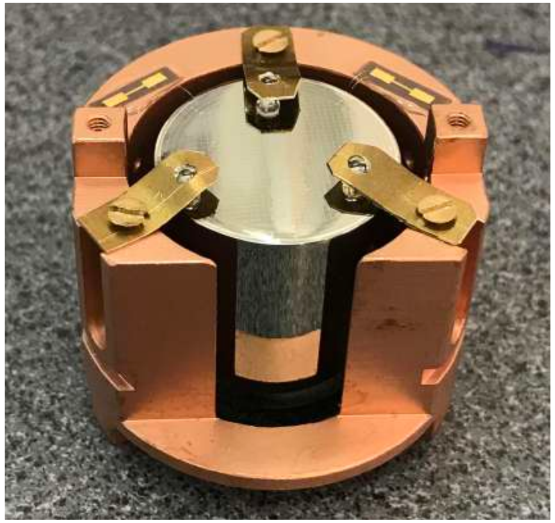
Cryogenic detectors for Dark Matter



- *Basic principles*
  - *Phonon*
  - *Scintillation*
  - *Ionization*
  - *Cryogenics*

J. Gascon
Lyon 1, CNRS/IN2P3/IP2I

Basic references:

Knoll, *Radiation Detection and Measurement*

Kittel, *Introduction to Solid State Physics*

LTD: Bi-annual worskhop on Low Temperature Detectors

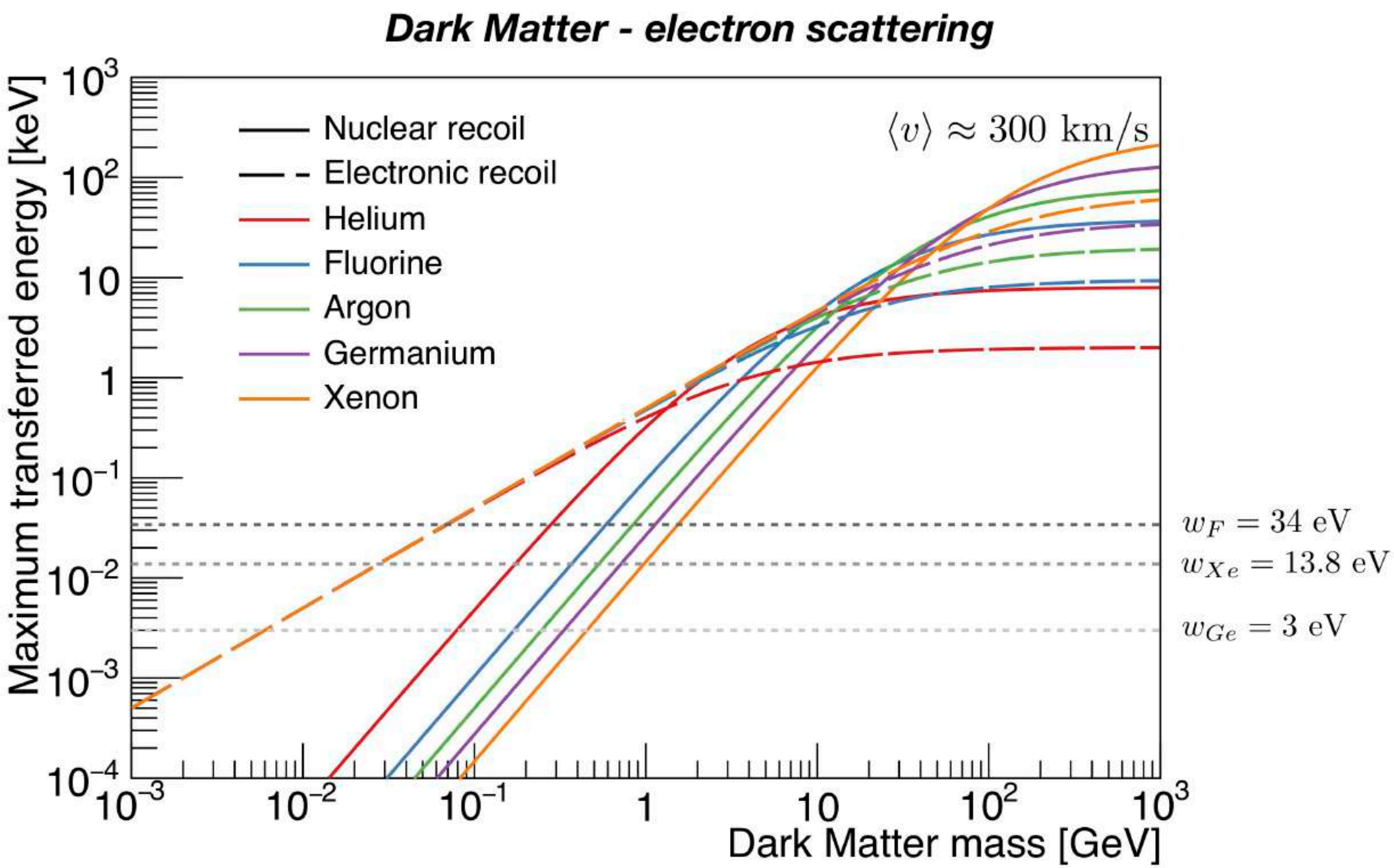
(ex.: http://ltd16.grenoble.cnrs.fr/)

IDM conferences (physics results)

BASIC PRINCIPLES

Note: I will have to skip many other applications where sub-K detectors have large impact: CMB, IR, $2\beta 0\nu$, metrology

Kinematics of a DM signal

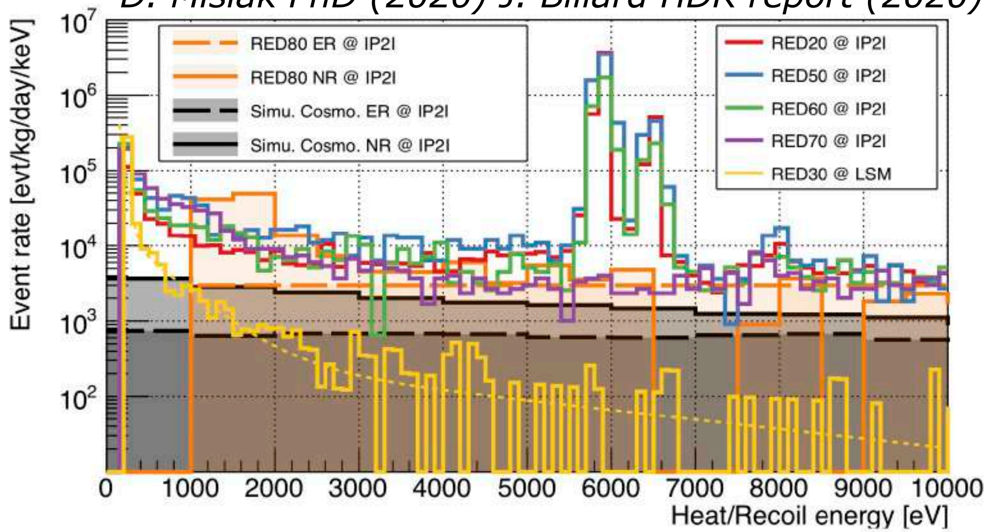


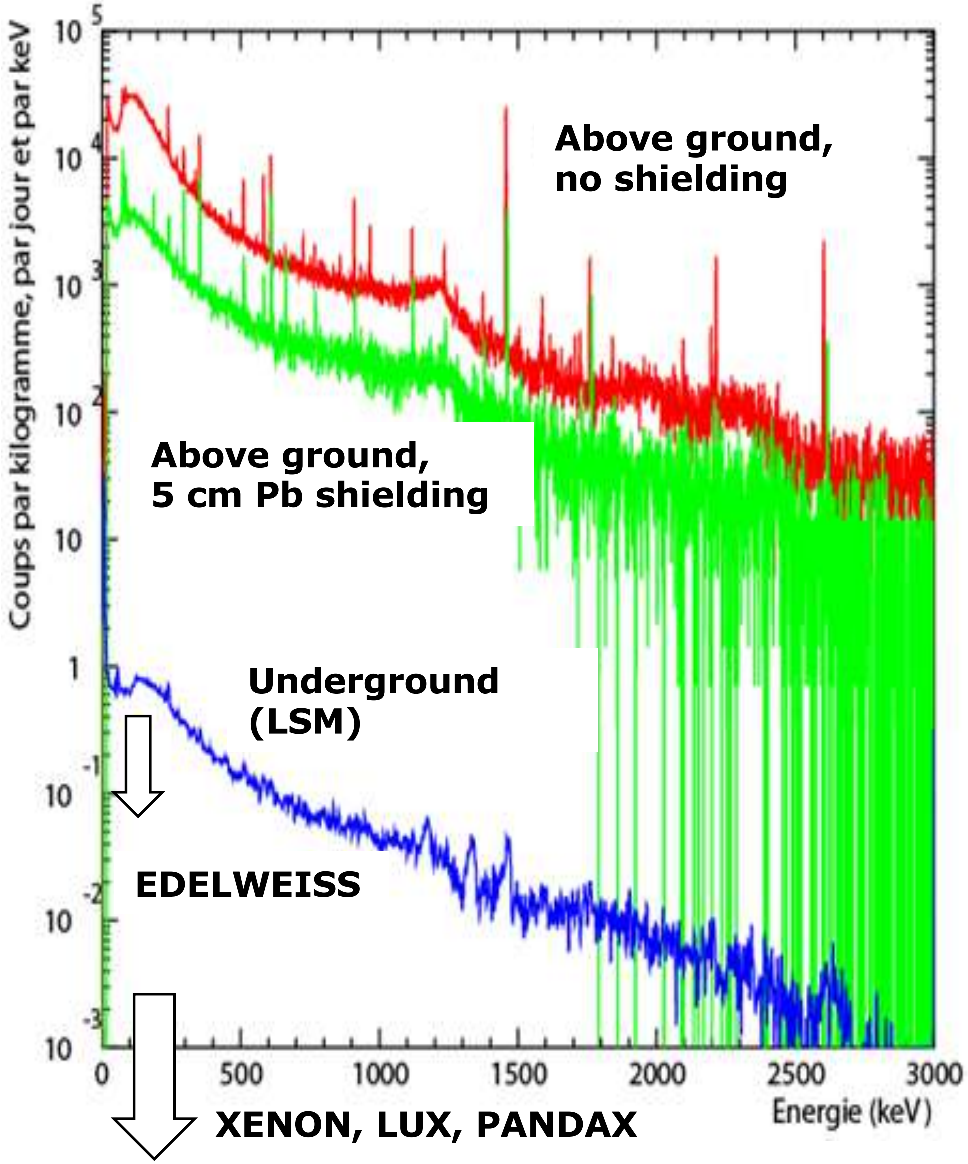
The backgrounds

Above ground:

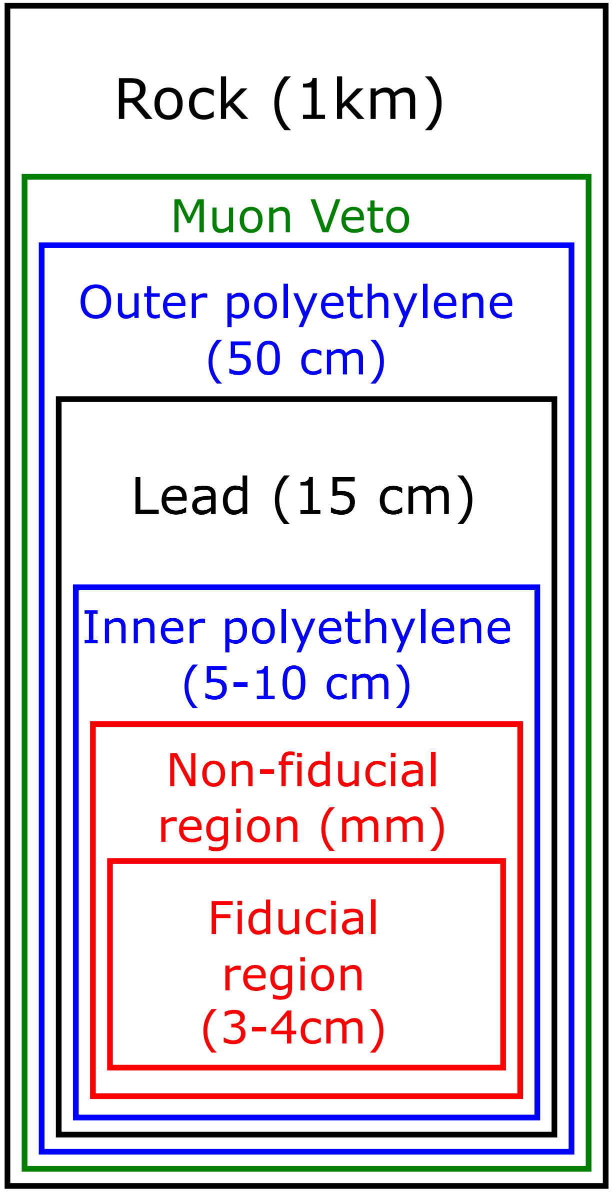
- Surface: α (μm) and β (mm)
- γ (with >> cm range) dominate keV-MeV range
- Neutrons (>>cm range) from cosmic rays important < 1 keV
- Neutrons from (α,n) & fission

D. Misiak PhD (2020) J. Billard HDR report (2020)





Shielding strategies



CDMS
EDELWEISS
10-20 detector
unit array

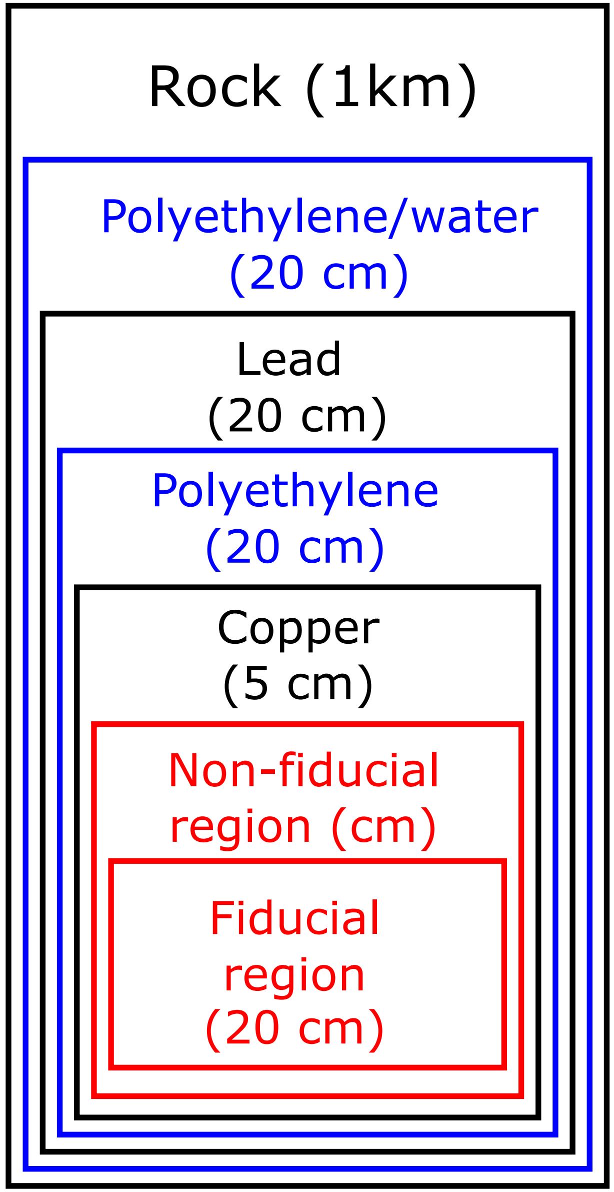
XENON100
1 detector
with x,y,z
measurement

DM Searches require shielding from environment

...

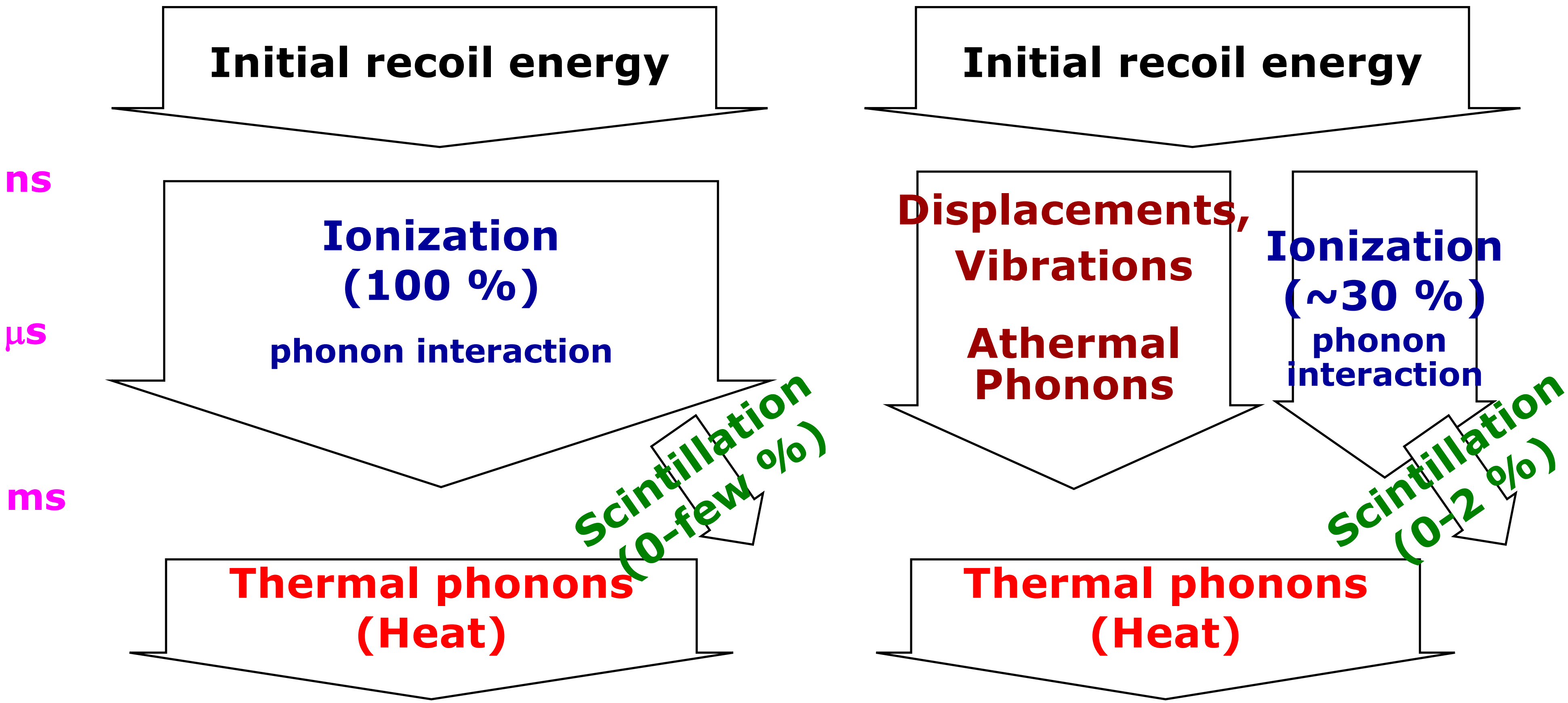
but also from experiment itself (in particular: front-end electronics

Depends on detector perfomance



Signals : two types of recoils

Electron recoil vs Nuclear recoil



(+ No permanent crystaline defects?)

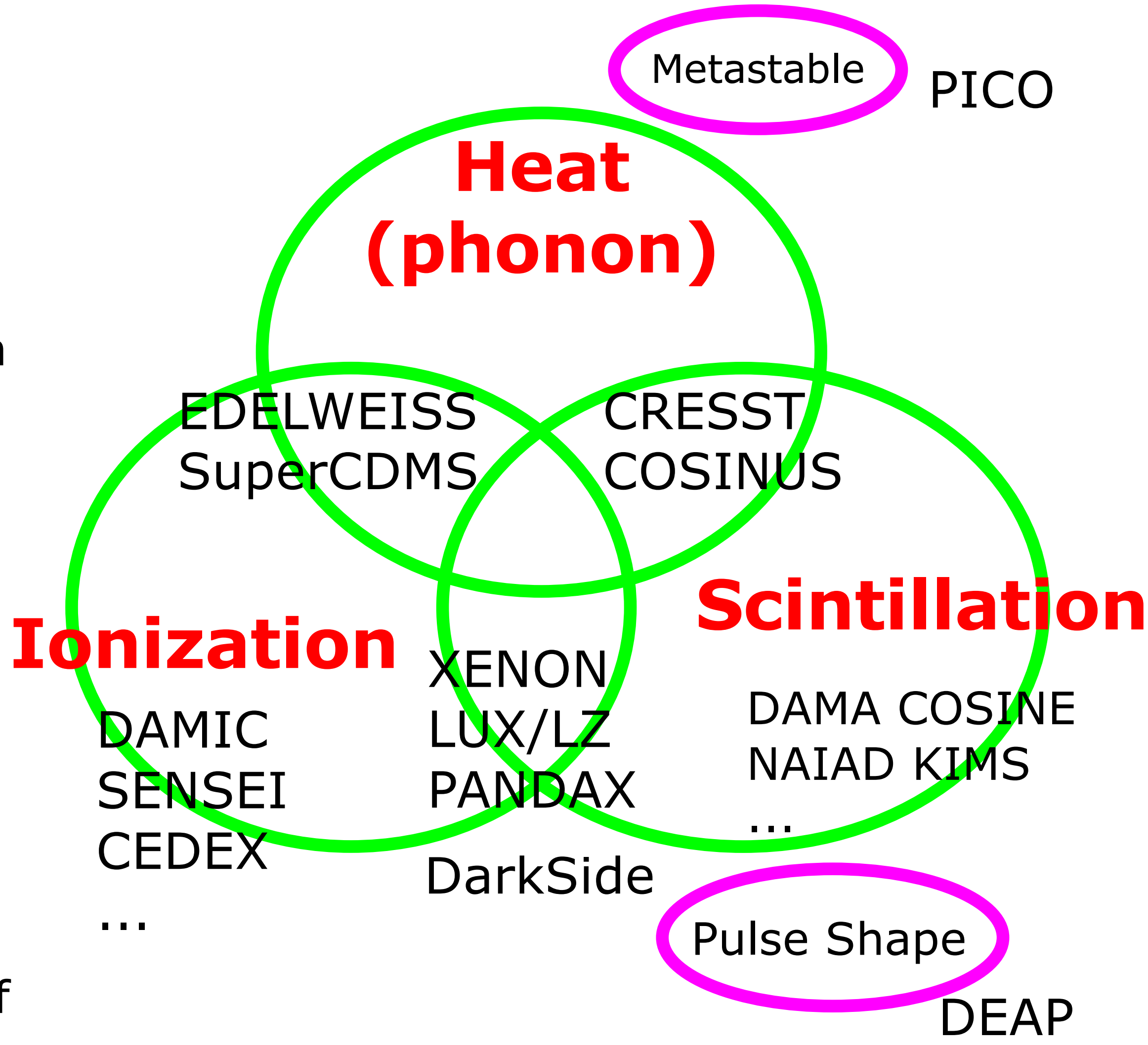
(+ Permanent crystaline defects?)

