# First results for Gallium Arsenide operated as mK calorimeter

# DAREDEVIL project

Andrea Melchiorre
on behalf of the Daredevil group

UNIVERSITÀ DEGLI STUDI DELL'AQUILA

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

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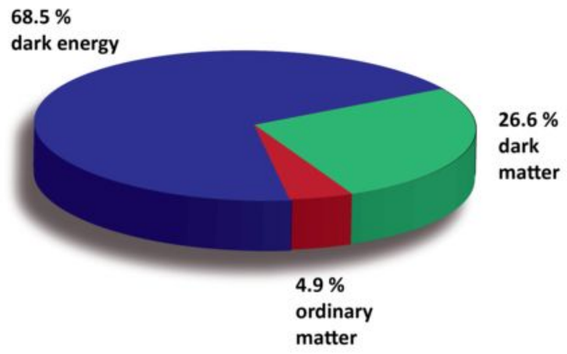
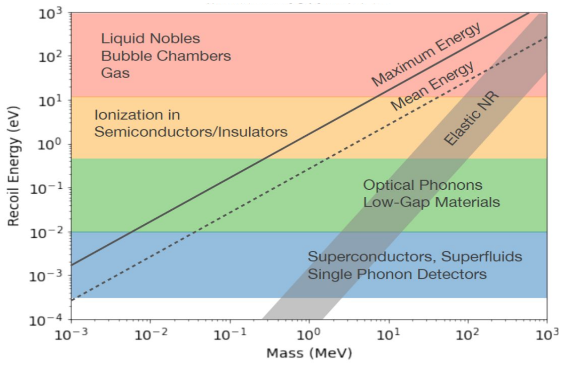
# DARK MATTER candidates and detection strategies



