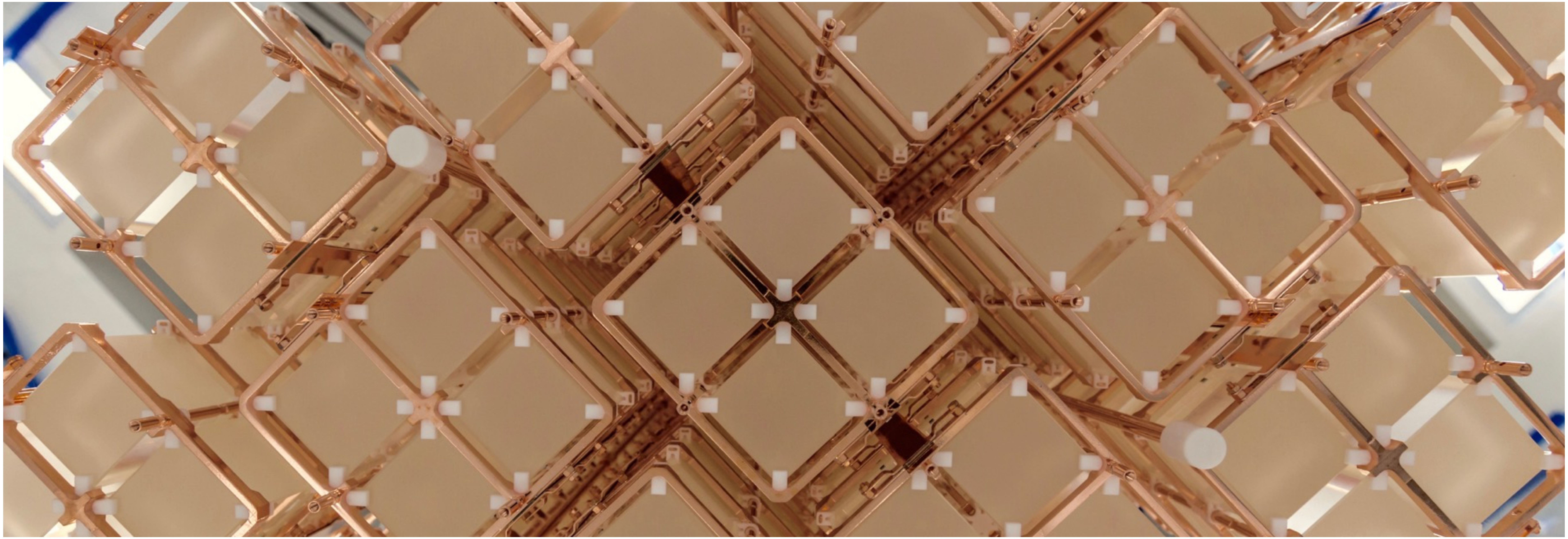

Hunt for neutrinoless double beta decay with large bolometric arrays: the CUORE experiment

Paolo Gorla

Laboratori Nazionali del Gran Sasso - INFN

Outline

- Majorana neutrinos
- Double Beta Decay
- CUORE-0 prototype
- Limit on 0vDBD and results on 2vDBD
- CUORE: status and prospects

Majorana neutrinos

The Majorana neutrino

E. Majorana (1937):
theory of massive and real fermions

$$\chi = C\bar{\chi}^t \quad \left(\bar{\chi} \;\equiv\; \chi^\dagger\gamma_0, \quad C\gamma_0^t = 1\right)$$

$$\mathcal{L}_{Majorana} = \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m)\chi$$

$$\chi(x) = \sum_{\mathbf{p},\lambda}(a(\mathbf{p}\lambda)\ \psi(x;\mathbf{p}\lambda) + a^*(\mathbf{p}\lambda)\ \psi^*(x;\mathbf{p}\lambda))$$

→ for any value of p, there are 2 helicity states: |p↑⟩ and |p↓⟩

- L will be violated by the presence of Majorana mass
- the Majorana hypothesis can be implemented in the SM

$$\chi \equiv \psi_L + C\bar{\psi}_L^t$$

to obtain the *usual* SM field $\psi_L \equiv P_L\chi$ $\left(P_L \equiv \frac{1-\gamma_5}{2}\right)$

The see saw mechanism

- Does the neutrino have a Majorana type mass?
    - Would imply that lepton number is not a conserved quantity in nature
    - Could explain why the neutrino is so light (compared to charged leptons) via see saw mechanism:

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$$\nu = \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} \qquad \mathscr{L}_{mass} = -\frac{1}{2} \overline{\nu} M \nu + h.c. \qquad M = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$$

if neutrinos are Majorana, diagonalising M we get the mass eigenstates:

$$m_{11} \cong \frac{m_D^2}{m_R}$$

$$m_{22} \cong m_R$$

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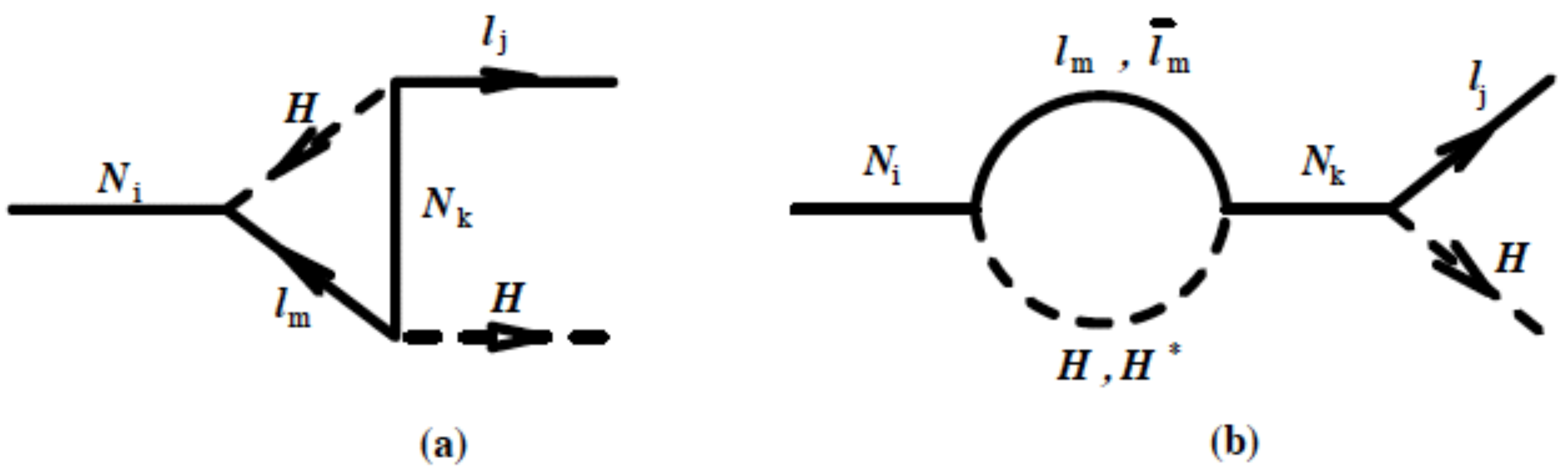
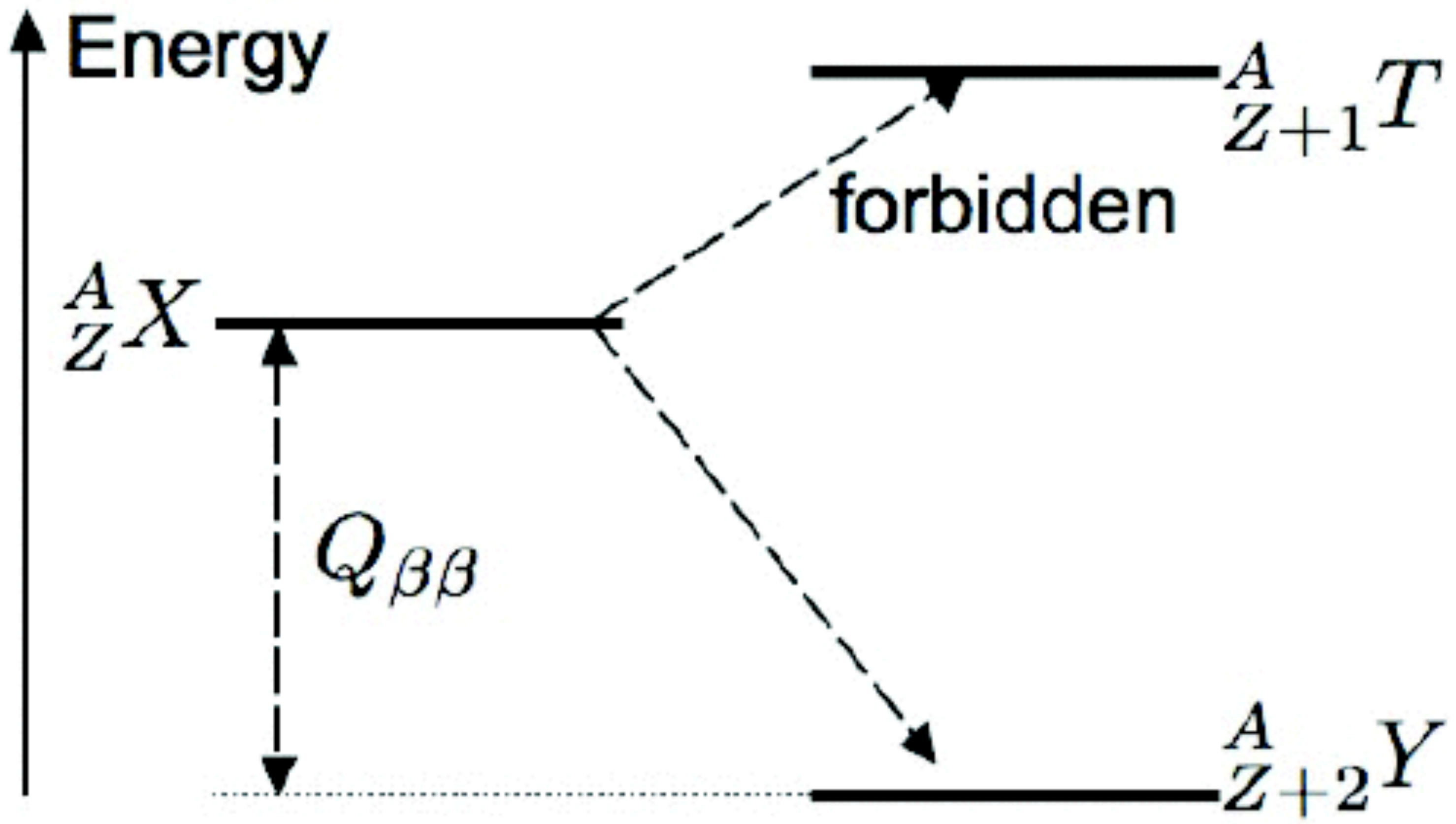


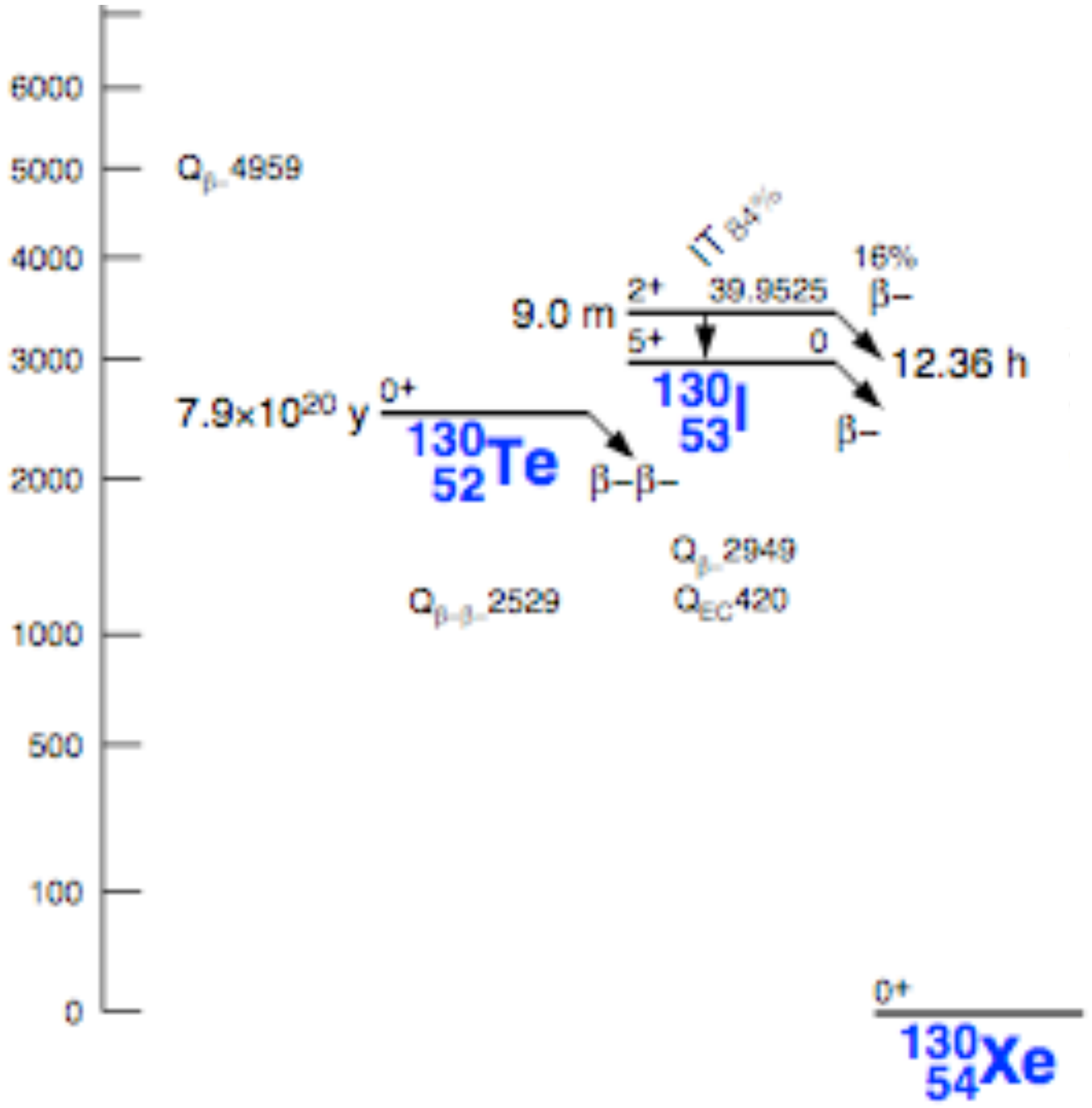
Figure 1: Diagrams contributing to the vertex (Fig. 1a) and wave function (Fig. 1b) CP violation in the heavy singlet neutrino decay.

L.Covi, E.Roulet, F.Vissani. Phys.Lett. B384 (1996) 169-174

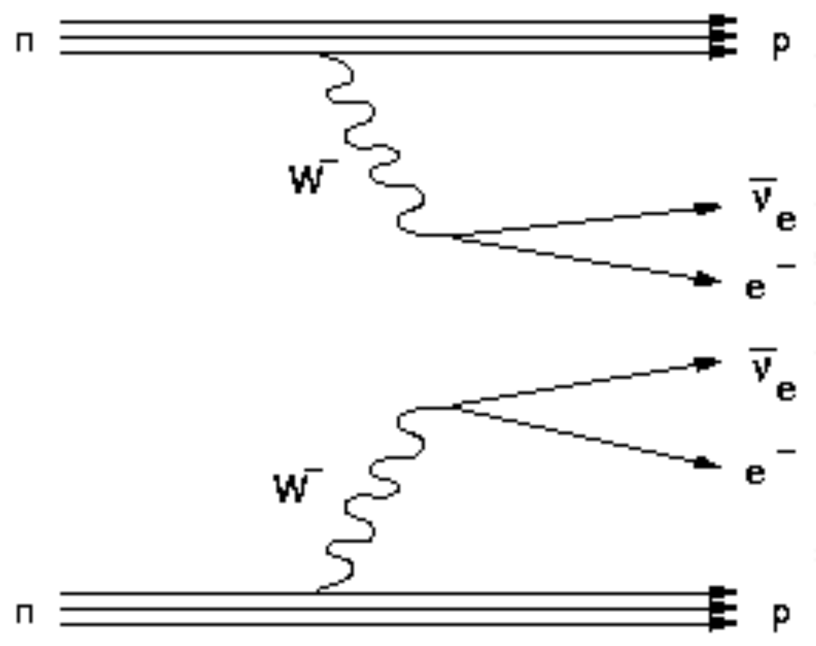
Double Beta Decay (I)

2ν-DBD (M.Goeppert-Mayer, 1935) is an extremely rare second order process allowed by SM. It take place when both the parent and the daughter nuclei are more bound than the intermediate one (or the transition on the intermediate one is strongly suppressed). Because of the pairing term, such a condition is fulfilled in nature for a number of even-even nuclei.





2ν-DBD: (A,Z) → (A,Z+2) + 2e$^-$ + 2ν



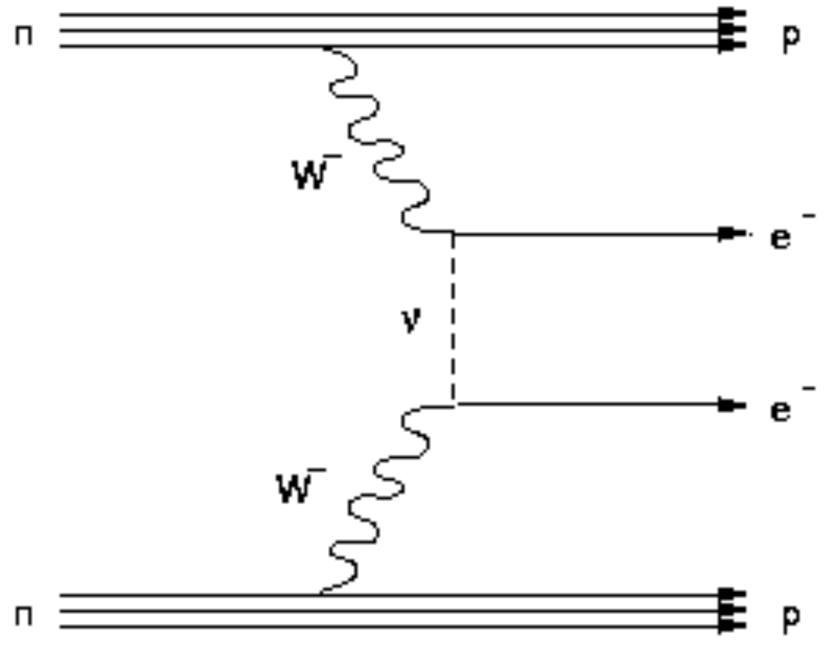
- Extremely rare second order process allowed by SM
- Observed for several nuclei
- Process: $\tau^{0\nu} \sim 10^{19}$-10^{21} y

Double Beta Decay (II)

0ν-DBD (W.H.Furry, 1939) is a lepton number violating (ΔL=2), not allowed by the Standard Model. The 0νDBD can occur only if two requirements are satisfied: i) the neutrino has to be a Majorana particle, and ii) the neutrino has to have a non-vanishing mass.

This is the crucial process for neutrino physics since can solve the puzzle of the Majorana nature of the neutrino

0ν-DBD: $(A,Z) \rightarrow (A,Z+2) + 2e^-$ ⟶ implies physics beyond SM

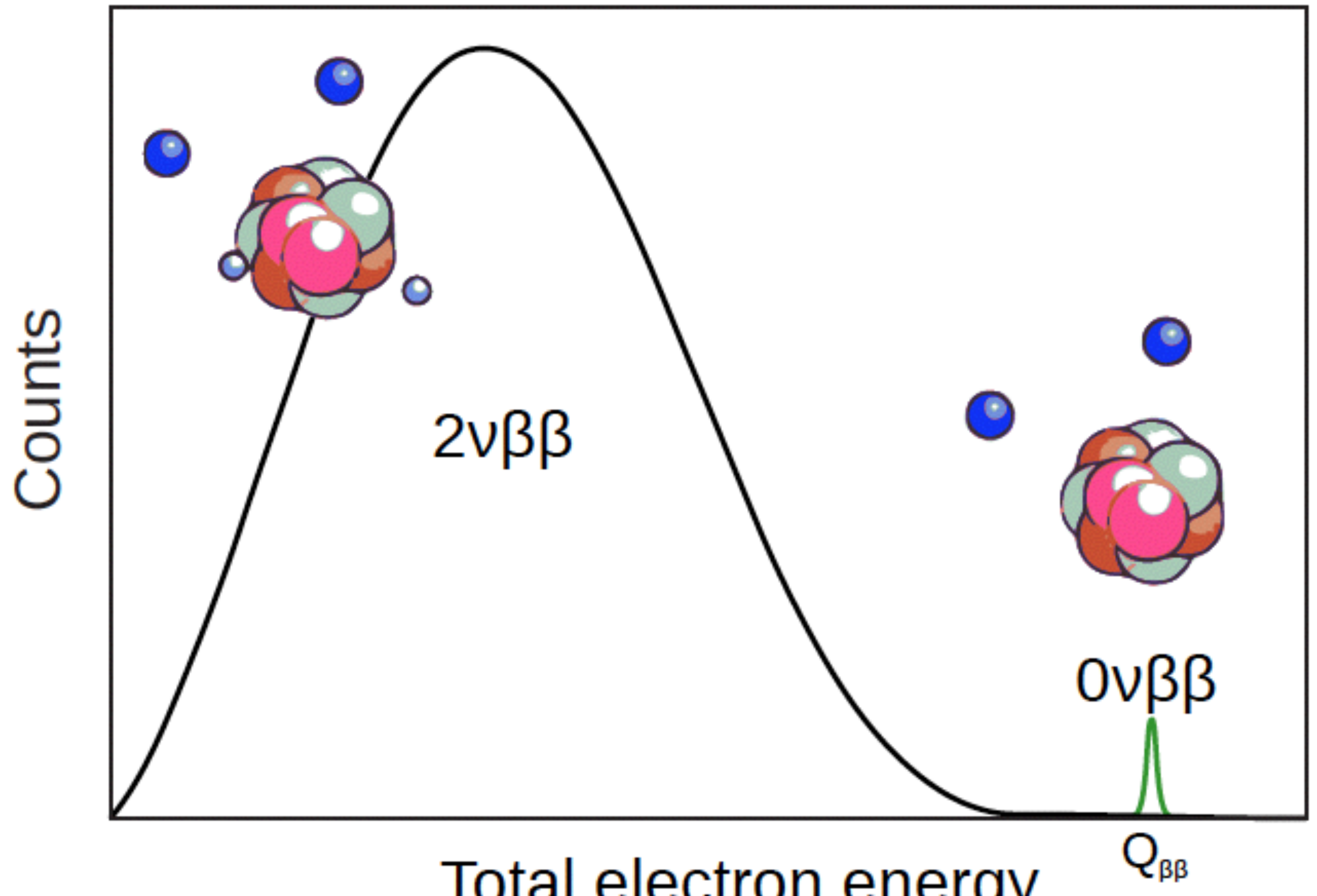


- 0ν-DBD is an extremely rare
- process: $\tau^{0\nu} > 10^{24}\text{-}10^{25}$ y
- β radiation

If 0ν-DBD is observed: neutrino is a Majorana particle and m_ν is measured

Schetcher, Valle Phys. Rev. D25 2951 1982

For $2e^-$ sum energy, expected signature is a peak with $E \equiv Q_{\beta\beta}$



Majorana Mass

Observation of 0vDBD can give informations on the absolute mass scale:

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}\, g_A^4 \,|M_{0\nu}|^2 \langle m_{\beta\beta}\rangle^2$$

0vββ decay rate

Phase space factor — Atomic physic

Axial vector coupling — Nuclear physic

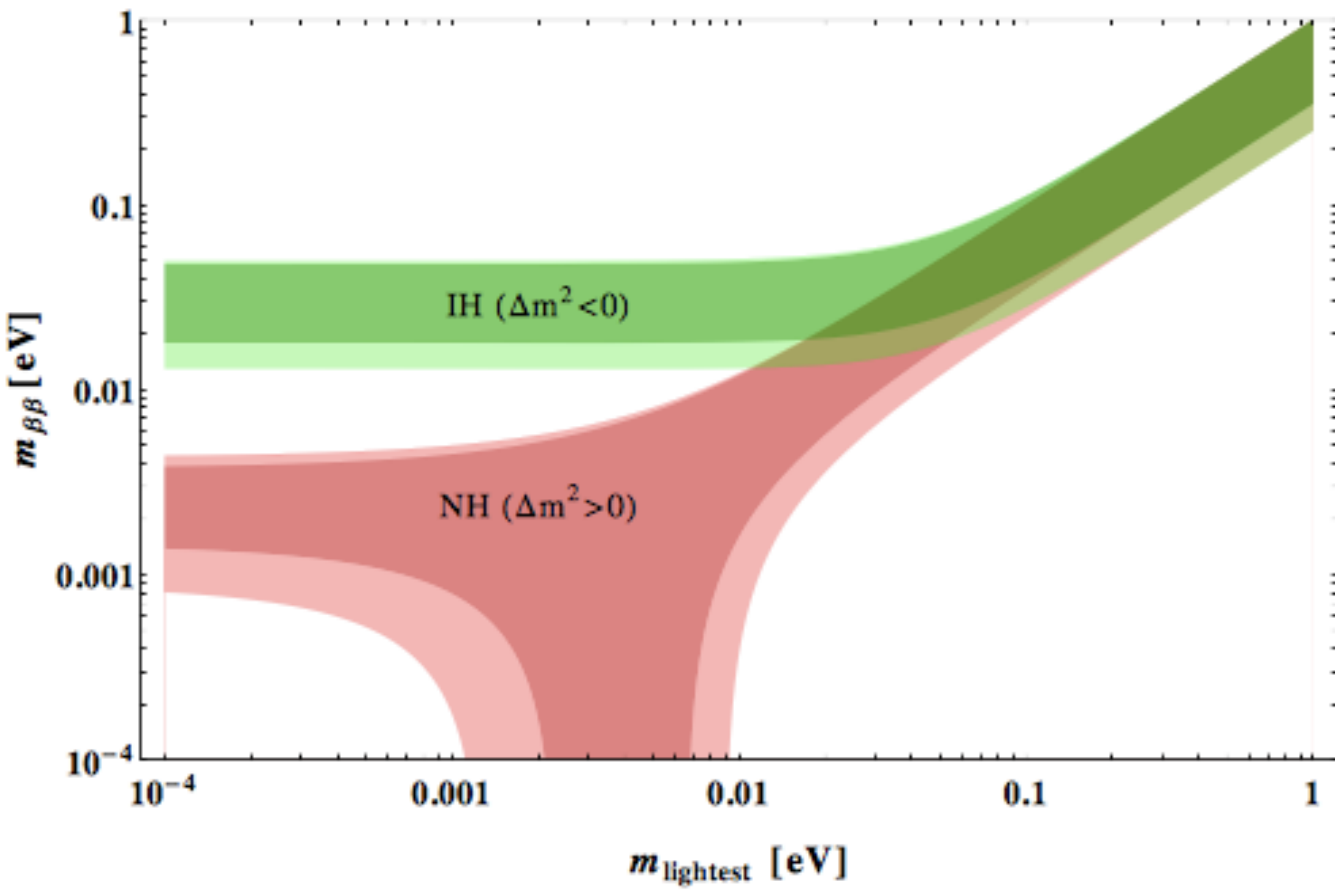
Nuclear matrix element — Nuclear physic

Effective Majorana mass — Particle physic

where

$$\langle m_{\beta\beta}\rangle = \left|\, |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \,\right|$$

$$\langle m_{\beta\beta}\rangle = F(m_1, \Delta m_{ij}{}^2, \theta_{ij}, \alpha_i)$$



Sensitivity (I)

Half-life corresponding to the maximum signal nB that could be hidden by the background fluctuations at a given statistical C.L.

$$S_{0\nu} \propto i.a. \cdot \sqrt{\frac{M \cdot T}{\Gamma \cdot b}}$$

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Mass: actually in the 10 -100 kg range; next generation in 1-ton scale

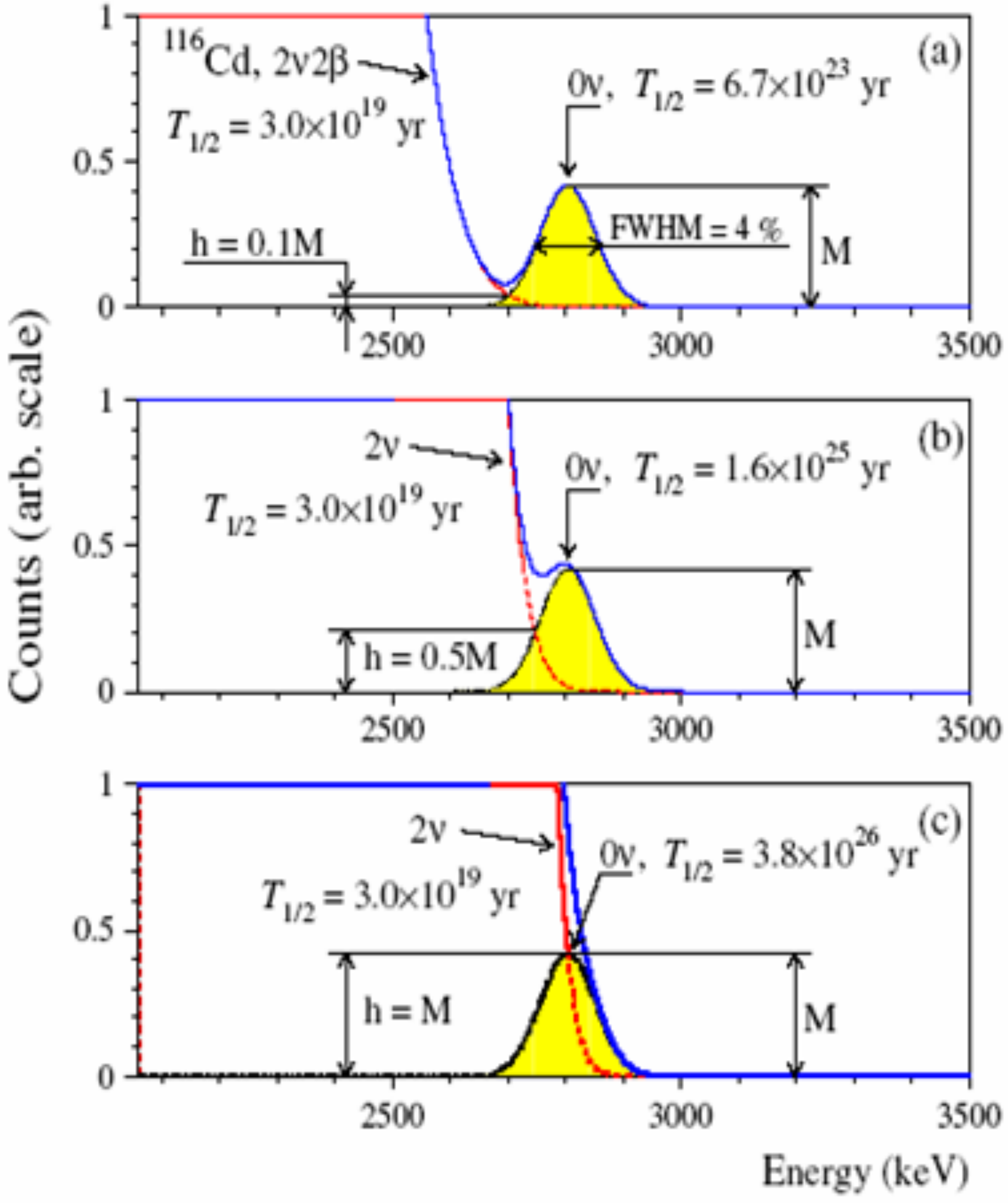
Live time: 5-10 y. Limited by scientists live time

Isotopic abundance: for most candidates enrichment is needed

Resolution: detector dependent. Not big improvements expected

Background: currently this is the ONLY tunable parameter to push sensitivities of order of magnitudes.

Sensitivity (II): discovery potential



Yu.G. Zdesenko, F.A. Danevich and V.I. Tretyak J.Phys. G: Nucl. Part. Phys. 30 (2004) 971

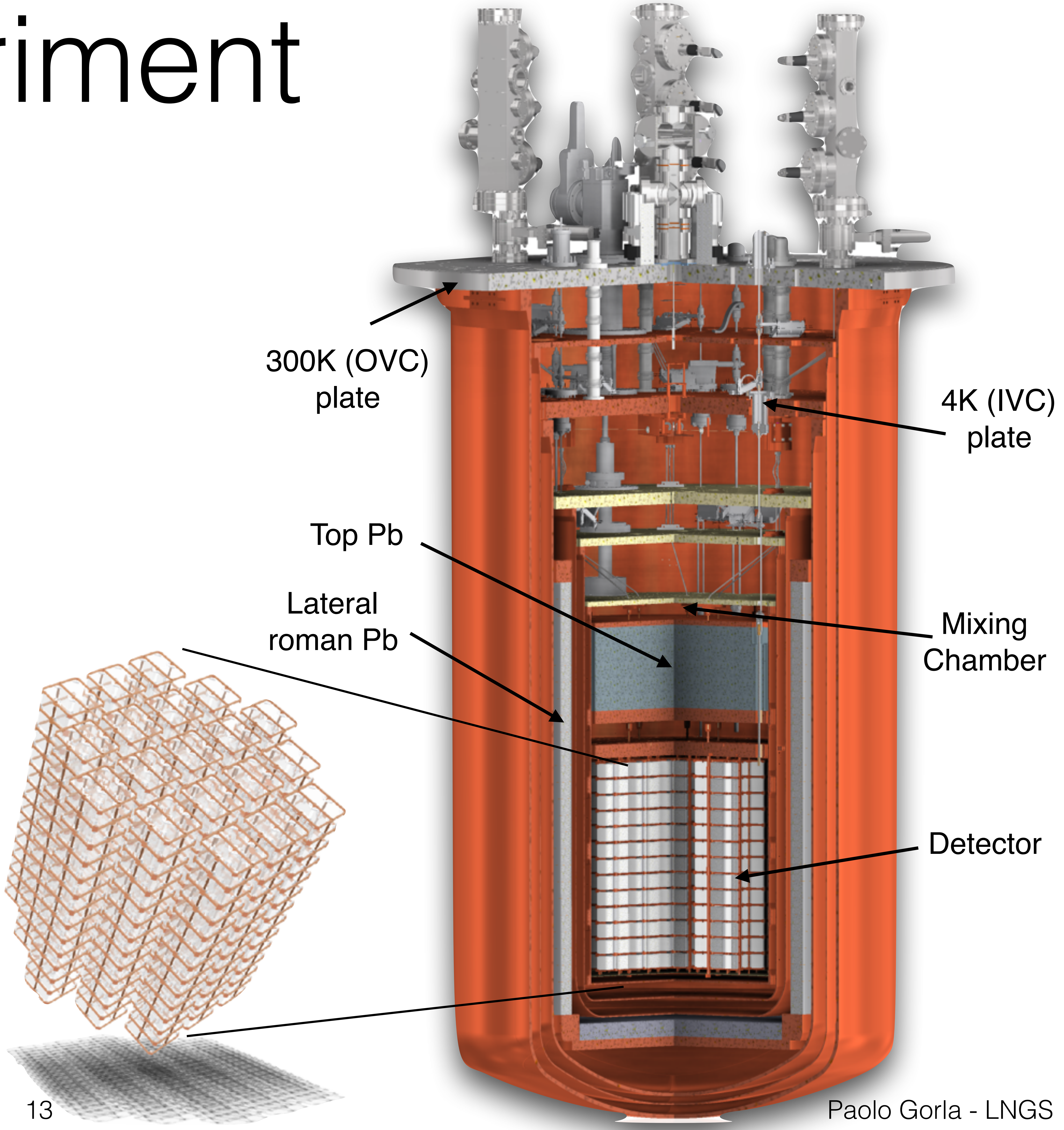
2vDBD is an unavoidable background for any 0vDBD (neutrino tagging?).

Energy resolution is a crucial parameter for any experiment aiming to measure 0vDBD and not just increasing the sensitivity on the not observed process.


