
- SuperCDMS

# Dark matter

- Evidence that much of the universe is not made up of Standard Model particles (rotation curves, lensing maps, cosmic microwave background)
- Theoretical bounds on the mass of dark matter candidates are very loose
- Weakly interacting massive particles (WIMPs) are a well-motivated candidate, in the mass range ~ GeV - TeV

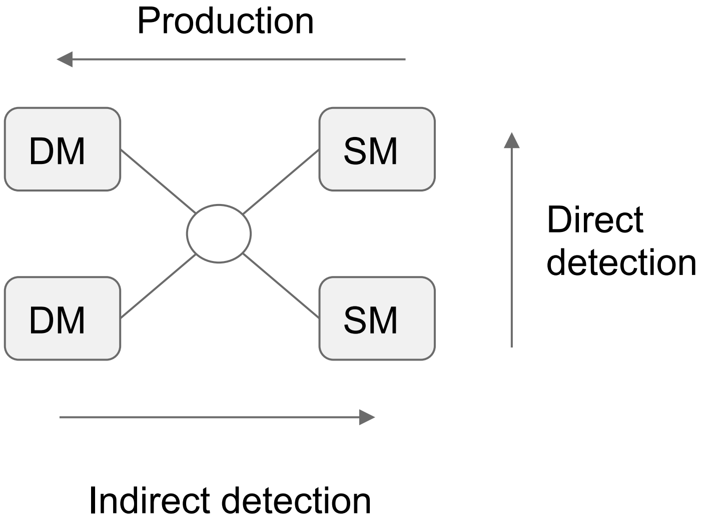




# WIMP detection

Direct detection: WIMP scatters off of nucleus, measure nuclear recoil.

