Cryogenic Detectors
for Dark Matter Searches and beyond

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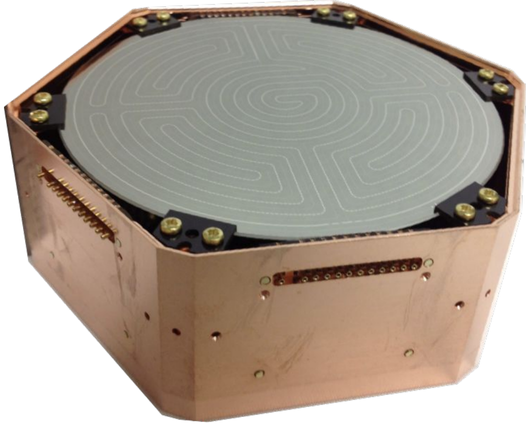
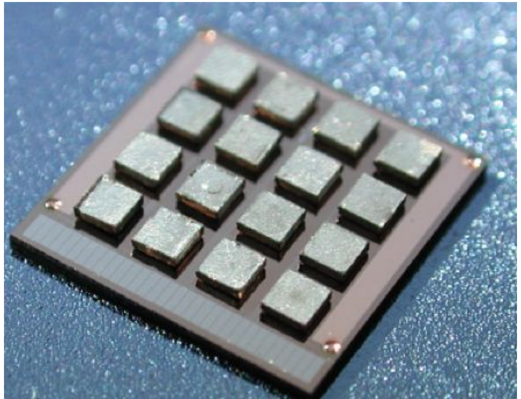
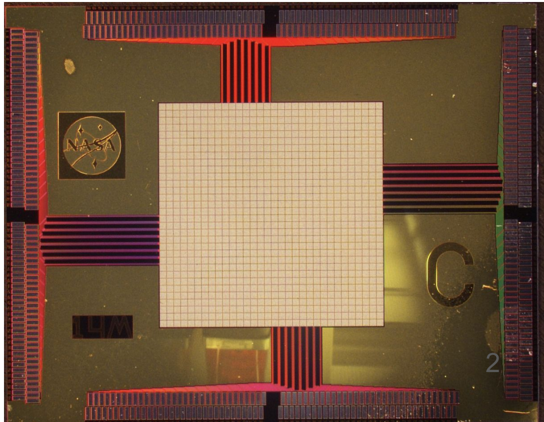
GRIDS 2025

Cryogenic Crystal Detectors are used in



- Particle Physics
  - Dark Matter Detectors
  - Neutrino Physics
    - Coherent Elastic Neutrino Nucleus Scattering (CEvNS)
    - Neutrinoless double-beta decay ($0\nu\beta\beta$)
- Astrophysics
  - mm to gamma-ray energies

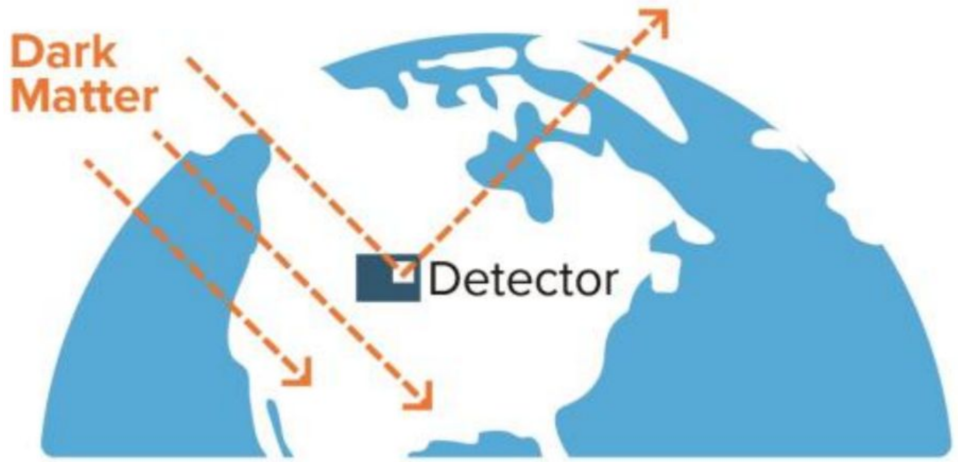




Disclaimer

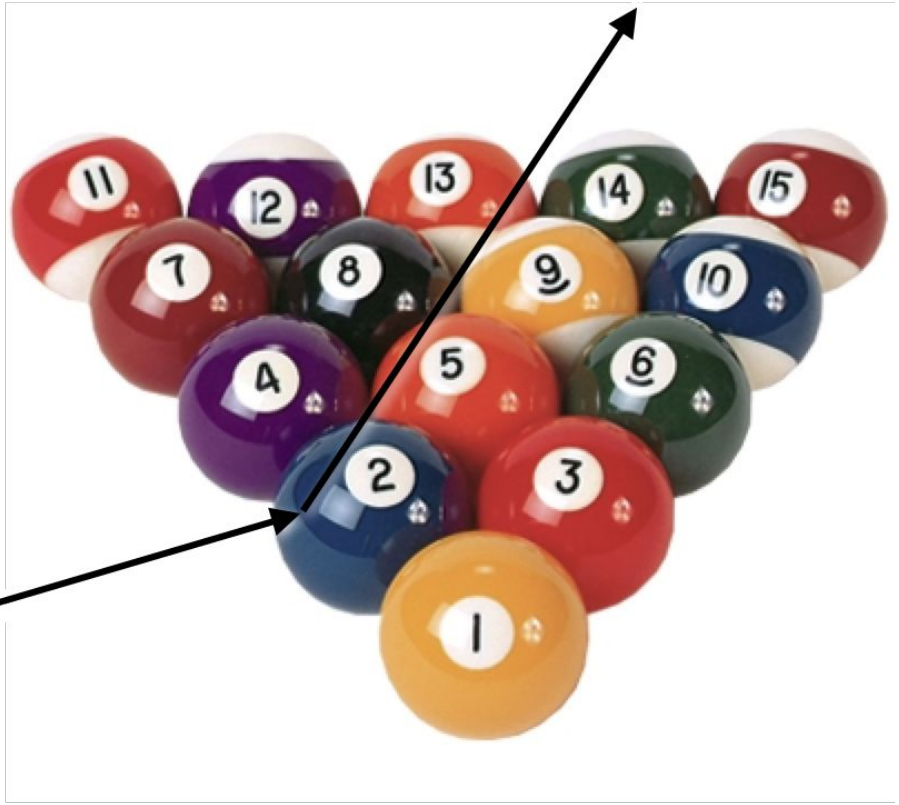
- This is my personal biased view focusing on solid state detectors working at < 1 K
- Lots of efforts ongoing with solid-state detectors for dark matter search efforts, a good fraction of them utilizing “cold” to battle against “noise”.
    - CCD-based detectors
    - High Purity Germanium detectors
    - …
- Also lots of fantastic cryogenic detectors I will likely fail to include here
- Apologies for efforts that I missed in this discussion

Physics case example I : Dark matter direct detection

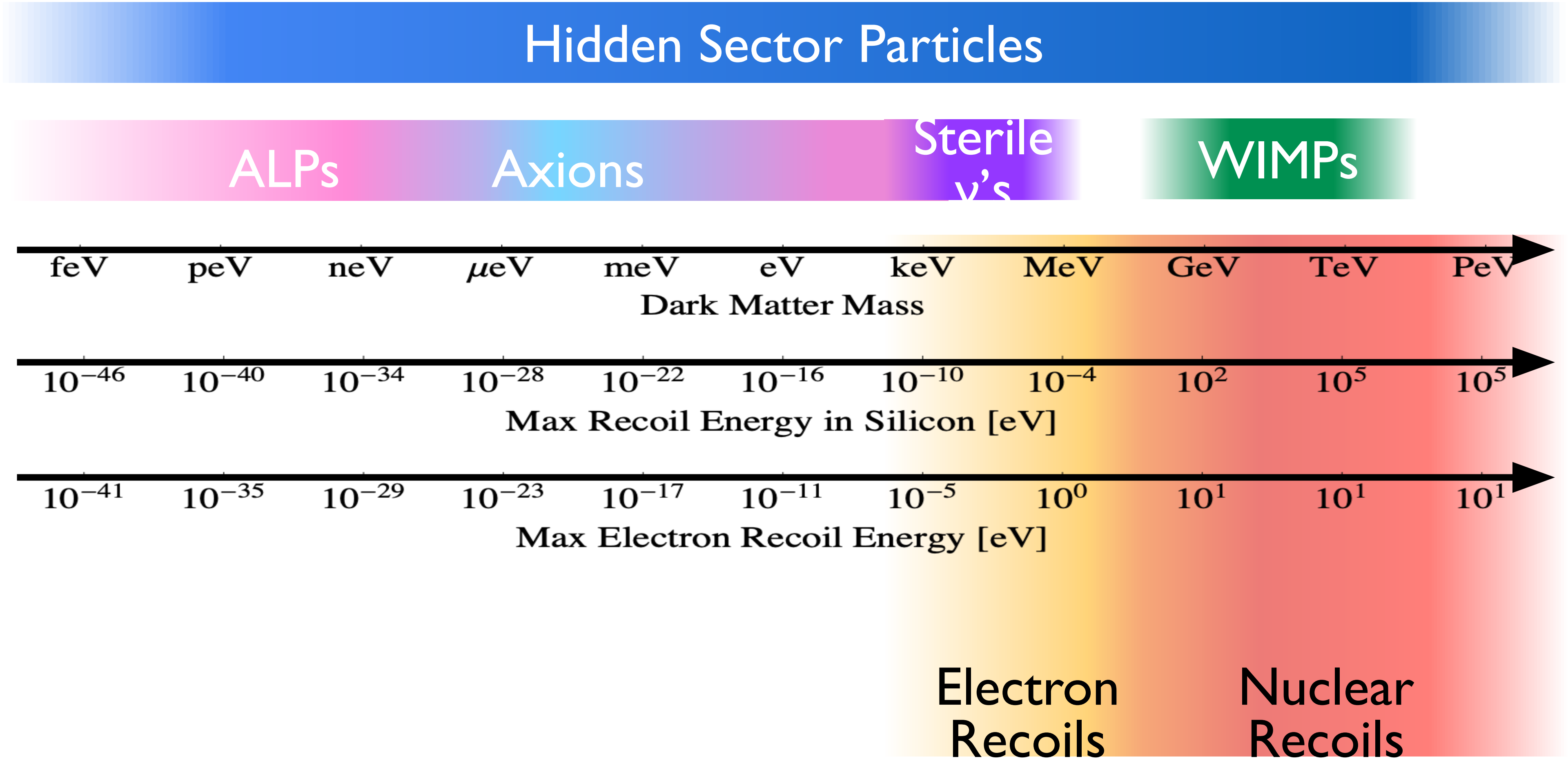


Dark matter direct detection

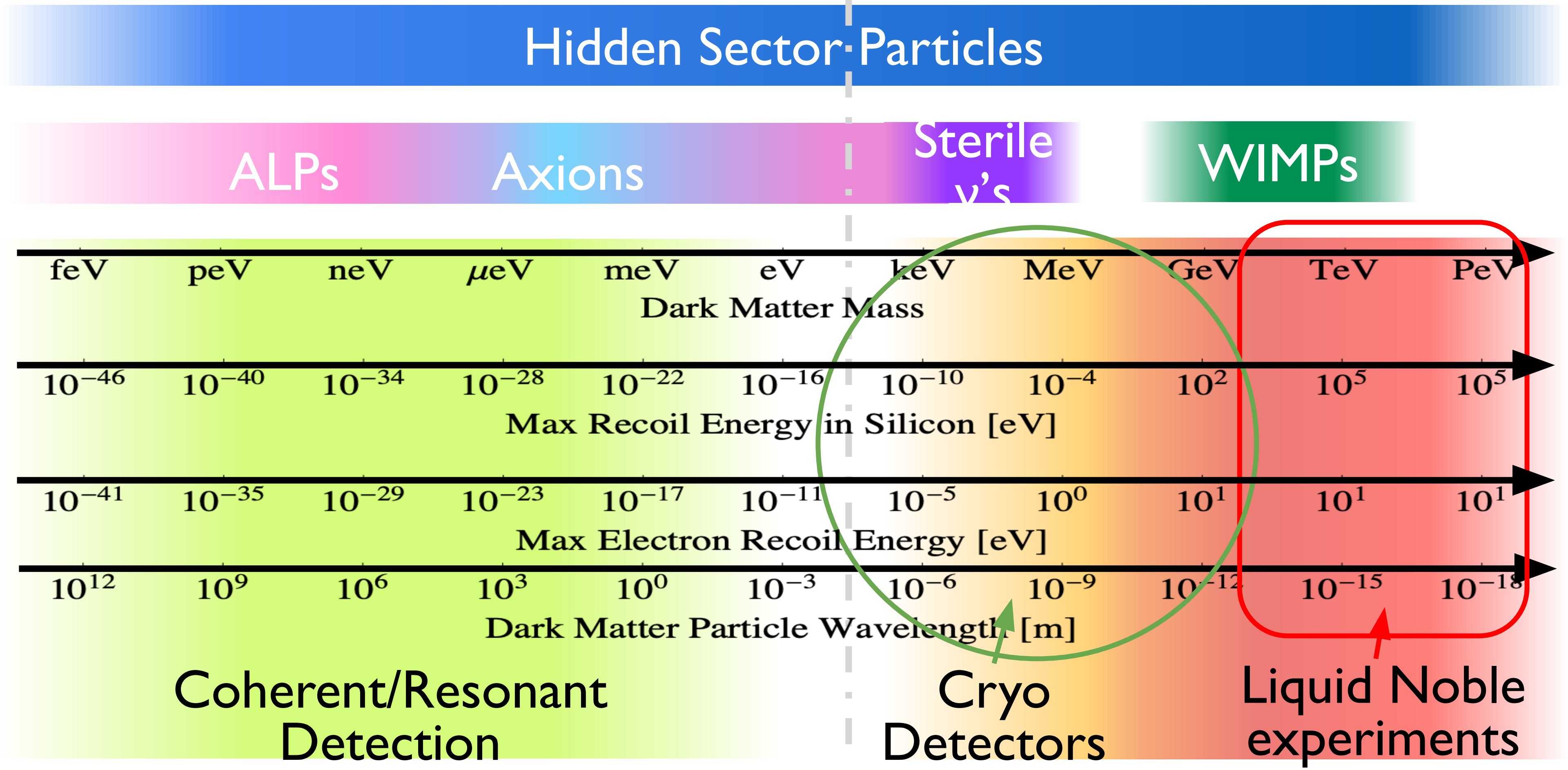
- Dark matter particle interaction deposits energy
- Detectors measure energy in forms of
  - Ionization → Charge
  - Scintillation → Light
  - **Heat → Phonons**
- Stealth signal calls for sensitive detectors

