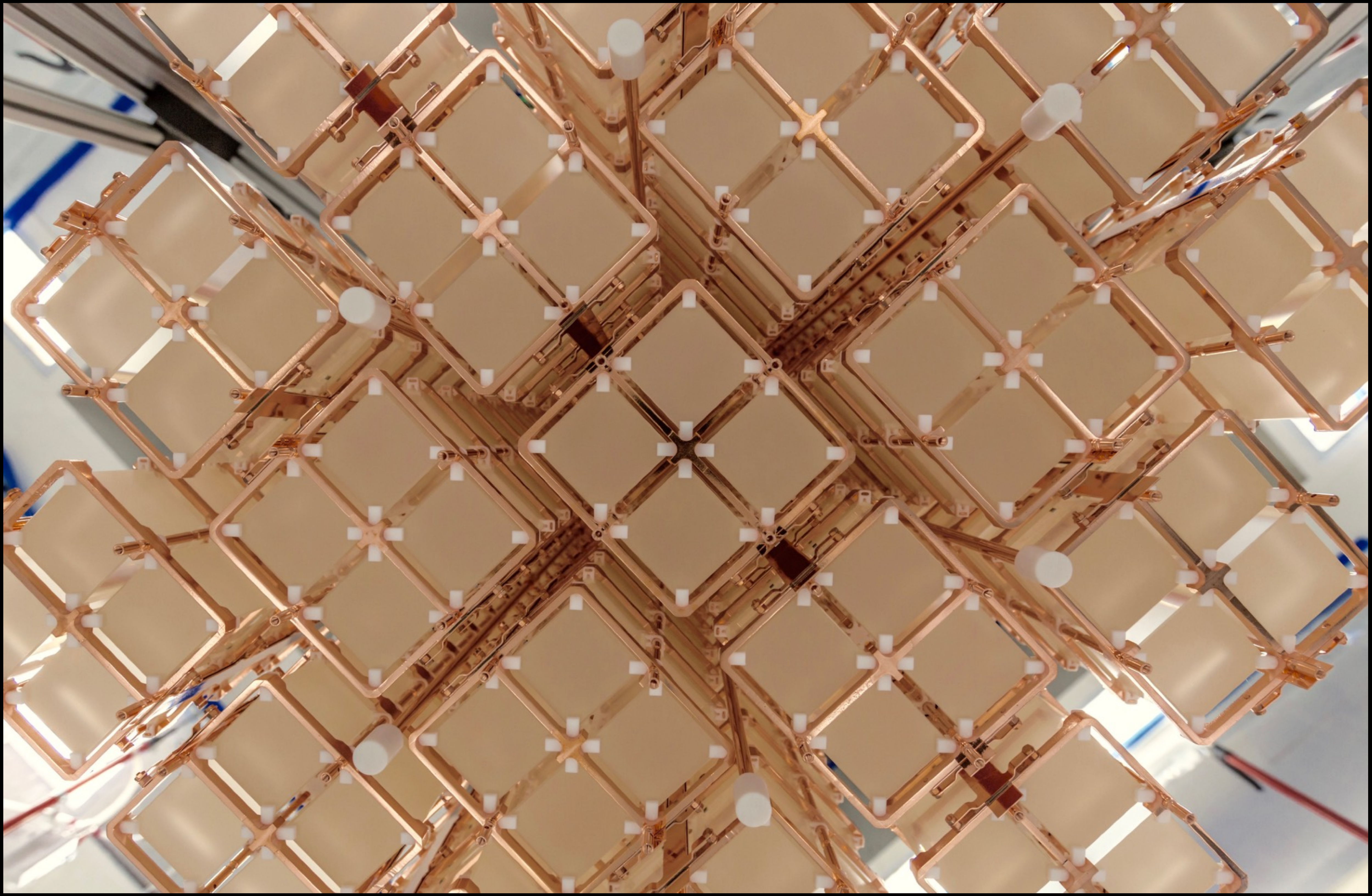


CUORE

First CUORE results

Carlo Bucci
on behalf of the CUORE Collaboration

INFN
LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

The CUORE collaboration

INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso

CUORE

CSNSM

Universitas Studii Paduani MCCXXII

Yale

INFN

Berkeley Lab

Cal Poly San Luis Obispo

Alma Mater Studiorum Università di Bologna A.D. 1088

Università degli Studi di Cassino e del Lazio Meridionale – 1979 – Sol per noctem

UCLA

SINAP

University of South Carolina 1801

The University of California 1868 Let there be light

Massachusetts Institute of Technology

VirginiaTech Invent the Future® 1872

Lawrence Livermore National Laboratory

Studium Urbis

Sapienza Università di Roma

Università degli Studi di Milano Bicocca

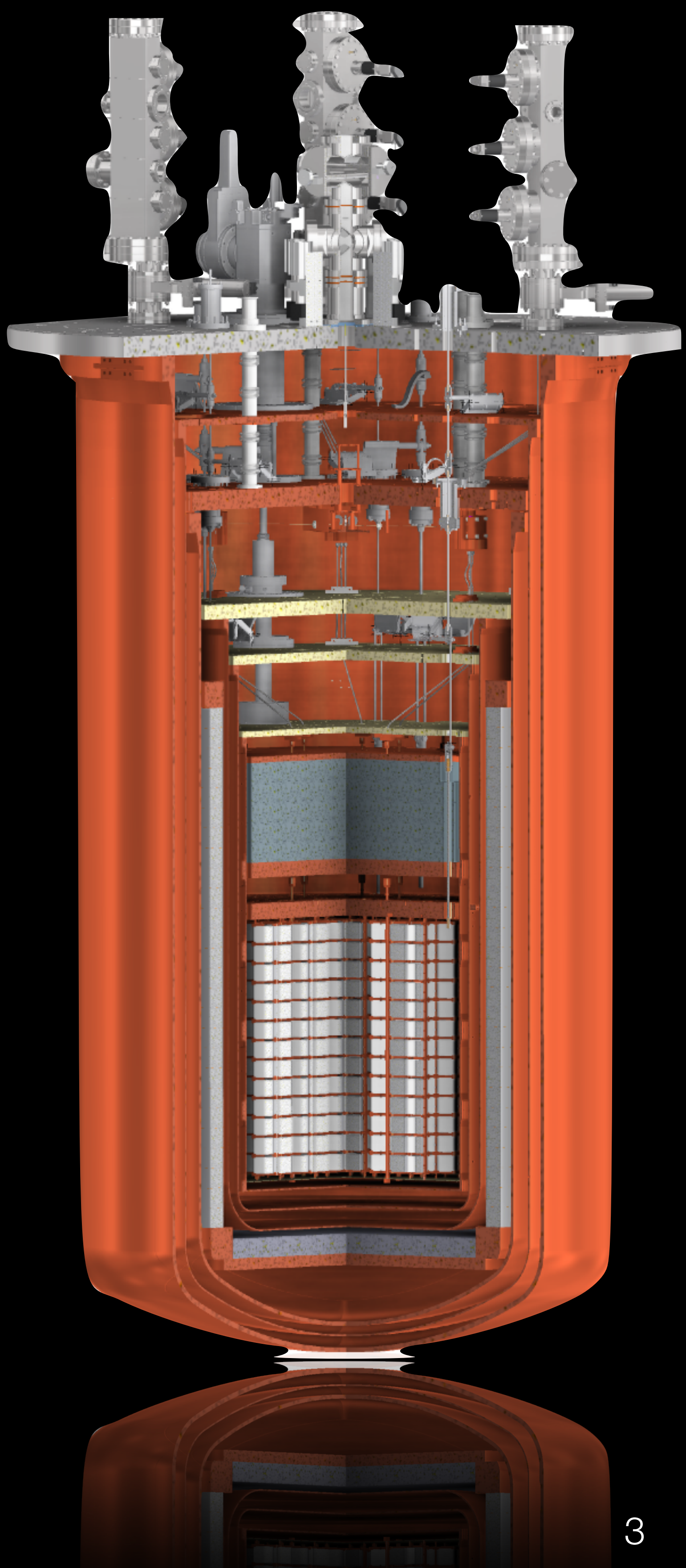
Shanghai Jiao Tong University 1896

CUORE

The CUORE challenge

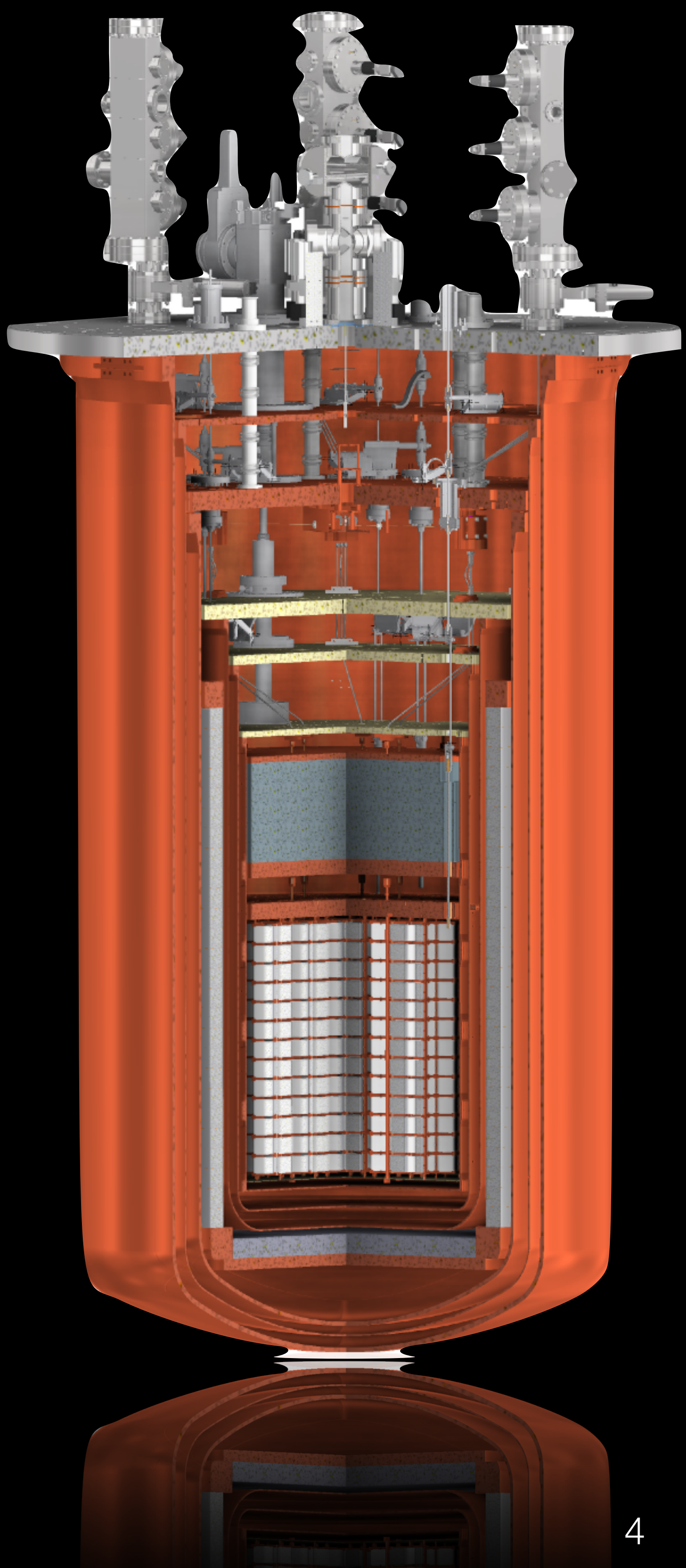
Operate a huge thermal detector array in a low radioactivity and low vibrations environment

- Closely packed array of 988 TeO_2 crystals (19 towers of 52 crystals $5{\times}5{\times}5$ cm^3, 0.75 kg each)
- Mass of TeO_2: 742 kg (206 kg of ^{130}Te)
- Energy resolution goal: 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.): ~ 9×10^{25} yr

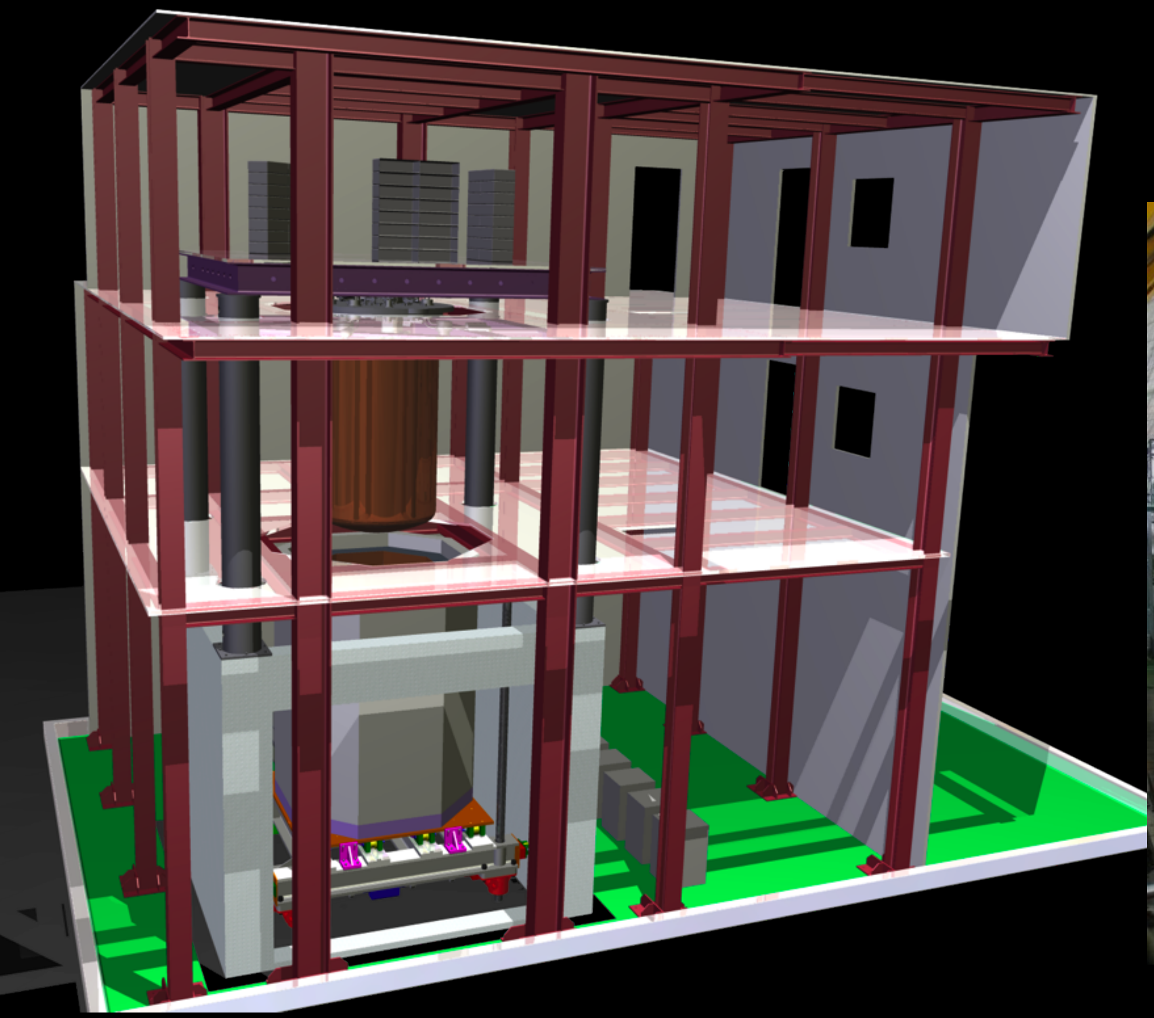


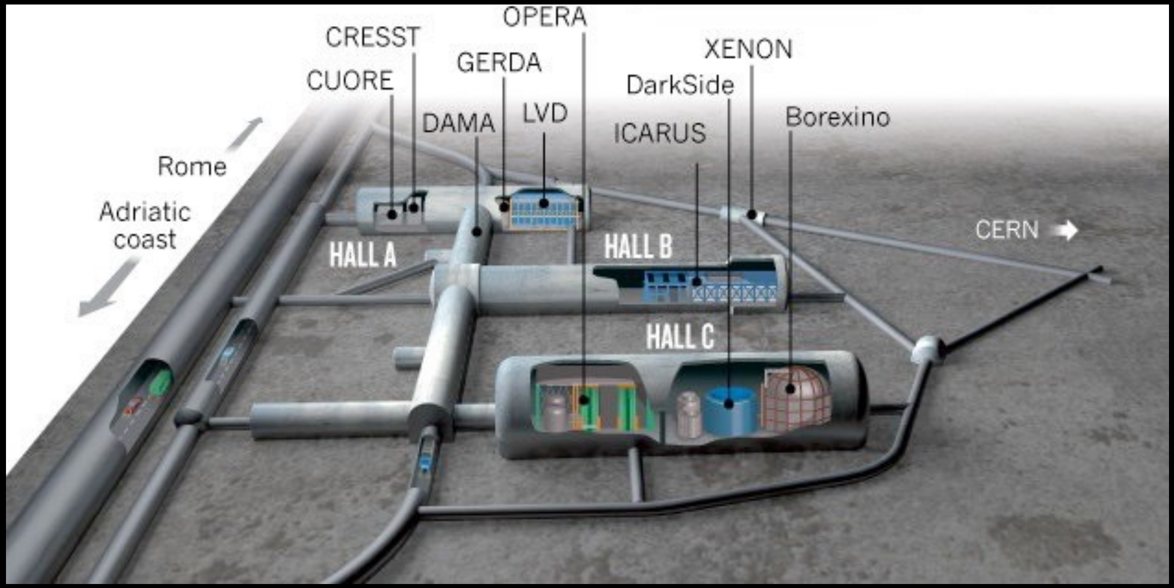
CUORE Design choices

- Cryogen-free
  - 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)
  - external dimension: ⌀ 1687 mm × h 3100 mm
    experimental volume: ⌀ 900 mm × h 1370 mm
- Large cold lead shielding close to 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…)
- 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





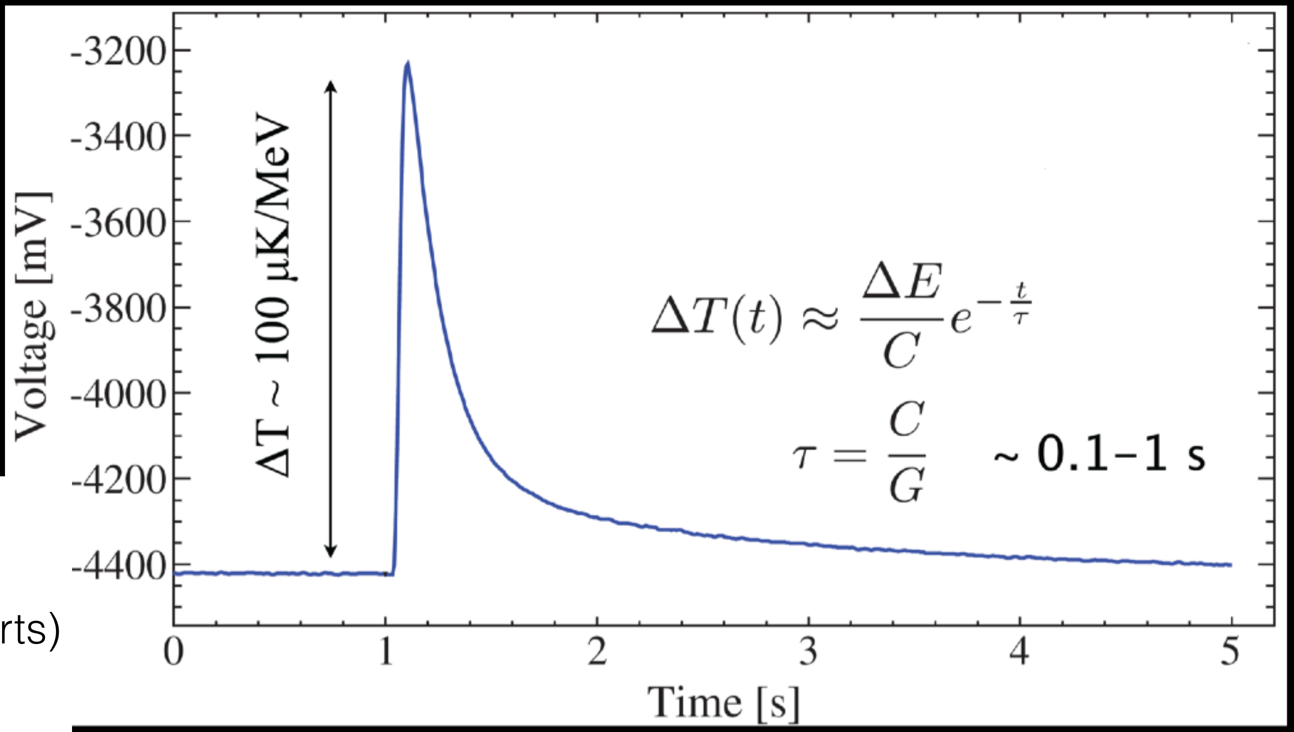
Three story building

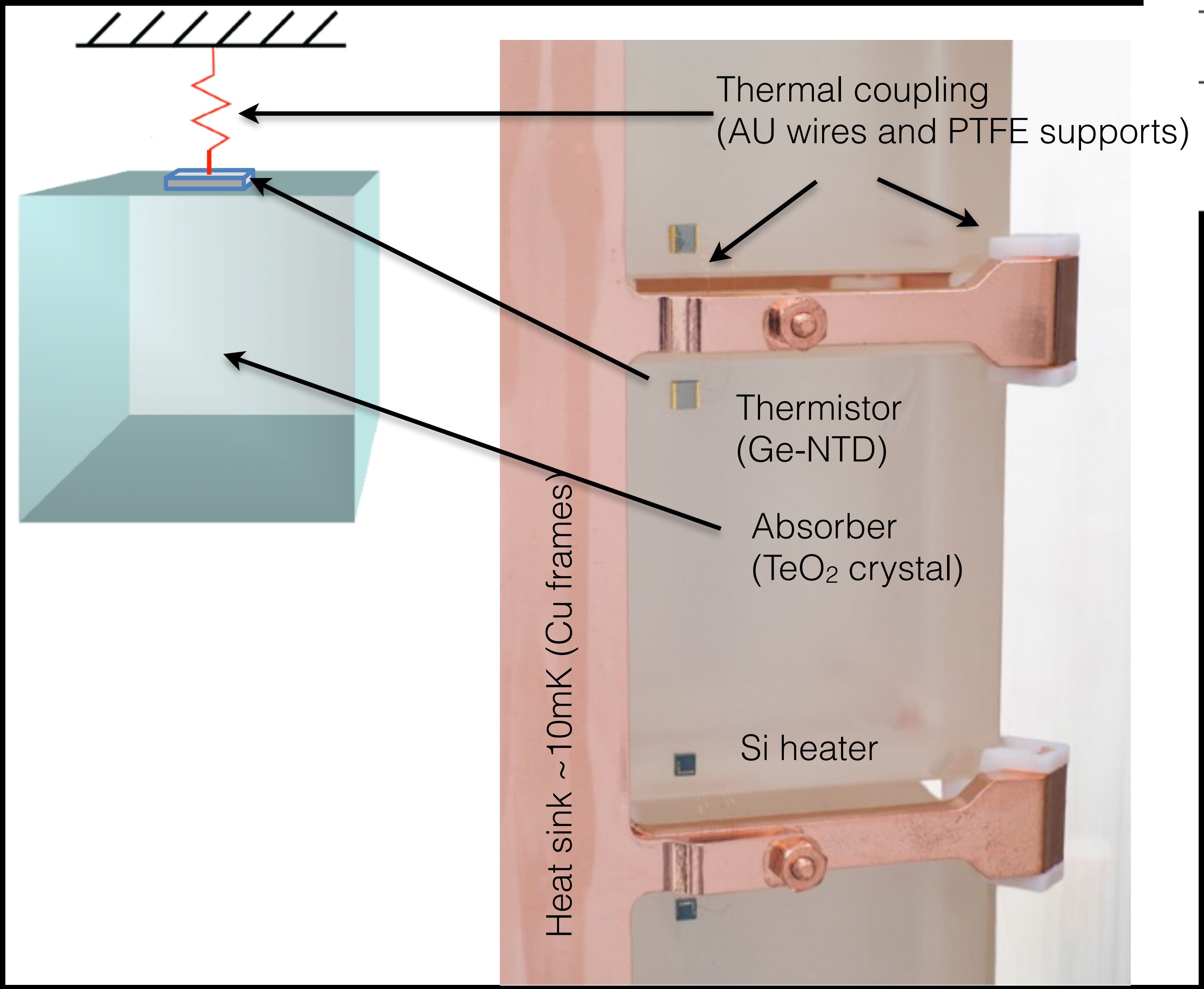
- Ground floor: pumps, compressors & shielding
- First floor: clean room (Gluing, Assembly & Cryostat)
- Second floor: service area, front-end & DAQ

