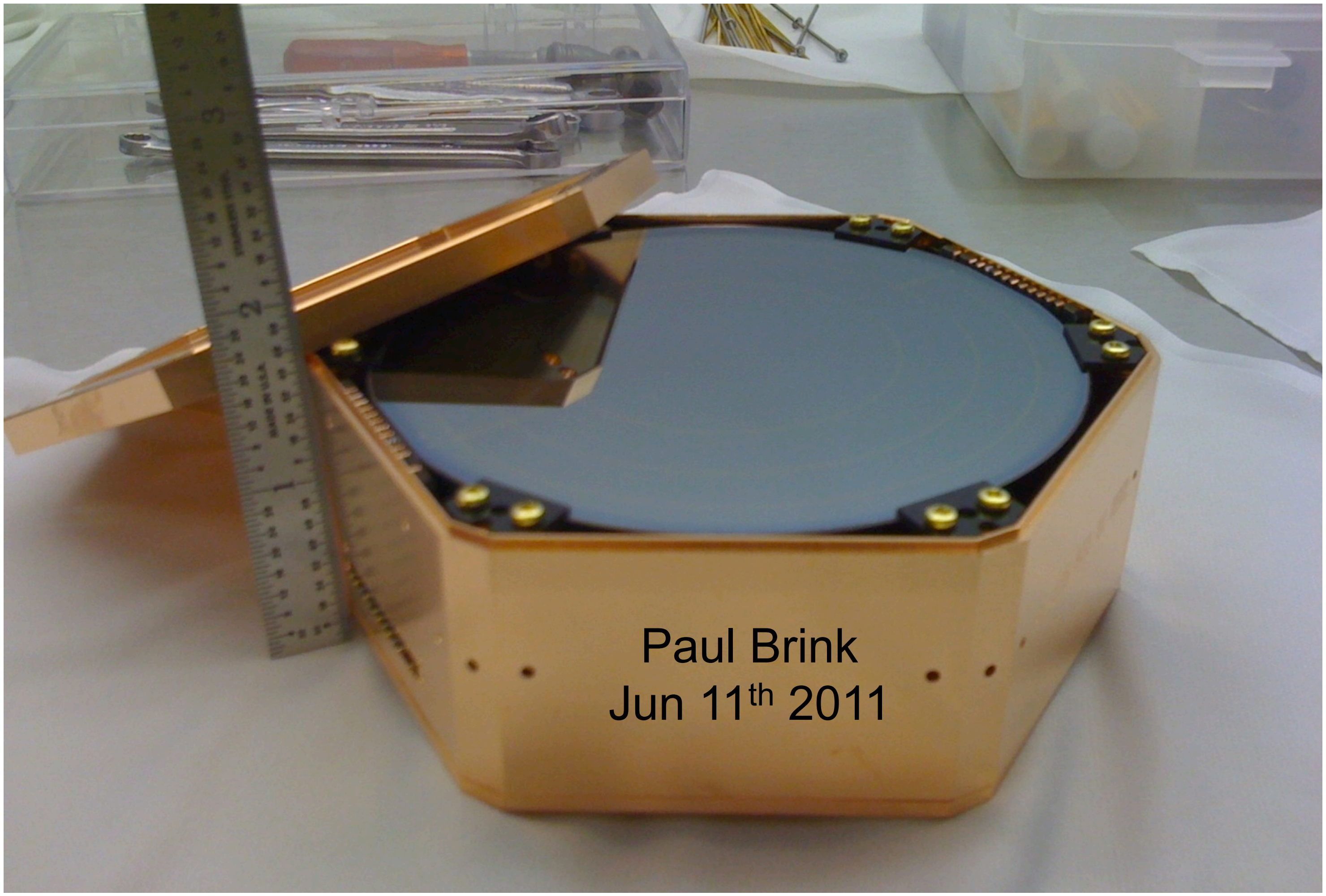
Large Diameter Cryogenic Germanium Detectors for Dark Matter Direct Detection Experiments



Paul Brink
Jun 11th 2011

SLAC
NATIONAL ACCELERATOR LABORATORY

CDMS Collaboration

California Institute of Technology
Z. Ahmed, J. Filippini, S.R. Golwala, D. Moore, R. Nelson, R.W. Ogburn

Case Western Reserve University
D. Akerib, C.N. Bailey, M.R. Dragowsky, D.R. Grant, R. Hennings-Yeomans

Fermi National Accelerator Laboratory
D. A. Bauer, F. DeJongh, J. Hall, D. Holmgren, L. Hsu, E. Ramberg, R.L. Schmitt, R. B. Thakur, J. Yoo

Massachusetts Institute of Technology
A. Anderson, E. Figueroa-Feliciano, S. Hertel, S.W. Leman, K.A. McCarthy, P. Wikus

NIST
K. Irwin

Queen's University
P. Di Stefano , C. Crewdson , J. Fox , S. Liu , C. Martinez, P. Nadeau , W. Rau, Y. Ricci

Santa Clara University
B. A. Young

Southern Methodist University
J. Cooley, B. Karabuga, H. Qiu

SLAC/KIPAC
M. Asai, A. Borgland, D. Brandt, P.L. Brink, W. Craddock, E. do Couto e Silva, G.G. Godfrey, J. Hasi, M. Kelsey, C. J. Kenney, P. C. Kim, R. Partridge, R. Resch, K. Schneck, M. Swiatlowski ,A. Tomada, D. Wright

Stanford University
B. Cabrera, M. Cherry , R. Moffatt, L. Novak, M. Pyle, M. Razeti, B. Shank, S. Yellin, J. Yen

Syracuse University
M. Kos, M. Kiveni, R. W. Schnee

Texas A&M
A. Jastram, K. Koch, R. Mahapatra, M. Platt , K. Prasad, J. Sander

University of California, Berkeley
M. Daal, T. Doughty, N. Mirabolfathi, A. Phipps, B. Sadoulet, D.N. Seitz, B. Serfass, D. Speller, K.M. Sundqvist

University of California, Santa Barbara
R. Bunker, D.O. Caldwell, H. Nelson

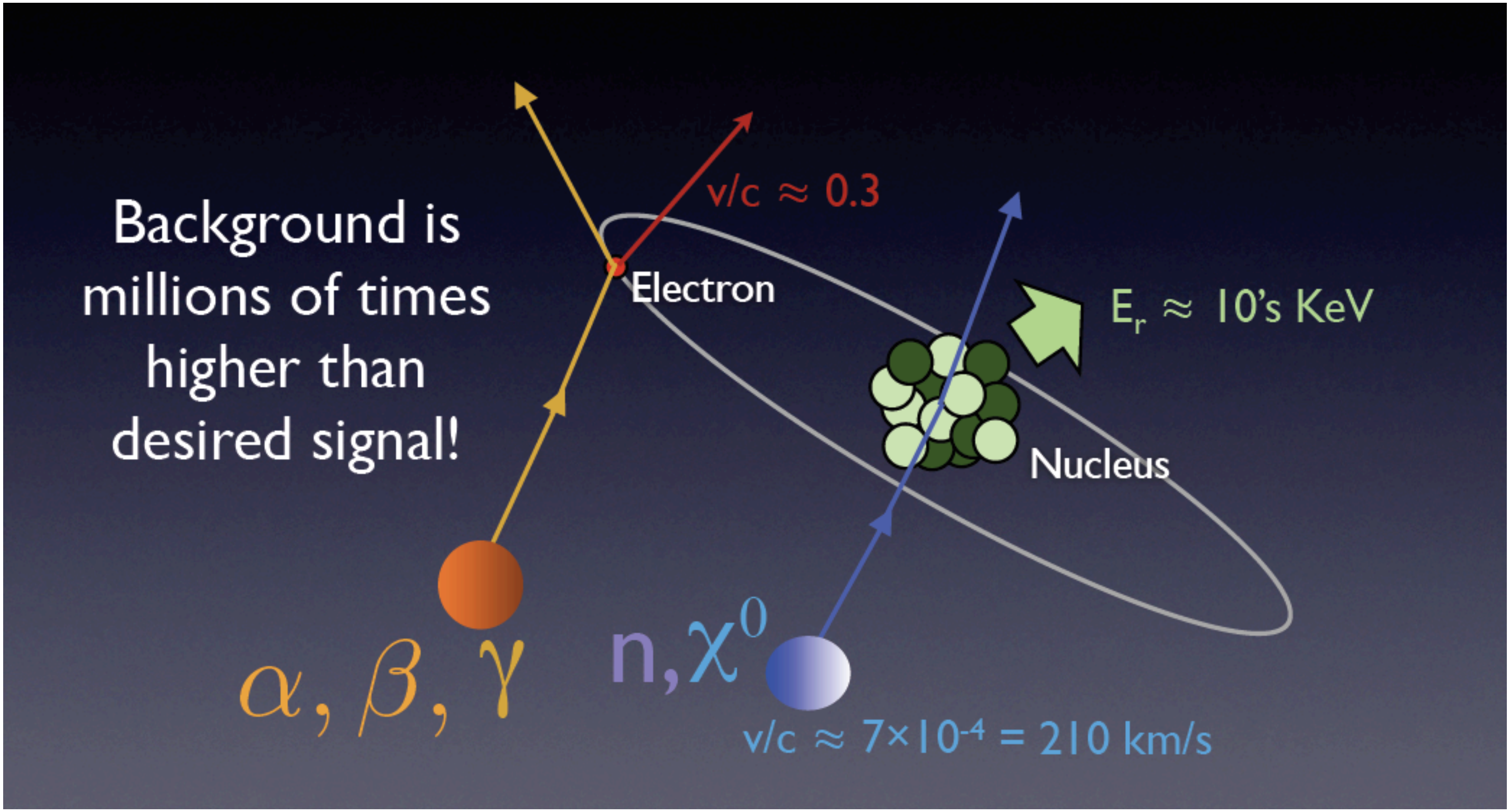
University of Colorado Denver
B.A. Hines, M.E. Huber

University of Florida
T. Saab, D. Balakishiyeva, B. Welliver

University of Minnesota
J. Beaty, H. Chagani, P. Cushman, S. Fallows, M. Fritts, O. Kamaev, V. Mandic, X. Qiu, A. Reisetter, J. Zhang

