Cryogenic Detectors for Non-Accelerator Particle and Nuclear Physics

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Overview

Motivation

Basic physics, history, and applications of cryogenic detectors

- Thermal phonons
- Athermal phonons
- Ionization and scintillation

Motivation

Consider a conventional ionization detector:

- Photon (or charged particle)
  - enters the detection medium
  - and creates ionization
  - photons:
    - photoelectric absorption
    - Compton scattering
    - pair creation
    - results in energetic free electrons
      (and maybe positrons)
  - heavy neutral particles
    - nuclear scattering results in a
      recoiling nucleus
  - all charged particles create ionization
    - in a semiconductor: electron-hole pairs
    - Note also the phonons...

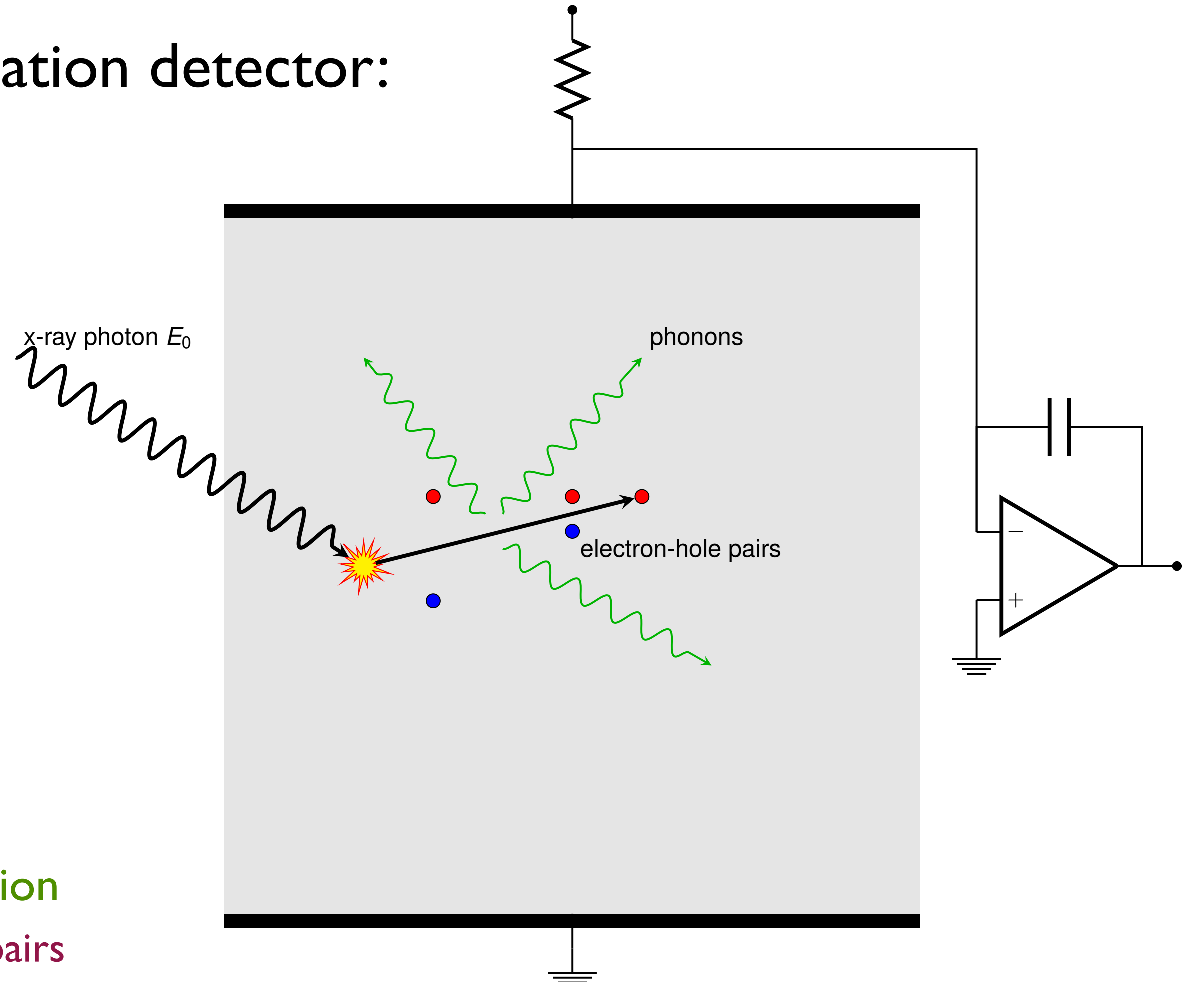


Figure by G. Hilton

- Electron-hole pairs drifted in electric field to electrodes and current integrated

Scintillation detector:

- scintillation photons emitted and collected by photodetector of some kind

Motivation: Counting Statistics

Limitations of conventional detectors

- Simple counting statistics:
  - semiconducting detectors: ~3-5 eV required to create an e-h pair → 300 pairs/keV
  - scintillitation detectors: 20-40 eV per scintillation photon + quantum efficiency of photodetector → few photoelectrons/keV
  - For keV energy depositions, σ_E/E ~ 5% to 50%! Poor energy resolution at low energies. Typically $\sigma_E/E \sim 1/\sqrt{E}$, so % levels at 100 keV for semiconductors, 1 MeV for scintillators.
  - Fano factor actually improves this somewhat; F = 0.1 in Si and Ge. [PDG]
  - But assumes no interesting physics:
    - ionization trapping
    - dead layers
    - secondary excitation mechanisms that inflate fluctuations, etc. (e.g., LXe)
- Further aggravated for particles that scatter with nuclei:
  - Quenching of ionization or scintillation for nuclear recoils can be QF = 3 to 10 or worse
  - σ_E/E scales as $\sqrt{QF}$

How to beat these limits?

- Use a smaller quantum: smaller ΔE to produce a single "energy carrier"
- Use a quantum whose production is independent of recoil type.

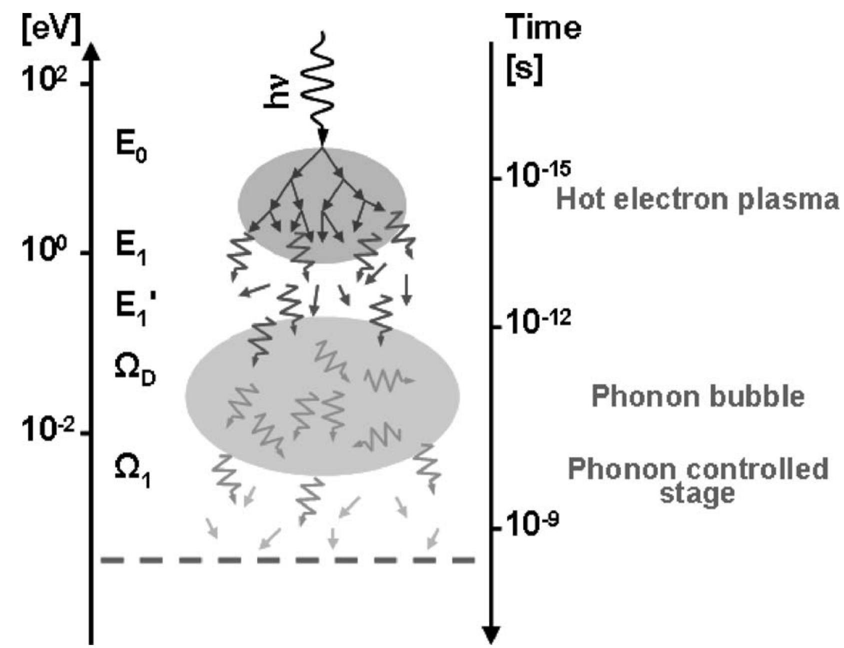
Motivation: Smaller Quanta

Smaller quanta: phonons and superconducting quasiparticles

- Phonons: quantized crystal acoustic vibrations.
  - Energy scale set by Debye temperature and operating temperature
  - e.g., germanium: Debye temperature = 360K, energy = 31 meV
  - 1K operating temperature → 86 μeV
- Superconductors have energy scale set by critical temperature
  - Pair-breaking energy: energy required to break a Cooper pair to create two quasiparticles ("qps", ~ free electrons) with energy Δ above Fermi level: $E = 2\,\Delta = 3.52\,k\,T_c = 300\ \mu eV$
- Clearly, one can beat the counting statistics problem

Phonon and qp production:

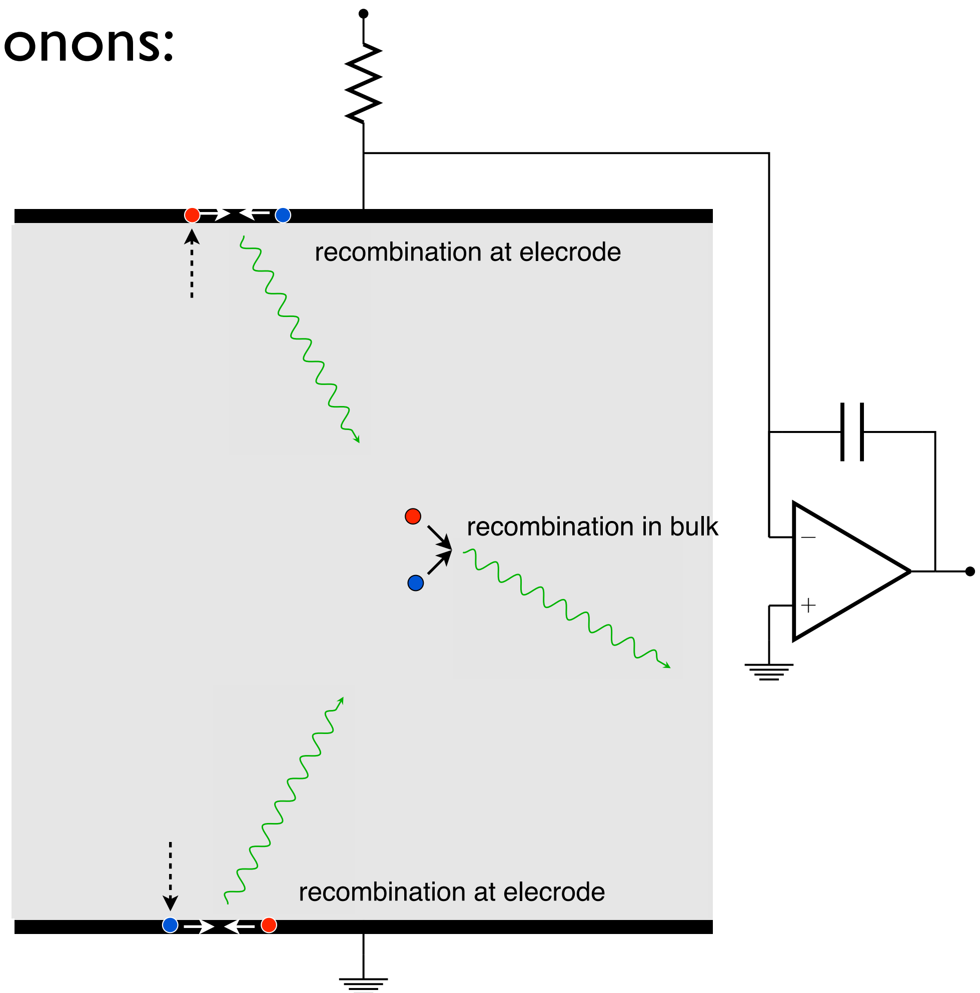
- What happens when energy is deposited in a material is very complex
- Even for MIP, energy is deposited in a hot plasma of electronic excitations:
  - MIP in silicon deposits 0.5 eV/nm
  - 1 eV/particle = 11000 K!
- This cloud radiates phonons up to > E_{debye}
- In SC, phonons break Cooper pairs too.



Kozorezov et al PRB: 75, 094513 (2007)

Motivation: Independence of Particle Type

- Energy scale of e-h pair/phonon cloud ≫ thermal phonon, qp energies
  - Phonon and qp production to first order do not care where the energy came from; knowledge of high energy scale processes are lost
  - Absolutely true for thermal phonons and thermal qp's; mostly true for athermals
- All the energy eventually goes into phonons:
  - ionization:
    - e-h pairs recombine in bulk or at the electrodes and radiate recombination phonons: recovers gap energy
    - though charge trapping and permanent crystal defect creation will also cause some loss of energy
  - scintillation:
    - scintillation photons escape and their energy is lost (or detected externally)
    - but scintillation photons (~1-few eV) carry a small fraction of energy needed to create them (20-40 eV/ph); the remainder goes into phonons



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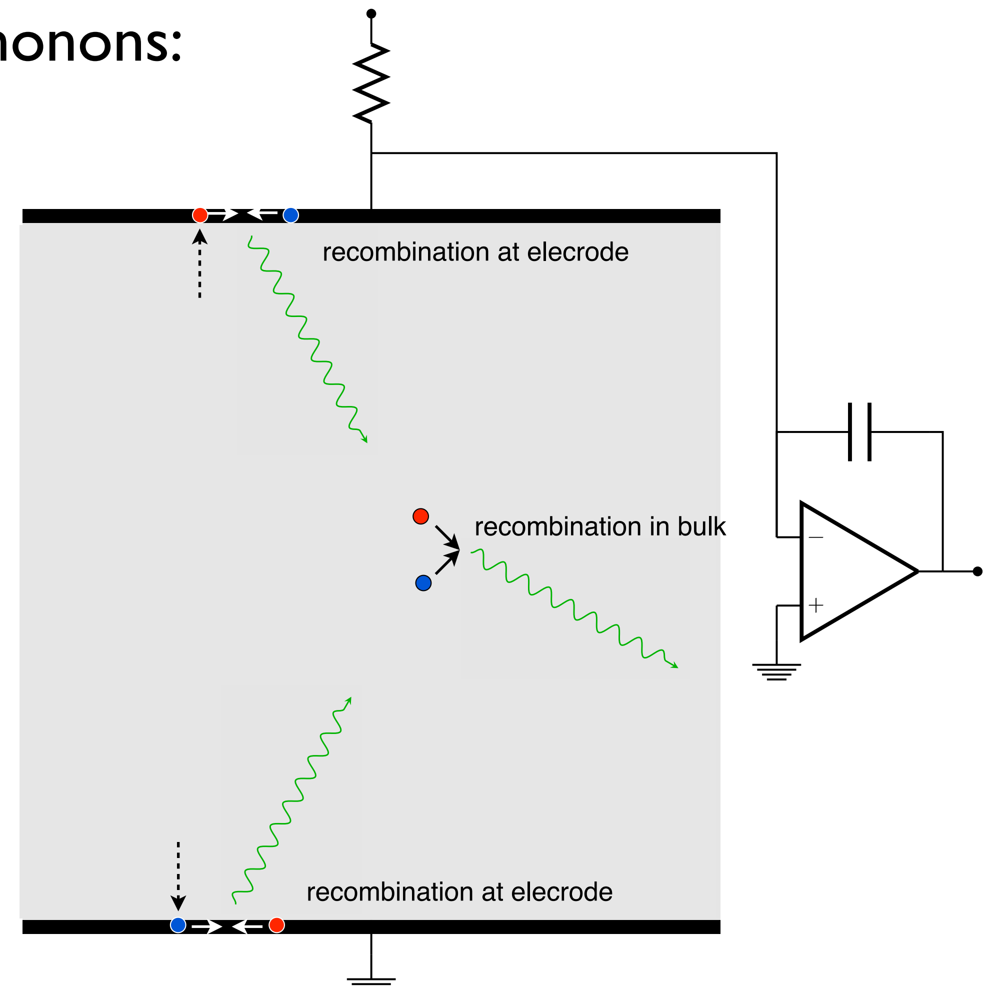
  - Absolutely true for thermal phonons and thermal qp's; mostly true for athermals
- All the energy eventually goes into phonons:
  - superconductor
    - Once quasiparticles created, they diffuse (cannot be drifted)
    - But otherwise similar to e-h pairs:
      - can recombine if they find another qp in bulk or at surfaces
      - will eventually decay and emit energy in phonons
      - even if trapped, usually will decay and emit energy in phonons, though timescale may be long



