CUORE

O.Cremonesi
INFN - Sez. Milano Bicocca

The US-Italy Physics Program @ LNGS - October 15, 2013 - Princeton NJ

Outline

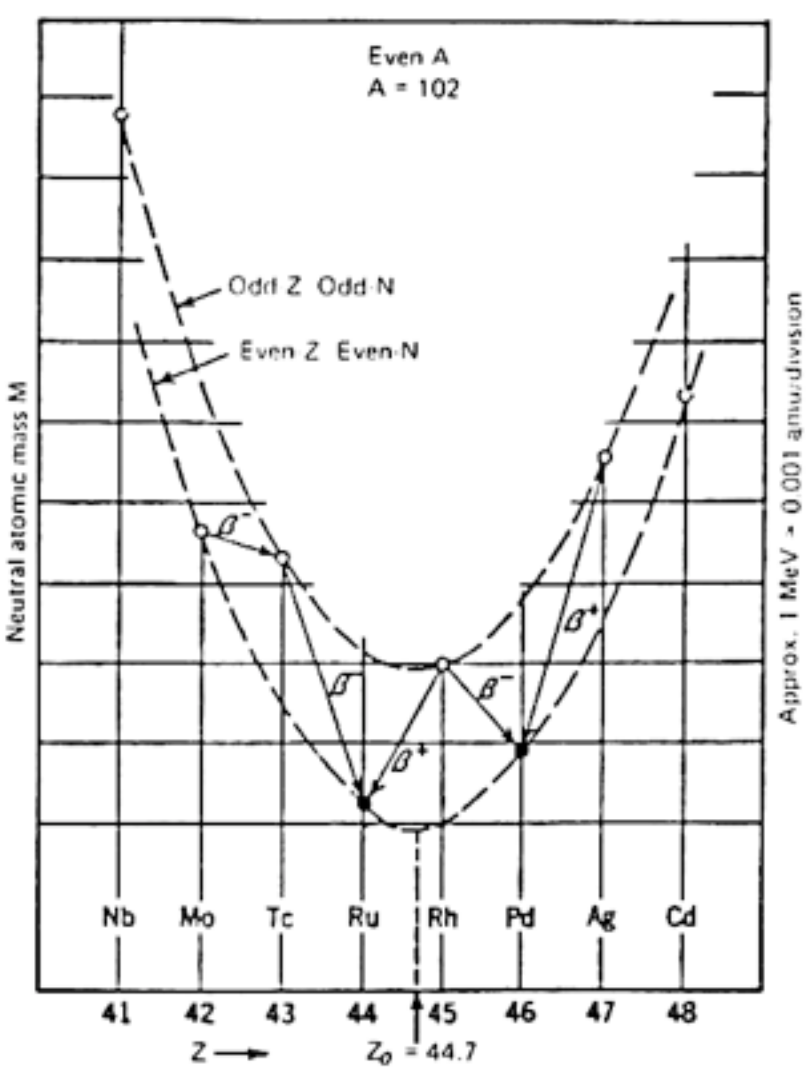
- Neutrinoless double beta decay
- Low temperatute detectors (LTD)
- *The CUORE project*
- *CUORE0*
- *CUORE status*
- Conclusions

Double beta decay

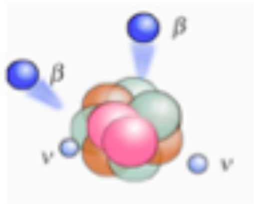
Very rare nuclear decay

(A,Z) → (A,Z+2) + 2e- (+?)

which can occurr according in different modes

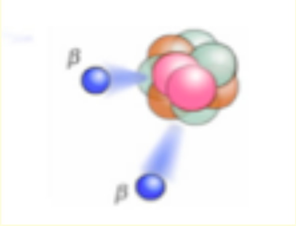


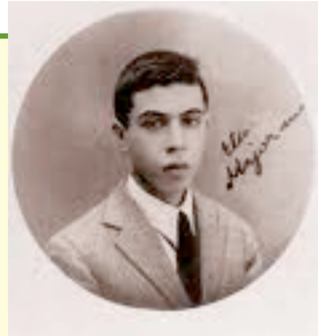
2νββ decay:



- allowed within Standard model,
  - 2nd order process in Fermi theory
- observed for 12 isotopes:
  - ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128,130}Te, ^{136}Xe, ^{150}Nd and ^{238}U
- First double beta plus decay: ^{130}Ba
- **$T^{2\nu\beta\beta}_{1/2} \sim 10^{(19-25)}$ y**
- Important constraint for nuclear matrix element calculation

0νββ decay (neutrinoless DBD):





→ violates lepton number by 2 units

→ Current bounds:

- $T^{0\nu\beta\beta}_{1/2} > \sim 10^{25}$ y
- $m_\nu \leq O(\mathbf{0.1 - 0.5})$ eV

→ Observation implies Physics beyond the standard model of particle physics

"Exotic" decays:

→ for example X = J, i.e. Majoron

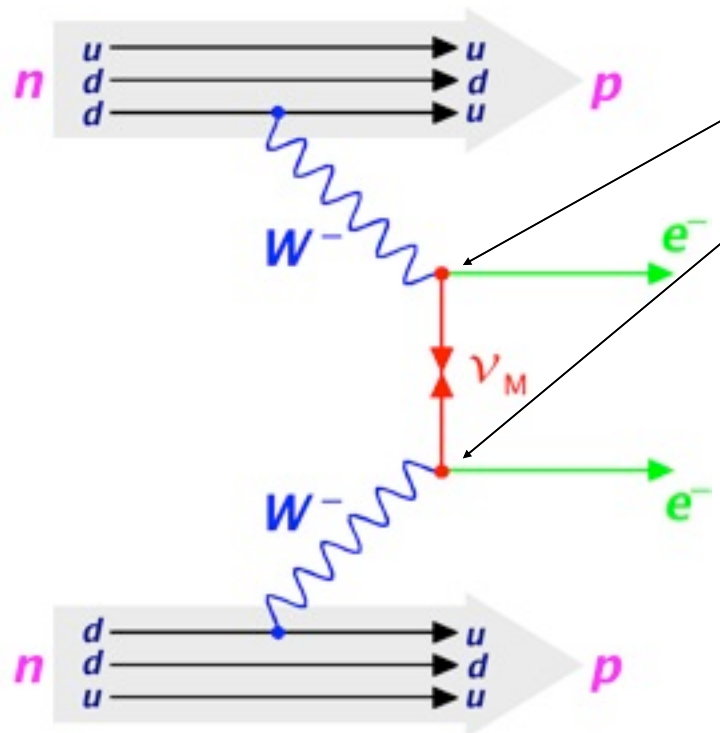
→ experimentally not observed (and no rumours!)

→ Best limit from:

$\tau^{\beta\beta J}_{1/2}(^{128}\mathrm{Te}) > \sim$ few 10^{24} y

Neutrinoless bouble beta decay

Exchange of a light Majorana neutrino



RH antineutrino (L=1) is emitted at one vertex
LH neutrino (L=-1) is absorbed at the other vertex

- **Majorana particle**
- **Helicity flip (neutrino mass dependence)**

Half lifetime can be expressed as

$$\lambda_{0\nu} = \frac{1}{\tau_{0\nu}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{\langle m_{ee}\rangle^2}{m_e^2}$$

F_N: Nuclear Factor of merit

PHASE SPACE FACTOR — NME — EFFECTIVE MAJORANA MASS

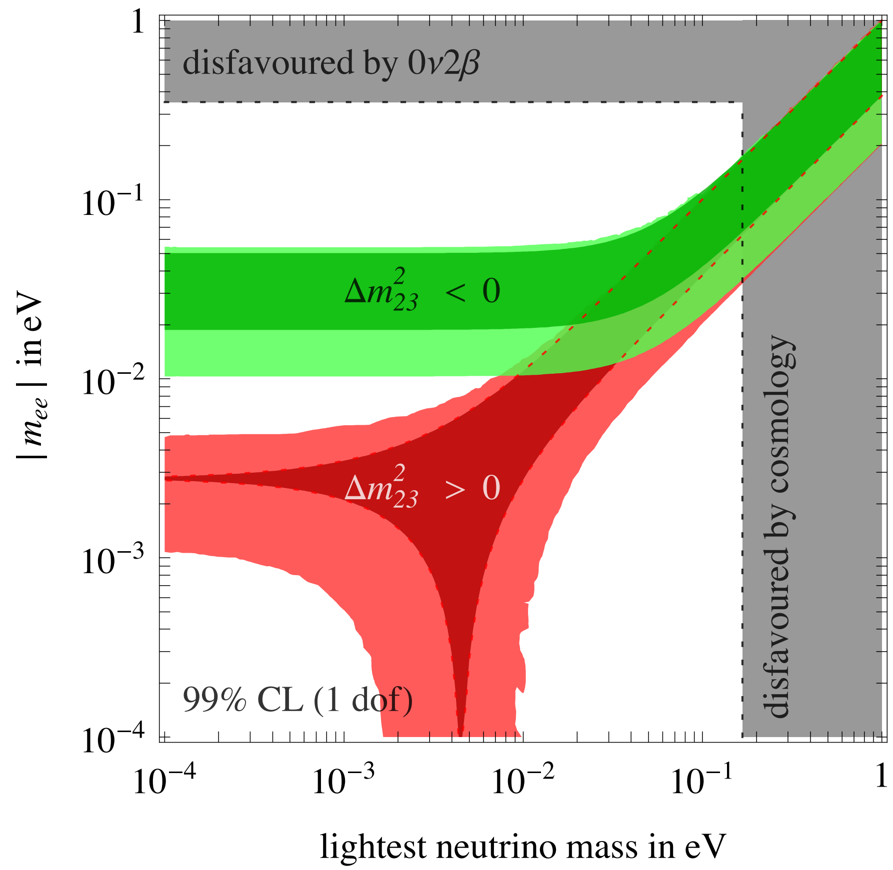
$$< m_{ee} >= \sum_k U_{ek}^2 m_k$$

NEUTRINO MIXING MATRIX — NEUTRINO MASS EIGENALUES

$$= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

N.B.: Majorana phases make m_{ee} cancellation possible (**m_{ee}** could be smaller than any of the **m_i**).

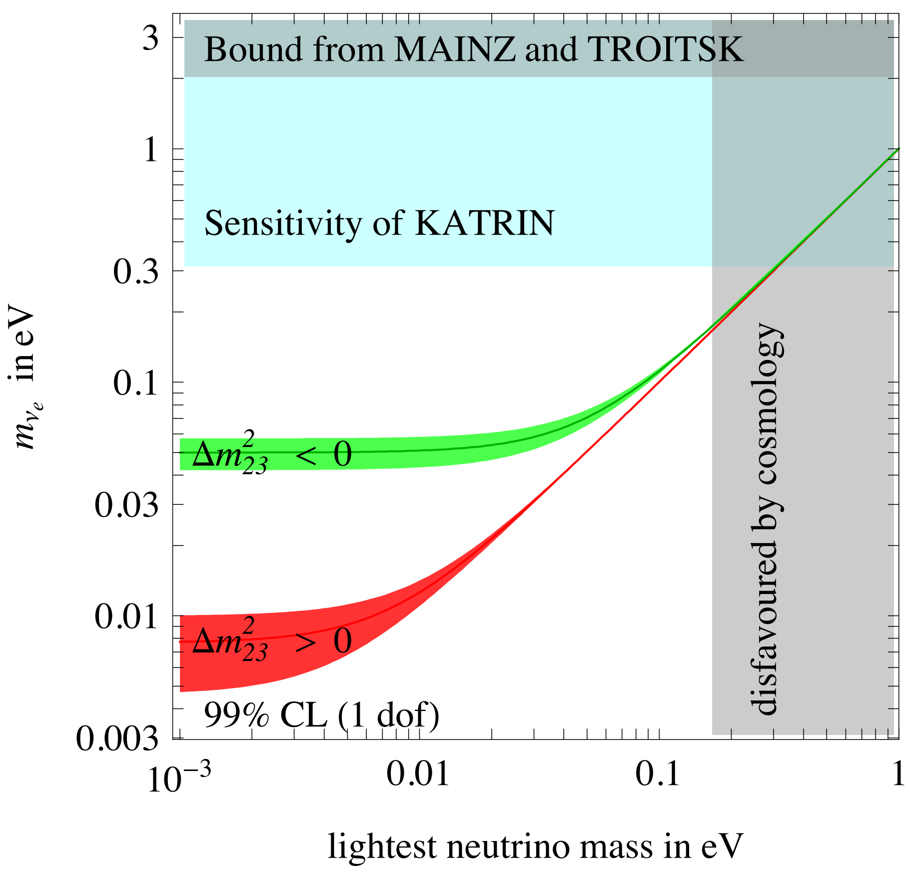
mν: Experimental methods

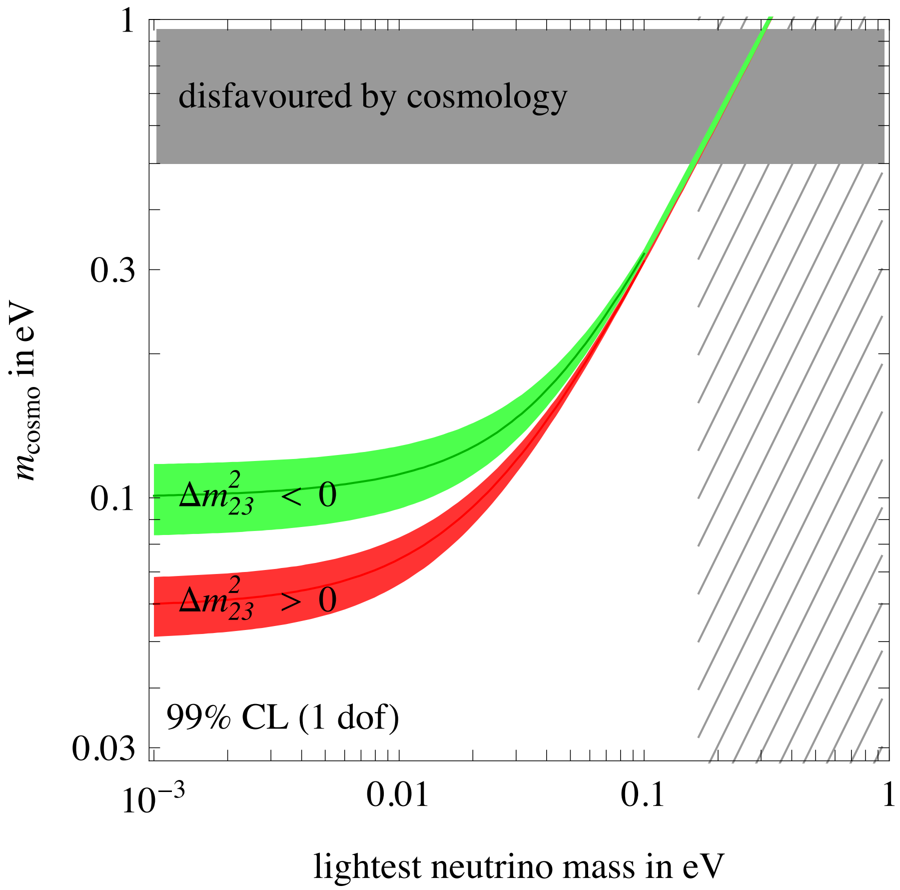


Experimental parameters are pictured as a function of the lightest mass eigenvalue:

- --- **Normal Hierarchy**
- --- **Inverted Hierarchy**

Bands arise from specific experimental and theoretical uncertainties)





- S.Pascoli et al., arXiv: 0505226
- R.Mohapatra et al., arXiv: 0510213
- A.Strumia and F.Vissani, IFUP-TH/2004-1; arXiv: 0606054

Experimental signature

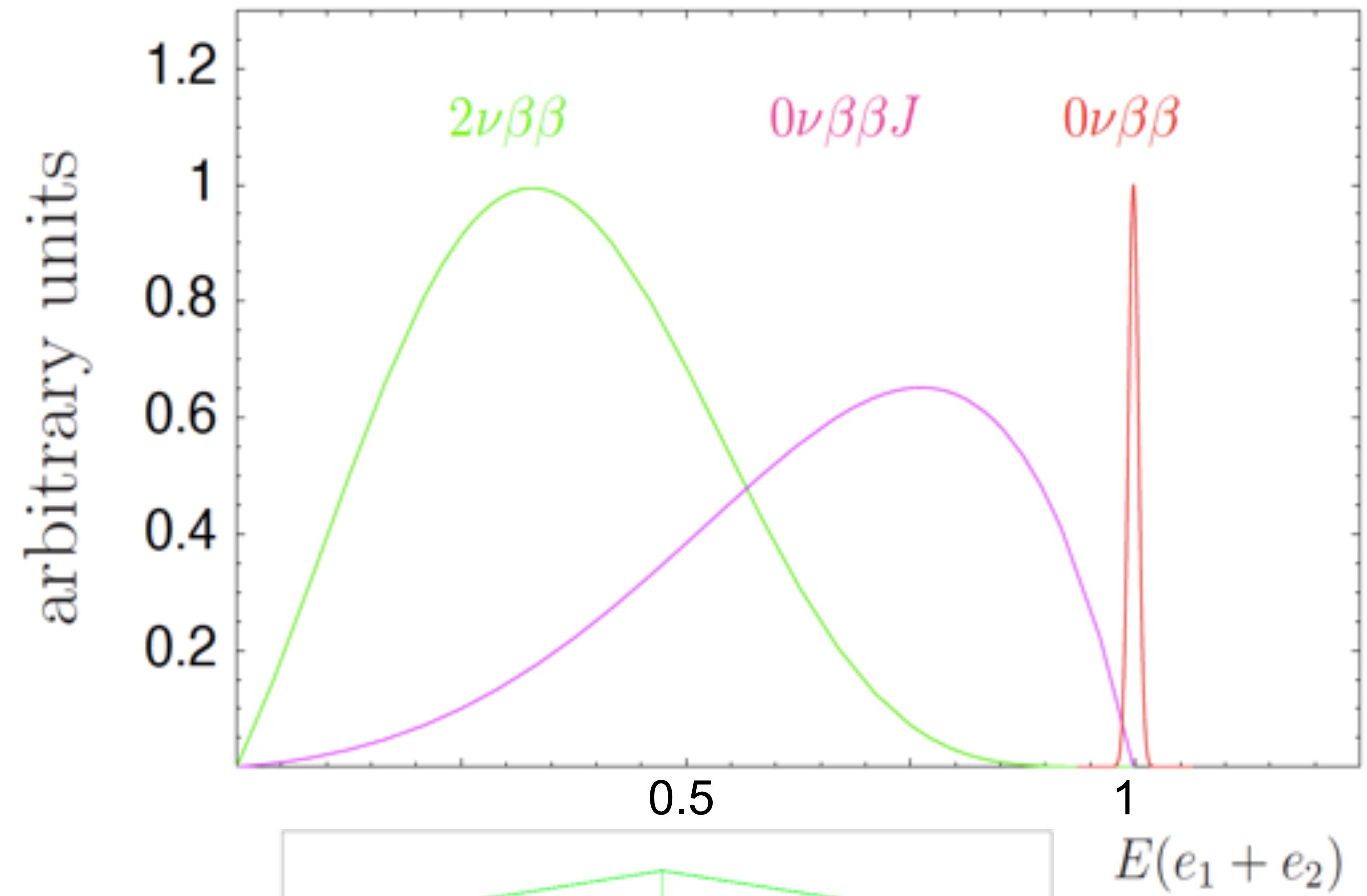
(A,Z) → (A,Z+2)$^{++}$ + 2 e-

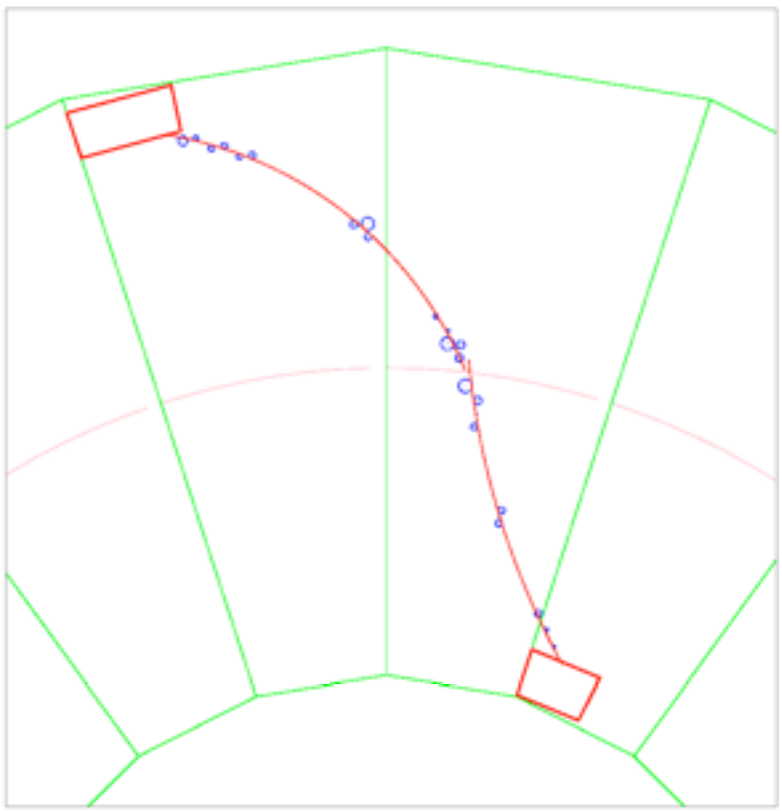
- A new (ionised) isotope
- Two electrons

Minimal information:

- two e^- energy sum spectrum

0νββ exhibits a **peak at Q** over 2νββ tail (and background contributions)





Additional signatures:

- Single electron energy spectrum
- Angular correlation between the two electrons
- Daughter nuclear species

Track and event topology
Time Of Flight

Moreover, to cure NME systematics:

- study as many as possible different isotopes

Experimental factor of merit

$$S^{0\nu}_{1/2}(m_{ee}) \propto \epsilon \frac{i.a.}{A} \frac{1}{\sqrt{G^{0\nu}}|M^{0\nu}|} \sqrt[4]{\frac{bkg \cdot \Delta E}{M \cdot t_{meas}}}$$

- Isotope choice

- Mass
- Energy resolution
- Background level
- Long measure time

- Deep underground location
- Large mass array
- Material selection
- Severe control of procedures
- Stable operating condition over several years

Bolometric approach →

ββ candidate: ^{130}Te **– Q** 2527.5 keV

Source Mass: 206 kg ^{130}Te – **$N_{\beta\beta}$** 9.6 x10^{26}

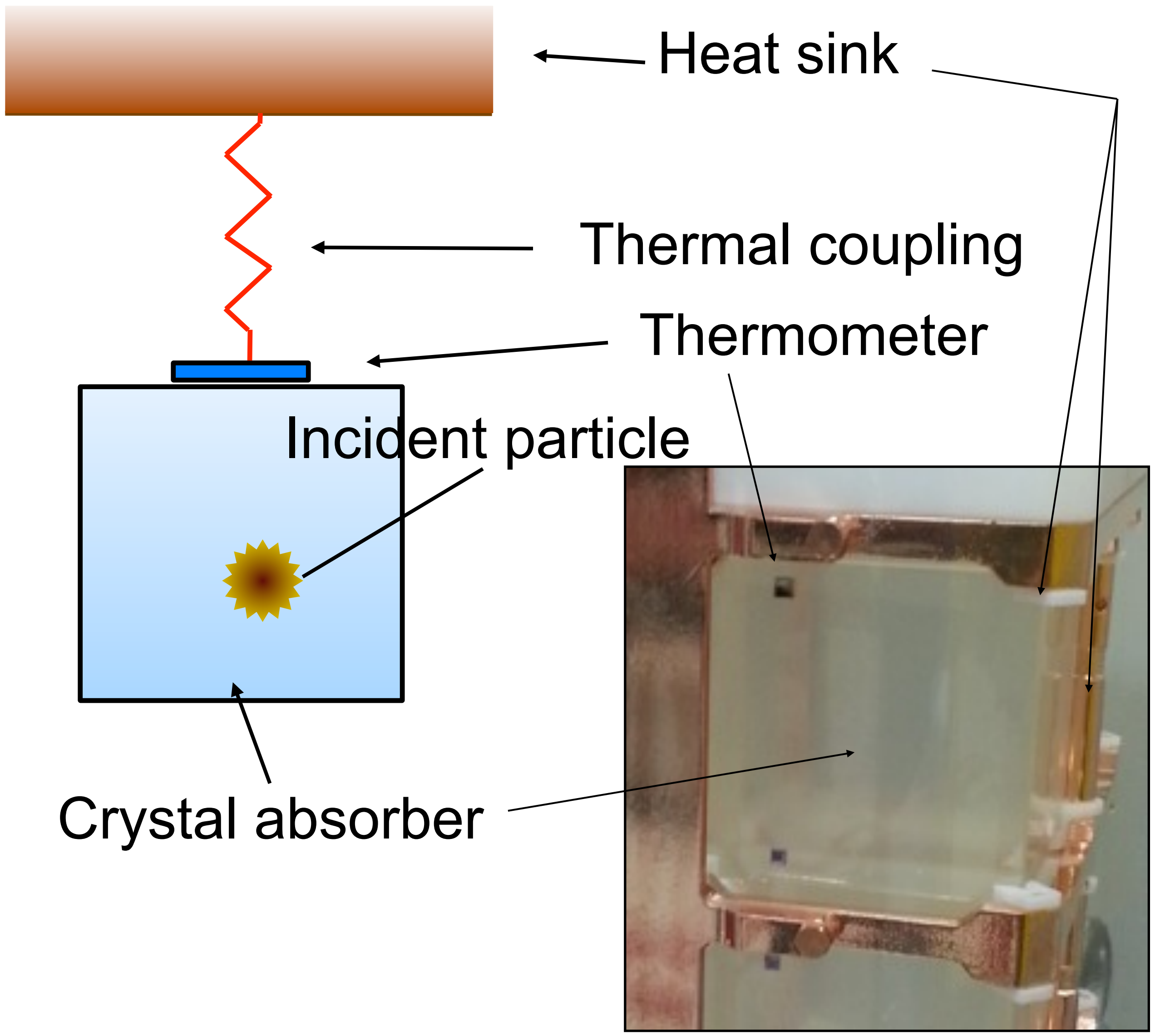
Projected Bkg: 0.01 c/keV/kg/y

Resolution: ~ 5 keV @ROI

Sensitivity $T_{1/2}^{0\nu}$: 1.6x10^{26} y in 5 y

Sensitivity $<m_{ee}>$: $<m_{ee}>$ < 40 ÷ 94 meV in 5y (IH)

Low temperature detectors



Detection Principle

$\Delta T = E/C$

C: thermal capacity

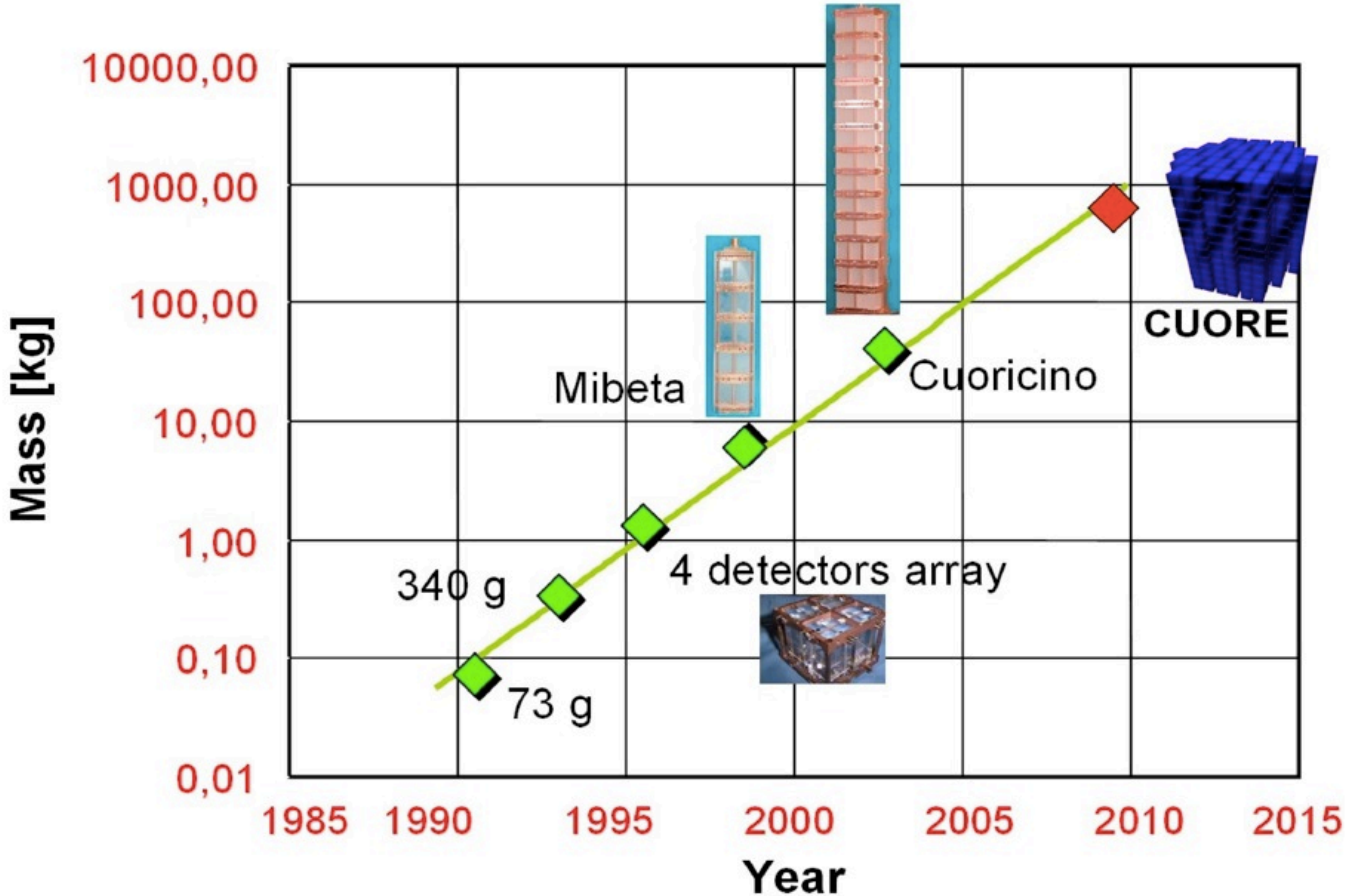
- low C
- low T (i.e. $T \ll 1$K)
  - dielectrics, superconductors
  - ultimate limit to E resolution: statistical fluctuation of internal energy U

$$\langle \Delta U^2 \rangle = k_B T^2 C$$

Thermal Detectors Properties

- **good** energy resolution
- wide choice of absorber materials
- true calorimeters
- slow $\tau = C/G \sim 1 \div 10^3$ ms

TeO_2 bolometers Evolution



CUORE

Cryogenic Underground Observatory for Rare Events

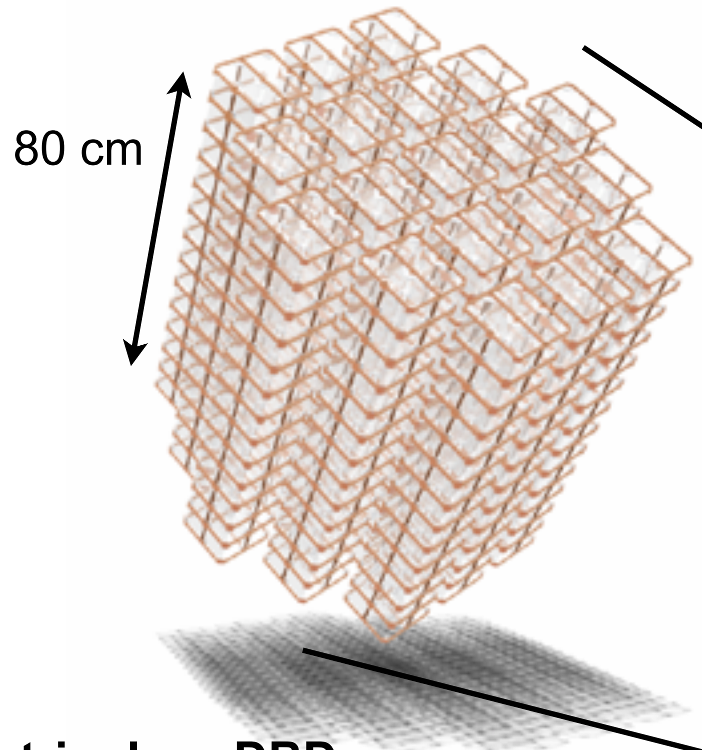
Closely packed array of 988 TeO_2 crystals 5×5×5 cm^3 (750 g)

