The Germanium Observatory for Dark Matter (GEODM)

Sunil Golwala

Caltech

DUSEL Lead Workshop

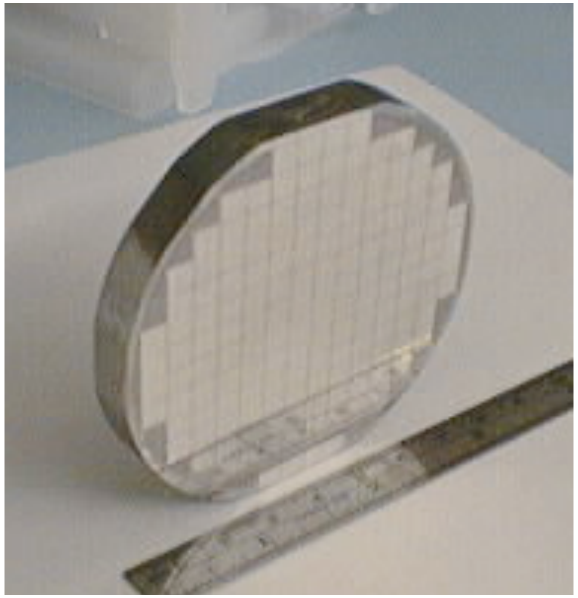
Oct 2, 2009

Outline

- Cryogenic Dark Matter Search (CDMS) II summary
- From CDMS II to SuperCDMS and GEODM
  - Backgrounds
  - Background rejection
  - Detector fab/test costs and timescales
  - Status/Timeline

The GEODM Collaboration

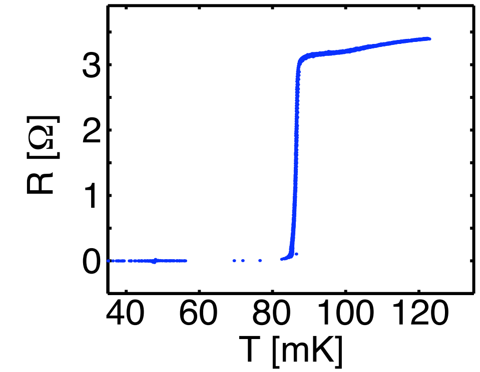
Caltech: S. R. Golwala
Fermilab: D. A. Bauer, R. Schmitt
MIT: E. Figueroa-Feliciano
NIST: K. Irwin
Queens University: W. Rau, P. di Stefano
Santa Clara University: B. A. Young
SLAC National Accelerator Lab: E. do Couto e Silva, J. Weisand
Southern Methodist University: J. Cooley
Stanford University: P.L. Brink, B. Cabrera, S. Yellin
St. Olaf College: A. Reisetter
Syracuse University: R.W. Schnee
Texas A&M: R. Mahapatra, M. Platt
University of California, Berkeley: N. Mirabolfathi, B. Sadoulet, D. Seitz
University of Colorado at Denver: M. E. Huber
University of Florida: T. Saab
University of Minnesota: P. Cushman, V. Mandic

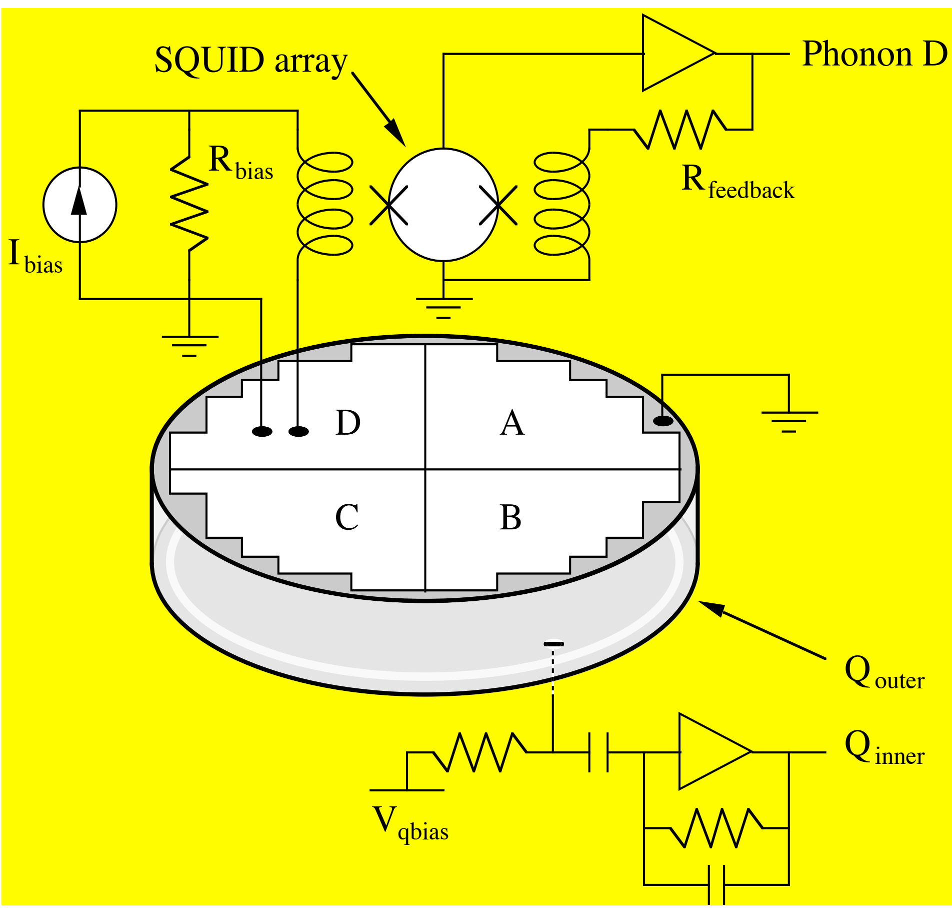


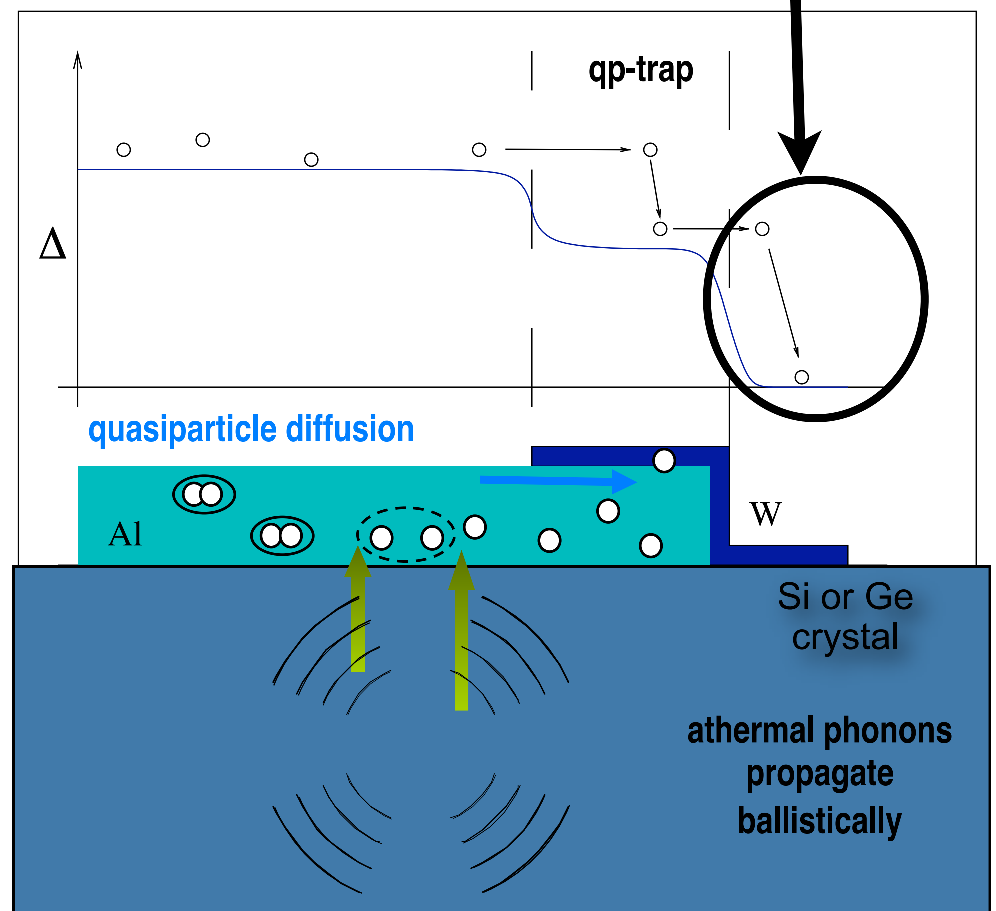
CDMS ZIP Detectors

Z-sensitive Ionization- and Phonon-mediated detectors: Phonon signal measured using photolithographed superconducting phonon absorbers and transition-edge sensors.

TES = transition edge sensor







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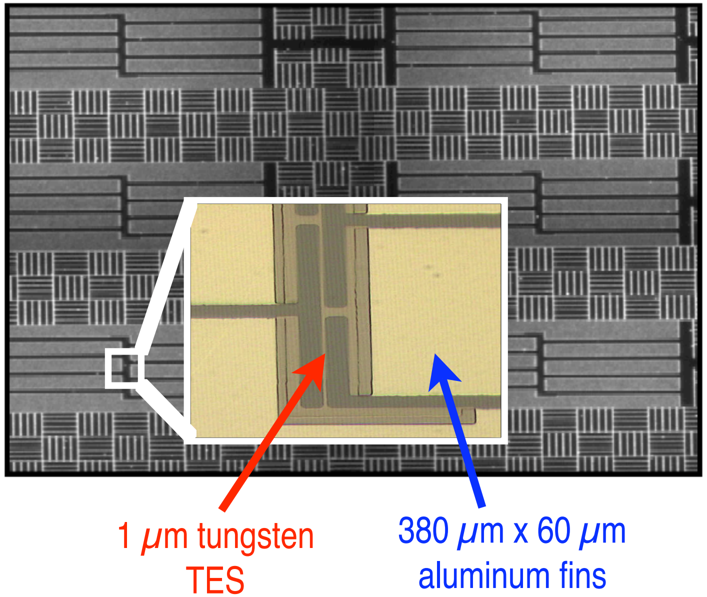

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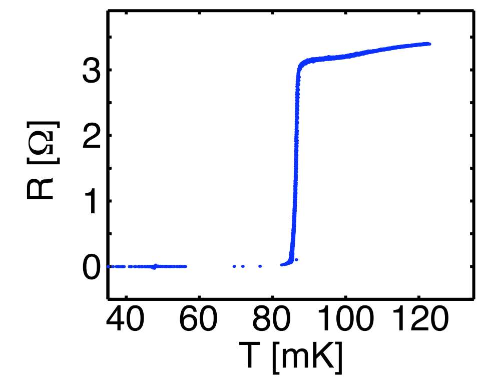