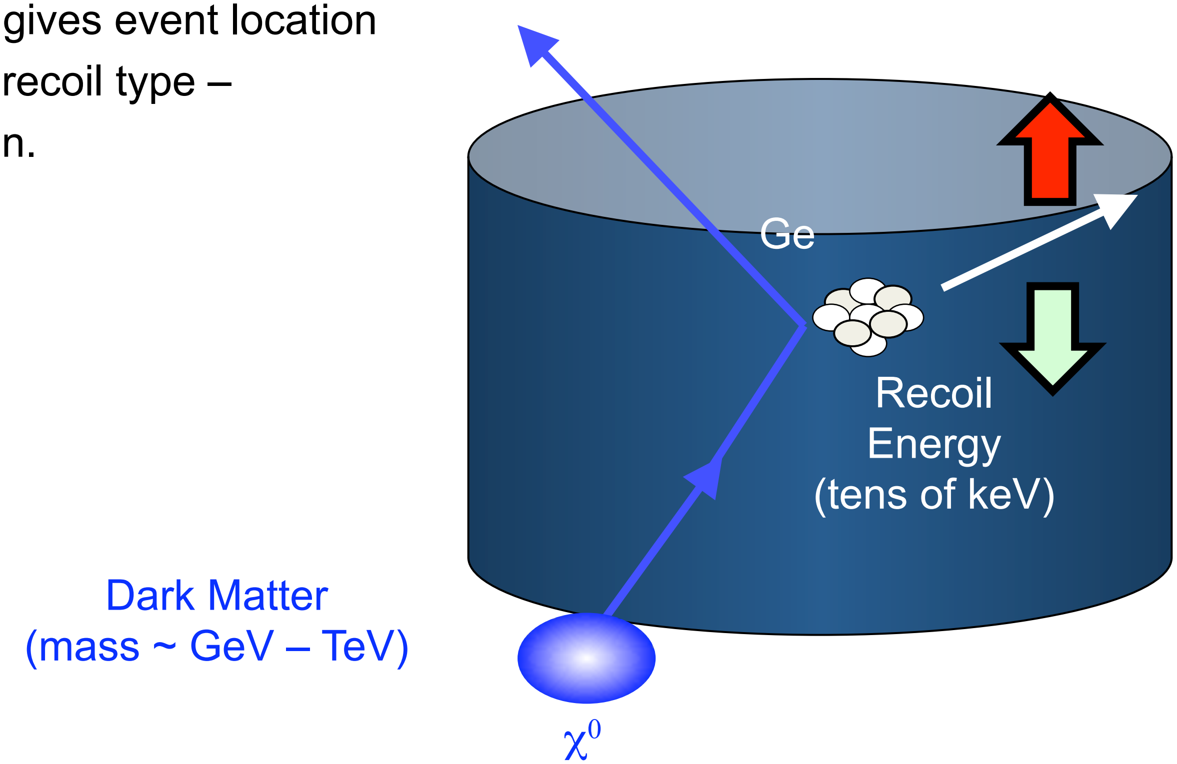
University of Zurich
S. Arrenberg, T. Bruch, L. Baudis, M. Tarka

WIMP (χ^0) direct detection

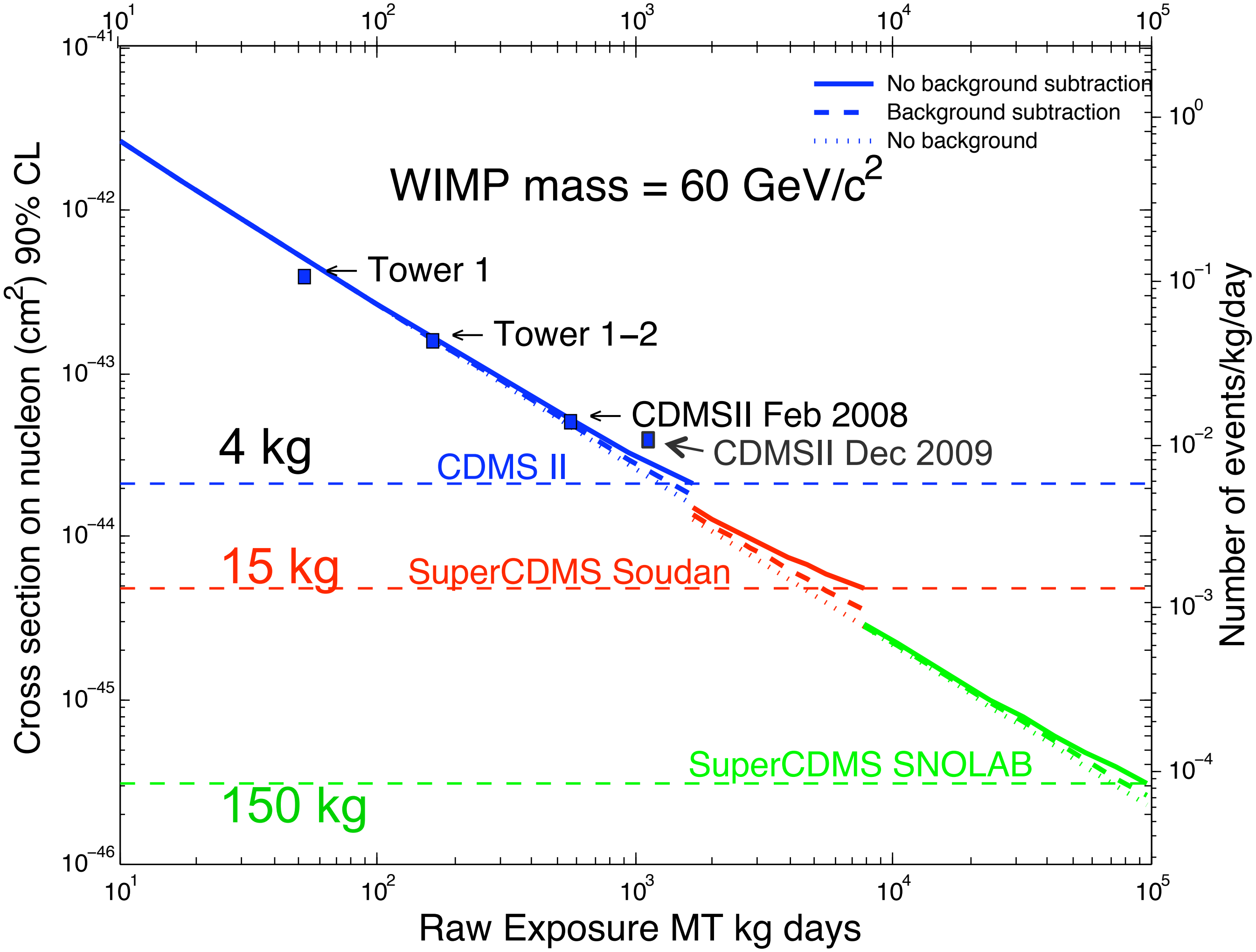


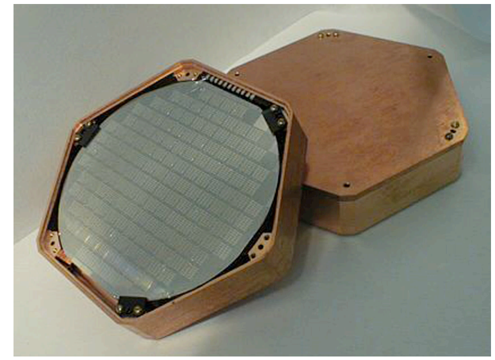
Why cryogenic Ge Detectors?

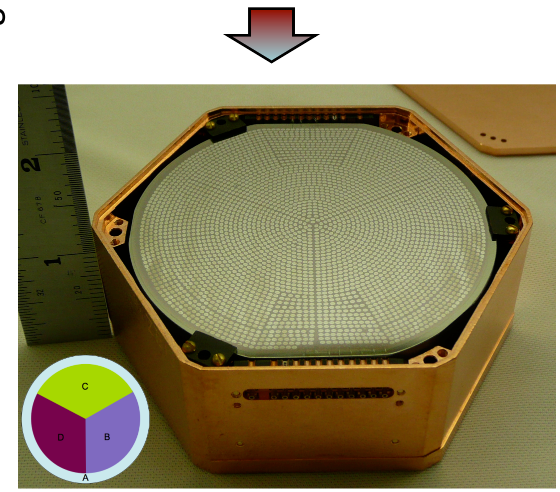
- Employ a robust and powerful recoil-event discrimination technique
  - Measure charge-carriers (ionization signal) and phonons generated by an event.
  - Most of the energy is in the phonon signal (small quanta) which are not statistically limited and give good energy resolution.
  - The signal in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

