New Directions and Developments in Dark Matter Searches with Solid-State Detectors

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Caltech

Workshop on Frontiers of New Physics: Colliders and Beyond

2014/06/25

Overview

Experimental generalities

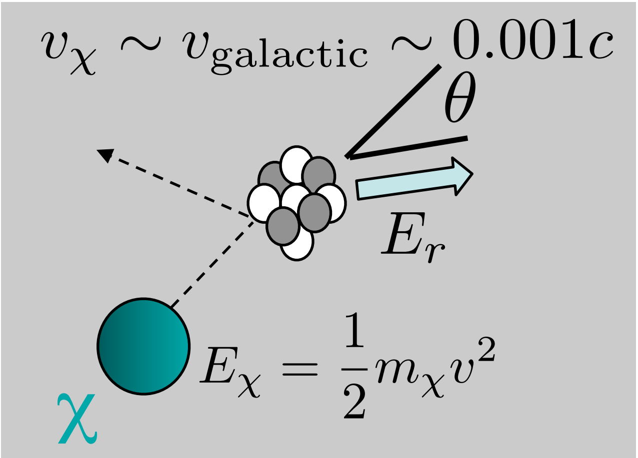
Past and present innovations in solid-state detectors and impact on sensitivity

Future directions to lower masses and cross sections

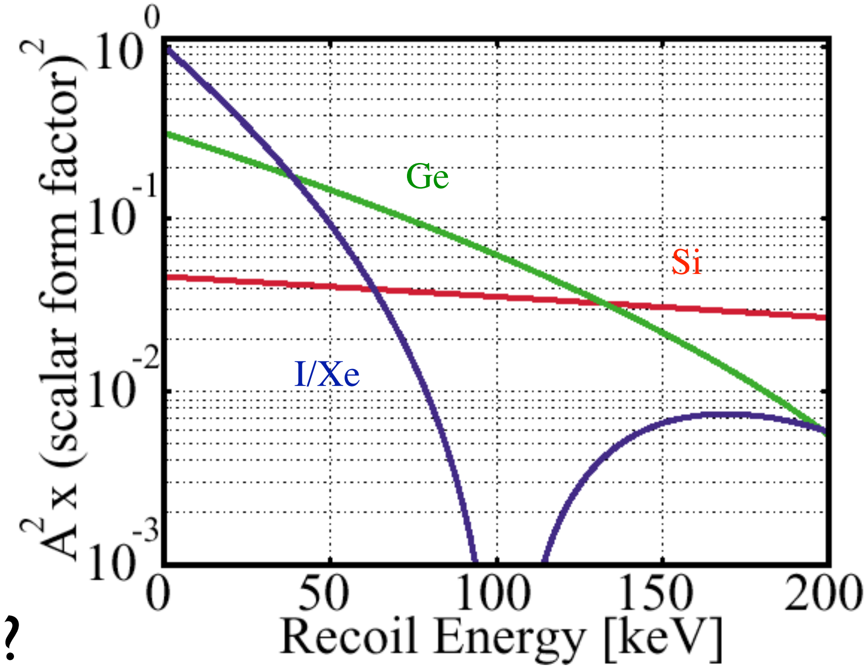
Dark Matter Direct Detection: Nuclear Recoil Signature

Nuclear recoil paradigm

- Non-relativistic limit: all interactions reduce to spin-independent or spin-dependent couplings of DM to quarks
  - Though now understood that one should not take non-rel limit for nucleons (Fitzpatrick, Haxton et al) has only x2 impact (Gresham and Zurek)
- Coherently sum over quarks in nucleon and nucleons in nucleus to obtain coupling proportional to A^2 or J^2
- Scattering with nuclei much higher rate than scattering with electrons: *signature of WIMPs is nuclear recoils*
- Billiard ball scattering of WIMP with nucleus: search constrains σ
  - Form factor describes breakdown of coherence: momentum transfer probes structure of larger nuclear at lower E_r than for smaller nuclei



$$\frac{E_r}{E_\chi} = \frac{4 m_N m_\chi}{(m_N + m_\chi)^2} \cos^2\theta$$

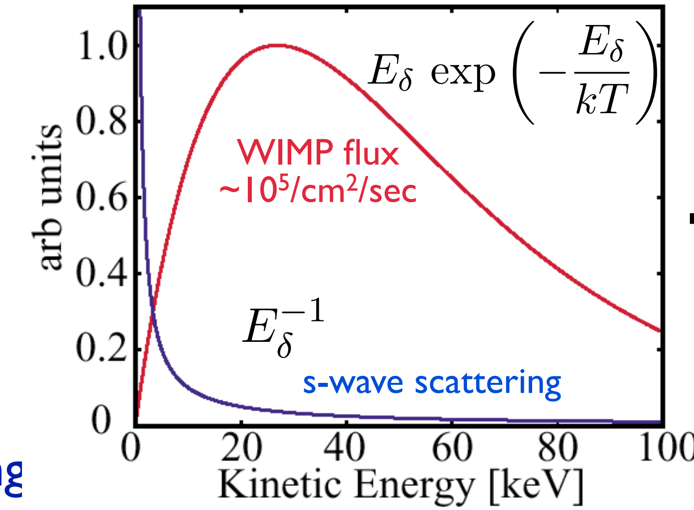


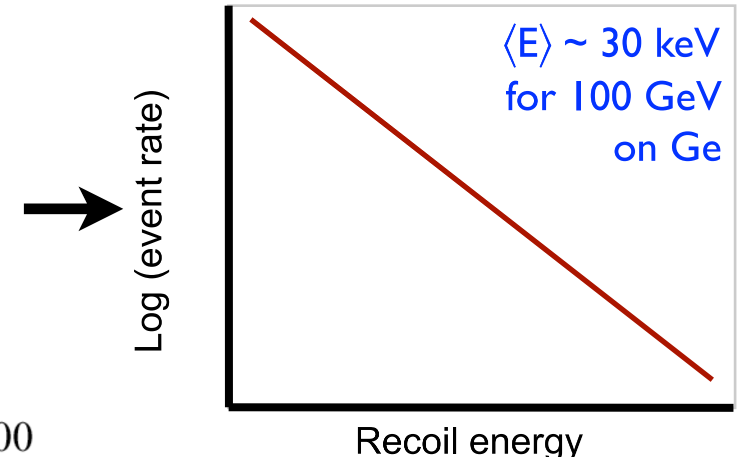
Electron recoils better for low-mass DM?

The Dark Matter "Beam" and Recoil Energy Spectrum

The basic model

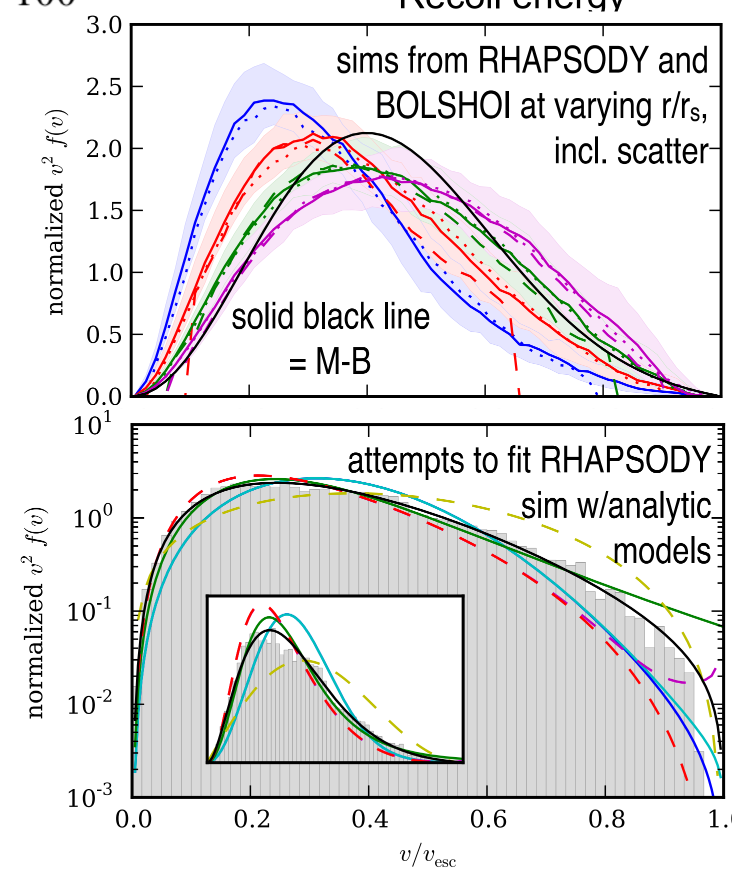
- Maxwell-Boltzmann halo
- v_c = 220 km/s
- σ_v = 270 km/s
- v_{esc} = 544 km/s
- flux × s-wave scattering → exponential recoil energy spectrum





Problems and perturbations

- M-B halo inconsistent with NFW/Einasto profiles seen in N-body simulations
- M-B halo does not match sims in detail
- Imperfect relaxation
  - Clumpiness, spikes in phase space due to tidal streams
- Dark disk?



Mao et al (2013)

Backgrounds

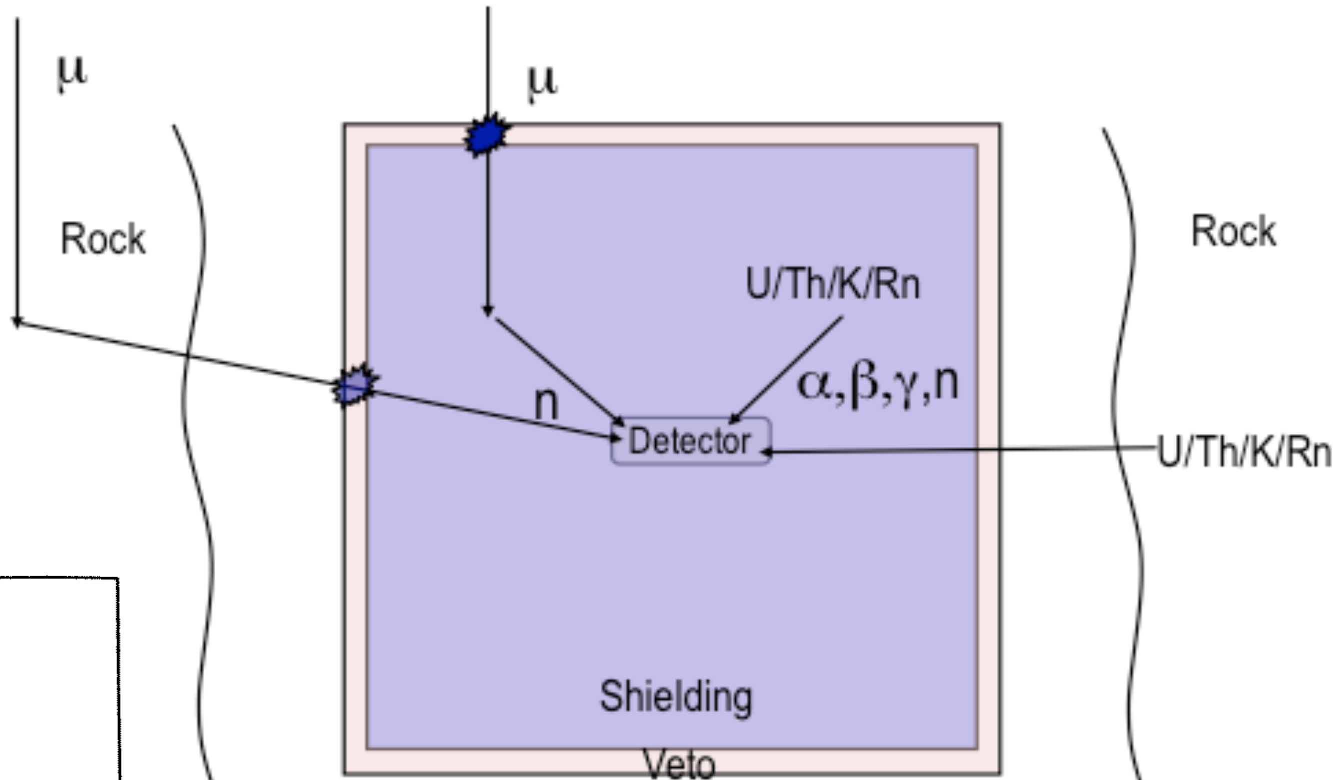
Particle types:

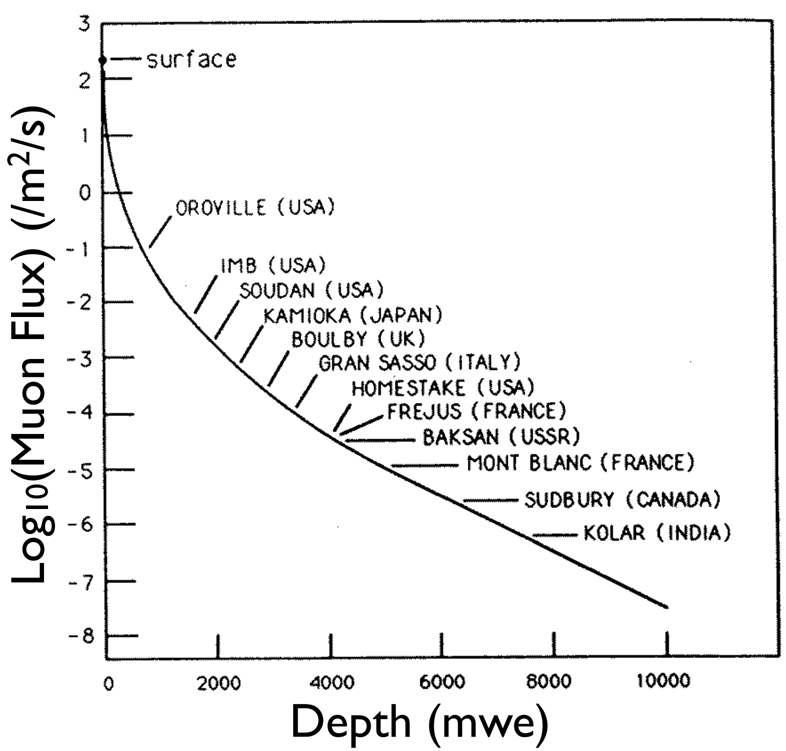
α, β, γ, n

Source:

radiogenic

cosmogenic





Parent location:

in the target

on the surface

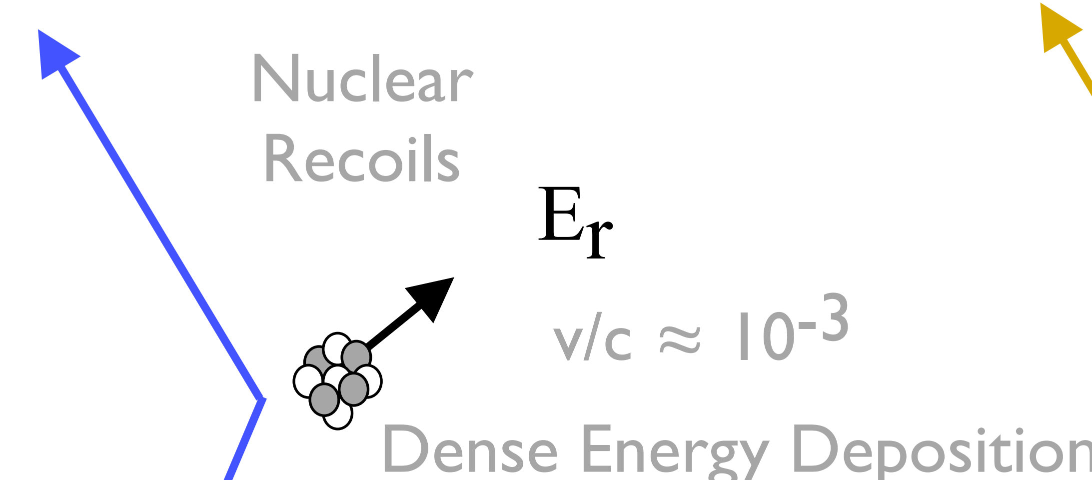
on nearby surfaces

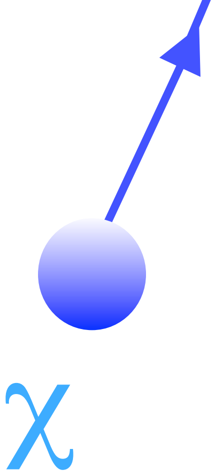
in surrounding materials

<u>+ eventually, the ultimate background:</u>
coherent nuclear scattering of solar, atmospheric, and diffuse supernova bgnd neutrinos. Irreducible!

Nuclear Recoil Discrimination

Signal

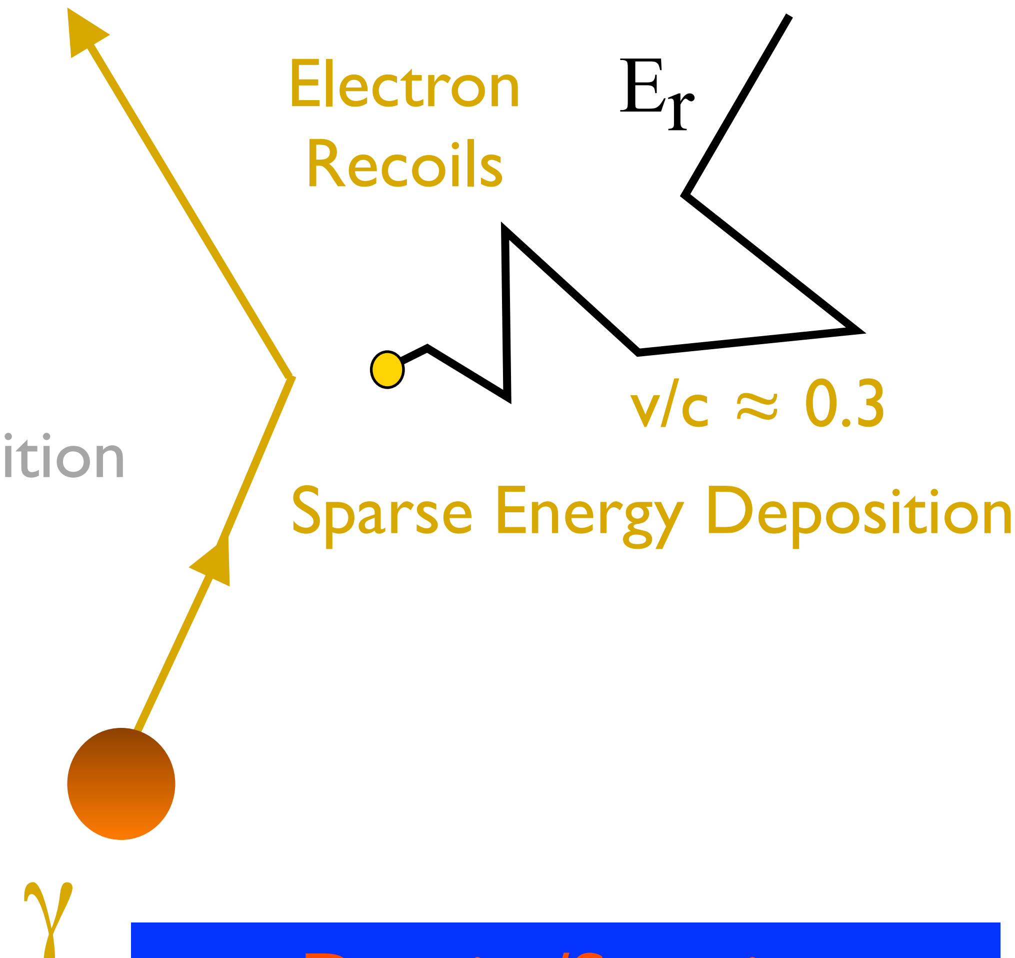




Neutrons same, but
$\sigma \approx 10^{20}$ higher;
must reduce/moderate

Alphas also have high
energy deposition
densities

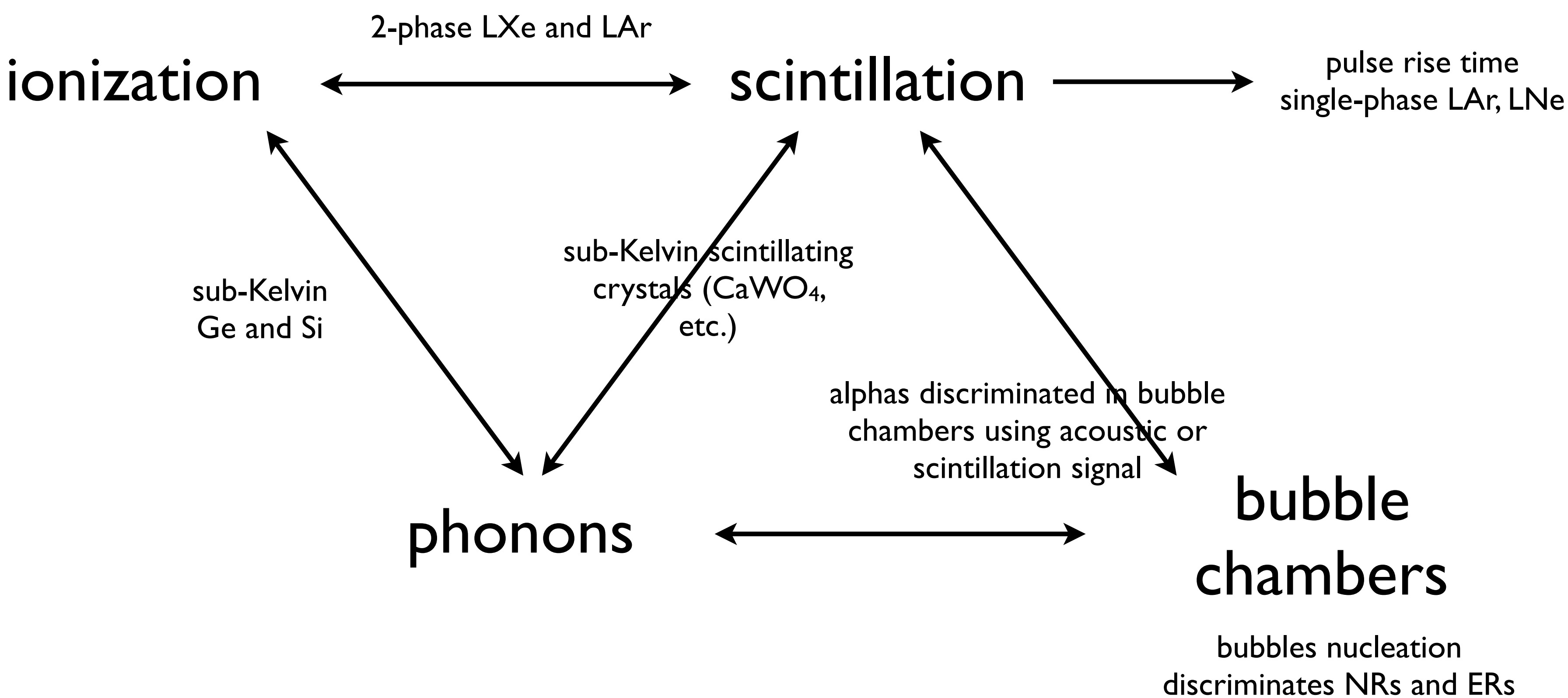
Background



Density/Sparsity: Basis of Discrimination

Discrimination Techniques

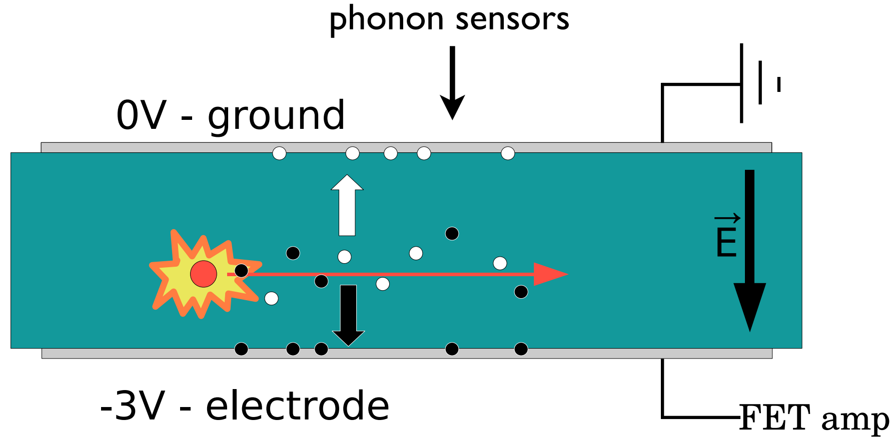
Need sensitivity to energy deposition characteristics (density, energy) to discriminate nuclear recoils (NRs), electron recoils (ERs), and alphas



Solid-State Detectors

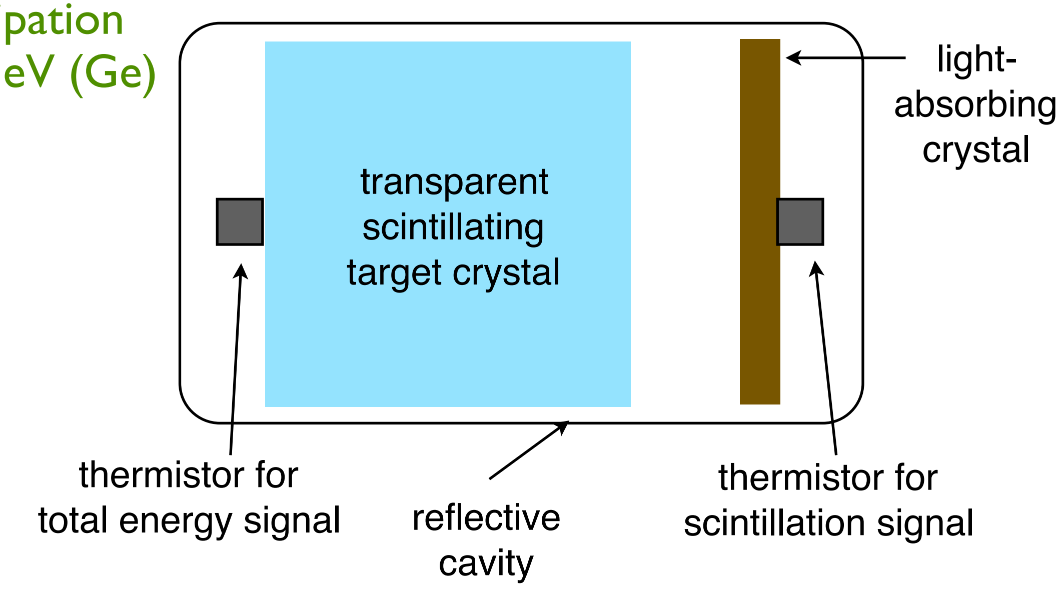
SuperCDMS/EDELWEISS

- Semiconducting crystals
- Ionization:
  - Ionization produced in interactions drifted w/low electric field
- Phonons (thermal and athermal)
  - Most energy goes into phonons. In Ge: 3.0 eV/e-h pair vs. 0.67 eV bandgap
- Energies:
  - "keV_r" = recoil energy, energy deposited by particle interaction = E_r
  - "keV_{ee}" = "electron-equivalent" energy = $N_{e\text{-}h}$ x 3.0 eV in Ge = E_q; $E_q = E_r$ for ERs
  - Luke-Neganov energy = drift heating dissipation $= E_{drift} = N_{e\text{-}h} \times e \times V_b = E_q \times e \times V_b / 3.0$ eV (Ge)
  - "keV_p" = phonon energy = $E_r + E_{drift}$

