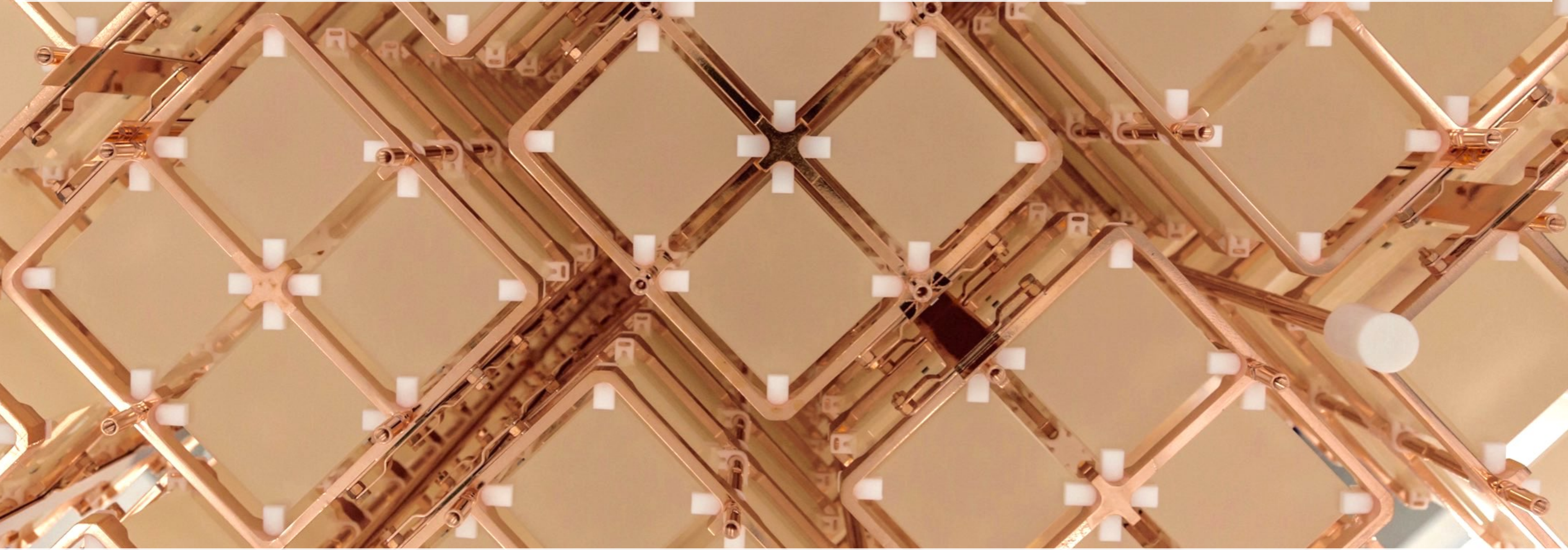
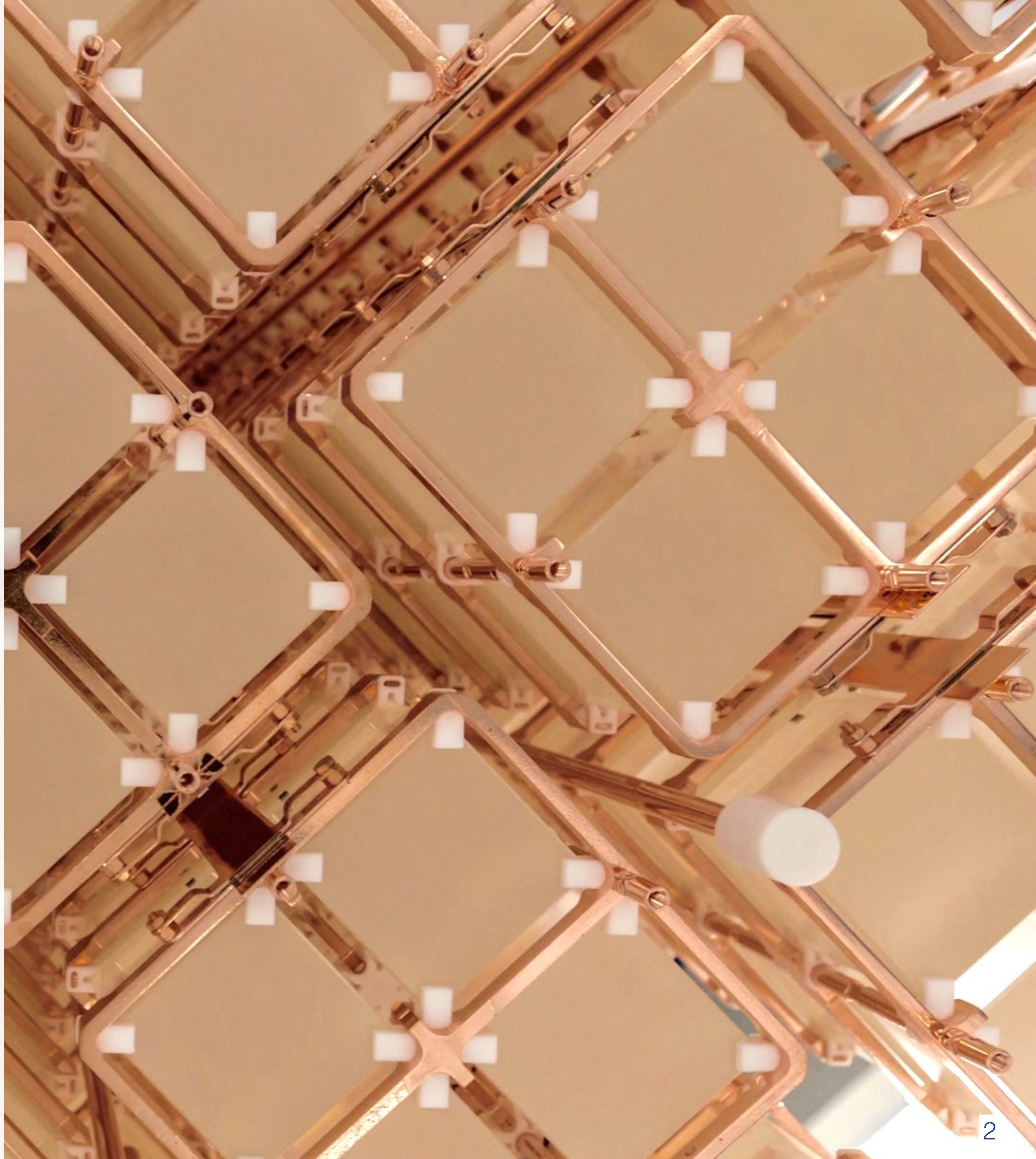
First Results from CUORE: A Search for Lepton Number Violation via 0νββ Decay of ^{130}Te