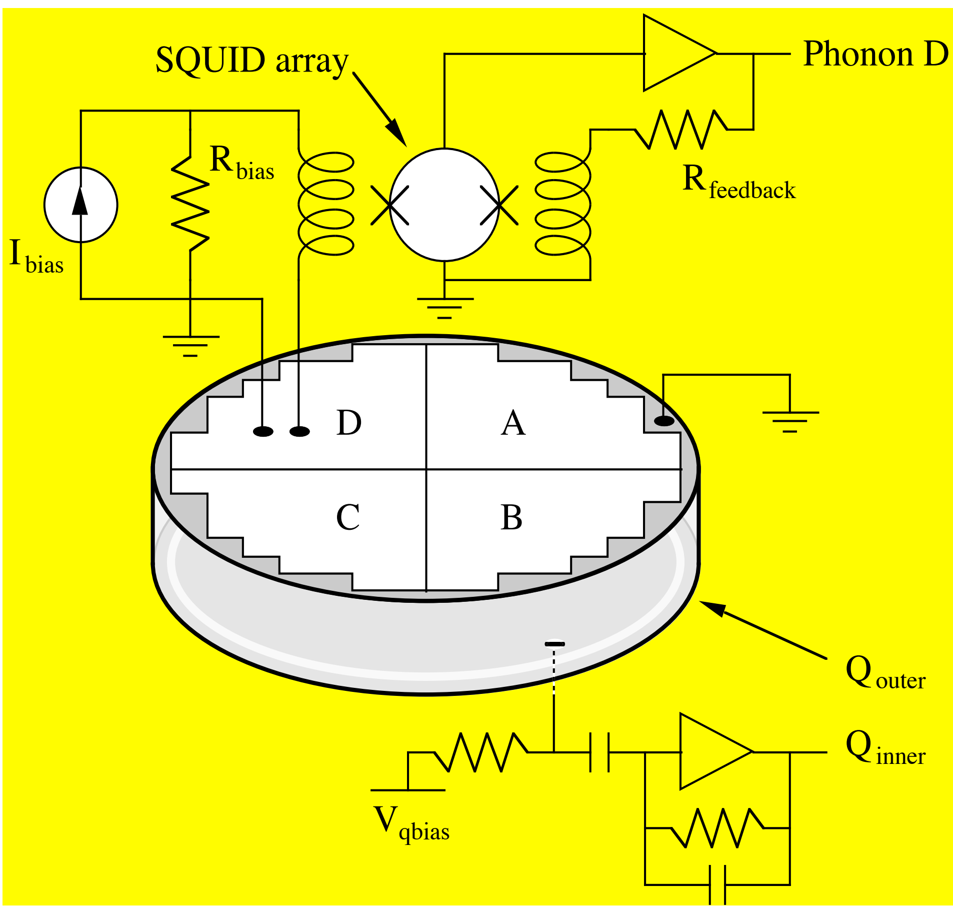

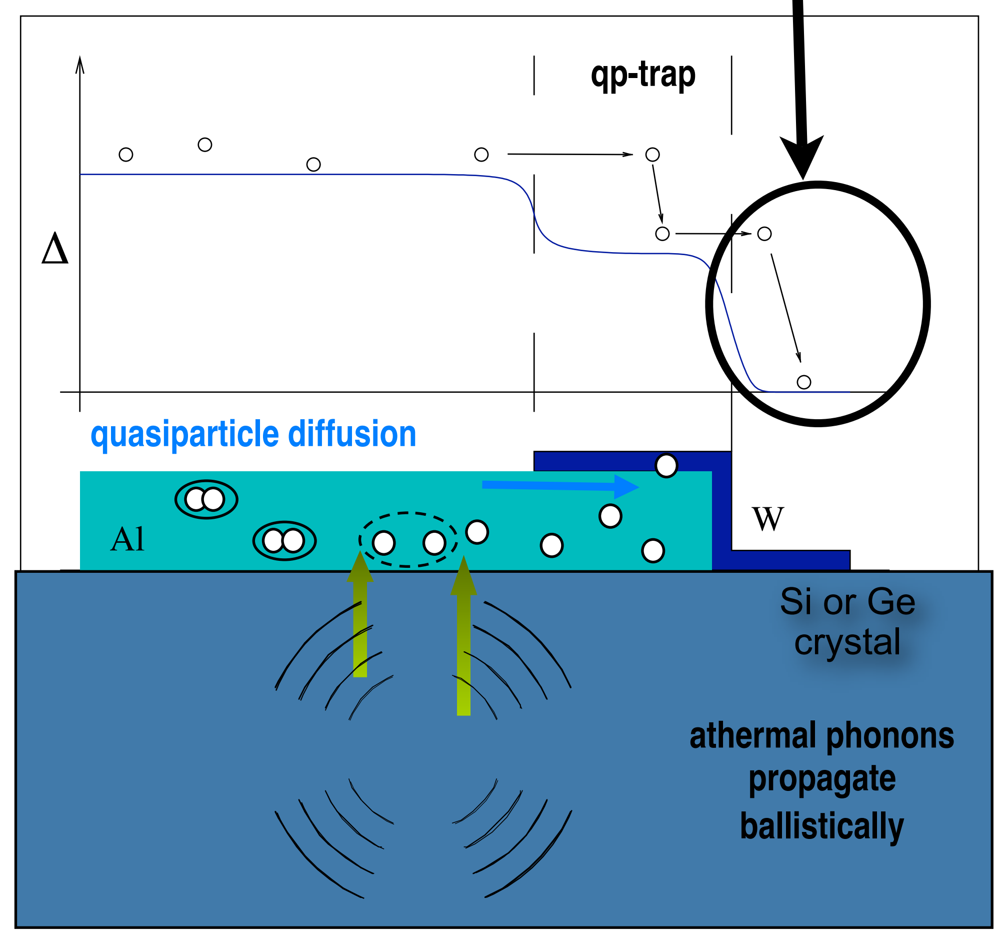

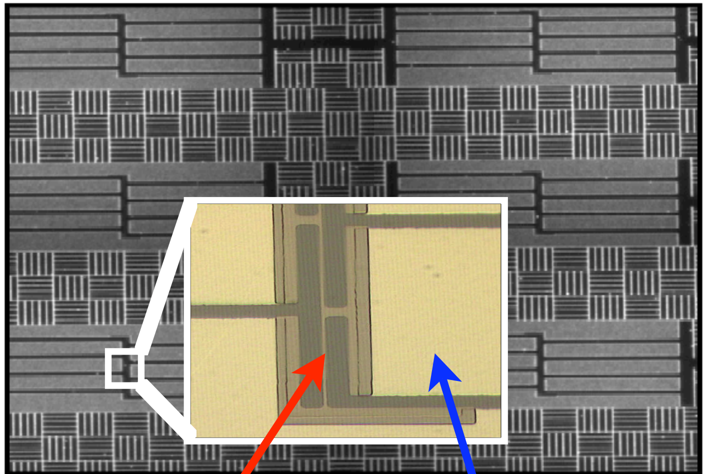

CDMS ZIP Detectors

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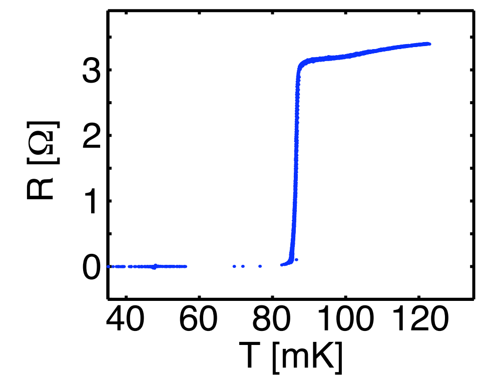

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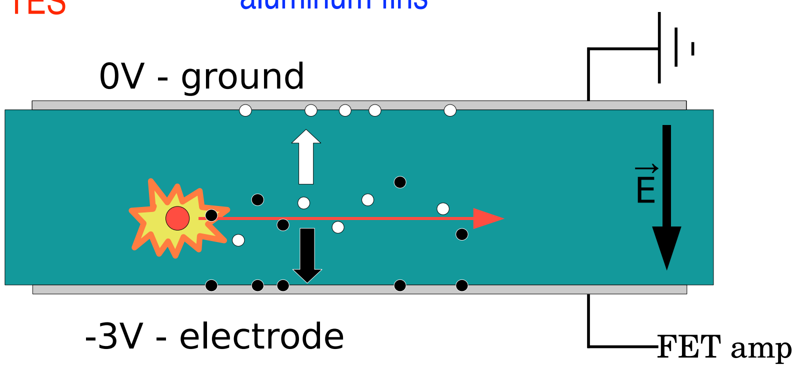
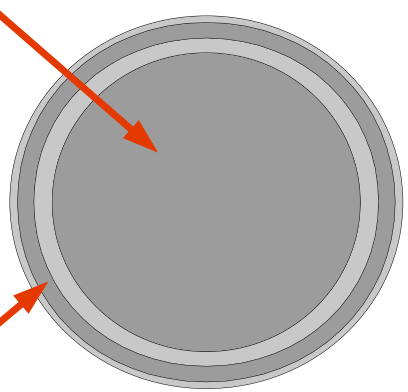
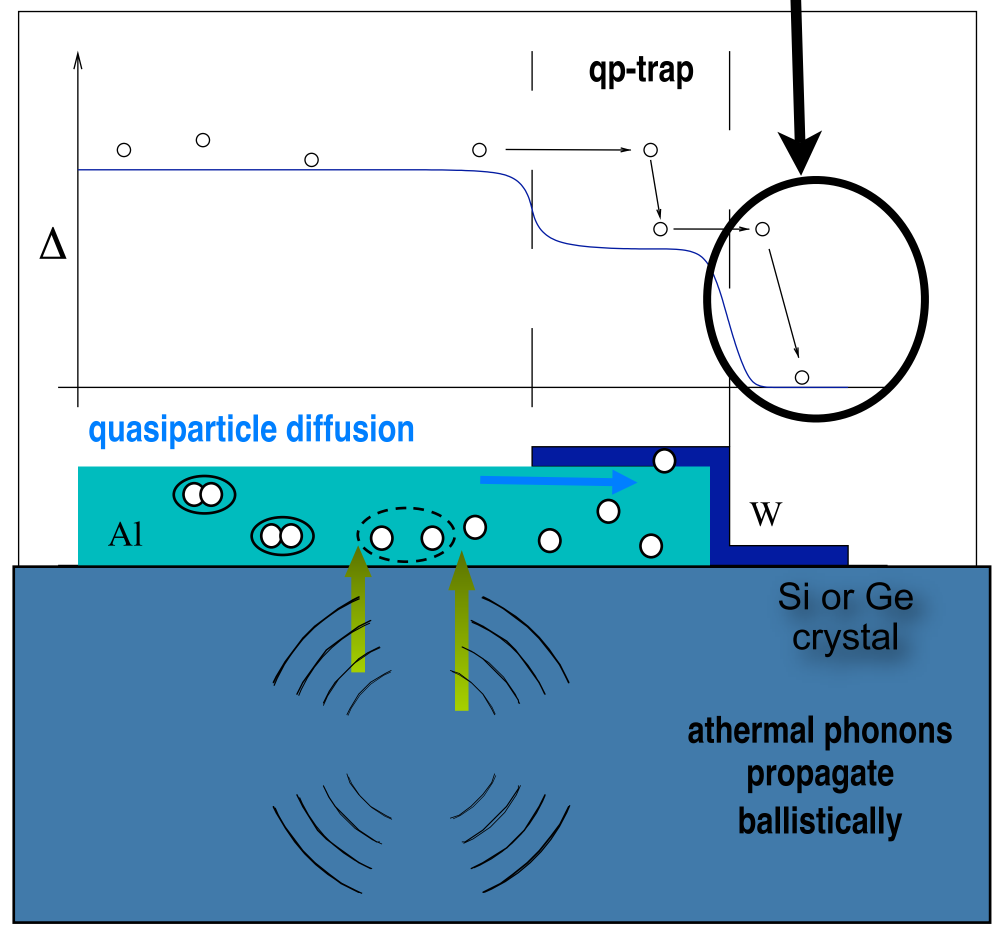
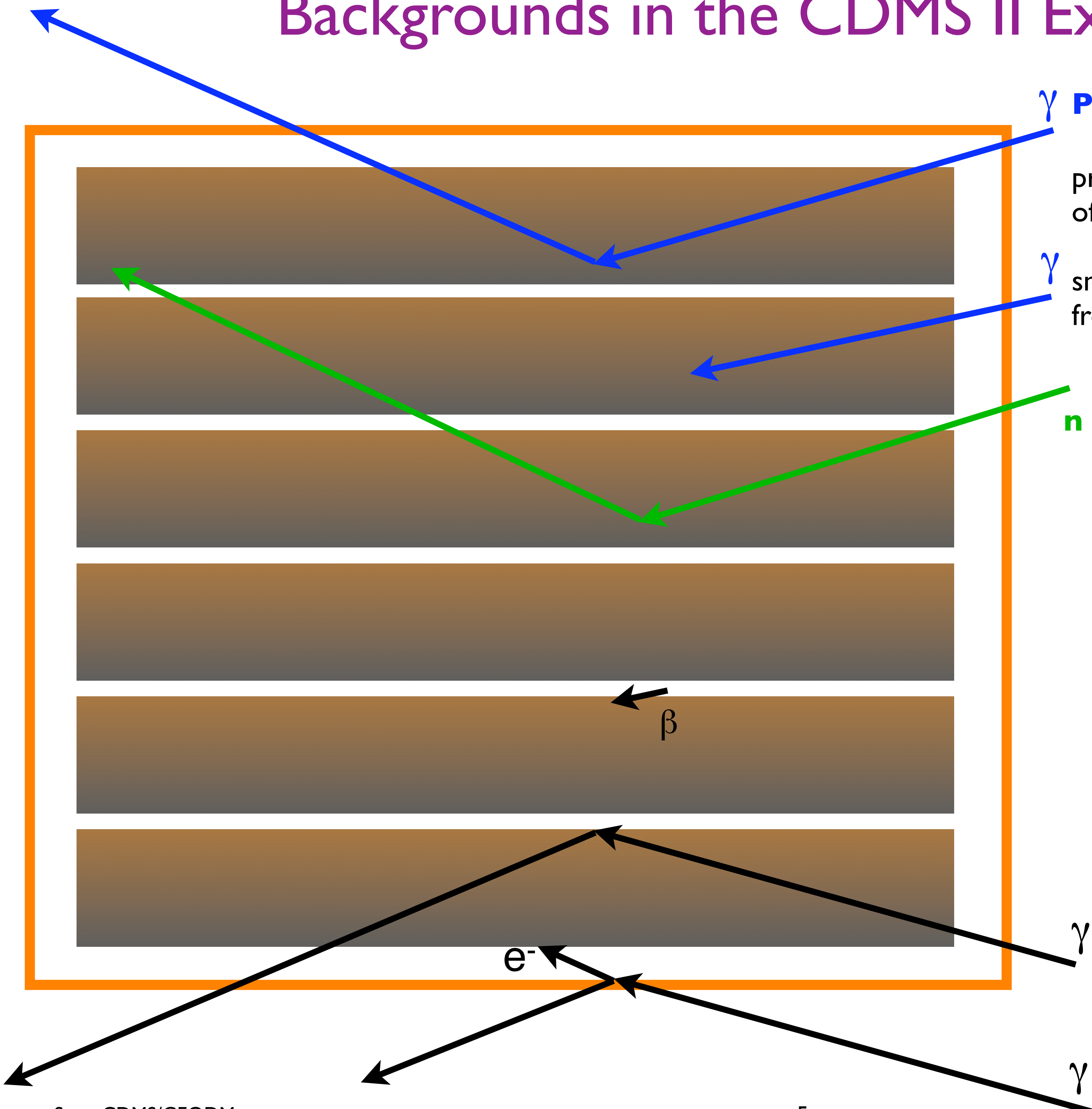






Backgrounds in the CDMS II Experiment



Photons (γ)

primarily Compton scattering of broad spectrum up to 2.5 MeV

small amount of photoelectric effect from low energy gammas

Neutrons (n)

radiogenic: arising from fission and (α,n) reactions in surrounding materials (cryostat, shield, cavern)

cosmogenic: created by spallation of nuclei in surrounding materials by high-energy cosmic ray muons.

