Cryogenics and cryogenic detectors

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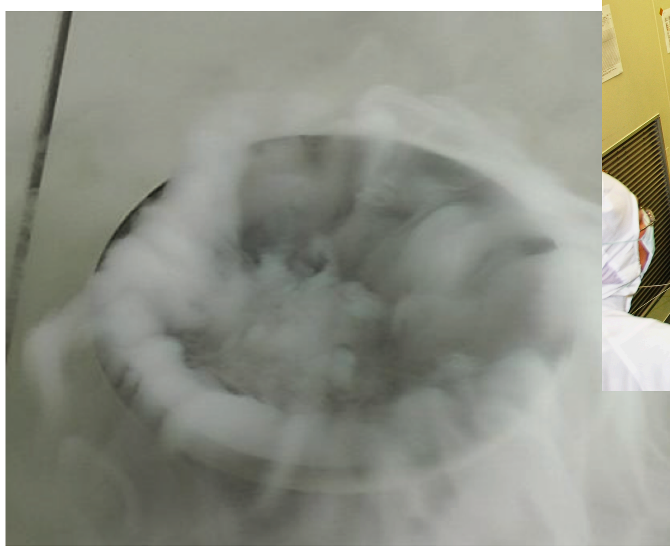
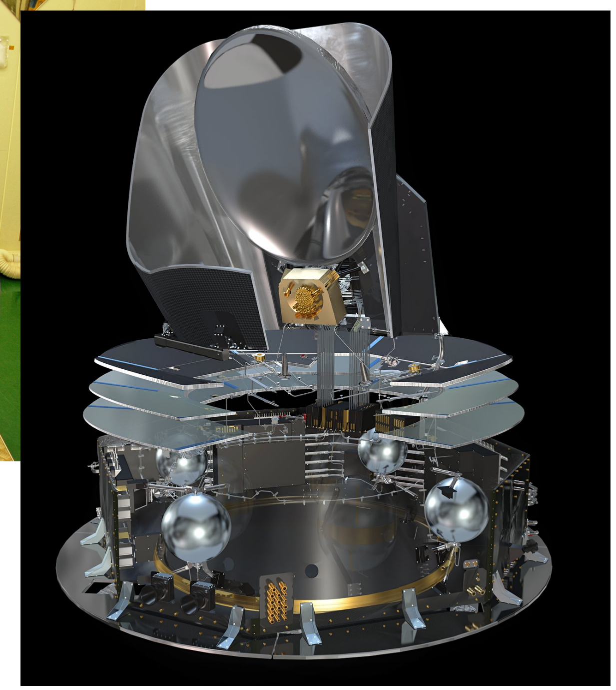
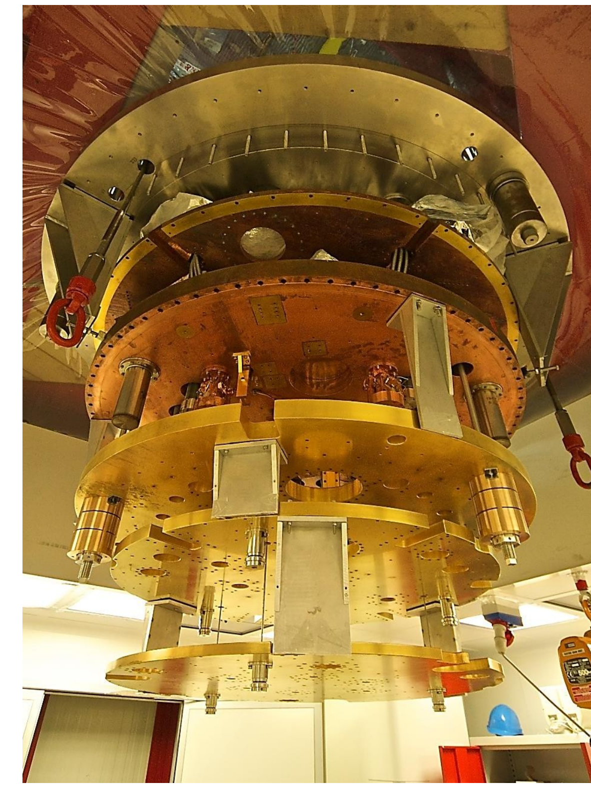
INFN-LNGS

Cryogenics and cryogenic detectors

CRYOGENICS: Science and technology of very low temperatures (common definition <120 K)



It's a very wide field with a large variety of applications

In this talk I will focus on ultra-cryogenic temperatures, which spans from few mK to hundreds of mK

Cryogenics below 1K underwent huge progresses in the last decades becoming extremely relevant in different particle and astroparticle physics applications and projects

Cryogenic detectors (aka LTDs)

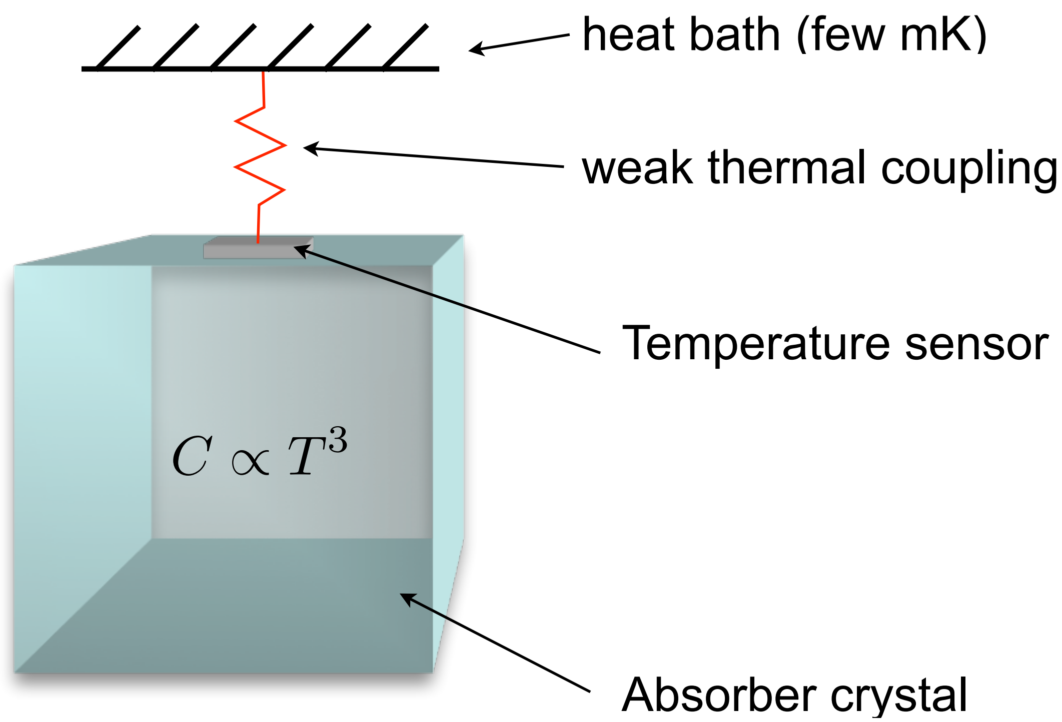
History of cryogenic detectors is relatively short

They started as a niche technology but today are vastly employed in a wide range of applications, both in fundamental science and technology

- Cosmology and astrophysics
- Beta decay, neutrinoless double beta decay, dark matter (WIMPs), CNNS
- Nuclear and atomic physics
- Quantum technologies
- Material and life science, cultural heritage, homeland security

Main advantages of cryogenic detectors are: excellent energy resolution, low energy threshold, ample choice of detector material

Cryogenic detectors



Several temperature sensors

- Semiconducting thermistors (Si o Ge-NTD)
- Superconducting Transition Edge Sensors (TES)
- Magnetic Metallic Calorimeters (MMC)
- Microwave Kinetic Inductance Detector (MKID)
- …

- Ample choice of detector materials

  low heat capacity @ T_{work}

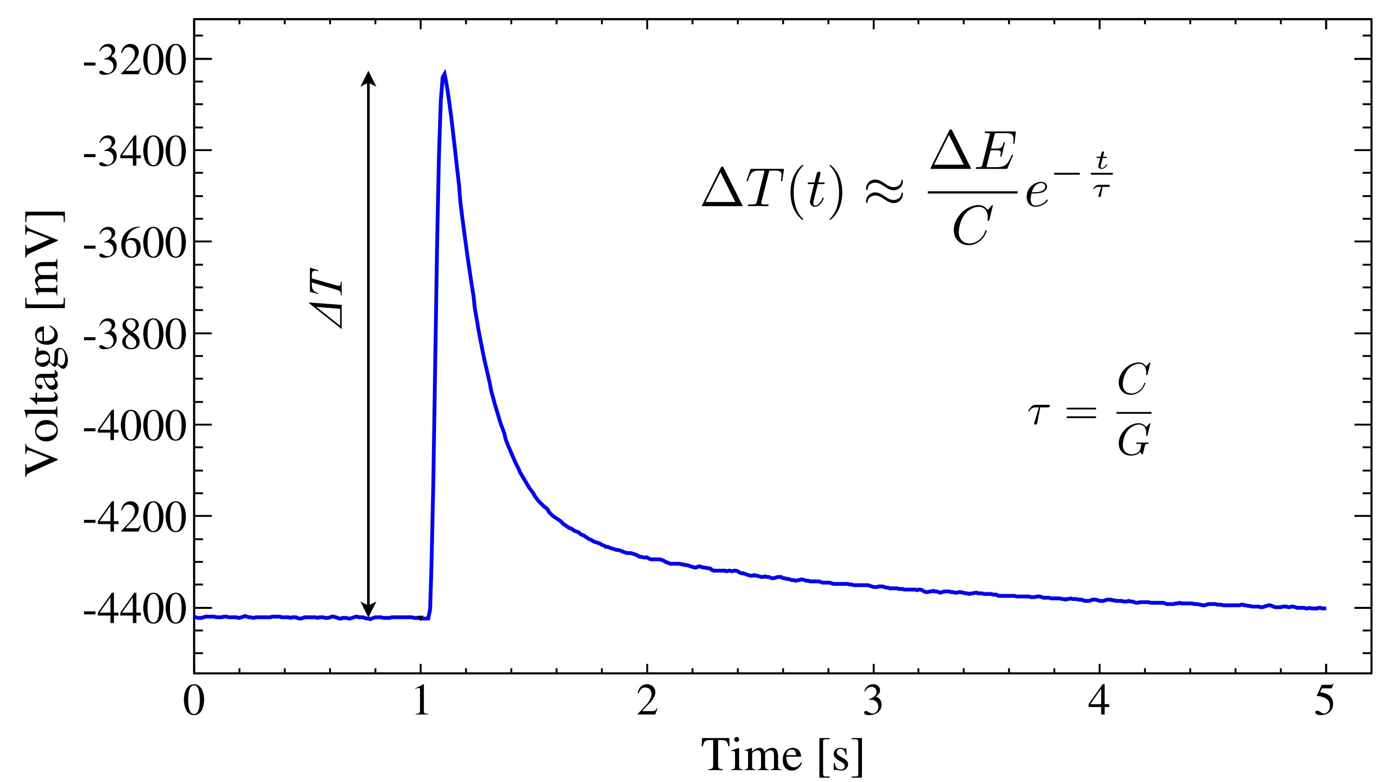
- excellent energy resolution (<1 ‰ FWHM)

  huge number of energy carriers (phonons)

- equal detector response for different particles

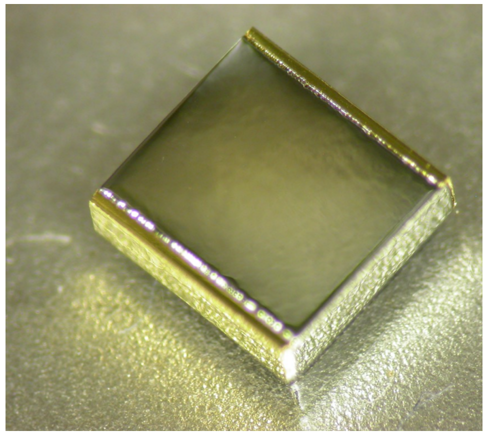
  true calorimeters

- slow respect to other particle detectors



T sensors @ mK

Nuclear Transmutation Doped Germanium: high resistivity thermistors



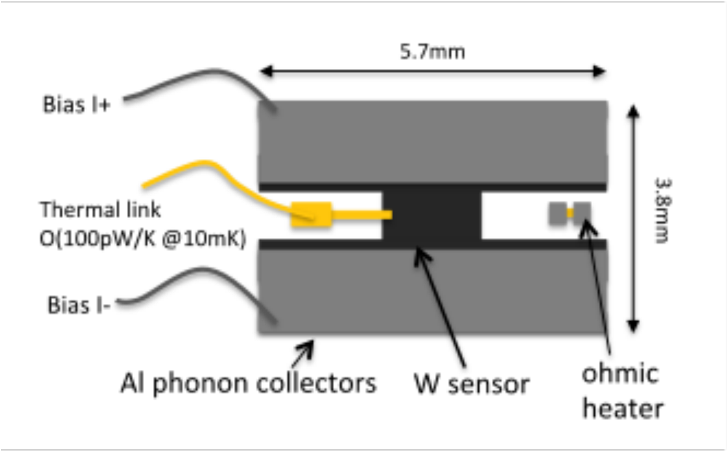
$$R(T) = R_0 e^{\sqrt{\frac{T_0}{T}}}$$

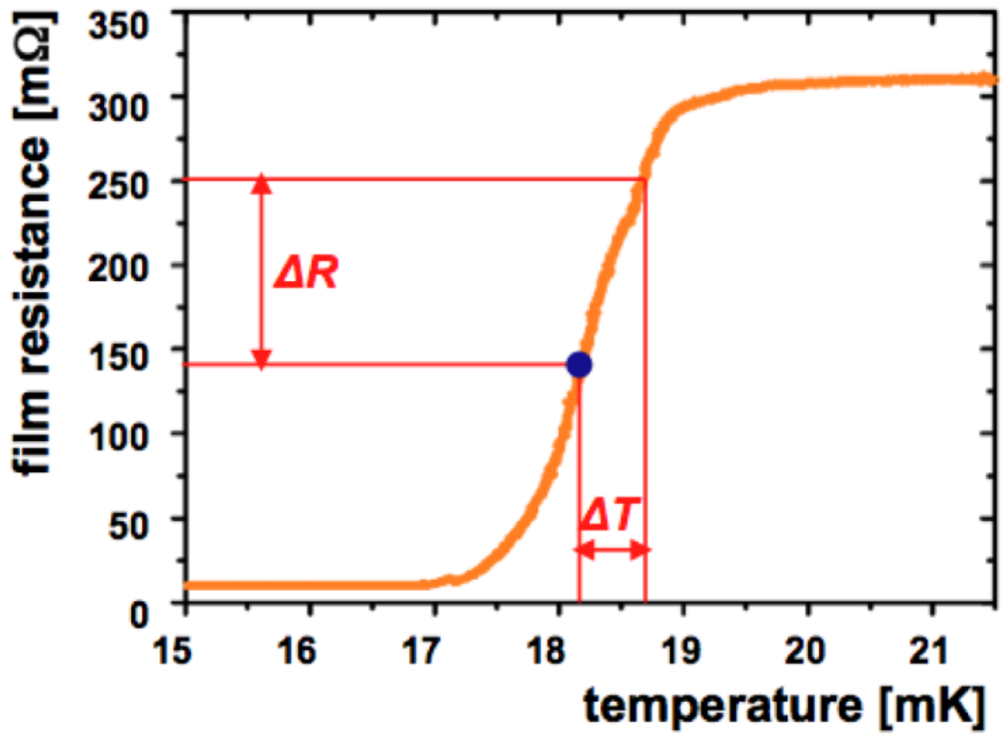
Variable Range Hopping

Transition Edge Sensors are superconducting films (W, Ir, Au/Ir, etc.)