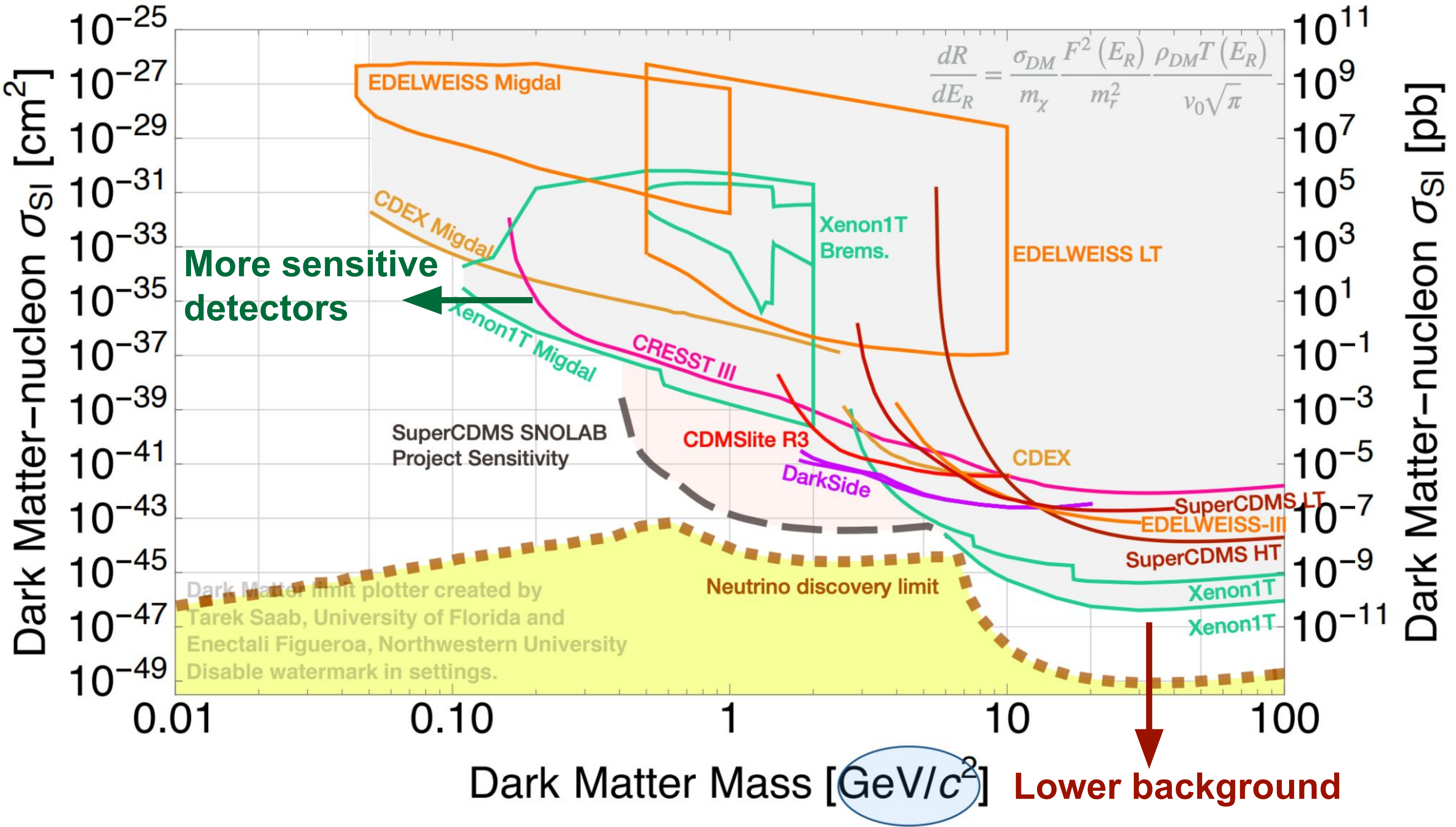


Dark Matter Detection Channels



Dark Matter Detection Channels

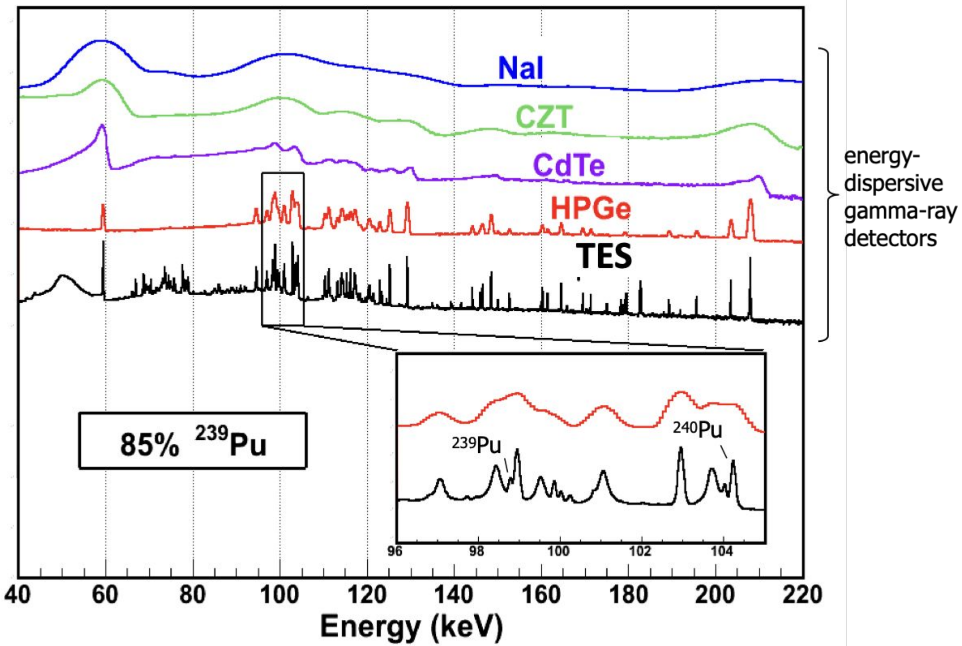




Dark Matter–nucleon σ_{SI} [cm^2]
Dark Matter–nucleon σ_{SI} [pb]
Dark Matter Mass [GeV/c^2]
$\frac{dR}{dE_R} = \frac{\sigma_{DM}}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_{DM} T(E_R)}{v_0\sqrt{\pi}}$
EDELWEISS Migdal
CDEX Migdal
Xenon1T Brems.
EDELWEISS LT
More sensitive detectors
Xenon1T Migdal
CRESST III
SuperCDMS SNOLAB
Project Sensitivity
CDMSlite R3
DarkSide
CDEX
SuperCDMS LT
EDELWEISS-III
SuperCDMS HT
Xenon1T
Xenon1T
Neutrino discovery limit
Dark Matter limit plotter created by
Tarek Saab, University of Florida and
Enectali Figueroa, Northwestern University
Disable watermark in settings.
Lower background

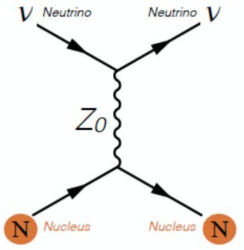
Why Use Cryogenic Crystal Detectors?

- Cryogenic detectors can provide a unique combination of energy sensitivity, low threshold and efficiency
- Exploiting the fundamental idea of lower temperature
  → Lower amount of random motions
  → Lower noise
  → Better energy sensitivity & low threshold

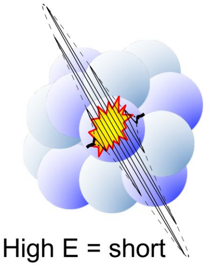


- Well matched to DM detection requirements
- CEvNS and 0νββ experiments share the same needs, thus cryogenic detectors are often developed by these fields jointly

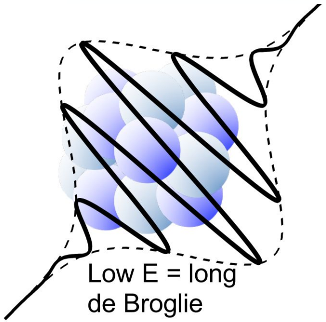
Physics case example II: Reactor CEvNS



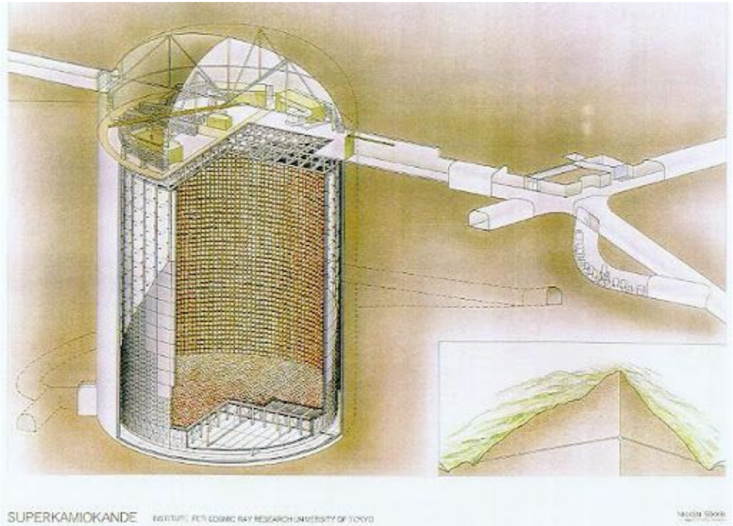
- Neutrinos exhibits properties beyond the Standard Model
  - But very hard to detector due to small cross section
- CEvNS has huge cross-section compared to conventional neutrino interactions, allowing for kg-scale detectors as opposed to ton-scale detectors
- **Need ultra sensitive detectors!**



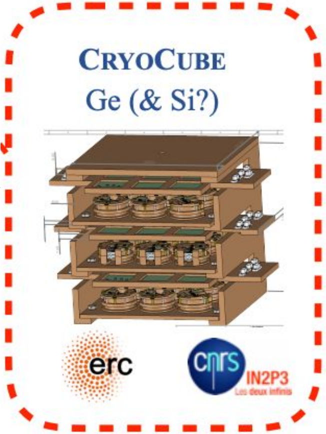
High E = short de Broglie wavelength



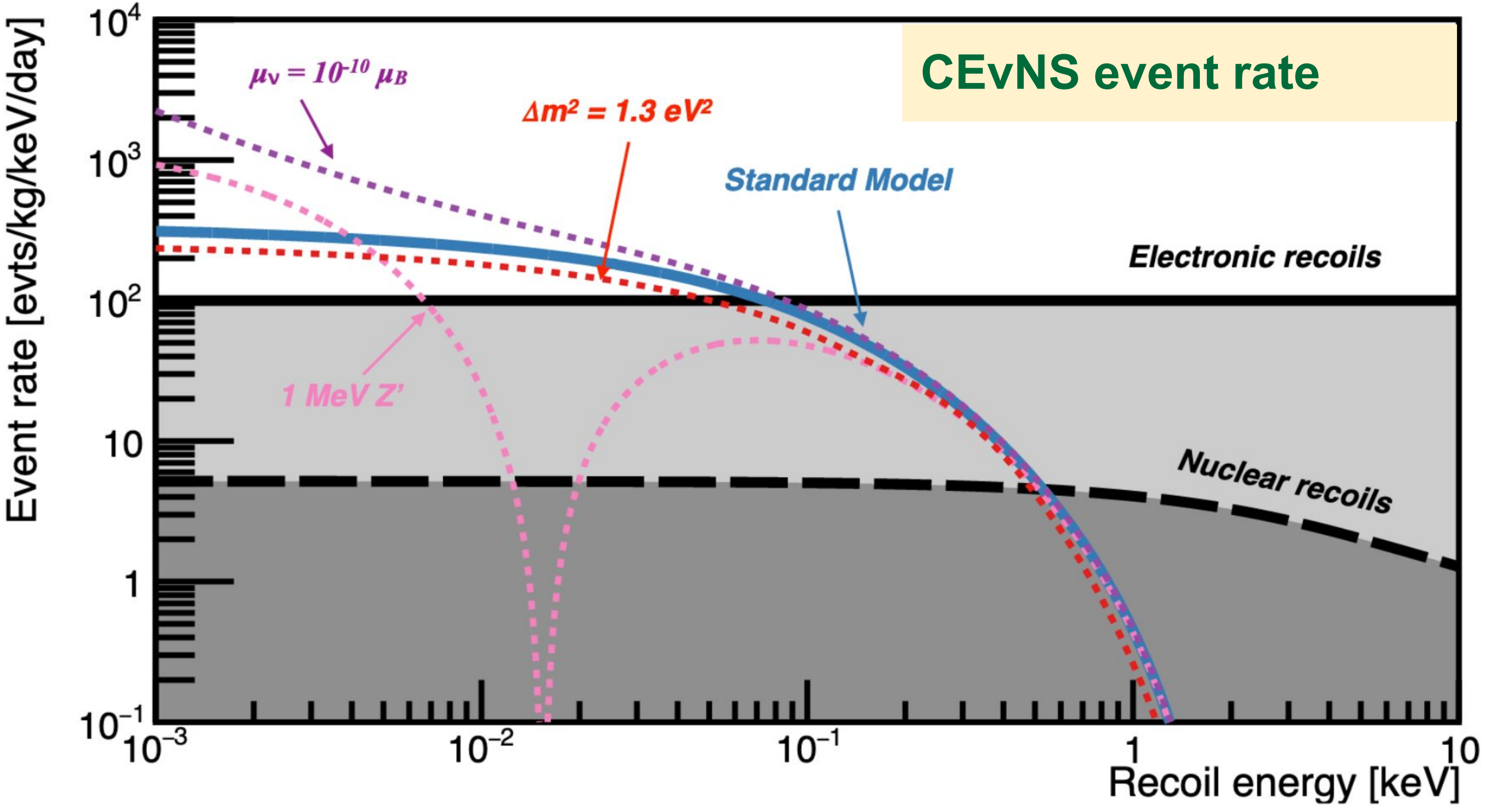
Low E = long de Broglie wavelength



Not to scale!

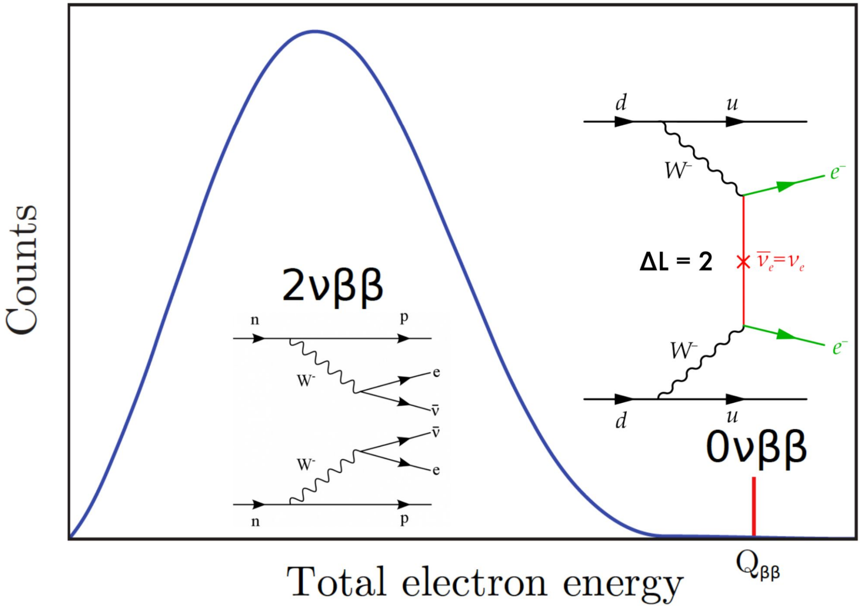


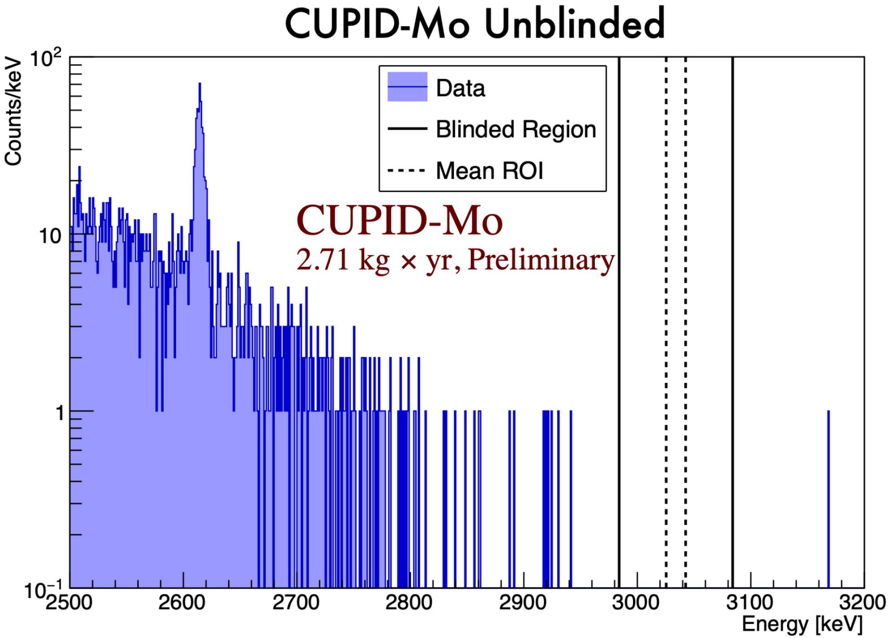
Physics case example II: Reactor CEvNS



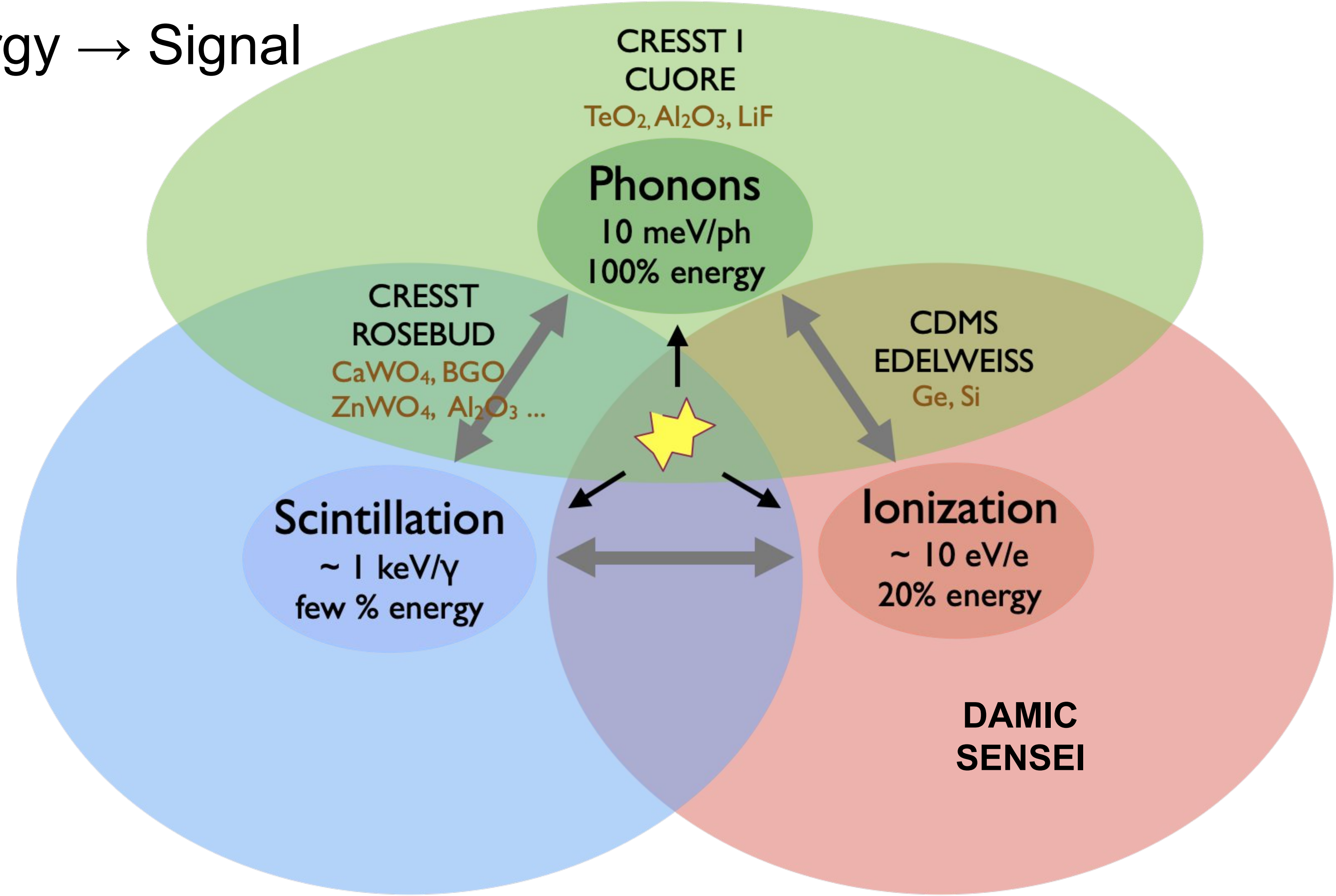
Figures from Bradford Welliver @ TAUP 2021 (link)