Detection techniques

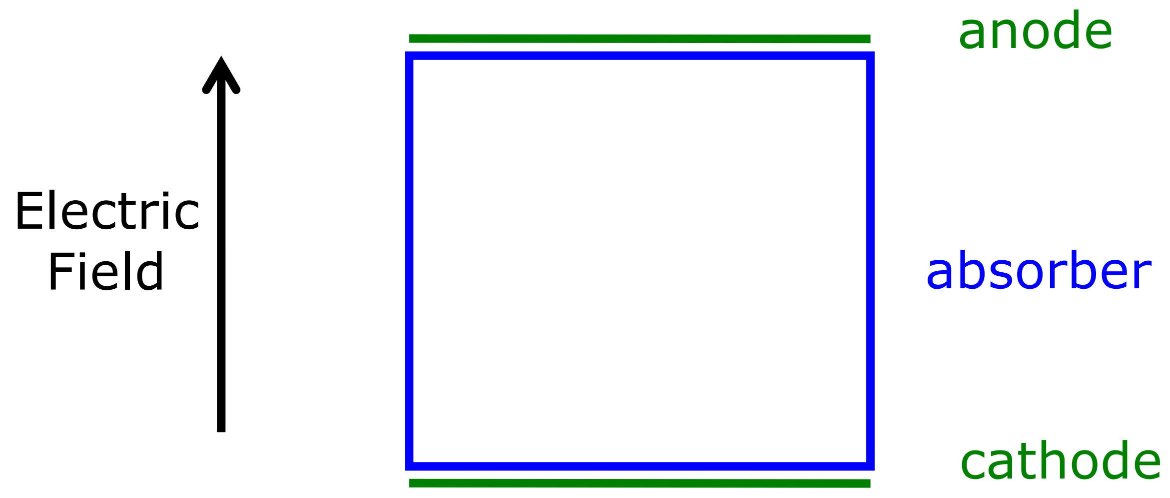
Choice based on two arguments:

- Resolution (threshold), related to eV/quanta
  - Scintillation ~100 eV needed for production of ~1 eV photon
  - Ionization: ~10 eV (gas), ~1 eV (semicond.)
  - Heat -> phonon: ~meV (depends on heat capacitance)
- Particle discrimination

  Using the combination of two signals

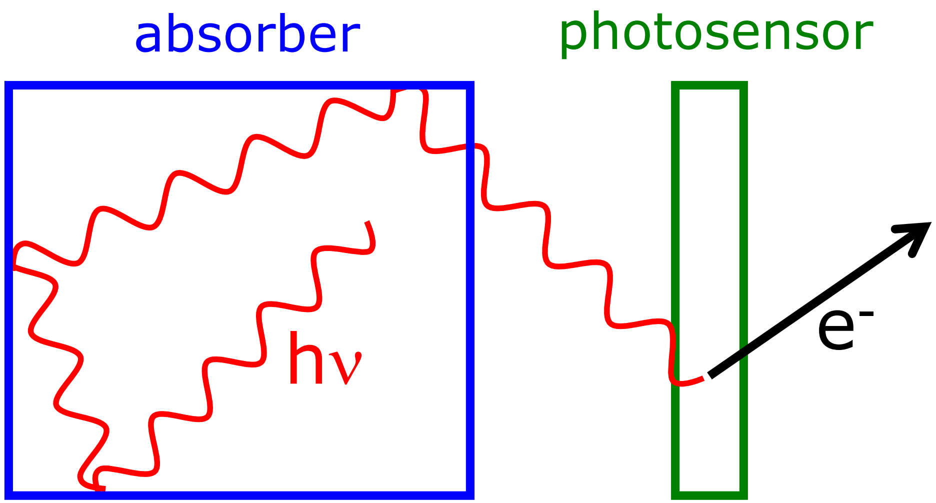


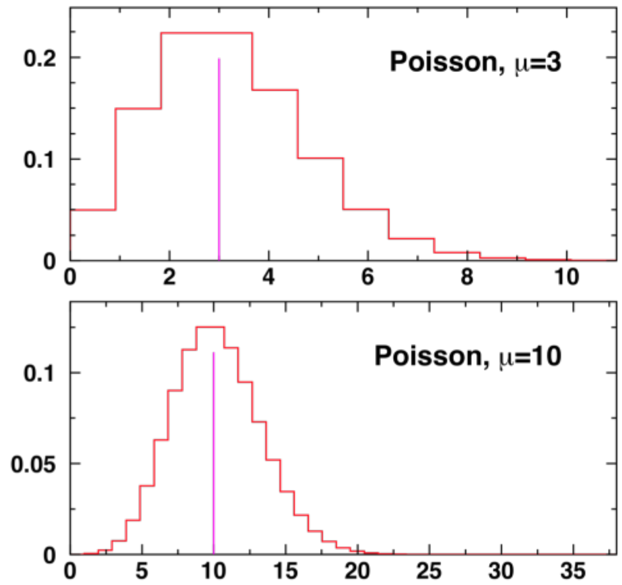
Rough picture of ionization signals



- Apply electric field on the detector volume to make the ionized charge drift to the surface, and "count the number of charges NQ arriving on the electrodes." E=NQ.
- Ge: 10 keV nuclear recoil ~ 800 e^--$hole^+$ pairs ~ 0.1 fC.
- Fano factor in Ge: $\sigma_E/E = \sqrt{0.13/N}$ = 1.3% for 800 pairs.
- Resolution in fact limited by readout noise *(detector capacitance)*
- Loss of charge during the drift deteriorates the resolution.

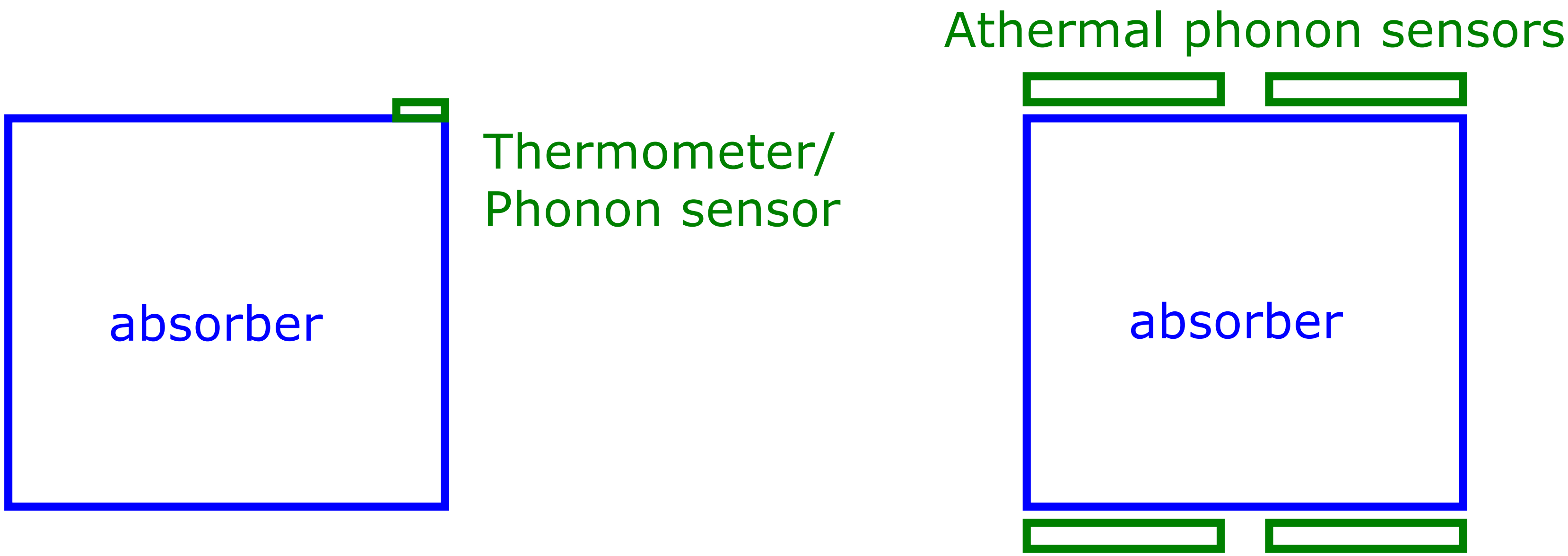
Rough picture of scintillation signals





- Count the number of photons (visible-UV) with a photoelectric tube, a photodiode or a bolometer
- Smaller number of quanta: resolution dominated by statistics
  - Xe: 10 keV nuclear recoil ~ 5 photons counted (depends on light collection efficiency)
  - NaI: 10 keV nuclear recoil ~ 3 (I) or 10 (Na) photons
- Advantage: sensor is separated from absorber. No physical contact.

Rough picture of heat/phonon signals



- "True calorimetric measurement": $\Delta T = \Delta E/C$, with C = heat capacity of absorber. ΔT ~ Large number ~meV phonons.
- Phonon sensor: start to "count phonons" even before they are fully thermalized: faster + position-sensitive device
- Debye: $C \sim T^3$ in insulator (e^- do not contribute): Ge, Si, $CaWO_4$, Al_2O_3... ($T_D = 374$ K for Ge; $T_D = 1042$ K for Al_2O_3)
- With T ~ 10-50 mK, can get ~ μK signal on ~kg absorber
- Baseline resolution can be as a good as ~~20-50 eV~~ ... few eV

Bolometer or calorimeter?

- Bolometric or calorimetric mode?

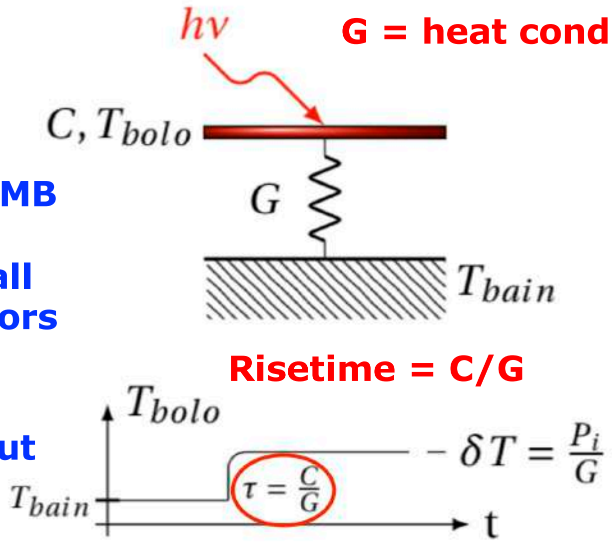
Bolometer: continuous flux of radiation

Calorimeter: discrete energy deposits

C = heat capacity (J)
G = heat conductance (W)

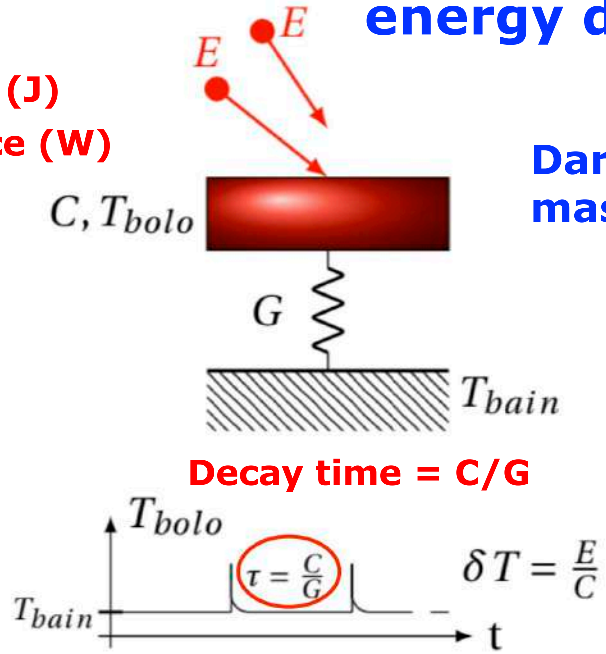
Example: Planck CMB measurement
Large array of small (~pixel-size) sensors

Push towards multiplexed readout (ex: 3000 pixels in NIKA2 camera, KIDS readout)



Signal = Power/G
Noise = $\sqrt{4k_BT^2G}$ in W/√Hz

Dark matter: massive units



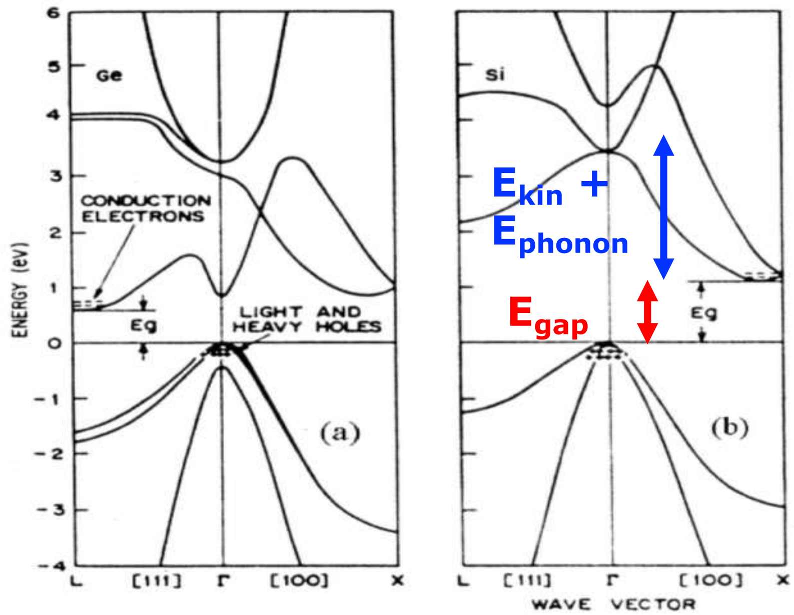
Signal = Energy/C
Noise = $\sqrt{4k_BT^2C}$ in J

- Dark Matter: discrete particles -> calorimetric mode...
  But often use the name "bolometer" anyways...

Particle ID: Ionization and Light Yields

Ionization yield (charge/eV)

- $<E_{e\text{-hole pair}}> = E_{gap} + <E_{kinetic}> + <E_{phonon}>$
- Phonons essential for dynamics of e^--hole
- 3.0 eV/pair in Ge (gap 0.7 eV)
- 3.8 eV/pair in Si (gap 1.2 eV)
- Very small temperature dependence between 0 and 77K (kT=0.006 eV)



Light yield (photoelectron/eV)

- Depends on scintillation center concentration in crystal
- Depends on density of energy deposition
- Non-linearities at low energy (NaI, CsI)
- Large T dependence of yield & time constants
- ~50 eV / photoelectron typical value

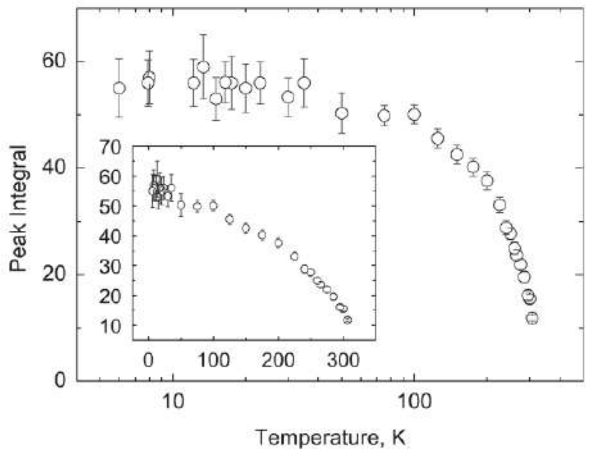


Fig. 1. Temperature dependence of the scintillation light response of BGO under α-excitation ([241]Am). The inset shows the dependence on a linear temperature scale.

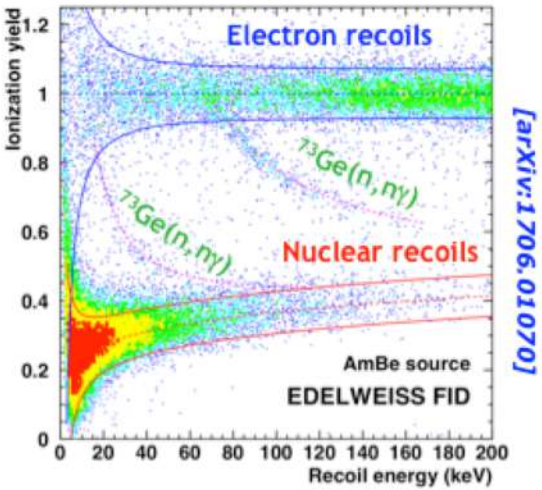
Total Energy

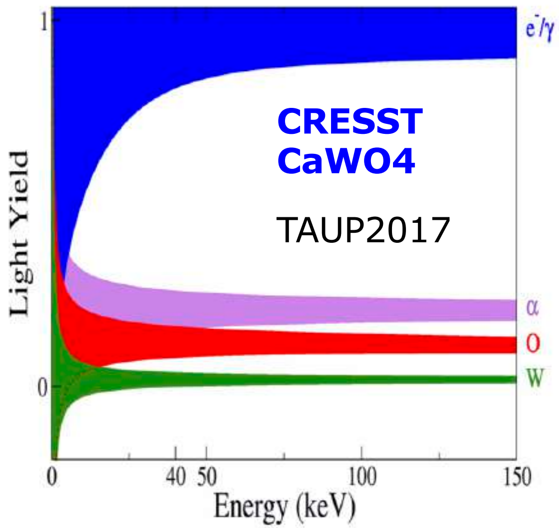
- Thermal measurement: in principle "perfect" measure of the total energy, irrespective of the particle type or interaction mechanism
  - If the absorber + sensor are a closed system, its energy is conserved (1st Thermodynamics Law)
  - Any form of energy deposited in the system will eventually get thermalized (2nd Thermodynamics Law)
- But:
  - Scintillation may escape
  - Ionization (with no collecting field): not a problem, electron-hole pairs recombine locally via phonons (if recombination time ok)
  - Ionization (with collecting field): recombination in electrode not a problem since it is part of the closed system: E_{gap} gained back
  - Permanent damage done to the absorber? (collision damage)
  - Energy stored+released after the thermalization time (charge traps)

QUENCHING

Why do we need quenching?