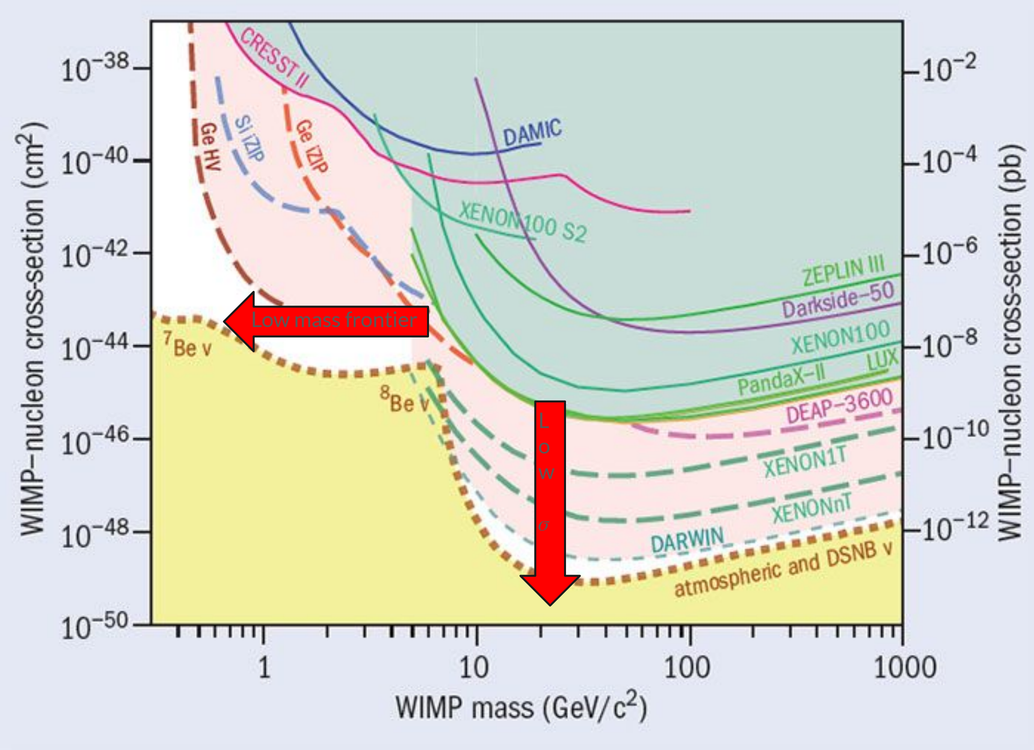

arXiv:2203.08297v2




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

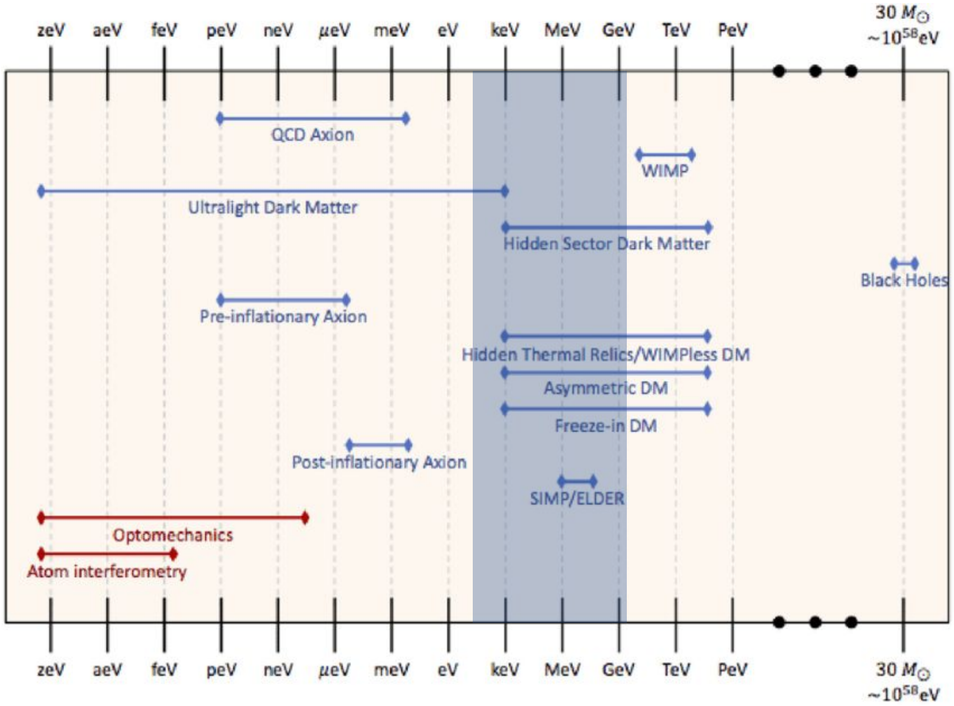


# LIGHT DARK MATTER

Various models of light dark matter have been proposed, including

- asymmetric dark matter,
- freeze-in,
- strong dynamics,

which hypothetically expand the search window to include dark matter particles at the eV scale



# DAREDEVIL

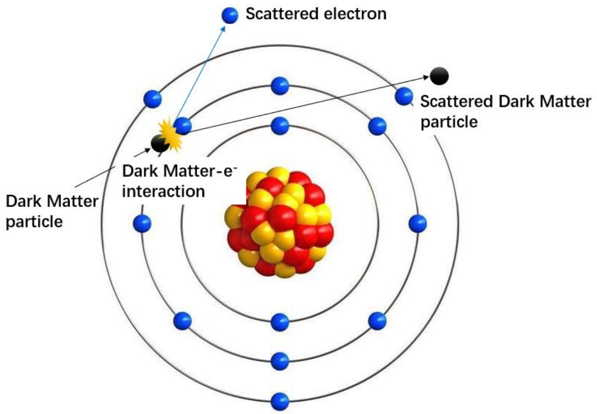
DARk-mattEr-DEVIces-for-Low-energy-detection

