Improved Electron Transport in G4CMP-276

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SuperCDMS Experiment

Direct detection search for dark matter (WIMP or axion-like)

Underground at Sudbury (Vale) mine, host of SNOLAB facility

Assembling now, commissioning early 2025, first science late 2025

Underground Lab:

37,000 m^3 volume

5000 m^2 Class 2000

0.27μ/m^2/day

Courtesy: SNOLAB

SuperCDMS

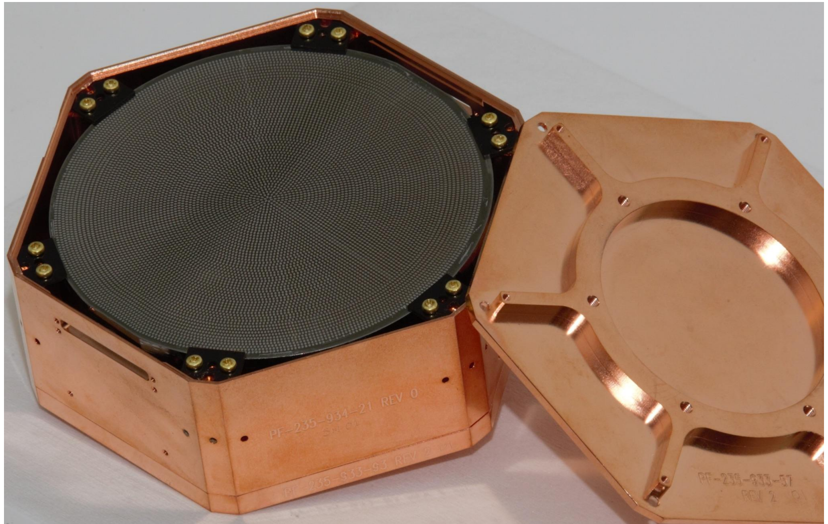
50 mK base temperature, 6-stage fridge

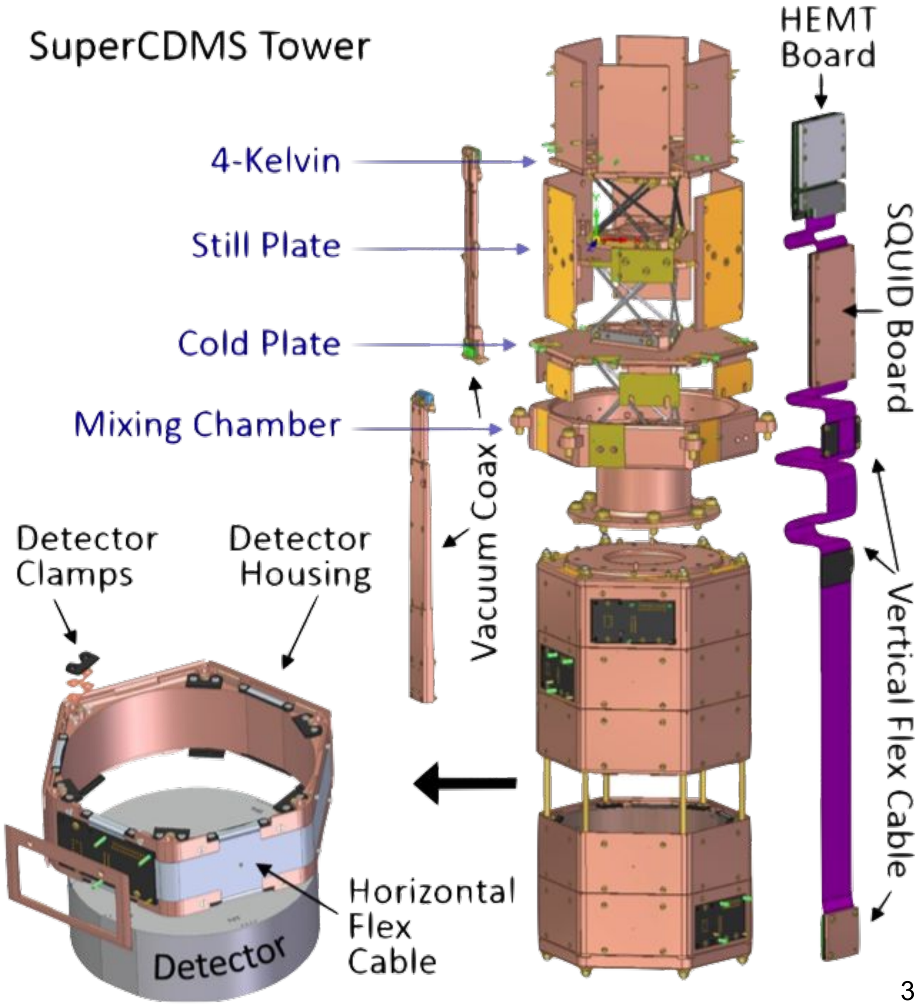
4 towers, 6 detectors each, 60° rotations

Ge(100), Si(100) detectors 100×33 mm

High (100V) and low (4V) voltage

Charge and phonon sensors





SuperCDMS Experiment – Detector Response

We use G4CMP to model e/h propagation and NTL phonon production

G4CMPKaplanQP models phonon collection and TES sensor response

A useful "truth" metric to evaluate detector performance compares total phonon energy collected (reported by KaplanQP) to expected phonon energy for a given energy deposit and voltage bias

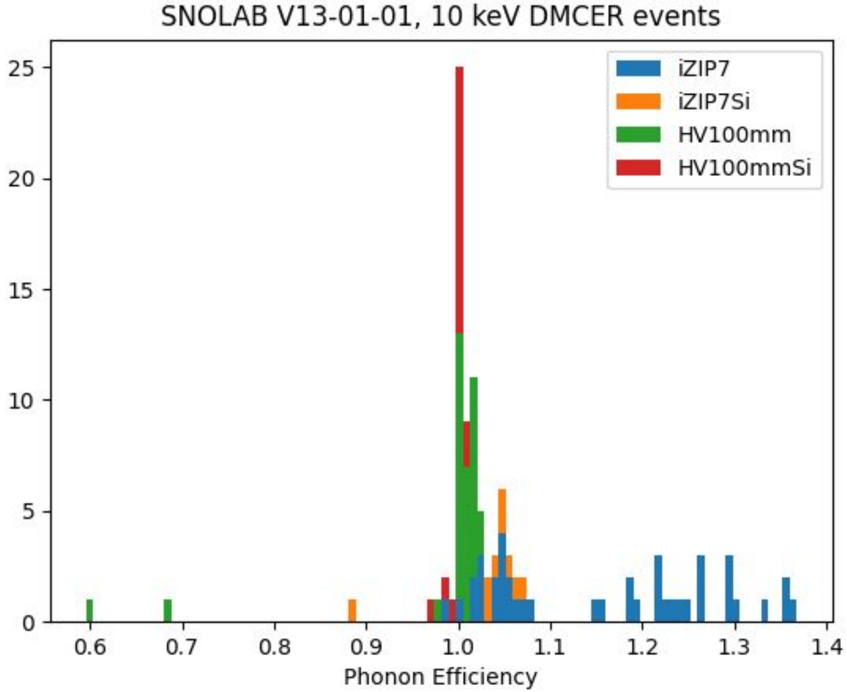
$$E_{expected} = E_{deposit} \times (1 + \text{Voltage}/\varepsilon_{pair})$$