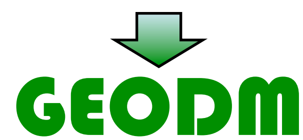


SuperCDMS – Moore's Law if zero bkgd

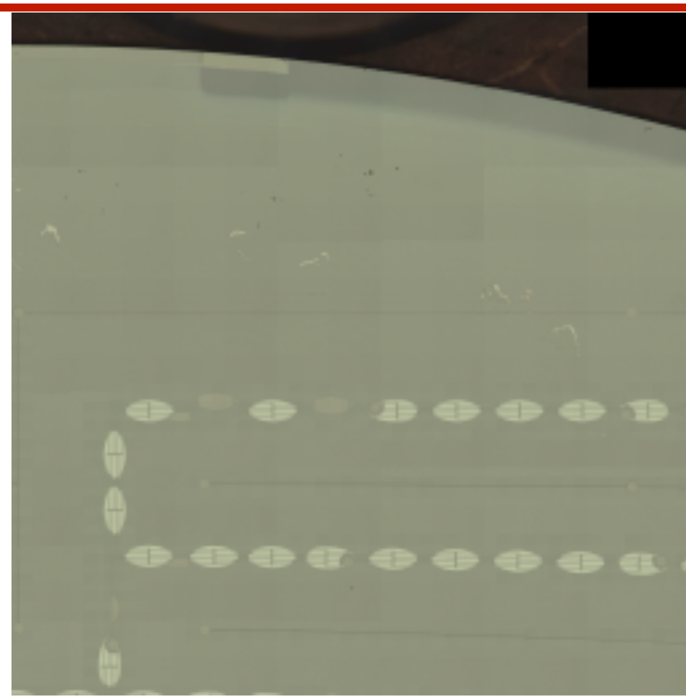


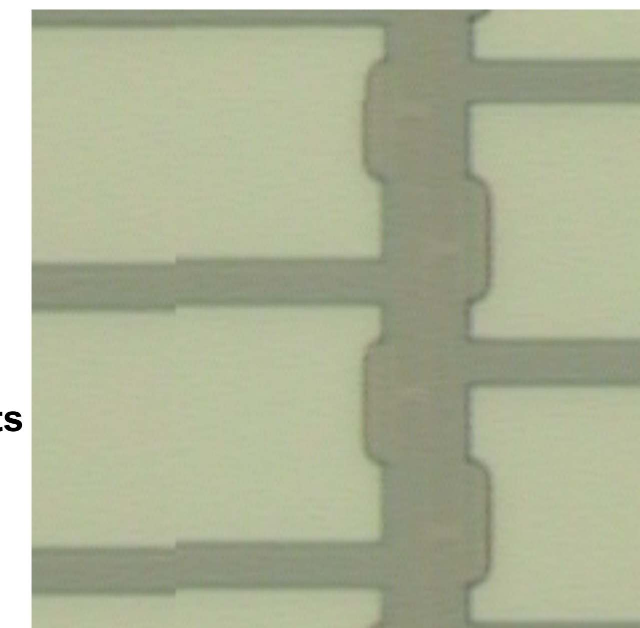






Ge iZIP detector : phonon sensors



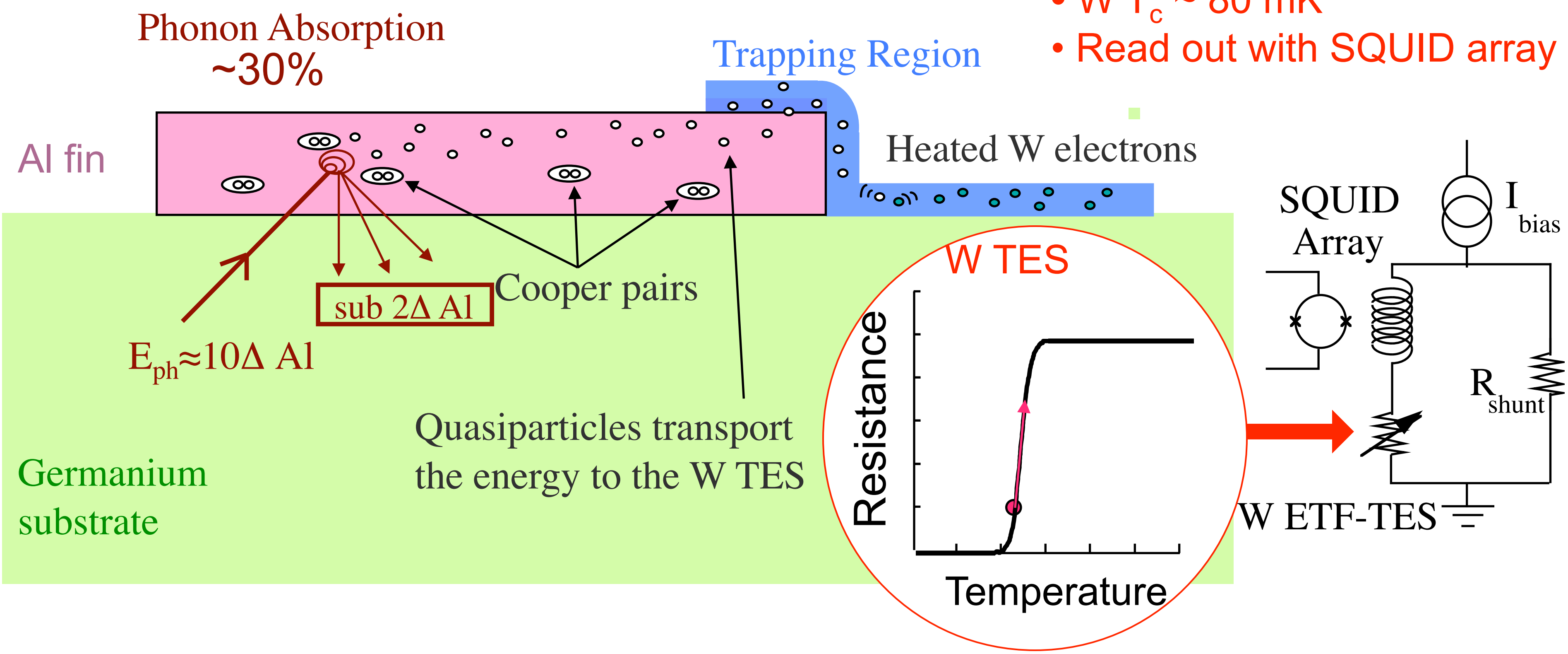


- Athermal phonon sensors operated at 80 mK.
  - Aluminum fins look white.
  - Tungsten transition edge sensor thin grey line.
  - aSi substrate (also) grey/green color.

CDMS Phonon sensor operation

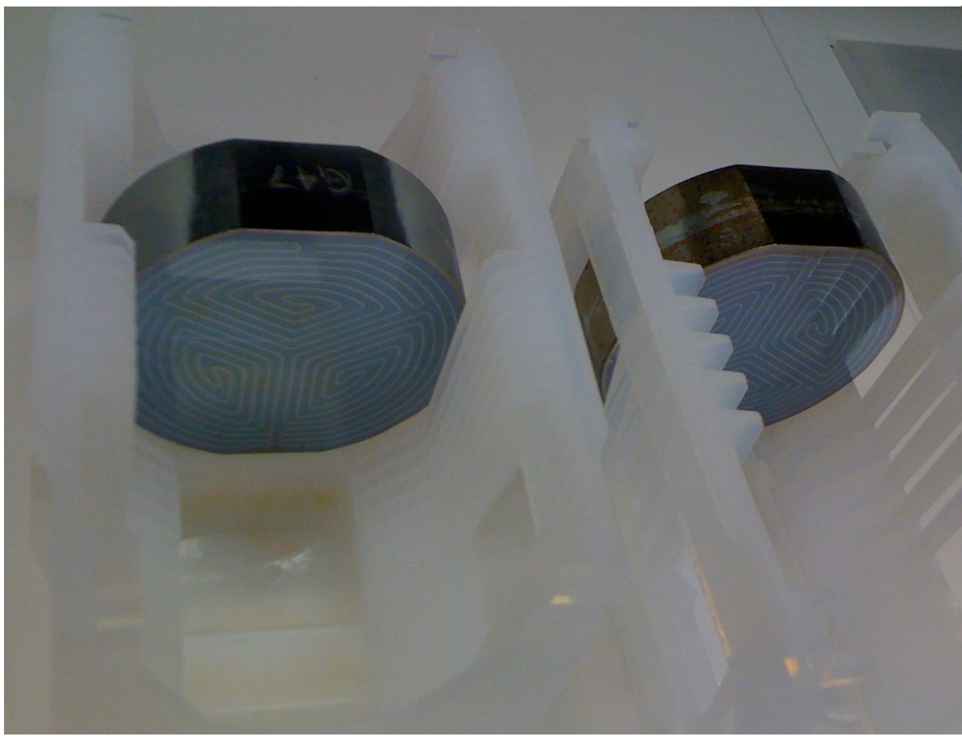
- Recoil event occurs in Germanium substrates, 76 mm diameter, 25 mm thick.
- Aluminum fins 300 nm thick absorb phonons arriving from substrate underneath.
- Fins connect to Tungsten transition edge sensors (W TESs).

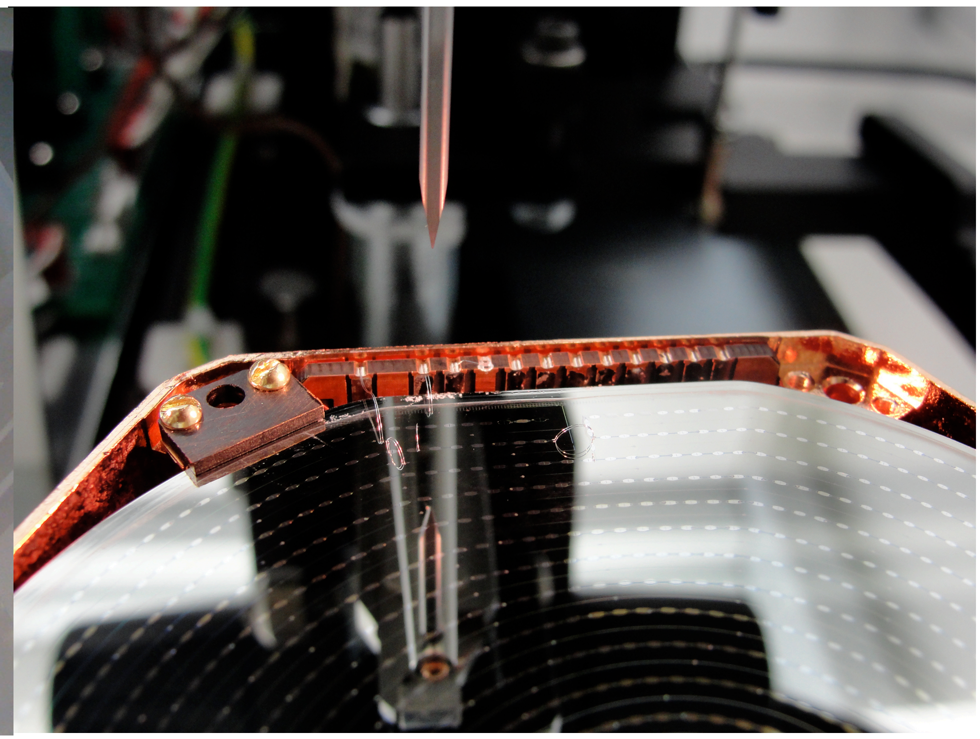
- W T_c ~ 80 mK
- Read out with SQUID array



Ge iZIP detector production

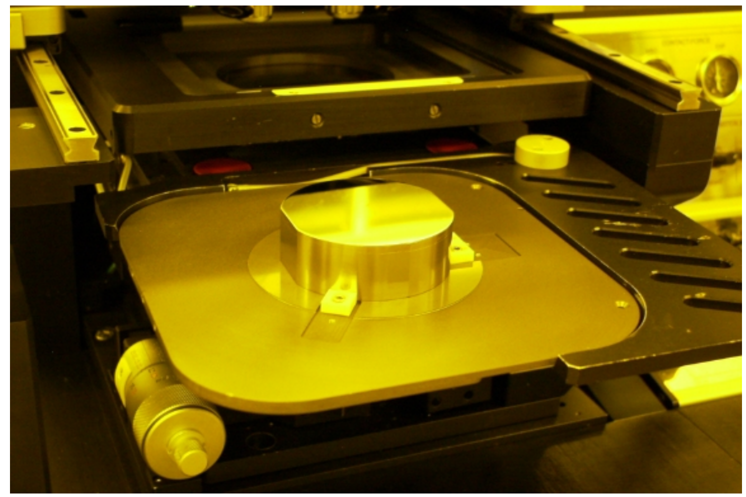
- All CDMS II and SuperCDMS Ge detectors fabricated in Stanford Nanofabrication Facility (SNF)
  - Double-sided optical photolithography (90% time)
  - Manual packaging and wire-bonding (10% time)

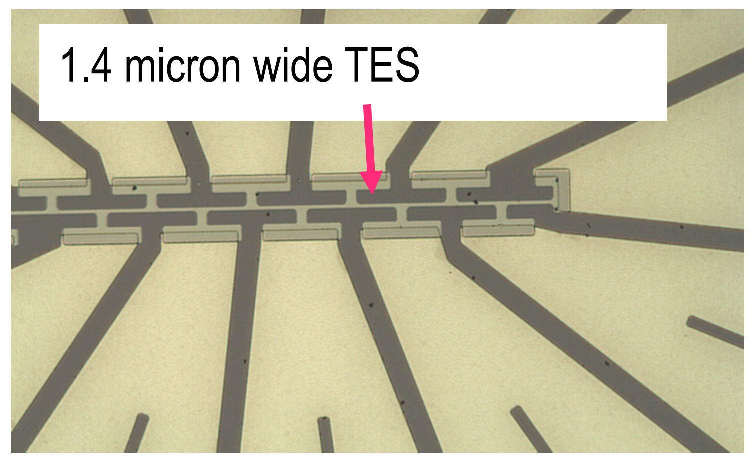




SuperCDMS: 1-inch thick substrates

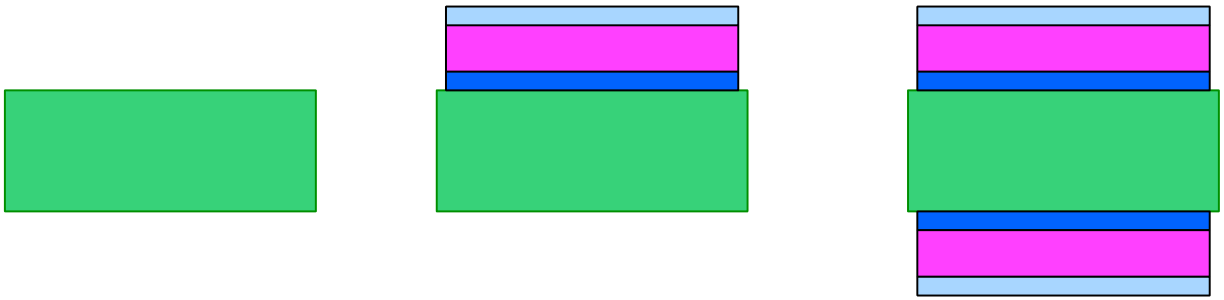
Photolithography for the 1-inch thick Ge and Si substrates required equipment modifications for the thin film depositions, photoresist coatings, U.V. exposures and plasma etching.

