Dark Matter Detection with Kinetic Inductance Detectors

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Berkeley Workshop on Dark Matter Detection

2015/06/09

Overview

Review: SuperCDMS SNOLAB low-mass reach with iZIPs and CDMS-HV

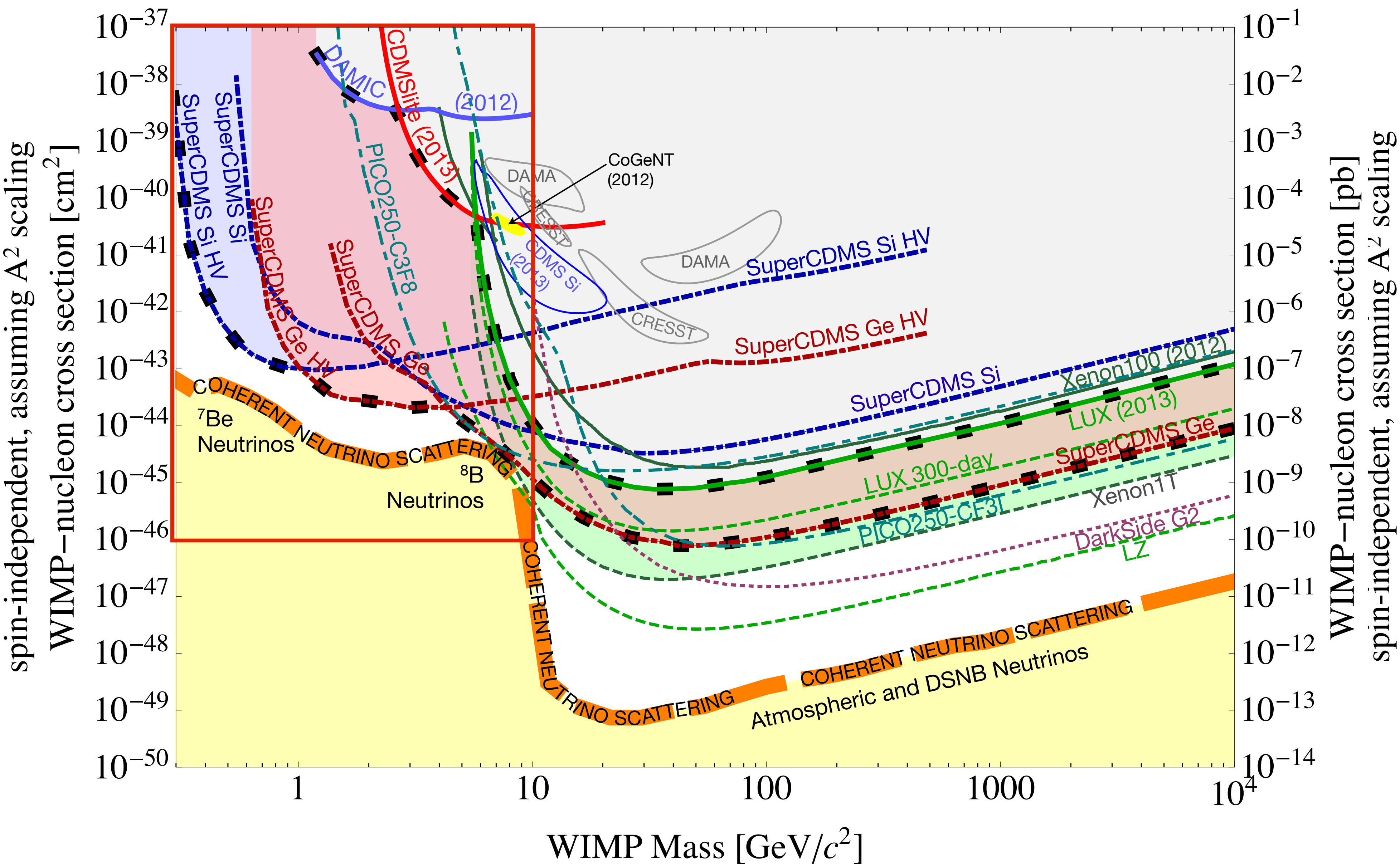
Motivation for kinetic inductance detectors in DM detection

- Multiplexability
  - improve fiducial volume for ionization-based surface-event rejection
  - phonon-only surface-event rejection and fiducial volume definition
- Sensitivity
  - reduced threshold, fiducial volume definition for CDMS-HV operation

Expected sensitivity

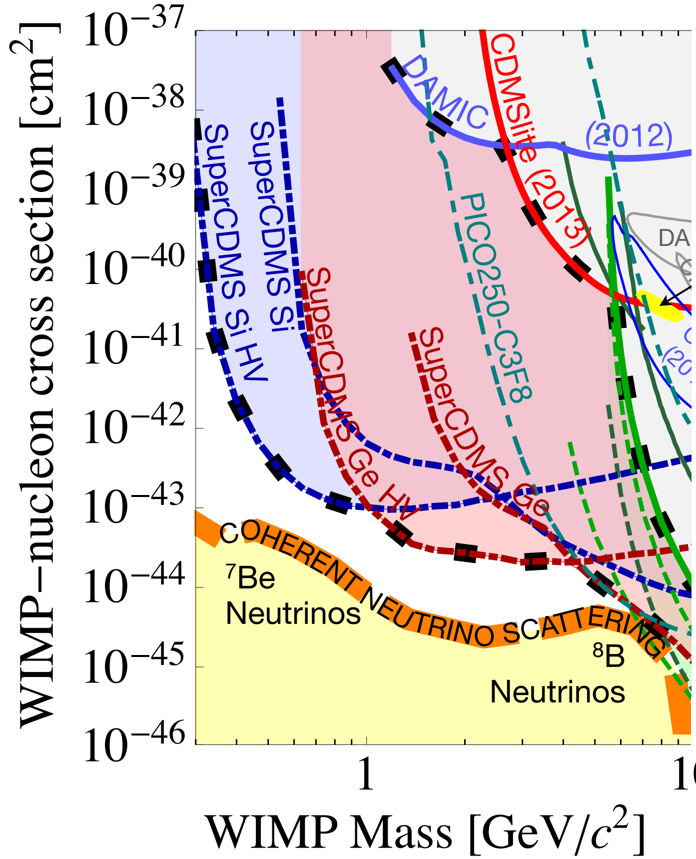
Progress to date

Searching for Low Mass DM with SuperCDMS SNOLAB



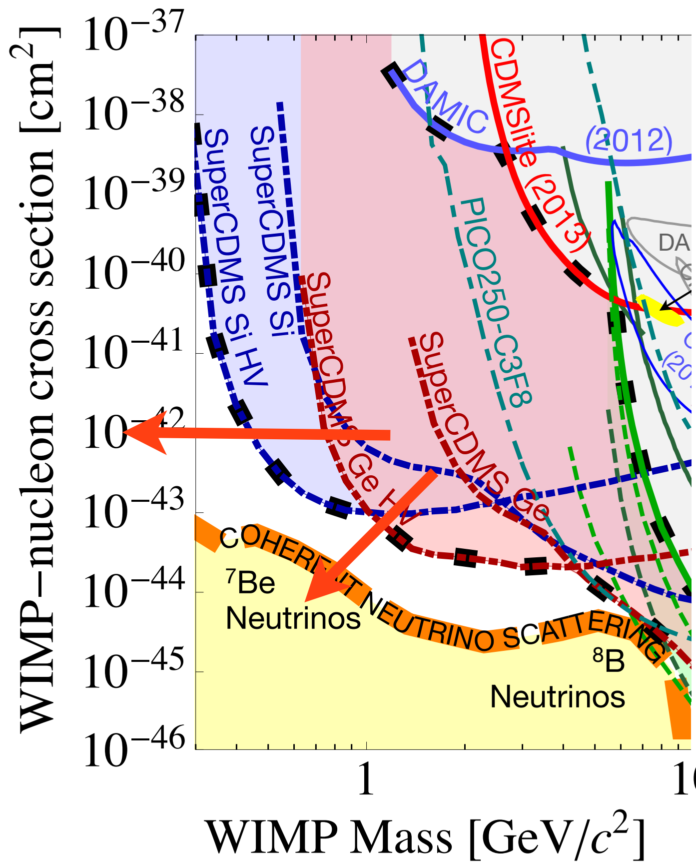
Searching for Low Mass DM with SuperCDMS SNOLAB

- Better energy resolution
  - Recently developed HEMTs + modified amplifier design:
    → σ_q = 300 eV_{ee} will improve to σ_q = 100 eV_{ee}
  - Reduced T_c (60 mK) phonon sensors are baseline
    → σ_p = 200 eV_p will improve to σ_p = 50 eV_p
- Ge low-mass dominates down to ~5 GeV
  - Ionization asymmetry-based rejection to ~10 GeV
  - Phonon asymmetry-based rejection to ~5 GeV
- HV search at 100 V bias 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



Beyond SuperCDMS SNOLAB Baseline

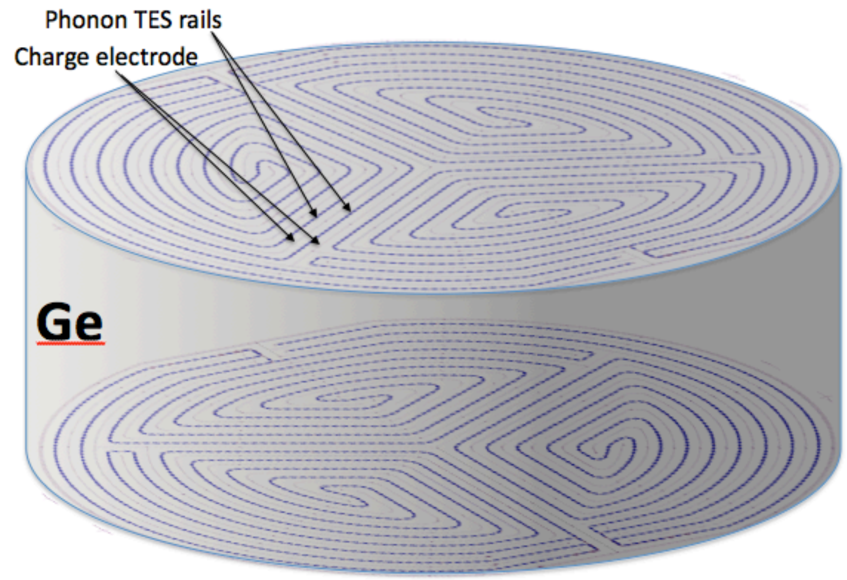
- Better σ_p (10 eV goal, T_c = 40 mK) will extend phonon asymmetry-based rejection
- Higher voltage operation
  - Initial tests of p-type point contact (PPC) Ge detectors, complementary amorphous Ge and Si blocking layers suggests $V_b \sim 400$ V
  - → lower threshold, stretch ER background
- Single e-h pair detection? (Pyle talk)
  - At large V_b and excellent σ_p, expect peaks in phonon spectrum due to integral e-h pairs
    - V_b = 100 eV, 3 eV to create e-h pair → peak at 103 eV
  - At $\sigma_p \sim 10$ eV$_p$ and V_b = 100 V, single e-h pair peaks become resolvable
  - At $\sigma_p \sim 3$ 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)
- Sub-GeV dark matter at CNS limit accessible with reasonable extrapolations of current technology

