

First CUORE results

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on behalf of the CUORE Collaboration

Outline



- CUORE and TeO₂ bolometers
- CUORE Status
 - Cryogenics
 - Installation
 - Pre-operation
- Preliminary results
- Conclusions

CUORE

(Cryogenic Underground Observatory for Rare Events)



Primary goal: search for $0\nu\beta\beta$ decay in ^{130}Te

Closely packed array of 988 TeO_2 crystals arranged in 19 towers

^{130}Te :

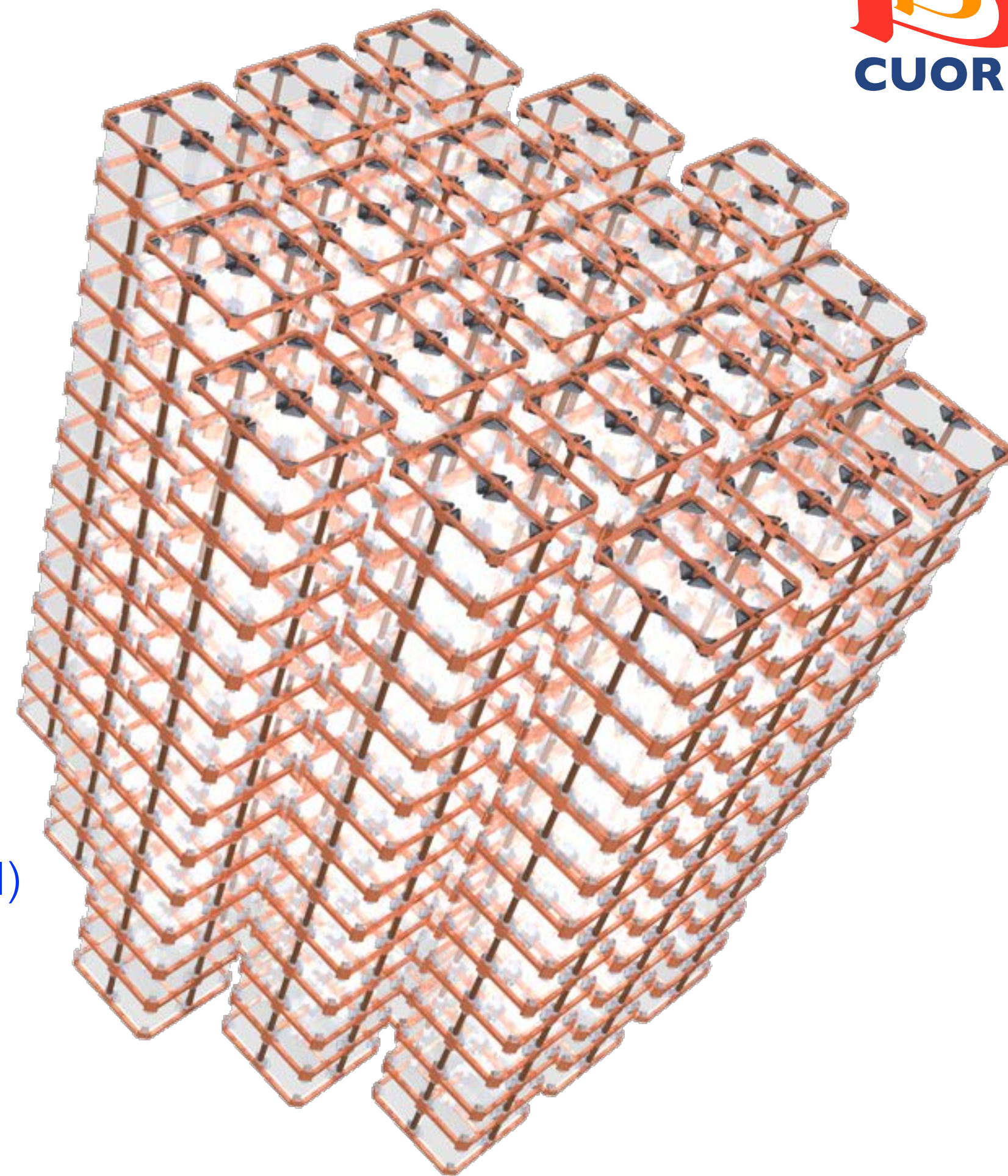
- large transition energy: $Q_{\beta\beta} (^{130}\text{Te})$ 2527.5 keV
- highest natural isotopic abundance (33.8%)

CUORE design parameters:

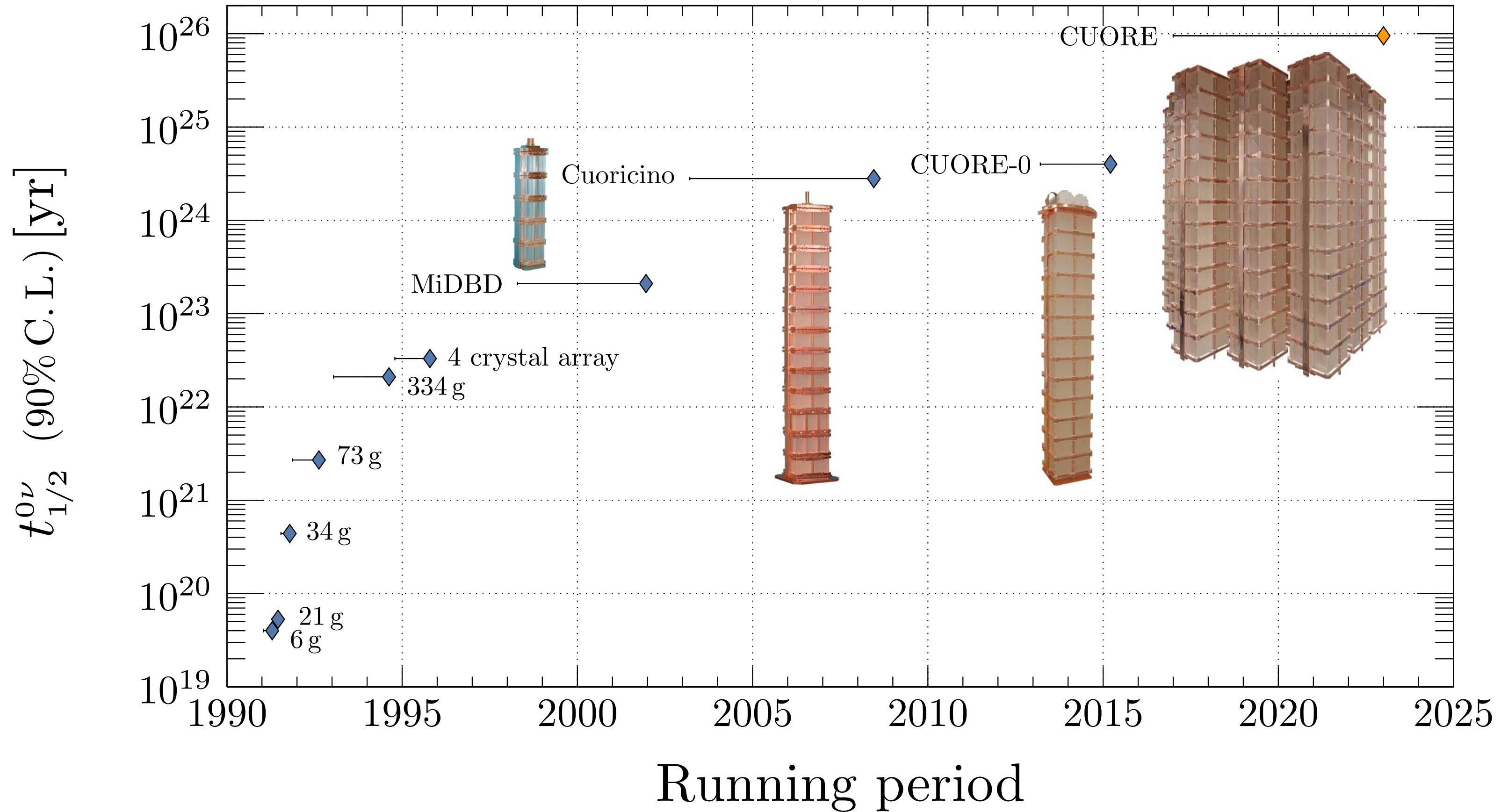
- mass of TeO_2 : **742 kg** (206 kg of ^{130}Te)
- low background aim: **10^{-2} c/(keV·kg·yr)**
- energy resolution: **5 keV** FWHM in the Region Of Interest (ROI)
- high granularity
- deep underground location
- strict radio-purity controls on materials and assembly

CUORE projected sensitivity (5 years, 90% C.L.):

$$T_{1/2} > 9 \times 10^{25} \text{ yr}$$



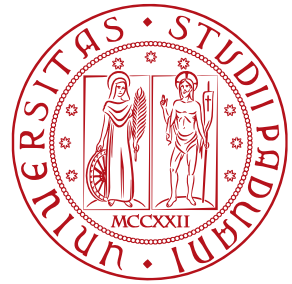
TeO₂ arrays



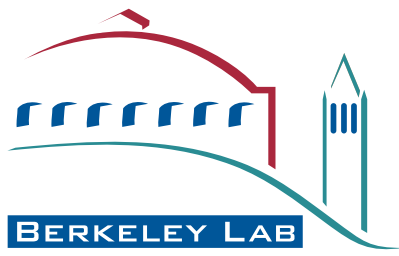
CUORE is the latest evolution of a long series of TeO₂ detectors which included two large demonstrators:

- Cuoricino
- CUORE-0

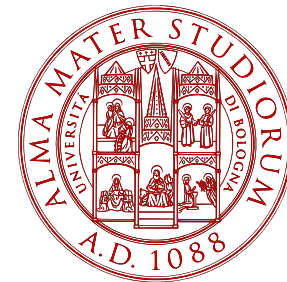
The CUORE Collaboration



Yale



CAL POLY
SAN LUIS OBISPO



CUORE @ LNGS



1400 m of rock (~ 3600 m.w.e.) deep

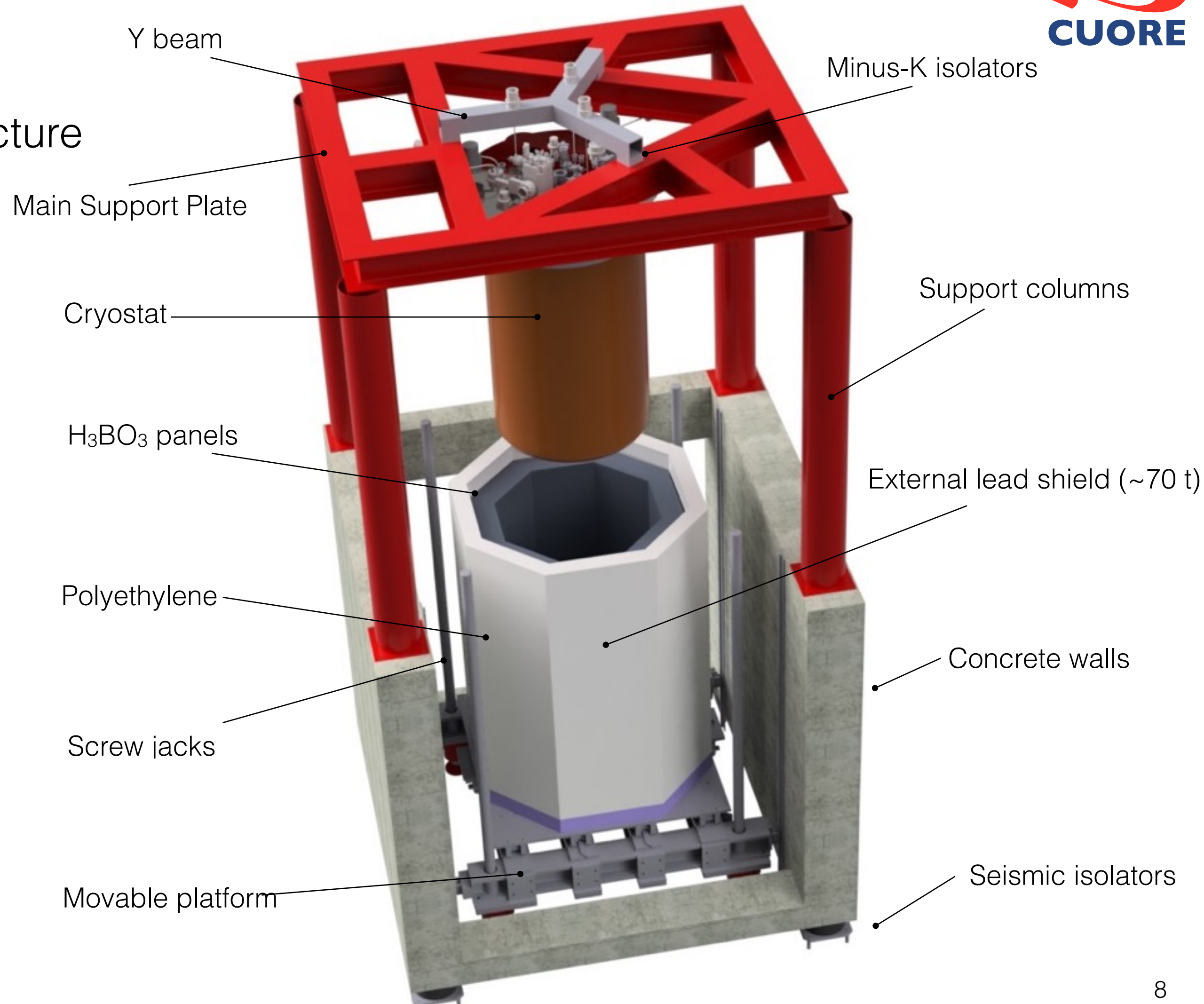
- μ 's: $\sim 3 \times 10^{-8} / (\text{s} \cdot \text{cm}^2)$
- γ 's: $\sim 0.73 / (\text{s} \cdot \text{cm}^2)$
- neutrons: $4 \times 10^{-6} \text{ n}/(\text{s} \cdot \text{cm}^2)$ below 10 MeV

