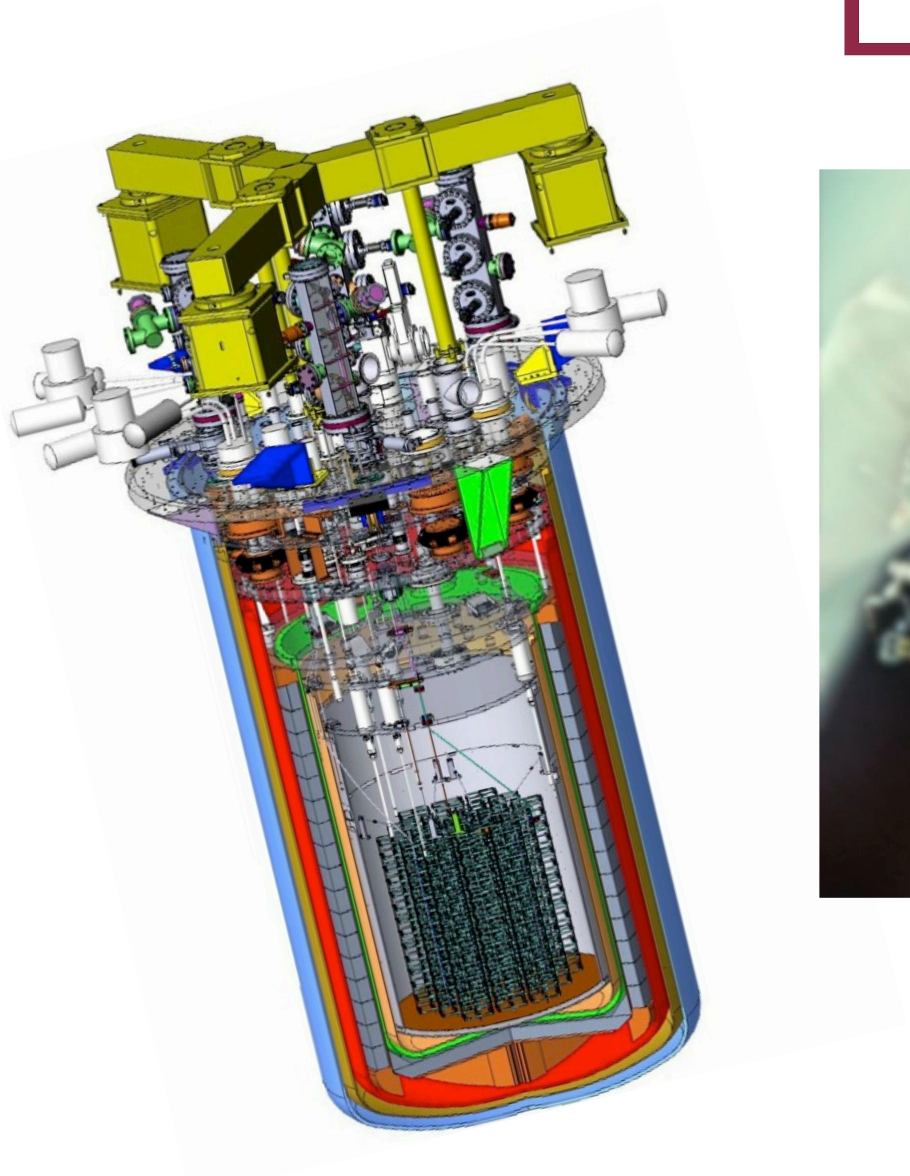
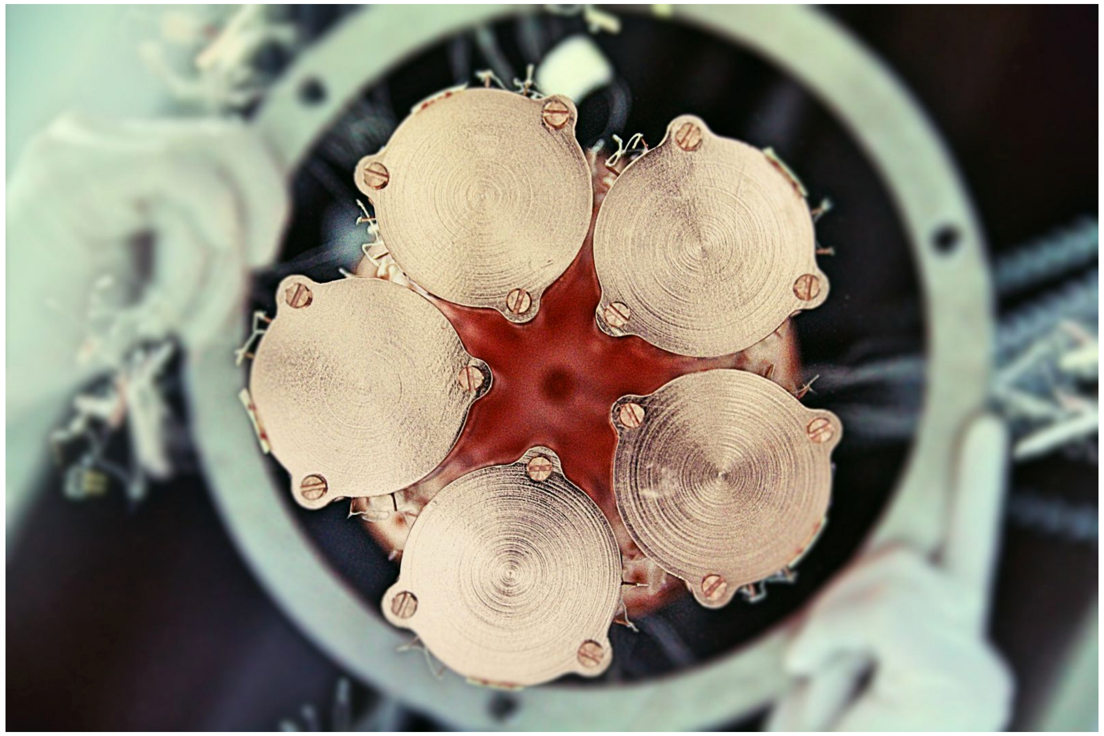
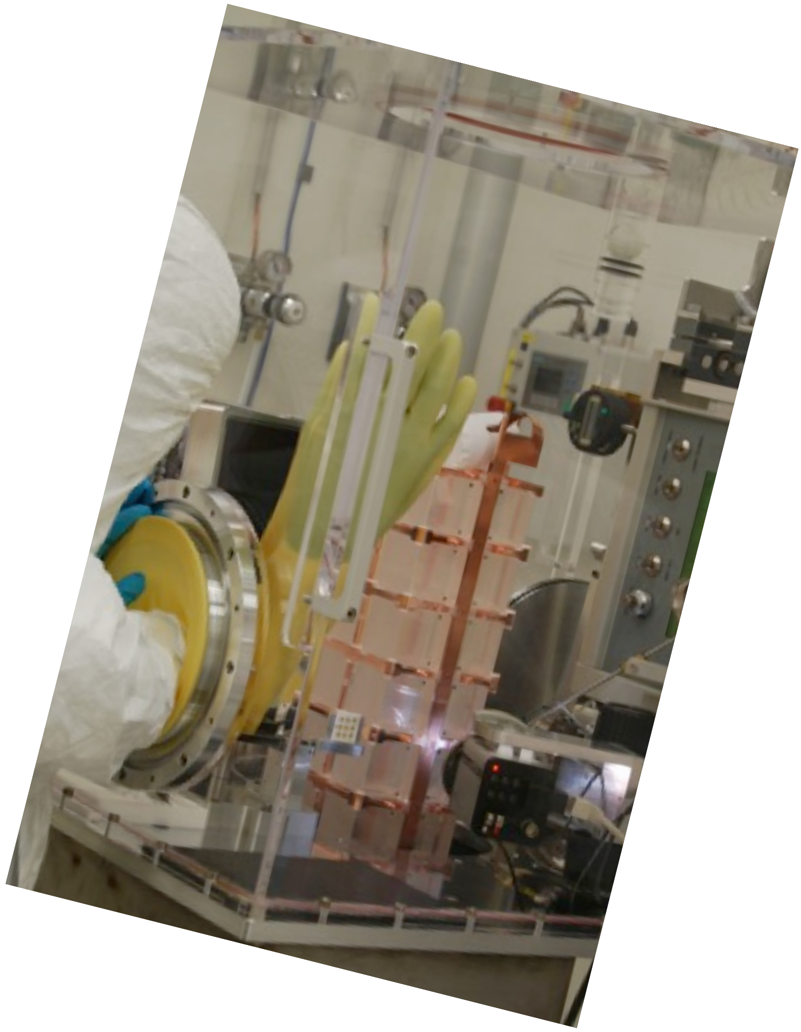
Istituto Nazionale di Fisica Nucleare

