The DAREDEVIL project
First results for a GaAs-based cryogenic calorimeter

16th international workshop on the Identification of Dark Matter
Zaragoza, Spain

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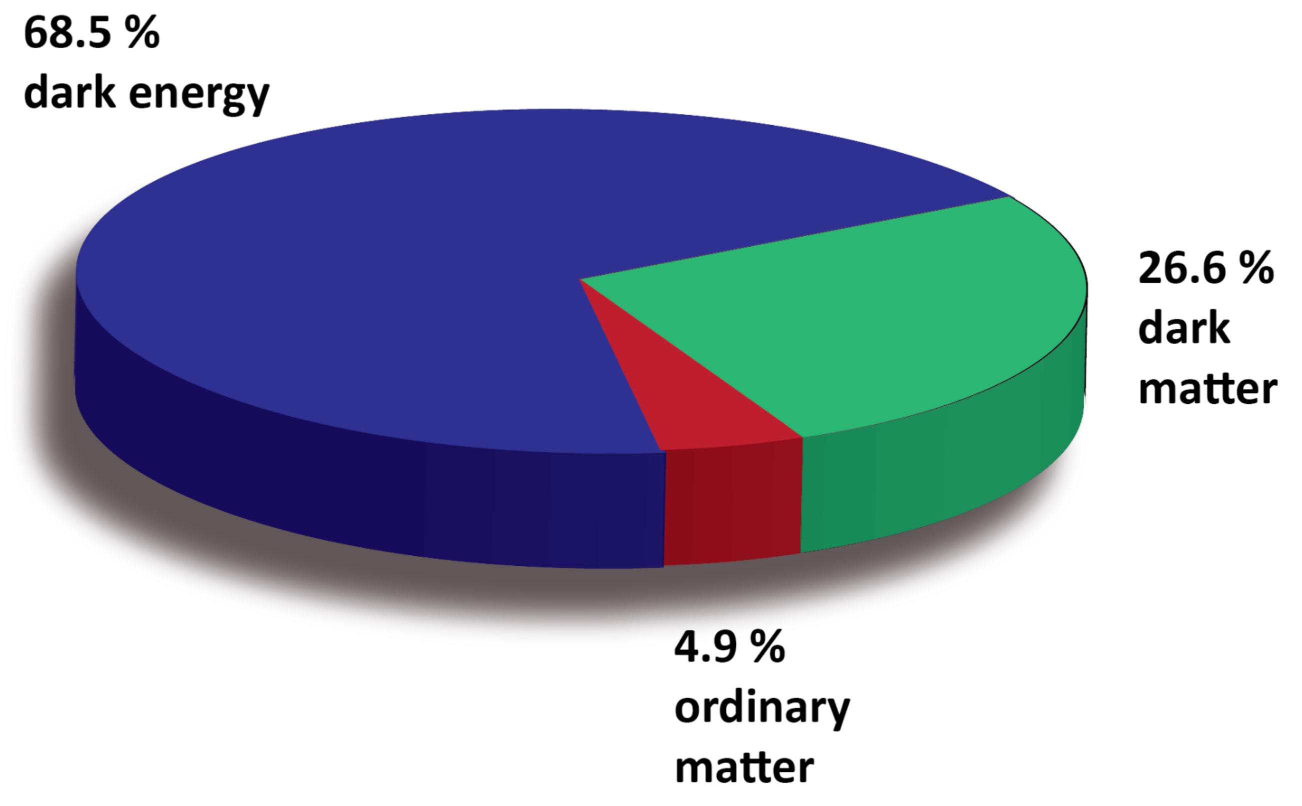
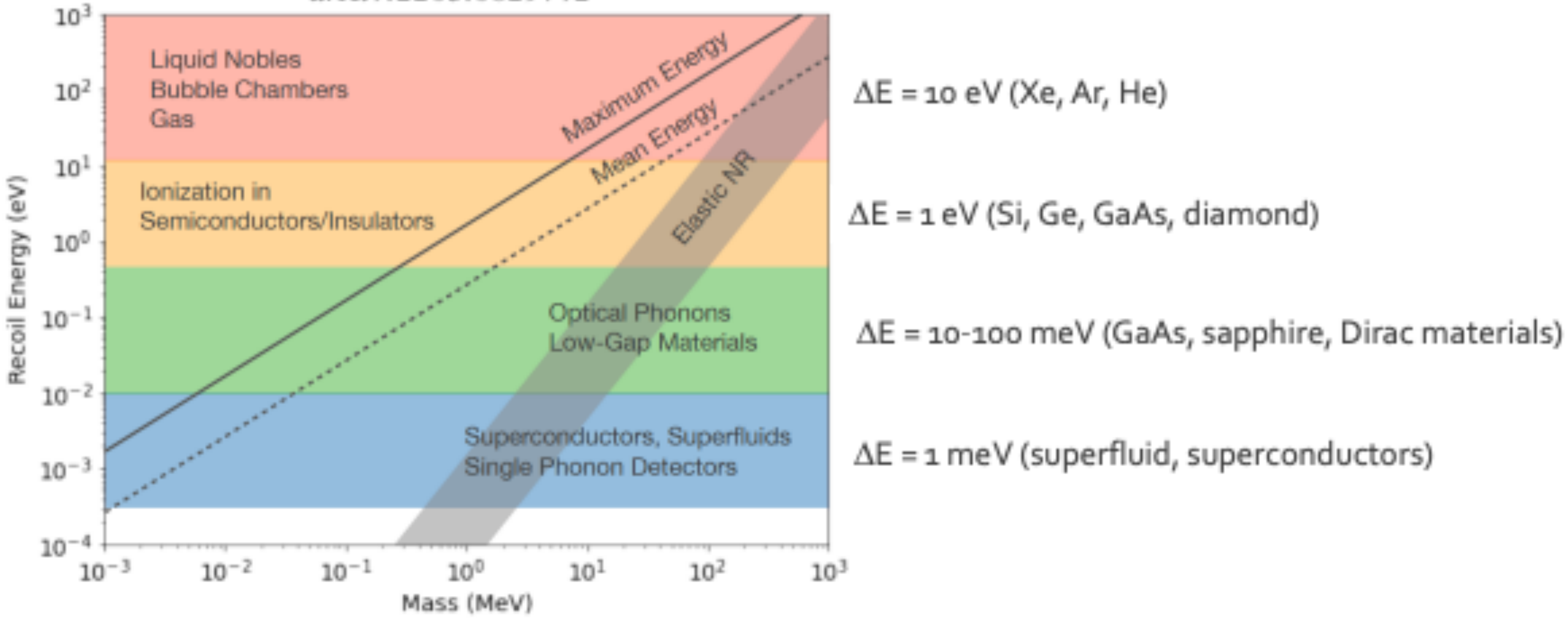
We have been talking about dark matter all week

And dark matter candidates

- Most of the universe is made of dark matter and dark energy
- Search for DM particles with ordinary matter via observables
- Direct detection observable
    - Annual modulation
    - Directionality
    - **Event rate**
        - **Elastic DM- nucleus scattering (NR)**
        - **DM-electron-scattering (ER)**



arXiv:2203.08297v2



What is DAREDEVIL?

DARk-mattER-DEVIces-forLow-energy-detection

- Goal: develop a detector able to probe dark matter candidates below 1 GeV
- Construction and characterization of low temperature calorimeters prototypes with low threshold and high resolution
- Funded by the Italian research ministry (PRIN 2022) involving 5 research units

INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso

GRAN SASSO SCIENCE INSTITUTE

CNR SPIN

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Detector production, testing and data analysis.

Materials and solid state modelling and simulation

TES fabrication

What target for DAREDEVIL?

Many, possibly

DARk-mattEr-DEVIces-for-Low-energy-detection

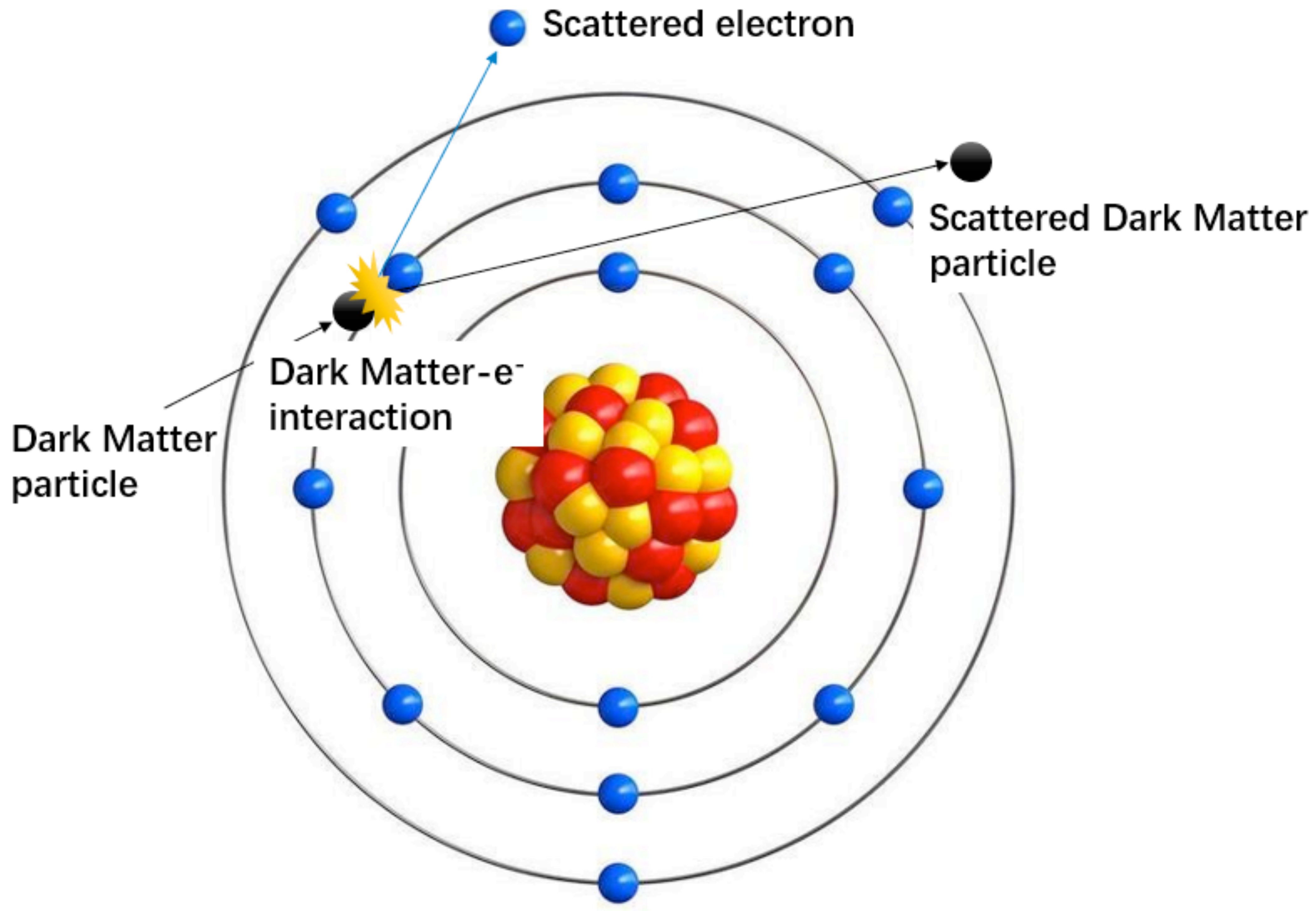
Develop a multi-target experiment to access DM candidates with mass in the sub-GeV range.

