Solid state detectors -
Cryogenic detectors

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OUTLINE

Part 1: physic of cryogenic detectors

- Cryogenic detectors: working principles
- Cryogenic techniques
- Temperature sensors
- Specific background components
- Composite detectors

Part 2: astroparticle physic applications

Part 1: physic of cryogenic detectors

Basic principles

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Scheme: composed by an **energy absorbe**r in which the radiation interacts, producing a T increase, and by a **T sensor** that reads the increase (sometimes sensor = absorber).

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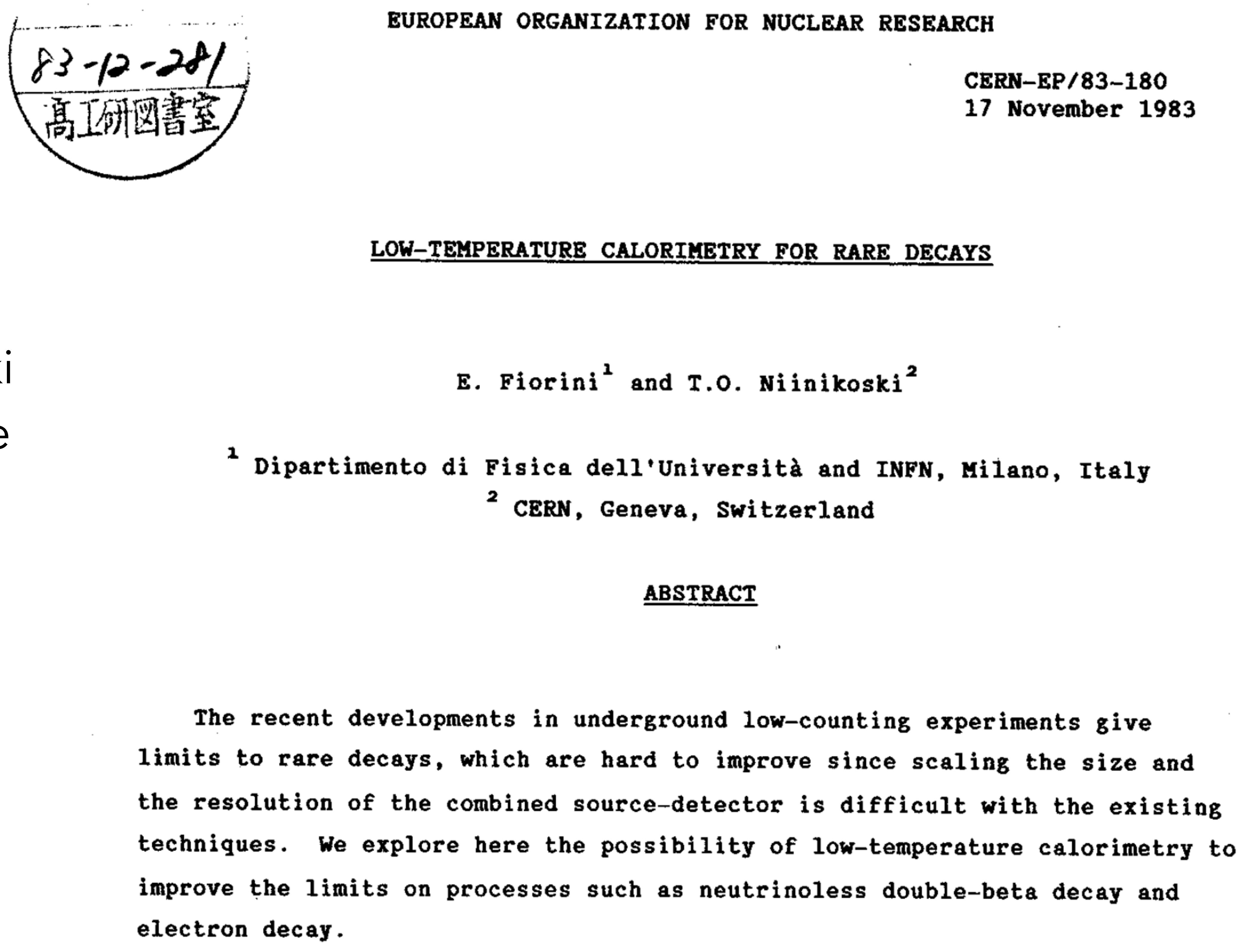

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/83-180
17 November 1983

LOW-TEMPERATURE CALORIMETRY FOR RARE DECAYS

E. Fiorini[1] and T.O. Niinikoski[2]

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ABSTRACT

The recent developments in underground low-counting experiments give limits to rare decays, which are hard to improve since scaling the size and the resolution of the combined source-detector is difficult with the existing techniques. We explore here the possibility of low-temperature calorimetry to improve the limits on processes such as neutrinoless double-beta decay and electron decay.

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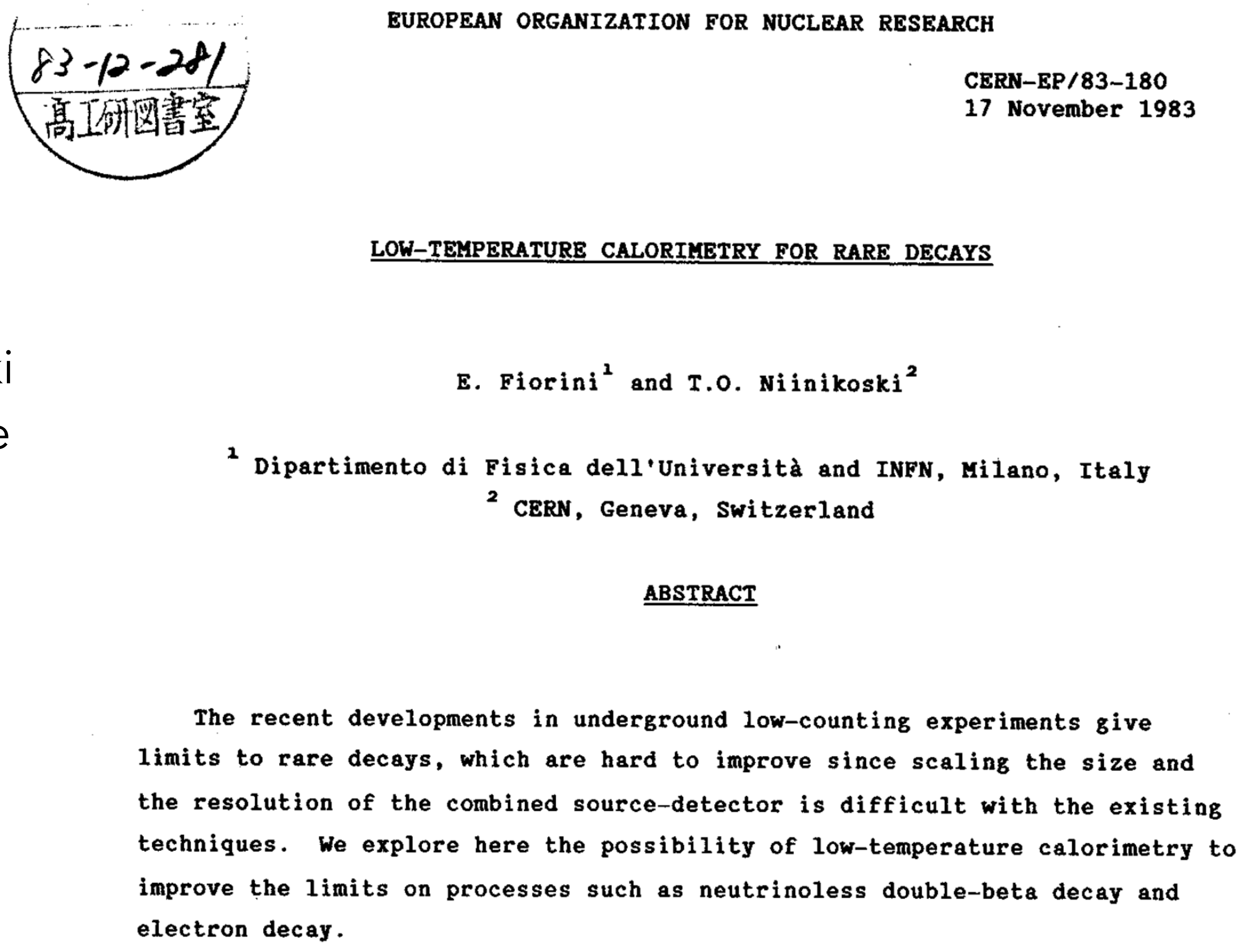

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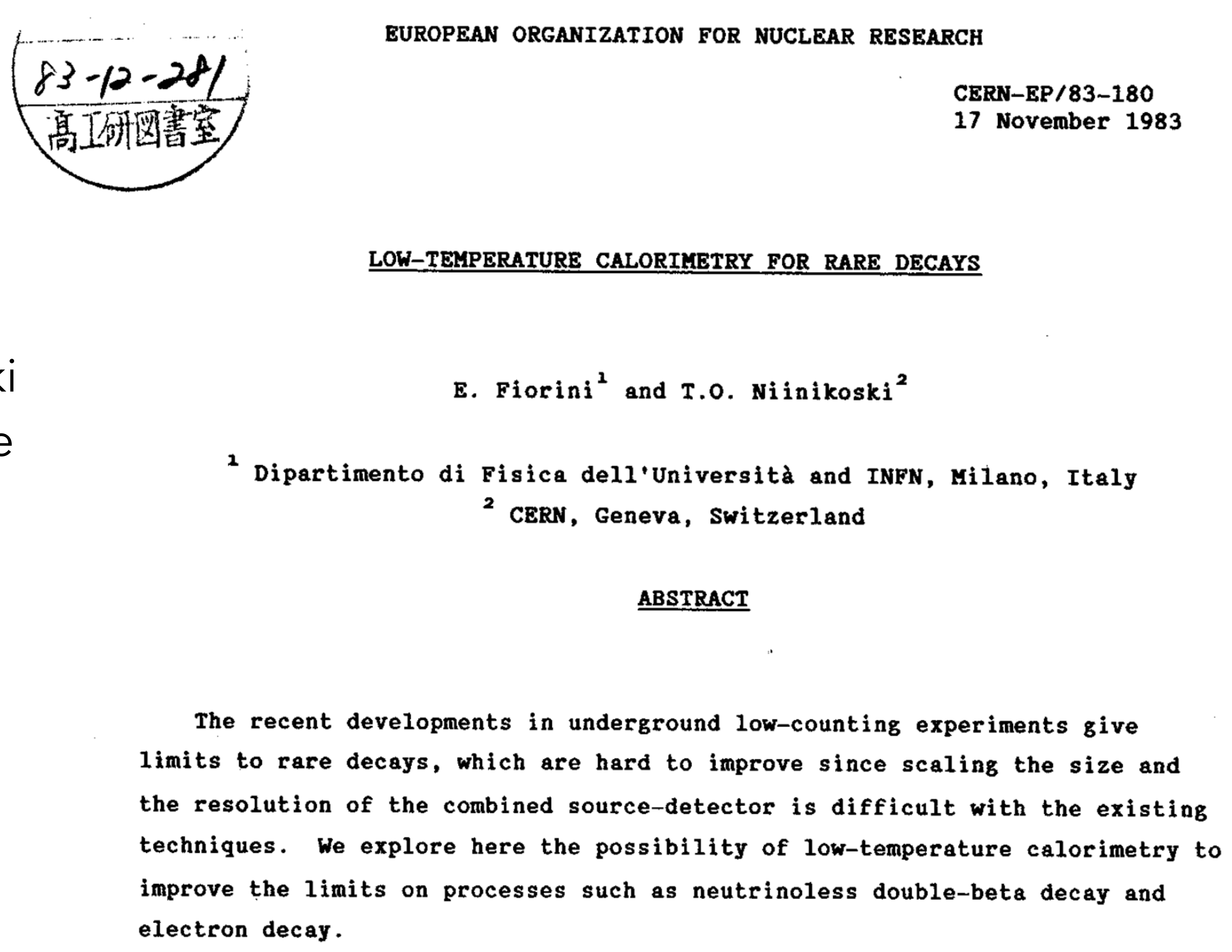

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Nowadays cryogenic detectors have found applications in a variety of fields and with extremely exciting results.

Characteristics of a Low Temperature Particle Detector (LTD)

- It is sensitive to **single quanta**
- The detection is mediated by elementary excitations in a solid (**Energy Absorber**)
- The **elementary excitation energy** is **≤ ~10 meV**

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- **Extra information** on the interacting quantum can be obtained, at least in principle

- Arrival time
- Quantum type
- Impact point
- Deposited energy
- Initial momentum

Advantages of Bolometers over conventional devices for radiation spectroscopy

Energy resolution

- ε: energy to produce an elementary excitation
- $N = E/\varepsilon$: number of elementary excitation
- $\Delta E = \varepsilon\, \Delta N = \varepsilon\, (N)^{1/2} = (\varepsilon E)^{1/2}$
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elementary excitations in LTD:
- phonons in a dielectric/semiconductor
- quasiparticles in a superconductor

Phonon-Mediated particle detectors

Quasiparticle-Mediated particle detectors

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A different spectrum in particular is expected for:

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- Initially, the phonons produced are out of equilibrium (**athermal phonons**) with about the Debye energy (≈10 meV)

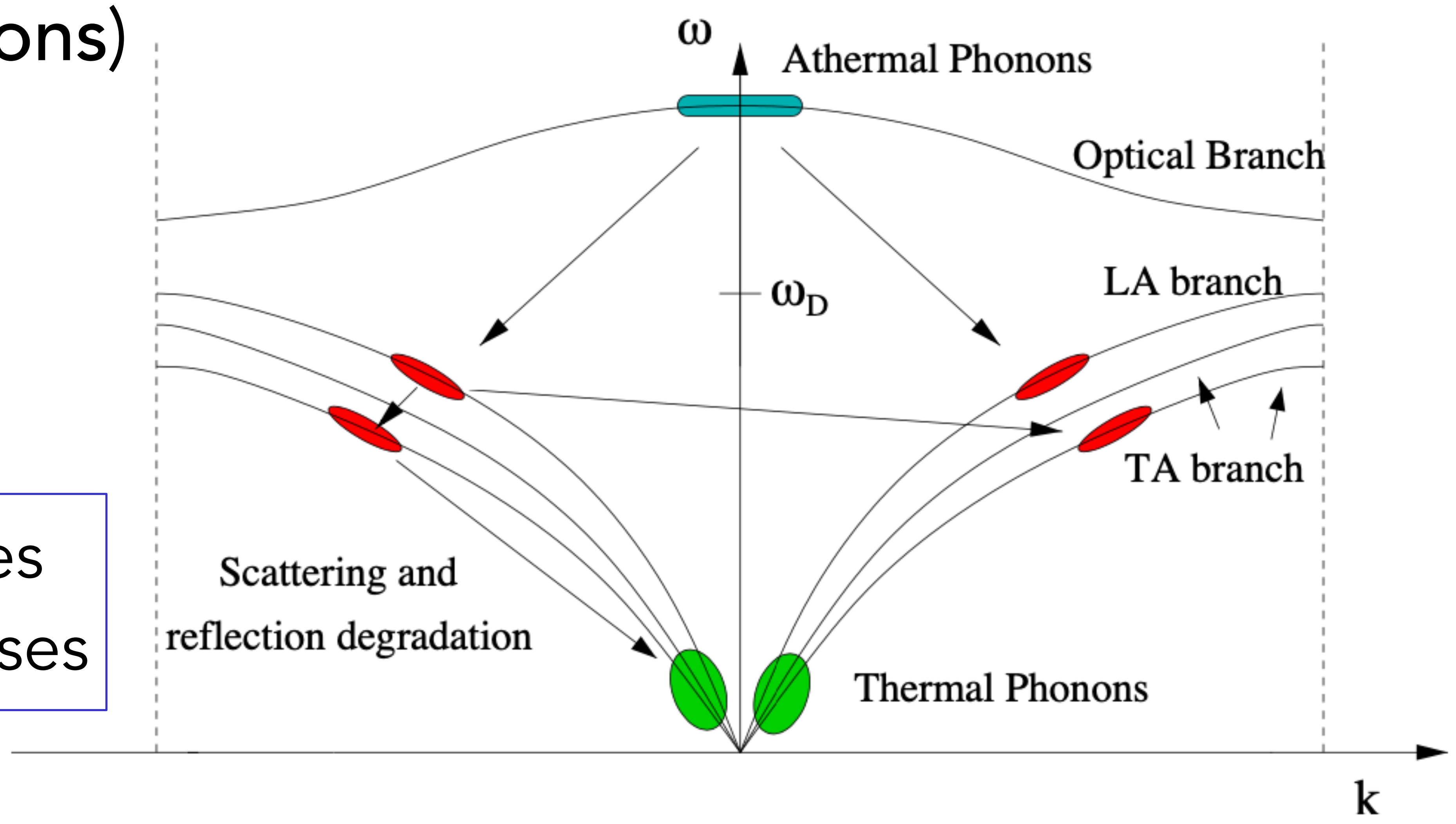
Athermal phonons propagate balistically and are long-living

Athermal phonons undergo anharmonic decay, isotope, surface and impurity scattering (quasi-diffusive propagation) ⇒ energy degradation

$\Gamma_{dec} \propto E_{ph}^{5}$

$\Gamma_{iso} \propto E_{ph}^{4}$

lifetime increases as energy decreases



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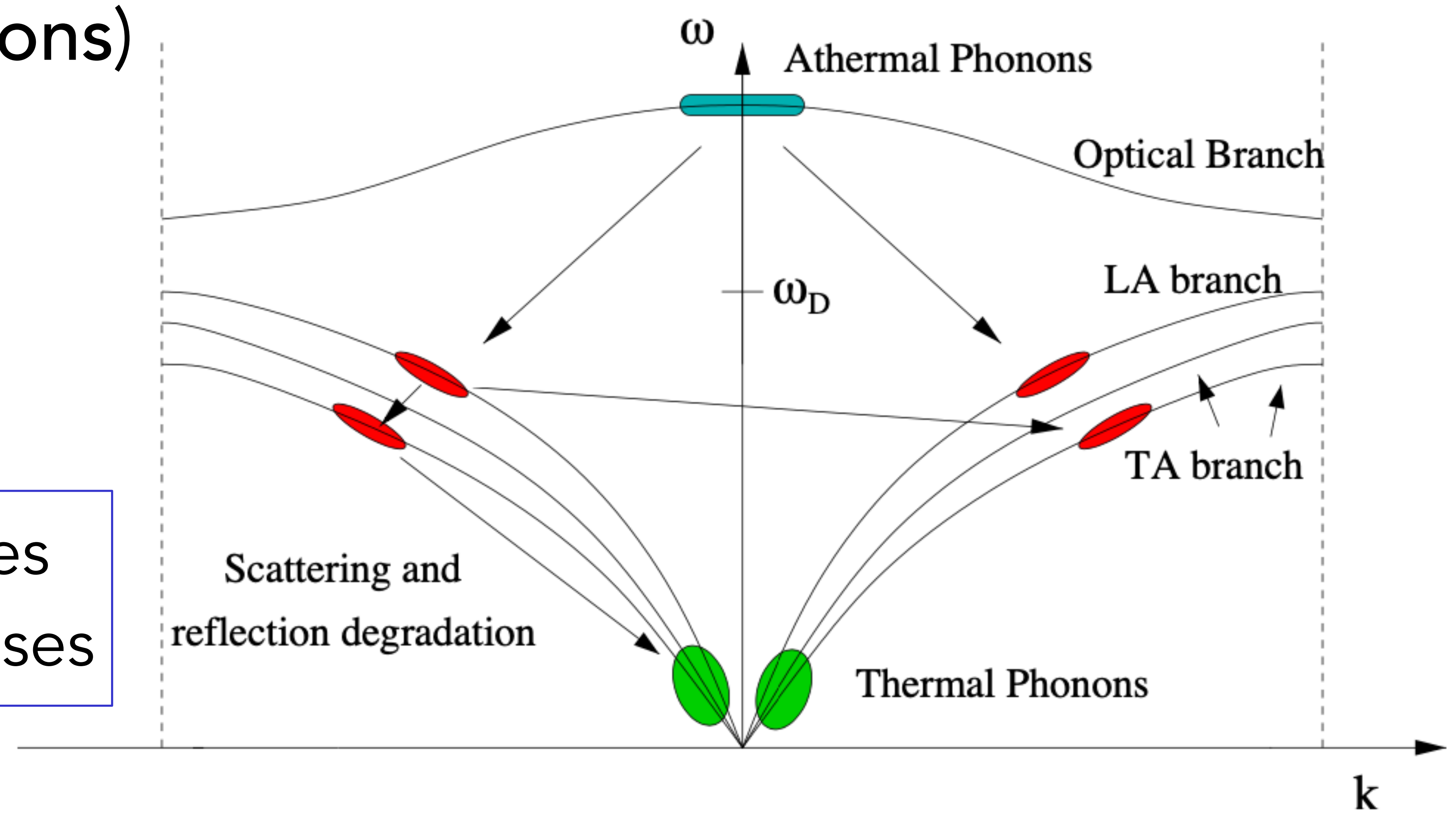

- Finally, phonons relax on a new **equilibrium distribution**

the deposited energy has produced a **temperature increase**

Thermal and athermal phonons

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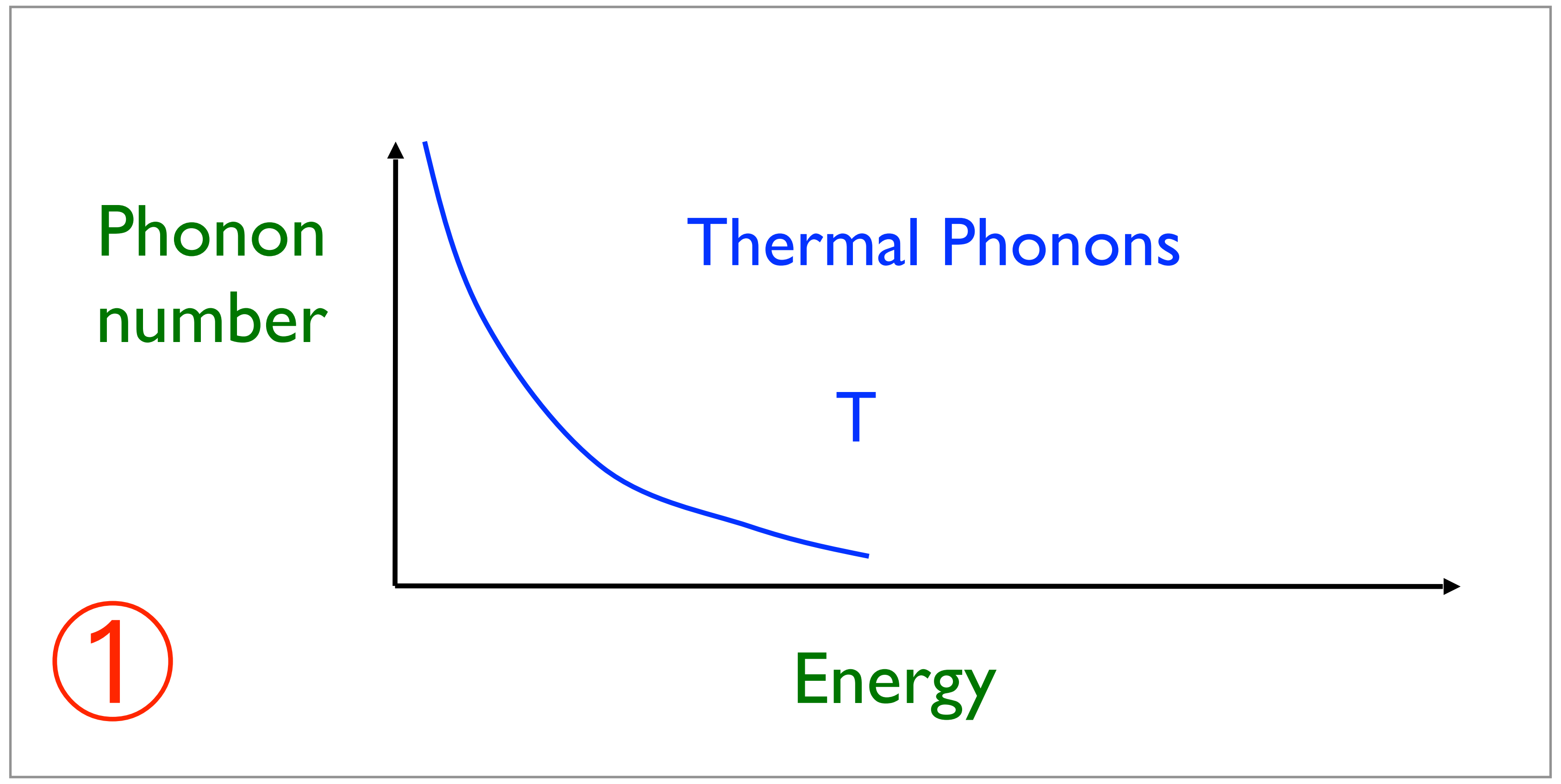
Before interaction



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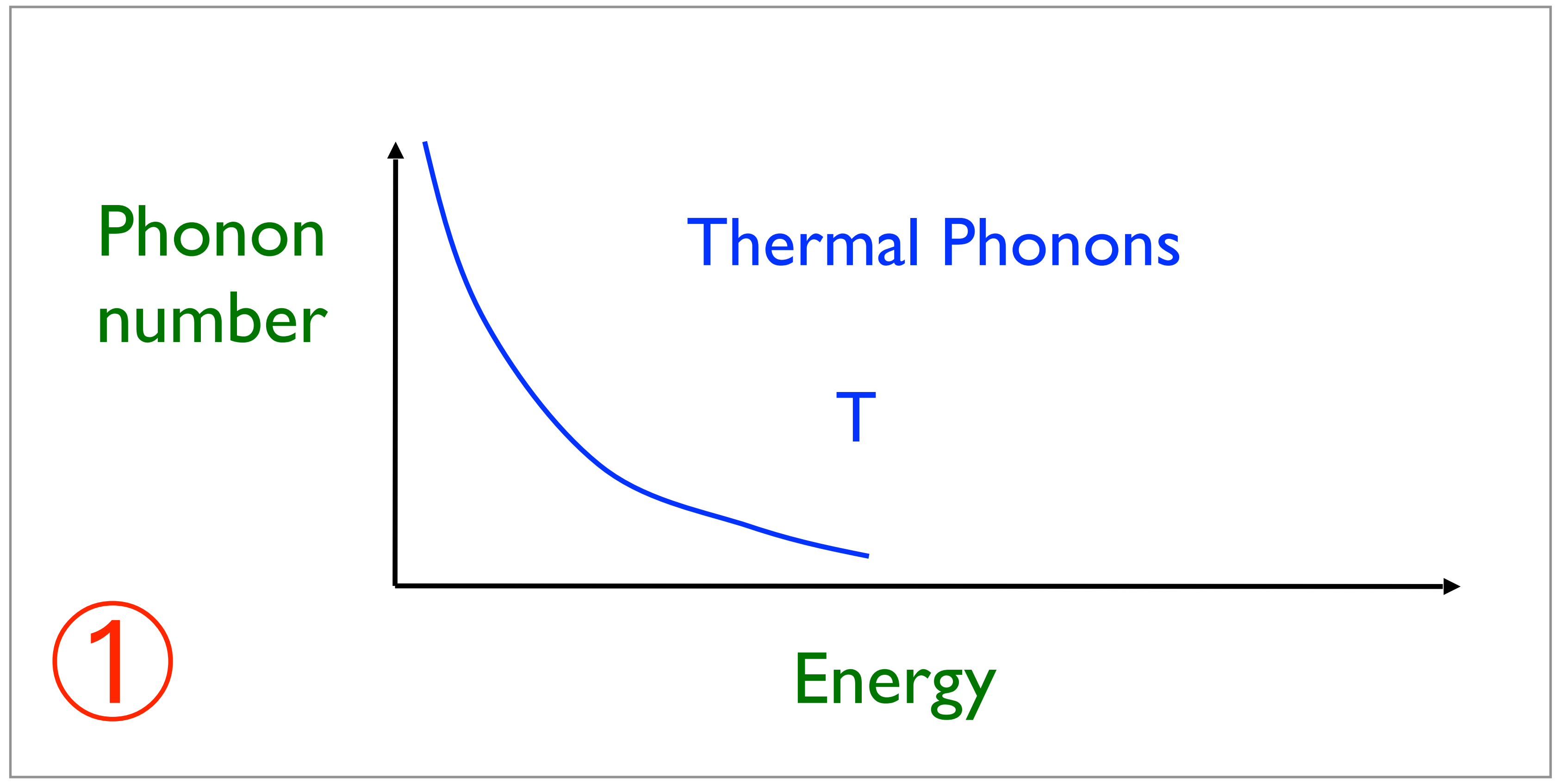
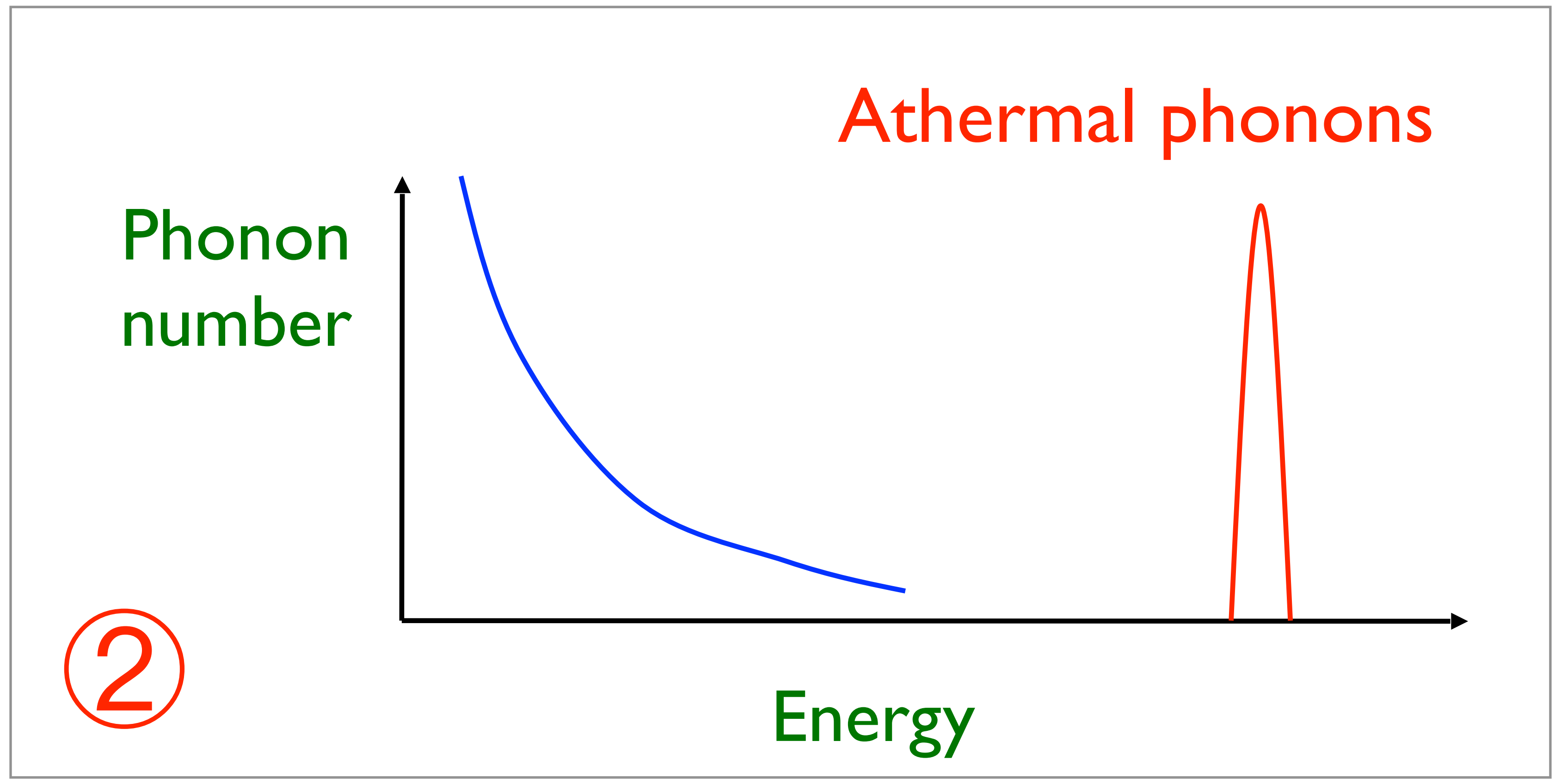


Immediately after interaction



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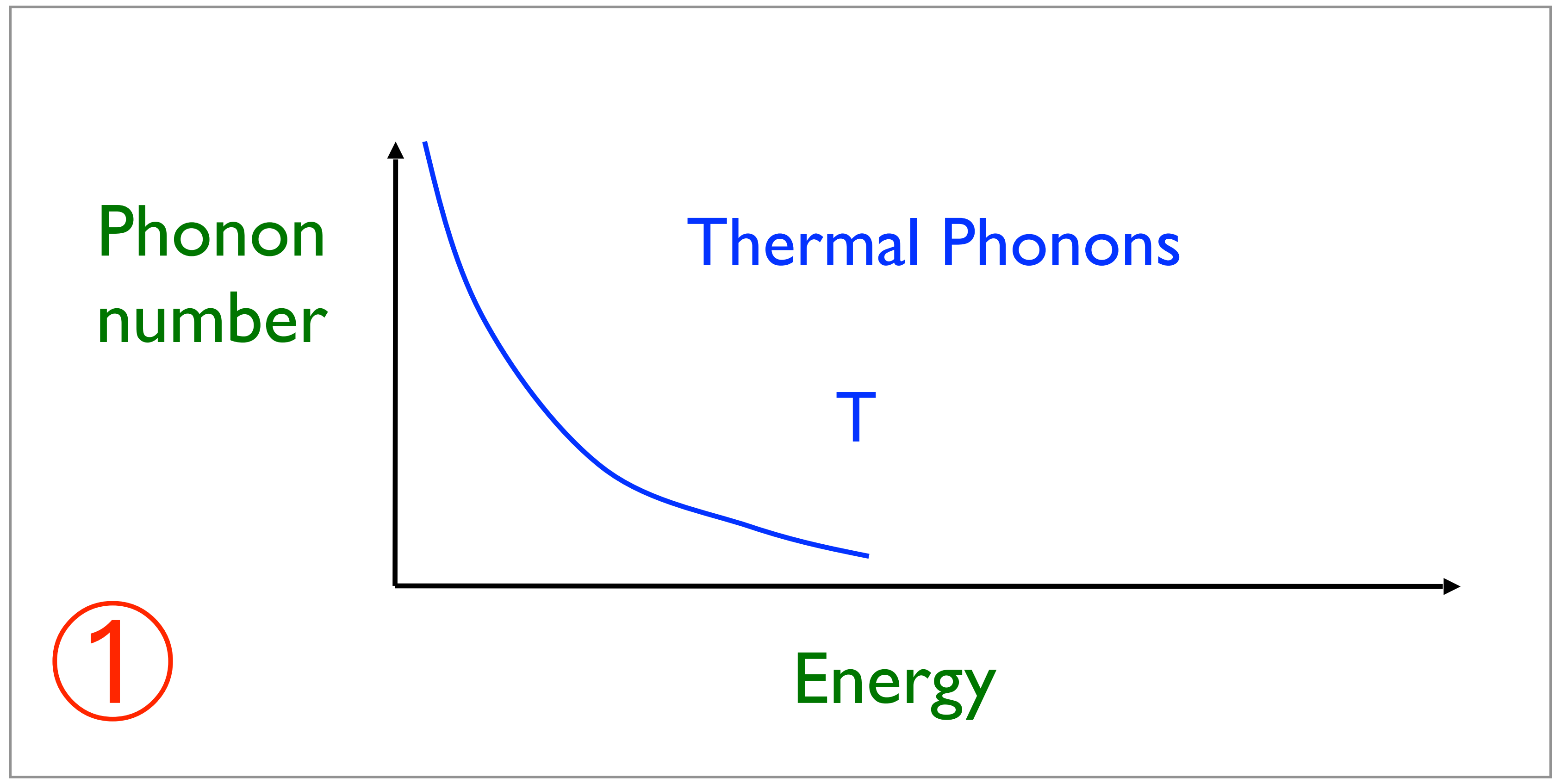

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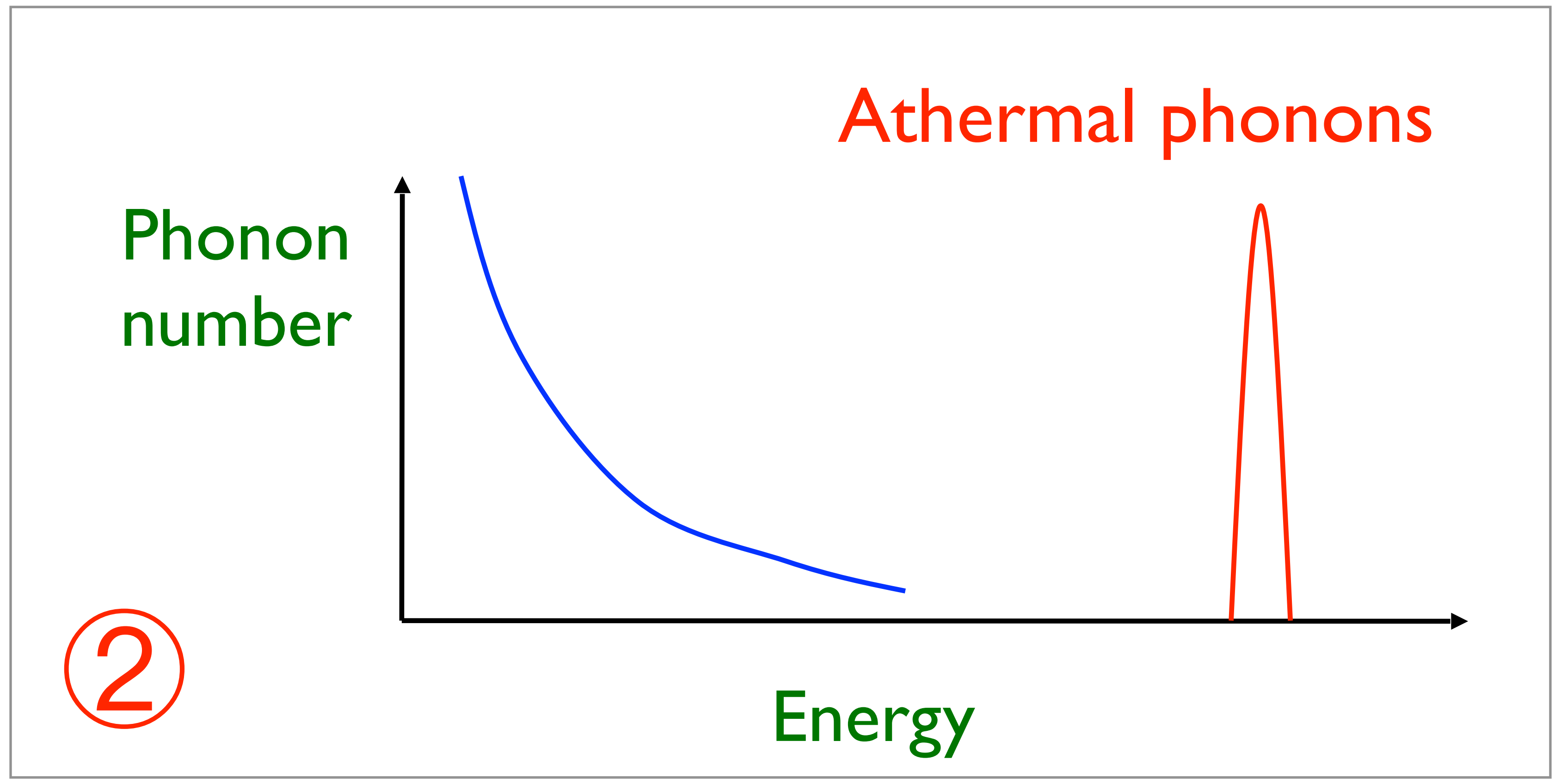
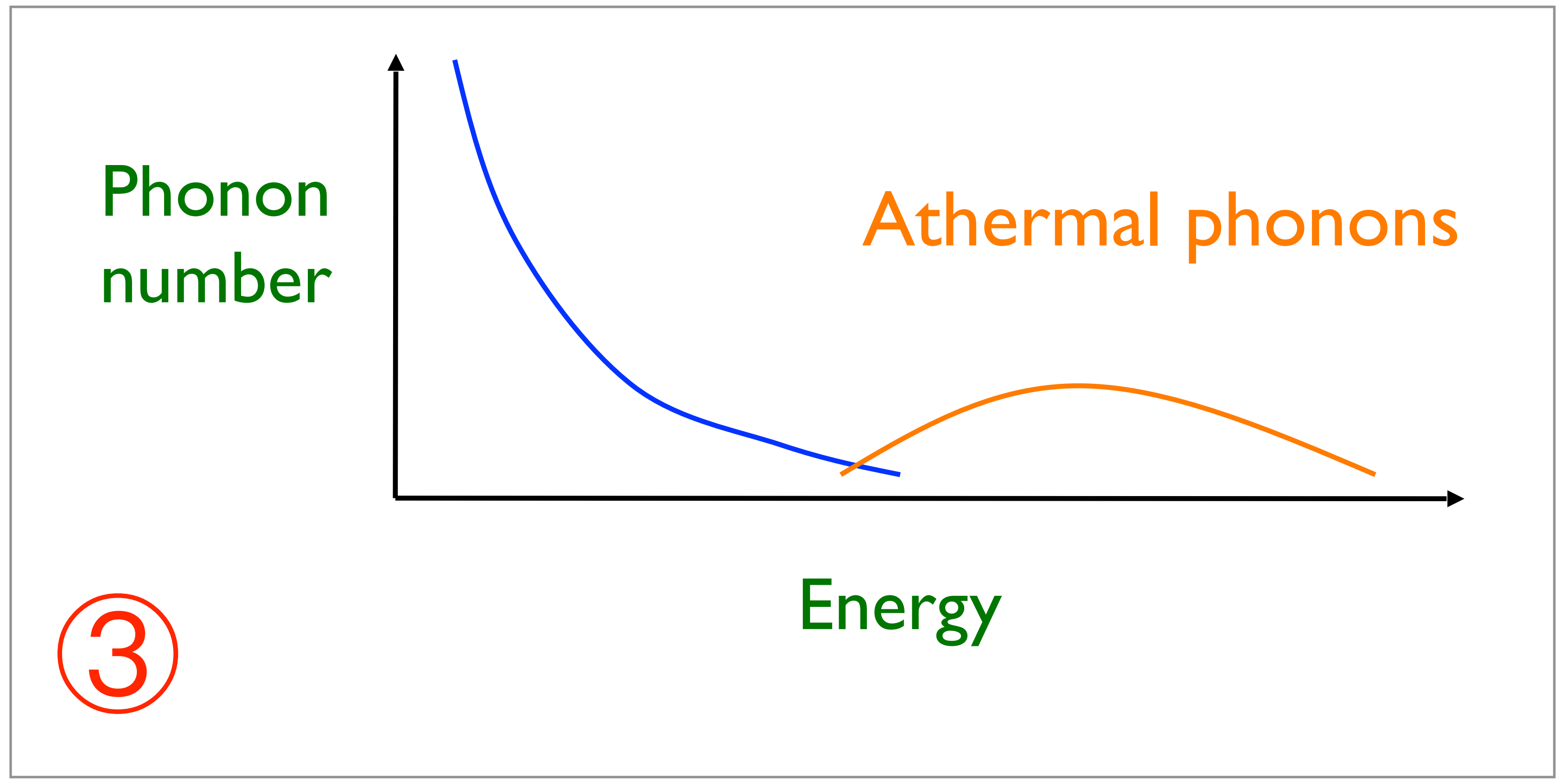