**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:**

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

GSSI – Gran Sasso Science Institute

CNR SPIN

INRiM – Istituto Nazionale di Ricerca Metrologica

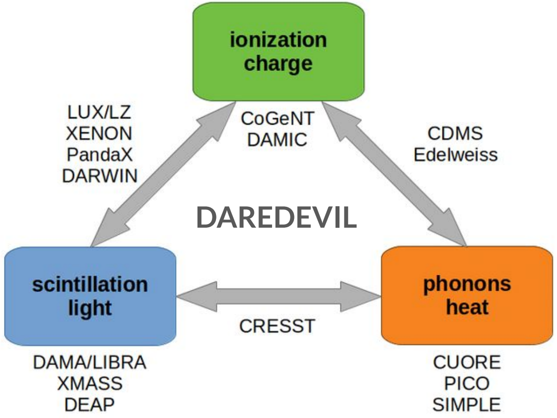
**Detector production**, testing and data analysis.

**Materials and solid state modelling** and simulation

**TES fabrication**

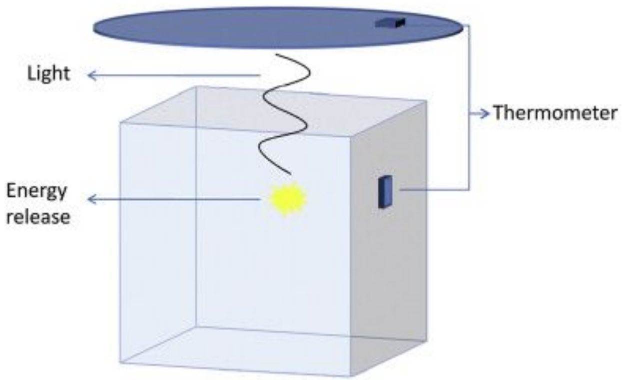
# Goal of detector development

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



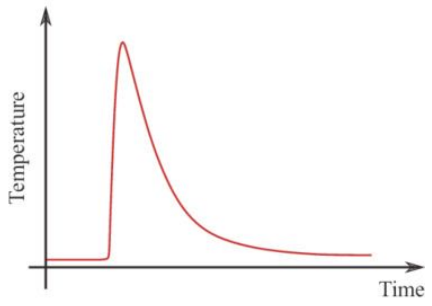

**Low temperature calorimetry**

# Low temperature calorimetry




Detection channels and sensors:

- **Phonon**: sensitive detectors (NTD, TES)
- **Light**: Cryogenic light detector based on photon absorber+phonon sensor
- **Charge**: SingleSite - MultiSite charge discrimination



# Gallium Arsenide

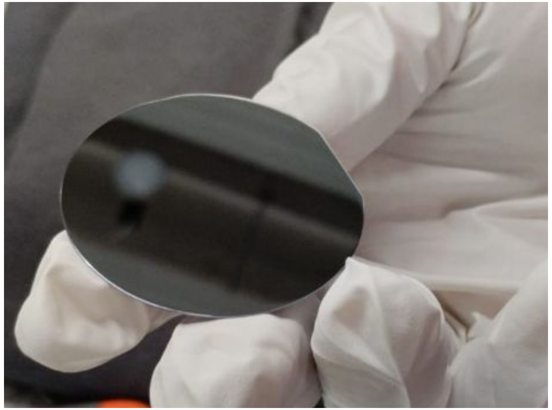
The intrinsic band gap of GaAs is direct and **1.42 eV** at room temperature, is crucial for its sensitivity to low-energy excitations.

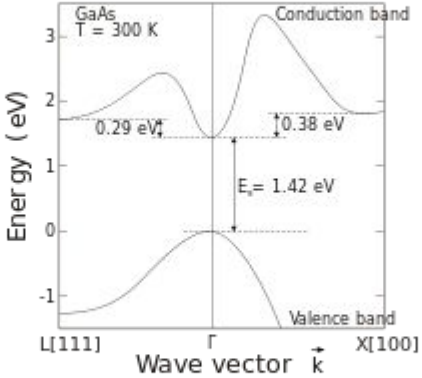
Thanks to these properties GaAs can be used as:

- Low temperature calorimeter
- Scintillator

Previous measurements show also that the light yield at 10 K can increase by more than an order of magnitude by doping GaAs with Si and B