The CUORE experiment

The CUORE experiment

- Investigates: $^{130}Te \rightarrow {}^{130}Xe + 2e^-$
- Array of 988 $^{nat}TeO_2$ thermal detectors, arranged in 19 towers, 13 floors each.
- Mass of TeO_2: 741 kg, ~**206 kg of 130Te**
- Operated at 10 mK
- Mass at < 4 K: ~ 15 tons (lead, copper and TeO2)
- Energy resolution of 5 keV FWHM at $Q_{\beta\beta}$ (2527 keV)
- Background goal: 10^{-2} c/keV/kg/year in the ROI.
- Sensitivity on $0\nu\beta\beta$ $T_{1/2}$ (5y, 90% C.L.): 9.5 x 10^{25} y
- Sensitivity on $m_{\beta\beta}$ (5y, 90% C.L.): 50 - 130 meV



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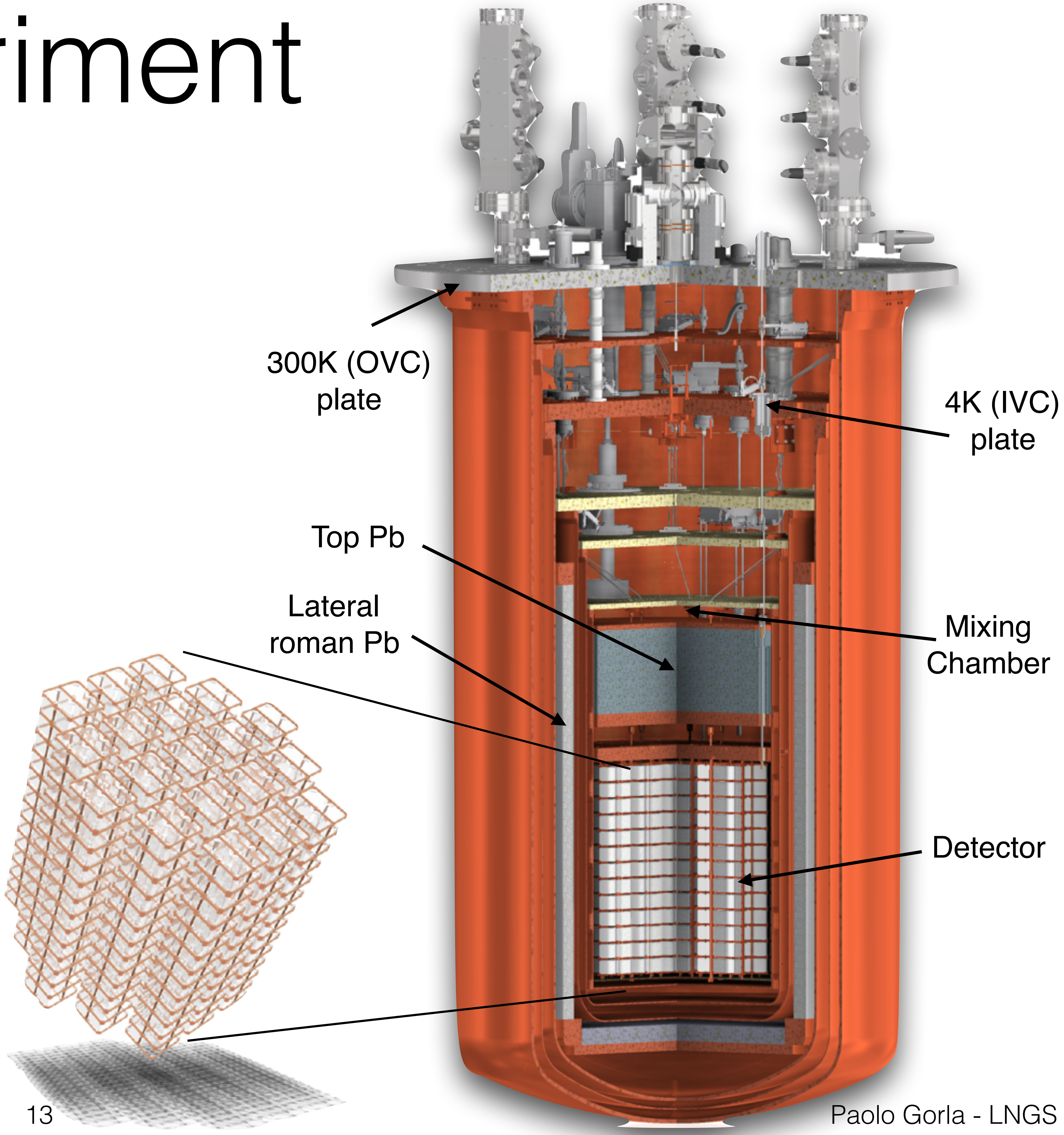
- CUORE-0 results



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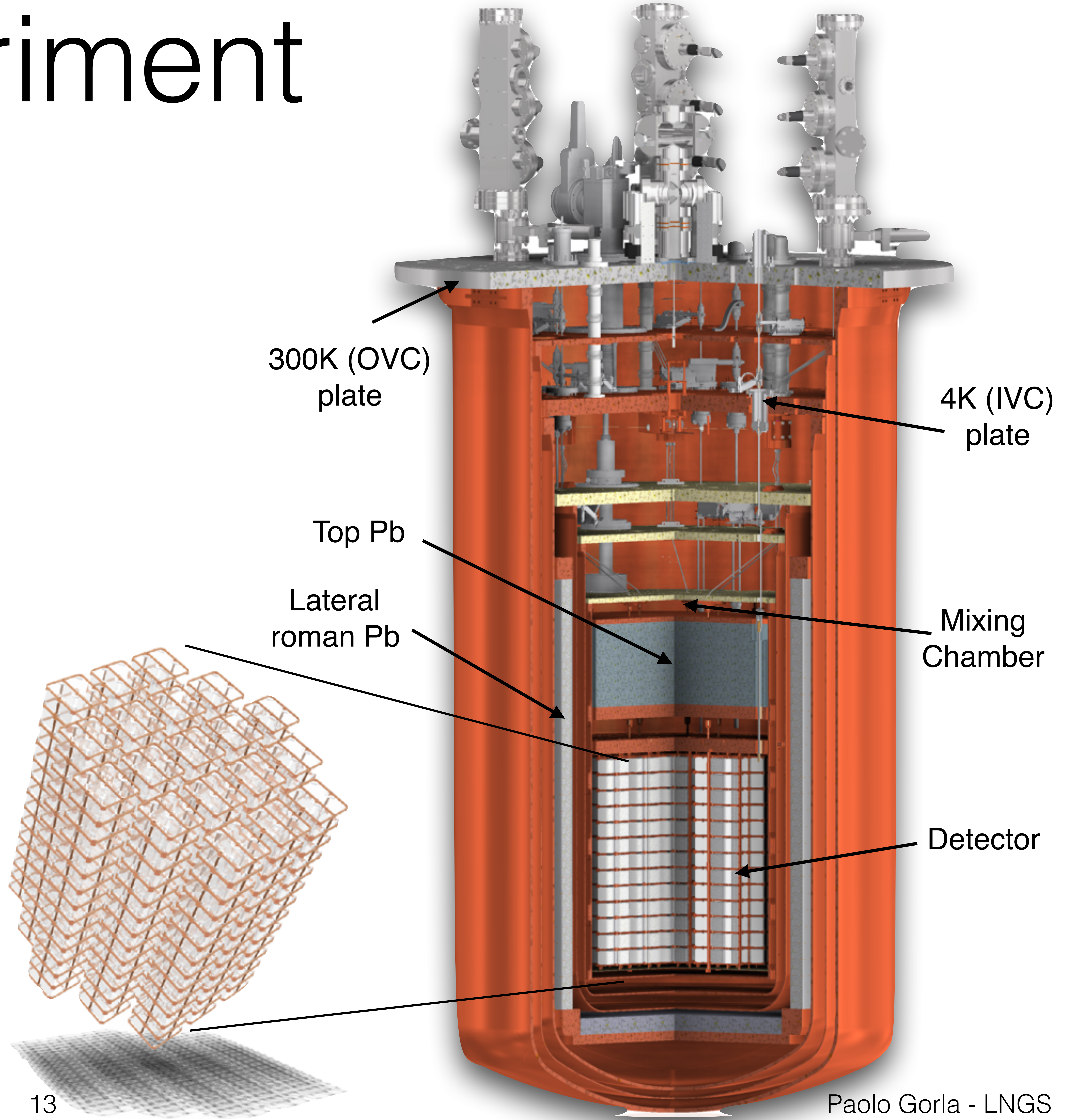

- CUORE-0 results
- CUORE commissioning

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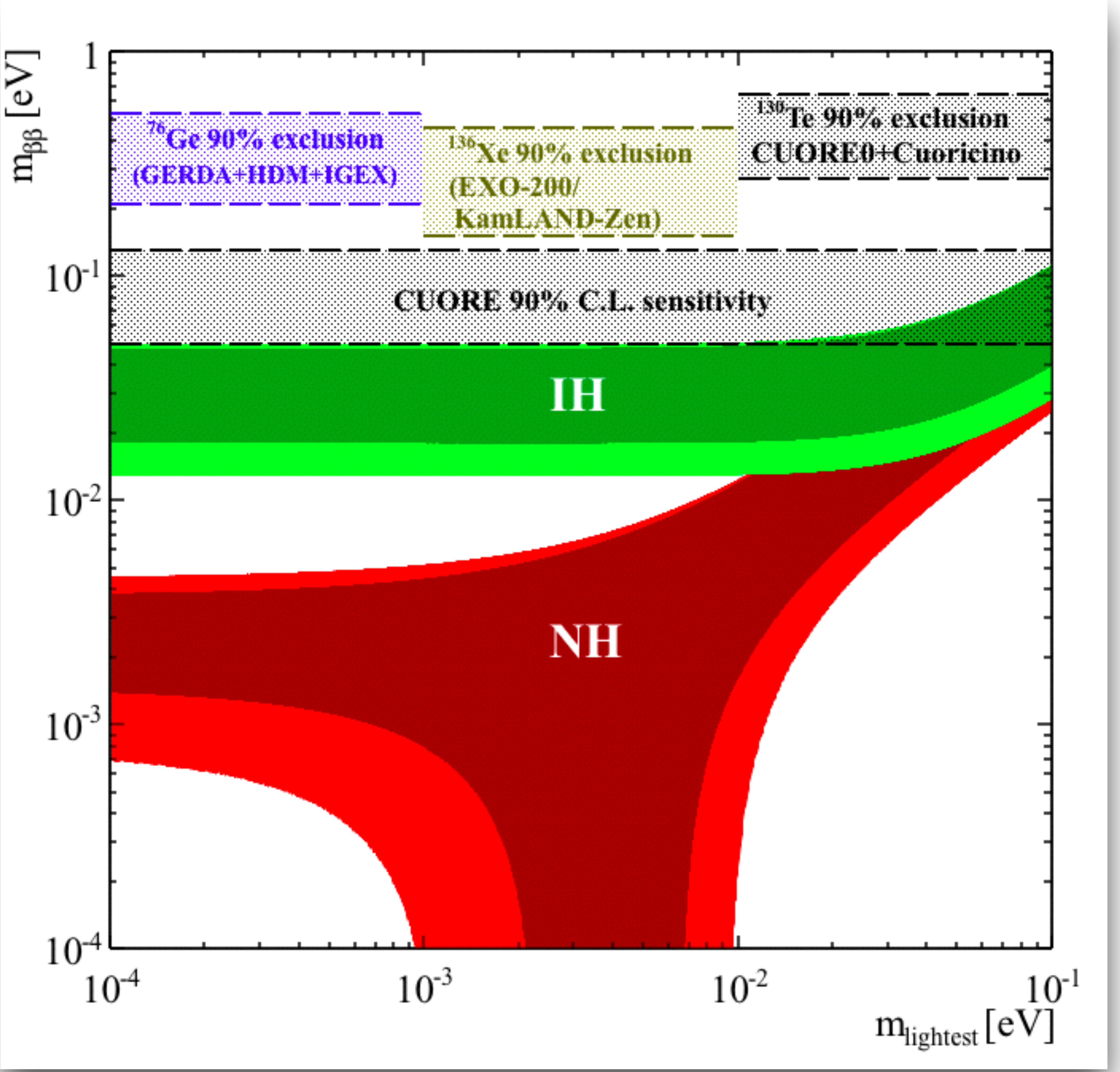

The CUORE collaboration

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CUORE @ Gran Sasso

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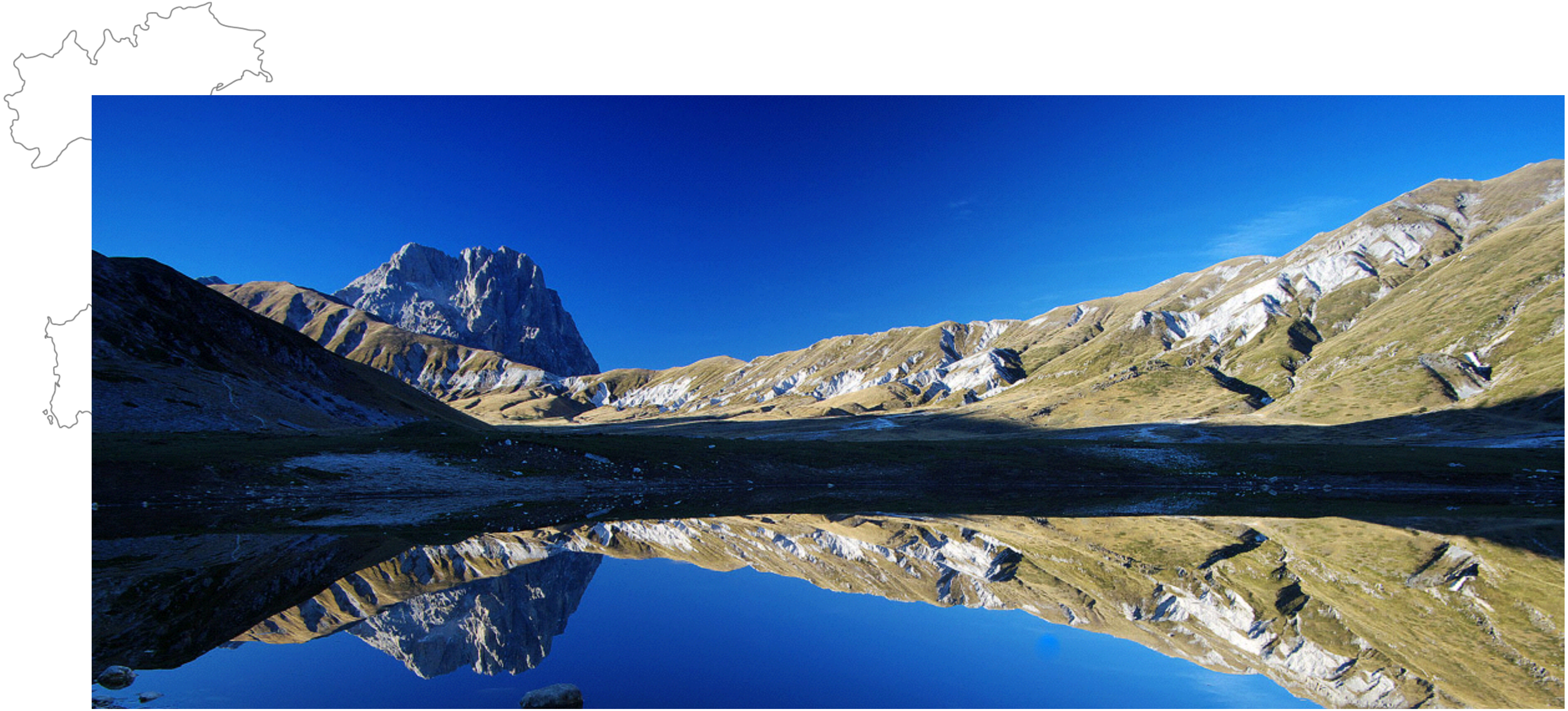
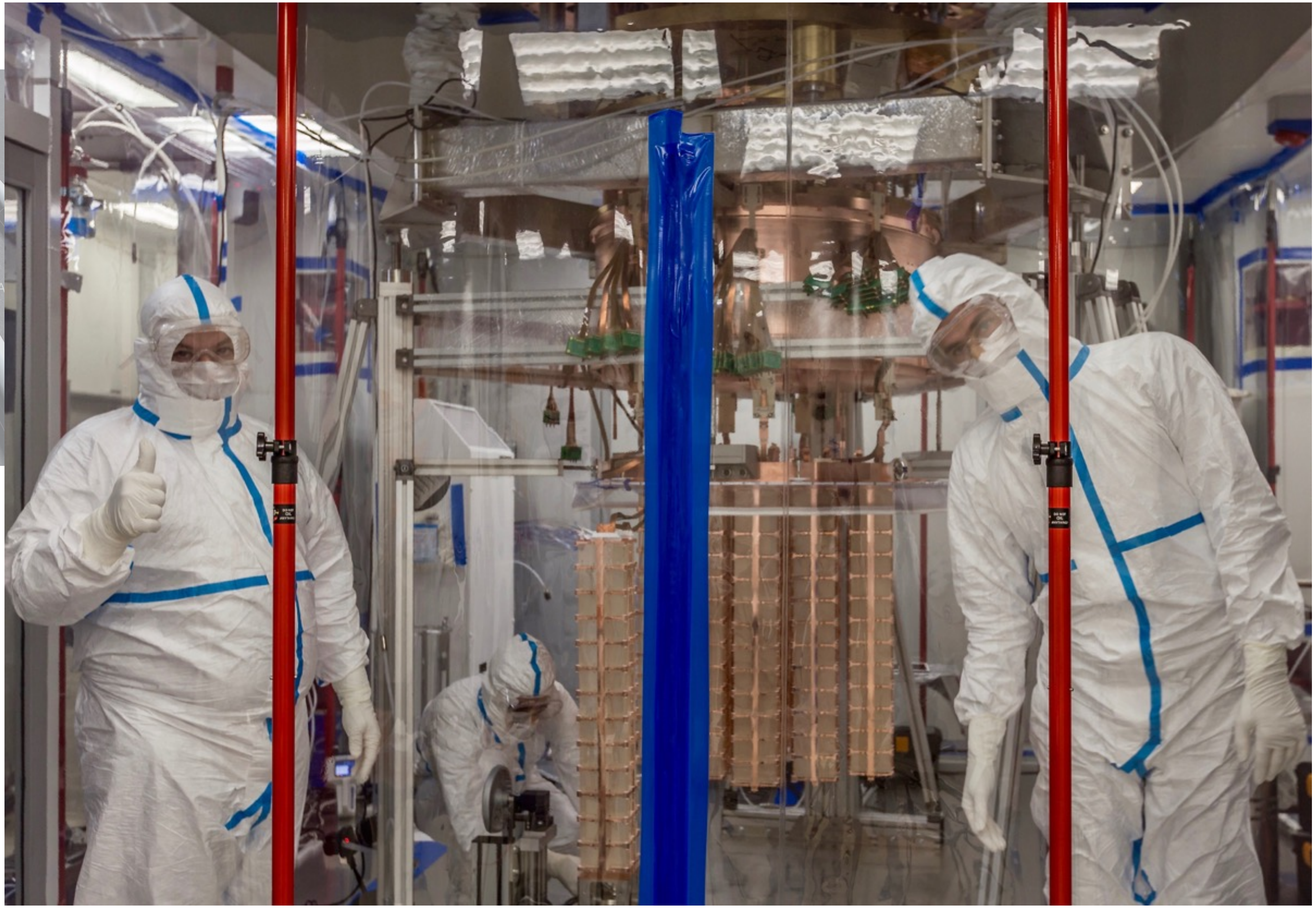


CUORE @ Gran Sasso

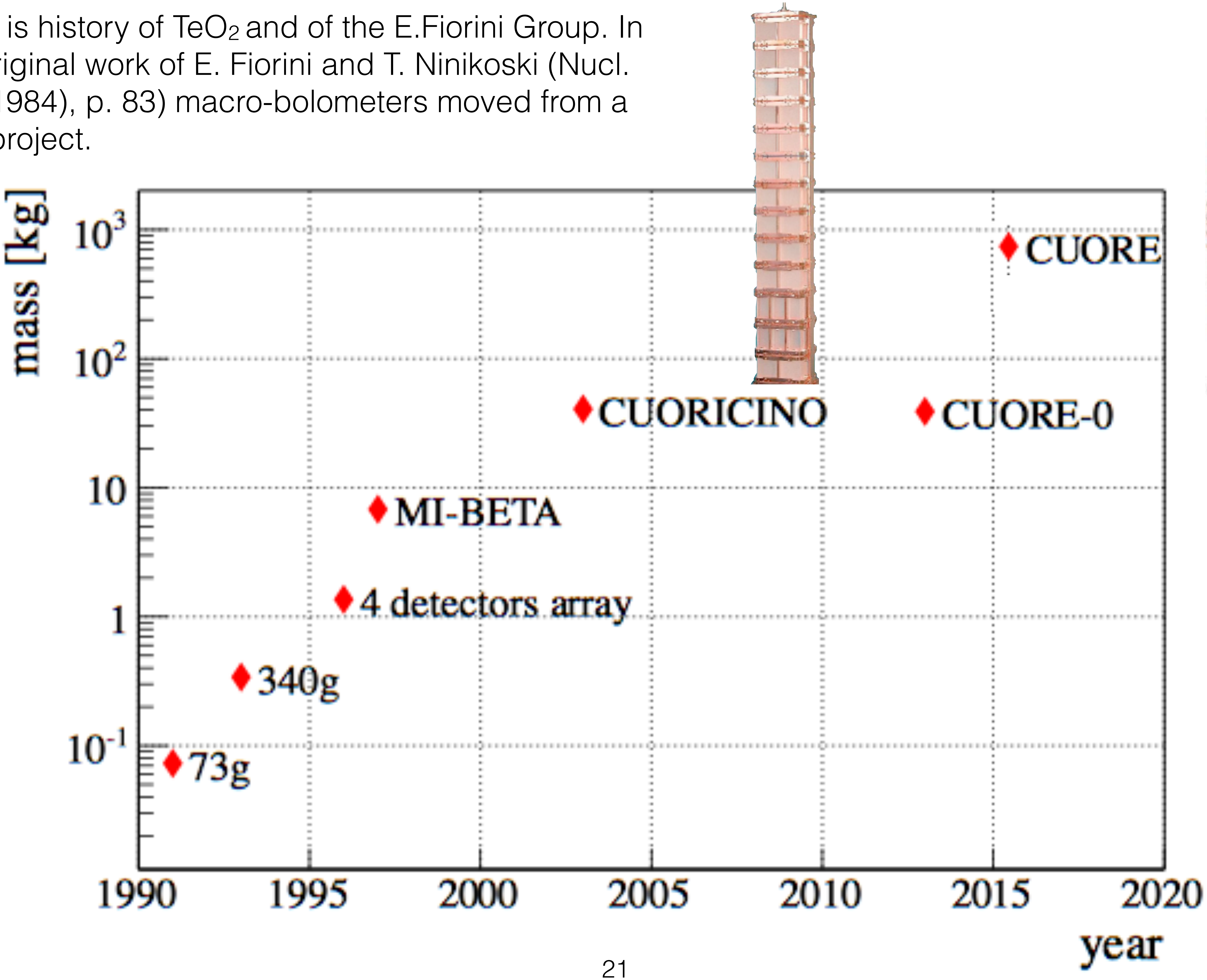
CUORE @ Gran Sasso

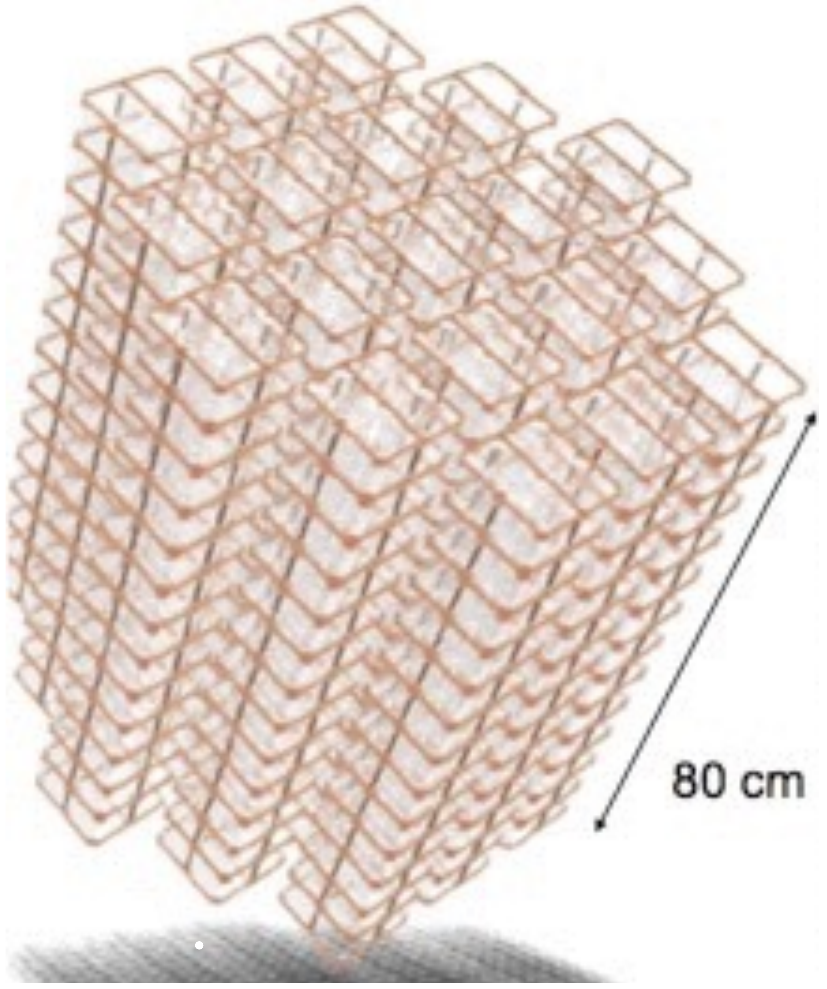
- ~3600 m.w.e. deep
- μs: ~3x10^{-8}/(s cm^2)
- γs: ~0.73/(s cm^2)
- neutrons: 4x10^{-6} n/(s cm^2)



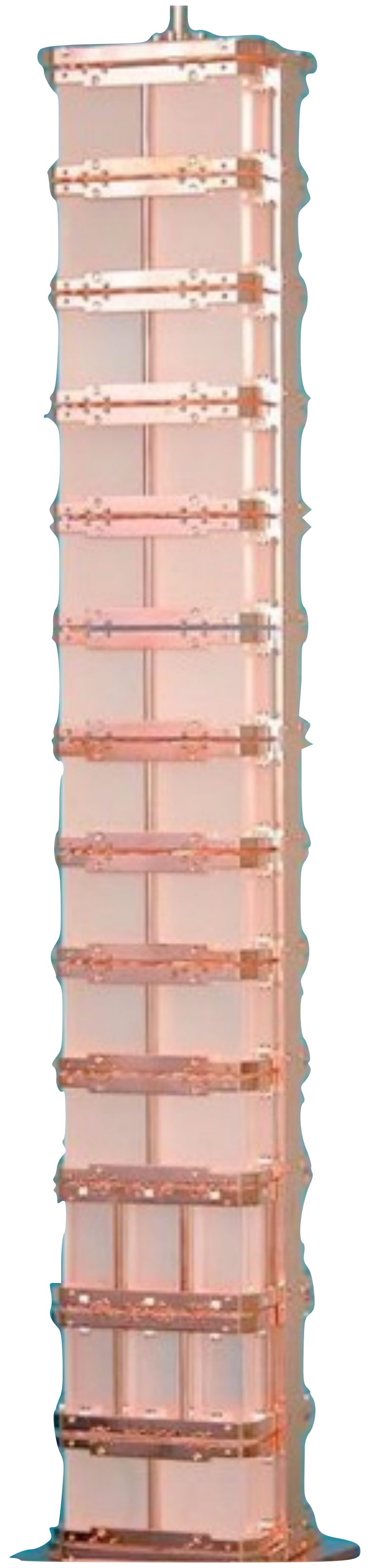
A little bit of history…

History of bolometric DBD is history of TeO_2 and of the E.Fiorini Group. In about 30 years from the original work of E. Fiorini and T. Ninikoski (Nucl. Instrum. And Meth., 224 (1984), p. 83) macro-bolometers moved from a smart idea to a ton scale project.

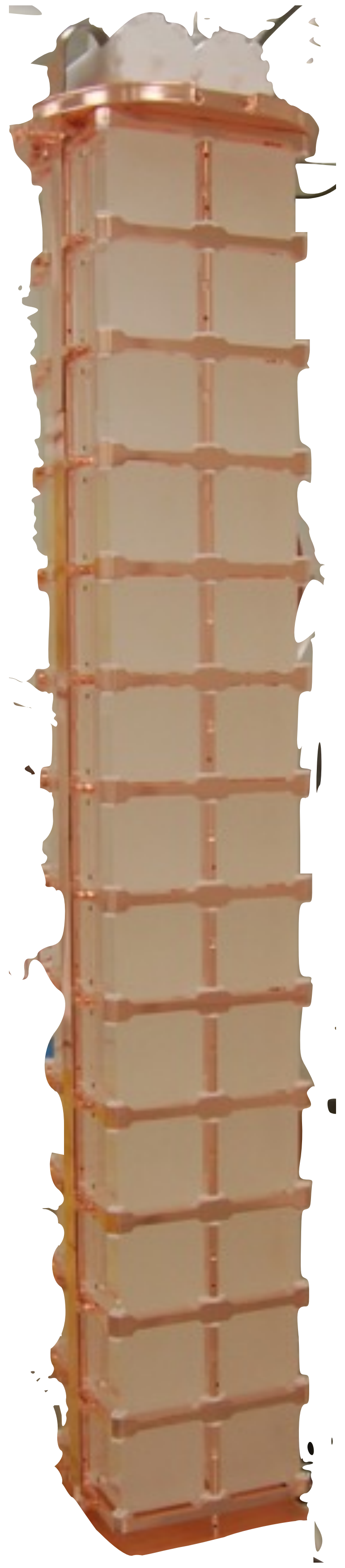




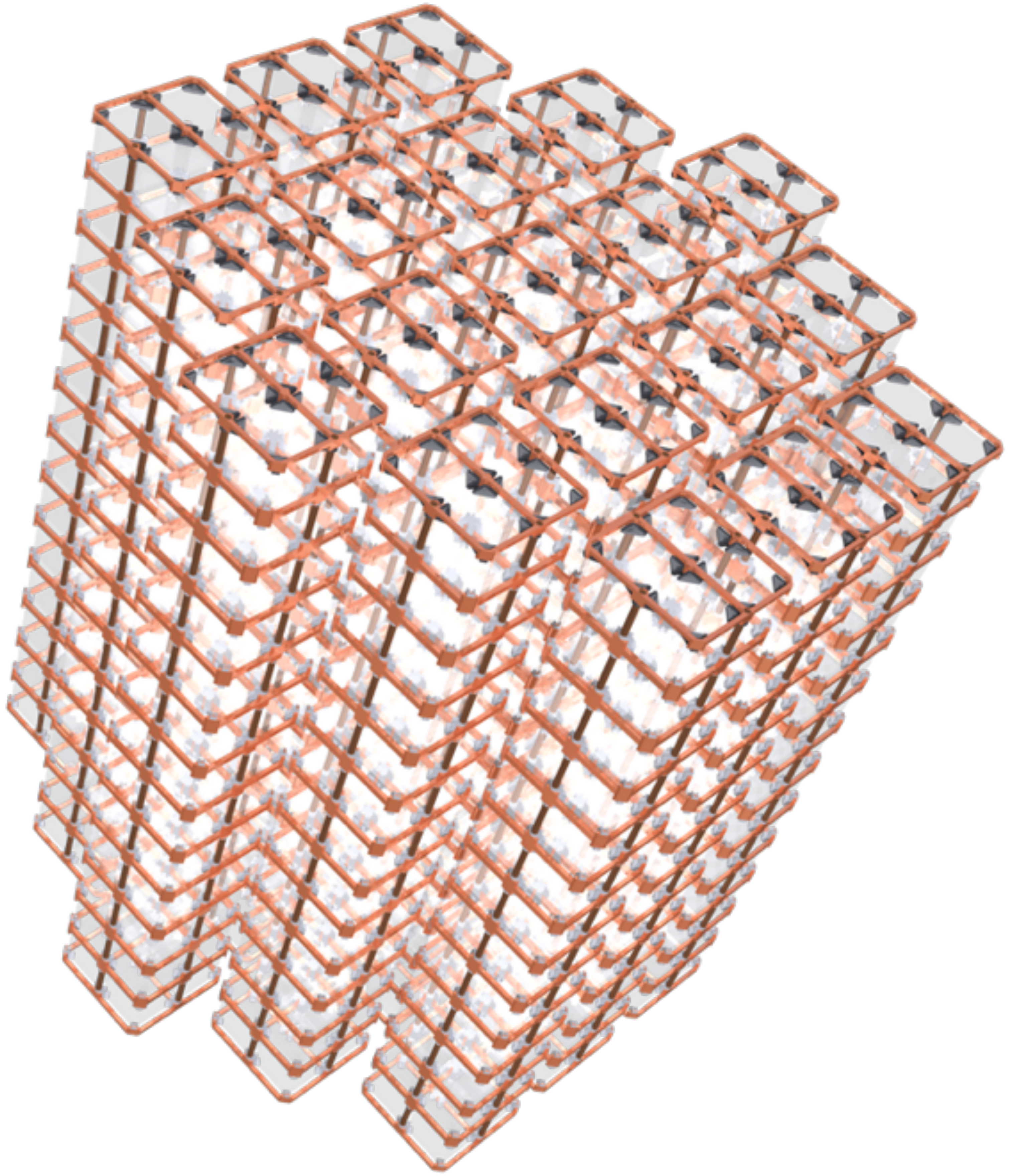
The CUORE program



CUORICINO
(2003-2008)

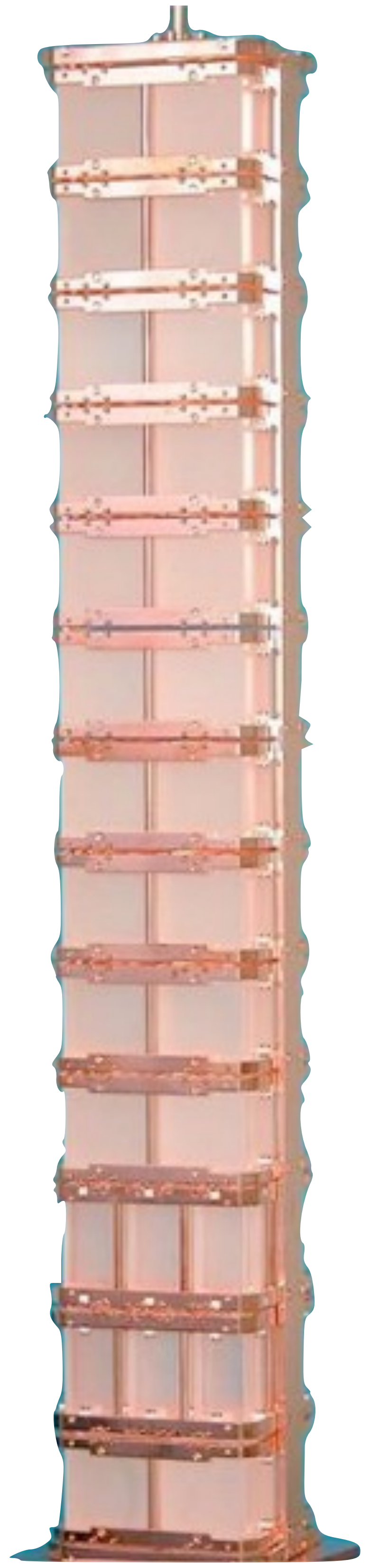


CUORE-0
(2012- 2015)



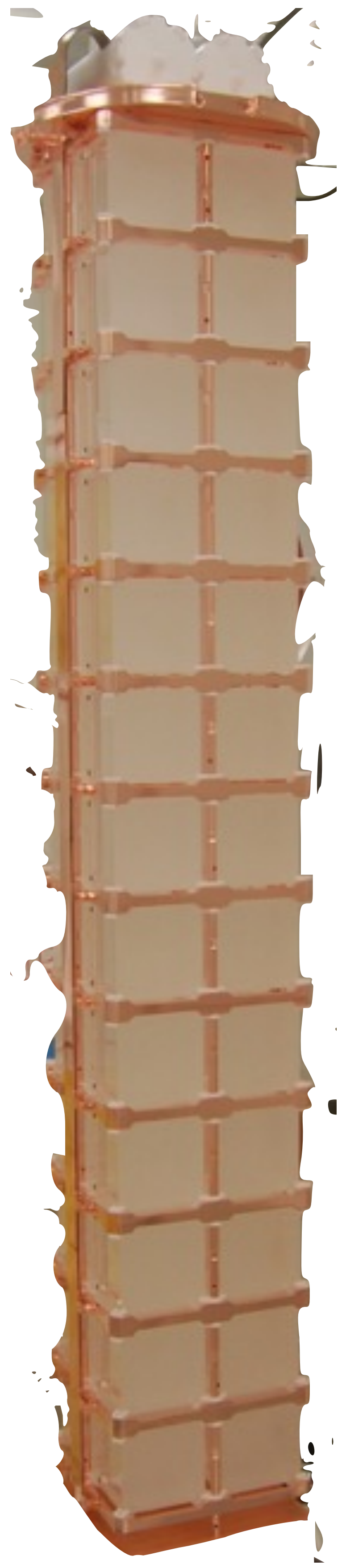
CUORE
2016

The CUORE program



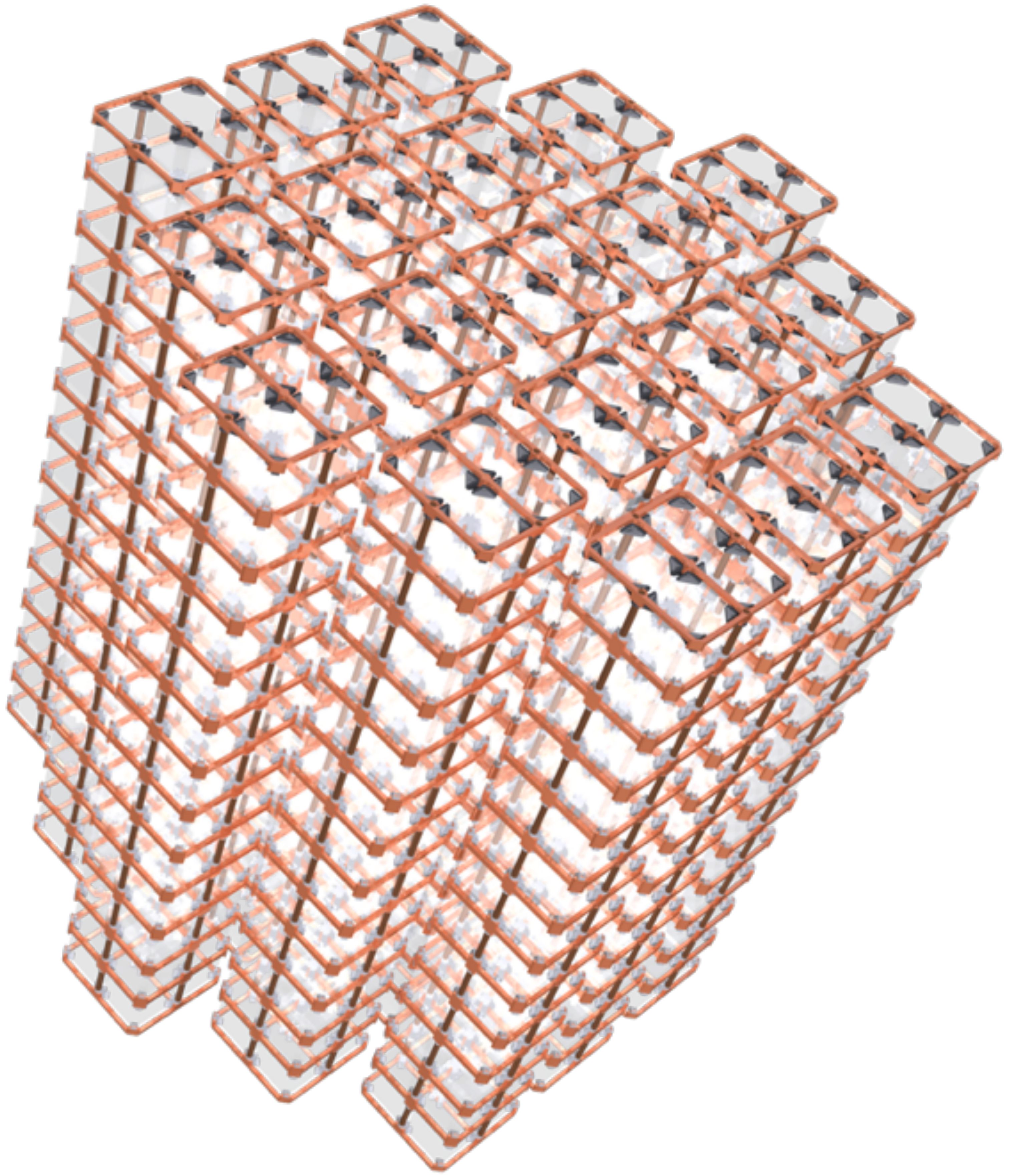
CUORICINO
(2003-2008)

COMPLETED



CUORE-0
(2012- 2015)