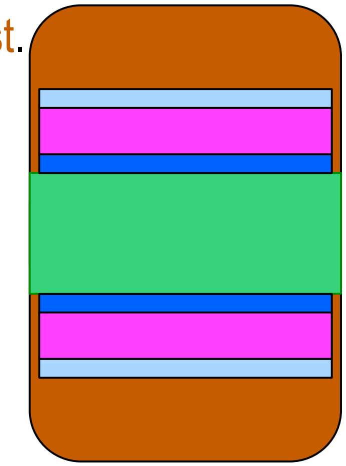




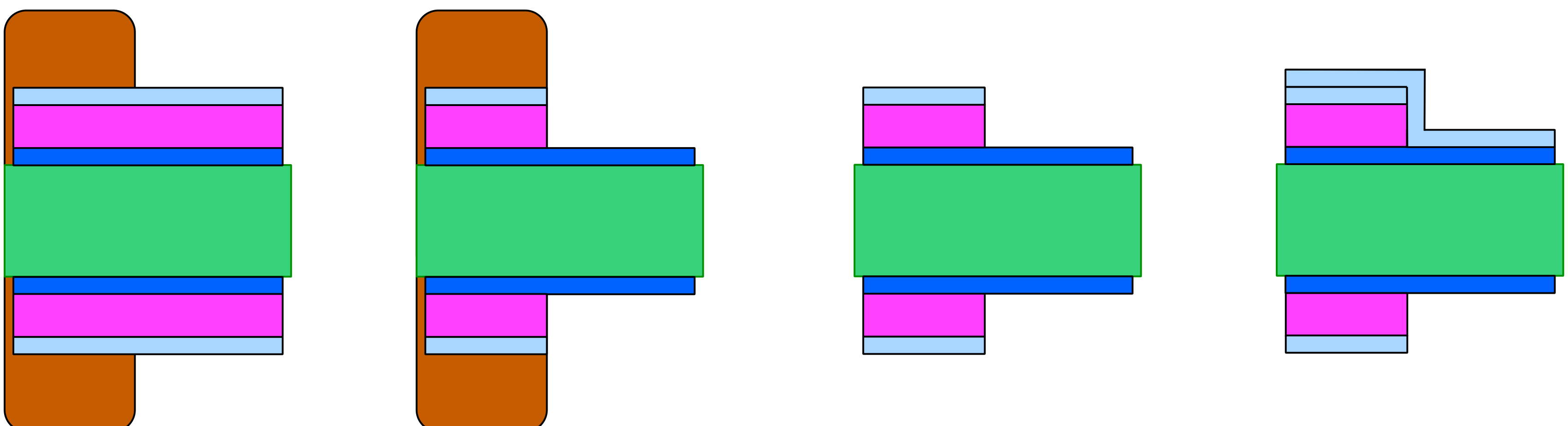
Ge Fabrication – photolithography (1)

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.

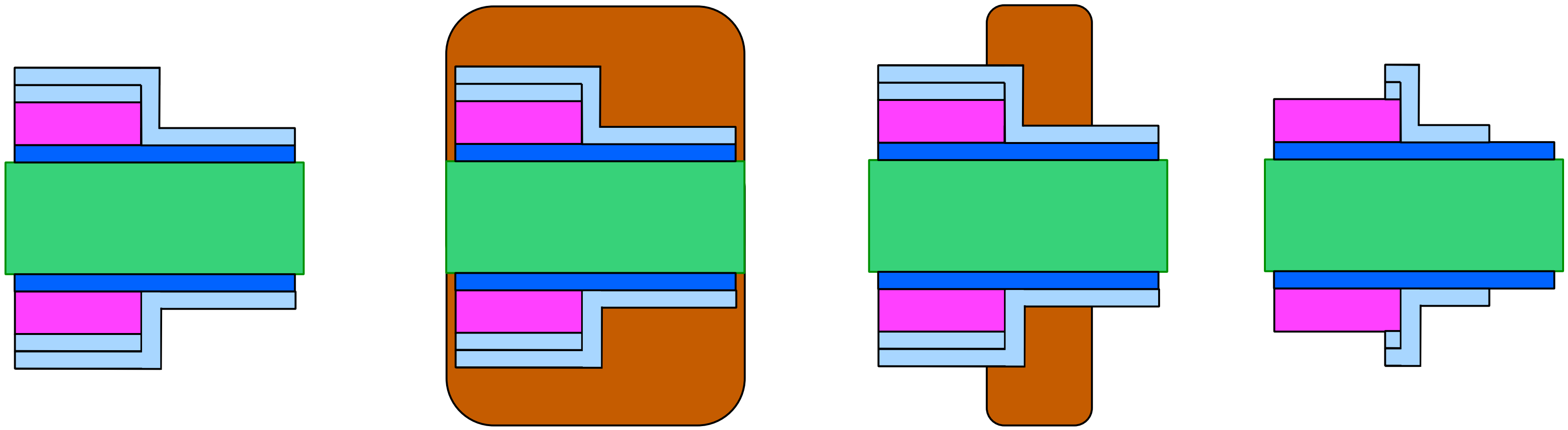




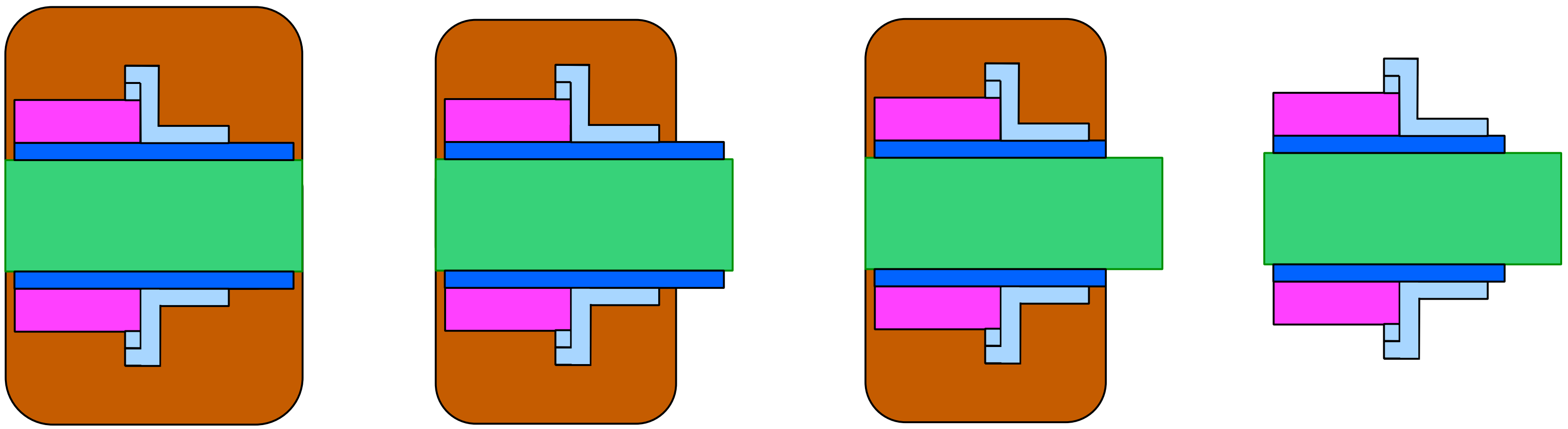
Both sides patterned simultaneously : exposed [EV-Align], developed, wet-etched (H2O2 for W, Al-etch for Al), photoresist stripped. Both sides receive W TES film deposition.



Ge Fabrication – photolithography (2)

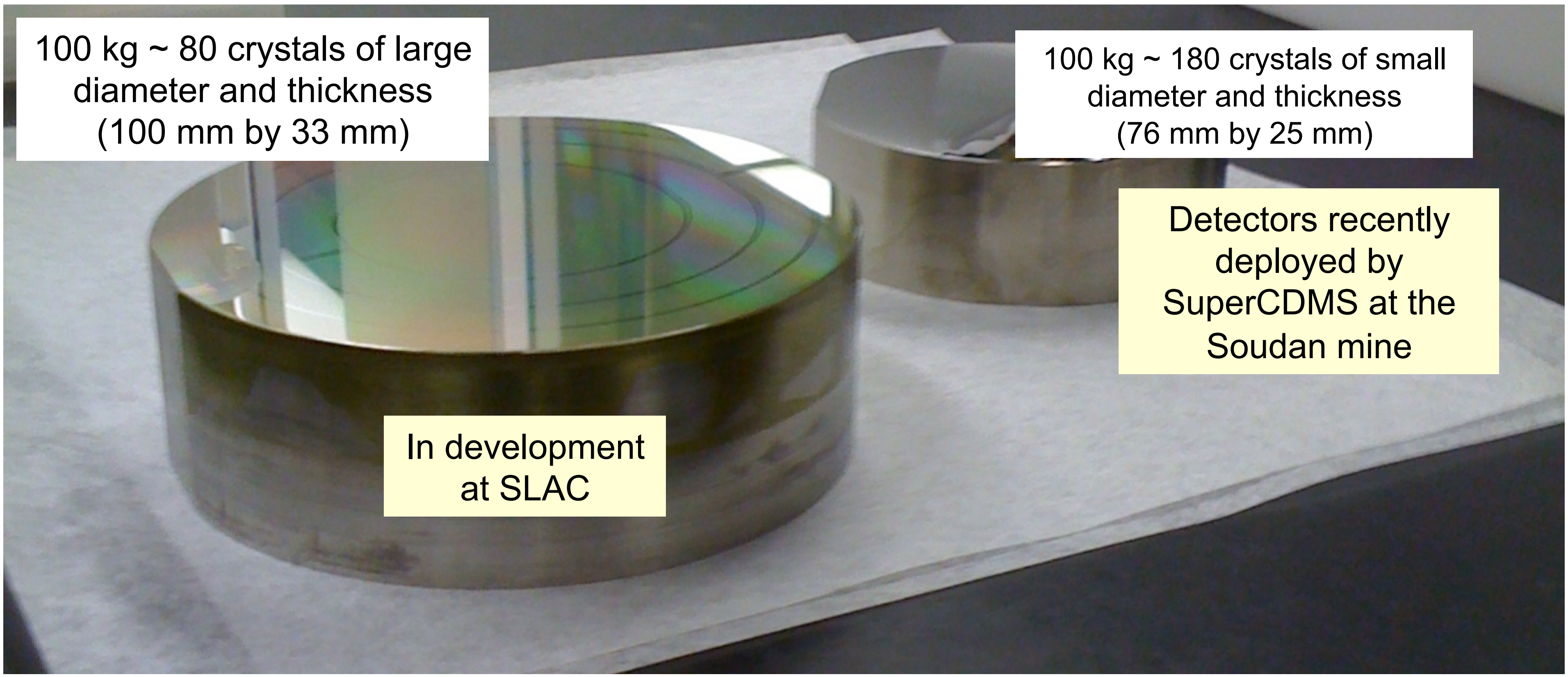


TES patterned for both sides : exposed [EV-Align], developed, W wet-etched, photoresist stripped. Both sides recoated and patterned for amorphous Si dry-etch.