CUORE @ LNGS



Underground lab

- Three-story building
- Hosting the cryostat supporting structure

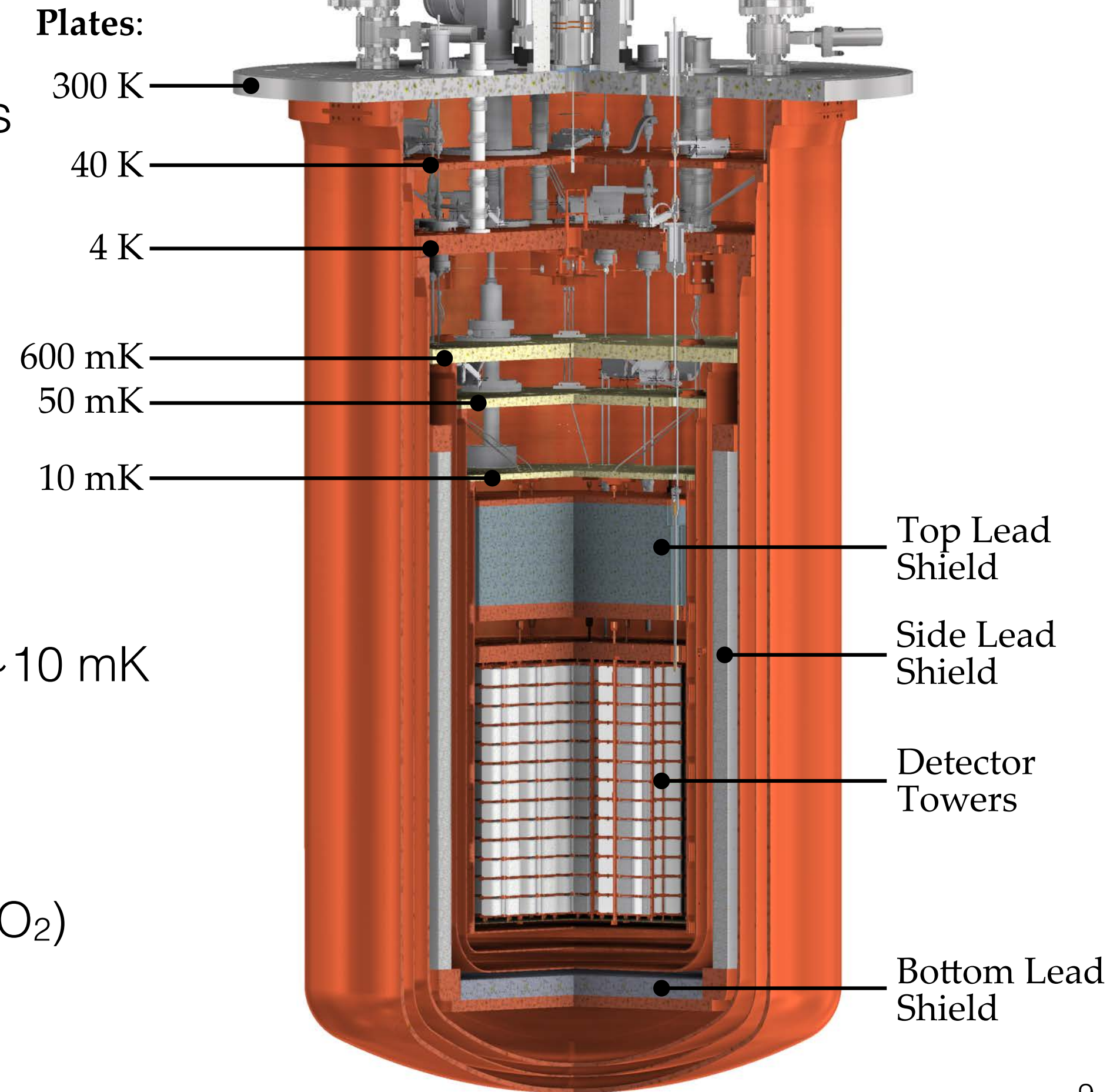


The CUORE cryostat



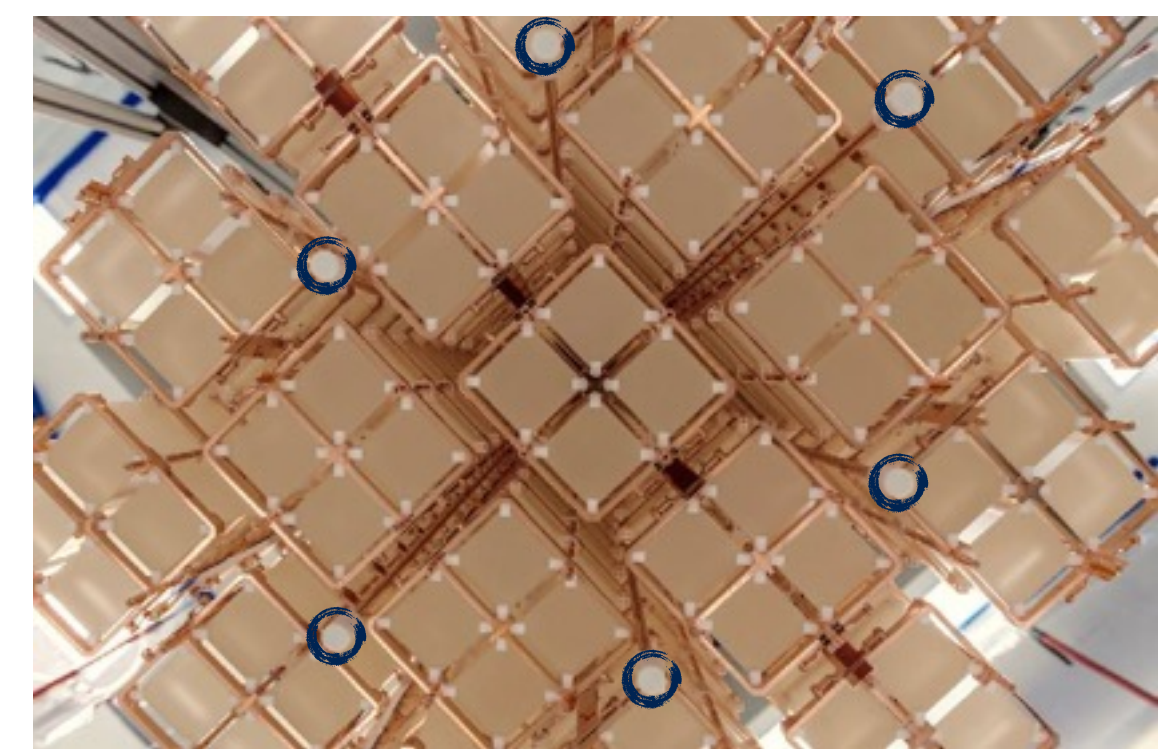
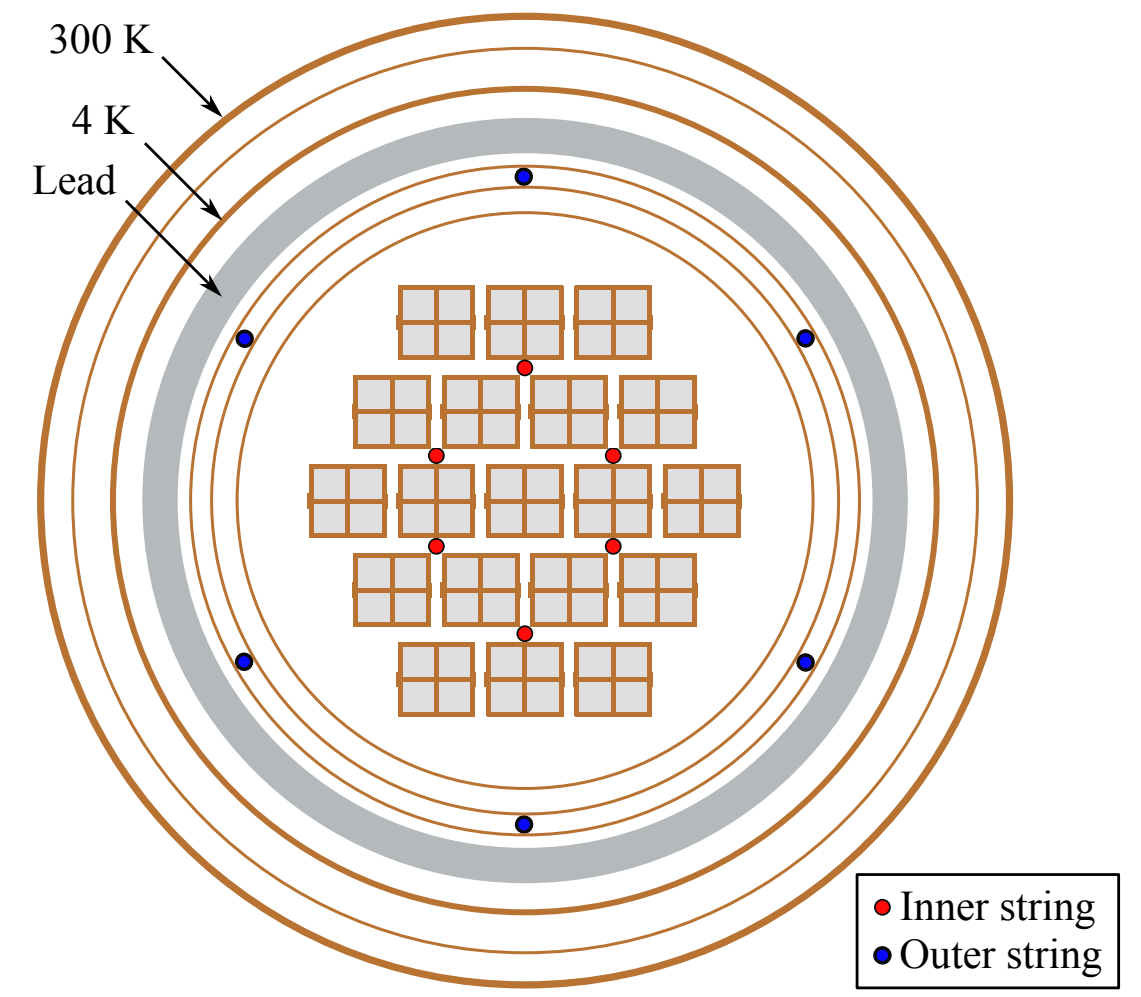
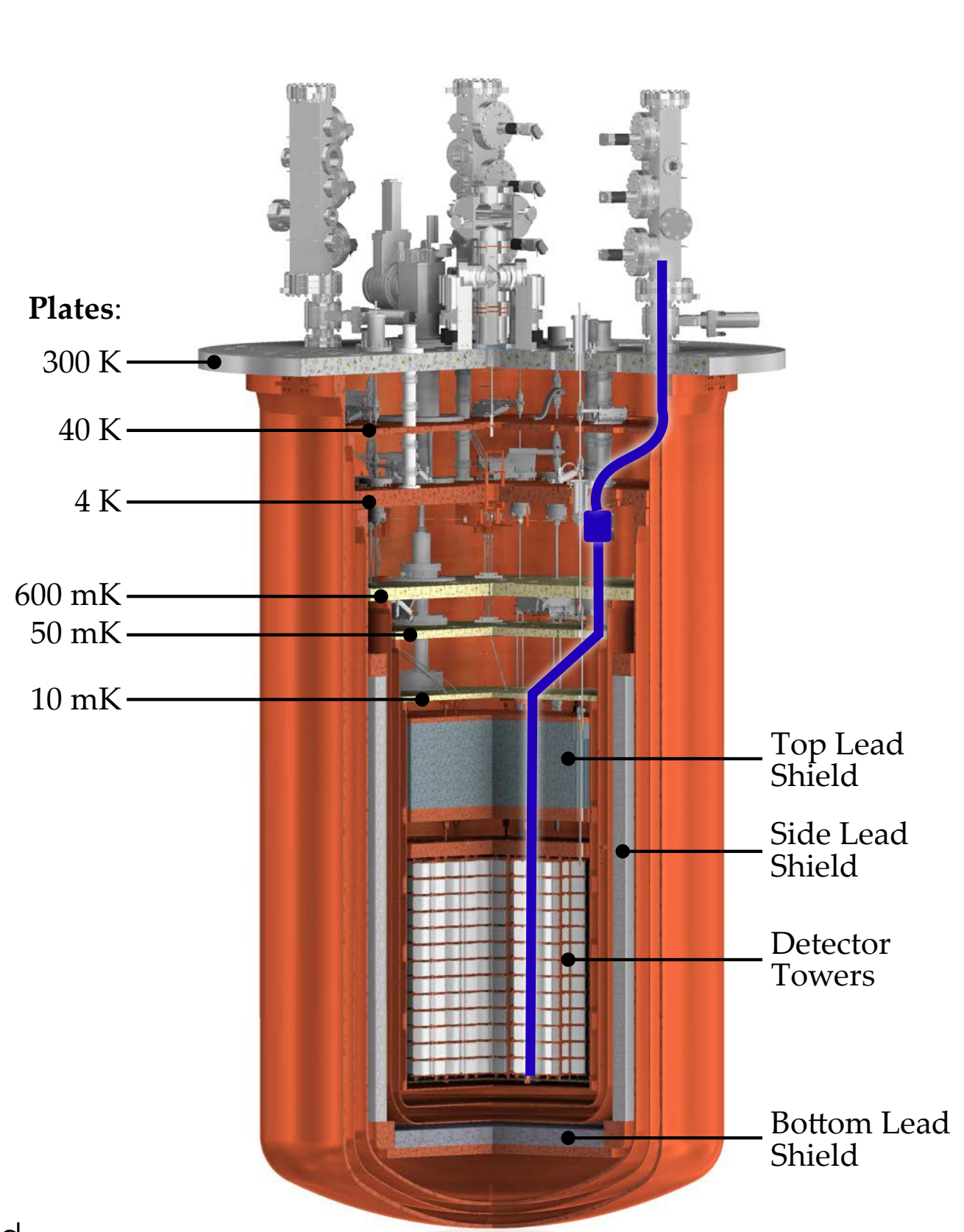
- Designed to cool down ~1 ton detector to ~10 mK
- Mechanically decoupled for extremely low vibrations
- Low background environment

- Cryogen-free cryostat
- Fast Cooling System (^4He gas) down to ~50K
- 5 pulse tubes cryocooler down to ~4K
- Dilution refrigerator down to operating temperature ~10 mK
- Nominal cooling power: $3 \mu\text{W}$ @ 10mK
- Cryostat total mass ~30 tons
- Mass to be cooled < 4K: ~15 tons
- Mass to be cooled < 50 mK: ~3 tons (Pb, Cu and TeO_2)



Detector calibration system

- Designed to provide a uniform calibration of all the CUORE detectors
- Deployment of ^{232}Th sources (strings) through the cryostat, from room temperature into the detector core



J. S. Cushman et al. The detector calibration system for the CUORE cryogenic bolometer array. Nuclear Instruments and Methods A 844, 32-44 (2017). arxiv:1608.01607

Cryogenic system commissioning

In February 2016 we completed the last test cool-down at full load:

- everything but the CUORE detector
- small test detector (“mini-tower”)

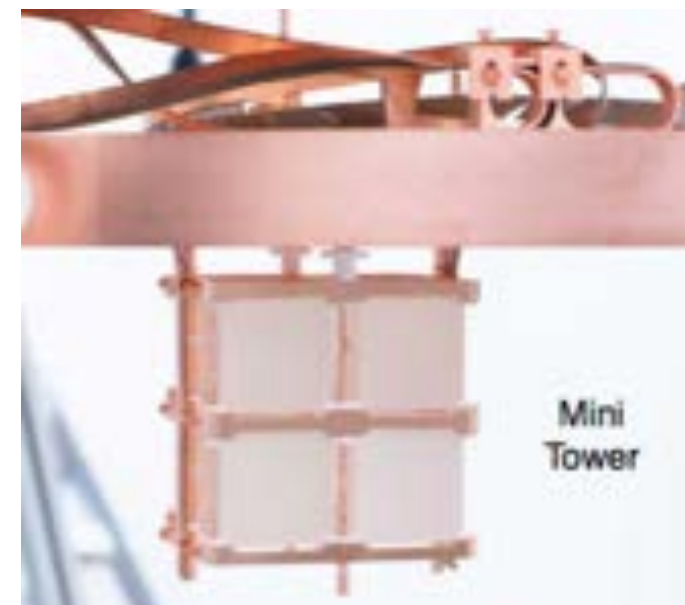
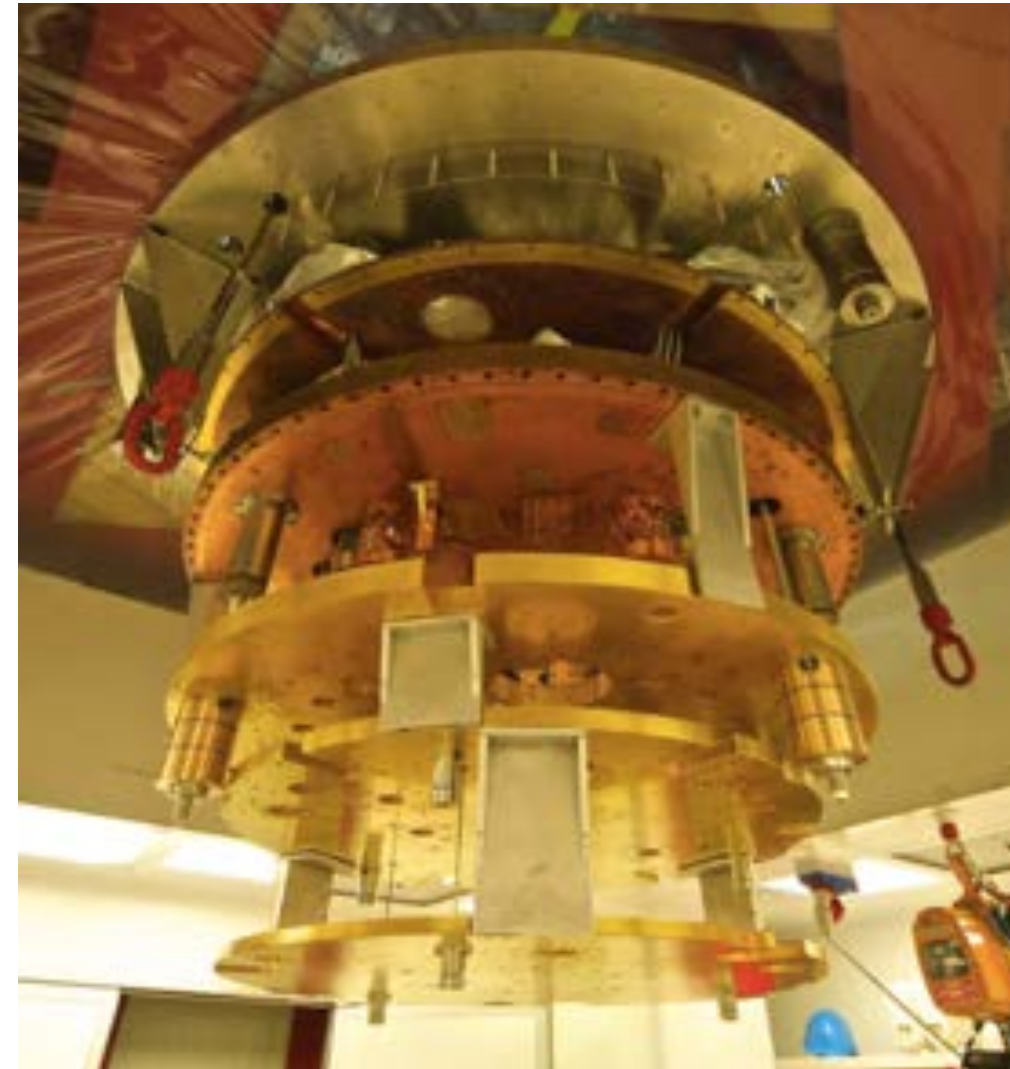
Excellent performance of the cryogenic system:

- base temperature below 7 mK
- stable operation

Important information on the noise sources and abatement

Successful deployment of the calibration sources at base temperature

Ready for the detector installation



Detector installation

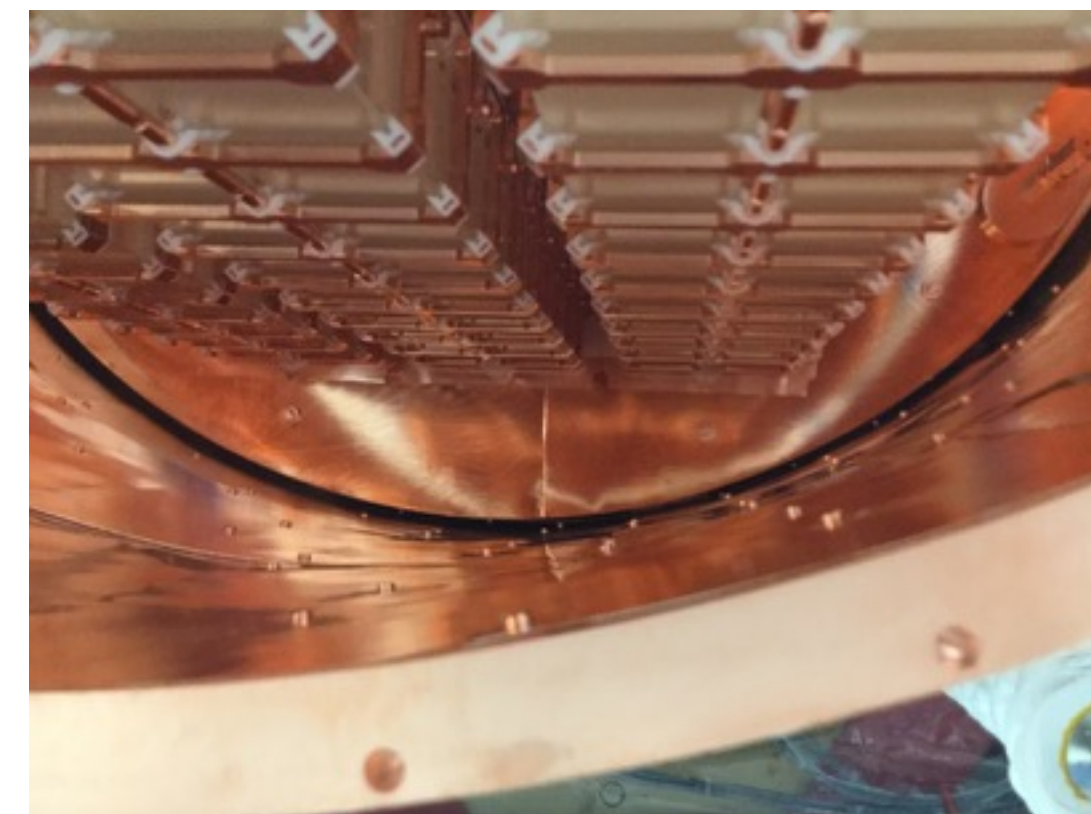
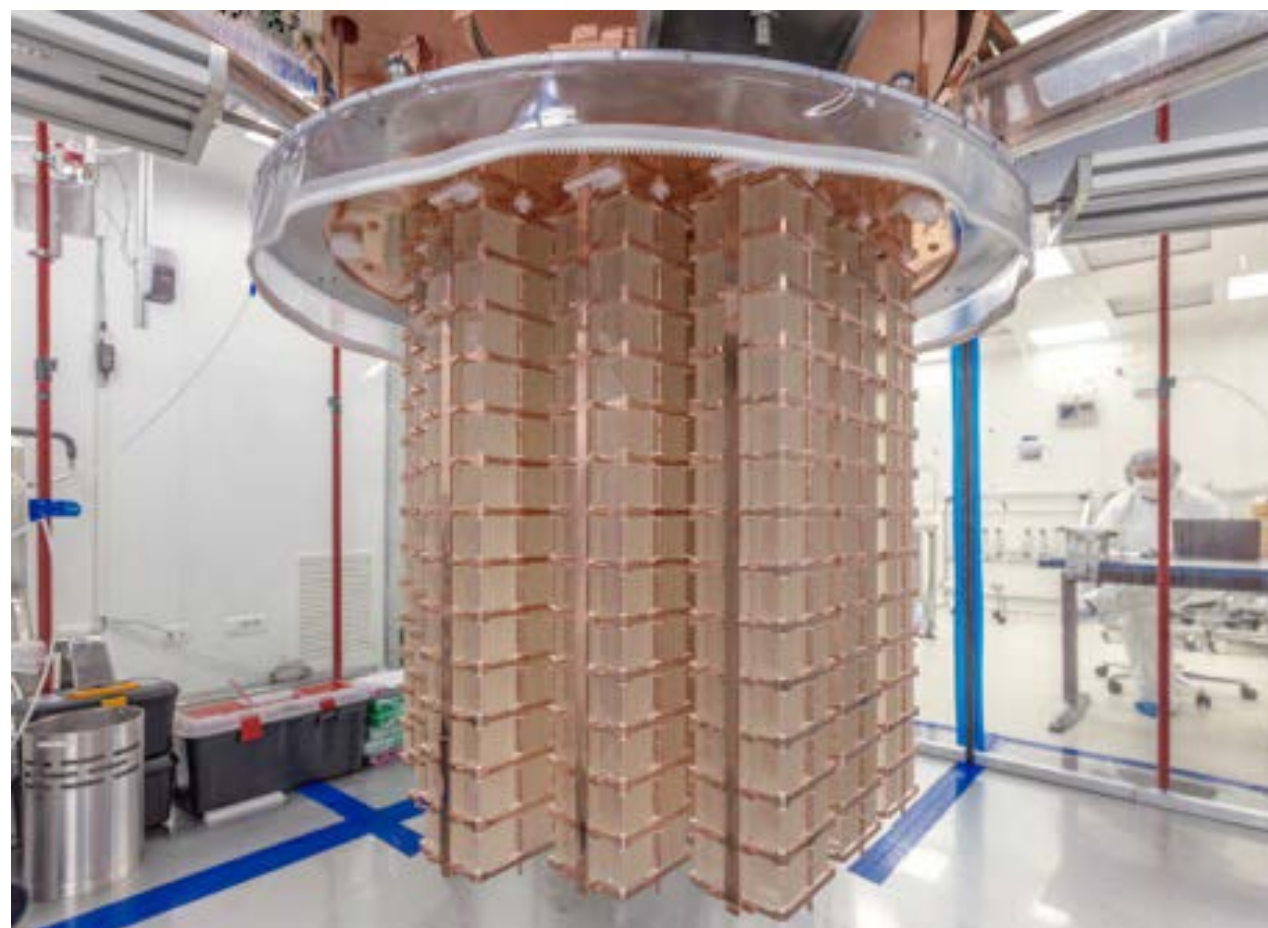
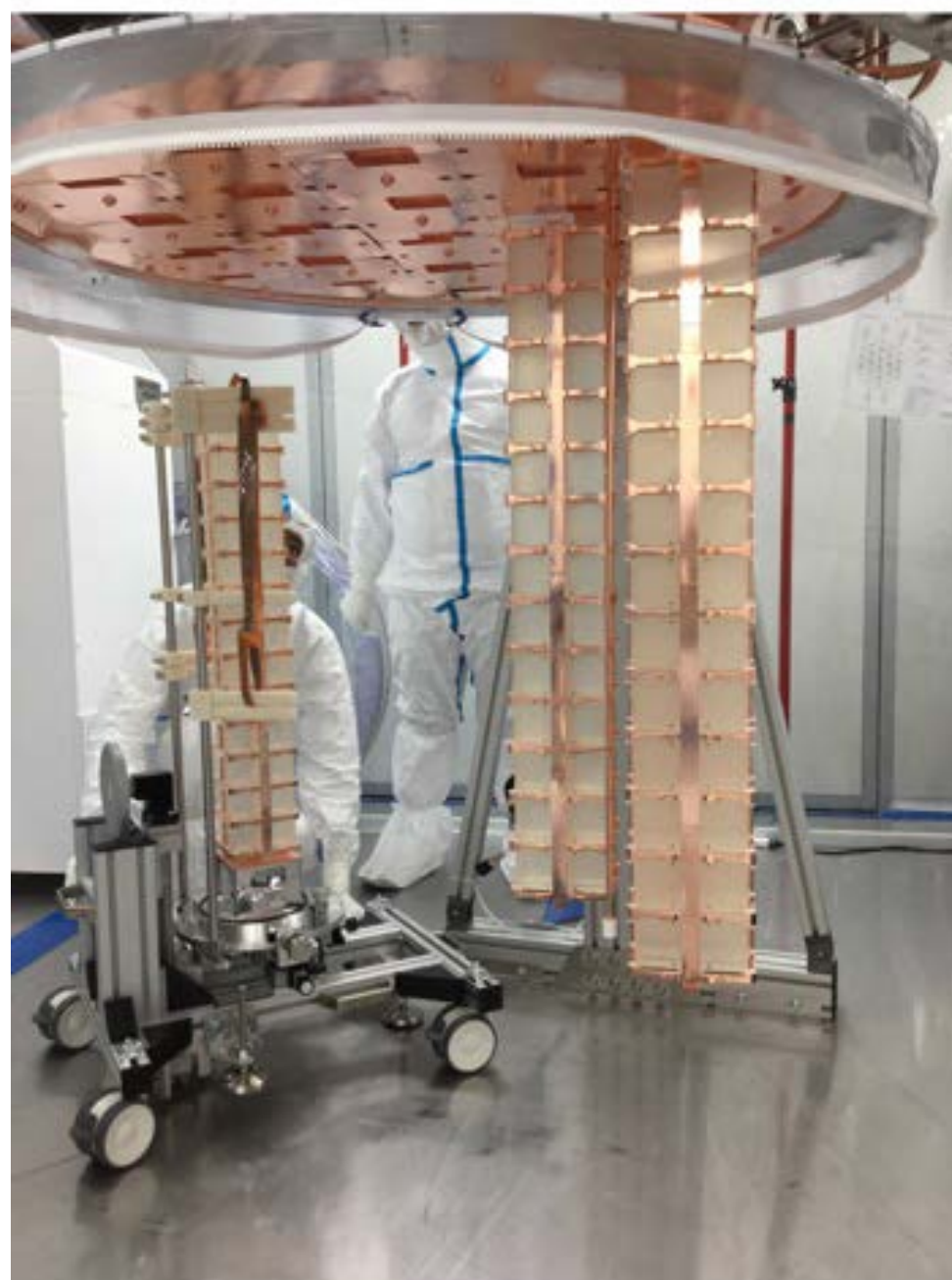
Performed in a radon-free environment:

- protected area inside the CUORE clean room flushed with radon-free air
- protective bags flushed with nitrogen

Completed on August 26, 2016

September-October 2016:

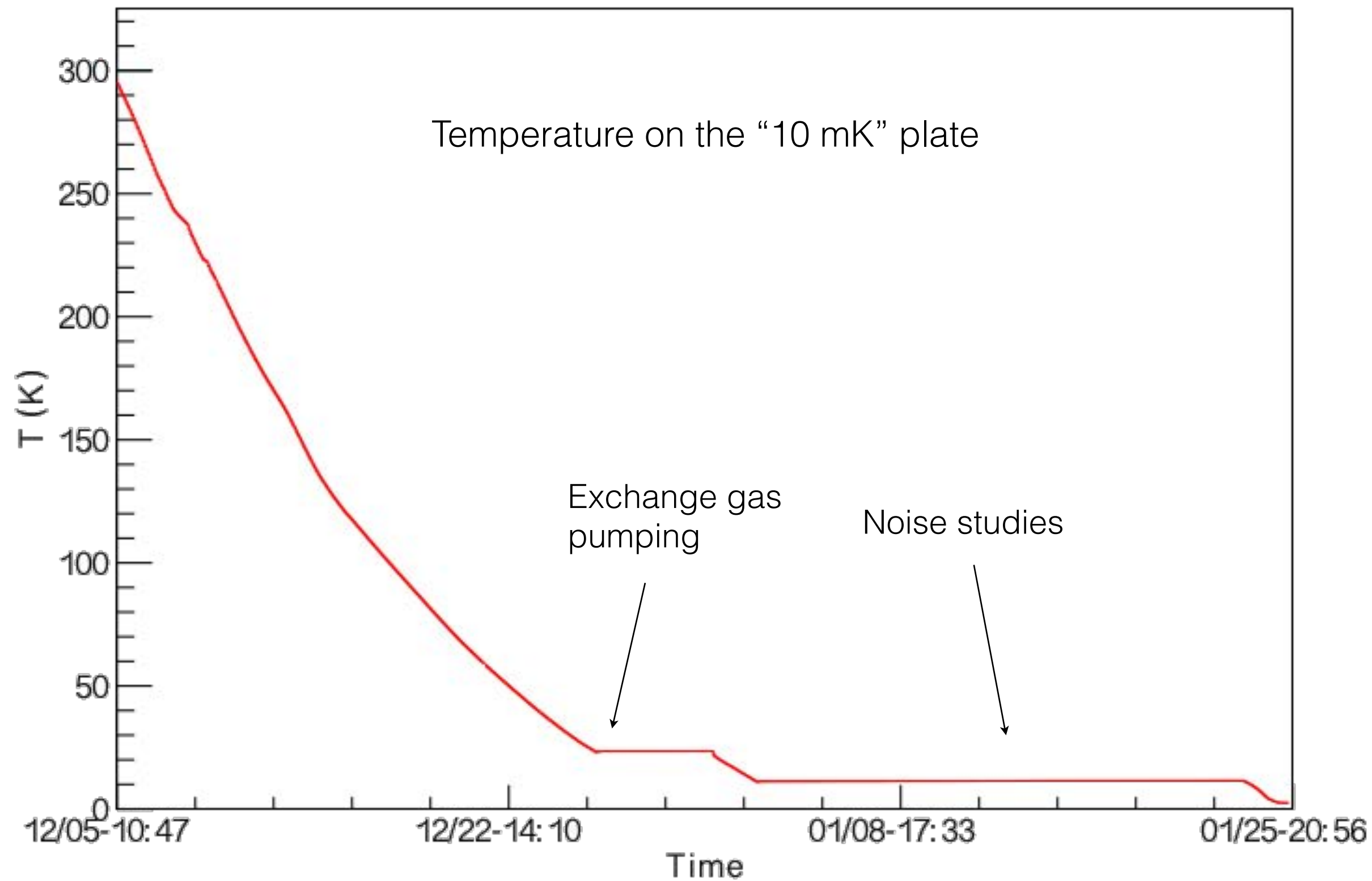
- installation of the cryostat interfaces (protective tiles) and radiation shields
- read-out tests



Detector cool down

Started at the beginning of December 2016:

- reached a stable base temperature of ~ 7 mK on Jan 27, 2017
- lowest observed temperature: 6.7 mK

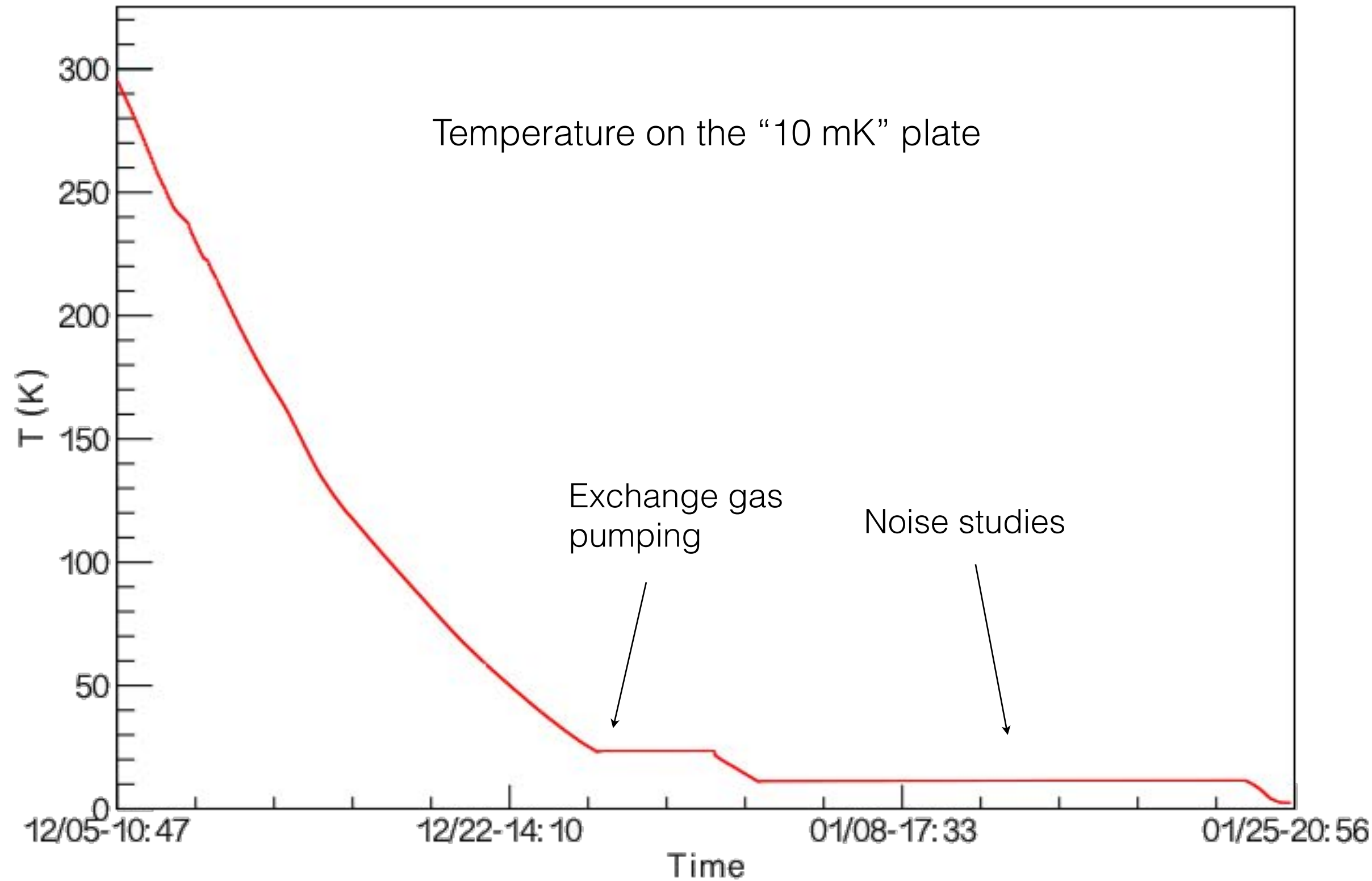
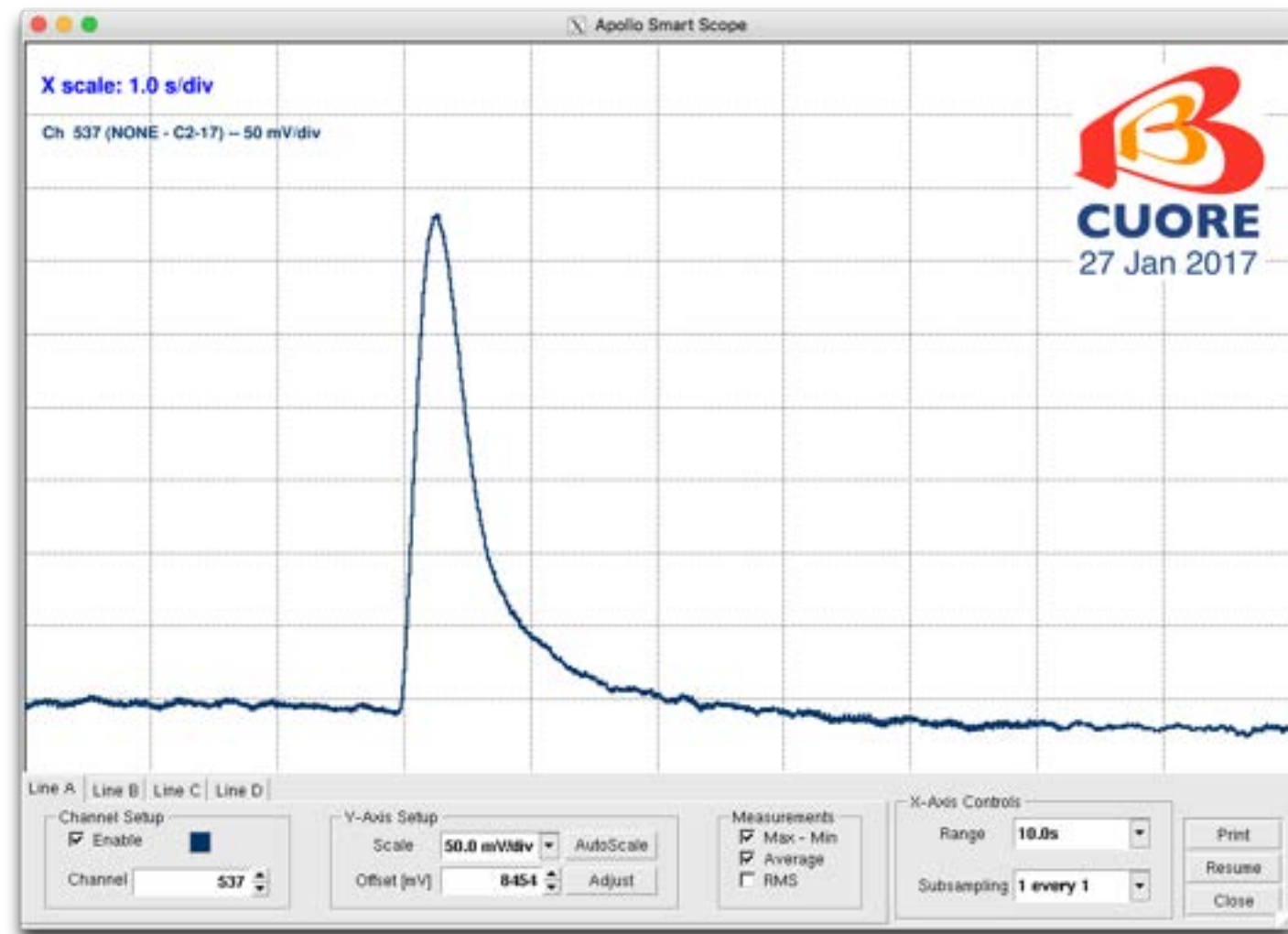


Detector cool down

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- lowest observed temperature: 6.7 mK

- observed first detector pulses just after the cool down without any optimization



Detector pre-operation

After the successful cool-down we faced the challenge to operate a thousand bolometers in a completely new system.

A long list of tests and activities

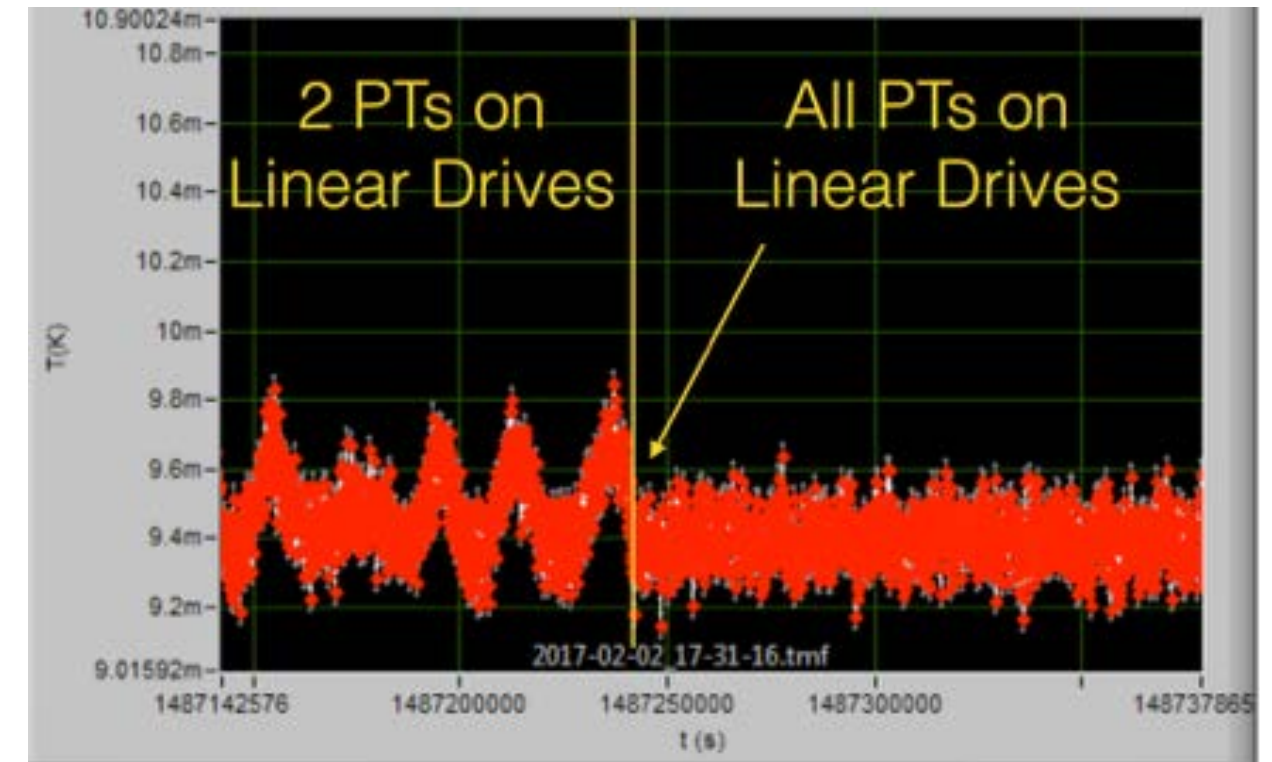
- DAQ and front-end electronics optimization
- Detector working points
 - Select representative subset
 - Load curves (to select optimal working points)
 - Temperature scan for the best operating conditions
- Noise reduction