Matteo Biassoni on behalf of the **CUORE** Collaboration
INFN - Sez. Milano Bicocca



Outline

- TeO_2 and thermal detectors for neutrino-less DBD
- CUORE setup
  - Cryogenics
  - Installation
  - Pre-operation
  - Science data taking
- Analysis procedures
  - Calibration and detector response
  - Event selection
  - Blinding
- Physics results
  - Fit
  - Systematics
  - Combination with other experiments
- Conclusions and outlook



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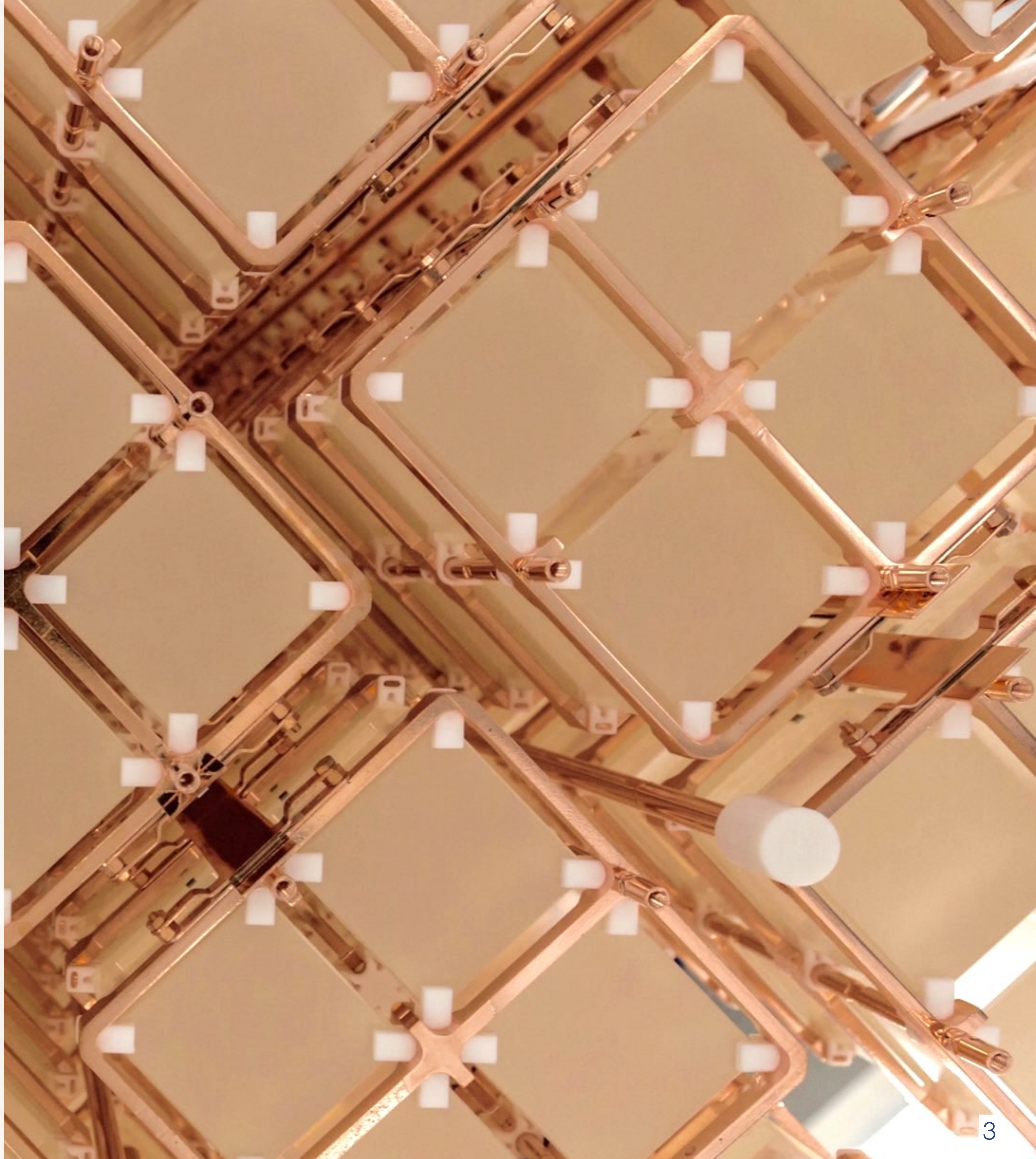