The CUORE and CUPID Experience

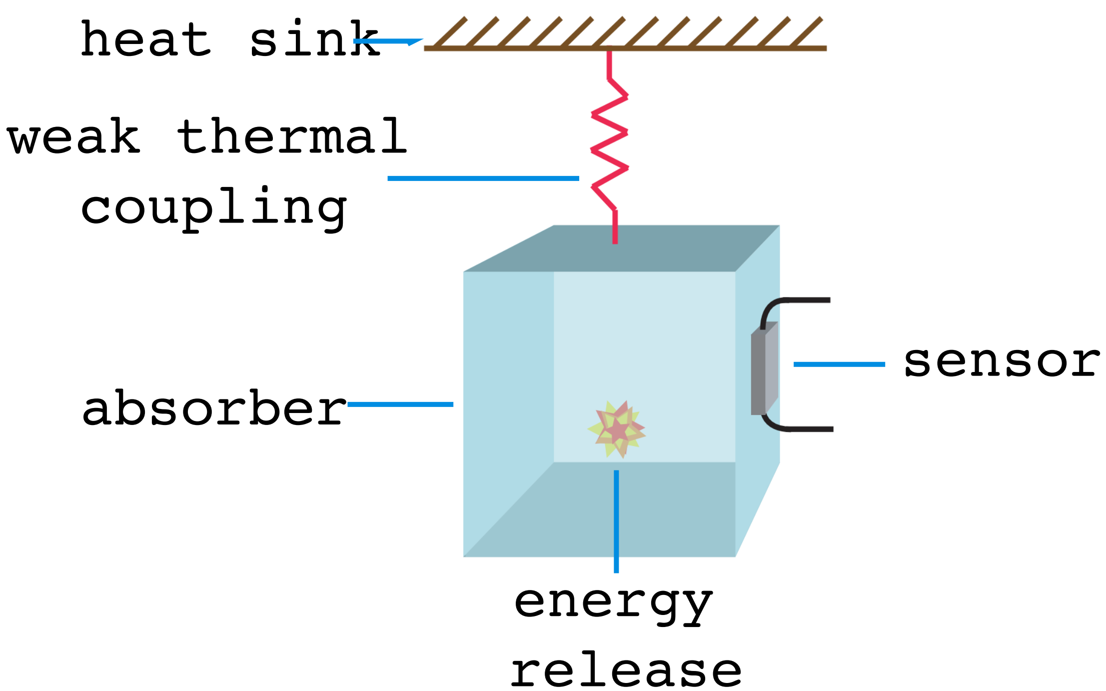




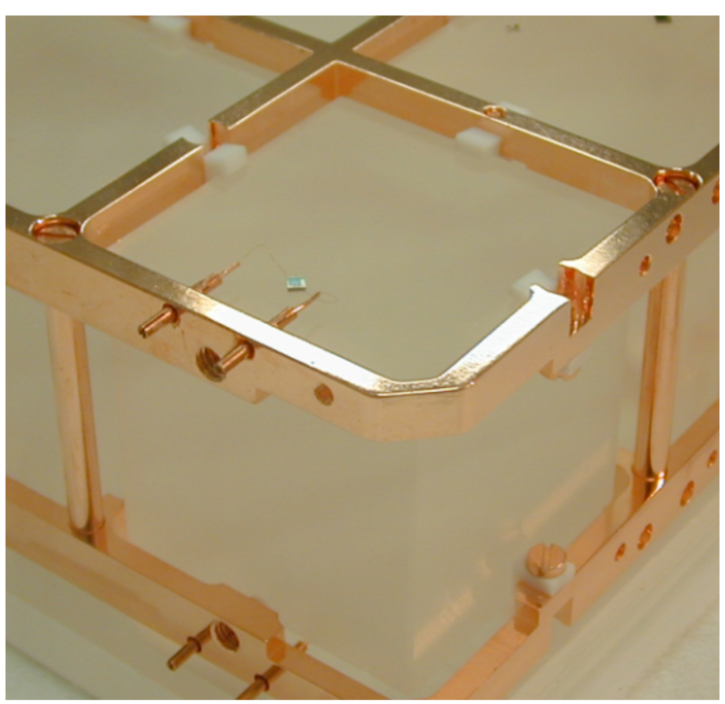


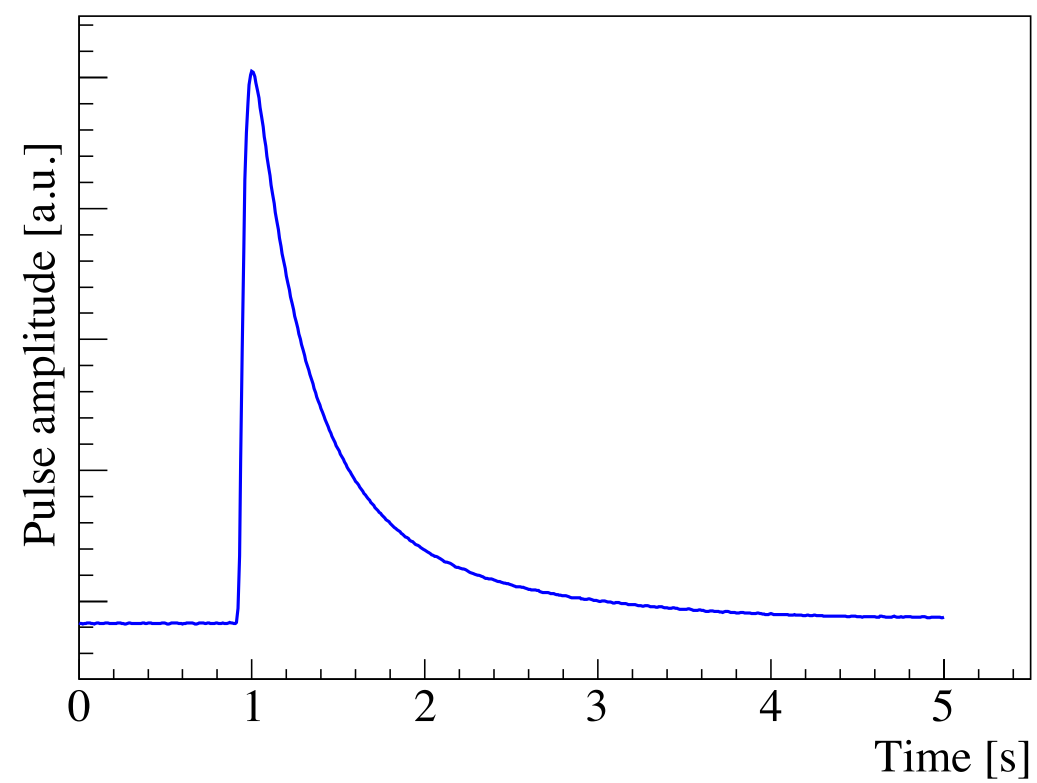
L. Cardani
26/06/2018

Cryogenic Calorimeters



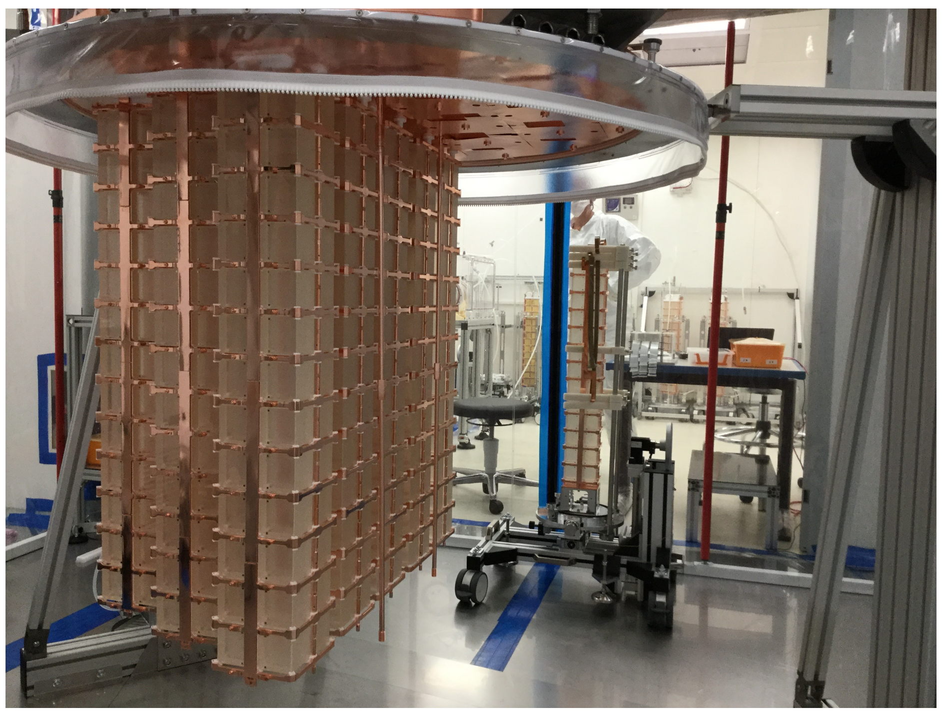
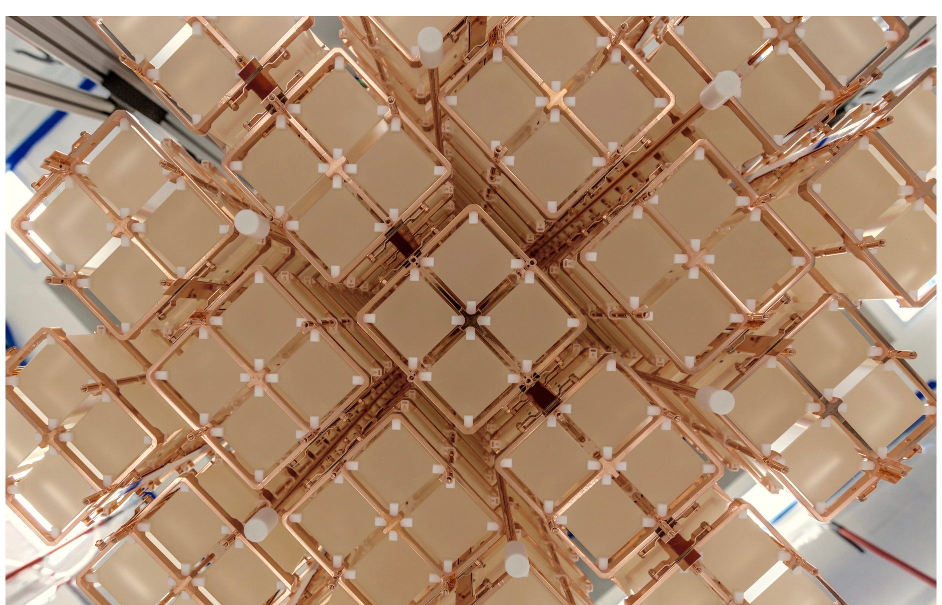