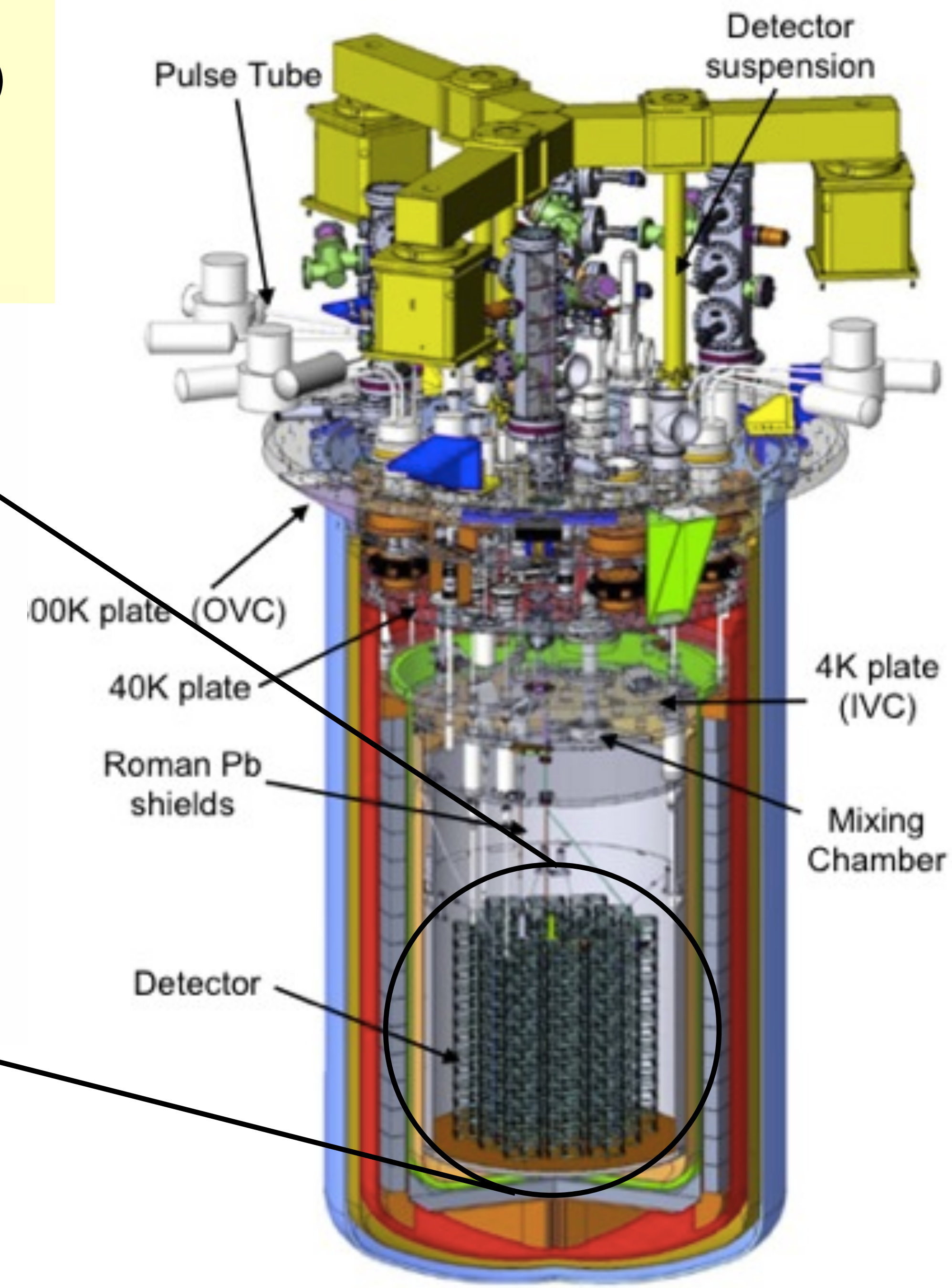
741 kg TeO_2 granular calorimeter

600 kg Te = 206 kg ^{130}Te

Single high granularity detector

19 towers
13 planes each
4 crystals each





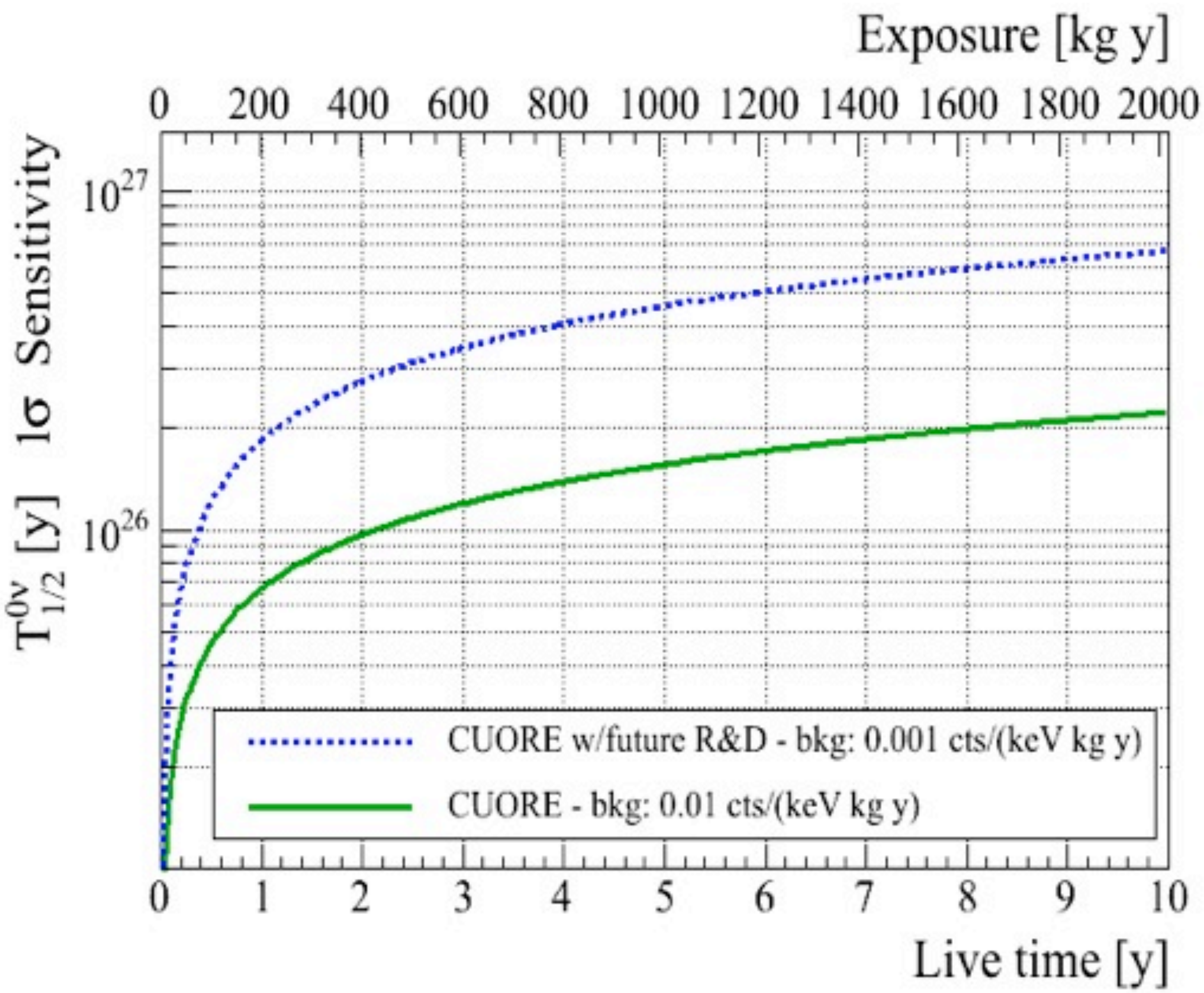
Calorimetric experiment on 130Te neutrinoless DBD

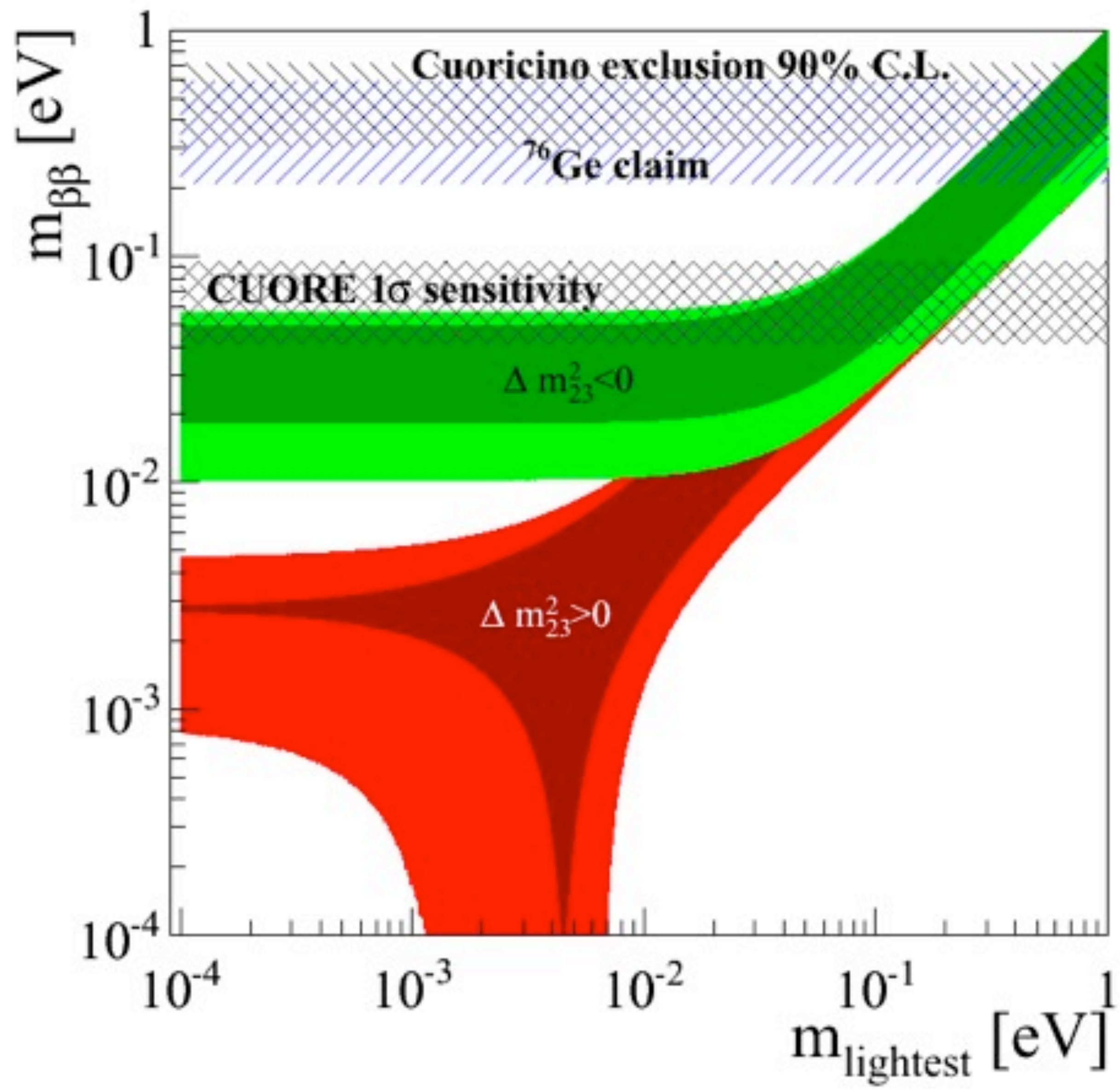
Background	ΔE	$T_{1/2}$	$<m_{ee}>$			
c/kev/kg/y	keV	10^{26} y	R(QRPA)[1]	np(QRPA)	ISM[3]	IBM-2[4]
0.01	5	1.6	35-66	41-67	65-82	41
0.001	5	6.5	20-38	23-38	37-47	23

1 Šimkovic et al., PRC 77 (2008) 045503
2 Civitarese et al., JoP:Conference series 173 (2009) 012012
3 Menéndez et al., NPA 818 (2009) 139
4 Barea and Iachello, PRC 79 (2009) 044301

Single cryogenic setup (T_{work}=10-15mK)
Complex system of radiation shields
Mechanical decoupling system
Detector calibration system
Underground laboratory (LNGS)

CUORE sensitivity





Background goal of
0.01 c/keV/kg/y

$T_{1/2} = 1.6 \times 10^{26}$ y

Cuoricino result and CUORE 1σ sensitivity overlaid on plots that show the bands preferred by neutrino oscillation data (inner region: best-fit data; outer region: at 3σ). Both normal (red) and inverted (green) hierarchies are shown.

Challenges

Two big challenges:

- tonne-sized bolometric detector
  - operate in stable conditions for very long measure time (years)
  - huge cryogenic system with unique features (e.g cryo-free), cold shields, embedded calibration system, mechanically decoupled, ...

- lowest possible background
  - selected materials
  - lowest mass
  - careful preparation
  - material assay
  - new detector design
  - selected procedures
  - underground location

CUORE Collaboration

Berkeley Lab
UCLA
Cal Poly
CUORE
INFN Istituto Nazionale di Fisica Nucleare
Università degli Studi di Milano Bicocca
Sapienza Università di Roma
Lawrence Livermore National Laboratory
University of South Carolina
The University of Wisconsin Madison
SINAP
unige

CUORE Collaboration

18 groups

- Italy 9
- USA 6
- France 1
- 3 associated institutions

145 collaborators

- 111 researchers/authors
- Italy: 61
- USA: 38
- France: 3
- Associated Institutions: 9

Italy	
Bologna	4
Firenze	1
Frascati (LNF)	3
Genova	4
Gran Sasso (LNGS)	9
Legnaro (LNL)	4
Milano Bicocca	25
Padova	1
Roma	10

USA	
Berkeley (UCB/LBNL)	13
Columbia (USC)	8
Livermore (LLNL)	6
Los Angeles (UCLA)	5
Madison (UW)	5
S. Louis Obispo (CalPoly)	1

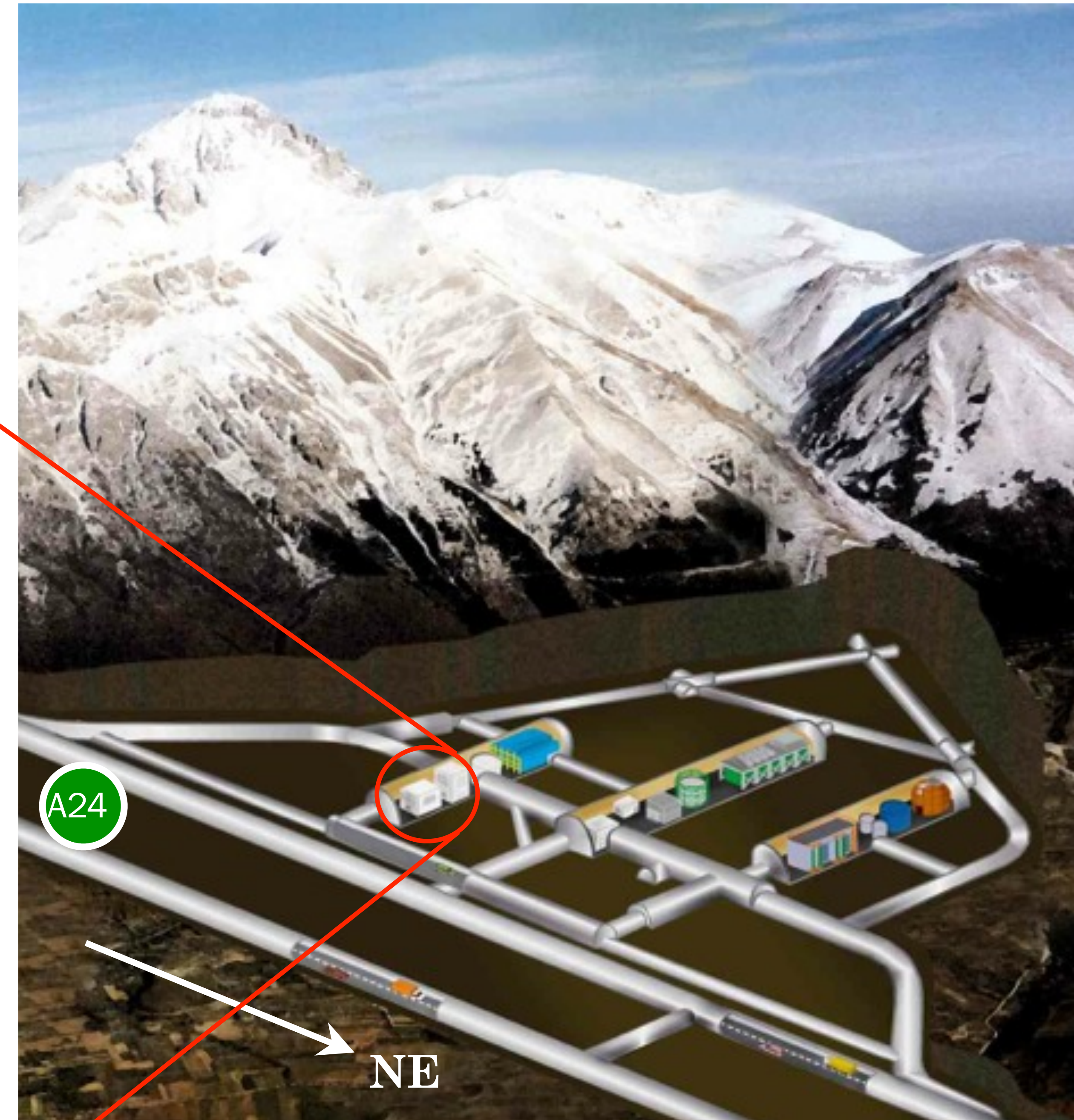
France	
Orsay	3

Associated	
Zaragoza	1
Edinburgh (SUPA)	1
Shanghai (SINAP)	7

The LNGS underground facility

CUORE hut (New Building)

Cuoricino/CUORE-0 hut



Underground facility

- Average depth ~ 3650 m.w.e.
- Factor 10^6 reduction in muon flux to ~ 3×10^{-8} μ/(s·cm^2)

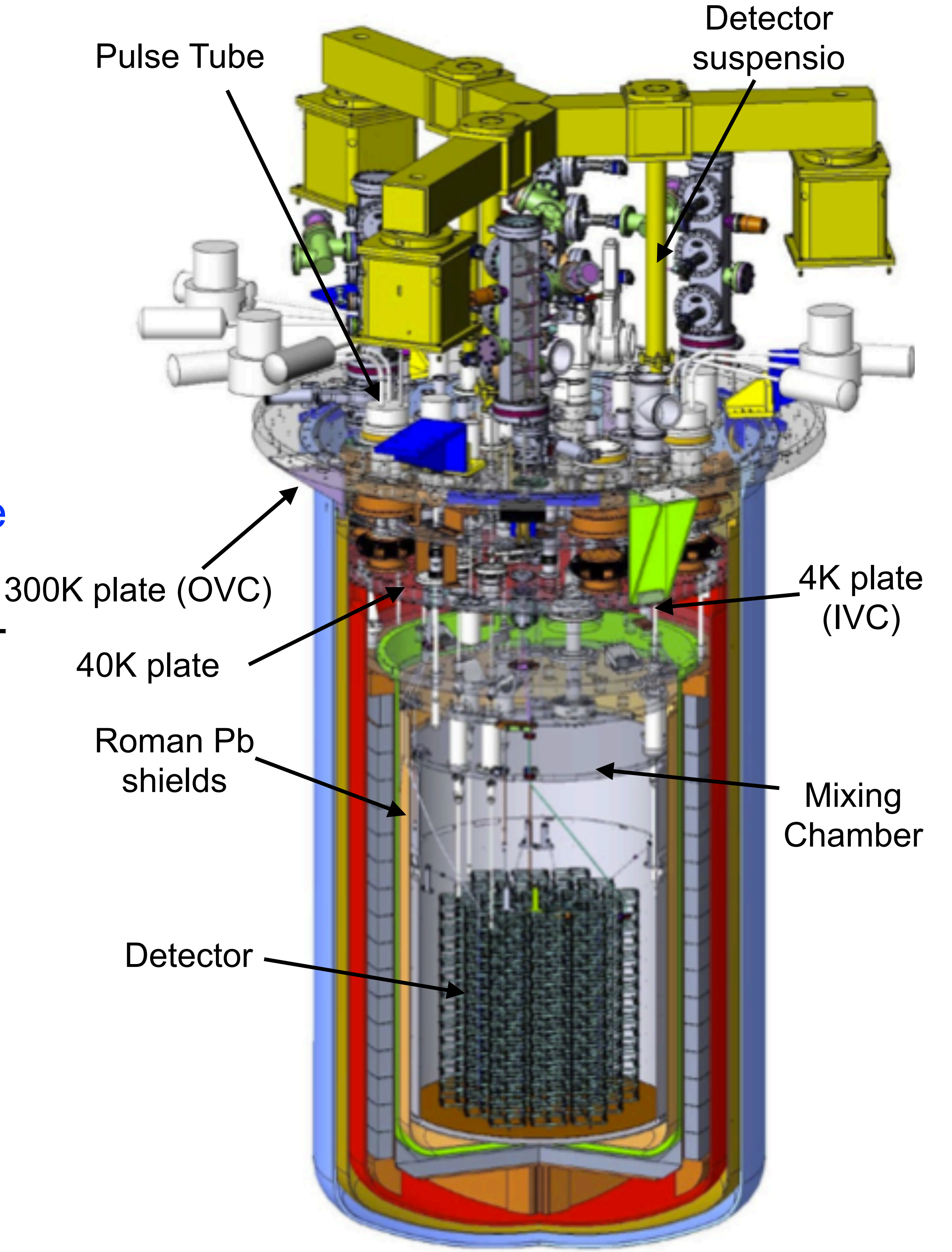
The CUORE experimental setup

Custom cryogenic system @ LNGS.

- Improved shielding and material selection.
- High efficiency in background rejection, due to the packed geometry: minimum lead thickness surrounding the detector ~ 36 cm
- No cryogenics liquids: better duty cycle
- Mechanical suspension of the detector assembly completely independent from the refrigeretor structure: better control of noise induced by vibrations
- Severe control of the radioactivity of the set-up

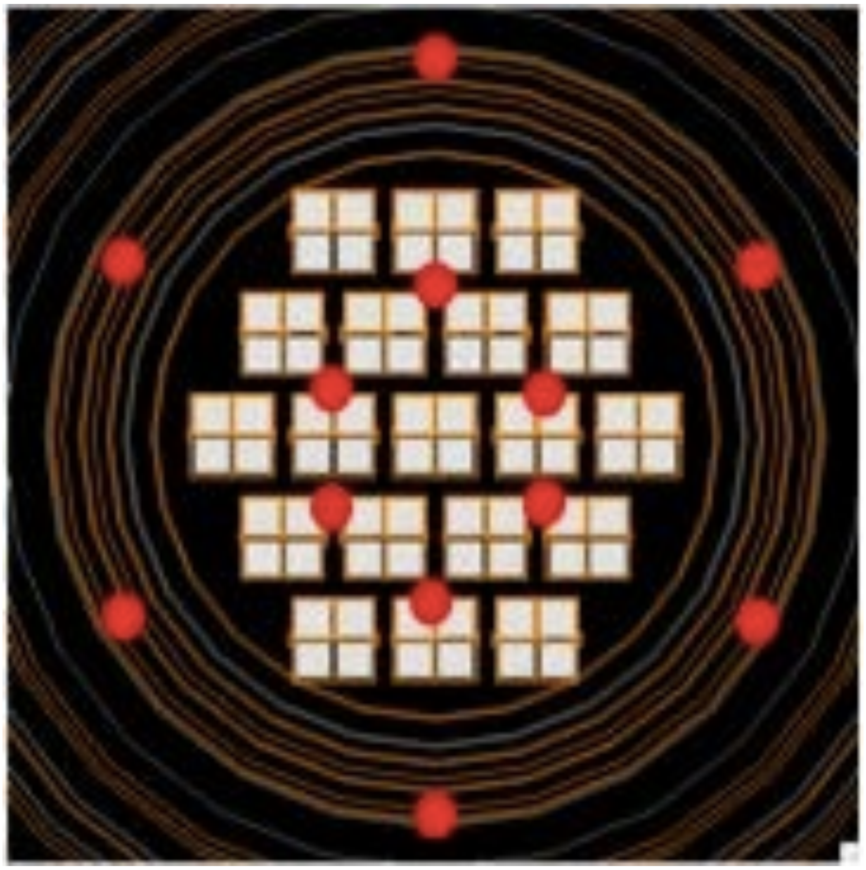
Embedded in the setup (after a severe control of the radioactivity of the materials):

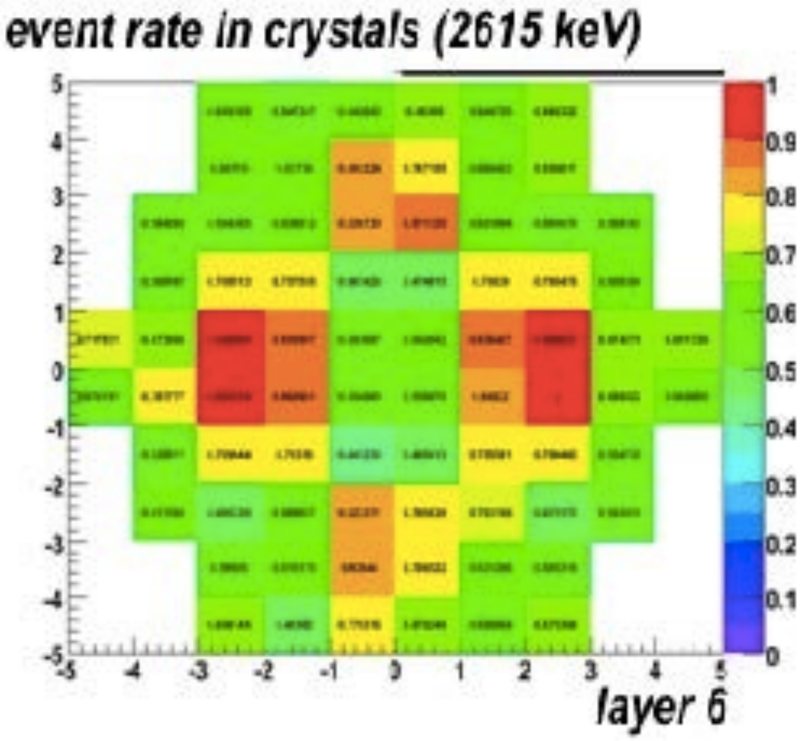
- Cryo-free dilution refrigerator (Leiden Cryogenics)
- Roman Lead (no ^{210}Pb) cold shield
- Detector and Pd shield suspension
- Calibration system

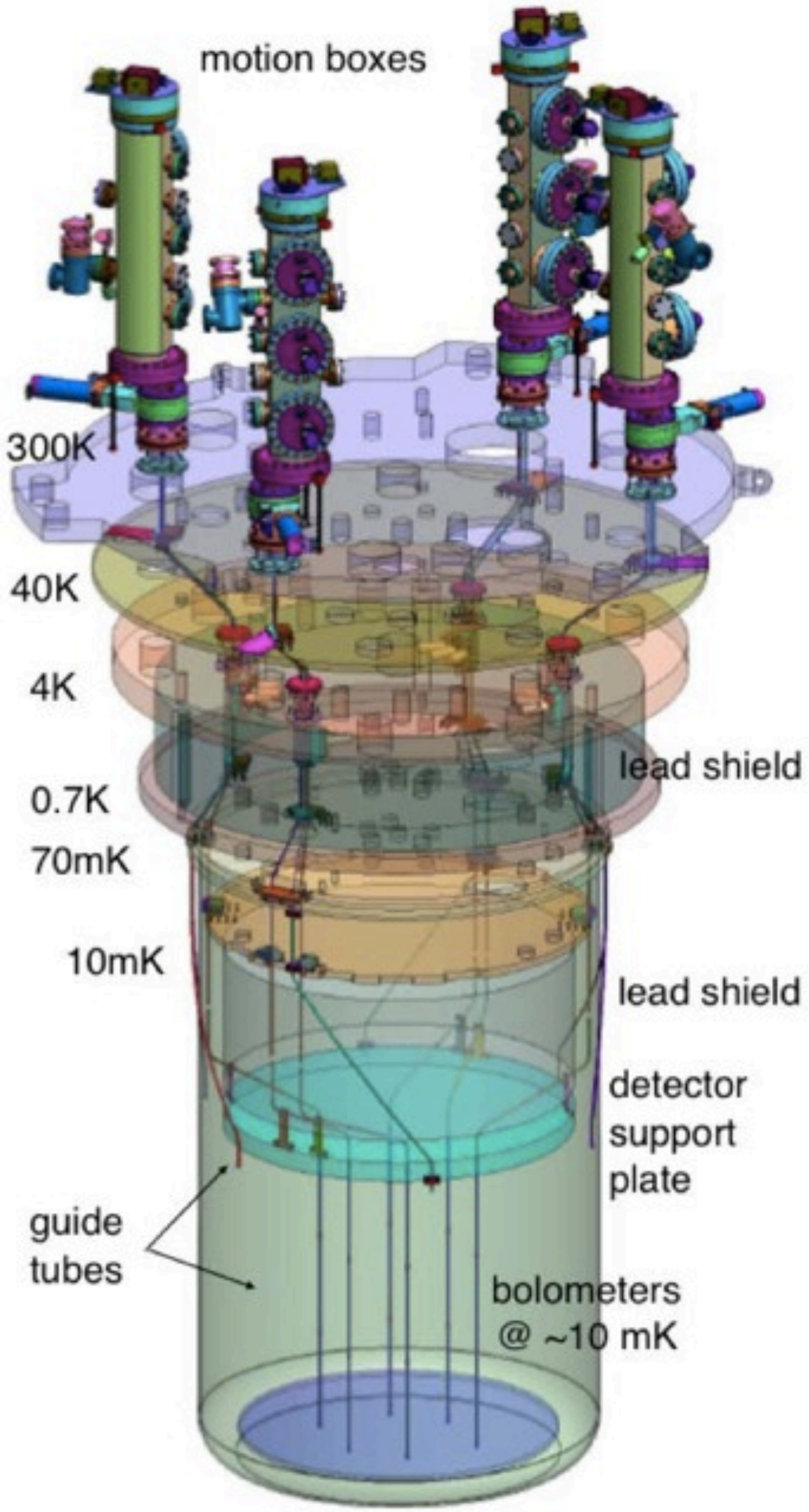


Detector calibration system

- 12 gamma source wires
  - o ^{232}Th: thoriated tungsten wire
  - o ^{56}Co: proton activated Fe wire
- Minimize down time but rate at each crystal not exceeding 150 mHz
- Stringent heat load requirement





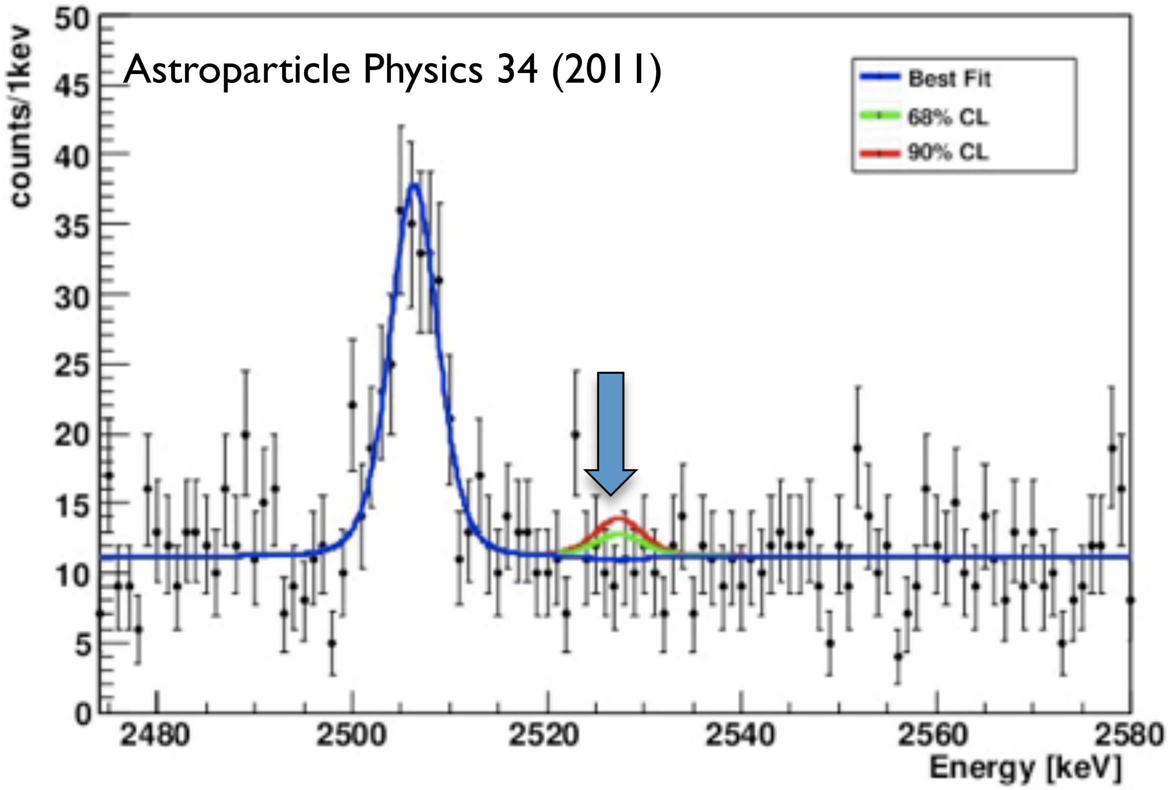


Detector evolution

ΔE = 6.2 ± 2.5 keV (~0.3% FWHM)

Bkg = 0.169±0.006 c/keV/kg/y

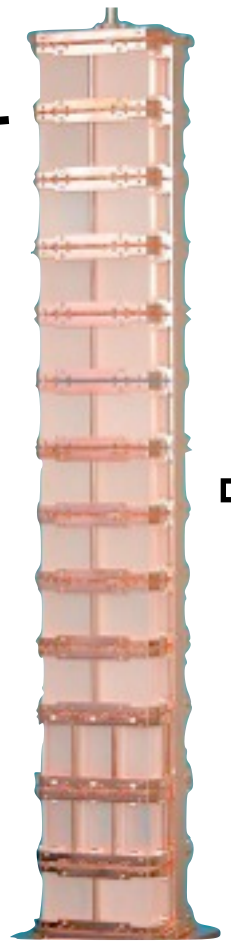
$T_{1/2}^{0\nu}$ (y) > 2.8 × 10^{24} y (90% CL)



