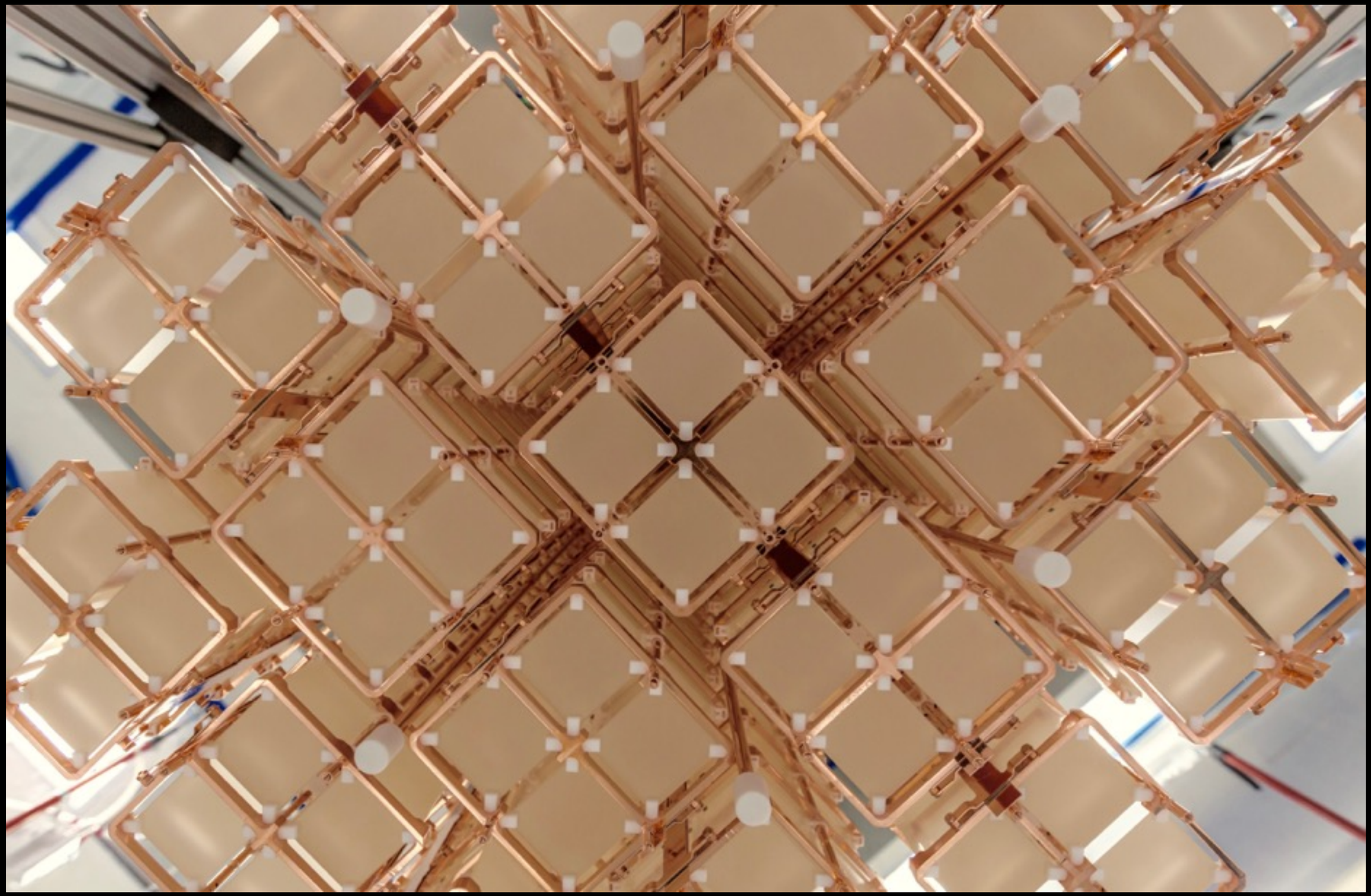


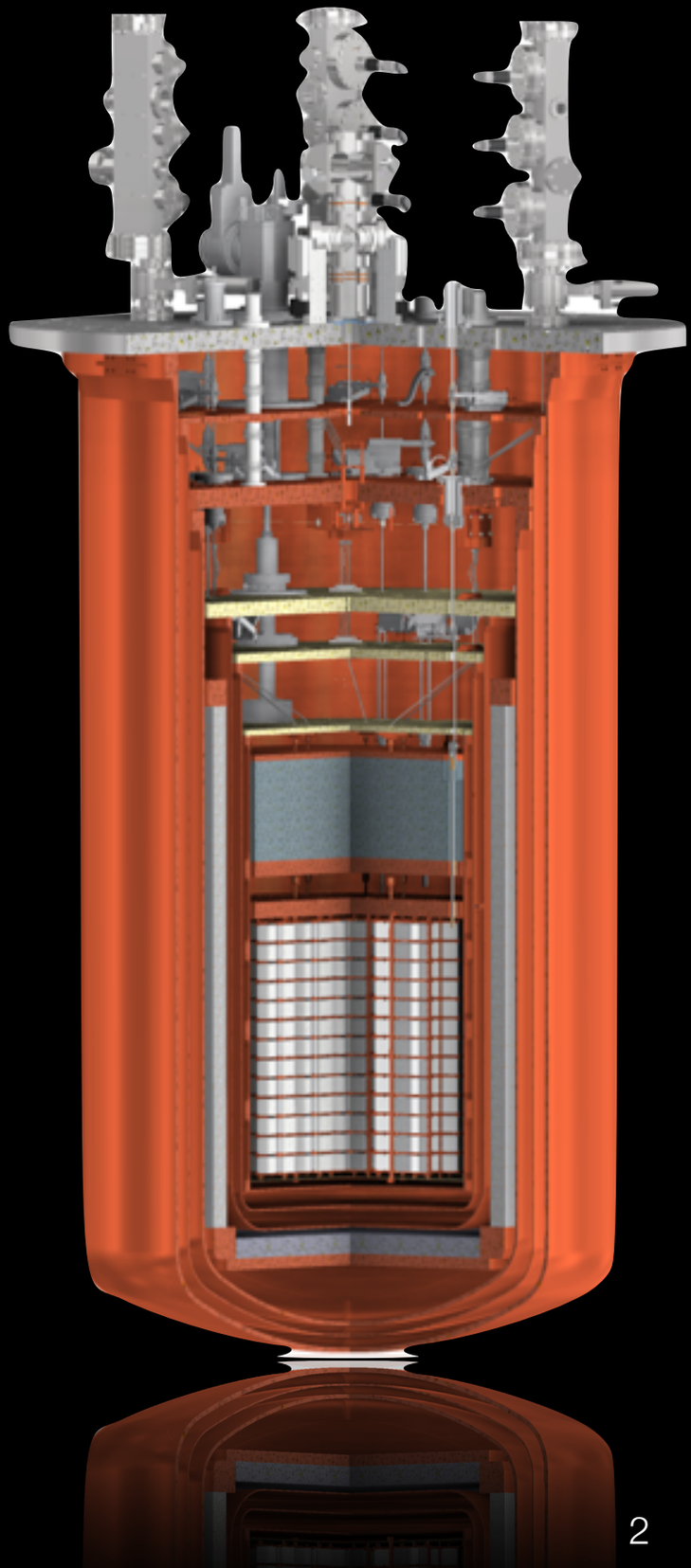
The construction of CUORE

Carlo Bucci
INFN-LNGS

The CUORE challenge

Build a cryogenic system with an experimental volume of ~1 m^3 in which operates a huge LTD array in a low radioactivity and low vibrations environment

- 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)
- Energy resolution: 5 keV FWHM @ 2615 keV
- Operating temperature: ~ 10 mK
- Mass to be cooled down: ~ 15 tonnes (Pb, Cu and TeO_2)
- Background aim: 10^{-2} c/keV/kg/year
- $T_{1/2}$ sensitivity in 5 years (90% C.L.): ~ 9 x 10^{25} yr



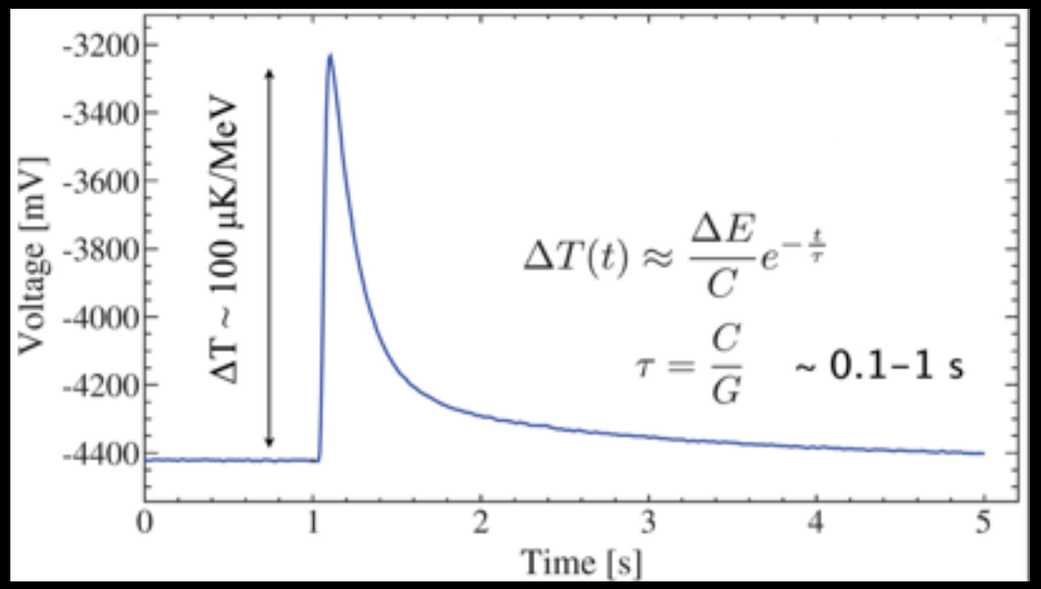
The CUORE detectors

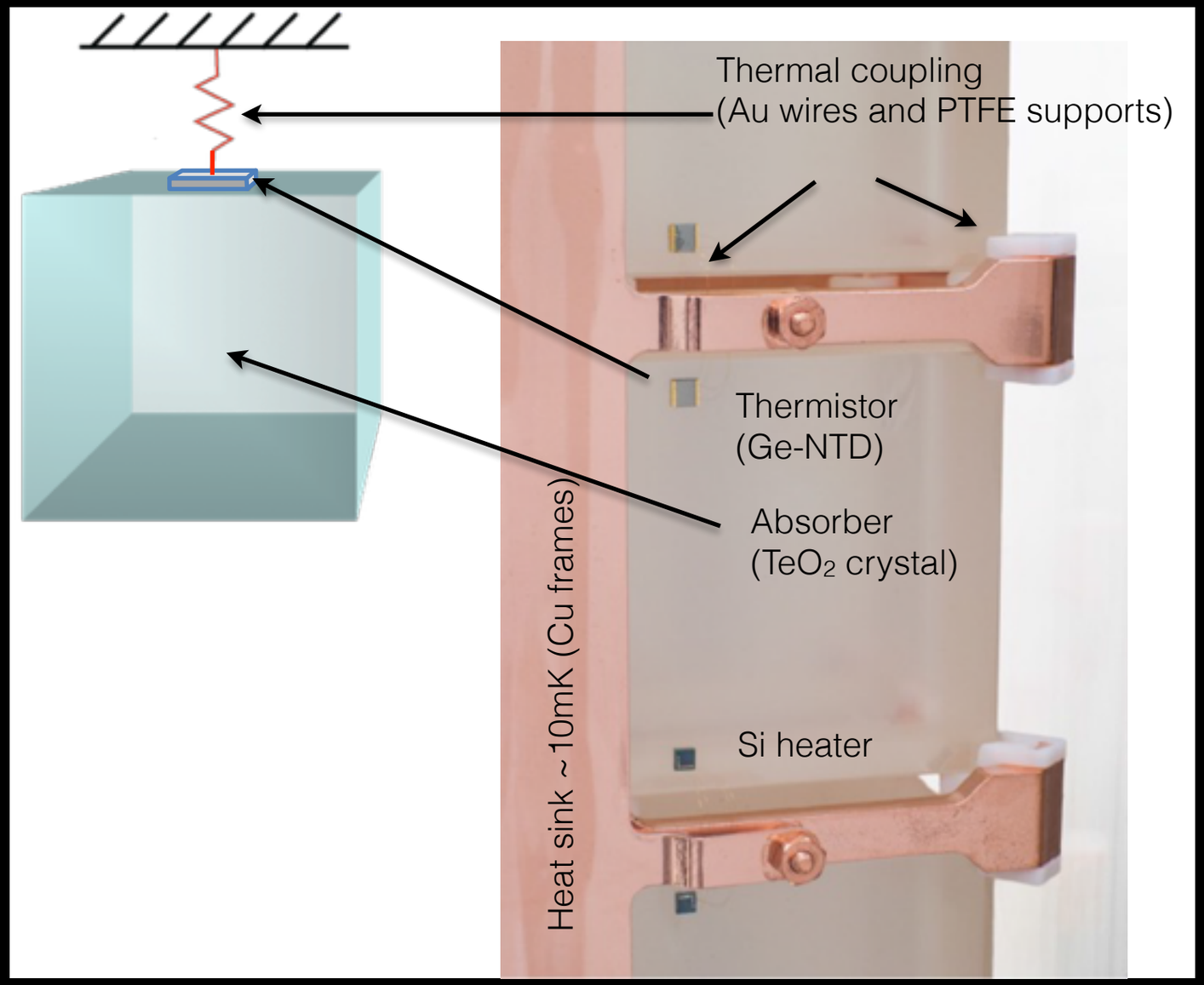
Thermal detector principle

- the absorbed energy is converted into a variation of the crystal temperature, measured by the thermistor