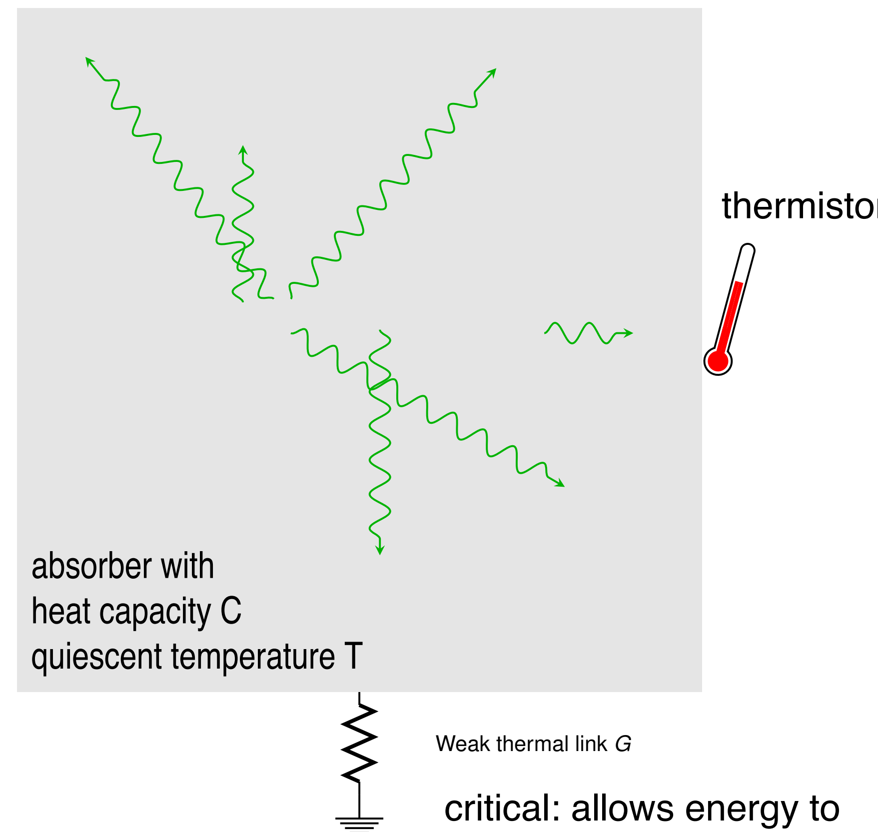
Physics of Thermal Phonon Detectors

Very simple: just measure the rise and decay of temperature of absorber

"Thermodynamic Limit": calculate variance of energy content of absorber in canonical ensemble (e.g., Kittel). Yields:

$$\sigma_E^2 = k_B T^2 C$$

C = heat capacity, T = temperature



Cause of fluctuations: stochastic "bouncing around" of absorber and bath between microstates around mean energy. The fractional fluctuations go as $1/\sqrt{C}$ because by standard Poisson fluctuation argument: C gives the number of modes that can carry energy.

But this argument is <u>wrong</u>.

Physics of Thermal Phonon Detectors

Must think in terms of power flows. Absorber obeys:

Energy content fluctuations related to temperature fluctuations and C

$$C\frac{d\delta T}{dt} = \frac{dE}{dt} = P(t) - G\,\delta T$$

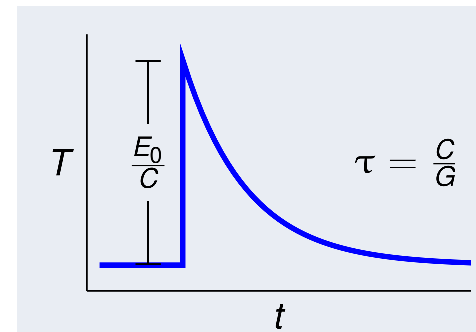
Power flow out through weak thermal link due to flucuation of temperature away from mean value

Rate of change of energy content of absorber

Input power e.g., $P(t) = E_0\,\delta(t)$ for event of energy E_0

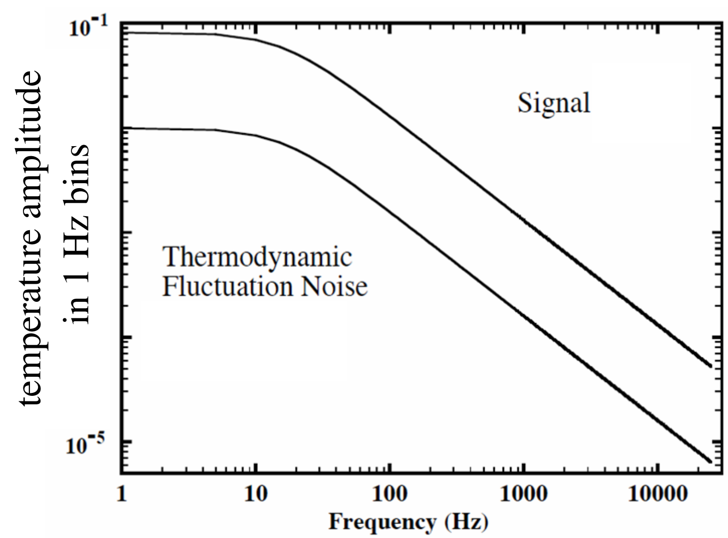
Reponse to a δ-function energy deposition E_0 is

Like a RC circuit, R = 1/G: $\delta T(t) = \frac{E_0}{C}\exp(-t/\tau)$ $\tau = \frac{C}{G}$



The fluctuations causing σ_E (“thermodynamic fluctuation noise”) are similar in flavor: they are due to stochastic energy transfer back and forth with bath via G (phonons)

But S/N ratio in frequency space is then fixed. With infinite detector bandwidth, get infinite signal to noise!

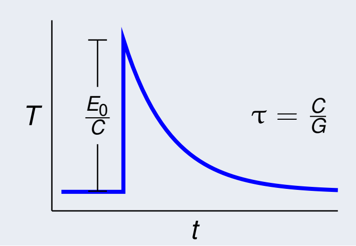


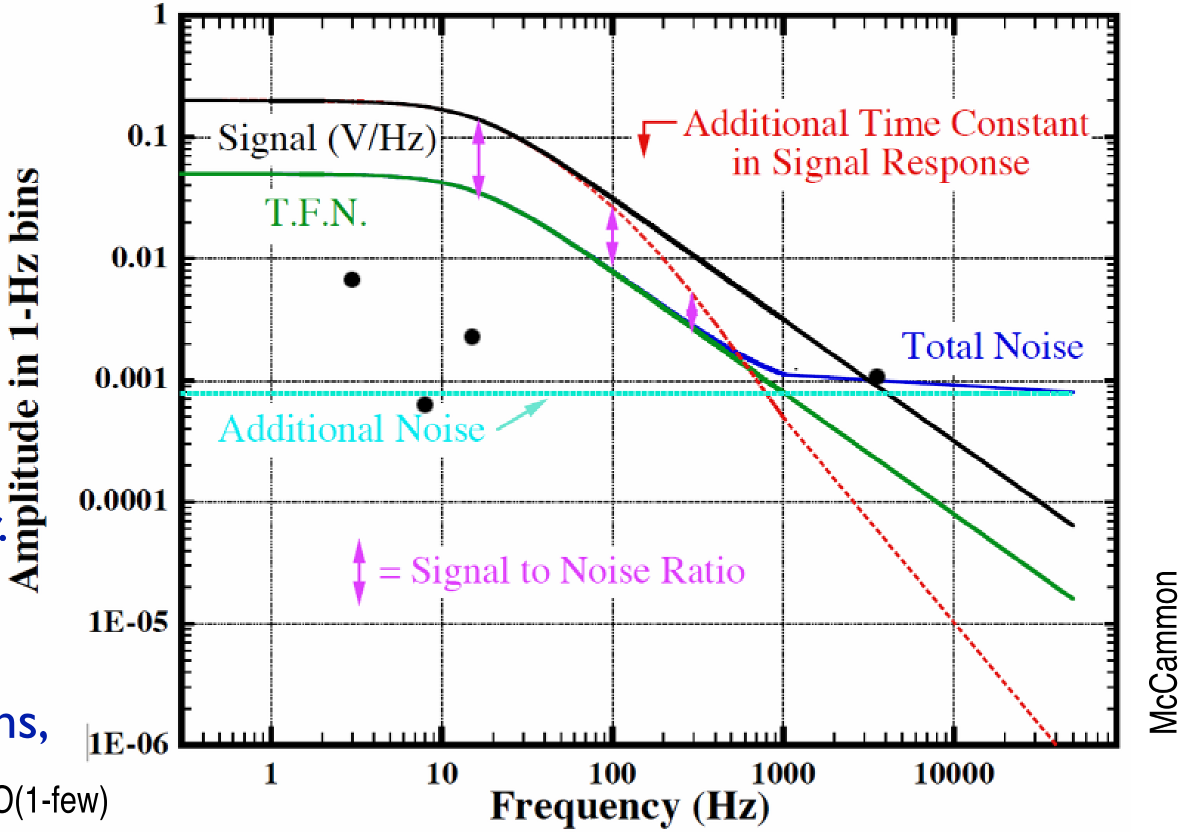
McCammon

Physics of Thermal Phonon Detectors

In reality, what limits S/N is the noise of the thermistor being used to measure the temperature and the microphysics of thermalization:

red: pulse rising edge not infinitely sharp (as we will see), results in add'l time constants and rolloff of signal





cyan: readout noise; e.g., Johnson noise of a thermistor. Usually white, limits useful signal bandwidth

For range of readout assumptions,

$$\sigma_E^2 = \xi^2 kT[T\,C(T) + \beta E] \qquad \xi = O(\text{1-few})$$

2nd term = phonon counting statistics,becomes appreciable when fractional energy/temperature change approaches 1

e.g. germanium, using Debye

$$C = \frac{12\,\pi^4}{5} N\,k \left(\frac{T}{\Theta_D}\right)^3$$

σ_E = 5.2ξ eV at 10 mK!

In practice, lose ~x5-10 from thermistor C and Joule power dissipation, excess readout noise, etc.

History

Clearly, energy resolution and low threshold are the advantages.

First applications considered: coherent scattering of MeV ν, neutrinoless double beta decay, dark matter:

Drukier and Stodolsky, "Principles and Applications of a Neutral Current Detector for Neutrino Physics and Astronomy", PRD 30: 2295 (1984)

Metastable superconducting grains for MeV neutrinos

Fiorini and Niinikoski, "Low-Temperature Calorimetry for Rare Decays", NIM 224:83 (1984)

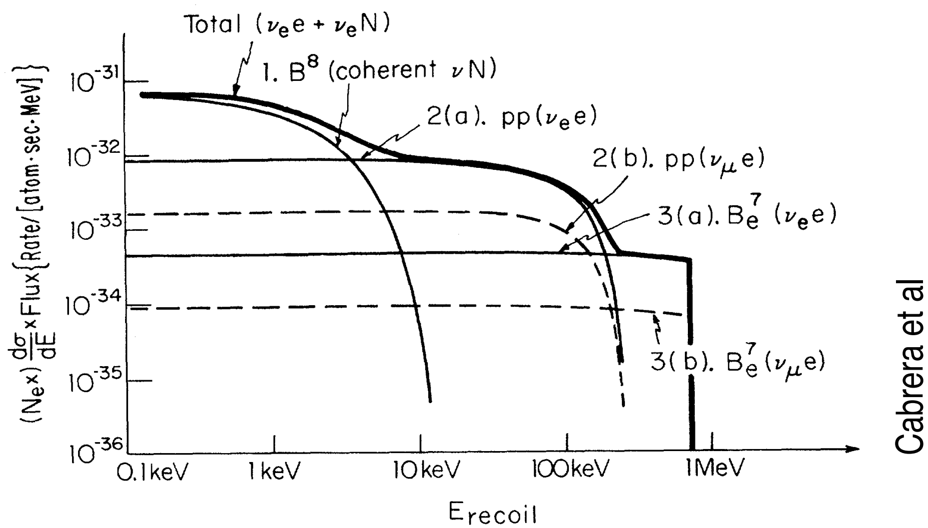


FIG. 1. Event rate vs recoil energy for solar-ν spectra. in silicon

Neutrinoless double-beta decay and electron decay.

Goodman and Witten, "Detectability of Certain Dark Matter Candidates", PRD 31: 3059 (1985):

Applies Drukier and Stodolsky to WIMP dark matter detection: low threshold critical

Cabrera, Krauss, and Wilczek, "Bolometric Detection of Neutrinos", PRL 55: 25 (1985)

True bolometric detection.

History

First demonstrations

Niinikoski et al., "Heat capacity of a silicon calorimeter at low temperatures measured by alpha-particles", Europhys. Lett. 1:499 (1986)

Wang et al., "Particle detection with semiconductor thermistors at low temperatures", IEEE Trans. Nucl. Sci. 36: 852 (1989).

X-ray astronomy: provides grating-spectrometer resolution but with high QE; useful for fine structure of X-ray lines, velocity structure, esp. ^{55}Fe in accretion disks around black holes

Moseley, Mather, and McCammon, "Thermal Detectors as X-ray Spectrometers", J. Appl. Phys. 56: 1257 (1984).

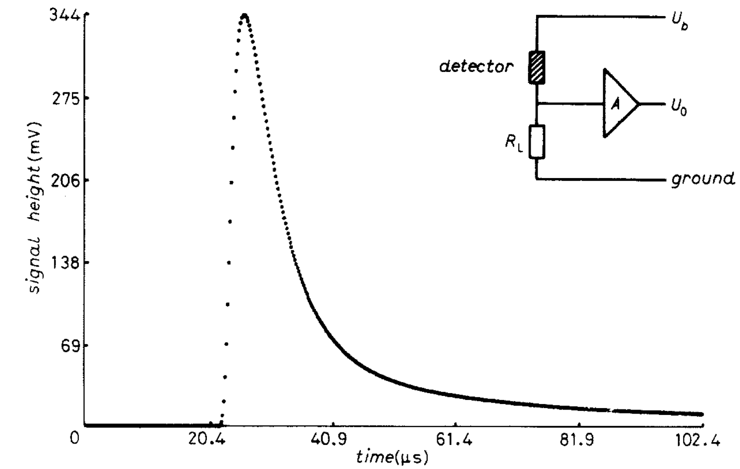


Fig. 2. – A typical pulse (at 500 mK). In the inset, the input circuit.

