Cryogenic Detectors for HEP and Nuclear Physics

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HEPCAT Summer School
August 21, 2024

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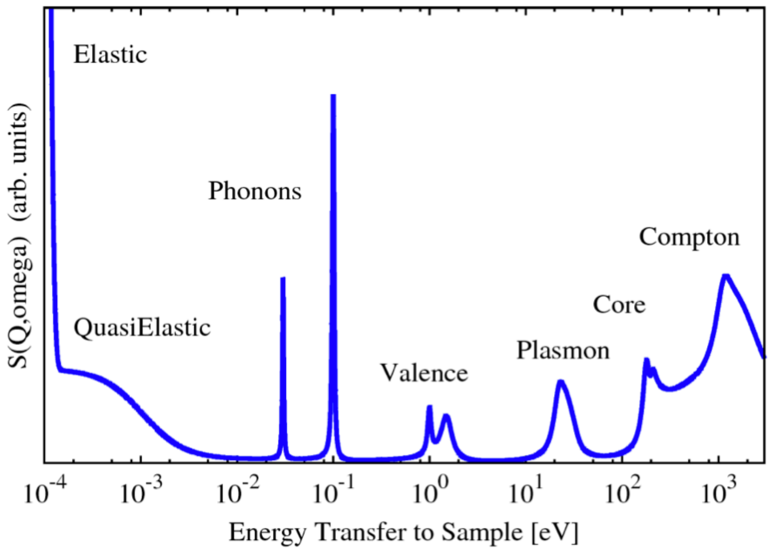
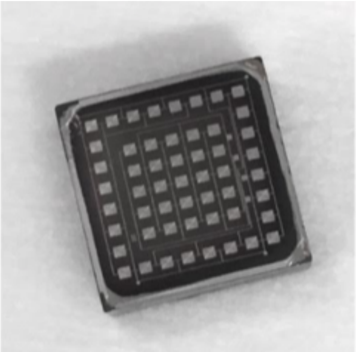
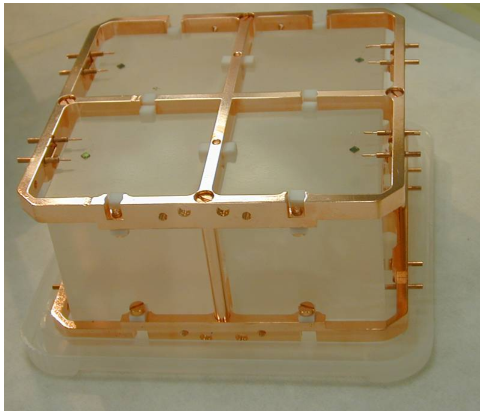
U.S. DEPARTMENT OF ENERGY Stanford University SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Solid State Physics in cold crystals - a quick refresher
  - Excitations in cryogenic crystals
  - Interactions of particles with crystals
- Readout technologies - principle of detection
  - Charge detectors
  - Phonon sensors
  - Qubit-based sensing
- Applications - examples in current experiments
  - Dark matter detectors
  - Double Beta Decay
  - Coherent neutrino scattering
  - Non-profileration
- Current Challenges
  - Lowering energy scales



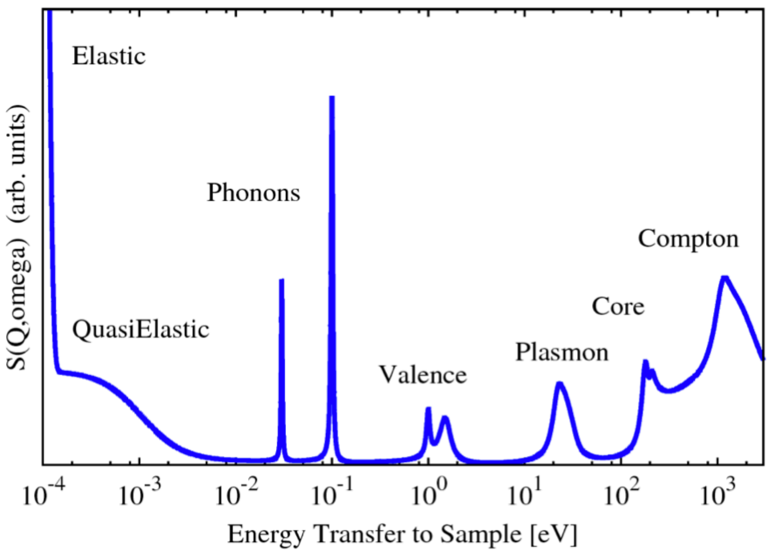


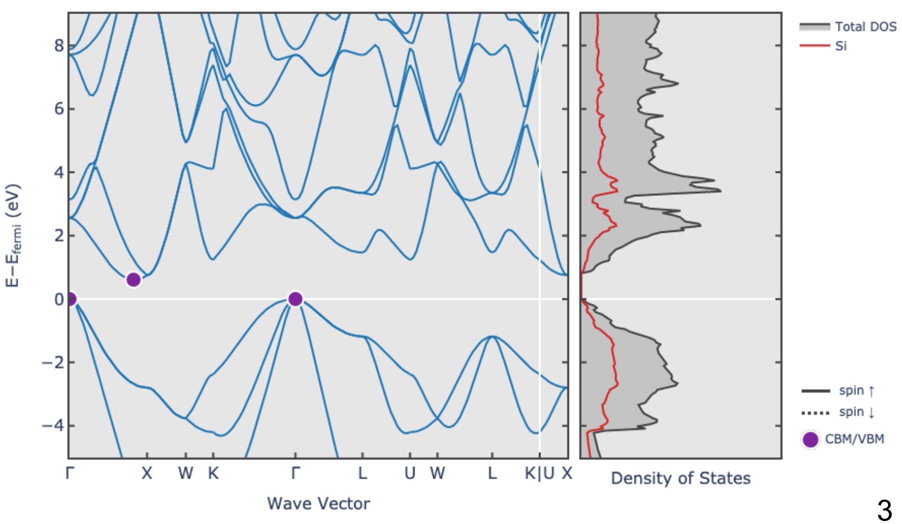


Solid-State Excitations

- The distribution of energy from a particle scattering event into a cryogenic crystal depends on coupling, energy, and momentum of the incident particle. Many combinations of excitations are possible, and choice of a crystal can greatly influence utility of different substrates for different physics.

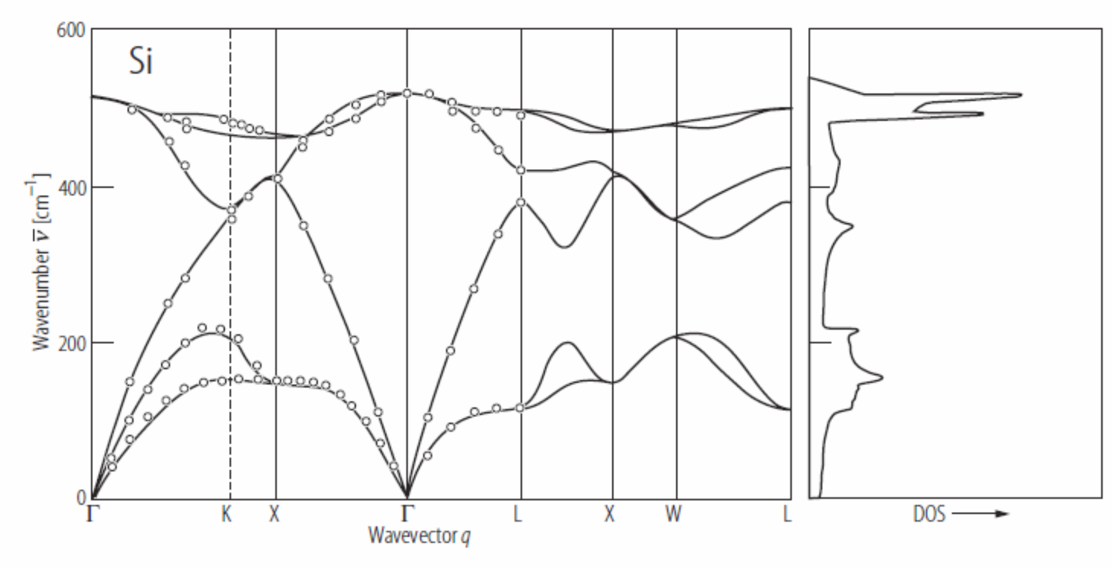
- While more exotic excitations are possible, there are three main classes active in particle scattering events:
  - Phonons
    - Optical (normal mode)
    - Acoustic (sound waves)
  - Free charges
    - Valence electron-hole pairs
    - Core and compton electrons
    - Recombination can produce phonons or photons depending on band structure
  - Bound excitations
    - Plasmons - akin to phonons in the electron system
    - Other inelastic modes - we won't discuss these further for today

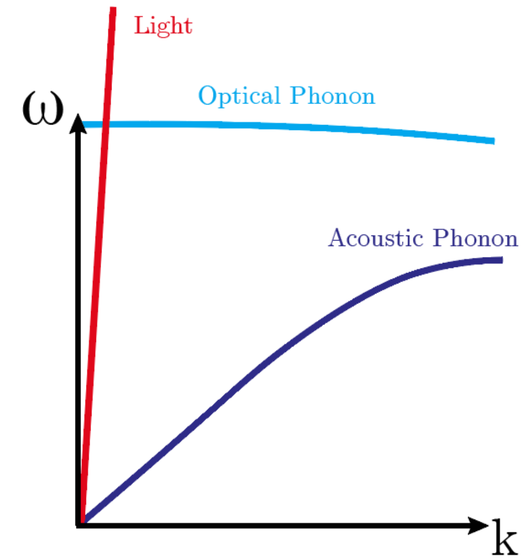




Phonons

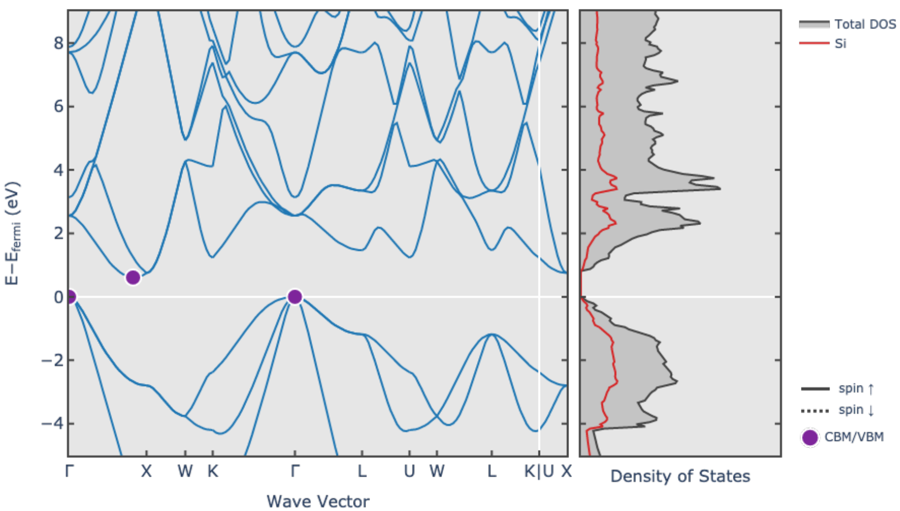
SLAC

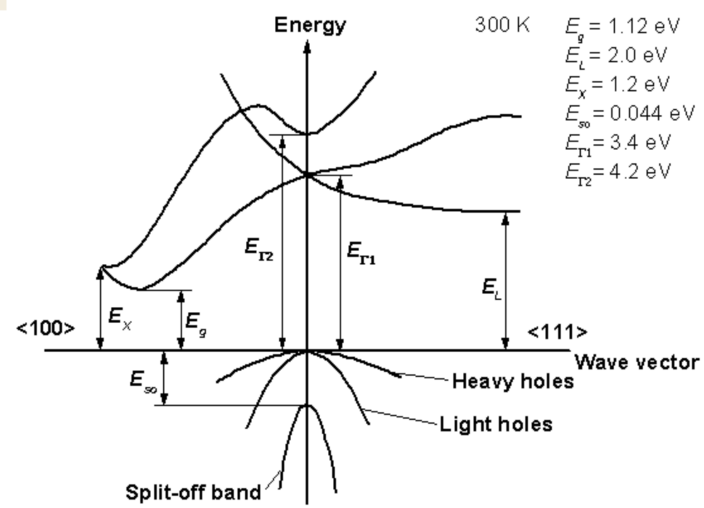




- Phonon modes can be computed numerically to fairly high accuracy - they are eigenmodes of the deformation tensor for a regular crystal lattice (tools such as phonopy can be used)
- For cold crystals, interactions primarily involve small momenta near the Gamma point (k=0) allowing us to consider dynamics of a simpler model:
  - Acoustic phonons - linear dispersion relation $\omega = c_s k$
  - Optical phonons (normal modes) - 'quantized', no momentum dependence
  - In a 2D model this is enough. In a real lattice there are two transverse and one longitudinal version of these executions (e.g. LA, TO)

Charge States





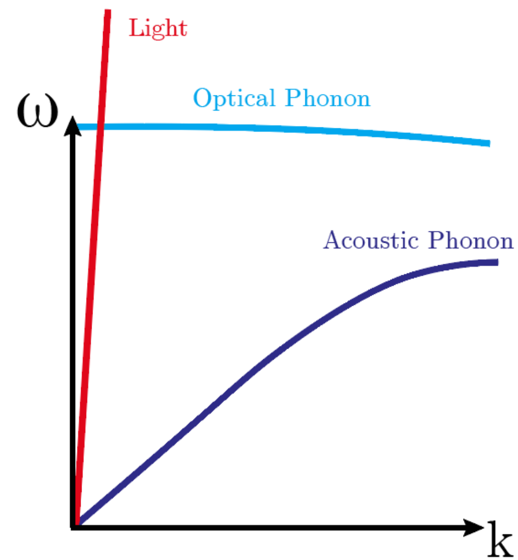
- Band structure of crystals can be computed using DFT, among other approaches, by considering overlap of valence bands in a crystal
- For scattering, unless this occurs near the gap, we can consider the electrons as being in a free electron gas
- In cryogenic crystals, charge is 'frozen out' - there are no free electrons in the conduction band, or holes in the valence band, and thus down-conversion is rapid
  - The down-conversion process depends on where the band minima are, and the charge lifetime is much longer in materials with indirect gaps

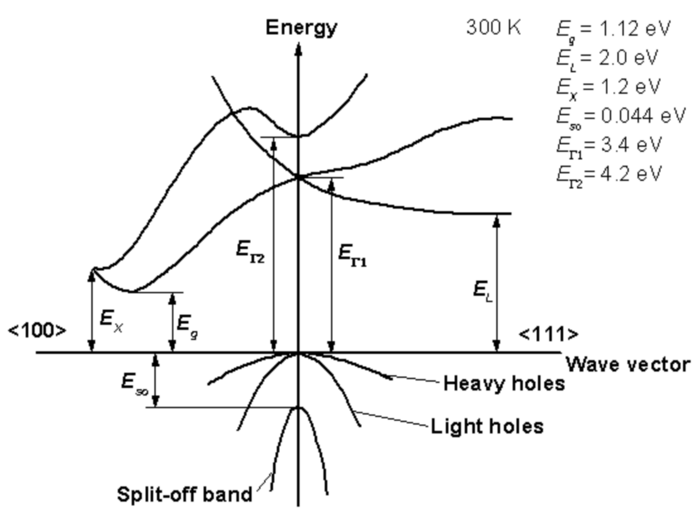
Summary of the Simplified Crystal Model (Electrons)

- Phonons:
  - Optical phonons have a fixed frequency
  - Acoustic phonons obey linear dispersion relations
- Charge:
  - Free charge is limited to the region near the valence/ conduction band minima
  - Dispersion relation is quadratic with an effective mass tensor about band minimum

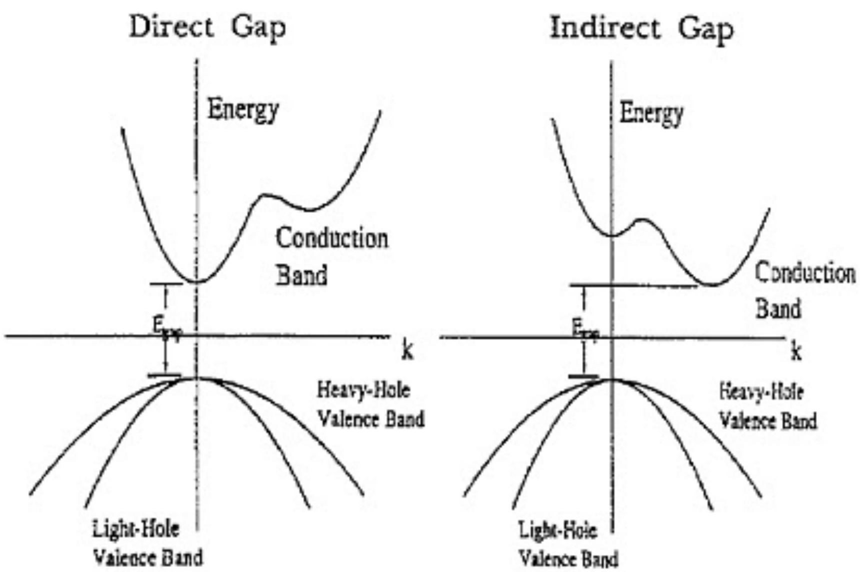
$$E = \langle k|\mathbf{M}^{-1}|k\rangle \approx \frac{k_x^2}{2m_x} + \frac{k_y^2}{2m_y} + \frac{k_z^2}{2m_z}$$

