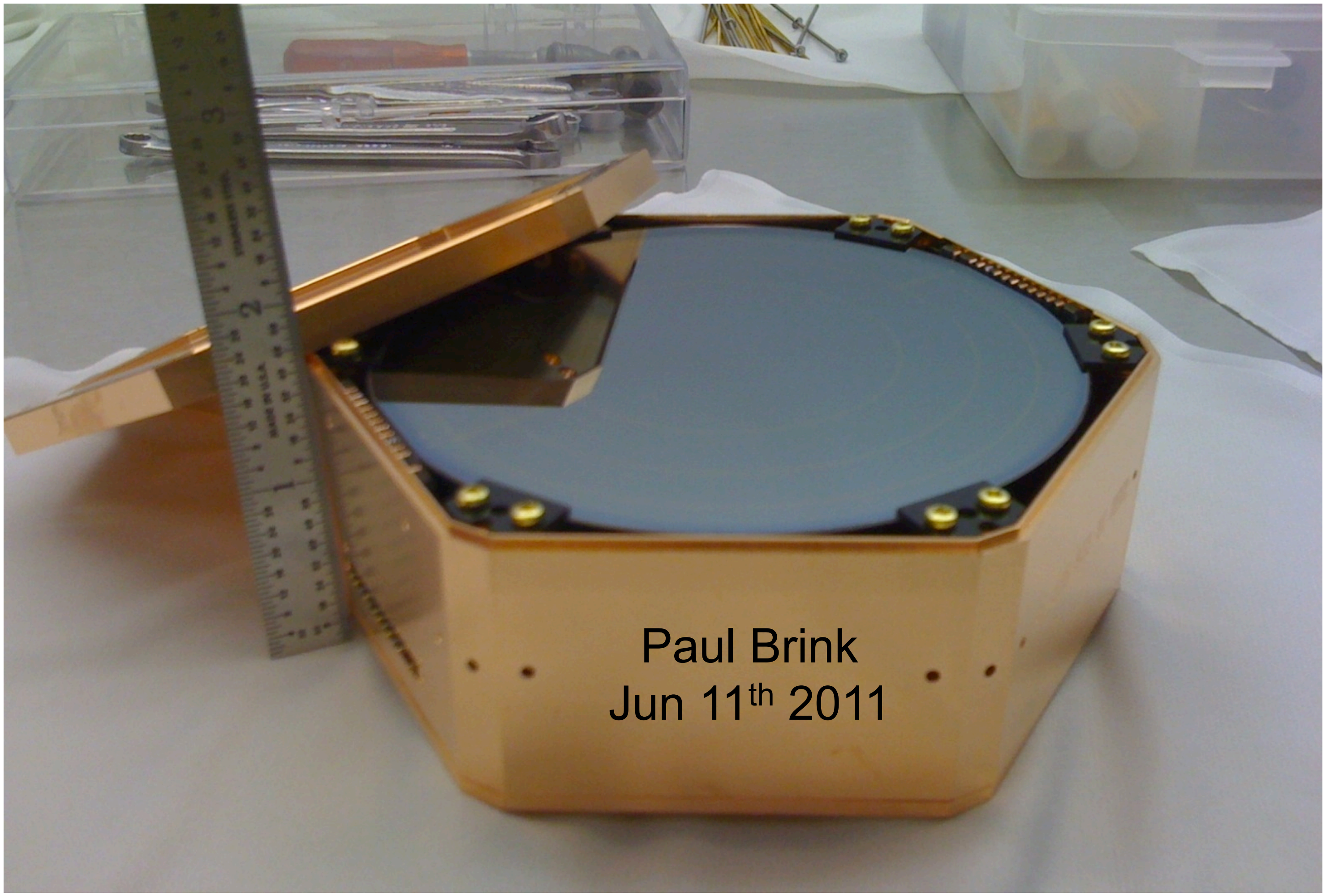
# Large Diameter Cryogenic Germanium Detectors for Dark Matter Direct Detection Experiments



Paul Brink
Jun 11$^{th}$ 2011

SLAC
NATIONAL ACCELERATOR LABORATORY

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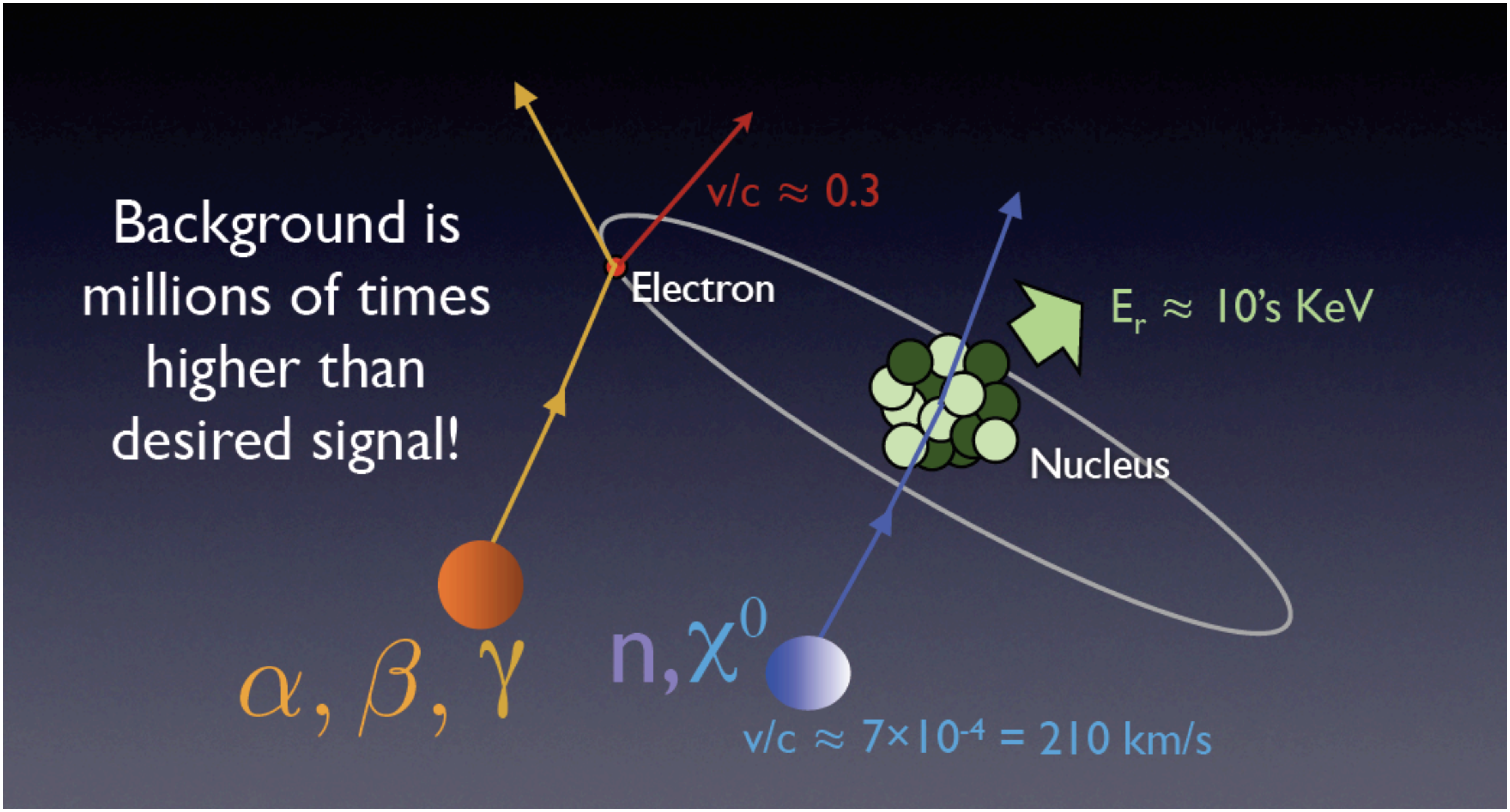
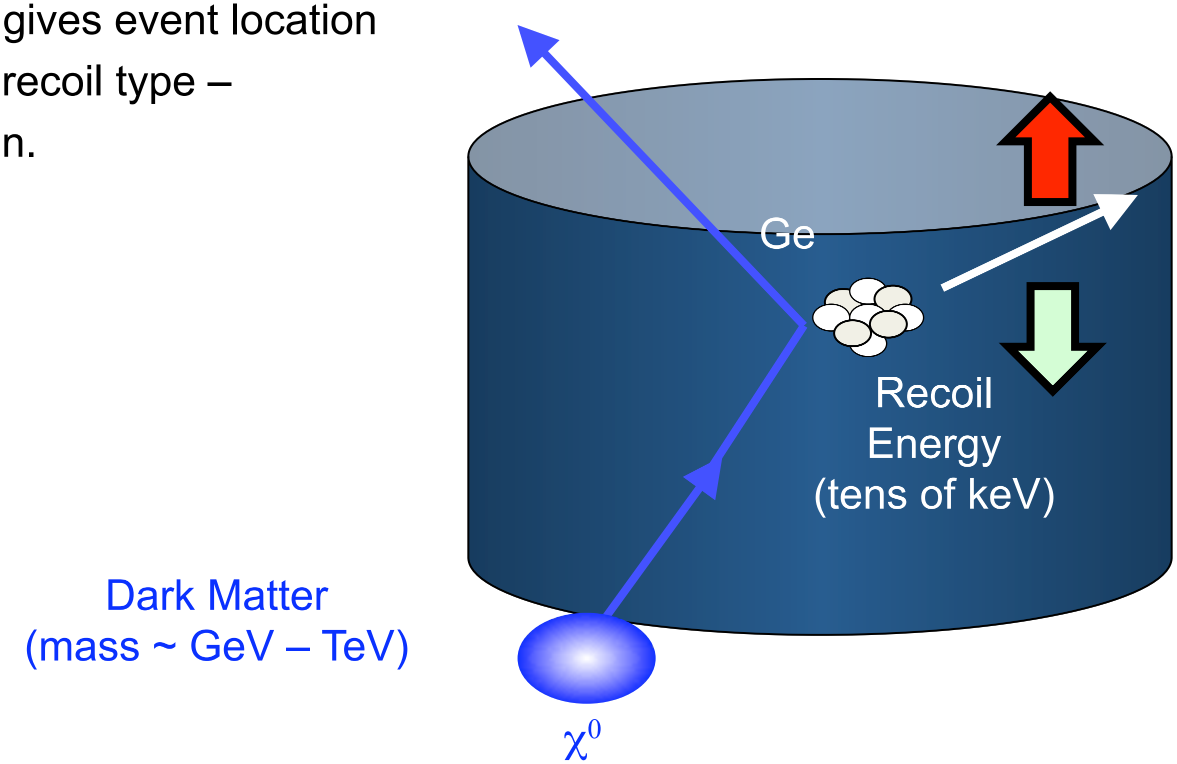
# WIMP ($\chi^0$) direct detection

