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Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

FIRST MEASUREMENT OF GaAs AS A SCINTILLATING CALORIMETER
DAREDEVIL PROJECT

UNIVERSITÀ
DEGLI STUDI
DELL'AQUILA

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

Andrea Melchiorre

on behalf of the Daredevil group

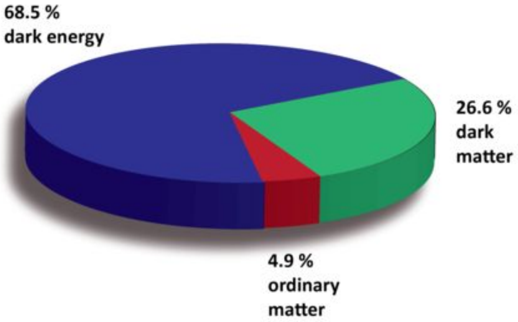
DARK MATTER CANDIDATES AND DETECTION STRATEGIES

Different observation at different scale:

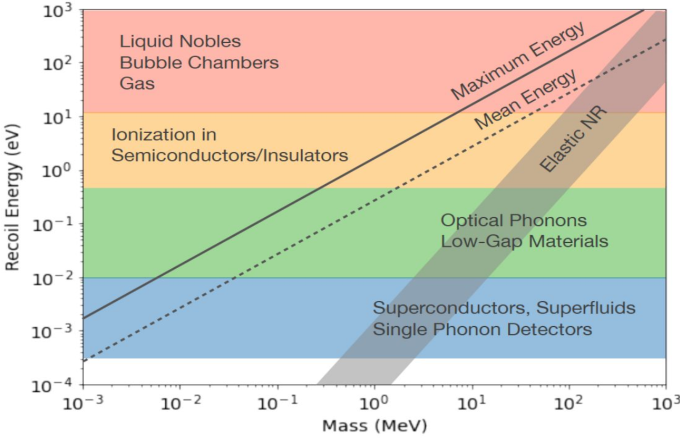
- Rotational curves
- Gravitational lensing
- CMB

Candidates must be:

- Neutral particle
- Cold or not too warm
- Weakly Interacting
- Stable or very long lived



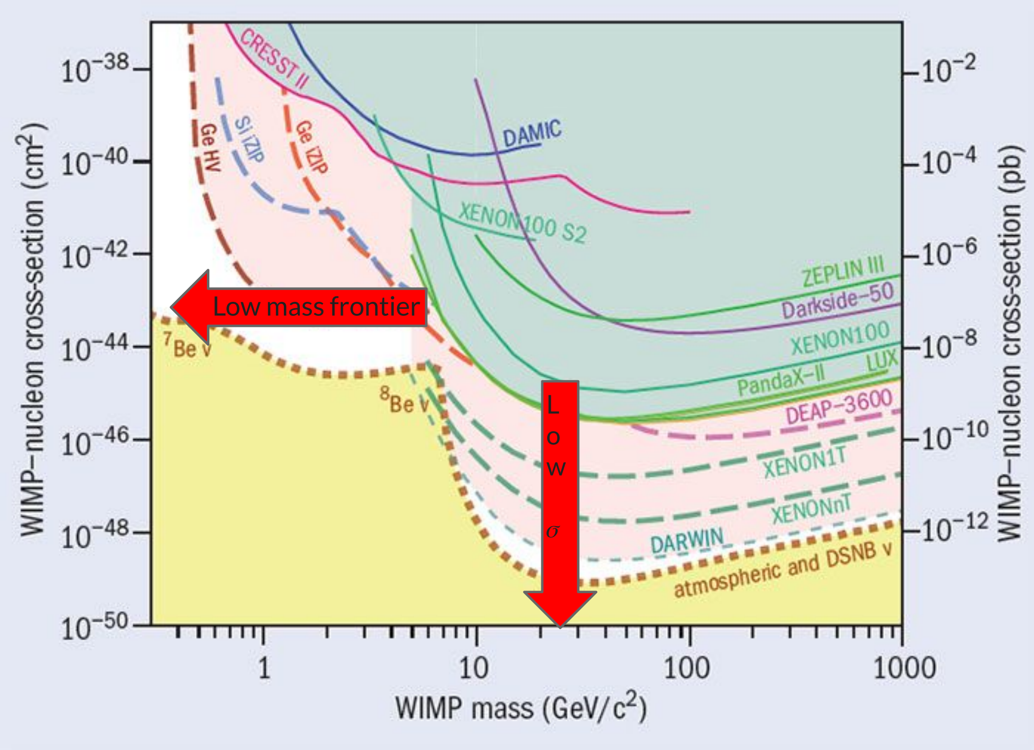
arXiv:2203.08297v2



ΔE = 10 eV (Xe, Ar, He)
ΔE = 1 eV (Si, Ge, GaAs, diamond)
ΔE = 10-100 meV (GaAs, sapphire, Dirac materials)
ΔE = 1 meV (superfluid, superconductors)

BEYOND WIMPS

- Current worldwide experiment focus on WIMP
- The increasing sensitivity has resulted in the exclusion of significant portions of the phase space.
- Future experiments on a multi-ton scale are expected to approach the neutrino floor