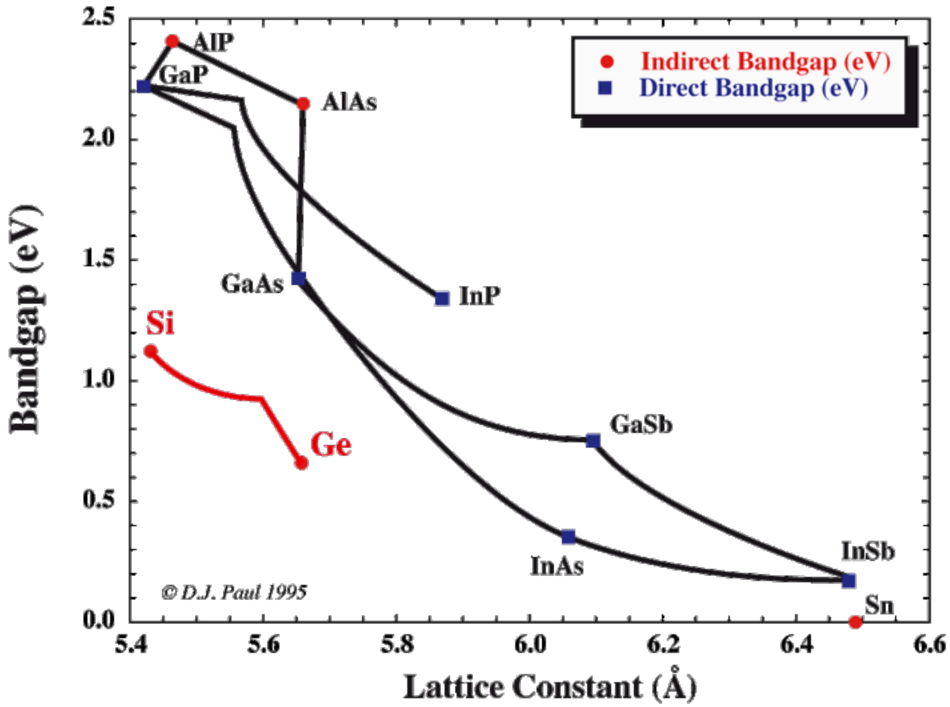
- Energy loss from free electrons/holes occurs through two processes
  - Phonon emission - optical emission dominates if energetically allowed, random momentum loss
  - Photon emission - if allowed by selection rules, q~0 photon emission occurs, though re-absorption is almost guaranteed (scintillators are a key exception, though this always occurs for electrons near gap)





Classes of Semiconductors





We further separate common gapped materials (here we use semiconductors as a loose term) into direct and indirect

- Direct gap can always recombine via photon emission (leading to light emission) - scintillators are exclusively direct-gap
- Indirect-gap requires simultaneous phonon emission and recombination is highly suppressed - charge collection only possible in indirect-gap materials

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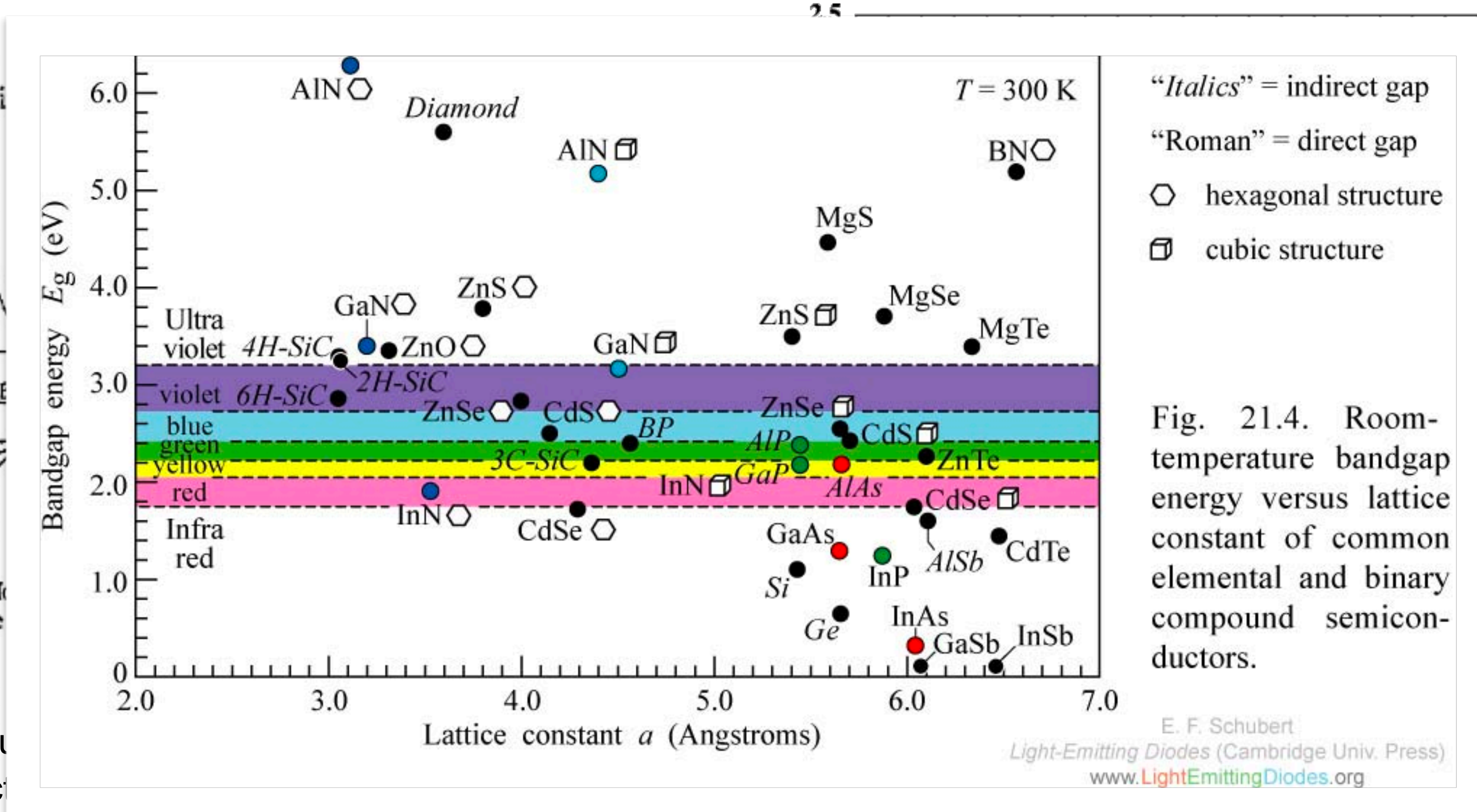
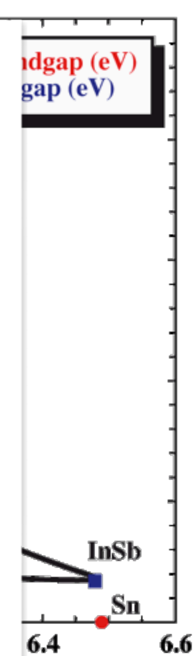


Fig. 21.4. Room-temperature bandgap energy versus lattice constant of common elemental and binary compound semiconductors.



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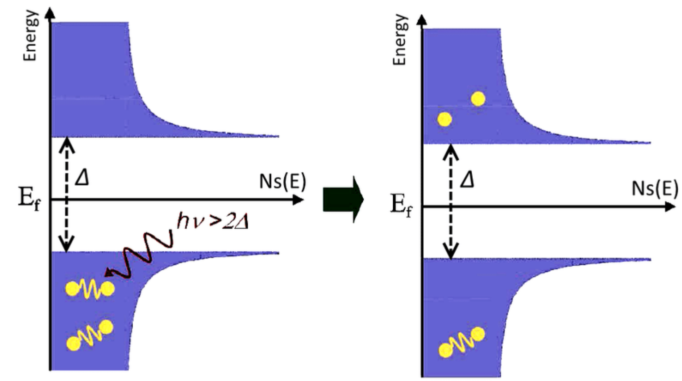
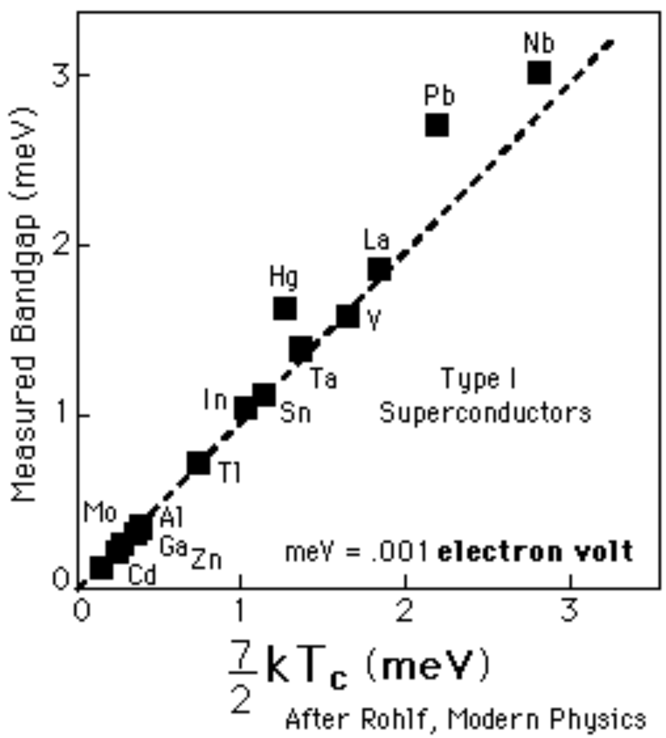
Superconductors - Charge/Phonon Bound States

- Superconductivity (for conventional superconductors) arises from pairing of electrons into boson-like cooper pairs
  - Bosonic properties explain infinite conductivity - rare free electrons exist in otherwise unoccupied superconducting ‘conduction’ band
  - This also produces a ‘semiconductor’ like model of superconductors, useful for understanding them as particle detectors

- The energy scale of this gap is much lower than easily usable semiconductors, and higher than thermal phonon population - otherwise superconductors couldn’t be stable



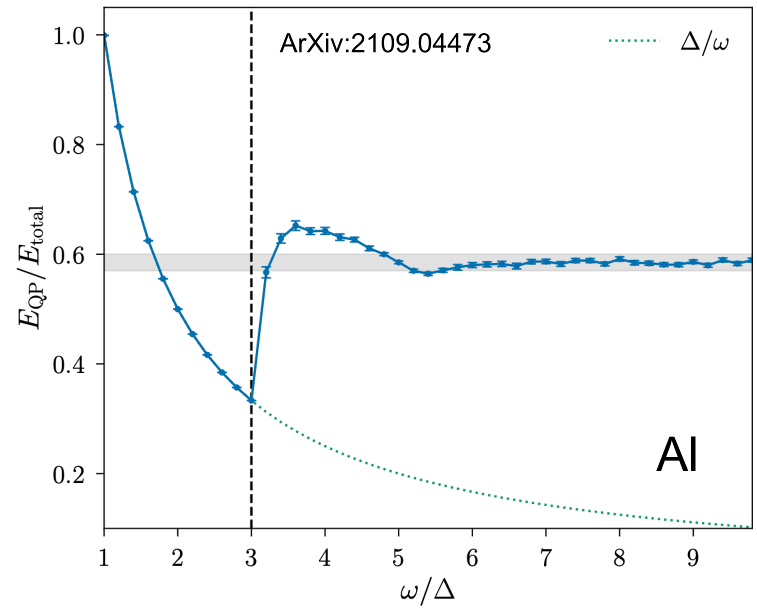


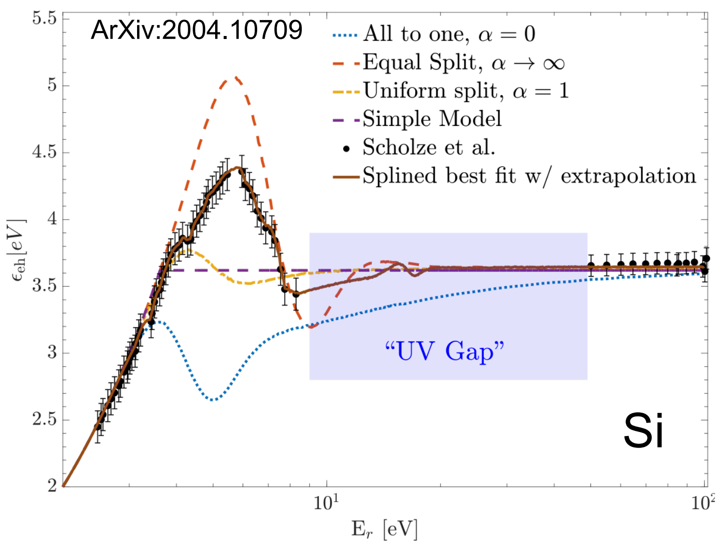
Charge/Phonon Balance in Conventional Materials

- Our simplified model of superconductors and semiconductors gives predictable behavior for electron scattering events
  - Above ~10x the energy gap, the cost per free charge is constant
  - The rest of the energy ends up in the phonon system as athermal acoustic phonons which slowly come into thermal equilibrium with their environment

- For direct-gap materials, a small fraction of the energy is also emitted as photons
  - This is highly suppressed in superconductors but is still present at small levels

- Charge readout in semiconductors, and qp measurement in superconductors, thus tracks energy deposition

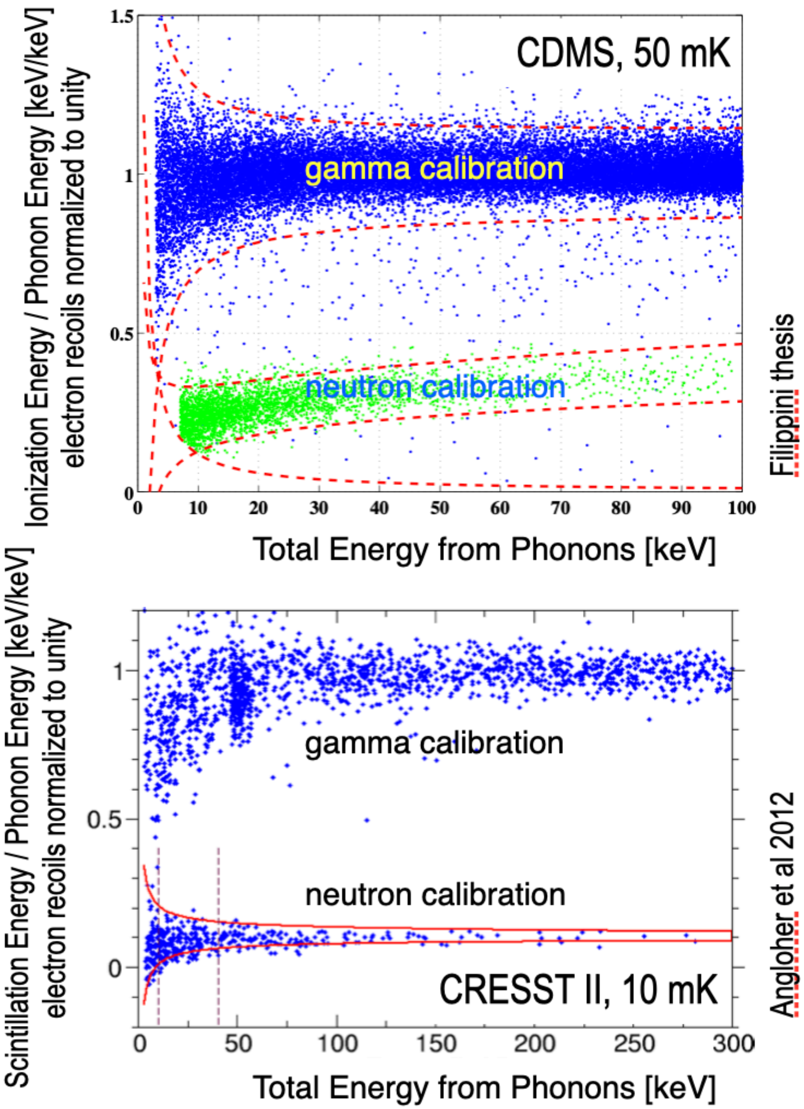




The Caveat: Nuclear Recoils

- Non-electronic interactions (direct nuclear scattering) is more complicated, involving defect formation and nucleon-nucleon interactions
  - At high energy, this is realized as a well-characterized loss in ionization (or scintillation) yield relative to electron recoils
  - The relative efficiency of charge production drops as event energy is reduced

- For energies at or below the defect creation energy of the lattice, it is likely that *only phonon production* occurs
  - This is an active field of study - it's hard to measure 100 eV nuclear recoils