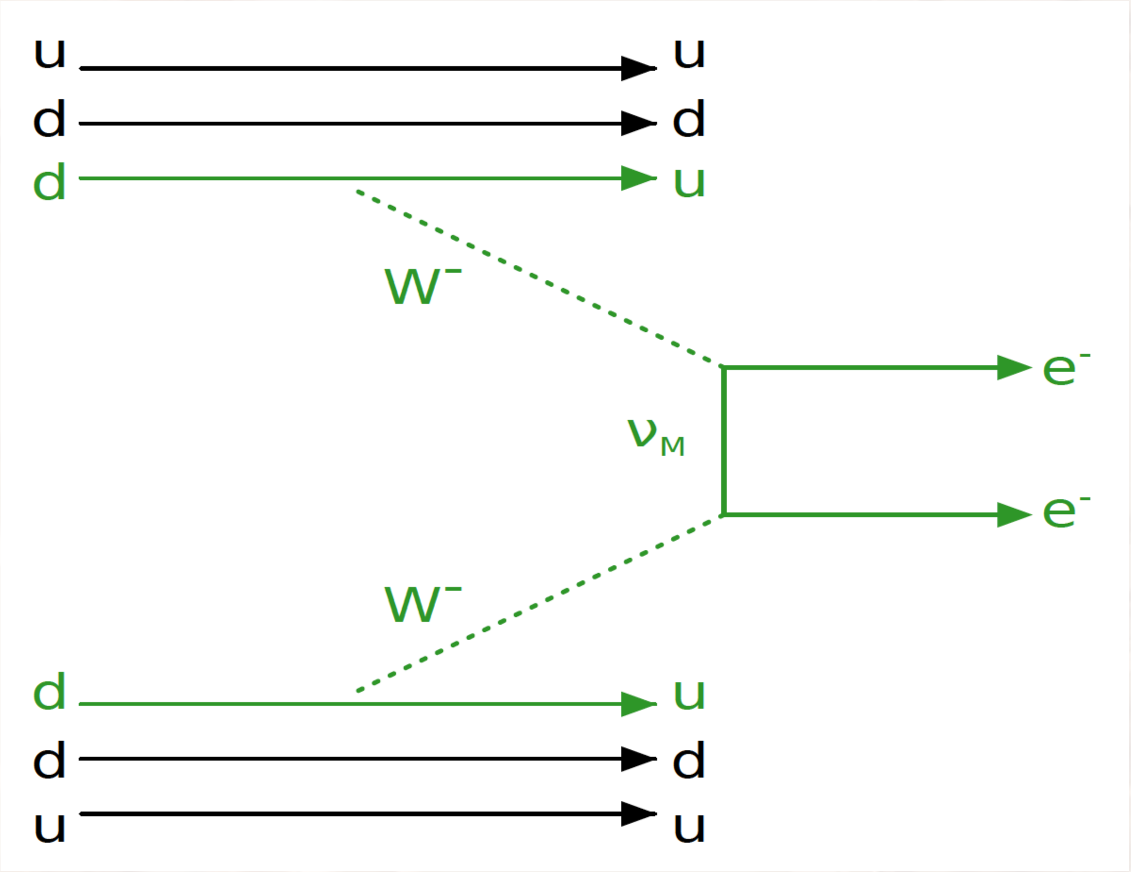


TeO_2 and thermal detectors for 0vDBD

Second order nuclear process, alternative to beta decay forbidden by mass difference for some even-even nuclei

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ 2nd order SM process, $T_{1/2} \sim 10^{18\sim24}$ years

$(A,Z) \rightarrow (A,Z+2) + 2e^-$



- SM forbidden, ΔL = 2
- **if** observed, **then** neutrino is a Majorana particle
- underlying mechanism can give insight into beyond SM physics
  - light neutrino mass scale and hierarchy
  - heavy neutrino
  - …