TeO_2 thermal detectors

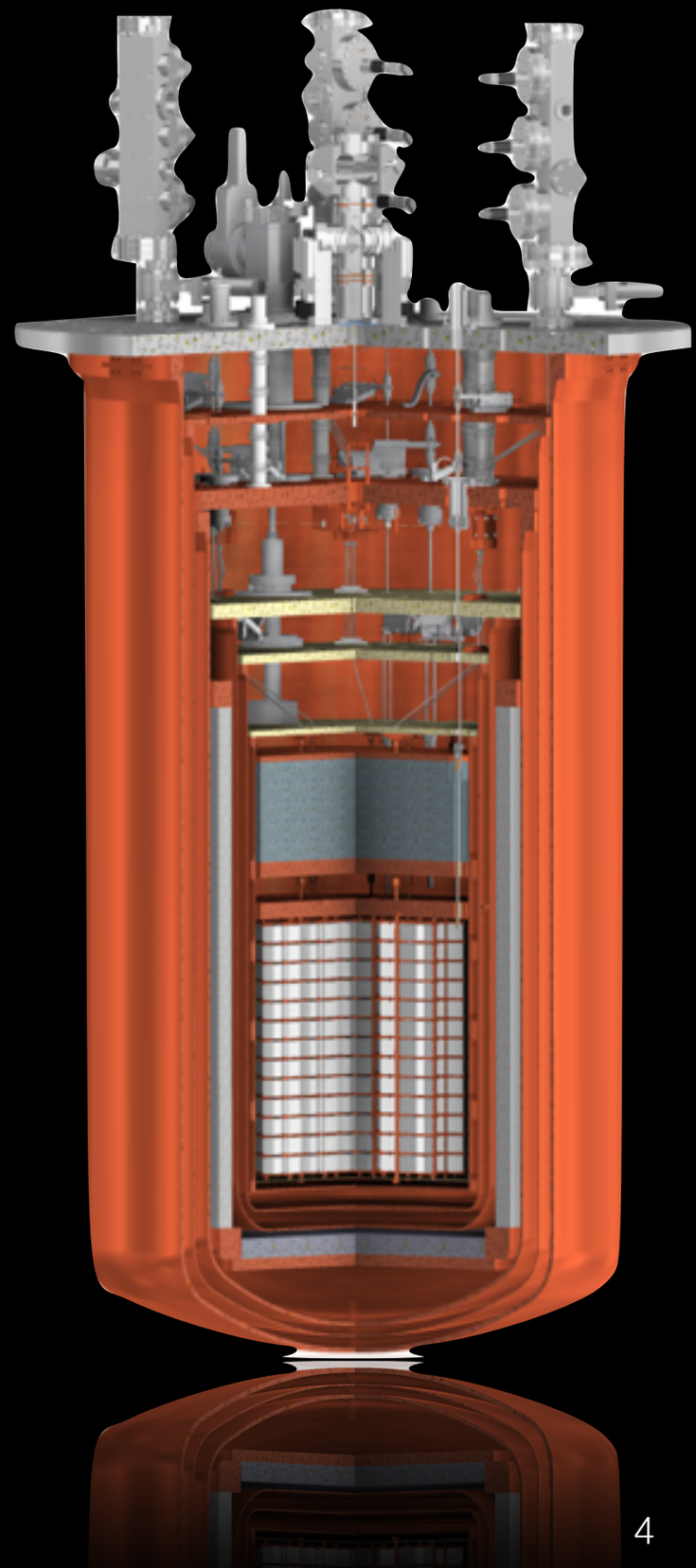
- low heat capacity @ T_{work} ($C \div T^3$)
- excellent energy resolution (~ 0.2% FWHM)
- slowness (suitable for rare event searches)



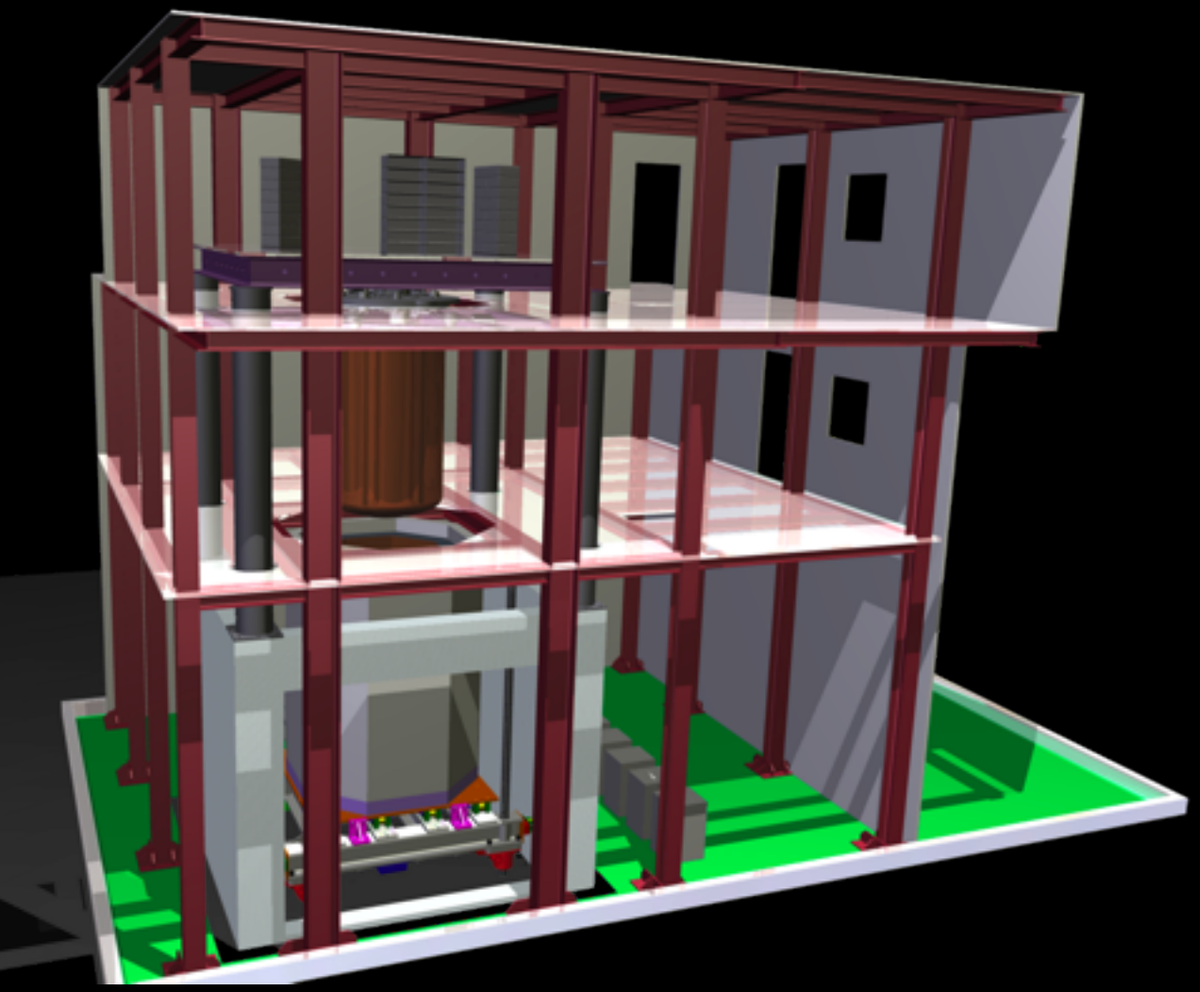


CUORE Design choices

- Dry cryostat
  - 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 ⌀ 1687 × h 3100, experimental volume ⌀ 900 × h 1370
- Large cold lead shielding surrounding the detector
- Heavy load support
  - detector ~ 1 tonne
  - lead 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

