Characterizing New Detectors for SuperCDMS SNOLAB

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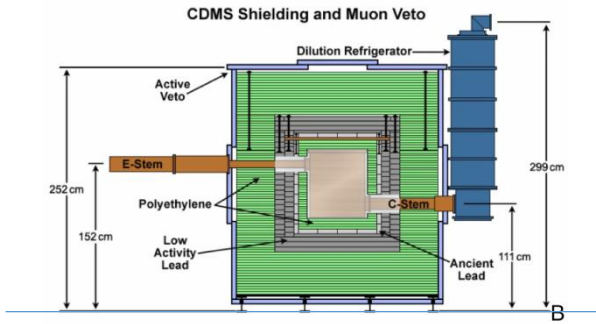
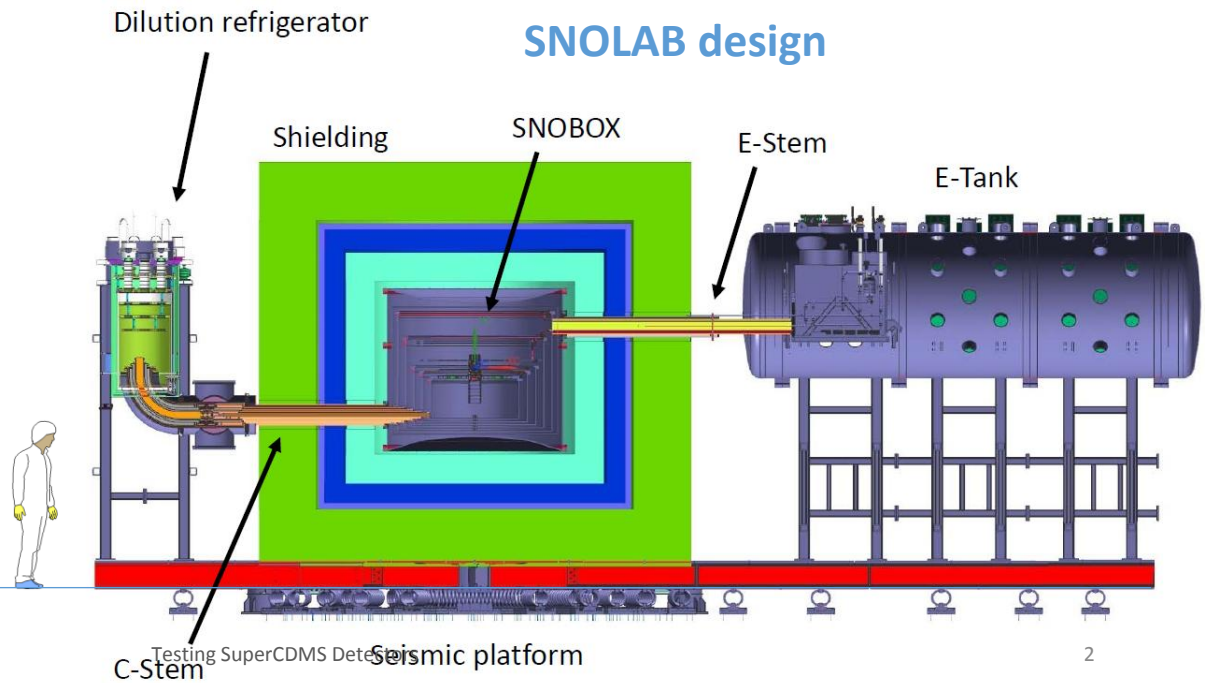
A new era for the Cryogenic Dark Matter Search

- 12 years of operation at the Soudan Underground Laboratory, now complete
- Currently building the next phase: SuperCDMS SNOLAB

Soudan setup

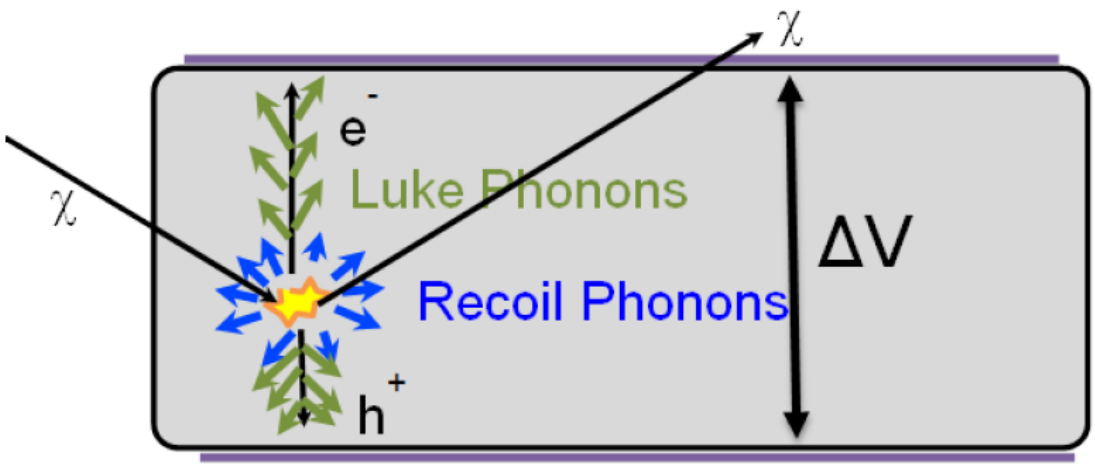


SNOLAB design



Basic CDMS Technology: Sensing Phonons

- Cryogenic semiconductor detectors:
  Ge or Si at < 0.1 K
- Athermal phonon sensors on detector surfaces
- Two populations of phonons:
  - Interaction energy
  - Neganov-Trofimov-Luke effect: phonons from drifting ionized charges through applied field



$$E_{phonon} = E_{interaction} + V_{bias} \times Q_{ionization}$$

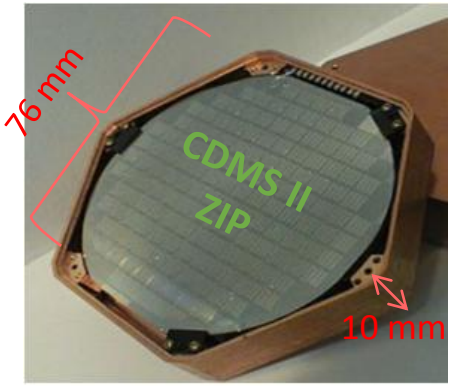
CDMS II Soudan era

The **ZIP** detector (Z-sensitive Ionization + Phonon)

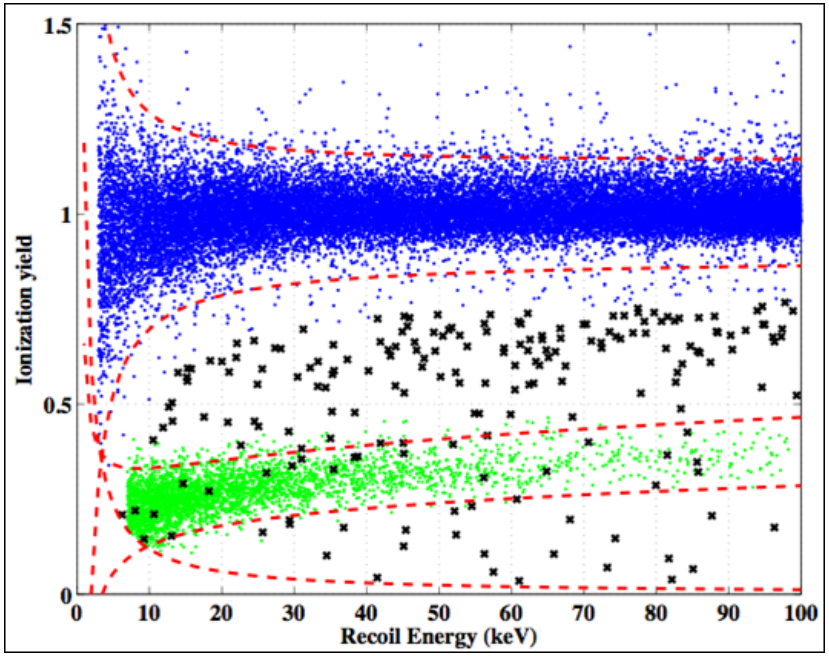
- Four phonon sensor arrays on 1 side
- Simultaneous ionization measurement
- V_{bias} of a few V

Sense phonons *and* ionization → independently determine
Interaction Energy &
Ionization Efficiency (Yield).

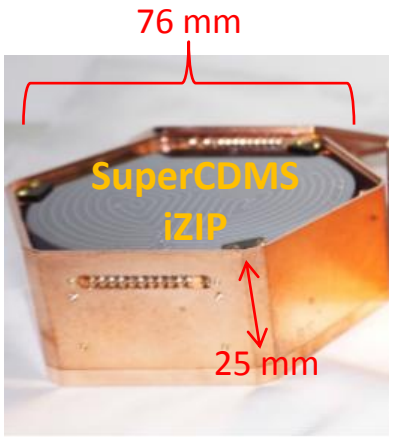
- Ionization Yield characteristically smaller for WIMP-signal (nuclear recoils, NR) versus γ and charged background (electron recoils, ER)



0.24 kg (Ge), 0.11 kg (Si)



SuperCDMS Soudan era: iZIP

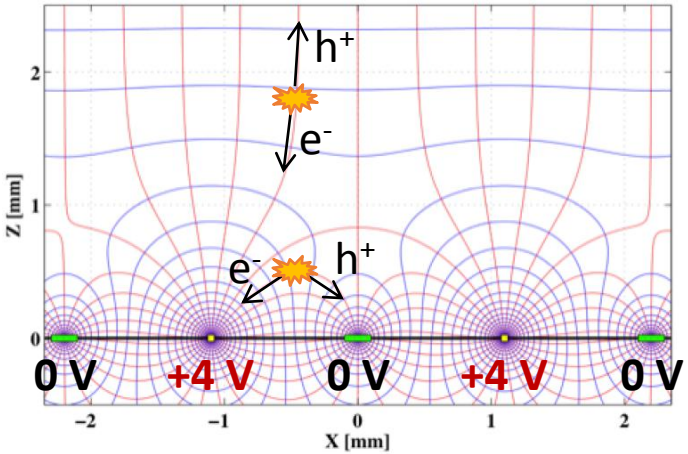


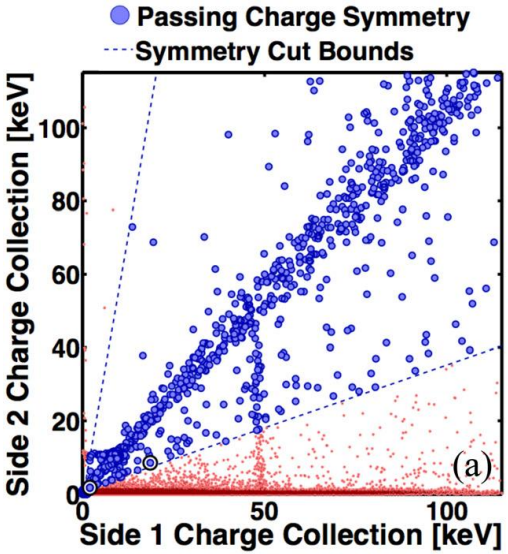
0.60 kg (Ge), 0.26 kg (Si)

