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
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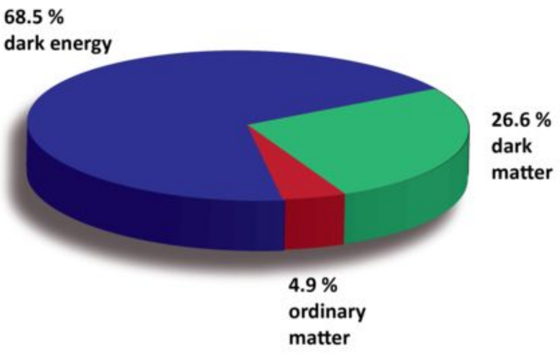
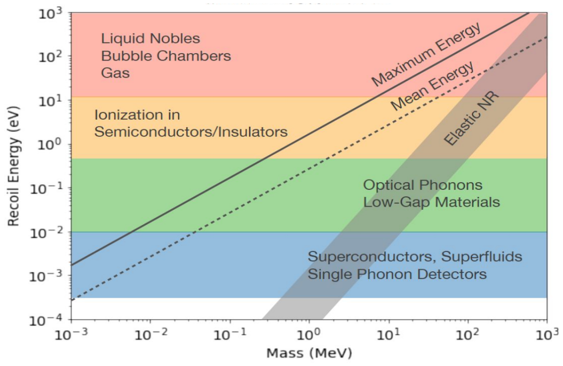
DARK MATTER candidates and detection strategies



