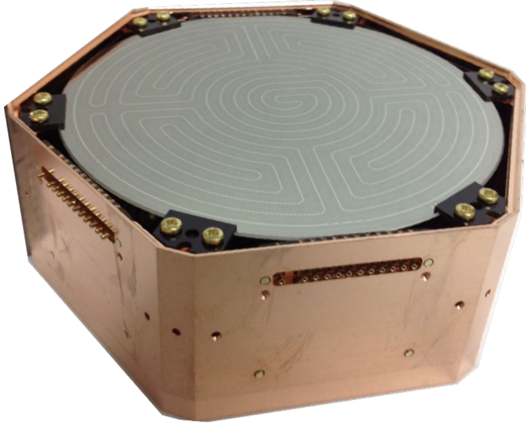
Cryogenic Solid-State Detectors

for Dark Matter Searches and beyond

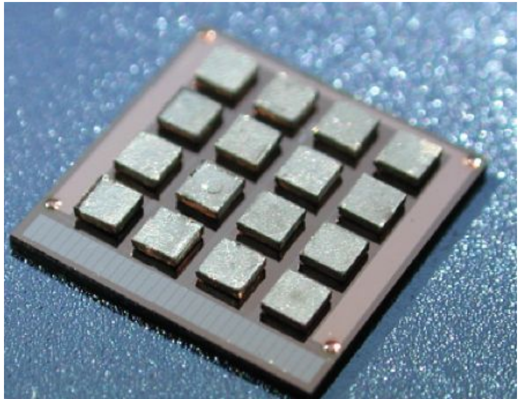
Ziqing Hong, University of Toronto

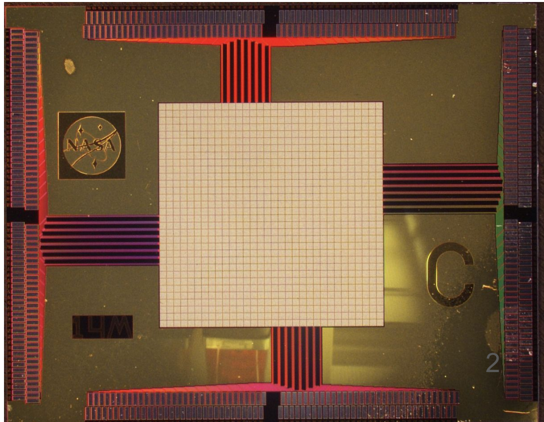
33rd Rencontres de Blois on "Exploring the Dark Universe"

Cryogenic Crystal Detectors are used in



- Particle Physics
  - Dark Matter Detectors
  - Neutrino Physics
    - Coherent Elastic Neutrino Nucleus Scattering (CEvNS) and neutrinoless double-beta decay (0νββ)
- Astrophysics
  - mm to gamma-ray energies

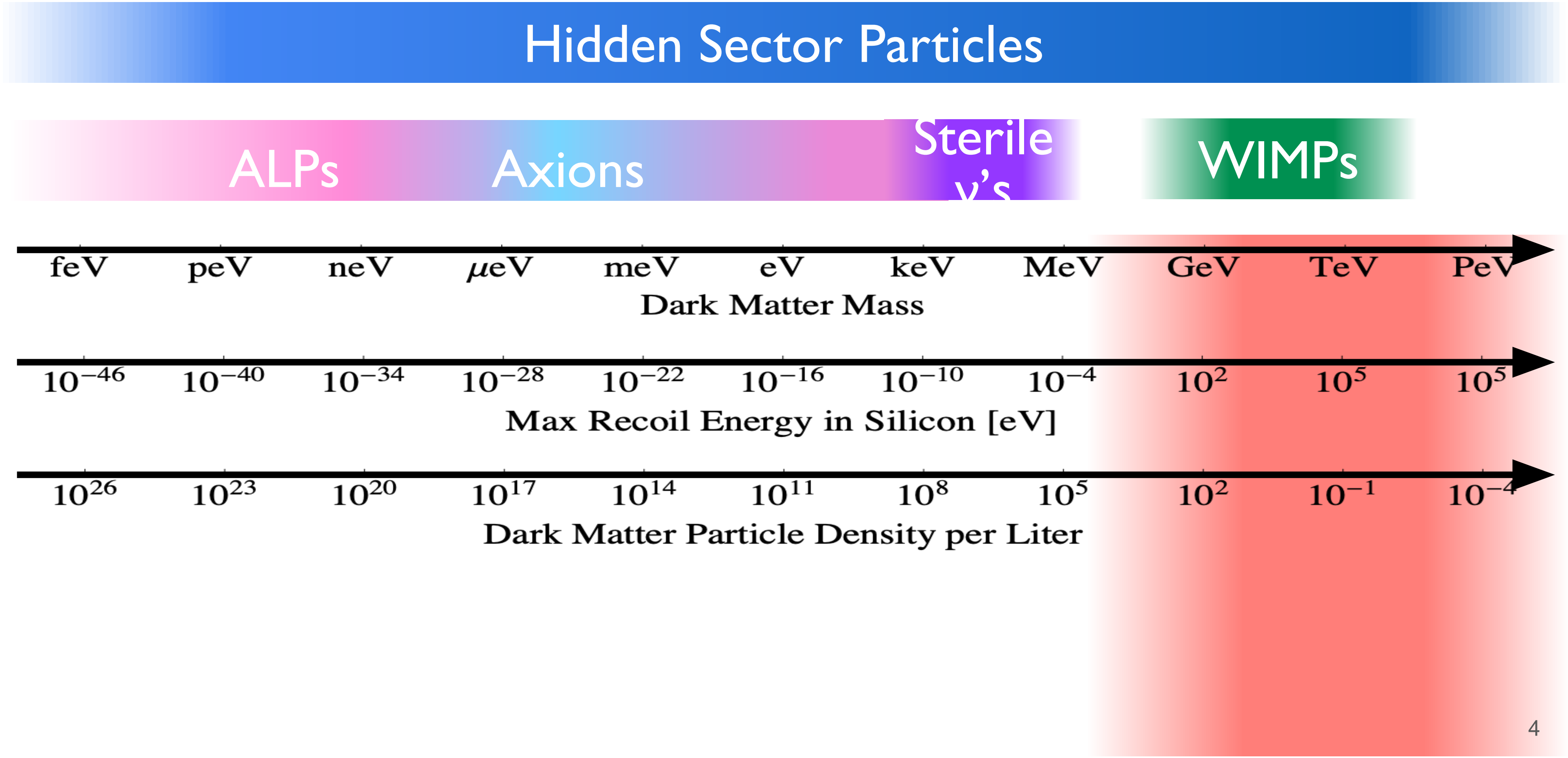




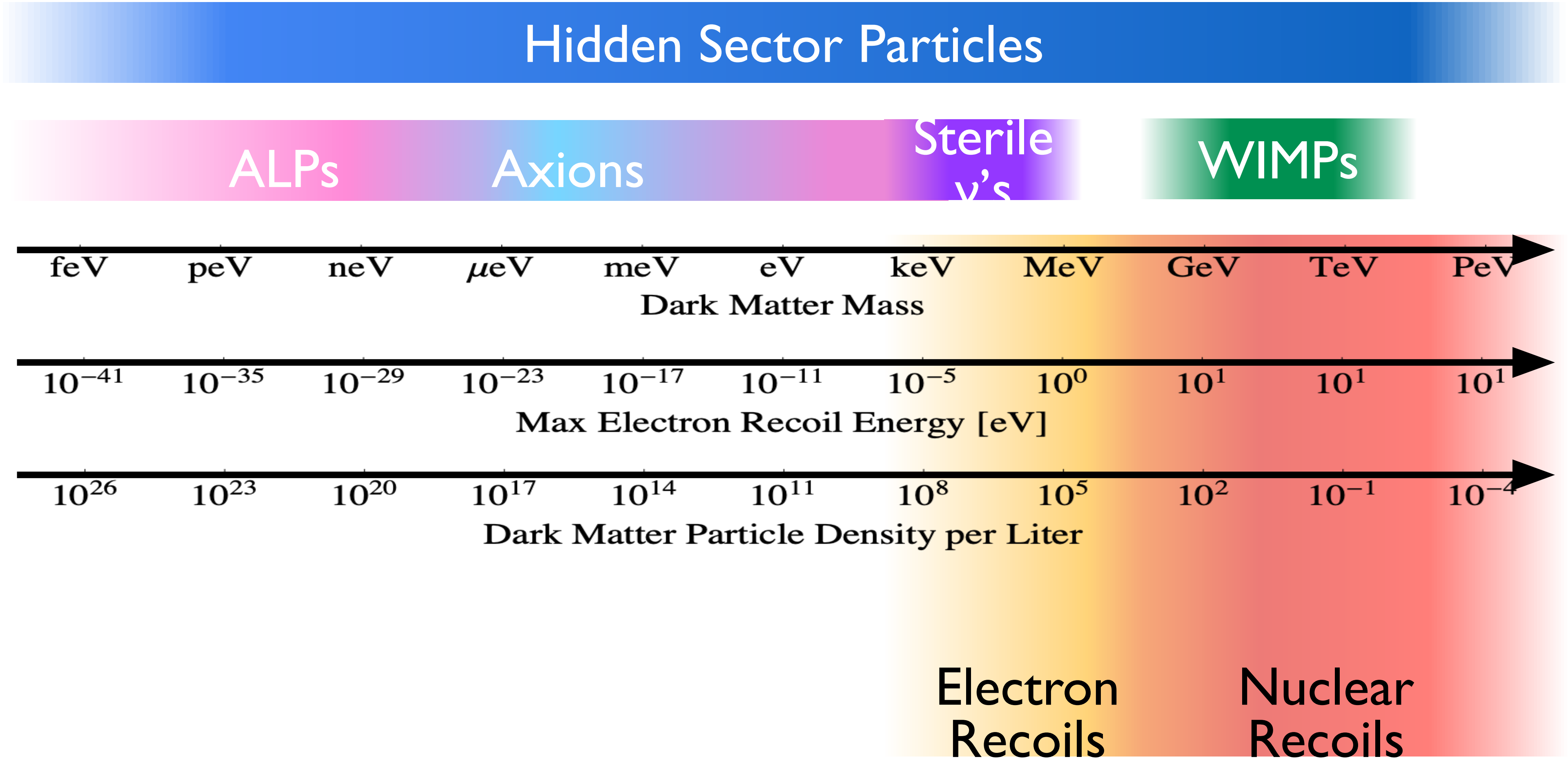
Disclaimer

- This is my personal biased view focusing on 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