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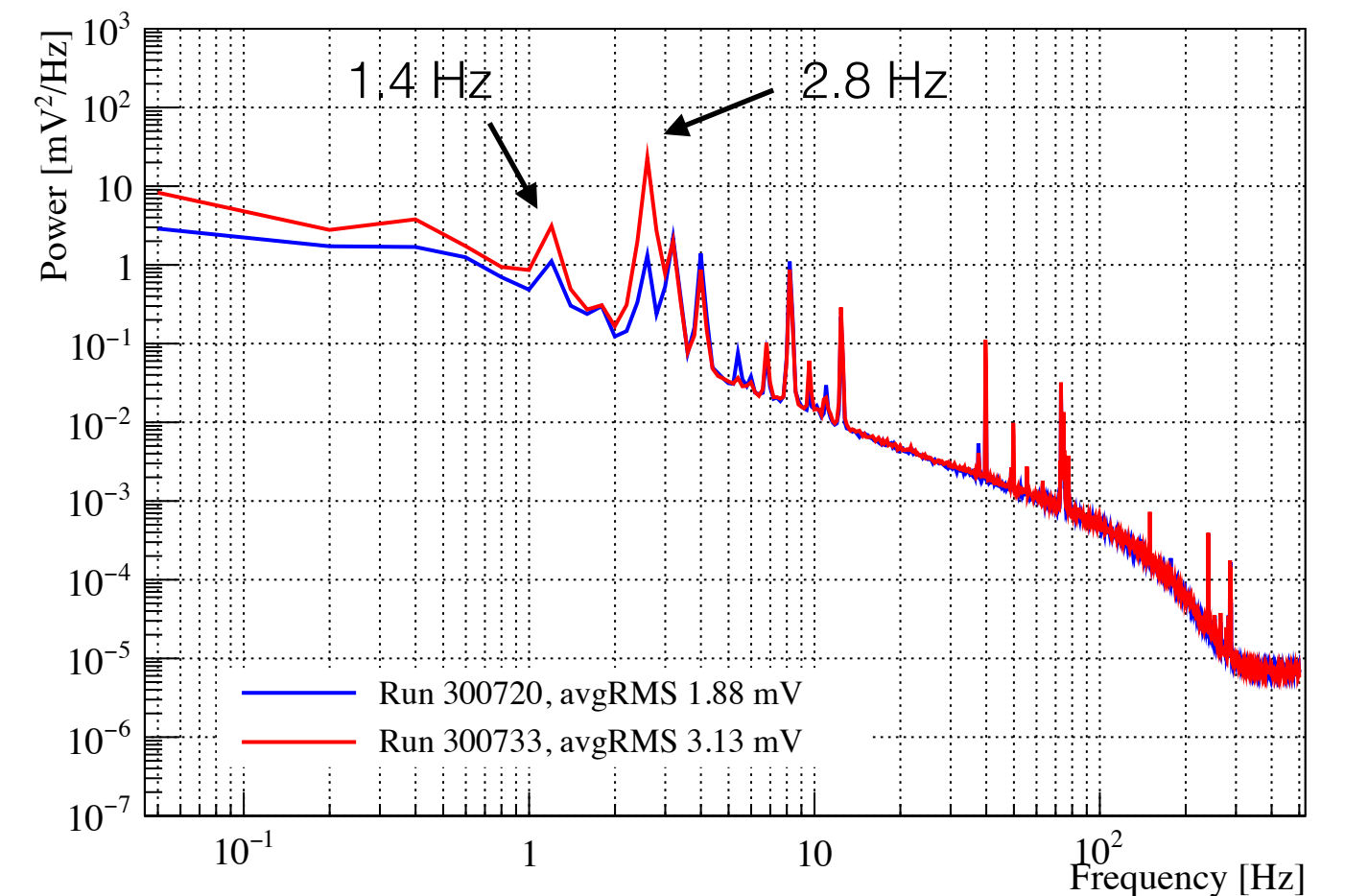
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- Linear drives to control the pulse tube (PT) motor-heads
- Monitor and control the relative phase shifts between different PT's using pressure sensors installed on the PT lines
- Impressive results both in terms of temperature stabilisation and noise abatement



Average Noise Power Spectrum: ch. 142 runs 300720, 300733



Detector pre-operation

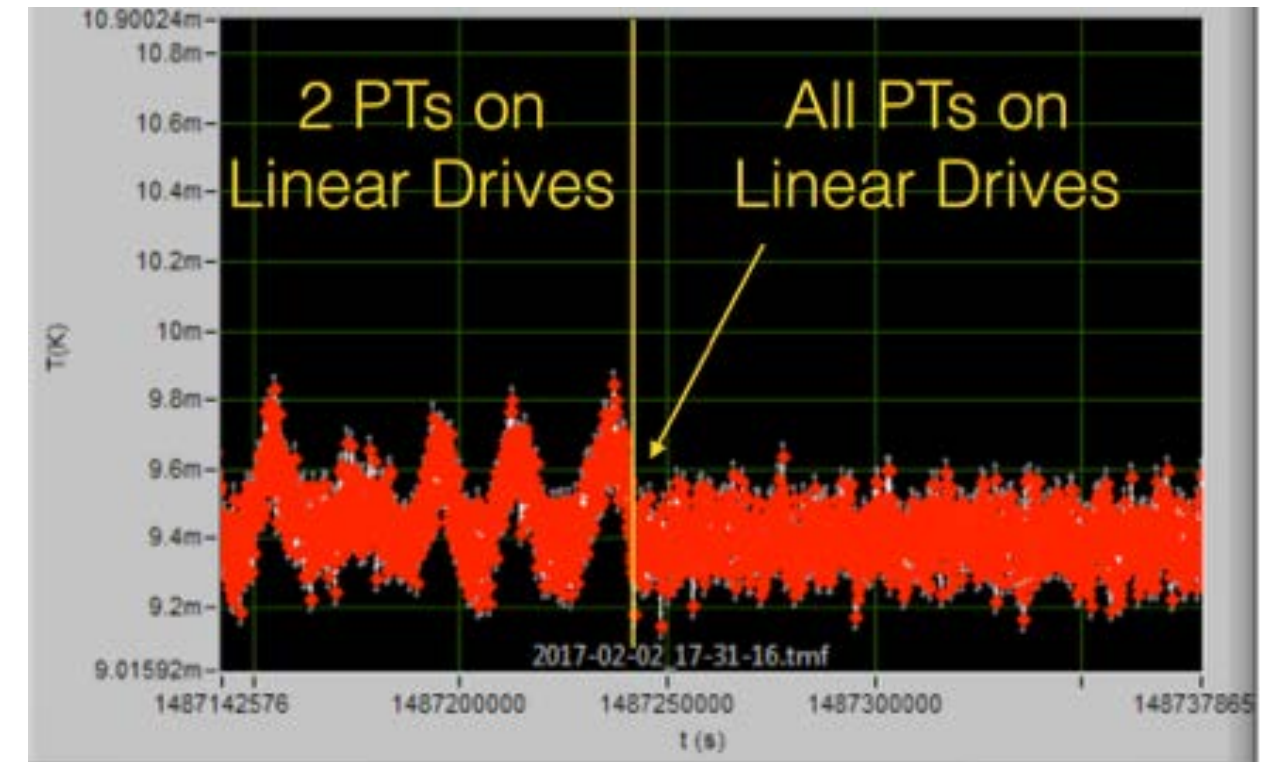
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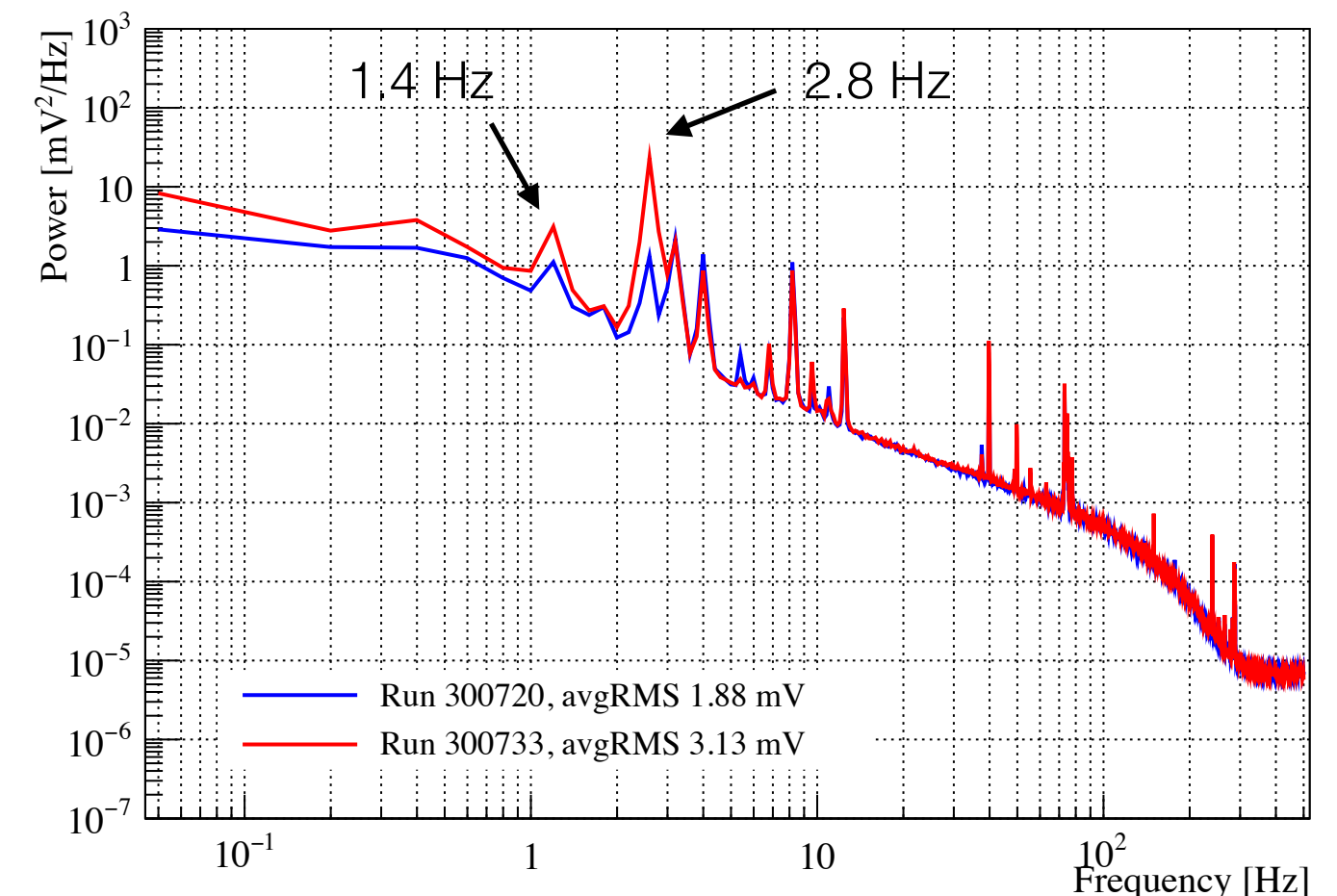
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End of March 2017:

- Closed first optimisation phase
- Ready to start calibrations and science runs
- Selected working temperature: 15 mK



Average Noise Power Spectrum: ch. 142 runs 300720, 300733



Science runs

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

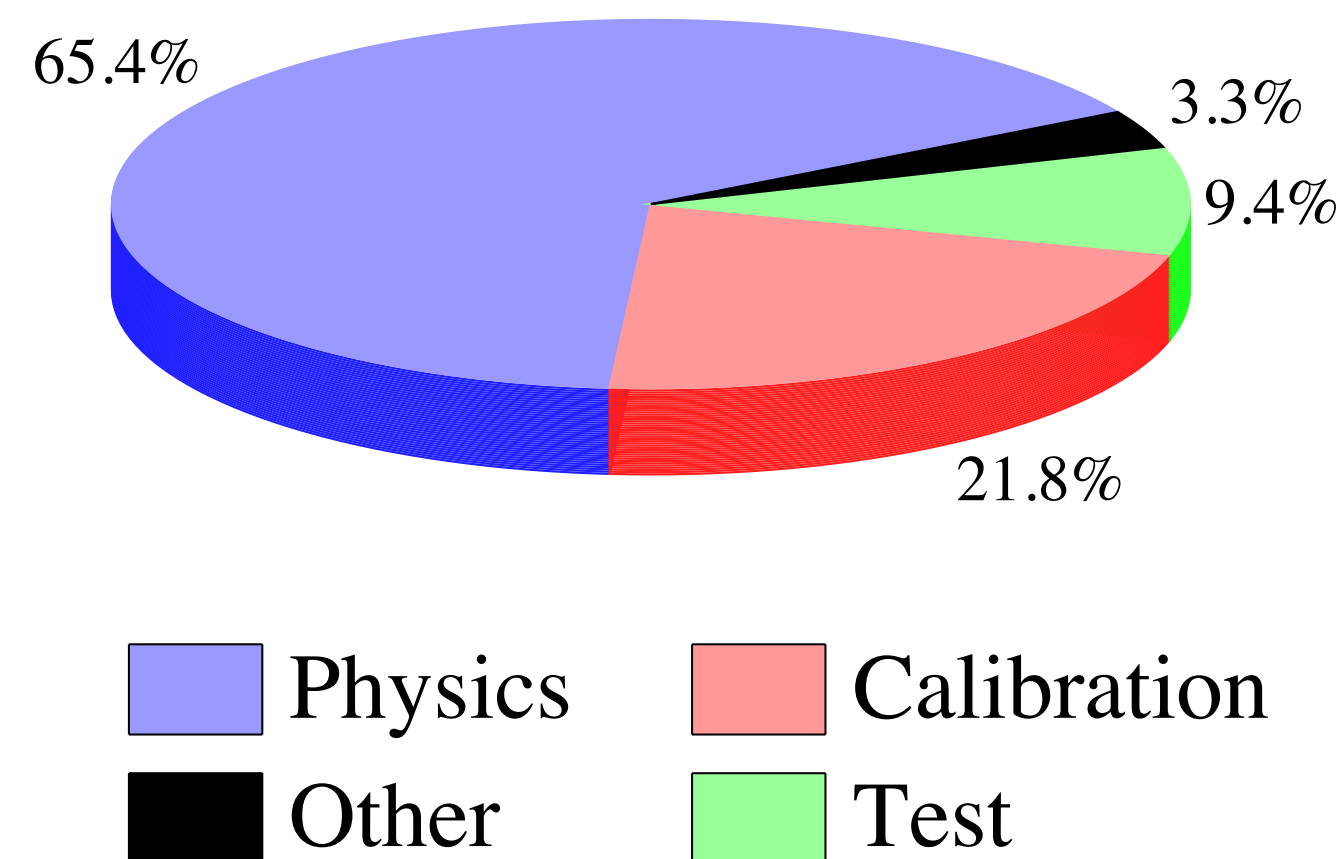
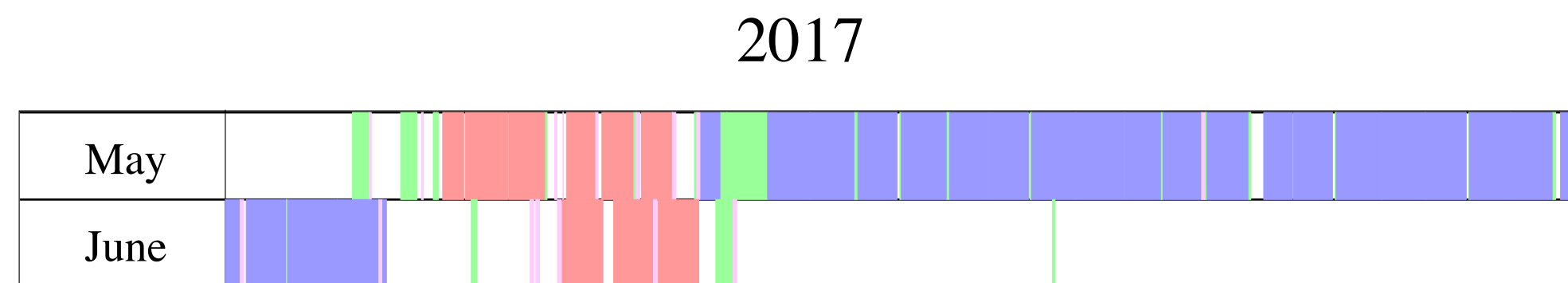
Operational performance:

- **984/988 operational channels**
- Excellent data-taking efficiency when in operations
- Much improved detector stability, compared to Cuoricino/CUORE-0
- Calibrations/physics ratio data still to be optimized to maximize $0\nu\beta\beta$ sensitivity

Acquired statistics for $0\nu\text{DBD}$ decay search:

- **$^{\text{nat}}\text{TeO}_2$ exposure: 38.1 kg yr**
- **^{130}Te exposure: 10.6 kg yr**