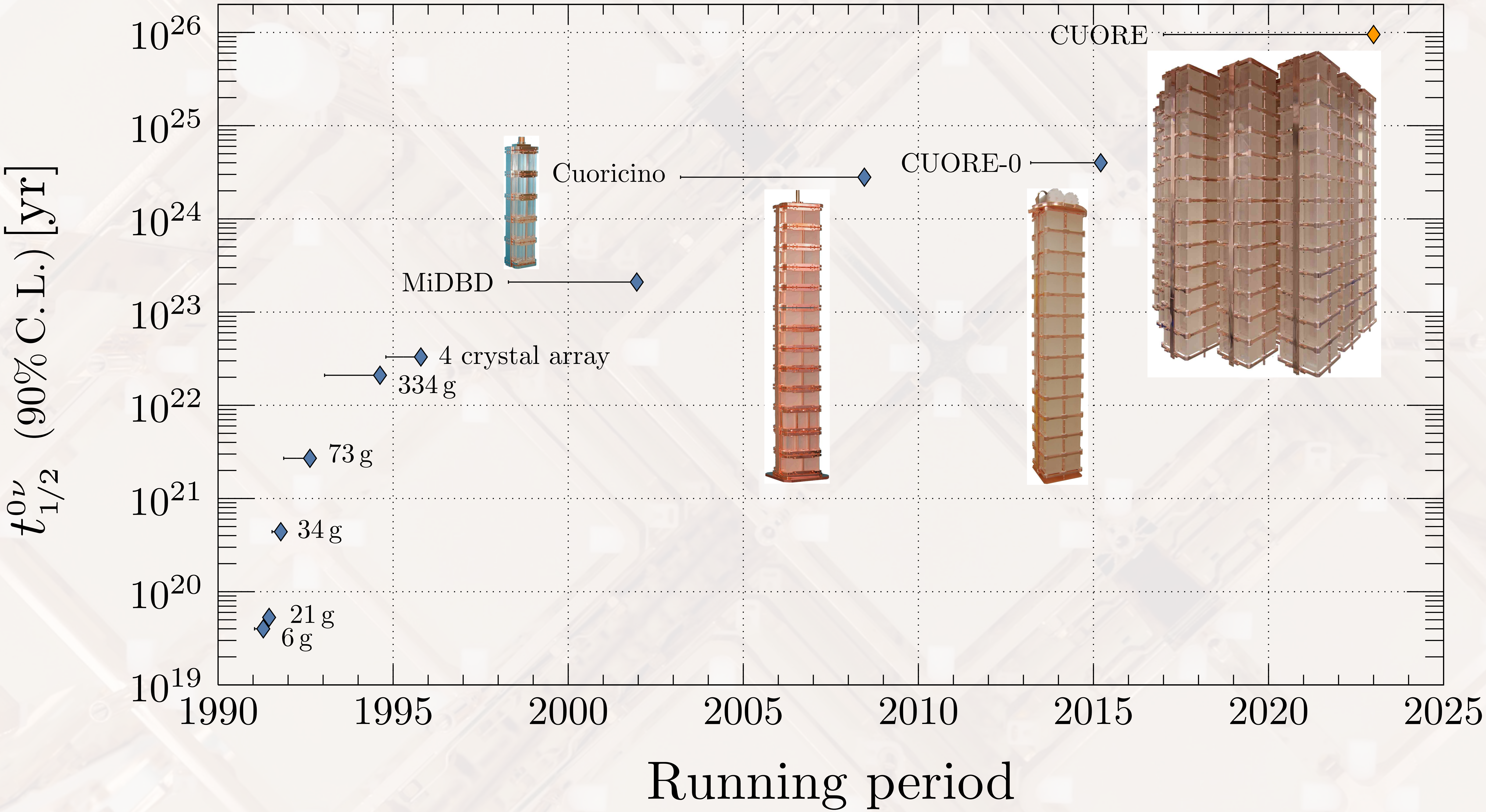
^{130}Te is a good candidate source for 0vDBD search:

- high natural isotopic abundance (~34%)
- NME and phase space on average
- Q-value (2528 keV) above most of the natural radioactivity
- easy to mix in convenient chemical compounds (TeO_2)

Thermal detectors are a good choice for 0vDBD search:

- excellent energy resolution
- large active mass and efficiency/unit cost
- fully active source and sensitive volume, no dead-layer

TeO_2 arrays: state of the art



CUORE is the latest in a long progression of TeO_2 detectors which included two large demonstrators:

- Cuoricino (2.8×10^{24} y)
- CUORE-0 (4.0×10^{24} y combined)