Phonon energy degradation



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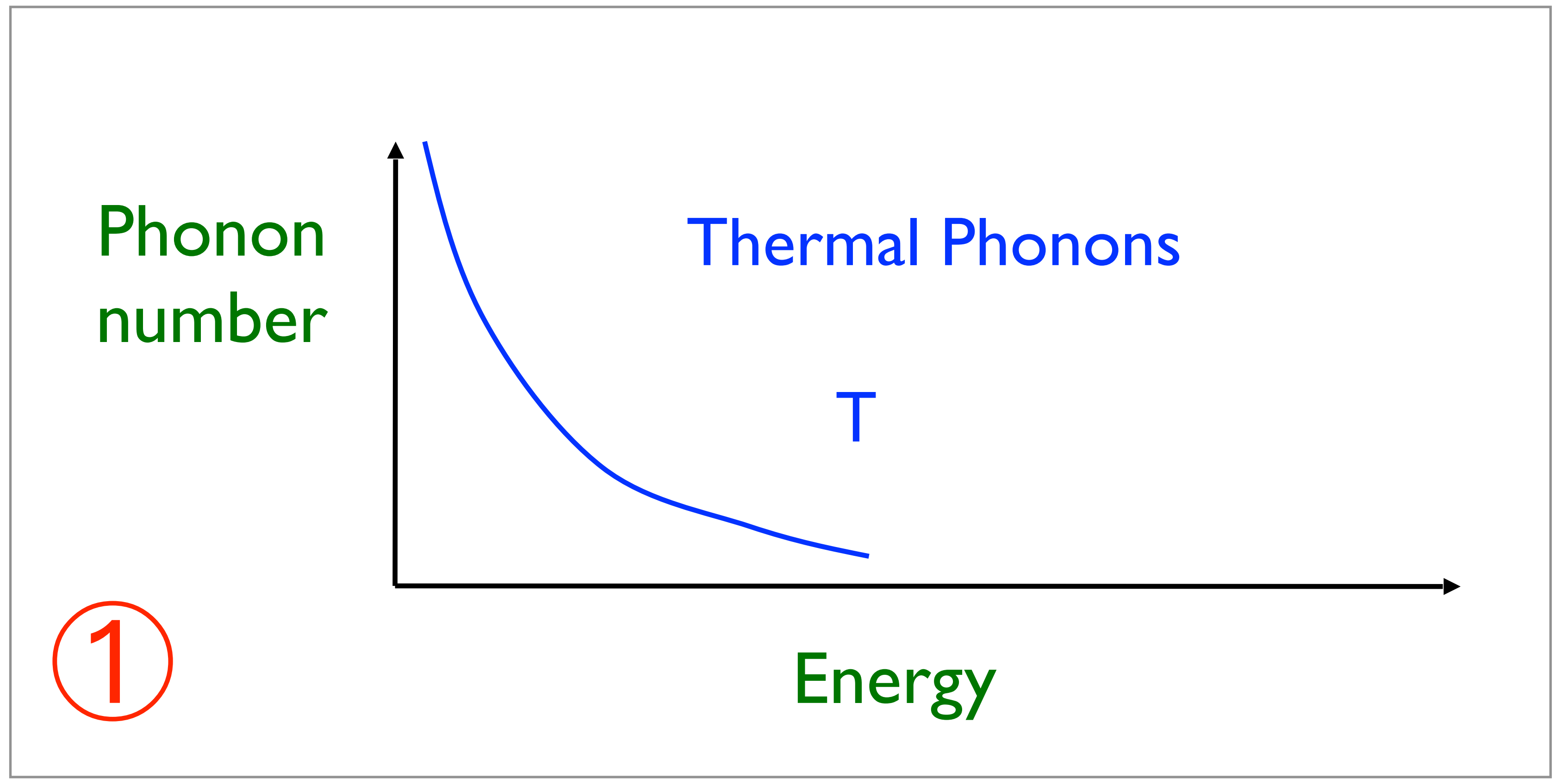

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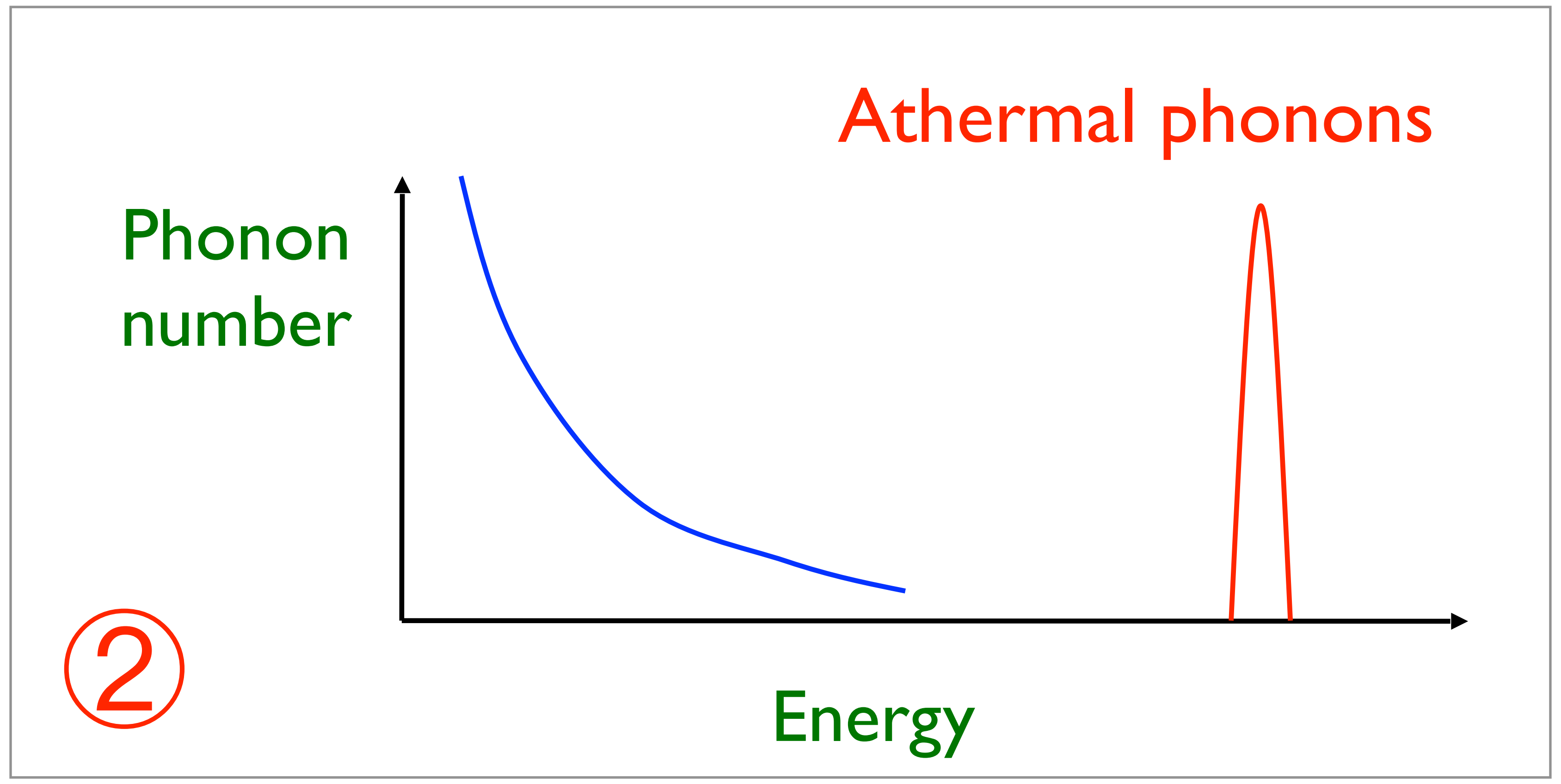

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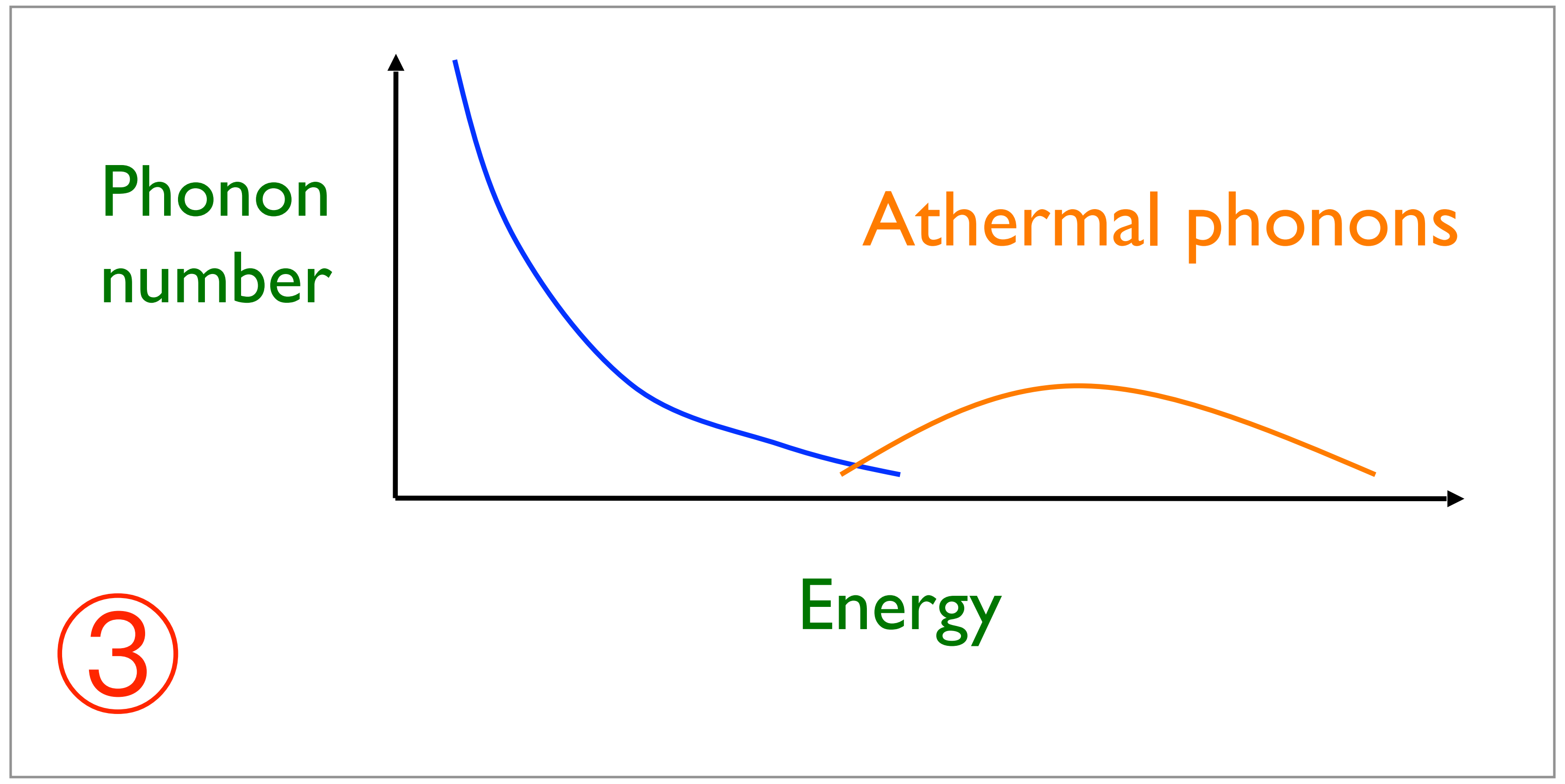
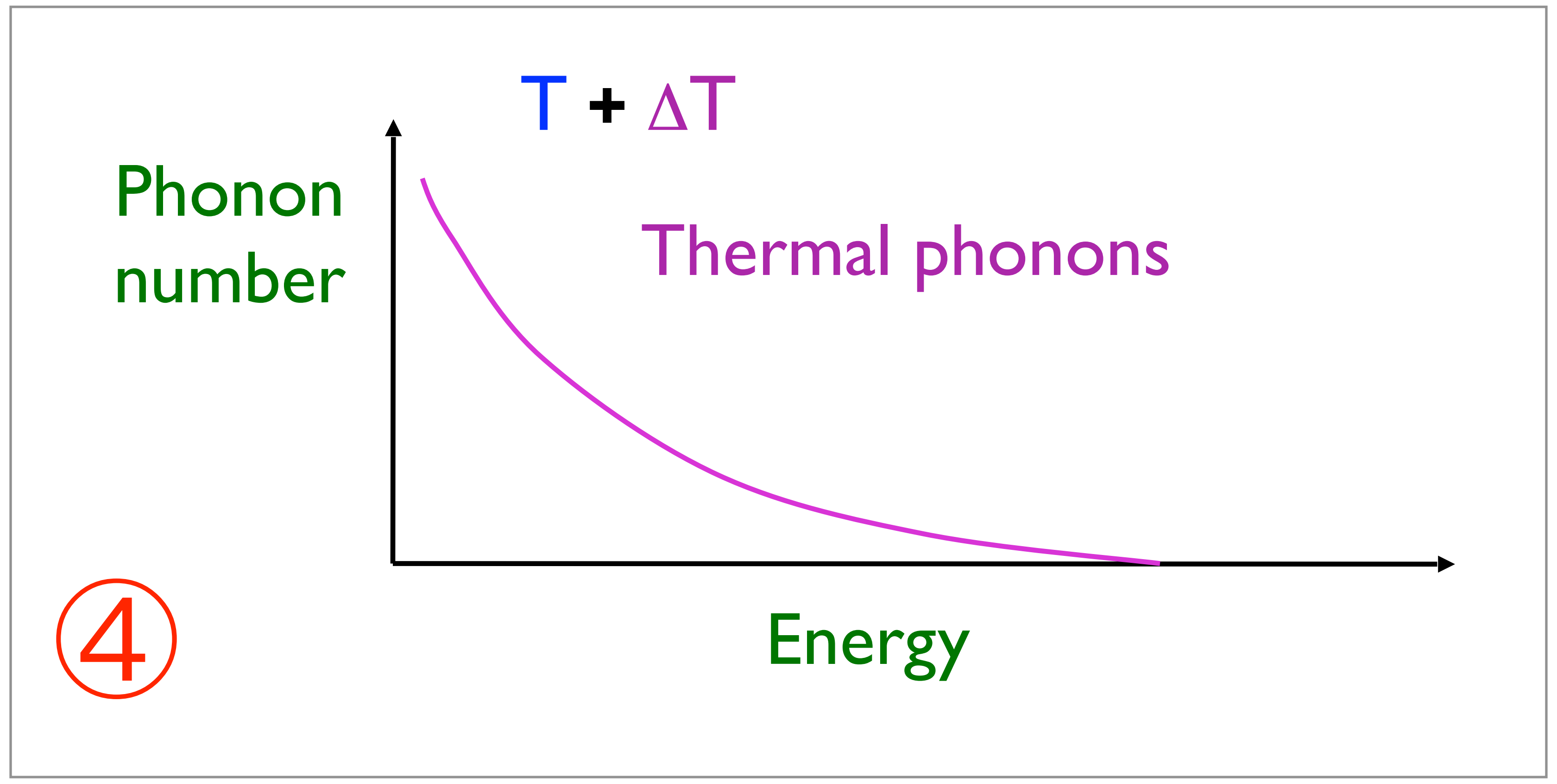


New thermal distribution



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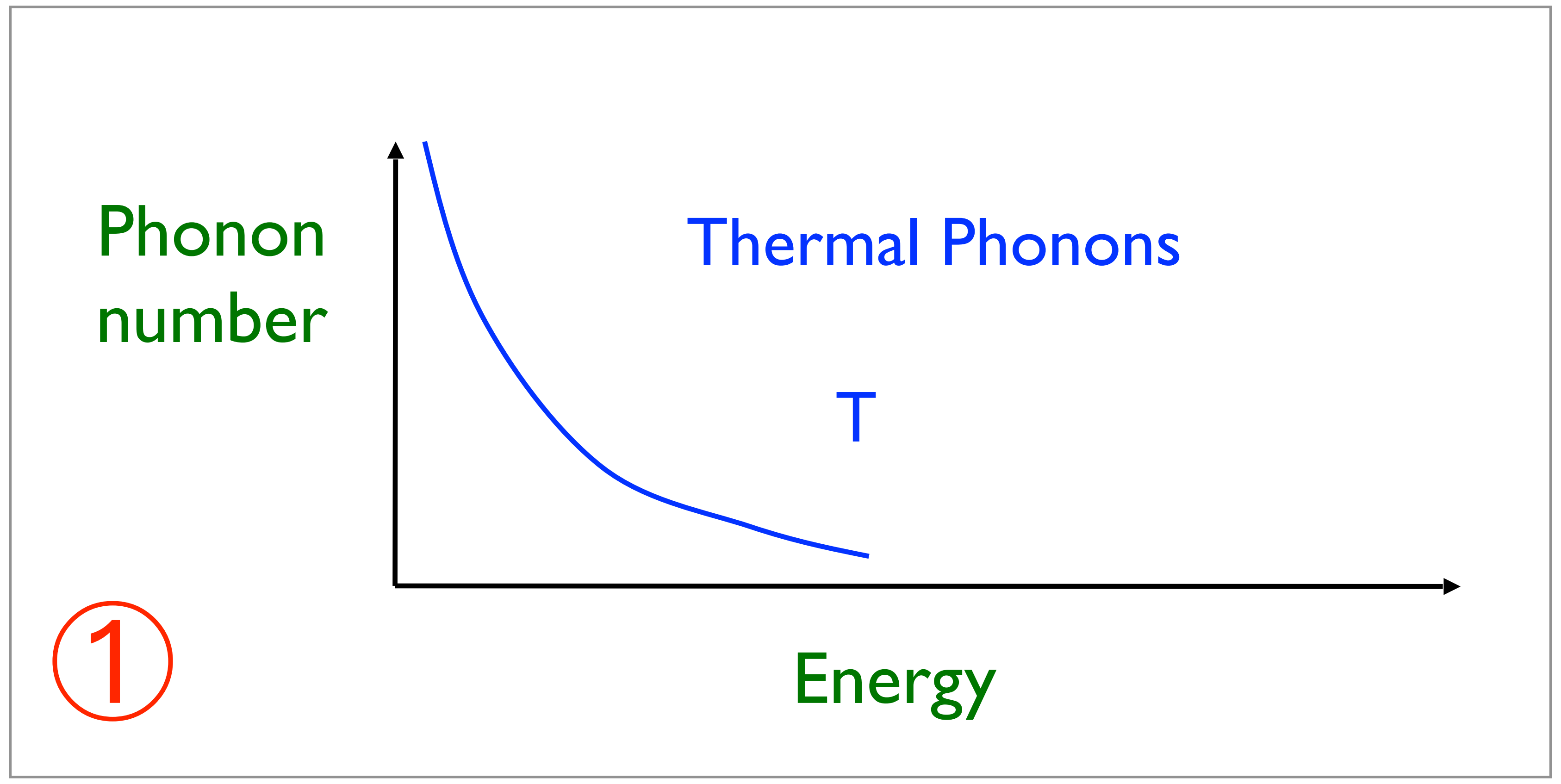

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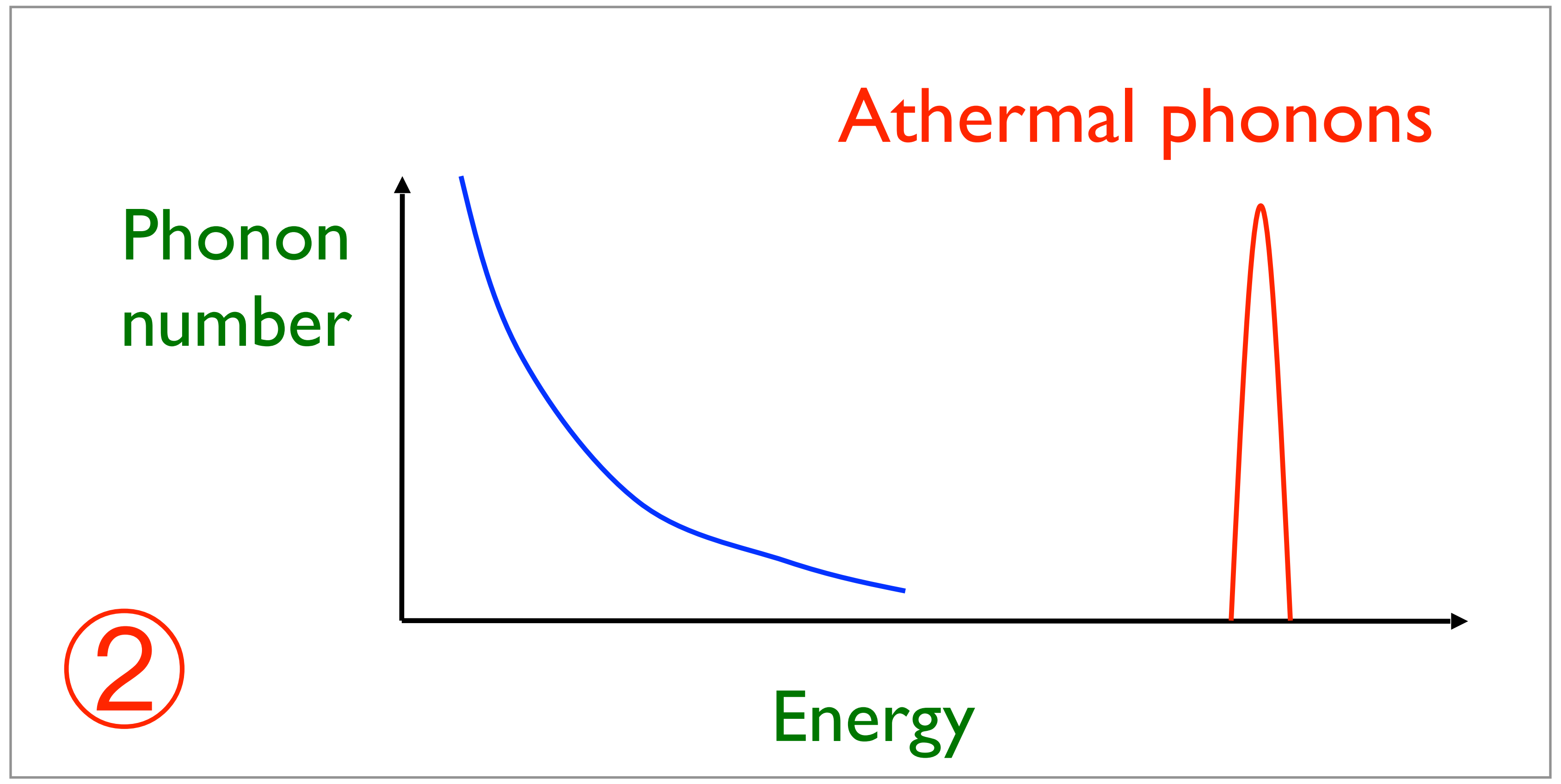

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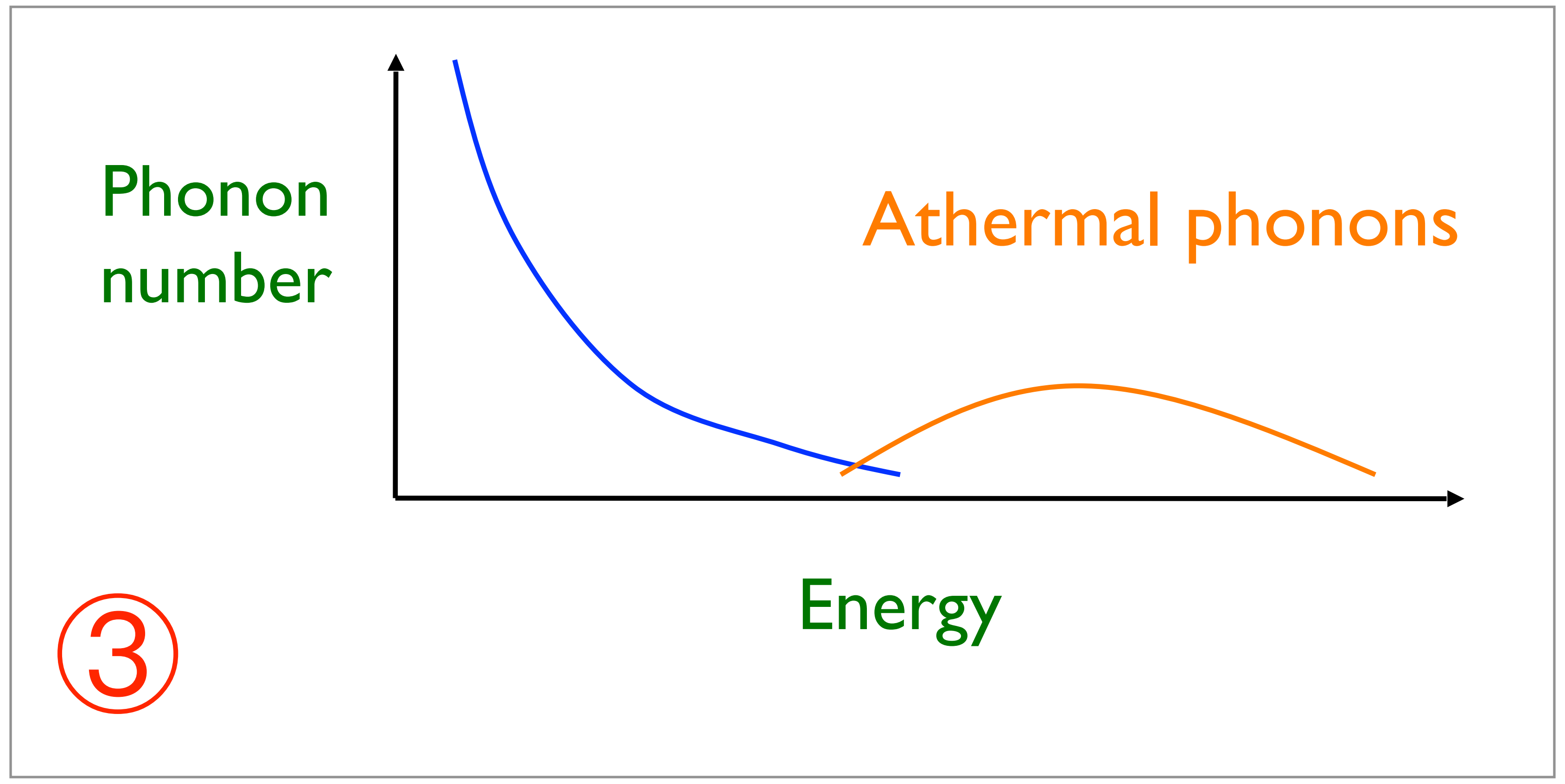
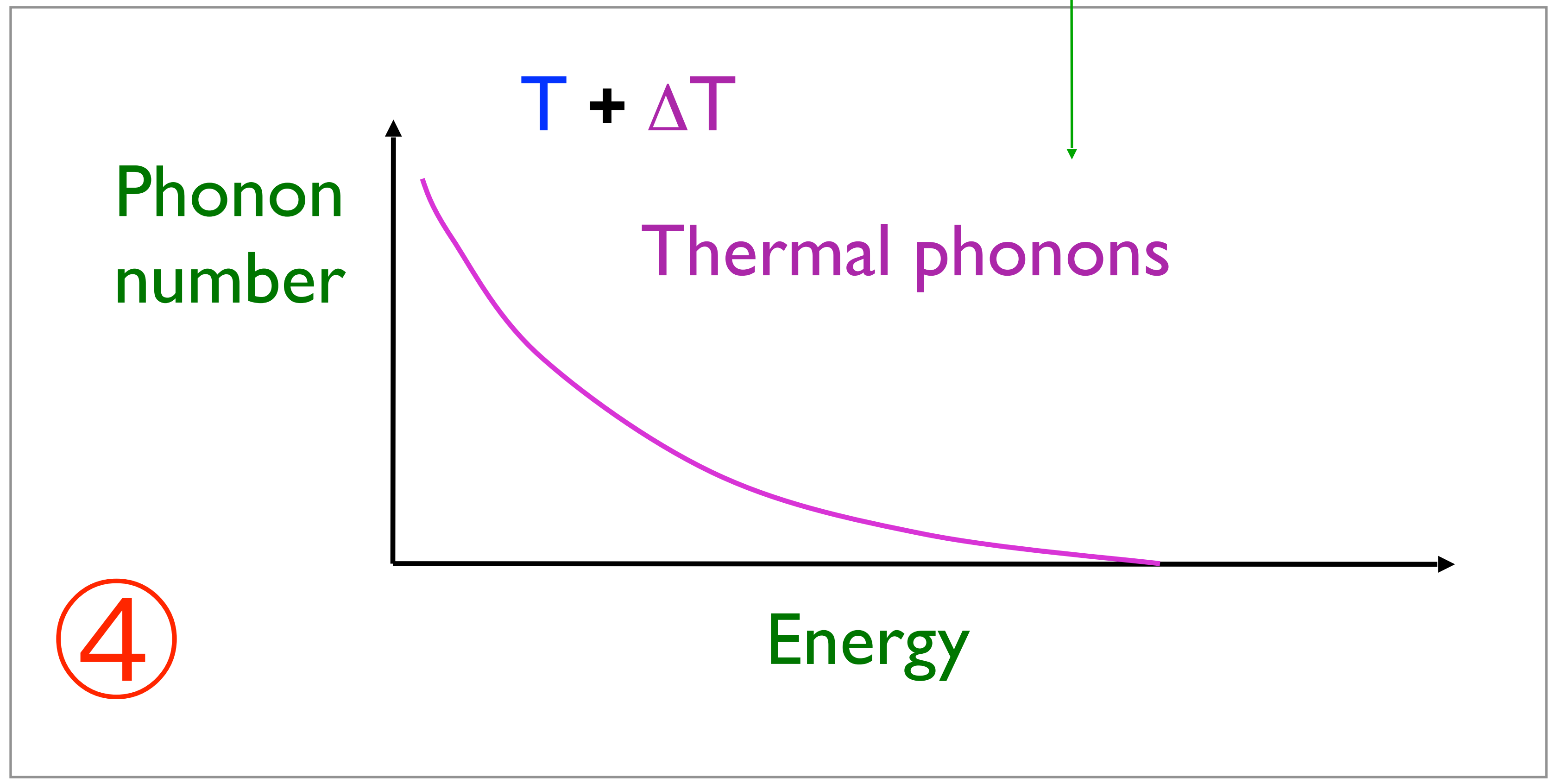


Detector operating here:
Perfect calorimeter
Energy

New thermal distribution



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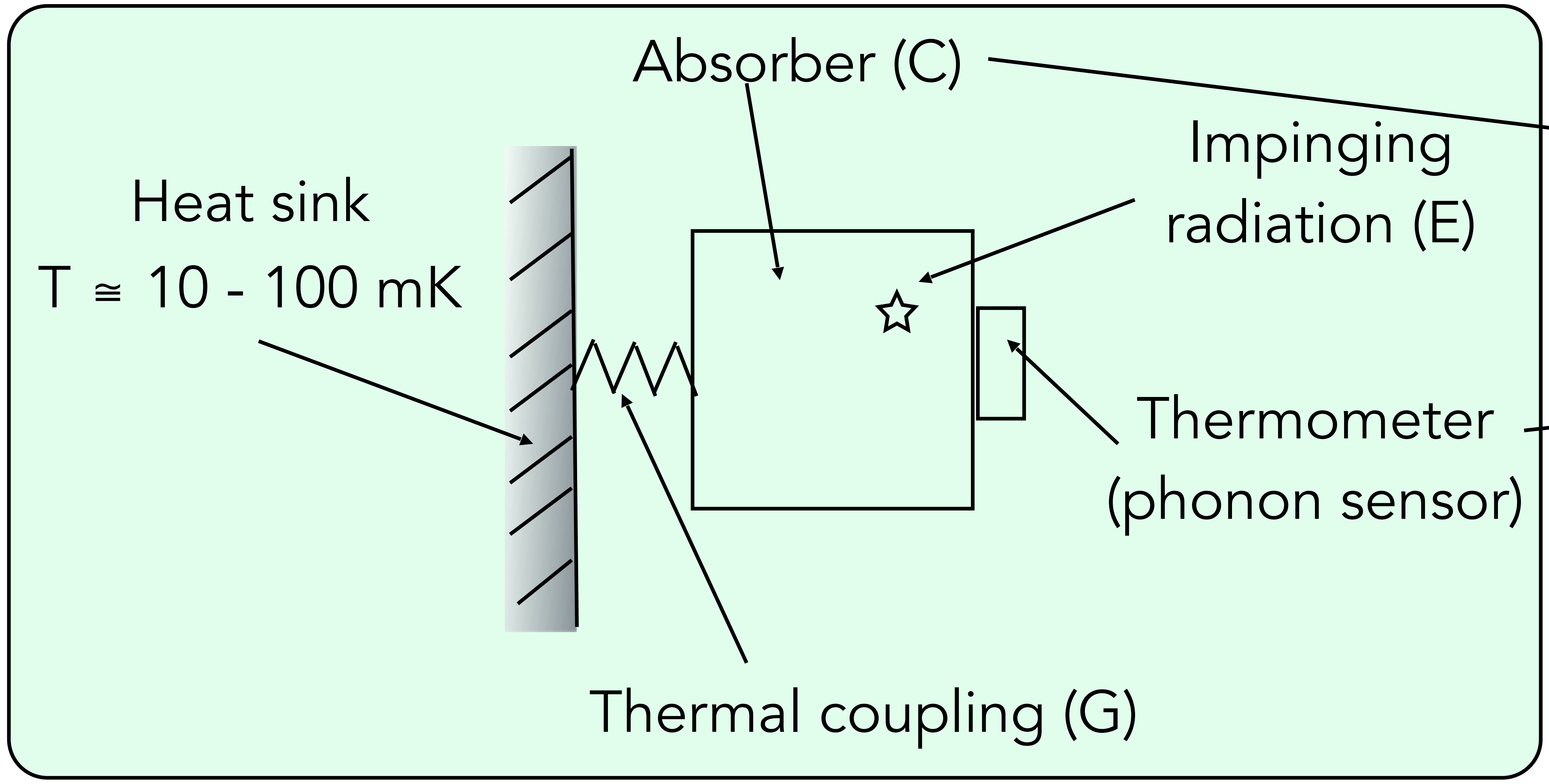


Absorber (C)

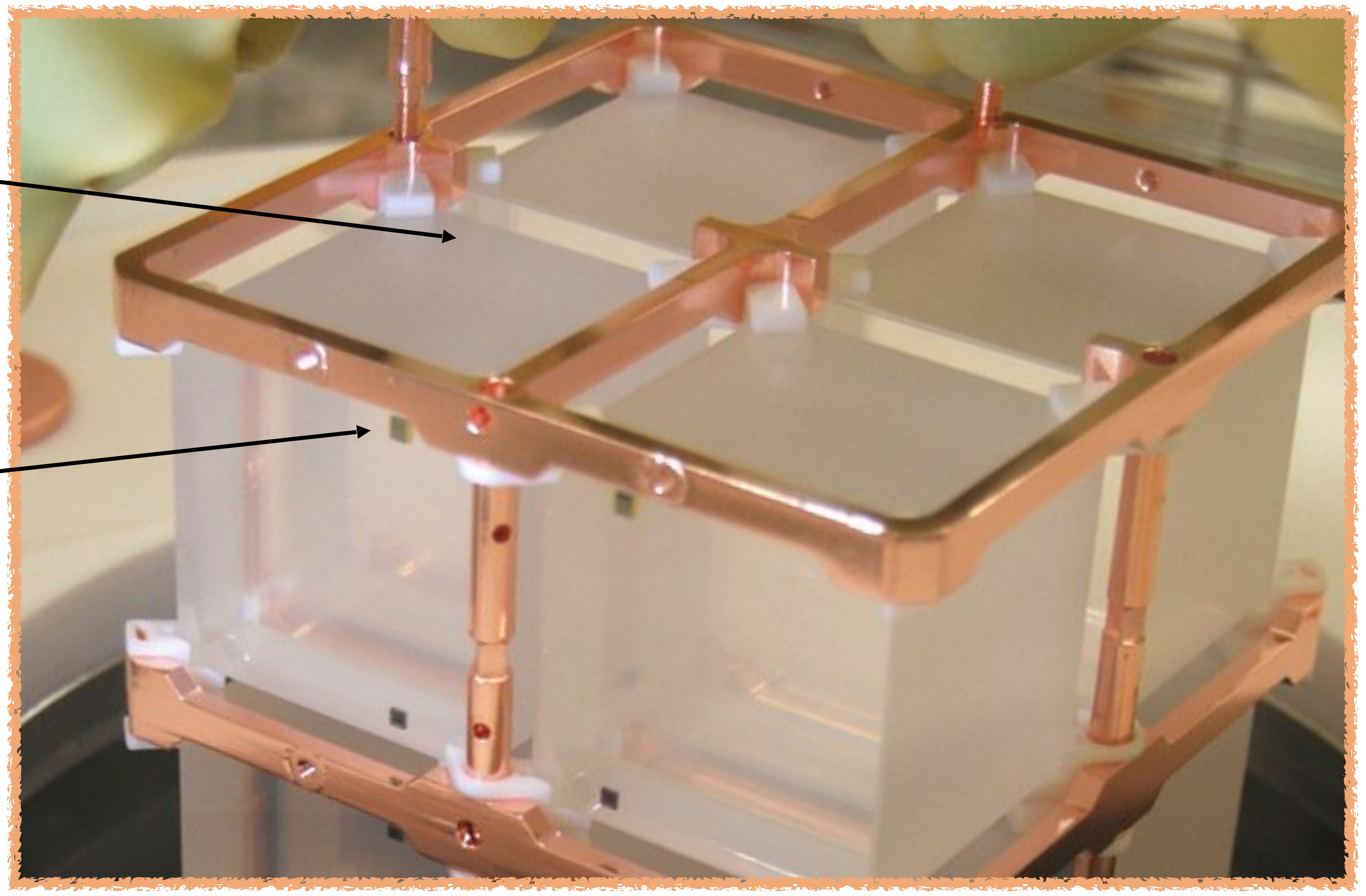
Impinging radiation (E)

Heat sink

T ≅ 10 - 100 mK

Thermometer (phonon sensor)

Thermal coupling (G)



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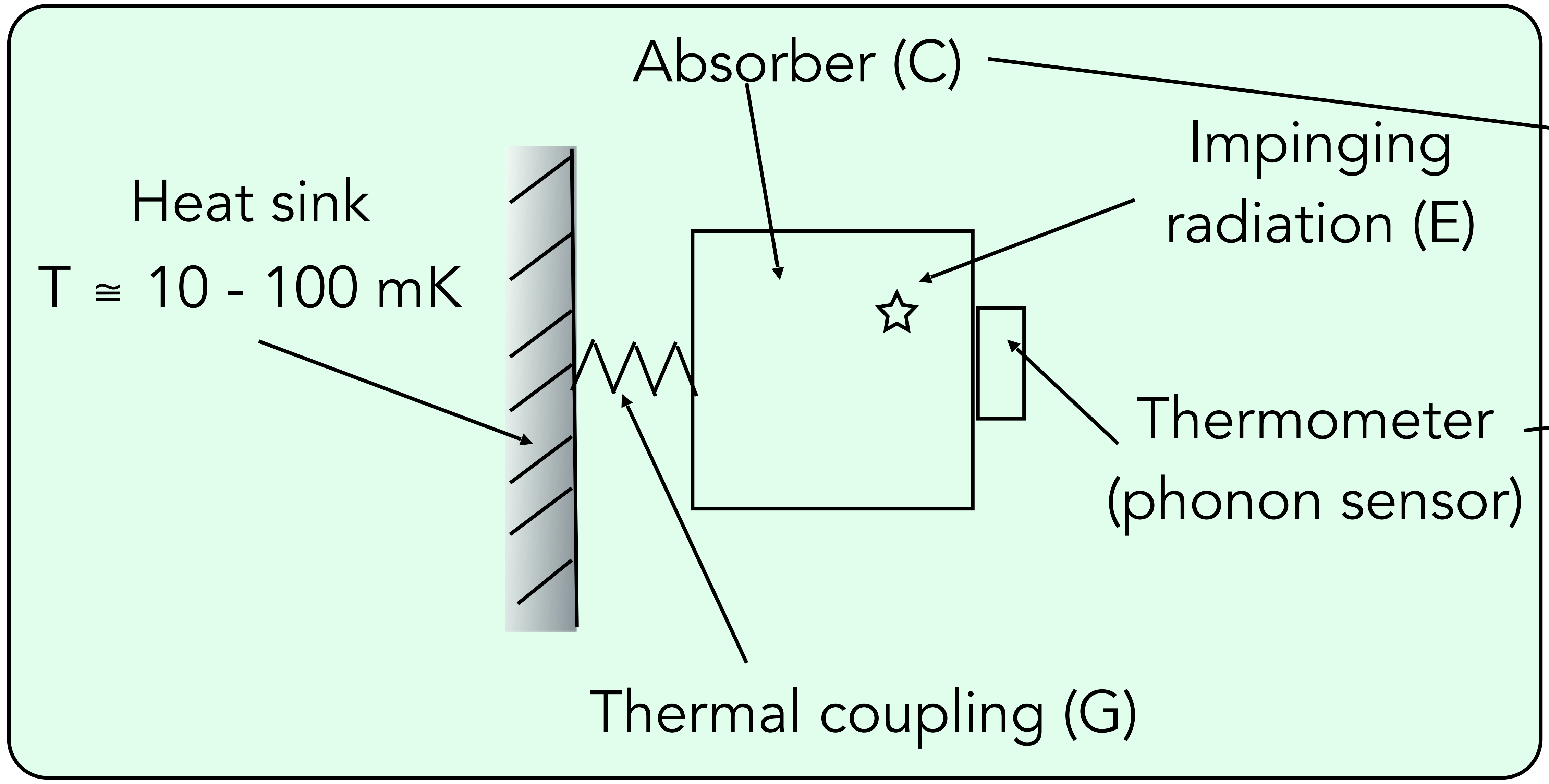

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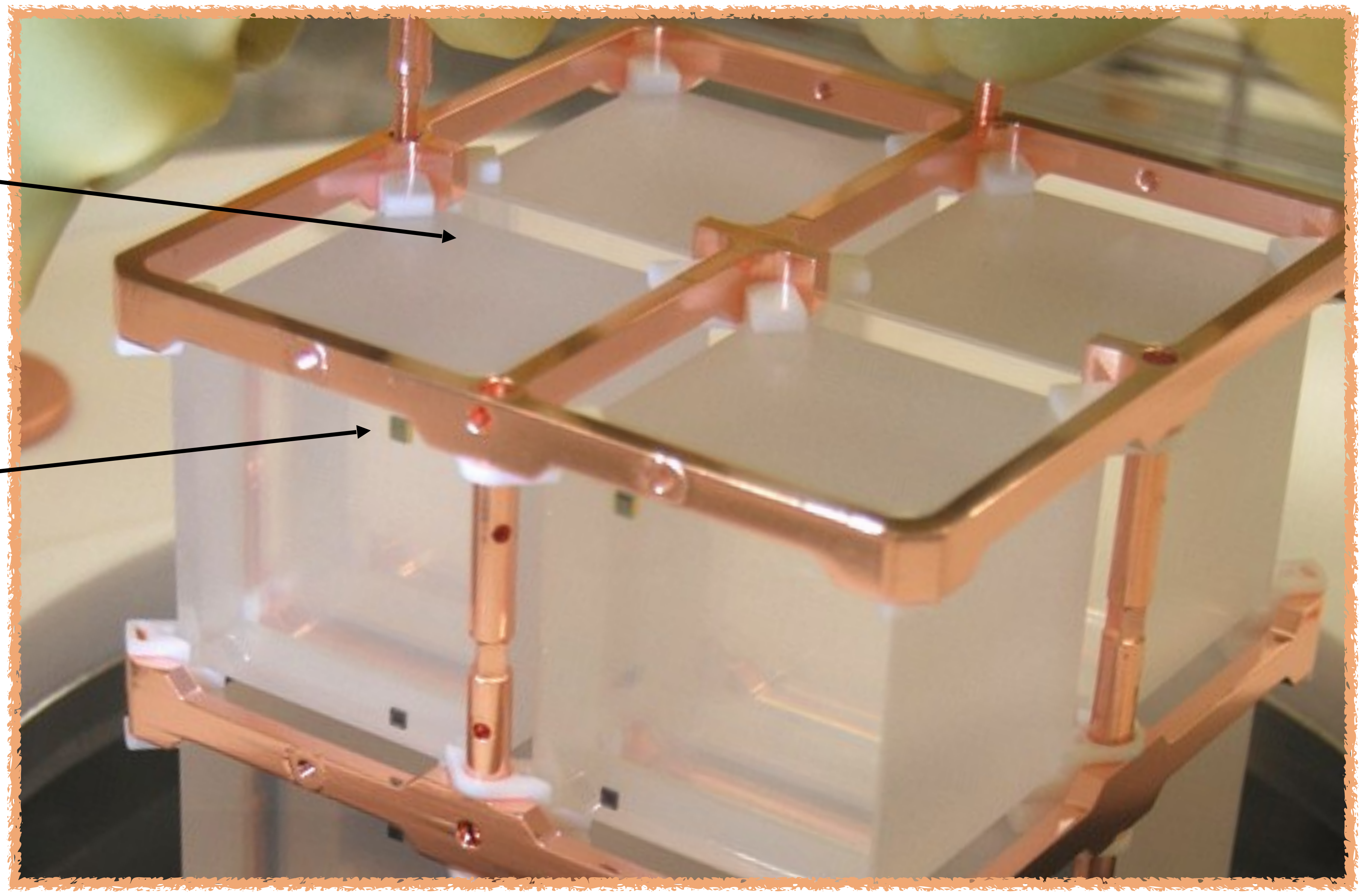
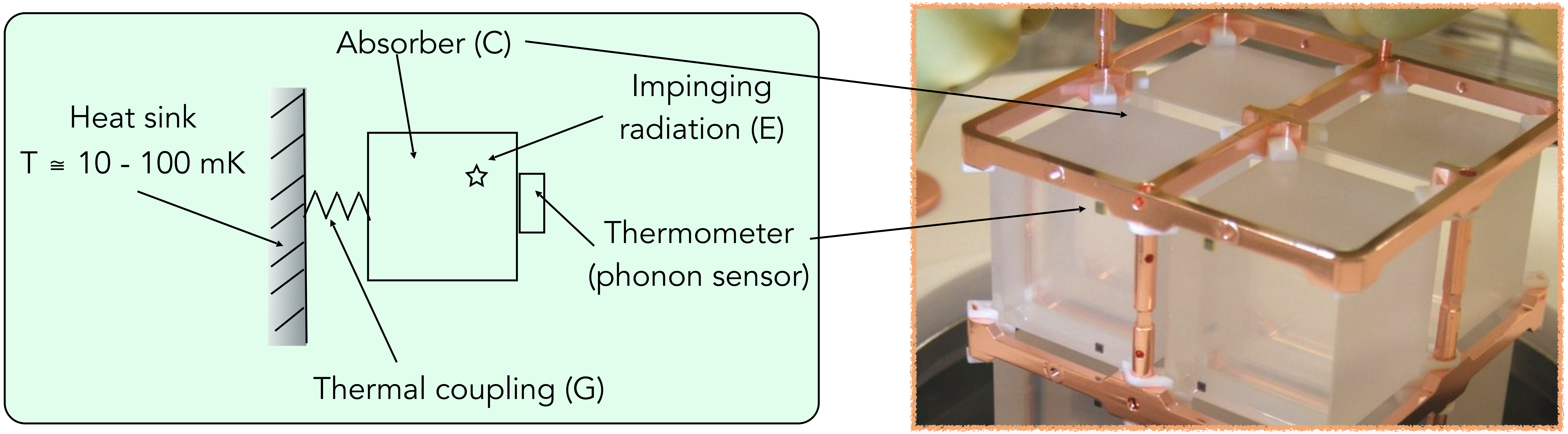


- The only relevant parameter for the energy absorber is the heat capacity C.
- The thermal conductance to the bath G enables the temperature recover.