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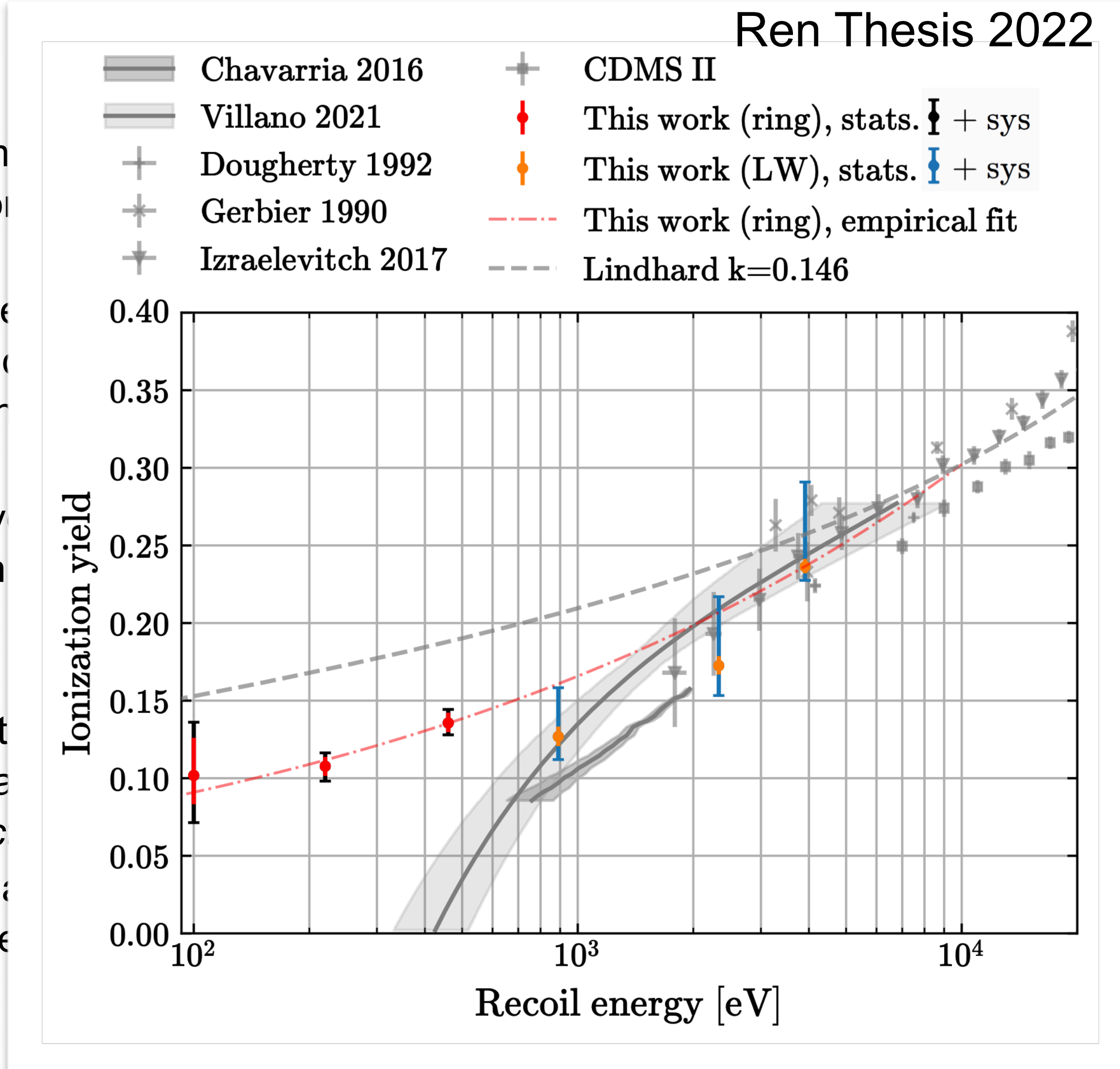
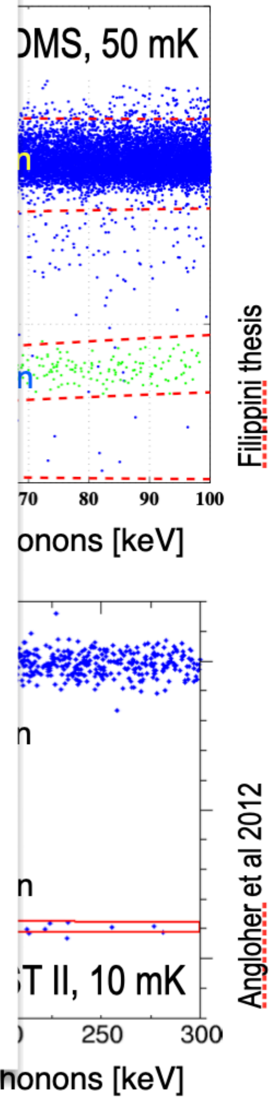




Combinations of S1/S2 Signals Are Numerous

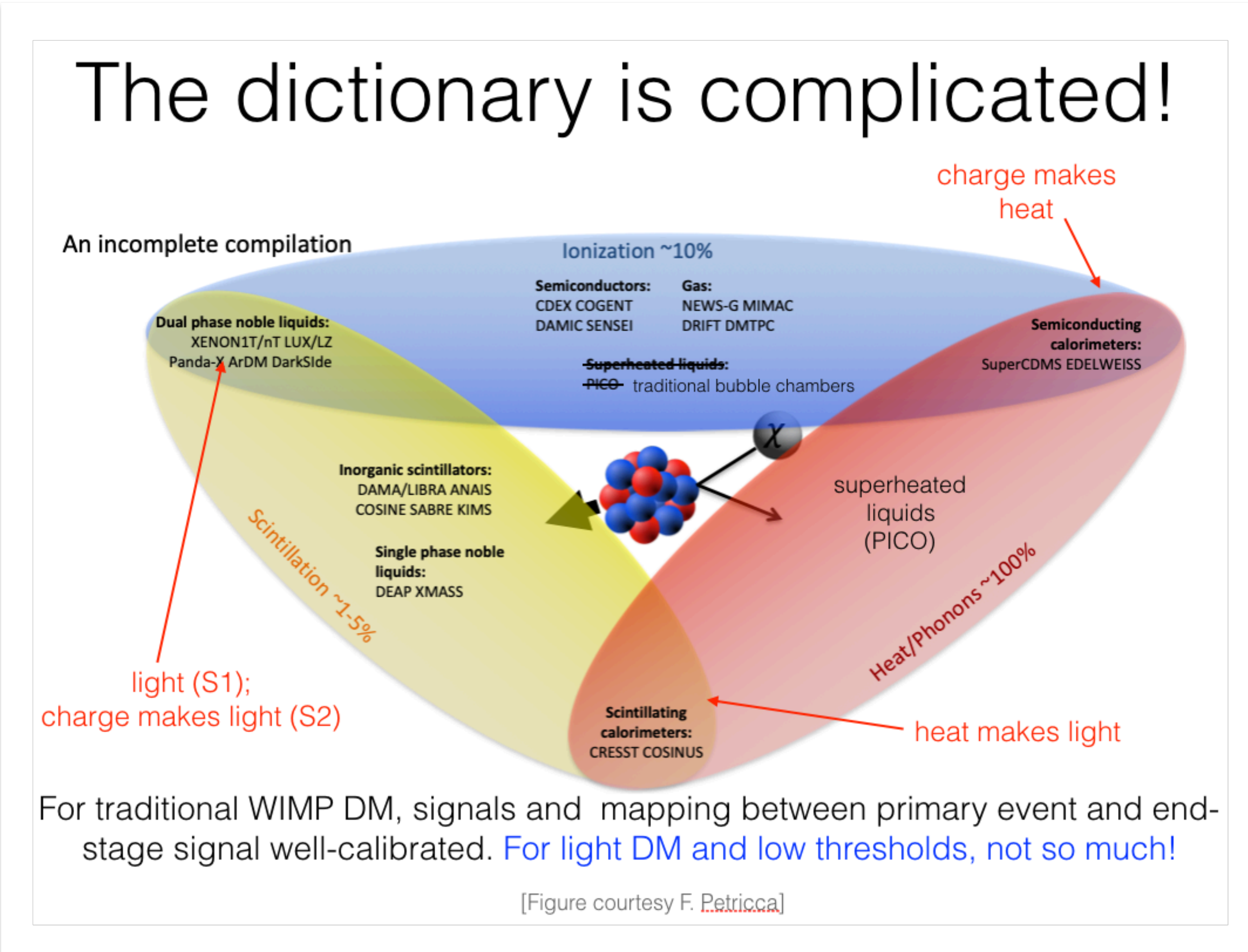
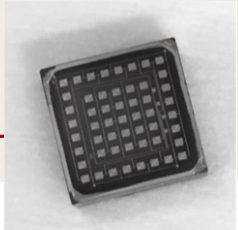
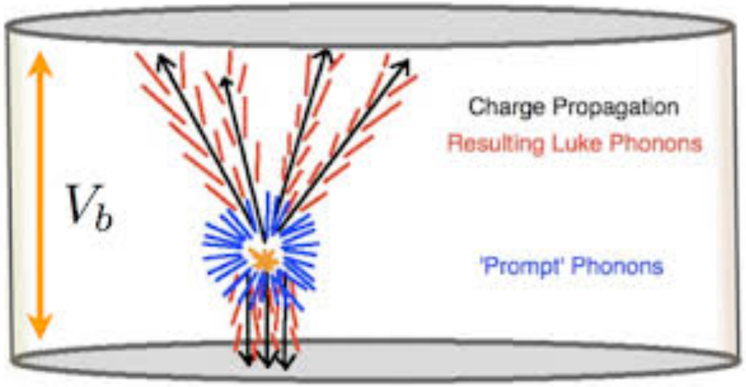


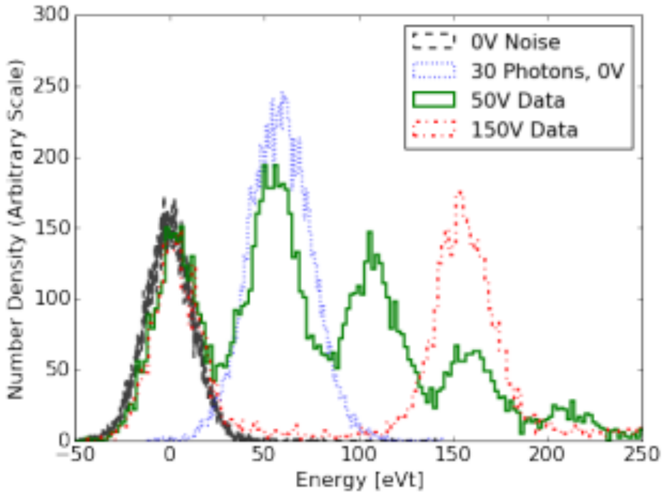
Figure from Yonatan Kahn

Phonon Sensors as Particle Detectors



- As we saw before, in any recoil event, all energy is eventually converted to heat
- Heat is also produced when charges are drifted in an electric field; makes sense by energy conservation alone
  - Referred to as Neganov-Trofimov-Luke (NTL) phonons
- Total heat is initial recoil energy energy produced by drifting charge, as shown at right.
- We collect and concentrate phonons in a much smaller volume
  - Thermal phonon detectors - thermistor thermalized with a target
  - Athermal phonon detectors - phonons collected in small sensor volume before thermalization





Romani et. al. 2017 (https://arxiv.org/abs/1710.09335)

Key Phonon Sensor Technologies

- Thermometry - resistance is a continuous function of effective temperature
  - Neutron Transmutation Doped (NTD) Ge
  - Magnetic Micro-Calorimeters (MMCs)

- Superconducting Calorimetry
  - Transition Edge Sensor (TES) - sharper R(T) by operating in SC transition
  - Microwave Kinetic Inductance Detector (MKID) - utilize L(T) from thermal quasiparticles to track QP density

- Superconducting Counting Detectors
  - Quantum Capacitance Detectors (QCDs) - tunnel junction integrated in to a cooper pair box
  - Quantum Inductance Detectors (QIDs) - qubit based sensors with weakly charge-sensitive transom’s

- Effects not currently utilized for phonon sensing, but still interesting:
  - Superconducting nanowires - unclear if there is strong phonon sensitivity, but very useful for photon detection
  - Pyroelectric detectors - capacitance is temperature dependent (not currently used cryogenically, but useful to be aware of), used for THz photon sensing

Thermal Phonon Sensors

Must think in terms of power flows. Absorber obeys:

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

Energy content fluctuations related to temperature fluctuations and C → (left-hand side, $C\,d\delta T/dt$)

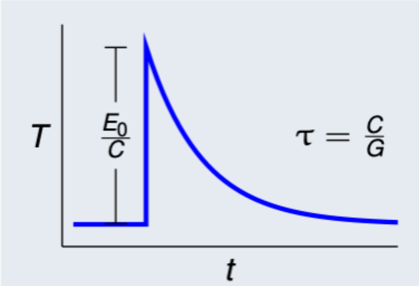
Rate of change of energy content of absorber → (dE/dt)

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

Power flow out through weak thermal link due to fluctuation of temperature away from mean value → ($G\,\delta T$)

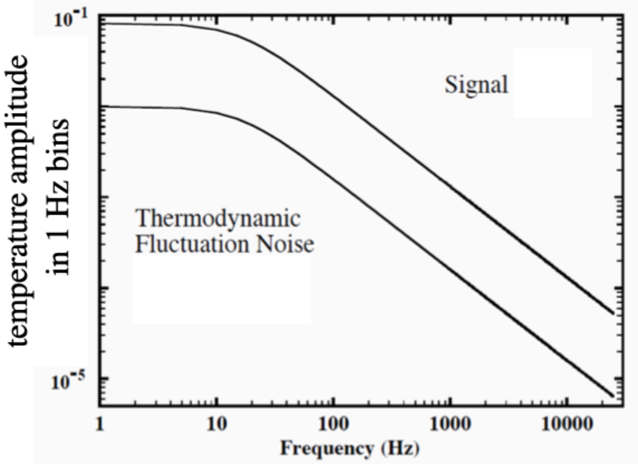
Reponse to a δ-function energy deposition E_0 is

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



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!



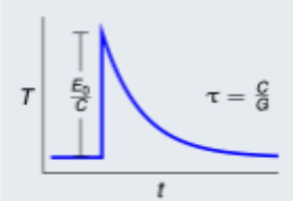
McCammon

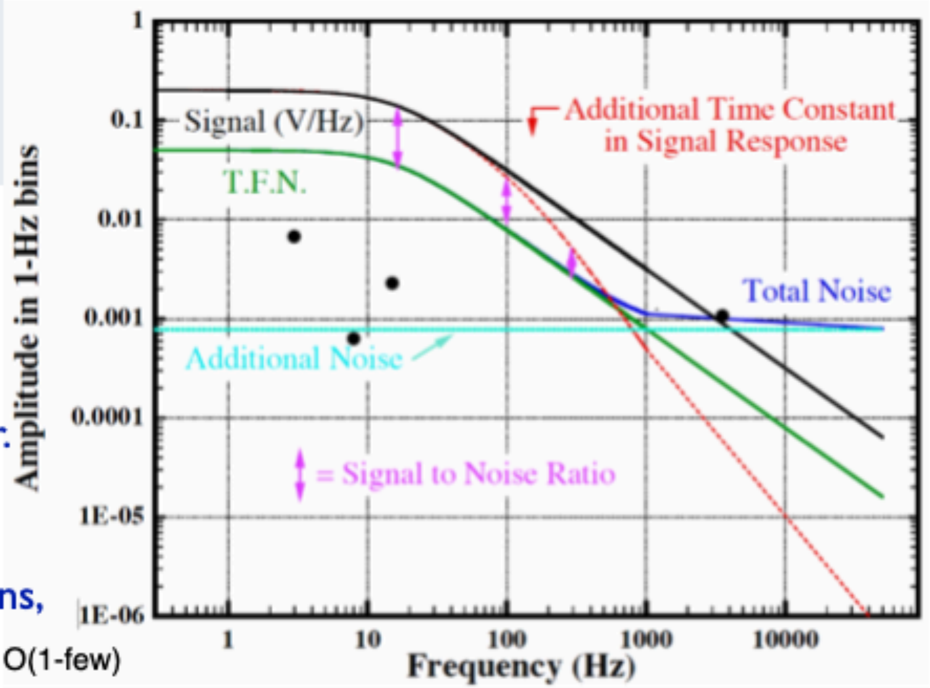
Slide from Sunil Golwala

Thermal Phonon Sensors

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





McCammon

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

For range of readout assumptions,

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

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

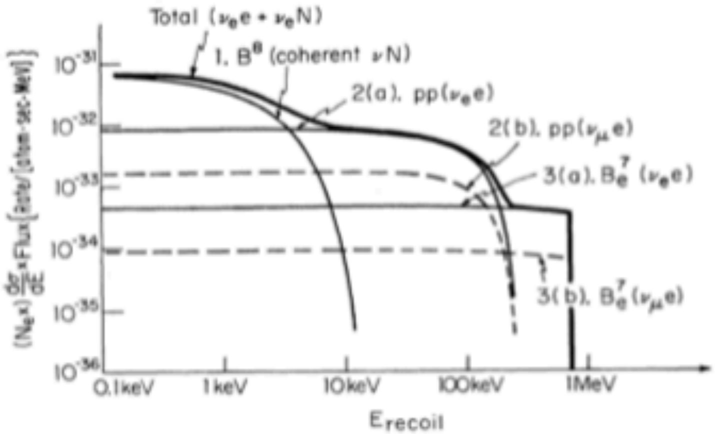
Clearly, energy resolution and low threshold are the advantages.