$$E_{recoil} = \frac{\mu^2 v^2}{m_T}(1 - \cos\theta_c)$$



Production

DM

SM

DM

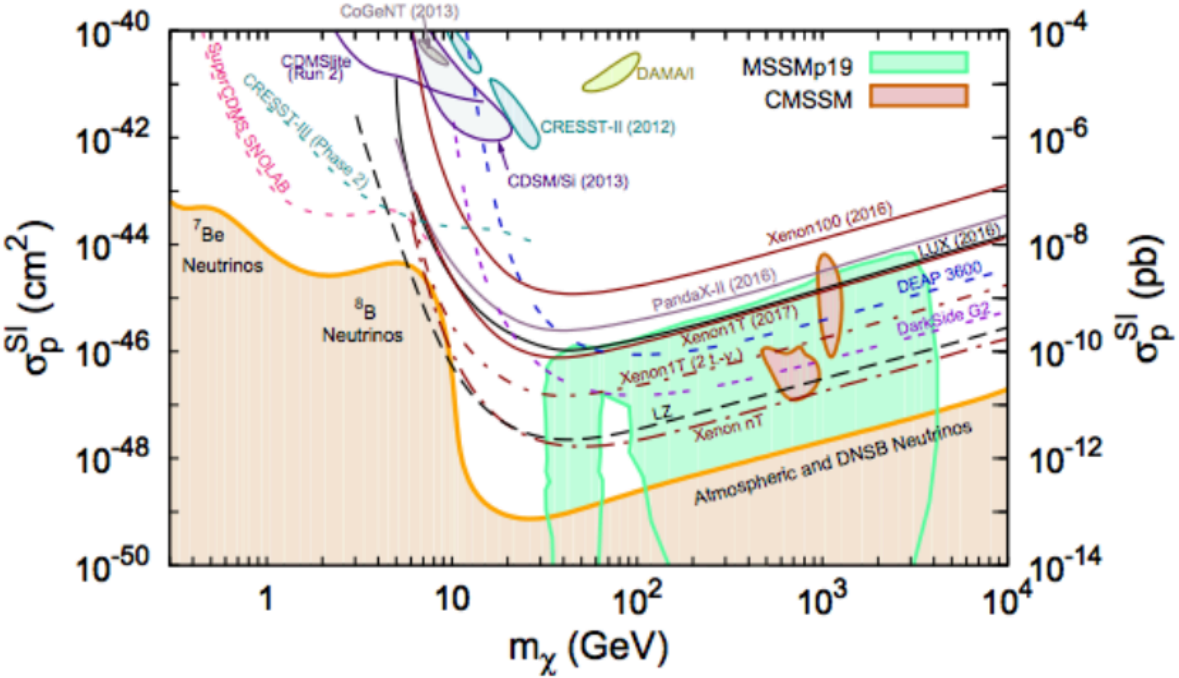
SM

Direct detection

Indirect detection

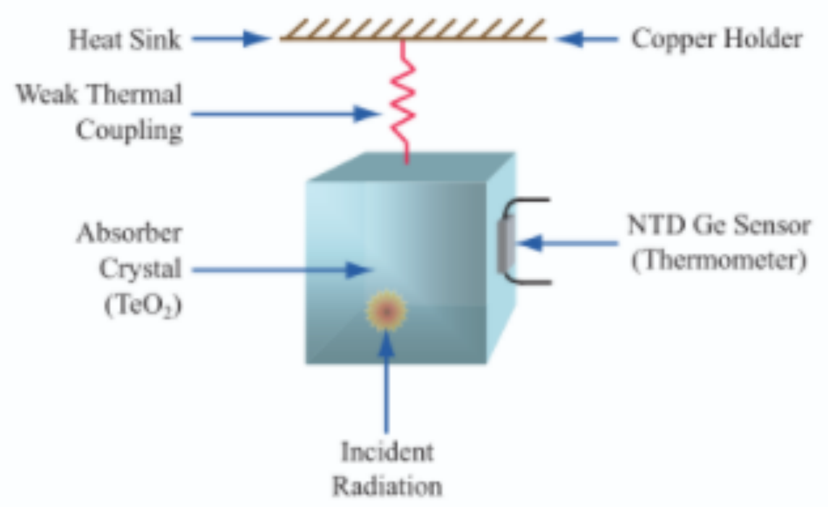
# WIMP experimental limits

- Upper end of WIMP mass scale: XENON1T, LUX (dual-phase xenon time projection chambers)
- Lower end of WIMP mass scale: bolometric experiments such as SuperCDMS, CRESST



# Basics of bolometers

- Microcalorimeter: $\Delta T = \Delta E / C$, detect energy deposits from temperature changes
- Convert temperature change to electronic signal with temperature-dependent resistance (e.g. neutron transmutation doped (NTD) thermistor)
- Heat capacity of a crystal $C \sim T^3$, temperature variance $\sim T^5$



*Schematic of a CUORE bolometer*

# Microcalorimeter advantages and disadvantages

Advantages:

- Phonons produced more readily than e/h pairs ($\lesssim$ 0.01eV compared to ~1ev) and scintillation (-> lower threshold)
- Excellent energy resolution (~eV at keV energies) for same reason:

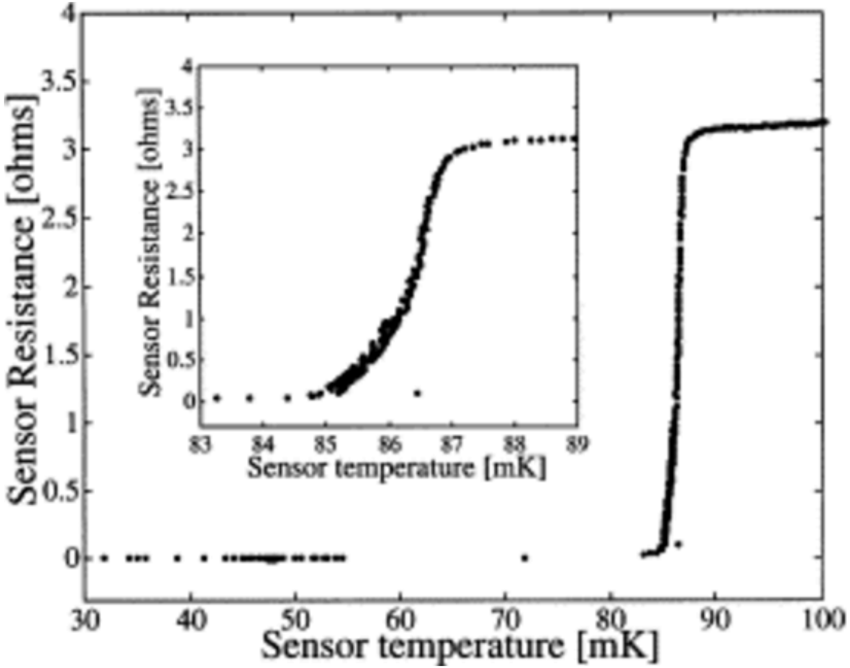
$$W_{stat} = 2.35\,\sigma(E) \qquad \frac{\sigma(E)}{E} = \sqrt{\frac{F}{N}} = \sqrt{\frac{F\epsilon}{E}}$$