Physics case example III: 0νββ with crystals

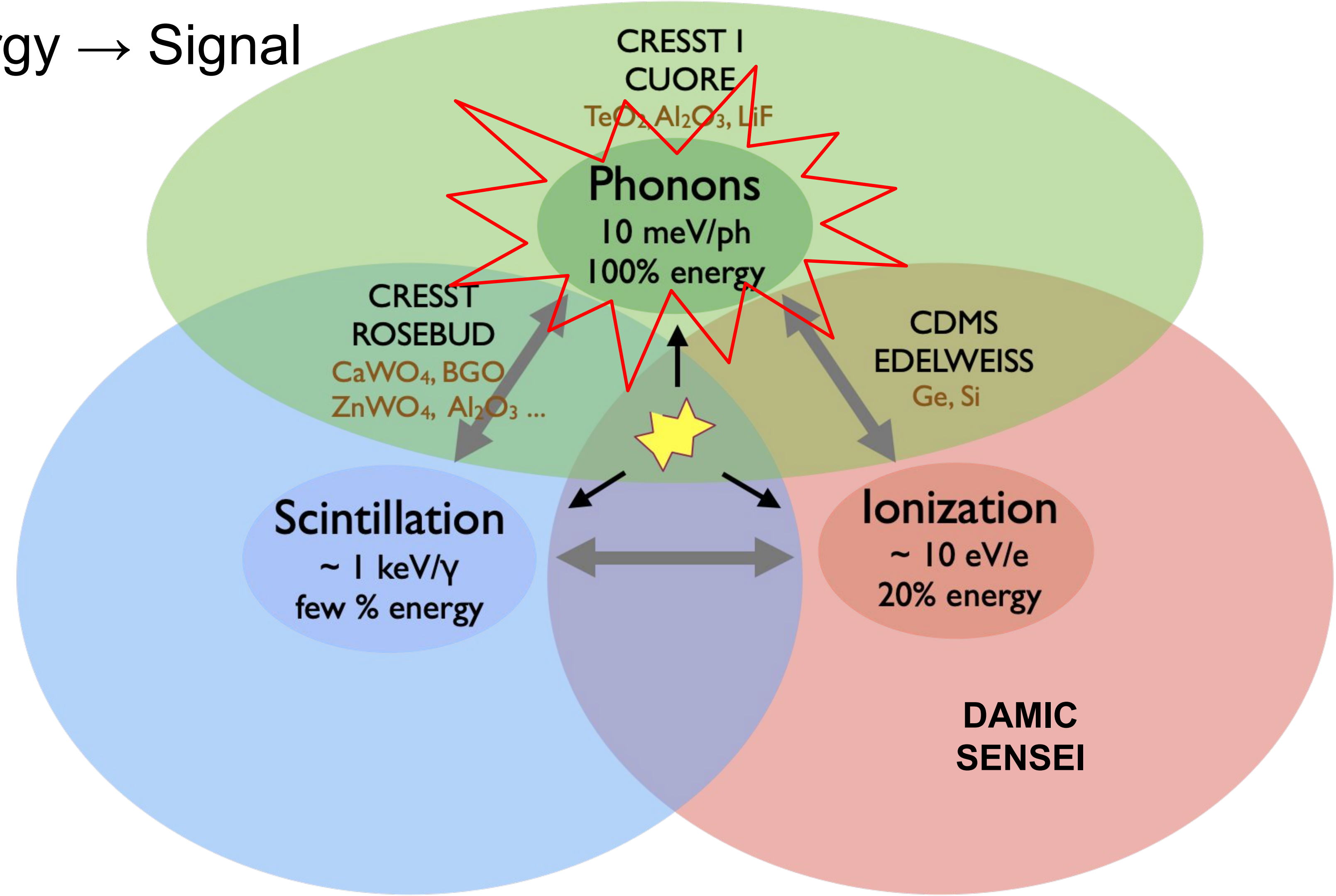




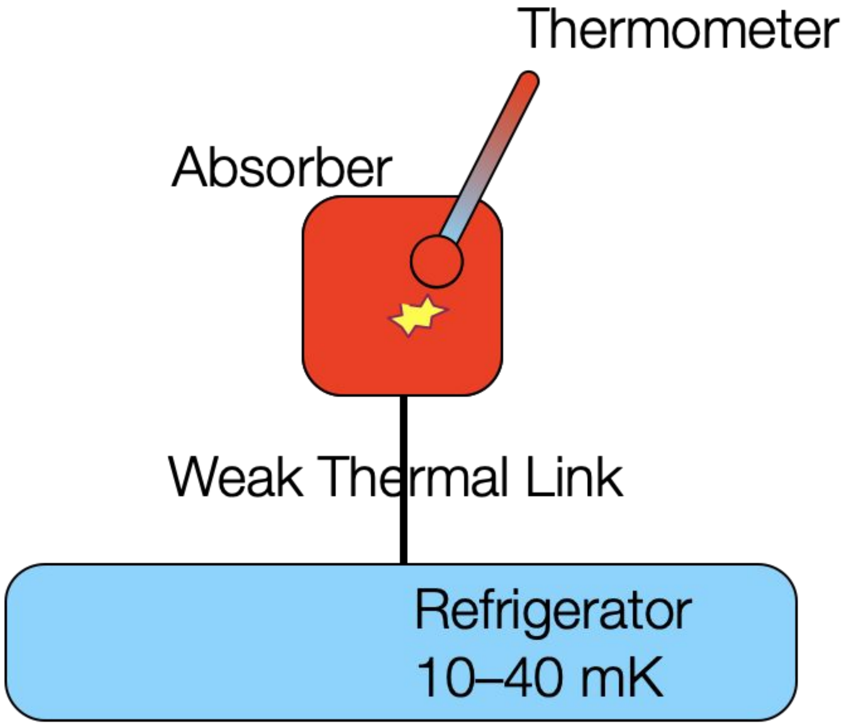
Energy → Signal

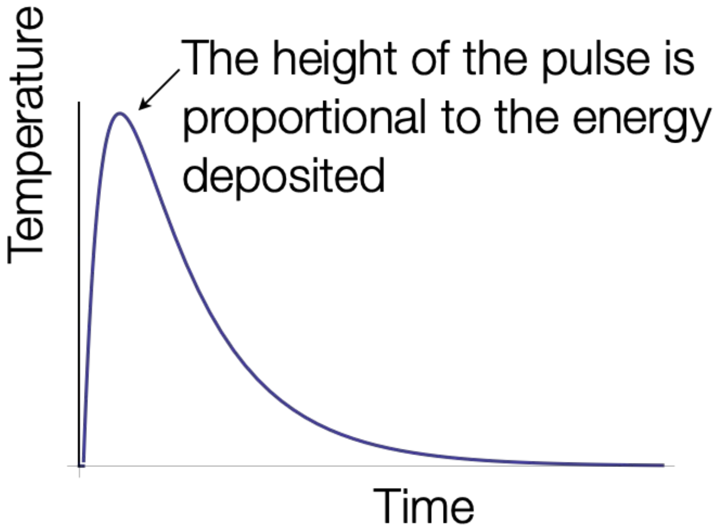


Energy → Signal



Cryogenic Phonon Detectors





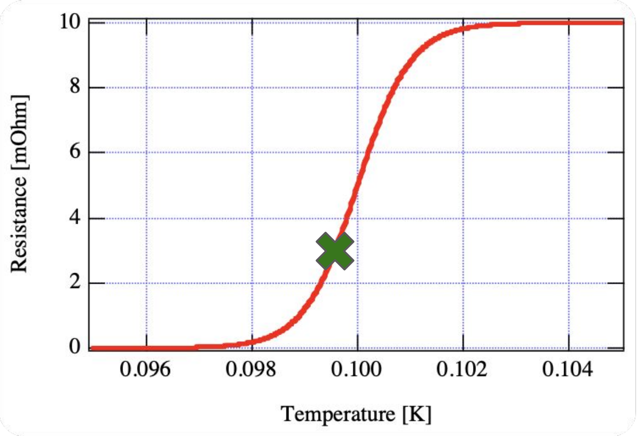
Everybody has their choice of the favourite thermometer!

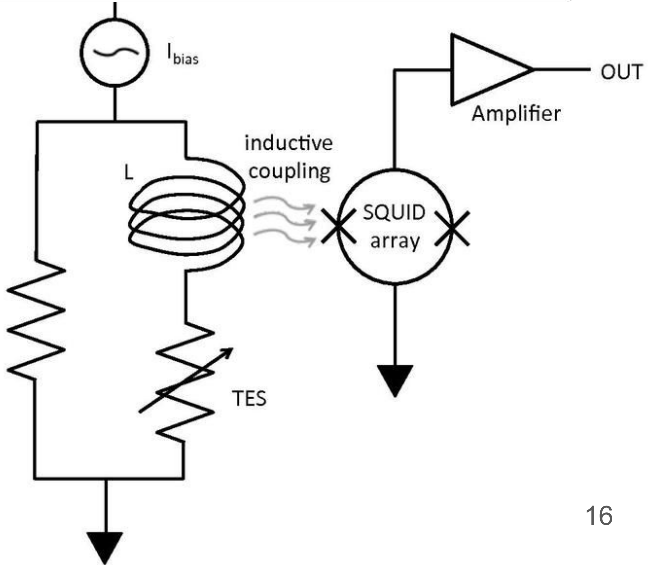
Thermometer #1

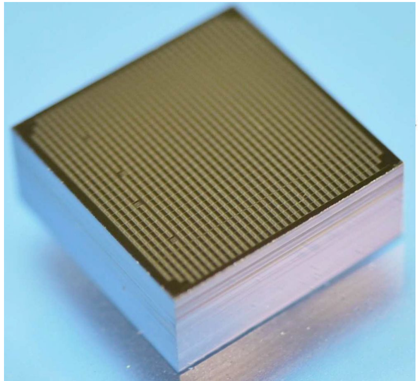
Transition Edge Sensor

- Metal films, tuned to have suitable superconducting transition temperatures
- Operating in the middle of its transition
- Heat warms up the sensor
  → Increase in resistance
- Often read out by Superconducting QUantum Interference Devices (SQUIDs)
- High resistivity films can also be readout with FETs (schematics in next slide)

Transition Edge Sensor (TES)







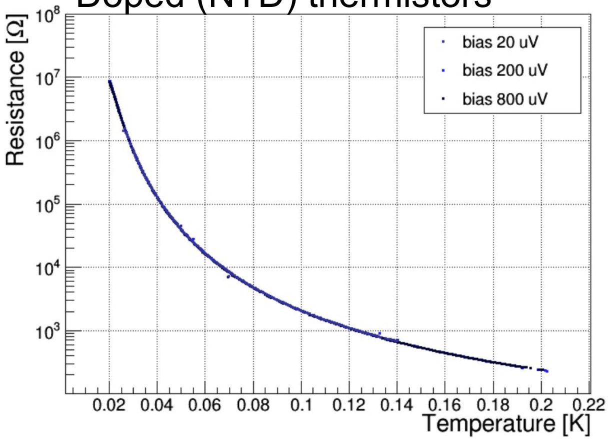
Thermometer #2

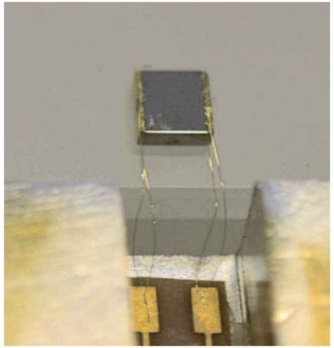
Neutron Transmutation Doped (NTD) thermistors

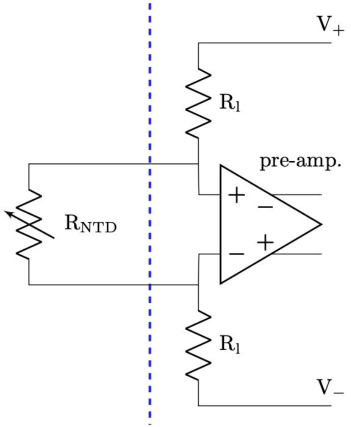
- Doped germanium/silicon chips
- Resistance follows Efros-Shklovskii law:

$$R = R_0 e^{\sqrt{T_0/T}}$$

- Taking advantage of the steep slope at low temperature
- Also comes with high dynamic range
- Readout with FETs, operating at room temperature or in cold







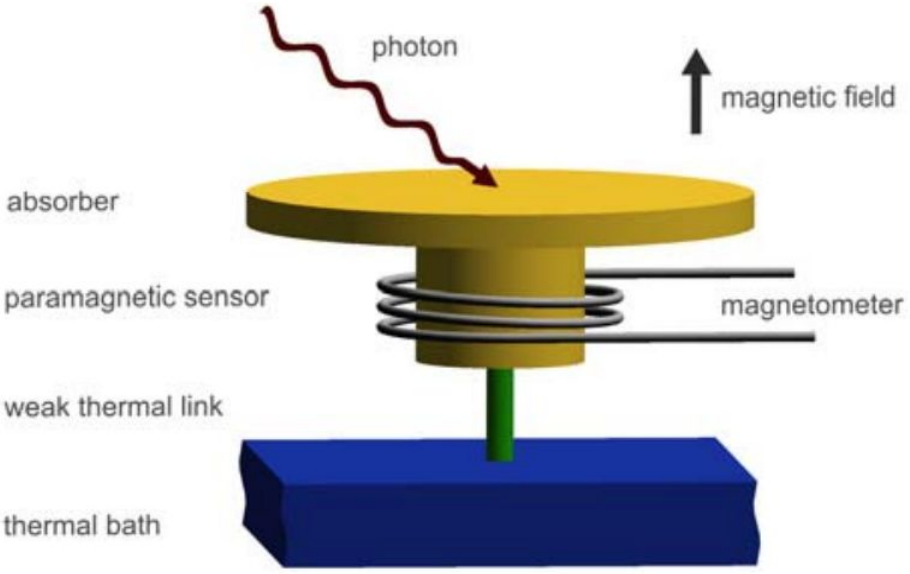
Figures from V. Novati

Thermometer #3

Metallic magnetic calorimeter (MMC)

- Paramagnetic sensor positioned in weak magnetic field
- Heat changes its induced magnetic field
- Readout by SQUIDs as magnetometer

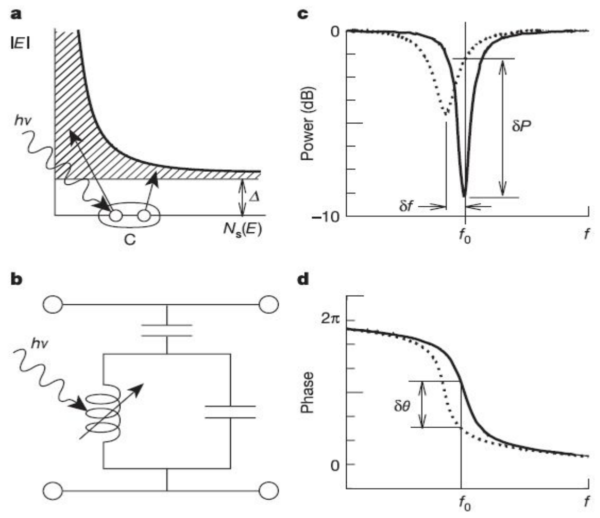
Metallic magnetic calorimeter (MMC)

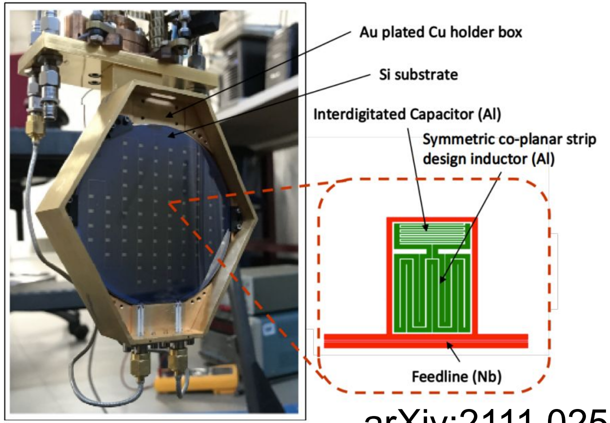


TASC.2009.2012724

Microwave Kinetic Inductance Detectors (MKIDs)

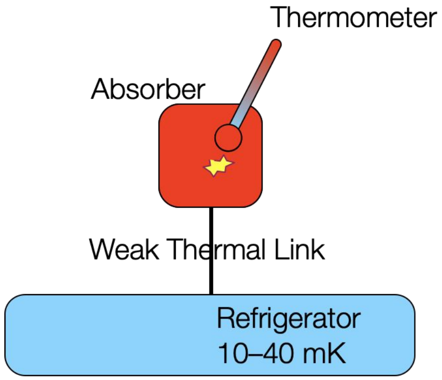
- Resonators made of superconducting metal films
- Resonance frequency and phase response depending on its temperature
- Radio-Frequency (RF) Readout system
- Intrinsic capability for multiplexing