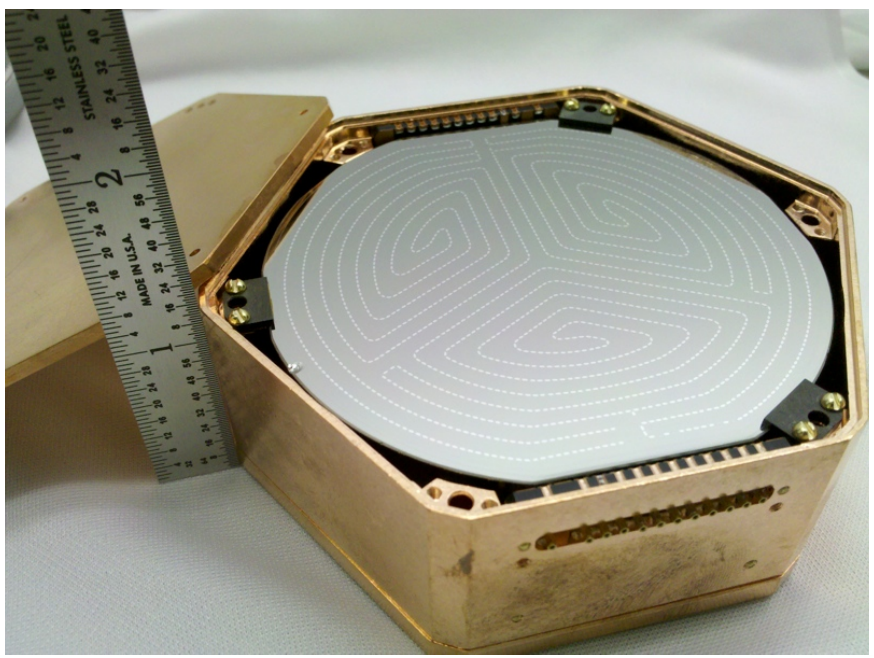


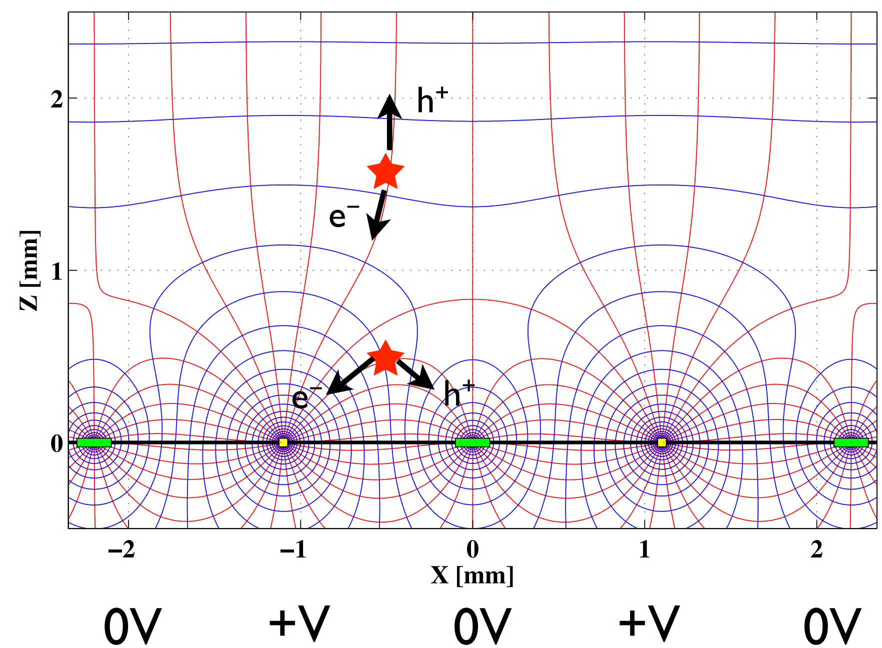
SuperCDMS iZIP Ionization-Based Surface Event Rejection

Alternating ground and biased electrodes yield rejection via sophisticated field configuration:

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







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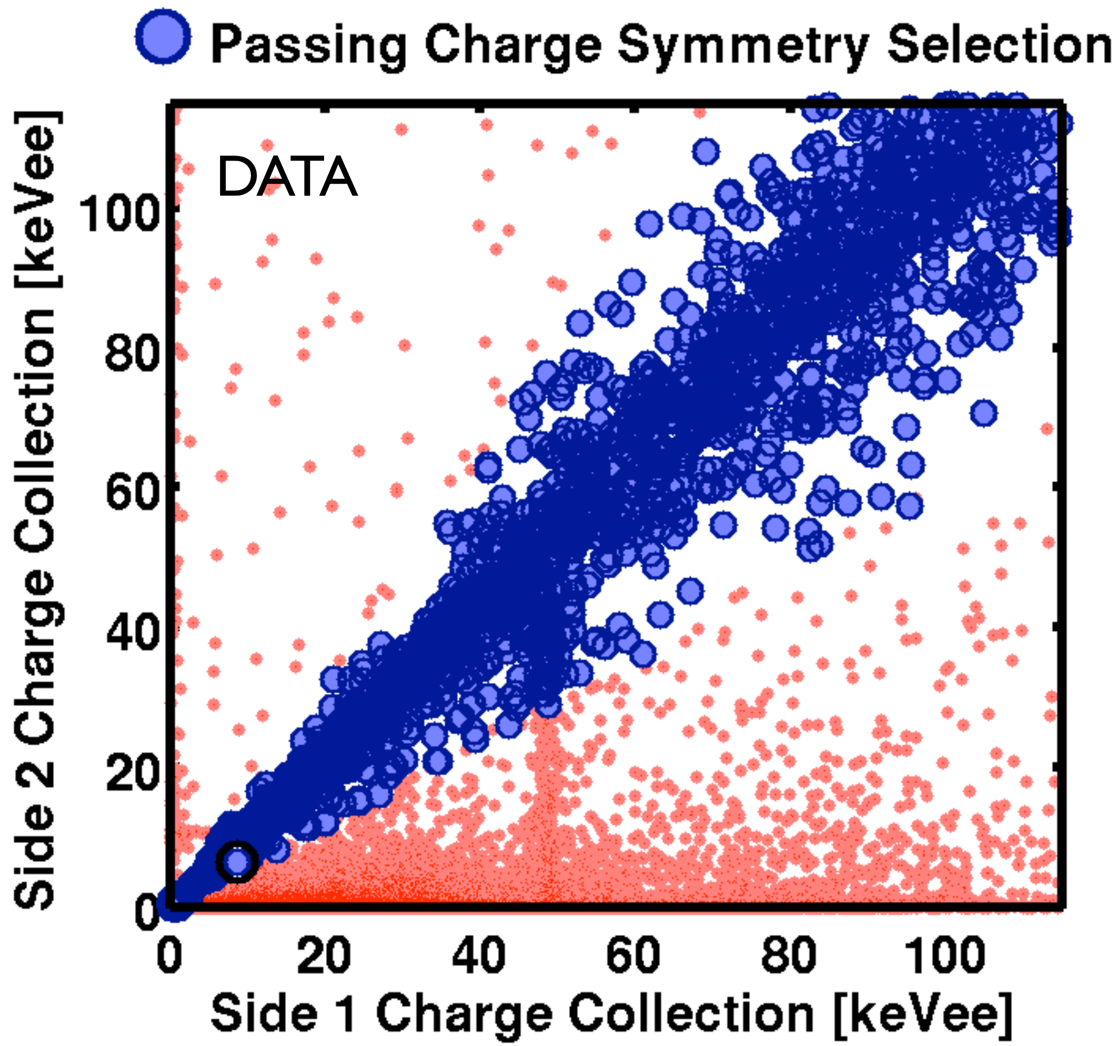