Disadvantages:

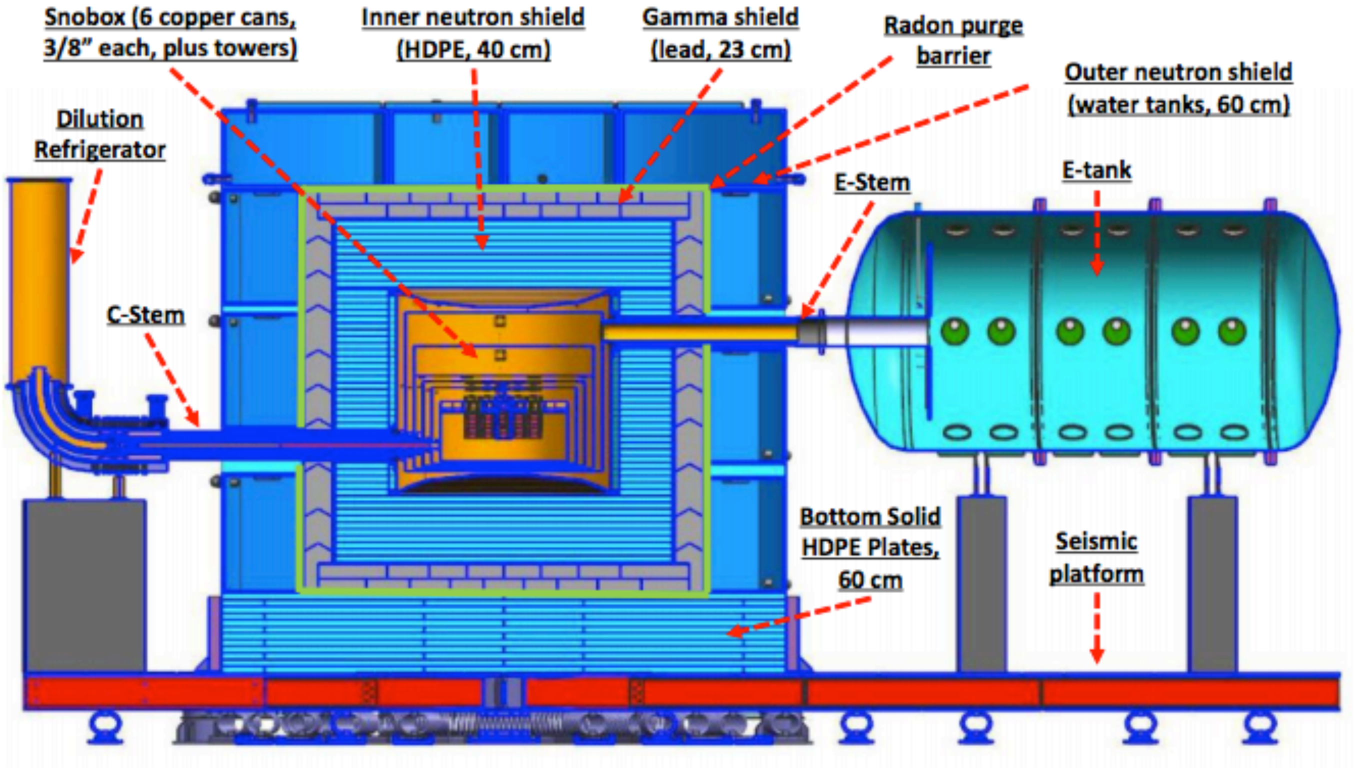
- Need dilution refrigerator
- Slow (components on ms scale or slower)
- Thermal equilibrium: losing information

# Transition edge sensors

- At transition edge, strong dependence of resistance on temperature
- By tuning voltage, TES can be held stable at transition edge (electrothermal feedback)
- Energy deposit compensated by drop in ohmic heating: faster
- Read out with SQUIDs, room temperature electronics
- Athermal: more information, larger detectors