$$\text{Efficiency} = E_{phonon} / E_{expected}$$

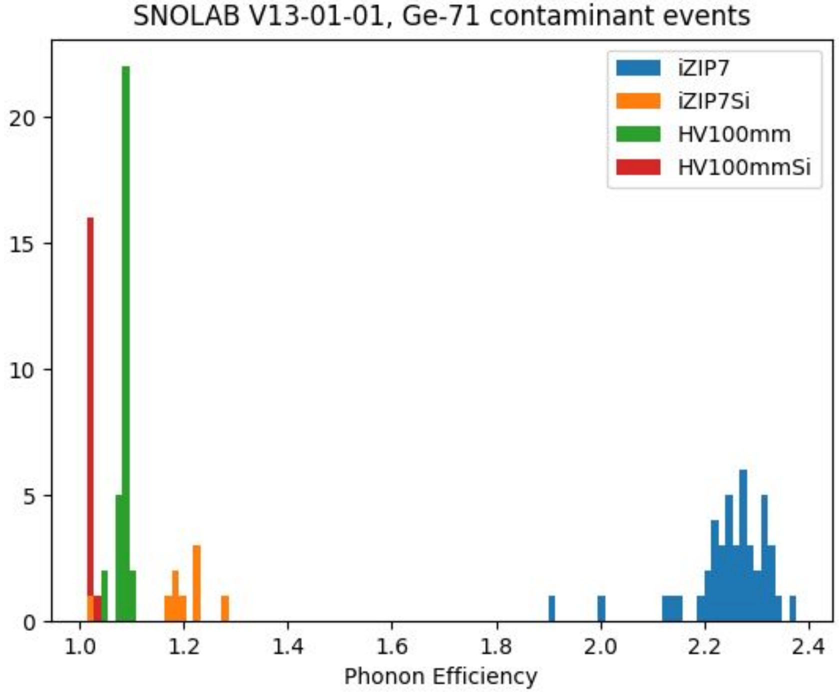
Next slide shows what we've been seeing (for three years) when we generate events in the full SuperCDMS geometry

Multiple SuperCDMS Detectors (V08-10-00)

Single hits show excess NTL energy at lower voltage, rotated detectors



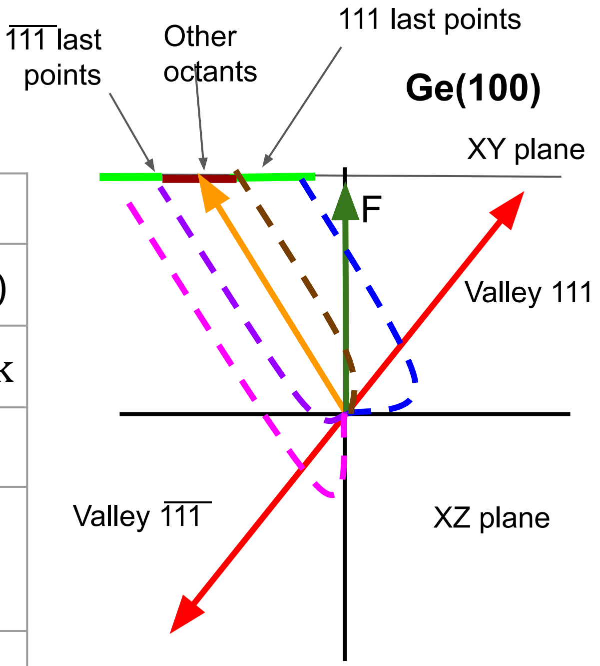
Multiple hits exacerbate NTL emission problems



Proper Electron Transport Kinematics

Wavevector momentum $p = \hbar k$ different from transport momentum $p =$ "mv", since "m" is tensor mass

	Free Electron	In Crystal
Lorentz Boost	$\gamma^{-1} = \sqrt{(1-v^2/c^2)}$	$\gamma'^{-1} = \sqrt{(1-\mathbf{M}v^2/m_0c^2)}$
Transport Momentum	$P = \gamma\, m_0 v = \hbar k$	$P = \gamma'\, m_0 v = m_0 \mathbf{M}^{-1}\, \hbar k$
Kinetic Energy	$E_{kin} = (\gamma-1)\, m_0 c^2$	$E_{kin} = (\gamma'-1)\, m_0 c^2$
Effective Mass	$m(\vec{k}) = m_0$	$m(\vec{k}) = \dfrac{P^2c^2 - E_{kin}}{2\,E_{kin}\,c^2}$
Acceleration	$a = F/m0$	$a = \mathbf{M}^{-1}\, F$

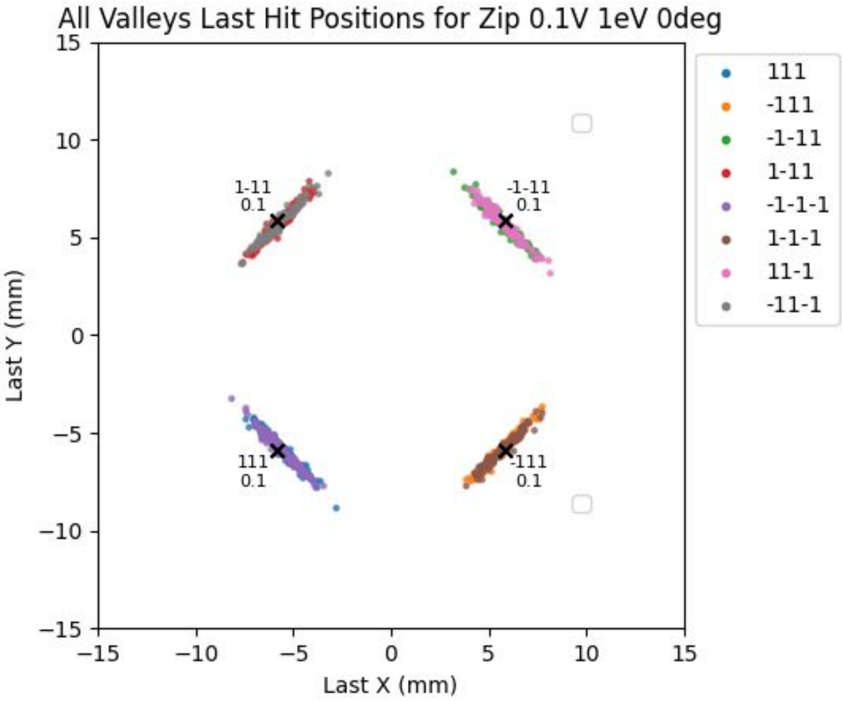


$\vec{a} = \mathbf{M}^{-1}\, \vec{F}$, not aligned!