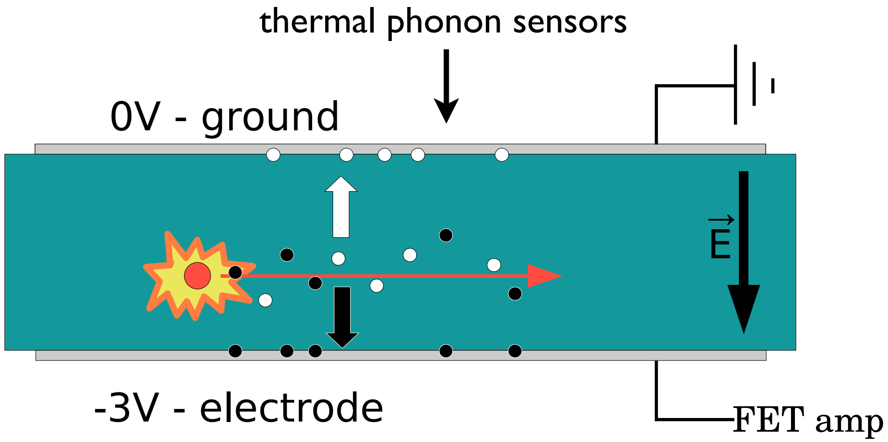


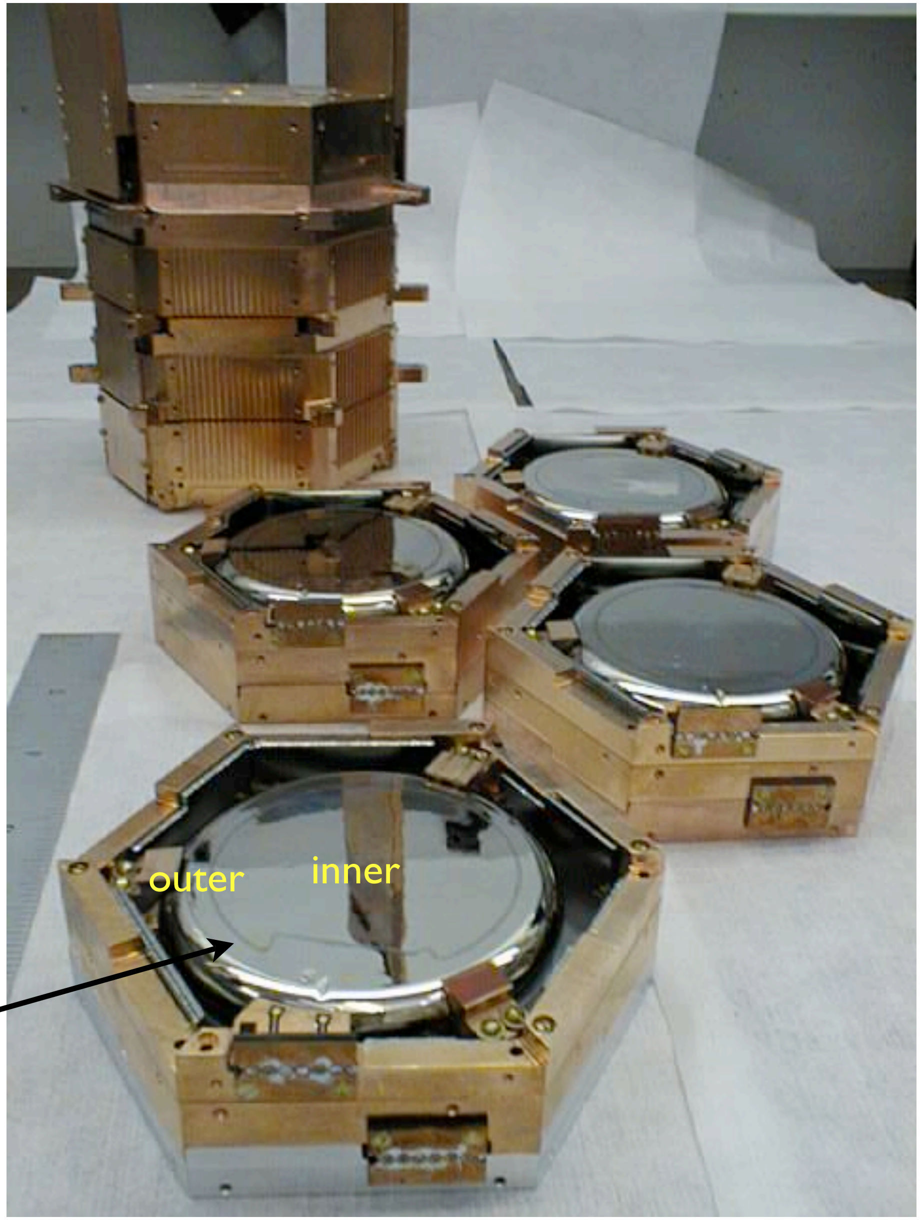
CRESST

- Photons from scintillating crystals instead of ionization (e.g. $CaWO_4$)
- Photons detected with separate "absorber crystal"



CDMS I: Event-by-Event NR Discrimination





phonons + ionization discriminate NRs from ERs at low bias (few V): first application of event-by-event nuclear recoil discrimination

ionization signal used to reject outer radius events that suffer poor ionization collection

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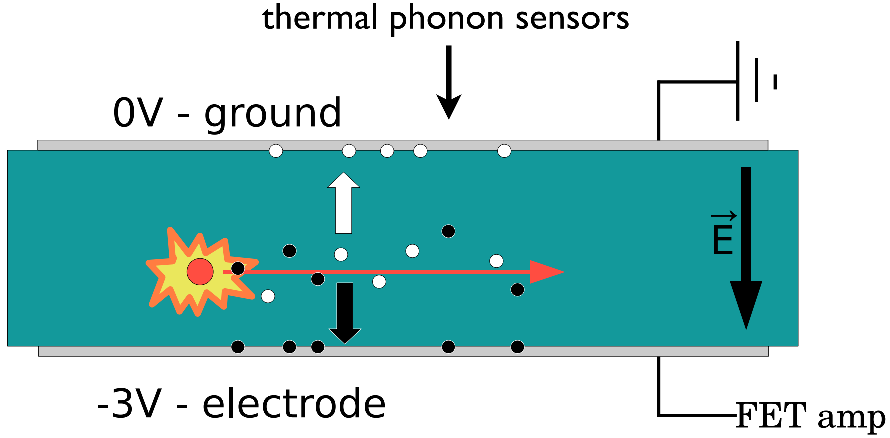

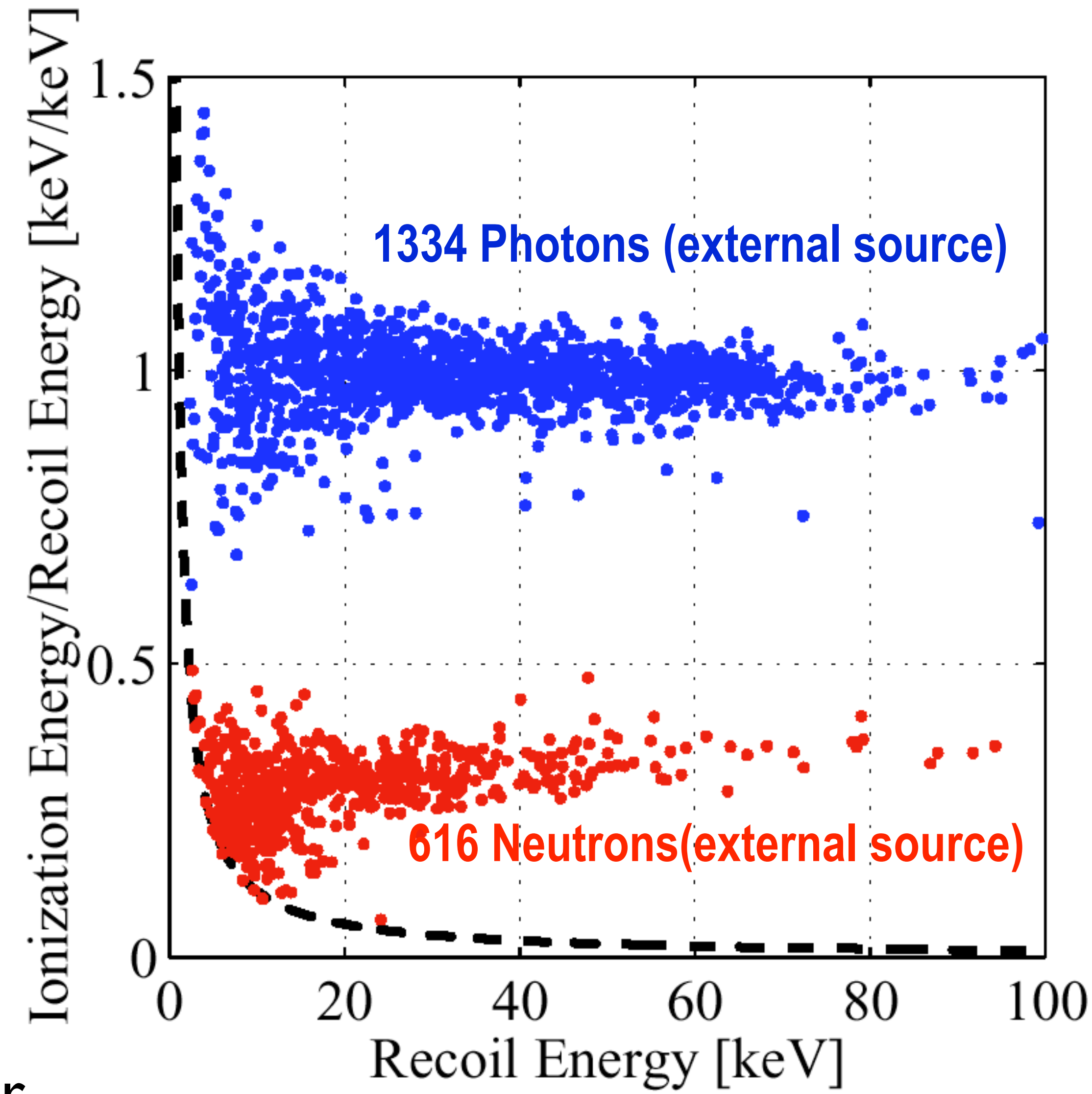

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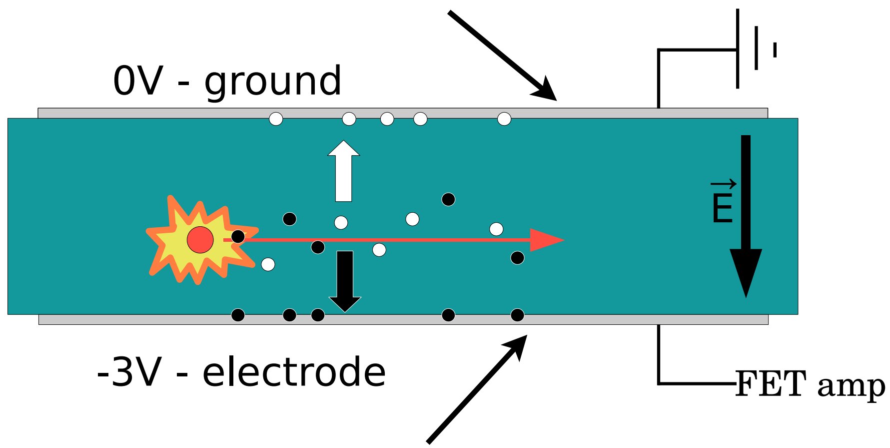
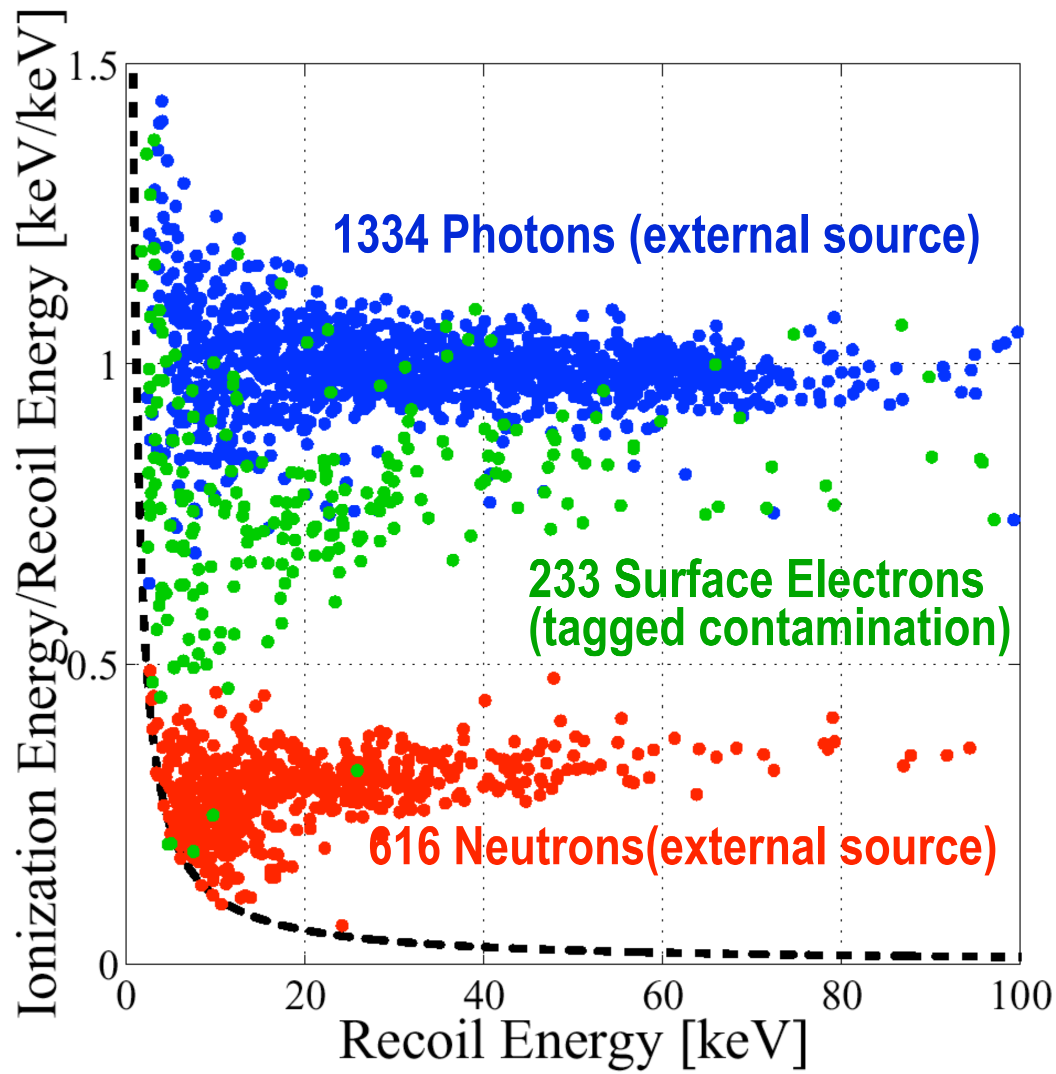
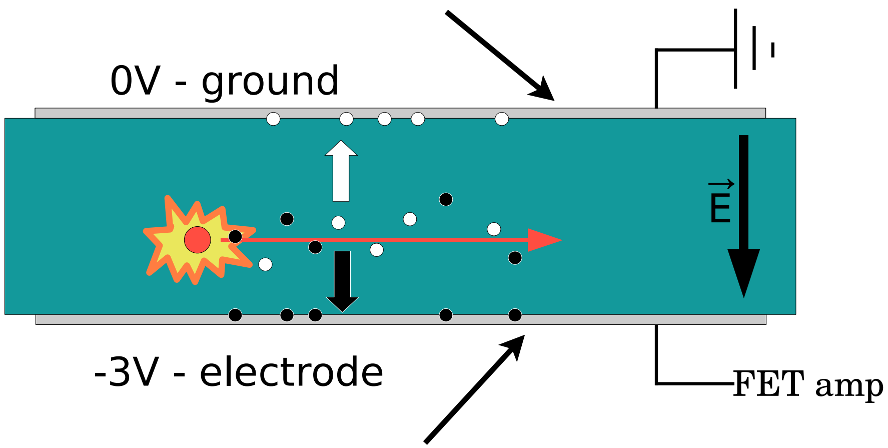
CDMS I: Surface Event Mitigation w/Electrodes