The CUORE detectors

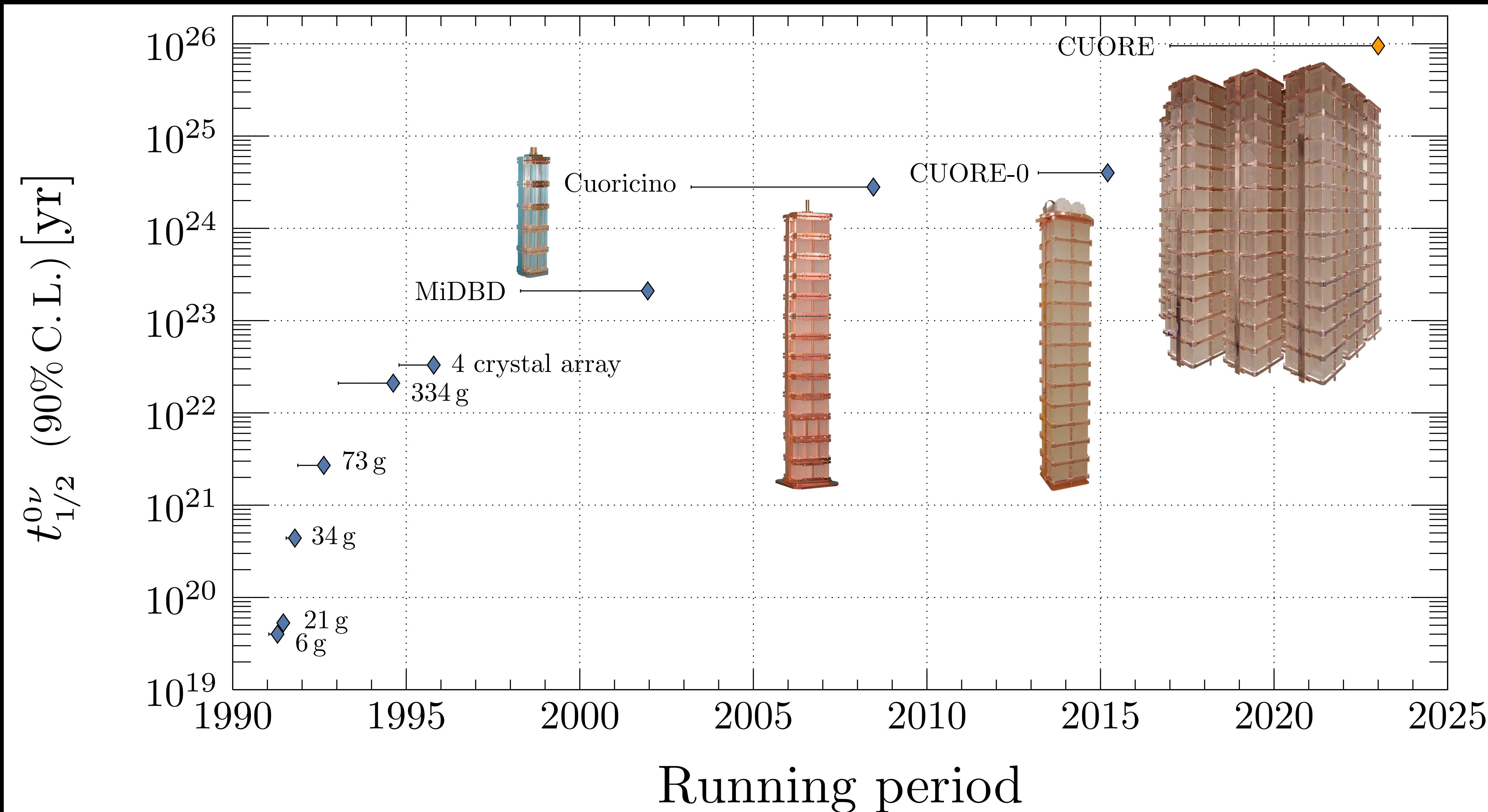
TeO_2 thermal detectors

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



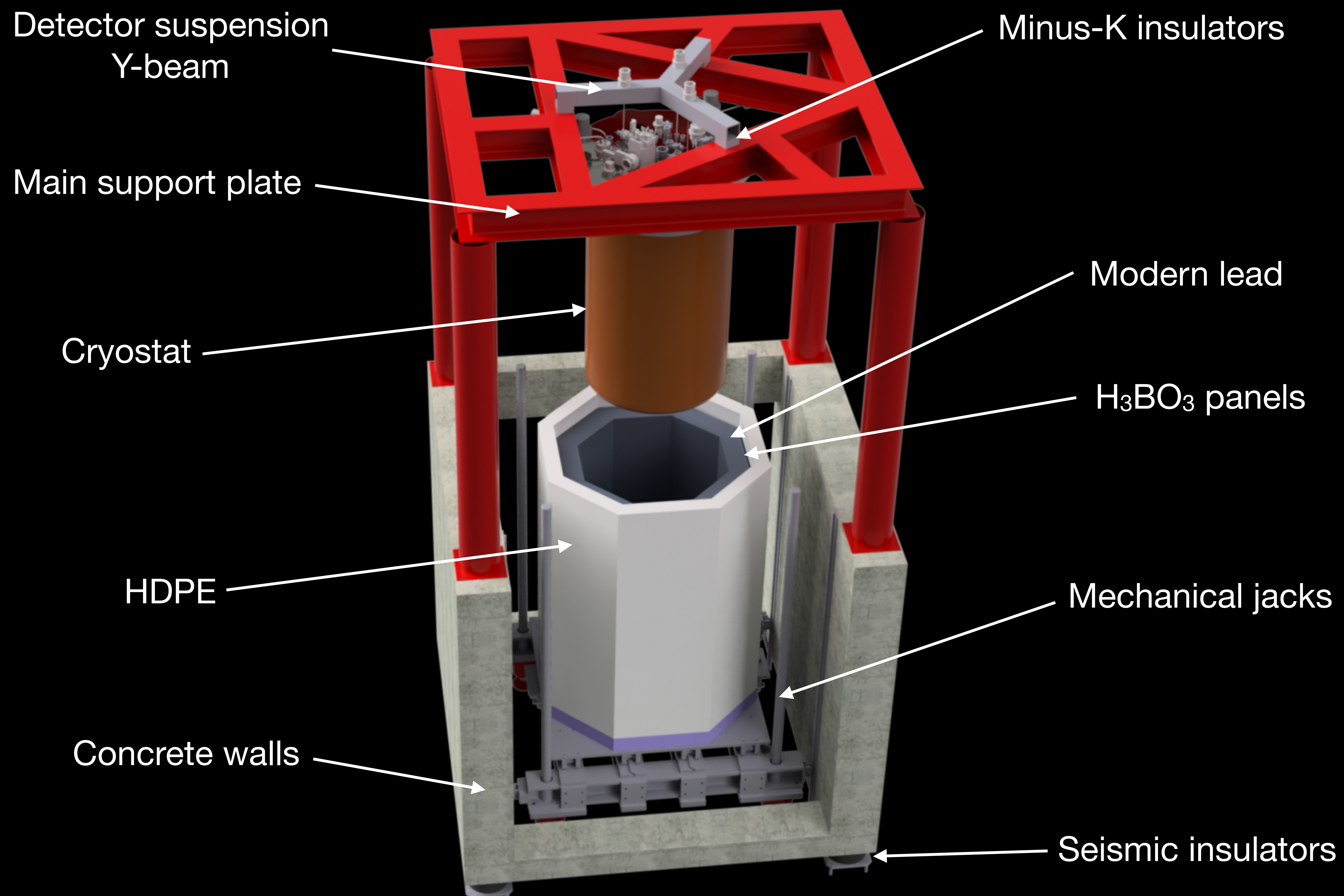


TeO_2 evolution



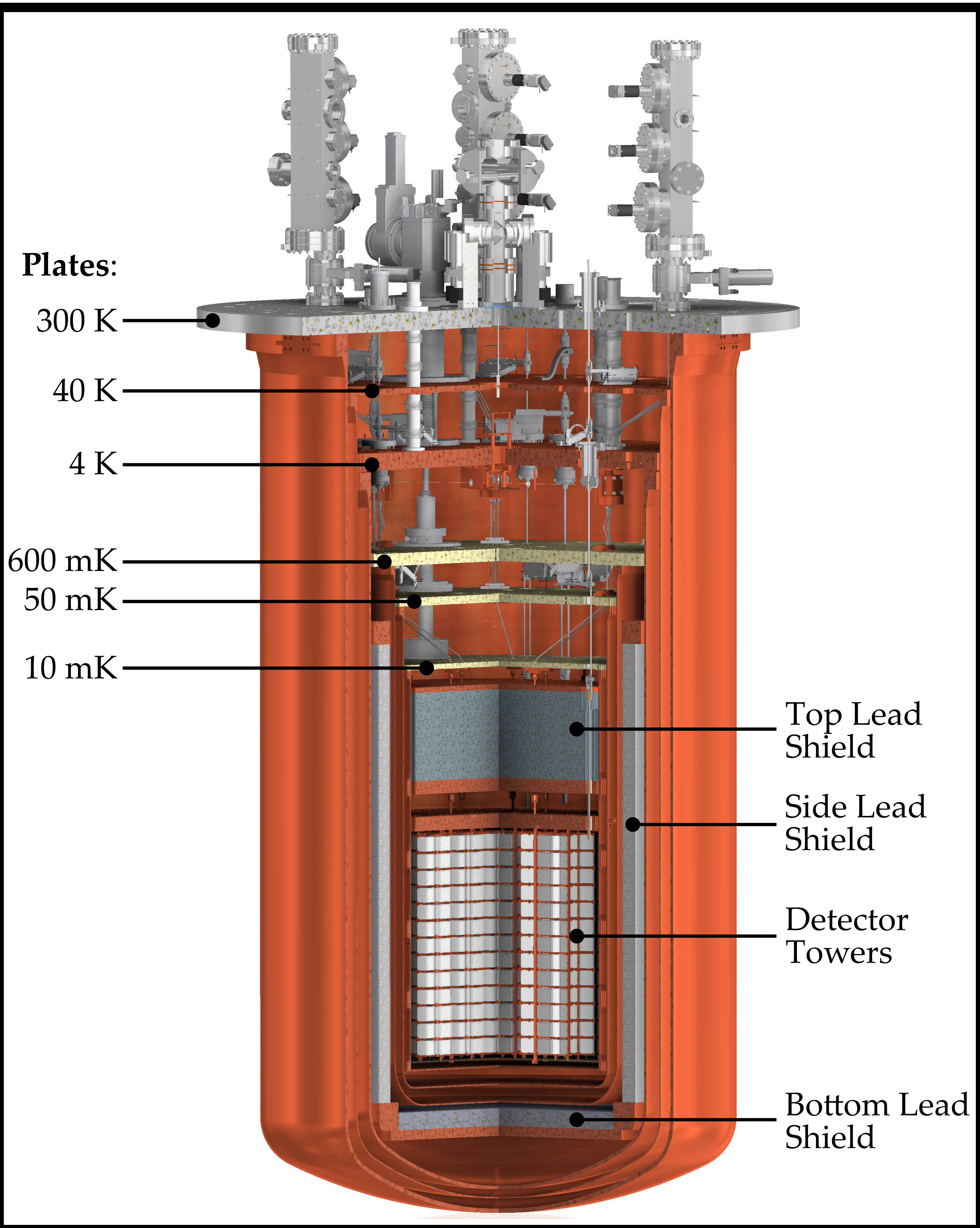
CUORE is the latest evolution of a long series of TeO_2 thermal detectors

Cryostat support structure



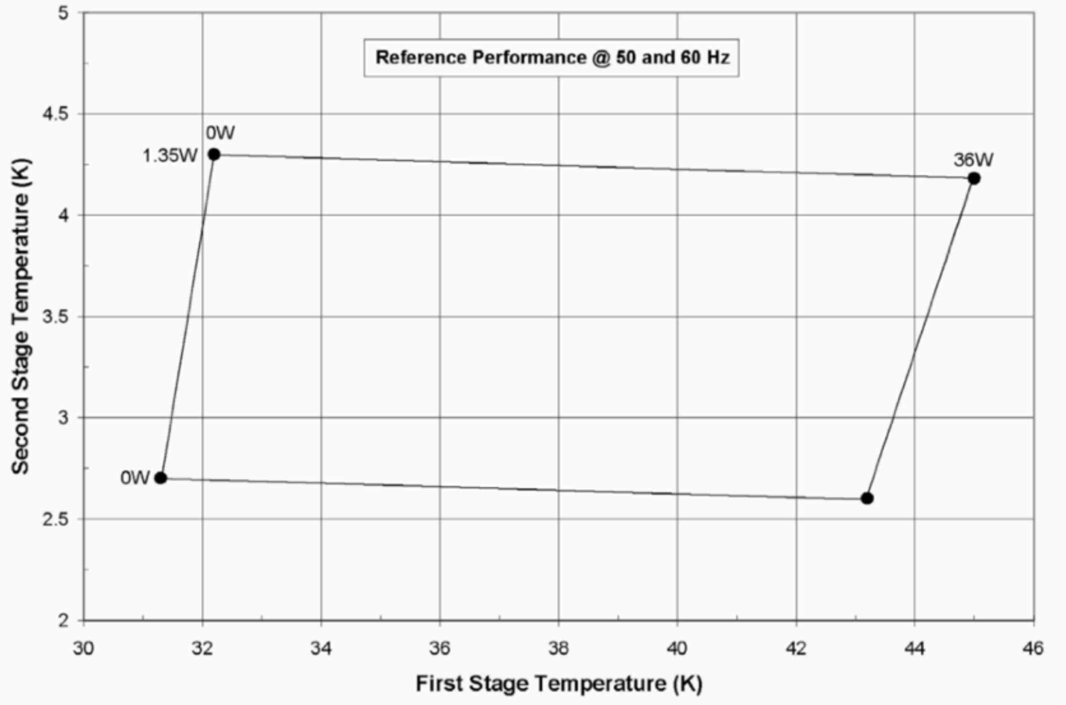
Cryogenic system

- 6 nested vessels
  - 300K (SS/Cu OFE)
  - 40 K @ PT 1st stage (Cu OFE)
  - 4 K @ PT 2nd stage (Cu OFE)
  - Still @ 800 mK (Cu OFE)
  - HEX @ 50 mK (Cu OFE)
  - MC @ 10 mK (Cu NOSV)
- 2 vacuum chambers
  - IVC (3.5 m^3)
  - OVC (2.5 m^3)
- 2 internal lead shields
  - Top Lead @ 50 mK (2.5 tonnes)
  - Lateral+bottom @ 4K (5.5 tonnes)
- 2+1 cooling systems
  - Pulse Tubes (PT)
  - Dilution Unit (DU)
  - Fast Cooling System
- All the copper parts @ 10 mK realized with Cu NOSV
  - selected for radiopurity, RRR, H_2 content
- Cu freshly made
- all welding performed with electron beam



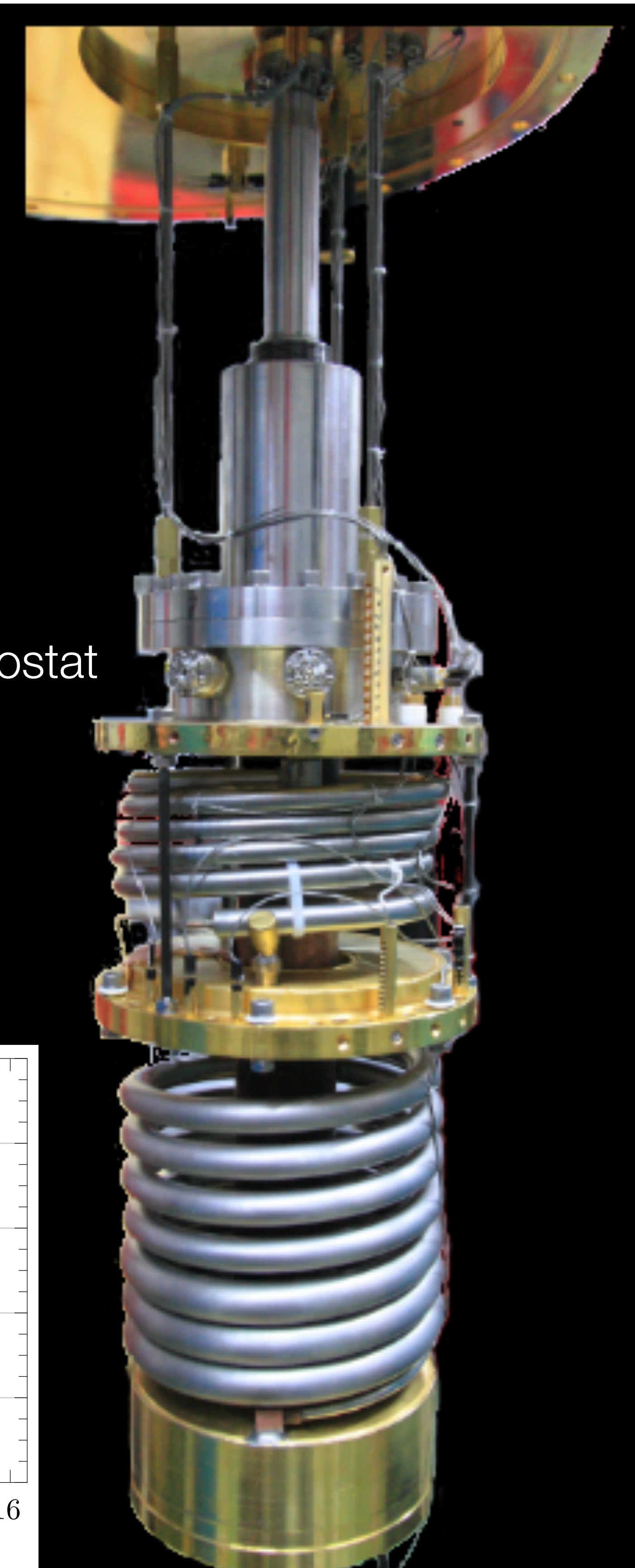
Pulse Tubes

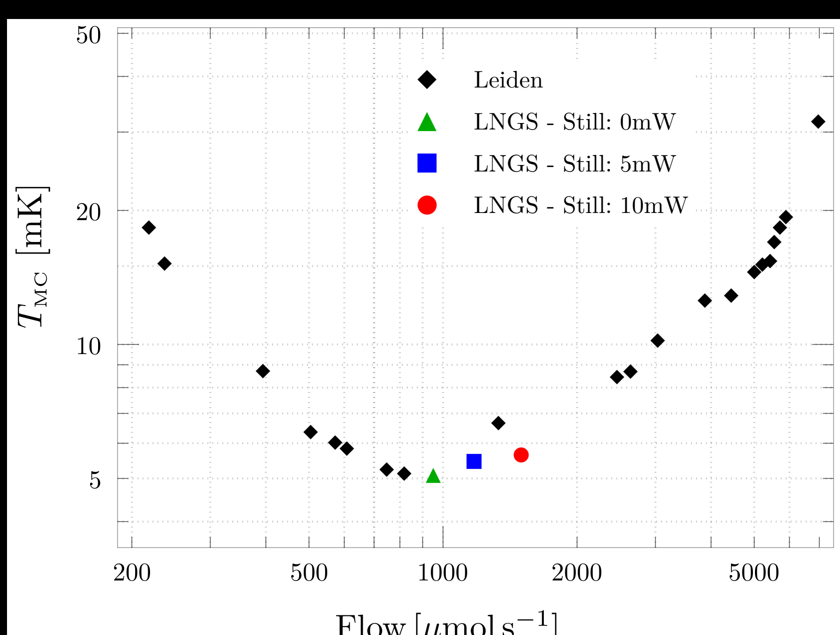
- 5 Cryomech PT415 with remote motor option
- 1.35 W @ 4.2K and 36 W @ 45K
- 3 PTs strictly needed for the operation + 2 PTs for redundancy
- 2 PTs have a condensing line of the DU soldered between the 1st and 2nd stage
- Custom thermalizations to the plates realized with high RRR copper
- Sliding seal on the 300 K plate to compensate for thermal expansion

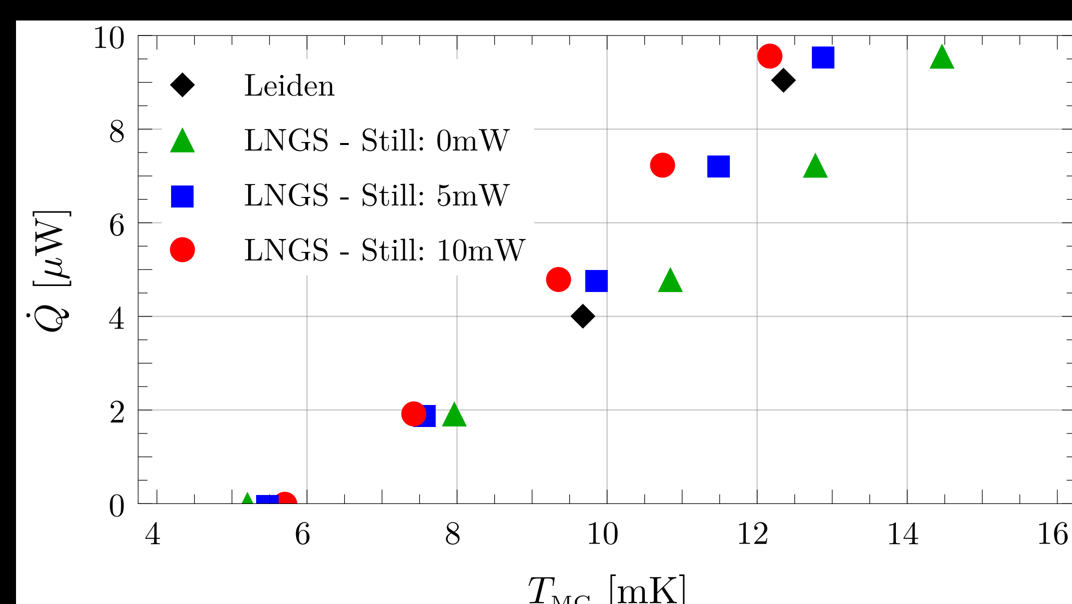


Dilution Unit

- Custom Dilution Unit built by Leiden Cryogenics
- Specs:
  - cooling power: 5 μW @ 12 mK; >1.5 mW @ 120 mK
  - base temperature: < 6 mK
  - condensation flow: > 10 mmoles/s
  - removable from the CUORE cryostat in order to be tested in a separate test cryostat
- Actual performances in the test cryostat were better than specs
  - cryogen-free DU with the largest cooling power ever built!