Niinikoski et al 1986

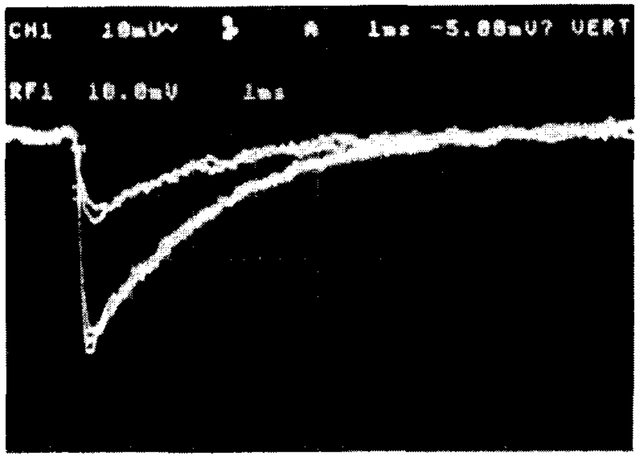


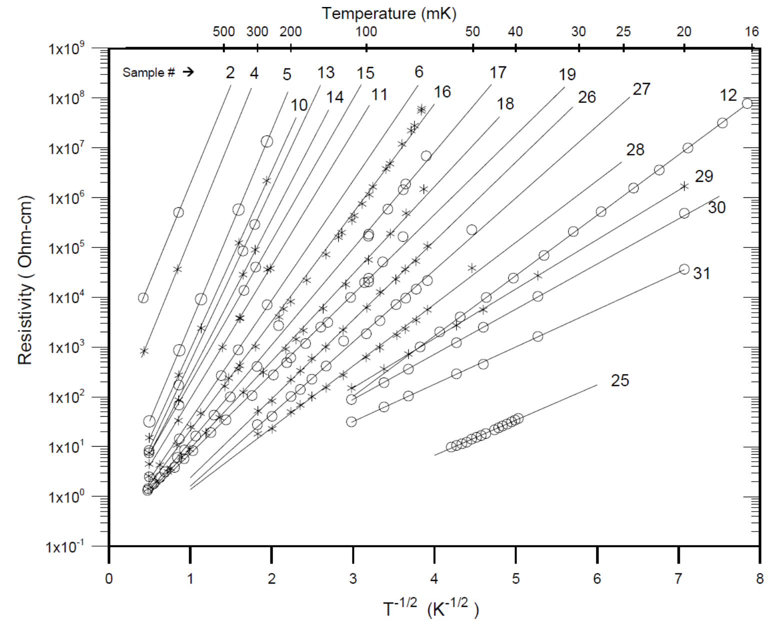
Figure 4. *Pulses from X-rays of* ^{241}*Am incident on thermistor b at 18 mK. We chose typical pulses corresponding to the two peaks shown in Figure 5. The vertical scale is 100 μV/div, and the horizontal scale is 1 ms/div.*

Wang et al 1989

Application Examples: Thermal Phonons

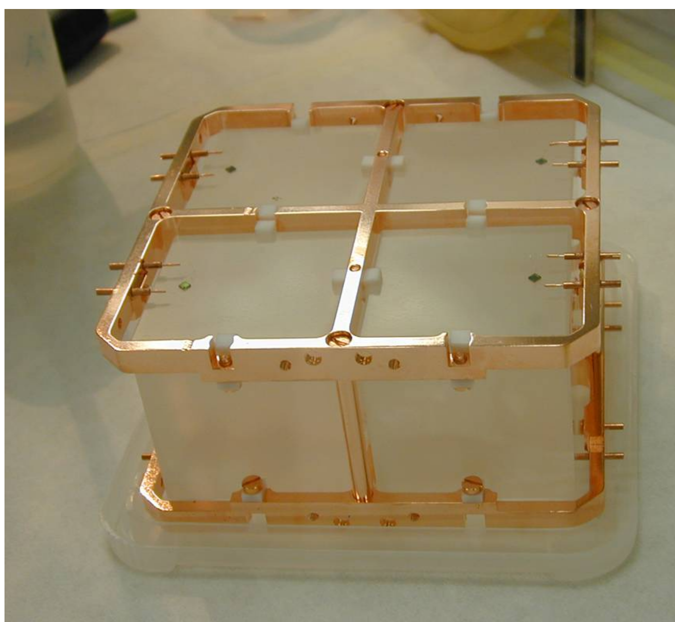
Neutrinoless Double Beta Decay: CUORE

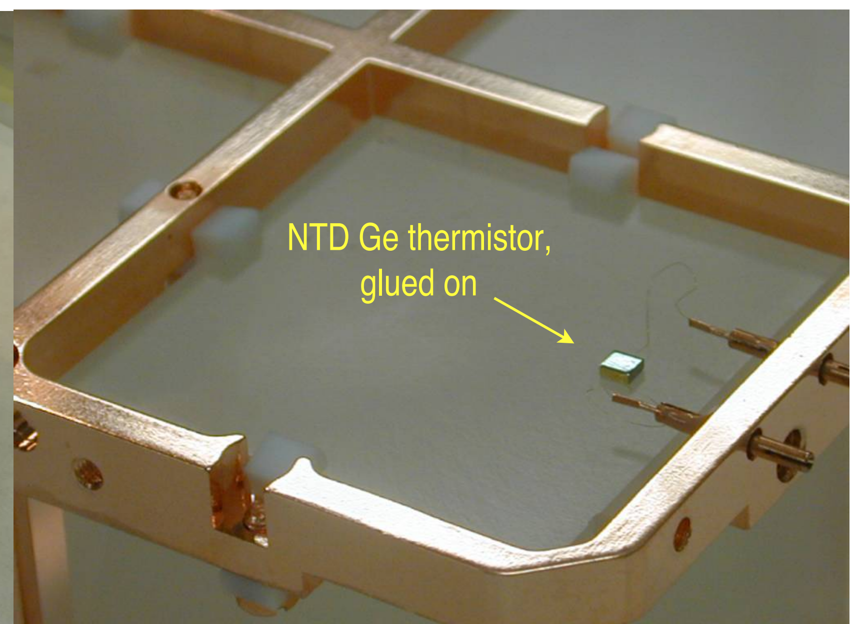
- Te as decay isotope, in TeO_2 crystals
- Thermometry by neutron transmutation doped (NTD) germanium thermistors
  - NTD converts Ge to Ga using neutron capture near a reactor; very uniform doping gives dR/dT
  - JFET voltage amplifier readout
- Source/absorber: 0.75 kg TeO_2 crystal, 5x5x5 cm^3
- 12 kg near-term, 200 kg long-term; 10 mK

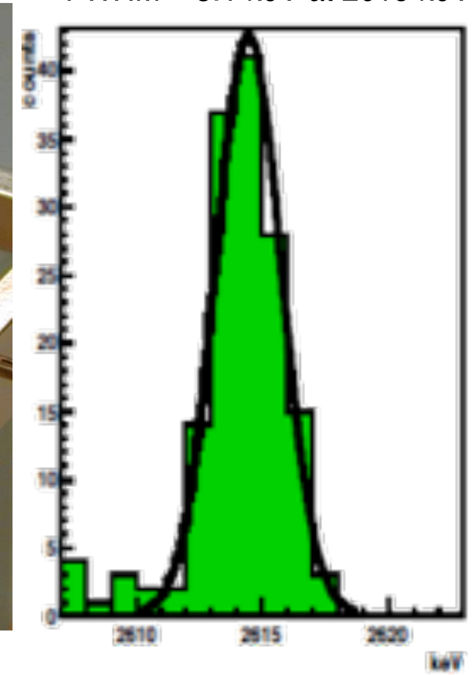


E Haller, J Beeman

FWHM = 3.1 keV at 2615 keV



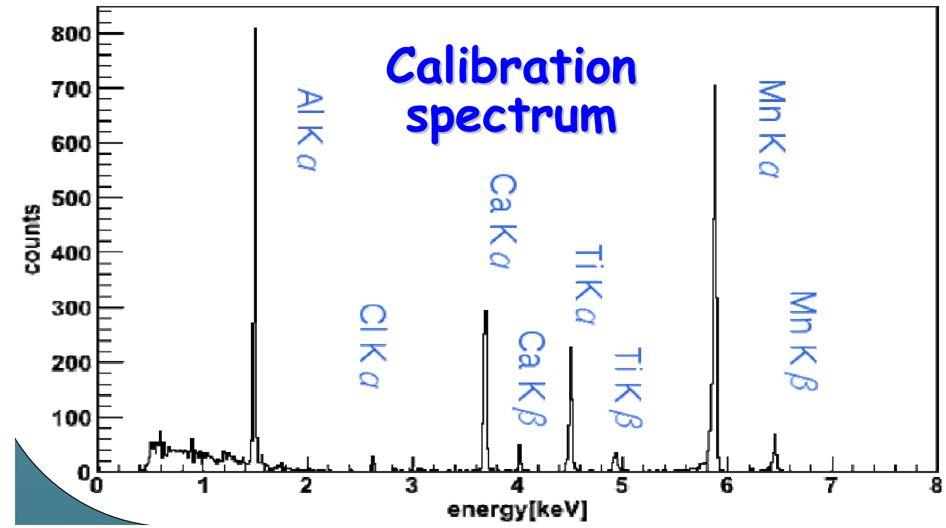


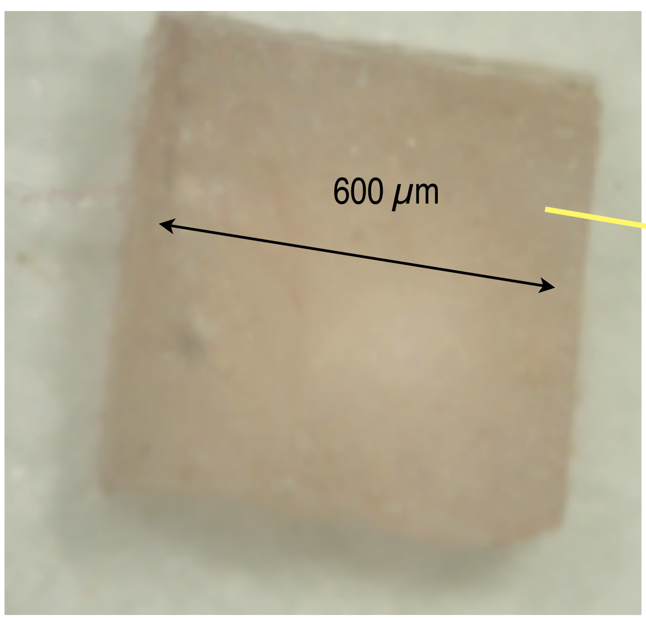


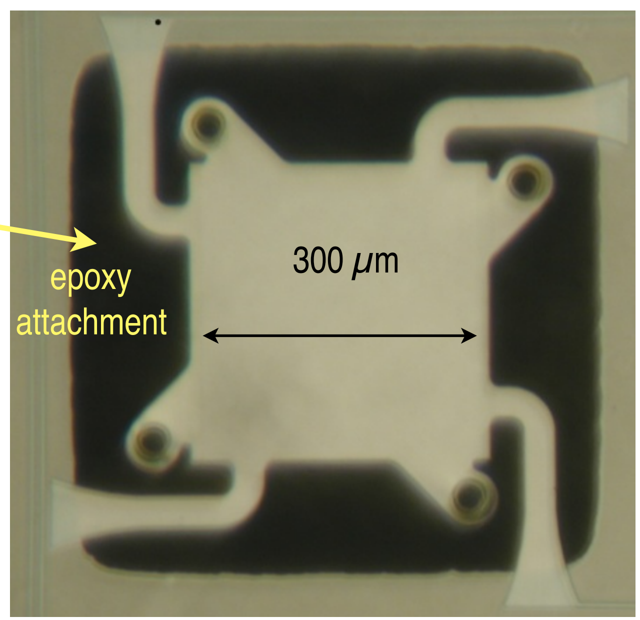
Application Examples: Thermal Phonons

Neutrino Beta Decay Endpoint: MARE

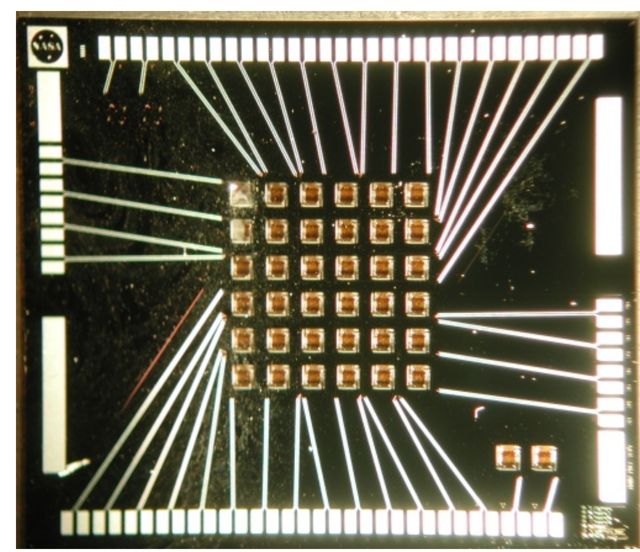
- ^{187}Re b-decay, E_0 = 2.47 keV
- Source material: 600x600x250 μm^3, 500 μg $AgReO_4$ xtals
- Thermistor: 300x300x1.5 μm^3 Si:P semiconducting
- FWHM = 33 eV at 2.6 keV
- t = 500 μs (sets count rate → decay statistics)







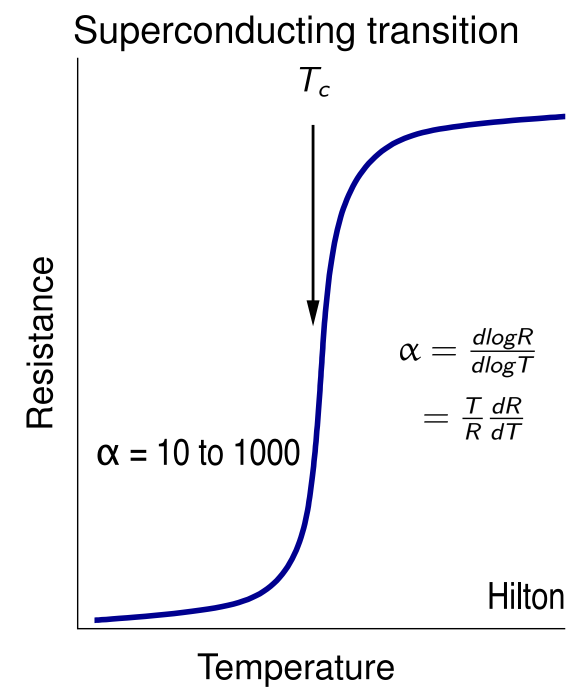
6x6 array

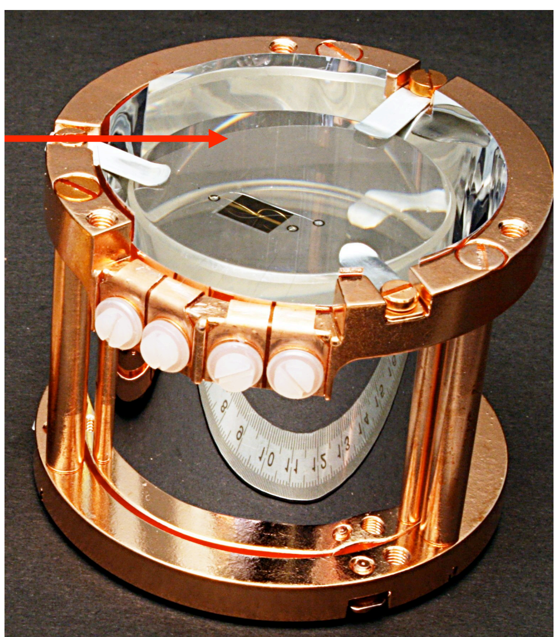


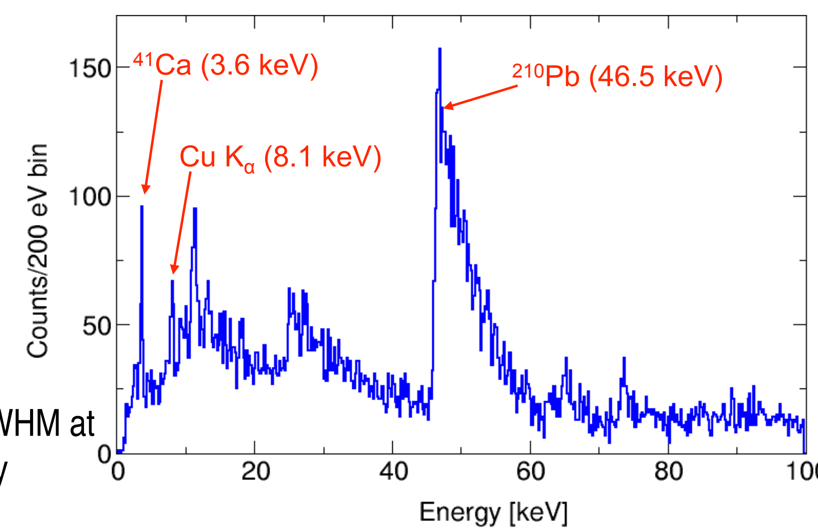
Applications Examples: CRESST I

Uses "superconducting phase transition" thermometer or "transition-edge sensor" (SPT, TES)