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DAREDEVIL

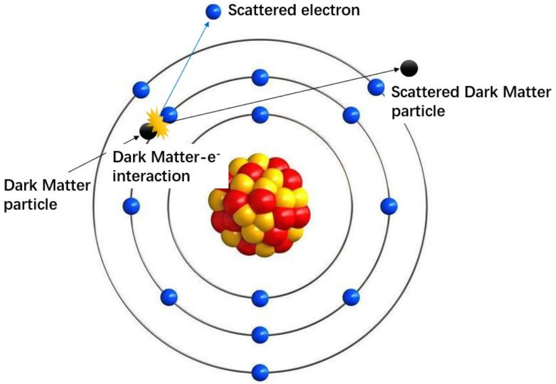
DARk-mattEr-DEVIces-for-Low-energy-detection

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:

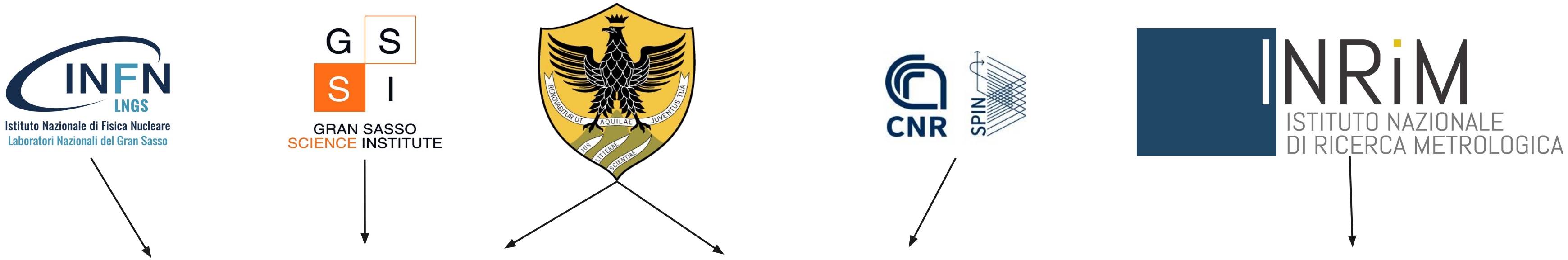
- Dirac semimetals (ZrTe5)
- Weyl semimetals (CaAuAs)
- Superconductors (Al)
- Low gap semiconductor (GaAs)



DAREDEVIL COLLABORATION

Different expertise brought together for new class of detectors.

The team:



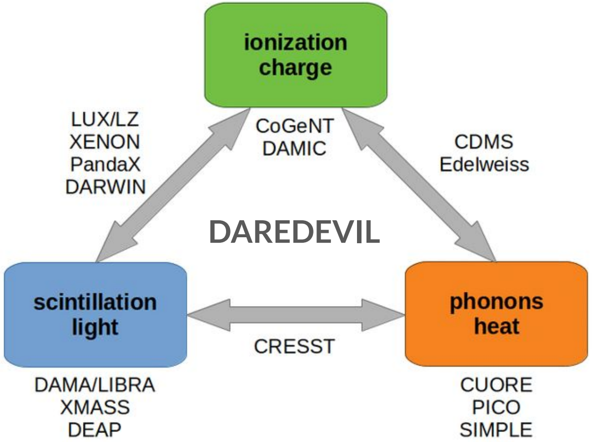
Detector production, testing and data analysis.

Materials and solid state modelling and simulation

TES fabrication

GOAL OF DETECTOR DEVELOPMENT

- Low threshold detection
- Linearity
- Particle identification
- 3 detection channels:
    - radiative - photons
    - not radiative - phonons
    - charge - electron/hole pairs

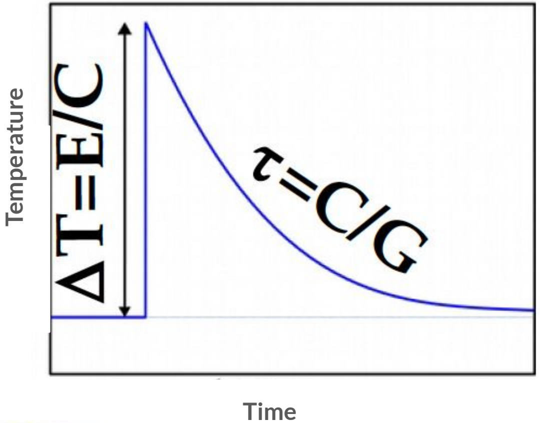


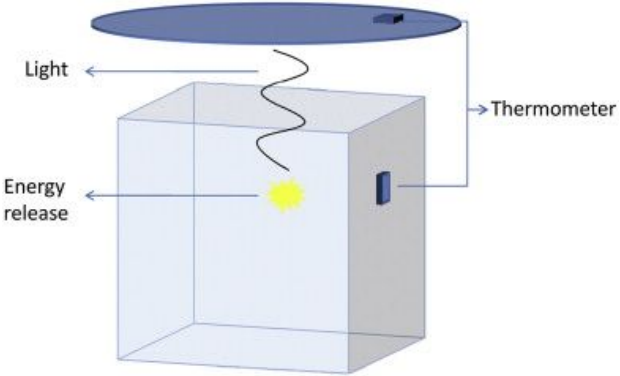
Low temperature calorimetry

LOW TEMPERATURE CALORIMETRY

Detection channels and sensors:

- **Phonon**: sensitive detectors (NTD, TES)
- **Light**: Cryogenic light detector based on photon absorber+phonon sensor
- **Charge**: Position reconstruction





GALLIUM ARSENIDE

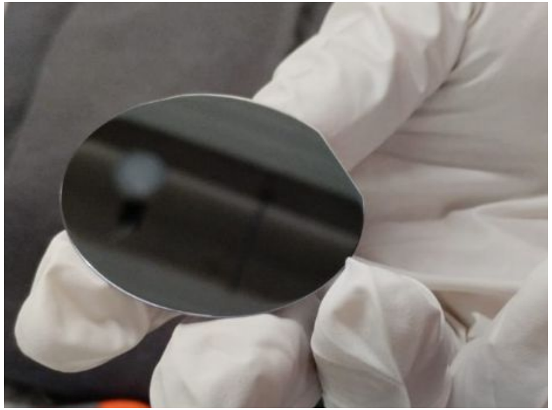
- scintillating material with direct band gap of 1.42 eV that will significantly improve the particle identification capability.

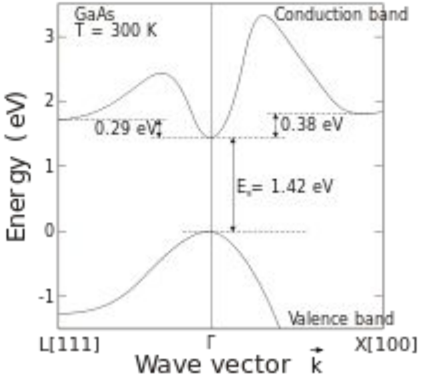
- It is a polar crystal, that would enhance sensitivity to dark photon absorption

- semiconductor material, allowing for controlled and effective charge collection

Thanks to these properties GaAs can be used as:

- Low temperature calorimeter
- Scintillator





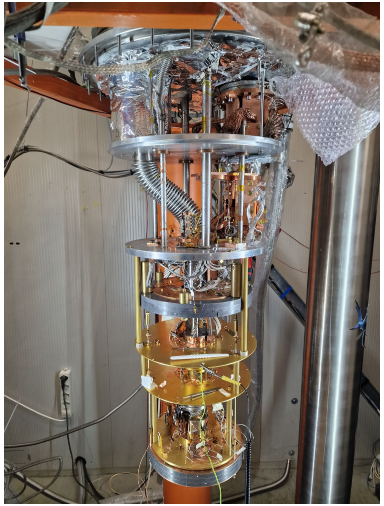
FIRST MEASUREMENT OF GaAs AS A LOW TEMPERATURE CALORIMETER

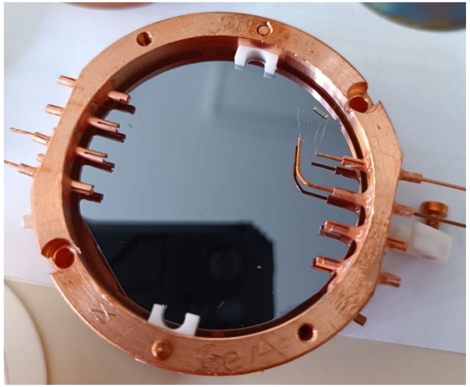
For this first measurement of GaAs as a cryogenic calorimeter, we used:

- 2-inch diameter and 0.5 mm thick wafer (5.35 g).
- The wafer was equipped with a 3 × 0.6 × 0.4 mm NTD (Neutron Transmutation Doped Ge thermistor) - phonon sensor

We conduct the measurement in PT assisted dilution refrigerator in HALL-C @LNGS

For the calibration we used an 55Fe and 238U sources





published on EPJ-C https://doi.org/10.1140/epjc/s10052-024-13123-8

RESULTS

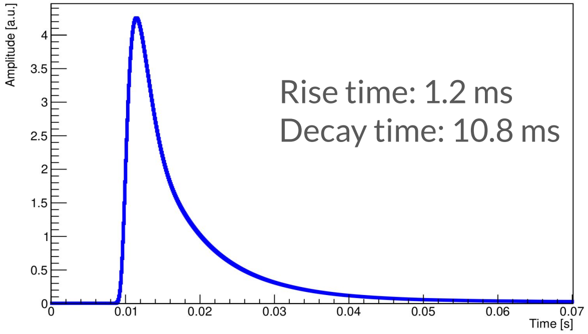
We conducted a 12-hour calibration. From the datastream we identify relevant signal events and several basic parameters are computed:

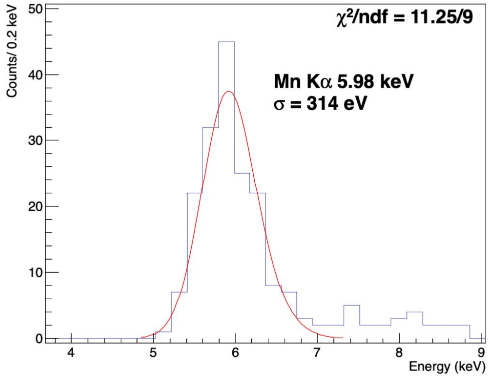
- Baseline level, slope, RMS
- Rise time
- Decay time
- Average pulse