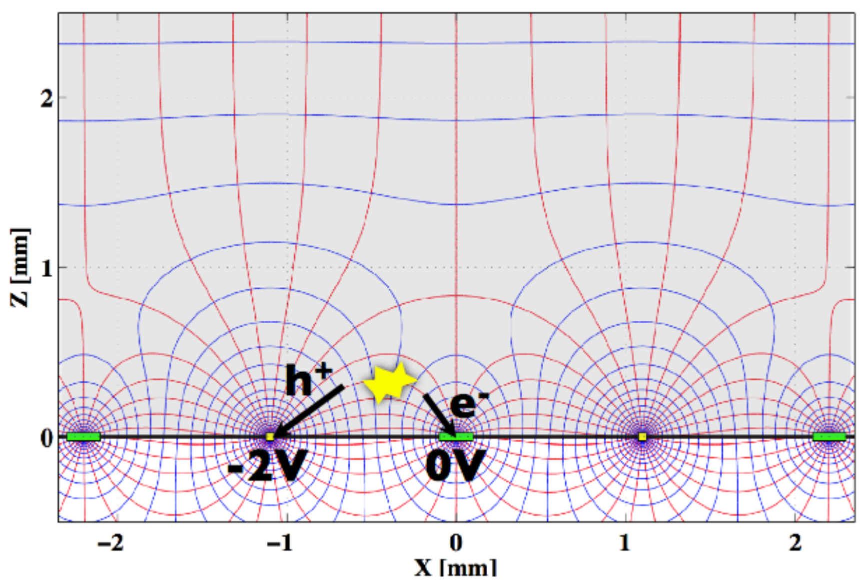
Scalability of Ge Detectors

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

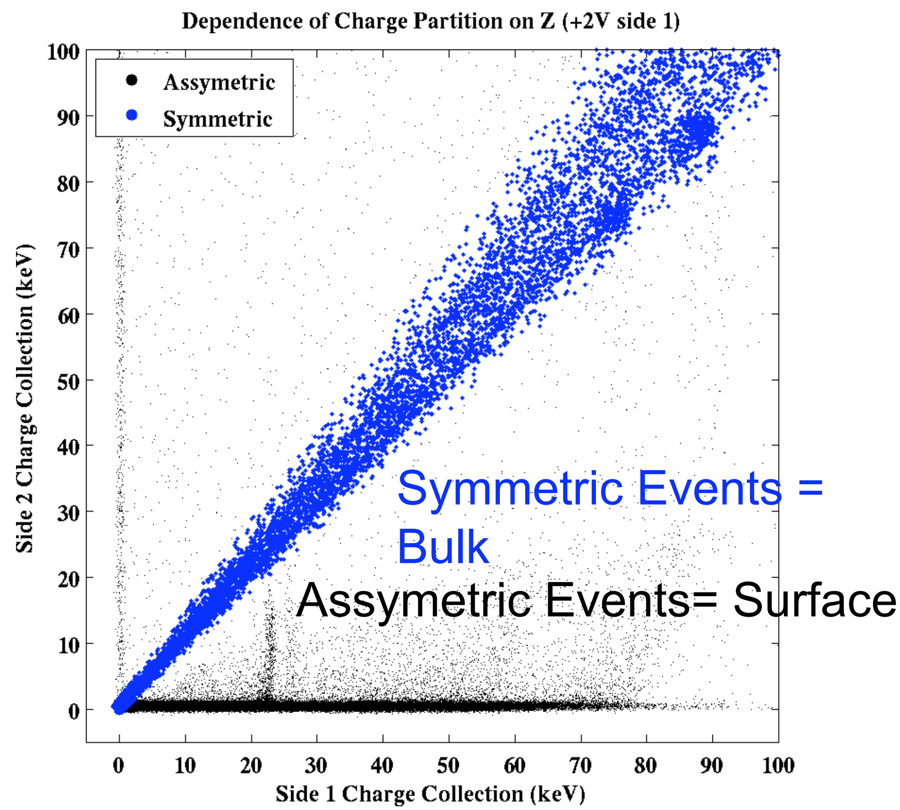


Charge signals give a fiducial volume

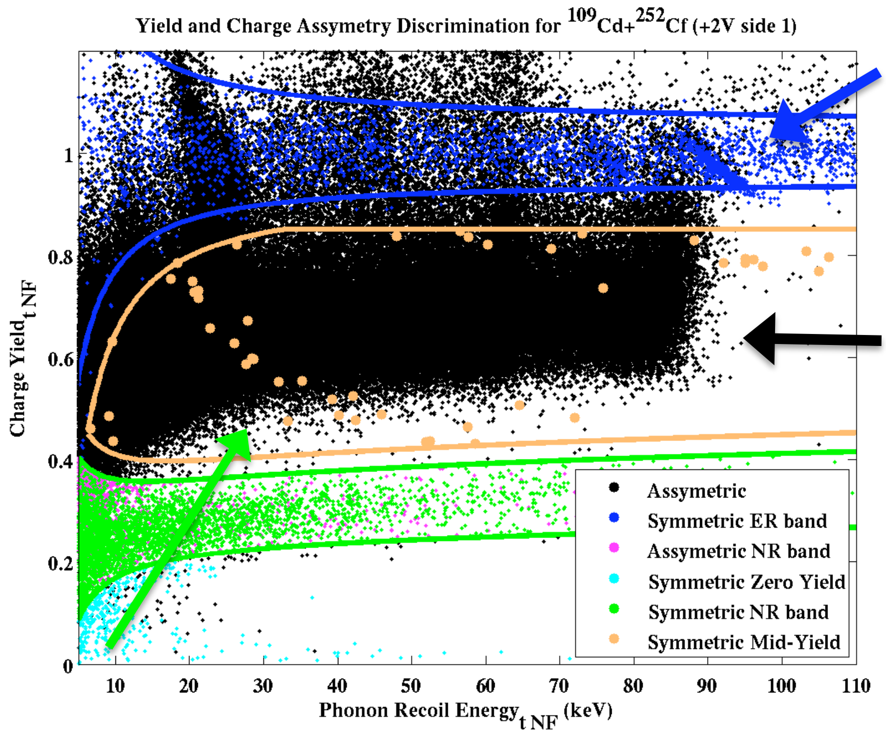
- Require 3D Fiducial Volume Definition
  - Outer charge electrodes separately measured for radial information
  - Complex E-fields produced by interleaving +2V/0V electrodes encode Position Information



Cryogenic Ge detectors for DM experiments Page 13



Electron/Nuclear Discrimination by Yield



Electron Recoils (133Ba)

β ^{109}Cd Internal source

Nuclear Recoils (252Cf source (external)

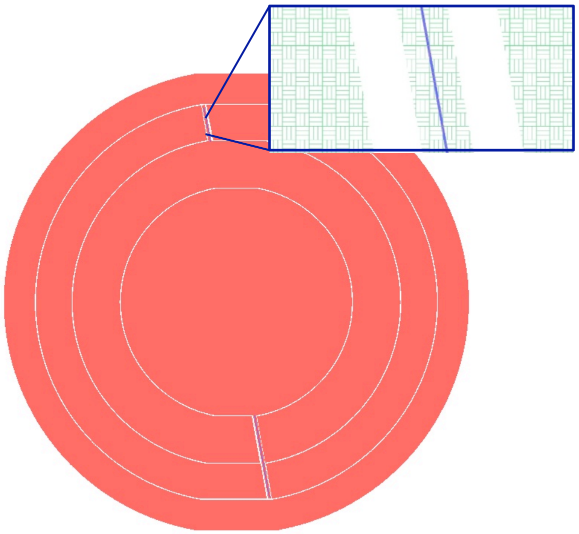
+ 7evt/hr background)

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

•Preliminary surface results -> overly conservative

- ER/NR well separated E > 6 keV$_{ne}$
  - σ_q ~ 300eV$_{ee}$ (measured)
  - σ_p ~ 192eV$_{ee}$ (measured)
  - Long thermal tails from (surface) muons dominate our sensitivity
  - Expect underground σ_p ~ 72eV$_{ee}$ (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

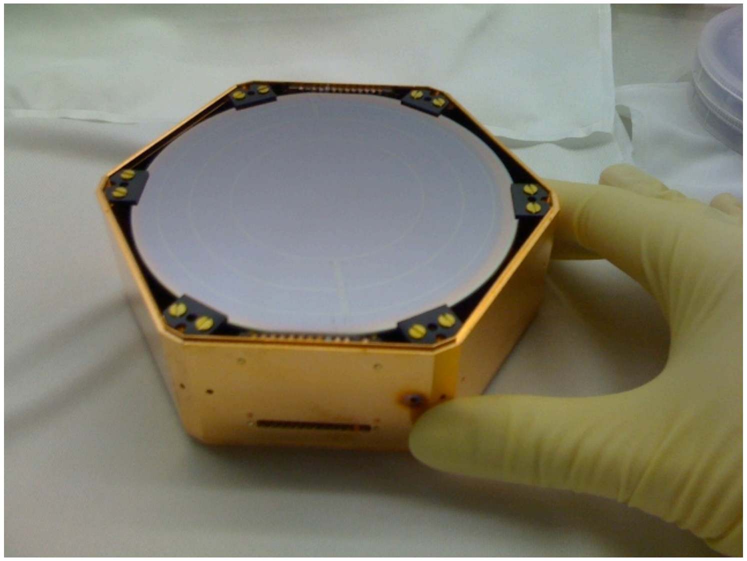


Charge-carrier performance mask (FY10)

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.