W: T_C ~ 15 mK

Ir: T_C ~ 110 mK;



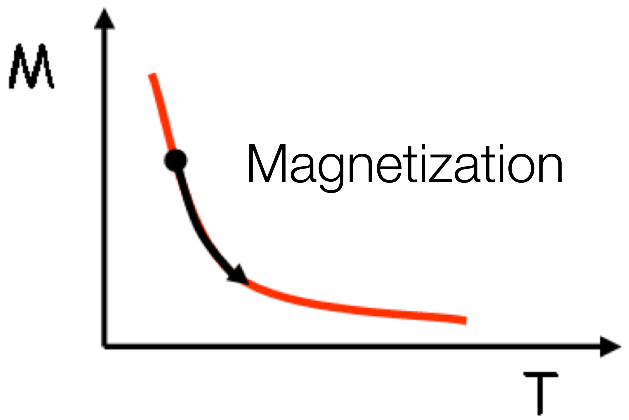


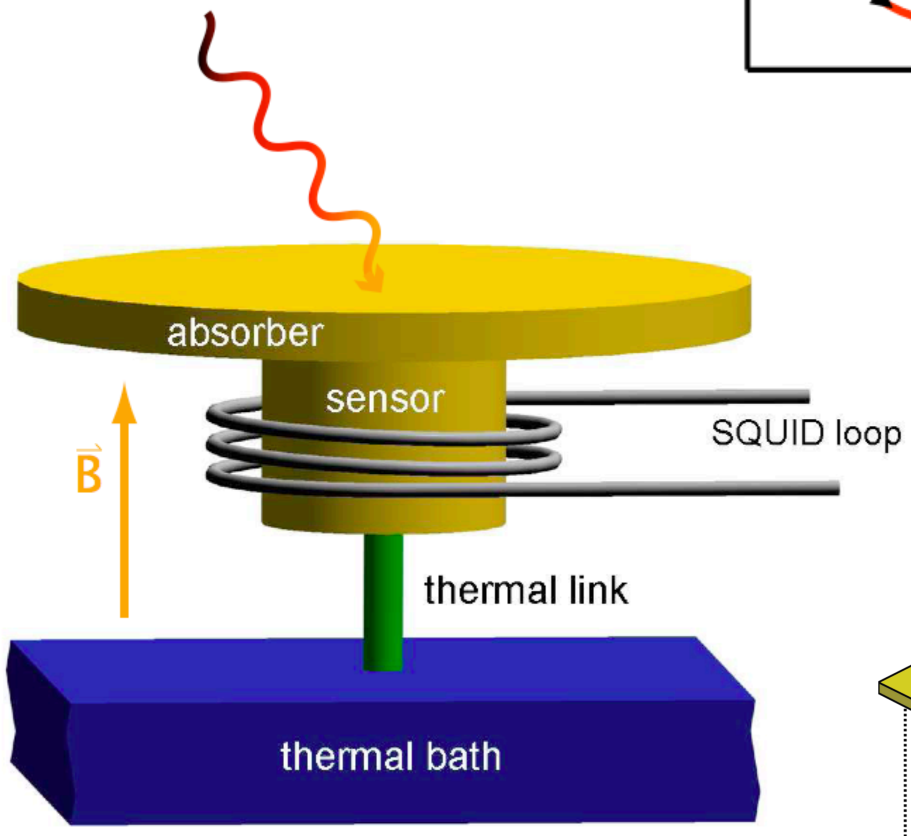
MicroLTD

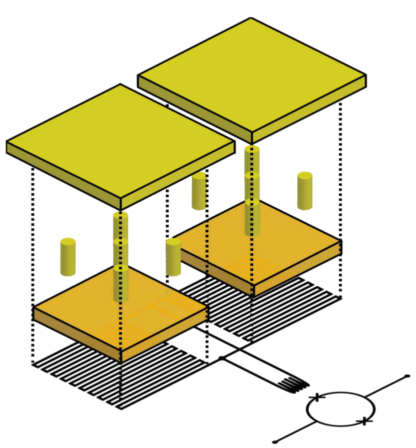
Metallic Magnetic Calorimeters (MMC)

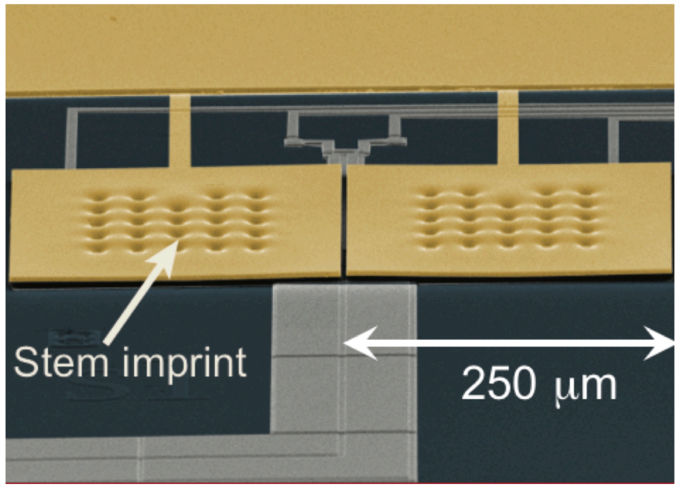
Absorber: 250 µm × 250 µm Gold, 5µm thick (6 µg)

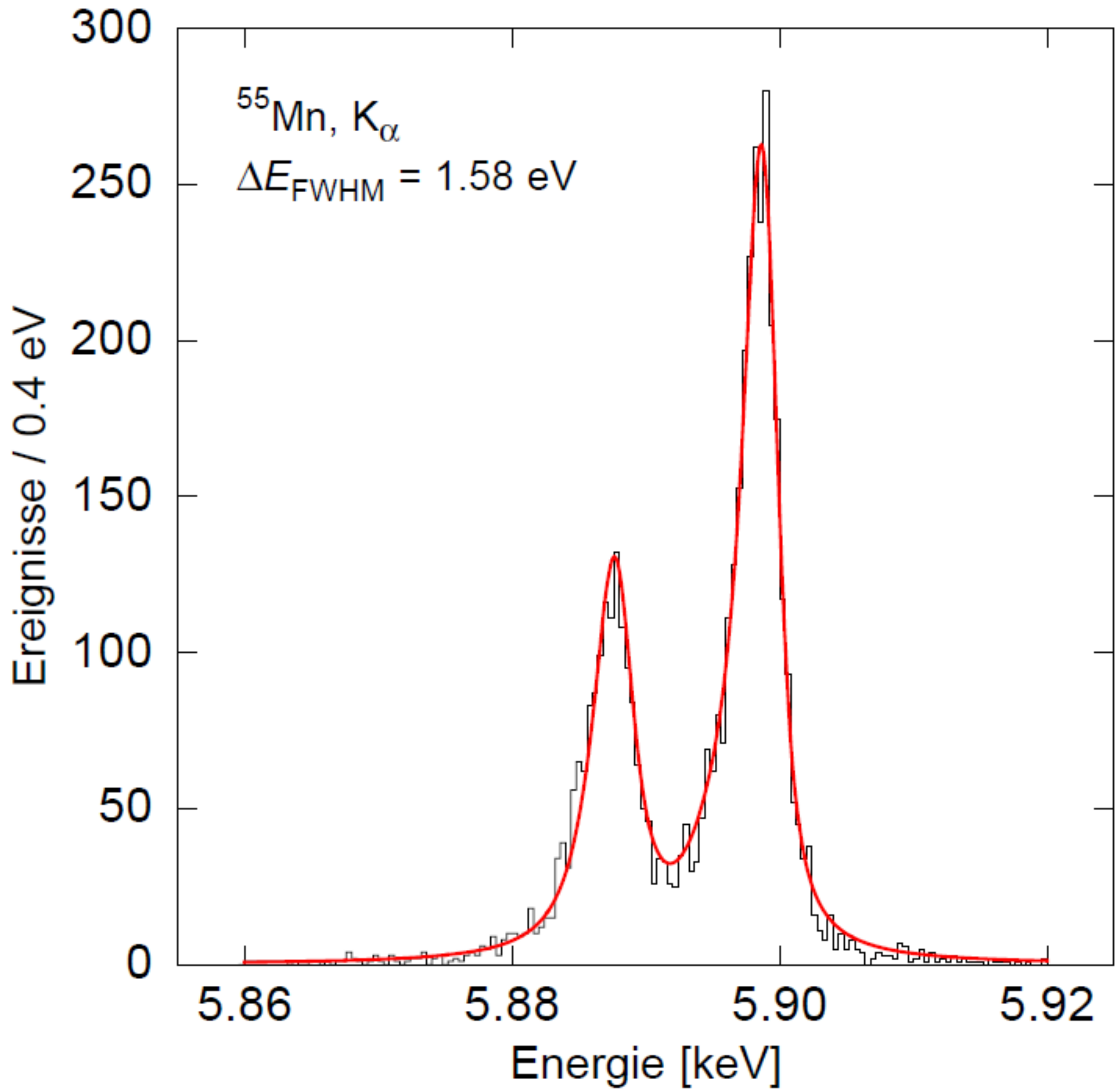
Au:Er paramagnetic sensor









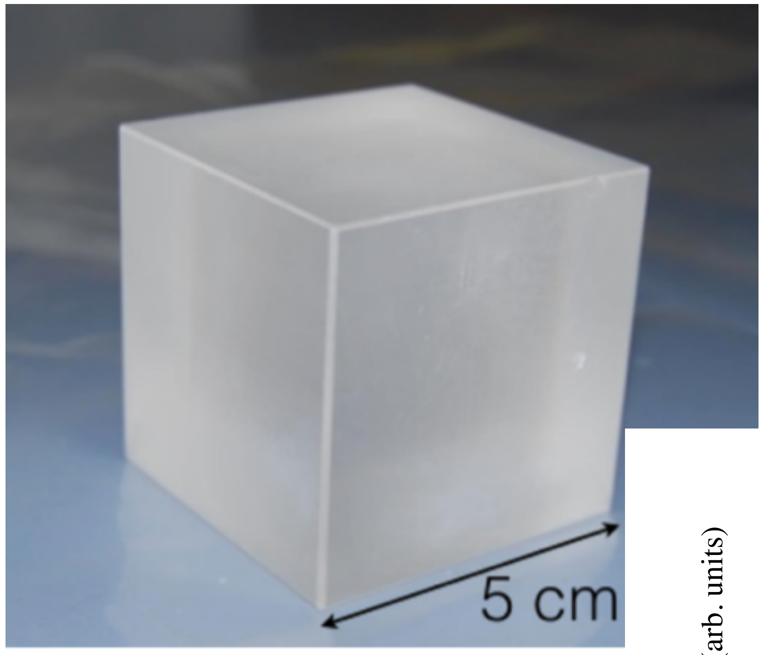


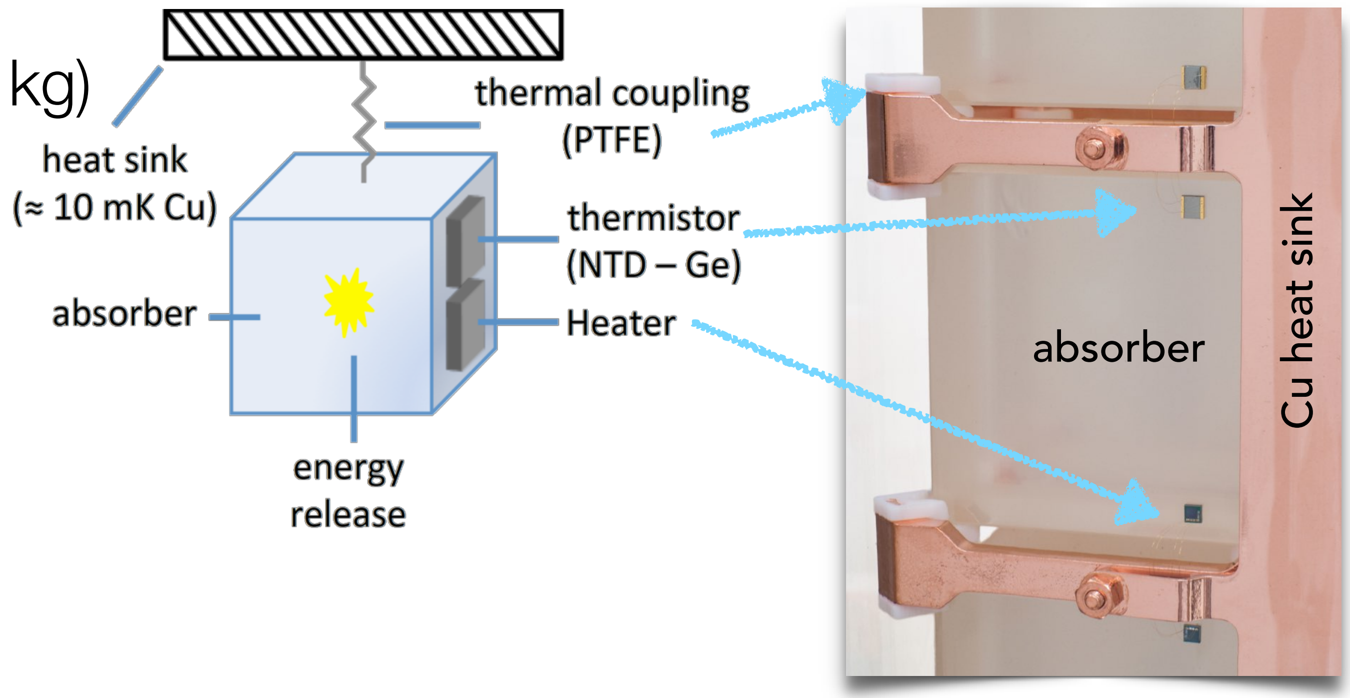
MacroLTD

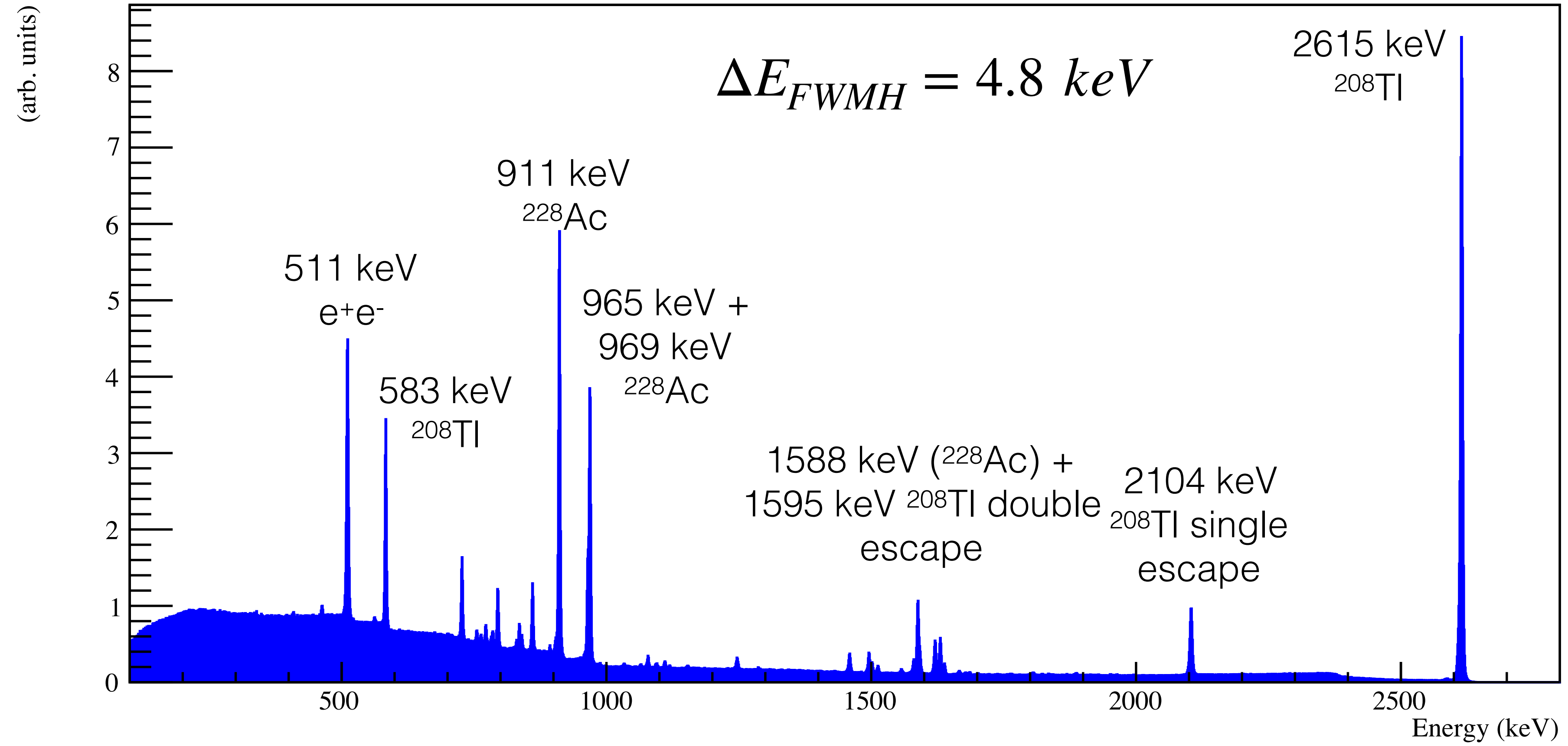
TeO_2 bolometer

Absorber: 5 cm × 5 cm x 5cm thick (0.75 kg)