$\langle M_{bb} \rangle < 0.3 - 0.7$ eV

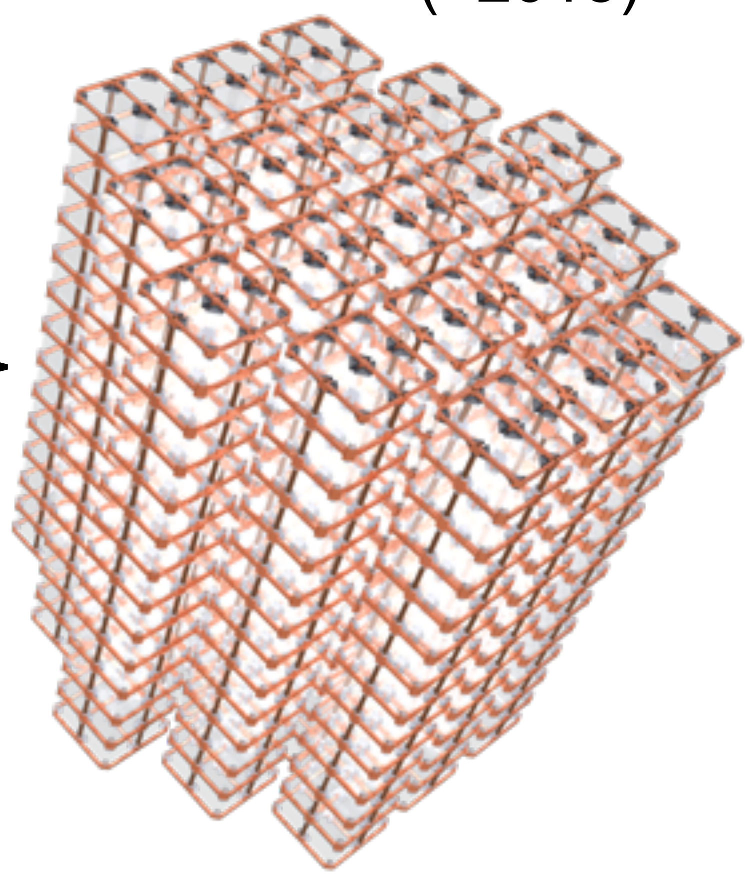
NME from F.Simkovic et al. Phys.Rev. C77
J.Suhonen et al. Int.Jou.Mod.Phys. E17
J.Menendez et al. Nucl. Phys. A818
J.Barea et al. Phys. Rev. C79

CUORICINO
40 kg
(2003-2008)



CUORE-0
(2013)

CUORE
1 ton
(~2015)



Extensive study of background sources

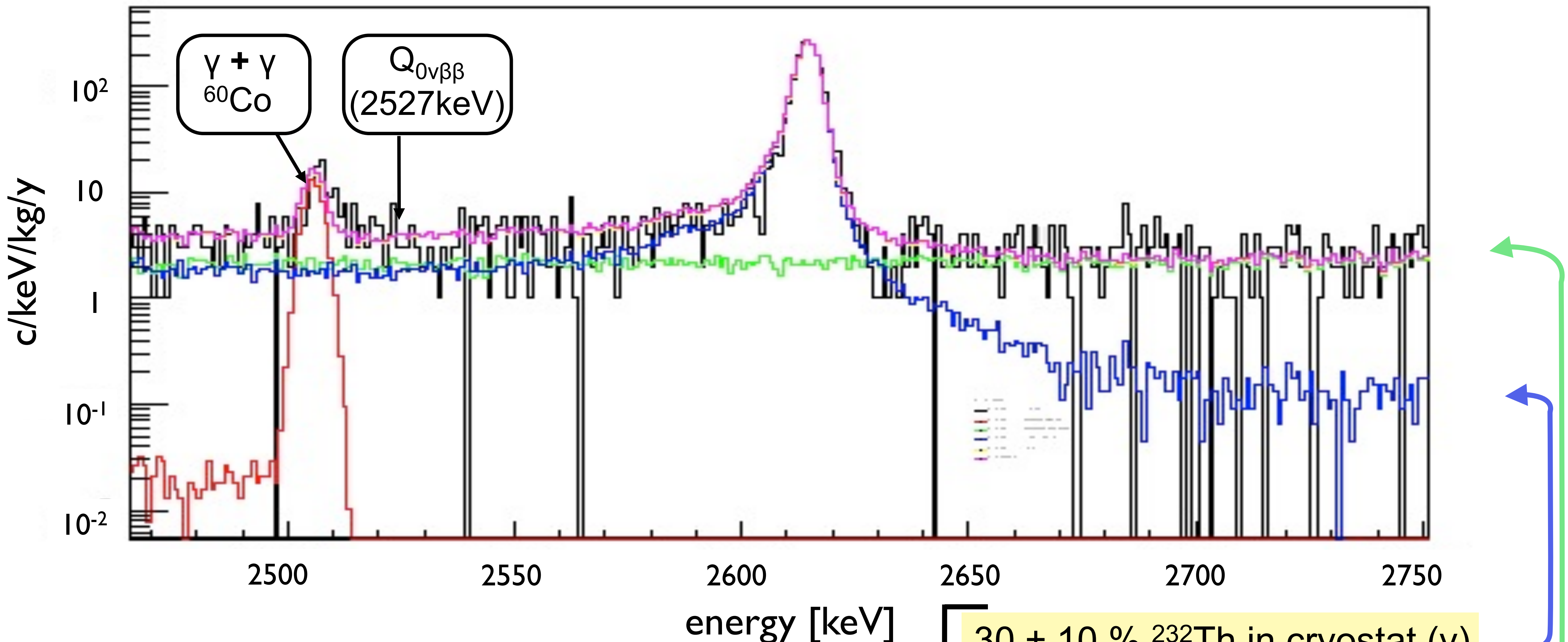
Careful design and construction of the setup

- Hut and infrastructures
- Detector
  - Crystals
  - Structure
  - Assembly
- Cryostat and shields
- Calibration system
- Electronics

Background model

Available data: Cuoricino + dedicated background studies @ LNGS R&D setup

MC: the background in Cuoricino is due to degraded alpha particles which release only part of their energy in the detector (surface contamination)



30 ± 10 % ^{232}Th in cryostat (γ)

10 ± 5 % TeO_2 surface (α)

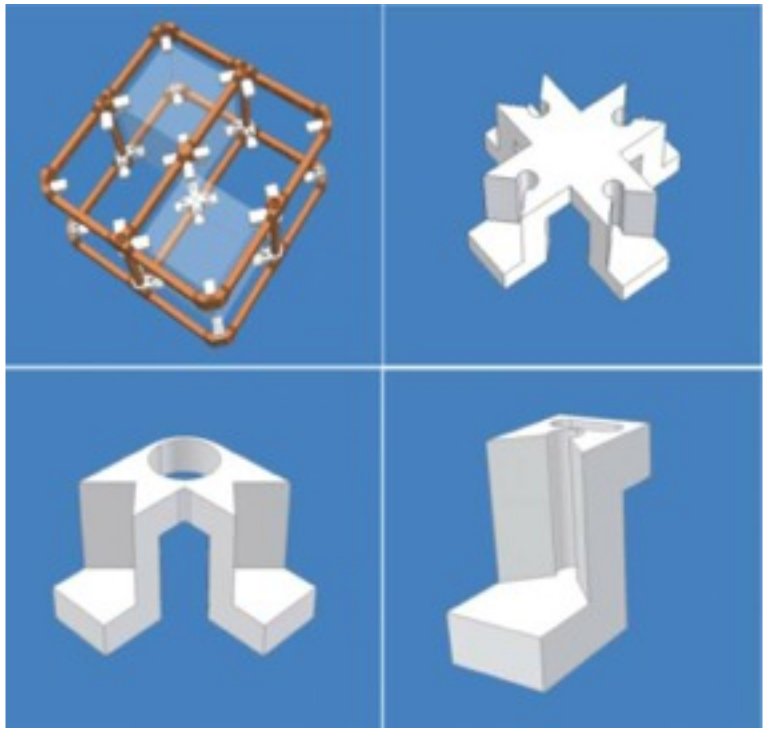
50 ± 20 % Cu surface (α)

Bkg @ 0vDBD region = 0.161 +/- 0.006 c/keV/kg/y
(ainticoincidence spectrum, 5x5x5 cm^3 crystals)

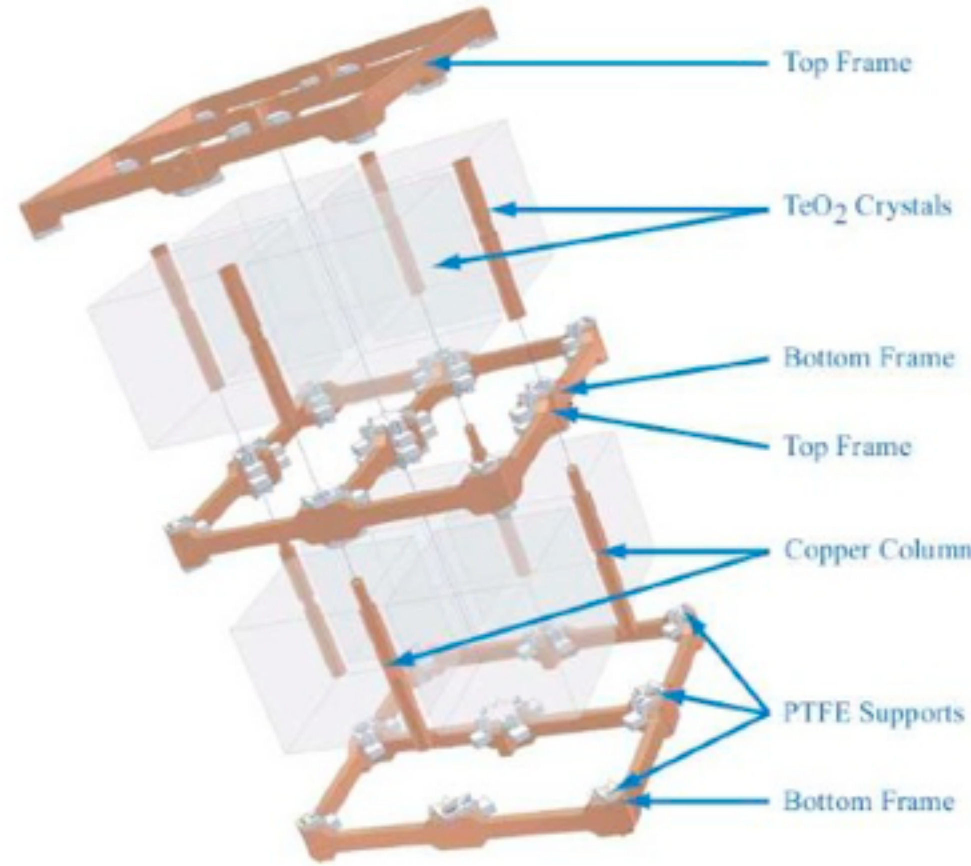
C.Arnaboldi et al. http://arxiv.org/abs/hep-ex/0212053

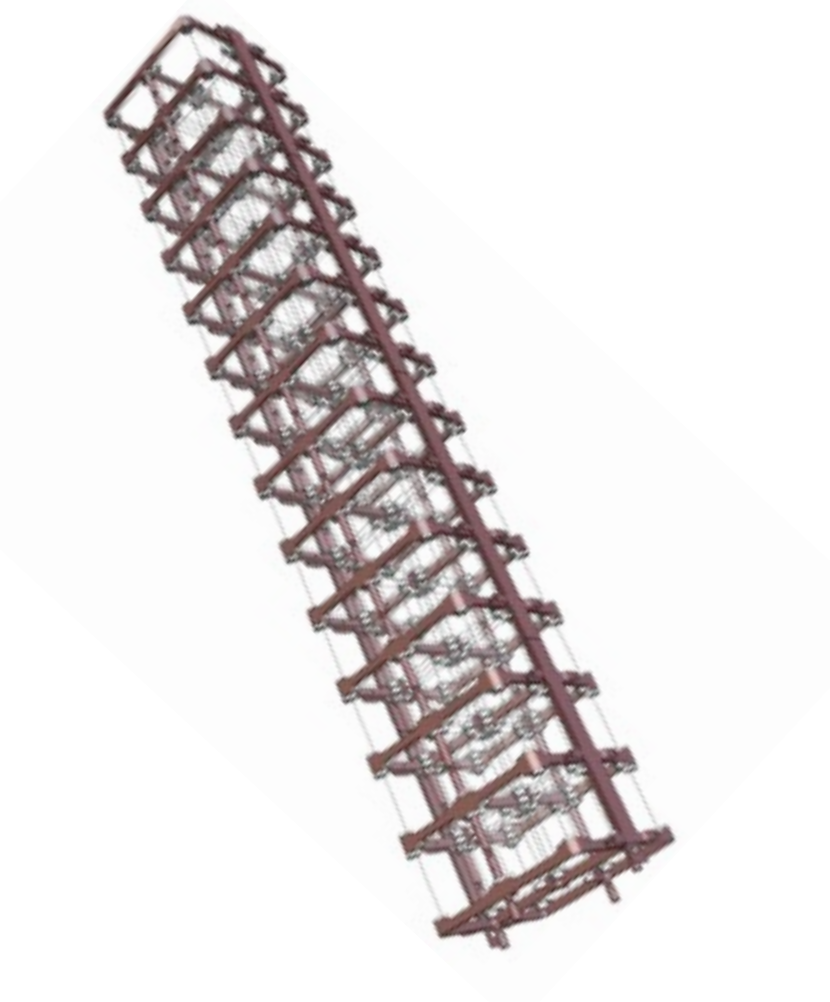
C.Arnaboldi et al. Phys. Rev C 78 (2008) 035502

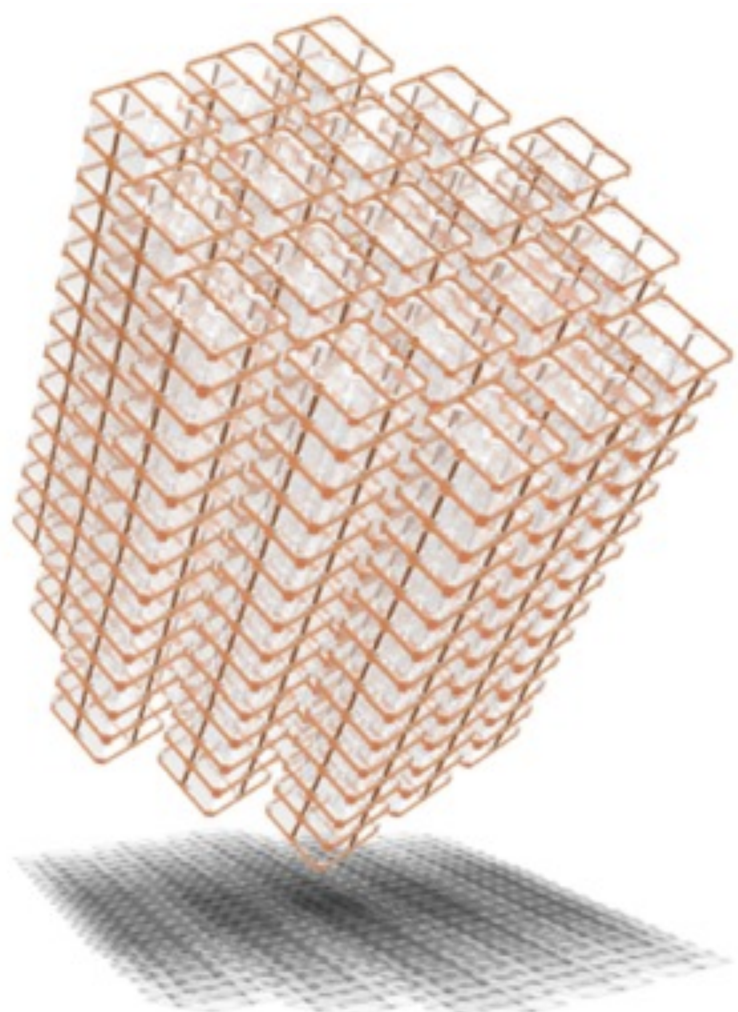
CUORE detector design

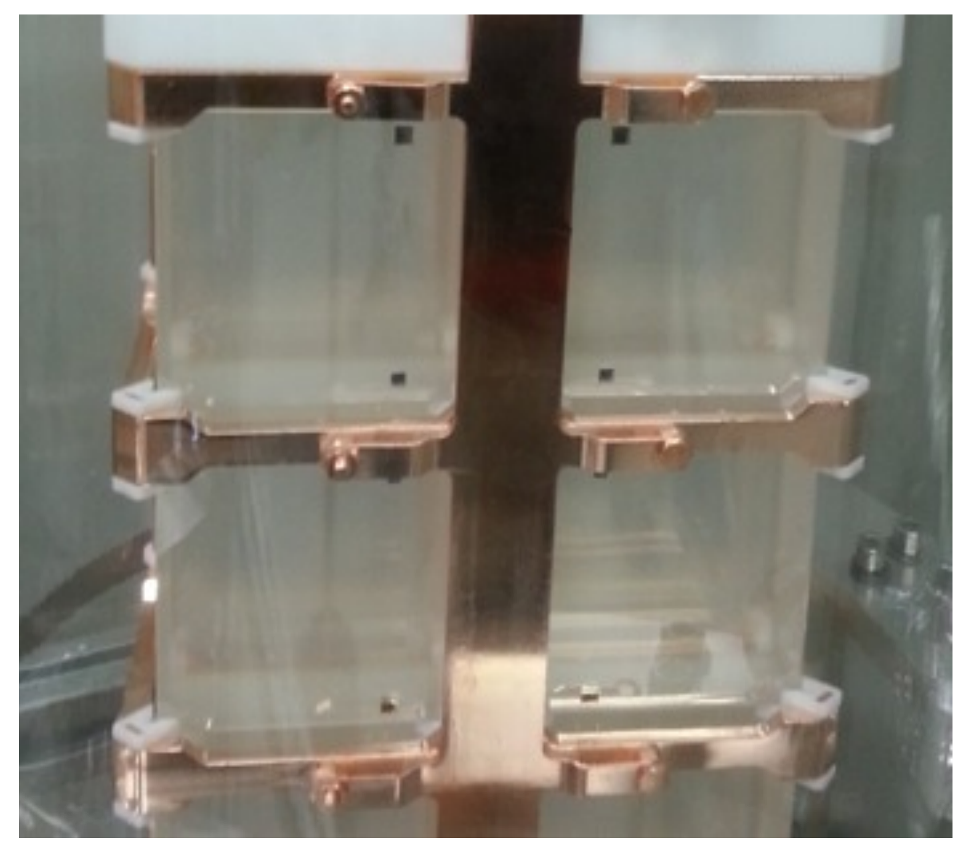


- Copper Frame:
  - Heat bath
  - Background source
- Teflon holders
  - The weak thermal link
  - Reduce vibration noise



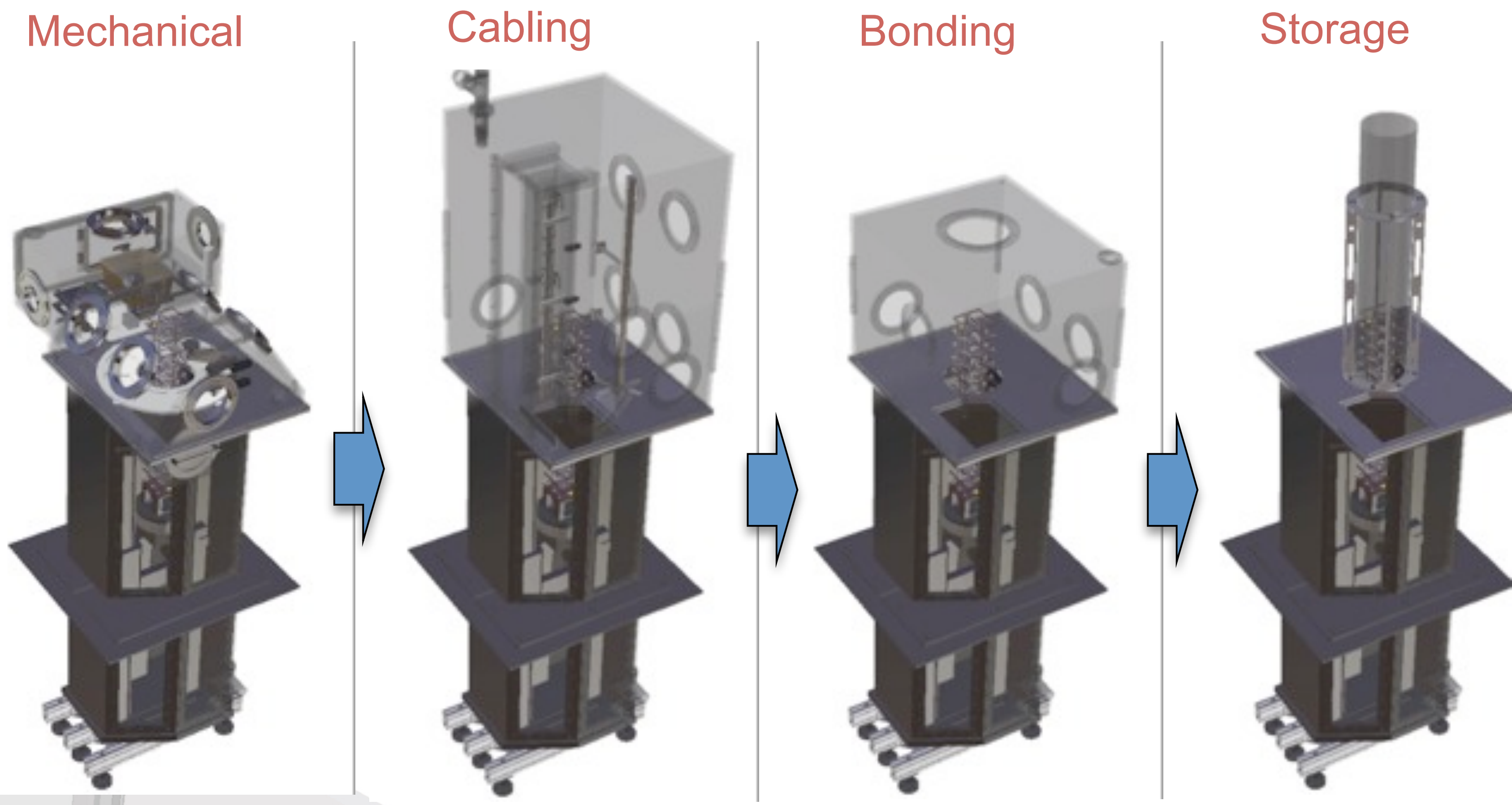


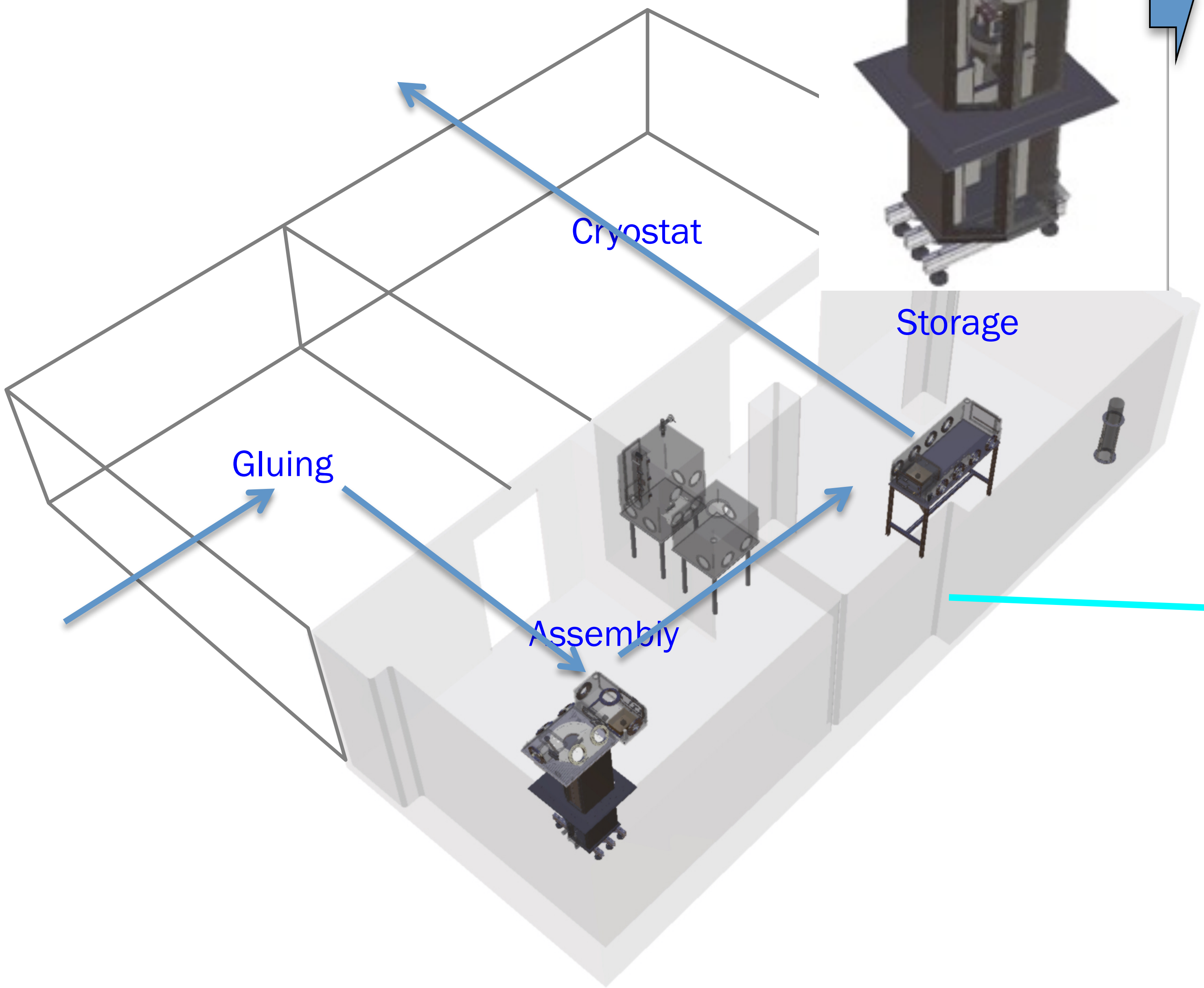


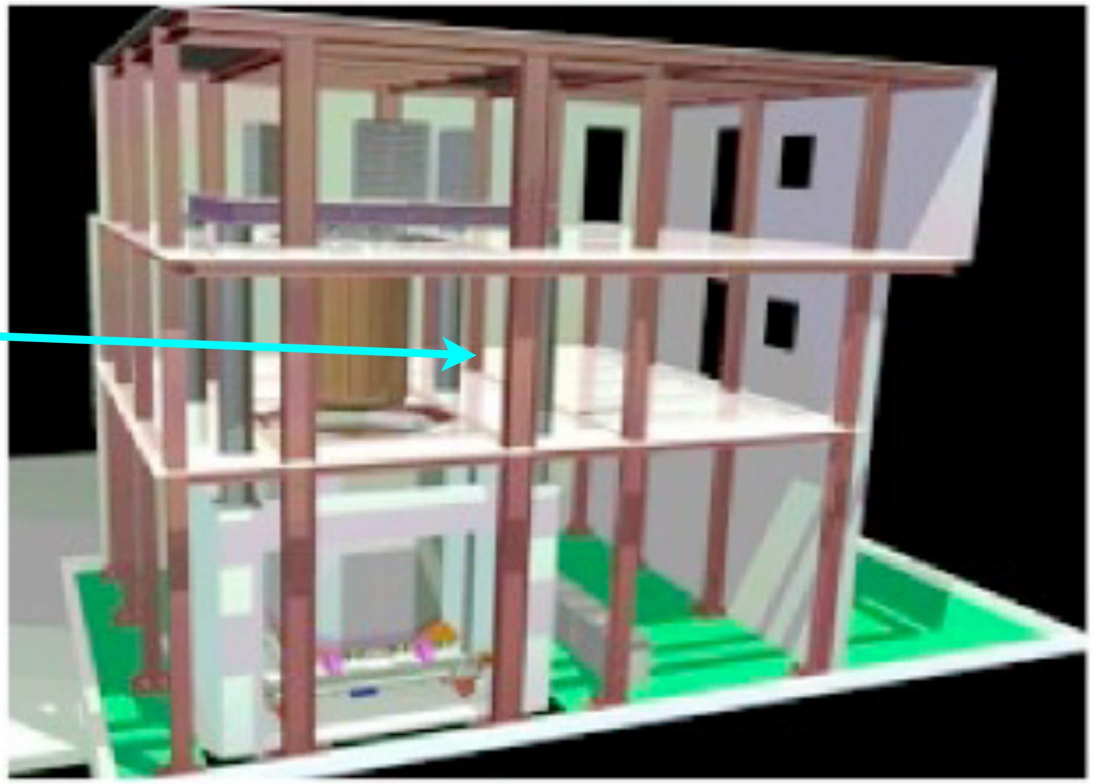


Detector assembly

Set of specially designed Glove Boxes
- Rn free atmosphere
- strict control of materials
- reproducible protocol







Ongoing activities

Setup and detector part preparation: almost completed

A LOT OF PROGRESS in 2013

Main activities moved to LNGS:

- **Detector construction**
  - **Detector construction: regular progress**
    - **>10 tower's worth "glued" crystals**
    - **9 mechanically assembled towers**
    - **5 completed towers**

- **Installation and test of cryogenic set-up**
  - Construction of the 3 inner chambers of the cryostat: completed timely and without major problems (delivered @ LNGS 06/05/2013)
  - Commissioning @ LNGS of dilution unit: completed in April.
  - PT characterization completed in January.
  - **Installation and test program proceeds regularly**. **2 successful cooldowns to 4K (Mach & June).**

- **CUORE-0**
  - Despite a non negligible number of adverse events mainly related to leaks of the (1989) Cuoricino cryostat ....
  - **Successful cooldown at February**. Optimization phase completed in April
  - **Background data taking started at the beginning of May! Promising preliminary results.**

CUORE-0

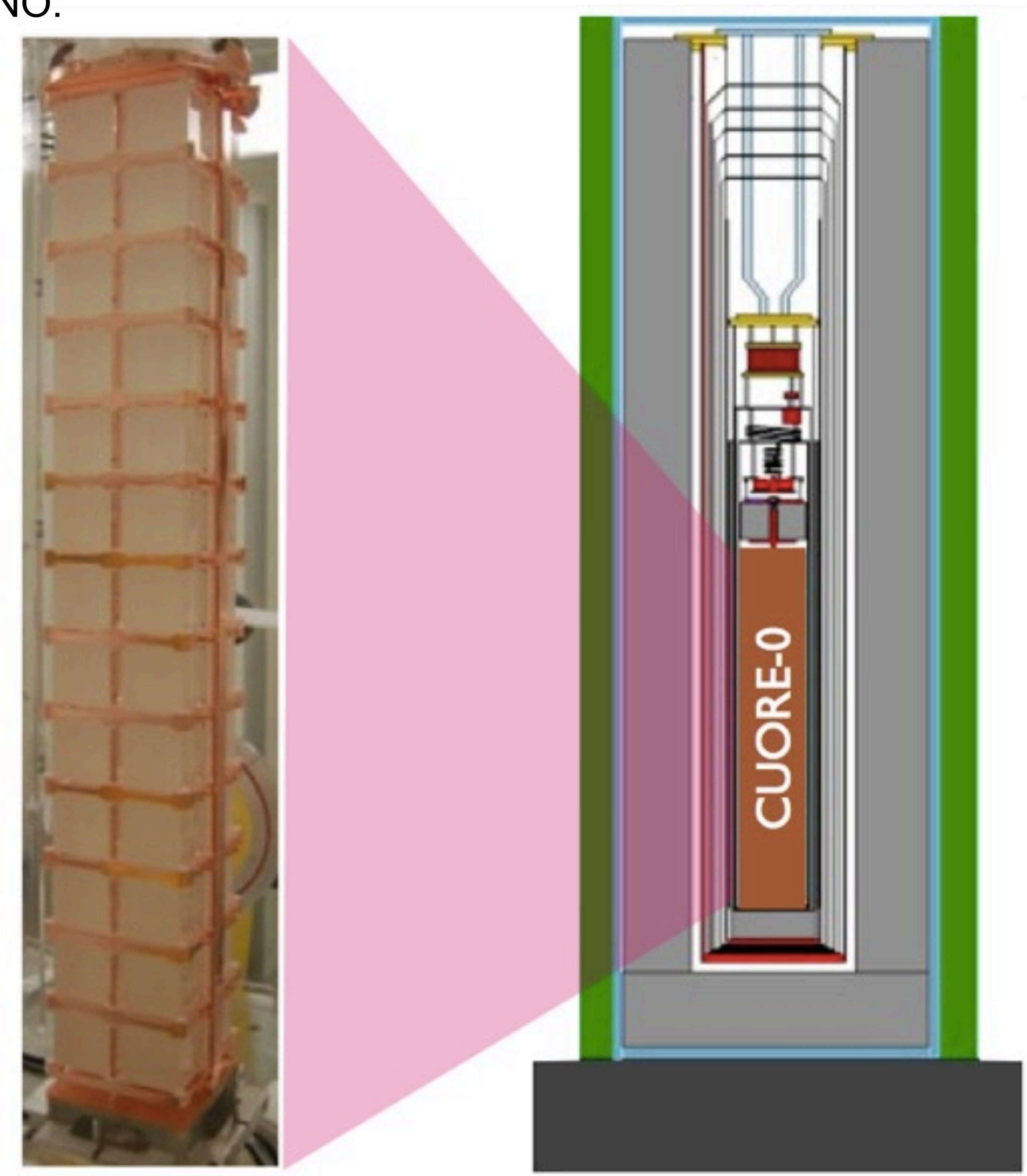
- **fully CUORE-like tower (parts, design, assembly)**
- operated as a stand alone experiment in the Cuoricino cryostat

Size similar to CUORICINO:
- 52x750g bolometers
- 13 floor of
- 4 crystals each

Active mass:
- TeO_2: 39 kg
- **^{130}Te: 11 kg**

goal:
full test and debug of the new CUORE design and assembly to identify:
- critical items
- flaws and inefficiencies