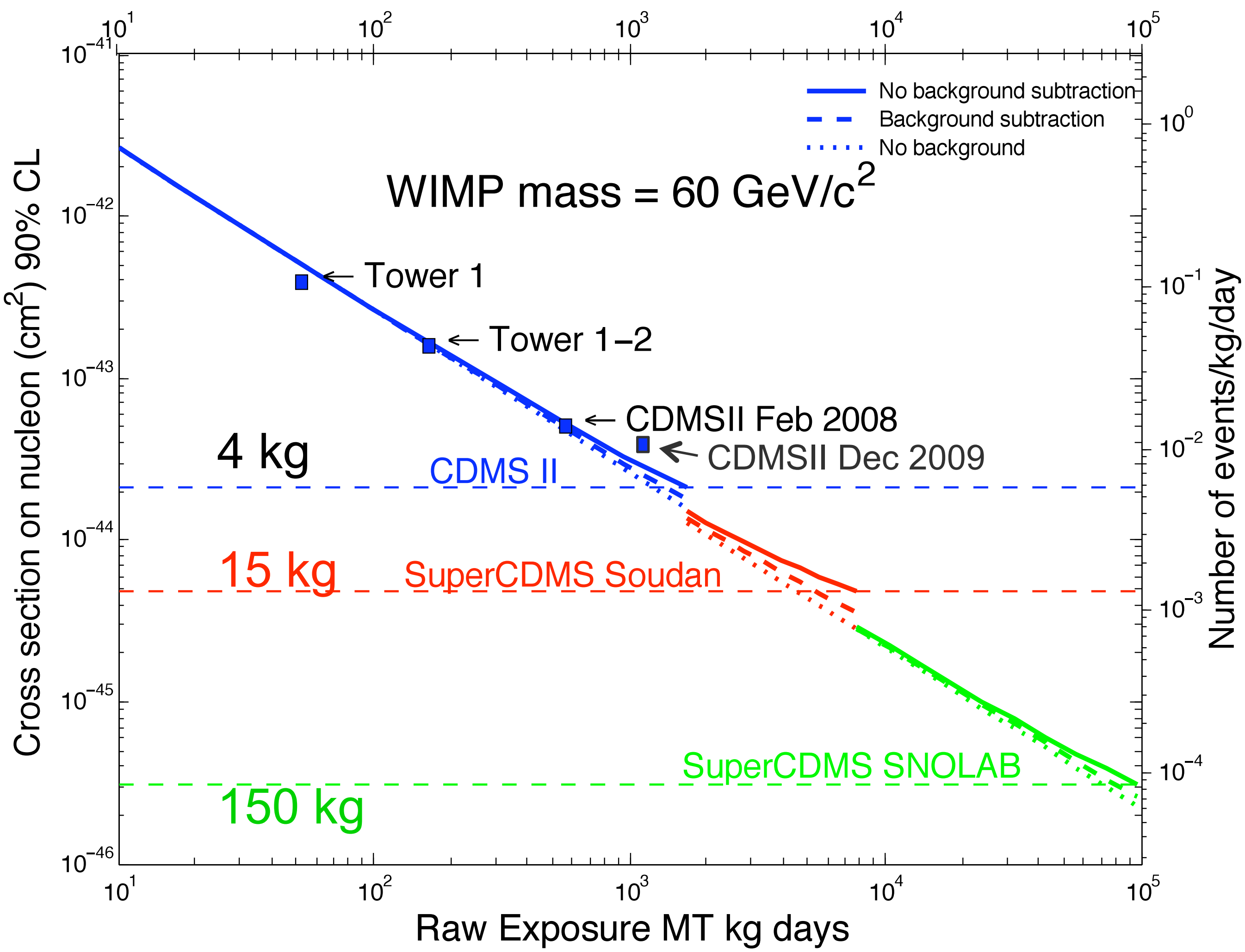


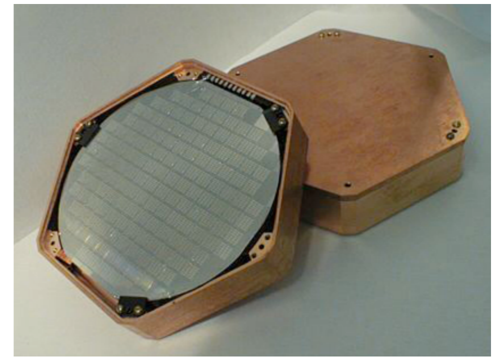
# Why cryogenic Ge Detectors?

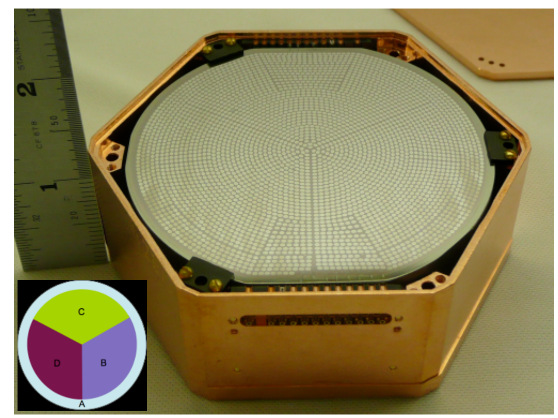
- Employ a robust and powerful recoil-event discrimination technique
  - Measure charge-carriers (ionization signal) and phonons generated by an event.
  - Most of the energy is in the phonon signal (small quanta) which are not statistically limited and give good energy resolution.
  - The signal in the charge carriers: holes + electrons gives event location in crystal and the recoil type – nuclear *vs* electron.



# SuperCDMS – Moore's Law if zero bkgd

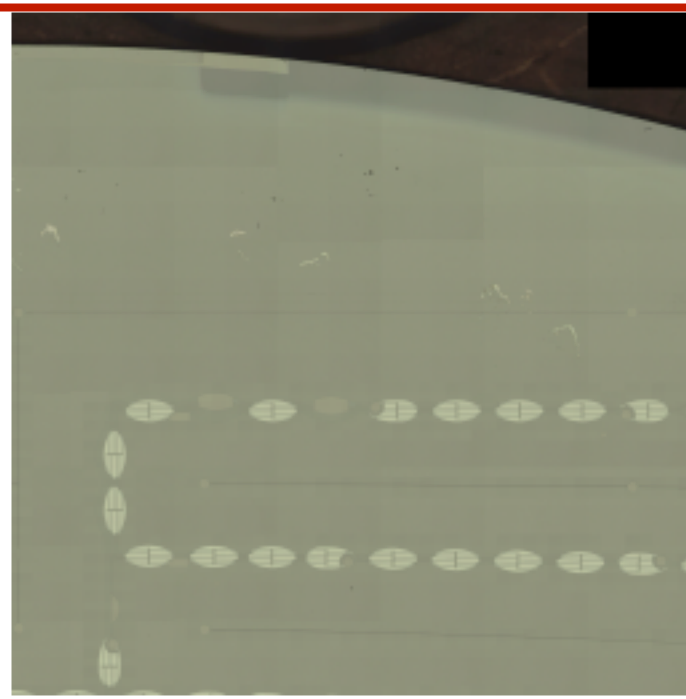


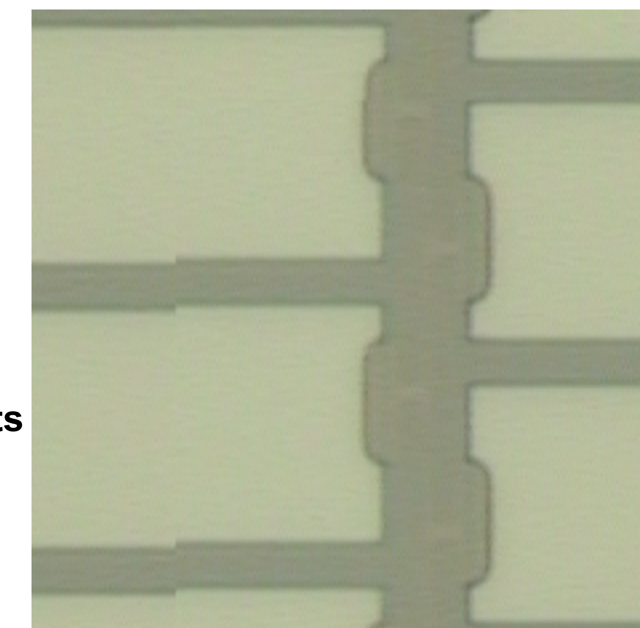





GEODM

# Ge iZIP detector : phonon sensors



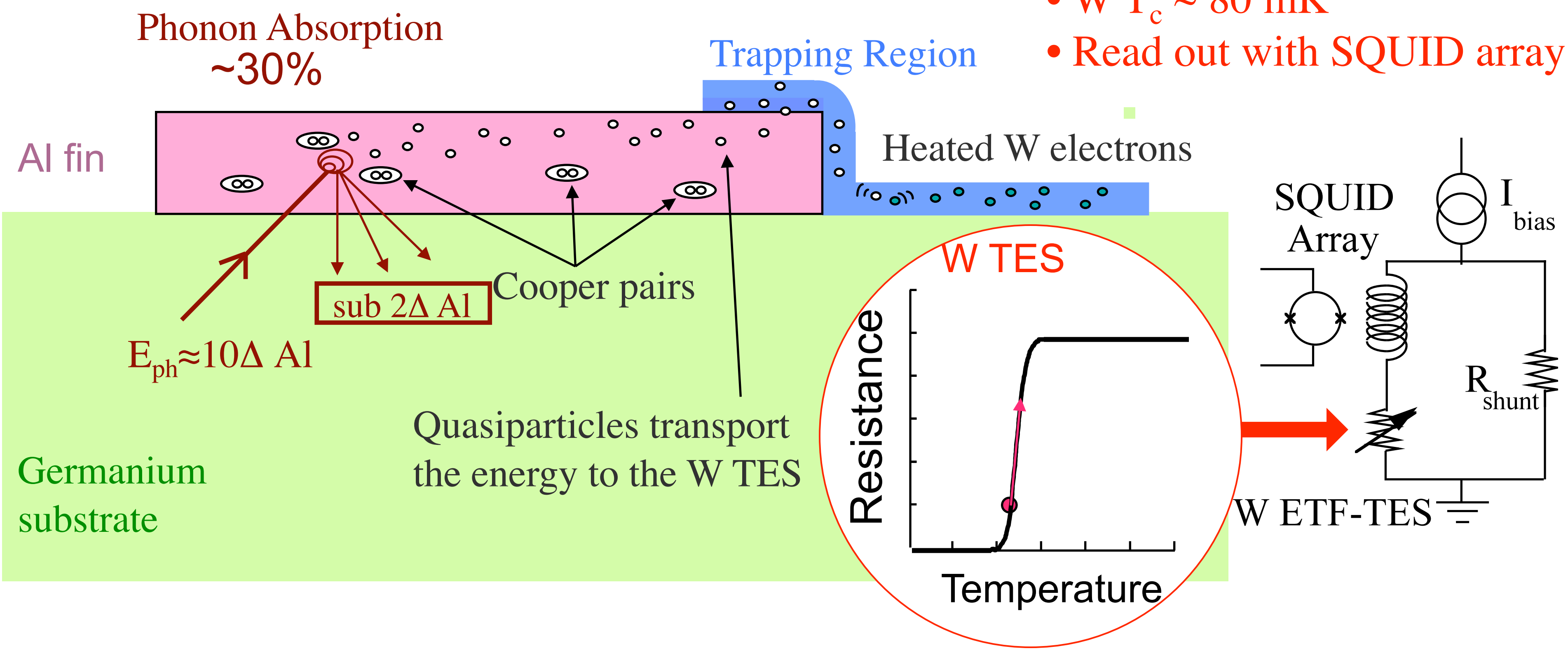


- Athermal phonon sensors operated at 80 mK.
  - Aluminum fins look white.
  - Tungsten transition edge sensor thin grey line.
  - aSi substrate (also) grey/green color.