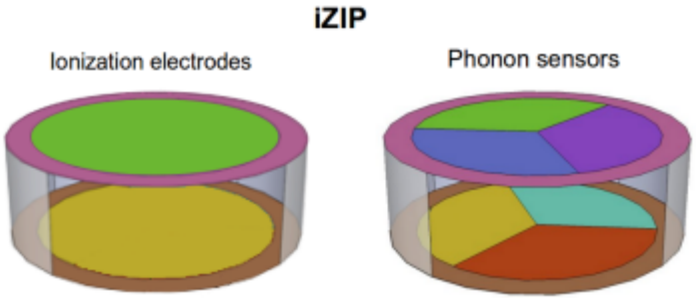


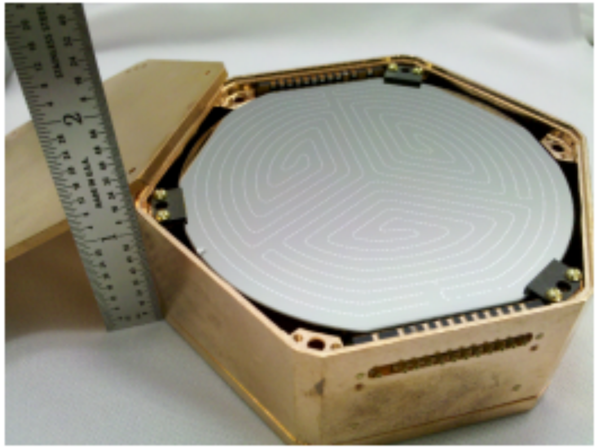
# SuperCDMS


Snobox (6 copper cans, 3/8" each, plus towers)
Inner neutron shield (HDPE, 40 cm)
Gamma shield (lead, 23 cm)
Radon purge barrier
Outer neutron shield (water tanks, 60 cm)
Dilution Refrigerator
E-Stem
E-tank
C-Stem
Bottom Solid HDPE Plates, 60 cm
Seismic platform

# SuperCDMS iZIP detectors

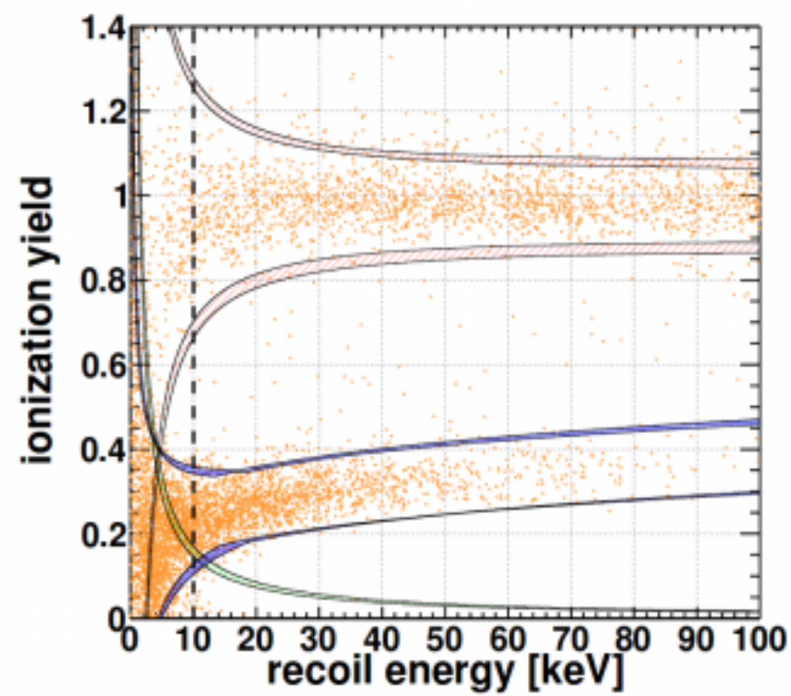
- Interleaved Z-sensitive Ionization Phonon detectors: bolometers plus charge channel
- 3” x 1” cylindrical germanium crystals with 4 tungsten TESs with aluminum fins (0V), 2 charge electrodes on each face (+2V on one toop, -2V on bottom)





# Electron recoil vs. nuclear recoil

- Electron recoil: loses energy at ~10keV/$\mu$m to other electrons, cascade continues until energies are lower than band gap, then phonons
- Nuclear recoil: more phonons produced at fixed energy
- Ionization yield: fraction of recoil energy that goes into ionization, scaled to 1 for electron recoils, ~30% for nuclear recoils