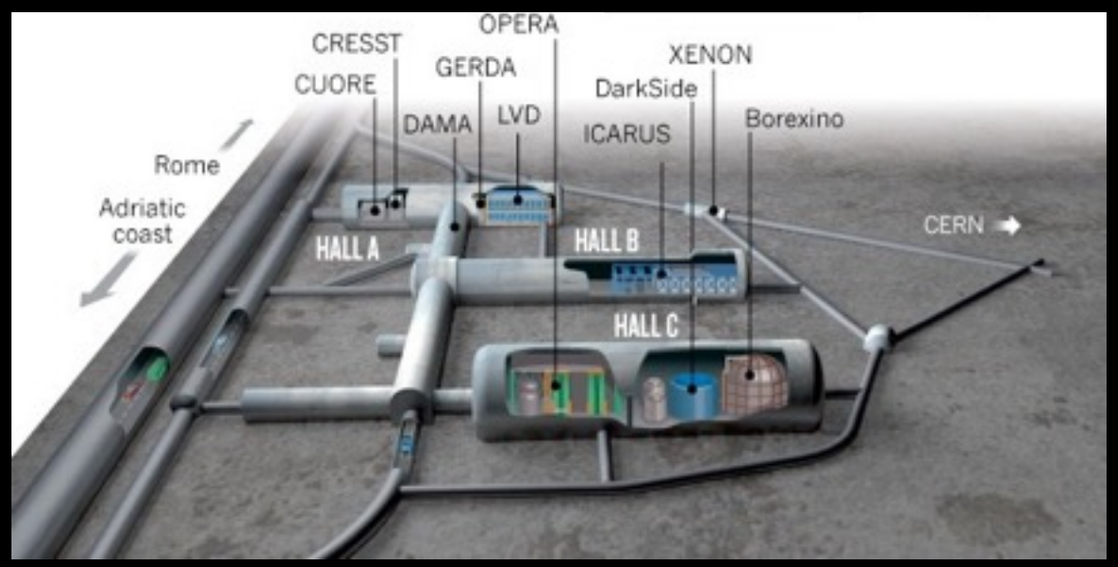


CUORE @ LNGS

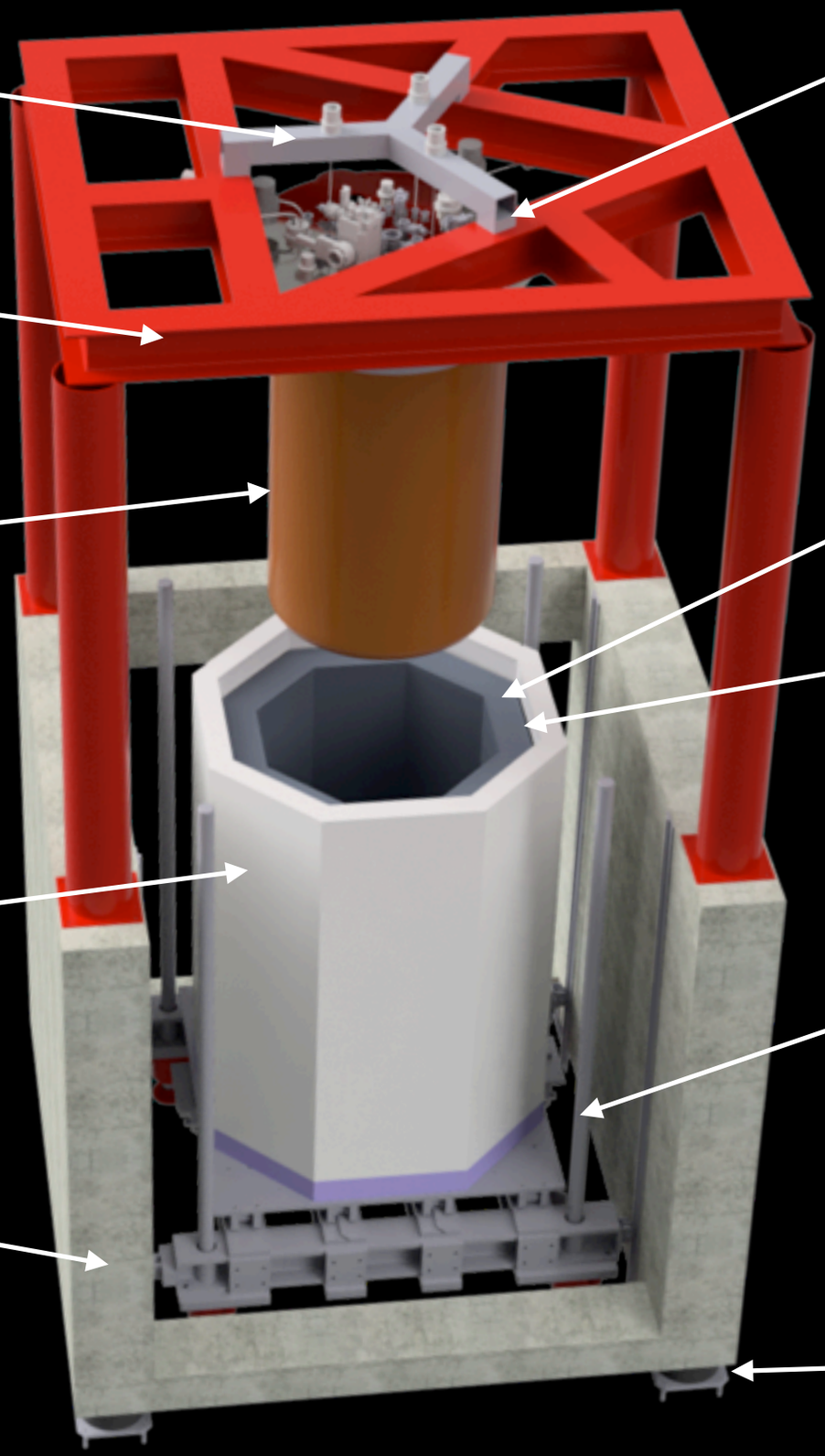


Three storey building

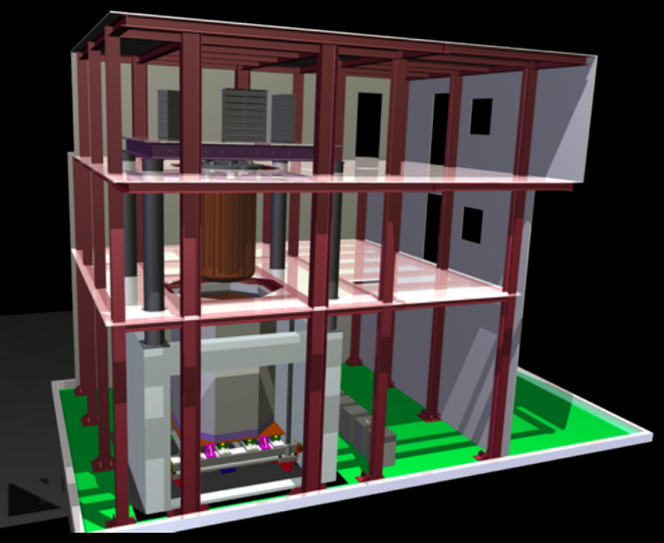
- Ground floor: pumps, compressors & shielding
- First floor: clean room (Gluing, Assembly & Cryostat)
- Second floor: service area, front-end & DAQ



Support structure



Hut



2007

March 2008

April 2008

May 2008

June 2008

May 2009

Detector components

The production of CUORE crystals started at SICCAS Jiading in 2008

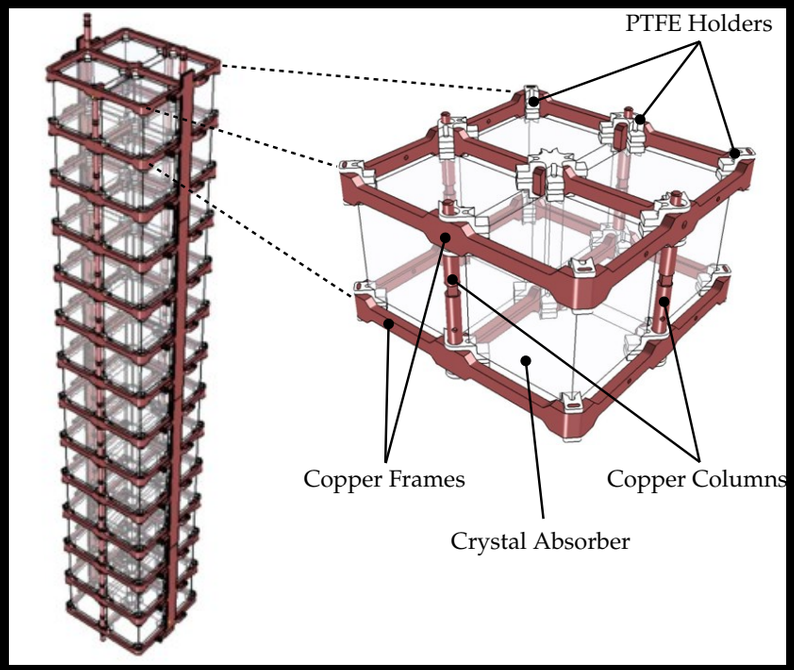
- selected raw materials
- periodical validation of detector performances and purity on samples from every production batch
- production rate of ~ 30 crystals/month

The copper used for the CUORE detector

- freshly casted NOSV copper from Norddeutsche Affinerie AG (now Aurubis AG)
- excellent radiopurity ($^{232}Th < 4.9\times10^{-13}$ g/g; $^{238}U < 5.3\times10^{-12}$ g/g)
- high thermal conductivity (RRR>400)
- low hydrogen content (at low T heat leak measured < 3.7 pW/g)

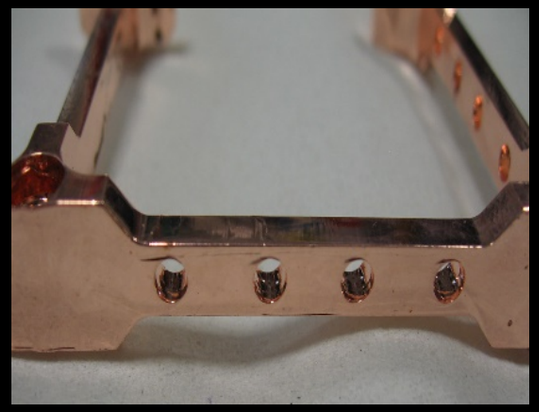
Machining, cleaning and storage were done with special care

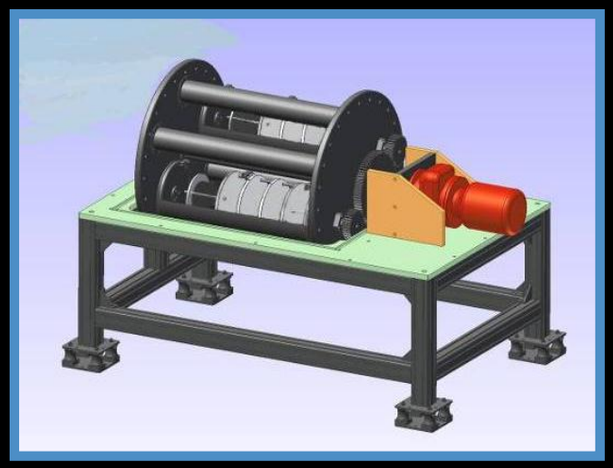
- frames were realized using Wire-EDM
- columns and other pieces we machined using selected tools and lubricants
- copper stored underground in every interval between machining and cleaning

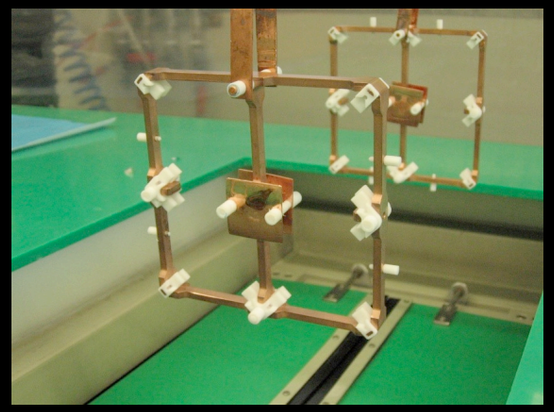


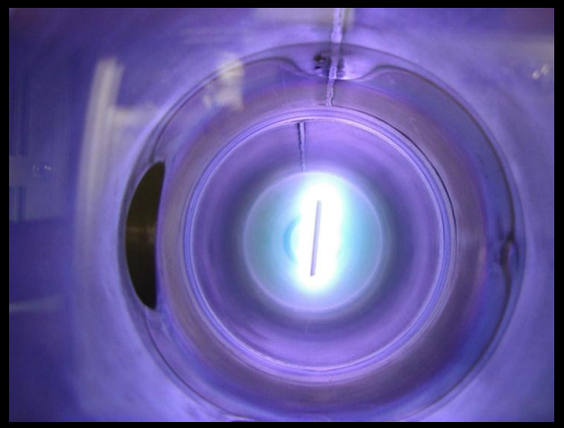
Copper ultra-cleaning

- Ultra-cleaning protocol developed at LNL using:
  - pre-cleaning
  - tumbling
  - electro-polishing
  - chemical etching
  - plasma cleaning
  - more than 8000 pieces have been ultra-cleaned to produce the 19 CUORE towers
- Final pieces stored underground in the CUORE PSA (Parts Storage Area) under N_2