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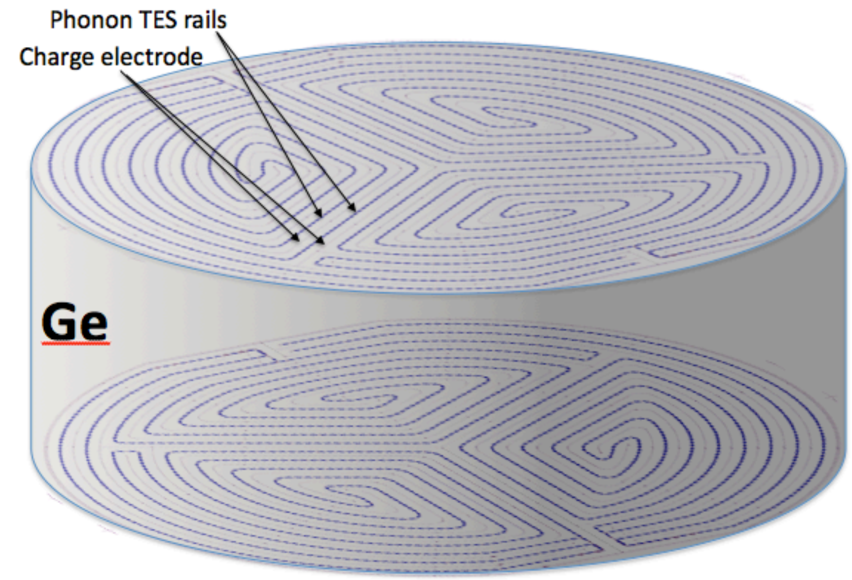
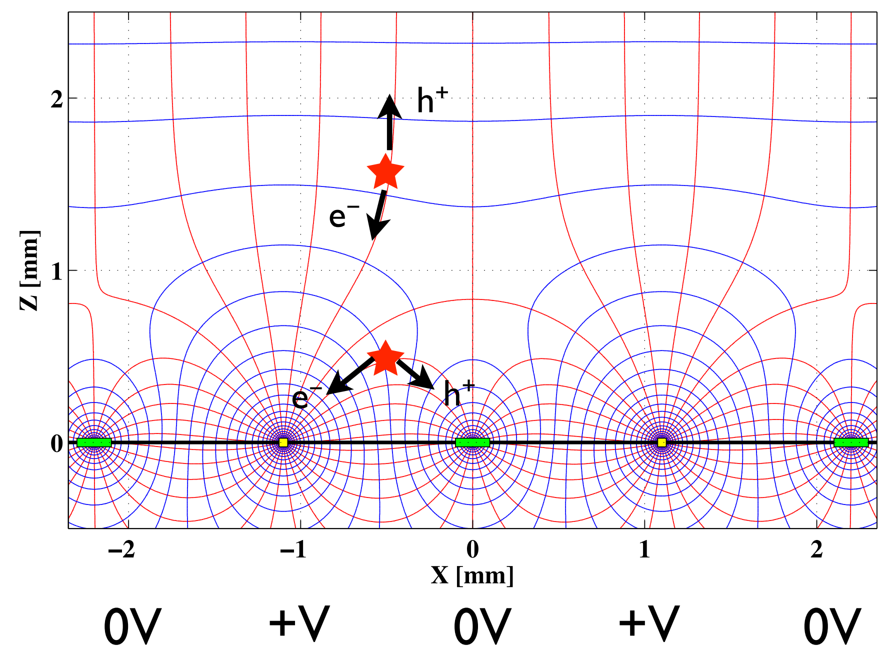
  - High field near surface raises ionization collection for surface electron recoils





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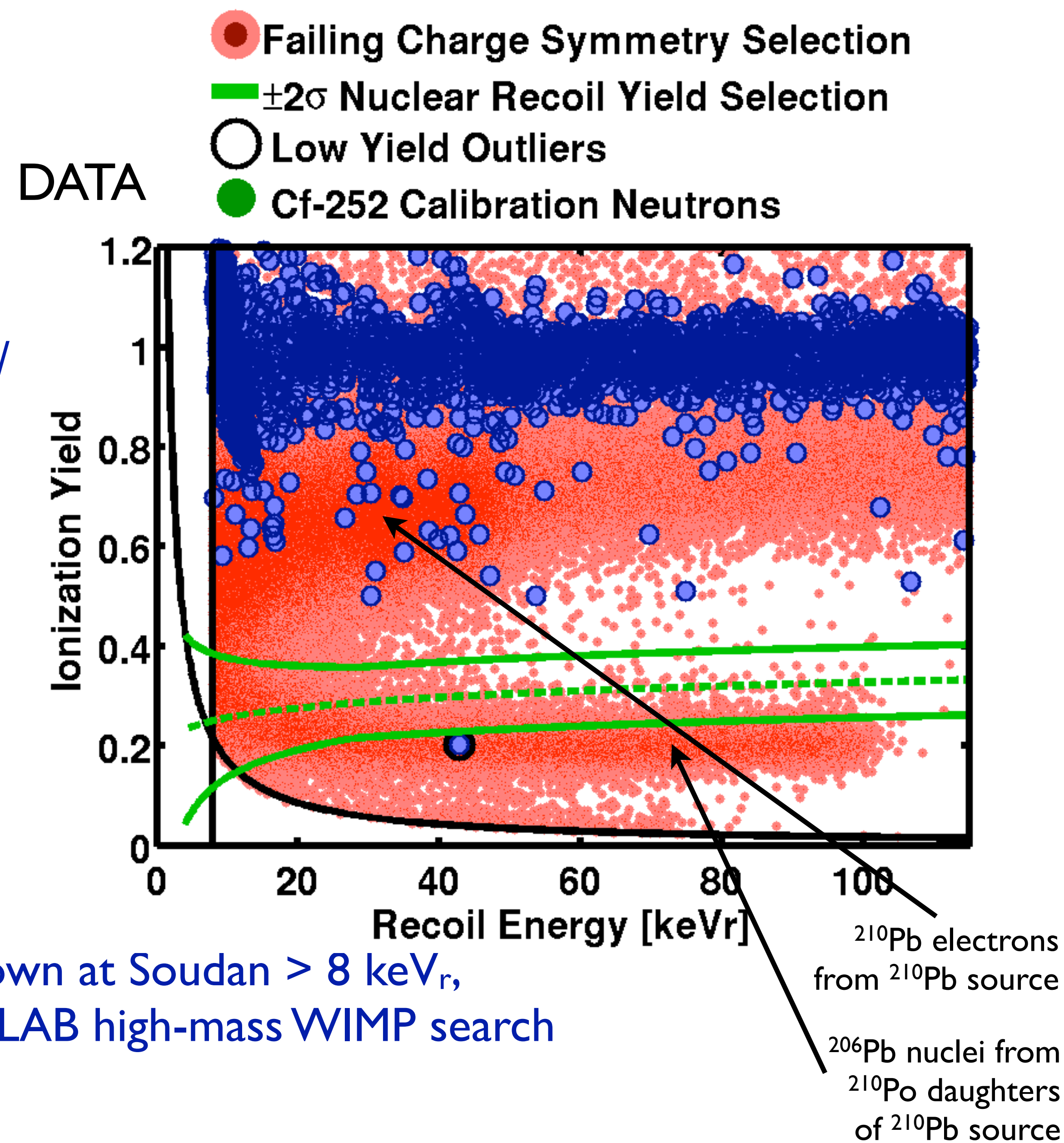
- Field strength
  - High field near surface raises ionization collection for surface electron recoils
  - ^{206}Pb nuclear recoils visible
- Achieves excellent rejection
  - Surface ER rejection ~ 1 x 10^{-5} shown at Soudan > 8 keV$_r$, sufficient for SuperCDMS SNOLAB high-mass WIMP search



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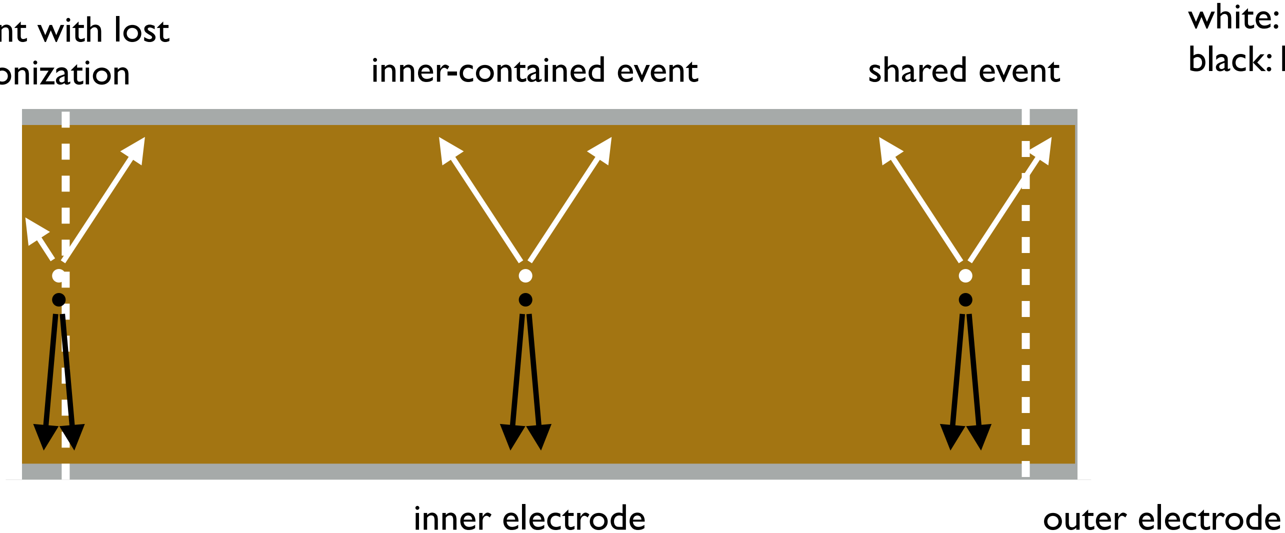

white: electrons
black: holes

also: near edge of detector, field lines bend outward and charge is lost to outer sidewall

Fiducialization: inner-electrode containment

- e^- propagate obliquely at low biases: 33° from z
- need full containment to trust both e and h side measurements to measure asym
- fiducial volume fraction for inner electrode = 55%

Implications

- Efficiency, obviously
- Threshold for surface-event rejection set by ionization resolution:
  doesn't benefit from excellent phonon energy resolution
- Would like to be able to rely on holes alone

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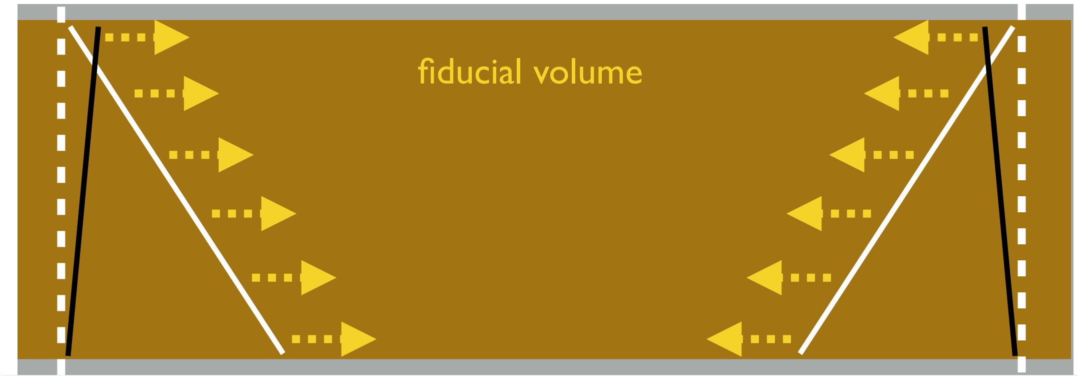

inner electrode
outer electrode

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SuperCDMS iZIP Phonon-Based Surface Event Rejection