Detection channel: scattering on target electrons

Possible target materials:

- Dirac semimetals (ZrTe5)
- Weyl semimetals (CaAuAs)
- Superconductors (Al)
- Small gap semiconductor (GaAs)

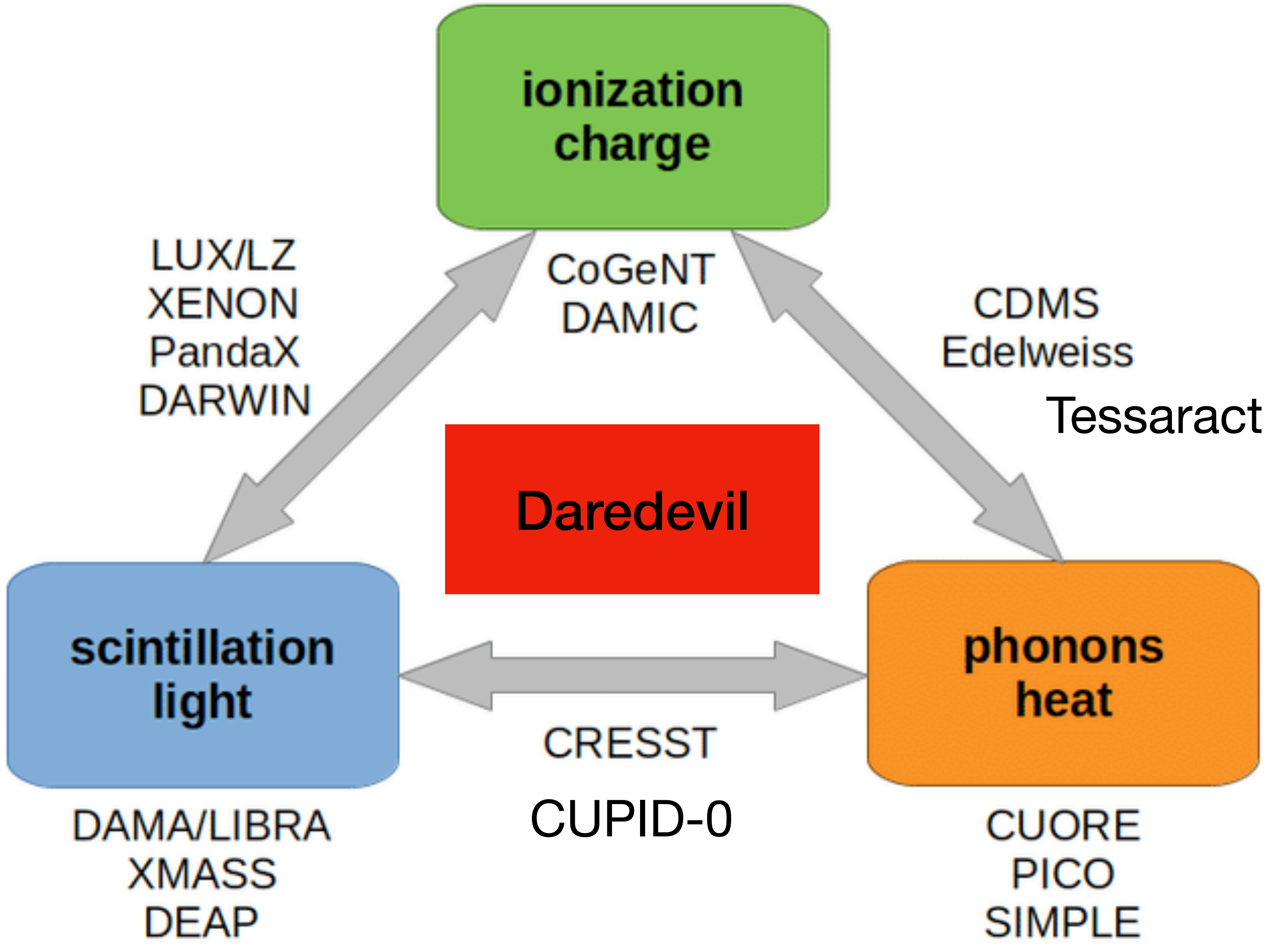
•Different processes will be studied



Detector development in DAREDEVIL

Multi-readout low temperature calorimetry

- Low threshold detection
- Particle identification
    - Radiative -> photons
    - Non radiative -> phonons
    - Charge -> electron- hole pairs