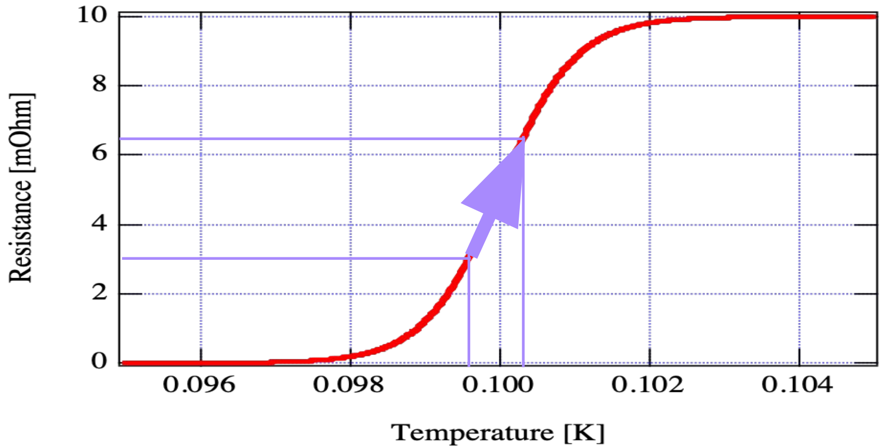


arXiv:2111.02587

Modeling Cryogenic Detectors
Transition-Edge Sensors as an example



- Superconductor biased in its transition
- Several metal systems are used:
  - Elemental: W, Al, Re, Pb, etc.
  - Paramagnetic impurity doped: Al/Fe, Al/Mn, etc.
  - Bi-layers: Mo/Au, Mo/Cu, Ti/Al, etc.
- $50 < \alpha < 1000$
- Low resistance allows read out with SQUIDs



$$\alpha = \frac{T}{R}\frac{dR}{dT}$$

Electro-thermal Feedback (ETF)

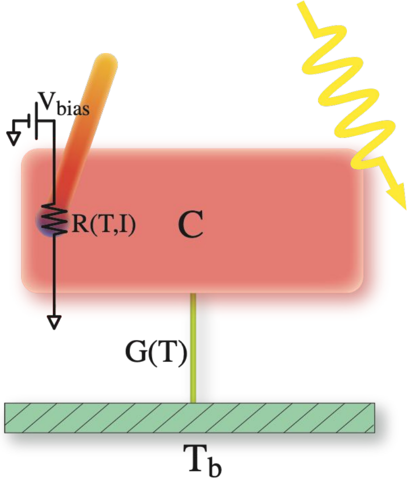
$$P = \frac{V_{\mathrm{bias}}^2}{R(T)}$$

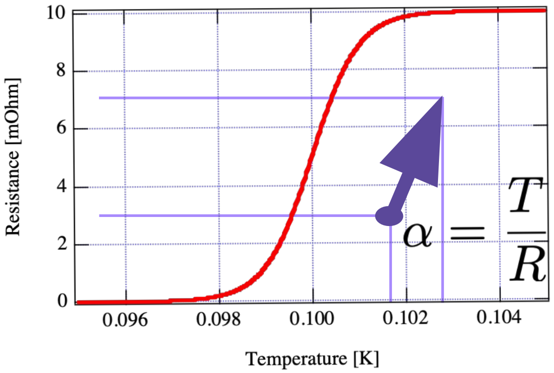
$$\delta P = -\frac{\alpha P}{T}\delta T$$

$$C\frac{dT}{dt} = P - G(T - T_b) + W(t)$$

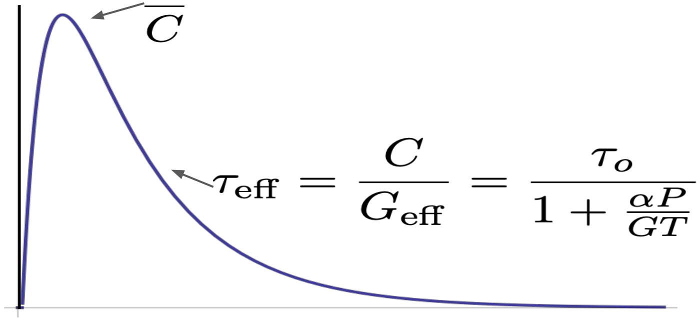
$$C\frac{d(\delta T)}{dt} + G\delta T - \delta P = W(t)$$

$$C\frac{d(\delta T)}{dt} + \left(G + \frac{\alpha P}{T}\right)\delta T = W(t)$$



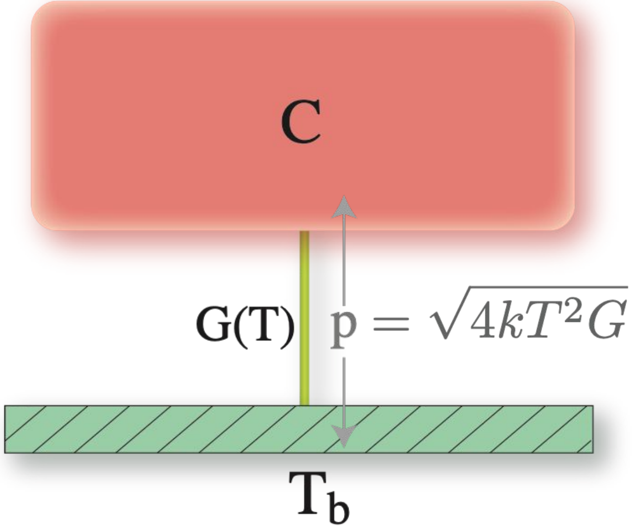


$$\alpha = \frac{T}{R}\frac{dR}{dT}$$



$$\tau_{\mathrm{eff}} = \frac{C}{G_{\mathrm{eff}}} = \frac{\tau_o}{1 + \frac{\alpha P}{GT}}$$

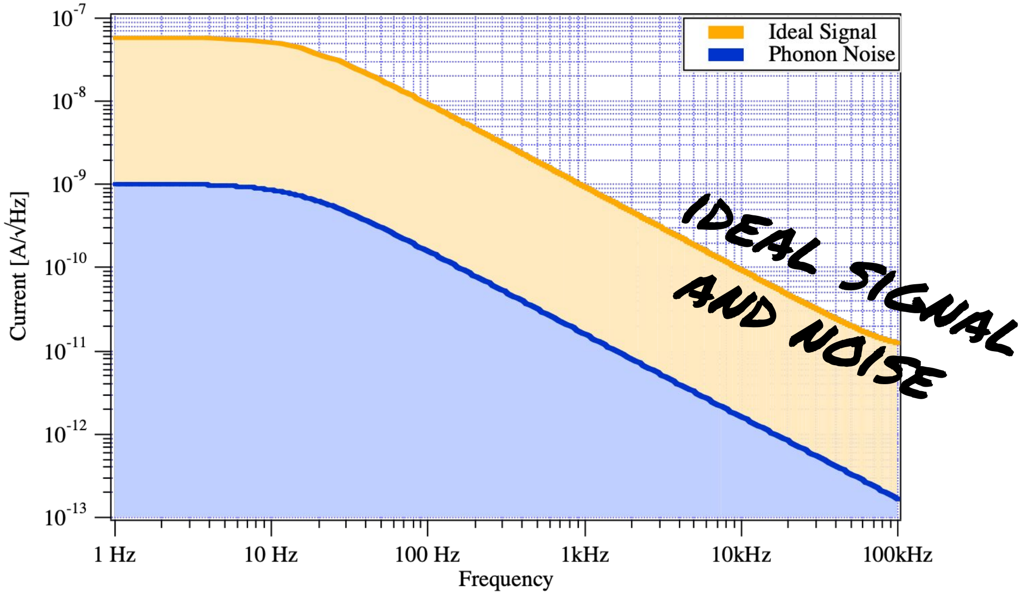
But are they any good?



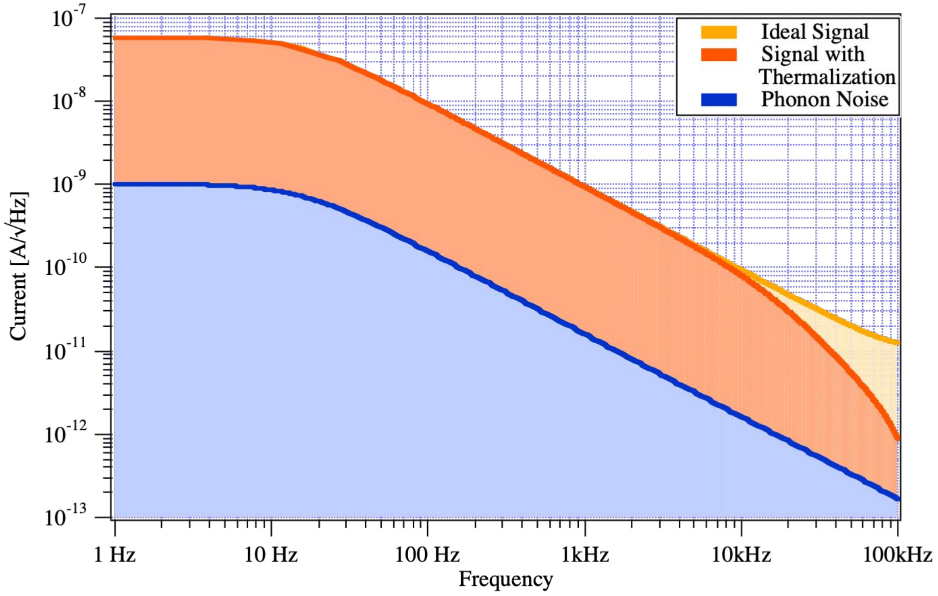
- Thermodynamic fluctuation noise
- Signal to Noise
- Energy Resolution

$$\Delta E_{rms} = \sqrt{kT^2C}$$

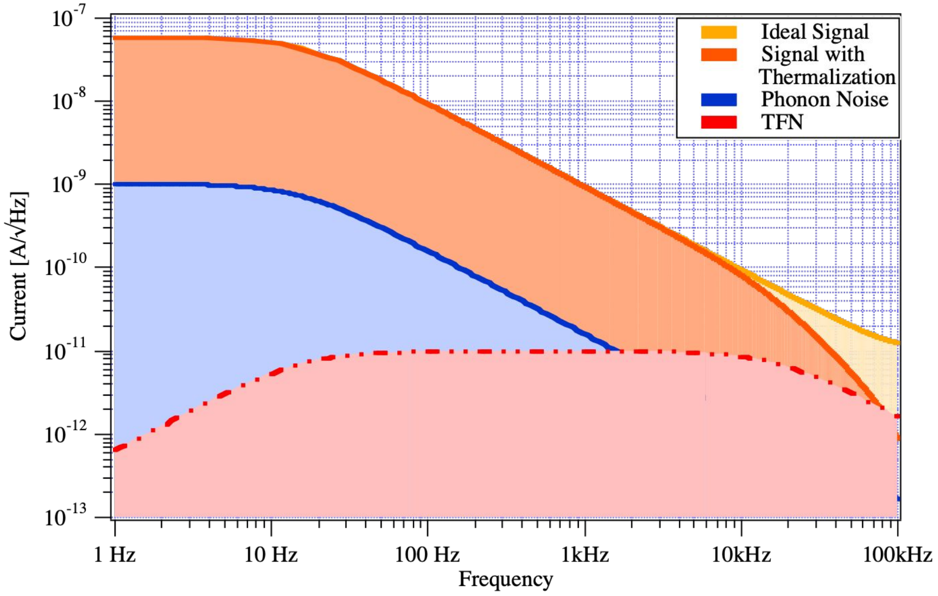
Resolution is all about noise and bandwidth



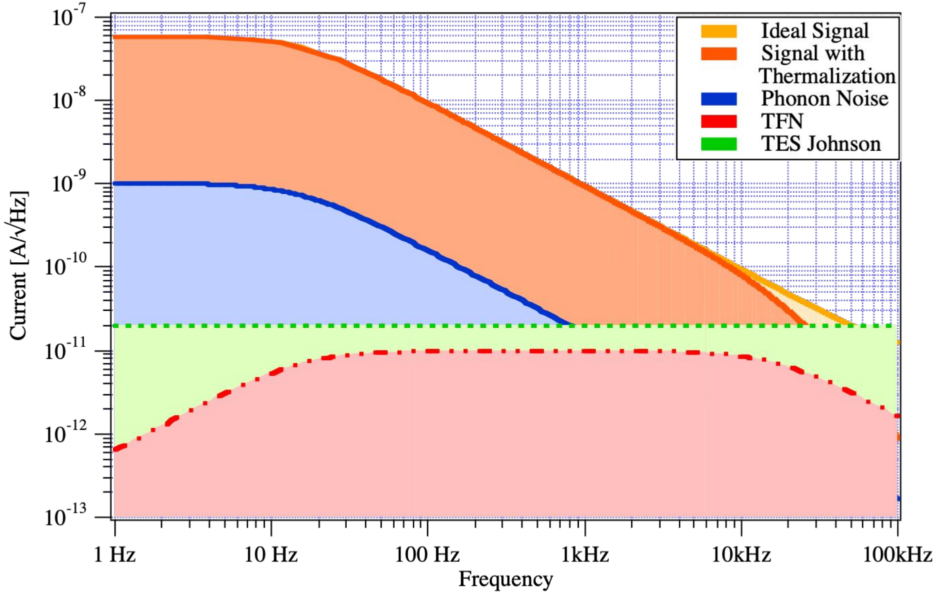
Resolution is all about noise and bandwidth



Resolution is all about noise and bandwidth

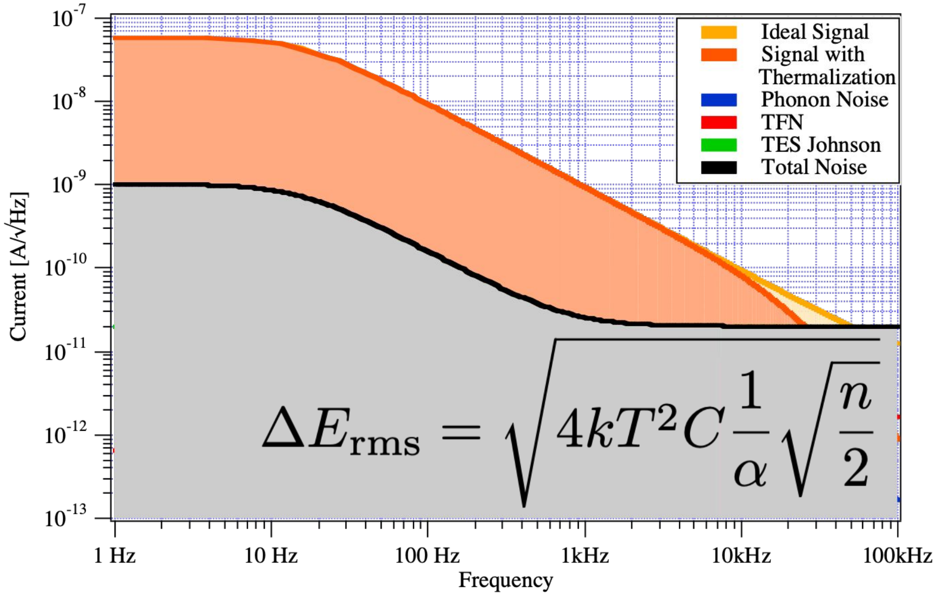


Resolution is all about noise and bandwidth



Resolution is all about noise and bandwidth

Full noise modeling can get a bit more involved than this…



$$\Delta E_{\mathrm{rms}} = \sqrt{4kT^2C\frac{1}{\alpha}\sqrt{\frac{n}{2}}}$$

Control noise → Cool it down

- Noise is often one of the limitations of particle detectors
- Especially true for lots of rare event search experiments
- Understanding & minimizing noise is a constant topic of the field…
- **One general method of reducing noise: cool it down**

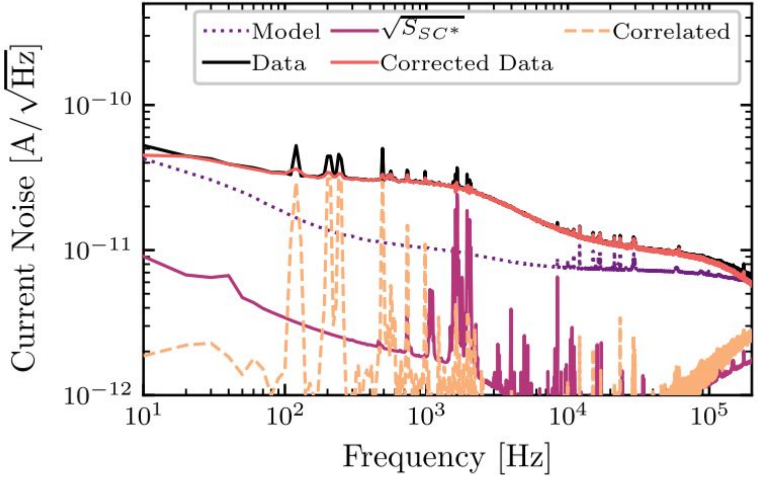
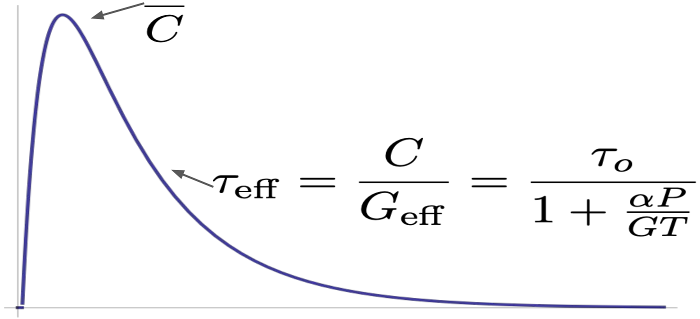


FIG. 6. Measured noise (black solid), modeled voltage-coupled noise (purple solid), correlated noise (yellow dashed), measured noise with voltage-coupled and correlated components subtracted (orange solid), and theoretical noise model (purple dots) shown for $R_0 \approx 15\% R_N$. The environmental noise model explains the peaks in the measured spectrum, but there is still a discrepancy between the environmental-noise-corrected data and the noise model.