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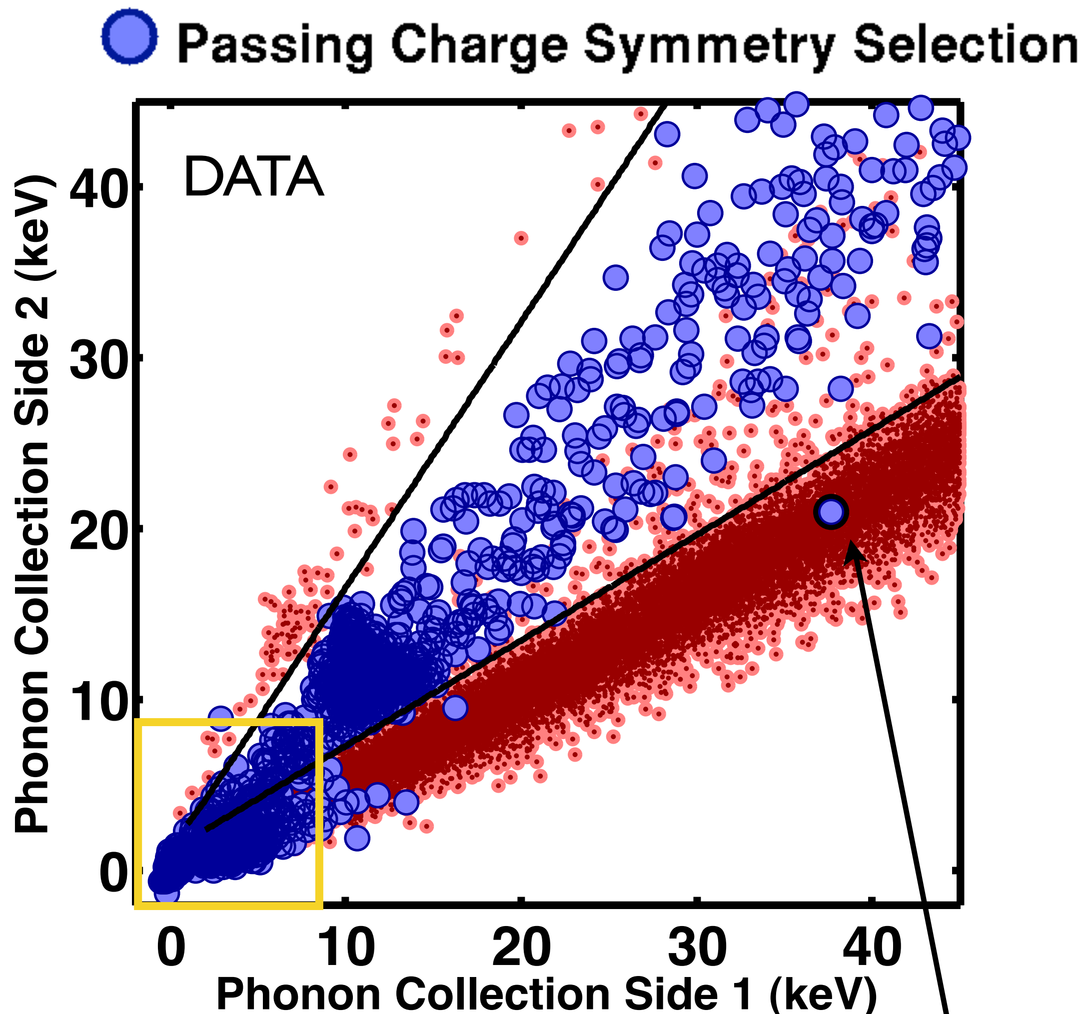
  - 200 eV_p now vs. 300 eV_{ee}
  - Ionization asymmetry only useful $\gtrsim$8 keV_r, $\gtrsim$10 GeV WIMP mass
  - Will improve for SNOLAB: → 50 eV_p vs. 100 eV_q, $\gtrsim$3 keV_r, $\gtrsim$3 GeV WIMP mass
- At low mass, define asymmetry using phonons only



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

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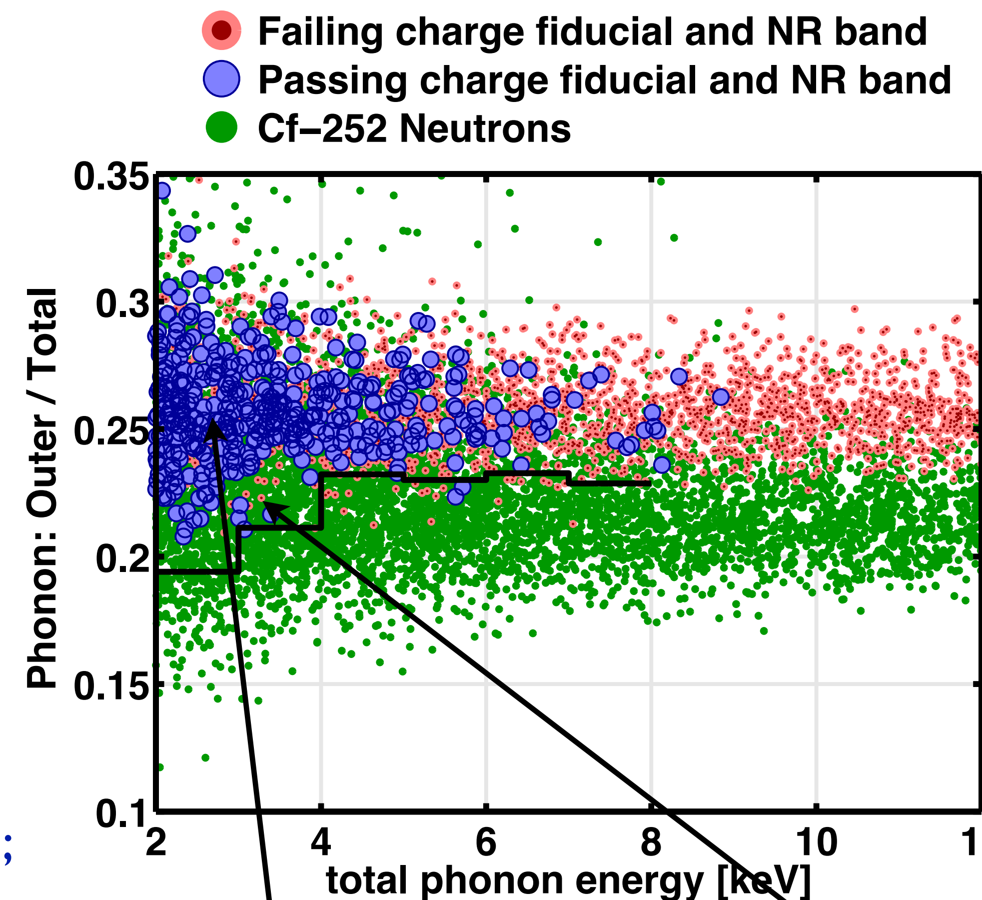
- At low mass, define asymmetry using phonons only
  - But can't use ionization to define fiducial volume (radial)
  - Use phonon radial partition instead; but phonon radial rejection of outer wall events not as good, yields analysis limited by radially misid'd ^{210}Pb; 30% fiducial volume

data-driven simulation



events that would have been accepted as bulk nuclear recoils by ionization asymmetry: rejected by phonon fiducialization cut

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

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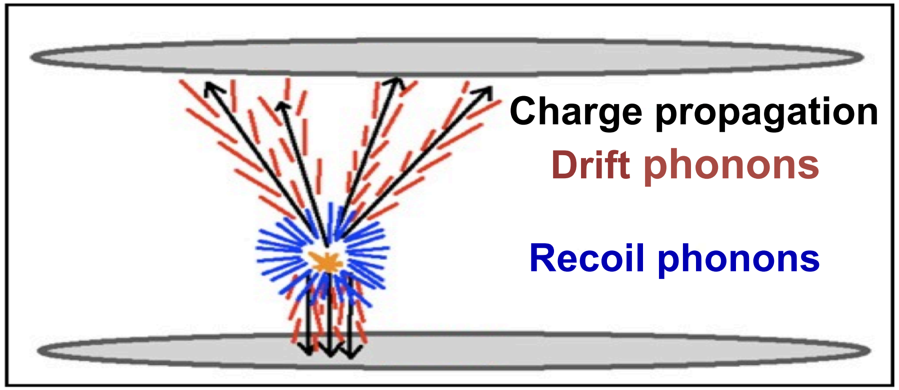
- Ideally:
  - Use phonons to define radial fiducial volume with high efficiency
  - Use phonons for surface-event rejection to accept hole-only collection
  - Use ionization signal only for defining bulk electron-recoil rejection (using holes only)
  - Requires much better position fidelity from phonon signal

SuperCDMS-HV: Technique and Challenges

Use phonons to measure e-h production via Luke-Neganov phonon production

- $E_p = E_r + N_Q\, eV_b = E_r + E_{ee}\,(eV_b / E_{Fano})$
- $eV_b >> E_{Fano} = 3$ eV $\rightarrow E_p >> E_r, E_{ee}$

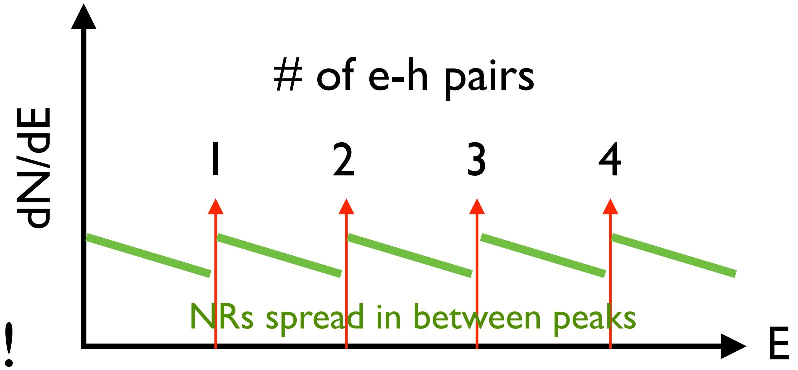


Gain = (eV_b / E_{Fano}) requires full drift of e and h through bias voltage

- At high bias, phonon emission isotropizes e^- drift → higher fiducial volume than iZIP