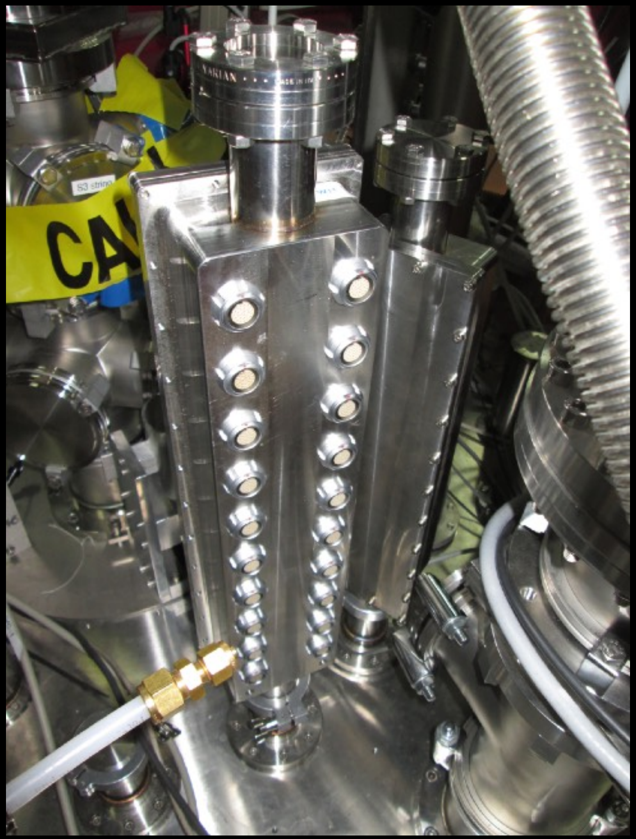


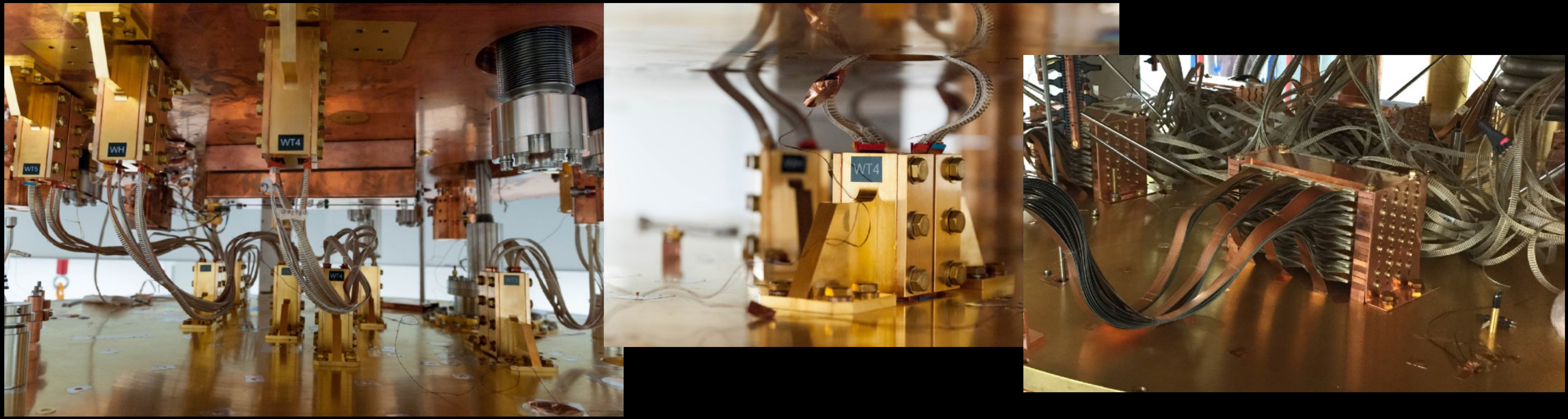




Wiring

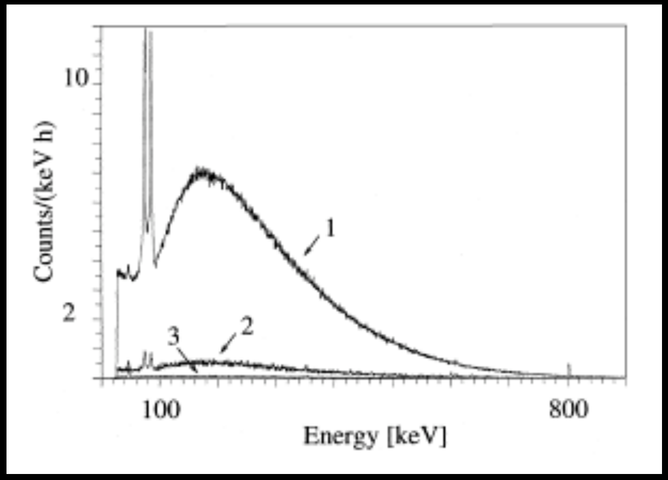
- 2600 wires from 300 K to Mixing Chamber
  - 100 woven ribbon cables (~ 2.5 meters long) with 13 twisted pairs of NbTi wires (100 μm diameter), CuNi coating (5 μm thickness) and a NOMEX texture
  - thermalized at every stage of the cryostat
- From Mixing Chamber to the detector
  - 152 Cu-PEN tapes (2.3 meters long, 80 μm thick), with a pattern of etched copper tracks.





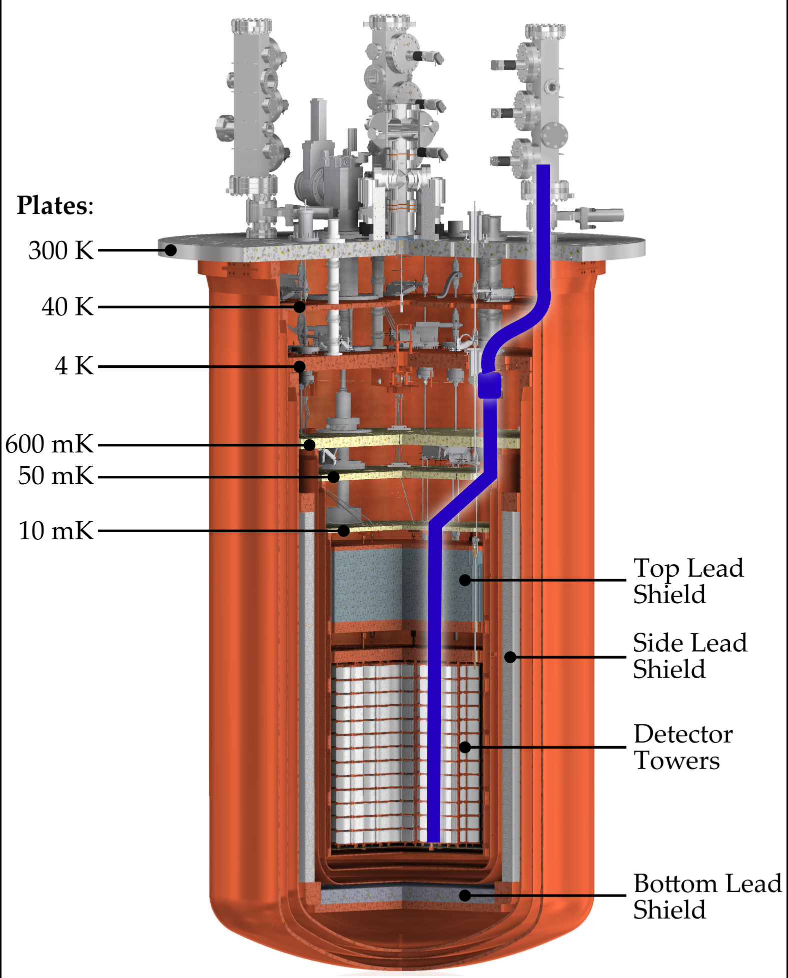
Roman lead shielding

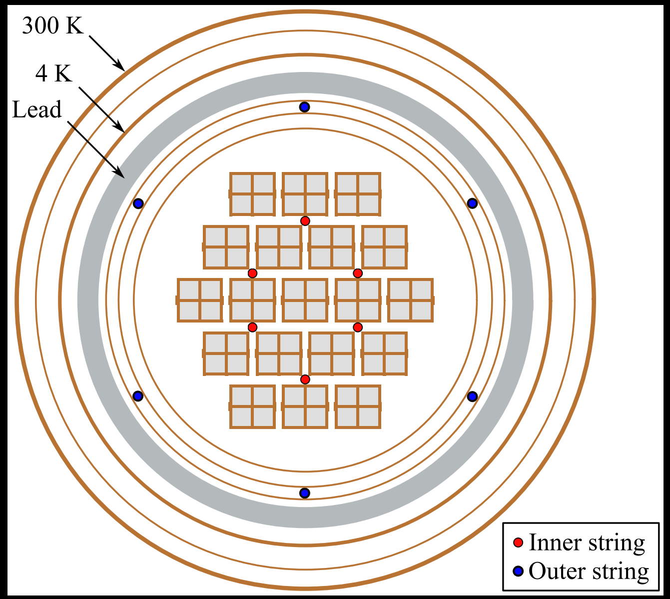
- Lead is an excellent material for shielding but normally it contains ^{210}Pb with 10-1000 Bq/kg (half life ~ 22 y)
- Ingots from a shipwreck found close to Sardinia coast (I sec b.C.)
- Romans extracted the Ag from the Pb (and ^{238}U with it)
  - ^{210}Pb in roman Pb < 4 mBq/kg
- Ancient Roman Pb is extremely precious!
  - agreement with the cultural heritage authorities 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
- Shield 6 cm thick (4.5 tonnes of Pb + 1 tonne of Cu)
  - realized in ring sectors with dovetail design to minimize holes
  - rings interleaved with copper foils to improve thermalization
  - mechanically attached to the still plate but thermalized @ 4K



Detector Calibration System

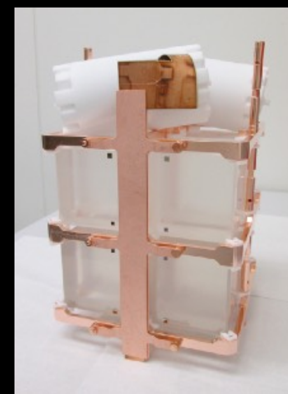
- The heavy internal shielding requires in situ energy calibration
- ^{232}Th γ-ray sources (thoriated tungsten) are outside cryostat during physics data-taking and lowered into cryostat and cooled to base temperature for calibration
- Sources are put on 12 Kevlar strings and are lowered under their own weight; a series of tubes in the cryostat guides the strings
- 6 outer strings are ~20 Bq, 6 inner are ~4 Bq
- Heat from sources is removed with:
  - A pair of copper blocks that mechanically squeezes on the sources at 4 K
  - Contact between the sources and their guide tubes, which are thermalized to different cryostat stages
- Temperature stabilization of the Mixing Chamber is able to compensate the power dissipation during the deployment





NIM A 844, 32-44 (2017). arxiv:1608.01607

Commissioning plan



Insertion of few TeO_2 detectors

Cryostat
+
Dilution Unit

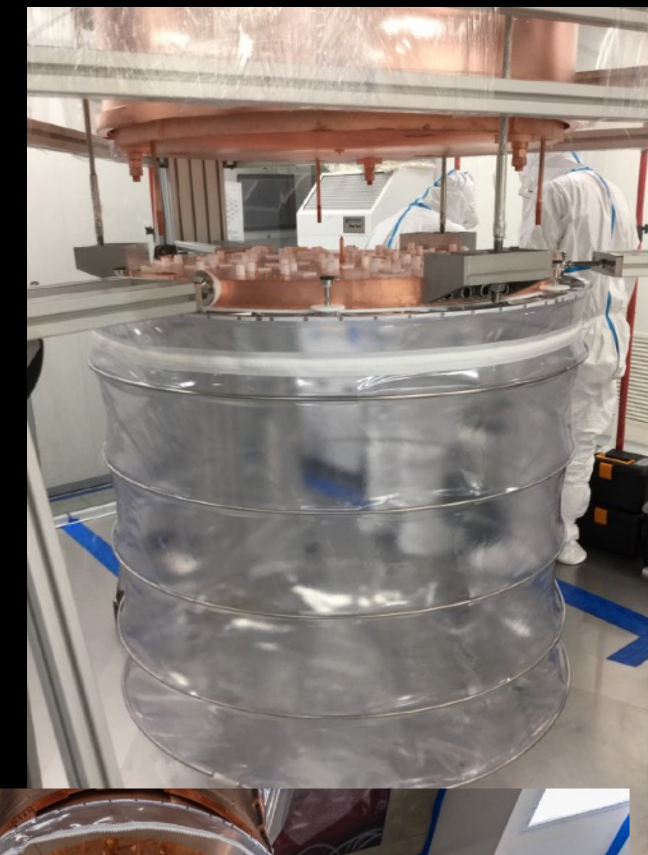
→ Wiring

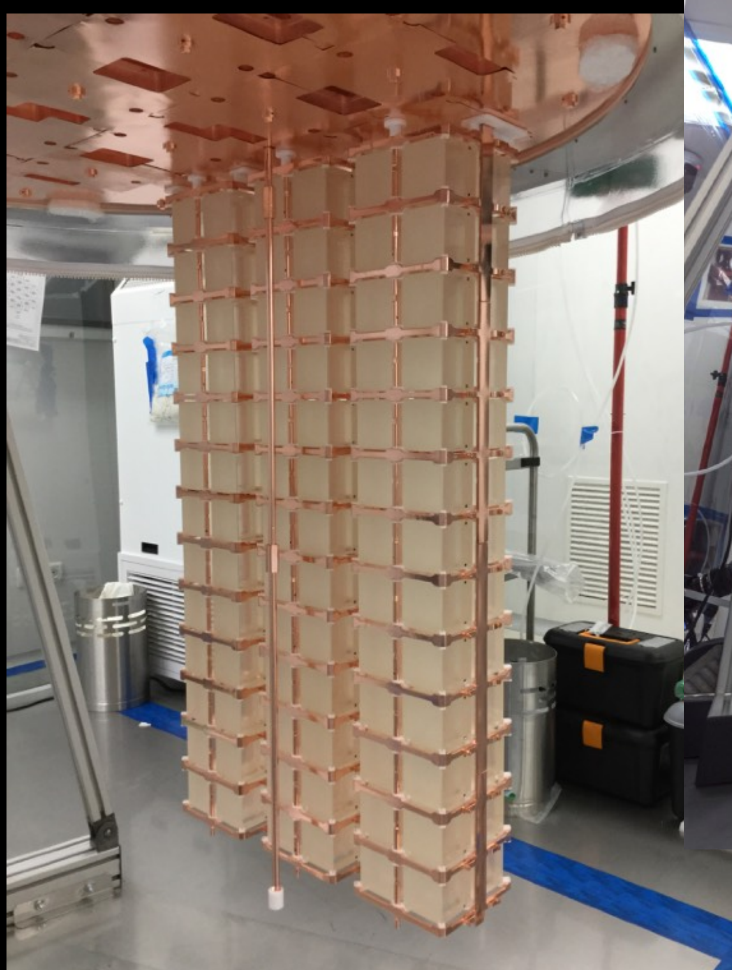
→ Top Pb shield
Detector Calibration System
Towers support plate
Fast Cooling System

→ side roman Pb shield

Detector Installation

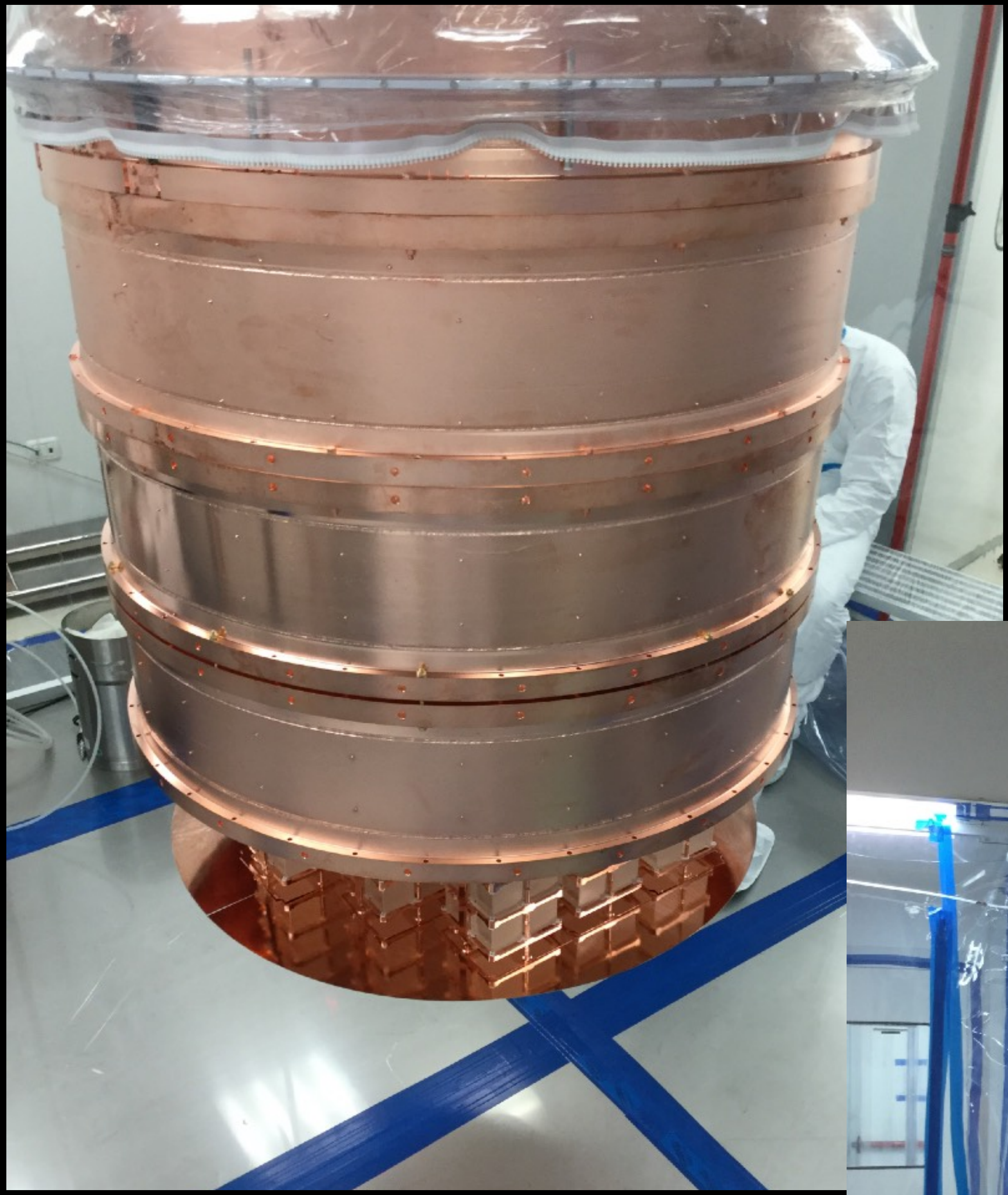
- The detector installation was the first period in which the detector was exposed to (Rn-free) air
- Custom-made clean room flushed with Rn-free air (Rn concentration <0.1 Bq/m^3)
  - Radon Abatement System
- Detector "protective bag" flushed with nitrogen during installation interruptions
- Strict installation protocol