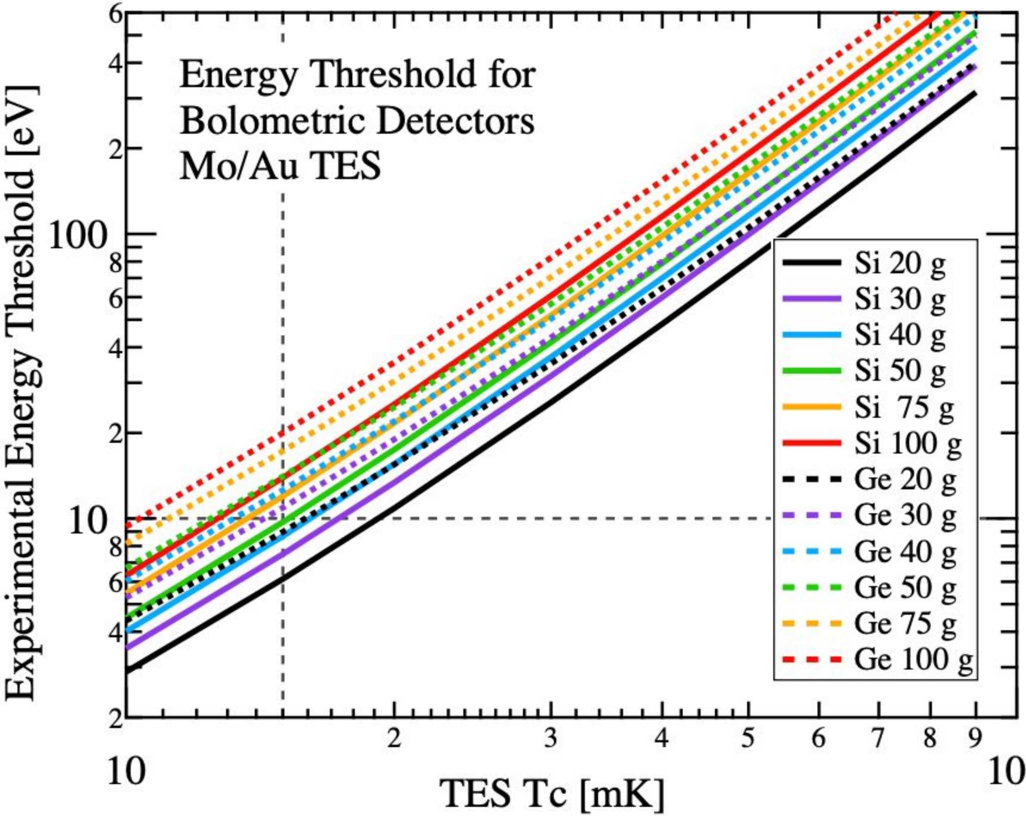
AIP Advances 1 August 2020; 10 (8): 085221

Cold reduces heat capacity → More sensitive detector!

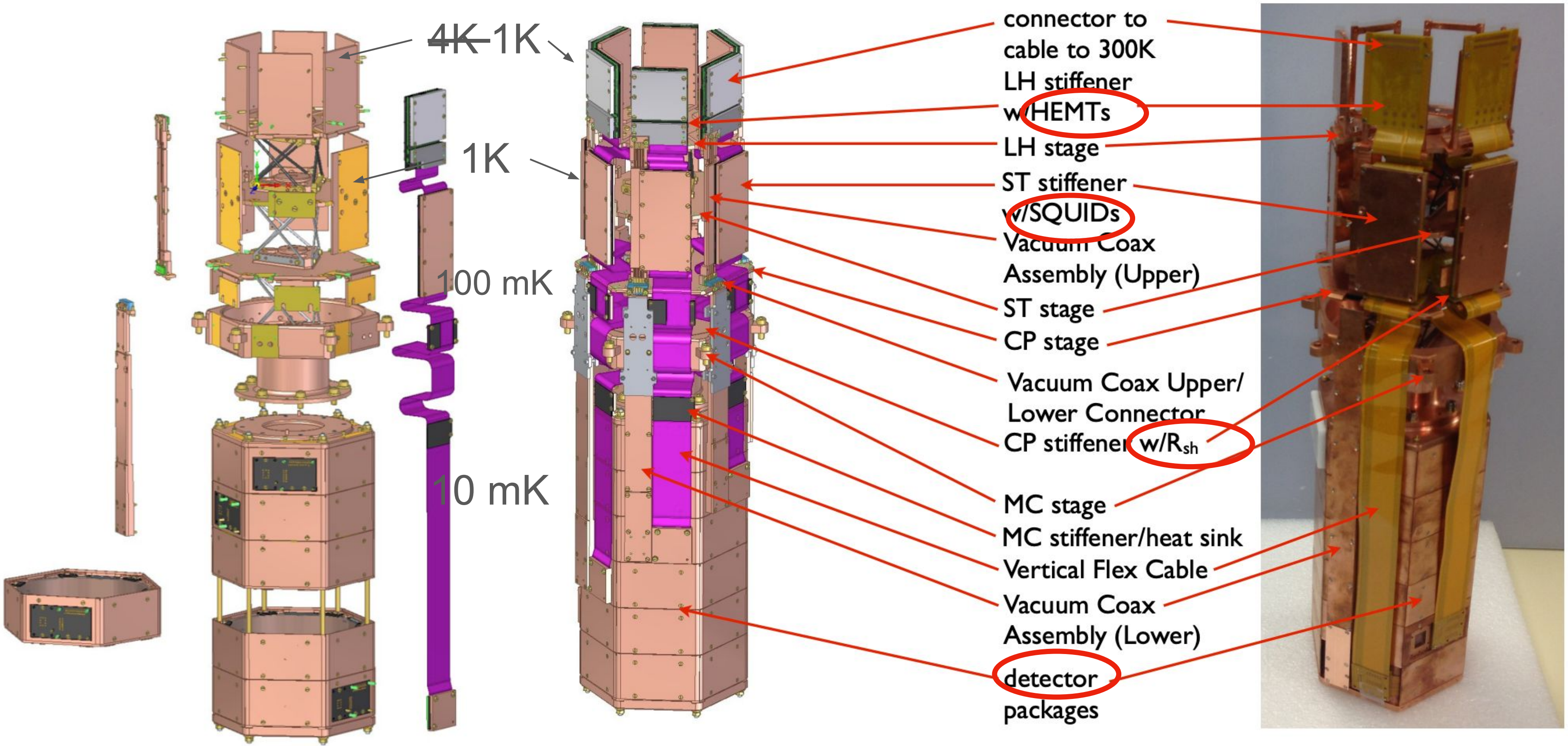


$$\frac{E}{C}$$

$$\tau_{\text{eff}} = \frac{C}{G_{\text{eff}}} = \frac{\tau_o}{1 + \frac{\alpha P}{GT}}$$

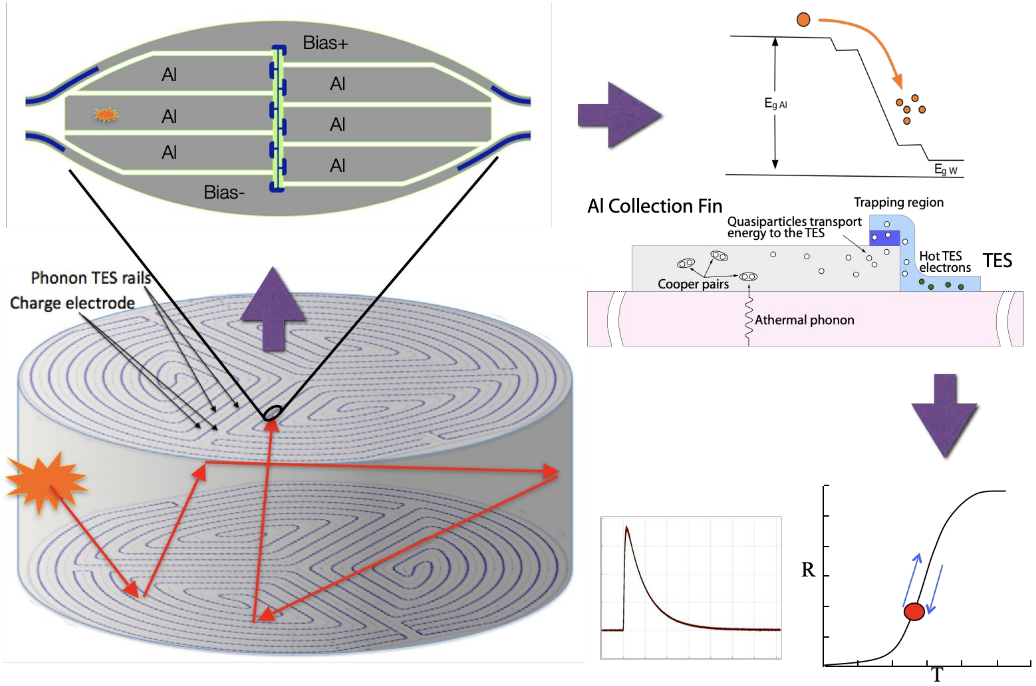


SuperCDMS Tower
Matching components to appropriate temperatures



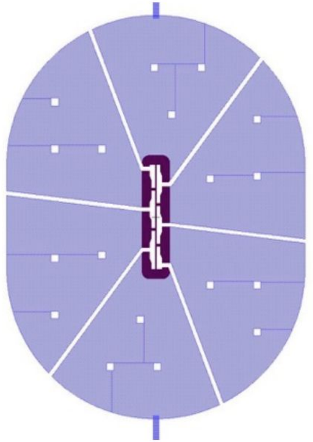
Funneling Energy to the Phonon Sensors (QETs)

- Quasiparticle-trap-assisted electrothermal-feedback TES (QETs)
- Targeting at high energy athermal phonons before they down-convert
- Utilizing superconducting “fins” to trap phonons and funnel them to TES
- Fast (O(10 us)) detector response (in cryogenic detector sense)

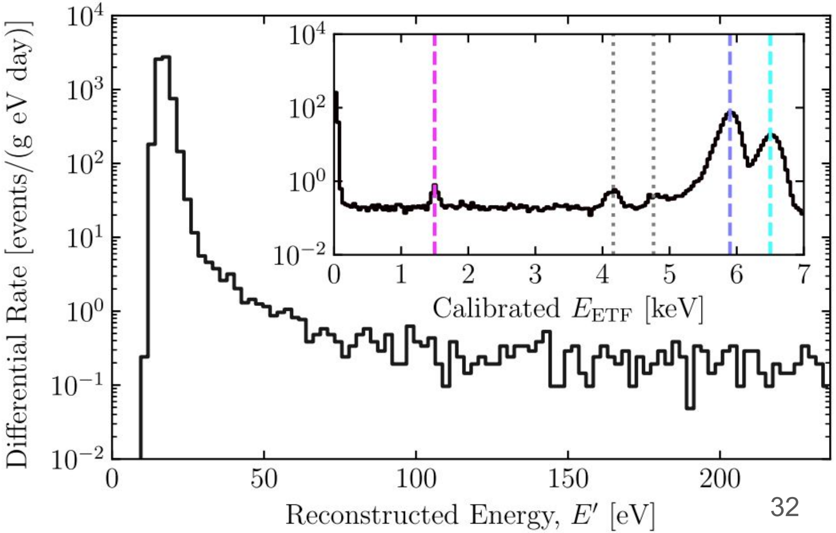


Cryogenic PhotonDetector (CPD) and TESSERACT

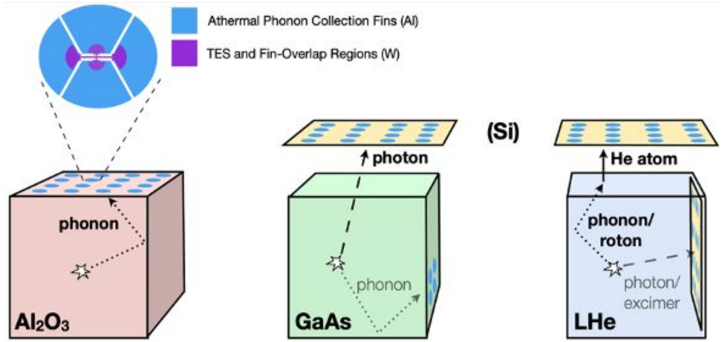
- 10 gram, silicon, QET-based
- 3.9 eV phonon resolution
- Works great in both sensing photons and DM direct detection
- Future development by TESSERACT



APL 118, 022601 (2021)



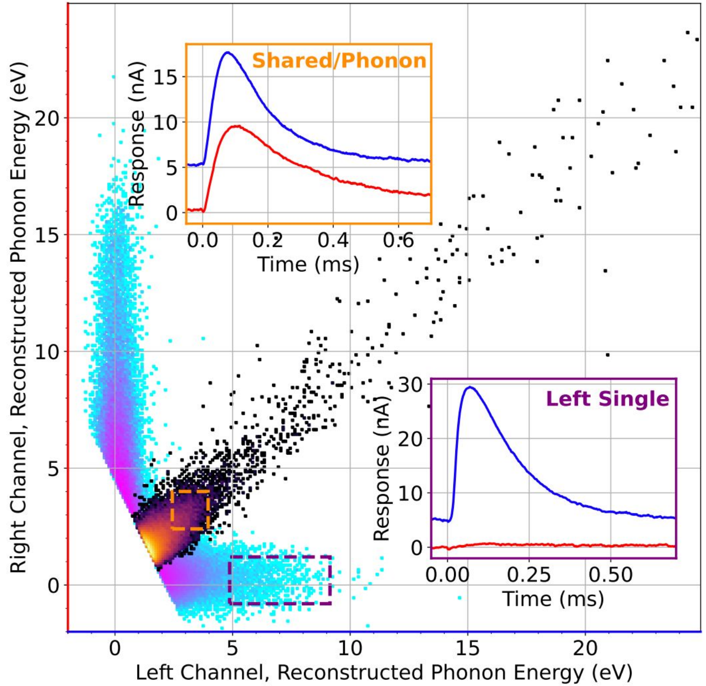
PRL 127, 061801 (2021)

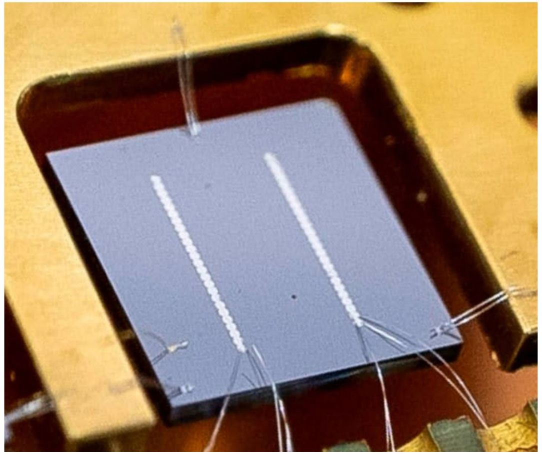


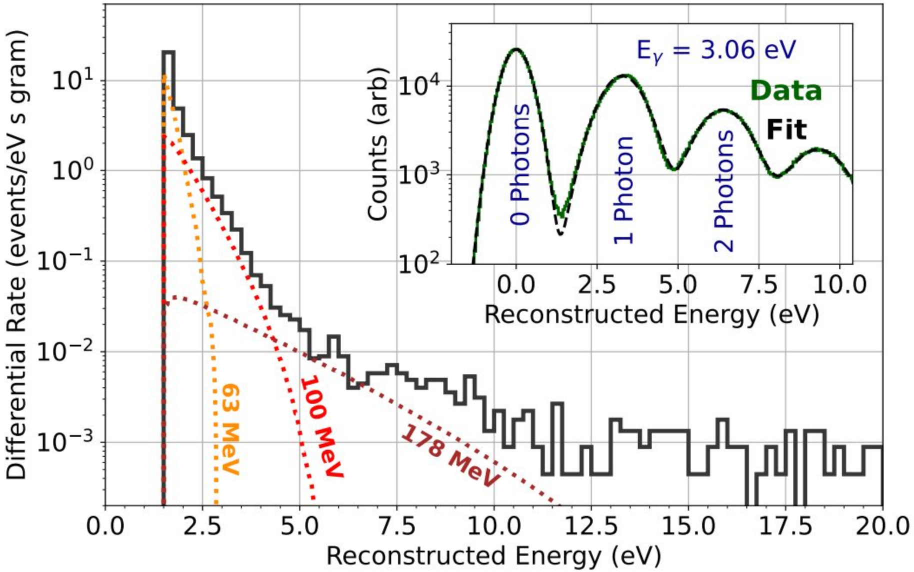
arXiv:2503.03683

Latest TESSERACT detector

- 1 gram, silicon, QET-based
- 0.361 eV phonon resolution

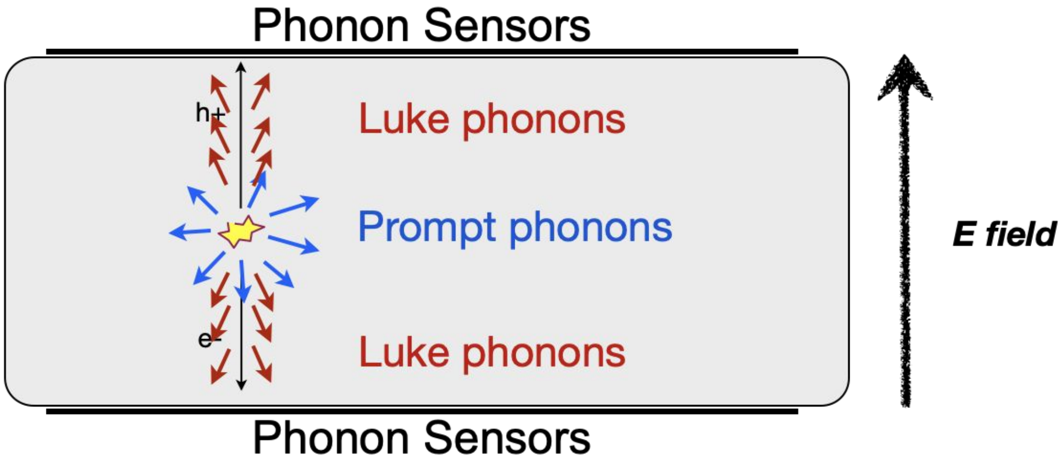






Internal amplification - the NTL effect

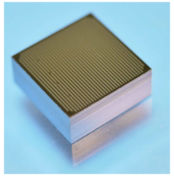
Phonon sensors measure amount of charge produced:
Phonon-based charge amplification!