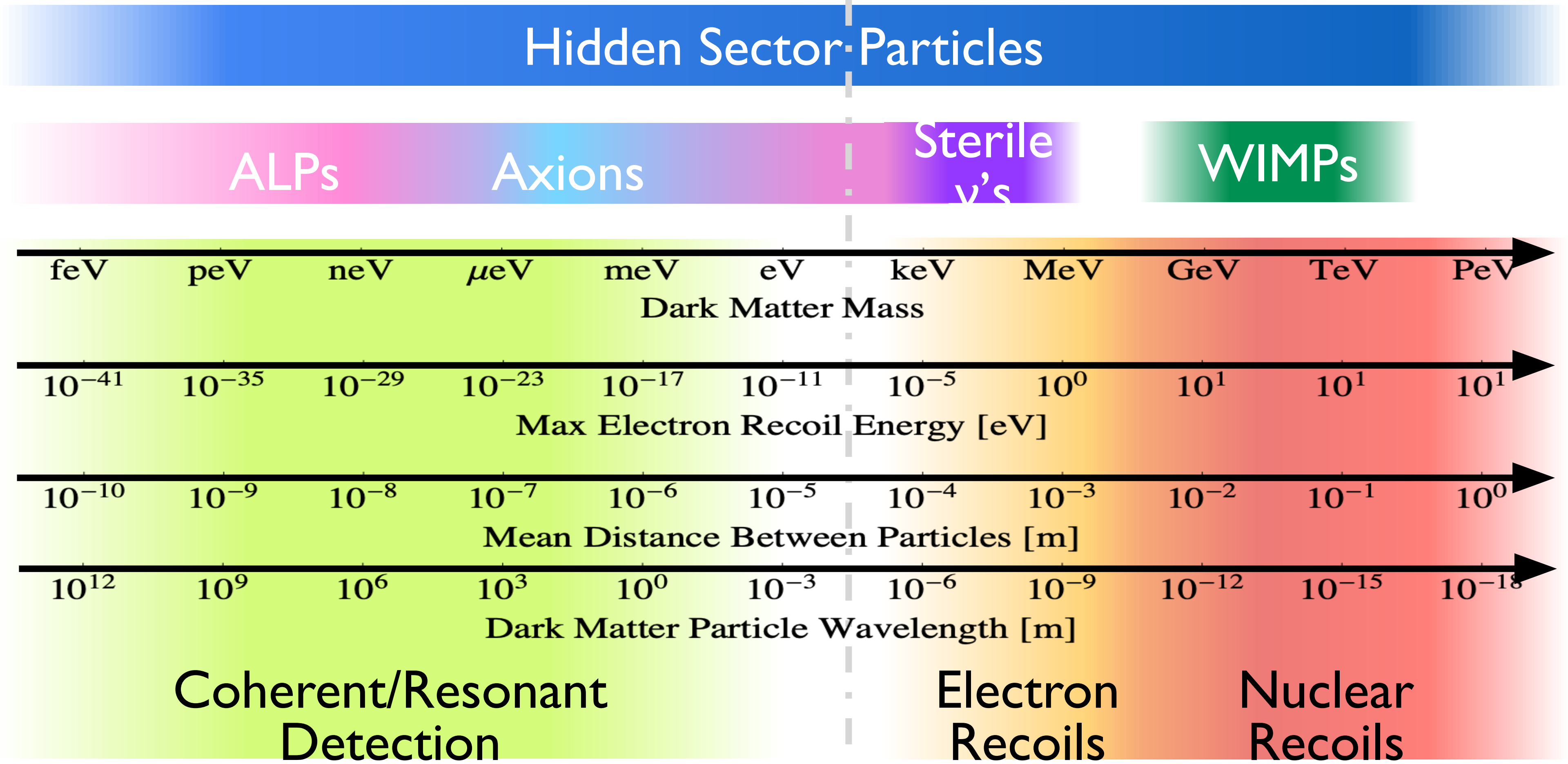
Dark Matter Detection Channels



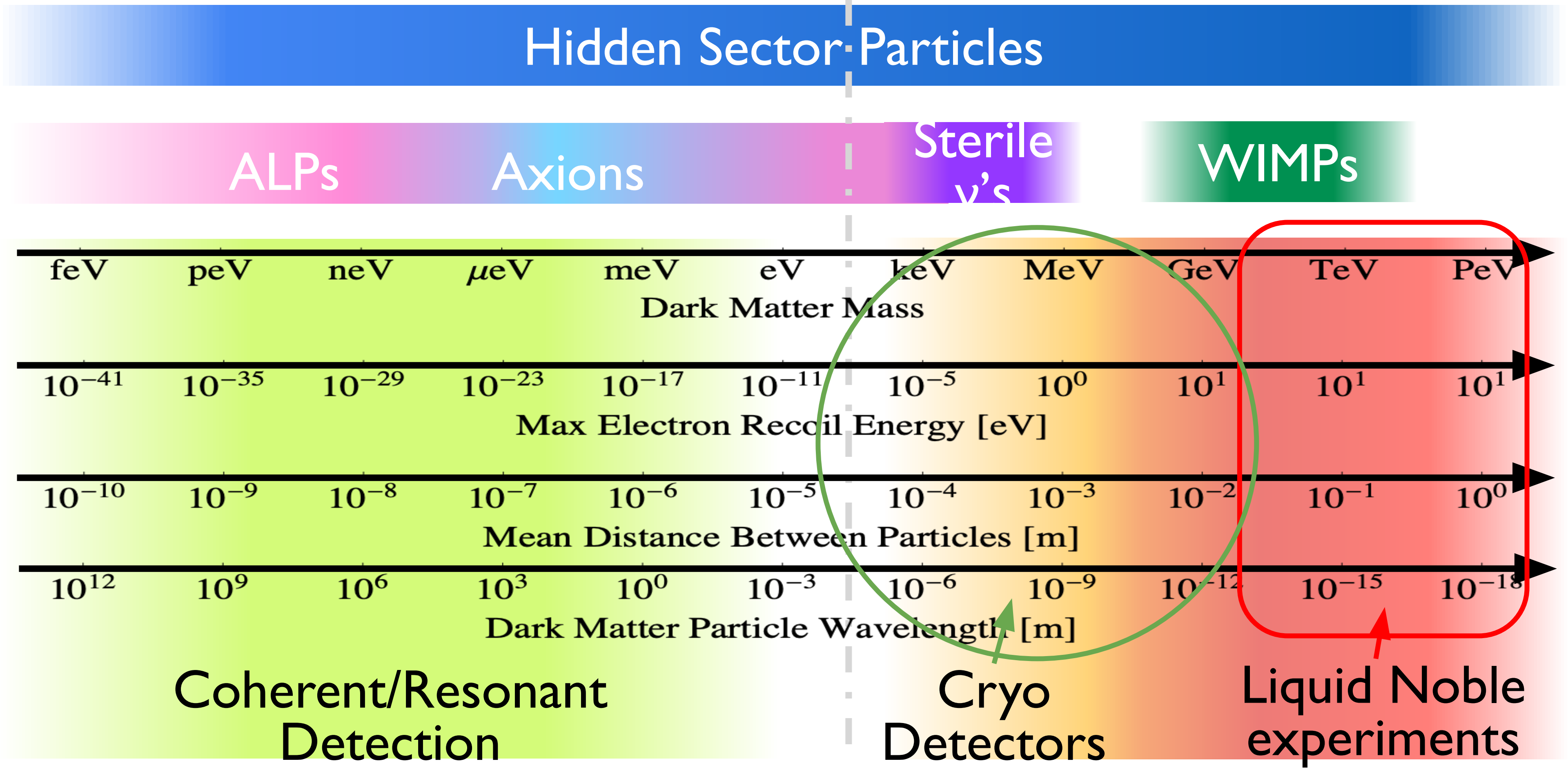
Dark Matter Detection Channels



Dark Matter Detection Channels

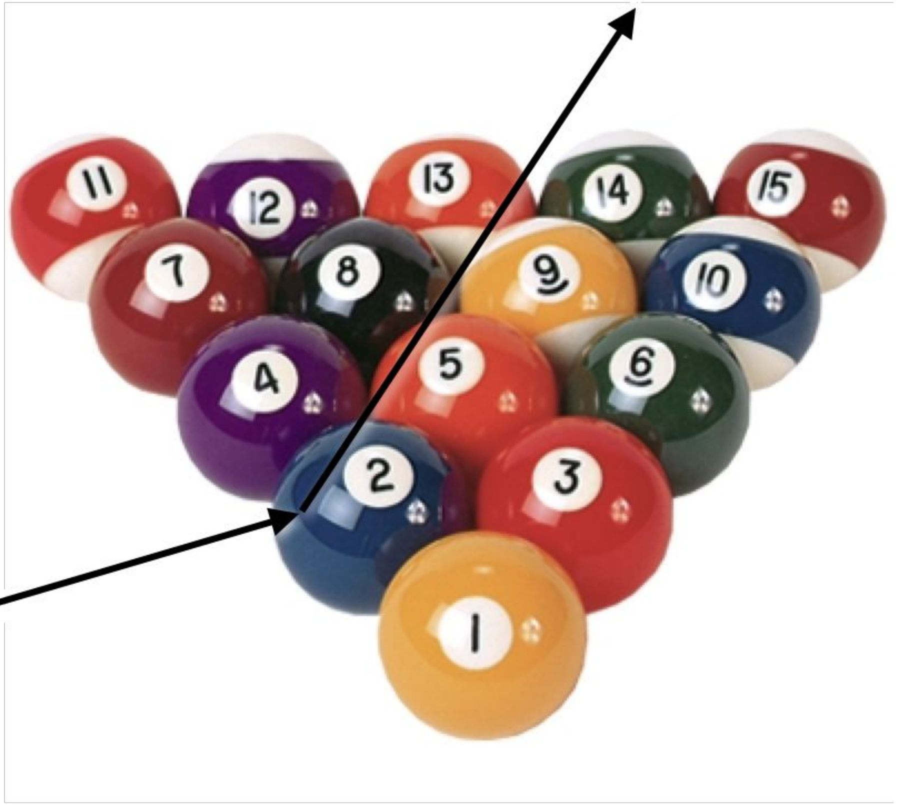


Dark Matter Detection Channels



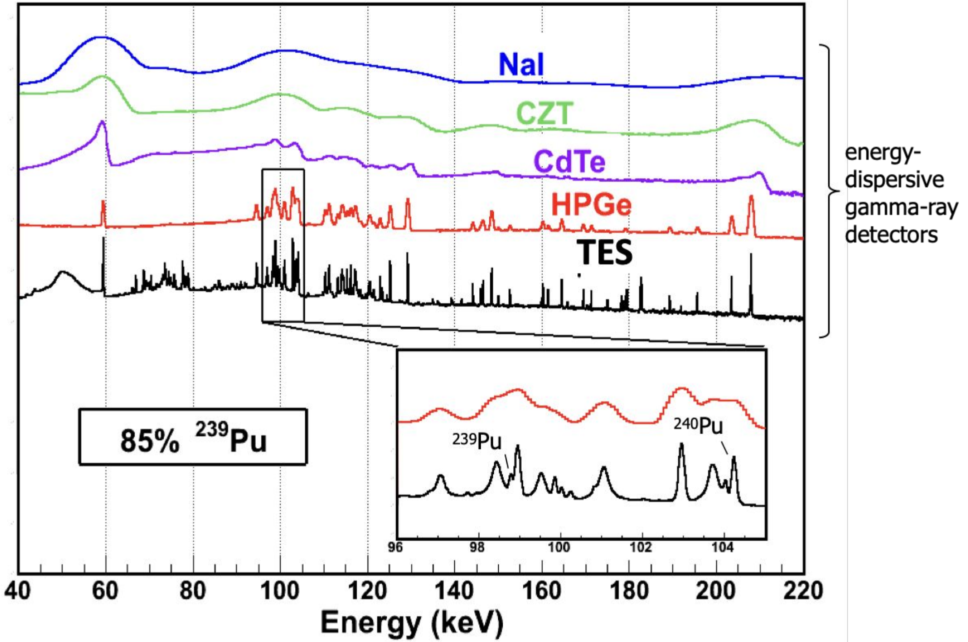
Dark matter direct detection

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