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)



Cabrera et al

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).

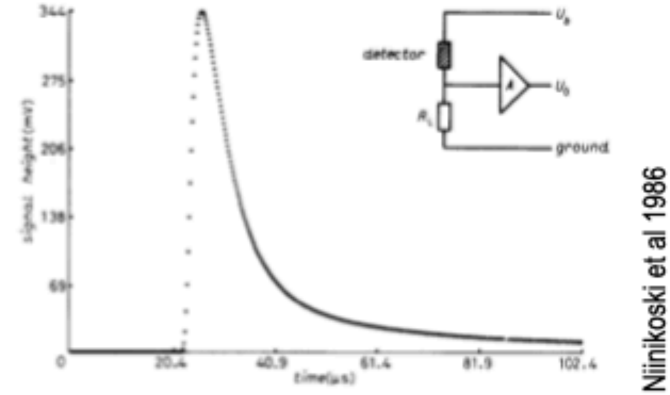


Fig. 2. – A typical pulse (at 500 mK). In the inset, the input circuit.

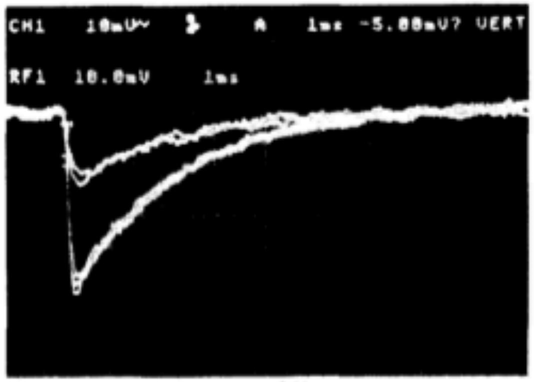
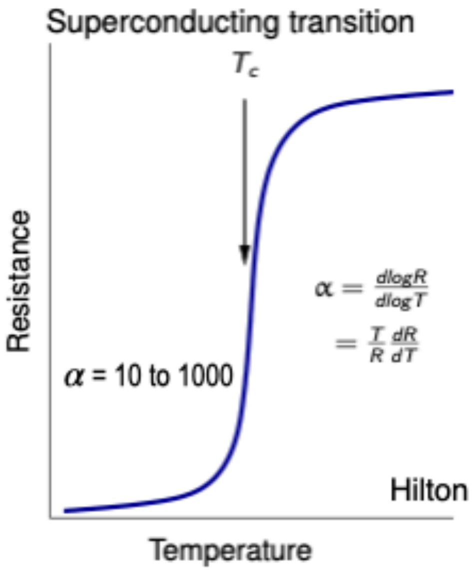


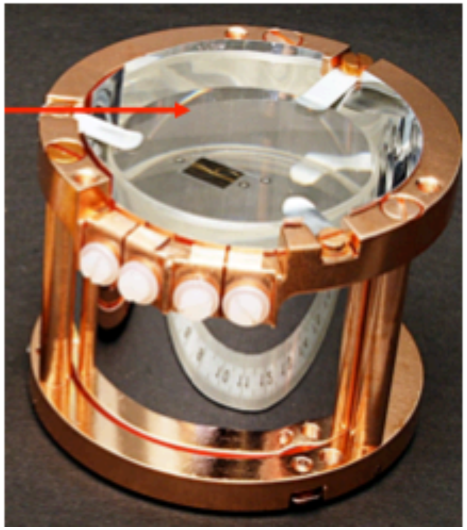
Figure 4. *Pulses from X-rays of ^{241}Am incident on thermistor b at 18 mK. We chose typical pulses corresponding to the two peaks shown in Figure 5. The vertical scale is 100 µV/div, and the horizontal scale is 1 ms/div.*

Example: CRESST I

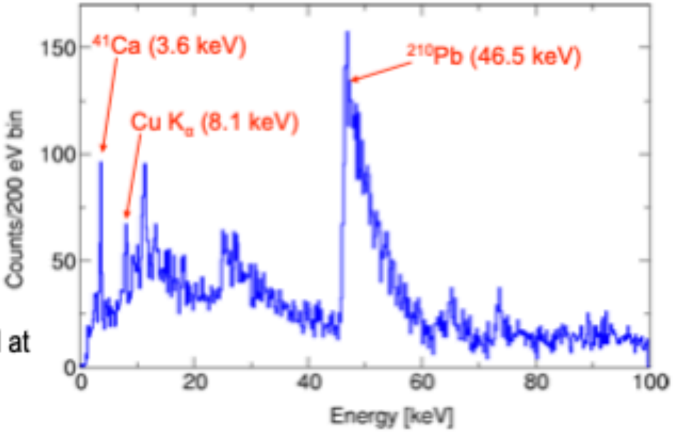
Uses "superconducting phase transition" thermometer or "transition-edge sensor" (SPT, TES)

- 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
- $\alpha \sim 10$





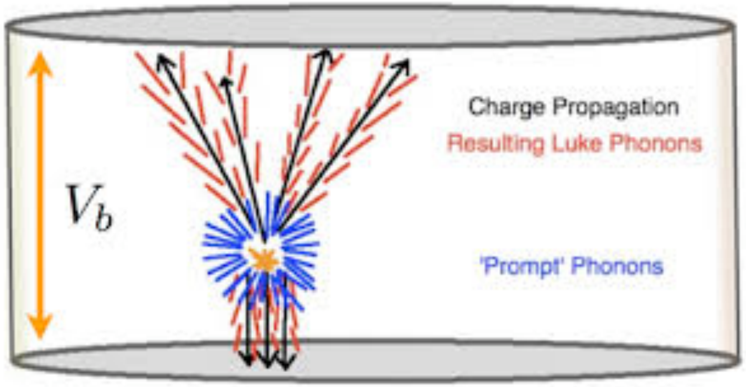
300 eV FWHM at low energy



Slide from Sunil Golwala

Multiple Approaches to Athermal Phonon Sensing

Interaction Produces Charge and Phonons in Solid State Target



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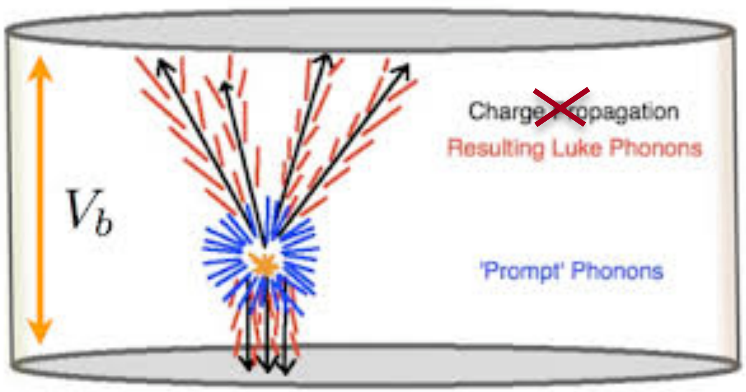
Interaction Produces Charge and Phonons in Solid State Target

More Phonons Produced,
Charge Cannot be Collected



Multiple Approaches to Athermal Phonon Sensing

Interaction Produces Charge and Phonons in Solid State Target

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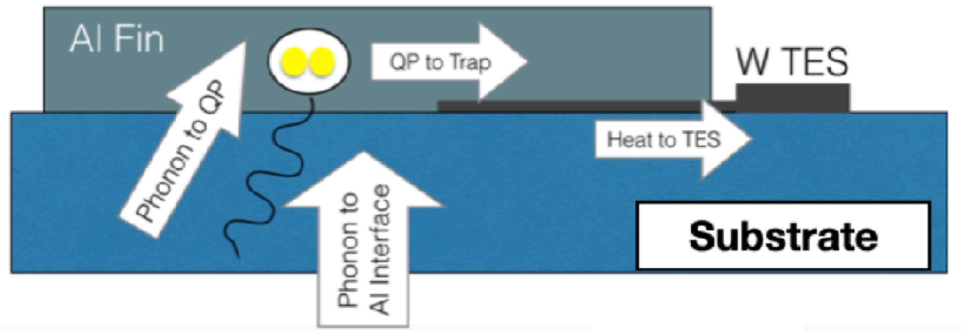
Phonons Captured in Small
Volume of Superconductor



Multiple Approaches to Athermal Phonon Sensing

Interaction Produces Charge and Phonons in Solid State Target

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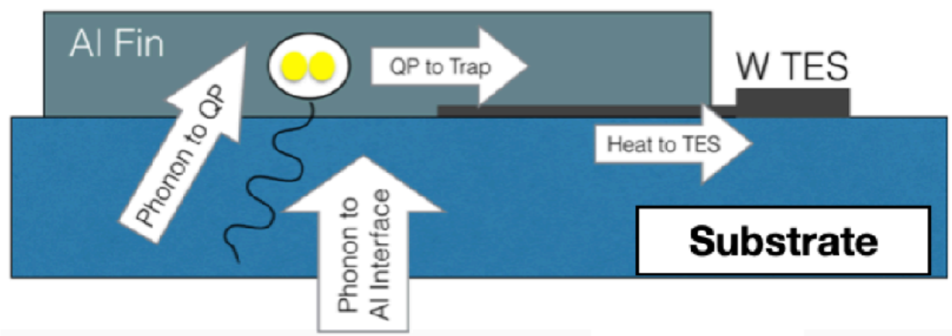
Phonons Captured in Small
Volume of Superconductor

Phonons increase quasiparticle
density in superconductor



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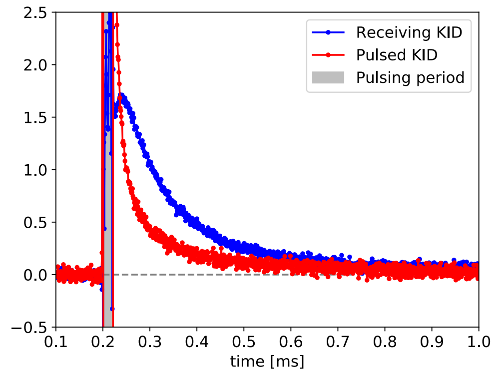
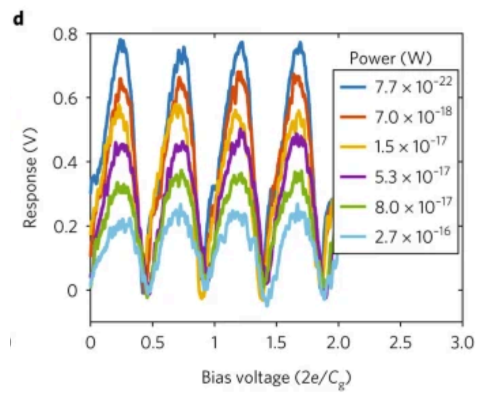
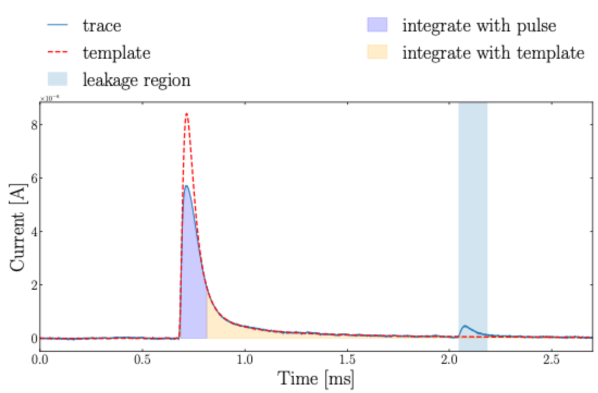


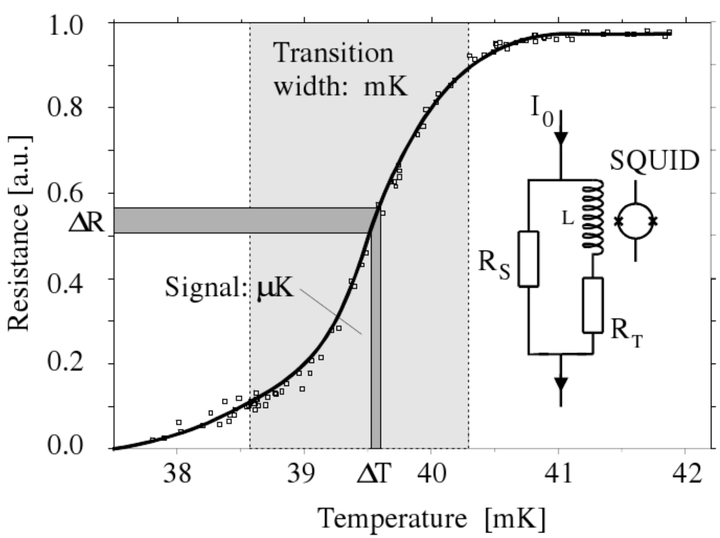


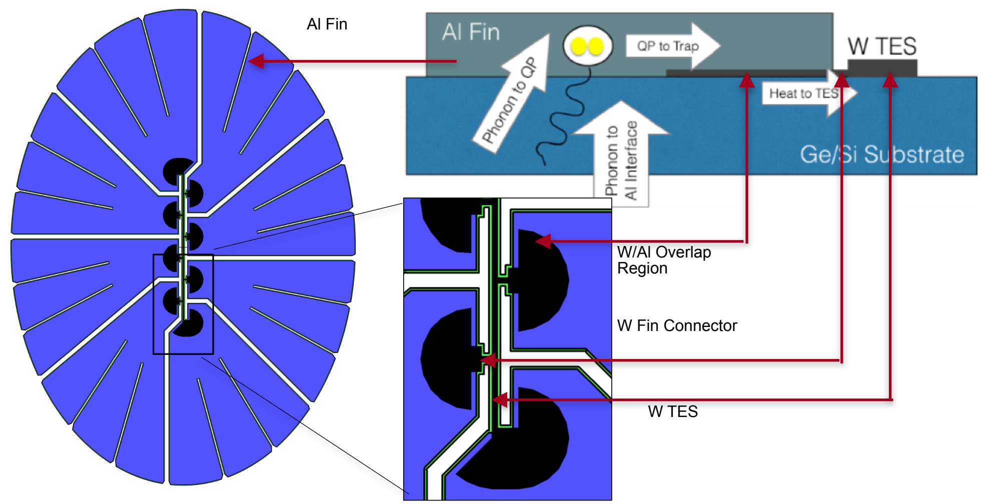


Sensor tracks
quasiparticle density
MKID, TES

Sensor tracks
quasiparticle tunneling rate
QCD, Transmon Qubit

Application Example: QETs (CDMS)





- Measuring electrical resistance at the superconducting transition temperature is a very sensitive temperature measurement!
- We can make the TES very small by using a heat 'lens' to focus heat energy into a small volume
- A full detector is a large array of these phonon focusing structures, and many small TES units combine to make a larger unit optimized to collect and readout sources of energy

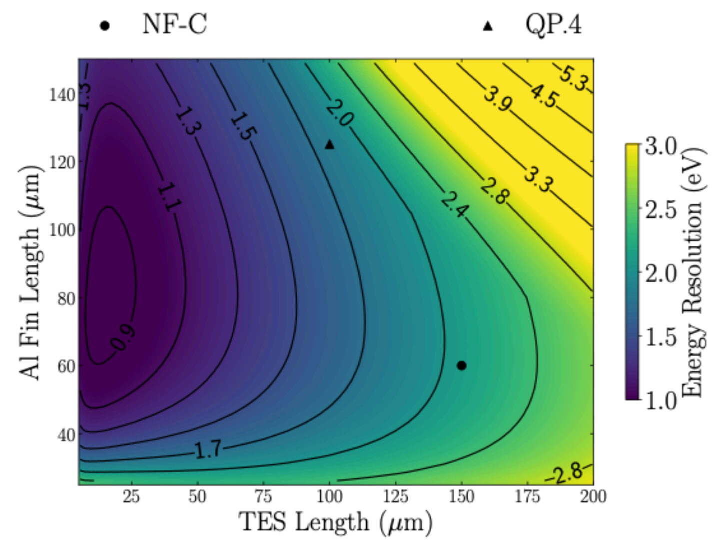
$$\sigma_{ph} = \frac{1}{\epsilon}\sqrt{2Gk_bT_0^2\tau_{\mathrm{BW}}},$$

$$\sigma_{ph} \approx \frac{T_c^3}{\epsilon}\sqrt{2n\Sigma\frac{v_{\mathrm{TES}}}{\zeta_{\mathrm{TES}}}k_b\left(\tau_{ph}+\tau_-\right)}$$

Application Example: QETs (CDMS)