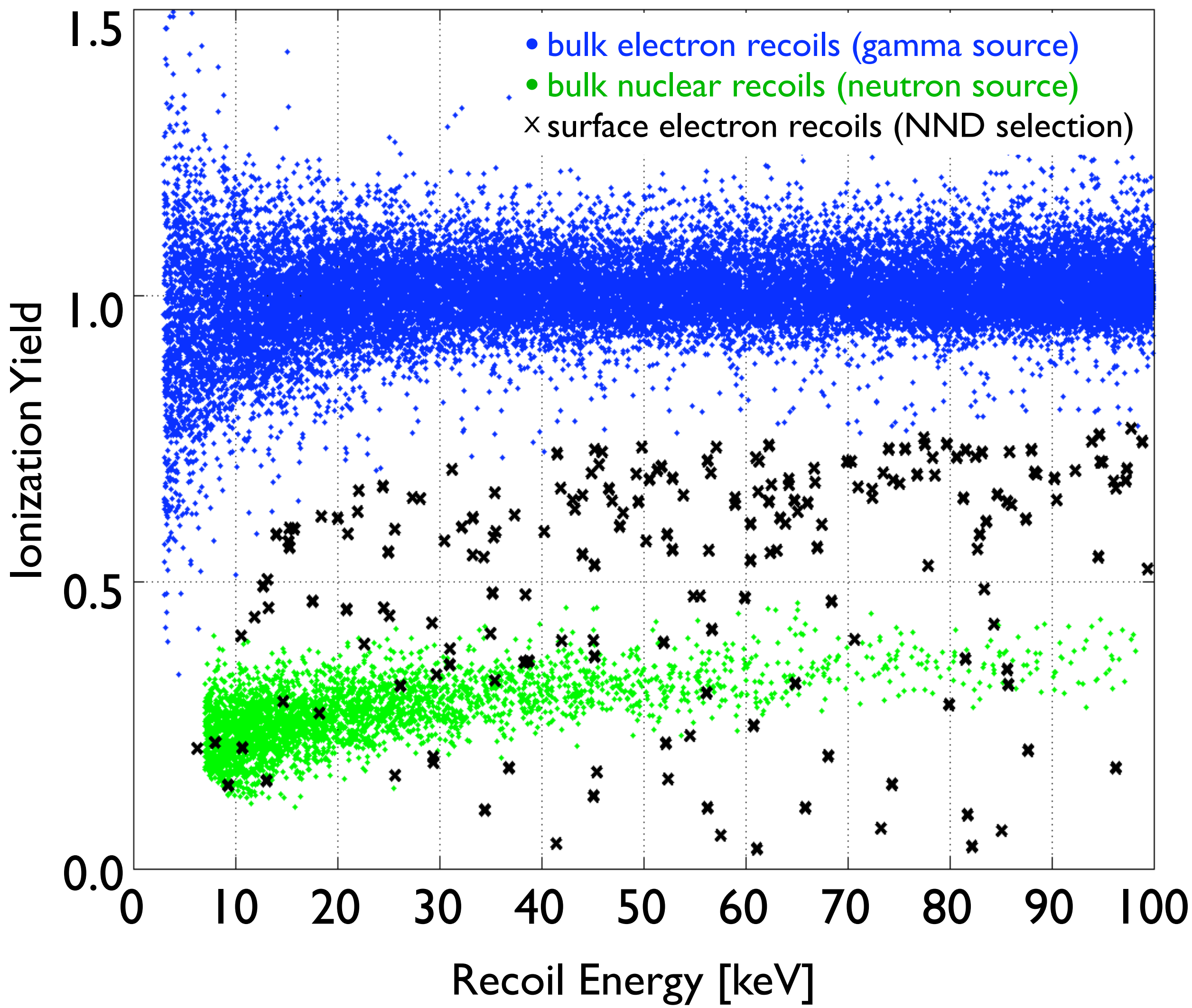
Surface events ("β")

radiogenic: electrons/photons emitted in low-energy beta decays of ^{210}Pb or other surface contaminants

photon-induced: interactions of photons or photo-ejected electrons in dead layer

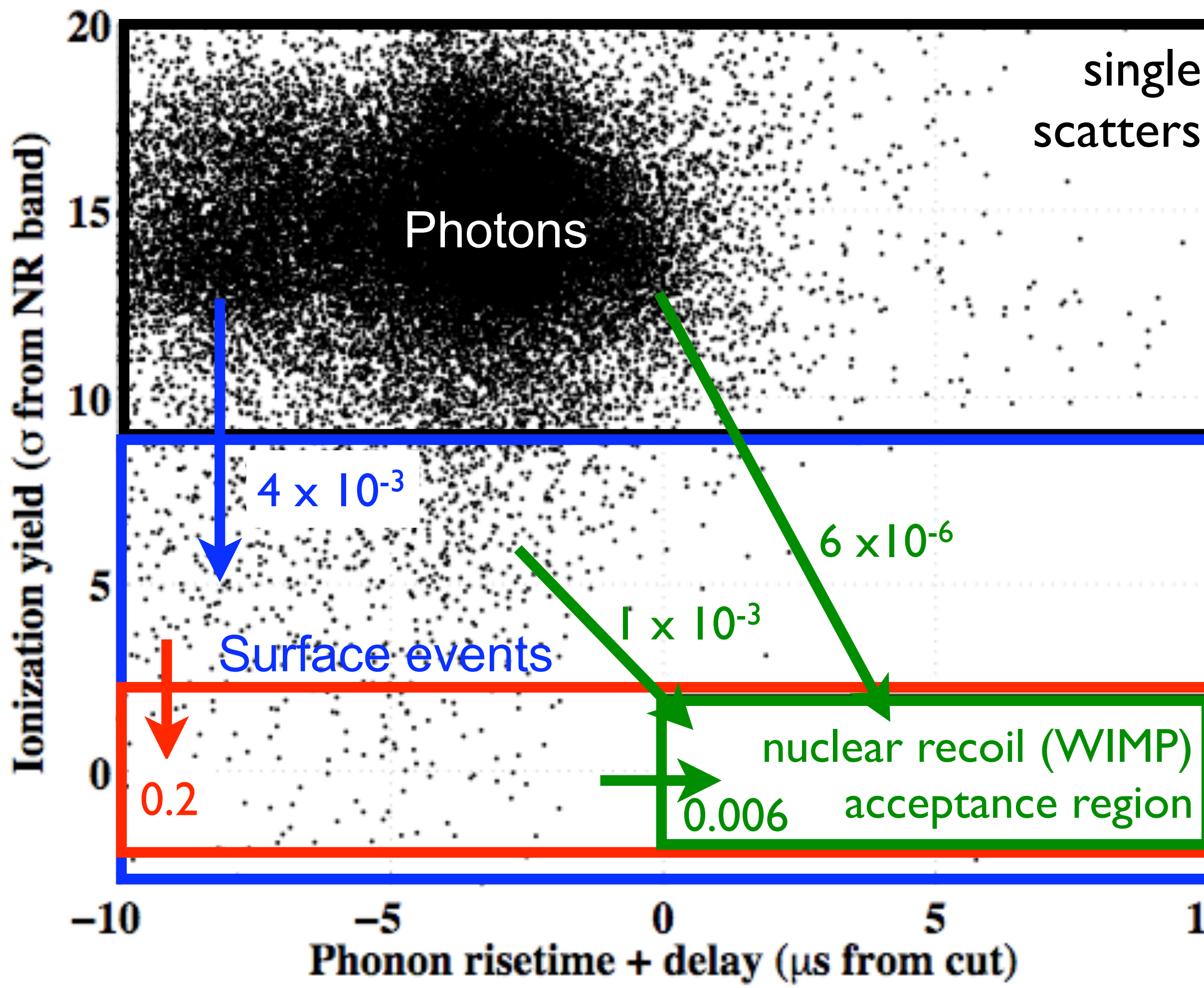
CDMS II Background Discrimination

- Recoil energy
  - Phonon (acoustic vibrations, heat) measurements give full recoil energy
- Ionization yield
  - ionization/recoil energy strongly dependent on type of recoil (Lindhard)
- Primary discrimination against photon bgnd by ionization yield



CDMS II Background Discrimination

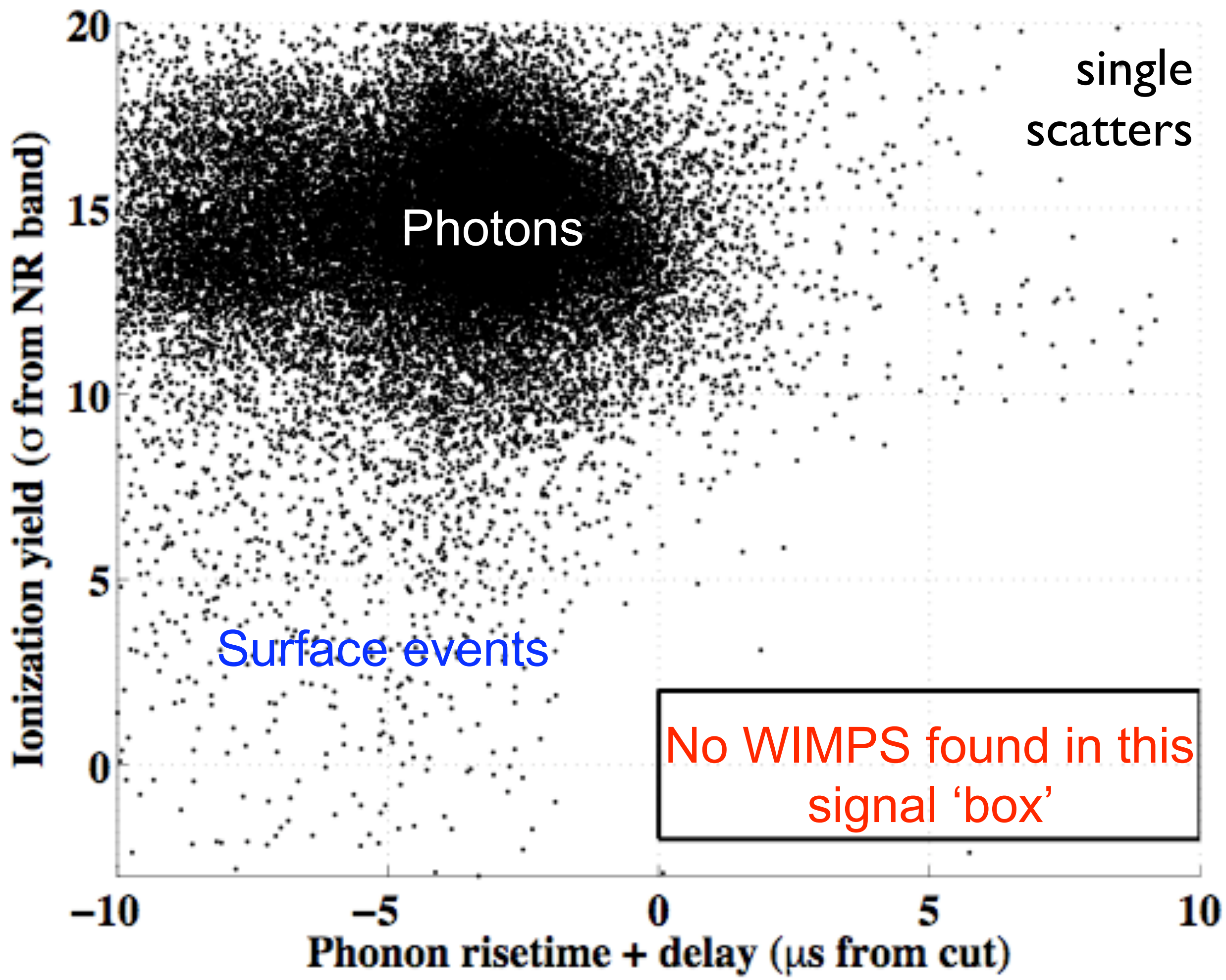
- Photon rejection
  - Bulk photon rate (bulk ER) = 300/kg/day. Single-scatters = 90/kg/day
  - Single-scatter surface ERs = 0.3/kg/day
  - Surface ER singles/ bulk ER singles = 4 x 10^{-3}
  - Surface ER singles misid'd as nuclear recoils (NRs) /surface ER singles = 0.2 (ionization dead layer)
  - Phonon timing rejects surface events: 0.006 misid. prob.
  - Overall misid probability: 2 x 10^{-6} for bulk ER, 6 x 10^{-6} for single-scatter bulk ER