- Needed for energy scale (non-phonon detectors) DAMIC, CoGeNT, DAMA... ... COHERENT
- Two-signal detectors: e⁻/NR/phonon-only discrimination

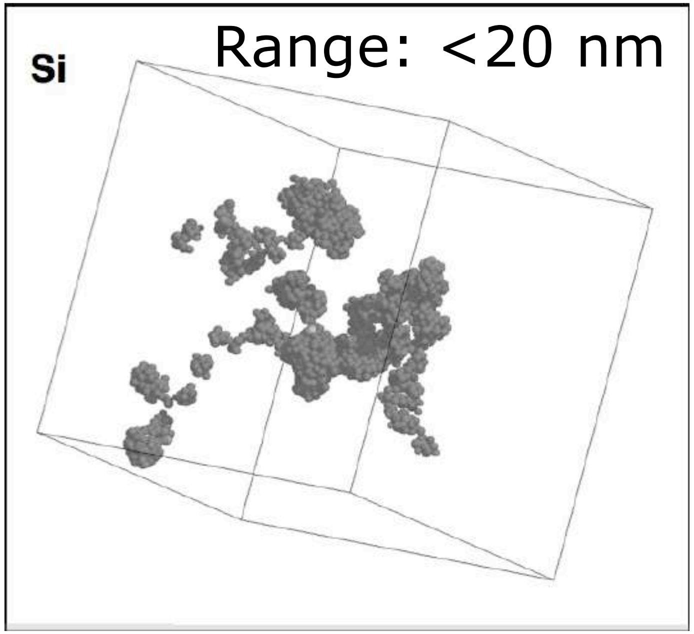


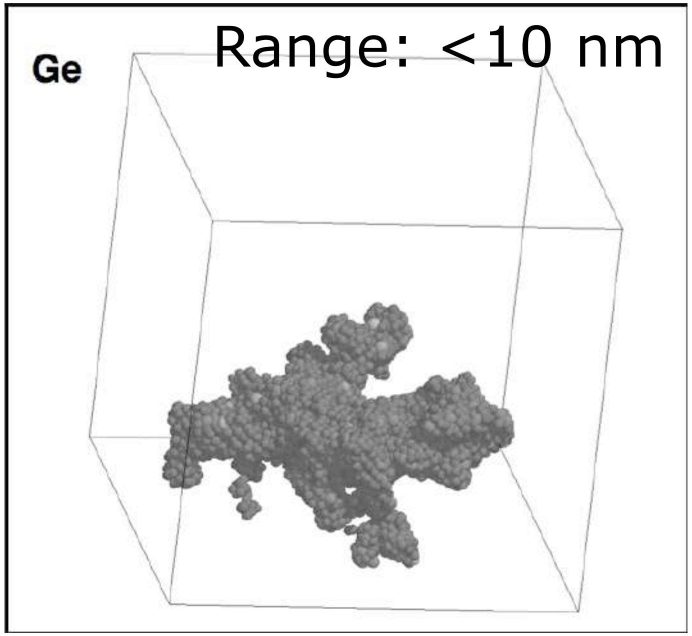


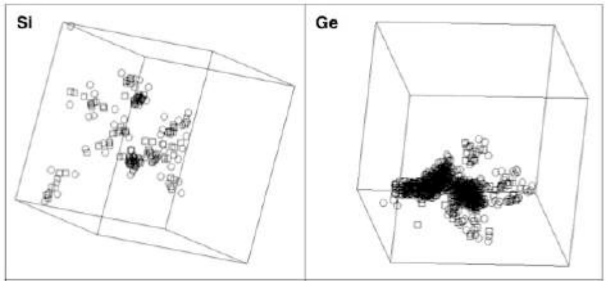
Signal	Quenching Needed for Energy scale	Provides good e⁻/NR discrimination	Good discrim. against phonon-only events
Phonon	No*		
Charge	YES	YES	YES (Q~0.3)
Scintillation	YES	YES	Not always (Q~0)

MD simulations of nuclear recoils

- Molecular Dynamic Simulations of « hot » atoms produced by a 10 keV Si or Ge recoil (Nordlund, 1998)



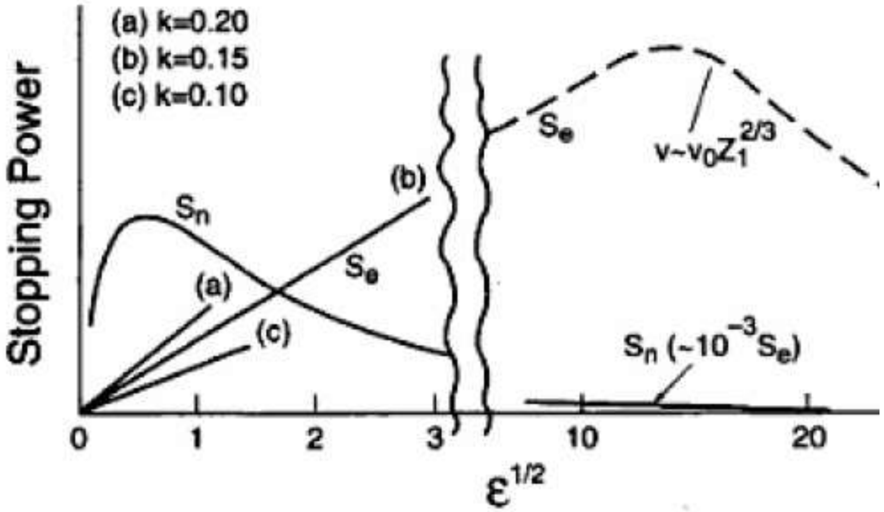




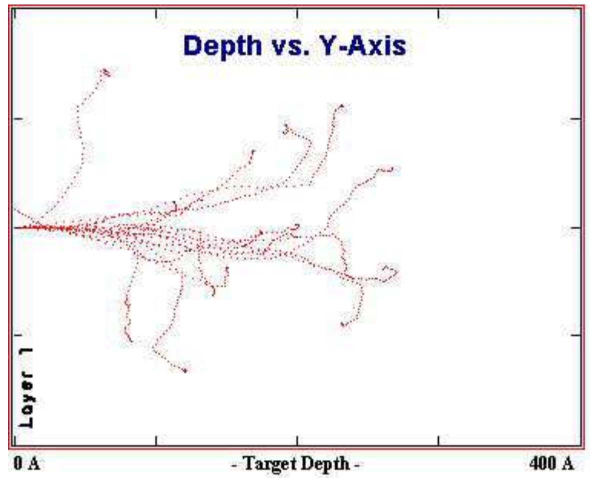
Permanent damages due to this « femtoGray » dose (negligible in metals, but maybe not in semiconductors?)

Ion recoils in crystal

- S_n and S_e: Nuclear and electronic stopping power dE/dx
  - S_n peaked at low energy (100 keV for Ge recoils in Ge)
  - $S_e = k\sqrt{\varepsilon}$ at low energy, and small compared to S_n at 100 keV
- Lindhard, Scharff and Schiøtt (1963): use S_n and S_e to model of the energy loss during the cascade of ion-ion collisions to calculate the range, *the ionization yield* and its dispersion
- Model extensively used and tested, parameterized (k) using data



20 keV Ge recoils in crystal Ge:
Range ~20 nm



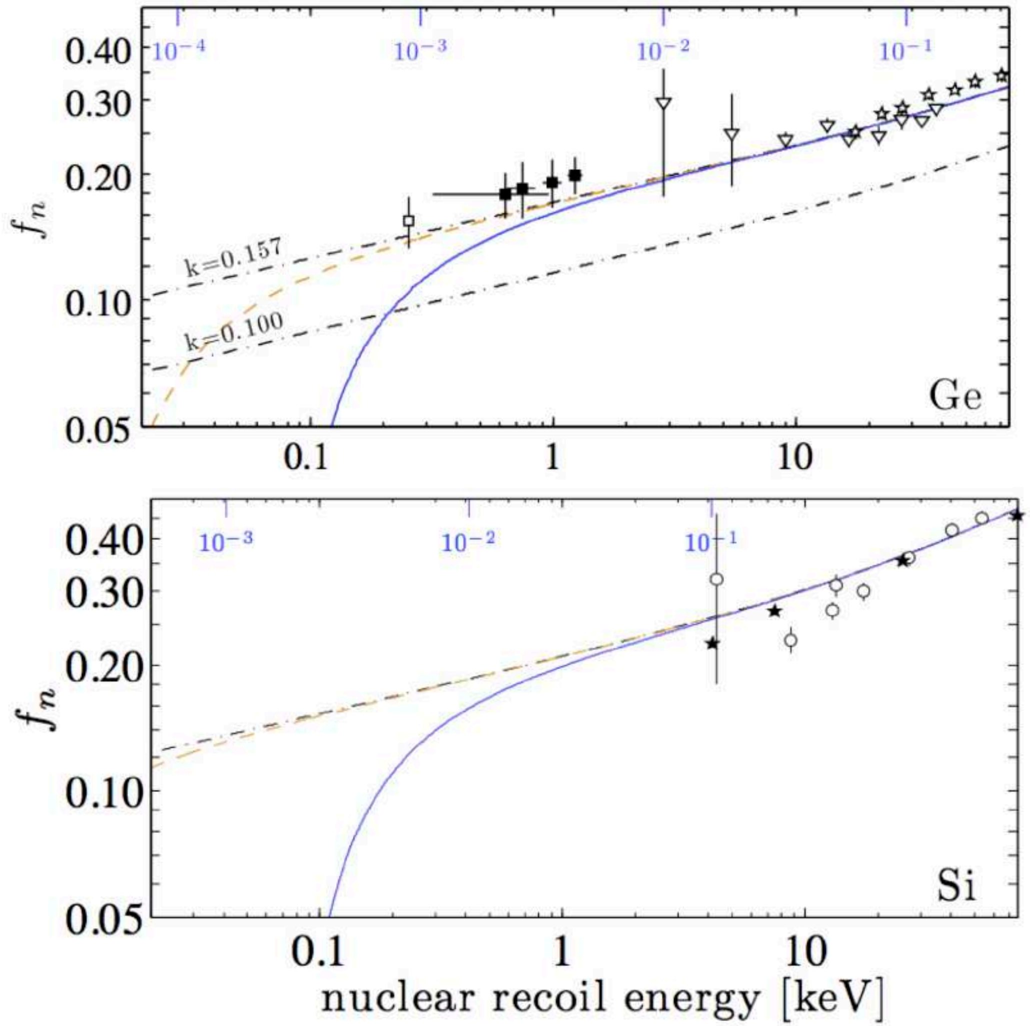
SRIM

Lindhard critique: threshold effects

See e.g. Sorensen, PRD91 (2015) 083509
Also in: https://kicp-workshops.uchicago.edu/2015-lowecal/index.php

- Lindhard model assumes interaction between two neutral atoms (with screened Coulomb potential)… too simple?

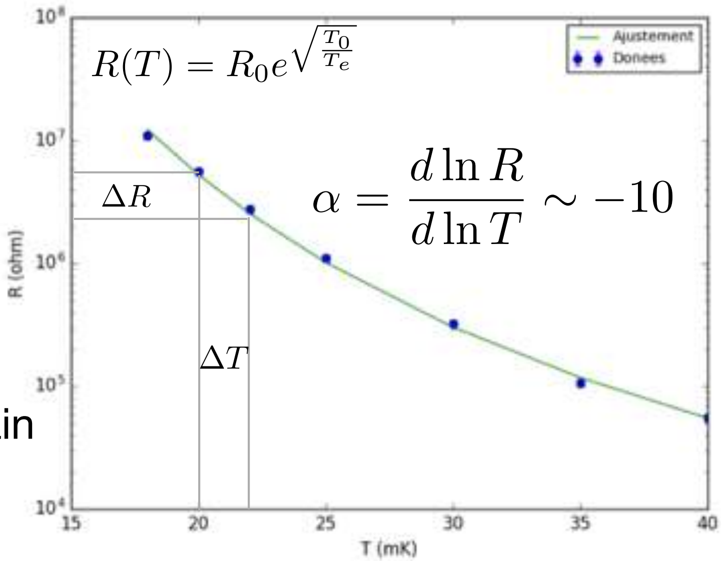
- But: Threshold energy to excite a e^+h^- pair (0.7 eV gap) ~100 eV for Ge?
- Also: should average energy to ionize an e^- play a role?
  $S_e = k\sqrt{\varepsilon} - cte$

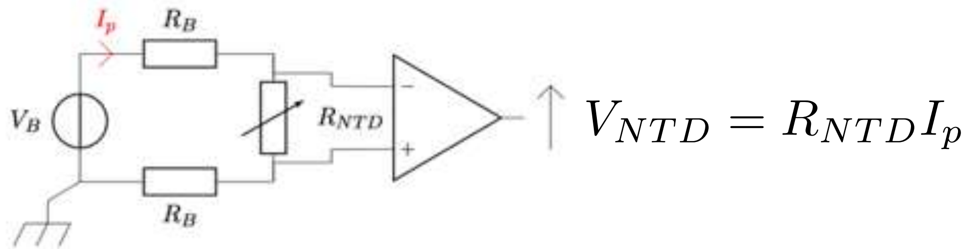


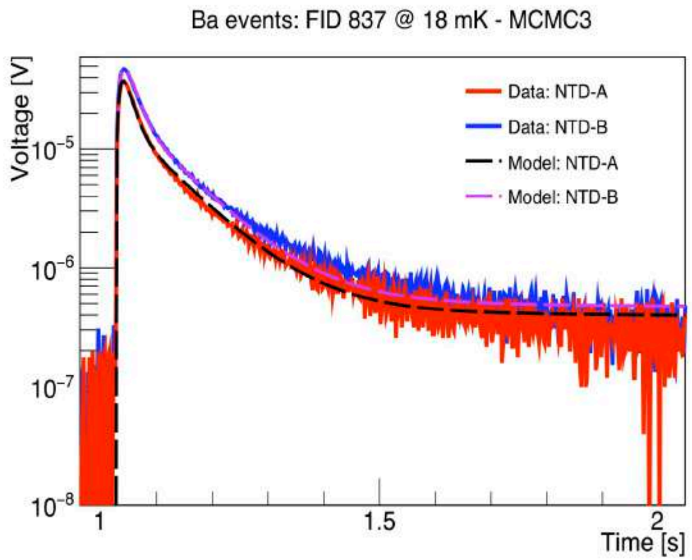
PHONON OR HEAT

Ge-NTD heat sensor

- NTD: Neutron Transmutation Dopped germanium
- Resistivity as a function of temperature follows Efros' law
- T0 depends on the neutron dose, R0 on the NTD geometry
- At working point, NTD resistance ~1-100 MOhm
- Current biased (α<0) with big bias resistors (R_b ~ 1 GOhm)
- I_p has to be optimized: too big -> heats up, too small -> no gain







- NTD readout are cheap and simple
- Thermal measurement: they are slow (~500 ms) and limited by the heat capacity of the crystal
- High impedance: sensitive to microphonic noise
- Limited to 100 eV (RMS) resolution for 800 g Ge detector

Julien Billard (IPNL) - GIF 2016

Phonons (3 different kind)

- Initial high-energy phonons
  - Keep memory of momentum of initial particle
  - High-energy phonon with very short pathlength
  - Rapidly degrade down to lower energy phonons

Position dependence (if sensor very close by)

- Ballistic phonons
  - Lower energy = longer lifetime (some μs)
  - Path >> detector size: multiple scattering on. surfaces, random position and direction
  - Degrade down through scattering on impurities and defects in crystals (mostly at surface: traps, amorphous layer, electrodes)

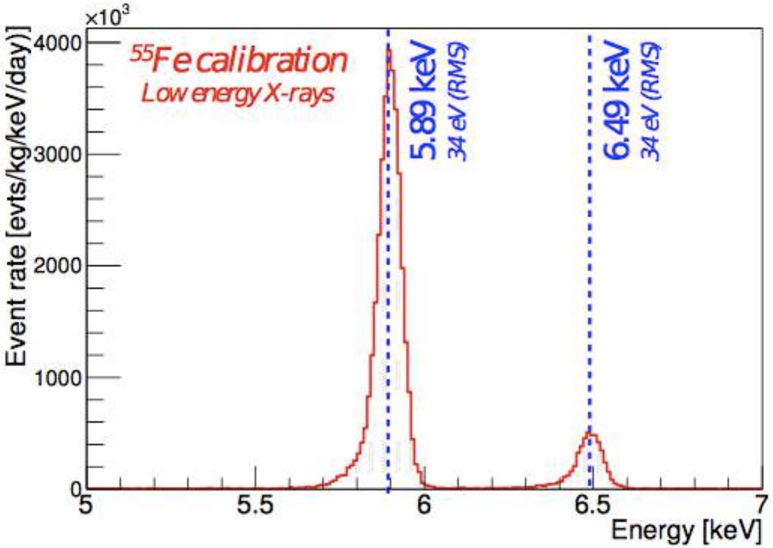
Fast response (<<ms)
Detection ∝ surface sensor/absorber

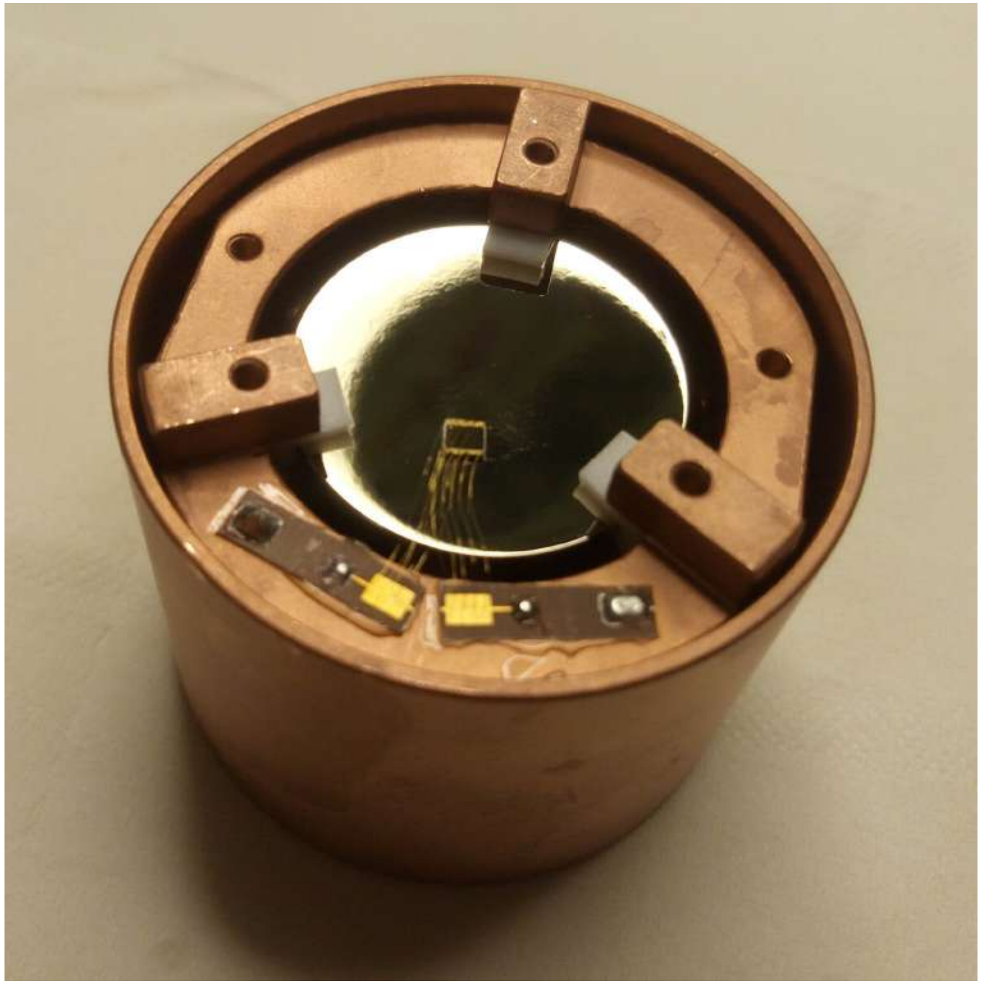
- Thermal phonon
  - Lifetime = C/G (tuned >> ms by adjusting the thermal link)
  - Insensitive to position of interaction
  - Sensor can be very small

Slow (ms to >100ms)
Most reliable energy measurement

Ge-NTD

- 33.4 g Ge
  (h20 mm x phi 20 mm)
- GeNTD: 2x2x0.5 mm^3
- Directly glued on Ge surface (epoxy)
- 17 mK
- *Achieves 17.8 eV resolution @ baseline*





Detector in Cu support
TEFLON holders

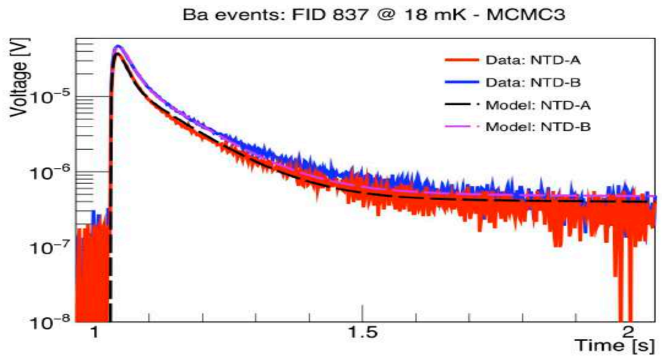
Thermal model of a pulse

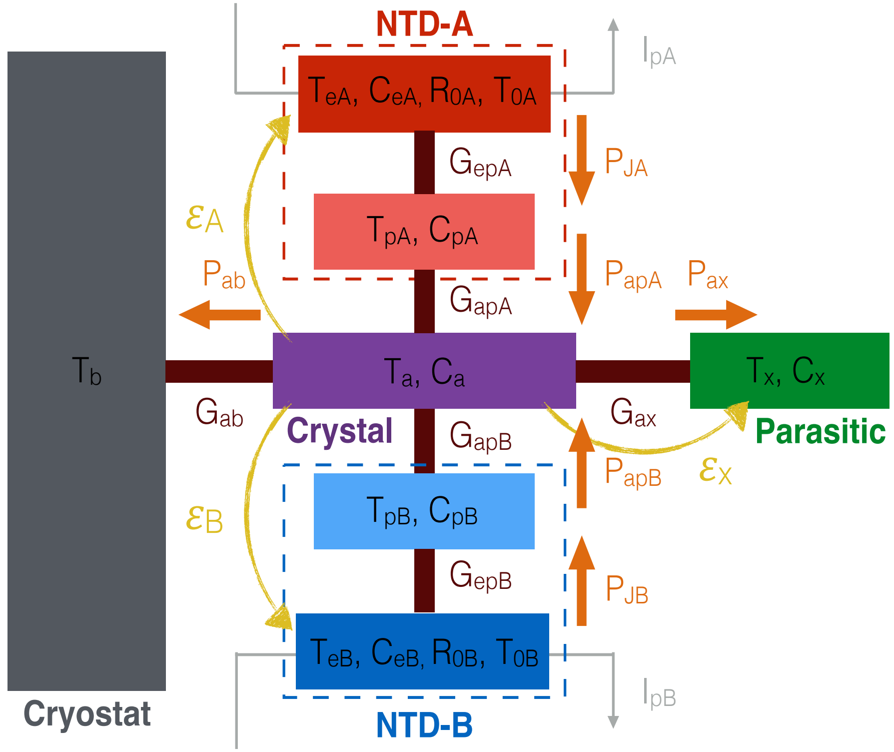
- Simple model of $T_{decay} = C_{abs}/G_{abs\text{-}bath}$ fails to describe presence of multiple decay times
- Other decay constant due to conductance G's:

1. $G_{abs\text{-}phonon}$ between the absorber and the phonons in the NTD
2. $G_{phonon\text{-}e}$ between the phonons in the NTD and its electrons

- Also, the NTD e⁻'s are heated up by the current used to measure RNTD: $T_e > T_{phonon} > T_{abs} > T_{bath}$
- The best performance are obtained by tuning all these elements

EDELWEISS: Two NTDs / detectors



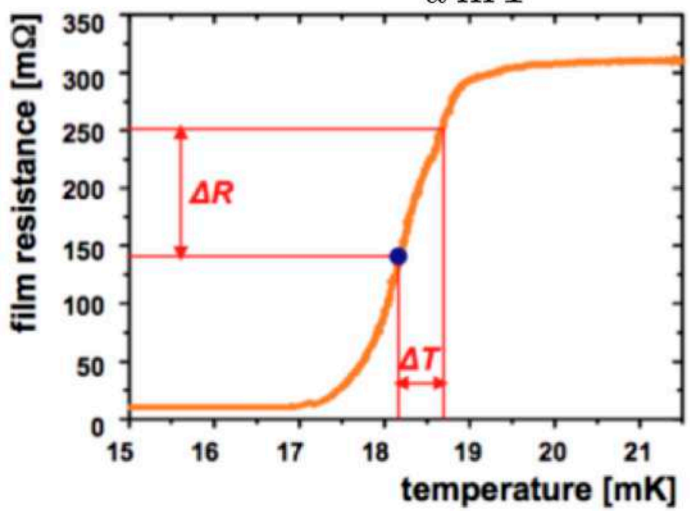


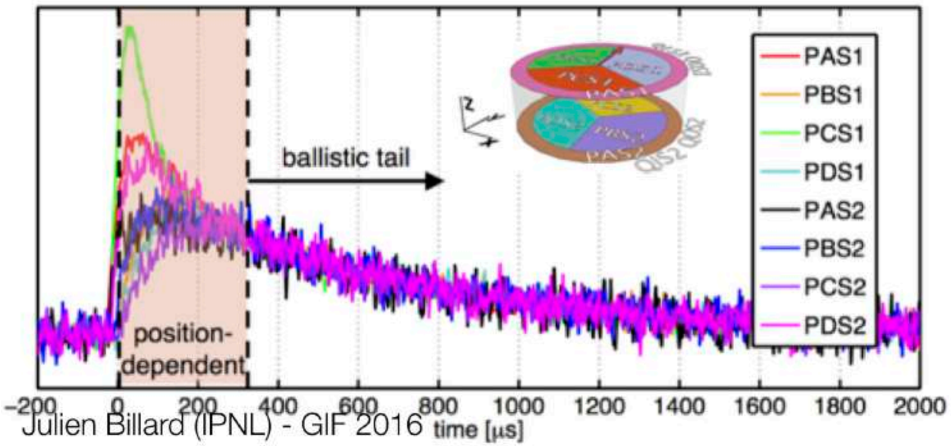
TES sensors

CRESST and CDMS heat sensor - TES

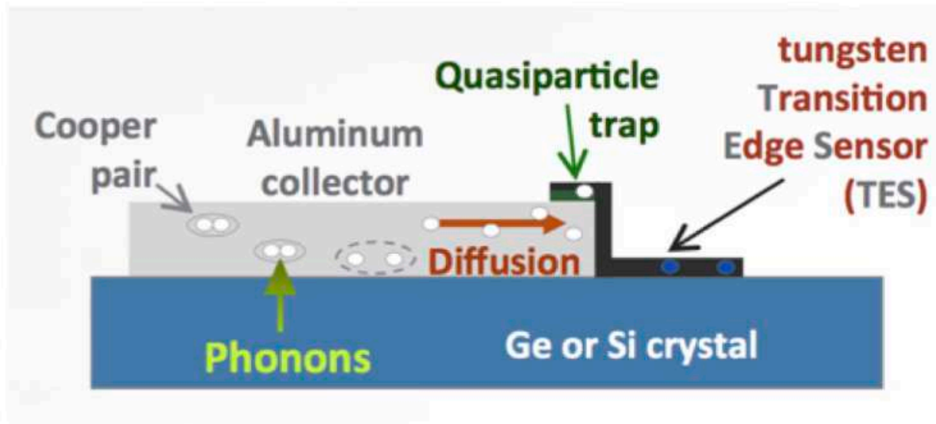
$$\alpha = \frac{d\ln R}{d\ln T} \sim 100$$

- TES: Transition Edge Sensor (in Tungsten)
- Sharp (α~100) transition supra/normal at Tc
- Sensitive to athermal phonons (above the Al gap 340 μeV)
- Voltage biased (α>0), readout by SQUIDs amplifier
- Complex and expensive
- Very sensitive to EM pick ups
- At first order not limited by crystal heat capacity (decoupled)
- Very fast, position sensitive, could reach few eV resolution



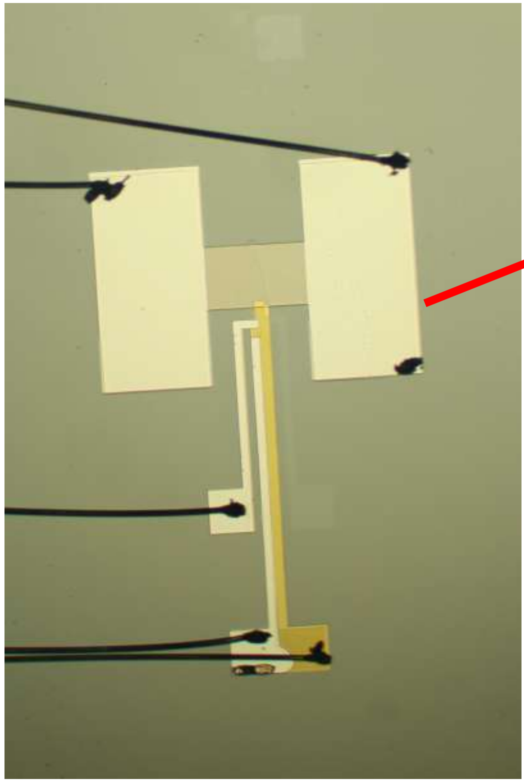


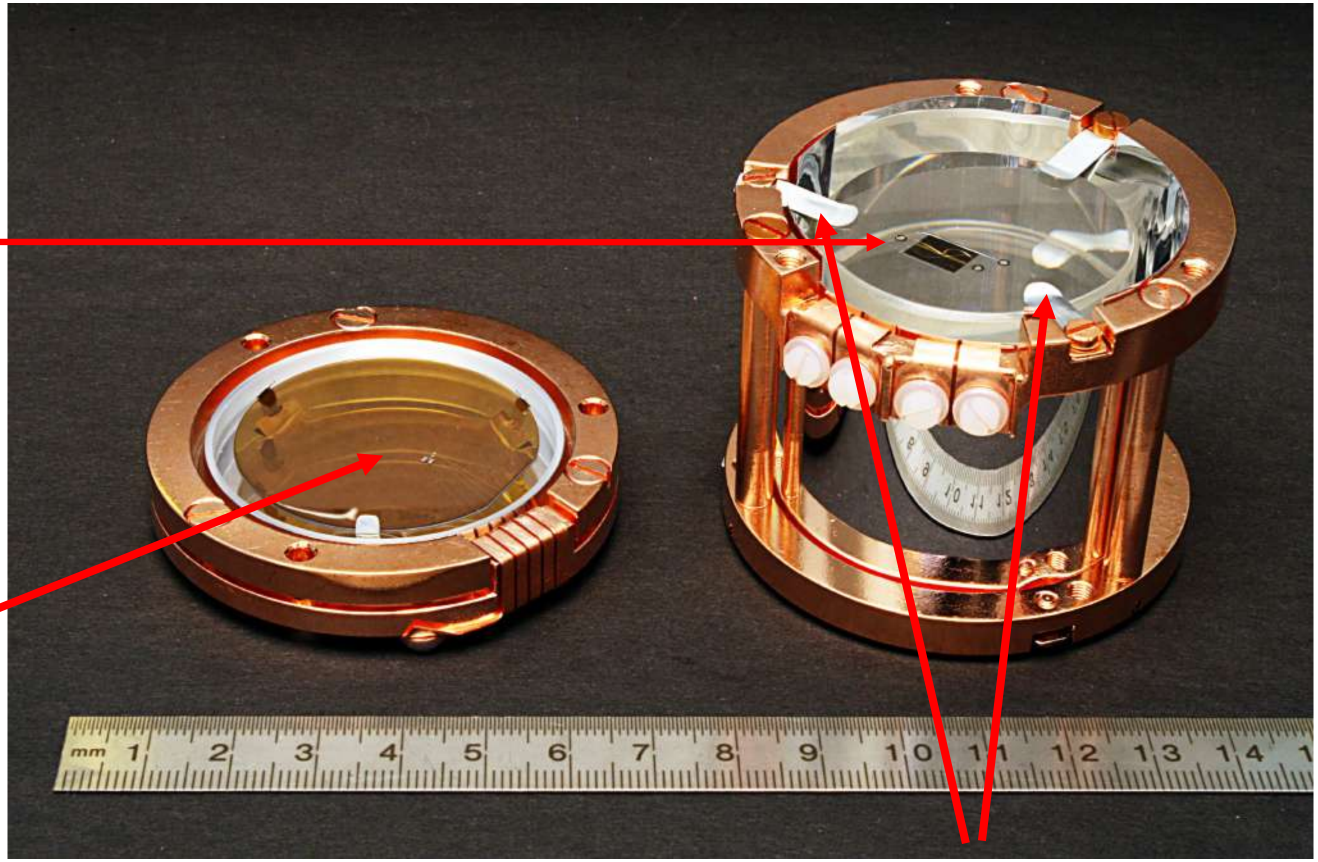
Julien Billard (IPNL) - GIF 2016



CRESST-II detectors

The phonon detector:
300 g cylindrical
$CaWO_4$ crystal.
Evaporated tungsten
thermometer with
attached heater.





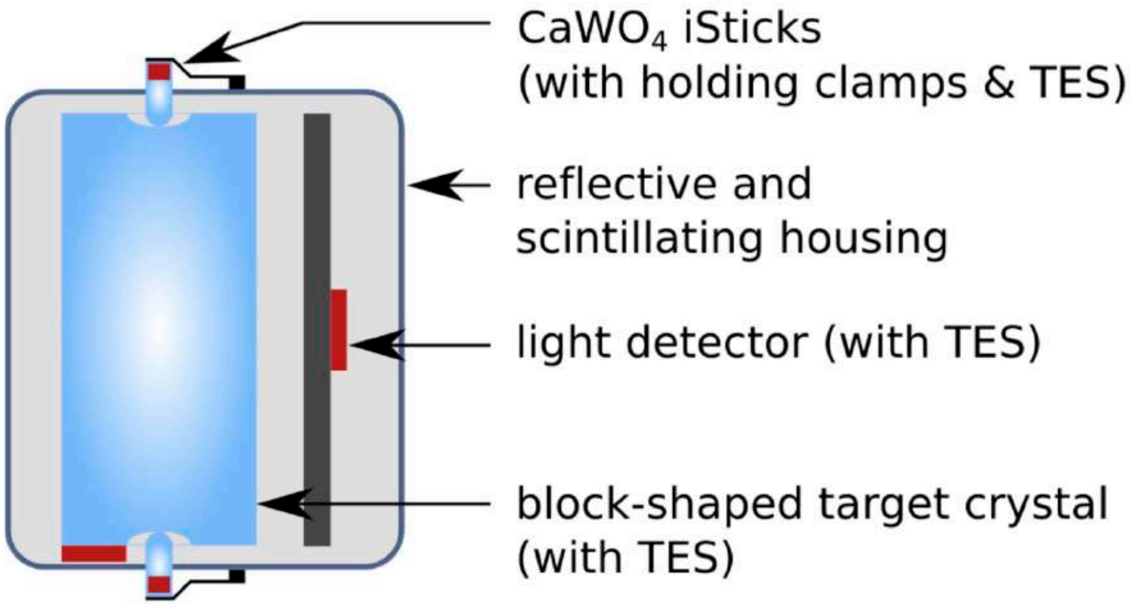
Clamps not
scintillating

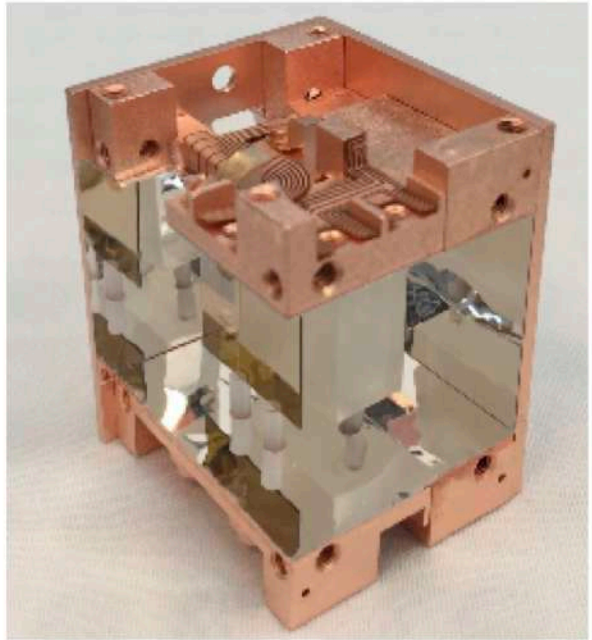
Light detector:
Ø=40 mm silicon on sapphire wafer.
Tungsten thermometer with attached
aluminum phonon collectors and thermal link.
Part of thermal link used as heater

CRESST-III detectors

- Smaller detectors (24g), to achieve lower thresholds (30 eV)

Reindl, IDM2018

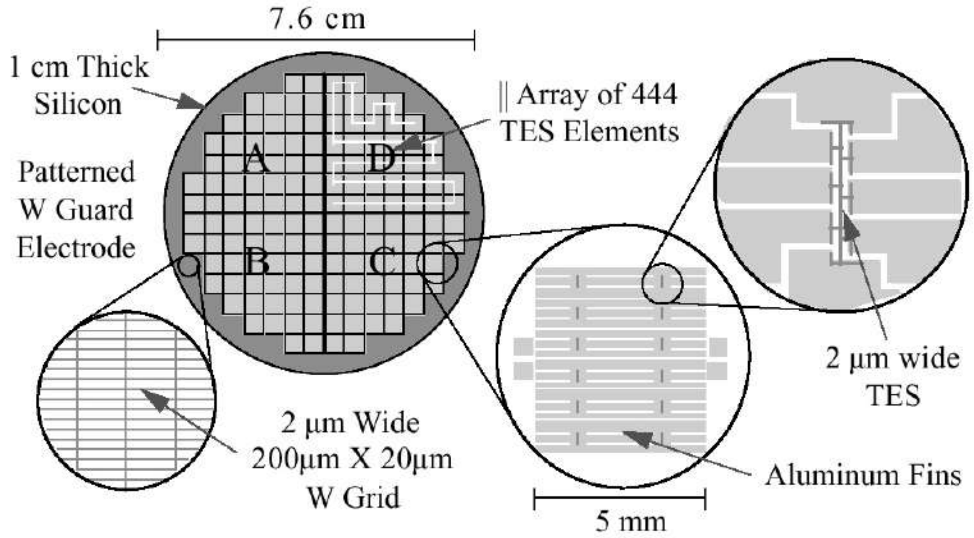


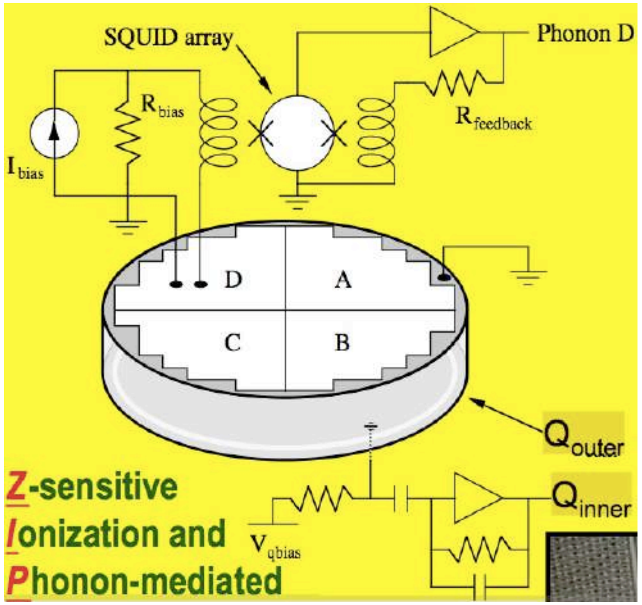


Data taking period:	10/2016 – 01/2018
Non-blind data (dynamically growing):	20% randomly selected
Target crystal mass:	23.6g
Gross exposure (before cuts):	5.7 kg days
Nuclear recoil threshold:	30.1 eV

CDMS ZIP detectors

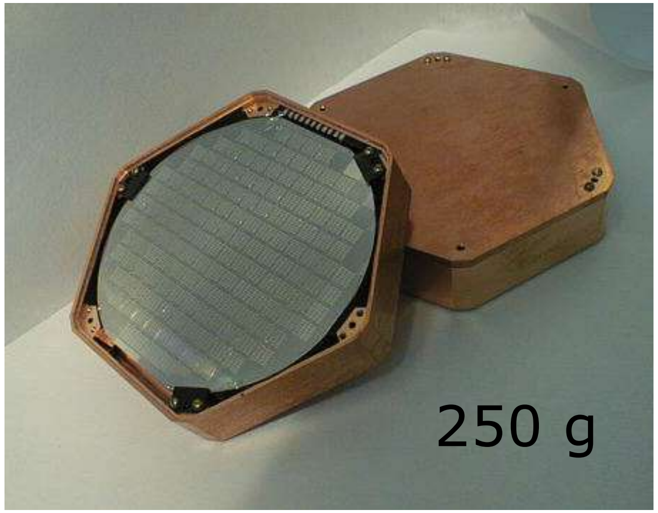
- Large area: sensitivity to athermal phonons
- *Sensitivity to surface interactions*
- Photolithographic patterns of W-TES + Al collector (CDMS)





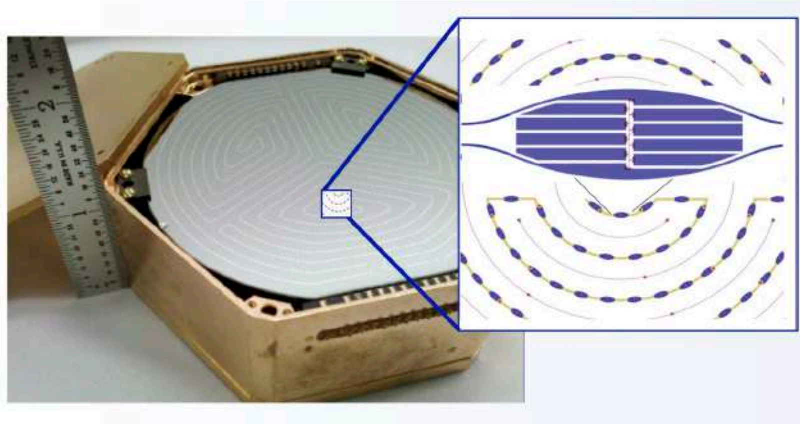
Heat signals:
4 quadrants

Ionization signals:
Q_inner
Q_outer

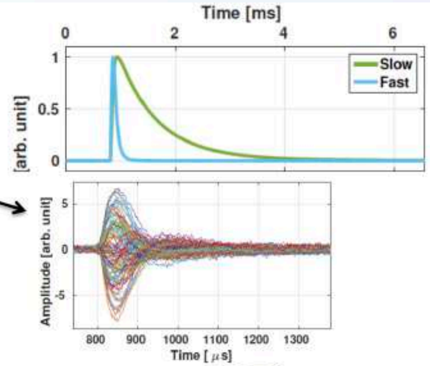


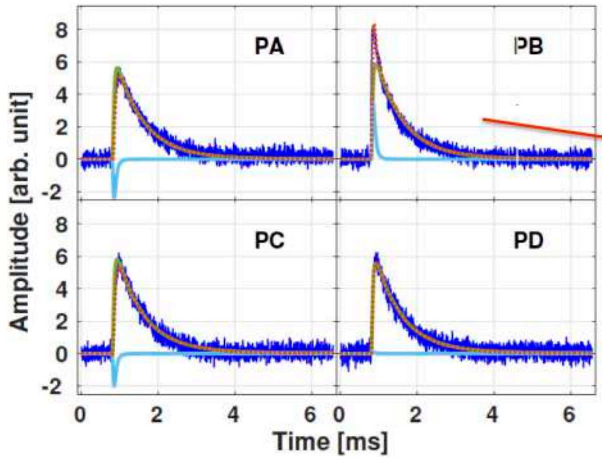
SuperCDMS iZIP position dependence

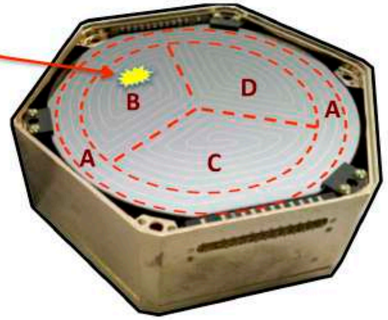
- TES linked in spiral-like pattern (see ionization topic, later)
- Separated in 4 groups on each side of the detector
- Outer ring A to reject events close to the side
- A/B/C/D give x-y coordinates
- Separation of slow (~Energy) and fast (~position) components



Initial absorption of phonons is localized.
Thus the fast component encodes for position
The fast template is formed from the residuals of the standard averaged template.