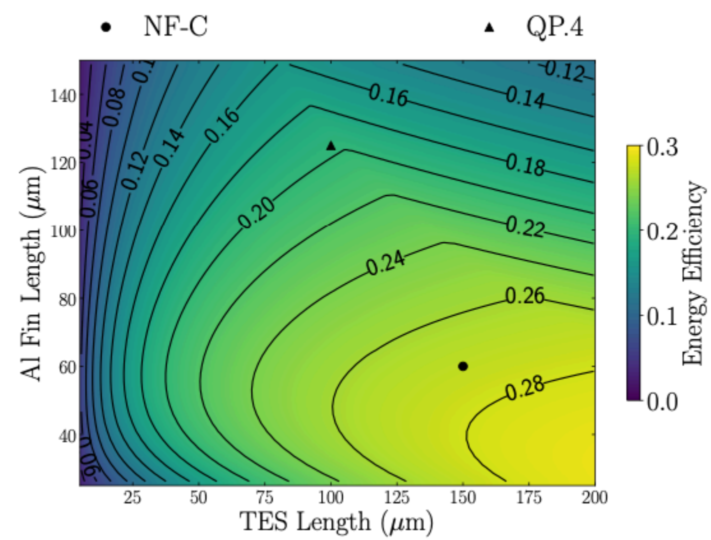
Phonon collection and time-dependence change how we optimize TES detectors compared to thermal detectors and photon detectors

- Larger TES volume implies higher coverage but larger thermal conductance
- Longer fins collect phonons faster but degrade overall collection efficiency
- Our biggest handle on tuning a fixed design is by tuning Tc of the TES, but there are consequences - generally slower TES response and more susceptibility to environmental effects



The biggest limitation of the TES run as an athermal detector is that it has to be operated well above Tb - so we have to intentionally produce quasiparticles in the operating state

- If Tc is too close to the bath temperature, the bandwidth is too slow to differentiate between thermal and athermal phonons



$$\sigma_{ph} \approx \frac{T_c^3}{\epsilon}\sqrt{2n\Sigma\frac{v_{\mathrm{TES}}}{\zeta_{\mathrm{TES}}}k_b\left(\tau_{ph}+\tau_{-}\right)}$$

Limitations of TES-based Athermal Readout

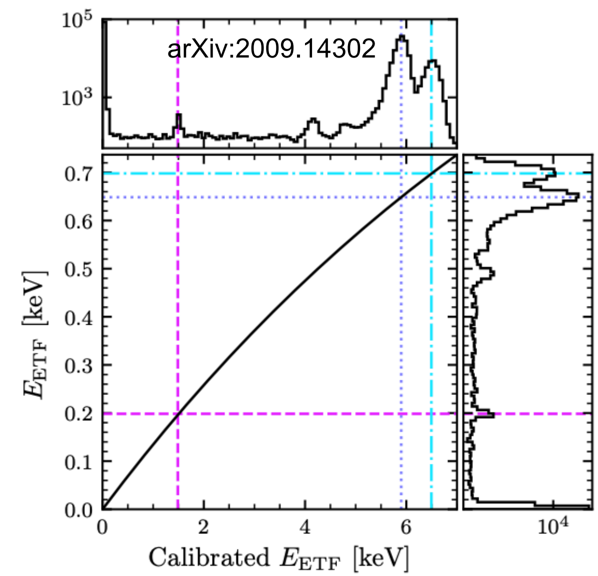
SLAC

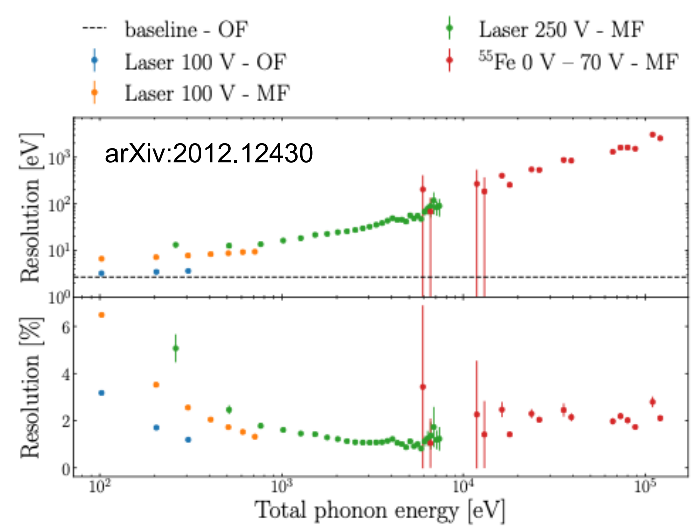
- Compared to using the TES for thermal detection, dynamic range is significantly degraded, though pulses can be reconstructed to higher energy
- Optimization depends on application
  - Dark matter detectors will be optimized as athermal detectors to optimize reconstruction near threshold and push sensitivity -
  - Double beta decay needs excellent resolution at the energy endpoint and thus cares about linearity at these energy scales
  - Coherent neutrino scattering lies somewhere in between

$$DR \sim \frac{E_{sat}}{\sigma_{ph}} \propto \frac{\sqrt{v_{TES}}}{T_c^2\sqrt{\tau_{BW}}}(\Delta T_c)$$

$$\sigma_{ph} = \frac{1}{\epsilon}\sqrt{2Gk_bT_0^2\tau_{\mathrm{BW}}}$$

$$\sigma_{ph} \approx \frac{T_c^3}{\epsilon}\sqrt{2n\Sigma\frac{v_{\mathrm{TES}}}{\zeta_{\mathrm{TES}}}k_b\left(\tau_{ph}+\tau_-\right)}$$





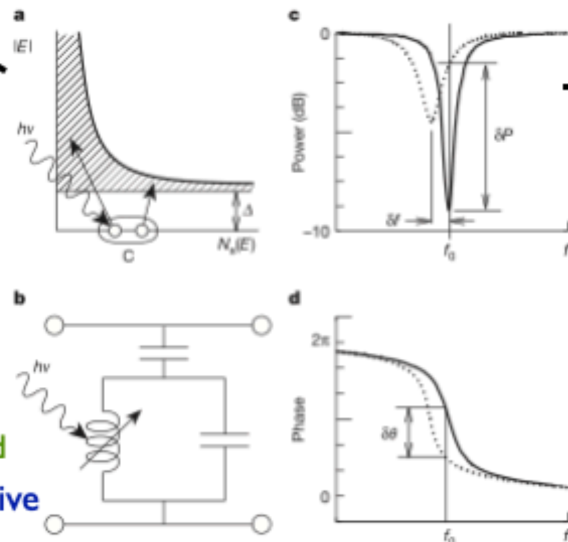
Phonon Sensing with KIDs

Kinetic Inductance Detectors (KIDs)

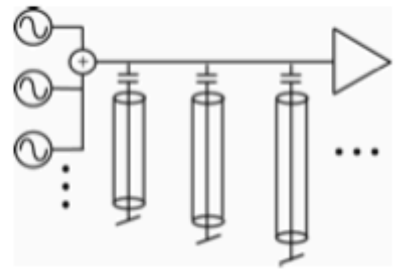
- Superconductors have an AC inductance due to inertia of Cooper pairs
- KID = superconducting film incorporated into LC resonator to sense change in L

Energy resolution:
sub-eV → meV
thresholds w/o HV

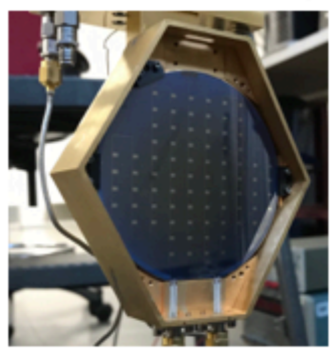
- Direct sensitivity to pair-breaking phonons
  - Large resonators obviate phonon collectors
- Gapped density of states
  - Thermal quasiparticles exponentially suppressed
- Fundamentally non-dissipative
  - Amenable to QIS techniques (e.g. squeezing, QND)
- Noise is limited by
  - quasiparticle population fluctuations
  - amplifier noise



Day

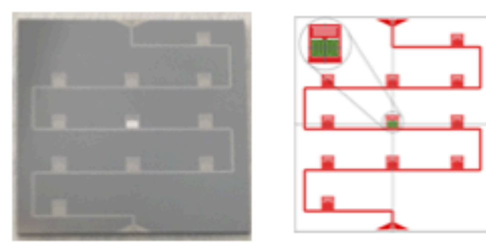


75 mm
x 1 mm



Multiplexing:

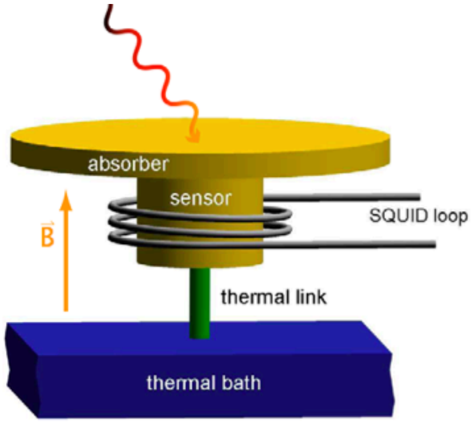
- KIDs are Q>10[5] resonators
- → Readout many with one cryo line/amplifier; most electronics at 300K
- → Highly position-resolved phonon detection

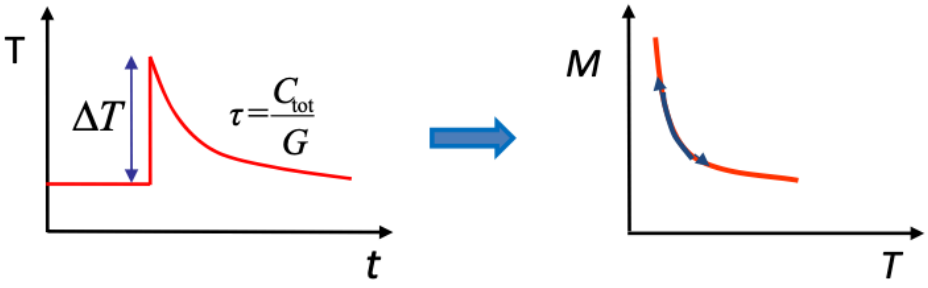


22 mm
x 1 mm

Slide from Sunil Golwala

Application Example: Metallic Magnetic Calorimeters





- Calorimetric principle

$$\Delta T \cong \frac{E}{C_{\mathrm{tot}}}$$

- Paramagnetic Au:Er sensor
  Ag:Er

$$\Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \rightarrow \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{\mathrm{sens}}+C_{\mathrm{abs}}}$$

A. Fleischmann et al.,
AIP Conf. Proc. **1185**, 571, (2009)

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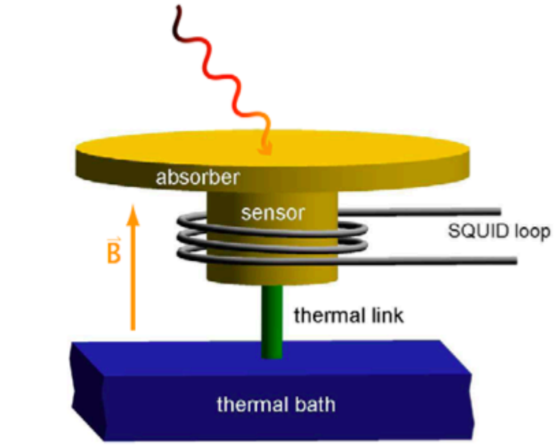
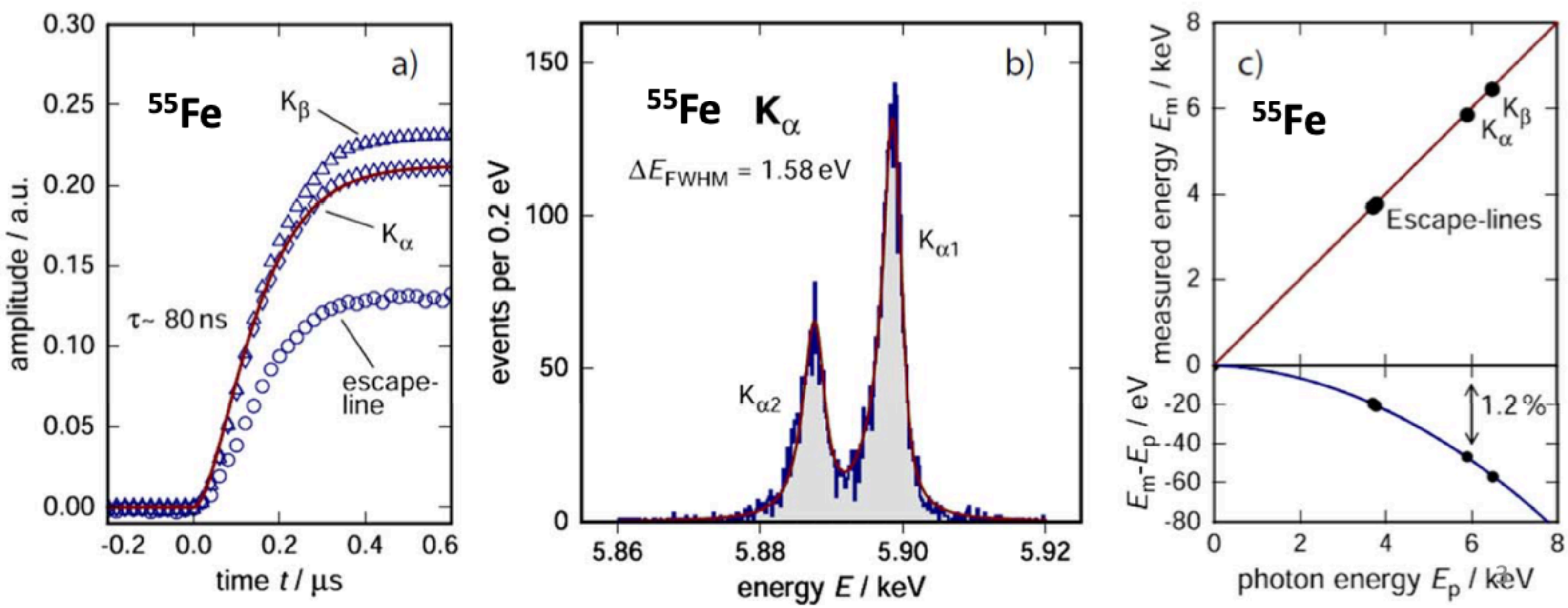
Application Example: Metallic Magnetic Calorimeters



Fast risetime
→ Reduction un-resolved pile-up

Extremely good energy resolution
→ Reduced smearing of resonances

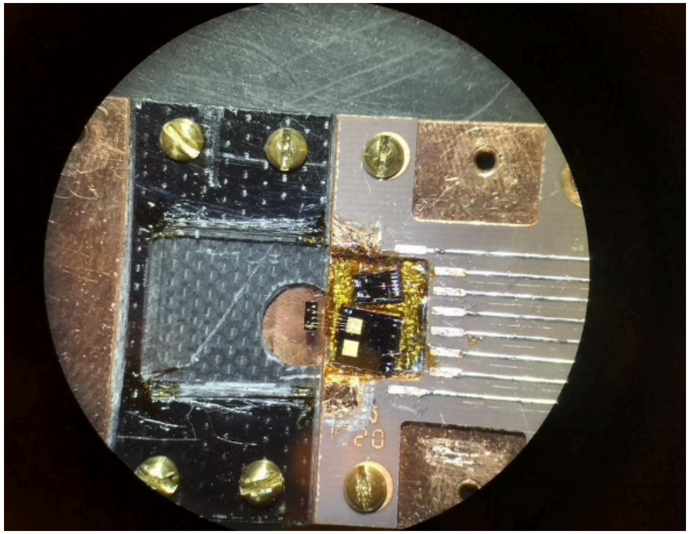
Excellent linearity
→ precise definition of the energy scale

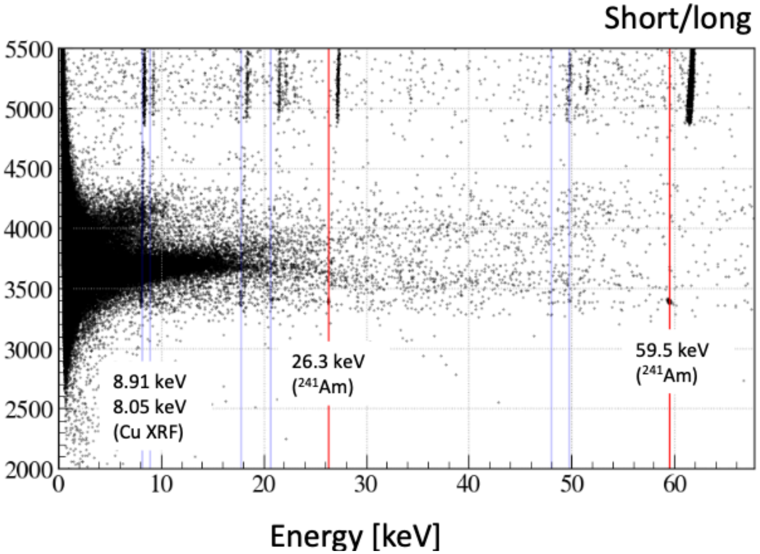


From “Metallic Magnetic Calorimeters for Dark Matter searches”, PATRAS 2019

Application: MMCs with Diamond Substrates

- MMCs combine some of the benefits of athermal TES readout (speed, small volume absorber, athermal phonon collection) with benefits of thermal TES readout (pre-fabricated sensor, simpler substrate fabrication)
- Discrimination of event type and location done using pulse rise time - MMCs utilize the high bandwidth of new SQUID systems to resolve physics at timescales shorter than a microsecond
- Similar types of readout also being pursued for other novel substrates (see e.g. Ricochet, SPLENDOR) using TES readout in a similar manner.