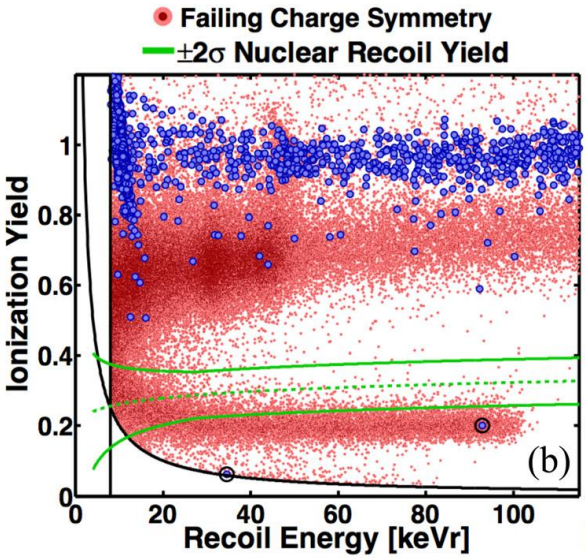
Near-surface ERs often have reduced yield, making them look like NRs…

The **iZIP** detector (ZIP with interleaved phonon and ionization sensors)

- Ionization electrodes on each side with interleaved ground rails – *improved sensitivity to surface events*
- Four phonon sensor arrays on each side
- Twice as many channels per detector, but detector more than twice as large
- V_{bias} of a few V





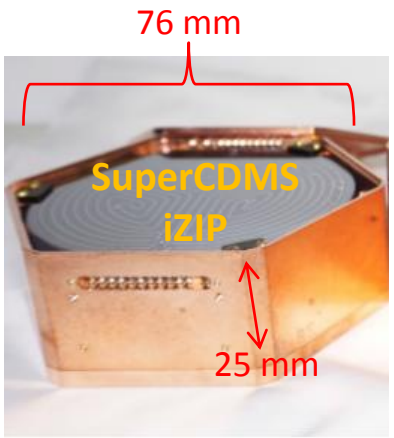


CDMSlite (Soudan era)

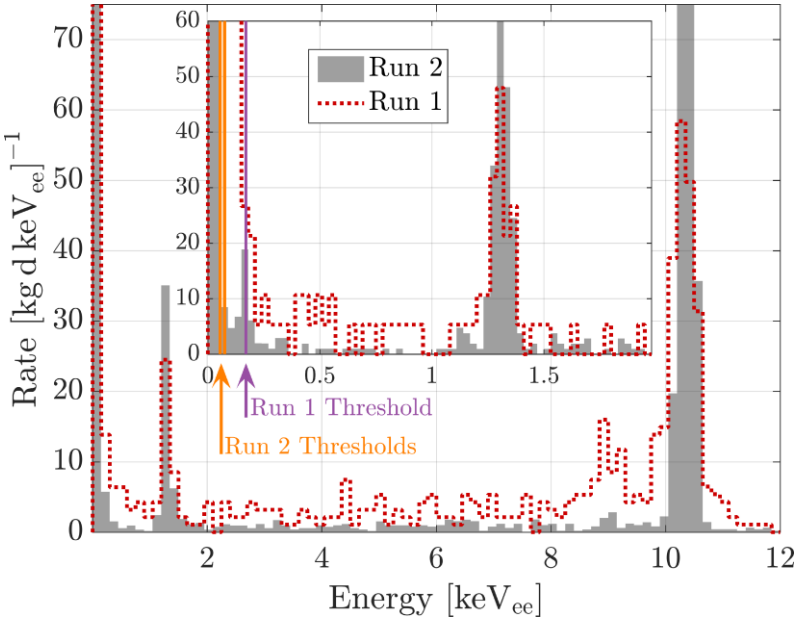
To probe smaller WIMP masses (<< 10 GeV), you need lower energy thresholds than ZIPs and iZIPs provide

CDMSlite: iZIP detectors wired and operated differently:

- Phonon channels read out on one side only (ground side)
- Other side biased to *>50 V*
- High gain from Luke phonons improves phonon energy resolution, reduces energy threshold
- ER/NR discrimination sacrificed for improved low-energy sensitivity



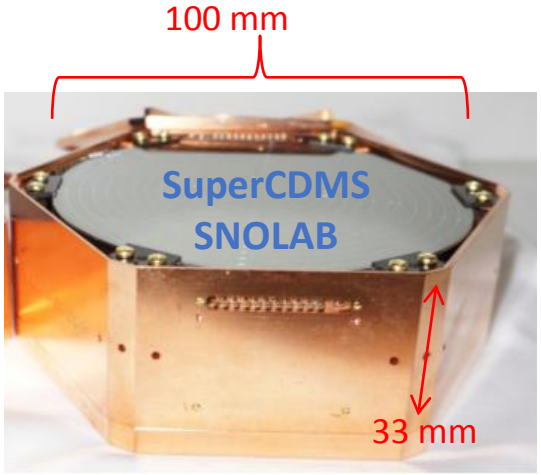
0.60 kg (Ge), 0.26 kg (Si)



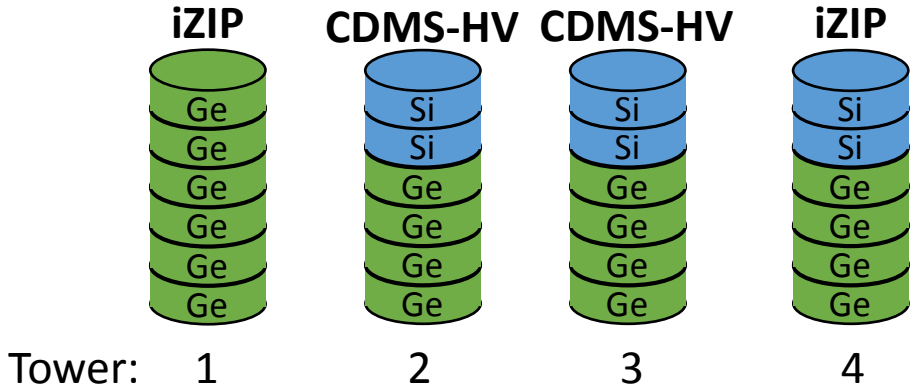
The future: SuperCDMS SNOLAB

Detector designs for SNOLAB build on past CDMS experience

- New **iZIP**s with more phonon sensors, sensor design improvements
- **CDMS-HV** detectors: inspired by CDMSlite
  - phonon readout on both sides
  - new optimized sensor design
- 2.4× larger detectors



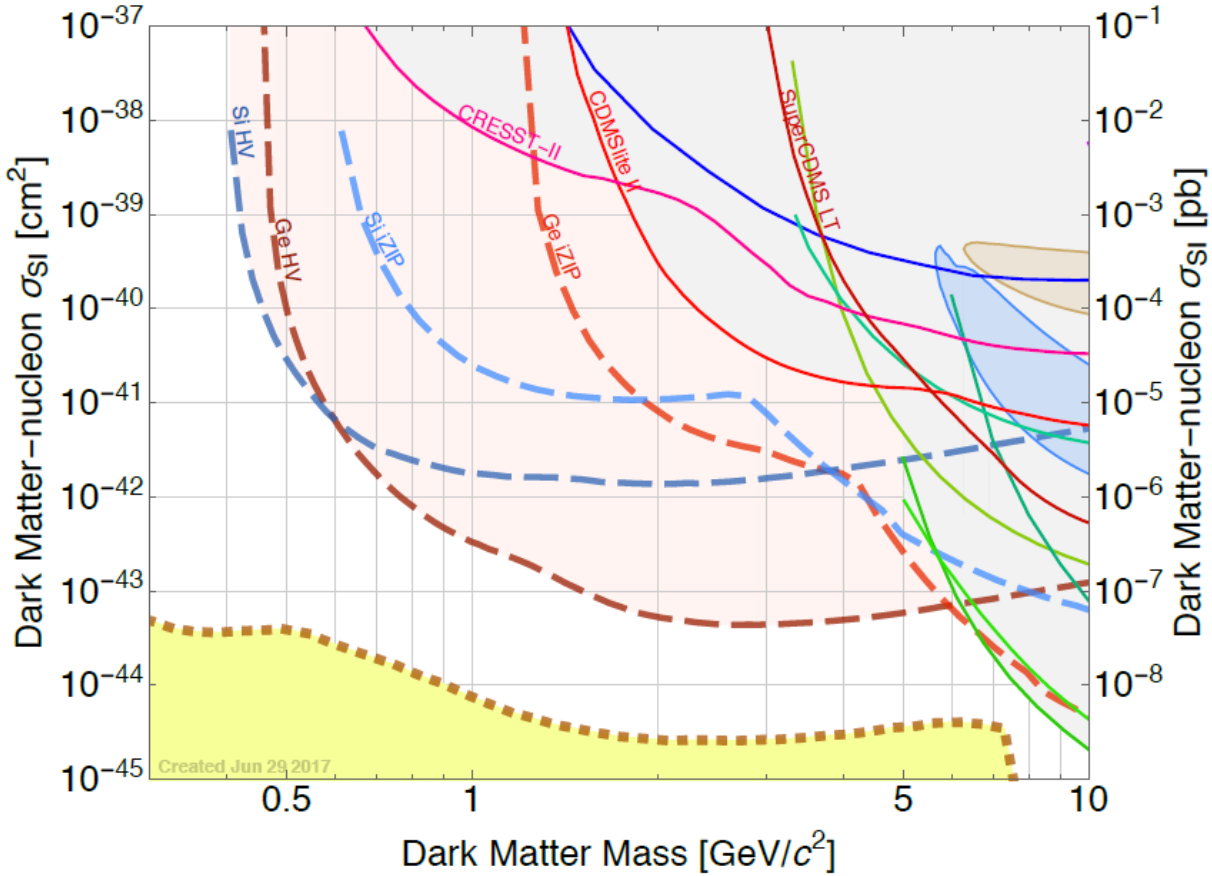
1.38 kg (Ge), 0.60 kg (Si)



Initial 4-tower payload

Room for a total of 31 towers

SuperCDMS SNOLAB science reach



Projected WIMP exclusion sensitivity (using the “goal” performance parameters)

SuperCDMS SNOLAB technical parameters

Description	Required	Goal
HV detectors		
Phonon energy resolution (σ) for Ge (Si)	50(35) eV_t	10(7) eV_t
Minimum bias voltage	50 V	100 V
iZIP detectors		
Phonon energy resolution (σ) for Ge (Si)	100(50) eV_t	50(25) eV_t
Charge energy resolution (σ) for Ge (Si)	300(330) eV_{ee}	160(180) eV_{ee}

Technical requirements and goals

Parameter	Design Value CDMS-HV	Design Value iZIP
TES Critical Temperature (T_c)	40-45 mK	40-60 mK
Energy Efficiency (ε_E)	15%	13%
Phonon Falltime (τ_{phonon}), Ge	200 µs	1400 µs
Phonon Falltime (τ_{phonon}), Si	40 µs	300 µs
Charge Collection Efficiency	N/A	95%

Design parameters

Design parameters projected from performance of previous designs & smaller R&D devices.