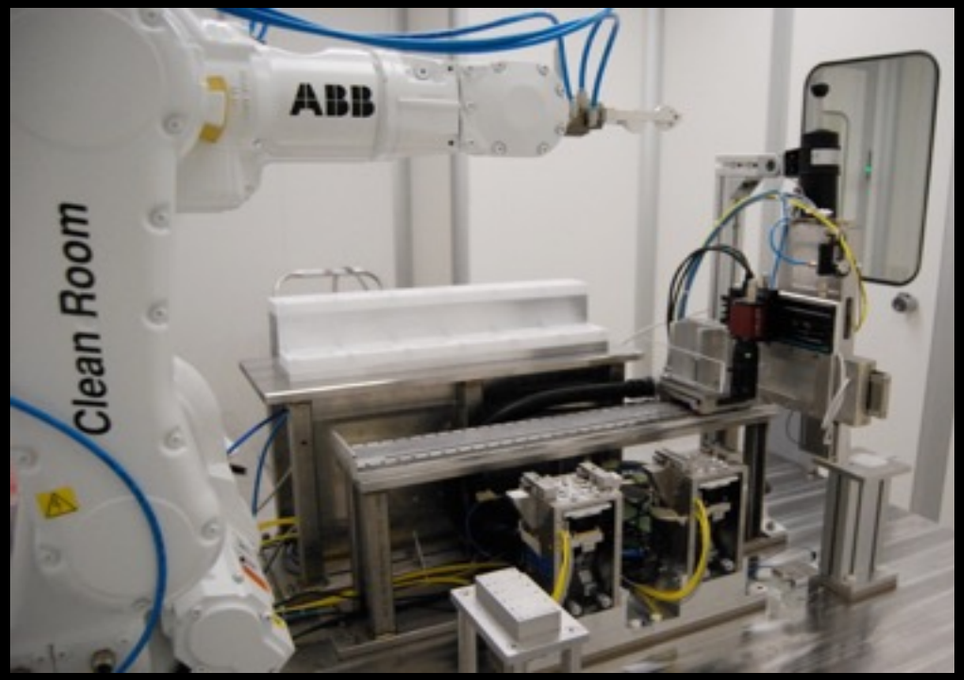


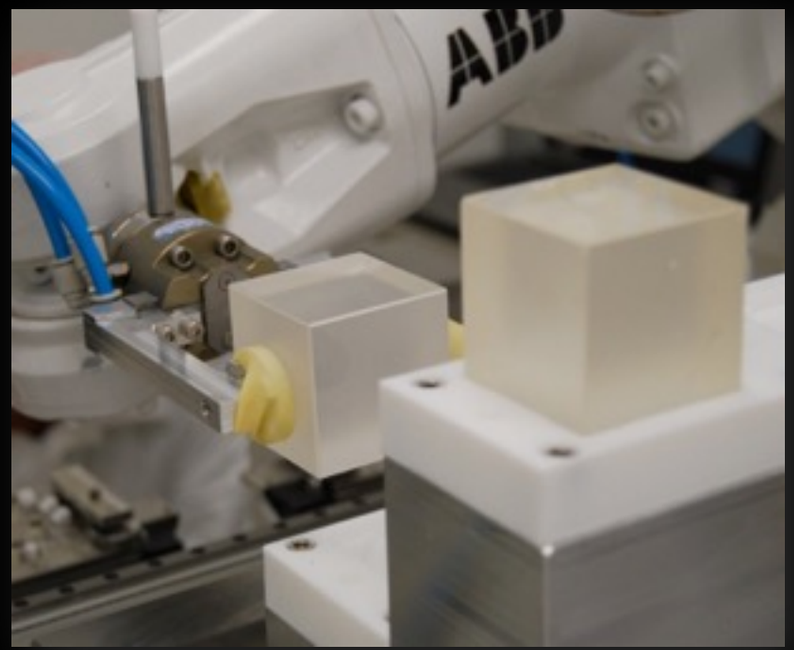




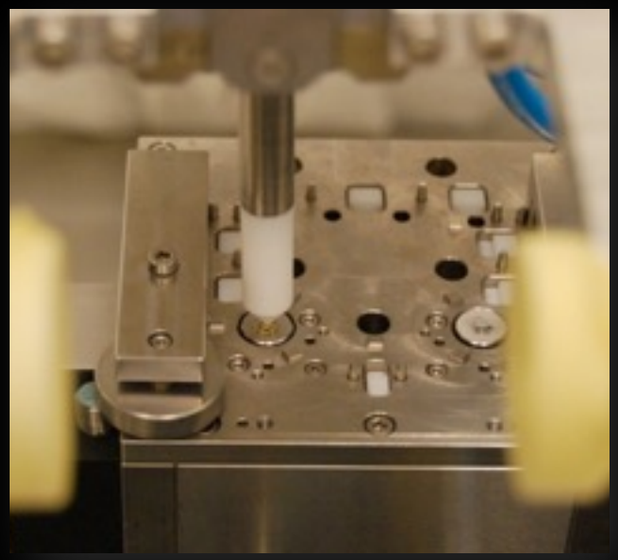


Sensor coupling

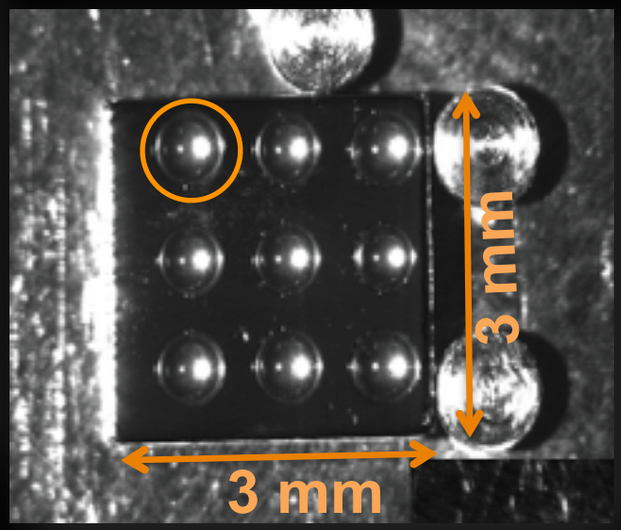


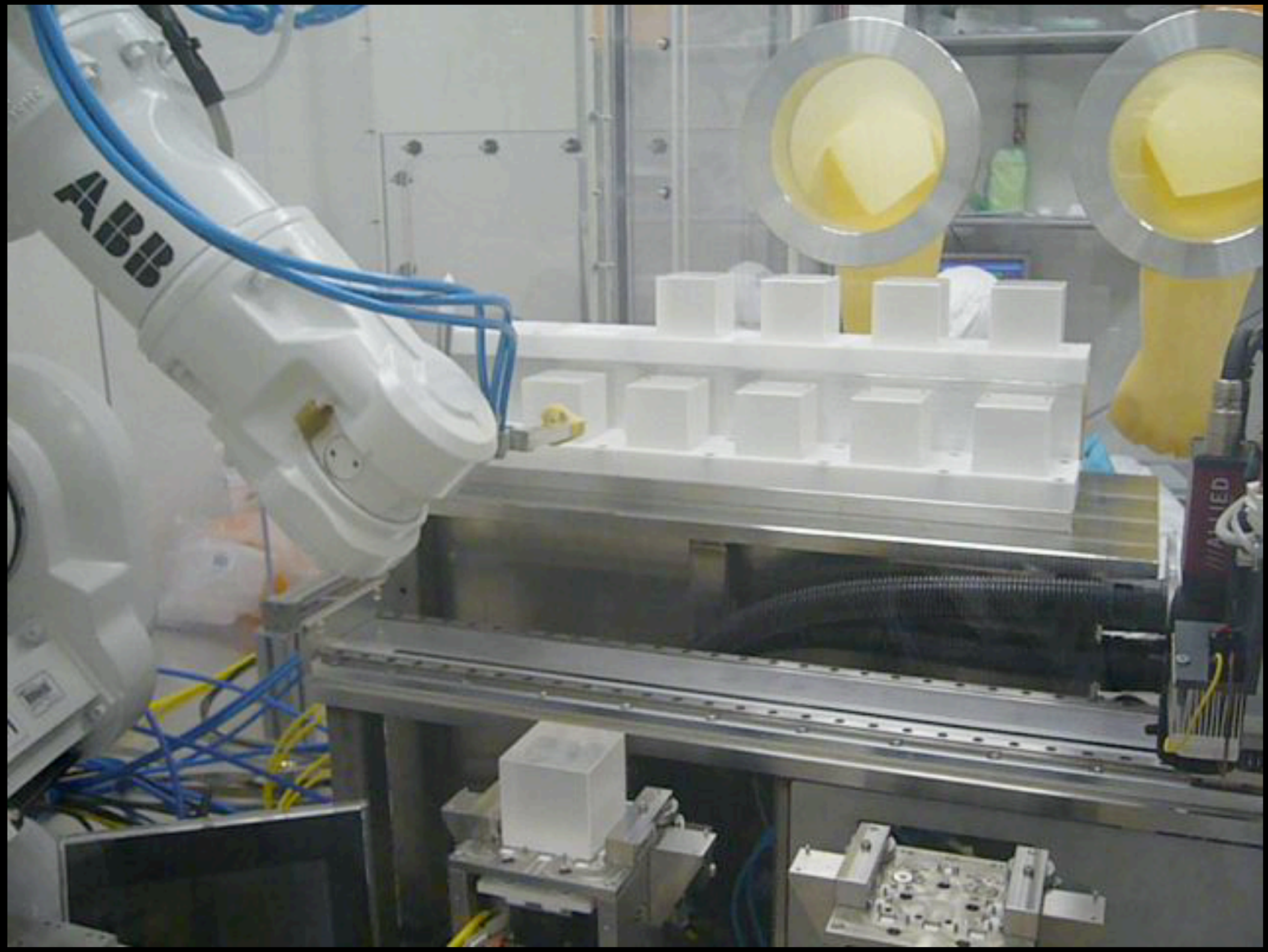


- The detector performances (e.g. energy resolution) are driven by the sensor-to-crystal coupling (glue spots).
- semi-automatic system
  - highly-reproducible
  - fully performed under N_2 atmosphere to minimize radioactive recontamination.