Data from In Wook Kim and GeonBo Kim, LLNL

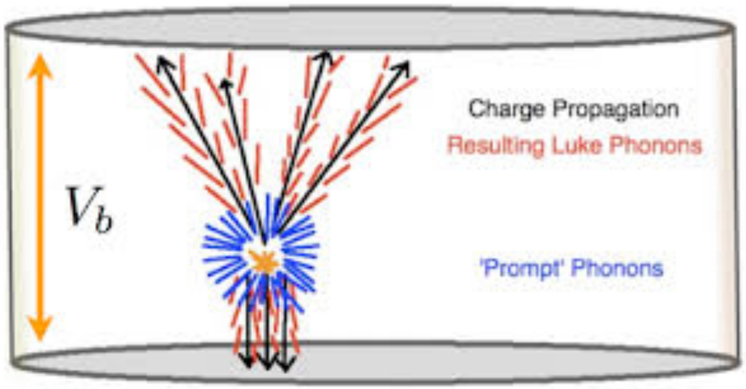
Multiple Approaches to Athermal Phonon Sensing

Interaction Produces Charge and Phonons in Solid State Target

More Phonons Produced, Charge Cannot be Collected

Phonons Captured in Small Volume of Superconductor

Charge and Phonons Share Energy, Easily Collected



Phonons increase quasiparticle density in superconductor

Sensor tracks quasiparticle density
MKID, TES

Sensor tracks quasiparticle tunneling rate
QCD, Transmon Qubit

Ren et al, Phys. Rev. D 104, 032010 (2021)

Multiple Approaches to Athermal Phonon Sensing

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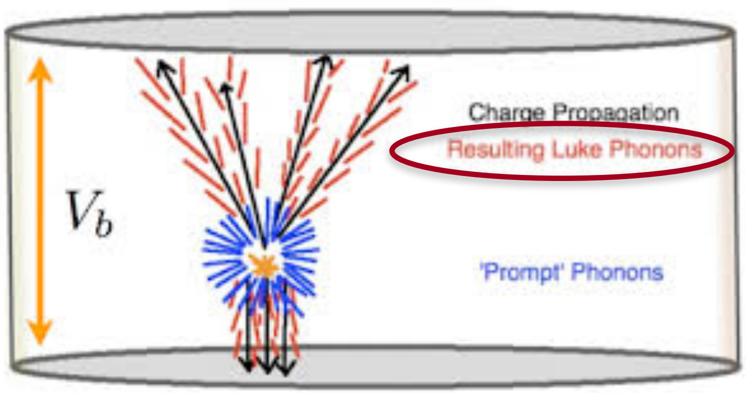


Phonons Captured in Small
Volume of Superconductor

Phonons increase quasiparticle
density in superconductor

Charge drift produces
more phonons

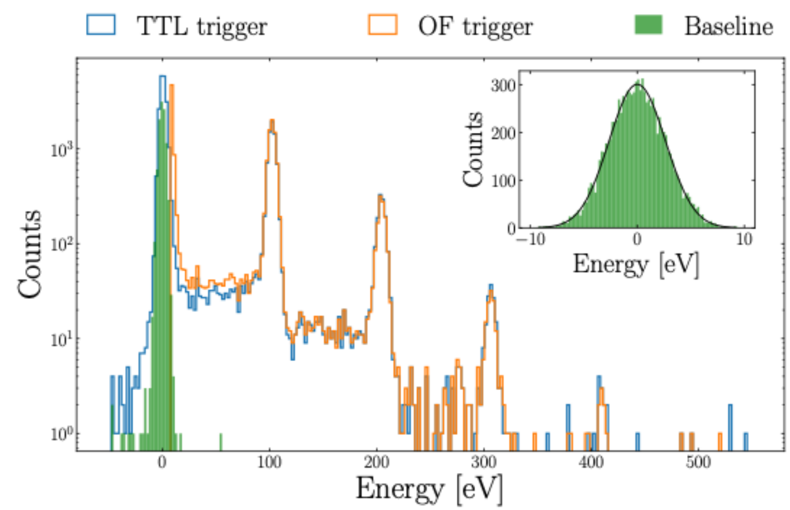
Sensor tracks
quasiparticle density
MKID, TES

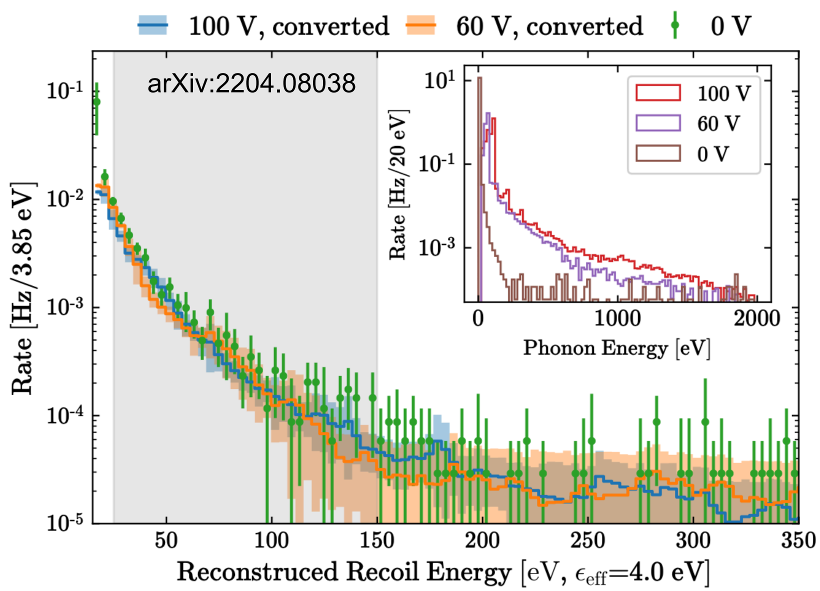
Sensor tracks
quasiparticle tunneling rate
QCD, Transmon Qubit

NTL Gain: Phonon-Amplified Charge Readout

- SuperCDMS HVeV demonstrates use of phonon gain to obtain sub-electron resolution
  - Phonon resolution of 3 eV
  - Single photon peaks seen at multiples of bias voltage (100V in example plot)

- This technique can be used to discriminate between charge producing and no-charge events, and has been used for:
  - Silicon nuclear recoil ionization yield measurement in a neutron beam
  - Demonstration of UV scintillation background in early HVeV data
  - Confirmation of zero-charge low-energy excess in the absence of UV photon background





Multiple Paths to meV-Scale Energy Sensitivity

Interaction Produces Charge and Phonons in Solid State Target

More Phonons Produced,
Charge Cannot be Collected

Charge and Phonons Share
Energy, Easily Collected

More Charge Produced,
Phonons Cannot be Collected

Phonons
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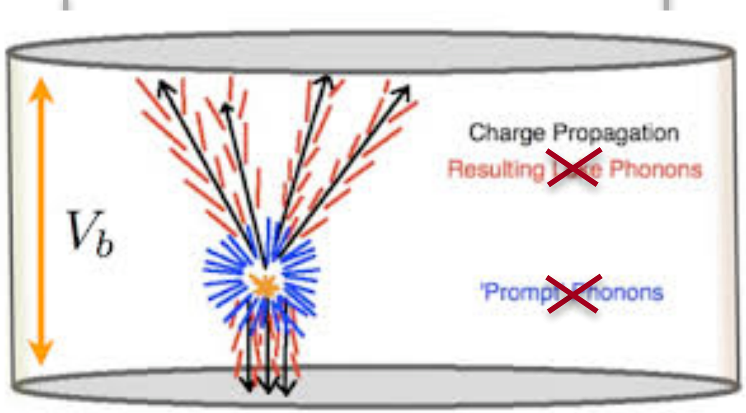
Phonons
density ir



duces

Charge drifted to concentrated
region of crystal or charge gate

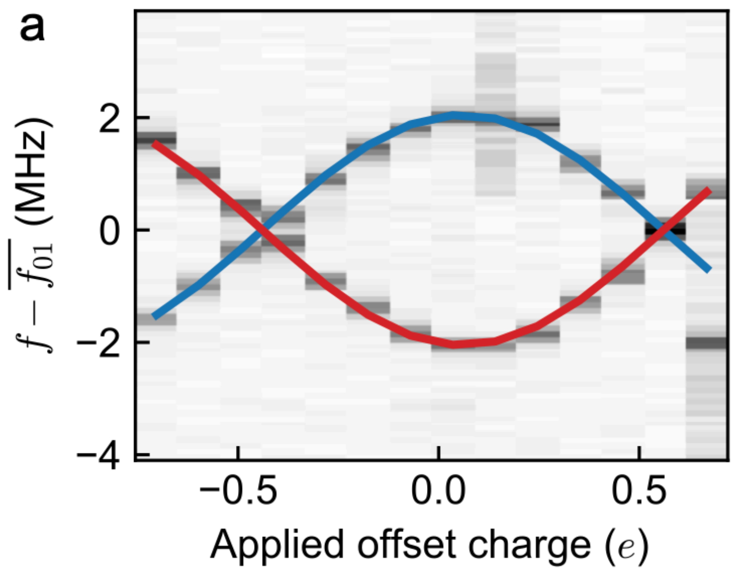
Sensor tracks
quasiparticle density
MKID, TES

Sensor tracks
quasiparticle tunneling rate
QCD, Transmon Qubit

Wilen et. al, Nature 594, 369-373

Multiple Paths to meV-Scale Energy Sensitivity

SLAC



ons in Solid State Target

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More Charge Produced,
Phonons Cannot be Collected

Charge drifted to concentrated region of crystal or charge gate

Phono
Volume

Phonons
density ir

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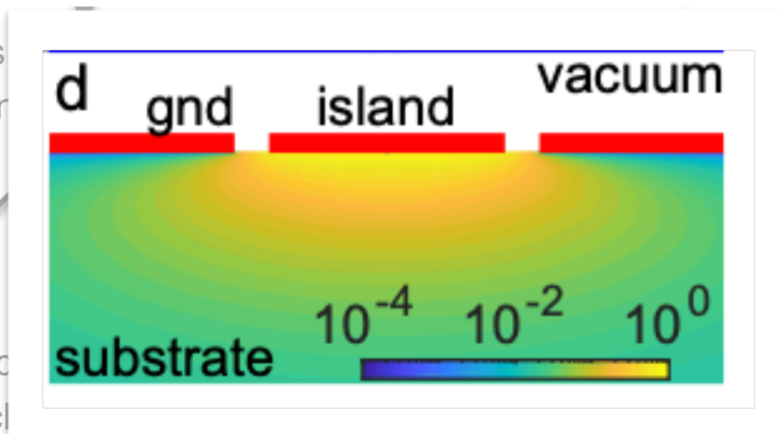
Charge induces offset voltage on sensor



$$\hat{H} = 4E_c(\hat{n} - n_g)^2 - E_J \cos(\phi)$$

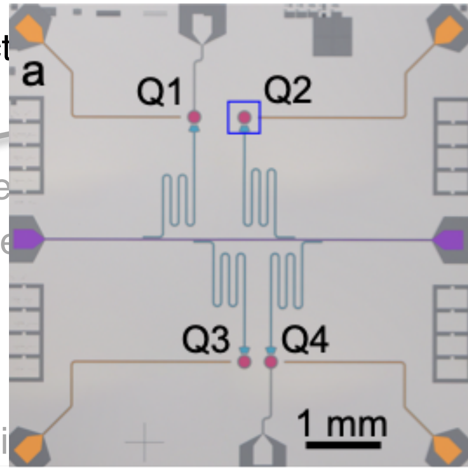
Sensor trac
quasiparticl
MKID, TES

rate
QCD, Transmon Qubit

Wilen et. al, Nature 594, 369-373

Multiple Paths to meV-Scale Energy Sensitivity

Interact



honons in Solid State Target

More Phonons Produce
Charge Cannot be Colle

onons Share
Collected

More Charge Produced,
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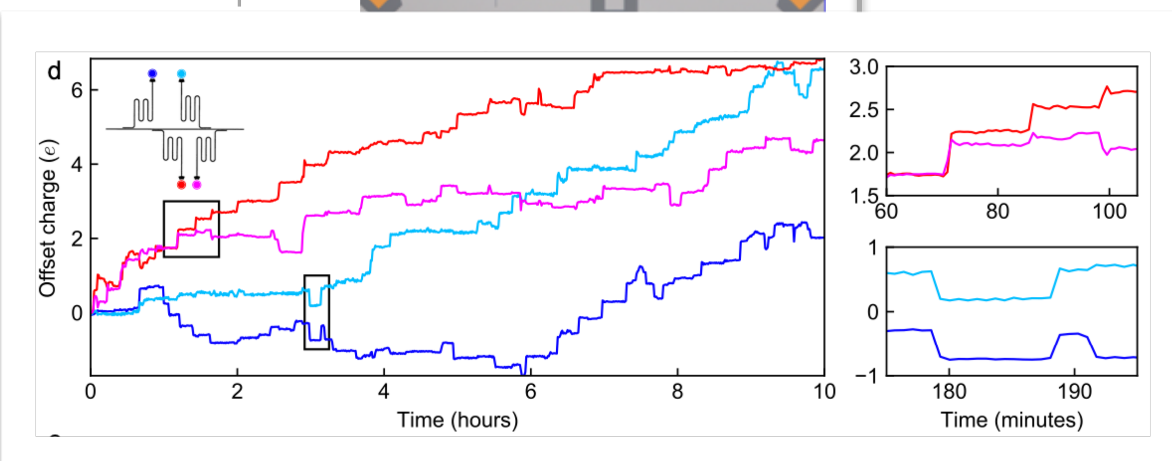
Phonons Captured i

Charge drifted to concentrated region of crystal or charge gate



Charge induces offset voltage on sensor

Sensor tracks
quasiparticle density
MKID, TES

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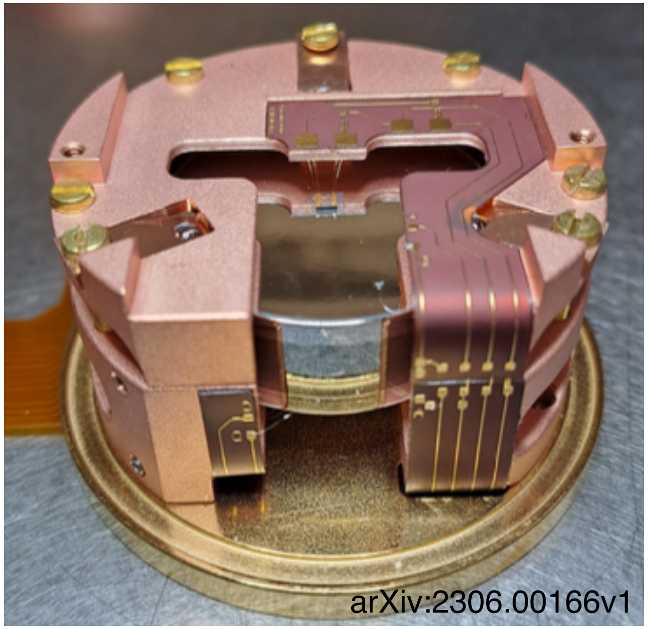
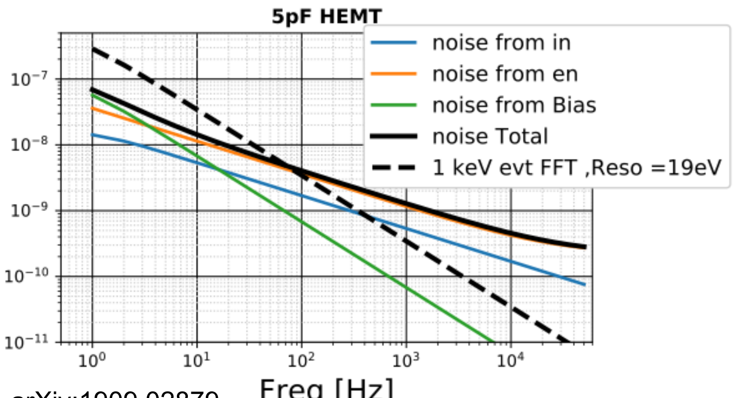
quasiparticle tunneling rate
QCD, Transmon Qubit

Sensor tracks integrated image charge
HEMT, CPB (Charge Qubit)

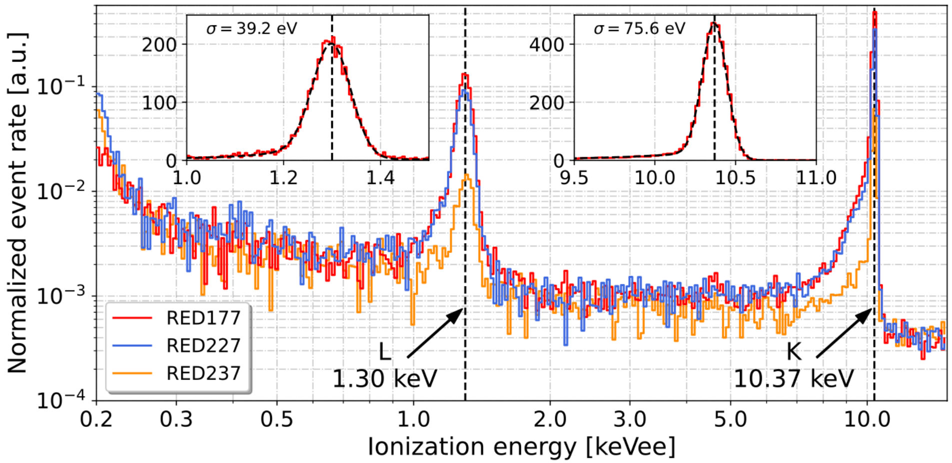
Example: Ricochet Charge Readout

- Coherent neutrino scattering detectors can achieve ~30 eVee (10 electron) resolution at 10 mK using HEMTs (high electron mobility transistors)
- Noise model is similar to that achievable in other charge readout detectors (see e.g. Si detectors lecture) but can operate at 10 mK to minimize dark rates and be run in conjunction with heat sensors.