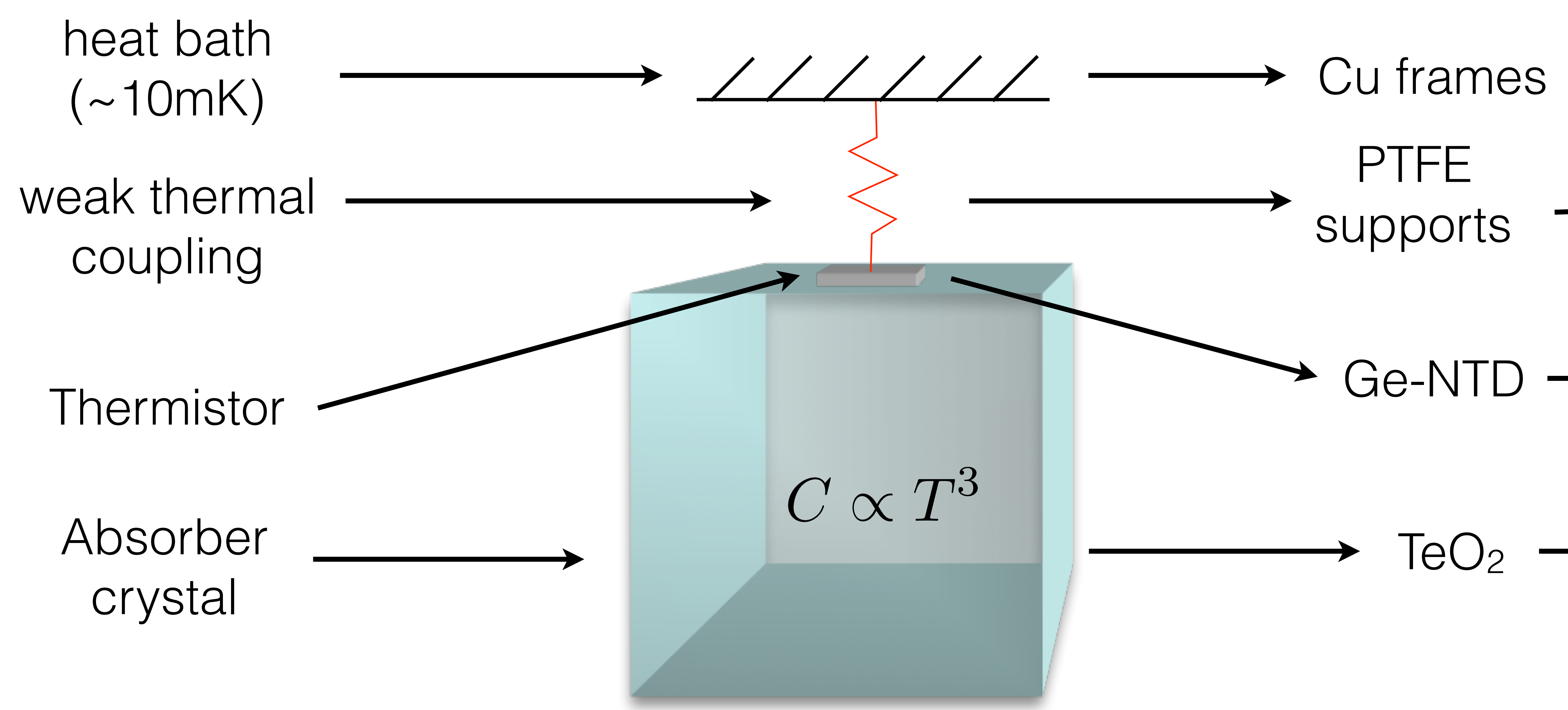
COMPLETED

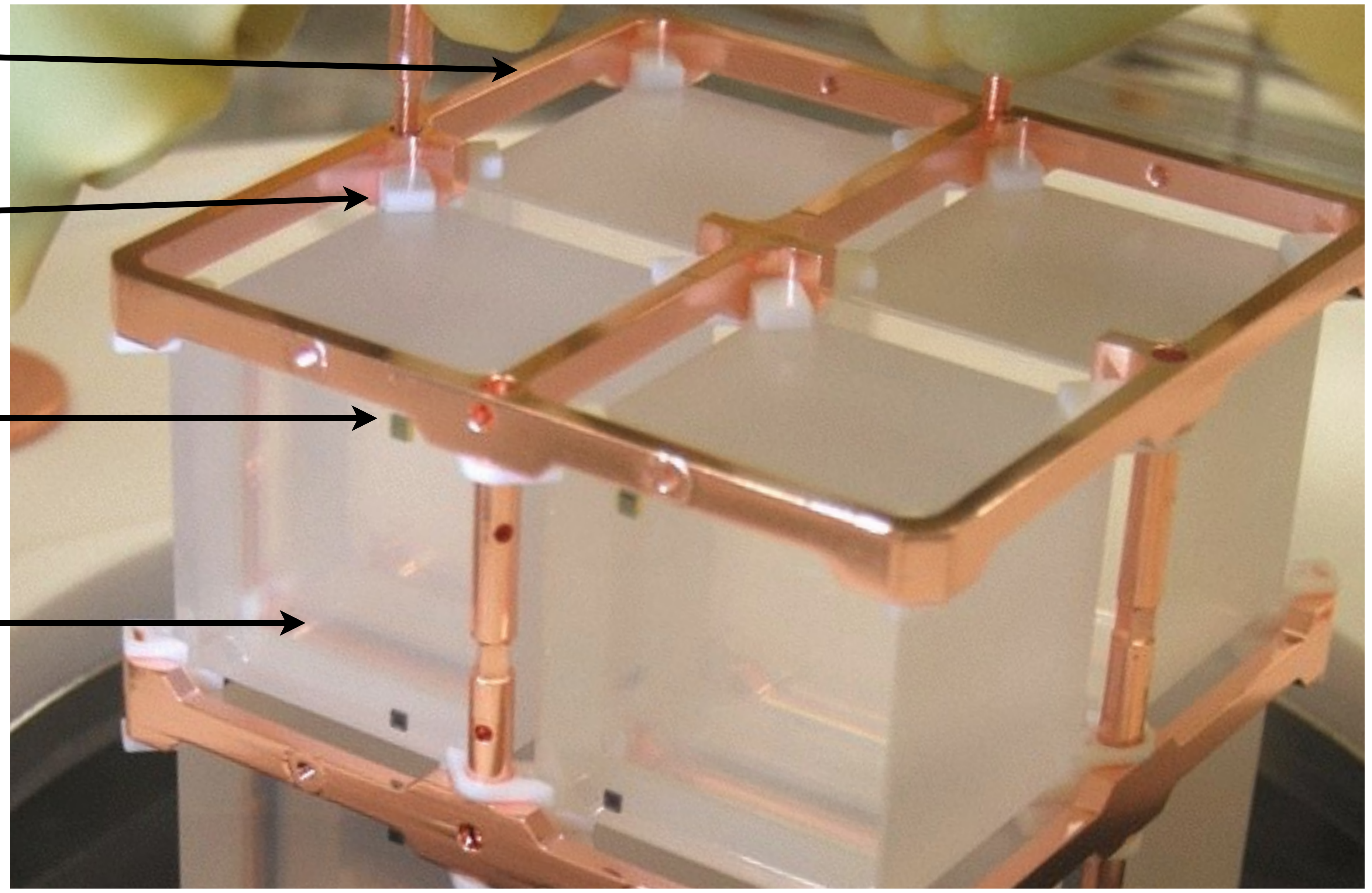


CUORE
2016

Ready for cool down

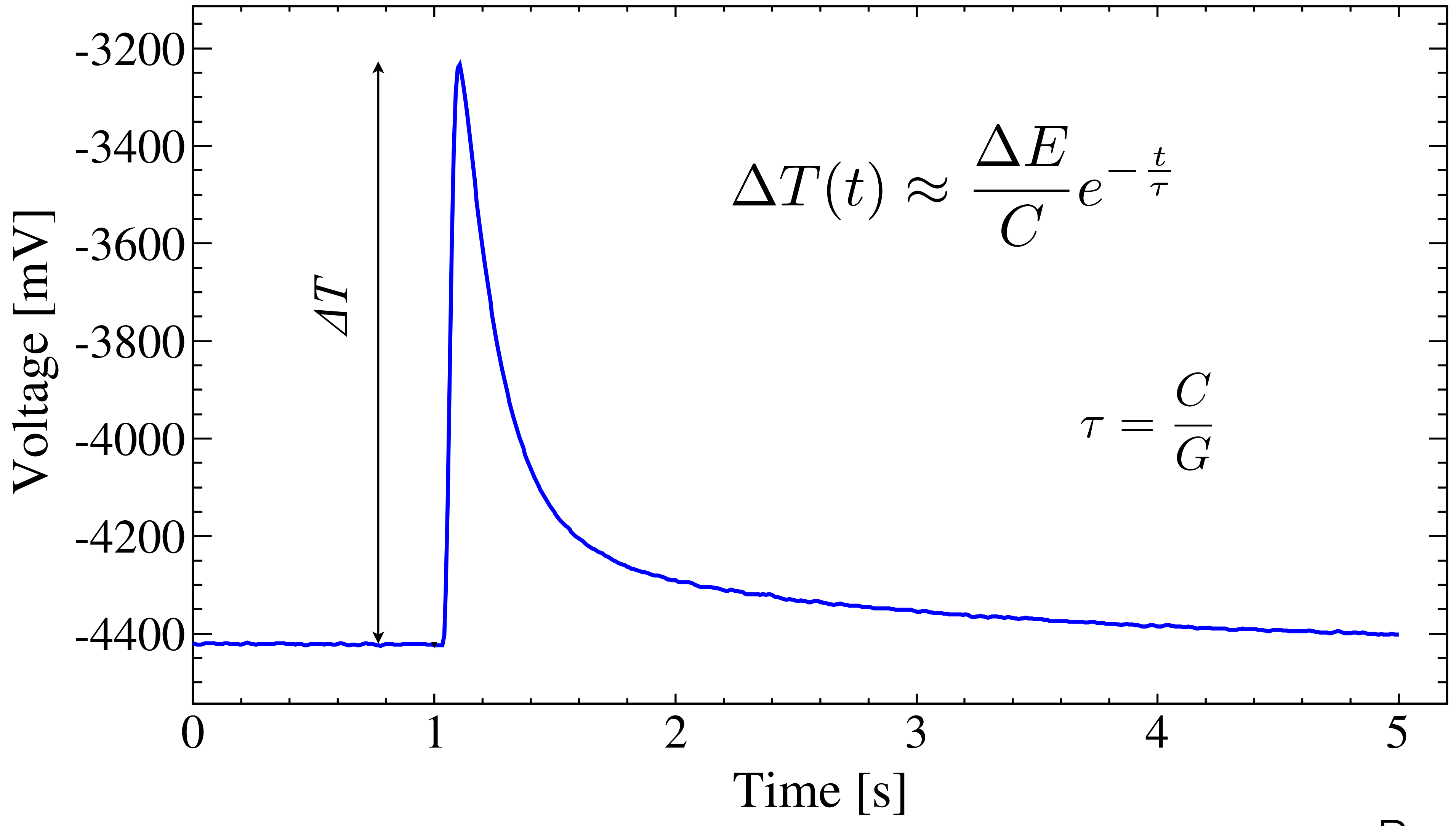
Thermal Detectors





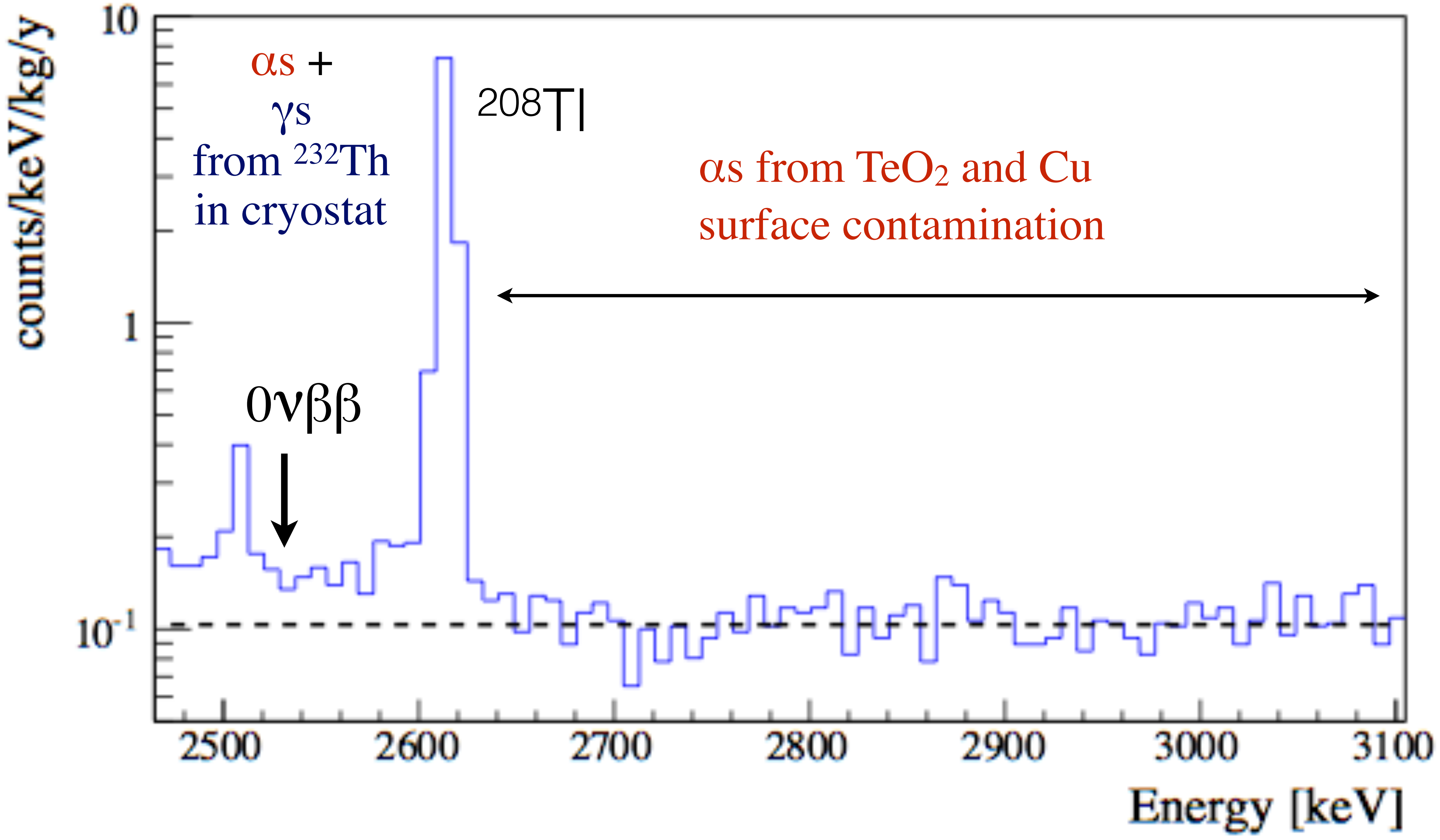
- low heat capacity @ T_{work}
- excellent energy resolution (~1 ‰ FWHM)

  huge number of energy carriers (phonons)
- equal detector response for different particles
- slowness (suitable for rare event searches)

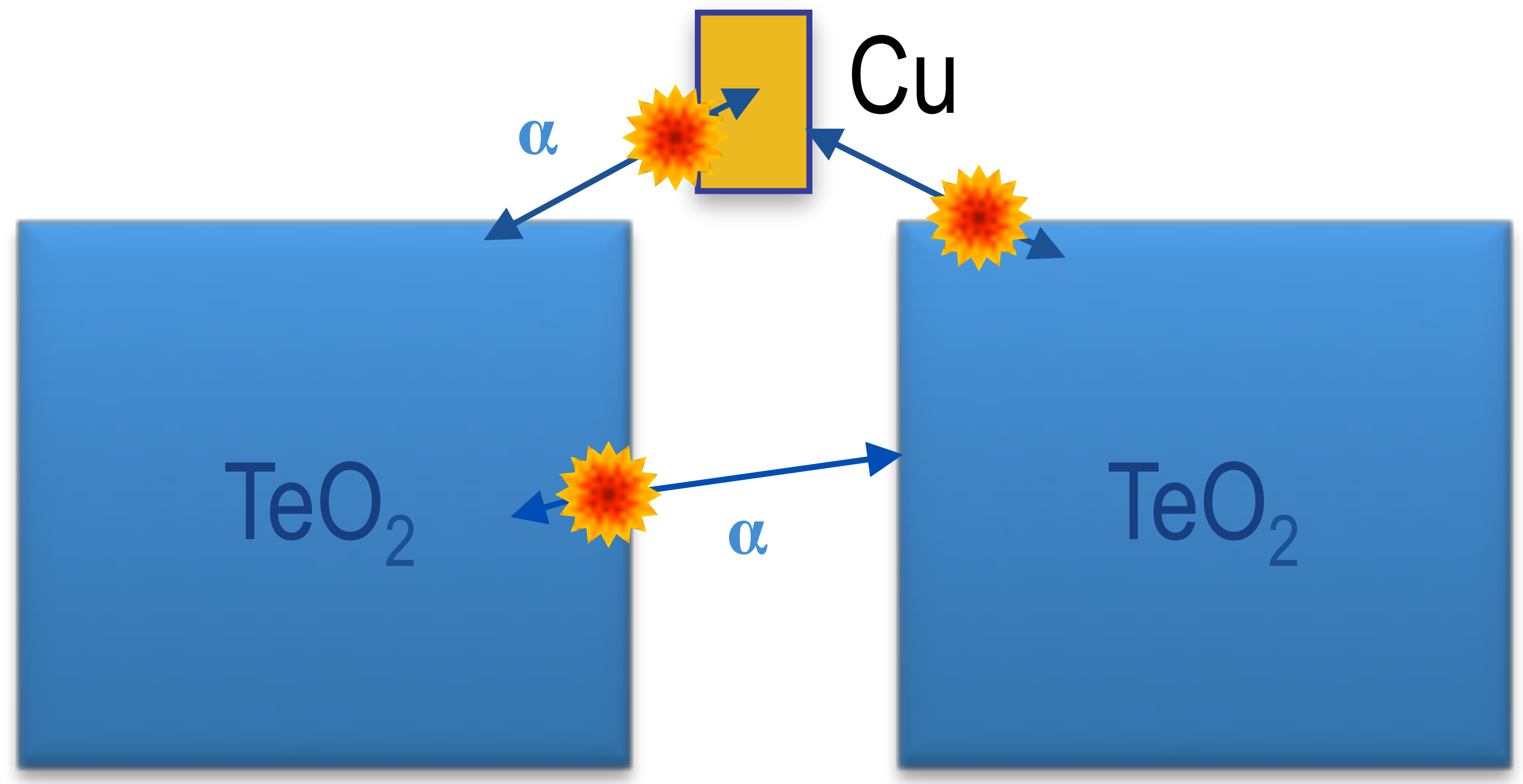


Cuoricino background

Cuoricino final energy spectrum



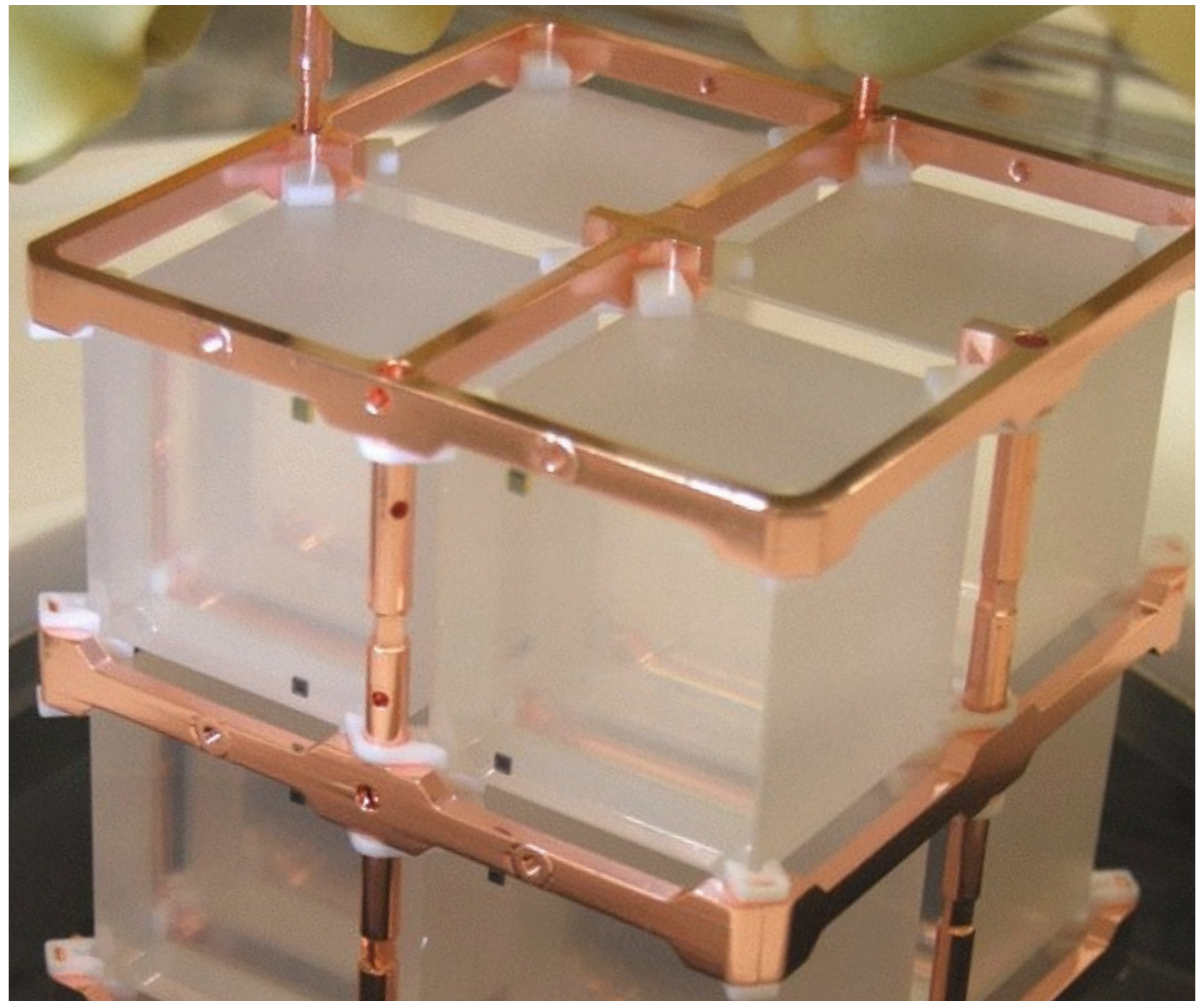
Background @ 0vDBD Q-value:
0.161 c keV^{-1} kg^{-1} y^{-1}

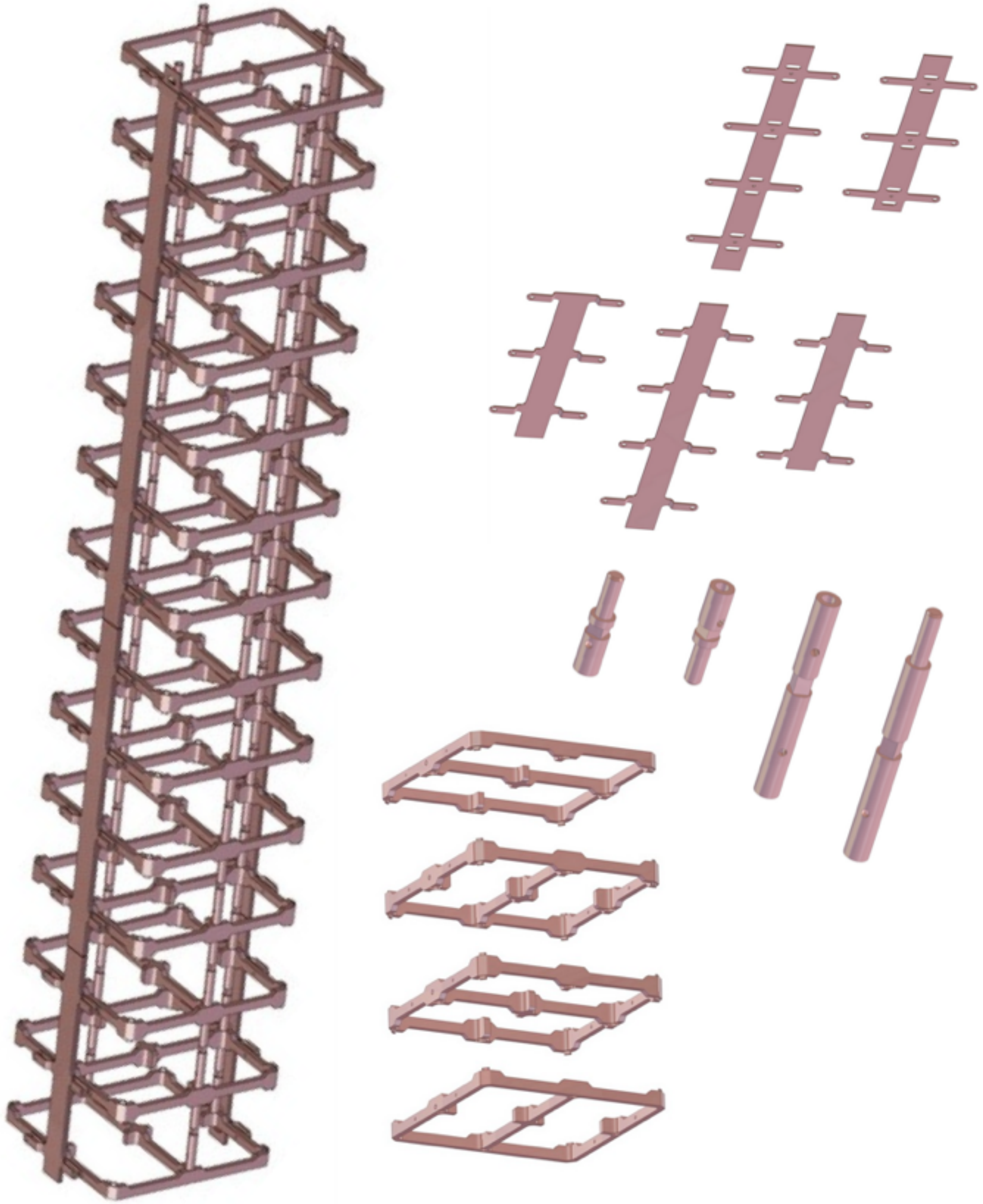


Source	^{208}Tl	$\beta\beta(0\nu)$ region	3-4 MeV region
TeO_2 ^{238}U and ^{232}Th surface contamination	-	10± 5%	20± 10%
Cu ^{238}U and ^{232}Th surface contamination	~15%	50± 20%	80± 10%
^{232}Th contamination of cryostat Cu shields	~85%	30± 10%	-

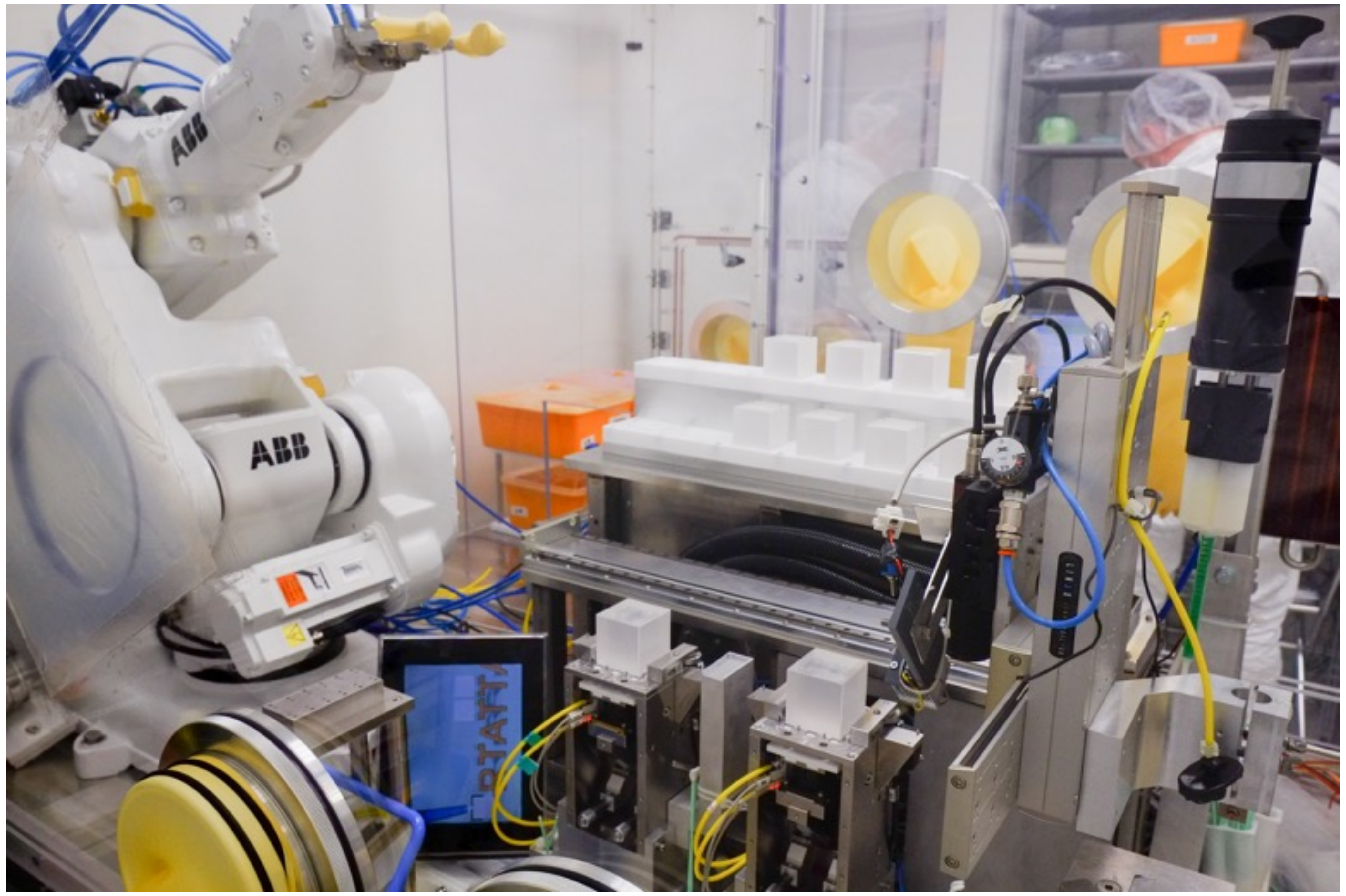
From CUORICINO to CUORE

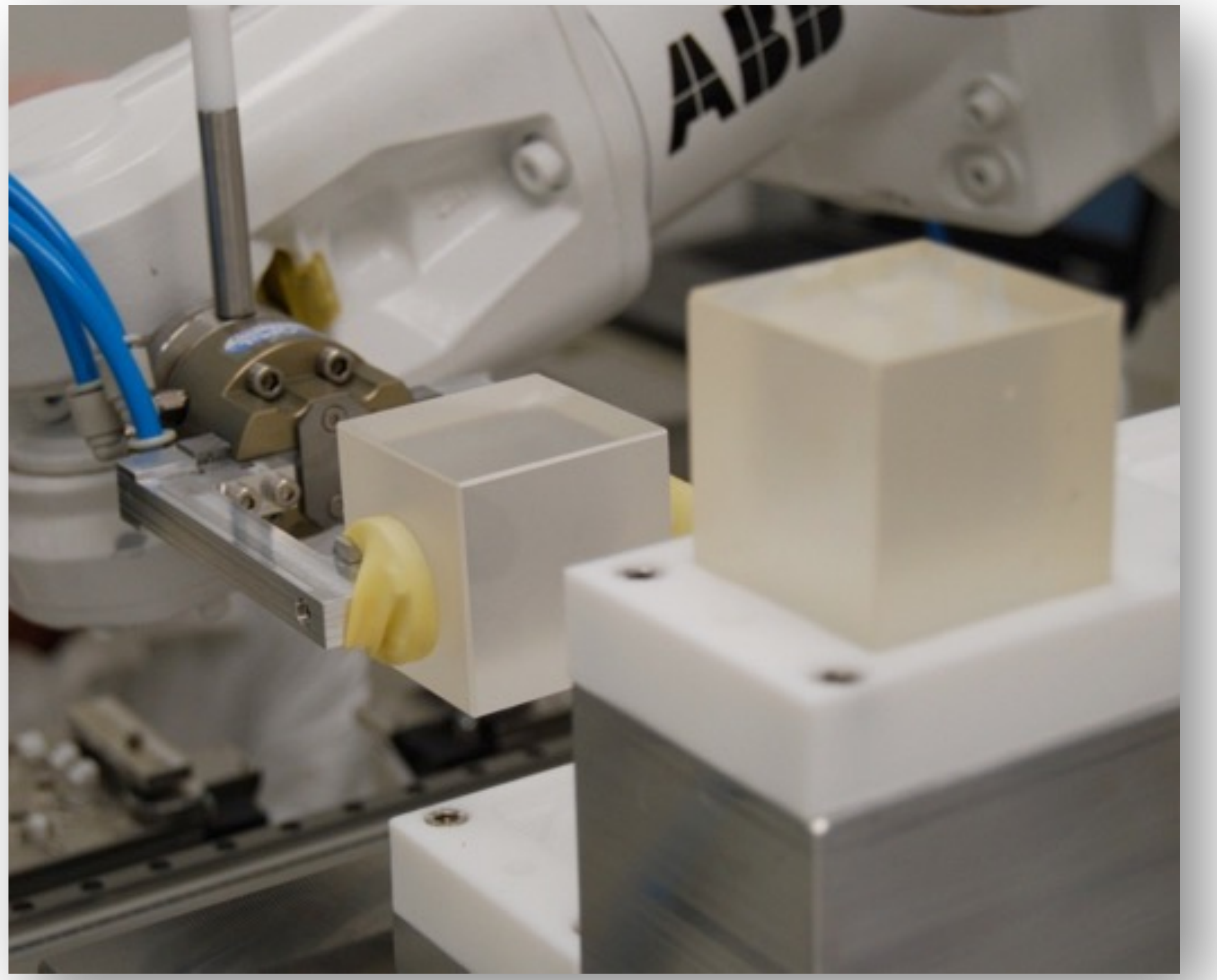
- Strict material selection
- New lighter detector design structure
- Reduced overall copper surfaces by a factor ~2
- New surface cleaning technique
- Strict production protocols for TeO_2 surface contamination
- Minimization of Rn exposure (N_2 glove box assembly)

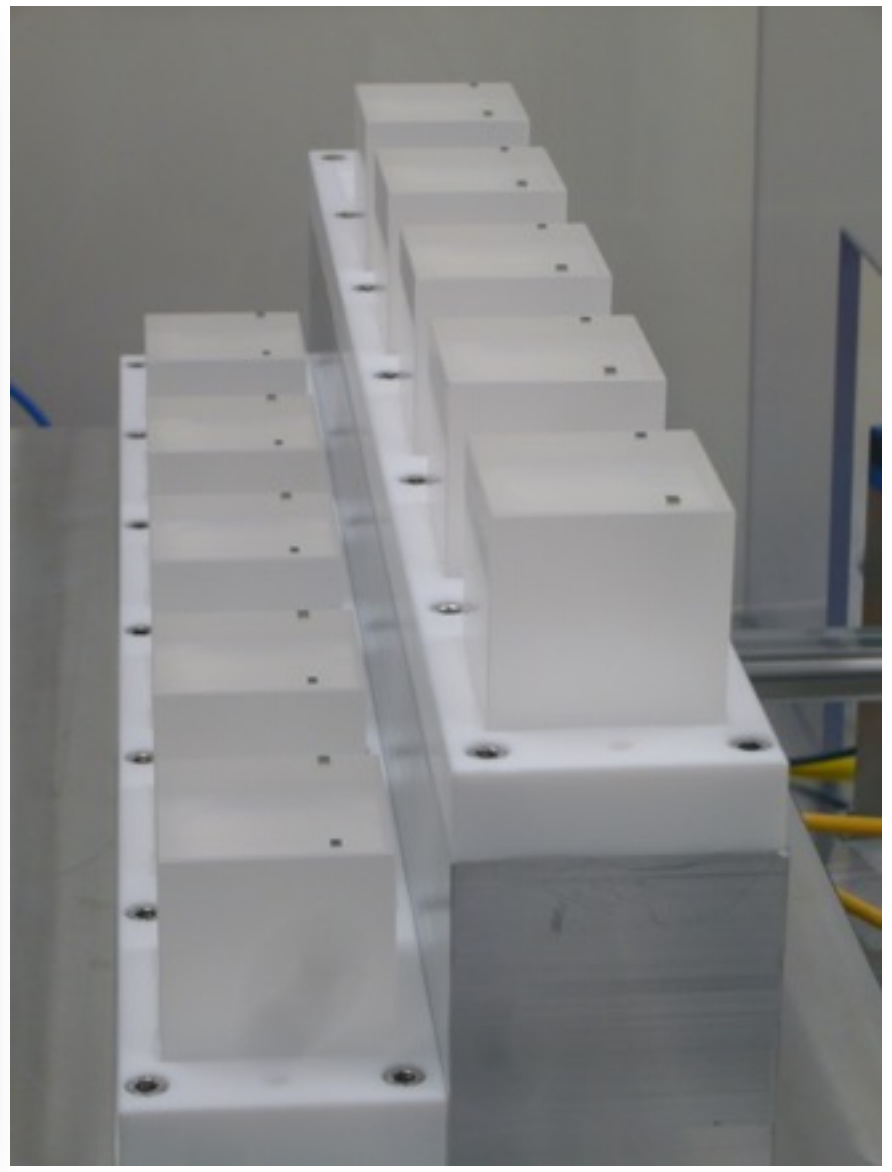


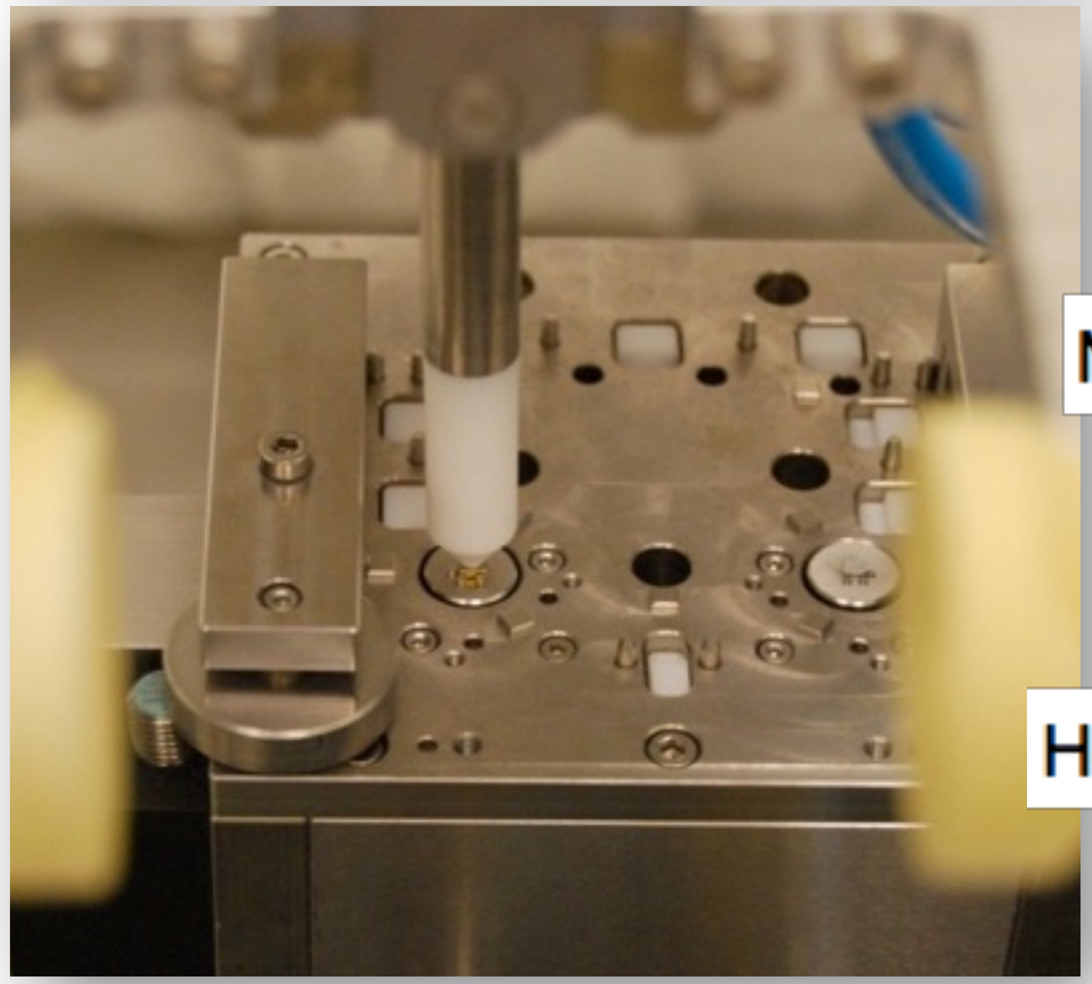


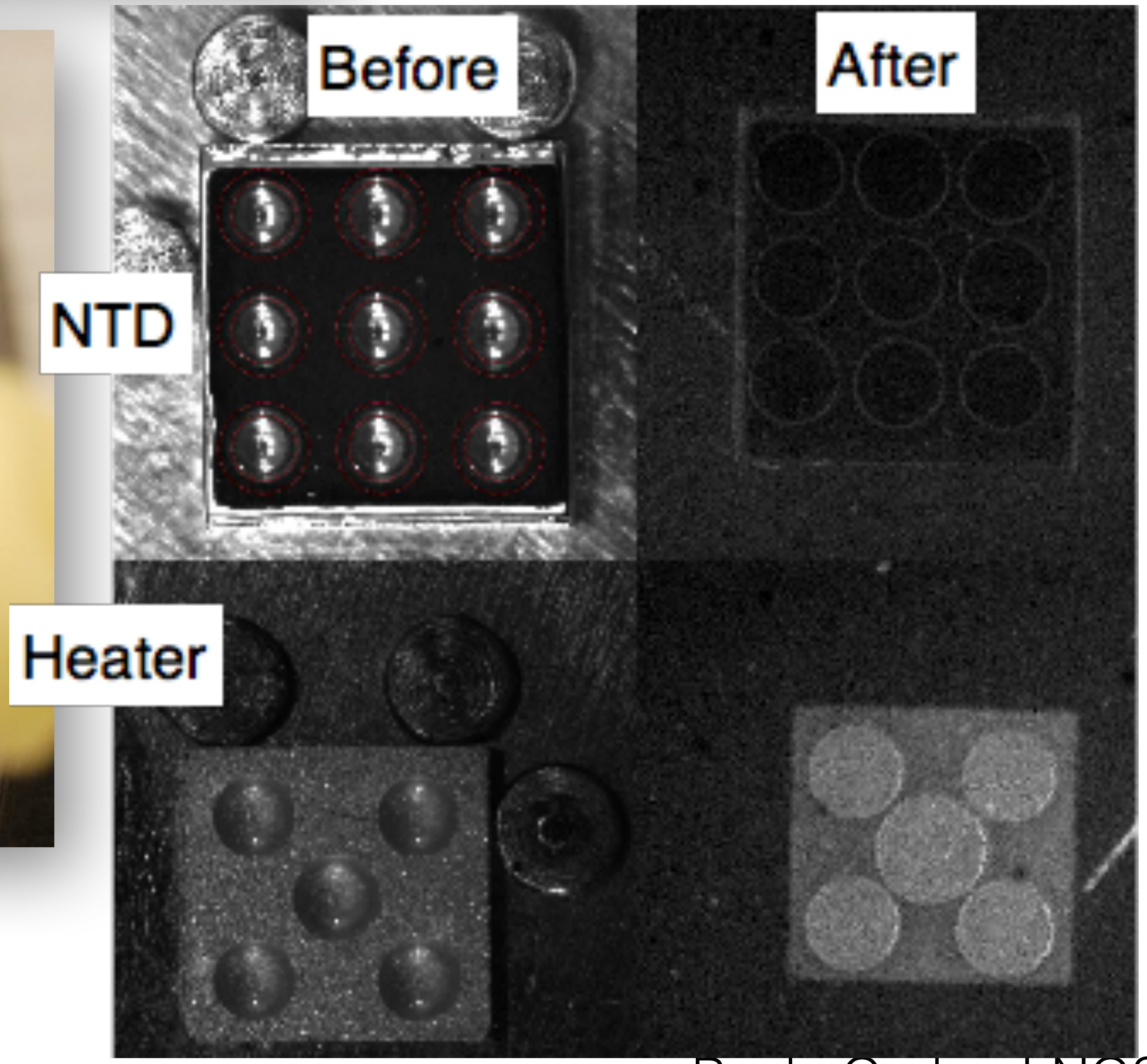
Thermistors & Heaters coupling







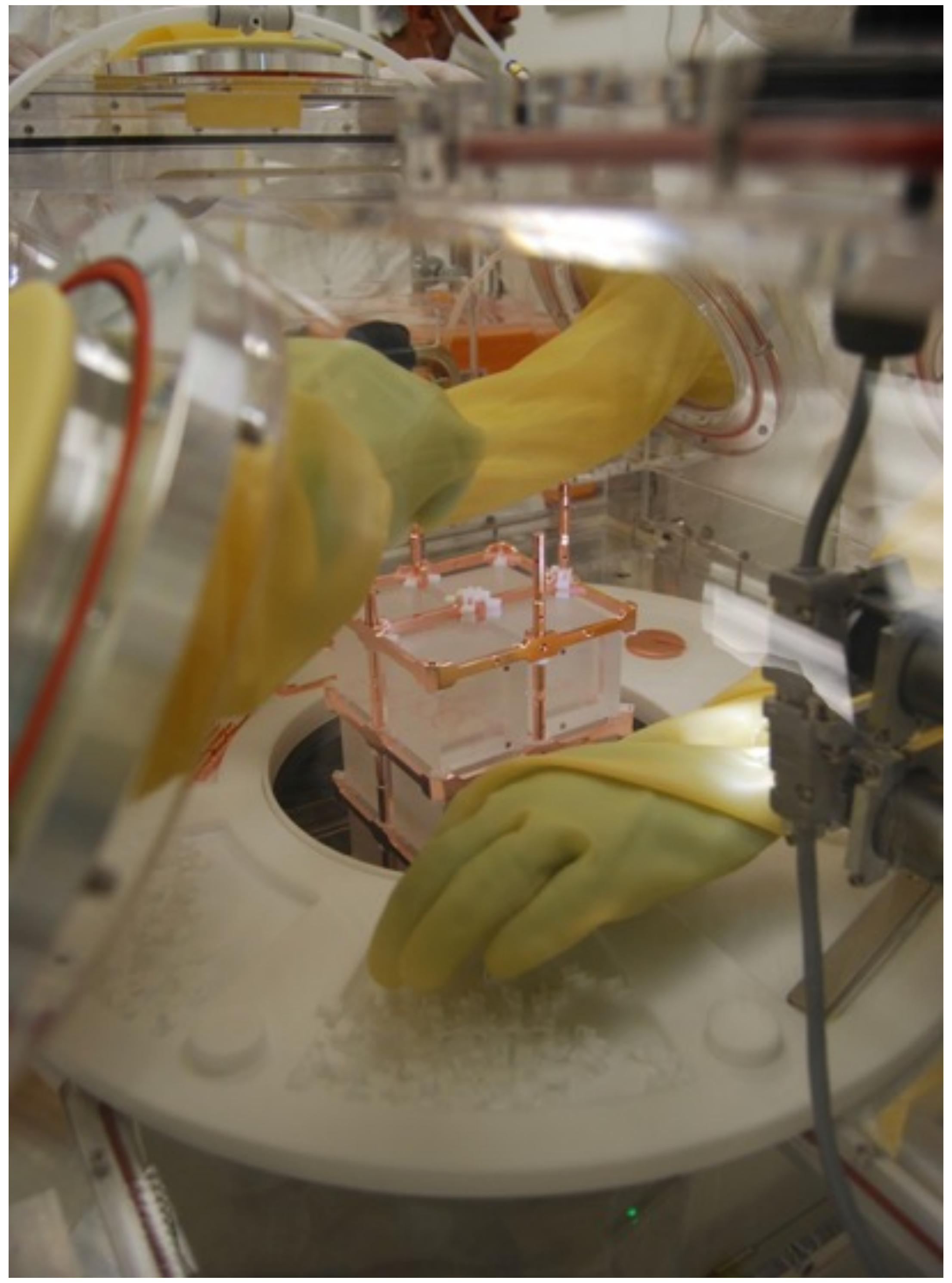


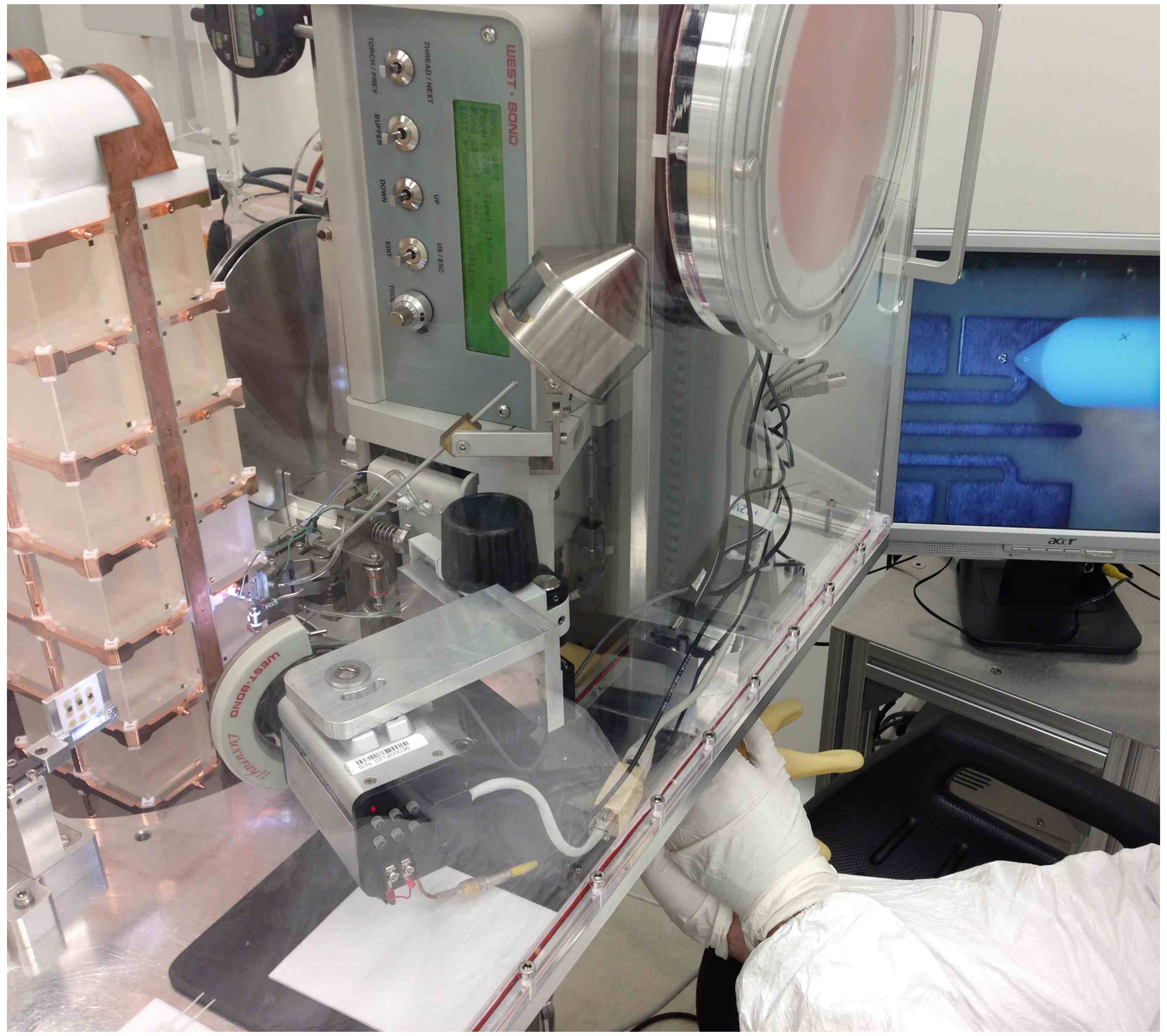


Features:

- new semi-automatic system
- highly-reproducible
- fully performed under N_2 atmosphere to minimize radioactive recontamination.