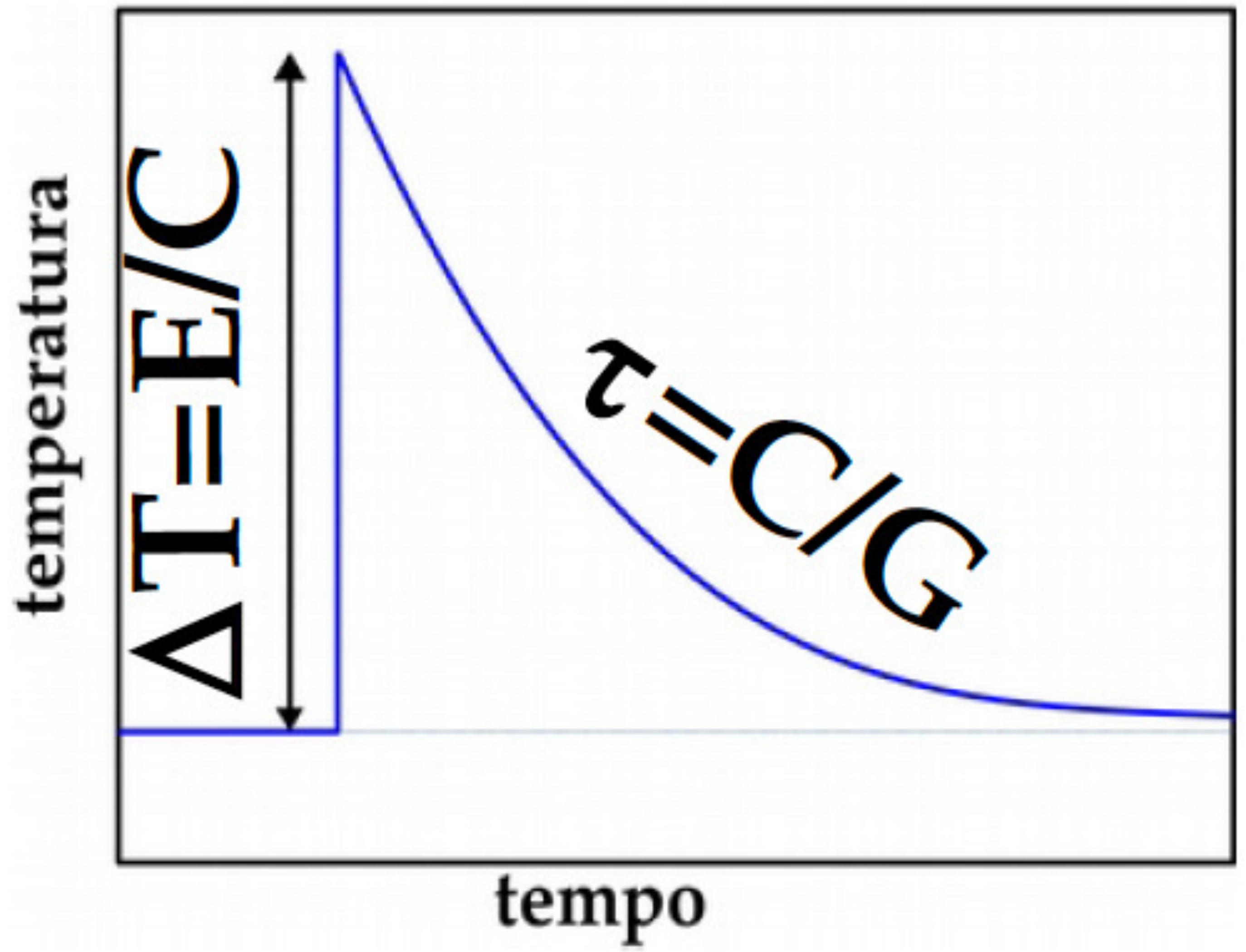


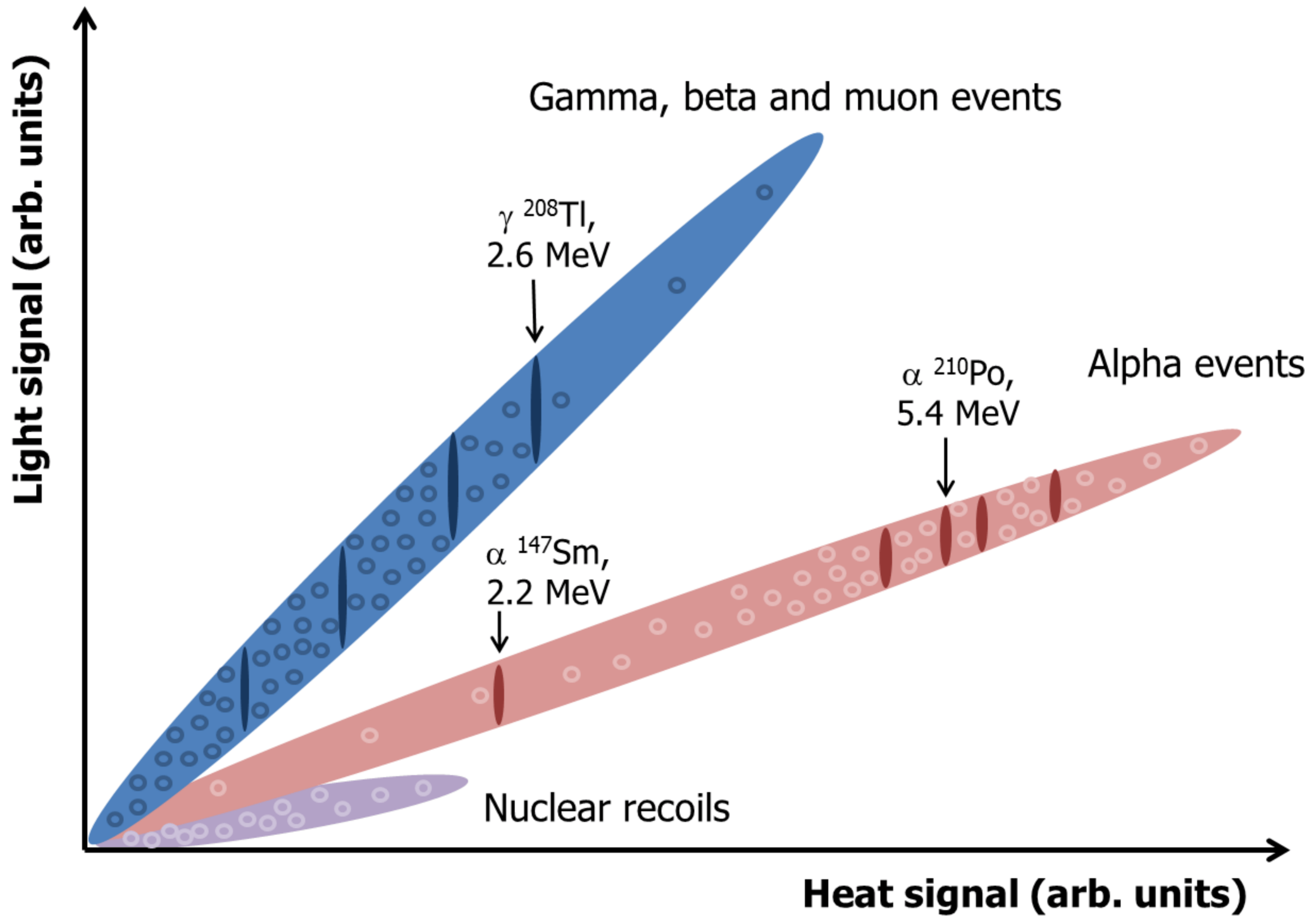
Low temperature calorimetry

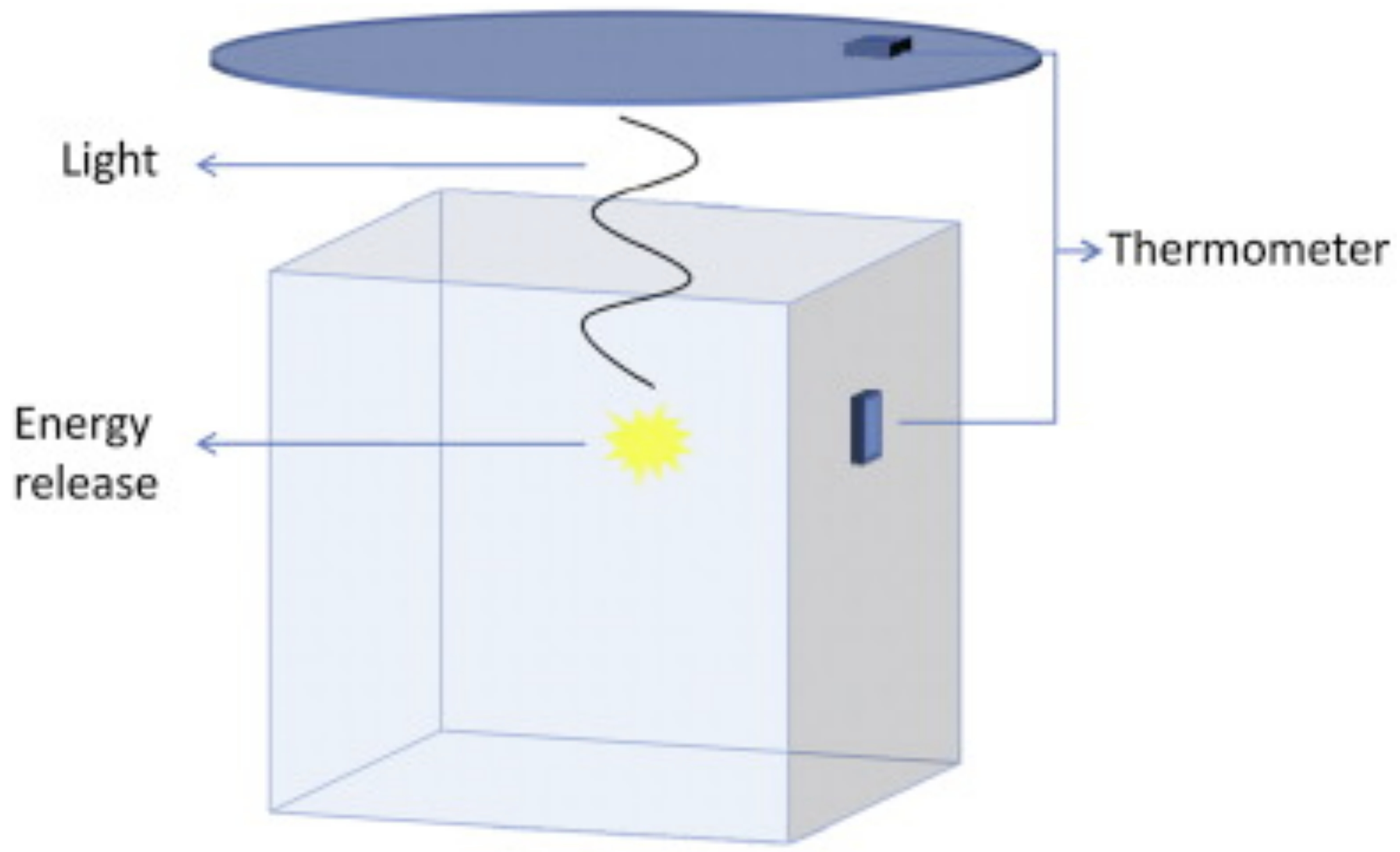
$$C(T) \propto \left(\frac{T}{\theta_D}\right)^3$$

How to measure energy depositions at the mK

- Working at T ~10-20 mK
- Particle identification using dual-readout to detect phonons and light
- Variety of thermal sensors: NTD, TES, MMC