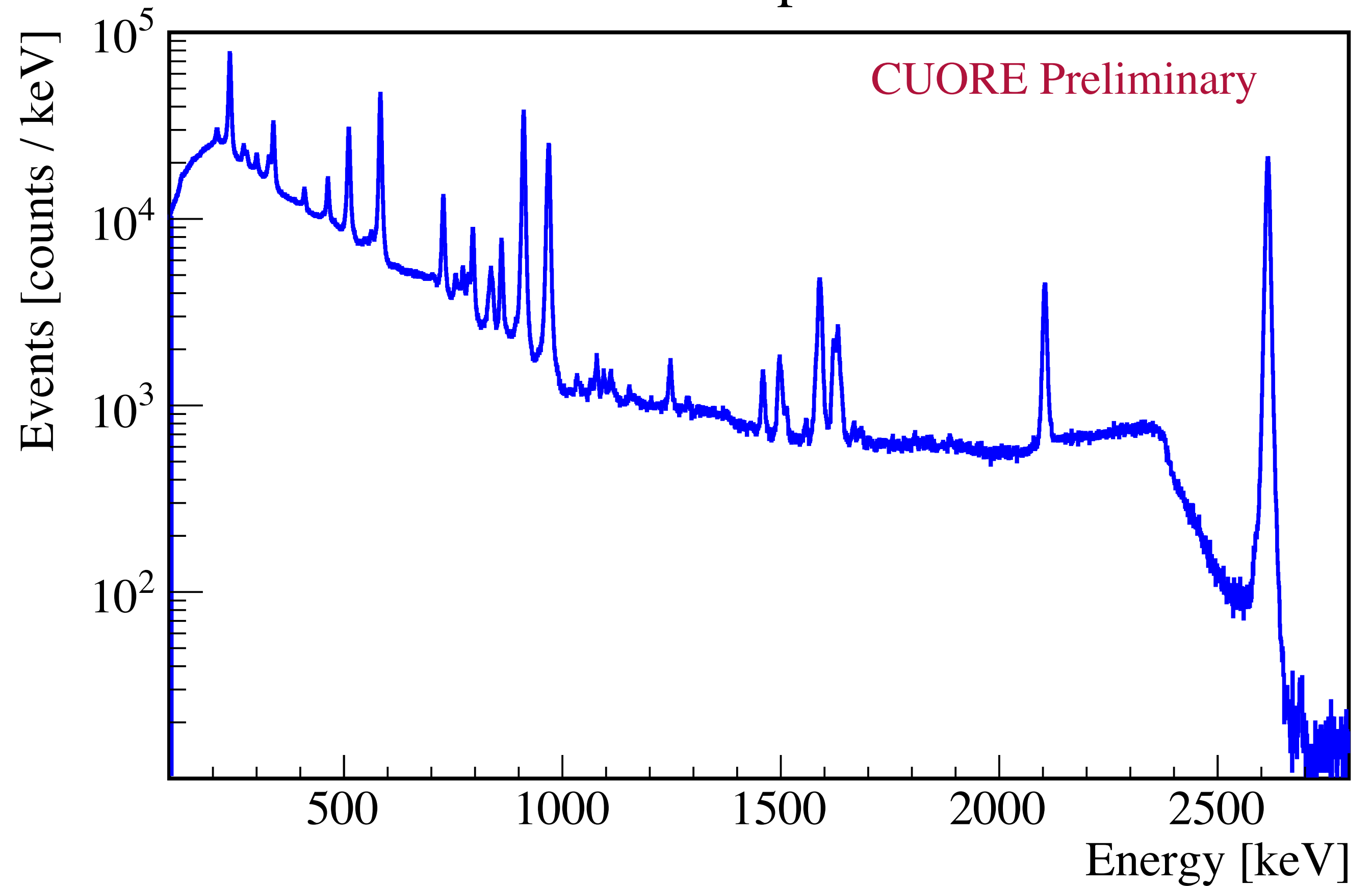
Dataset 2 time breakdown



Calibration spectrum

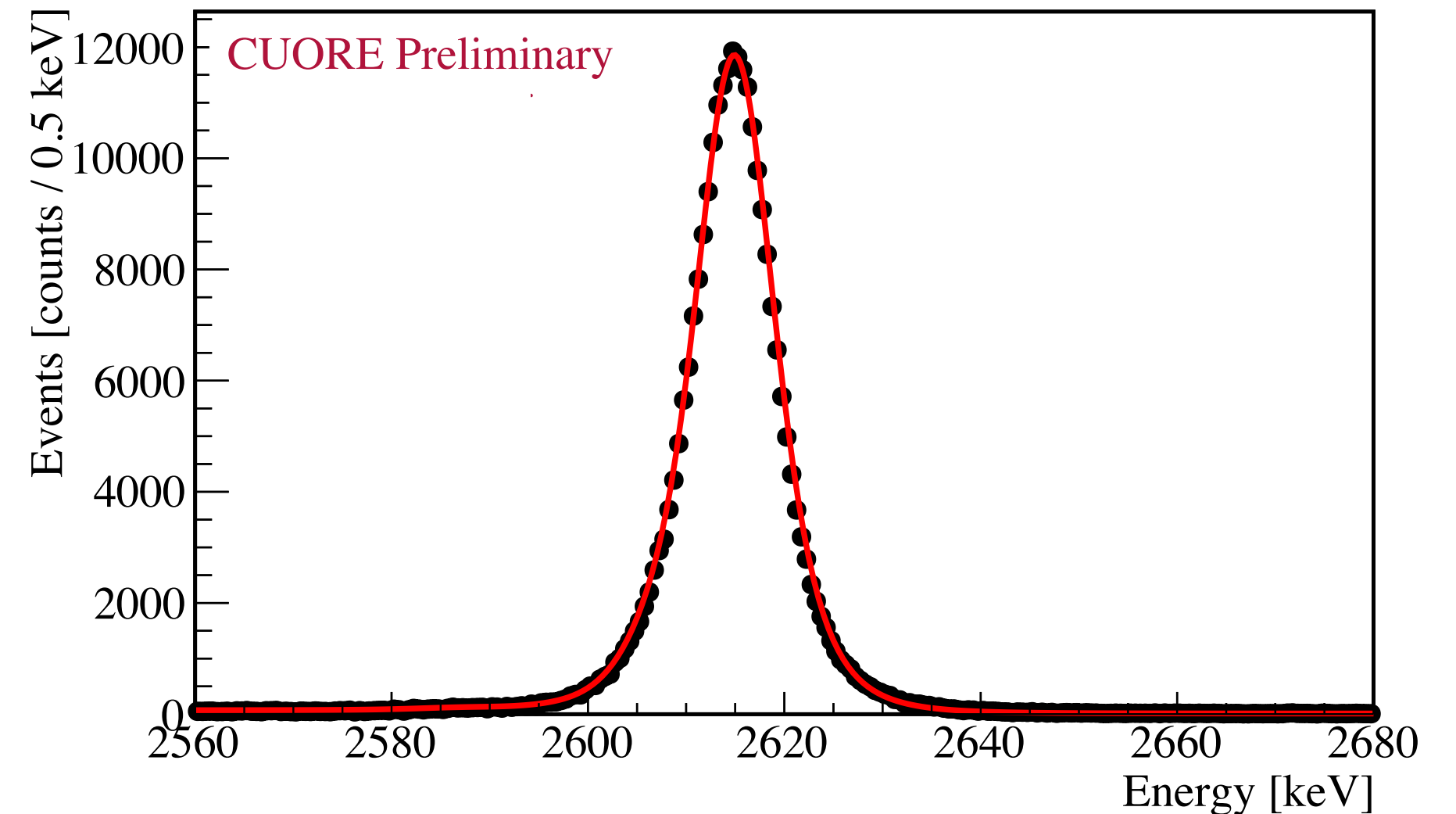
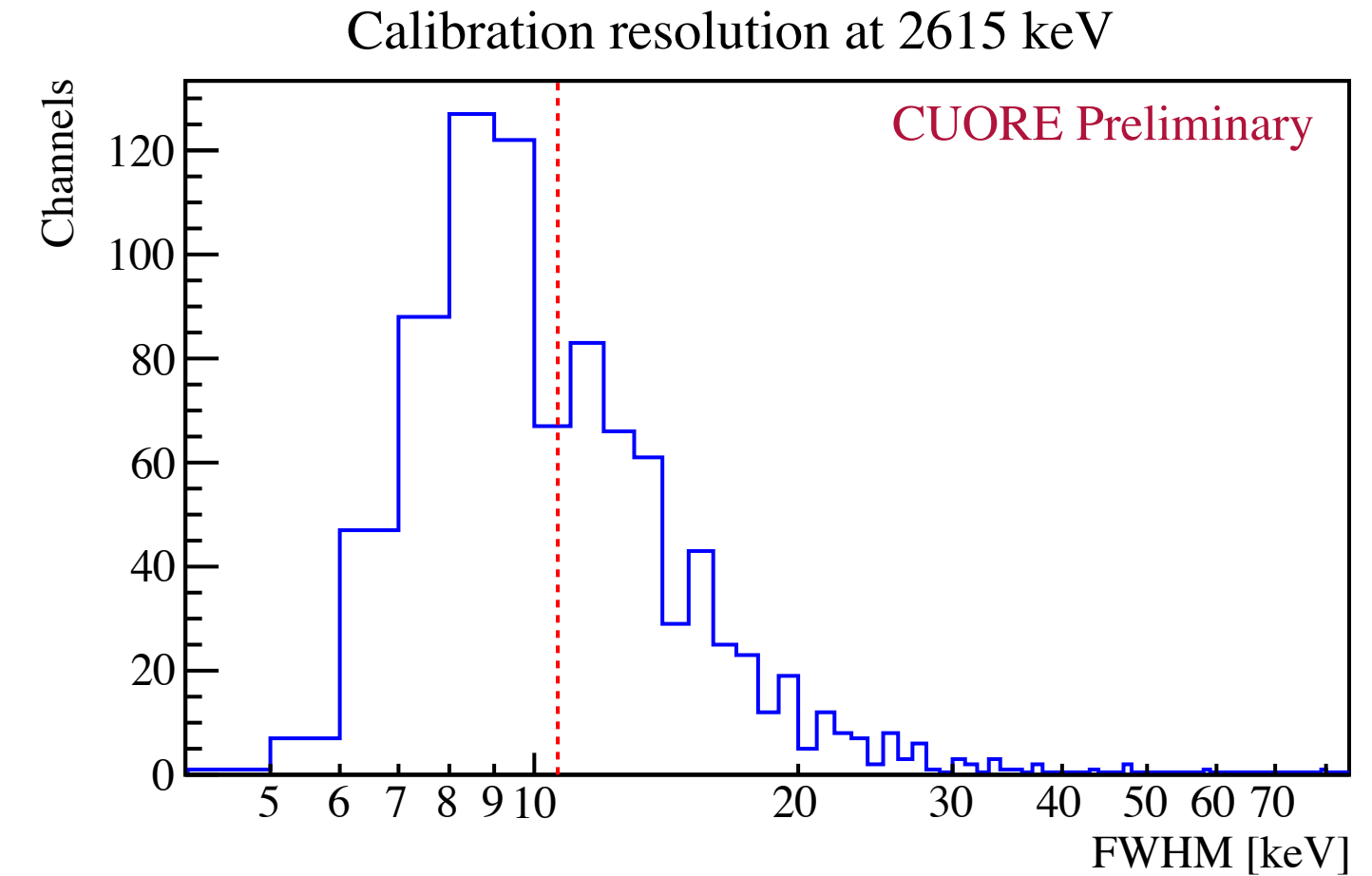
- ^{232}Th sources deployed inside the CUORE detector
- Energy spectrum of all the CUORE detectors

Calibration spectrum



Detector performance: energy resolution

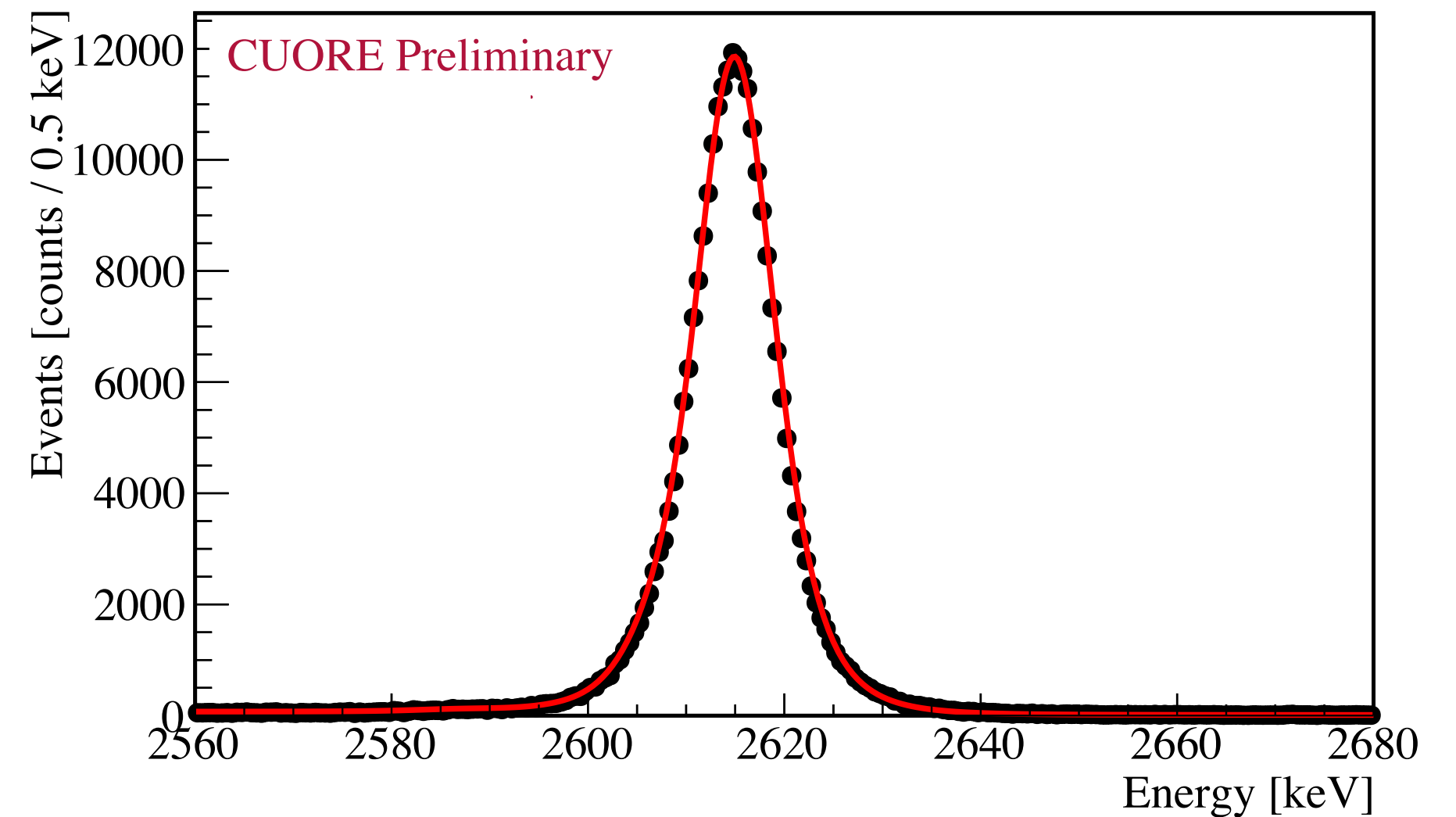
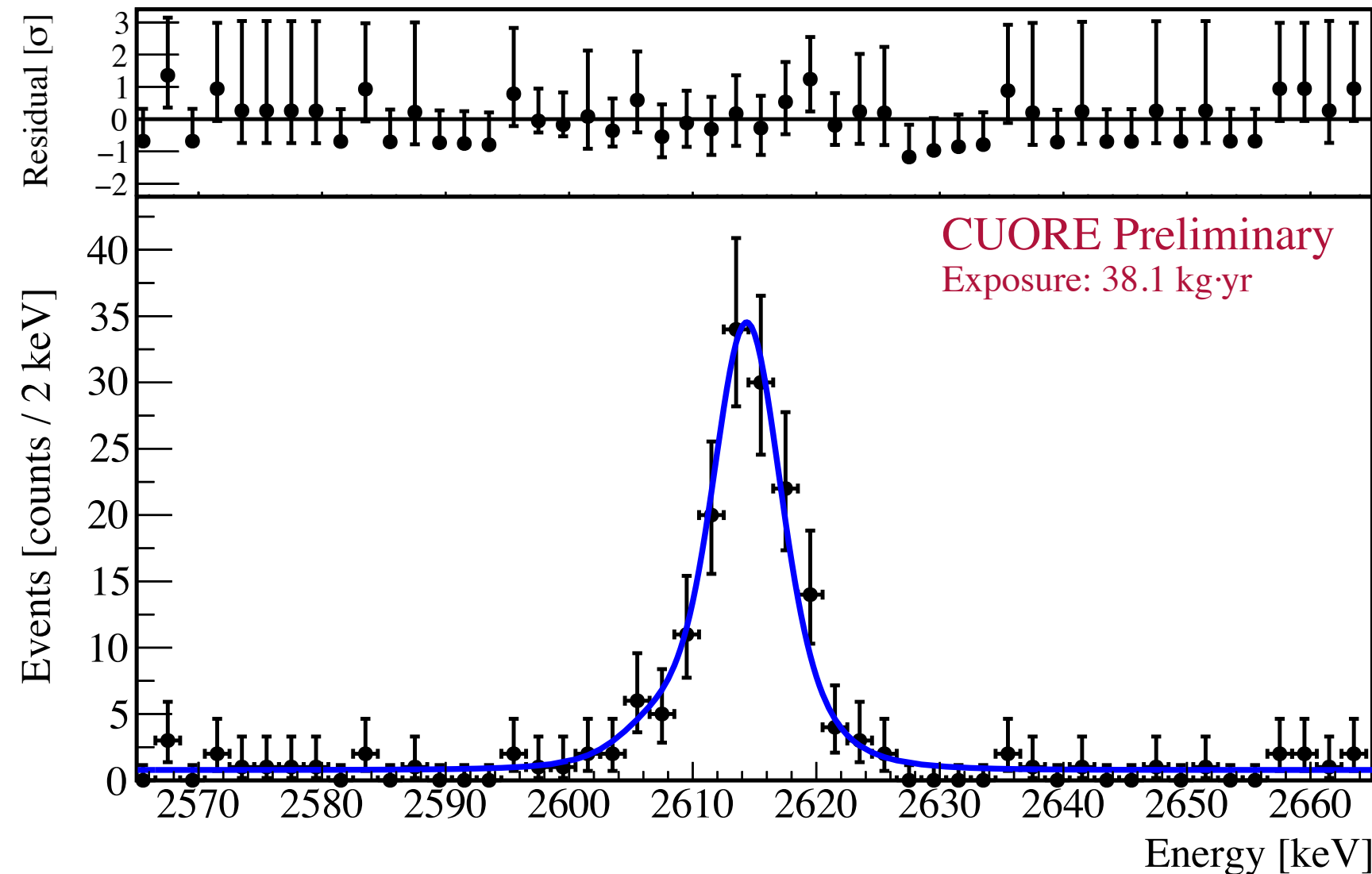
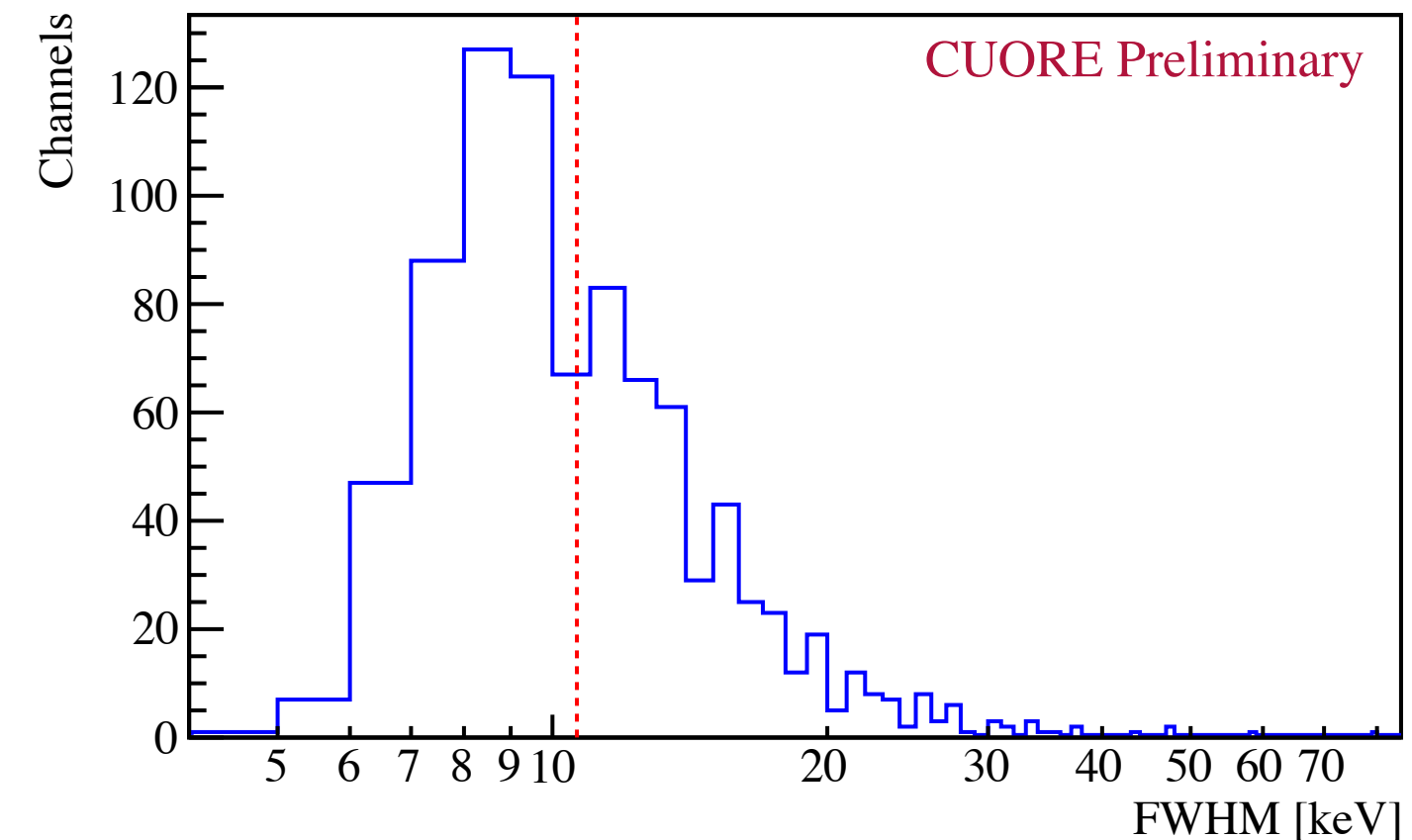
- 899 (90%) best performing channels used for initial analysis; most discarded channels had poor line or pulse shapes, and should be recovered in future runs
- Average (“harmonic mean”) energy resolution in calibration runs: **10.6 keV FWHM @ 2615 keV**