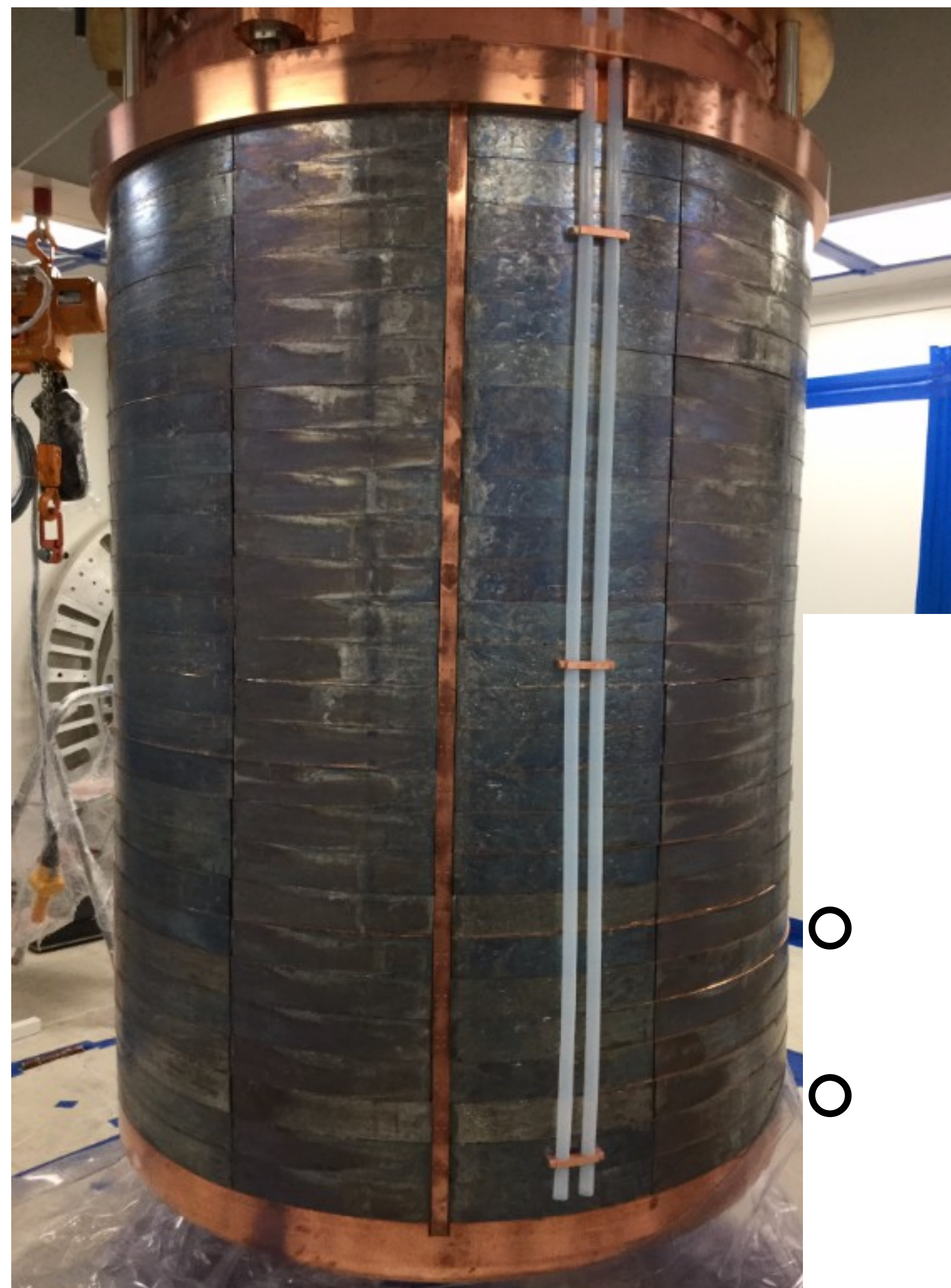
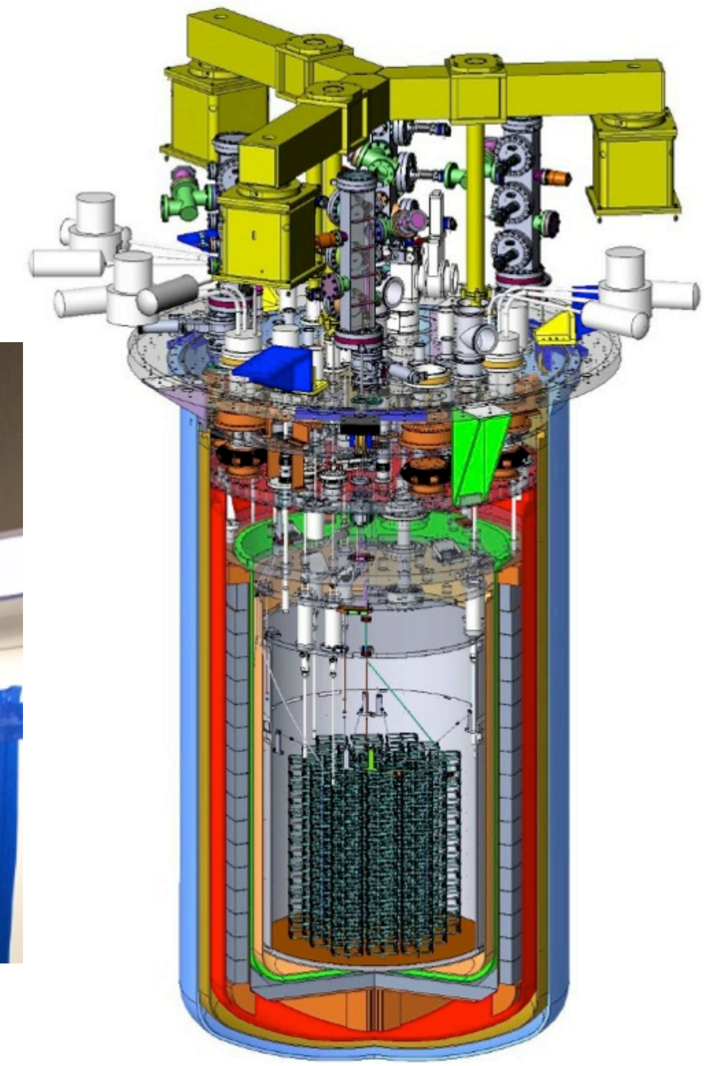
- Convert **energy** in **temperature:** ΔT ~ ΔE/C
- To obtain sizable ΔT we need a small C
- Crystals **cooled at 10 mK**: C ~ T^3
- ΔT converted into electrical signals