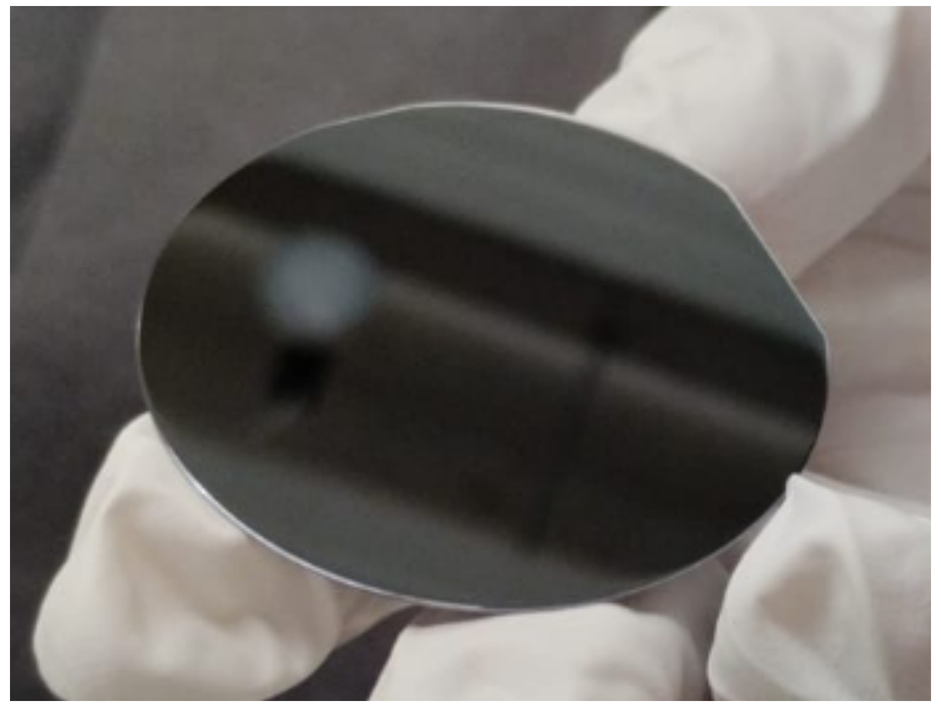




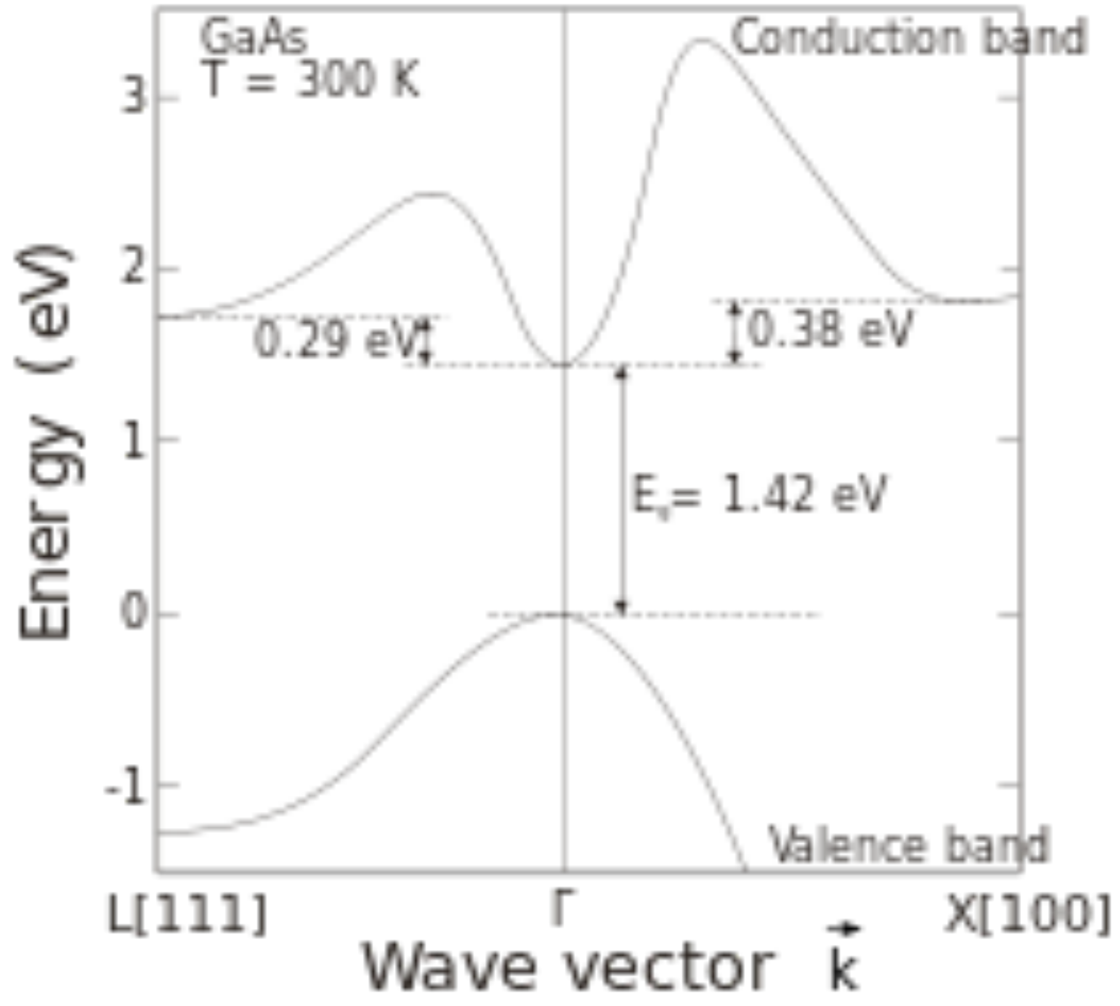


First detector prototype in DAREDEVIL

GaAs case



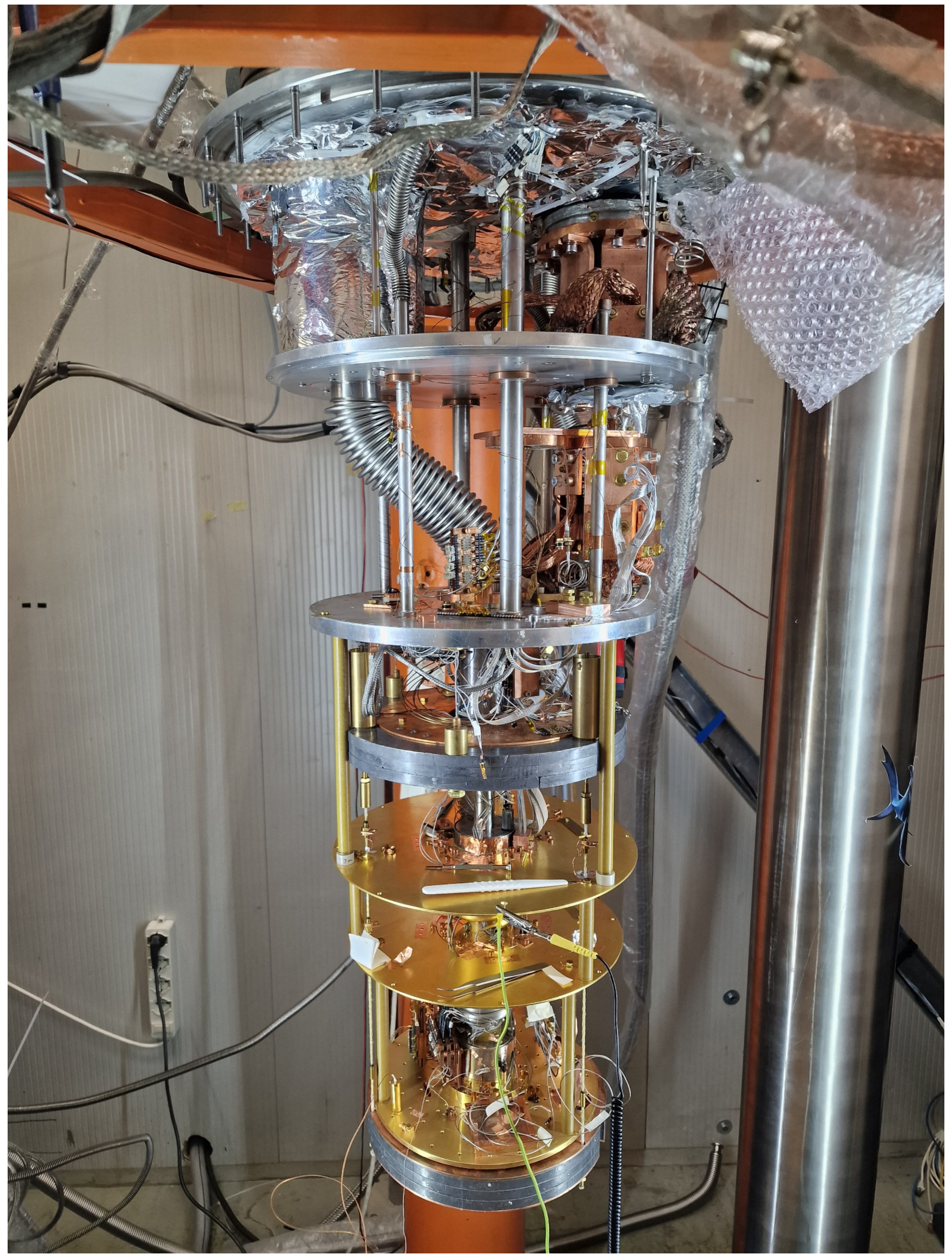
- Scintillator with a gap smaller than NaI or CsI (1.42 eV)
- Polar crystal —> high sensitivity to dark photons absorption
- Ability to tune the gap with dopping
- Semiconductor—> possibility to collect charges
- Previous measurements show also that the LY at 10K can be increased wrt to Si
- GaAs can be used as a low temperature calorimeter and scintillator

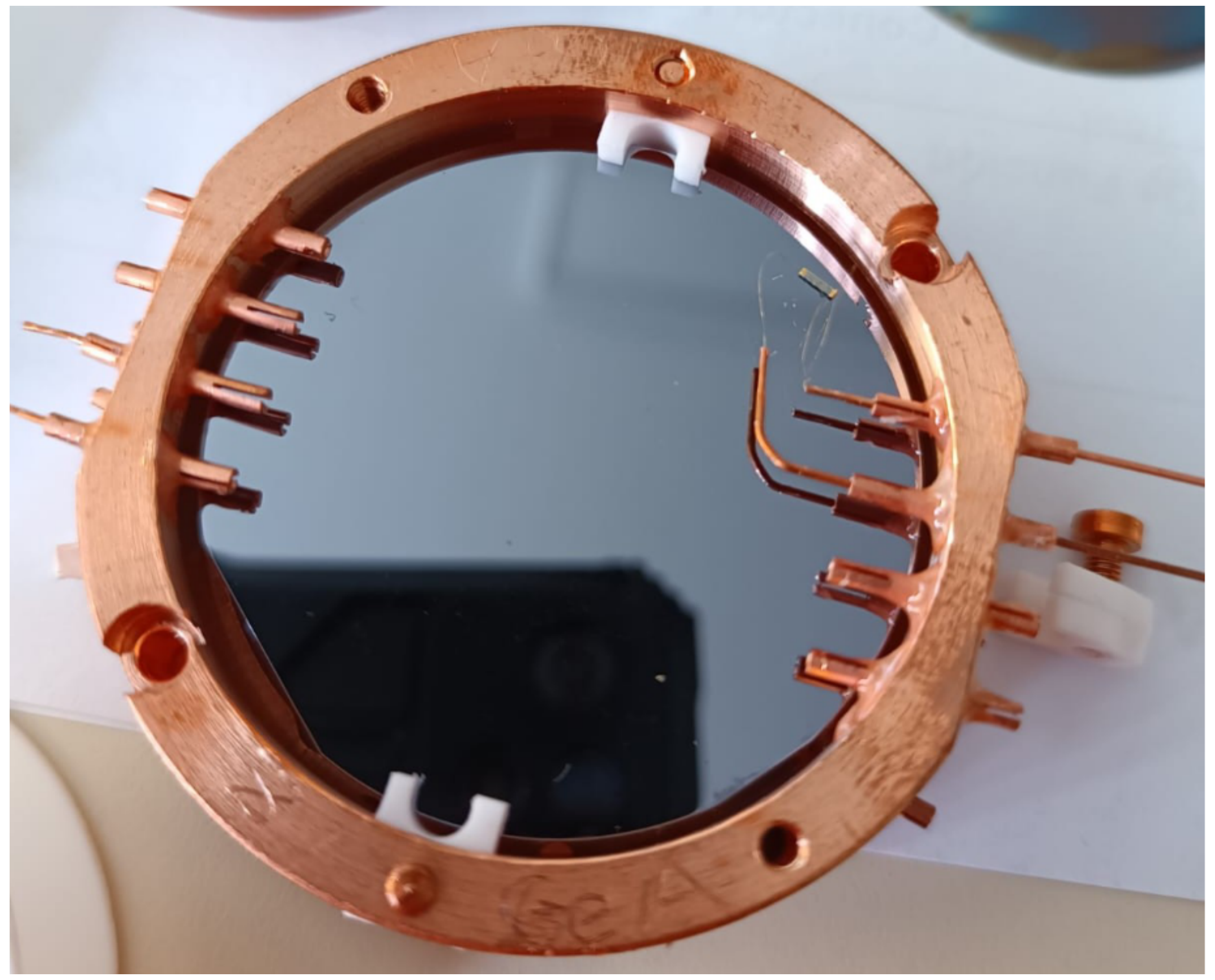


First test with DAREDEVIL

With GaAs

- 2-inch diameter and 0.5 mm thick wafer (5.35 g)
- Equipped with NTD-Ge for phonon sensing
- Mounted a in copper holder
- Calibration sources: Fe-55 and U-238
- PT assisted dilution refrigerator @ LNGS
- Not optimized experimental conditions
  - The cryostat was not designed for low noise measurements