This talk:

first test results from full-sized prototype detectors

Testing prototypes at Minnesota

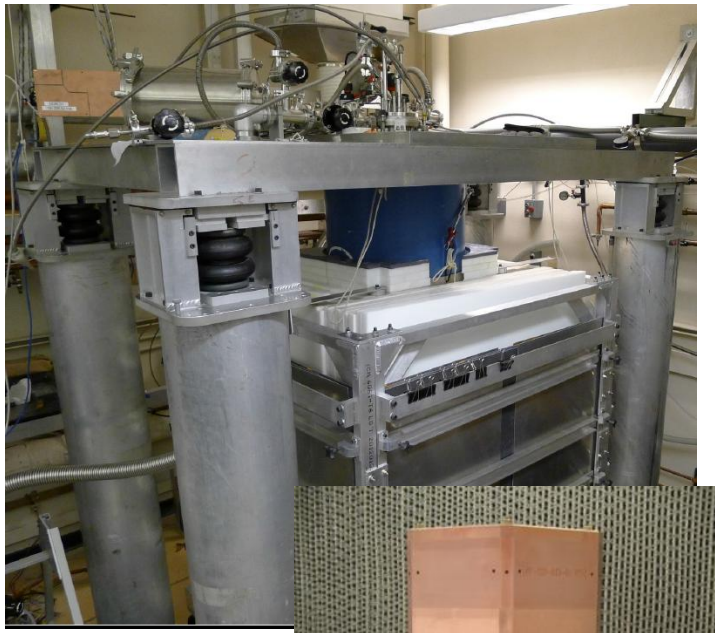
Limitations:

- Retrofitting to old electronics and hardware
- Only 1-sided readout on HV detectors
- Unavoidable muon background, much higher than deep underground sites

Detector resolutions can't be directly measured due to limitations in the test electronics

What can be measured:

- Charge collection efficiency
- Phonon collection efficiency
- Ability to hold high bias voltage
- Phonon sensor critical temperatures
- Phonon pulse rise and fall times
- Qualitative event reconstruction characterization



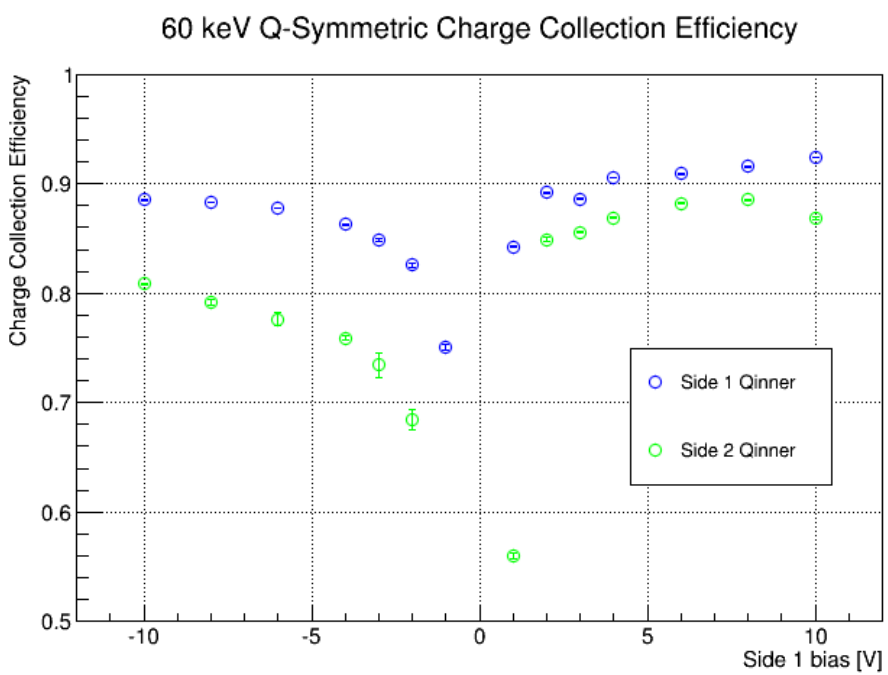
K100 test facility at UMN

Charge collection efficiency

At low iZIP biases , charge signals can be degraded due to carrier trapping.

Bigger problem in larger crystals. Also uniformity with radius must be verified.

High efficiency → improved ionization resolution, reduced position variations



100mm Ge iZIP prototypes have been shown to achieve near-maximum efficiency at biases around 4 V or less

Charge collection efficiency

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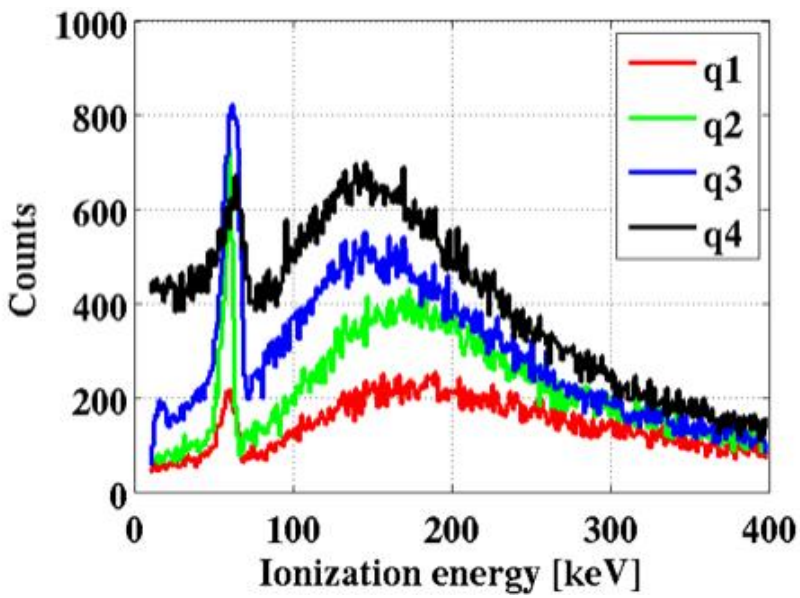
Bigger problem in larger crystals. Also uniformity with radius must be verified.

High efficiency → improved ionization resolution, reduced position variations



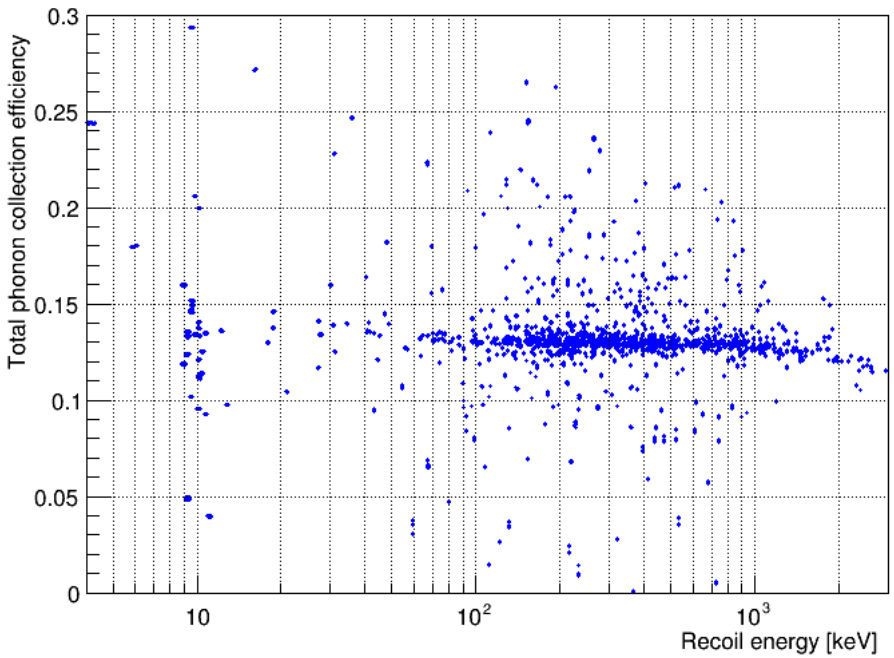
60 keV peak position constant at four different radial positions. Verification that charge collection is uniform across entire 50mm radius.

Phonon collection efficiency

Phonon collection efficiency (PCE): fraction of phonons that are collected to produce a signal

Direct effect on phonon energy resolution.

$$\sigma_{p,E} \approx \frac{T_c^3}{\epsilon_E}\sqrt{\frac{2}{5}k_B K \tau_{phonon}}$$



Ge iZIP PCE versus interaction energy

Measured efficiency is 13% and constant up to nearly 1 MeV

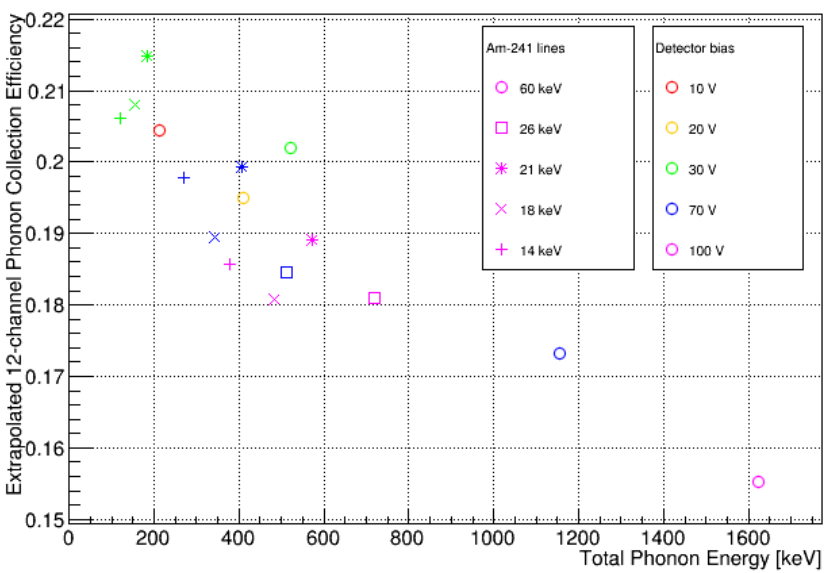
Good match to design goal

Phonon collection efficiency

Phonon collection efficiency (PCE): fraction of phonons that are collected to produce a signal

Direct effect on phonon energy resolution.

$$\sigma_{p,E} \approx \frac{T_c^3}{\epsilon_E}\sqrt{\frac{2}{5}k_B K \tau_{phonon}}$$