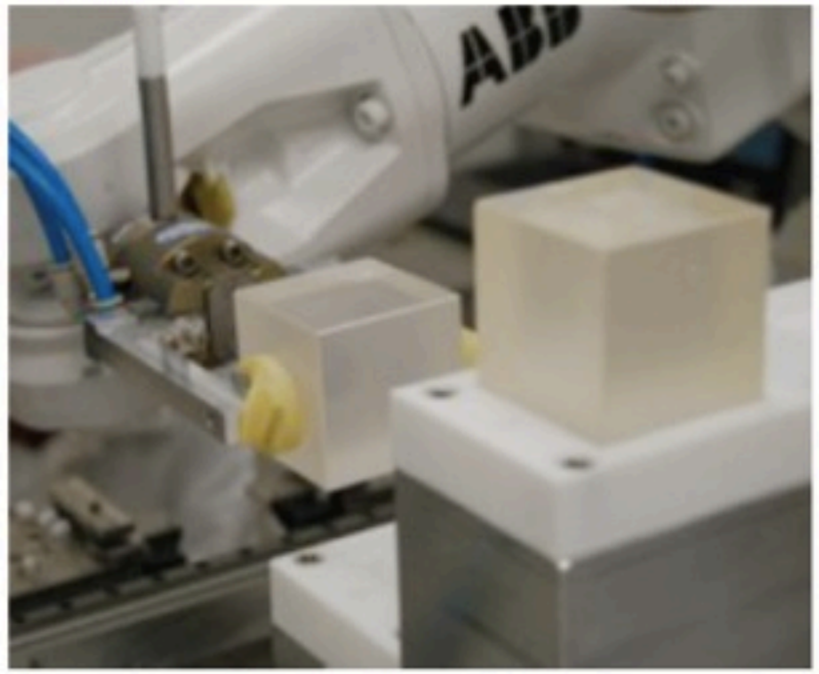
DATA TAKING started MAY 2013

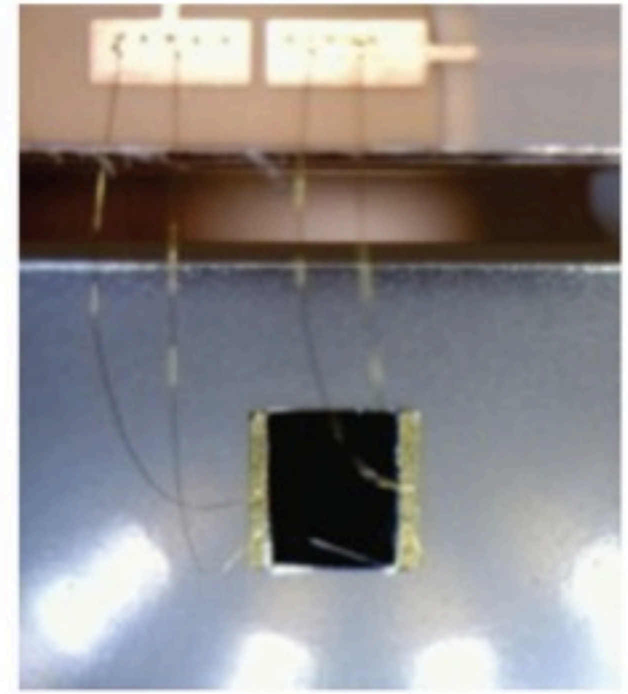


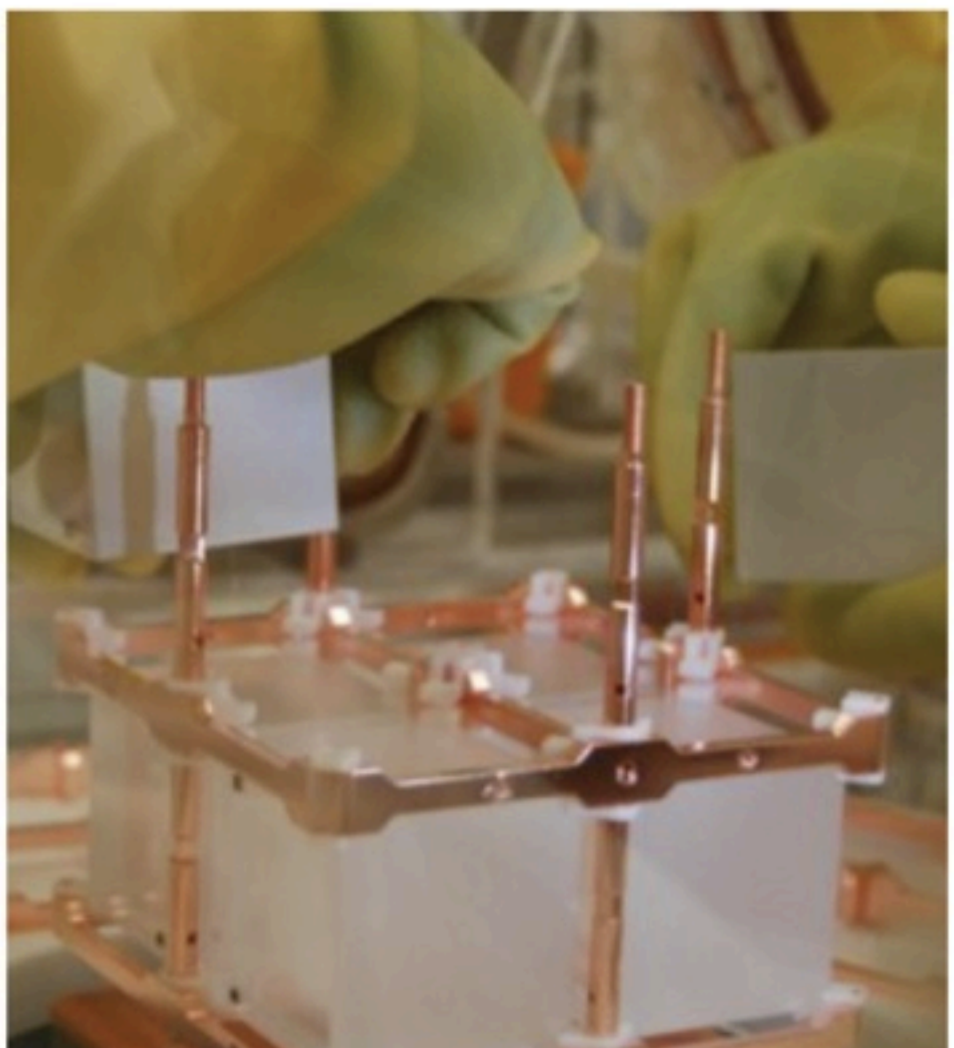
Cryostat:
- Inner shield:
  - 1cm Roman Pb A (^{210}Pb) < 4 mBq/Kg
- External Shield:
  - 20 cm Pb 10 cm Borated polyethylene
- Nitrogen flushing
  - to avoid Rn contamination.

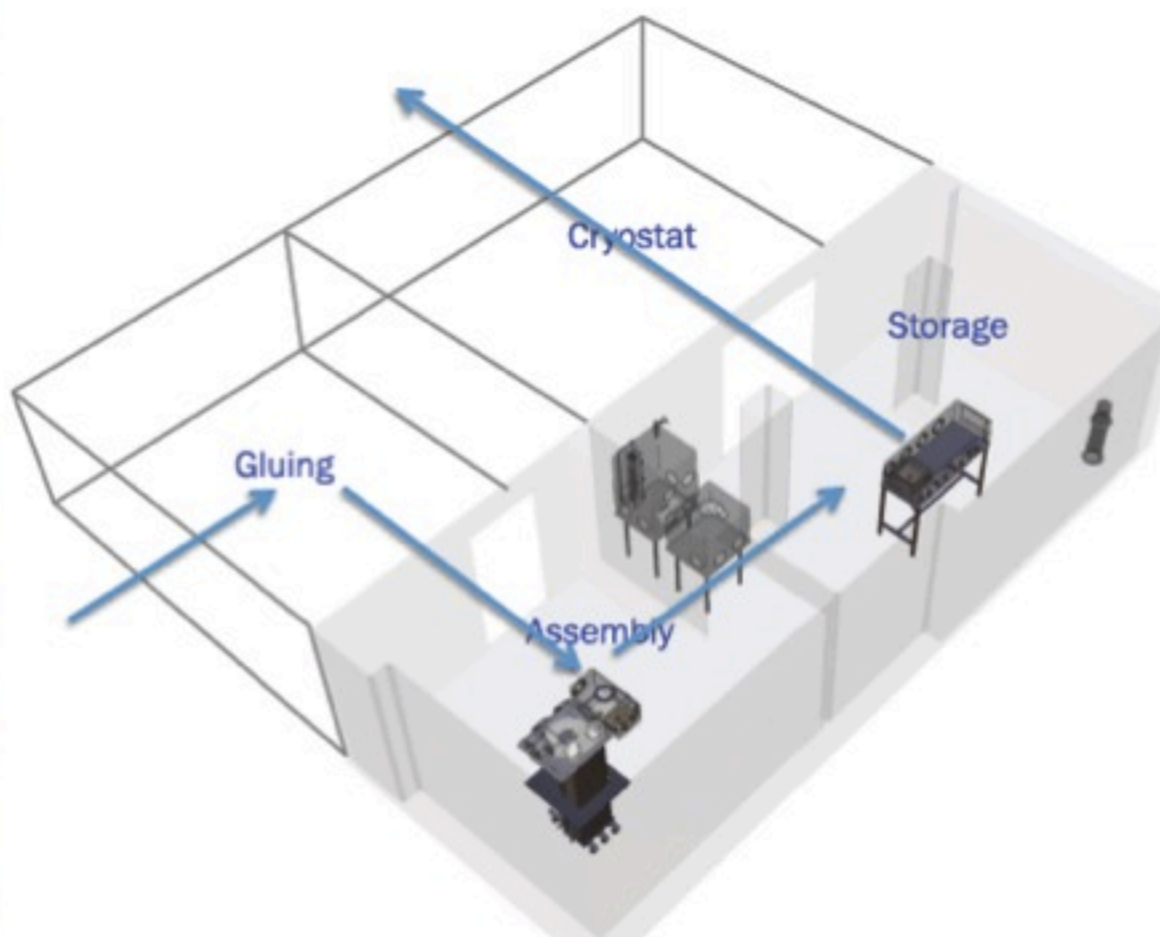
Same as for Cuoricino:
- γ background (232Th) not expected to change
- test the α background

Construction & Installation

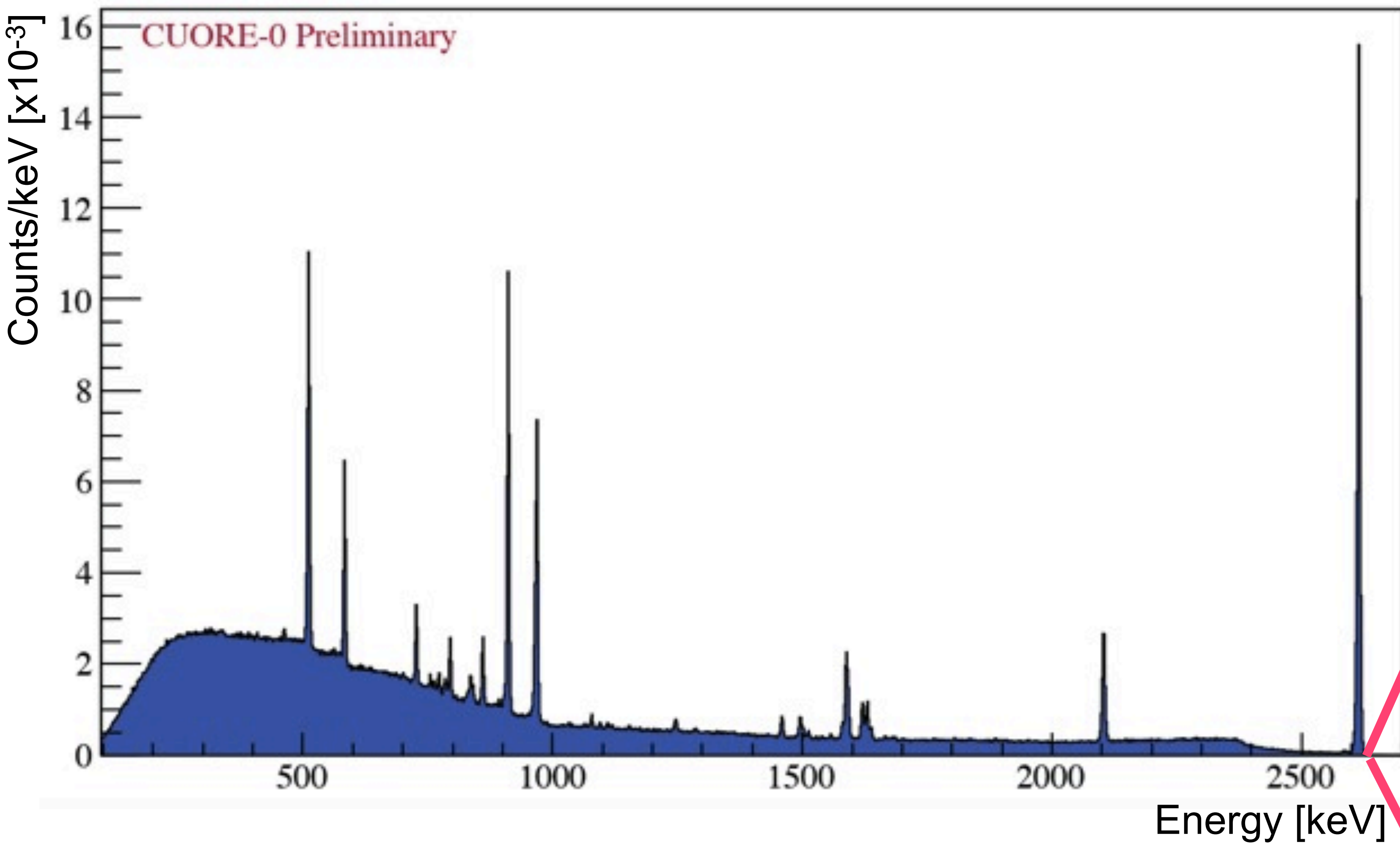


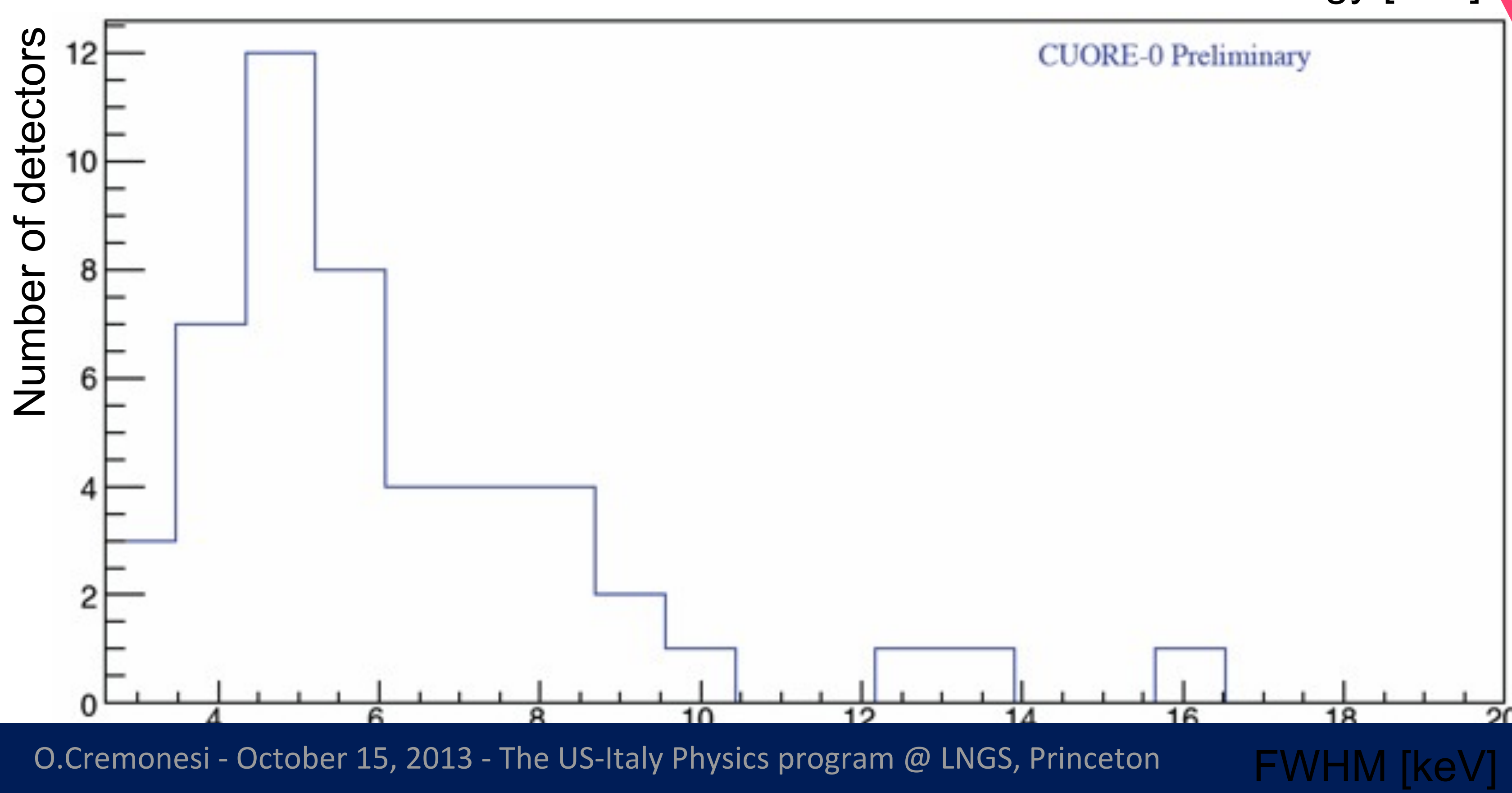




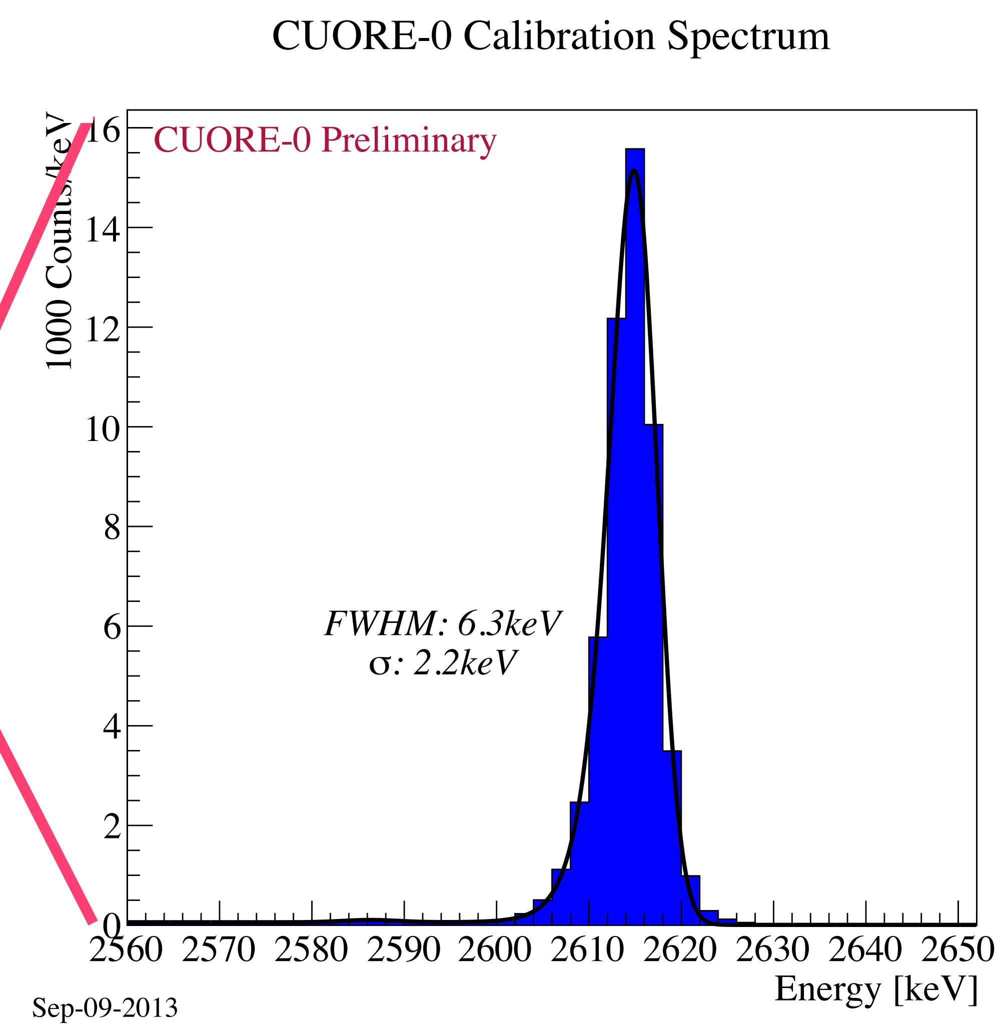


Energy resolution: calibration



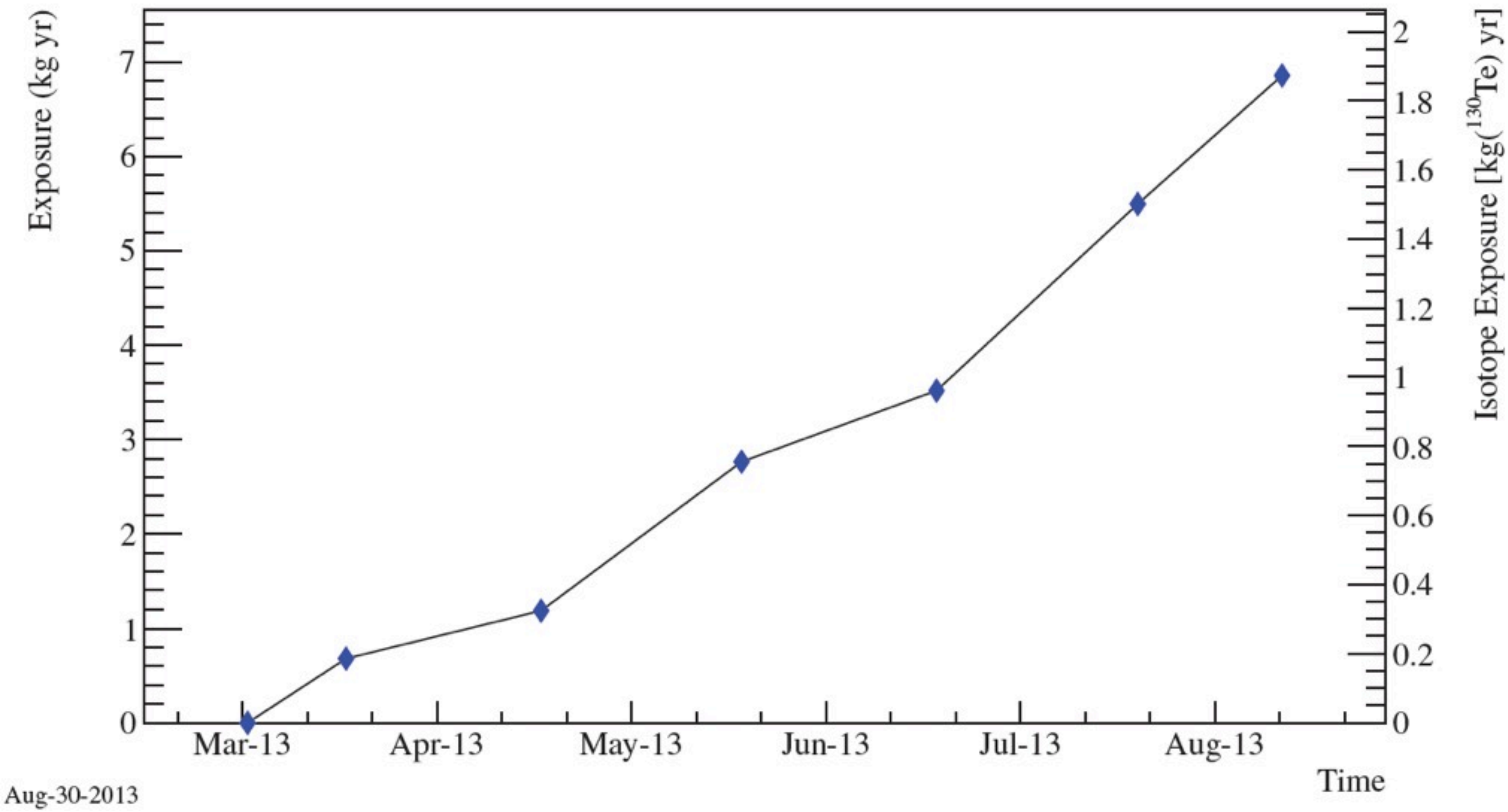


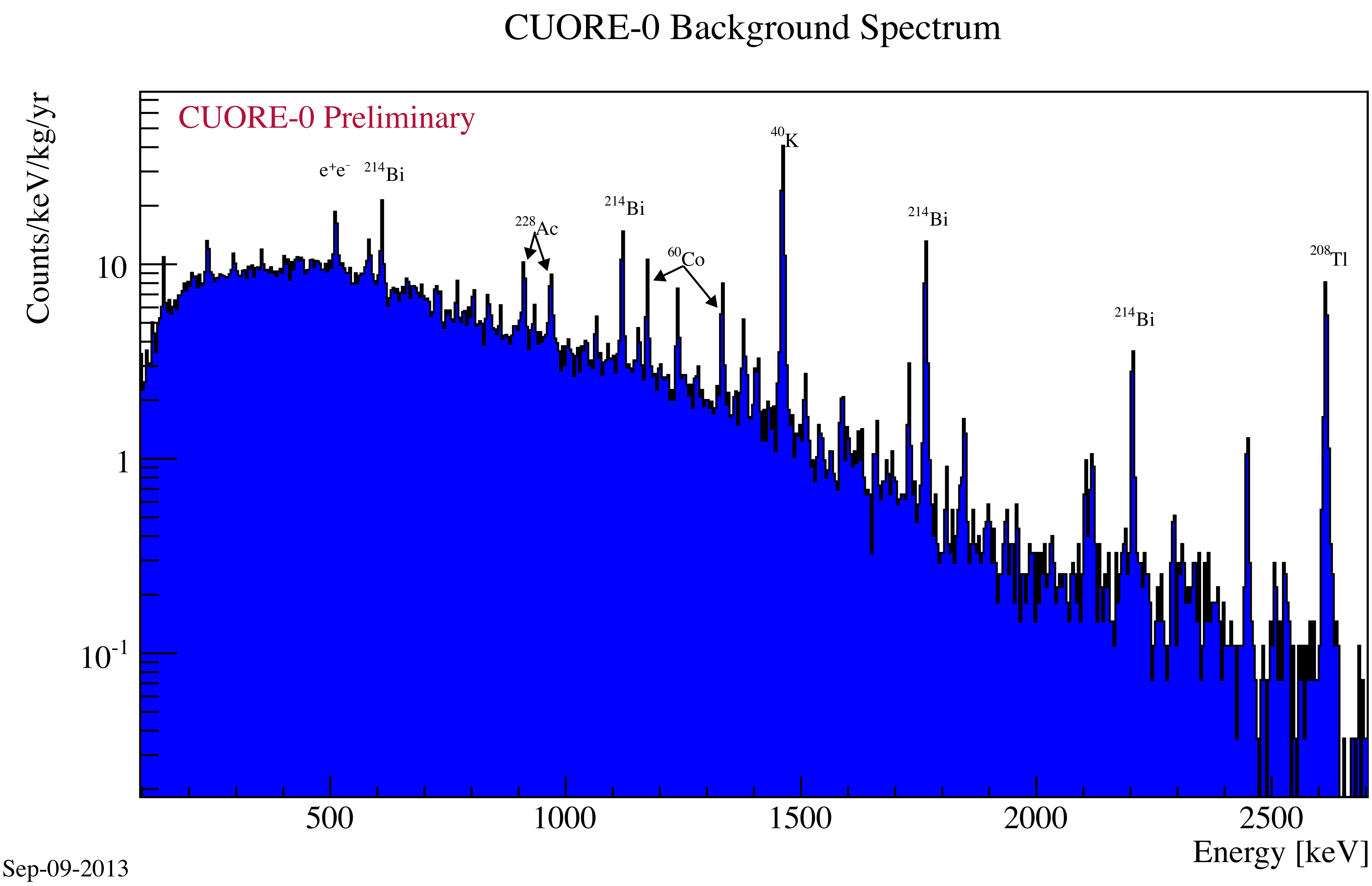
Energy resolution at the ^{208}Tl peak:
calibration spectrum



CUORE0 exposure

Data taking since May 2013

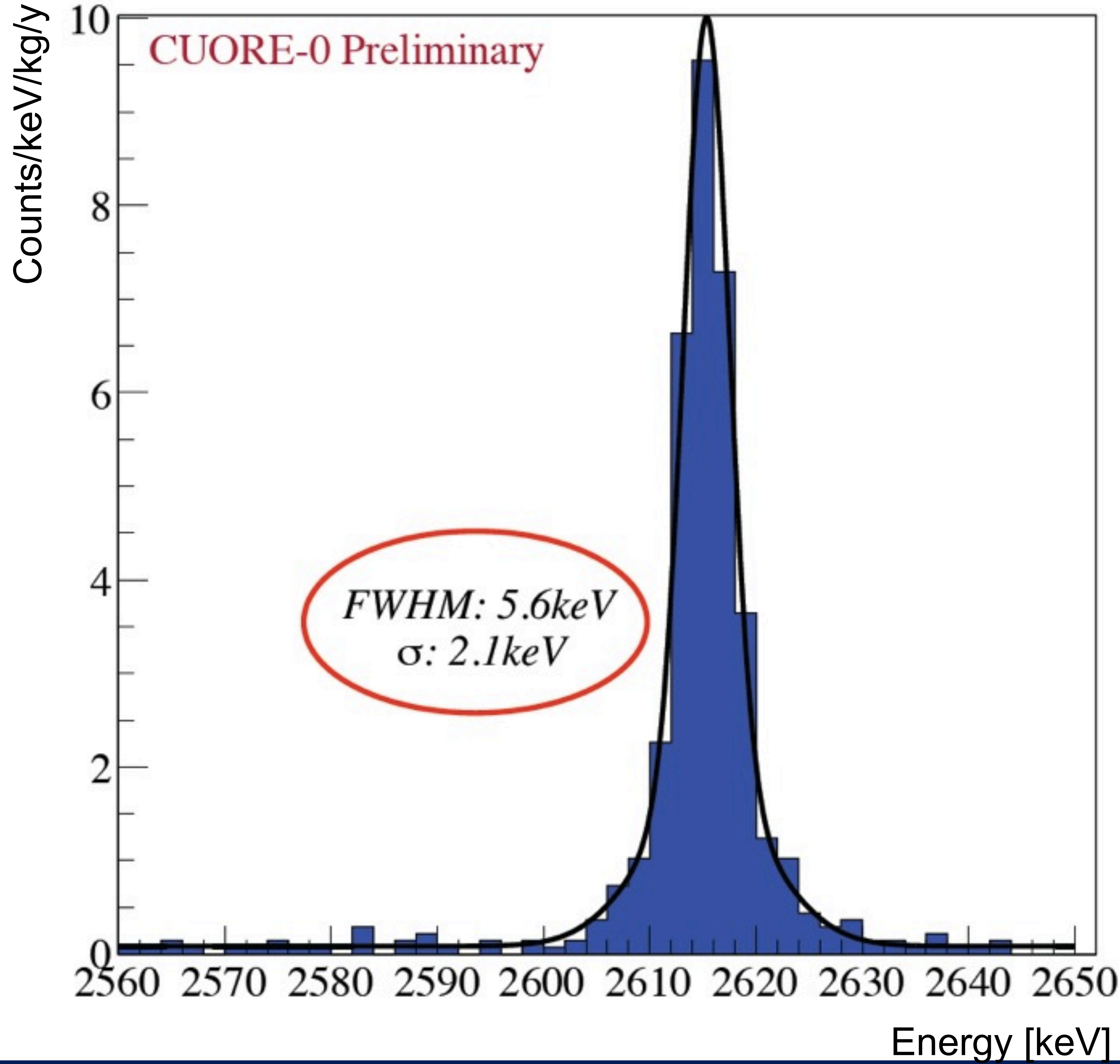


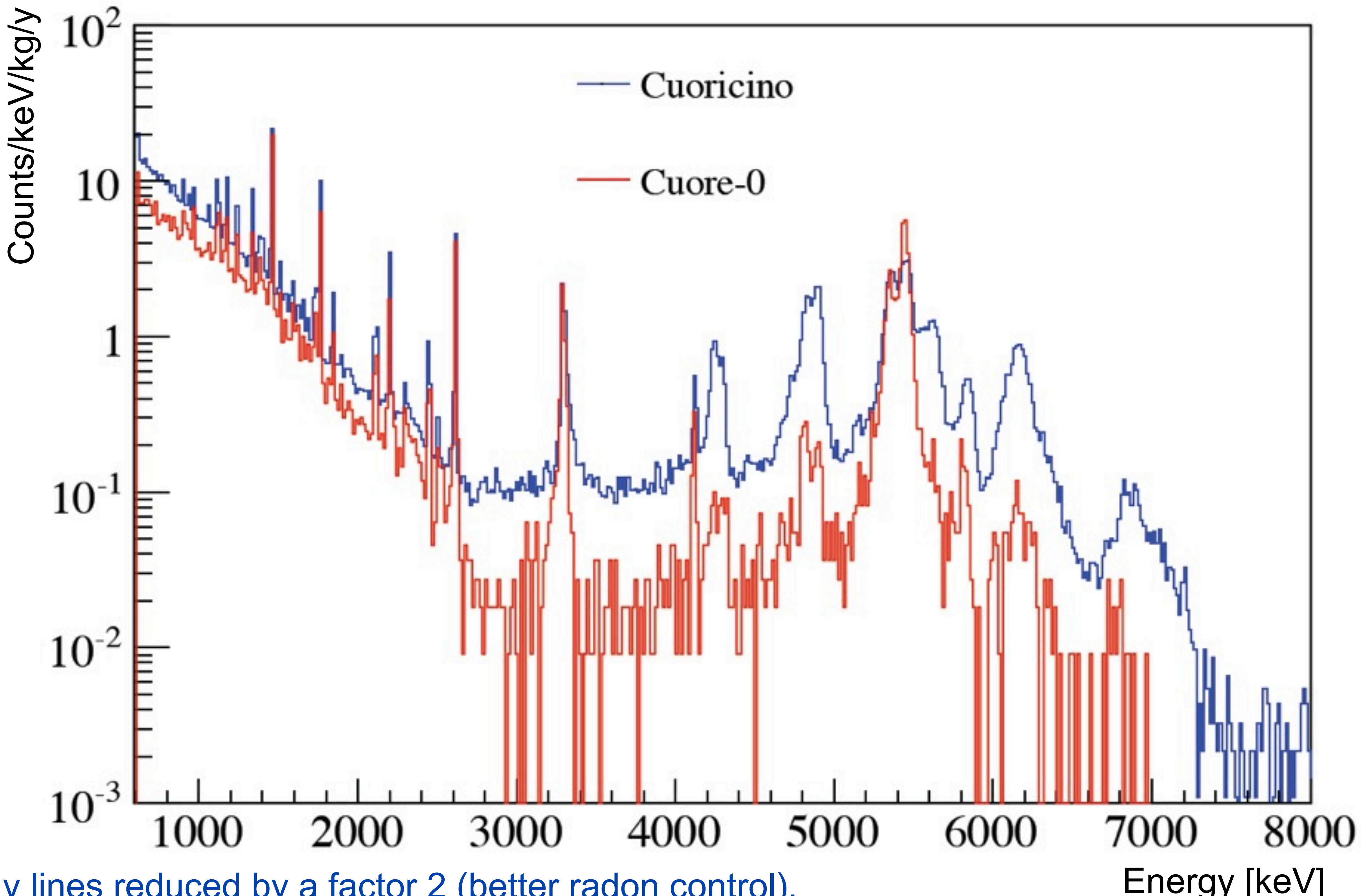


CUORE-0 Background Spectrum
CUORE-0 Preliminary
Counts/keV/kg/yr
Energy [keV]
e+e-
214Bi
228Ac
214Bi
60Co
40K
214Bi
214Bi
208Tl
10
1
10-1
500
1000
1500
2000
2500
Sep-09-2013