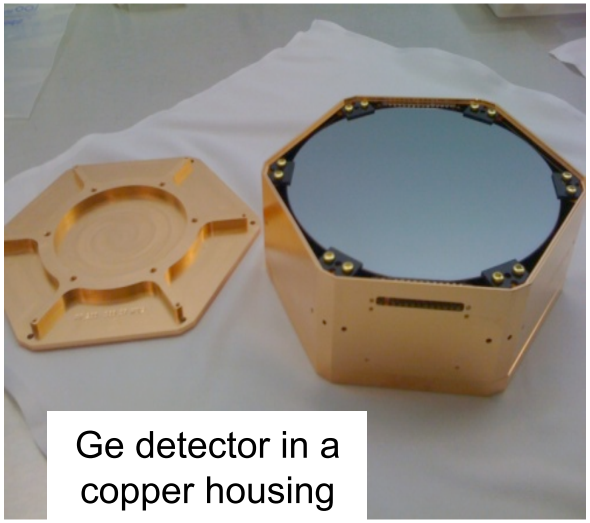


Fabricated Second Ionization detector (FY11)

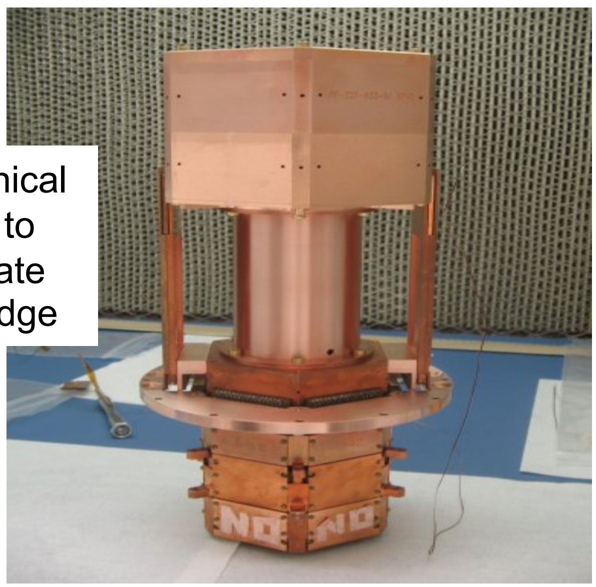
Faster fabrication recipe: more processes conducted in 'parallel' for this double-sided geometry.

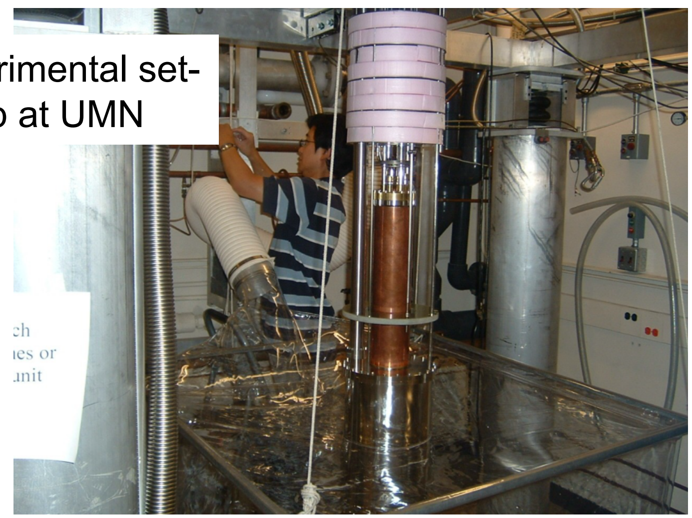
Final 100-mm-diameter-detector recipe will be based upon this double-sided recipe.

First 100 mm diameter Ge Detector

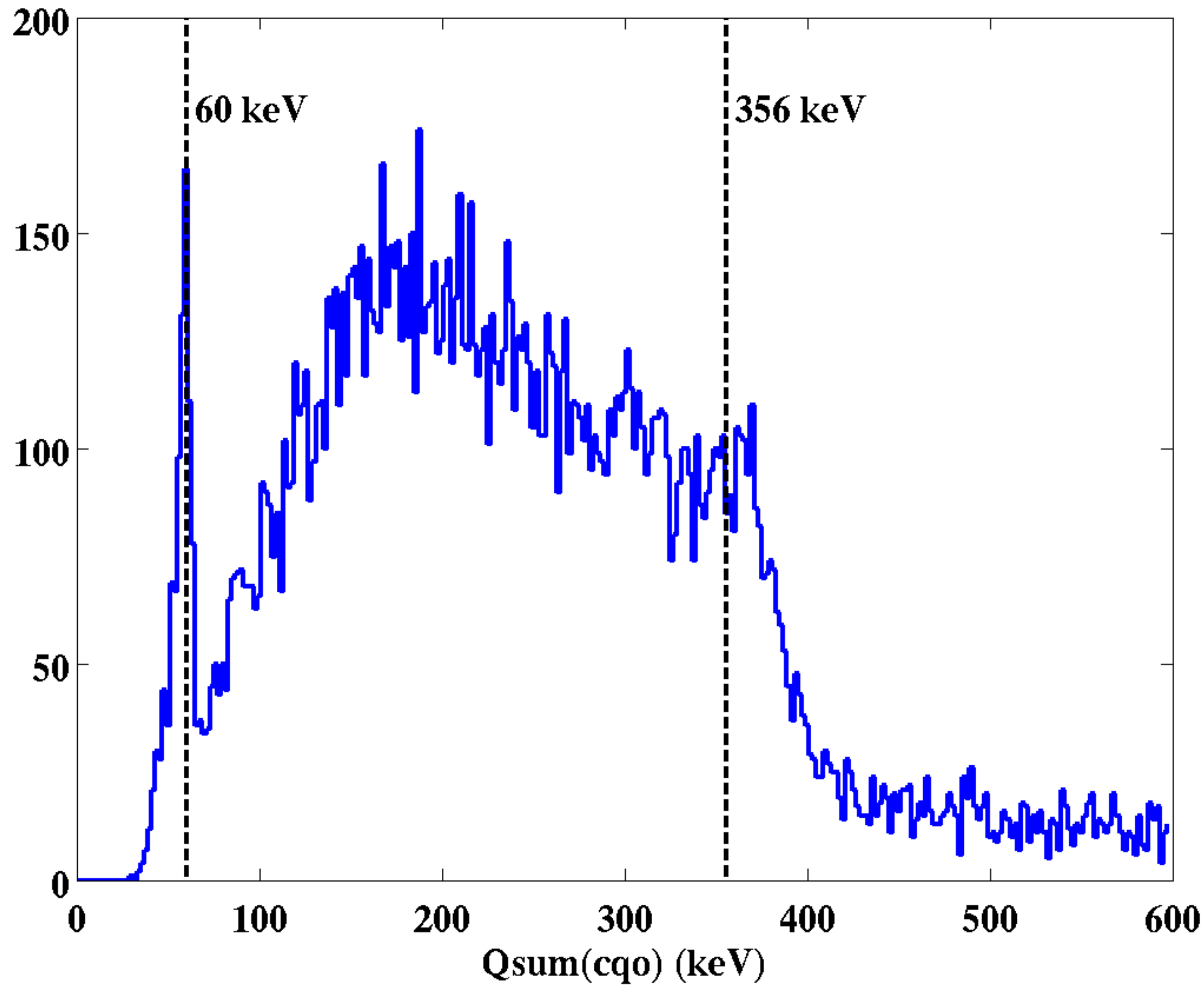

Ge detector in a copper housing

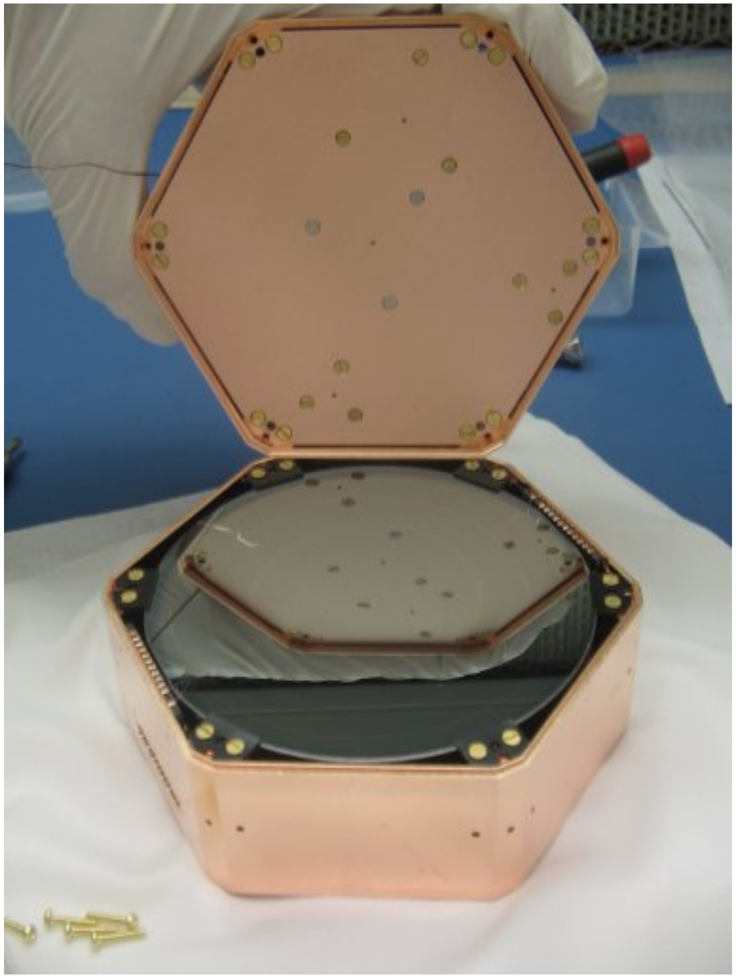

Transportation container


Mechanical parts to integrate with fridge


Experimental set-up at UMN

Energy Spectrum (Am-241, Ba-133)





