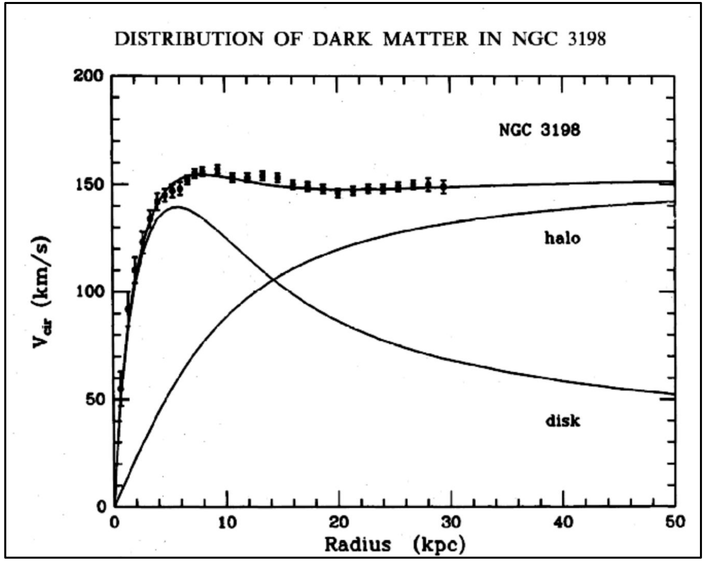
Low Mass Dark Matter Search

The Evidence for Dark Matter

Gravitational Lensing

smithsonianmag.com

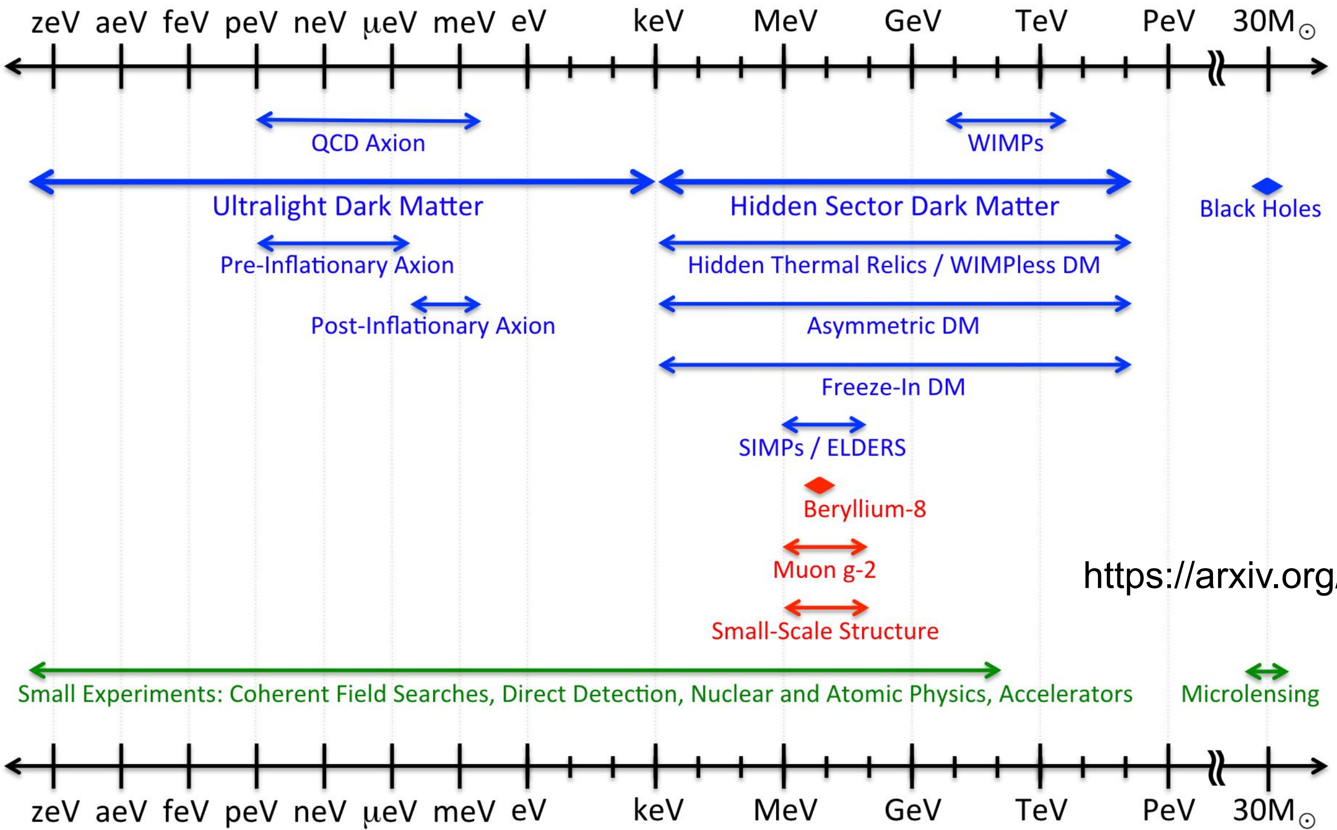
Galactic Rotation Curves



physicsanduniverse.com

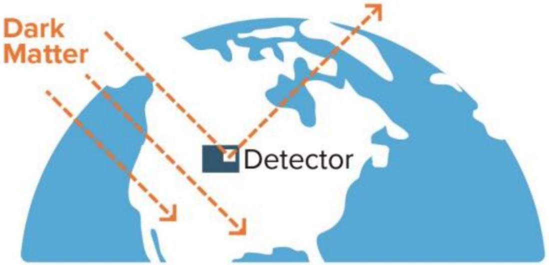
~5 times as much dark matter in the universe as regular matter

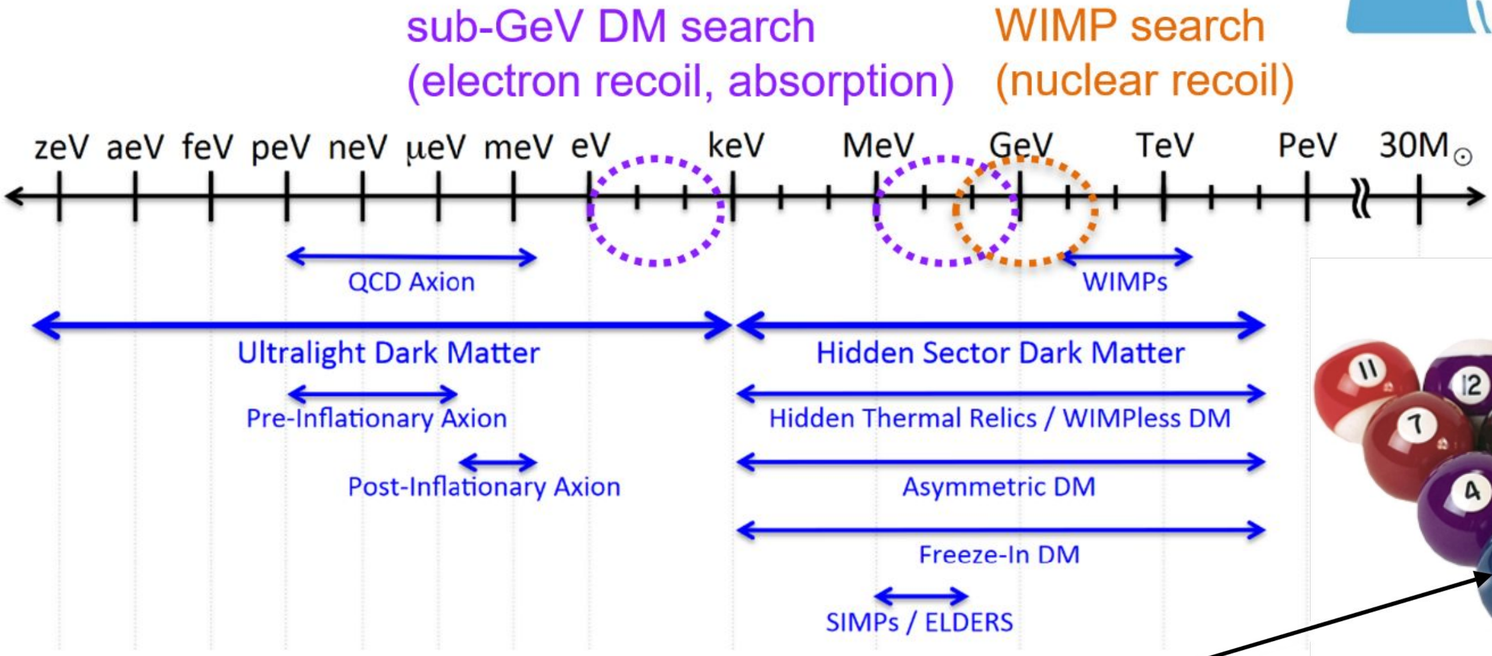
US Cosmic Visions: New Ideas in Dark Matter 2017 Community Report



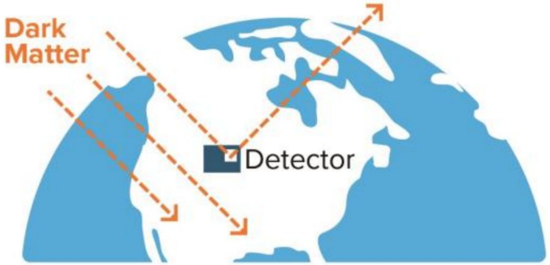
https://arxiv.org/pdf/1707.04591

Low Mass (but still particle like) Dark Matter Search



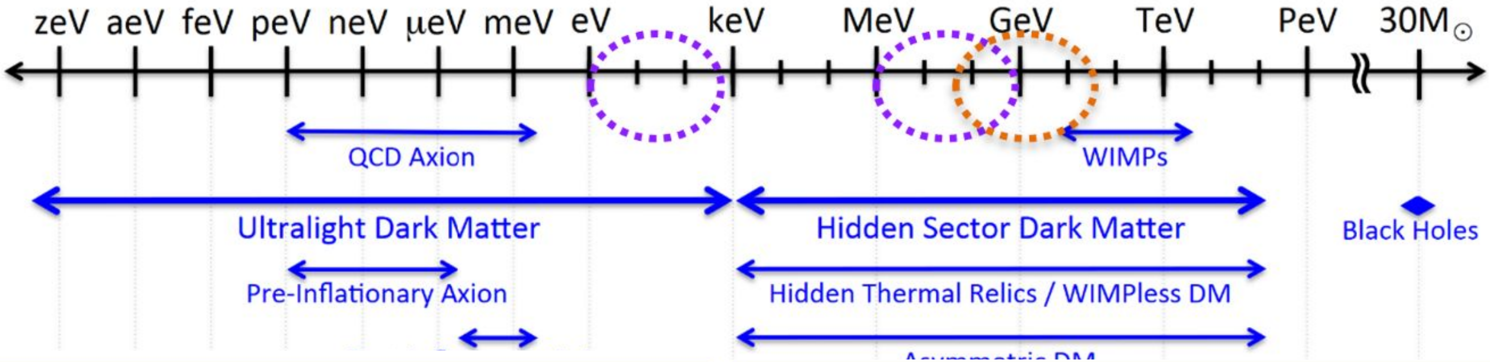


Low Mass (but still particle like) Dark Matter Search



sub-GeV DM search
(electron recoil, absorption)

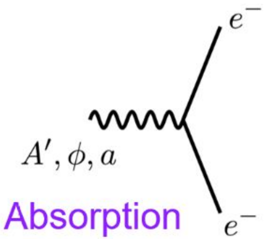
WIMP search
(nuclear recoil)



Nuclear interaction processes:

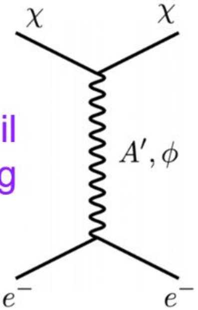
Nucleus-recoil scattering

Electronic interaction processes:



Absorption

Electron-recoil scattering



Reminder: still a needle search in a haystack

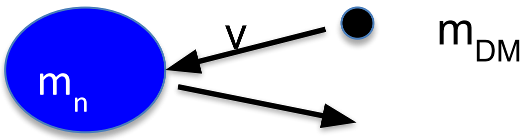
Theme: more signal, less background, then try to tell them apart…

Focusing on the signals here

- Since I like detectors, we'll talk about how to make them see these signals

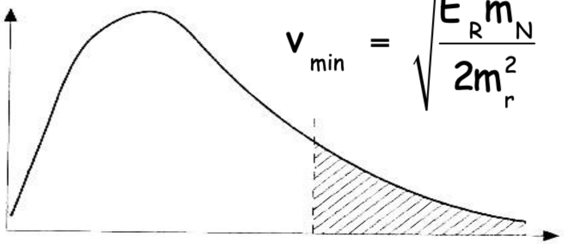
- Start with low mass "WIMP" searches

The low-mass WIMP challenge

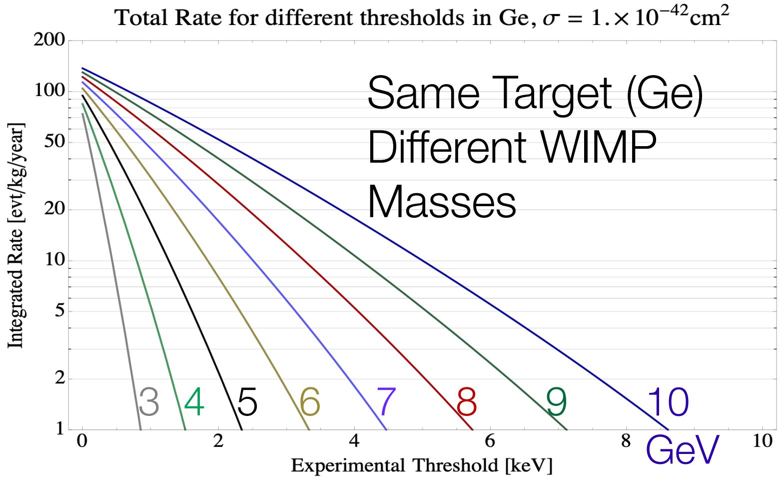


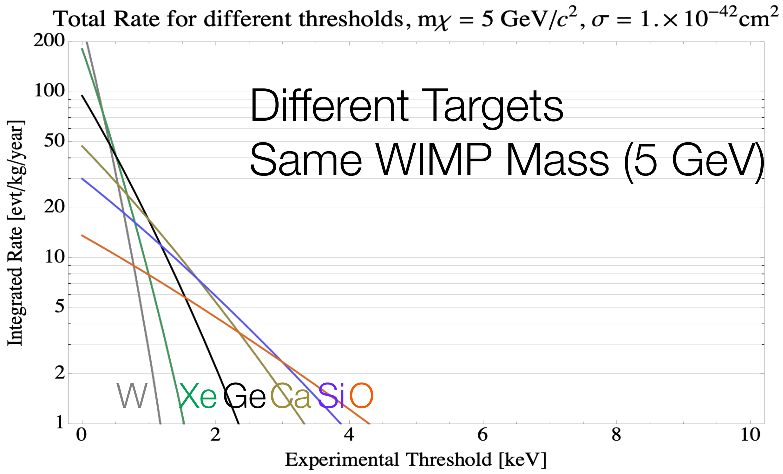
$$\Delta E = \frac{\Delta P^2}{2M_n} \lesssim \frac{2M_{DM}^2 v^2}{M_N}$$

A WIMP must have a minimum velocity to produce a recoil of a specific energy



$$v_{min} = \sqrt{\frac{E_R m_N}{2m_r^2}}$$



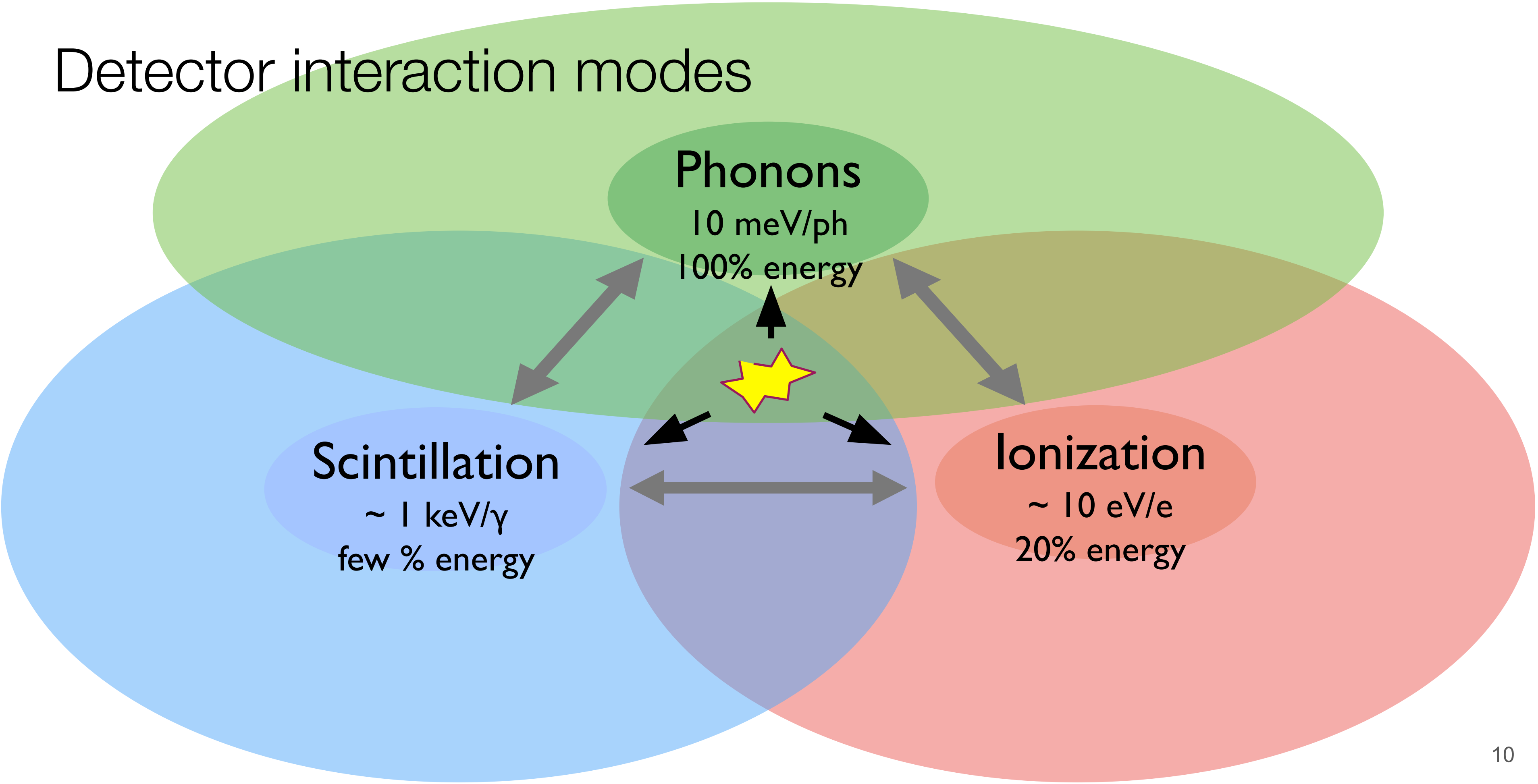


Nuclear Recoil Direct Detection Requirements

1: Large Exposure (Mass x Time)
2: Low background
3: Low Energy Threshold

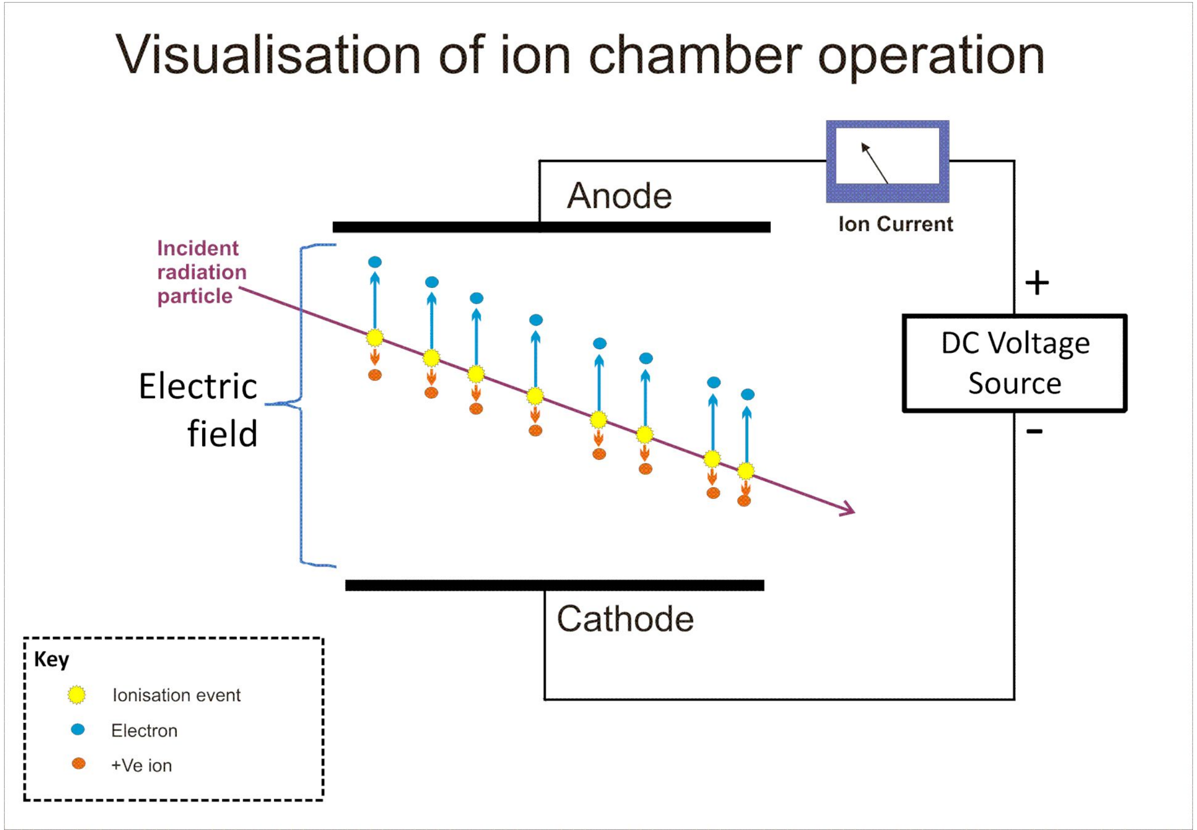
Turns out that this is applicable for any dark matter search…

Detector interaction modes



https://en.wikipedia.org/wiki/Gaseous_ionization_detector

Ionization/Charge Detectors



Mean number of electron-ion pairs in gas

- For energy deposition E in a media with mean ion-electron pair creation W, the mean number of ion-electron pair is
  <N> = E / W
- W~30 eV for gas
- Note, W is higher than the excitation or ionization potential

Table 6.1. Excitation and ionization characteristics of various gases

	Excitation potential [eV]	Ionization potential [eV]	Mean energy for ion-electron pair creation [eV]
H_2	10.8	15.4	37
He	19.8	24.6	41
N_2	8.1	15.5	35
O_2	7.9	12.2	31
Ne	16.6	21.6	36
Ar	11.6	15.8	26
Kr	10.0	14.0	24
Xe	8.4	12.1	22
CO_2	10.0	13.7	33
CH_4		13.1	28
C_4H_{10}		10.8	23

Ionization in semi-conductor

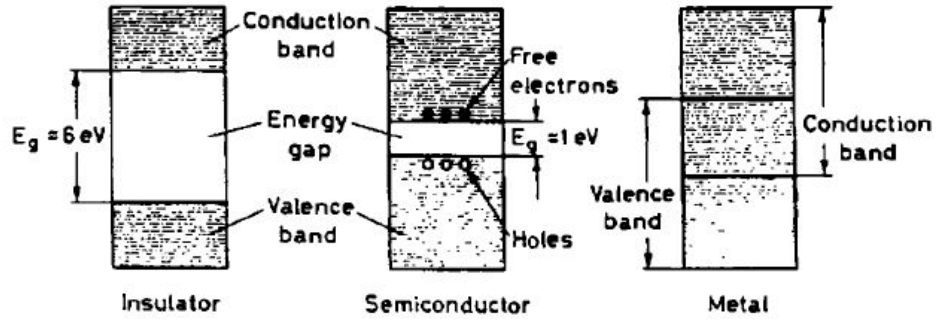
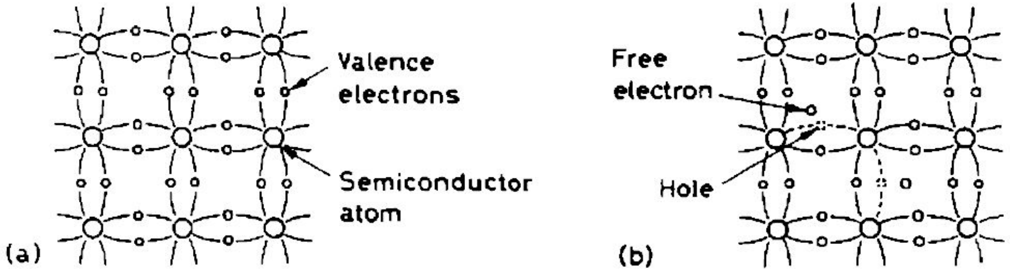