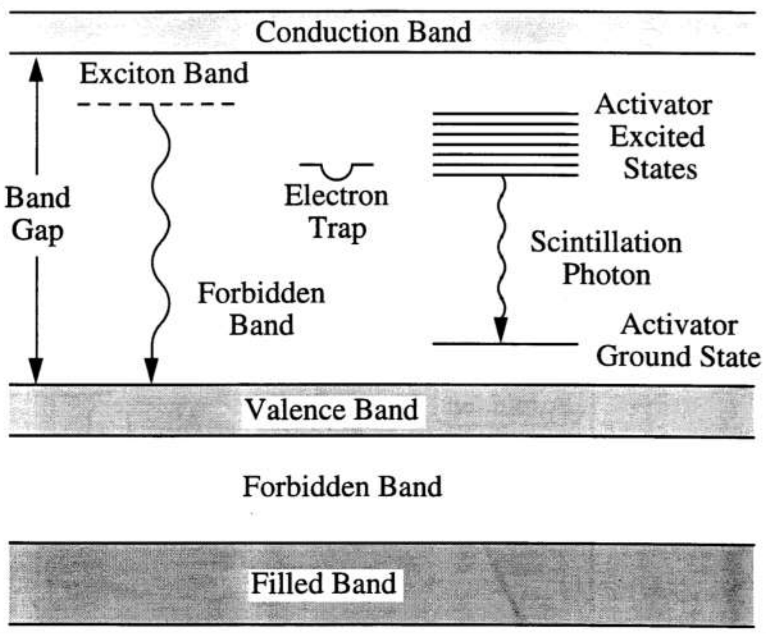
SCINTILLATION

Inorganic scintillators (NaI, CsI, $CaWO_4$, …)

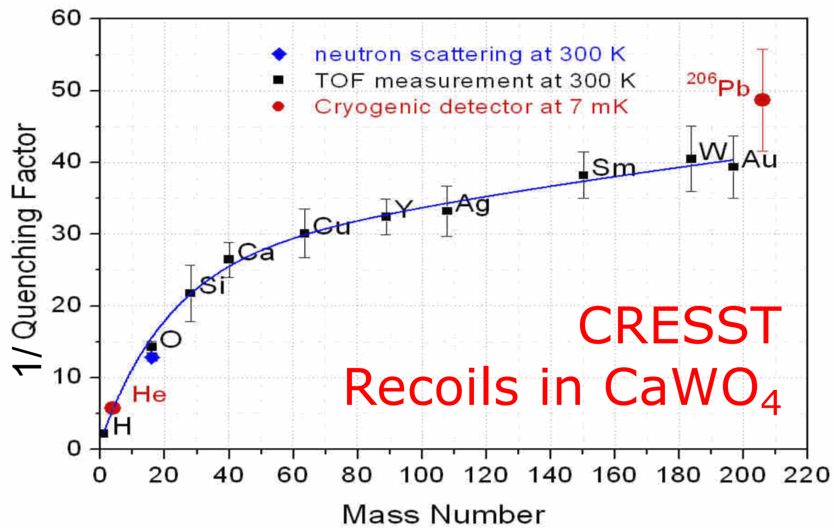
- A good scintillator should NOT reabsorb its own light

  Emission $h\nu > E_{gap}$ from e^- conduction band is easily absorbed by valence e^-
- *Emission from less abundant in-gap states is much less absorbed*
- ~Birk's rule: if dE/dx is large, the population of the in-gap states is saturated: reduced emission per incident keV.
- Electron recoils are subject to this (E-dependent) quenching.

  Additional Lindhard quenching for nuclear recoils.
- Scintillation time constants may be affected: pulse shape discr.



Derenzo



CRESST-III low energy

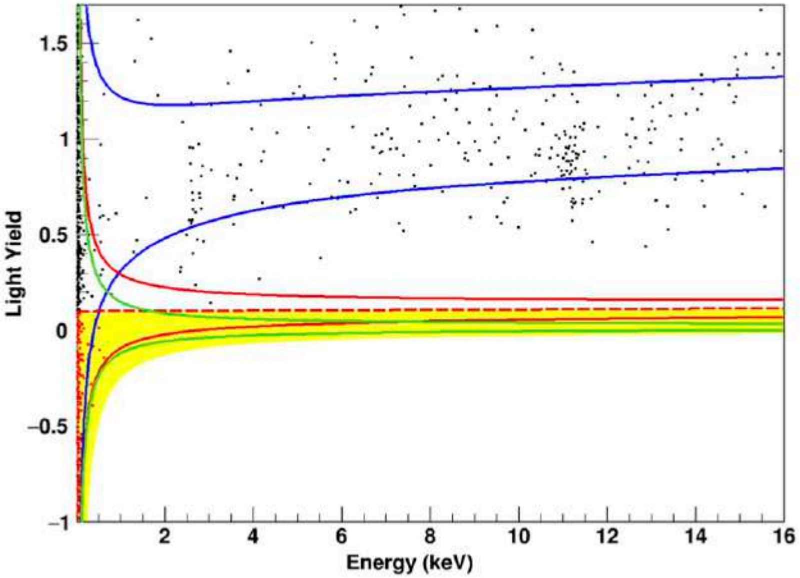


FIG. 5. Light yield versus energy of events in the dark matter data set, after selection criteria are applied (see Sec. III D). The blue band indicates the 90% upper and lower boundaries of the β/γ-band; red and green show the same for oxygen and tungsten, respectively. The yellow area denotes the acceptance region reaching from the mean of the oxygen band (red dashed line) down to the 99.5% lower boundary of the tungsten band. Events in the acceptance region are highlighted in red. The position of the bands is extracted from the neutron calibration data as shown in Fig. 3. A zoom to the low-energy region is given in Appendix A 2.

PHYS. REV. D 100, 102002 (2019)

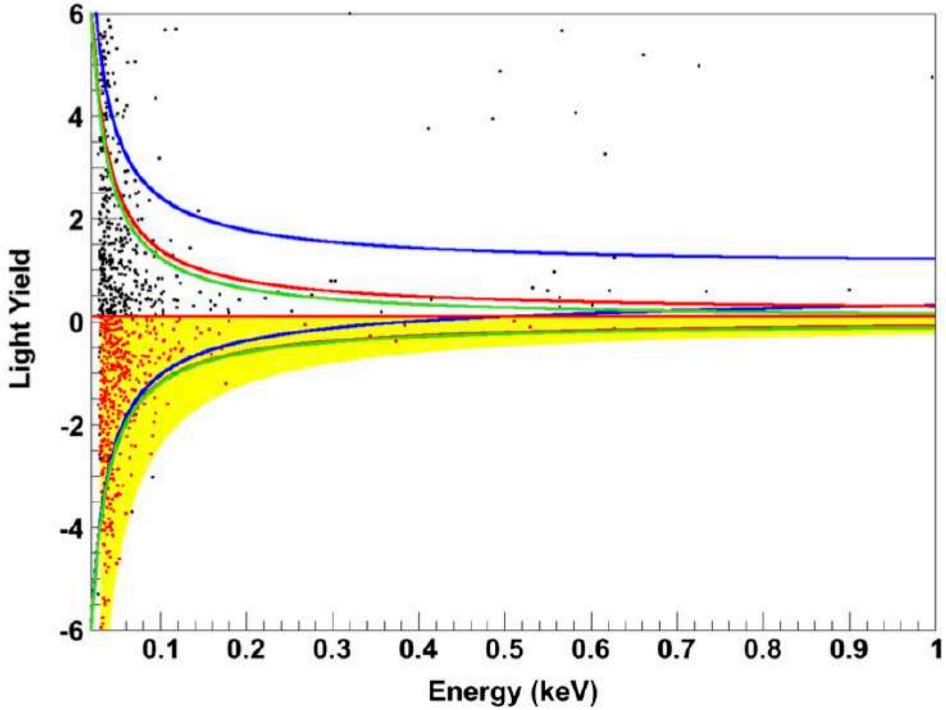


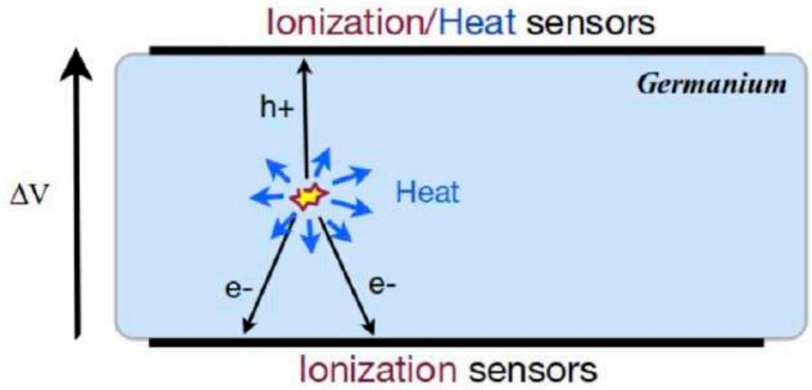
FIG. 9. Zoomed version of Fig. 5 showing the data in the dark matter data set. Yellow shows the acceptance region, blue shows the β/γ-band, and red and green show the oxygen and tungsten recoil bands. For details see Fig. 5 and Sec. III B.

Separation of ER/NR band not decisive in low-energy region sensitive to Sub-GeV WIMPs, but essential for understanding the backgrounds

IONIZATION

Ionization in cryogenic detector

- Silicon + Germanium: zone-refined crystals (low trap density) already nearly radiopure
  - Except if exposed too long to cosmic rayS



- Ionization channel: electrode **keV_{ee}**
  - Electron Recoils: $N_{pairs} = E_{recoil} / 3$ eV
    Independent of bias V

Neganov-Trofimov-Luke (NTL) heating

[equivalent to Joule effect]

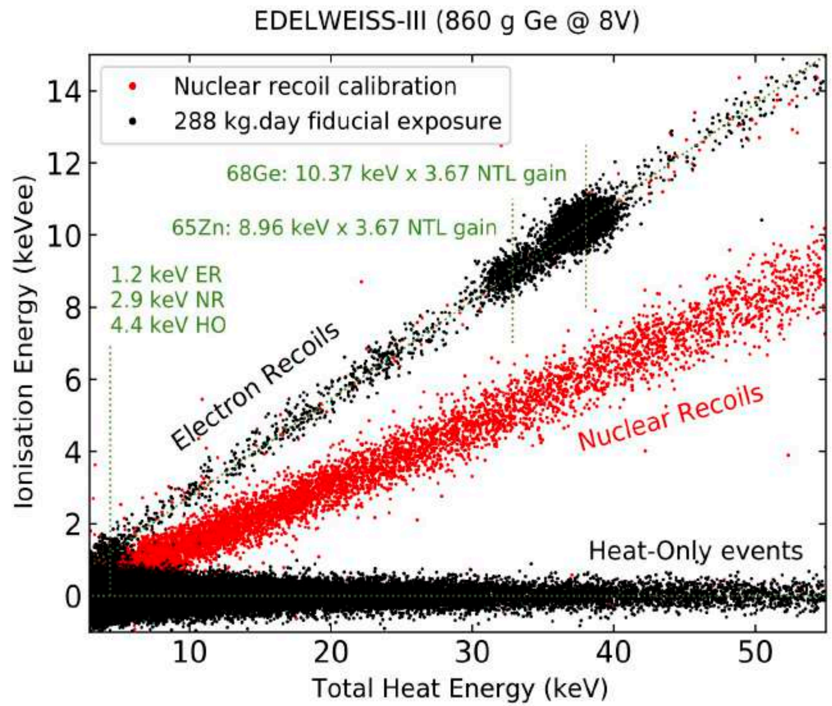
$$E_{heat} = E_{recoil} + N_{pairs} V$$ **keV**

- Reduced ionis. yield for Nuclear Recoils

  $N_{pairs} = Q * E_{recoil} / 3$ eV

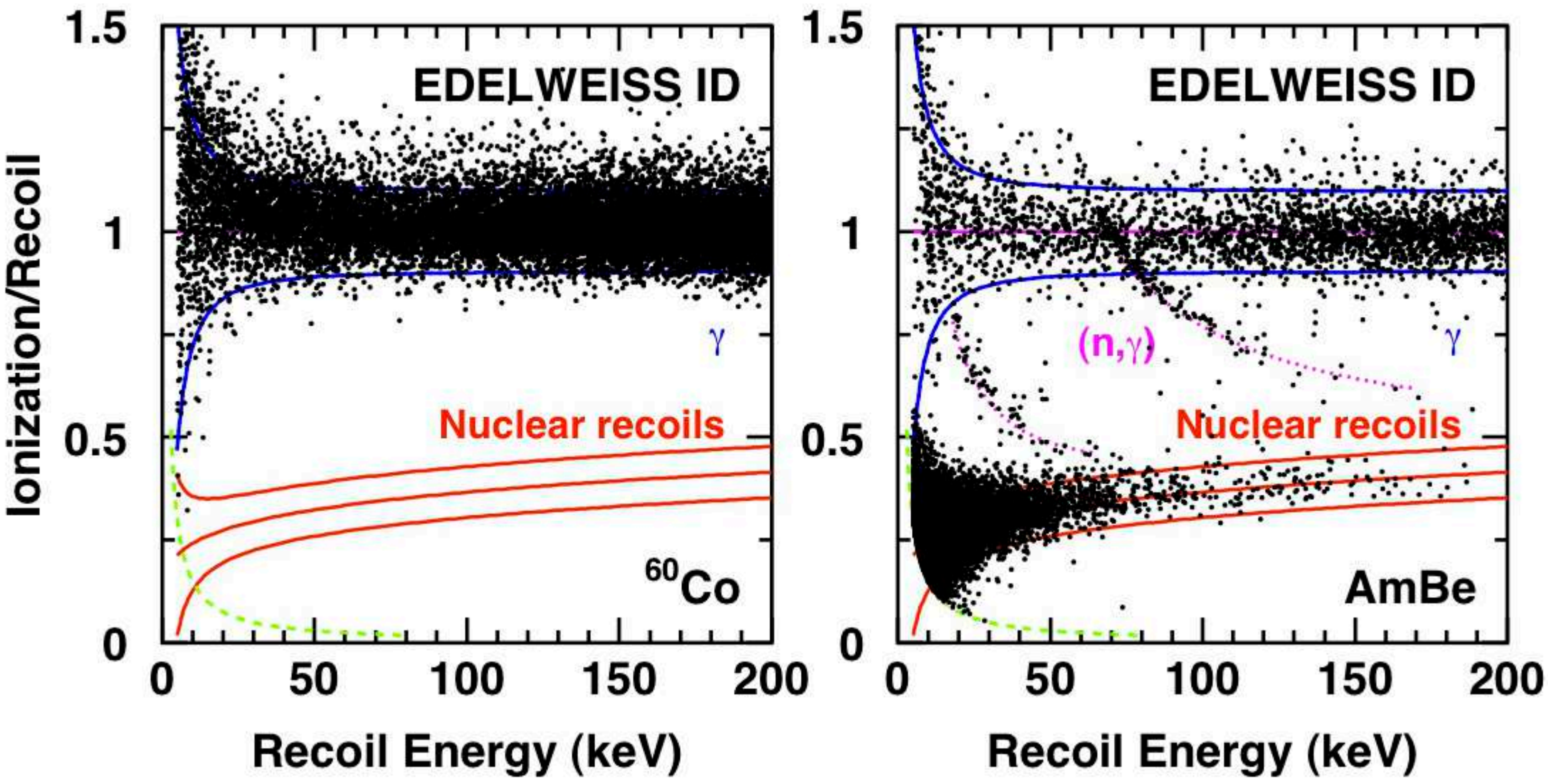
  with Q ~ 0.2 for 5 keV NR

- (3^{rd} category: "Heat-only events")



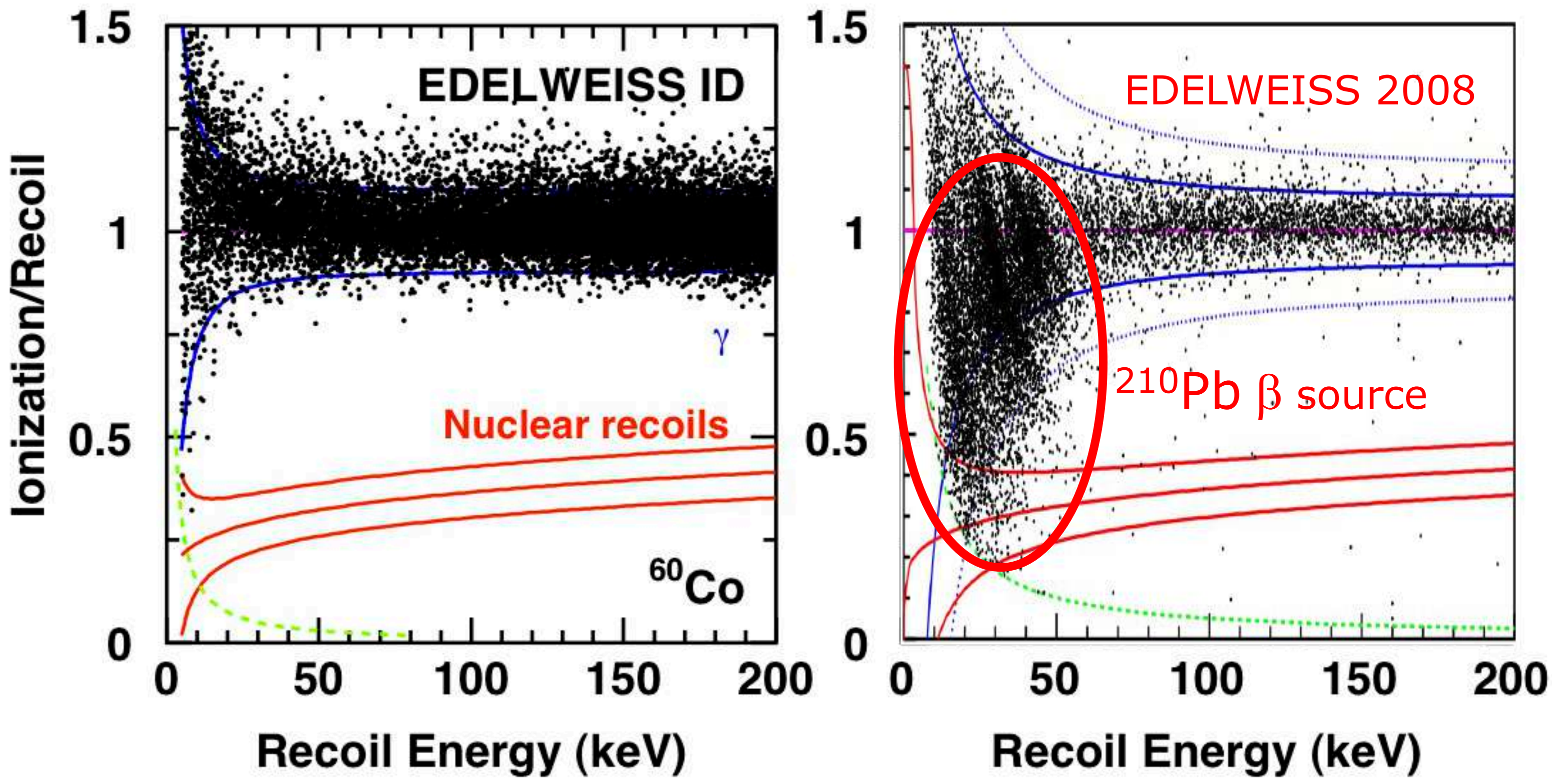
Nuclear recoil / gamma discrimination

- With good resolution on both ionization & heat, very clear discrimination based on the different ionization yields for *nuclear recoils* (WIMP or neutron scattering) and *electronic recoils* (β,γ decays)
  - discrimination of dominant background
  - Stable and reliable rejection performances