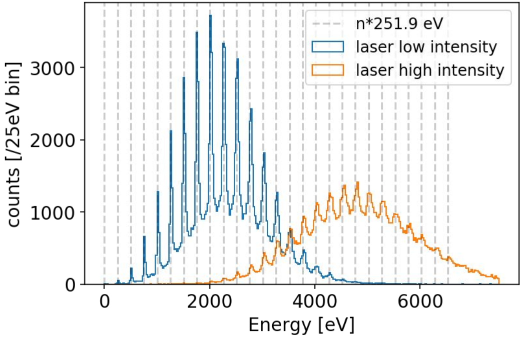
$$\text{Phonon energy} = E_{recoil} + E_{Luke}$$
$$= E_{recoil} + n_{eh}\, e^{-}\, \Delta V$$

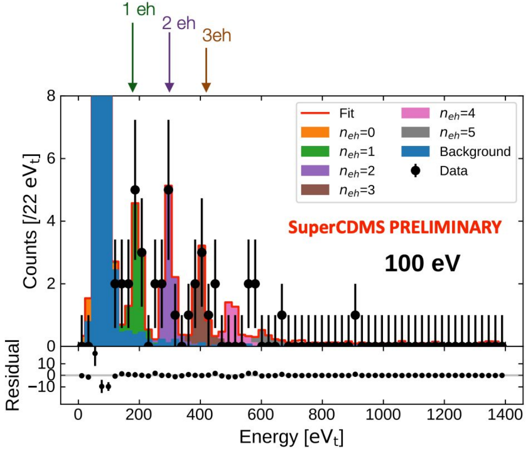
SuperCDMS High Voltage eV sensitivity Detector (HVeV)

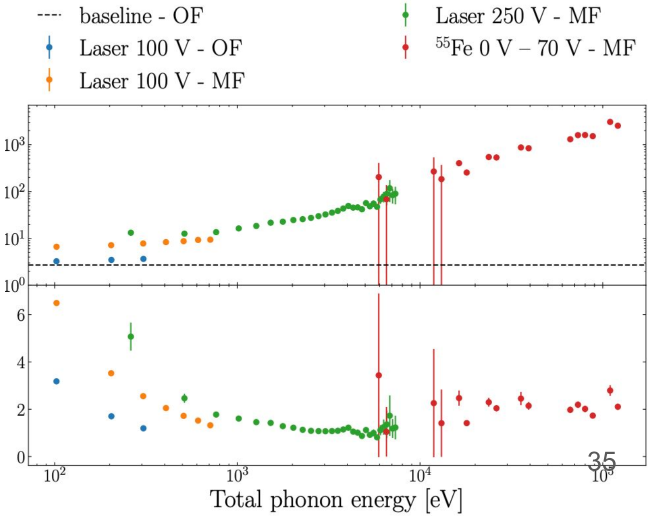
- 1 gram, silicon, QET-based, 2.7 eV resolution
- Can apply O(100 V) for NTL boost
  or operate at 0 V as pure phonon sensors
  - Particle identification by statistics
- Quantized electron-hole pair sensitivity for both ER and NR
- Scaling it up to 1 kg
  SuperCDMS HV detector

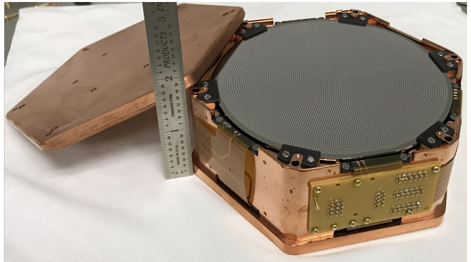


PRD 104, 032010 (2021)



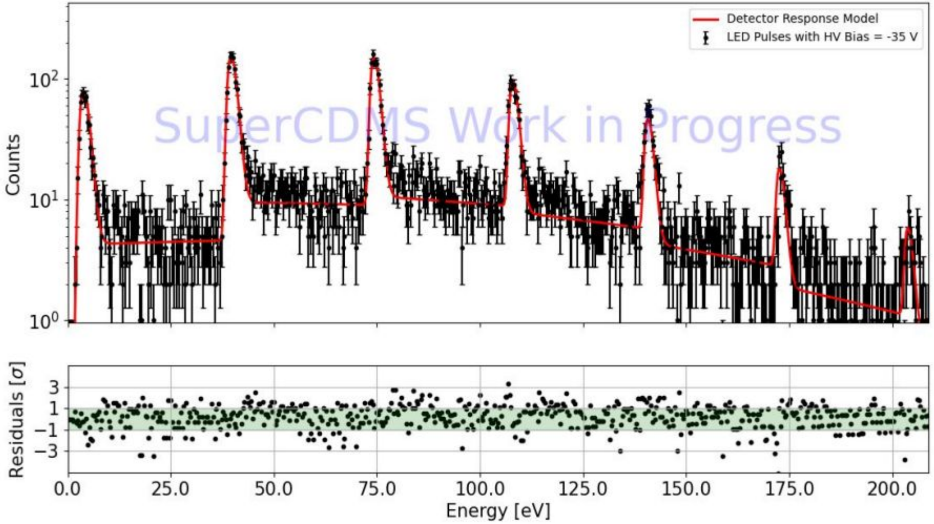




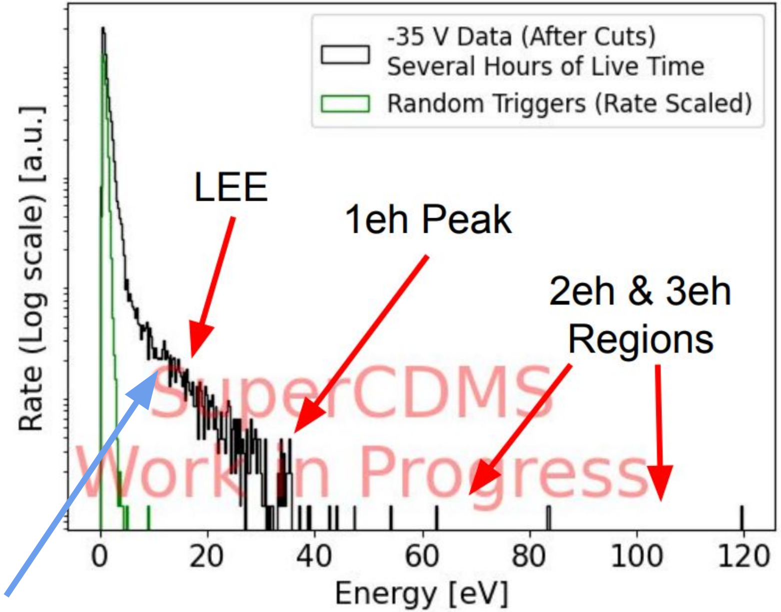


SiO_2 HVeV achieved **0.573 eV baseline resolution!**

Detector response model fit to LED calibration data



Sample Spectrum from Unblinded DM Search Data

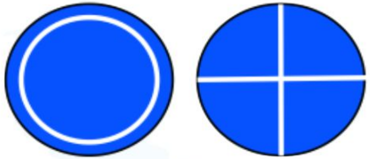


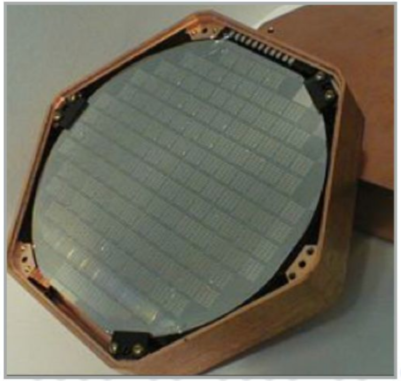
0V data in hand to help model this

SuperCDMS detector evolutions: Retaining Position information

CDMS II (Ge+Si)

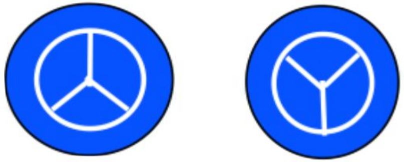
- 4.6 kg Ge (19 x 240 g)
- 1.2 kg Si (11 x 106g)
- 35% NR acceptance

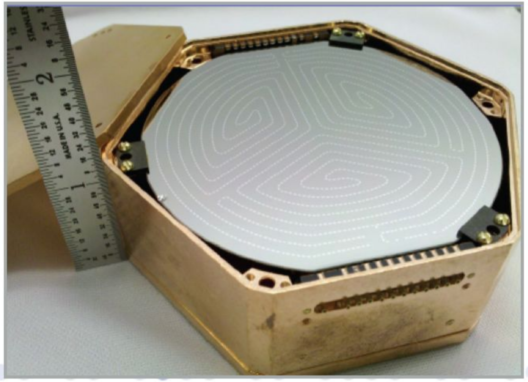




SuperCDMS Soudan

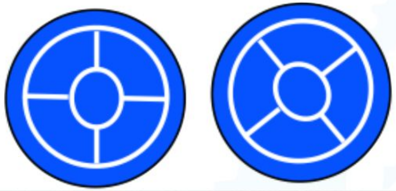
- 9.0 kg Ge (15 x 600 g)
- Increased acceptance
- Improved surface event discrimination
- Demonstrated HV performances with CDMSlite detectors

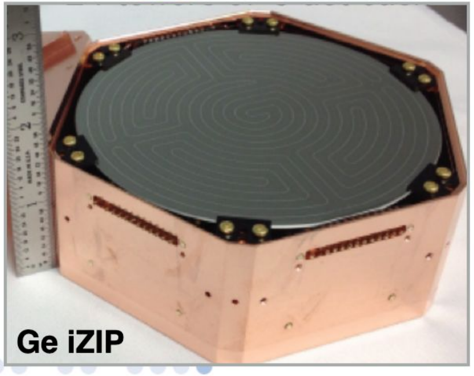




SuperCDMS SNOLAB

- Four towers of mixed Ge and Si, iZIP and HV detectors
  - iZIP: detectors with full background rejection capabilities
  - HV: detectors with lowered energy thresholds

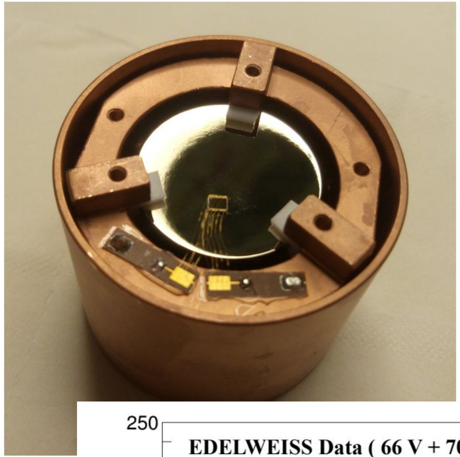


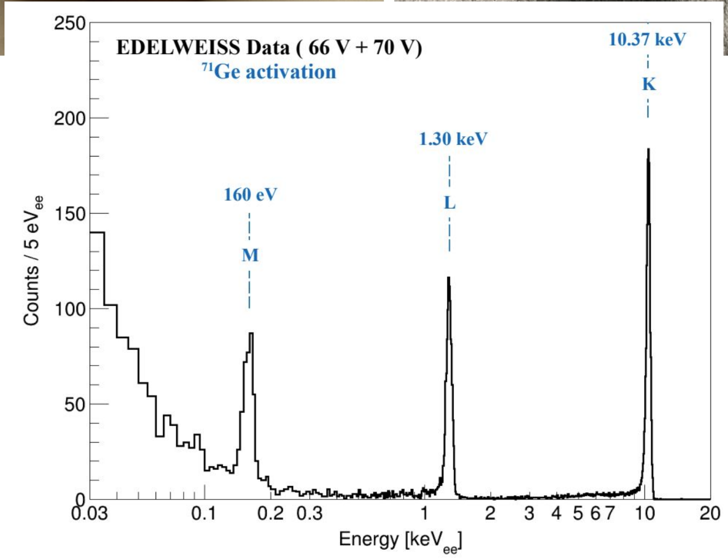


Figures from arXiv: 2202.05097
PRD 99, 082003 (2019)
PRL 125, 141301 (2020)

Edelweiss: RED20 and RED30

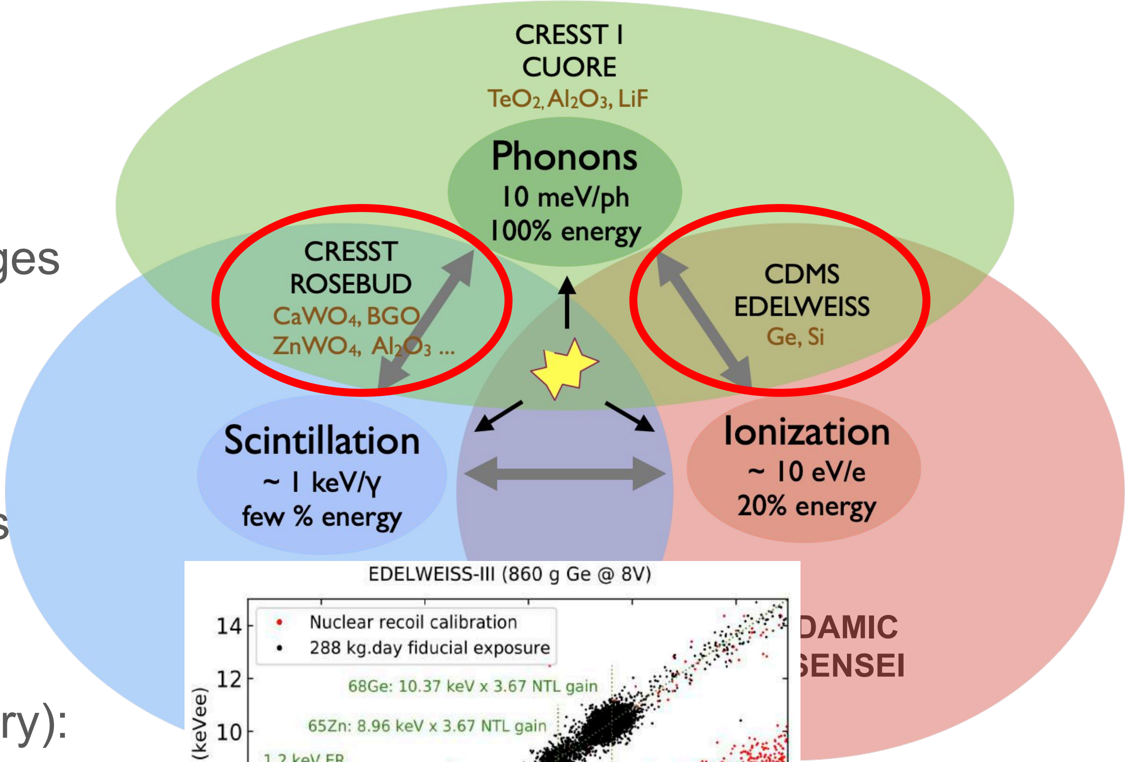
- 33 gram, germanium, NTD-based
- 18 eV phonon resolution
- RED20 operated with no E-field
- RED30 employs NTL gain to boost signals
  - With a planar electrode design
  - 8 eVee at 160 eV, consistent with Fano fluctuations





Adding information for particle identification

- Electron recoil (ER): lots of charges and scintillation lights
  - Source: photons, electrons alphas, ER DM particles
- Nuclear recoil (NR): less charges and scintillation lights
  - Source: neutrons, WIMPs
- Heat only (newly realized category): well… heat (phonon) only…
  - Source: unknown
- **Adding information sometimes degrades phonon information**
  - Careful trade-off needed