- Sharper dR/dT than thermistors → more sensitivity
- Thin film fabrication directly on substrate:
  - simple W thermometer
  - Au heater to apply feedback heating
- 300 g $CaWO_4$ substrate, 10 mK
- $\alpha \sim 10$



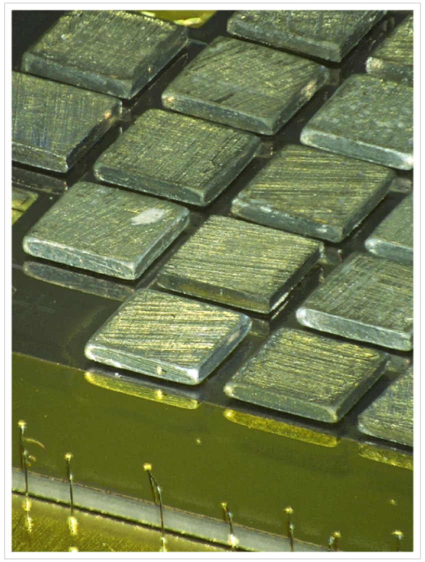




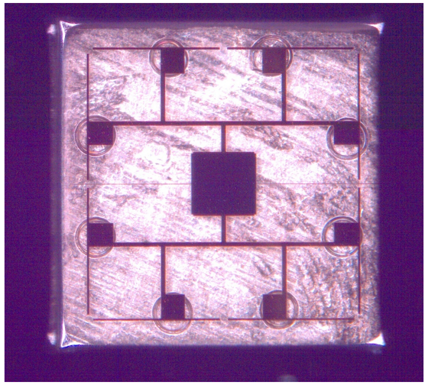
300 eV FWHM at low energy

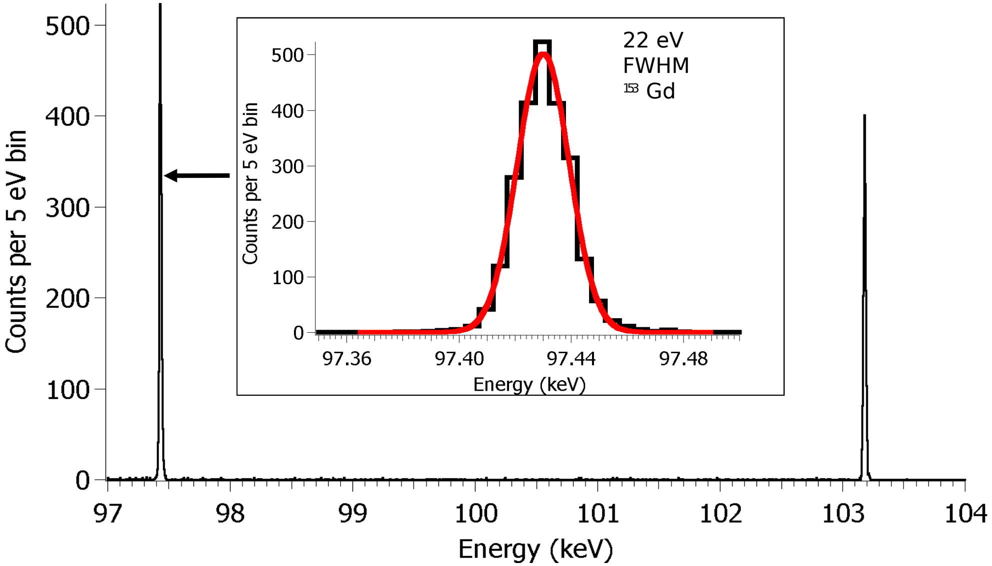
Applications Examples: Gamma-Ray Spectroscopy

Nuclear non-proliferation via gamma-ray spectroscopy. 0.02%@100 keV!



Tin absorbers attached to TESs





Motivation for Athermal Phonon Detectors

For thermal phonon detectors, $\sigma_E \propto \sqrt{C} \propto \sqrt{M}$

- Does not scale well with mass

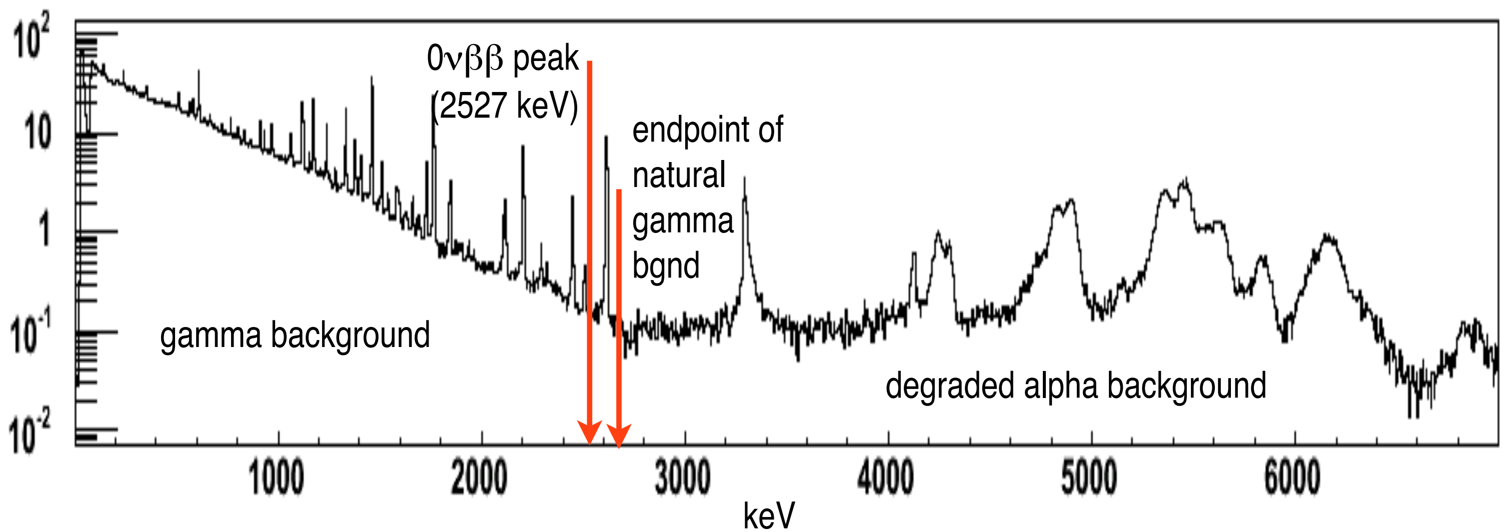
In principle, no position information

- In practice, enough variation of thermal pulse shape with position to degrade energy resolution at higher energies, $\sigma_E \propto E$, but no information to use to correct!

Problematic backgrounds are usually more prevalent at detector surface

- e.g., CDMS II: surface events due to electrons impinging on the detectors, penetrate only 10s of μm into 1-cm thick detector
- e.g., CUORE: degraded alpha decays overlap ROI for $0\nu\beta\beta$ decay

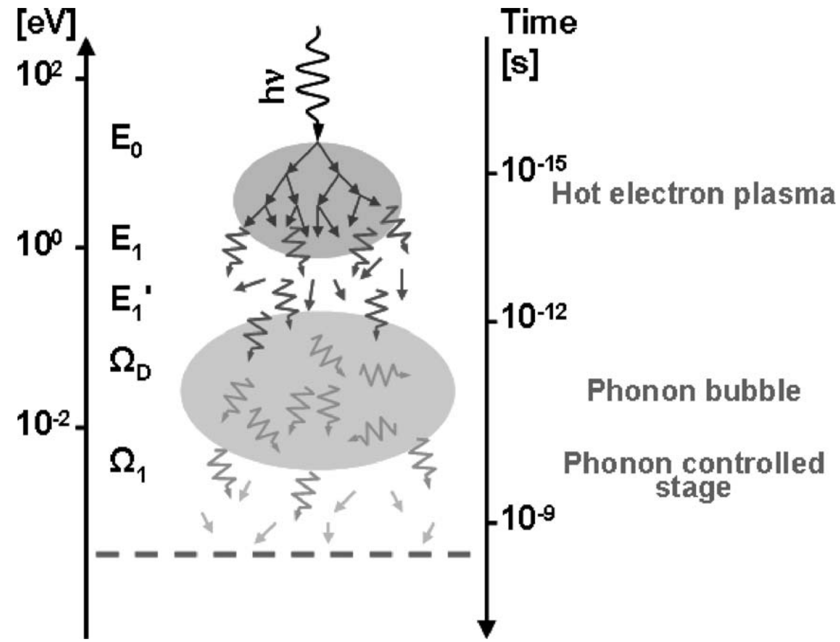
Athermal phonons can solve these problems



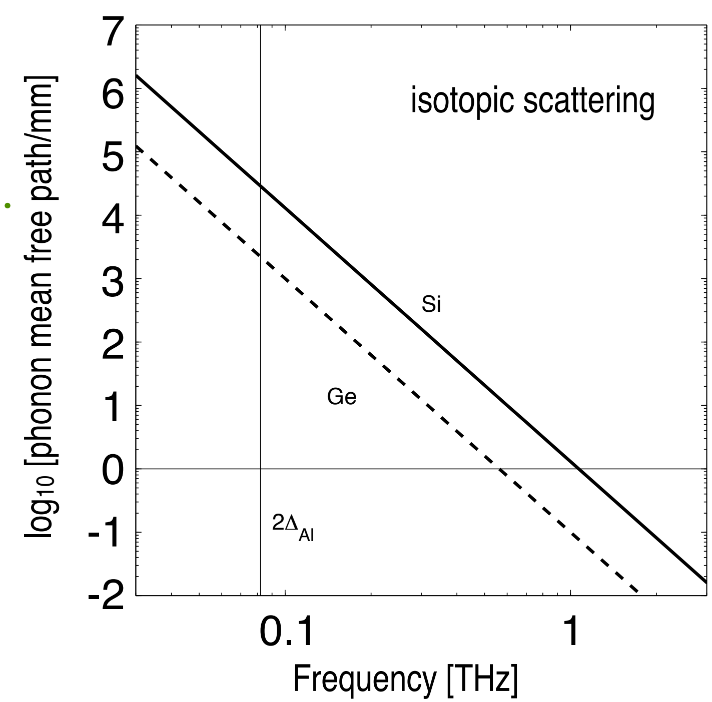
Physics of Athermal Phonons

How to get from the hot bubble of ionization to thermal phonons?

- Hot bubble radiates phonons like crazy
- But there are scattering mechanisms:
  - Isotopic scattering: lattice ions vary in atomic mass, τ = 0.41 μs $(\nu/1\ \mathrm{THz})^{-4}$ in Si.
    <u>Elastic</u>: phonon energy unchanged, but direction changes.
  - Anharmonic scattering: restoring forces for ions are not perfectly simple harmonic. τ = 10 μs $(\nu/1\ \mathrm{THz})^{-5}$ in Si.
    <u>Inelastic</u>: phonon splits into two lower energy phonons (and direction changes).
  - Isotopic decay prevents propagation outside of phonon bubble until ν < 1 THz (4 meV).
  - Anharmonic decay promotes downconversion, causing increase of mean free path to ~ 1 cm after ~10 μs, can propagate, "ballistic".
- Many ms before phonons reach thermal energies (10 μeV, ~2 GHz). Lots of time!

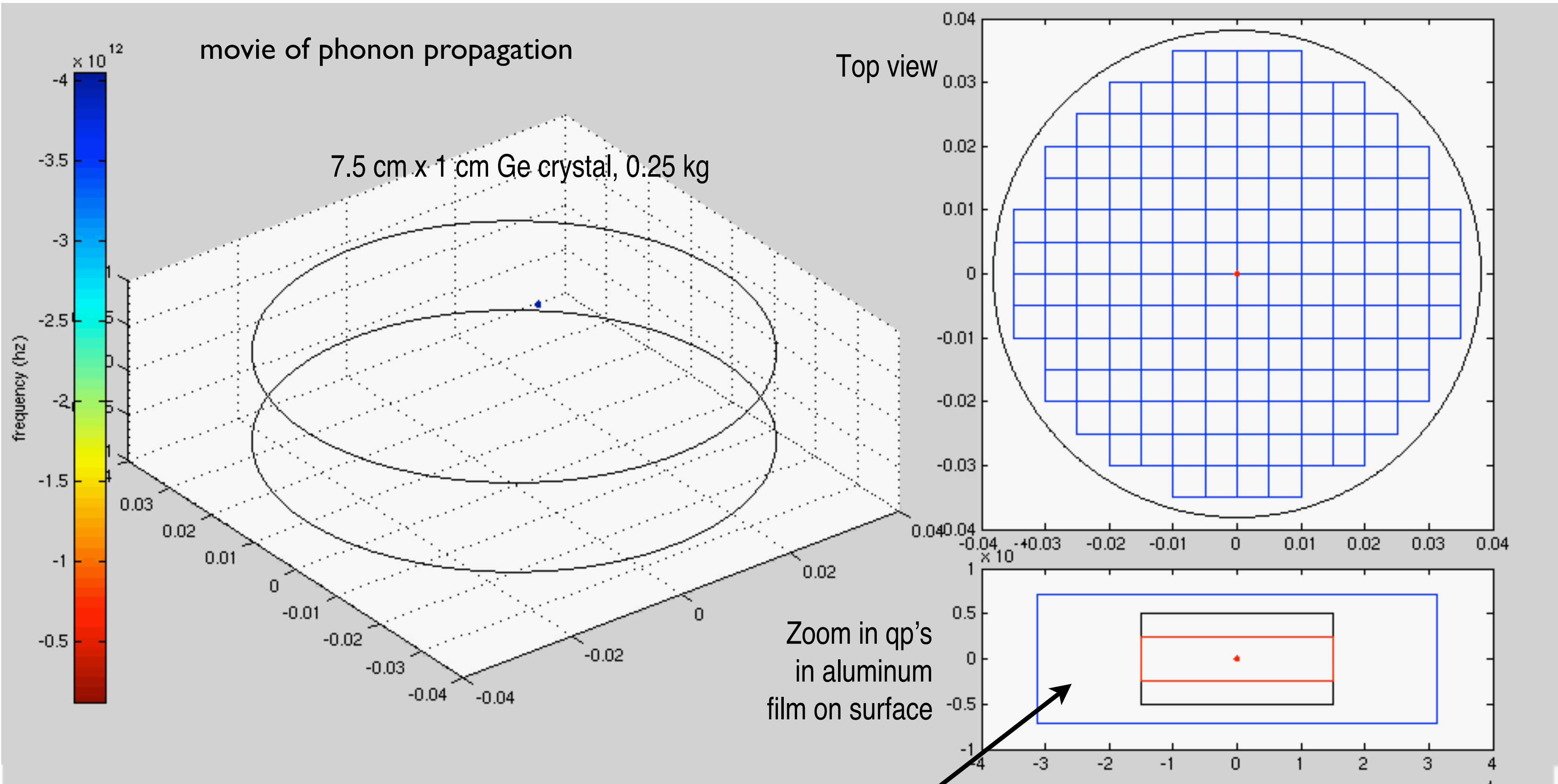


Kozorezov et al PRB: 75, 094513 (2007)



Mandic, after Wolfe and Clarke

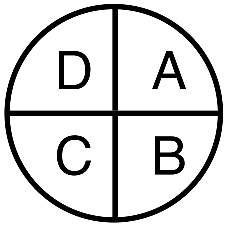
Physics of Athermal Phonons



How to detect?