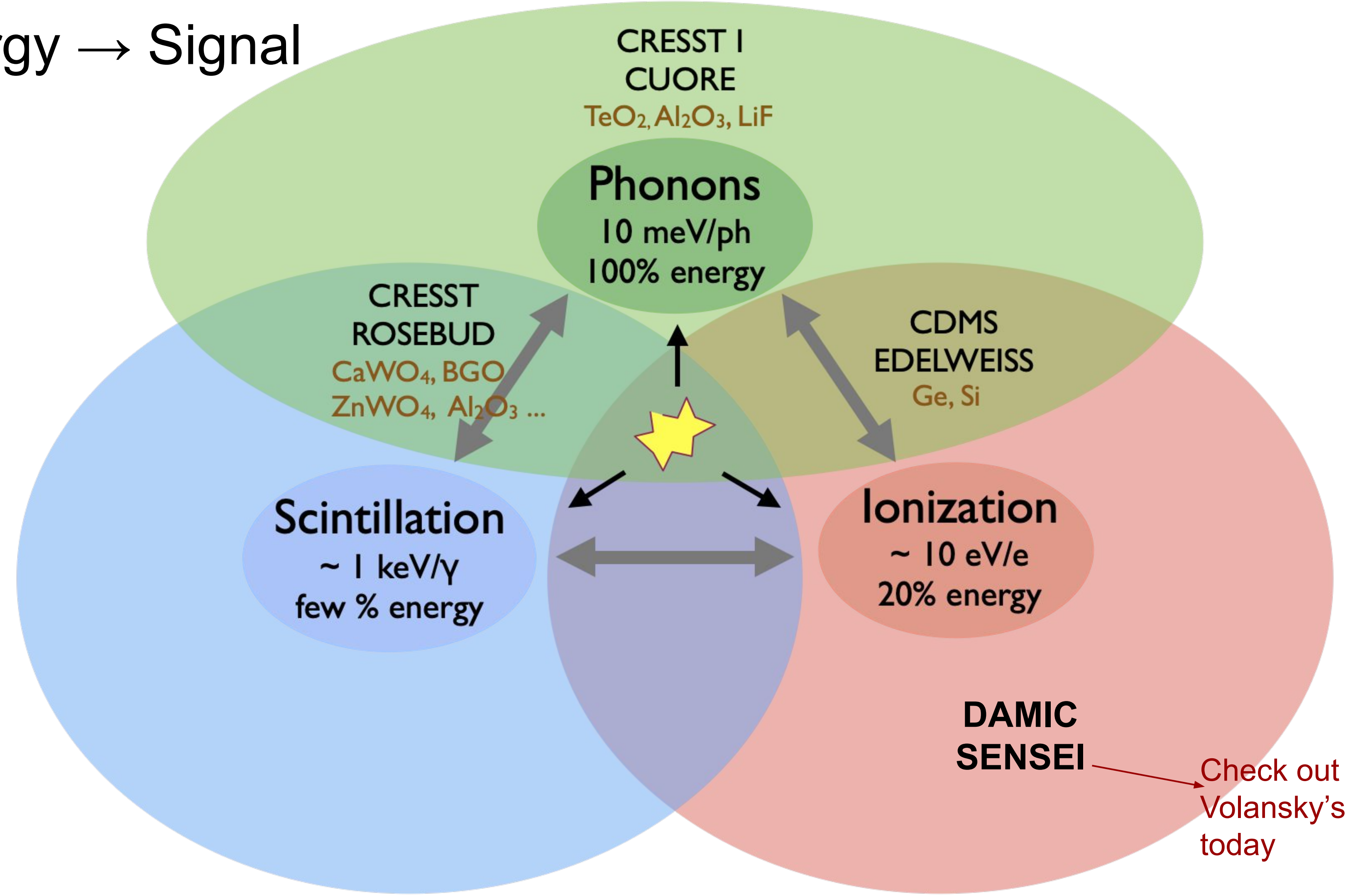
Why Use Cryogenic Crystal Detectors?

- 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



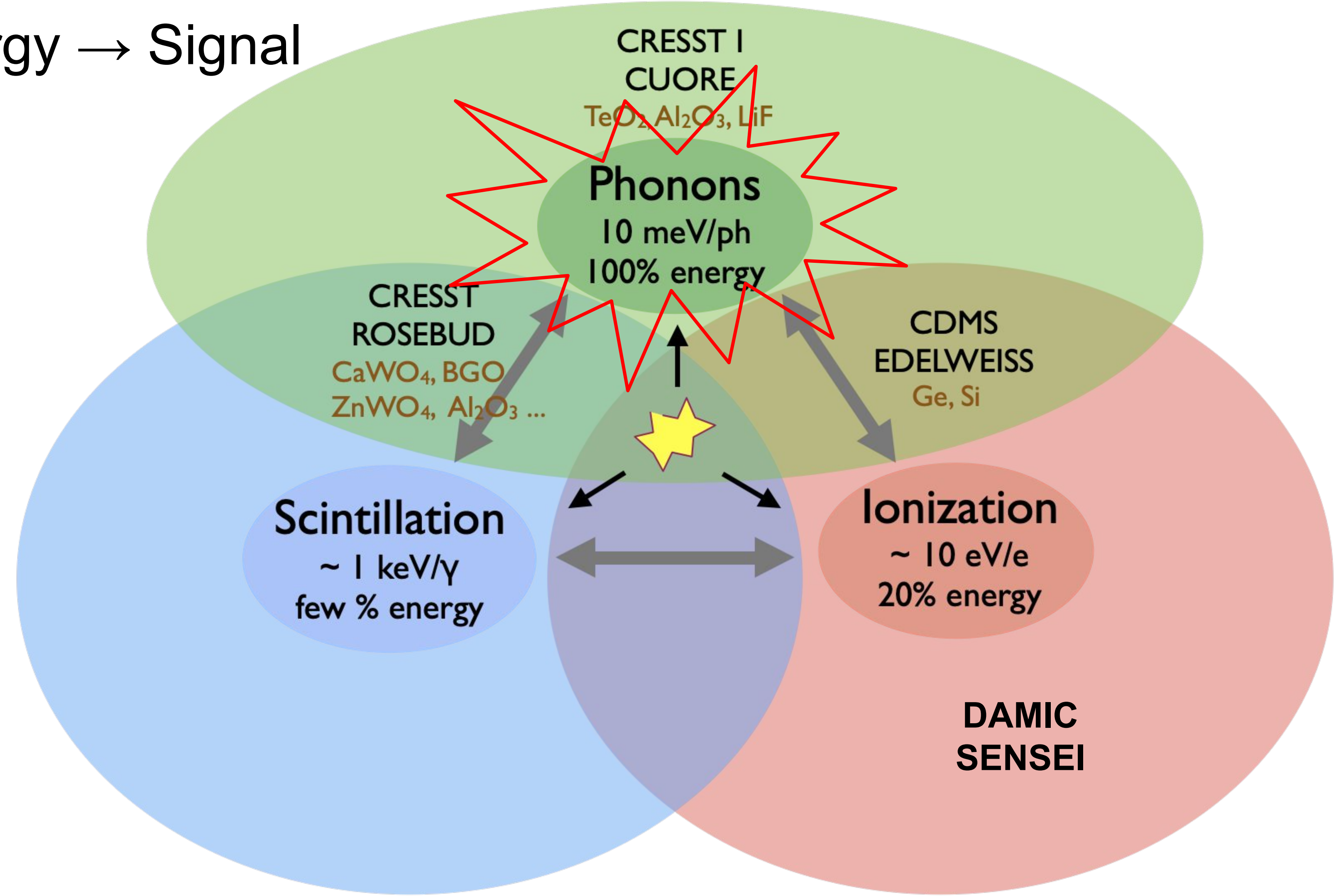
- Well matched to DM detection requirements
- CEvNS and 0νββ experiments share the same needs, thus cryogenic detectors are often developed by these fields jointly