Fig. 10.1. Energy band structure of conductors, insulators and semiconductors



- In semiconductor, ionization is the process of exciting electron-hole pairs
  - Instead of completely free electrons
- Initial ionization can excite electrons to completely free state (or not), then cascade to multiple electron-hole pairs
- All interactions dumping energy into the **electron system** go through the same electron-hole cascade process
  - Processes depositing energy into the **nuclear system** is a bit different

Ionization yield in semiconductor

- W for semiconductor (often denoted as ϵ), is (again) higher than band gap
- Can be explain by kinematic phase space
  - Electron and hole split energy
  - Secondary ionizations doesn't always have perfect energy split
- ~x10 lower than gas
  - More charge carriers generated
  - Often a good thing, though could cause a dense cloud if too many are generated

Table 10.1. Some physical properties of silicon and germanium

	Si	Ge
Atomic number Z	14	32
Atomic weight A	28.1	72.6
Density [g/cm^2]	2.33	5.32
Dielectric constant (relative)	12	16
Intrinsic resistivity (300 K) [Ωcm]	230000	45
Energy gap (300 K) [eV]	1.1	0.7
Energy gap (0 K) [eV]	1.21	0.785
Electron mobility (300 K) [cm^2/Vs]	1350	3900
Hole mobility (300 K) [cm^2/Vs]	480	1900

Table 10.2. Average energy for electron-hole creation in silicon and germanium

	Si	Ge
300 K	3.62 eV	–
77 K	3.81 eV	2.96 eV

https://en.wikipedia.org/wiki/Shockley%E2%80%93Ramo_theorem

Shockley–Ramo theorem

The Shockley–Ramo theorem states that the instantaneous current i induced on a given electrode due to the motion of a charge is given by:

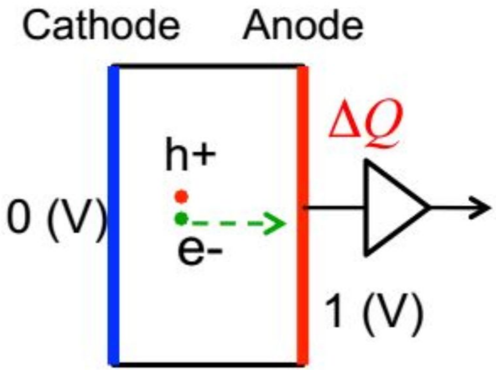
$$i = E_v q v$$

where

q is the charge of the particle;

v is its instantaneous velocity; and

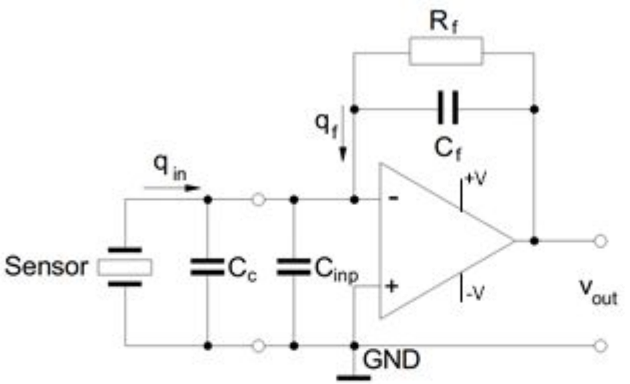
E_v is the component of the electric field in the direction of v at the charge's instantaneous position, under the following conditions: charge removed, given electrode raised to unit potential, and all other conductors grounded.



Take away: The signal measured is charge-drifting induced signal…
The stronger the E-field, the larger the induced signal

https://en.wikipedia.org/wiki/Charge_amplifier

Charge amplifier



- Detector design is often integrated with readouts
- Charge detector:
  - Collecting charge on its capacitance
  - Amplifying via “charge amplifier”
  - Discharge via feedback resistor

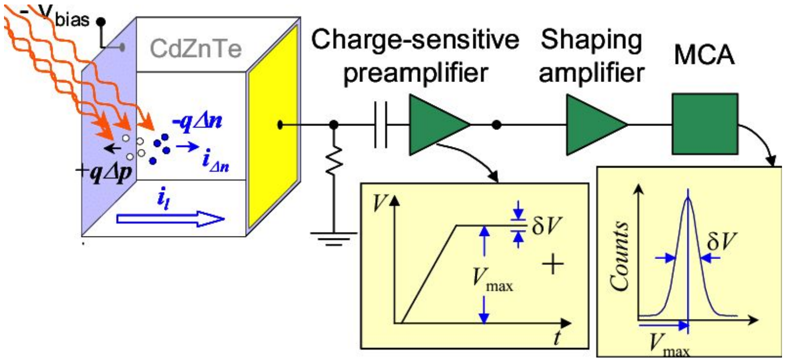
$$q_{in} = q_f$$
$$V_{out} = q_f / C_f = q_{in} / C_f$$

Decay time: R_f*C_f

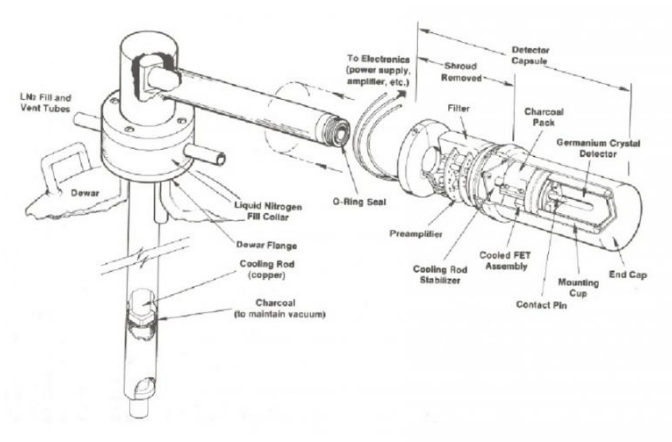
- Detector capacitance critical for noise
  - **Voltage noise (v_n) amplified by C_{in}/C_f**
  - **Often sensor capacitance drives resolution and threshold**

Charge detector examples

- CdTe/CdZnTe
  - Work at room temperature
  - Resolution ~ a few keV



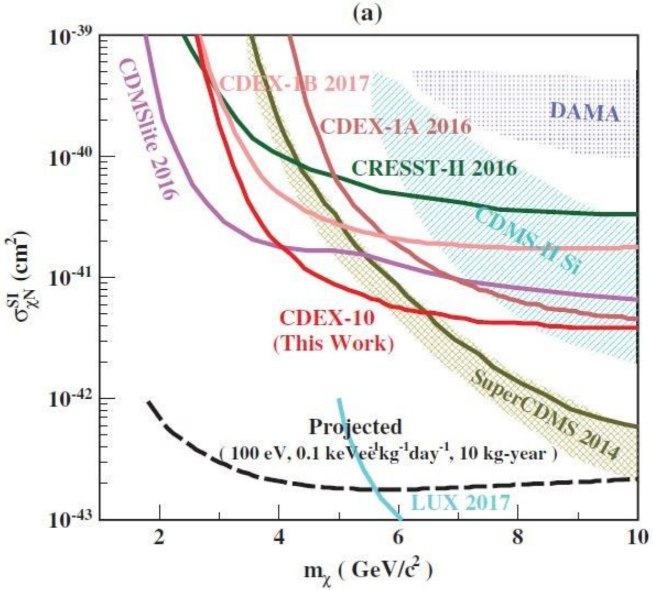
- High purity germanium (HPGe)
  - Work at liquid Nitrogen temperature
  - Can cool down electronics
  - Resolution ~keV

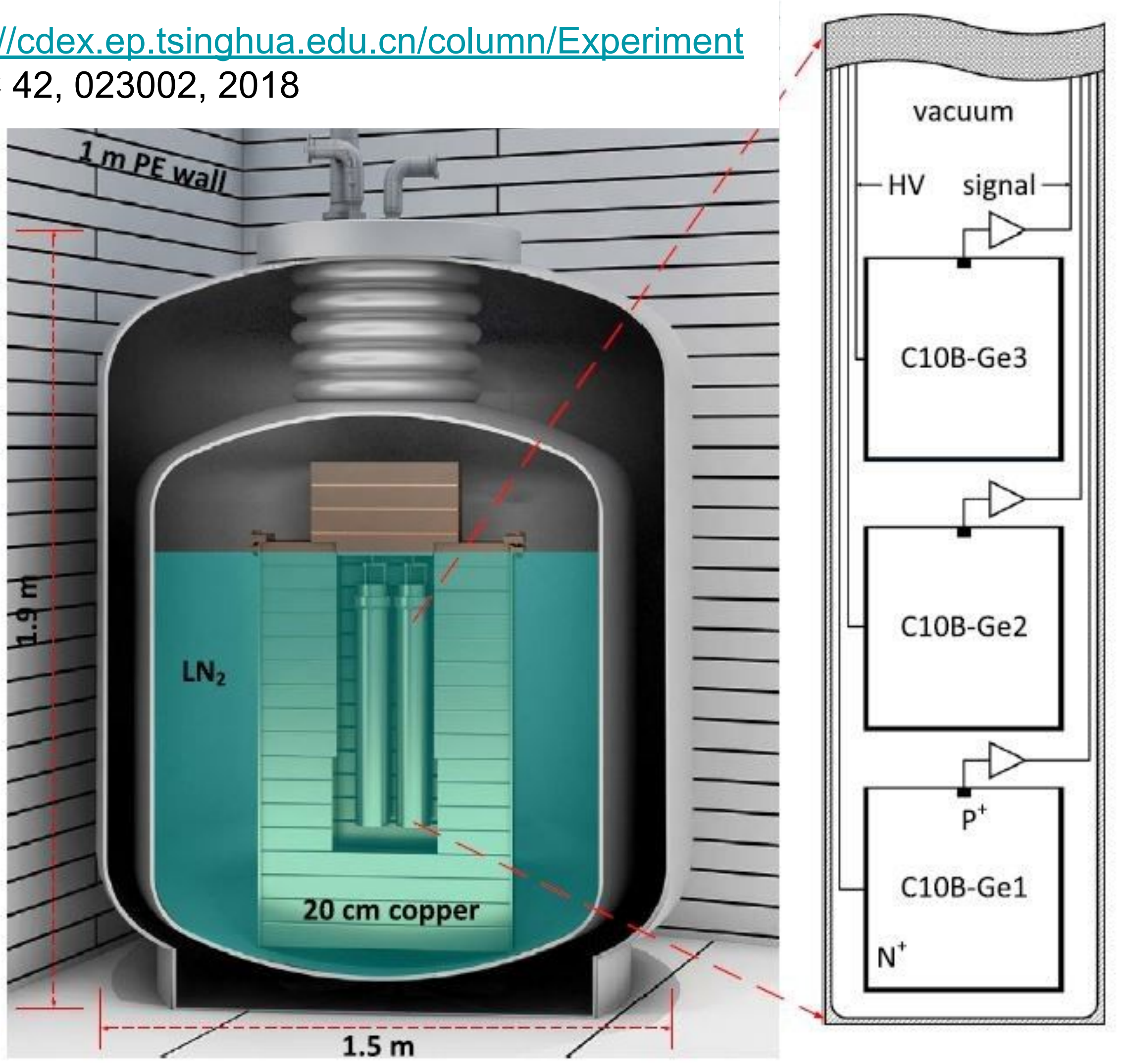


http://cdex.ep.tsinghua.edu.cn/column/Experiment
CPC 42, 023002, 2018

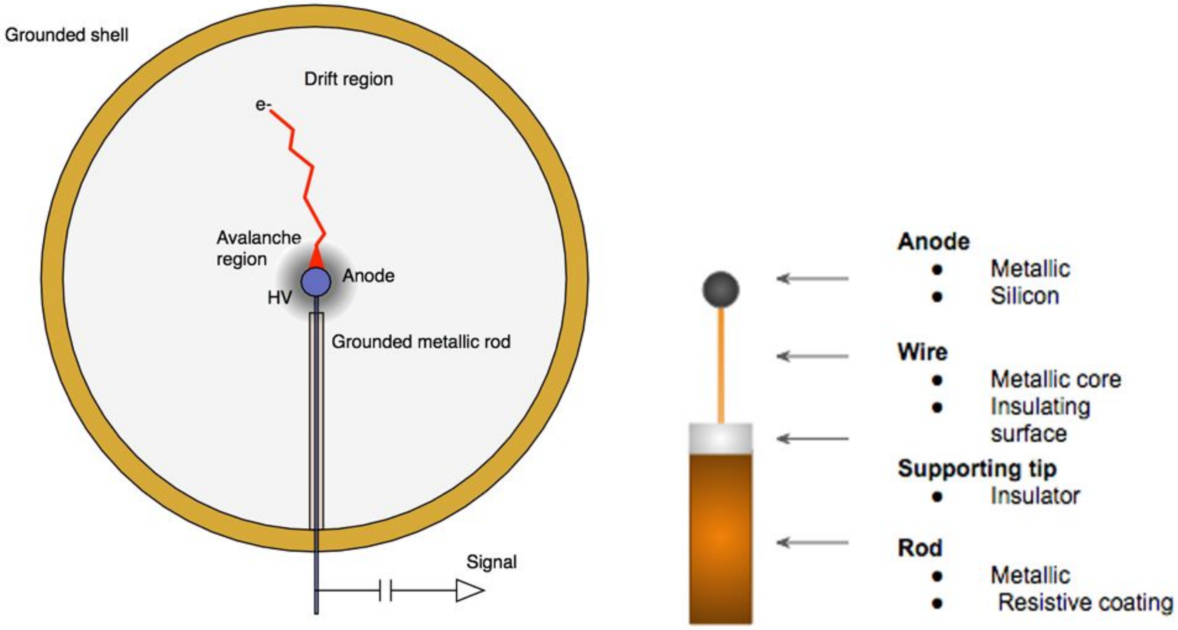
CDEX

- Array of “p-type point contact germanium detector (pPCGe) “
- 160 eVee threshold





NEWS-G



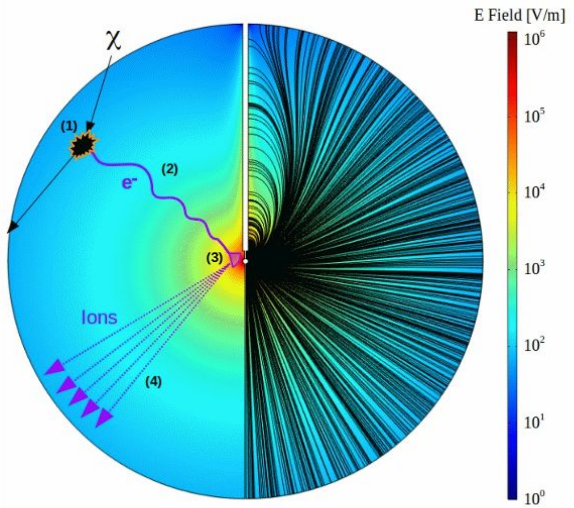
(a) (b)

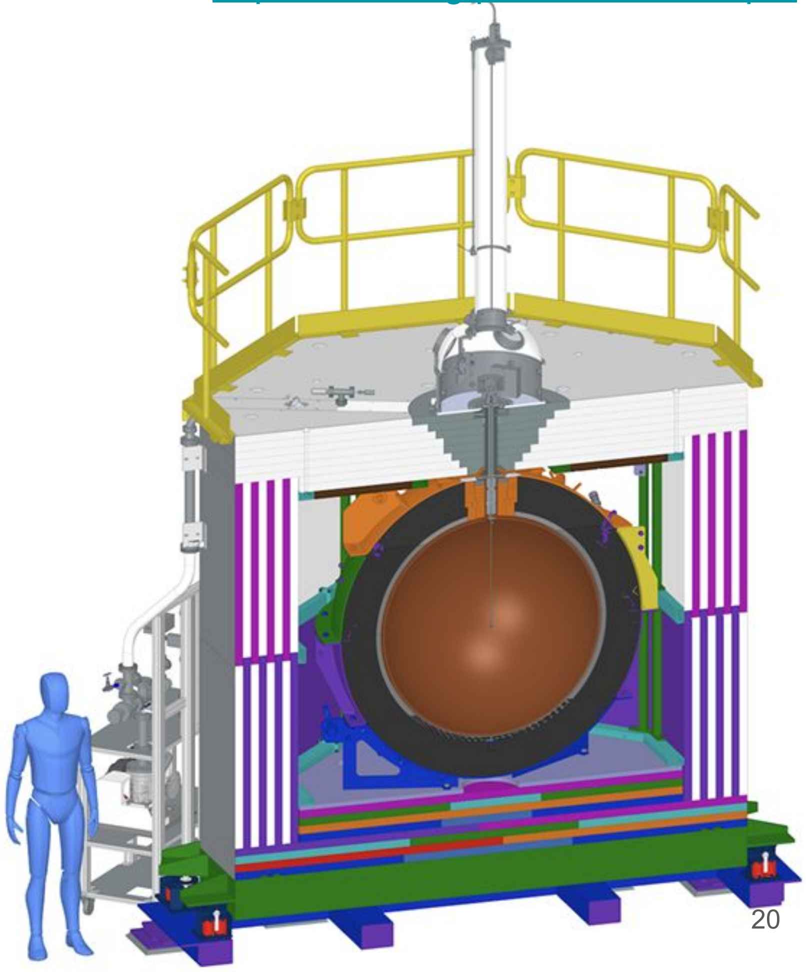
Figure 1: (a) SPC design and principle of operation and (b) illustration of the basic read out sensor [5].

https://arxiv.org/pdf/1809.02485.pdf
https://arxiv.org/pdf/2205.15433.pdf

NEWS-G

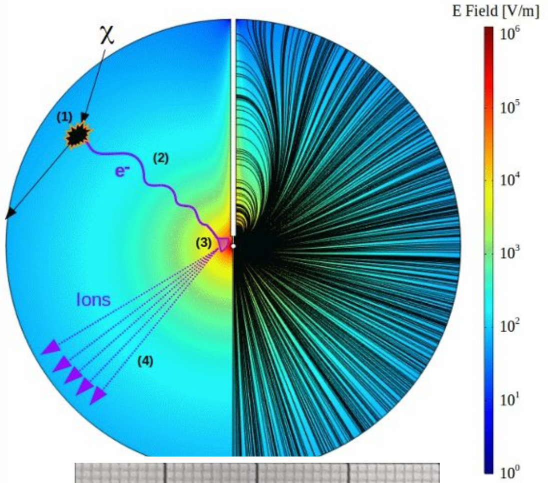
- New Experiments With Spheres-Gas
- Spherical Proportional Counter
- Noble gases as targets
- Search for light dark matter
    - Down to sub-GeV mass region





NEWS-G -- Electrode

- Most signal induced near the surface of Anode
  - Large E-field $$E(r) \approx \frac{V}{r^2} r_A$$
  - Strong E-field also induces 2nd ionization
    - Amplifying signals
  - Tend to make anodes small
- For small r_A, E field at large r becomes small as well
- Attachment & recombination becomes a problem
- → "Achinos" sensor:
  - Large r E-field determined by overall sensor shape
  - Local E-field determined by individual anode



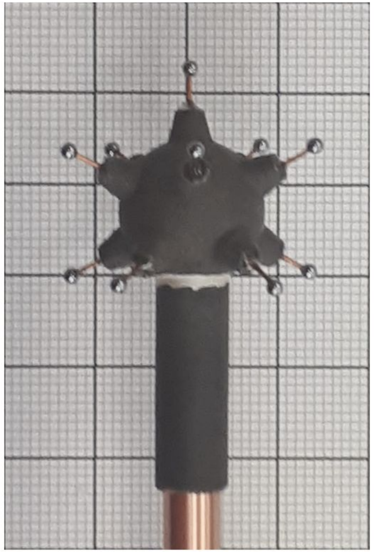
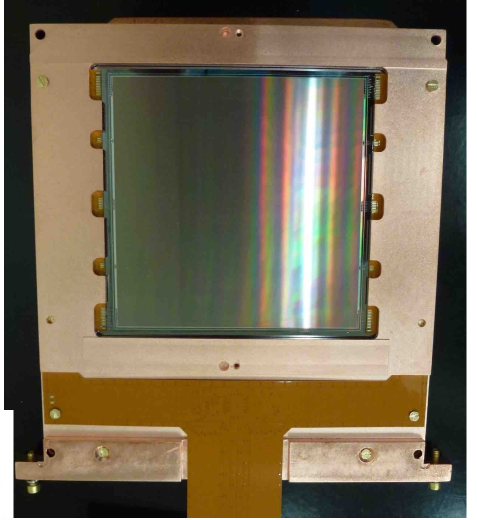


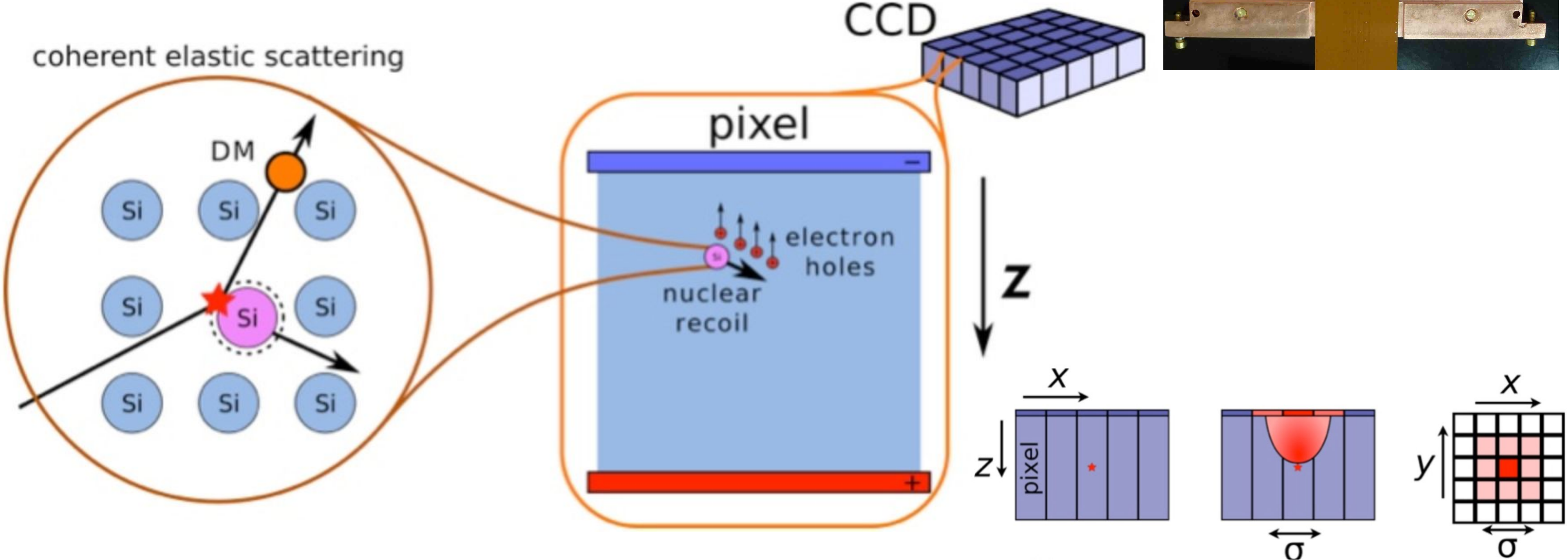
Figure 2. An 11-anode ACHINOS sensor.

https://www.npl.washington.edu/damic/description
https://damic.uchicago.edu/detector.php