Absorb them in a superconductor (2Δ ~ 0.1 THz ~ 400 μeV) at the surface (converts phonons to quasiparticles) and then detect them there using qp detector (TES, MKID, etc.). Position resolved detection important!

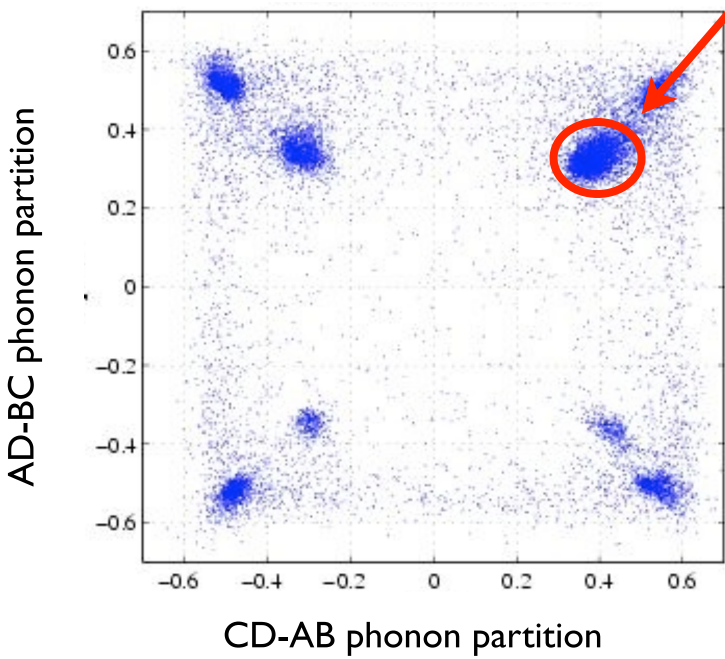
Application Example: CDMS II



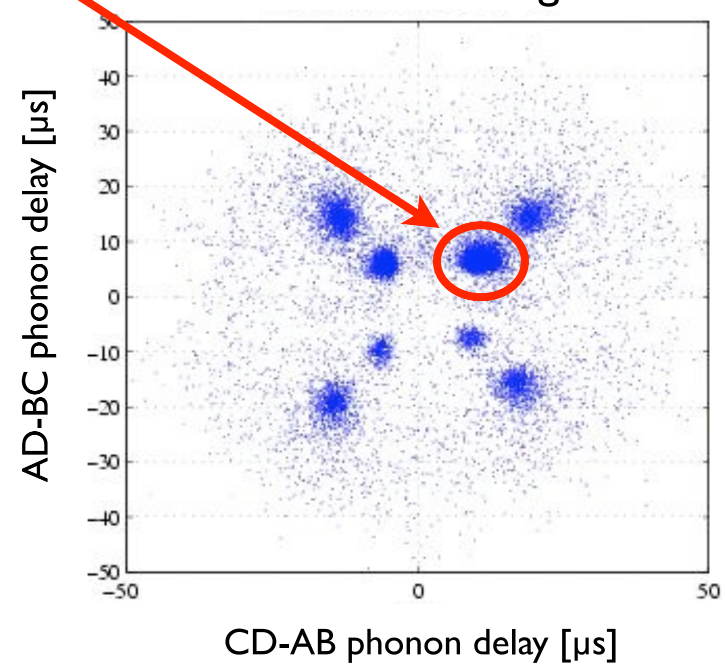
Sound speed ~ 1 cm/μs
Allows one to measure
position using arrival times
and energy sharing among
4 phonon sensors on surface

Collimated ^{109}Cd sources (β, 22 keV γ)

Phonon Energy Partition



Phonon Timing



Data from UC Berkeley calibration of T2Z5, née G31
V. Mandic et al., NIM A **520**, 171 (2004)

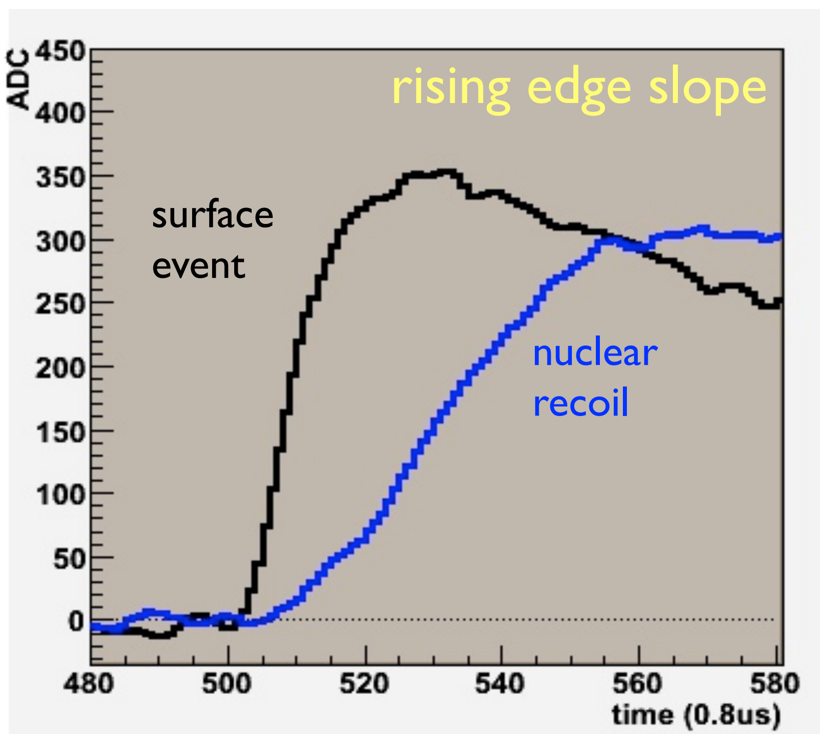
Application Example: CDMS II

Z-position sensitivity:

Surface events produce faster phonon pulses

Why? Surface, esp. metal films, promote downconversion to ballistic phonons.

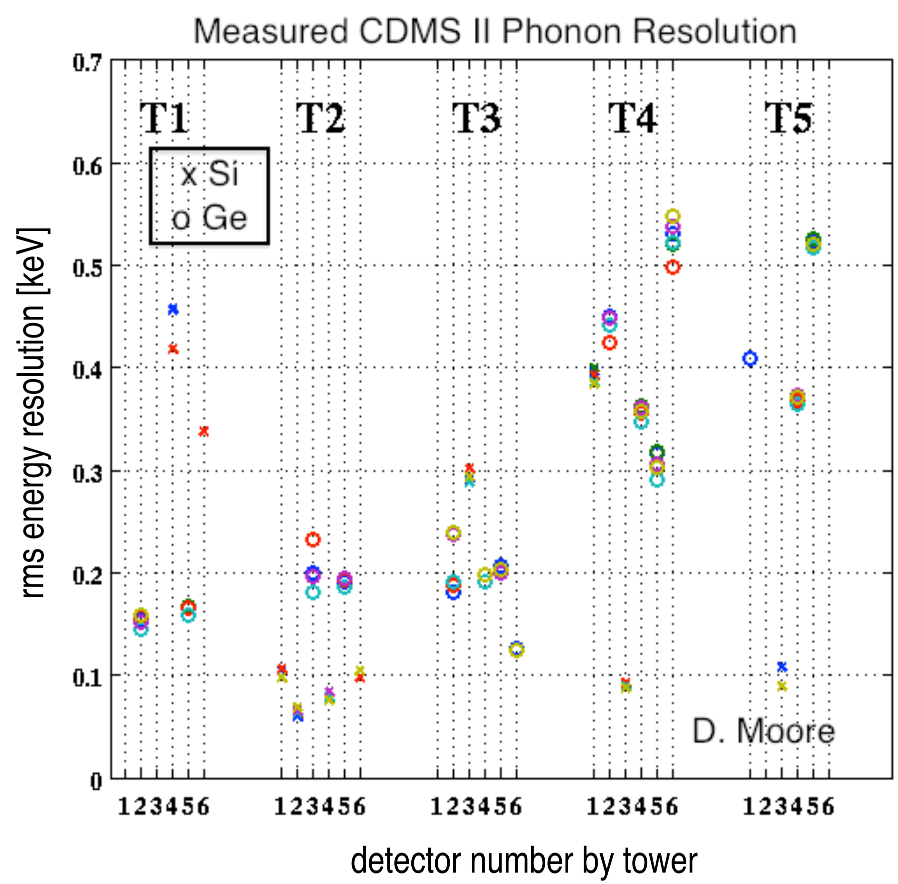
Additional position information from athermal phonons.



Energy sensitivity is exquisite:

σ_E as good as 0.1 keV when fabrication is well controlled

But position variation causes degradation:
FWHM = 0.4 keV @ 10.4 keV



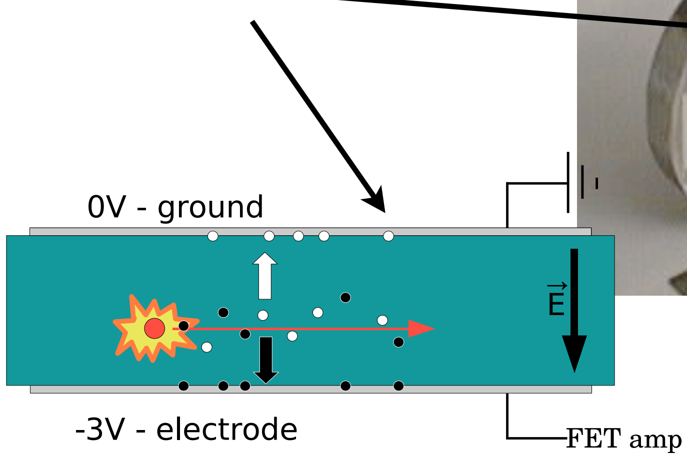
Cryogenic Ionization and Scintillation: Motivation

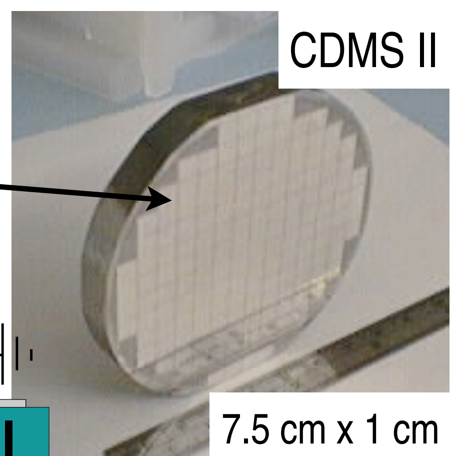
Or, making quenching your friend

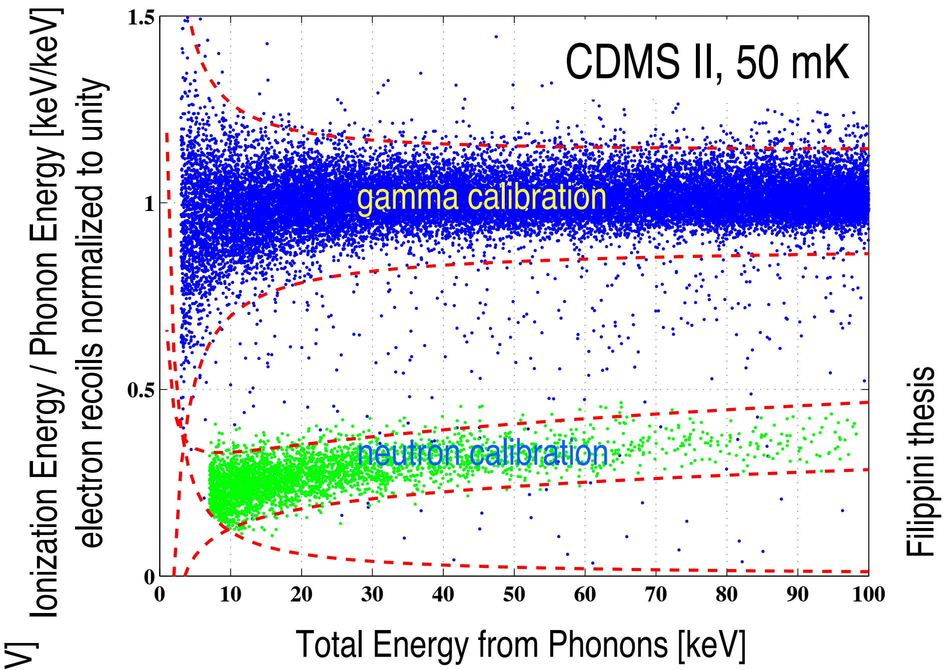
Nuclear recoil discrimination

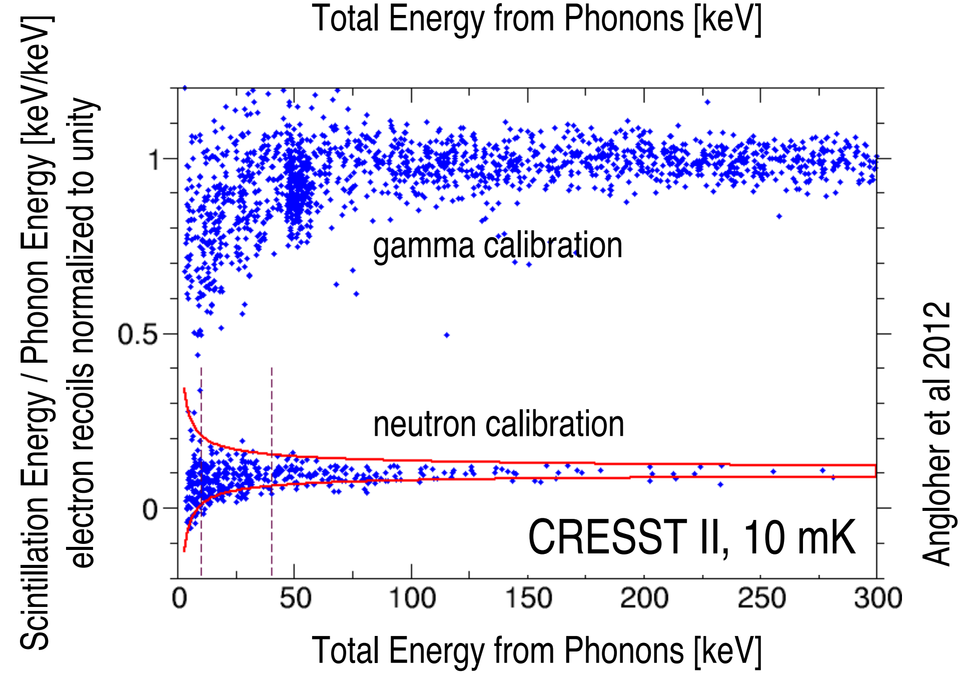
- Dark matter particles (& ν) expected to interact primarily with nuclei.
- Most backgrounds at low energy interact with electrons (Compton scattering, low energy electrons)
- Use simultaneous measurement of phonons and quenched channel to identify!