Energy → Signal

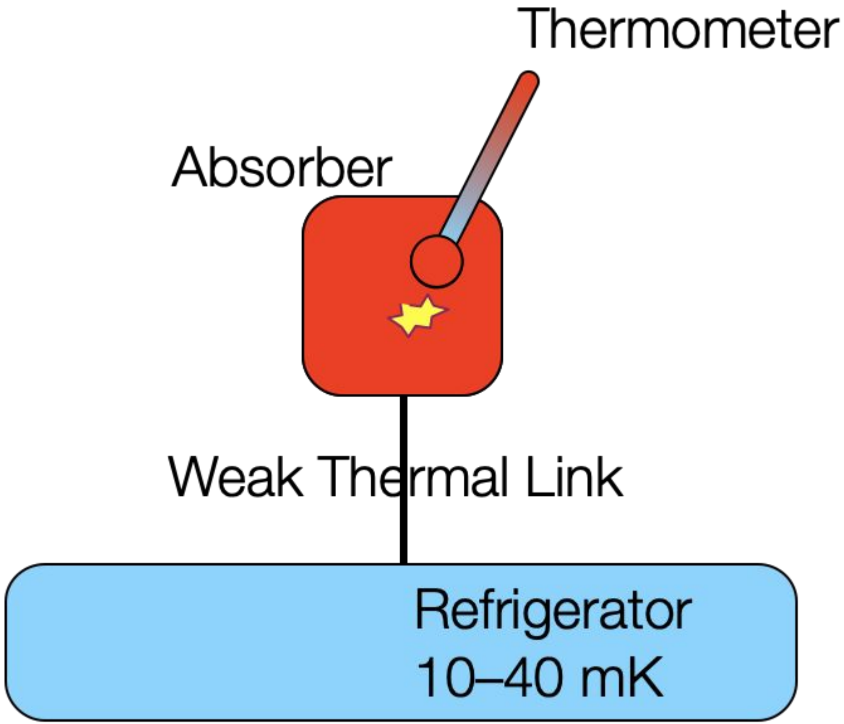


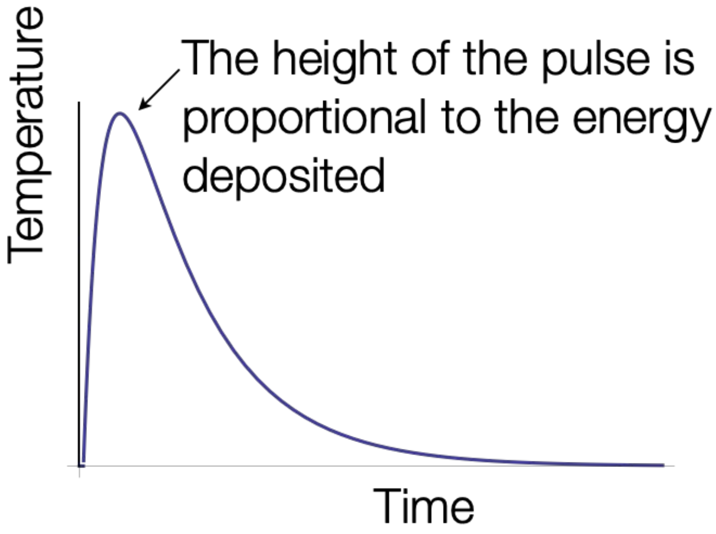
Check out Tomer Volansky's talk later today

Energy → Signal



Cryogenic Phonon Detectors





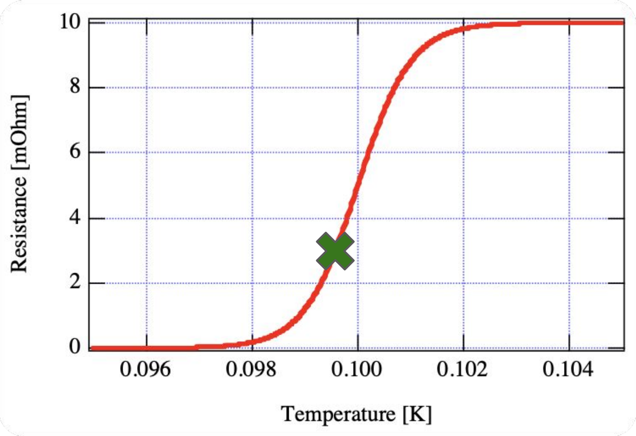
Everybody has their choice of the favourite thermometer!

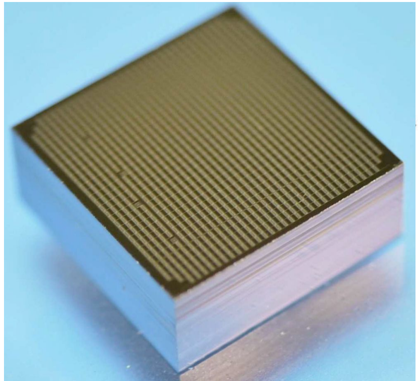
Thermometer #1

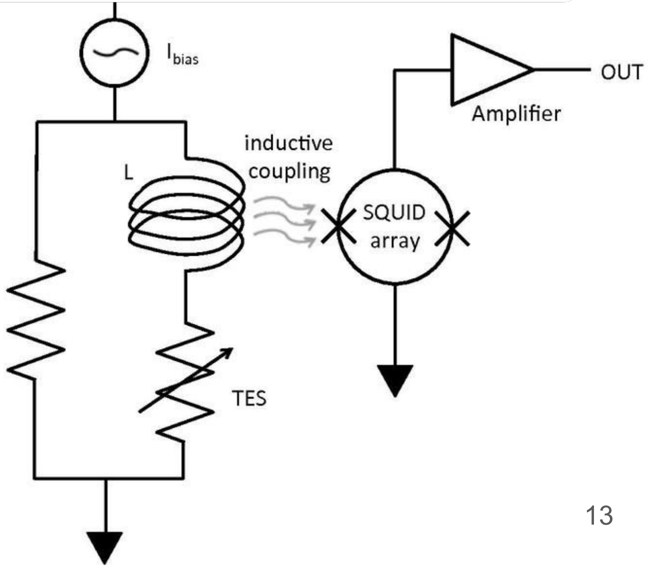
Transition Edge Sensor

- 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

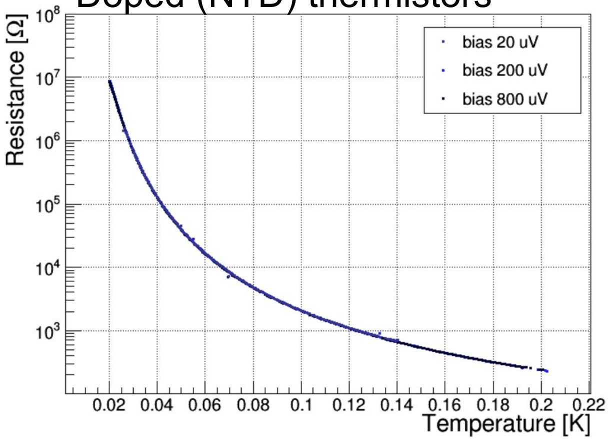
Neutron Transmutation Doped (NTD) thermistors

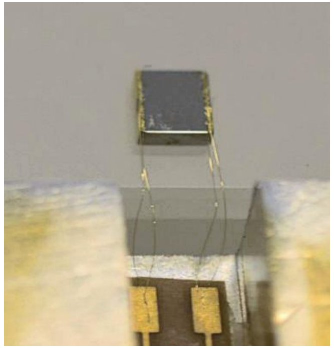
- Doped germanium/silicon chips
- Resistance follows Efros-Shklovskii law:

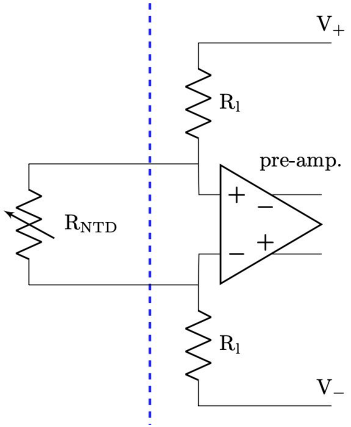
$$R = R_0 e^{\sqrt{T_0/T}}$$

- 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

Neutron Transmutation Doped (NTD) thermistors







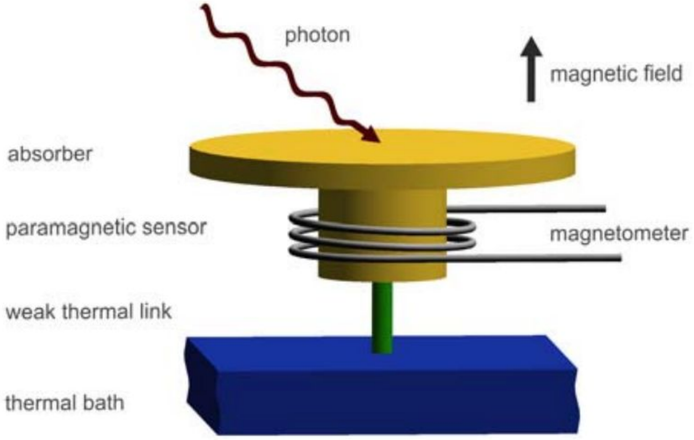
Figures from V. Novati

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)