CUORE

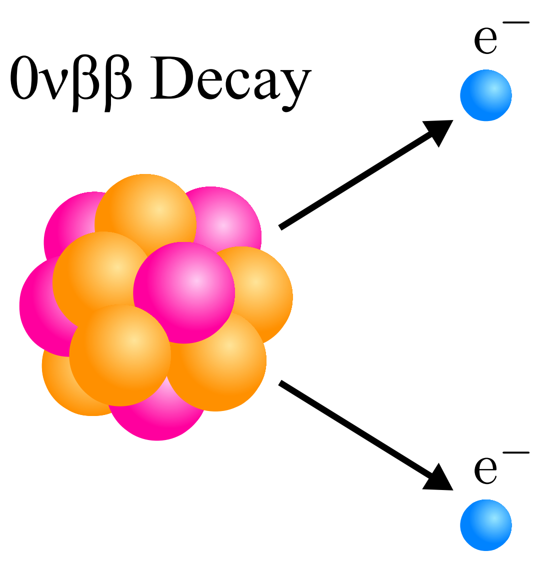
- **988 TeO_2** crystals (~1 ton) + other 2 tons of copper at **10 mK**
- **~20 tons** at different T stages

- Jan 2017: base T **reached**
- Now taking data at LNGS

Physics Motivation

Main goal: search for **0νββ**: hypothesized, **never observed**, nuclear transition



- Forbidden by SM: it **violates L** (actually B-L) conservation
- Can occur **only if ν is a Majorana** particle
- It **creates matter** (no anti-matter balancing)
- Majorana phases: **other sources of CPV**?

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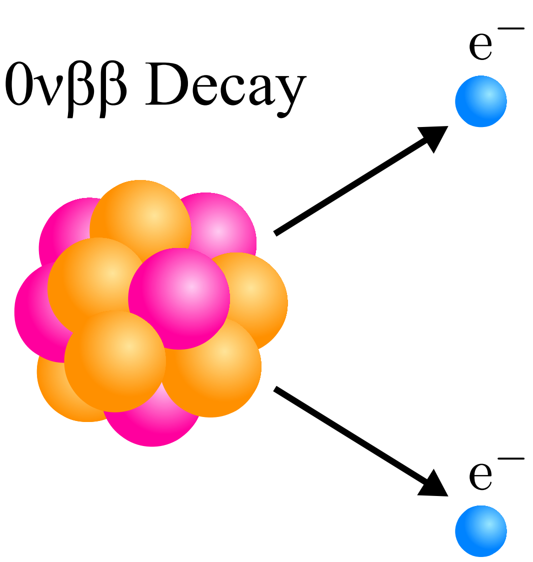

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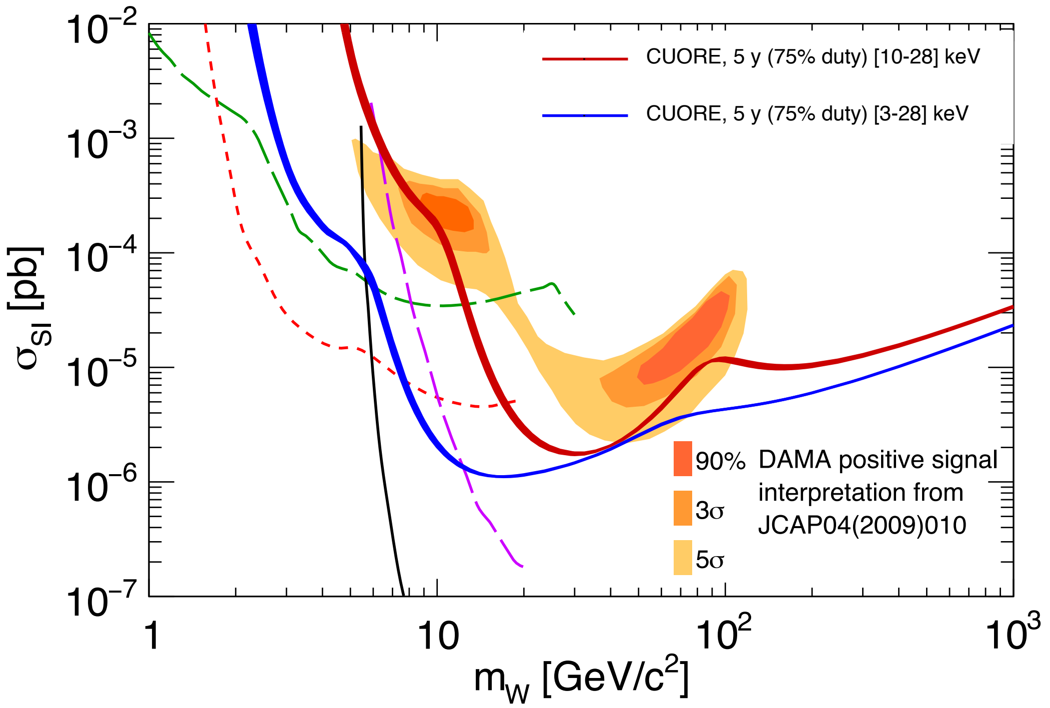
But large mass, low threshold, low background and Quenching~1:

- Annual modulation of nuclear recoils induced by **WIMPs** (tens of keV for ~100 GeV WIMPs)
- **Solar axions** by inverse Primakoff effect: M1 transition of ^{57}Fe, expected at **14.4 keV**



The Nightmare: Radio-Activity

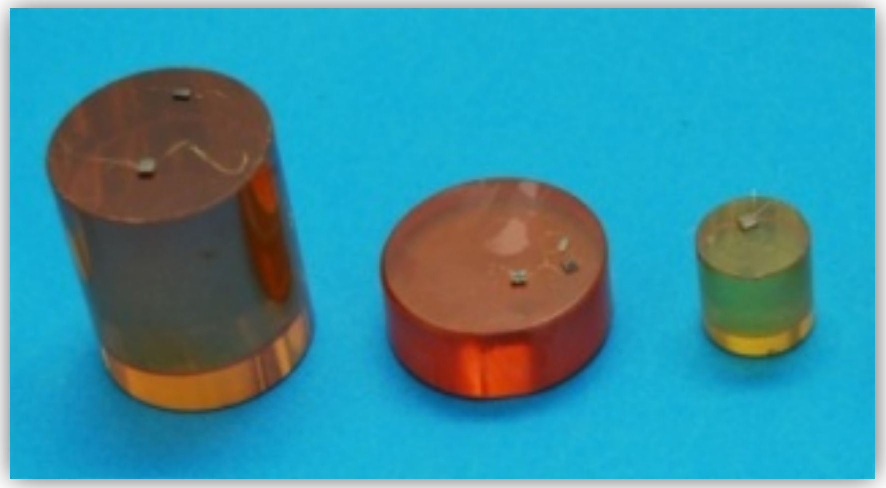
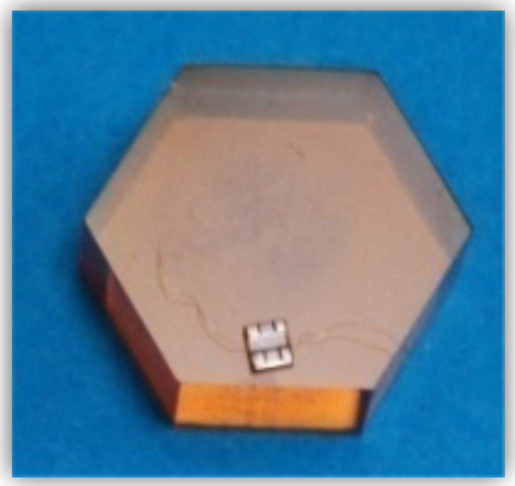
- In CUORE (but not only) the **external background** can be effectively **suppressed**
- **The detector itself** becomes the main problem!
- Challenge: such small contamination levels required, that **no screening techniques** available!

ACTIVE MATERIALS	PASSIVE MATERIALS
Can often be used as detectors to assess their own contaminations	Can be more problematic, especially when dealing with surface contaminations

Crystals

- Used by many experiments as calorimeters, scintillators…
- CUORE (TeO_2), CUPID (ZnSe and $LiMoO_4$), AMoRE ($^{40}Ca^{100}MoO_4$), GERDA and Majorana (Ge)…
- CRESST ($CaWO_4$), Edelweiss, CoGeNT (Ge)…
- NaI (DAMA, SABRE, ANAIS, DM-Ice..)