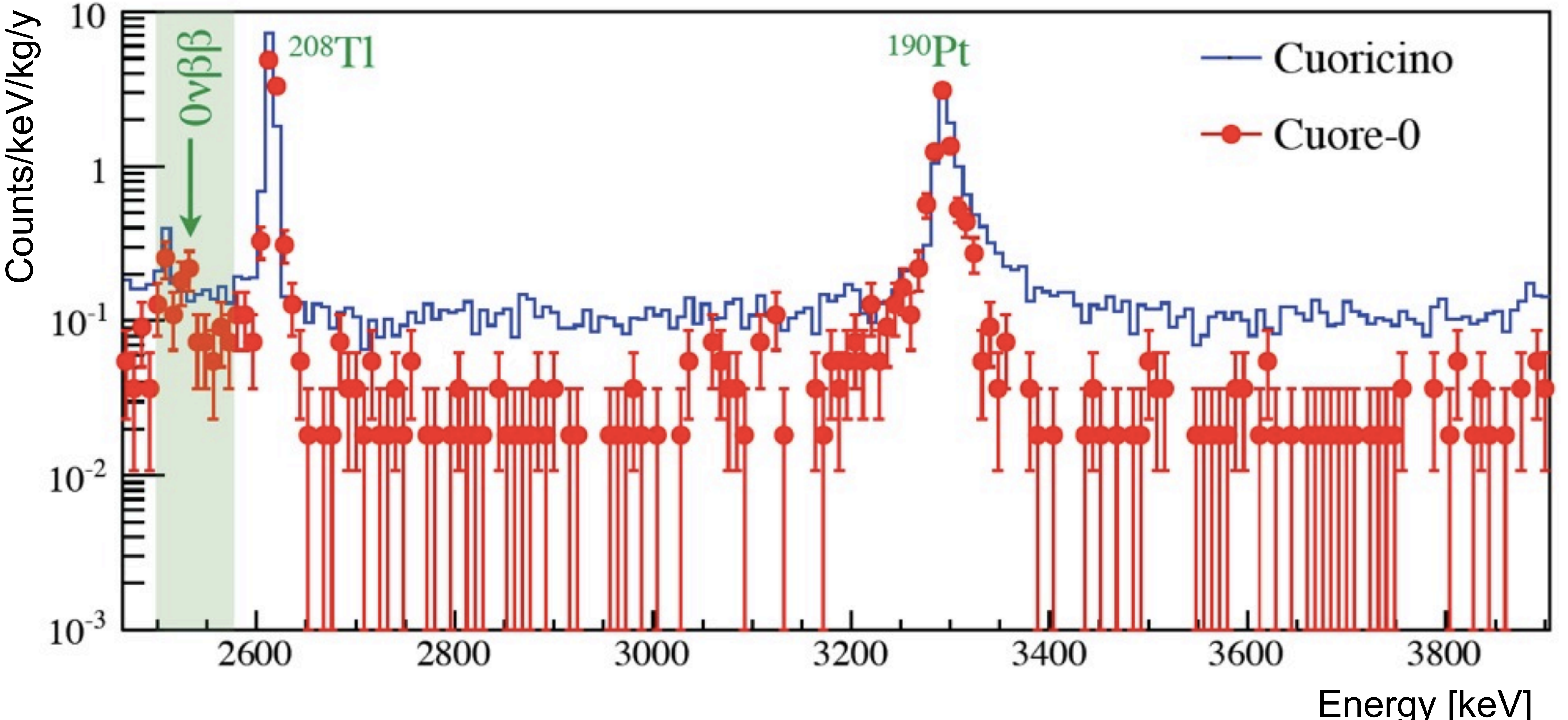
Energy resolution

Energy resolution at the ^{208}Tl peak: background spectrum





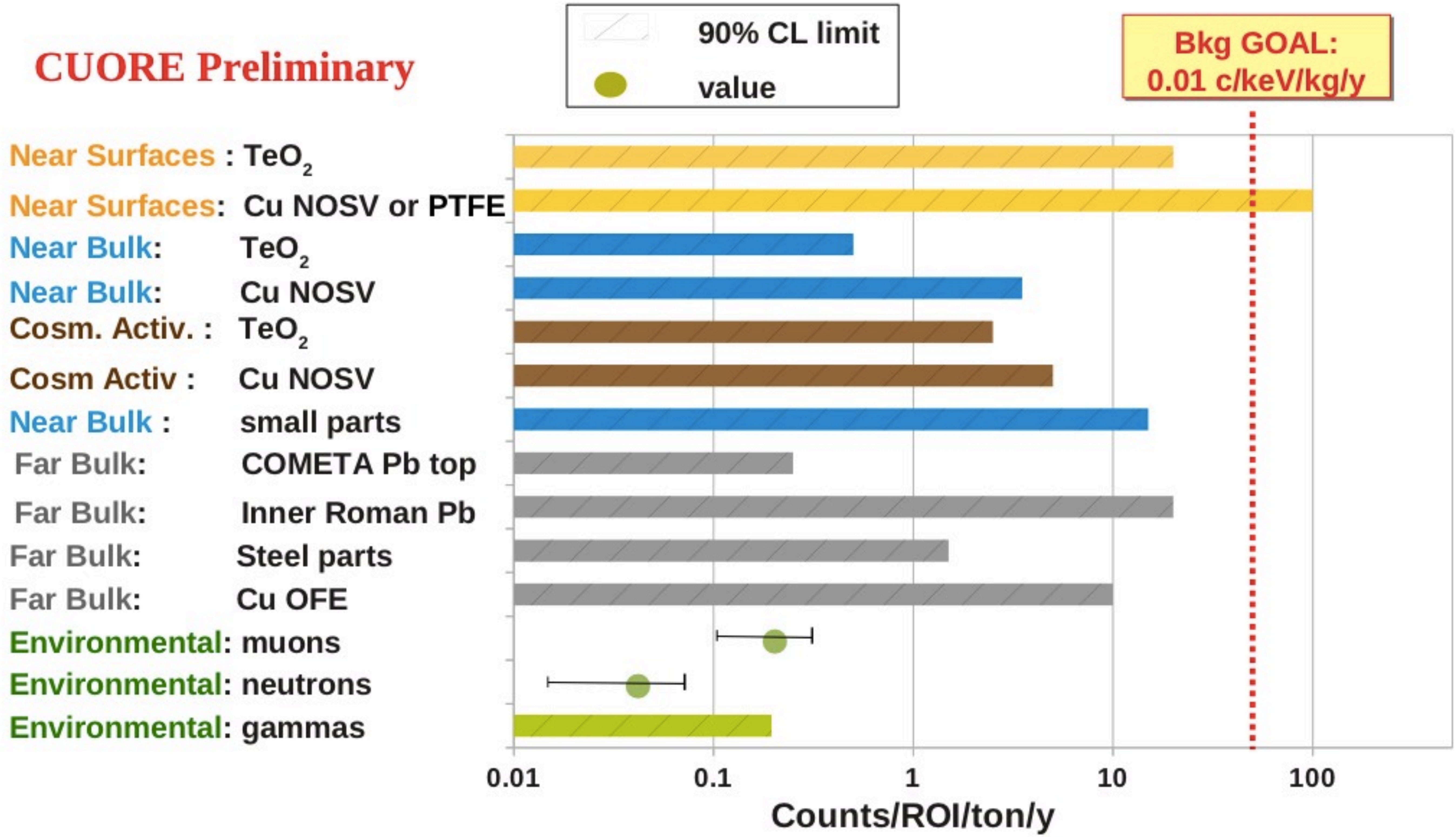
^{238}U γ lines reduced by a factor 2 (better radon control),
^{232}Th γ lines not reduced (originate from the cryostat).
^{238}U and ^{232}Th α lines reduced thanks to the new detector surface treatment.



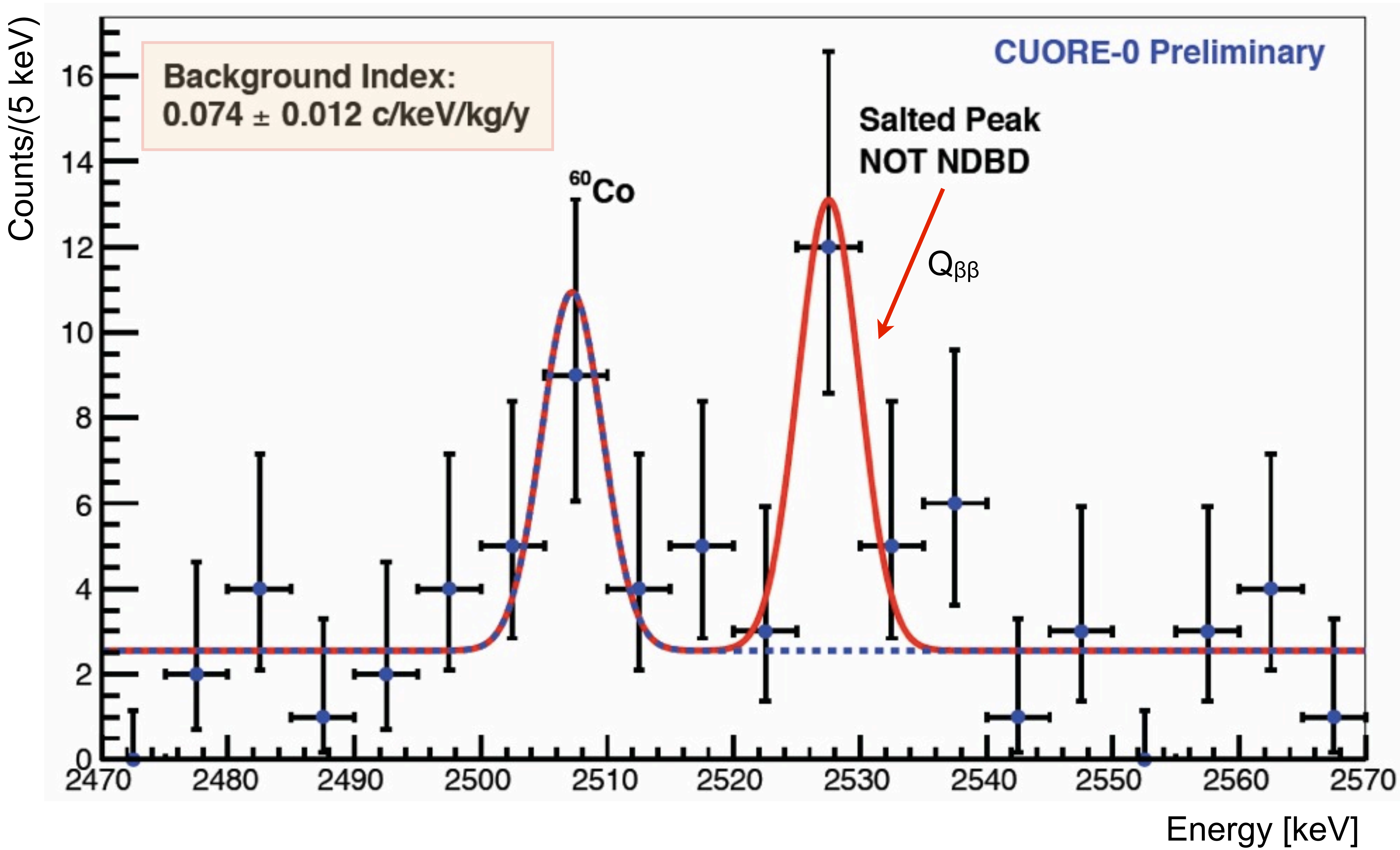
	Avg. flat bkg. [counts/keV/kg/y]		Signal eff. [%]
	0νββ region	**2700-3900 keV**	**(detector+cuts)**
CUORICINO	0.153 ± 0.006	0.110 ± 0.001	83 ± 1
CUORE0	0.074 ± 0.012	0.019 ± 0.002	78 ± 1

includes containment $\varepsilon_{\beta\beta}$ = 87.4%

CUORE background budget

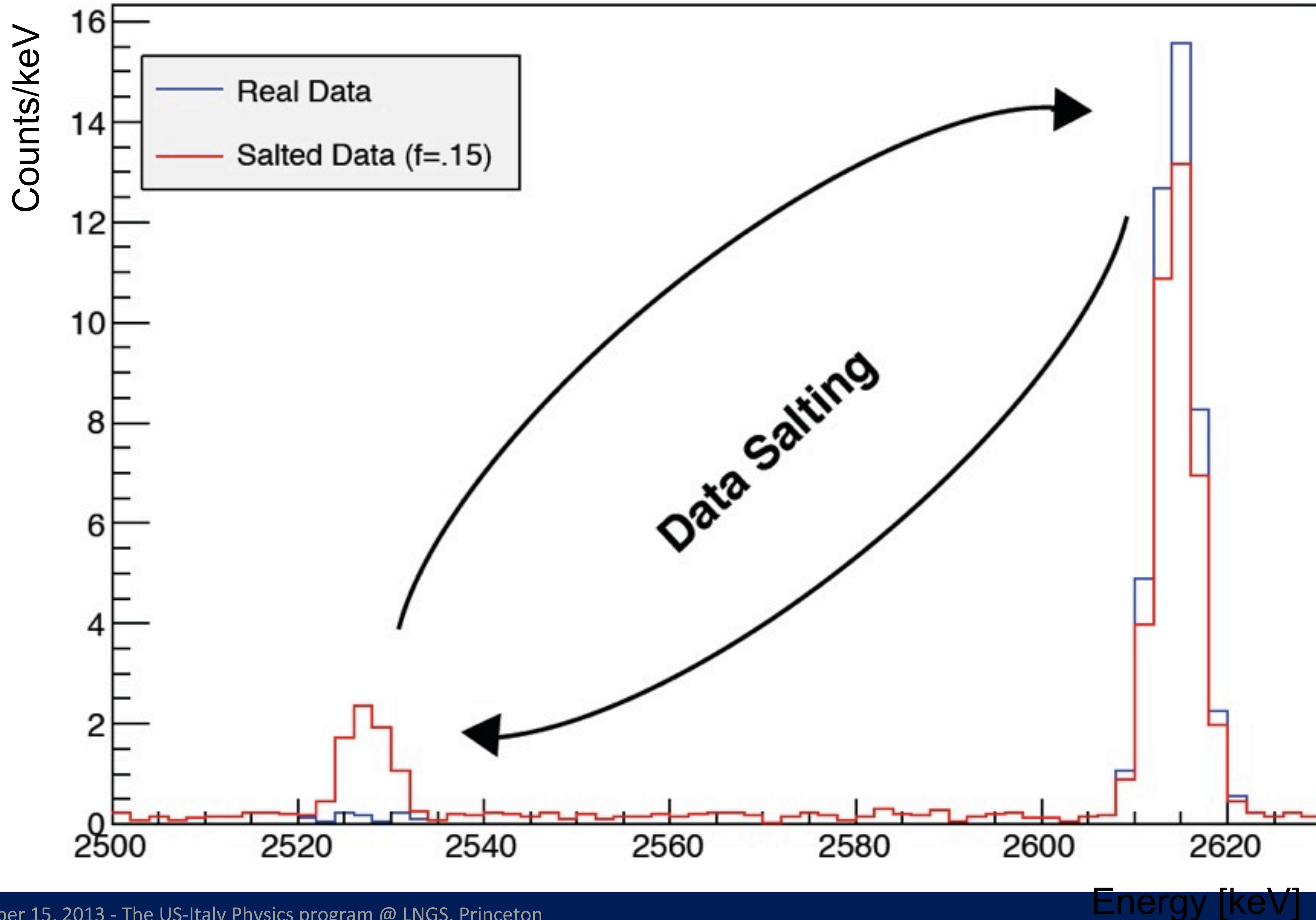


0νββ region: CUORE0 blind analysis

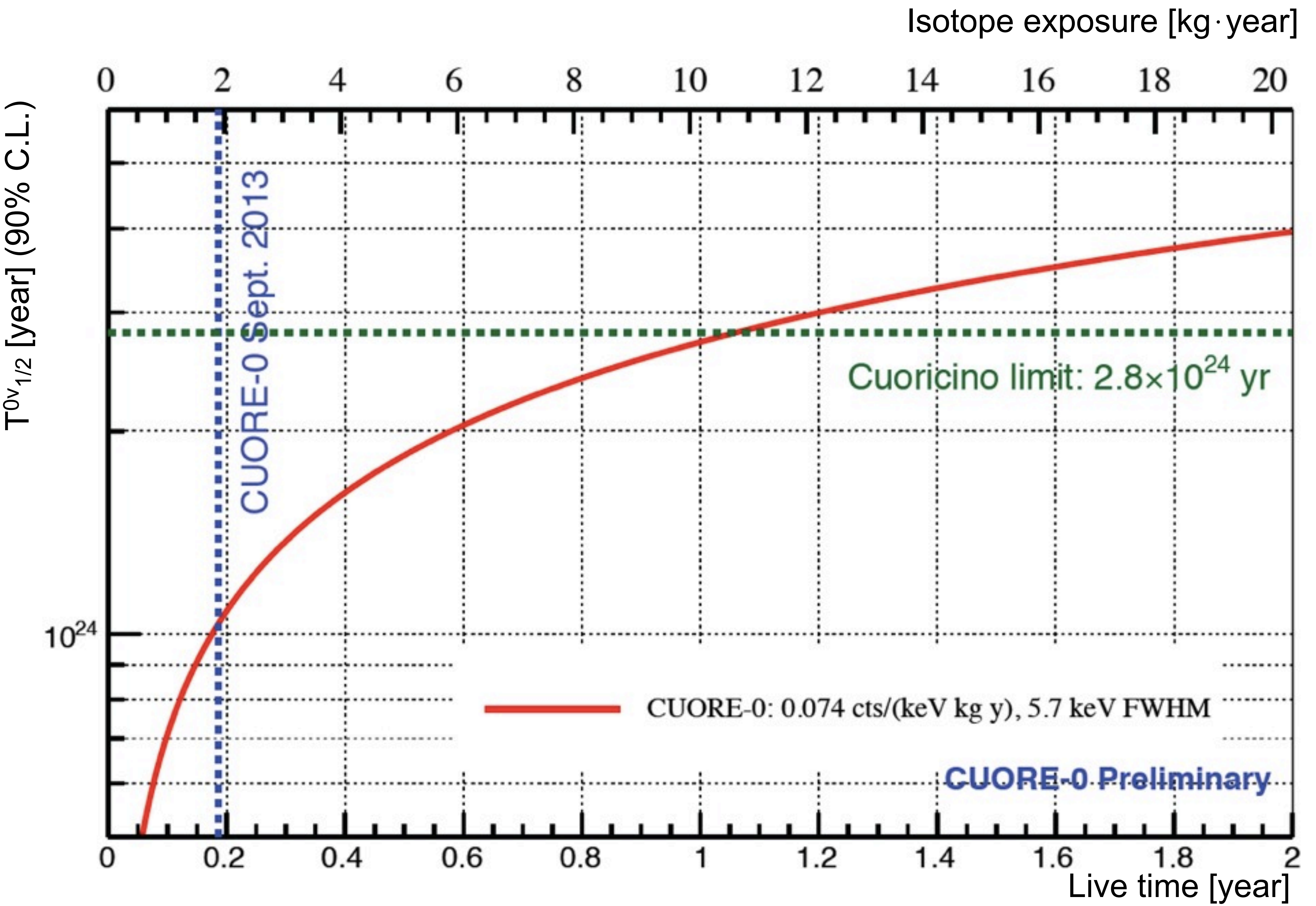


CUORE0 blinding

Exchange a small (and blinded) fraction of ^{208}Tl events (2615 keV) with events in the **0**νββ region, producing a fake peak

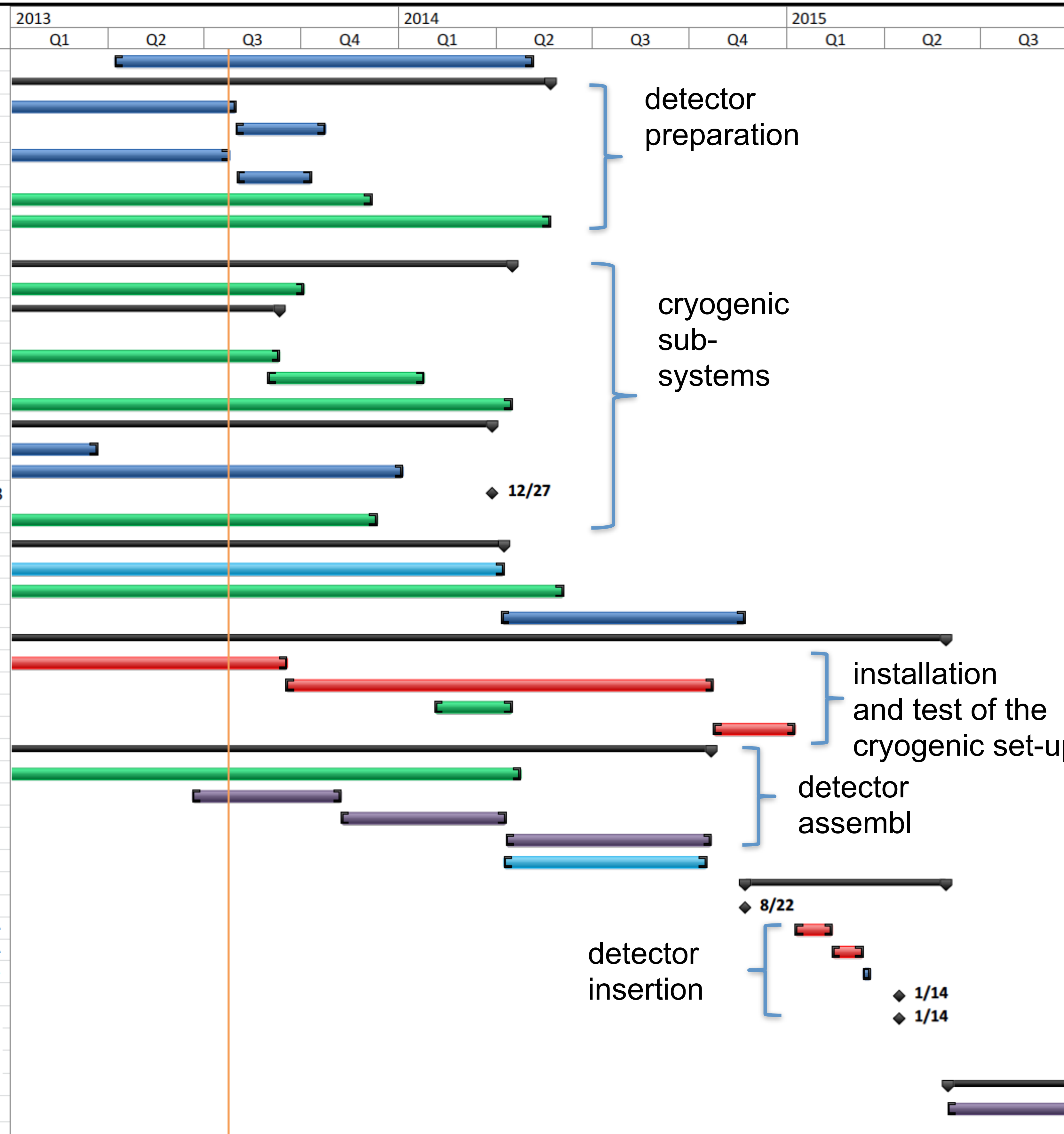


CUORE0 sensitivity



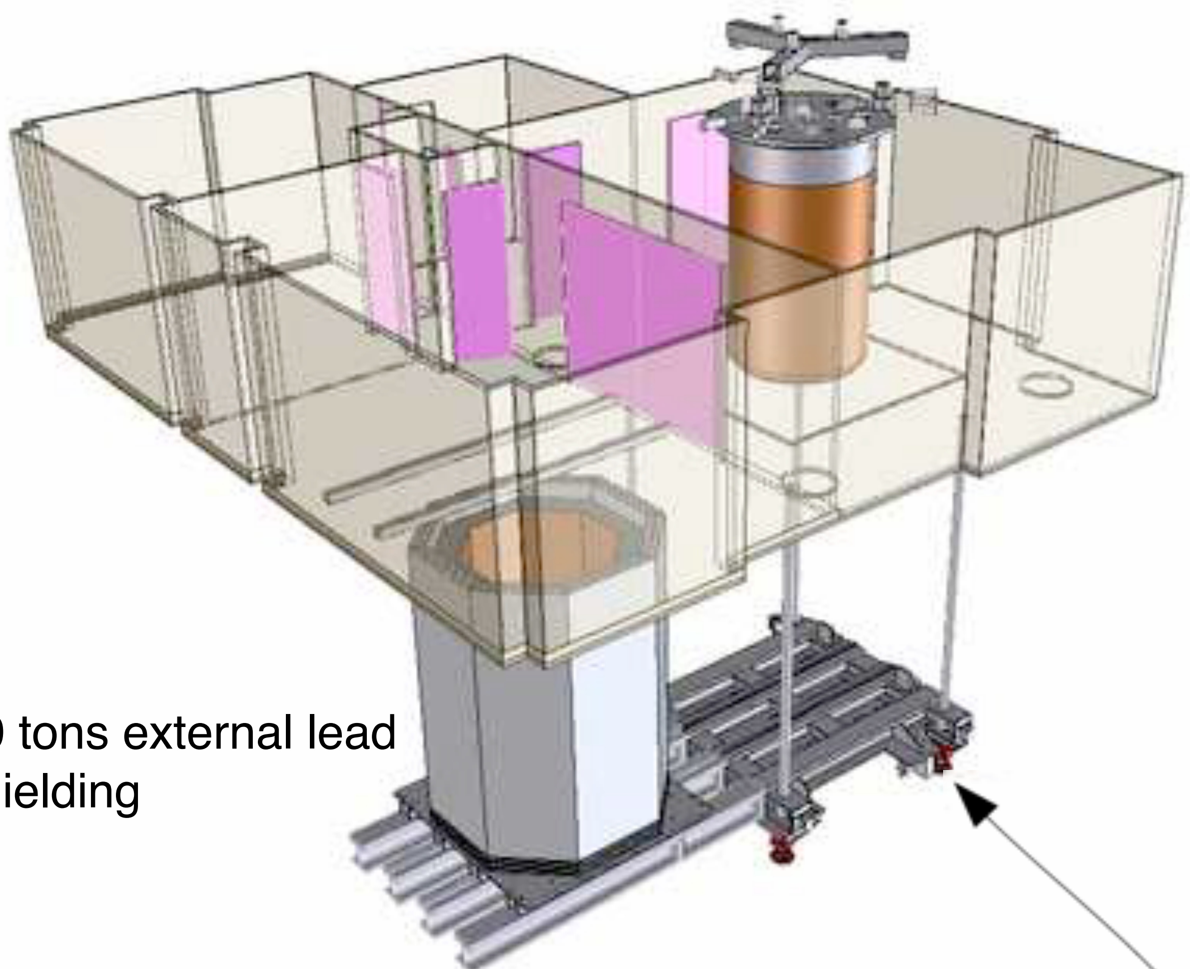
CUORE schedule

Task Name	Start	Finish
1.0 Hut (Faraday Cage)	**1/7/13**	**2/4/14**
2.0 Detector	**8/1/07**	**2/20/14**
Crystal Procurement	6/30/10	4/30/13
Crystal Refurbishment	5/1/13	7/23/13
Thermistors	3/16/11	4/24/13
Thermistors (spares)	5/2/13	7/10/13
Structure - Design, Prod.	8/1/07	9/5/13
Surface Cleaning	4/16/12	2/20/14
3.0 Cryogenics	**8/1/07**	**1/15/14**
3.1 Cryo Design & Construction	**8/1/07**	**1/15/14**
Cooling Units and Test Dewar	8/1/07	7/3/13
Cryostat Construction	**5/10/10**	**6/10/13**
300K - 4K Chamber Fab	5/10/10	7/23/12
600mK - MC Fab	8/17/12	6/10/13
Wiring for Commissioning	5/31/13	10/24/13
Internal Lead Shielding	12/1/08	1/15/14
3.2 Calibration System	**4/23/09**	**12/27/13**
Calibration Prototypes	4/23/09	12/21/12
Calibration Construction and Testing	7/2/12	10/4/13
Calibration System Fabrication Complete	12/27/13	12/27/13
3.3 Interfaces between Towers and Cryostat	6/20/11	9/10/13
4.0 Front End Electronics	**12/22/09**	**1/7/14**
Elec. Production & Testing	12/22/09	1/7/14
5.0 Data Acquisition Systems	1/9/12	3/4/14
6.0 Data Analysis Tools	**1/6/14**	**8/22/14**
7.0 Assembly Integration & Test	**5/7/12**	**2/27/15**
Initial Installation and 4K Tests - Commissioning Phase I	7/31/12	6/17/13
Base T no Load - Commissioning Phase II	6/17/13	7/23/14
Installation of external shield	11/4/13	1/15/14
Base T Full Load - Commissioning Phase III	7/24/14	10/8/14
7.3 Tower Assembly & Integration	**5/7/12**	**7/21/14**
Crystal Gluing	5/7/12	1/23/14
Assemble Towers 1 to 5	3/21/13	8/7/13
Assemble Towers 6 to 11	8/8/13	1/9/14
Assemble Towers 12 to 19	1/10/14	7/21/14
7.4 Electronics Install & Commissioning	**1/8/14**	**7/17/14**
7.5 Detector Insertion & Sys. Testing	**8/22/14**	**2/27/15**
US Scope Complete	8/22/14	8/22/14
Open and prepare for Installation	10/9/14	11/12/14
Installation of the 19 CUORE Towers	11/13/14	12/11/14
DCS Internal Guide Tube Installation and Connections	12/12/14	12/18/14
Detector Insertion Complete	**1/14/15**	**1/14/15**
System Closeout Complete	**1/14/15**	**1/14/15**
Pre-Ops	**3/2/15**	**8/14/15**
Pre-Ops	3/2/15	8/14/15
Start Data Taking	**8/14/15**	**8/14/15**