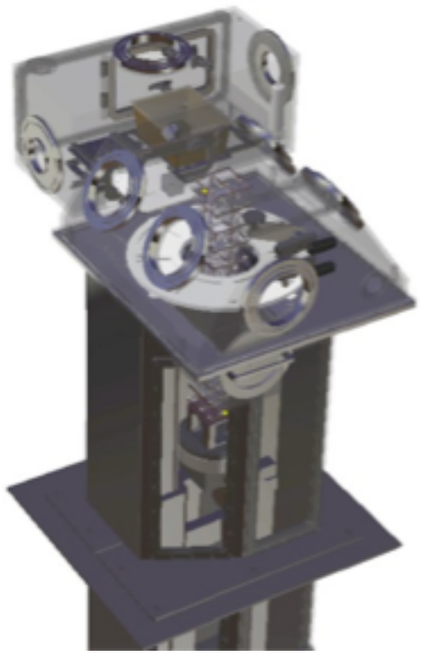
Thanks to M.D. Automazione



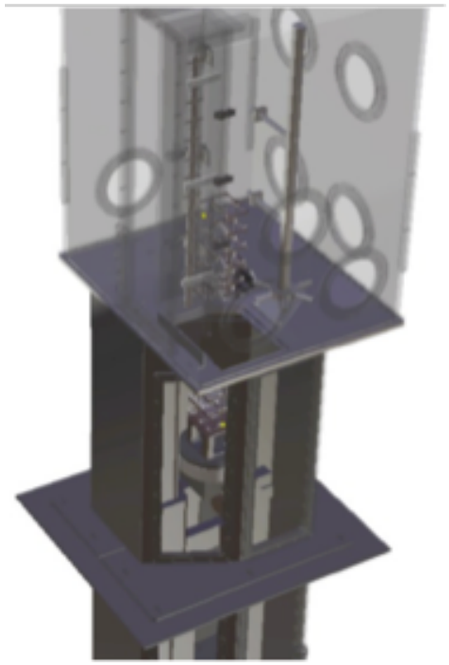


ABB

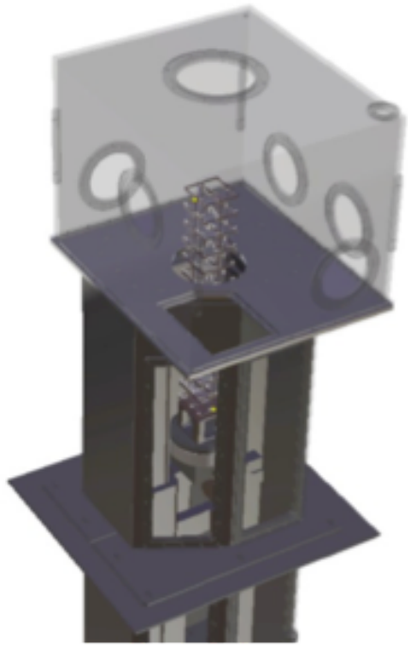
Detector assembly line



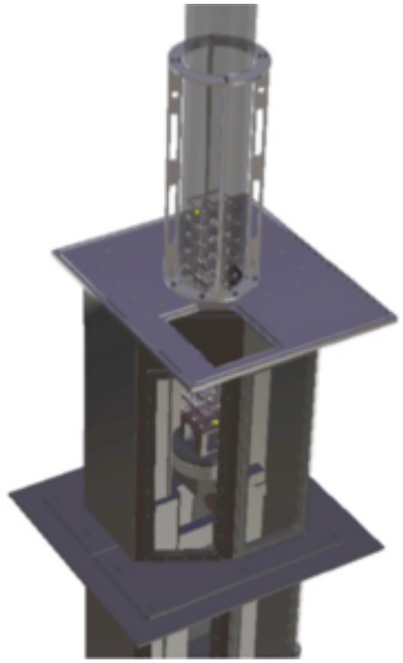
1. Assembly box



2. Cabling box



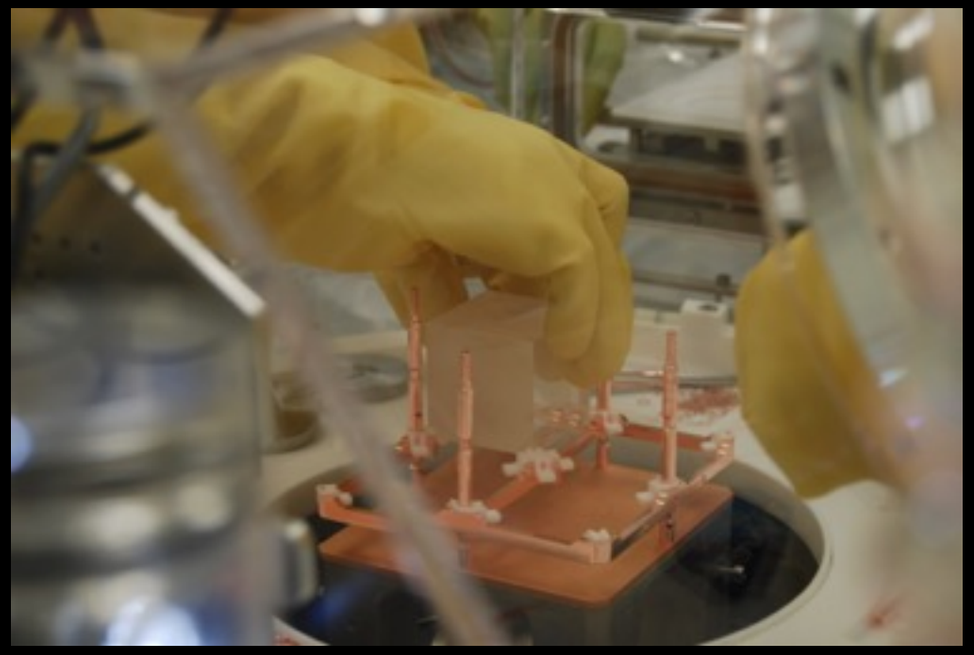
3. Bonding box

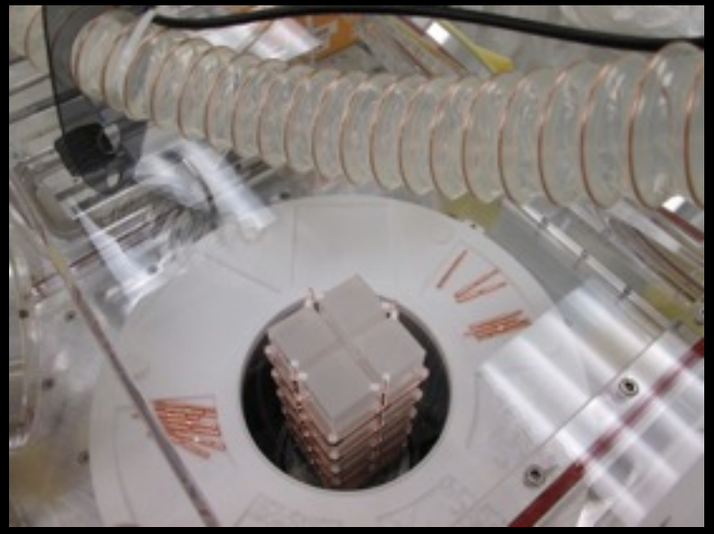


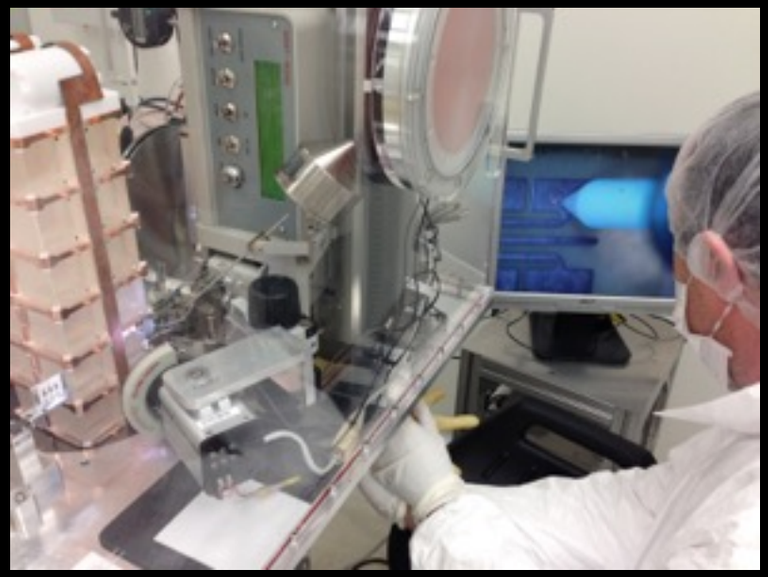
4. Storage box

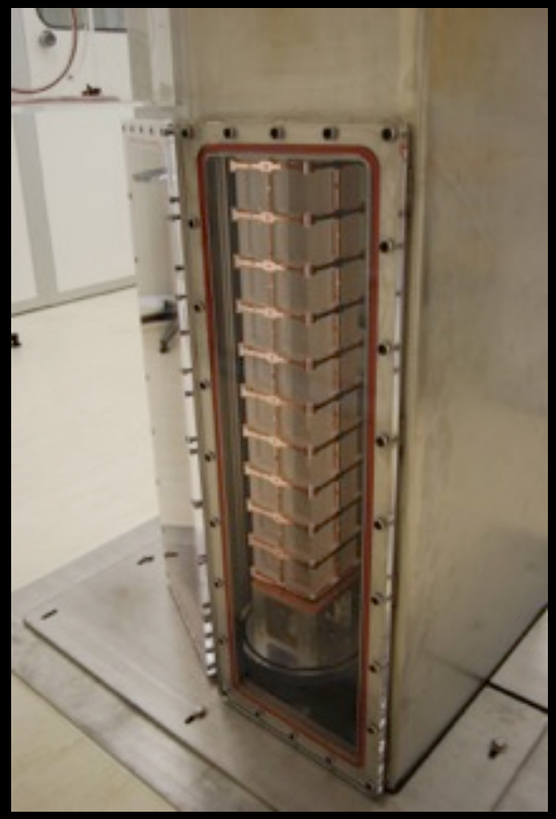
- Single workstation with 4 interchangeable glove boxes for specific tasks
- Transform ~ 10,000 components into 19 ultra-clean towers
  - fully performed under N_2 atmosphere to minimize radioactive recontamination.
  - strict control of materials
  - reproducible procedures

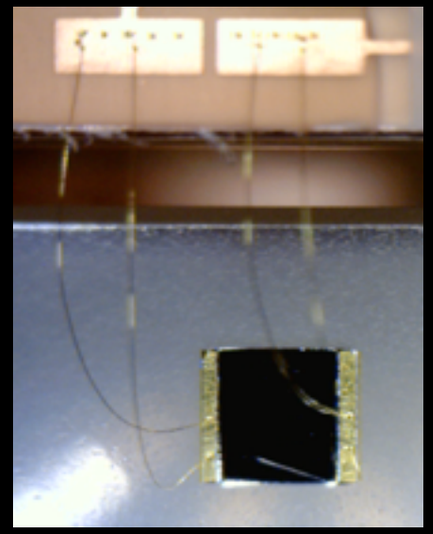
Detector assembly







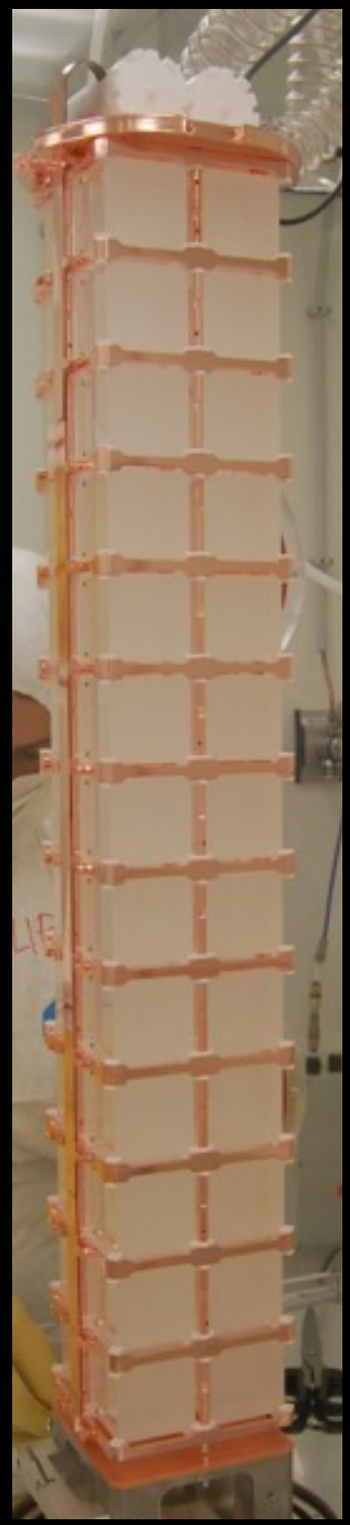




CUORE-0

CUORE-0 was the **first tower** produced out of the CUORE assembly line.

- 52 TeO_2 5x5x5 cm^3 crystals (~750 g each)
- 13 floors of 4 crystals each
- total detector mass: 39 kg TeO_2 (10.9 kg of ^{130}Te)



CUORE-0 has been taking data in the years 2013-2015

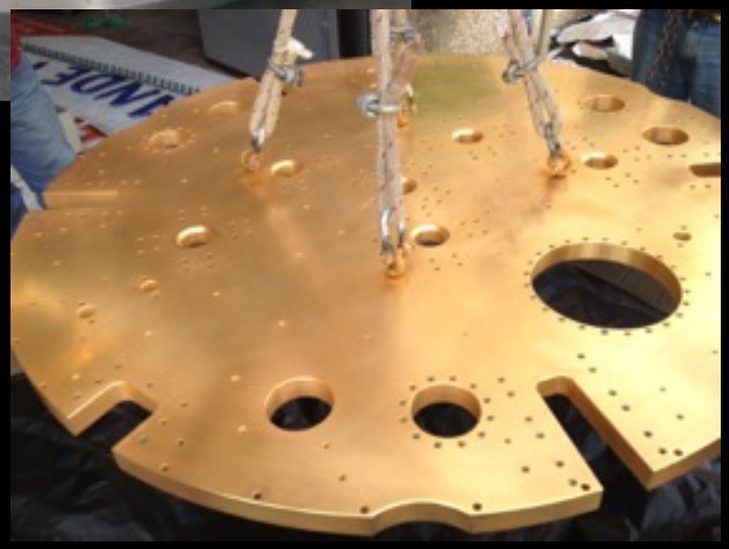
- Proof of concept of CUORE detector in all stages
- Test and debug of the CUORE tower assembly line
- Test of the CUORE DAQ and analysis framework

All the 19 CUORE towers

- Assembly of the 19 CUORE towers completed in 2014

Cryostat

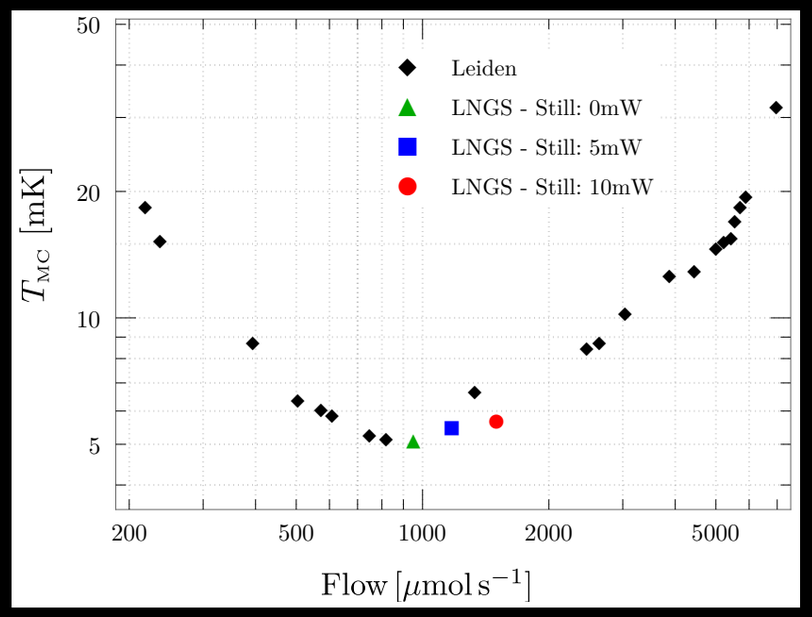
- Initial bid in 2015 to realise the full cryogenic system
  - Soon we realised that was a too complex object and we started to design the cryostat by ourself
- The cryostat is composed by 6 nested vessels at decreasing temperature
  - 300K, 40K, 4K, 0.6 K, 50 mK, 10 mK