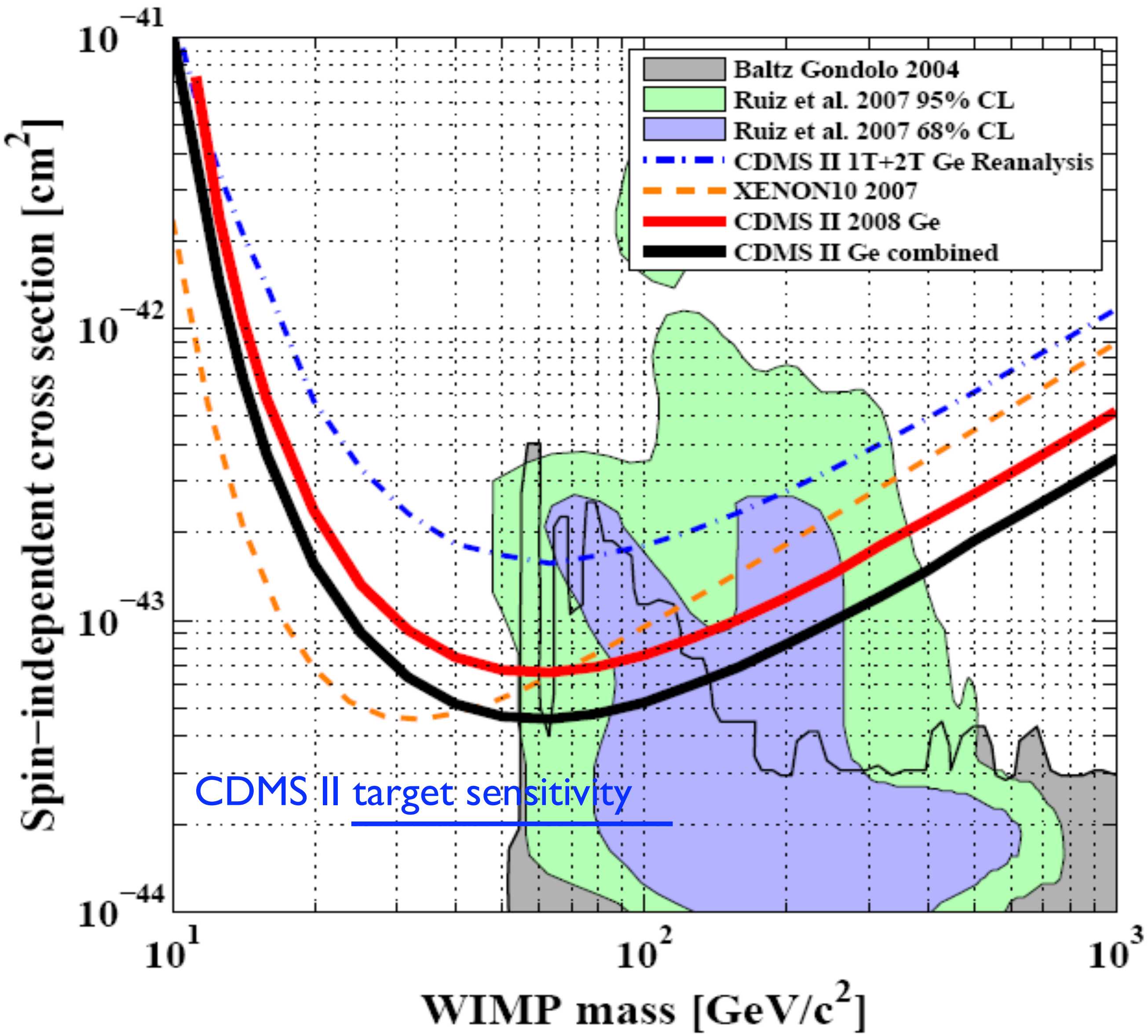
- Beta rejection
  - Comparable single-scatter ER rate of low-energy beta emitters (mainly ^{210}Pb)
  - 0.2 misid by yield and 0.006 misid by timing: 1 x 10^{-3} misid probability

CDMS II 2008 Results

- 398 kg-d raw exposure (4 kg Ge at Soudan mine, 2000 mwe, 10/06-7/07)
- Single-scatter events
- Estimated leakage of misid'd surface events based on
  - photon cal data
  - WIMP-search multiples
  - Cuts defined to obtain ~0.5 misid'd events: optimal balance of efficiency and leakage
- Expect 0.6 +0.5-0.3 (stat) +0.03-0.02 (syst) misid'd surface events
- Expect < 0.1 unvetoed single-scatter neutrons (conservative)
- **0 events observed**



Spin-Independent Exclusion Limit



- Zero events observed
- Including reanalysis of prior data set, obtain best spin-independent limit for M > 40 GeV/c^2; published in PRL, Filippini thesis
- 2.5X exposure in hand and being analyzed
  - many analysis improvements
  - should reach CDMS II target sensitivity of 2×10^{-44} cm^2

From CDMS II to SuperCDMS and GEODM

CDMS II (2008)

∅7.5cm x 1cm ZIP
0.25 kg/detector

16 detectors = **4 kg**
2 yr, 1700 kg-d

SuperCDMS Soudan (2012)

∅7.5cm x 2.5cm mZIP
0.64 kg/detector

25 detectors = **15 kg**
2 yr, 8000 kg-d

SuperCDMS SNOLAB (2016)

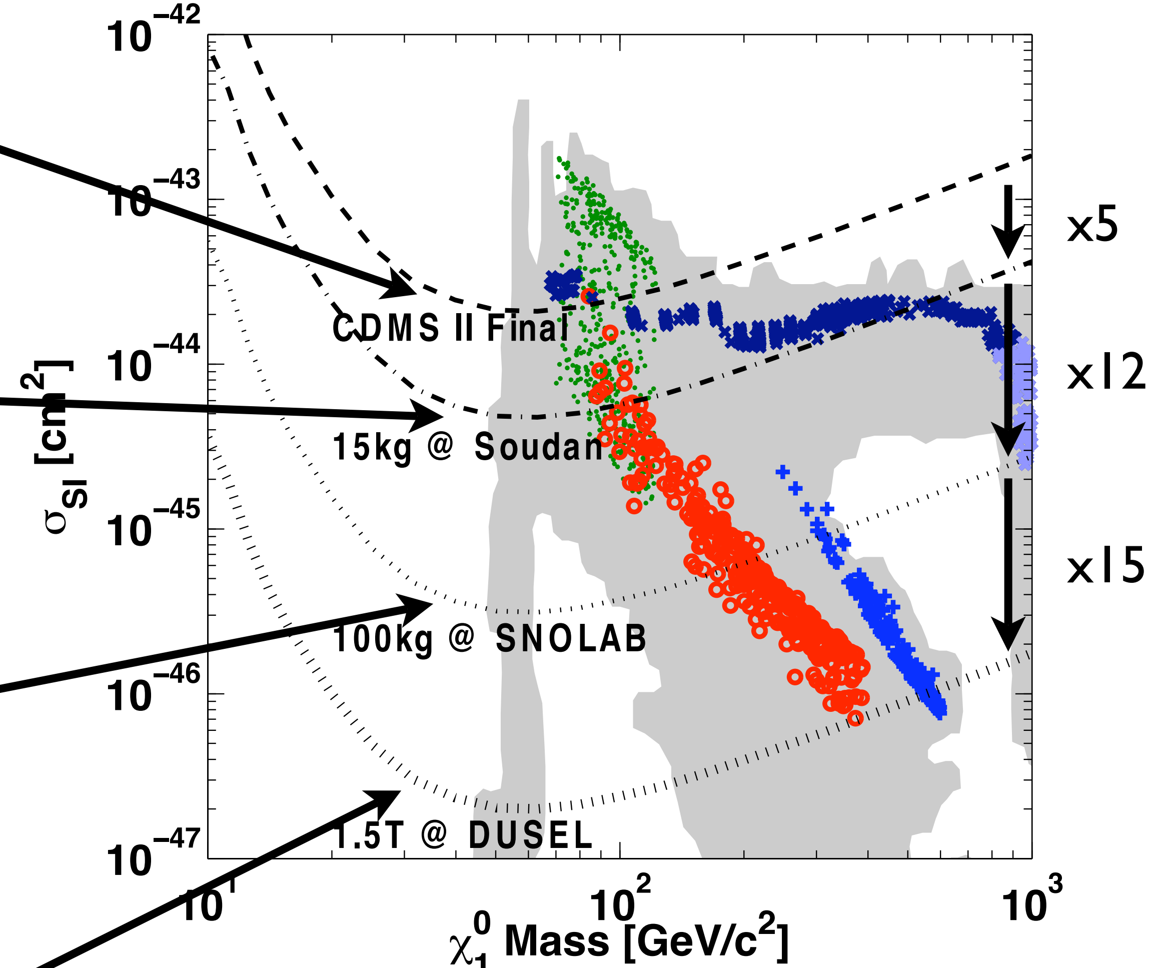
∅10cm x 3.5cm iZIP
1.5 kg/detector

70 detectors = **105 kg**
3 yr = 100,000 kg-d

GEODM DUSEL (2021)

∅15cm x 5cm iZIP
5.1 kg/detector

300 detectors = **1.5 T**
4 yr, 1.5 M kg-d



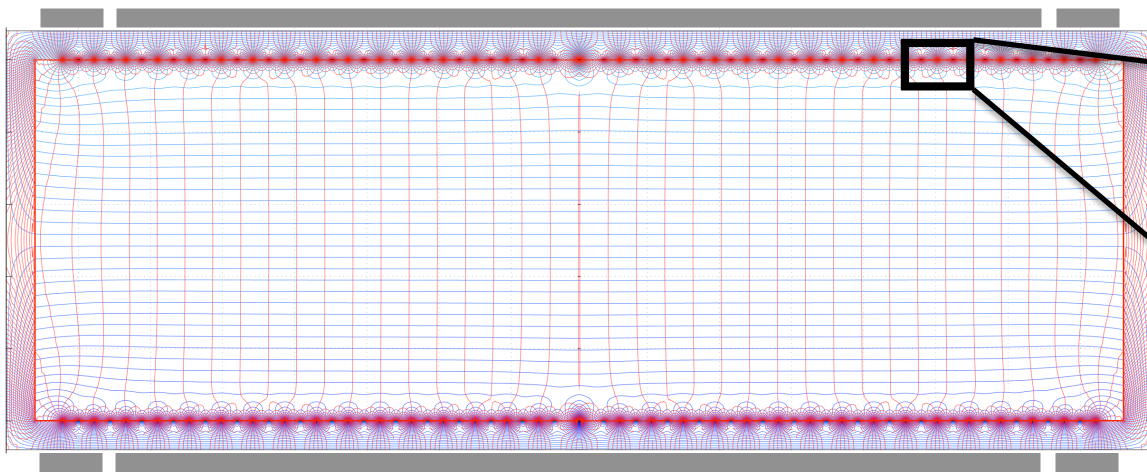
Staged three-prong program to explore MSSM or study a signal:

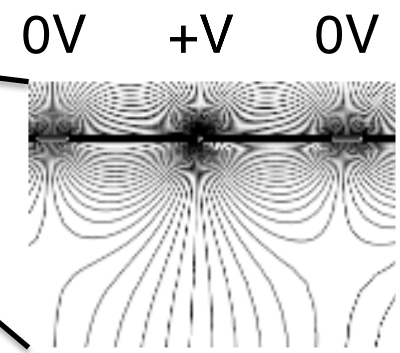
- (mildly) decreased backgrounds
- (vastly) improved background rejection
- increase in mass/detector and decrease in cost/detector