Signal amplitude $\Delta T = E/C$ Relaxation time $\tau = C/G$

Perfect calorimeter



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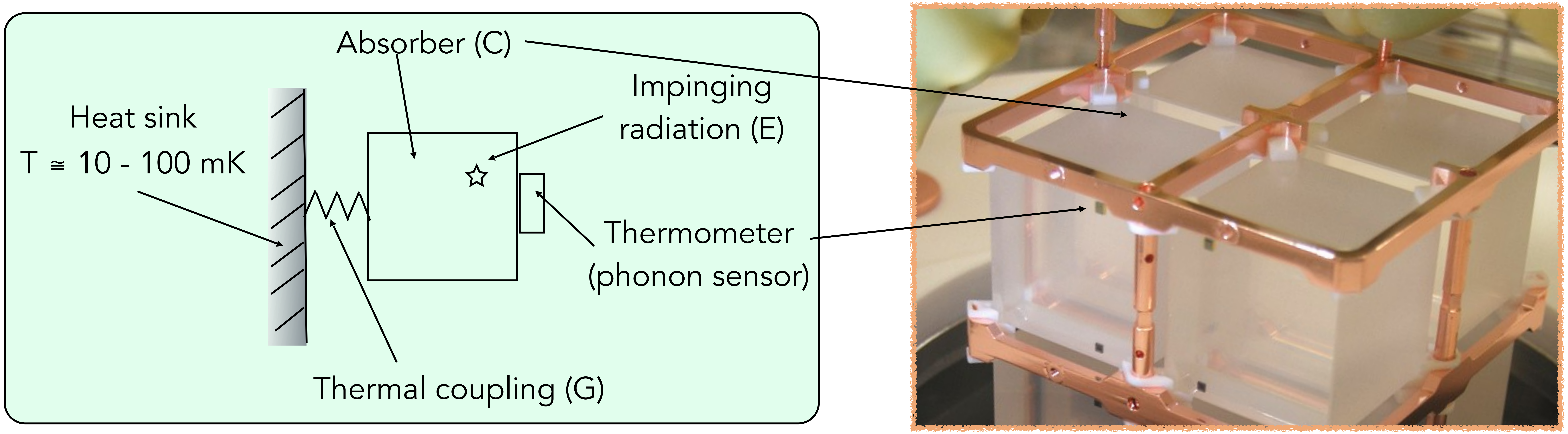
- Dielectric and diamagnetic materials are preferred

$$C \propto (T/\Theta_D)^3 \text{ (Debye Law)}$$

Wide choice of materials!

Perfect calorimeter



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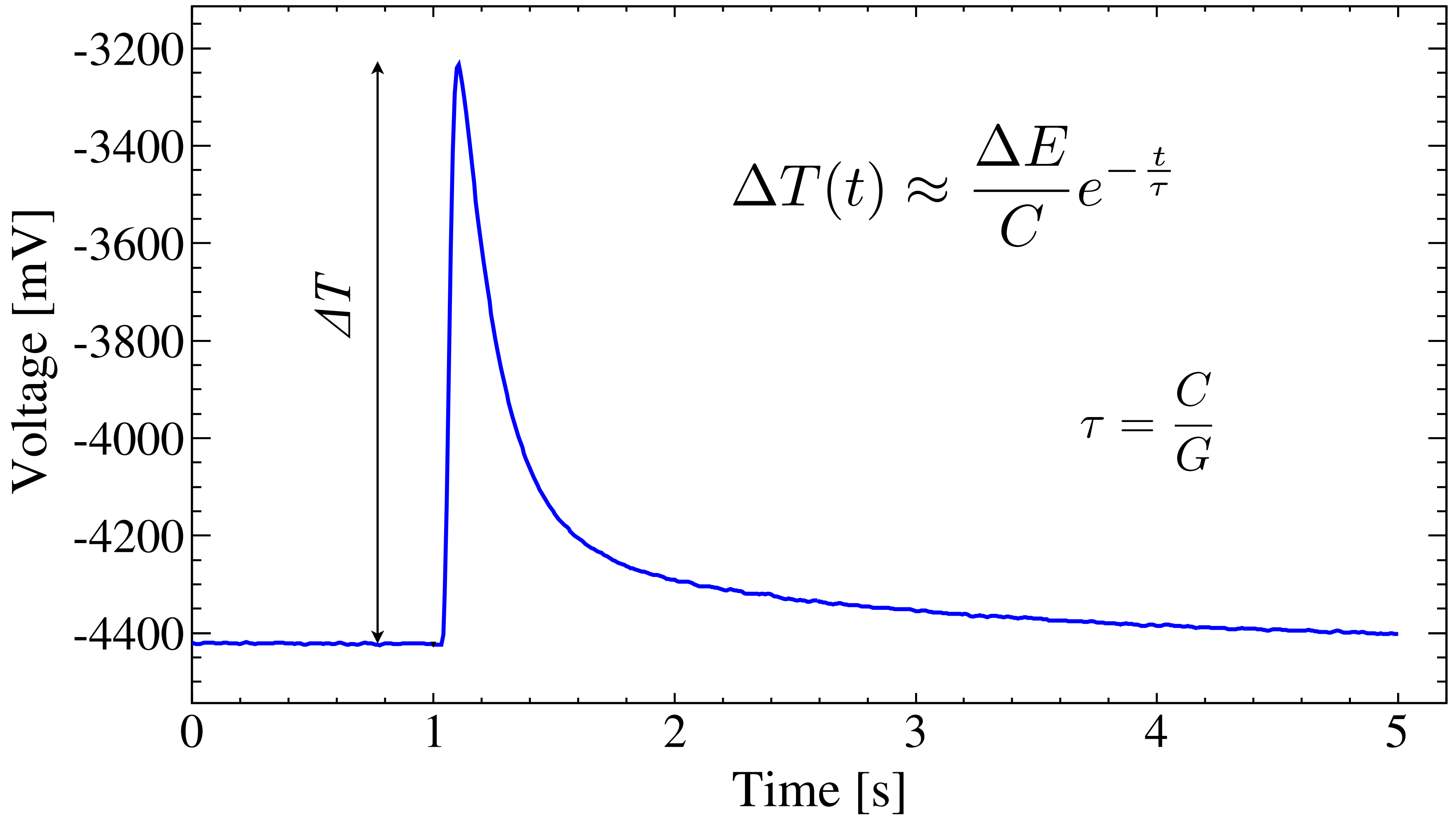

$$\Delta T(t) \approx \frac{\Delta E}{C} e^{-\frac{t}{\tau}}$$

$$\tau = \frac{C}{G}$$

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$C \propto (T/\Theta_D)^3$ (Debye Law)

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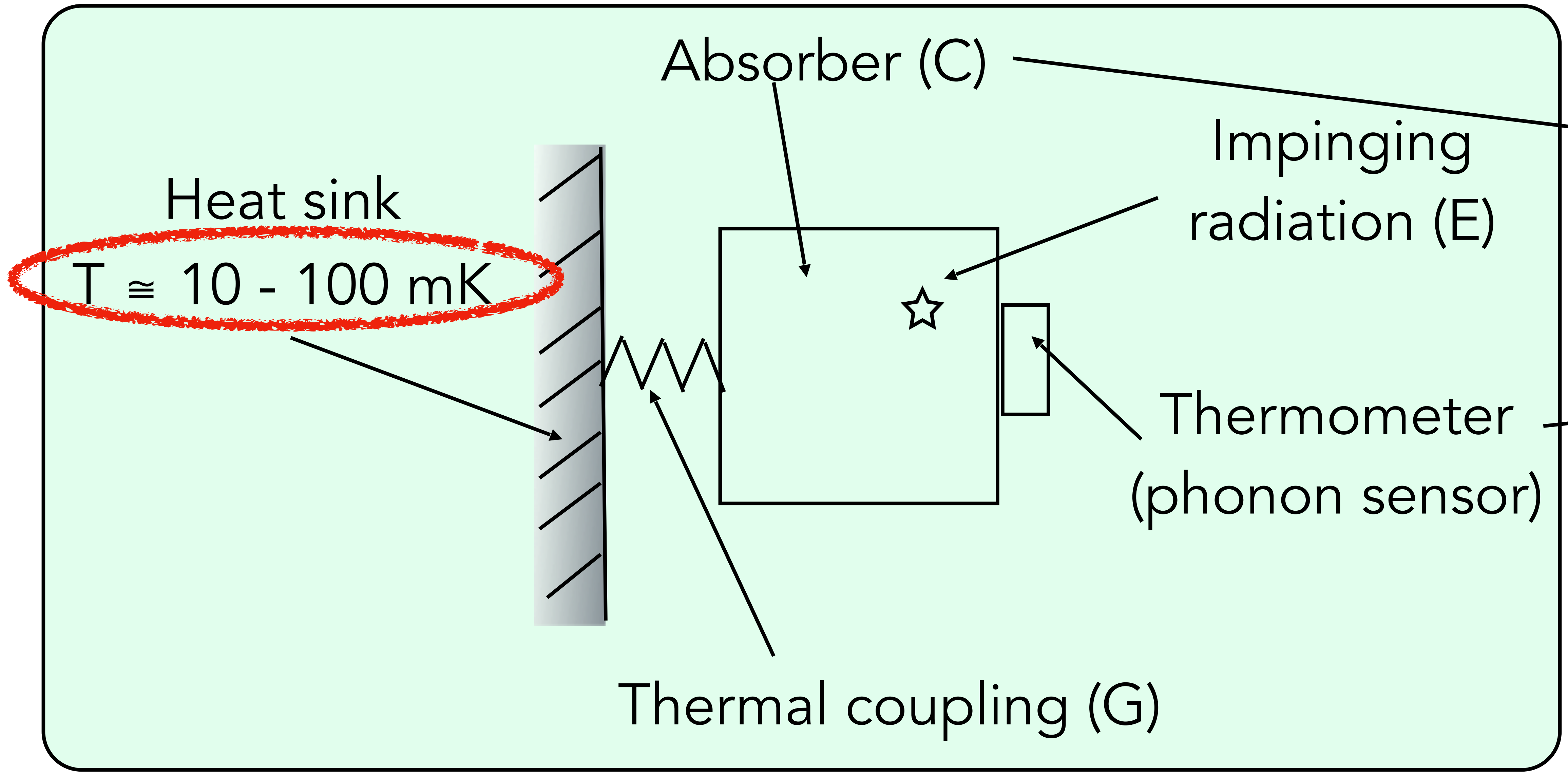
Perfect calorimeter



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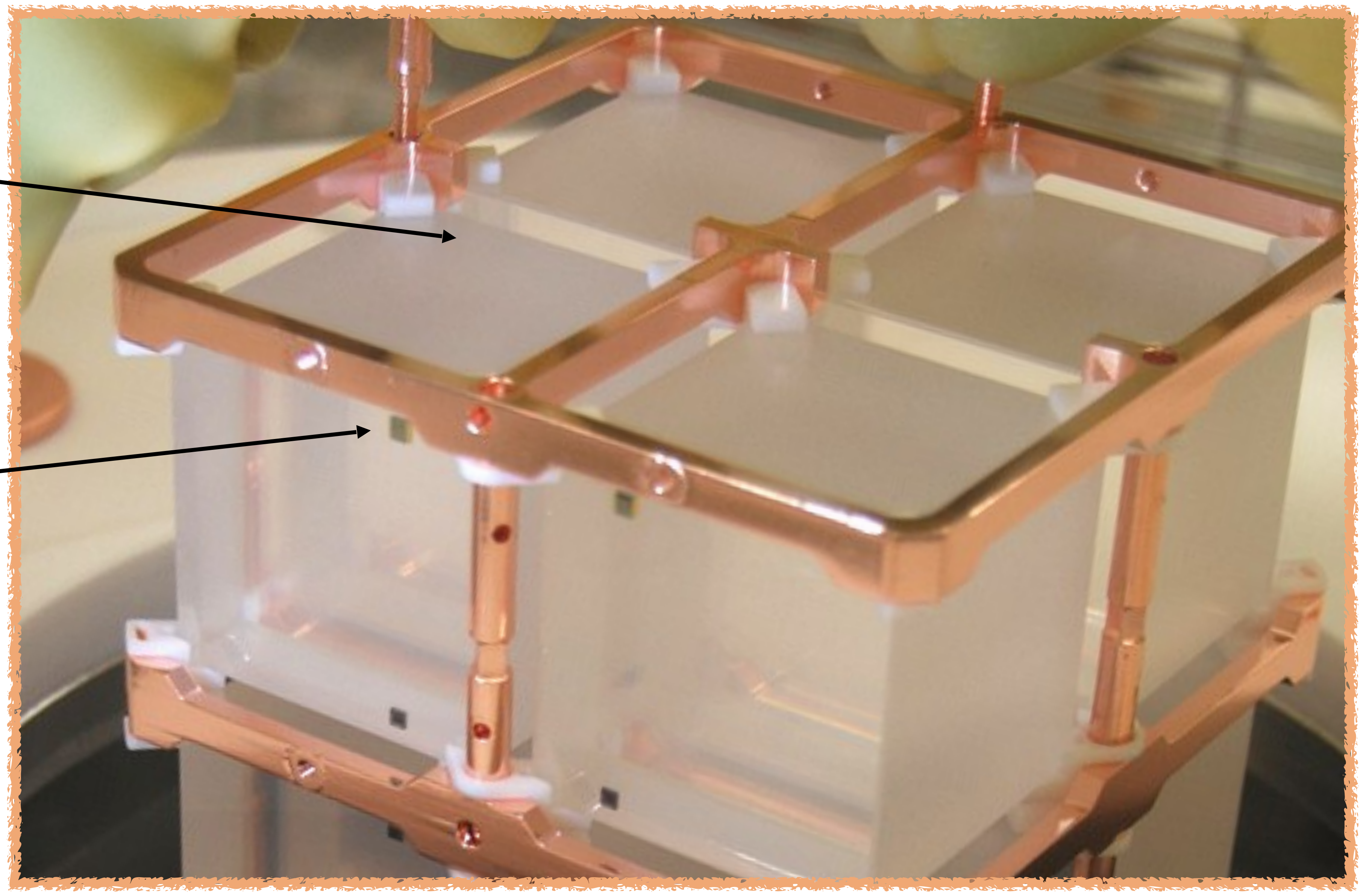

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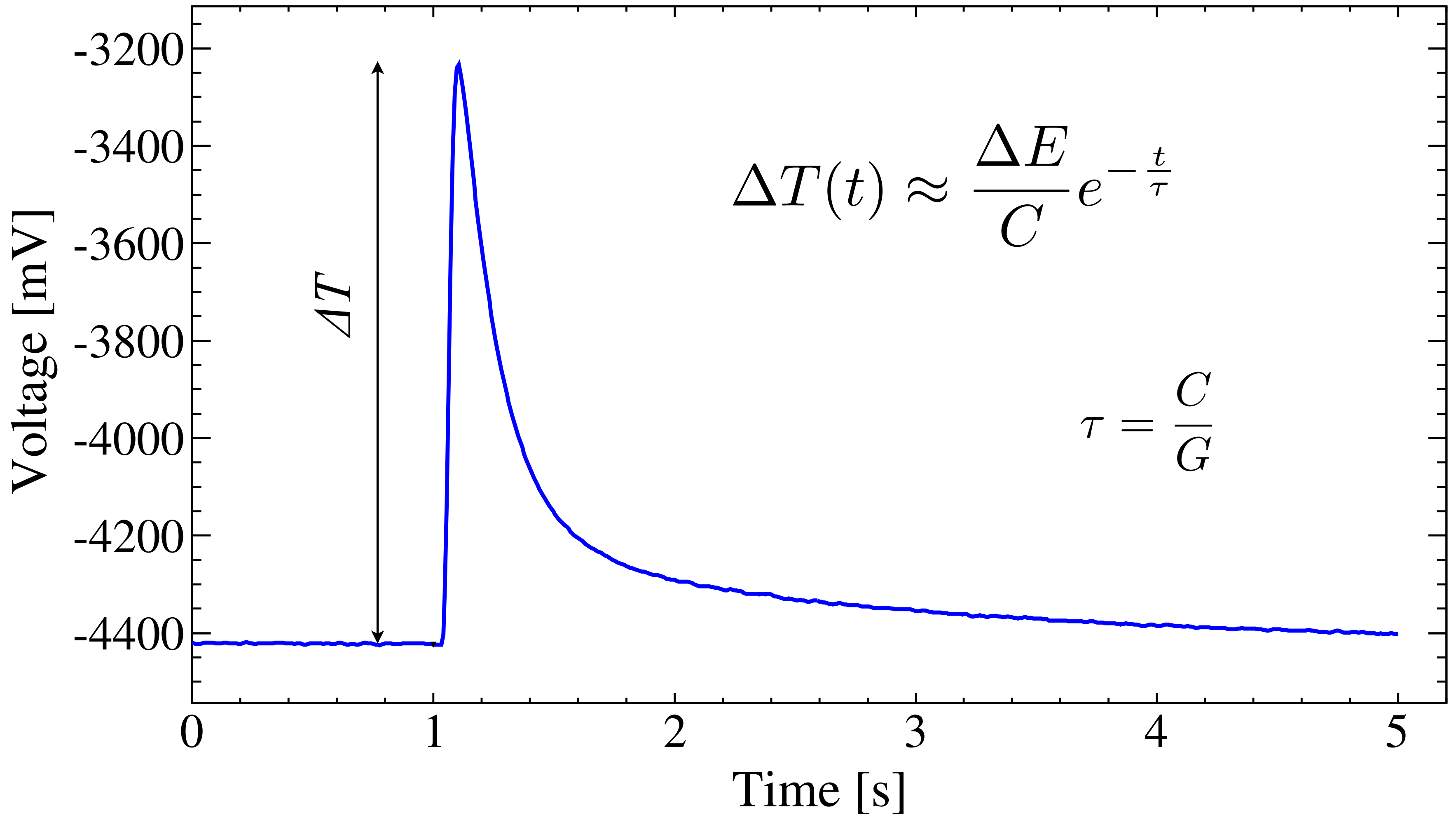


- Dielectric and diamagnetic materials are preferred

$C \propto (T/\Theta_D)^3$ (Debye Law)

Wide choice of materials!

1 keV in 1 g of TeO_2 at 300 K produce a T increase signal of ~10^{-16} K, while at 10 mK ~1 μK

Summary

PROs:

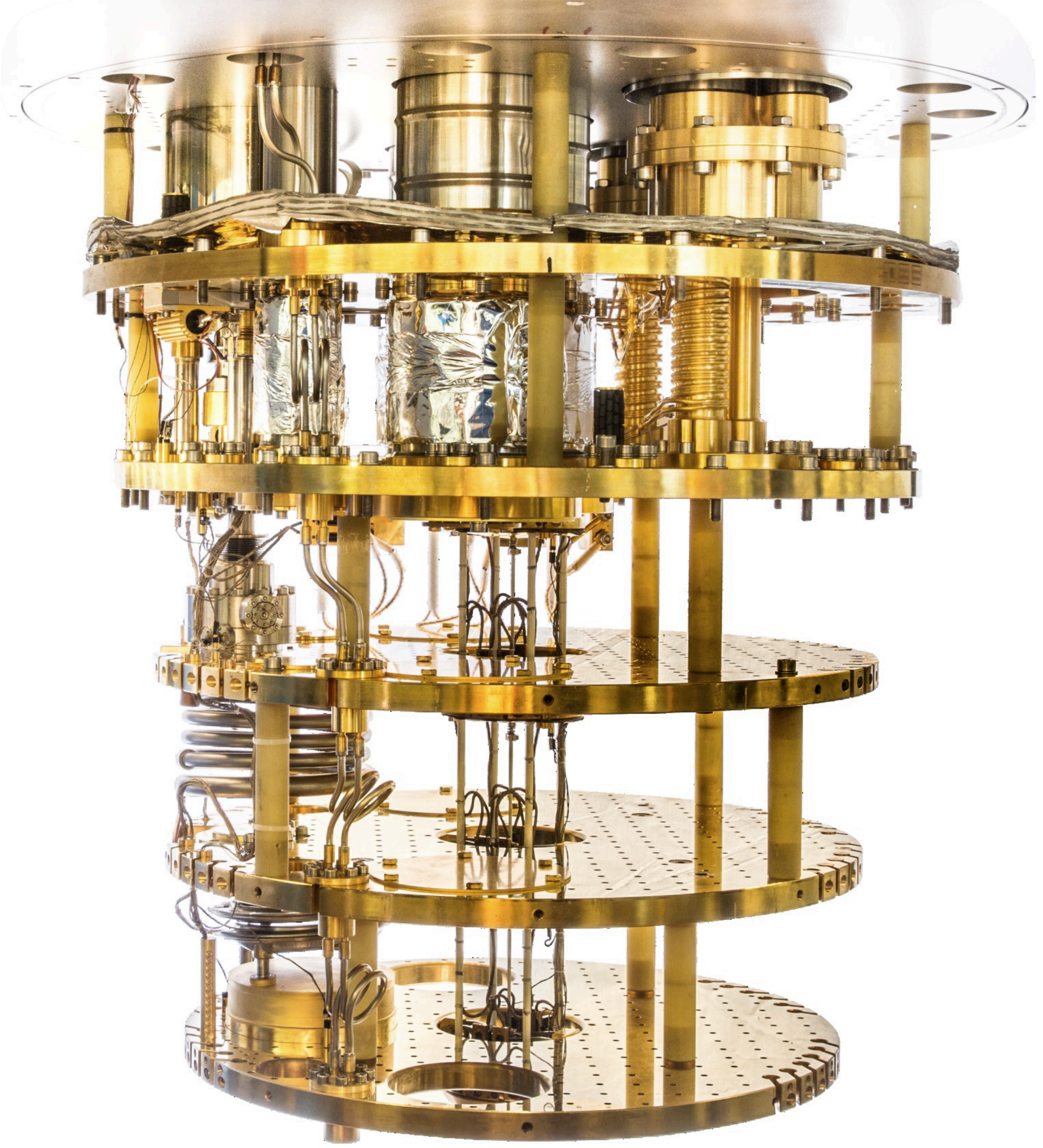
- Very good energy resolution
- Wide choice of materials for the energy absorber (also multi-target)
- Possibility of building big detectors (~kg scale)

CONs:

- Very slow signal (50 msec - 2 sec, depends on sensor and mass)
- Need to work at low temperature
- No radiation identification (?)
- Difficult to scale at very large masses (>multi-tonne)

A (short) digression: physic of low temperature

Dilution Refrigeration



In 1900 century many development have been performed in cryogenic physics leading to the capability of reaching mK temperatures with reliable systems. Dilution units have open the way to mK applications in a wide range of physic fields.

A bit of history

1951: idea proposed by H. London

1962: H. London, G. R. Clarke, and E. Mendoza, *Phys. Rev.* **128**, 1992

1964: First Dilution Unit (DU) in operation (Leiden)

1967: First commercial DU by Oxford Instruments

Dilution refrigerators are the “workhorse” of mK temperature physics

- Pomeranchuk cooling
- Adiabatic demagnetisation

Today producers

- Oxford Instruments
- Bluefors
- Leiden Cryogenics
- Cryoconcept
- JanisULT

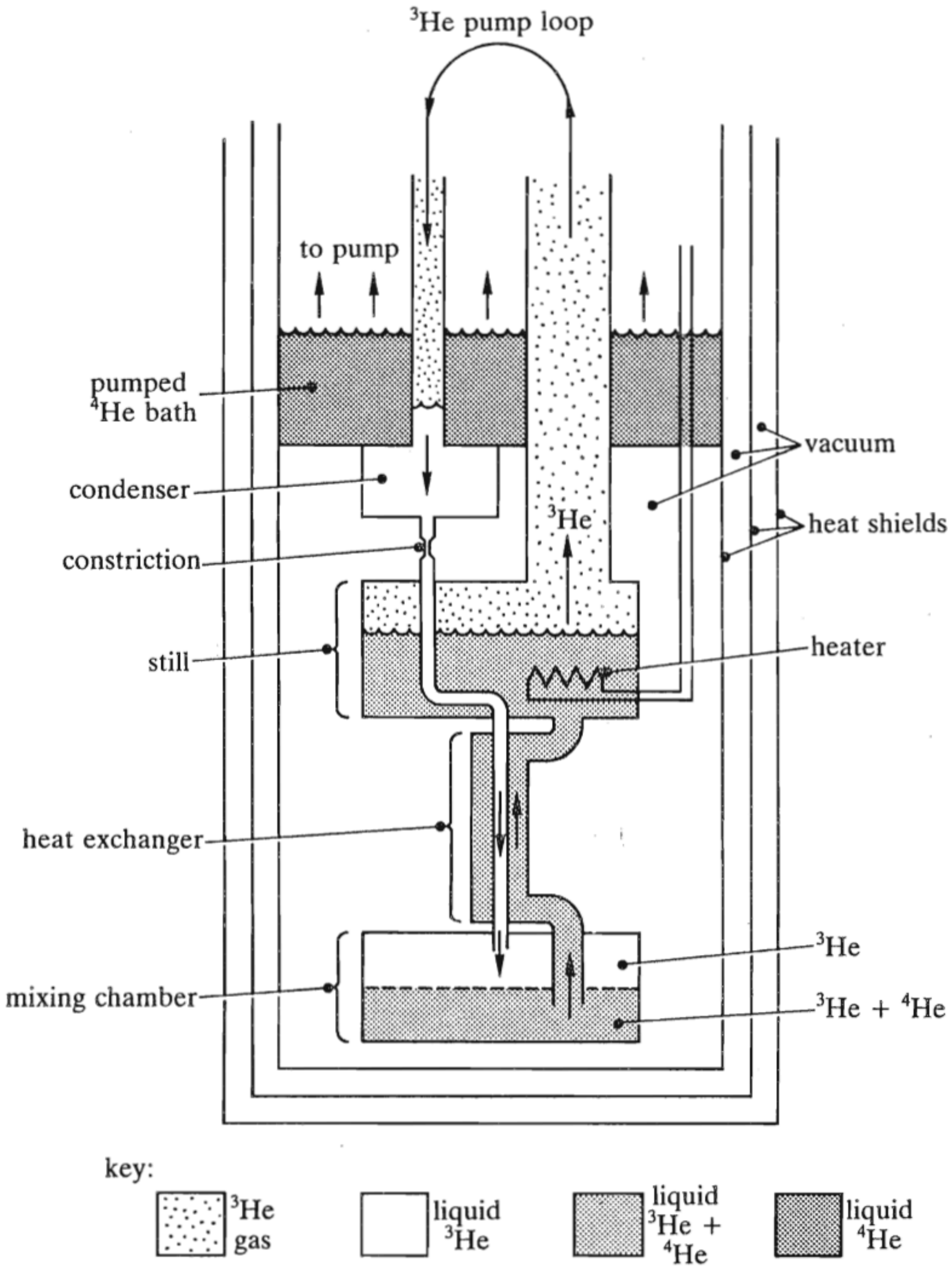
DU concept

Principal parts of a Dilution refrigerator

- 4K stage (not drawn)
- 1K stage (pumped LHe bath)
- Still
- Heat exchanger (usually more than one)
- Mixing Chamber

Important aspects

- Ultra high vacuum
- Thermometry
- Heat transfer
- Heat sources



Enthalpy

- Enthalpy is a fundamental quantity in cryogenics defined as

$$H = U + pV$$

- The pressure–volume term expresses the work required to establish the system's physical dimensions, i.e. to make room for it by displacing its surroundings
- Depends only on the final configuration of internal energy, pressure and volume, not on the path taken to achieve it, therefore is a state function
- It is particularly useful if you want to estimate the amount of heat to be removed (added) to cool-down (heat-up) a mass
- E.g. how much liquid nitrogen is needed to cooldown 1 kg of Aluminum from 300K to 77K?

$$H^{Al}_{300K} = 170.4\ J/g$$

$$H^{Al}_{77K} = 8.4\ J/g$$

$$\Big\downarrow$$

$$\Delta H^{Al}_{300K-77K} = 162\ J/g$$

$$H^{N_2\,gas}_{300K} = 462.1\ J/g$$

$$H^{N_2\,gas}_{77K} = 228.7\ J/g$$

$$\longrightarrow \quad \Delta H^{N_2}_{300K-77K} = 233.4\ J/g$$

$$H^{N_2\,liq}_{77K} = 29.4\ J/g$$

$$\longrightarrow \quad L^{N_2}_{vap} = 199.3\ J/g = 160.7\ kJ/l$$

- 1.01 liters using only the latent heat
- 0.41 liters using also the enthalpy to 300K

Cooling with cryogenic fluids

Amount of cryogenic fluid required to cool metals (litres/kg)

Cryogen		**N_2**	**^4He**	**^4He**
From		300 K	77 K	300 K
To		77 K	4.2. K	4.2 K
Using only L_{vap}	Aluminum	1.01	3.20	66.6
	Copper	0.64	2.16	31.1
	Stainless Steel	0.53	1.43	33.3
Using $\Delta H+L_{vap}$	Aluminum	0.41	0.22	1.61
	Copper	0.29	0.15	0.79
	Stainless Steel	0.33	0.11	0.79

- A fast transfer of liquid is highly inefficient (especially for LHe)
- A separate transfer of LN_2 and LHe is advisable

Dilution refrigerator T stages

4.2 K stage

Dilution refrigerator T stages

4.2 K stage

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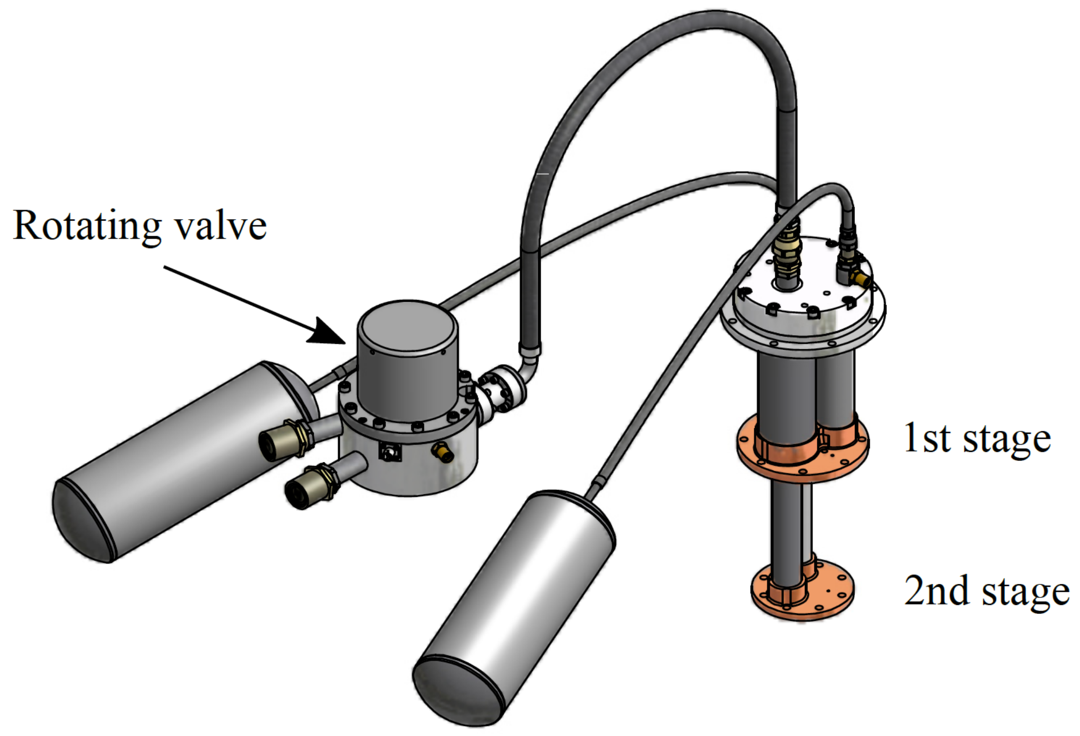
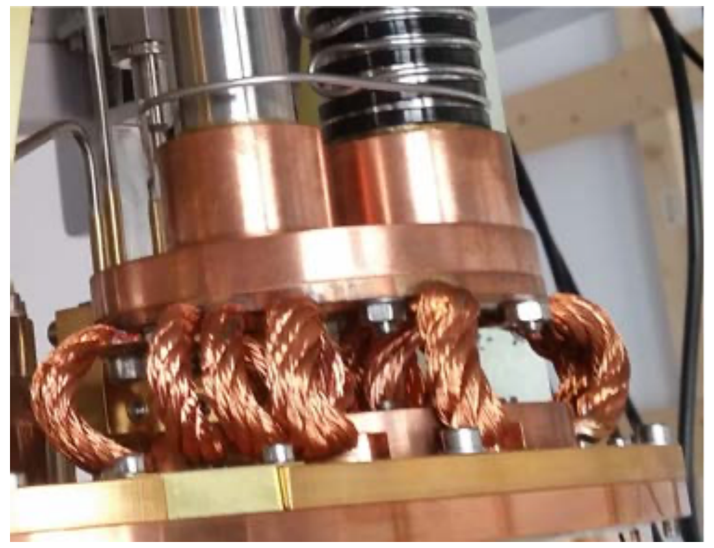
- In recent years liquid helium bath has been replaced by Pulse Tube cryocoolers due tu their fundamental advantages:

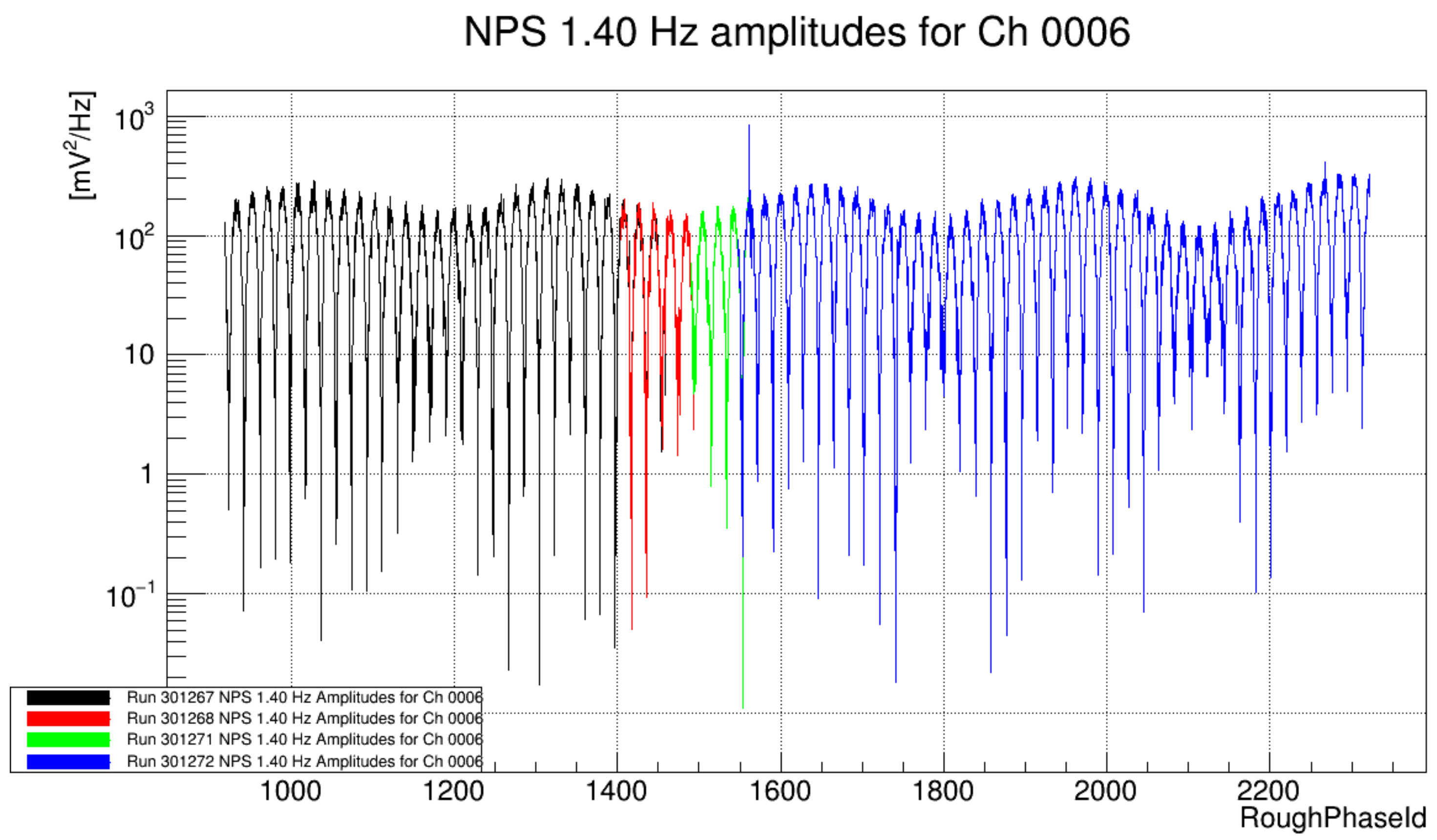


- Operation is greatly simplified
- Can provide two temperature stages (~ 40 K & ~ 4K)
- Liquid helium is getting more and more expensive
- Less leaks
- PT cooling power is constantly improving (2.5 W @ 4K)



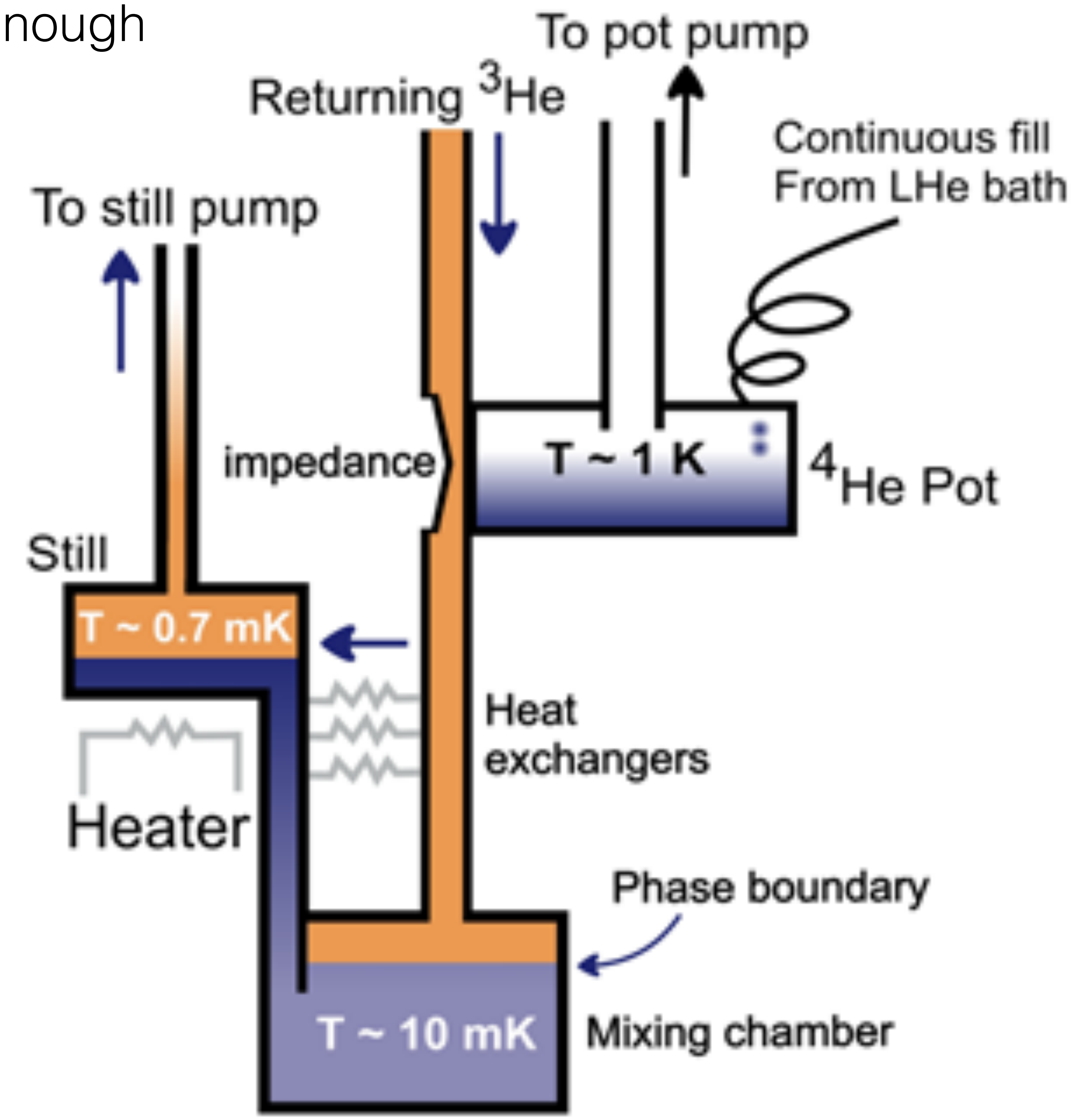
Main drawback is the induced vibrations:

