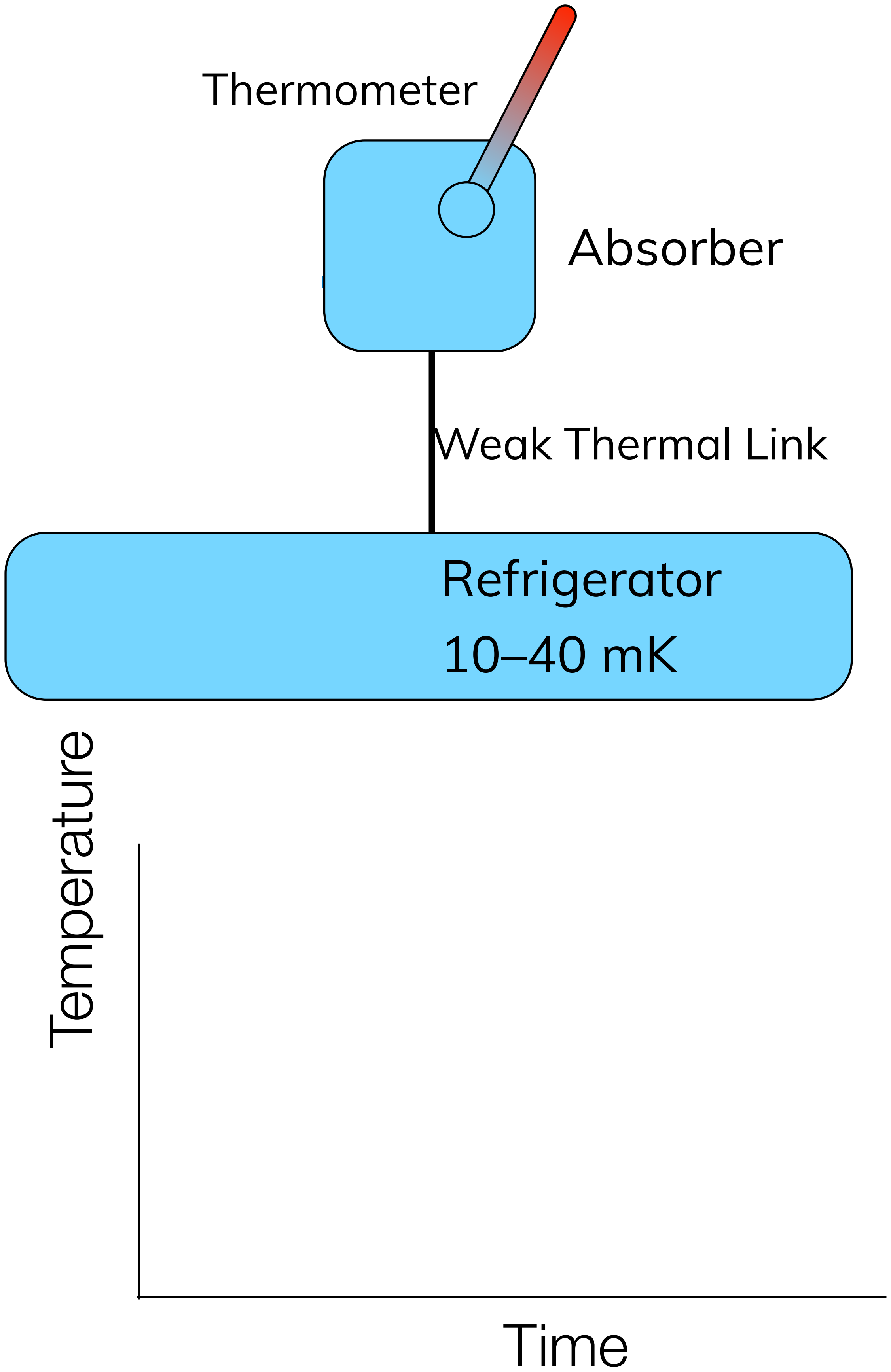
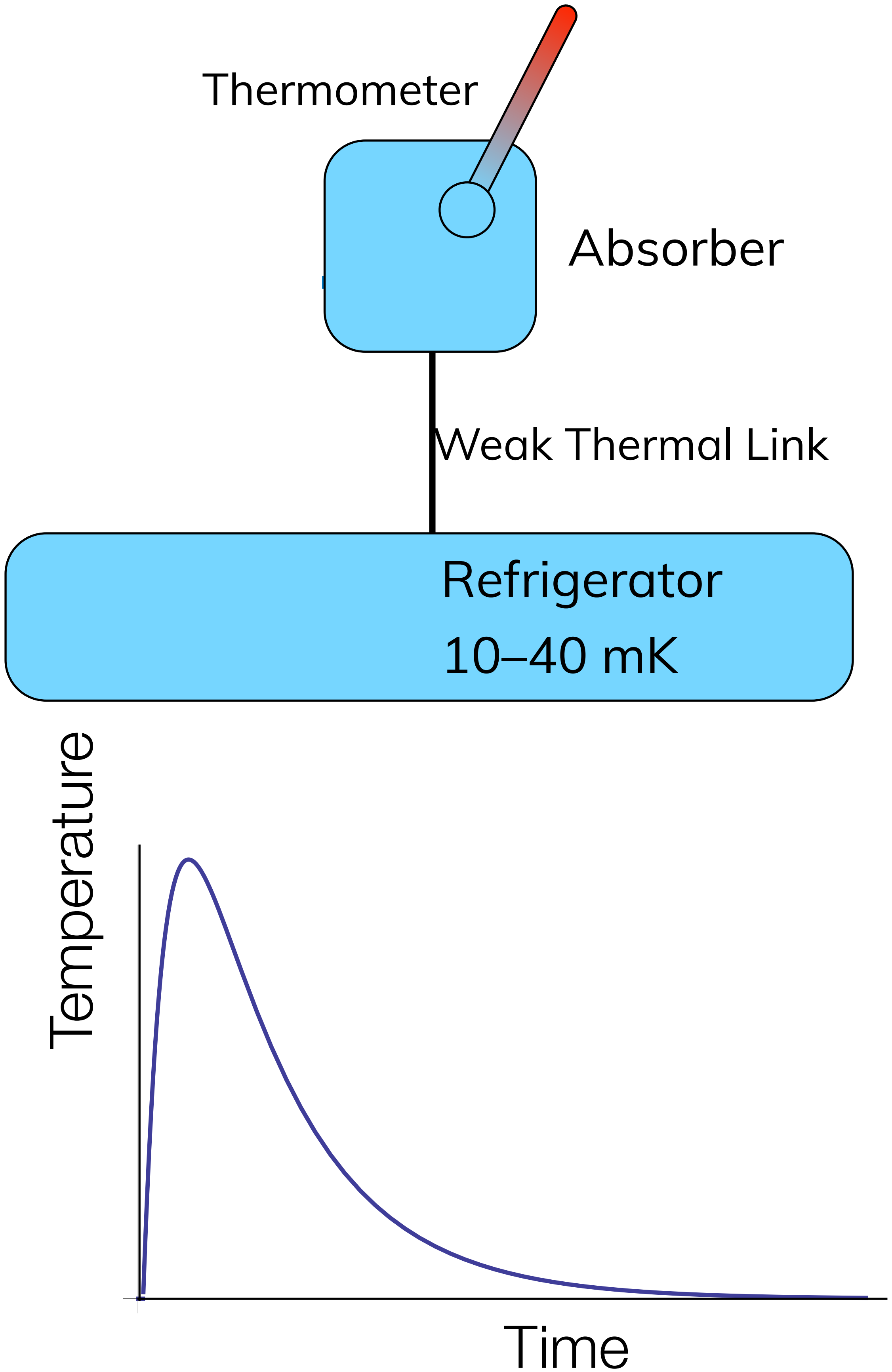
Cryogenic Detectors


Thermometer
Absorber
Weak Thermal Link
Refrigerator
10–40 mK
Temperature
Time


Thermometer
Absorber
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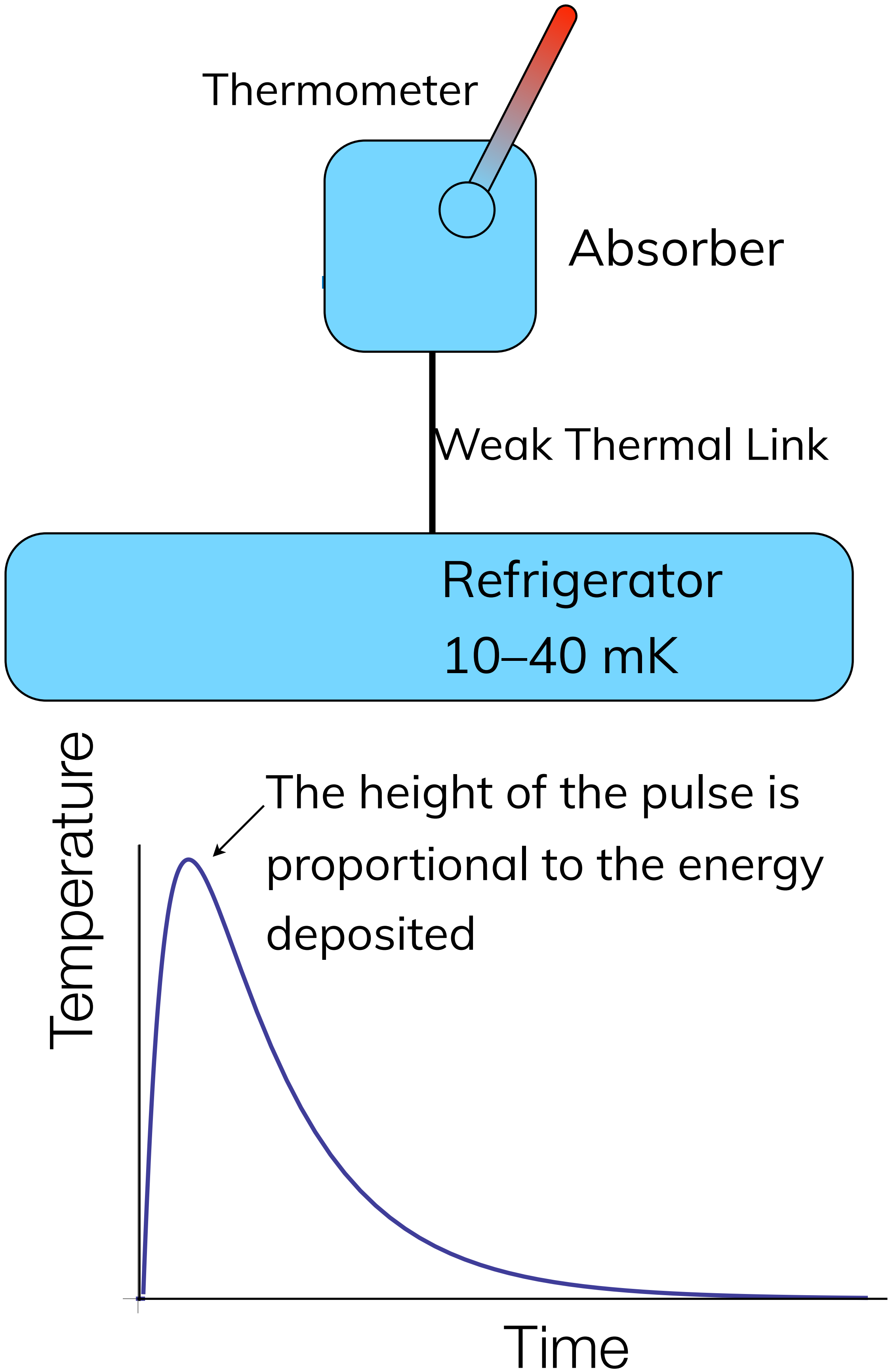
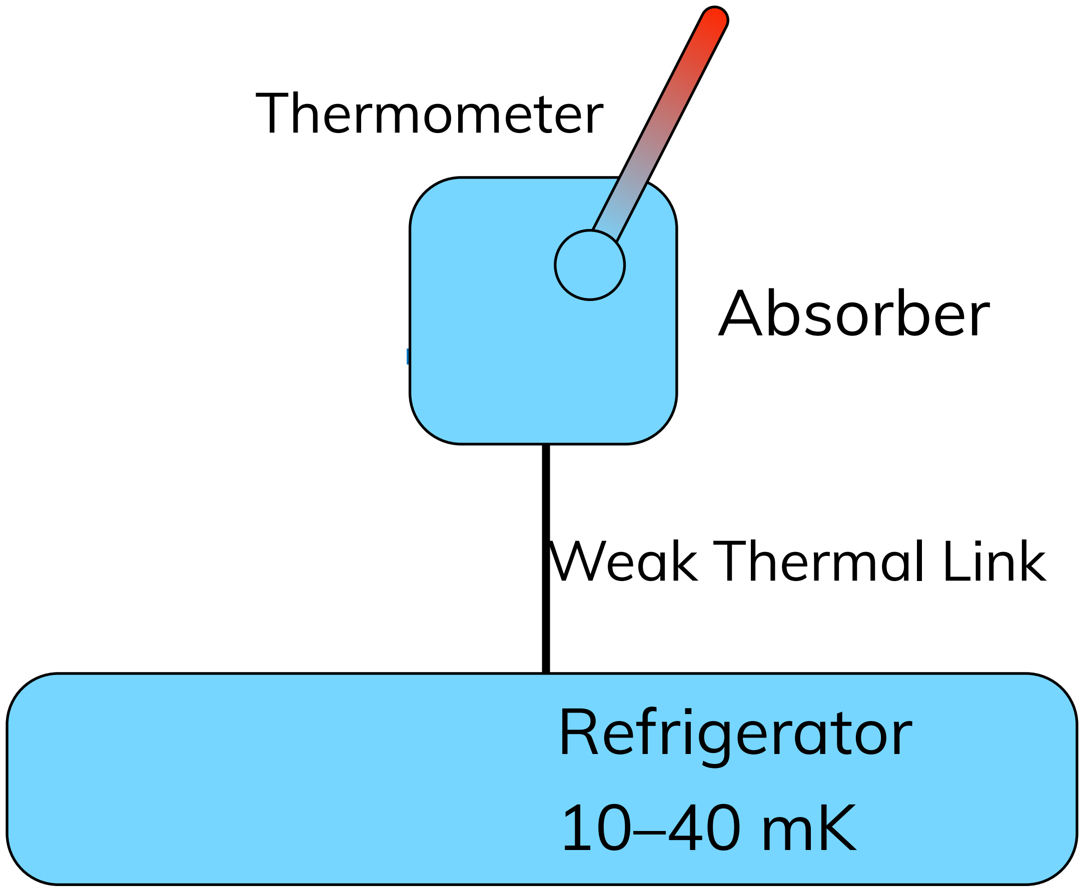
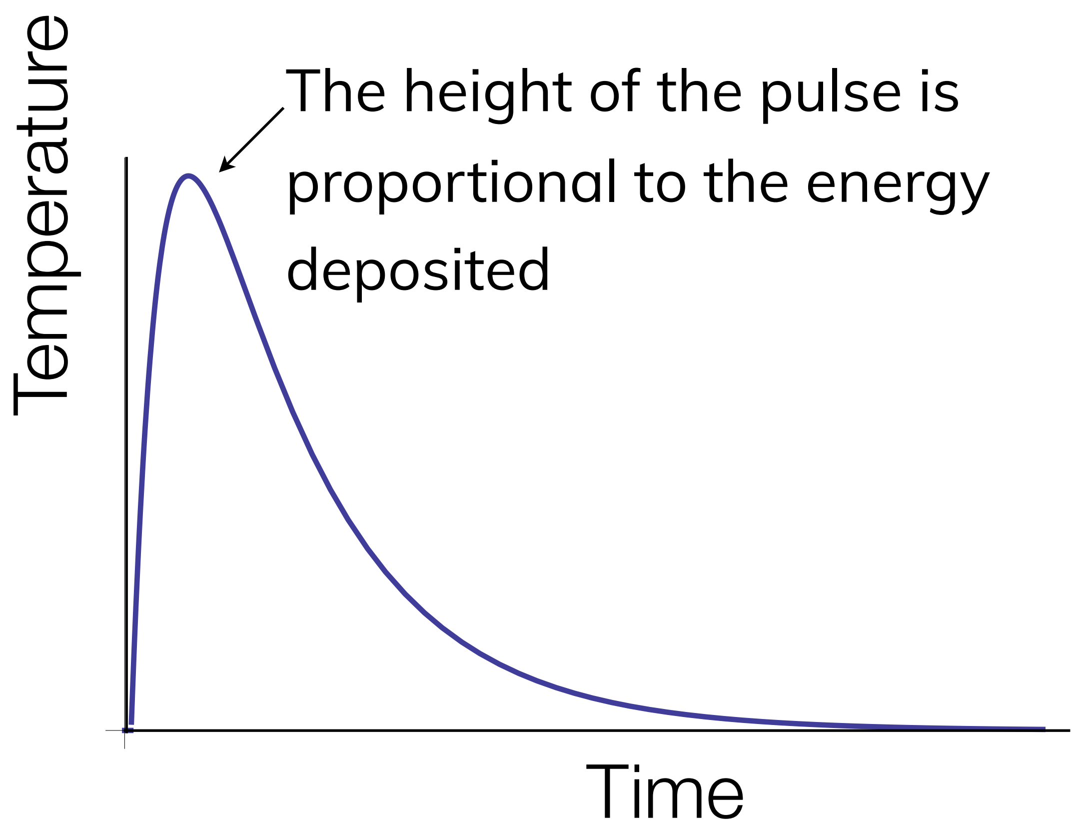
Refrigerator
10–40 mK
Temperature
Time


Thermometer
Absorber
Weak Thermal Link
Refrigerator
10–40 mK
Temperature
The height of the pulse is proportional to the energy deposited
Time





Advantages of phonon readout:

- Direct measurement of nuclear recoil energy; **no quenching factors involved**
- ~100% of the recoil energy is sensed, **allowing for low thresholds**
- Good energy resolution near threshold (**~eV (RMS) for ~ 10 g detectors**),

Phonon Readout

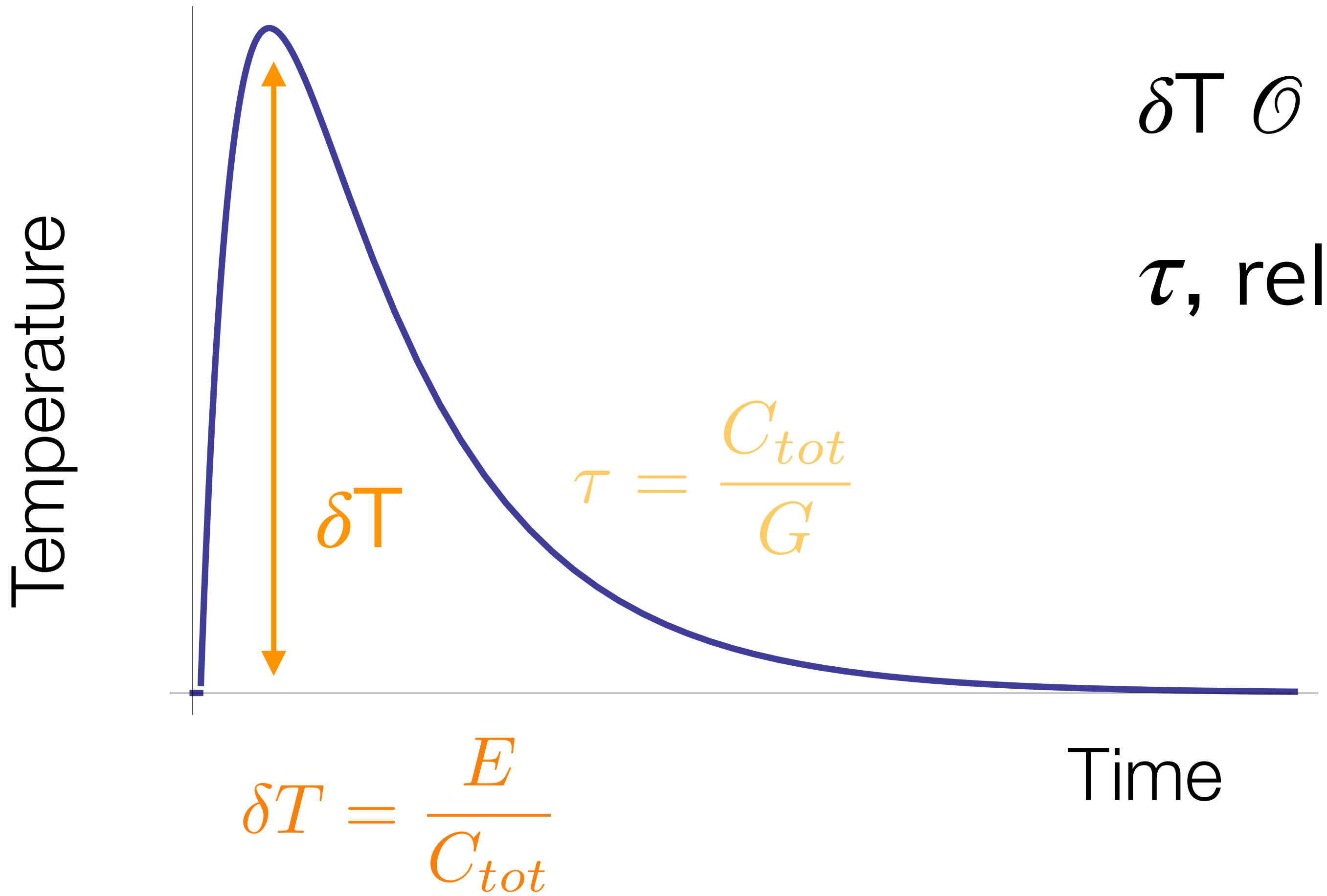
- Thermal measurement (EDELWEISS)
- Athermal measurement (SuperCDMS/ CRESST)

Detector Response

Thermal bath ~10-100mK

δT $\mathcal{O}$ (100)uK

τ, relaxation time $\mathcal{O}$ (1-100)ms



G: thermal conductance

C_{tot}: total heat capacity

Thermodynamic Noise

Noise comes from irreducible random thermodynamic fluctuations in energy due to transport across the thermal link.
Ultimate energy sensitivity is determined by how well you can measure δT against thermodynamic fluctuations