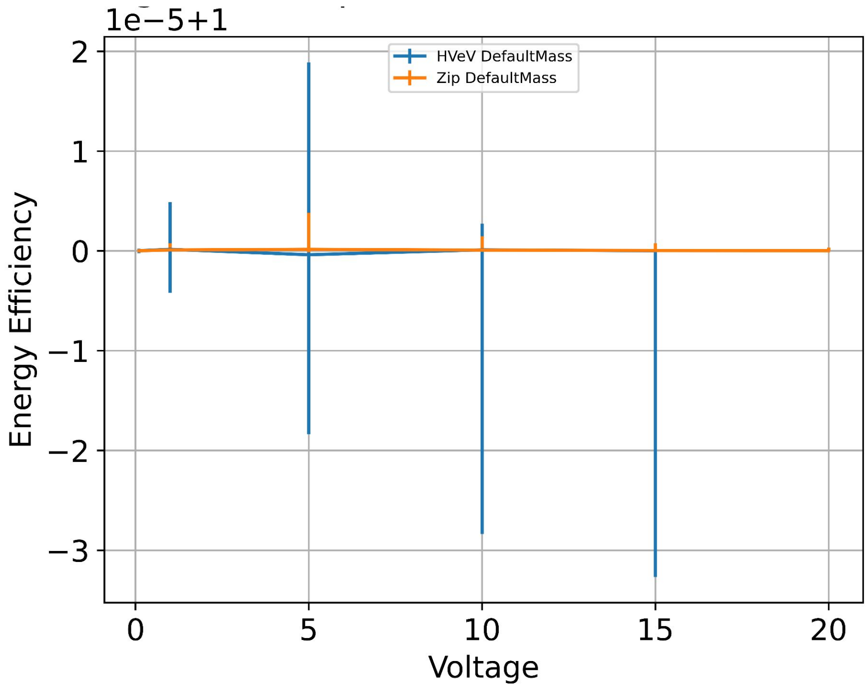
Iman Ataee Langroudy, TAMU

Transport and Efficiency, May 2024 (Without IV)

Ge(100) shows expected four spots



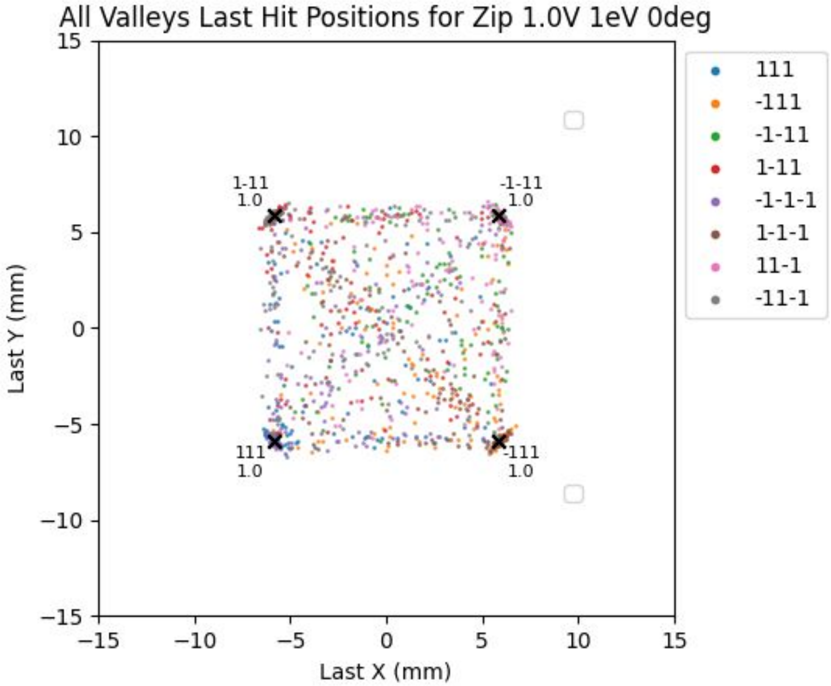
Efficiency precision better than $\mathbf{10^{-6}}$



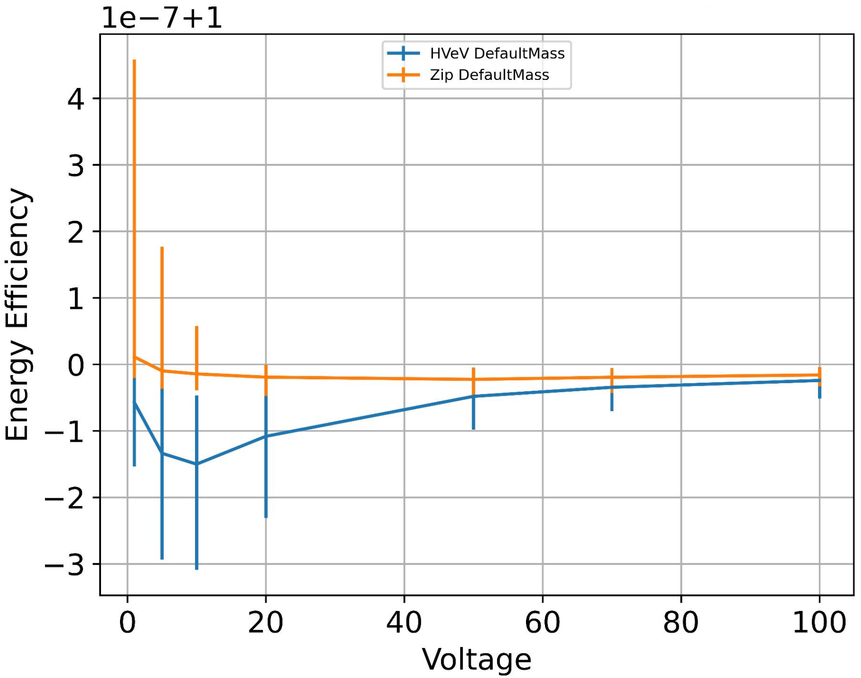
Plots courtesy of Iman Ataee

Transport and Efficiency, July 2024 (With IV)