phonon sensors on this side









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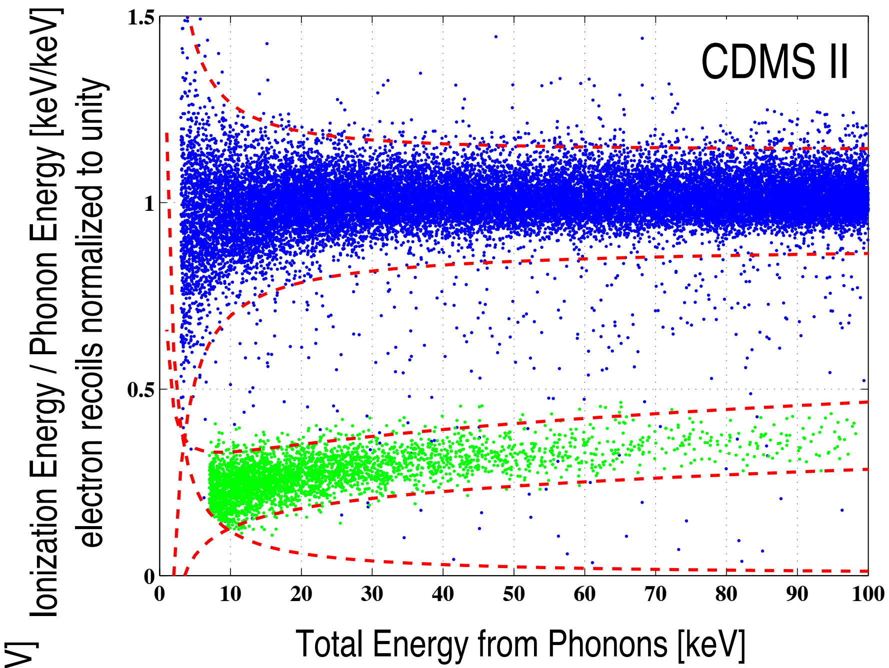
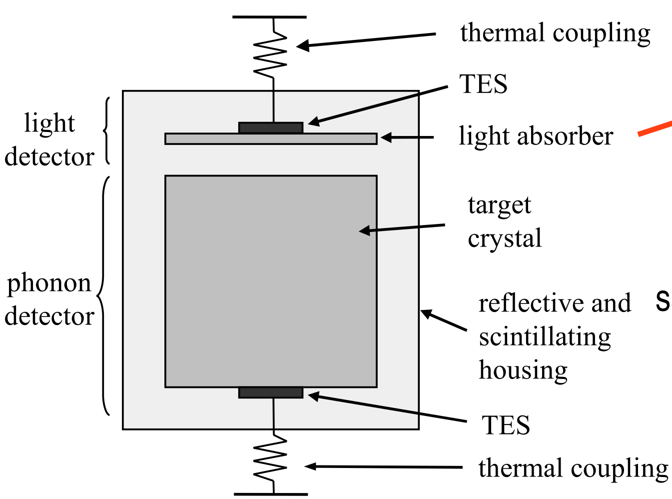
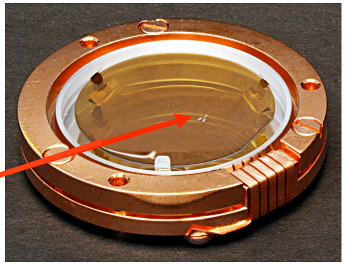


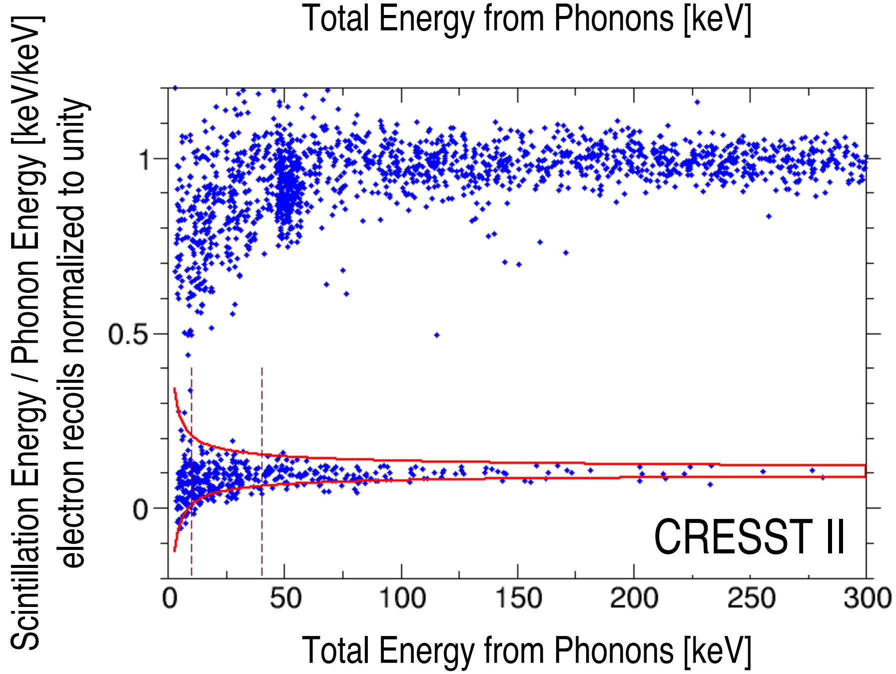
Filippini thesis





light detector = silicon on sapphire w/TES thermometer

CRESST II



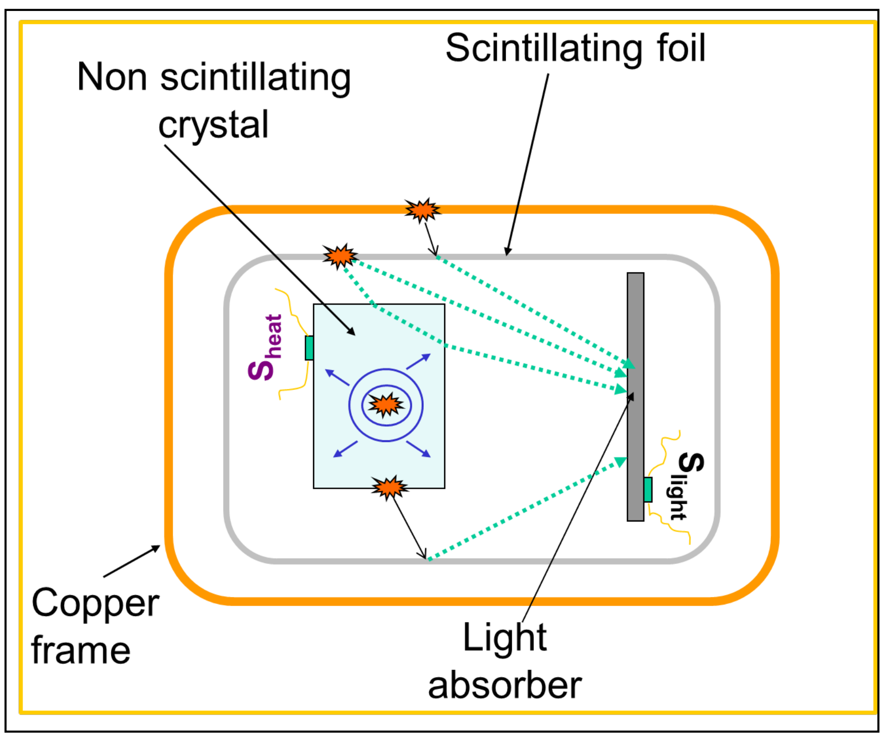
Angloher et al 2012

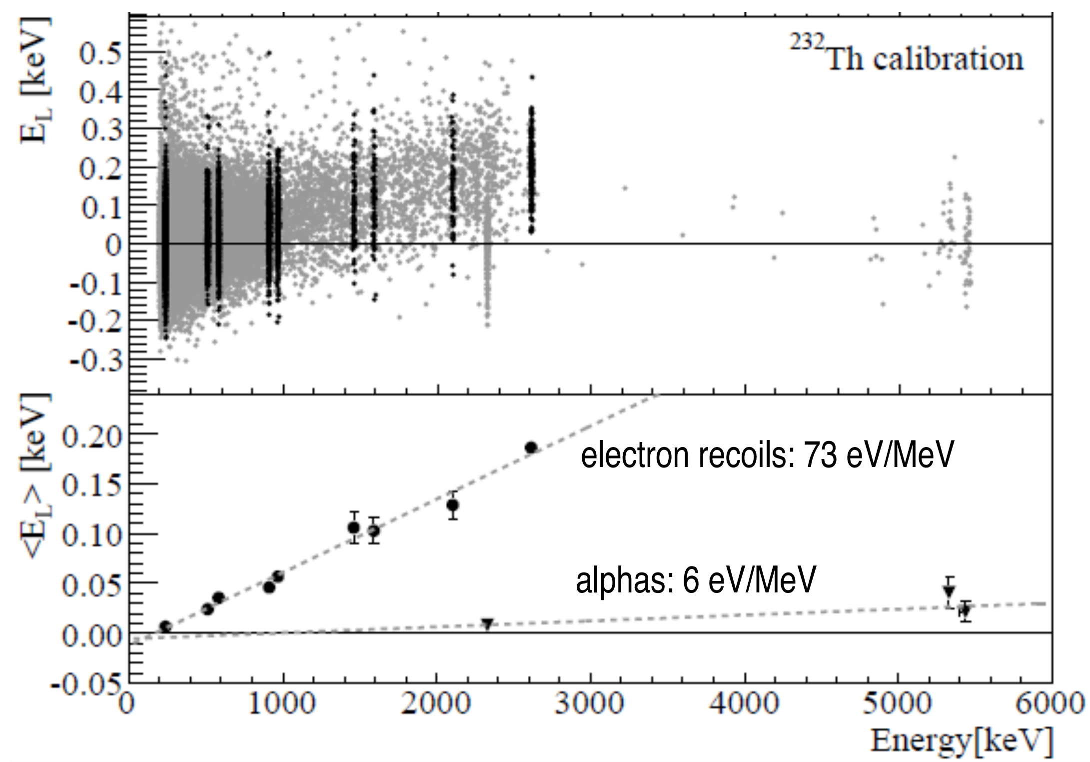
Cryogenic Ionization and Scintillation: Motivation

Or, making quenching your friend

Electron recoil discrimination

- $0\nu\beta\beta$ should produce pure electron recoils
- Recall α contamination for TeO_2 due to surface contamination
- Very weak luminescence seen, much weaker for α particles than for electron recoils. Enables rejection of α events.