DAMIC/SENSEI

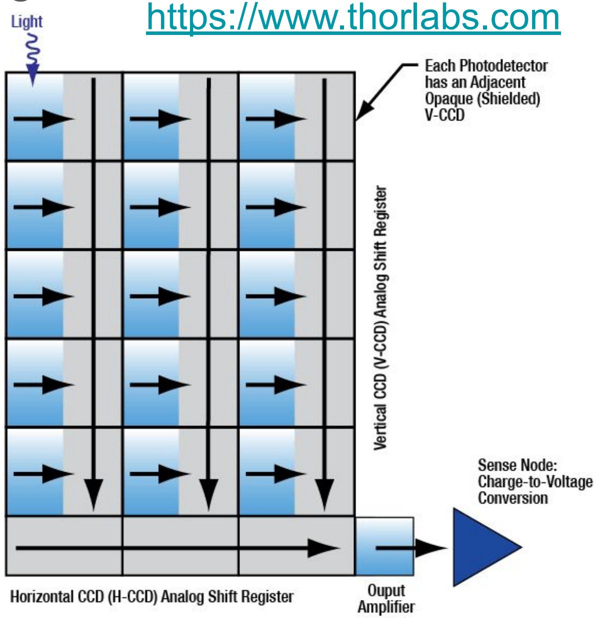
- Taking a “photo” for Dark Matter with a thick CCD
- Pixelated silicon charge detector

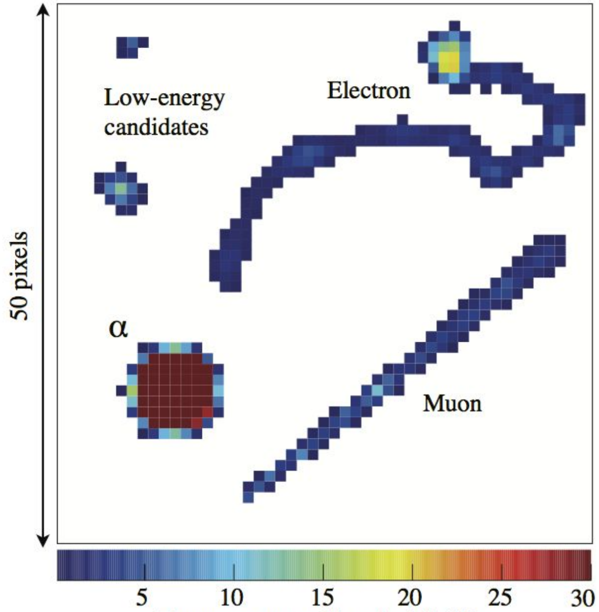


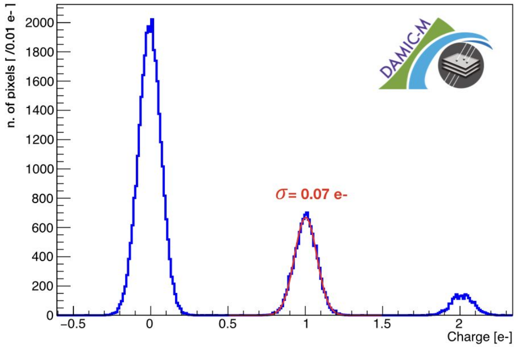
DAMIC/SENSEI

- CCD readout pixel by pixel
- Modern “SENSEI” electronics has single charge resolution by re-sampling
- Particle identification based on shape of clusters
- Current generation at SNOLAB
- Next generation DAMIC-M at LSM

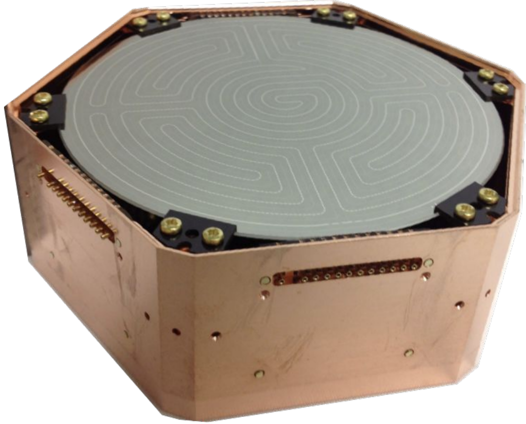
https://www.thorlabs.com



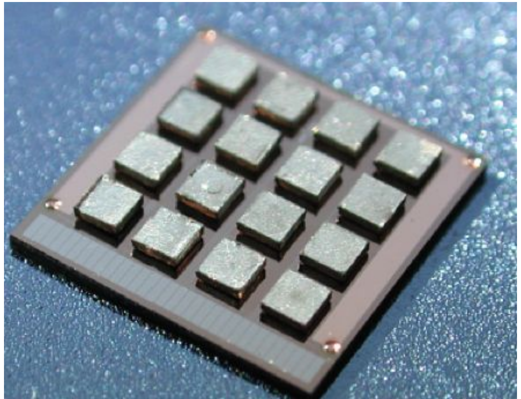


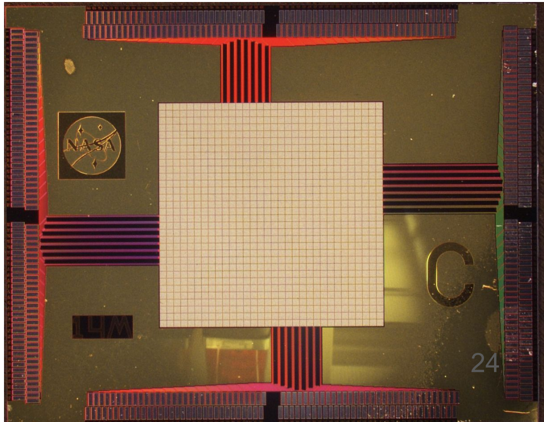


Cryogenic Crystal Detectors for **Phonons**



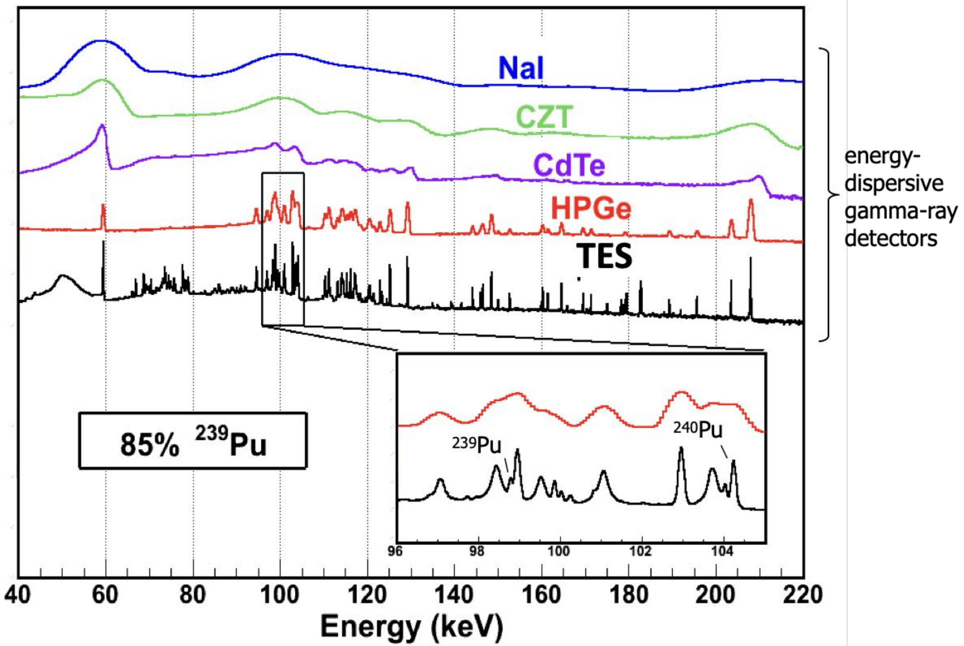
- Particle Physics
  - Dark Matter Detectors
  - Neutrino Physics
    - Coherent Elastic Neutrino Nucleus Scattering (CEvNS)
    - Neutrinoless double-beta decay (0νββ)
- Astrophysics
  - mm to gamma-ray energies



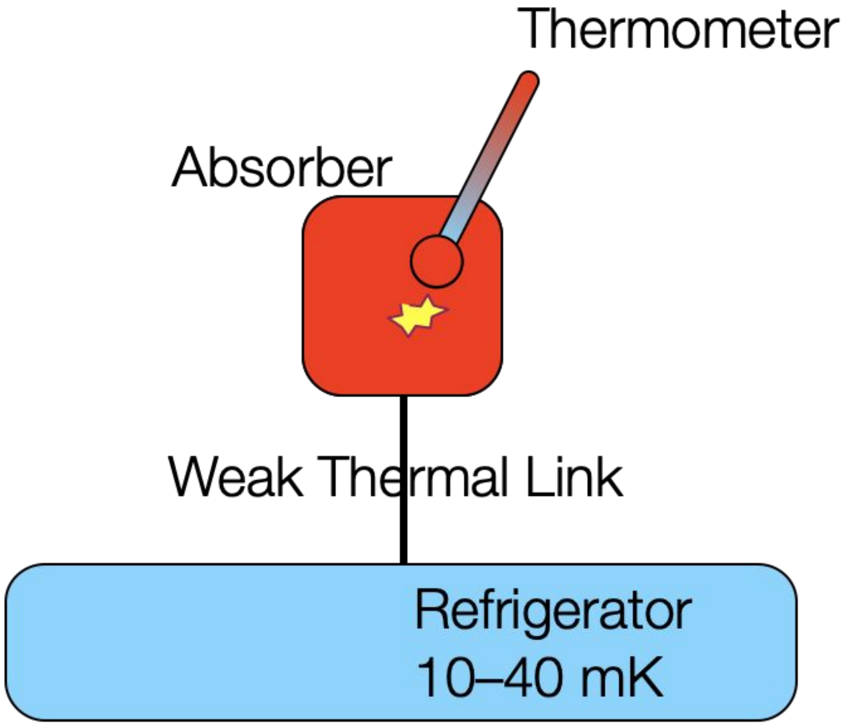


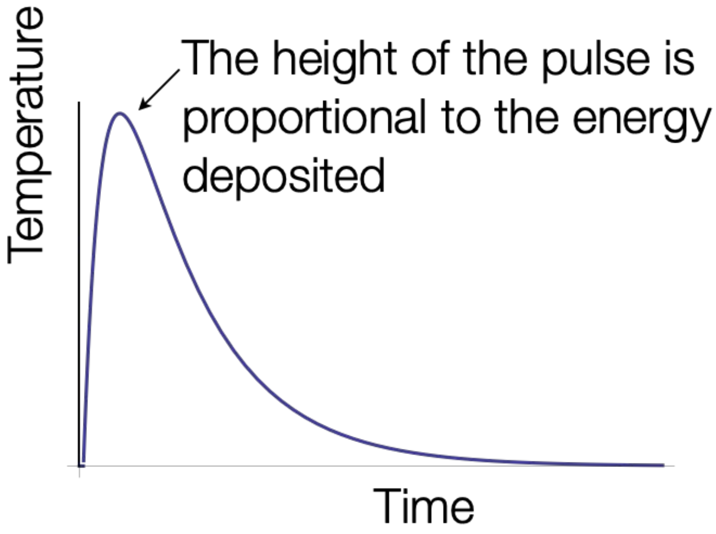
Why Use Cryogenic Crystal Detectors?

- 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



Cryogenic Phonon Detectors





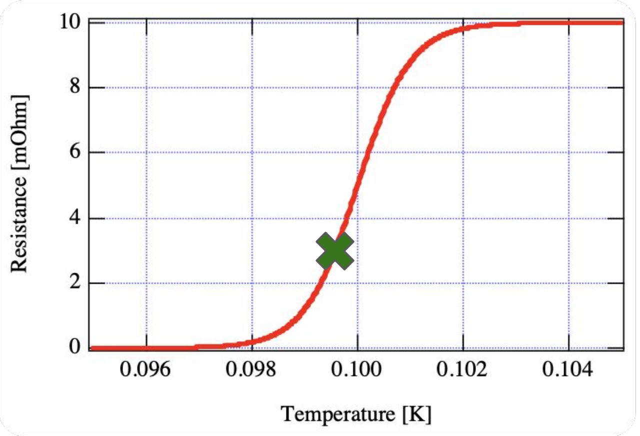
Everybody has their choice of the favourite thermometer!

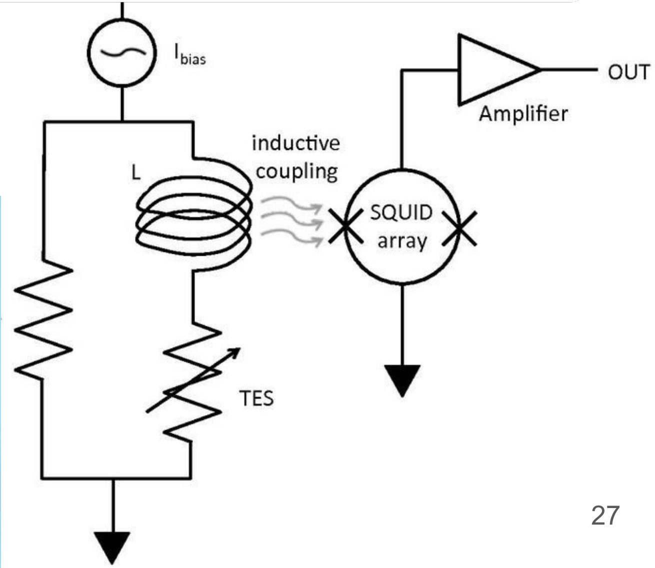
Thermometer #1

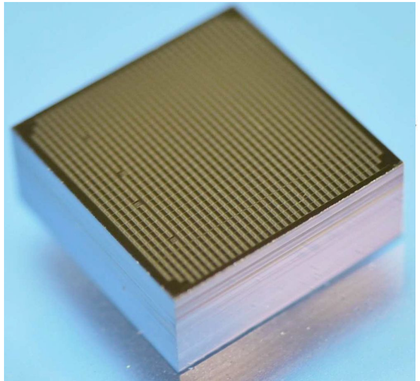
Transition Edge Sensor

- 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

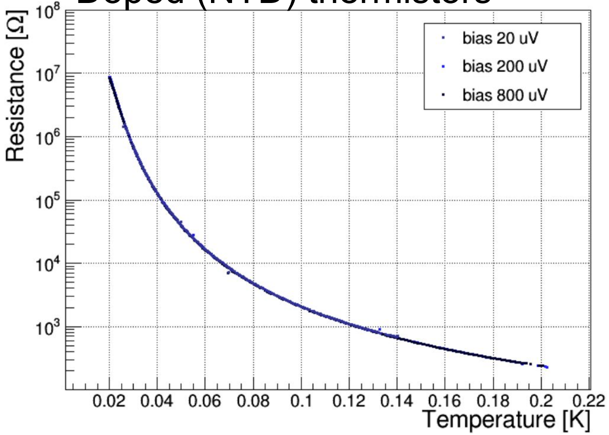
Neutron Transmutation Doped (NTD) thermistors

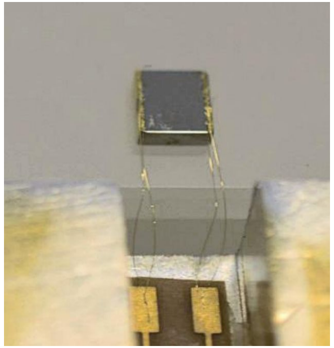
- Doped germanium/silicon chips
- Resistance follows Efros-Shklovskii law:

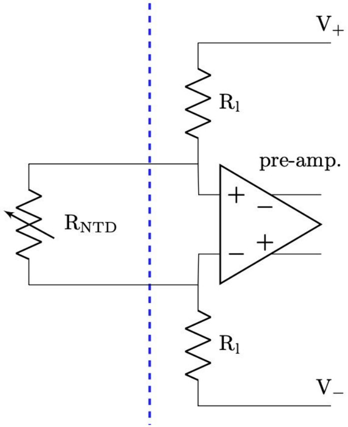
$$R = R_0 e^{\sqrt{T_0/T}}$$

- 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





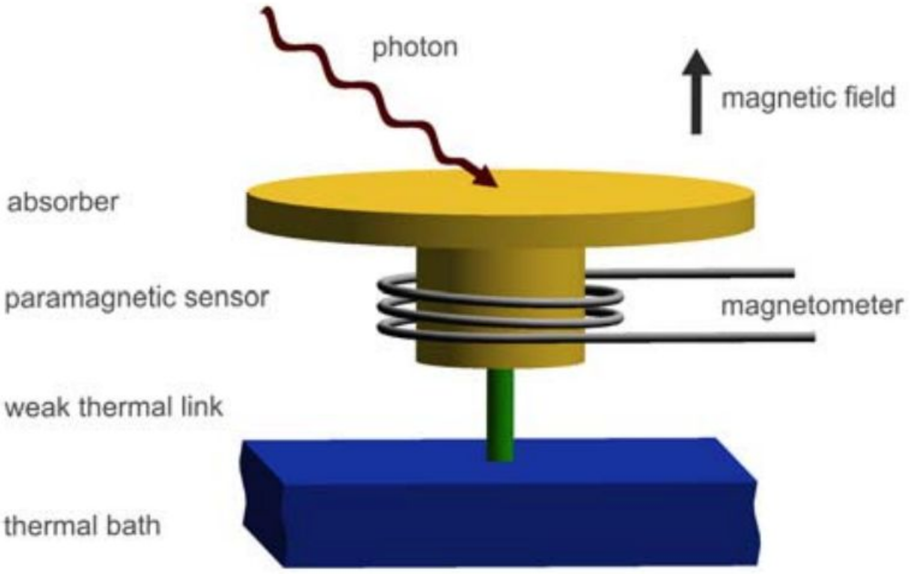


Figures from V. Novati

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)

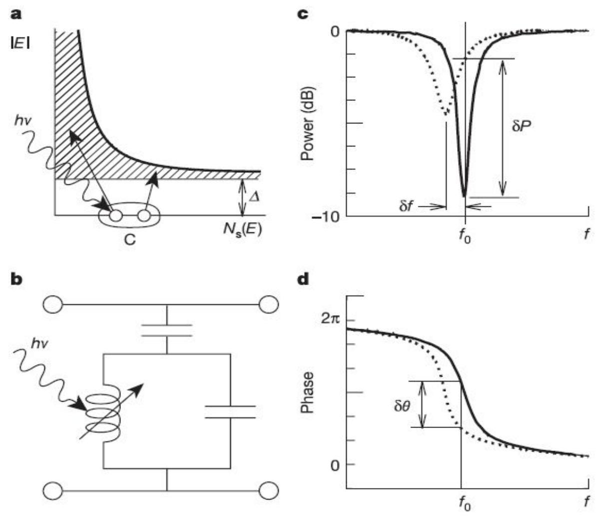


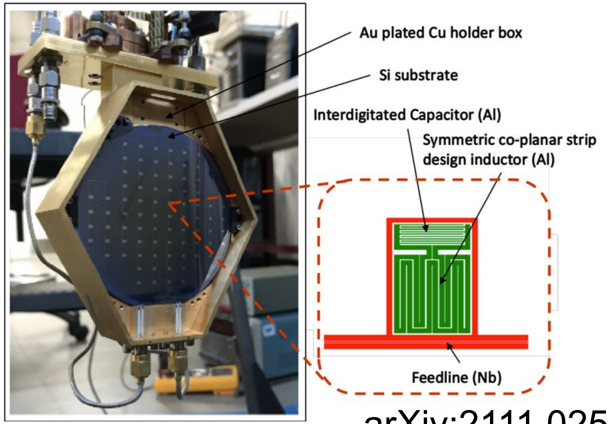
TASC.2009.2012724

Thermometer #4

Microwave Kinetic Inductance Detectors (MKIDs)

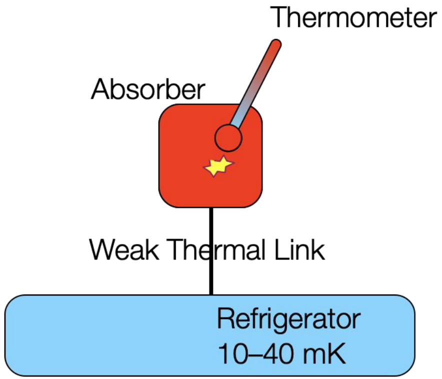
- Resonators made of superconducting metal films
- Resonance frequency and phase response depending on its temperature
- Radio-Frequency (RF) Readout system
- Intrinsic capability for multiplexing



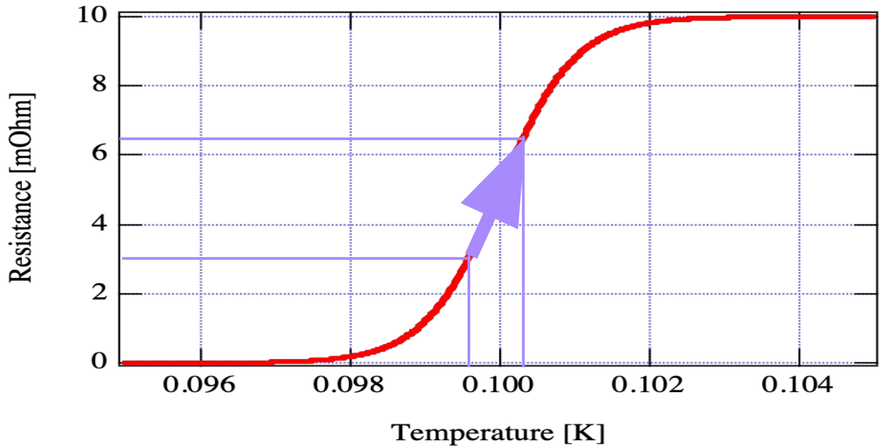


arXiv:2111.02587

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)

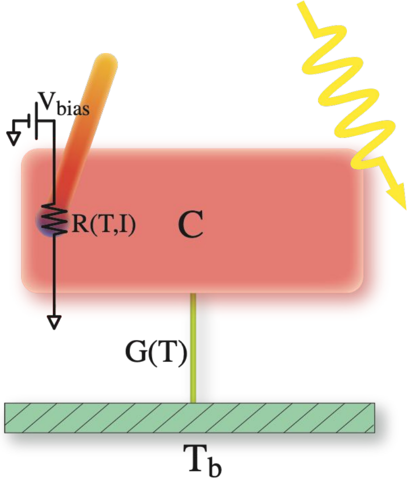
$$P = \frac{V_{\text{bias}}^2}{R(T)}$$

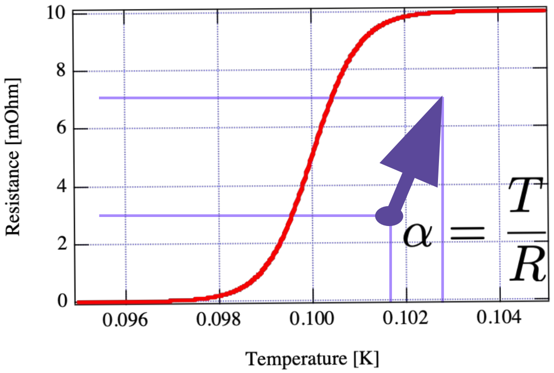
$$\delta P = -\frac{\alpha P}{T}\delta T$$

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

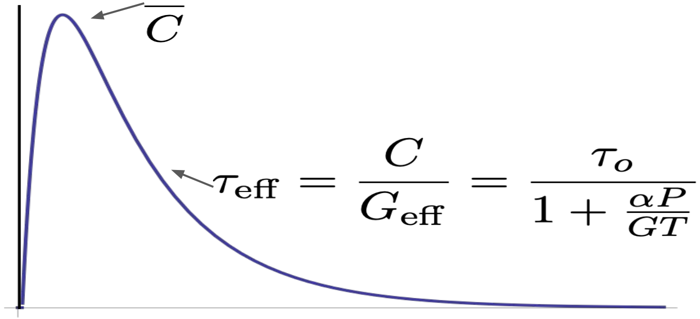
$$C\frac{d(\delta T)}{dt} + G\delta T - \delta P = W(t)$$

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





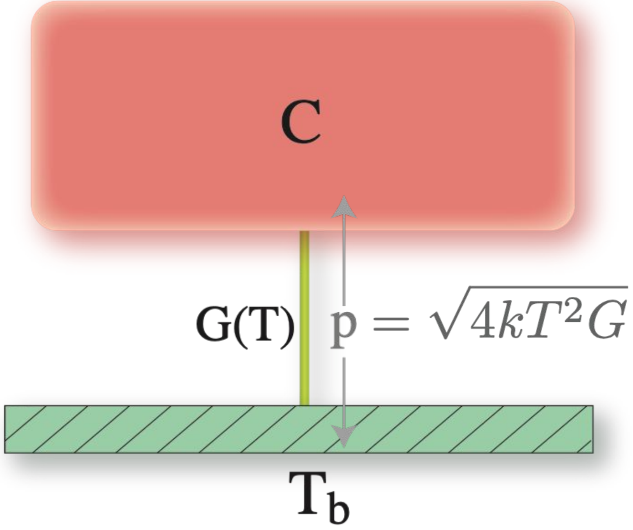
$$\alpha = \frac{T}{R}\frac{dR}{dT}$$



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

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

But are they any good?