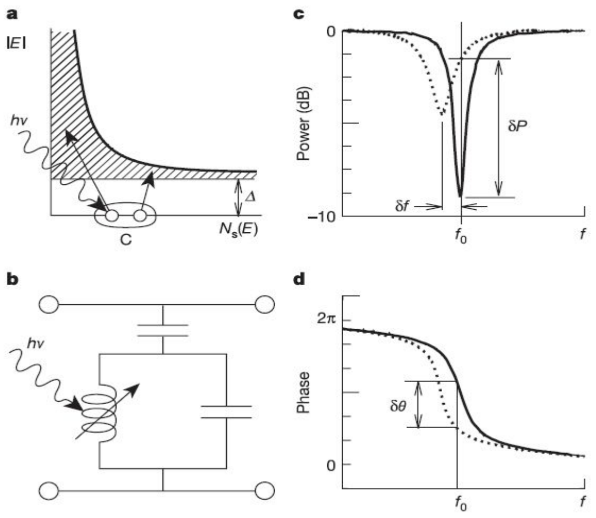


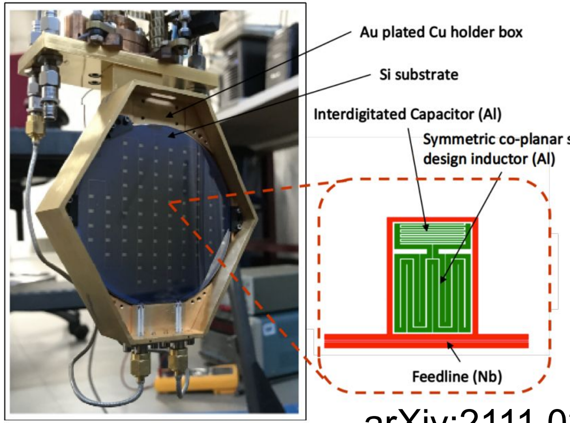
TASC.2009.2012724

Thermometer #4

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

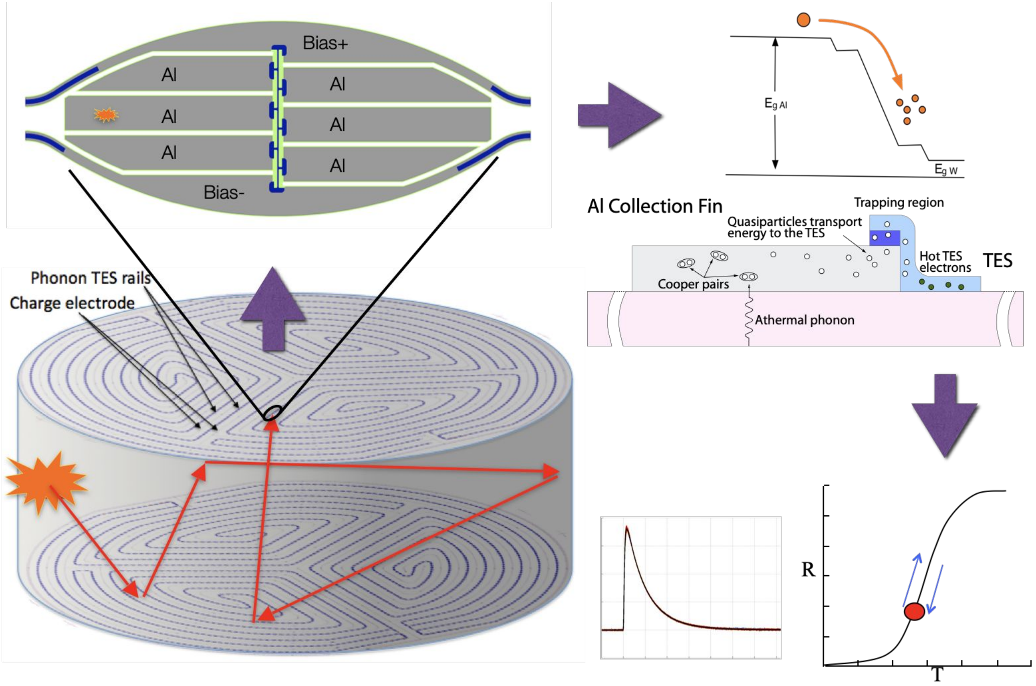




arXiv:2111.02587

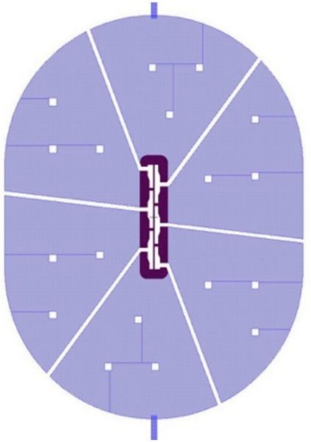
Funneling Energy to the Phonon Sensors (QETs)

- 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)

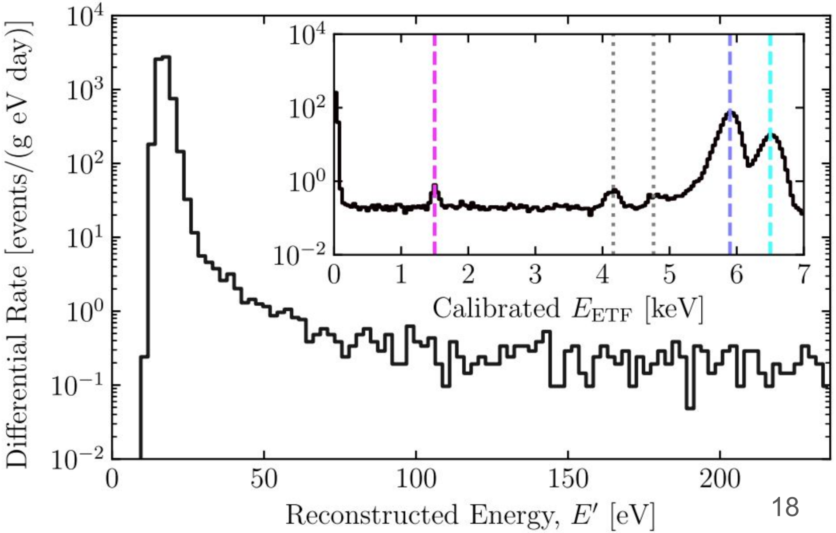


Cryogenic PhotonDetector (CPD)

- 10 gram, silicon, QET-based
- One channel construction, easy to operate
- 3.9 eV phonon resolution
- Works great in both sensing photons and DM direct detection
- Future development by TESSERACT collaboration
  - See D. Mckinsey's presentation on Wed.



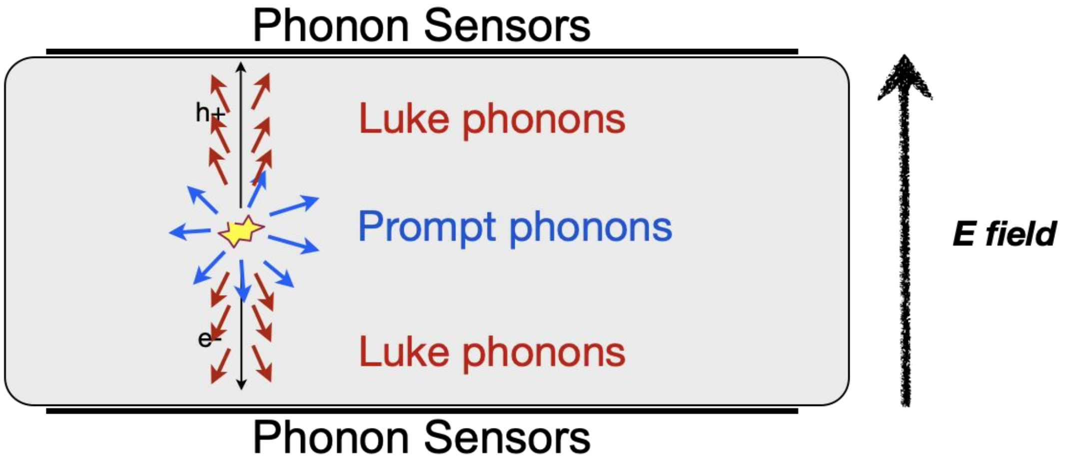
APL 118, 022601 (2021)



PRL 127, 061801 (2021)

Internal amplification - the NTL effect

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

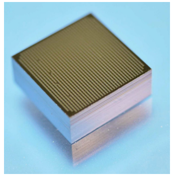


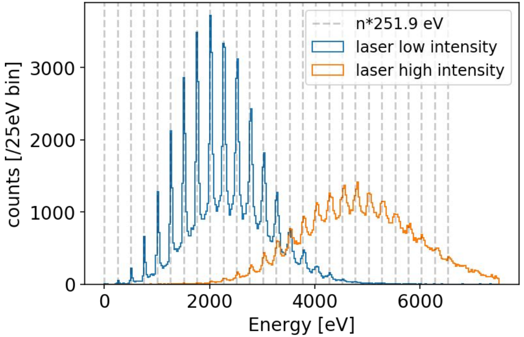
$$\text{Phonon energy} = E_{recoil} + E_{Luke}$$
$$= E_{recoil} + n_{eh}\, e^{-}\, \Delta V$$

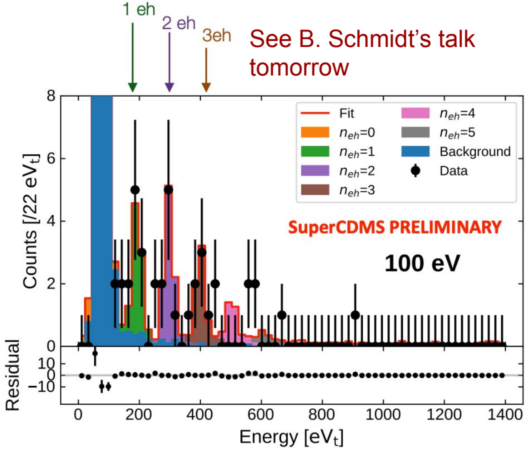
SuperCDMS High Voltage eV sensitivity Detector (HVeV)