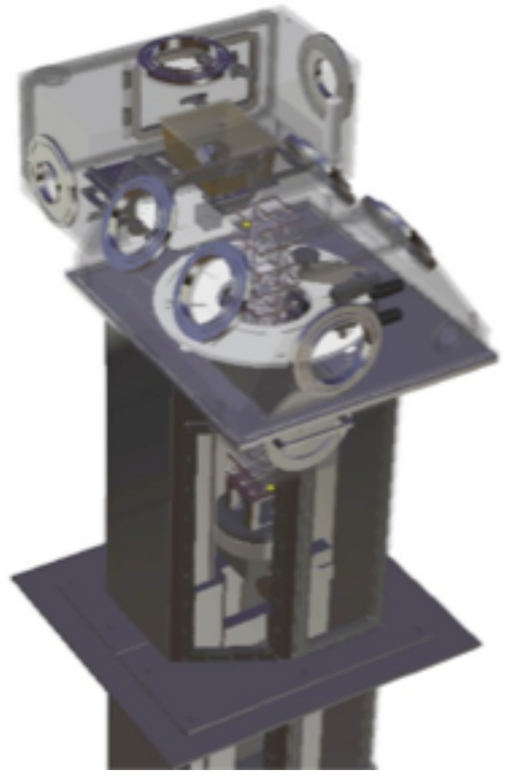
CUORE-0 Assembly & Bonding



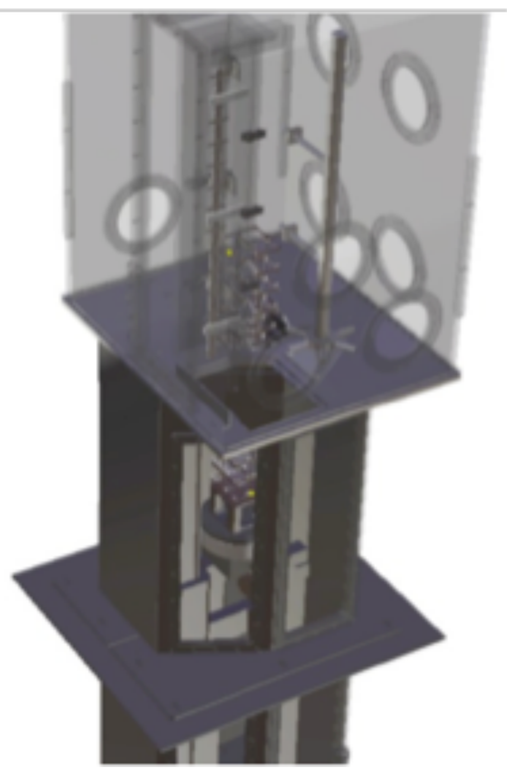


Contact less approach:

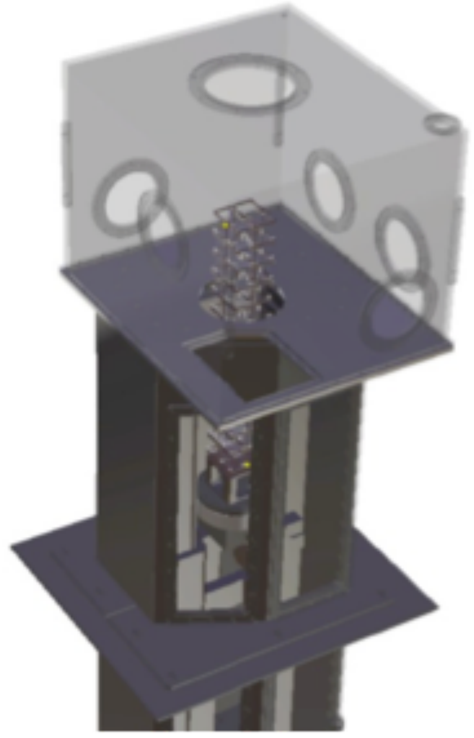
- All the operations carried out in N2 atmosphere



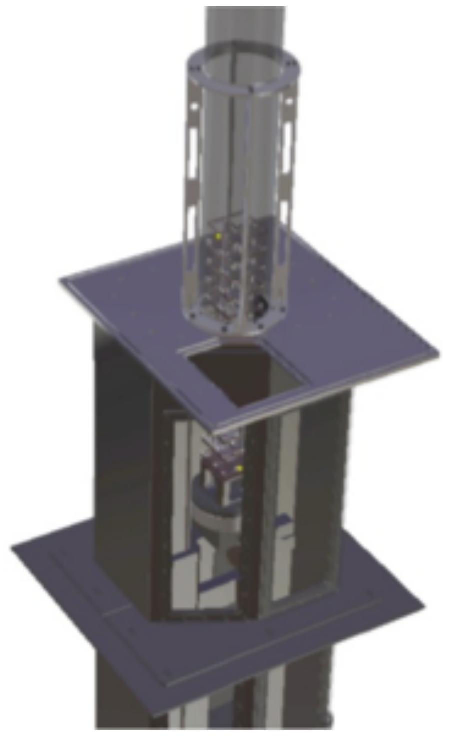
1. Assembly box



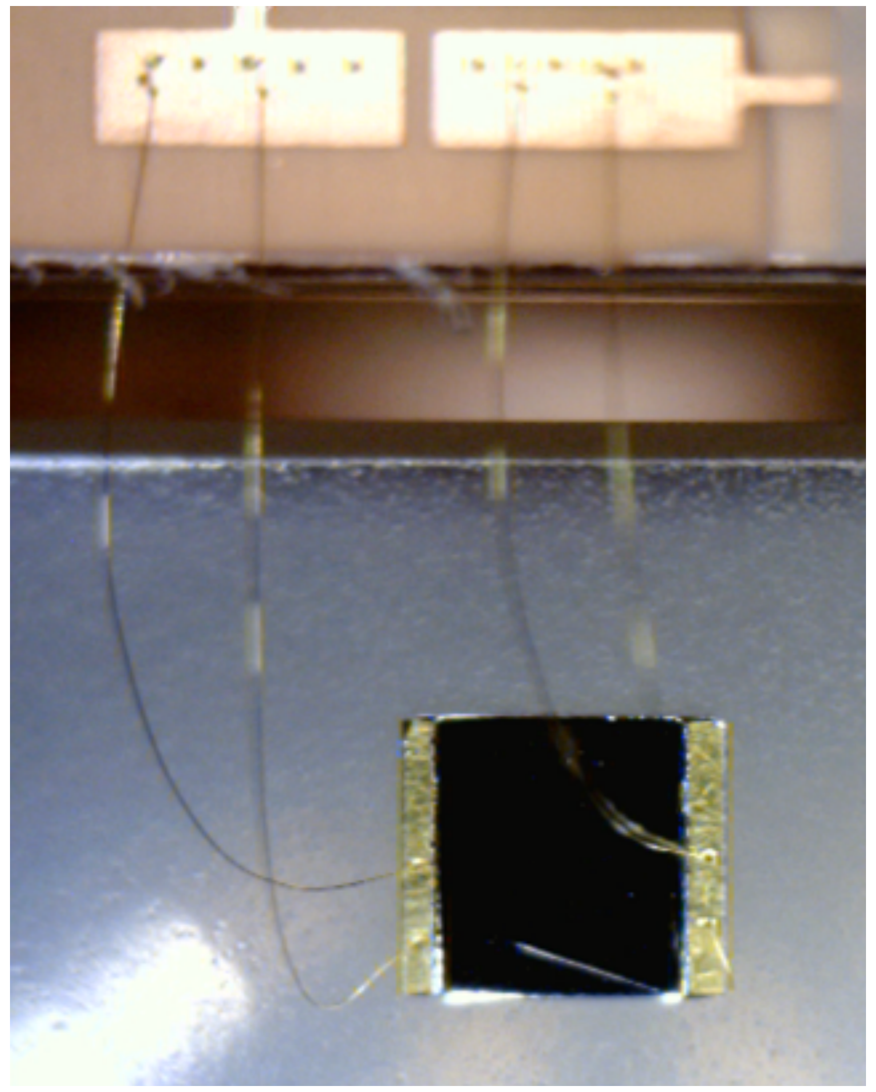
2. Cabling box



3. Bonding box



4. Storage box

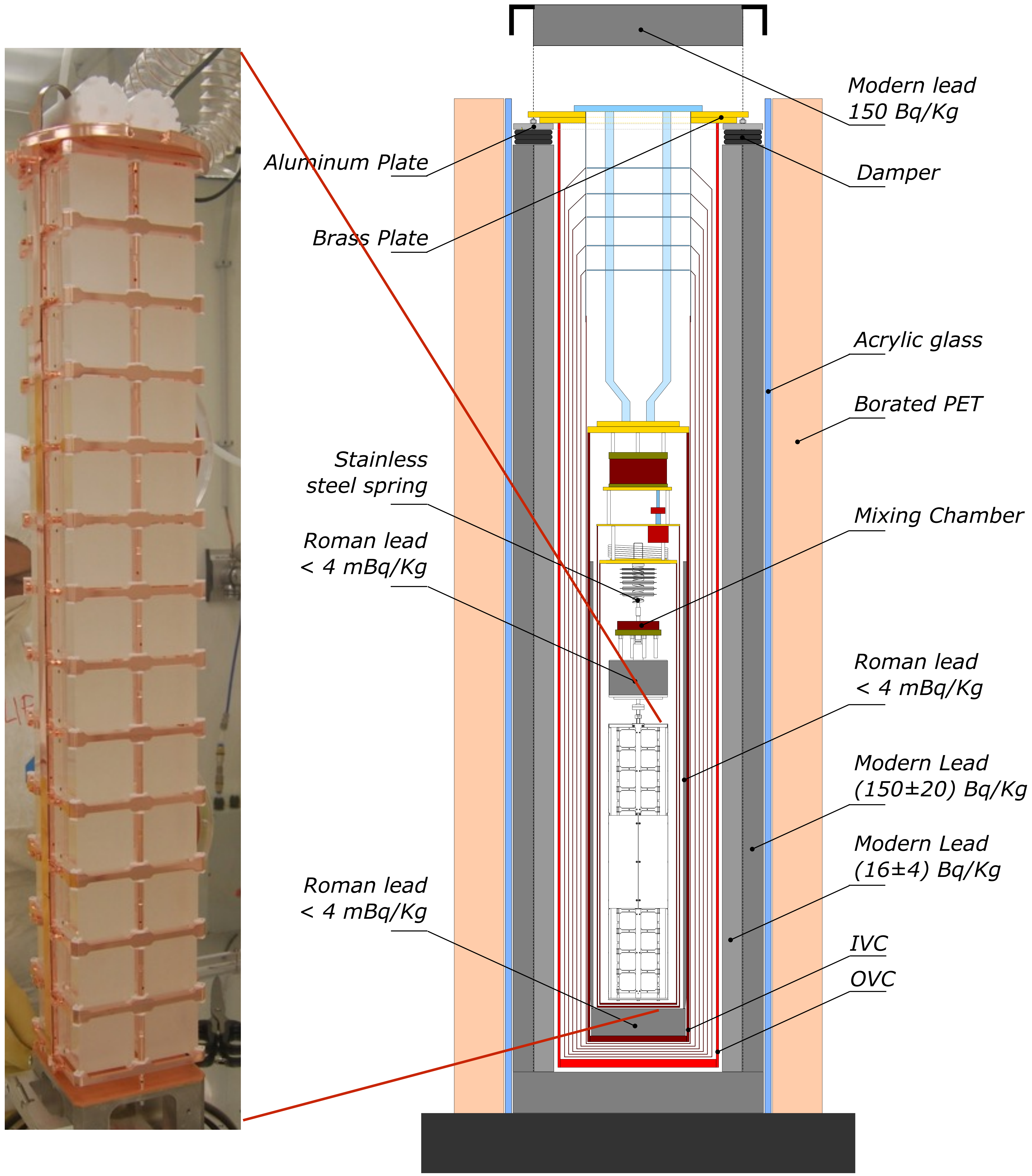


CUORE-0

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)

JINST 11 (2016) P07009



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- 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
- Check of the radioactive background reduction
- Statistics accumulated: 9.8 kg·yr 130Te
- Duty cycle: 78.6%
- Sensitive 0vDBD experiment

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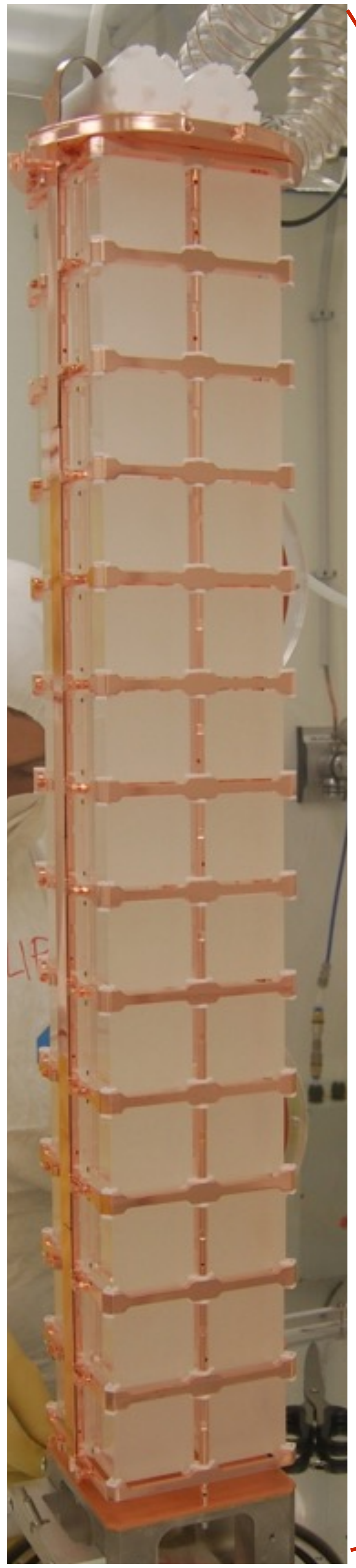

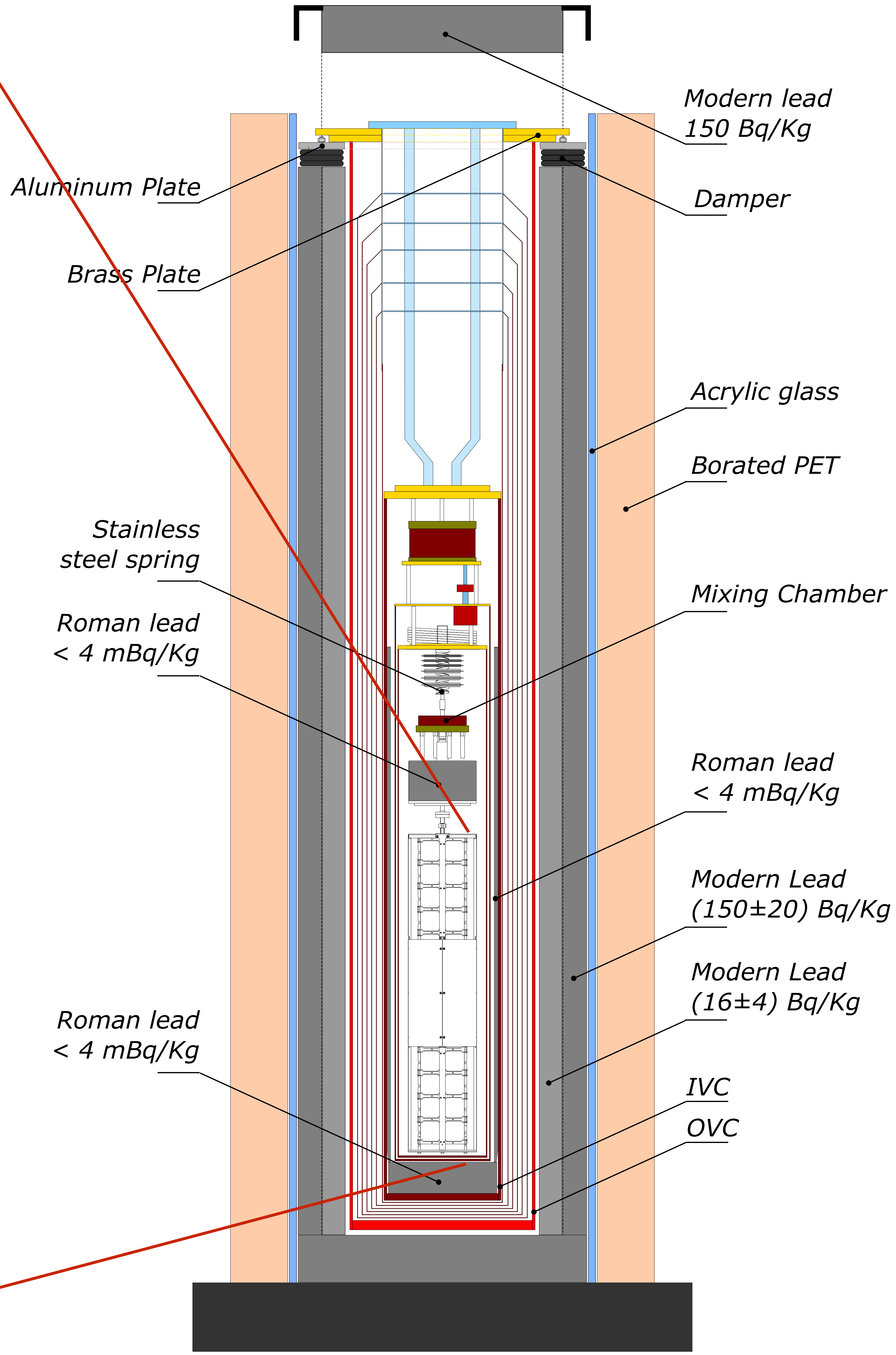

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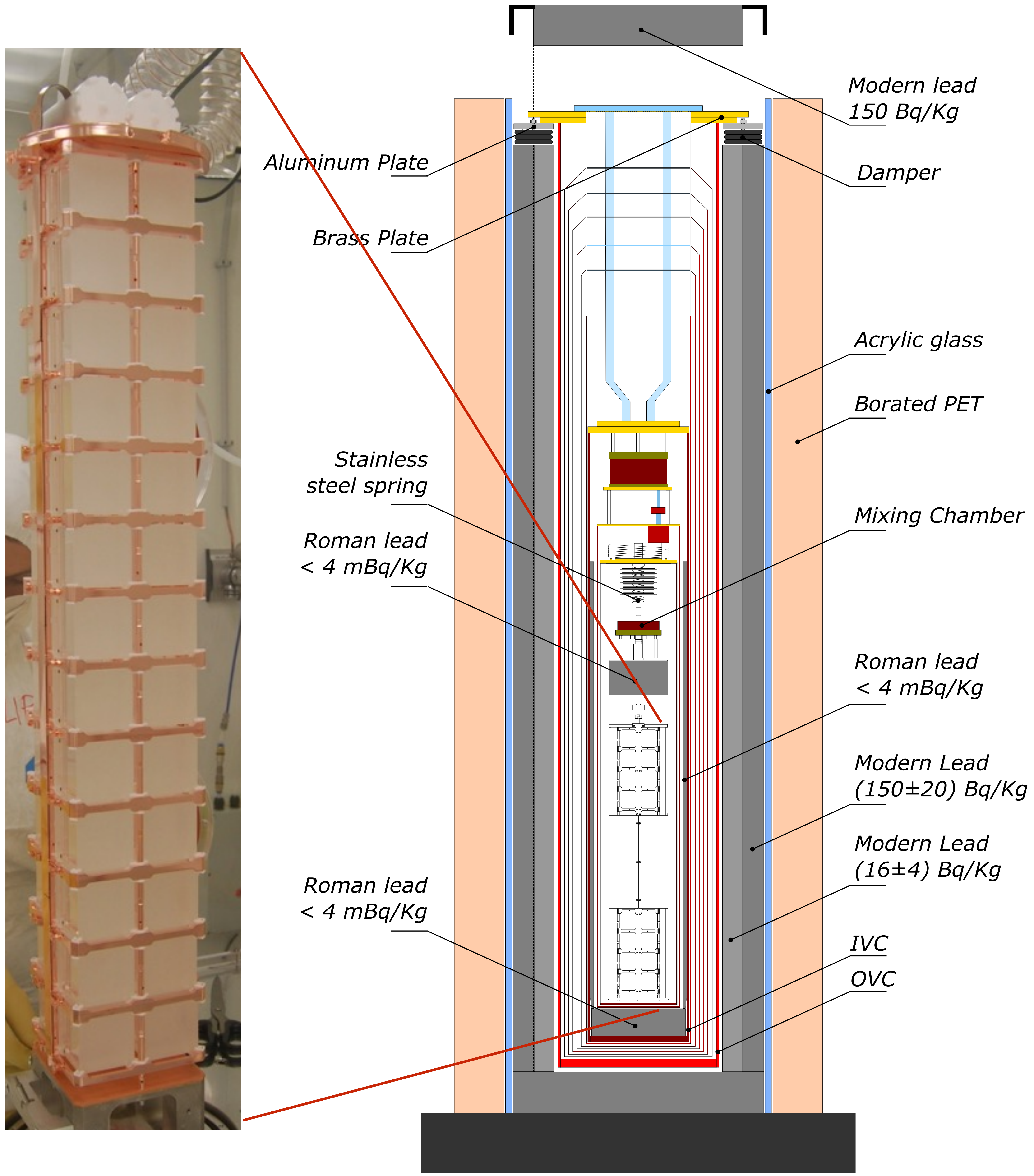
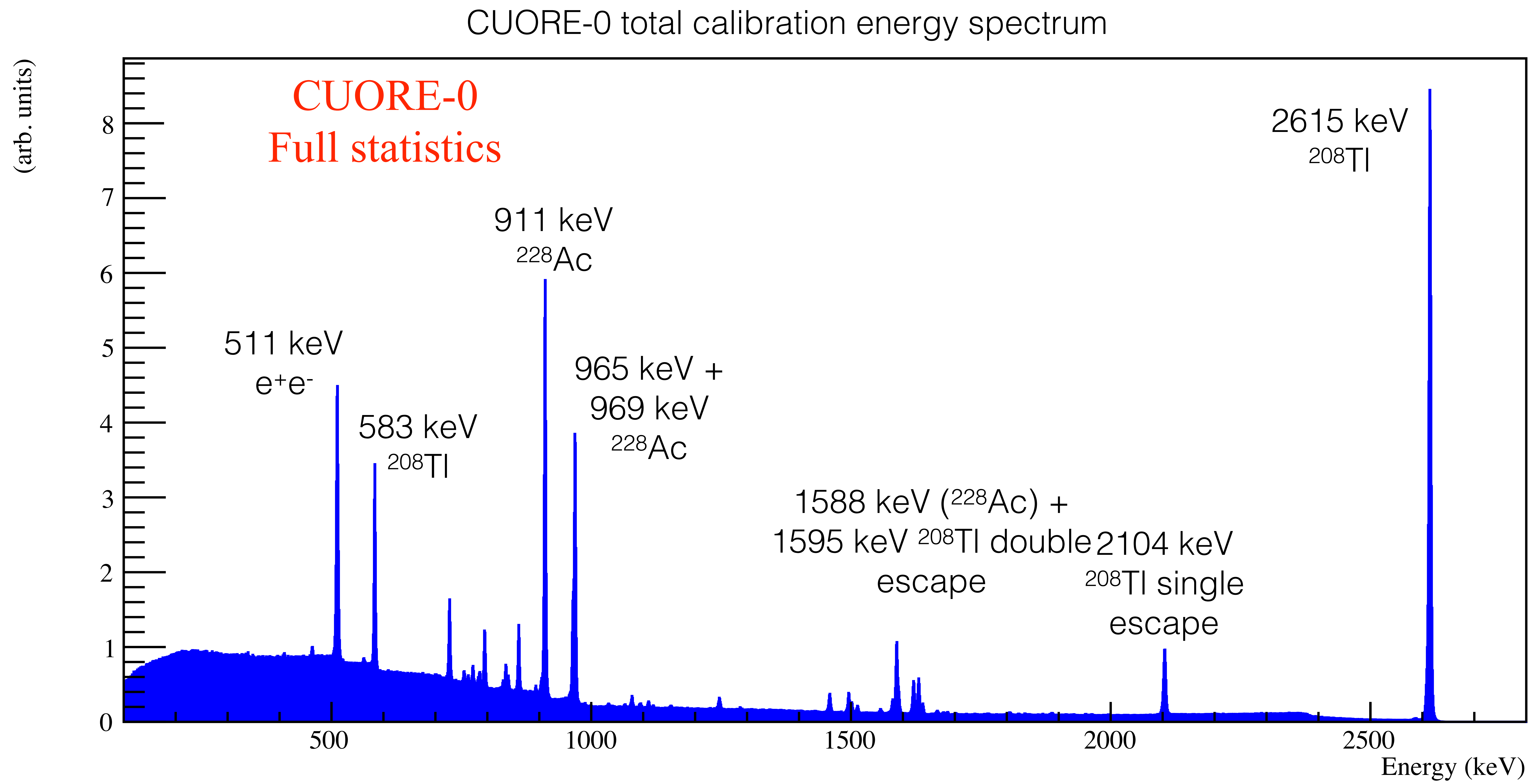
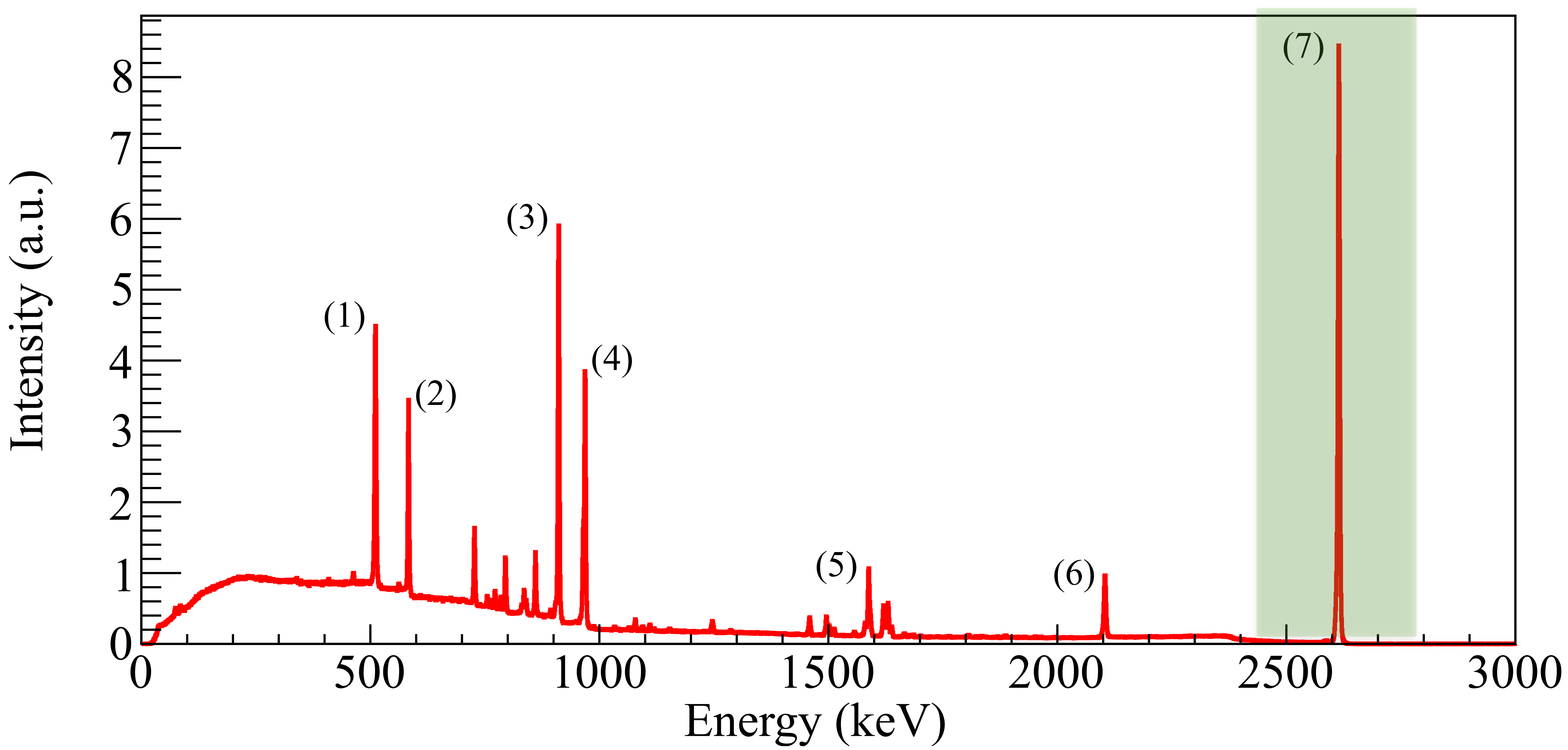


CUORE-0 ^{232}Th calibration



CUORE-0: detector performances



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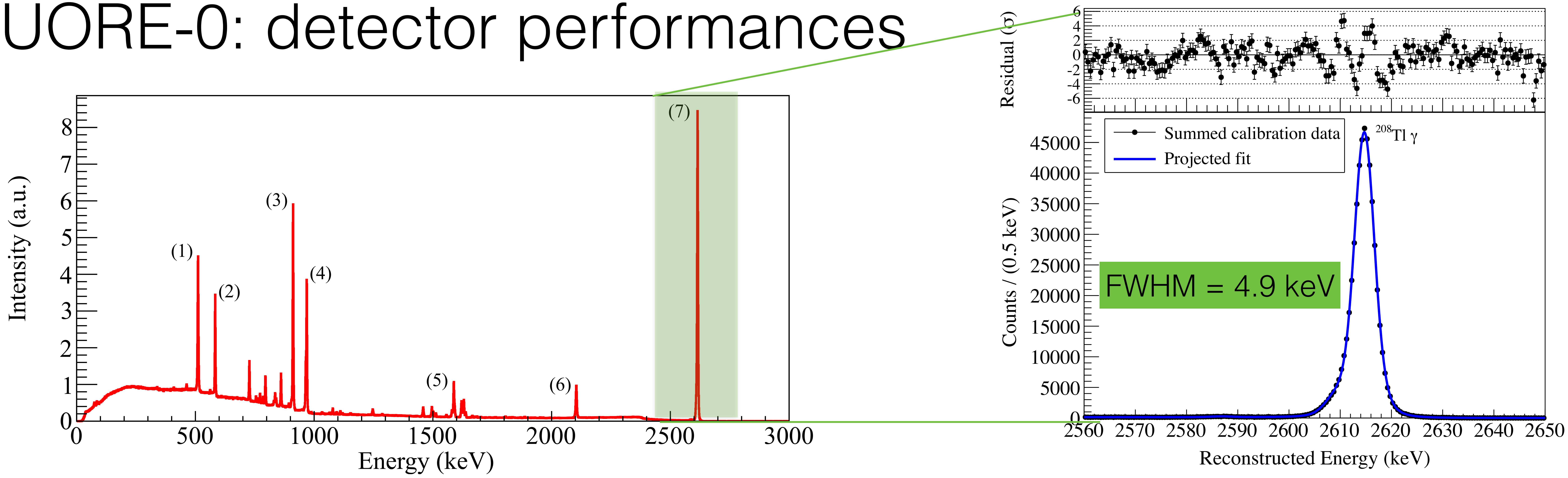

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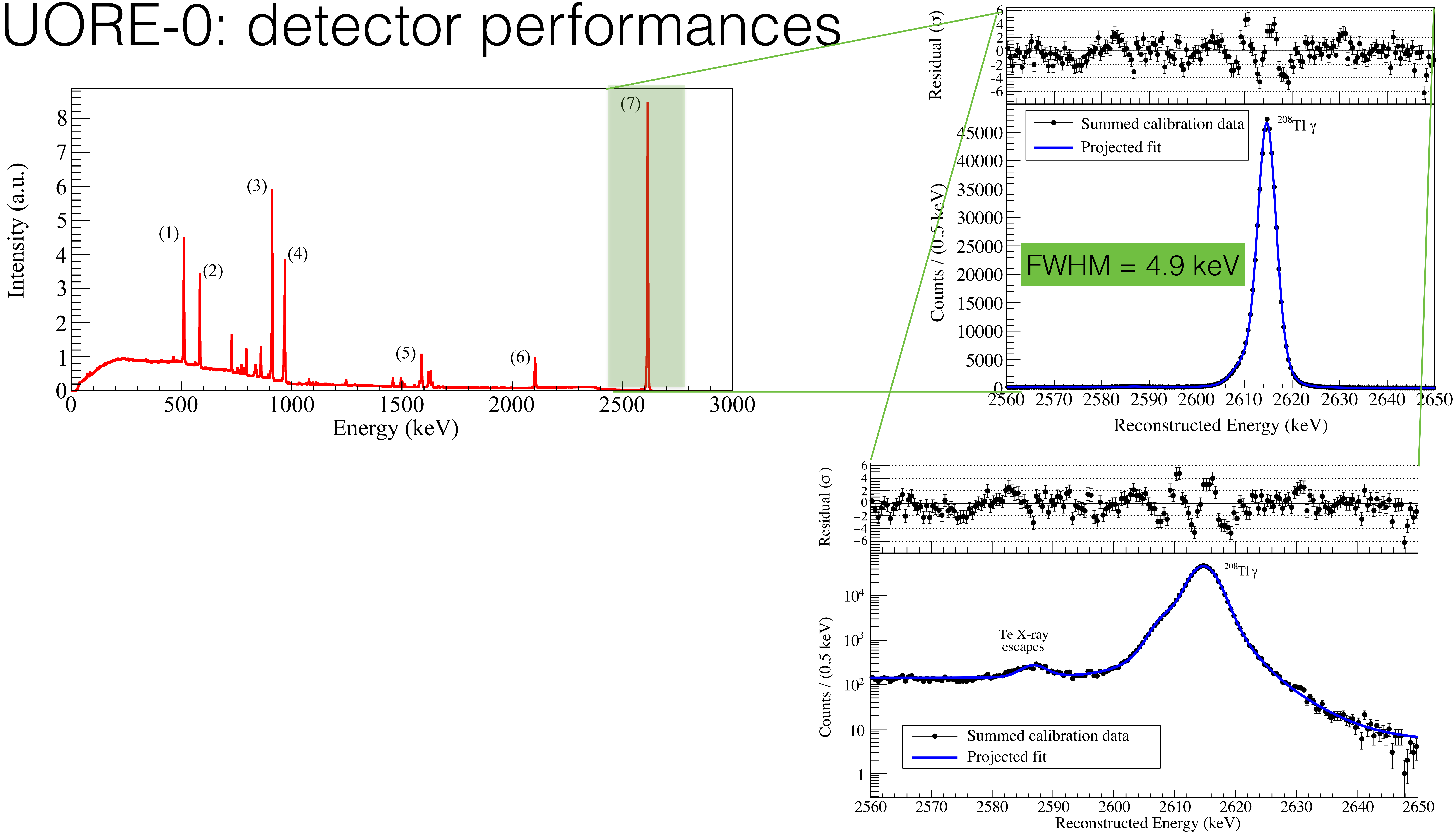