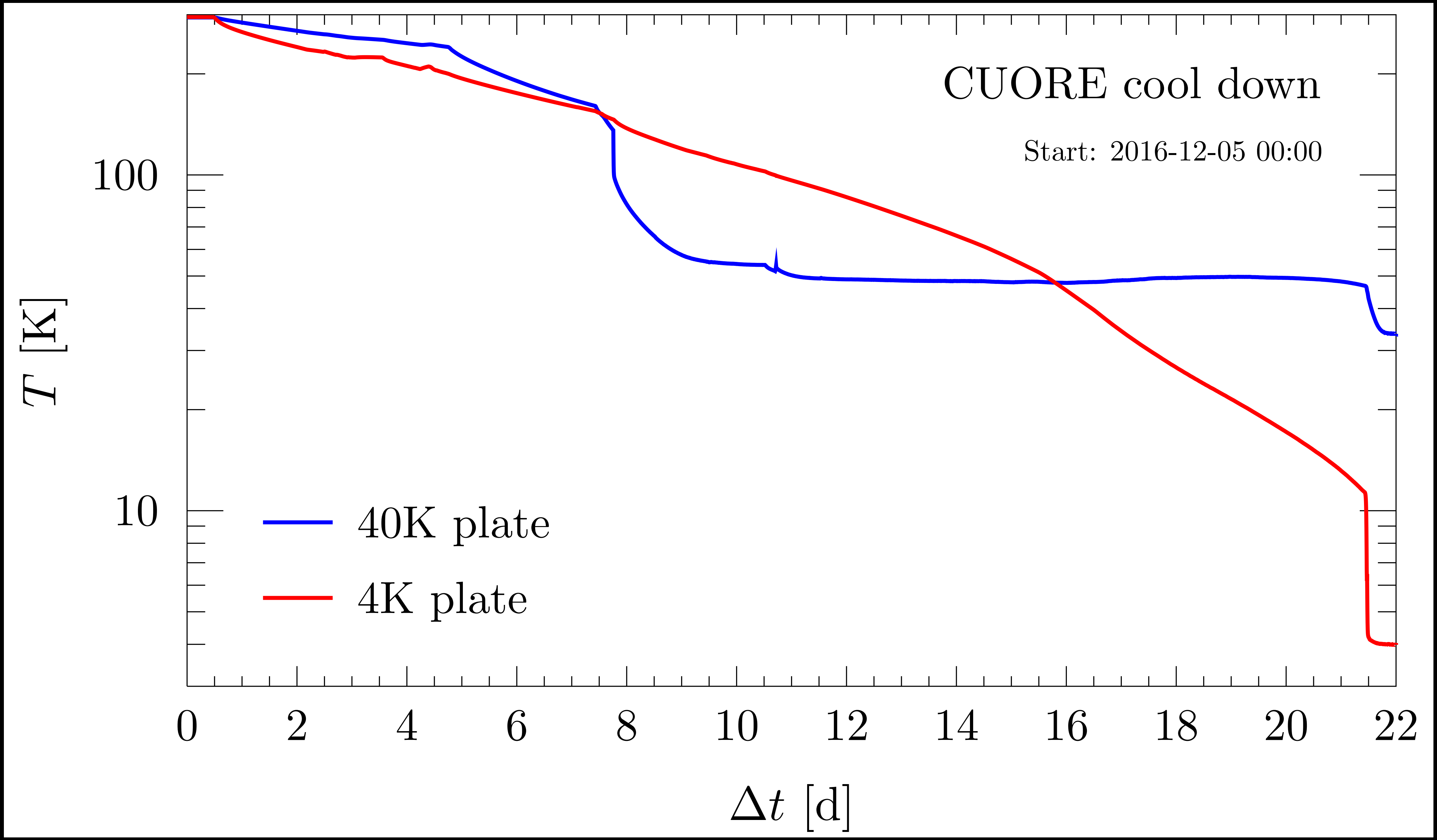
- Detector installation completed on August 26, 2016

Cryostat closure



Cryostat closure

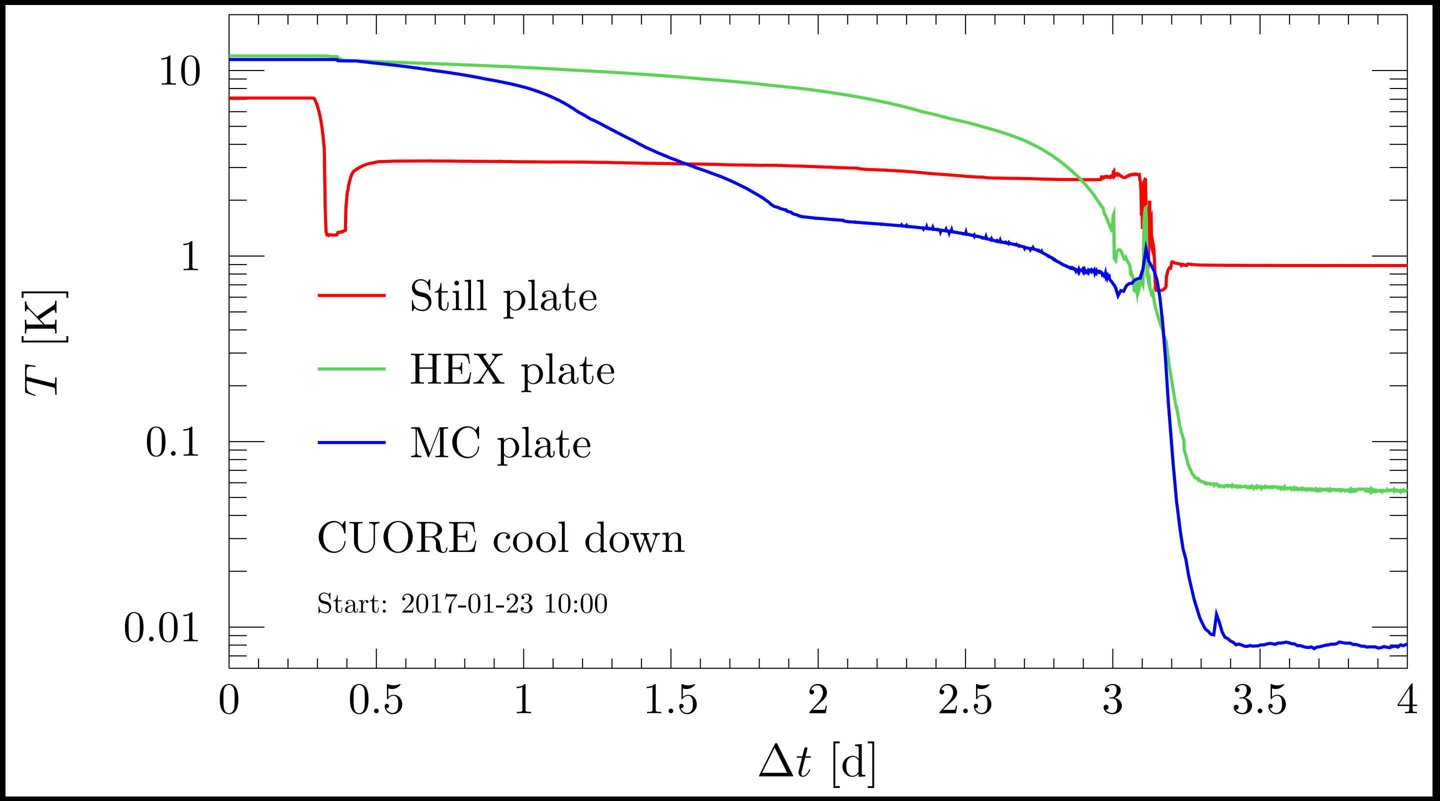
CUORE cooldown

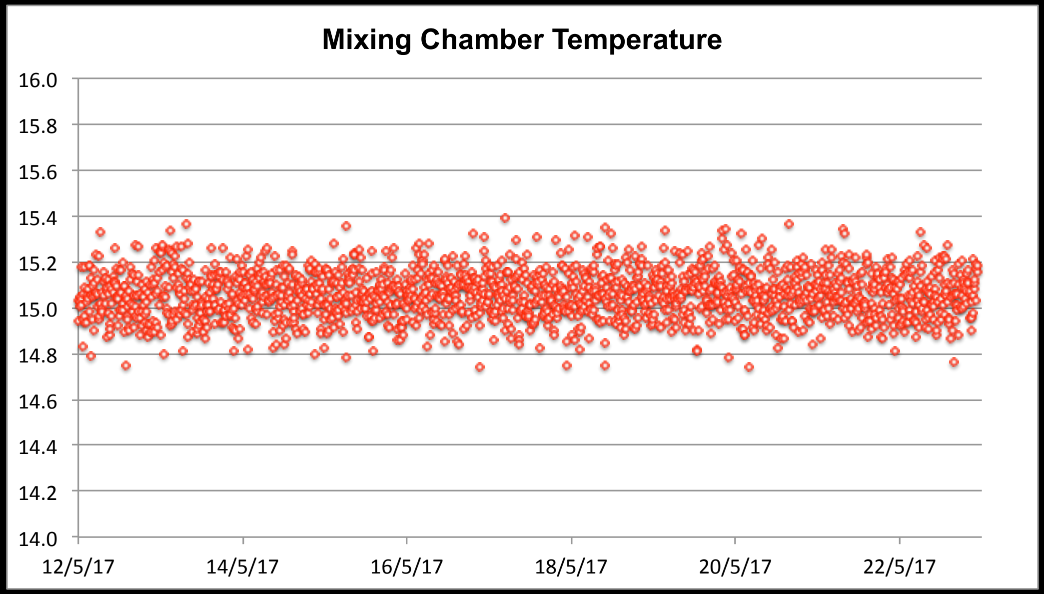


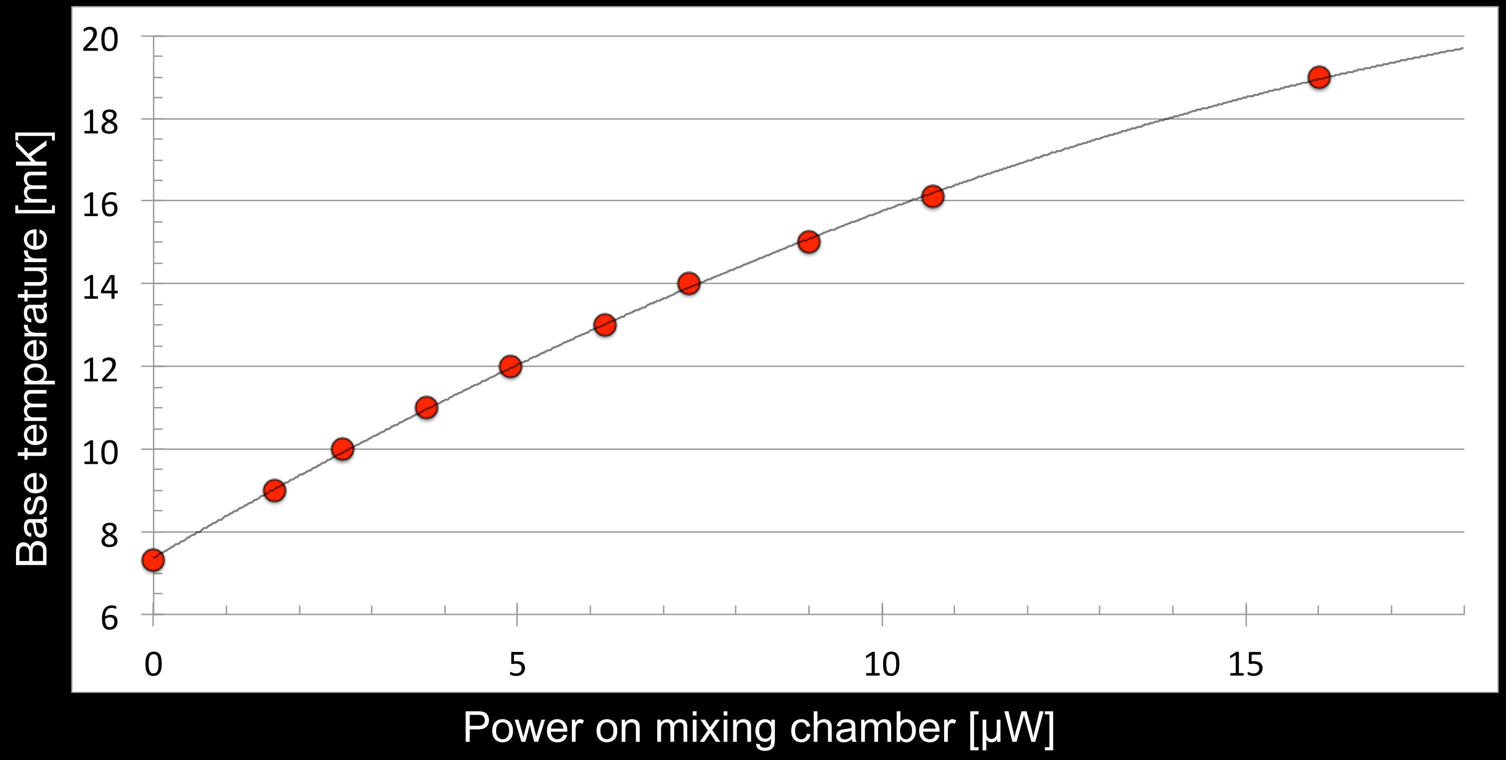
- Cooldown to 4K: ~ 22 days
- 1st stage T: ~ 35 K
- 2nd stage T: ~ 3.4 K
- Enthalpy removed: almost 10^9 J

CUORE cooldown

- Cooldown to base T: ~ 3 days
- Lowest temperature reached: 6.7 mK







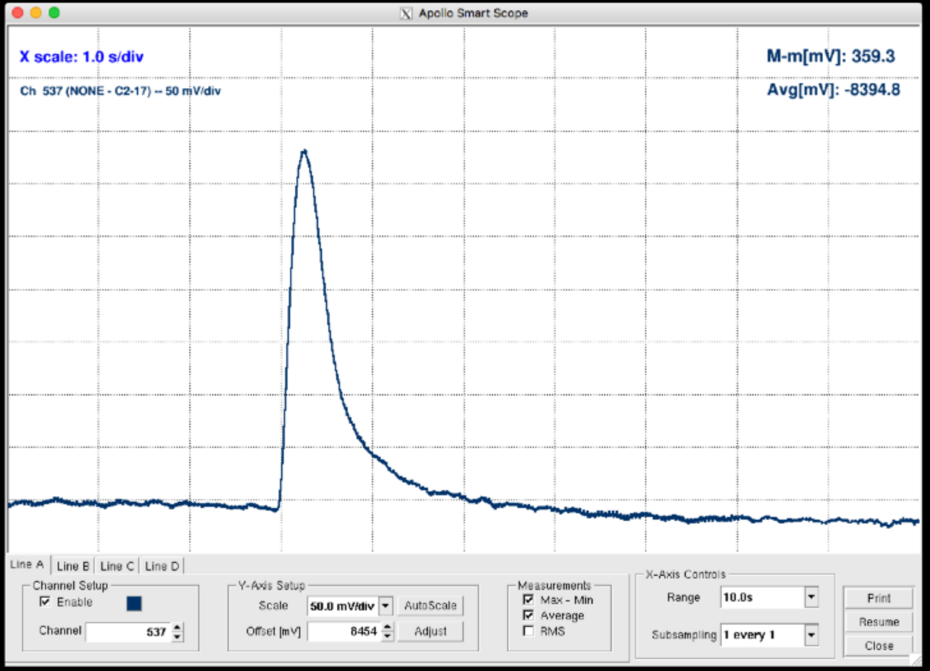
- 984/988 working detectors

Pre-operation

After the successful cool-down we faced with the challenge of operating a thousand bolometers in a completely new system

A long list of activities

- DAQ and front-end electronics optimization
- Detector working points
  - Select representative subset
  - Load curves
  - Temperature scan for the best operating conditions
- Noise reduction
  - vibration induced
  - electrically induced

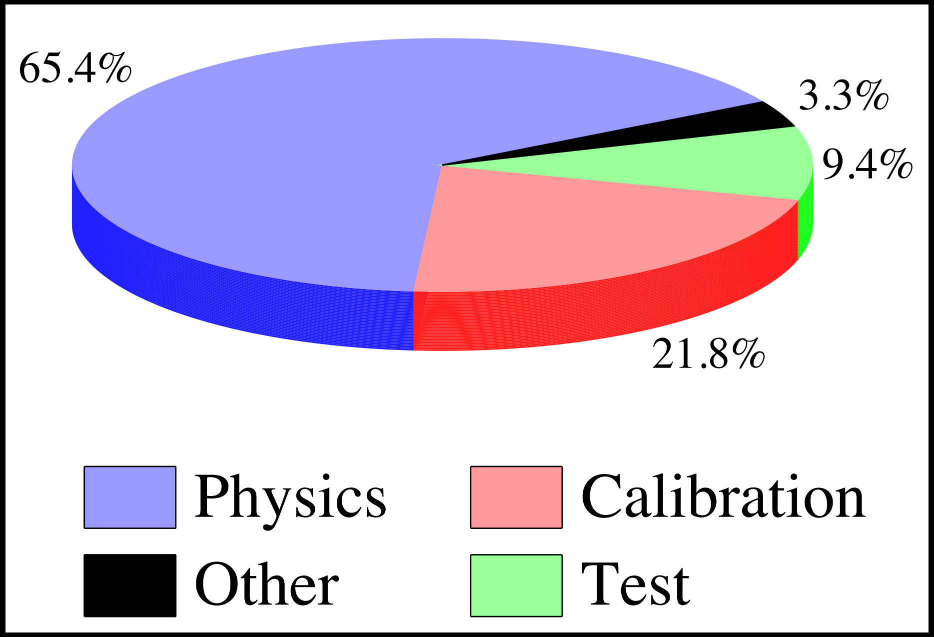


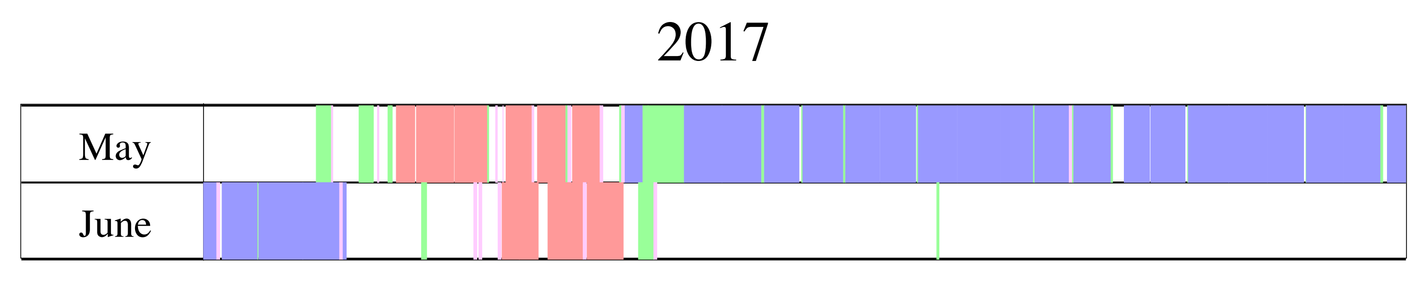
End of March 2017:

- optimization not yet complete
- decision to start calibrations and science runs
- selected working temperature: 15 mK

Science runs

- Physics data taking started on April 14, 2017
  - **Dataset 1:**
    - very short
    - identified issue with the thermistor bias on about 1/3 of the channels
    - re-optimization of the detector working point
  - **Dataset 2:**
    - 3 weeks of physics data bracketed by 2 calibration periods (May 4 - June 11)
  - Second optimization campaign going on now
  - **Dataset 3:** August - September 2017





Operational performance:

- 984/988 operational channels
- Improved detector stability, compared to Cuoricino/CUORE-0
- Calibrations/physics ratio data still to be optimized to maximize 0vDBD sensitivity

Data presented today are from Dataset 2:

Acquired statistics for 0vDBD decay search:

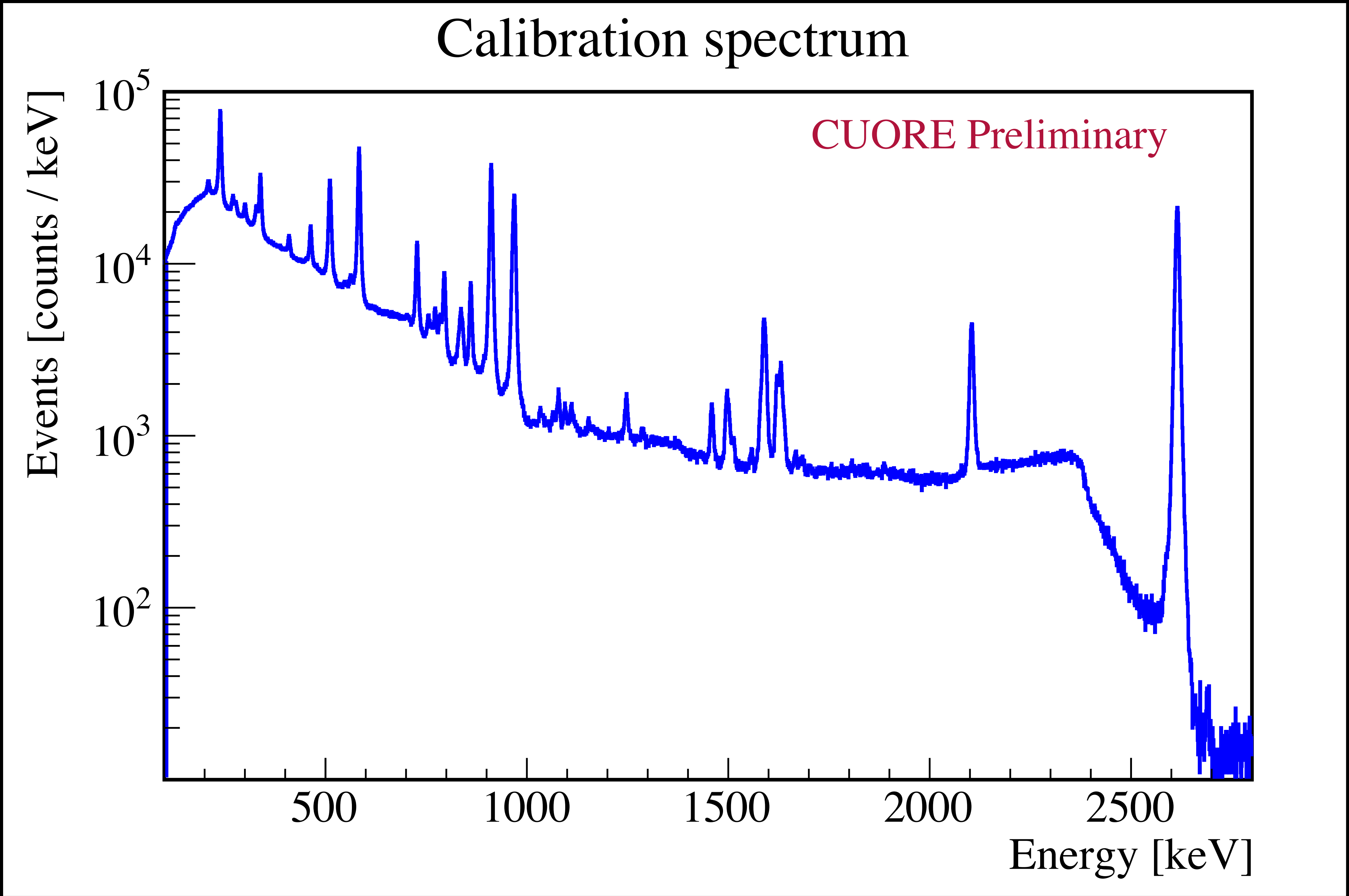
- $^{nat}TeO_2$ exposure: 38.1 kg yr
- ^{130}Te exposure: 10.6 kg yr