Expected mix of 0,1,2 IV scatters



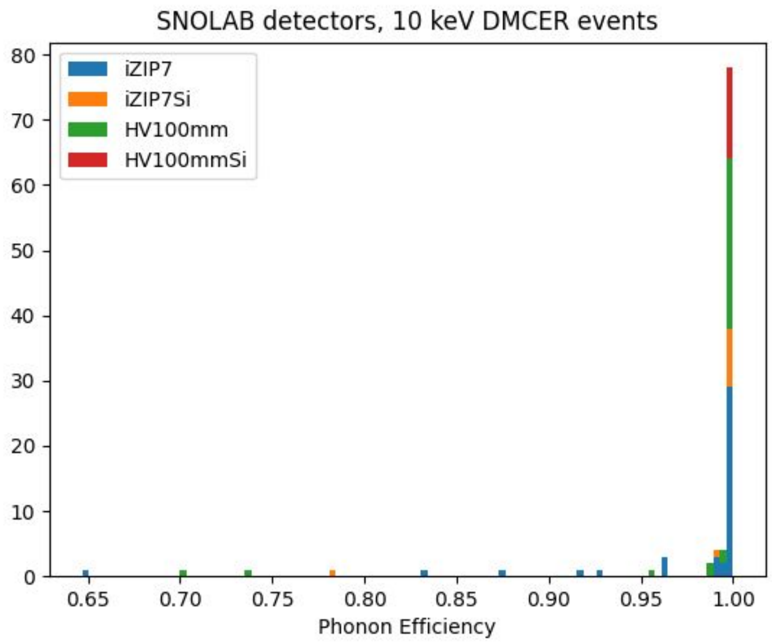
Efficiency precision on order of **10^{-7}**



Plots courtesy of Iman Ataee

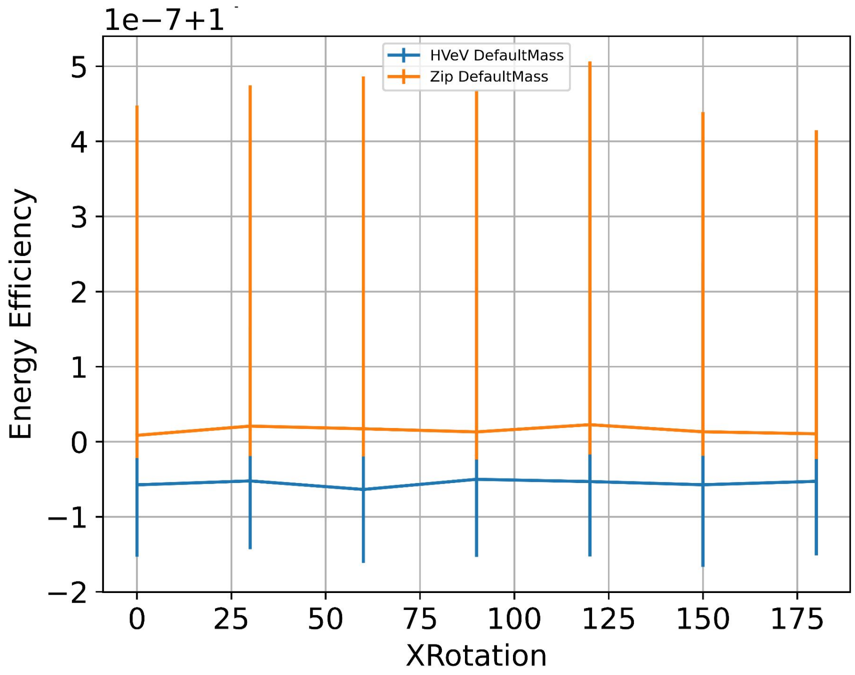
Multiple Detectors in SNOLAB Towers

Efficiency for single 10 keV deposit



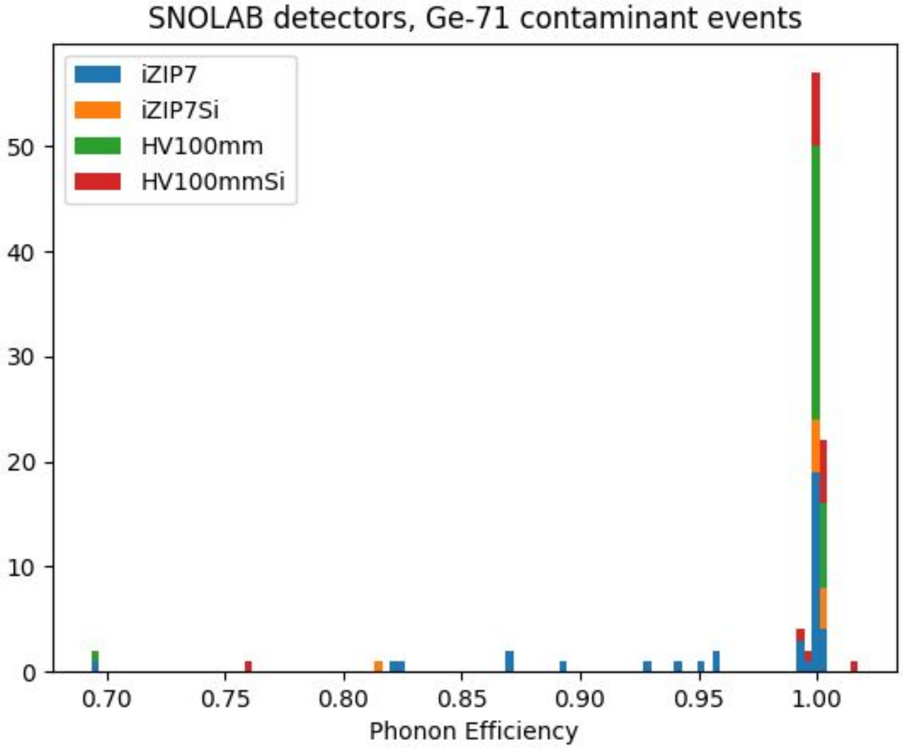
Stragglers are events outside of well-measured volume; see p. 23

Efficiency unaffected by orientation



Plot courtesy of Iman Ataee

Multiple Detectors in SuperCDMS (Ge-71)



[Multiple hits per event, including non-zero nuclear recoil]()

Compute Eexpected per hit individually, then sum for each event/detector

Narrow peak at 100% for events within fiducial region, straggler events (partially) outside fiducial

Deployment to G4CMP (will be V09-00-00)

Results here presented to SuperCDMS Simulations WG (DMC sub-WG)

Shown to small group of G4CMP users "known to be" using e/h transport

Rapid consensus that improvements significant and correct enough to warrant immediate release

Merged onto G4CMP **develop** branch and included in new major release **V09-00-00**, 6 Aug 2024

Want a substantial validation campaign to catch any problems early

Systematic Performance Validation

Energy deposits spread through detector: charge and phonon efficiency

- Phonon efficiency for hits as detectors are rotated around Z and X axes
- Use phonon efficiency to (re)identify SimFiducial boundaries
- Charge and phonon efficiency using new 3D EPot files?