$$N = CT/K_B T$$

number of excitations with mean energy $K_B T$

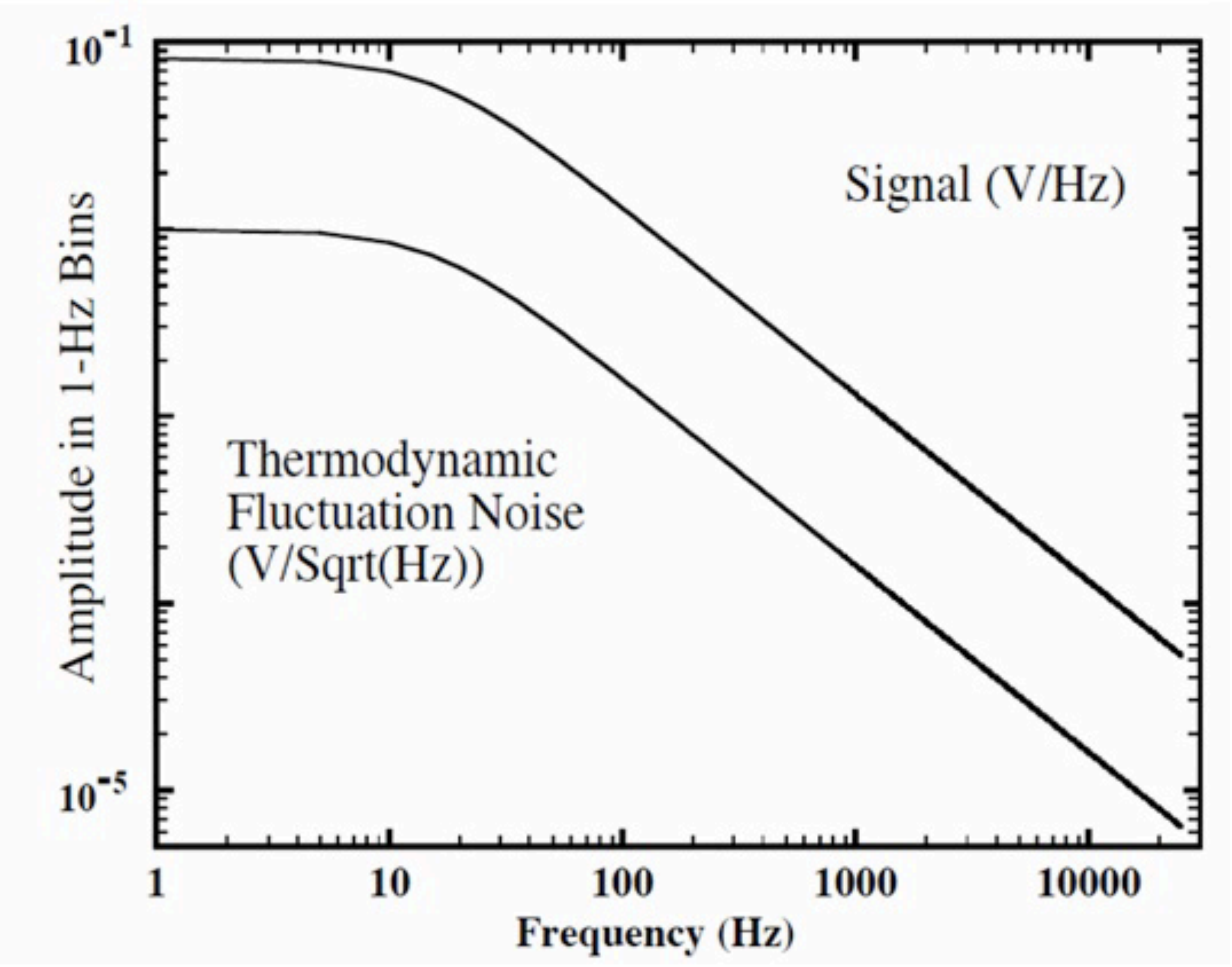
$$\delta N = \sqrt{N}$$

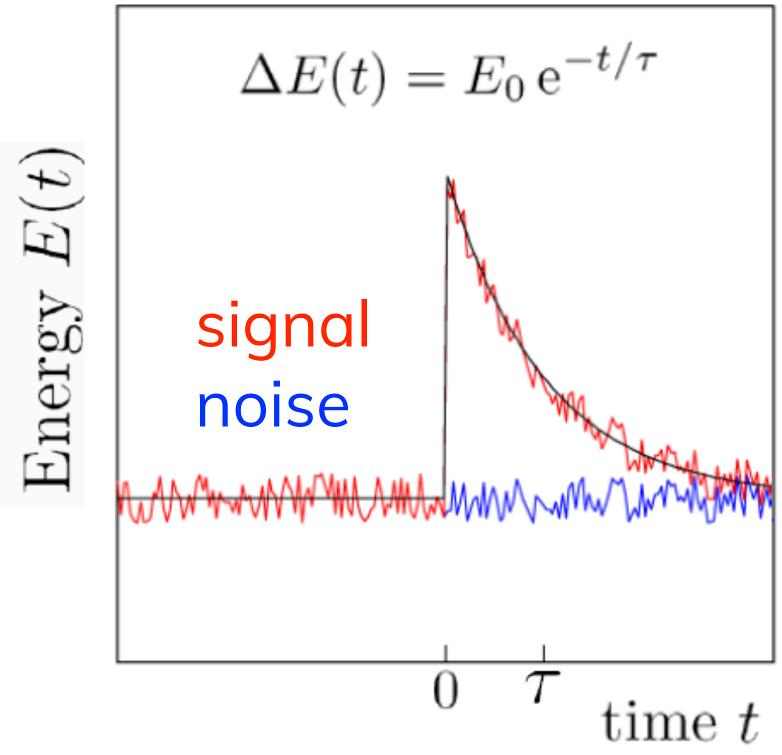
random statistical fluctuation

$$\delta E_{tf} = \sqrt{C K_B T^2}$$

preferred:
low temperatures
low heat capacity

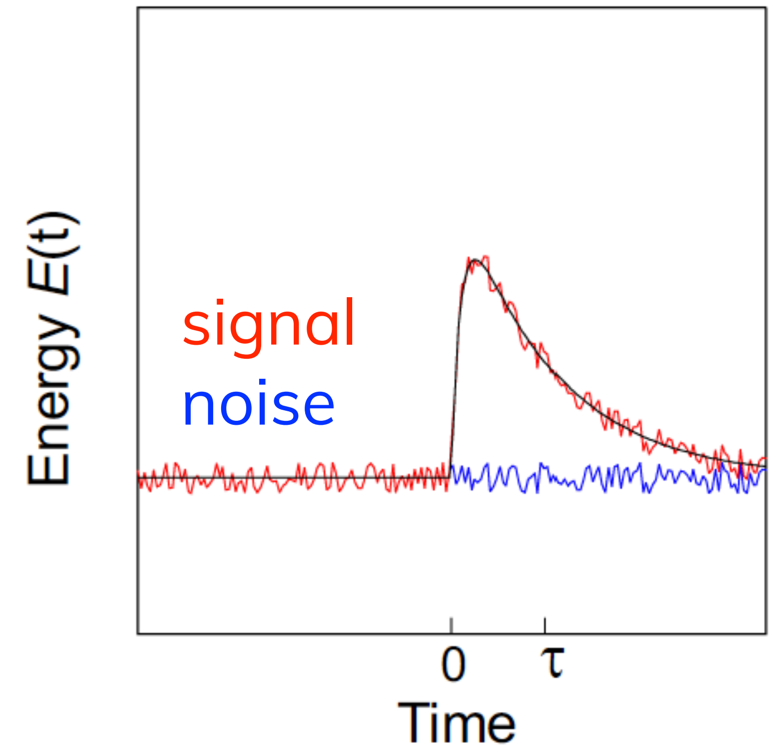
Signal-to-Noise-Ratio

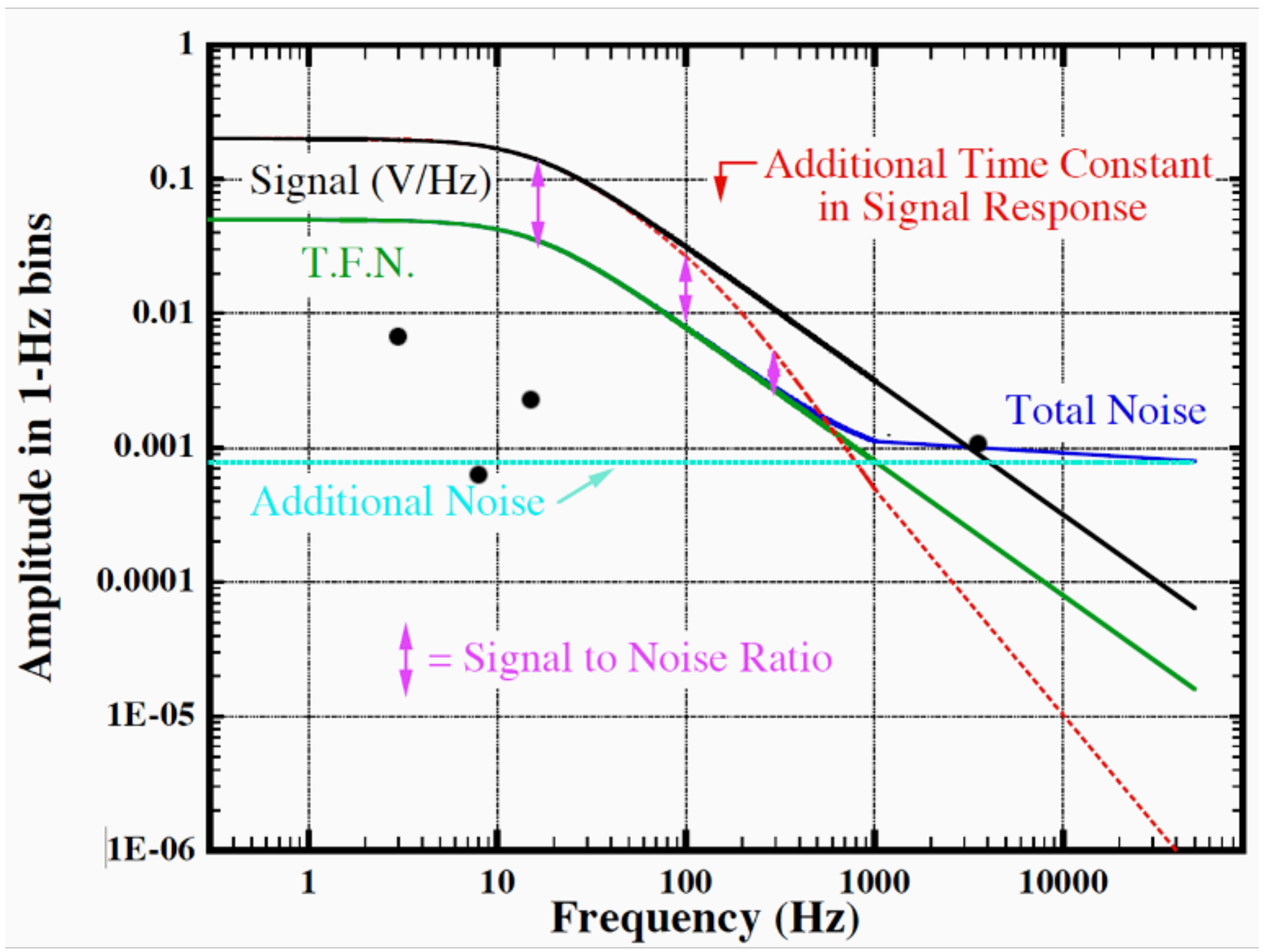




signal to noise ratio
independent of frequency

Signal-to-Noise-Ratio





In reality, additional noise and some more time constants

- Preamplifier noise: white noise, 1/f noise..
- Johnson noise
- discret noise sources: vibrations, electrical, interference
- excess noise: additional unexplained noise

-> signal to noise ratio dependent of frequency
-> finite energy resolution ΔE_{FWHM}

SNOLAB

How to Measure the Temperature Increase?

Phonon Detectors

EQUILIBRIUM DETECTORS

- Semiconductor Thermistor (NTD)
- Transition Edge Sensors (TES)
- Metallic Magnetic Calorimeters (MMC)

Equilibrium detectors are weakly coupled to thermal bath so thermal equilibrium is reached

NON-EQUILIBRIUM DETECTORS

- SuperconductingTunnel Junctions (STJ)
- Microwave Kinetic Inductance Detectors MKID

Non-equilibrium detectors have an energy gap which is much larger than kT and allows long-lived excitations which we count.

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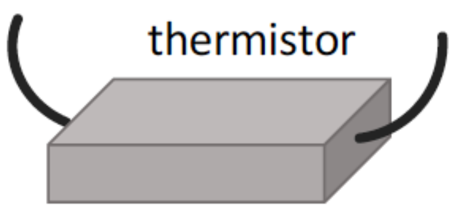
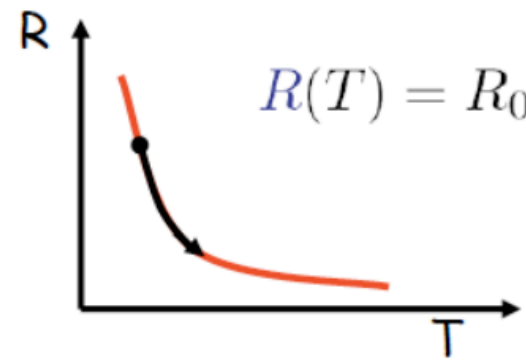
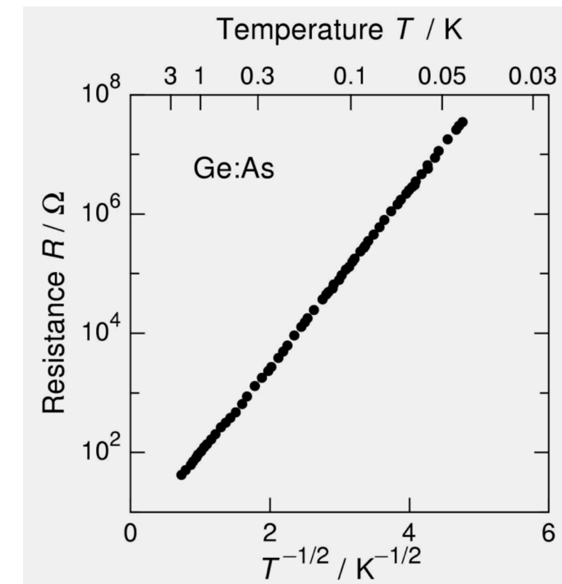
Semiconductor Thermistor



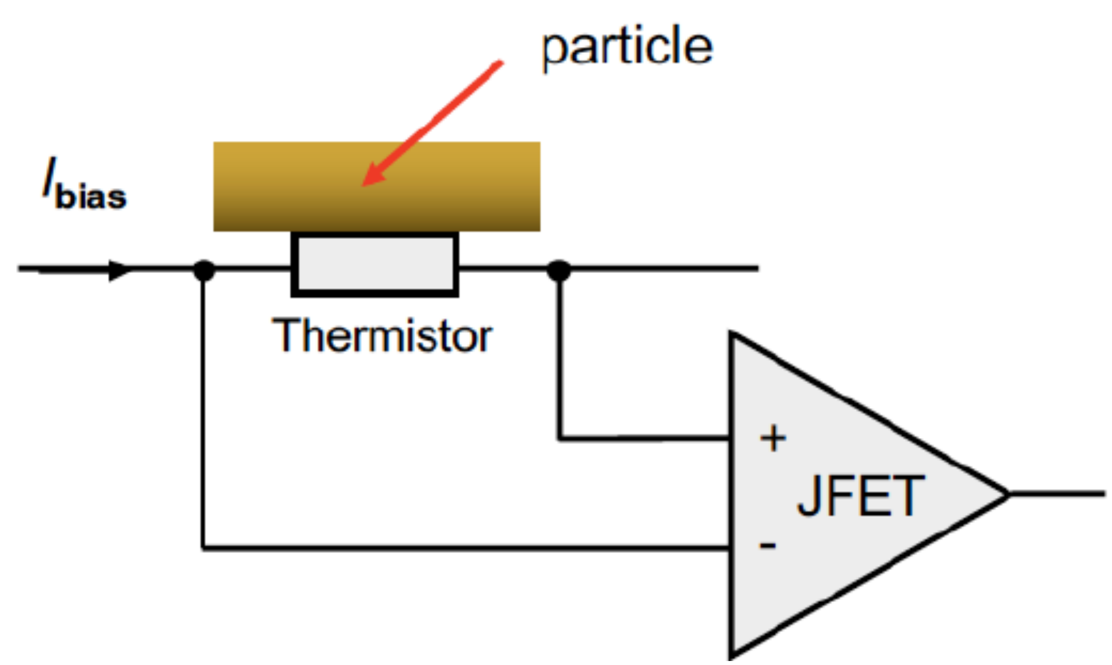


$$R(T) = R_0 \exp\left(\frac{T_0}{T}\right)^{1/2}$$

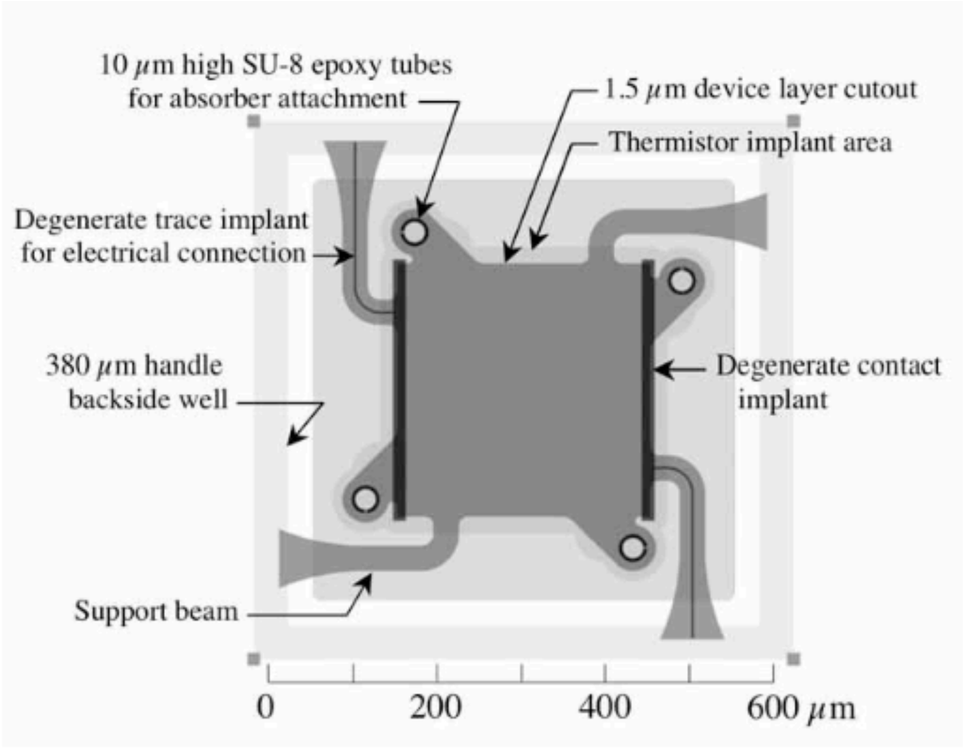


HIGH IMPEDANCE DEVICE (1-10MΩ):

- resistance changes vs. temperature
- current bias and read voltage
- use a FET (Field-Effect Transistor)

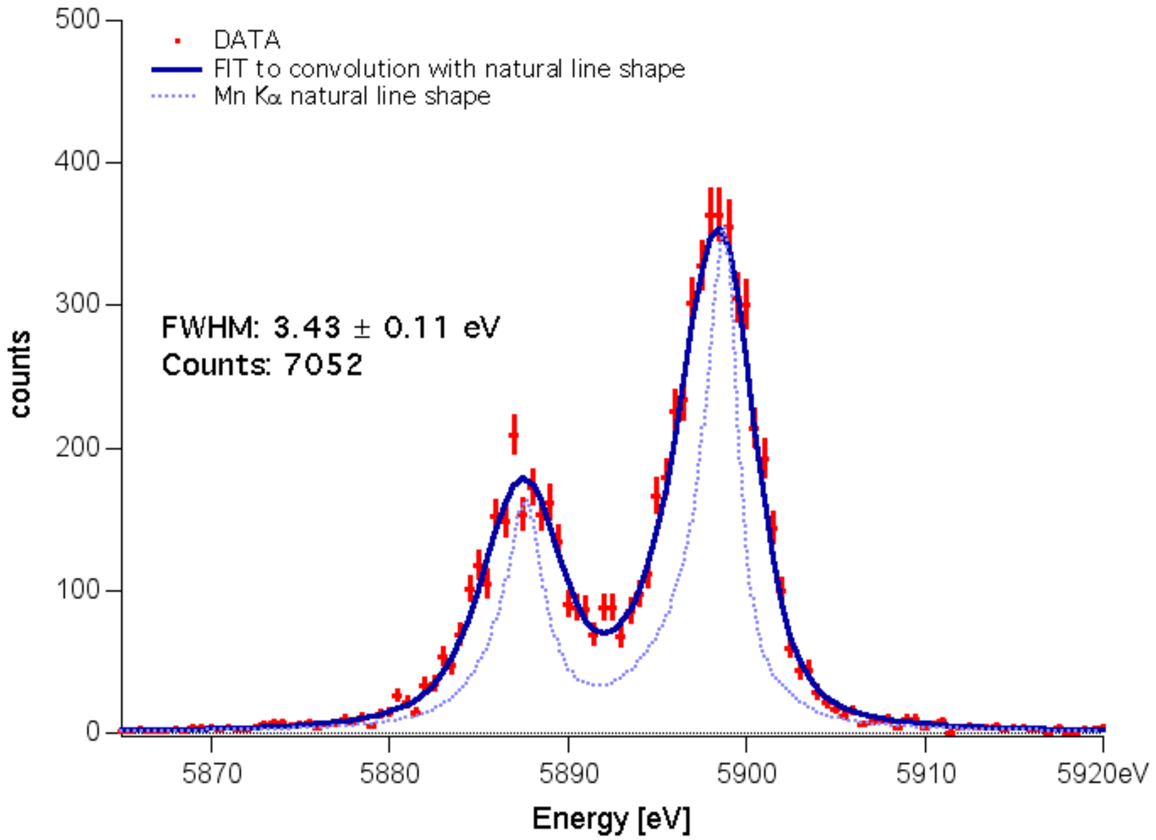


Silicon Thermistor



Silicon

- ion implantation of P, B in Si
- anneal
- attach absorber (e.g. HgTe)



HgTe absorber

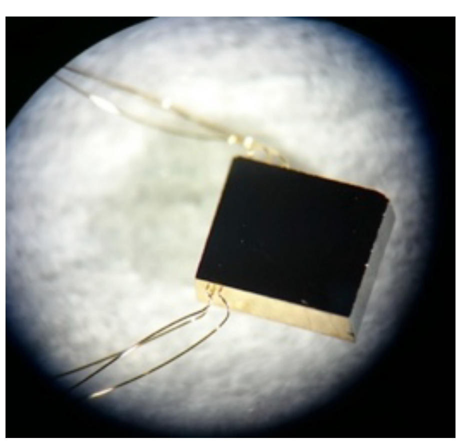
0.4 x 0.4 mm^2

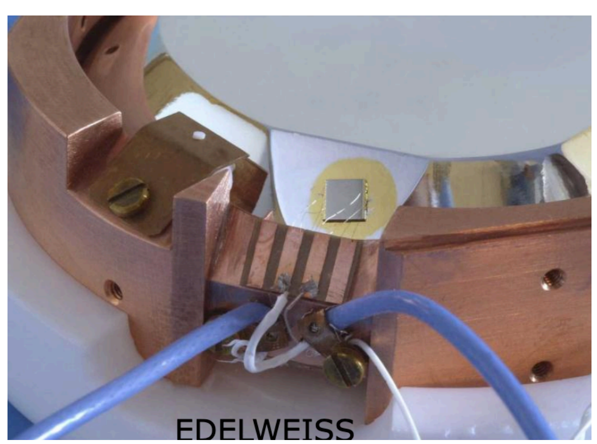
Energy resolution at 5.9 keV is 3.43 eV

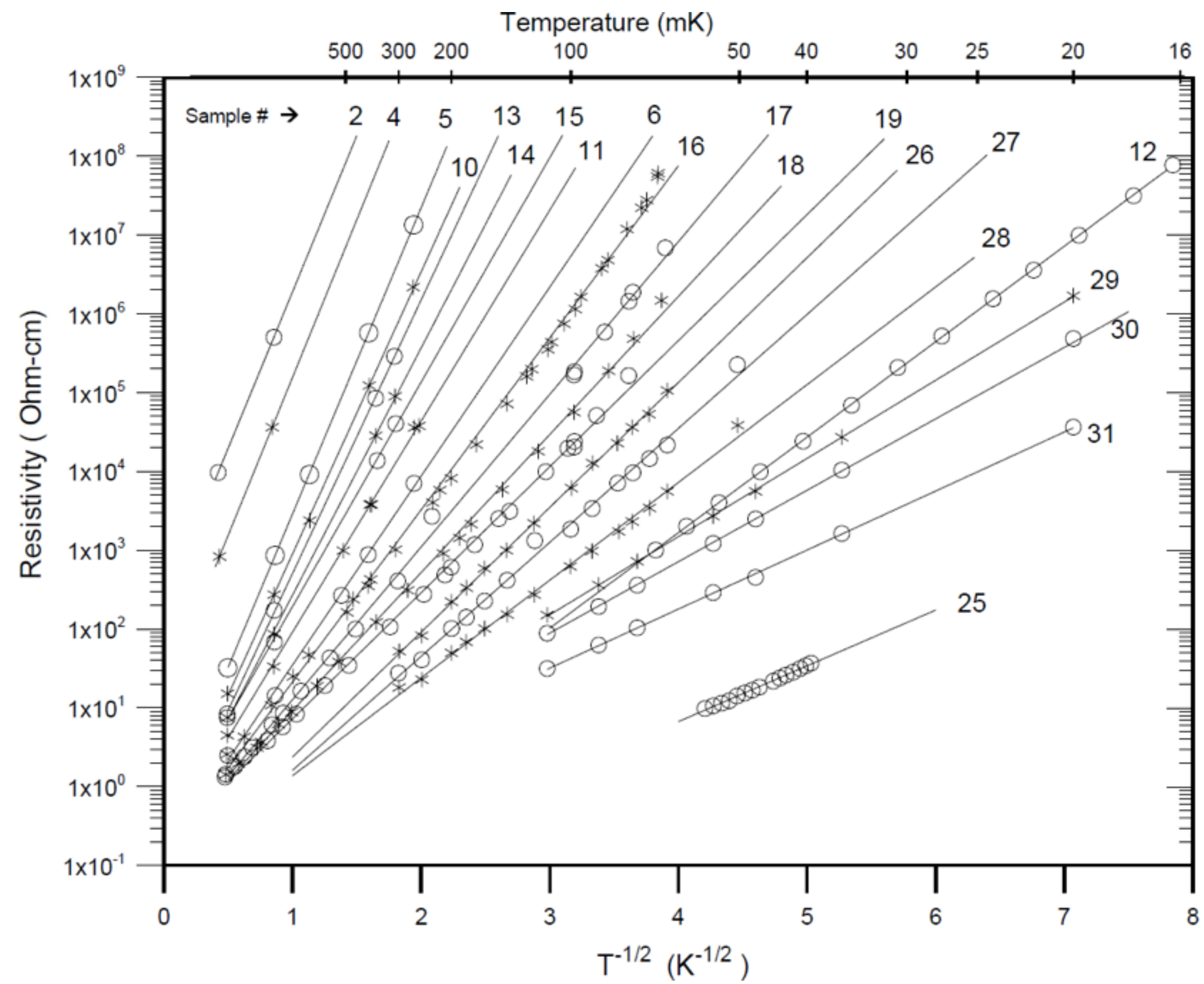
Germanium NTD

Germanium (NTD)

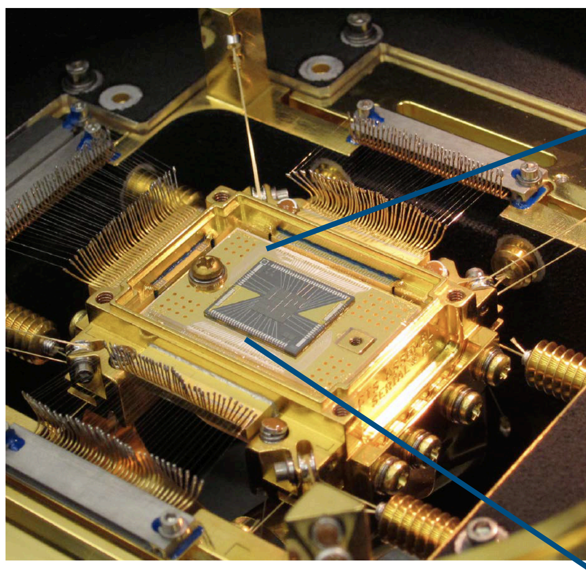
- expose Ge wafer to high neutron flux
- … wait …
- anneal
- cut