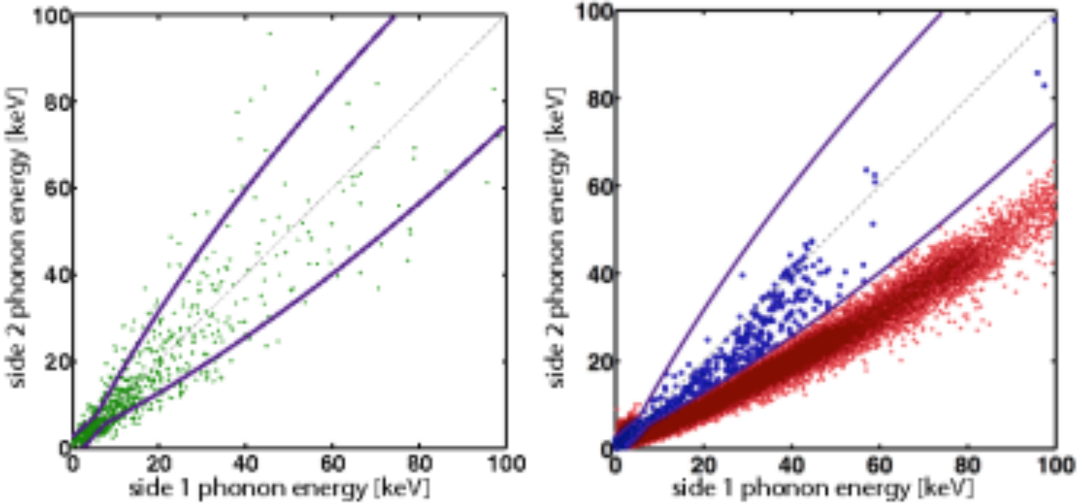


# ER -> NR leaks due to surface events

- Initially, self-interactions dominate motion of electrons and holes: back diffusion of both holes and electrons near top and bottom (~10$\mu$m from surface) into metal causes loss of charge
    - Add amorphous silicon between crystal and metal
- Irregularity of side wall can lead to charge trapping
- Either of these reduce measured ionization yield

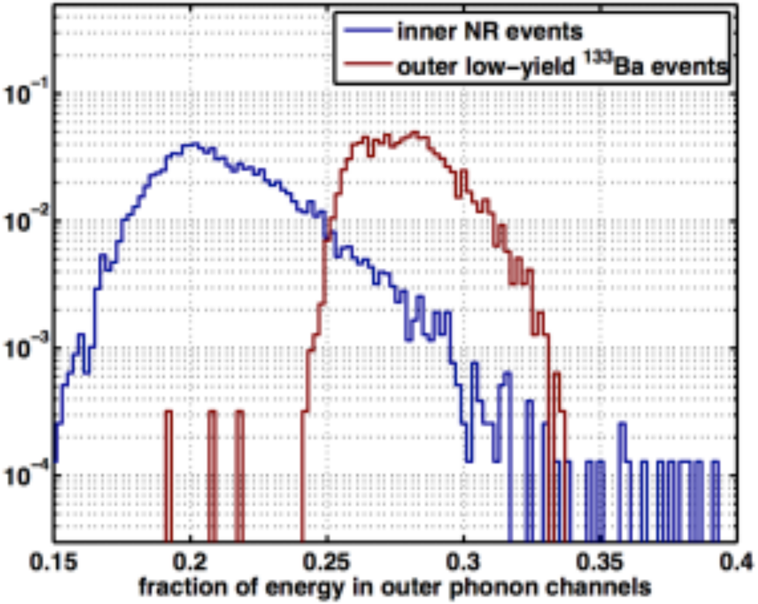
# Surface event rejection using TESs

Prompt phonons with frequencies ~THz have high scattering rate, lifetimes of ~40$\mu$s, concentrated over ~0.2mm. Frequent interaction with nearby TESs produces pulses with fast rising edge, high amplitude relative to those at further sensors, which only detect phonons after they downconvert and mean free paths lengthen. Position discrimination using TESs demonstrated with $^{210}$Pb (faces): able to limit leakage of surface events by fraction of $(4.5\pm0.9)\times10^{-4}$, with 46% NR acceptance