Energy estimator: Optimum Filter - maximises signal to noise ratio

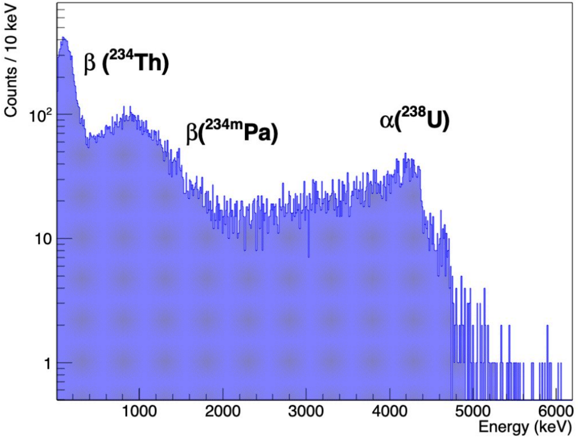
Baseline resolution (RMS) PT off	283 ± 48	eV
Peak σ at 5.9 keV PT off	314 ± 22	eV
Baseline resolution (RMS) PT on	542 ± 6	eV
Peak σ at 5.9 keV PT on	546 ± 21	eV

Average pulse

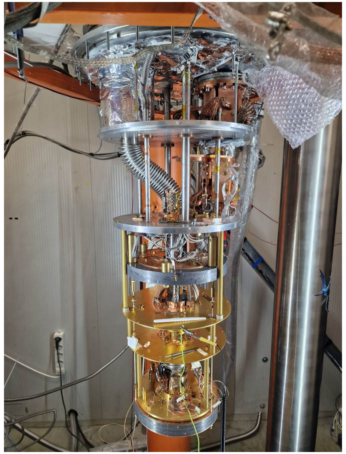

Rise time: 1.2 ms
Decay time: 10.8 ms



Total energy spectrum



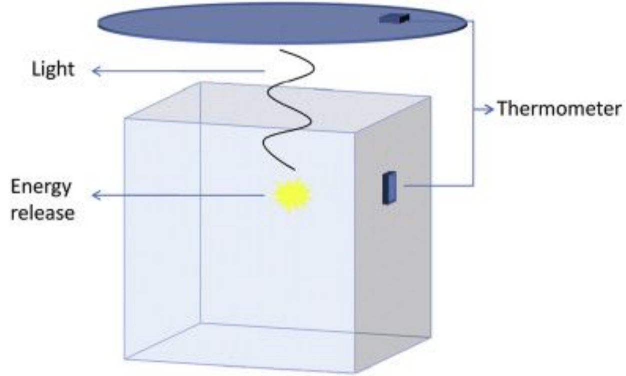
CRYOGENIC FACILITY UPGRADES



Another decoupling spring

Pulse tube mounted on independent support

LIGHT AND HEAT READOUT



Particle interaction in GaAs crystal

↳ Deposits energy in the main absorber

Phonon signal

A portion of the energy is converted into phonons

↳ Detected by an **NTD** attached to the GaAs crystal

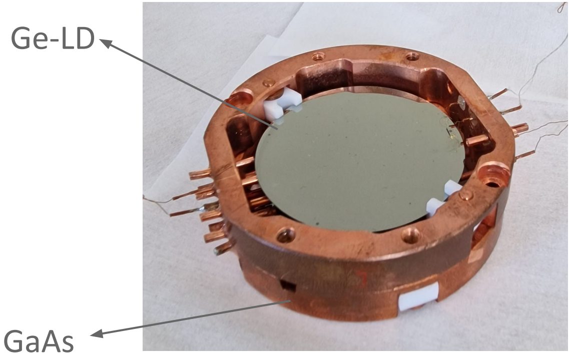
Light signal

The remaining energy is emitted as **light (scintillation)**

↳ Collected by a **secondary calorimeter**: a **Germanium crystal**

↳ Light absorbed in Ge produces a thermal signal

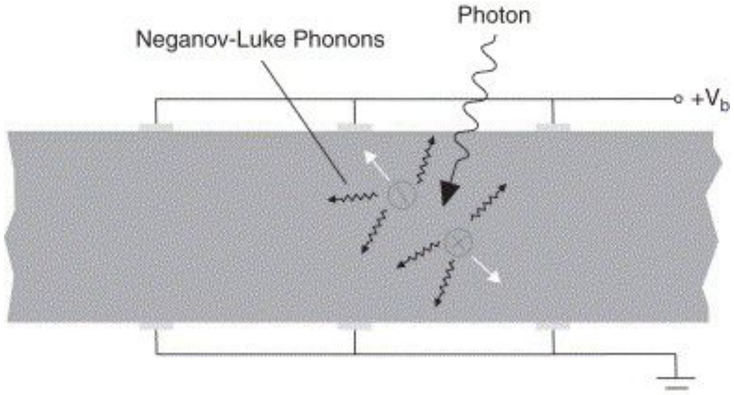
↳ Read out by a second **NTD** on the Ge crystal