Individual e/h pairs produced at center of each detector, suppress phonon tracks

- Record individual electron and hole hits
- Plot hit positions on each face to show "valley spots" and intervalley scatters
- Measure $\mathbf{Vdrift = (Z3 - Z1)/(Time3 - Time1)}$ for range of voltages

Other systematic performance measurements

Summary and Conclusions

Iman Ataee has completely revised electron transport in G4CMP

Compiles, links and runs with SuperCDMS Simulation Framework

Excellent performance for all SuperCDMS detectors

- High and low voltage, rotated detectors
- Results taken with uniform field

Code merged onto G4CMP develop branch and released **6 Aug 2024**

Broader validation campaign should be started soon

Backup Slides

Updated Feature Branch to Latest Develop

Software work on branch **G4CMP-276** started in 2021

No updates from main development or production had been ported to **G4CMP-276**

May 2024: Back-merged **develop** branch onto **G4CMP-276**, incorporating production development with G4CMP-276 kinematics changes

Consistent with before-merge results, performance with intervalley scattering included matches expectations

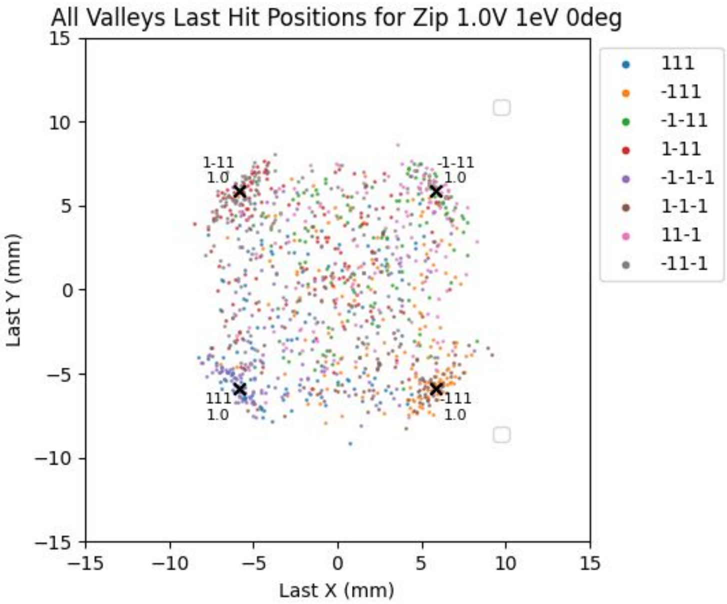
Some additional minor issues were found and addressed during validation

Final Software Improvements since May 2024

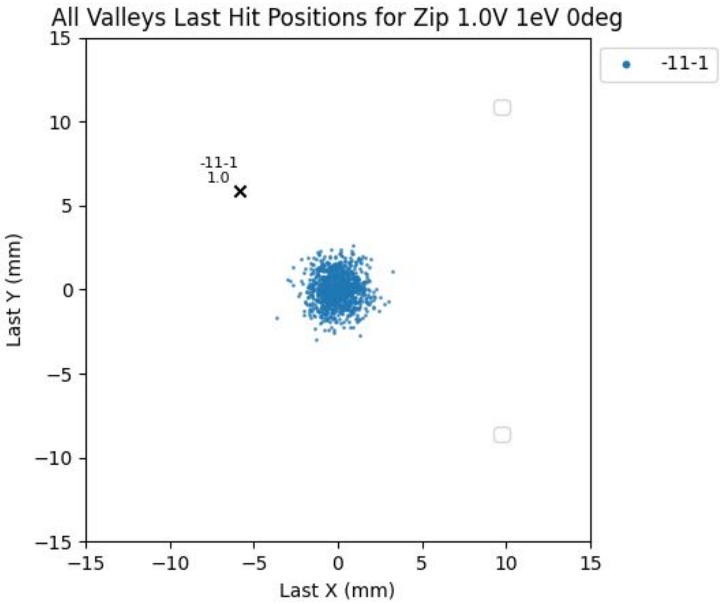
G4CMP-408 G4CMP-417	Ensure Luke scattering (phonon-electron) done properly in Herring-Vogt frame, and transformed back to position space
G4CMP-409	Ensure that new momentum/energy initialization is done at start of Scattering process
G4CMP-412	IVScattering should preserve wavevector angle, not transport momentum; don't transform E-field for rate calculation
G4CMP-413 G4CMP-415	Compute minimum step in TimeStepper to handle low-energy states, with protection against divide by zero in zero-field case
G4CMP-414	Address compilation warnings in debugging, function name change

With these changes, G4CMP-276 appears ready for deployment

After G4CMP–417/418: 1V bias on Ge(100)