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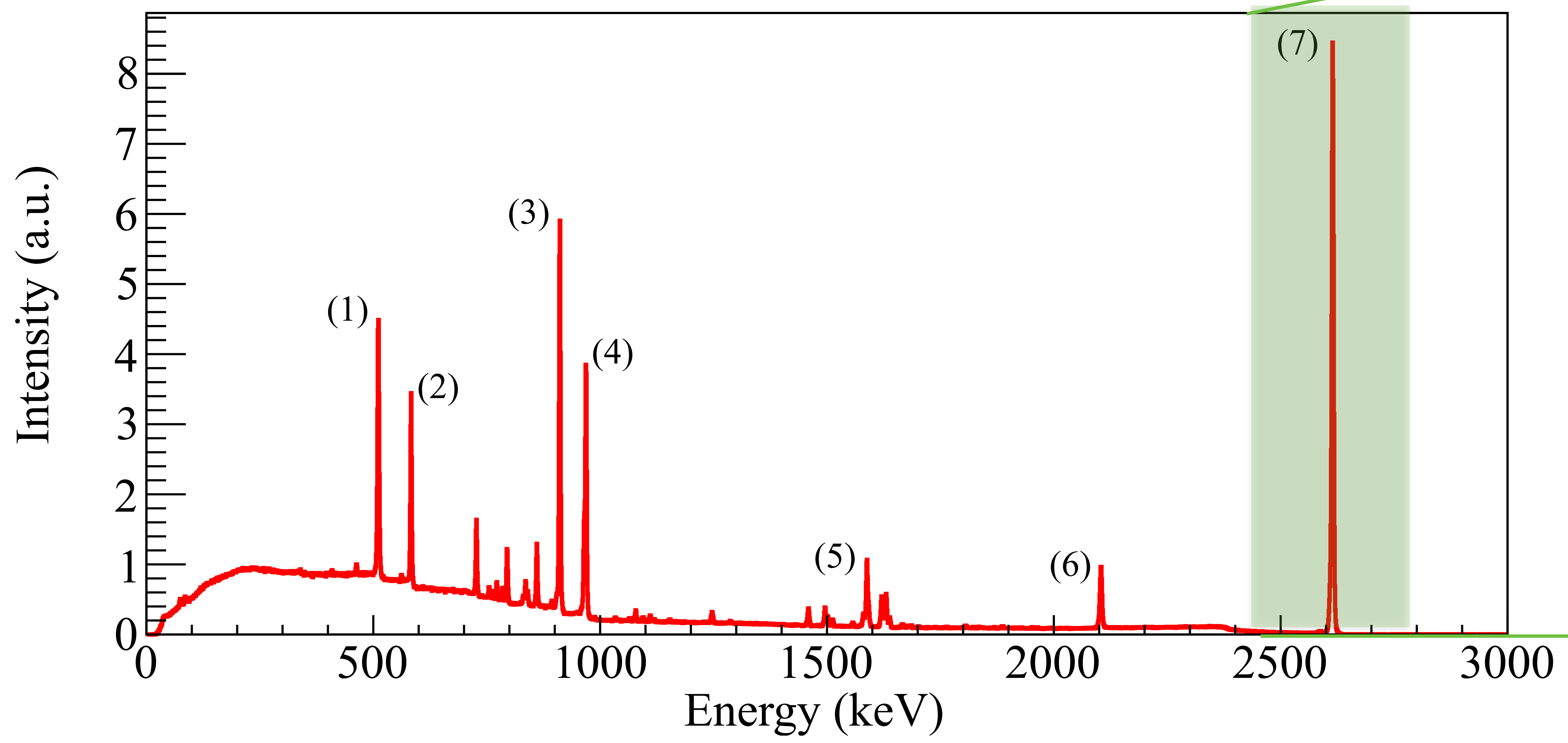
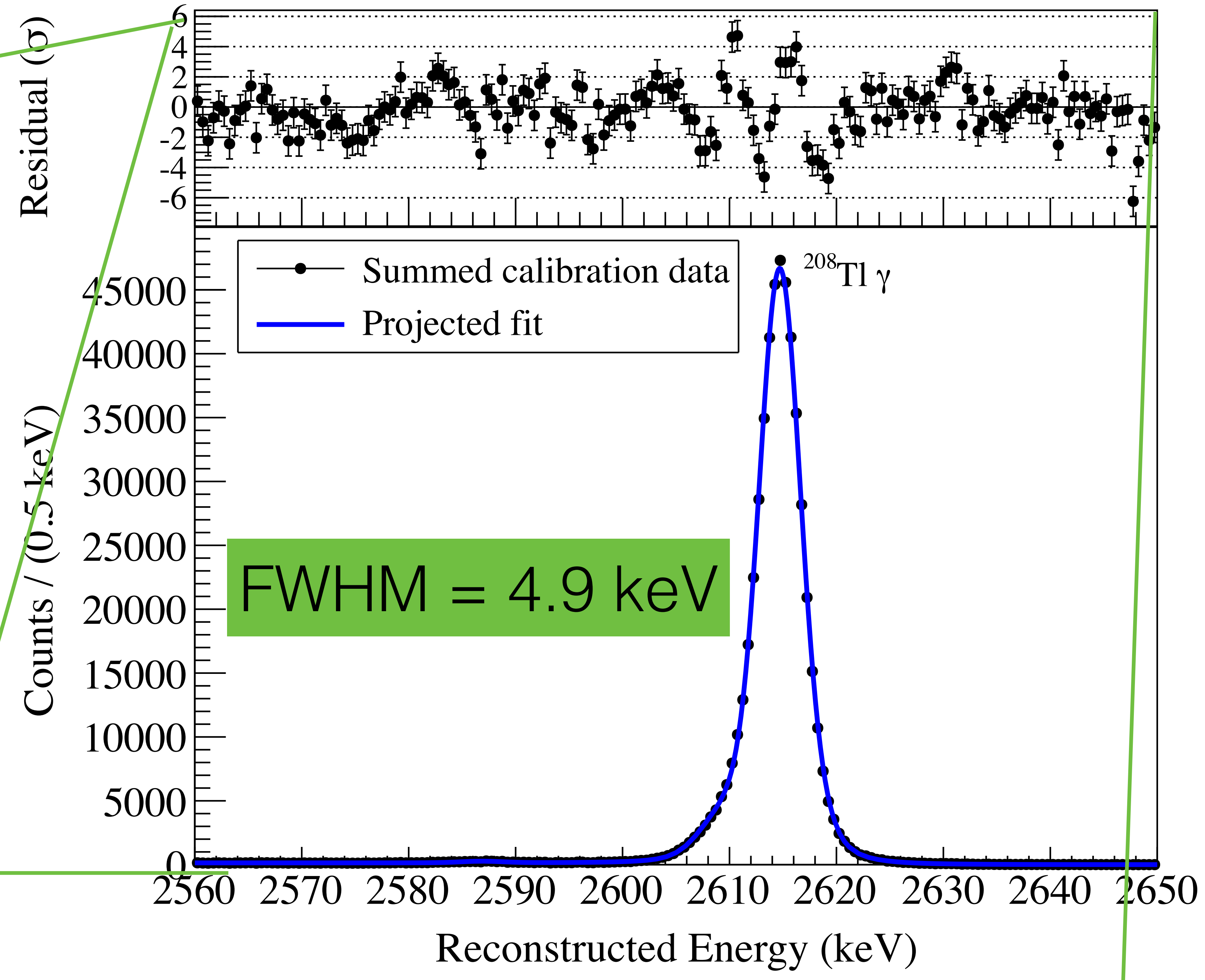
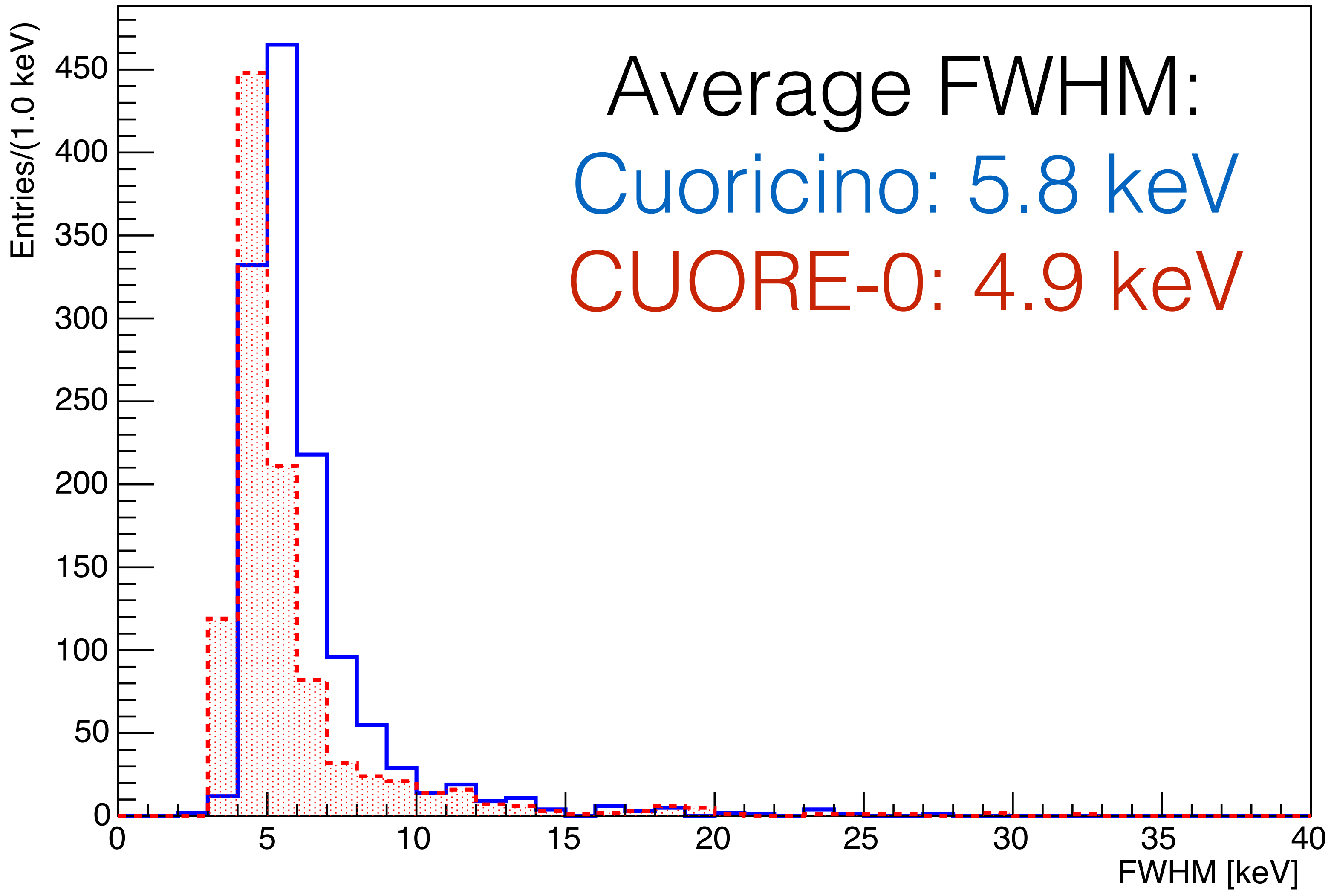
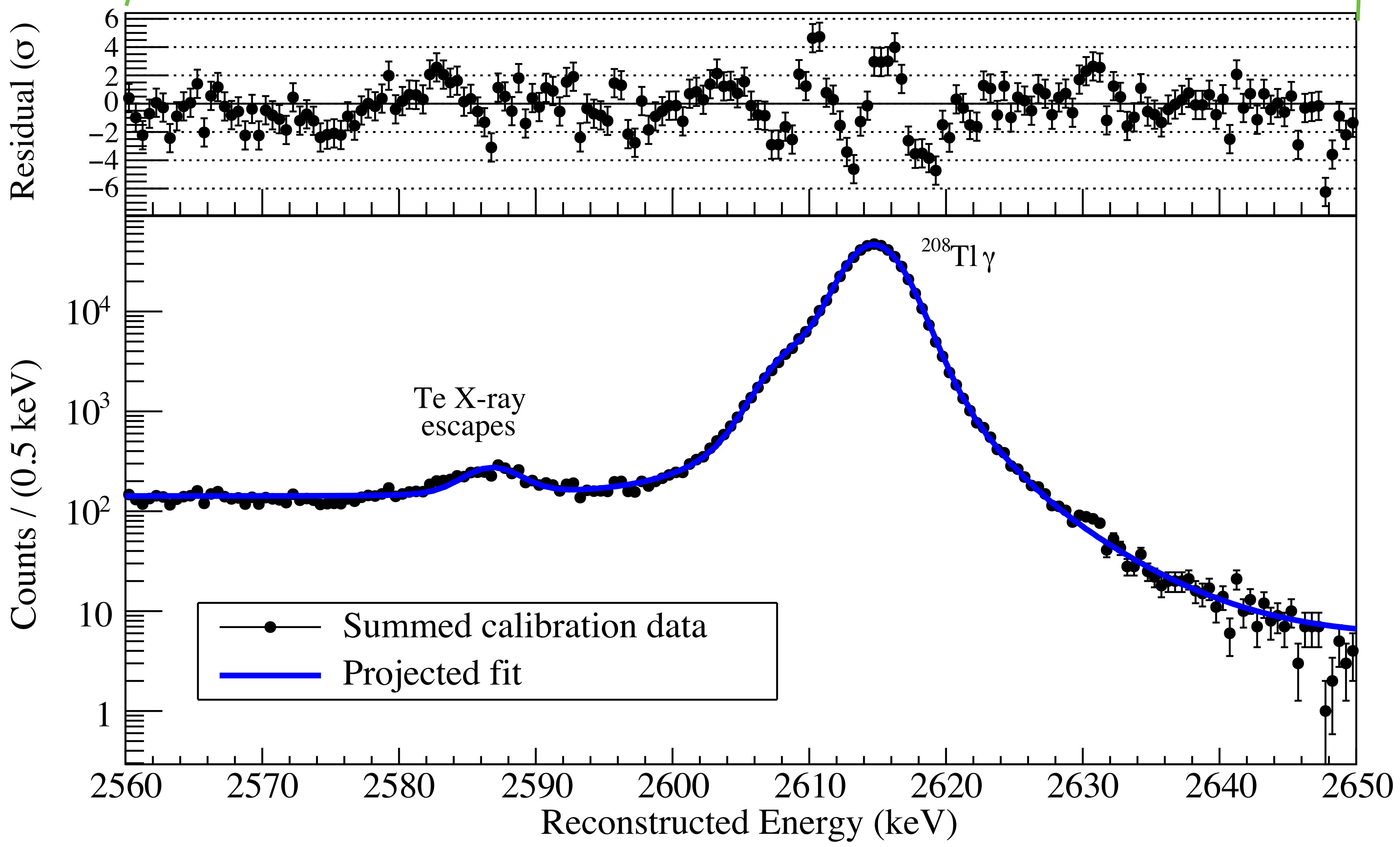


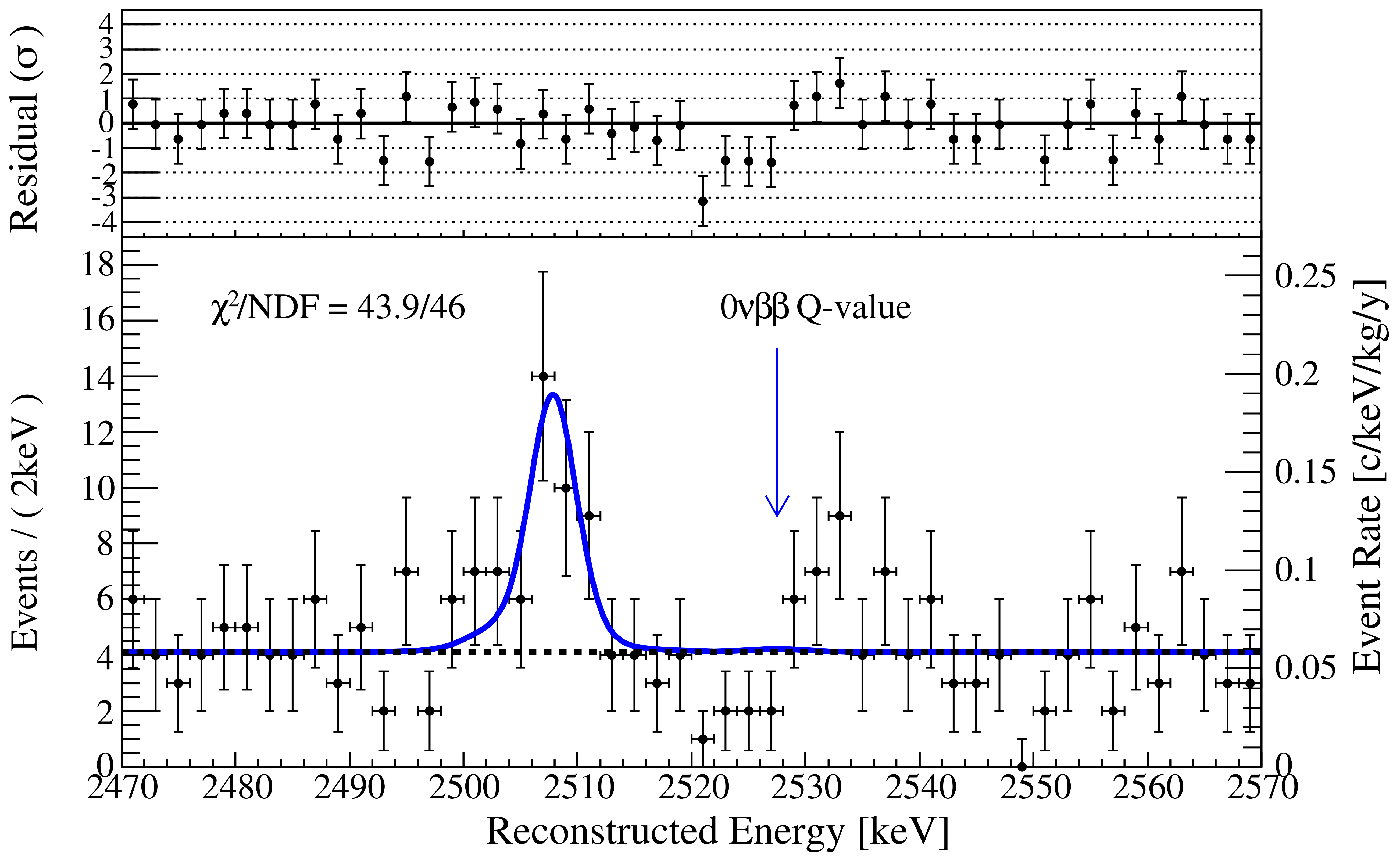




The 5 keV CUORE goal has been reached



CUORE-0 results



Exposure: 9.8 kg·yr ^{130}Te

- Fit function in the energy region 2470-2570 keV, composed of 3 elements:
    1. Peak with calibration-derived line- shape at the Q-value of ^{130}Te
    2. Peak at 2507 keV attributed to the summed γ peak of ^{60}Co
    3. Flat continuum background attributed to multi scatter Compton events from ^{208}Tl and surface α events

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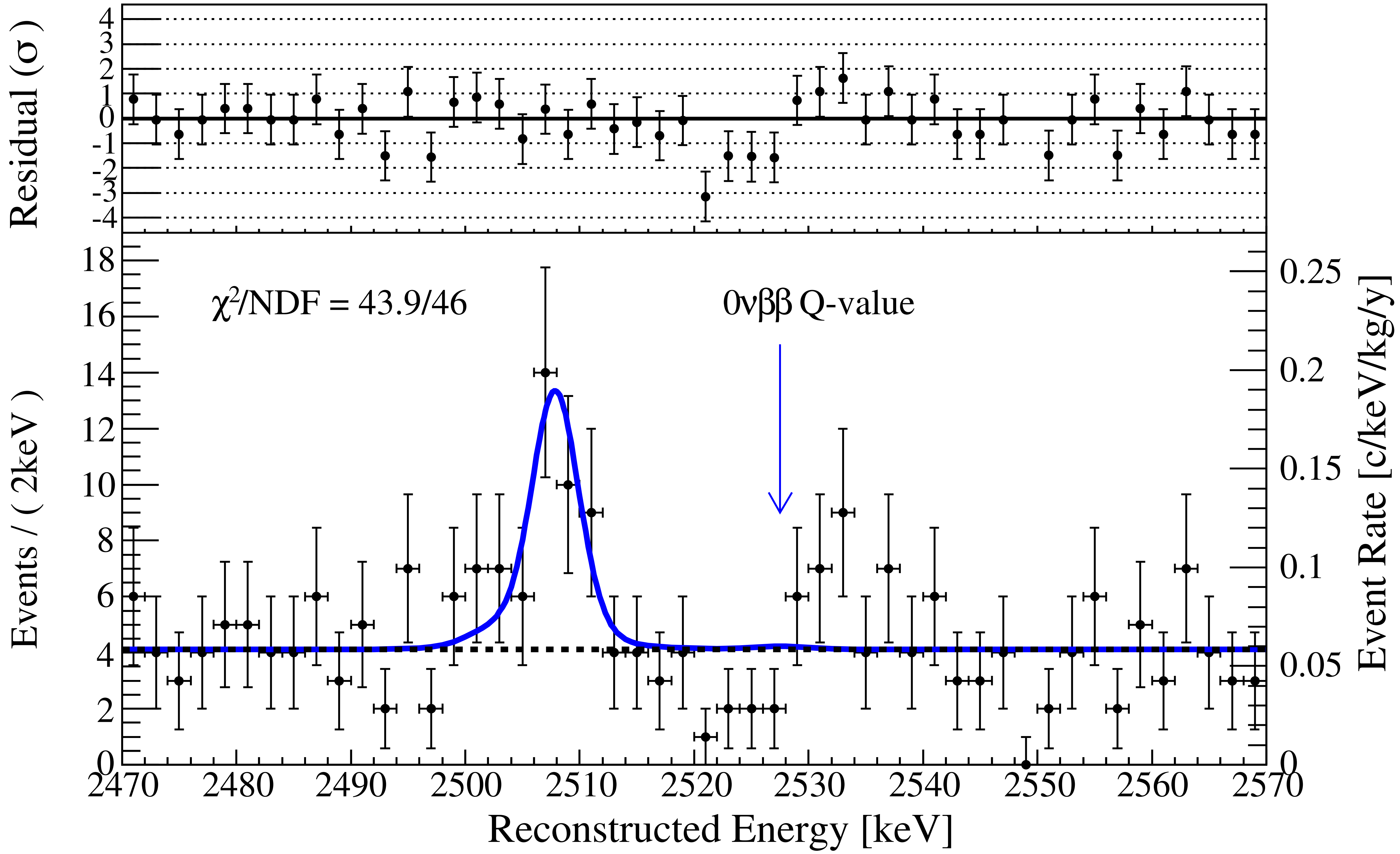

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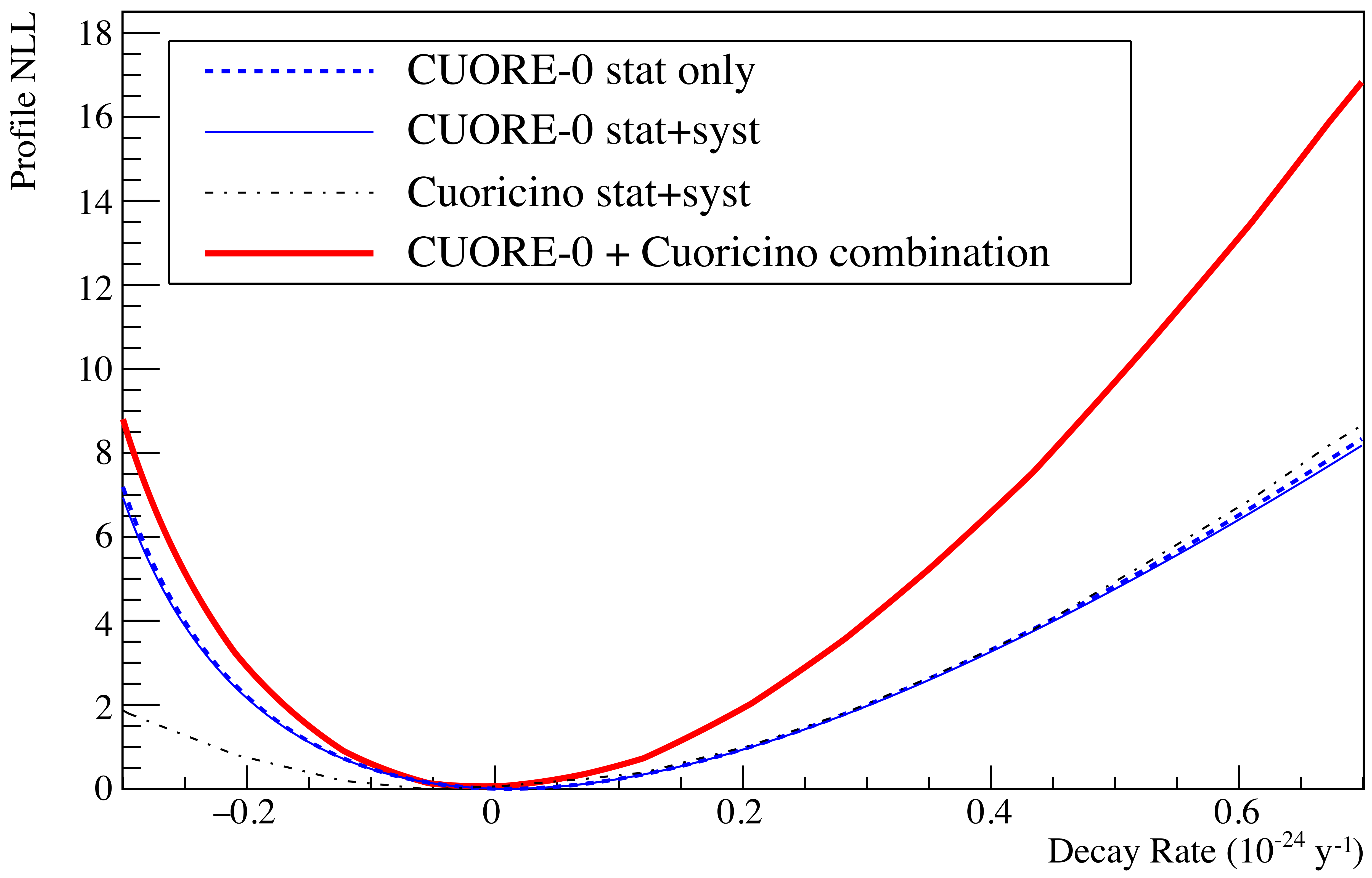
Best Fit Background index: **0.058 ± 0.004 (stat.) ± 0.002 (syst.) c keV^{-1} kg^{-1} yr^{-1}**

Best Fit Decay Rate: $\Gamma^{0\nu\beta\beta}$ (130Te) = 0.01 ± 0.12 (stat.) ± 0.01 (syst.) × 10^{-24} yr^{-1}

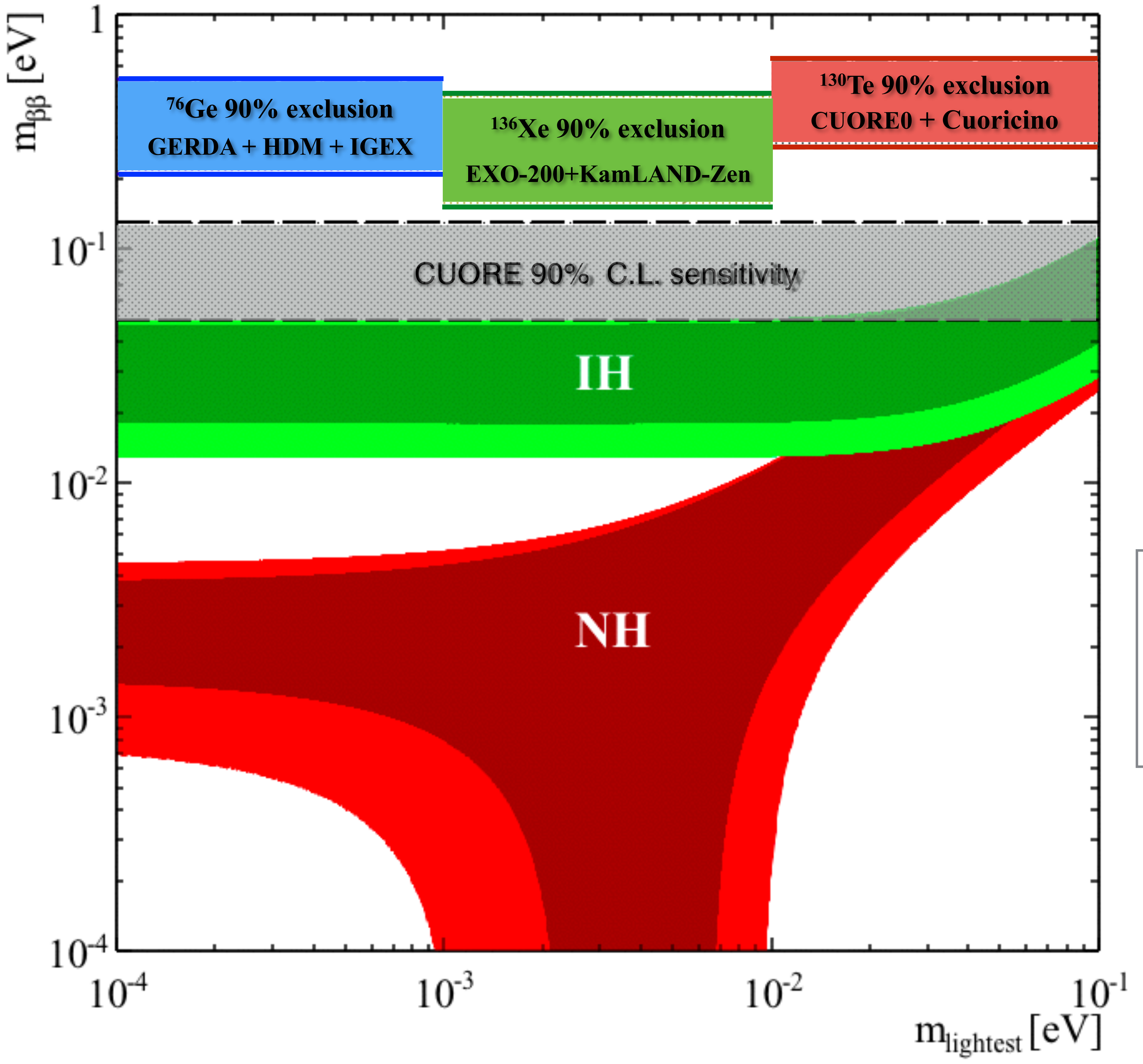
Combining CUORE-0 and Cuoricino

- Combination of the CUORE-0 result with the existing 19.75 kg · yr of ^{130}Te exposure from Cuoricino
- The combined 90% C.L. limit is $\mathbf{T_{1/2} > 4.0 \times 10^{24}}$ **yr**



Phys. Rev. Lett. 115, 102502

Limit on the effective Majorana mass

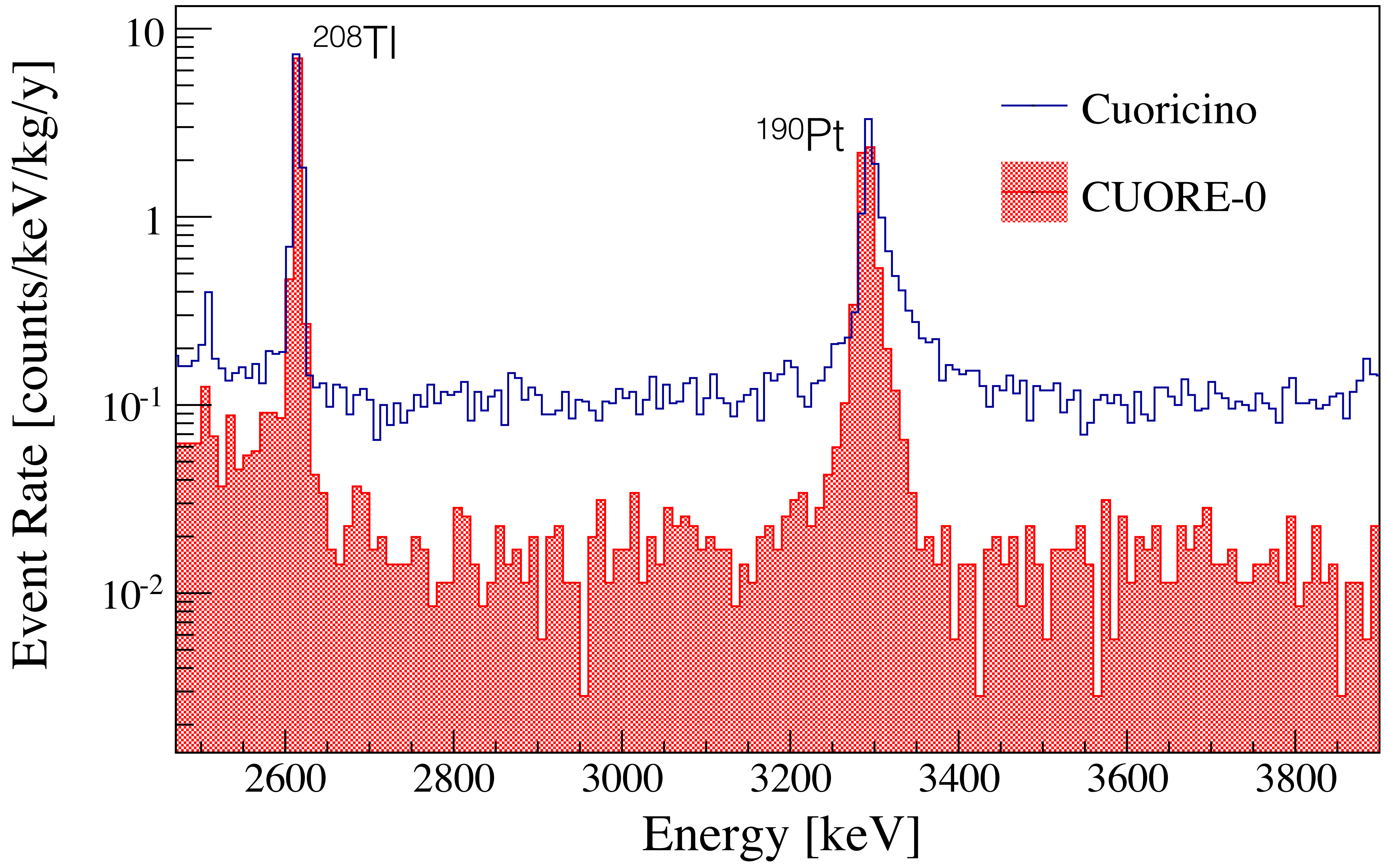


The combined result gives a limit on the effective Majorana neutrino mass:

$\langle m_{\beta\beta} \rangle <$ (270-650) meV

IBM-2 Phys. Rev. C 91, 034304 (2015)
QRPA-TU Phys. Rev. C 87, 045501 (2013)
pnQRPA Phys. Rev. C 91, 024613 (2015)
ISM Nucl. Phys. A 818, 139 (2009)
EDF Phys. Rev. Lett. 105, 252503 (2010)

CUORE-0 background



	2.7-3.9 MeV [counts/keV/kg/y]	ROI [counts/keV/kg/y]
CUORE-0	0.016 ± 0.001	0.058 ± 0.004
Cuoricino	0.110 ± 0.001	0.169 ± 0.006

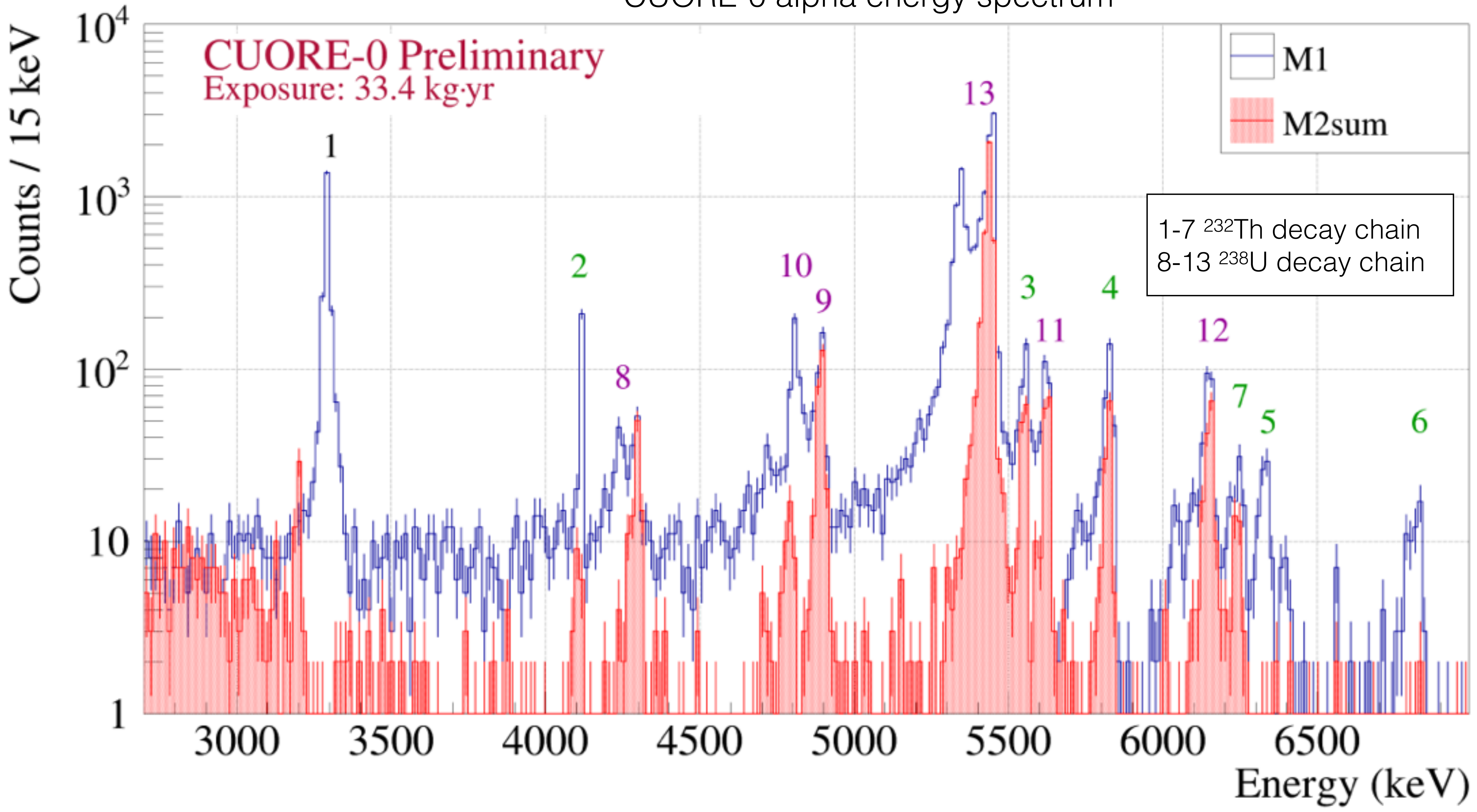
~ factor 7 reduction in the alpha continuum region

CUORE-0 background model

Developed for understanding of bkg contribution in the ROI.

1) Identification of the bkg sources:
   I. CUORE-0 analysis
   II. radio-assay measurements
   III. cosmogenic activation analysis

CUORE-0 alpha energy spectrum



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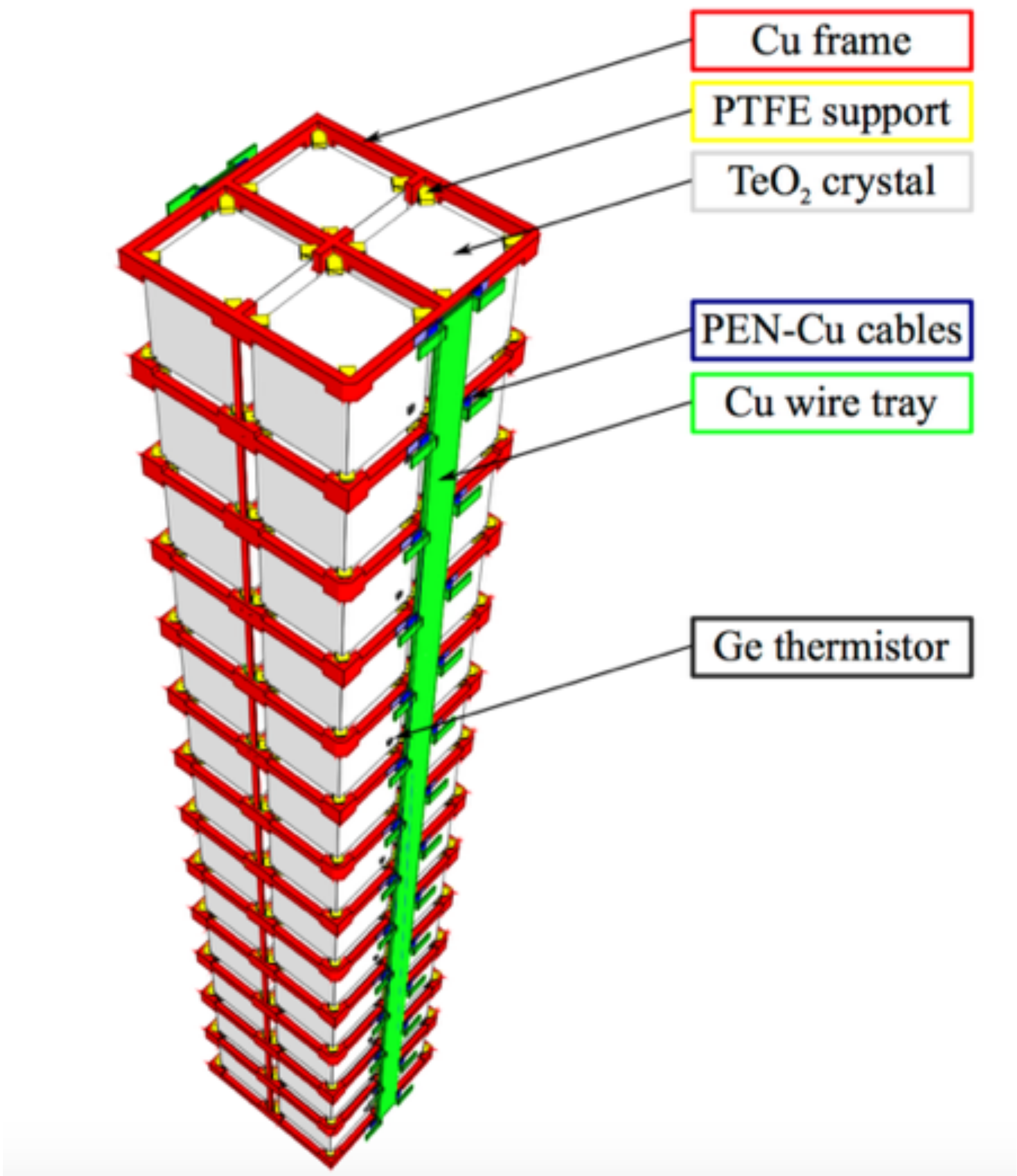
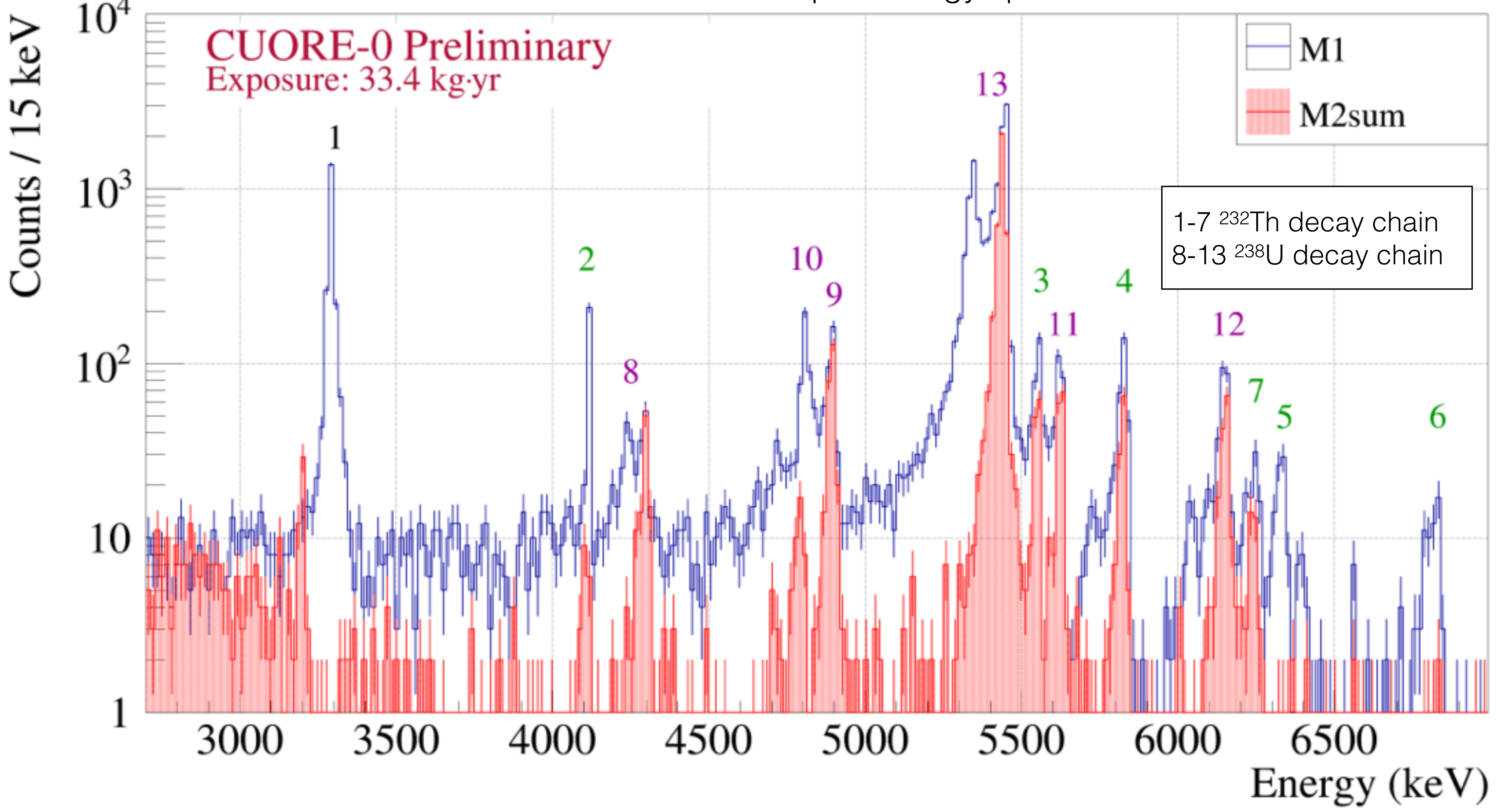
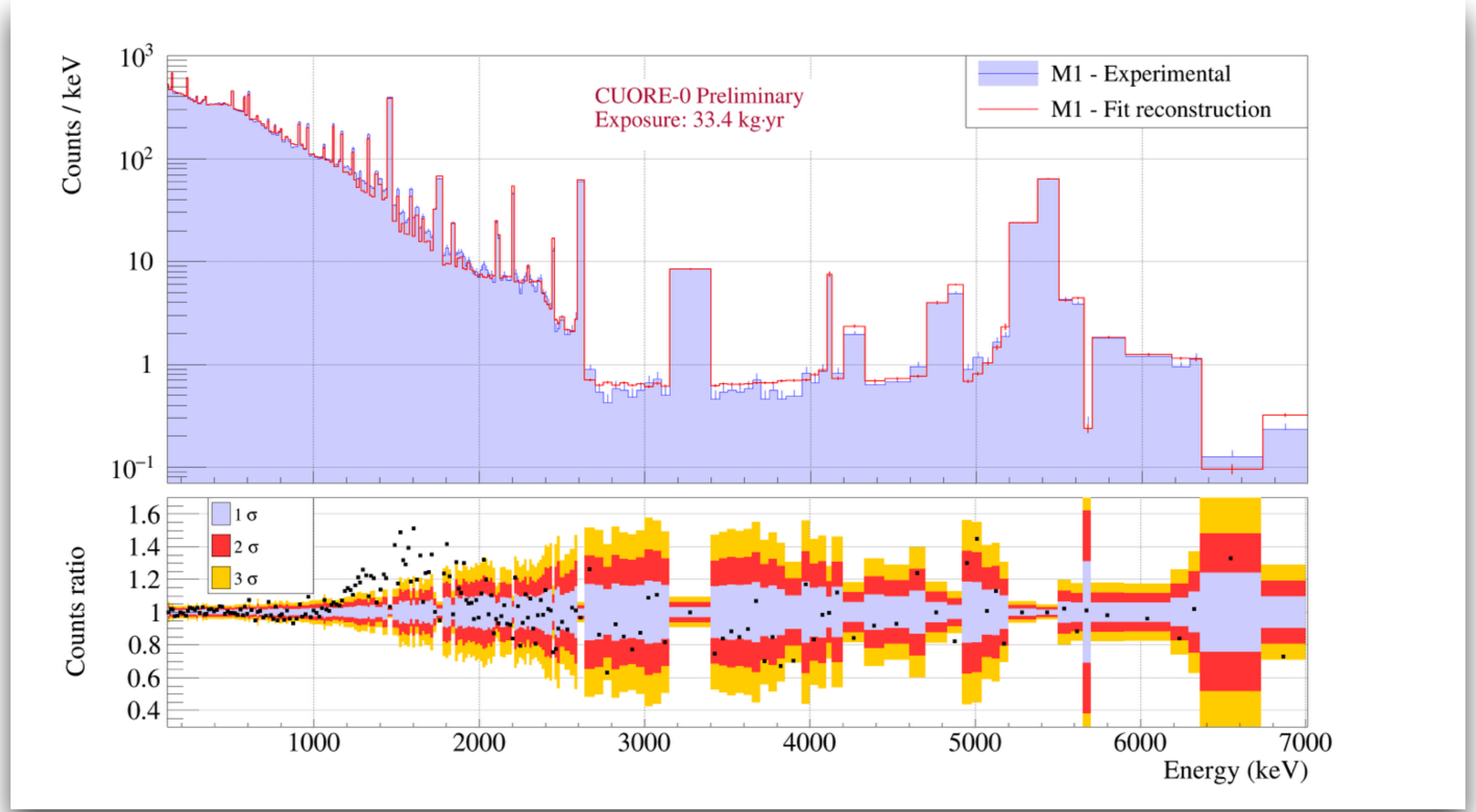