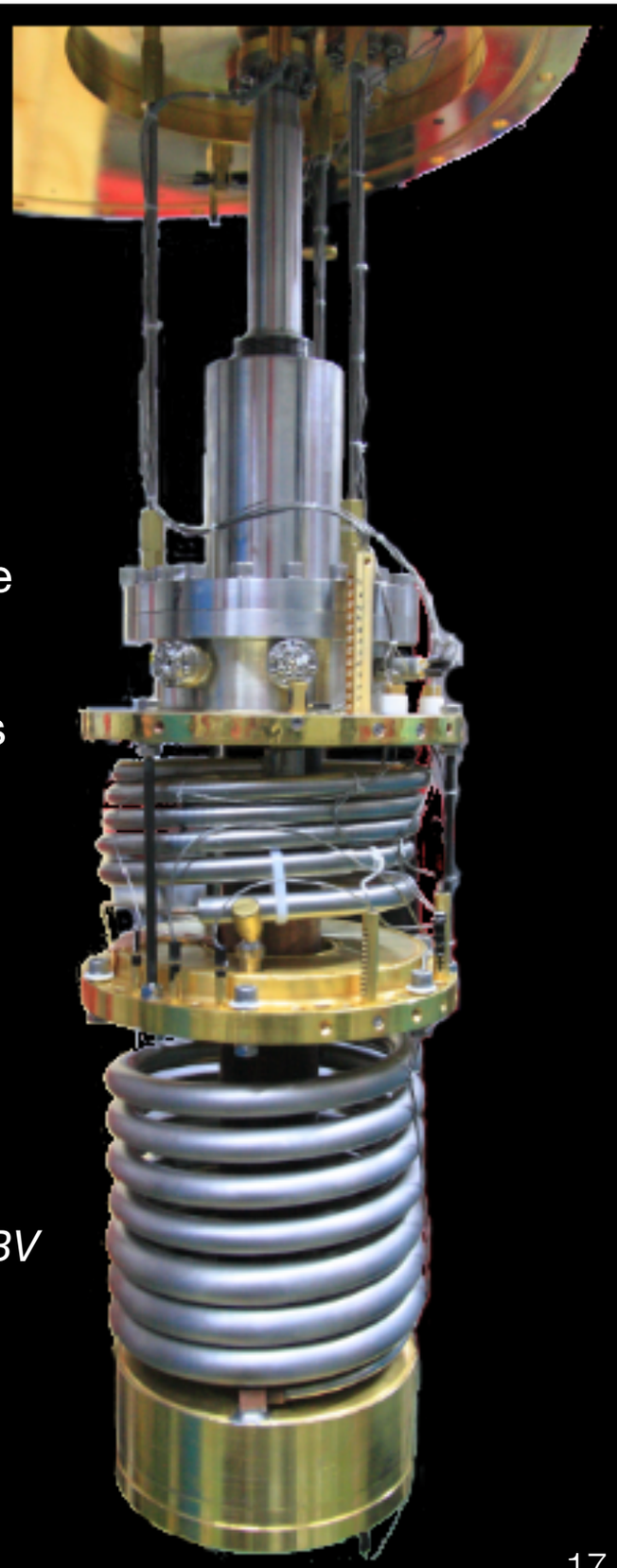


Thanks to Simic S.p.A.

Dilution Unit

- Custom ^{3}He/^{4}He Dilution Unit built by Leiden Cryogenics BV
- Specs:
  - 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
  - dry DU with the largest power ever built!

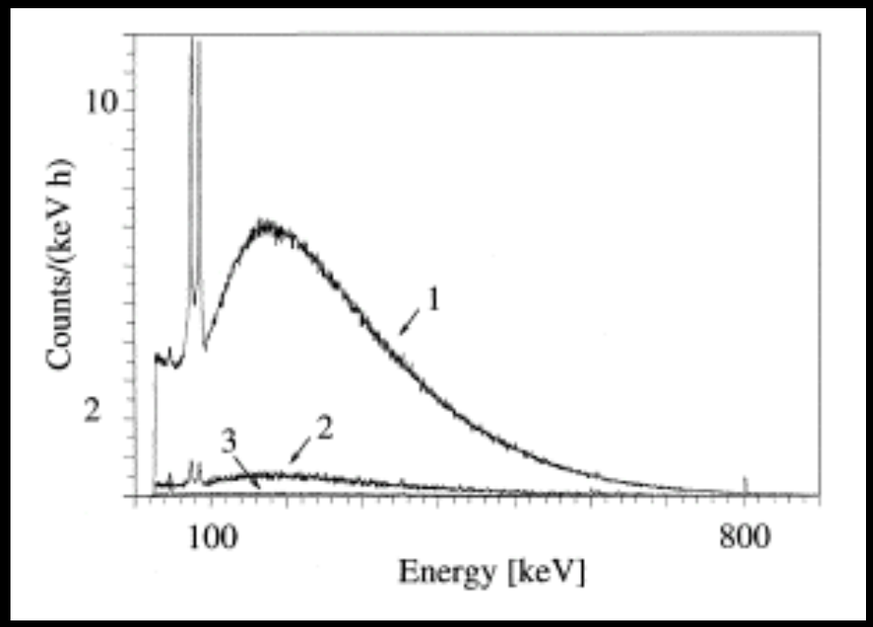




Thanks to Giorgio Frossati & Leiden Cryogenics BV

Roman lead shielding

- Lead is an excellent material for shielding (high Z)
- Normally it contains ^{210}Pb with 10-1000 Bq/kg (half life ~ 22 y)
- Ingots from a shipwreck found close to Sardinia coast (I sec b.C.)
- Romans extracted the Ag from the Pb (and ^{238}U with it)
  - ^{210}Pb in roman Pb < 4 mBq/kg



- Ancient Roman Pb is extremely precious!
  - agreement with the cultural heritage authorities
  - we had to preserve the external part of the ingots
  - casting done in N_2 atmosphere with a clean SS mould
  - machining with selected tools and liquids

Roman lead shielding

- Shield 6 cm thick (4.5 tonnes of Pb + 1 tonne of Cu)
  - realised in ring sectors with dovetail design to minimise holes
  - rings interleaved with copper foils to improve thermalization
  - mechanically attached to the Still plate (~0.8 K) but thermalized @ 4K

Thanks to MTH Metalltechnik Halsbrücke GmbH & Co KG

Commissioning plan

Insertion of few TeO_2 detectors

Cryostat
+
Dilution Unit

Wiring

Top Pb shield
Detector Calibration System
Towers support plate
Fast Cooling System

side roman Pb shield

Thanks to Low Temperature Solutions UG

Coldest m^3

- After the successful completion of the cryostat+DU integration we got a nice press release

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21 October 2014 http://www.interactions.org
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Source: INFN
Content: Press Release
Date Issued: 21 October 2014
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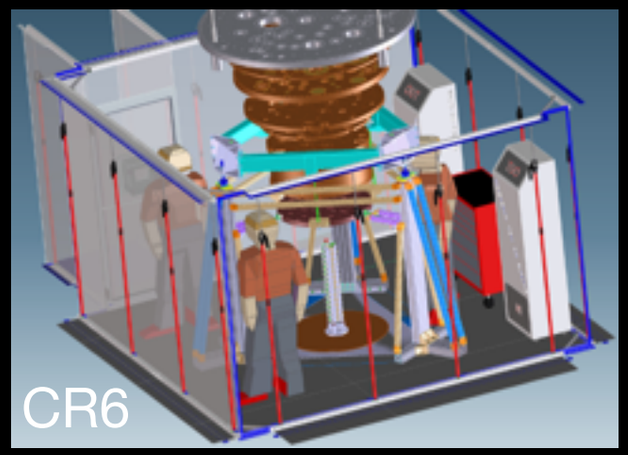
CUORE: The Coldest Heart in the Known Universe

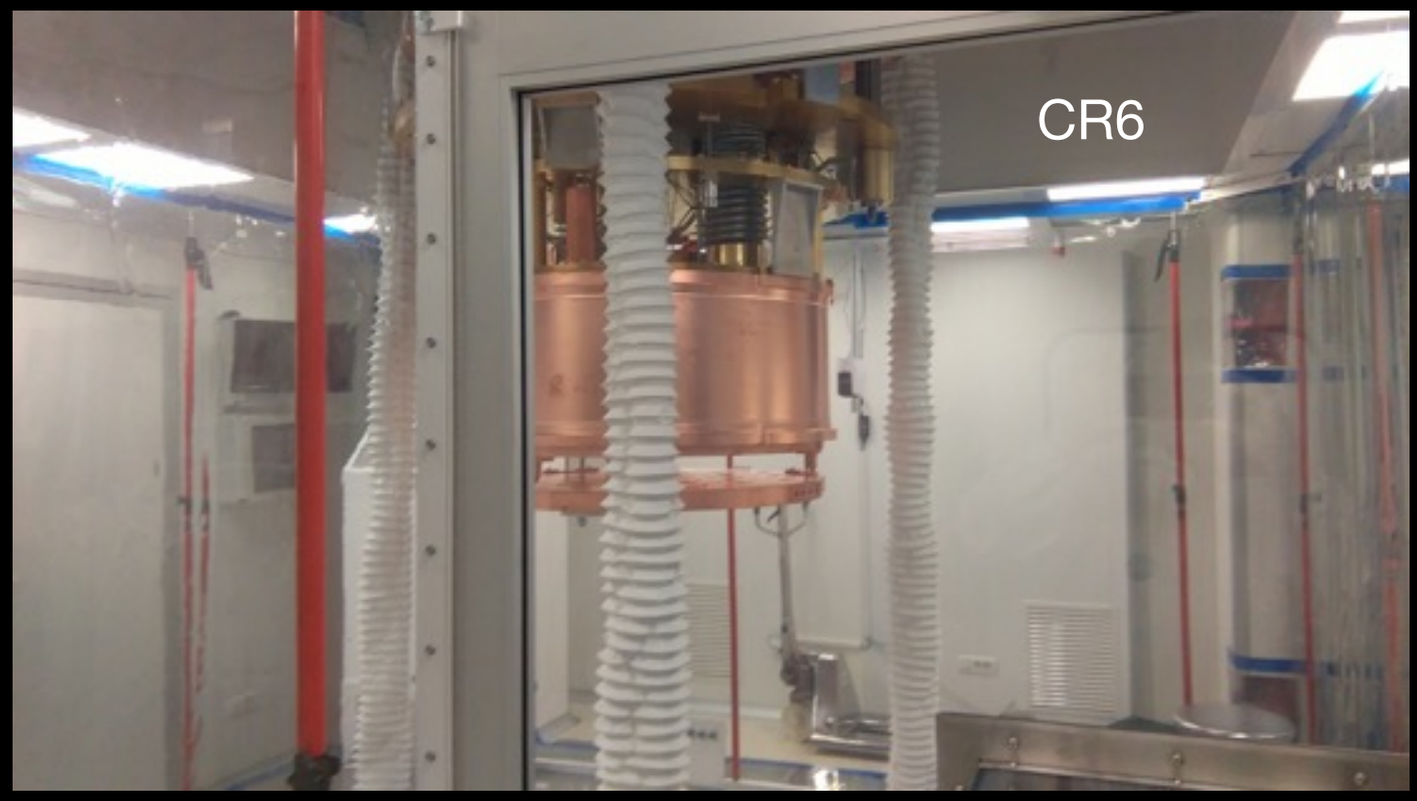
The CUORE collaboration at the INFN Gran Sasso National Laboratory has set a world record by cooling a copper vessel with the volume of a cubic meter to a temperature of 6 milliKelvins: it is the first experiment ever to cool a mass and a volume of this size to a temperature this close to absolute zero (0 Kelvin). The cooled copper mass, weighing approx. 400 kg, was the coldest cubic meter in the universe for over 15 days.

CUORE is an international collaboration involving some 130 scientists mainly from Italy, USA, China, Spain, and France. CUORE is supported by the Istituto Nazionale di Fisica Nucleare (INFN) in Italy; the Department of Energy Office of Science (Office of Nuclear Physics), the National Science Foundation, and Alfred P. Sloan Foundation in the United States.