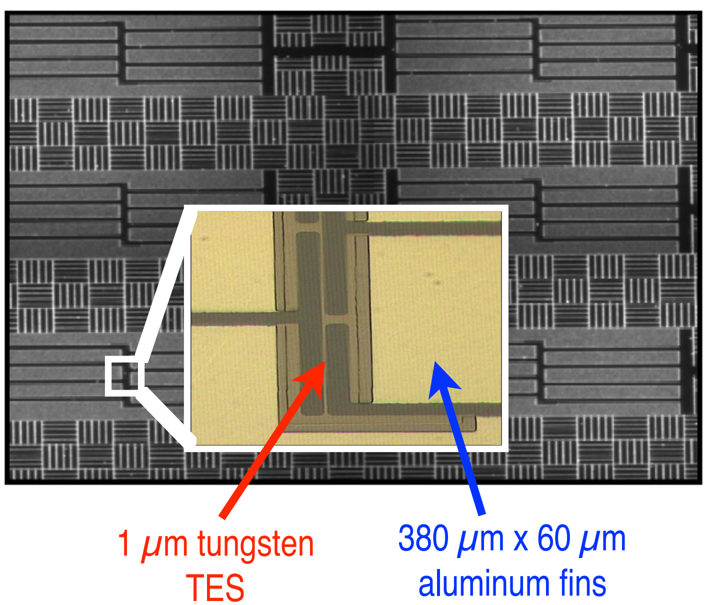


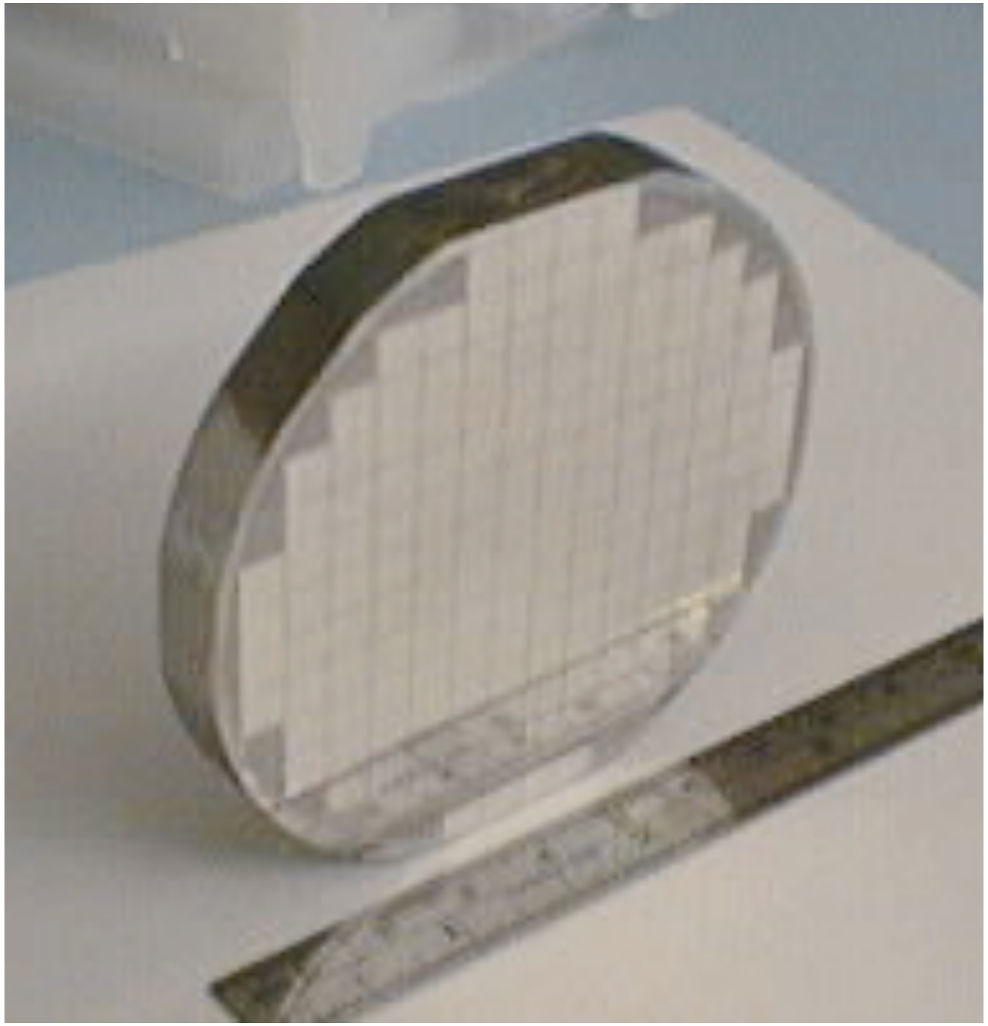
- discovered surface events suffering poor ionization collection
- new electrode structure (high bandgap blocking layer) mitigates by raising ionization yield

CDMS II: Surface Event Rejection w/Athermal Phonons



Athermal phonon sensors: ZIPs





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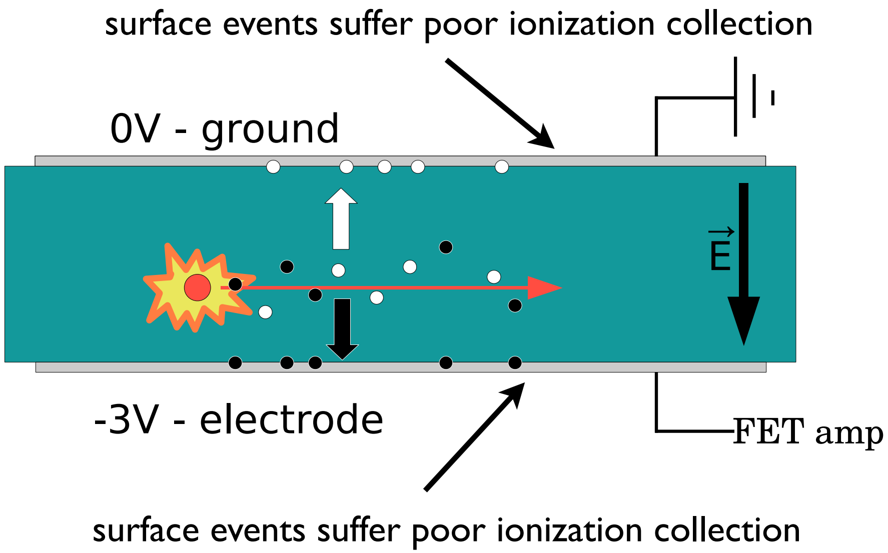
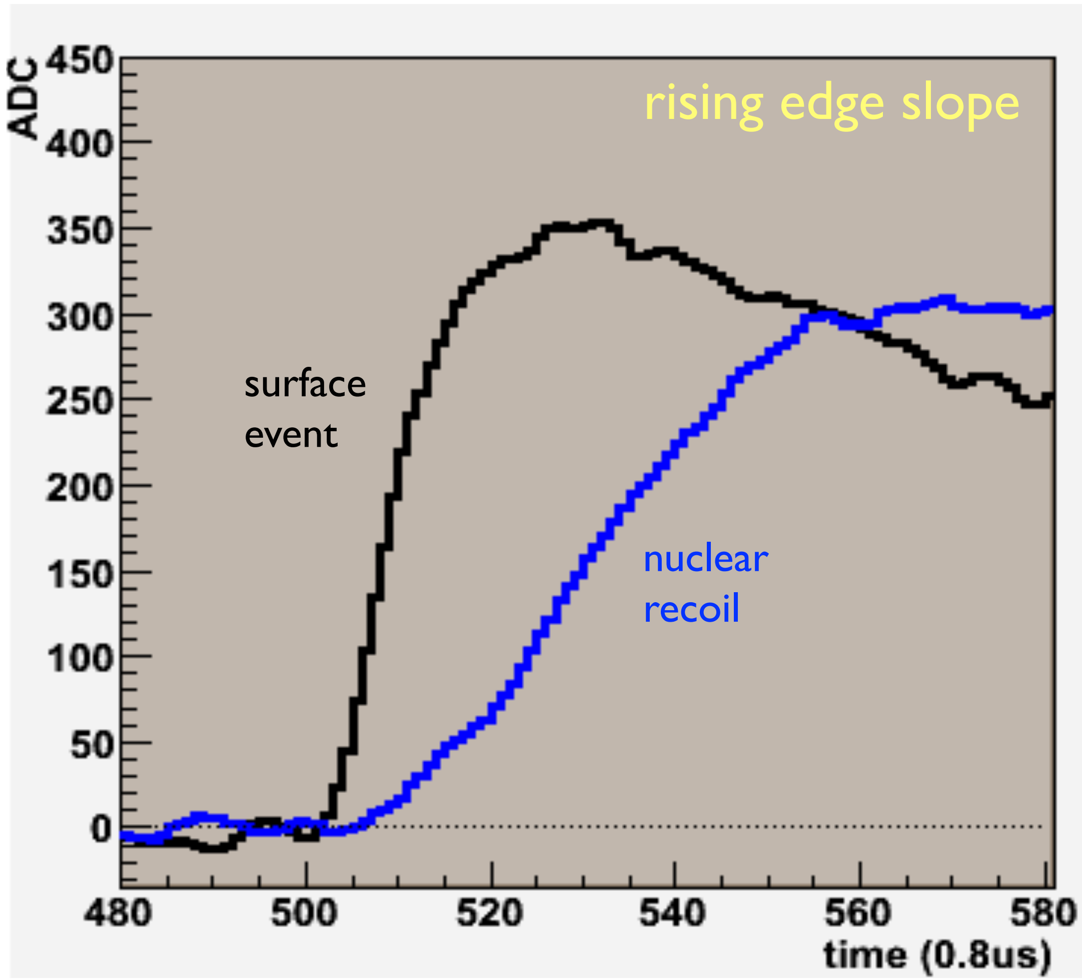


Athermal phonon sensors: ZIPs

Surface events rejected using phonon pulse shape

phonons produced in interactions near surface downconvert to propagating phonons more quickly; faster rise time



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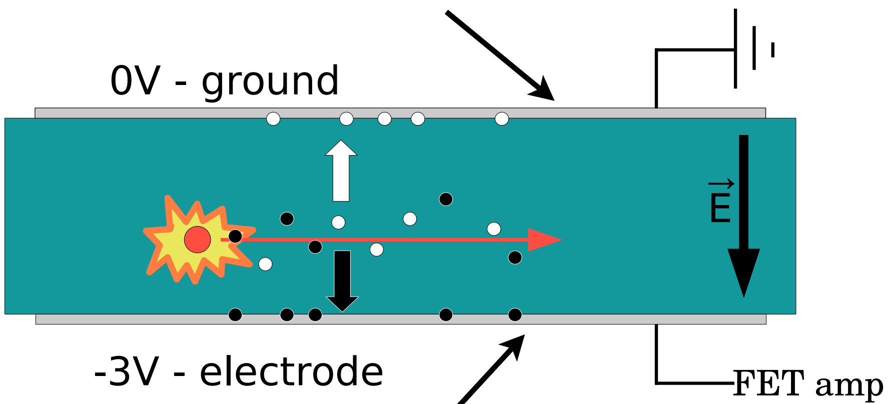