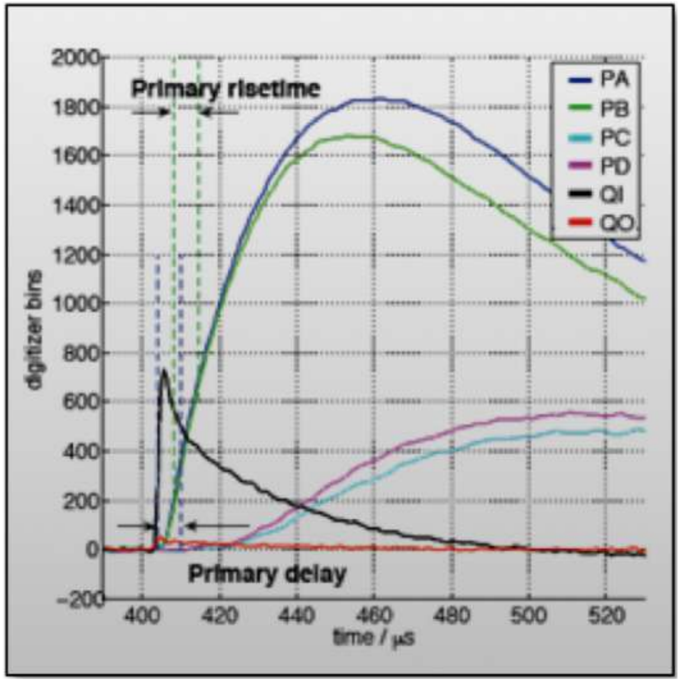
Ionization yield of surface events

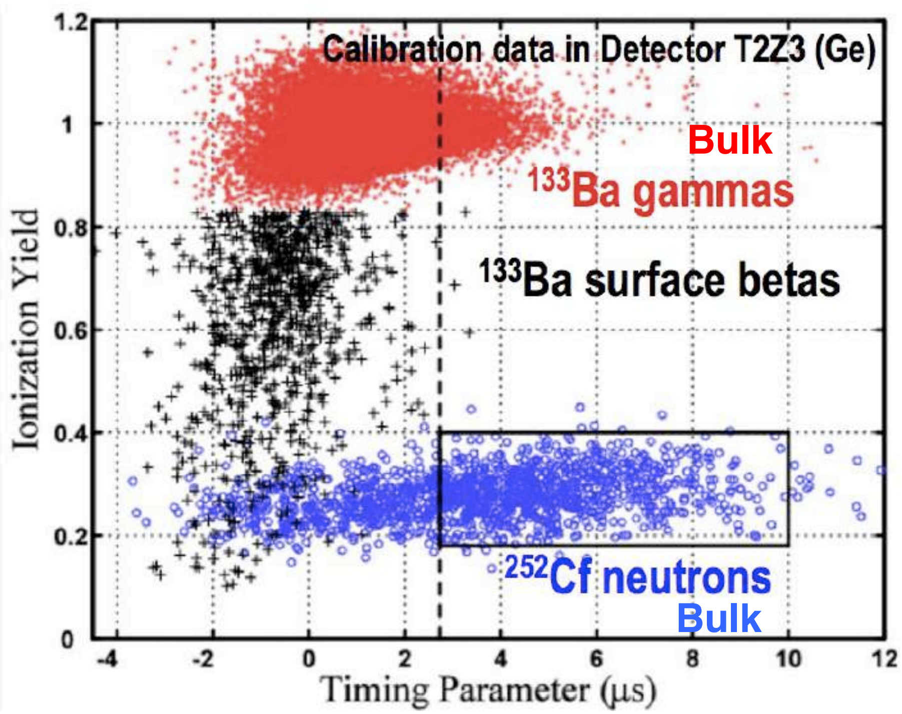
- With good resolution on both ionization & heat, very clear discrimination based on the different ionization yields for *nuclear recoils* (WIMP or neutron scattering) and *electronic recoils* (β,γ decays)
- *Limitation: deficient charge collection near surface (trapping, dead layer)*
  => surface rejection possible via phonon or ionization channel



Phonon time discrimination

- Phonon risetime < 50 μs
- Ionization risetime < 1 μs
- « Timing parameter » combines *rise time* and *phonon-ionization delay*
- Nuclear/electronic recoil discrimination!



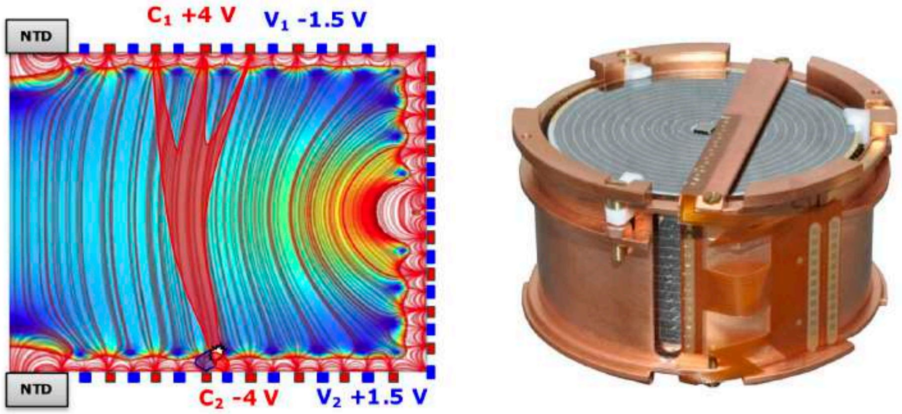


- Sensivity to « z »? (no, works even if sensors on only one side)
- Due instead to a difference between the phonons produced in the primary interaction and in the Luke-Neganov process.

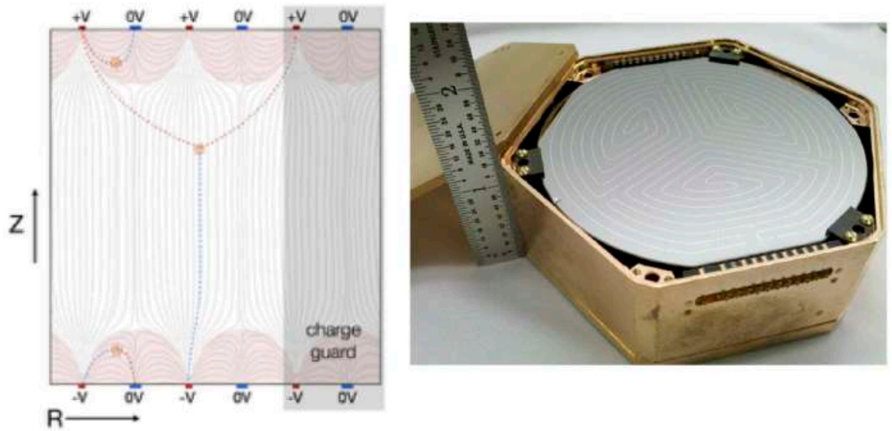
Interleaved electrodes

- Adopted for large detectors by both EDELWEISS and SuperCDMS

EDELWEISS FID800



SuperCDMS iZIP



- Concentric electrode rings with alternate bias values
  - Bulk event charge collected C1 and C2 rings
  - (Top) surface event charge collected on C1 and V1 rings
  - CDMS veto on asymmetry between C1 and C2 (V1, V2 not read: TES lines)
  - EDELWEISS veto events with V1 or V2 or C1-C2 asymmetry
- Reject 1-2 mm on all surfaces (EDELWEISS) or flat surfaces (CDMS)
- Added bonus: ”grid effect”: high fields (good collection) close to surface

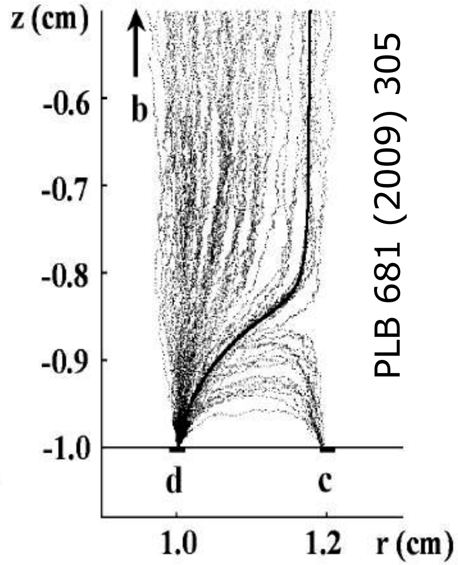
Surface Event Identification

Added bonus: "Grid effect":

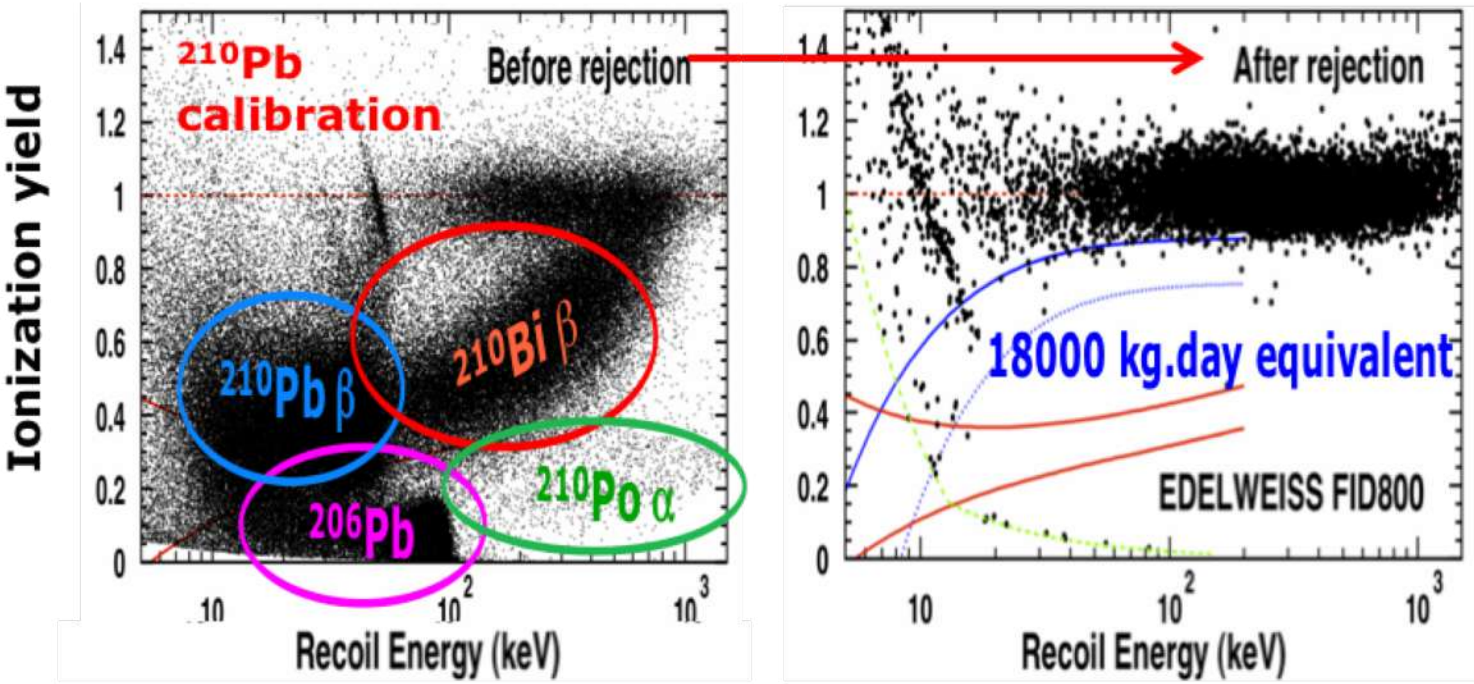
- High-field region close to the fiducial electrodes improves charge collection in that critical region close to the surface

Charge transport effects:

- Diffusion (T=20mK) and charge repulsion insures that charges are never "stuck" in zero-field regions



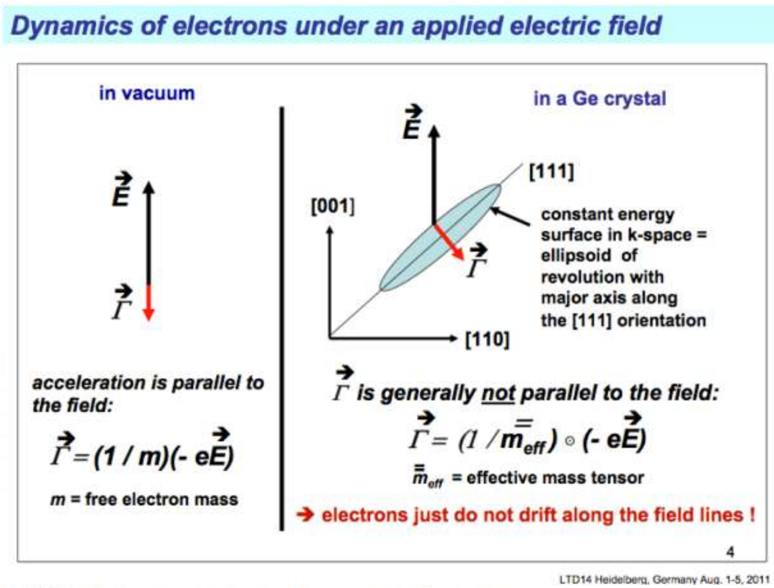
PLB 681 (2009) 305

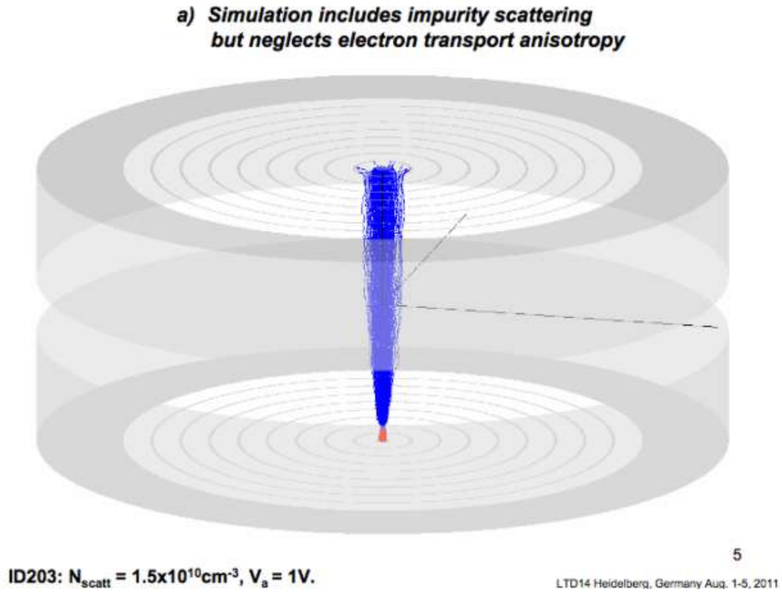


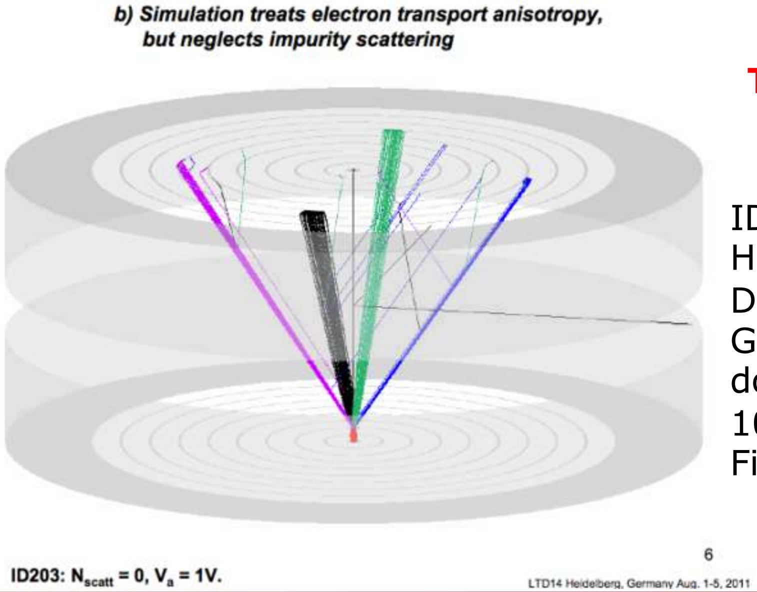
<4x10^{-5} **surface event rejection**.

Charge transport in Germanium

Broniatowski, LTD14

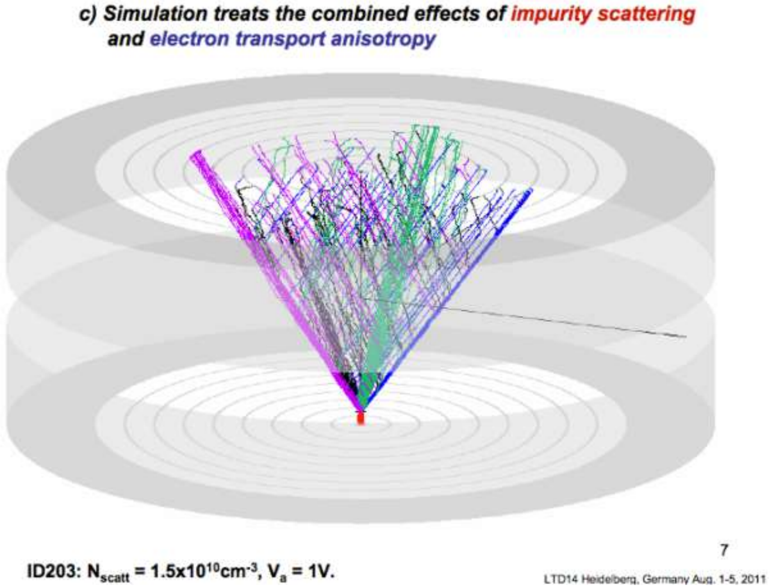






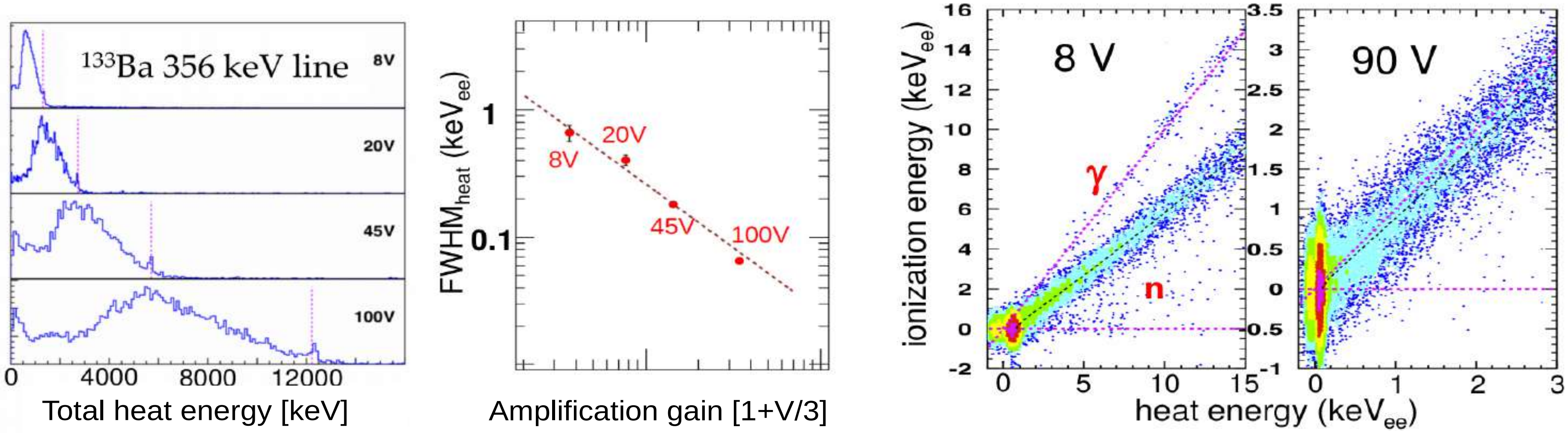
T = 20 mK

ID203
Height 20 mm
Diam. 50 mm
Ge p-type
doped to
10^{11} cm^{-3}
Field: ~0.5V/cm

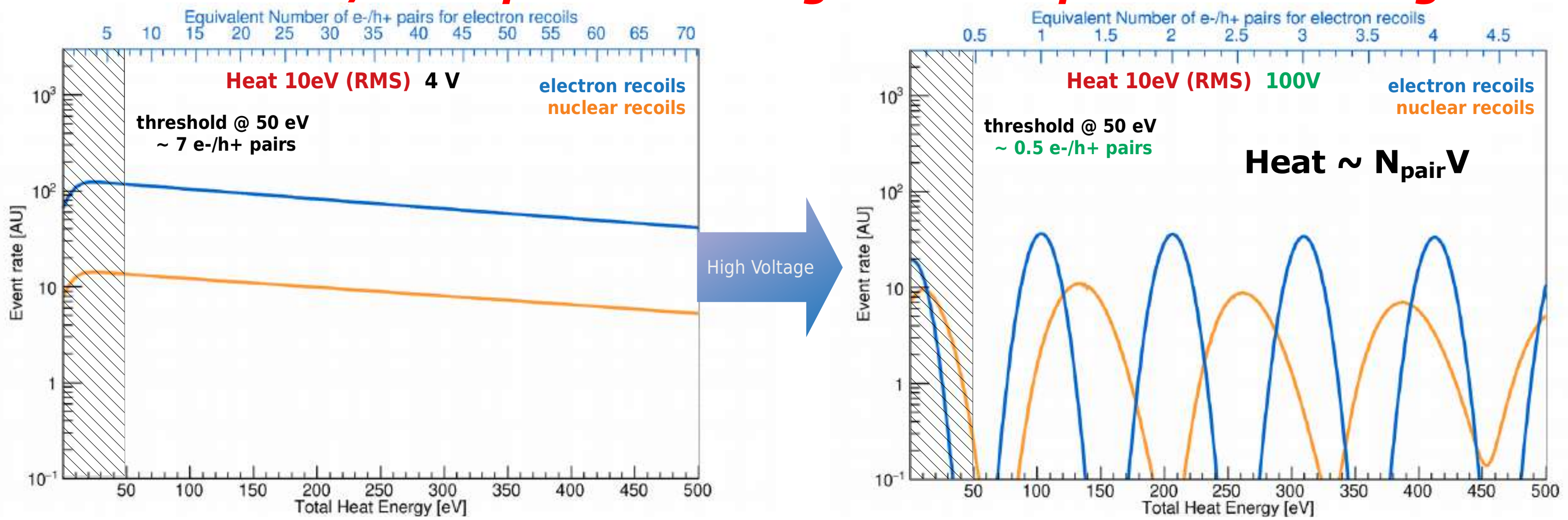


Lower thresholds: Neganov-Luke amplification

- ***Gain in resolution by a factor (1+ΔV/3) for electron signals***



- ***With loss of ER/NR separation… Regained if separation of charge achieved?***



- In Ge, ε_γ = 3 eV and E_{gap} = 0.7 eV (at 20 mK)
- Does it mean that a DM particle cannot give less than 3 eV to an electron?
- Obviously not, because the photoelectric effect starts to work with $h\nu = E_{gap}$ photons.