Detector performance: energy resolution

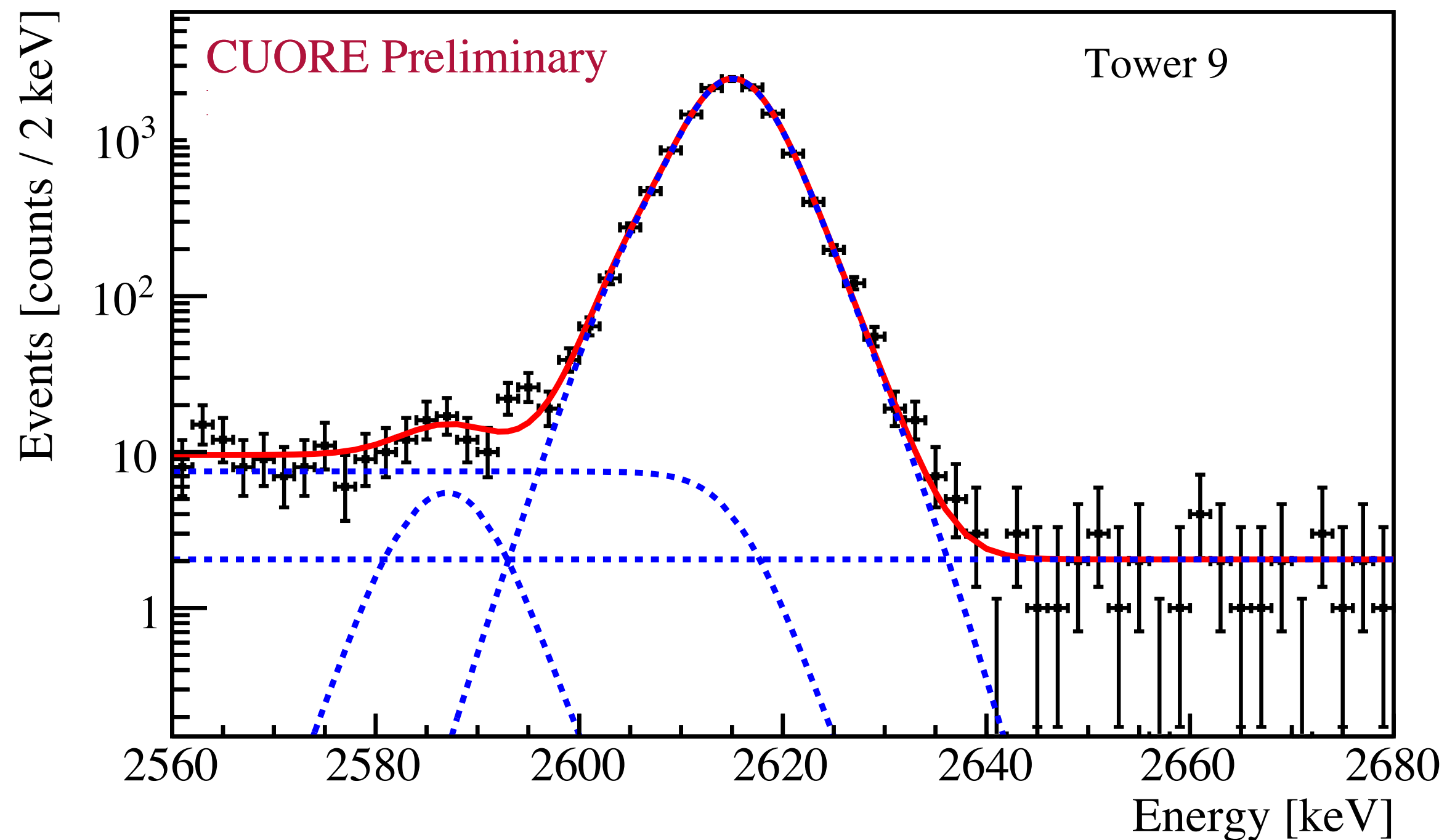
- 899 (90%) best performing channels used for initial analysis; most discarded channels had poor line or pulse shapes, and should be recovered in future runs
- Average (“harmonic mean”) energy resolution in calibration runs: **10.6 keV FWHM @ 2615 keV**
- Significantly better performance in physics data: **(7.9 ± 0.6) keV FWHM @ 2615 keV**

Calibration resolution at 2615 keV



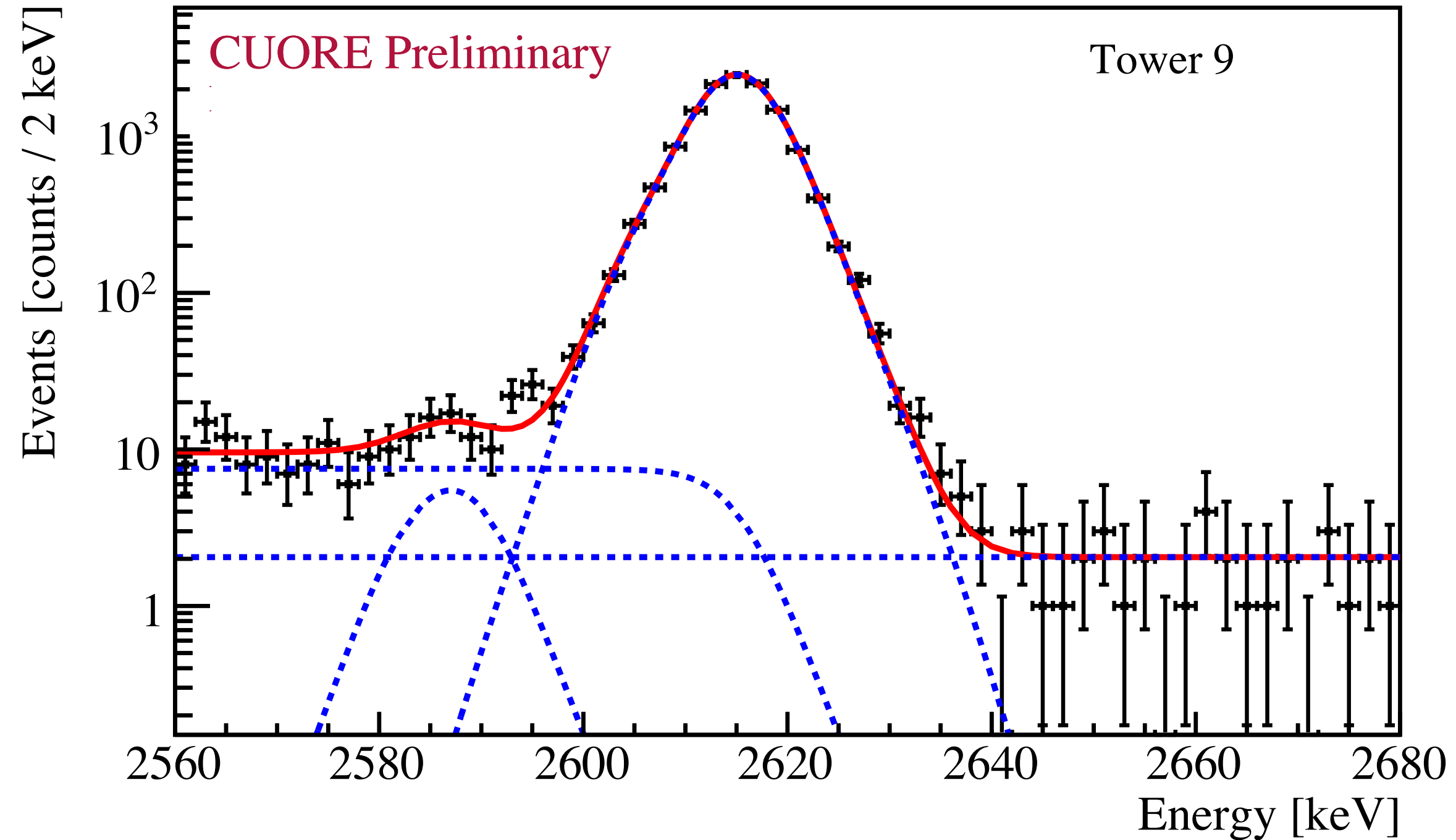
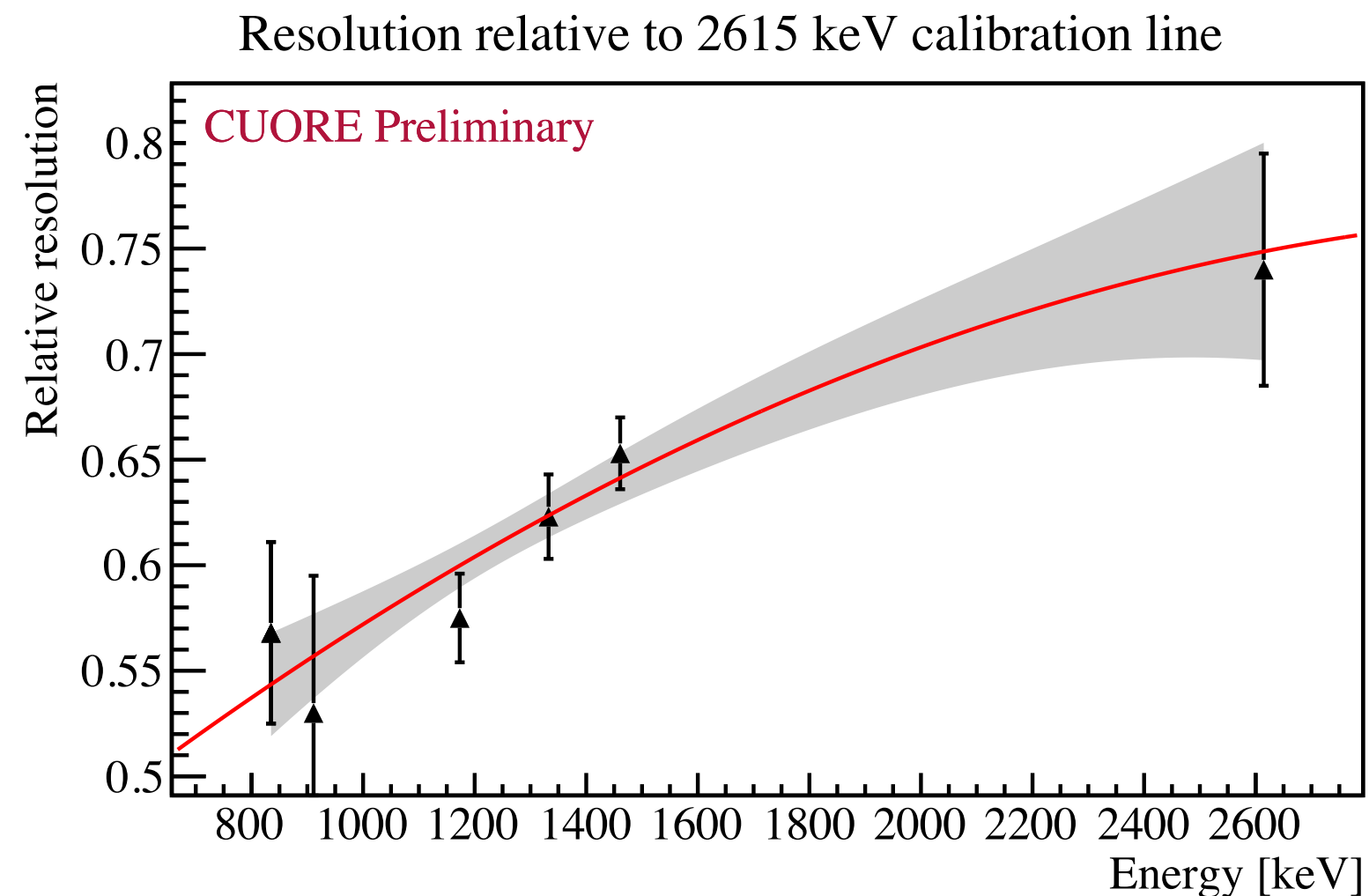
Detector performance: line shape

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



Detector performance: line shape

- Fit components:
 - a flat background
 - a step-wise smeared background
 - a double gaussian for the main peak
 - a combination of gaussian 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



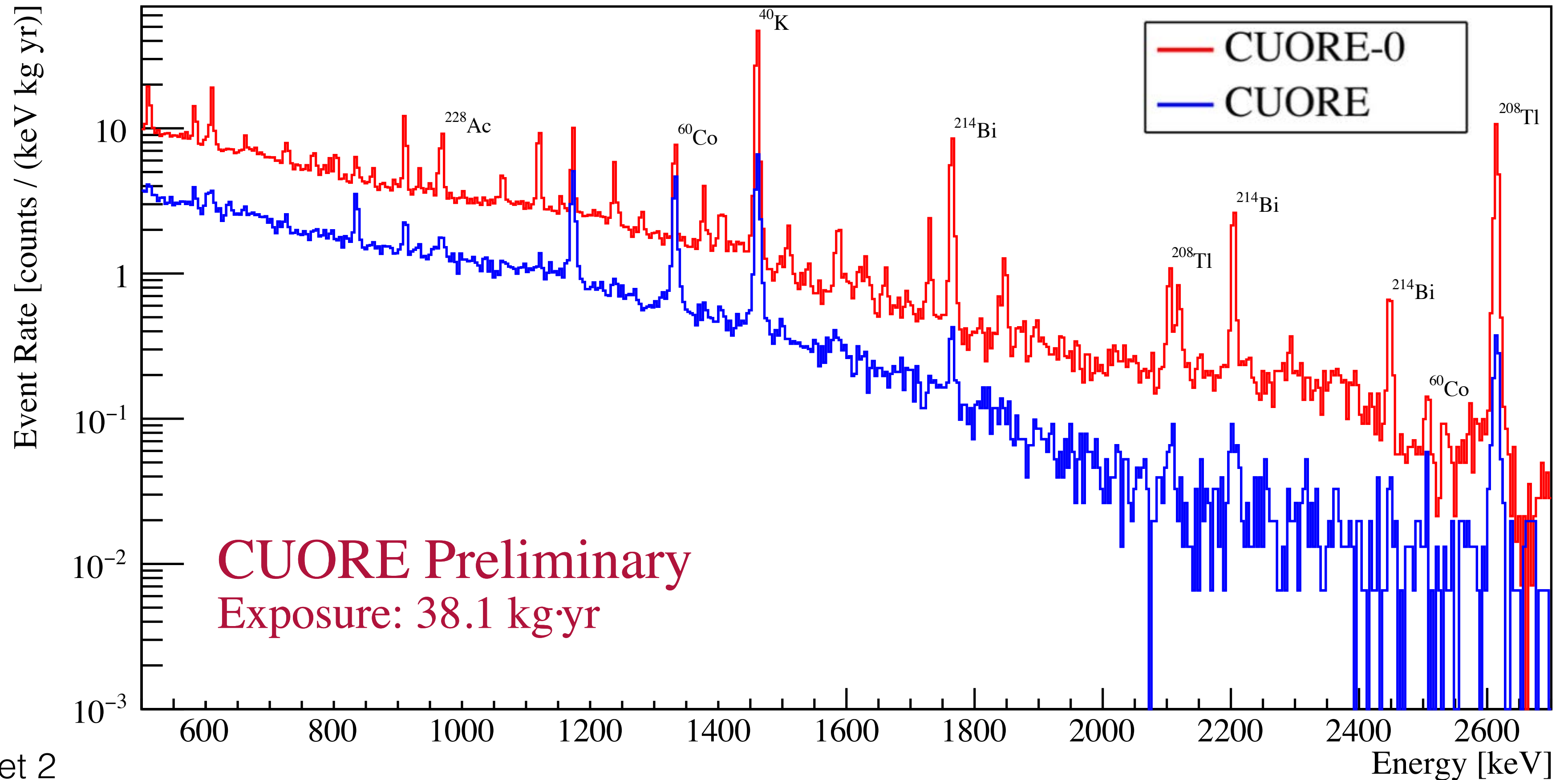
Analysis steps



- Acquisition of triggered signals
- Data preprocessing: estimation of raw parameters
- Pulse filtering
- Thermal Gain Stabilization (TGS)
- Energy calibration
- Particle event selection
- Coincidence analysis
- Energy spectrum

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

Background spectra: γ region

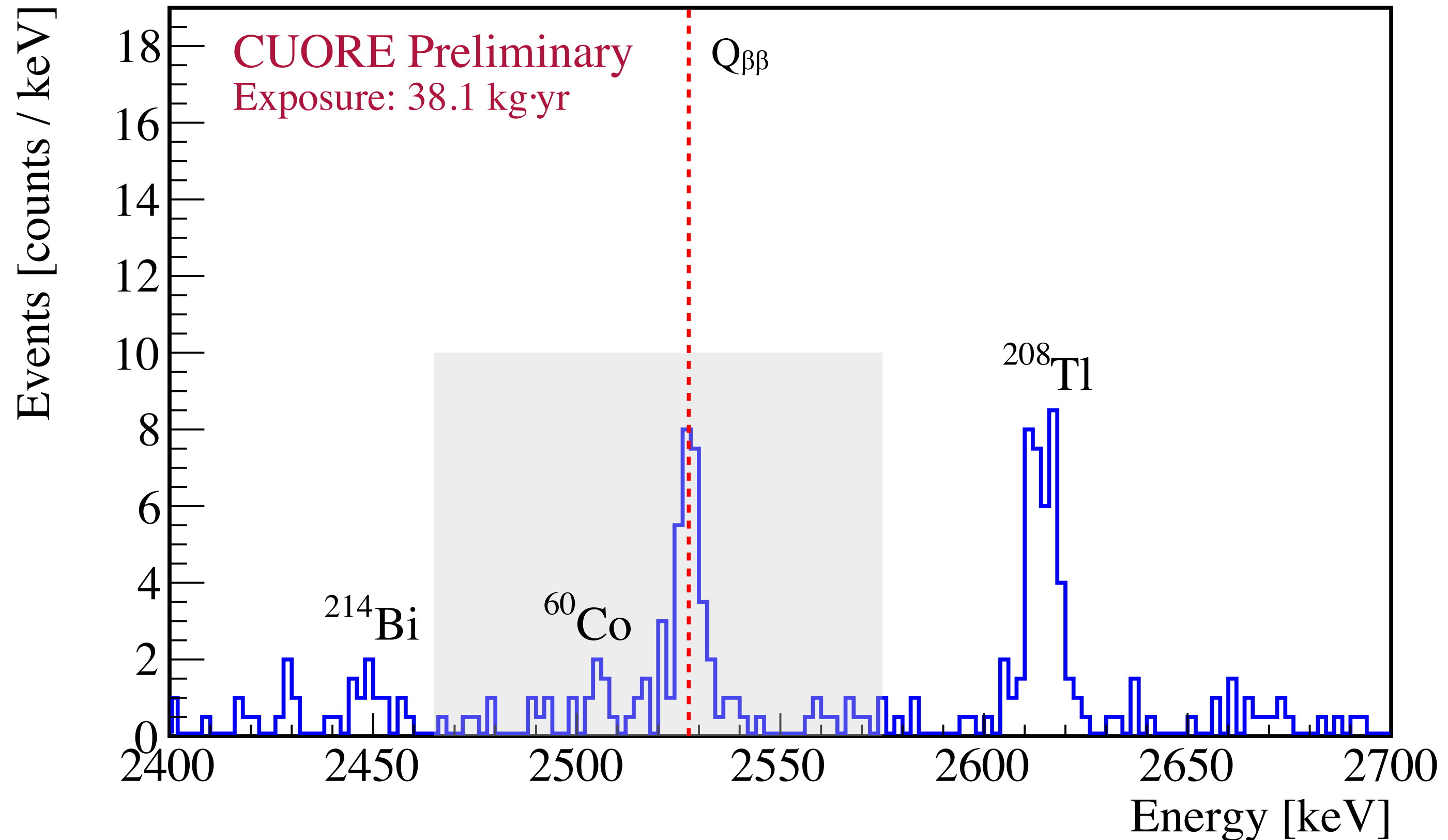


Dataset 2

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 0νDBD Q-value and blinds the real 0νDBD rate of ^{130}Te .
- This method of blinding the data preserves the integrity of the possible 0νDBD events while maintaining the spectral characteristics with measured energy resolution and introducing no discontinuities in the spectrum.