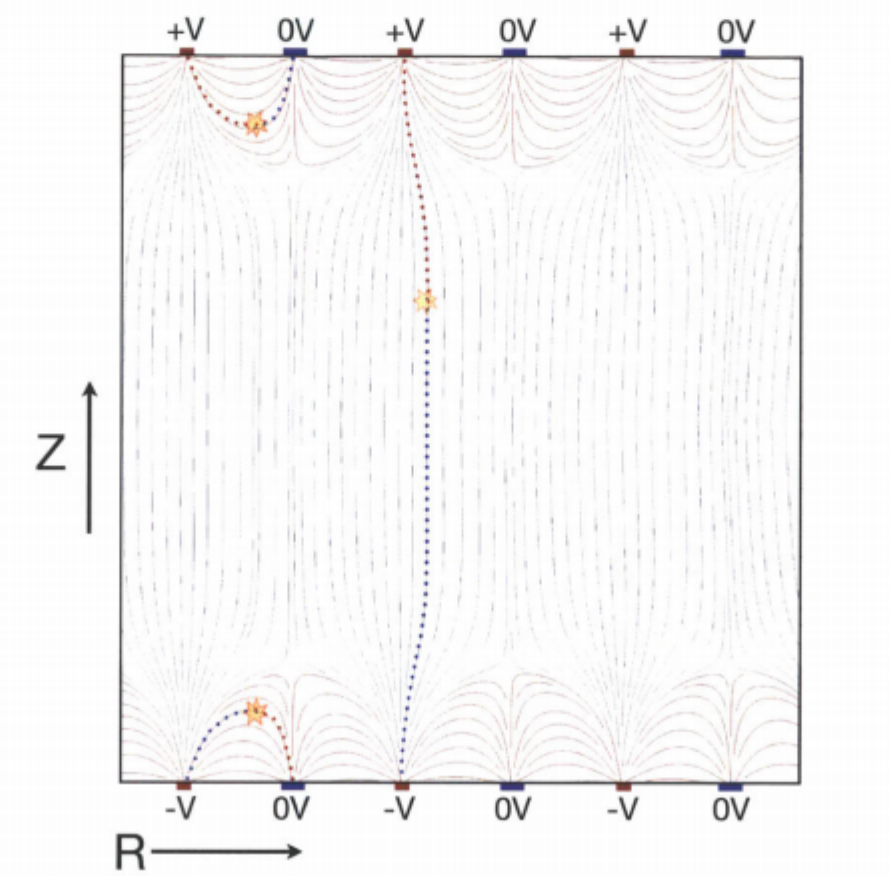
# Sidewall event rejection using TESs

Same technique, demonstrated for sidewall events using $^{133}$Ba source: rejection of 99.9% of sidewall events, 85% acceptance of NR