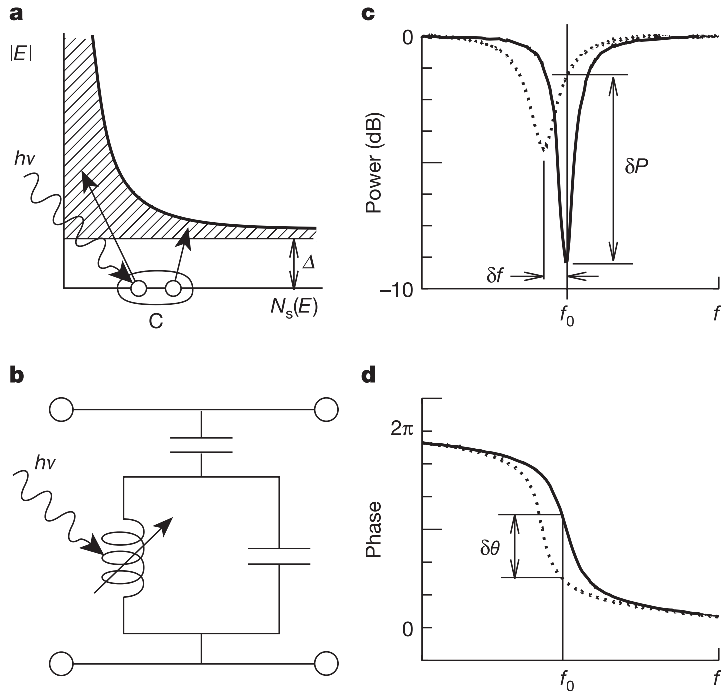
Fiducialization, background rejection critical to sensitivity

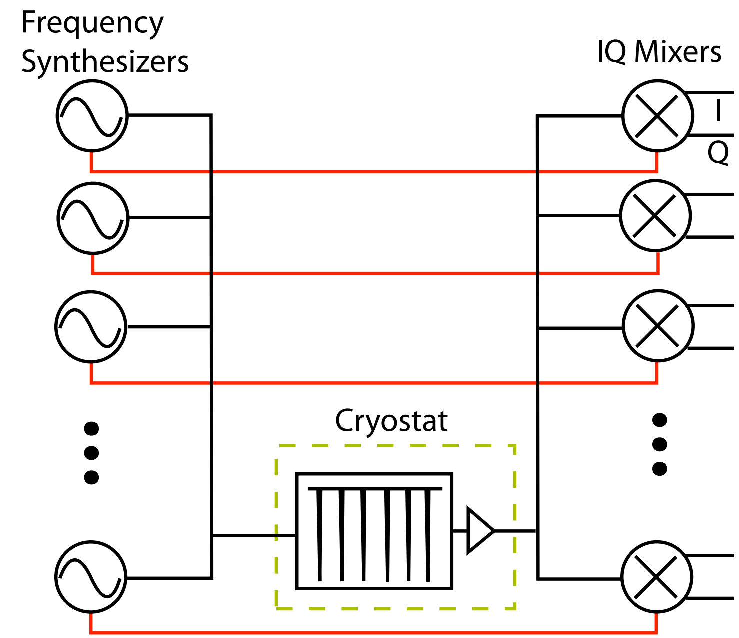
- For continuum operation (not single e-h mode)
  - Lost ionization smears ER and NR spectra: not a big problem
  - But backgrounds are larger at outer walls, so want to reject to reduce bgnd because continuum operation is a bgnd-limited experiment
- For single e-h operation
  - Lost ionization smears ER peak: degrades ER rejection
  - Still need to worry about bgnd rejection: ^{210}Pb nuclei from sidewalls, housing



Need phonon position reconstruction!

Basics of Kinetic Inductance Detectors





Superconductors have an AC inductance due to inertia of Cooper pairs

alternately, due to magnetic energy stored in screening supercurrent

Changes when Cooper pairs broken by energy, creating quasiparticles (qps)

Sense the change by monitoring a resonant circuit

Key point: superconductors provide very high Q ($Q_i > 10^7$ achieved), so thousands of such resonators can be monitored with a single feedline

enormous cryogenic multiplex technology relative to existing ones

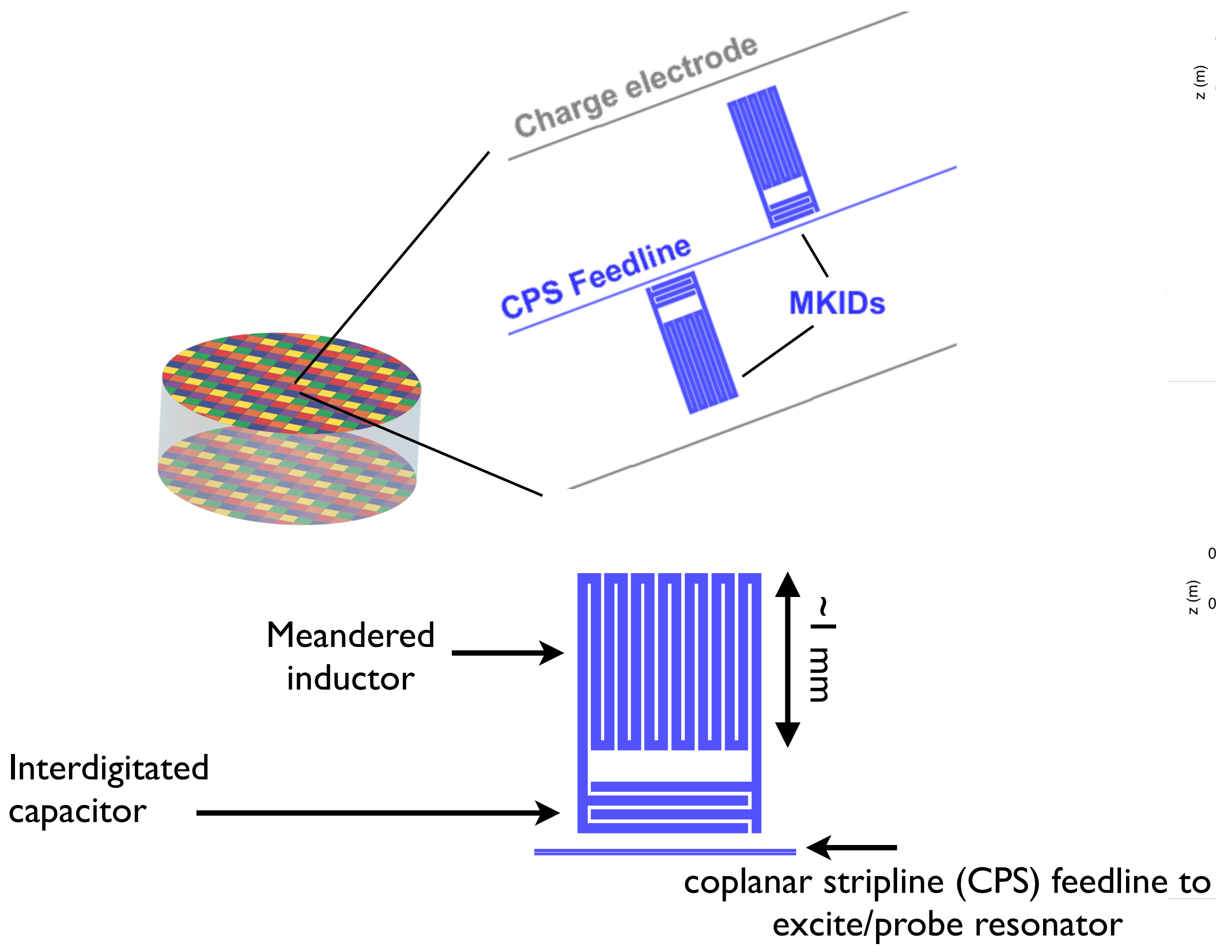
very simple cryogenic readout components

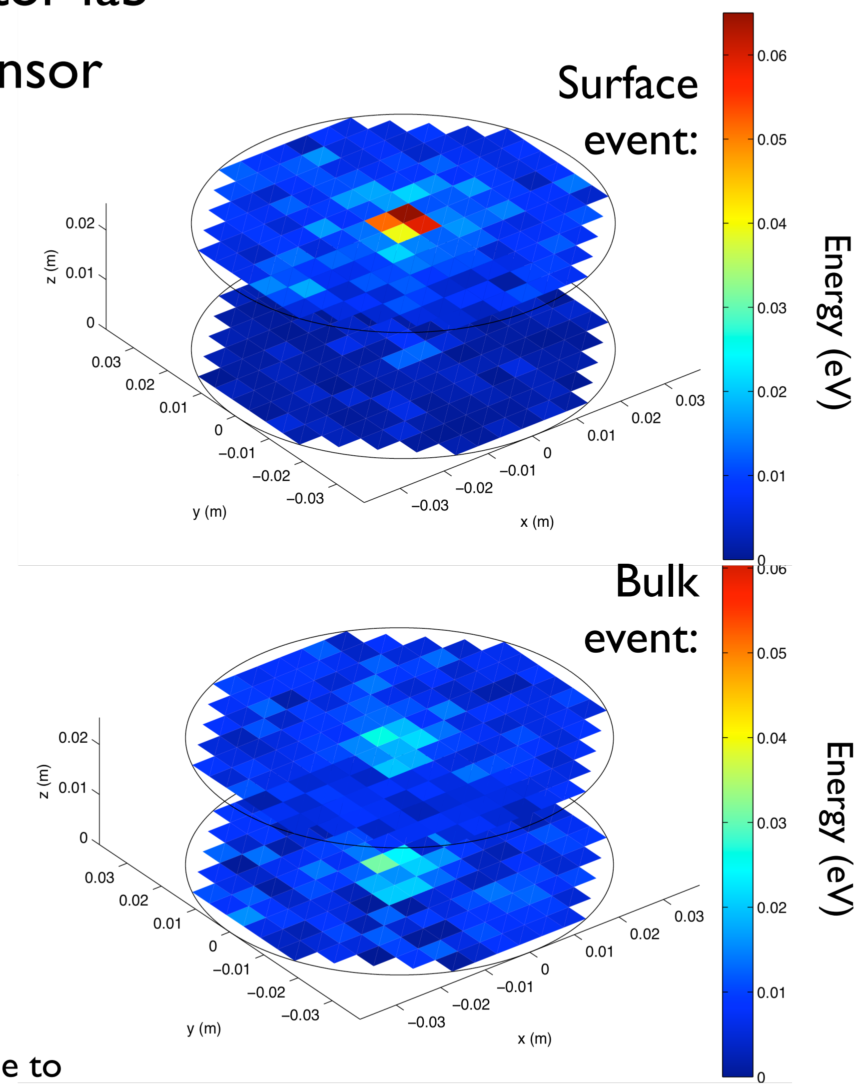
Phonon-Mediated DM Detection Using KIDs

Lumped-element designs enables large-area resonators for phonon sensing

Single film, 10 μm features would simplify detector fab

Multiplexing enables finely pixellated phonon sensor
→ better surface event rejection