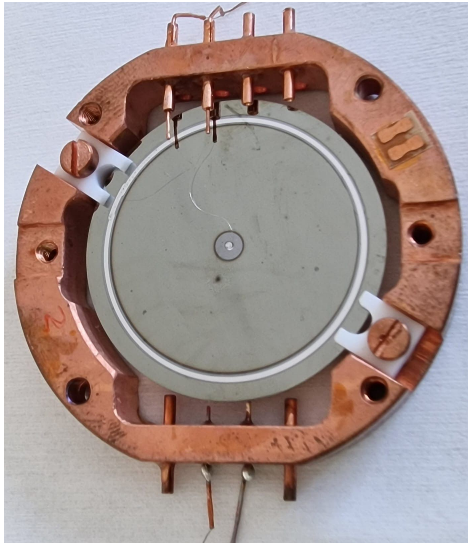


NEGANOV-TROFIMOV-LUKE EFFECT

Amplification of phonon signal with static electric field:

- electron-hole pairs created by interacting photons are accelerated
- during the acceleration they scatter along crystal lattice
- phonon signal will be increased by a factor of 10





EXPERIMENTAL SET-UP

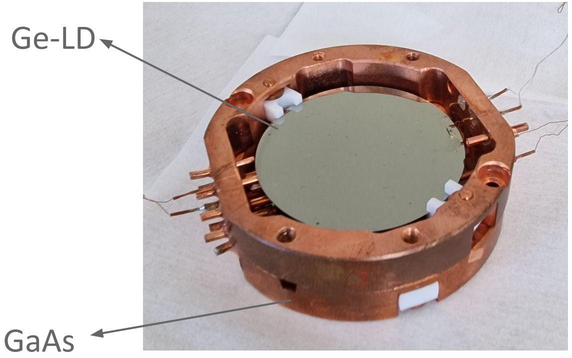
GaAs crystal:

- 2-inch diameter and 0.5 mm thick wafer
- 3 × 0.6 × 0.4 mm NTD
- γ-ray source : Thorium tungstate (74W and 90Th) wire and 55Fe
- α source 238U

Ge-LD

- 2-inch diameter and 0.5 mm thick wafer
- 3 × 0.6 × 0.4 mm NTD
- 55Fe source for the calibration

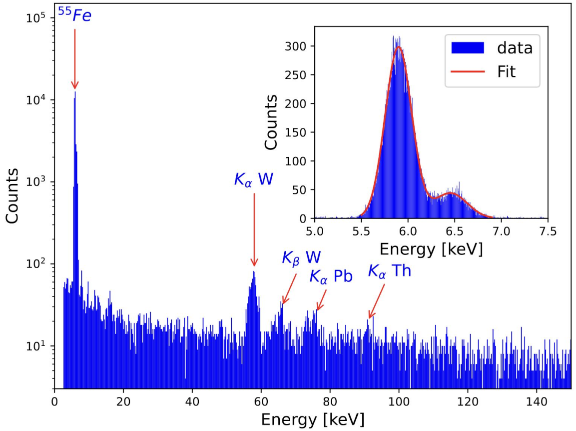
The distance between the two crystals is 10 mm.



DATA ANALYSIS AND RESULTS - GaAs

After upgrades

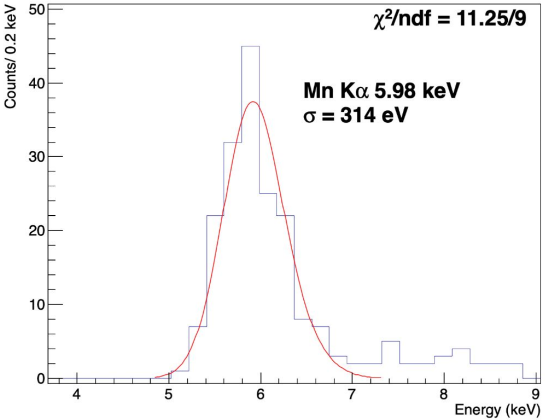
Low energy spectrum



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

Before upgrades

Low energy spectrum



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

DATA ANALYSIS AND RESULTS - Ge-LD

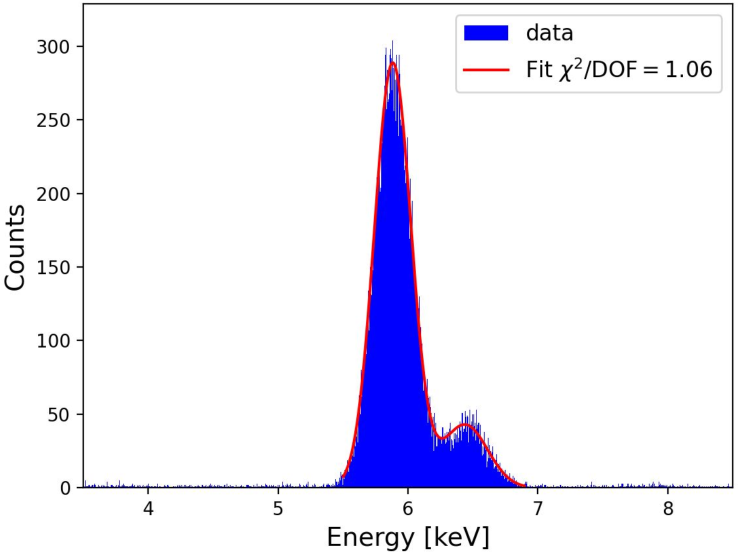
55Fe source used for the calibration of the LD.
After the calibration :