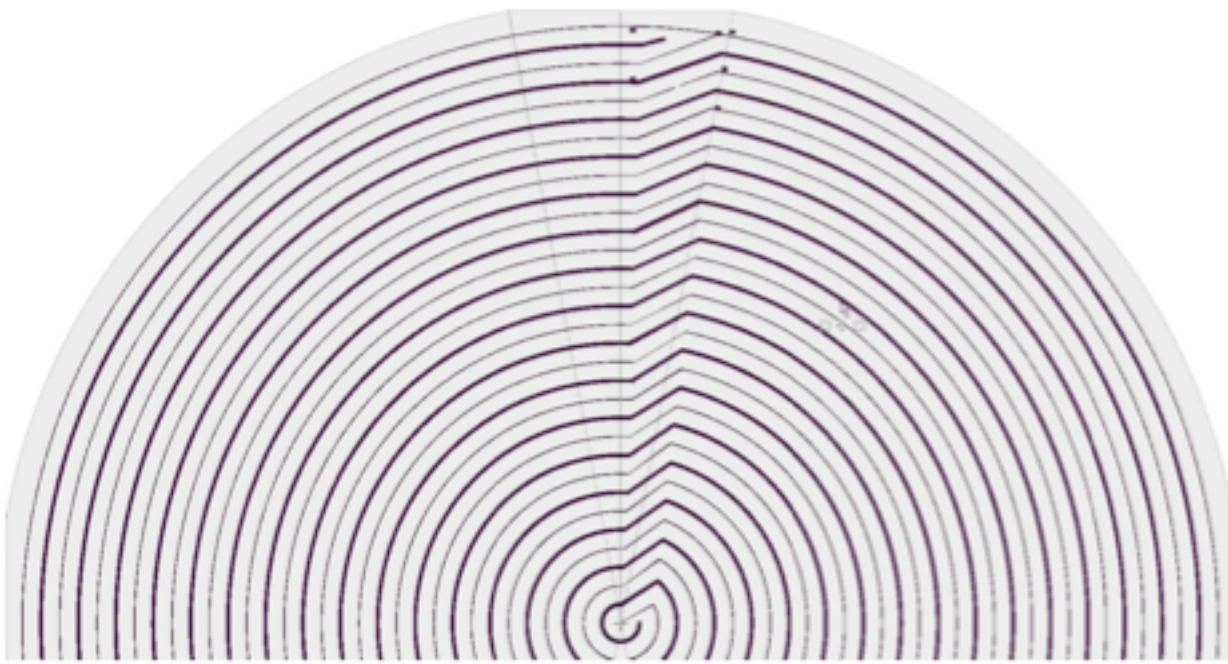
Large detector Electrode configuration

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

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

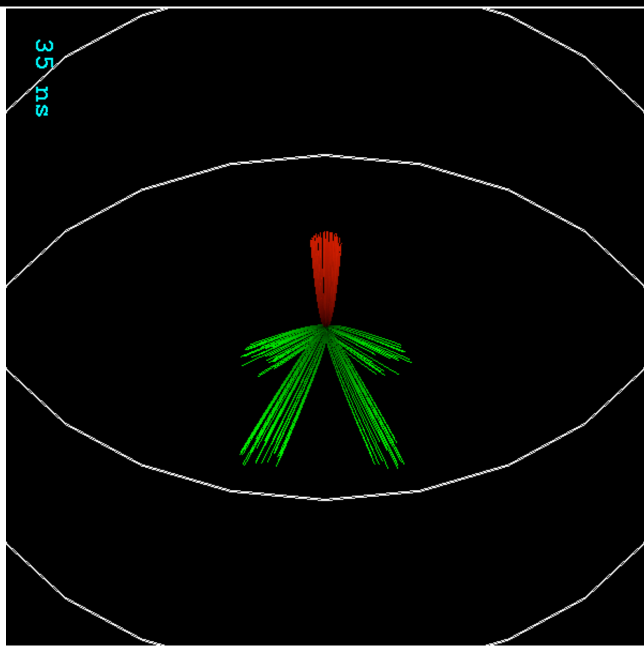
Interleaved electrodes are arranged simply as a spiral. Electrode spacing 1.5 mm.

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

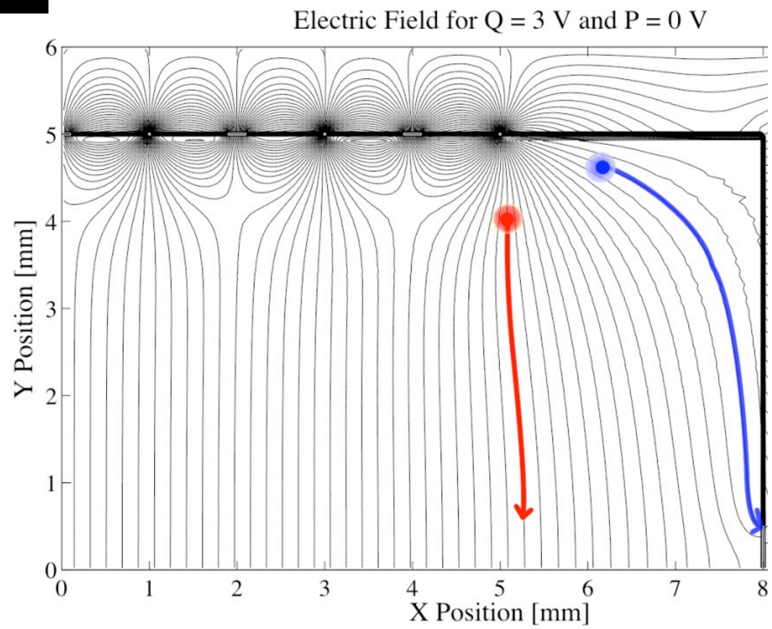


Monte Carlo simulations of charge propagation

Anisotropic propagation in Ge!

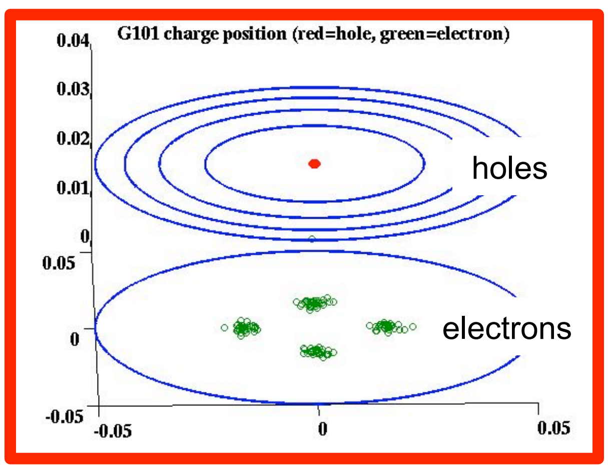


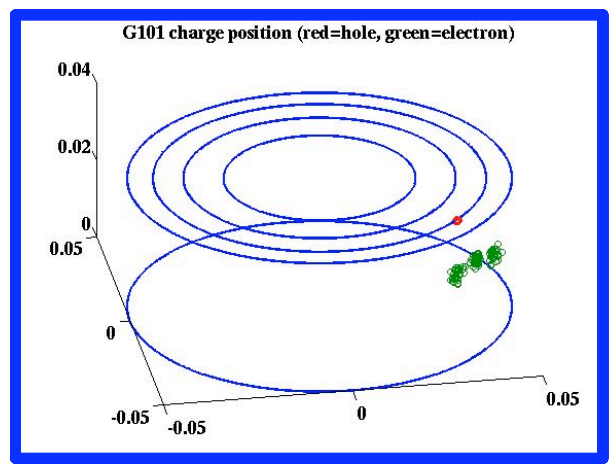
Electric field lines in a detector.



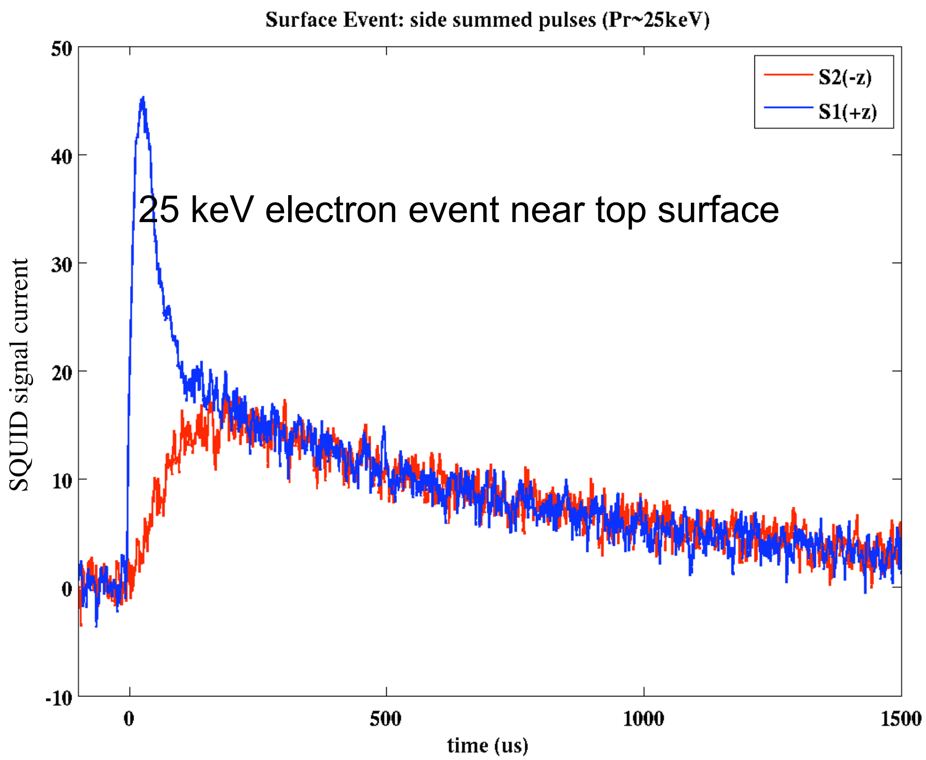
Events deposited on a field line which ends on a side wall have incomplete charge collection.

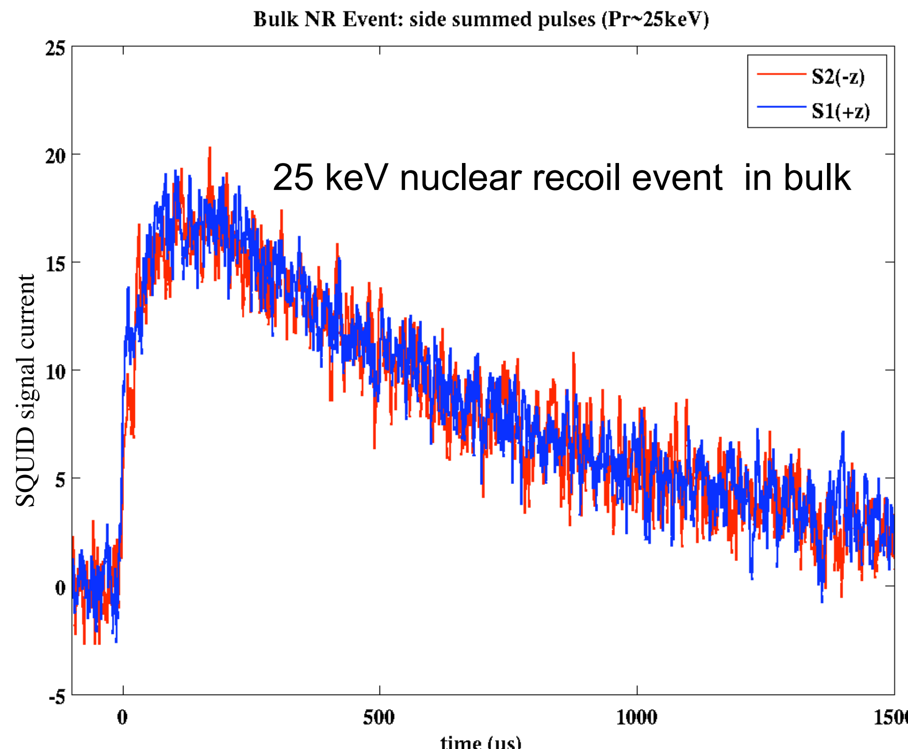
Events deposited on a ‘bulk’ field line have very good charge collection.