- The relationship $N_{pair} = E_{recoil} / \varepsilon_\gamma$ is not valid if E_{recoil} << few eV
- For instance, a photon may be absorbed by an exciton, with no electron-hole pair created. Or immediately recombine.
- The value of ε_γ = 3 eV correspond to the limit when the initial impact energy is >> E_{gap}.
- However, the formula:

$$E_{heat} = E_{recoil} + N_{pairs}\, V$$

is always valid.

- And also the energy calibration of the sensor performed with high-energy photons is still valid!

Room temperature measurements

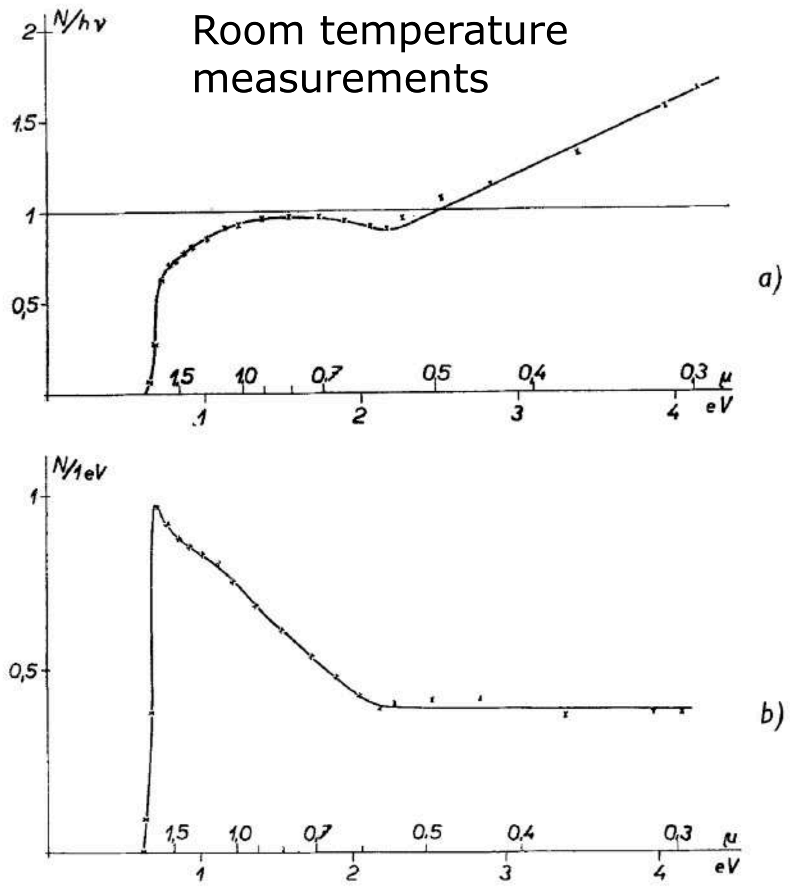


Fig. 1. a) Number of electron-hole pairs generated in germanium by the absorption of one photon as a function of the energy of the incident radiation.
b) Number of electron-hole pairs generated in germanium by the absorption of the total energy of one electronvolt as a function of the energy of the incident radiation.

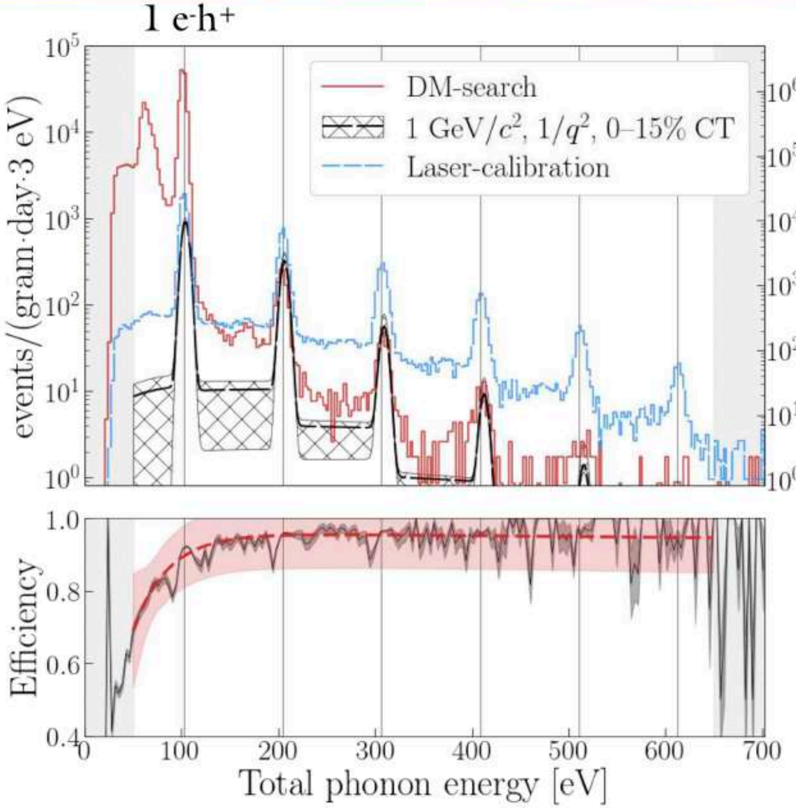
S. Koc, *Czechosl. Journ. Phys.* 7 (1957) 91-95.

CDMS HVeV detector

arXiv:2005.14067
PRL 121, 051301 (2018)
APL 112, 043501 (2018)
NIM A 963, 163757 (2020)

HVeV Detectors

- Single-hole e/h-pair resolution devices will have sensitivity to a variety of sub-GeV DM models with g*d exposures
- 0.93 g Si crystal (1 x 1x 0.4 cm³) operated at 50-52 mK at a surface test facility.
- Exposure: 3.0 gram-days (collected over 3 days)
  - -operation voltage: 100 V
  - -energy resolution: $\sigma_{ph} = 3$ eV
  - -charge resolution: $\sigma_{eh} = 0.03$ e^-h^+
- Calibrations with in-run monochromatic 635 nm laser fiber-coupled to room temperature.
- Data selection criteria were applied to remove leakage and surface events.



- Impact ionization and charge trapping were incorporated into DM signal models.

J. Cooley, IDM2010

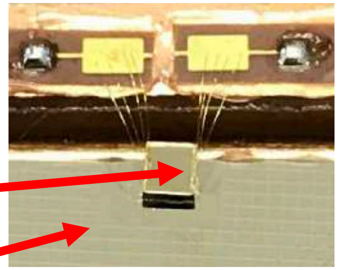
[PRL 125, 141401 (2020)]

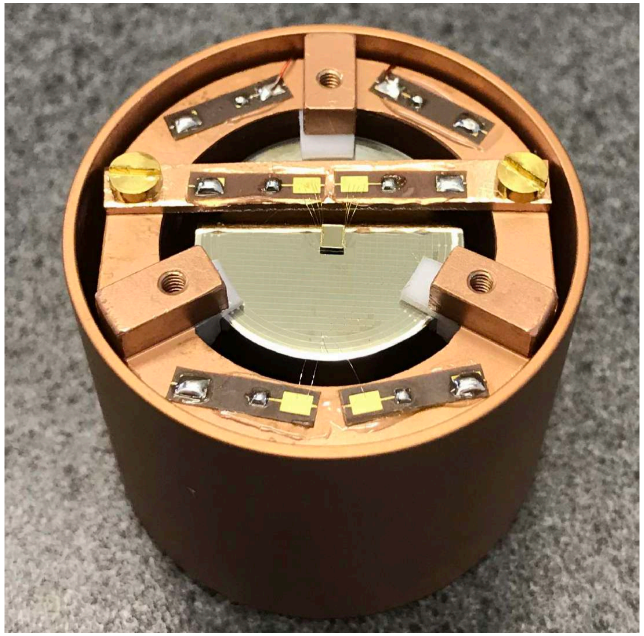
EDELWEISS HV operation

- **EDELWEISS-surf detector with electrodes + operated at LSM (5 μ/m²/day)**
- Ge ϕ 20 x H 20 mm² (33.6 g)
- 1 Ge-NTD sensor (1.6 mm³) glued bottom Ge surface

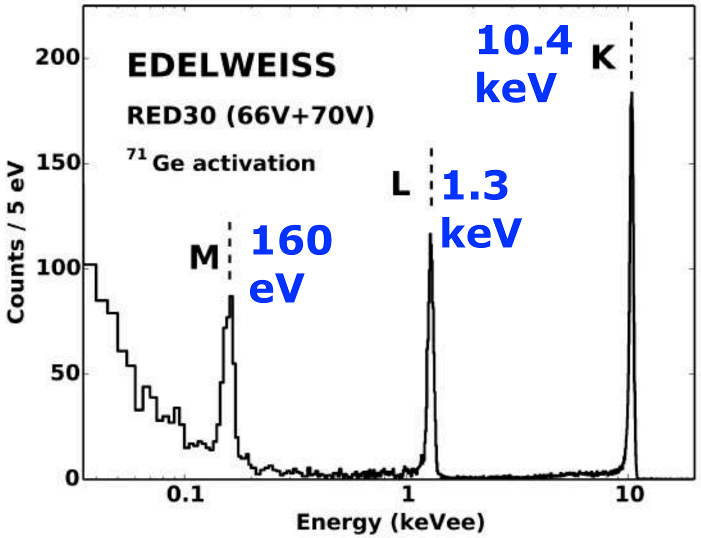
NTD sensor

Al grid electrode



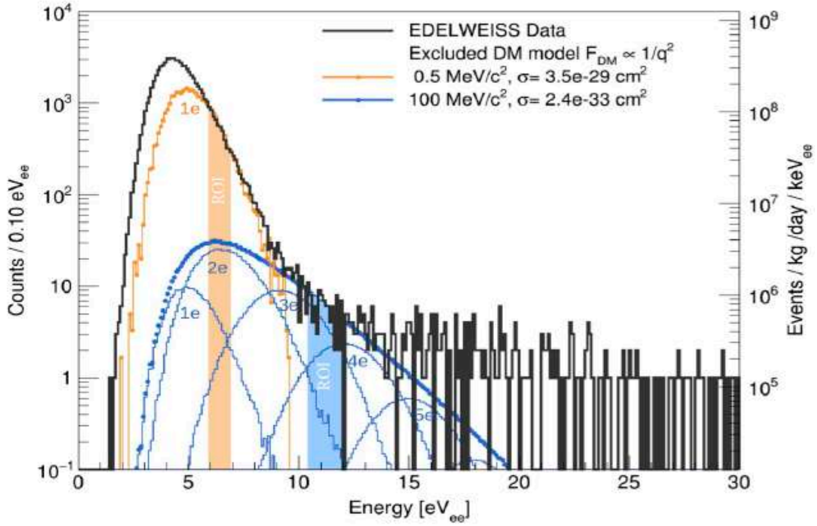


- Flat surface electrodes: lithographed Al grid (500 μm pitch, 4% coverage) to reduce phonon trapping)



calibration

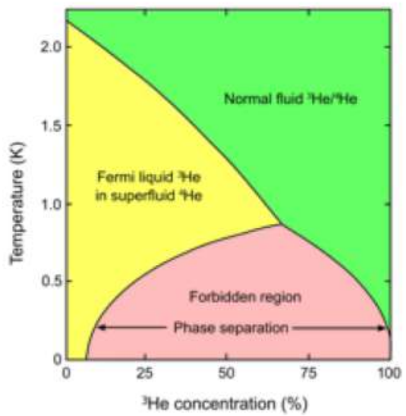
Not yet able to separate charges, but backgrounds provide better DM limits

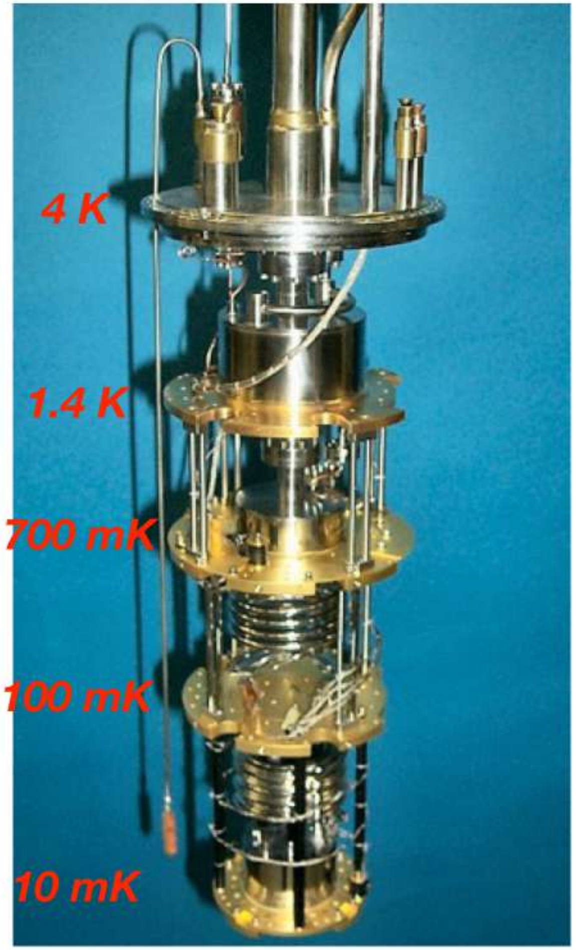


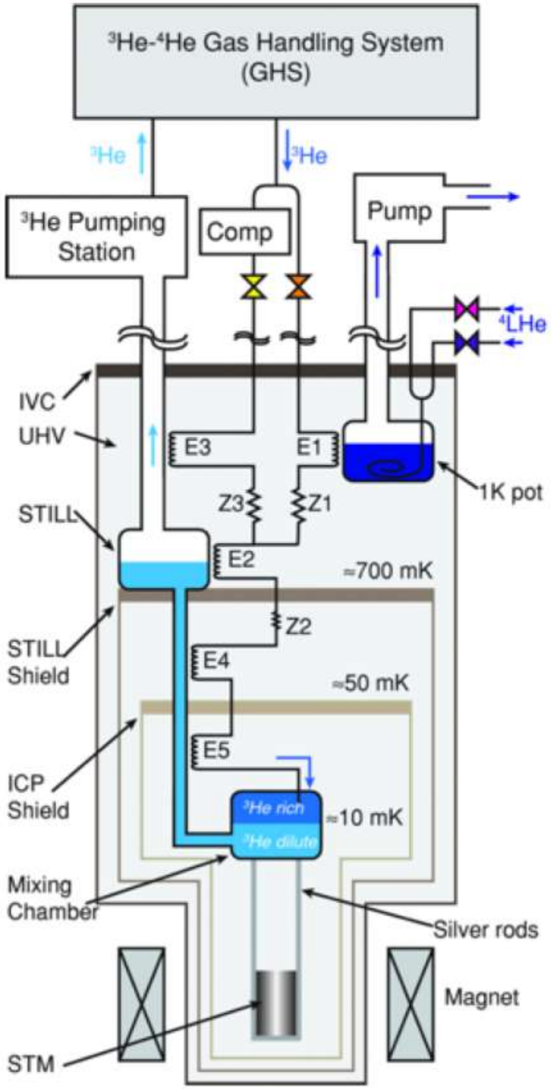
CRYOGENICS

To reach 10 mK we need to use He3/He4 dilution refrigerator

- **Cool down to 4K:**
  - thanks to pre-cooling LN2 and LHe
- **Reach 1 K thanks to evaporative cooling**
  - Done by pumping on LHe in 1K pot
- **Condense the He3/He4 mix**
- **Reach 700 mK thanks to Joule-Thompson**
- **Below 800 mK: phase separation (rich/poor)**
- **10 mK thanks to He3/He4 dilution**
  - Forcing He3 through poor phase is endothermic
  - Done by pumping on dilute phase (poor)







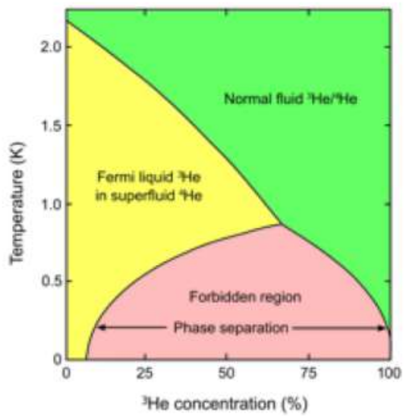
J. Billard, GIF school 2016

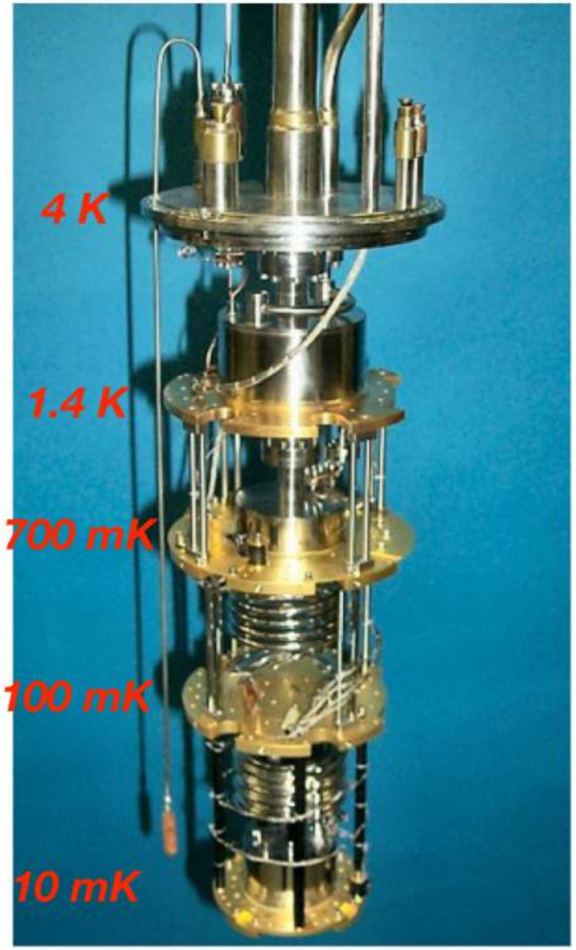
Dilution refrigerators

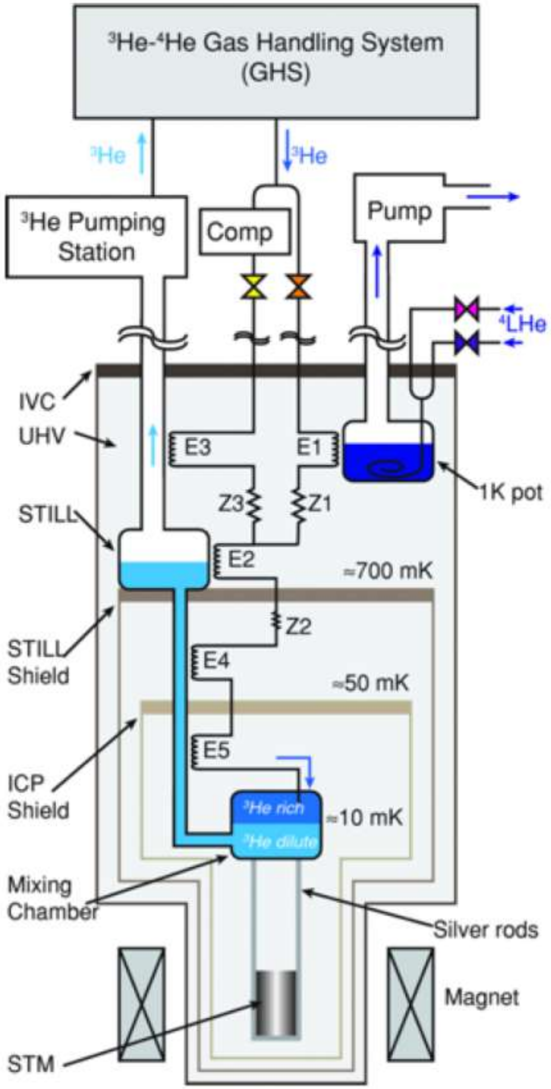
To reach 10 mK we need to use He3/He4 dilution refrigerator

Cool down to ~1K using mechanically decoupled Pulse Tubes

- **Condense the He3/He4 mix**
- **Reach 700 mK thanks to Joule-Thompson**
- **Below 800 mK: phase separation (rich/poor)**
- **10 mK thanks to He3/He4 dilution**
    - Forcing He3 through poor phase is endothermic
    - Done by pumping on dilute phase (poor)