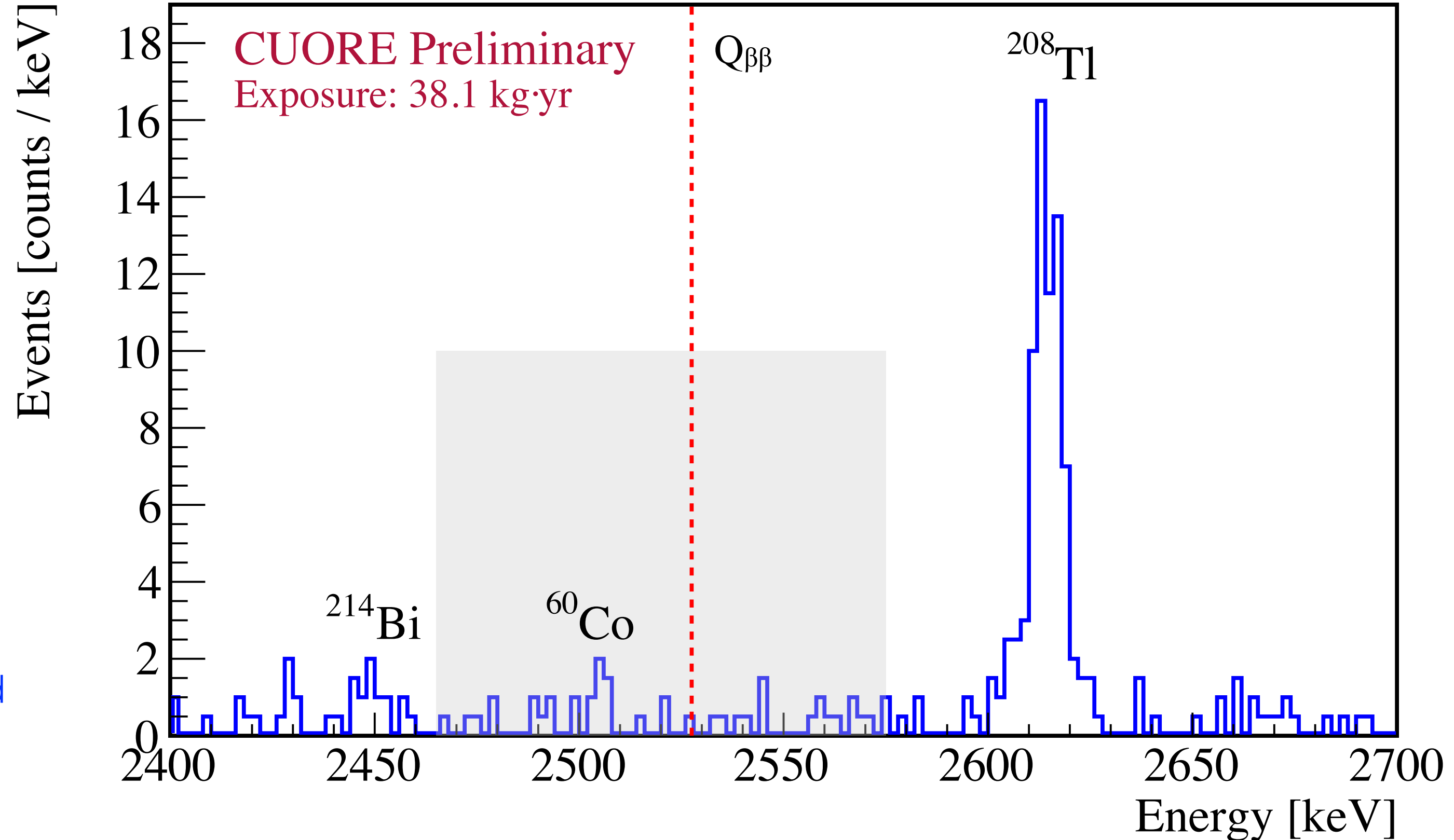
CUORE physics spectrum (blinded)



Blinded spectrum

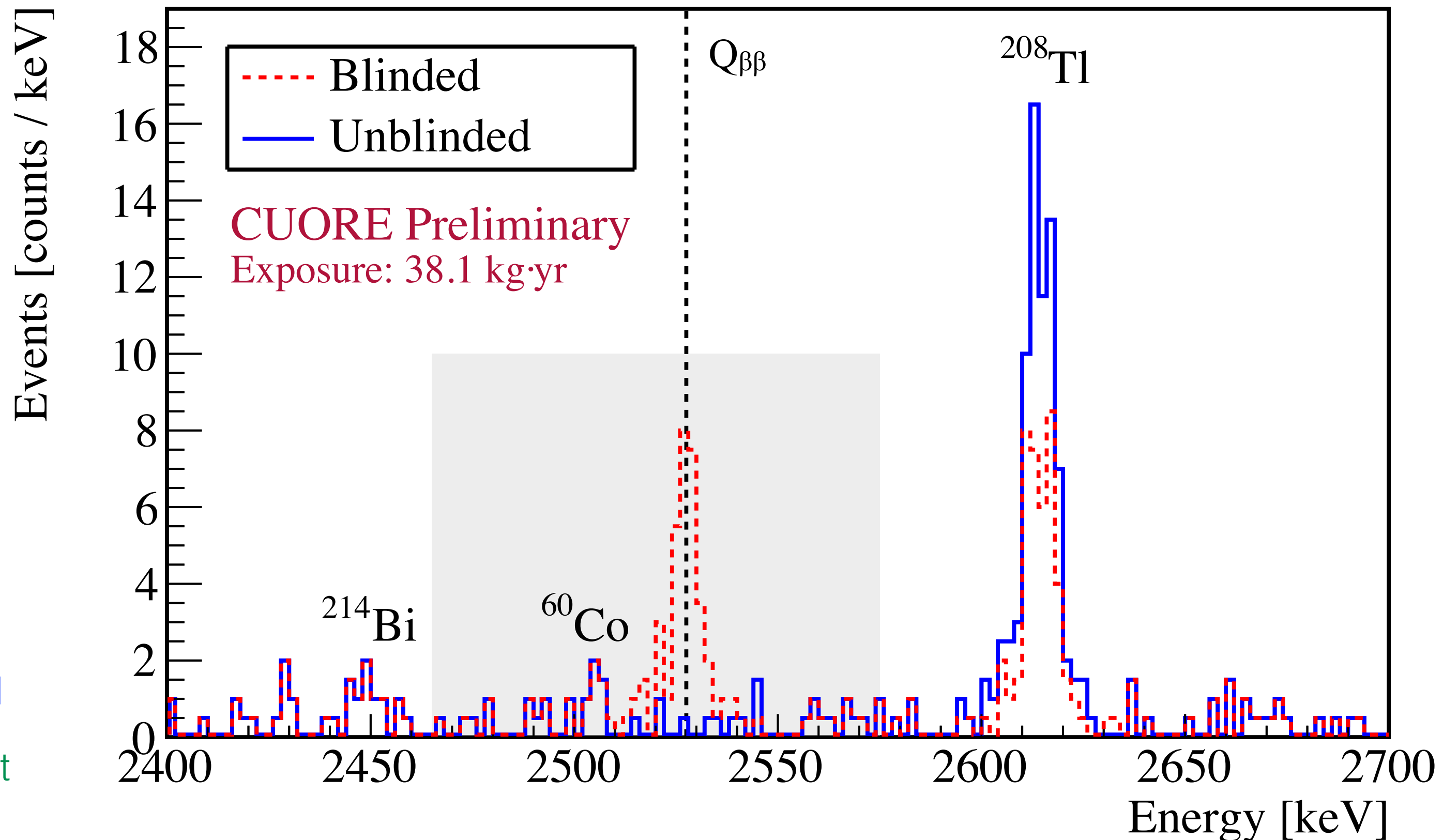
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- When all data analysis procedures are fixed the data are eventually unblinded

CUORE physics spectrum (unblinded)



Blinded spectrum

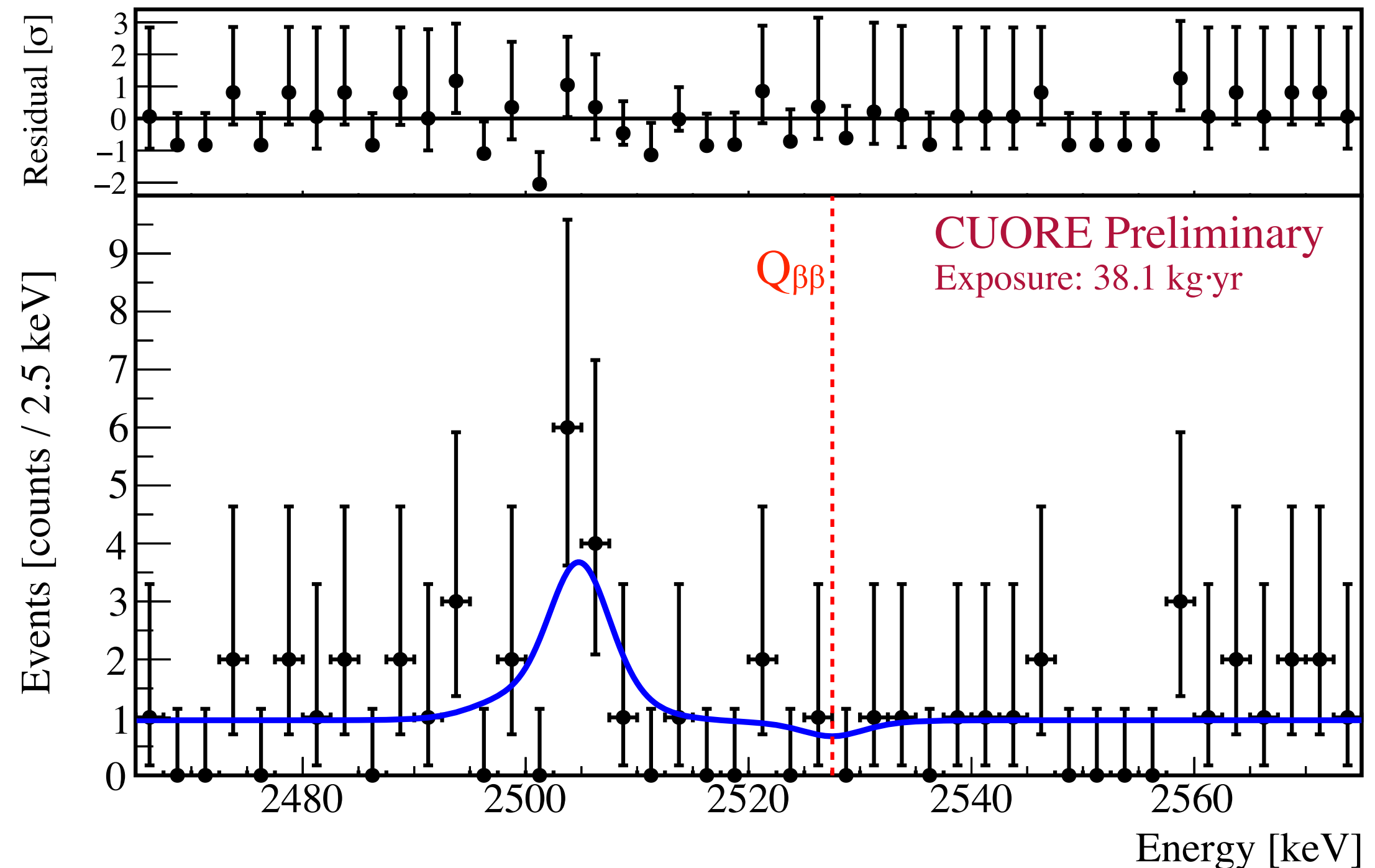
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- When all data analysis procedures are fixed the data are eventually unblinded
- The blinding procedure is more evident by comparing directly the two spectra



Fit in the ROI

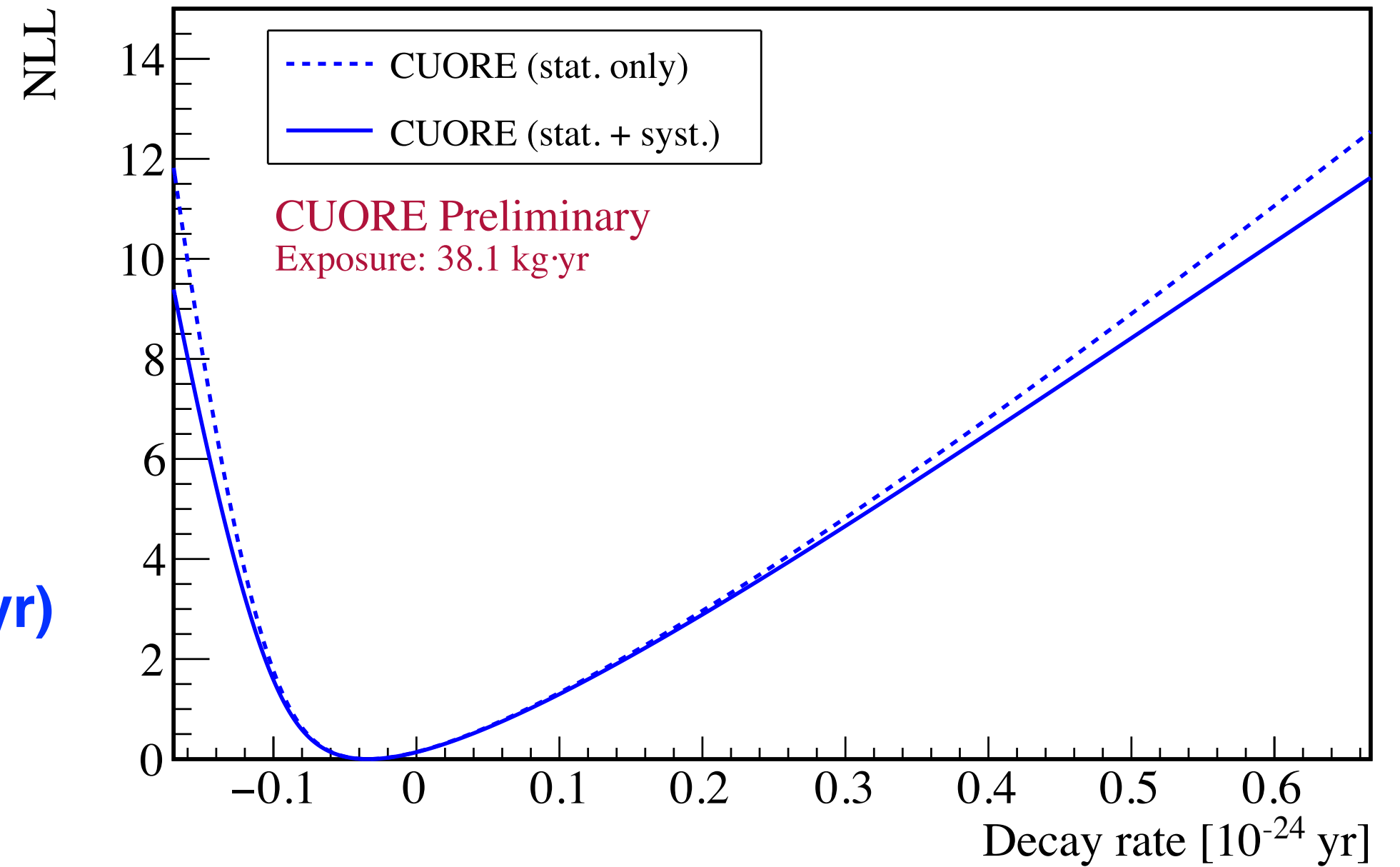
- We determined the yield of $0\nu\beta\beta$ events by performing a simultaneous UEML fit in the energy region 2465-2575 keV
- The fit has 3 components:
 - a posited peak at the Q-value of ^{130}Te
 - a floating peak to account for the ^{60}Co sum gamma line (2505 keV)
 - a constant continuum background, attributed to multi scatter Compton events from ^{208}Tl and surface alpha events

Unblinded
spectrum fit



Fit in the ROI

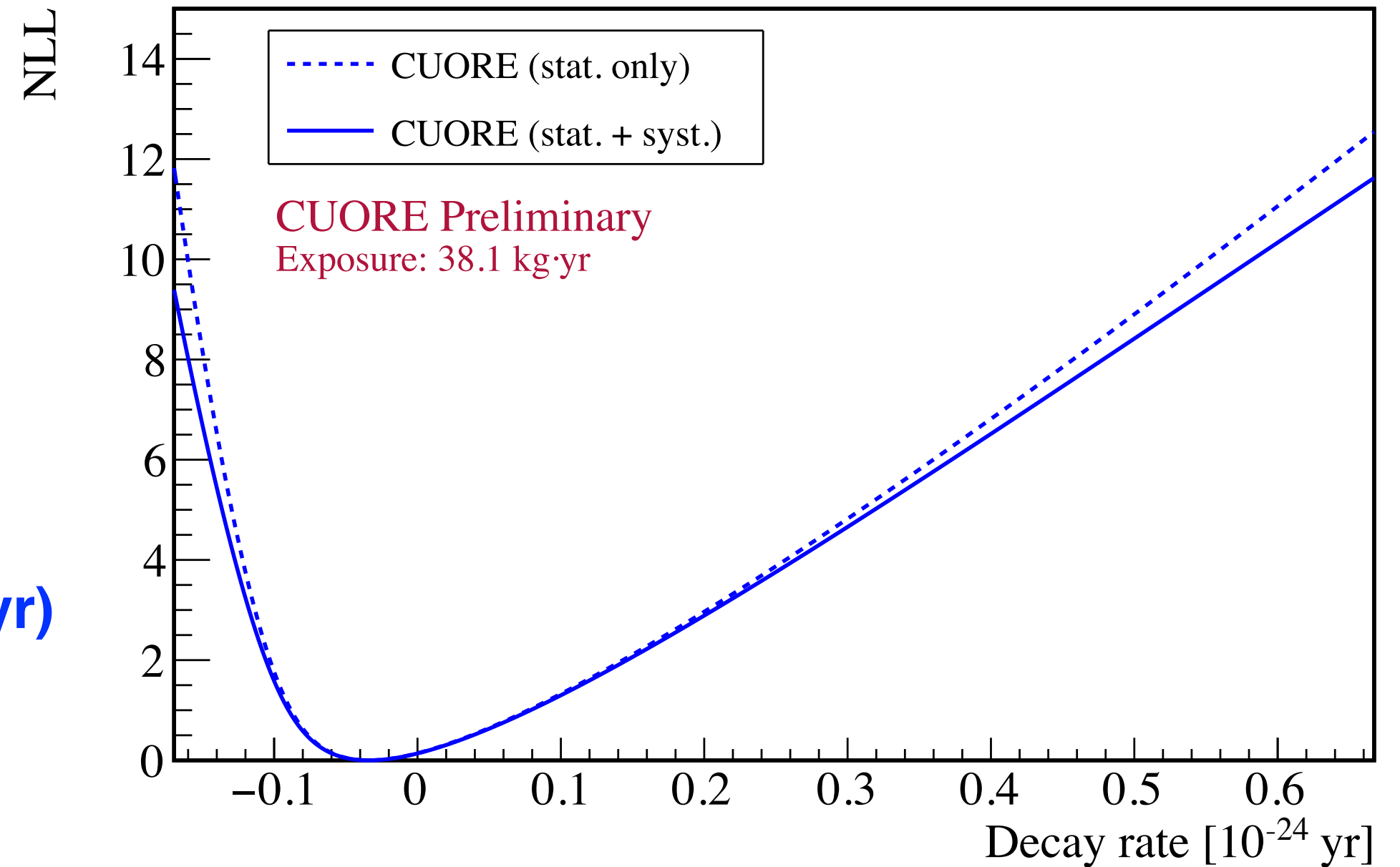
- Profile likelihood
 - Integrated on the physical region
-
- Region of interest: **2565 to 2575 keV**
 - Overall signal efficiency ; **(55.3 ± 3.0)%**
 - ROI background index: **(9.8_{-1.5}^{+1.7}) × 10⁻³ c/(keV · kg · yr)**
 - Events in the region of interest: **50**
 - Best fit for ⁶⁰Co mean: **(2504.8 ± 1.2) keV**