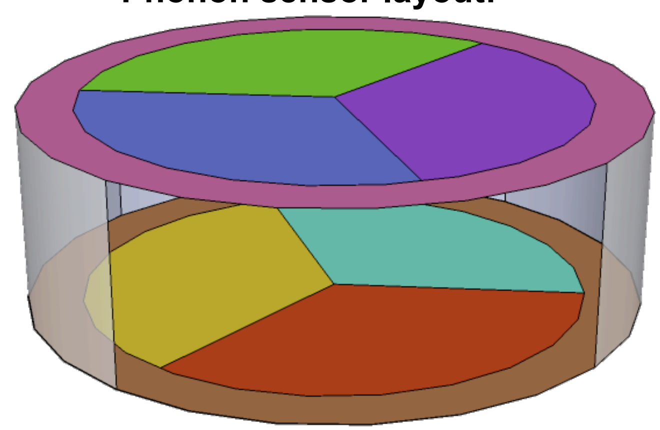
Observed iZIP Phonon Pulse Shape Discrimination





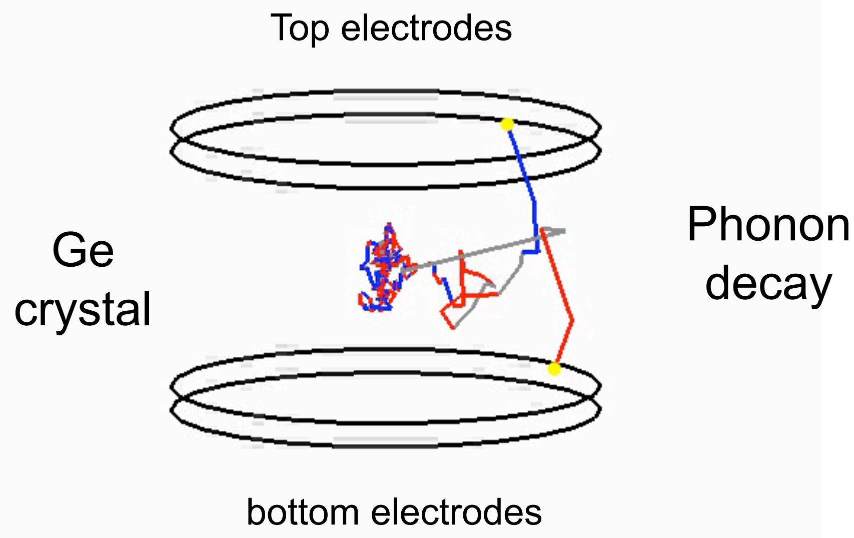
Surface Electron *vs* Nuclear Recoil discrimination seen in operating iZIP detectors in both pulse shape differences and energy partition in z-direction.

Phonon sensor layout:



Geant4 simulations of phonons

SIMULATION



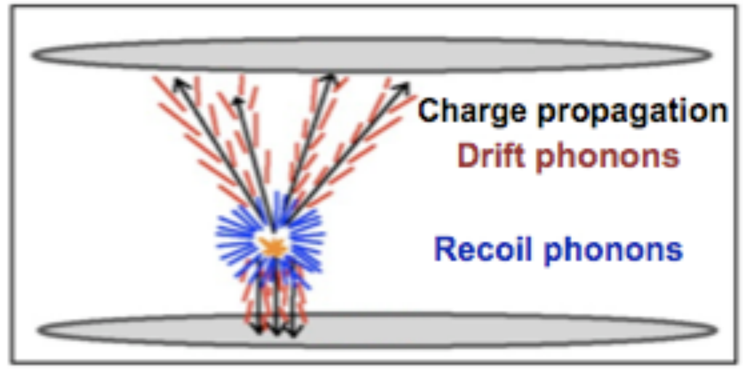
Colors correspond to different phonon polarization states: (Fast Transverse, Slow Transverse, Longitudinal)

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.

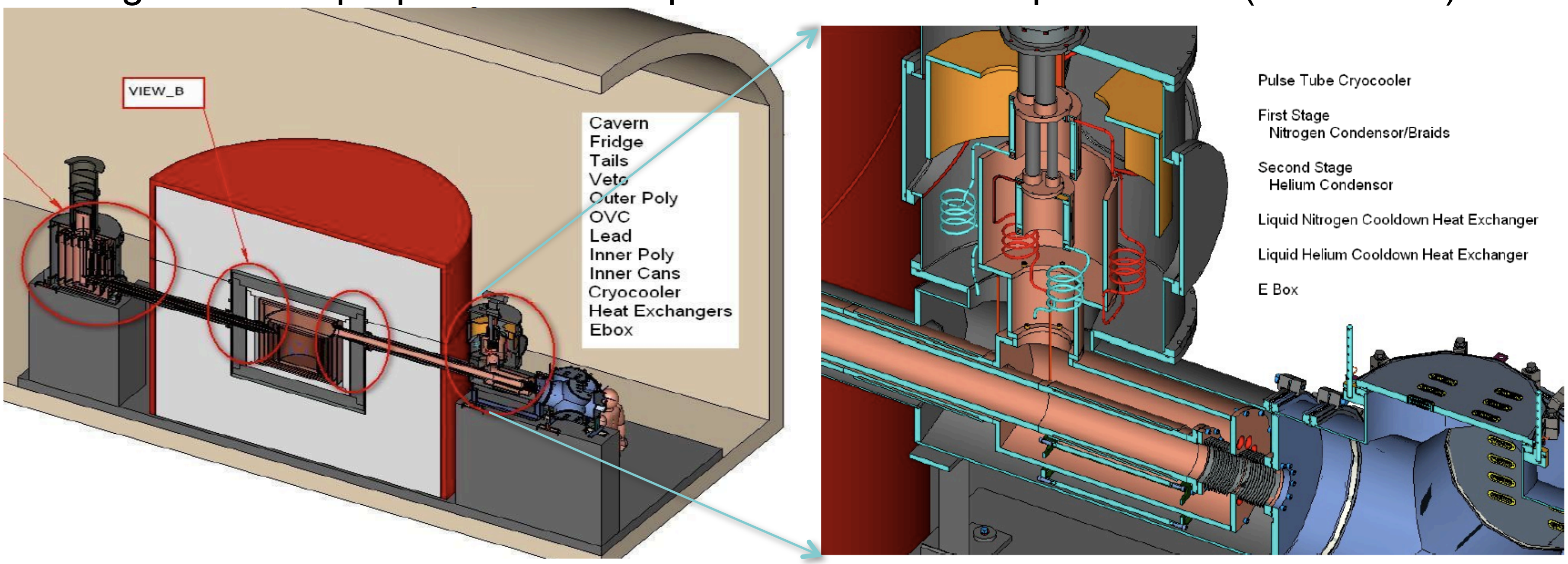


Neganov and Trofimov, Otkryt. Izobret., **146**, 215 (1985)
Luke, J. Appl. Phys., 64, 6858 (1988)

- "CDMS-lite"
  Q bias ~ 30 V
  ⇒ 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)

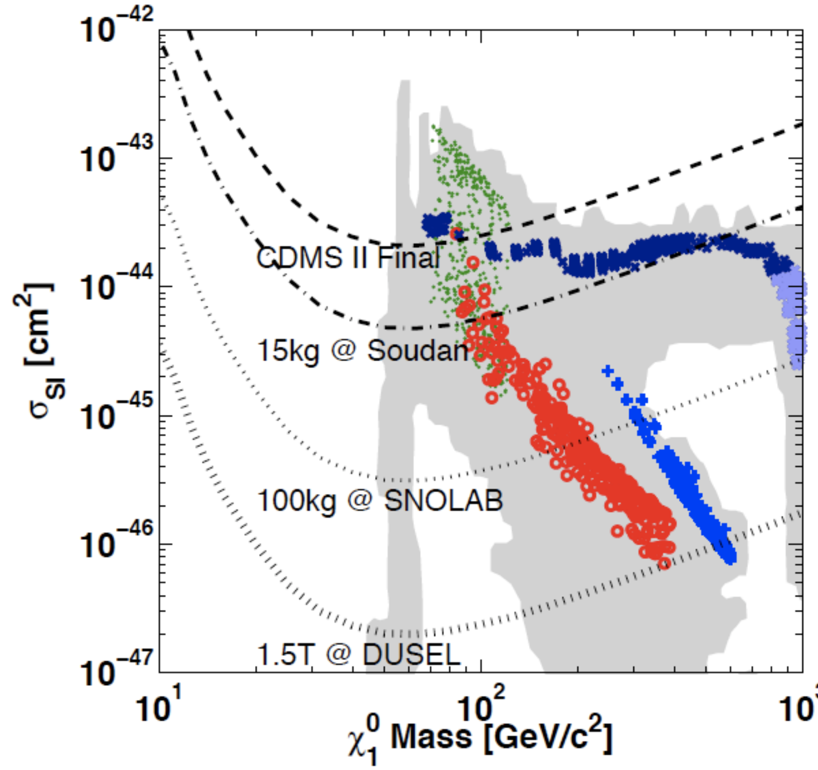


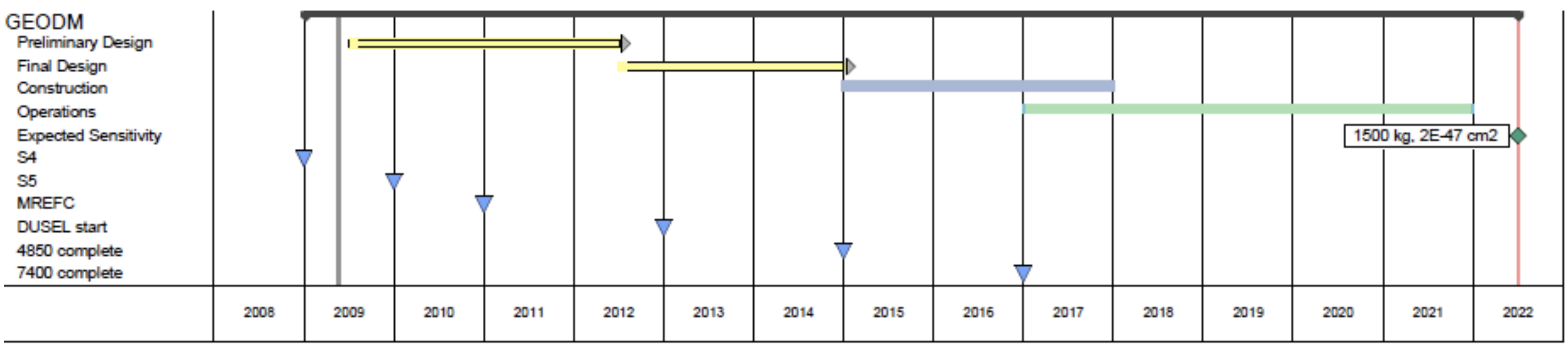
- Need deeper site than Soudan, > 4000 mwe. Need new fridge and shield.
  - New fridge and shield design work in progress at FNAL.
- Select iZIP detector technology ~ 1 kg each.
  - Detector fabrication at Stanford/SLAC (baseline).
  - Direct readout of all electrical channels, similar to CDMS II.

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.