[arXiv:1904.09362]



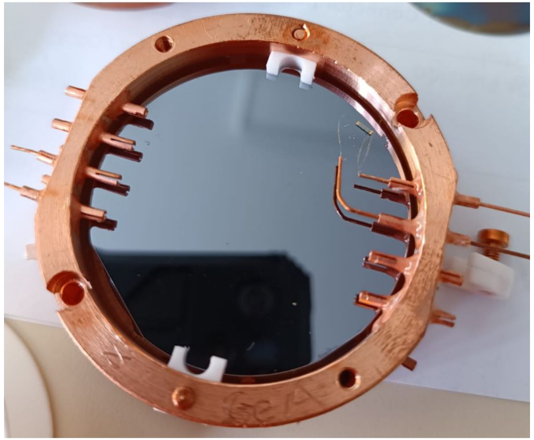


# First measurement of GaAs as a calorimeter

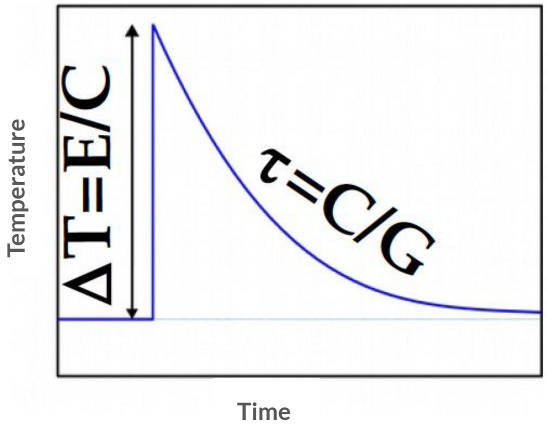
For this first measurement of GaAs as a cryogenic calorimeter, we used:

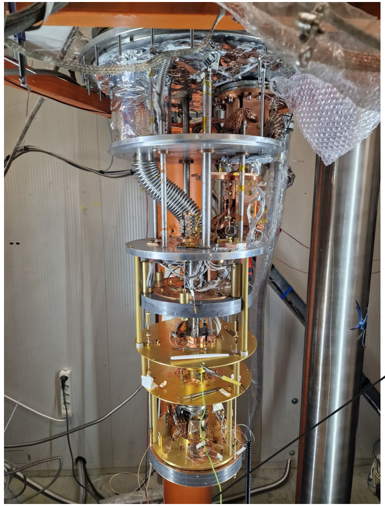
- 2-inch diameter and 0.5 mm thick wafer (5.35 g).
- The wafer was equipped with a 3 × 0.6 × 0.4 mm NTD (Neutron Transmutation Doped Ge thermistor) - phonon sensor

After each interaction in GaAs most of the released energy is recombined in the phonon channel and measured with the NTD.