Figures by D. Moore

Energy Resolution

Assume:

- readout noise dominates ($T << T_c$ ensures g-r noise subdominant)
- qp density determined by readout power generation
- resonator is coupling dominated ($Q_c << Q_i$)
- quasiparticle lifetime in KID << phonon absorption timescale ($\tau_{qp} << \tau_{abs}$)

$$\Delta E = 2.355 \frac{\Delta}{\eta_{ph}} \sqrt{\frac{\eta_{read}}{2\pi\alpha p_t}} \sqrt{\frac{A_{sub}\lambda_{pb}}{f_r \tau_{qp}}} \sqrt{\frac{k T_N N_0}{\gamma_s S_1(f_r, T_{qp}, \Delta)}}$$

$$= (0.052\ \mathrm{keV}) \left(\frac{1}{\eta_{ph}} \sqrt{\frac{1}{\alpha p_t}}\right) \left(\frac{\Delta}{200\ \mu\mathrm{eV}}\right) \sqrt{\frac{A_{sub}}{100\ \mathrm{cm}^2} \frac{\lambda_{pb}}{1\ \mu\mathrm{m}} \frac{5\ \mathrm{GHz}}{f_r} \frac{100\ \mu\mathrm{s}}{\tau_{qp}} \frac{T_N}{3\ \mathrm{K}} \frac{1.18}{S_1(f_r, T_{qp}, \Delta)}}$$

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superconducting
gap energy

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KID resonant frequency

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$$= (0.052\ \mathrm{keV}) \left(\frac{1}{\eta_{ph}} \sqrt{\frac{1}{\alpha p_t}} \right) \left(\frac{\Delta}{200\ \mu\mathrm{eV}} \right) \sqrt{\frac{A_{sub}}{100\ \mathrm{cm}^2} \frac{\lambda_{pb}}{1\ \mu\mathrm{m}} \frac{5\ \mathrm{GHz}}{f_r} \frac{100\ \mu\mathrm{s}}{\tau_{qp}} \frac{T_N}{3\ \mathrm{K}} \frac{1.18}{S_1(f_r, T_{qp}, \Delta)}}$$

efficiency for converting phonons to qps

fraction of inductance due to KI (~1)

probability for phonon to enter KID per try

KID resonant frequency

quasiparticle lifetime

Energy Resolution

Assume:

- readout noise dominates ($T << T_c$ ensures g-r noise subdominant)
- qp density determined by readout power generation
- resonator is coupling dominated ($Q_c << Q_i$)
- quasiparticle lifetime in KID << phonon absorption timescale ($\tau_{qp} << \tau_{abs}$)

superconducting gap energy

efficiency of qp creation by readout power (assume = 1 to be conservative)

area of substrate (including sidewalls)

pair-breaking length in KID film

amplifier noise temperature

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superconducting gap energy

amplifier noise temperature

density of states

superconductivity factors, ~1

$$\Delta E = 2.355 \frac{\Delta}{\eta_{ph}} \sqrt{\frac{\eta_{read}}{2\pi\alpha p_t}} \sqrt{\frac{A_{sub}\lambda_{pb}}{f_r \tau_{qp}}} \sqrt{\frac{k T_N N_0}{\gamma_s S_1(f_r, T_{qp}, \Delta)}}$$

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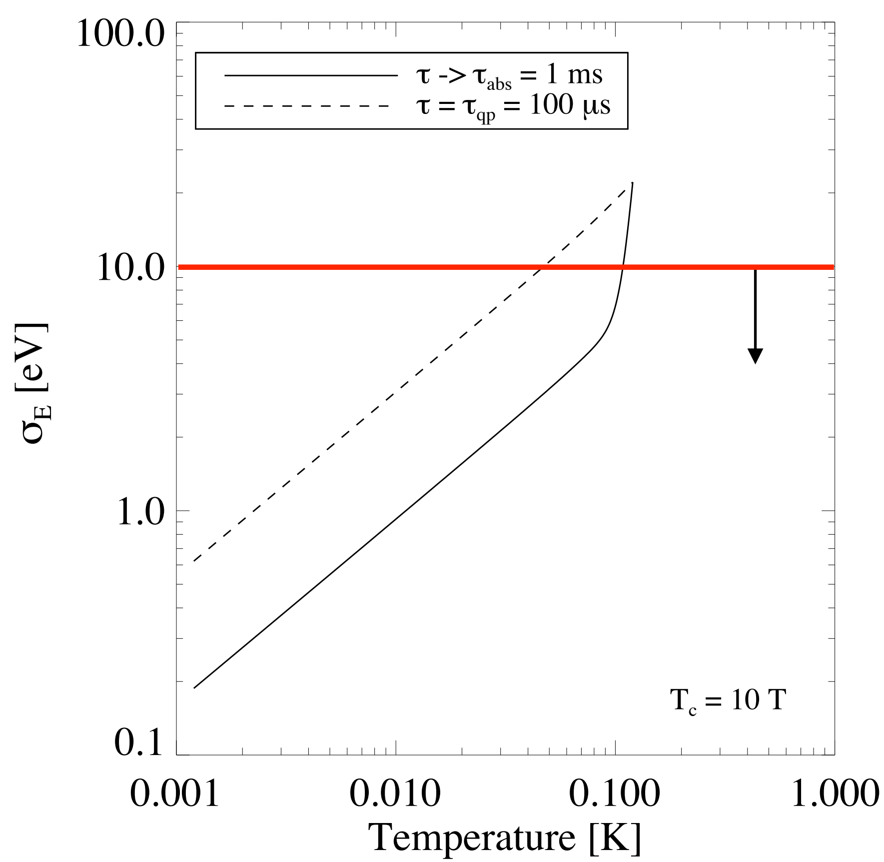
very competitive and interesting resolution possible if most phonons can be collected!



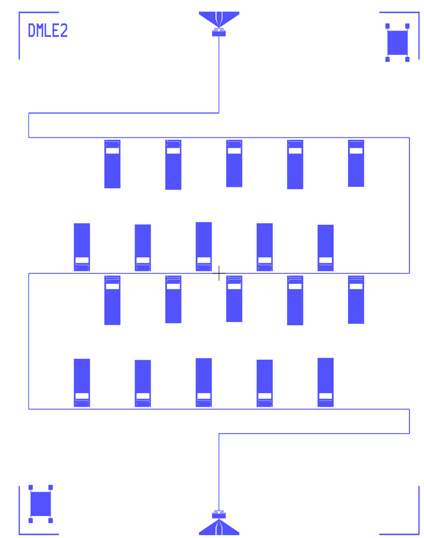
η_{ph} = 1 assumed

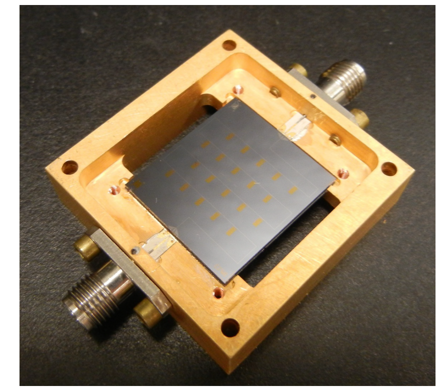
single e-h pair detection possible

Small Prototype

12 mm x 16 mm arrays of 20 resonators on 22 mm x 22 mm x 1 mm silicon substrates show excellent performance

- position correction recovers close to baseline performance; energy resolution ~ existing phonon-mediated detectors
- τ_{qp} = 13 μs measured (low!)
- η_{ph} = 0.07: large phonon losses
- expected $\sigma_E = 0.48\ \mathrm{keV}\sqrt{(\eta_{read}/p_t)}$: consistent with measurement
- Performance limited by lifetime and phonon losses

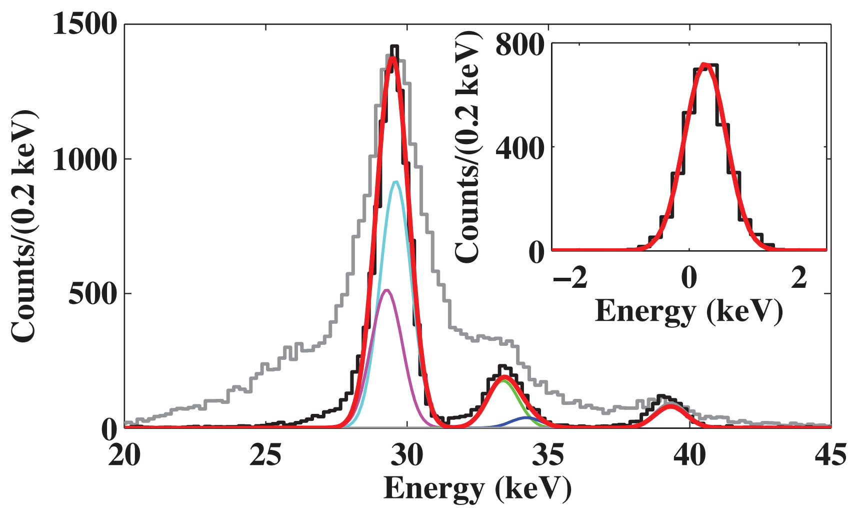


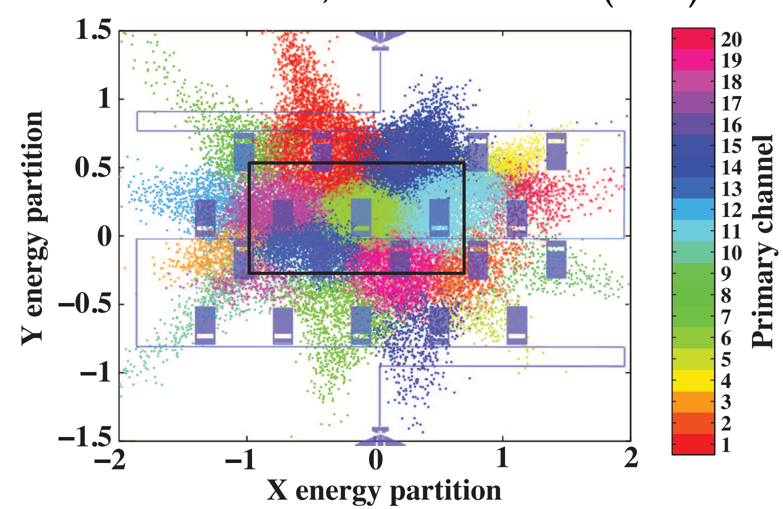


collimated 30 keV ^{129}I source incident on bottom side of silicon wafer

Moore et al, APL **100**: 232601 (2012)