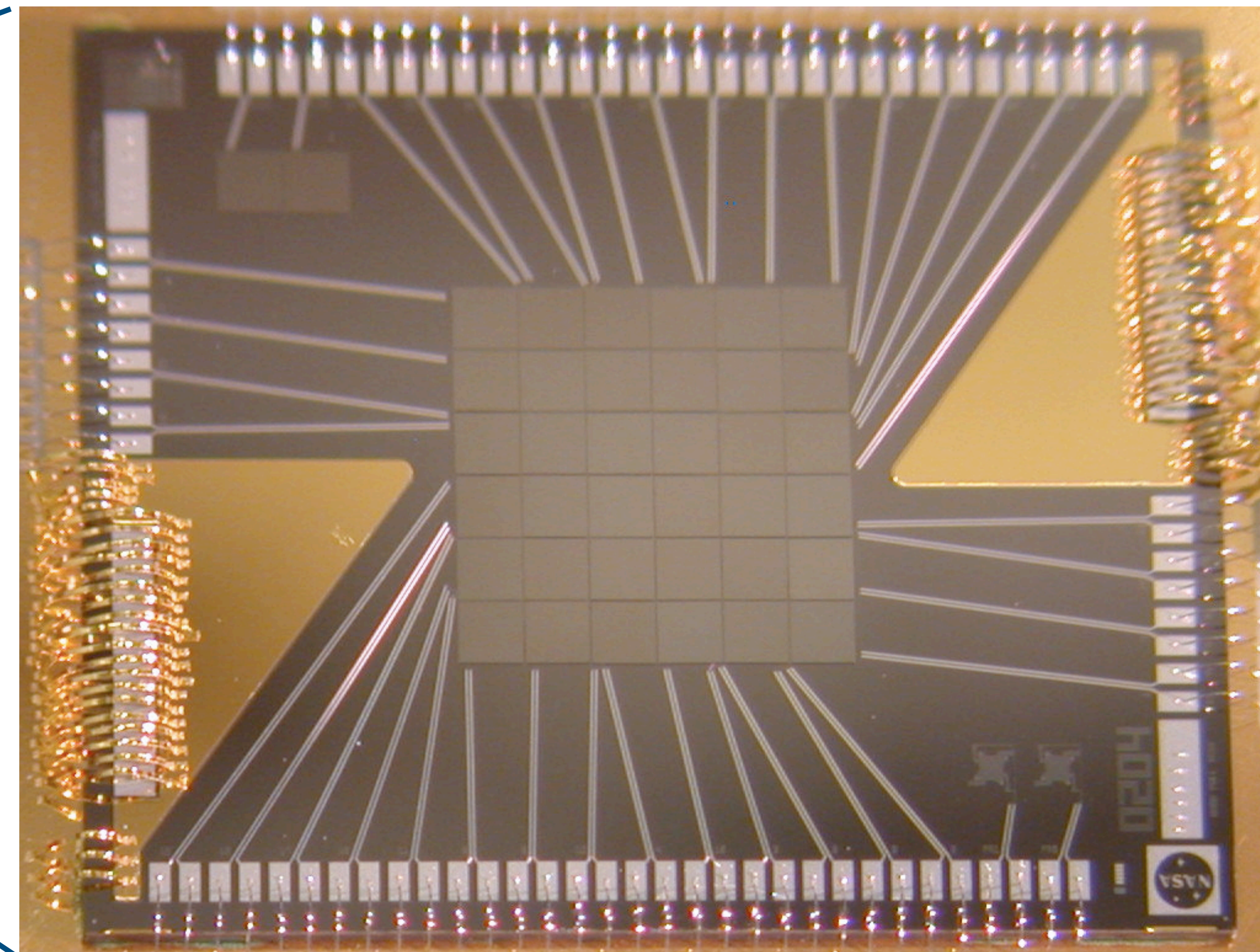






Application: X-ray Astronomy



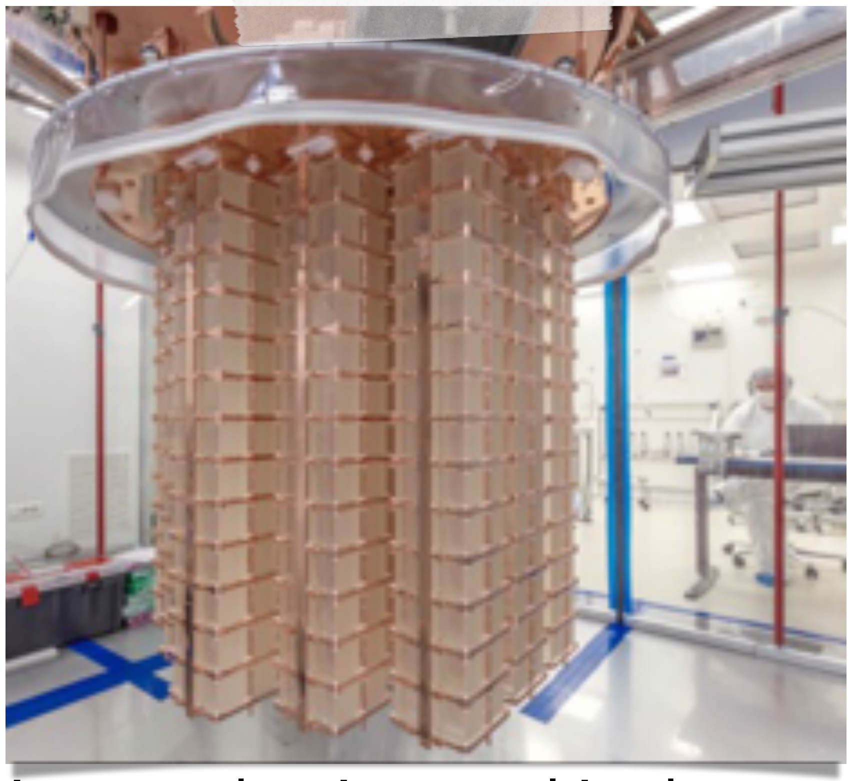


6 x 6 array of 0.4 x 0.4 mm^2
Thermistor with HgTe absorber
energy resolution: ≈ 4.2 eV
energy range: 0.3 – 12 keV

Hitomi Focal Plane Detector: SXS

Application: Rare Search Event

CUORE at LNGS



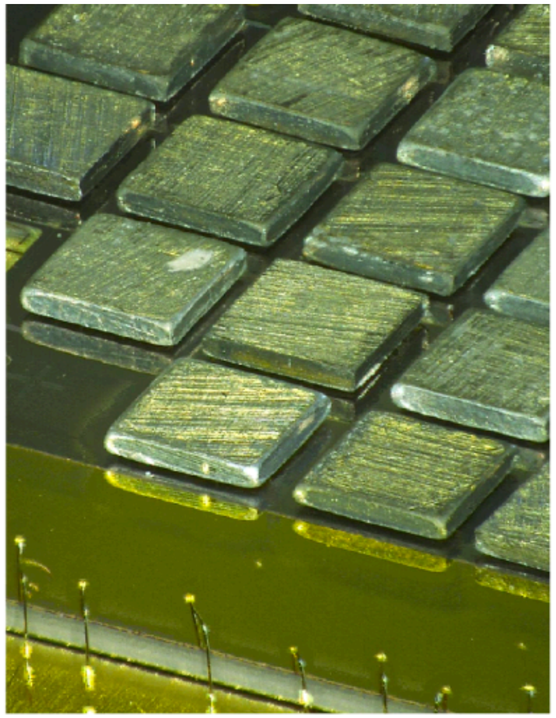
Primary physics goal is the search for $0\nu\beta\beta$ decay of 130Te

- Array of 988 TeO2 bolometers
- Energy resolution goal of 5 keV FWHM at $Q\beta\beta$ of 2527 keV

EDELWEISS at LSM

Primary physics goal is the search for Dark Matter with HPGe detectors (ionization and phonon measurements)

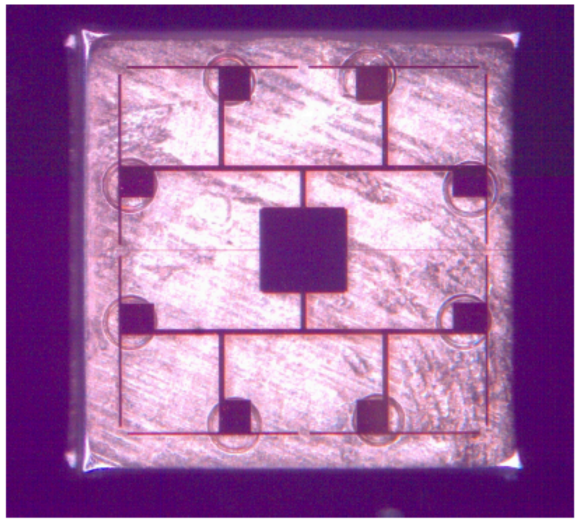
Application: Gamma Spectroscopy

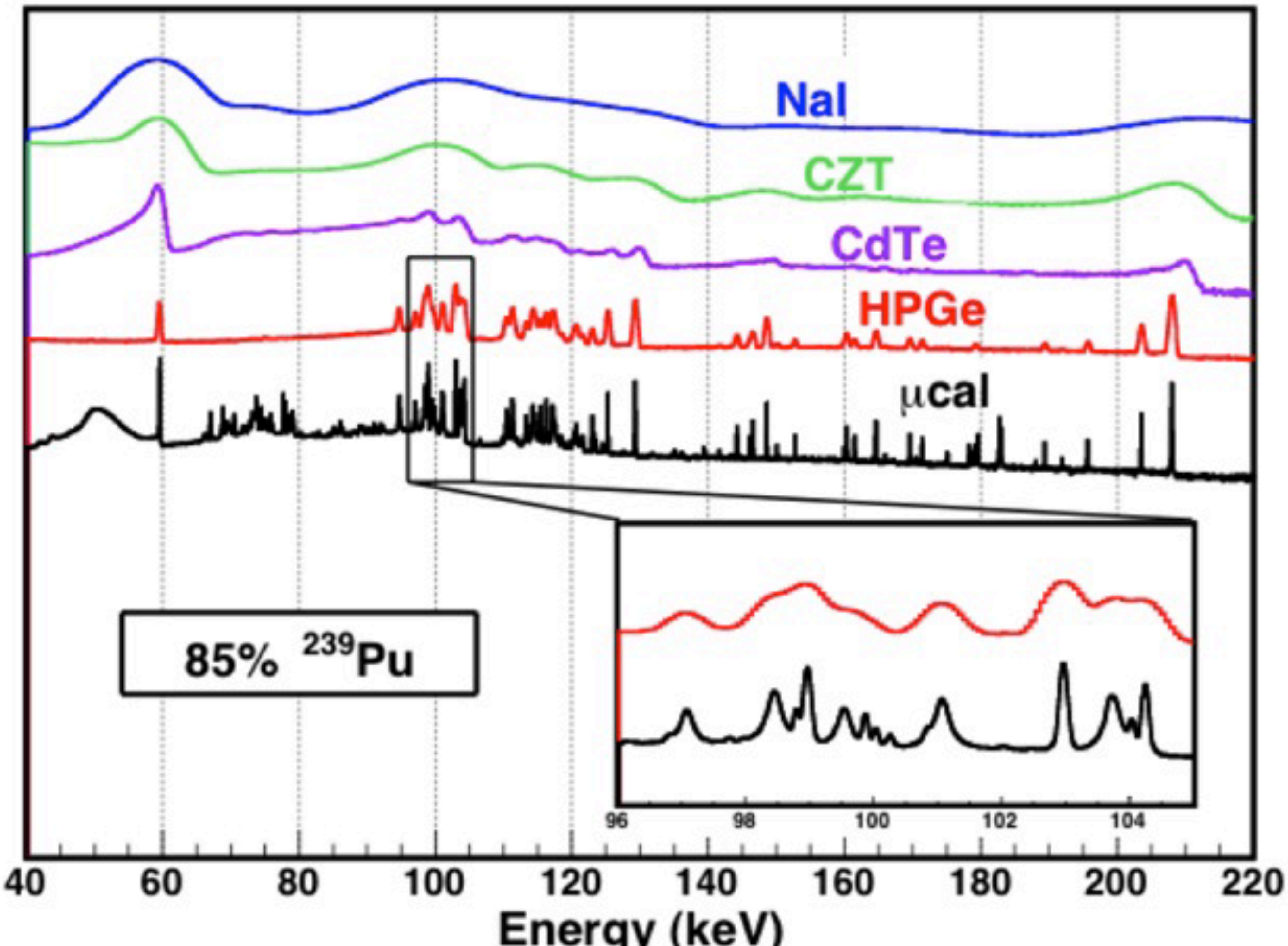


Ultra low-level chemistry
Space science (e.g. micro meteorites, Mars samples, cosmic activation products, comet tail samples)
Atmospheric samples (very short lived isotopes, radionuclide composition, stratospheric samples)
Ocean samples (e.g. deep ocean water - 60Fe)

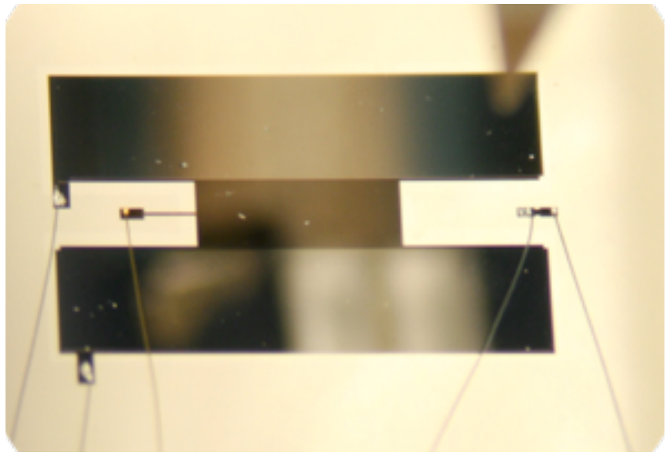
In general application of low background techniques to interdisciplinary fields:

- Low-level environmental radioactivity measurement and monitoring
- Radiodating (extension of determined ages towards the past)
- Geophysics (palaeoseismology, palaeogeology, sedimentation)



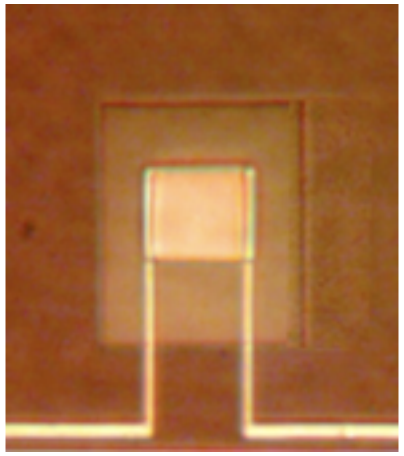

NaI
CZT
CdTe
HPGe
µcal
85% ^{239}Pu
96
98
100
102
104
40
60
80
100
120
140
160
180
200
220
Energy (keV)

TES - Superconducting thin films



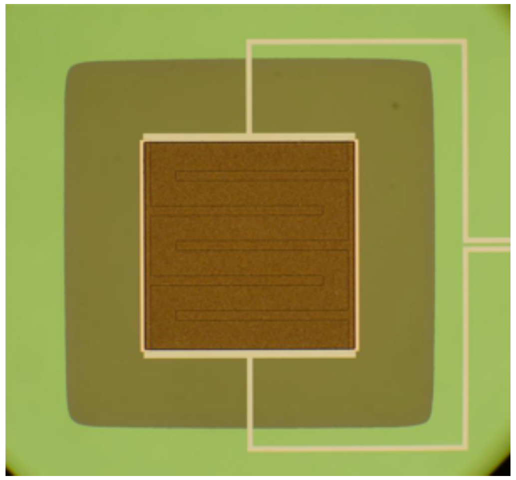
W – TES

Tc ~ 15mK



Ir/Au – TES

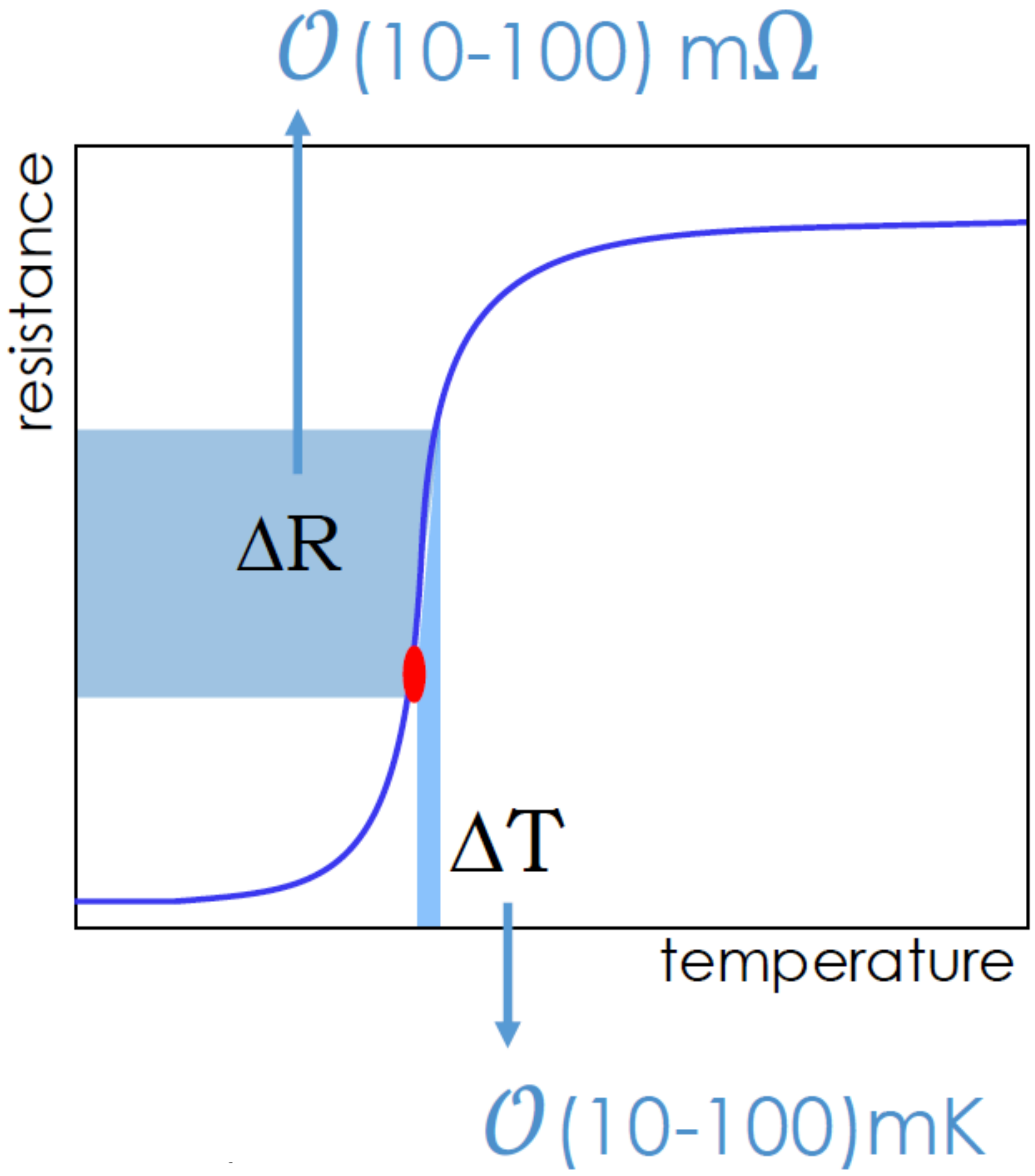
Tc ~ 70mK

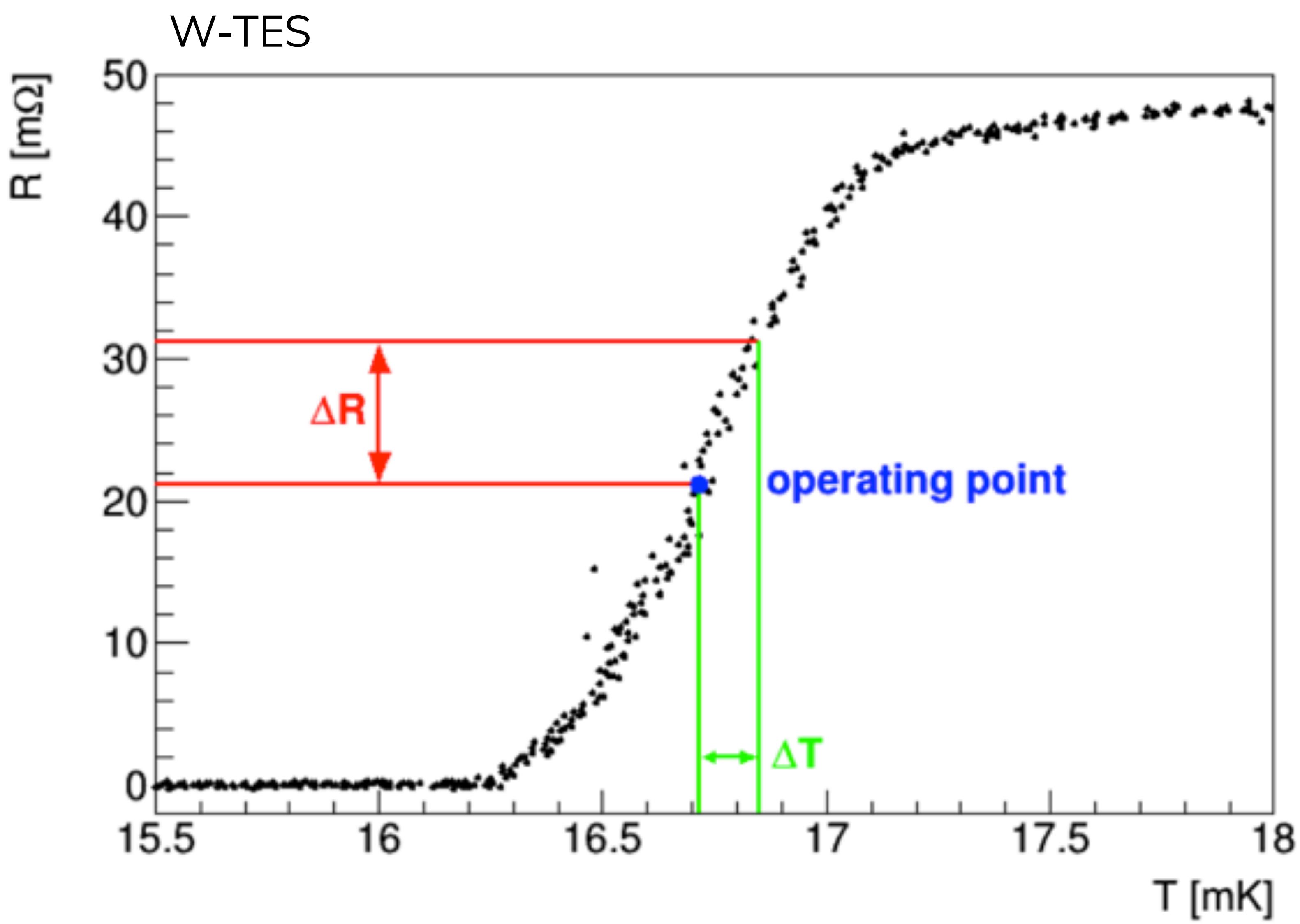


Mo/Cu – TES

Tc ~ 100mK

TES - Superconducting thin films





Johnson noise $I_J \sim \sqrt{\frac{4k_B T_C}{R}}$

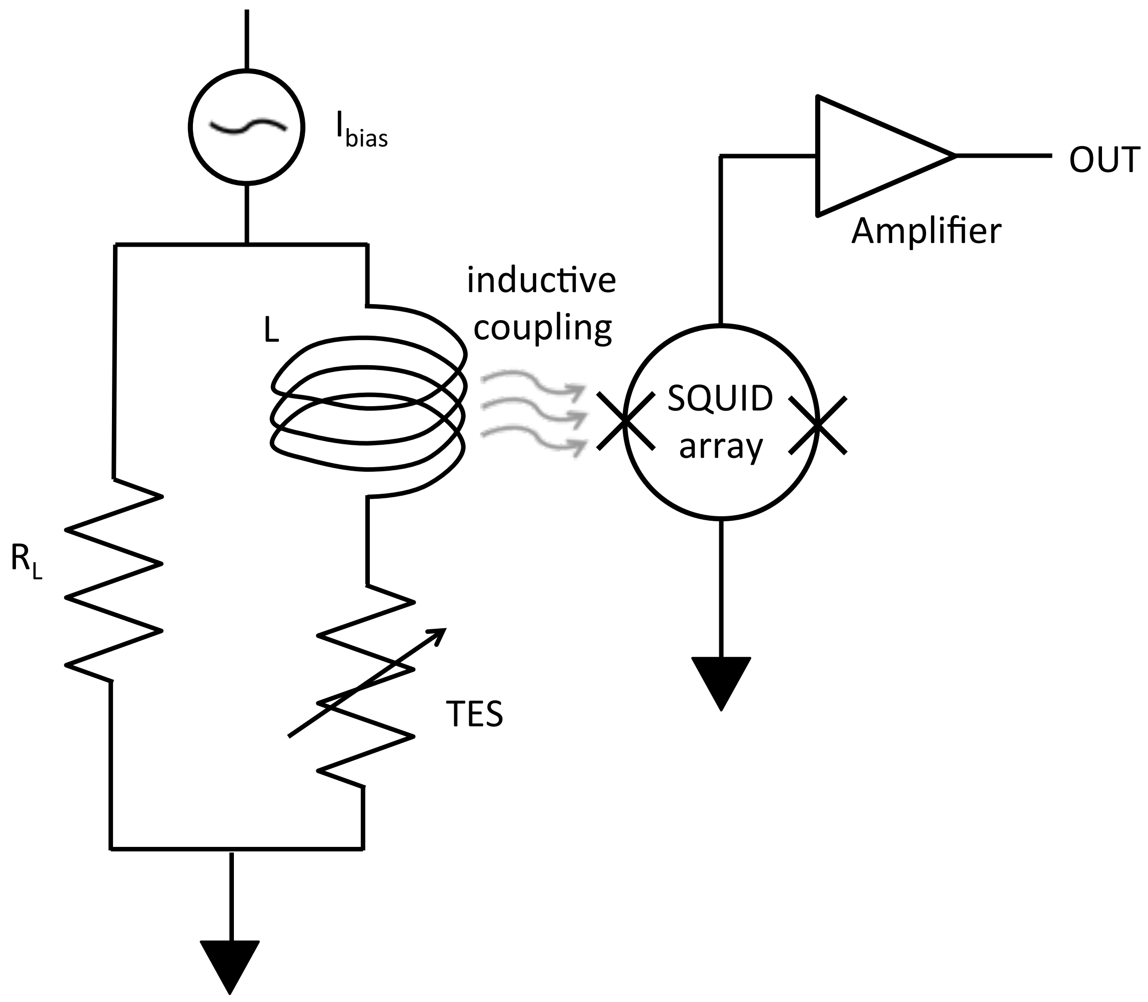
Including both Johnson and the thermodynamic fluctuations noise:

$$E_{FWHM} \sim 2.355\sqrt{\frac{4k_B T_C^2 C}{\alpha}}$$

-> small T_c and low C

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

TES-SQUID circuit

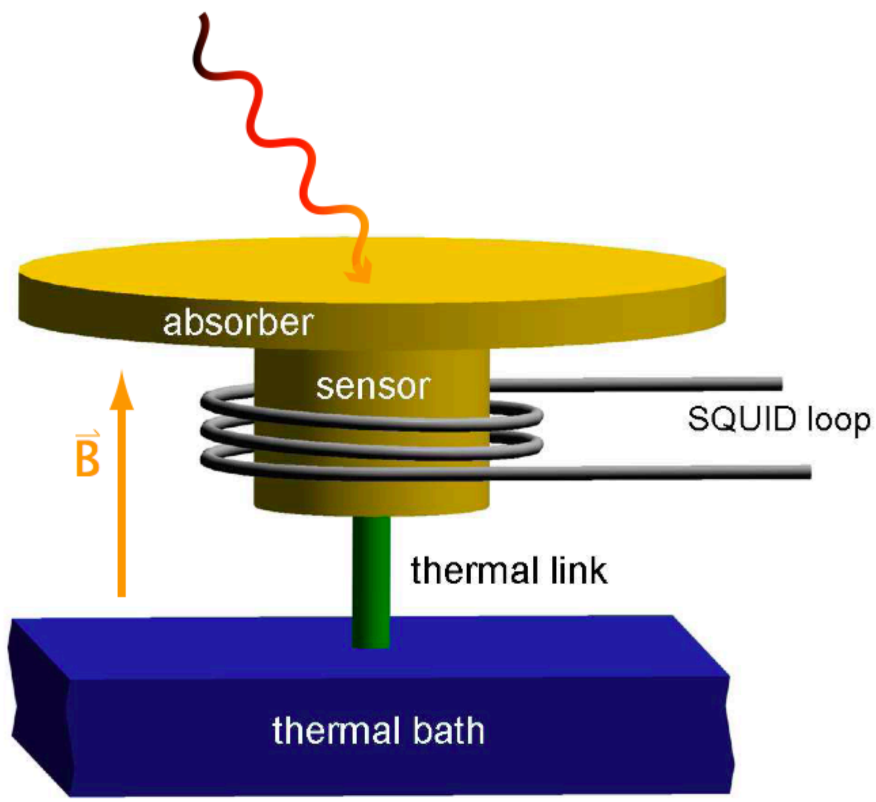


SQUID = Superconducting Quantum Interference Device based on the Josephson effect: if two pieces of superconductor separated by a thin layer of insulator a supercurrent can flow between them.