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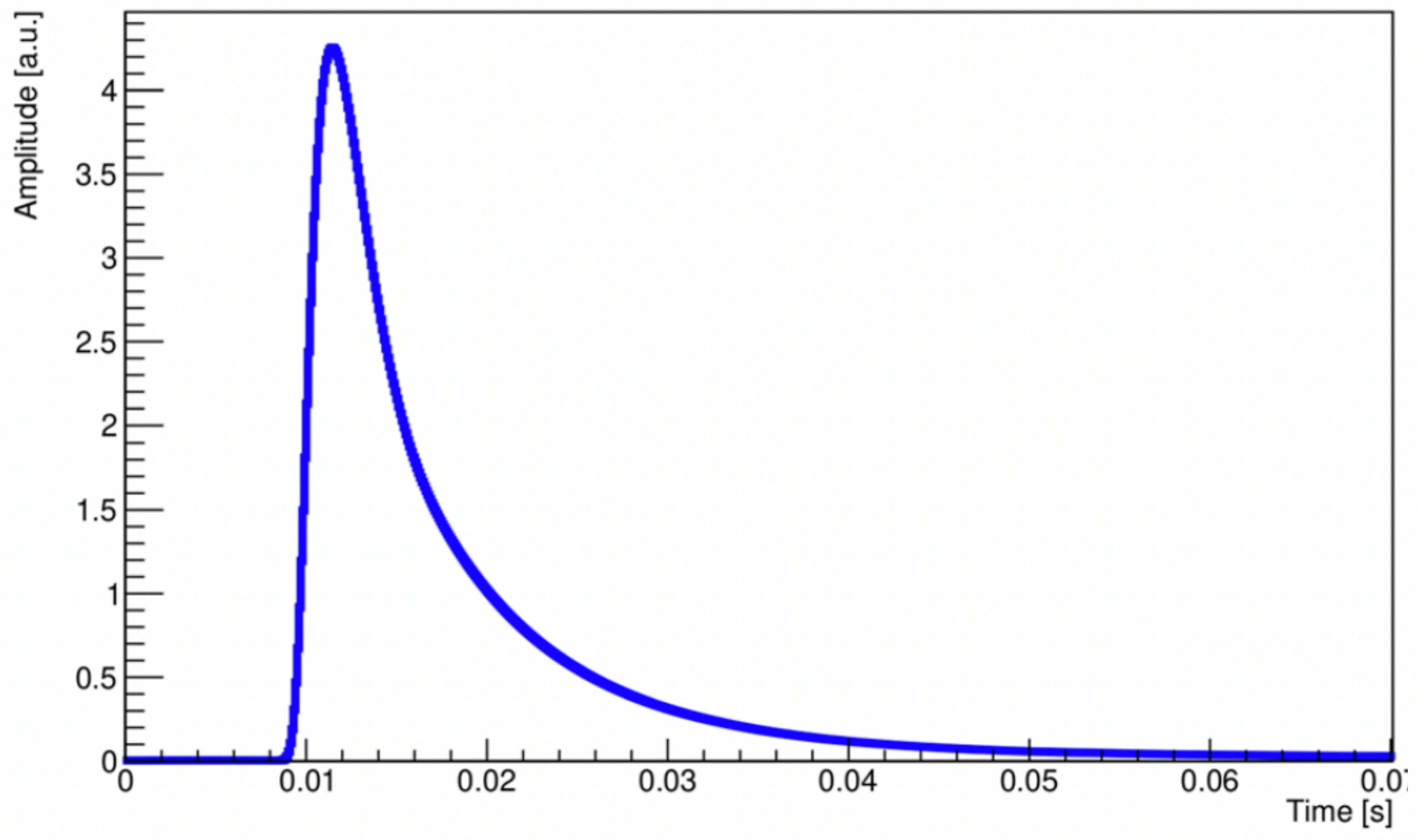
First test with DAREDEVIL

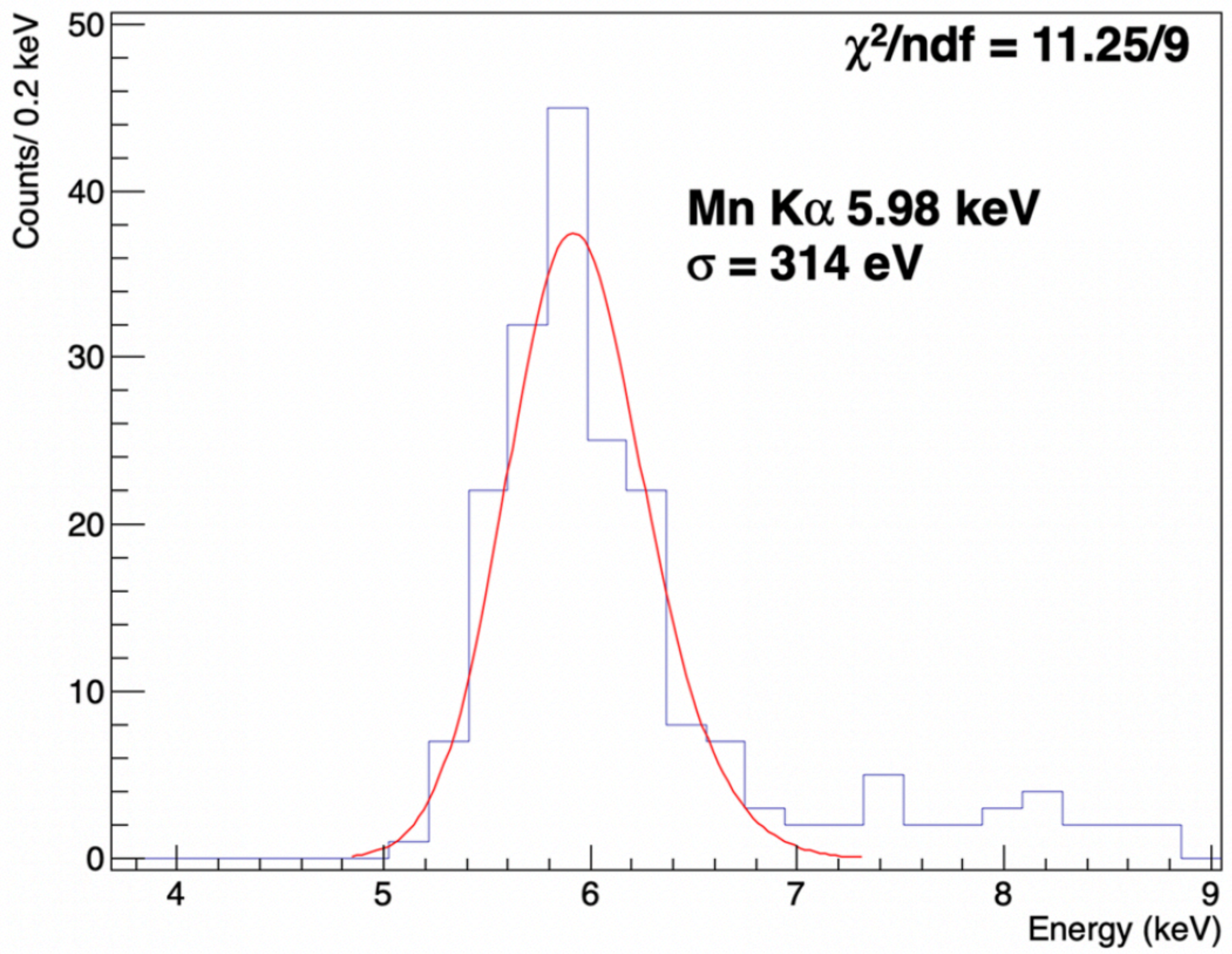
Results for a 12h calibration

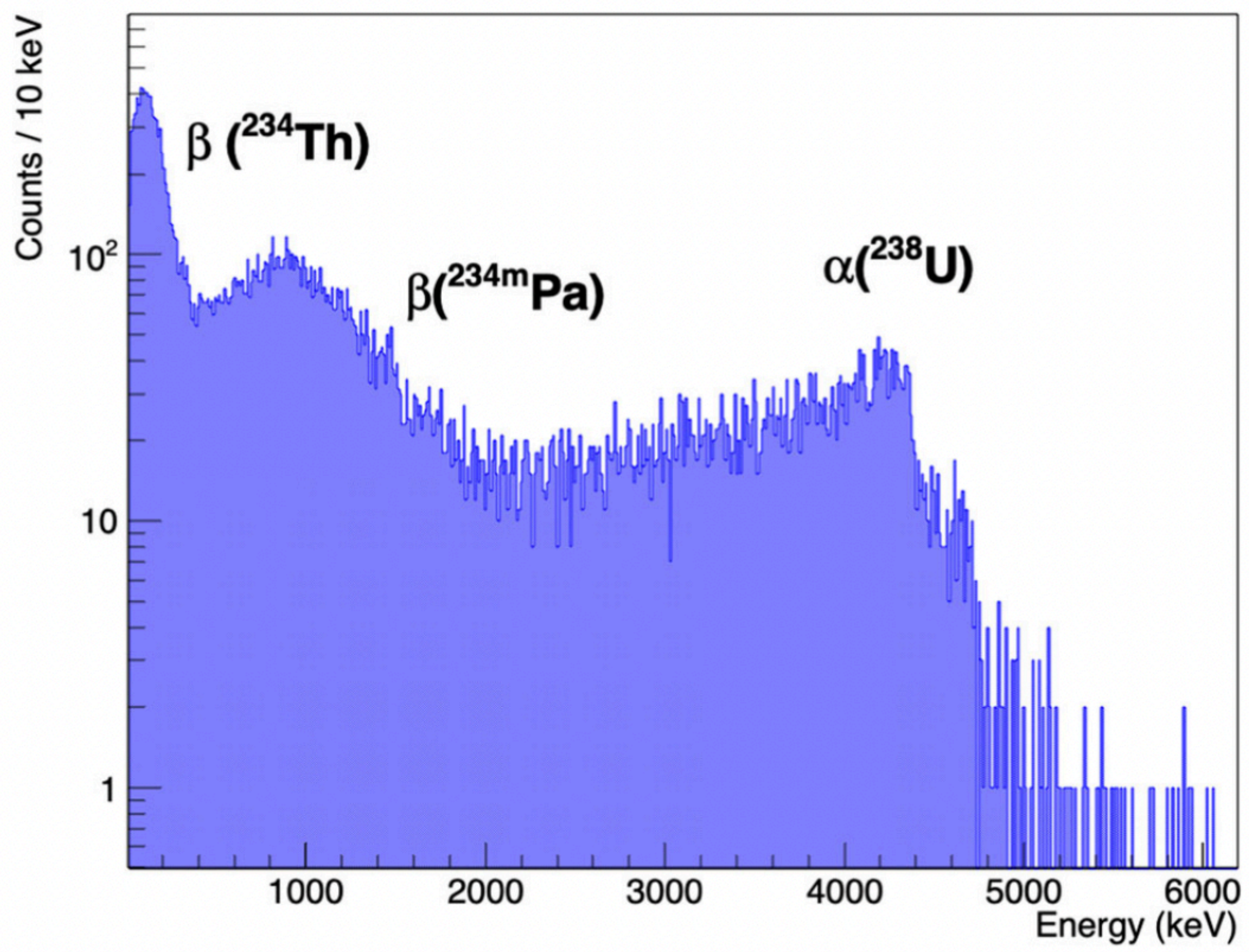
Baseline resolution (RMS) PT off	283 ± 48	eV
Peak σ at 5.9 keV PT off	314 ± 22	eV
Baseline resolution (RMS) PT on	542 ± 6	eV
Peak σ at 5.9 keV PT on	546 ± 21	eV