# CDMS Phonon sensor operation

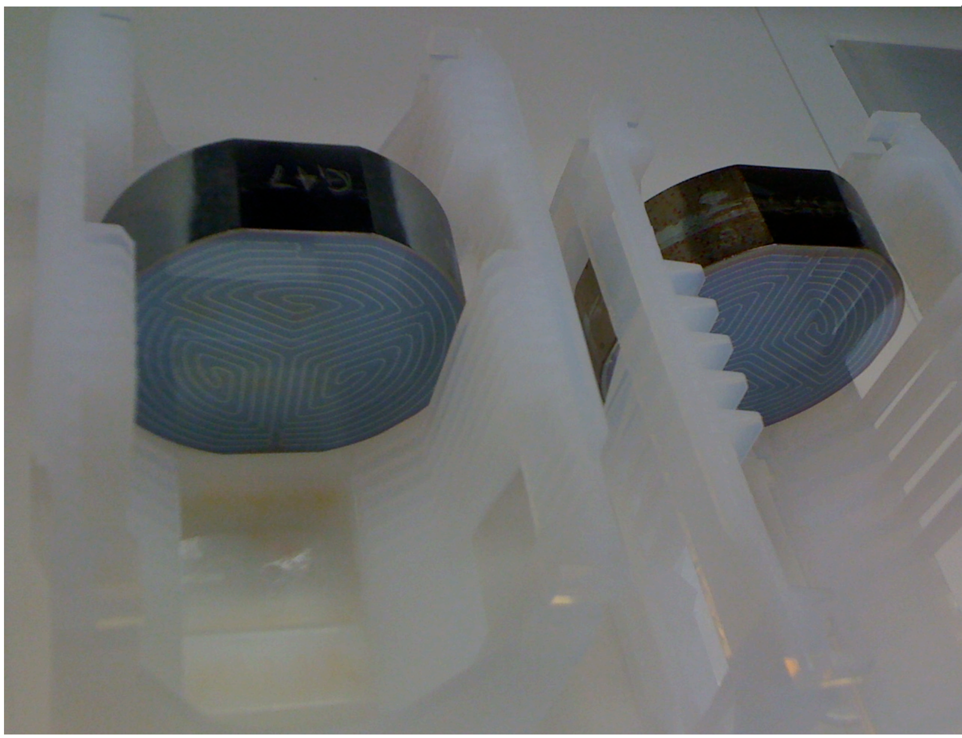
- Recoil event occurs in Germanium substrates, 76 mm diameter, 25 mm thick.
- Aluminum fins 300 nm thick absorb phonons arriving from substrate underneath.
- Fins connect to Tungsten transition edge sensors (W TESs).

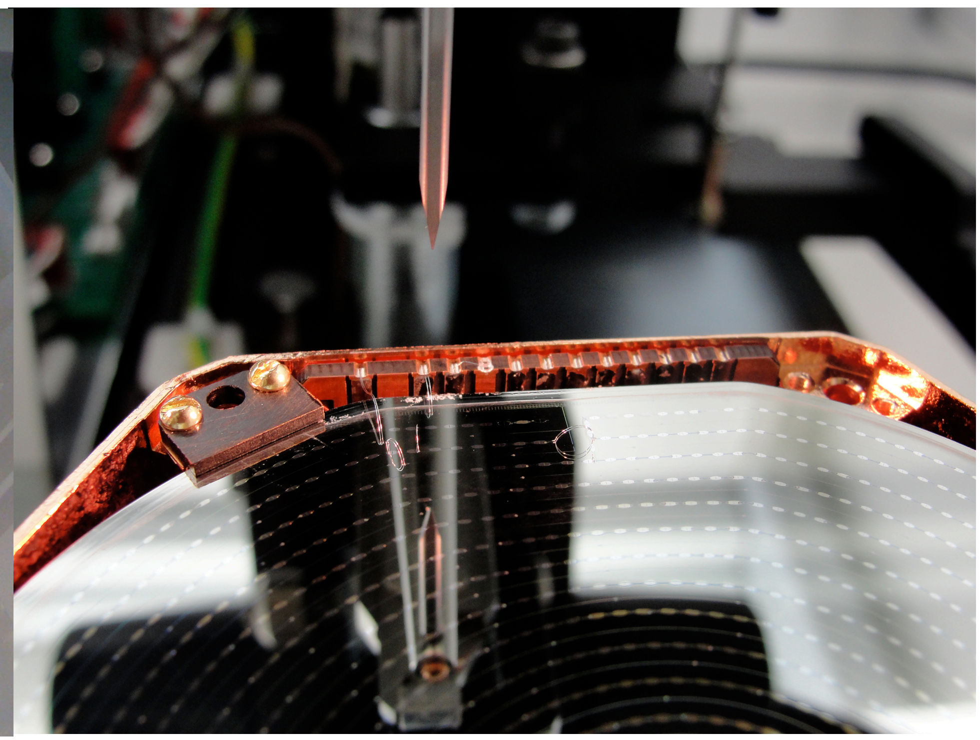
- W $T_c$ ~ 80 mK
- Read out with SQUID array



# Ge iZIP detector production

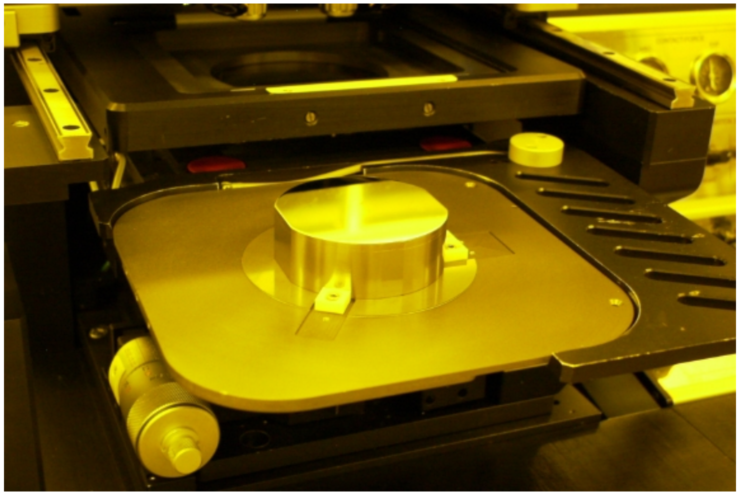
- All CDMS II and SuperCDMS Ge detectors fabricated in Stanford Nanofabrication Facility (SNF)
  - Double-sided optical photolithography (90% time)
  - Manual packaging and wire-bonding  (10% time)

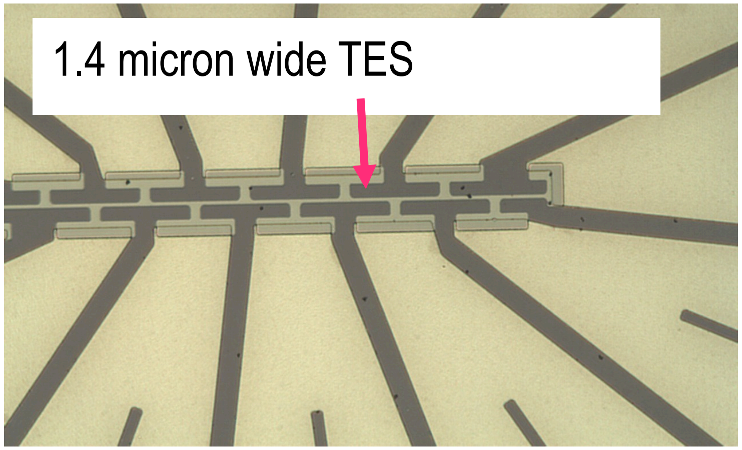




# SuperCDMS: 1-inch thick substrates

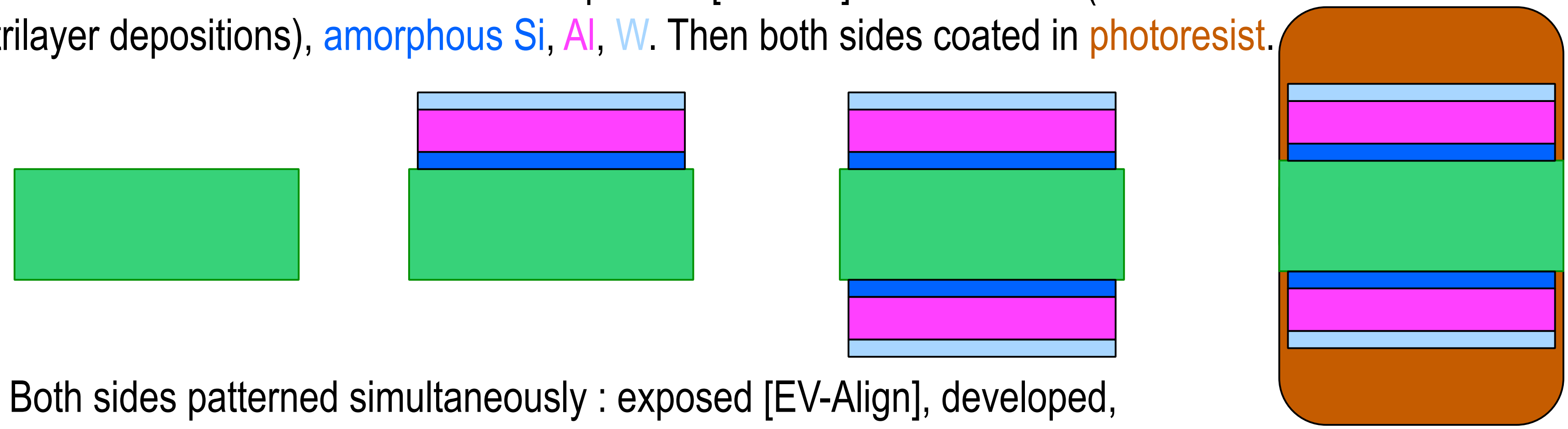
Photolithography for the 1-inch thick Ge and Si substrates required equipment modifications for the thin film depositions, photoresist coatings, U.V. exposures and plasma etching.