CUORE-0 alpha energy spectrum



2) MC model of the detector to simulate background source

Fit spectrum w/o 2νββ



Full reconstruction between: 118 keV - 7 MeV

Reconstruction within 3σ range for most of bins (also in multiplicity 2 spectra)

Binning: optimized to maximize the informative content and minimize the effects of peculiar detector features (line shape…)

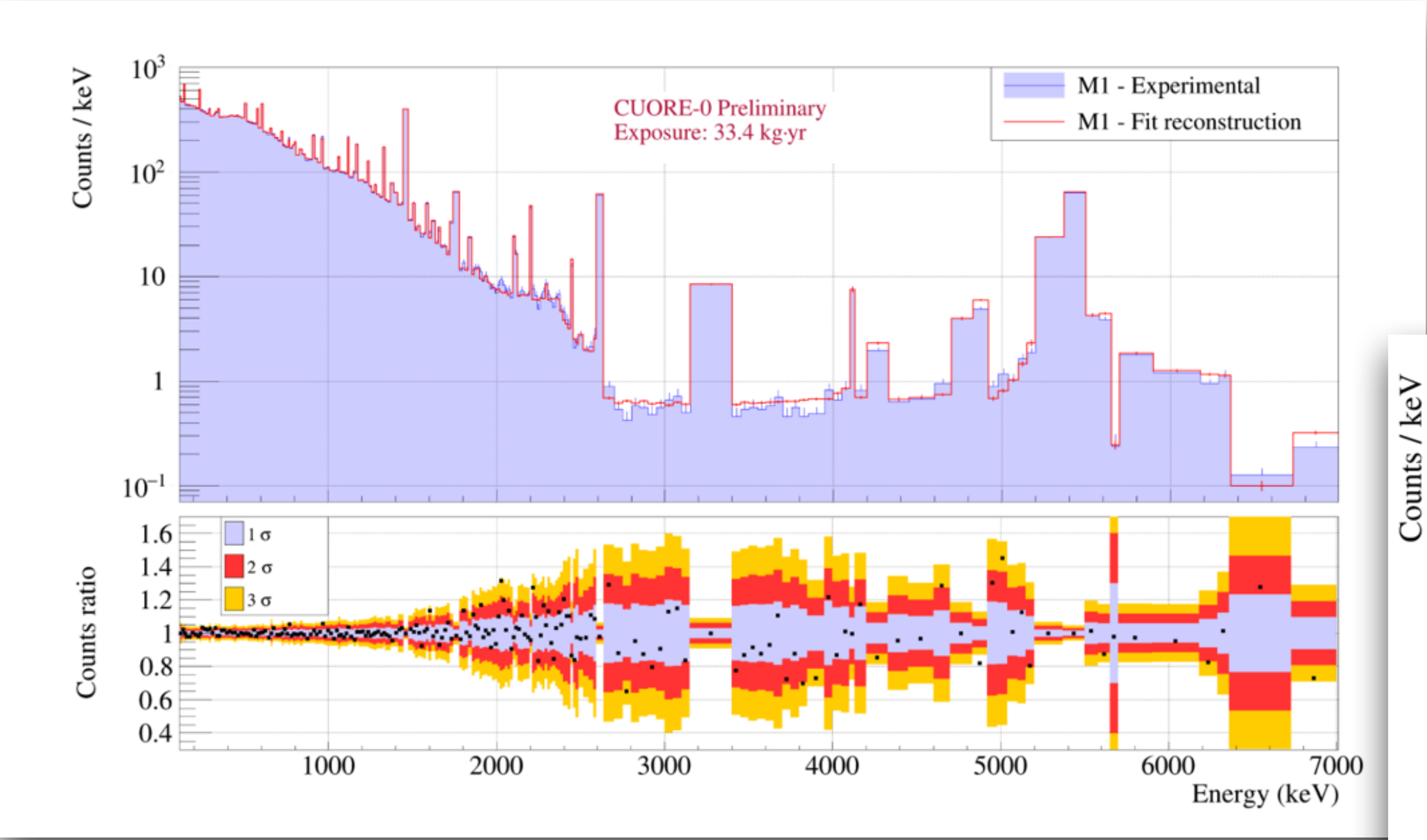
Fit spectrum w/o 2νββ

Full reconstruction between:
118 keV - 7 MeV

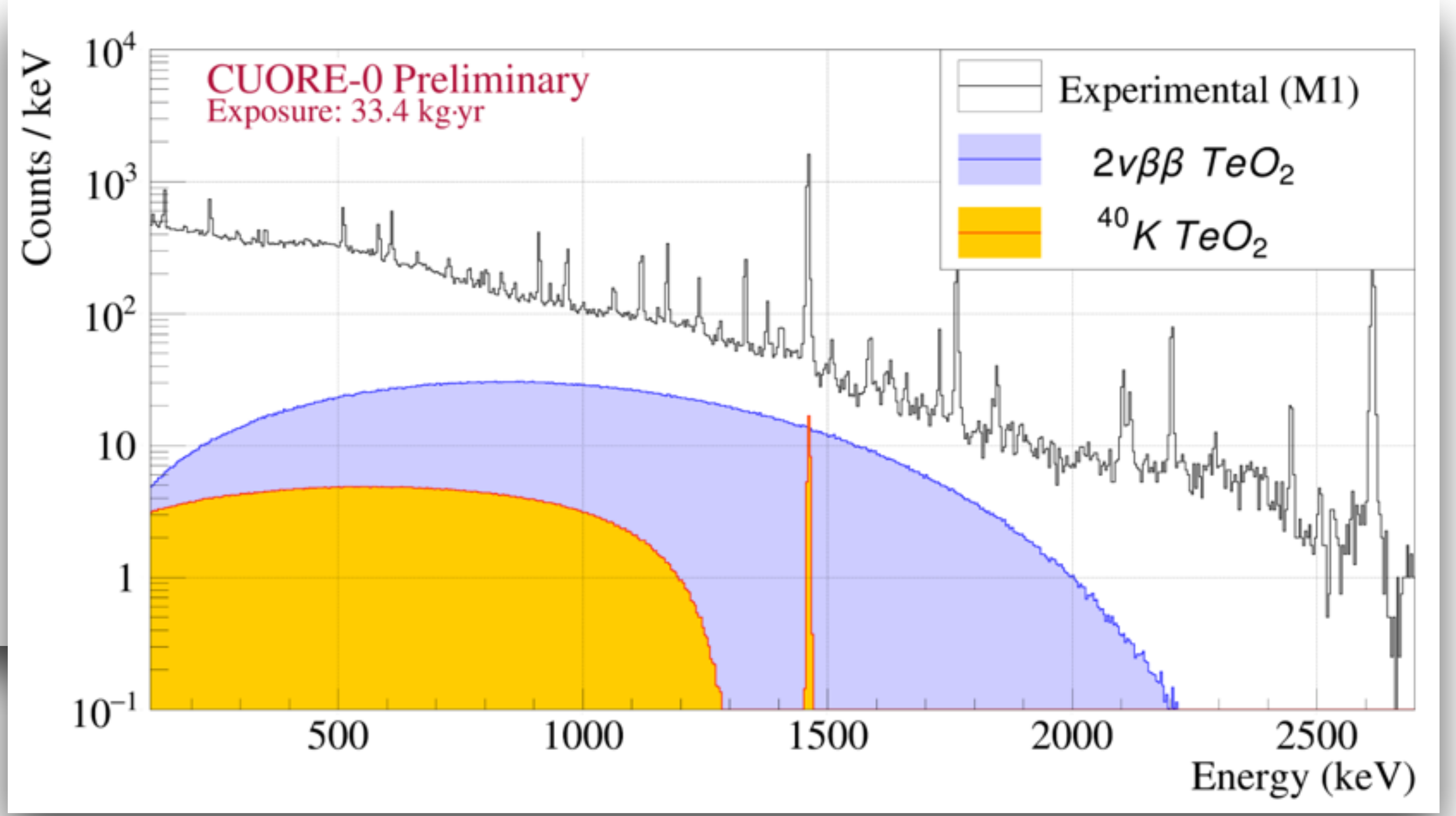
Reconstruction within 3σ range for most of bins (also in multiplicity 2 spectra)

Fit spectrum with 2νββ

arXiv:1609.01666



57 sources used to reproduce CUORE-0 bkg



$$\text{CUORE-0: } T^{2\nu}_{1/2} = [8.2 \pm 0.2 \text{ (stat.)} \pm 0.6 \text{ (syst.)}] \times 10^{20} \text{ y}$$

$$\text{NEMO: } T^{2\nu}_{1/2} = [7.0 \pm 0.9 \text{ (stat.)} \pm 1.1 \text{ (syst.)}] \times 10^{20} \text{ y}$$

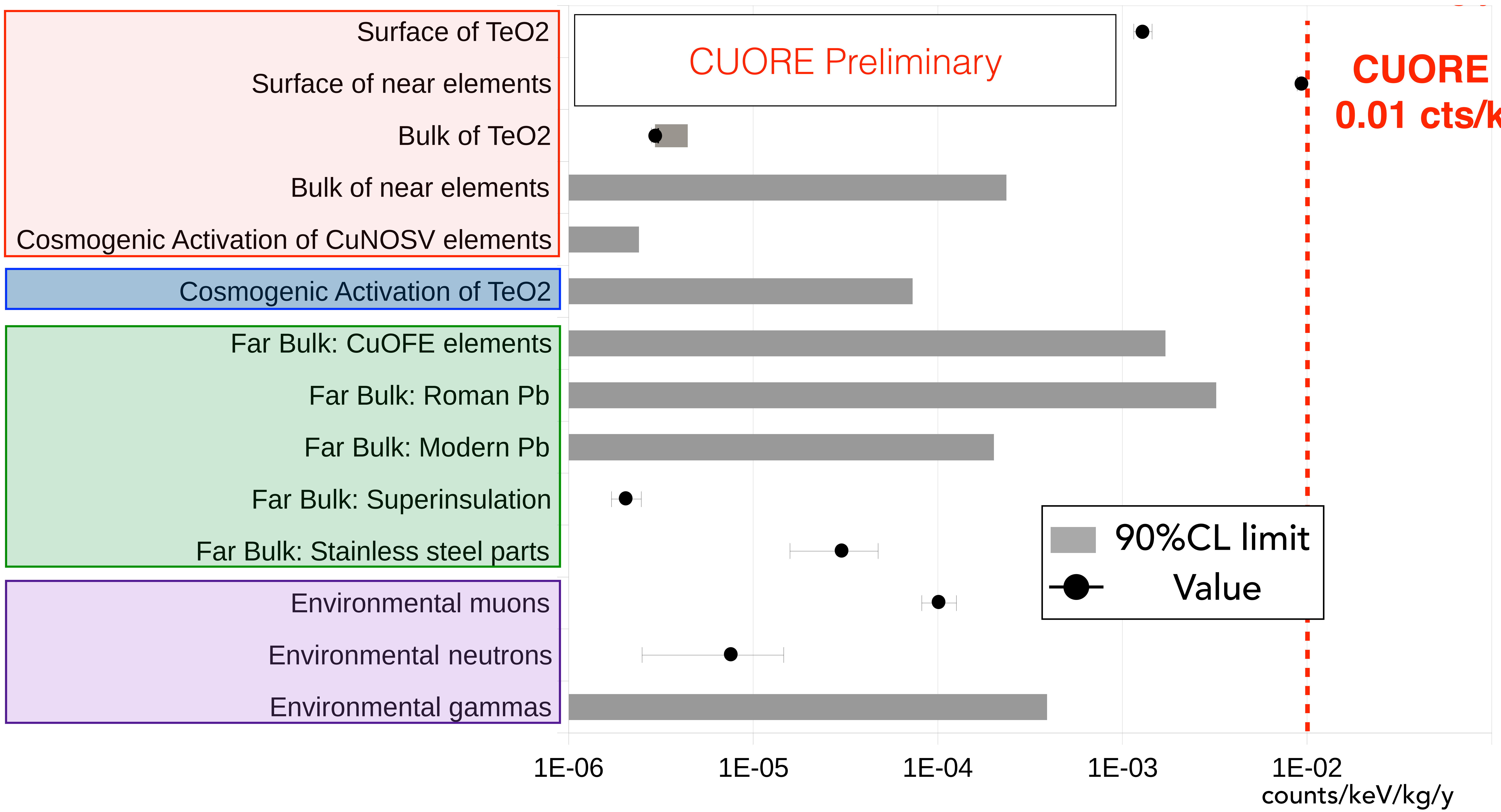
$$\text{MiDBD: } T^{2\nu}_{1/2} = [6.1 \pm 1.4 \text{ (stat.)} \;^{+2.9}_{-3.5} \text{ (syst.)}] \times 10^{20} \text{ y}$$

NEMO-3 Collaboration, Phys. Rev. Lett., 107, 062504 (2011).
C. Arnaboldi et al., Phys. Lett. B, 557, 167 (2003).

CUORE Background budget

arXiv:1609.01666

Geometry in the MC simulations was updated to the final CUORE design

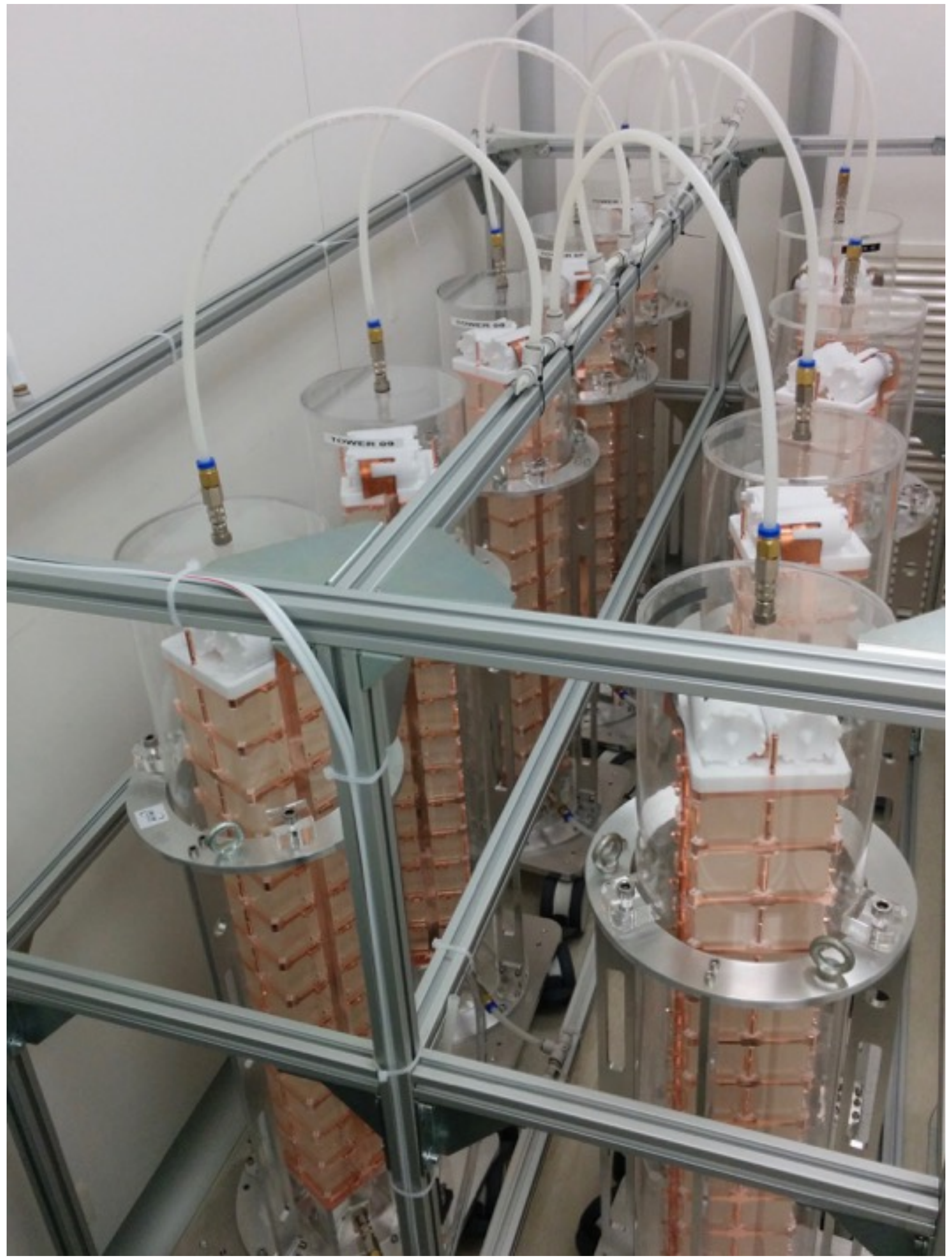


- CUORE-0 bkg model
- Cosmic activation of Te
- HPGe and NAA
- γ, μ, n fluxes at LNGS


CUORE commissioning

CUORE Towers Assembly

- Assembly of all the 19 CUORE towers completed in 2014



Assembly line improved after CUORE-0

CUORE-0

51/52 NTD connected

51/52 heaters connected

CUORE

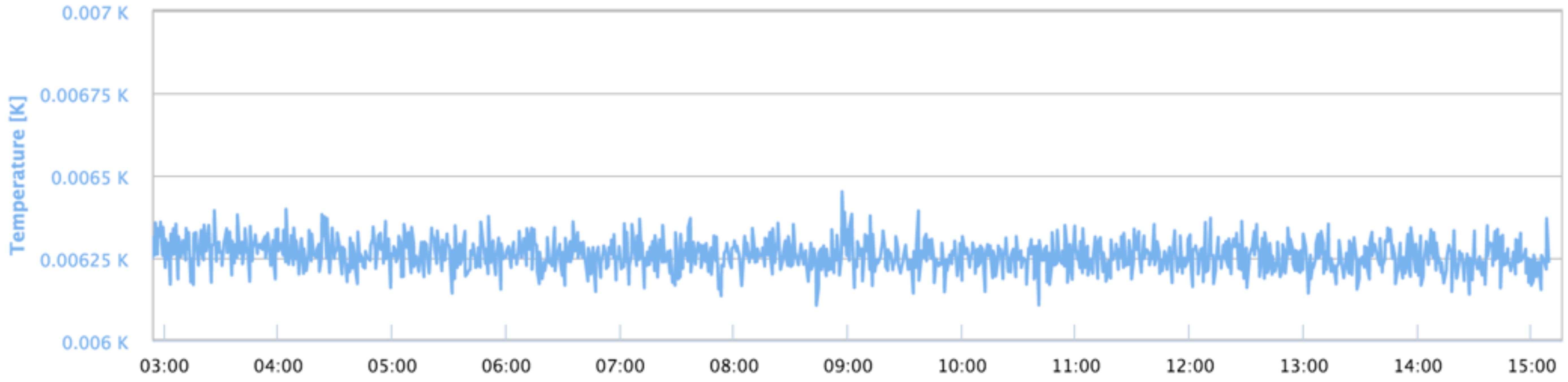
983/988 NTD connected

- Also a mockup tower for the Detector installation phase and a minitower to be used during the cryostat commissioning runs were produced

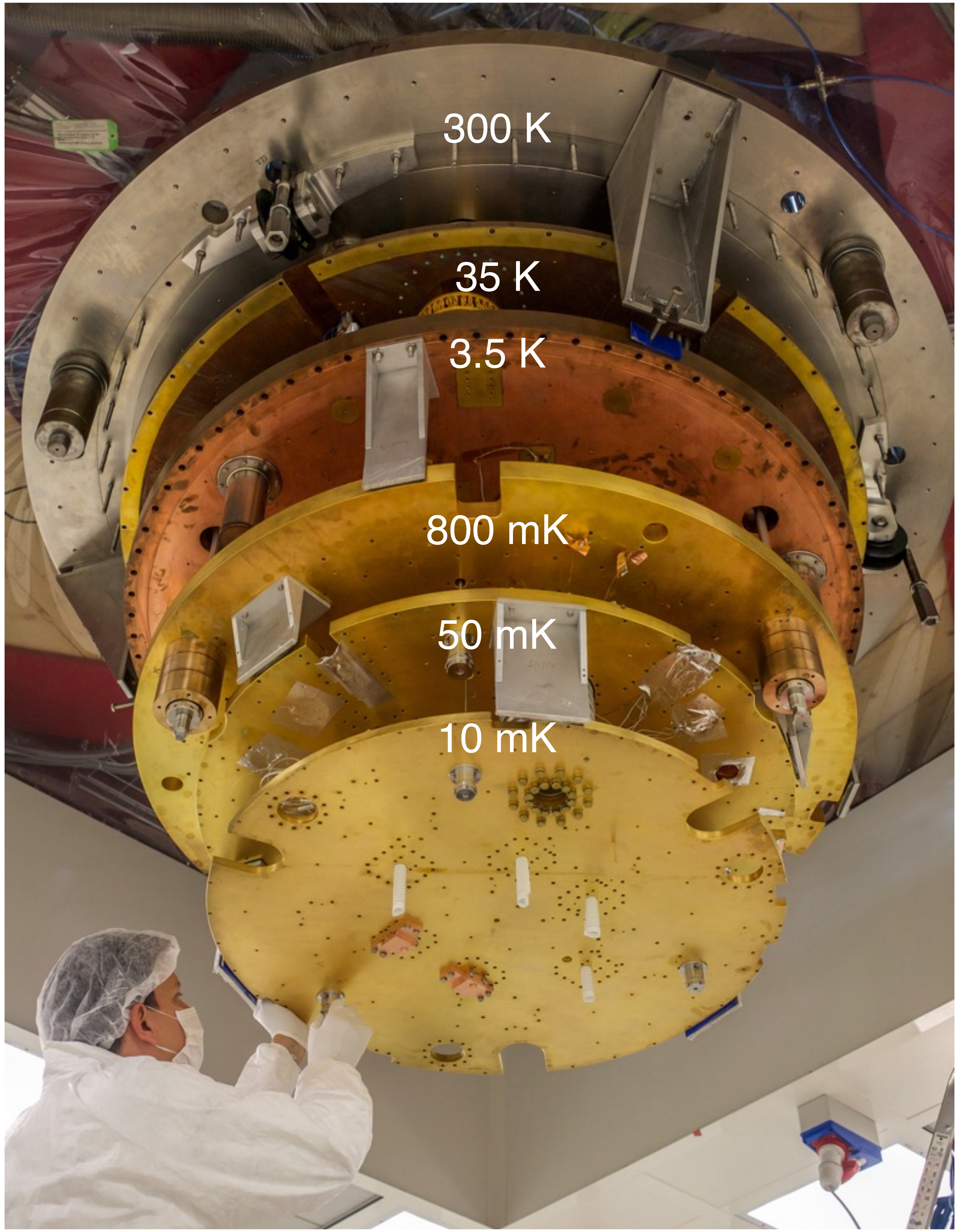
Cryogenic system commissioning

Goal was to develop a cryogenic system capable to deliver stable base T (~10 mK) together with reduced vibrations (baseline RMS at few keV) and a radio clean environment (selected material, cold Pb shields).

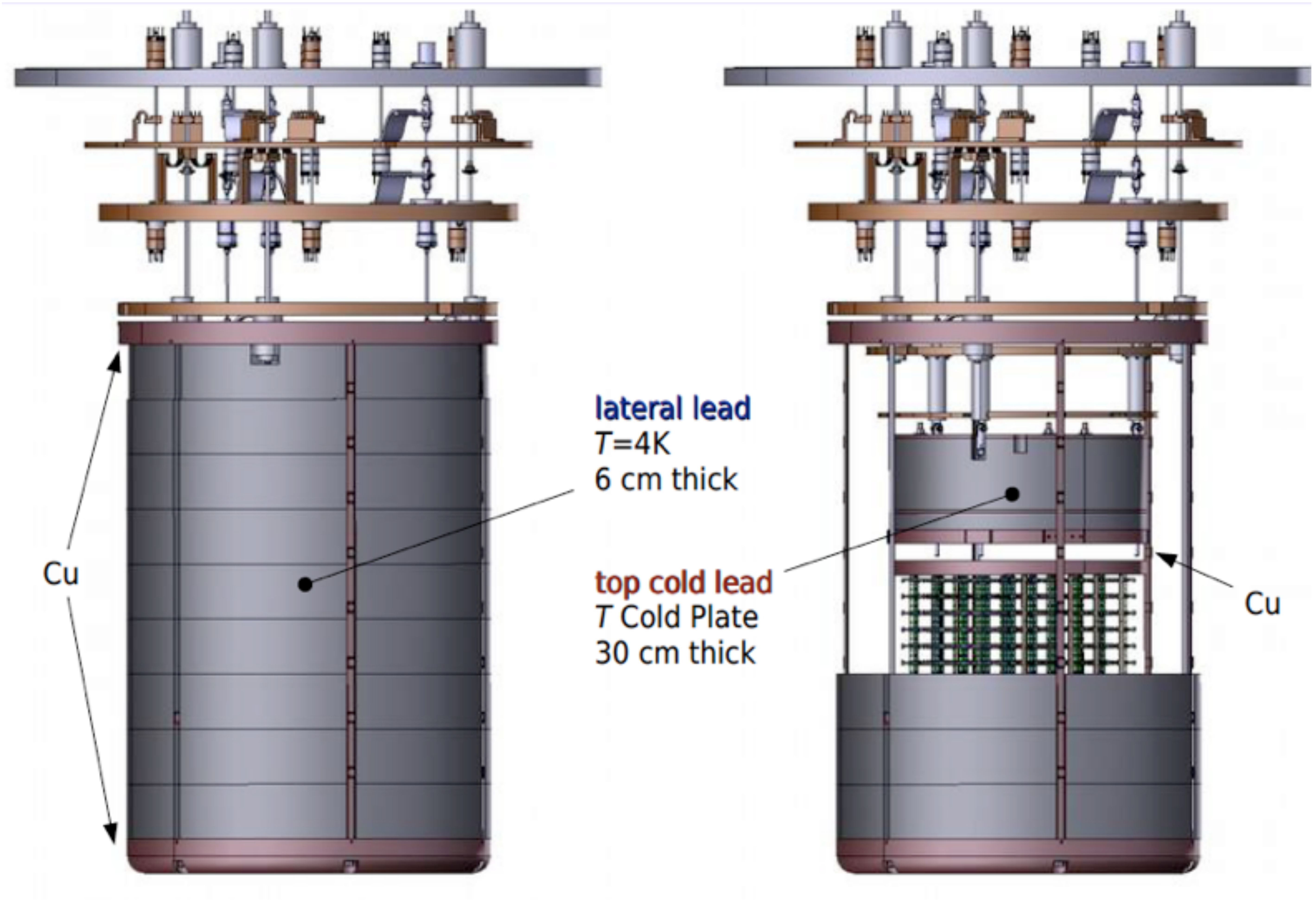
- All the cryostat components well thermalized at the different stages (including top Pb @ 50 mK and lateral roman Pb @ 3.5 K). No evident temperature gradient or heat leak.
- Stable base temperature -that allows CUORE bolometers operation- **6.3 mK**. Base T stable for more than 70 days. Proved nominal cooling power: **3 μW @ 10 mK**.



- Base temperature allows to stabilise operating temperature around 10 mK for a stable detector response.



Cold Pb shields



2 main elements

- side & bottom: roman Pb, 6 cm thick
- top: 5 discs (6 cm thickness each) of modern lead

Roman Pb

We have to preserve the inscription

needs to strictly follow the agreement

horizontal cut of the top part

230 ingots were cut

Bolometers and readout commissioning

- Encouraging detector performance (energy resolution) on 8 detectors array (Mini-Tower)
- Commissioned electronics, DAQ, temperature stabilization, and detector calibration systems

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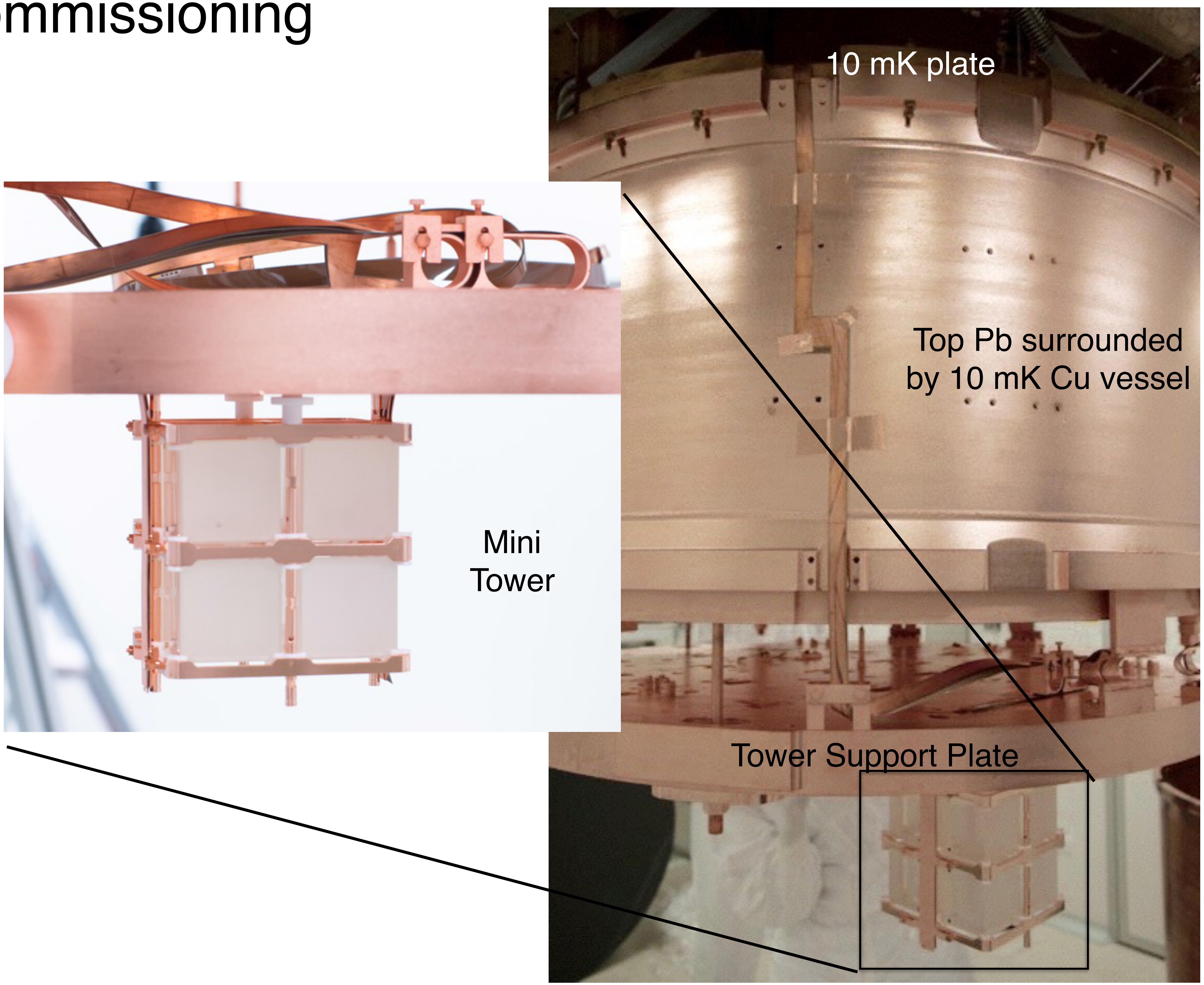

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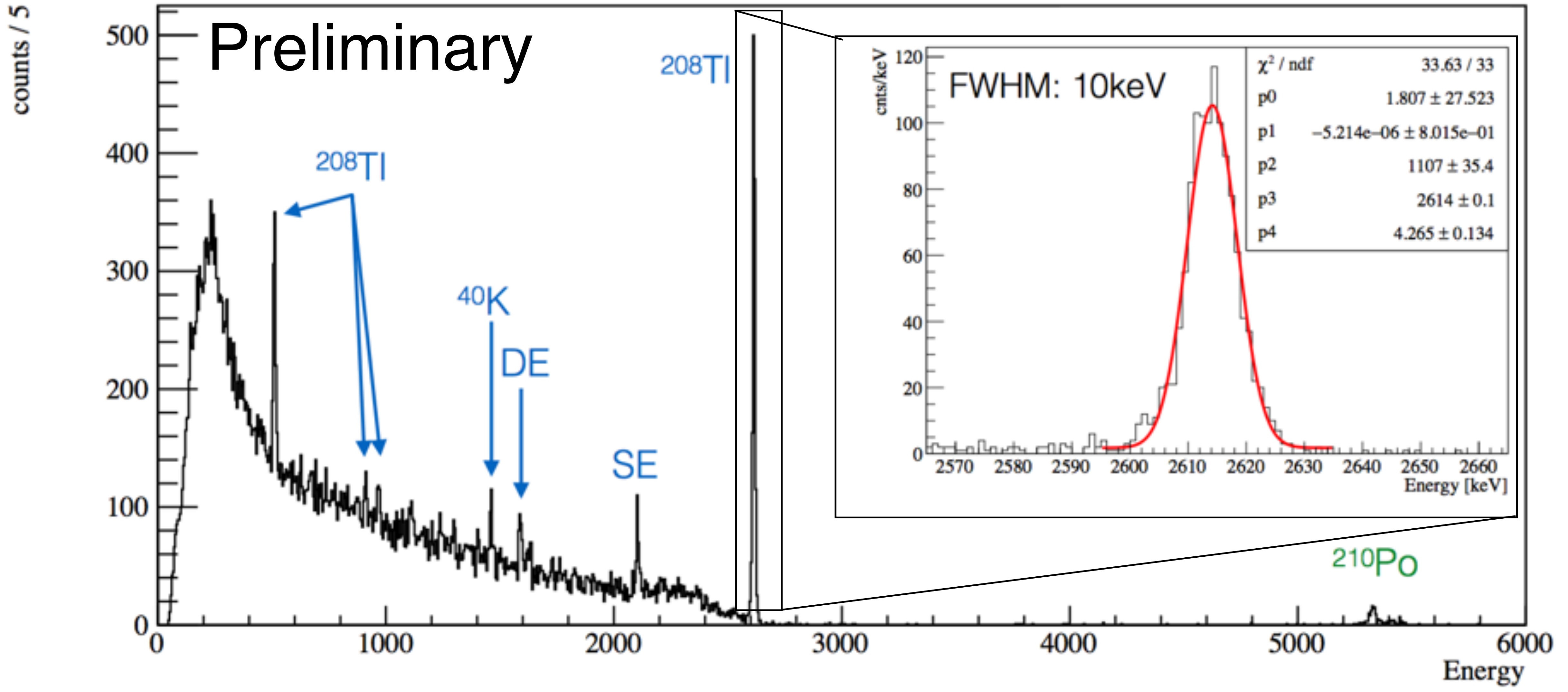
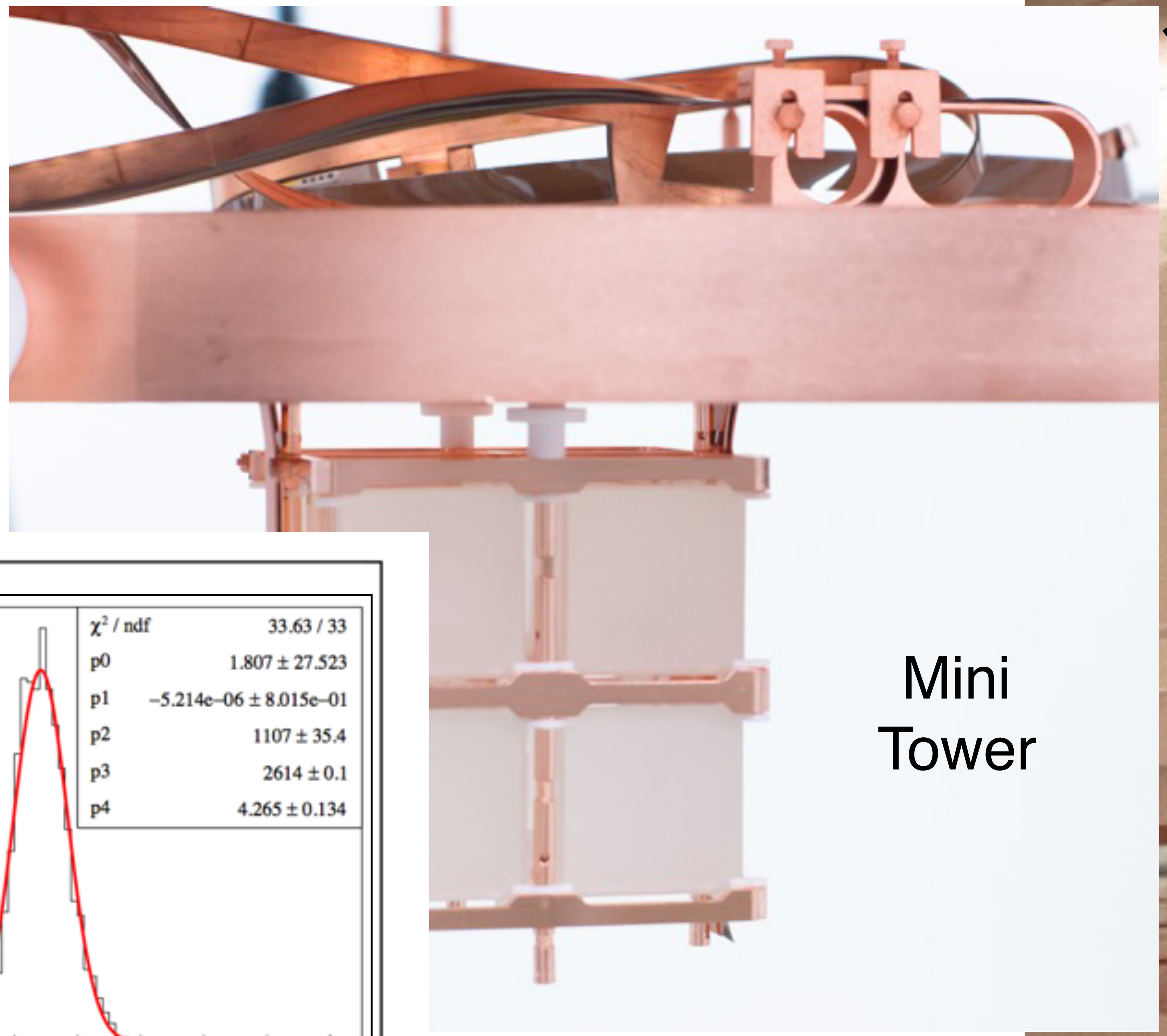
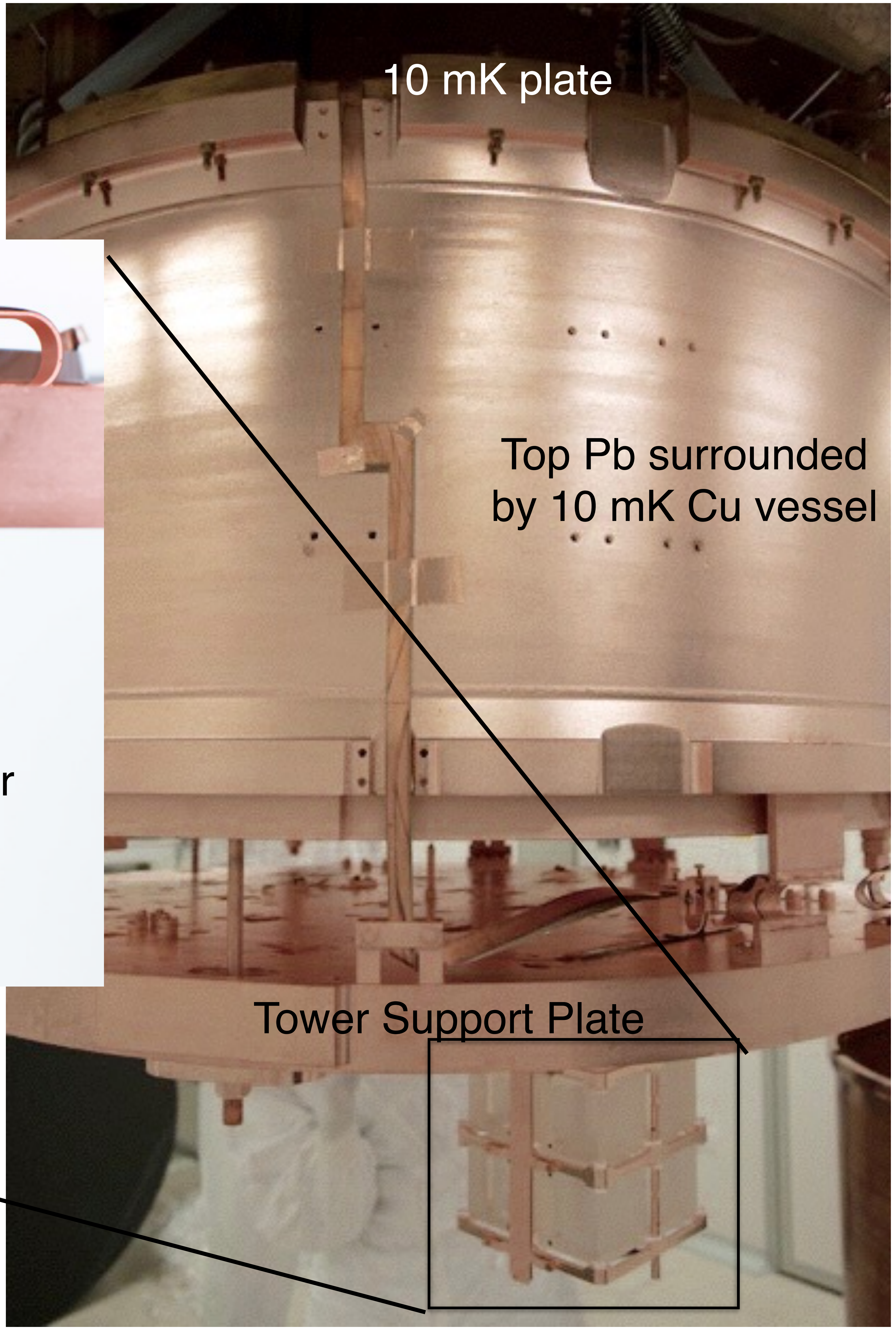
Calibration energy spectrum