- passive decoupling
- active noise cancellation



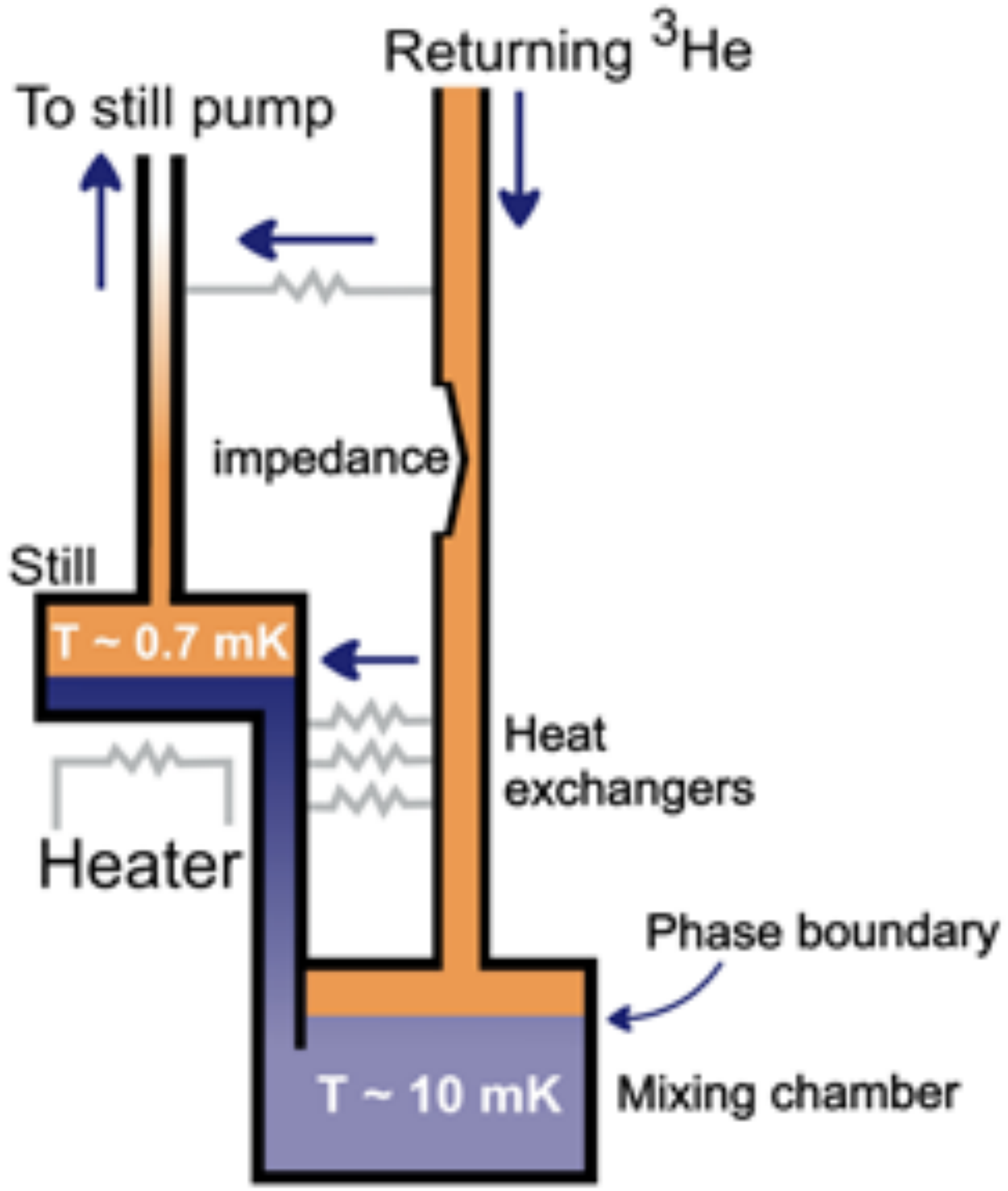
“Wet” DU (with LHe)

- A small amount of liquid helium from the LHe main bath feeds the 1K Pot
- A dedicated pot pump keeps the 1 K pot cold
- An impedance ensures the condensing pressure is high enough (~0.3 bar) for the returning ^{3}He to liquefy



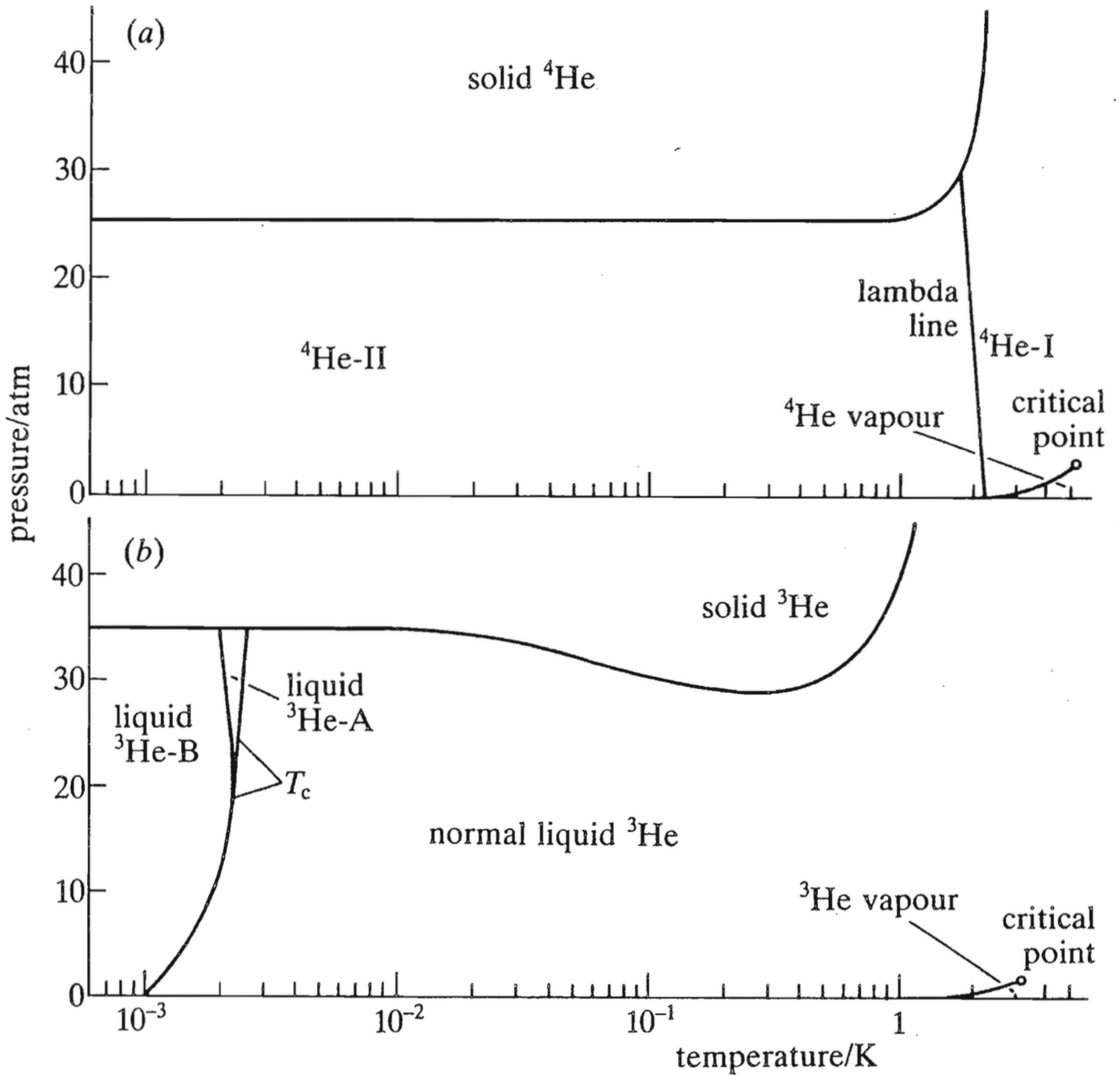
“Dry” DU (with PT)

- The 1 K pot is replaced by an extra heat exchanger located just before the impedance. The returning ^{3}He is cooled by the outgoing ^{3}He vapour from the still
- This heat exchanger in combination with the Joule-Thompson (JT) expansion happening in the impedance is enough to condense the gas
- The JT stage is not as efficient as a 1 K pot, so the condensing pressure is higher: typically 2.5 bar during the initial condensation, which drops to ~0.5 bar near base temperature where the circulation rate is lower
- The higher condensing pressure means an additional high pressure pump (or compressor) is required when circulation is started. It can be switched off when the system has reached base temperature



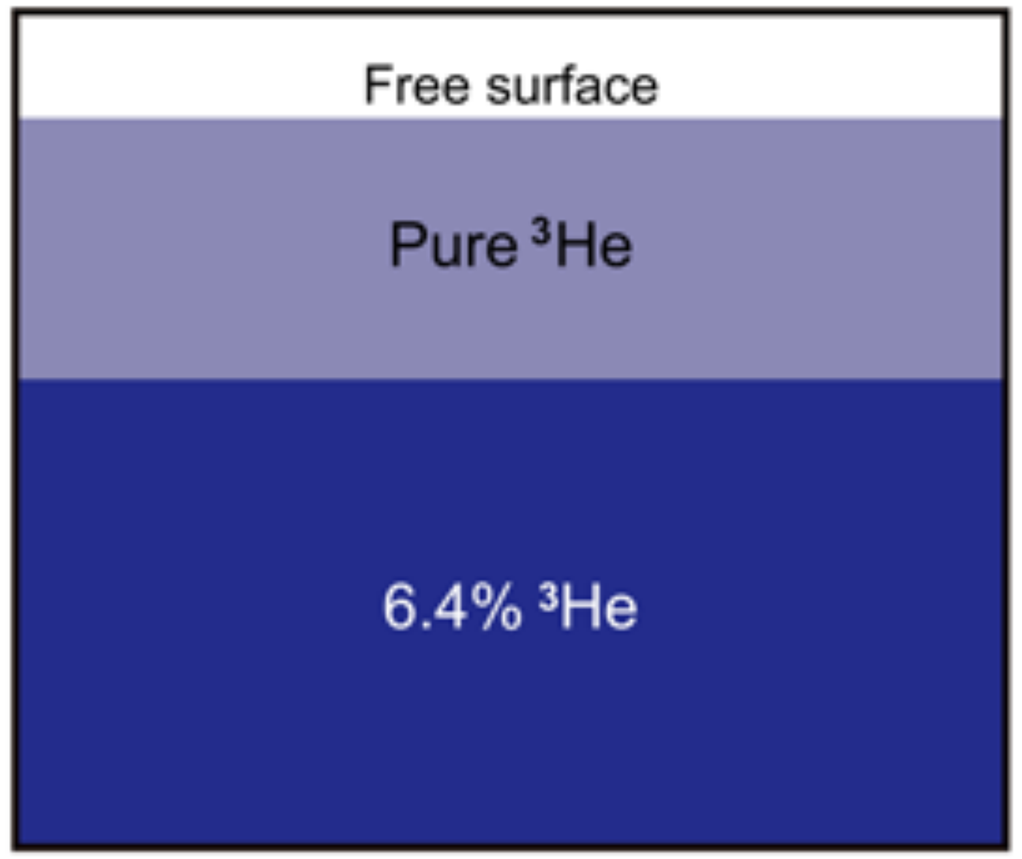
^{4}He & ^{3}He phase diagrams

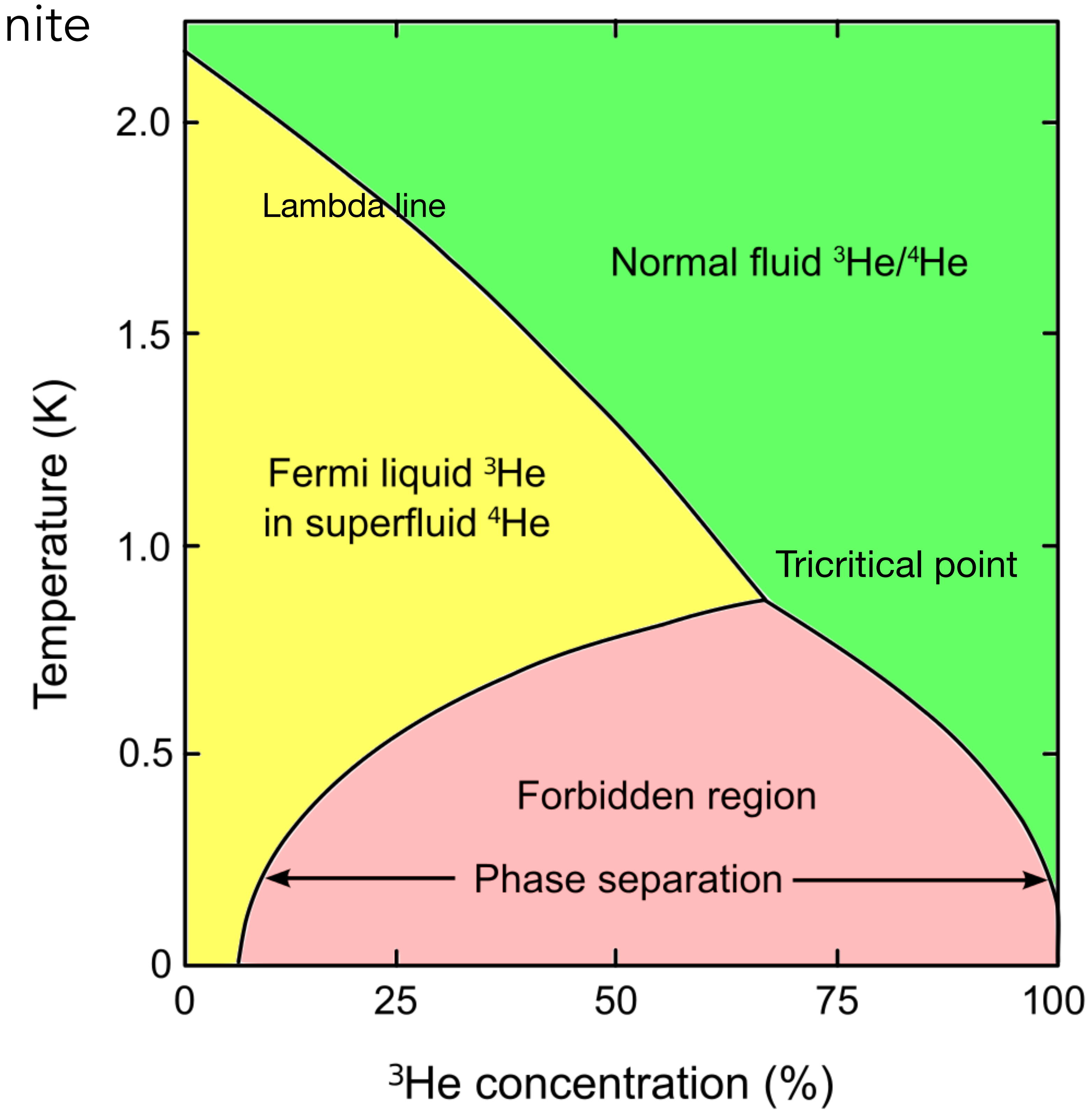
- Pure ^{4}He, with a nuclear spin of I = 0, obeys Boson statistics and undergoes a transition to superfluid at 2.17 K
- Pure ^{3}He, with a nuclear spin of I =1/2, obeys Fermi statistics and the Pauli Exclusion principle; this prevents ^{3}He from undergoing a superfluid transition until much lower temperatures at which the spins pair up and then obey Boson statistics



^{3}He-^{4}He mixtures

- The superfluid transition temperature of a ^{3}He - ^{4}He mixture depends on the ^{3}He concentration
- When a mixture is cooled below the lambda line it undergoes a superfluid transition.
- Cooling the mixture further, it separates into two phases with the ^{3}He-rich phase floating on top of the heavier ^{4}He-rich phase
- The ^{4}He-rich phase (so called 'dilute' phase) contains 6.4% ^{3}He all the way down to 0 K. This finite solubility of ^{3}He in ^{4}He is the key to dilution refrigeration

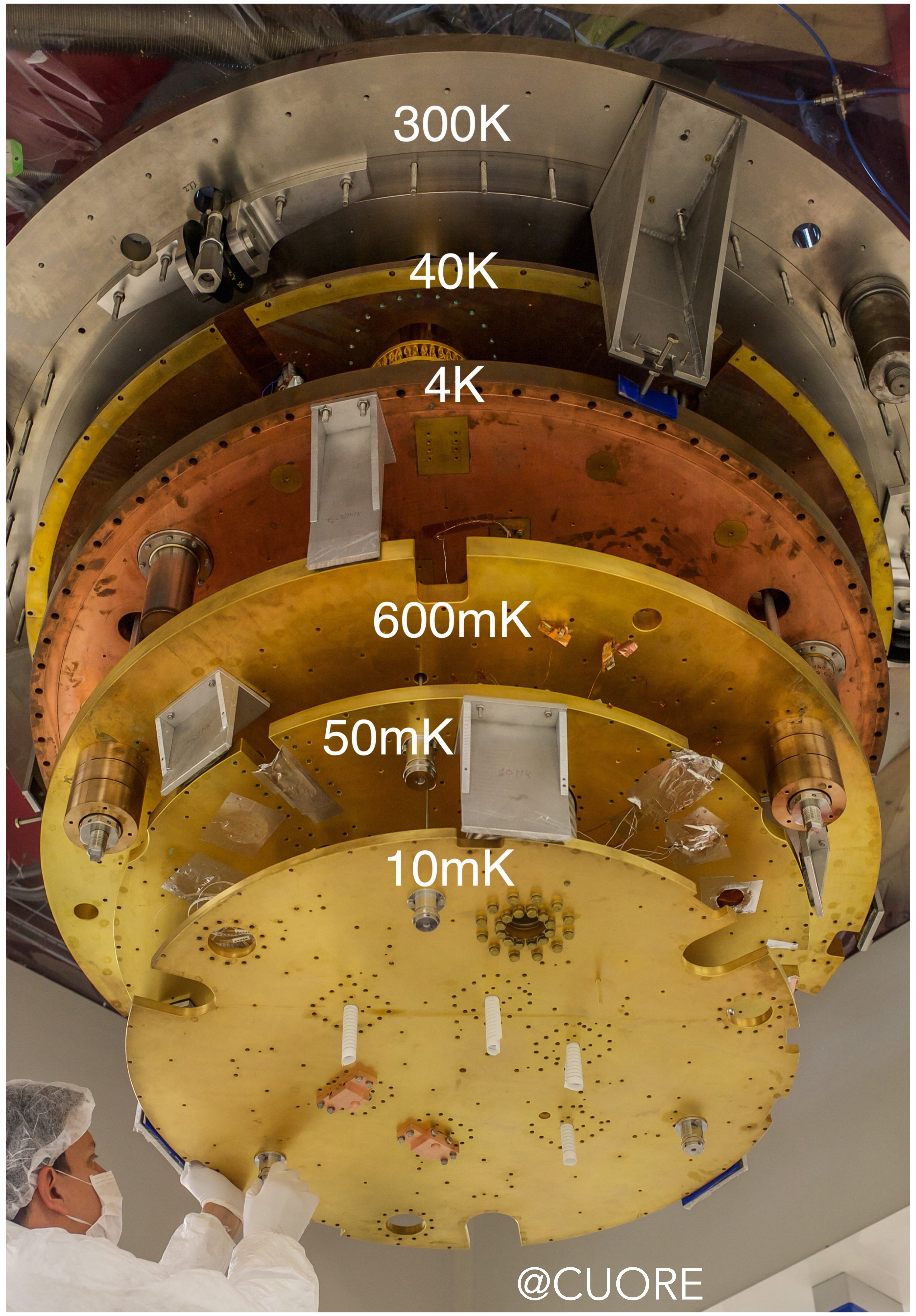




DU design criteria

- Minimise the effect of thermal resistance between liquid helium and metals (Kapitza resistance). This enables efficient heat exchangers and therefore a lower base temperature
- Minimise the effect of viscous heating. This enables a high ^{3}He circulation rate and therefore a higher cooling power
- Limit the superfluid film flow in the still. This ensures about 90% pure ^{3}He is being circulated
- Minimise the amount of ^{3}He required for operation
- Remain leak tight for many years

Dilution Refrigerators



300 K

35 K

3.5 K

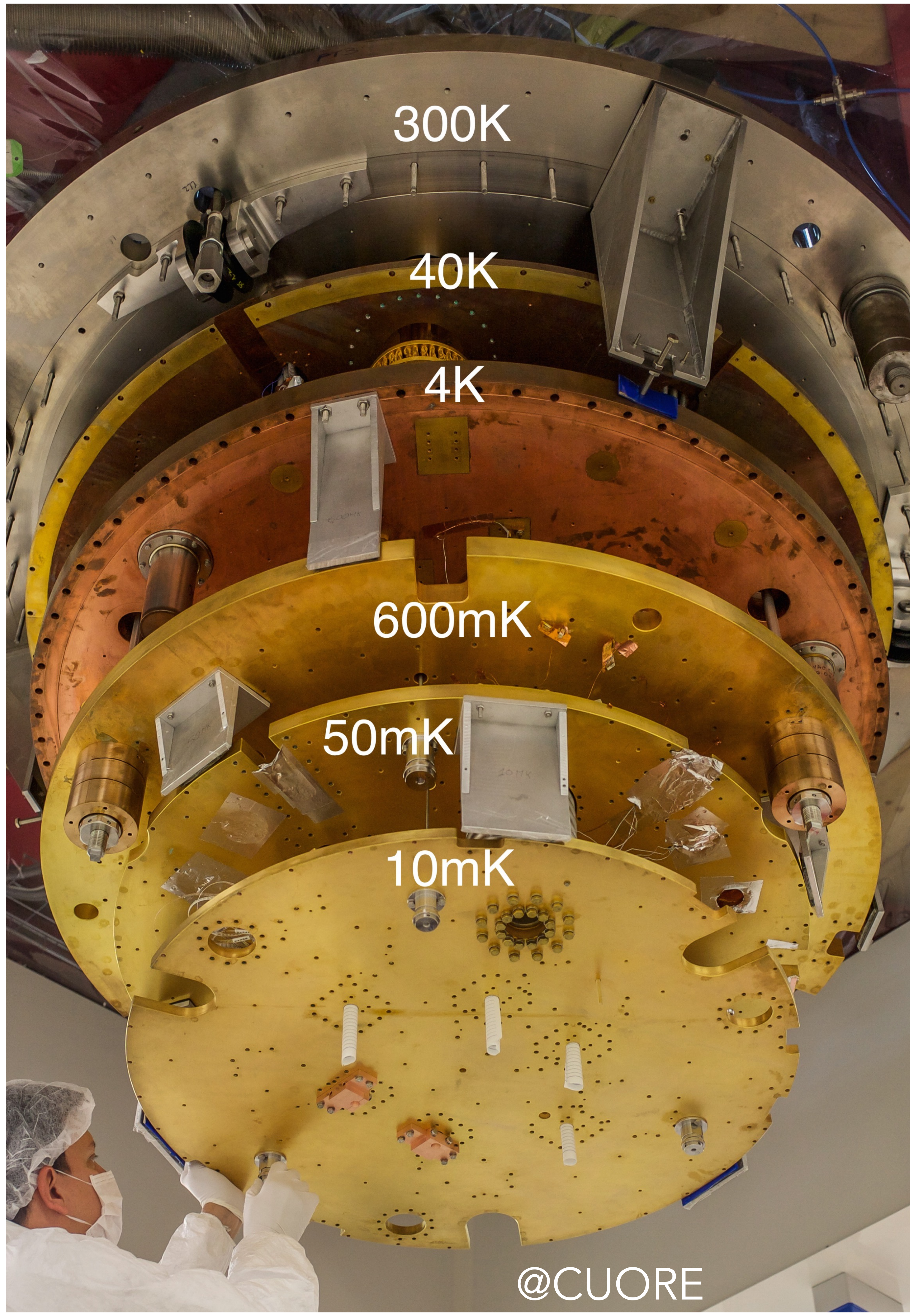
800 mK

50 mK

7 mK

Nowadays DR offer solution to host LTDs for many different application. The CUORE cryostat have paved the way to new generation fo tonne-scale cryogenic project, capable to operate steadily for years, and proved that PT vibrations can be controlled.

Dilution Refrigerators



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Quantum computing requests for new, larger, and more performing DR has strongly boosted the field offering now plug and play solution for LTDs operation.

Phonon sensors

Phonon Sensors

A phonon sensor is a device that collects phonons and generates or modulates an electrical signal, proportional to the energy contained in the collected phonons. If the PMD is operated as a perfect calorimeter, the phonon sensor works as a thermometer.

In practical devices, there are two classes of phonon sensors extensively employed:

- Semiconductor Thermistors (ST)
- Transition Edge Sensors (TES)

There are in addition other devices that can be used as phonon/temperature sensors:

- Kinetic Inductance Detectors (KID)
- Magnetic Micro-Calorimeters (MMC)
- …

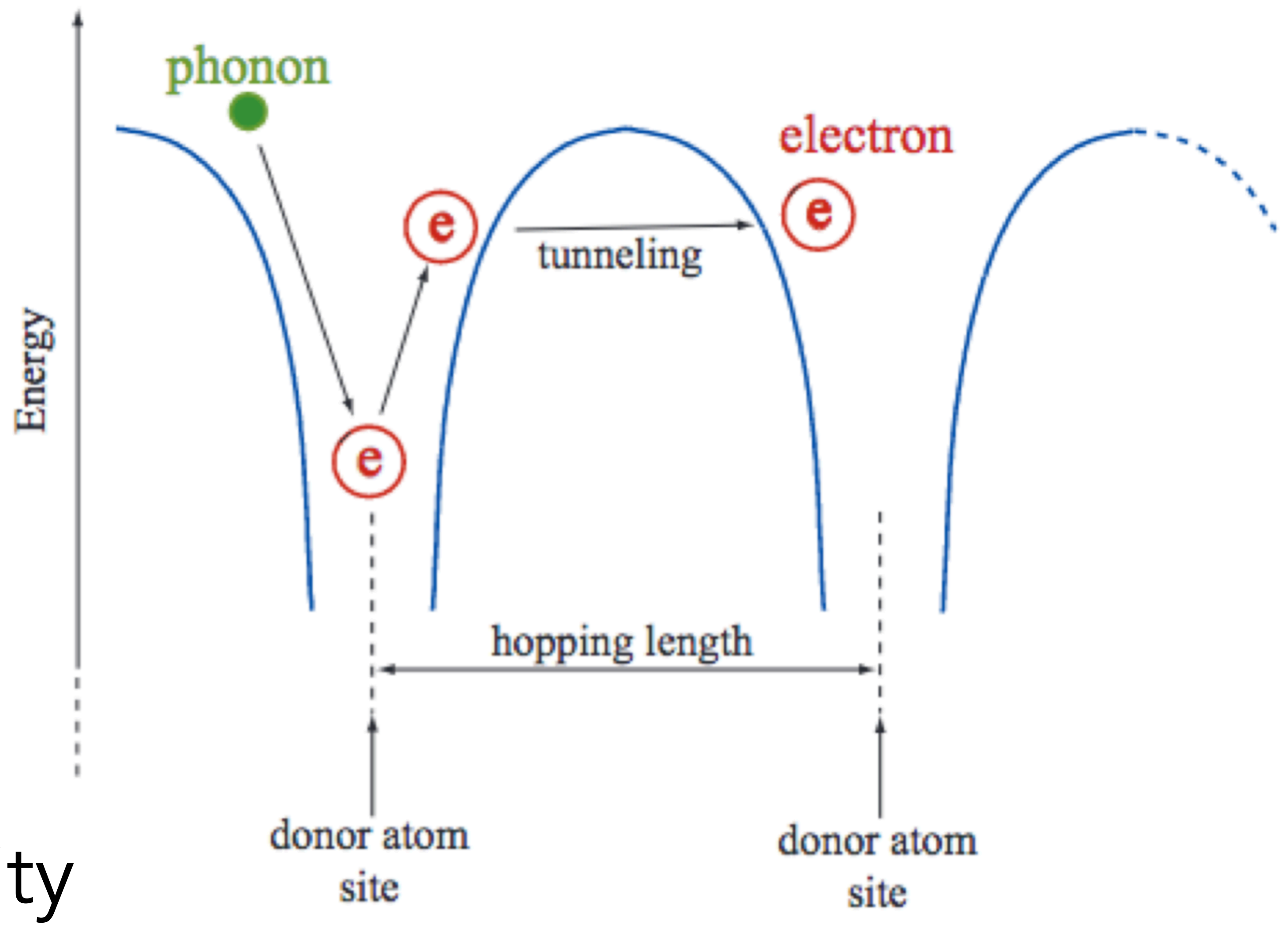
Semiconductor Thermistors

Doped semiconductors close to the **Metal to Insulator Transition (MIT)**

At low temperatures (< ~10 K), the resistivity is given by:
(Variable Range Hopping with Coulomb gap conduction regime)

$$\boxed{\rho(T) = \rho_0 \exp\left[(T_0/T)^{1/2}\right]}$$

T_0 depends on the doping level → it fixes ρ_0 and the sensitivity



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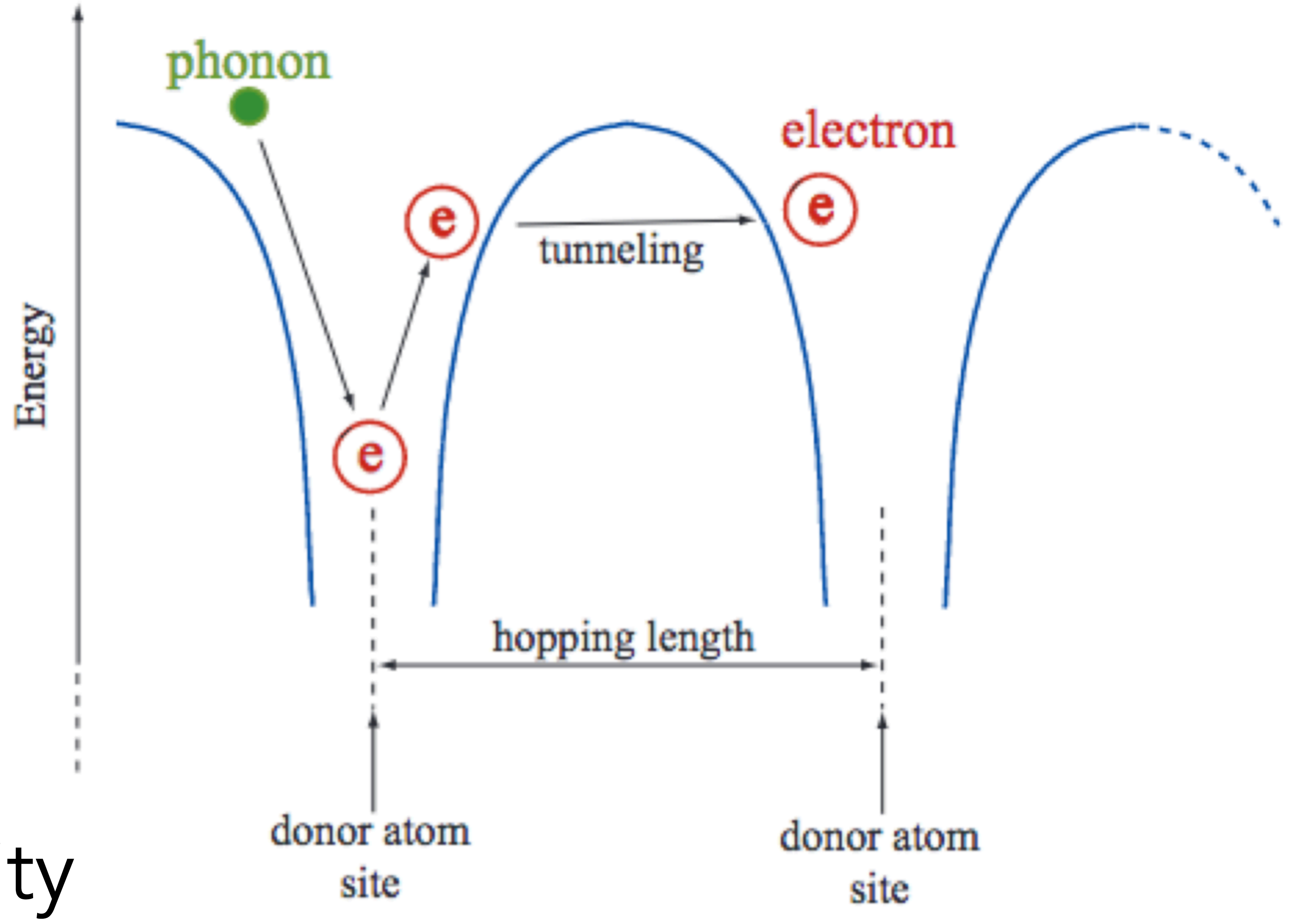

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Two main types:

① **Neutron Transmutation Doped** (NTD) **Ge** thermistors

- Ge crystal exposed to neutron bombardment
- Neutron capture and subsequent β and EC decays produce p and n doping.
- Neutron dose fixes net doping.
- MIT: 6×10^{16} cm $^{-3}$

② **Si-implanted** thermistors;

- Standard microelectronic technology
- Implantation of P, As (n-doping), B (p-doping)
- MIT (Si:P): 3×10^{18} cm $^{-3}$

Characteristics of Semiconductor Thermistors

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- Read-out: a current I is flown in the thermistor

in case of thermal phonons

Signal: $\Delta V = I\,\Delta R = I\,(\partial R/\partial T)\,\Delta T$

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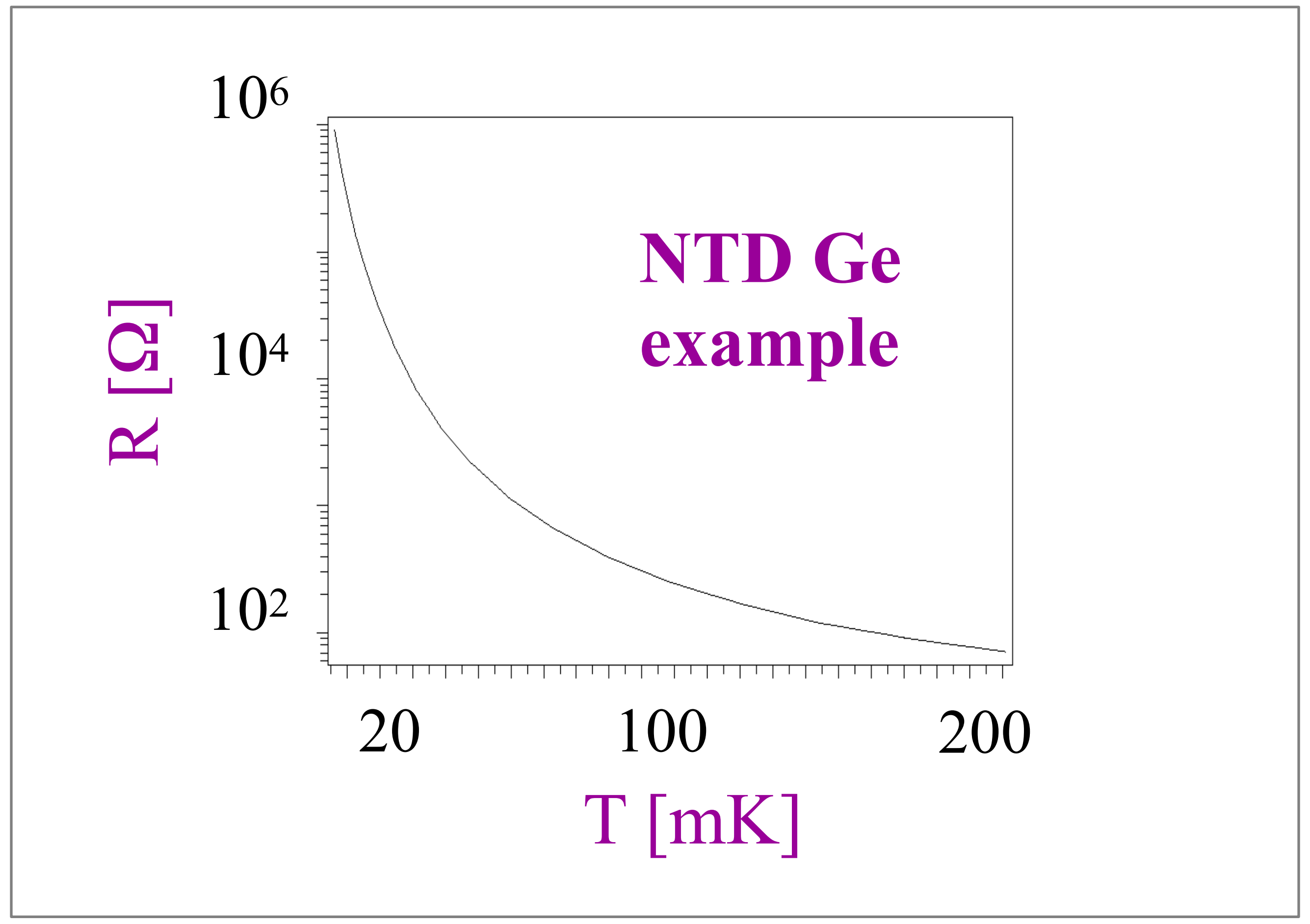

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⇒ Quite sensitive to spurious noise sources

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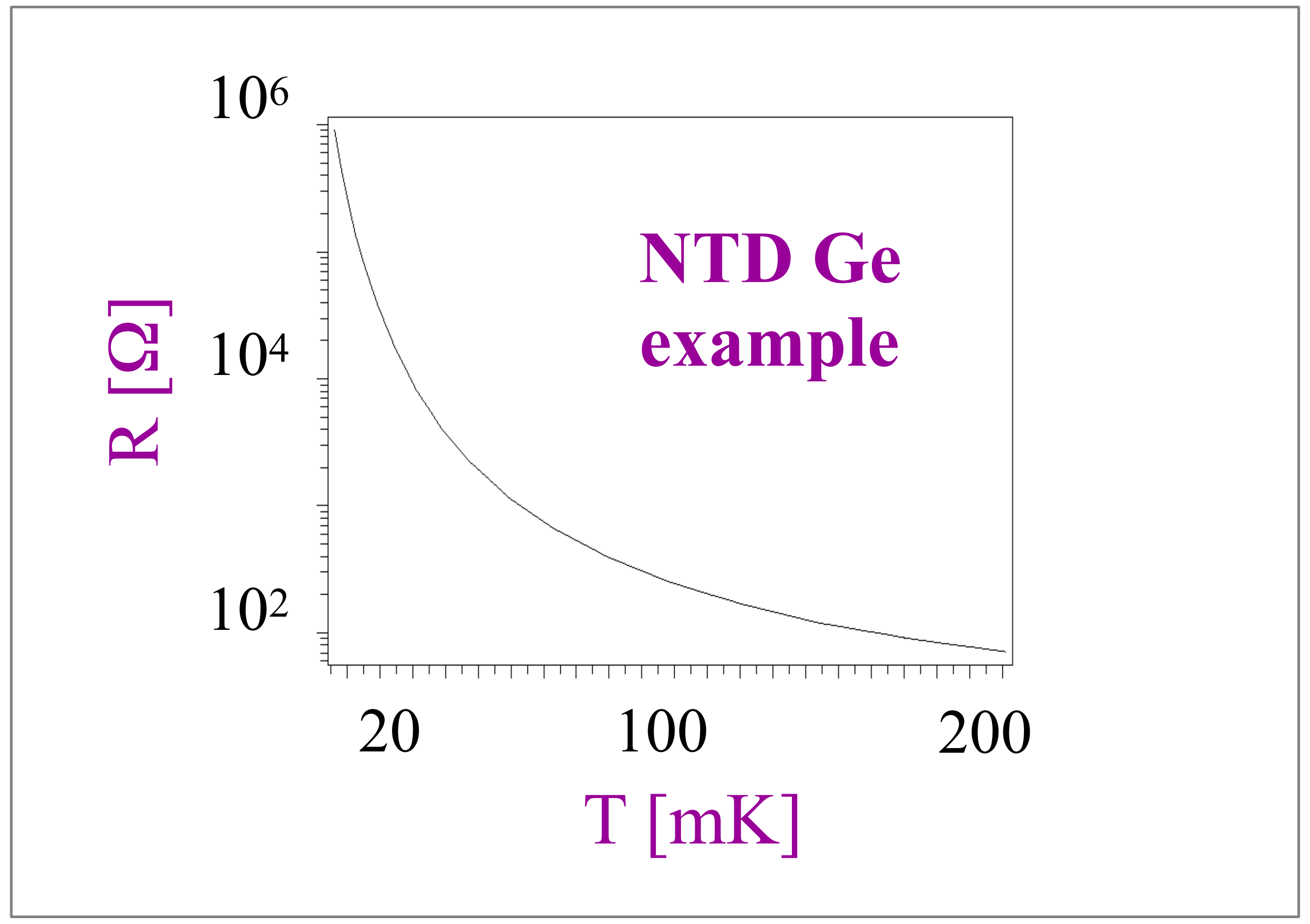

High impedance (1 MΩ - 1 GΩ):

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- Ge and Si STs are:

⇒ Easy to handle (usually epoxied at the energy absorber)
⇒ Scarcely sensitive to athermal phonons

Transition Edge Sensors

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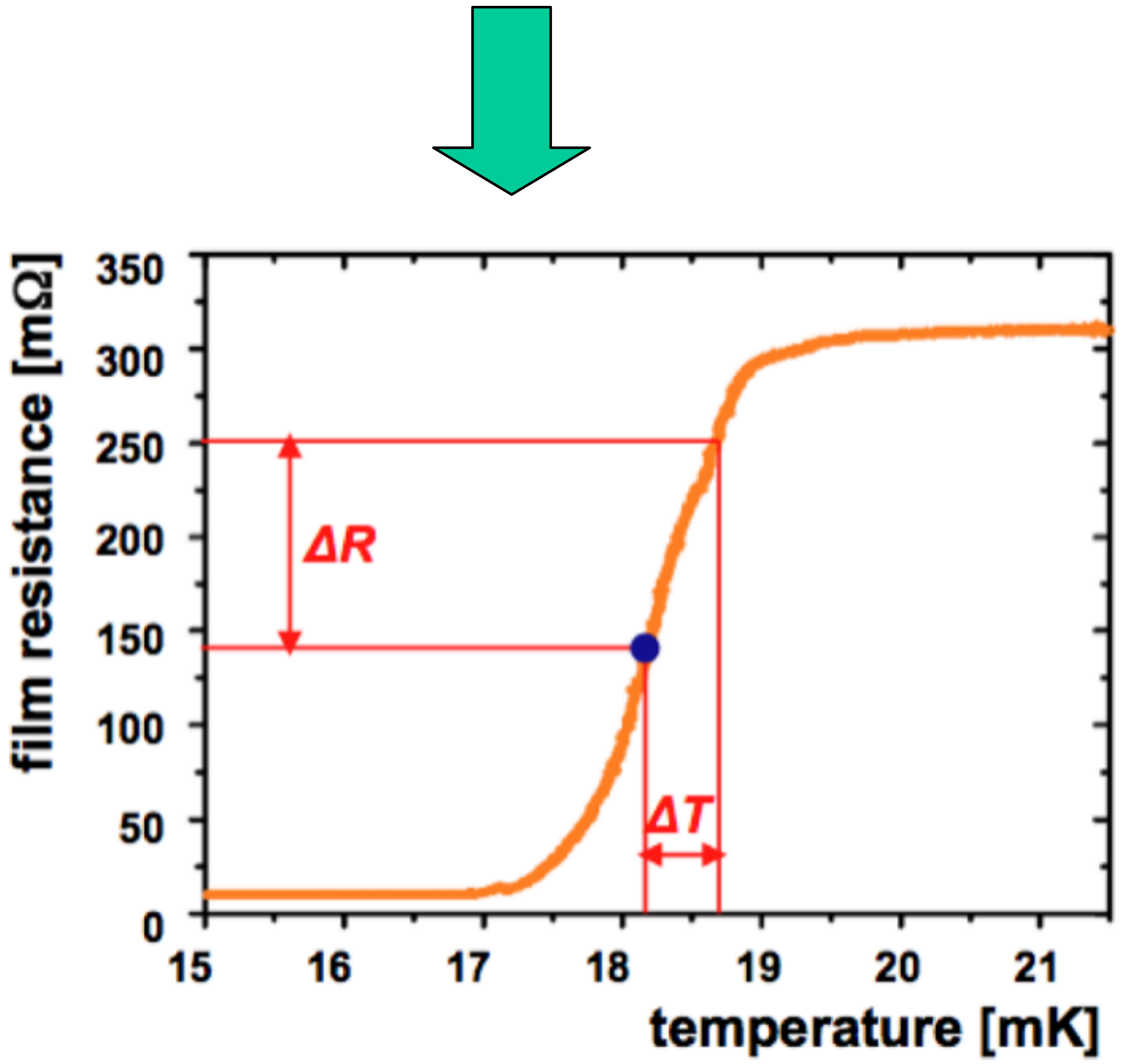