< 1 event misid'd bgnd at each stage

Improving Background Rejection

- Interdigitated ZIP (iZIP) design meets needs for SuperCDMS SNOLAB and GEODM

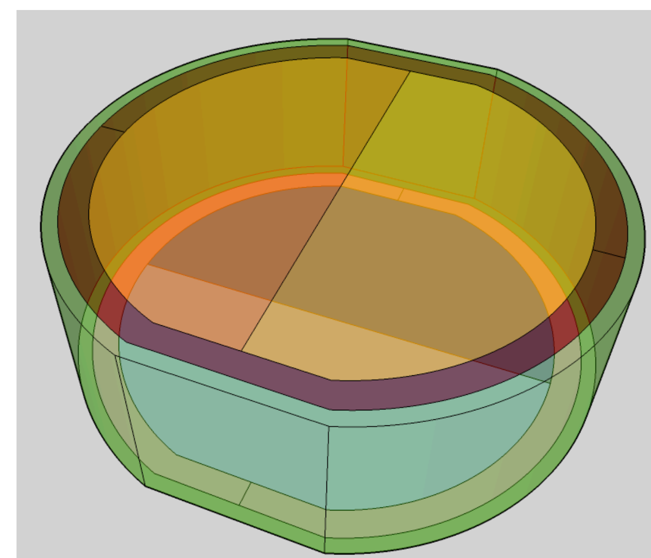




negative version on other face

Edelweiss proved low field regions not a problem

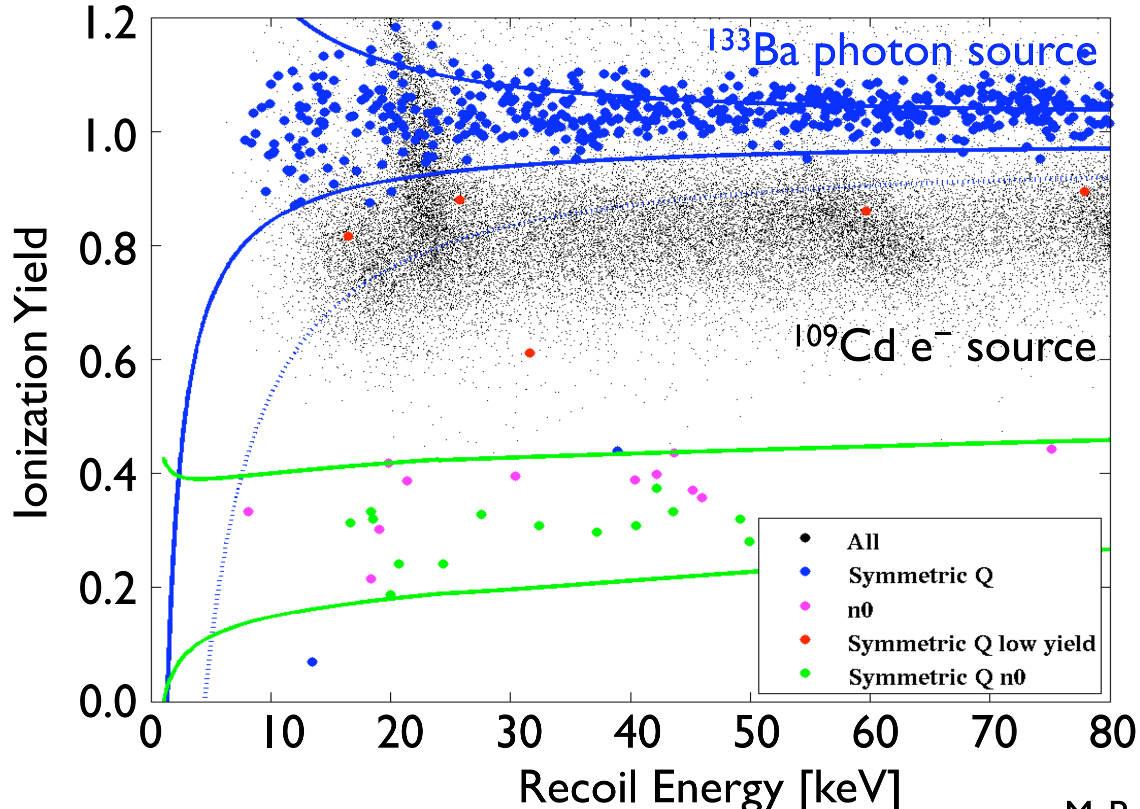
M. Pyle



- Interleaved ionization electrodes cause ionization to partition differently for surface and bulk events
- High field near surface increases ionization yield for surface events
- Top/bottom phonon sensors (ground rails) provide simpler, more direct z information

Improving Background Rejection

- Interdigitated ZIP (iZIP) design appears to meet needs of SuperCDMS SNOLAB and GEODM
  - High field at surfaces increases ionization yield: 0.2 misid → < 3 x 10^{-4} misid
  - Surface events share charge differently than bulk events: < 10^{-3} misid
  - Phonon partition and timing z position: < 10^{-3} misid



M. Pyle, B. Serfass

- All measurements limited by neutron background in surface test facilities
- Ionization yield and Q/P asymmetry likely uncorrelated; if true, then overall misid 10^{-4} → < 3 x 10^{-7}, far better than needed for GEODM

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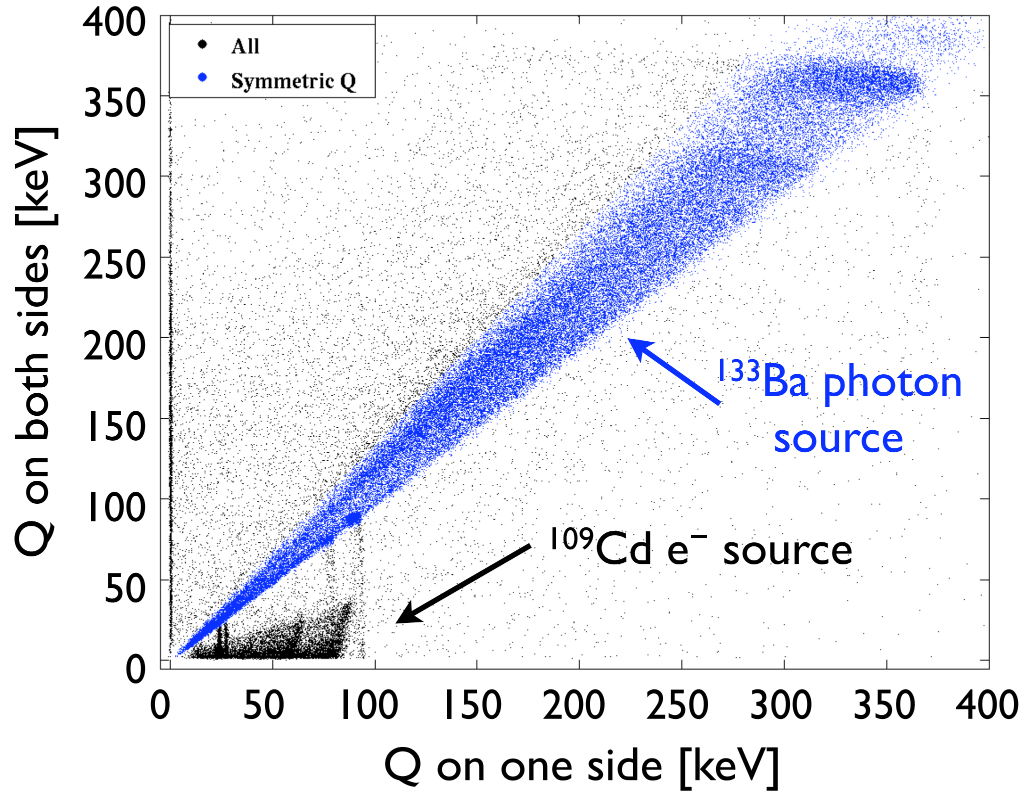

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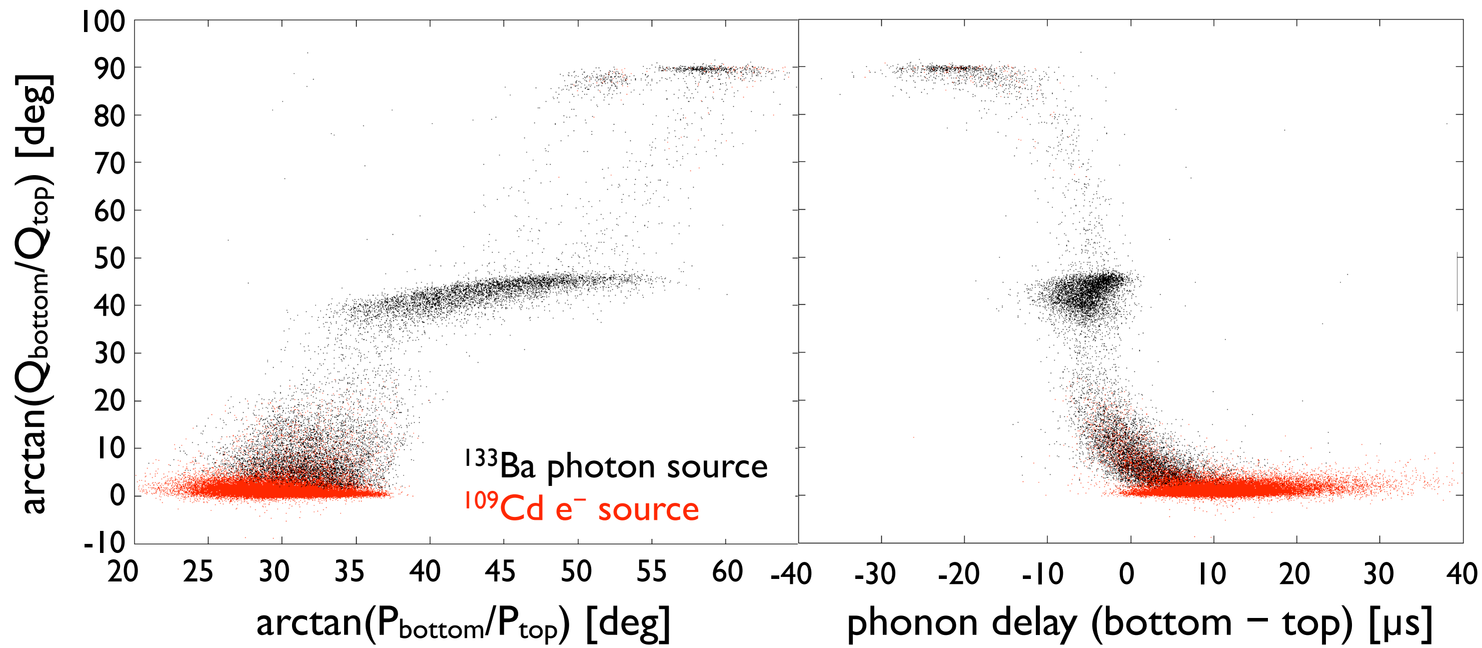

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Reducing Cost/Time: Larger Substrates

- Larger substrates provide gains in bgnds and in cost/time per kg
- Step 1: 10-cm HPGe substrates for SNOLAB (Ortec)
- Step 2: Dislocation-free Ge for GEODM
  - deep (E_v + 0.080 eV) V_2H impurity ruins 77K HPGe γ spectrometers; inhibited via dislocations at $10^{2\text{-}4}$ cm^{-3} created by thermal gradients during crystal pulling
  - impurities no problem for CDMS: they can be neutralized
  - dislocation-free xtals available up to 30 cm diameter!

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Divacancy–hydrogen complexes in dislocation-free high-purity germanium †

E E Haller‡, G S Hubbard‡, W L Hansen‡ and A Seeger§
‡ Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, USA
§ Max-Planck-Institut für Metallforschung, Stuttgart, Germany

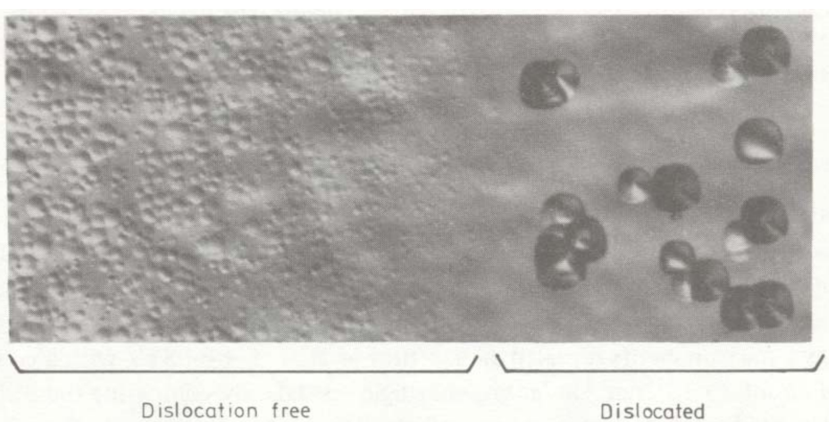


Figure 2. Photograph of a partially dislocated (100) surface of a hydrogen-grown Ge crystal. The large etch pits with four-fold symmetry in the right half of the picture are due to dislocations. The hemispherical pits in the left half of the picture are attributed to vacancy and hydrogen complexes.