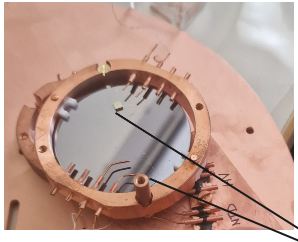


# Experimental setup

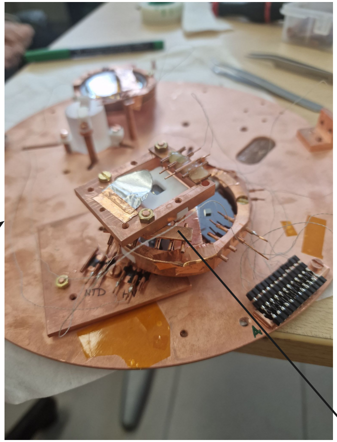


Pulse tube assisted dilution refrigerator in Hall C LNGS



NTD



55Fe 238U

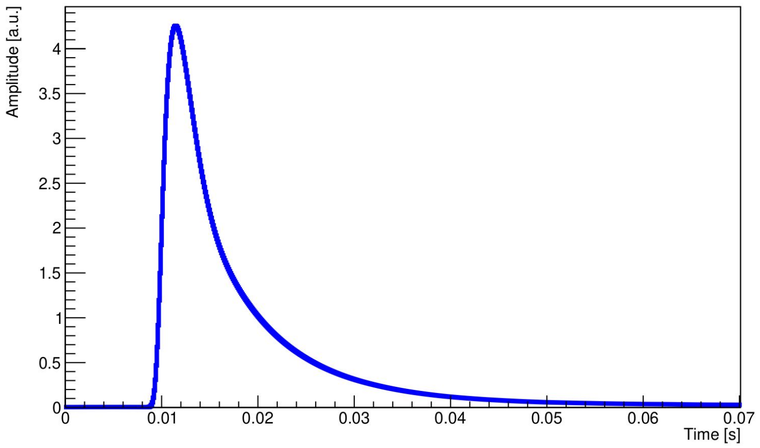
# Data Analysis and Results

We conducted a 12-hour long 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

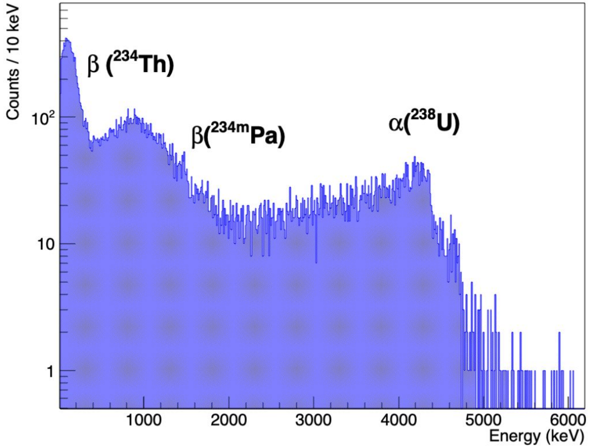
Average pulse



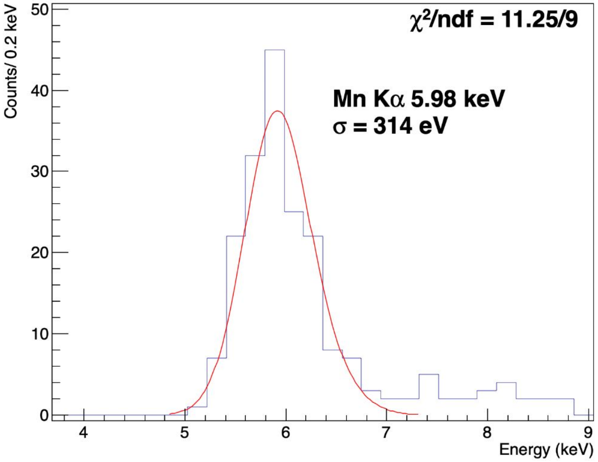

Rise time: 1.2 ms
Decay time: 10.8 ms

# Data Analysis and Results

Total energy spectrum




Low energy spectrum

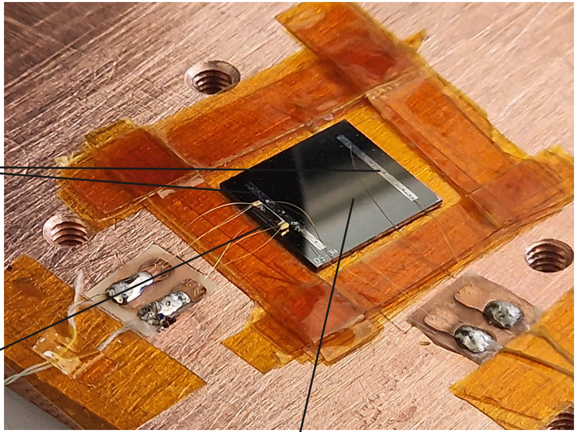



Detector performance summary

| | | |
|---|---|---|
| Mass | 5.35 | g |
| Density | 5.32 | $g/cm^3$ |
| Diameter | 5.08 | cm |
| Rise time 10-90 | $1.2 \pm 0.1$ | ms |
| Decay time 90-30 | $10.8 \pm 0.5$ | ms |
| NTD response | 450 | $\mu V/MeV$ |
| Baseline resolution (RMS) PT off | $283 \pm 48$ | eV |
| Peak $\sigma$ at 5.9 keV PT off | $314 \pm 22$ | eV |
| Baseline resolution (RMS) PT on | $542 \pm 6$ | eV |
| Peak $\sigma$ at 5.9 keV PT on | $546 \pm 21$ | eV |