10.1140/epjc/s10052-024-13123-8

- The data is acquired in stream and triggered offline
- C++ based software to filter the data
- Build the average signal and use of the optimum filter to reconstruct the energy



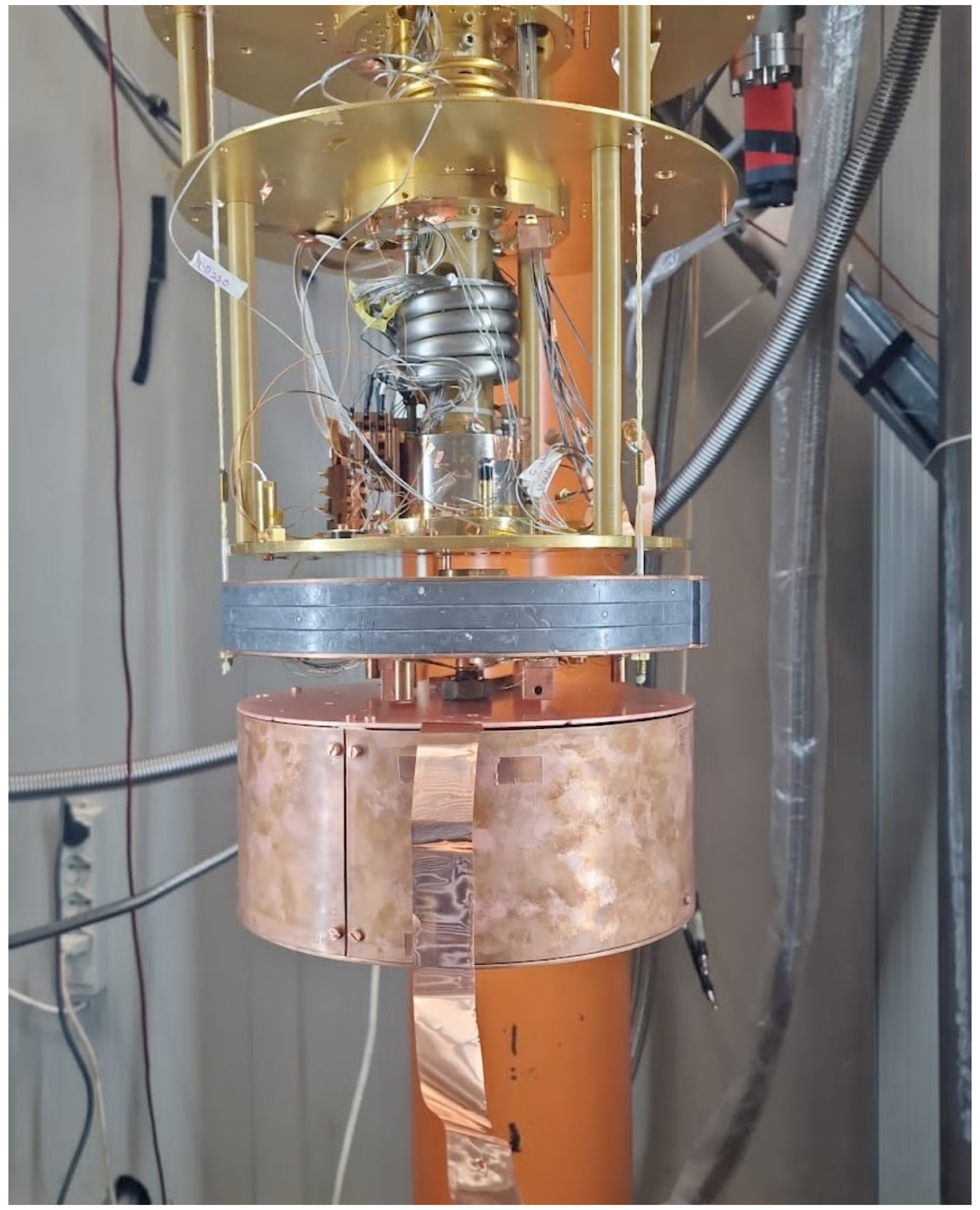


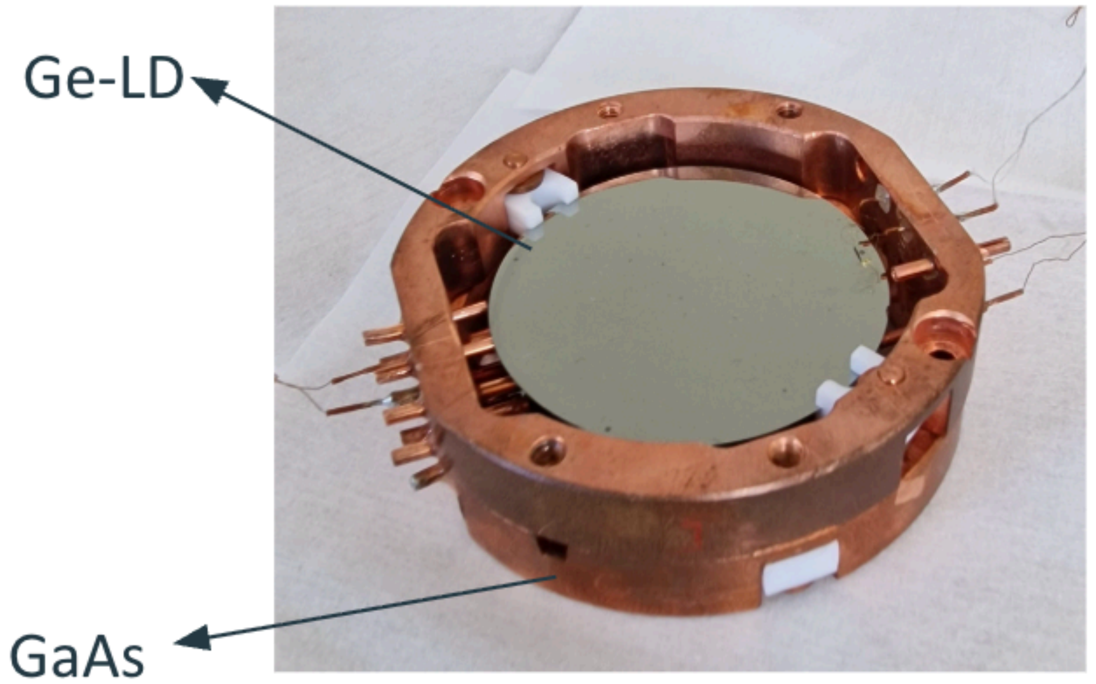


Upgrade of the cryogenic facility

Maybe we can have low vibrational measurements?

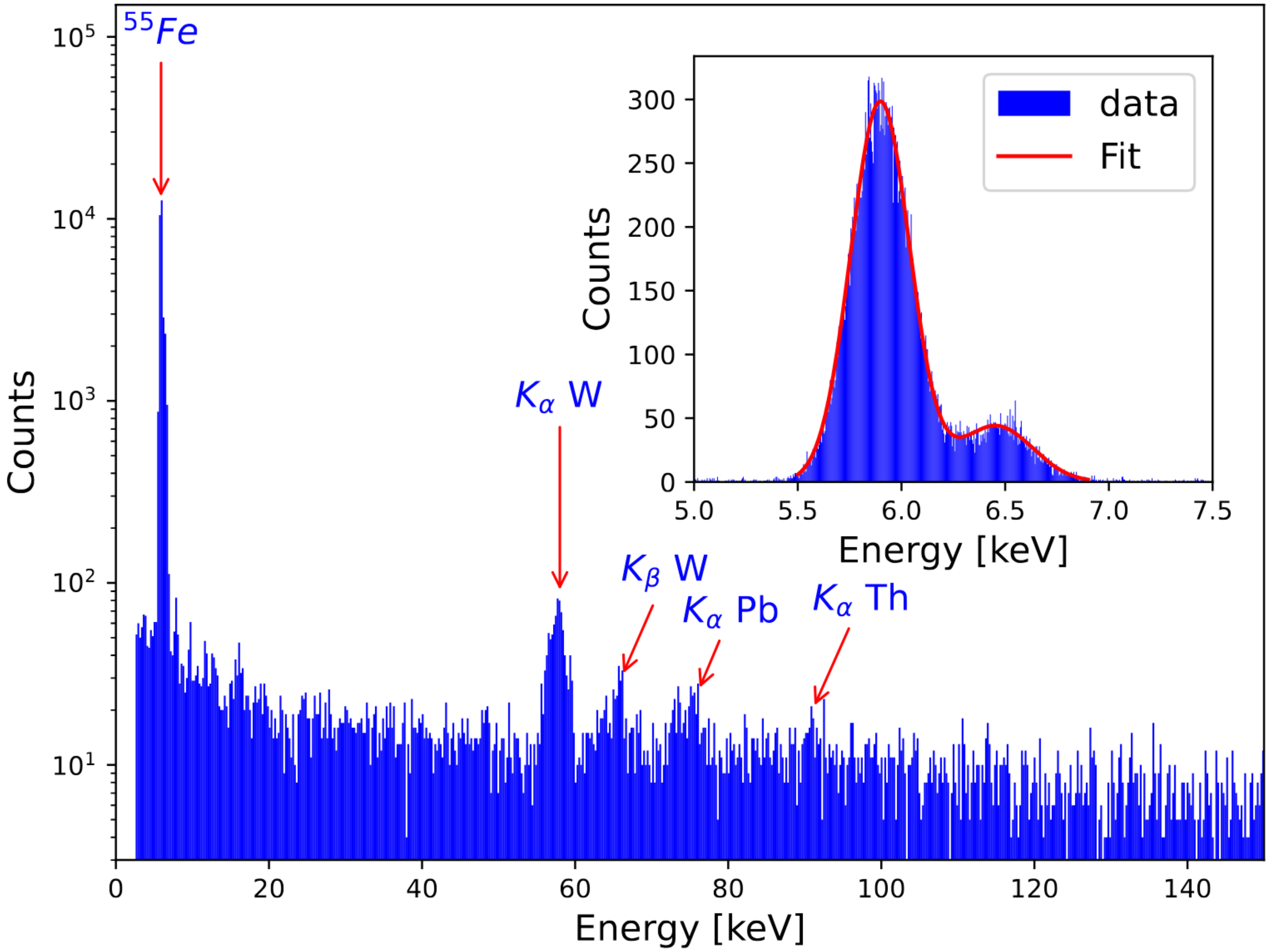
- Cryostat upgrade with a new damping system (new spring and better PT decoupling)
- Use of Fe-55 and U-238 to characterize the LY
- Dual readout detector
    - GaAs: main channel
    - Ge-LD: for scintillation light readout