Data analysis steps

- Acquisition of triggered signals
- Data preprocessing: estimation of raw parameters
- Pulse filtering
- Thermal Gain Stabilization
- Energy calibration
- Particle event selection
- Coincidences
- Energy spectrum

Essentially the same steps and procedures developed and used for CUORE-0 (Phys. Rev. C 93, 045503 (2016) - arXiv:1601.01334)

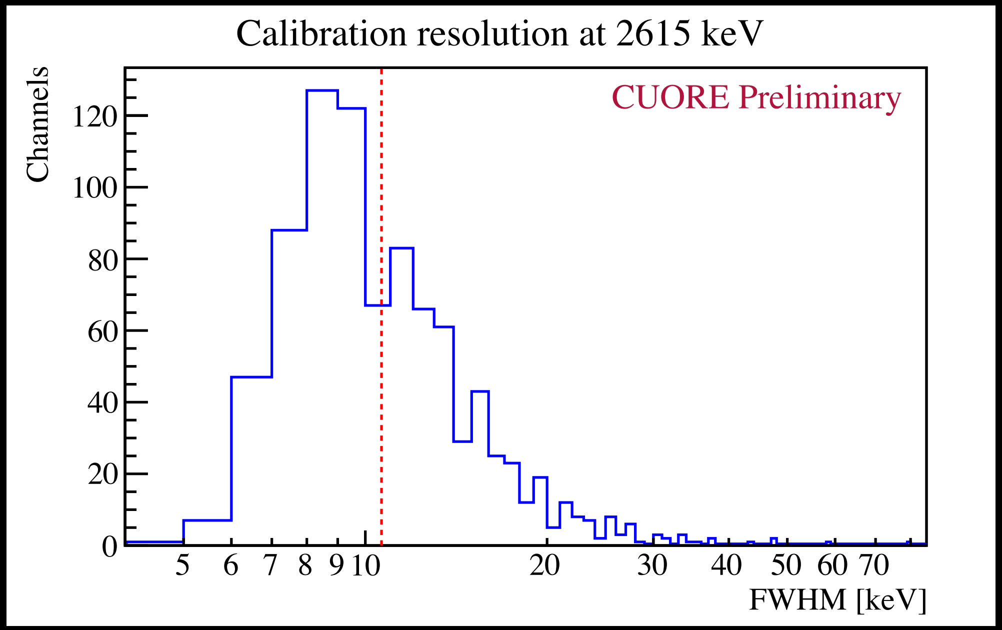
Calibration spectrum



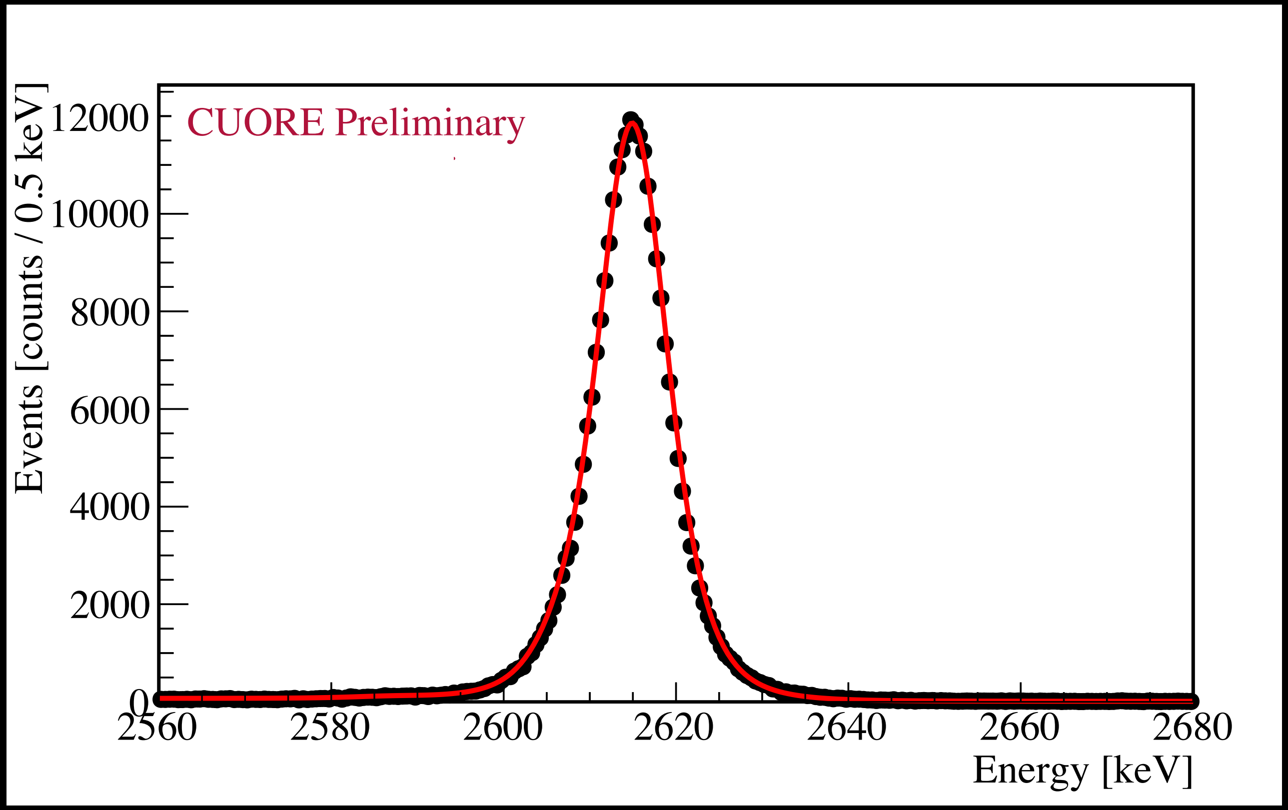
- ^{232}Th sum energy spectrum of all the CUORE detectors

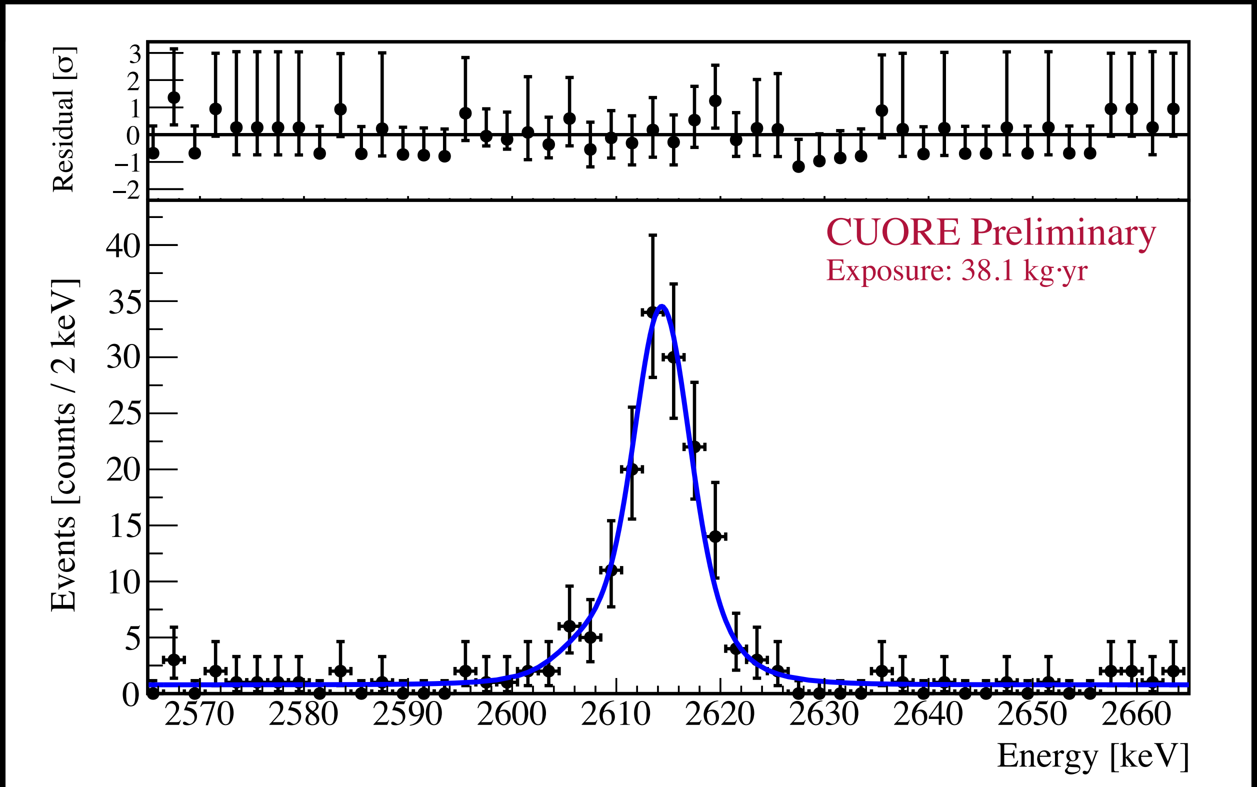
Energy resolution

- 899 channels selected for analysis: 90% best performing channels for initial analysis
  - most discarded channels had poor line or pulse shapes, and should be recovered in future runs
- Average (harmonic mean) energy resolution in calibration runs: **10.6 keV FWHM**



- Significantly better performance in physics data: (7.9 ± 0.6) keV FWHM





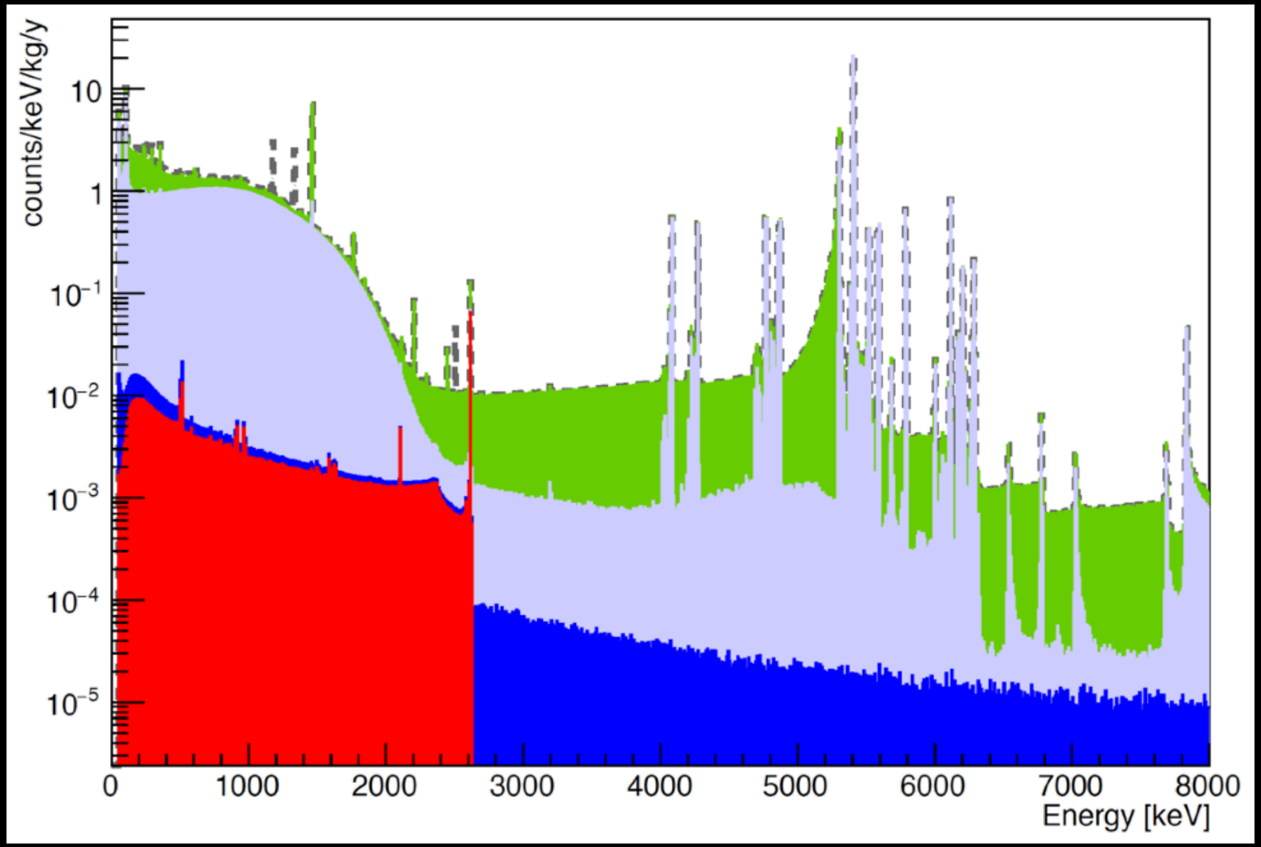
Background budget

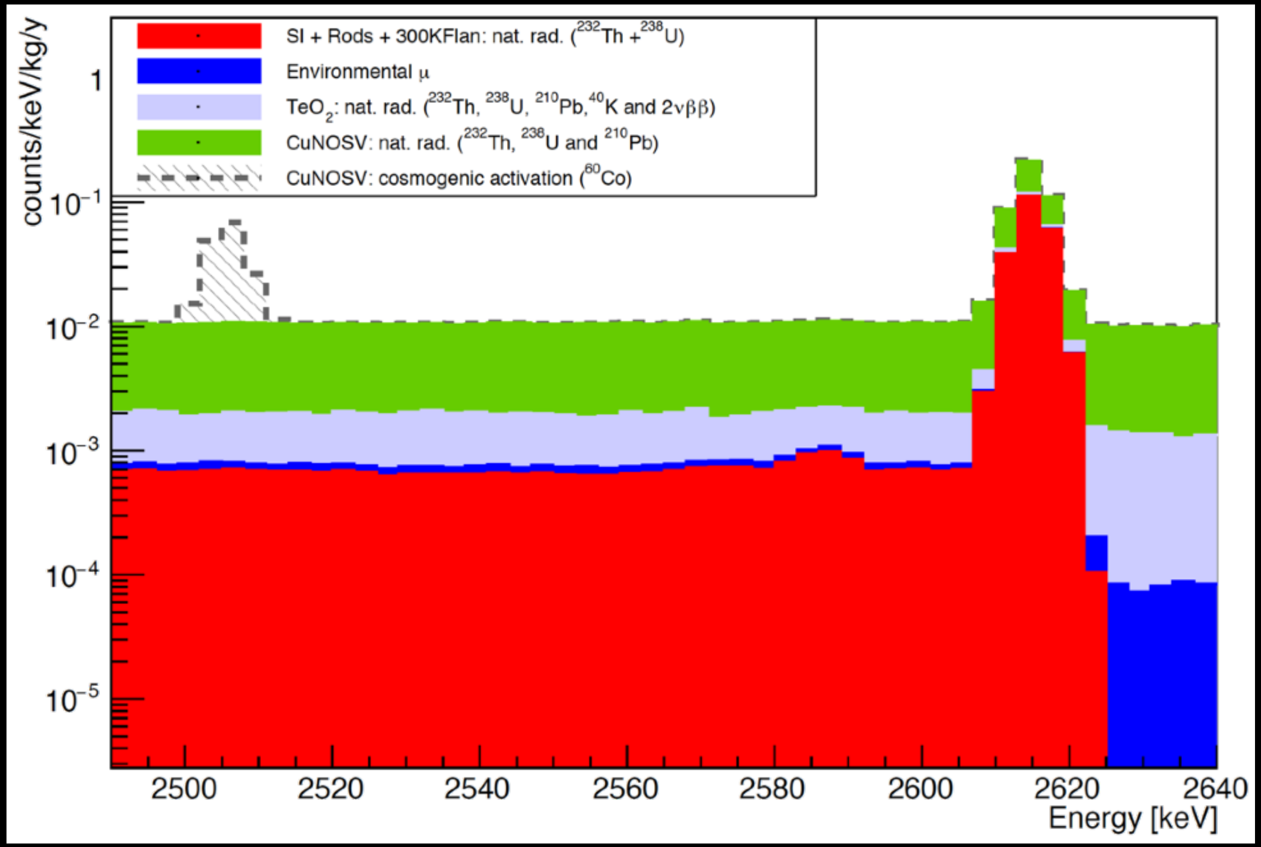
Based on:

- radioactive assay of the CUORE construction materials
- CUORE-0 background model

Propagated through a model of the CUORE setup by means of Monte Carlo simulations (Geant4)