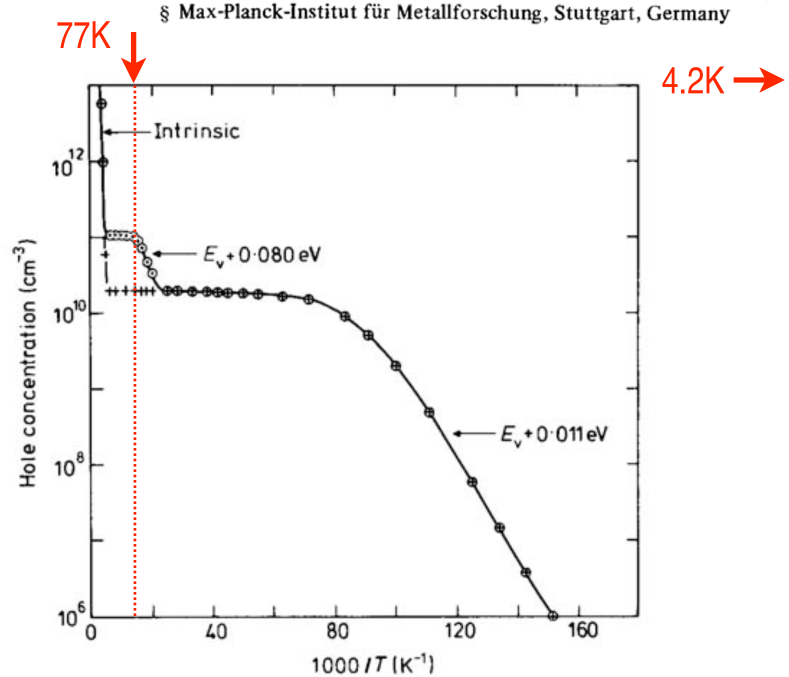
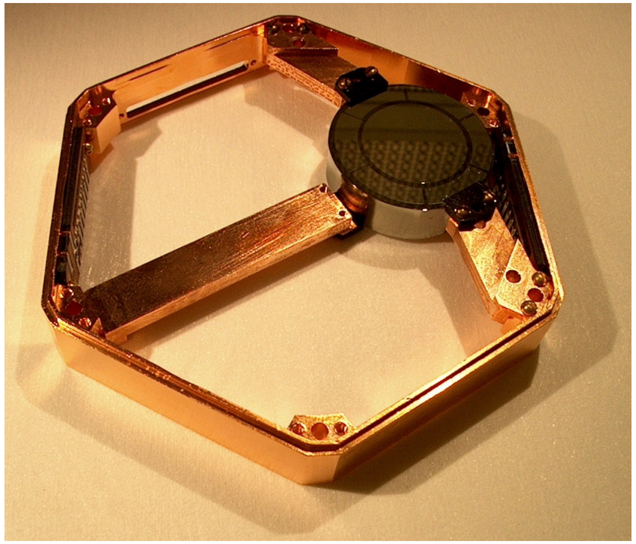
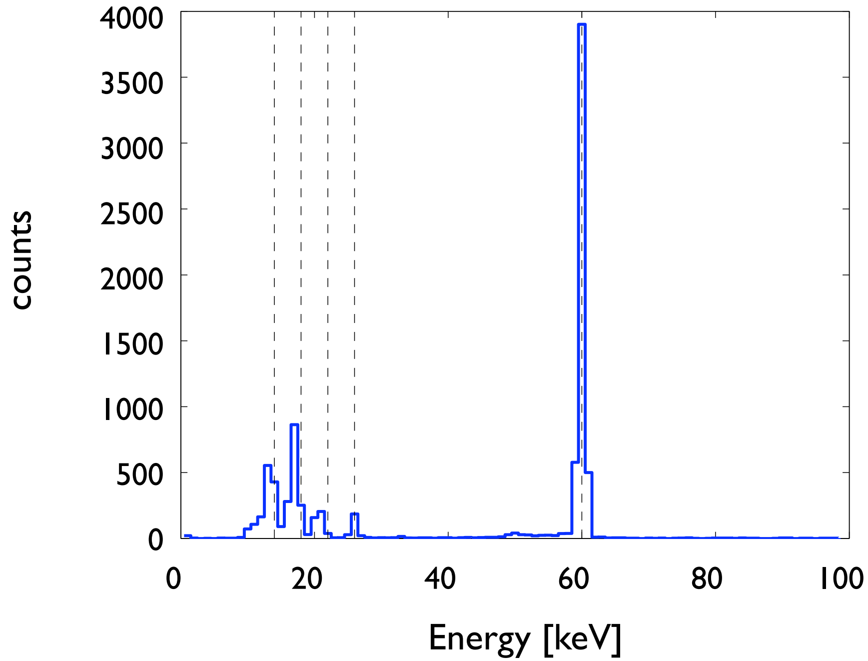


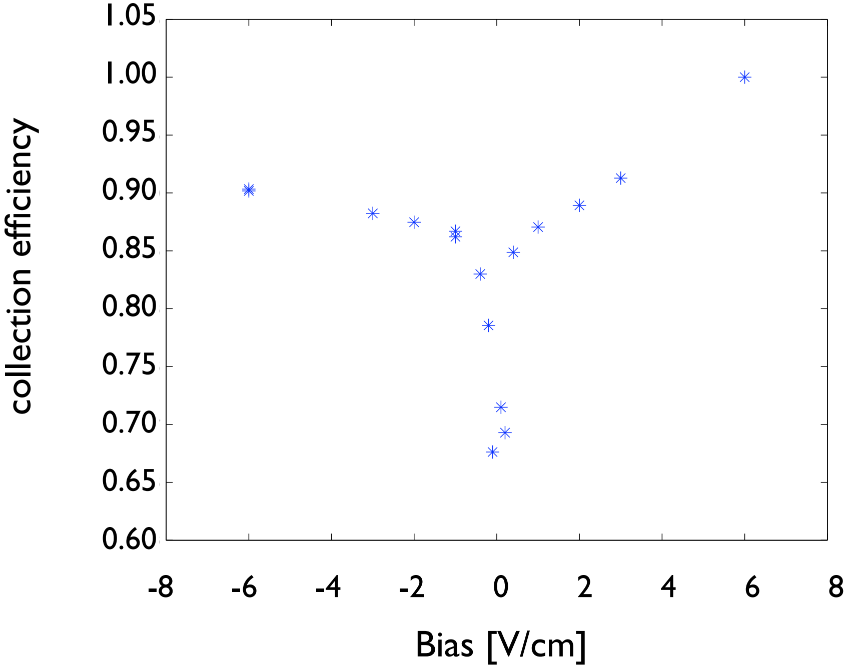
Figure 1. Hole concentration against reciprocal temperature $1/T$ of a dislocated and an undislocated Ge sample cut from the same crystal slice. The net impurity concentration of shallow acceptors and donors is equal for both samples. The E_V + 0·08 eV acceptor only appears in the dislocation-free piece; its concentration depends on the annealing temperature. ⊙ dislocation free; + dislocated.

Reducing Cost/Time: Larger Substrates

- Proof-of-principle from Haller sample of dislocation-free Ge (3 cm x 1 cm)
  - Good collection at 1 V/cm (reasonable field)
- Working with Umicore and Photonic Sense to demonstrate 15-cm fab at necessary purity/compensation levels
  - DUSEL R&D grant, DUSEL S4 grant
  - Germanium workshop in Berkeley this fall







Backgrounds and Background Rejection: Photons

- Consider together bulk scattering and surface events due to photon background
  - Moderate improvements in raw rates; *already shown in CDMS I*
  - Moderate reductions in surface area/volume ratio via increased mass/detector
  - More significant improvements in background rejection via iZIP

reduction of raw background rate via better shielding/reduced contamination

improvement in background rejection via better discrimination

Stage	Rate [/kg/d]	Relative Rate	Sgl. Scatter x Misid. Prob.	Relative Misid. Prob	Misid. Rate [/kg/d]	Gain	σ [cm^2]
CDMS II published	296	1	1.2×10^{-6}	1	7.2×10^{-4}	1	4.5×10^{-44}
CDMS II final	296	1	5.9×10^{-7} (analysis)	0.5	3.6×10^{-4}	2	2.3×10^{-44}
SuperCDMS Soudan	296	1	1.9×10^{-7} (mZIP)	0.17	1.2×10^{-4}	6	5×10^{-45}
SuperCDMS SNOLAB	90 (CDMS I rate)	0.3 internal shield, better stock	$< 1.7 \times 10^{-8}$ (iZIP)	< 0.014	1.5×10^{-6}	> 250	3×10^{-46}
GEODM DUSEL	90 (CDMS I rate)	0.3 internal shield, better stock	$< 1.2 \times 10^{-11}$? (iZIP)	$< 10^{-5}$?	1.1×10^{-9} ?	$> 3.3 \times 10^{5}$?	2×10^{-47}

Backgrounds and Background Rejection: Betas

- Surface events from low-energy beta decays
  - Significant reductions in raw rate/kg-d from reduced surface area/volume ratio and best CDMS II detector ^{210}Pb rate
  - More significant improvements in background rejection via iZIP
  - *No reduction in ^{210}Pb beyond already achieved is required!*

reduction of raw background rate via better shielding/reduced contamination

improvement in background rejection via better discrimination

Stage	Rate [/kg/d]	Relative Rate	Sgl. Scatter x Misid. Prob.	Relative Misid. Prob	Misid. Rate [/kg/d]	Gain	σ_{goal} [cm^2]
CDMS II published	3.4	1	1.0×10^{-4}	1	7.6×10^{-4}	1	4.5×10^{-44}
CDMS II final	3.4	1	5.3×10^{-5} (analysis)	0.5	3.8×10^{-4}	2	2.3×10^{-44}
SuperCDMS Soudan	0.83 x0.6 ^{210}Pb 2.5cm thickness	0.25	4.4×10^{-5} (mZIP)	0.42	7.9×10^{-5}	10	5×10^{-45}
SuperCDMS SNOLAB	0.60 3.5cm thickness	0.18	$< 5 \times 10^{-6}$ (iZIP)	< 0.05	$< 3 \times 10^{-6}$	250	3×10^{-46}
GEODM DUSEL	0.41 5cm thickness	0.12	$< 5 \times 10^{-9}$? (iZIP)	$< 5 \times 10^{-5}$?	$< 2 \times 10^{-9}$?	$> 3.7 \times 10^{5}$?	2×10^{-47}

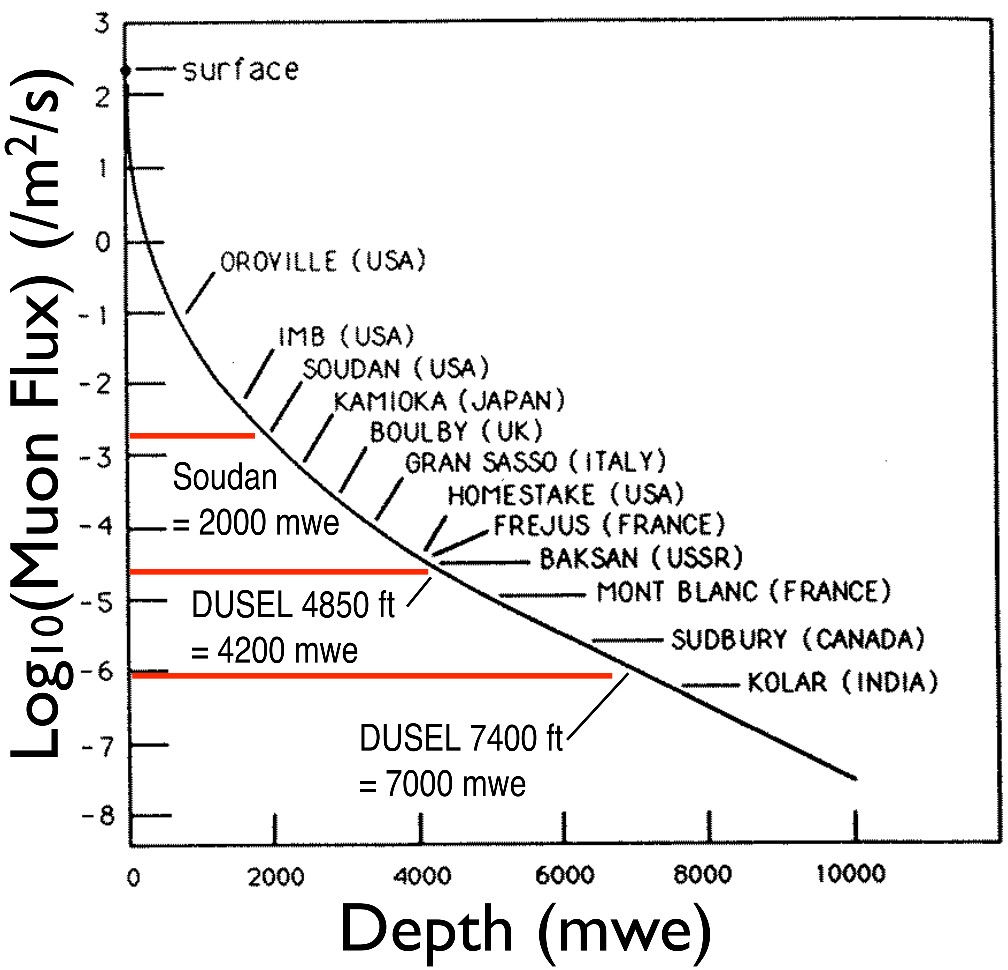
Backgrounds and Background Rejection: Neutrons

- Radiogenic neutrons: U/Th fission and (α,n)
  - Cryostat Cu:
    - 0.2 ppb U, 0.6 ppb Th currently, predicts 7.4 x 10^{-5} single n/kg/day, expected to be the limiting bgnd for SuperCDMS Soudan
    - Electroformed Cu should have < 0.1 ppt U/Th (EXO < few ppt already demonstrated); don't need underground fab
  - Pb in shield
    - 50 ppt *upper limit* on U/Th in existing shield, expected levels much lower
    - 1 ppt U/Th (Heusser *upper limit*) yields 6 x10^{-6} single n/kg/day for SuperCDMS Soudan; ok for SNOLAB, need to improve upper limit by x15 for GEODM
  - Polyethylene:
    - 0.2 ppb U, 0.2 ppb Th upper limits on existing material yield 1.6 x 10^{-5} single n/kg/day
    - Need improved poly (x3 and x45) or replace with water