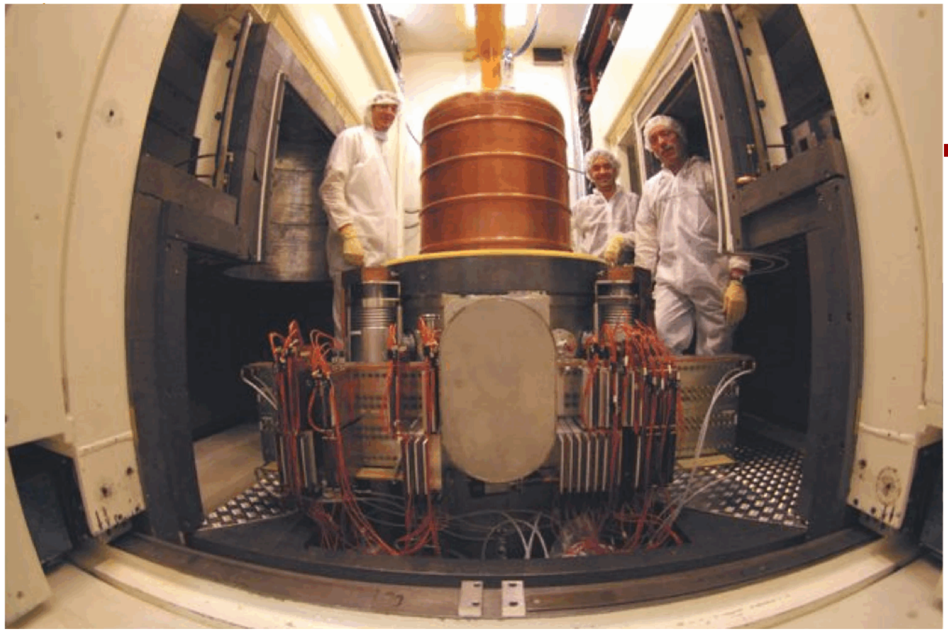


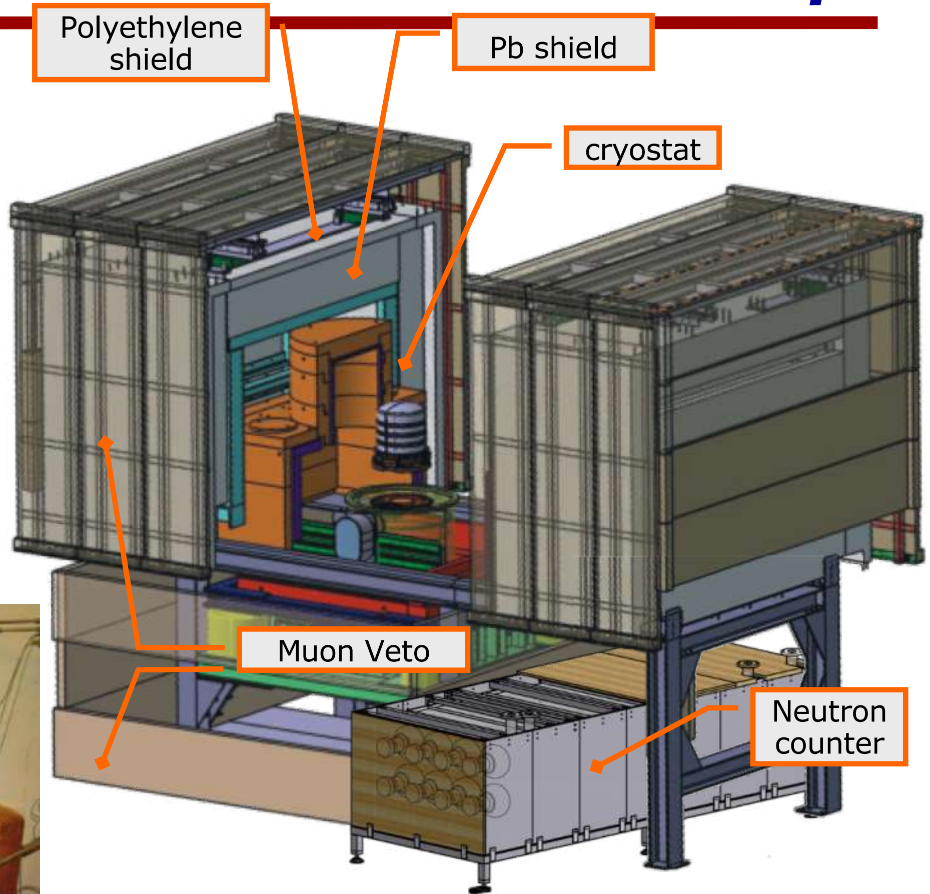


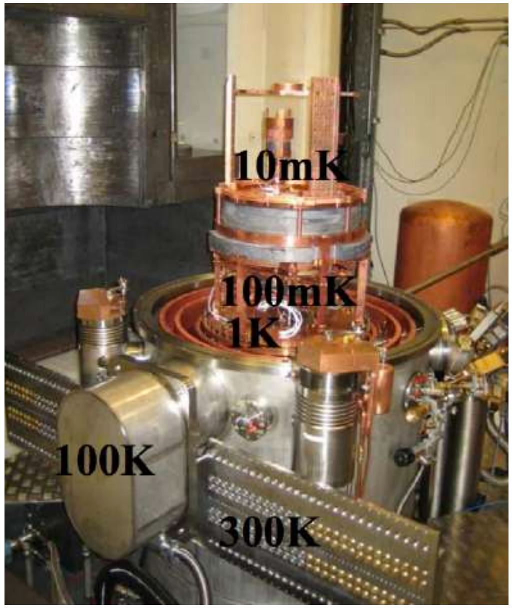


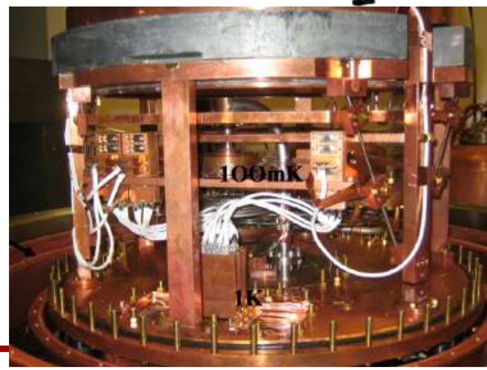
J. Billard, GIF school 2016

EDELWEISS setup





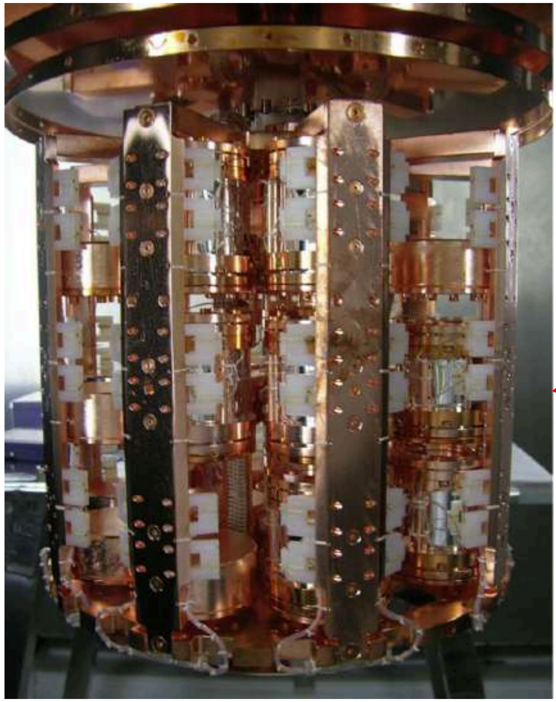


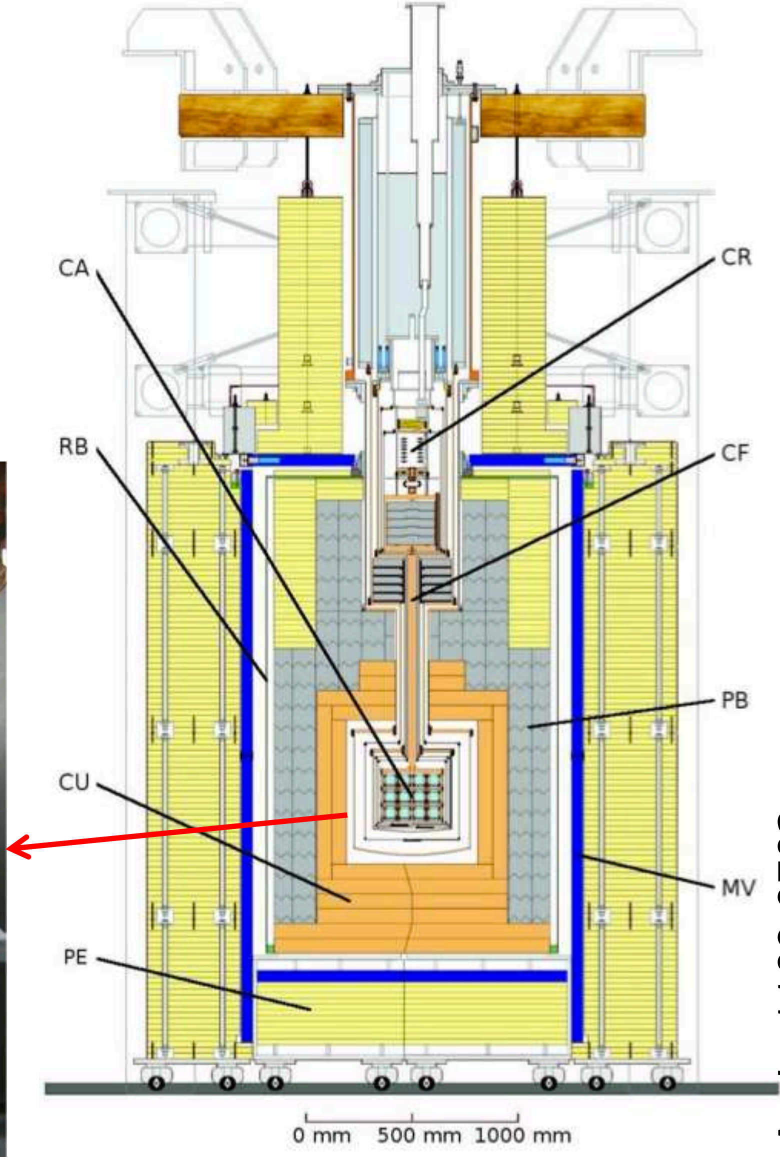


CRESST Cryostat and shield

66 SQUID channel readout (33 detectors)

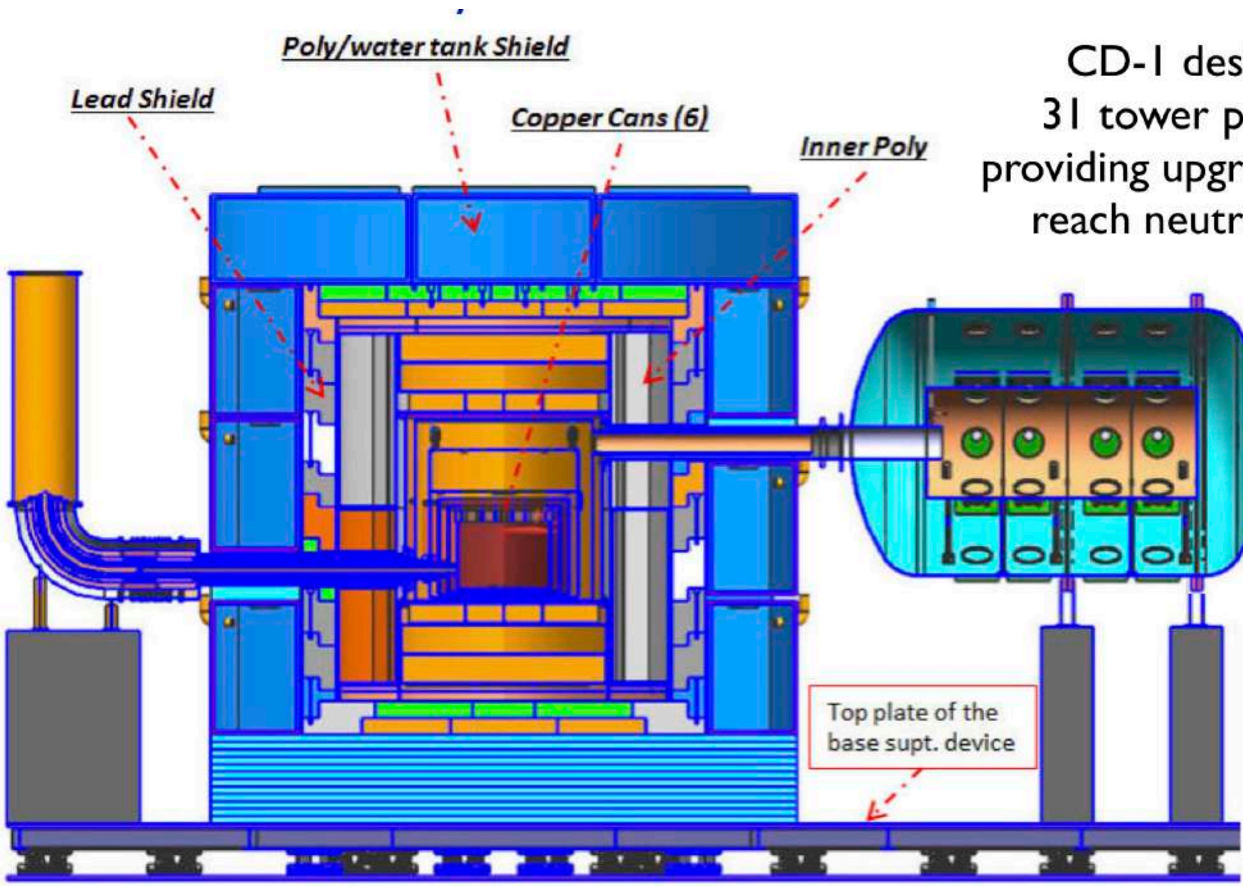
Detector carroussel





Arxiv:1109.0702

SuperCDMS at SNOLAB



CD-1 design has
31 tower positions,
providing upgrade path to
reach neutrino floor

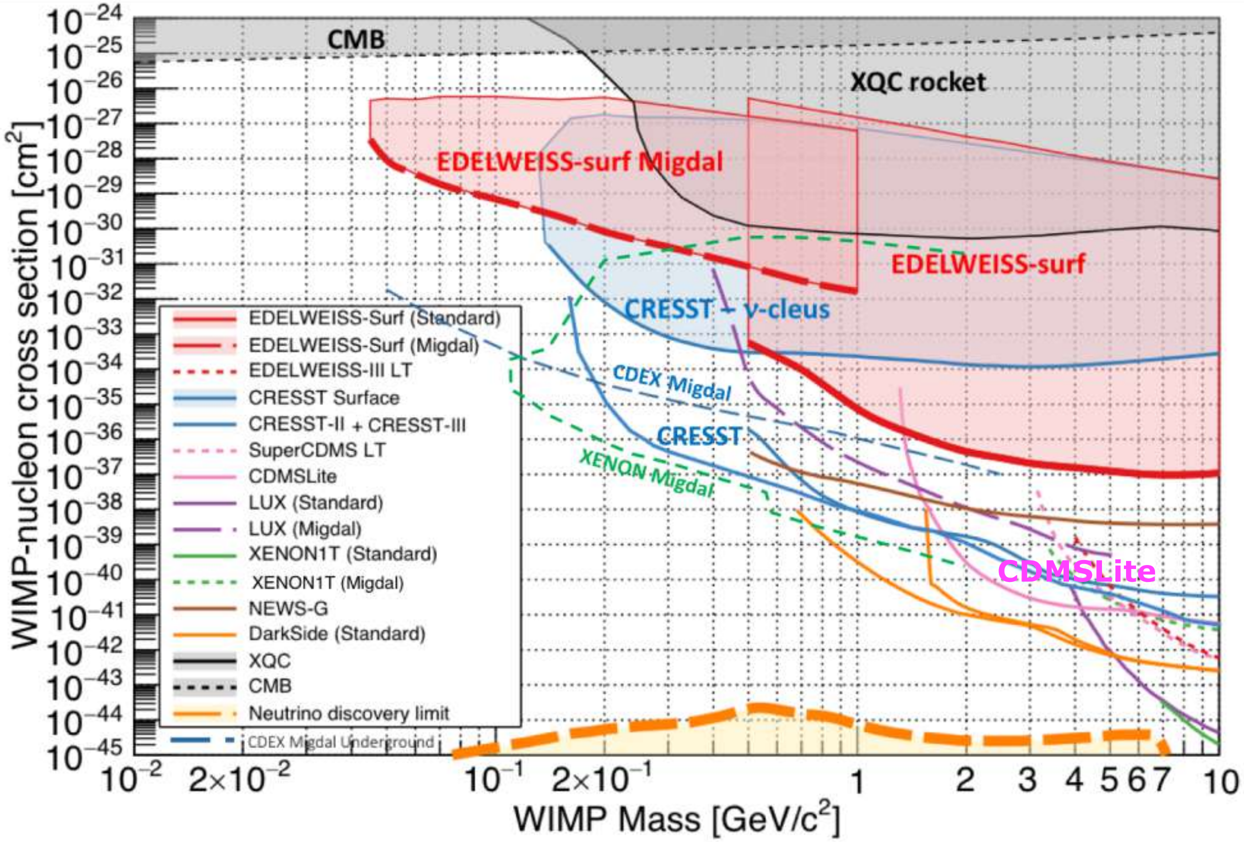
Detector Payload:
- 3 Ge iZIP towers (50 kg)
- 1 Si iZIP tower (4 kg)
- 1 HV tower:
  - 4 Ge (5.6 kg)
  - 2 Si (1.4 kg)

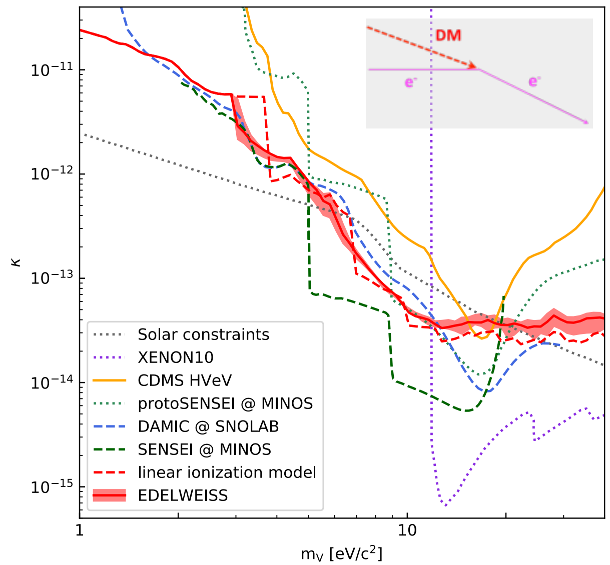
SuperCDMS SNOLAB/DM2016 11 Sunil Golwala

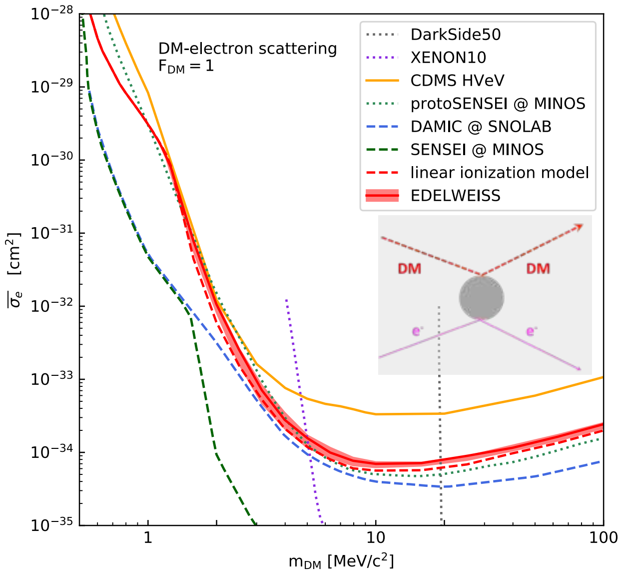
CONCLUSION: RESULTS?

Conclusion: results?

- Cryogenic detectors highly competitive in searches for <GeV WIMPs (NR)
- With NTL amplification, can also compete in DM-electron and Dark Photon searches (ER)







QUESTIONS

Question 1

Let's define the true energy of a particle as E_R (and assume E_R>10 eV). If the quenching of the ionisation signal for this particle is Q, then the ionization signal for the particle is $E_I = QE_R$. For electron recoils Q=1. For nuclear recoils Q<1.

- From the equations on slide 33, find the total heat energy E_{tot} as a function of E_R, Q, the bias V, and the average energy needed to create a electron-hole pair ε_γ.
- Show that, for any value of Q, the following formula always give the correct value of E_R: $E_R = E_{tot} - E_I V / \varepsilon_\gamma$.
- Deduce that, for any value of E_R, $Q = 1/(E_{tot}/E_I - V/\varepsilon_\gamma)$

In cryogenic heat-and-ionization detectors, it this thus possible to measure Q without any assumption on E_R, and vice-versa

Question 2

- Show that in a simple system made of a heat capacitance C linked to a heat bath through a conductance G, the heat signal following a sudden energy deposit E_0 at $t=t_0$ is $\Delta T = (E_0/C) \exp(-(t-t_0)/(C/G))$

- What is the pulse shape if the initial energy deposit is thermalized at a rate $(1/E)\, dE/dt = \lambda$?