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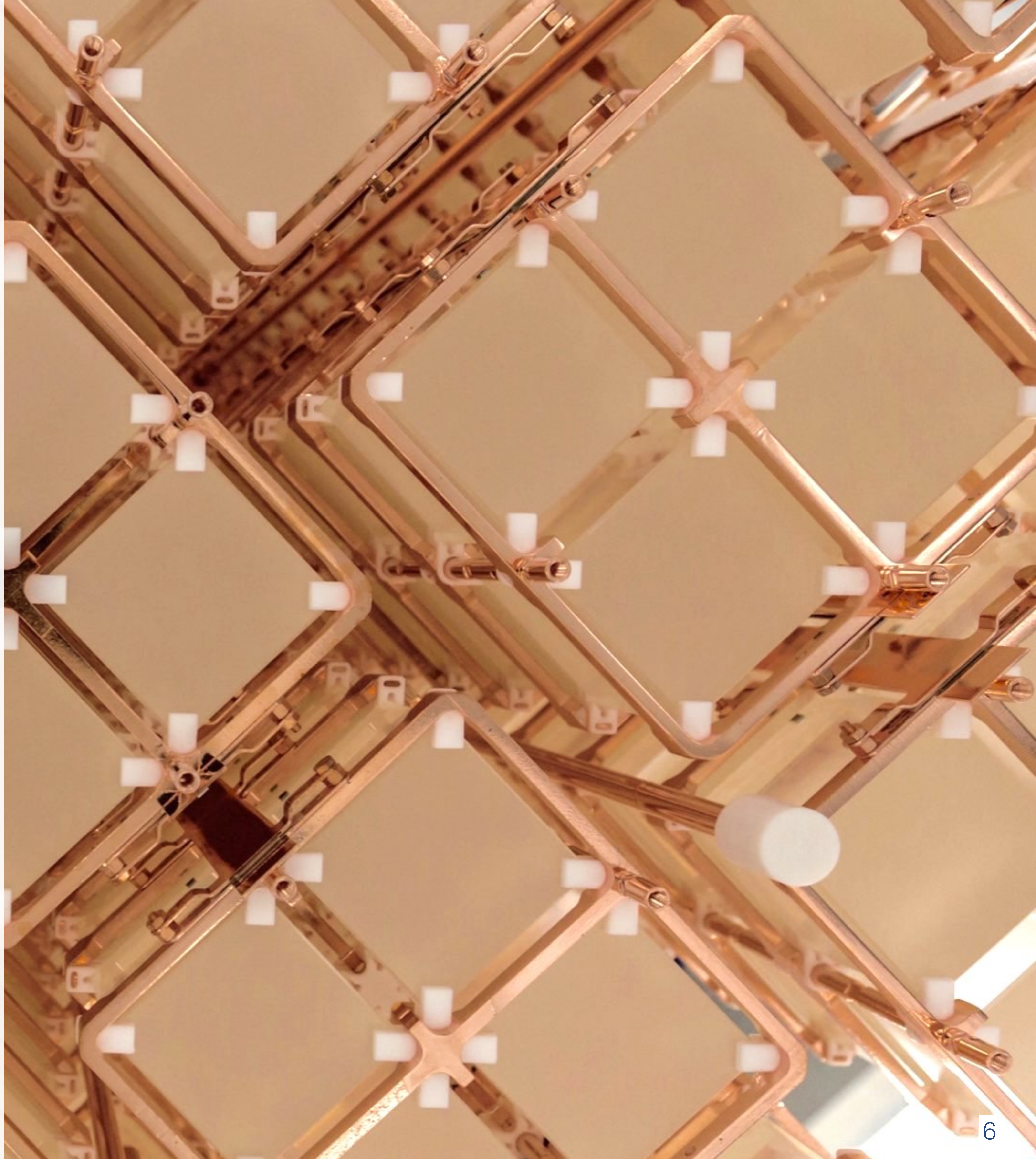