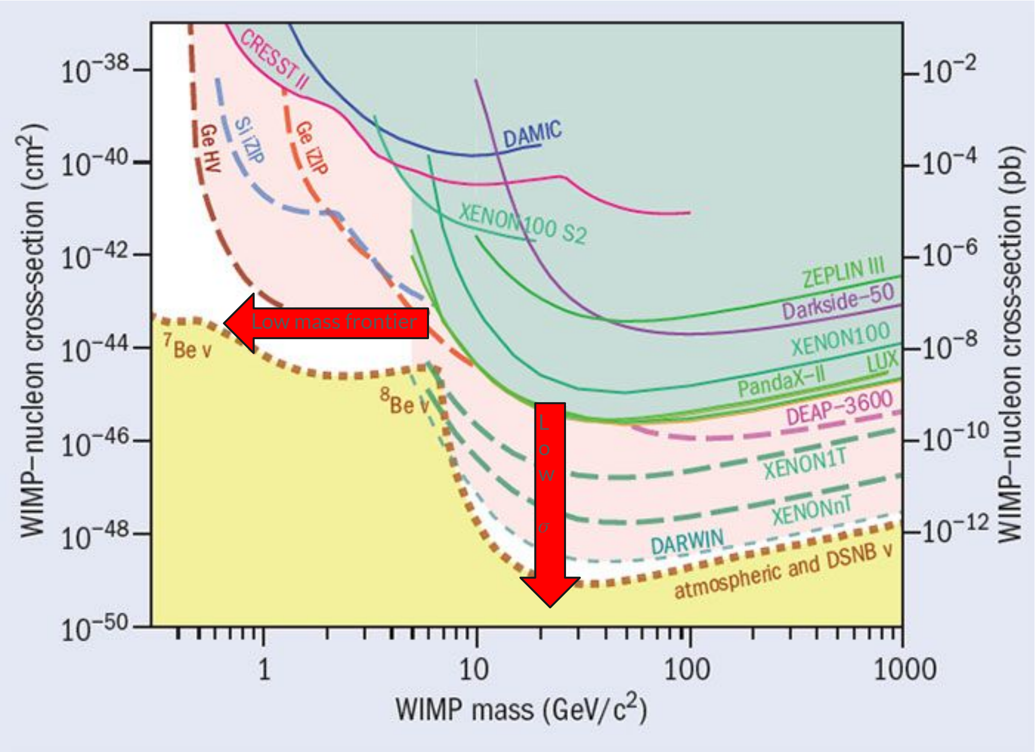
arXiv:2203.08297v2



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

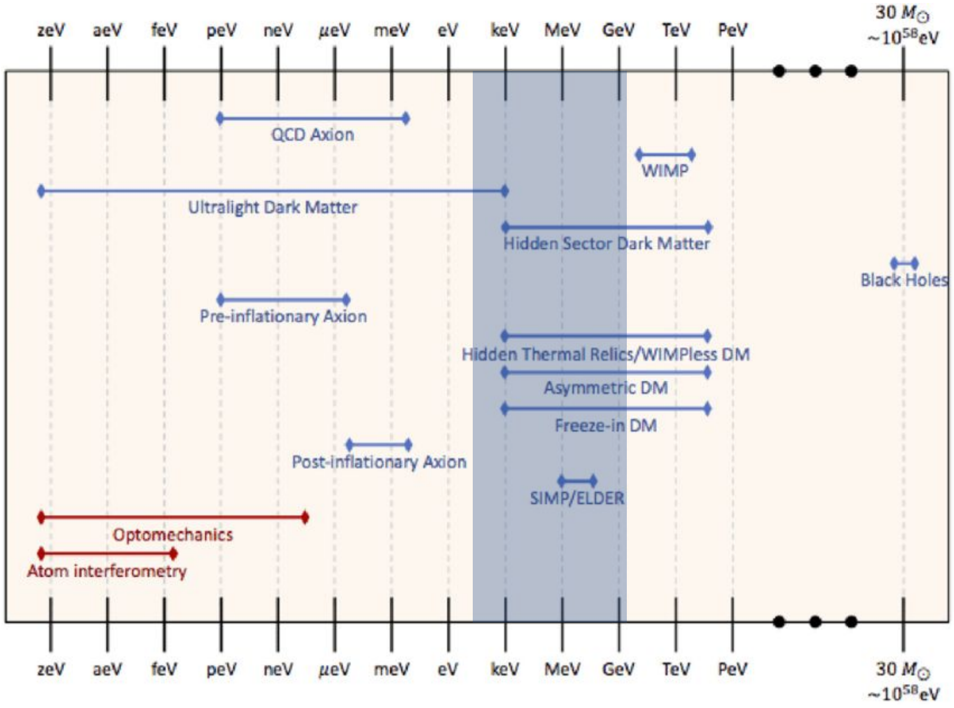


LIGHT DARK MATTER

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



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DAREDEVIL

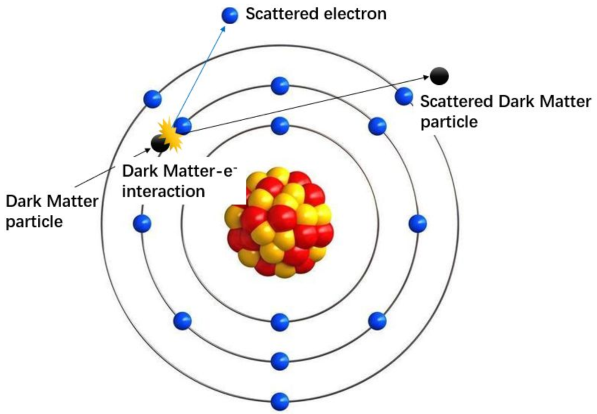
DARk-mattEr-DEVIces-for-Low-energy-detection

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 ($ZrTe_5$)
- Weyl semimetals (CaAuAs)
- Superconductors (Al)
- Low gap semiconductor (GaAs)



DAREDEVIL COLLABORATION

Different expertise brought together for new class of detectors.

The team:

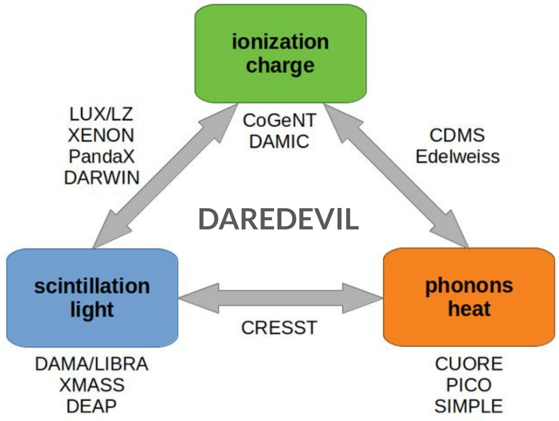
Detector production, testing and data analysis.