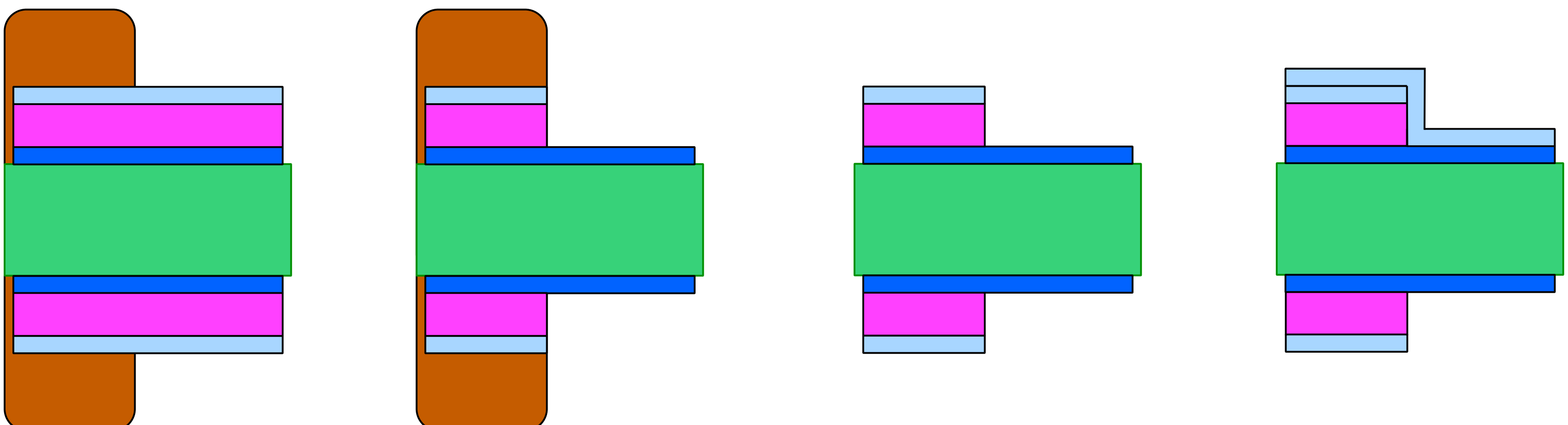


# Ge Fabrication – photolithography (1)

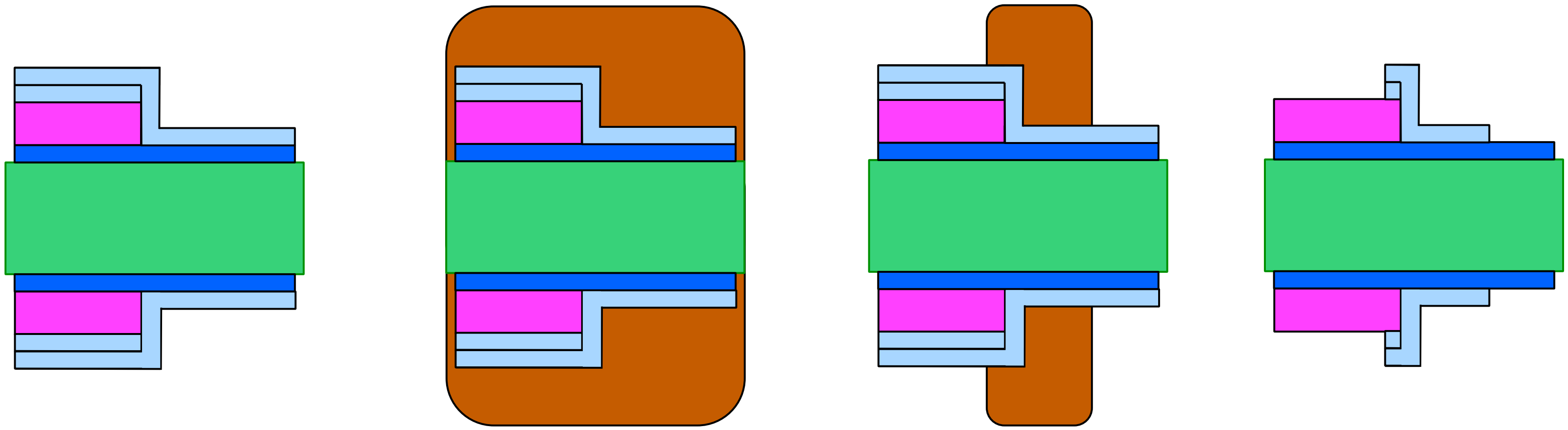
Ge substrates cleaned. Thin films deposited [Balzers] on both sides (the A and B trilayer depositions), amorphous Si, Al, W. Then both sides coated in photoresist.



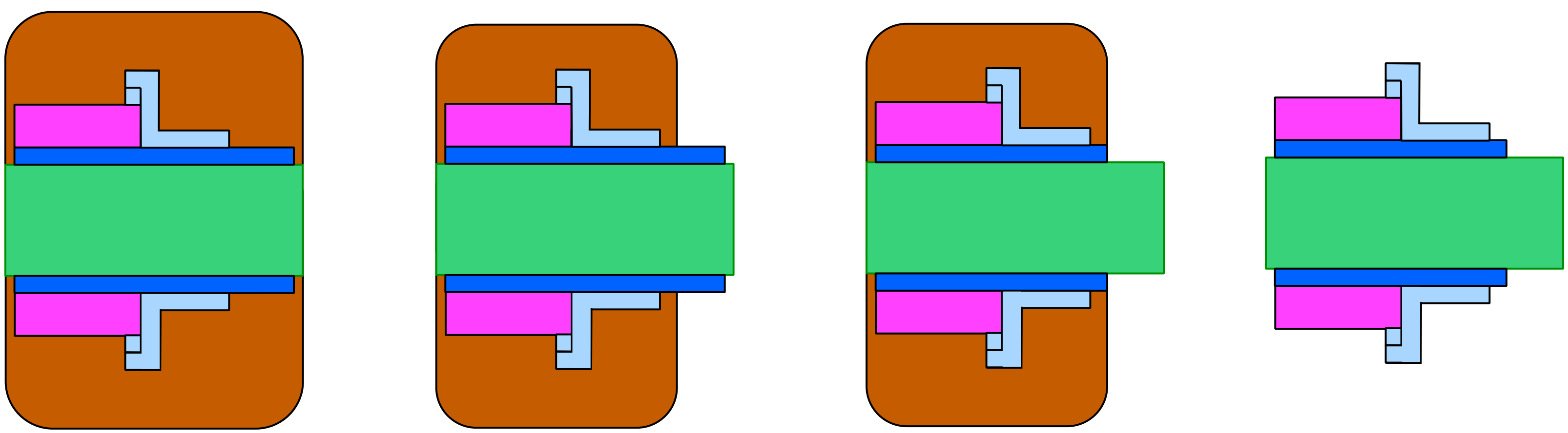
Both sides patterned simultaneously : exposed [EV-Align], developed, wet-etched (H2O2 for W, Al-etch for Al), photoresist stripped. Both sides receive W TES film deposition.



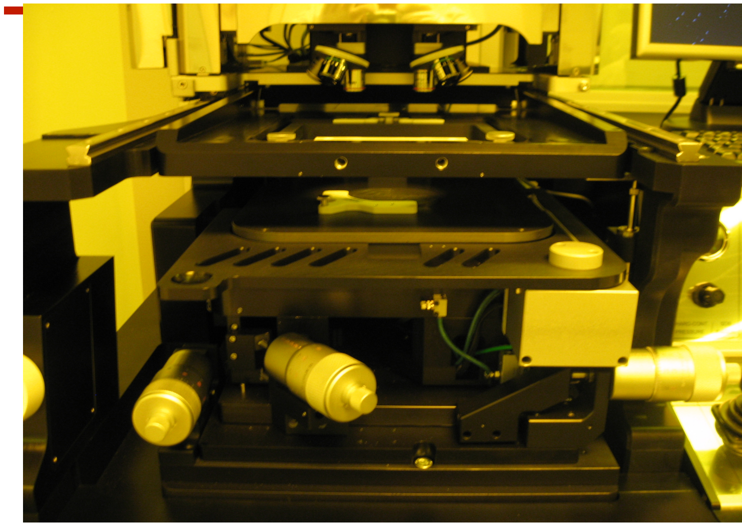
# Ge Fabrication – photolithography (2)



TES patterned for both sides : exposed [EV-Align], developed, W wet-etched, photoresist stripped. Both sides recoated and patterned for amorphous Si dry-etch.

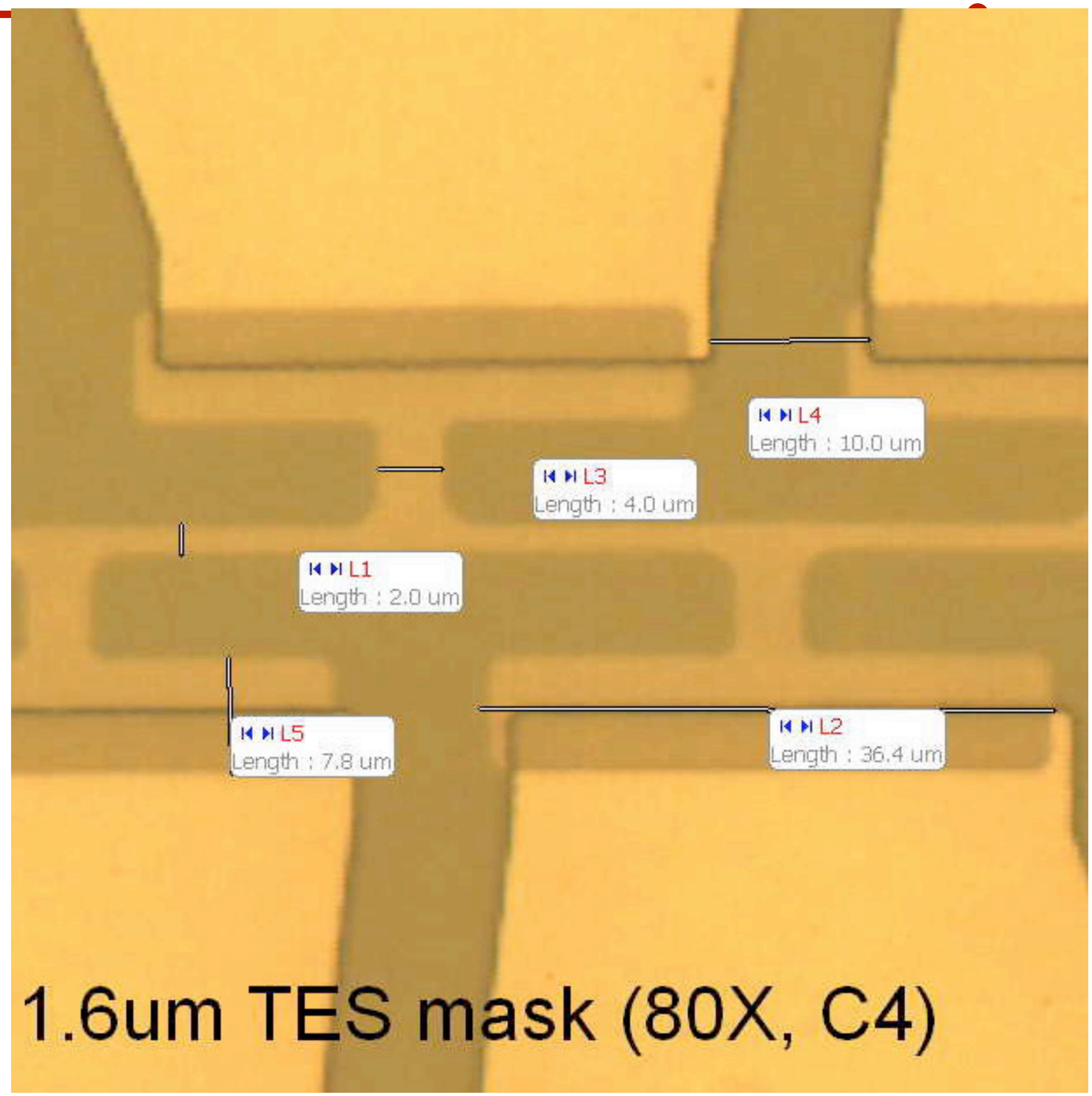


# New SuperCDMS EV-Align



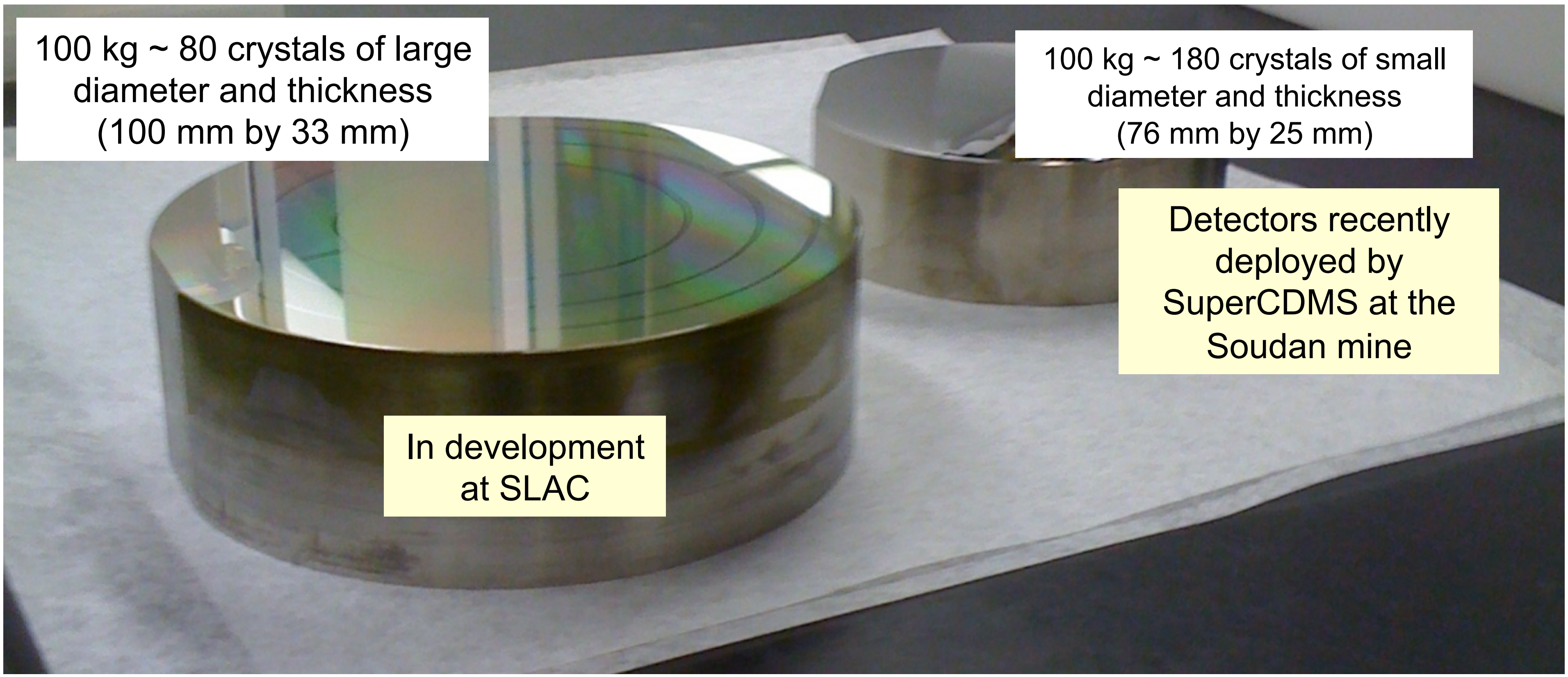
Rapid change in substrate thickness (2 inch max). Uniform line-width for TESs a

Used for veto detectors for SuperCDMS at Soudan and first 3 Ge 1-inch detectors of SuperTower 1.