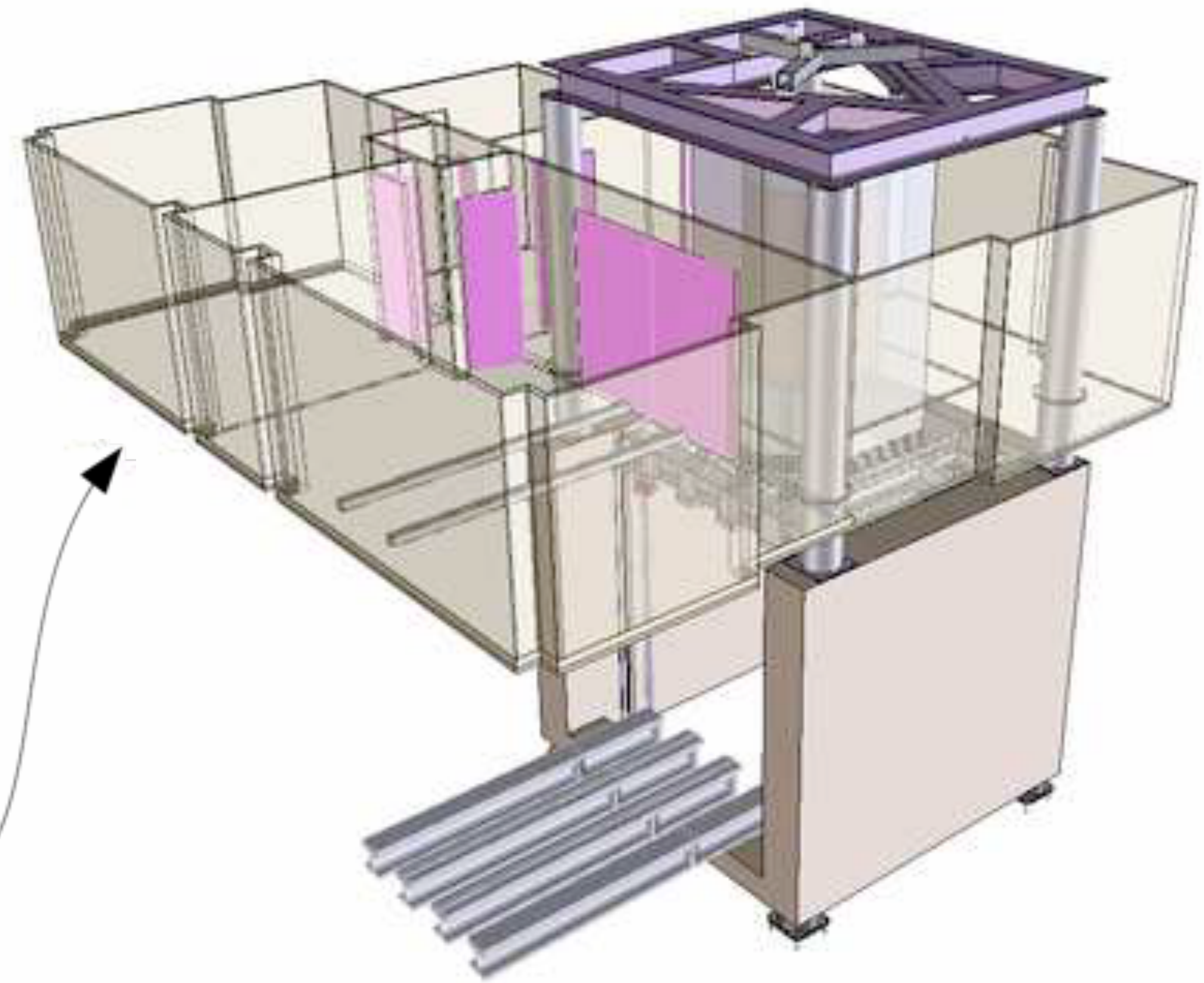


Building

20 tons external lead shielding



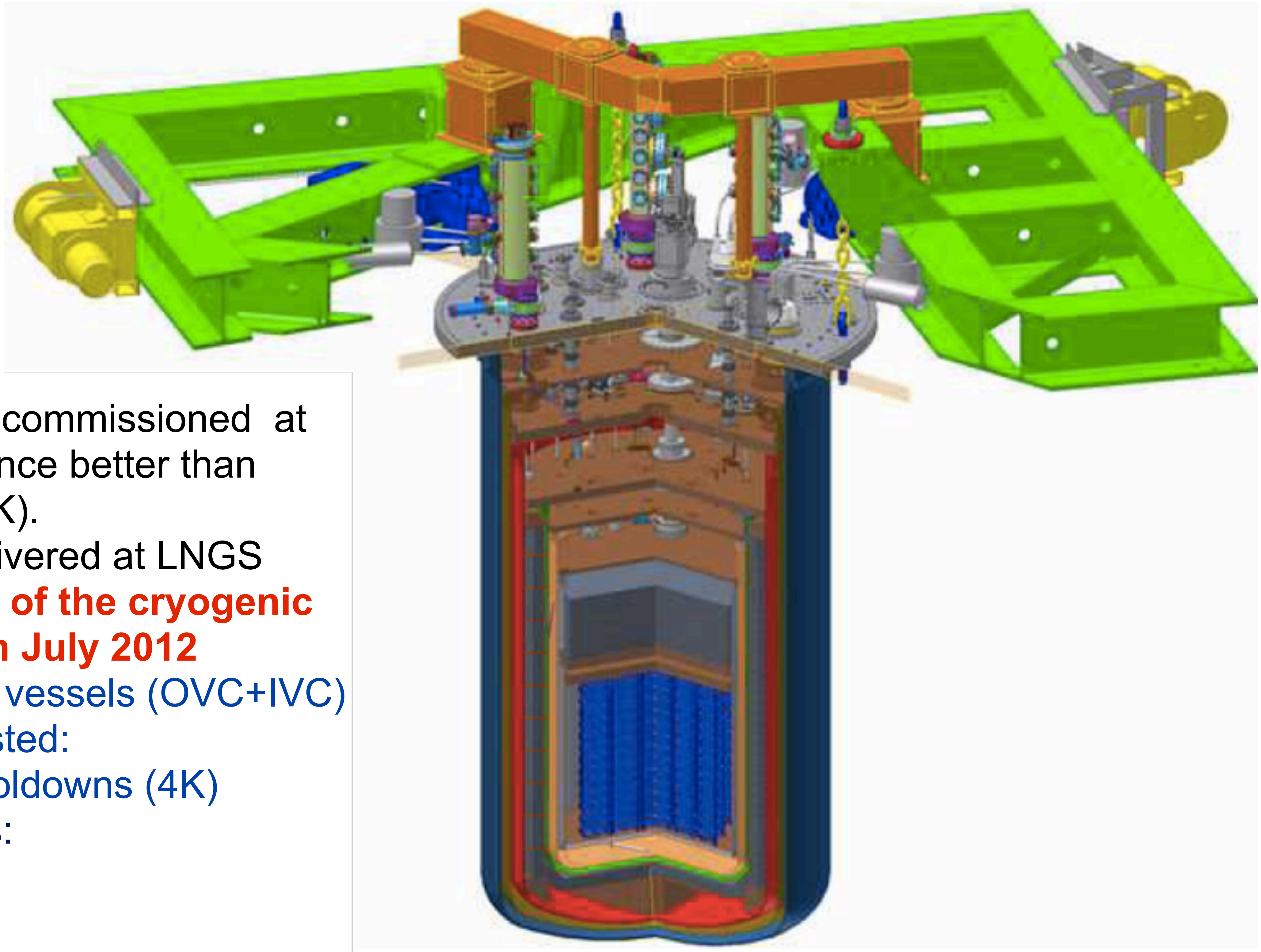
2nd Level
- Top flange access
- Suspension access
- Electronics & DAQ



1st Level
- Cryostat access
- Clean room

ground floor
- services (pumps, DU gas handling, compressors...)
- shields and screens storage

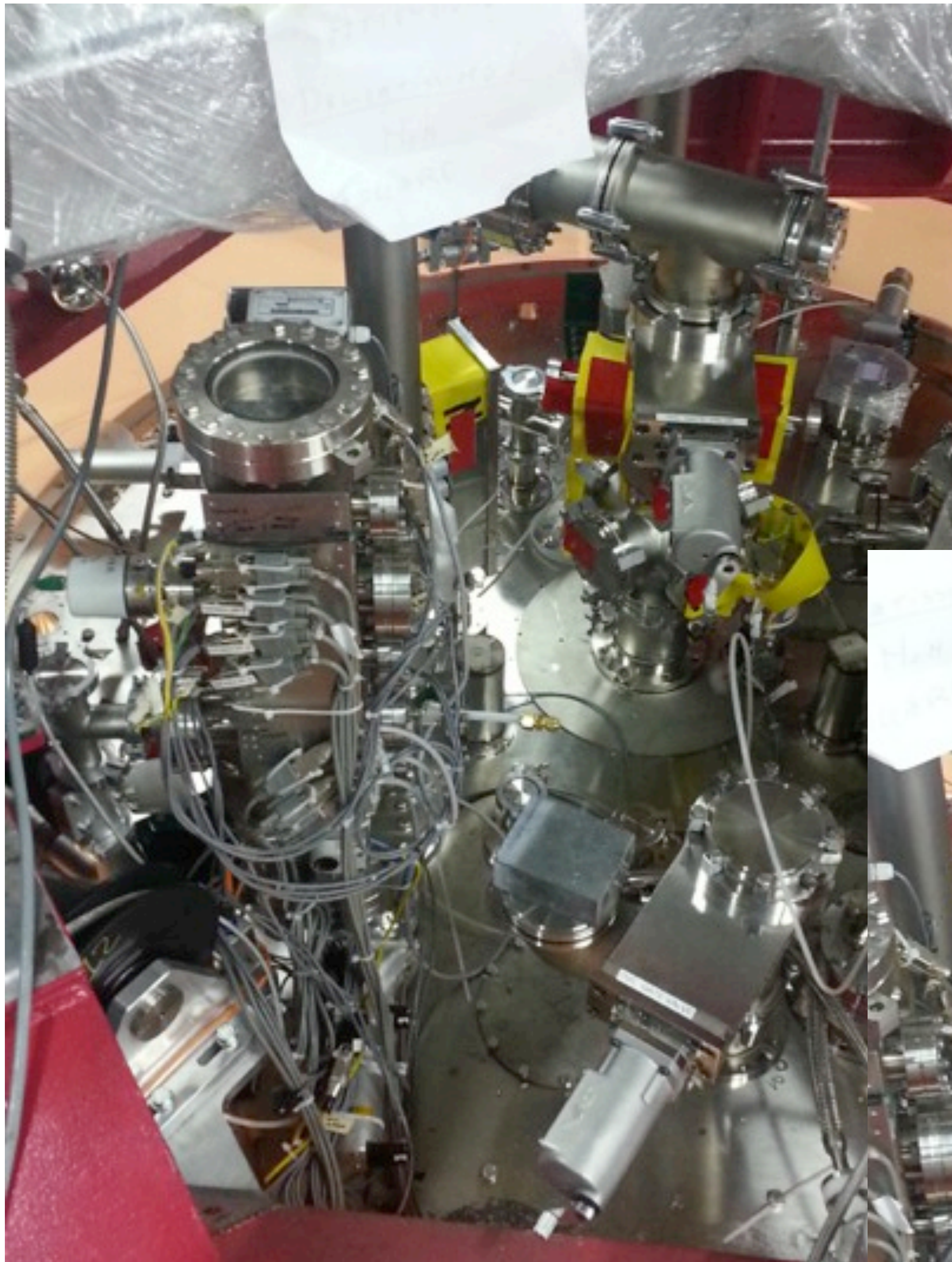
Cryogenic Set-up



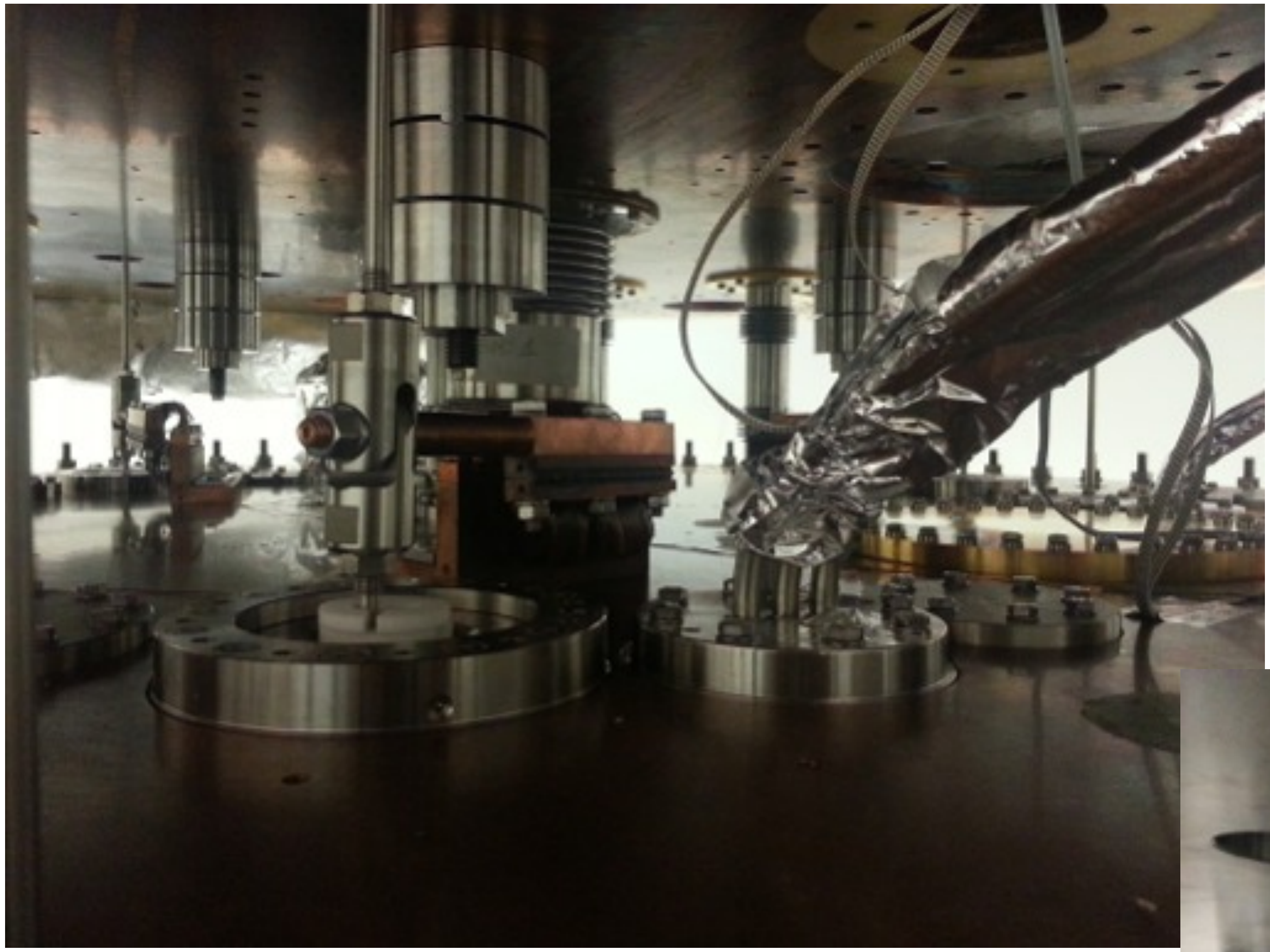
- Dilution unit fully commissioned at LNGS. Performance better than expected (T<5mK).
- Cryostat fully delivered at LNGS
- **Commissioning of the cryogenic setup started on July 2012**
  - 3 (of 6) cryostat vessels (OVC+IVC) installed and tested:
  - 2 successful cooldowns (4K)
  - subsystem tests:
    - suspension
    - DCS
    - cooling units

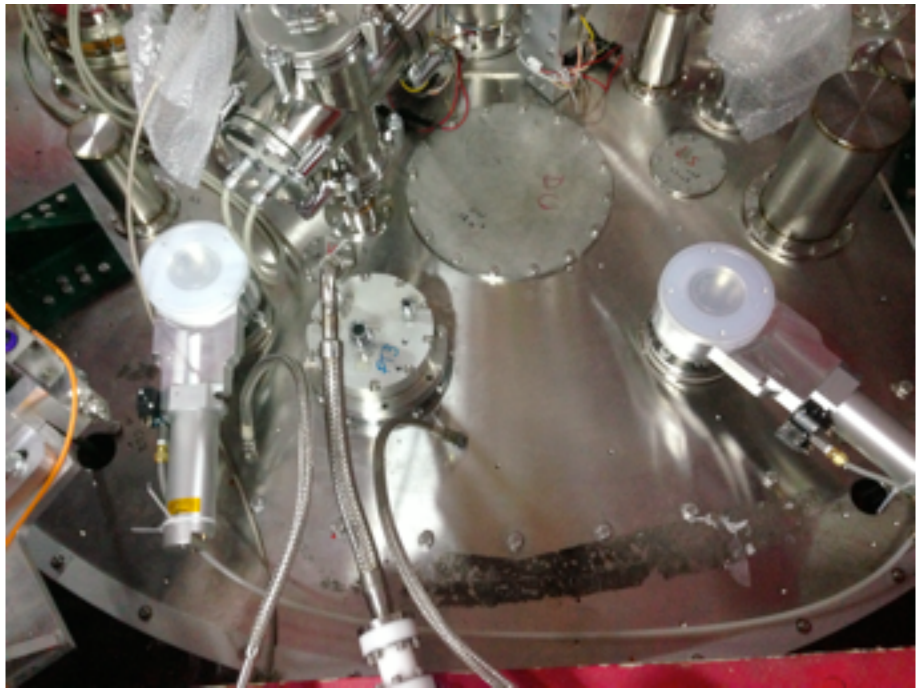
Installation & test

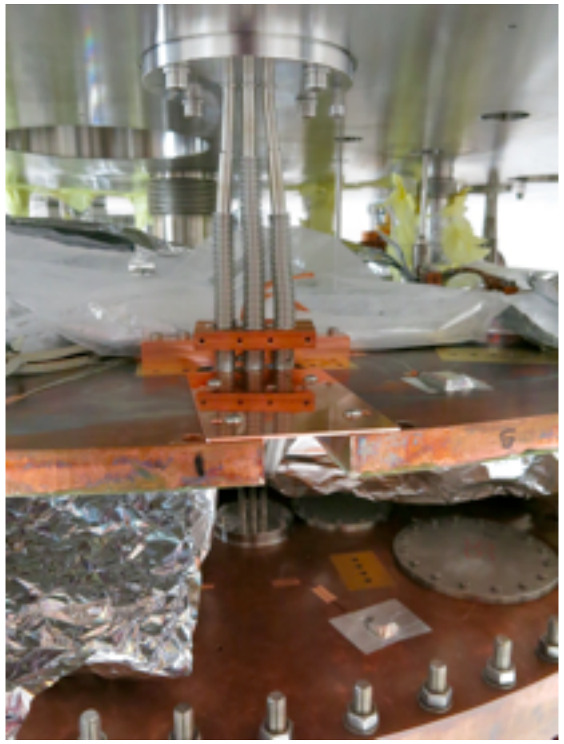
DCS (top view)

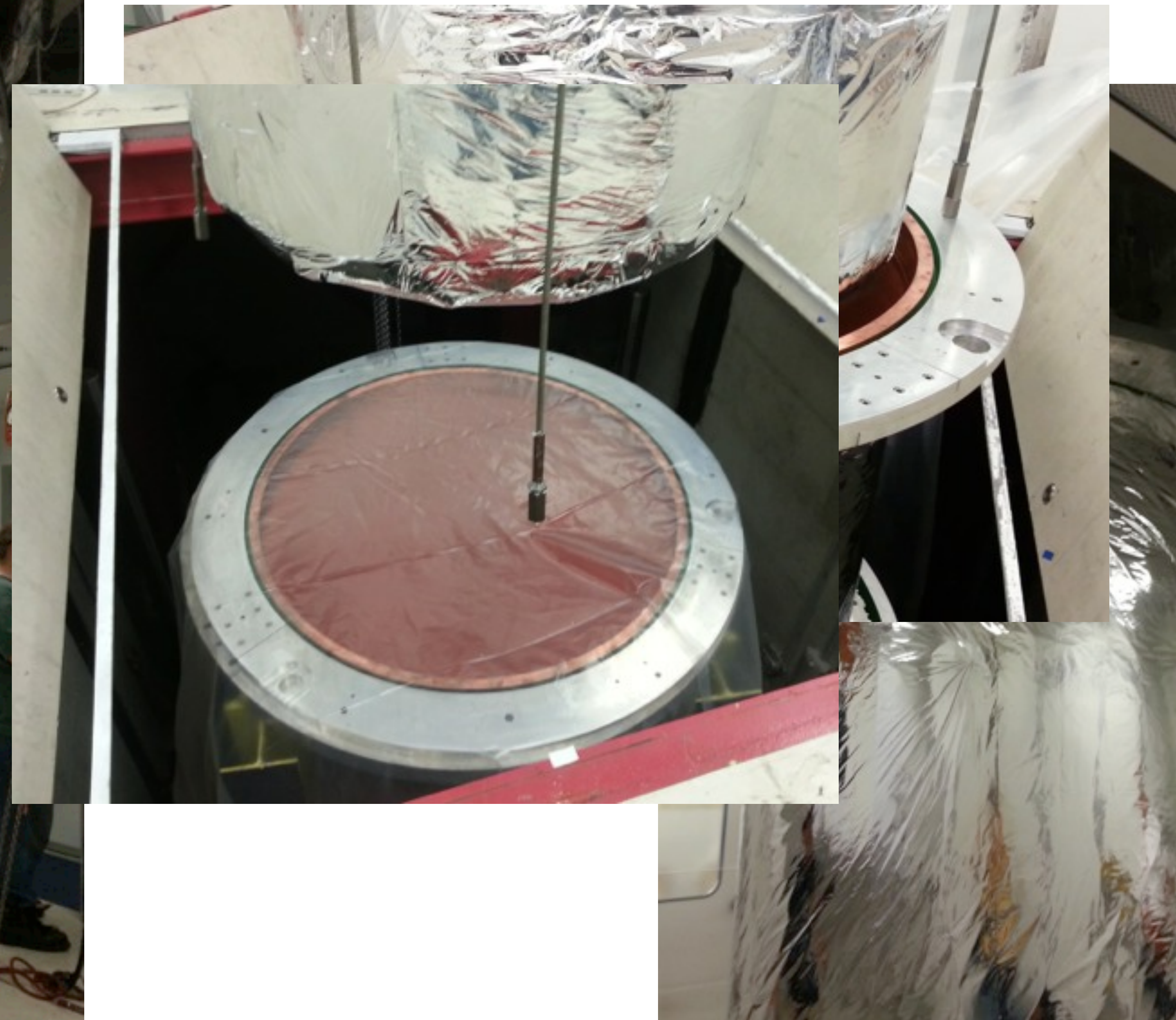


Details inside the cryostat

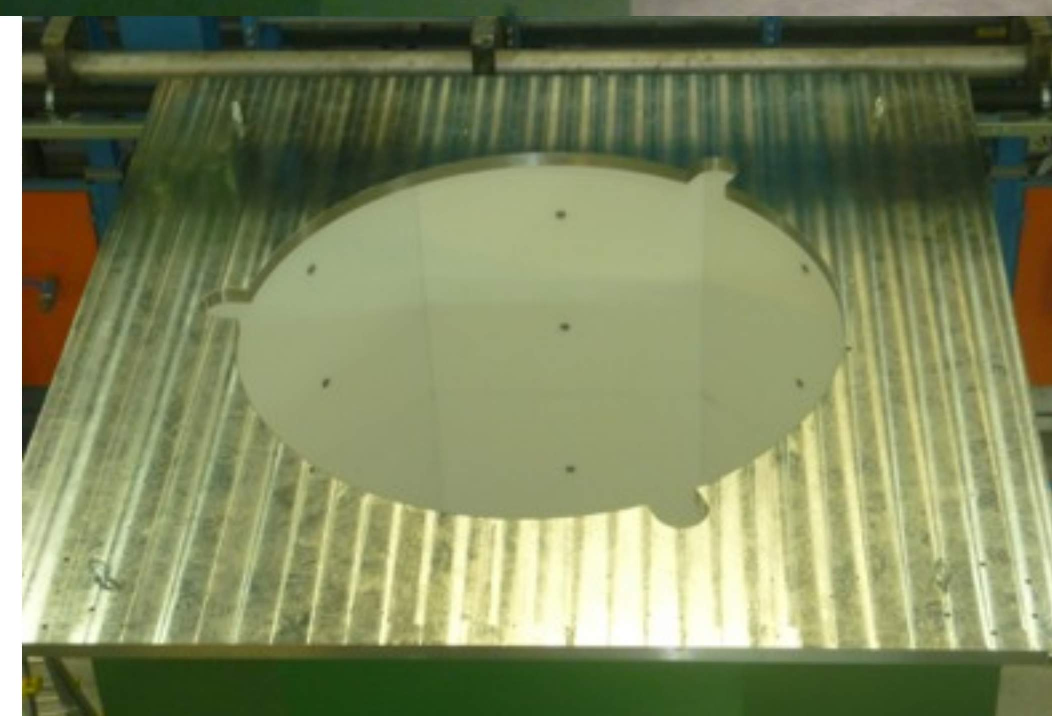




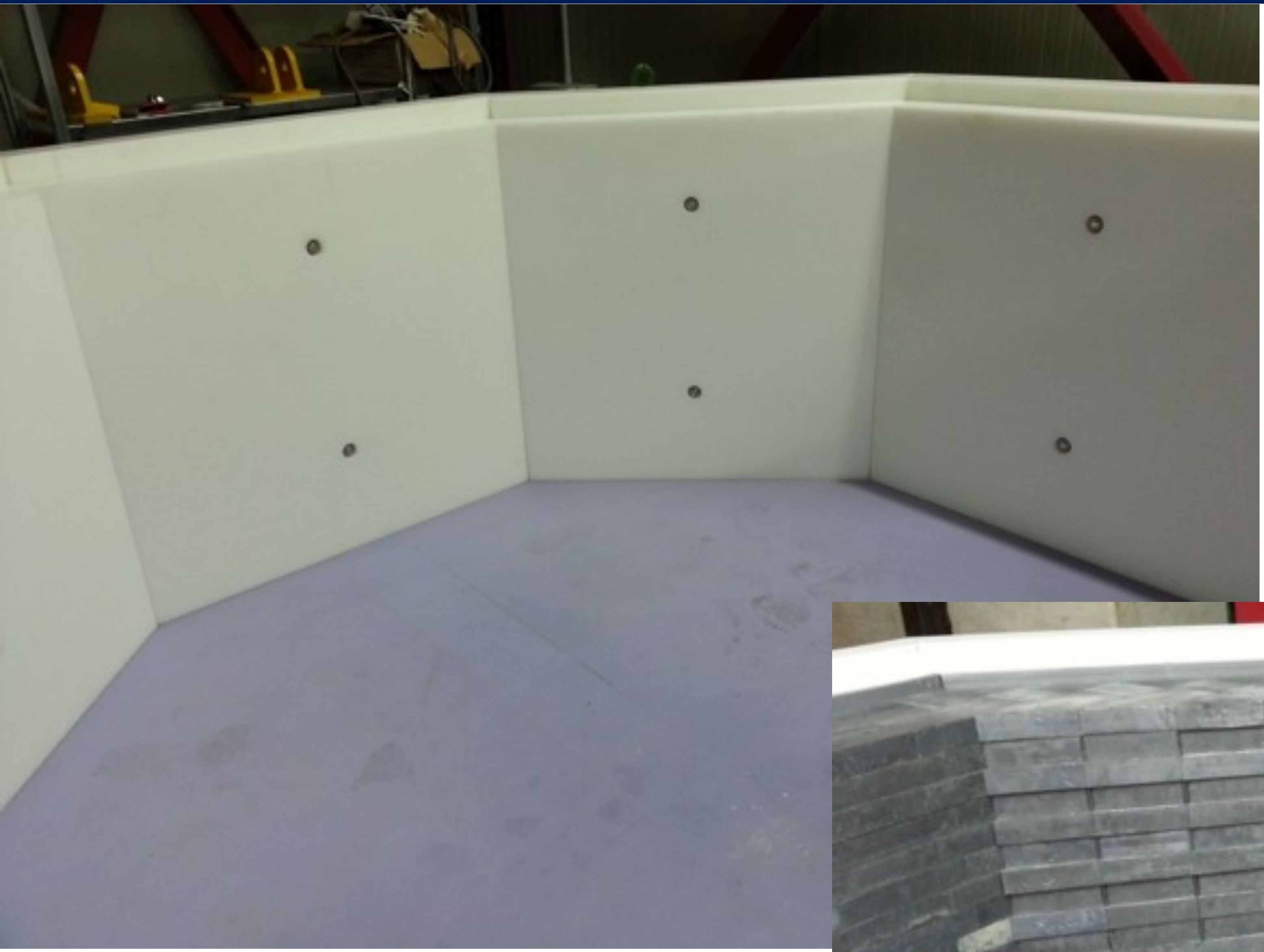


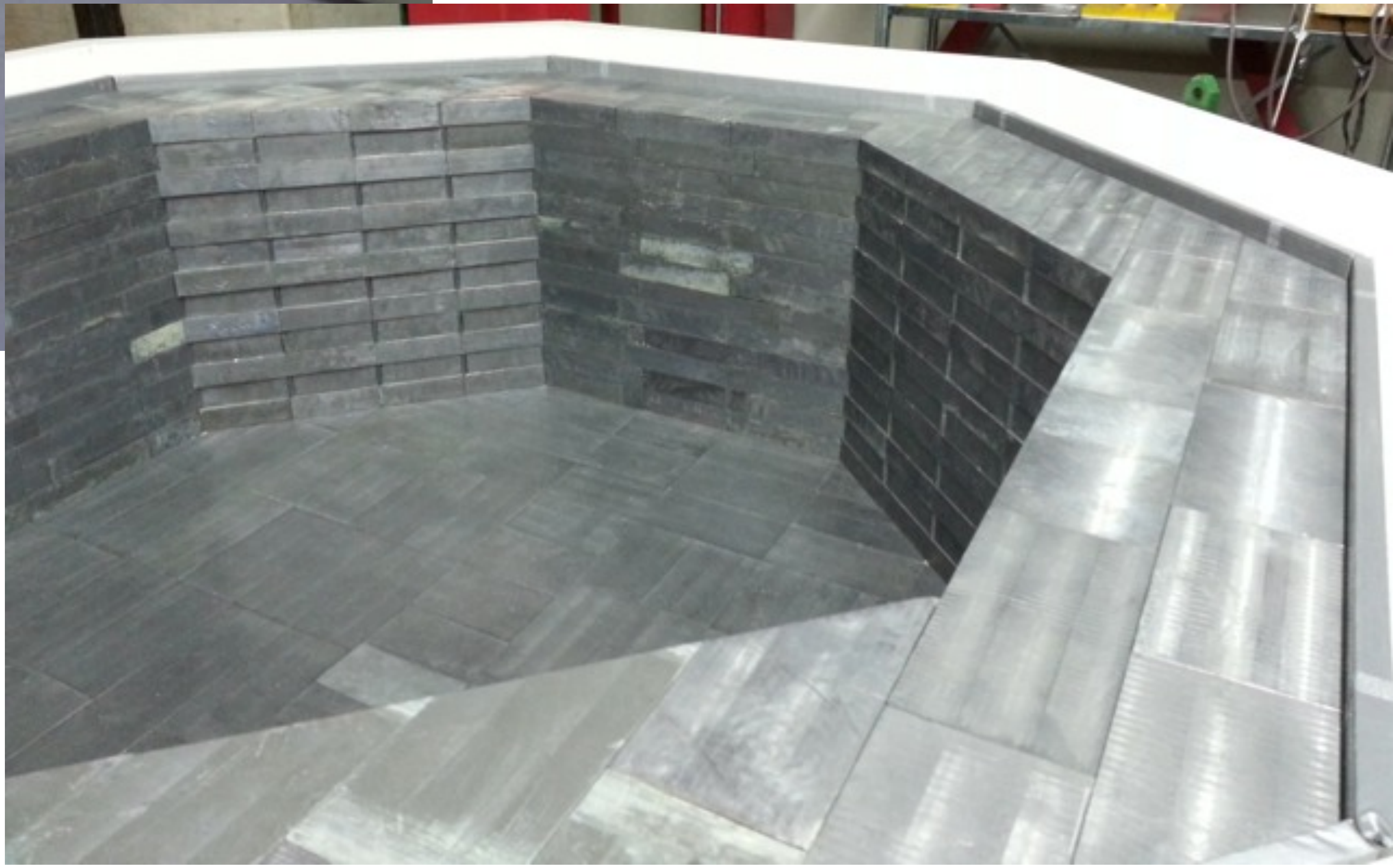


External shield

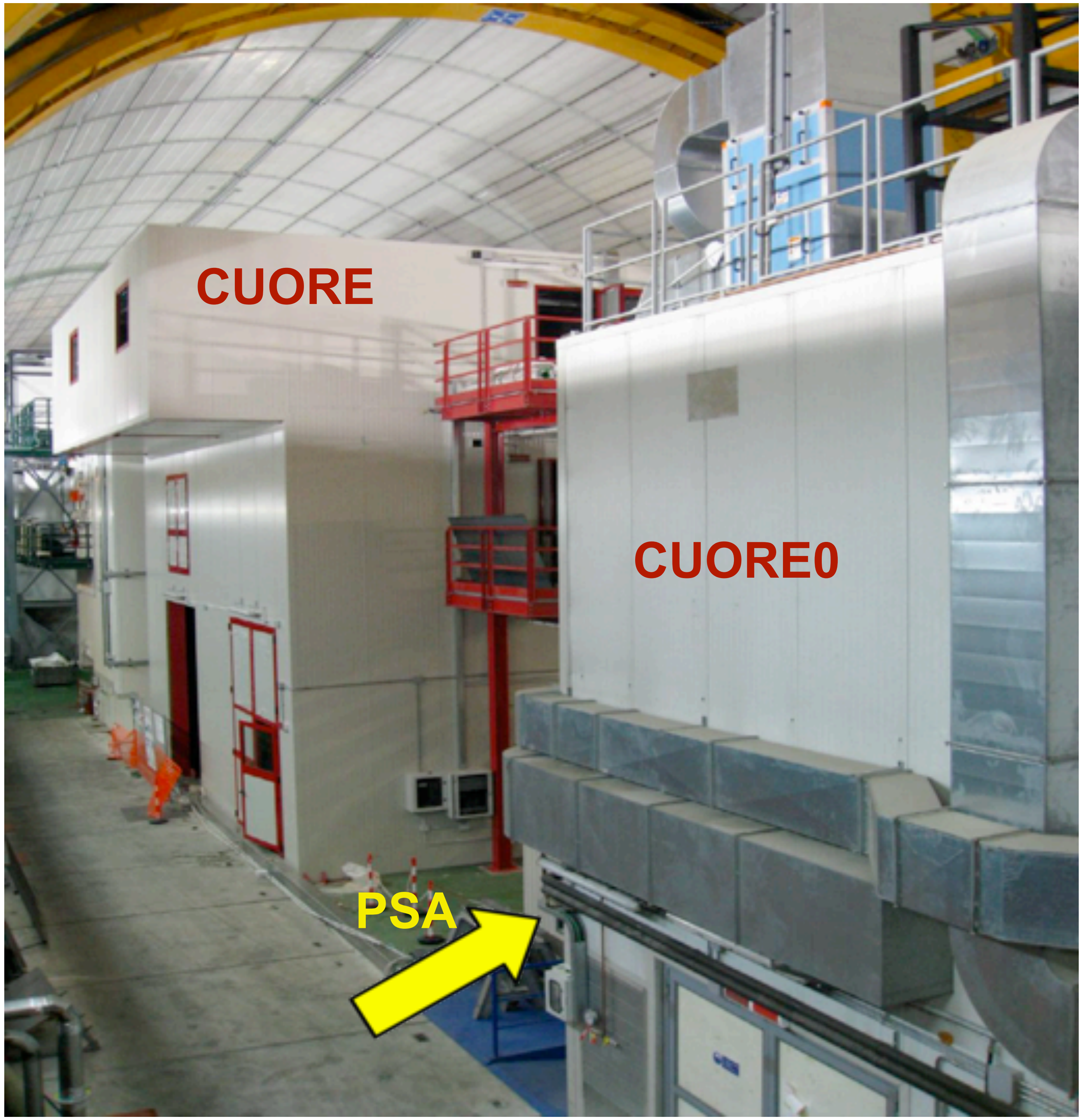


Room Temperature (ext) shield





PSA (Part Storage Area)



- Boxes of glued crystals are put inside N_2-fluxed
- PSA storage cabinets to await assembly

Detector assembly

Organized in 4 main operations

1. Cleaning of the copper wiring strips as well as assembly tools and equipment;
2. Gluing of thermistors and heaters to the TeO_2 crystals;
3. Mechanical assembly of the glued crystals, copper, PTFE, and wire strips into towers;
4. Bonding of Au wires between the crystals' thermistors & heaters and the wire strips

- All activities are carried out inside the clean room on the second floor of the CUORE hut.