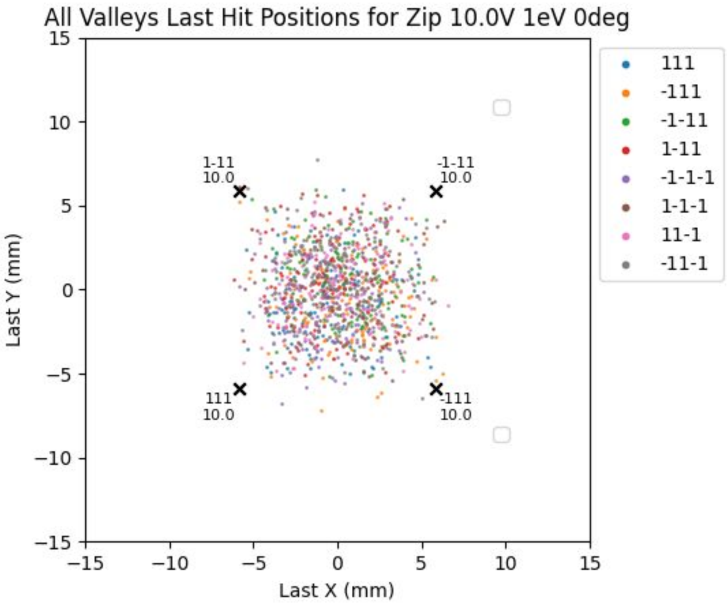


Electrons

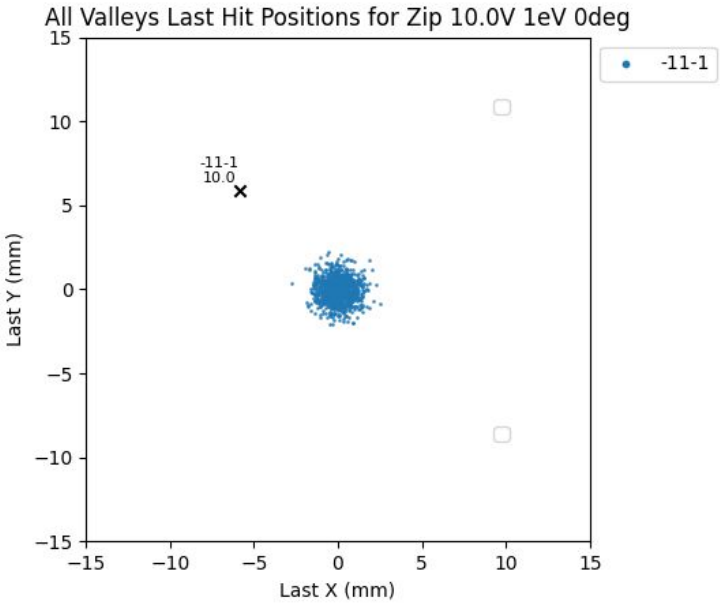


Holes

After G4CMP–417/418: 10V bias on Ge(100)

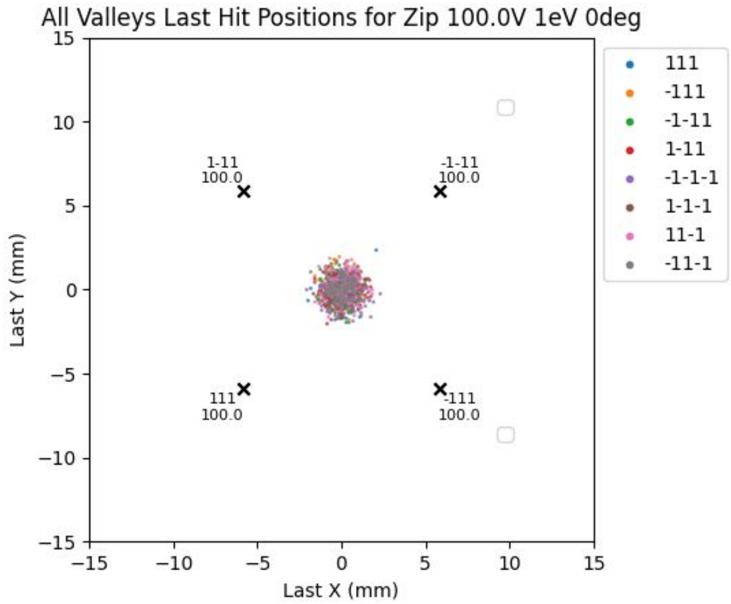


Electrons

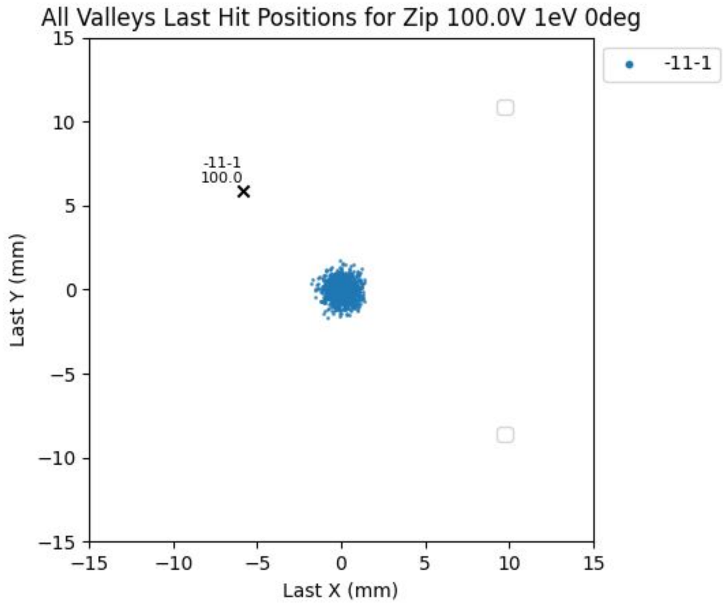


Holes

After G4CMP–417/418: 100V bias on Ge(100)



Electrons



Holes

Example Ge-71 event (#3) in Ge(100) Detector

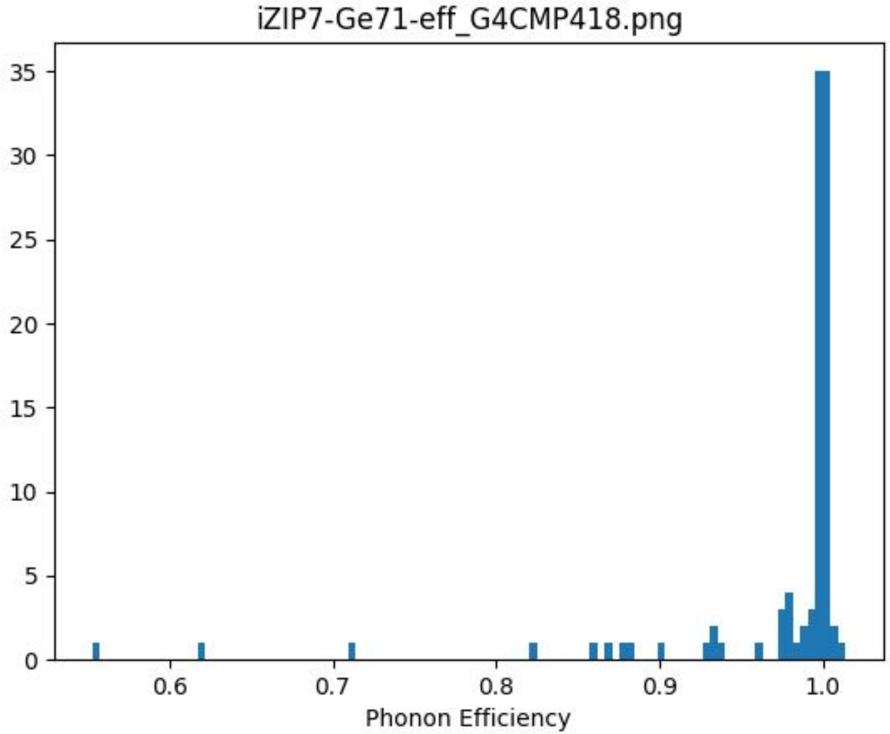
PName	Position [mm]	Edep [eV]	dE/dx [eV]	NIEL [eV]	N(e/h)	NTL [eV]
Ga71	-16.19404, -3.712992, -7.954497	0.3741150	0.0218406	0.3522745	0	0.0
gamma	-16.19586, -3.716519, -7.957554	9209.0218	9209.0218	0	3096	12384.0
e-	-16.19404, -3.712994, -7.954495	984.19523	984.19523	0	343	1372.0
e-	-16.19404, -3.712992, -7.954497	56.786866	56.786866	0	21	84.0
e-	-16.19404, -3.712992, -7.954497	10.794077	10.794077	0	4	16.0
e-	-16.19404, -3.712992, -7.954497	70.311582	70.311582	0	26	104.0