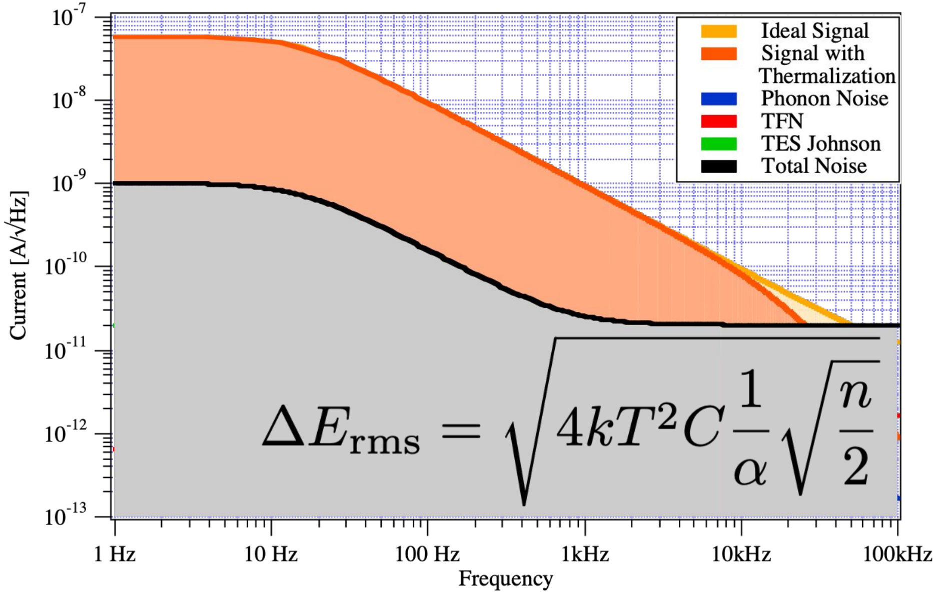


- Thermodynamic fluctuation noise
- Signal to Noise
- Energy Resolution

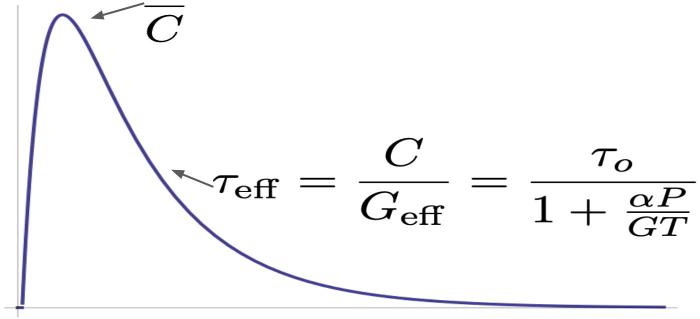
$$\Delta E_{rms} = \sqrt{kT^2C}$$

Resolution is all about noise and bandwidth

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

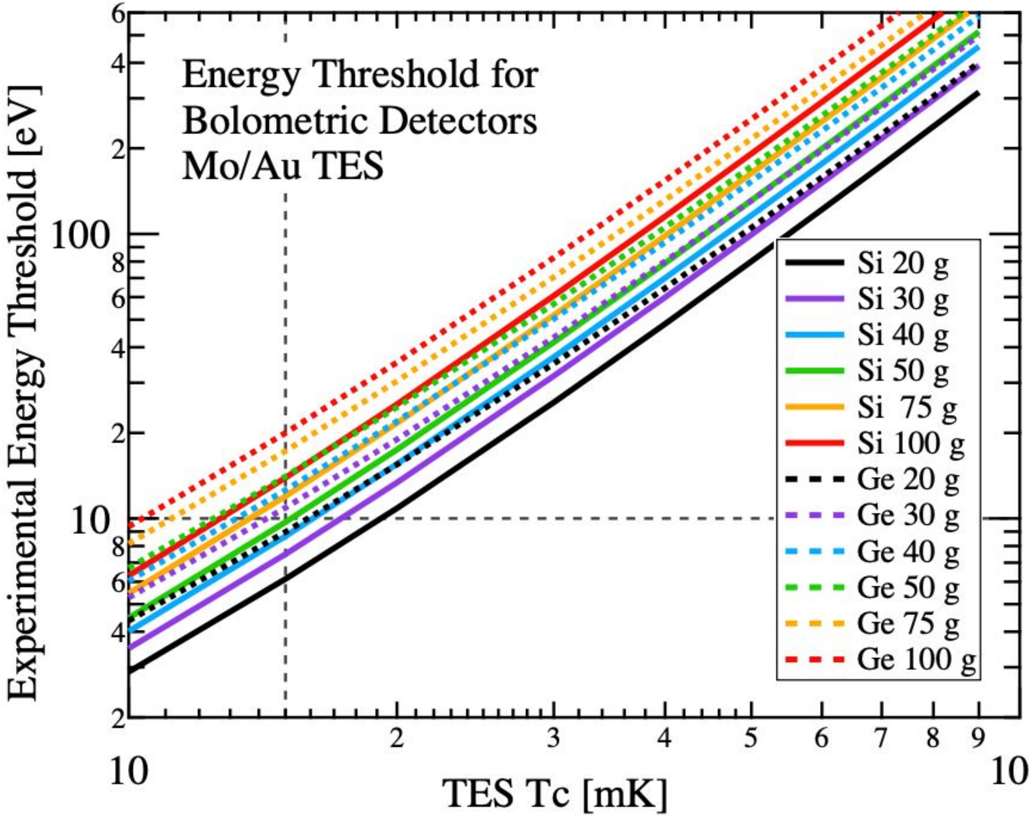


Cold reduces heat capacity → More sensitive detector!

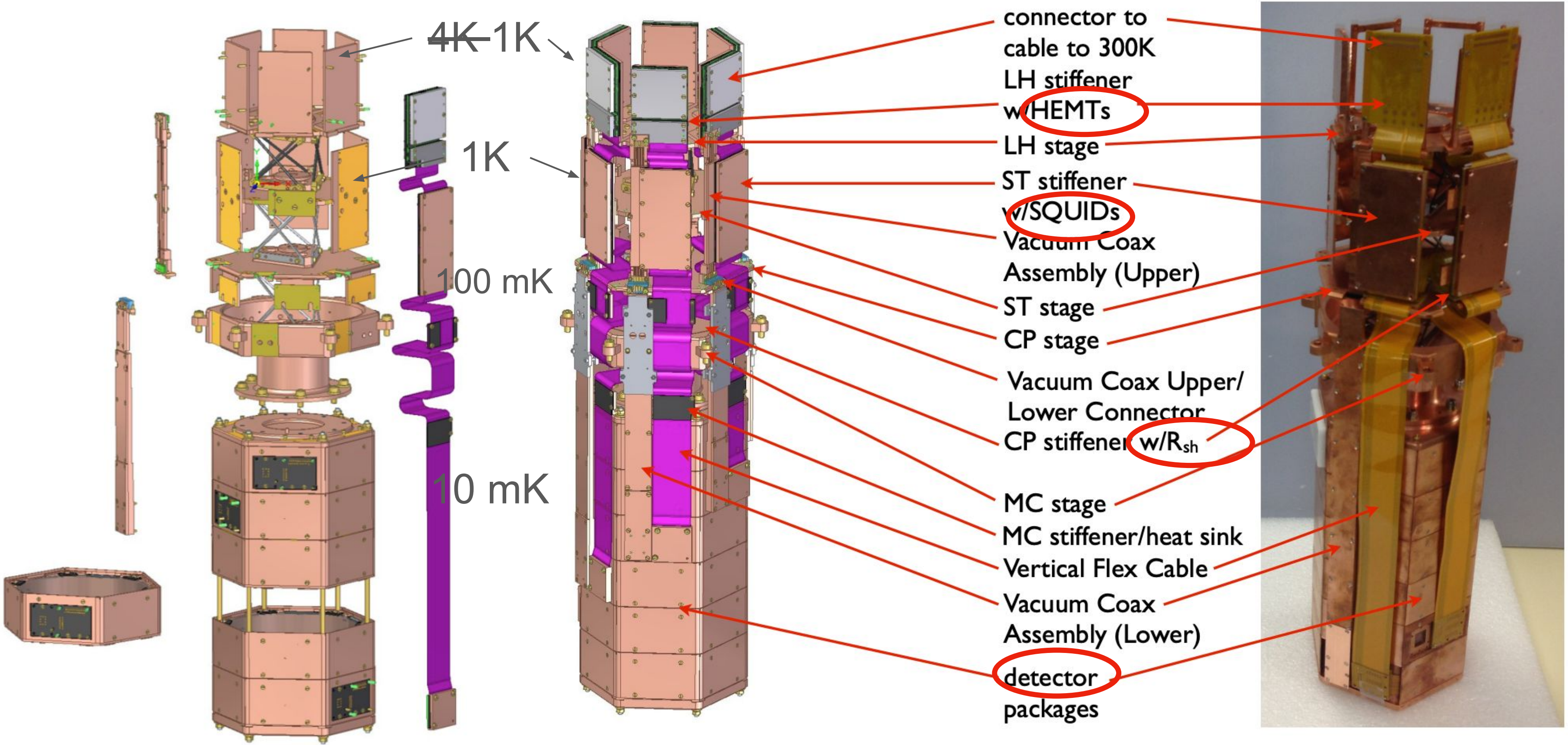


$$\frac{E}{C}$$

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

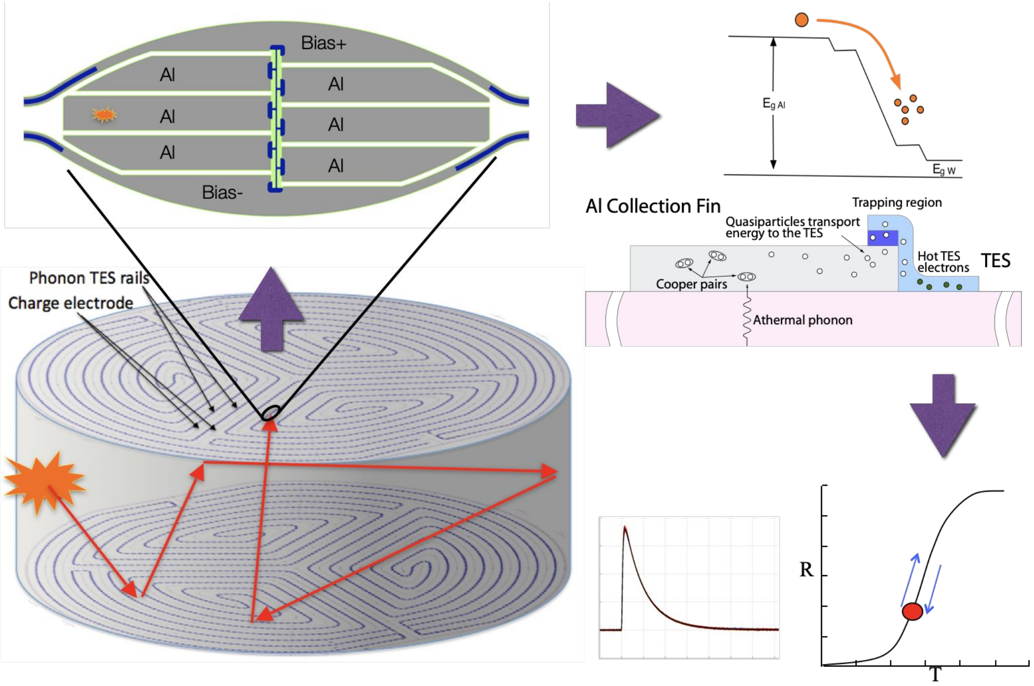


SuperCDMS Tower
Matching components to appropriate temperatures



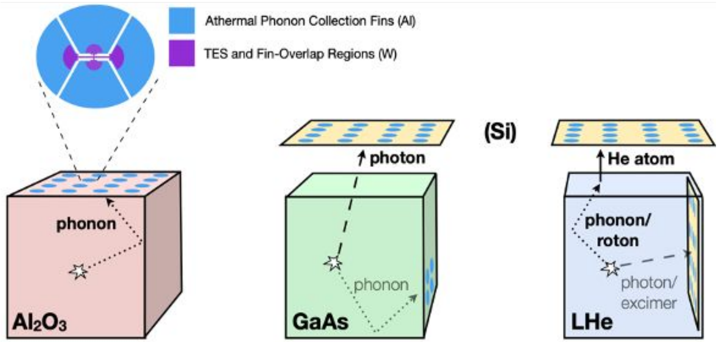
Funneling Energy to the Phonon Sensors (QETs)

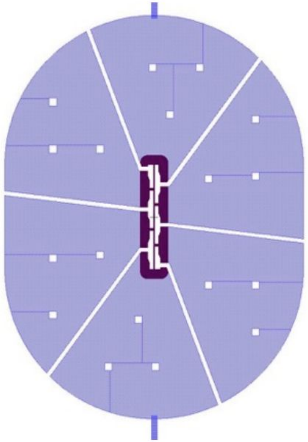
- Quasiparticle-trap-assisted electrothermal-feedback TES (QETs)
- Targeting at high energy athermal phonons before they down-convert
- Utilizing superconducting “fins” to trap phonons and funnel them to TES
- Fast (O(10 us)) detector response (in cryogenic detector sense)



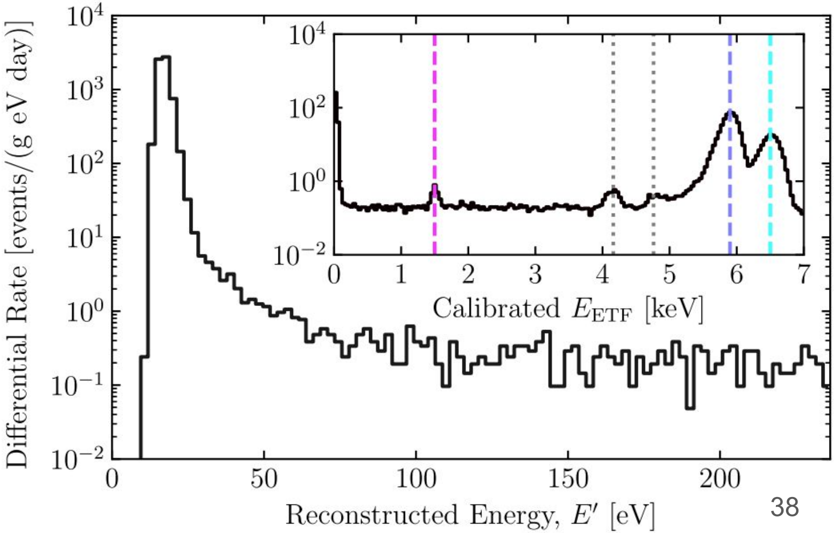
Cryogenic PhotonDetector (CPD) and TESSERACT

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





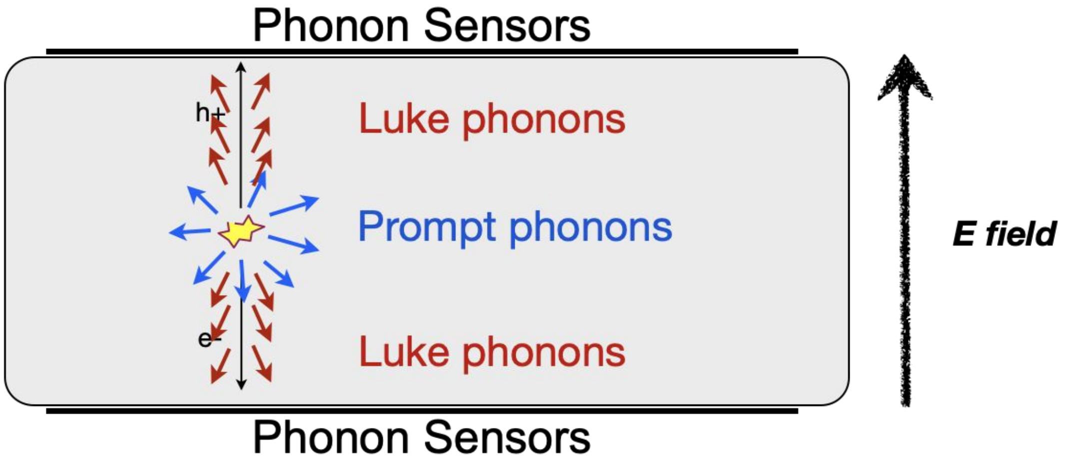
APL 118, 022601 (2021)



PRL 127, 061801 (2021)

Internal amplification - the NTL effect

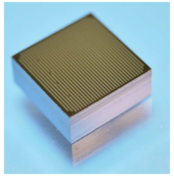
Phonon sensors measure amount of charge produced:
Phonon-based charge amplification!



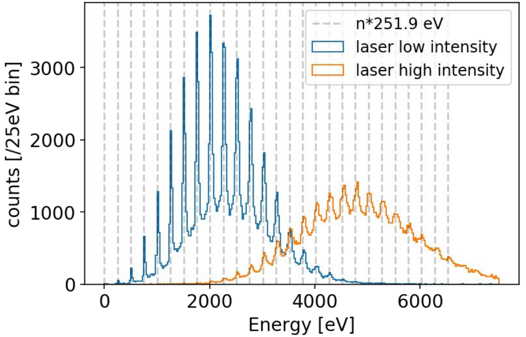
$$\text{Phonon energy} = E_{recoil} + E_{Luke}$$
$$= E_{recoil} + n_{eh}\, e^{-}\, \Delta V$$

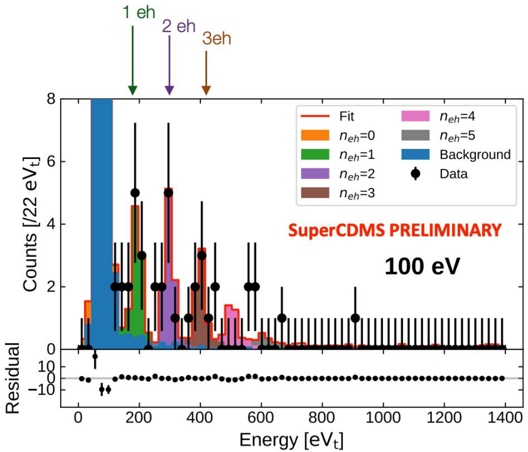
SuperCDMS High Voltage eV sensitivity Detector (HVeV)

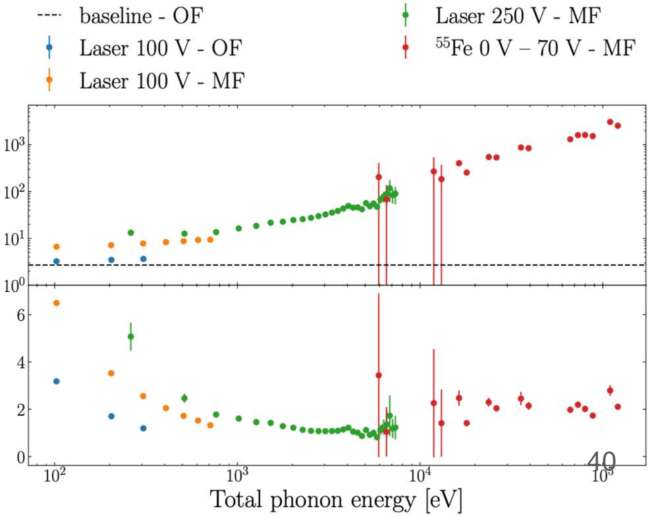
- 1 gram, silicon, QET-based, 2.7 eV resolution
- Can apply O(100 V) for NTL boost
  or operate at 0 V as pure phonon sensors
  - Particle identification by statistics
- Quantized electron-hole pair sensitivity for both ER and NR
- Scaling it up to 1 kg
  SuperCDMS HV detector

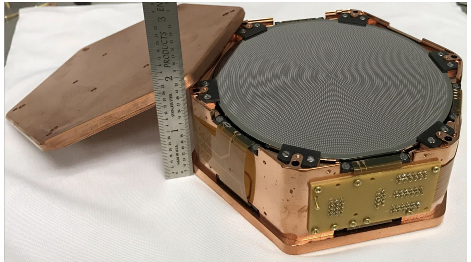


PRD 104, 032010 (2021)





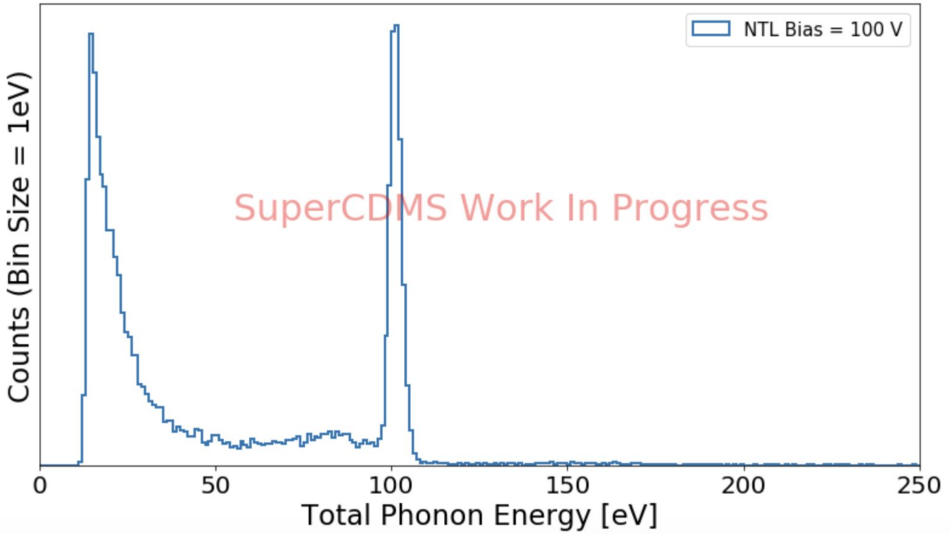




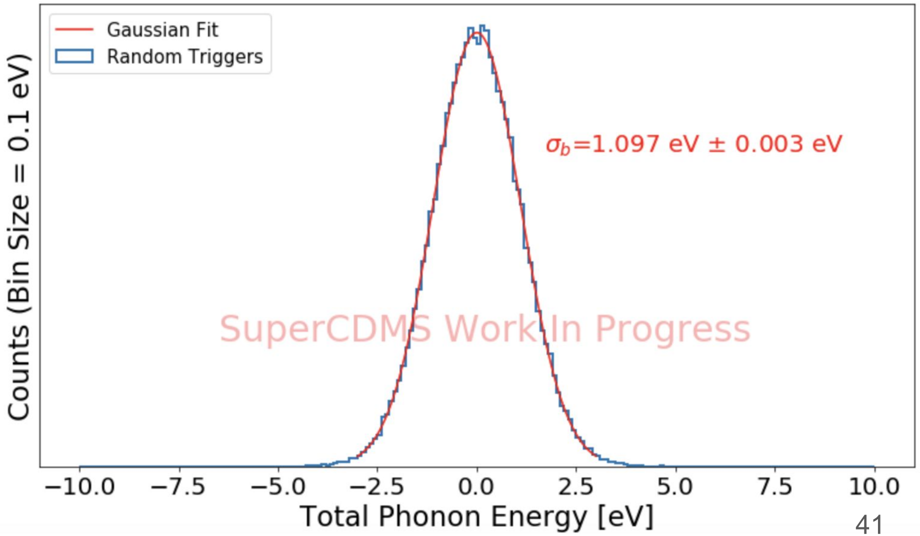
Latest Detector Performance

- “Version 3” of HVeV detectors
- Lower transition temperature
- Achieve σ_b = 1.097 eV ± 0.003 eV

Detector Spectrum



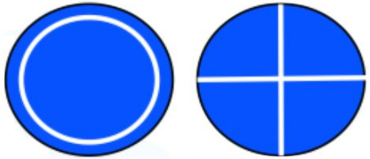
Energy of Random Triggers

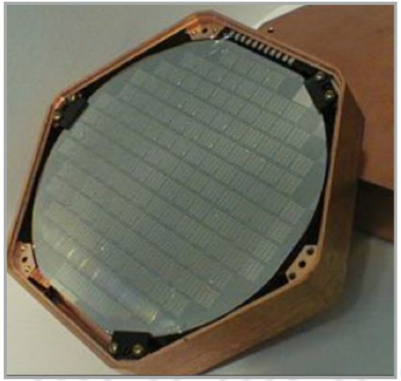


SuperCDMS detector evolutions: Retaining Position information

CDMS II (Ge+Si)