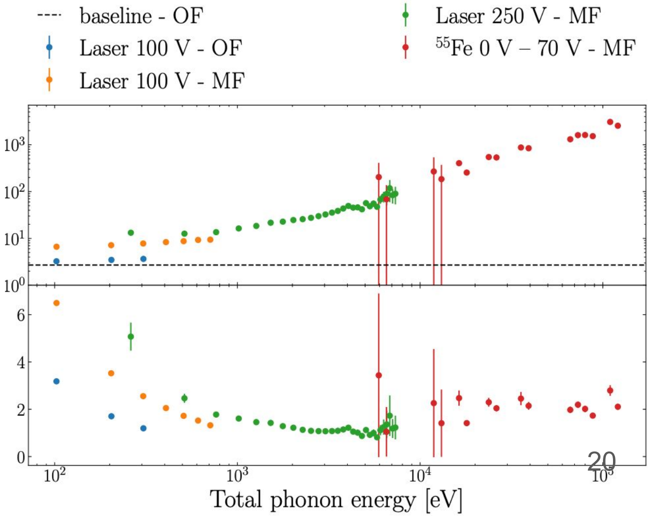
PRD 104, 032010 (2021)

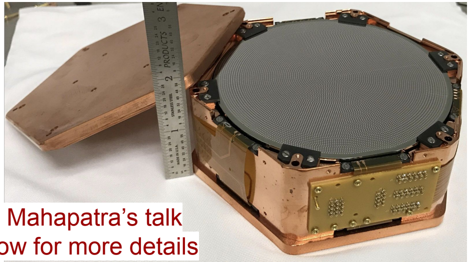
- 1 gram, silicon, QET-based, 2.7 eV resolution
- Can apply O(100 V) for NTL boost
  or operate at 0 V as pure phonon sensors
  - Particle identification by statistics
- Quantized electron-hole pair sensitivity for both ER and NR
- Scaling it up to 1 kg
  SuperCDMS HV detector







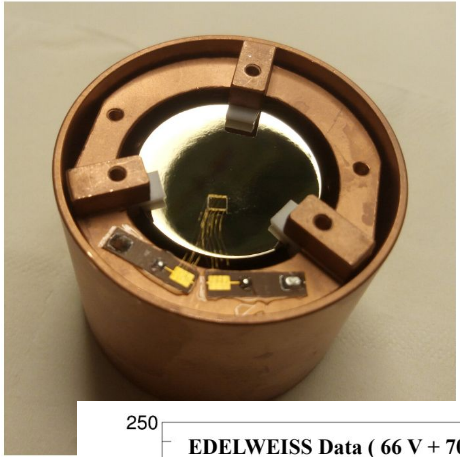


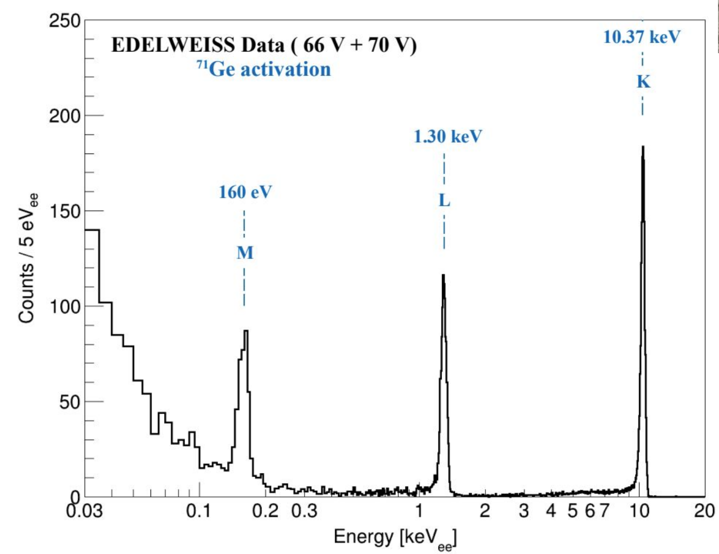


See R. Mahapatra's talk tomorrow for more details

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
- See E. Guy's presentation on Wed.





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

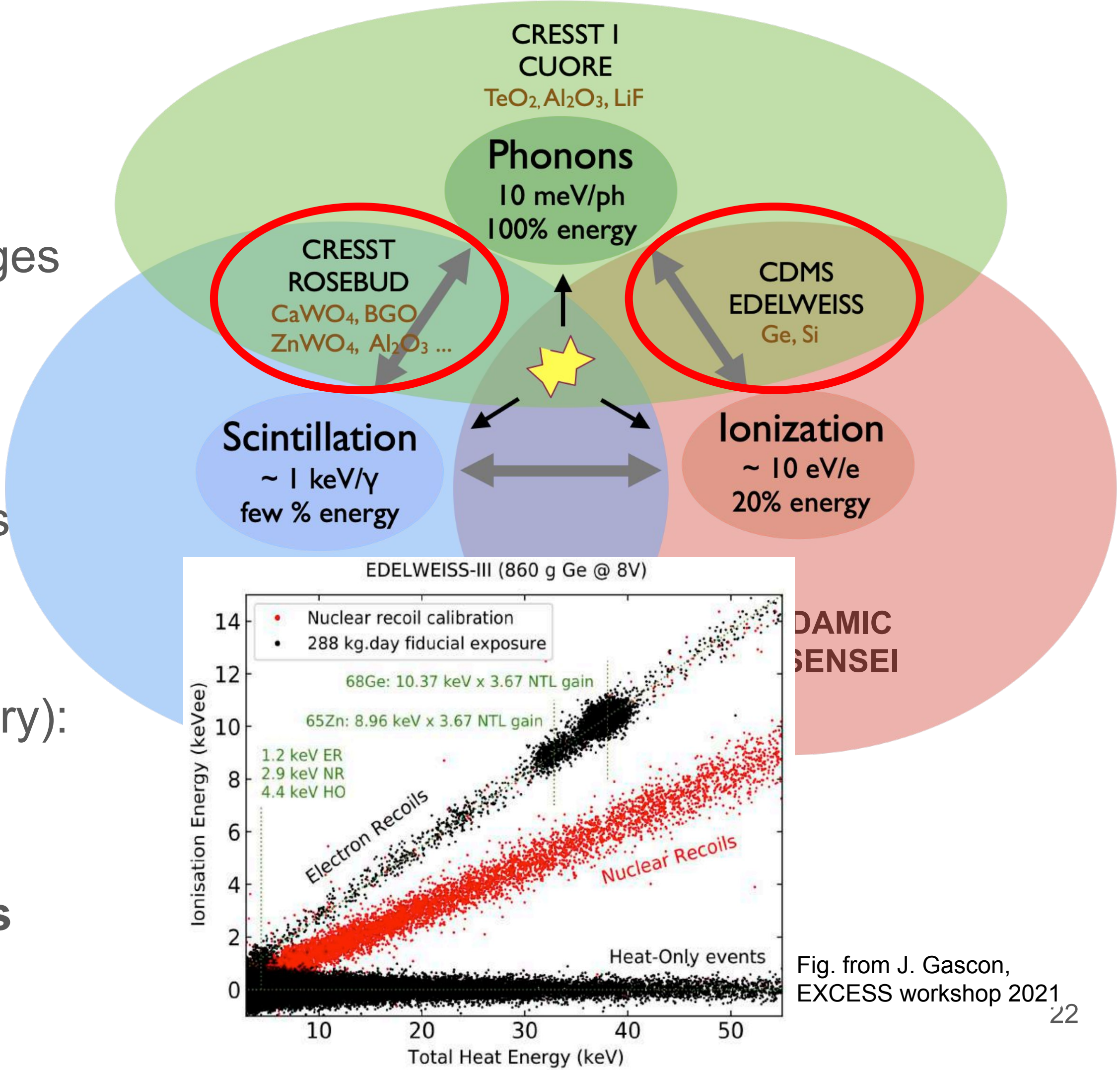
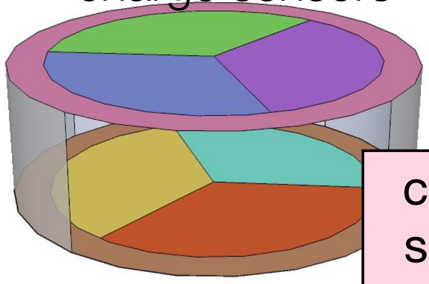
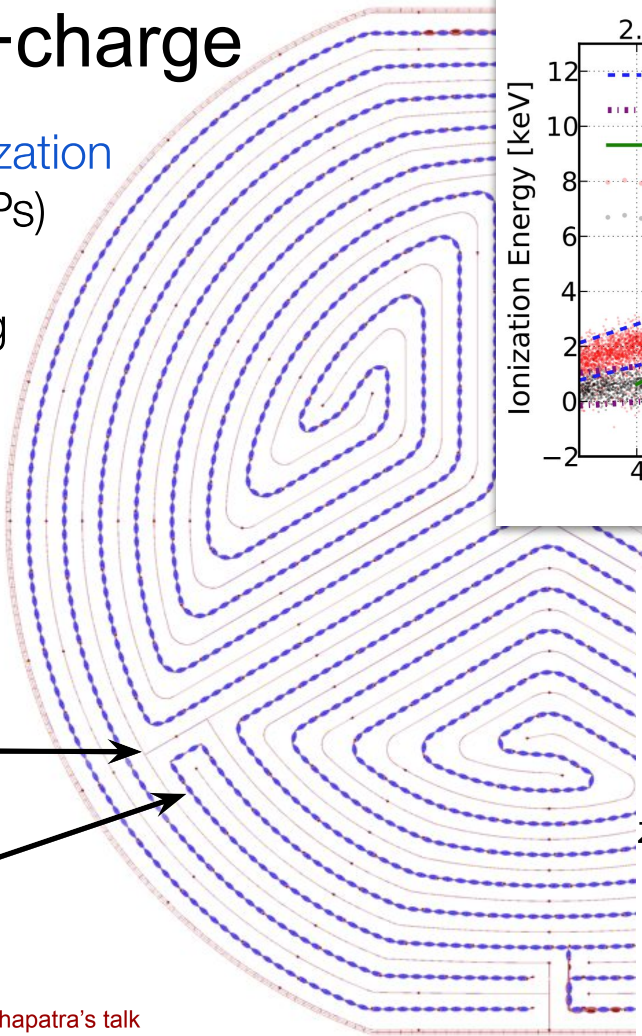