σ = 0.55 keV
baseline σ = 0.38 keV
grey: before position correction
black: after position correction

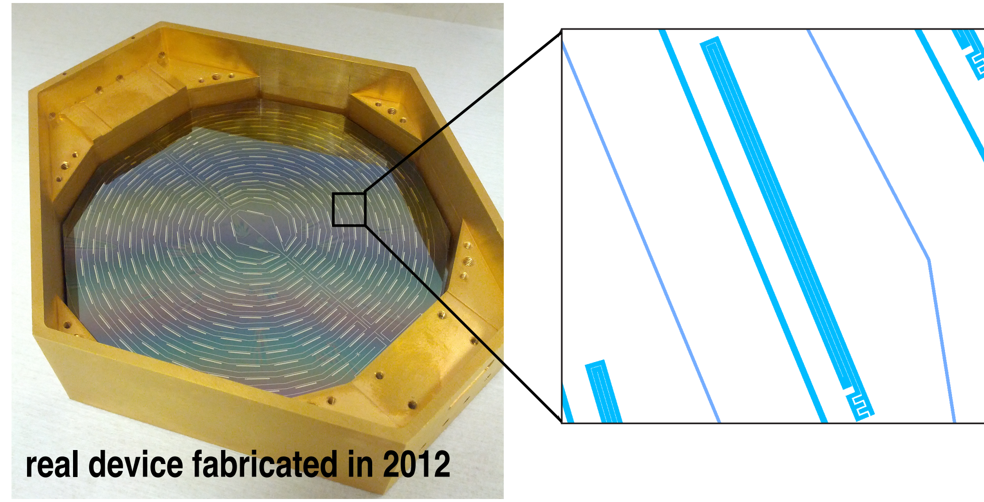


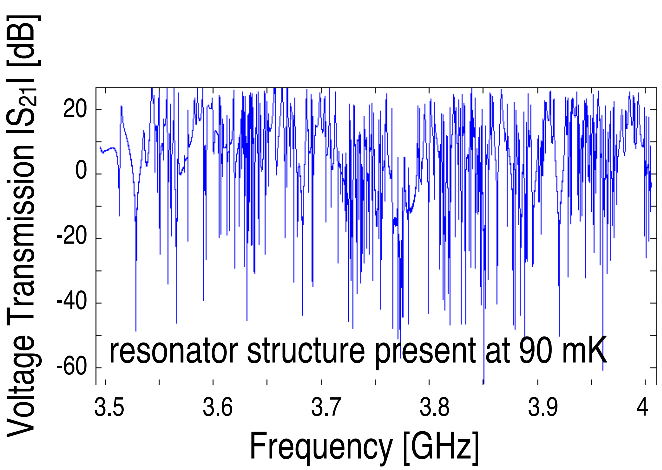


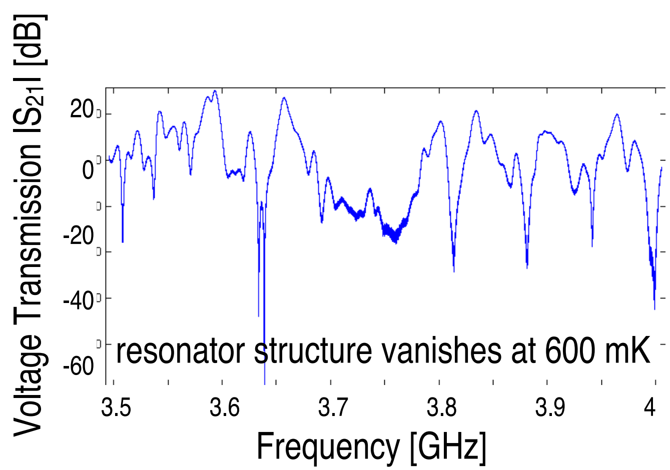
Full Size Prototype

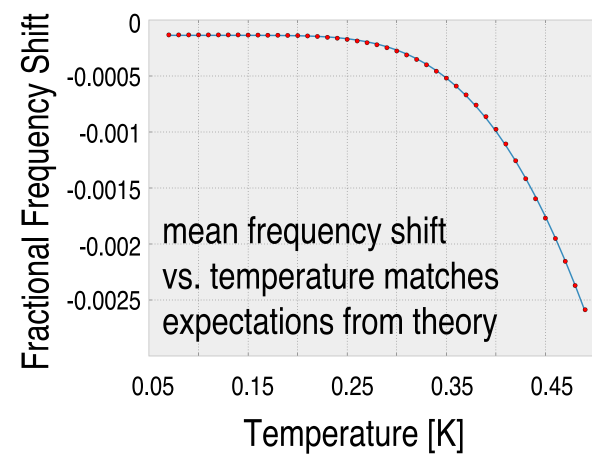
Working on scaling to 7.5-cm x 1-cm substrates

Have designed and fabricated devices and acquired characterization data









Working to understand RF structure of device with Nb version (4K testing)

Then pulse data

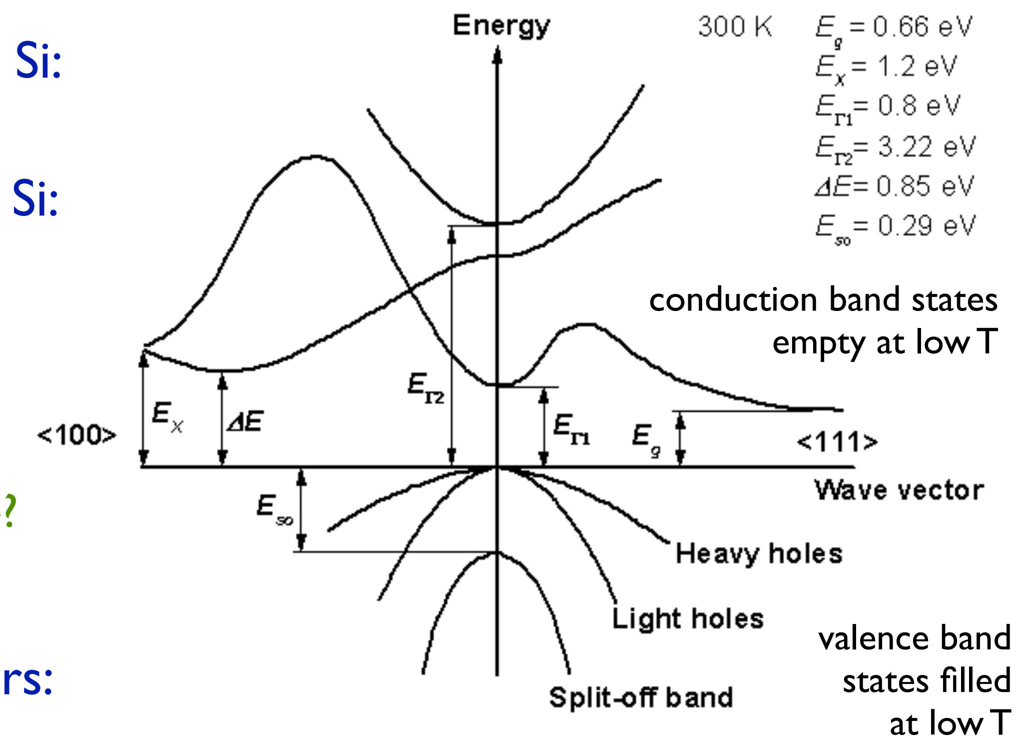
DOE HEP detector R&D grant awarded

Exploring nuclear nonproliferation funding options (high-res γ spectroscopy)

Beyond Detection of Individual e-h Pairs: < 100 MeV

Qualitative change in response below ~100 MeV

- 100 MeV: $\langle E_R \rangle$ = 12 eV in Ge, 22 eV in Si:
  - accessible with V_b = 100 V, σ_{pt} = 3 eV
- 10 MeV: $\langle E_R \rangle$ = 1.2 eV in Ge, 2.2 eV in Si:
  - below e-h pair threshold:
  - there are no states that electrons can scatter into
  - Except possible relatively low density impurity states → ER-insensitive regime?



σ_p < 1 eV in principle accessible

- Like IR and FIR photon counting detectors:
  - Resolve depositions less than 1 eV

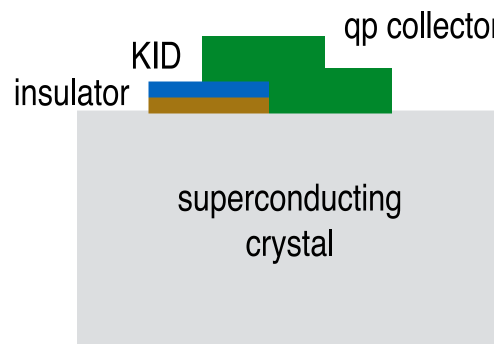
No quantization effects until reach ~ meV depositions

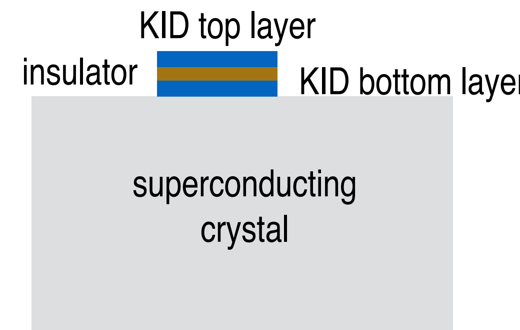
- meV deposition → 10 keV DM mass

KID advantage?