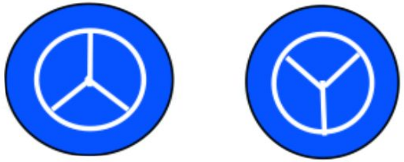
- 4.6 kg Ge (19 x 240 g)
- 1.2 kg Si (11 x 106g)
- 35% NR acceptance

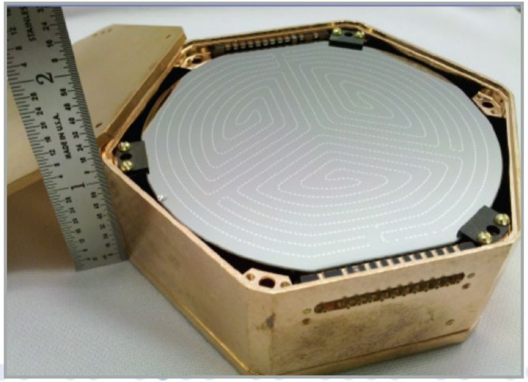




SuperCDMS Soudan

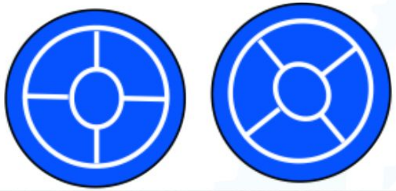
- 9.0 kg Ge (15 x 600 g)
- Increased acceptance
- Improved surface event discrimination
- Demonstrated HV performances with CDMSlite detectors

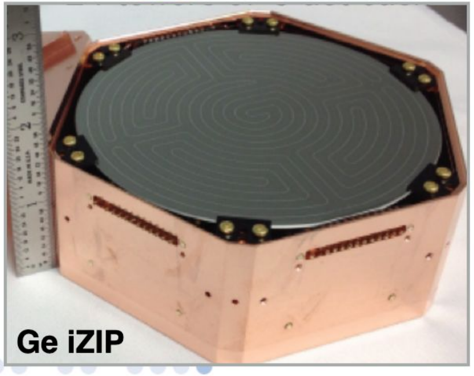




SuperCDMS SNOLAB

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

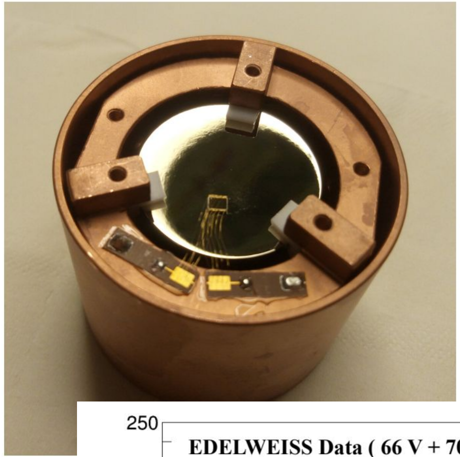


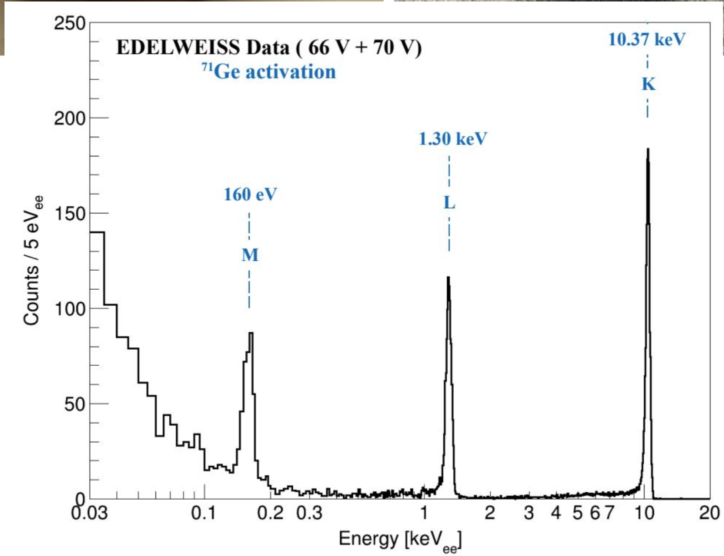


Figures from arXiv: 2202.05097
PRD 99, 082003 (2019)
PRL 125, 141301 (2020)

Edelweiss: RED20 and RED30

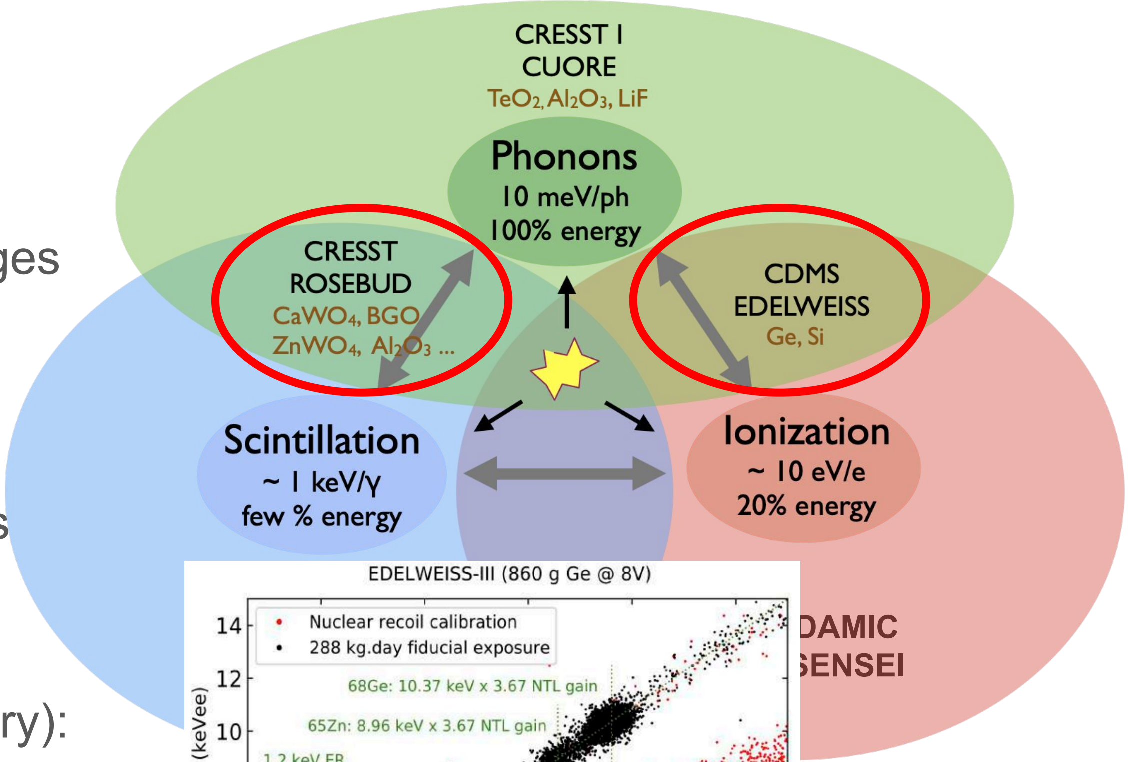
- 33 gram, germanium, NTD-based
- 18 eV phonon resolution
- RED20 operated with no E-field
- RED30 employs NTL gain to boost signals
  - With a planar electrode design
  - 8 eVee at 160 eV, consistent with Fano fluctuations





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



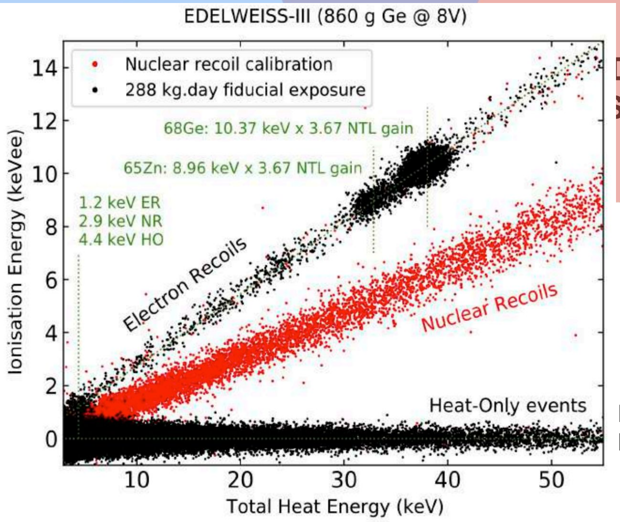
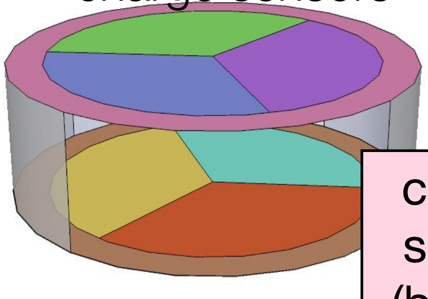
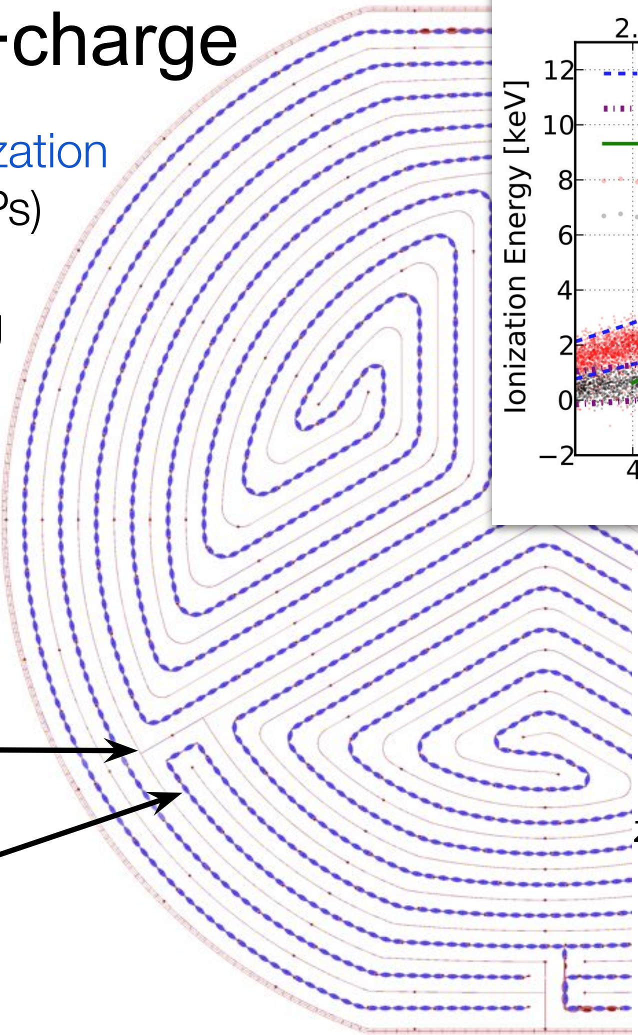


Fig. from J. Gascon, EXCESS workshop 2021

SuperCDMS: TES+charge

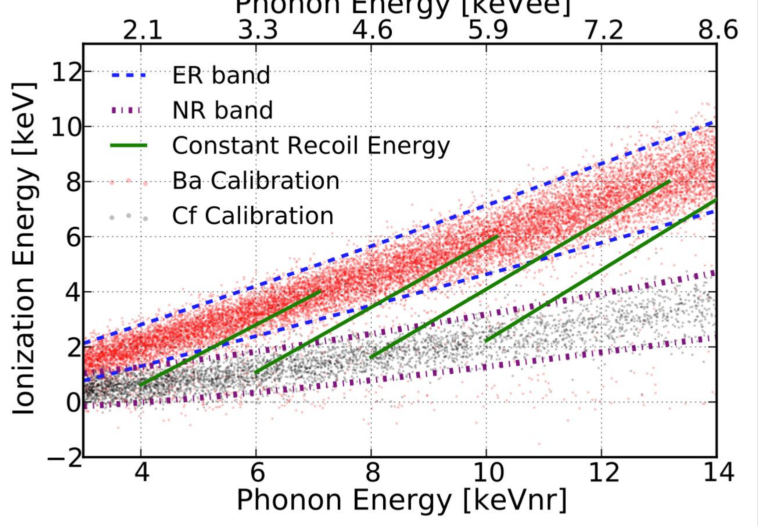
- Interleaved z-sensitive ionization and phonon detectors (iZIPs)
- Silicon and Germanium
  - Next generation ~1 kg
- 8-12 phonon channels + 4 charge sensors

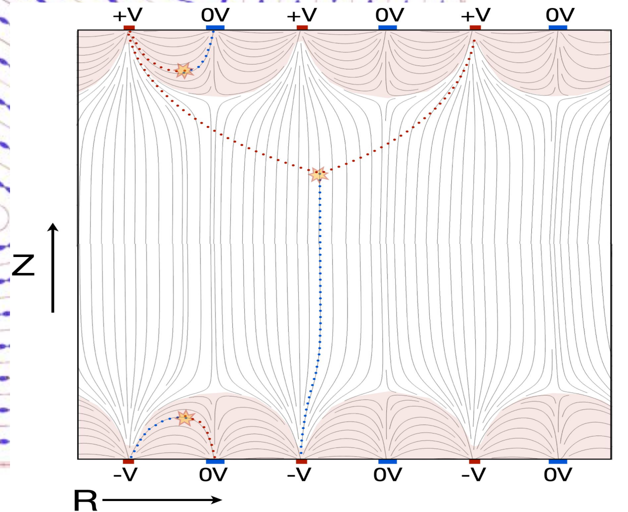




charge sensor (biased)

phonon sensor (grounded)

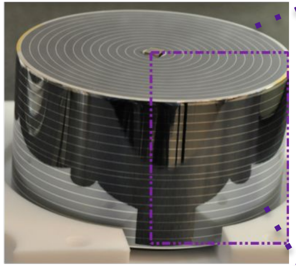




EDELWEISS: NTD/TES + charge

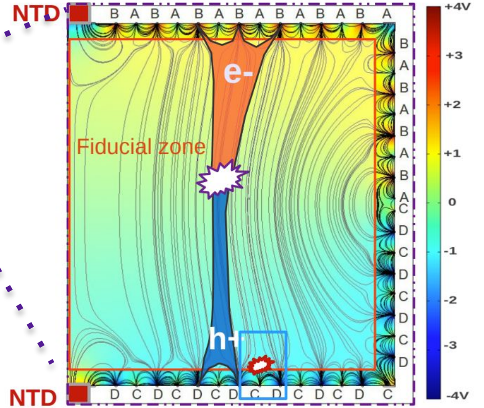
- Fully Inter-Digitized (FID) detector
  - 800 g germanium
  - 2 NTD + 4 charge channels
- NbSi209
  - 200 g germanium
  - 2 TES channel + 2 charge planar electrodes
  - TES vs NTD tests origin of the HO events
  - Charge channels help rejecting HO events
- FID38 & PL38
  - 38 gram germanium detectors,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

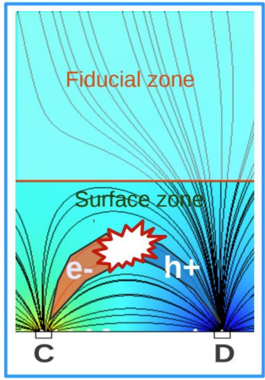
Height : 4cm



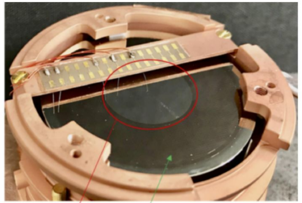
Width : 7cm

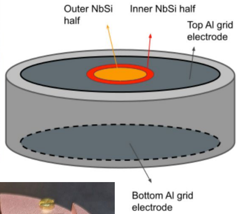
PRD 97 (2018) 022003



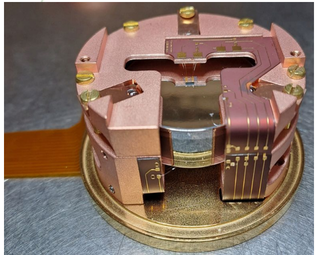


arXiv: 2203.03993



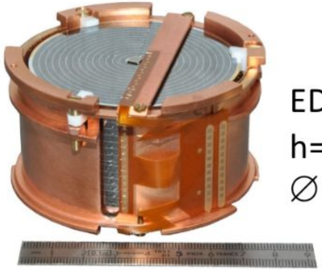


Nb_xSi_{1-x} spiral

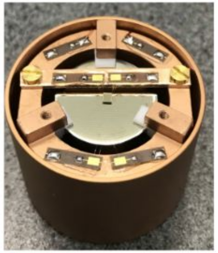


Ricochet CryoCube detector: Edelweiss legacy

Cryogenic Ge semiconductor detectors



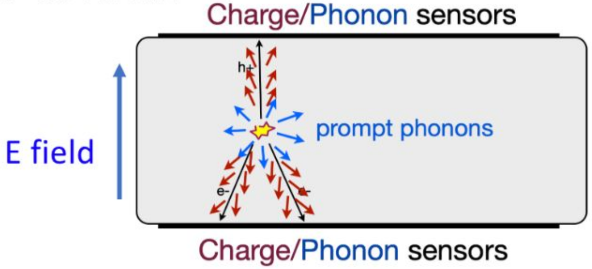
EDW ~800g
h=40mm
∅ 70mm



EDW RED30 ~*32-g*
h=20mm
∅ 20mm

Ricochet ~*42-g*
h=10mm
∅ 30mm

T~10-20 mK

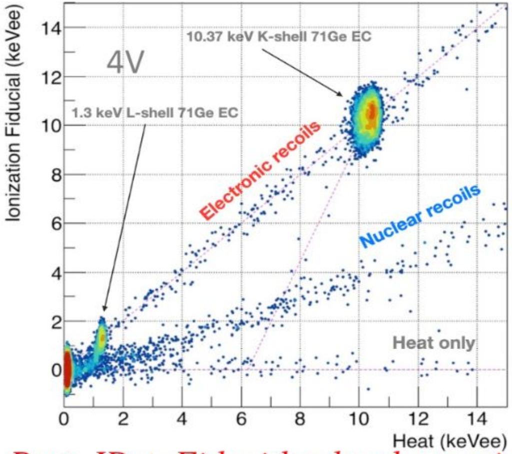


$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + \frac{1}{3\ eV} E_{ion} \Delta V$$

Particle ID based on **Ionization/heat** ratio

$Q = E_{ion}/E_{recoil}$

- Q=1 for **electron recoils** (γ,β)
- Q ≈ 0.3 for **Ge nuclear recoils** (neutrons, CEvNS, WIMPs)

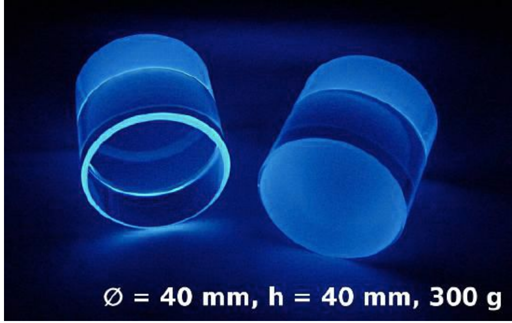


Excess Workshop 2023, Excess Workshop 2024, July 6th

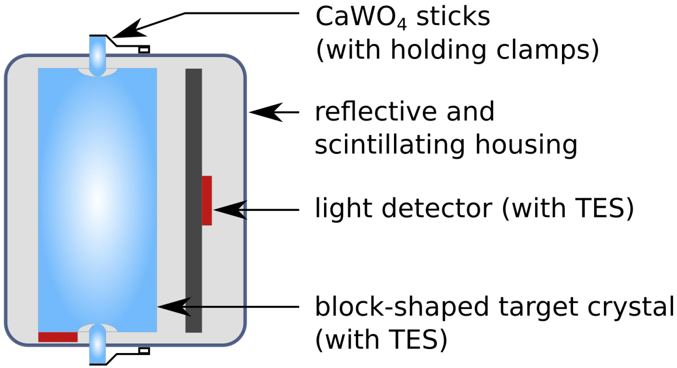
Part. ID + Fid with edw electronics in LIO cryostat @ ip2i

Slide from Maryvonne De Jesus

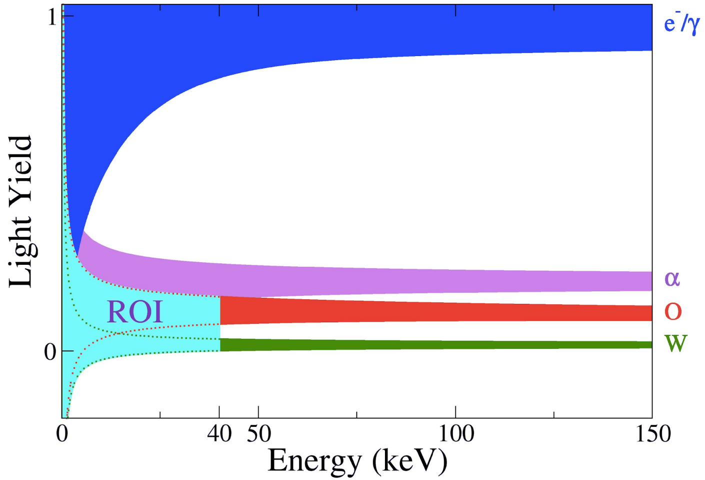
CRESST: TES + Light + Active Veto



- $CaWO_4$ 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



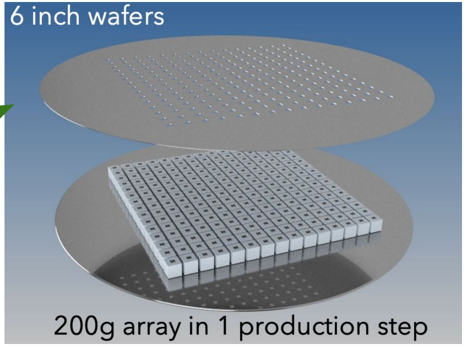
J. Phys.: Conf. Ser. 1342 012076

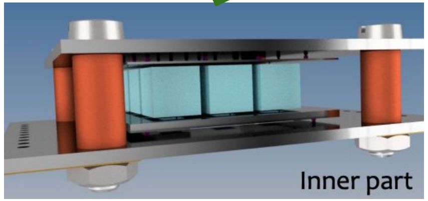


NUCLEUS: TES + Active Veto

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

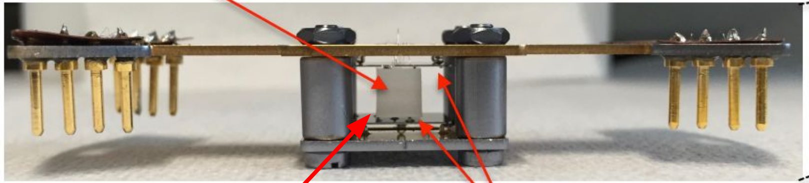
Further up

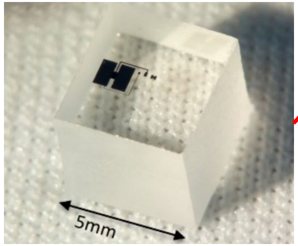




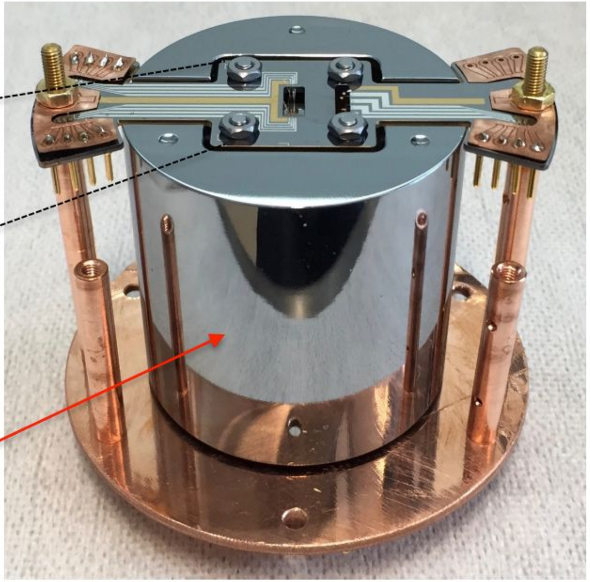
Scale up

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





Inner veto (Si)



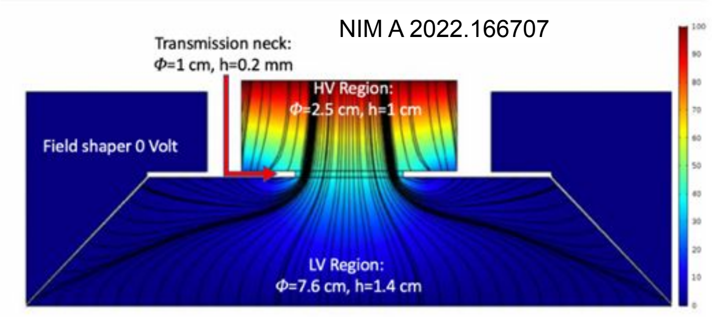
Outer veto (Ge, $LiWO_4$)