Hits at R = 16.614 or 16.617 mm, within fiducial volume

Σ [Edep+NTL] 24291.483 eV (expected PhononE)
Σ PhononE 24304.267 eV 99.95% efficiency

G4CMP-416 – dE/dx < bandgap added to NIEL

Ge(100) Detector Efficiency (Ge-71 decays)



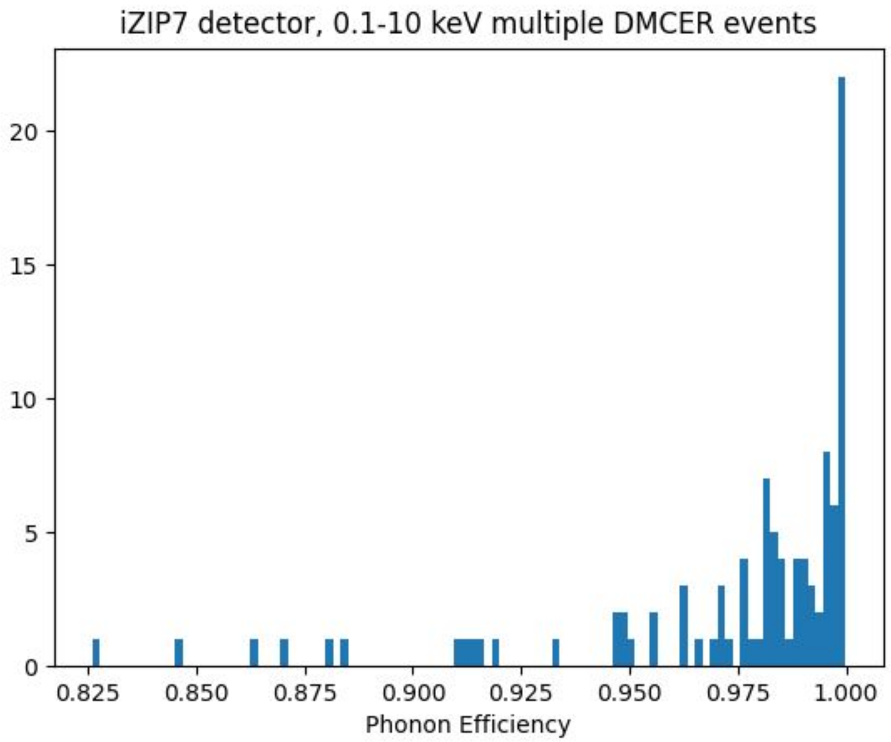
This looks sensible

Peak at 100% where all hits within fiducial region

Tail and "subpeak" below 100% where some hits went outside fiducial region

Dribble of events where whole decay was outside fiducial region

Multihit Events in Ge(100) look reasonable

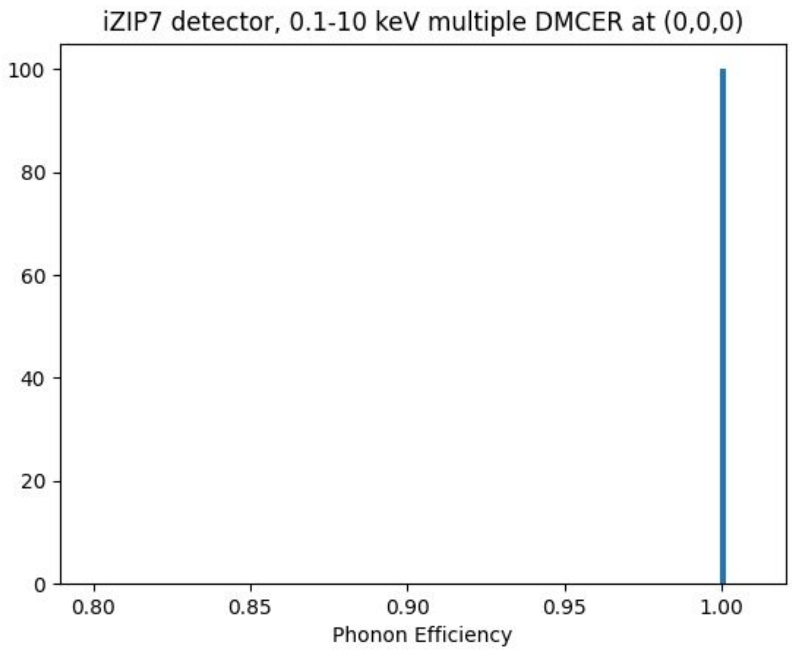


Five model hits per event, scattered through detector (not like Ge-71)

```
/CDMS/Source contam
/CDMS/Contaminant/Volume Zip
/CDMS/Contaminant/bulk
/CDMS/Contaminant/Generator dmcgun
/CDMS/Contaminant/energyRange 0.1 10 keV
/CDMS/Contaminant/partition
/CDMS/Contaminant/Particles 5
```

Tail due to one or more hits within events outside fiducial

Multihit Events in Ge(100) do not have problems



Five model hits per event, all at center of detector (like Ge-71)