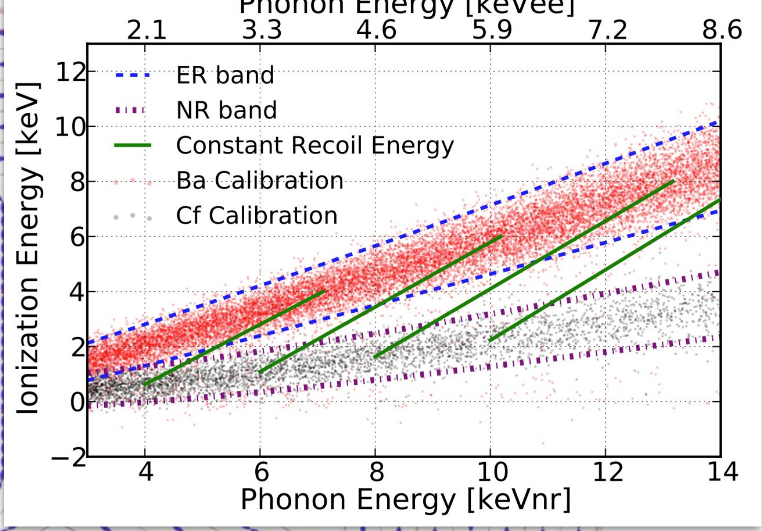
Fig. from J. Gascon, EXCESS workshop 2021

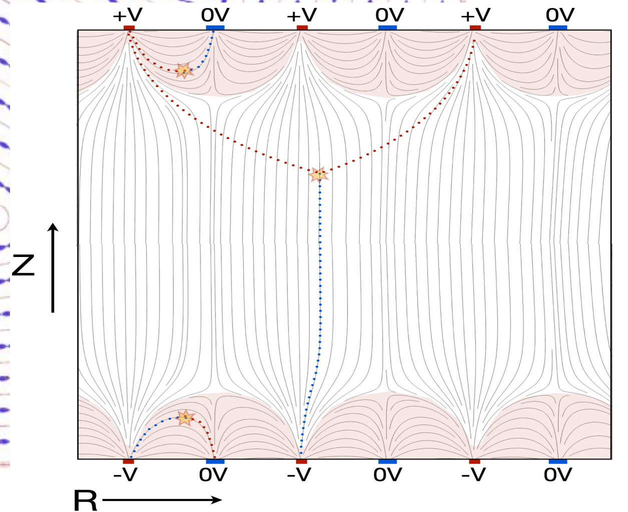
SuperCDMS: TES+charge

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





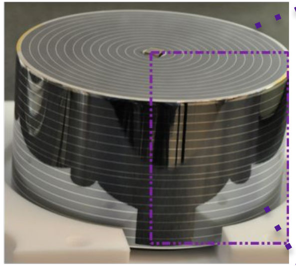




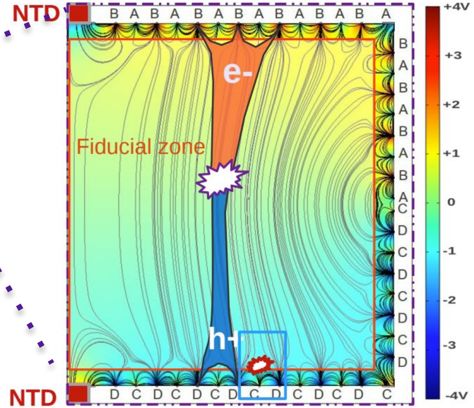
See R. Mahapatra's talk tomorrow for more details

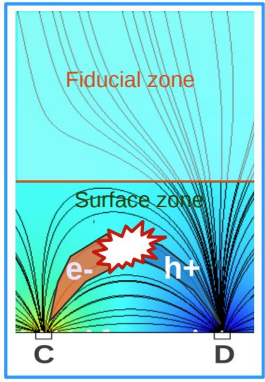
EDELWEISS: NTD/TES + charge

- 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
  - Next-stage 38 gram germanium detectors, with NTD+charge
  - Expect better phonon and charge resolutions with cryogenic HEMTs

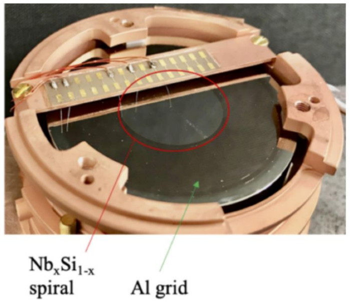


PRD 97 (2018) 022003

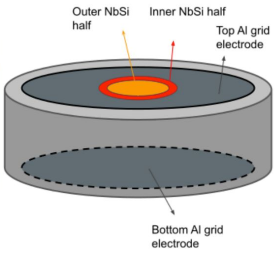




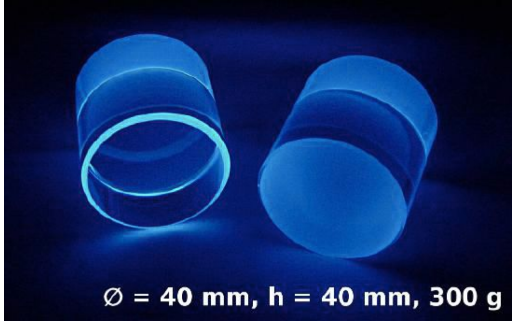
See E. Guy's presentation on Wed. for more details



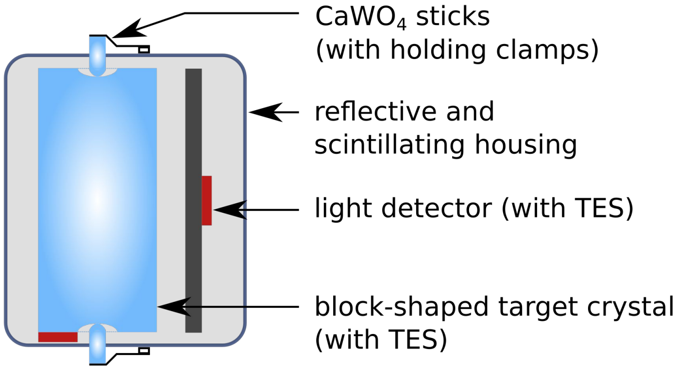
arXiv: 2203.03993



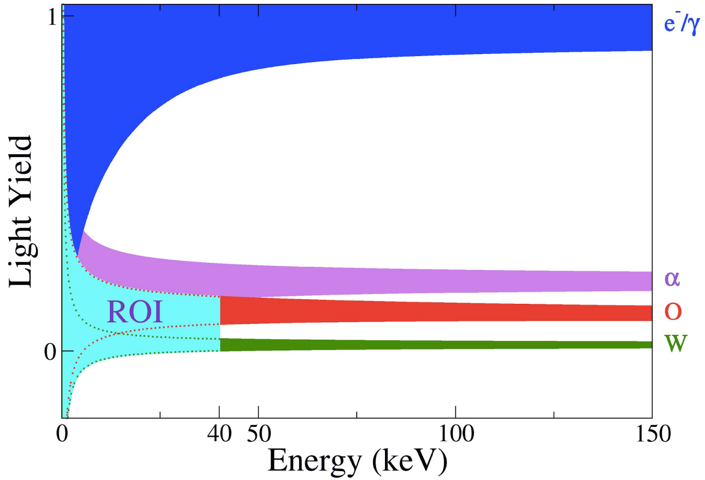
CRESST: TES + Light + Active Veto



- $CaWO_4$ 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

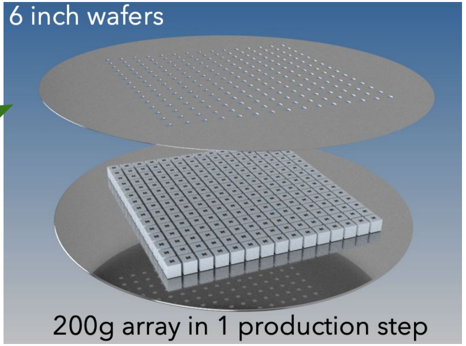


J. Phys.: Conf. Ser. 1342 012076

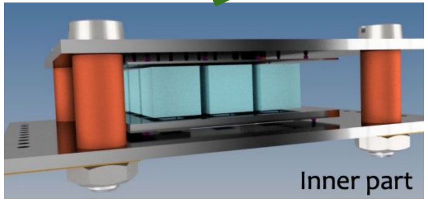


NUCLEUS: TES + Active Veto

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

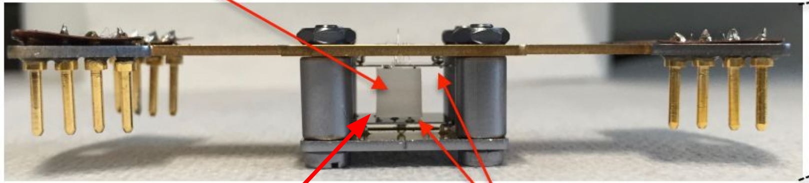


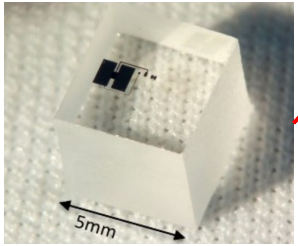
Further up



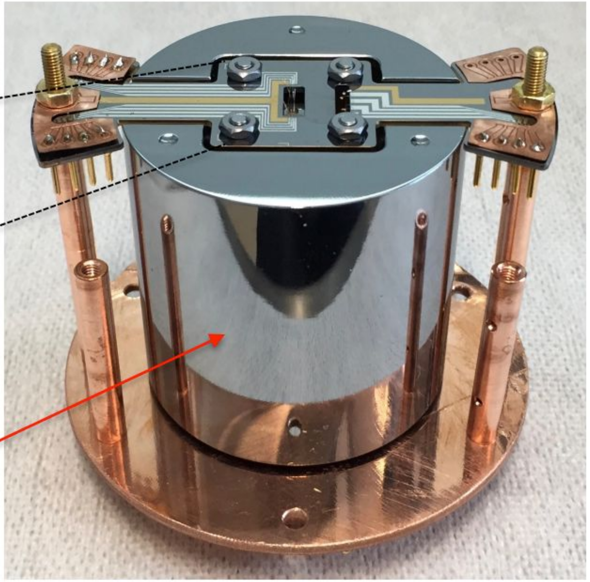
Scale up

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





Inner veto (Si)