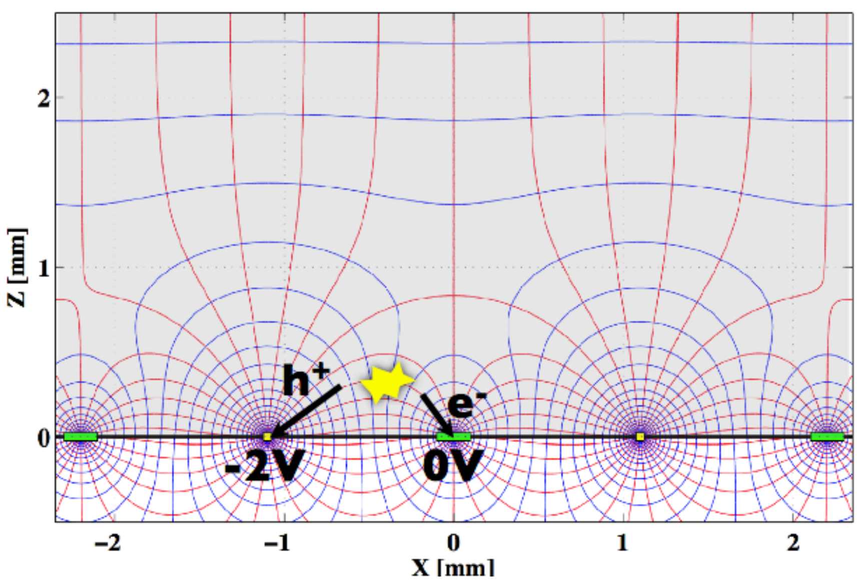
# Scalability of Ge Detectors

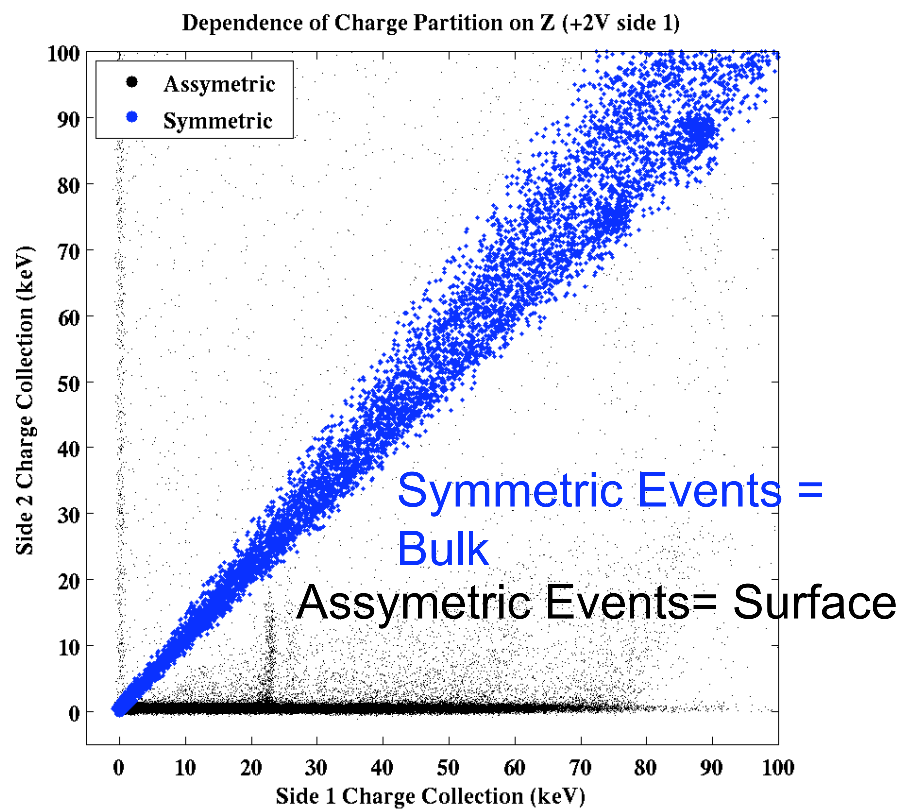
- Qualify vendors and procure high-quality large diameter Ge crystals
- Develop larger detector fabrication recipe
- Optimize design for cost and performance (backgrounds rejection)



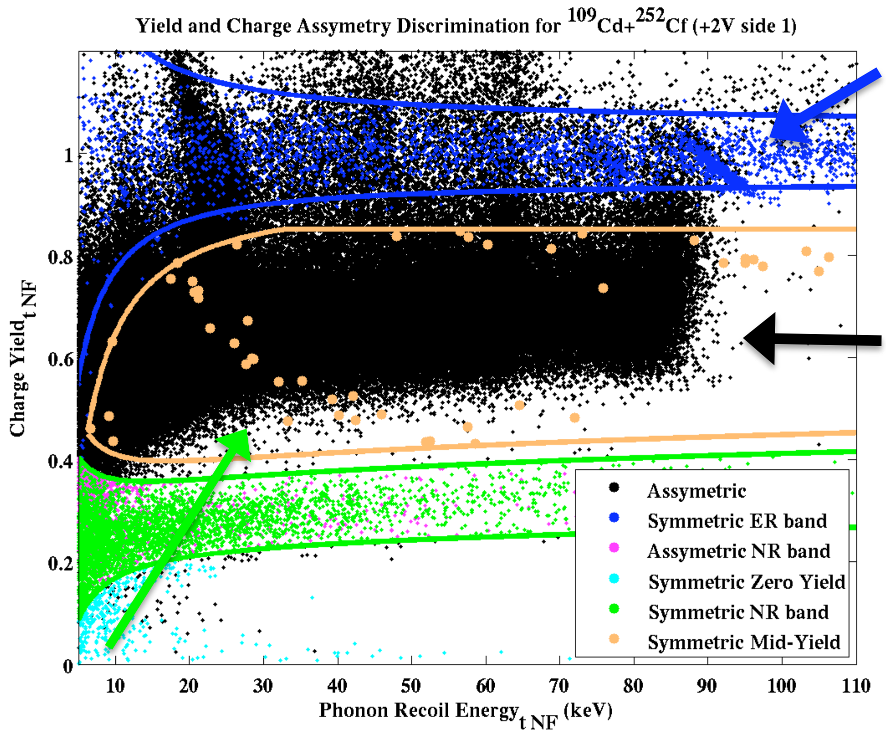
# Charge signals give a fiducial volume

- Require 3D Fiducial Volume Definition
  - Outer charge electrodes separately measured for radial information
  - Complex E-fields produced by interleaving +2V/0V electrodes encode Position Information



# Electron/Nuclear Discrimination by Yield




Electron Recoils (133Ba)

β $^{109}$Cd Internal source

Nuclear Recoils (252Cf source (external)

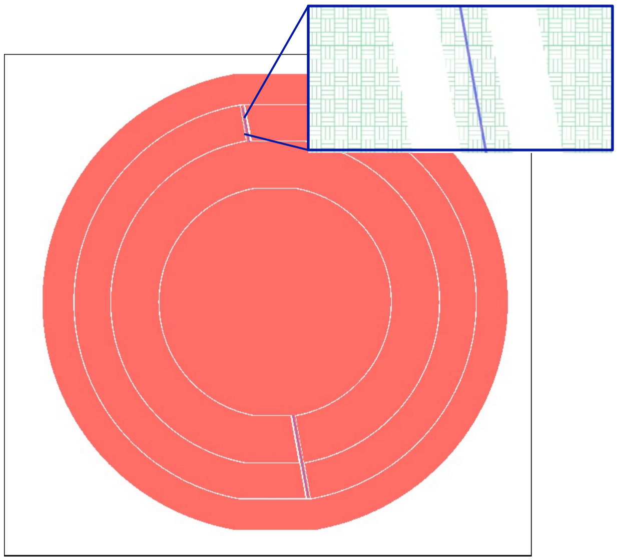
**+ 7evt/hr background)**

- Surface Electron Recoils have suppressed Yield
- Internal $^{109}$Cd β rate 70Hz

•Preliminary surface results -> overly conservative

- ER/NR well separated E > 6 $keV_{ne}$
  - $\sigma_q \sim 300 eV_{ee}$ (measured)
  - $\sigma_p \sim 192 eV_{ee}$ (measured)
  - Long thermal tails from (surface) muons dominate our sensitivity
  - Expect underground $\sigma_p \sim 72 eV_{ee}$ (x3 improvement)
  - Tungsten Tc ~ 100mK higher than necessary and degraded phonon resolution
  - Ion implantation of W with Fe-56 reduces W Tc (CDMS II)

# R&D of Charge-carrier  Performance

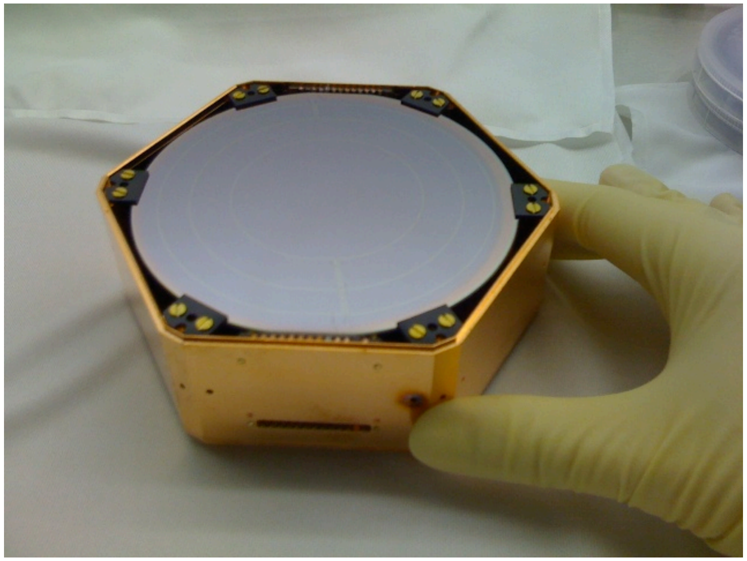


**Charge-carrier performance mask (FY10)**

Test 100 mm diameter Ge crystal quality.