- Threshold for qp creation in KIDs perhaps provides some insensitivity to environmental noise, esp. vibrational noise

What About Direct Quasiparticle Creation?





- Long scattering length superconducting crystal: qp's diffuse
- Architectures:
  - KID on insulator, qps collected via thick superconducting film
    - Technically straightforward to imagine a design:
    - Avoids having to deal with operating KID on superconductor
    - Requires good trapping: qps from crystal into collector film, from collector film into KID
      - Problem: fast trapping require large Δ ratio; large Δ ratio $\rightarrow$ lots of energy lost to phonon emission
      - Maybe still ok if just interesting in counting substrate qps (still can get meV threshold)
  - KID on crystal
    - Need to avoid short-circuiting KID: microstrip structure?
    - Film needs to be thick to avoid being proximitized by crystal (Δ_{KID} pulled to $\Delta_{crystal}$)
- No obvious advantage over phonon mediation *for NR detection*
  - Phonons already provide sensitivity to meV scale
  - KIDs are already pair-breaking detectors: insensitive to sub-gap phonons in principle
- But definitely interesting for electron scattering

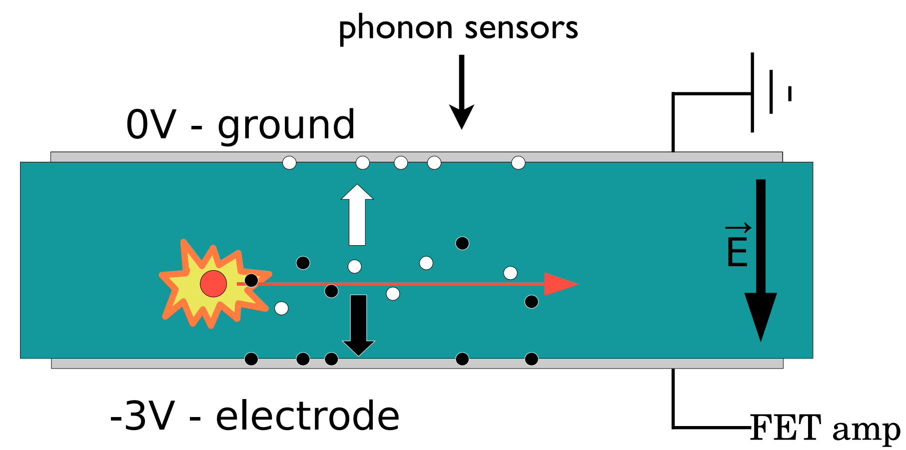
Conclusions

- Improved imaging of phonon signal from substrate can provide significant gains for phonon-mediated detectors
  - In phonons+ionization mode: fiducialization using phonons, bulk ER rejection using ionization
  - In HV mode: fiducialization using phonons
- Improved energy resolution would reach single e-h pair detection regime

- KIDs can provide these improvements
  - Multiplexability of KIDs promises finer imaging of phonon signal
  - KID sensitivity promises to reach single e-h pair regime

- KID demonstration in hand, working on scaling up to massive substrates

Solid-State Detectors

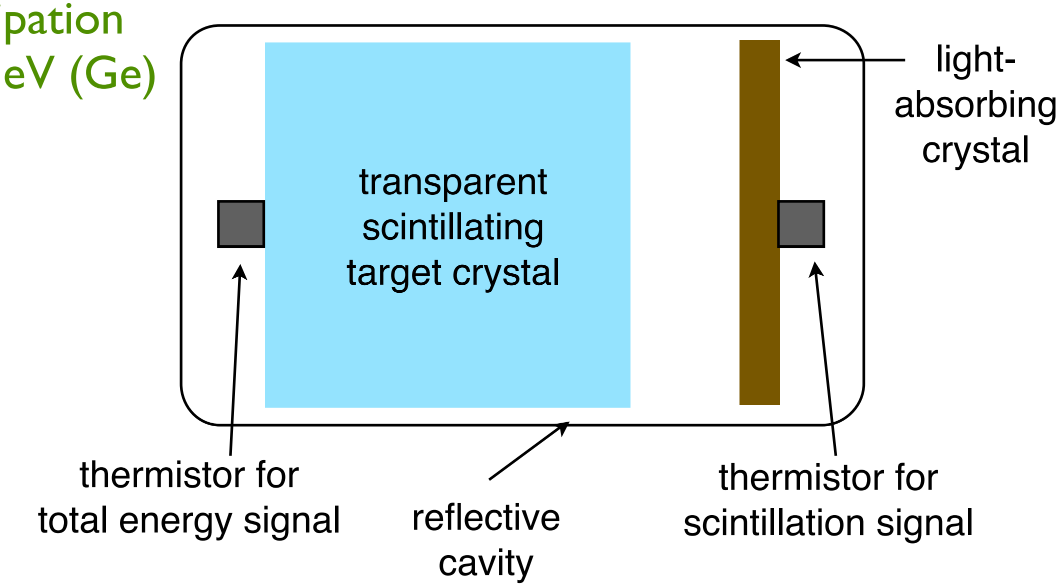


SuperCDMS/EDELWEISS

- 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} = $N_{e\text{-}h}$ x e x V_b = E_q x e x V_b/3.0 eV (Ge)
  - "keV$_p$" = phonon energy = E_r + E_{drift}

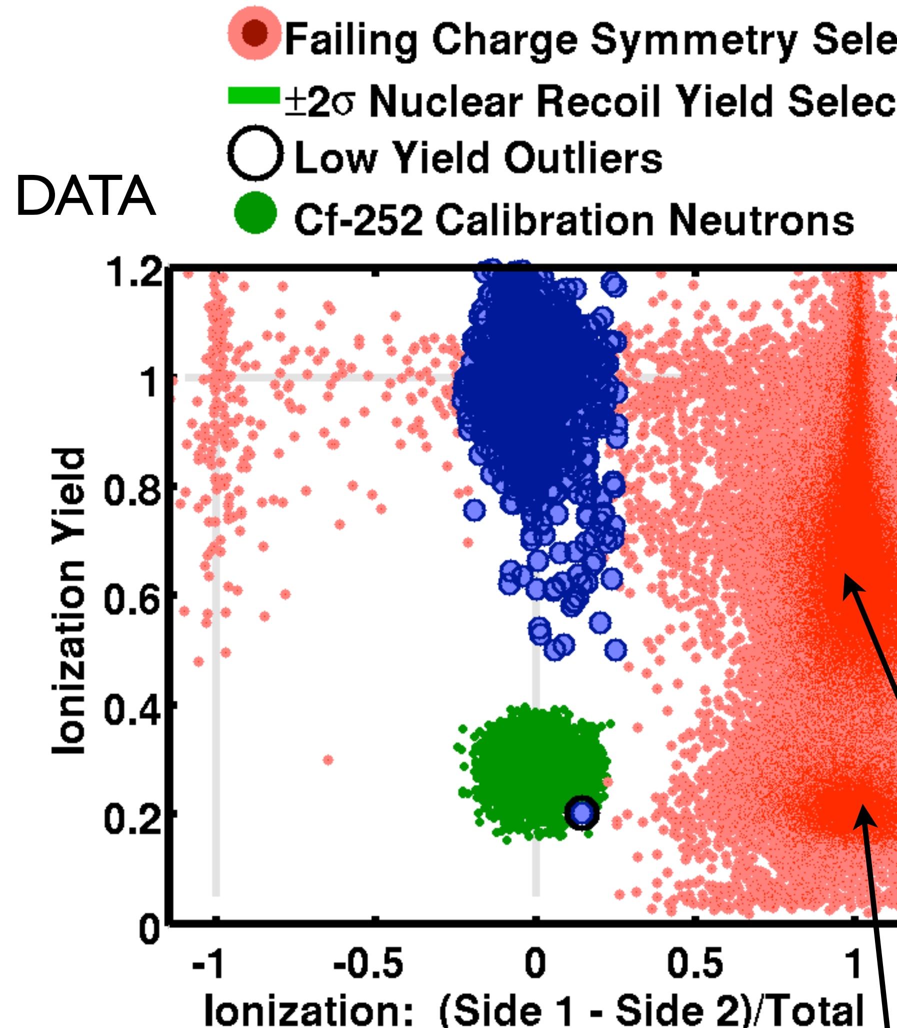
CRESST

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



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
- Field strength
  - High field near surface raises ionization collection for surface electron recoils
  - ^{206}Pb nuclear recoils visible
- Important goals achieved
  - Surface ER rejection ~ 1 x 10^{-5} shown at Soudan > 8 keV_r, sufficient for SuperCDMS SNOLAB high-mass WIMP search

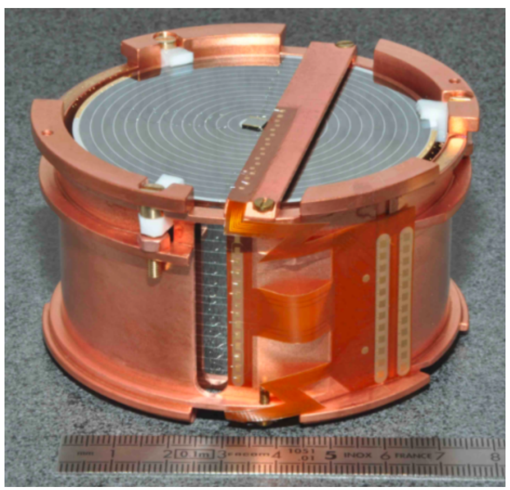


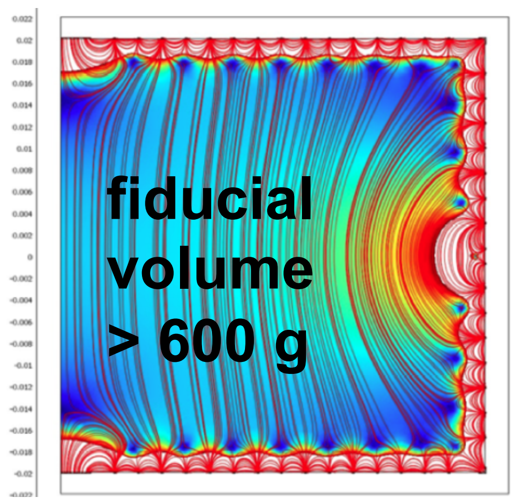
EDELWEISS: Surface Event Rejection w/Interdig. Electrodes

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





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