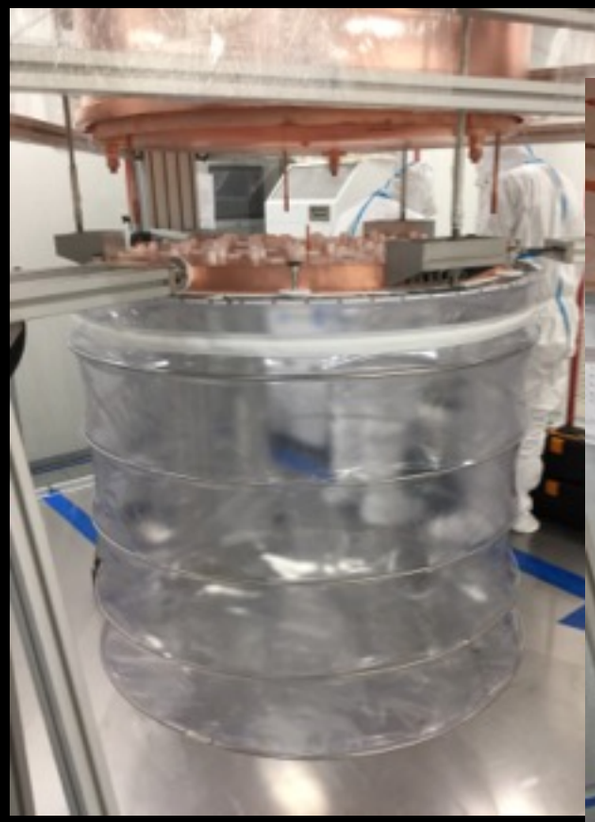
Detector installation

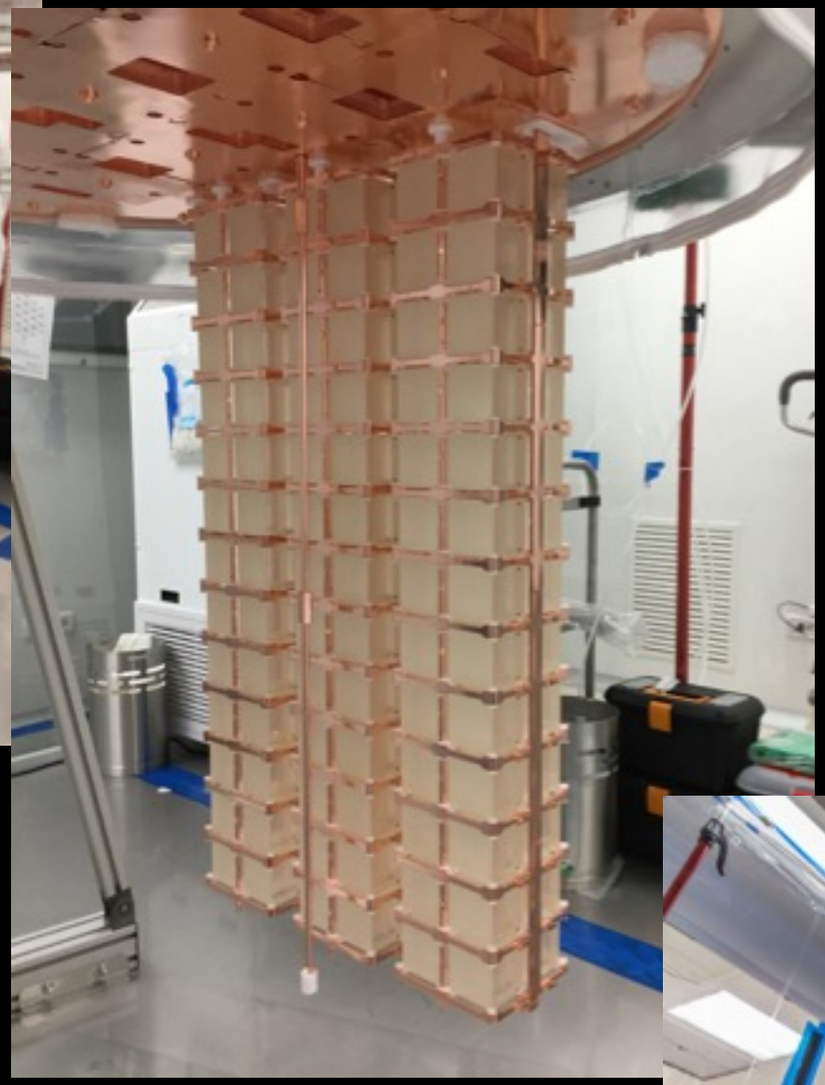


- The detector installation was the first period in which the detector was exposed to (Rn-free) air
- Radon Abatement System: provides 150 m^3/h of air with Rn concentration <0.01 Bq/m^3
- CR6: Custom-made clean room flushed with Rn-free air (Rn concentration inside CR6 <0.1 Bq/m^3)
- Detector “protective bag” flushed with nitrogen during installation interruptions
- Strict installation protocol



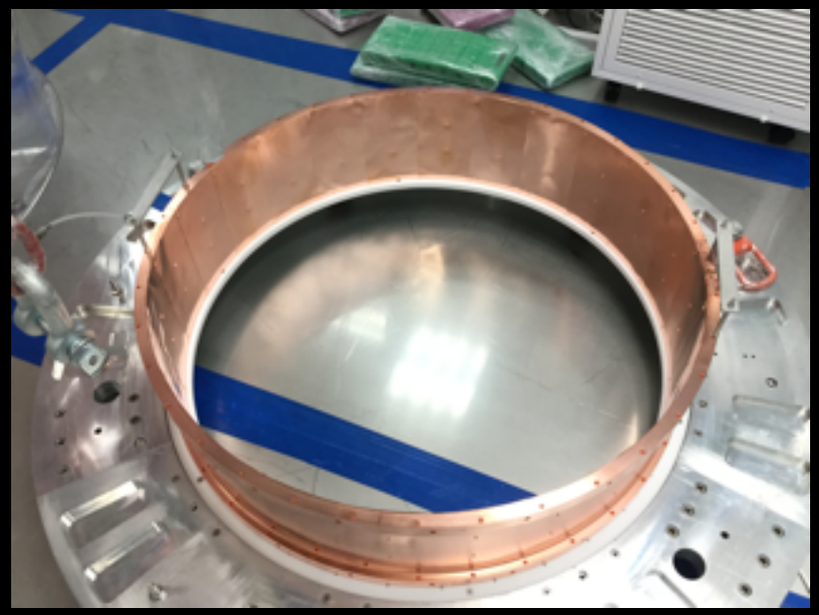
Detector installation

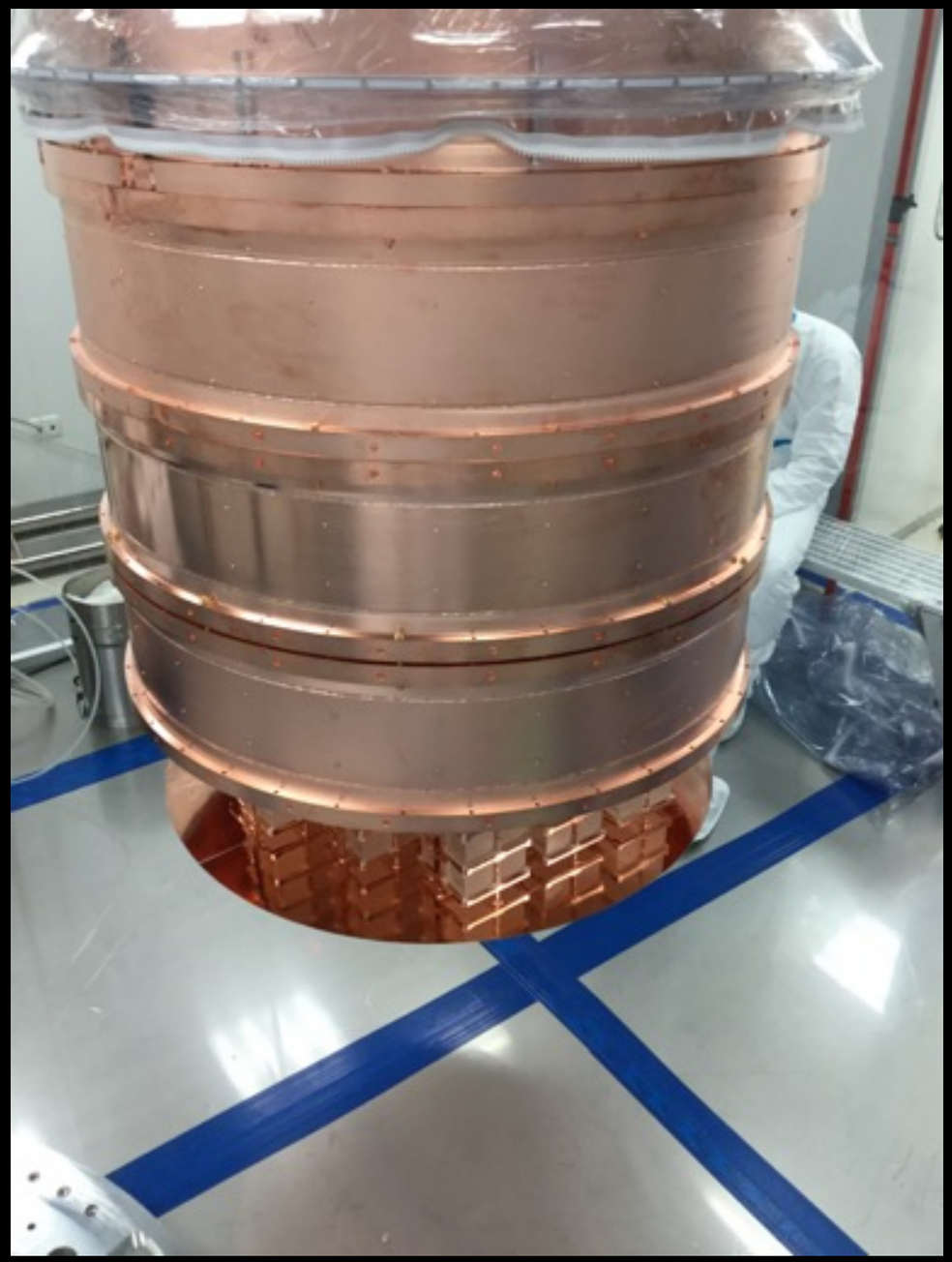




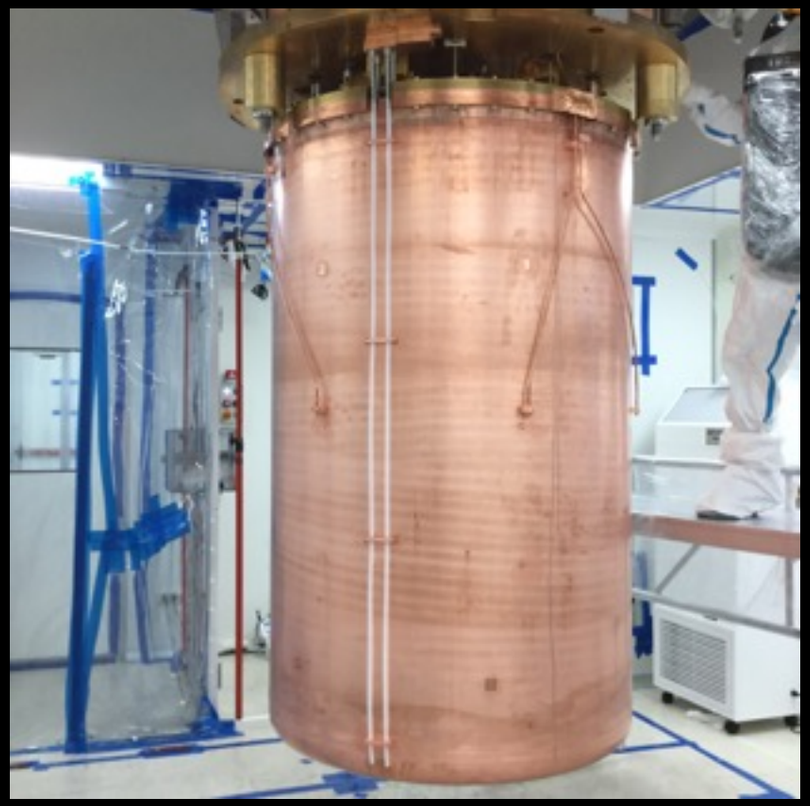
- Detector installation completed on August 26, 2016