Test optical photolithography steps for 1.4 kg Ge substrates

This mask has 4 charge electrodes separated by 400um trench.

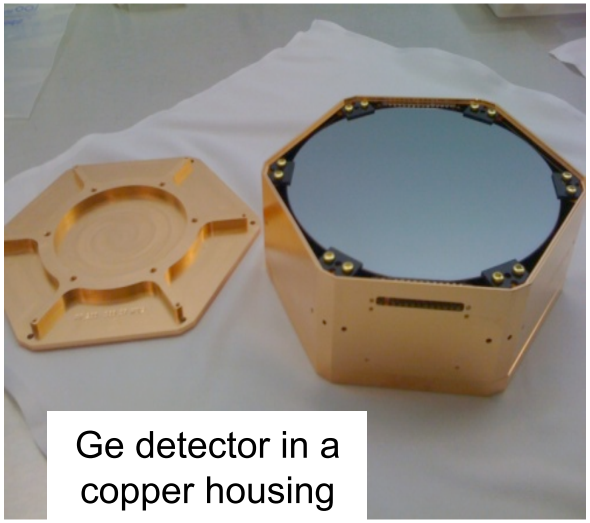


**Fabricated Second Ionization detector (FY11)**

Faster fabrication recipe: more processes conducted in 'parallel' for this double-sided geometry.

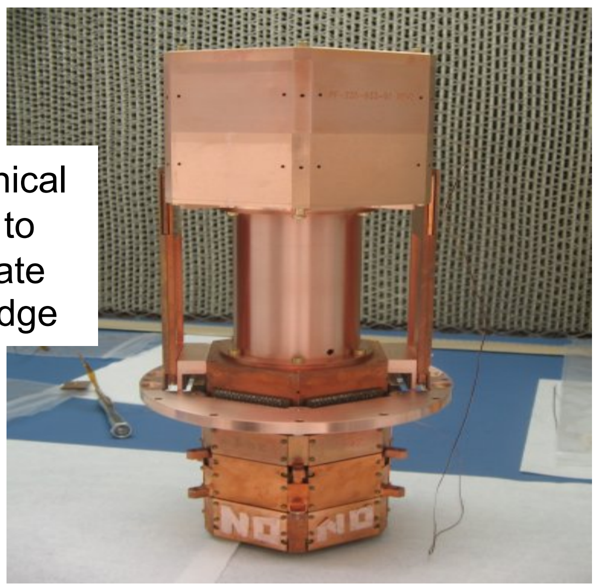
Final 100-mm-diameter-detector recipe will be based upon this double-sided recipe.

# First 100 mm diameter Ge Detector

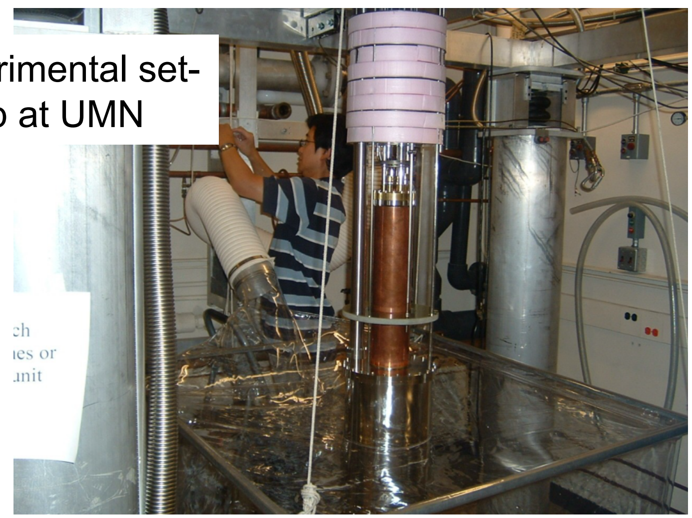


Ge detector in a copper housing

Transportation container

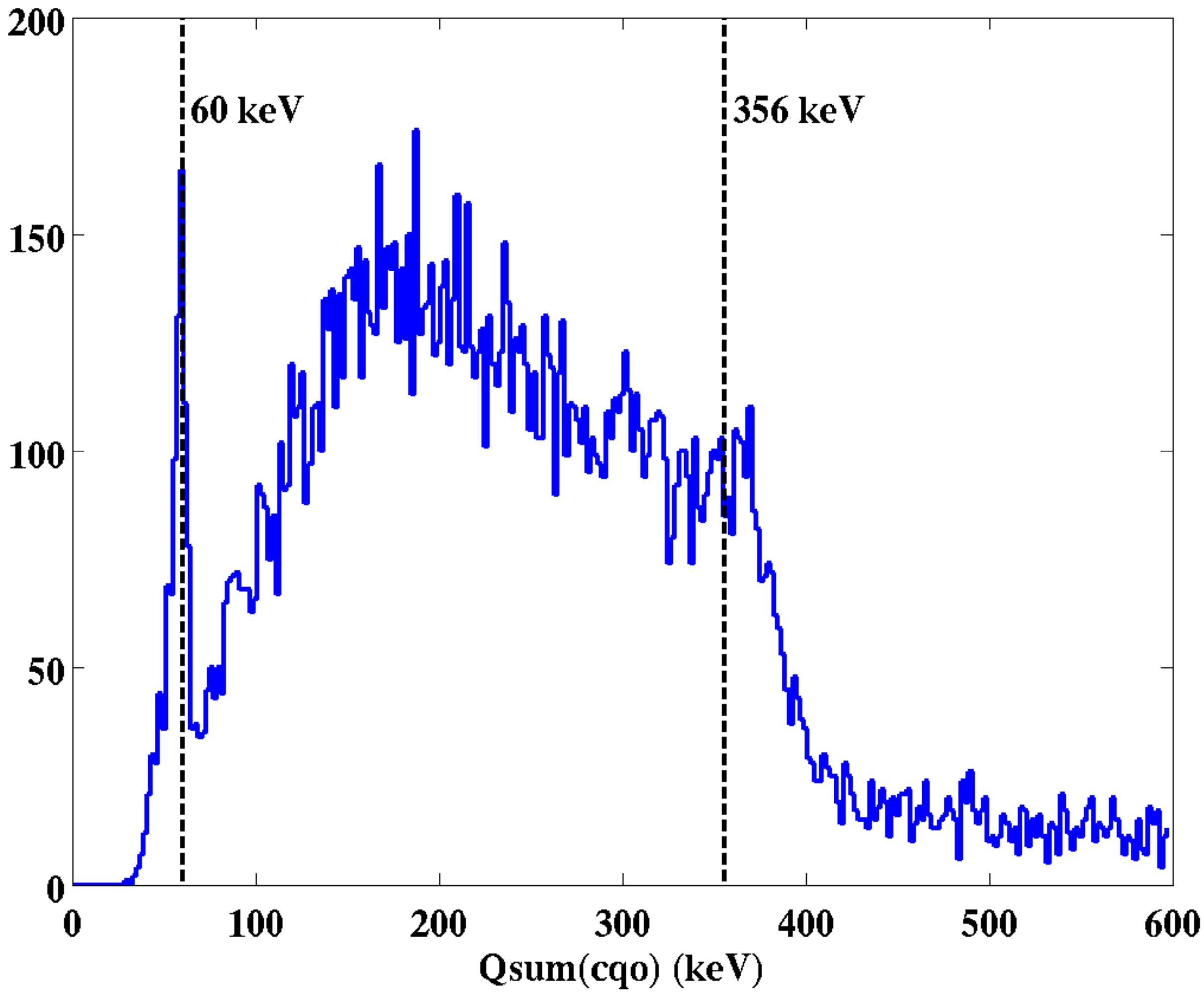


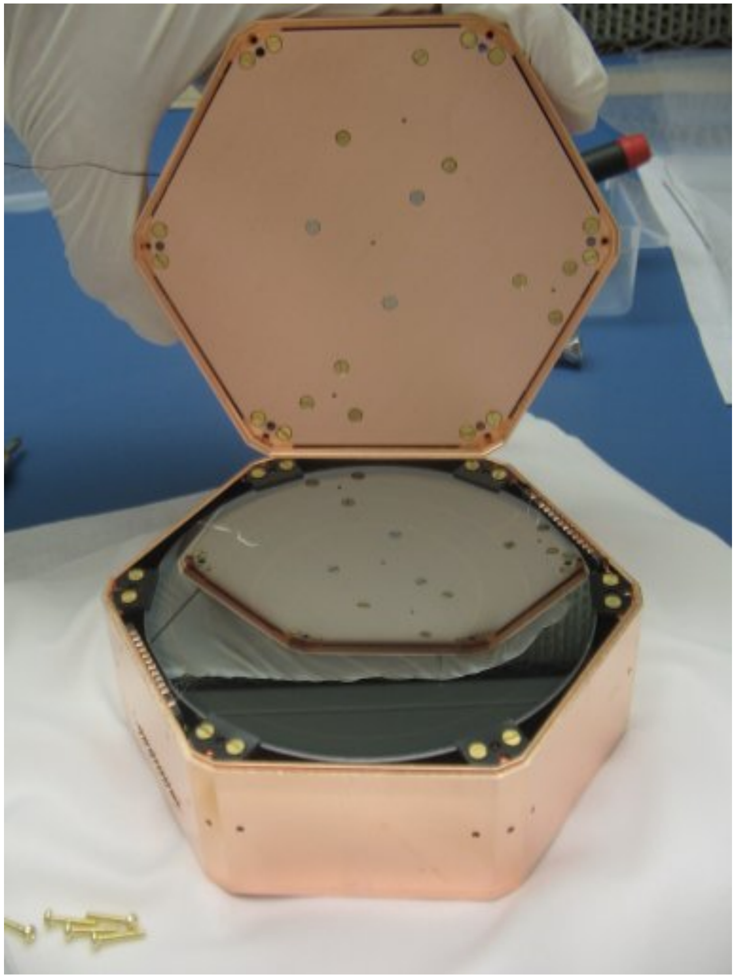
Mechanical parts to integrate with fridge



Experimental set-up at UMN

# Energy Spectrum (Am-241, Ba-133)



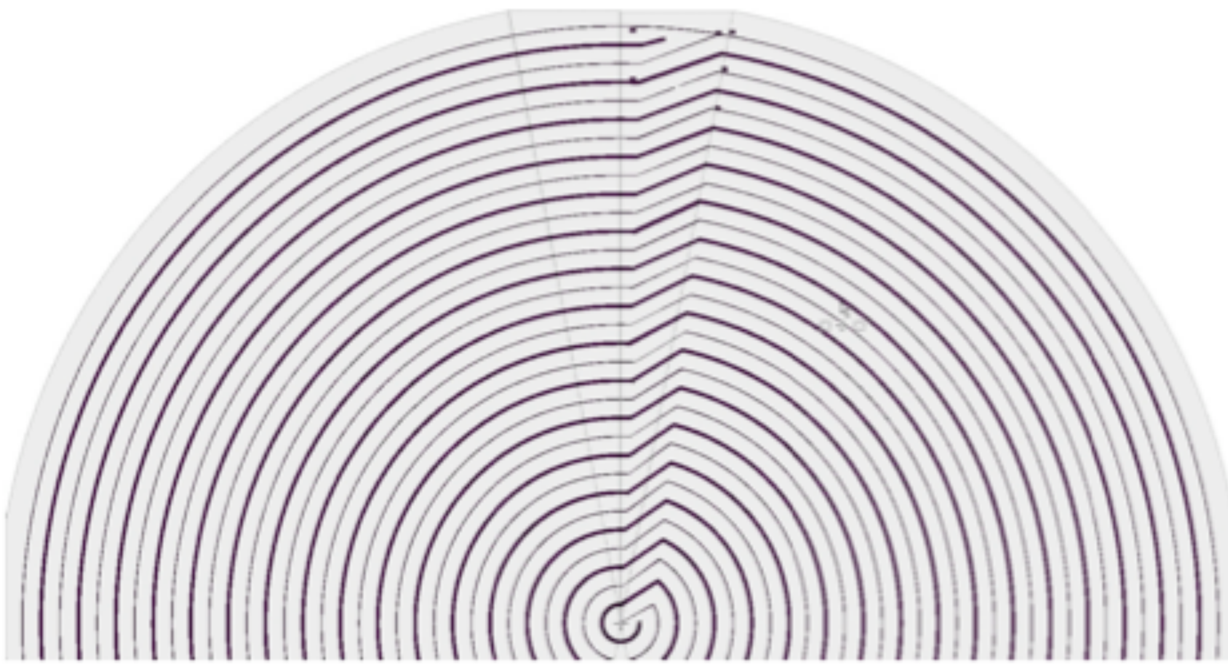
# Large detector Electrode configuration

**New masks and detector housing for 100 mm diameter Ge presently being designed:**

Validate electric-field configuration necessary for final detector – compare to simulations.