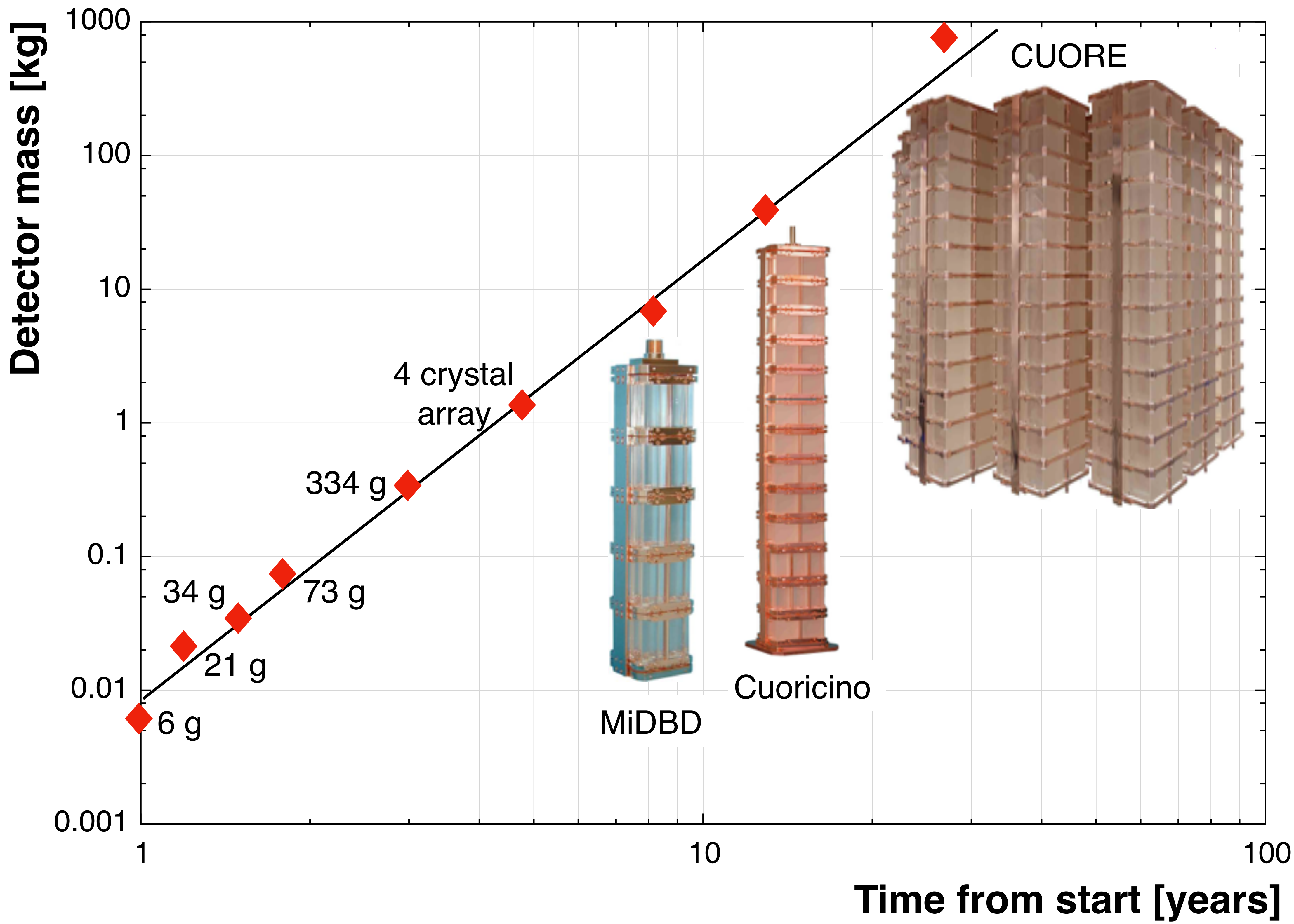
NTD-Ge sensor







CUORE TeO_2 bolometers history

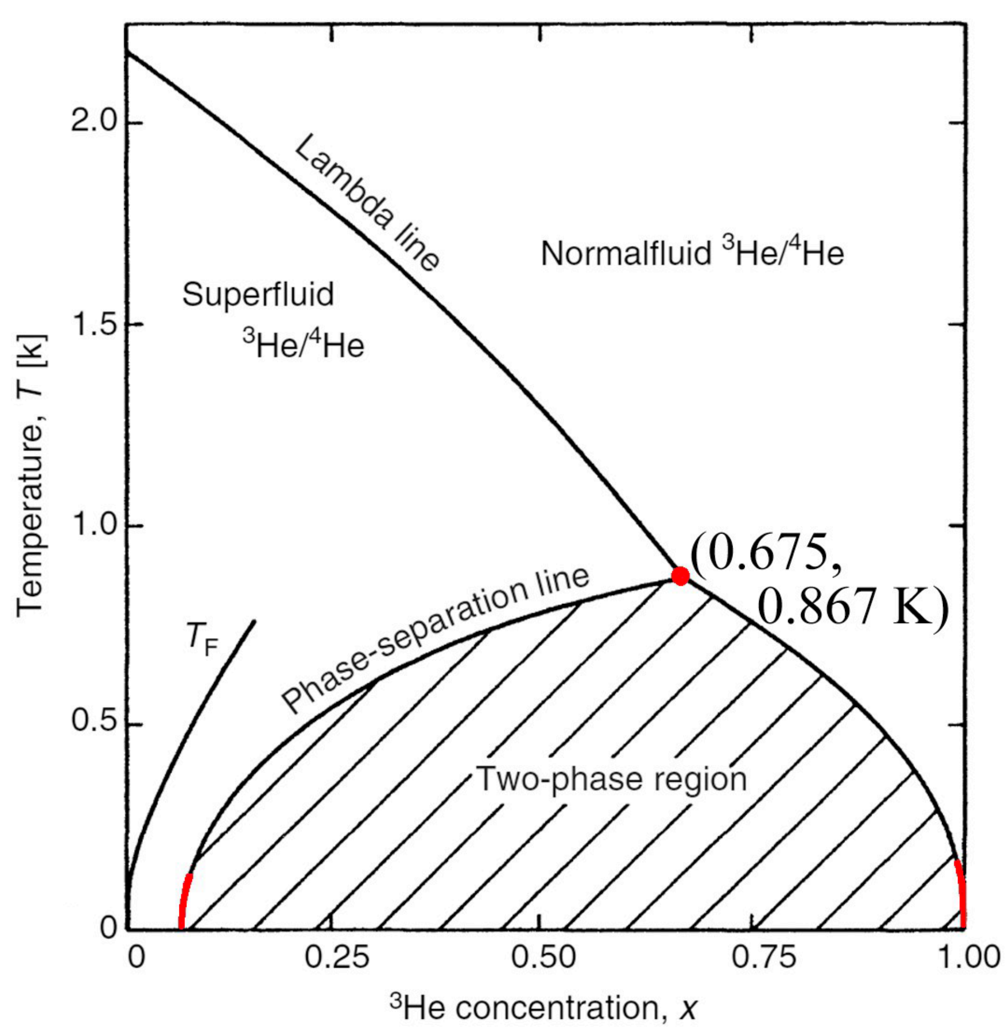


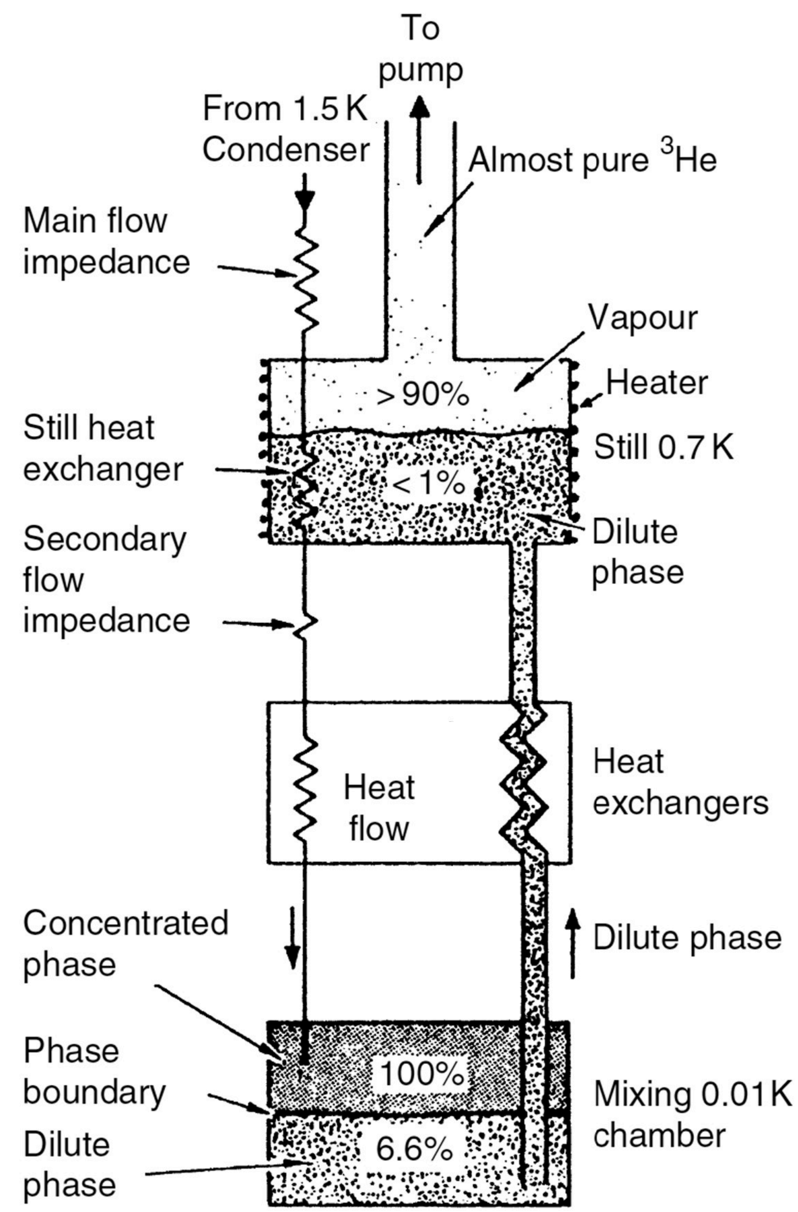
Refrigeration at mK temperature

Dilution refrigerators are the workhorse at mK temperature

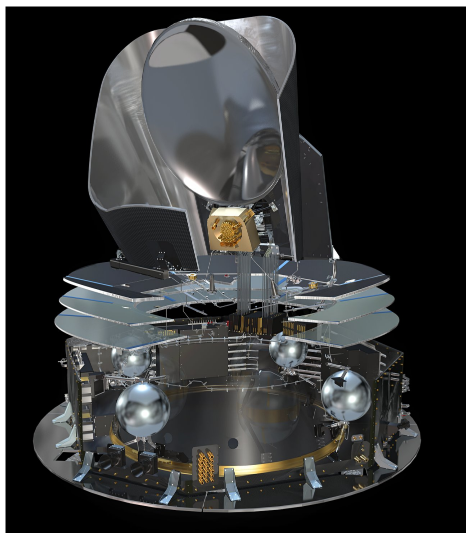
- Based on quantum properties of ^{3}He-^{4}He mixtures
- Continuous flow refrigerators
- Cooling power ~ µW @ 10 mK

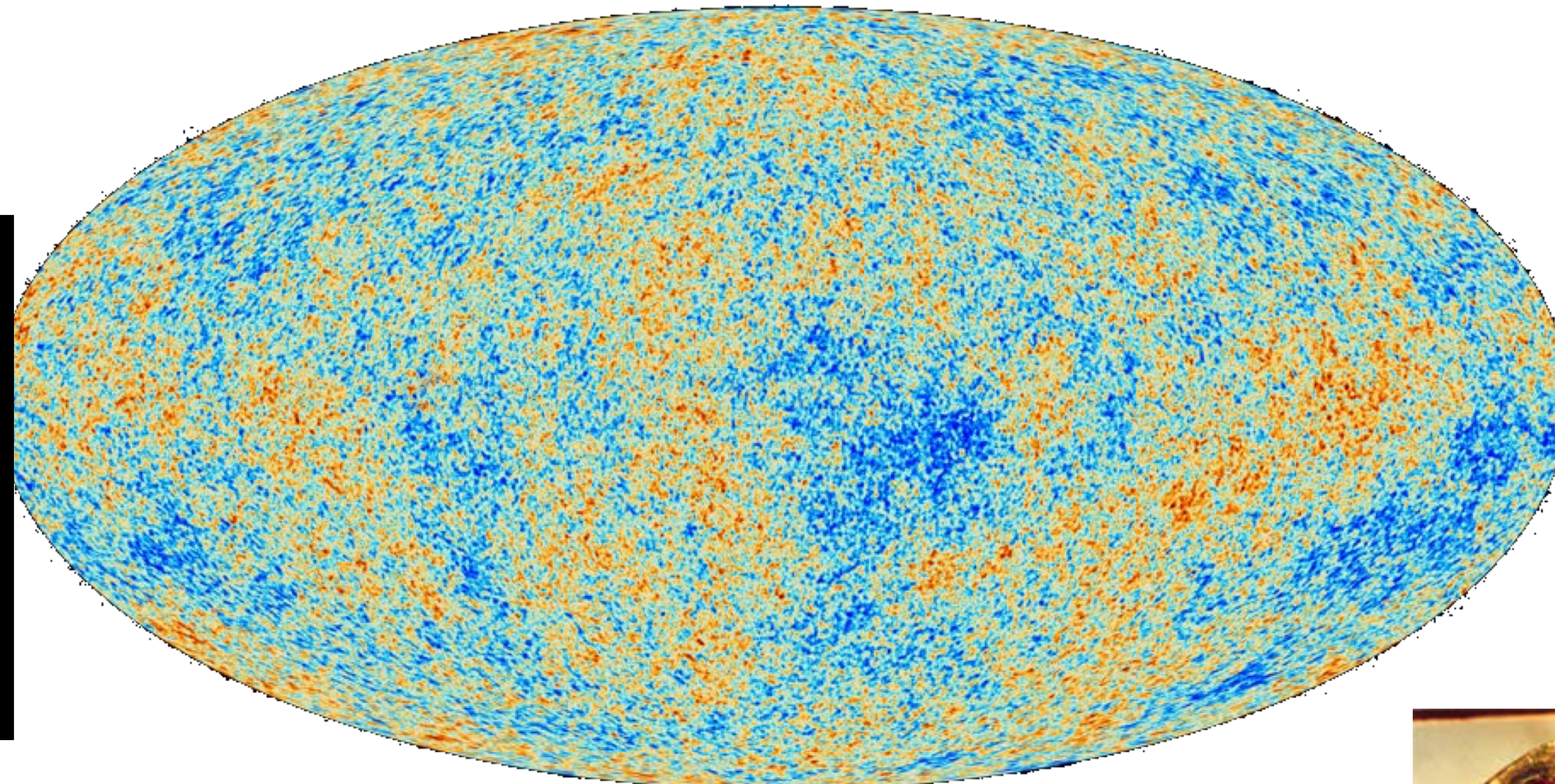
Phase diagram of liquid ^{3}He-^{4}He mixtures

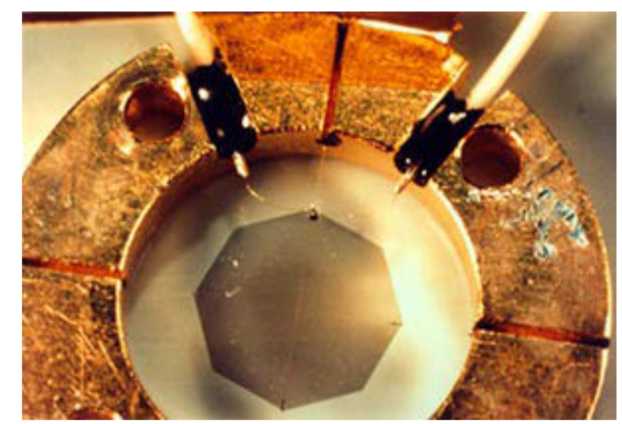




CMB





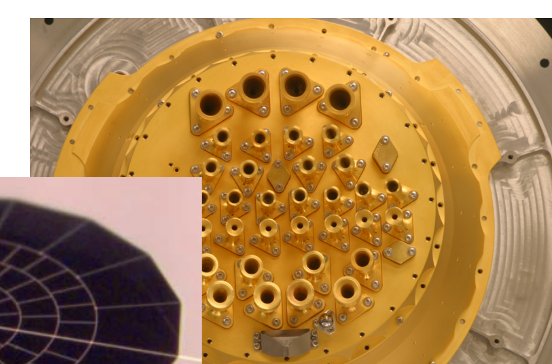


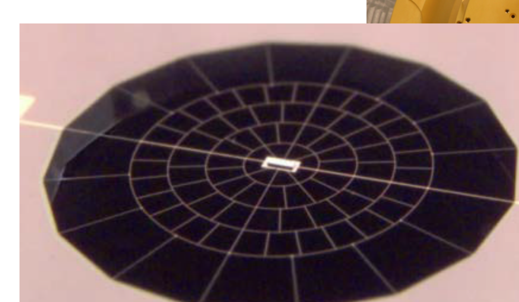
COBE (1989-1993) measured CMB showing that has a nearly perfect black-body spectrum

- FIRAS instruments (4 diamond absorbers on Si thermistors @ 1.6 K

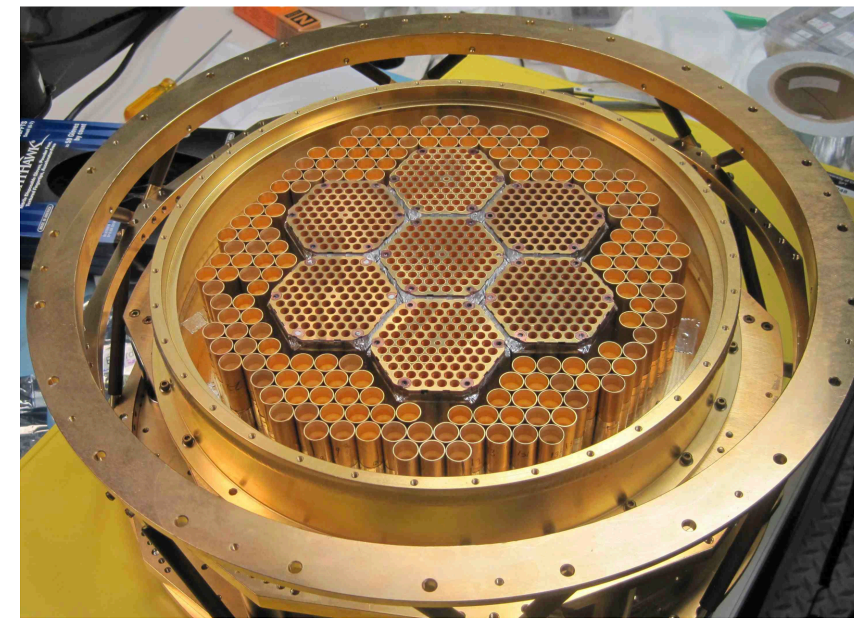
PLANCK (2009-2013) provided the most precise measurements of several key cosmological parameters

- HFI instruments covering 6 frequencies from 100 to 857 GHz (56 spiderweb NTD-Ge @ 100 mK)



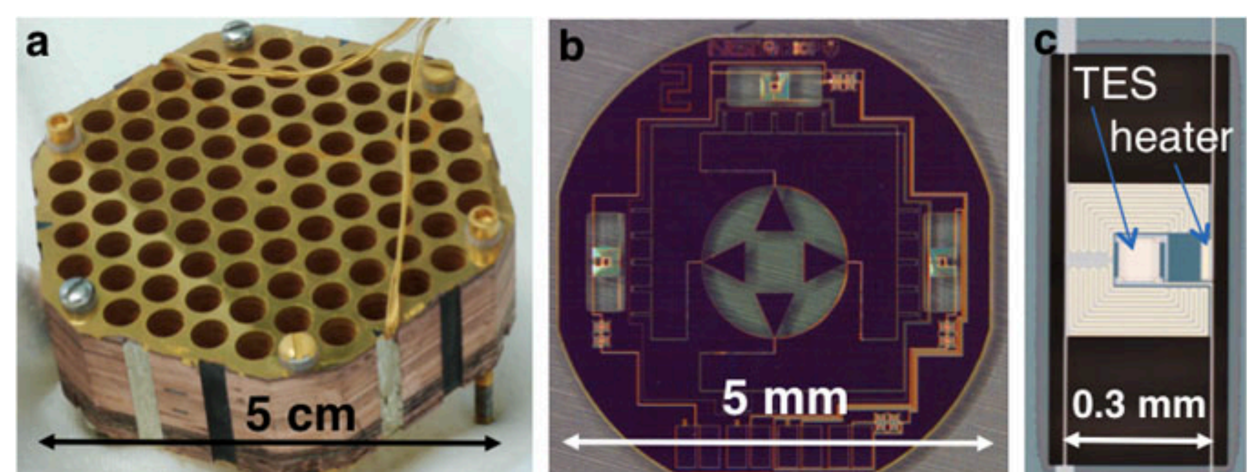


CMB



95 GHz, 150 GHz and 220 GHz

The focal plane of the STP is composed by 960 Al/Ti spiderweb TES operated at ~ 500 mK