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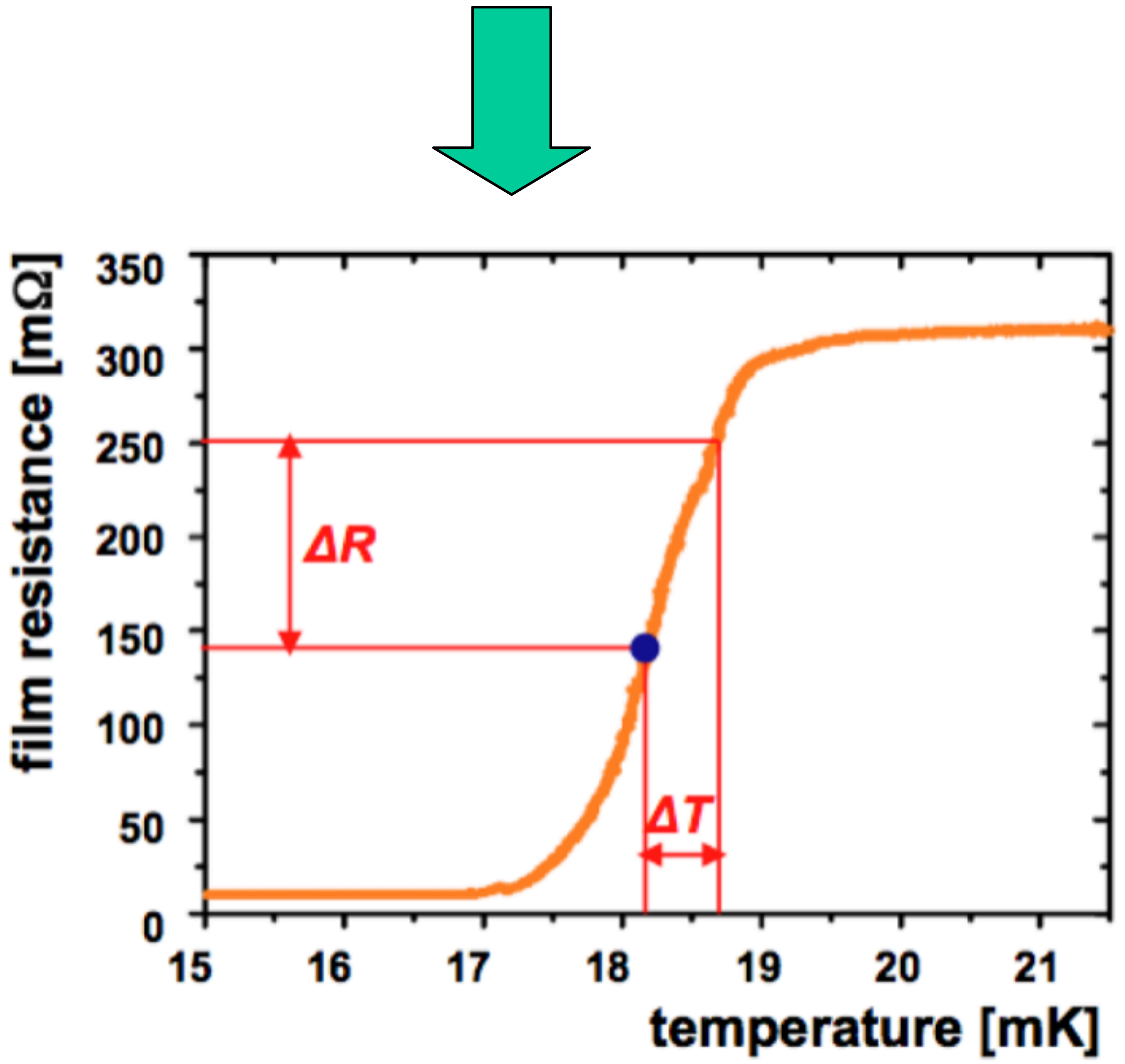

if we define the sensitivity as

$$A \equiv \left| d \log R / d \log T \right|$$

$A \cong 10$ for ST

⇕

$A \cong 1000$ for TES

Low impedance thermistors ⇒ SQUID readout

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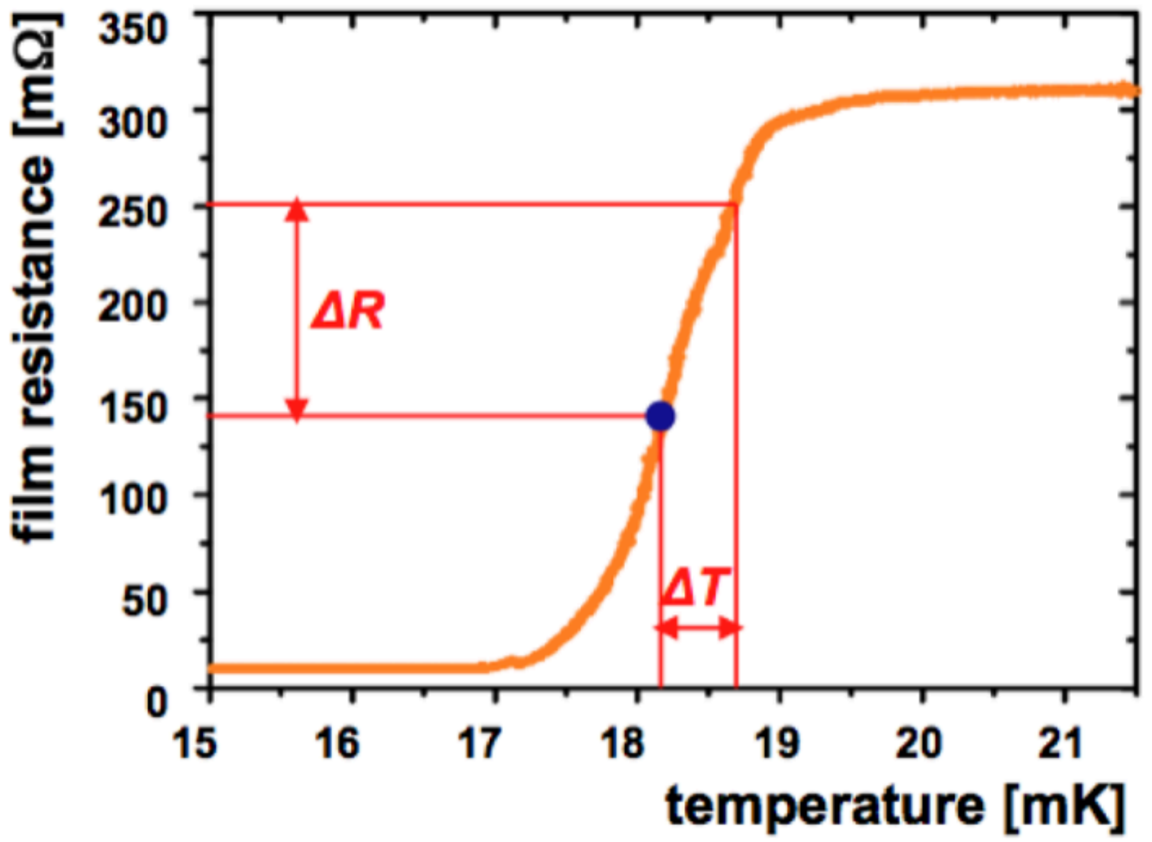

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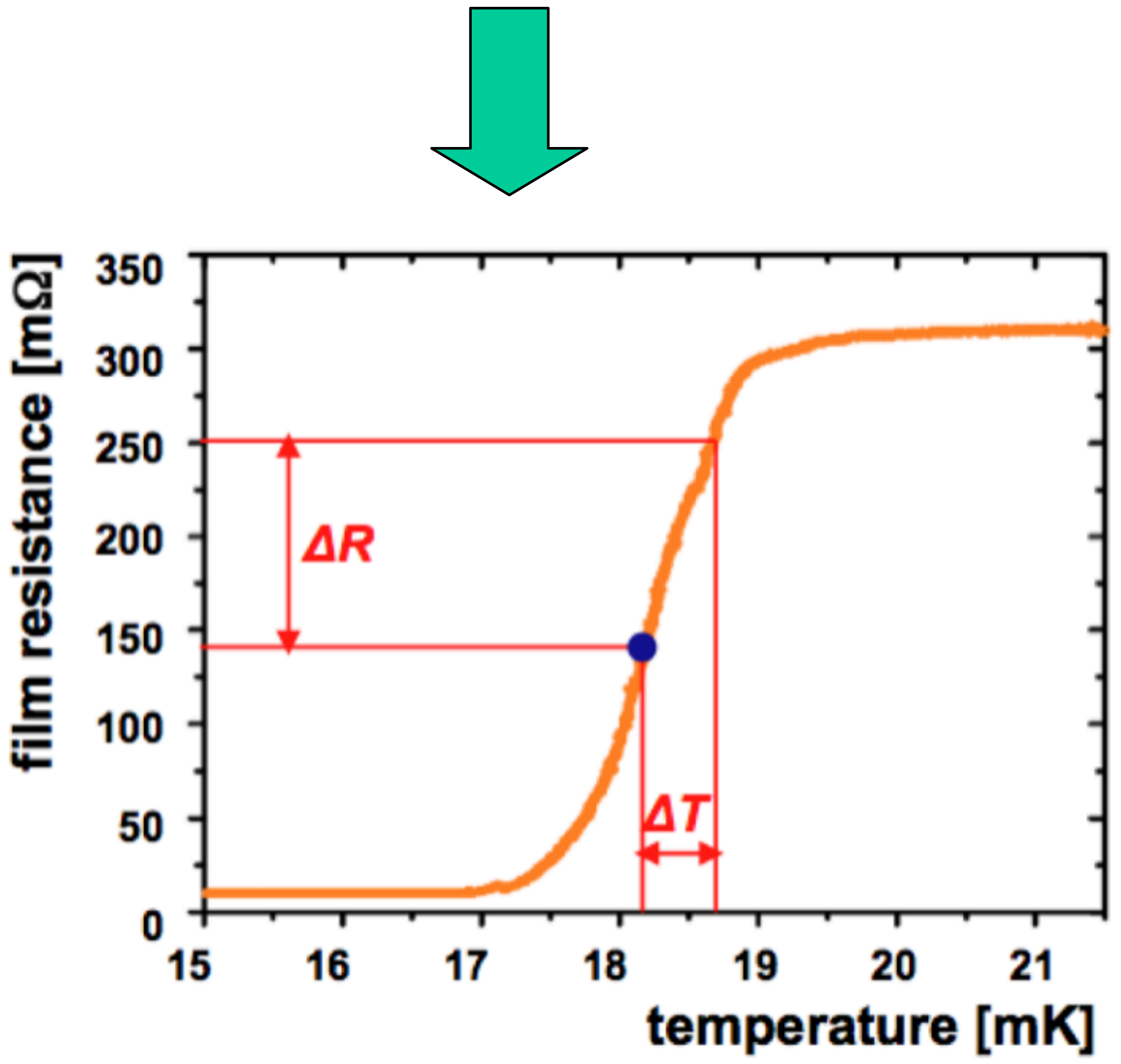

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Low impedance thermistors ⇒ SQUID readout

Much higher S/N ratio with respect to ST

- Film is deposited on the energy absorber:

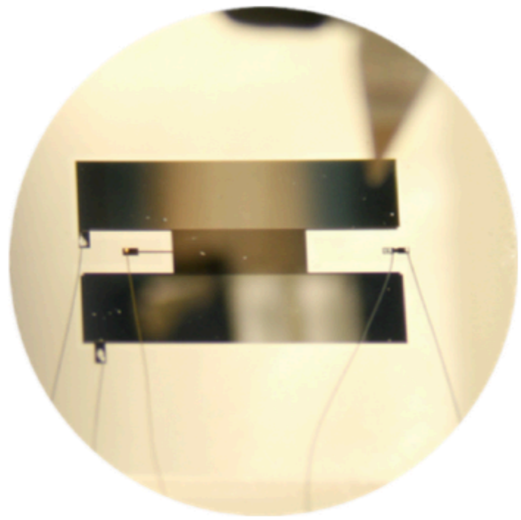
→ sensitive to athermal phonons

→ fast response

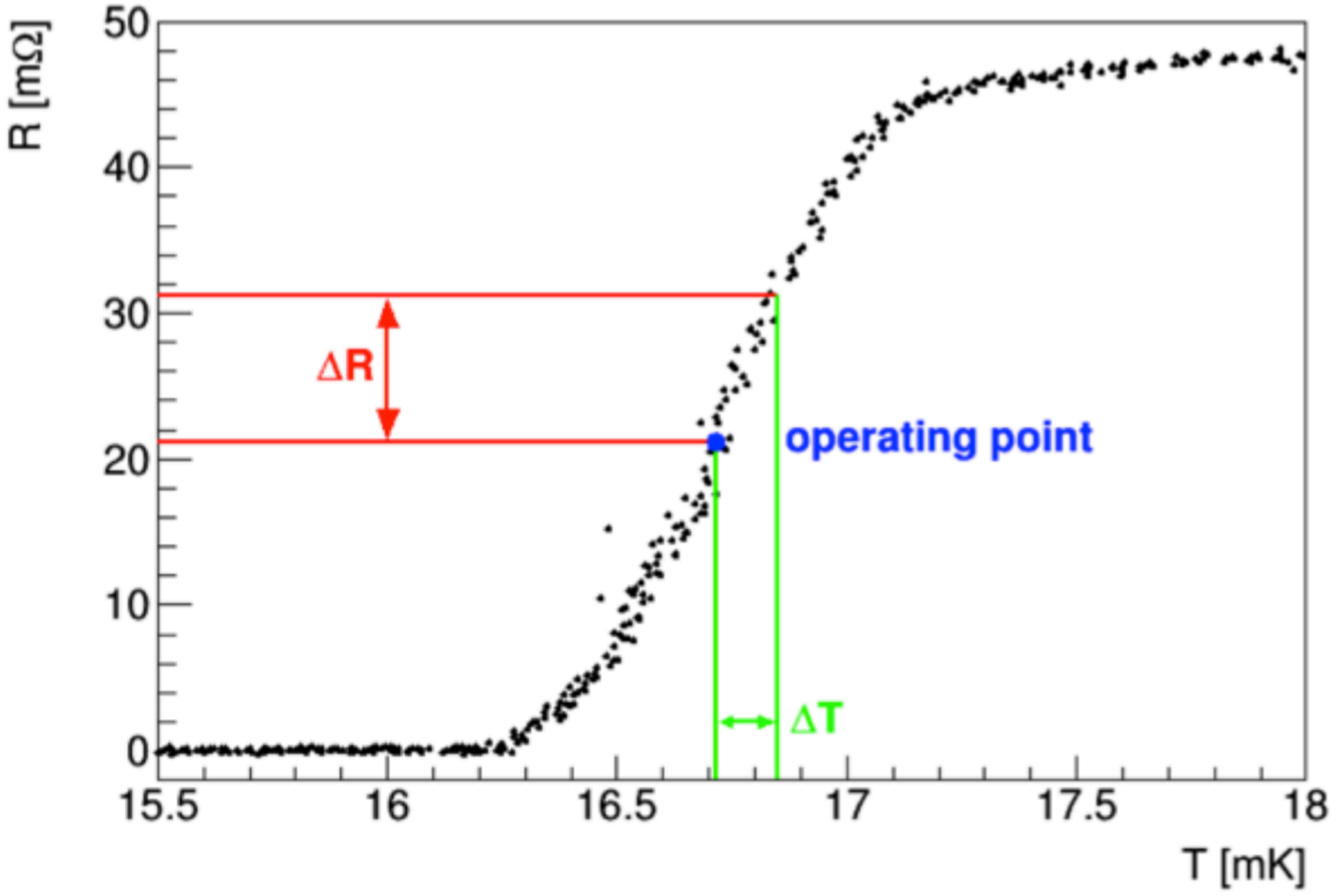
BUT not easy and not always reproducible procedure

W TES

Superconducting tungsten thin films:



W – TES, CRESST



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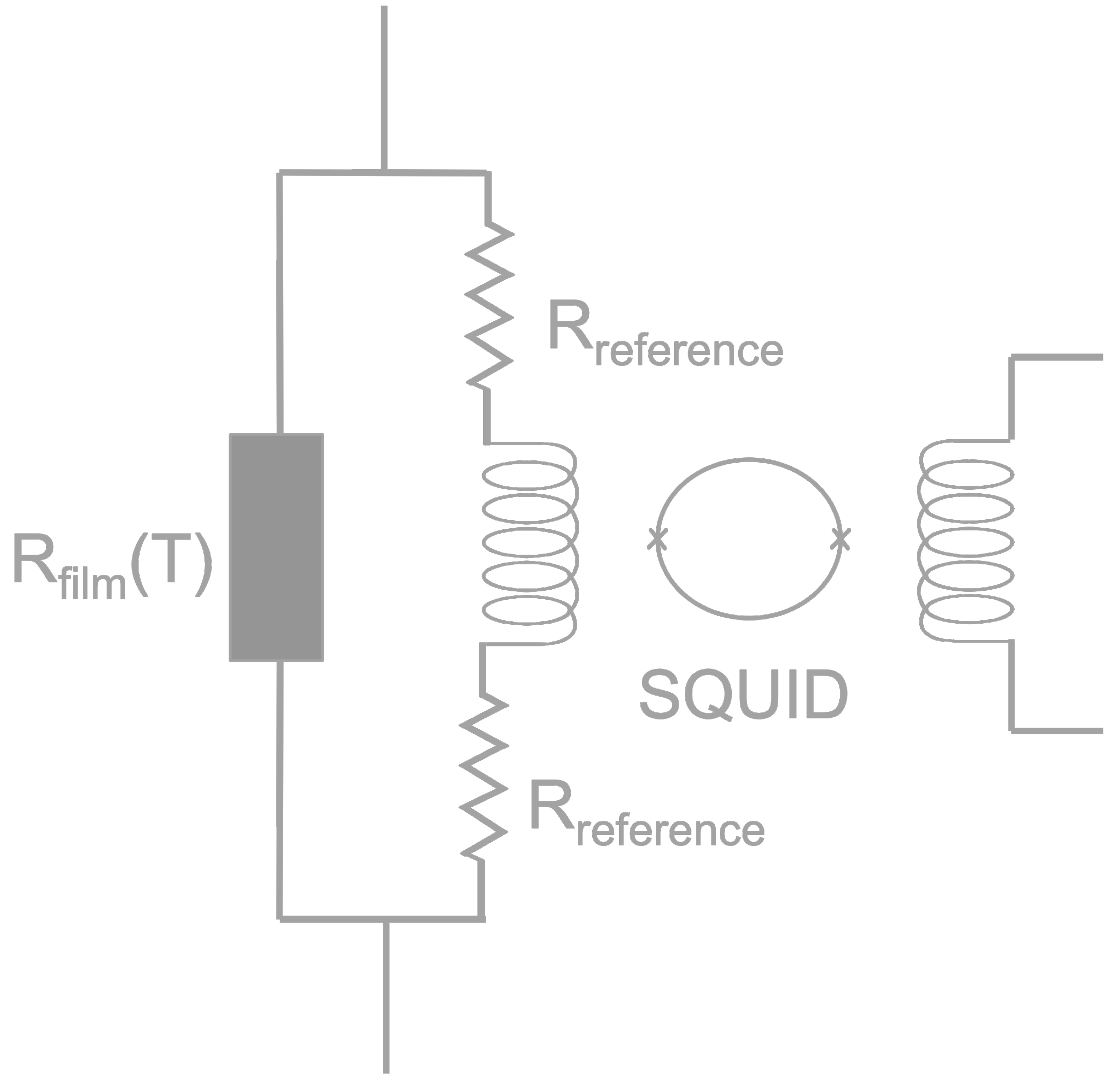

SQUID readout circuit

TES is a resistor
→ Johnson noise

$$I_{Johnson} \sim \sqrt{\frac{4k_B T_c}{R}}$$

Including both Johnson and the thermodynamic fluctuations noise:

$$E_{FWHM} \sim 2.355\sqrt{\frac{4k_B T_c^2 C}{\alpha}}$$

Best ΔE for small T_C and low C

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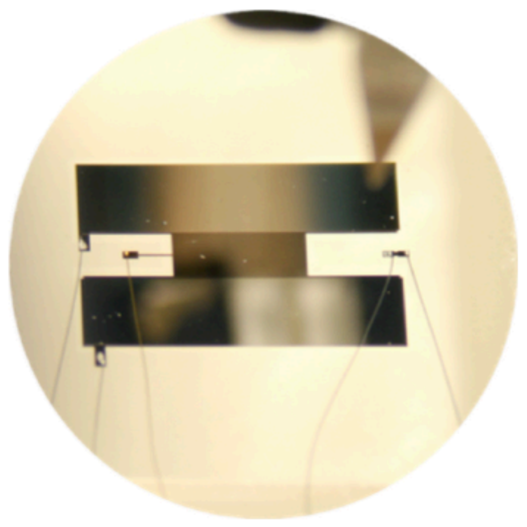

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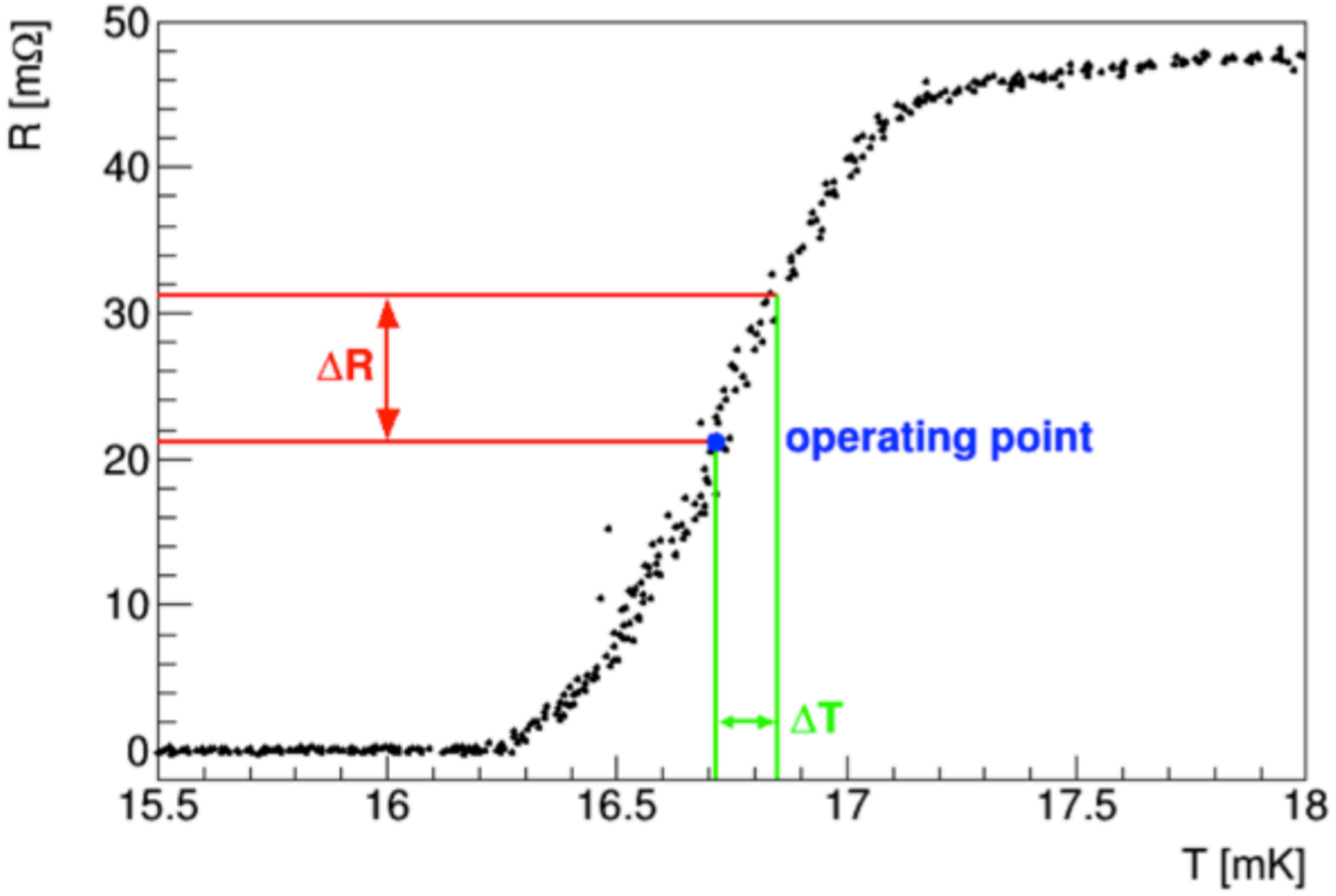

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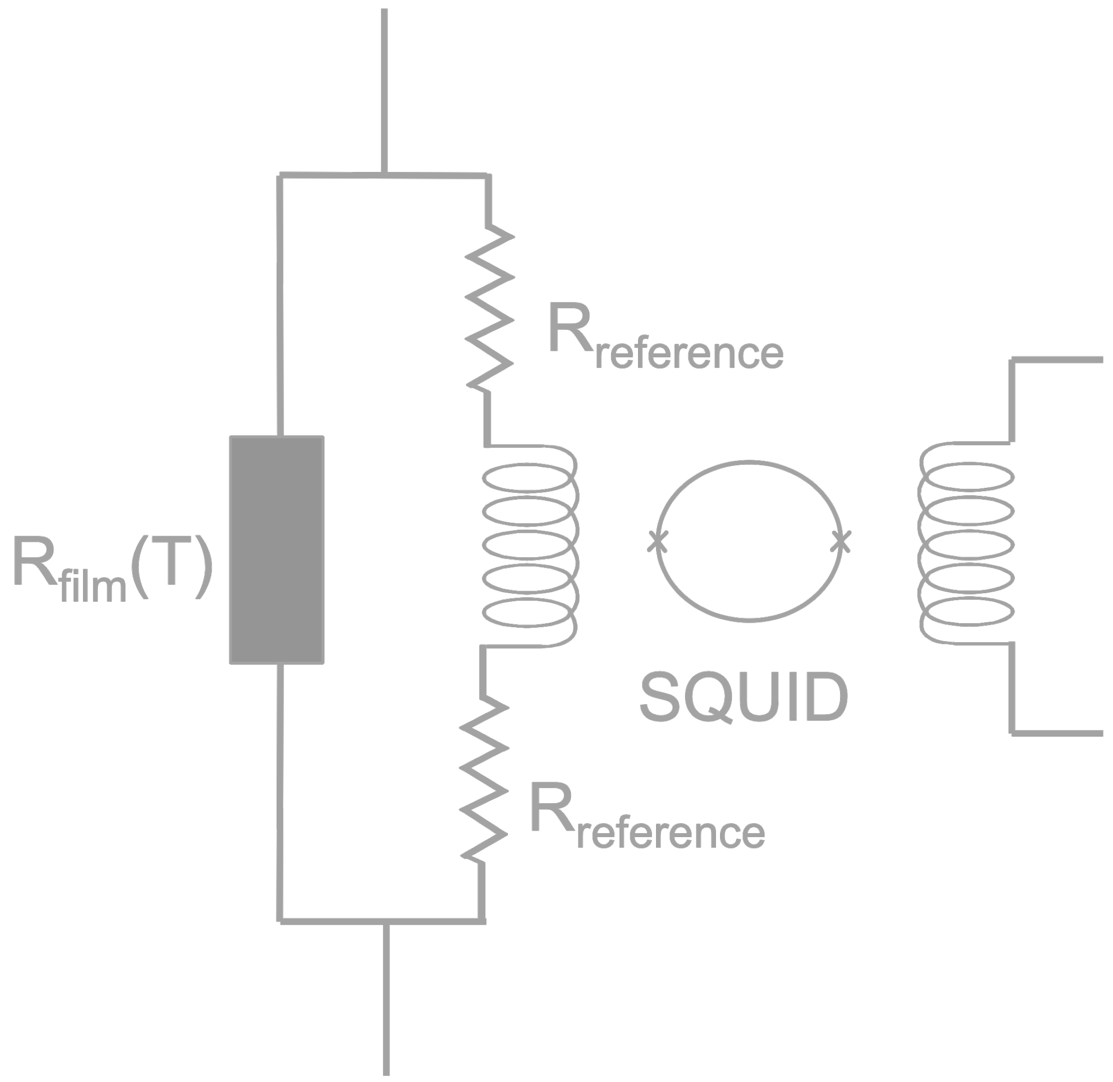

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Energy deposition in absorber
~keV

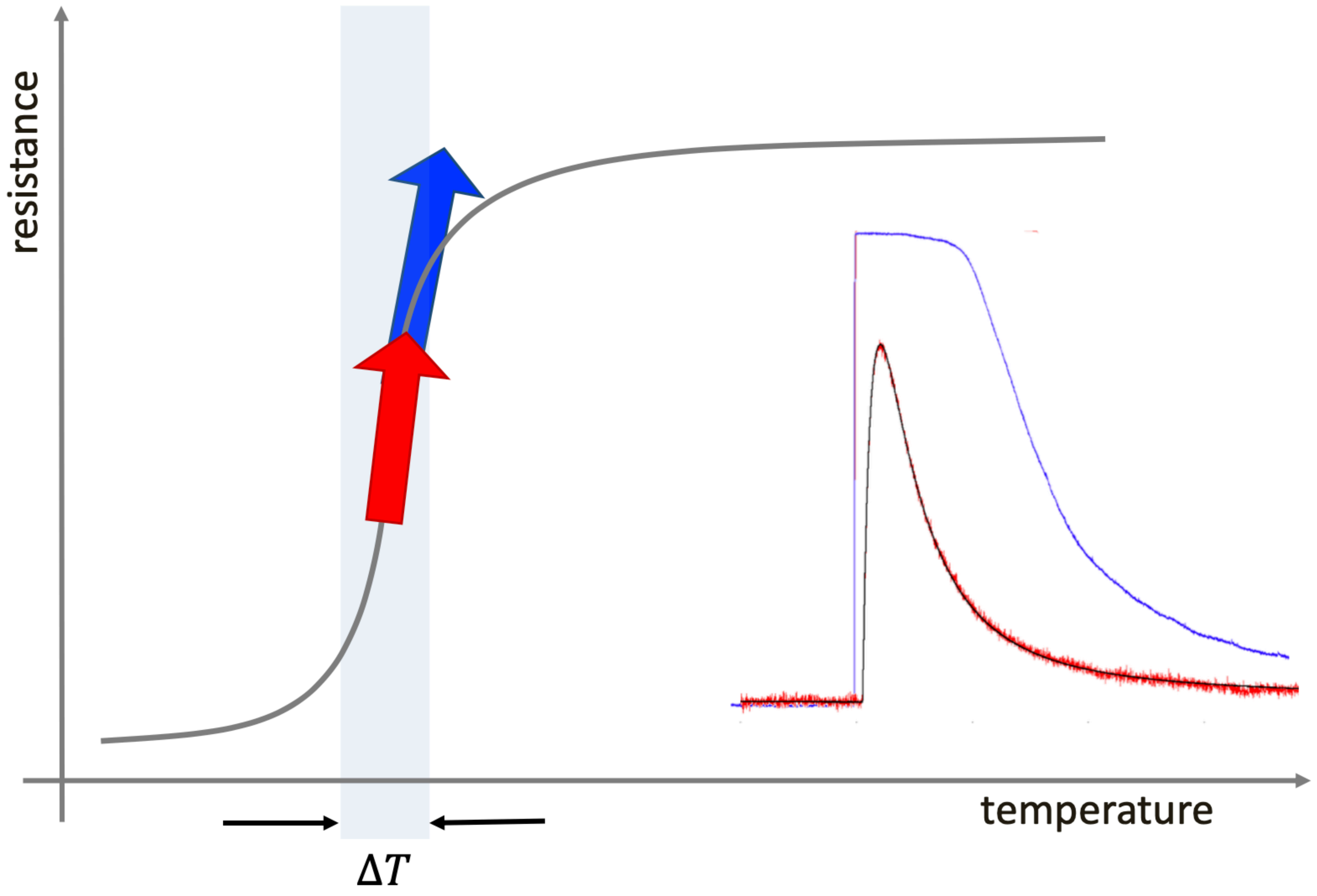
↓

Temperature rise in TES
~μK

↓

Resistance change
~mΩ

TES dynamic range



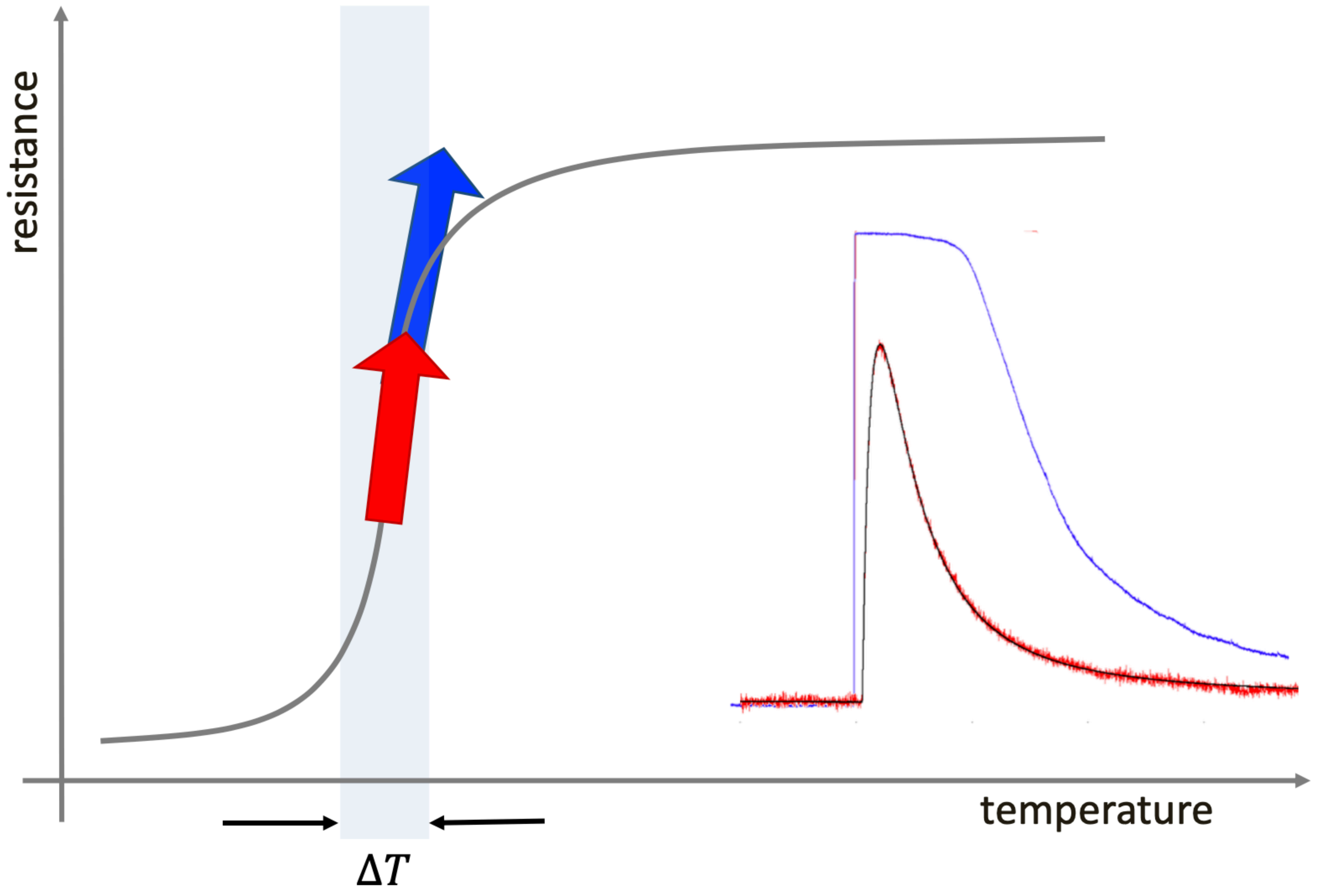
One of the Major limitation of TES sensor is te reduced dynamic range:

Once ΔT > transition width

→ Dynamic range exceeded

→ Resistance does not vary anymore with T

TES dynamic range



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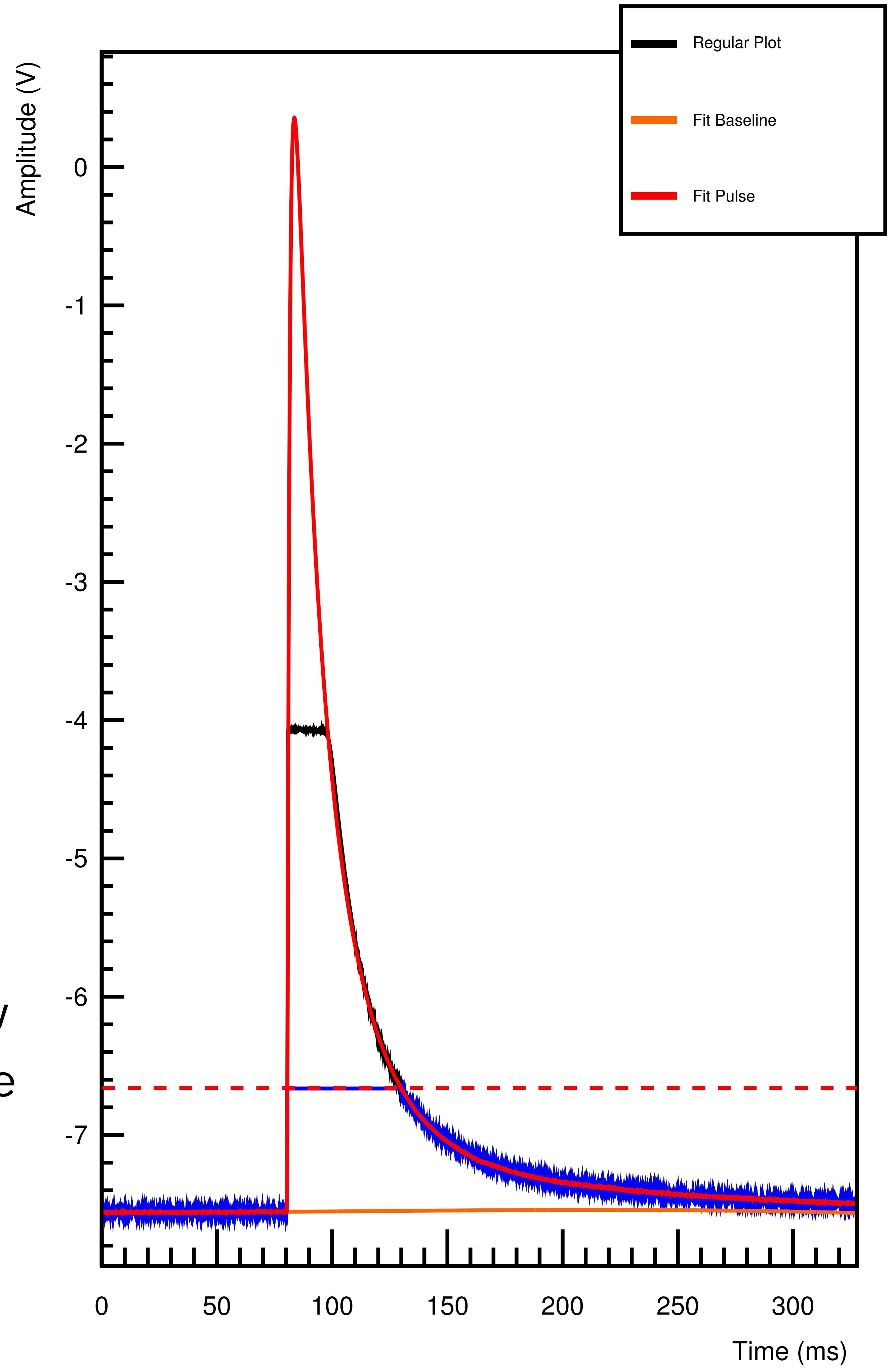
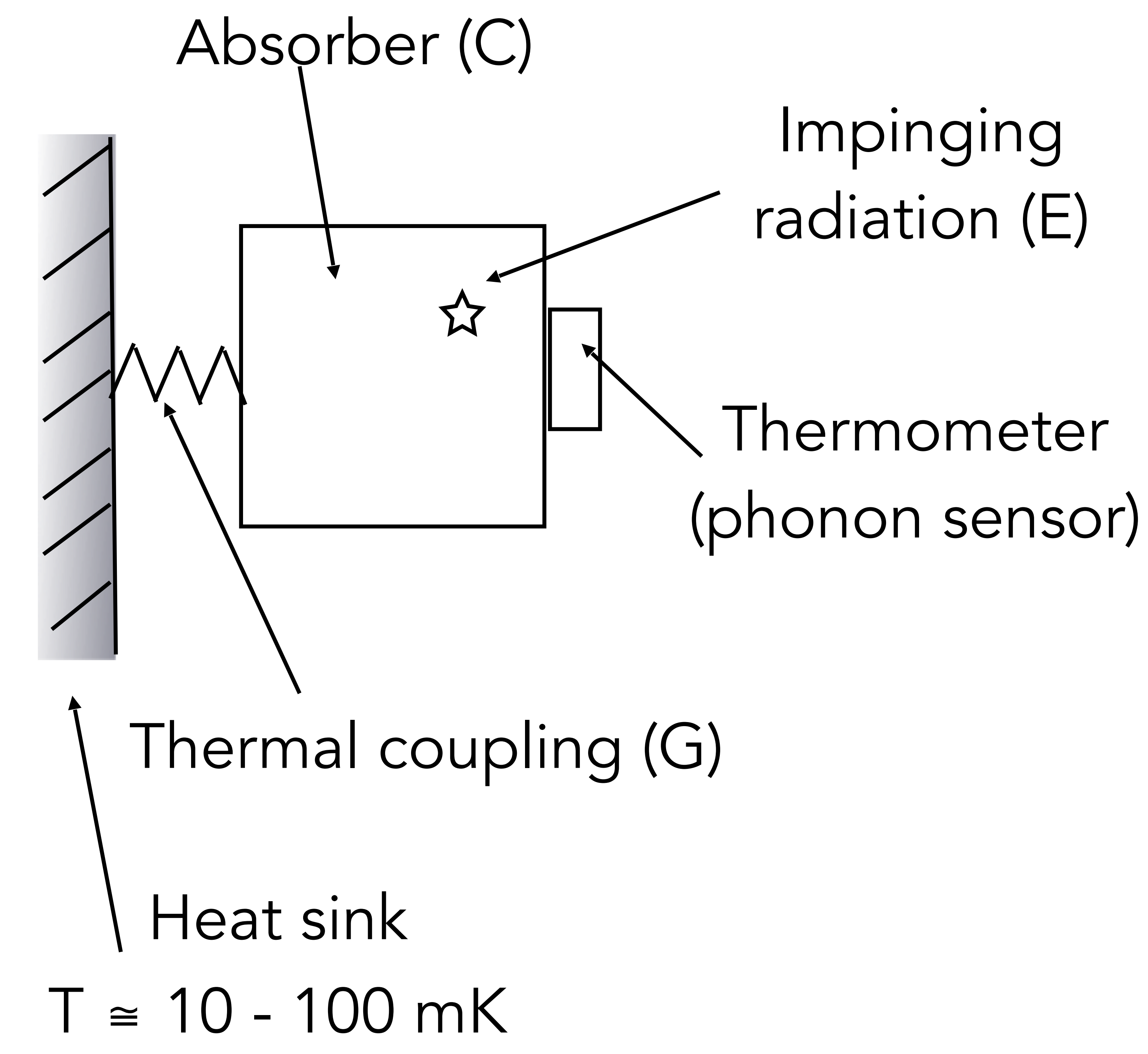


Template based Pulse reconstruction allow extension of the dynamic range well above the transition dynamics
(e.g. from 200 keV to several MeV)

Background features of LTDs



Any detector application has to face its own specific backgrounds but there are some aspects that are characteristic of cryogenic detectors.