Outer veto (Ge, $LiWO_4$)

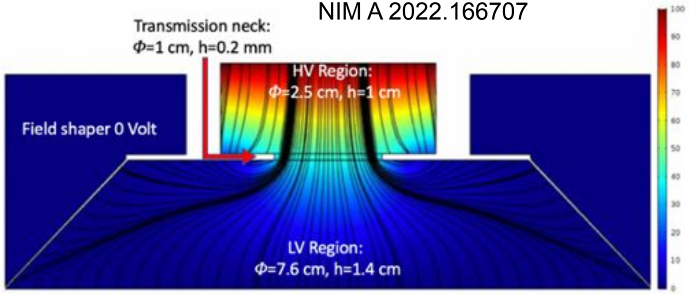
Fig. from R. Strauss, m7s 2019
PRD 96, 022009 (2017)

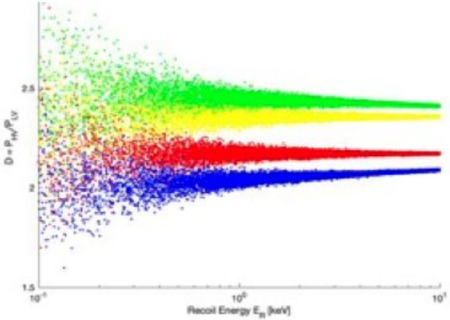
BASKET@CEA

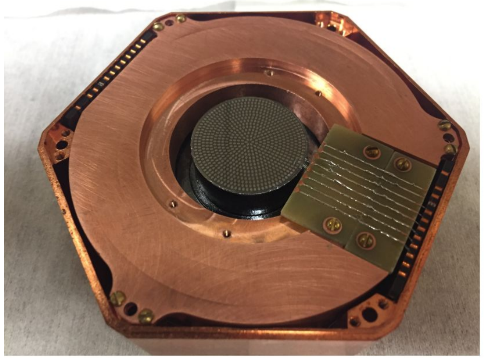
MINER: Hybrid Phonon detector

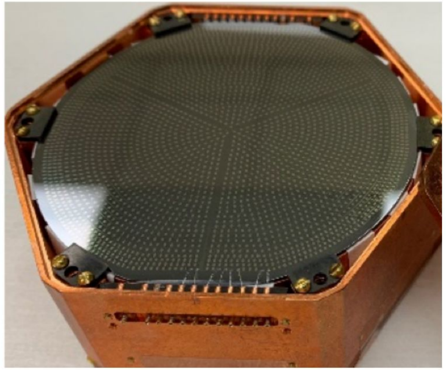
- Separate crystal into a low-voltage (LV) and a high-voltage (HV) region
- Phonon sensors on both sides
- Use the LV region as the fiducial volume
- Shape E-field to guide charges through the “neck”
- NTL phonons from the charges dominates in the HV side, whereas recoil phonons dominate the LV side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

NIM A 2022.166707





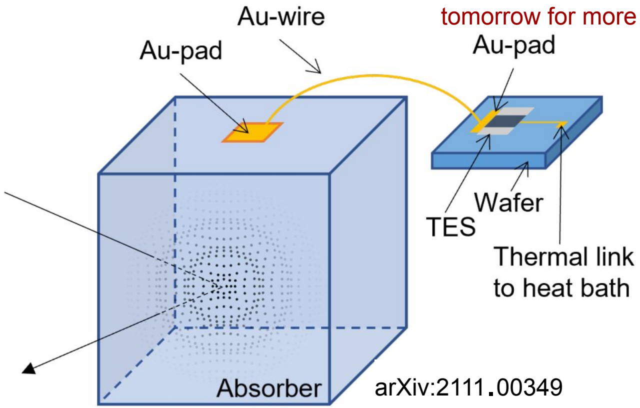




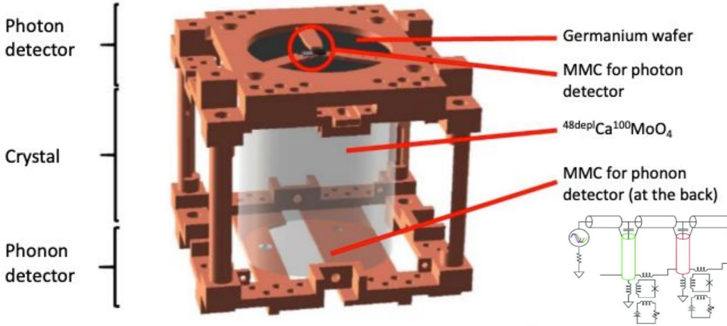
See R. Mahapatra’s talk tomorrow for more details

Modular design: detaching thermometer from absorber

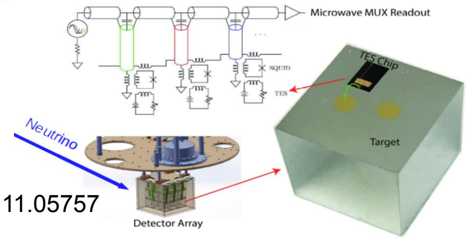
See M. Kellermann's talk tomorrow for more details



arXiv:2111.00349



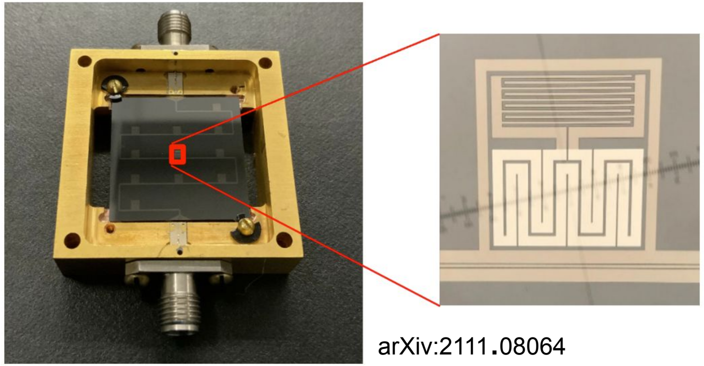
arXiv:1903.09483



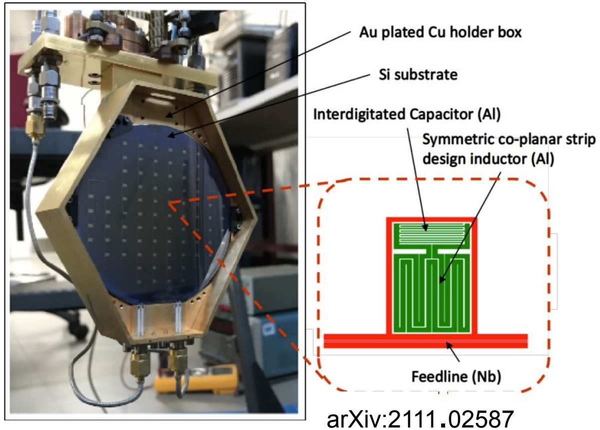
arXiv:2111.05757

- Decoupling thermometer from crystals for ease of fabrication
- Thermal conduction facilitated by a gold wirebond
- Can be coupled to a wide variety of target materials
- RemoTES from COSINUS achieved <100 eV resolution with a 2-gram target
- Similar designs include
  - MMC based AMORE detector for 0νββ
  - TES-based Ricochet Qarray for CEvNS

Multiplexing with RF resonators



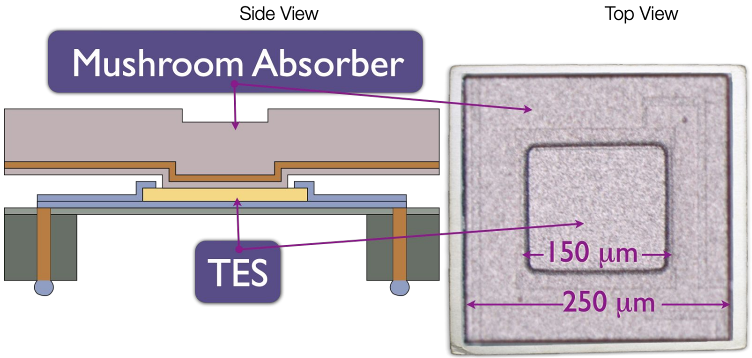
arXiv:2111.08064



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



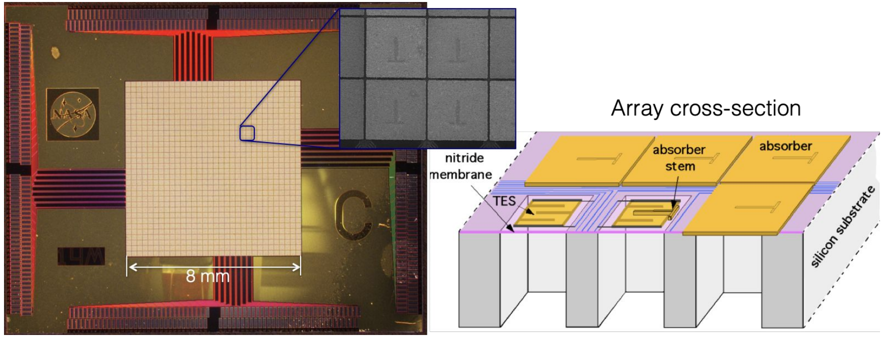


Fig. from E. Figueroa, COFI PIRE 20017

- 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

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