- A voltage of **130 V** was applied to the electrodes
- Gain of ~12

Improved baseline resolution

From **σ = 60 eV** → To **σ = 5 eV**
(w/o NTL effect) (with NTL effect)

W/O NTL-Effect



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

DATA ANALYSIS AND RESULTS

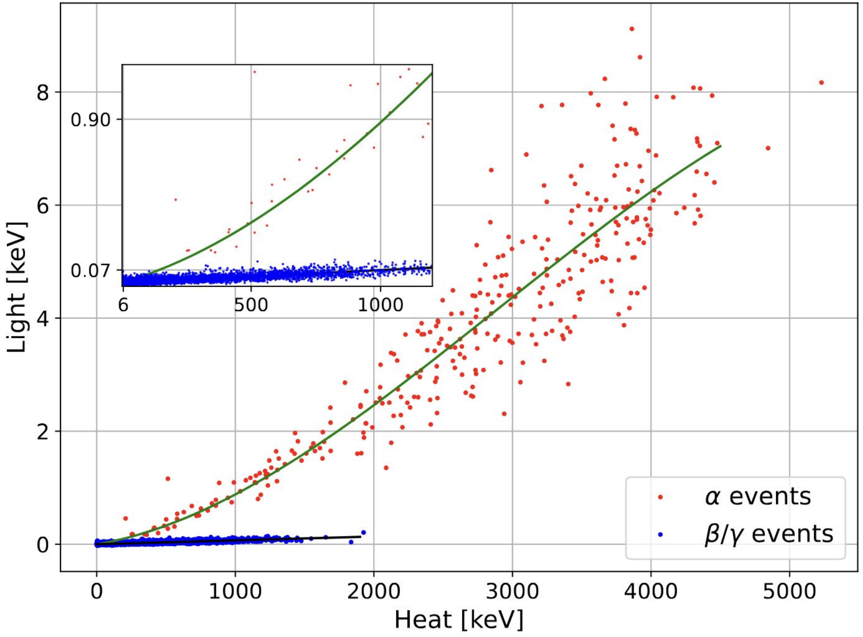
After the calibration of GaAs and Ge-LD:

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

2 "Anomalies":

- **Alpha events** show **higher scintillation light** than beta/gamma events (see ZnSe and ZnO)
- **Non-linear** response is observed in **alpha events.**

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

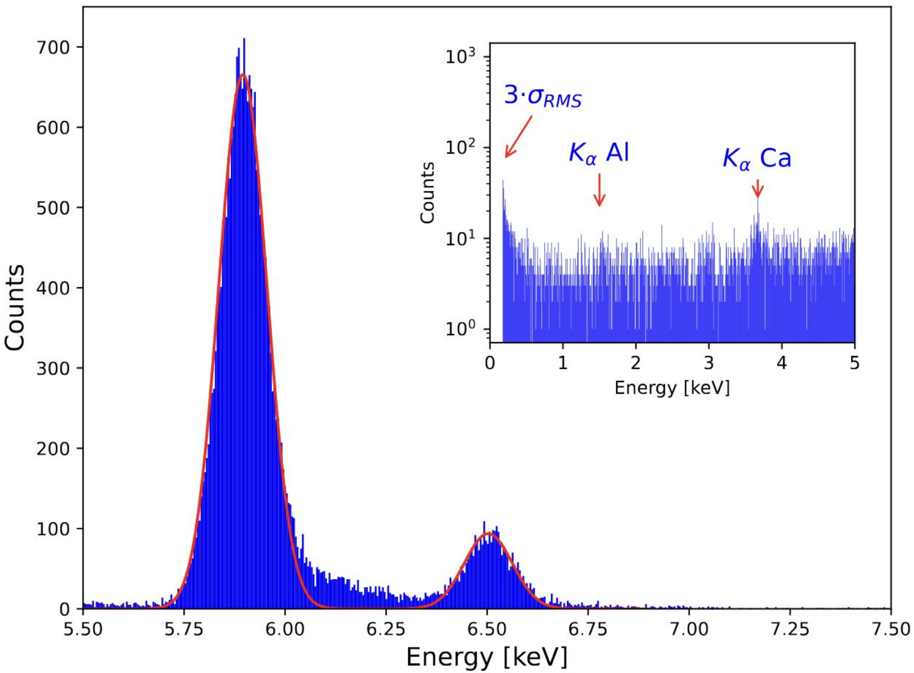


published on EPJ-C https://doi.org/10.1140/epjc/s10052-025-15073-1

NEW GaAs CRYSTAL

The new crystal was measured under identical conditions to the previous sample.

- 2-inch diameter and 0.325 mm thick wafer (3.5 g).
- The wafer was equipped with a 3 × 0.6 × 0.4 mm NTD .
- For the calibration we used an 55Fe.