GaAs as a dual readout calorimeter

Results: heat channel



Baseline resolution (RMS)	121 ± 2	eV
Peak σ at 5.9 keV	140 ± 8	eV

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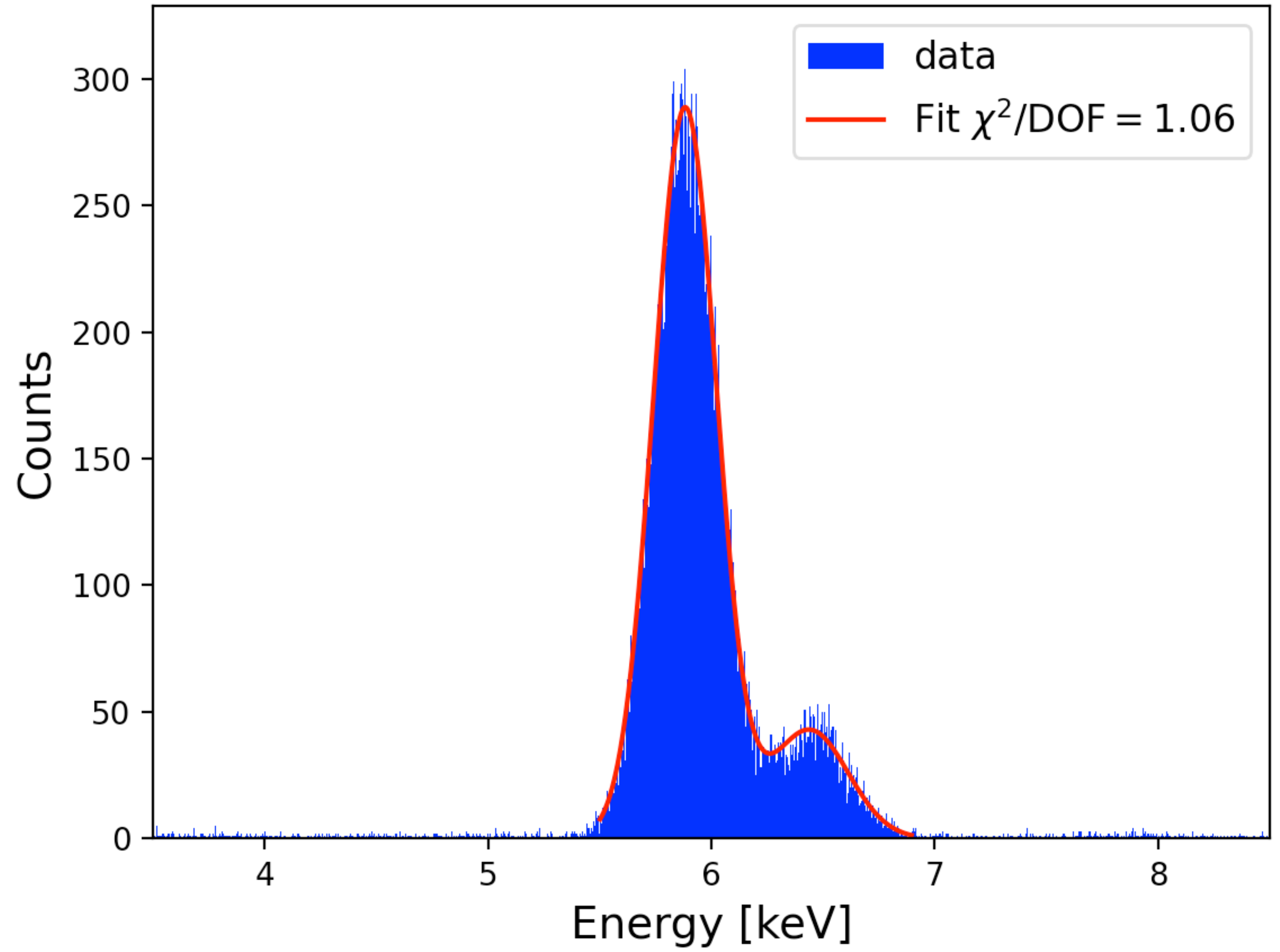
Improved energy resolution after the cryostat upgrade

GaAs as a dual readout calorimeter

Results: light channel

- Signal amplification by applying 130 V using the NTL effect
- Improved baseline resolution (gain ~12)
    - 5 eV with voltage applied



Baseline resolution (RMS)	60.4 ± 0.5	eV
Peak σ at 5.9 keV	102 ± 8	eV

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GaAs as a dual readout calorimeter

Light vs Heat

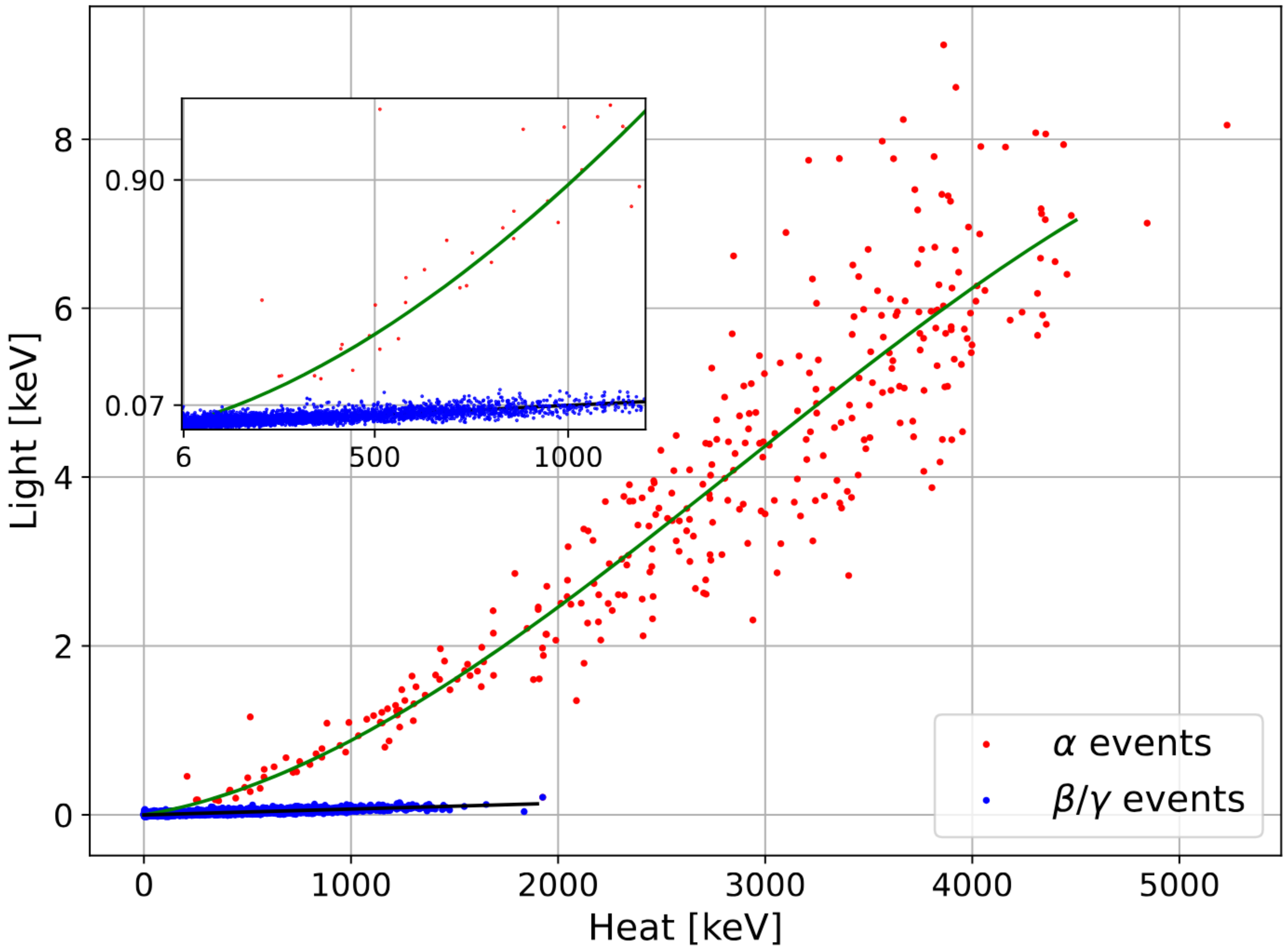
After the calibration of GaAs and Ge-LD:

- For each heat event, the corresponding **light window** was analyzed
- Built the light vs heat scatter plot
- Particle discrimination proven!

2 “Anomalies”:

- **Alpha events** show **higher scintillation light** than beta/gamma events (see ZnSe and ZnO)

Non-linear response is observed in **alpha events.**



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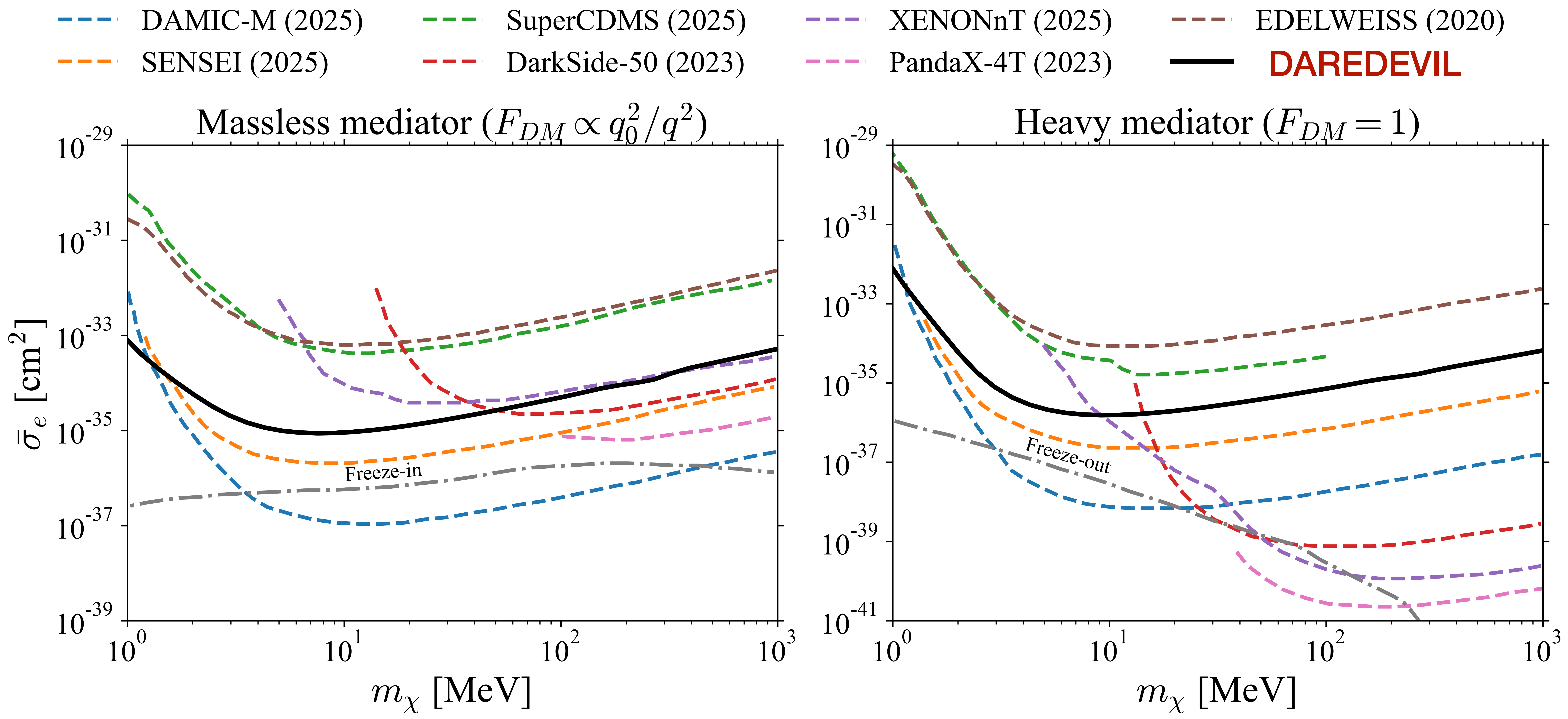
What about sensitivity?