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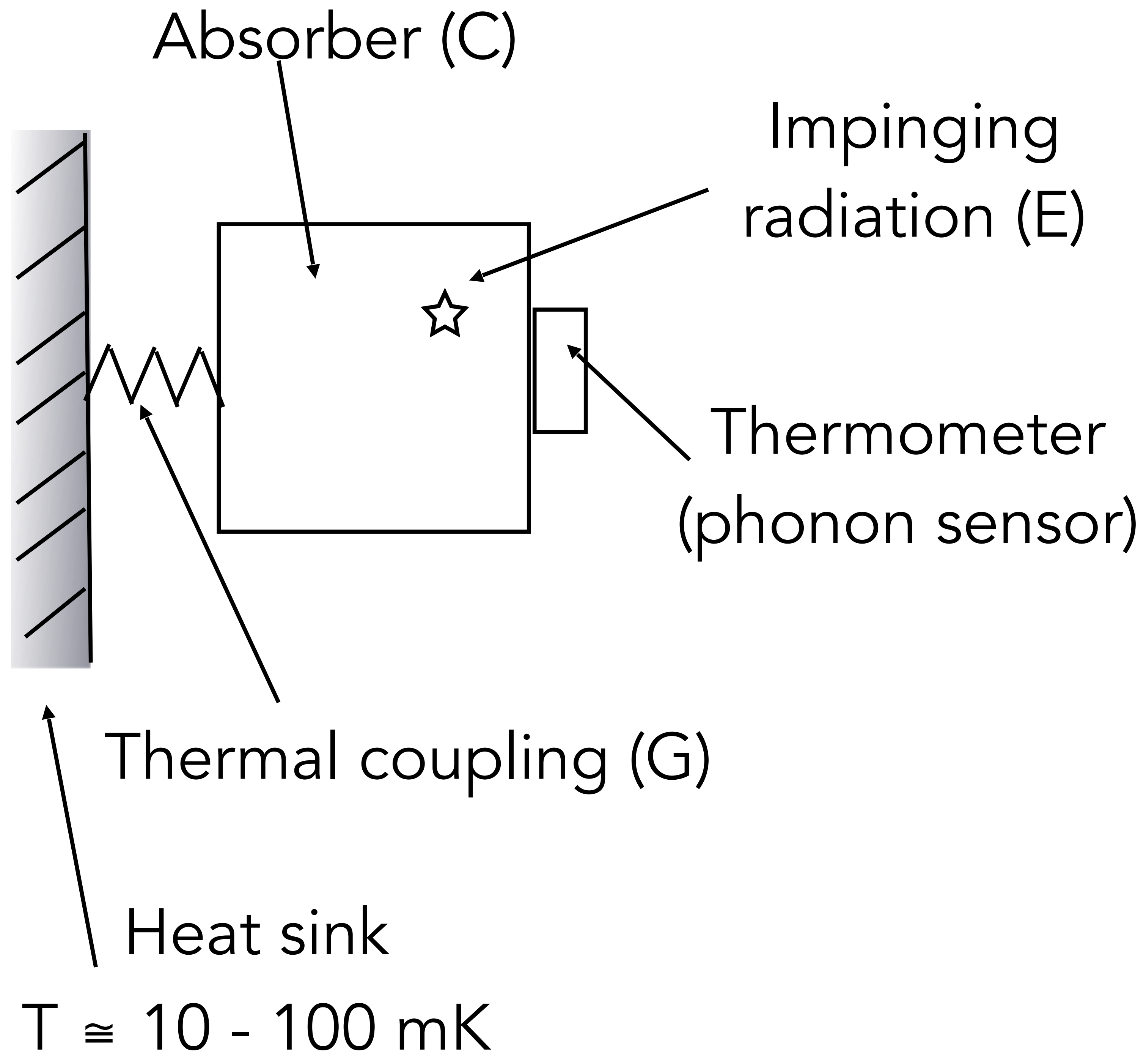

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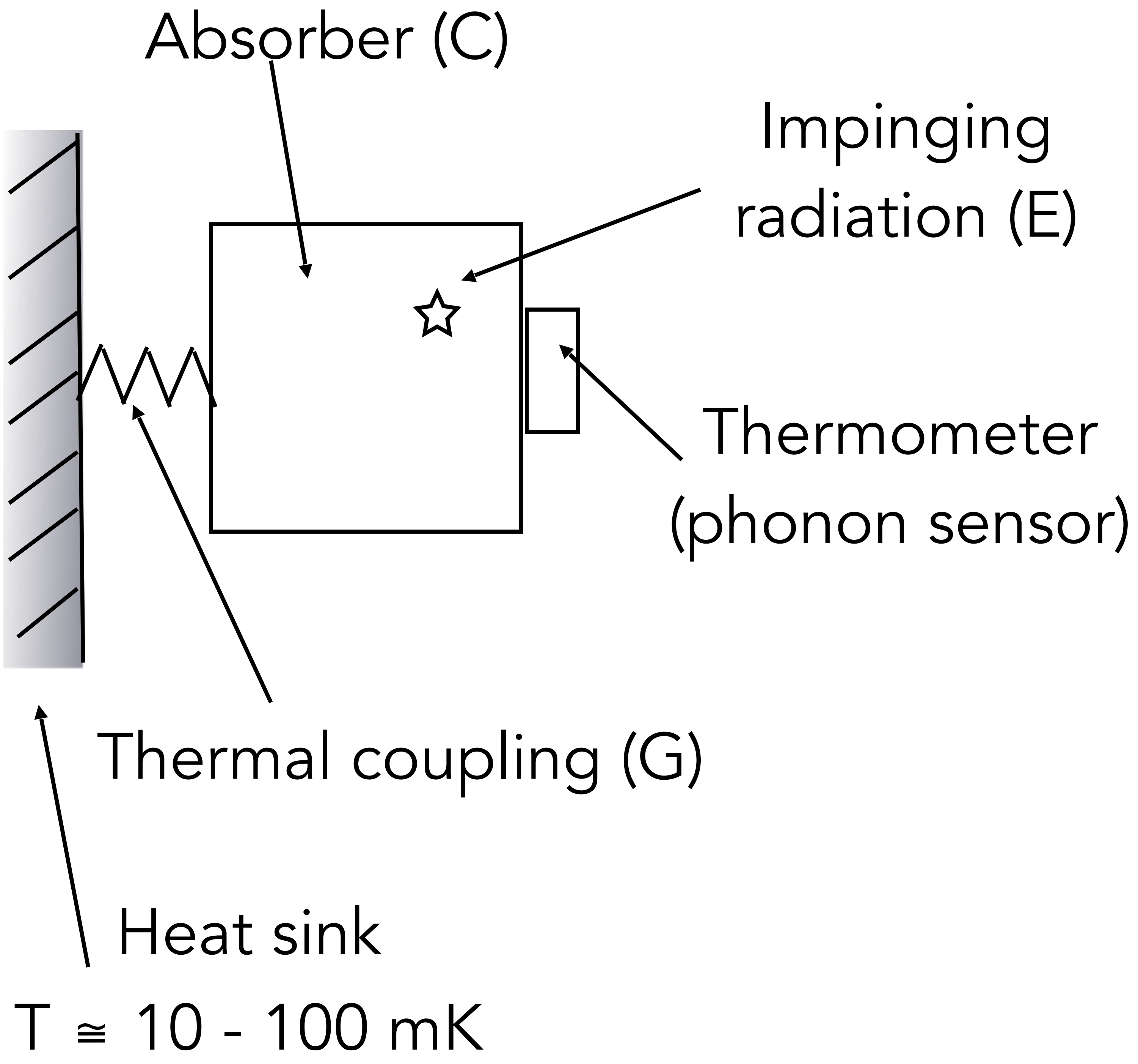

Absorber (C)

Impinging radiation (E)

Thermometer (phonon sensor)

Thermal coupling (G)

Heat sink

T ≅ 10 - 100 mK

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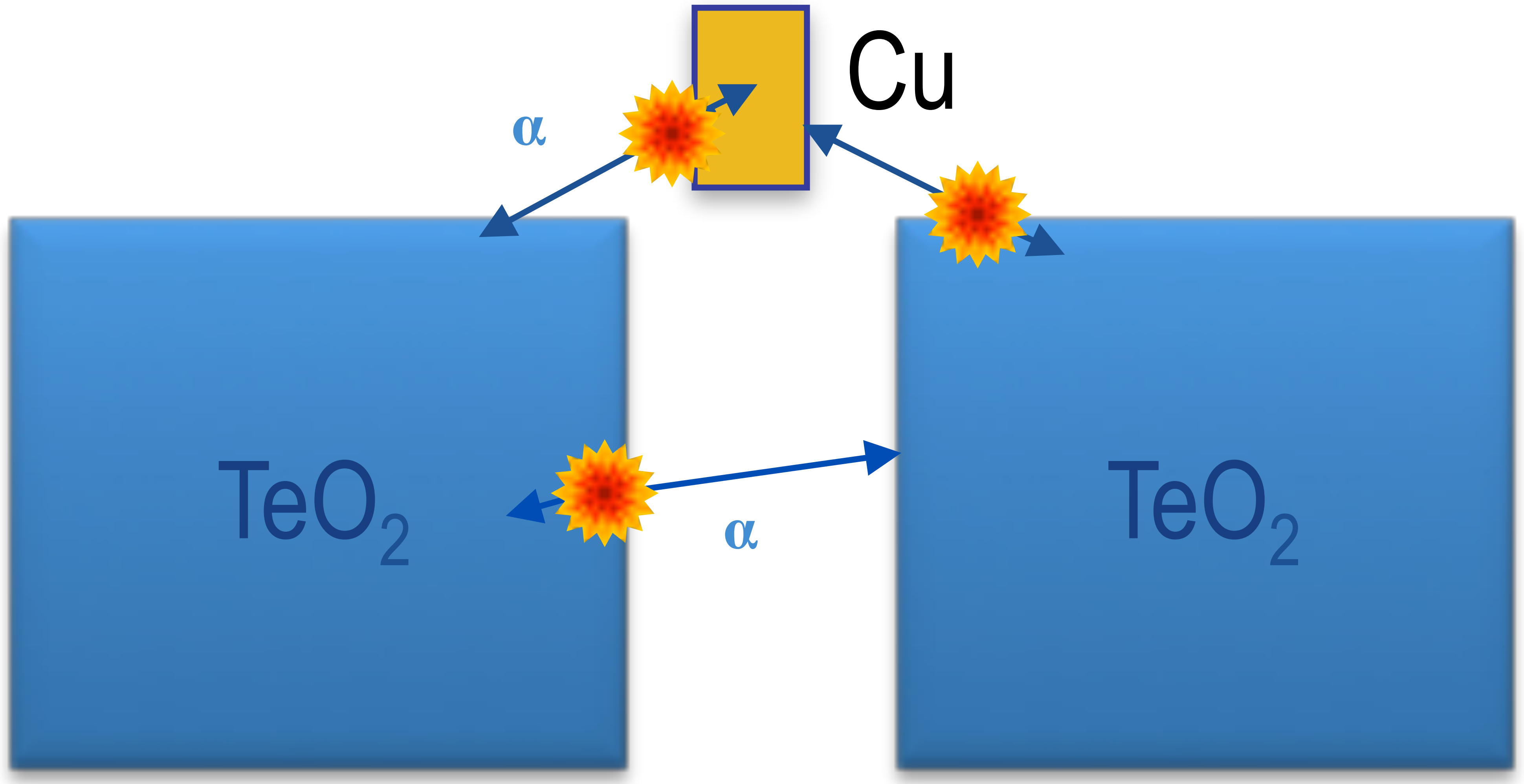
Radiation emitted near the surface of materials surrounding the active volume can travel trough vacuum and reach the detector.

—> Degraded alpha particles



Surface α background

- The background of most thermal detector is dominated by surface alpha background.
- An alpha particle generated near the surface of a detector component will release only a part of its energy before escaping.
- The alpha will eventually hit another component of the detector. If one of the two component is non-active (e.g. copper supports) the alpha energy cannot be reconstructed, generating a continuum bkg at all energies.

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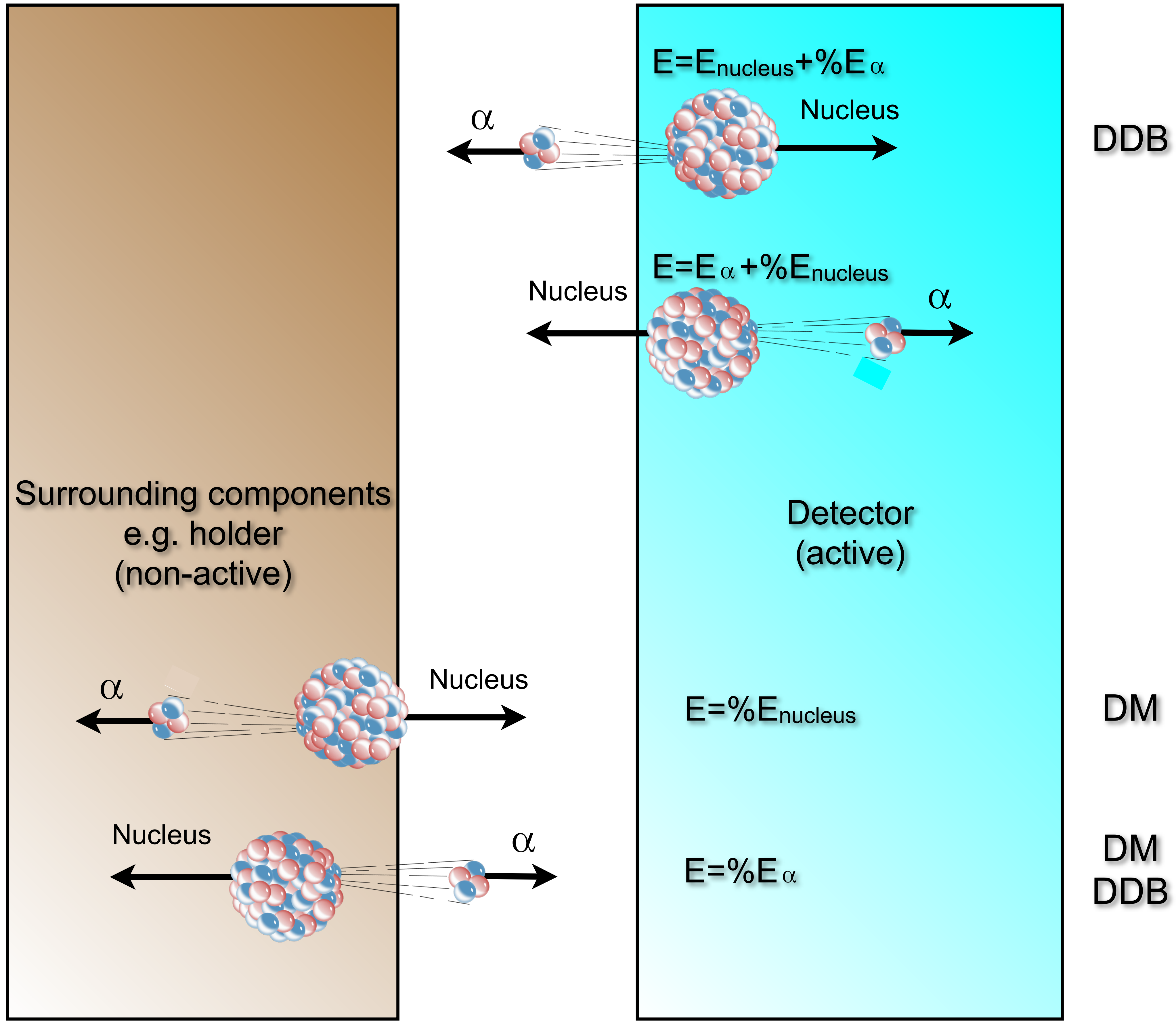
$Q=E_\alpha+E_{nucleus}$



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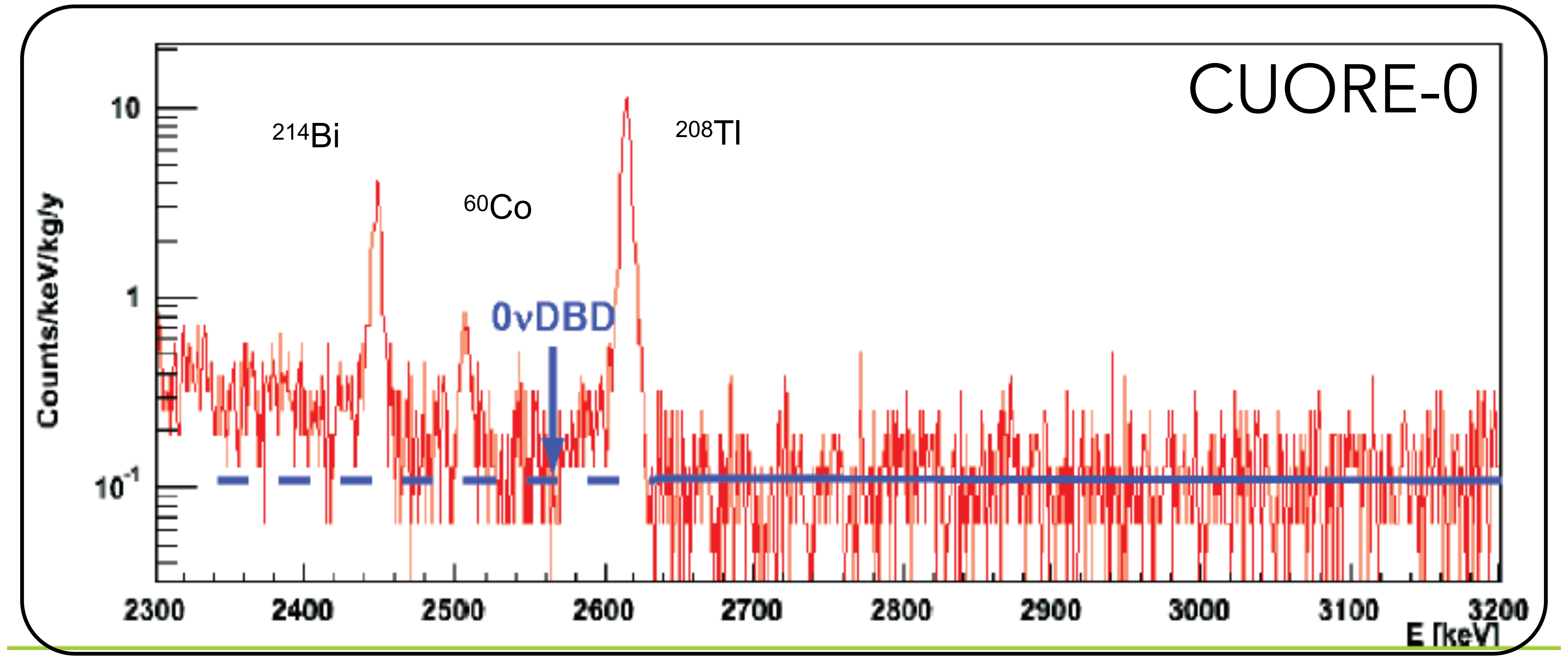
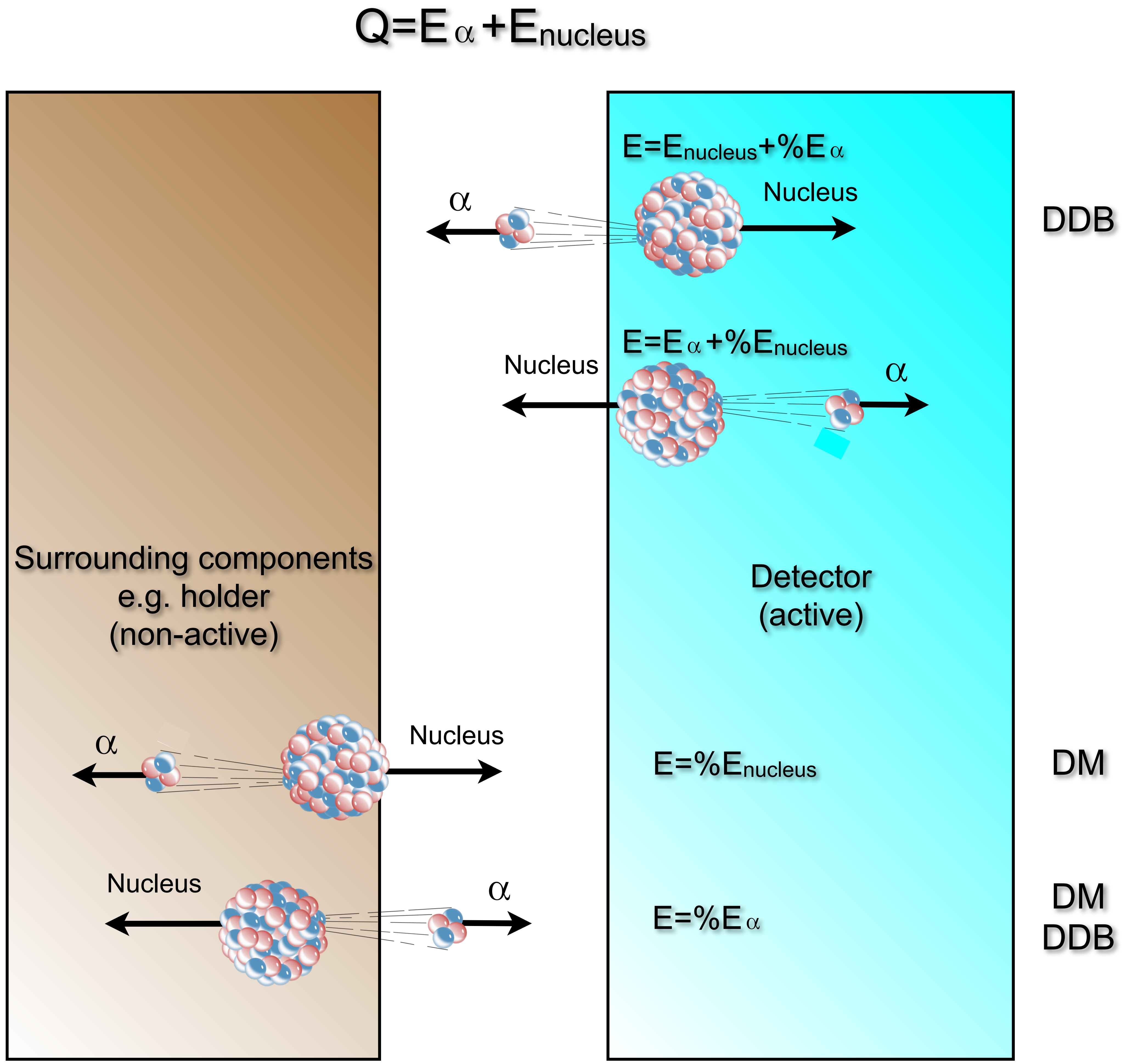




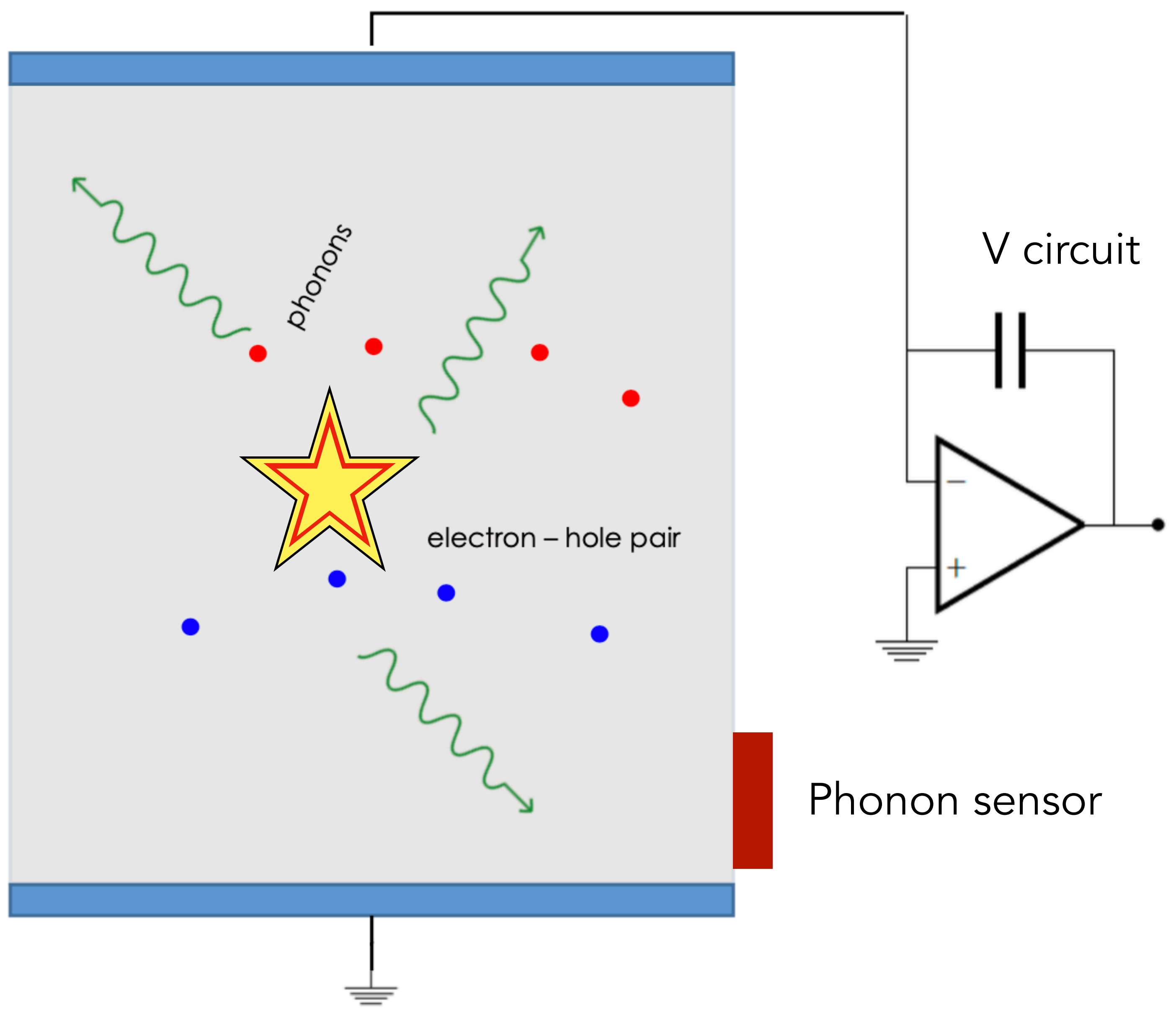
Composite bolometers

The need of rejecting specific backgrounds in cryogenic detectors and the request of radiation identification capabilities have driven the development of double reading bolometers.

2 main channels have been explored:

- heat + light
- heat + ionization

Composite bolometers



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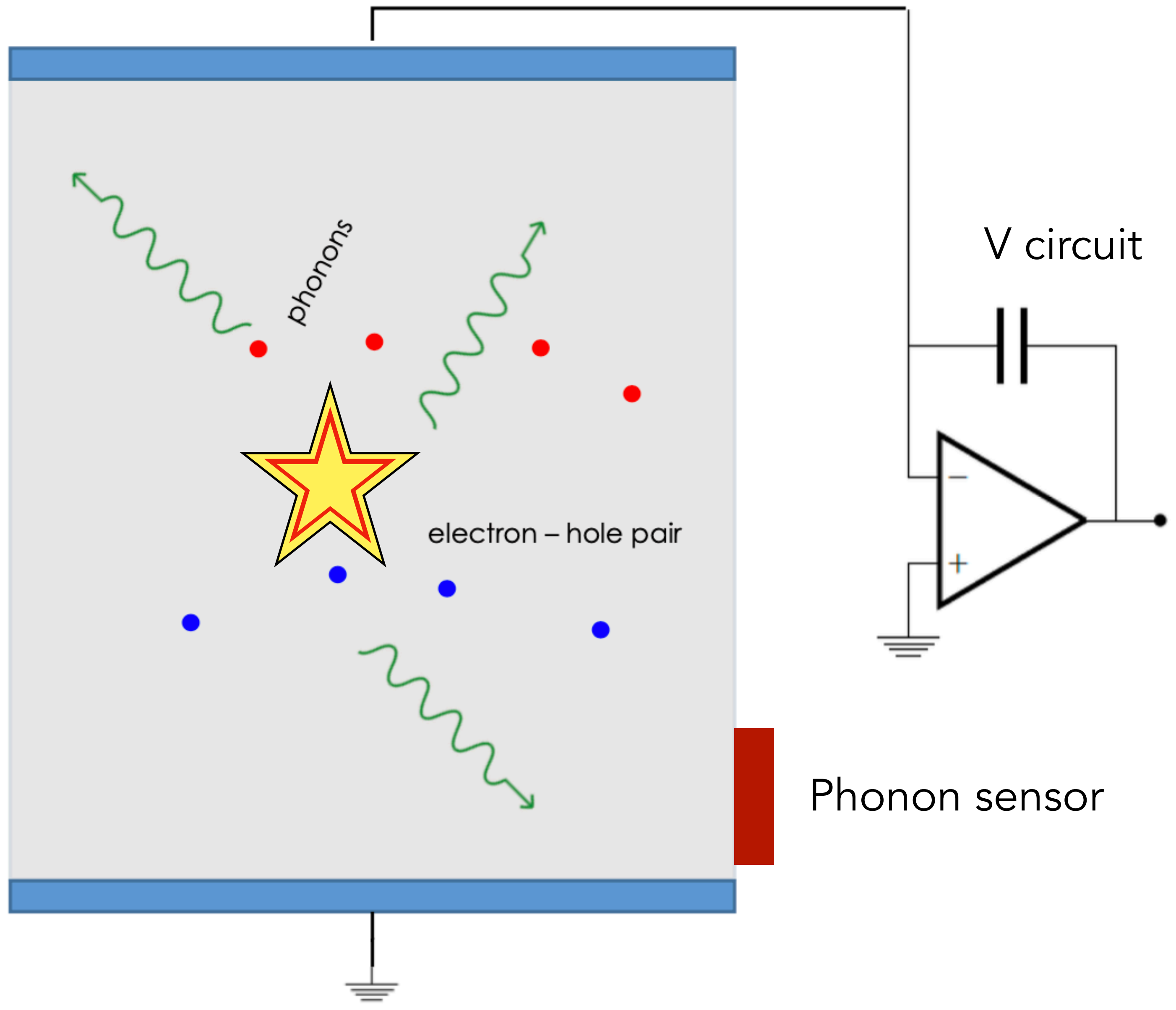

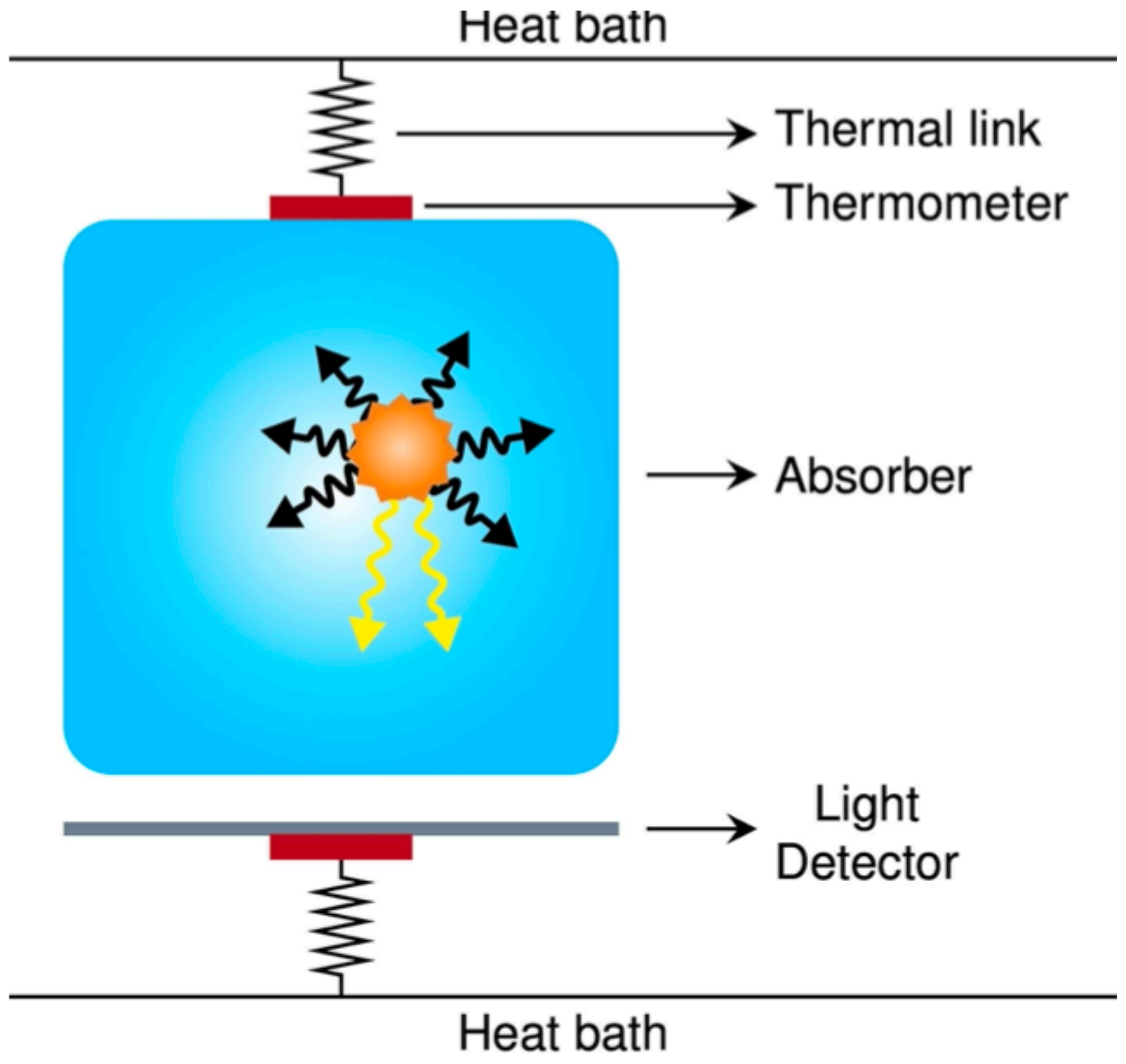

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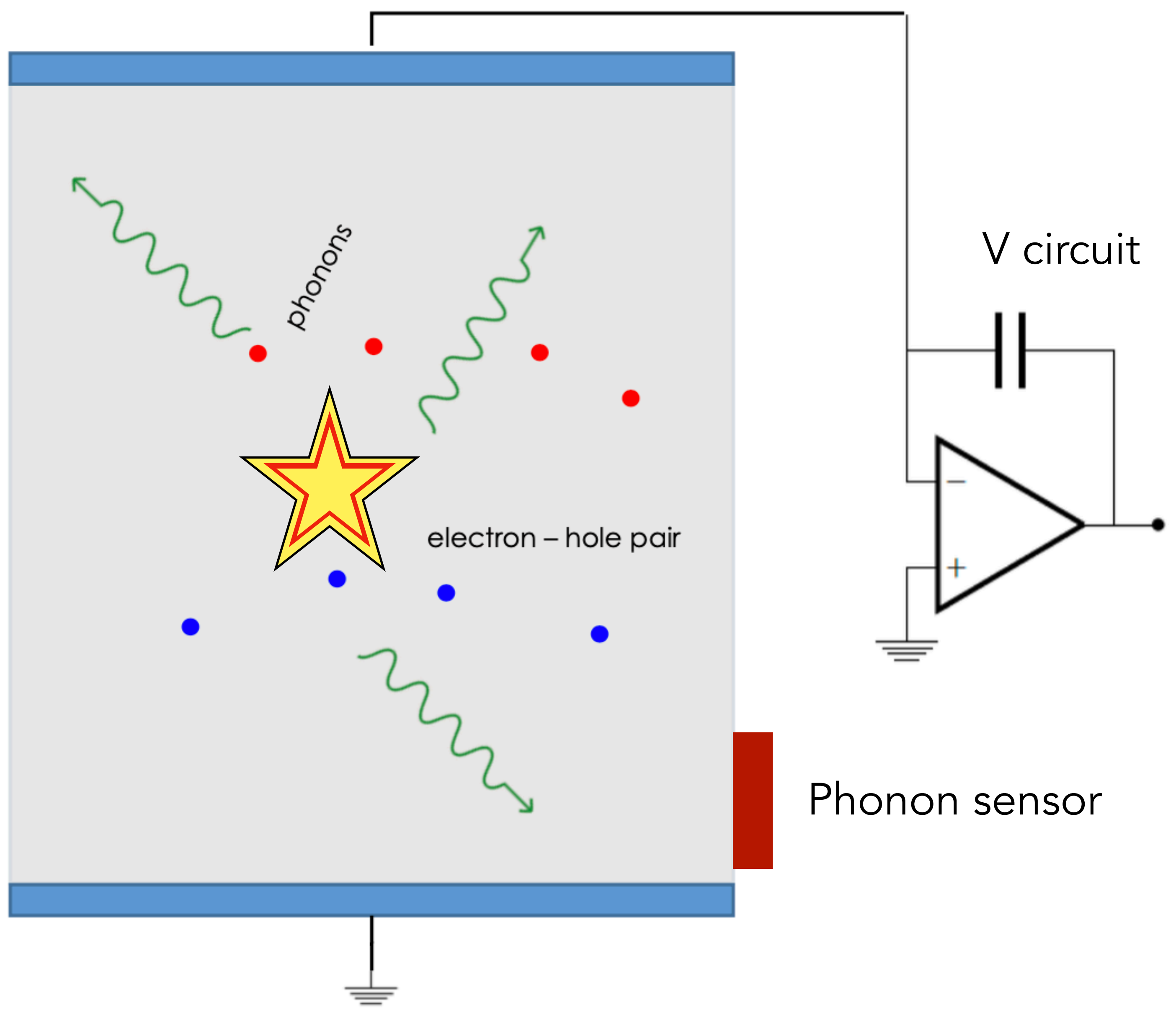

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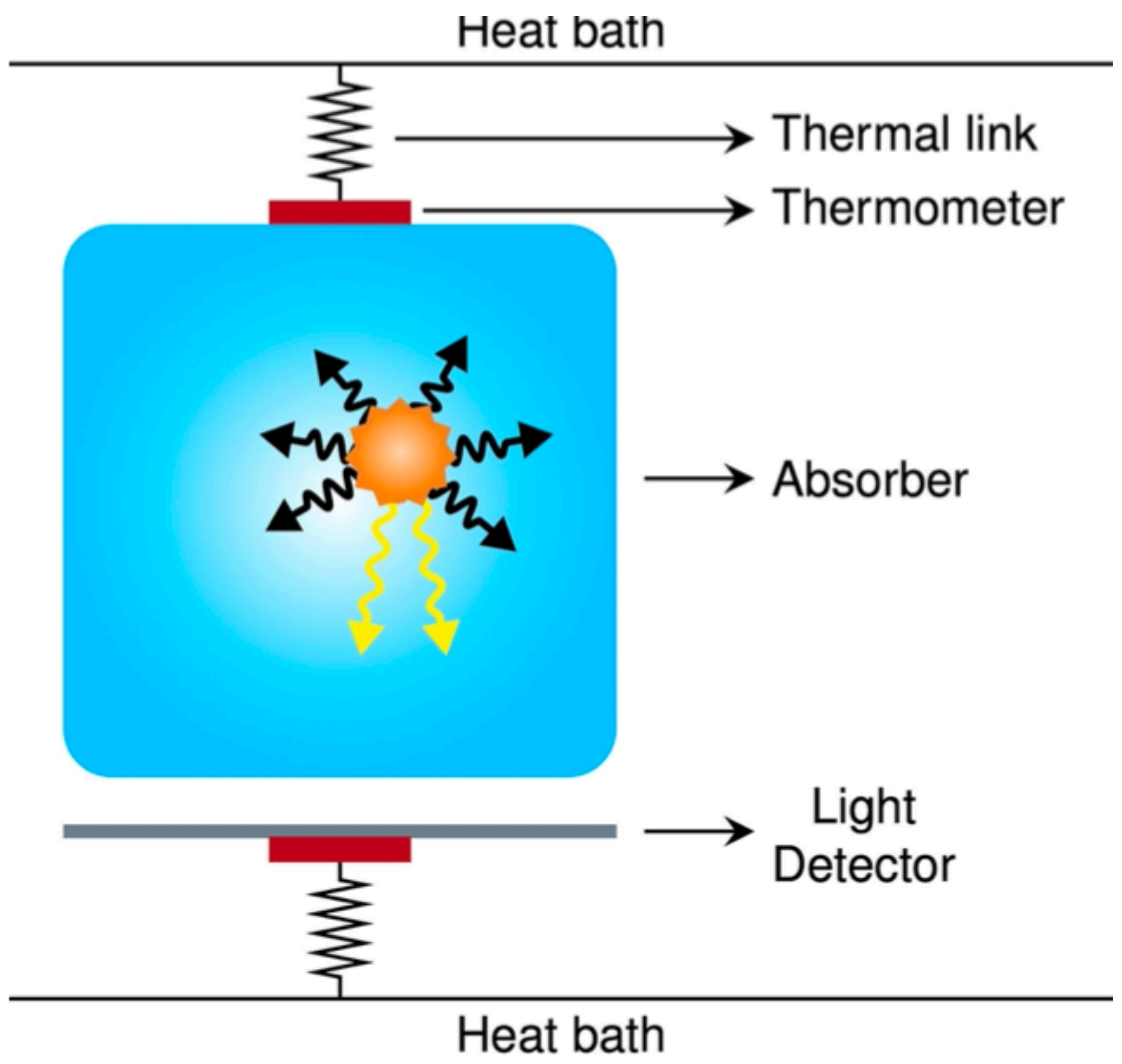
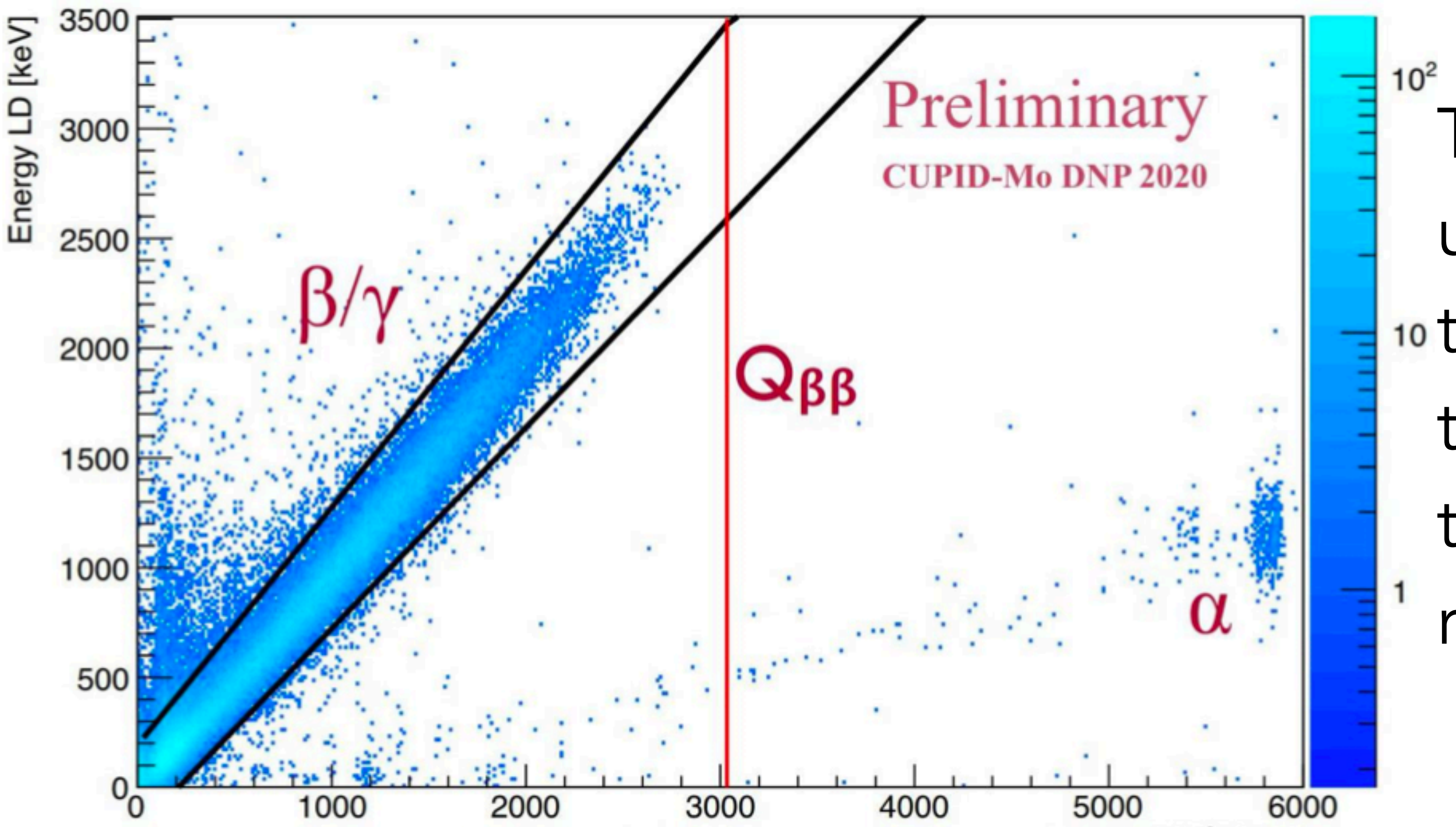