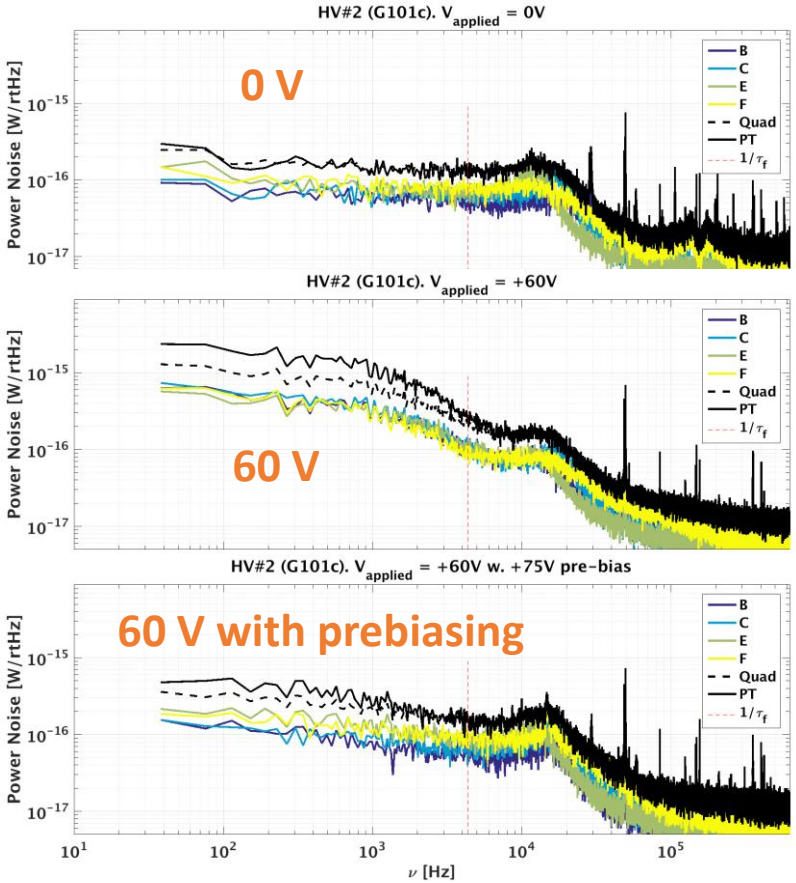
Si CDMS-HV PCE versus total phonon energy, based on several Am-241 peaks at various biases.

Efficiency falls at high energies due to localized sensor saturation. Region of interest is low energies, where efficiency approaches 21-22%.

Good match to design goal.

Ability to hold high bias voltage

At high bias, current leakage can occur (seen as strong noise in all channels) – "breakdown" voltage. Design aim to minimize this effect.



Ge and Si CDMS-HV prototypes show breakdown at or below 100 V

Below breakdown less dramatic effects can still occur – higher bias → higher phonon sensor noise (possibly related to high muon-rate in surface testing.)

"Pre-biasing" – overshooting the bias by ≈ 10% for a few minutes – significantly decreases the extra noise.

Good match to performance goal.

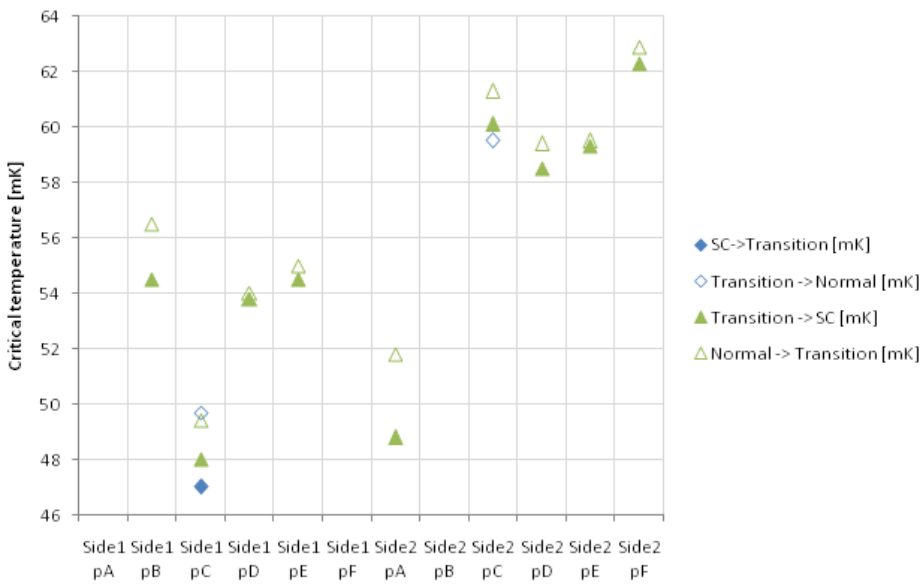
Phonon sensor critical temperatures

Phonon sensors operated at their s/c critical temperatures (transition-edge sensors)

$$\sigma_{p,E} \approx \frac{T_c^3}{\epsilon_E}\sqrt{\frac{2}{5}k_B K \tau_{phonon}}$$

Strong effect on resolution

Design target: minimize T_c within cryogenic system constraints .



Critical temperatures measured for Ge iZIP pathfinder detector (final design qualification for production of Tower 1 detectors)

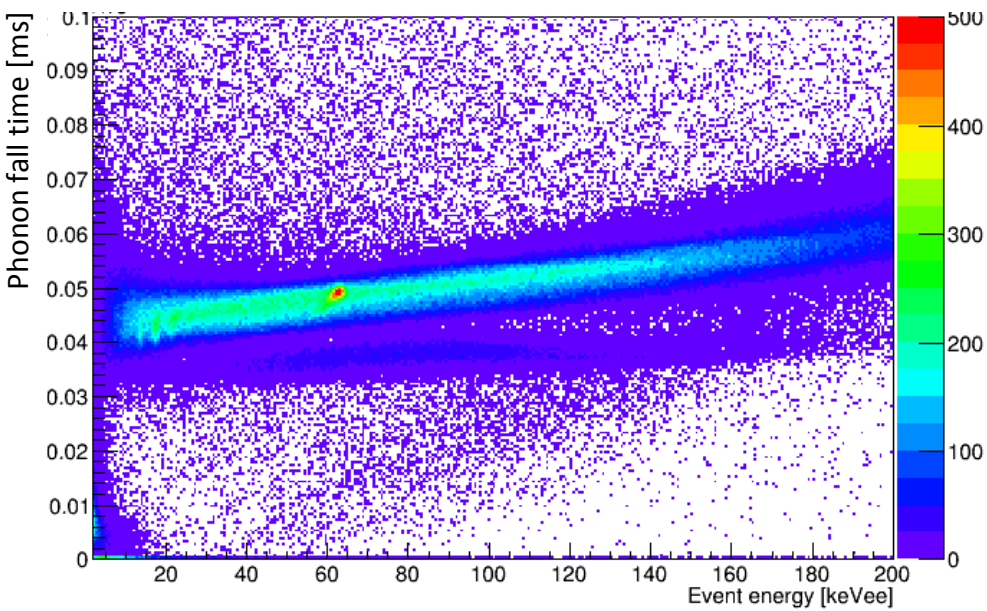
Acceptable match to design goal.

Phonon pulse fall time

Phonon resolution weakly dependent on phonon pulses fall time.

$$\sigma_{p,E} \approx \frac{T_c^3}{\epsilon_E}\sqrt{\frac{2}{5}k_B K \tau_{phonon}}$$

Fall times are also strong indicator of position sensitivity (small fall times → more position information), important for fiducialization in CDMS-HV detectors



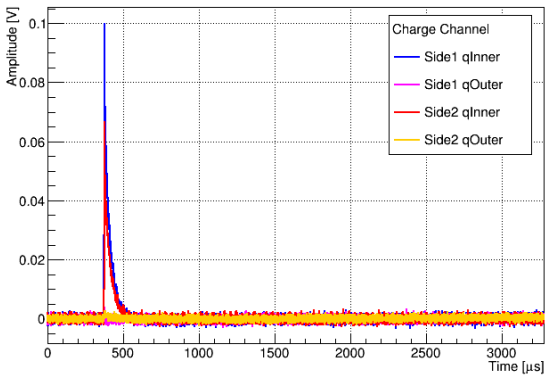
Phonon pulse fall time versus interaction energy measured for Si CDMS-HV prototype.

Increasing fall time with energy is likely a saturation effect.

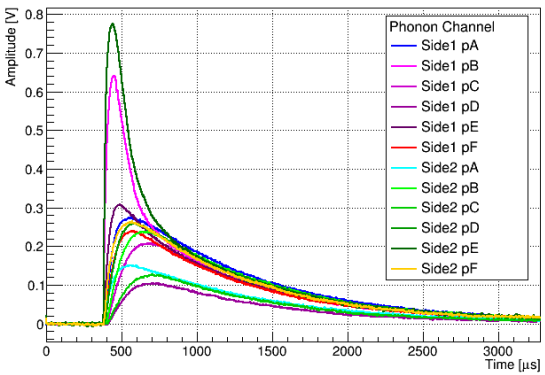
Fall time approaches 45 μs at low energy.

Close match to design goal.

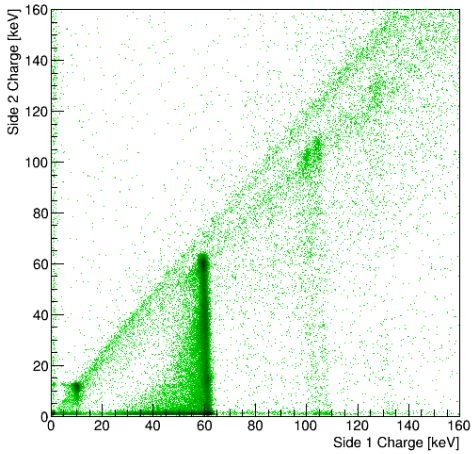
Position reconstruction in iZIP prototype