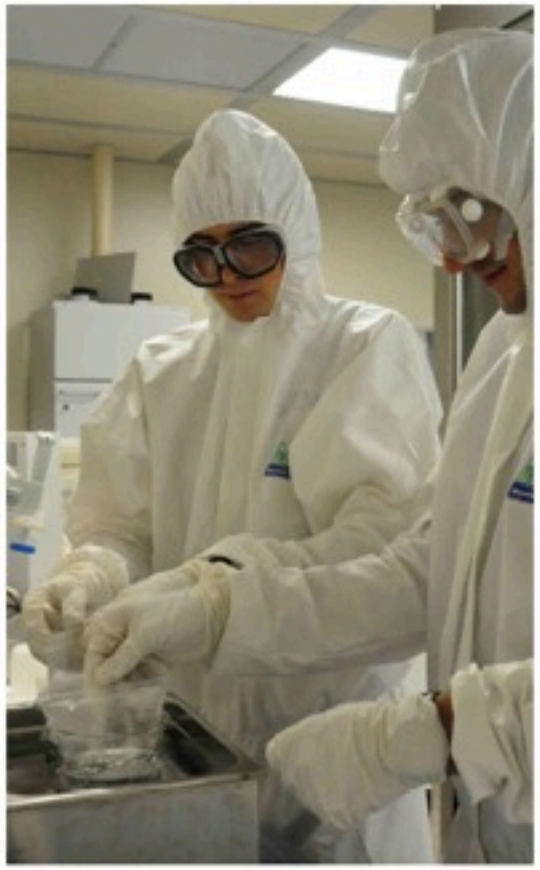
- **Started gluing operations in late February 2013.**

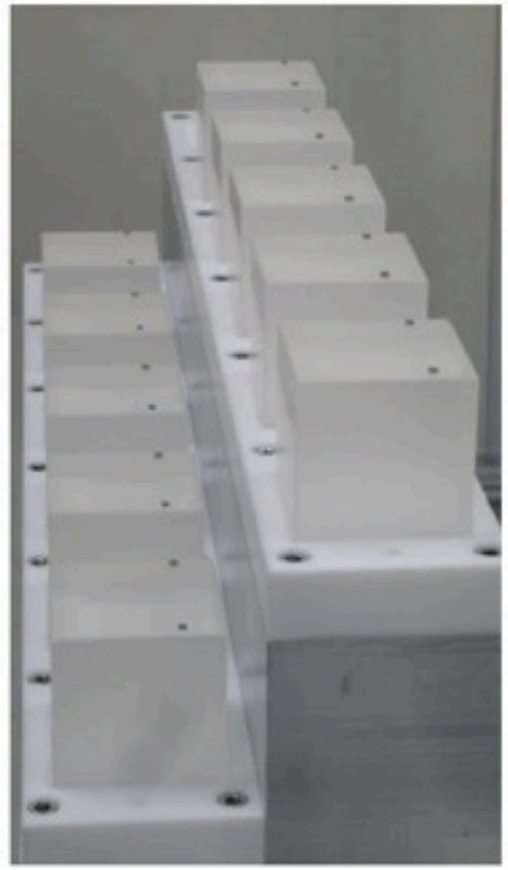
Presently:

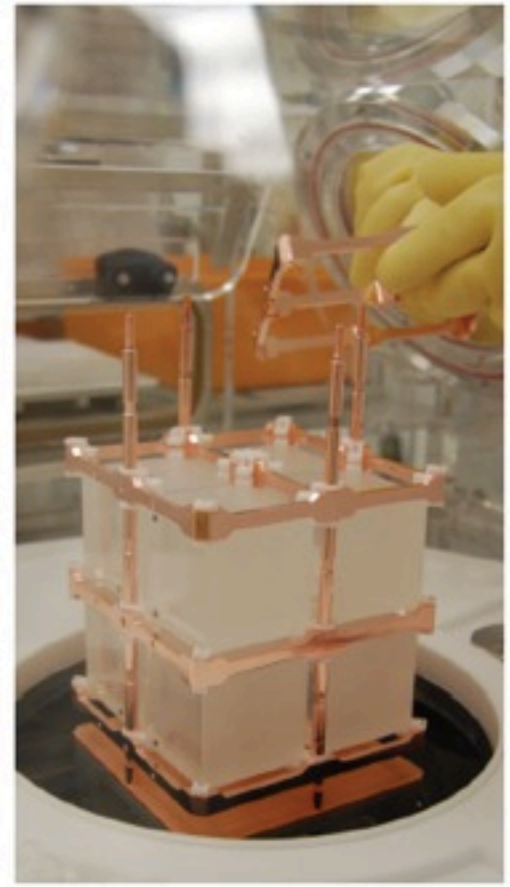
- **glued crystals for about 10.5 towers**
- **assembled (mechanically): 9 towers**
- **bonded: 5 (soon 7).**
- **Bonding problem with T5 and T6. Different recovery options**

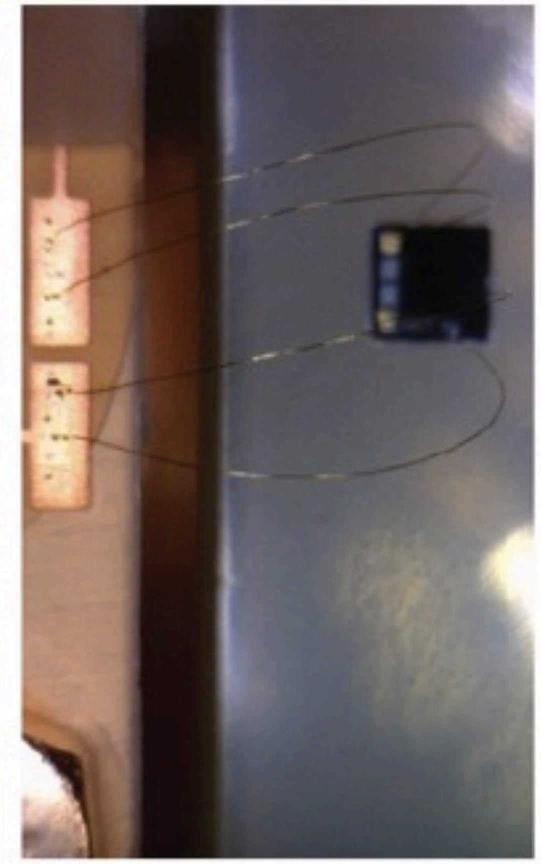
Detector assembly

CLEANING | GLUING | ASSEMBLY | BONDING









CLEANING | GLUING | ASSEMBLY | BONDING

CLEANING

- Gluing consumables
- Periodic cleaning of glove boxes (every ~ 3 towers)

GLUING

- Attach NTDs & heaters to crystals

ASSEMBLY

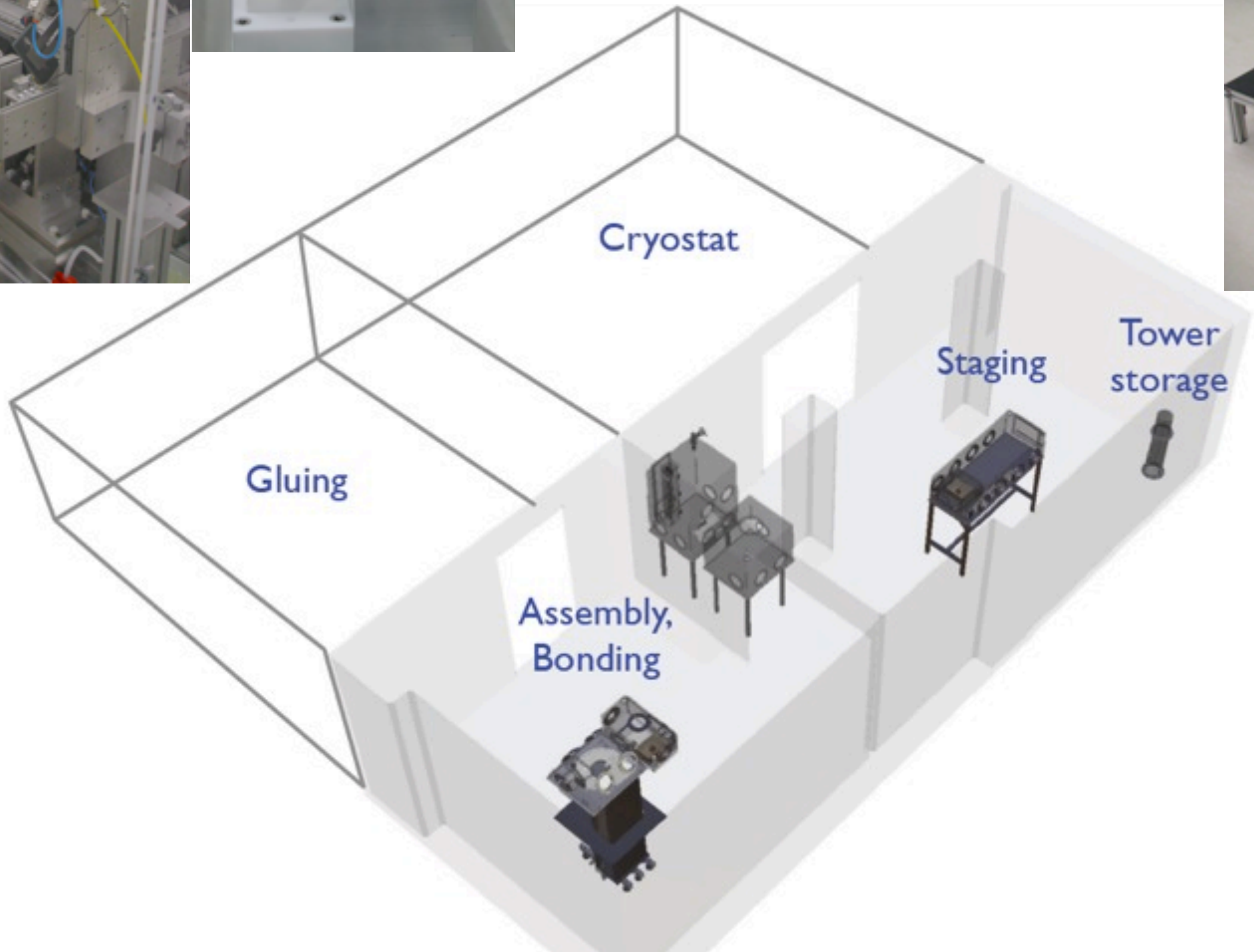
- Mechanical assembly of crystals and copper into towers

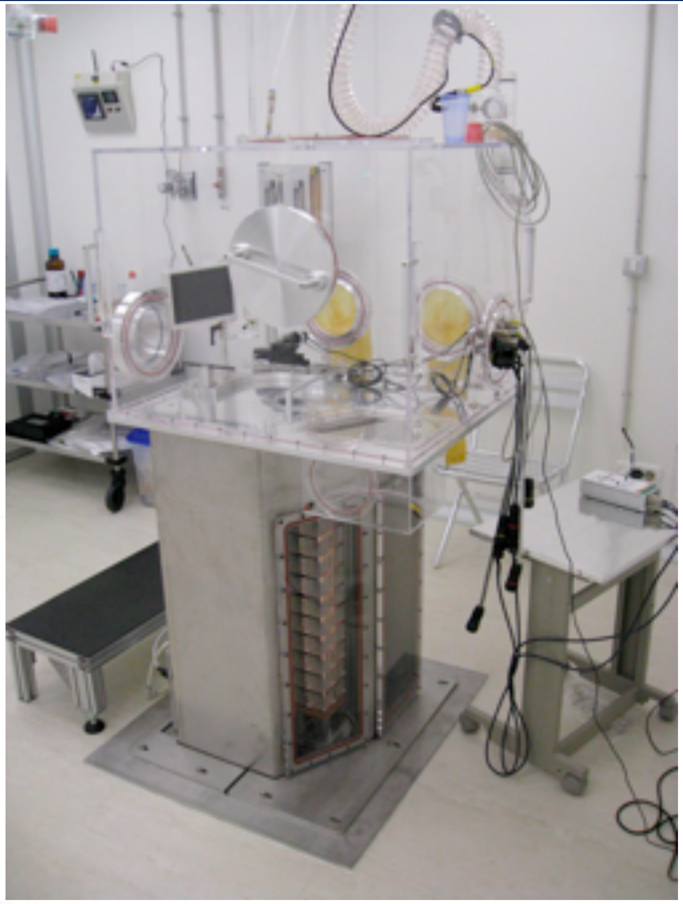
BONDING

- Bond Au wires connecting NTDs & heaters to external traces

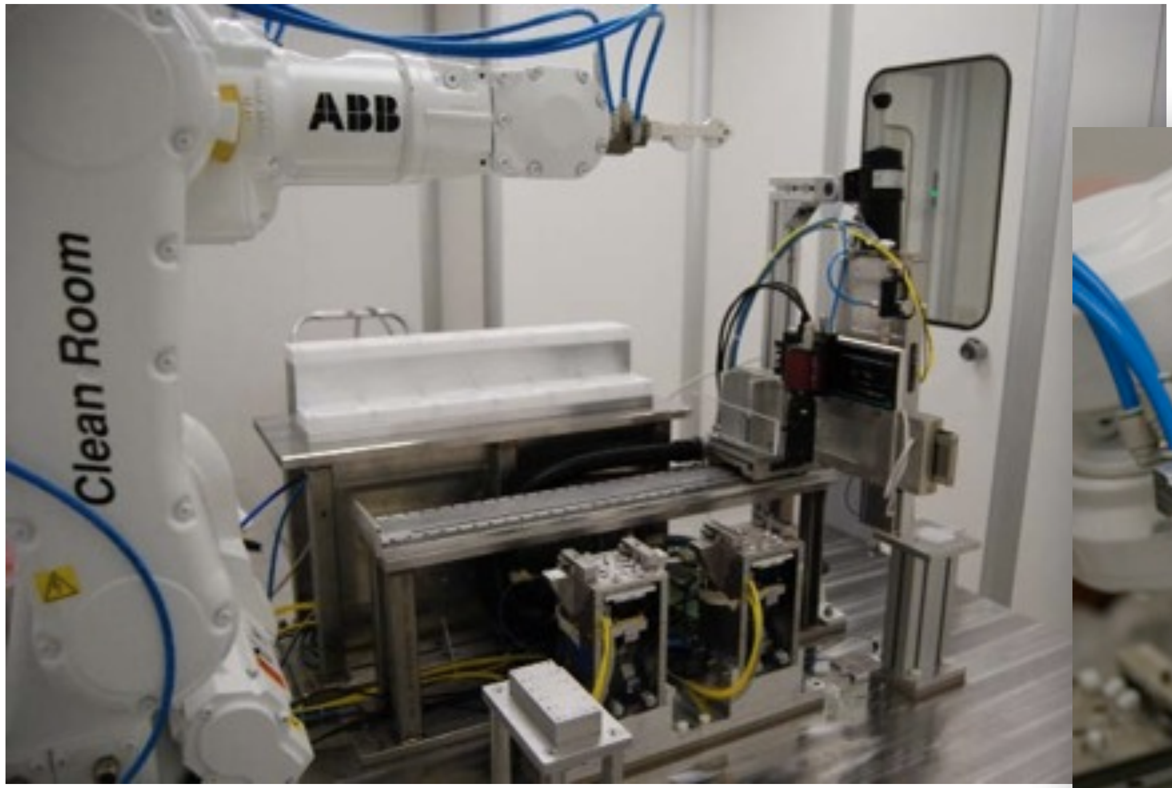
Many tasks can be done in parallel, but there are constraints

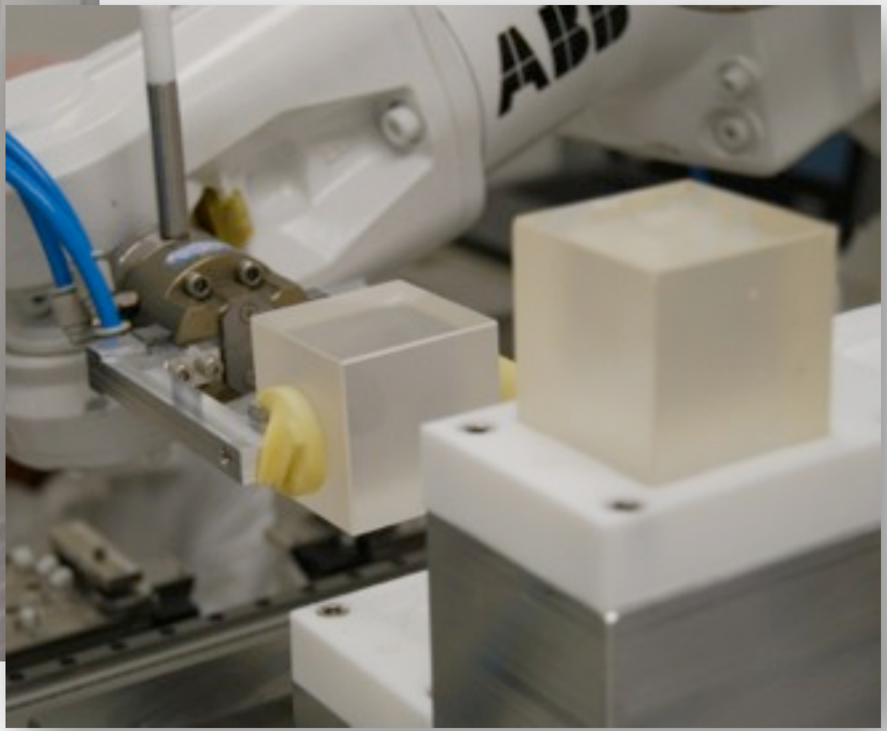
CUORE Clean Room





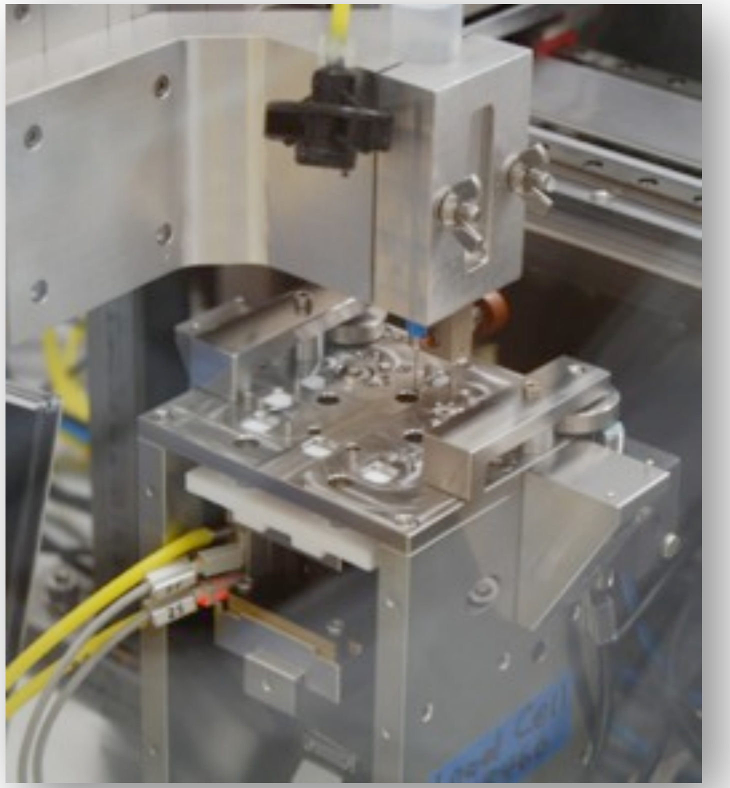
Sensor gluing

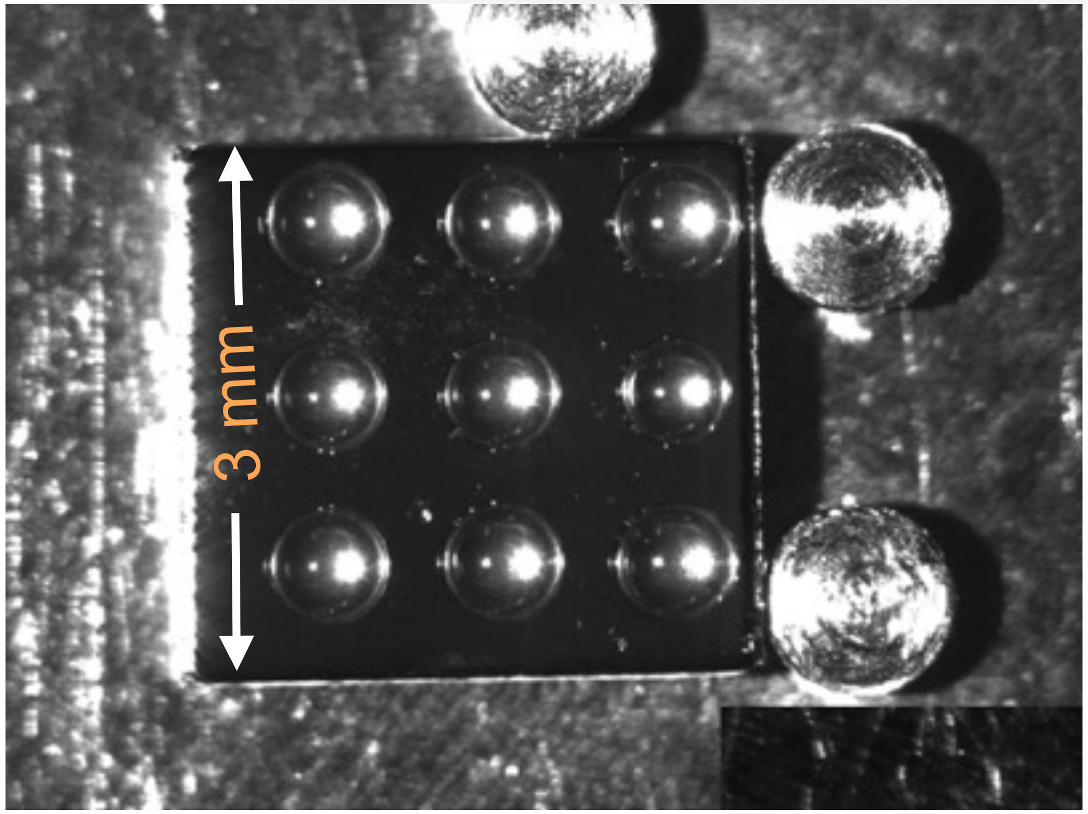




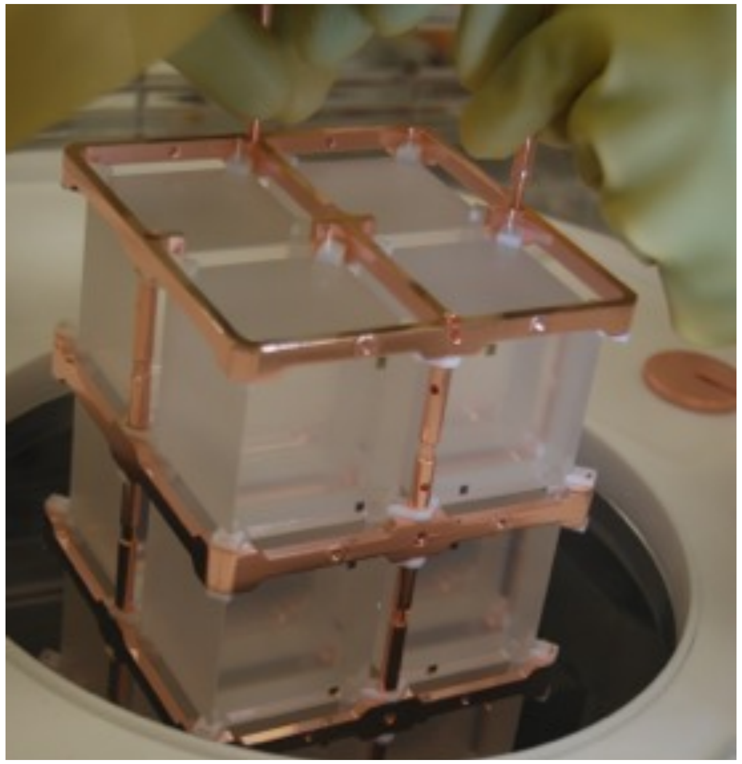
Robotic gluing for
- Uniformly sized
- Repeatable
- Controllable

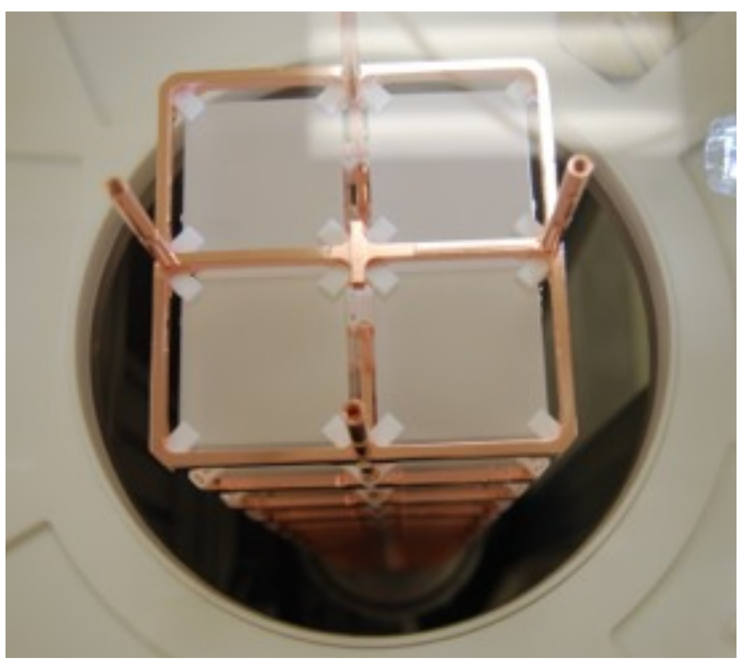
glue spots (and coupling)