LD energy is cross-calibrated to LMO energy

The basic idea is to use the heat signal to measure E and the additional signal to discriminate radiation type

Part 2: physic applications

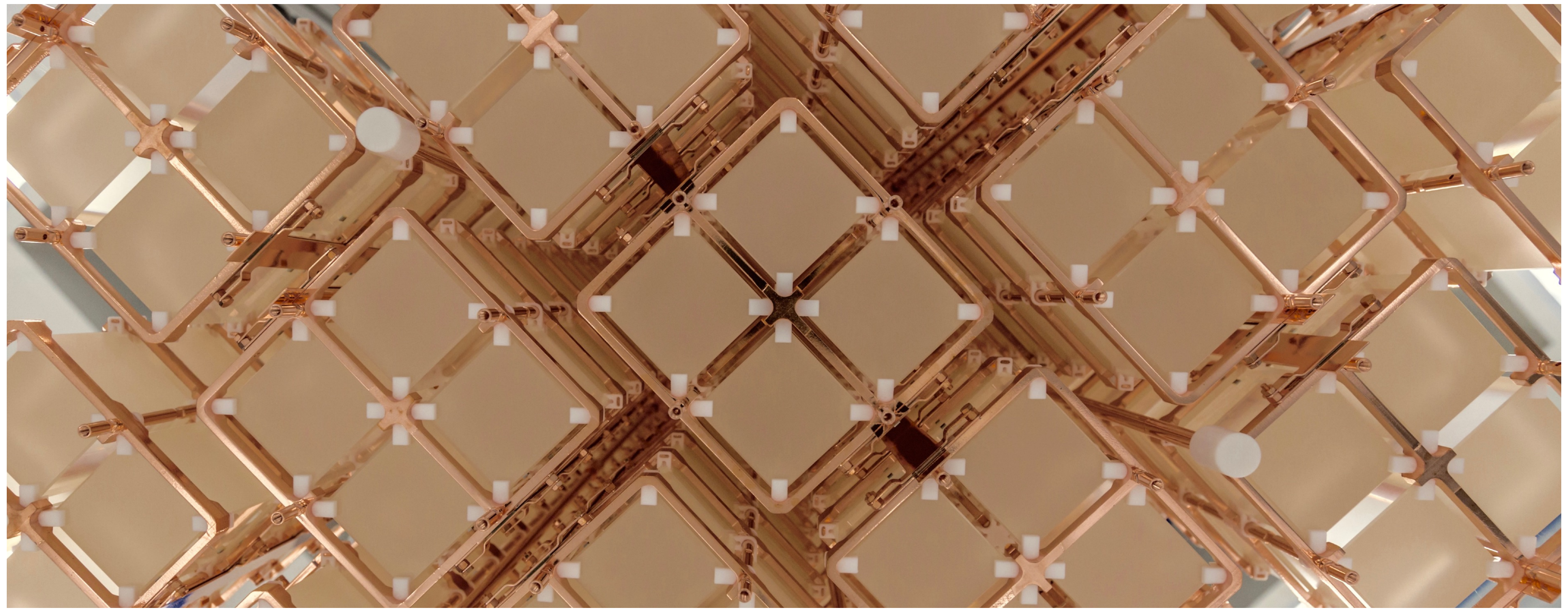
(a very incomplete list…)

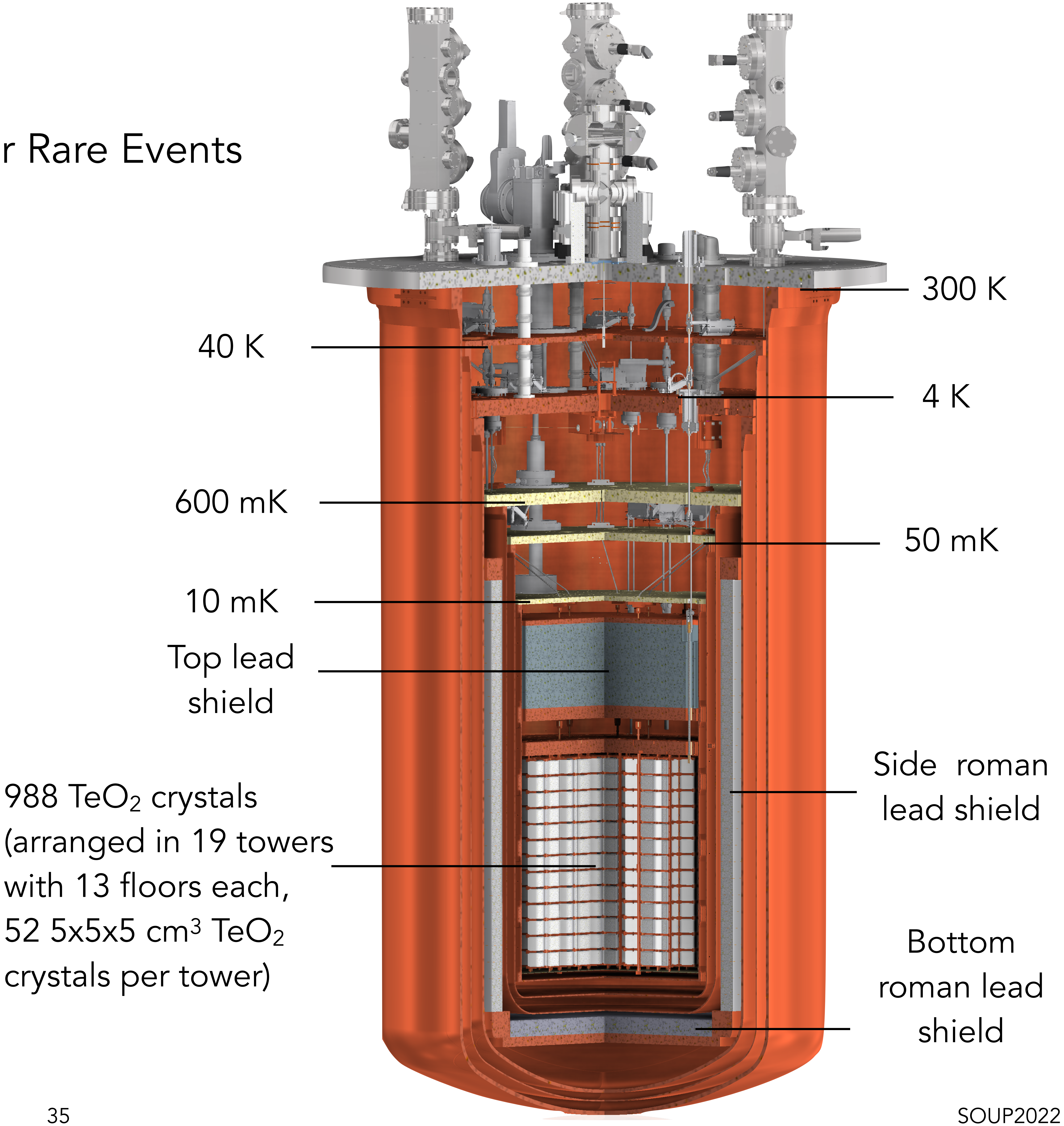
CUORE

Cryogenic Underground Observatory for Rare Events

Main goal: detect $0\nu\beta\beta$ in ^{130}Te, in cryogenic TeO_2 bolometers, to prove the Majorana nature of the neutrino

- The CUORE detector is hosted in a cryogen-free cryostat (mass < 4K: ~15 tons of Pb, Cu and TeO_2)
- Operating temperature 11 mK (base T~7 mK)
- Designed to guarantee extremely low radioactivity and low vibrations environment
  - Energy resolution: goal of 5 keV at $Q_{\beta\beta}$
  - Low background: goal of 10^{-2} cts/(keV·kg·yr) at $Q_{\beta\beta}$





988 TeO_2 crystals (arranged in 19 towers with 13 floors each, 52 5x5x5 cm^3 TeO_2 crystals per tower)

Large masses

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CUORE demonstrates the feasibility of a tonne-scale experiment employing cryogenic calorimeters (for the search of the 0νββ decay) and set a new benchmark for upcoming generation of projects

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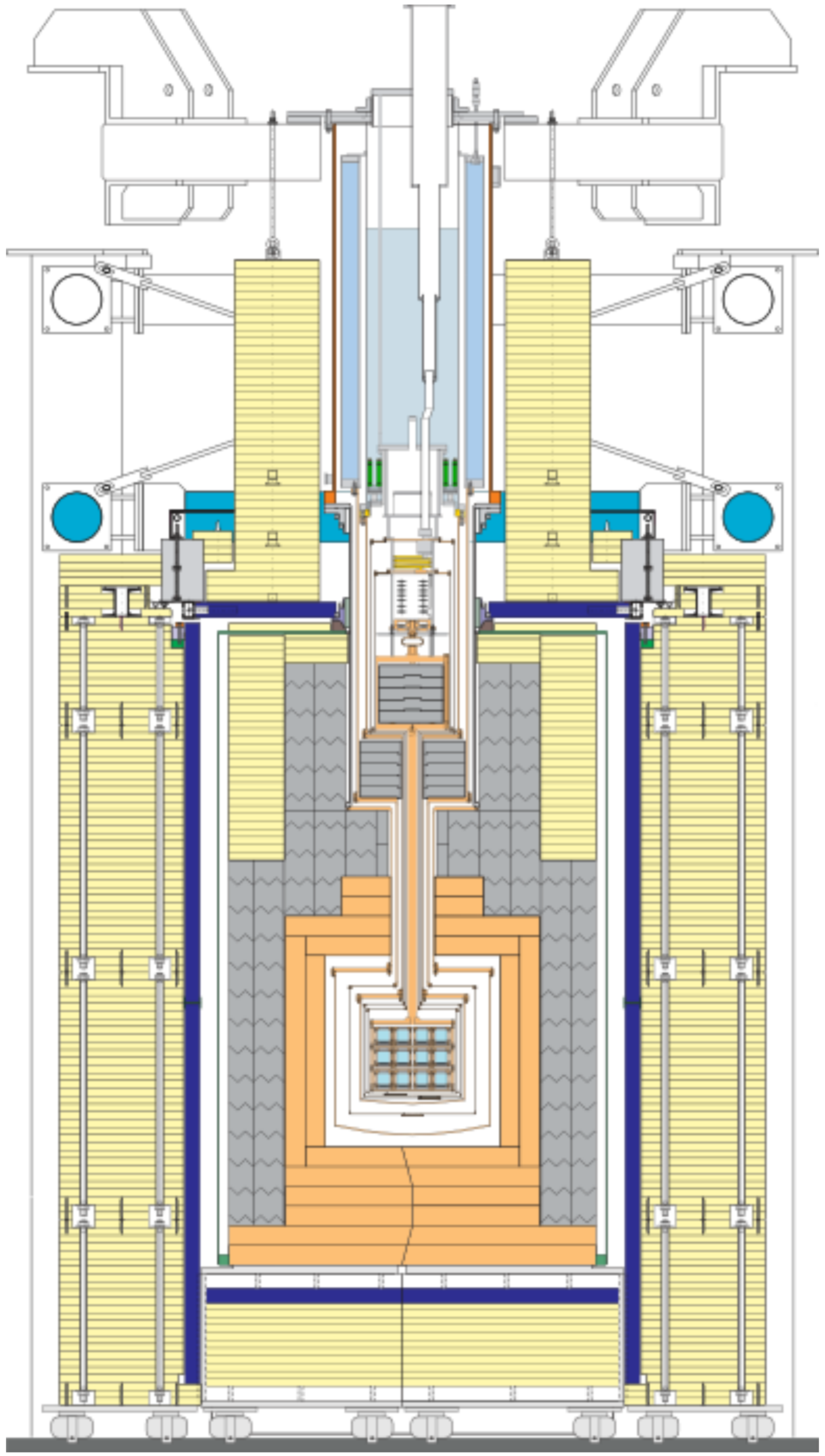
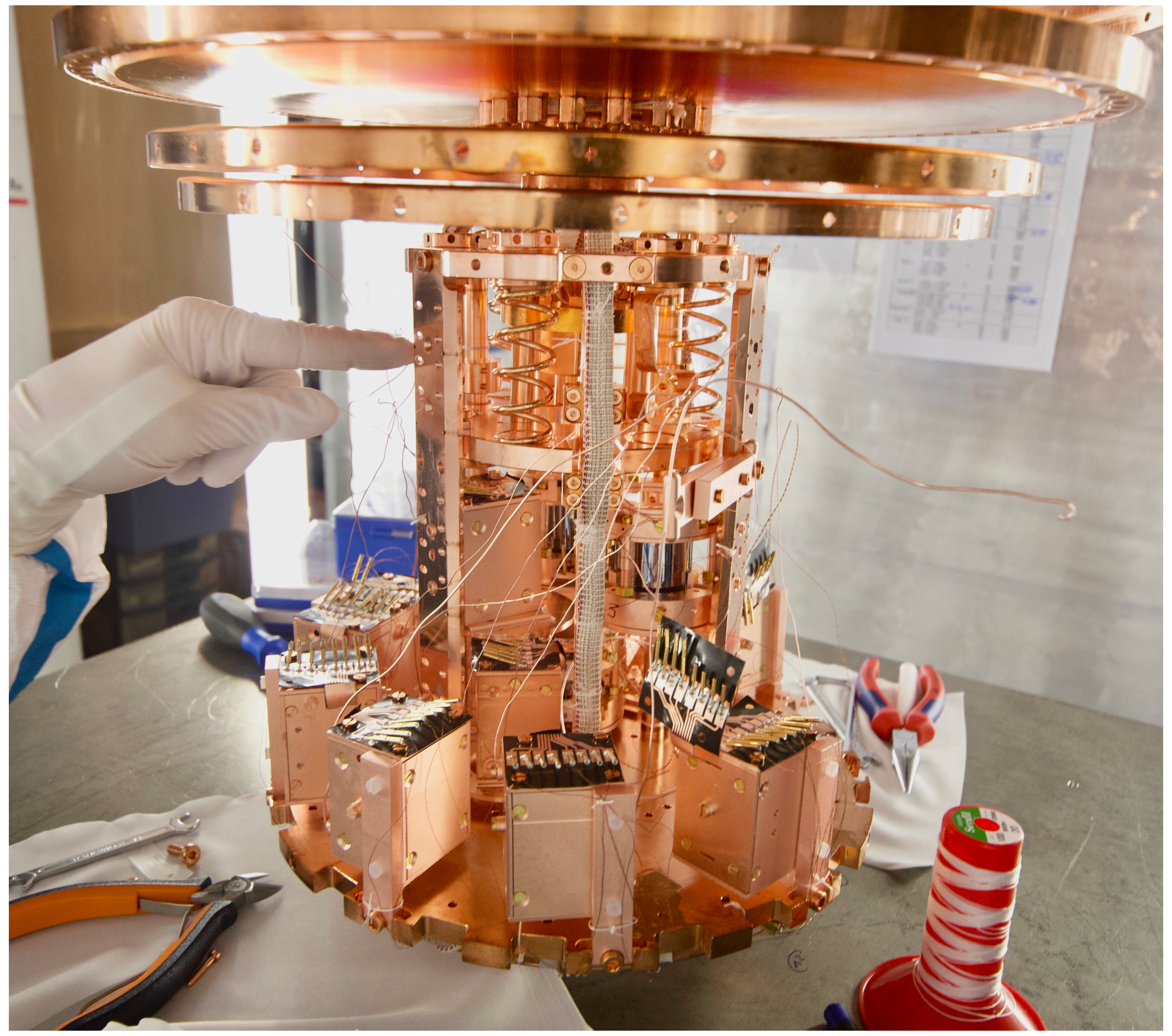
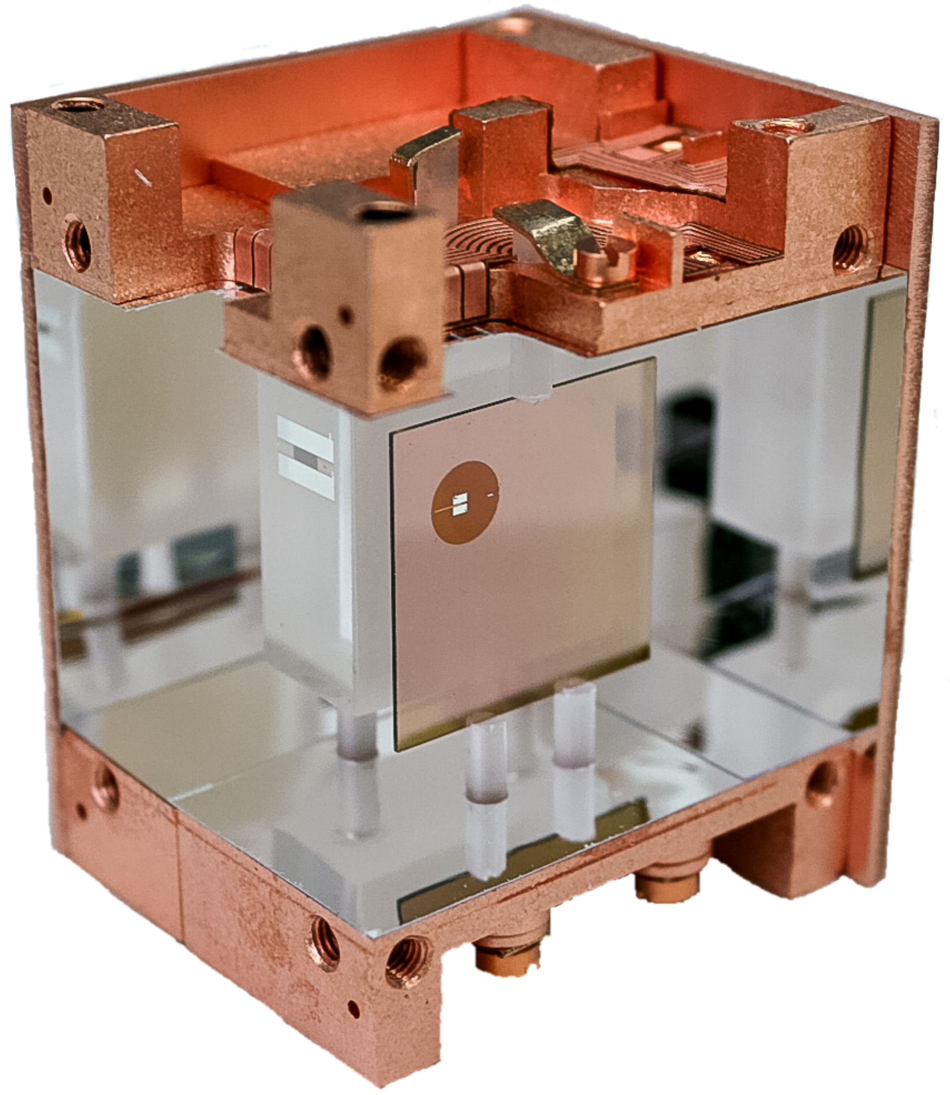
CUORE granularity offers a crucial tool for specific kind of signatures (e.g. processes with associated gammas) and to reject specific bakgrounds.

The CRESST Experiment

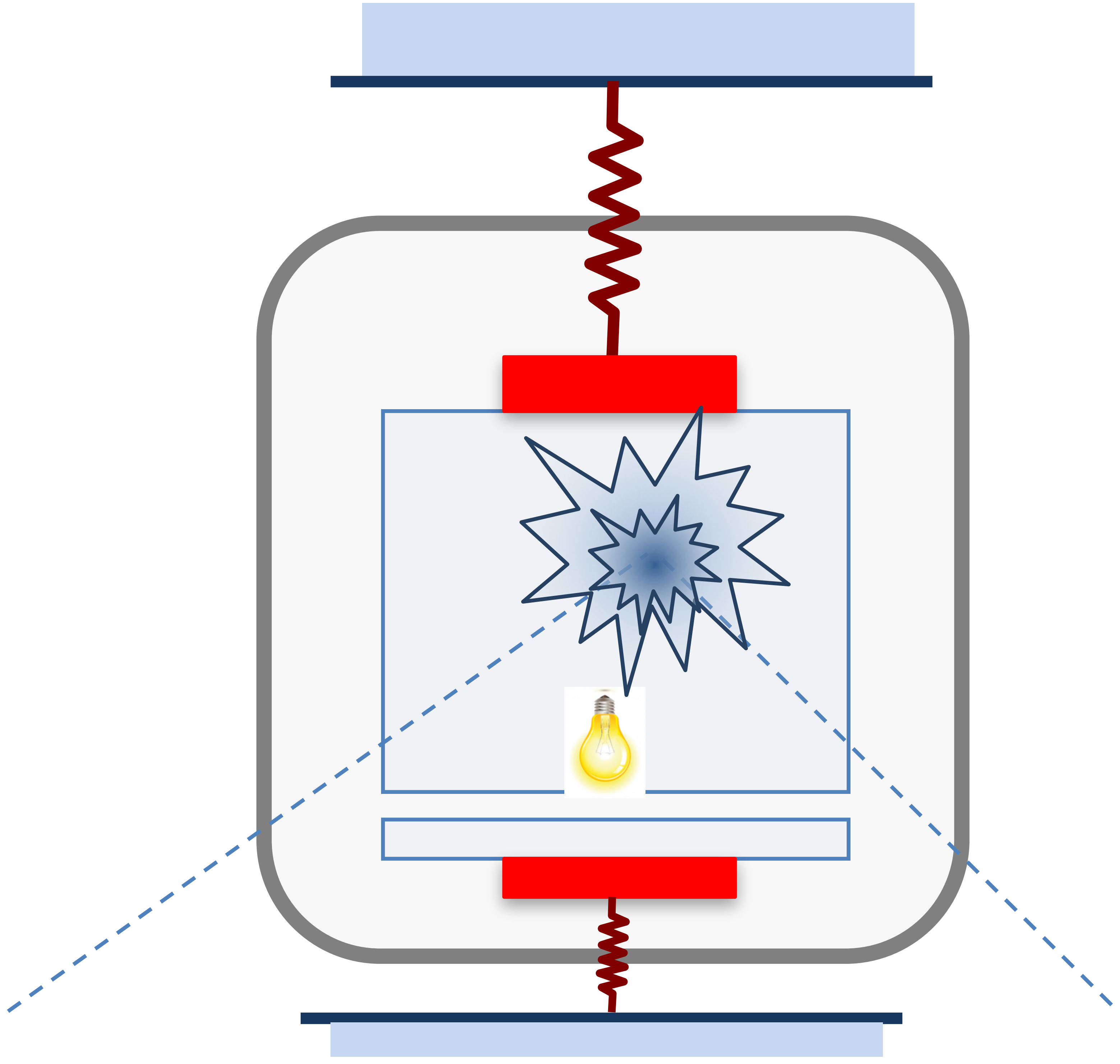
Cryogenic Rare Event Search with Superconducting Thermometers







Scintillating $CaWO_4$ crystals as target + Separate **cryogenic light detector operated at 15 mK** with TES readout



CRESST: DARK MATTER DATA

Det A: 24 g, E_{th} = 31 eV

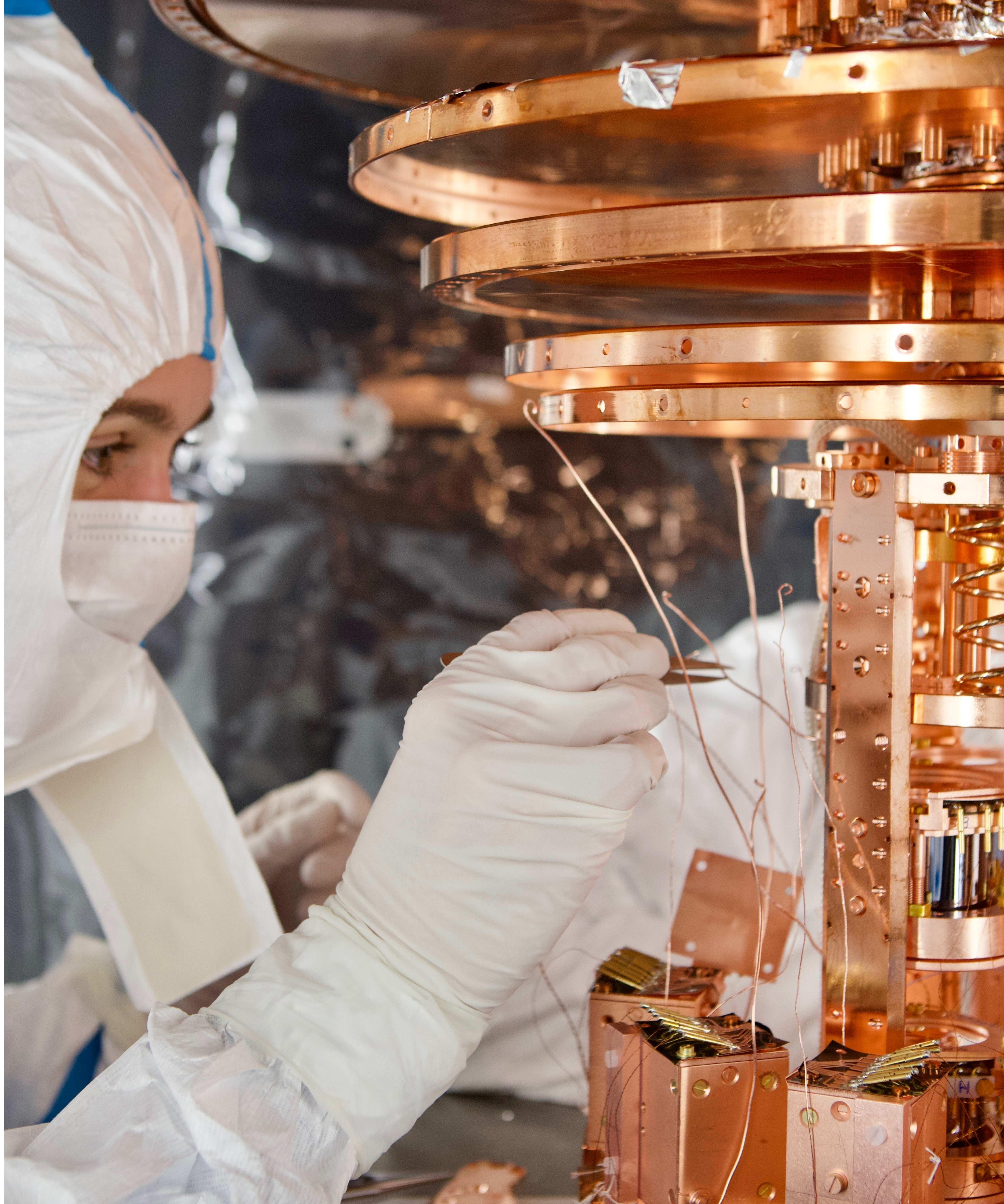
Analysis optimized for very low energies: 31eV —> 16keV

Acceptance region fixed before unblinding


50 % O recoils below

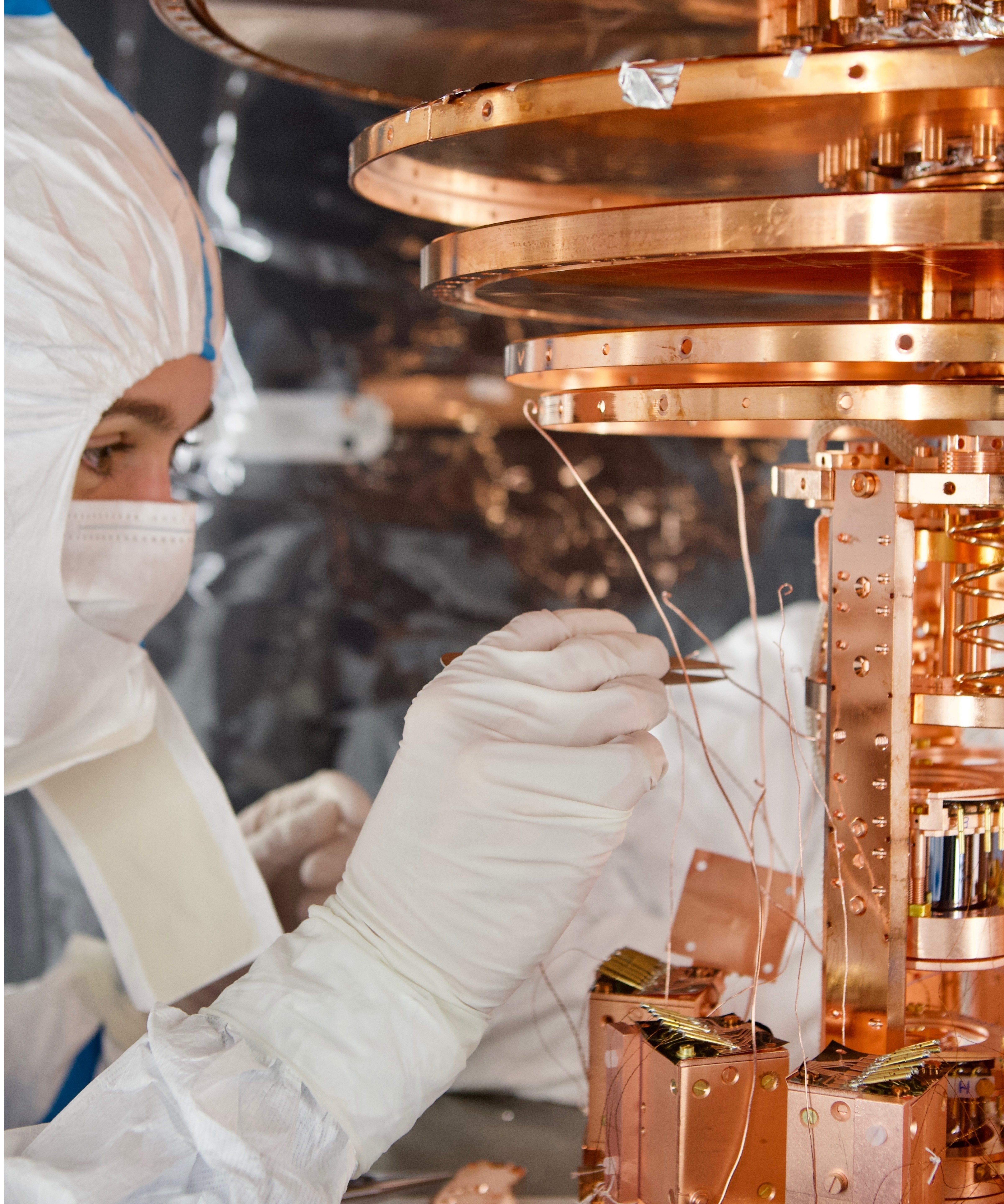
99.5 % W recoils above

Low threshold



Low threshold

CRESST set a new benchmark for energy threshold in cryogenic detectors. Thresholds as low as 10 eV are the new target for next generation of experiment with detector masse s in the O(10 g) scale.



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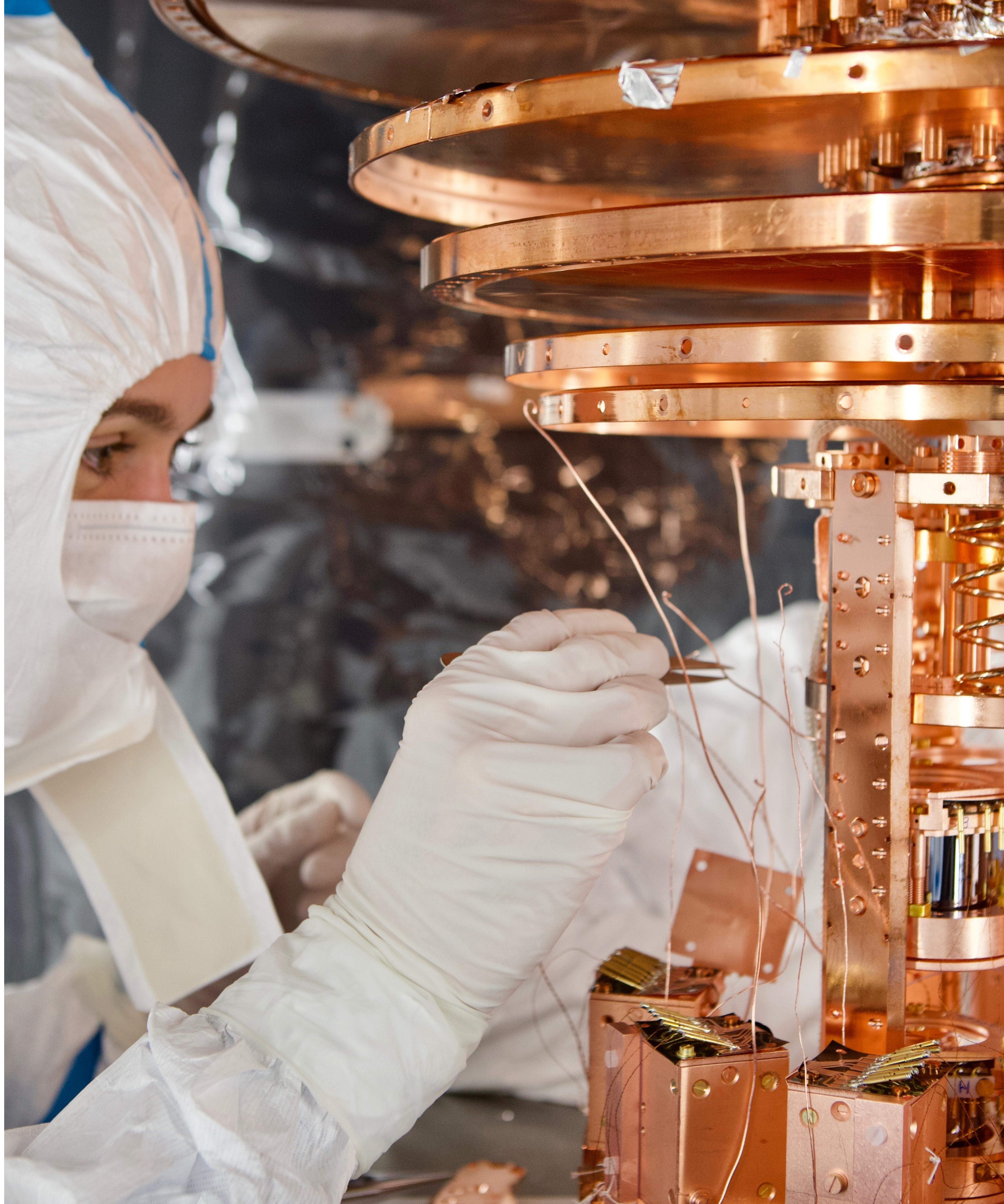

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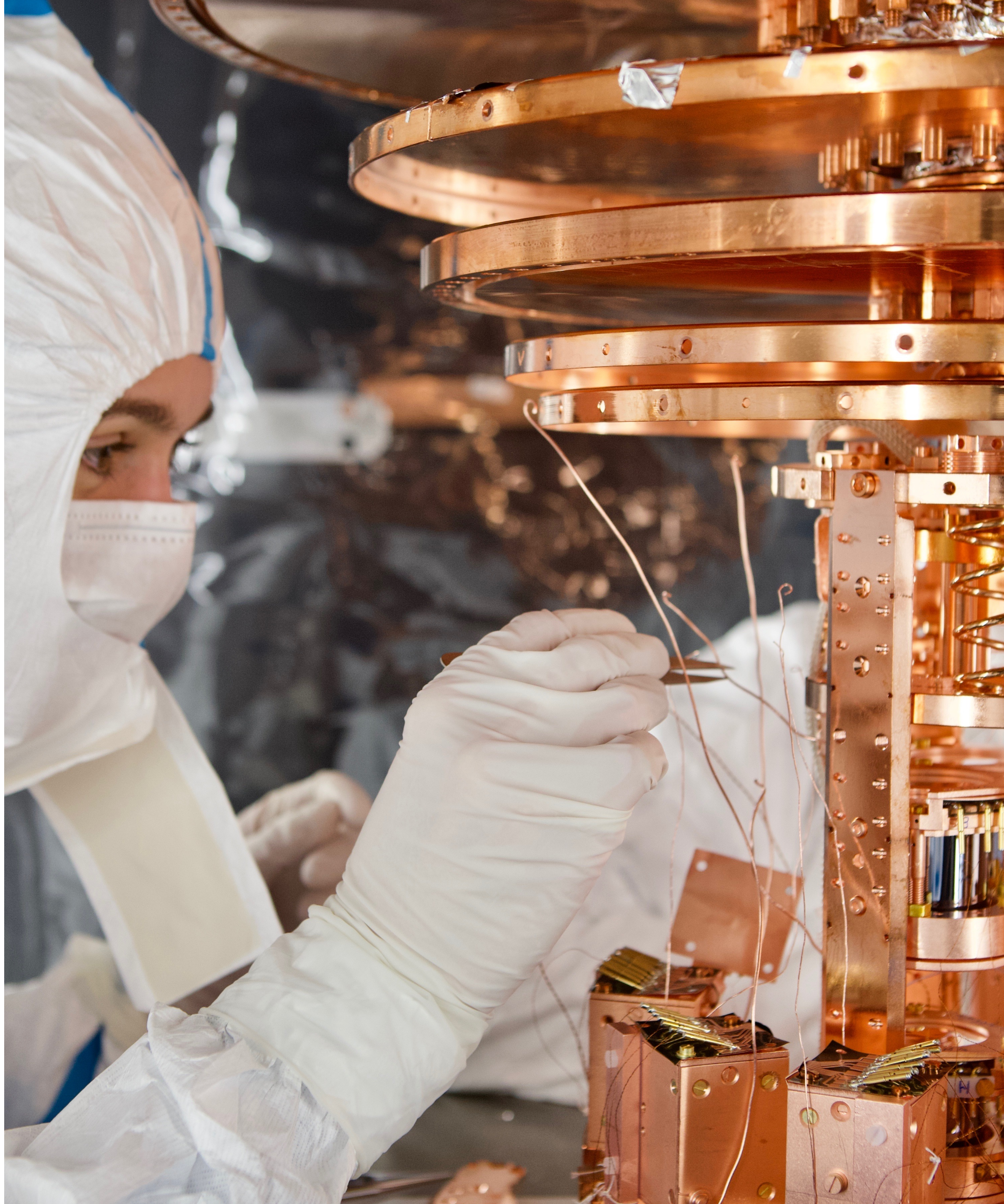
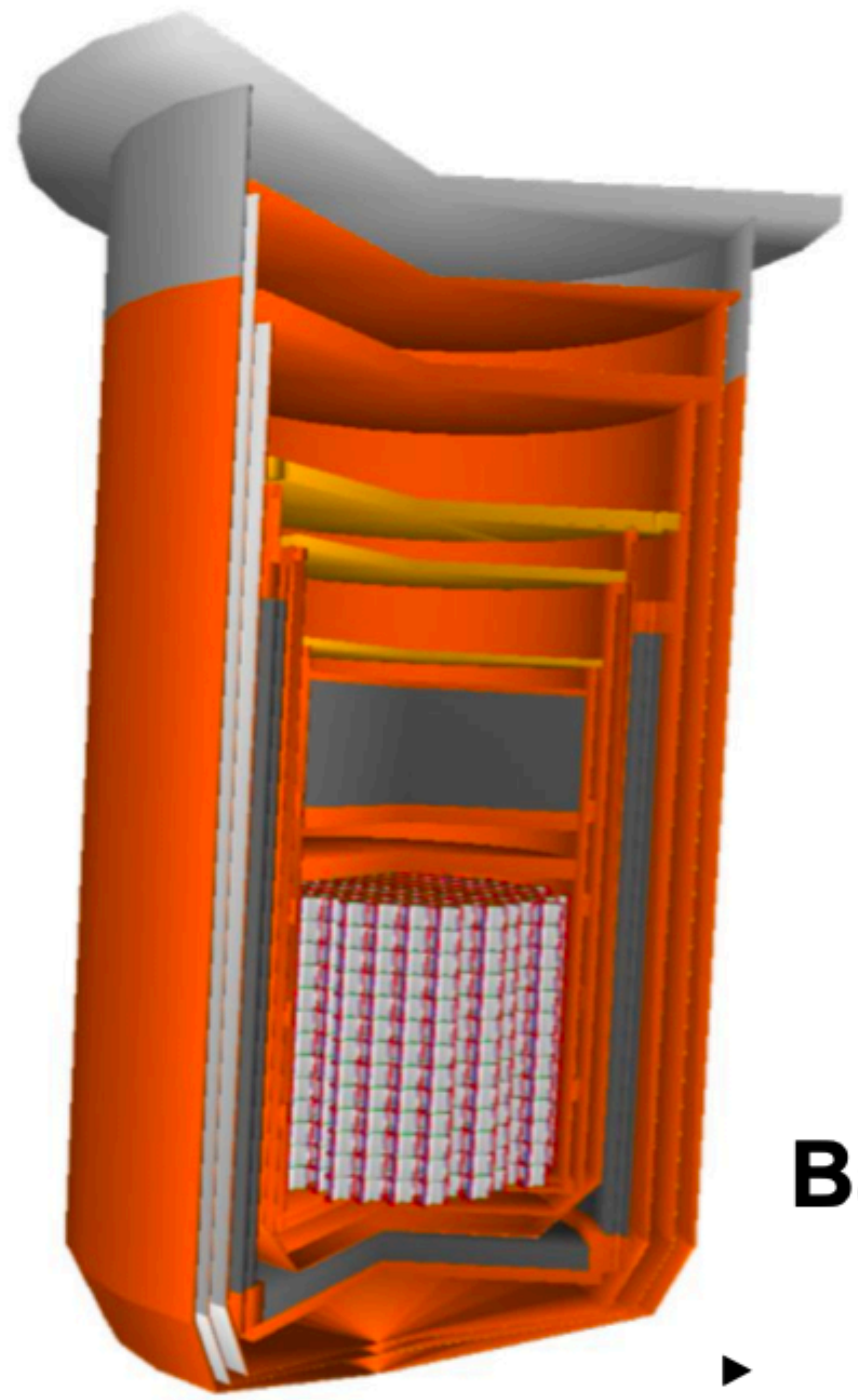
CRESST-like TES are now being used in many different projects exploiting low energy threshold benefits (neutrino physics, Dm search,…).