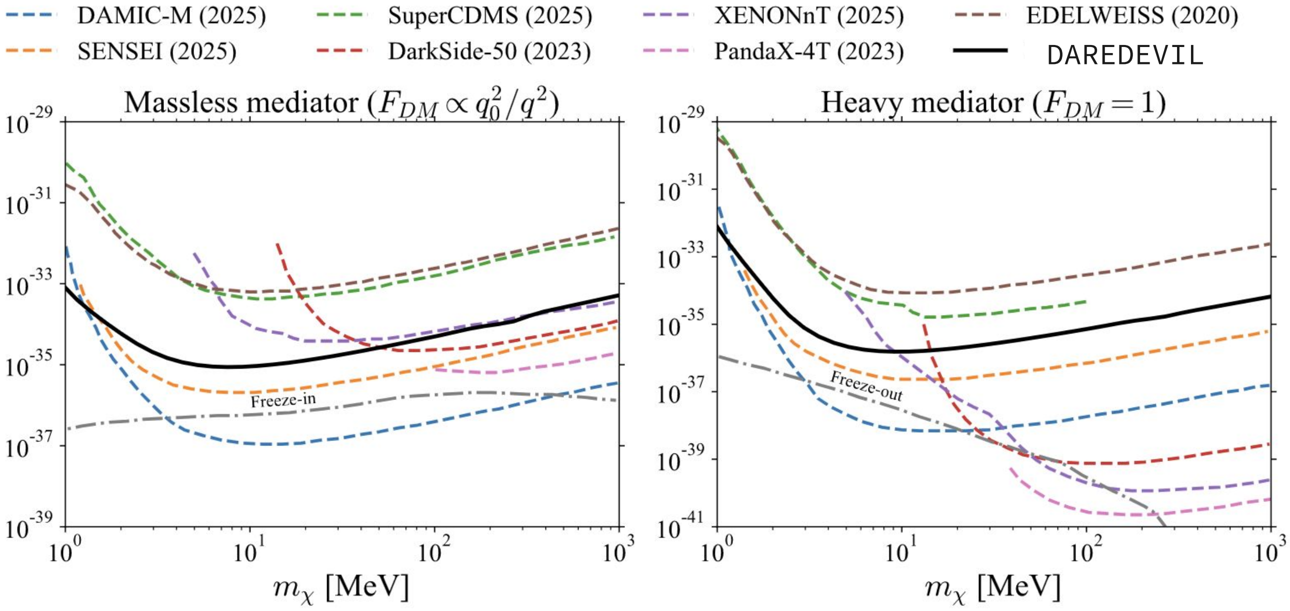
Baseline resolution (RMS)	44.5 ± 0.8	eV
Peak σ at 5.9 keV	59 ± 1	eV

SENSITIVITY OF DARK MATTER

$$\begin{aligned} R_{\mathrm{DM-e^-}} = & \frac{1}{\rho_{\mathrm{T}}}\frac{\rho_\chi}{m_\chi}\frac{\bar{\sigma}_e}{(2\pi)^2\mu_{\chi e}^2}\frac{1}{2\alpha}\int dq\; q^3 F_{\mathrm{DM}}(q)^2 \times \\ & \times \int d\omega\; \overline{\mathcal{W}}(q,\omega)\;\eta(v_{\min})\;; \end{aligned}$$

Sensitivity projection for DM-e scatterings in GaAs, was calculated:

- Taking into account the dielectric function of GaAs
- Background-free experiment
- 90% C.L.
- Exposure: 40 g day
- Threshold: $2E_{\mathrm{gap}} = 2.84$ eV



CONCLUSION AND PERSPECTIVES

- **Cryostat upgrades successful**
  ⤷ GaAs detector threshold improved from 1.5 keV to 360 eV

- **First demonstration of particle discrimination in GaAs via light yield**

- **New GaAs crystal further improved analysis threshold**
  ⤷ from 360 eV to 133.3 eV

- **Ongoing background data-taking campaign**
  ⤷ detector currently running without calibration/source to assess intrinsic background levels

- **Next goal: reach few-eV threshold**
  ⤷ Use Transition Edge Sensors (TES) as thermal sensors

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THANK YOU FOR YOUR ATTENTION