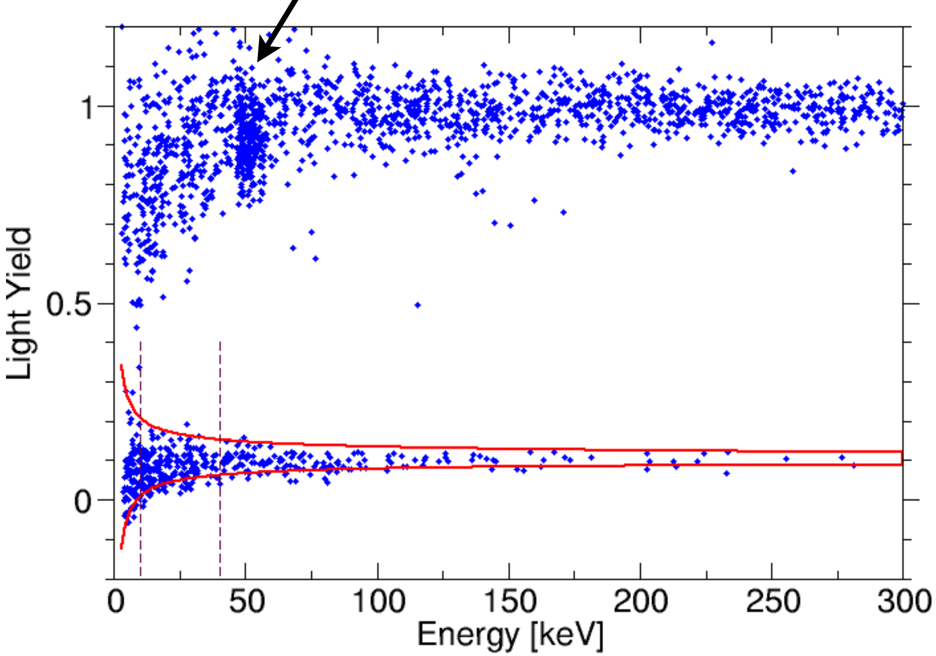


Cryogenic Ionization and Scintillation: In Practice

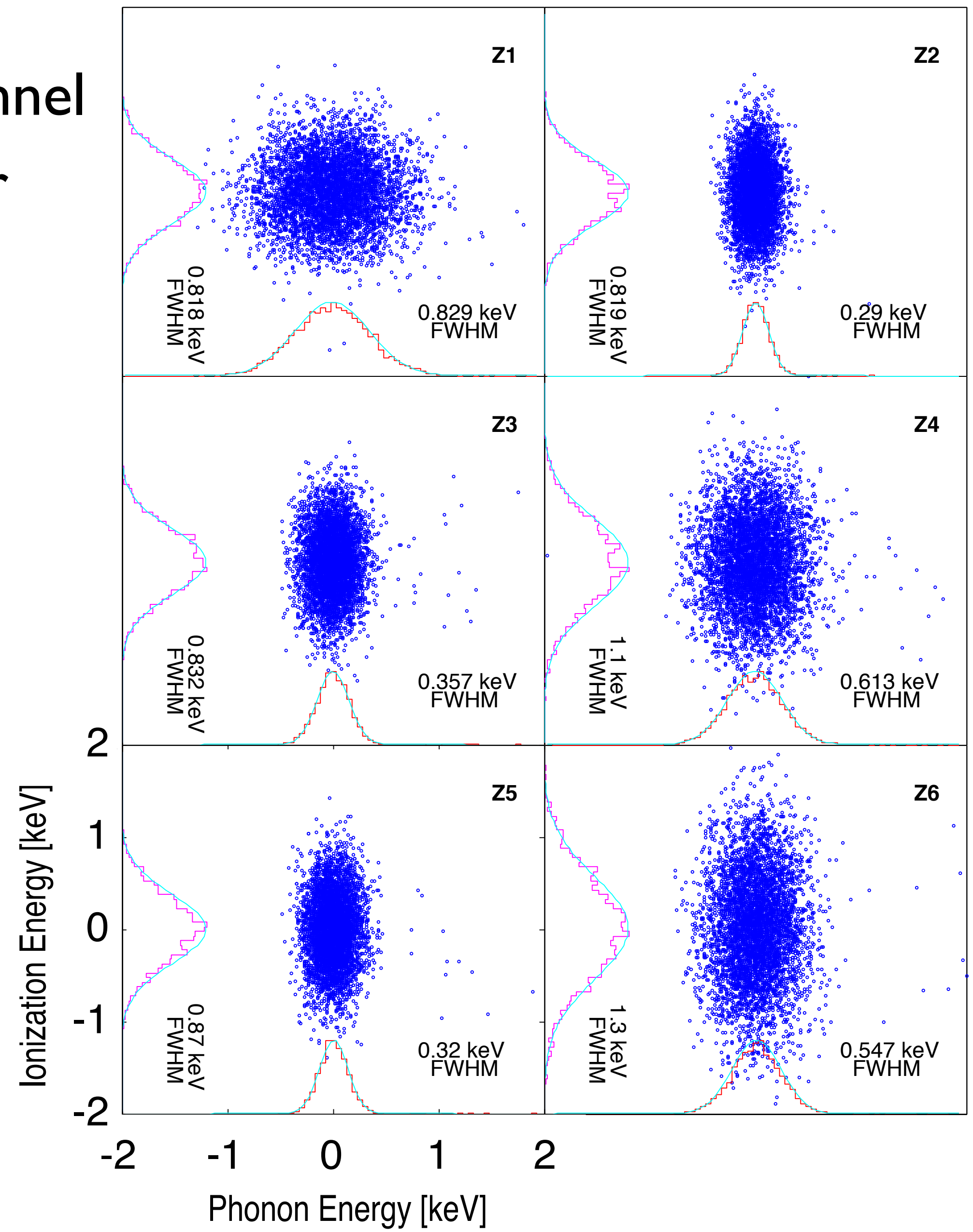
- Resolution in ionization/scintillation cannot match that in phonon channel
- Threshold for science set by poorer channel

clear from width of line in phonon and light dimensions that light resolution much poorer than phonon resolution

CRESST II



CDMS II



Application Example: CDMSLite, Coherent ν Scattering

Ionization performance limits event-by-event rejection to E > 10 keV$_{recoil}$

- Can we get around this?

Yes, sort of, in two ways, using quenching:

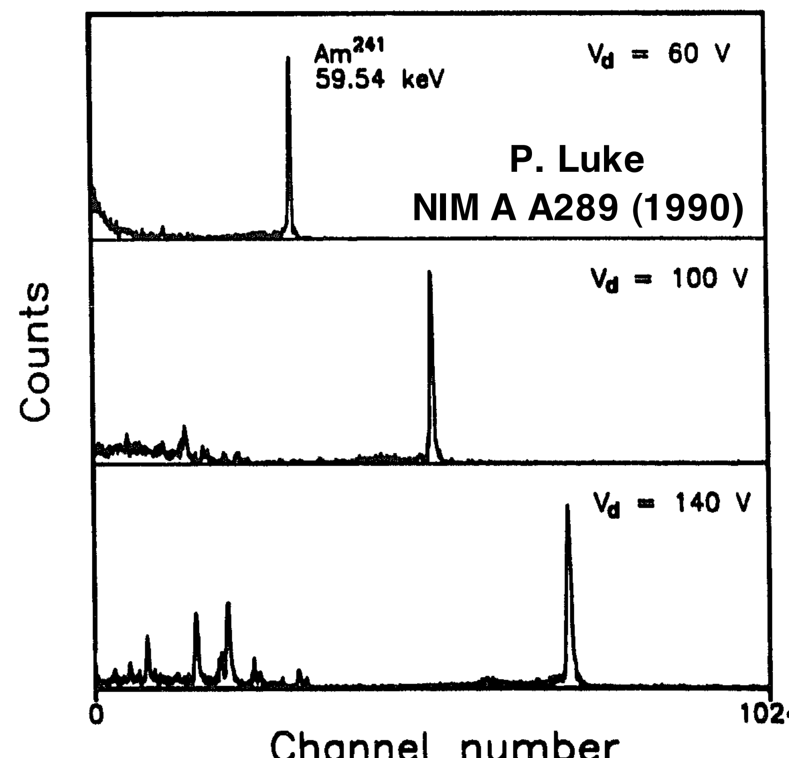
- In phonon-mediated detectors with an electric field applied, all events have Luke-Neganov phonon ("drift heating") contribution:

$$E_{tot} = E_r + E_{luke} = E_r + n_{eh} e V_b = E_r \left(1 + \frac{eV_b}{\epsilon_{eh}}\right)$$

~3 eV for CDMS

in Ge, ~3 eV for ERs, ~9 eV for NRs

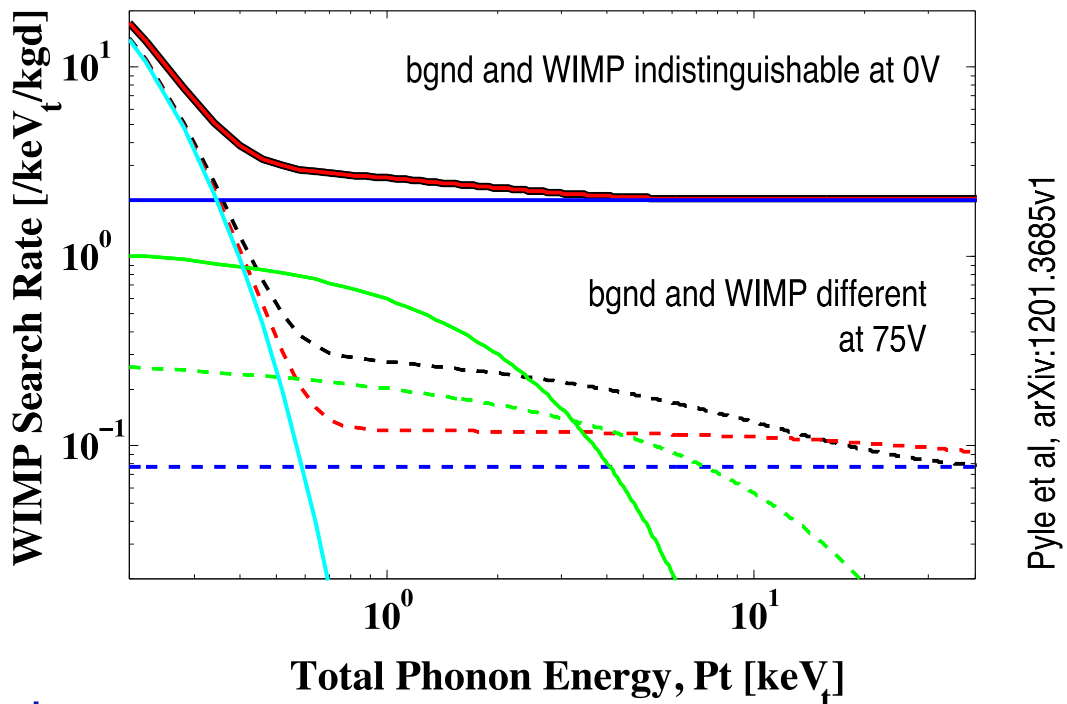
- Normally, we use ionization signal to measure and subtract (which further degrades performance!)
- Paul Luke pointed out that one could apply a high field to make drift heating dominant and use thermal phonons to measure. Beats electronics noise in ionization (which typically limits baseline σ_E).



Application Example: CDMSLite, Coherent ν Scattering

In principle, lose nuclear recoil discrimination, but aided in two ways:

- Different drift heating for electron and nuclear recoils "stretches out" ER bgnd: ER bgnd rate effectively decreased by QF.
- Take data at different biases: ER bgnd and NR signal behave differently.
  - solid: 0V bias
  - dashed: 75V bias
  - cyan: noise triggers
  - green: WIMP signal
  - blue: constant ER bgnd
  - black: WIMP signal + constant ER bgnd
  - red: exponential increasing ER bgnd + constant ER bgnd



- Constant + exponential ER bgnd indistinguishable from WIMP at 0V bias, very different at 75V bias because of different stretching of WIMP and ER signals in phonon energy

SuperCDMS planning high bias running, coherent ν scattering expt in the works (Figueroa, Pyle, Mahapatra et al)

Cryogenic Ionization and Scintillation: In Practice

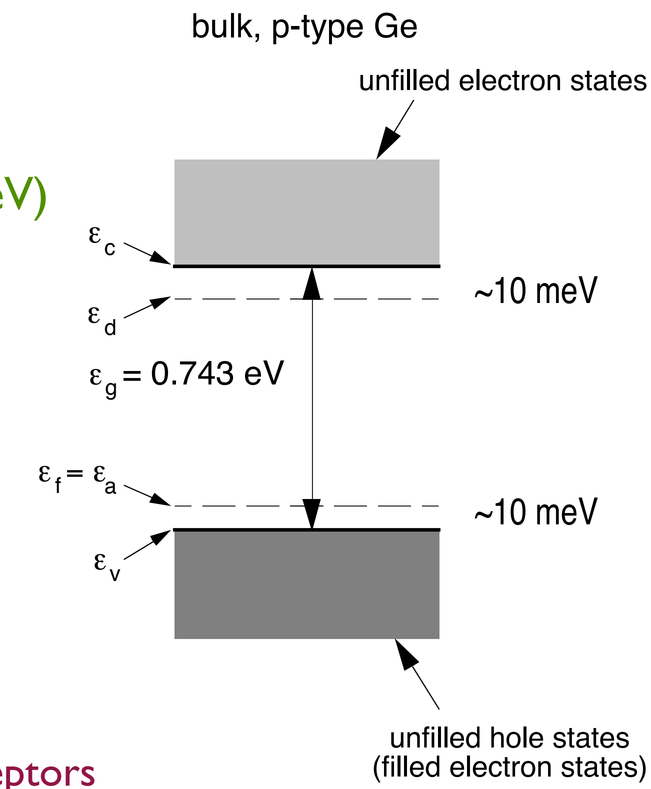
"Neutralization"

77K germanium ionization spectrometers:

- large numbers of thermally excited carriers because thermal energy ~ donor/acceptor binding energy (~10 meV)
- high voltage (few kV) applied to sweep all thermally generated carriers out: depleted
- ionized impurity sites would act as traps, but v. high E-field prevents trapping

sub-Kelvin ionization collection:

- No thermal carriers: $kT \ll 10$ meV. Depletion unneccessary. Only a few V need to be applied
- But some donors/acceptors are ionized:
  - e.g., for p-type, $N_a \gg N_d$, so N_d electrons fall from donors to acceptors creating N_d ionized impurities: traps for drifting charge
- Empirically, find these traps can be "neutralized" by creating free charges with radioactive source exposure or LED
- "Neutralized state" remains for extended periods, esp. if detectors regularly grounded and flashed with LED.

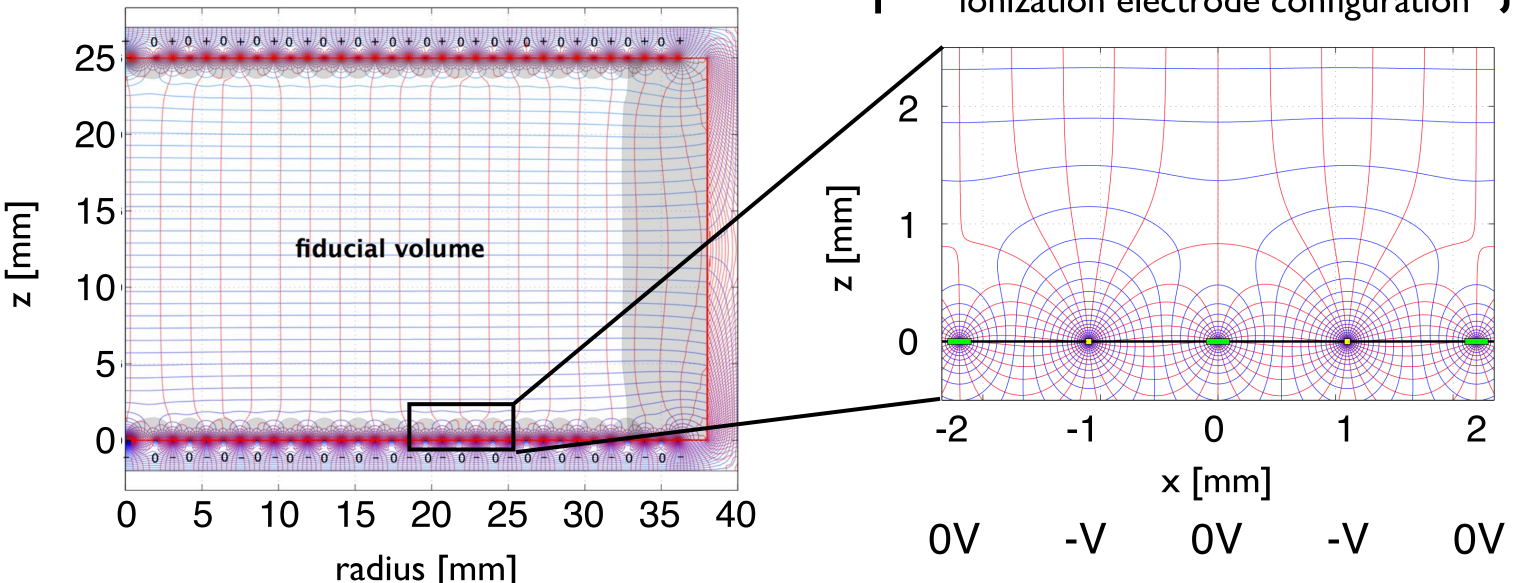


Cryogenic Ionization: Interdigitated Electrodes

Surface events (fast phonon signal) also have suppressed ionization: can be misidentified as nuclear recoils.

Phonon pulse shape provides ~5 x 10^{-3} misid probability, but better is needed.