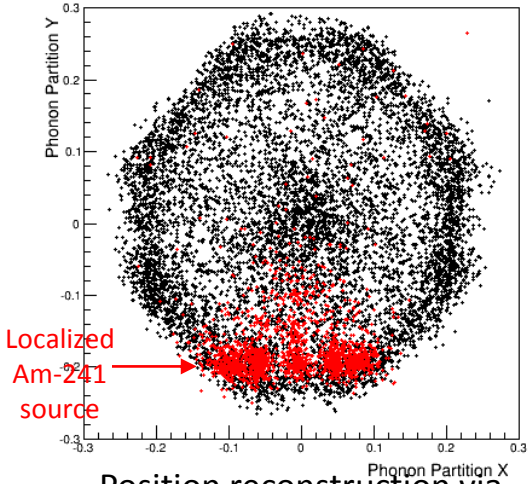
Ionization pulses



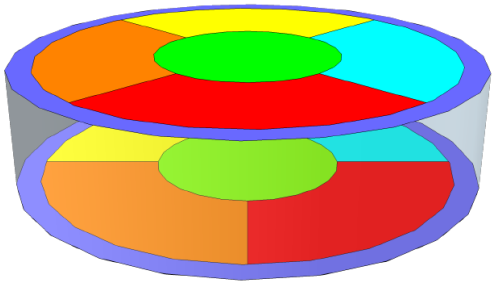
Phonon pulses



Position reconstruction via ionization channels

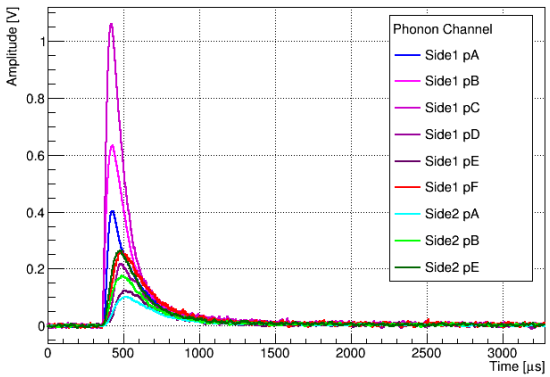


Position reconstruction via phonon channels

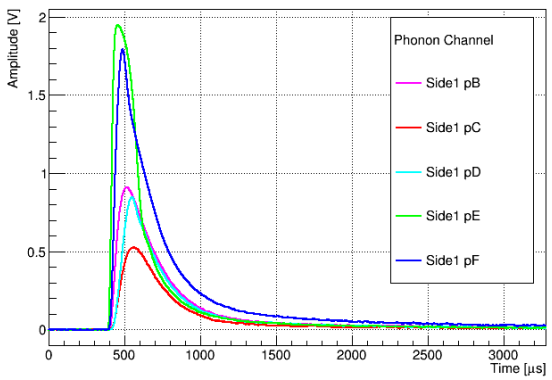


Phonon channel layout

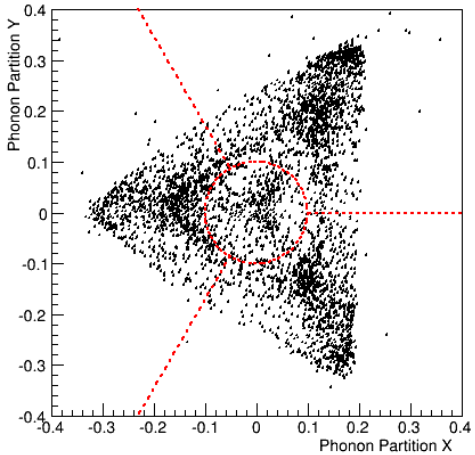
Position reconstruction in CDMS-HV prototype



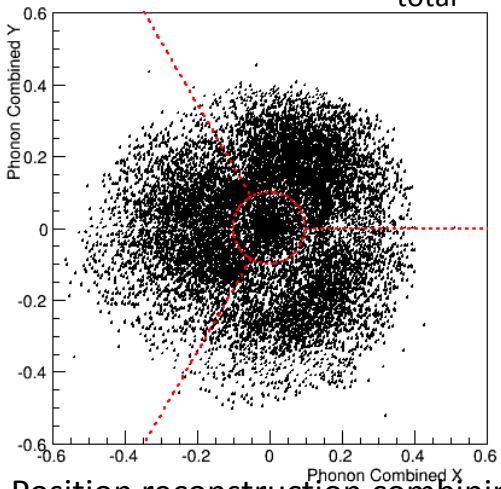
Phonon pulses ,
E_{total} = 200 keV



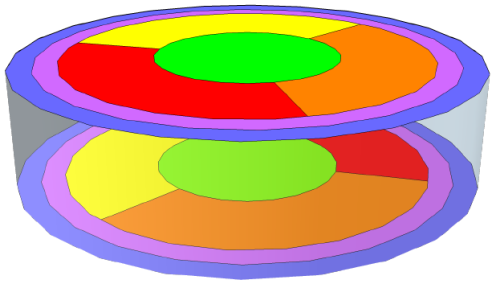
Phonon pulses,
E_{total} = 1.3 MeV



Position reconstruction via energy partition



Position reconstruction combining energy partition and pulse timing



Phonon channel layout

Future detector tests

- Run detectors with new electronics chain, demonstration of detector resolution
  - at SLAC
- Run detectors in deep underground site, with very low muon rate
  - at CUTE, testing facility under construction in SNOLAB

Technical requirements have been satisfied; future tests will show to what extent we've exceeded performance goals

Learn more about

SuperCDMS SNOLAB

at the

<u>SiDet Tour</u>

Friday 1:30 – 3:00

The CDMS Collaboration

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

NIST* | Northwestern U. | PNNL | Queen's University | SLAC

Southern Methodist U. | Santa Clara U. | 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

Measured performance parameters

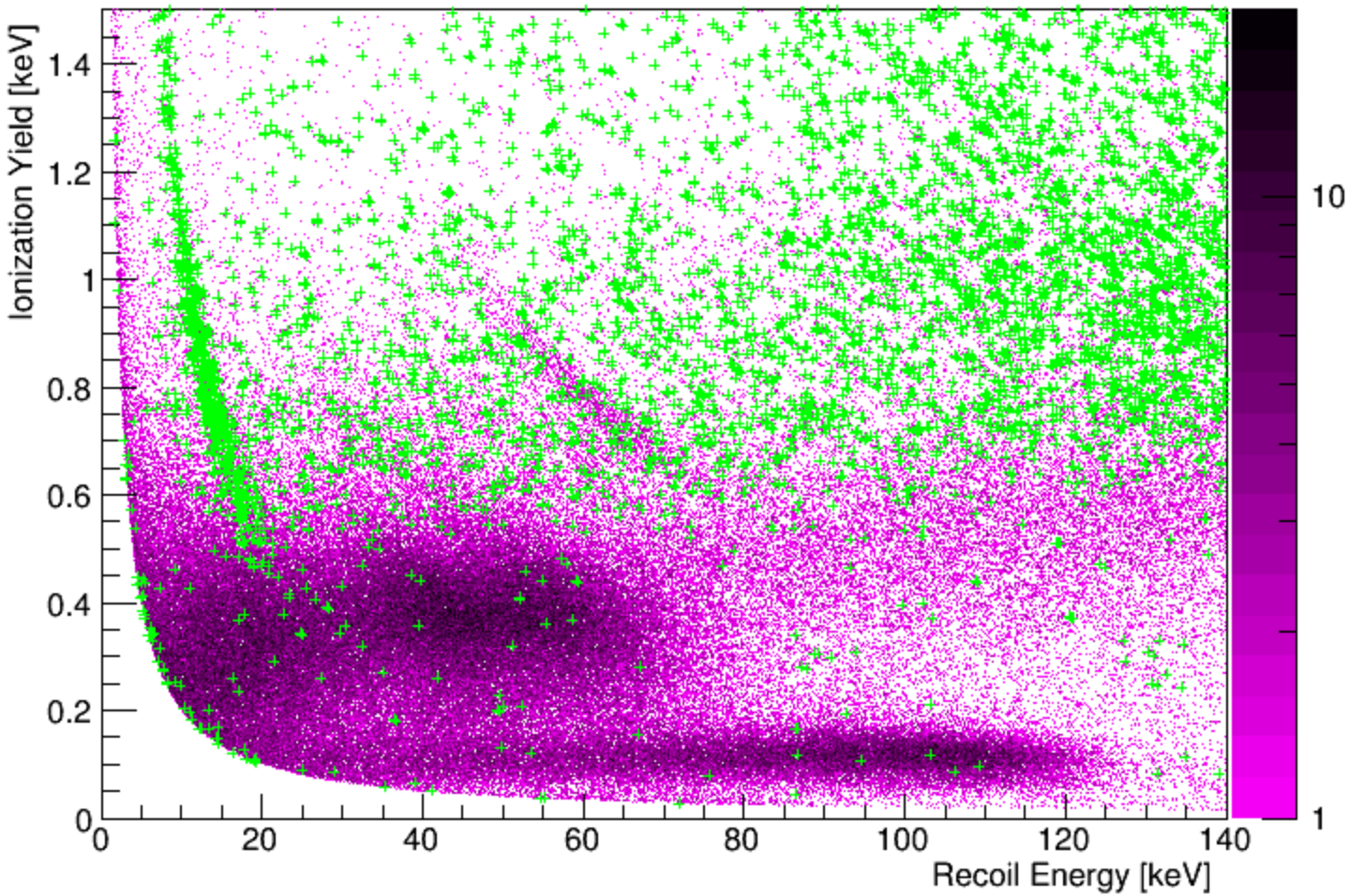
Parameter	Requirement	Design Value	Measurement	Reference
ϵ_{eh}	70%	95%	90-100%	Figure 29
			90%	Figure 33
ϵ_E				
iZIP Ge	8%	13%	13%	Figure 30
iZIP Si	8%	13%	22%	Figure 31
CDMS-HV Ge	8%	15%	12%	Figure 30
CDMS-HV Si	8%	15%	12%	Figure 32
τ_{phonon} (μs)				
iZIP Ge	2000	1400	~1500	Figure 34
iZIP Si	600	300	~300	Scaled from Figures 32&34
CDMS-HV Ge	400	200	~200	Figure 35
CDMS-HV Si	80	40	45	Figure 32

Table 5: **Measured detector signal performance, including ionization collection efficiency, phonon collection efficiency, and phonon falltime (bandwidth) measurements.** The measurements include references to figures in this section. **In all cases, the measurements exceed by large margins the values needed to achieve the Table 2 technical requirement values, demonstrating full validation of the signal aspect of the resolution modeling for all four detector types.**