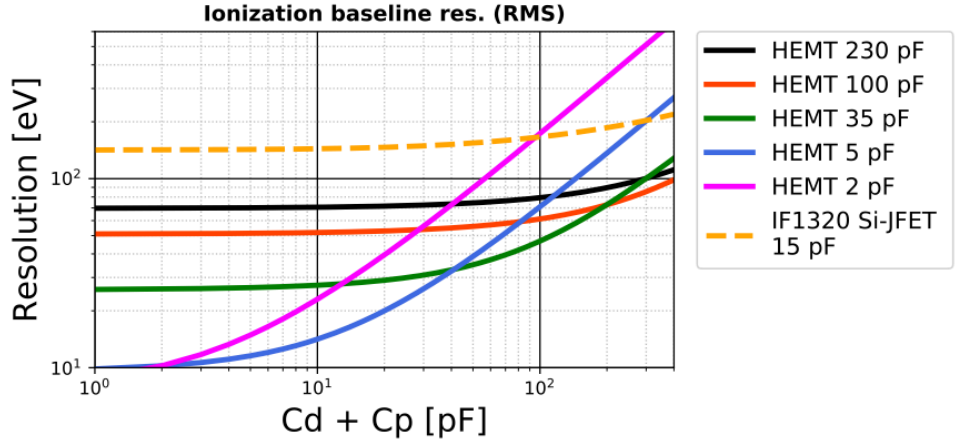


arXiv:1909.02879

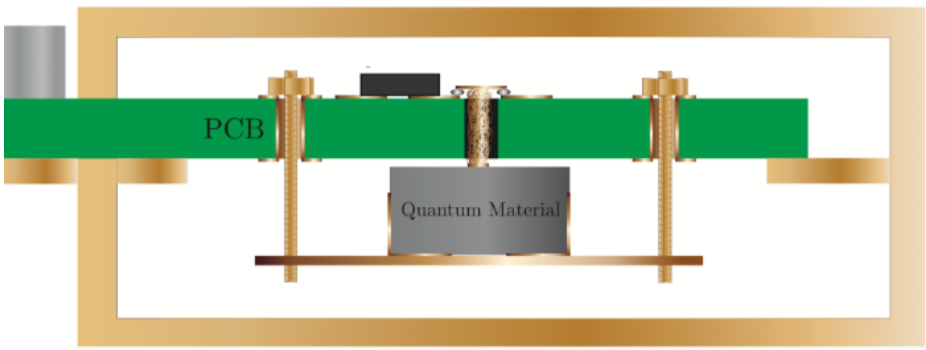


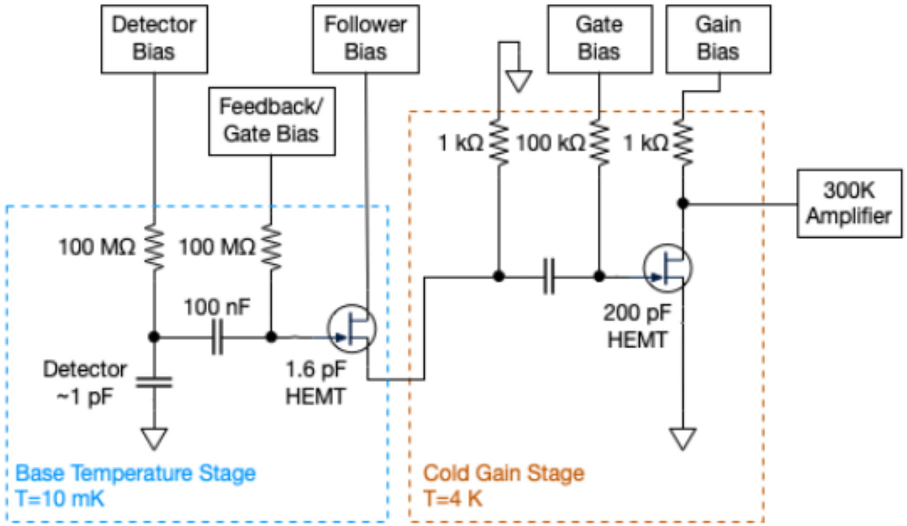
Example: SPLENDOR Charge Readout

- Minimize parasitic capacitance by operation with HEMT directly on sample at 10mK, use smallest commercial HEMT (5 electron resolution)
    - for Ge, resolution in eVee = 3*charge charge resolution



- Use to readout low-gap materials with 1-100 meV gaps, to achieve sub-electron resolution for scattering events



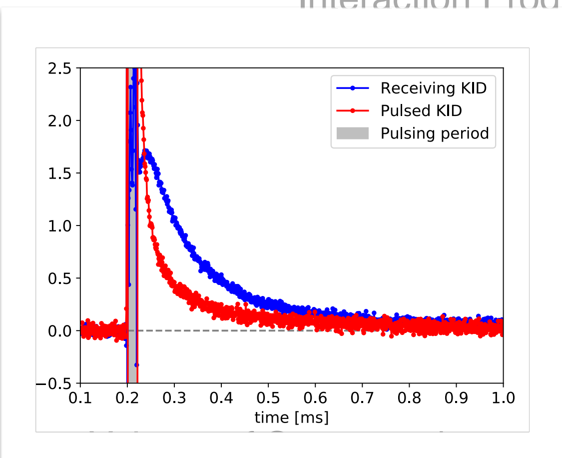


$$\sigma_E \sim E_{gap} \times \sigma_V \times (C_{detector} + C_{input} + C_{parasitic})$$

Multiple Paths to meV-Scale Energy Sensitivity

SLAC

Interaction Produces Charge and Phonons in Solid State Target



Charge and Phonons Share Energy, Easily Collected

More Charge Produced, Phonons Cannot be Collected

Charge drifted to concentrated region of crystal or charge gate

Phonons increase quasiparticle ... or

$$\sigma_e = \sigma_{N_{qp}}(2\Delta) = \sigma_{n_{qp}} V(2\Delta)$$

Charge drift produces more phonons

Charge induces offset voltage on sensor

Sensor tracks quasiparticle density
MKID, TES

Sensor tracks quasiparticle tunneling rate
QCD, Transmon Qubit

Sensor tracks integrated image charge
HEMT, CPB (Charge Qubit)

Multiple Paths to meV-Scale Energy Sensitivity

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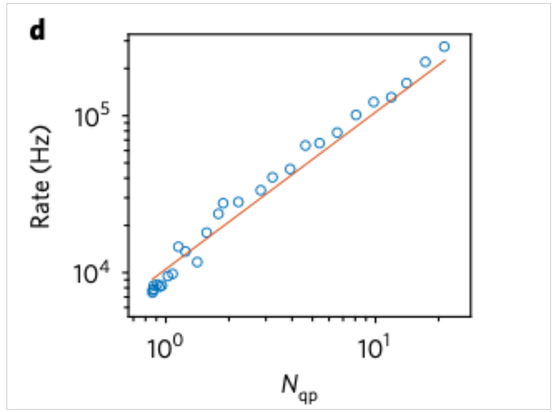

More Phonons Produced,
Charge Cannot be Collected

Phonons Captured in Small
Volume of Superconductor

Phonons increase quasiparticle
density in superconductor

$$E = N_{qp}(2\Delta)$$

$$= \epsilon_{capture}\left[\int_0^{\tau_{pulse}} (\Gamma_{tunnel}(t) - \Gamma_0)dt\right](2\Delta)$$

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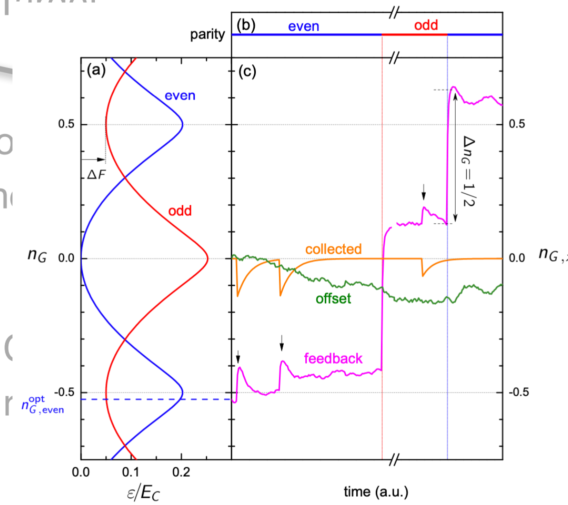

Charge induces offset voltage on

$$\sigma_E = \sigma_q E_{gap}$$
$$\approx (C_{det} + C_g)\sigma_V E_{gap}$$

ArXiv:1711.08758

Sensor tracks
quasiparticle density
MKID, TES

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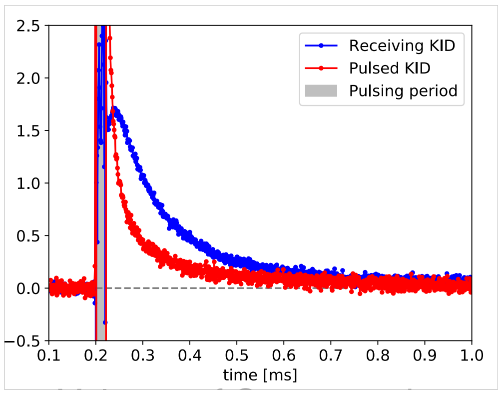

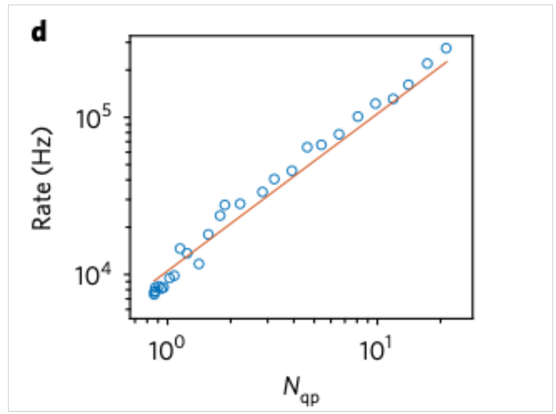

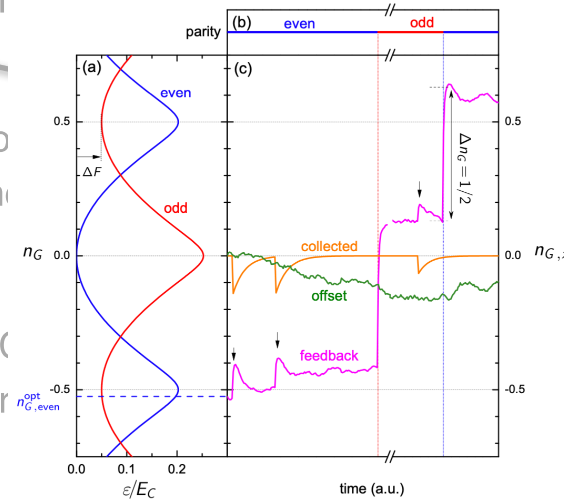

$$\sigma_e = \sigma_{N_{qp}}(2\Delta) = \sigma_{n_{qp}} V(2\Delta)$$

$$E = N_{qp}(2\Delta) = \epsilon_{capture}\left[\int_0^{\tau_{pulse}} (\Gamma_{tunnel}(t) - \Gamma_0)dt\right](2\Delta)$$

$$\sigma_E = \sigma_q E_{gap} \approx (C_{det} + C_g)\sigma_V E_{gap}$$

ArXiv:1711.08758

Sensor tracks quasiparticle density
MKID, TES

Sensor tracks quasiparticle tunneling rate
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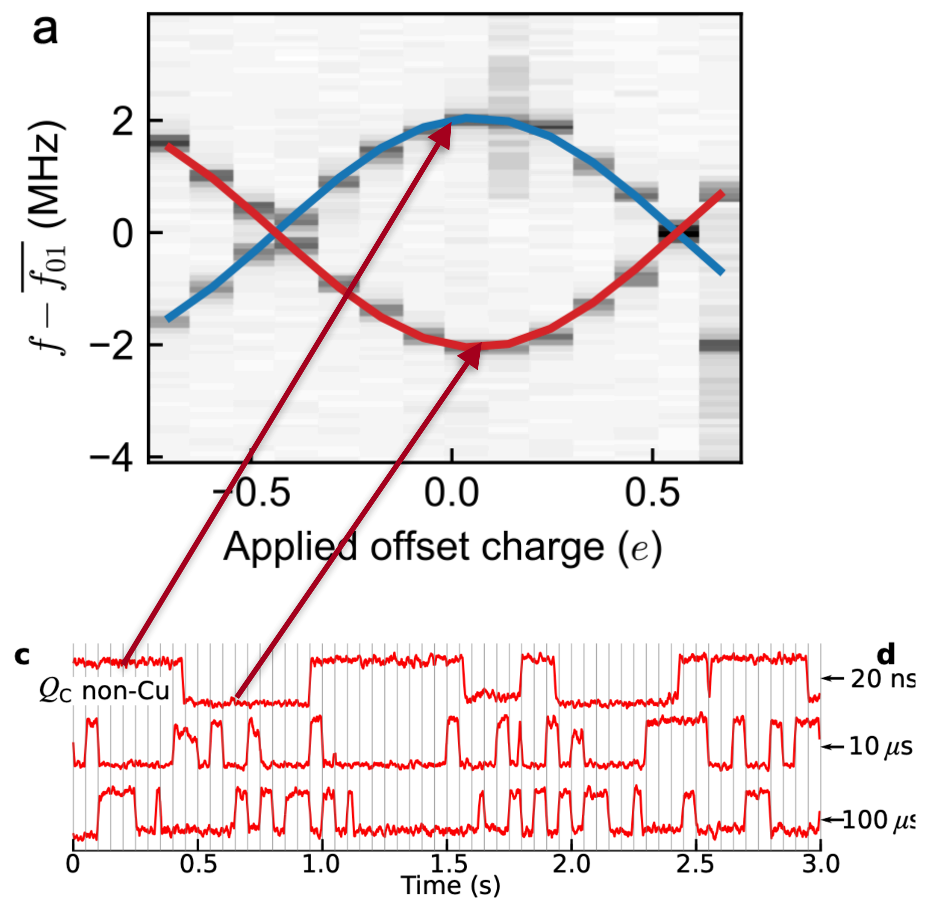
Sensor tracks integrated image charge
HEMT, CPB (Charge Qubit)

Energy Sensing with Qubits

- Qubit-based sensing relies on weakly charge-sensitive qubits, which have ‘even’ and ‘odd’ parity states
- The transition between these states is mediated by quasiparticle transitions
- The rate of these transitions depends on the ambient quasiparticle density near the junctions, created by pair-breaking radiation

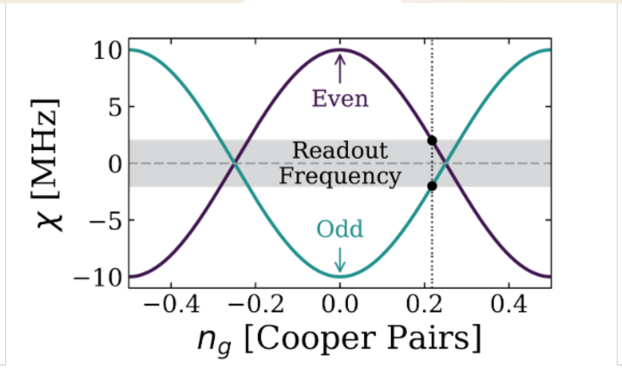


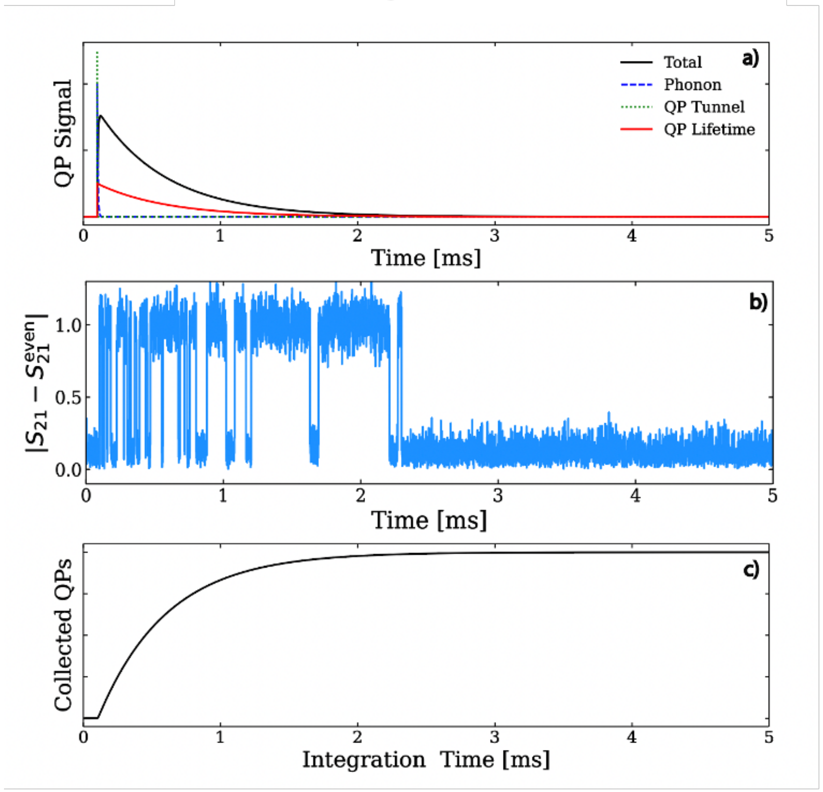
$$\hat{H} = 4E_c(\hat{n} - n_g)^2 - E_J \cos(\phi)$$