Taking into account the dielectric function of GaAs



Exposure 4 gr.day, threshold ~ 3 eV

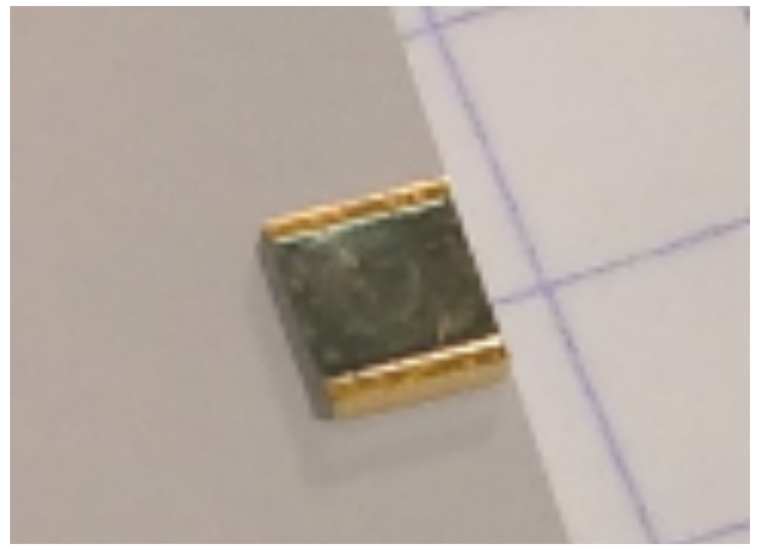
Conclusions and perspetives

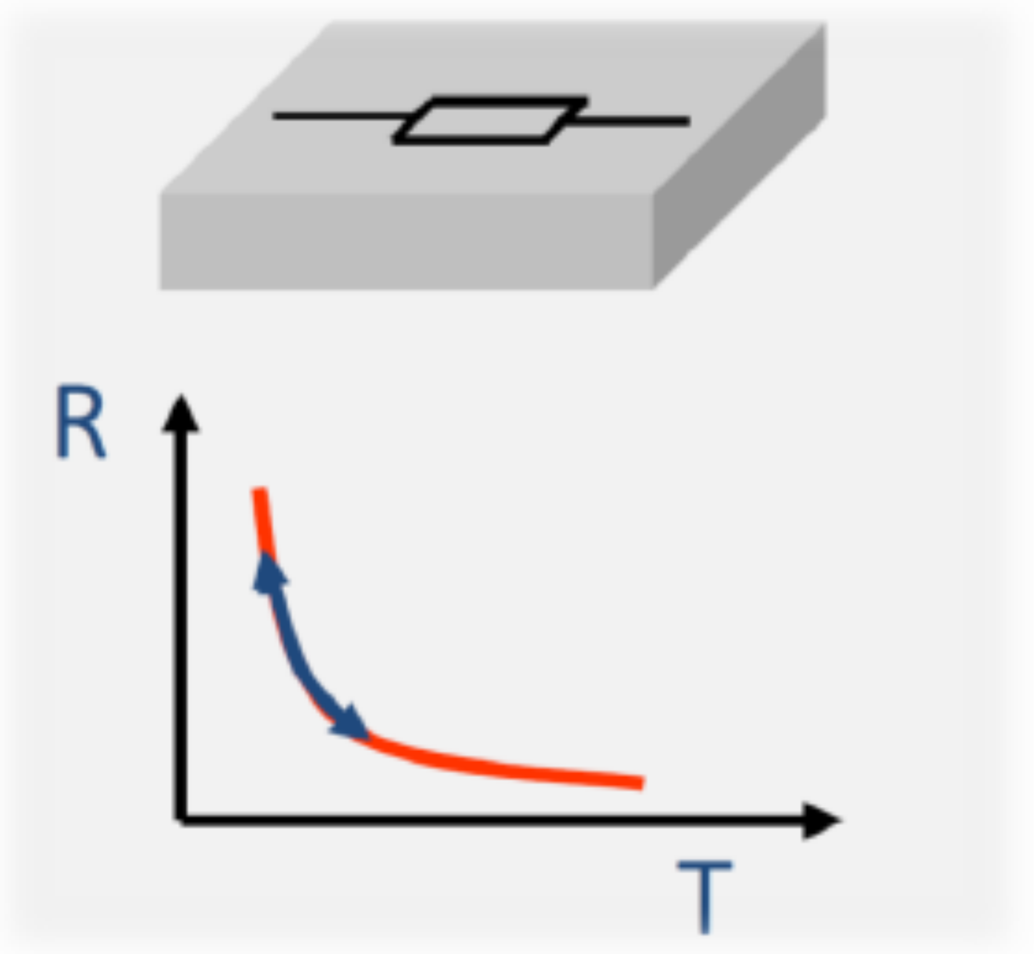
- Focus on the search for **lower-mass dark matter**
- Advancing **detector development** is essential for future **progress**
- Exploration and testing of a **variety of crystals** are crucial
- Synergy with **solid state physics experts**!
- New GaAs-based samples with improved design are in preparation. Stay tuned!
- Currently taking data in low background conditions
- White paper in preparation!

Backup slides

What is a low T calorimeter?

Thermal sensors: Neutron Transmutation Doped Ge





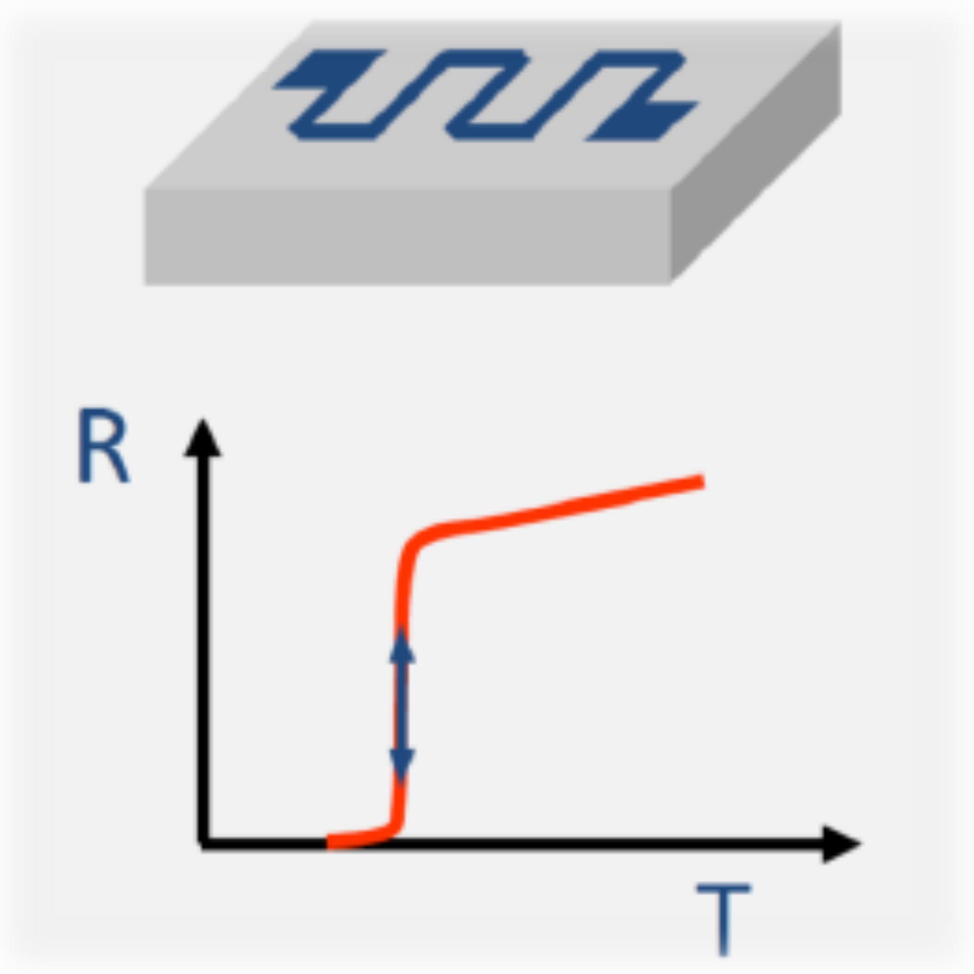
- The absorber needs to have low C
- The rise of T causes a R variation
- A low T, the resistivity of a critically doped semi-conductor below the MIT p = 0.5

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

What is a low T calorimeter?

Thermal sensors: Transistor Edge Sensors

- Superconducting films deposited on the absorber
- Measure an energy deposited as an increase of R
- TES are very sensitive to very small energy deposits
- More sensitive than NTD



Studied materials

- **Polar crystals** are characterized by the presence of a permanent dipole moment. This dipole moment results from an asymmetric distribution of electrical charges.

- **Weyl semimetals** are a class of topological materials that possess Weyl fermions as low-energy excitations and with a nontrivial topological aspects of their band structure.

- **Dirac semimetals** are characterized by their unique electronic properties due to Dirac points where the conduction and valence bands touch at discrete points.

Scintillation light from GaAs

Table 3 Light yield values for β/γ and α induced events

	Light yield (keV/MeV) @ 1 MeV
β/γ	0.07 ± 0.01
α	0.9 ± 0.2

(a)