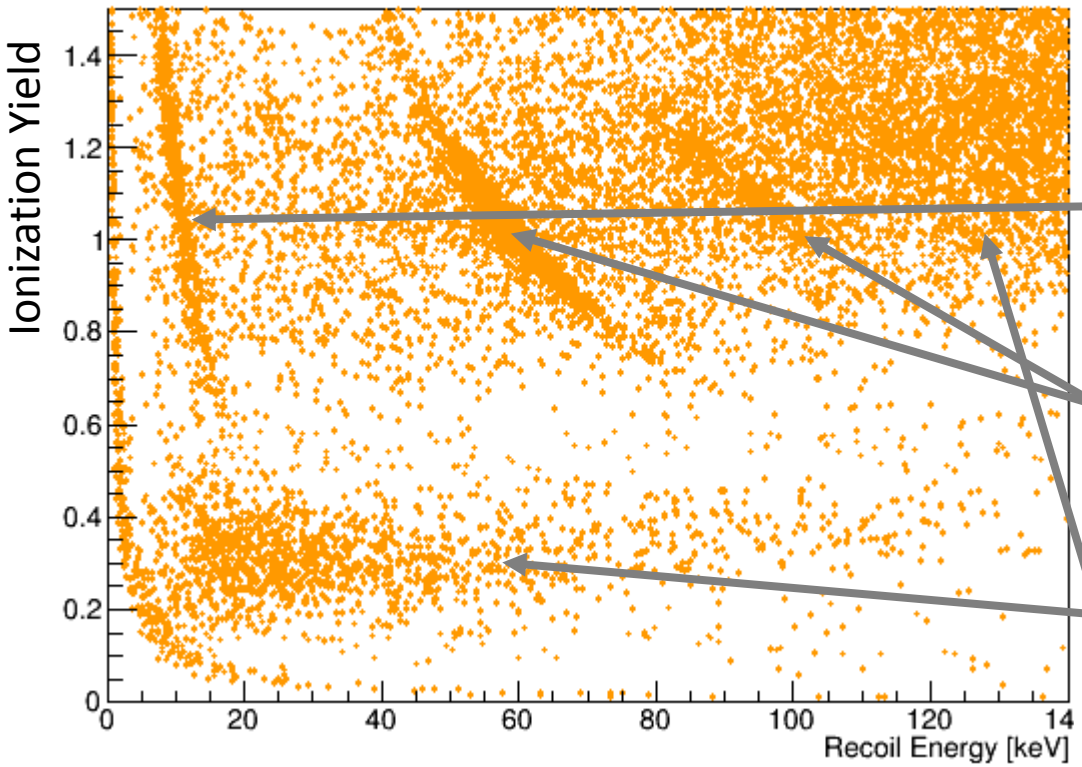
Ionization yield in iZIP prototype

Pb-210 source pointing at Side 1

Green events pass charge-symmetry cut



Ionization Yield-based discrimination

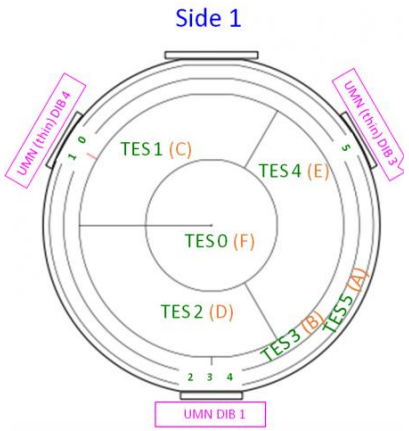


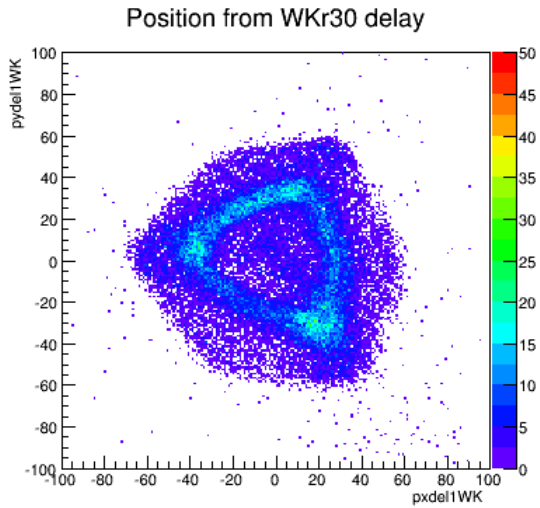
Calibration sources:

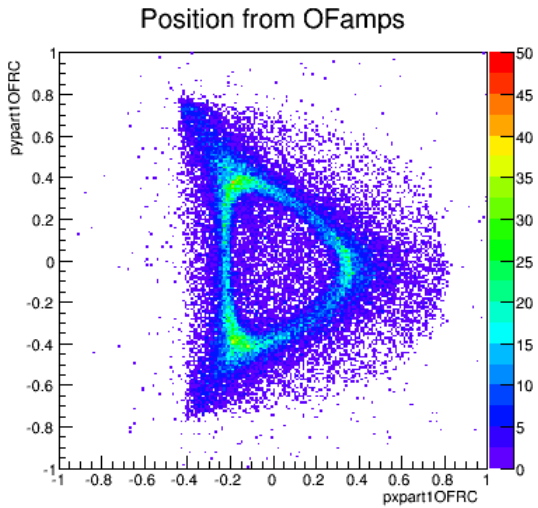
- ^{71}Ge internal activation (gamma)
- ^{241}Am near detector (gamma)
- ^{252}Cf outside fridge (gamma and neutron)

- Ionization Yield (defined as charge/energy normalized to the electron-recoil value) as a tool for discriminating the most common events: gammas from radioactivity in the materials near the detector.
- Requires ionization measurement plus an independent measurement of deposited energy

CDMS-HV prototype position reconstruction

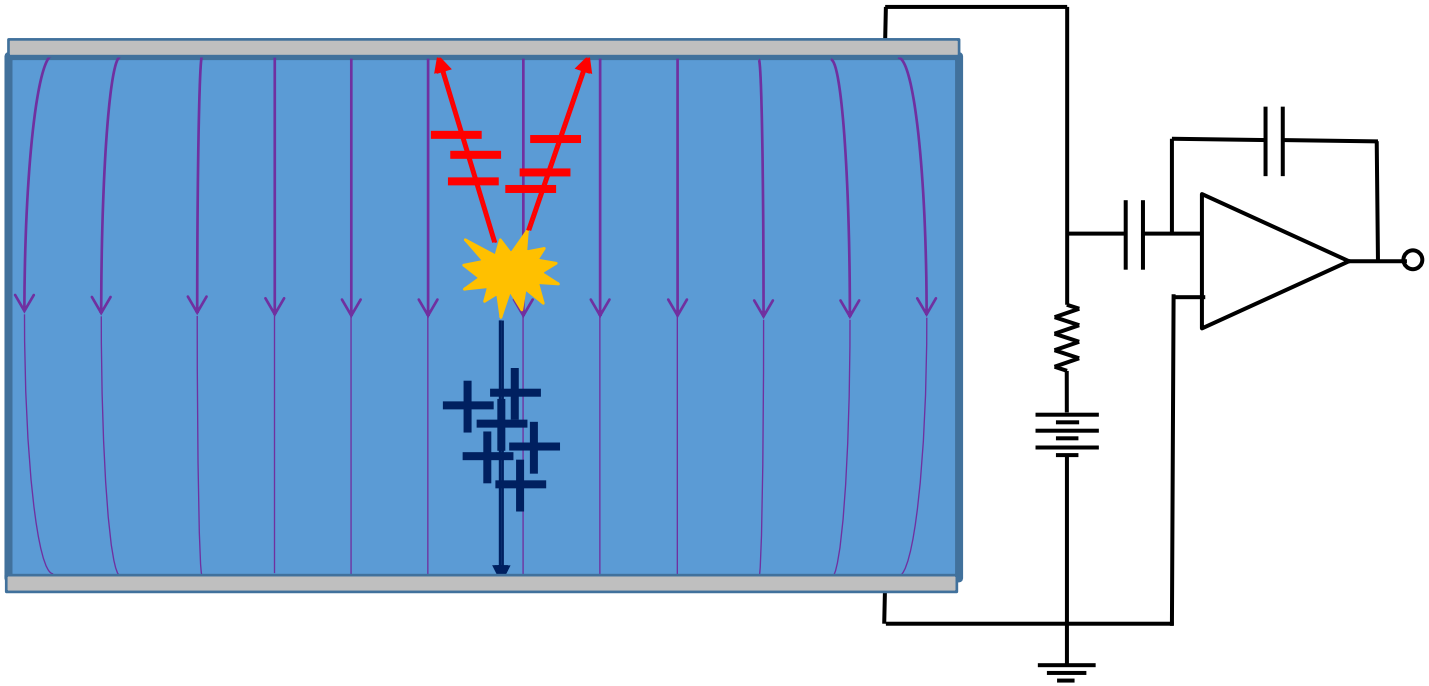






Example of position sensitivity: x-y position based on only the Side 1 inner-ring channels. “Delay” and “partition” reconstruction have complementary angular sensitivity

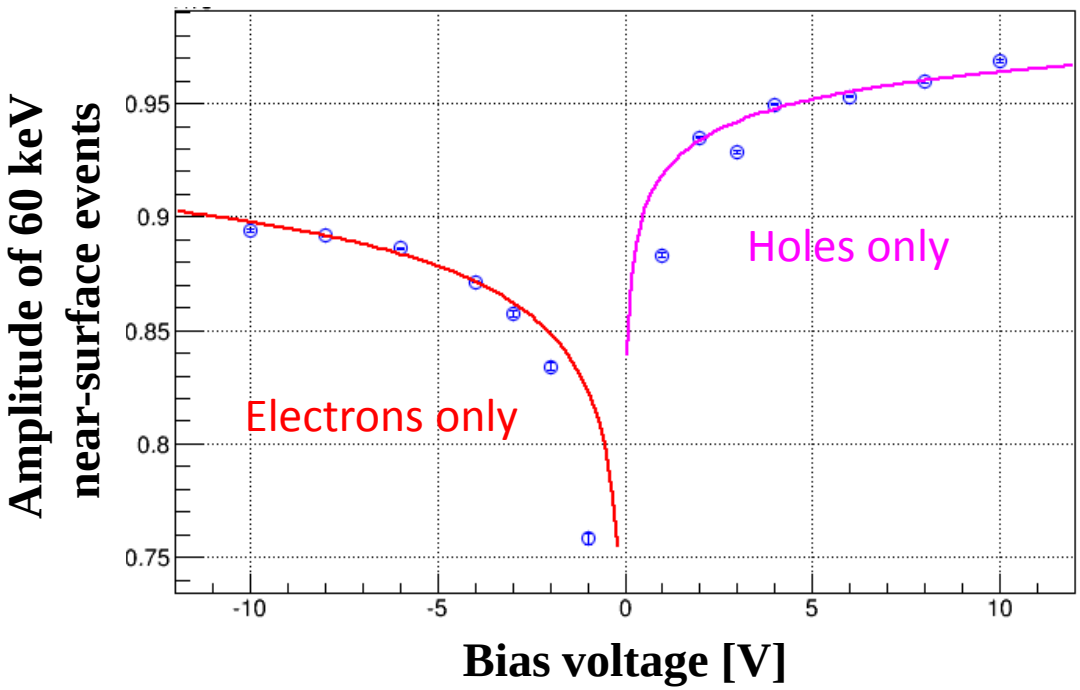
Measuring ionization



- Establish electric field through detector to drift charges to surfaces
  - sub-Kelvin Ge and Si are good insulators → nearly zero “leakage” current
- Current induced on electrodes as ionization charges move
- Signal amplified
- Total charge in current pulse = magnitude of ionization