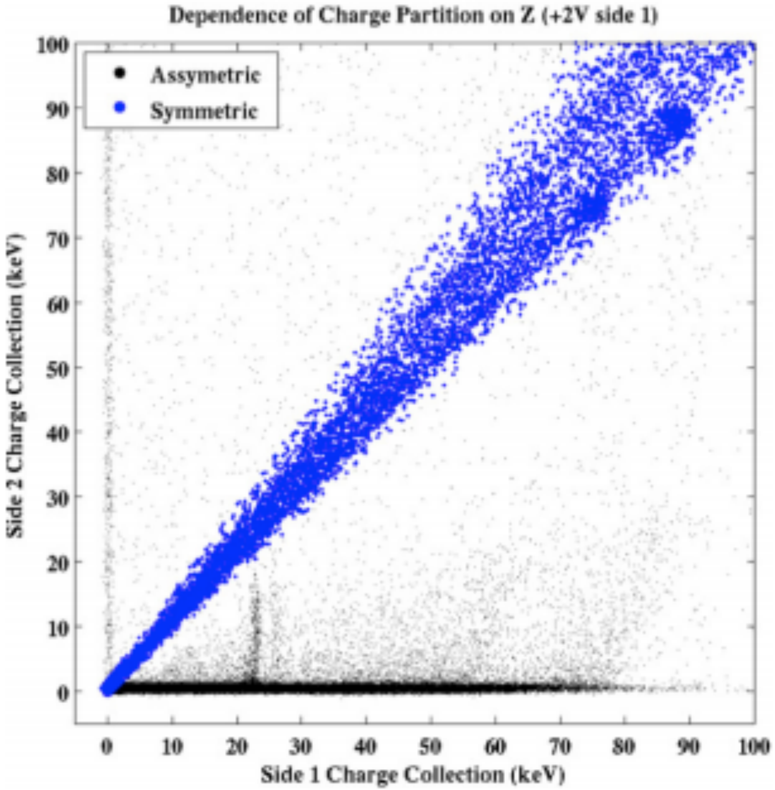
# Surface event rejection with charge

Earlier detectors were one-sided (phonon sensors on one end, charge sensors on other) with roughly uniform electric field. Interleaved pattern of charge sensors and phonon sensors results in stronger lateral electric fields near top and bottom, but still roughly uniform (and axial) in bulk. Reject asymmetric charge signals. Also, outer electrode ring provides veto for sidewall.



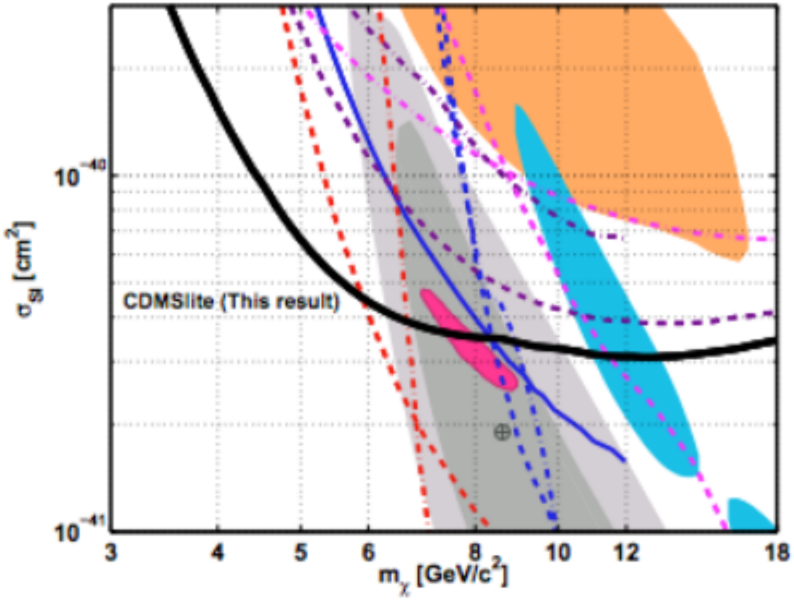
# Surface event rejection with charge

By cutting on symmetry of charge collection between top and bottom, and on fraction of ionization signal in outer ring, fraction of surface events misidentified as bulk NR is $< 10^{-4}$ with acceptance efficiency ~50%



# Low threshold search with Luke amplification

- In addition to primary phonons, Luke phonons from electrons and holes in electric field
- Small energies in electron and holes converted to detectable phonon signal with stronger electric field (70V instead of 4V)
- Sacrifice ER/NR discrimination
- Demonstrated in CDMSLite



# Summary

- Bolometers provide excellent energy threshold and resolution, and speed can be improved by use of TESs
- Using bolometers with additional signal channels provides valuable event discrimination for dark matter searches
- These detectors require dilution refrigerators, which are costly and cause challenges with scaling
- Such technology is at the forefront of WIMP searches on the lighter end of the mass scale

# References

R. Agnese et al., Projected Sensitivity of the SuperCDMS SNOLAB experiment. (2016) arXiv:1610.00006v1

R. Agnese et al., Demonstration of Surface Electron Rejection with Interleaved Germanium Detectors for Dark Matter Searches. (2013) arXiv:1305.2405v3

Anderson, A., Phonon-Based Position Determination in SuperCDMS iZIP Detectors. (2014) arXiv:1405.4215v1

Aprile, Elena. Dark Matter Direct Detection Experiments: part 1. https://indico.cern.ch/event/630418/contributions/2813743/attachments/1577607/2491735/Aprile_Lecture2.pdf

Knoll, G., Radiation Detection and Measurement. (2000)

Hertel, S. Advancing the Search for Dark Matter: from CDMS II to SuperCDMS. (2012)

Scorza, S., Background discrimination in new iZIP detectors at SuperCDMS. Journal of Physics: Conference Series 375 (2012)