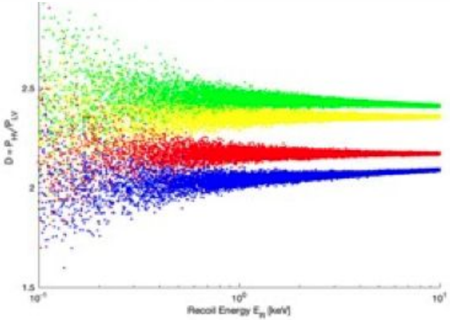
Fig. from R. Strauss, m7s 2019
PRD 96, 022009 (2017)

BASKET@CEA

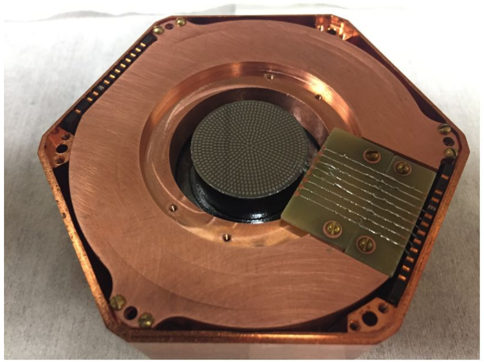
MINER: Hybrid Phonon detector

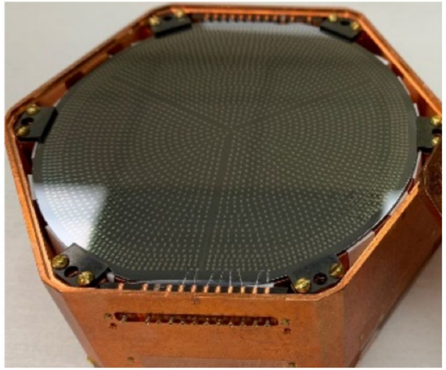
NIM A 2022.166707



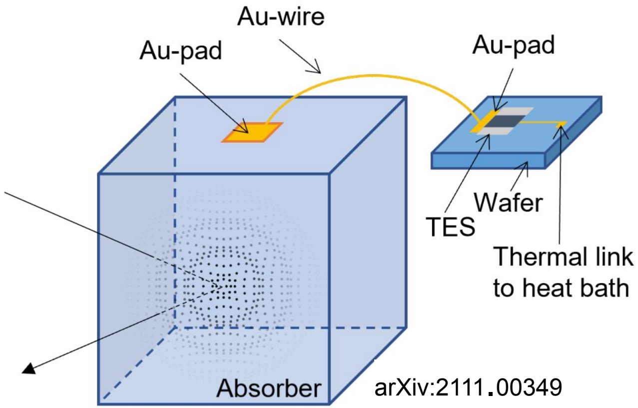


- Separate crystal into a low-voltage (LV) and a high-voltage (HV) region
- Phonon sensors on both sides
- Use the LV region as the fiducial volume
- Shape E-field to guide charges through the “neck”
- NTL phonons from the charges dominates in the HV side, whereas recoil phonons dominate the LV side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

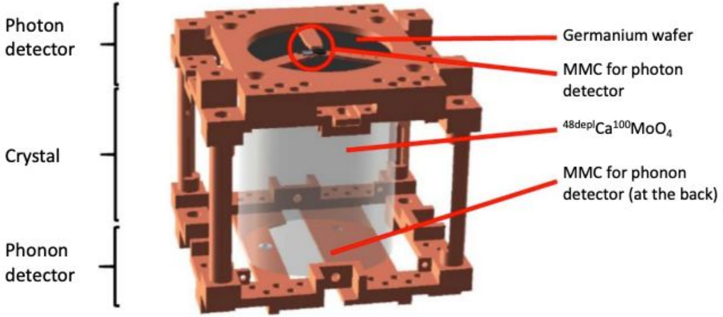




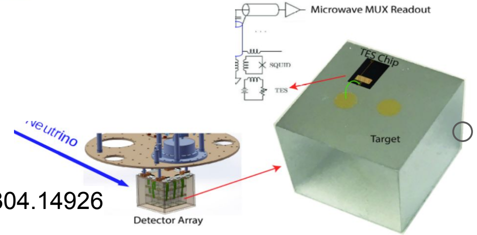
Modular design: detaching thermometer from absorber



arXiv:2111.00349



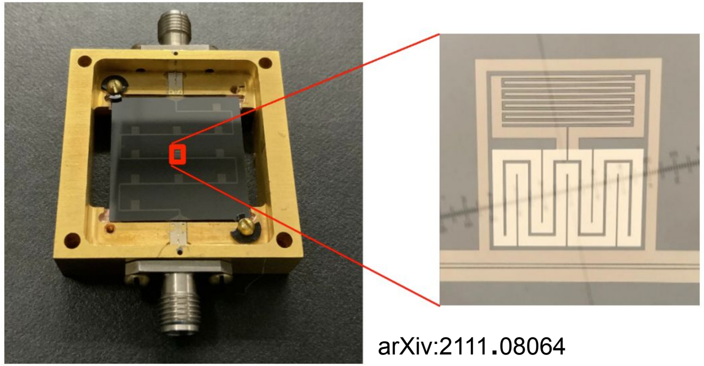
arXiv:1903.09483



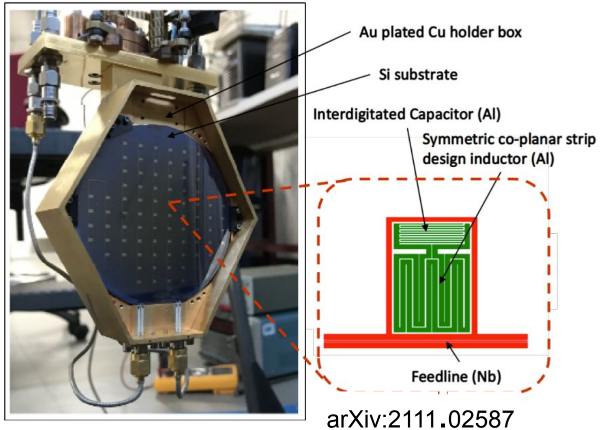
arXiv:2304.14926

- 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 0νββ

Multiplexing with RF resonators



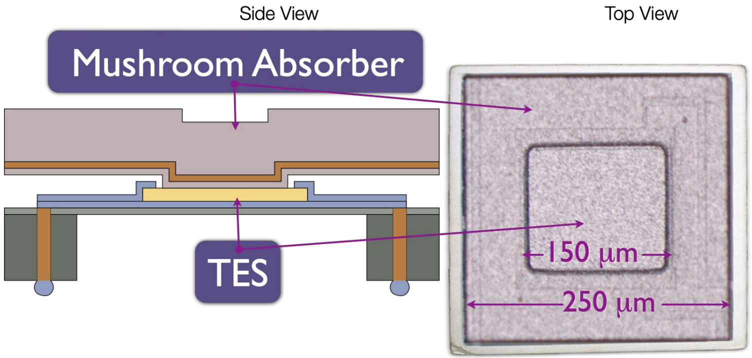
arXiv:2111.08064



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



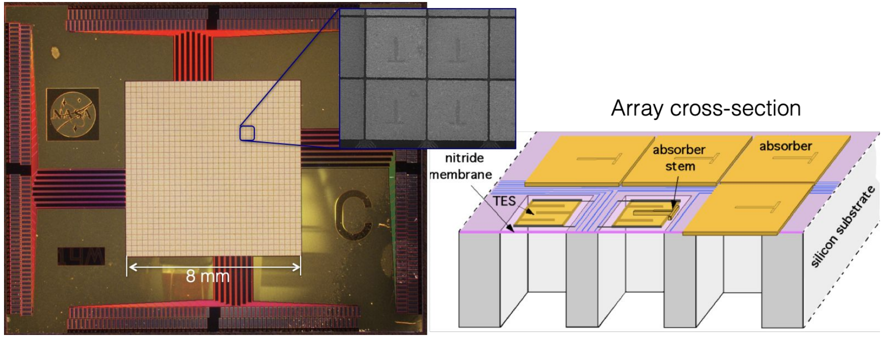


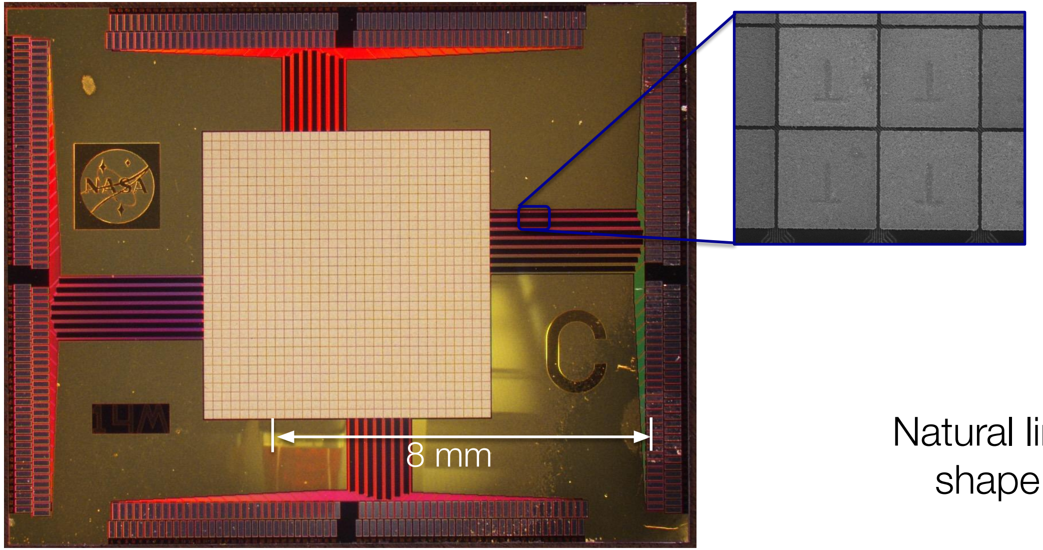
Fig. from E. Figueroa, COFI PIRE 20017

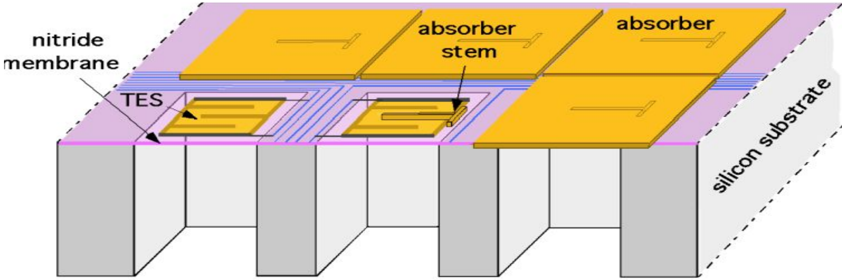
- Cryogenic microcalorimeters also contributes in DM studies in astrophysics and indirect searches
- Arrays of eV-resolution sensors make perfect X-ray detectors
  - Like an ultra-sensitive camera
- Widely used in earth-based X-ray telescopes as well as rocket and satellite-based detectors

Transition-edge sensor arrays

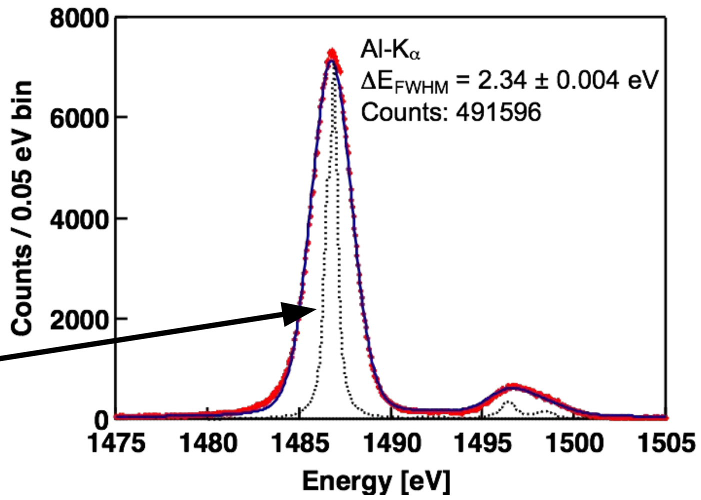
- NASA Goddard Space Flight Center TES Arrays

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



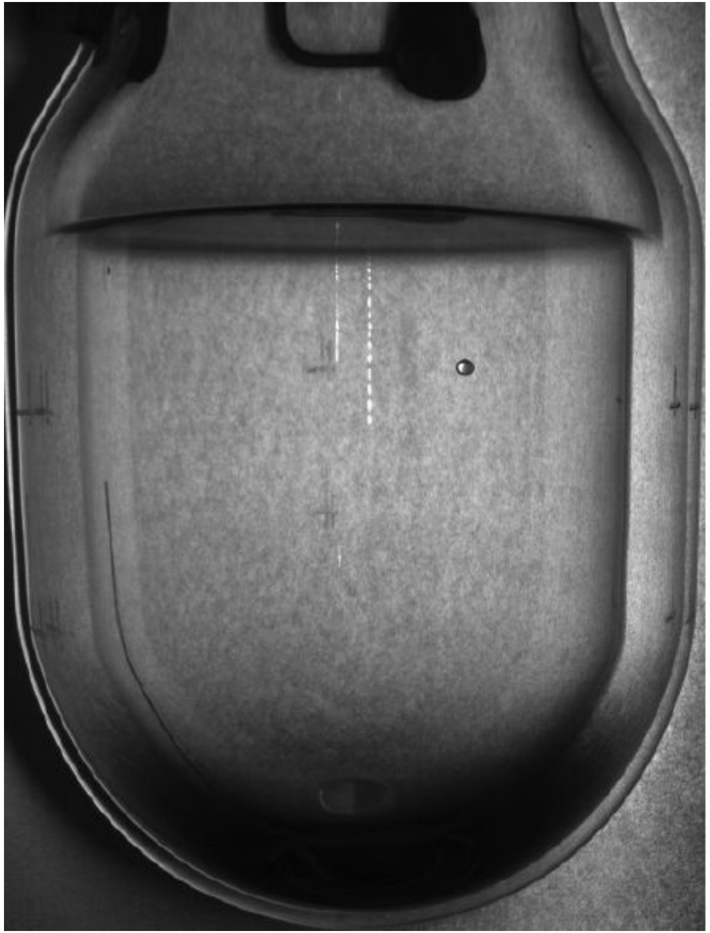


Natural line shape

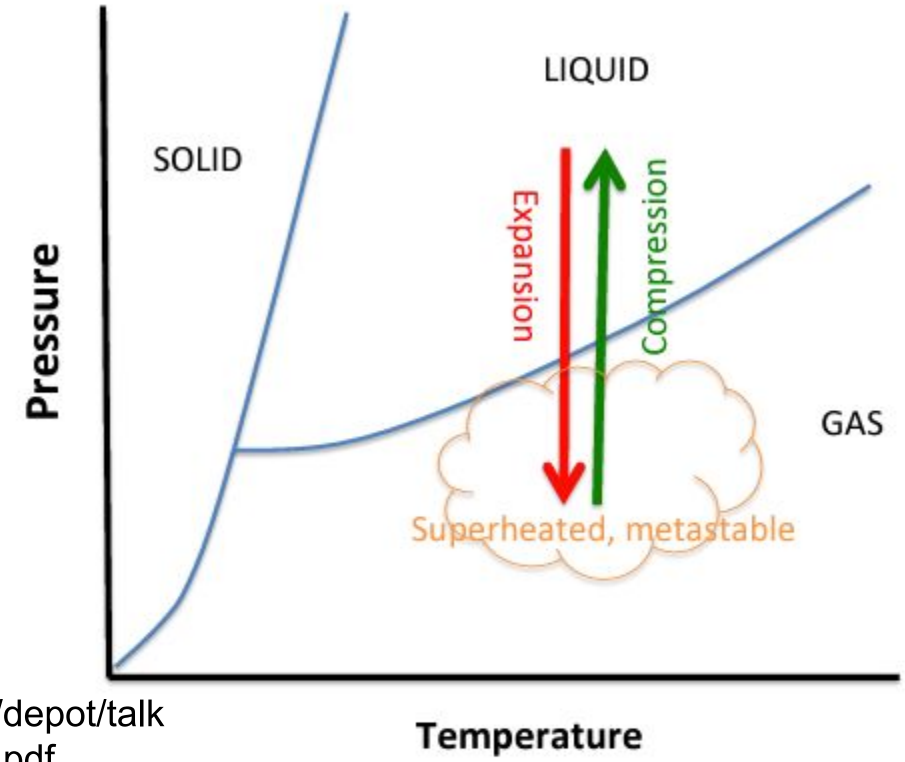


PICO Bubble Chamber

- Insensitive to gamma backgrounds due to dE/dx needed to nucleate a bubble.
- Slow detector, but OK for rare event searches
- Alpha discrimination by **acoustic**
    - Alpha popping is x4 louder



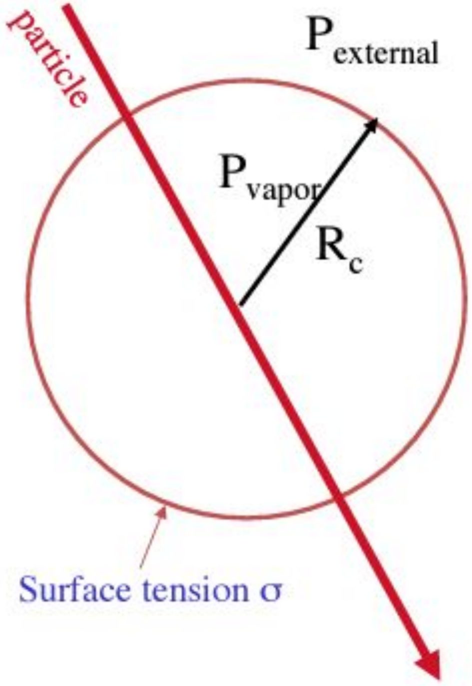
Bubble Chamber Expansion/ Compression Cycle



https://kicp.uchicago.edu/depot/talks/2016-01-19-colloquium.pdf

Bubble Nucleation by Radiation

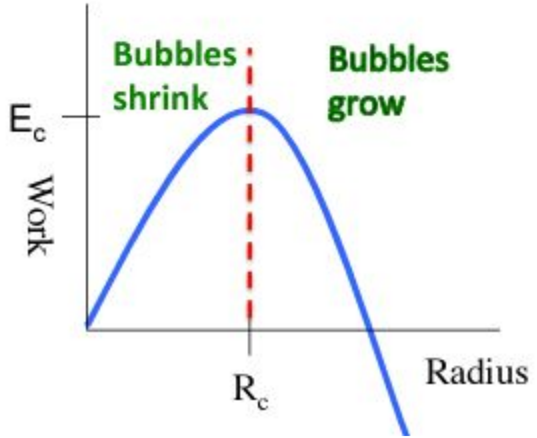
(Seitz, "Thermal Spike Model", 1957)



- Pressure inside bubble is equilibrium vapor pressure.
- At critical radius R_c surface tension balances pressure.

$$R_C = \frac{2\sigma}{P_{vapor} - P_{external}}$$

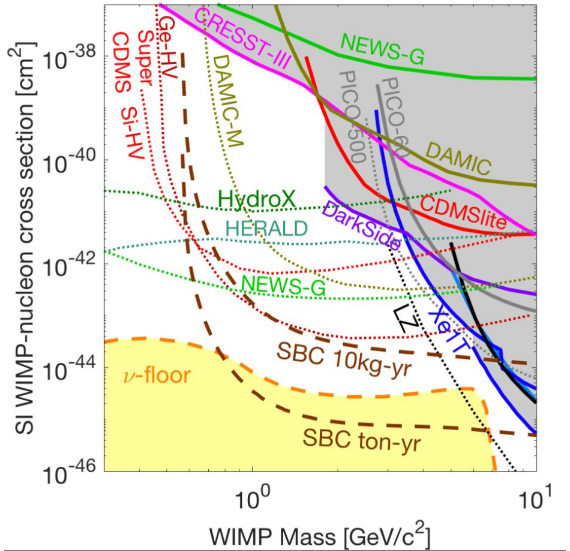
- Bubbles bigger than the critical radius R_c will grow; smaller bubbles will shrink to zero.



https://kicp.uchicago.edu/depot/talks/2016-01-19-colloquium.pdf

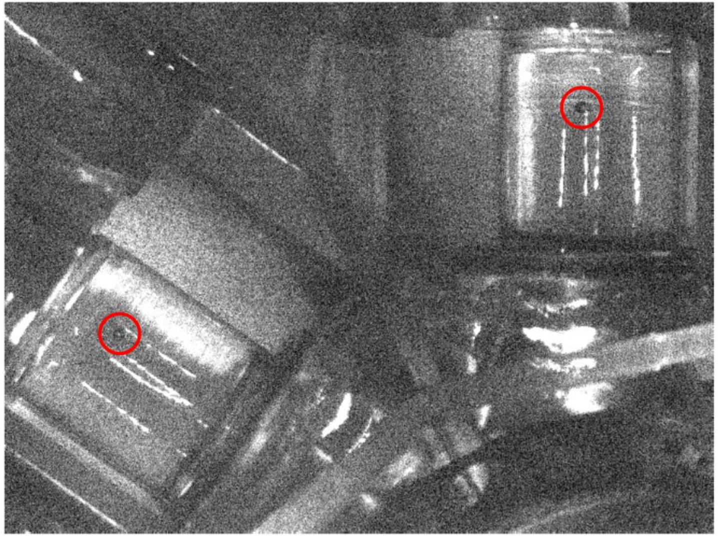
Scintillating Bubble Chamber

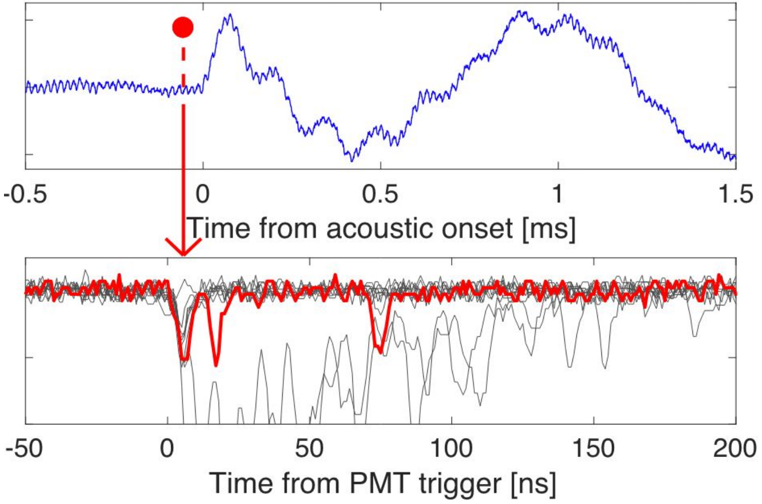
- Bubble + Popping sound + light
- "Combine the electron recoil discrimination of bubble chambers with the event-by-event energy resolution of scintillation detectors"