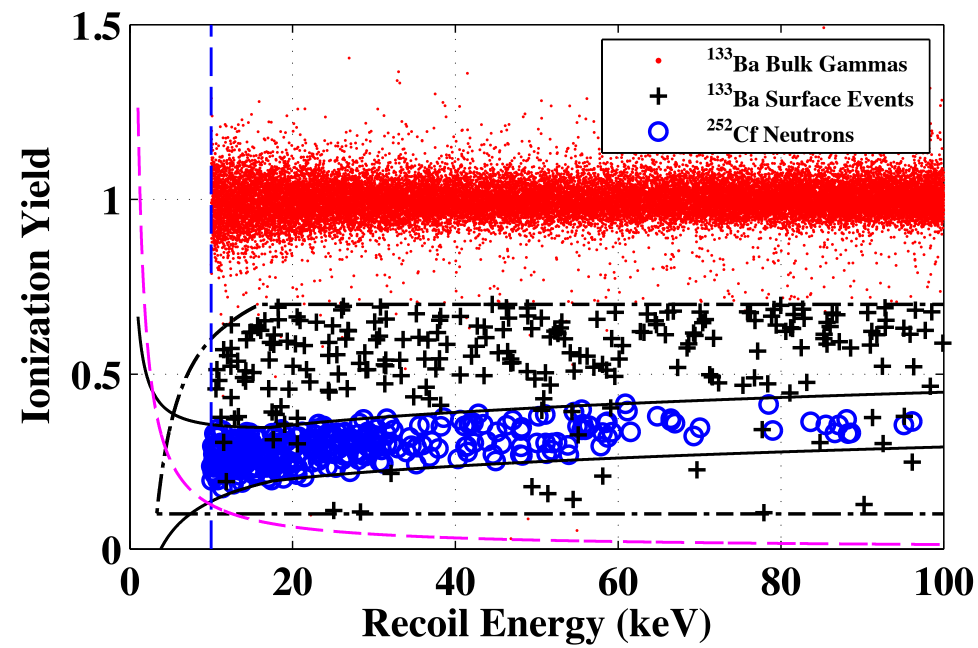

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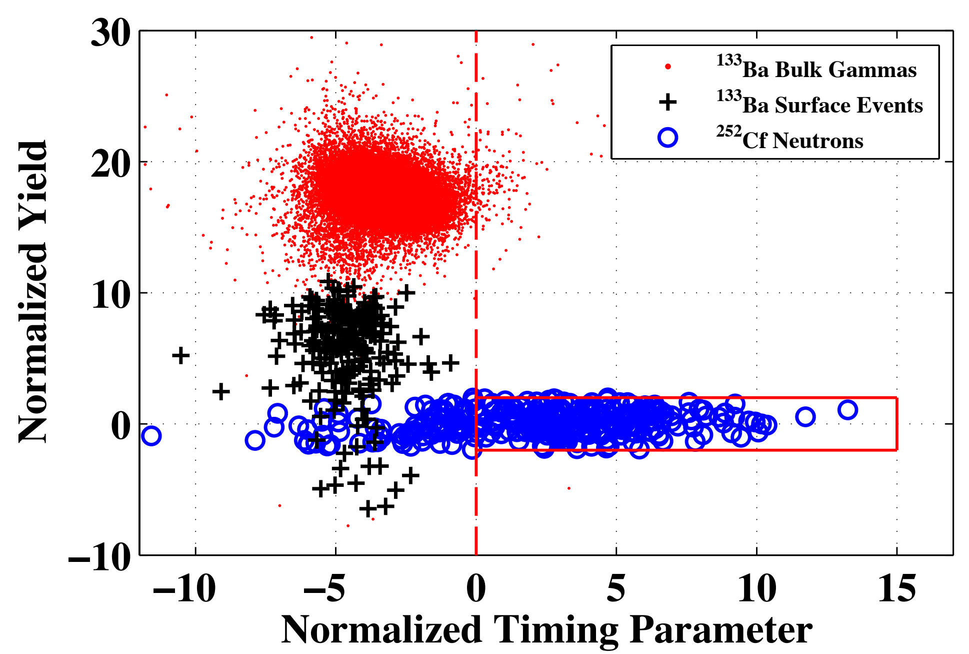
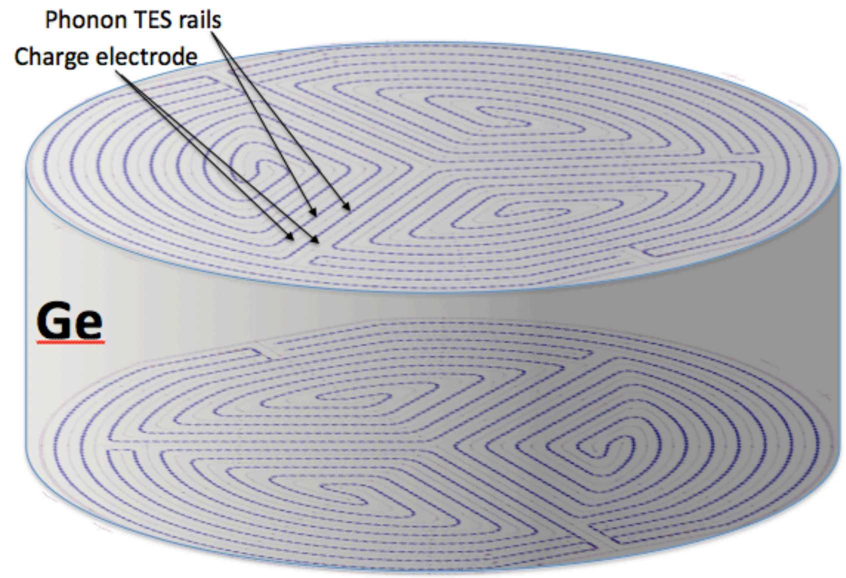


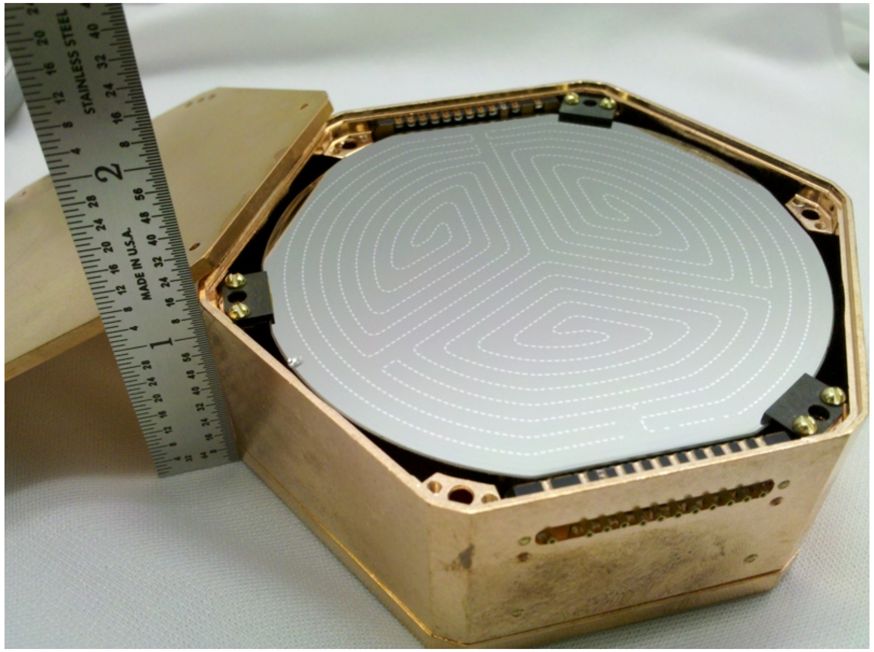
SuperCDMS: Surface Event Rejection w/Interdig. Electrodes

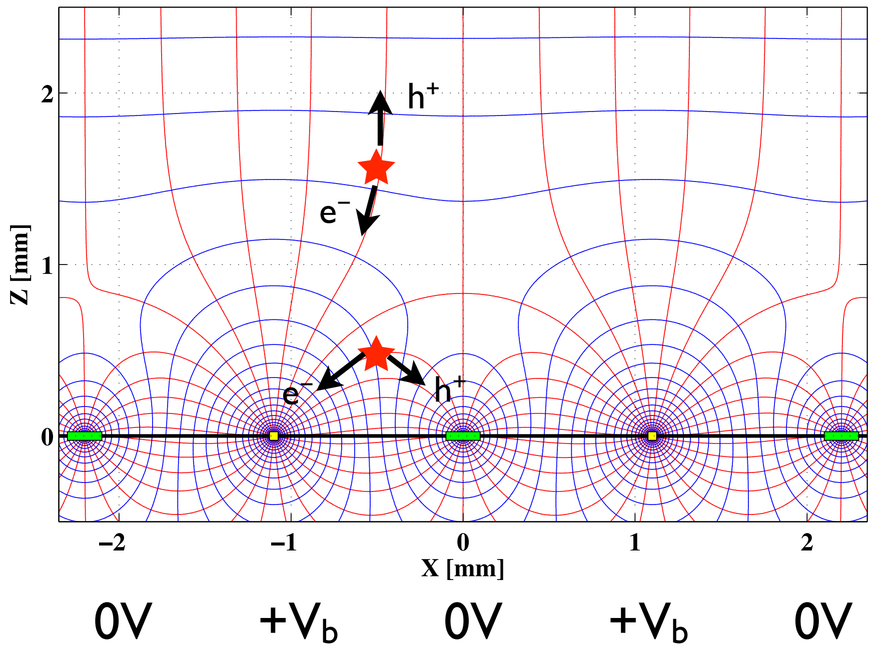
Alternating ground and biased electrodes further improve rejection

Field configuration:

- Bulk events have symmetric hole/electron collection
- Surface ERs are asymmetric







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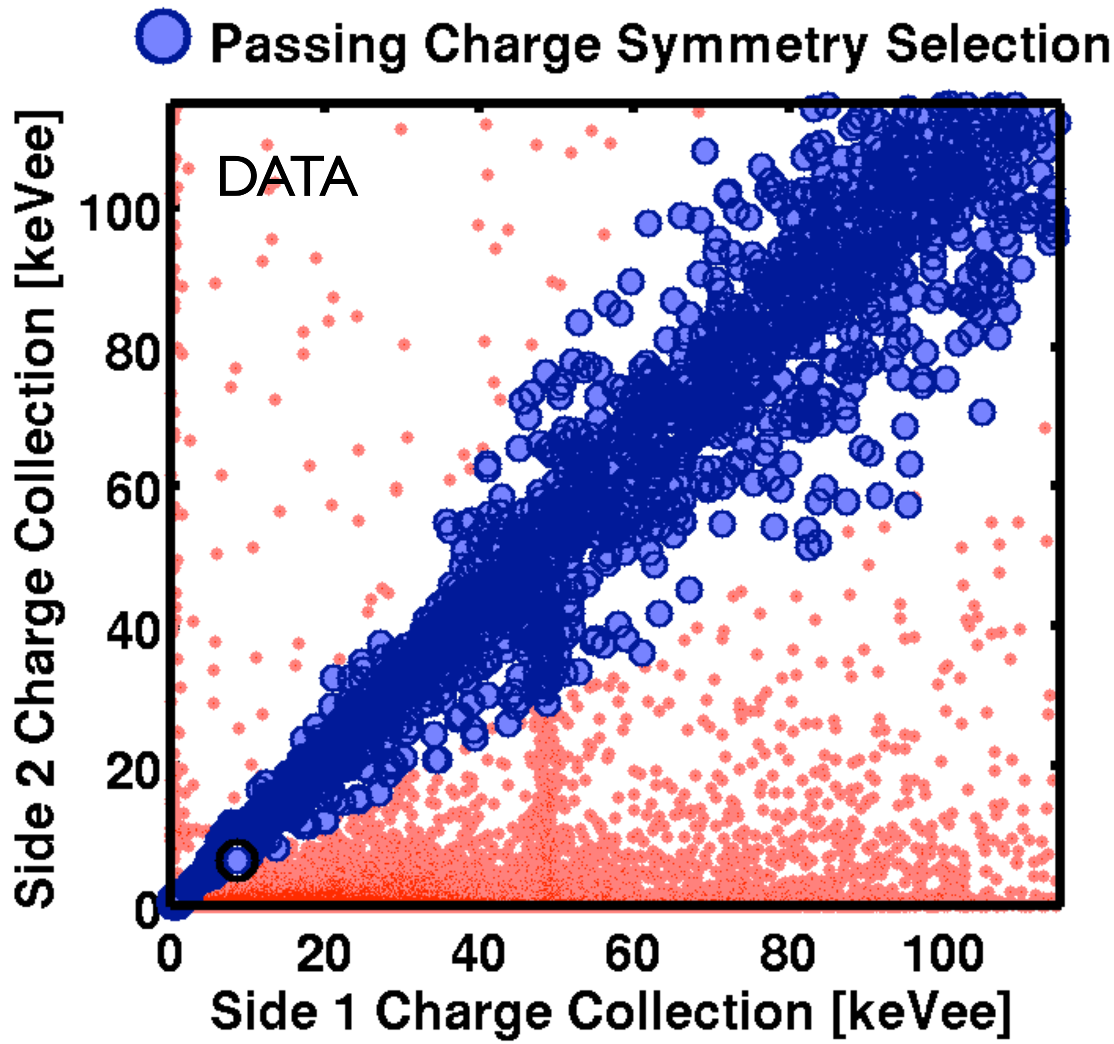