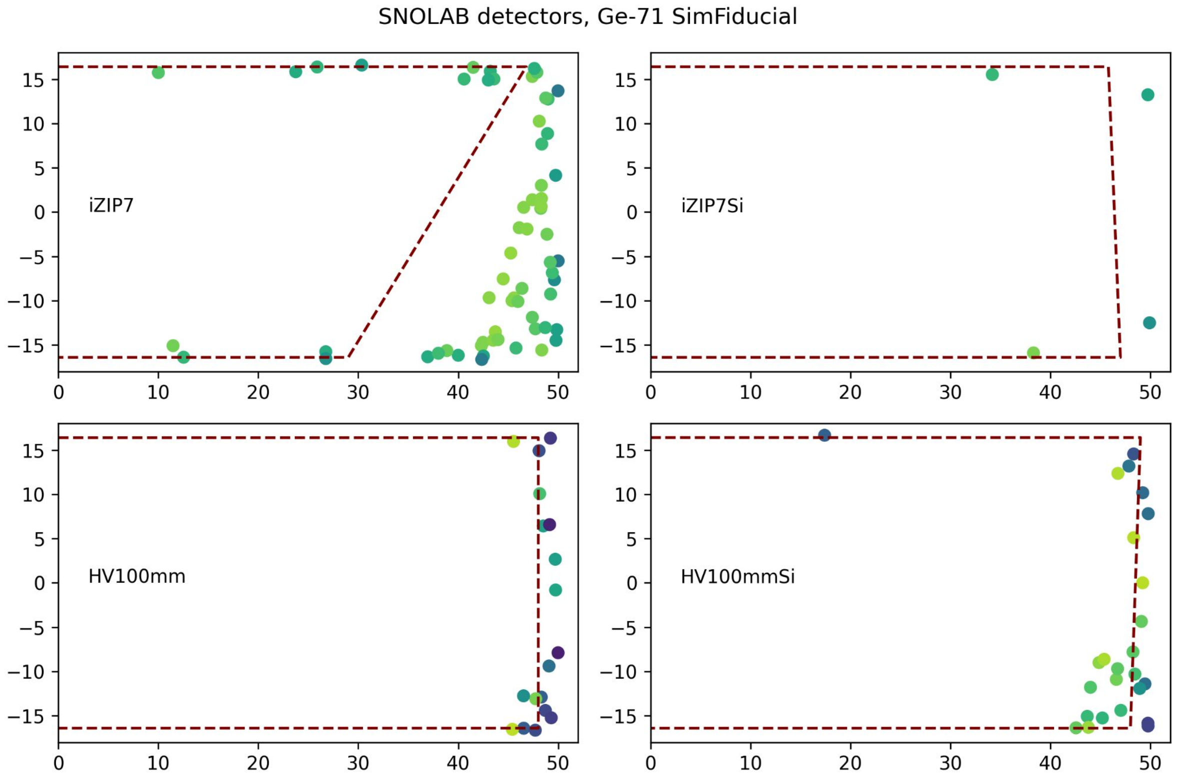
```
/CDMS/Source point
/CDMS/Point/Position 0 0 0 mm
/CDMS/Point/Generator dmcgun
/CDMS/Point/energyRange 0.1 10 keV
/CDMS/Point/partition
/CDMS/Point/Particles 5
```

Efficiency 100% within 1e-5

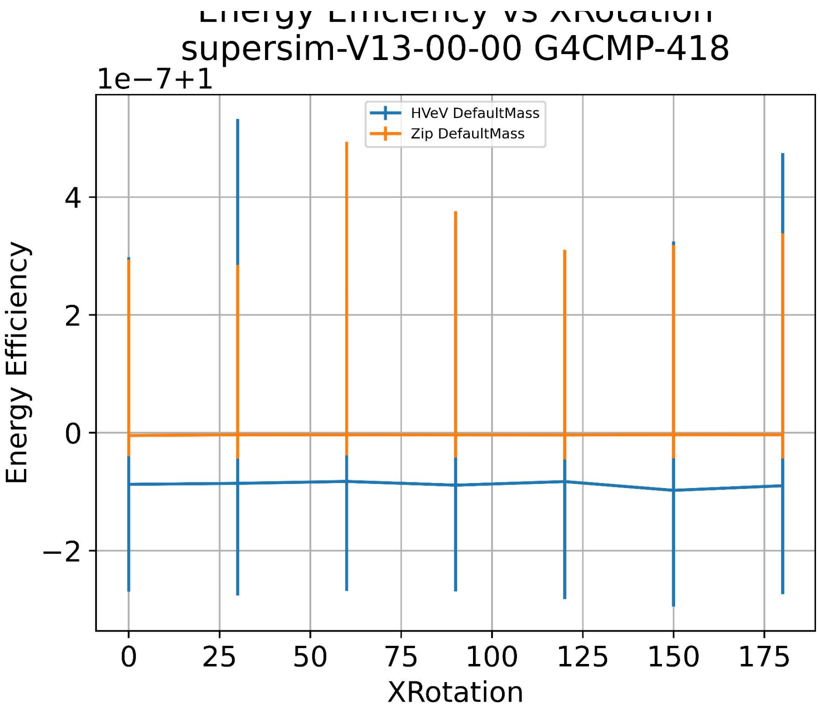
Fiducial Regions in SuperCDMS Detectors

Single hit (10 keV) sample of 100 events point are for **eff < 0.99**

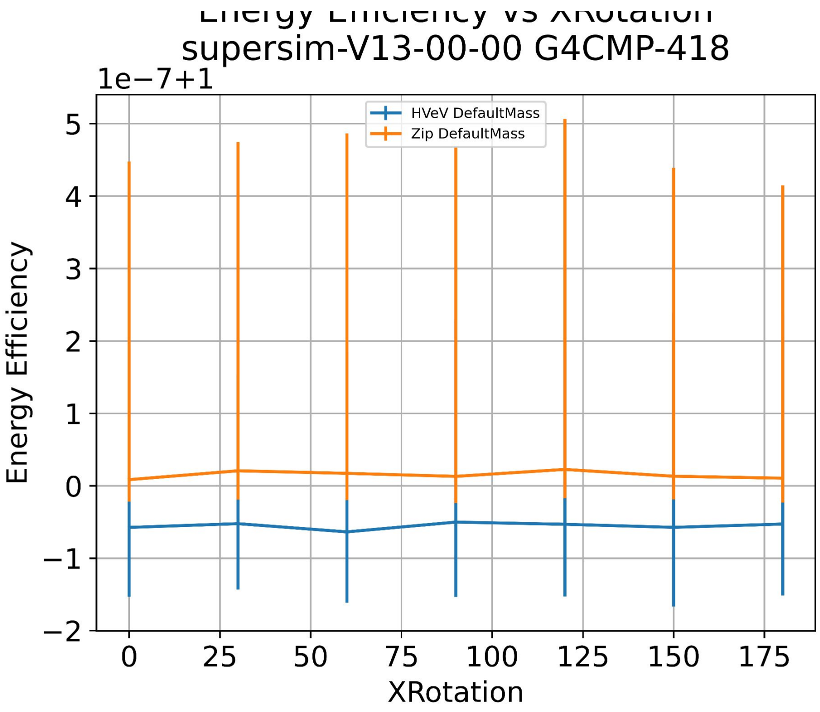
Fiducial regions consistent with past determinations (dotted lines), but statistics are very low



Ge(100) and Si(100) Phonon Collection Efficiency



1eV Single Electron



3.9eV Deposition