Charge collection efficiency

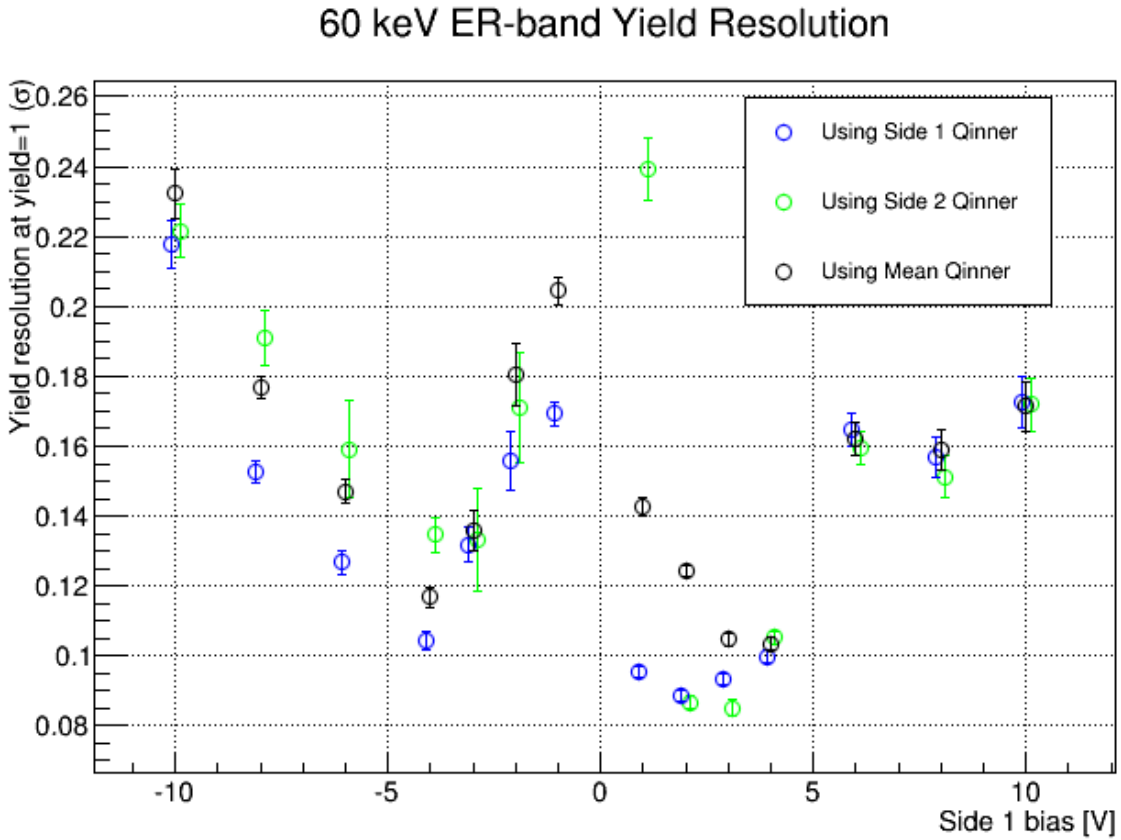
- ^{241}Am source near detector surface provides single-carrier event population – probe electron and hole transport properties separately



Fit to model implies

- Electron lifetime ≈ 3 μs
- Hole lifetime ≈ 6 μs

Optimizing ionization yield resolution

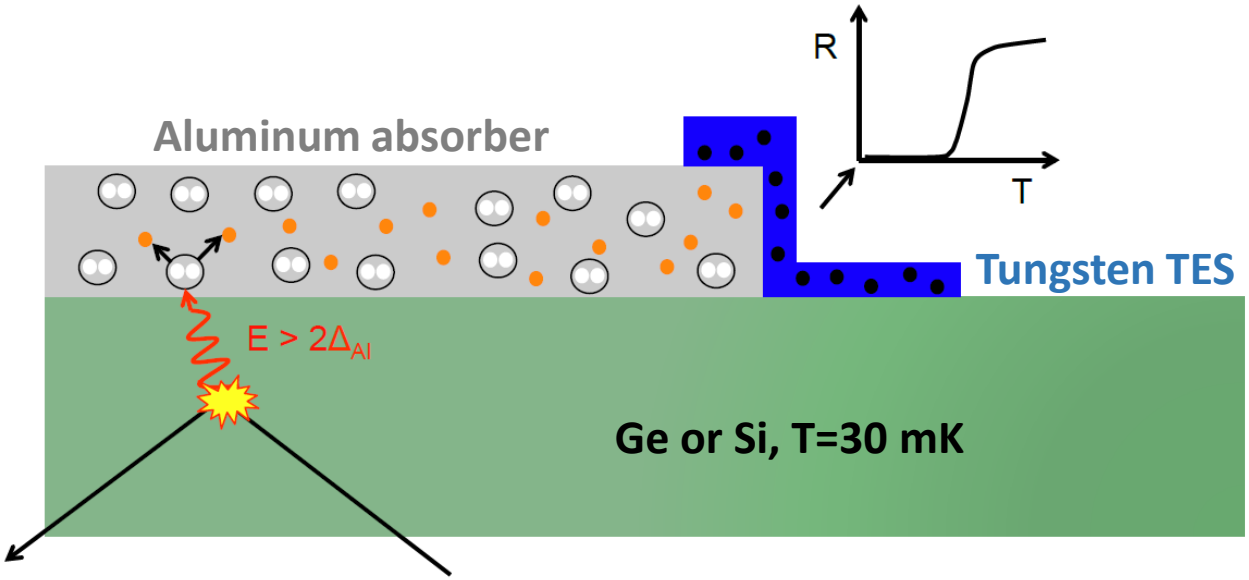


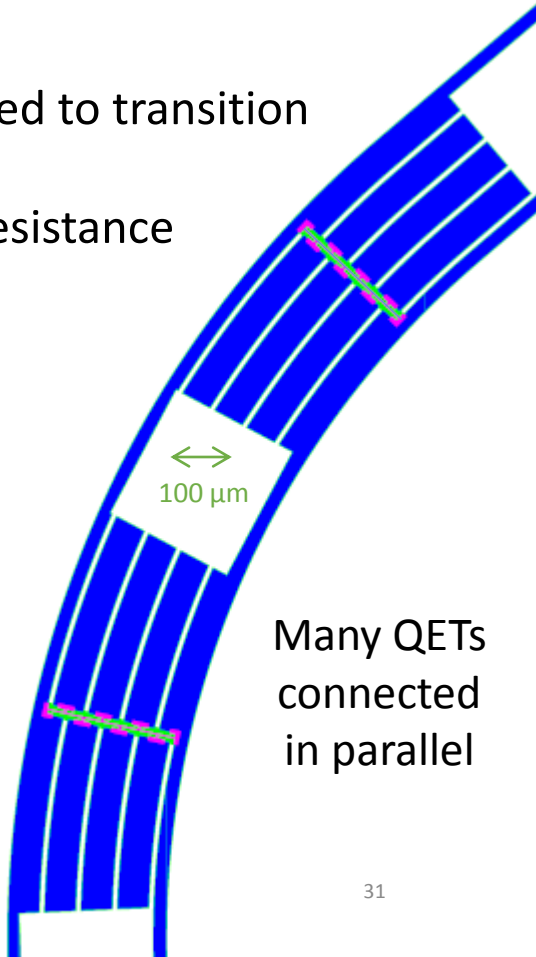
- With "iZIP" detectors we typically apply equal and opposite biases to the two sides. For this iZIPv6, the optimal voltage is around +4/-4 V (8 V in terms of Luke phonon production).

CDMS phonon detectors: QETs

Quasiparticle-assisted Electrothermal Feedback = QET

- Superconducting aluminum phonon absorber, T_c = 1.2 K
- Broken Cooper-pair quasiparticles
- Diffuse and get trapped by superconducting tungsten biased to transition temperature (Transition Edge Sensor = TES), $T_c \approx$ 80 mK
- Temperature increase in TES causes very large change in resistance



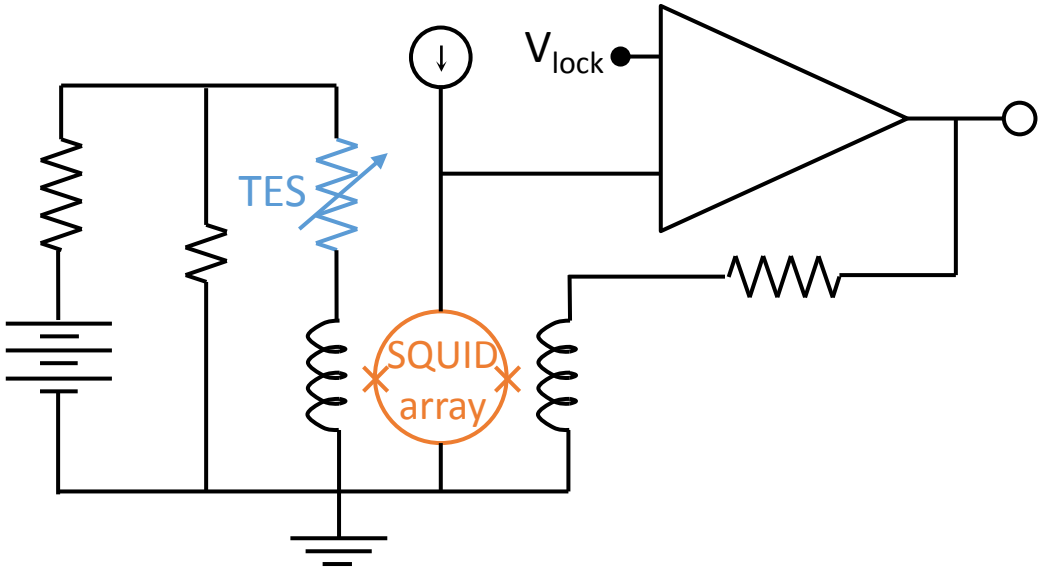


Many QETs connected in parallel

Phonon signal amplification

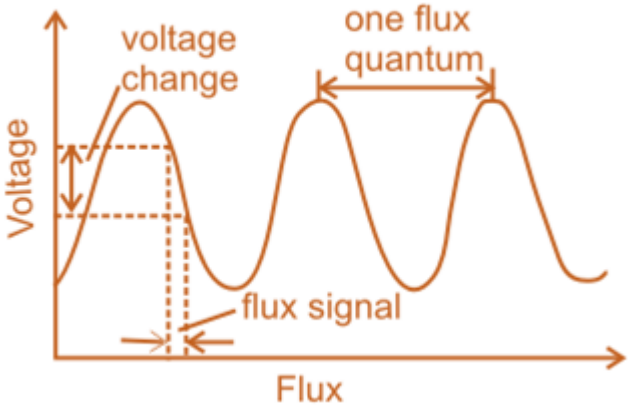
Electrothermal feedback:

- Phonons heat TES
- TES resistance increases
- Bias current through TES is reduced
- which allows TES to cool back to T_c



Superconducting Quantum Interference Device (SQUID):

- Change in TES current measured by SQUID array (low-noise, very sensitive)
- Feedback circuit keeps SQUID array at lockpoint voltage