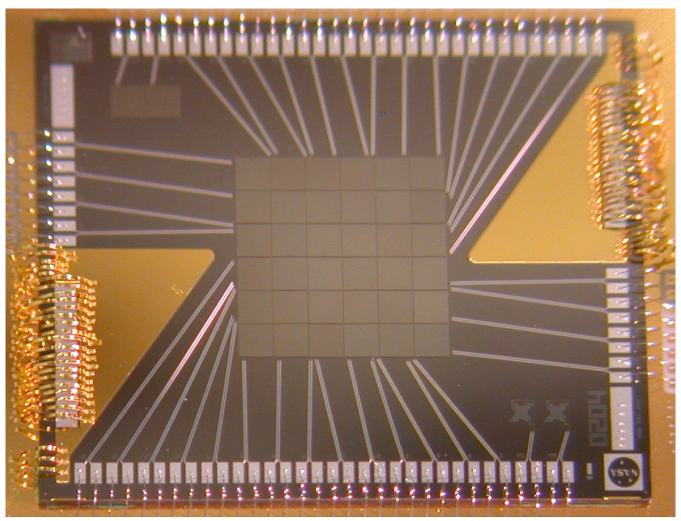


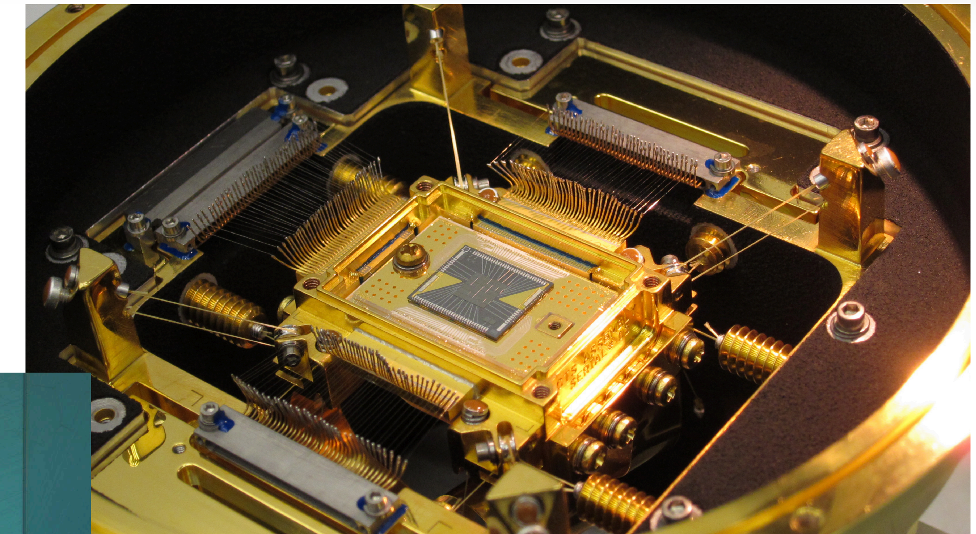
X-ray astrophysics

ASTRO-H (Hitomi) mission (2016)

SXS instrument: 6x6 HgTe absorbers with Si thermistors

7 eV FWHM in the energy range 0.3-12 keV

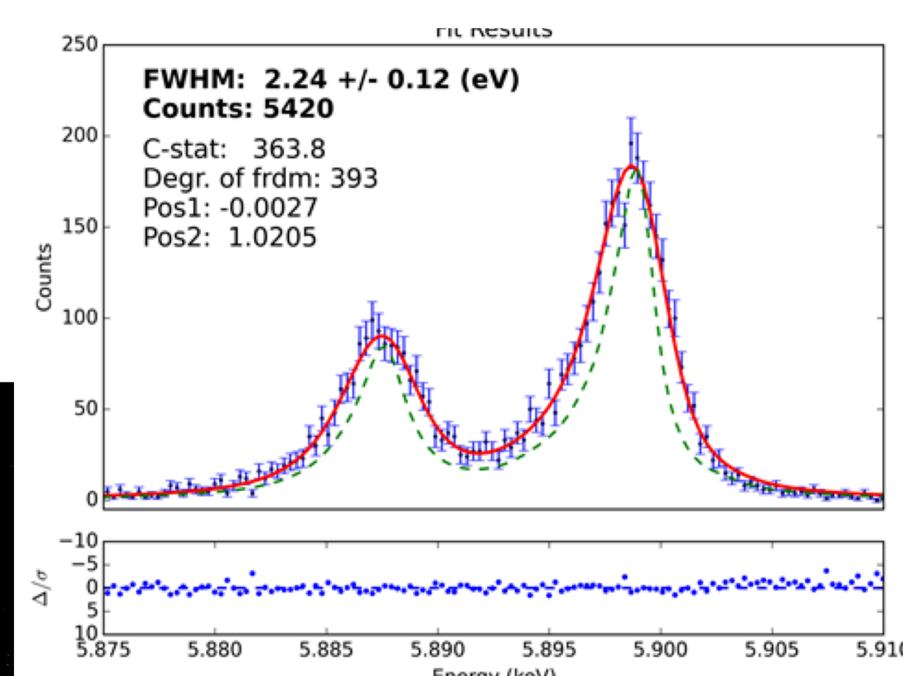


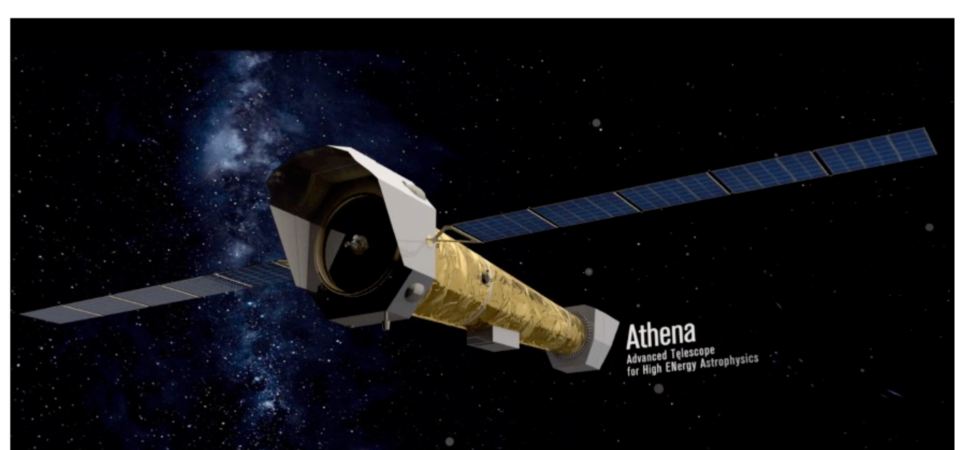


ATHENA mission (2028)

SXS instrument: 3840 Si absorbers with MoAu TES

<2.5 eV FWHM in the energy range 0.2-12 keV



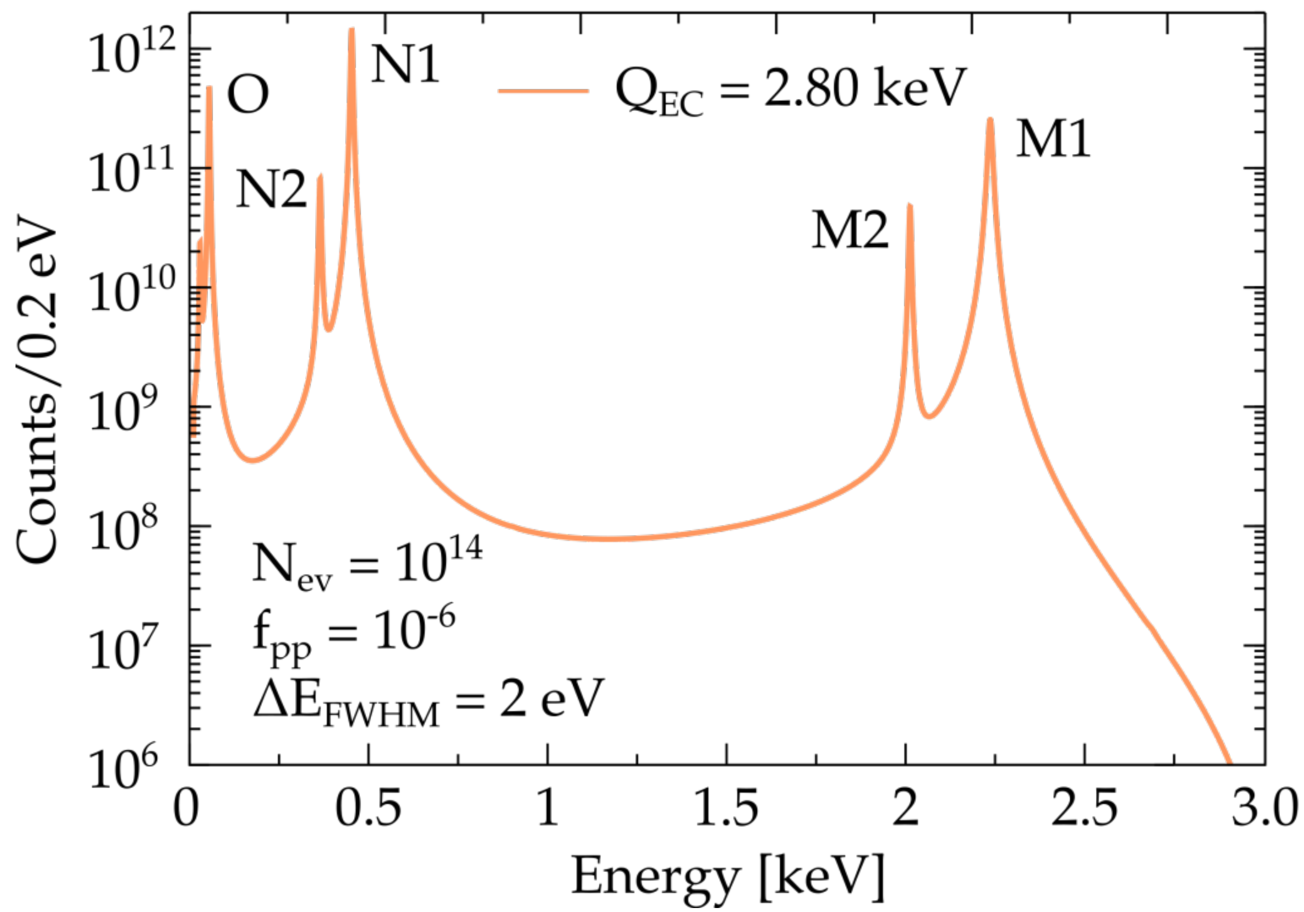


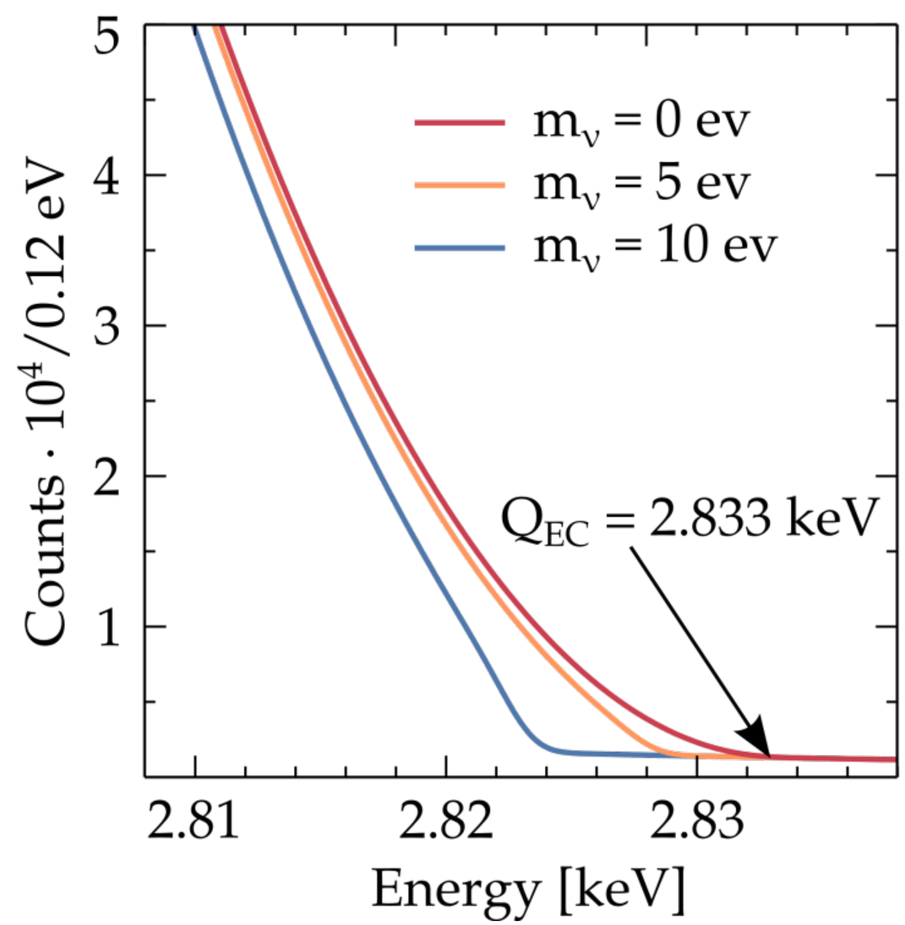
LTDs for neutrino mass

$$^{163}Ho + e^- \rightarrow \; ^{163}Dy^* + \nu_e$$

Proposed by A. De Rujula and M. Lusignoli, Phys. Lett. B 118 (1982) 429

- Holmium experiments: calorimetric measurement of the Dy atomic de-excitation (mostly non-radiative)
- rate at the end point depends on (Q–EM1): the proximity to M1 resonance peak enhances the statistics at the end point (i.e. sensitivity on m_ν)
- $t_{1/2}$~4570 years: few nuclei are needed (2x10^{11} ^{163}Ho nuclei = 1 Bq)



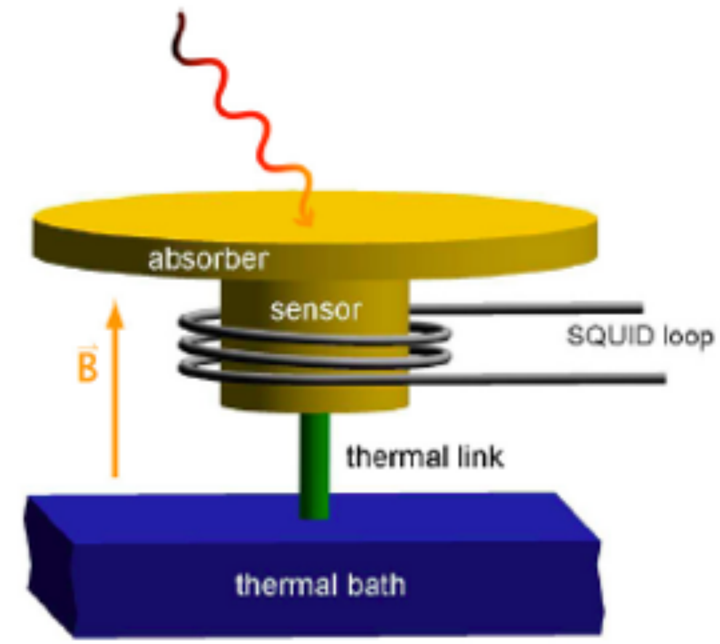


ECHo

Detectors: Au:Er Metallic Magnetic Calorimeter (MMC) with implanted ^{163}Ho

Activity: 6.5×10^{13} nuclei per detector → 300 dec/s

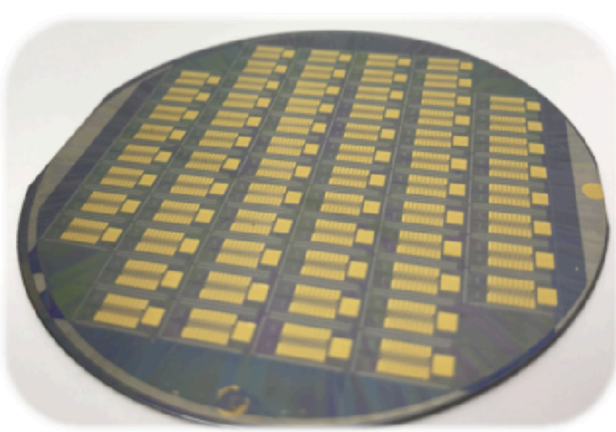
Performances: $\Delta E \approx 1$ eV, $\tau_R \approx 1$ μs