ArXiv:2310.01345

SQUAT Real-Time Readout

- Tunneling events flip the parity state of the qubit, thus changing its transition frequency
- By monitoring the qubit transition frequency, we can count single tunneling events
- SQUAT detector is designed without a readout resonator to reduce pixel size, limit coupling to TLSs, and increase detector efficiency
    - This increases bandwidth relative to Ramsey readout for quantum-limited amplification



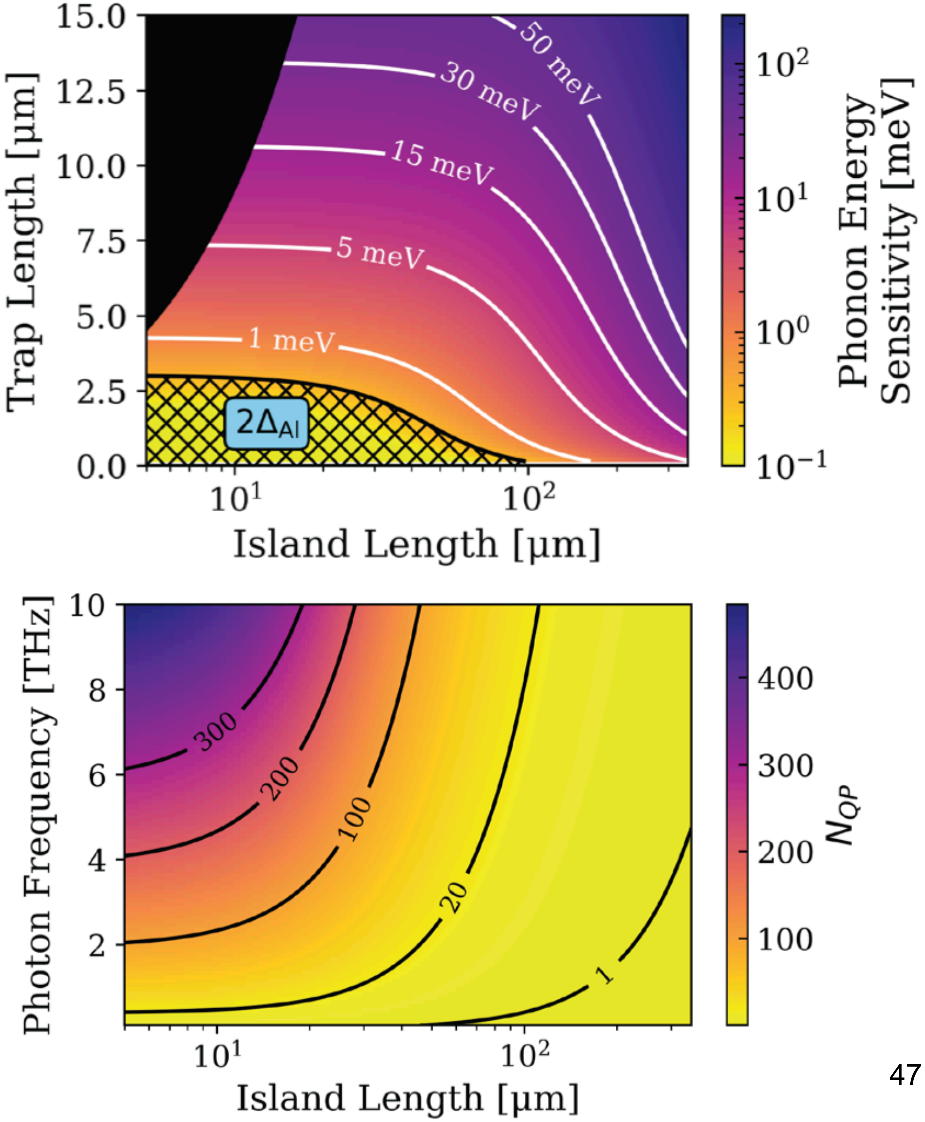


ArXiv:2310.01345

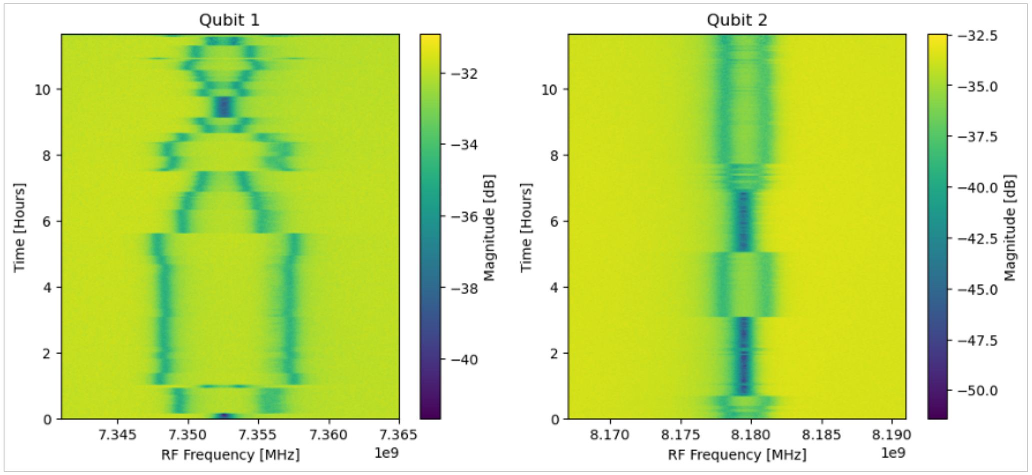
Projected Sensitivity

- Small trapping regions enable high tunneling efficiency and gap-limited performance
    - Performance will vary based on trapping and tunneling efficiency - all designs are sub-eV for this range of parameters
    - First devices will help benchmark these design parameters

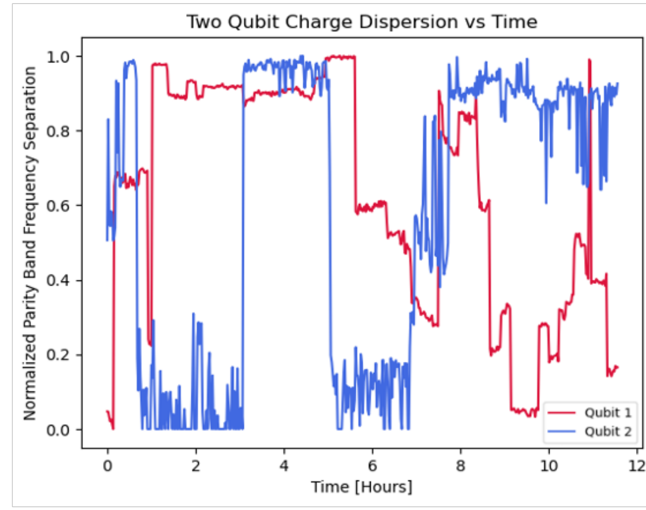
- Single photon detection achievable with a wide range of designs down to 1 Thz - more on this at the end of the talk



SQUATs as Charge and Parity Sensors



Repeated frequency scans display charge jumps over time for two SQUATs on the same chip



Charge dispersion fit values plotted for each qubit

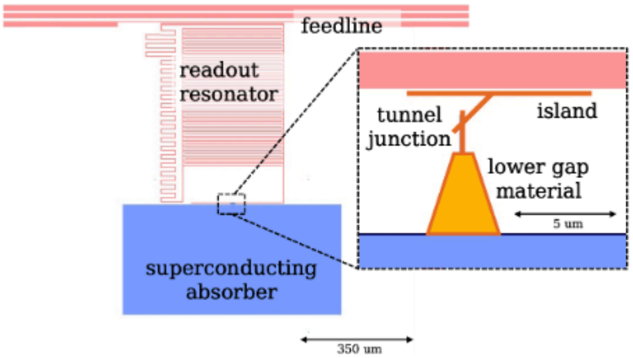
- We can take long frequency scans of these devices to monitor island offset charge and measure state switching!
    - This is the first observation of this type of correlated charge switching in Sapphire - and it was just done with a VNA, instead of needing complex qubit control schemes

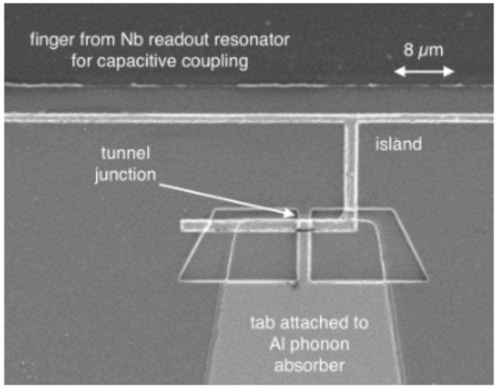
- Our next task is to automate slow charge feedback to stabilize the SQUATs are their optimal charge bias points
    - Biasing in their degenerate state gives the highest charge sensitivity
    - Biasing in the maximally separated state the highest sensitivity to parity switching

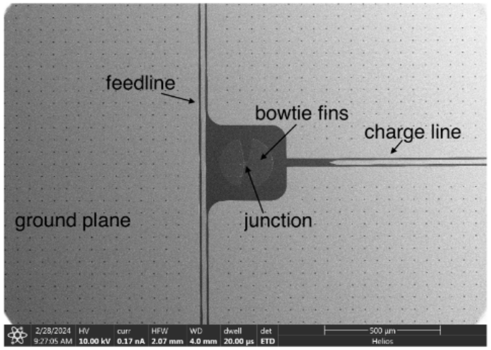
Qubit-Based Sensor Prospects

- Many open questions remain
  - What is the right architecture (do we include resonators)?
  - How do we make low-Tc junctions?
  - Are we going to be limited by blackbody backgrounds?

- We have seen phonon-induced decoherence in qubits, so the main uncertainty is in how effectively we can couple to and readout these types of events







Proof of Concept: Quantum Capacitance Detector

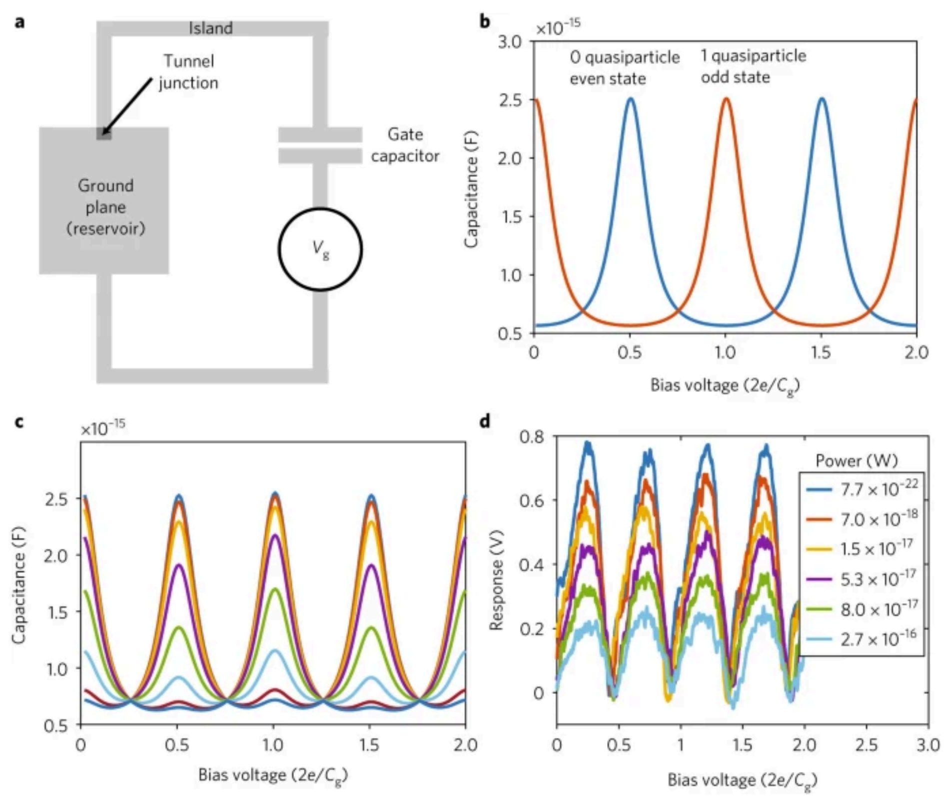
SLAC

- This detector employs a cooper pair box (charge qubit) coupled to a resonator to probe tunneling probability
- The transition frequency depends on steady-state power absorption by the small island between the capacitor and junction
- This detector has the lowest ever achieved noise equivalent power - simply because it is sensitive to individual quasiparticle tunneling events
- How do we apply this to larger detectors?

Single photon detection of 1.5 THz radiation with the quantum capacitance detector

P. M. Echternach, B. J. Pepper, T. Reck & C. M. Bradford

Nature Astronomy **2**, 90–97 (2018) | Cite this article

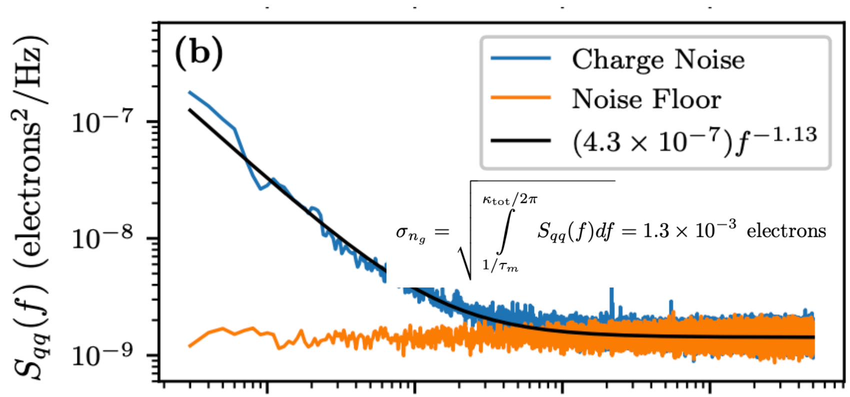


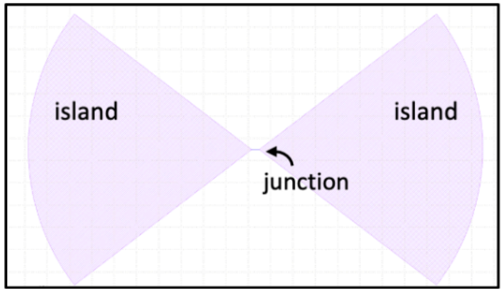
Novel Applications of Qubit Readout

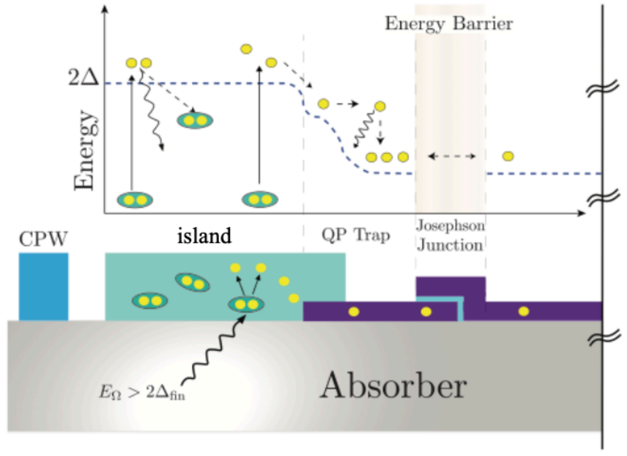
- Demonstration of photon detection with QCD opens up new sensing pathways

- We can remove the absorber and add a feedback gate to the QCD to produce multiplexable charge sensors - this has been proposed and basic electrometers demonstrated with sub-electron resolution

- We can modify qubits to more closely resemble the phonon readout architectures described here to couple high energy collection to much more sensitive sensors to achieve lower thresholds for future HEP applications (currently calling these Quantum Inductance Detectors, or QIDs)







Takeaways

SLAC

- There is a rich history of HEP detector physics with cryogenic crystals
- Phonon physics allows us to reduce the size of energy quanta and improve resolution - it is at the core of all crystalline and superconducting detector technology
- Progress continues on both conventional sensors and with a new class of qubit-based readout devices
- More progress can be made at multiple energy scales - current experiments draw on each other to keep pushing technology forward