Fit in the ROI

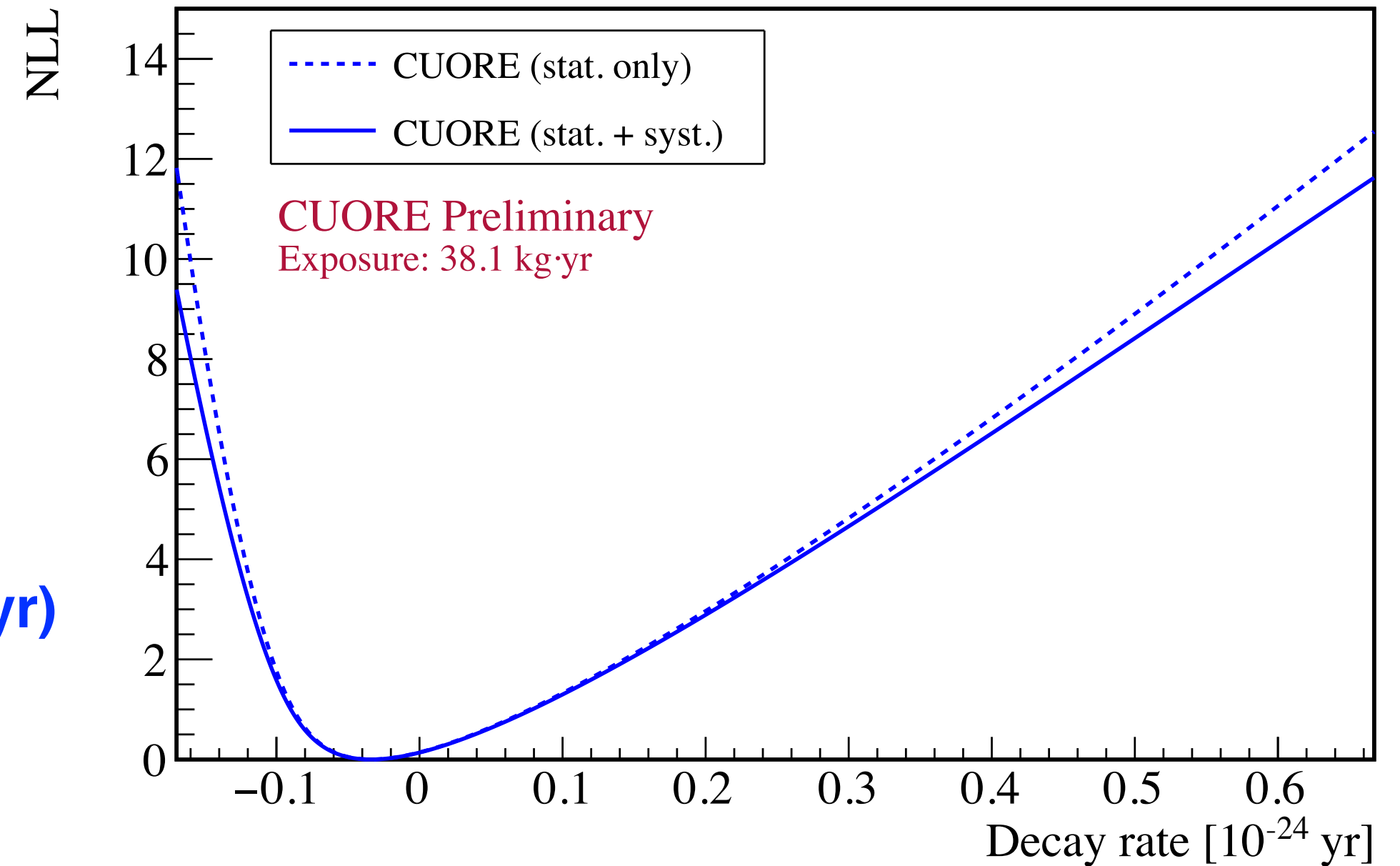
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- Best fit decay rate: **(-0.03_{-0.04}^{+0.07} (stat.) ± 0.01 (syst.)) × 10⁻²⁴ / yr**
- Decay rate limit (90% CL, including systematics): **0.15 × 10⁻²⁴ / yr**
- Half-life limit (90% CL, including systematics): **4.5 × 10²⁴ yr**
- Median expected sensitivity: **3.6 × 10²⁴ yr (arXiv:1705.10816)**



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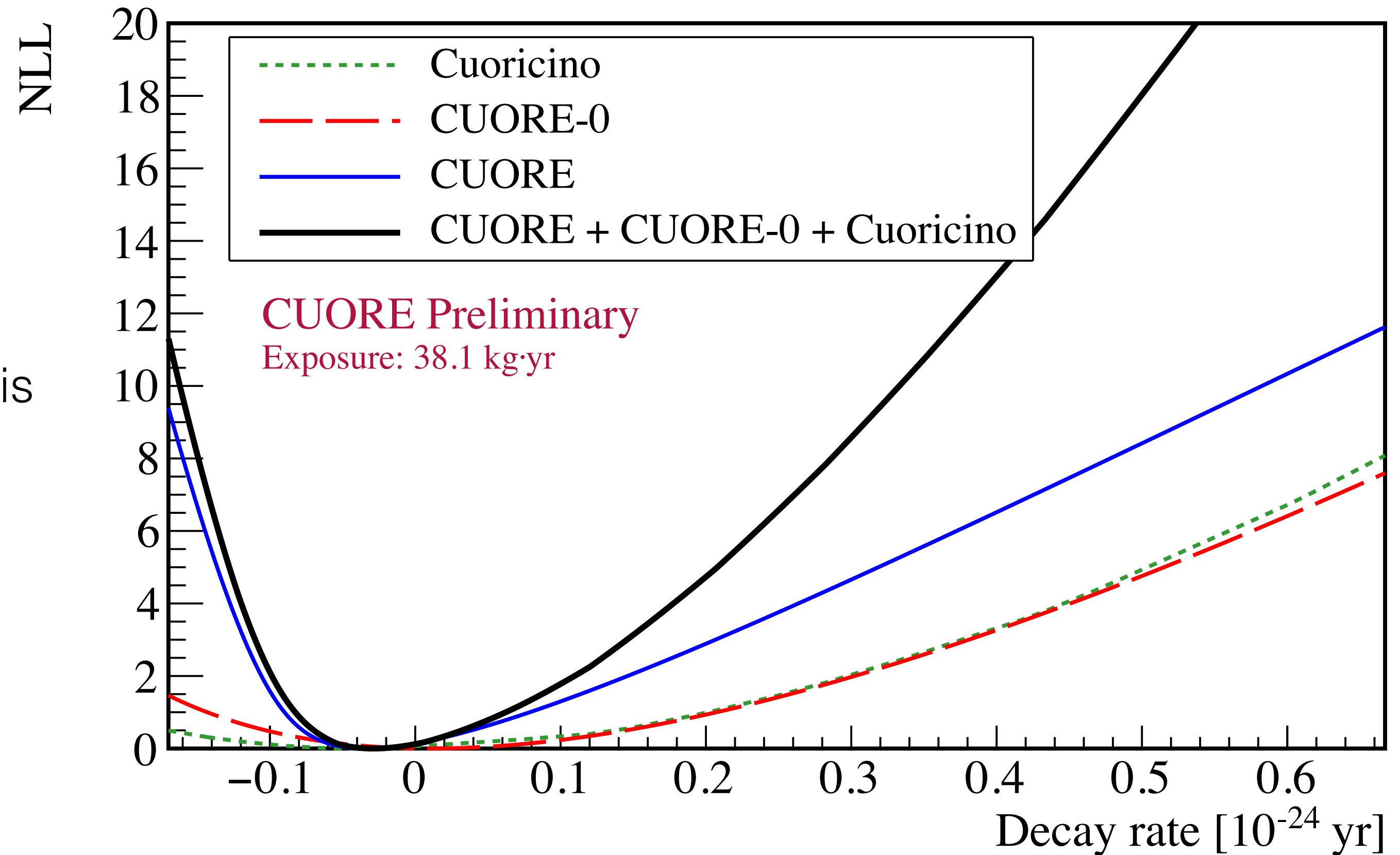
We have also evaluated limits according to “W. Rolke et al., Nucl. Instrum. Meth. A 551, 493-503 (2005)”:

- Half-life limit (90% CL, including systematics): 6.1 × 10²⁴ yr
- Decay rate limit (90% CL, including systematics): 0.11 × 10⁻²⁴ / yr
- Median expected sensitivity: 3.7 × 10²⁴ yr

Combination with previous results



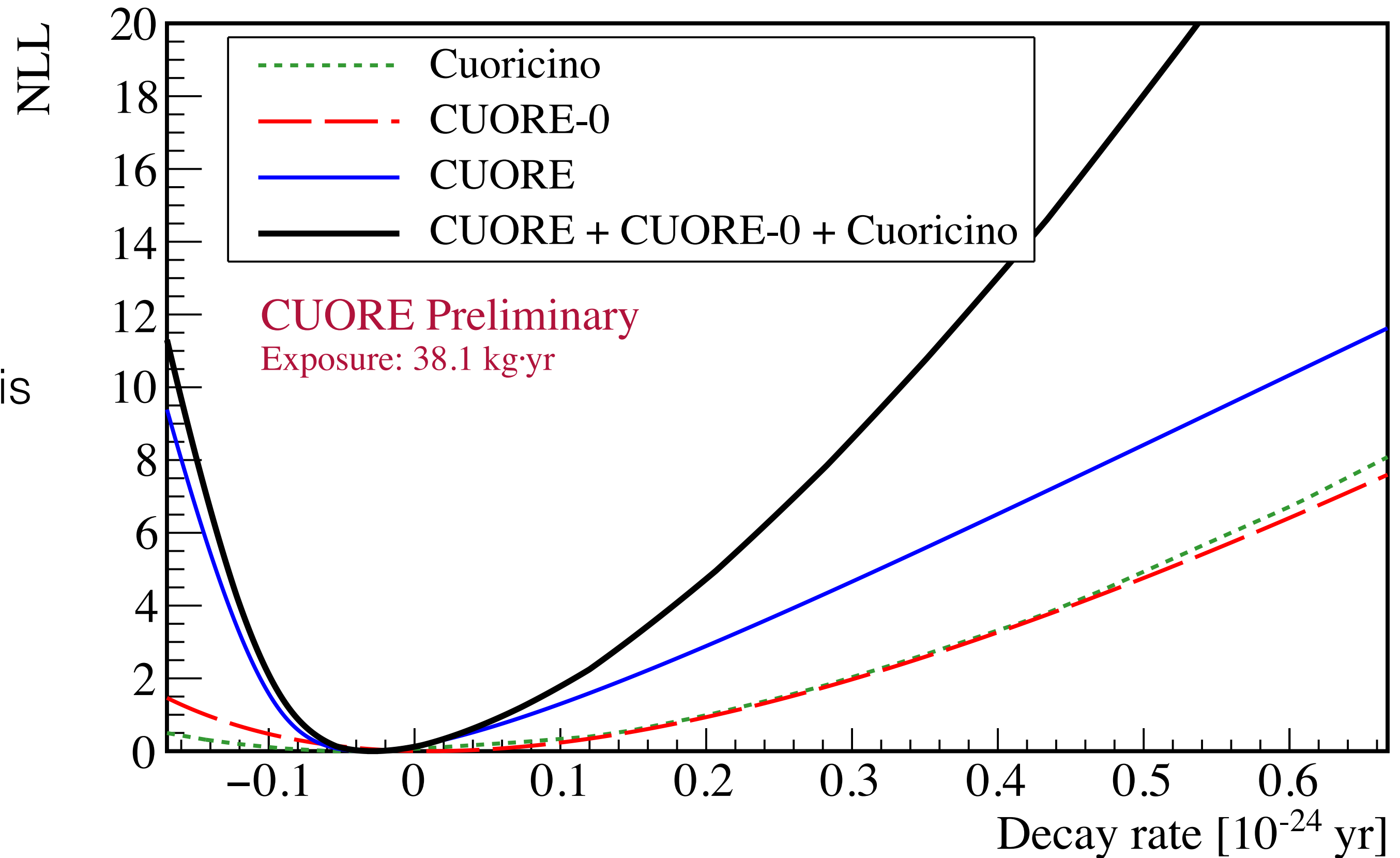
- We combined the CUORE result with the existing ^{130}Te
 - 19.75 kg·yr of Cuoricino
 - 9.8 kg·yr of CUORE-0
- The combined 90% C.L. limit is **$T_{0\nu} > 6.6 \times 10^{24}$ yr**



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Combined “Rolke” limit: 8.1×10^{24} yr

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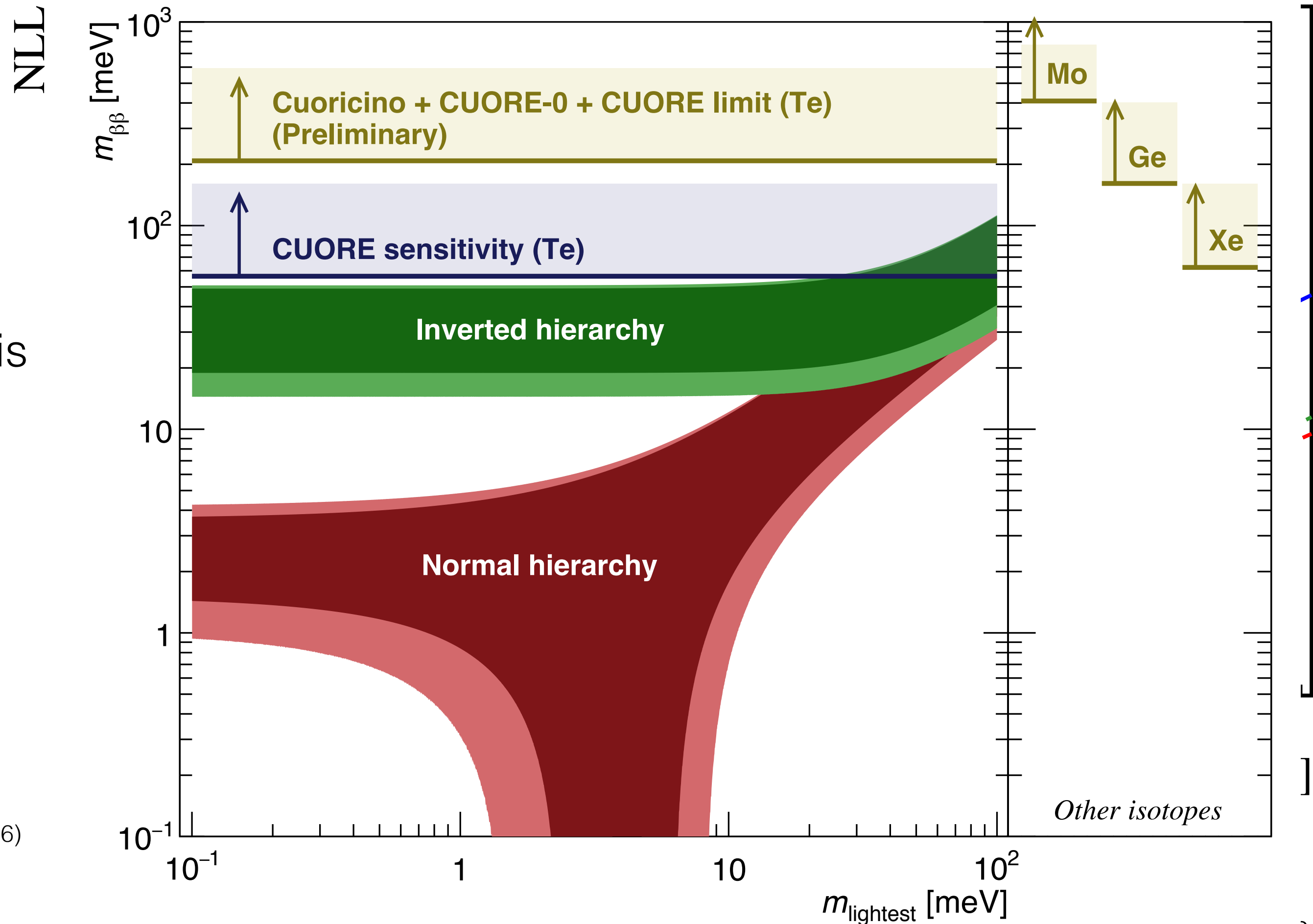
$m_{\beta\beta} < 210\text{--}590$ meV

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)

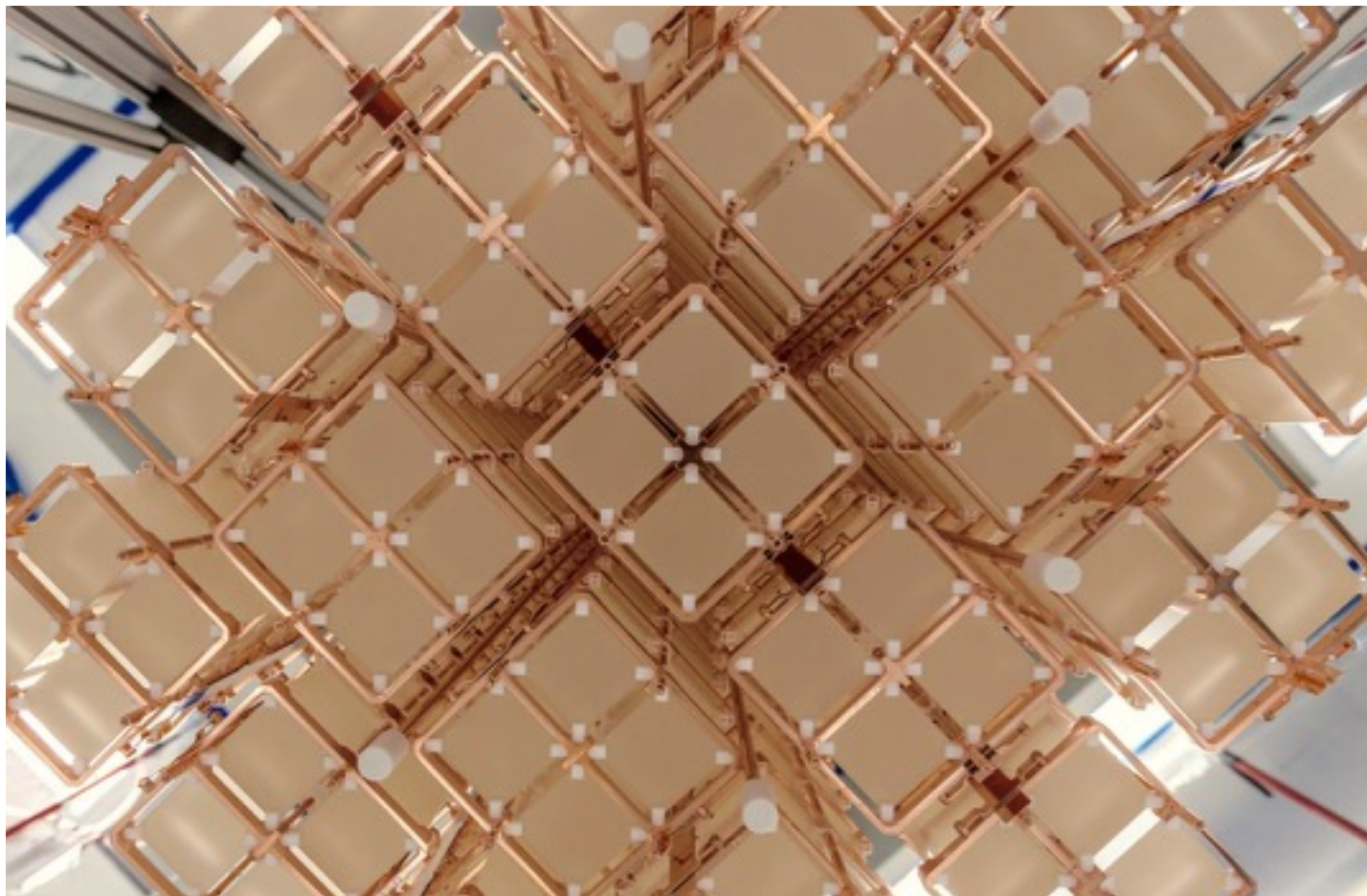
Experiments:

- ^{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



Conclusions

- The cryostat is working spectacularly well.
- With 3 weeks of physics data we have accumulated higher exposure than CUORE-0/ Cuoricino and surpassed their limit.
 - Total exposure: 38.1 kg·y
 - Invaluable operational experience
 - Important information on detector performance, noise, resolutions, background levels
- Further improvement possible:
 - A detector optimization campaign is underway, focused on improving the resolution through noise reduction.



- 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