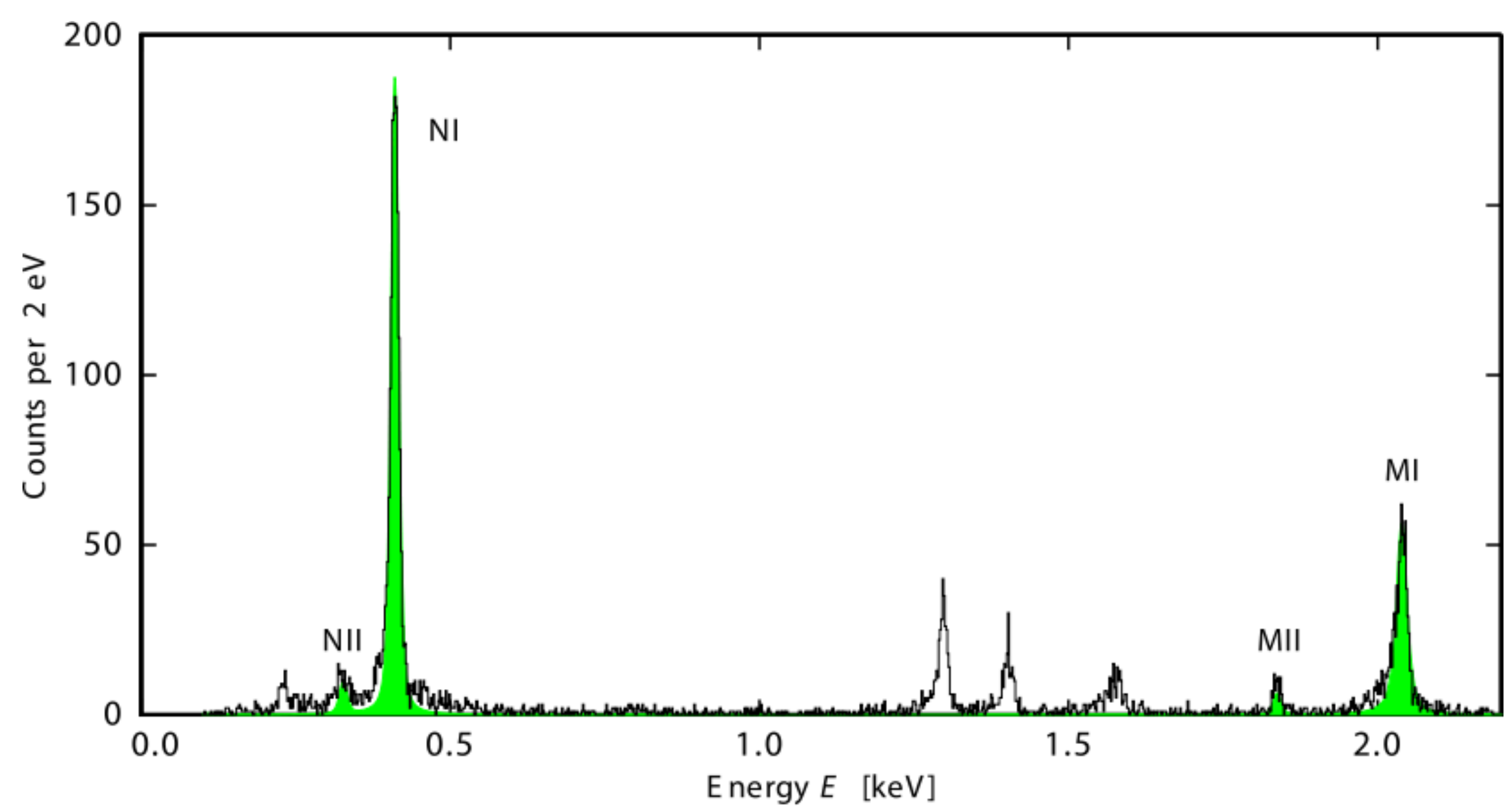


Prove scalability with medium large experiment ECHo-1k (2015-2018)

- total activity 1 kBq, high purity ^{163}Ho source (produced at reactor)
- $\Delta E_{FWHM} < 5$ eV, $\tau_R < 1$ μs
- multiplexed arrays → microwave SQUID multiplexing
- 1 year measuring time 10^{10} counts → neutrino mass sensitivity m < 10 eV
- Data taking will starting early 2018

Future: ECHo-10M sub-eV sensitivity





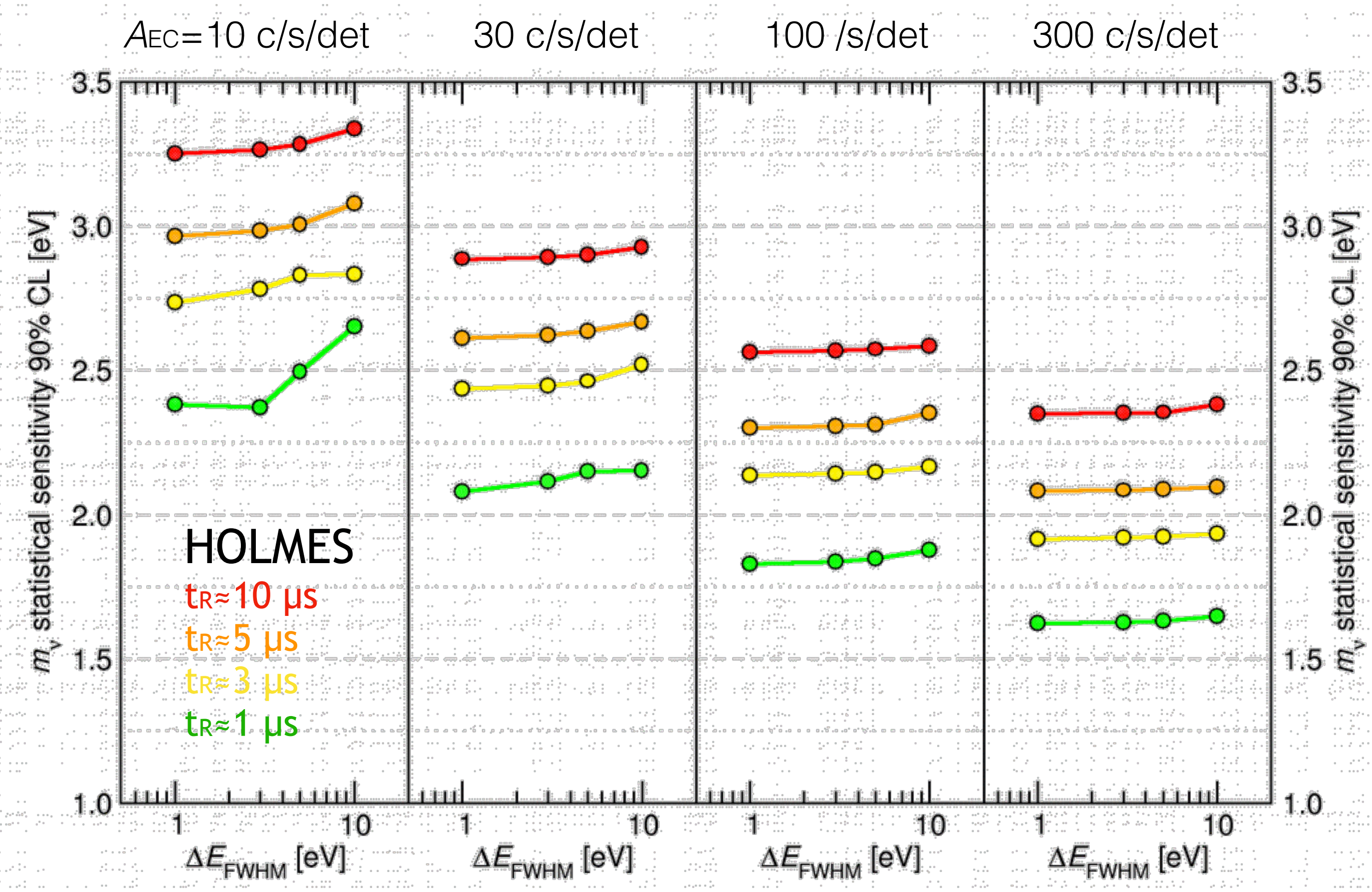
HOLMES

Detectors: Transition Edge Sensor with ^{163}Ho implanted in Au absorbers

Activity: 6.5x10^{13} nuclei per detector → 300 dec/s

Performances: $\Delta E_{FWHM} \approx$ 1 eV, $\tau_R \approx$ 1 μs

MonteCarlo with 1000 detectors x 3 years



B. Alpert et al., Eur. Phys. J. C, (2015) 75:112

GOAL

Neutrino mass determination with a sensitivity as low as ~1 eV

- proof potential and scalability of the approach
- precise calorimetric determination of Q
- systematic errors assessment

Two steps approach:

- 64 channels mid-term prototype, (t_M= 1 month, m_ν< 10 eV)
- full scale: 1000 channels, 3x10^{13} events collected in 3 years
- 6.5x10^{16} ^{163}Ho nuclei (≈18 mg)

HOLMES (ERC-Adv. Grant 340321)
5 years project started on Feb. 1st 2014

LTDs for Dark Matter (WIMPs)

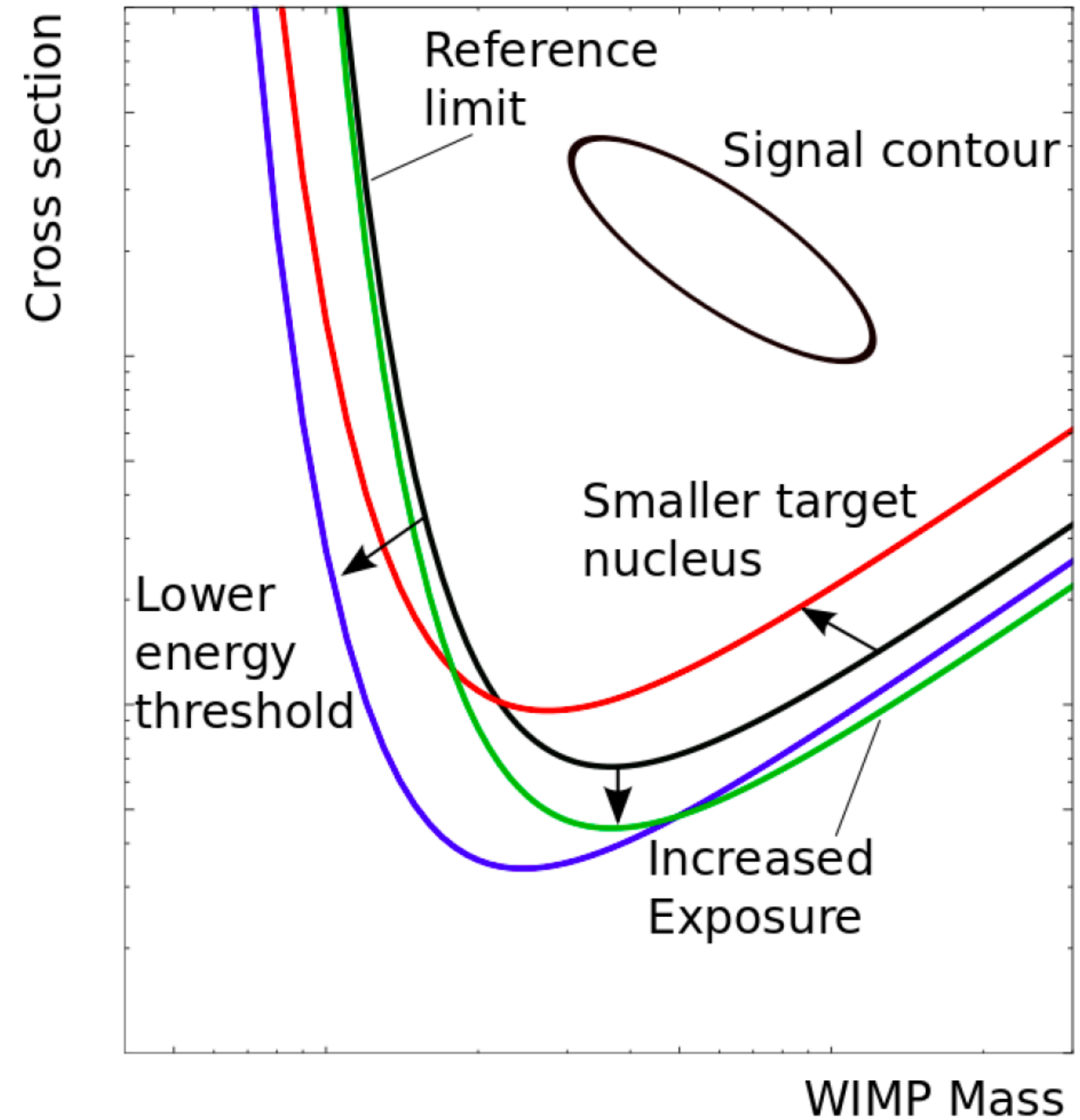
At large dark matter masses sensitivity is dominated by exposure:

- large mass noble liquid detectors prevail

At light dark matter masses sensitivity is dominated by energy threshold:

- cryogenic detectors are superior

J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767



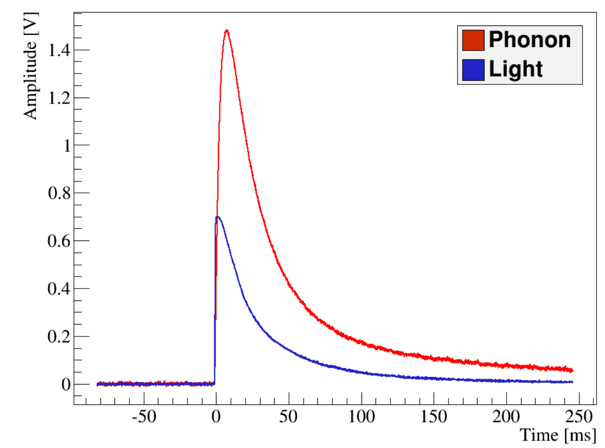
LTDs for Dark Matter (WIMPs)

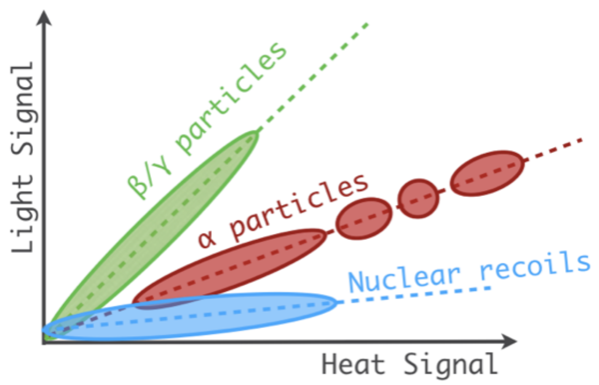
Electron/Nuclear recoil discrimination

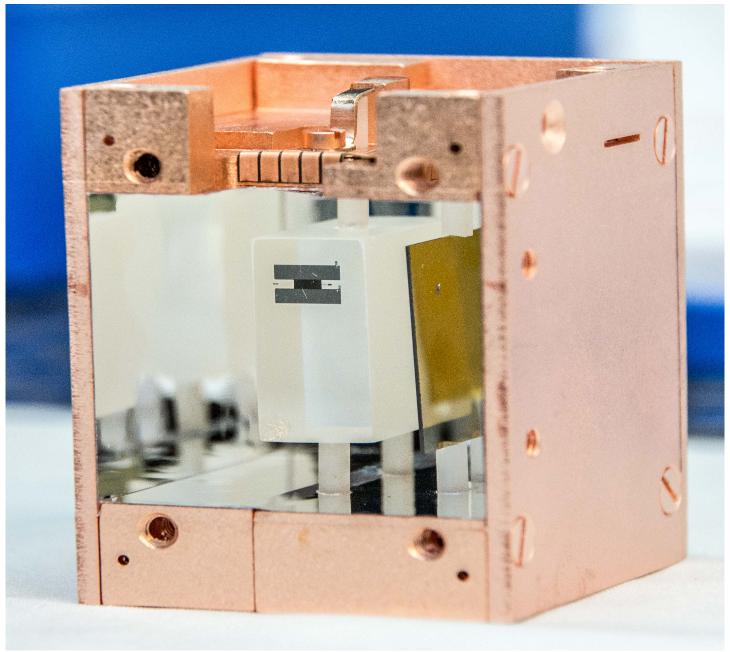
Double readout

- phonons-ionization (Edelweiss, CDMS)
- phonons-scintillation (CRESST)

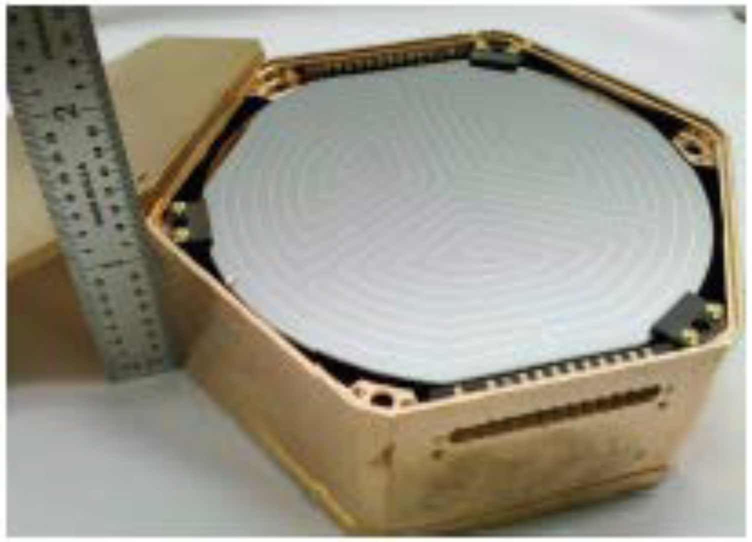
Low energy threshold (<100 eV)