CUORE

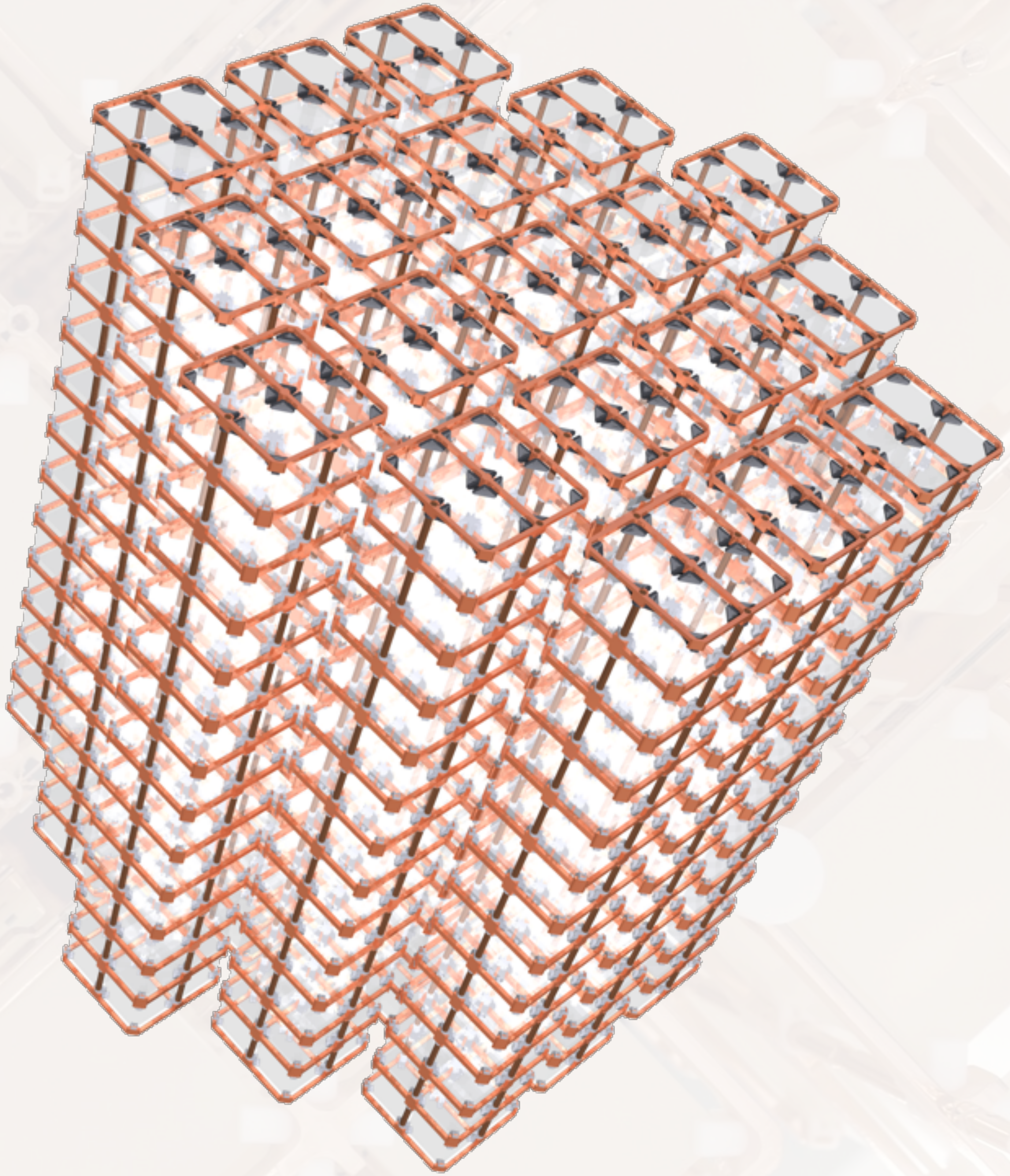
Cryogenic Underground Observatory for Rare Events

Primary goal: search for 0νββ decay in ^{130}Te

Detector design:
closely packed array of 988 TeO_2 crystals
arranged in 19 towers

Design parameters:

- mass of TeO_2: **742 kg** (206 kg of ^{130}Te)
- low background aim: **10^{-2} c/(keV·kg·yr)**
- target 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.):

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

The CUORE Collaboration

CUORE

UCLA

UNIVERSITAS STUDII PADUANI MCCXXII

Yale

INFN

BERKELEY LAB

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UNIVERSITÀ DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE 1979