Materials and solid state modelling and simulation

TES fabrication

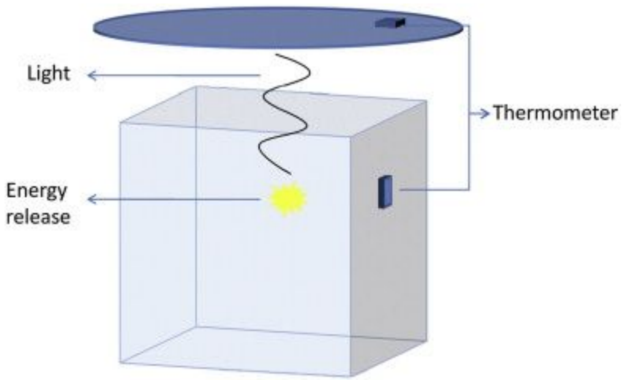
Goal of detector development

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



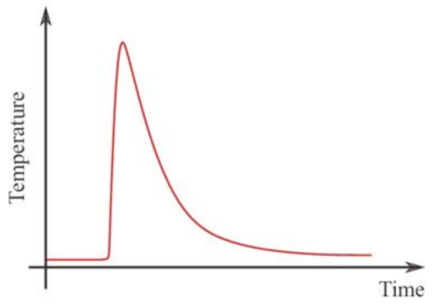
Low temperature calorimetry

Low temperature calorimetry



Detection channels and sensors:

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



Gallium Arsenide

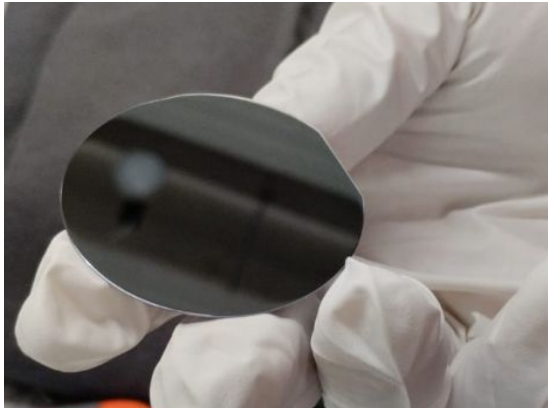
The intrinsic band gap of GaAs is direct and **1.42 eV** at room temperature, is crucial for its sensitivity to low-energy excitations.

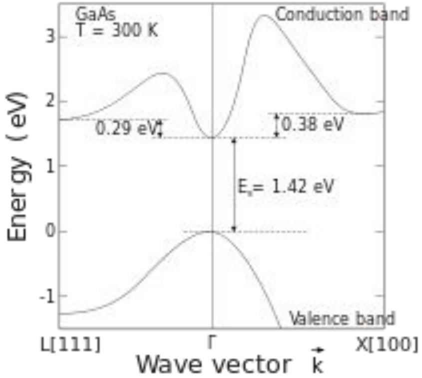
Thanks to these properties GaAs can be used as:

- 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]

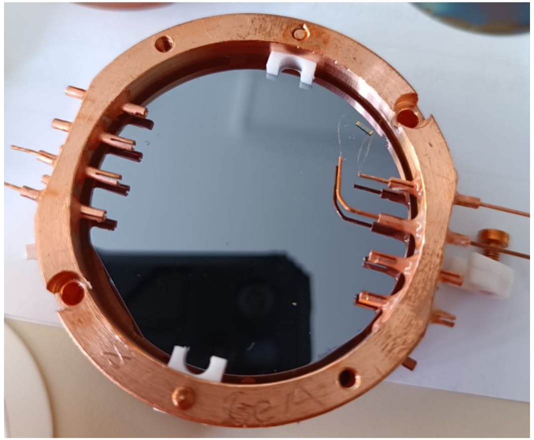




First measurement of GaAs as a calorimeter

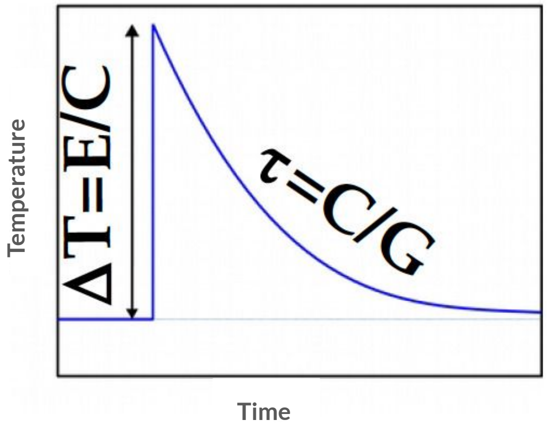
For this first measurement of GaAs as a cryogenic calorimeter, we used:

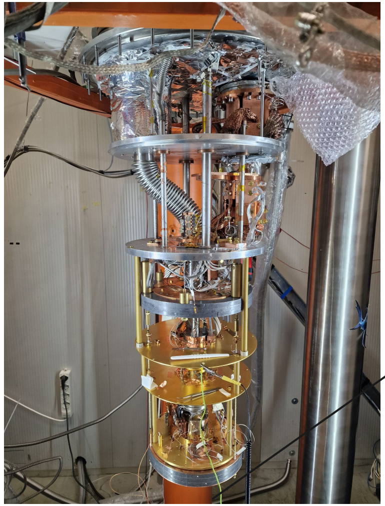
- 2-inch diameter and 0.5 mm thick wafer (5.35 g).
- The wafer was equipped with a 3 × 0.6 × 0.4 mm NTD (Neutron Transmutation Doped Ge thermistor) - phonon sensor



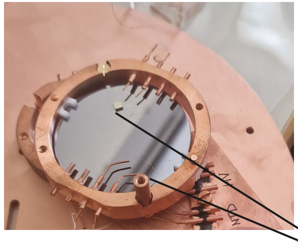
After each interaction in GaAs most of the released energy is recombined in the phonon channel and measured with the NTD.

Experimental setup

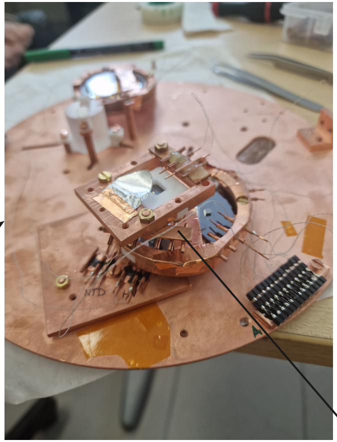




Pulse tube assisted dilution refrigerator in Hall C LNGS



NTD



55Fe 238U

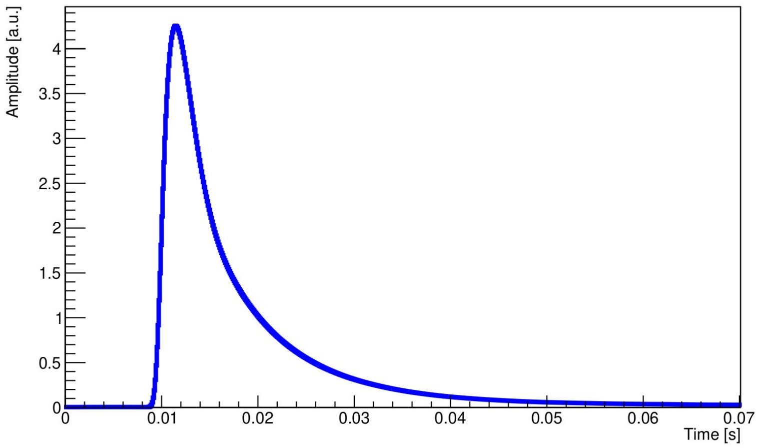
Data Analysis and Results

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

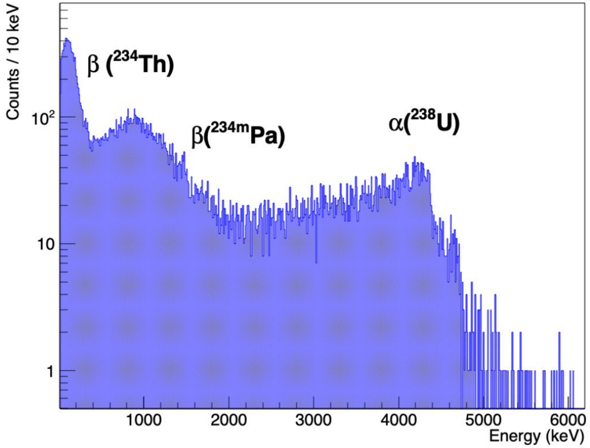
Average pulse



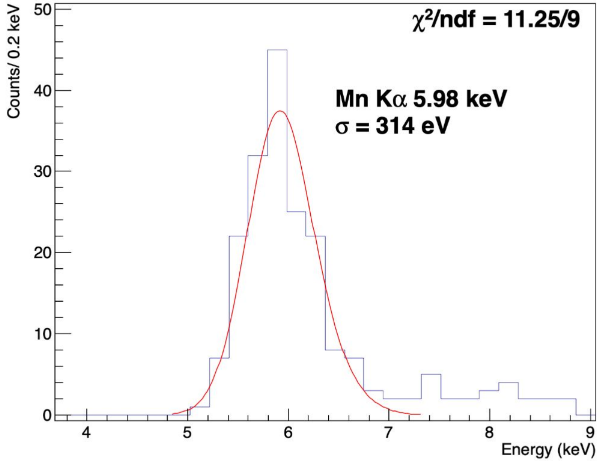
Rise time: 1.2 ms
Decay time: 10.8 ms

Data Analysis and Results

Total energy spectrum