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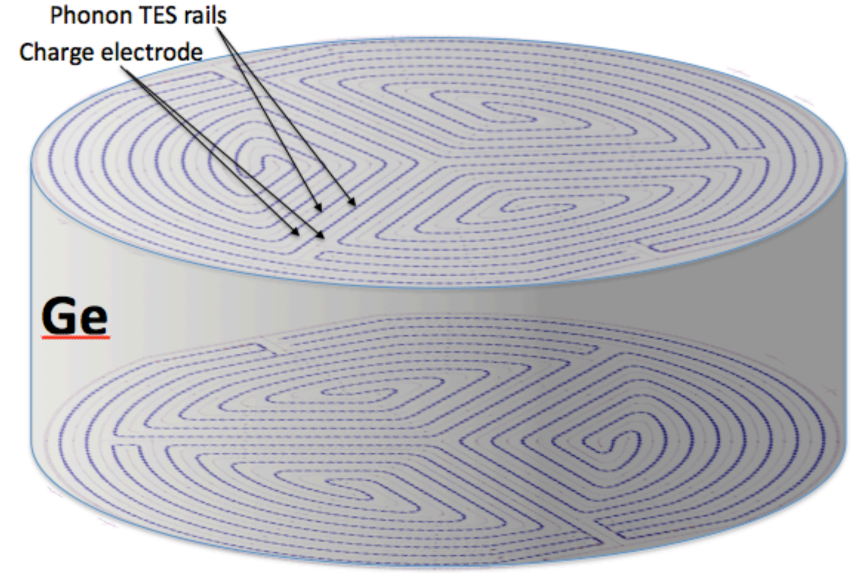
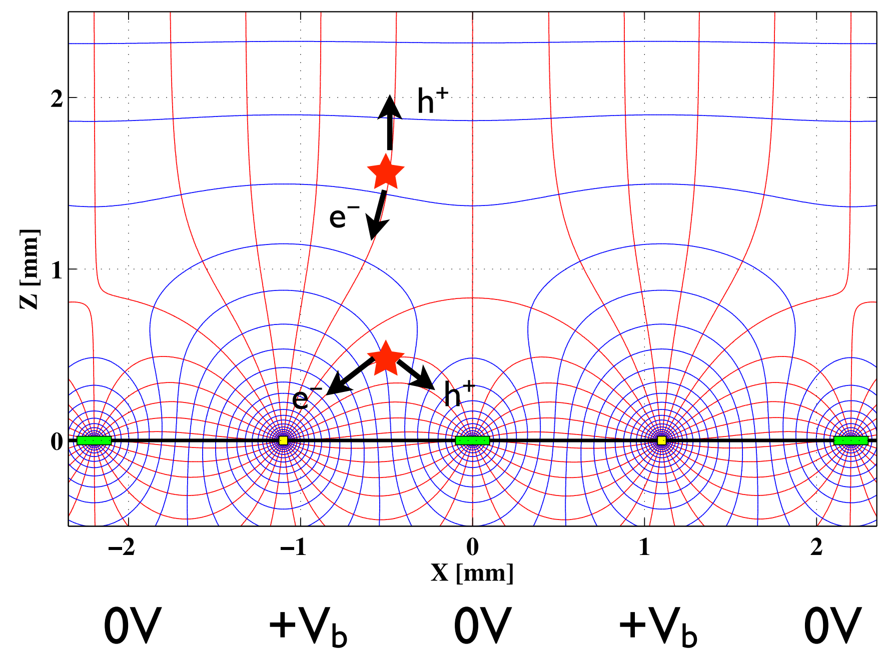
- Field strength
  - High field near surface raises ionization collection for surface electron recoils





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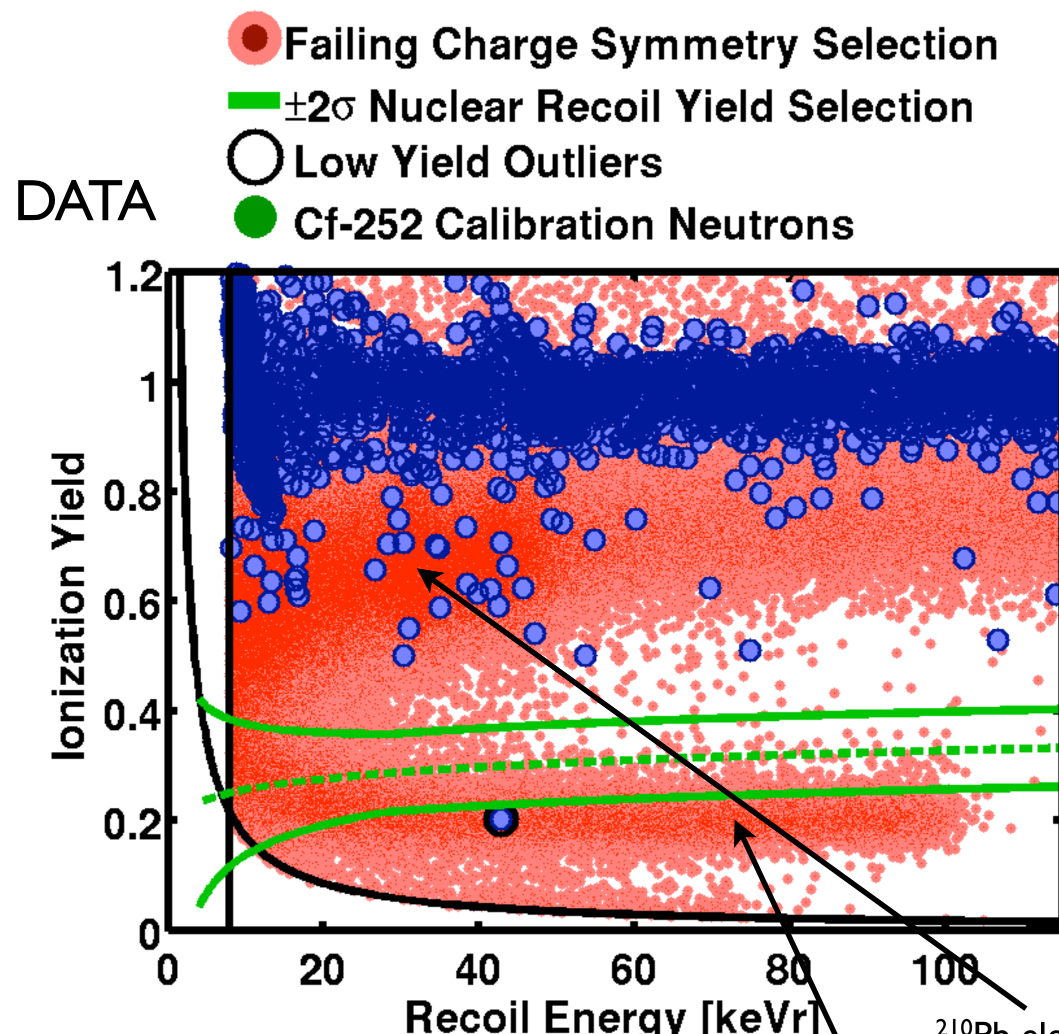
- ^{206}Pb nuclear recoils visible

Important goals achieved

- Surface ER rejection ~ 1×10^{-5} shown at Soudan > 8 keV$_r$, sufficient for SuperCDMS SNOLAB high-mass WIMP search



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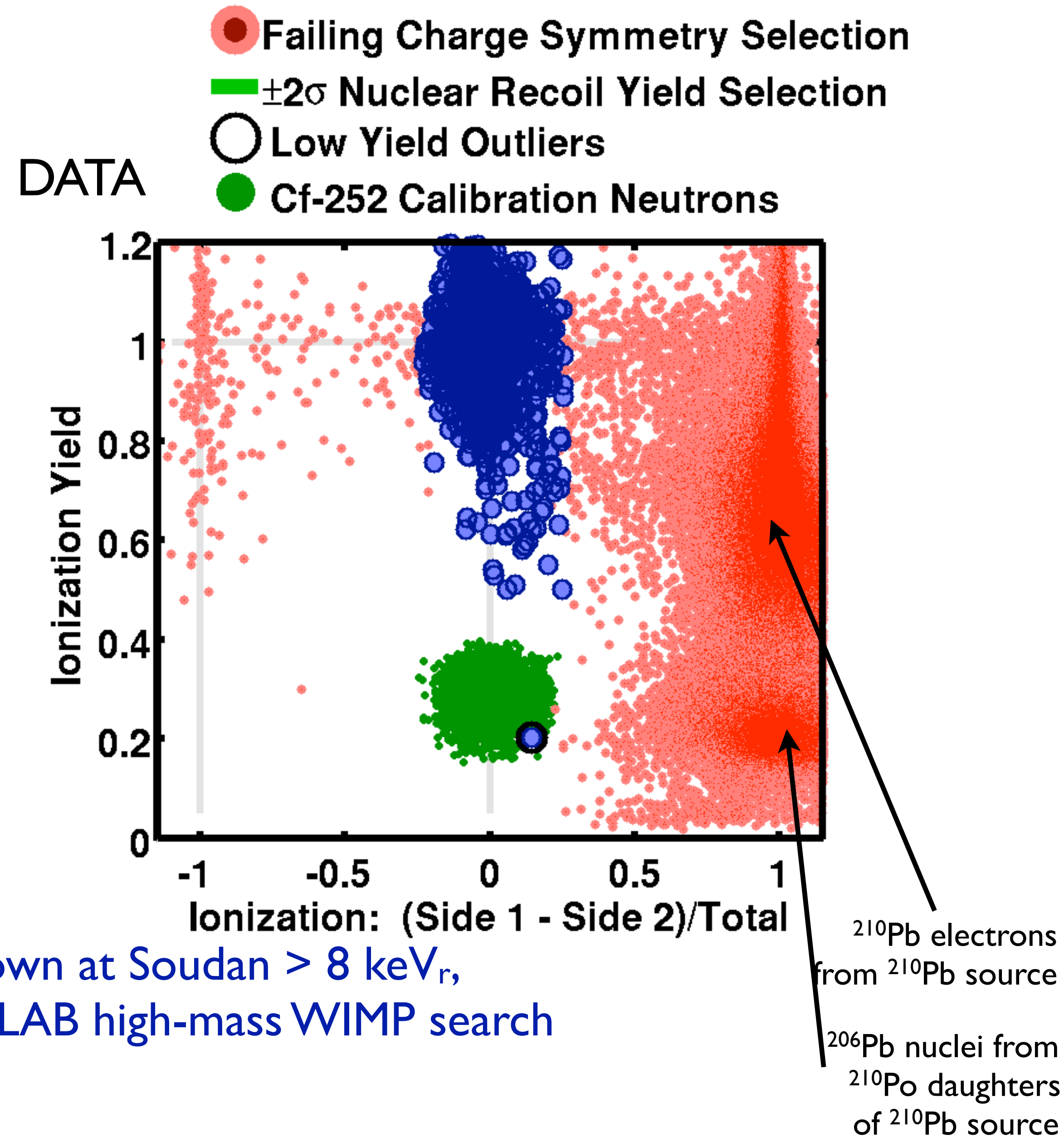
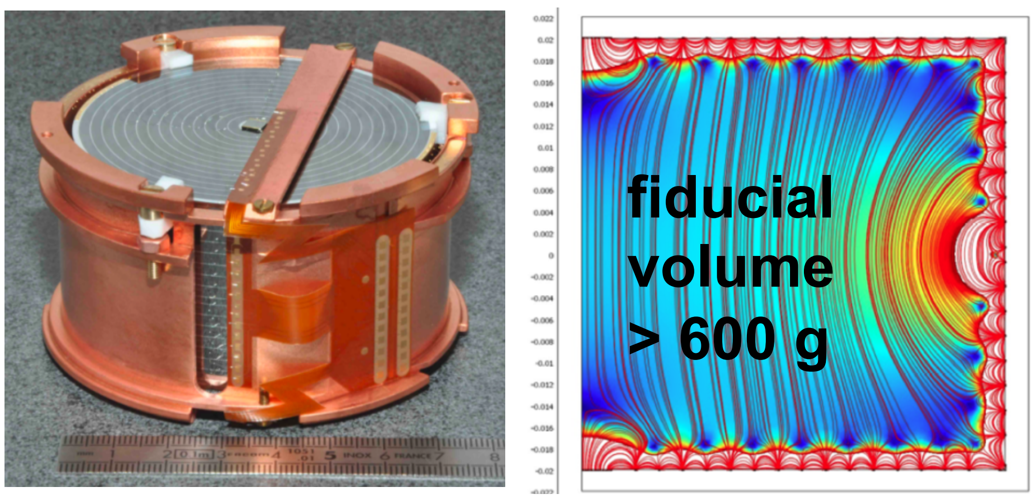


EDELWEISS: Surface Event Rejection w/Interdig. Electrodes

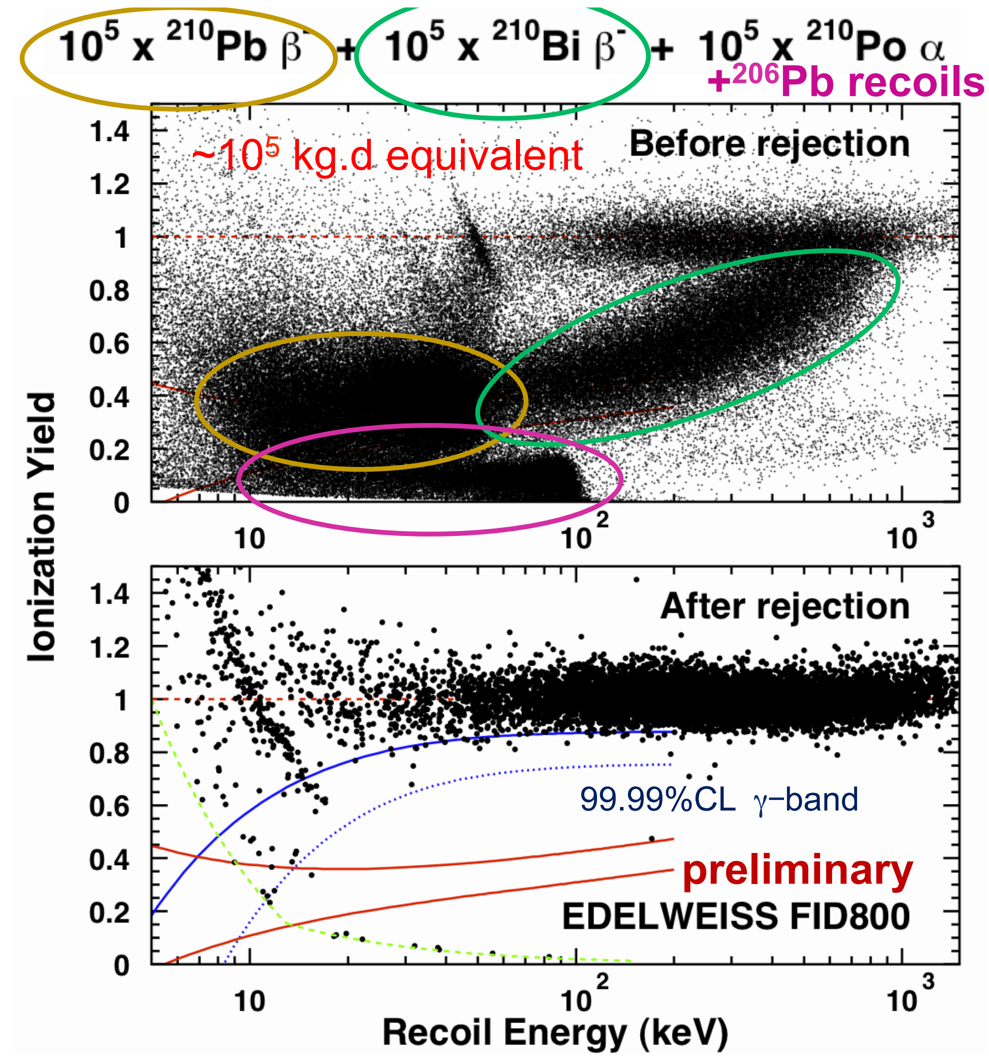
EDELWEISS also has demonstrated this technology