Scintillating bolometer
24 g $CaWO_4$ crystals
Best energy threshold: 30 eV

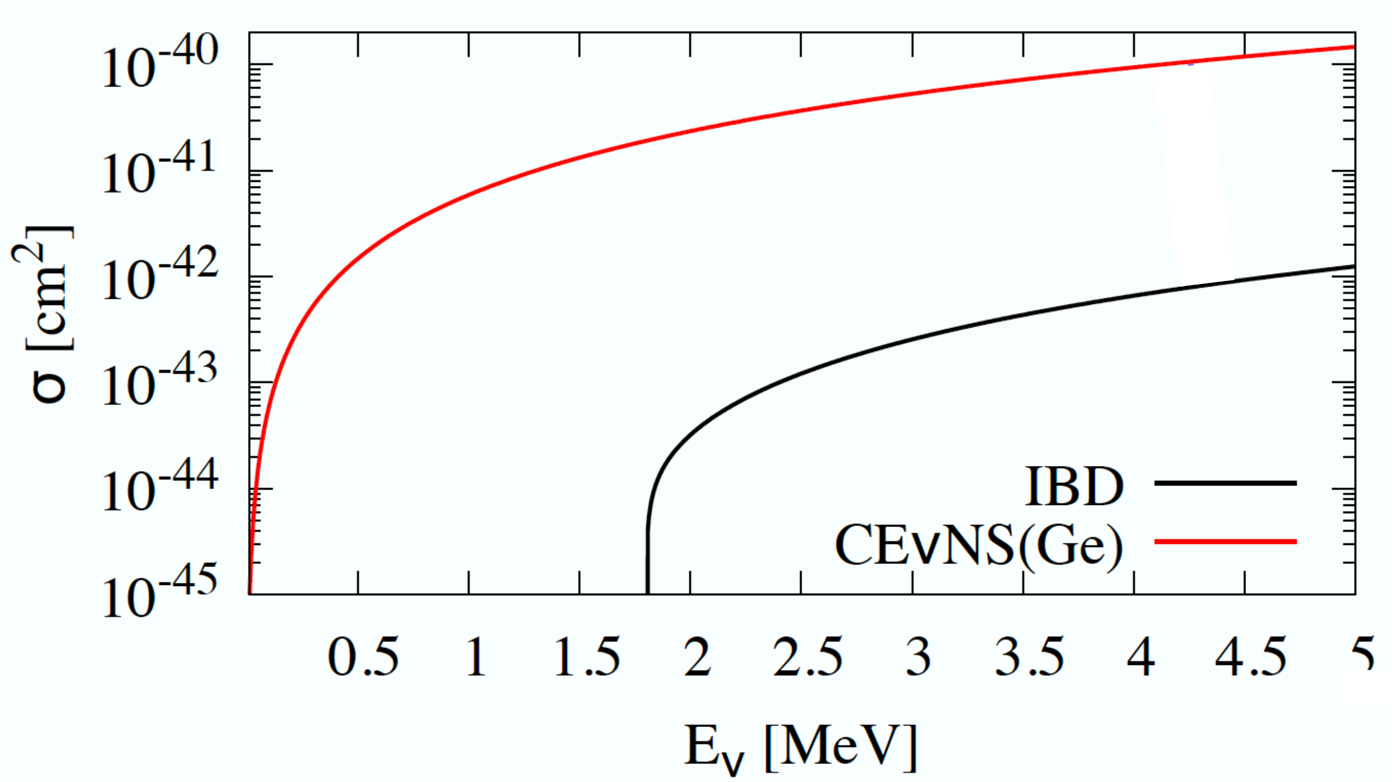


Ionization+athermal phonons
600 g Ge crystals

Ionization + heat
850 g Ge crystals

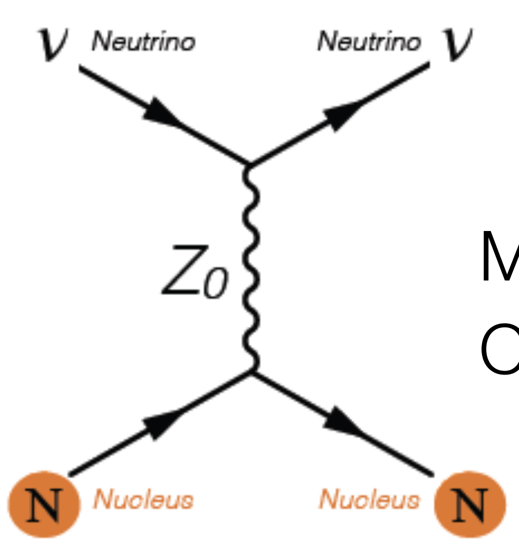
LTDs for CNNS

Coherent neutrino-nucleus elastic scattering

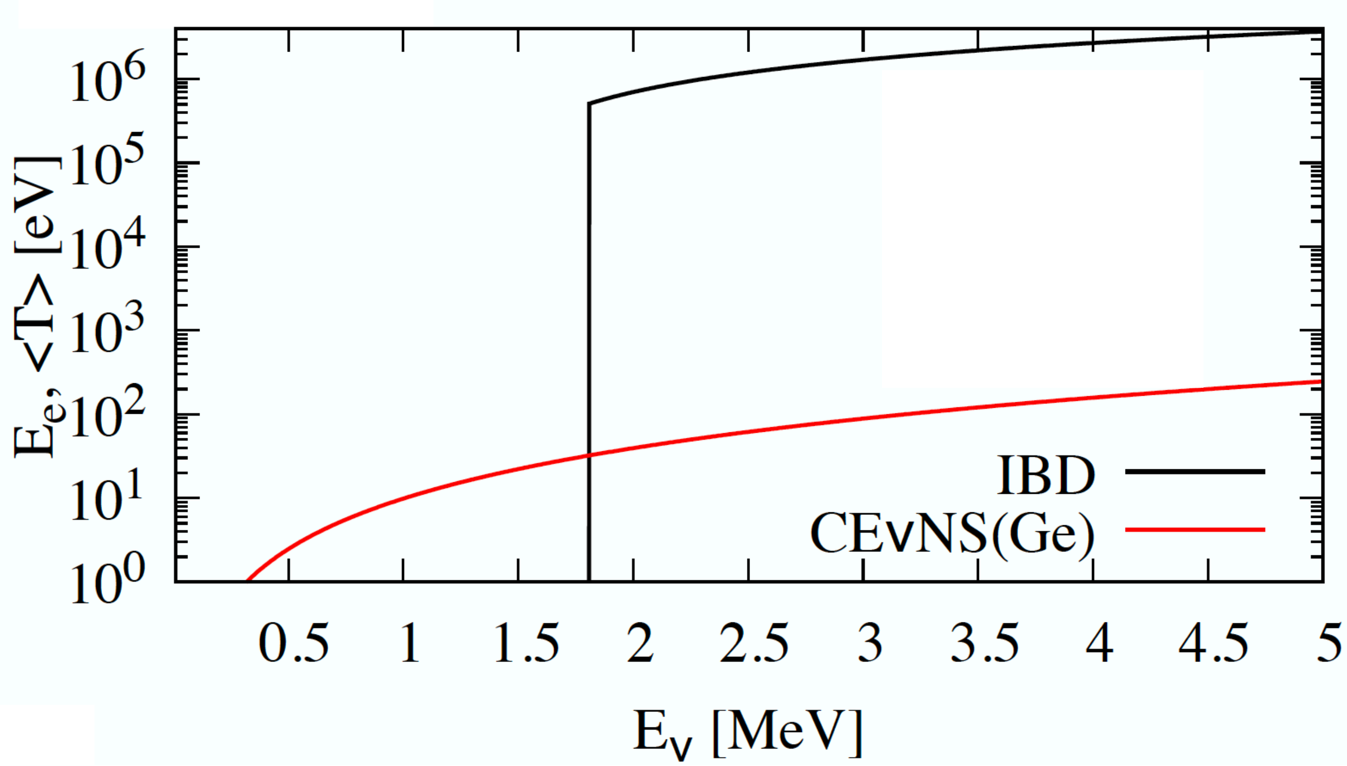


CNNS vs inverse beta decay:

- Larger cross section
- Smaller measurable energy (few tens of eV)



Measured in 2017 in the COHERENT experiment

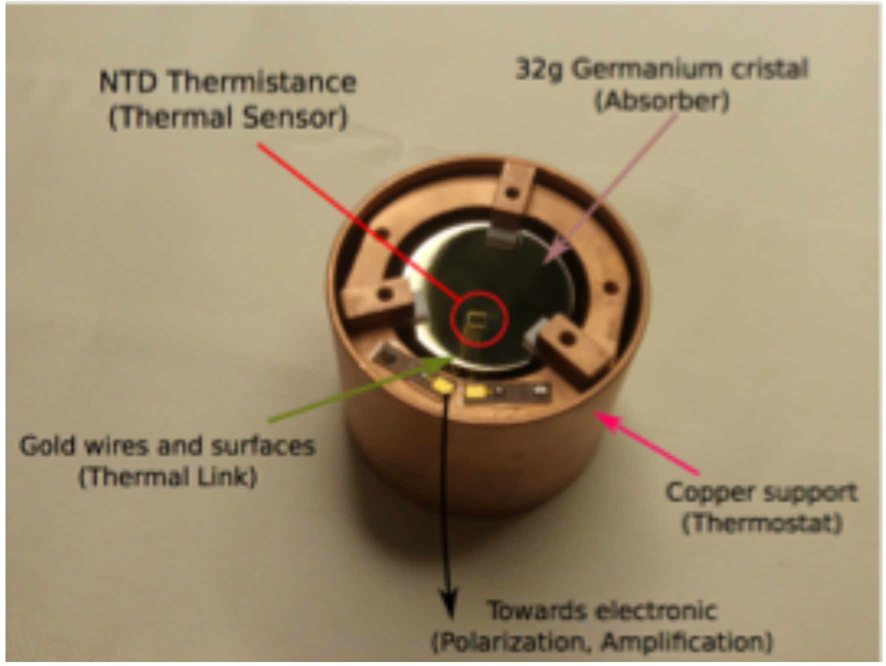


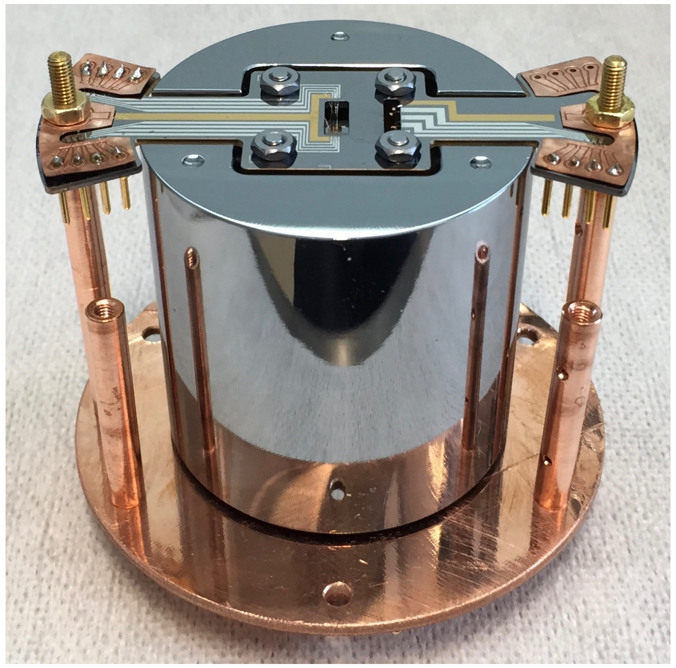
LTDs for CNNS

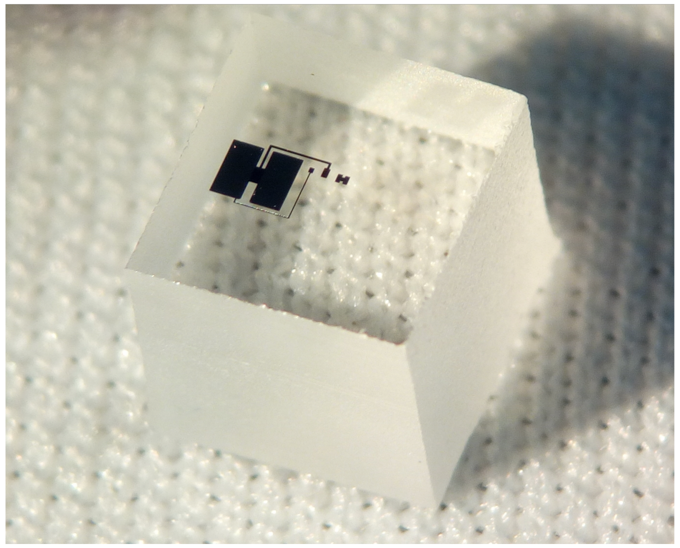
LTDs are suitable for this challenge

NUCLEUS, MINER and RICOCHET aim to detect neutrinos from nuclear reactors measuring cross section at 10% precision

Non-proliferation application







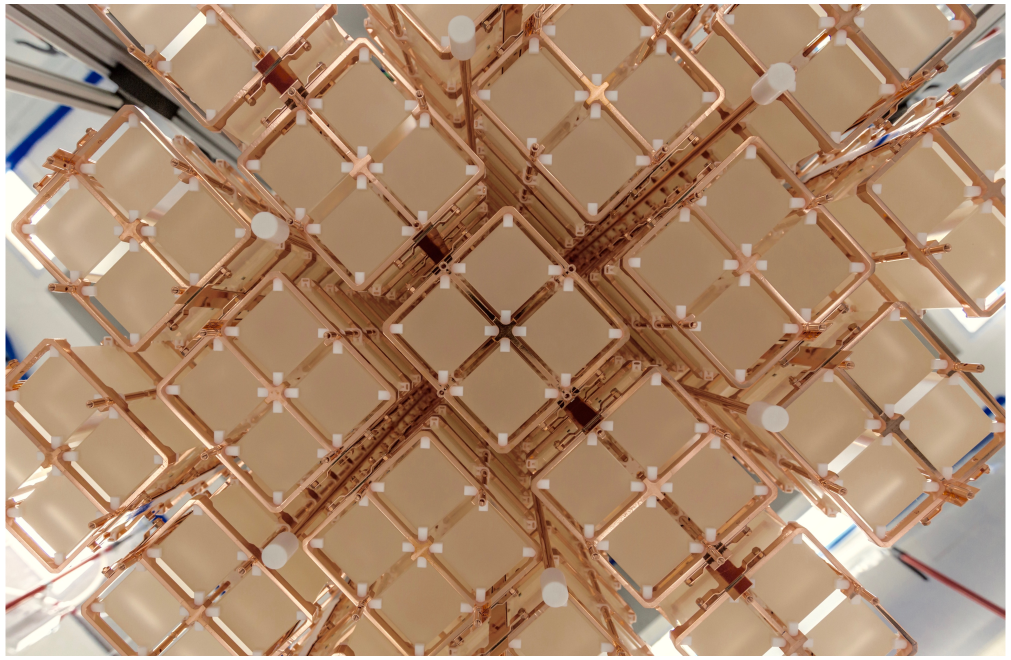
LTDs for 0νββ searches

LTDs are ideal for 0νββ

- Detectors with embedded 0νββ isotope candidate (TeO_2, Li_2MoO_4, ZnSe, etc.)
- Excellent energy resolution
- Background reduction through particle identification

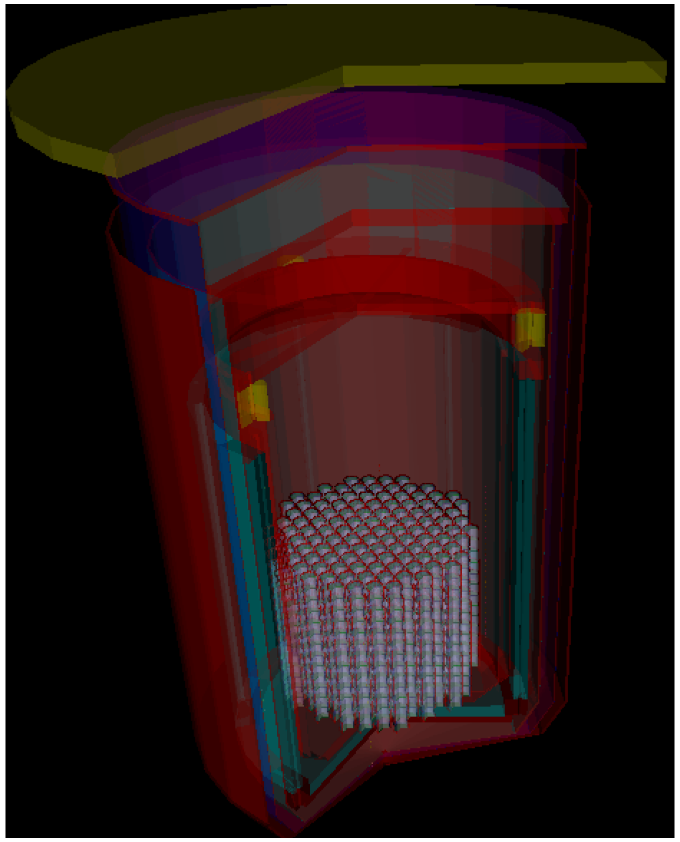
CUORE: Ge-NTD on 750g TeO_2 absorbers

only phonons



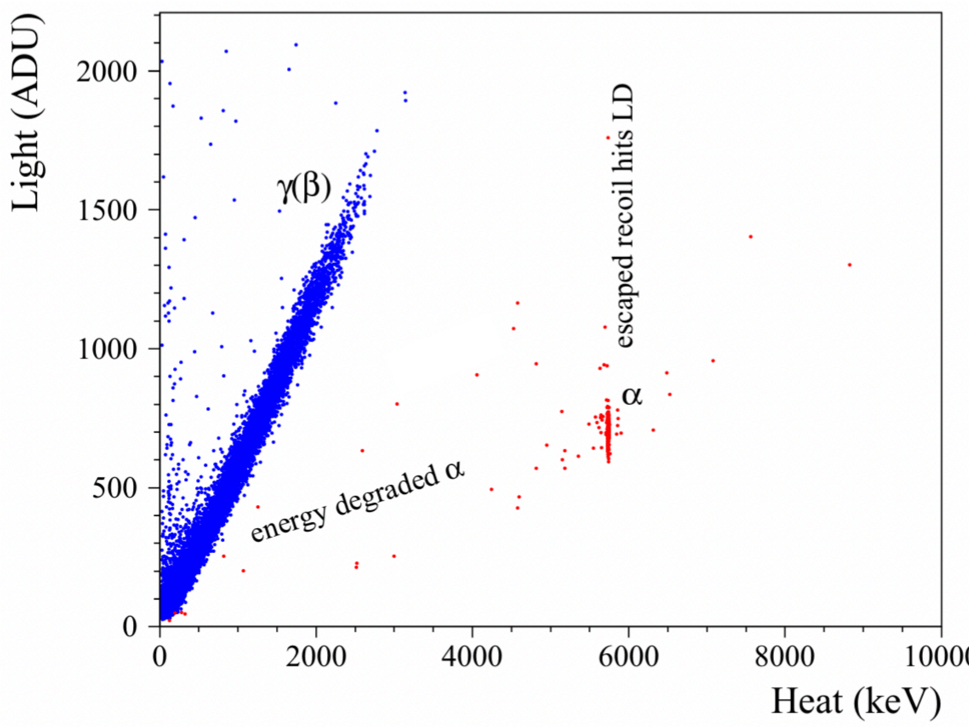
CUPID: Ge-NTD on 300g Li_2MoO_4 absorbers