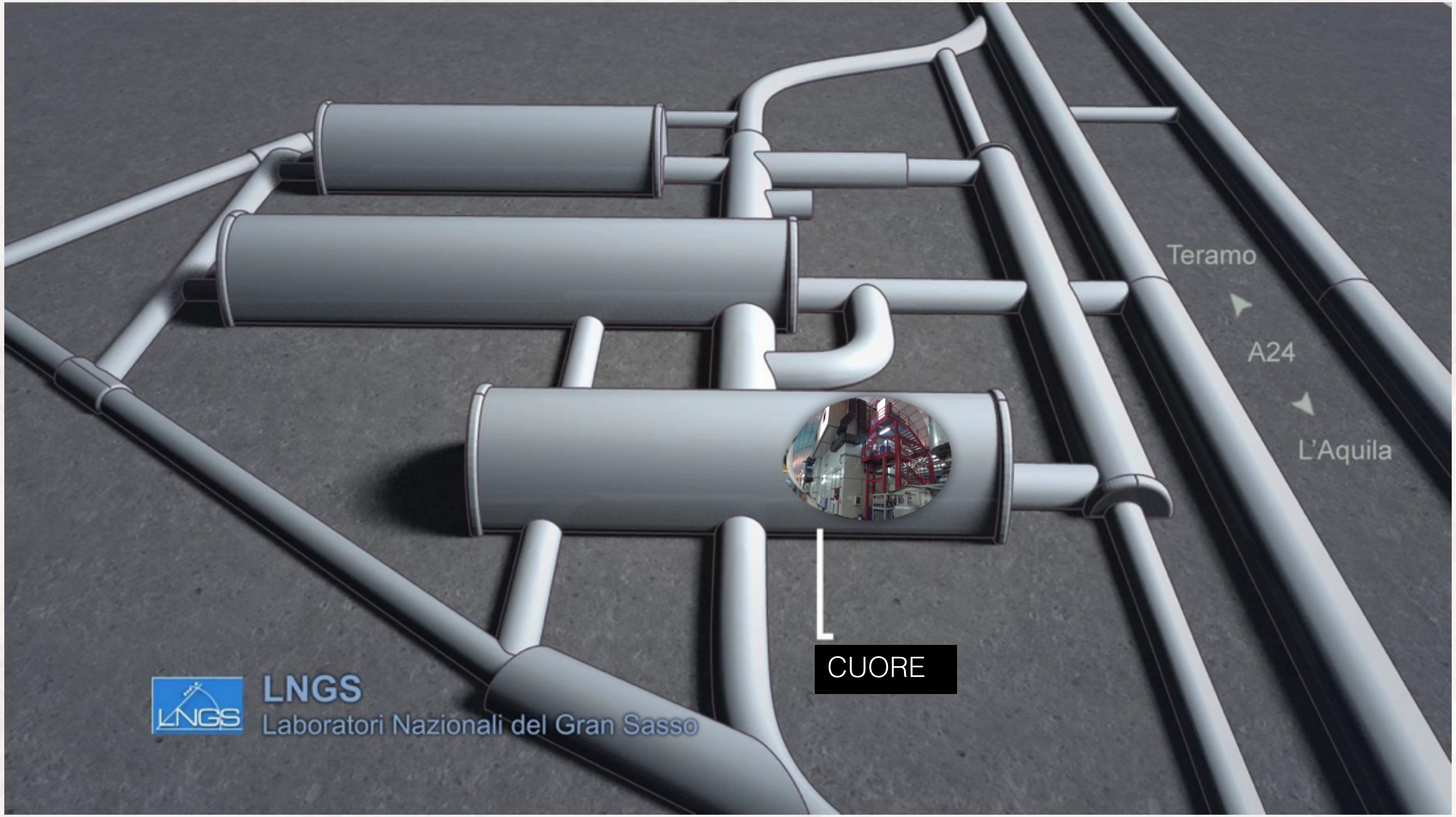
UNIVERSITY OF SOUTH CAROLINA

CUORE @ LNGS

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

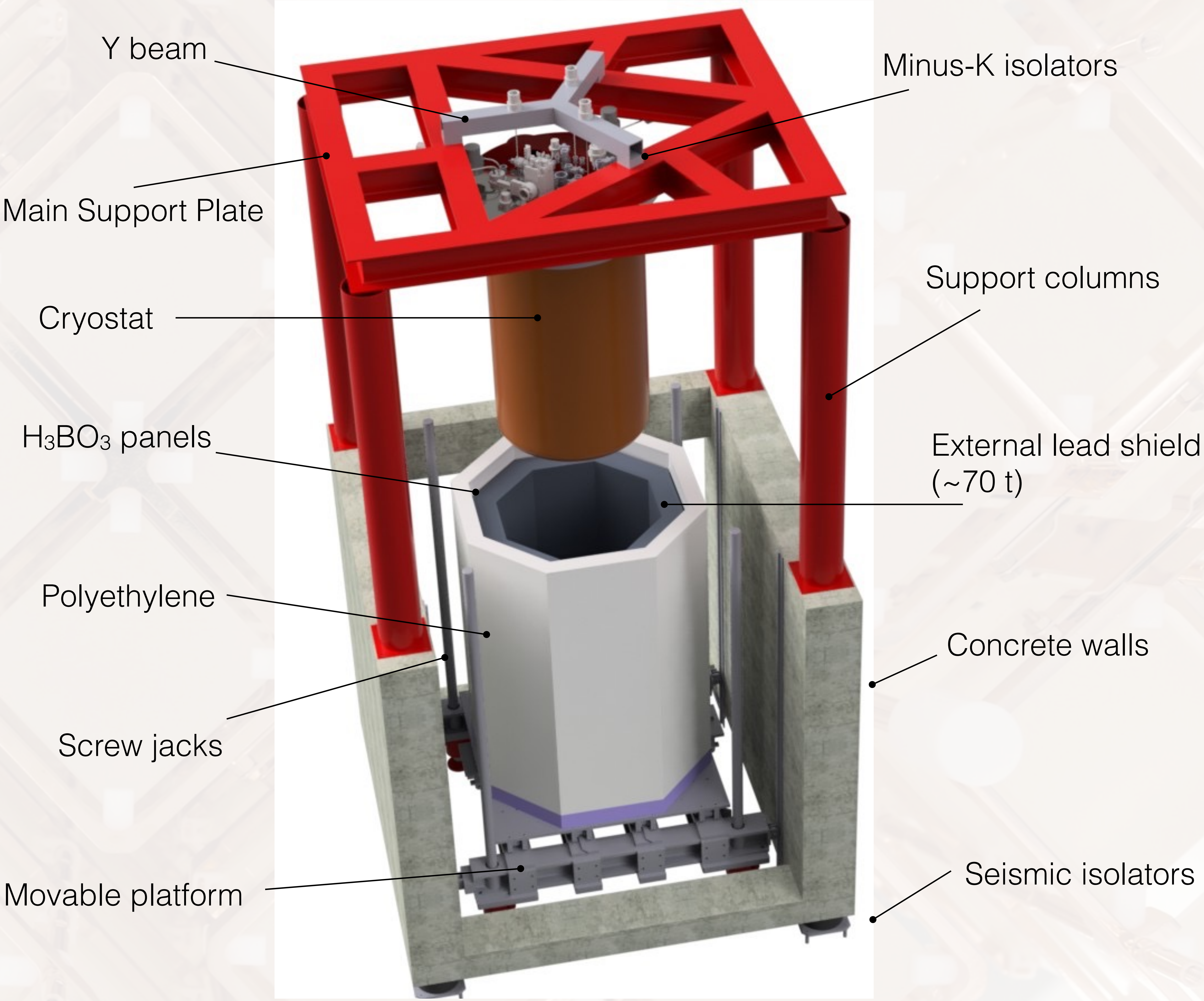
- μ's: ~3 × 10^{-8} / (s·cm^2)
- γ's: ~0.73 / (s·cm^2)
- neutrons: 4 × 10^{-6} n/(s·cm^2) below 10 MeV