# Mercury Cadmium Telluride - CdTeHg

high voltage electrodes



NTD

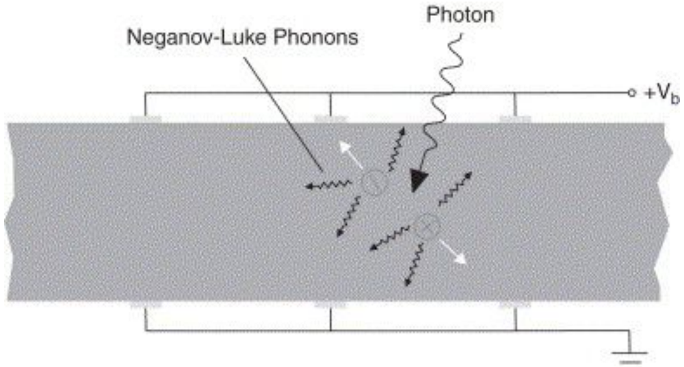
surface where the CdTeHs is deposited

- We want to use it as **light detector** for the radiative signal from GaAs, because the stoichiometry was tuned to achieve 0.2 eV gap suitable scintillation light from GaAs.
- photons generated in GaAs interact in a CdTeHg layer sputtered on a square silicon substrate
- the temperature increase is too low -> **Neganov-Trofimov-Luke** (NTL) **amplification**

# Neganov-Trofimov-Luke amplification

Amplification of phonon signal with static electric field:

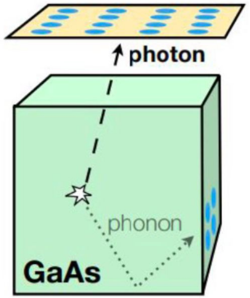
- electron-hole pairs created by interacting particle are accelerated
- during the acceleration they scatter with crystal lattice
- phonon signal will be increased by a factor of 10

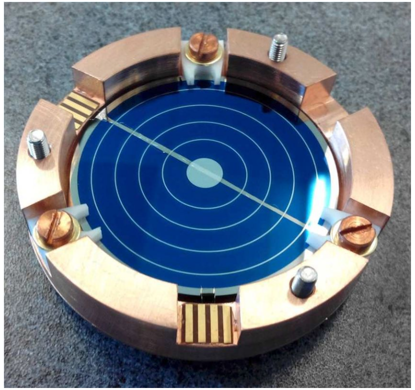


# Next steps

These results are highly promising for the search for low-mass dark matter using GaAs crystals. As a future development we plan:

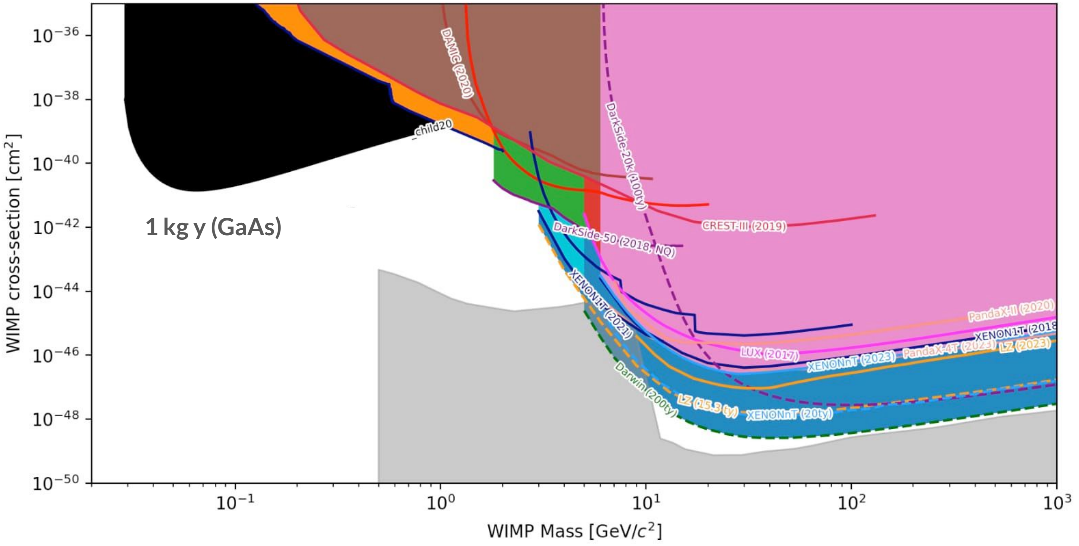
- **Double readout** of light channel (scintillation photons) heat channel (phonon) to particle identification
- **Luke amplification** to increase the phonon signal
- **Charge collection** installing electrodes
- **TES** (Transition Edge Sensors) as a thermal sensor



# Conclusion

- We successfully conduct the first measurement of GaAs as cryogenic calorimeter
- published on arXiv [arXiv:2404.15741]
- It opens the door for new class of detectors for dark matter searches
- We want to access on black region of phase space



# Thank you for your attention

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# backup slide

# 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.

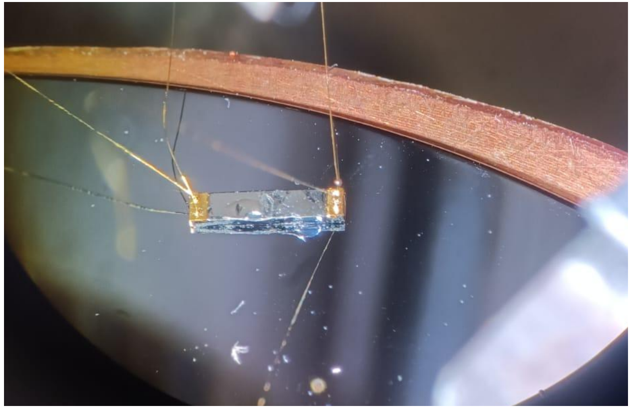
- **Weyl semimetals** are a class of topological materials that possess Weyl fermions as low-energy excitations and with a nontrivial topological aspects of their band structure.

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

# NTD

Highly resistive devices with:

- $\alpha$=dlogR/dlogT ~ 5
- Small heat capacity



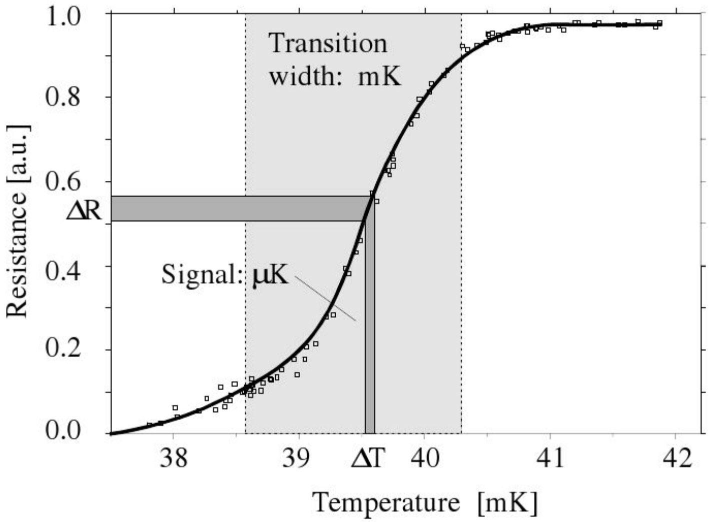
$$R(T) = R_0 \exp\left(\frac{T_0}{T}\right)^p$$

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




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

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