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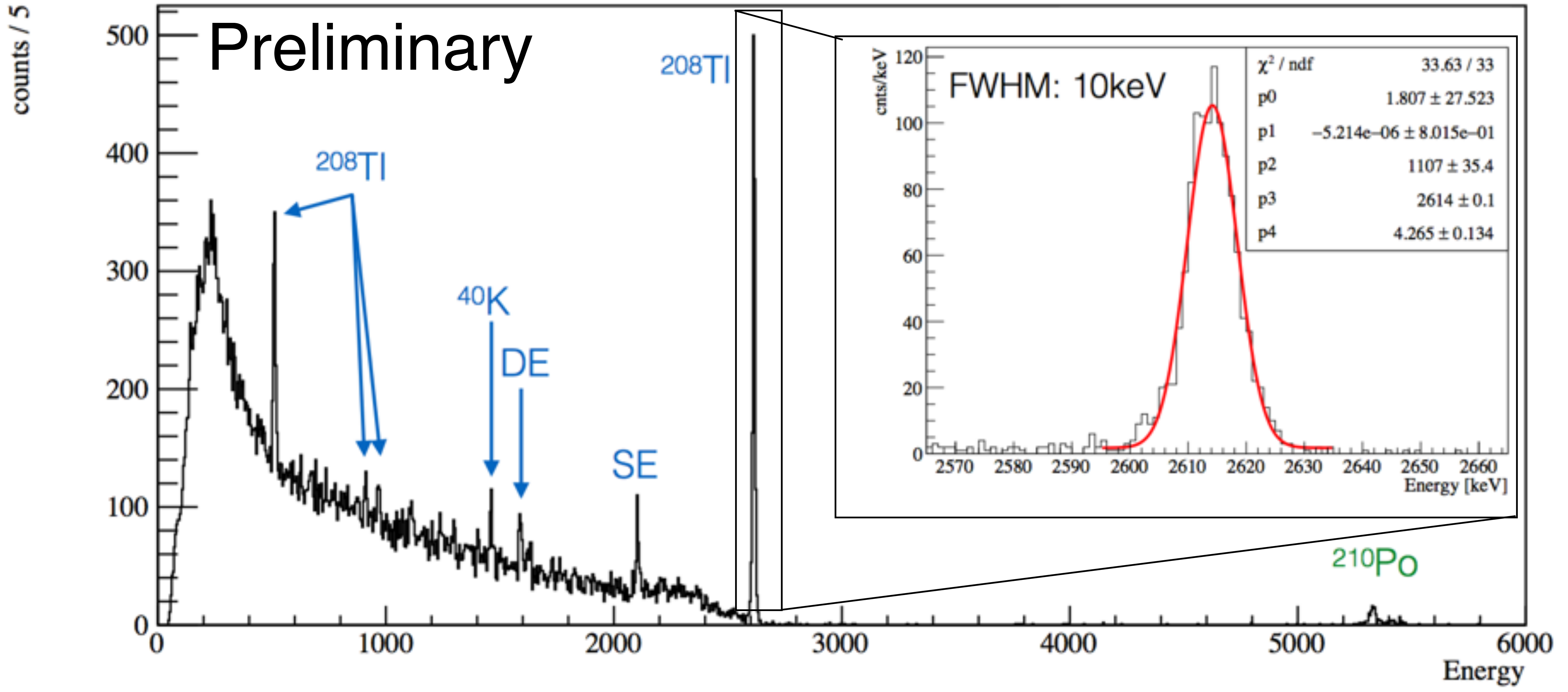
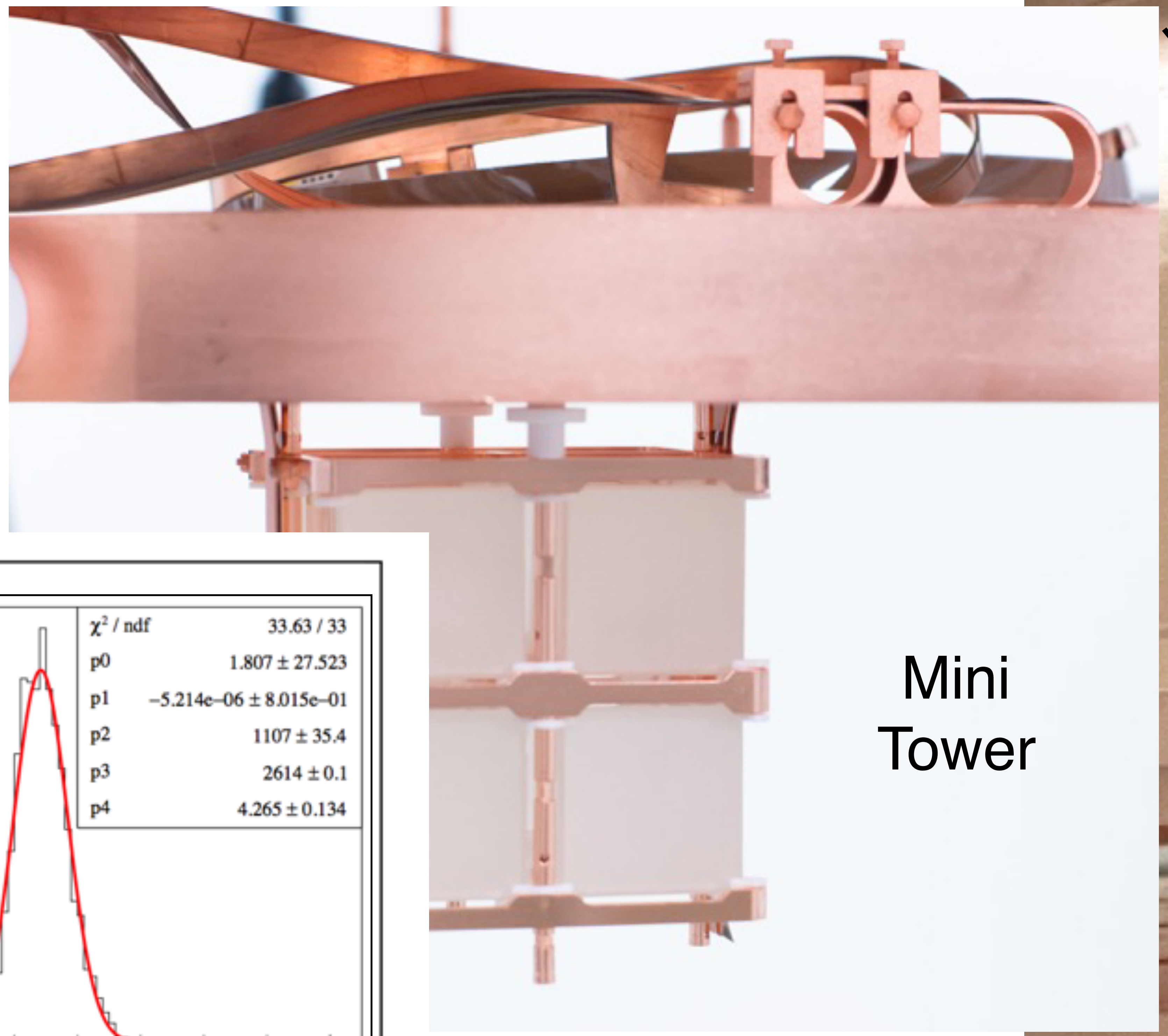
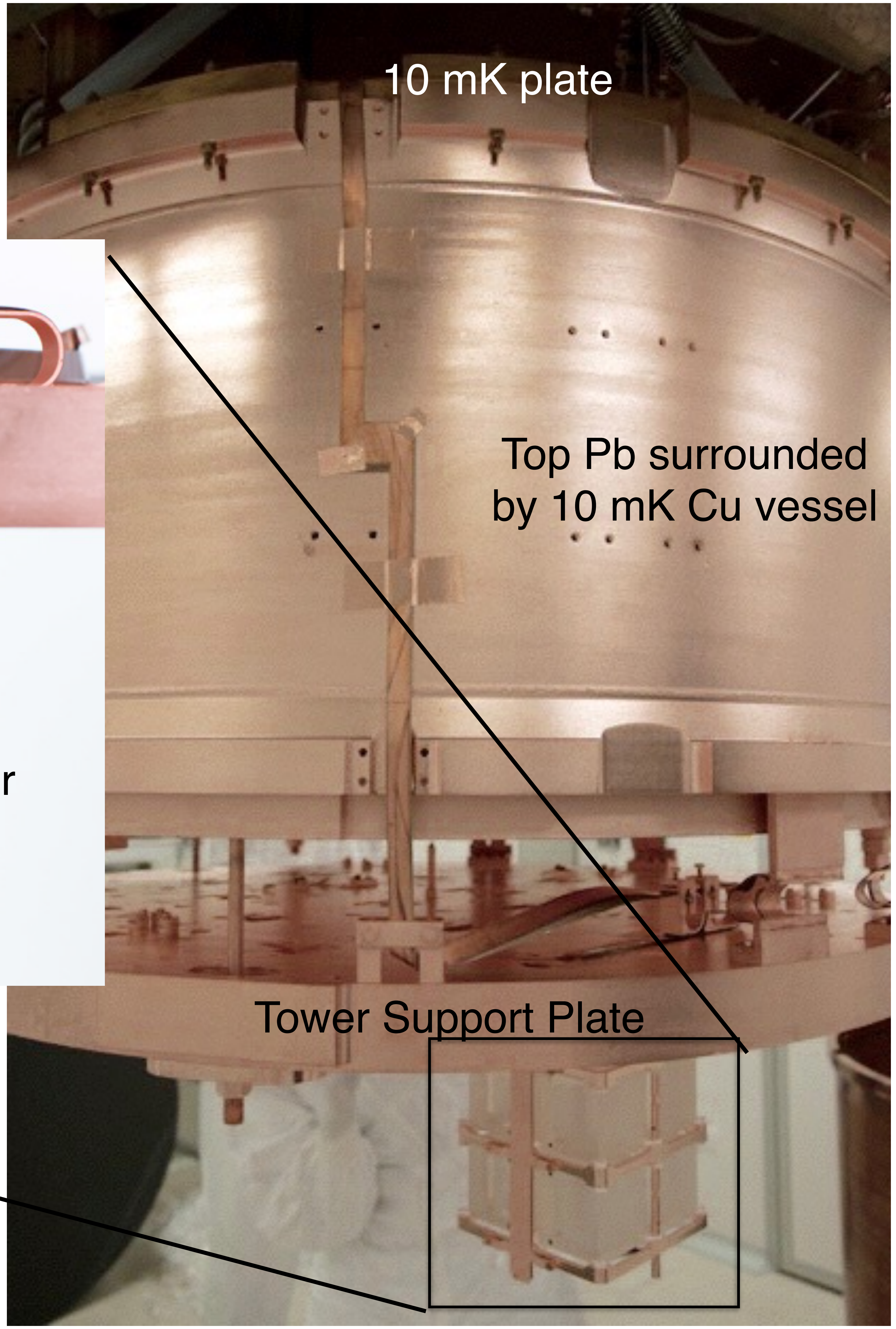


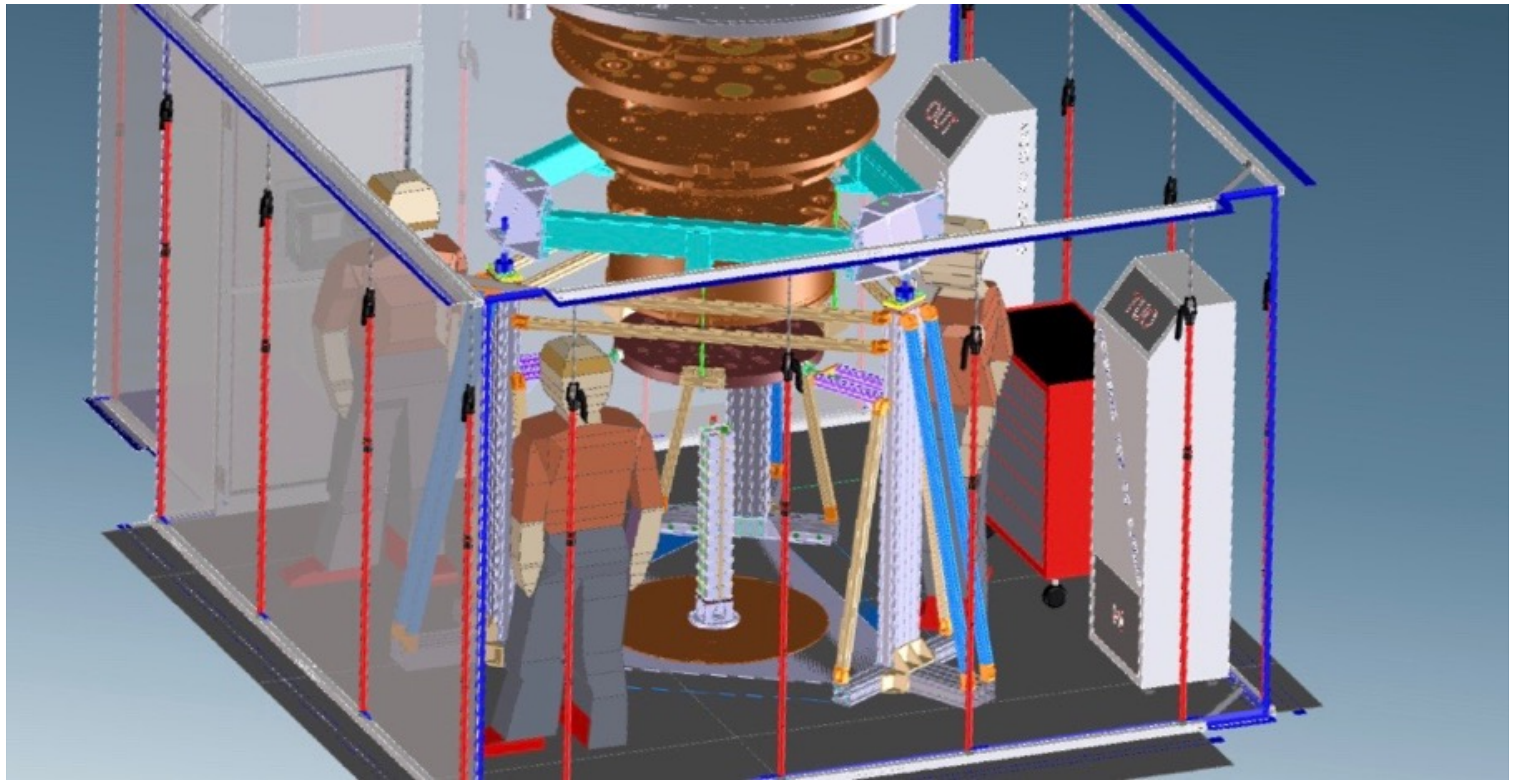


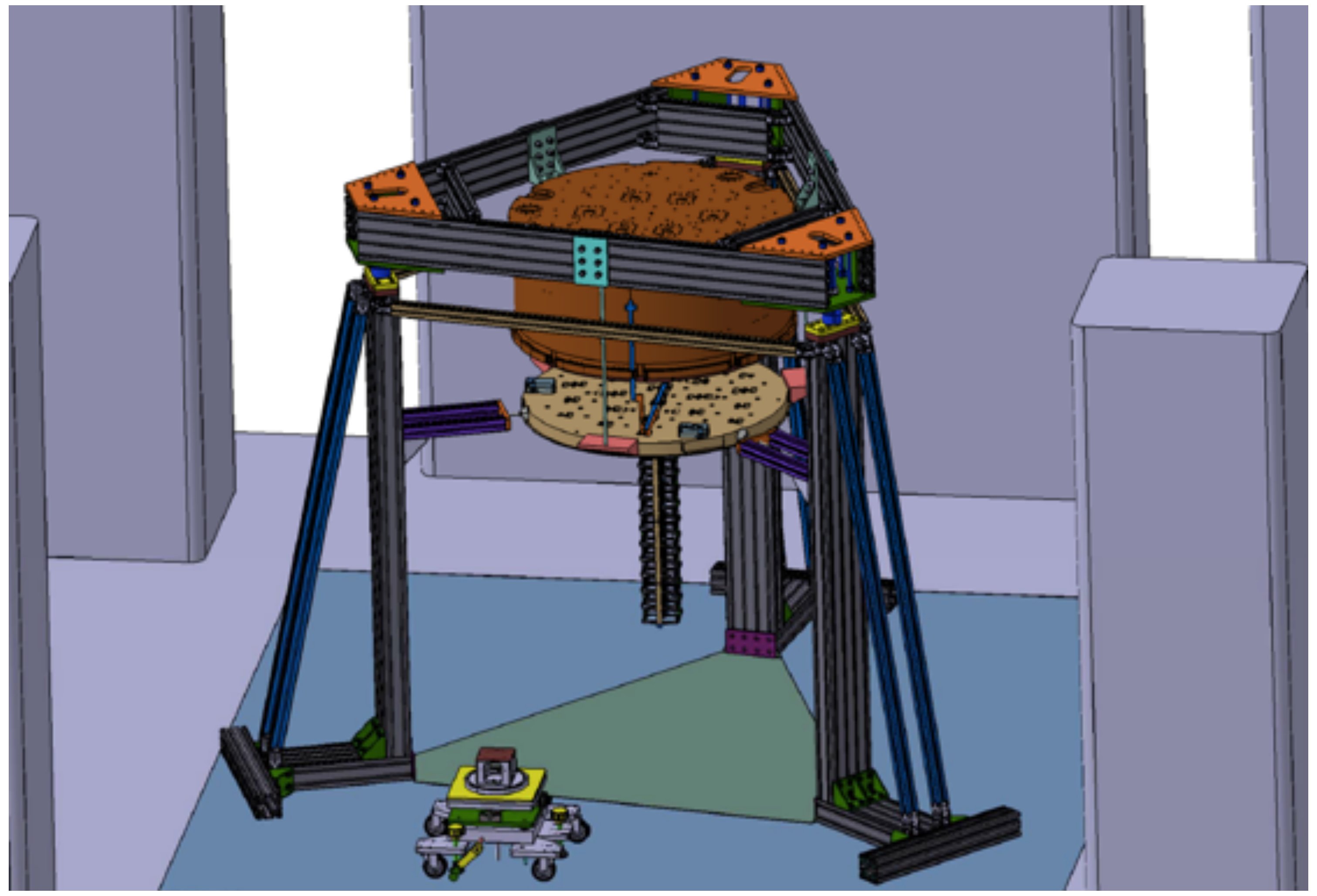


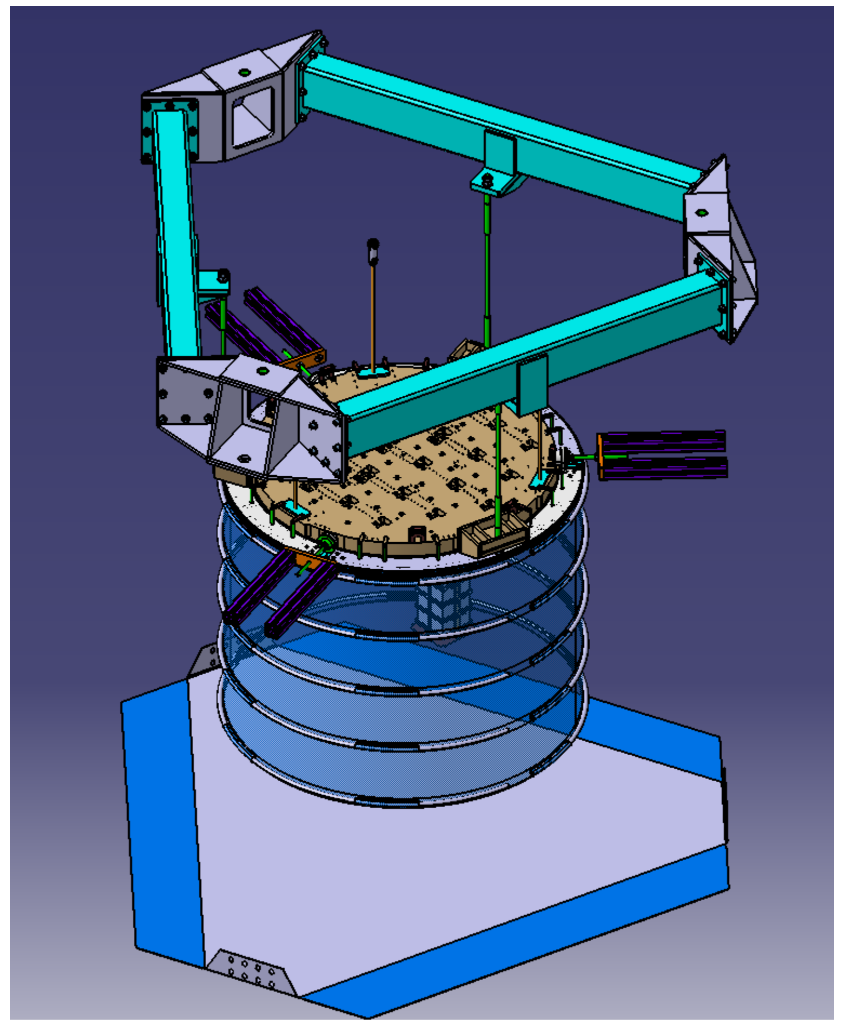
March 2016: cryogenic commissioning completed

Detector installation

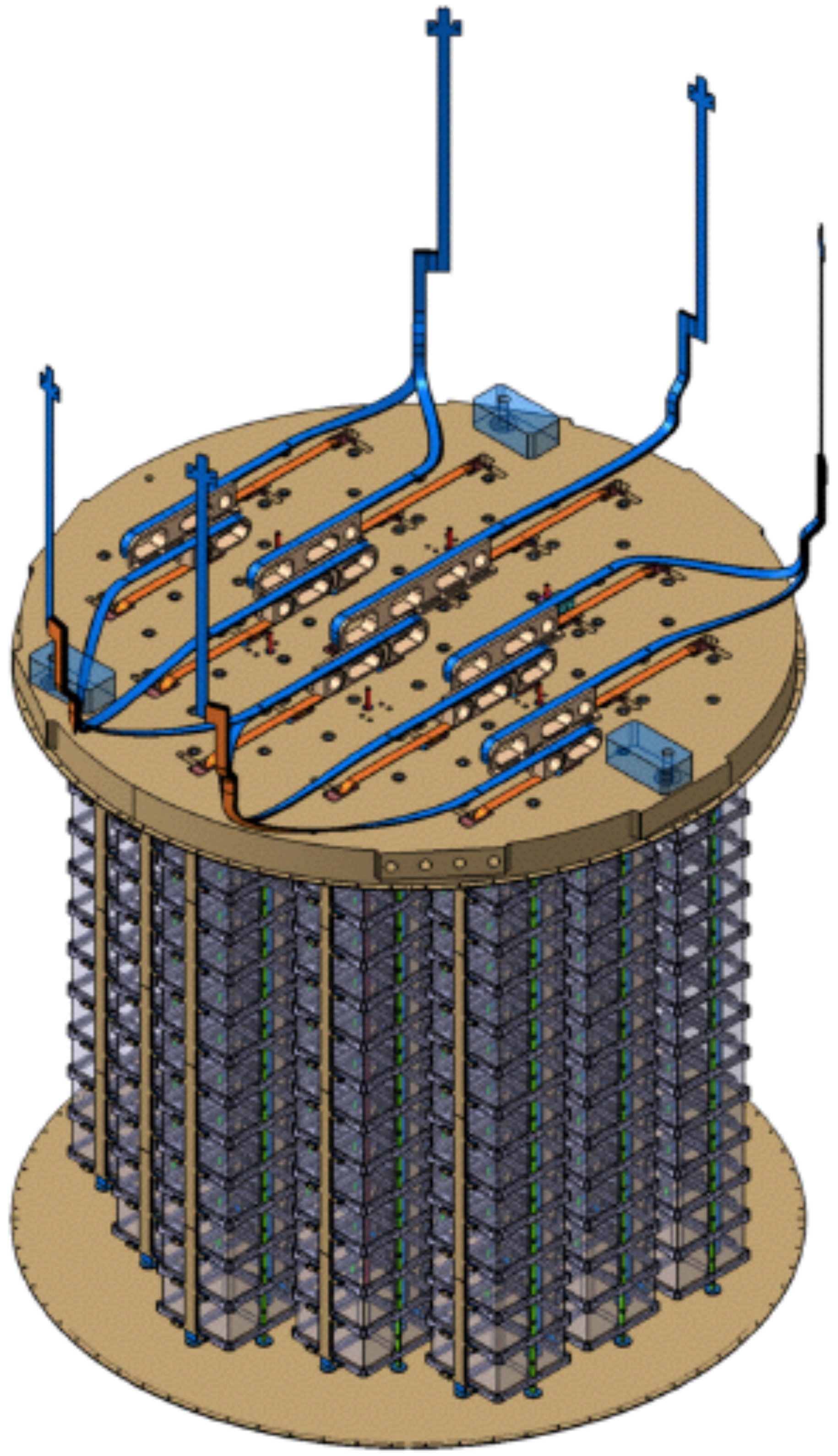
Detector Installation







- First time towers exit N_2 atmosfere. Rn free air mini-clean room (CR6) <50 mBq/m^3
- Special procedure to access CR6
- Complex set of tools to install towers under Tower Support Plate (TSP)