Many astroparticle physic applications

CUPID

CUORE **U**pgrade with **P**article **ID**entification



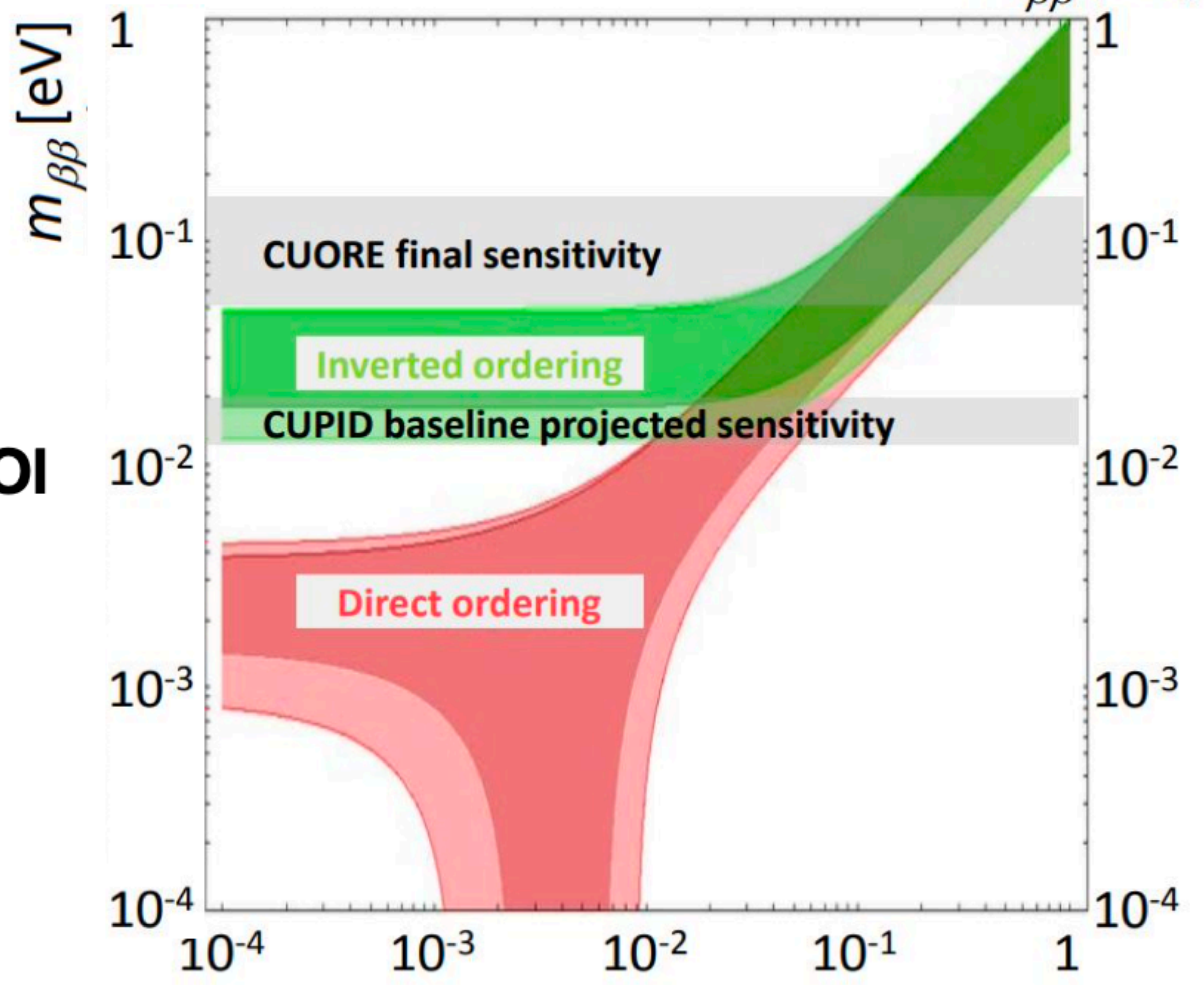
1 tonne of scintillating LiMoO$_4$ detectors

- ~1500 calorimeters, each cubic crystal ~300g
- Crystal enriched >95% in ^{100}Mo (~250 kg of ^{100}Mo)
- Ge light detectors
- LMO and LD read via NTD
- CUPID detector hosted in CUORE cryostat

Background goal B < 10^{-4} c/(keV · kg · yr) in the ROI

- Particle ID (α vs β/γ) with scintillation light
- Possible discrimination of $2\nu\beta\beta$ pile-up from pulse shape
- Background reduction: underground location at LNGS, passive shields (Pb/Cu), high-radiopurity in assembly and storage of detectors and materials, muon veto, profit of detector high granularity

CUPID pre-CDR

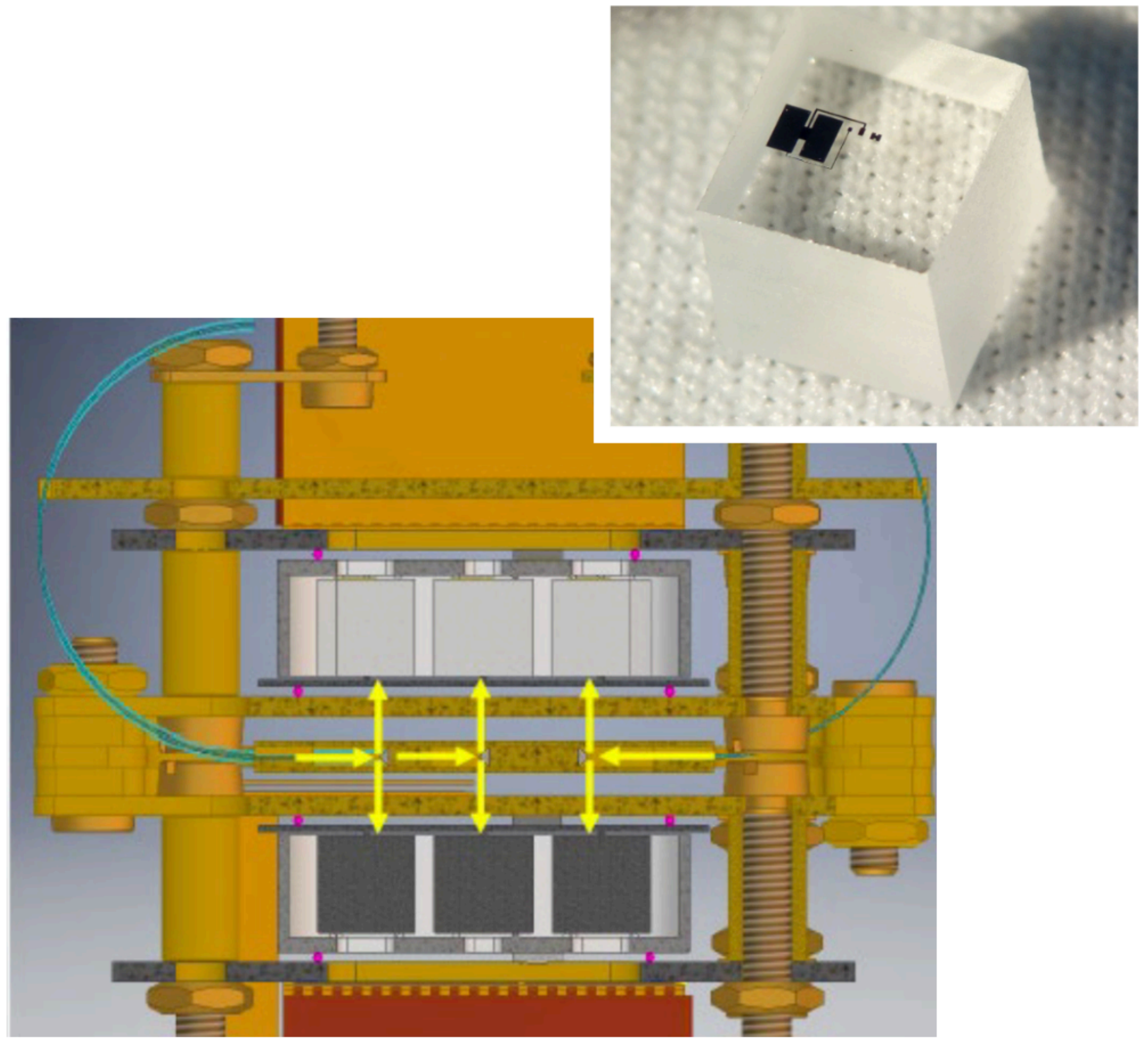


Nuclear reactors

NUCLEUS

nucleus
EXPERIMENT

- g-scale $CaWO_4$ (CEvNS) and Al_2O_3 (Bkg) crystals @ mK temperatures
  - 2 arrays of 3 x 3 cryogenic crystals (gram scale)
- Detector threshold ~ 20 eV
- Target background 100 events/kg/day/keV
- 102 m & 72 m of 2 reactors of the Chooz-B plant of 4.25 GW each
- Flux: $1.7 \cdot 10^{12}\ \bar{\nu}_e\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

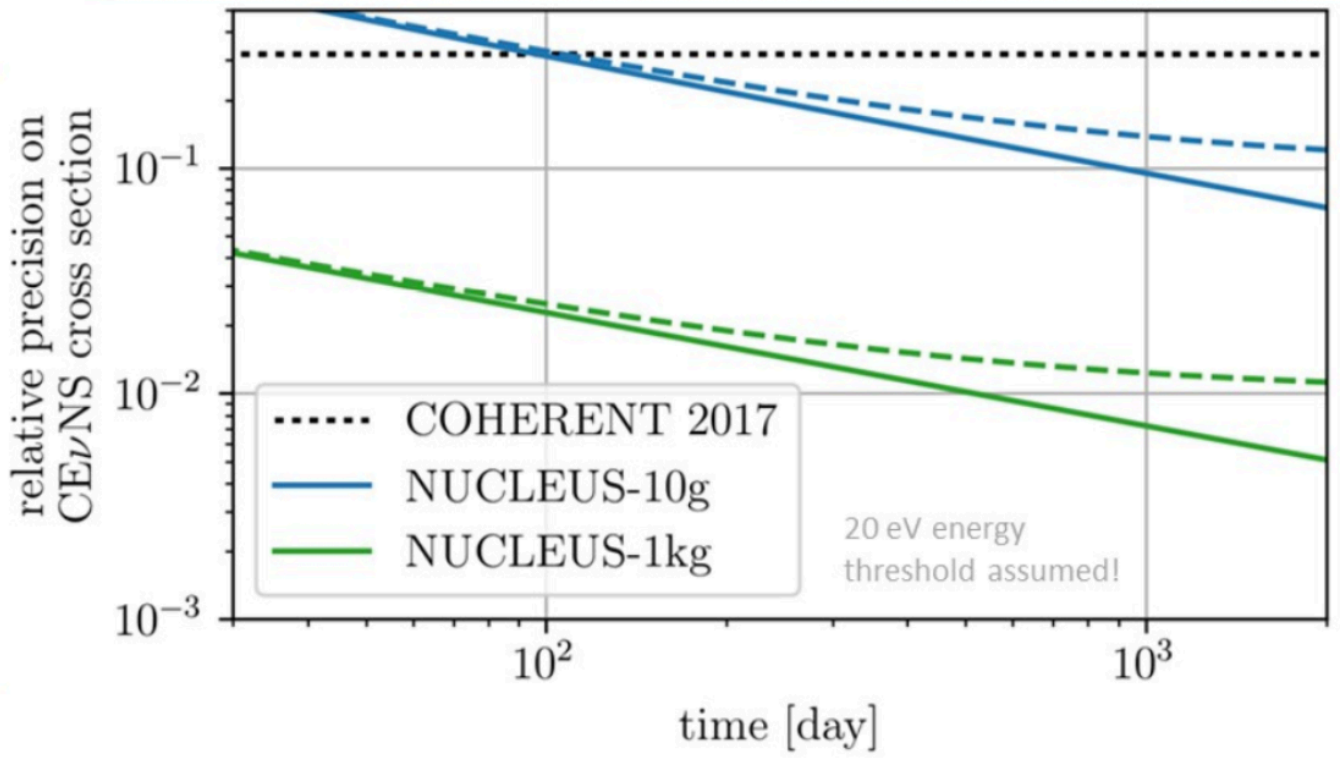


- Multi-layer passive shield + active vetos
  - Muon veto with plastic scintillators
  - 20 cm 5%-borated polyethylene
  - 4 cm boron carbide
  - Cryogenic outer veto (COV) – HPGe crystals (4 kg)


Chooz–B plant
in France

NEUTRINO 2022
XXX International Conference on Neutrino Physics and Astrophysics
May 30 - June 4, 2022
Virtual Seoul

3F Majorana, MT16-158
6F Dirac, DT06-166
7F Dirac, DT06-738



20 eV energy threshold assumed!

43

- NUCLEUS 10 g 5σ observation of CEvNS in < 1 year

Background contribution Rates in kg^{-1} d^{-1} ***(Preliminary)***	$CaWO_4$ array			Al_2O_3 array		
	10-100 eV	100 eV – 1 keV	1 keV – 10 keV	10-100 eV	100 eV – 1 keV	1 keV – 10 keV
Ambient gammas	1.7 ± 0.2	5.3 ± 0.4	≈ 45	3.9 ± 0.4	10.4 ± 0.6	≈ 90
Atmospheric muons	< 1.9	< 1.9	< 1.9	< 2.9	< 2.9	0.4 – 2.8
Atmospheric neutrons *(with a factor 5 from VNS building)*	≈ 7	≈ 23	≈ 64	≈ 1.5	≈ 15	≈ 44
Total	**≈ 10**	**≈ 30**	**≈ 110**	**≈ 6**	**≈ 30**	**≈ 140**
CEυNS signal	≈ 30	≈ 9	-	≈ 2	≈ 4	-

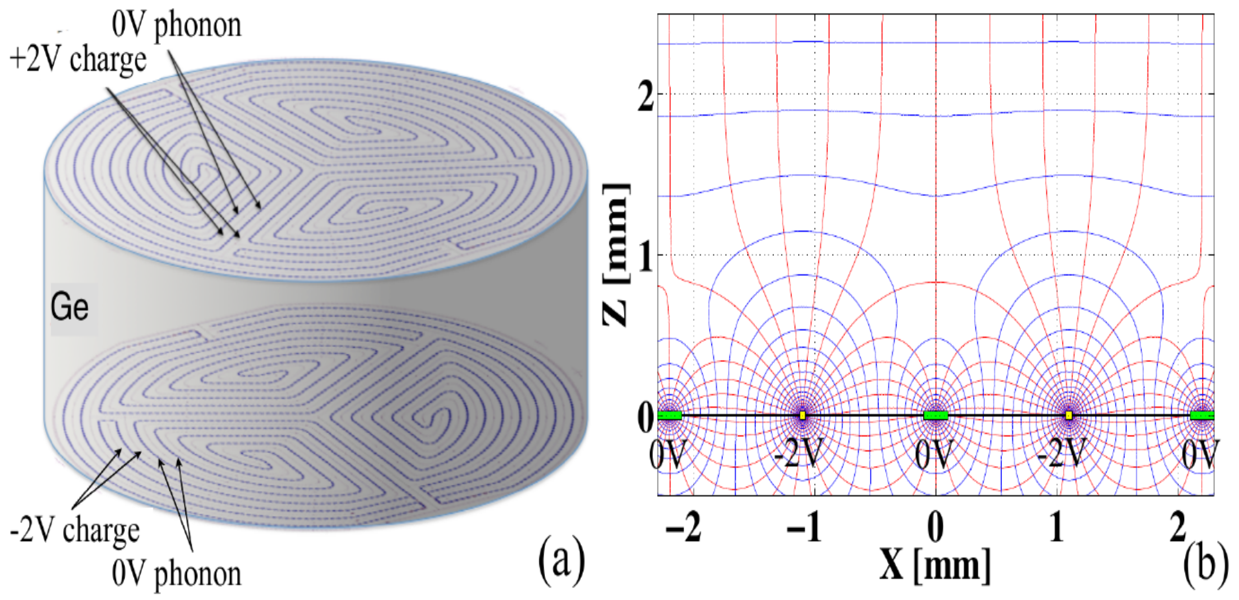
EDELWEISS, SuperCDMS

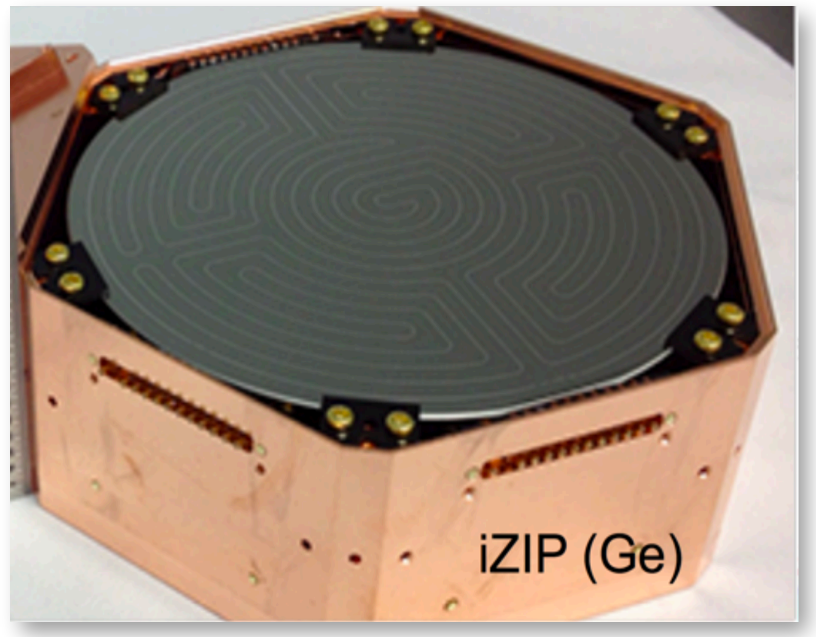
Phonon + Ionization

- Phonon and charge sensors on the target crystal
- Particle identification via ratio of ionization to primary phonon
- Surface events identified thanks to ID electrodes

SuperCDMS interleaved Z-sensitive Ionization Phonon (iZIP) detector

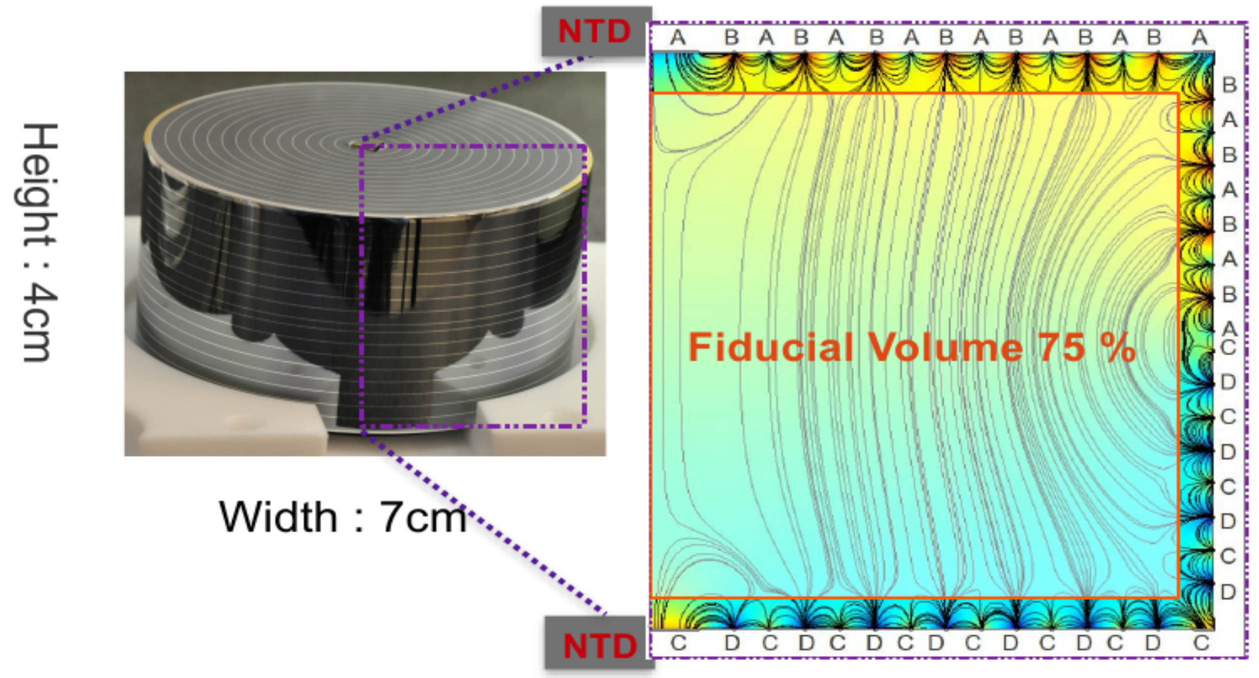
- 15 x 600g detectors
- 2 charge + 2 charge
- 4 + 4 TES – fast phonon channel

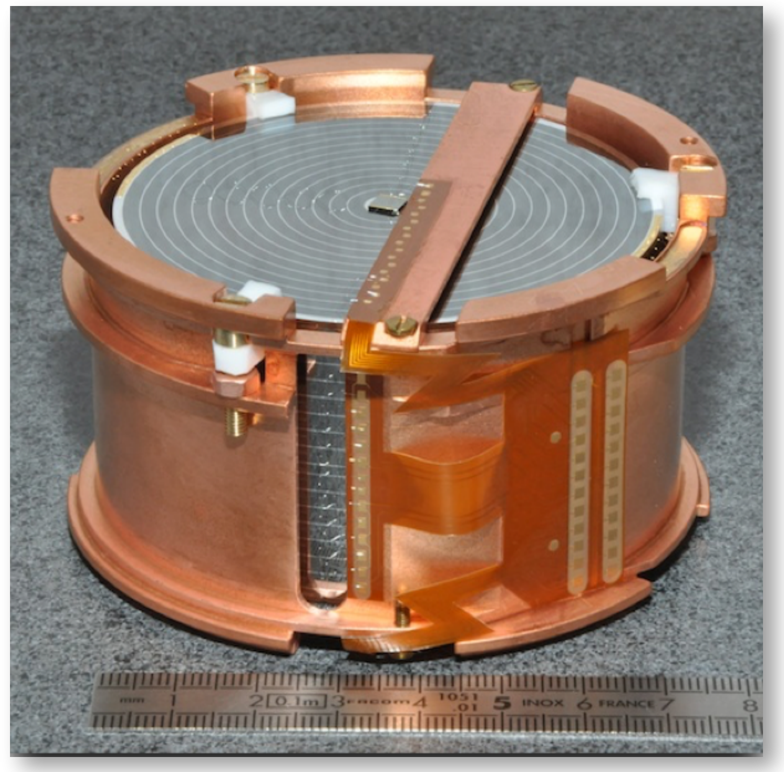




EDELWEISS FID800

- 36 x 800 g detectors
- 2 charge + 2 charge
- 2 NTD – simple phonon channel





RES-NOVA

Supernova neutrino detection with archeo-Pb based cryo detectors

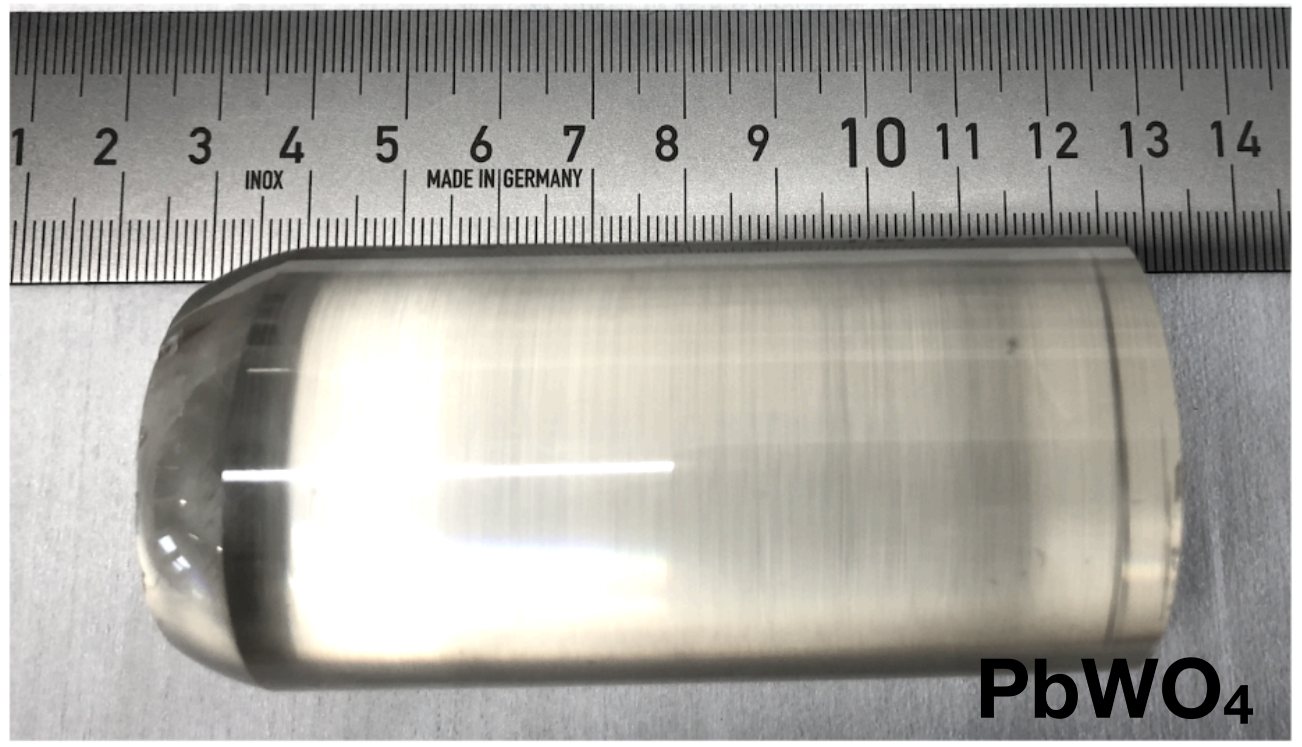
Coherent Elastic neutrino-Nucleus Scattering

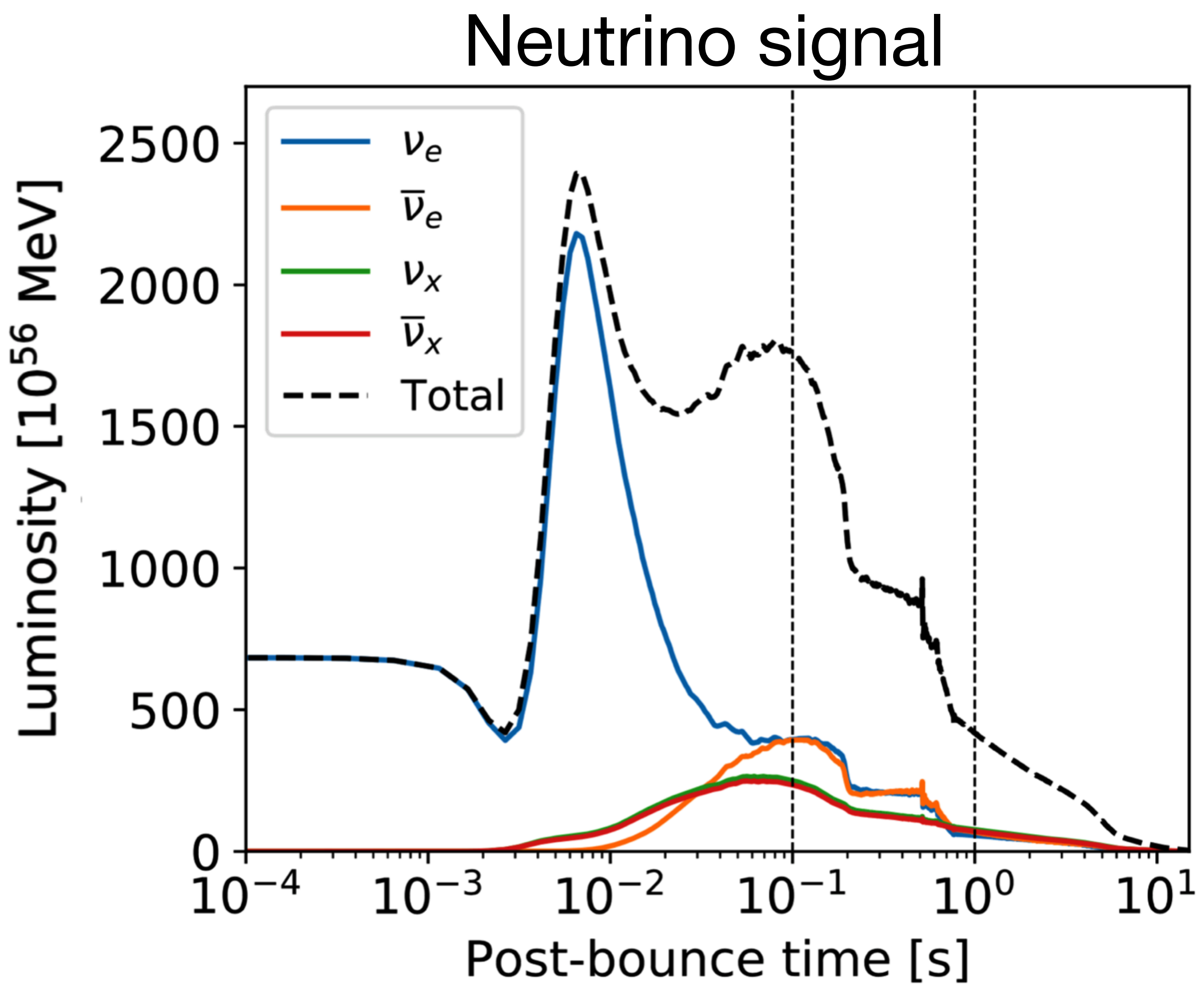
$$\overline{\nu}_x/\nu_x + A \rightarrow \overline{\nu}_x/\nu_x + A$$

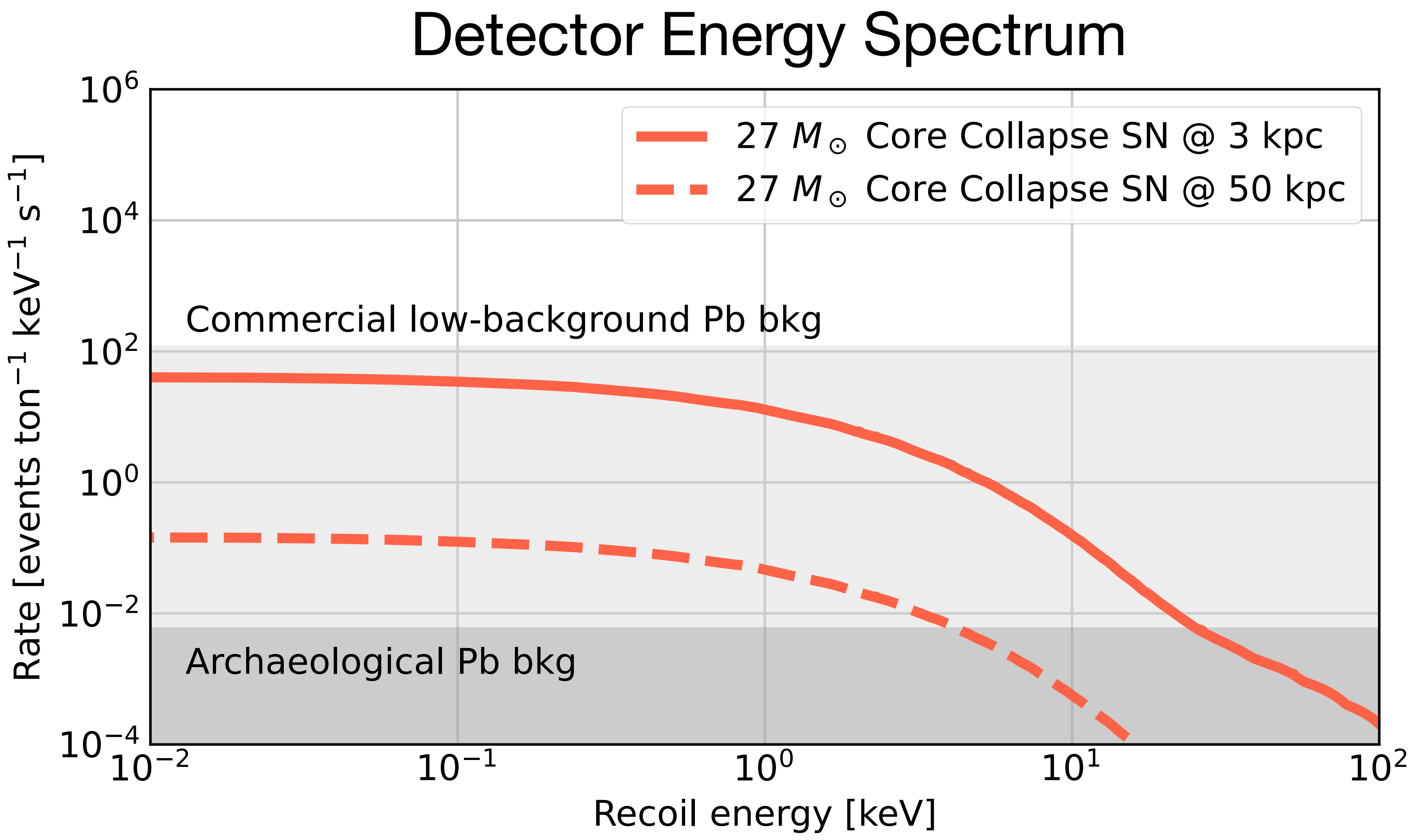
$$\sigma_{CE\nu NS} \sim N^2 \cdot E_\nu^2$$

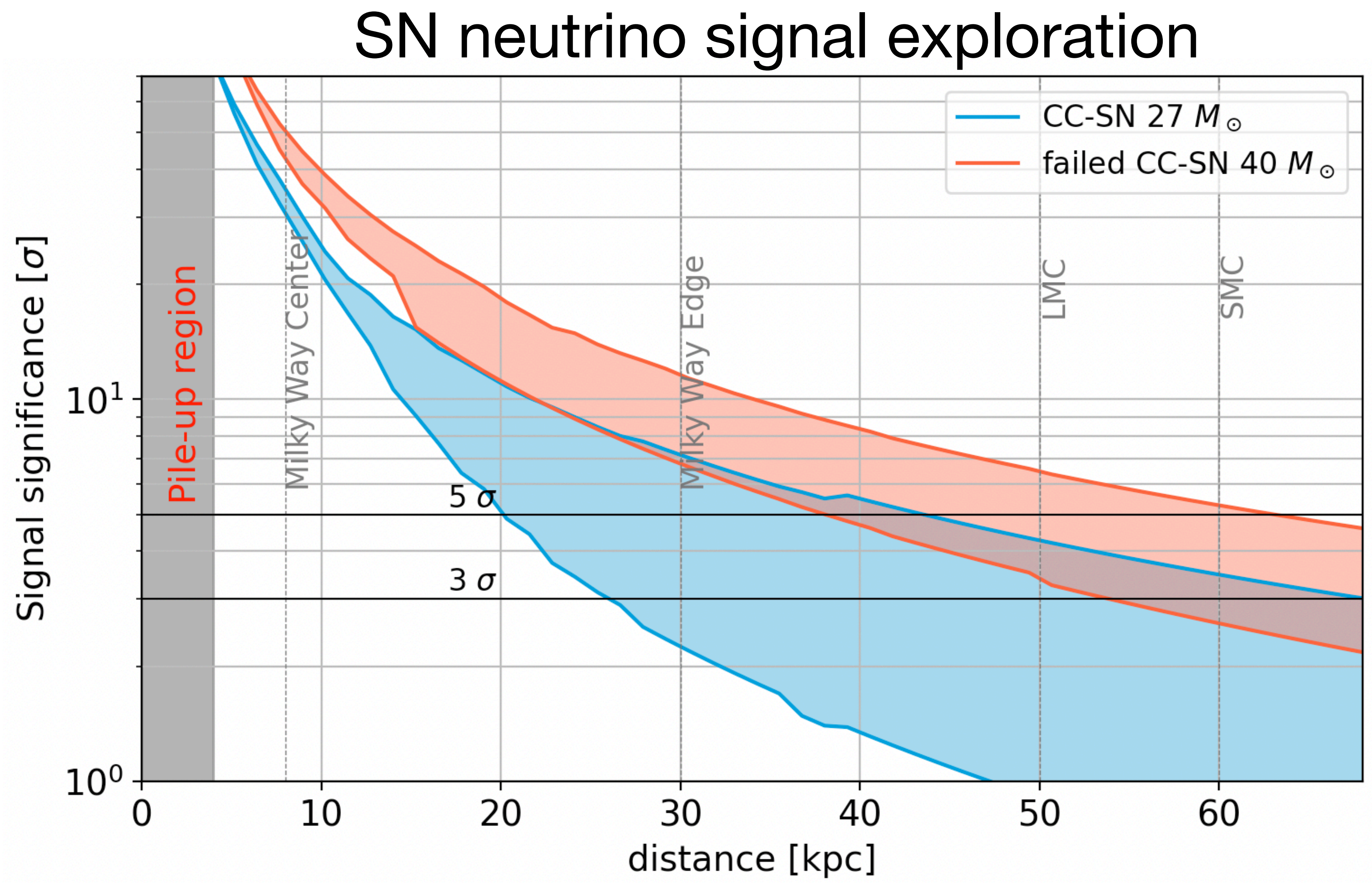
Neutron number of target material

Energy of incoming neutrino







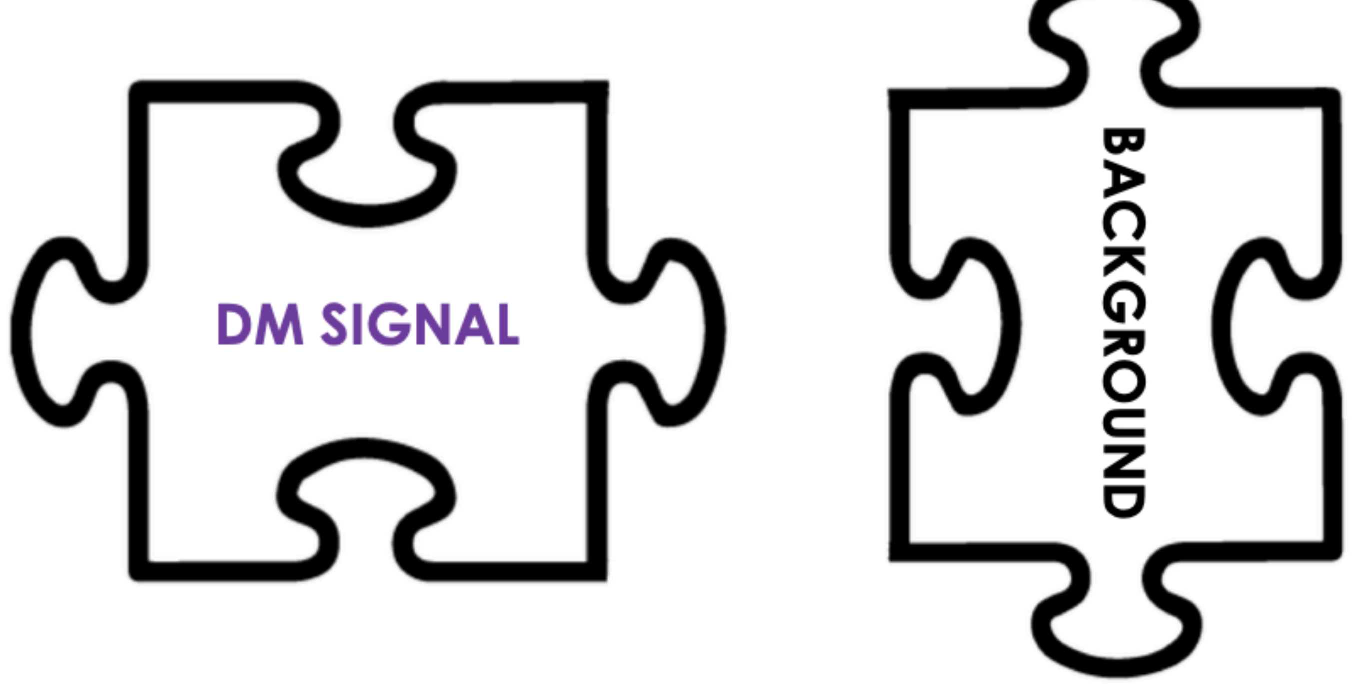


COSINUS project

MATERIAL	NaI (undoped)
SIGNAL(s)	Light and heat (TES)
LOCATION	LNGS Italy
β/γ-DISCRIMINATION	YES!
THRESHOLD GOAL	1 keV
BONUS	Particle discrimination

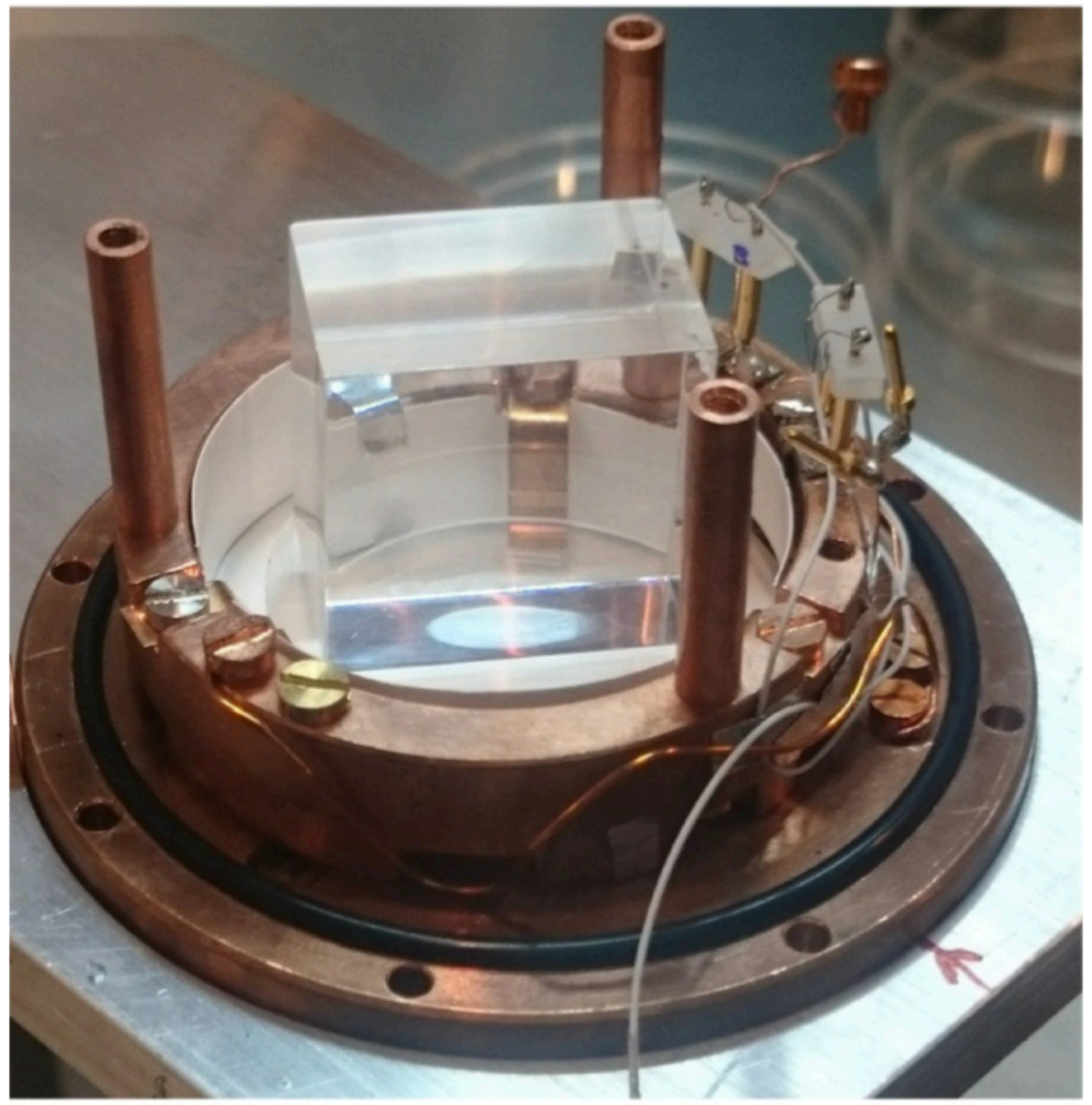
NEW

NEW



www.cosinus.it

Eur. Phys. J. C (2016) 76:441



And many others…