CDMS-HV phonon sensor design

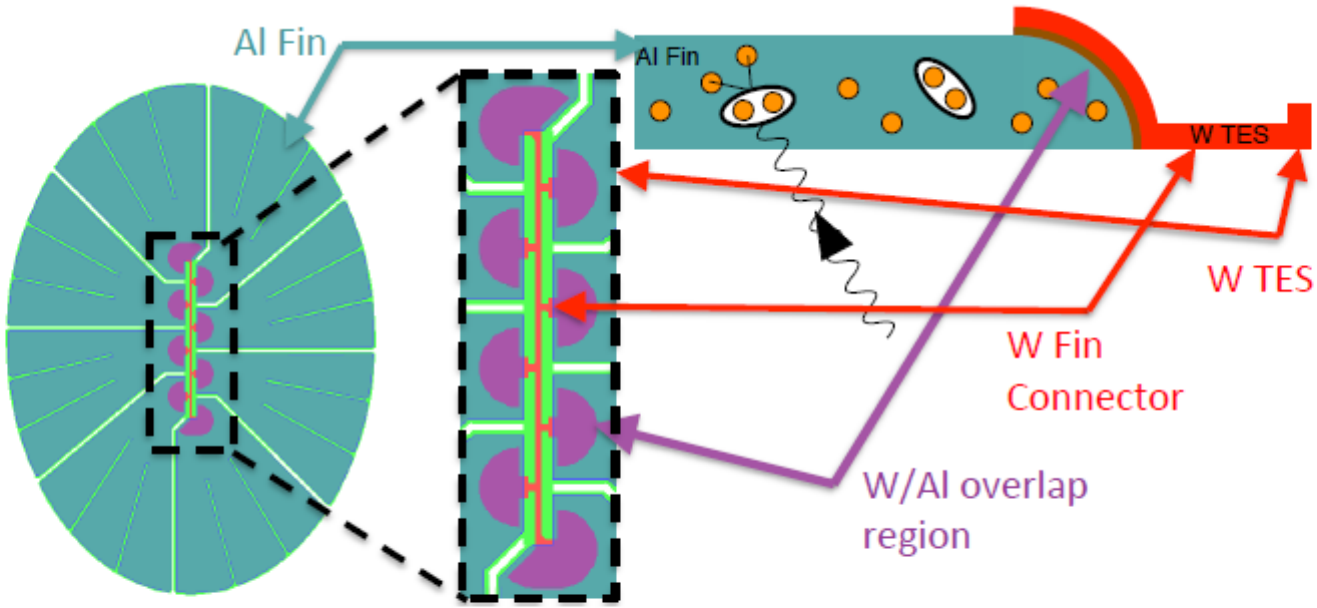
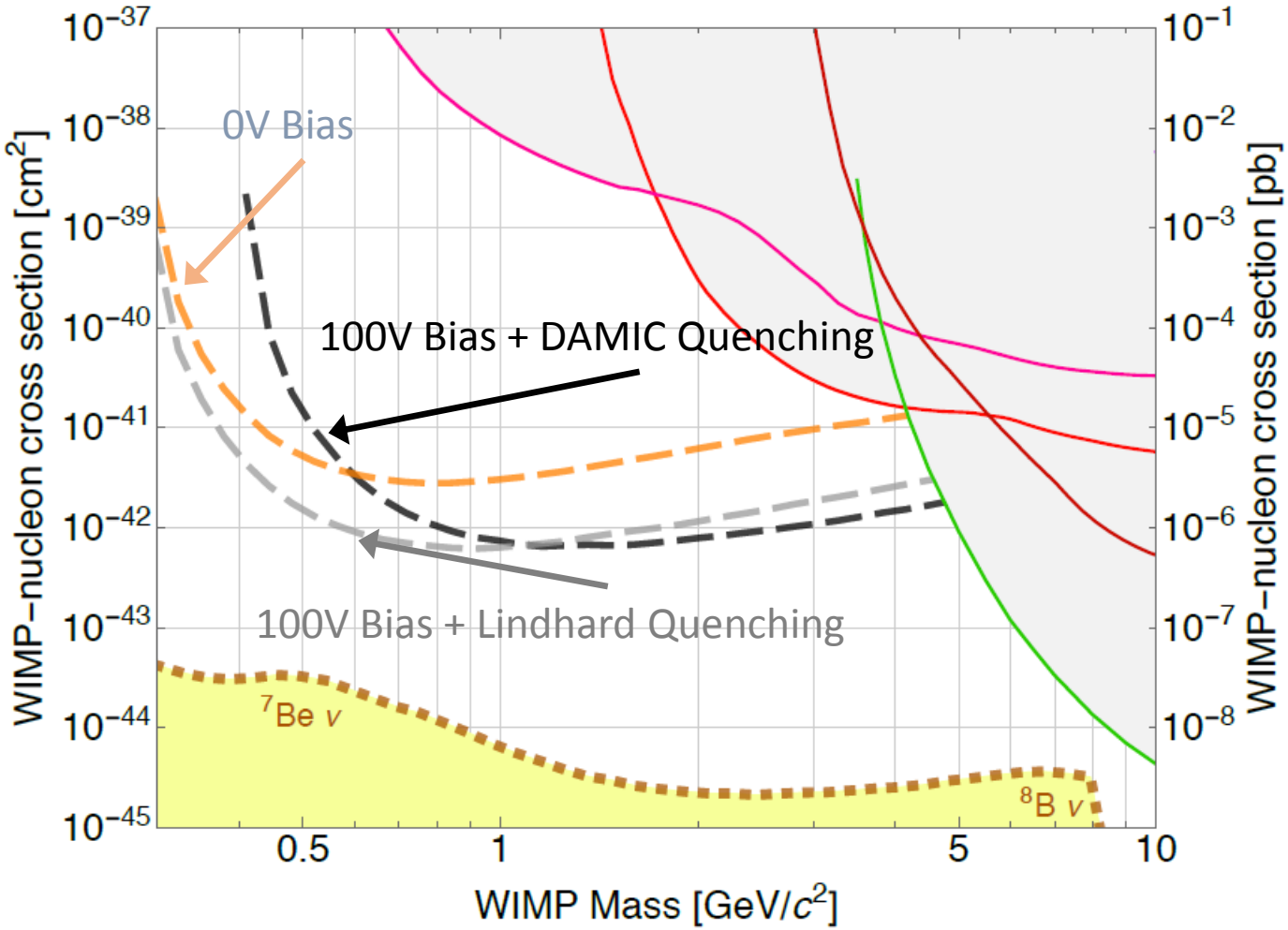


Figure 11: (Left) Diagram of the SuperCDMS HV athermal phonon sensor design. (Middle) Close-up of the W TES and its connections to the Al phonon collection fins. (Right top) Heuristic cross-sectional view of the athermal phonon sensor.

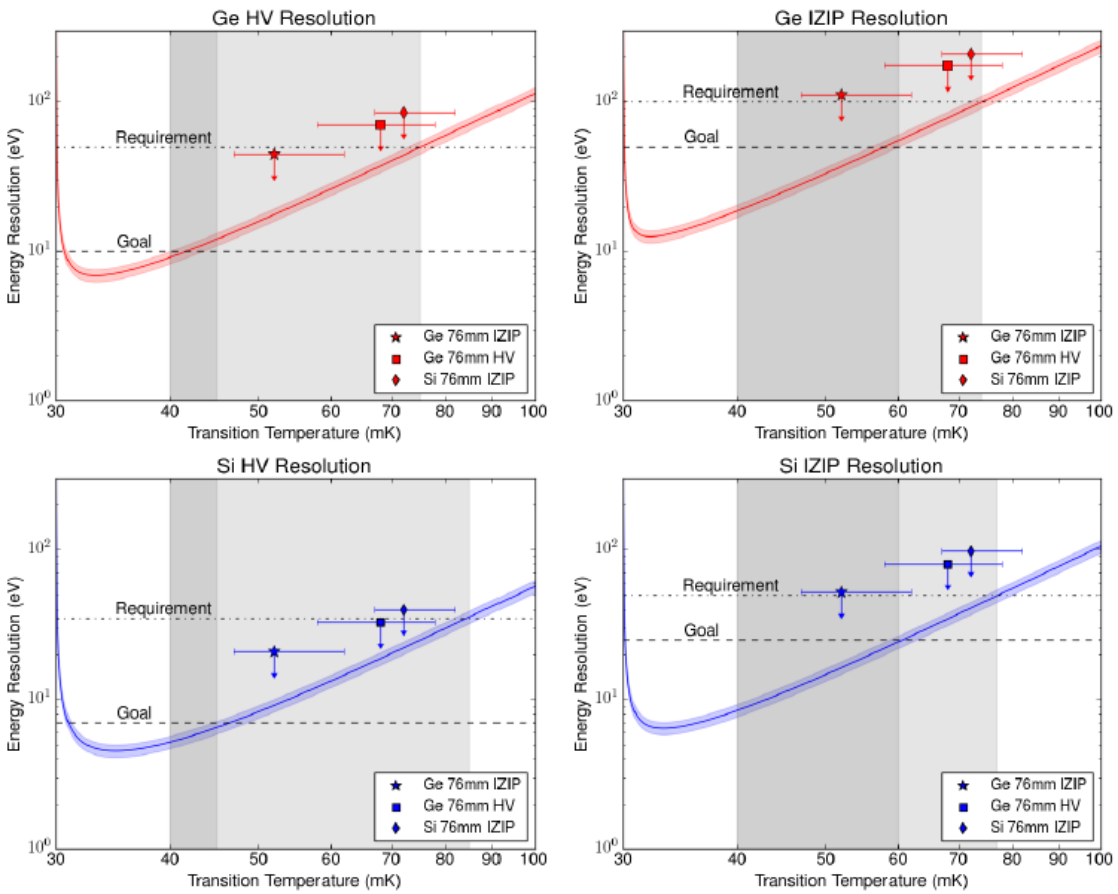
Si CDMS-HV Sensitivity



Design validation

Detector performance parameters have been estimated based on measurements from previous detector designs and smaller R&D devices.

Some full-sized SNOLAB detector prototypes have been tested at surface facilities, mostly at the K100 test facility at the University of Minnesota.



Detector design parameters

Parameter	Design Value CDMS-HV	iZIP
Crystal Temperature	<30 mK	
TES Parameters		
Length	200 μm	155 μm
Normal State Resistance	150 mΩ	
Operating Resistance	50 mΩ	
Loop Inductance	$\ll$ 500 nH	
Shunt Resistance	5 mΩ	
Parasitic Resistance	< 5 mΩ	
$\alpha \left(\frac{R_0}{T_c} \frac{dR}{dT} \Big\vert_{I_0} \right)$	$\sim$ 150	
$\vert\beta\vert \left(\frac{R_0}{I_0} \frac{dR}{dI} \Big\vert_{T_c} \right)$	< 0.3	
T_c	40-45 mK	40-60 mK
Risetime (L/R)	2-3 μs	2-4 μs
Falltime (τ_{TES})	30-40 μs	10-40 μs
QET Parameters		
Geometry	"Stadium"	"Linear"
Fin Length	240 μm	80-110 μm
Trap Geometry	"Semicircle"	"Rectangle"
Trap Length	20 μm	5 μm
QET Number	$\sim$1800	$\sim$1400
Energy Efficiency (ϵ_E)	15%	13%
Aluminum Coverage	35%	4%
Phonon Falltime (τ_{phonon}), Ge	200 μs	1400 μs
Phonon Falltime (τ_{phonon}), Si	40 μs	300 μs
Charge Input Capacitance	N/A	$\leq$300 pF
Charge Channel		100-180 pF
HEMT Input		100 pF
Parasitic		20 pF
Charge Collection Efficiency	N/A	95%