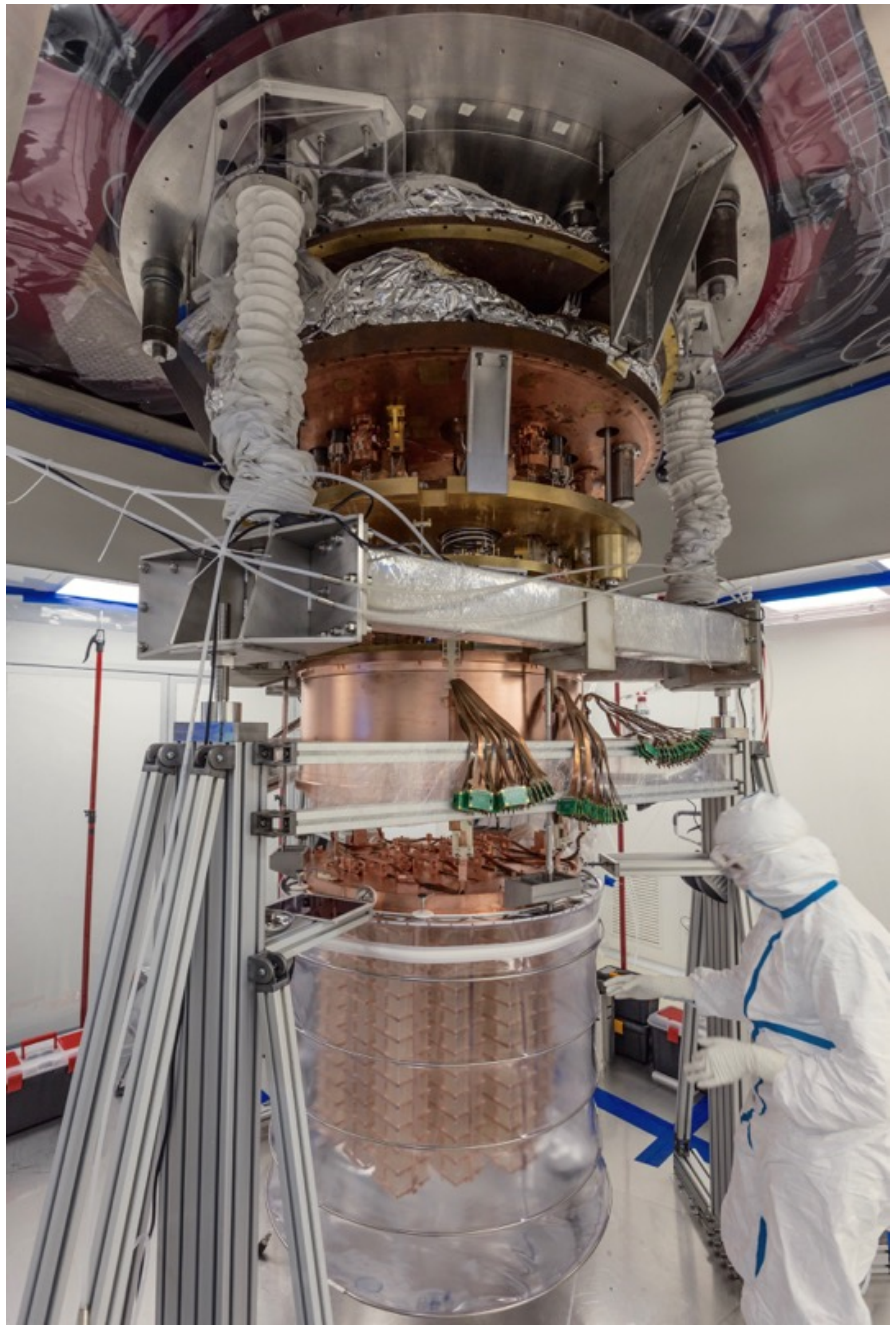


Detector Installation

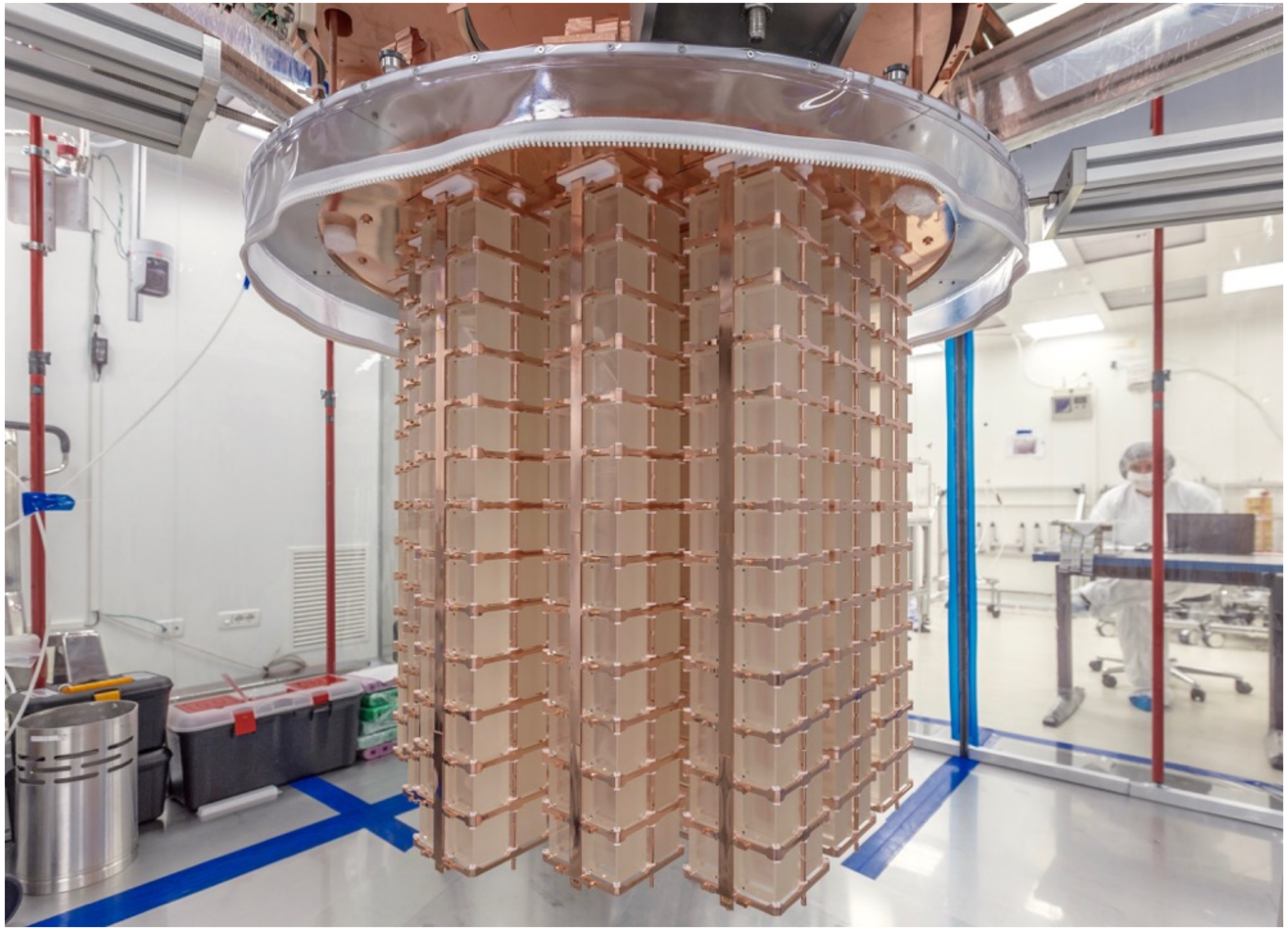
Preparation of the tower wiring

Tower installation under TSP

Detector stored in N_2 atmosfere



The CUORE detector



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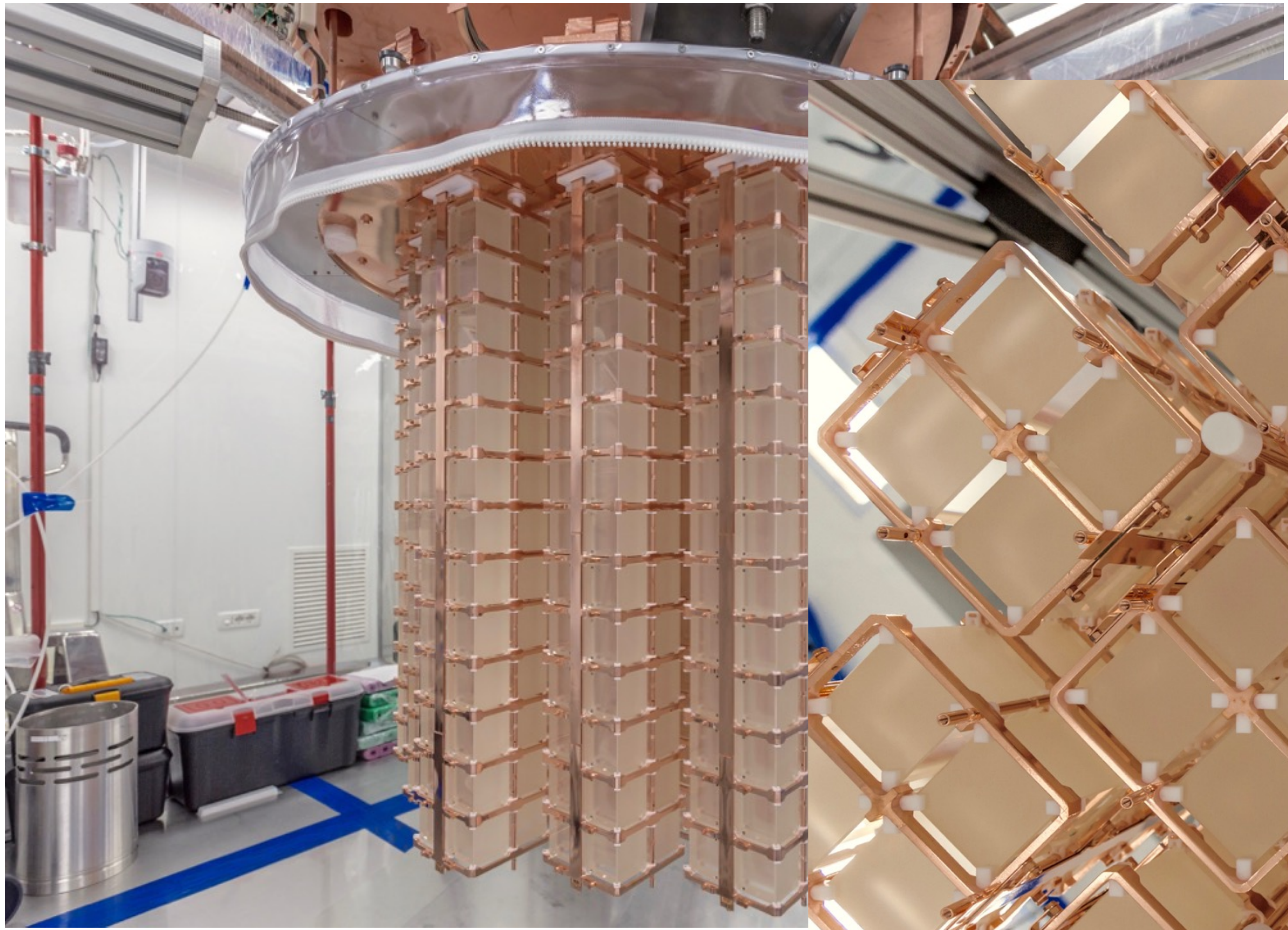
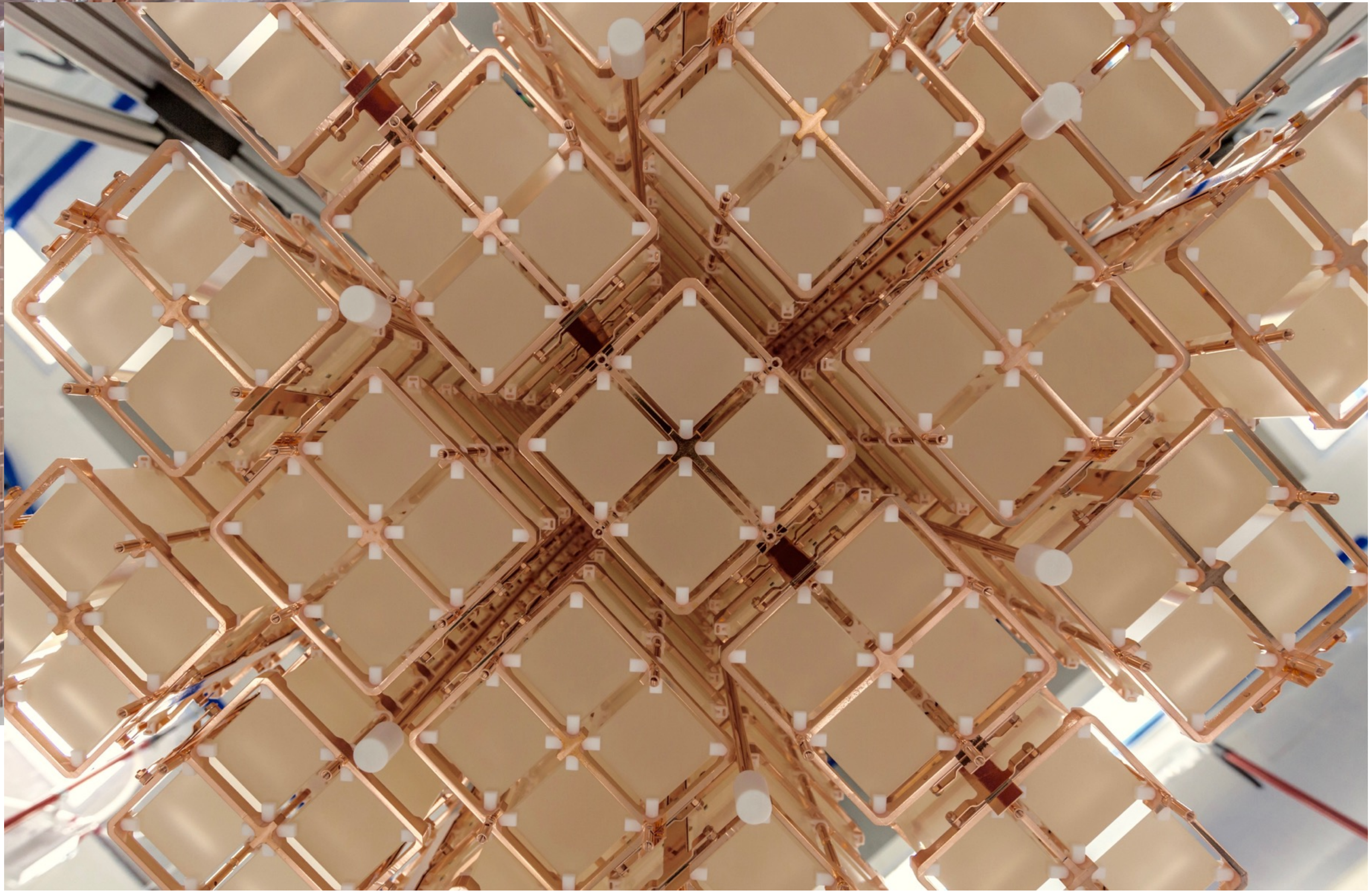
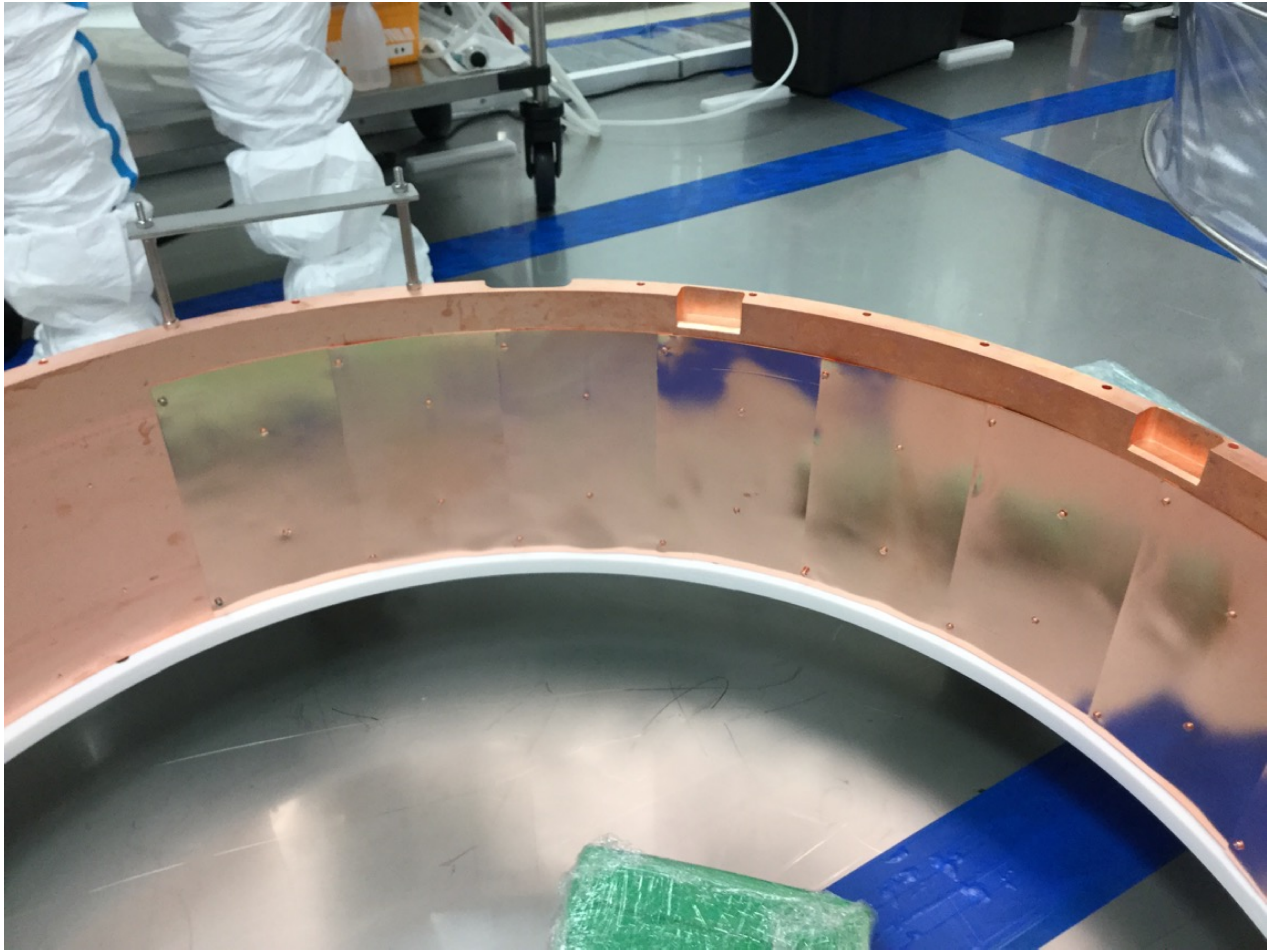




10 mK shield



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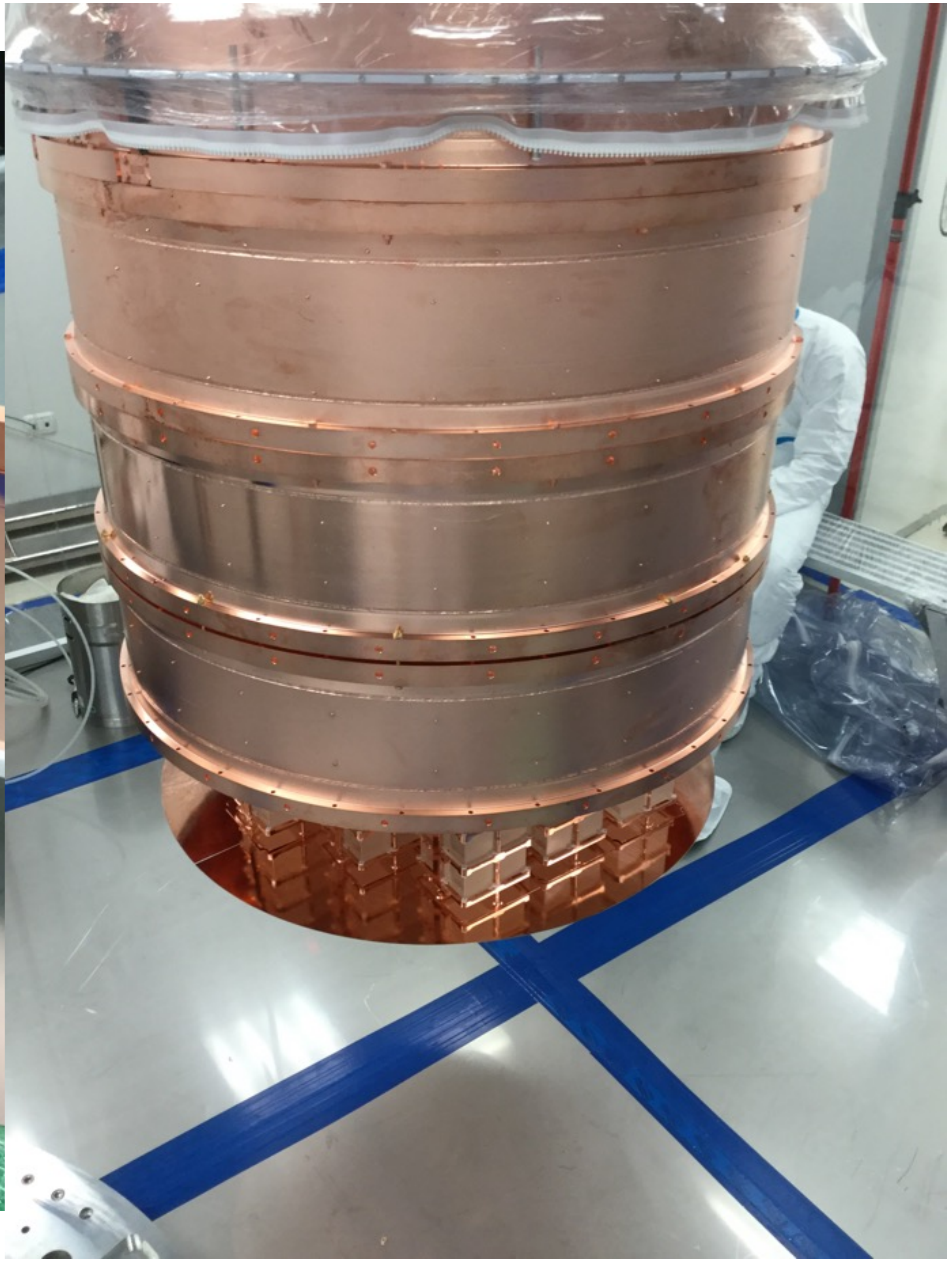
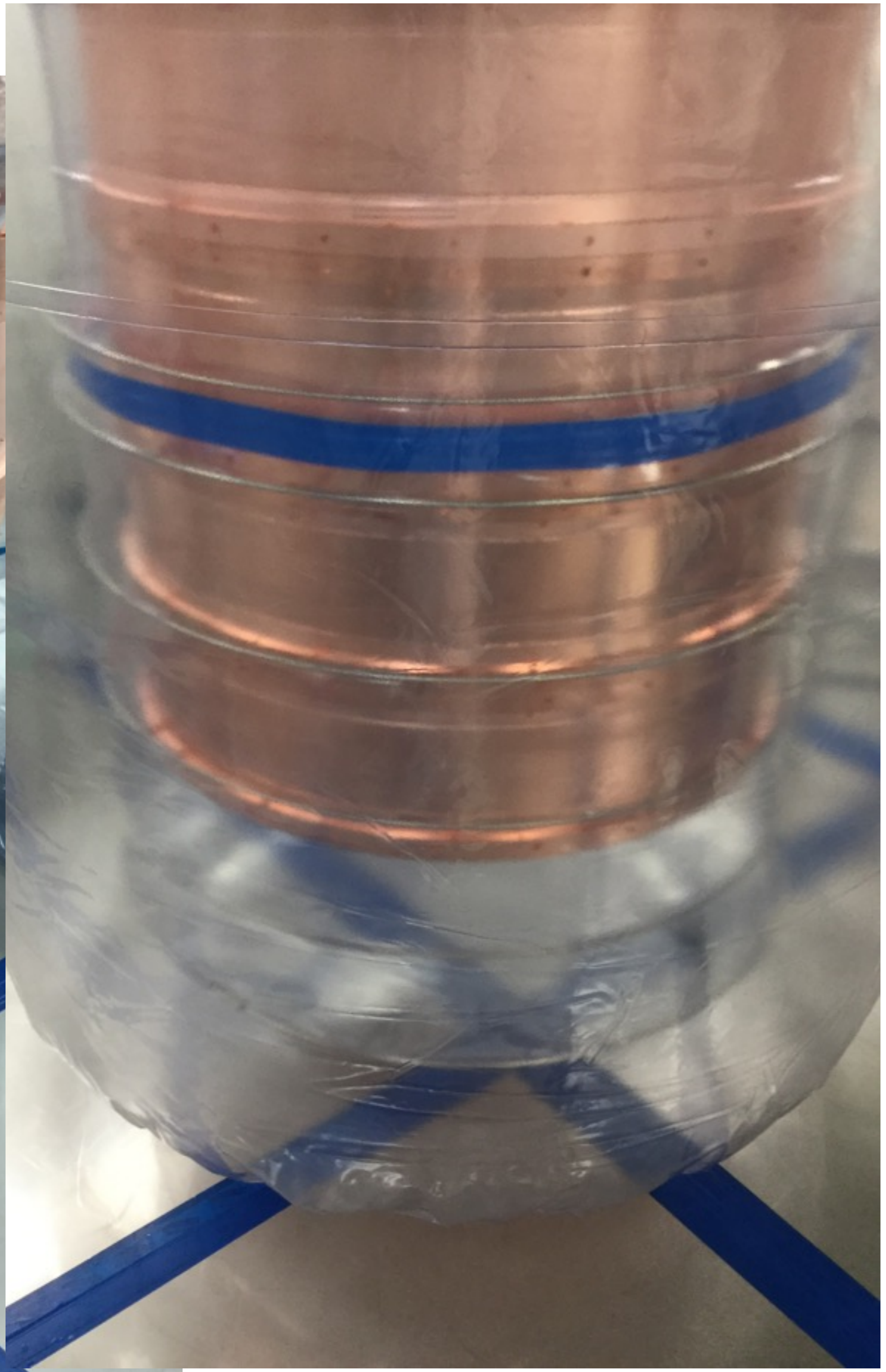
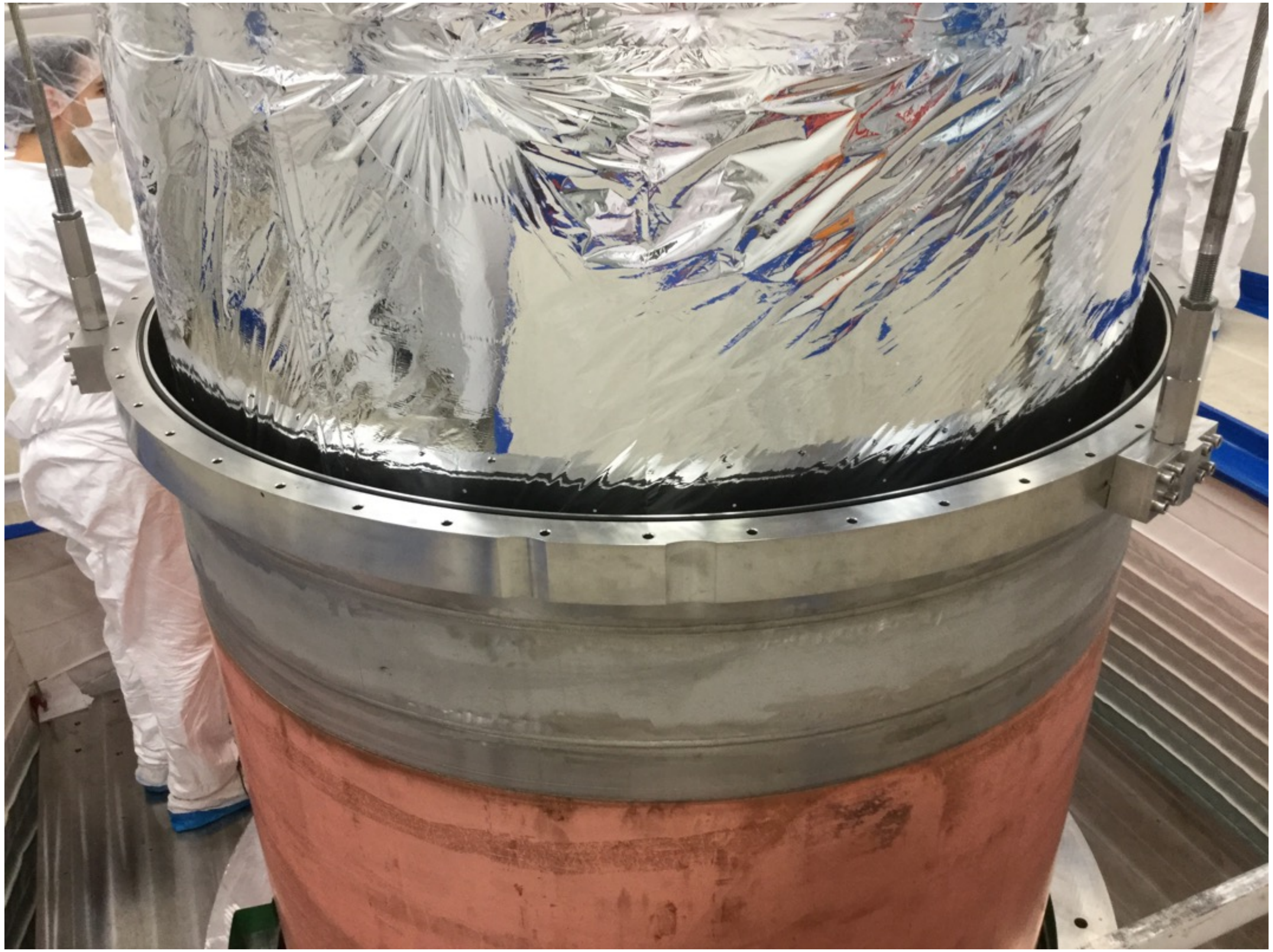


10 mK shield



Closing the cryostat



Completed in November 2016: cryogenic pre operation started. Cool down foreseen in December 2016

Summary

CUORE-0

- Achieved its energy resolution and background level objectives: CUORE sensitivity goal is within reach
- Improved 0vDBD limit for ^{130}Te (no 0vDBD evidence) and measured 2vDBD

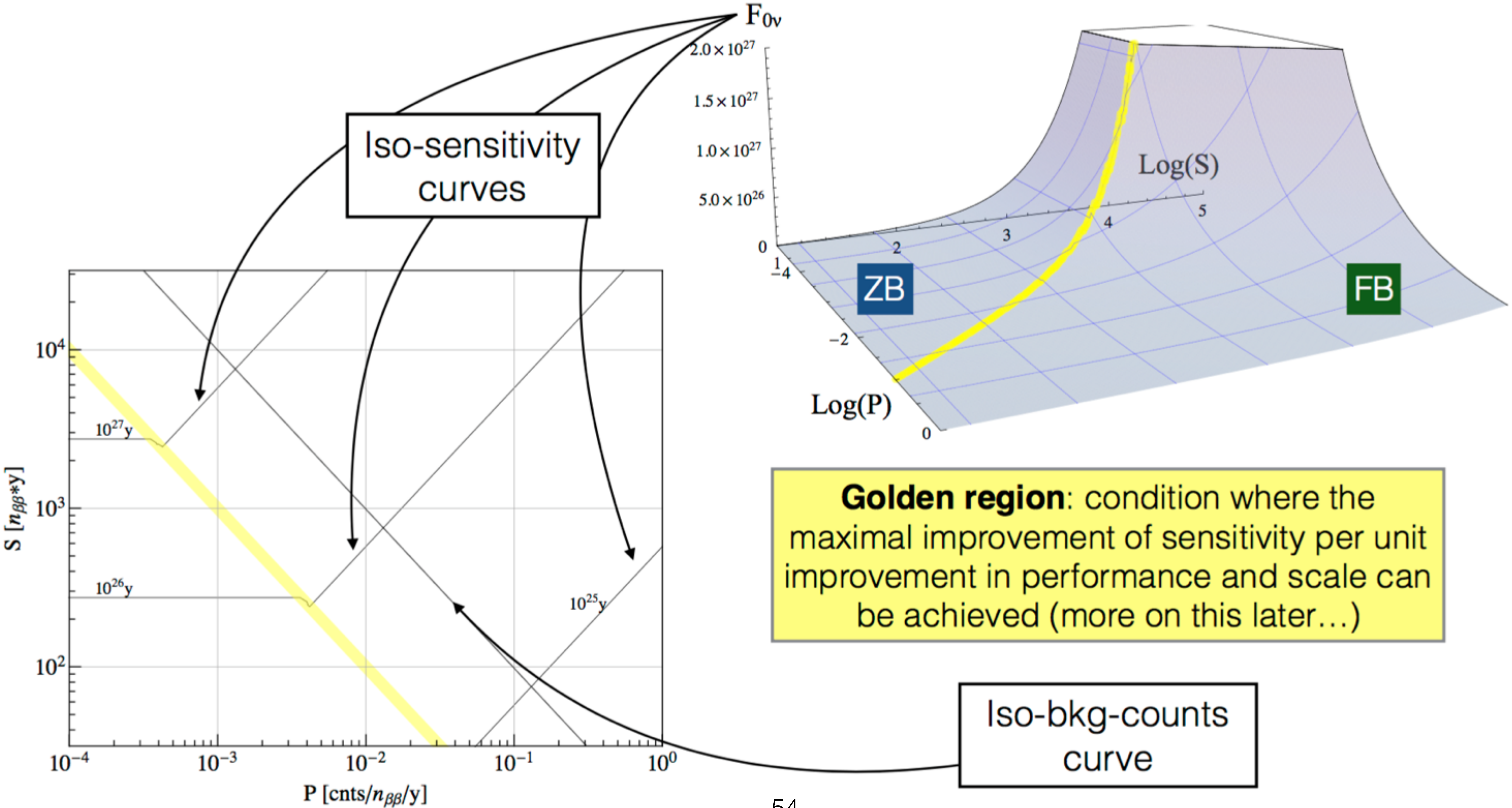
CUORE

- CUORE cryostat assigning is completed
- The 19 CUORE towers were successfully installed in the cryostat.
- CUORE in cryogenic pre-operation to start cool down. Cool down will start before the end of 2016.
- CUORE will open the way to high sensitivity DBD experiments

BACK-UP

The (P,S,$F_{0\nu}$) space

Each experiment can be represented in the same (*P*,*S*,*$F_{0\nu}$*) space as a point on the *$F_{0\nu}$*(*P*,*S*) surface representing the sensitivity

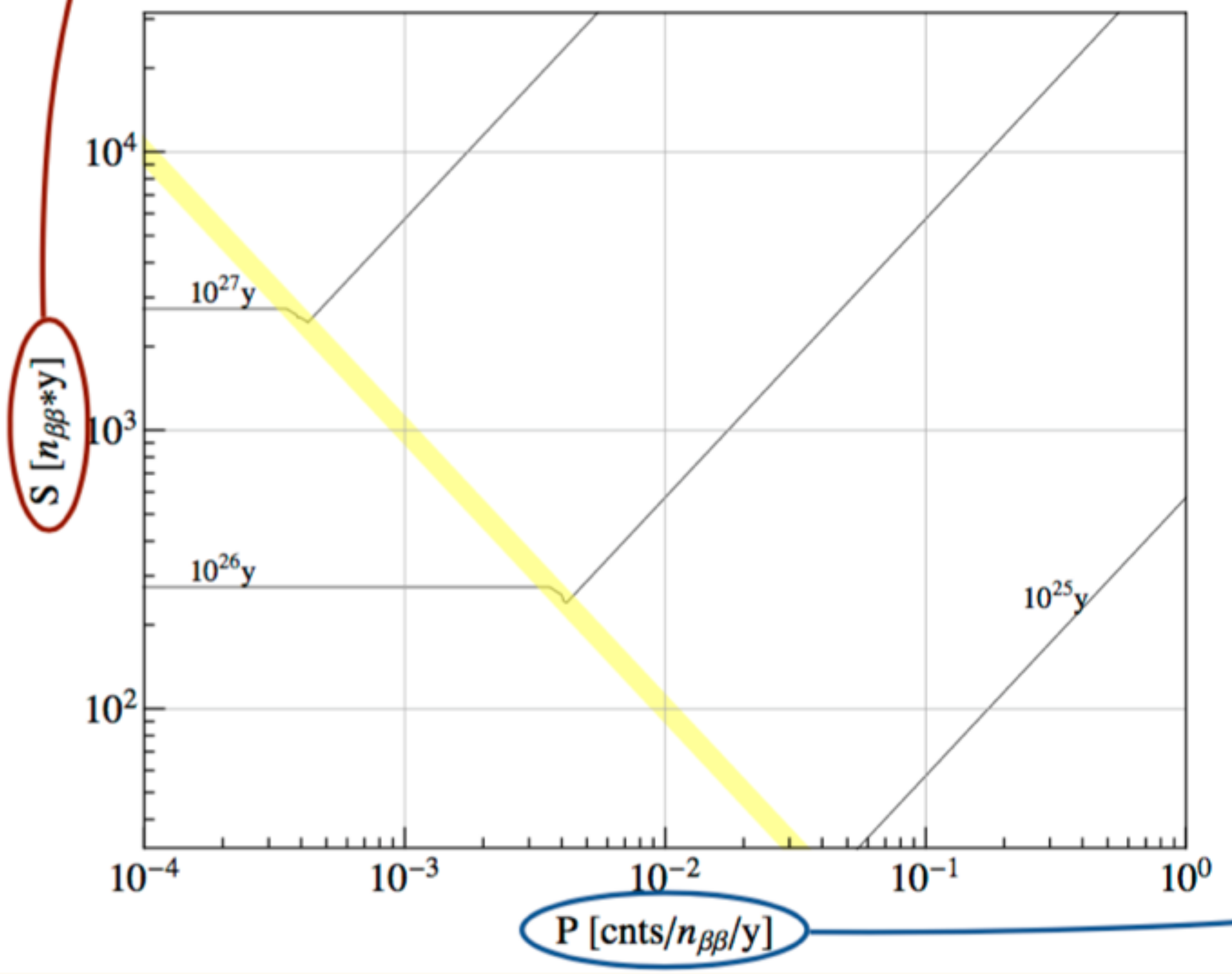


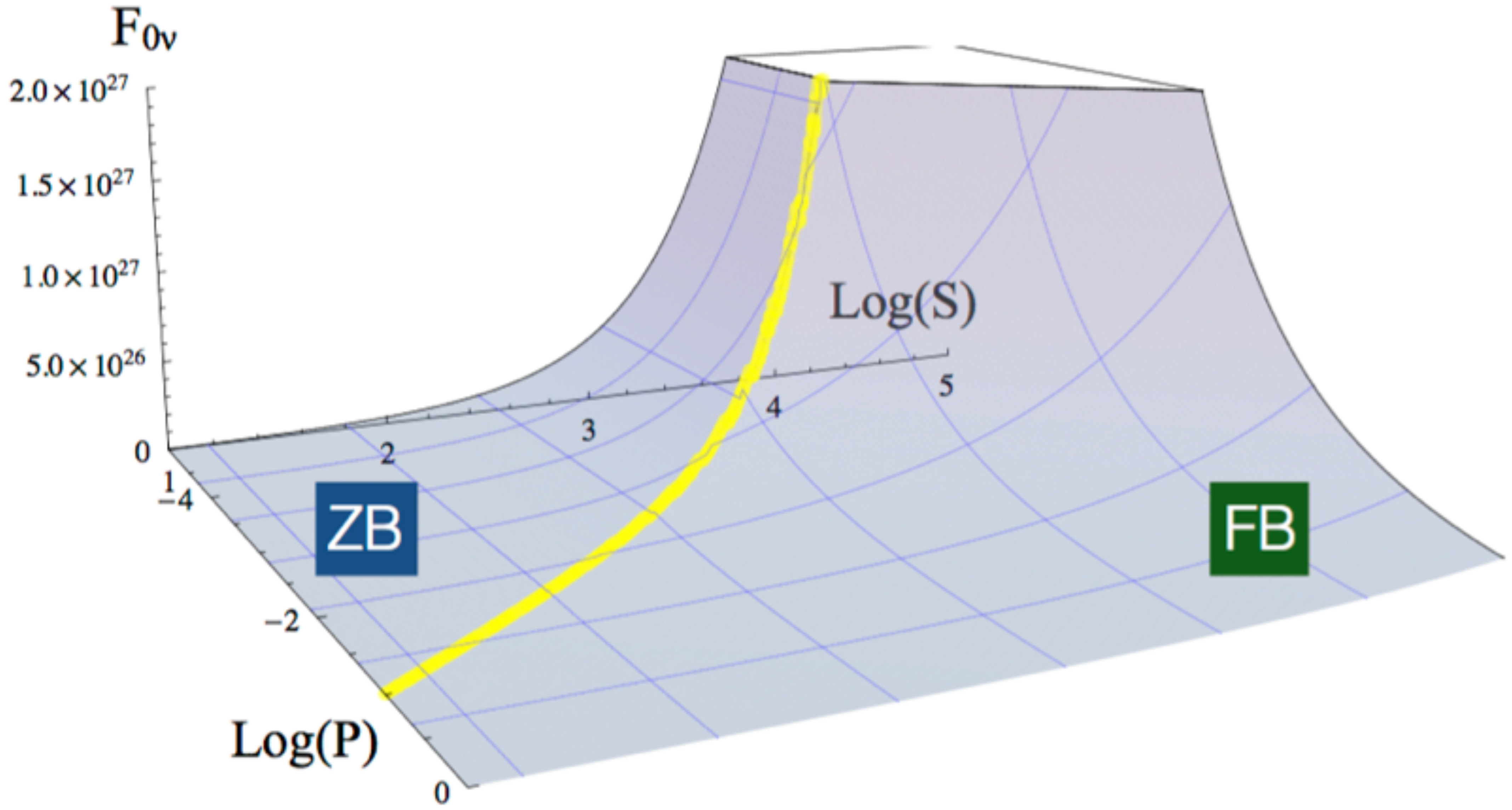
Golden region: condition where the maximal improvement of sensitivity per unit improvement in performance and scale can be achieved (more on this later…)

The (P,S,$F_{0\nu}$) space

Each experiment can be represented in the same (P,S,$F_{0\nu}$) space as a point on the $F_{0\nu}(P,S)$ surface representing the sensitivity

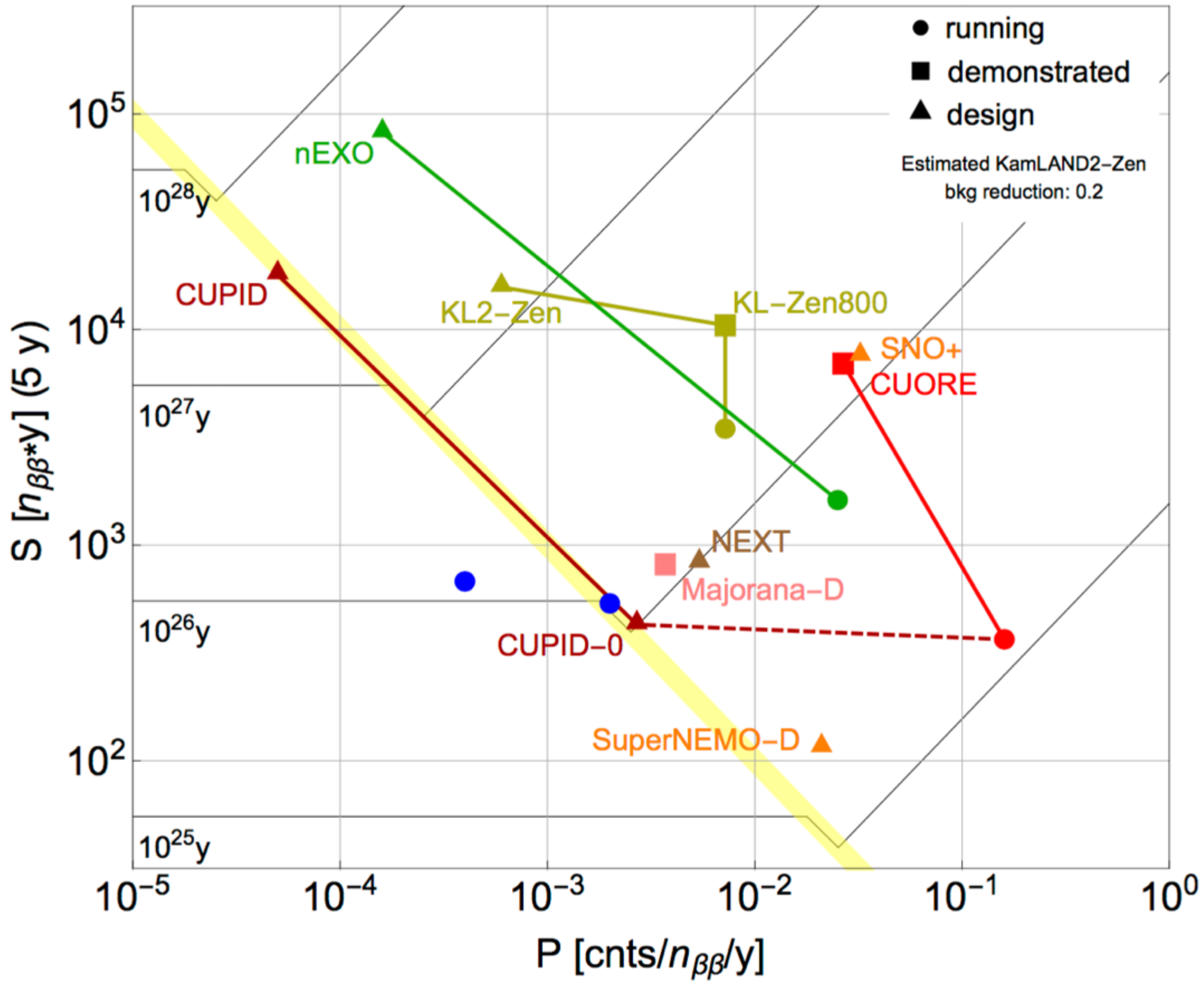
10-1000kg of isotope (100kg-10ton of active material depending on i.a. and fiducial volume)



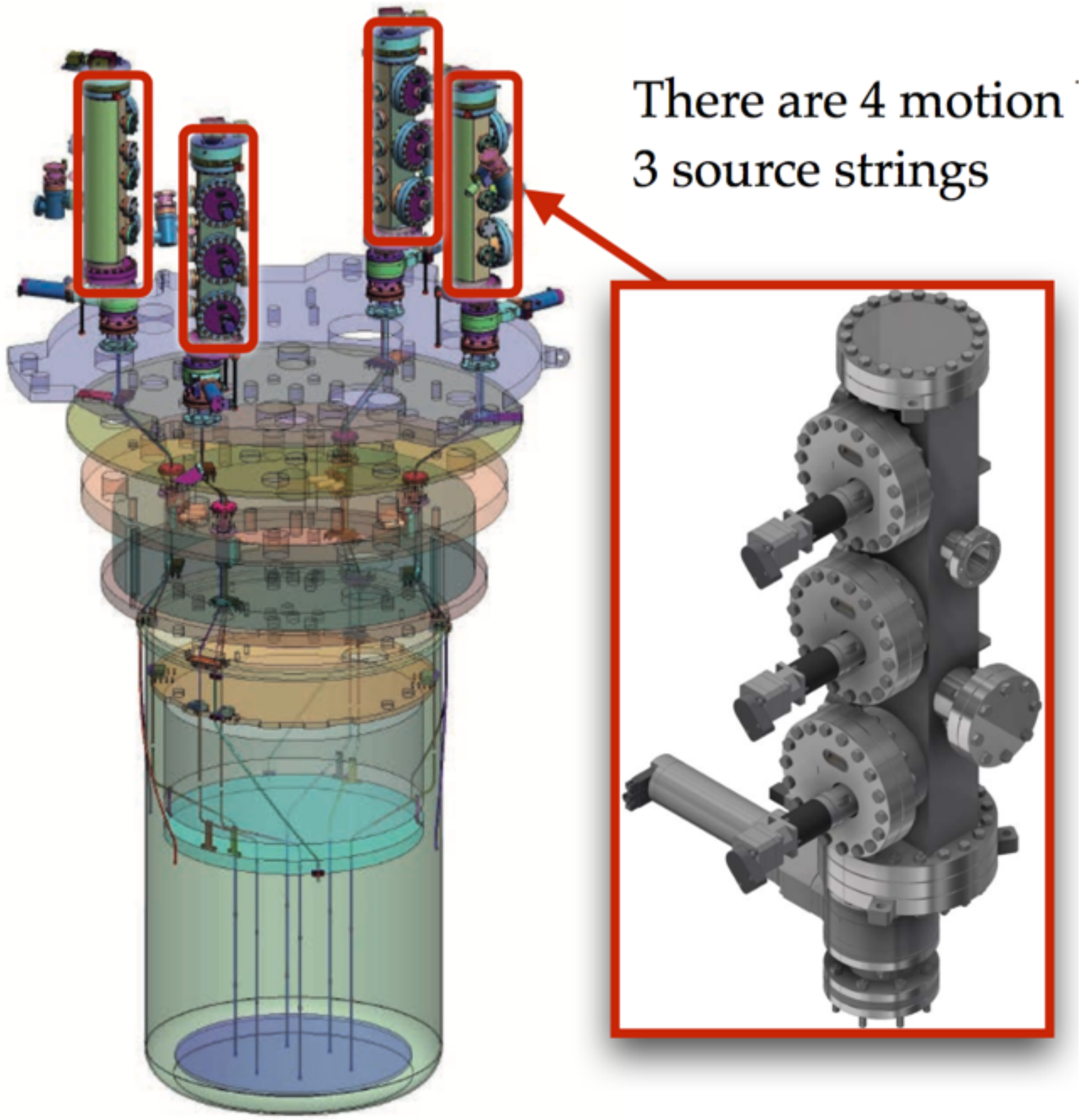


From few tens to 0 background counts (including 2νββ) in the ROI per year

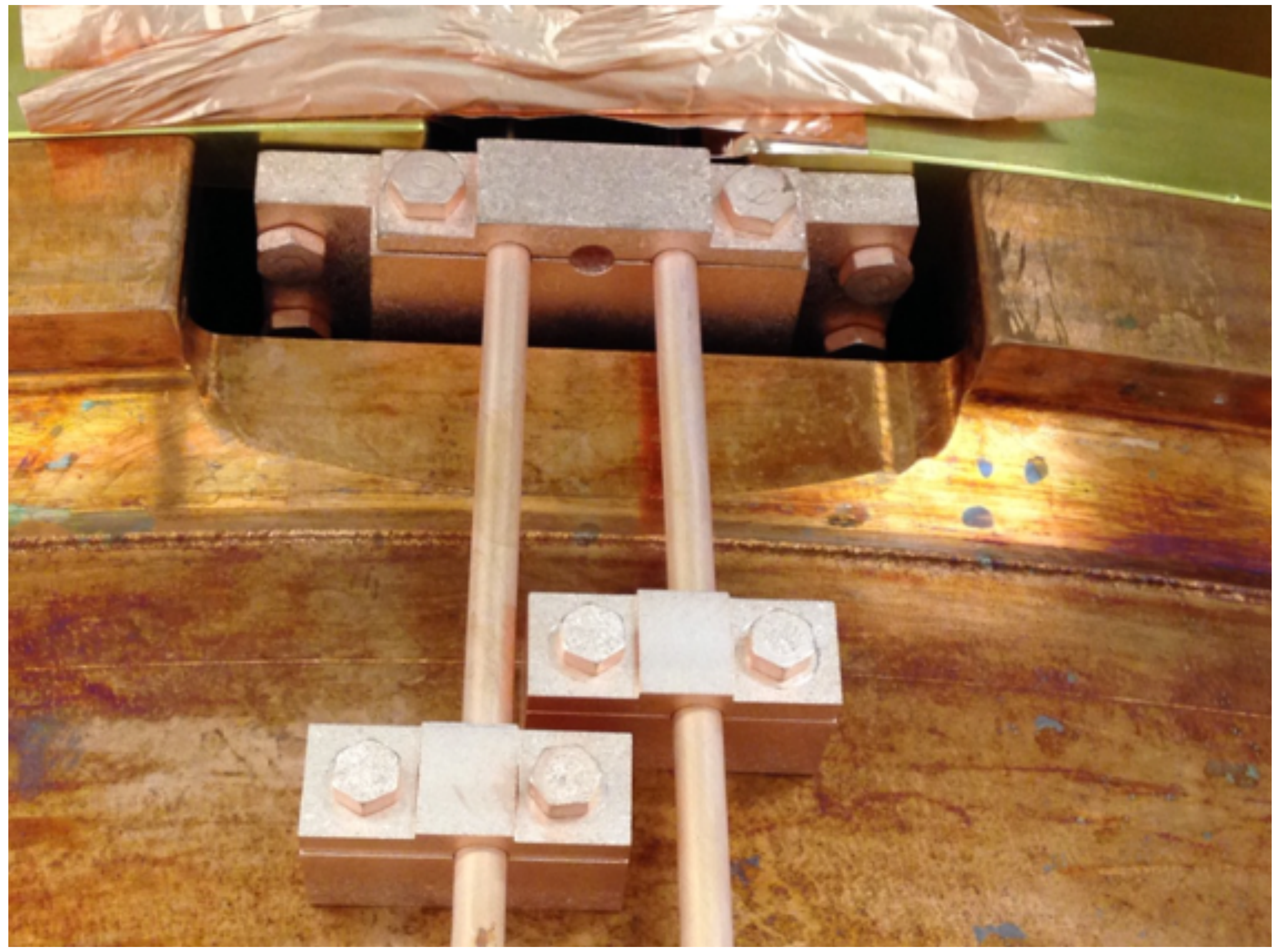
Towards next generation



Detector calibration system



- Successful deployment of calibration sources to 10 mK (6 internal) and 50 mK (6 external)
- Power dissipation compatible with CUORE specs



Fast cooling system

- Cool down to 4 K of about 15 tonnes was performed in 17 days
- Fast cooling was used up to ~ 75 K