https://www.osti.gov/servlets/purl/2202831

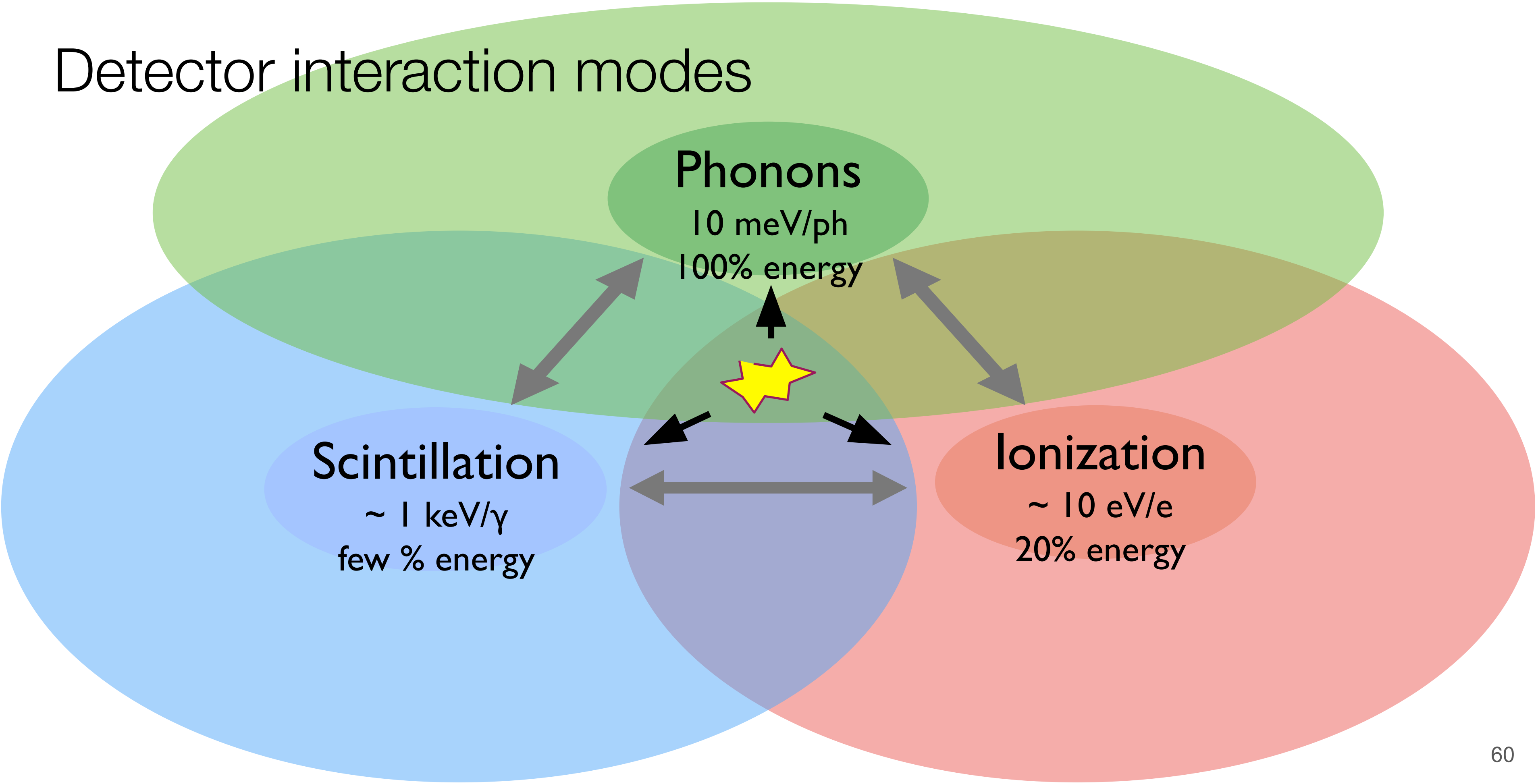
FERMILAB-SLIDES-21-064-E





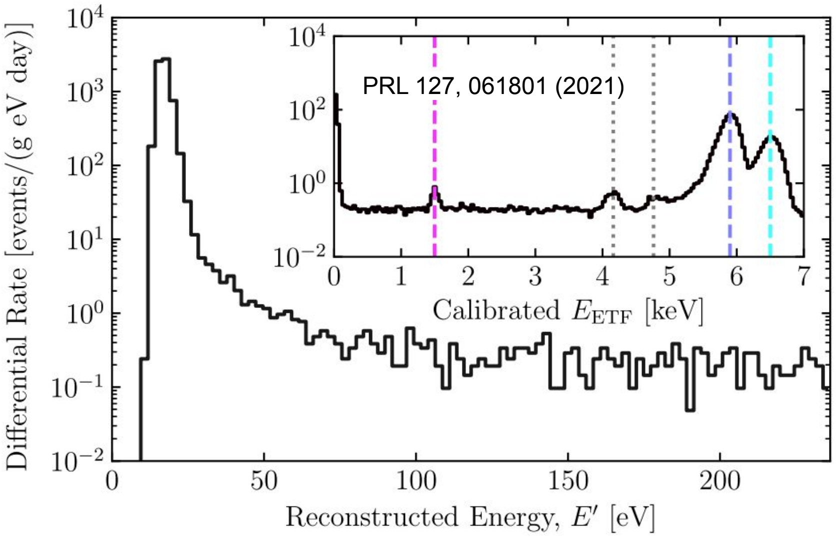
How to interpret the signal?

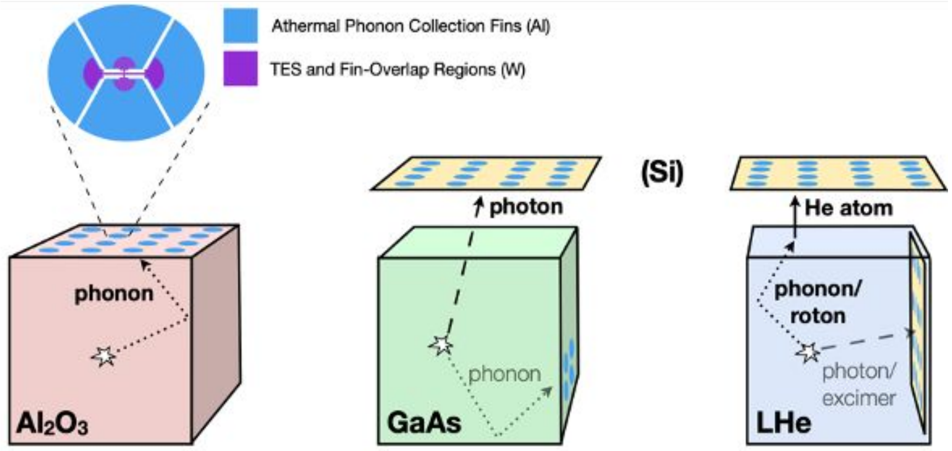
Detector interaction modes



Some phonon only detectors can be straight forward

- CPD/TESSERACT
- **No voltage on crystal**
- Phonon sensed == energy deposited

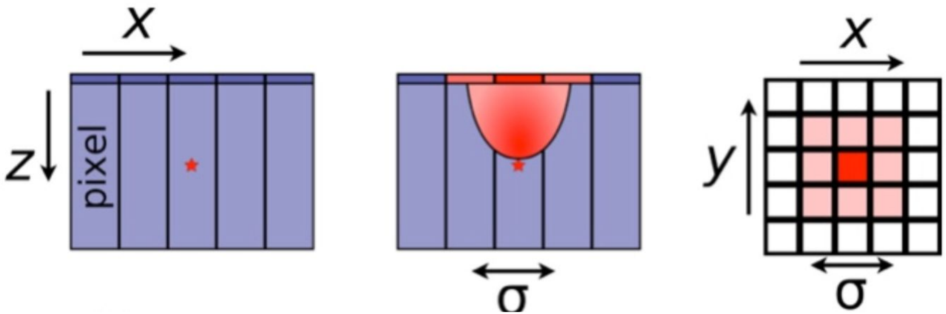


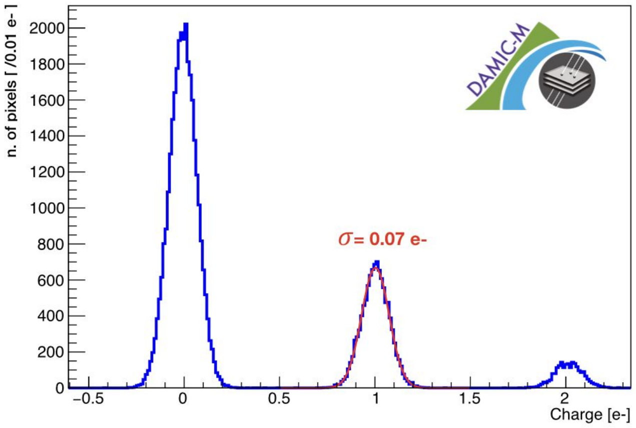


https://www.npl.washington.edu/damic/description
https://damic.uchicago.edu/detector.php

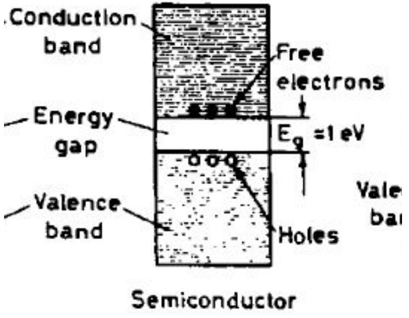
Charge detectors need some translations

- Eg. DAMIC/SENSEI takes a picture of particle interaction
- Charges generated per pixel is precisely counted
- Need a relation between # of charge <-> Energy
- → **“Ionization Yield”**
- Different between electron recoil and nuclear recoil





Ionization Yield for Electron Recoils



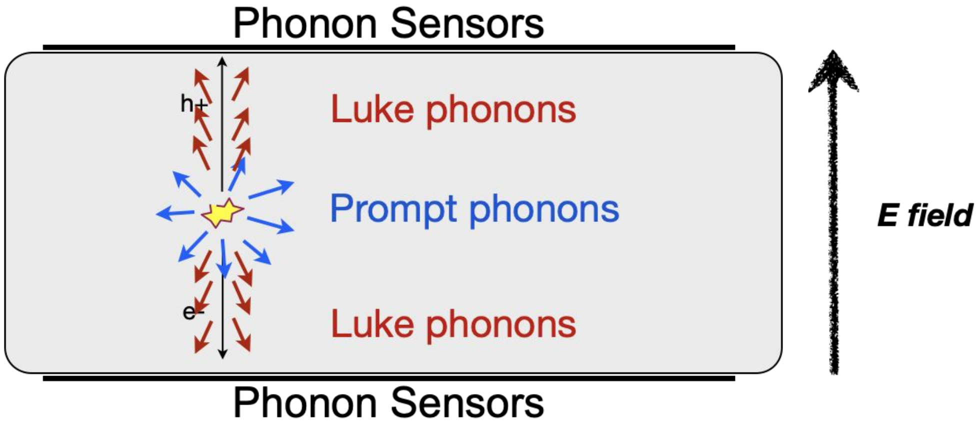
- Initial electron recoil can excite electrons to completely free state (or not), then cascade to multiple electron-hole/ electron-ion pairs
- Averaged number of charge carriers

$$\langle N \rangle = E / \epsilon$$

- ϵ = 3 eV for Germanium, ~30 eV for gas
- All interactions dumping energy into the **electron system** go through the same electron-hole cascade process
- Processes depositing energy into the **nuclear system** is a bit different

Phonon detectors can also be complicated after Voltage applied

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



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

Fluctuation of ionization yield

Si:	0.128 ± 0.001[7] (at 5.9 keV)
Ar (gas):	0.20 ± 0.01/0.02[8]
Xe (gas):	0.13 to 0.29[9]
CZT:	0.089 ± 0.005[10]

- $\langle N \rangle = E / \epsilon$
- Doesn’t follow Poisson distribution…
- Lots of charges comes from secondary ionizations
  - Breaks the “independent” condition in Poisson distribution
- “Fano Factor”
  - $\sigma^2(N) = F * \langle N \rangle$, F ofen <1
  - Energy conservation constraining randomness of ionization

PHYSICAL REVIEW VOLUME 72, NUMBER 1 JULY 1, 1947

Ionization Yield of Radiations. II. The Fluctuations of the Number of Ions

U. Fano
X-Ray Section, National Bureau of Standards, Washington, D. C.
(Received March 7, 1947)

The ionization produced by individual fast charged particles is frequently used as a measure of their initial energy; fluctuation effects set a theoretical limit to the accuracy of this method. Formulas are derived here to estimate the statistical fluctuations of the number of ions produced by constant amounts of radiation energy. The variance of the number of ionizations is found to be two or three times smaller than if this number were governed by a Poisson distribution. An improved understanding is gained of the statistical treatment of fluctuation phenomena.

https://arxiv.org/pdf/2004.10709.pdf

Near ionization threshold

- These averaged behaviors break near ionization threshold
- Example scenarios:
  - Photon incident on silicon (band gap 1.1 eV, ϵ = 3.8 eV)
    1. 2 eV photon on silicon
    2. 10 eV photon on silicon
    3. 0.9 eV photon on silicon…
- Both ϵ and F seem to be temperature and energy dependent…

Parameter	Value	Temperature	Source	Reference
F	0.118	110 – 240 K	5.9 keV γ	[25]
	0.117	180 K	5.9 keV γ	[26]
	0.14 – 0.16	180 K	2 – 3.7 keV γ	[27][a]
	0.128	130 K	5 – 8 keV γ	[28]
	0.119	123 K	5.9 keV γ	[29]
ϵ_{eh}	3.66 eV	300 K	1 eV – 1 keV γ	[30]
	3.66 eV	300 K	115 – 136 keV e,γ	[31]
	3.63 eV	300 K	1 MeV e^-, 5.5 MeV α	[32]
	3.62 eV	300 K	5.5 – 6.3 MeV α	[31]
	3.67 eV	180 K	2 – 3.7 keV γ	[27]
	3.749 eV	123 K	5.9 keV γ	[29]
	3.75 eV	110 K	5.9 keV γ	[25]
	3.70 eV	100 K	5.5 MeV α	[33]
	3.72 eV	6 – 70 K	480 keV γ	[34]
	3.72 eV	5 K	5.5 MeV α	[33]
E_g	~1.12	300 K	Photoabsorption	[23]
	1.127	290 K		[24]
	1.164	110 K		[24]
	1.166	90 K		[24]
	1.169	0 K		[23]
	1.170	0 K		[24]
A	5.2 eV^2[b]	300 K	2 – 5 eV e^-	[19]
$\hbar\omega_0$	59 meV (TO), 62 meV (LO)	N/A	DFT[c]	[17]
$\hbar\omega_{pl}$[d]	16.6 ± 0.1 eV	N/A	EELS[e]	[35]

Modeling (near threshold) ionization yield

- Often model ionization yield with some integral equation
  - Eg.

$$n(E_r) = 1 + \int_{E=0}^{E_r - E_g} dE P(E, E_r) \langle N(E) \rangle$$

- Based on micro physics with assumptions
  - Eg. how does energy split between electrons and holes
- Specify initial and boundary conditions
- Solve integral equation numerically, or via Monte Carlo methods
- Similar approach used to model nuclear recoil ionization yield

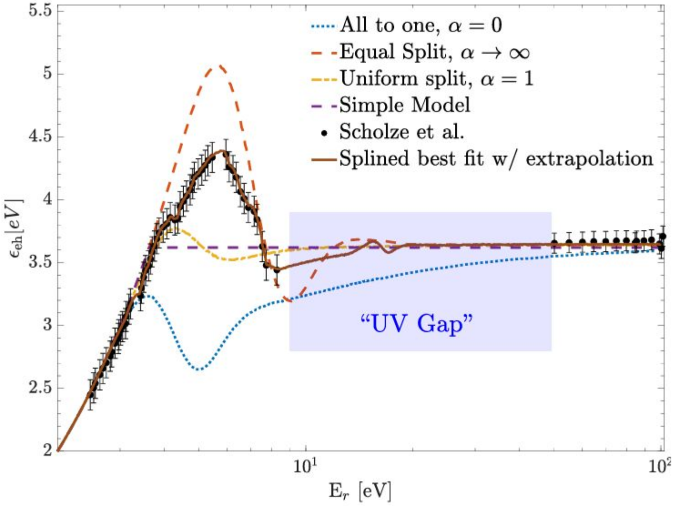
$$\epsilon_{eh}(E_r) = \begin{cases} \infty & E_r < E_g \\ E_r & E_g \le E_r < 2E_g \\ \epsilon_{imp}(E_r) & E_r \ge 2E_g \\ \epsilon_{eh,\infty} & E_r \to \infty \end{cases}$$

$$F(E_r) = \begin{cases} 0 & E_r < 2E_g \\ F_{imp}(E_r) & E_r \ge 2E_g \\ F_\infty & E_r \to \infty \end{cases}$$

https://arxiv.org/pdf/2004.10709.pdf

Near threshold ionization yield

- Result of a recent model



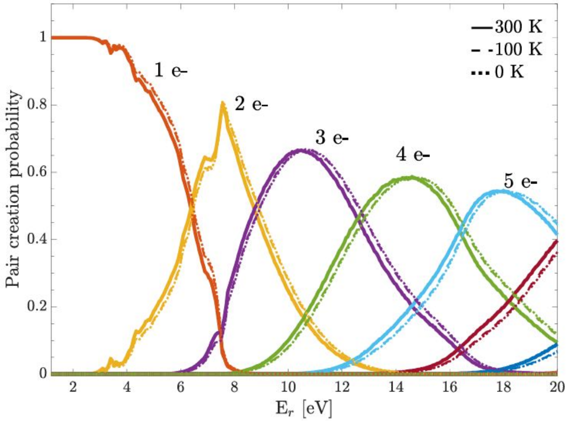
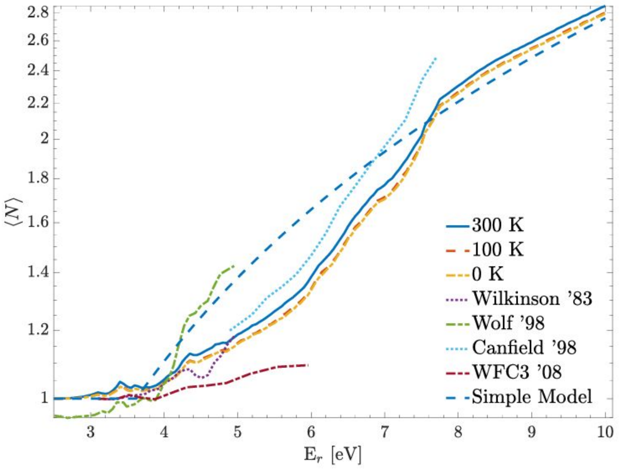
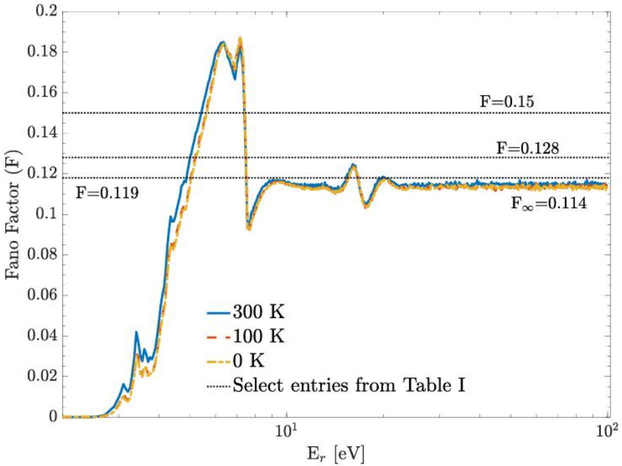


FIG. 6. Pair-creation probability distributions for best-fit model at 0 K, 100 K and 300 K (former curves effectively overlap). These lines are to be interpreted as the probability to ionize the labeled number of charge pairs for a given deposited energy. These are *not* PDFs in that only the sum of curves across a given point in energy is normalized to 1.



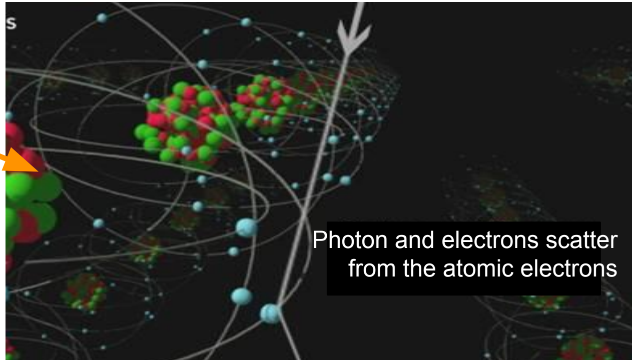


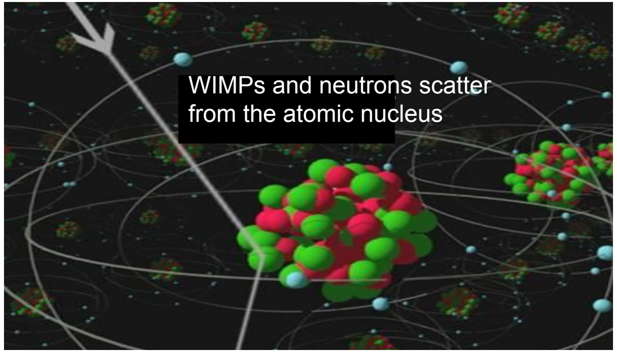
Nuclear Recoils

ELECTRON RECOILS (ER)

Gamma: Most prevalent background

Beta: on the surface or in the bulk





NUCLEAR RECOILS (NR)

Neutron: NOT distinguishable from WIMP

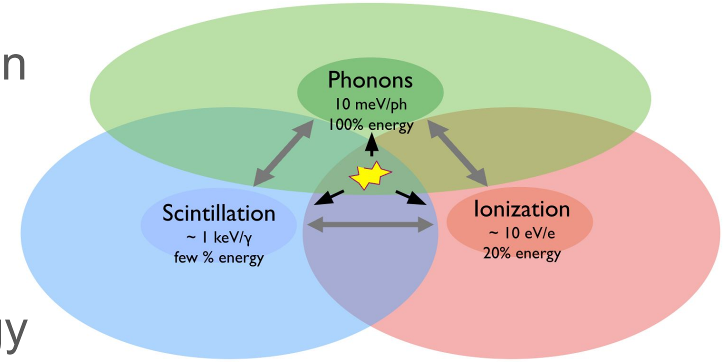
Alphas: almost always a surface event

Recoiling parent nucleus: yet another surface event

Energy loss of a recoiling nucleus in a medium

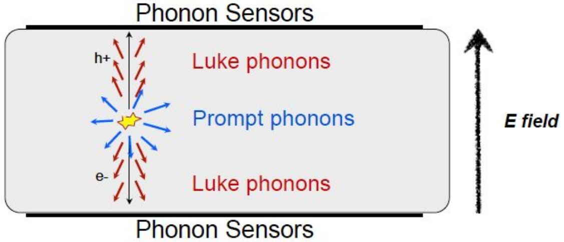
- Energy transfer from a slow-moving nucleus to electrons is inefficient
  - Due to large mass disparity
- Only a small fraction of energy is channeled into the electron system
  - → Ionization, excitation, scintillation, etc.
- Majority of energy is transferred to atomic motion
  - → Heat
- Ionization/scintillation yield (Quenching factor)

  $Q = \frac{E_I}{E_R}$, E_I: ionization energy; E_R: recoil energy
- Can model with software like SRIM
- Or with analytical models
- (Neither is great for near threshold)



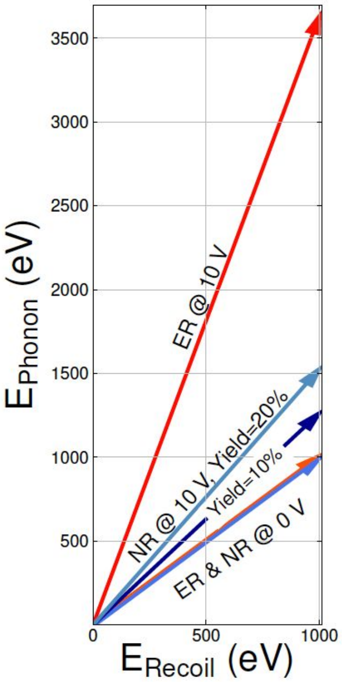
Why is this important?