…and many others

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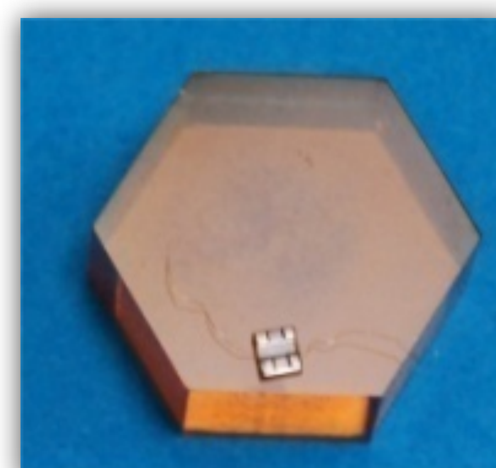
- Contaminations from ^{40}K, ^{238}U, ^{232}Th and daughters
- Cosmogenic activation of materials
- Selection and monitoring of all materials, tools and facilities for crystal growth
- Selection of equipment for chemical and mechanical processing, storage





An excellent result: TeO_2

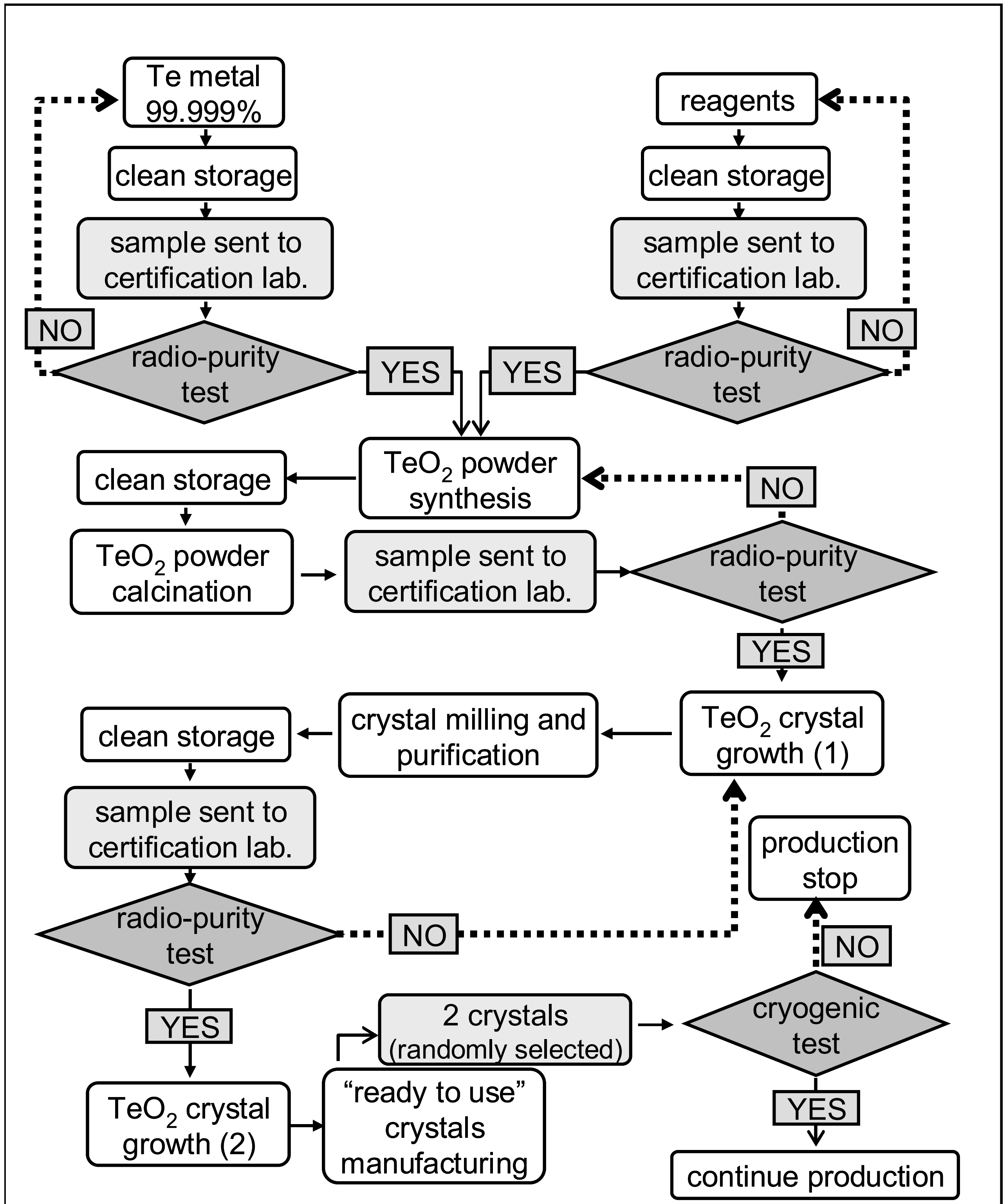
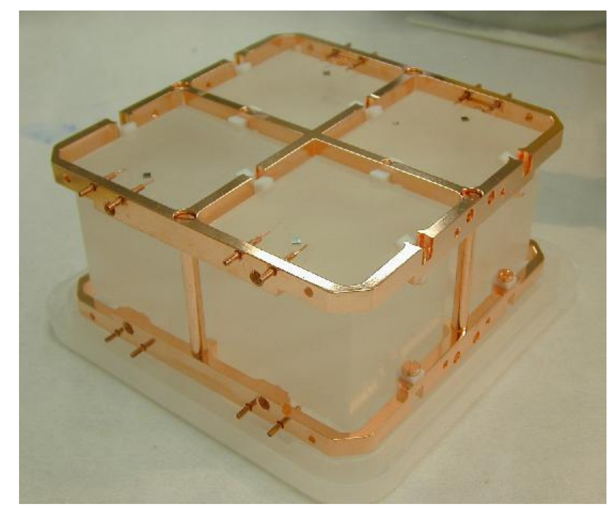


Fig. 2 Radio-purity certification protocol applied for TeO_2 crystals.

- Must be <3x10^{-13} g/g in ^{238}U, ^{232}Th
- Contribution of **I.Dafinei** (INFN Roma)
- Strict protocol for each step of crystal production



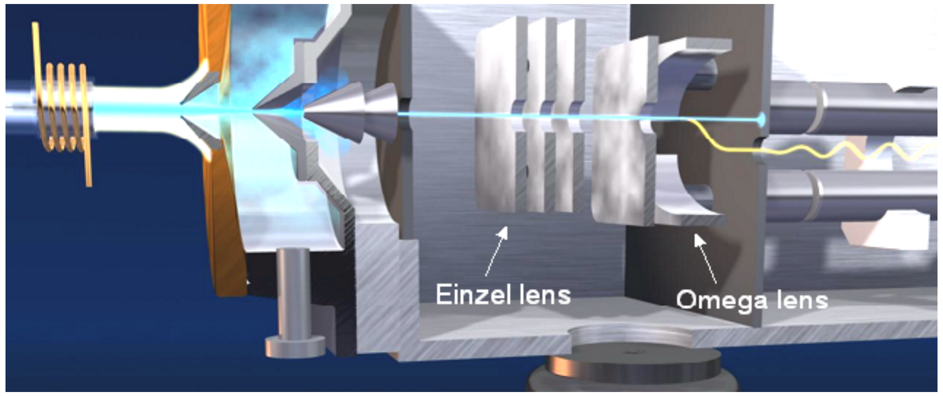
- In clean room, etching and polishing
- Packaging and underground storage

doi:10.1016/j.jcrysgro.2010.06.034

Screening Technologies

Each stage of production is monitored accurately:

- ICP-MS for contaminations in ^{232}Th and ^{238}U in Te, TeO_2 and consumables and in all other reagents. Sensitivity of 10^{-12} g/g achievable.
- HPGe to be sensitive also to broken chains and ^{40}K. For our purposes, 10^{-10} g/g on Th and U was enough, but 10^{-12} g/g achievable (long run)
- SBD for surface contaminations of specific materials ad monitoring of selected components (in particular for lapping cloths, packaging…)