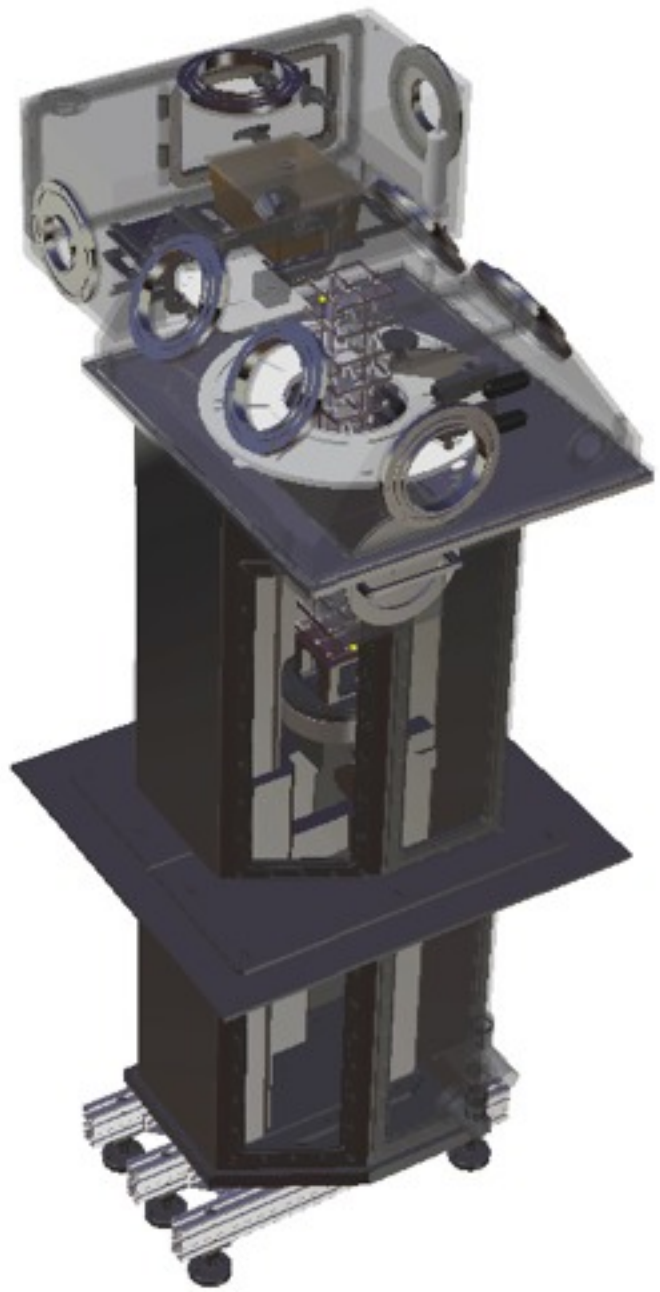


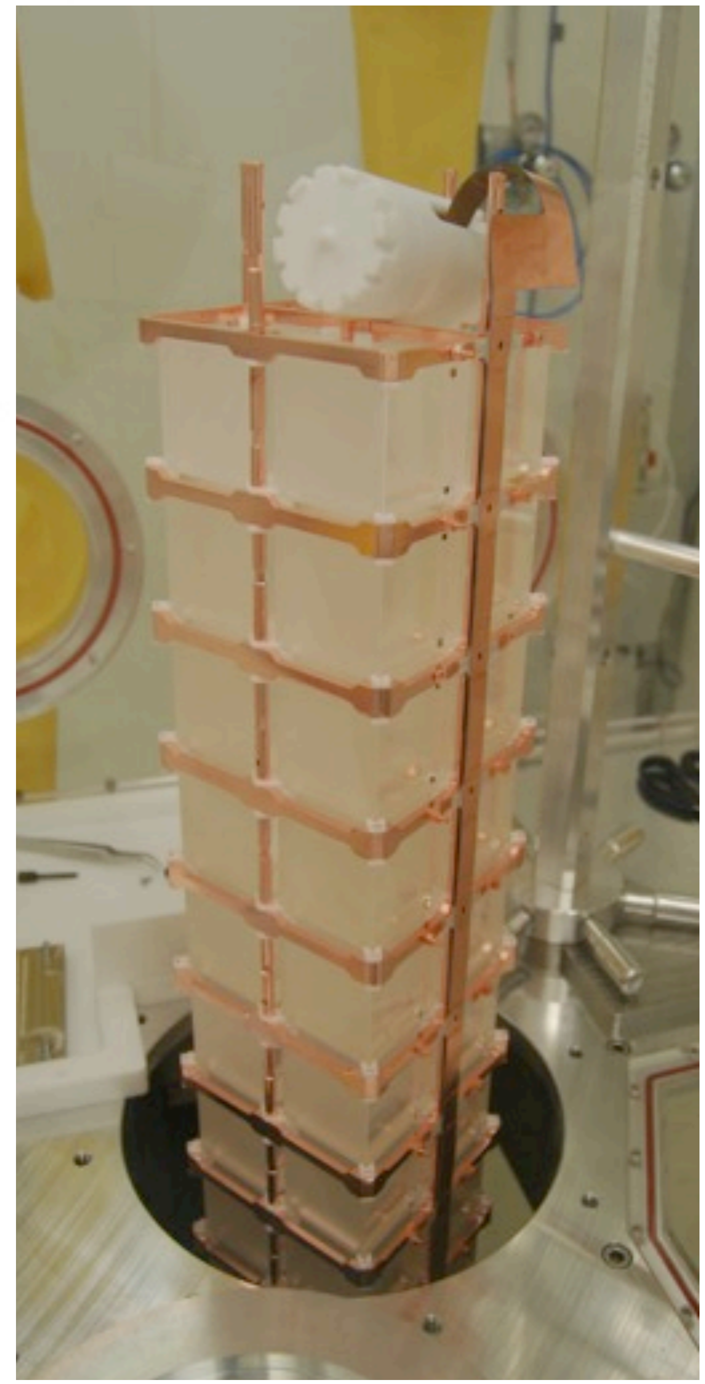


Mechanical assembly

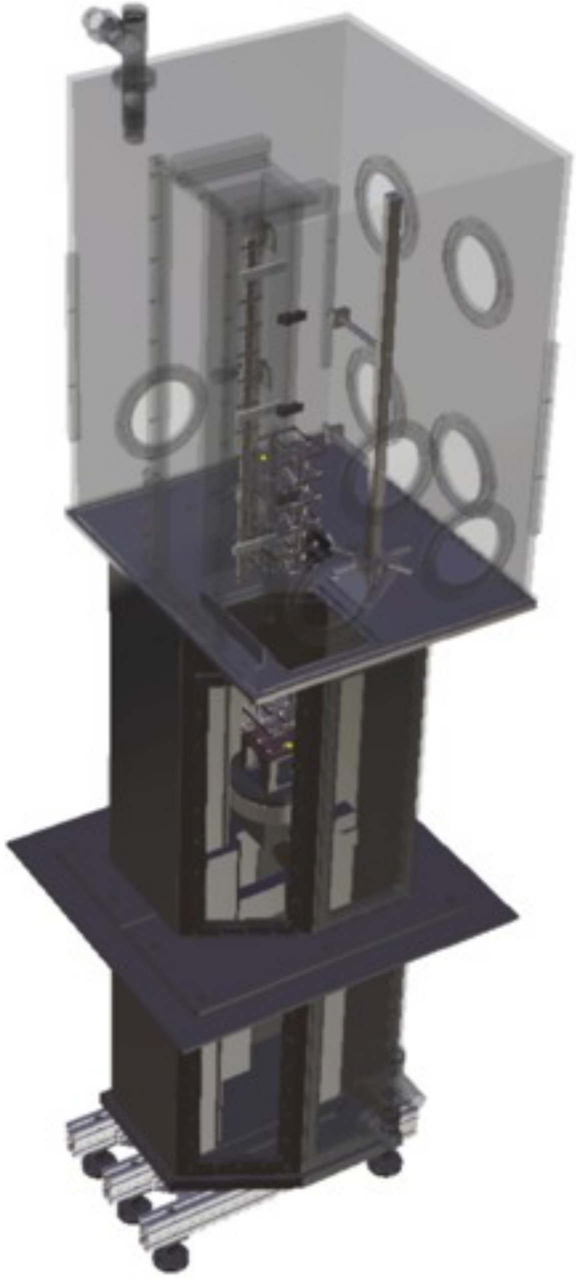


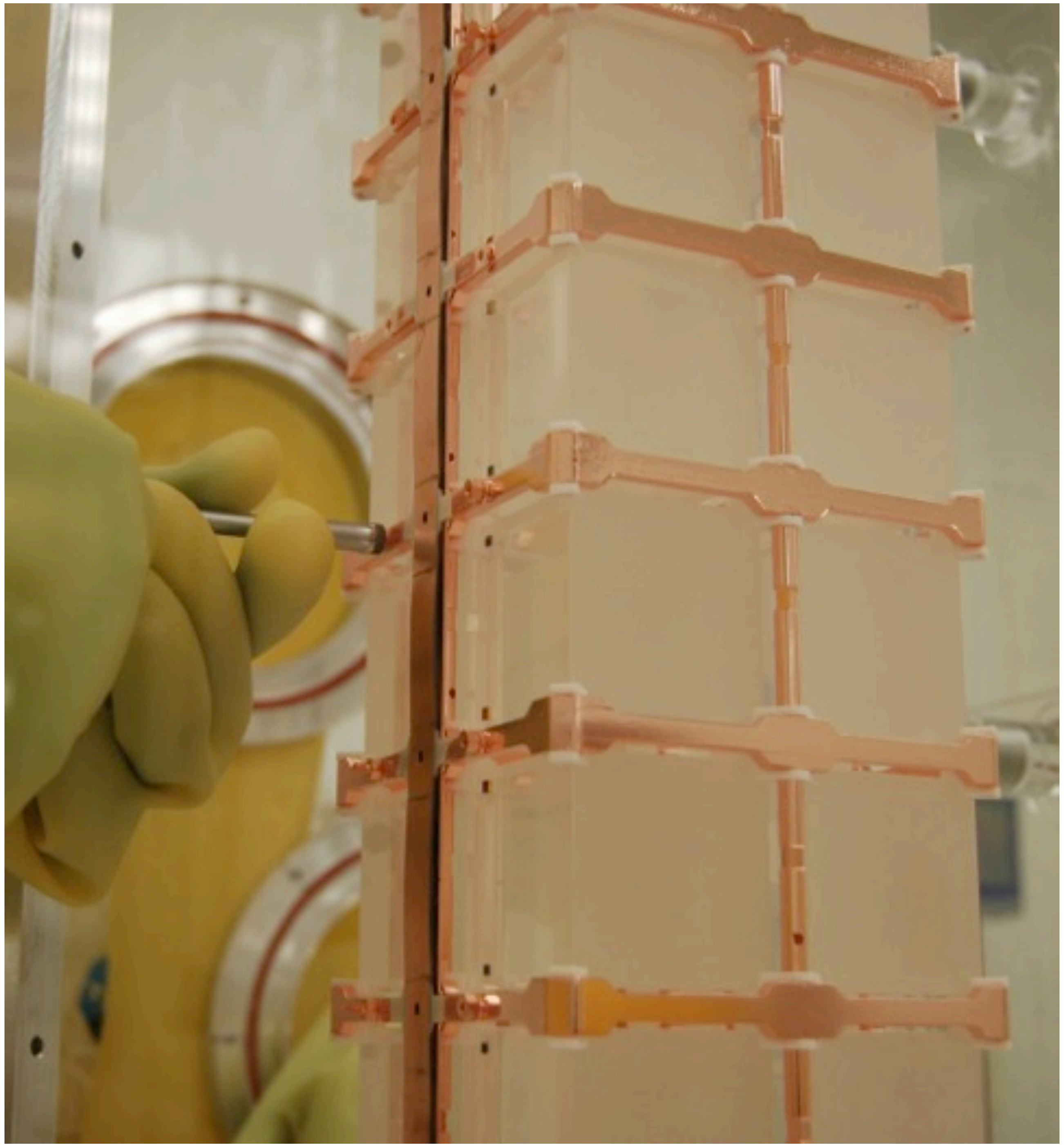




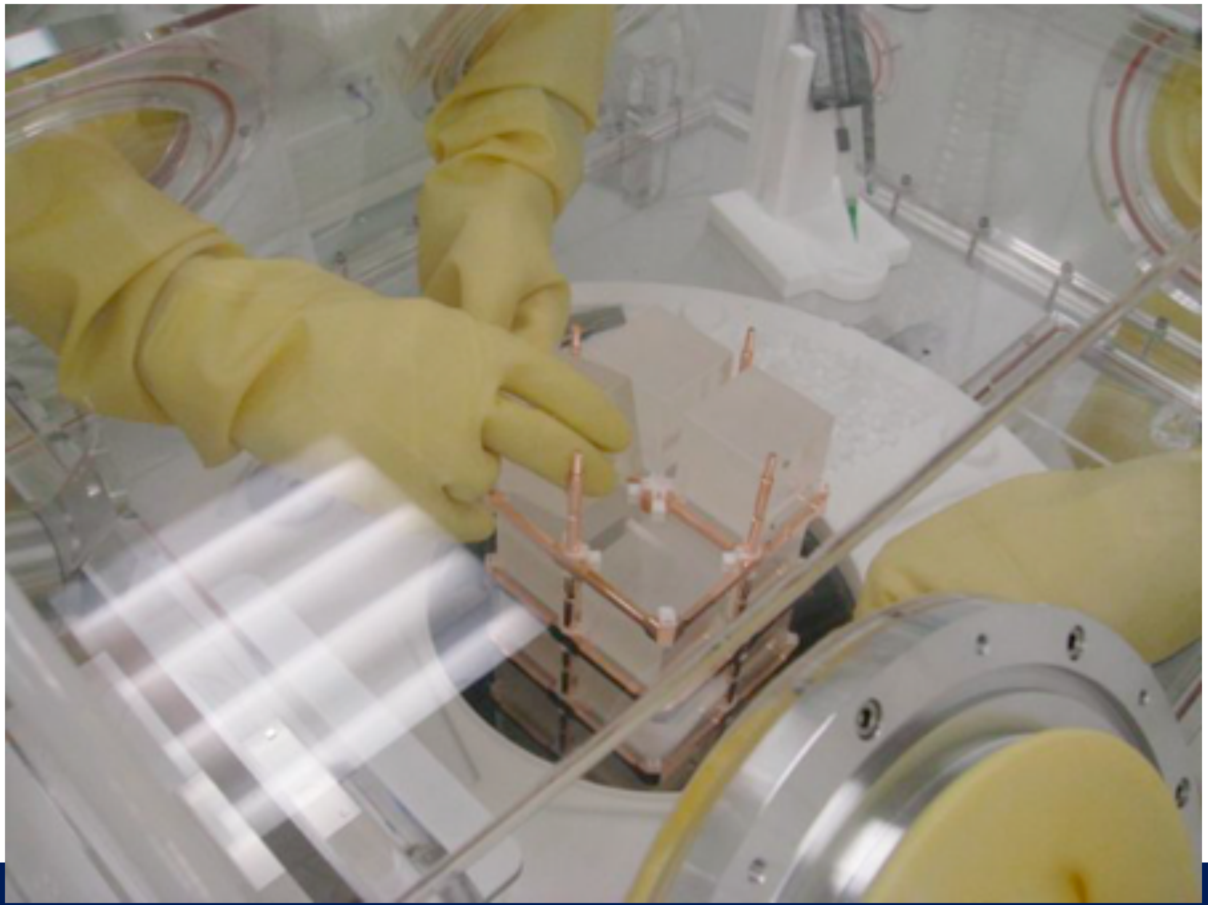


Cabling

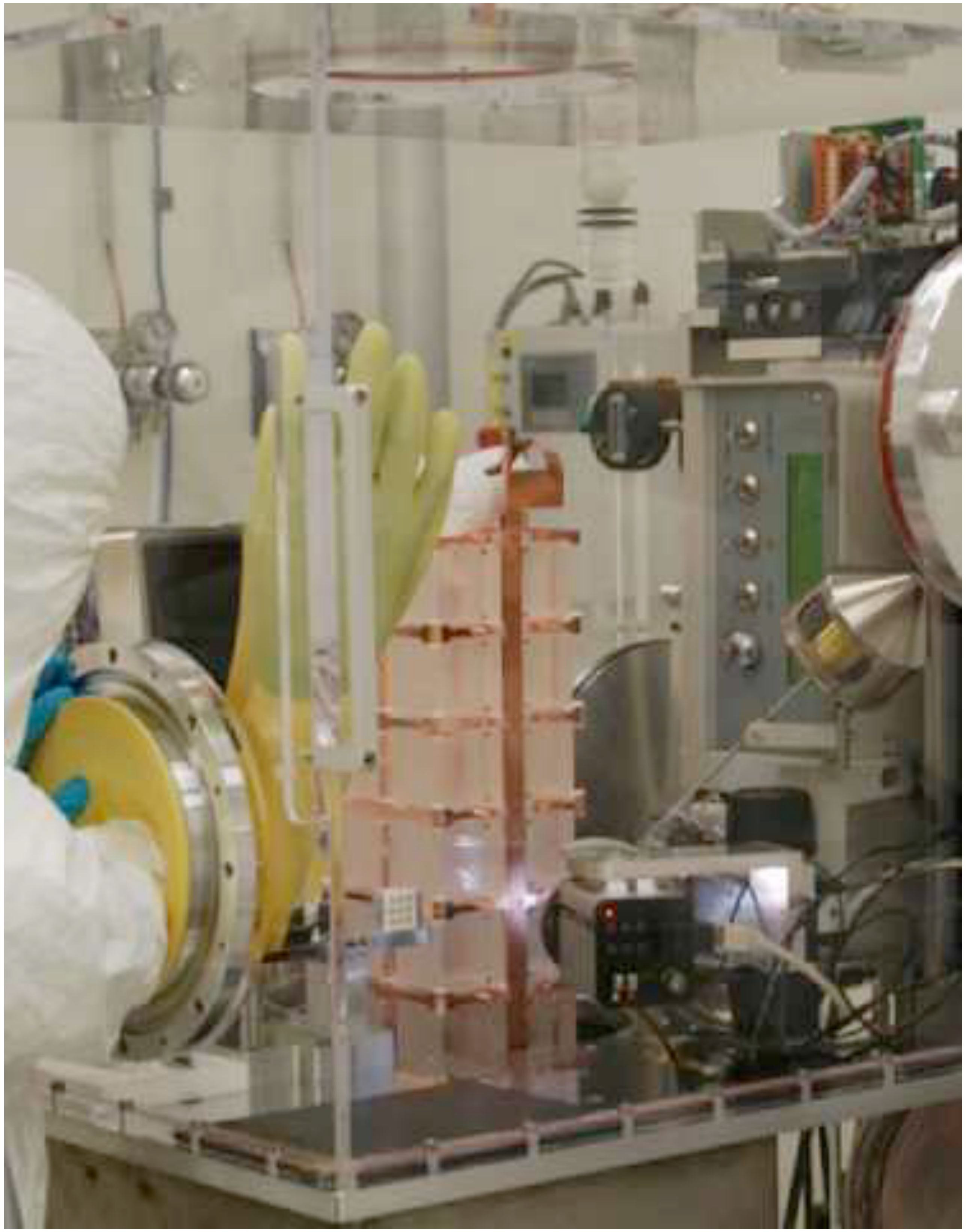


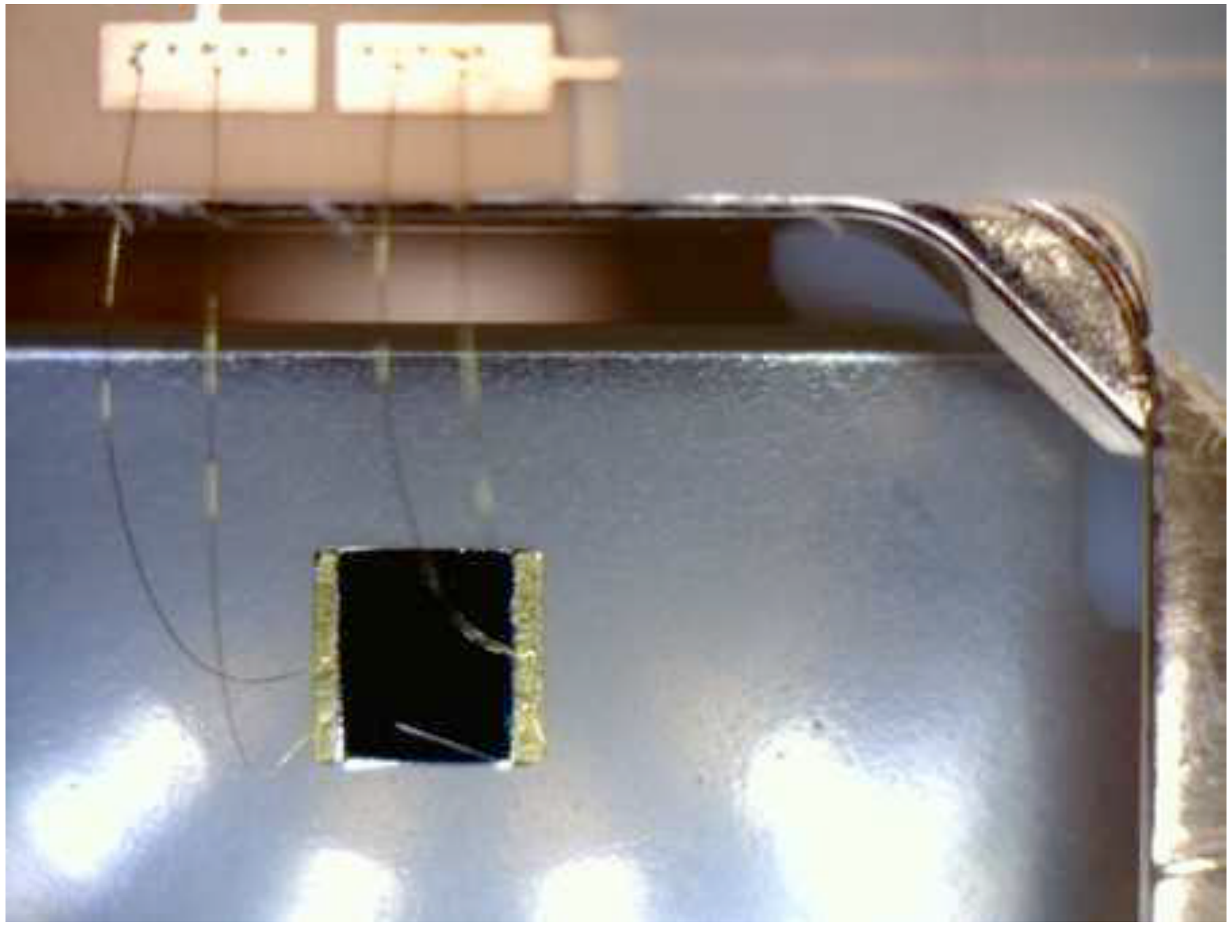


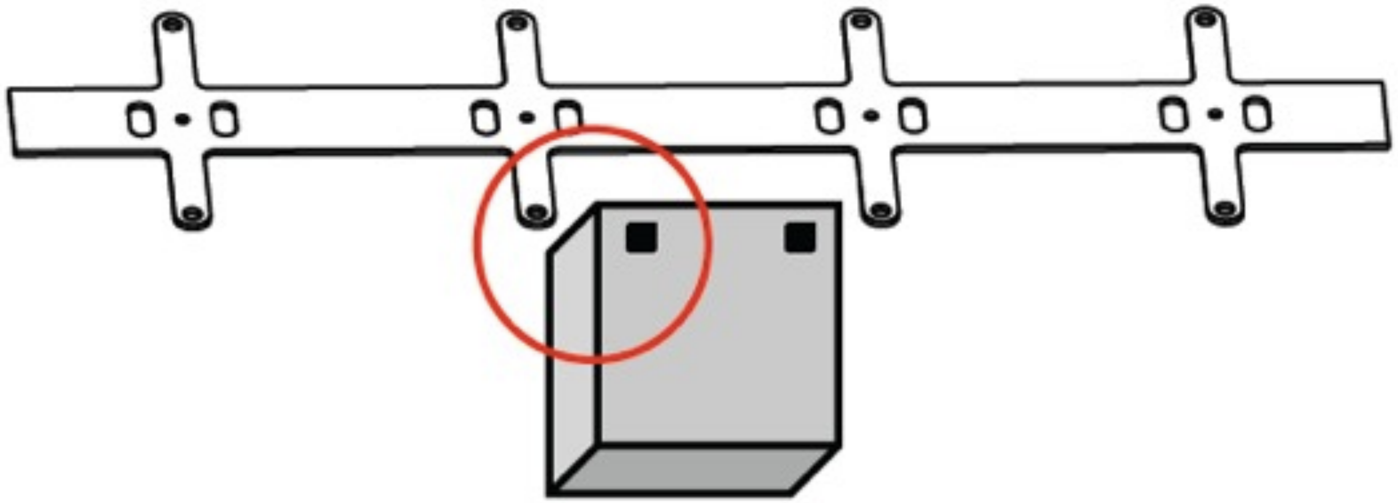
Assembly: tower n.2



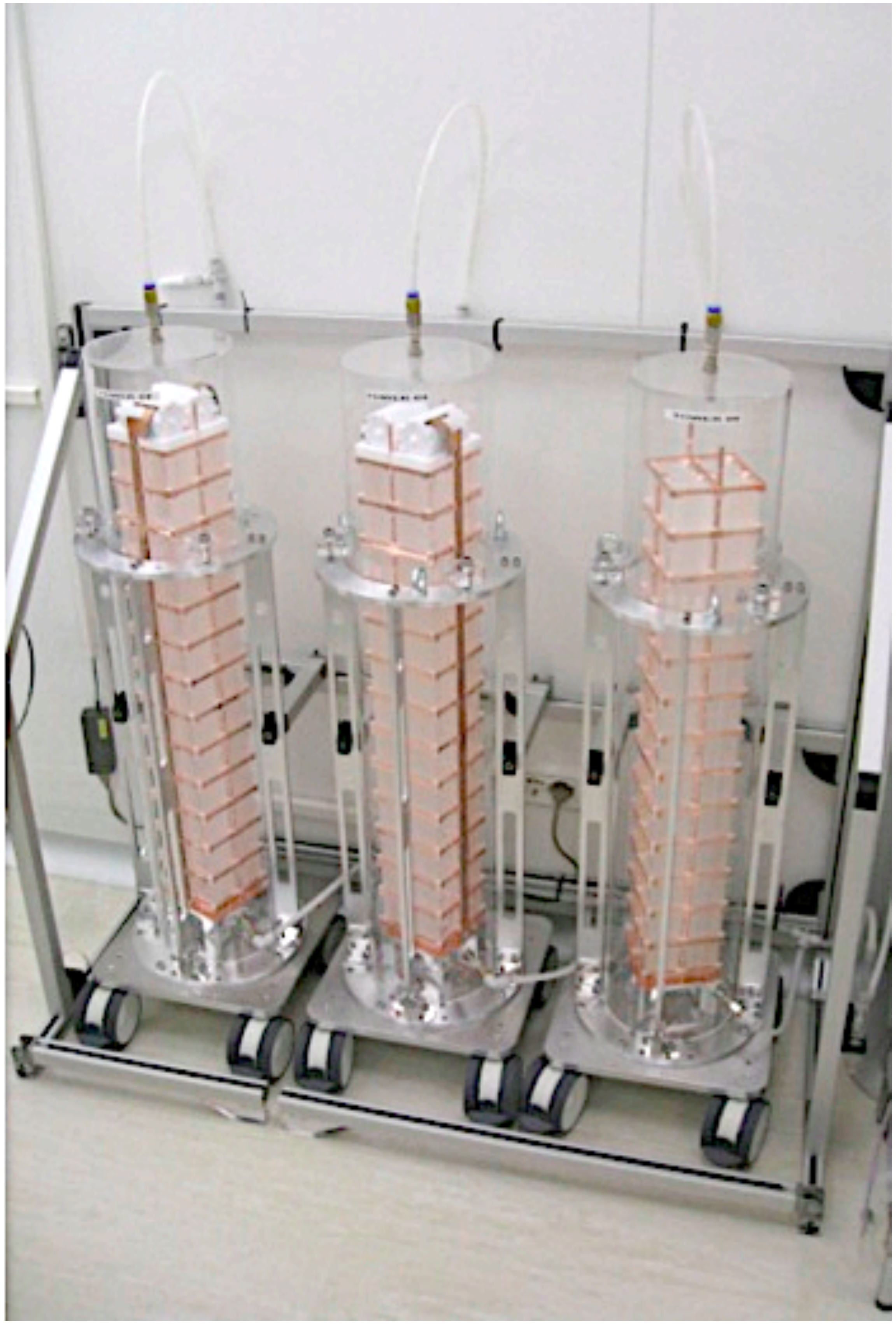
Bonding







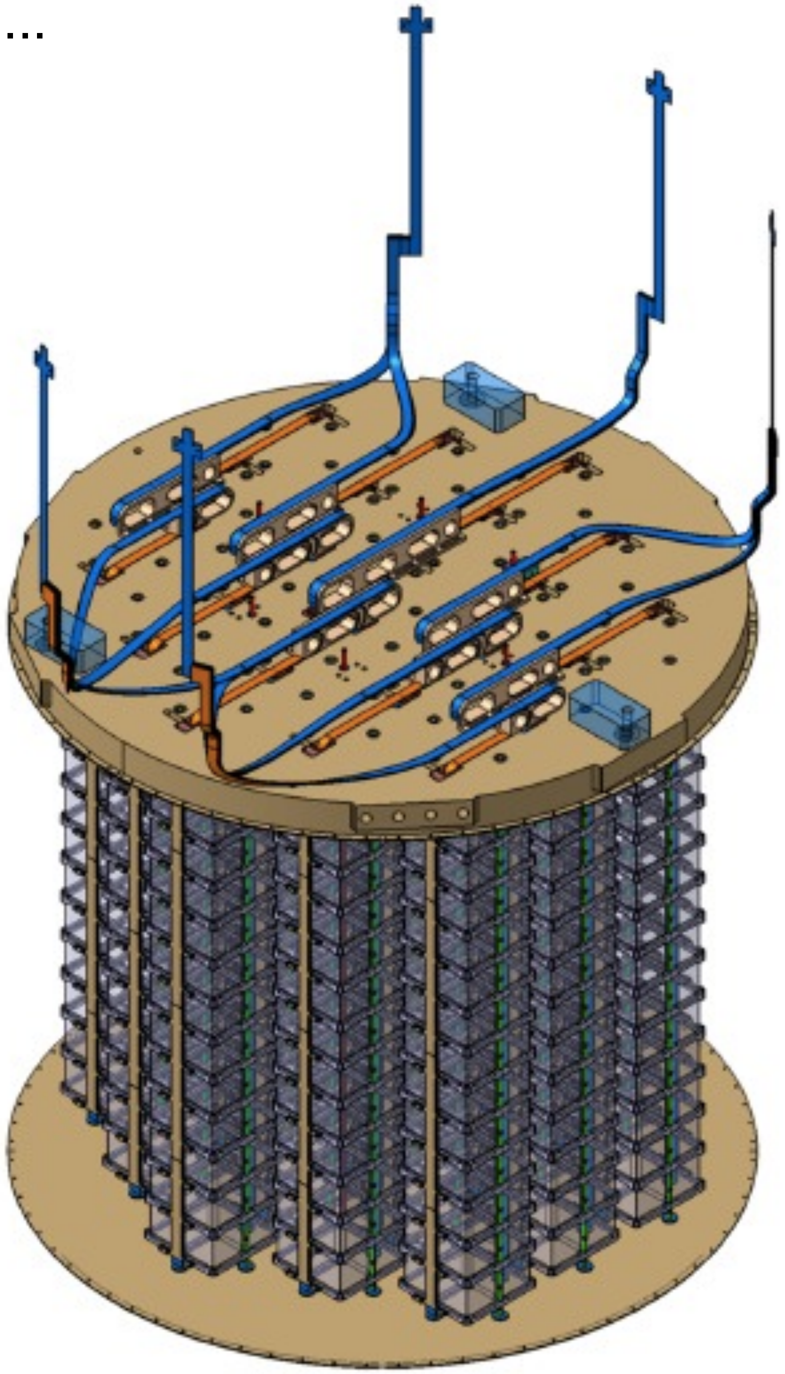
Storage

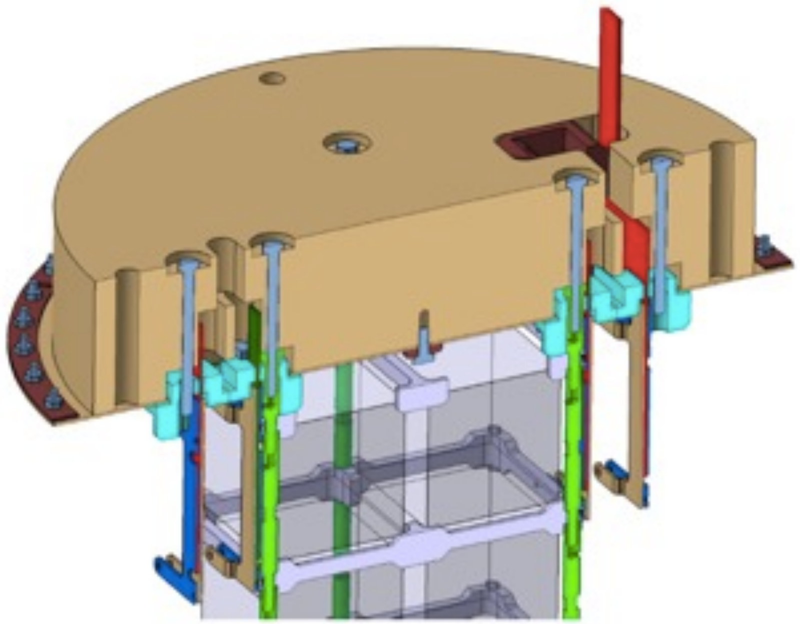


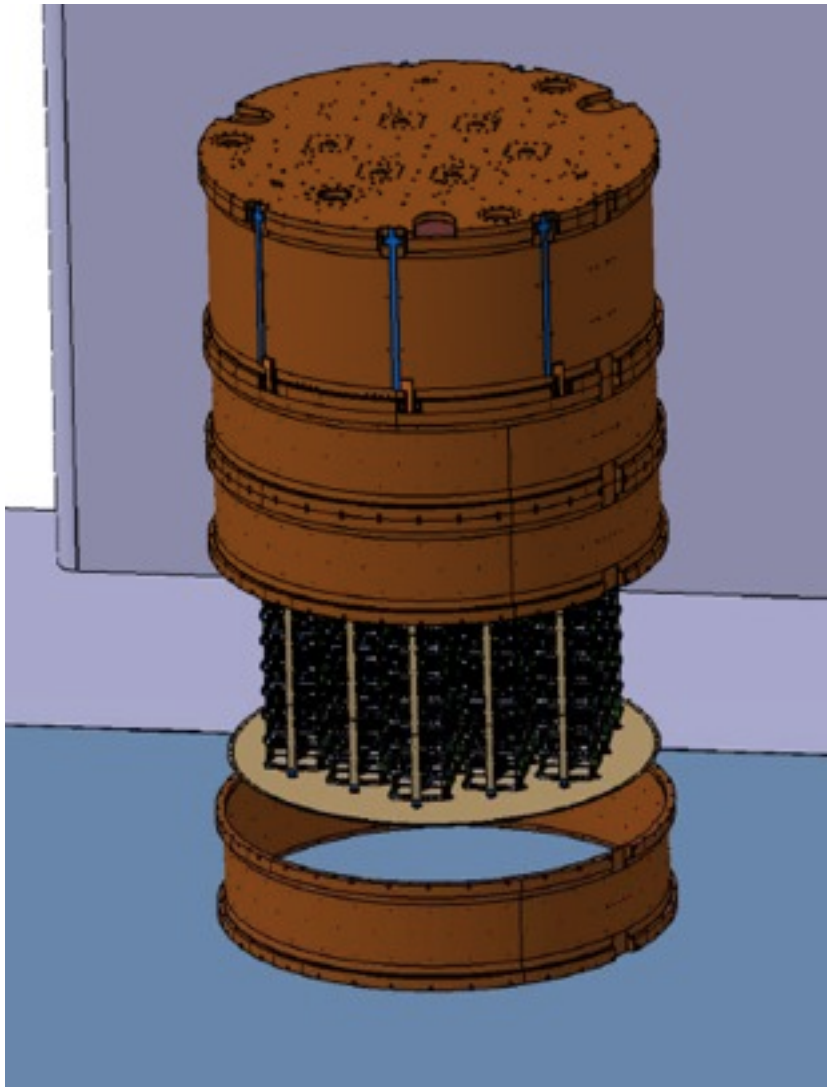
- 6 storage stations inside clean room
- 13 more stations planned for upstairs electronics room

Detector finalization

TSP (Tower Support Plate)
- Detector suspension
- Wire routing/installation
- DCS routing
- Cryostat & suspension interface
- ...

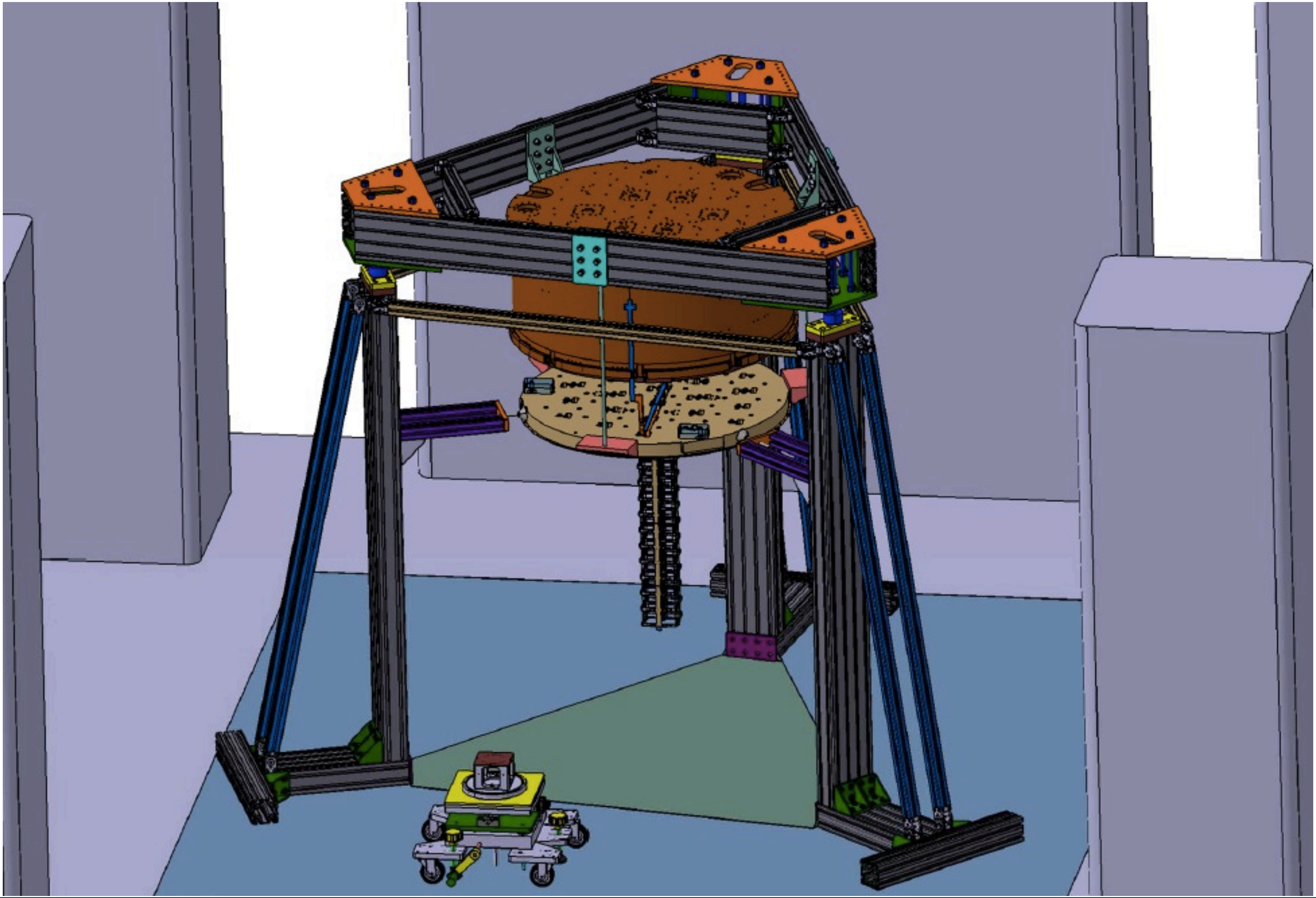






Mockup

Tower installation



Conclusions

CUORE-0

- After a series of problems mainly related to yieldings of the old Cuoricino cryostat (installed at Gran Sasso since 1989) CUORE-0 has entered data taking phase.
- Preliminary informations on detector performance and background are already available
- According to CUORE0 performance, CUORE0 will overtake Cuoricino sensitivity in spring 2014. It is providing important information for CUORE

CUORE

- Preparation phase almost completed or going to completion (crystals, copper parts, cryogenics, shields,...)
- Detector construction and setup installation are well advanced.
- Construction and installation programs constantly checked against master plan
- Cryostat construction has been completed.
- The commissioning of the 3 external chambers at 300, 40 e 4 K has beeen completed. The system has been cooled successfully to 4K twice .
- According to present plan the first cool-down of CUORE cryostat to base T is expected for the beginning of 2015