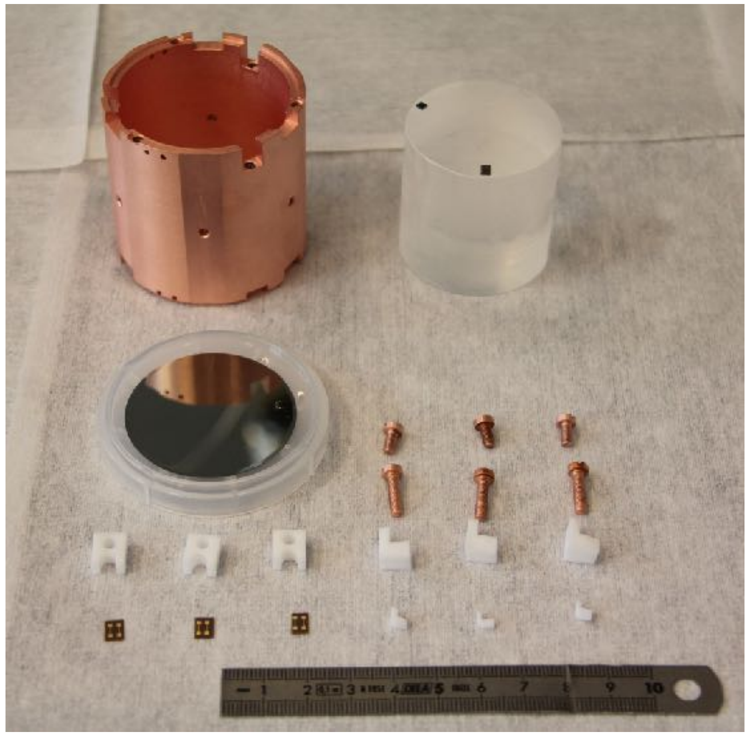
phonons & scintillation

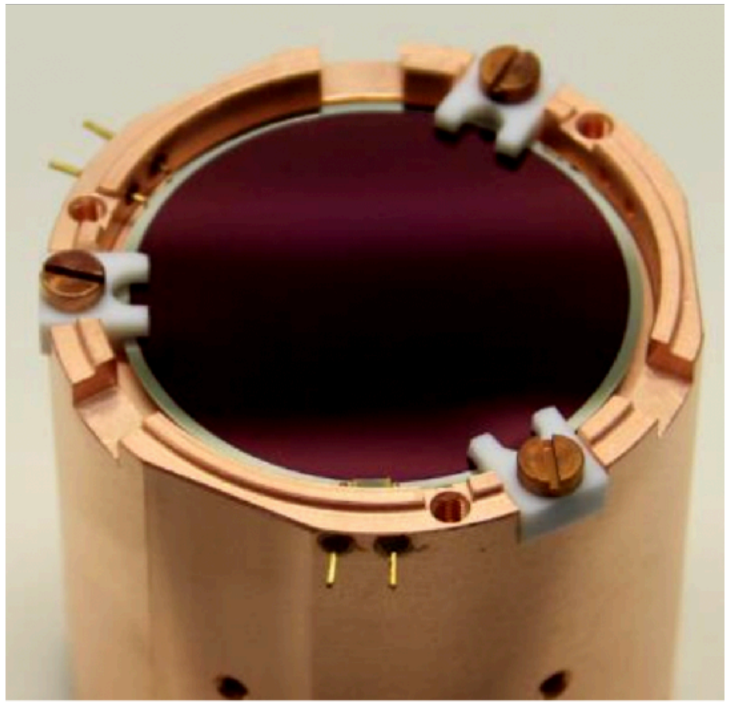


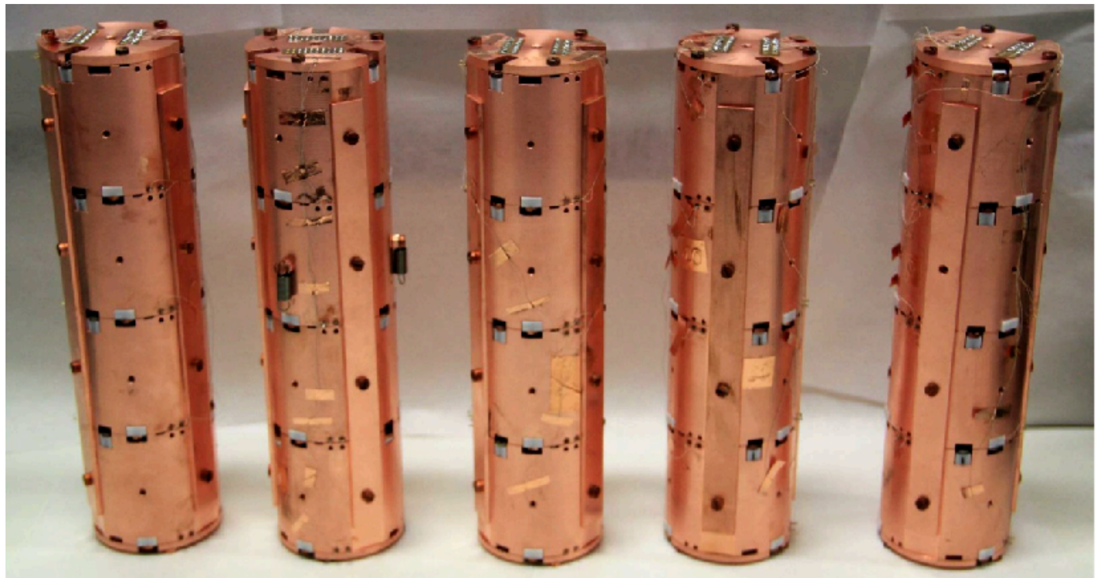
CUPID-Mo

- 20 $Li_2{}^{100}MoO_4$ scintillating crystals instrumented with light detectors in the Edelweiss cryogenic setup at the Modane underground lab
- Cylindrical crystals: ⌀ 43.8 × 45 mm
- 2.34 kg of ^{100}Mo
- Light detectors: ⌀ 44.5 mm×170 μm Ge wafer with SiO coating on both sides, instrumented with NTDs





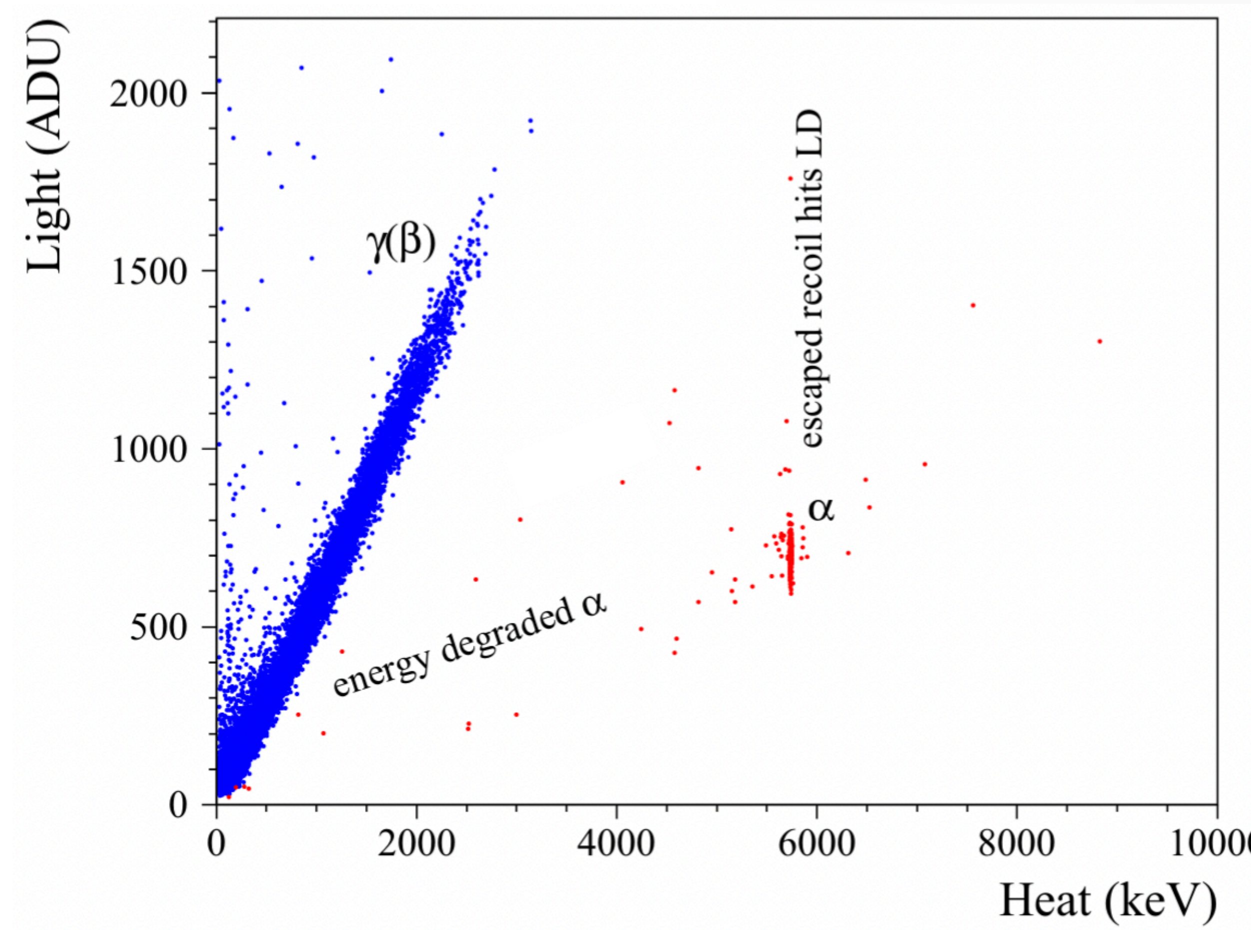




CUPID-Mo

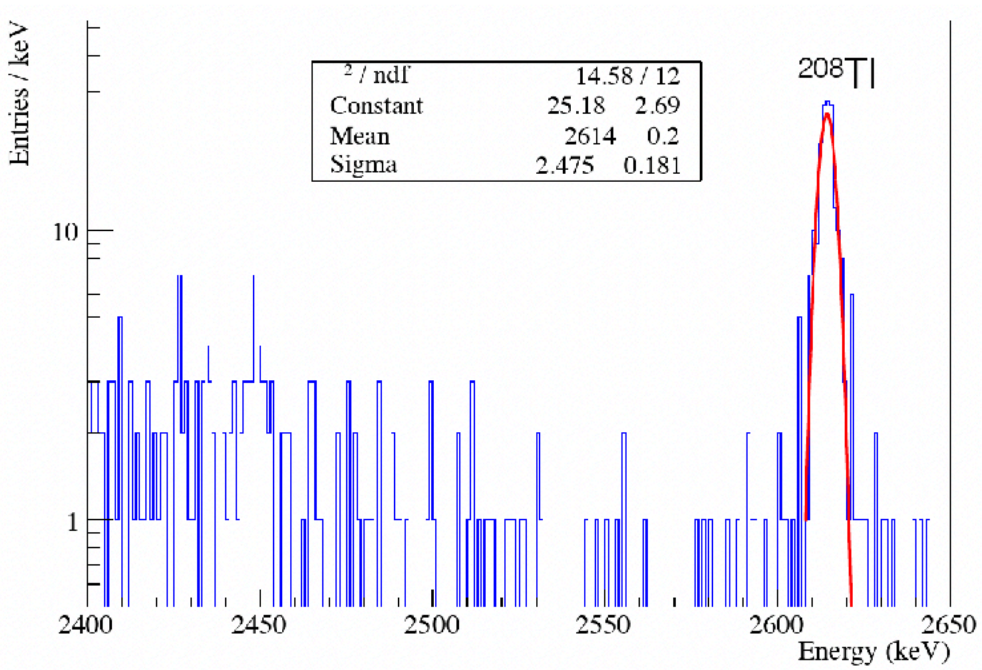
Demonstrated

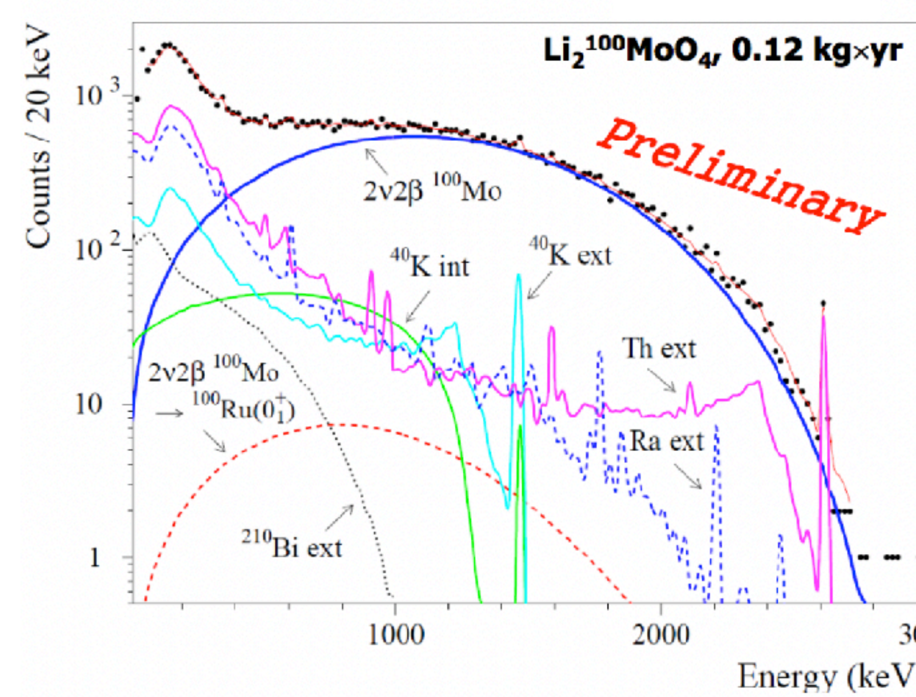
- Energy resolution ~ 5-6 keV FWHM
- Light Yield: 0.5-1 keV/MeV for β/γ
- Discrimination at 9 σ level



To be improved

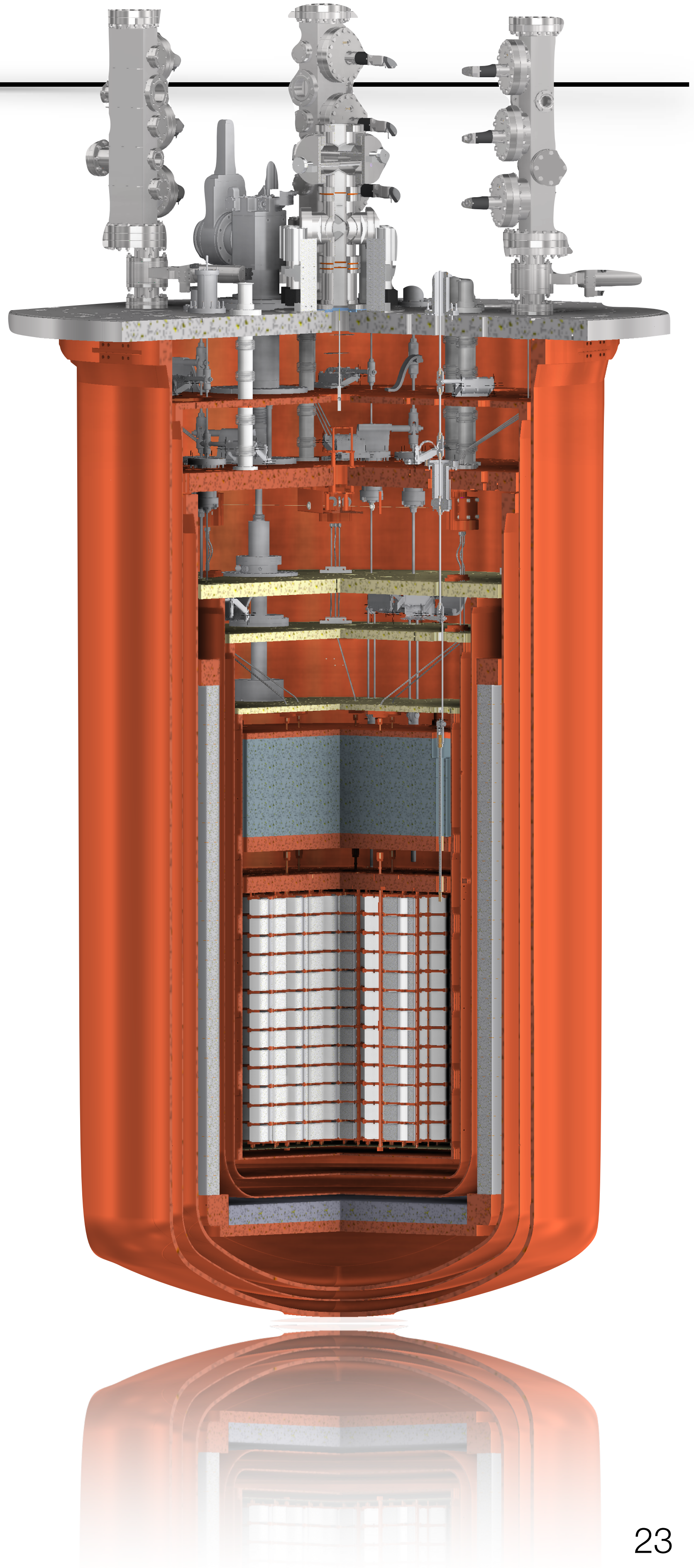
- Pileup events induced by short 2νββ decay half-life
  - ➡ Time resolution ≤ 1 ms required