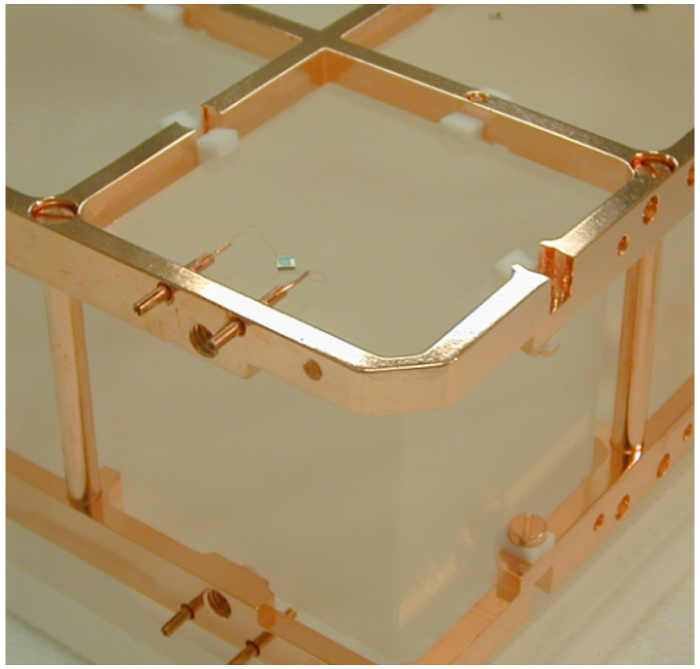


Cryogenic test

Bulk: <1.8x10^{-14} g/g in ^{238}U and <5.5x10^{-14} g/g in ^{232}Th

Passive Materials: Copper

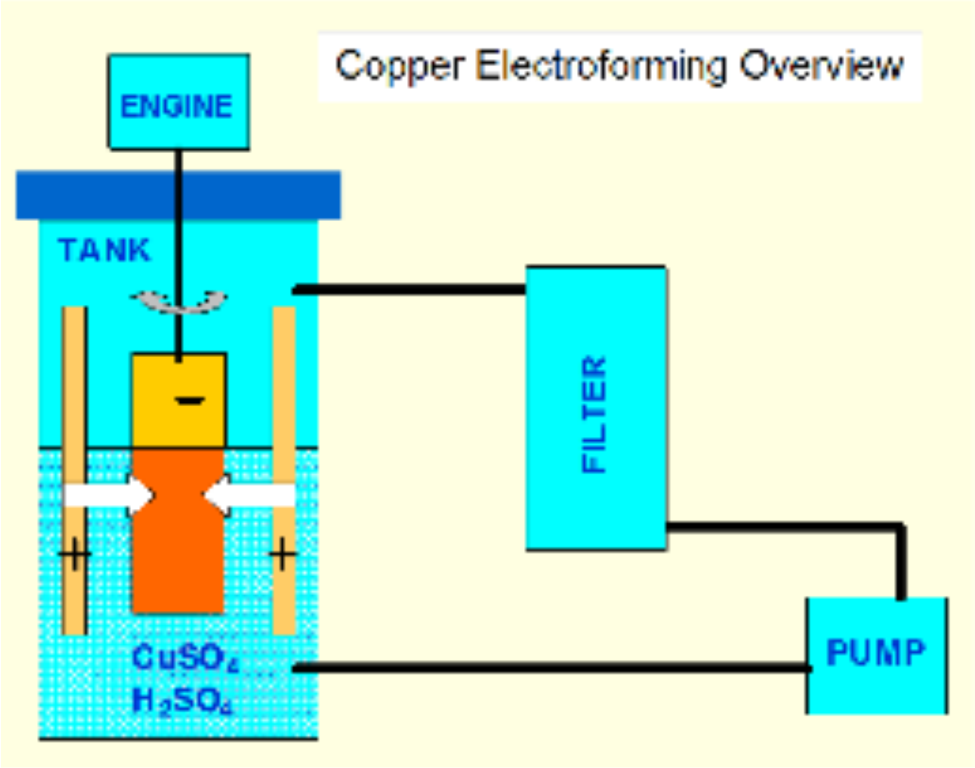
Good mechanical/thermal properties, radio-pure —> structural parts of many detectors



1st problem: how to make it more radio-pure

2nd problem: how to check the purity level

Electro-formed Copper



S.Borjabad LRT 2017

- When electro-plating copper from a solution onto cathodes, most of the contaminants do not follow copper (different electrochemical value)
- Electrodeposition OFHC copper on stainless steel forms
- Everything done underground (reduce activation)
- Outstanding purity: 0.3 µBq/kg for ^{232}Th and ^{238}U

- Originally proposed at PNLL
- Now CES (Copper Electroforming Process) at CANFRANC
- Not (yet) able to clean surface of the materials but efficient for the purification in many materials

3D-Printed Copper

HAMMER

HAMMER

Hub for Additive Manufacturing Materials Engineering and Research

V. Pettinacci (INFN Roma) - D. Orlandi, S.Nisi, M. Laubenstein (INFN LNGS)

OFHC copper converted into powder and used via 3D-printers in controlled environment

Radio-purity measured at LNGS

Improvement of surface roughness at LNL

Characterization at low temperatures at Roma (**N.Casali**)

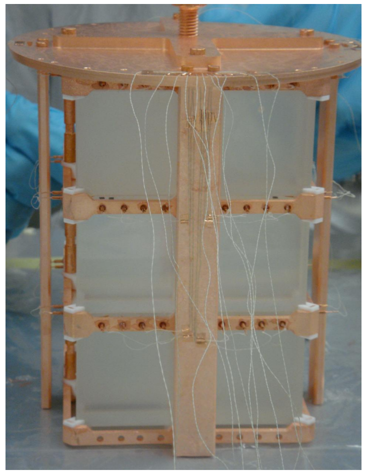
Radio-Assay

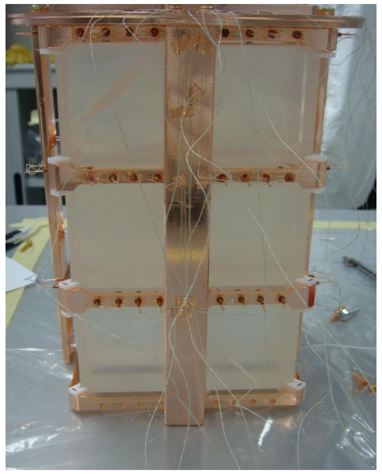
Neutron Activation Analysis and HPGe spectroscopy showed no traces for contaminations

	μBq/kg	g/g
^{232}Th	<2	$<0.5\times10^{-12}$
^{238}U	<70	$<6\times10^{-12}$

Study of surface contaminations is difficult

doi:10.1016/j.astropartphys.2013.02.005





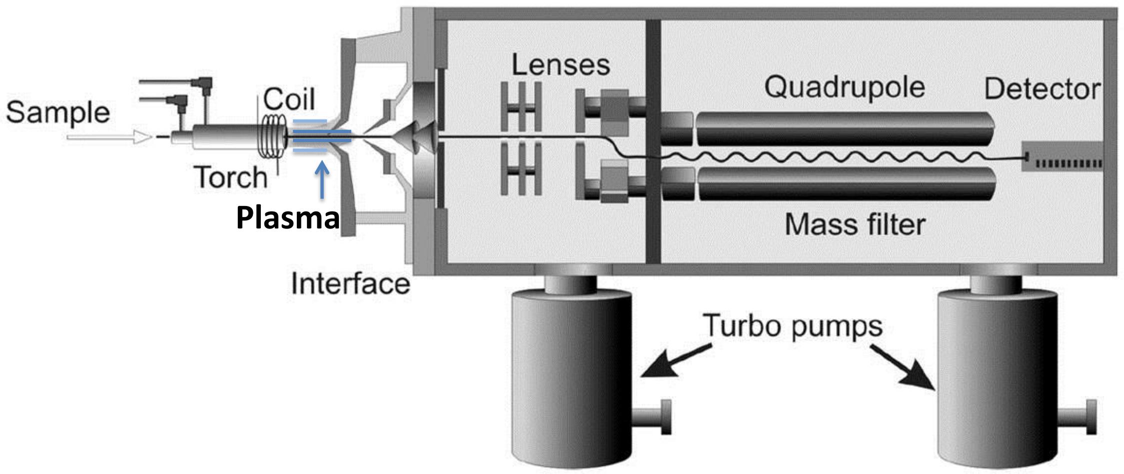
T1 **T2** **T3**

Large arrays provide sensitivities of tens of nBq/cm^2

For next generation detectors, we must ensure an even better purity (~ a factor of 10)

This becomes a problem also for assay

Improving Sensitivity: Bulk



- ICP-MS with pre-concentration of contaminants
- Current goal: automation and ^{40}K assay

Material	Th, U Detection Limits	
	μBq/kg	ppt
Copper (Electroformed or commercial OFHC)	<0.1	<0.01
Lead	<1	<0.1
Titanium	<1	<0.1
Stainless Steel	<1	<0.1
Polymers (PTFE, PVDF, Acrylic, Bioabsorbables, *etc.*)	<1	<0.1
Linear Alkyl Benzene (LAB)	<0.1	<0.01
Quartz, Fused Silica	<1	<0.1
Electronic Components: FETs, resistors, thermocouples, etc	<0.1 pg/component	
Solutions	<0.01	<0.001

Improving Sensitivity: Surface

Scintillating bolometers allow to achieve an extremely high sensitivity on surface contaminations in a few weeks of measurements.