Provides an estimate of the expected counting rates and background spectra





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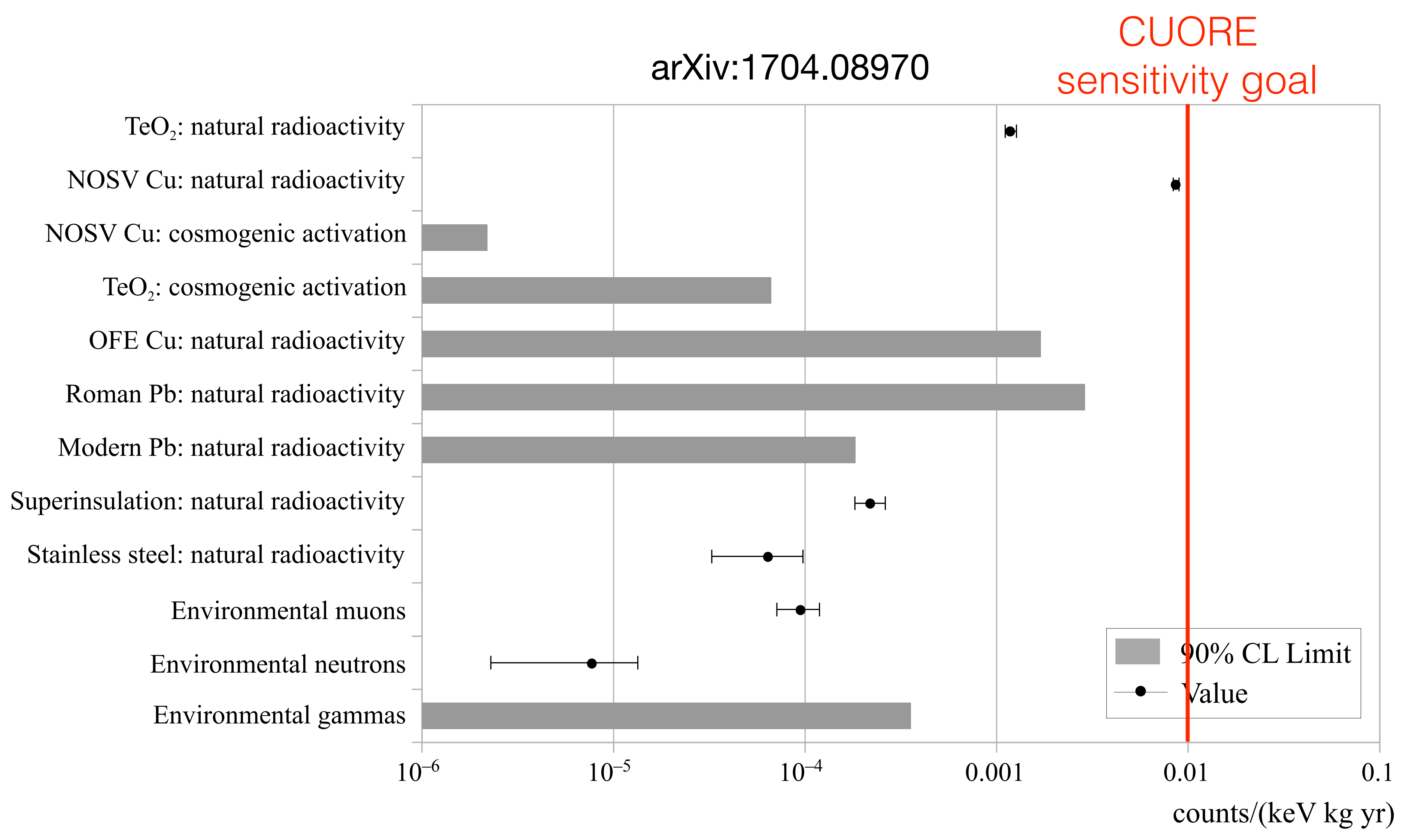
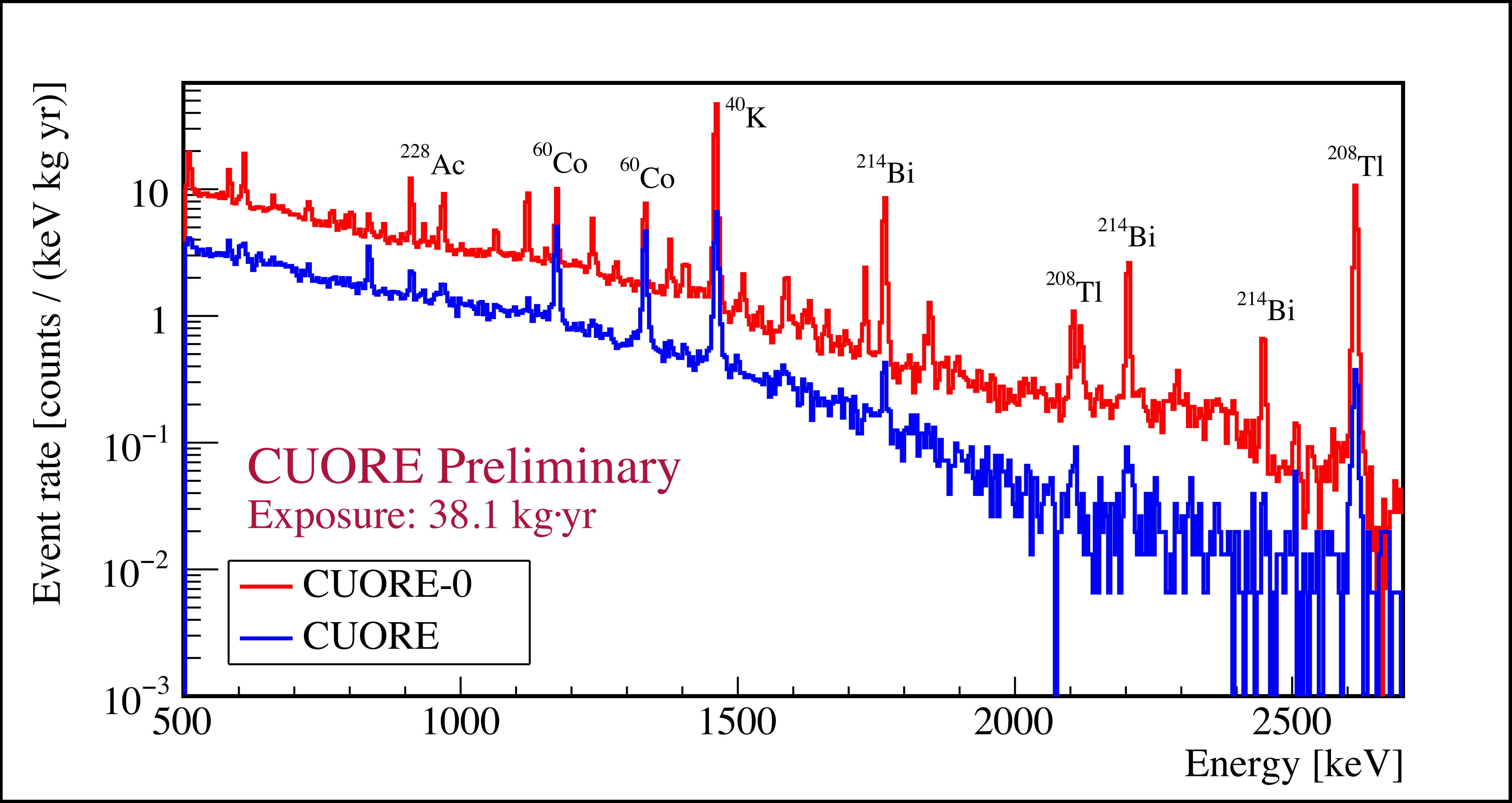
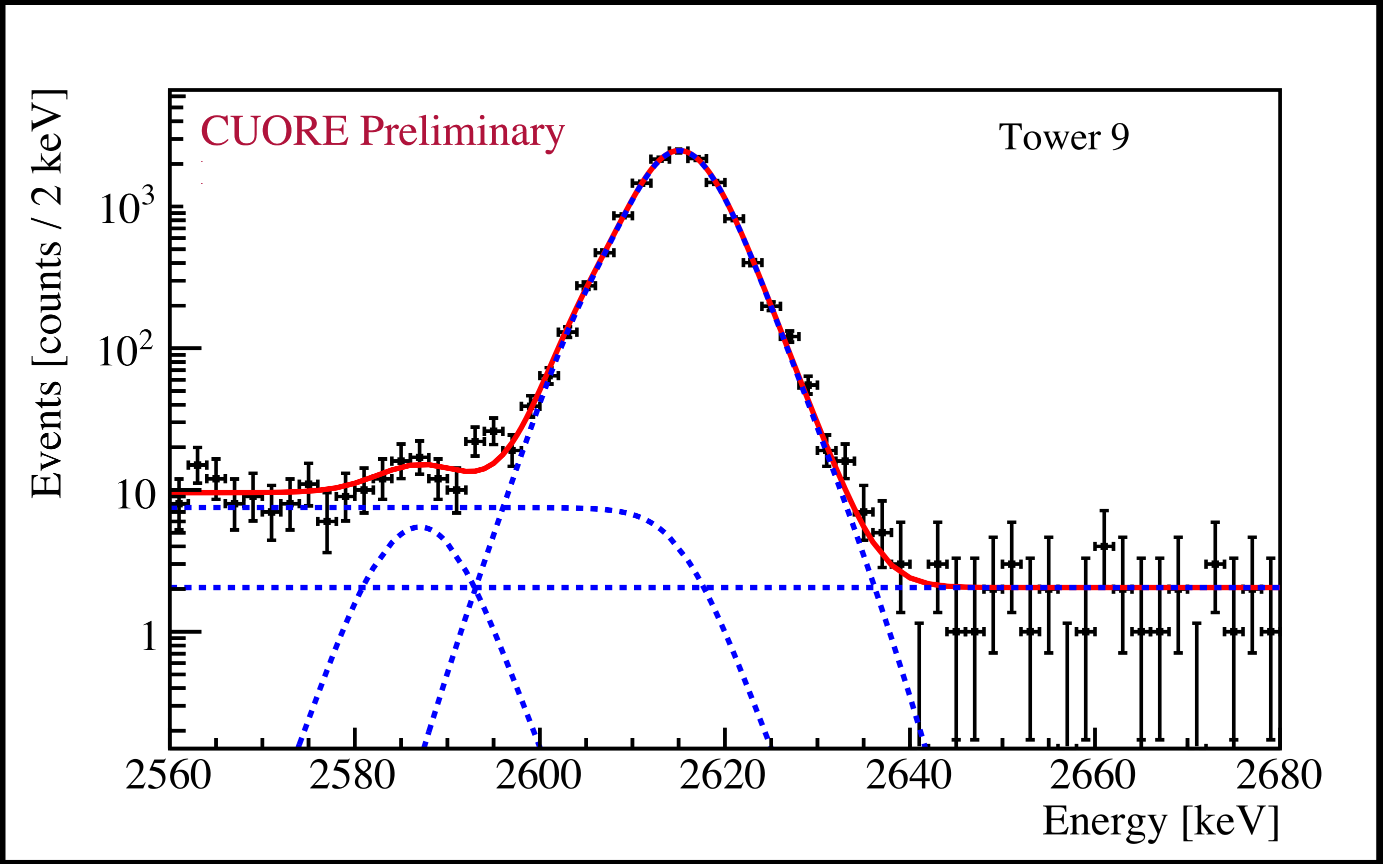


Background spectrum

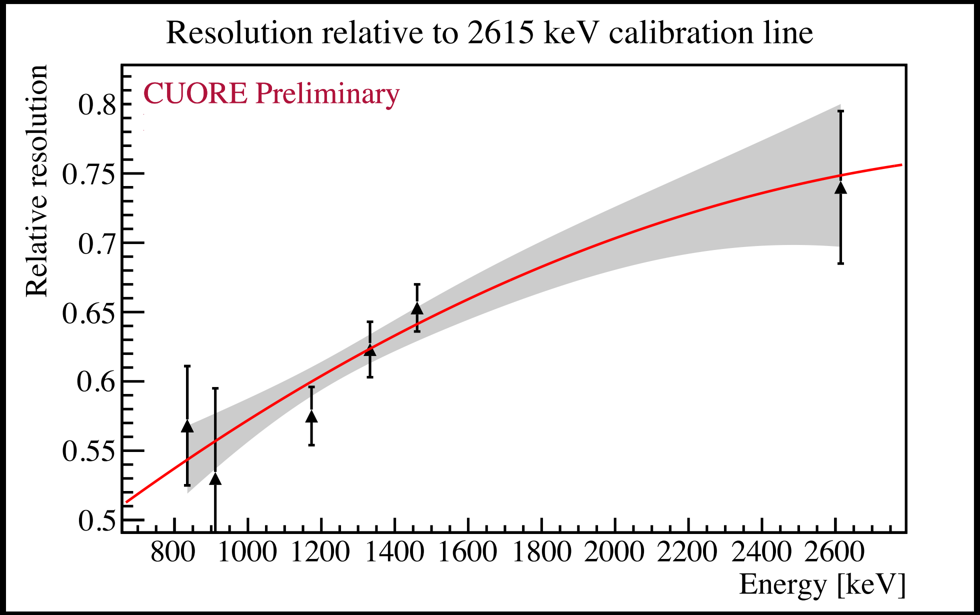


- Relevant reduction in the γ region with respect to CUORE-0
- Spectrum is consistent with the background budget

Line shape



- Fit components:
  - a flat background
  - a step-wise smeared background
  - a double gaussian for the main peak
  - a gaussian combination of escape lines
- Fit on a tower by tower basis



- A quadratic dependence of the energy resolution is determined from gamma lines in the physics spectrum

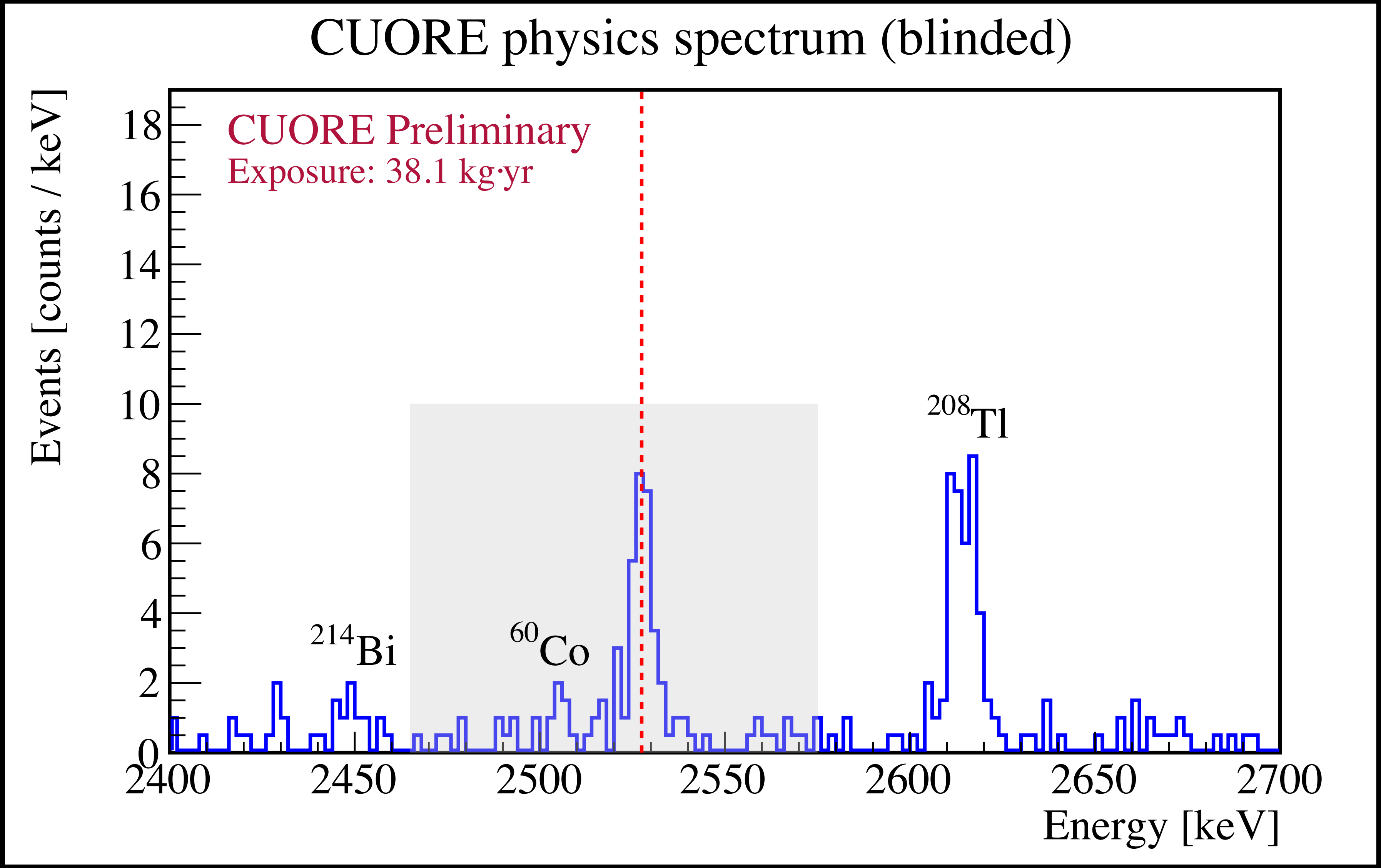
Event selection: efficiencies

- First we remove events from periods of low-quality data (~1% of total live time)
- Efficiencies
  - Trigger and energy reconstruction: (98.469 ± 0.009)%
  - Anti-coincidence: (99.3 ± 0.3)%
  - Pulse shape analysis: (64 ± 3)%
- All previous efficiencies: (62.6 ± 3.4)%
- $0\nu\beta\beta$ containment: (88.345 ± 0.085)%

The total efficiency is: (55.3 ± 3)%

Blinded spectrum

- To blind our data we randomly move a fraction of events from ± 20 keV of 2615 keV to the Q-value and vice versa
- The blinding algorithm produces an artificial peak around the 0vDBD Q-value and blinds the real 0vDBD rate



- This method of blinding the data preserves the integrity of the possible 0vDBD events while maintaining the spectral characteristics with measured energy resolution and introducing no discontinuities in the spectrum
- When all data analysis procedures are fixed the data are eventually unblinded

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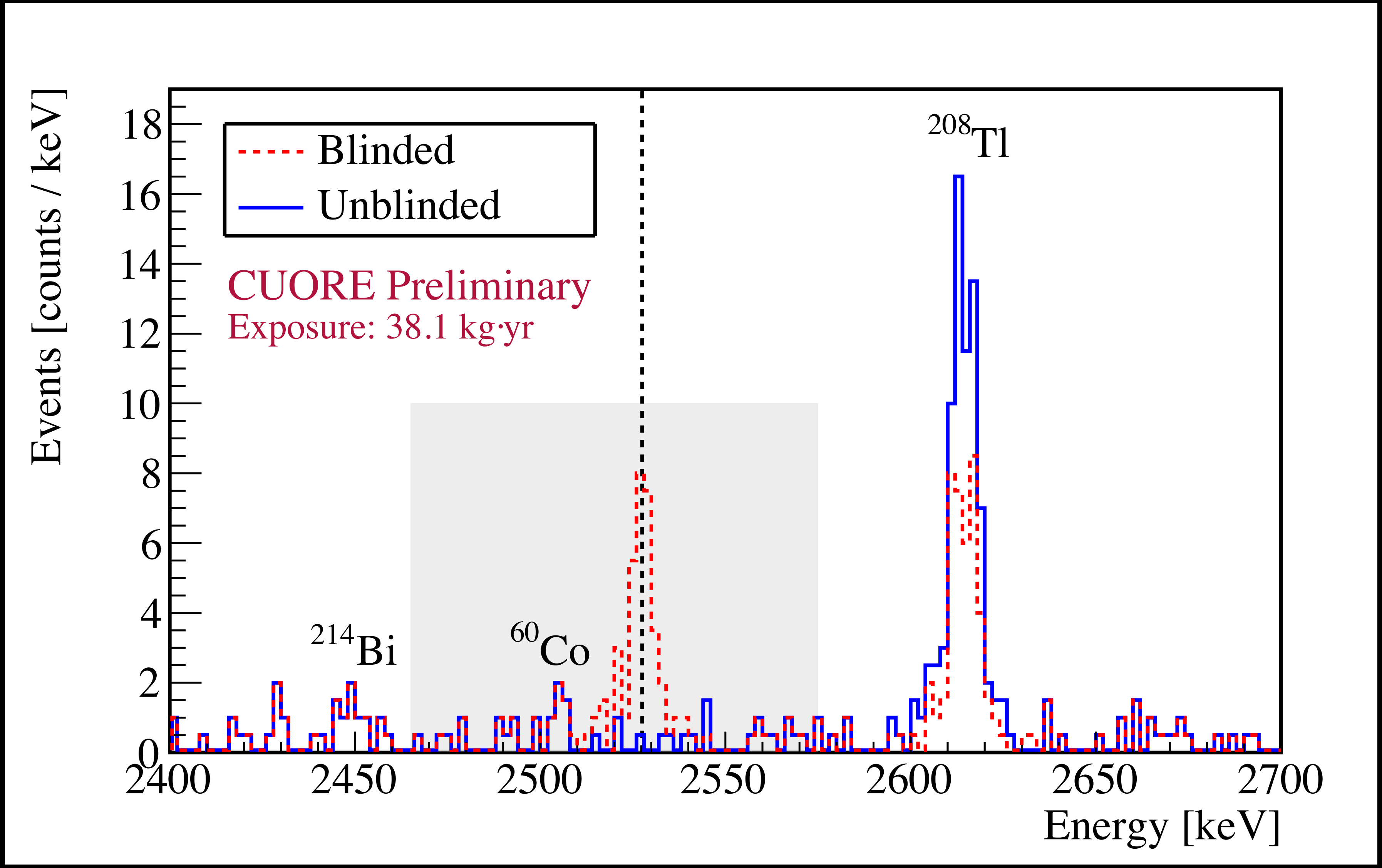

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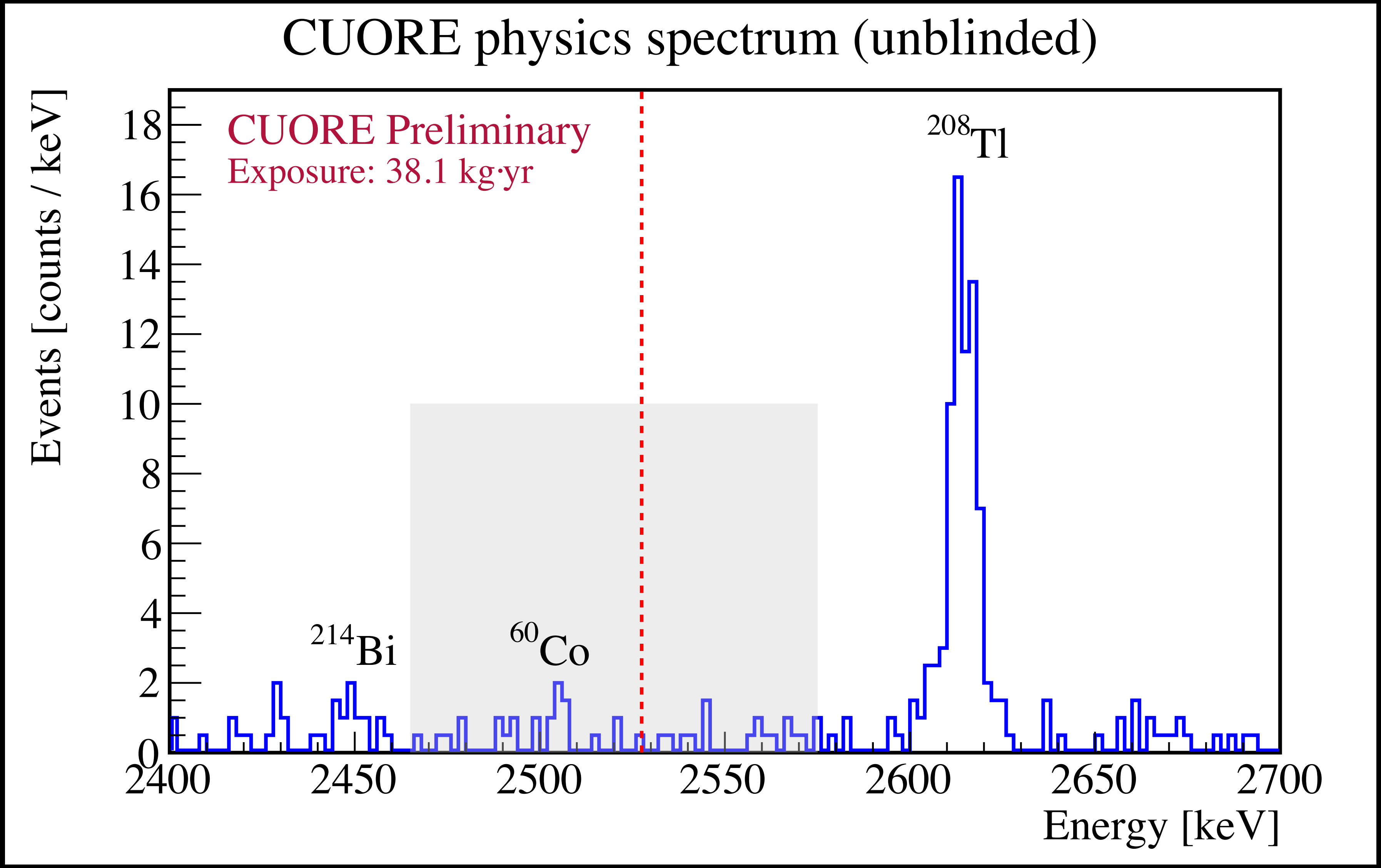