Stage	Rate [/kg/d]	Relative Rate	Gain	σ [cm^2]
CDMS II published	1.2 x 10^{-4}	1	1	4.5 x 10^{-44}
CDMS II final	1.2 x 10^{-4}	1	1	2.3 x 10^{-44}
SuperCDMS Soudan	1.2 x 10^{-4}	1	1	5 x 10^{-45}
SuperCDMS SNOLAB	6.0 x 10^{-6}	0.05	20	3 x 10^{-46}
GEODM DUSEL	4.0 x 10^{-7}	0.003	300	2 x 10^{-47}

Backgrounds and Background Rejection: Neutrons

- Cosmogenic neutrons:
  - cosmic-ray muon spallation of nuclei in rock walls
  - muon rate is >1000x lower than Soudan at DUSEL 7400 ft level
  - showering greatly aids in vetoing
  - Would need to go to DUSEL 7400 ft level to reduce cosmogenic vs. SNOLAB



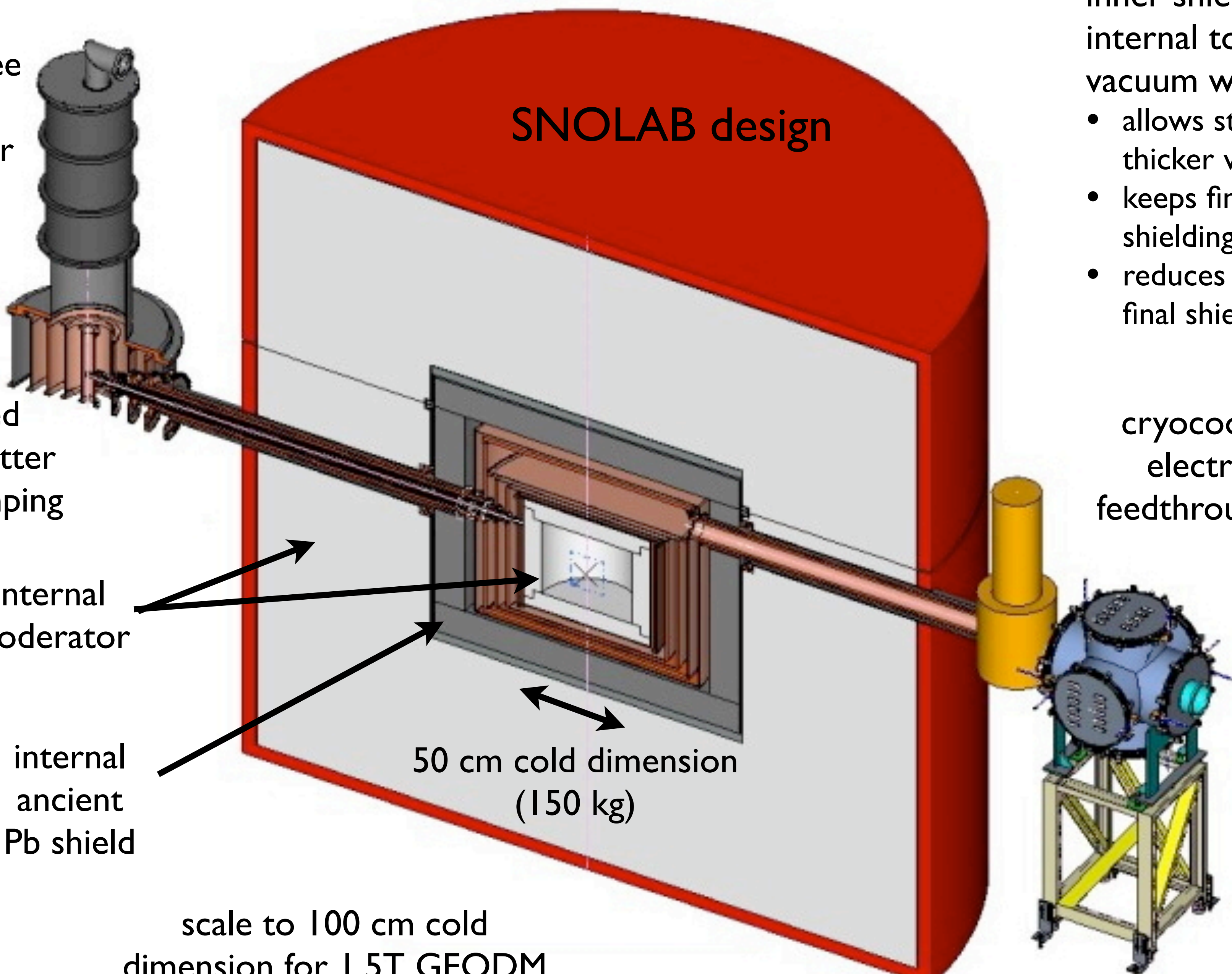
Reducing Backgrounds: SNOLAB/GEODM Cryostat/Shield

cryogen-free dilution refrigerator

expanded tails for better access/pumping

internal moderator

internal ancient Pb shield



inner shielding layer internal to cryostat vacuum wall

- allows stronger/ thicker vacuum wall
- keeps final layer of shielding clean
- reduces mass of final shield (esp. Pb)

cryocooler on electronics feedthrough stem

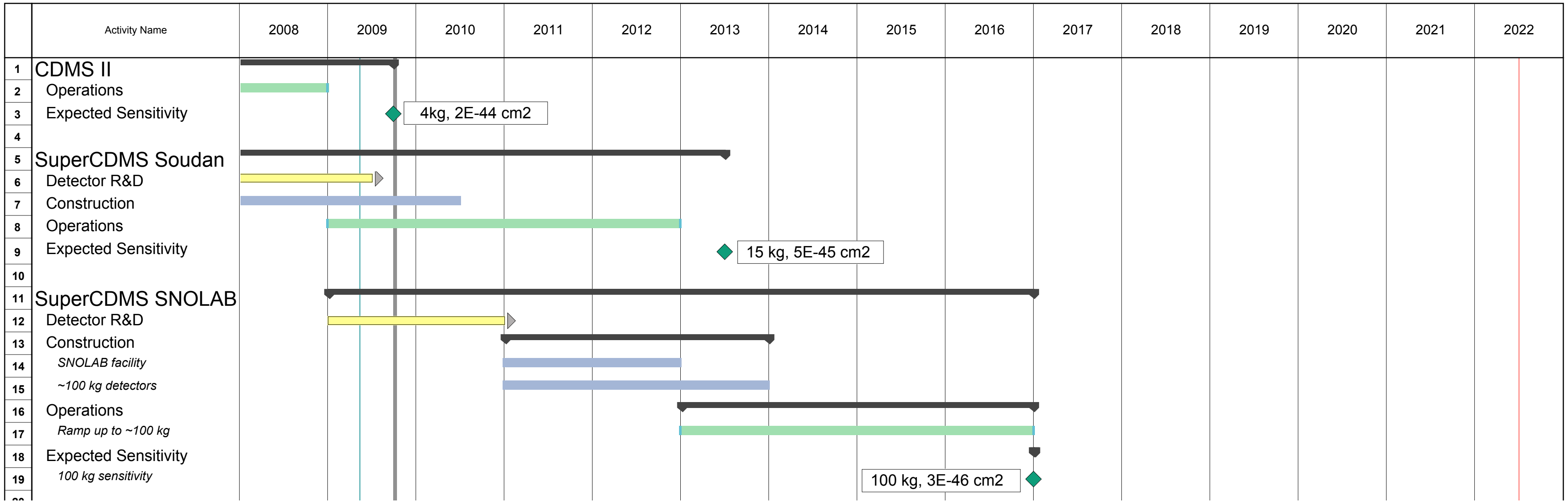
scale to 100 cm cold dimension for 1.5T GEODM

Reducing Cost/Time: Doing the Numbers

- Costs for fab *and* test; product = detector ready for installation in experiment
  Has driven experiment cost in past.

	CDMS II	SuperCDMS Soudan	SuperCDMS SNOLAB	GEODM
Cost basis	actual	approved	to be proposed	
total mass	4 kg	16 kg	105 kg	1500 kg
# detectors, mass	16 x 0.25 kg (+ 14 x 100g Si)	25 x 0.64 kg	70 x 1.5 kg	300 x 5.1 kg
cost/detector	$200K-$300K	$225k	$225k	$120k
rate [det/mo]	0.5-0.75/mo	1/mo	2/mo	8/mo
cost/kg	$800k-1200k	$350k	$150k	$24k
rate [kg/mo]	0.1-0.2 kg/mo	0.64 kg/mo	3 kg/mo	40 kg/mo
total detector cost	$4.8M (+ $4.2M)	$5.6M	$16M	$36M
total detector time	2.7 yrs (+ 2.3 yrs)	2 yrs	3 yr	3 yrs