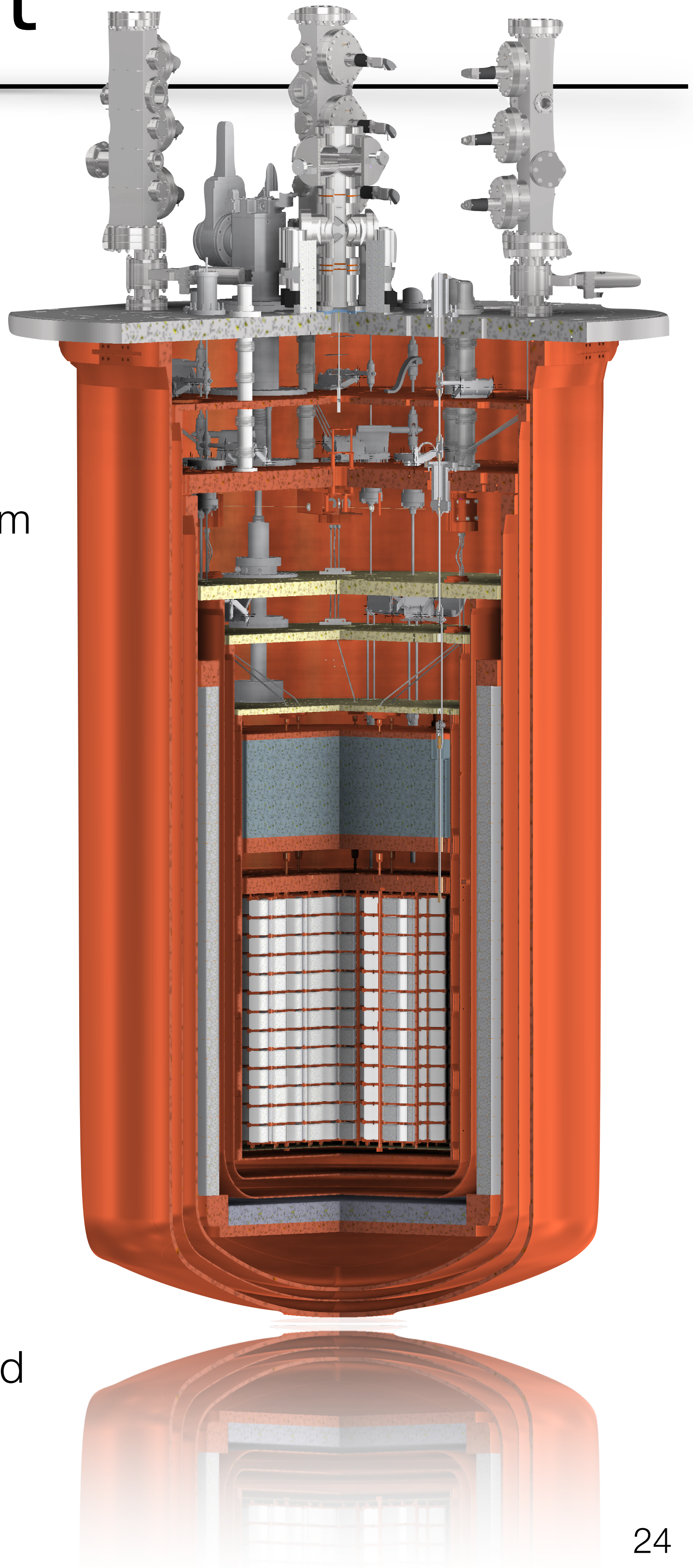
CUORE

Cryogenic Underground Observatory for Rare Events



- Closely packed array of 988 TeO_2 crystals (19 towers of 52 crystals 5×5×5 cm^3, 0.75 kg each)
- Mass of TeO_2: 742 kg (~206 kg of ^{130}Te)
- Operating temperature: ~ 10 mK
- Mass to be cooled down: ~ 15 tonnes (Pb, Cu and TeO_2)
- Background aim: 10^{-2} c/keV/kg/year
- Target energy resolution: 5 keV FWHM @ 2615 keV
- Projected sensitivity in 5 years (90% C.L.): $T_{1/2} > 9 \times 10^{25}$ yr

CUORE cryostat



- Cryogen-free
  5 Pulse tubes, JT expansion instead of 1K Pot
- Base temperature <10 mK
  high cooling power custom Dilution Unit
- Straight cryostat (more mass to cool down, simpler design)
  dimensions: external ⌀ 1.7 m × h 3.1 m, experimental volume ⌀ 0.9 m × h 1.37 m
- Large cold lead shielding close to detector
- Heavy load support
  detector ~ 1 tonne
  lead radioactivity shielding ~ 10 tonnes
- Redundancy (to improve reliability)
- Strict material selection
  mainly pure copper
  other selected materials only in small amounts (SS, TiAlSn, Kevlar…)
  limited amount of Multi Layer Insulation (MLI)
- Low mechanical vibration input on detector
  independent detector suspension
- The design was an iterative process in which every choice had to be validated from the thermal and radioactivity budget point of view

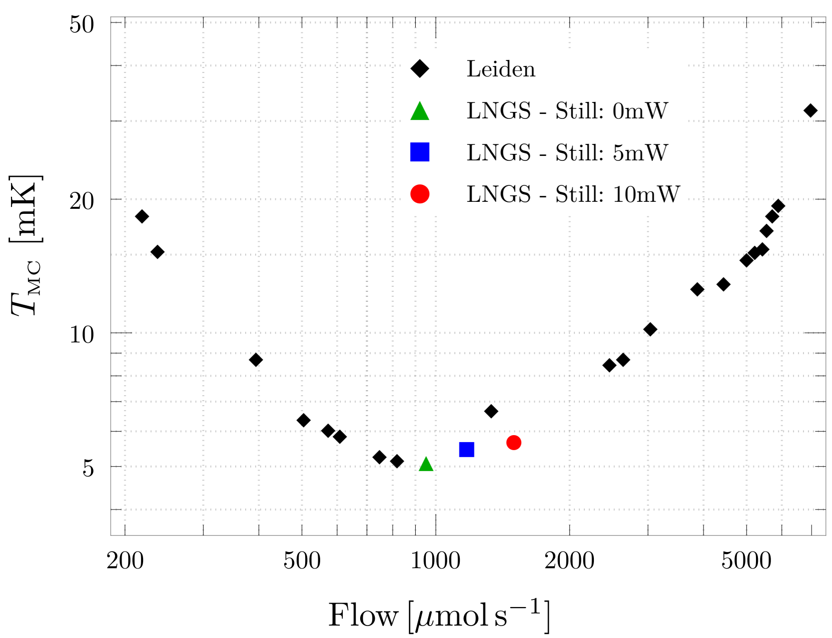
Dilution unit

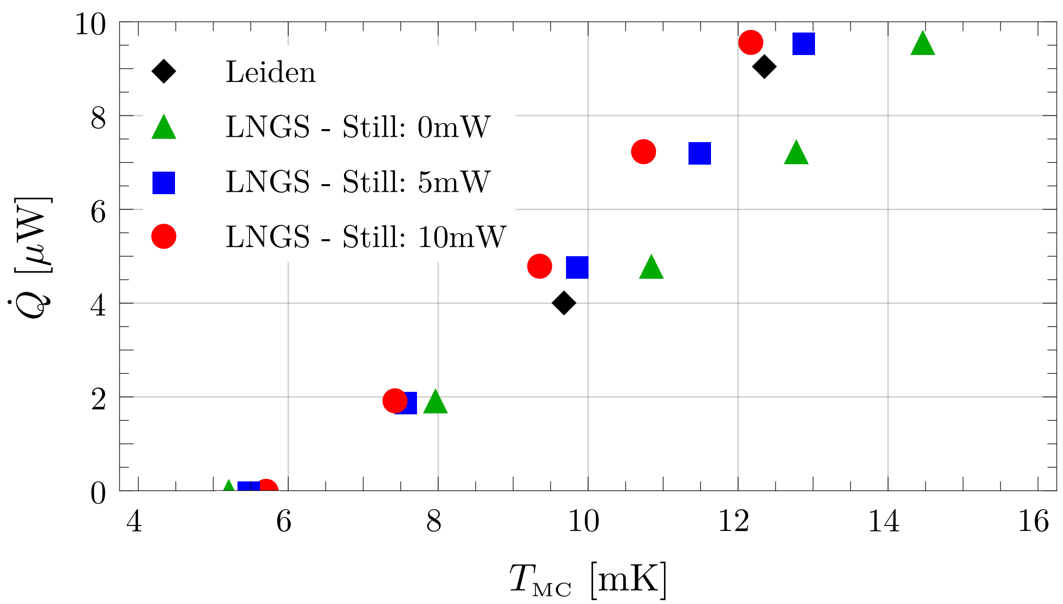
Custom Dilution Unit:

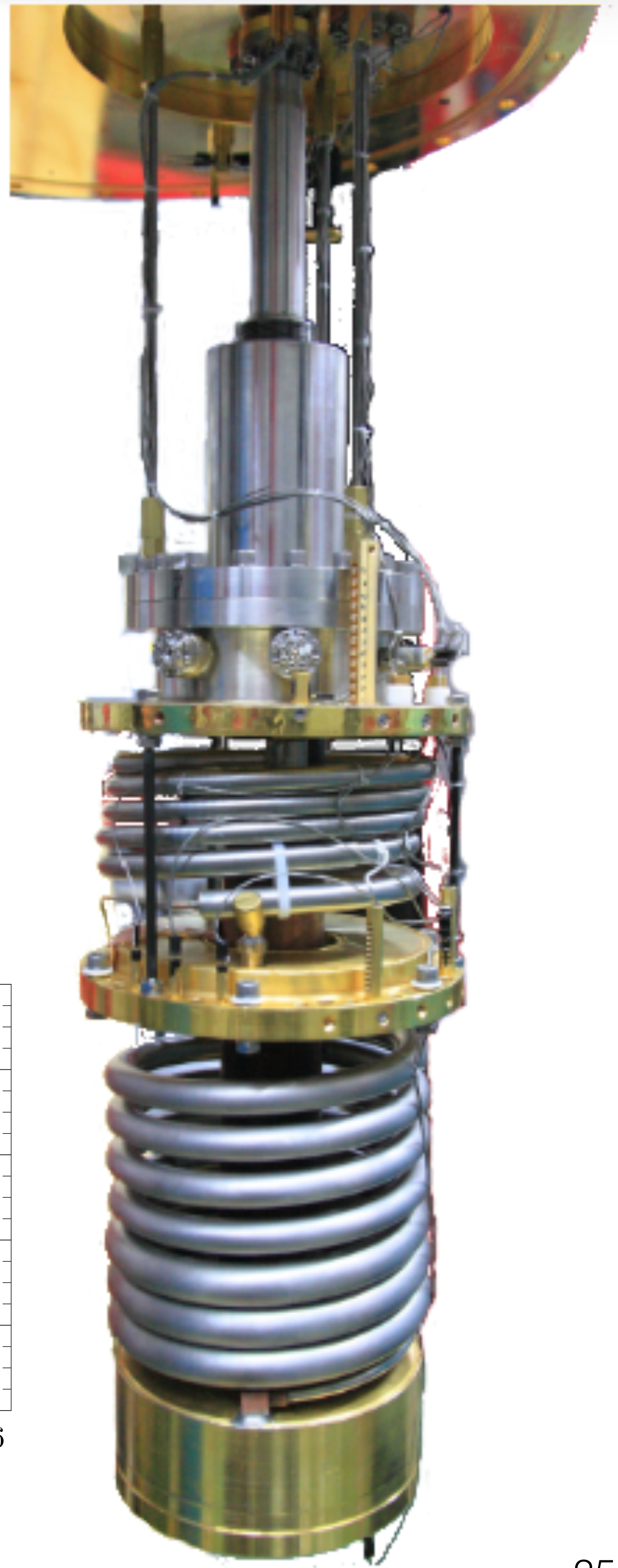
- cooling power: 5 μW @ 12 mK; >1.5 mW @ 120 mK
- base temperature: < 6 mK
- condensation flow: > 10 mmoles/s
- easily removable from the CUORE cryostat in order to be tested in a separate test cryostat
- 2 independent condensing lines with spring loaded variable flow impedances

Actual performances in the test cryostat were better than specs

- cryogen-free DU with the largest power ever built!



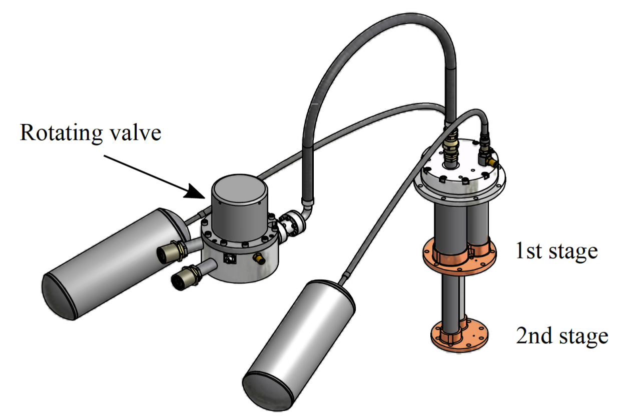


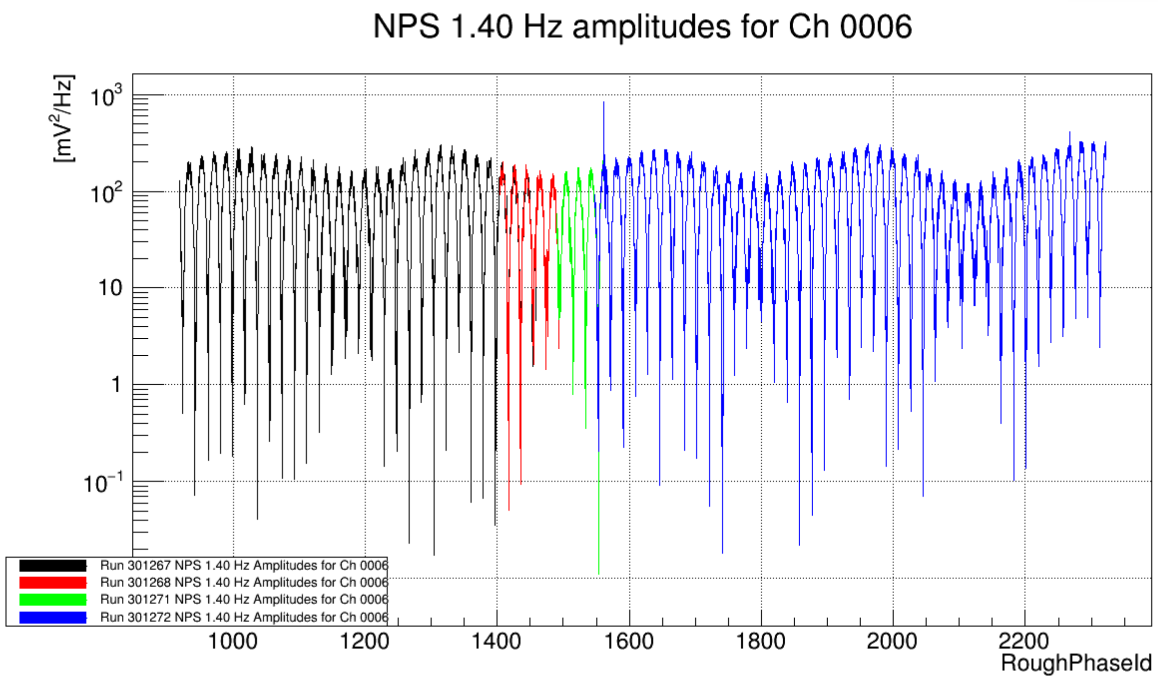


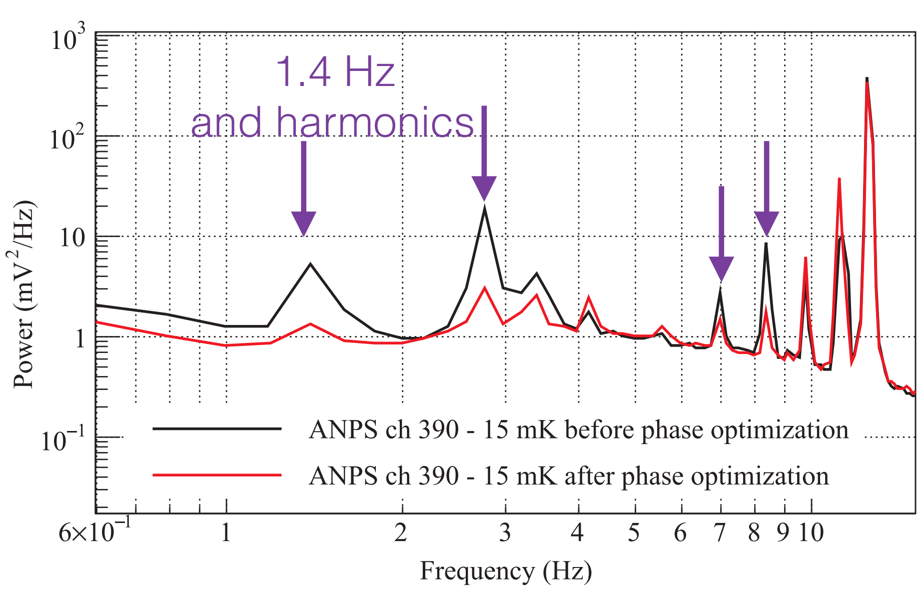
PT noise cancellation

Pulse Tubes are substituting liquid helium for a number of reasons

- Main drawback are the induced vibrations: active noise cancellation
- Relevant technological development in CUORE
- Interesting for all the PT based project (e.g. Einstein Telescope)







Conclusions

Cryogenic detectors have a solid present and brilliant future

Are crucial instruments for all the future astrophysics missions

Will play a dominant role in search for low-mass WIMPs

Will have a prominent role in the $0\nu\beta\beta$ search in the next decade

Many other science and technology fields will benefit from their characteristics