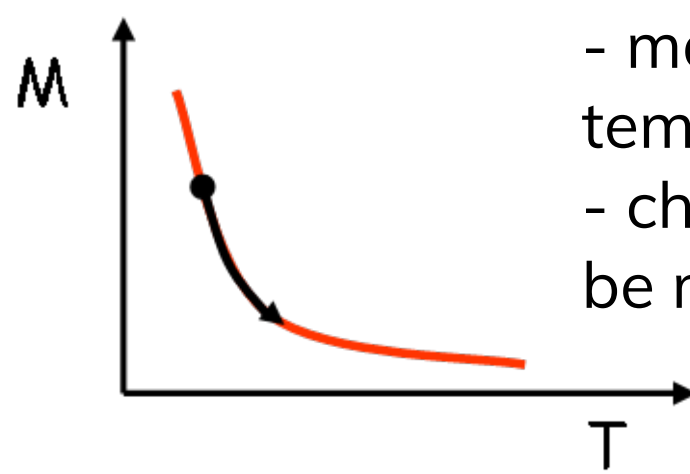
SQUIDs are the equivalents of transistors for superconducting electronics

A change in TES current manifests as a change in the input flux to the SQUID, whose output is further amplified and read by room-temperature electronics.

MMC



paramagnetic sensor: Au:Er, Ag:Er, ...

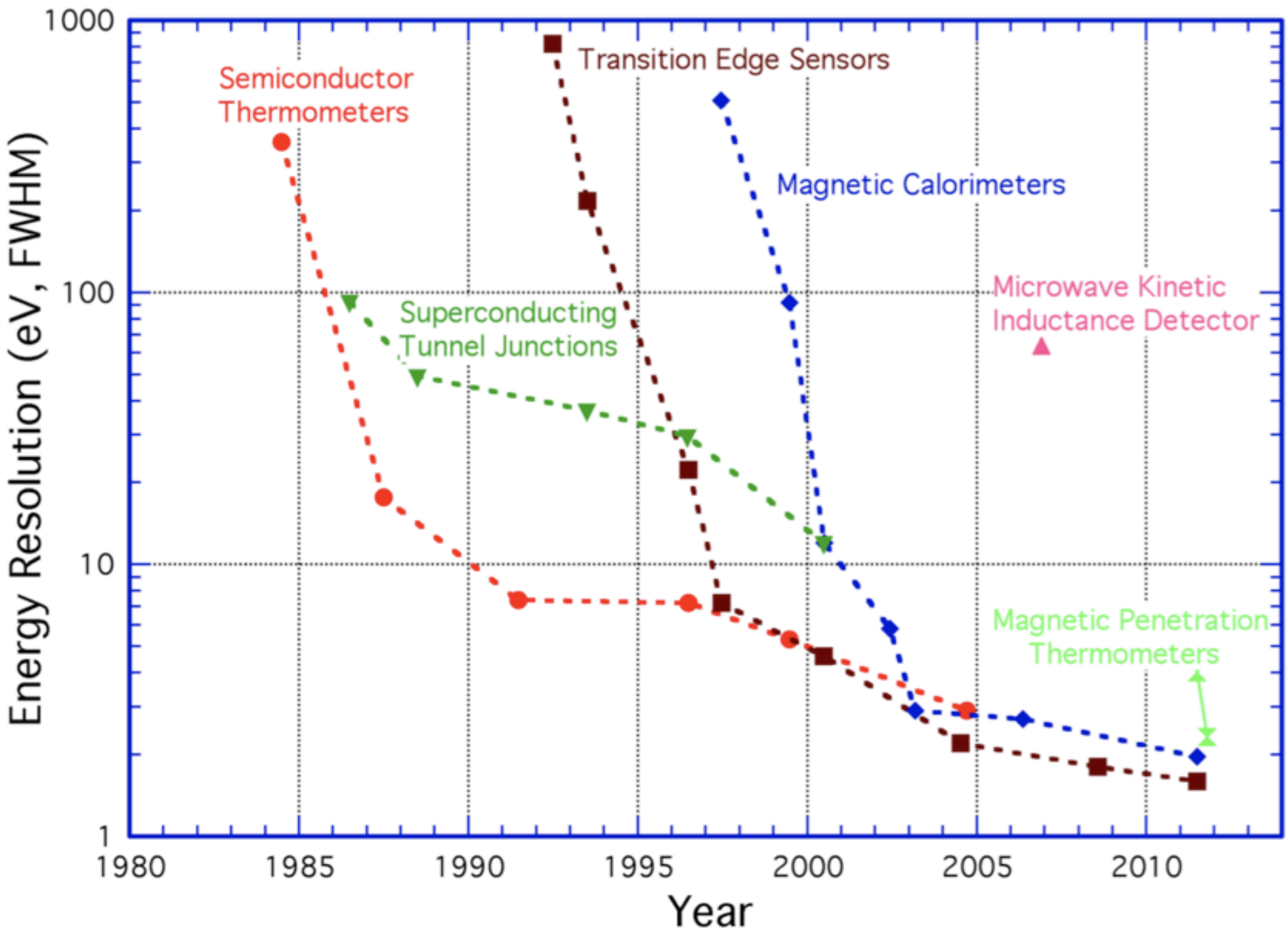


- magnetization varies with temperature
- change in magnetization can be measured with a SQUID

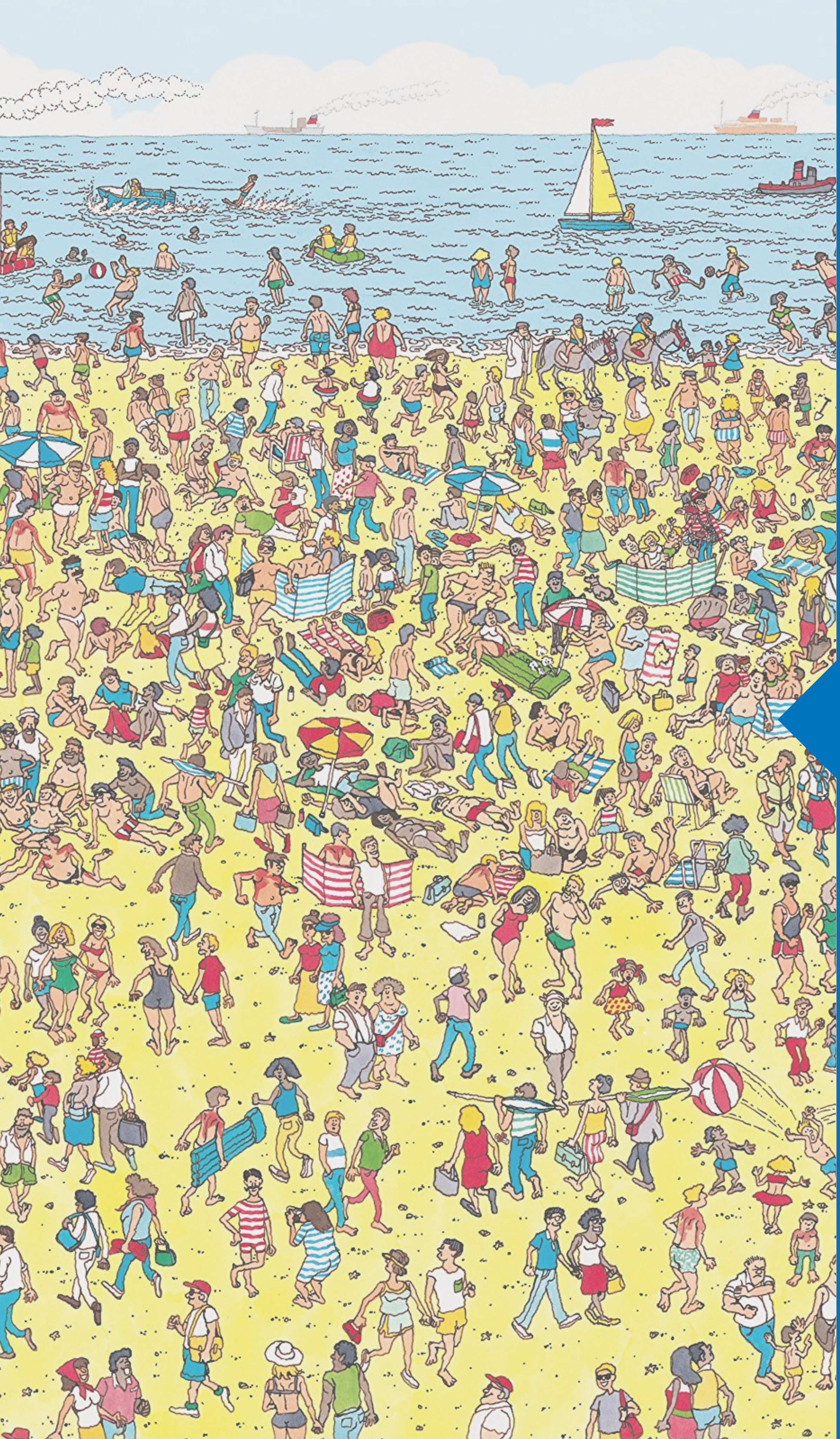
signal size $$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E_0}{C_{\mathrm{tot}}}$$

SQUID flux signal: $\delta\Phi_{\mathrm{sq}} \propto \delta M$

main difference to resistive calorimeters:
no dissipation in the sensor itself
no galvanic contact to the sensor



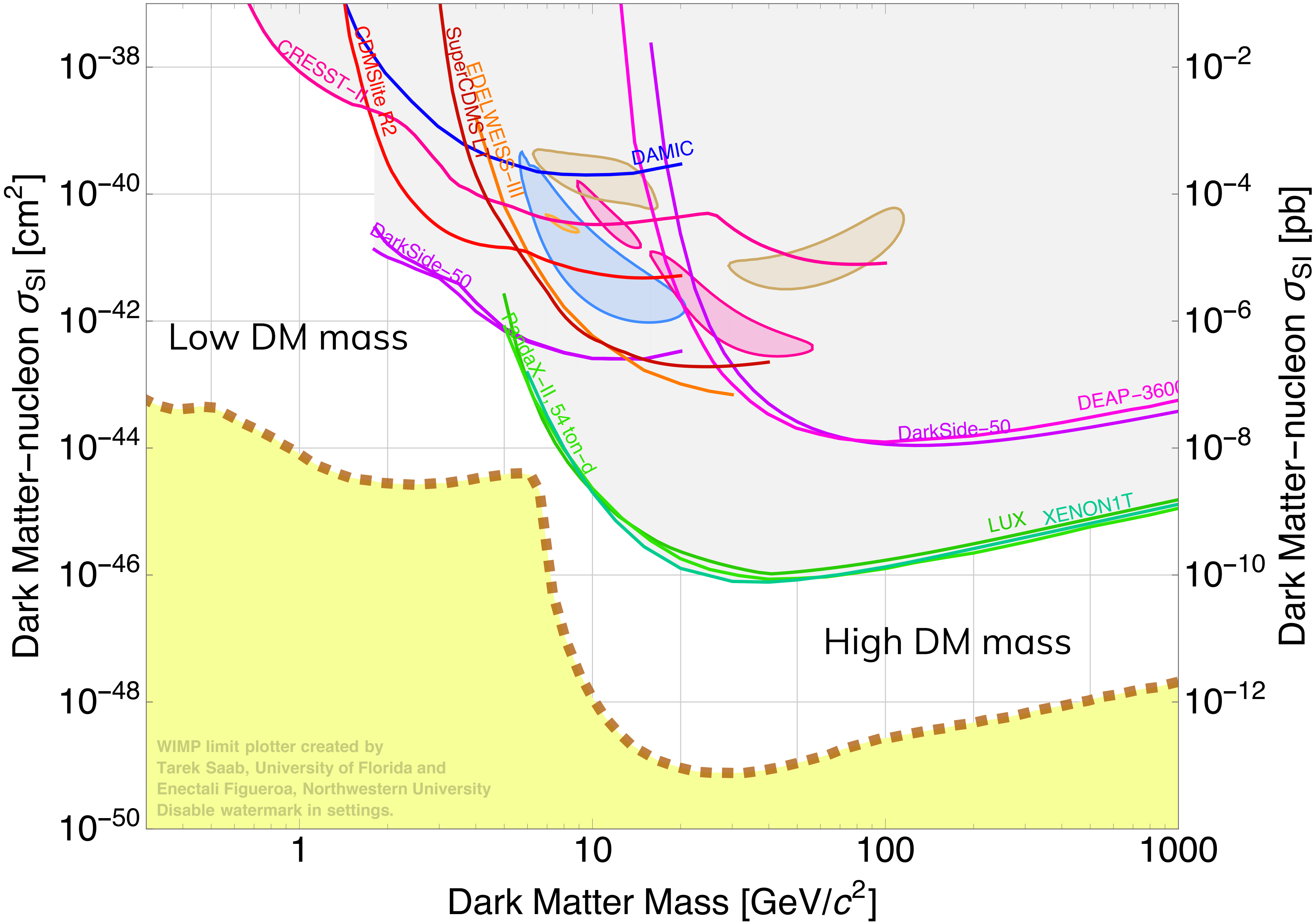
1000
100
10
1
Energy Resolution (eV, FWHM)
1980
1985
1990
1995
2000
2005
2010
Year
Semiconductor Thermometers
Transition Edge Sensors
Magnetic Calorimeters
Superconducting Tunnel Junctions
Microwave Kinetic Inductance Detector
Magnetic Penetration Thermometers

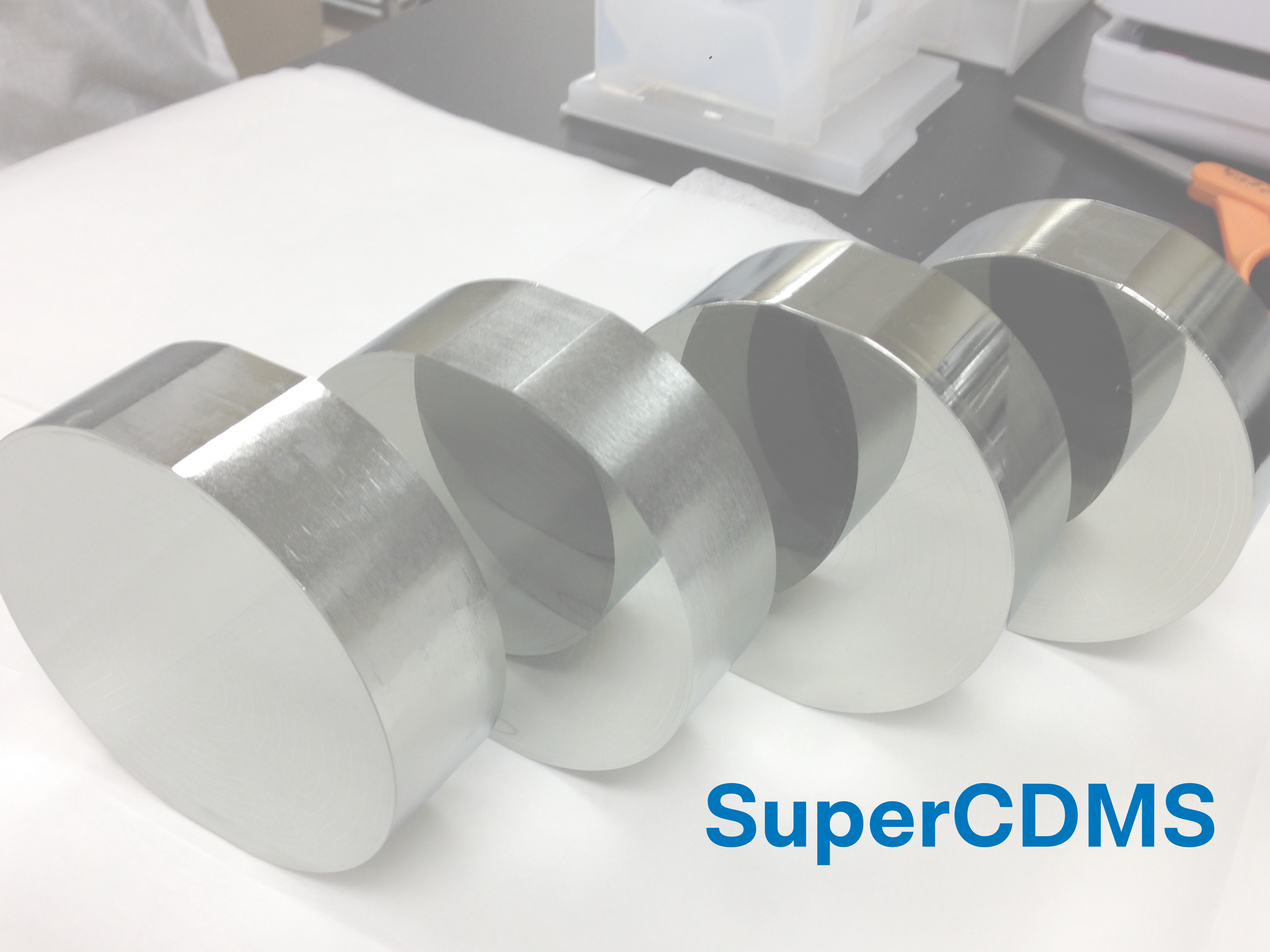


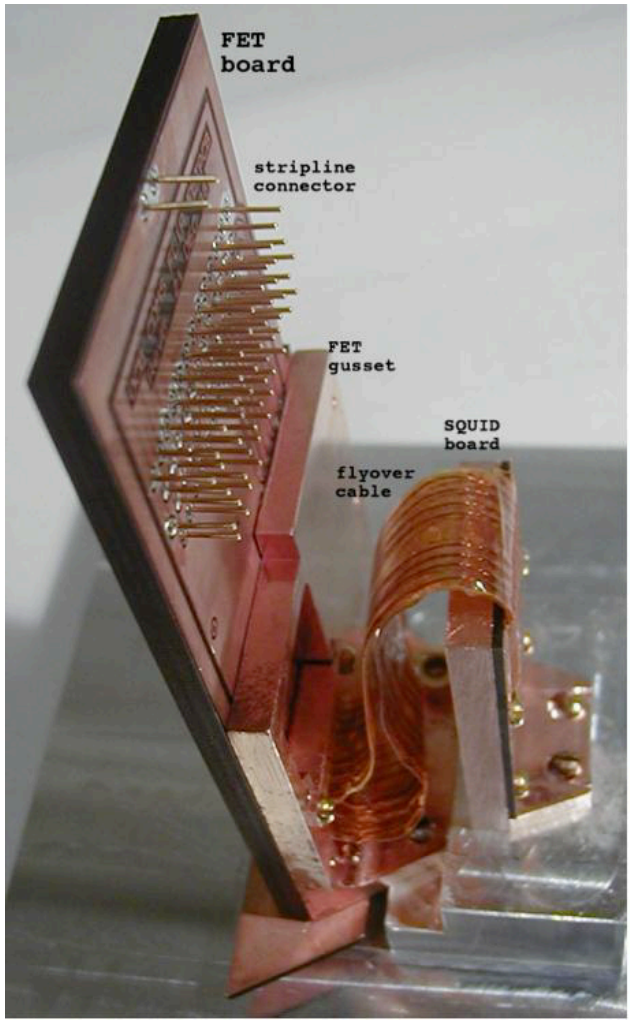
Application to Direct Dark Matter Search Experiments

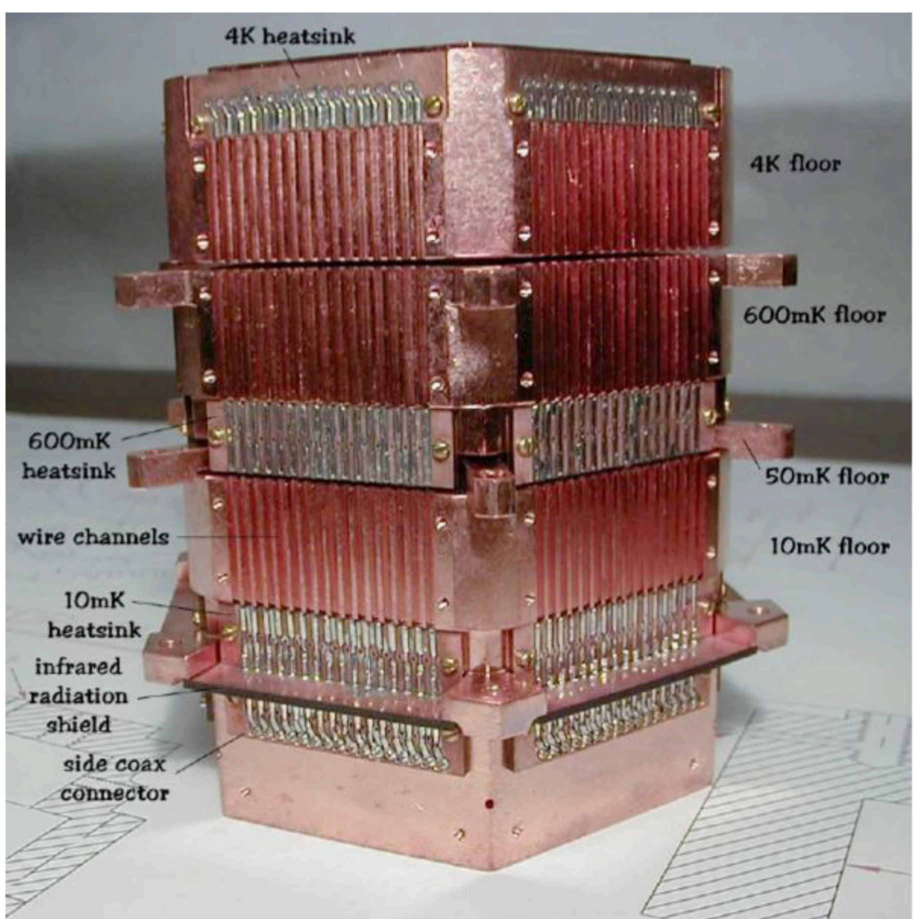
Direct DM Search - State of Art

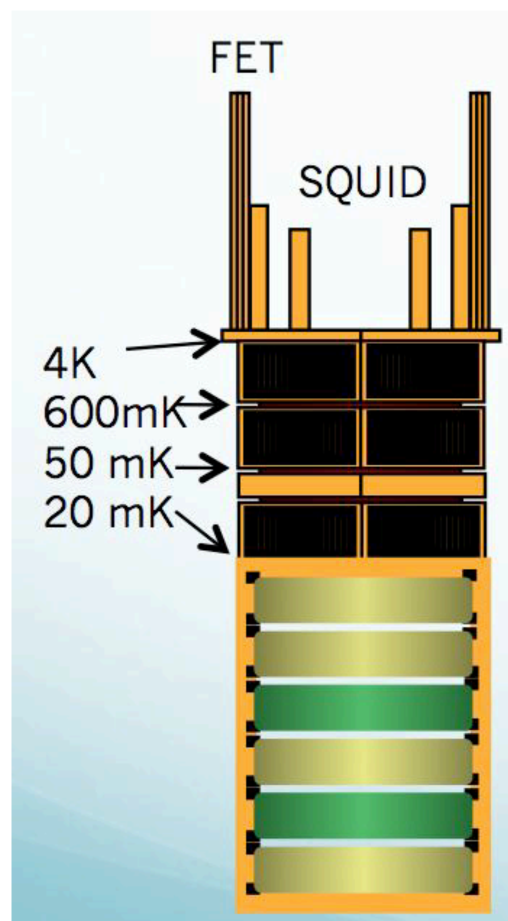
Detection of the energy deposited due to scattering off target