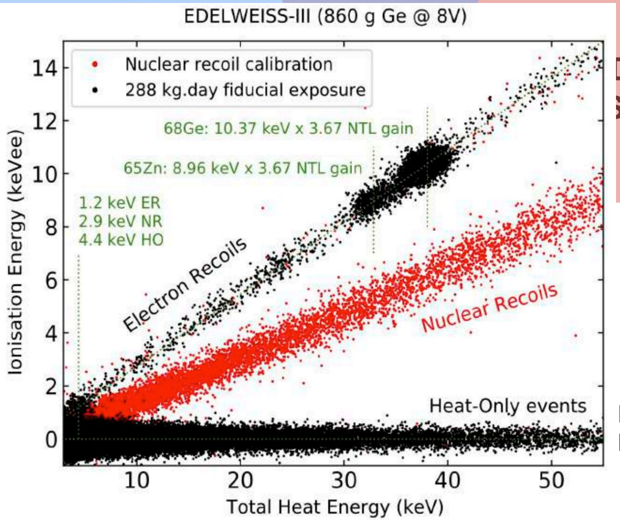
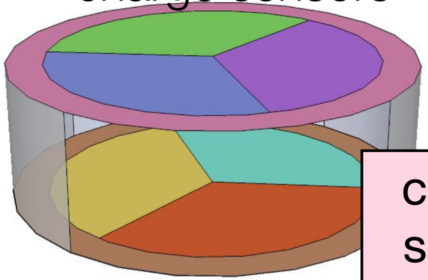
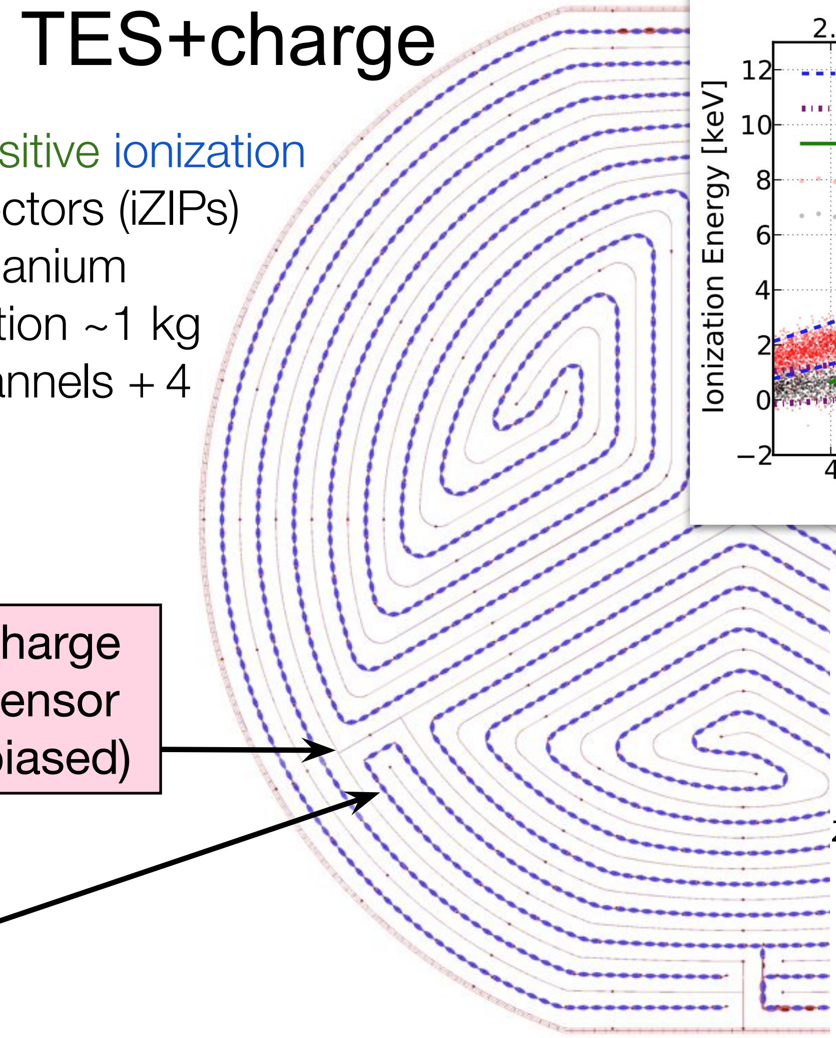


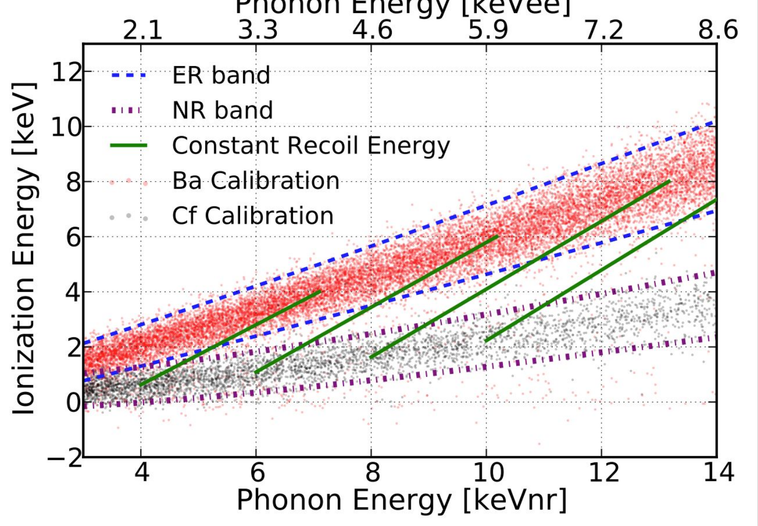
Fig. from J. Gascon, EXCESS workshop 2021

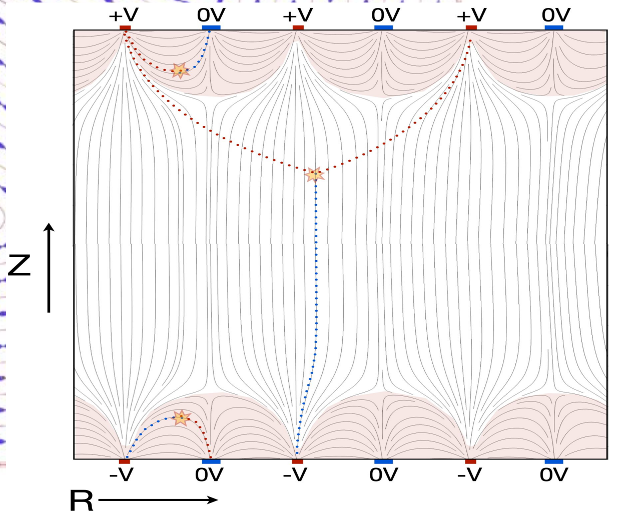
SuperCDMS: TES+charge

- Interleaved z-sensitive ionization and phonon detectors (iZIPs)
- Silicon and Germanium
  - Next generation ~1 kg
- 8-12 phonon channels + 4 charge sensors





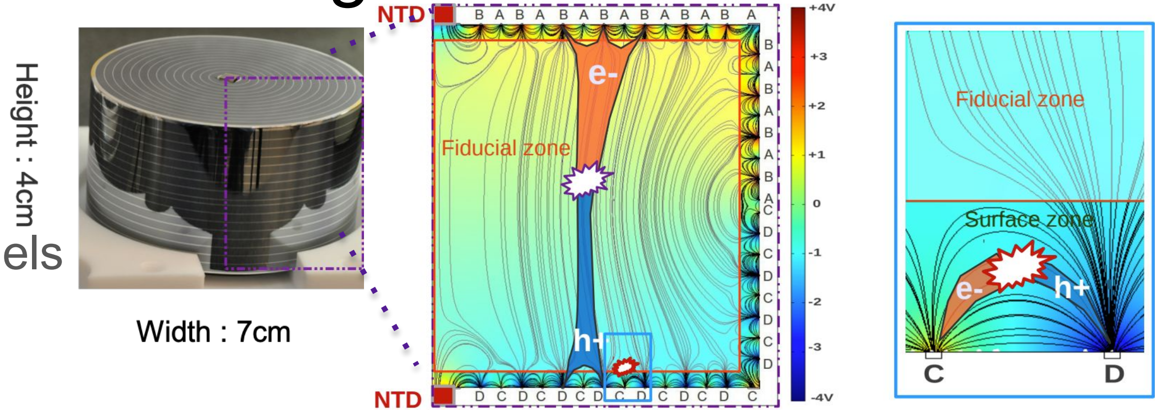




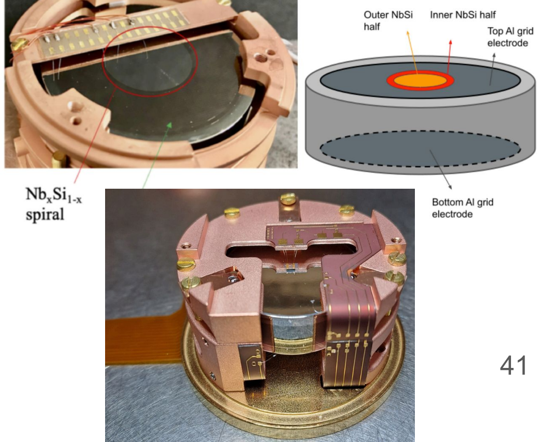
EDELWEISS: NTD/TES + charge

- Fully Inter-Digitized (FID) detector
  - 800 g germanium
  - 2 NTD + 4 charge channels
- NbSi209
  - 200 g germanium
  - 2 TES channel + 2 charge planar electrodes
  - TES vs NTD tests origin of the HO events
  - Charge channels help rejecting HO events
- FID38 & PL38
  - 38 gram germanium detectors, with NTD+charge
  - 30 eVee charge resolutions achieved with cryogenic HEMTs (EPJC 84, 186 (2024))

PRD 97 (2018) 022003



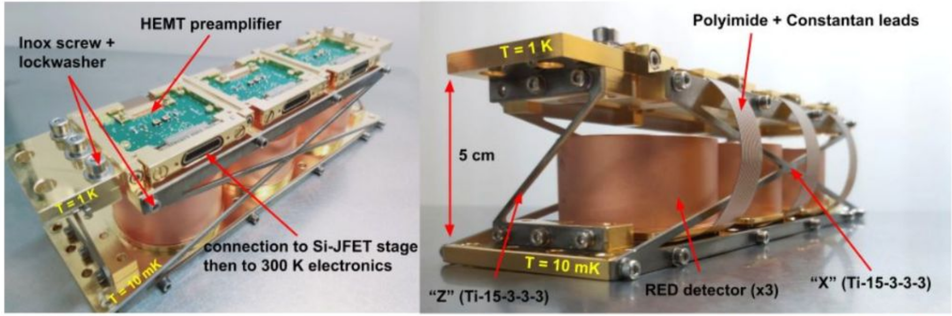
arXiv: 2203.03993



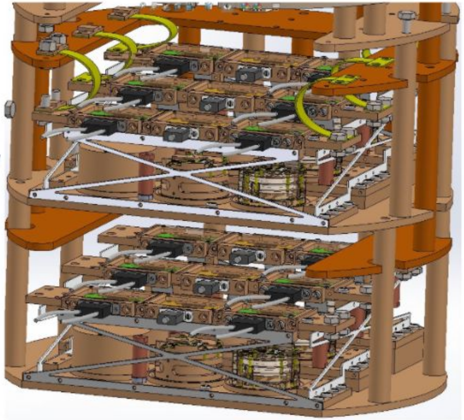
Slide from Nicolas MARTINI, Magnificent CEvNS, 2024

Ricochet CryoCube -- Edelweiss Legacy

MiniCryoCube:
3 Ge bolometers with their cold electronics (1 K)



CryoCube (Spring 2025):
3 MiniCryoCubes per level,
2 levels
→ **Array of 18 x 38 g @ ~10 mK**

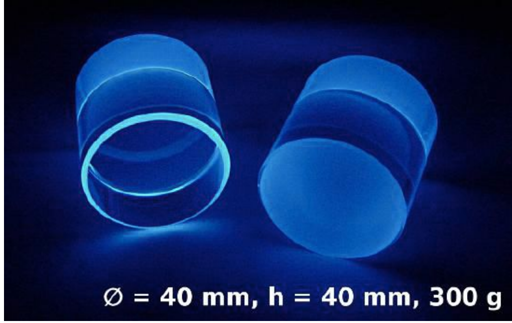


- Heat resolution: **20 eV (RMS)**
- Ionization resolution: **20 eVee (RMS)**
- Timing resolution: **~100 us @ 100 eV**
- Detector payload: **680 g**
- Two detector technologies: **planar and FID electrodes**

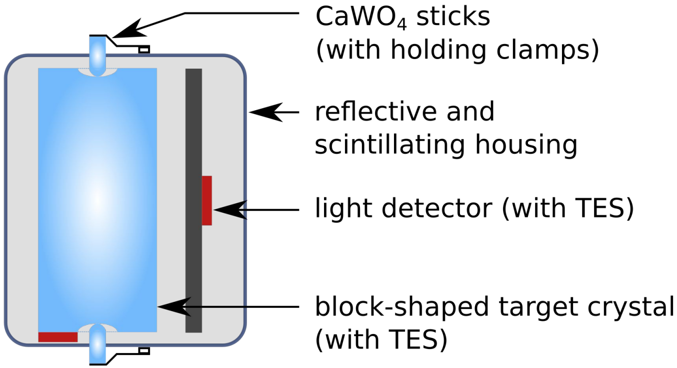
→ Achieve Particle ID down to O(10) eV with a rejection > 10^3

Paper on Ionization performances of the MiniCryoCube:
RICOCHET Coll. EPJC **84** (2024), 186

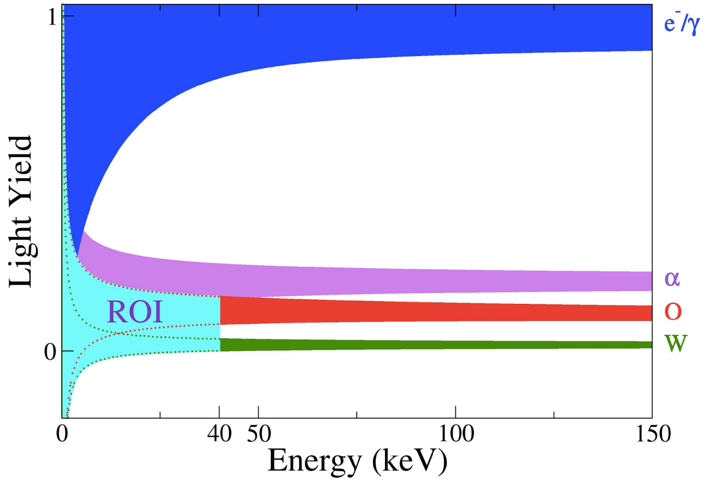
CRESST: TES + Light + Active Veto



- $CaWO_4$ scintillating crystals, with phonon + light readout
- Mechanical structure instrumented with active sensors as well
- 300 g in CREST II → 24g crystal in CRESST III
  - 4.6 eV resolution

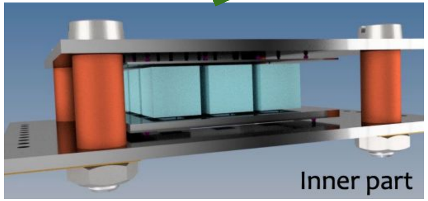


J. Phys.: Conf. Ser. 1342 012076

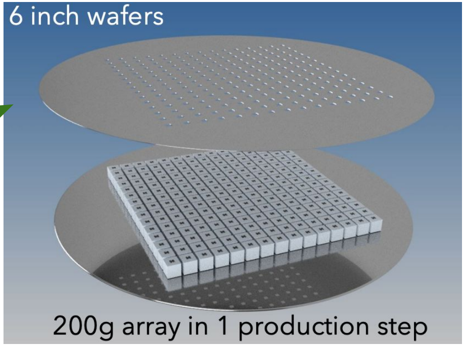


NUCLEUS: TES + Active Veto

- 1 gram crystal, read out with TES
  - 3.7 eV resolution
- Outer detector provides active veto

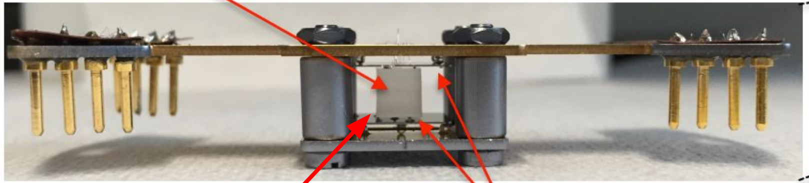


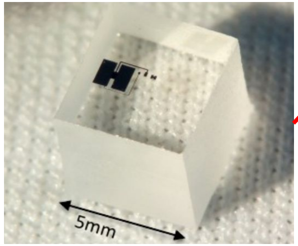
Further up



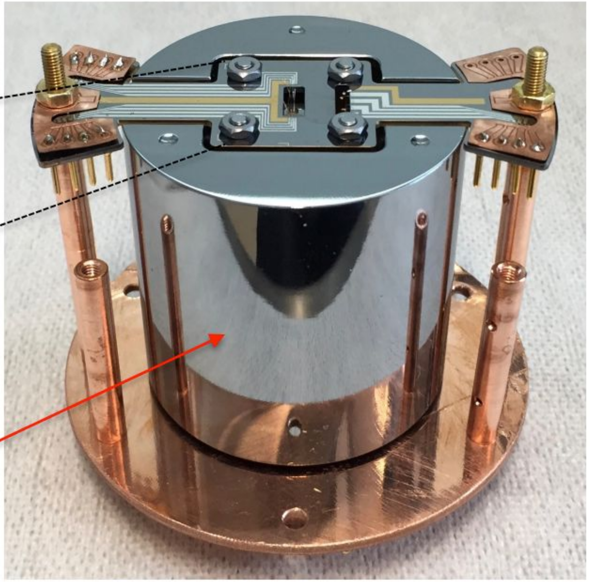
Scale up

Target (Al_2O_3, $CaWO_4$, Si, Ge, ...)