Low energy spectrum



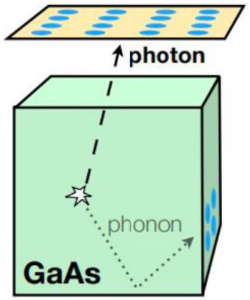
Detector performance summary

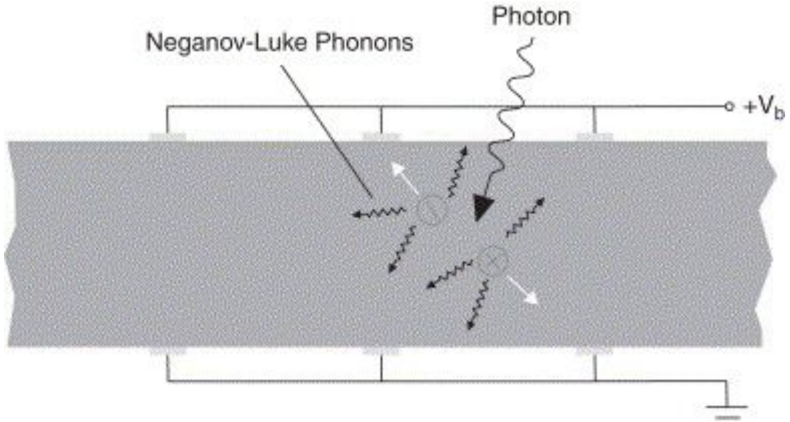
Mass	5.35	g
Density	5.32	g/cm^3
Diameter	5.08	cm
Rise time 10-90	1.2 ± 0.1	ms
Decay time 90-30	10.8 ± 0.5	ms
NTD response	450	$\mu V/MeV$
Baseline resolution (RMS) PT off	283 ± 48	eV
Peak σ at 5.9 keV PT off	314 ± 22	eV
Baseline resolution (RMS) PT on	542 ± 6	eV
Peak σ at 5.9 keV PT on	546 ± 21	eV

Next steps

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

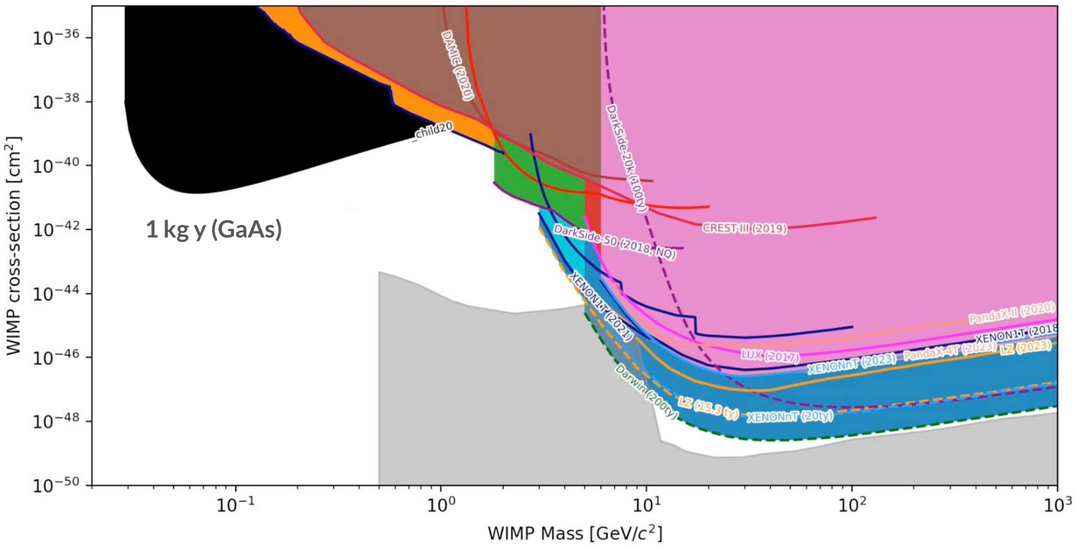
- **Double readout** of light channel (scintillation photons) heat channel (phonon) to particle identification
- **Luke amplification** to increase the phonon signal
- **Charge collection** installing electrodes
- **TES** (Transition Edge Sensors) as a thermal sensor