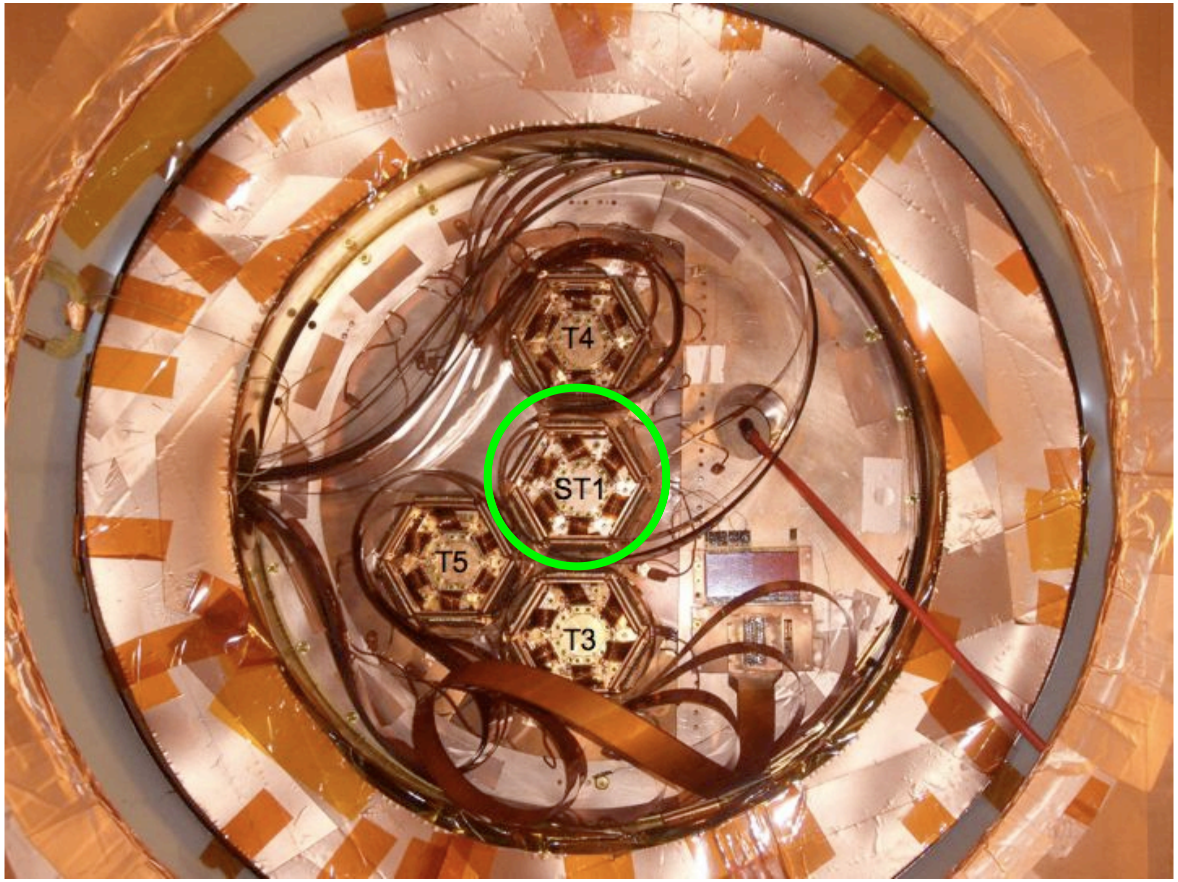
Status/Schedule

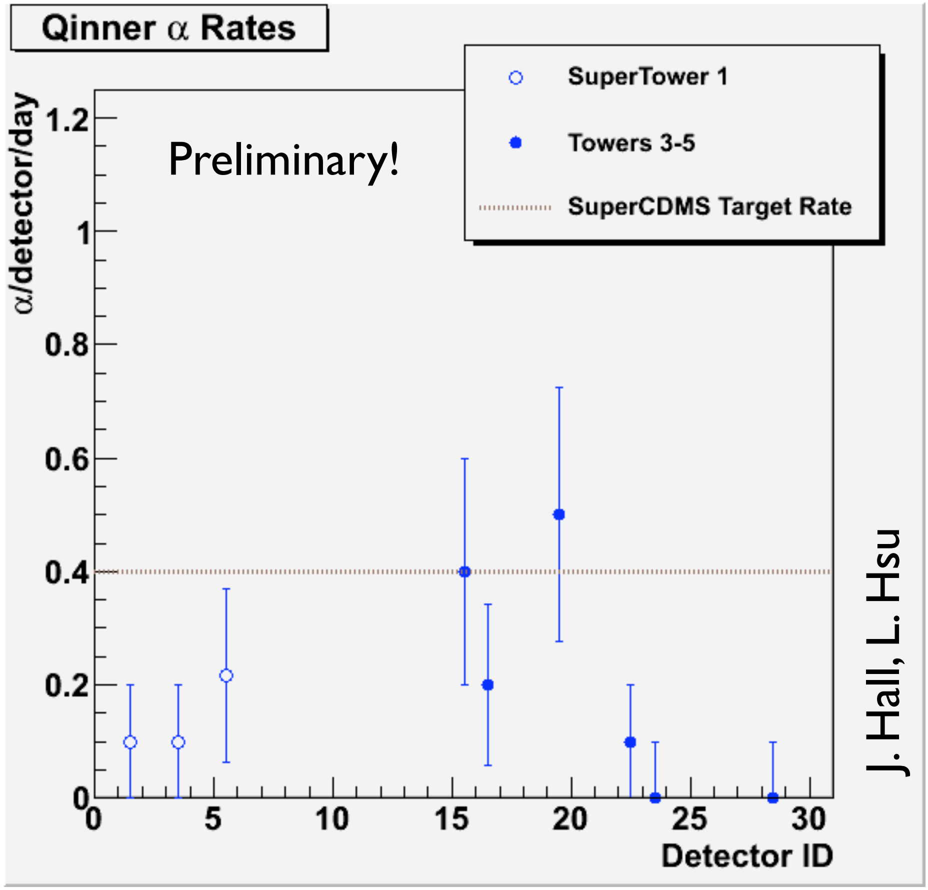


- CDMS II:
  - data taking complete
  - final analysis proceeding, expected to be out this fall
- SuperCDMS Soudan:
  - First 3.2 kg of detectors installed in Soudan (along with existing 2.4 kg), second 3.2 kg of detectors fab'd and awaiting surface testing
  - Approved in Aug 2008 to fab remaining 9.6 kg of detectors and run for 2 yrs

SuperTower 1 Running at Soudan!

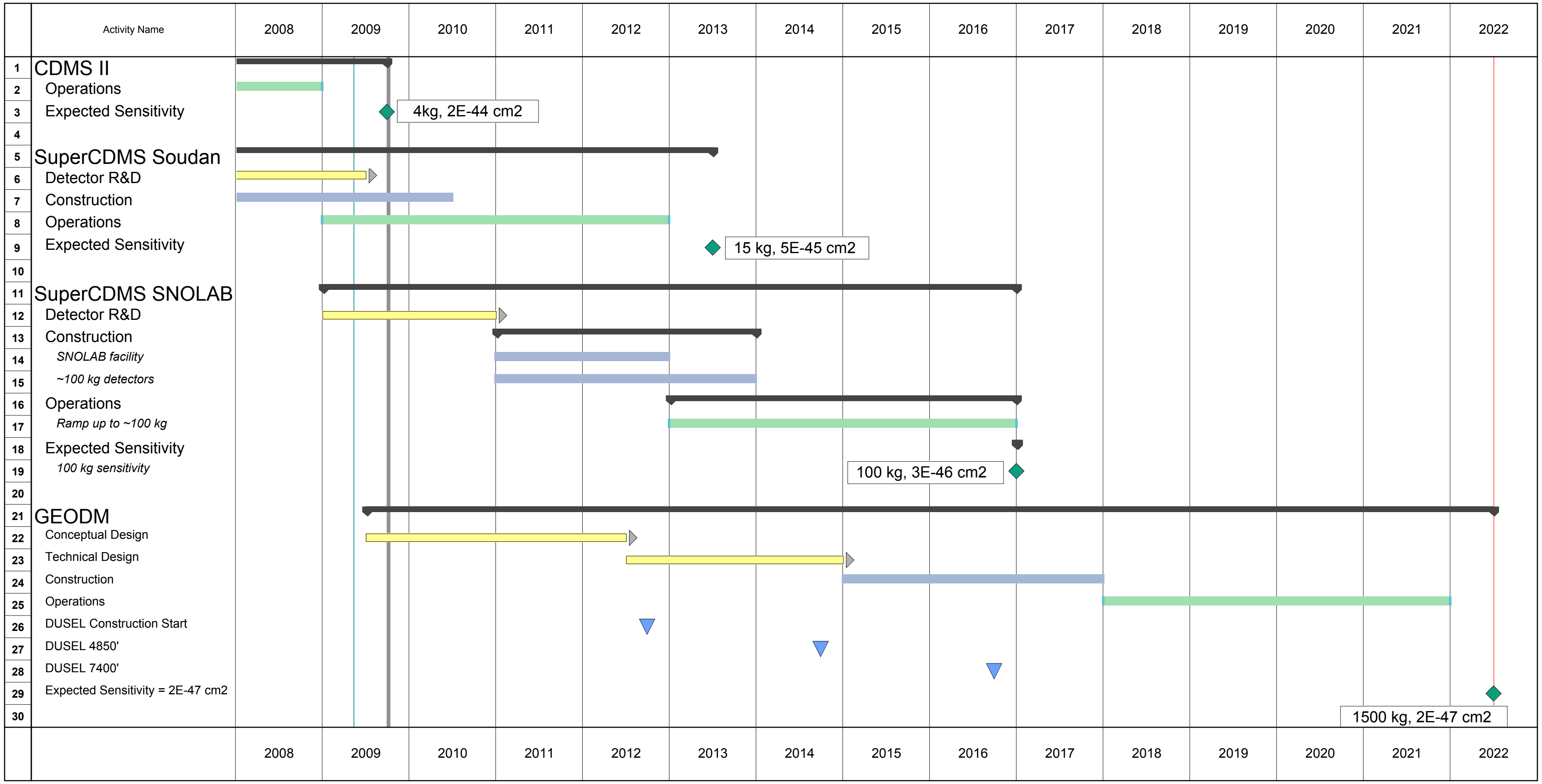
- ST1 installed April 16, 2009, cold June 4, and in stable running by Aug 1
- Best 3/5 of CDMS II also remains in place: total 4 kg → 5.6 kg
- ^{210}Po α rate verified; surface-event rates and rejection need more data
- will run ST1 alone until ST2-5 ready





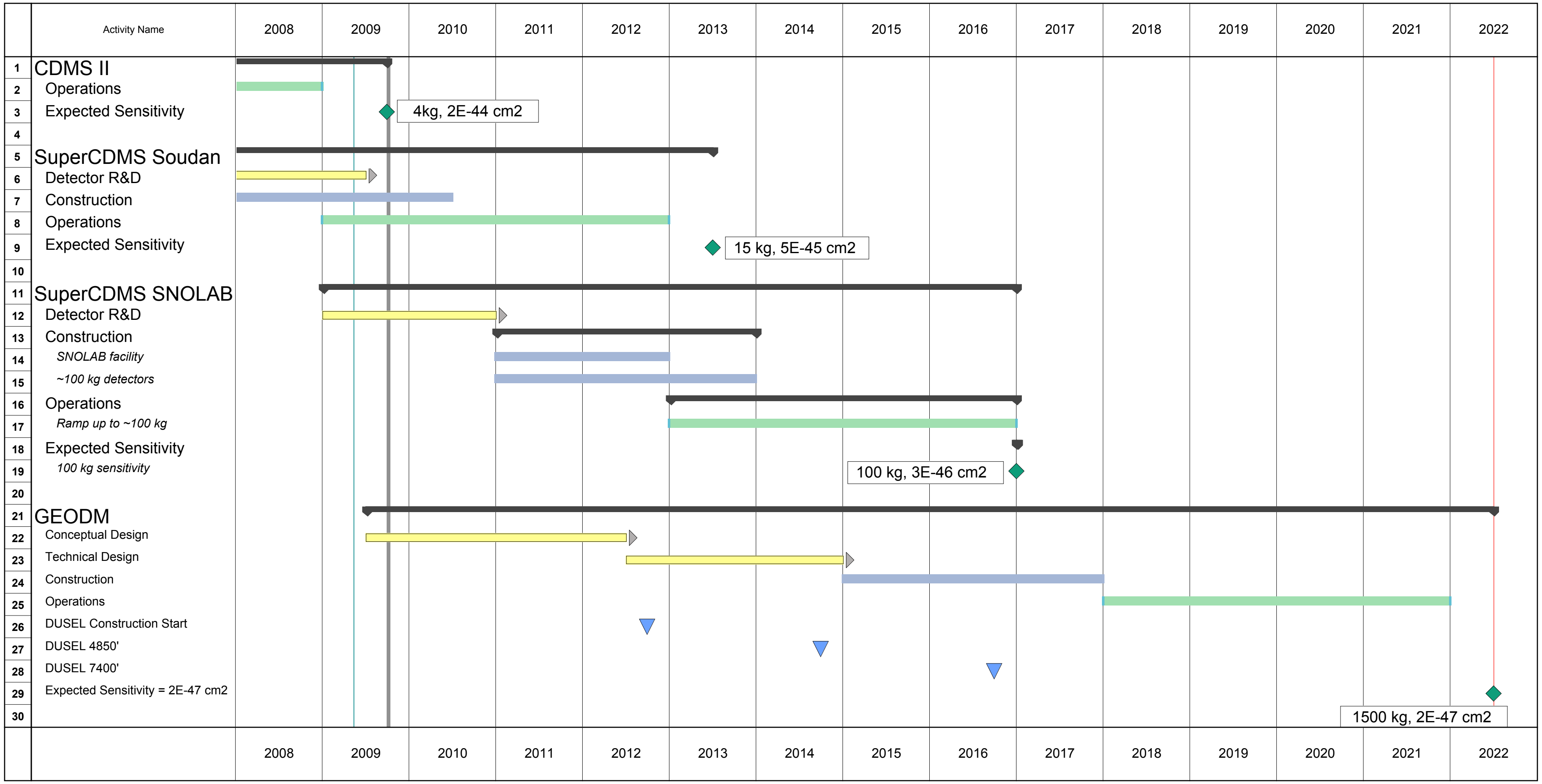
J. Hall, L. Hsu

Status/Schedule



- SuperCDMS SNOLAB:
  - R&D funding likely in FY10, proposal to be submitted in FY10 for FY11 start
  - Cryostat/shield and electronics design proceeding at FNAL under base funding; critical to get release of funds to order long-lead-time dilution refrigerator ASAP
  - SNOLAB is enthusiastic, space has been set aside, initial test setup in FY10
  - Overlap with DUSEL provides prototyping in v. similar environment

Status/Schedule



- DUSEL GEODM
  - Design through 2014
  - Construction 2015-2017
    - 7400 ft level occupancy in 2018 would be a substantial delay; were aiming for 2017
  - Operations 2018-2021 (4 yrs running)

Status/Schedule

- DUSEL GEODM
  - Conceptual design and initial cost estimate ($50M construction) in hand
  - DUSEL S4 engineering study phase
    - $2.1M proposed over 3 yrs, $1.3M funded
    - Goal: arrive at "preliminary design" of experiment by end of funding in 2012, with infrastructure needs incorporated in DUSEL preliminary design in 2010.
    - SNOLAB development work under DOE R&D and NSF/DOE project funding would also contribute positively
      - Completion of SNOLAB cryostat/shield design (scale-up for GEODM)
      - Study of active neutron veto for SNOLAB (radiogenic backgrounds)
      - Development of SLAC and TAMU fab capabilities and testing setup
      - Reengineering of cold hardware for iZIP, better reliability, easier fabrication
      - Screening of materials with aim to SNOLAB and GEODM needs

Conclusions

- CDMS II reaching successful completion
- SuperCDMS Soudan ramping up
  - 7.5-cm x 2.5-cm ZIP, 15 kg, 5×10^{-45} cm^2
  - ST1 installed and ^{210}Po verified, ST2 to be tested
  - approved for ST3/4/5 + science running
  - reach: 5×10^{-45} cm^2
- SuperCDMS SNOLAB to be proposed soon
  - 10-cm x 3.5-cm iZIP, 105 kg, 3×10^{-46} cm^2
  - new SLAC involvement
- GEODM
  - 15-cm x 5-cm iZIP, 1.5T, 2×10^{-47} cm^2
  - conceptual design in place
  - preliminary design beginning
  - fleshing out lab interface details for DUSEL PDR

The GEODM Collaboration

Caltech: S. R. Golwala
Fermilab: D. A. Bauer, R. Schmitt
MIT: E. Figueroa-Feliciano
NIST: K. Irwin
Queens University: W. Rau, P. di Stefano
Santa Clara University: B. A. Young
SLAC National Accelerator Lab: E. do Couto e Silva, J. Weisand
Southern Methodist University: J. Cooley
Stanford University: P.L. Brink, B. Cabrera, S. Yellin
St. Olaf College: A. Reisetter
Syracuse University: R.W. Schnee
Texas A&M: R. Mahapatra, M. Platt
University of California, Berkeley: N. Mirabolfathi, B. Sadoulet, D. Seitz
University of Colorado at Denver: M. E. Huber
University of Florida: T. Saab
University of Minnesota: P. Cushman, V. Mandic