Inner veto (Si)



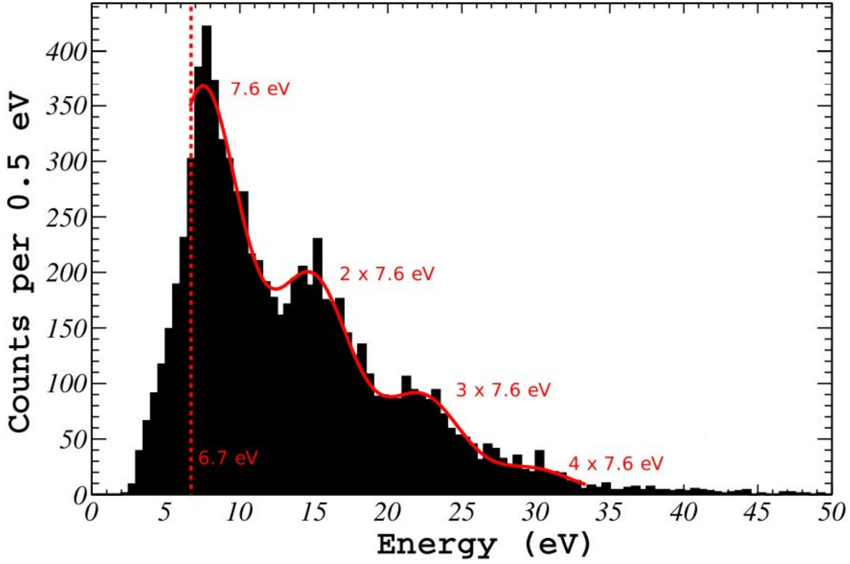
Outer veto (Ge, $LiWO_4$)

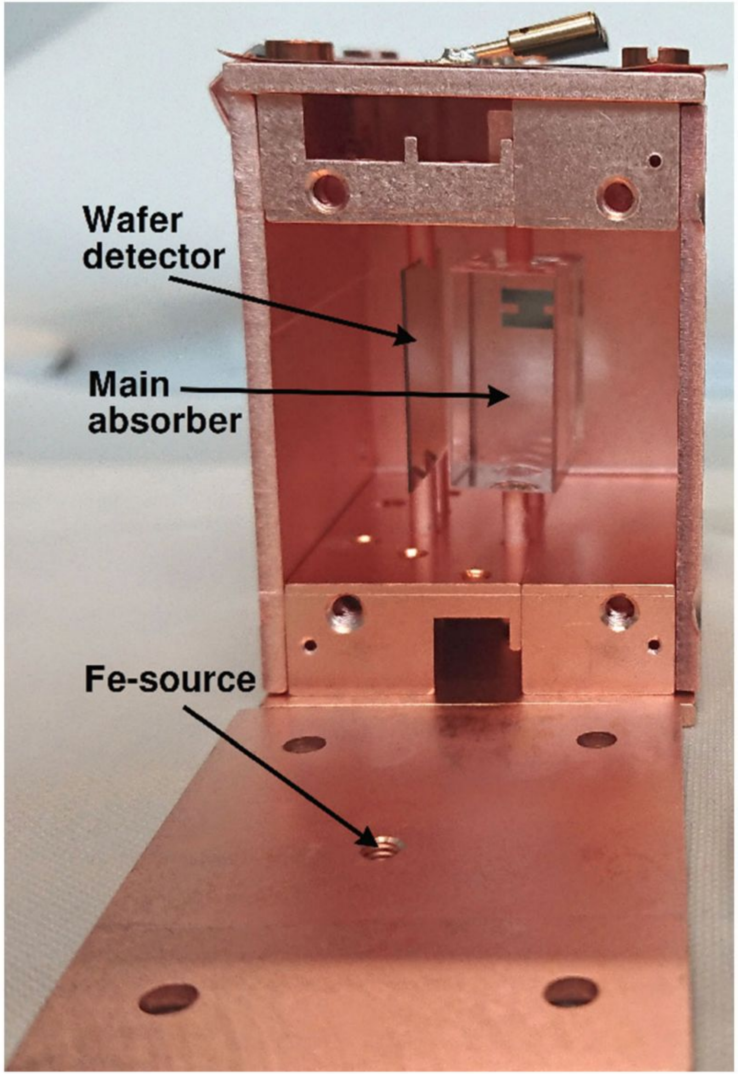
Fig. from R. Strauss, m7s 2019
PRD 96, 022009 (2017)

BASKET@CEA

Latest CRESST detector

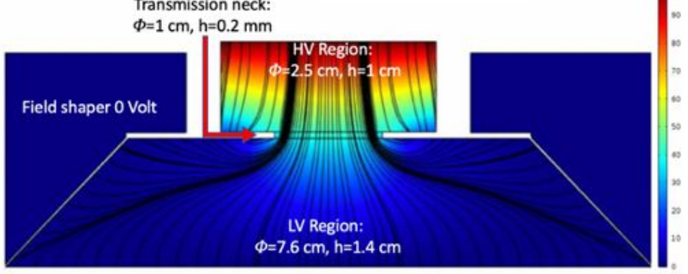
- Sapphire main absorber
- Silicon-on-sapphire (SOS) wafer detector
- 1 eV resolution achieved with SOS

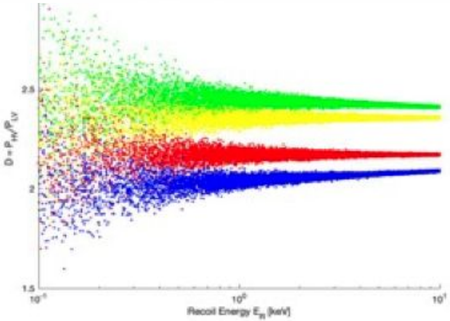




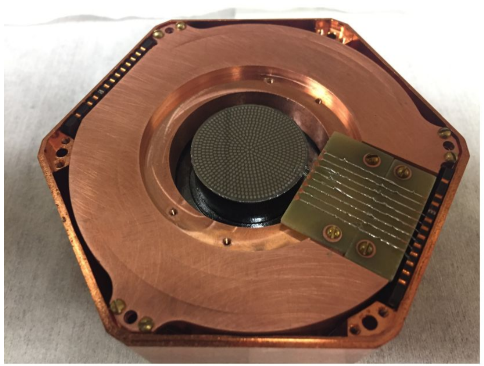
MINER: Hybrid Phonon detector

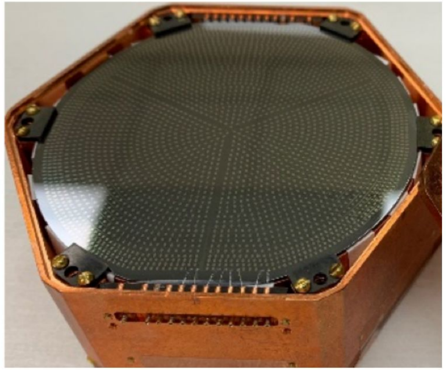
NIM A 2022.166707



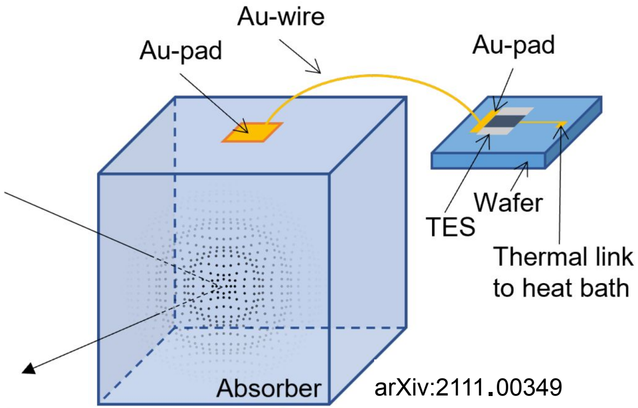


- Separate crystal into a low-voltage (LV) and a high-voltage (HV) region
- Phonon sensors on both sides
- Use the LV region as the fiducial volume
- Shape E-field to guide charges through the “neck”
- NTL phonons from the charges dominates in the HV side, whereas recoil phonons dominate the LV side
- E_{HV}~ charge measurement
  E_{LV} ~ recoil phonon measurement

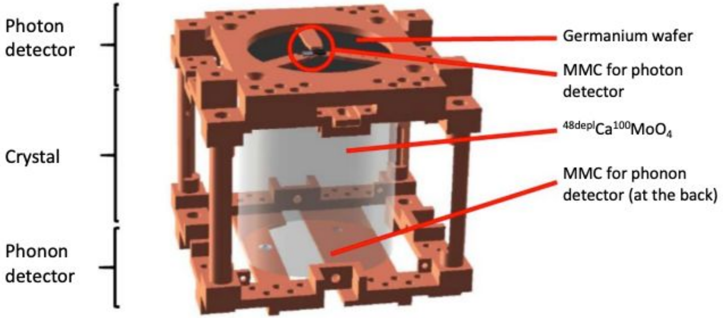




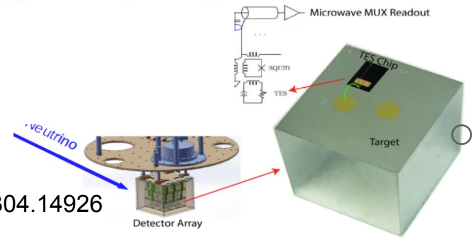
Modular design: detaching thermometer from absorber



arXiv:2111.00349



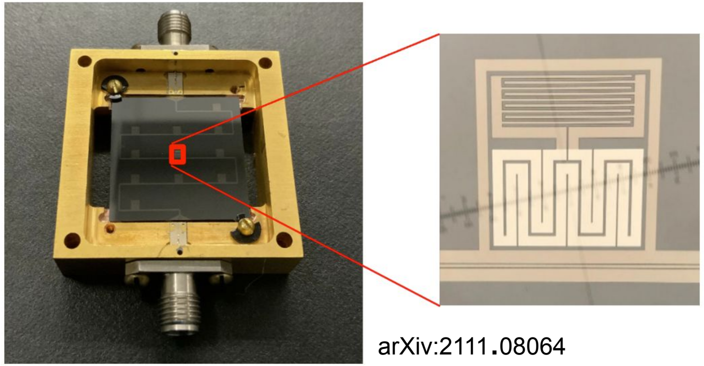
arXiv:1903.09483



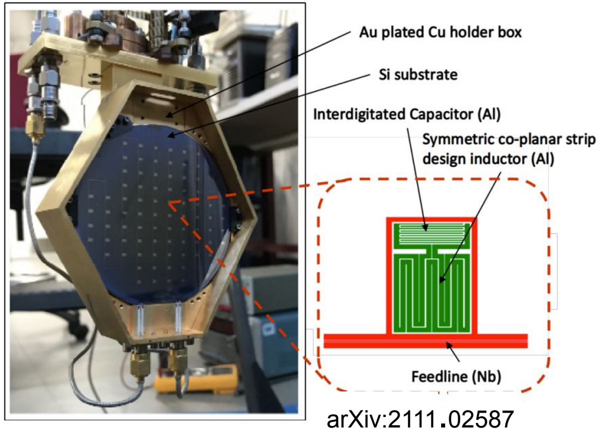
arXiv:2304.14926

- Decoupling thermometer from crystals for ease of fabrication
- Thermal conduction facilitated by a gold wirebond
- Can be coupled to a variety of target materials
- Multiple applications:
  - RemoTES from COSINUS achieved <100 eV resolution with a 2-gram target
  - TES-based Ricochet Qarray for CEvNS achieved 40 eV resolution with 1-gram target
  - MMC based AMORE detector for $0\nu\beta\beta$

Multiplexing with RF resonators



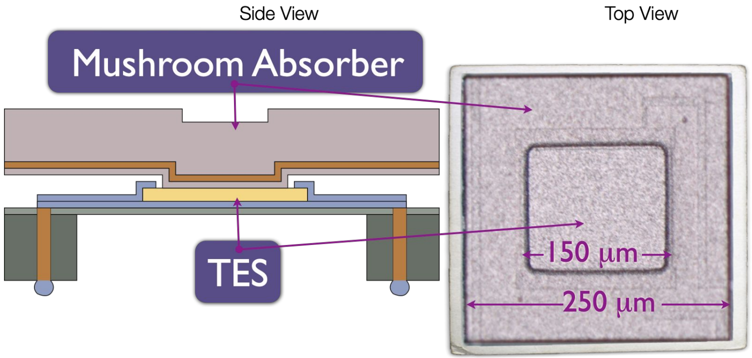
arXiv:2111.08064



arXiv:2111.02587

- Significant improvement has been made on mKIDs recently
- 6 eV resolution for energy deposited in resonator demonstrated
  - Translates to a few tens of eV of resolution for energy deposited in the crystal
- Also with intrinsic capability of multiplexing
  → Promising candidates for next generation rare-event experiments

Cryogenic detector in Astrophysics and Indirect searches



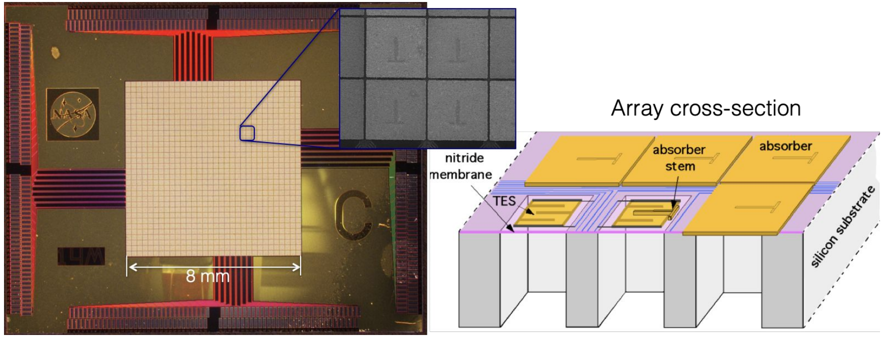


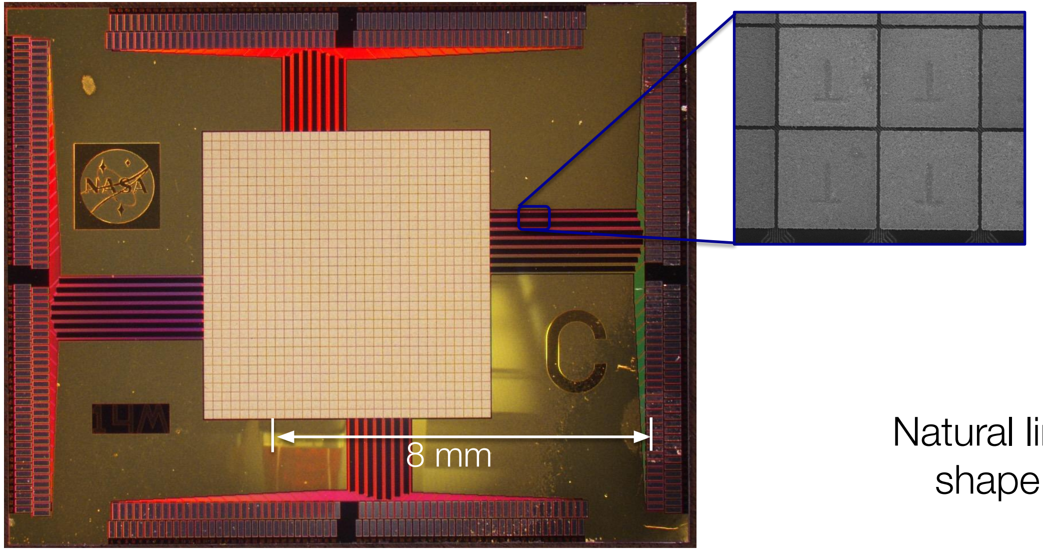
Fig. from E. Figueroa, COFI PIRE 20017

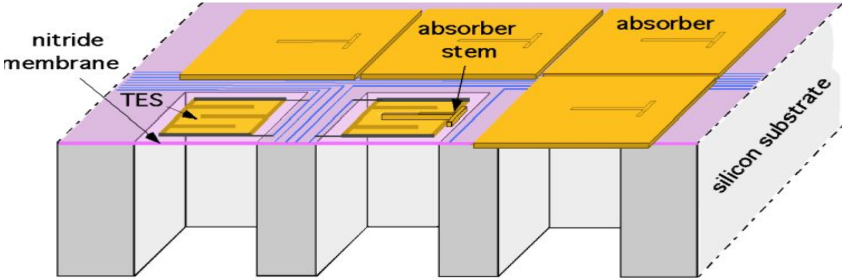
- Cryogenic microcalorimeters also contributes in DM studies in astrophysics and indirect searches
- Arrays of eV-resolution sensors make perfect X-ray detectors
  - Like an ultra-sensitive camera
- Widely used in earth-based X-ray telescopes as well as rocket and satellite-based detectors

Transition-edge sensor arrays

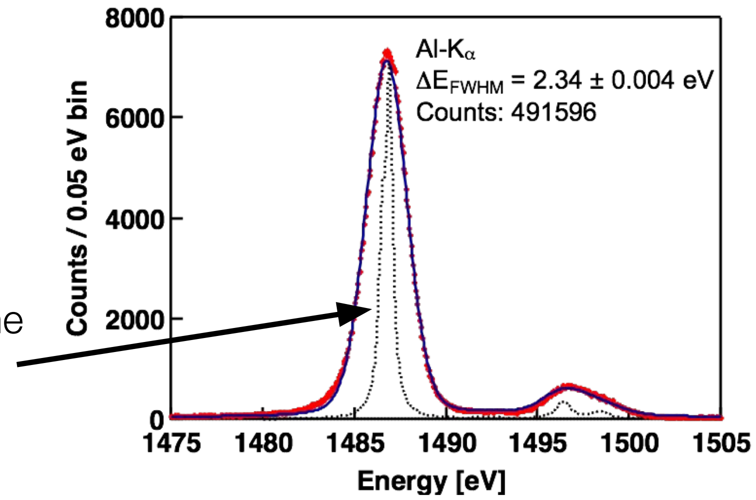
- NASA Goddard Space Flight Center TES Arrays

Fully wired 32x32 array (8x8 mm^2) with
64 pixels connected to bond pads on each side





Natural line shape



Conclusions

- Cryogenic detectors play an important role in dark matter search
  - Both in direct search and in indirect and astro approaches
- Resistance-based phonon detectors (TES and NTD) are approaching an eV-resolution regime
  - Also exploiting techniques including quasi-particle traps and internal amplifications via NTL effect
- Alternative sensing mechanisms (MMC and mKIDs) are advancing as well
  - Promising candidates for next-generation DM search detectors
- Information with phonon + charge, phonon + light, or with layered detector structure can help with particle identifications
- Stay tuned for more results -- the discovery might be around the corner