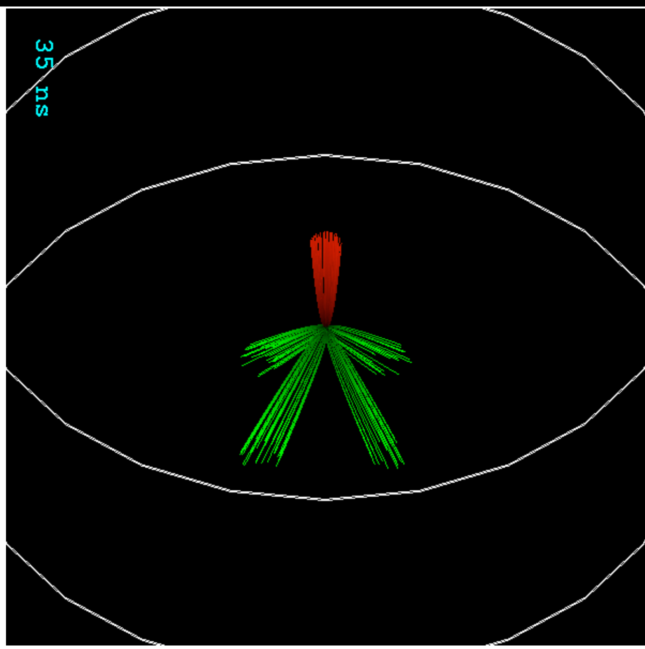
Interleaved electrodes are arranged simply as a spiral. Electrode spacing 1.5 mm.

The surface tangential field configuration is similar to that required by the iZIP Dark matter detector for surface-event rejection.

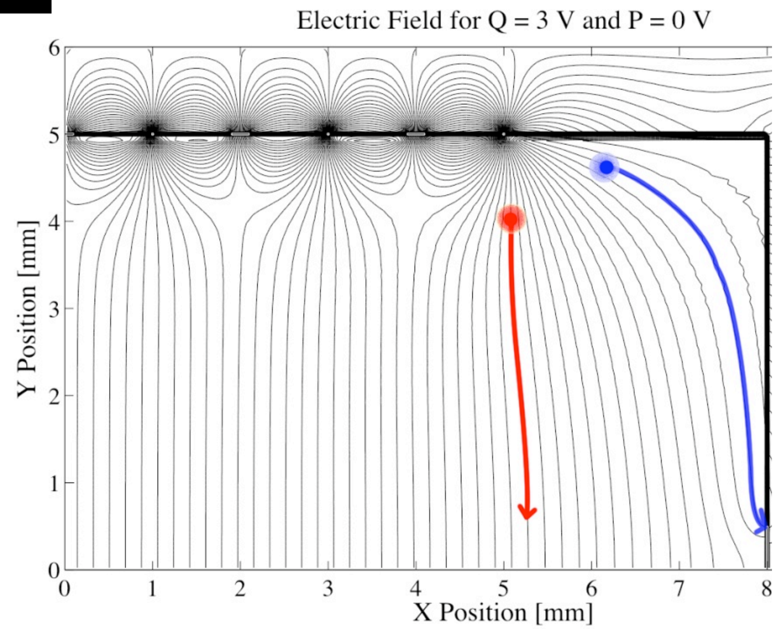


# Monte Carlo simulations of charge propagation

Anisotropic propagation in Ge!

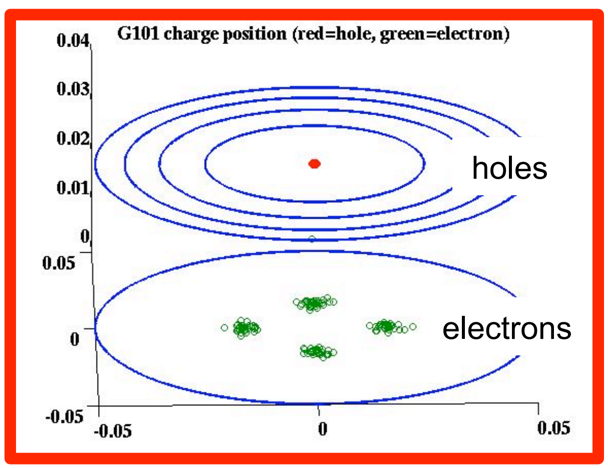


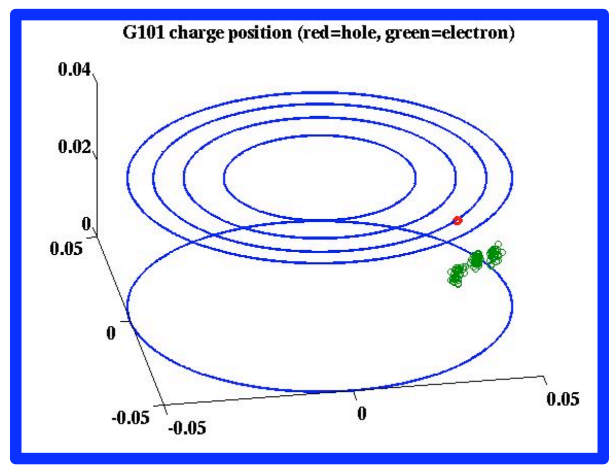

Electric field lines in a detector.



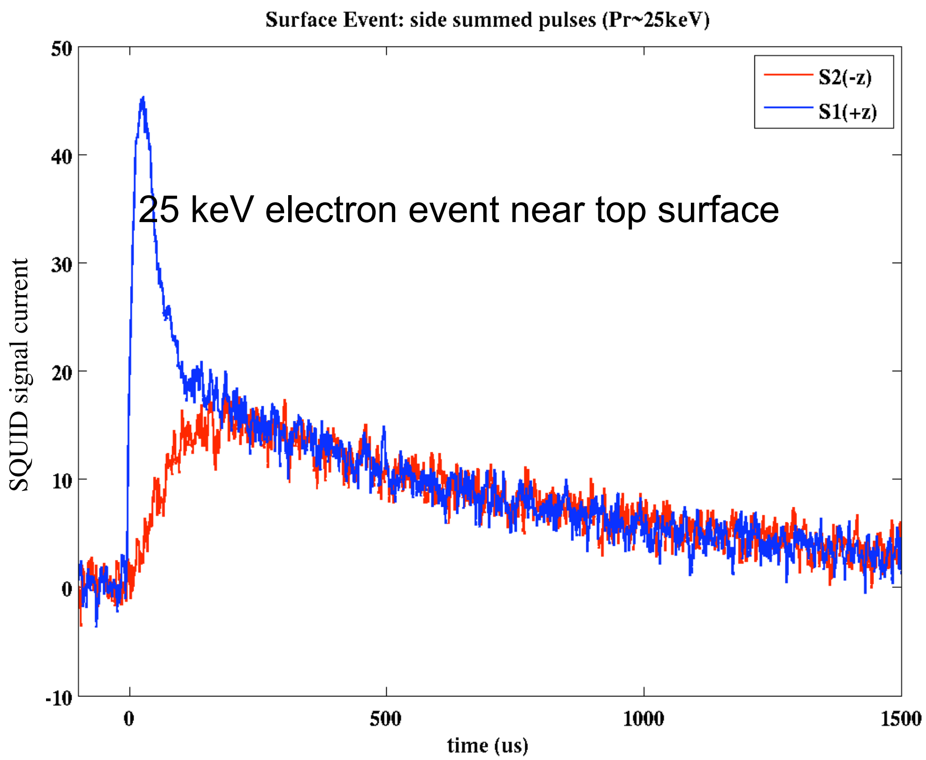

Events deposited on a field line which ends on a side wall have incomplete charge collection.

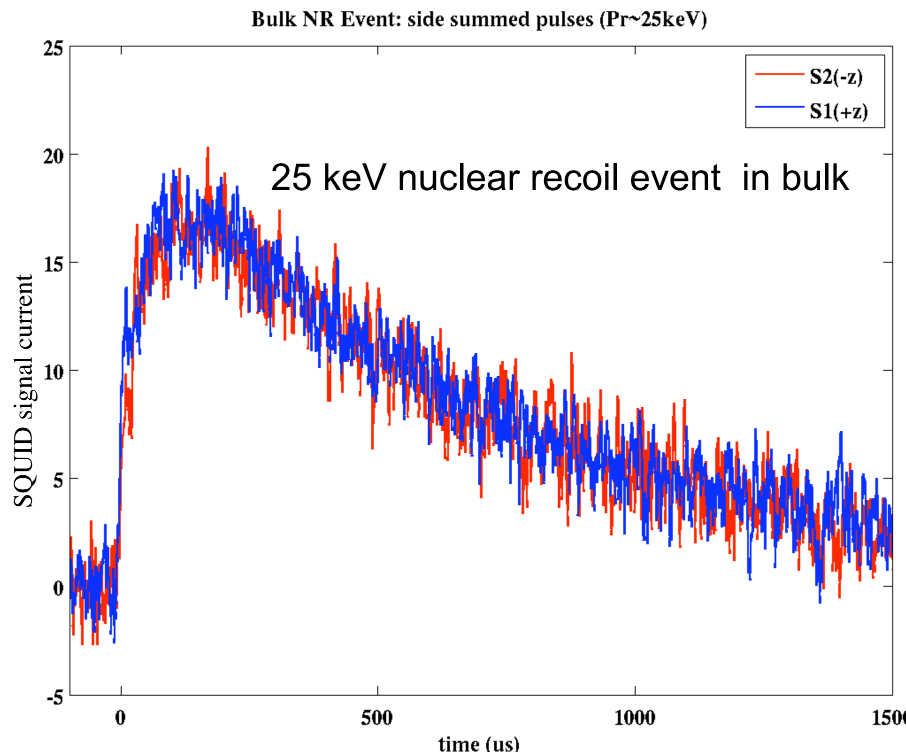
Events deposited on a 'bulk' field line have very good charge collection.