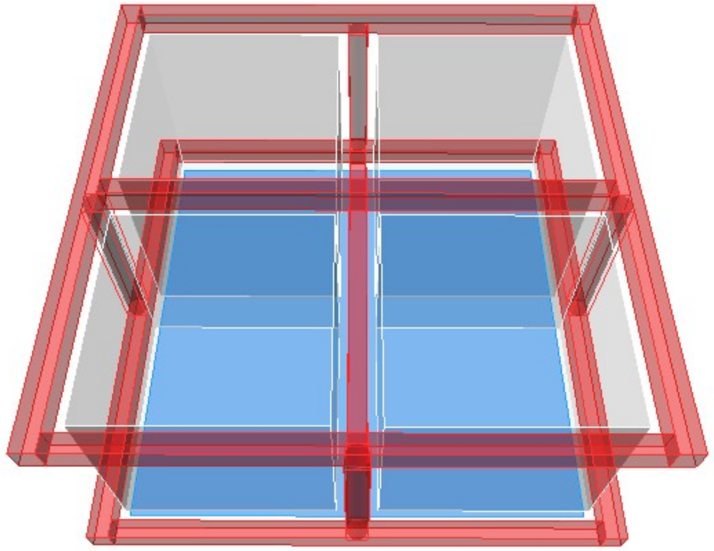
L.Cardani

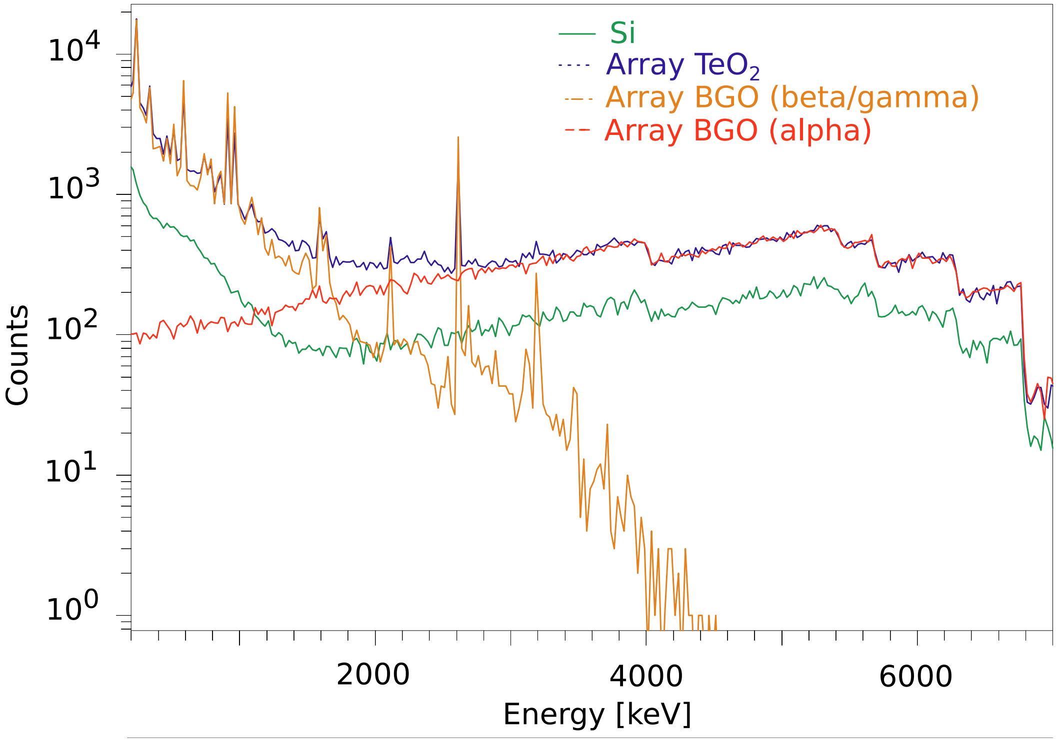
Advantages:

- Simultaneously α and γ spectroscopy
- Wide active surface (hundreds of cm^2)
- No dead layers
- Excellent energy resolution (< %)
- Low intrinsic background