EDELWEISS III: More mass than SuperCDMS Soudan (30 kg vs. 9 kg), but higher threshold (15 keV_r vs. 8 keV_r)

FID 800g with 40x ~**600g** fiducial mass

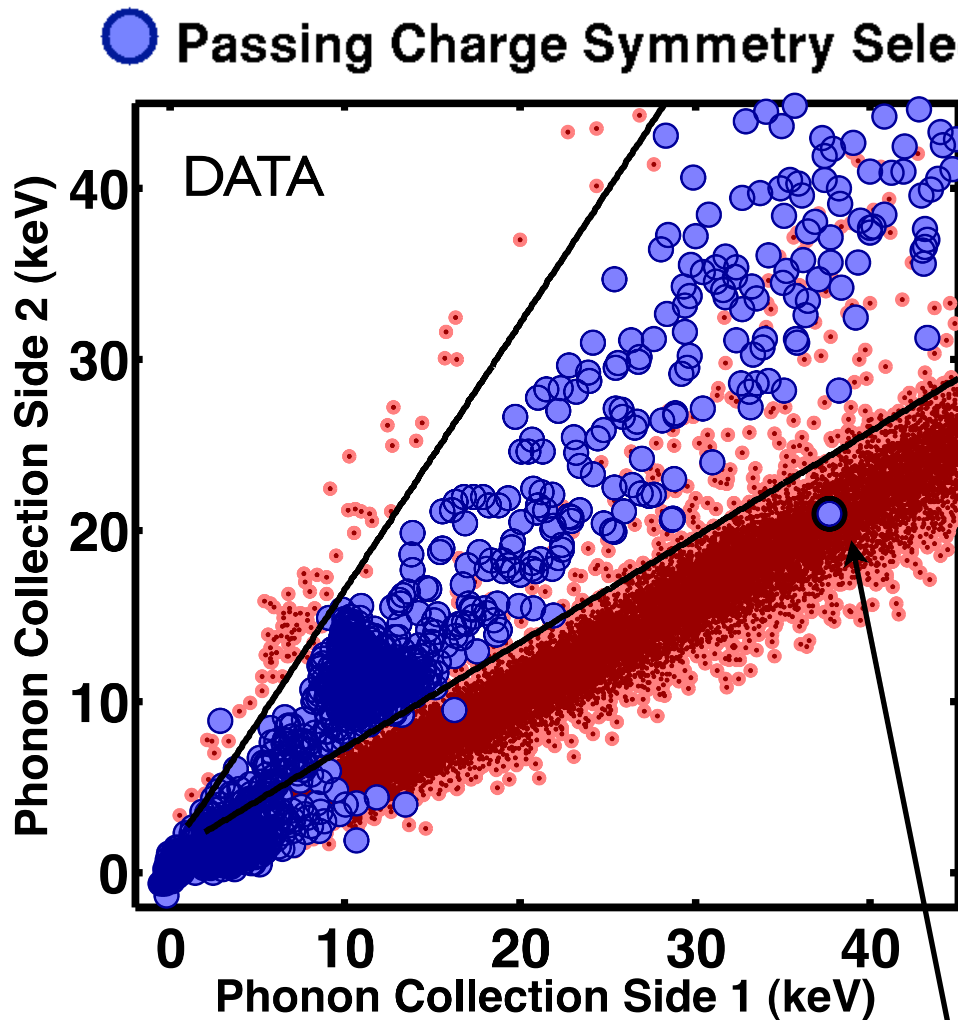


« **F**ull **I**nter**D**igitised »



SuperCDMS: Surface Event Rejection w/Phonon Asymmetry

- Phonon energy resolution much better than ionization
  - 200 eV_p vs. 300 eV_{ee} (1 keV_r)
  - Ionization asymmetry only useful > 8 keV_r, 10 GeV WIMP mass
- At low mass, define asymmetry using phonons only
  - Rejects outliers from ionization asymmetry cut at low keV_{ee}



outlier event at 42 keV_r, 8 keV_{ee} in prior slide; easily rejected using phonon asymmetry

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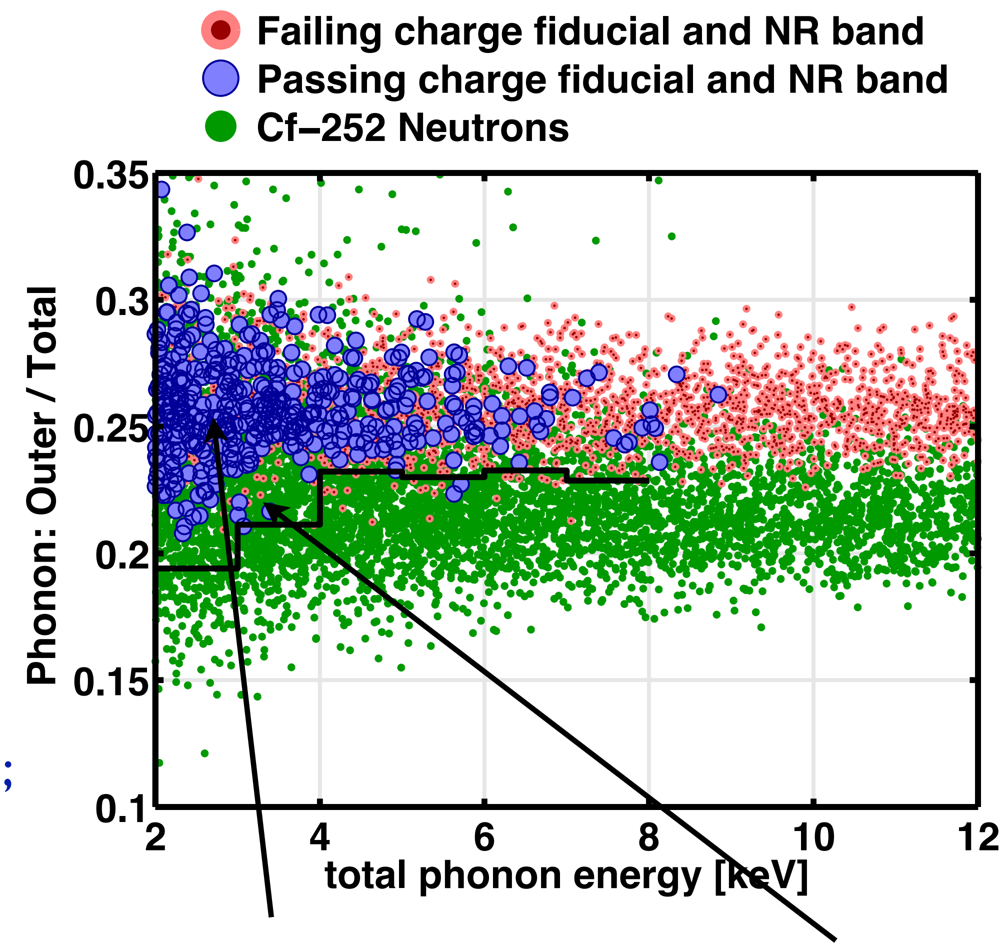
  - Use phonon radial partition instead; but phonon radial rejection of outer wall events not as good, yields analysis limited by radially misid'd ^{210}Pb; 30% fiducial volume

DATA-DRIVEN SIMULATION



events with ionization signal consistent with bulk, central even rejected by phonon radial partition

phonon radial rejection cut limited by radial misid of ^{210}Pb

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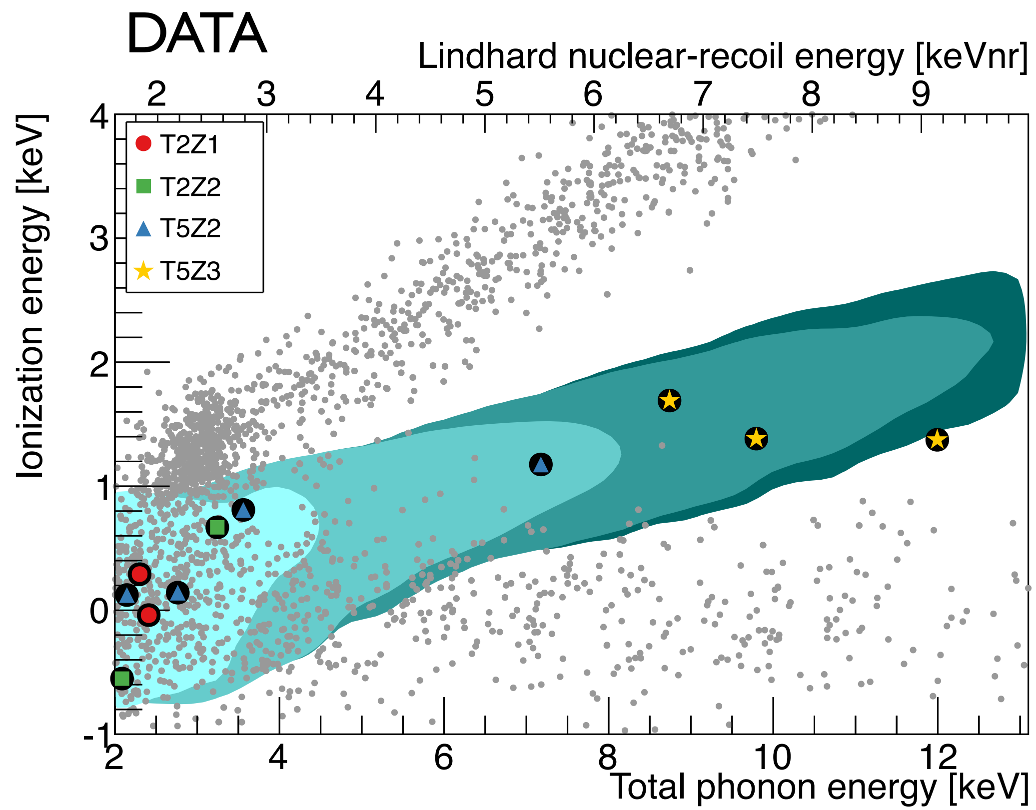

- Low mass analysis down to 2 keV_r using E_p, E_{ee}, phonon radial and z asymmetry from Soudan data published, excludes new parameter space down to 4 GeV WIMP mass

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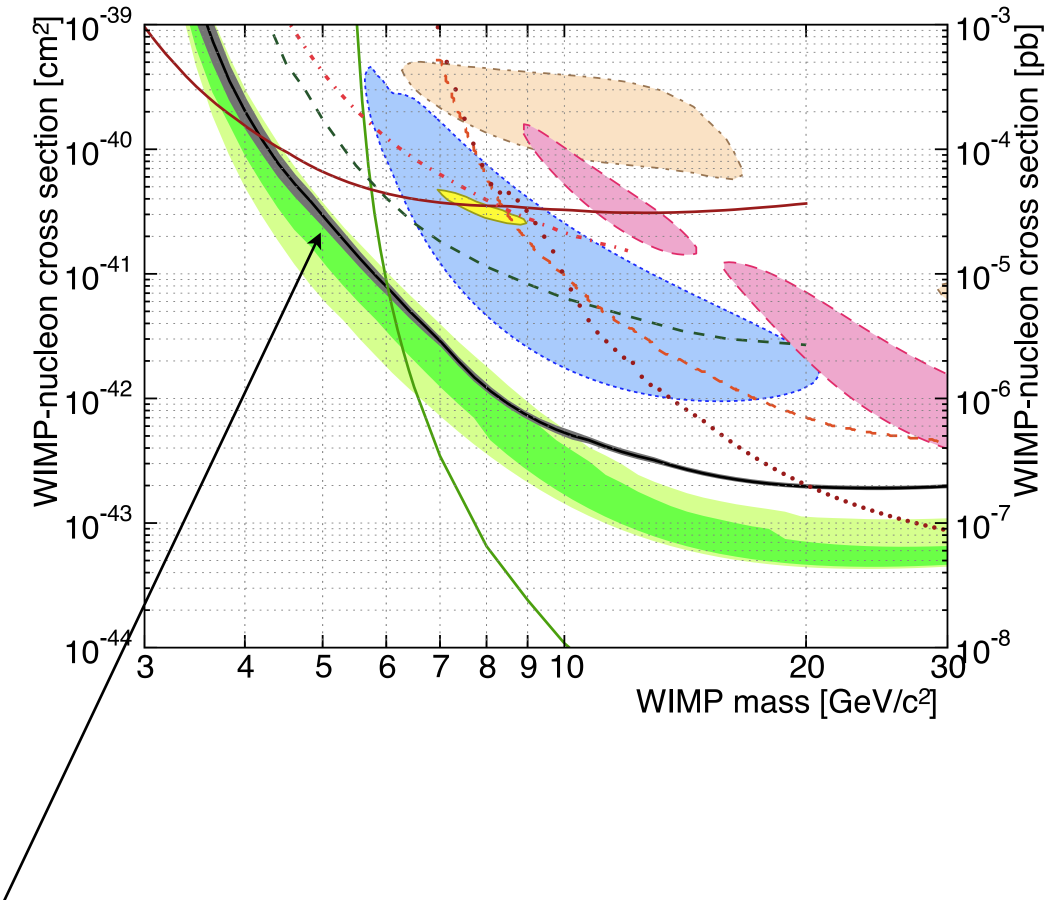