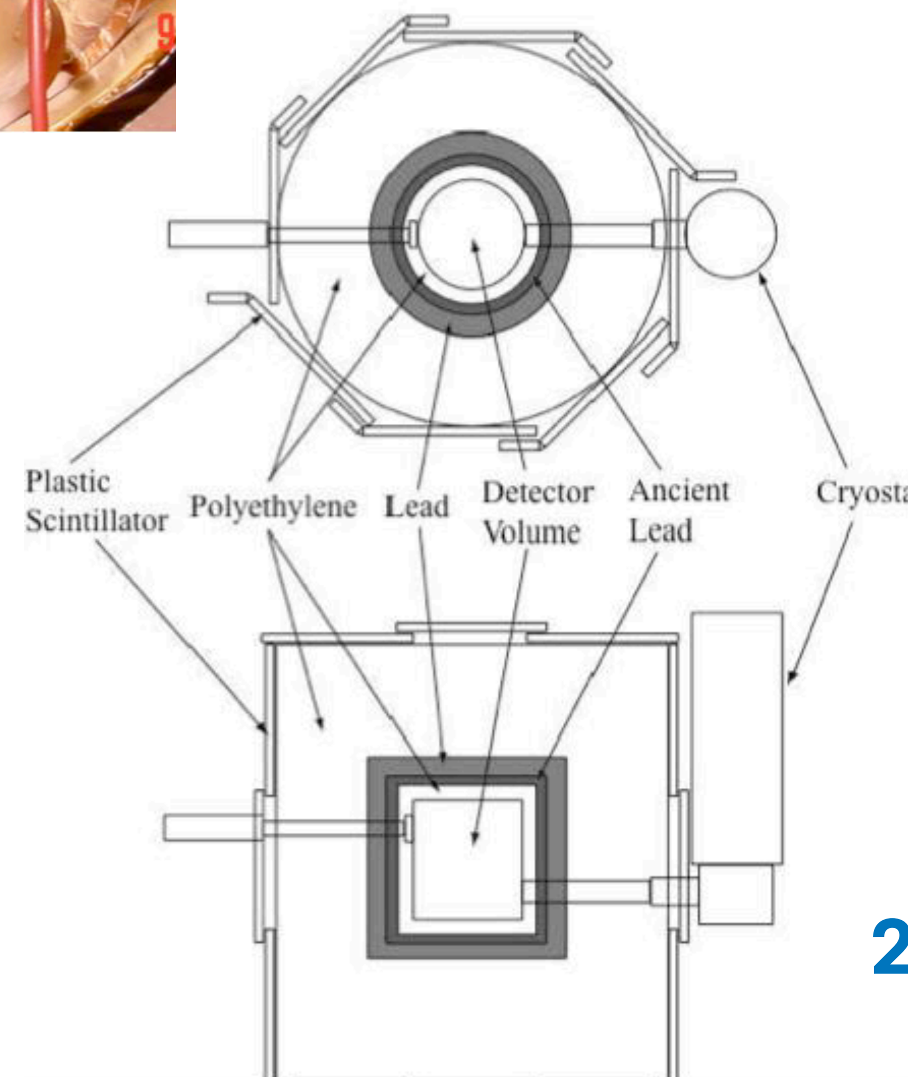



SuperCDMS


FET board
stripline connector
FET gusset
SQUID board
flyover cable


4K heatsink
4K floor
600mK floor
600mK heatsink
50mK floor
wire channels
10mK floor
10mK heatsink
infrared radiation shield
side coax connector

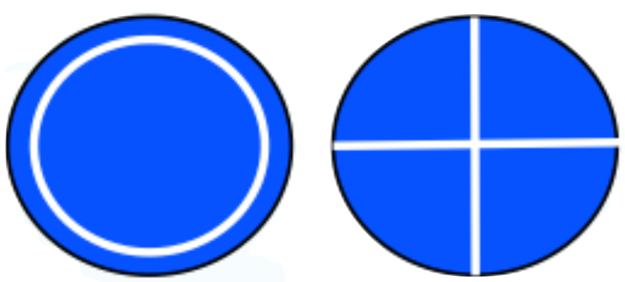

FET
SQUID
4K
600mK
50 mK
20 mK


Plastic Scintillator
Polyethylene
Lead
Detector Volume
Ancient Lead
Cryostat

Detectors

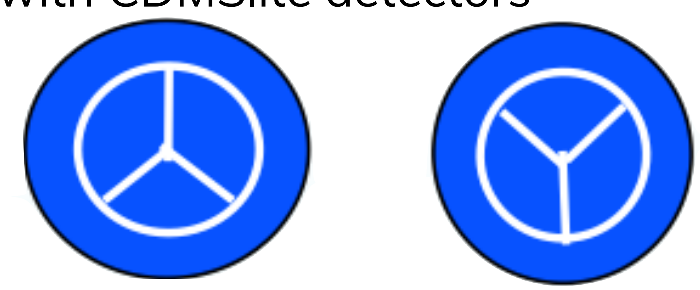
CDMS II (Ge+Si)

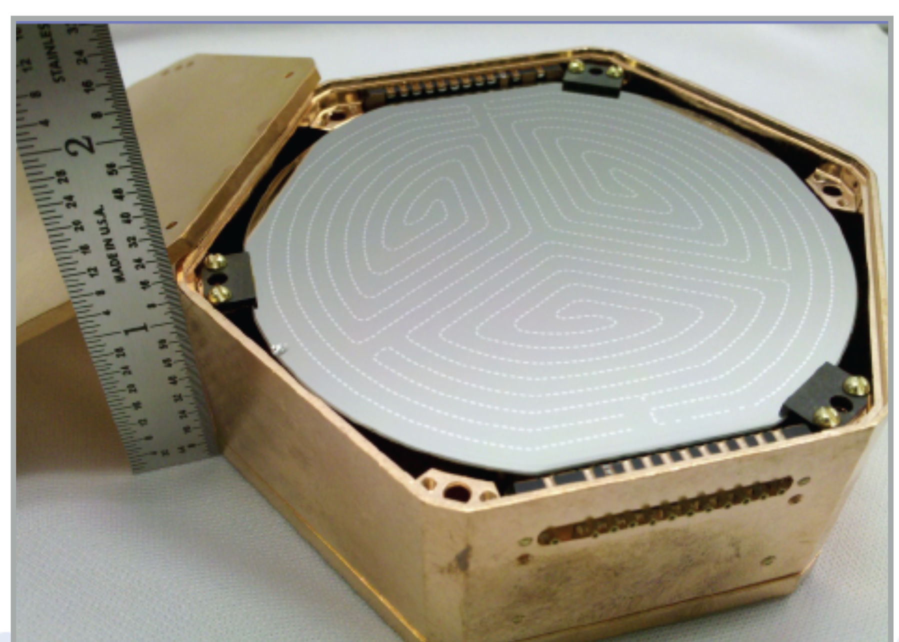
- 4.6 kg Ge (19 x 240 g)
- 1.2 kg Si (11 x 106g)
- 35% NR acceptance



SuperCDMS Soudan

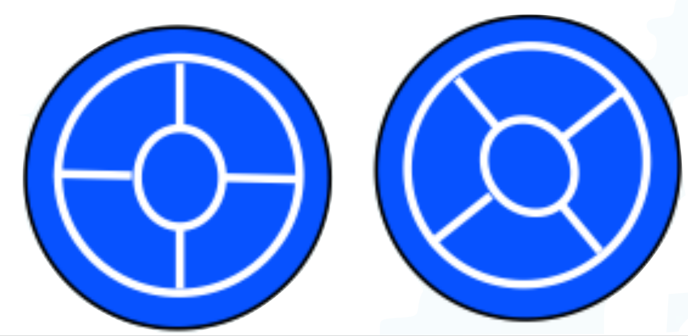
- 9.0 kg Ge (15 x 600 g)
- Increased acceptance
- Improved surface event discrimination
- Demonstrated HV performances with CDMSlite detectors





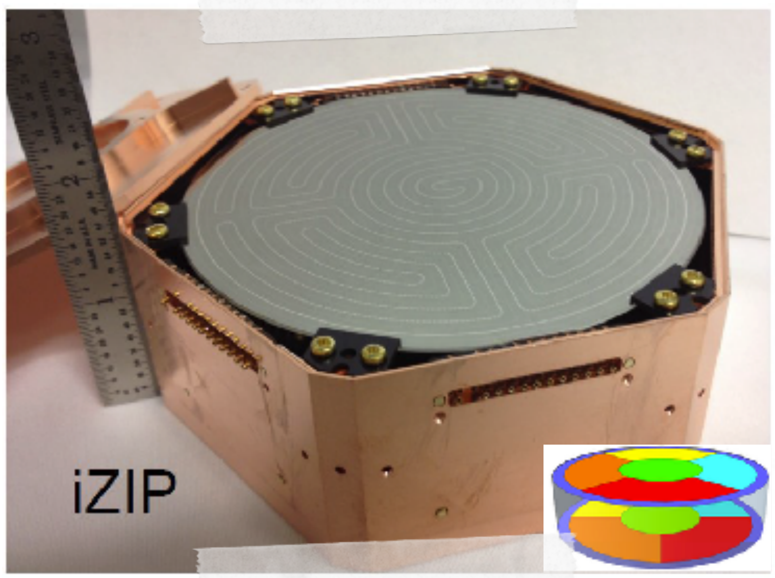
SuperCDMS SNOLAB

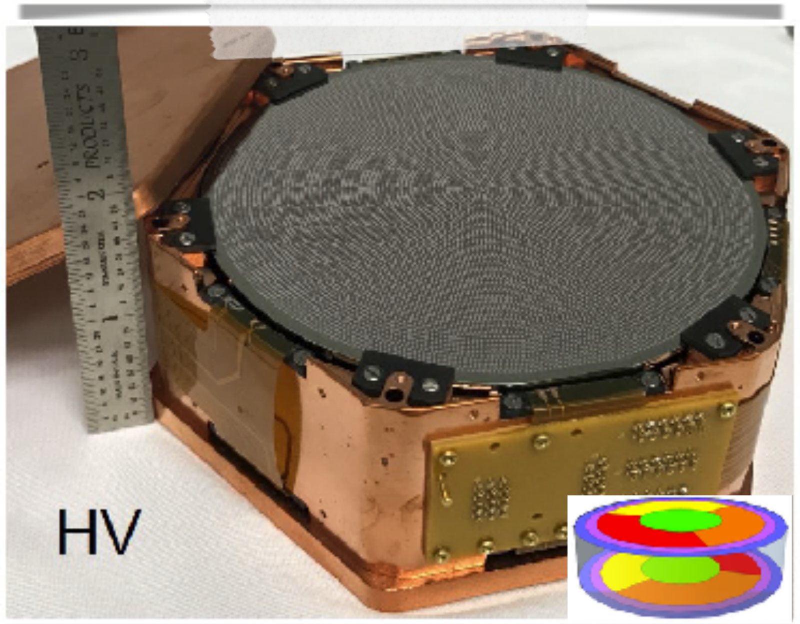
- Four towers of mixed Ge and Si, iZIP and HV detectors
  - iZIP: detectors with full background rejection capabilities
  - HV: detectors with lowered energy thresholds



SuperCDMS Detectors

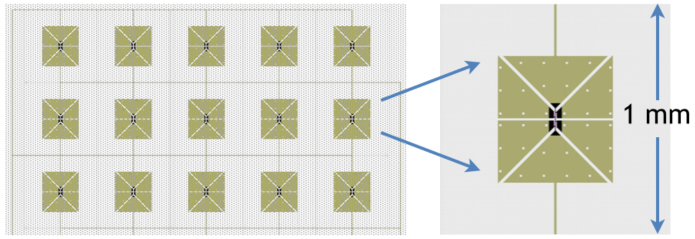
Technique: Heat+Ionization





- Ultra-pure ~kg Ge and Si crystals operated at 10’s of mK

- Measure athermal phonon signal via transition edge sensor



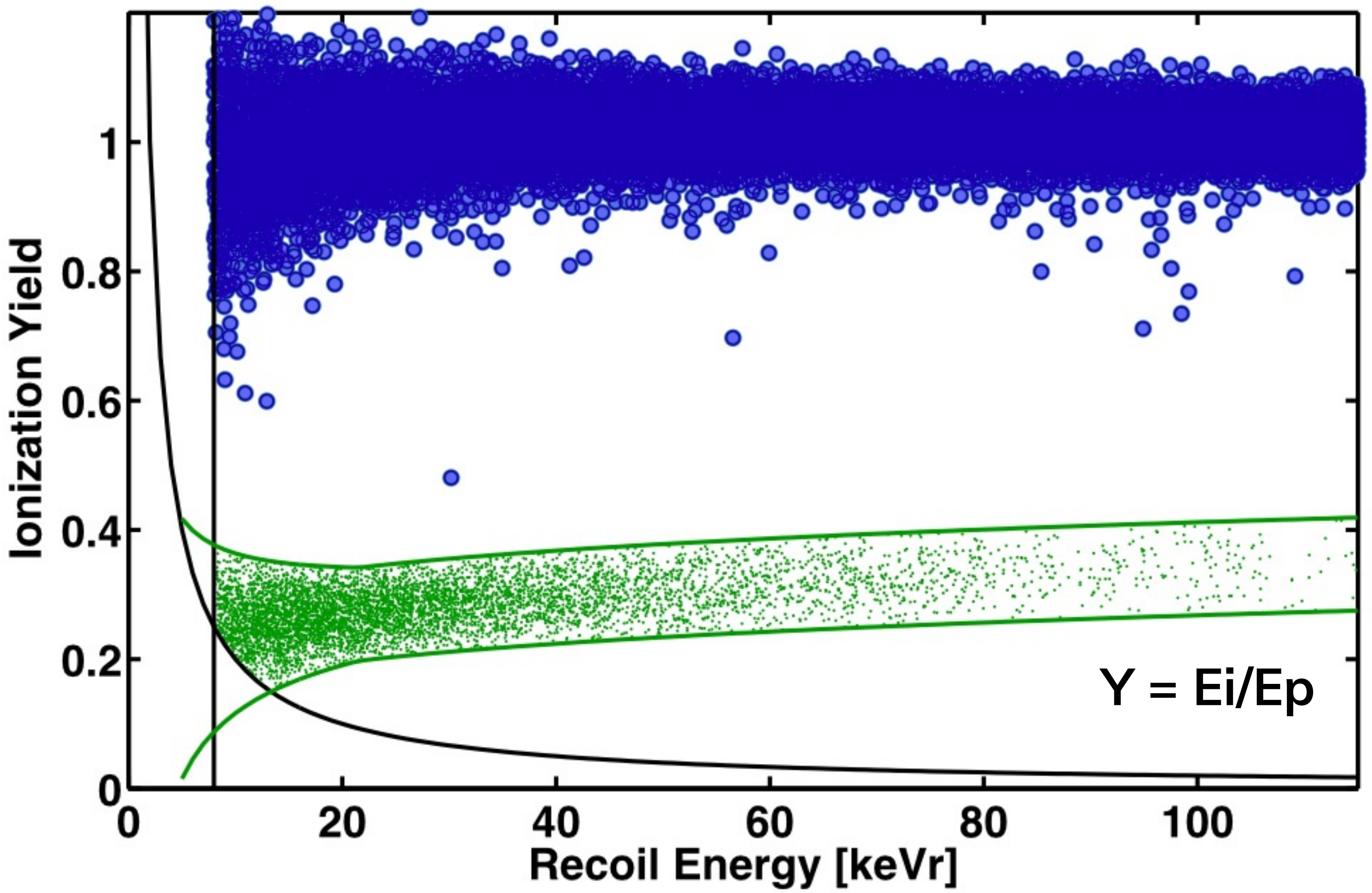
- Multiple channels give position information
- Outer “guard” rings fiducialize high radius events

- Surface/Bulk event discrimination via charge face symmetry

iZIP Technology

Background Discrimination

Electron recoils have a **higher ionization yield** than nuclear recoils



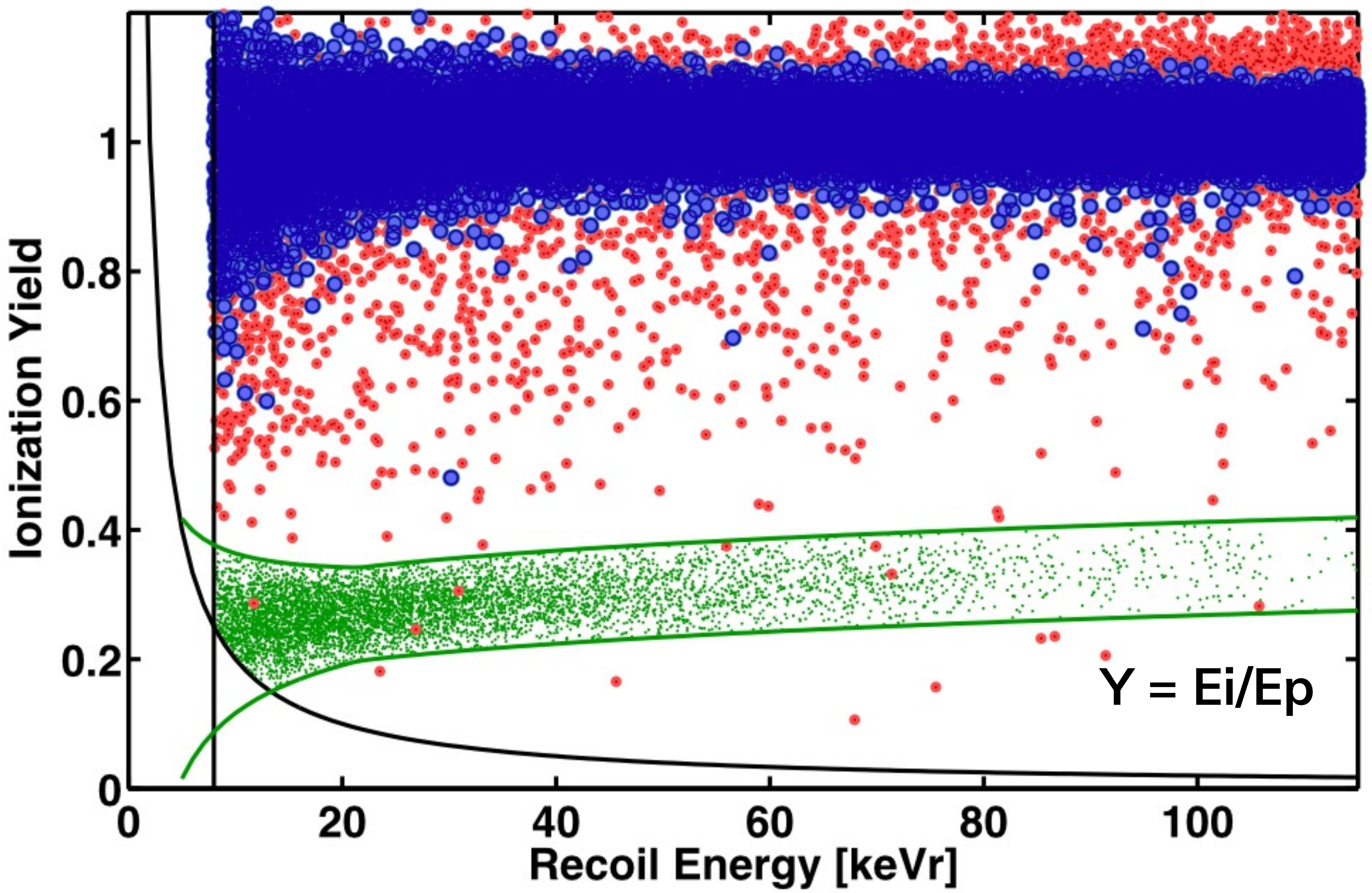
γ : ^{133}Ba calibration

n: ^{252}Cf calibration

iZIP Technology

Background Discrimination

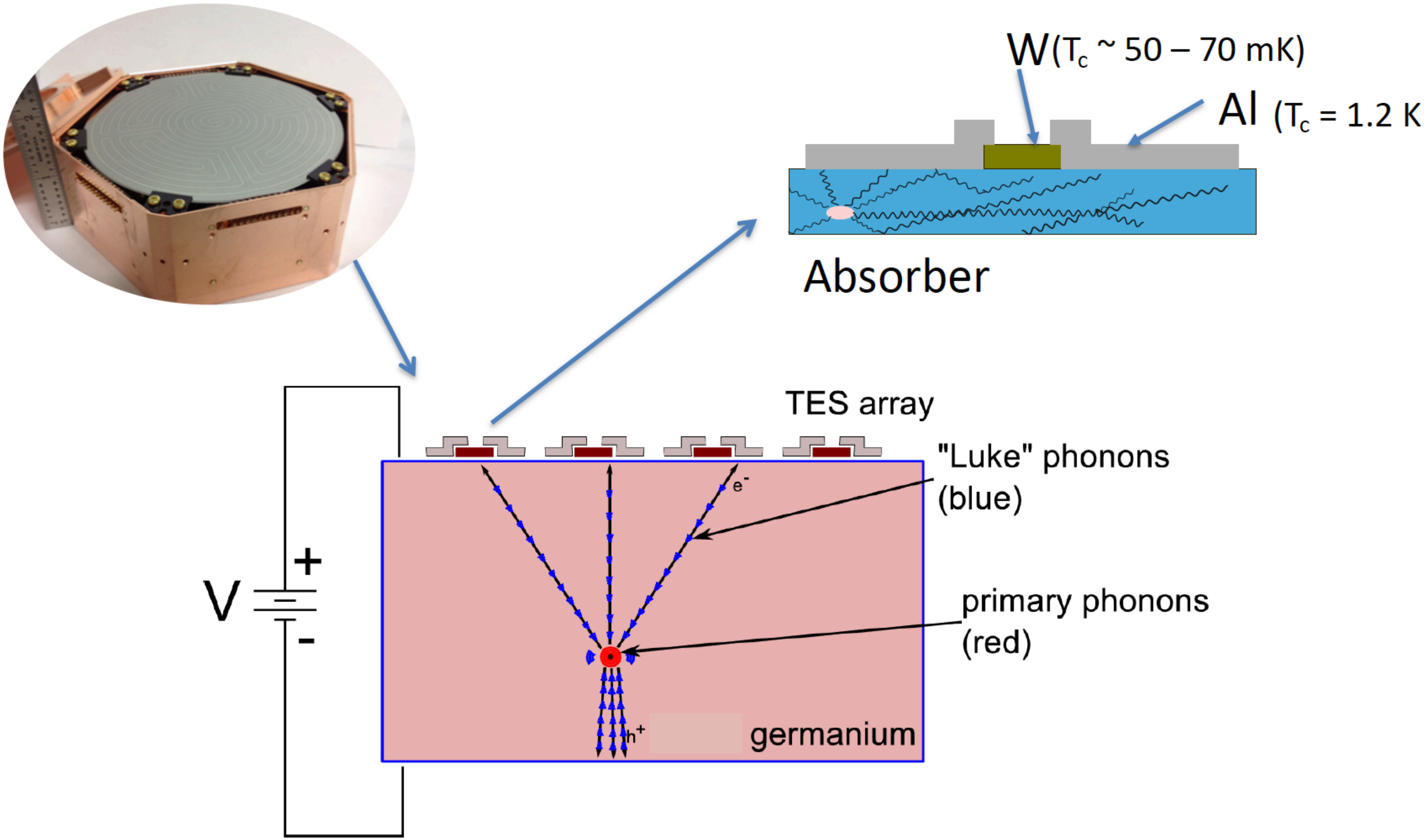
Electron recoils have a **higher ionization yield** than nuclear recoils
Surface events have a **reduced ionization yield** and can mimic nuclear recoils



γ : ^{133}Ba calibration

^{133}Ba surface events

n: ^{252}Cf calibration

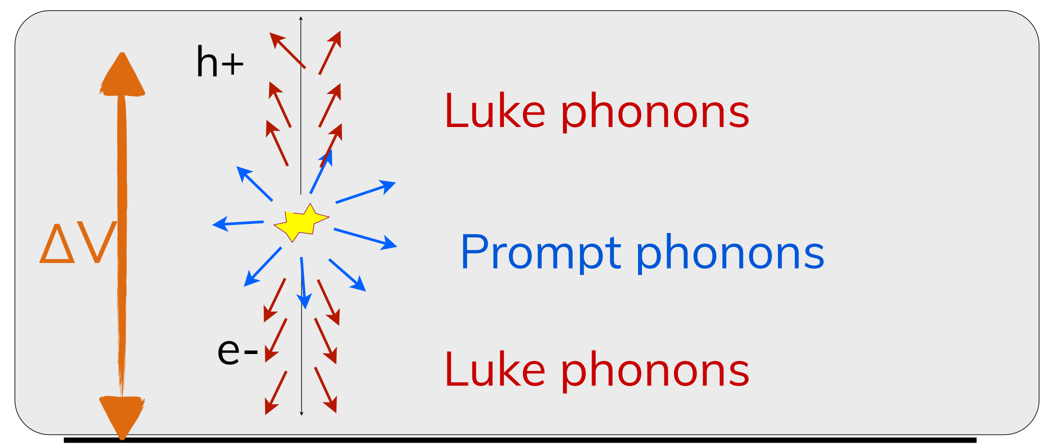

W(Tc ~ 50 – 70 mK)
Al (Tc = 1.2 K)
Absorber
TES array
"Luke" phonons
(blue)
primary phonons
(red)
e-
h+
germanium
V
+
-

HV Technology

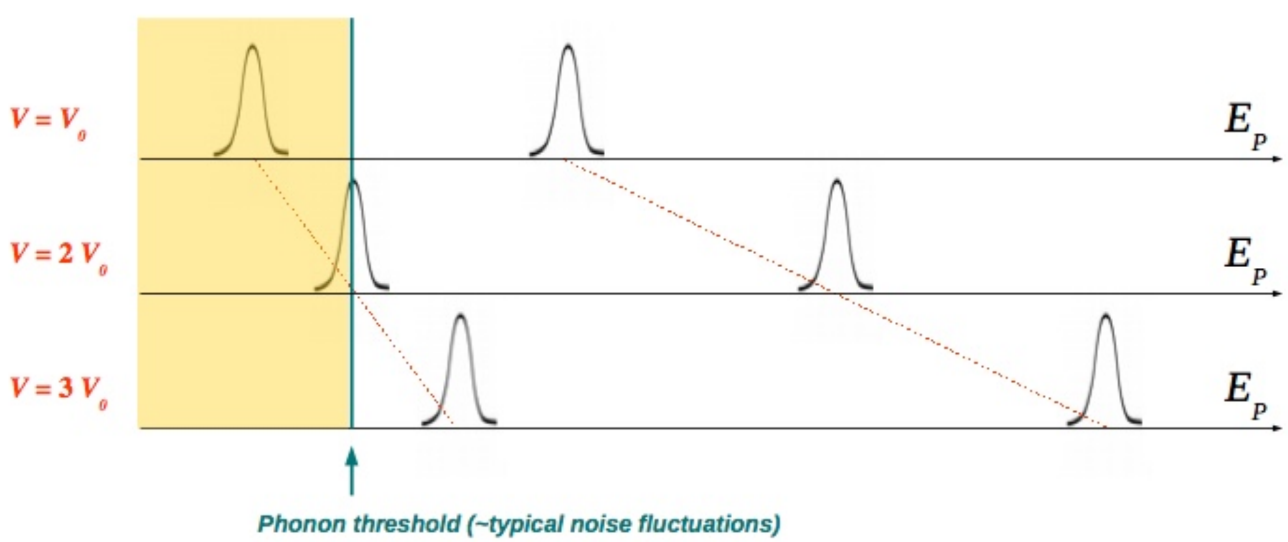
$$E_P = E_R + n_{eh} e \Delta V$$

Drifting charges produce large phonon signal proportional to ionization (Neganov-Luke Effect)

Low Energy Threshold



Heat signal boosted by Neganov-Luke effect (~Joule heating, factor [1+V/3] for Ge, factor [1+V/3.8] for Si)