Interleaved ionization electrodes provide surface event rejection

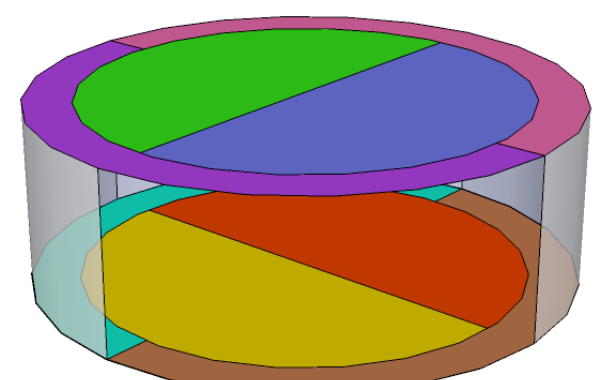


negative version on other face

also used for EDELWEISS II w/thermal phonon sensing

M. Pyle

phonon sensor configuration



Interleaved ionization electrodes causes different distribution of ionization signals among electrodes for surface and bulk events

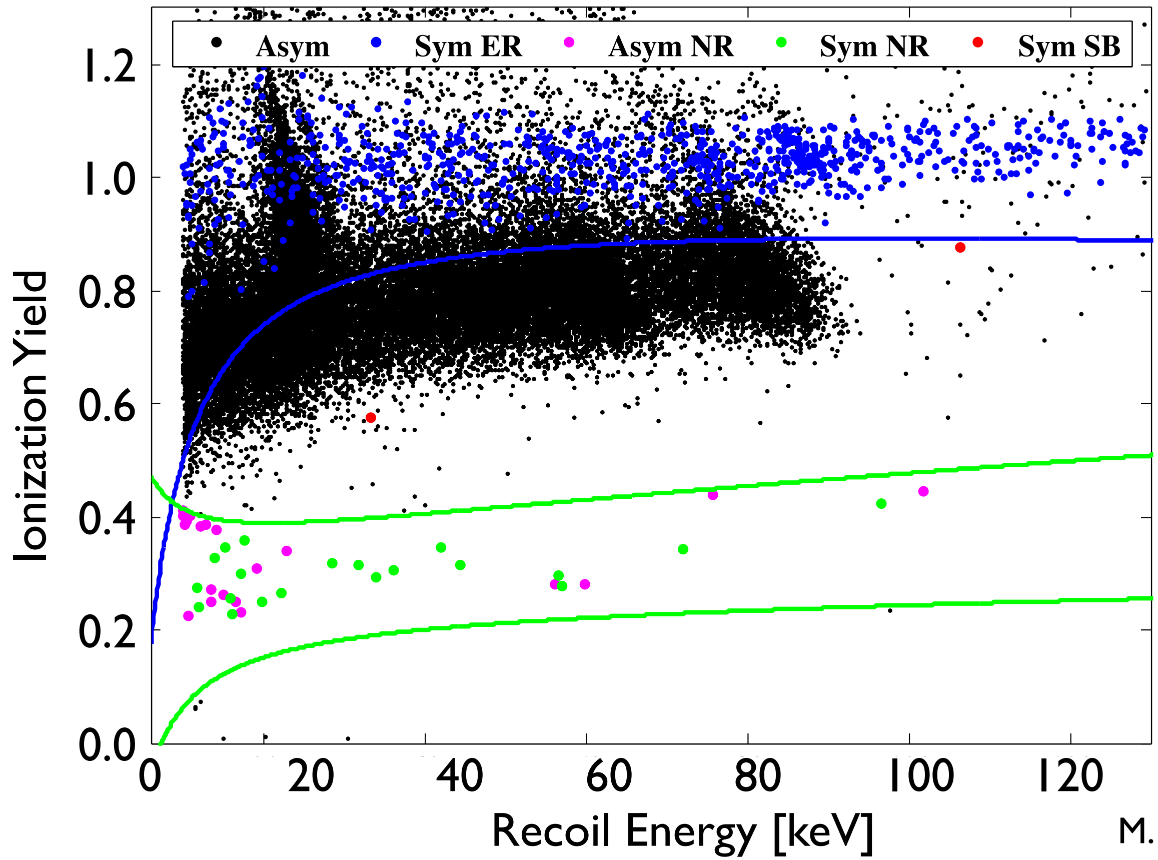
High field near surface increases ionization yield for surface events

Cryogenic Ionization: Interdigitated Electrodes

Interleaved ionization electrodes provide surface event rejection

- High field at surfaces increases ionization yield
- Surface events share charge asymmetrically
- Phonon energy sharing and timing z position
- Also used by EDELWEISS II w/thermal phonon sensing
- History:
  First suggested by Paul Luke. Tested for CDMS, but not much effort put in. Demonstrated by EDELWEISS, then retested by CDMS. Now in use by both.

^{109}Cd e^{-} source ^{133}Ba photon source



M. Pyle, B. Serfass

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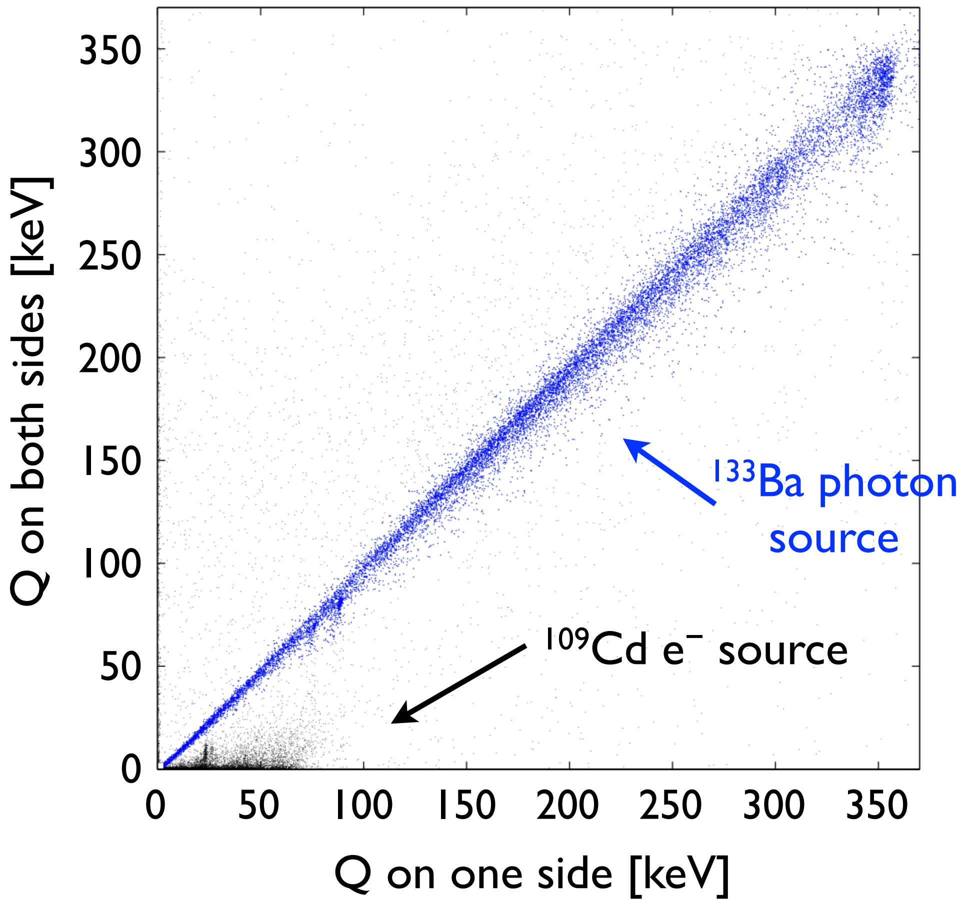

M. Pyle, B. Serfass

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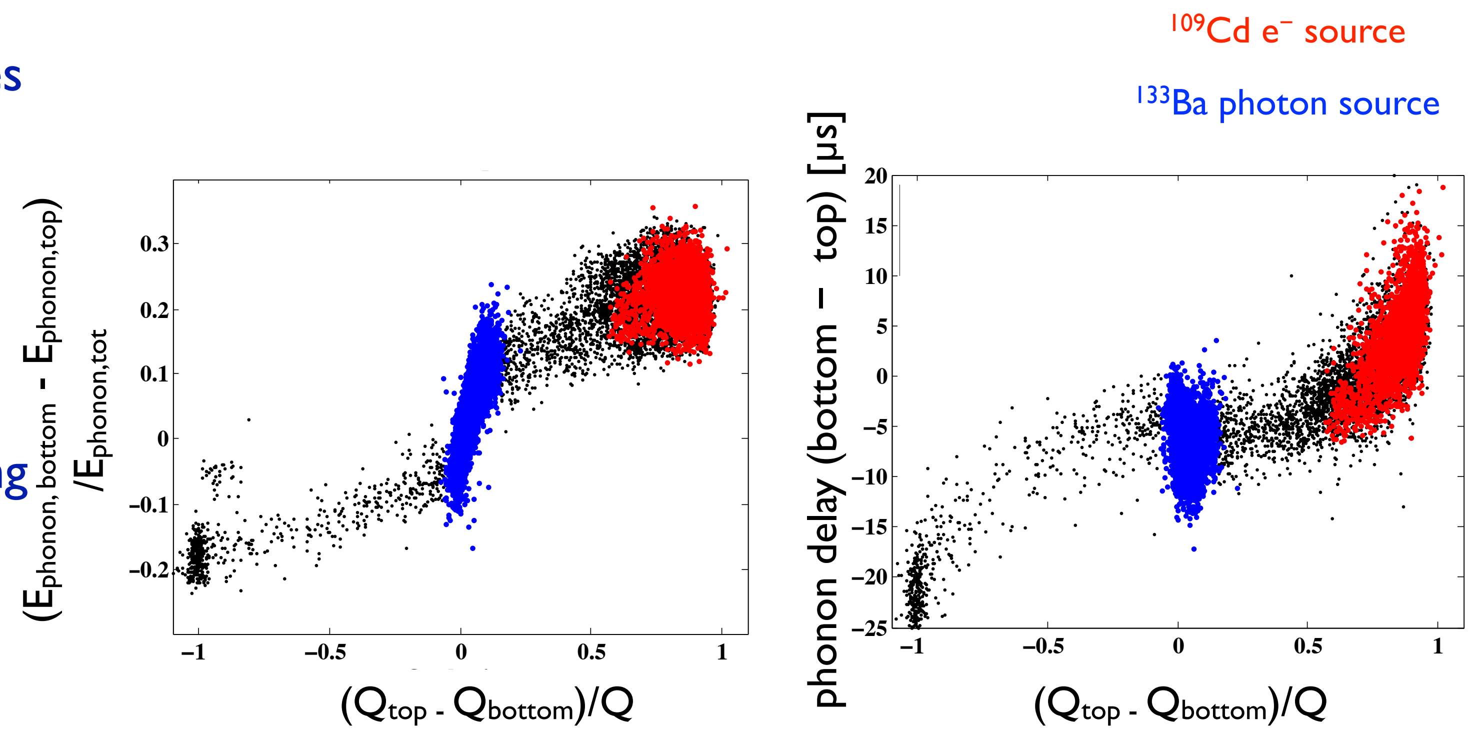

M. Pyle, B. Serfass

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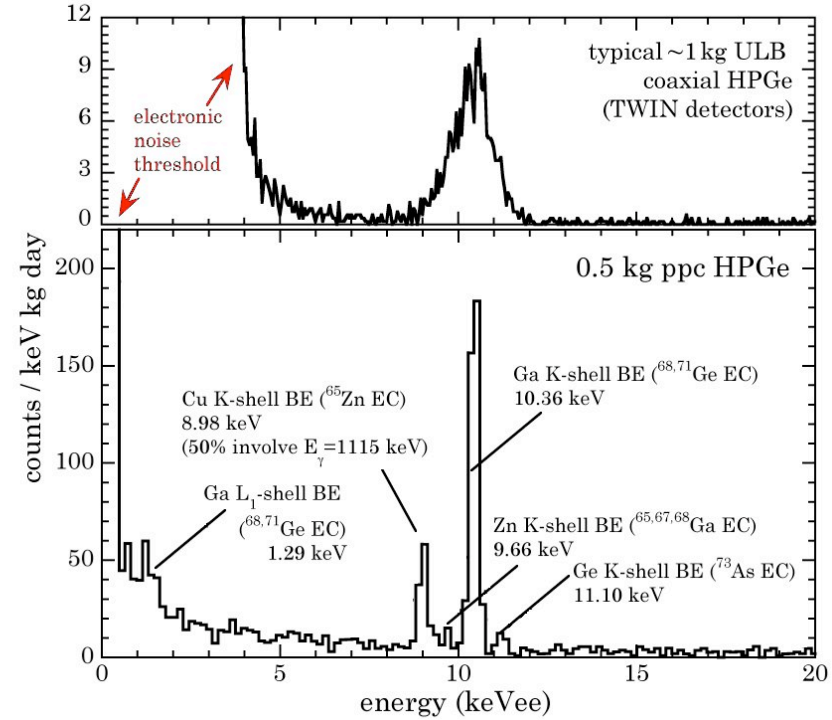
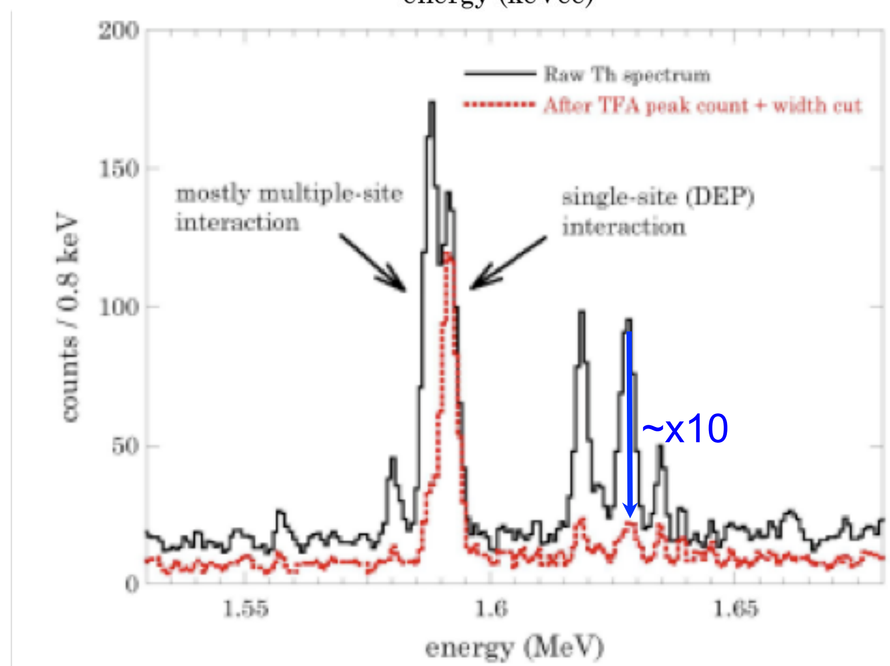
First suggested by Paul Luke. Tested for CDMS, but not much effort put in. Demonstrated by EDELWEISS, then retested by CDMS. Now in use by both.

Truth in Advertising

- Ge ionization spectrometers (p-type point contact, Collar et al) can offer excellent low-energy resolution, electronics FWHM = 160 eV via low capacitance and modern FET technology
- Ge ionization spectrometers show comparable energy to, e.g., TeO_2, for $0\nu\beta\beta$
  - FWHM = 3-4 keV at 2039 keV
  - But, restricted to Ge; phonon-mediated detectors allow wide range of substrates



Barbeau, Collar et al



Barbeau et al., JCAP 09:009 (2007);
Luke et al., IEEE Trans. Nucl. Sci. 36 , 926 (1989).

Conclusions

Cryogenic detectors have a number of advantages that make them appropriate for applications in non-accelerator particle and nuclear physics:

- excellent energy resolution
- low thresholds
- wide applicability to different substrates
- ability to combine with "quenched" signals to provide discrimination power

In many cases, the challenge of operation is worth the qualitatively new physics that can be studied!