Conclusion

- We successfully conduct the first measurement of GaAs as cryogenic calorimeter
- published on arXiv [arXiv:2404.15741]
- It open doors such detector for dark matter
- We want to access on black region of phase space



Thank you for your attention

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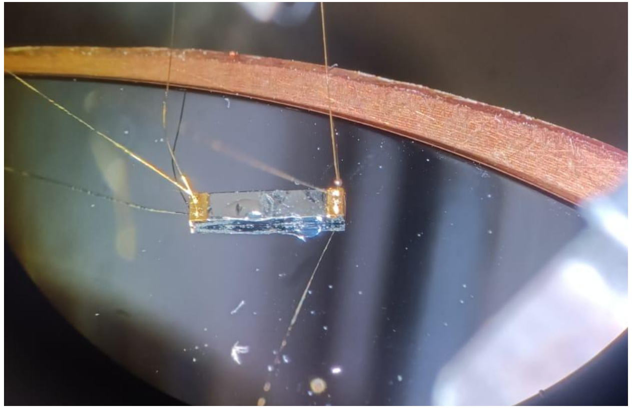
backup slide

NTD



Highly resistive devices with:

- α=dlogR/dlogT ~ 5
- Small heat capacity

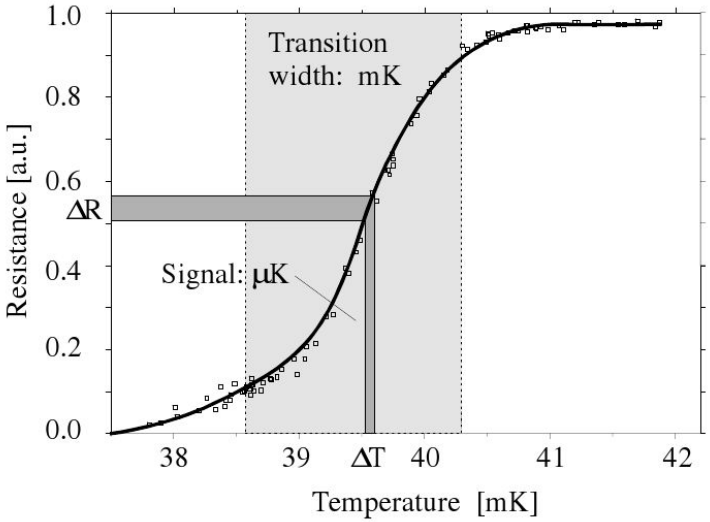
$$R(T) = R_0 \exp\left(\frac{T_0}{T}\right)^p$$

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



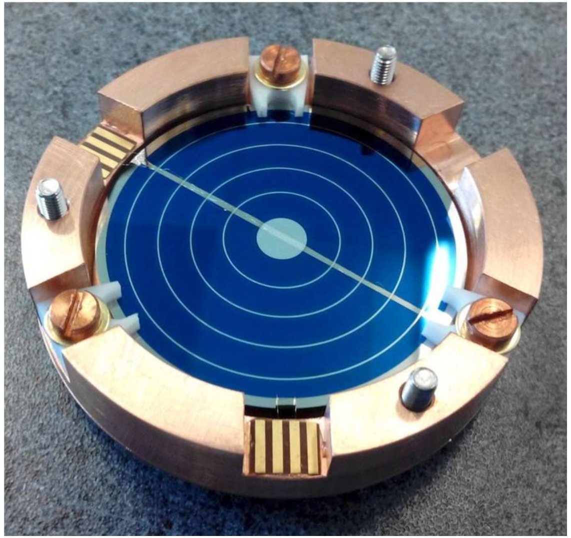
$$\alpha = \frac{d \log(R)}{d \log(T)}$$

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

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



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.