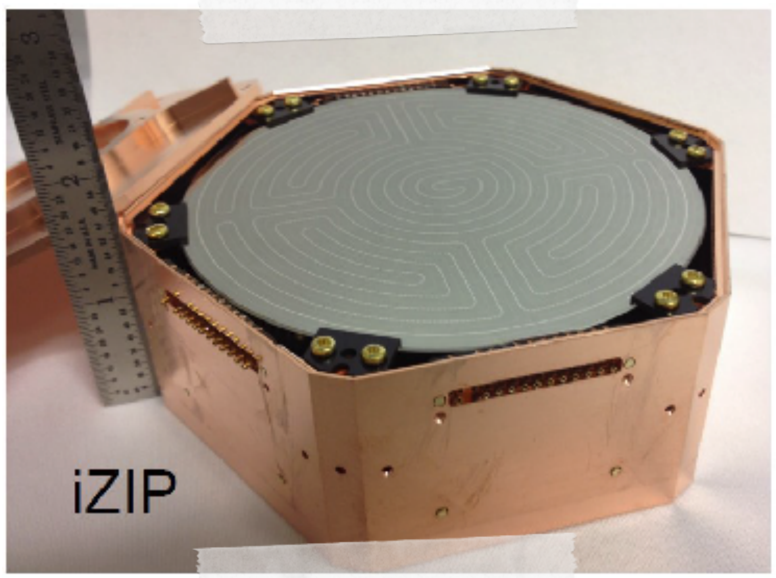


Note that only E_P can be amplified, but not n_{eh}

Particle identification & fiducialisation compromised

ER reconstruction requires assumptions on Yield

Detectors Advantages

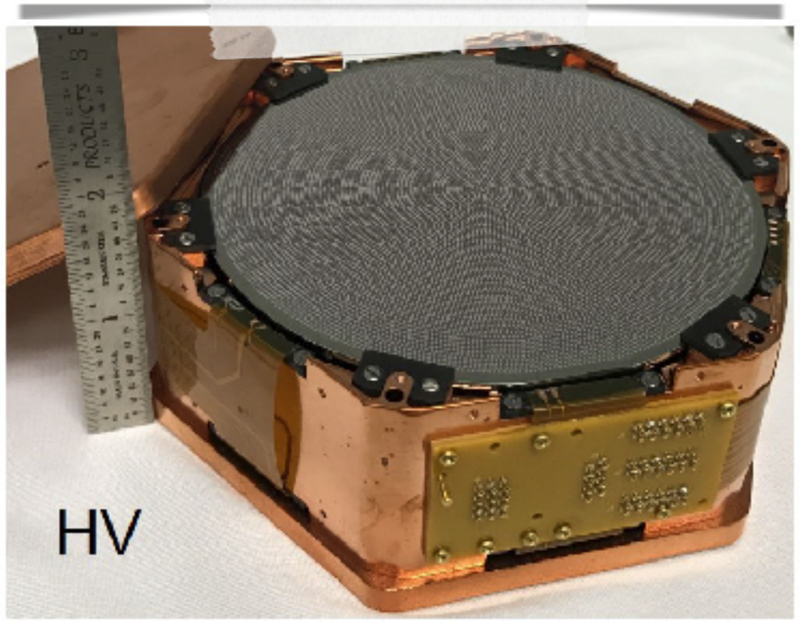


iZIP Detector

(10 Ge, 2 Si)

heat+ionization

- ER/NR discrimination
- Full fiducialisation
- $M_{DM} > 5GeV/c^2$



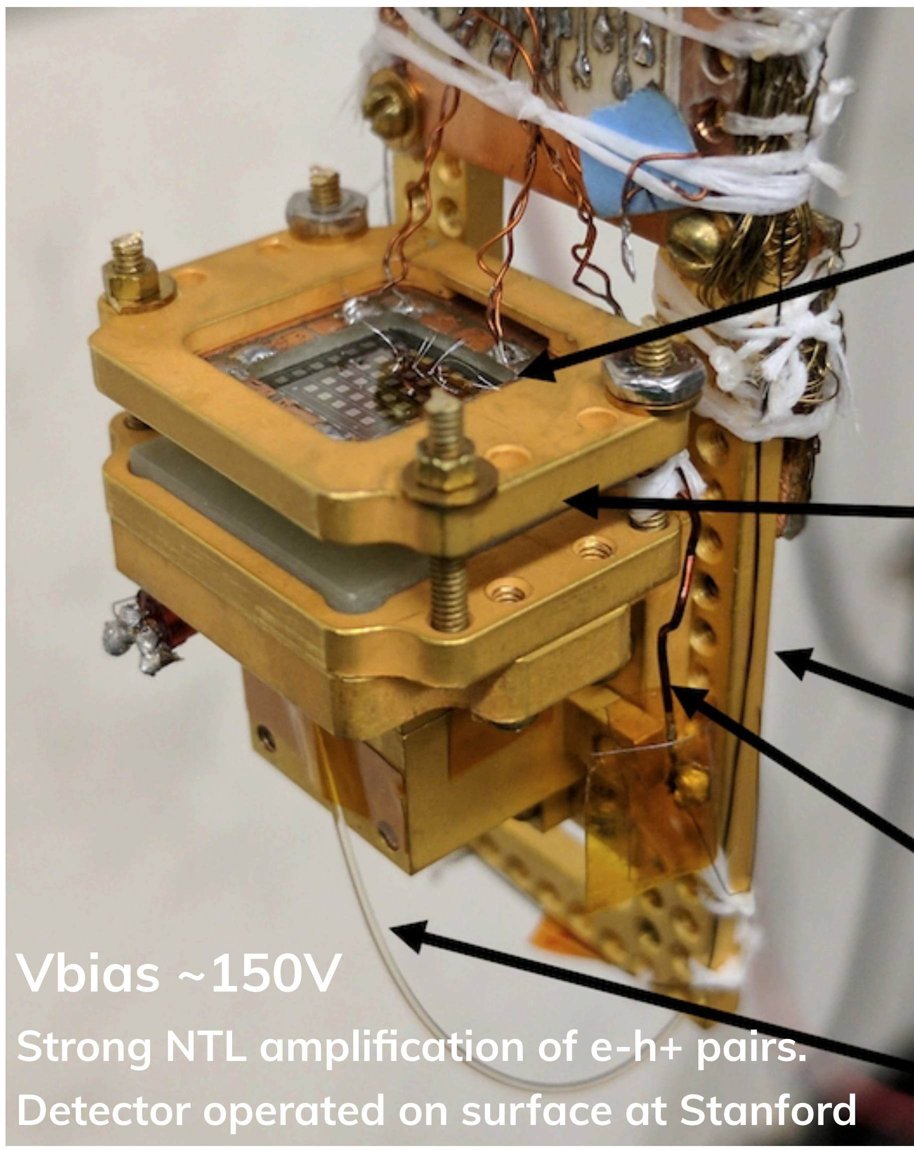
HV Detector

(8 Ge, 4 Si)

heat+ionization

- Radial fiducialisation
- Lower thresholds
- (75 eV_{ee} and 56 eV_{ee})
- $M_{DM} < 5GeV/c^2$

Prototype HVeV Detector



Si crystal/
phonon sensors

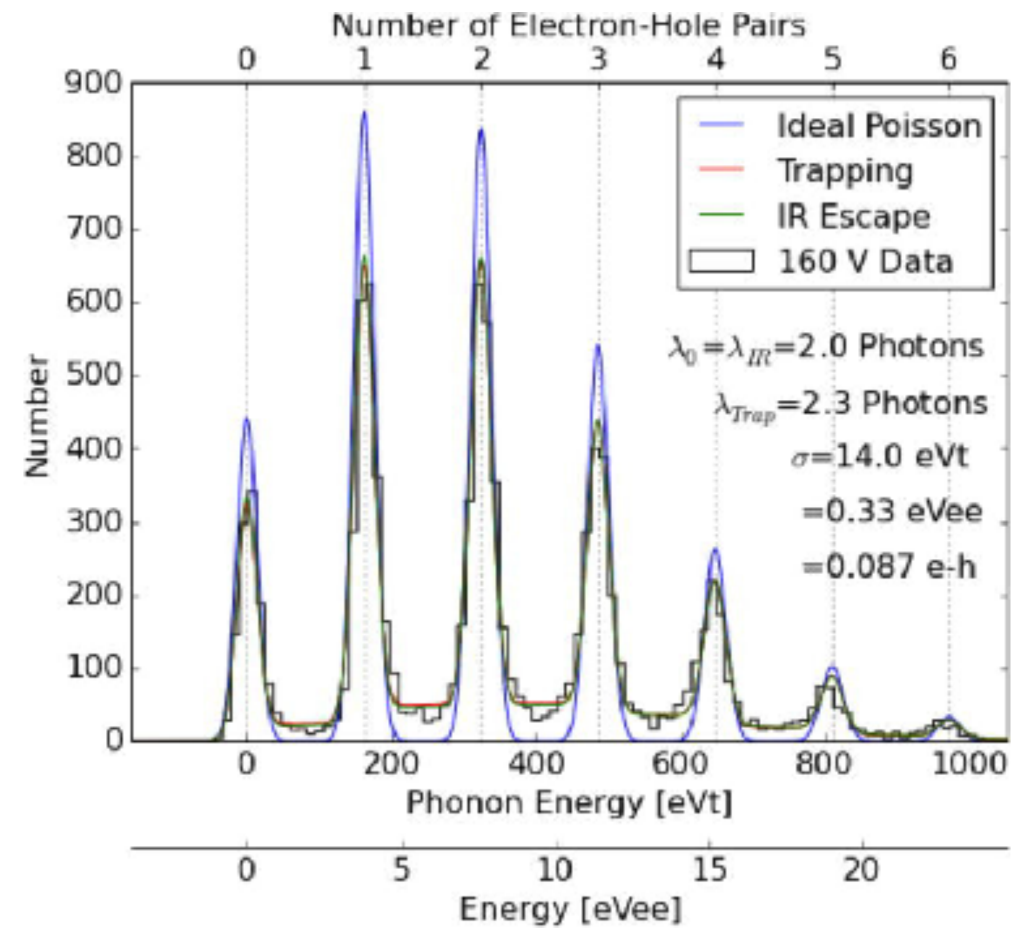
Crystal holder

Dilution refrigerator
sample stage (3mK)

Bias voltage line

Fiber optic

Appl. Phys. Lett. 112, 043501



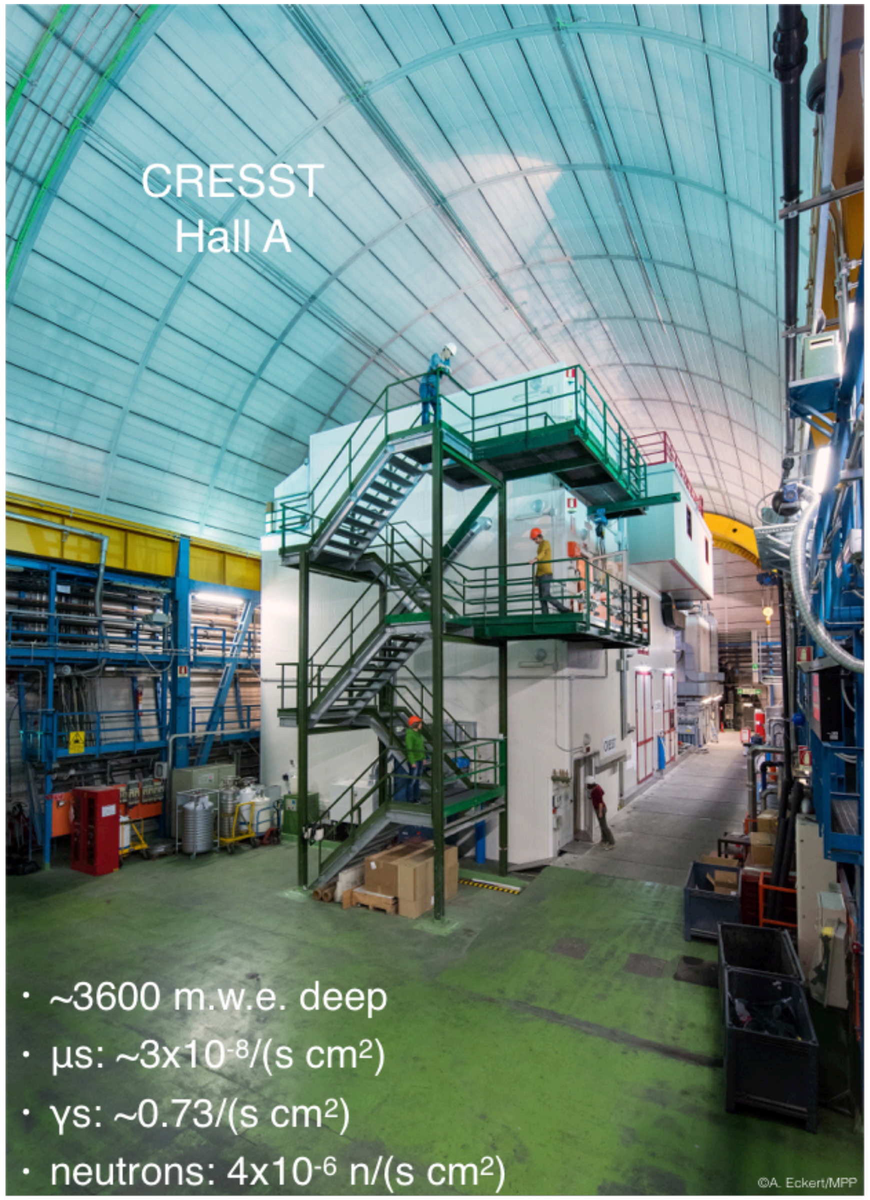
Single e/h-pair sensitivity has been recently demonstrated in 0.93 g Si crystal

Sensitivity to a variety of sub-GeV DM models with g*d exposures

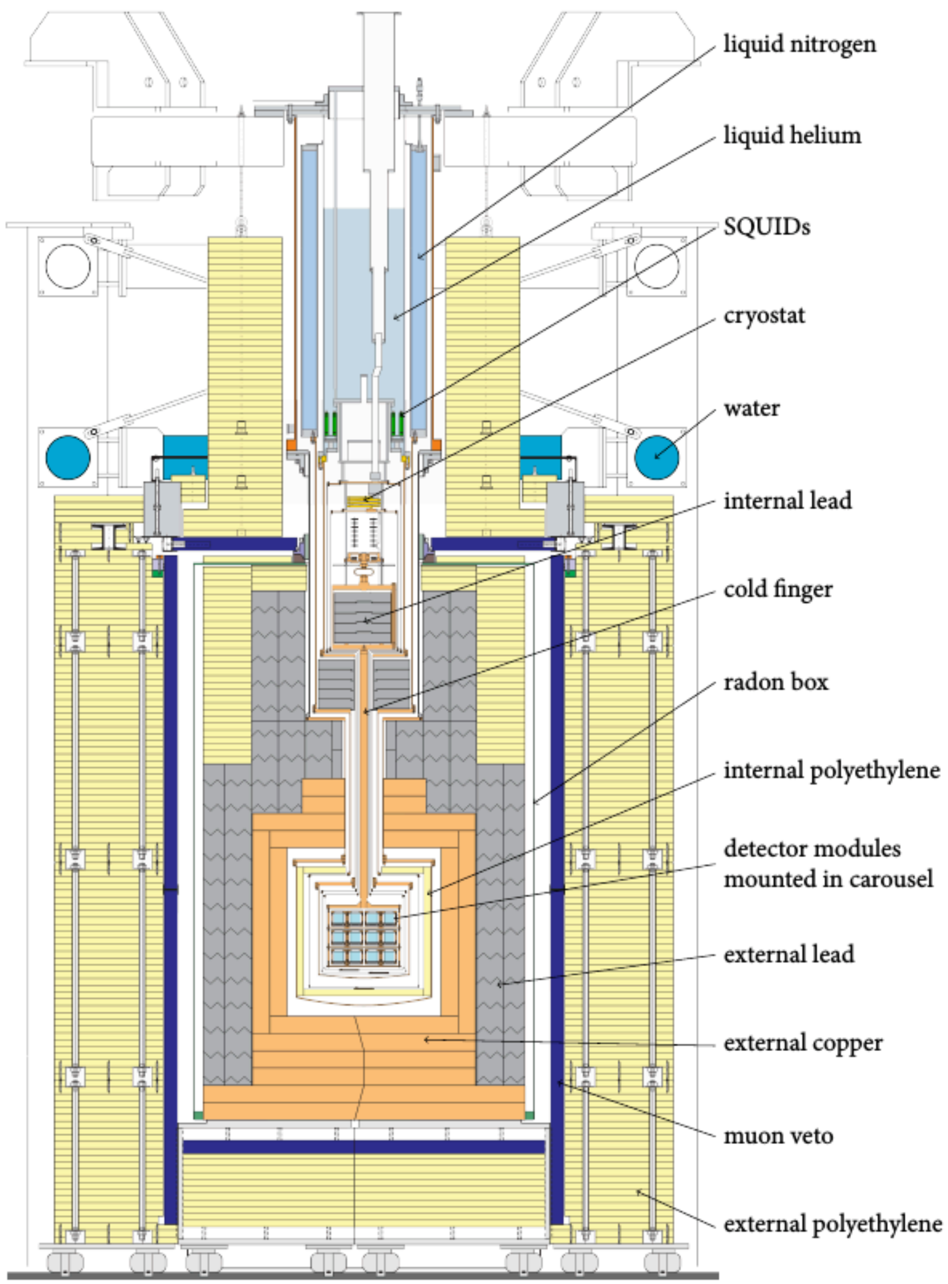
CRESST

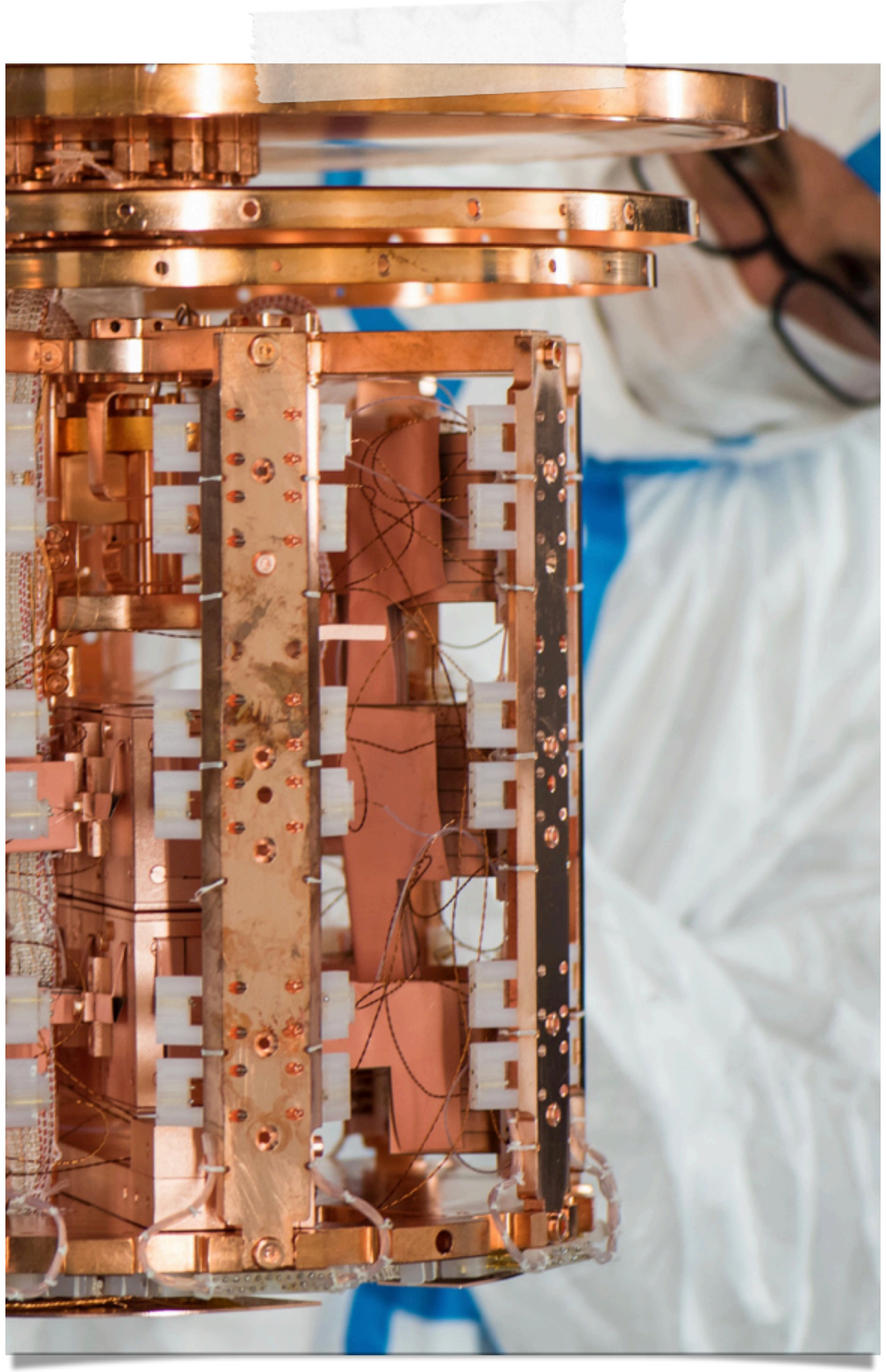
CRESST @ LNGS


Teramo
A24
L'Aquila
CRESST
LNGS
Laboratori Nazionali del Gran Sasso


CRESST
Hall A
• ~3600 m.w.e. deep
• μs: $\sim 3 \times 10^{-8}/(s\ cm^2)$
• γs: $\sim 0.73/(s\ cm^2)$
• neutrons: $4 \times 10^{-6}\ n/(s\ cm^2)$
©A. Eckert/MPP

Experimental Setup





CRESST Detector

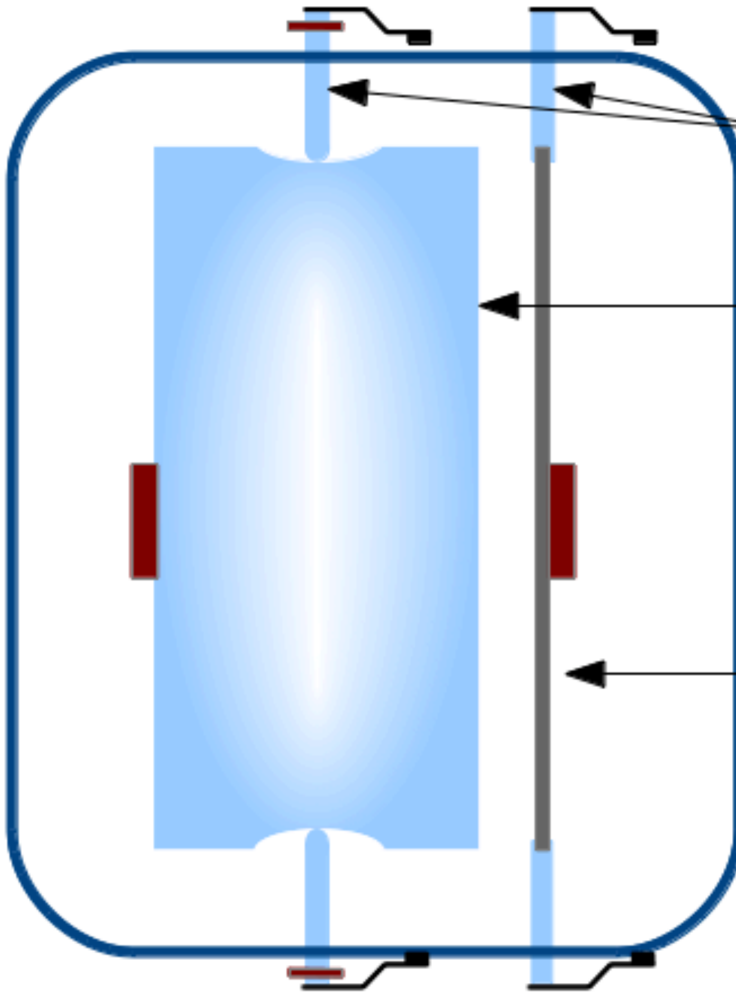
Technique: Heat+Scintillation

Scintillating $CaWO_4$ crystals as target

Target crystals operated as cryogenic calorimeters (~15mK)

Collect both phonon and scintillating signals.

- Tungsten TES reads out phonon signal
- Light absorber (Si on sapphire) collects scintillation signal.