Getting Y wrong → Misinterpreting WIMP signal!



$$
\begin{aligned}
E_{\text{Phonon}} &= E_{\text{Recoil}} + E_{\text{NTL}} \\
&= E_{\text{Recoil}} + n_{\text{eh}} e^{-} V \\
&= E_{\text{Recoil}} + E_{\text{Recoil}}/\epsilon \cdot Y(E_{\text{Recoil}}) e^{-} V
\end{aligned}
$$

- ϵ: average e-h creation energy
  - $\sim$4 eV for Si, $\sim$3 eV for Ge
- $Y(E_{\text{Recoil}})$: ionization yield/quenching factor
  - For electron recoil, $Y = 1$
  - For nuclear recoil, it's energy dependent



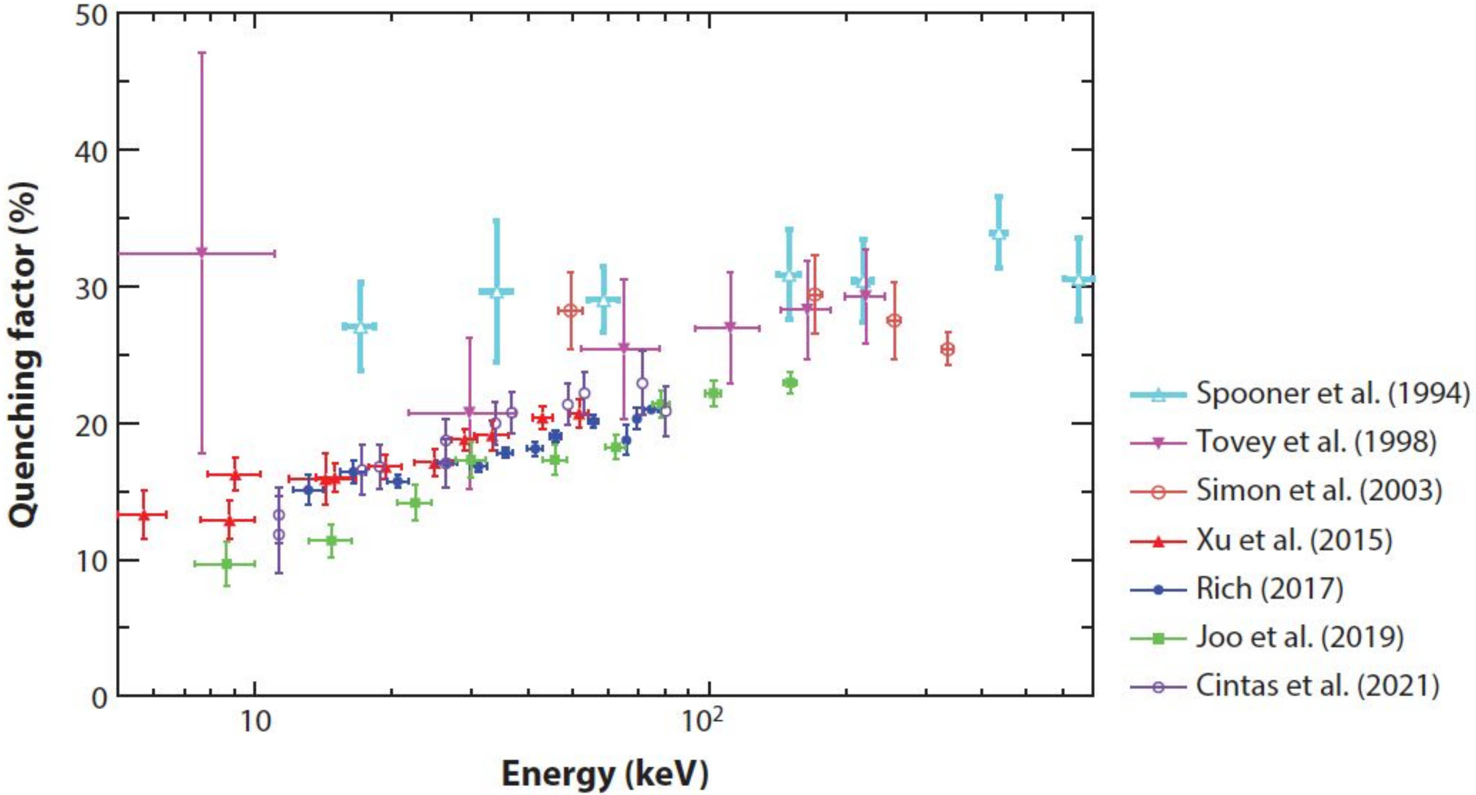
Scintillation yield -- Birks' law

- Scintillation yield per path length

$$\frac{\mathrm{d}L}{\mathrm{d}x} = \frac{S}{1 + kB\frac{\mathrm{d}E}{\mathrm{d}x}}\frac{\mathrm{d}E}{\mathrm{d}x},$$

- S is the scintillation efficiency
  dE/dx is the linear energy transfer by the ionizing particle to the medium
  kB is the Birks quenching coefficient
- Derived for organic scintillators
- Applicable to some inorganic scintillators as well

Near threshold scintillating yield (Quenching factor)



Slide from Y. Sarkis @ Magnificent CEvNS 2020
Phys.Rev.D101,102001(2020)

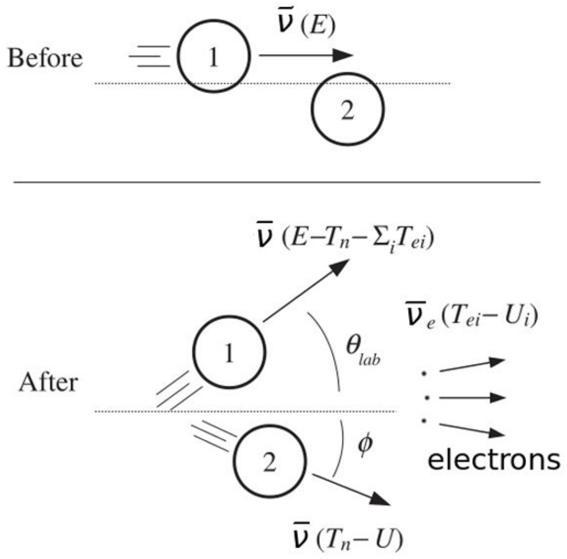
Trying to relax a few of these assumptions

Ionization yield -- Lindhard model

$$\underbrace{\int d\sigma_{n,e}}_{total\ cross\ section}\left[\underbrace{\bar{\nu}\left(E-T_n-\sum_i T_{ei}\right)}_{A}+\underbrace{\bar{\nu}\left(T_n-U\right)}_{B}-\underbrace{\bar{\nu}(E)}_{C}+\underbrace{\sum_i \bar{\nu}_e\left(T_{ei}-U_{ei}\right)}_{D}\right]=0 \qquad (2)$$

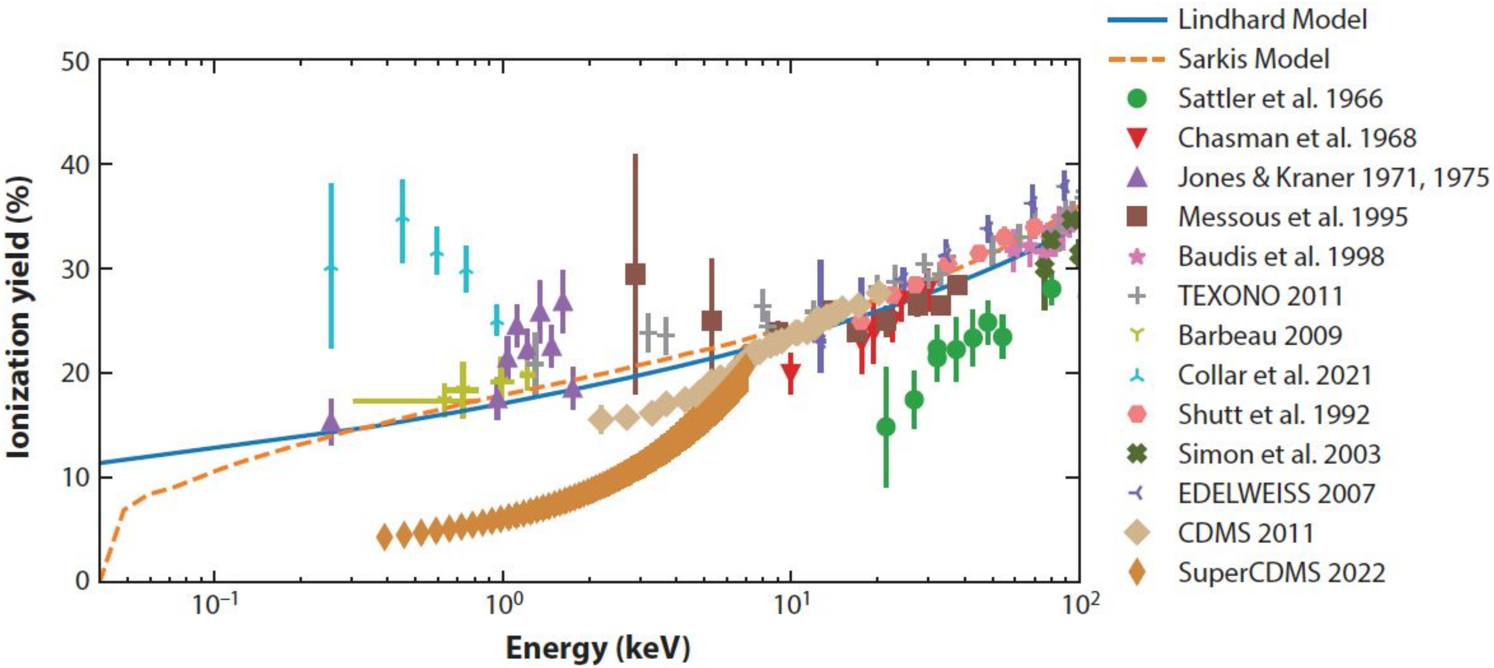
Lindhard's (five) approximations

- I Neglect contribution to atomic motion coming from electrons.
- II **Neglect the binding energy, U = 0.**
- III The energy transferred to ionized electrons is small compared to that transferred to recoiling ions.
- IV Effects of electronic and atomic collisions can be treated separately.
- V T_n is also small compared to the energy E.

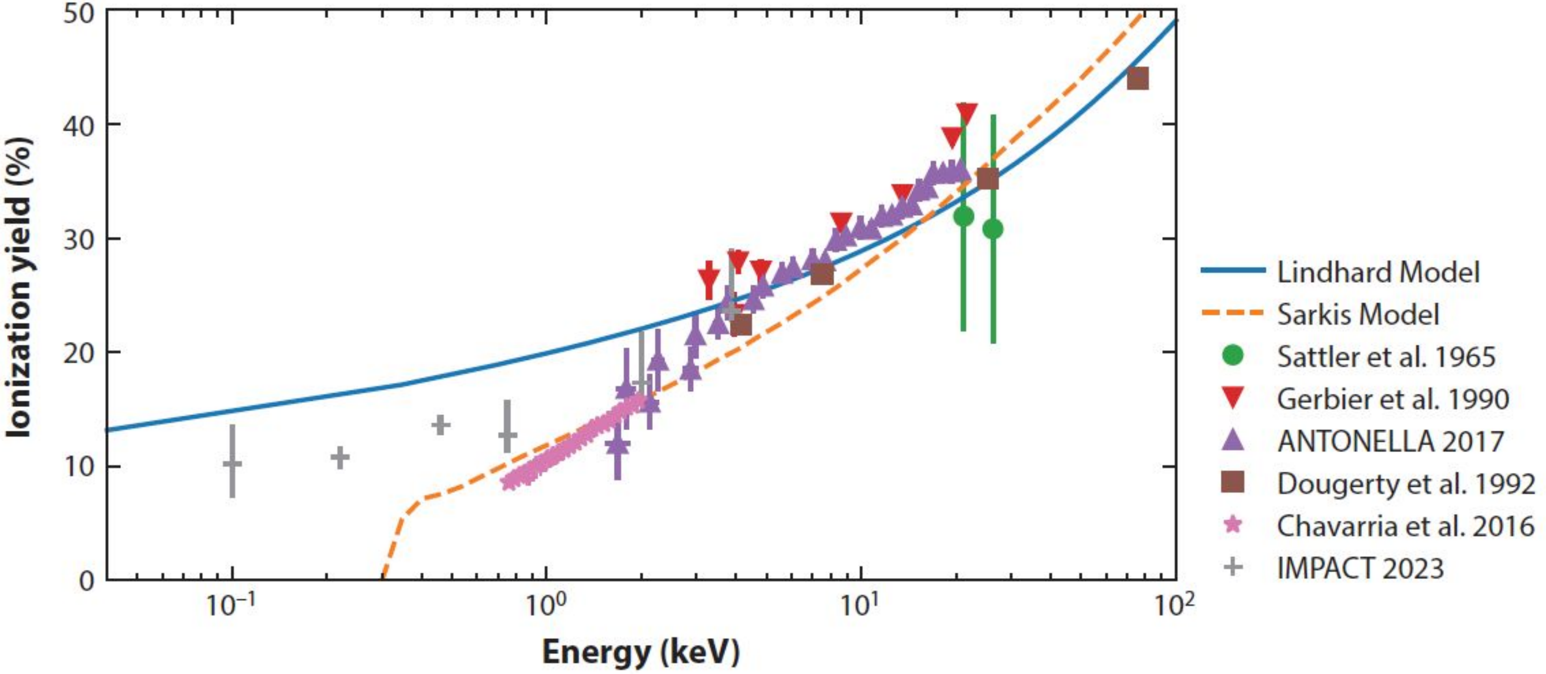


Germanium NR ionization yield

- State of the “art”



Silicon NR ionization yield



Typical measurement scheme

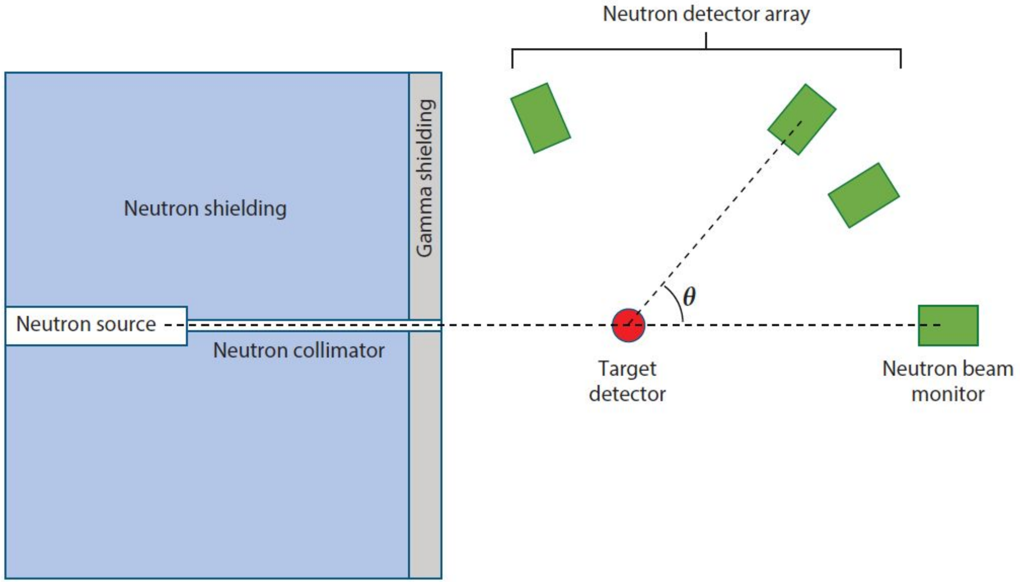
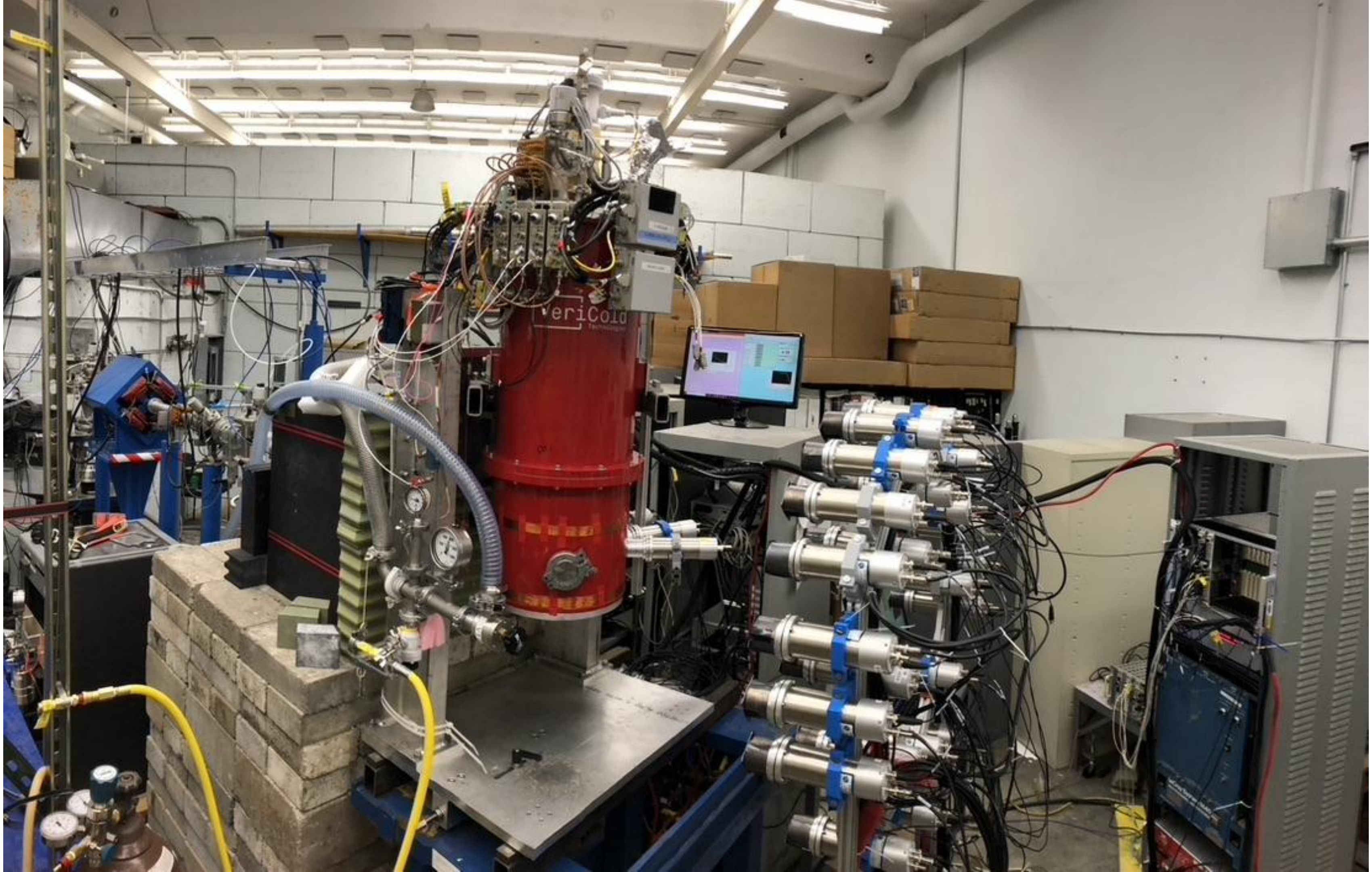


Figure 1

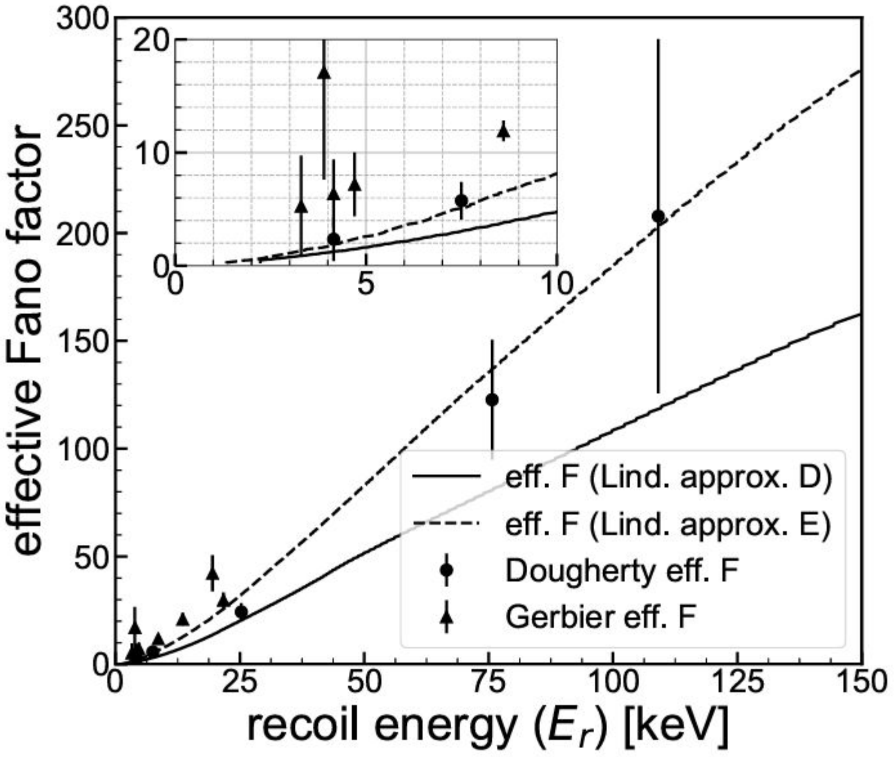
Illustration of a typical experimental setup to measure nearly monoenergetic nuclear recoils using elastic neutron scatters. Neutrons of known energy produce nuclear recoils with a well-defined energy distribution when scattering off a target at a specific angle. The neutron scatter angle is usually informed by placing detectors with gamma-neutron discrimination capabilities at fixed locations, where direct neutrons from the source should be suppressed with shielding. The neutron passage inside the shielding (collimator) may be tapered to improve beam purity, and a neutron detector may be placed right behind the target detector as a beam monitor.


VeriCold

https://arxiv.org/pdf/2206.13639.pdf

Nuclear Recoil “Fano Factor”?

- Multiple random processes
  - Nucleus vs electron energy partitioning
  - Electron cascade
- Resulting in an inflated effective Fano Factor
- In principle do not even expect Poisson/Gaussian distributions
- Might need more data to tell…



Migdal effect

- Lower probability, but unquenched ionization
- Lots of experiments use this to lower detection threshold

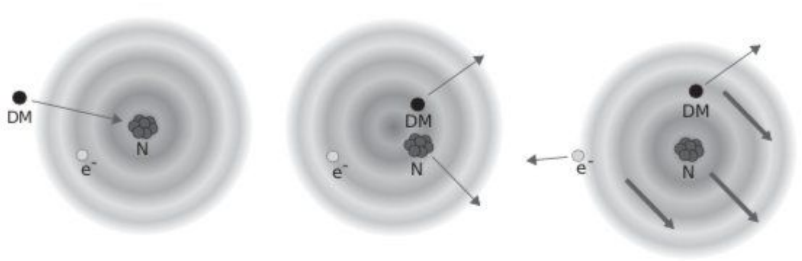
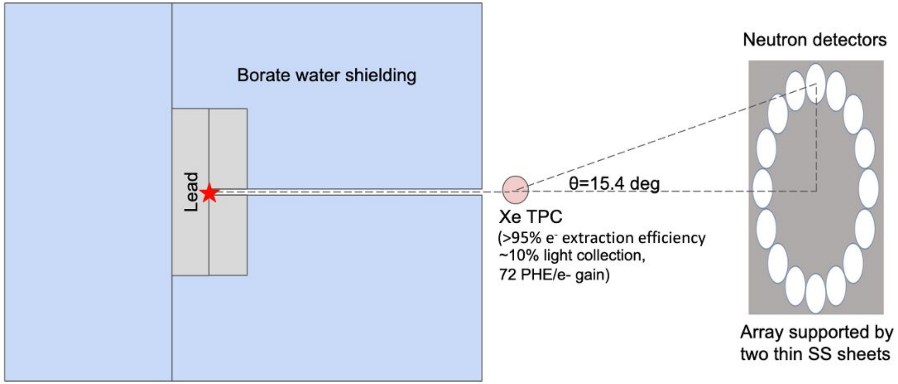


FIG. 1. Illustration of electron emission from nuclear recoils. If a DM particle scatters off a nucleus (left), we can assume that immediately after the collision the nucleus moves relative to the surrounding electron cloud (middle). The electrons eventually catch up with the nucleus, but individual electrons may be left behind and are emitted, leading to ionization of the recoiling atom (right).

Phys. Rev. Lett. **121**, 101801

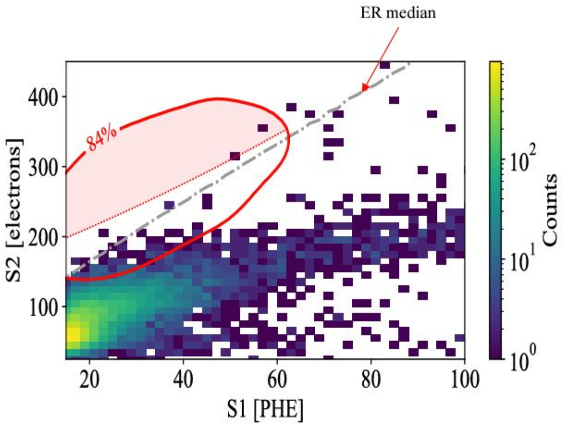
arXiv:2307.12952

(Maybe?) Migdal non-observation?



L-shell (>3keV) Migdal search

- ~410k NRs for L-shell search
  - Larger S1 signals → less stringent S1 cleanliness cut → increased event statistics
- Signal ROI defined as within 84% contour (E_{ER}>3keV) and above signal median
  - Well separated from NR population
- 5.7+/-1.2 signals expected
- 2 events observed
- 2.1+/0.9 backgrounds expected



Data set used for the L-shell Migdal interaction (E_{ER}>0.5keV) search

Need more data……

Conclusions

- Low mass dark matter search poses stringent requirements on experiments
- Especially in low-threshold detector technology
- Various extremely-optimized detectors developed
  - To maximize sensitivity to these scenarios
- Understanding detector response has become renewed challenges
- Luckily, we're moving forward!