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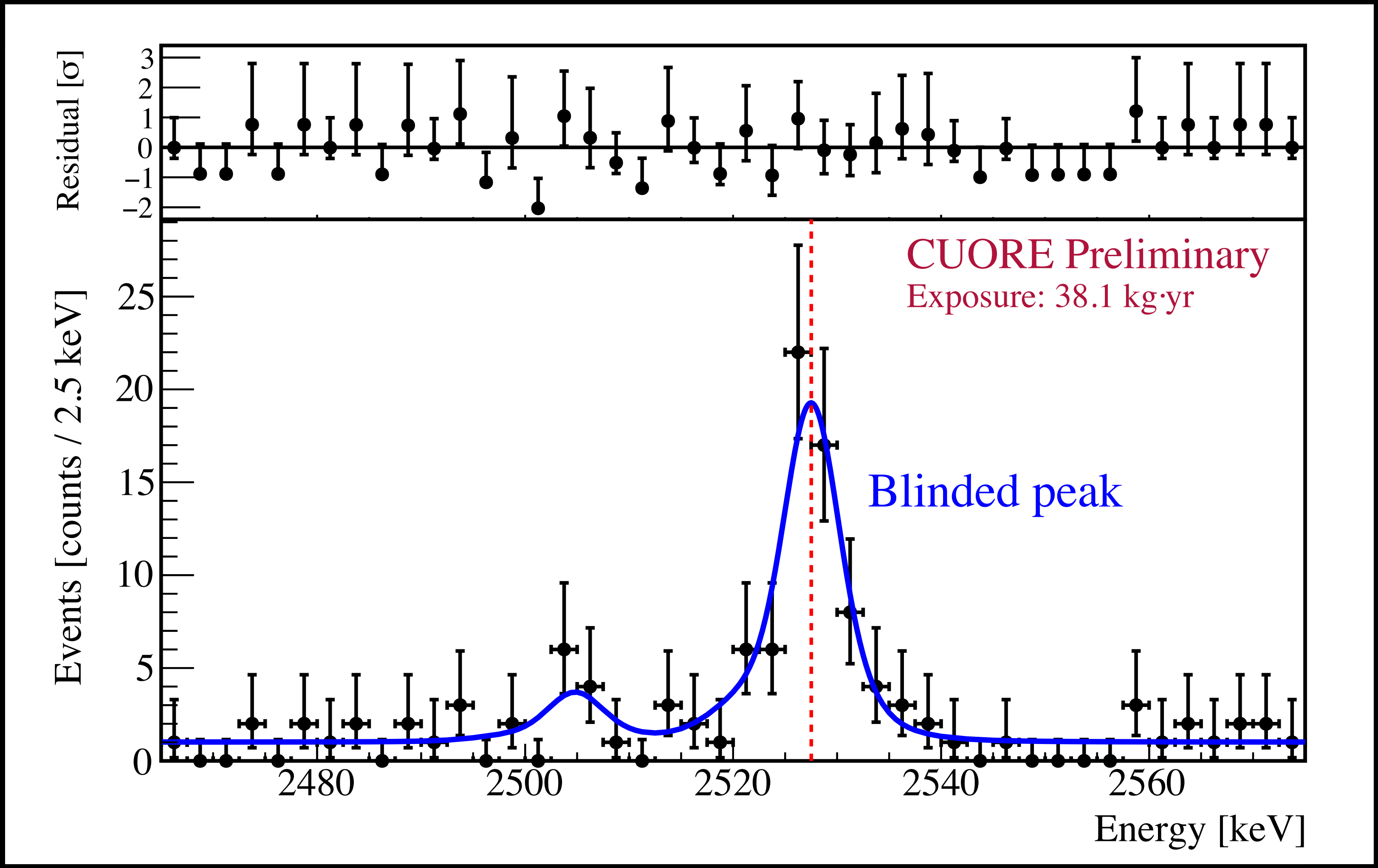
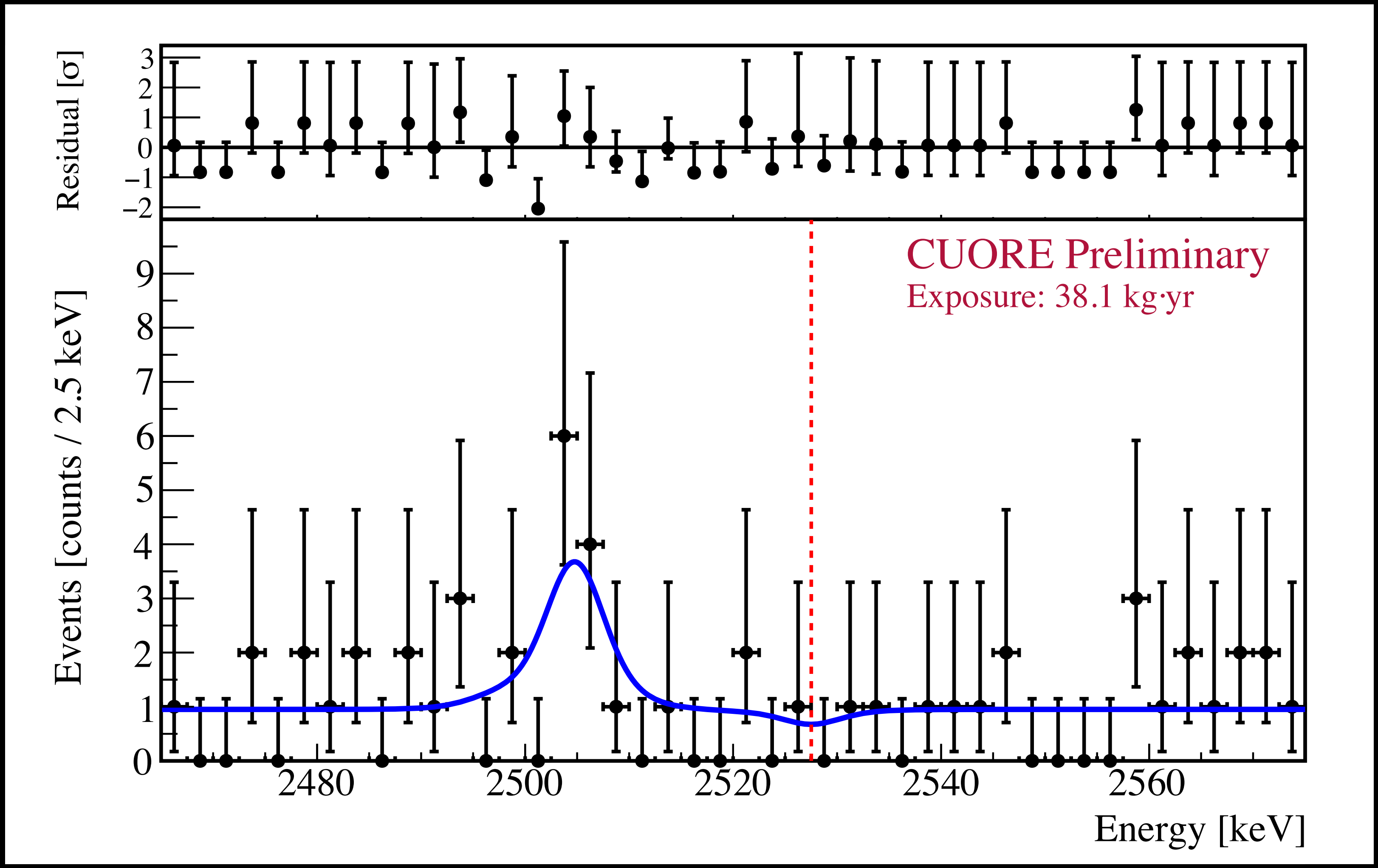
Fit in the ROI

- We determined the yield of 0vDBD events by performing a simultaneous unbinned extended maximum likelihood fit in the energy region 2465-2575 keV
- Fit procedures developed on blinded data
- The fit has 3 components:
  - a posited peak at the Q-value of ^{130}Te
  - a floating peak to account for the ^{60}Co sum gamma line (2505 keV)
  - a constant continuum background, attributed to multi scatter Compton events from ^{208}Tl and surface alpha events



Fit in the ROI

- We determined the yield of 0vDBD events by performing a simultaneous unbinned extended maximum likelihood fit in the energy region 2465-2575 keV
- Fit procedures developed on blinded data
- The fit has 3 components:
  - a posited peak at the Q-value of ^{130}Te
  - a floating peak to account for the ^{60}Co sum gamma line (2505 keV)
  - a constant continuum background, attributed to multi scatter Compton events from ^{208}Tl and surface alpha events



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• Region of interest	from 2565 to 2575 keV
• Overall efficiency	(55.3 ± 3.0)%

• Events in the ROI	50
• Best fit for ^{60}Co mean	(2504.8 ± 1.2) keV
• ROI background index	$(9.8_{-1.5}^{+1.7}) \times 10^{-3}$ c/(keV·kg·yr)
• Best fit decay rate	$(-0.03_{-0.04}^{+0.07}$ (stat.) ± 0.01 (syst.)) $\times 10^{-24}$ yr^{-1}
• Bayesian halflife limit (including systematics)	4.5×10^{24} yr

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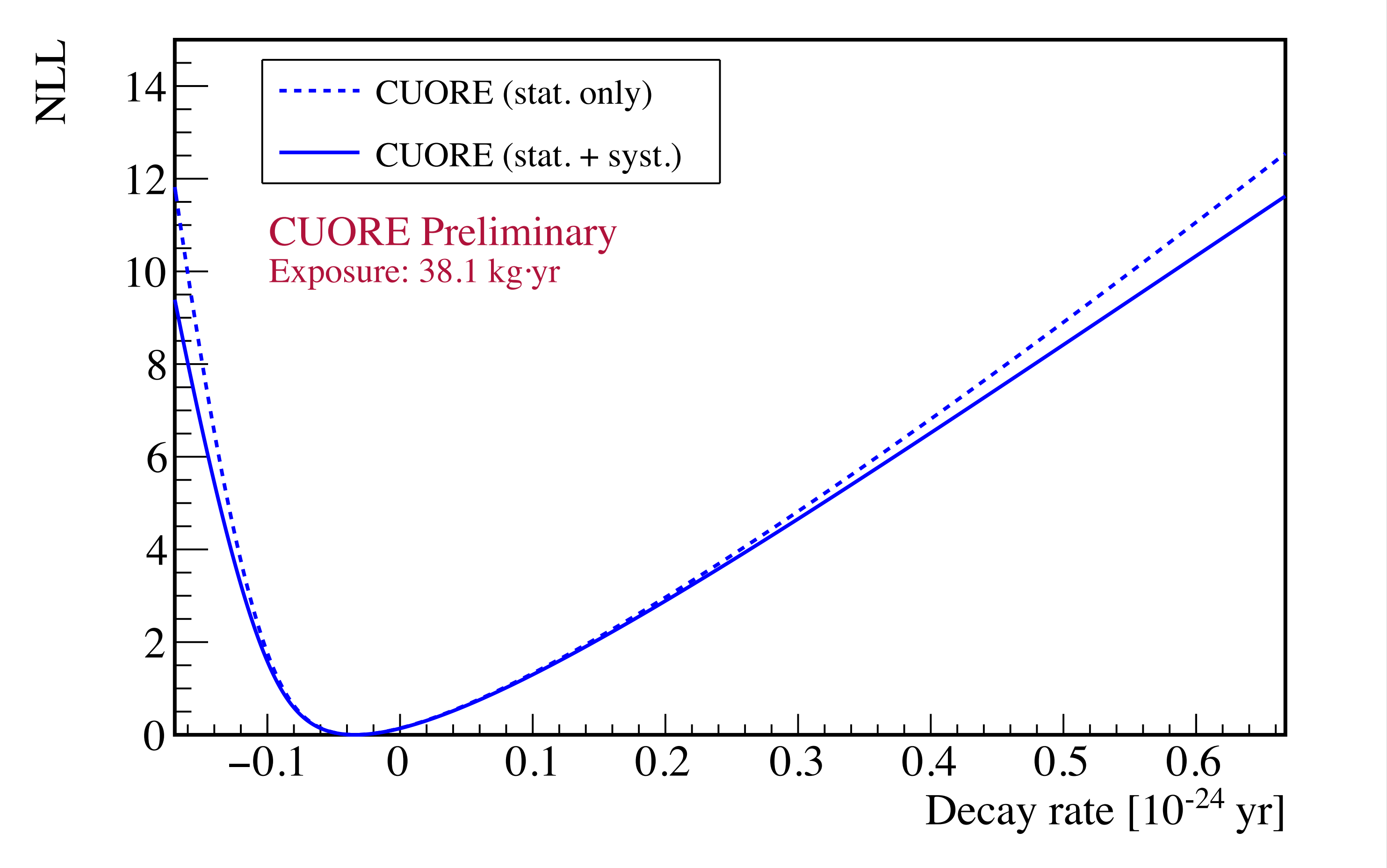
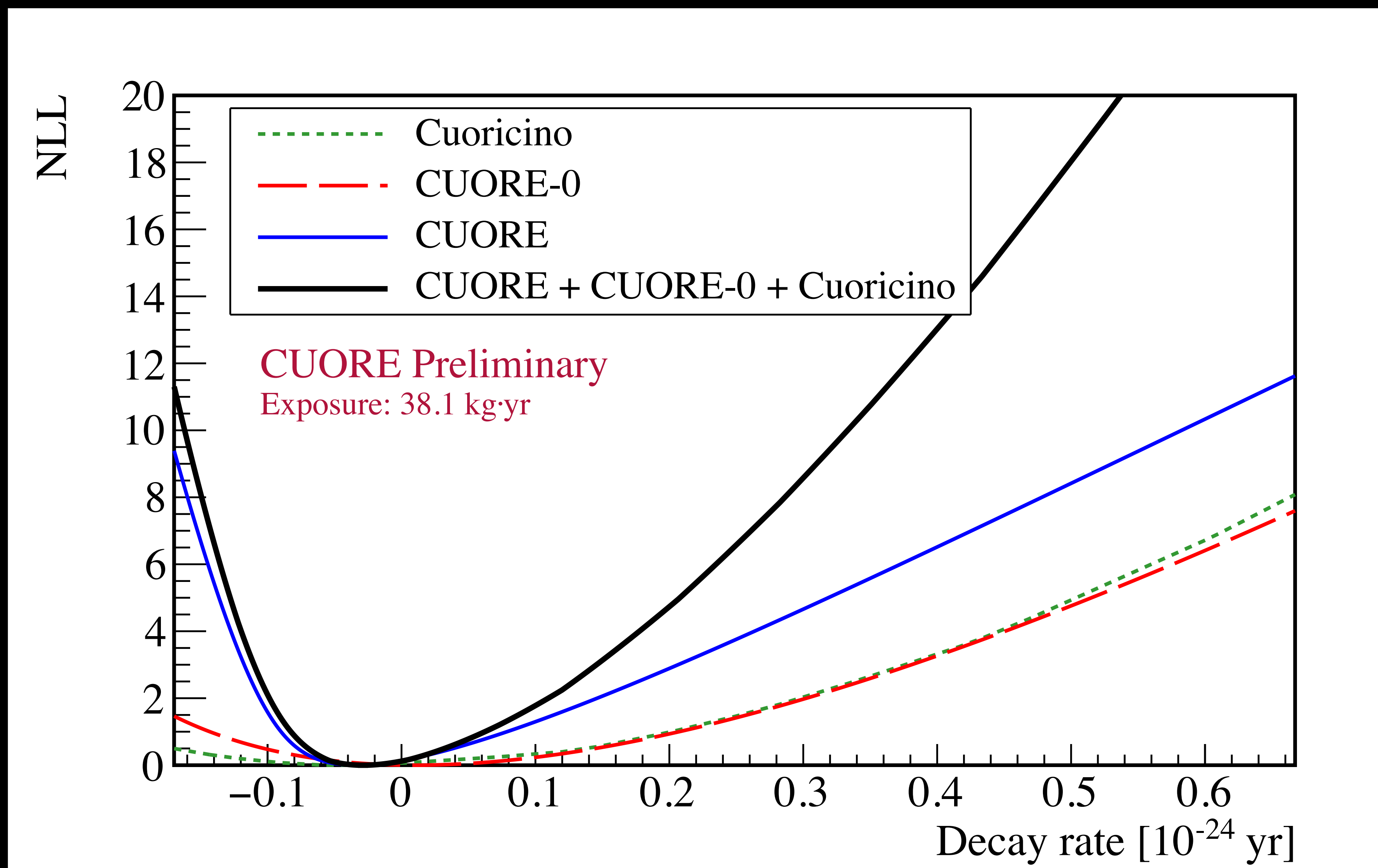
- Profile likelihood
- Integrated on the physical region



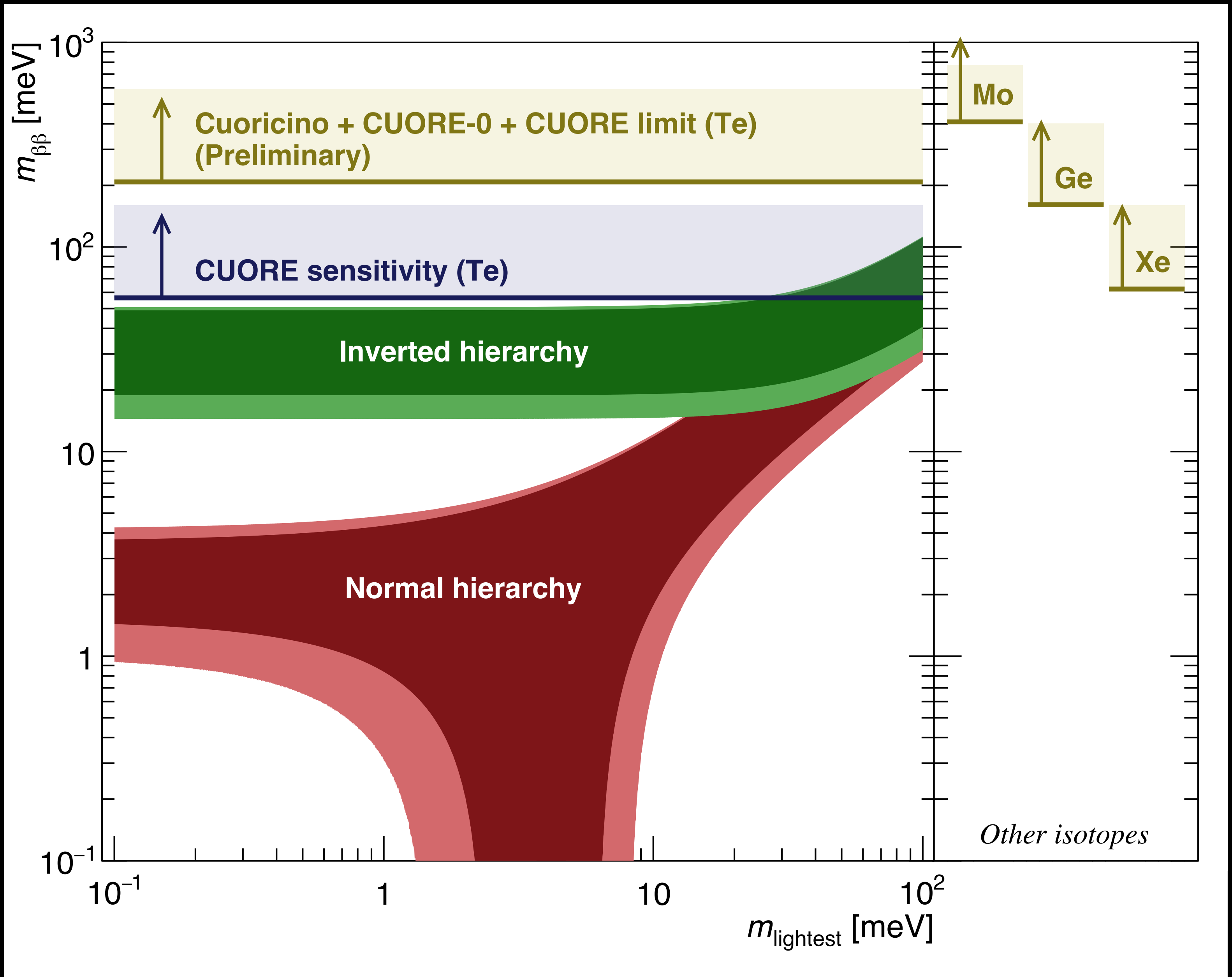
Combination with previous results

- We combine the CUORE result with the existing ^{130}Te
  - 19.75 kg·yr of Cuoricino
  - 9.8 kg·yr of CUORE-0



- The combined 90% C.L. limit is $T_{0\nu} > 6.6 \times 10^{24}$ yr
- Frequentist limit (W. Rolke et al., NIM A 551, 493-503 (2005)) is $T_{0\nu} > 8.1 \times 10^{24}$ yr

Combination with previous results



- The combined 90% C.L. limit is
  $T_{0\nu} > 6.6 \times 10^{24}$ yr
  $m_{\beta\beta} <$ 210 - 590 meV

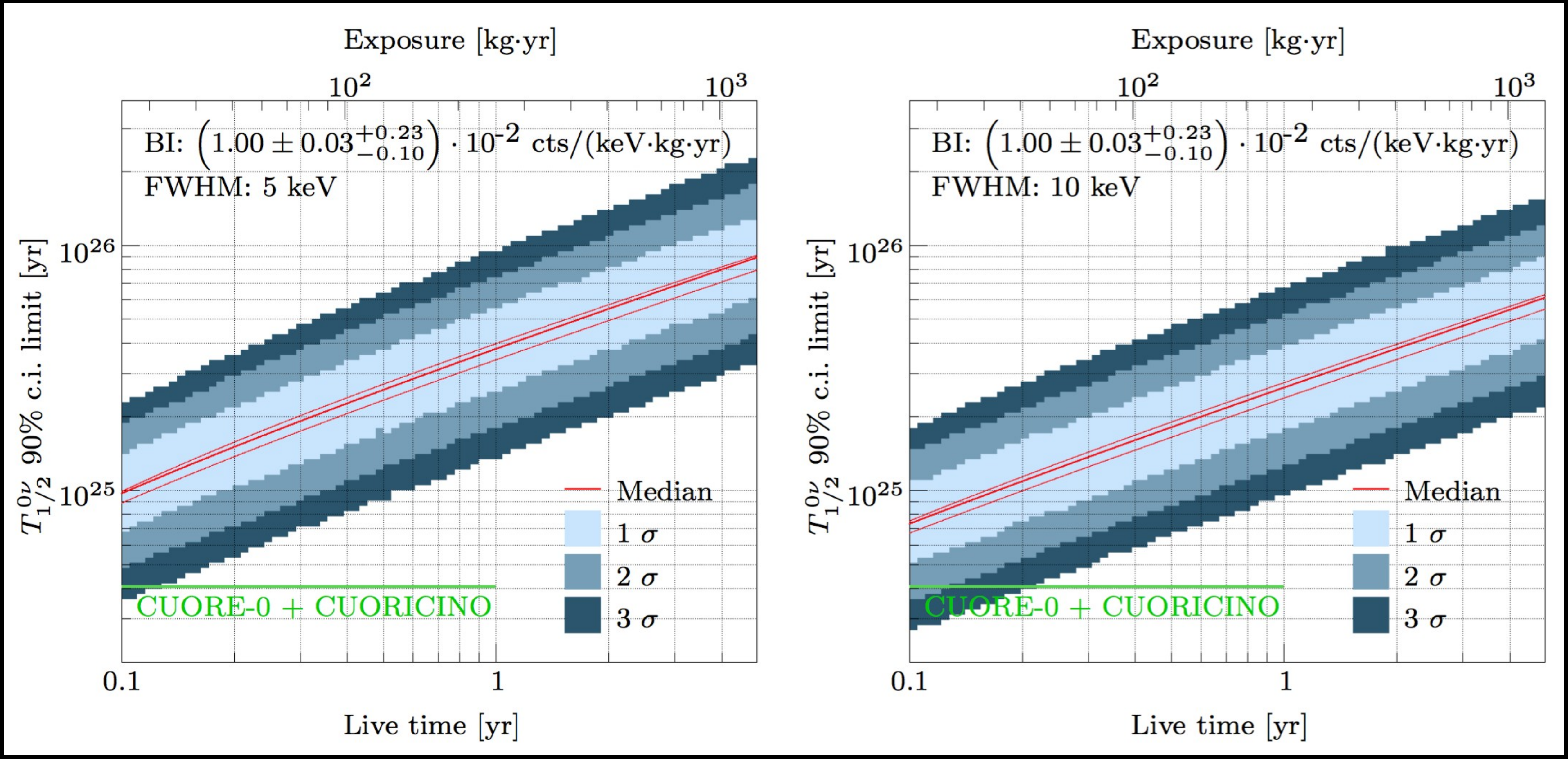
Experiments:

^{130}Te: 6.5 × 10^{24} yr from this analysis
^{76}Ge: 5.3 × 10^{25} yr from Nature 544, 47–52 (2017)
^{136}Xe: 1.1 × 10^{26} yr from Phys. Rev. Lett. 117, 082503 (2016)
^{100}Mo: 1.1 × 10^{24} yr from Phys. Rev. D 89, 111101 (2014)
CUORE sensitivity: 9.0 × 10^{25} yr

NME:

Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 91, 024613 (2015)
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. Lett. 105, 252503 (2010)

Expected sensitivity



- arXiv:1705.10816 “Cuore Sensitivity to 0νββ Decay” - accepted for publication on EPJ C
- arXiv:1704.08970 “The projected background for the CUORE experiment” - accepted for publication on EPJ C

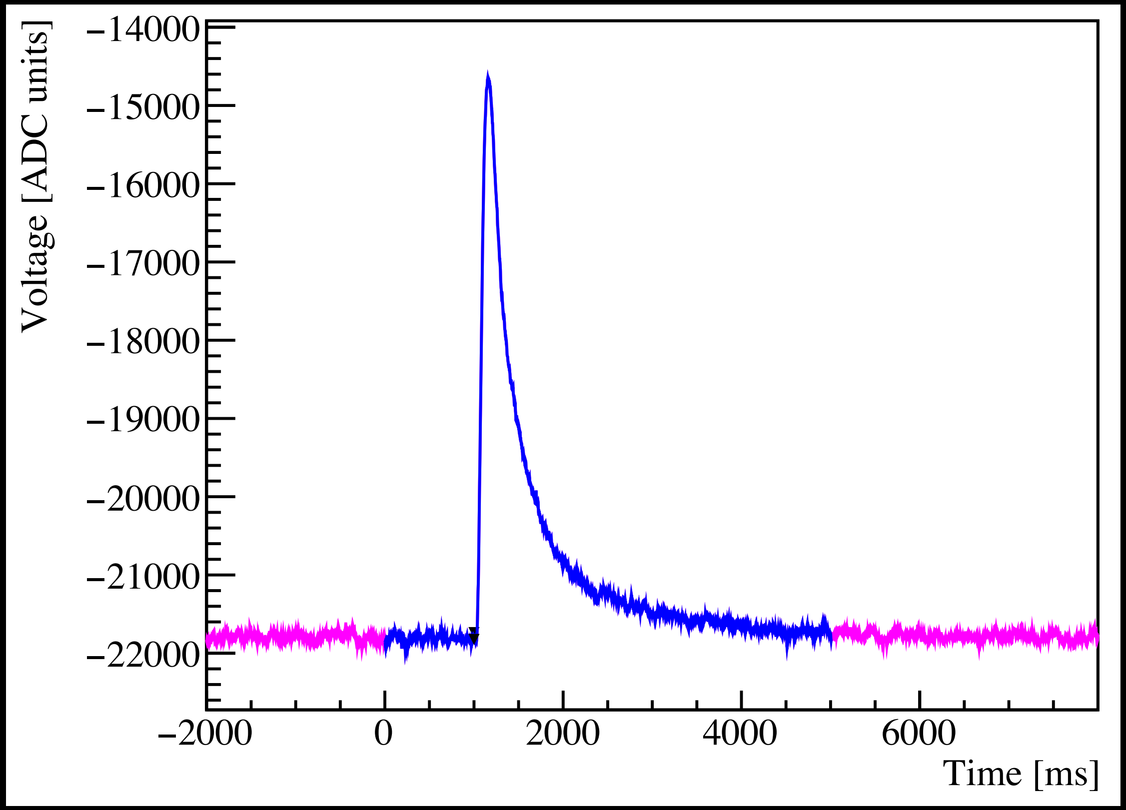
Energy resolution improvements

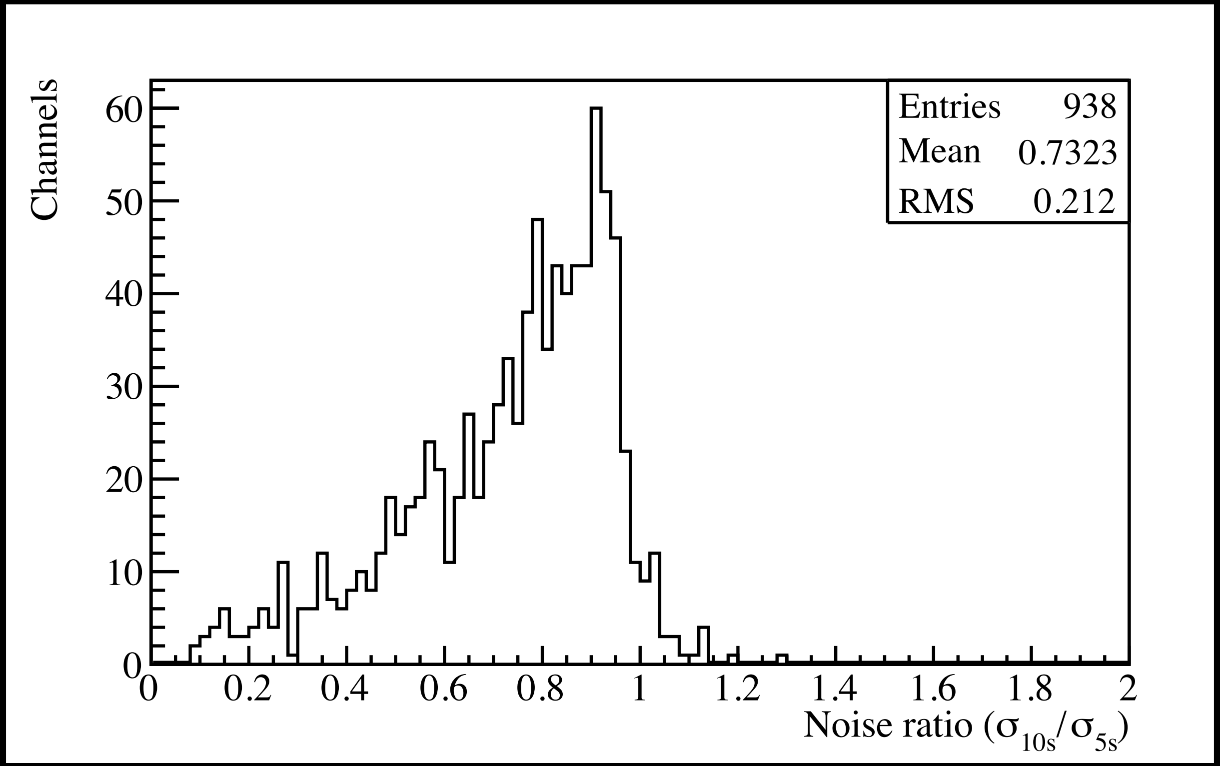
- Detector commissioning stopped in April to start science runs
- Still room for improvements

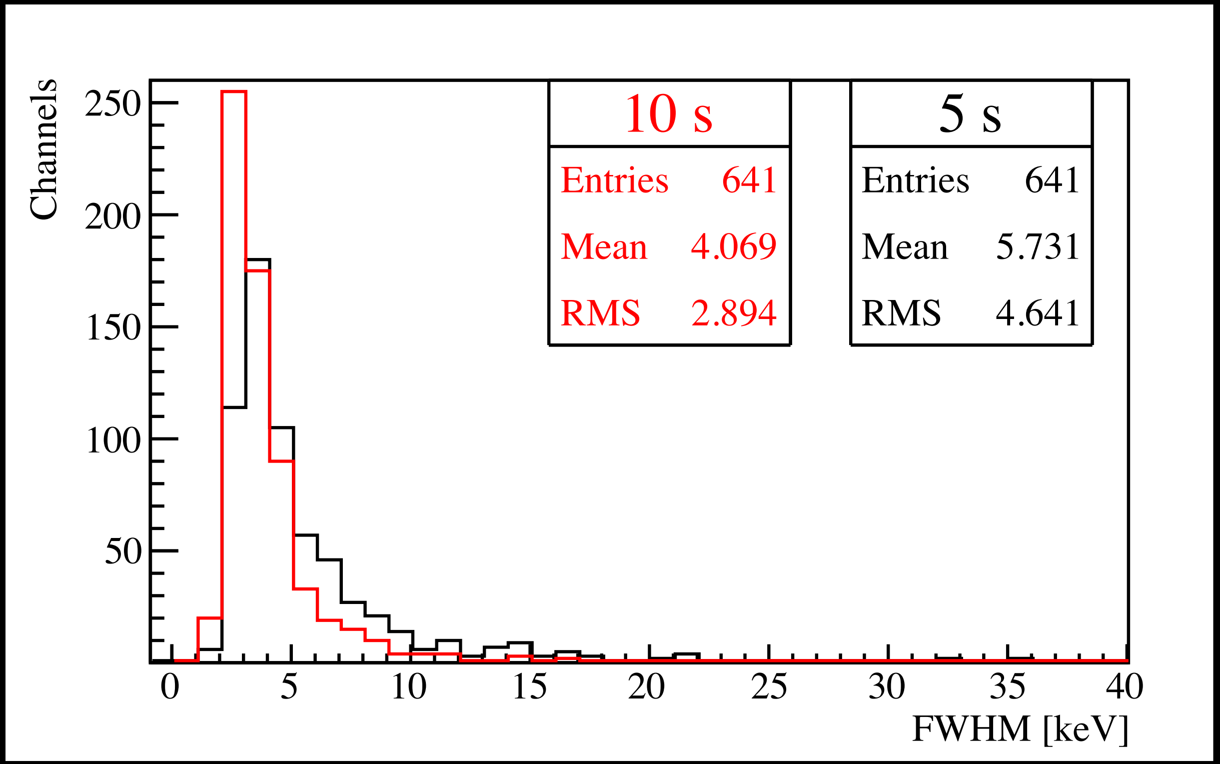
- Detector optimization campaign restarted in June-July:
  - Upgrade of the electronics grounding in the CUORE Faraday cage
  - Active cancellation of the PT-induced noise
  - Optimization of the operating temperature and detector working points
  - Software and analysis upgrades

Analysis upgrades

- Optimization of software bandwidth for pulse amplitude analysis
- Extend software trigger window from 5s to 10s
- Improves “baseline resolution” (energy resolution for 0 keV pulses) by ~25%

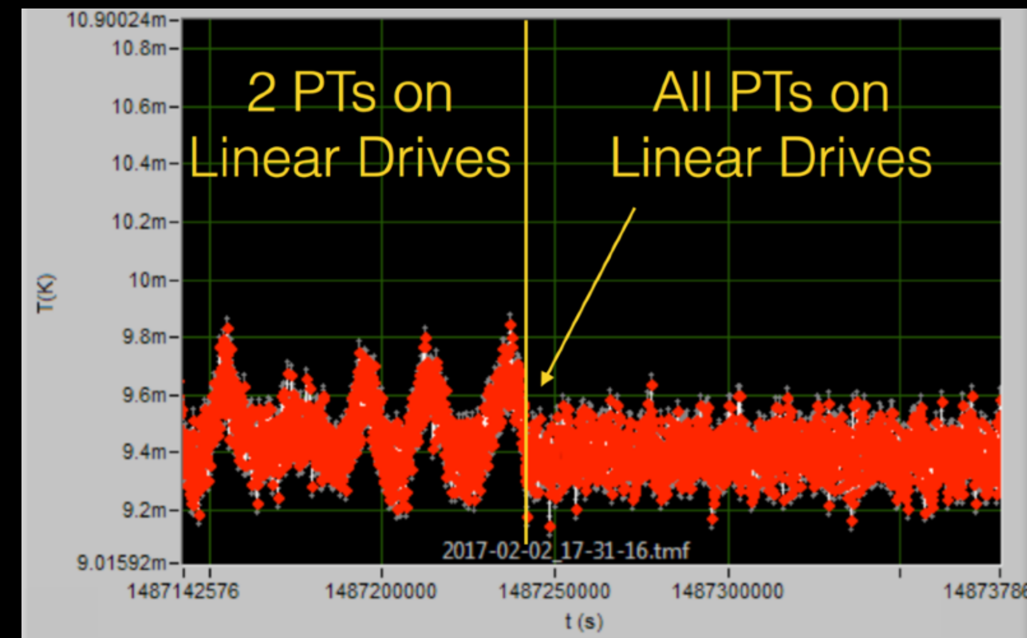


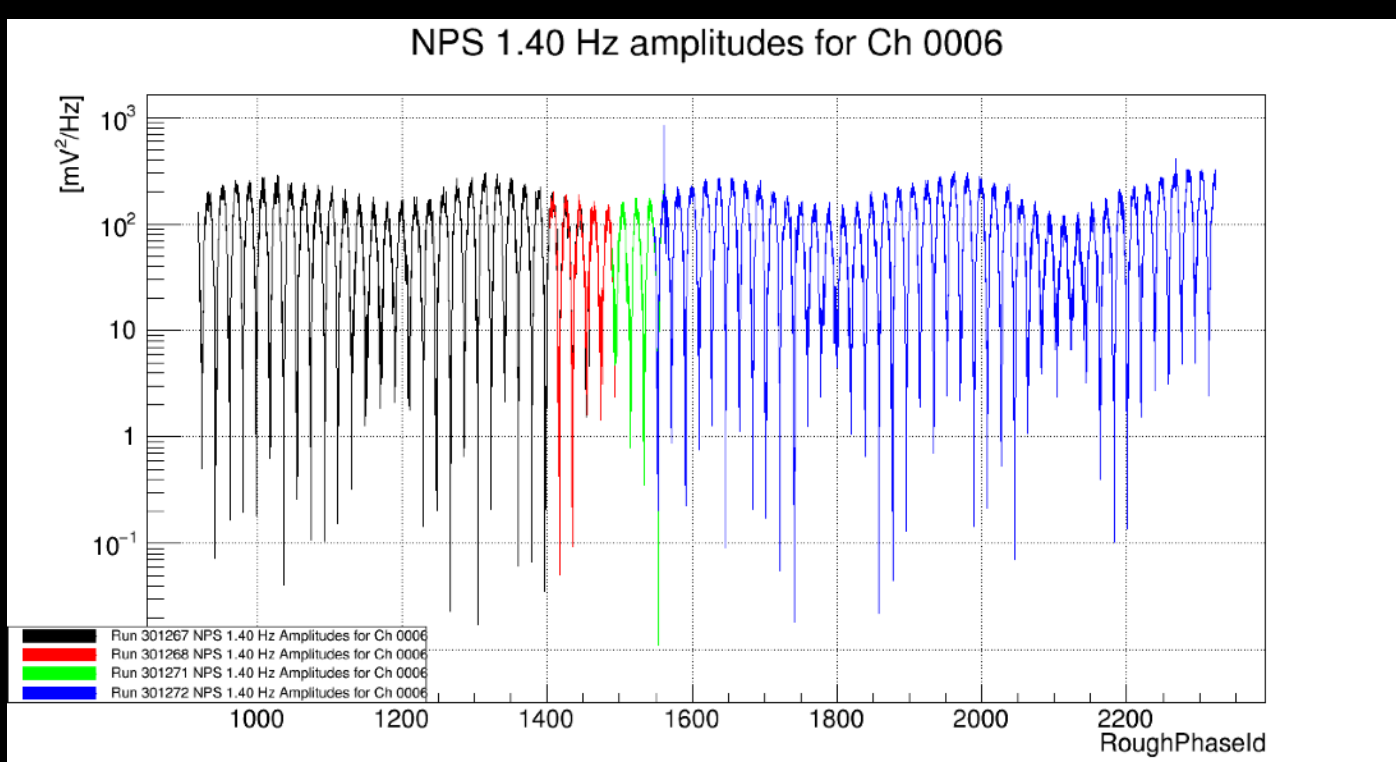


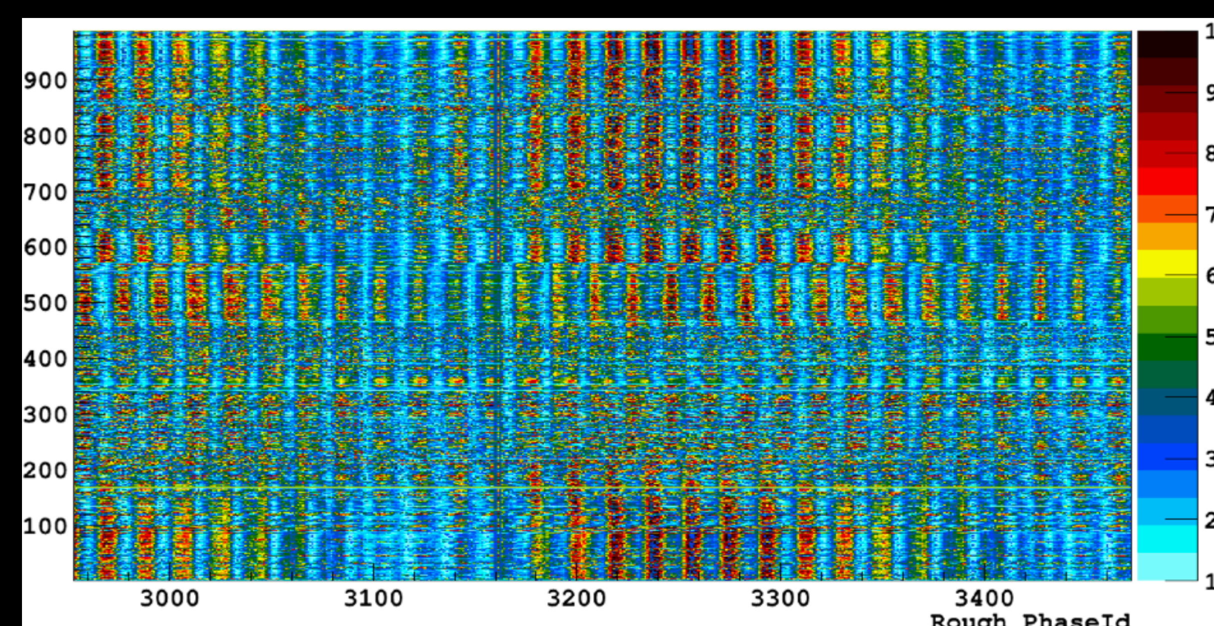


PT noise cancellation

- The main vibrational noise comes from the PTs
- Running the PT motor head valves using linear drives decrease the vibrations
- Moreover allows a fine tuning of the PT frequency
- By regulating the PT phase differences and inducing destructive interference, we can reduce the vibrational noise induced by the PTs

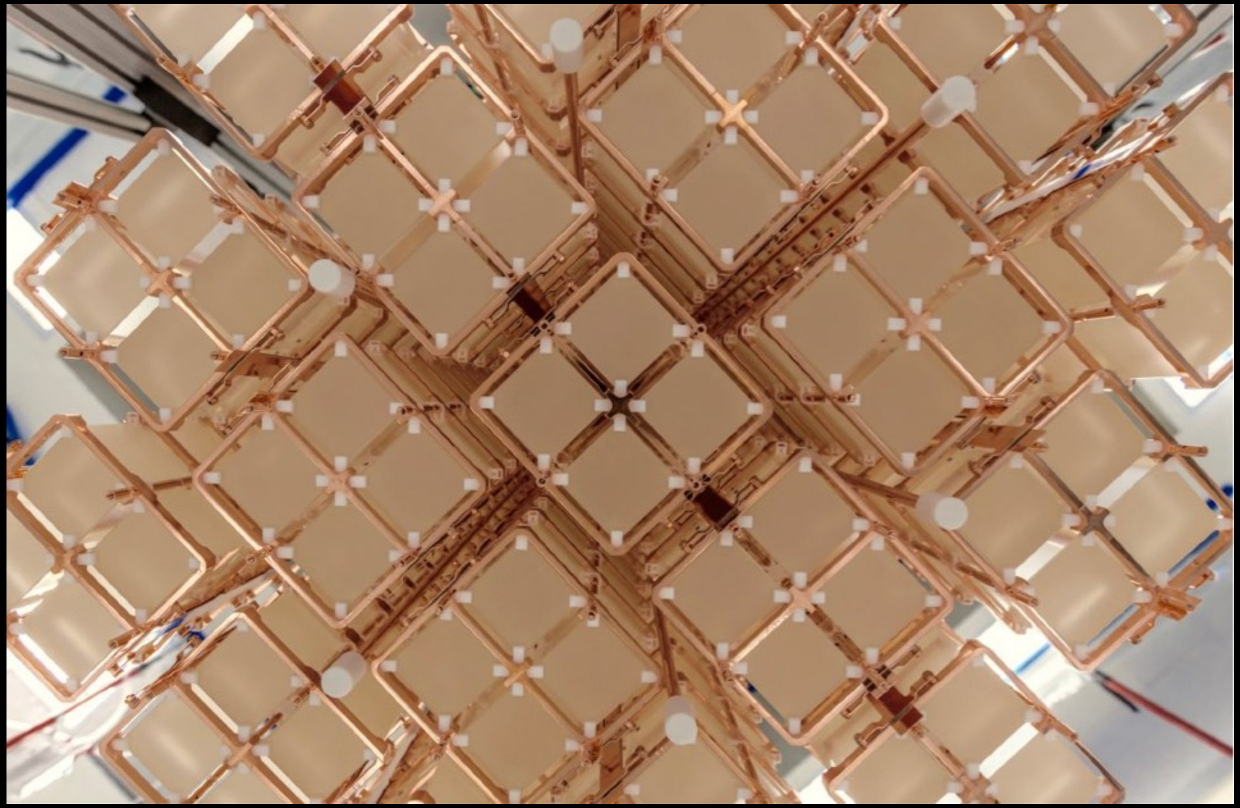






Conclusions

- The cryostat is working spectacularly well
- With just 3 weeks of physics data we have accumulated higher exposure than CUORE-0/Cuoricino and surpassed their limit
  - Total exposure: 38.1 kg·yr
  - Invaluable operational experience
  - Important information on noise sources, energy resolution, background level
- Further improvements possible
- A detector optimization campaign is presently underway, focused on improving the energy resolution



- Developed and debugged physics tools, stress-tested end-to-end data processing with quality appropriate for science results
- Background rates are consistent with the background model
- More to come