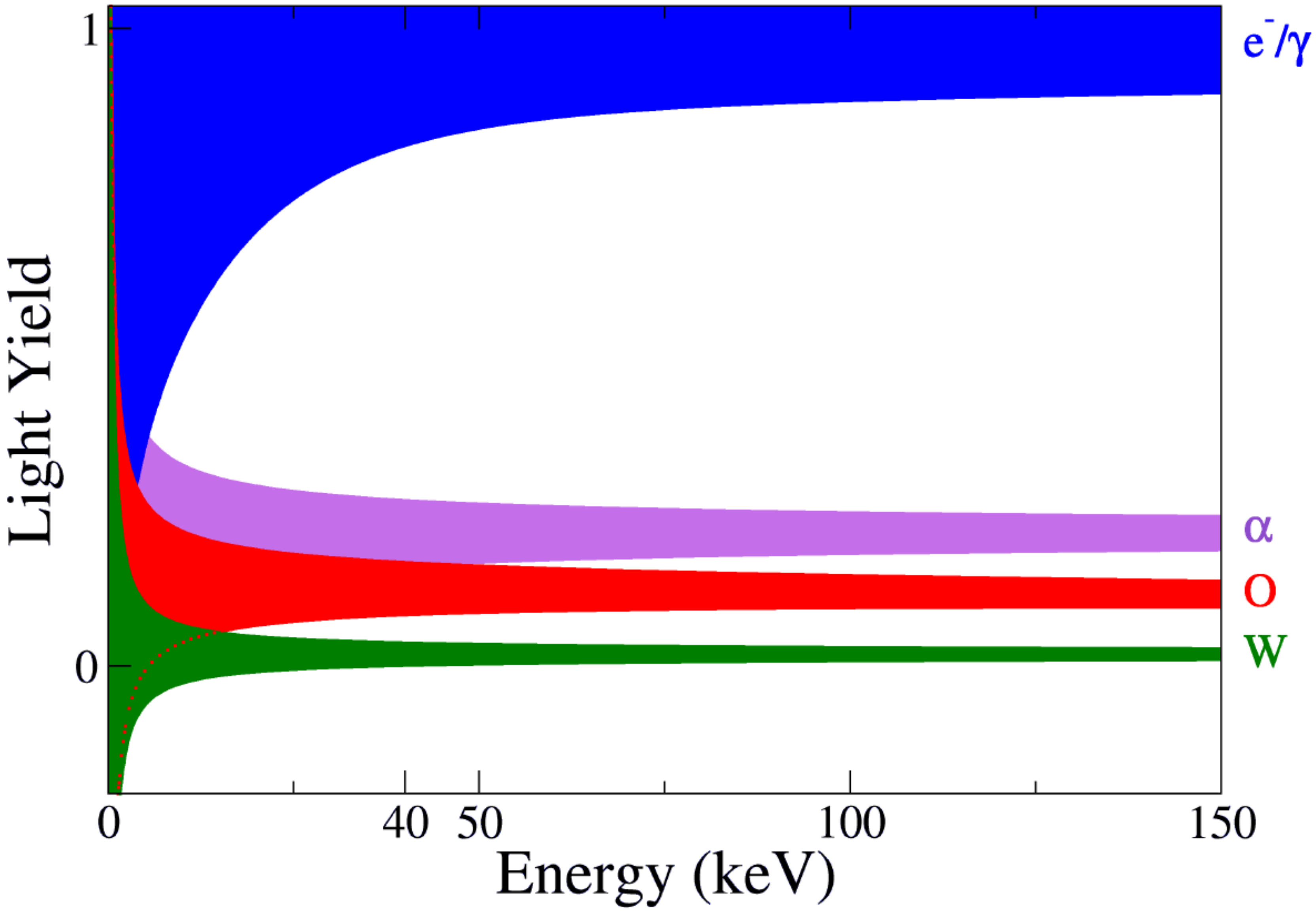


Particle Identification

Technique: Heat+Scintillation

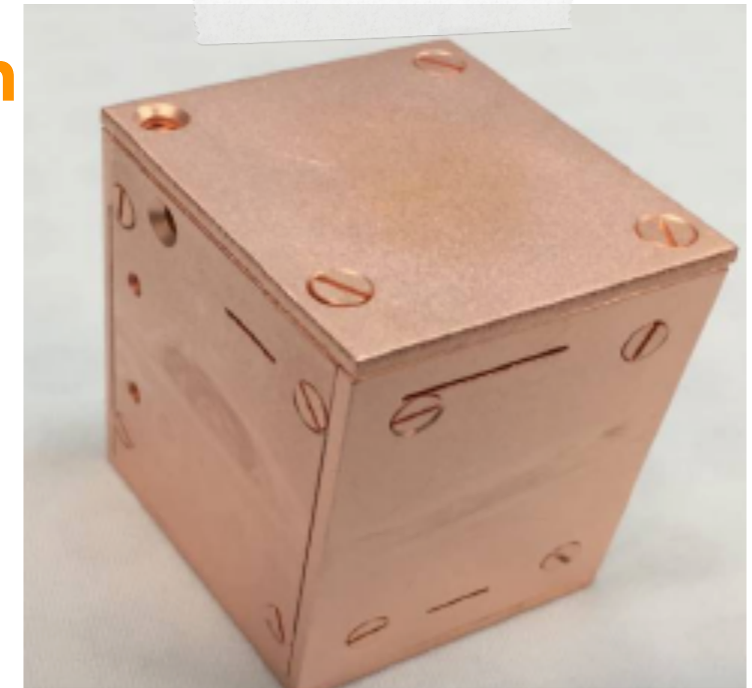
The scintillation light is particle dependent

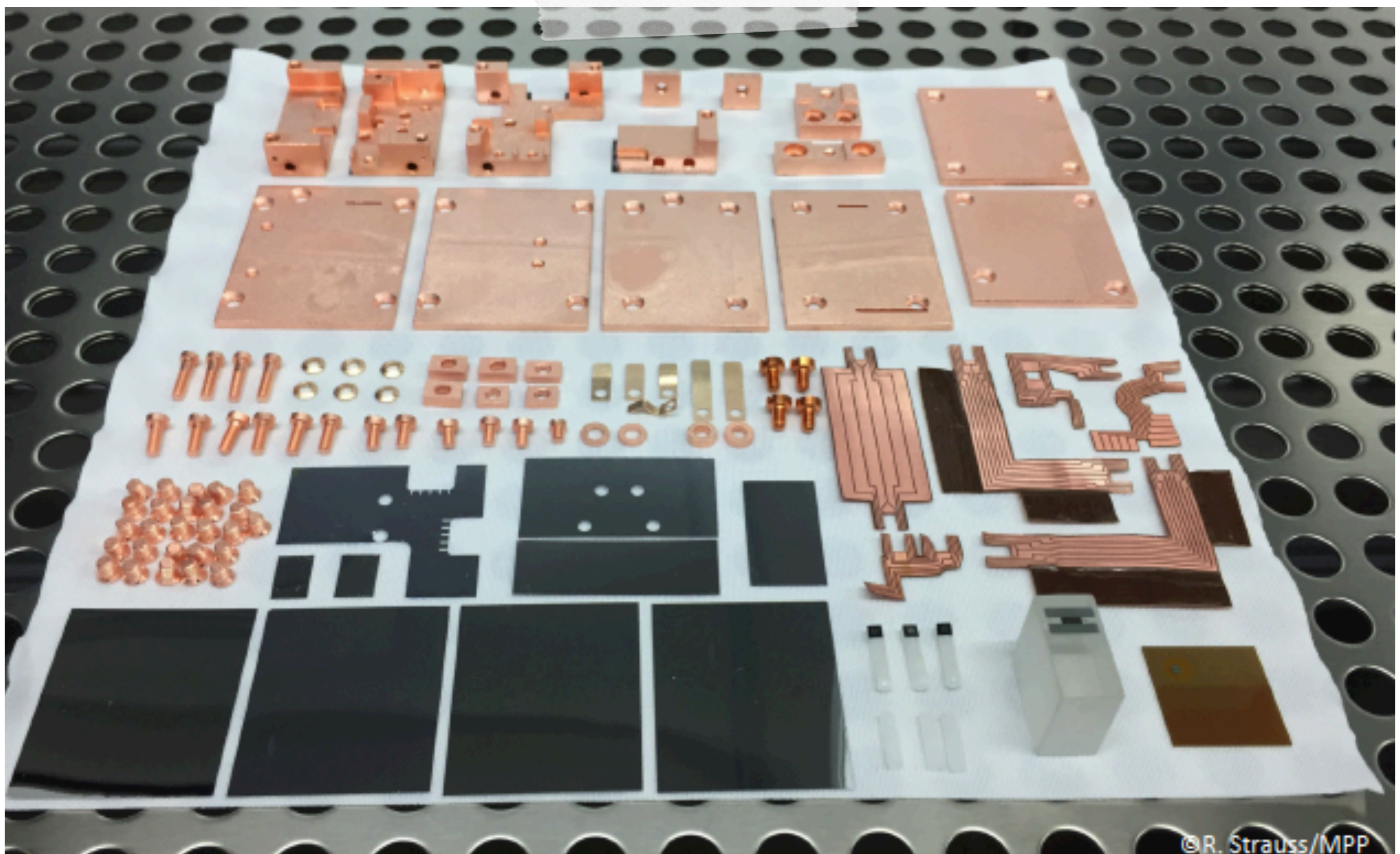
Discrimination between
- Electron recoils (radioactive background)
- Nuclear recoils (potential DM signal)



CRESST Detector

Technique: Heat+Scintillation

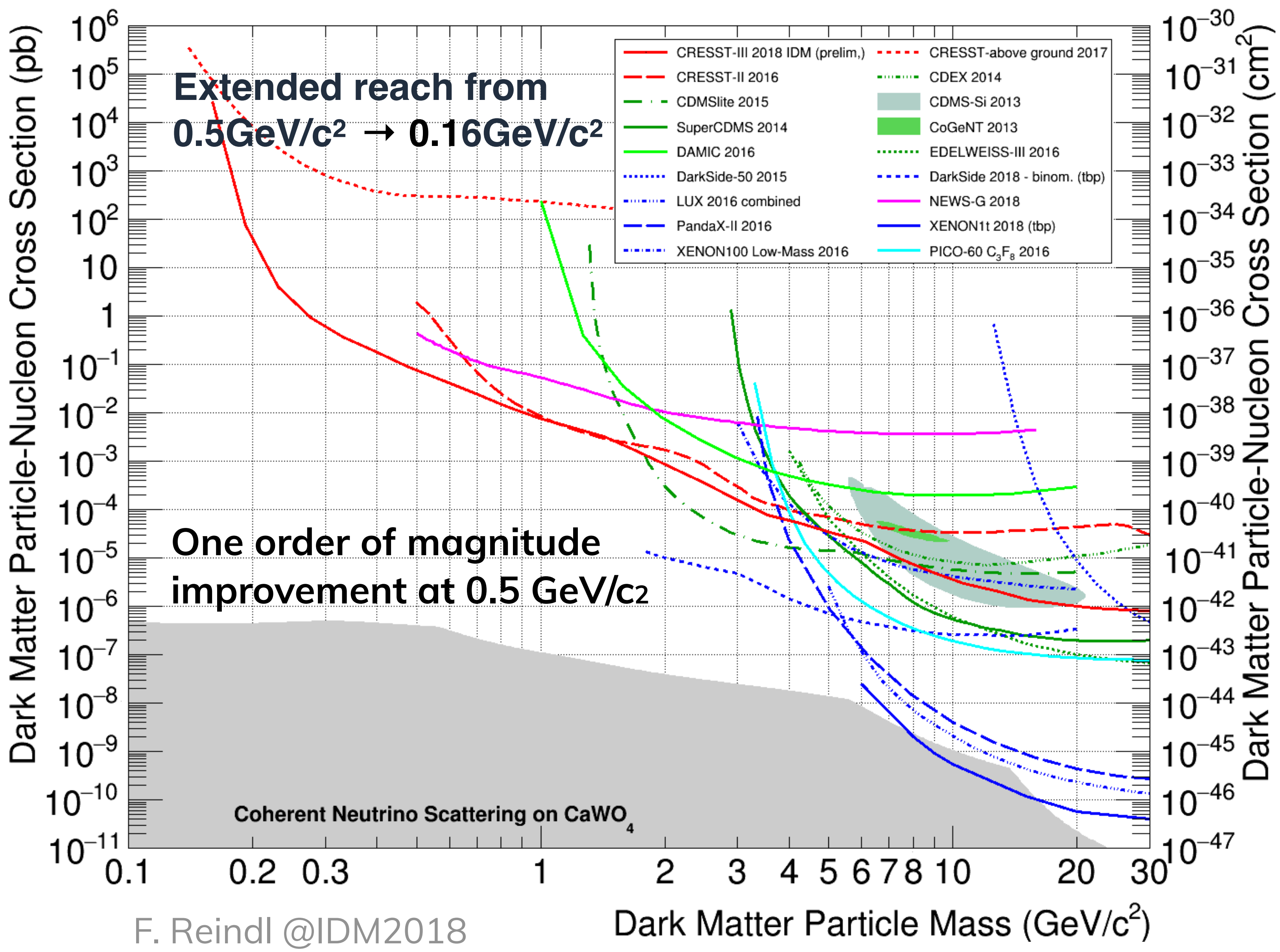




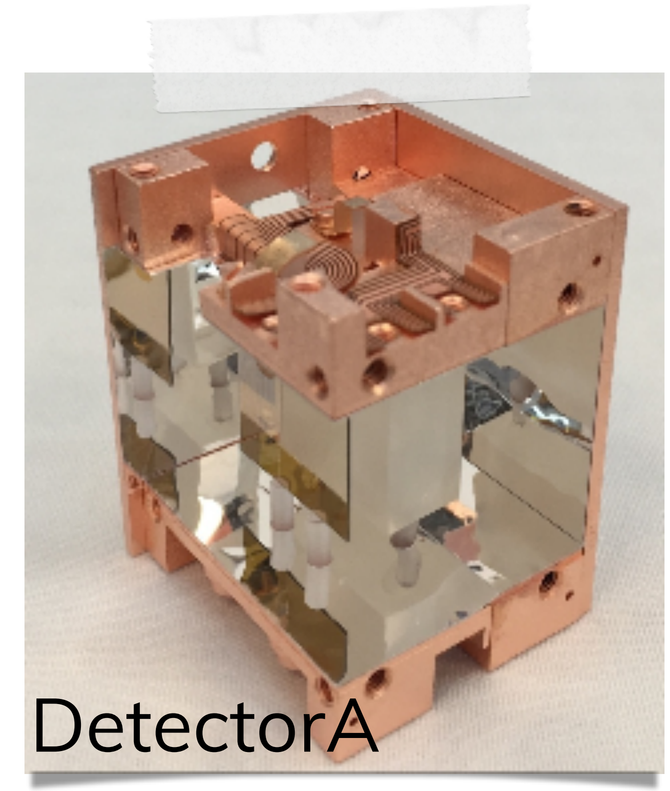
- Cuboid crystal (20 mm x 20 mm x 10 mm) ~ 24 g
- Goal: detection threshold of **100 eV**
- Self-grown crystal with low total background of ~**3 dru** [1-40 keV]
- Veto against surface related background: **fully scintillating housing** and instrumented sticks ("iSticks")

Results - Detector A

Technique: Heat+Scintillation



F. Reindl @IDM2018



Data taking period: 10/16 –01/18

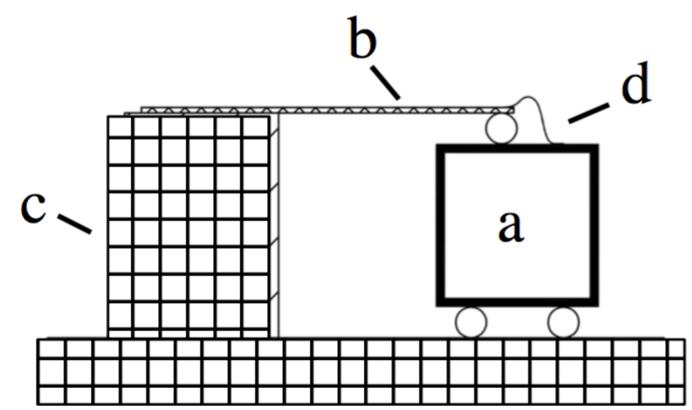
Target crystal mass: 24g

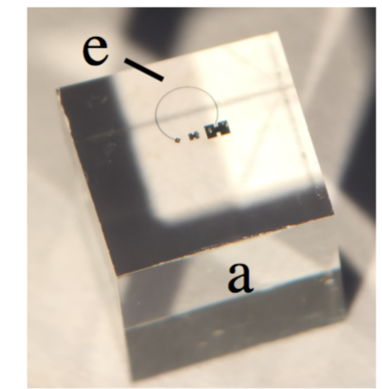
Gross exposure: 5.7 kg days

Nuclear recoil threshold: 30.1 eV

CRESST Detector

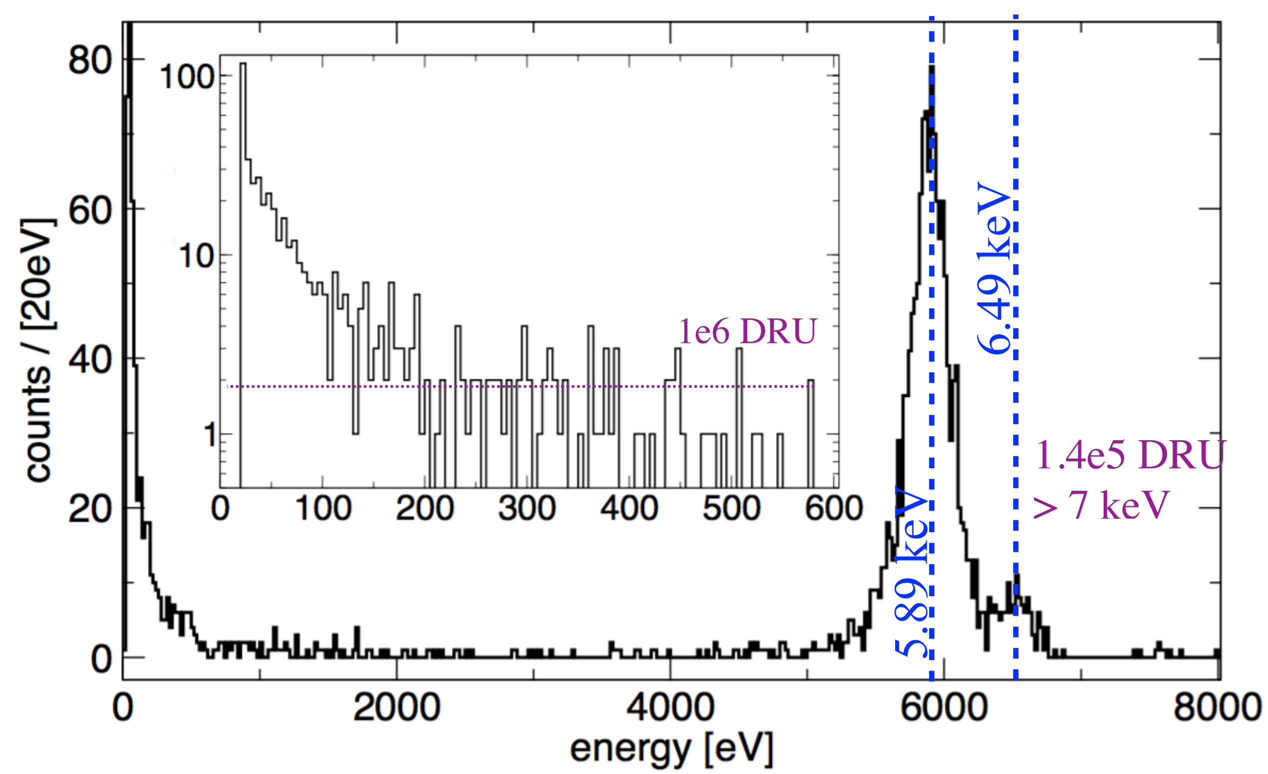
Technique: Heat Only





Detector layout optimized for **VERY low threshold**, further reduction of dimensions:

- Cuboid Al_2O_3 crystals (5 x 5 x 5) mm^3 ~ **0.49 g** with no light detector (**no particle identification**)
- Dedicated to CENNS science at nuclear reactors: NuCleus
- Achieved a **19.6 eV** energy threshold
- **Above ground operation** from MPI in Munich with no passive / active shielding
- Non-blind analysis with no event selection cut, only stability cuts (62 % efficiency)



R. Strauss et al., EPJC 2017

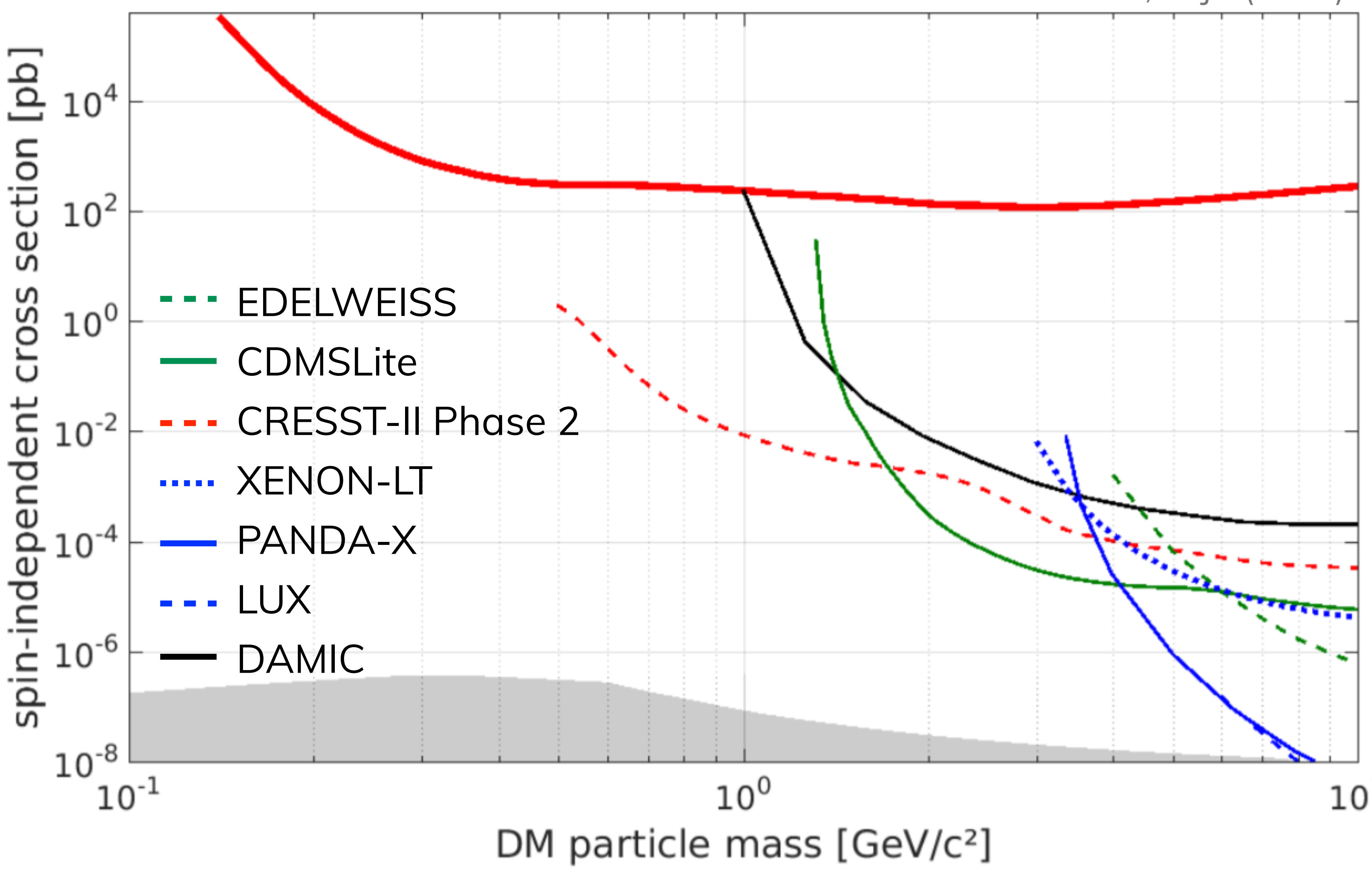
CRESST Detector

Technique: Heat Only

Leading limit from 500 MeV to 140 MeV

Above ground operation « OK »: CENNS at reactors (NuCleus)

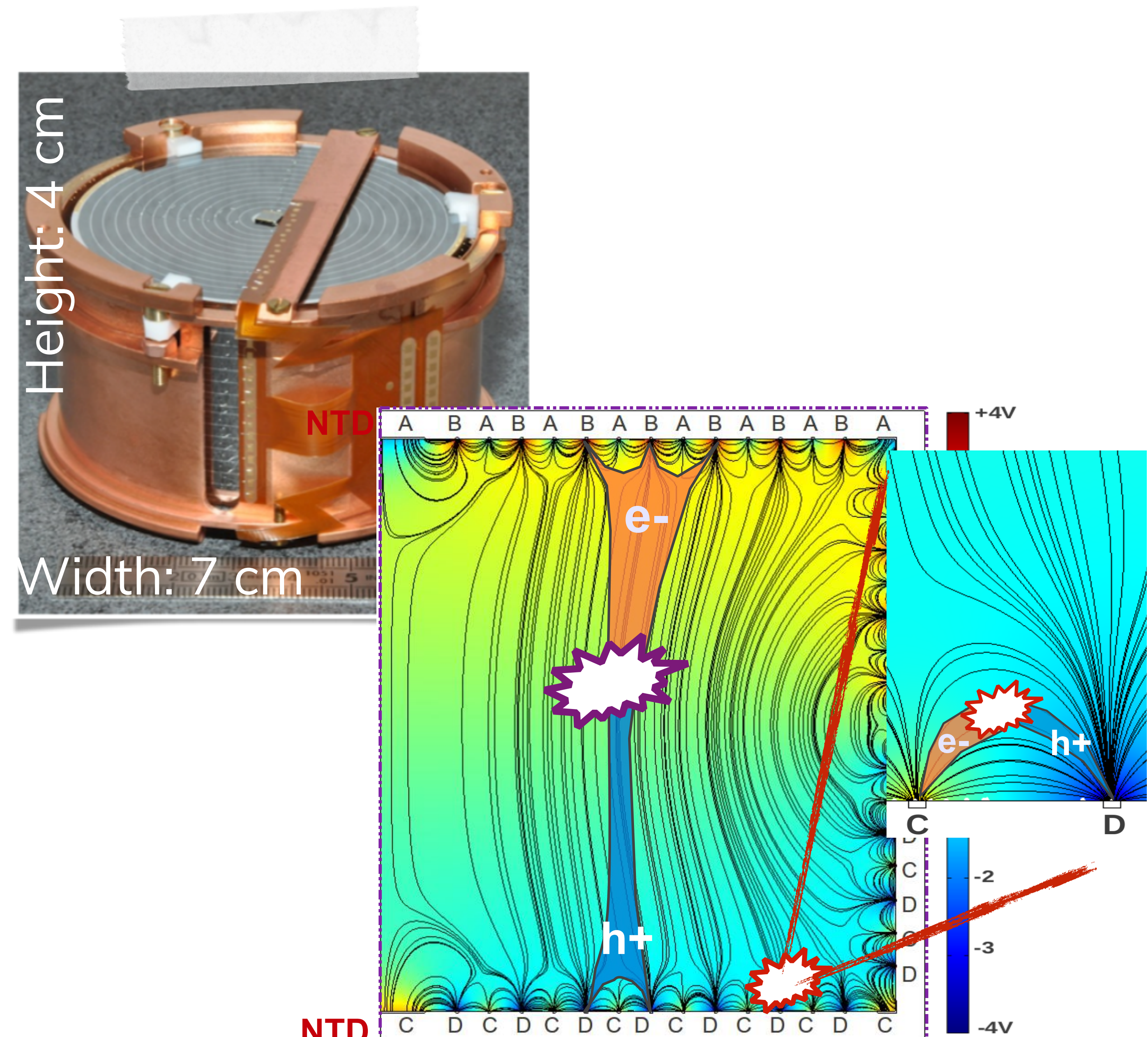
CRESST Coll., EPJC (2017)