with these features, we can achieve a ~tens of nBq/cm^2 in a few weeks

http://stacks.iop.org/1748-0221/7/i=10/a=P10022

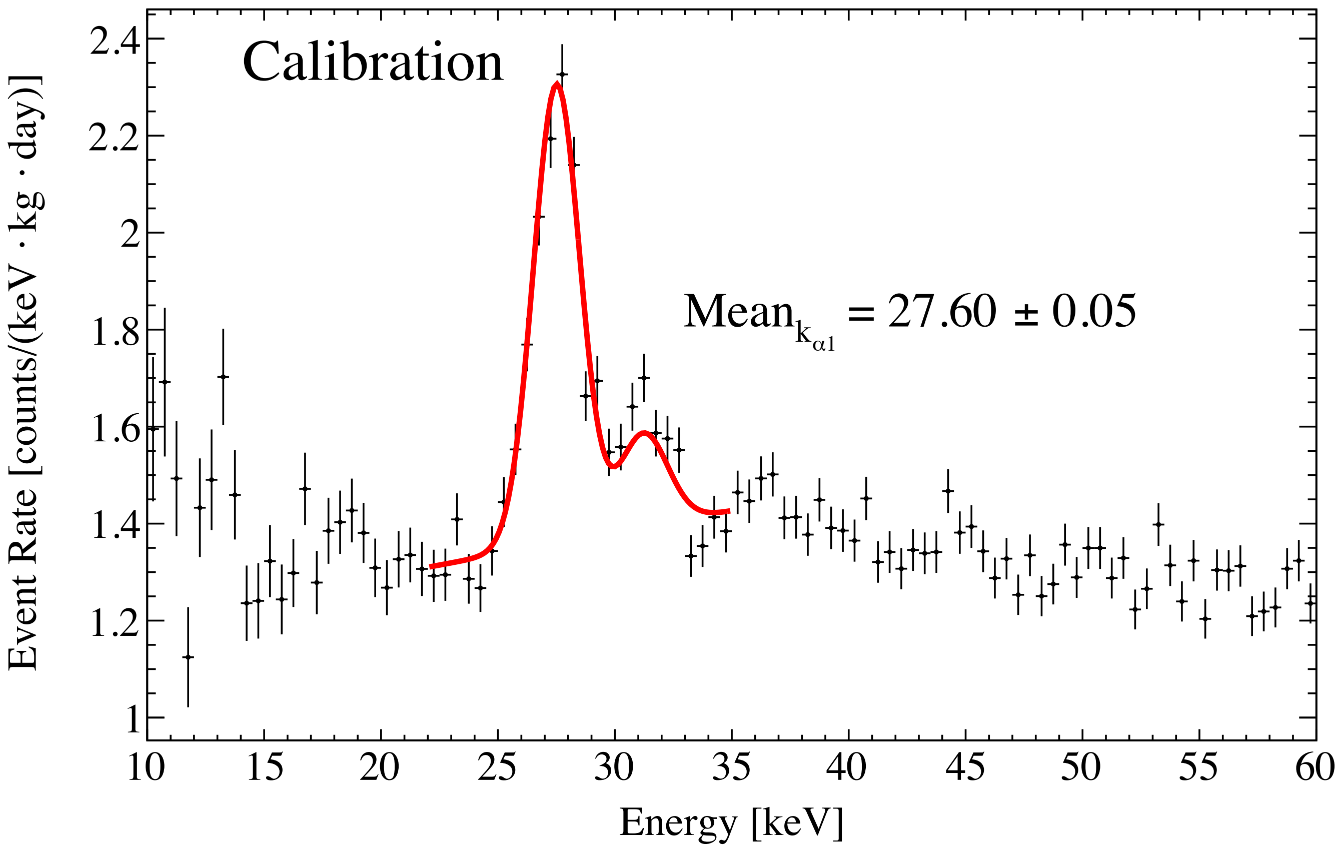


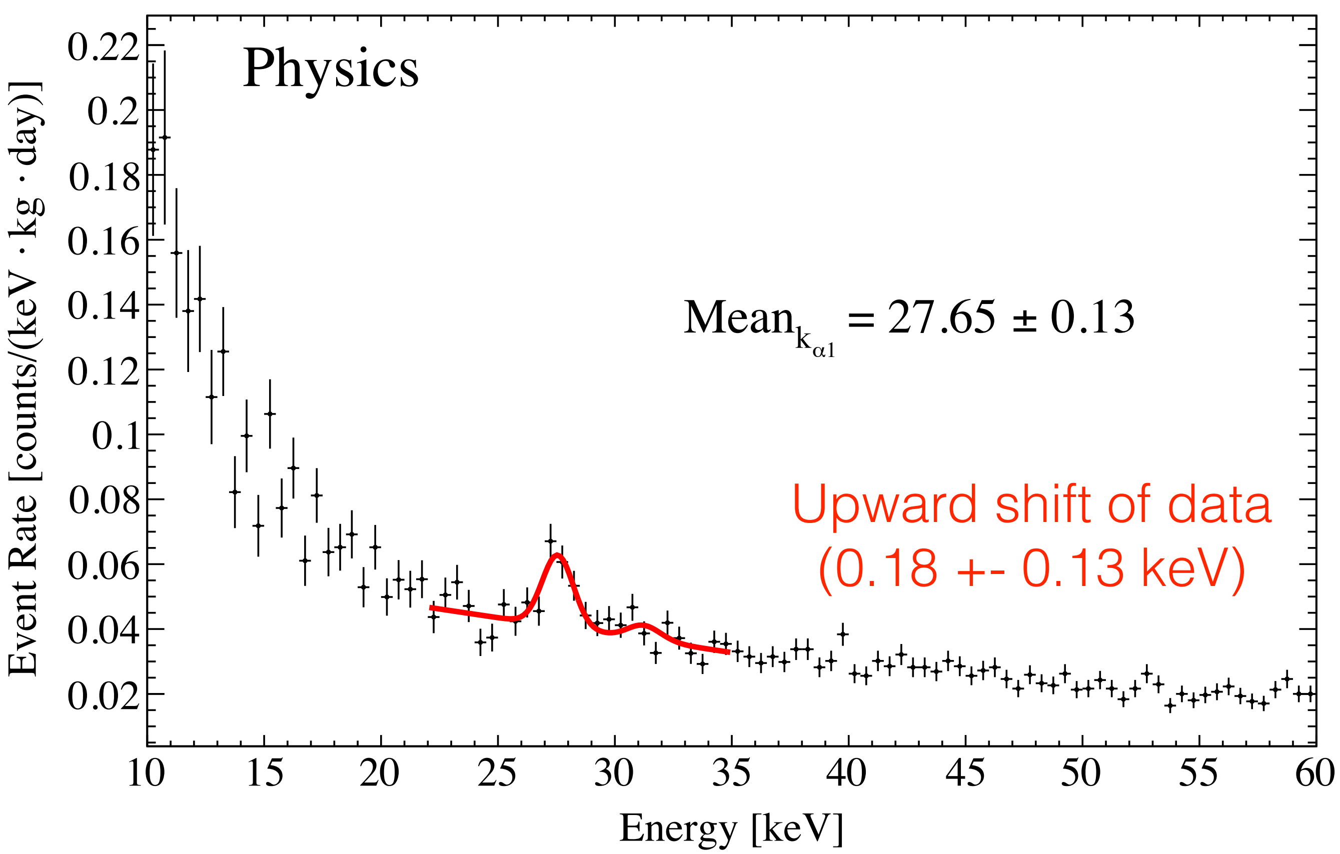


Conclusions

- **A long R&D on materials allowed to reach a very low background with CUORE**
- **The development of pure material is crucial for many experiments in different fields**
- **Most of the purity levels are extremely difficult to assess with conventional techniques**
- **New, versatile technologies have been proposed**

M2 spectra
(X-rays)





Efficiency - corrected
energy spectrum

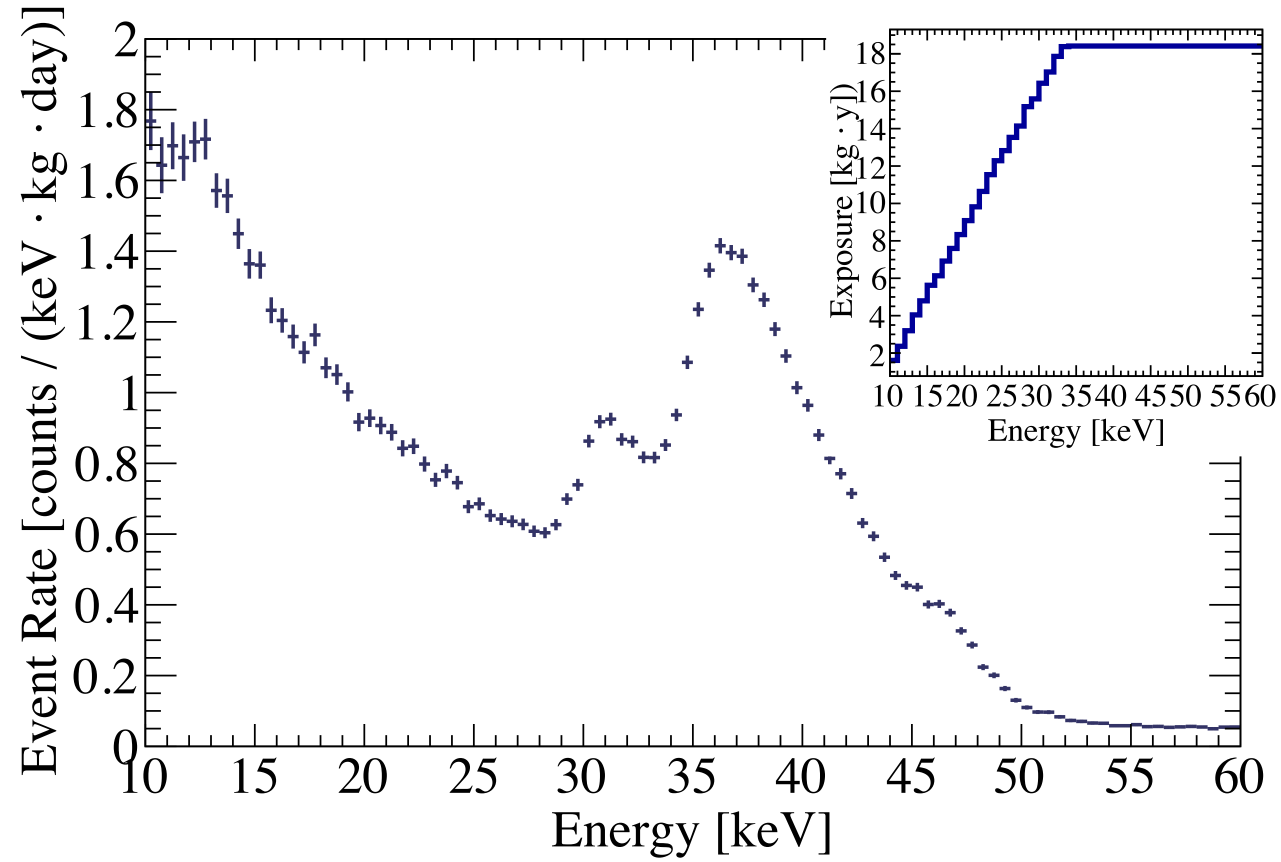


Table 3 Expected energy, measured energy obtained from fits, and resulting quenching factors (QFs) for the selected recoiling nuclei. Only statistical uncertainties are shown in the QFs.

Recoiling Nuclei	$E_{expected}$	$E_{measured}$	QF
^{206}Pb	103.12	95.62 ± 0.24	0.927 ± 0.002(stat.)
^{218}Po	100.8	100.0 ± 0.9	0.992 ± 0.009(stat.)
^{220}Rn	103.50	100.45 ± 1.21	0.971 ± 0.012(stat.)
^{214}Pb	112.13	110.92 ± 0.96	0.989 ± 0.009(stat.)

- Assuming coherent scattering (A^2) TeO2 is interesting both for high and low masses
- Only spin-independent
- Coherent isospin-invariant coupling and the Helm model for nuclear form factors
- For WIMP velocity, standard halo model (SHM)
- WIMP local density 0.3 GeV/c^2, local circular velocity 220 km/s, galactic escape velocity 650 km/h, orbital velocity of Earth around the Sun 29.8 km/s,

- For each (mW, σSI) we generate 100 toy MC simulations
- For each MC spectrum, maximum likelihood analysis for annual modulation and no modulation hypothesis
- Significance of modulation quoted as log-likelihood ratio of the best fits
- The likelihood is calculated using a PDF containing the target mass, the detection efficiency (BoD) and the background pdf (no temporal dependency)
- ROI: 10-28 keV to exclude peaking background (most of the signal expected at low energy)
- Uncertainty on energy scale dominated by QF (consevatively 7%)
- Sensitivity computed requiring a 90% CL in 90% of the toy experiments