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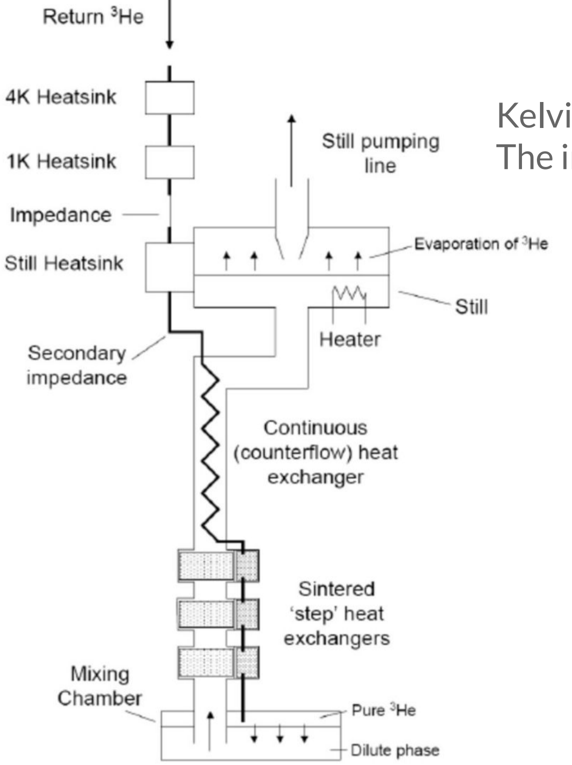
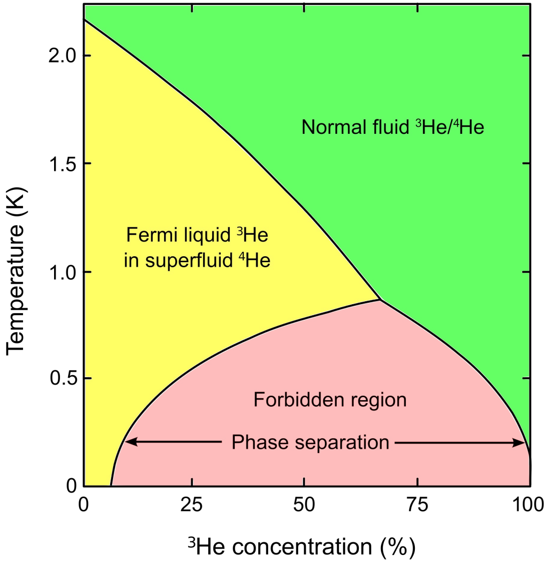
DILUTION REFRIGERATOR



Kelvin temperature is easily reached with Liquid He or Pulse tubes
The interesting part is from K to 0.01 K: dilution mechanism

- 4He (Bose) / 3He (Fermi) mixture
- Phase separation below 0.87 K
  - Phase rich in 4He
  - Phase rich in 3He
- Inside the mixing chamber, the ^{3}He flows from the concentrated phase to the dilute phase
- The ^{3}He then leaves the mixing chamber and enters the still



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.

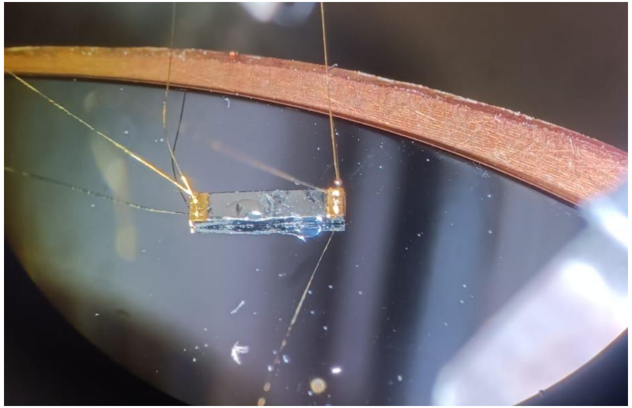
- **Weyl semimetals** are a class of topological materials that possess Weyl fermions as low-energy excitations and with a nontrivial topological aspects of their band structure.

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

Neutron Transmutation Doped Thermistors (NTD):

Highly resistive devices with:

- Neutron-doped germanium crystals
- Tuned to the temperature of metal-insulator transition (MIT)
- Small heat capacity
- High impedance
- The logarithmic sensitivity α=dlogR/dlogT ~ 5



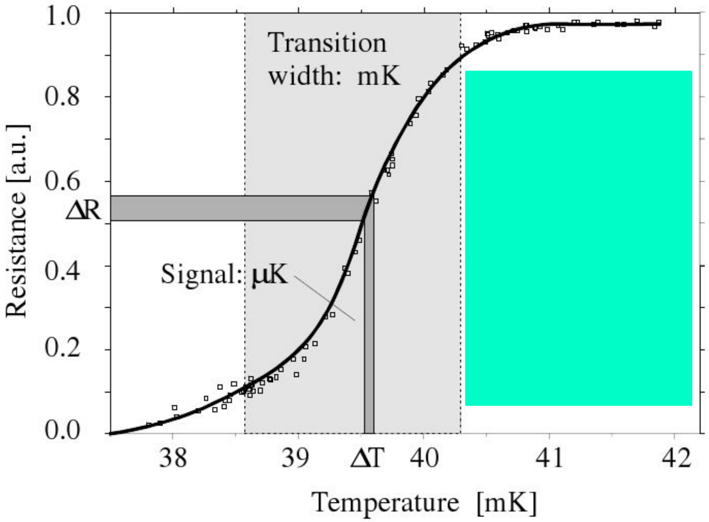
$$R(T) = R_0 \exp\left(\frac{T_0}{T}\right)^p$$

At low temperature the resistivity of a critically doped semi-conductor below the MIT follows the exponential rule, with p=1/2.

TES

superconducting transition-edge sensors

- measures an energy deposition by the increase of resistance
- The resistivity varies between 0 and its normal value
- A TES can be used to measure a single energy deposition



$$\alpha = \frac{d\log(R)}{d\log(T)} \longrightarrow$$

The logarithmic sensitivity of the TES is two order of magnitude higher than for a NTD (~100)