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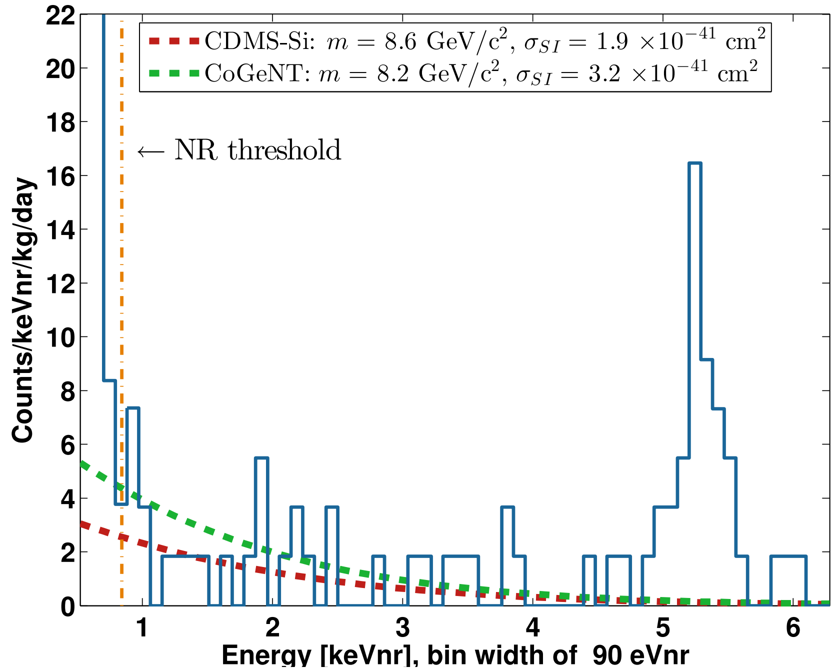
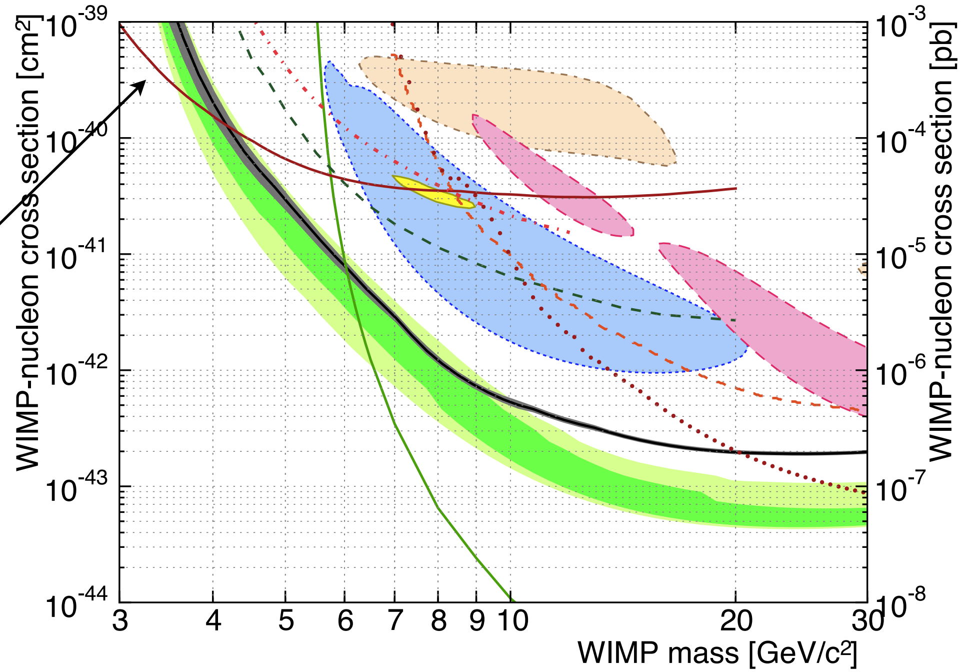
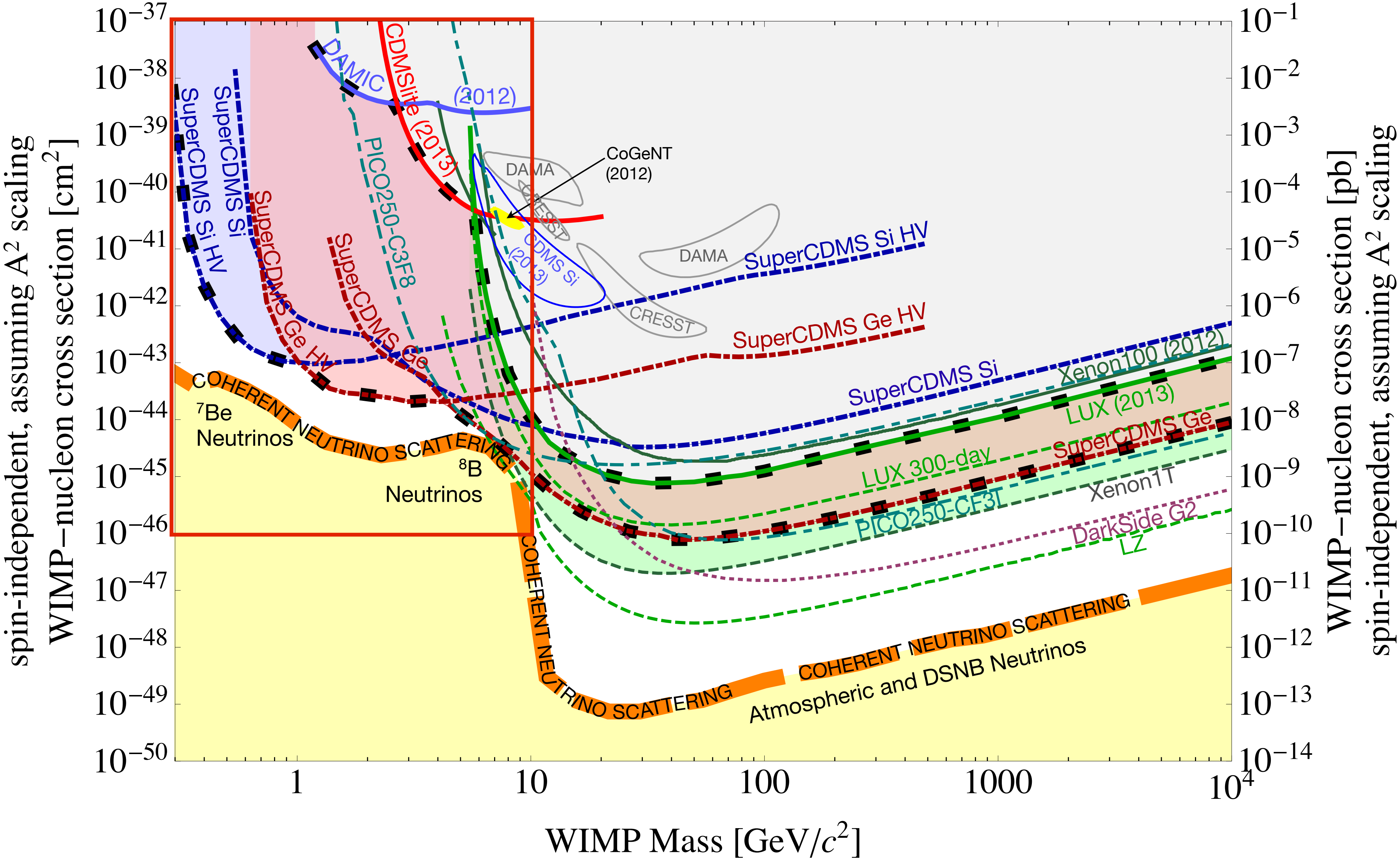
SuperCDMS: Accessing Lower Masses with HV Operation

- Phonon energy resolution much better than ionization
  - $\sigma = 300\ eV_{ee} \sim 1\text{-}1.5\ keV_r$, vs. $\sigma = 200\ eV_p$: factor of 5-8!
- Use phonons to detect ionization by applying high voltage (HV)
  - $E_p = E_q \times e \times V_b/(3.0\ eV)$
  - $V_b = 69\ V \rightarrow \sigma = 14\ eV_{ee}$, threshold = 170 eV_{ee} demonstrated at Soudan
    - Threshold/σ = 12 because noise very non-Gaussian with episodic excursions at Soudan
  - No event-by-event NR/ER discrimination, but stretches ER bgnd
  - Background-limited analysis sensitive down to 3 GeV published





Path to SuperCDMS SNOLAB Low-Mass Searches



Path to SuperCDMS SNOLAB Low-Mass Searches

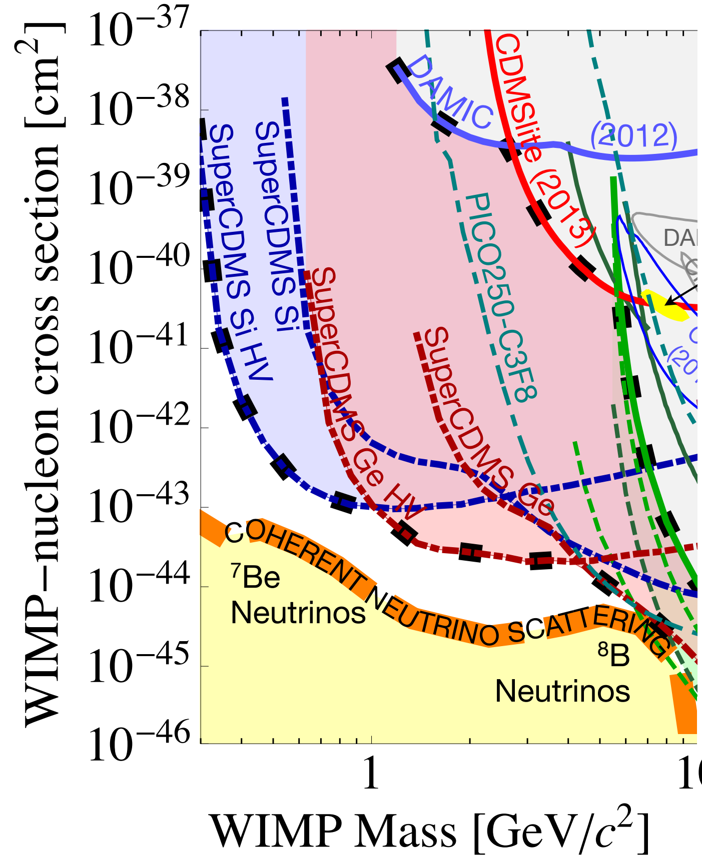
Better energy resolution

- Recently developed HEMT amplifiers + modified amplifier design: σ_q = 300 eV_{ee} will improve to σ_q = 100 eV_{ee} for SuperCDMS SNOLAB
- T_c = 60 mK phonon sensors are baseline for SuperCDMS SNOLAB
  → σ_p = 200 eV_p will be improved to σ_p = 50 eV_p

These resolutions extend Ge low-mass search to ~2-3 GeV

Addition of Si pushes to < 1 GeV

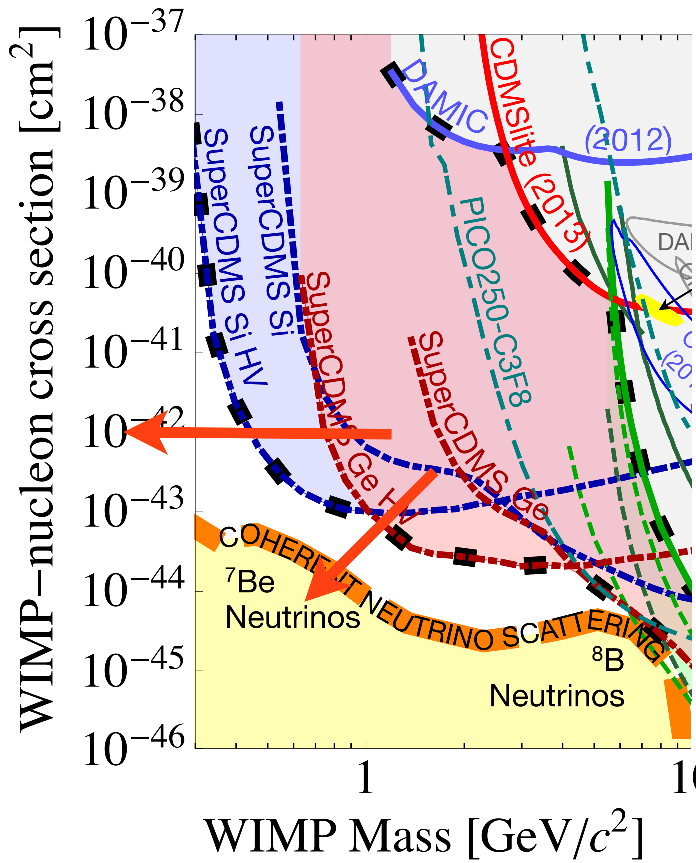
HV search extends down to < 1 GeV with Ge, to 0.5 GeV with Si



Also, need to reduce backgrounds (lower cross sections)

- Compton background reduced by improved materials selection, shielding (200x)
- ^{210}Pb background from Cu will be reduced to levels observed on Ge (20x)
- Should enable reach approaching coherent solar neutrino scattering background
- ^{32}Si (225 keV endpoint, 150 yr half-life) contamination in detector-grade Si unknown

Innovations Beyond SuperCDMS SNOLAB Baseline



Lower transition temperature?

- If the cryostat operates well, then T_c = 40 mK yields σ_p ~ 3x improved ~ 10 eV_p

Higher voltage operation

- Initial tests of CoGeNT/Majorana-style p-type point contact (PPC) Ge detectors suggests V_b ~ 400 V achievable
- → lower threshold, lower WIMP masses

Single e-h pair detection?

- At σ_p ~ 10 eV_p and V_b = 100 V, single e-h pair peaks become resolvable at V_b = 100 V
- At σ_p ~ 3 eV_p and V_b = 100 V, single e-h pair peaks are separated and NRs can occupy empty space (because more recoil energy per e-h pair)

Conclusion: Sub-GeV dark matter at CNS limit accessible with reasonable extrapolations of current technology

Conclusions and Discussion

There is a long history of innovations in solid-state detectors to reject backgrounds and reduce thresholds

These developments promise accessibility of sub-GeV masses at solar neutrino CNS limit

Questions to the audience:

- How hard should we push on thresholds vs. backgrounds?
  - Lower threshold → lower mass reach
  - Lower backgrounds → lower cross section reach
  - (w/ some level of complementarity)
- Do we understand the response at single e-h pair detection?
  - i.e., what surprises do nuclear/atomic/condensed matter physics hold for us
- What new backgrounds might arise?