Cryostat closure

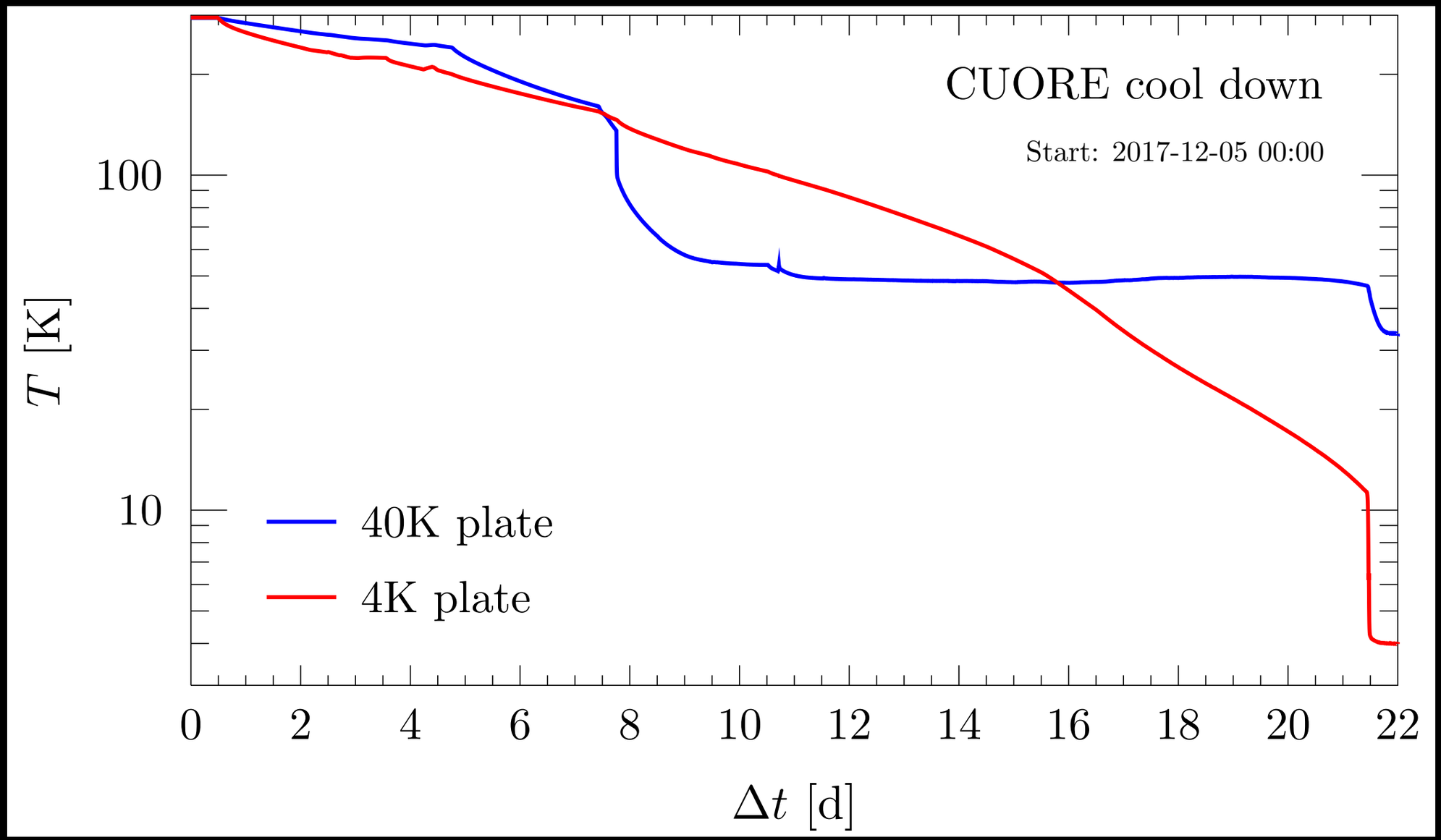




Cryostat closure

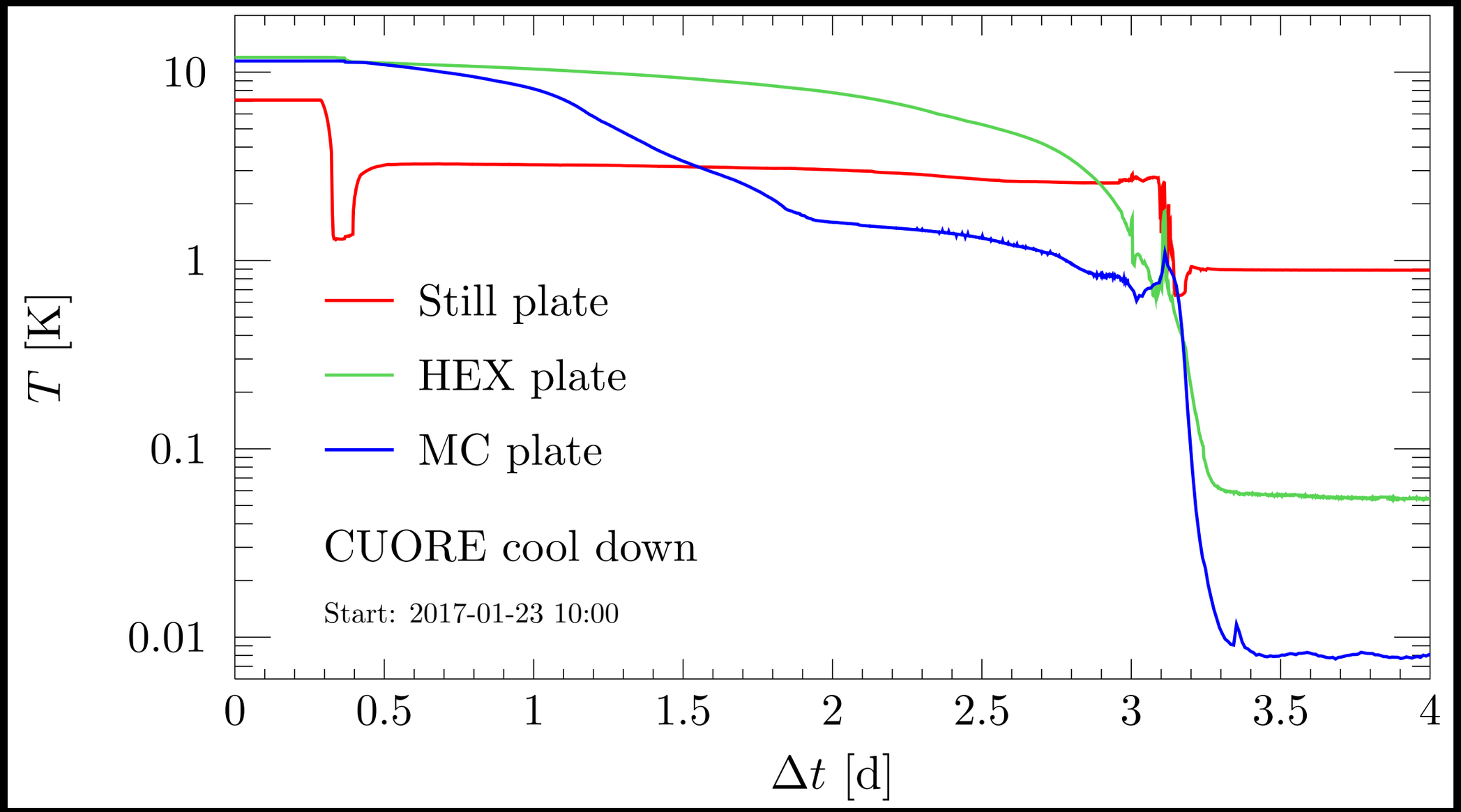


CUORE cooldown



- Cooldown time to 4K: ~ 22 days
- 1st stage T: ~ 35 K
- 2nd stage T: ~ 3.4 K
- Enthalpy removed: ~ 1 GJoule

CUORE cooldown



- Cooldown time to base T: ~ 3 days
- Temperature reached: 6.7 mK

Happy ending…

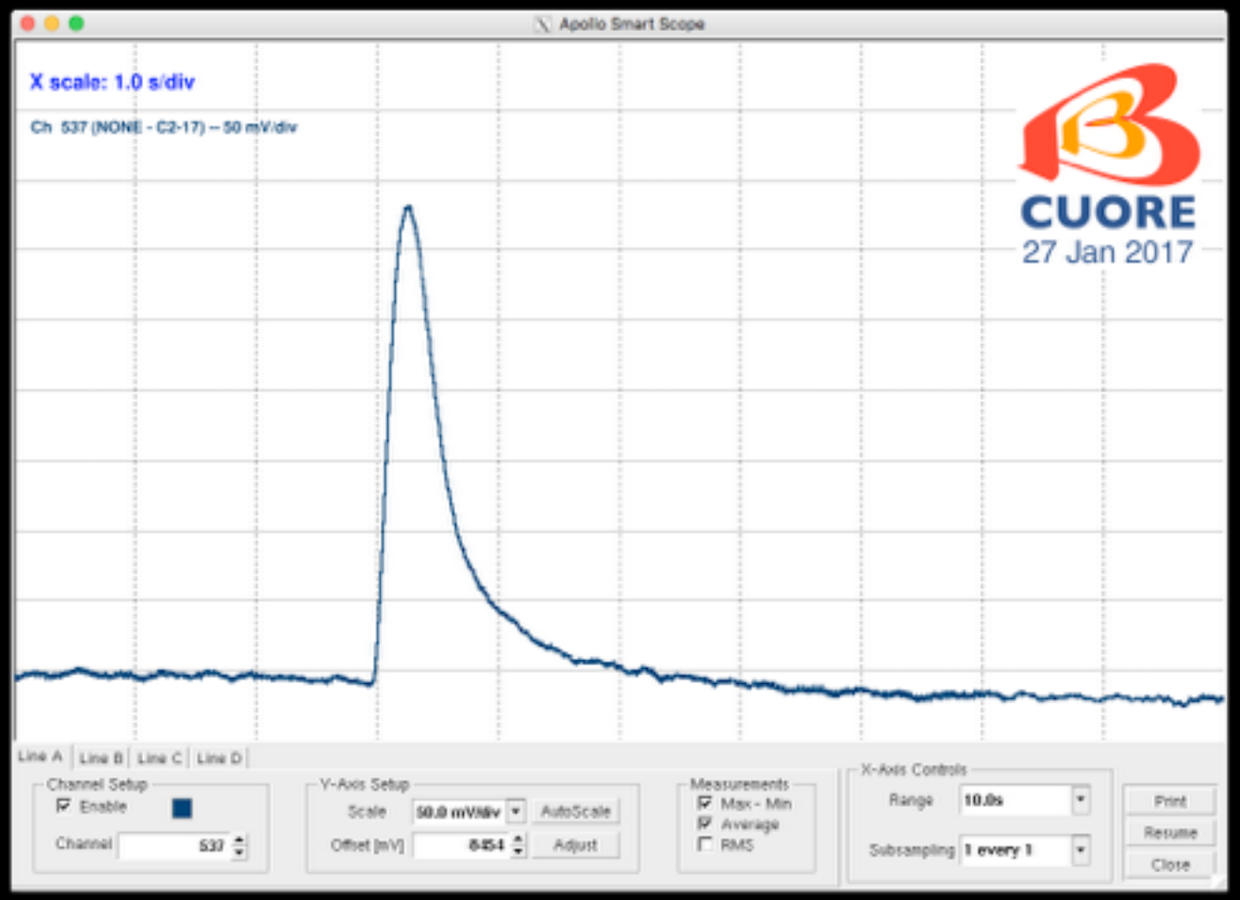
- After more than 10 years the CUORE construction and commissioning is completed

- The cryostat is working spectacularly well

- 984/988 working detectors

- This unprecedented challenge required an incredible effort in different physics fields in order to match the stringent experiment requirements

… and a good start



- First particle event seen on 27 Jan 2017

- After a campaign of noise optimisation and detector characterisation we started to collect physics data

- The first CUORE physics results have been just submitted to PRL