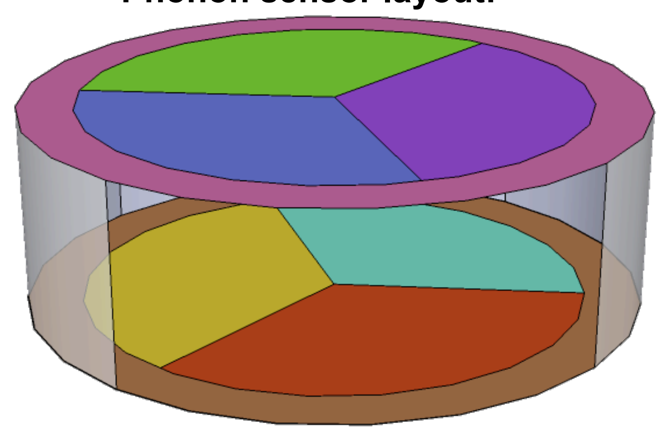
# Observed iZIP Phonon Pulse Shape Discrimination



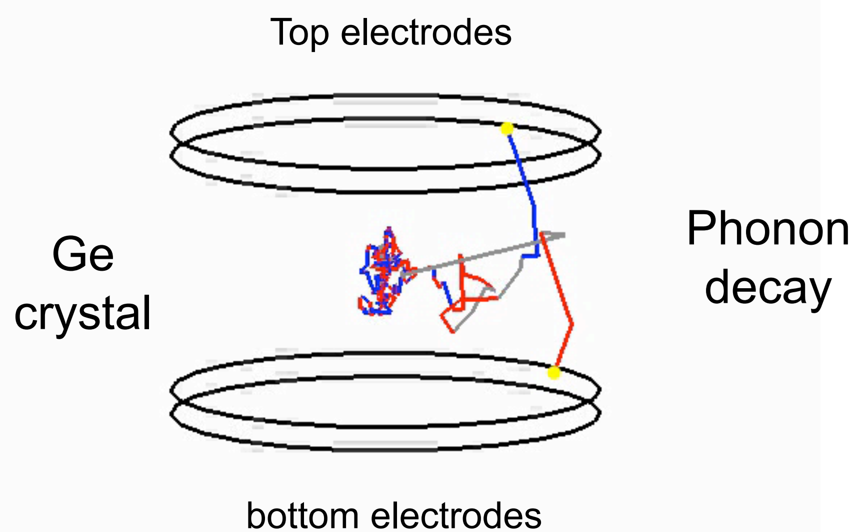

Surface Electron *vs* Nuclear Recoil discrimination seen in operating iZIP detectors in both pulse shape differences and energy partition in z-direction.

**Phonon sensor layout:**



# Geant4 simulations of phonons

SIMULATION




Colors correspond to different phonon polarization states: (Fast Transverse, Slow Transverse, Longitudinal)

Investigating possible new avenues for improving background rejection with Geant4

GEANT4 phonon transport test code includes

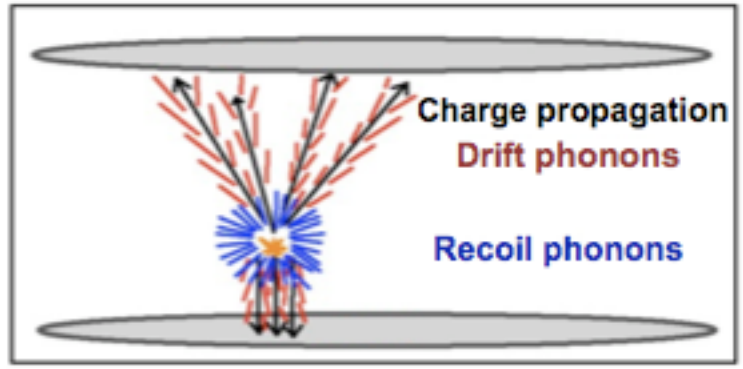
- Crystal lattice orientation
- Anisotropic scattering (k space)
- Speed of sound (not light!) propagation for massless particles

# CDMS – Neganov/Luke phonons

- Ionization yield *Y*~ 0.2 at these low recoil energies.

- Only ~ 20% contribution to phonon recoil energy scale if Q bias = 3 Volts for Ge.

- Initial tests with CDMS detectors indicate ~ 50 eV recoil detection threshold.

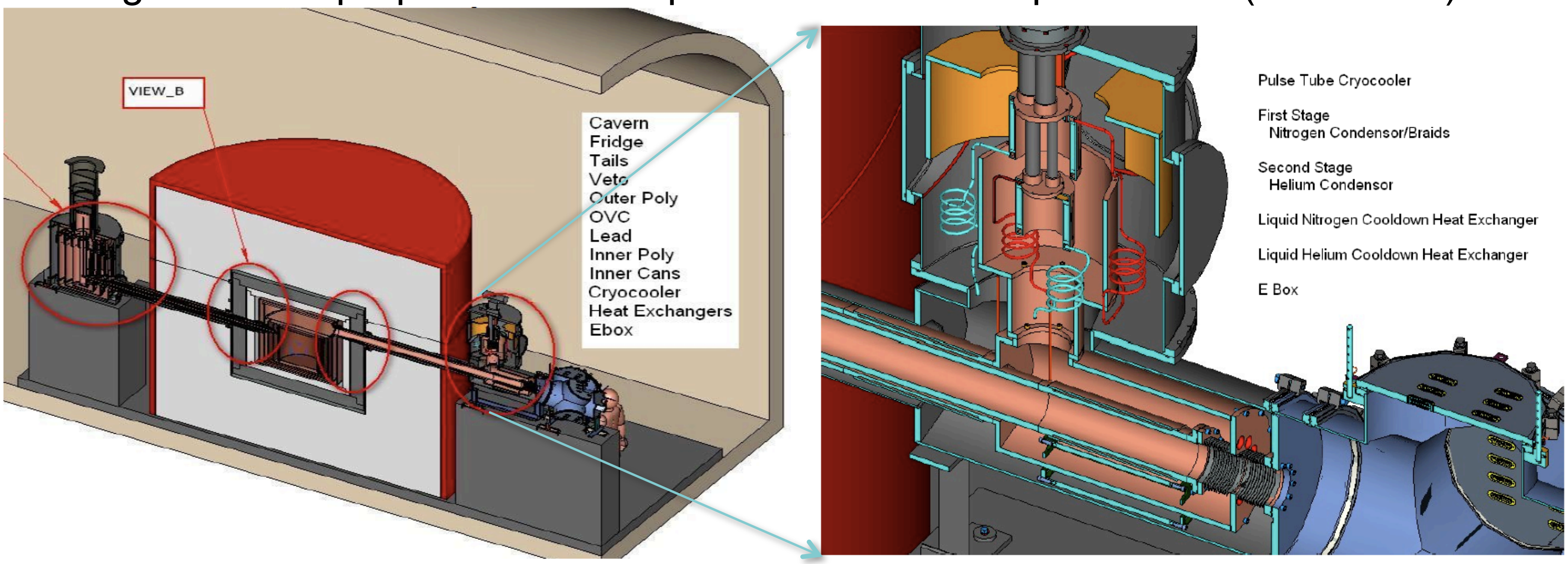



*Neganov and Trofimov, Otkryt. Izobret.,* **146**, *215 (1985)*
*Luke, J. Appl. Phys., 64, 6858 (1988)*

- "CDMS-lite"
  Q bias ~ 30 V
  $\Rightarrow$ WIMP mass
  down to sub GeV.

# SuperCDMS SNOLAB (150 kg Ge)

Planning to submit proposal 2011. Expected reach 0.3 zepto-barnes (3e-46 $cm^2$)

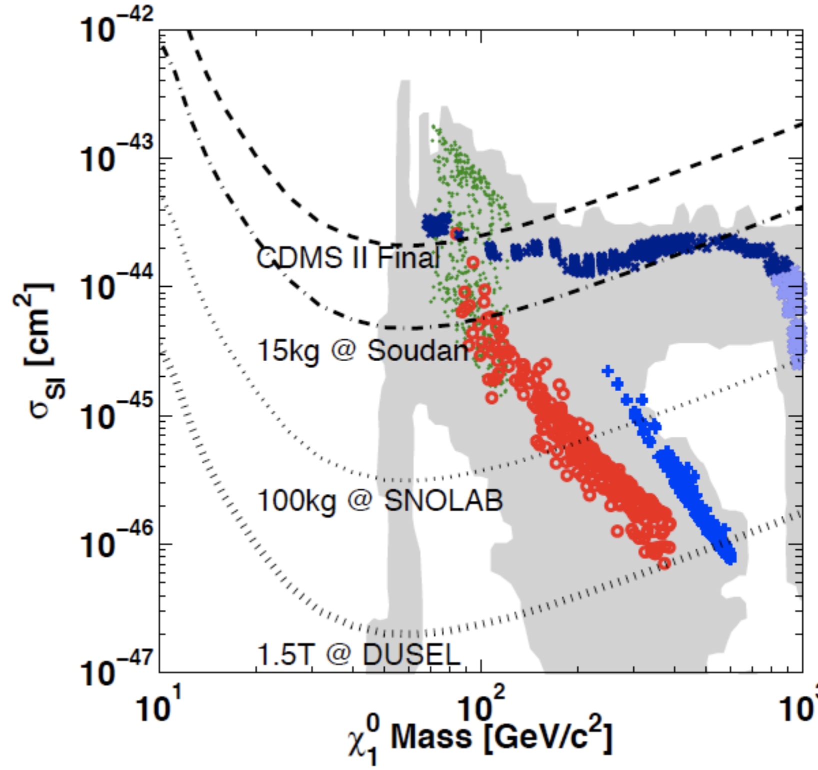


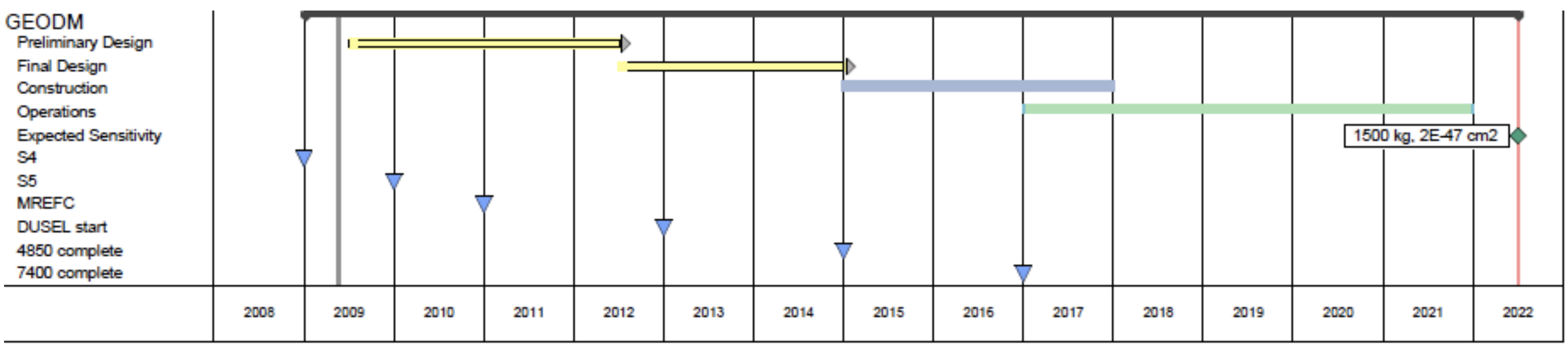

- Need deeper site than Soudan, > 4000 mwe. Need new fridge and shield.
  - New fridge and shield design work in progress at FNAL.
- Select iZIP detector technology ~ 1 kg each.
  - Detector fabrication at Stanford/SLAC (baseline).
  - Direct readout of all electrical channels, similar to CDMS II.

# GEODM for 1.5 tonne Ge target

DUSEL design study (NSF S4) funded

- Deliver study end of 2012.
  - Cryogenic engineering
  - Electrical readout, multiplexing (NIST & MIT)
  - Detector fabrication scalability (TAMU & SLAC)
  - Material screening, background studies.
- Rapid advance on high risk items could feed into earlier programs.



# Summary

- Cryogenic Ge dark matter detectors excellent track record.
- Essential to have multiple target materials – and different technologies even if the same material.
- Redundancy, redundancy, redundancy. As many handles as possible to assess the nature of any candidate events seen. Burden of proof for discovery is very high.
- Scalability: reduce costs in the fabrication and testing programs. Maintain construction phase for future experiments that is only 2 years.
- Starting a Critical Design (CD) process for CDMS detectors sited at SNOLAB for 150 kg scale experiment could start later this year.