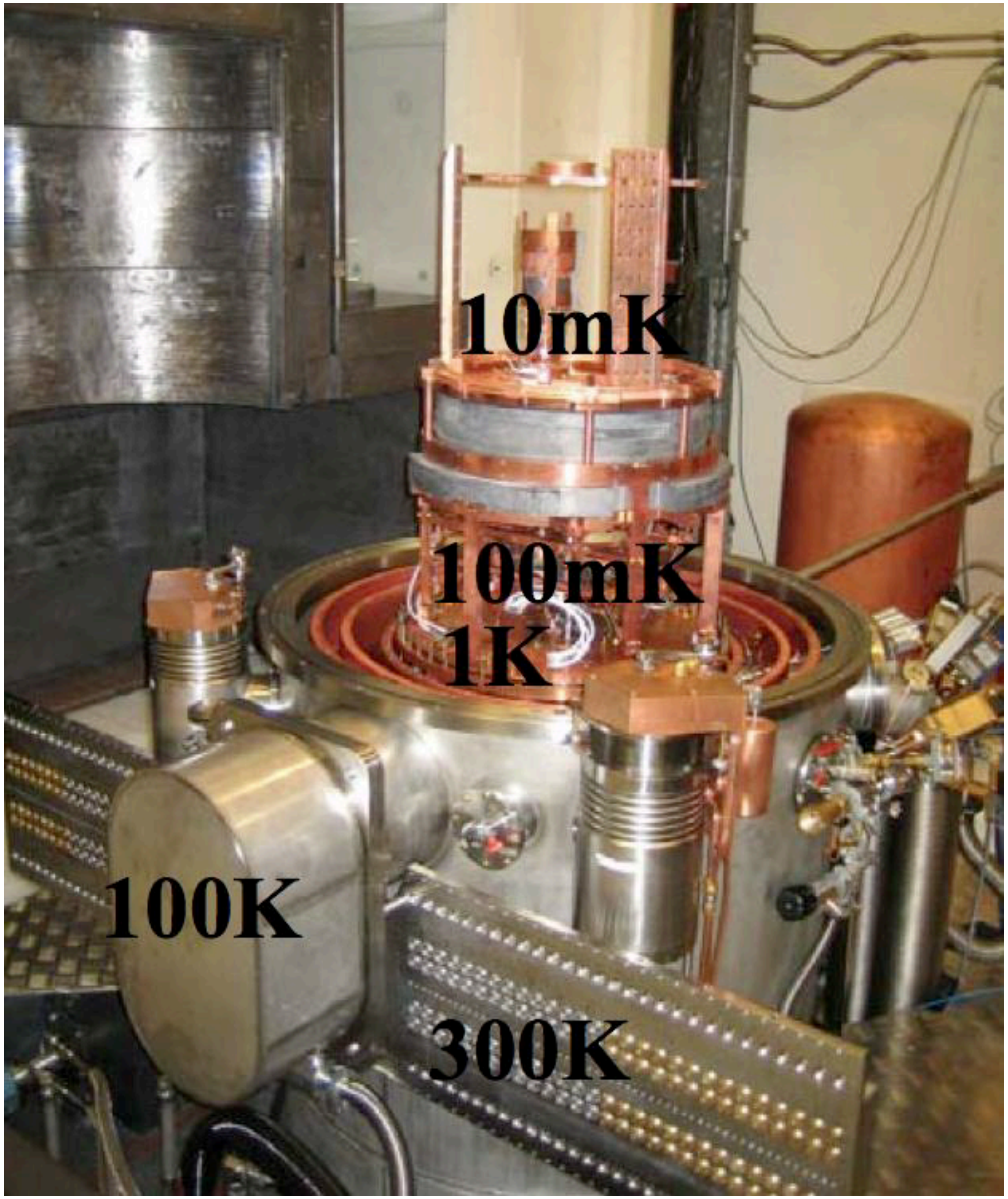


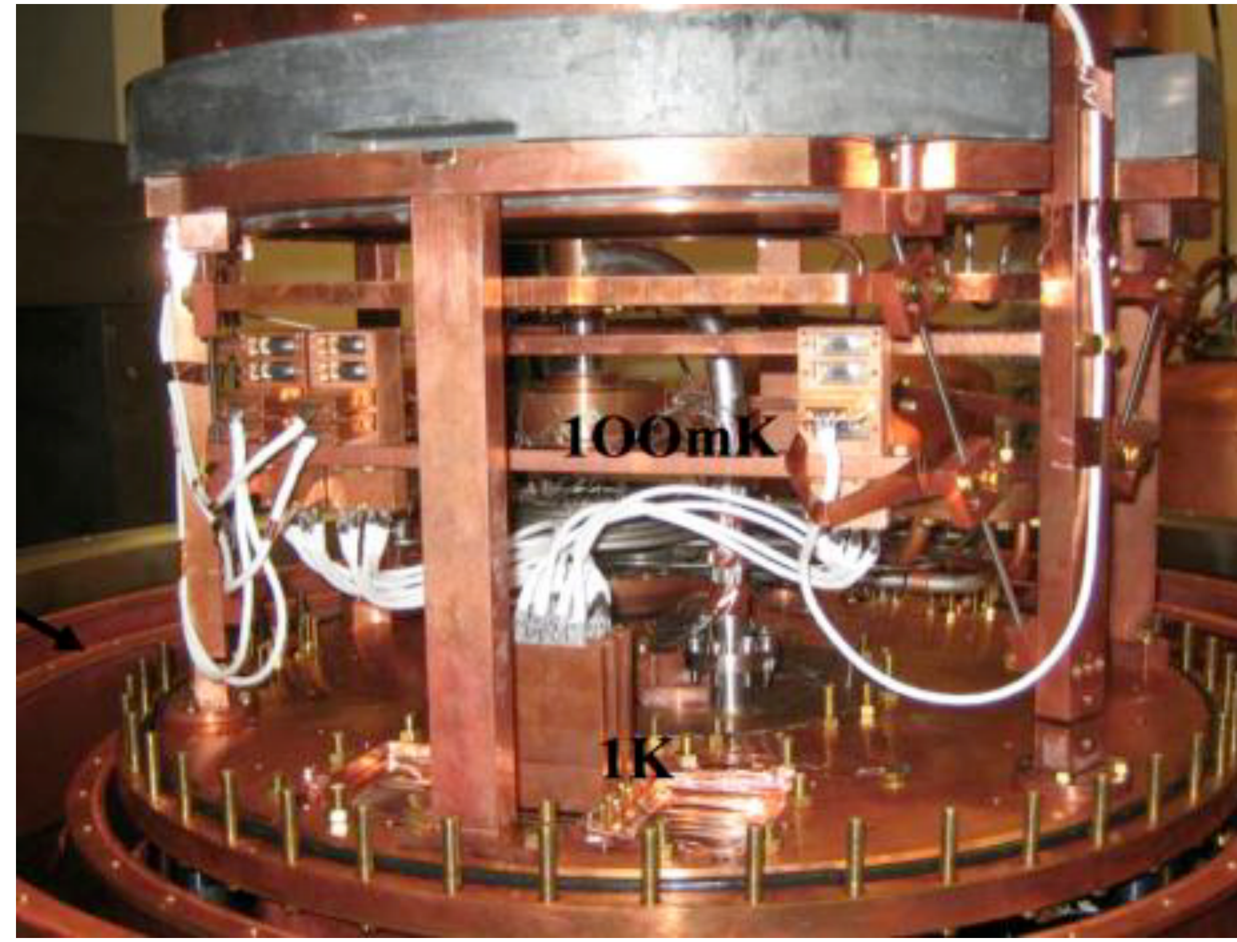

EDELWEISS III

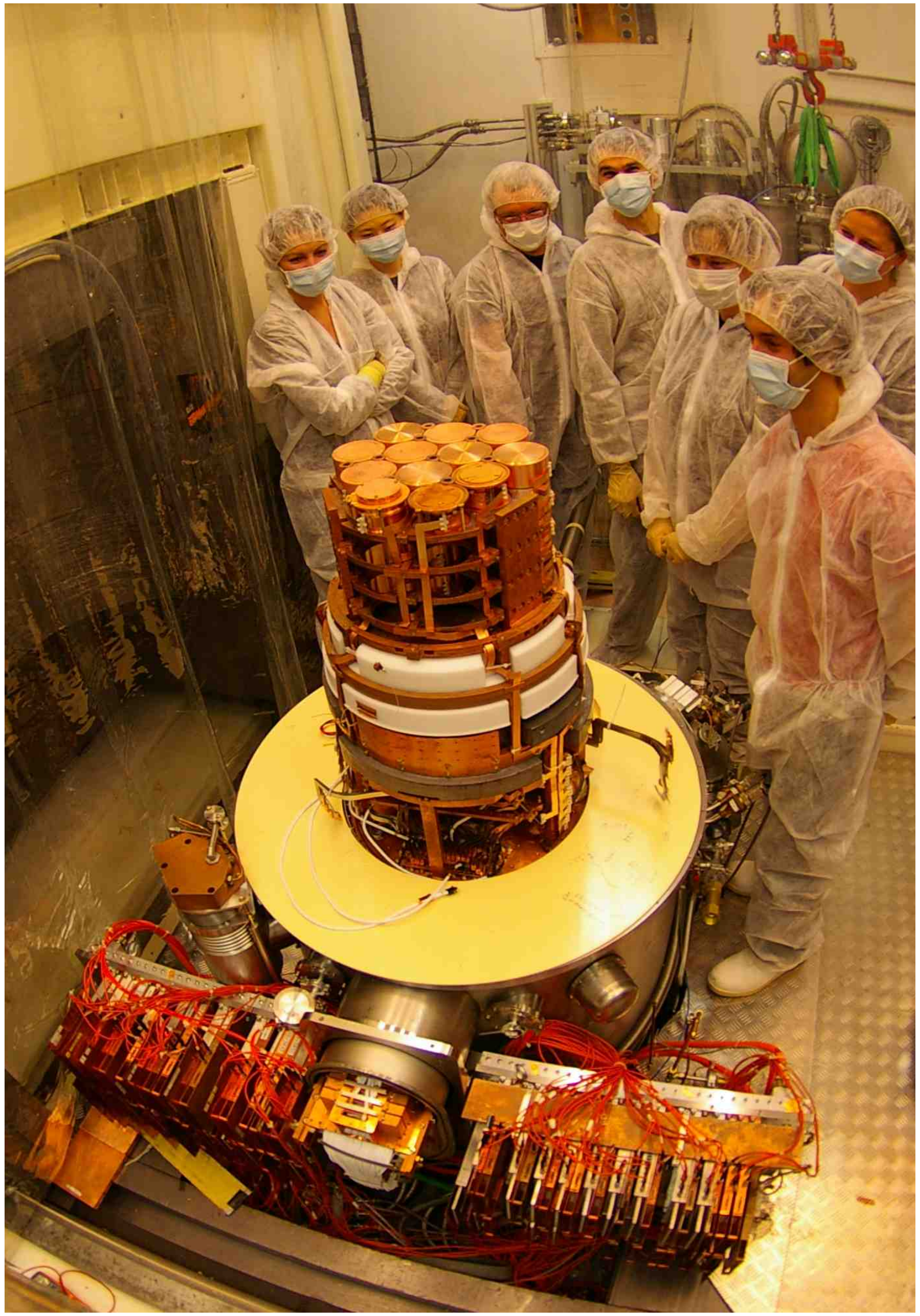
Detector Specs

- Fully InterDigitized (FID) technology.
- Ge crystal target: ~870 g each
- Two Ge NTDs heat sensor per detector
- Electrodes: concentric Al rings (2 mm
  spacing) covering all faces
- XeF2 surface treatment to ensure low
  leakage current (<1 fA) between
  adjacent electrodes




10mK
100mK
1K
100K
300K

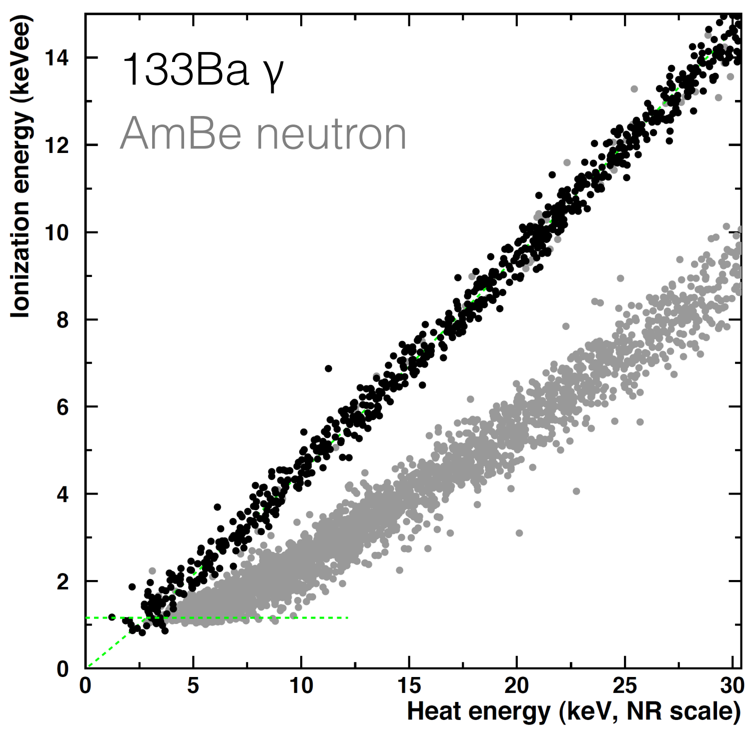

100mK
1K



EDELWEISS Results

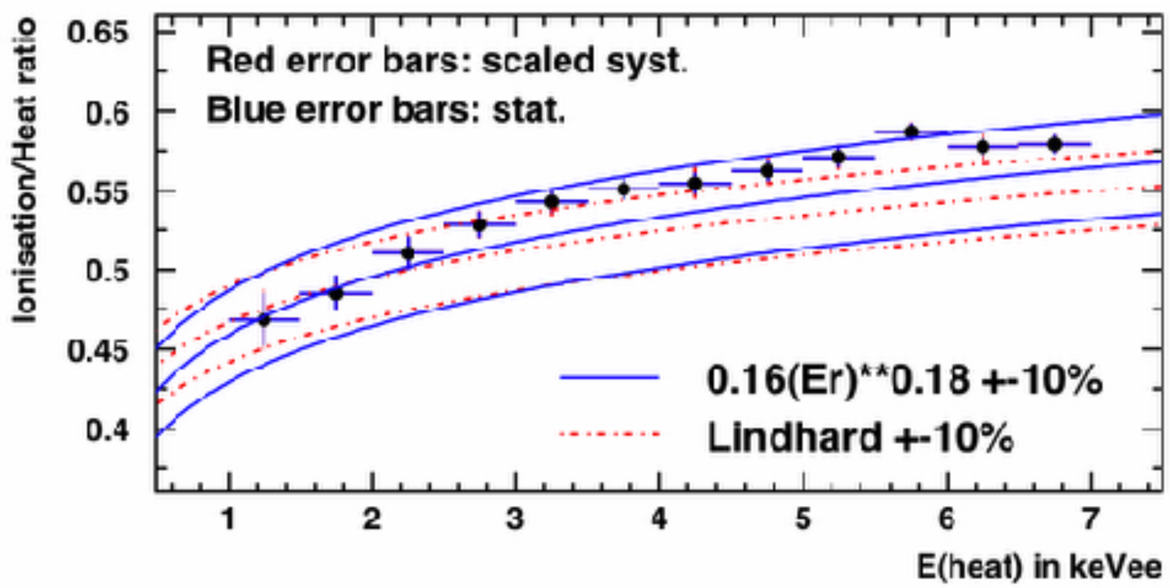
Robust design, good reproducibility of performances

[JINST 12 (2017) no.08, P08010]



Improved ionization resolution & thresholds lead to x40 improvement of WIMP sensitivity at ~5-10 GeV wrt EDELWEISS-II.

[JCAP05 (2016) 019] [EPJC 76 (2016) 548]

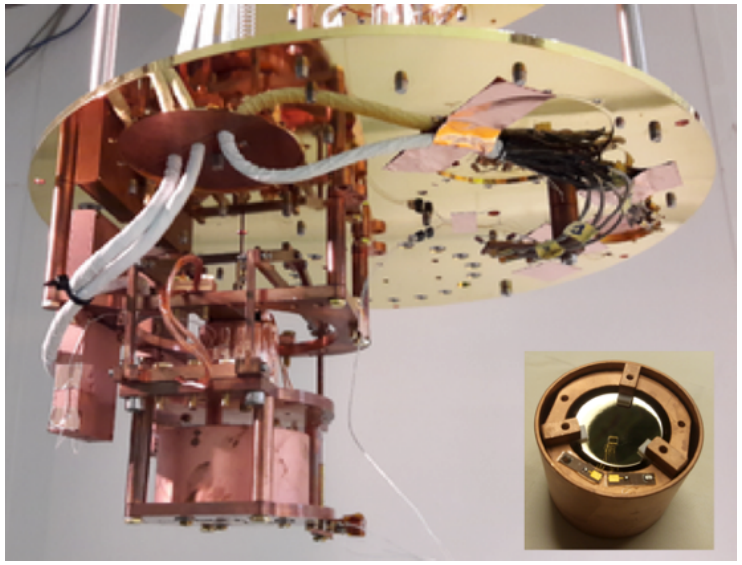


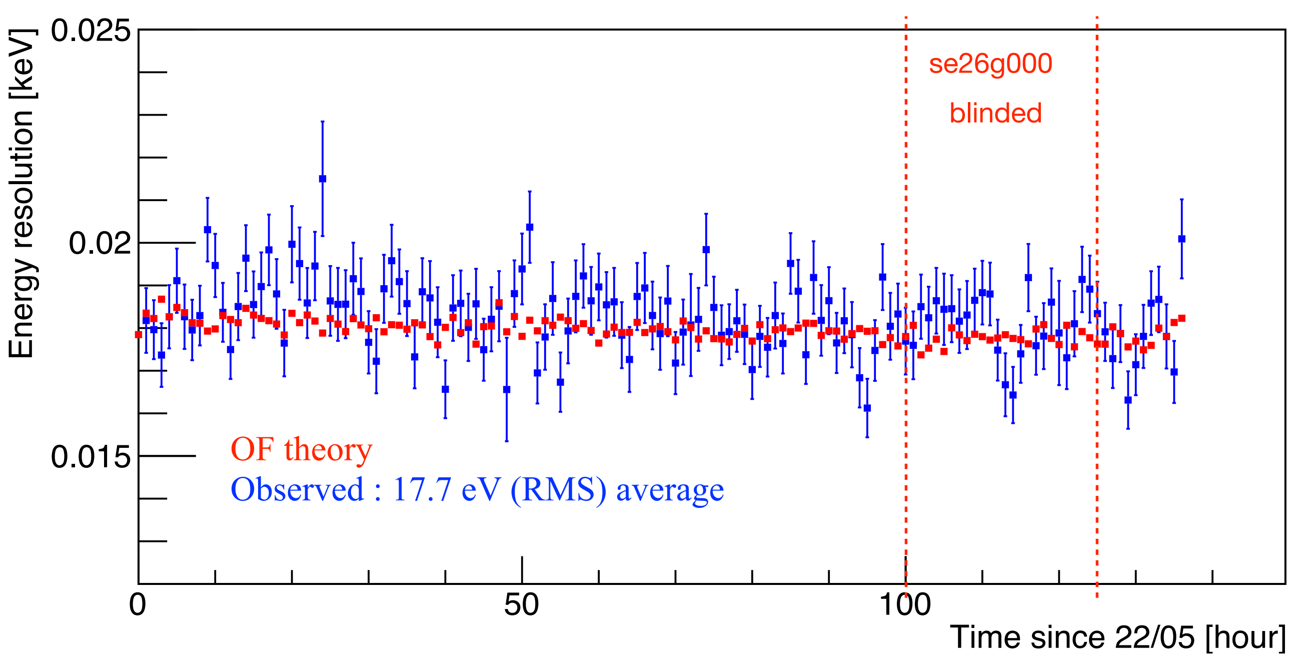
EDELWEISS-Surf

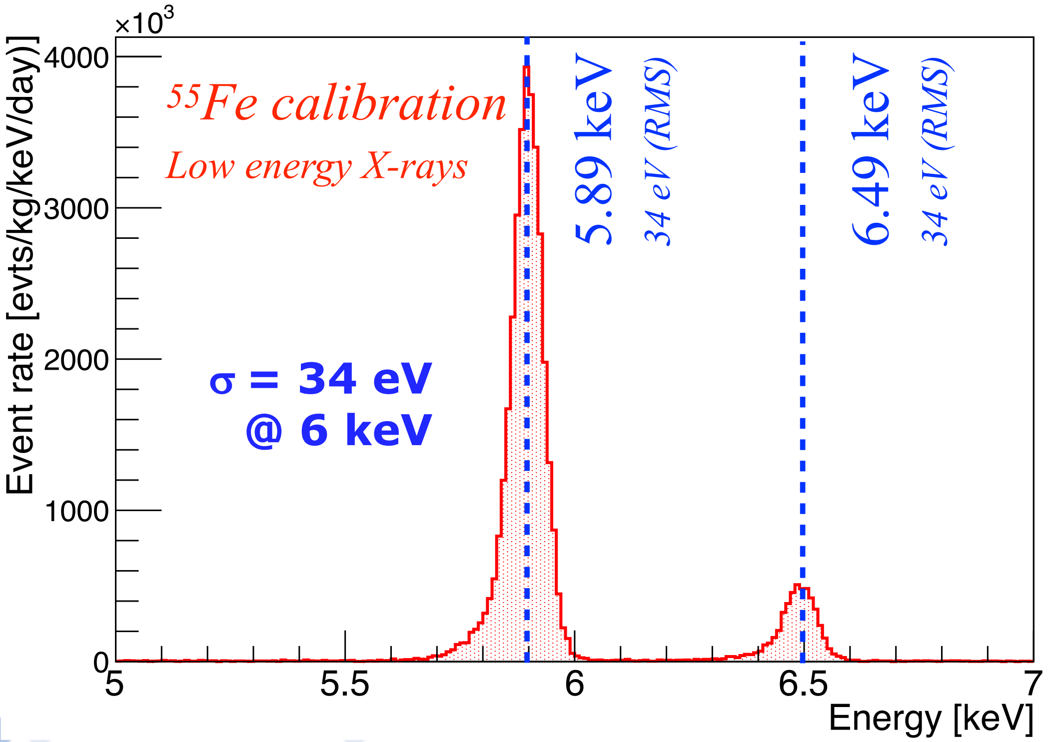
Technique: Heat Only

R&D with 32 g combined with the objective of testing the above-ground sensitivity to sub-GeV WIMPs

Kept at 17 mK in IPNL low-vibration dilution fridge [arXiv:1803.03463]







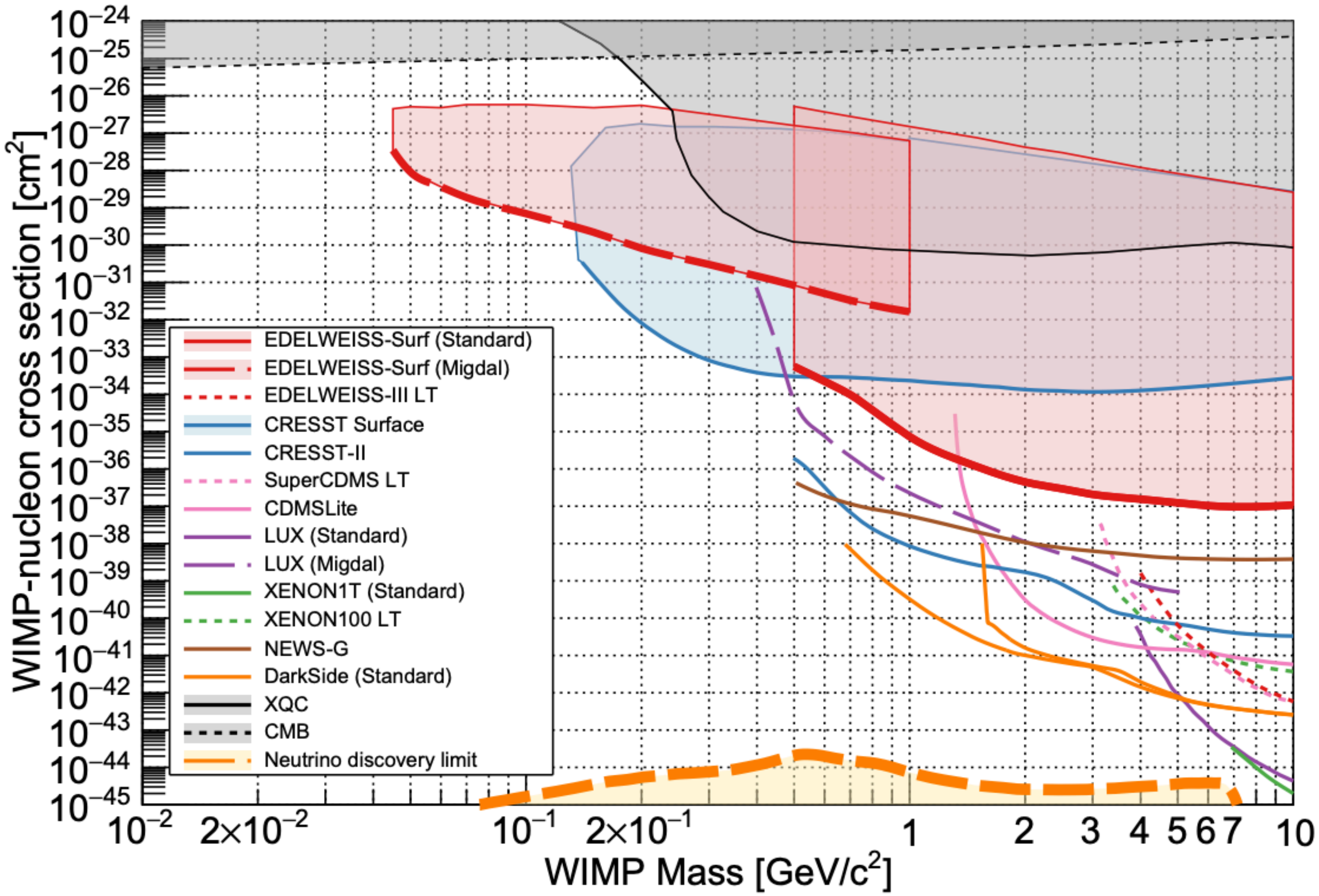
EDELWEISS-Surf

Technique: Heat Only

Best above-ground limit down to 600 MeV/c^2

First sub-GeV limit with Ge, down to 500 MeV/c^2

Opens the way for the 0.1 – 1 GeV/c^2 range



Conclusion

Original science motivations for cryogenic detectors were neutrinos and dark matter, but great success in many other areas continuing to the present day.

Many recent advances in single sensor performance and more importantly in large array performance.

Continued improvements in our fundamental understanding of these devices