CUORE @ LNGS


Teramo
A24
L'Aquila
CUORE
LNGS
Laboratori Nazionali del Gran Sasso

Underground Laboratory

- Three-story building
- Hosting the cryostat supporting structure

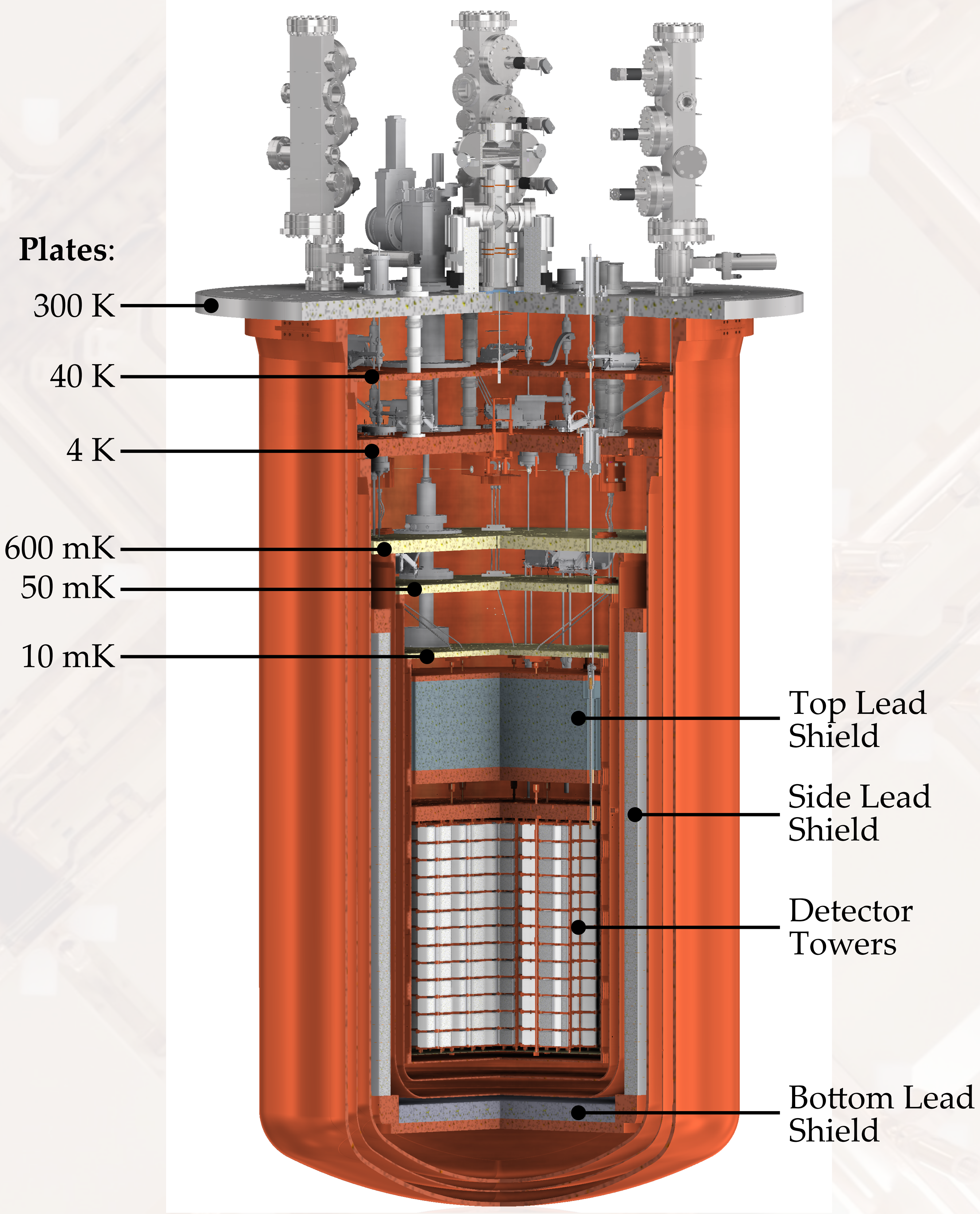


The CUORE cryostat

Challenges:

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

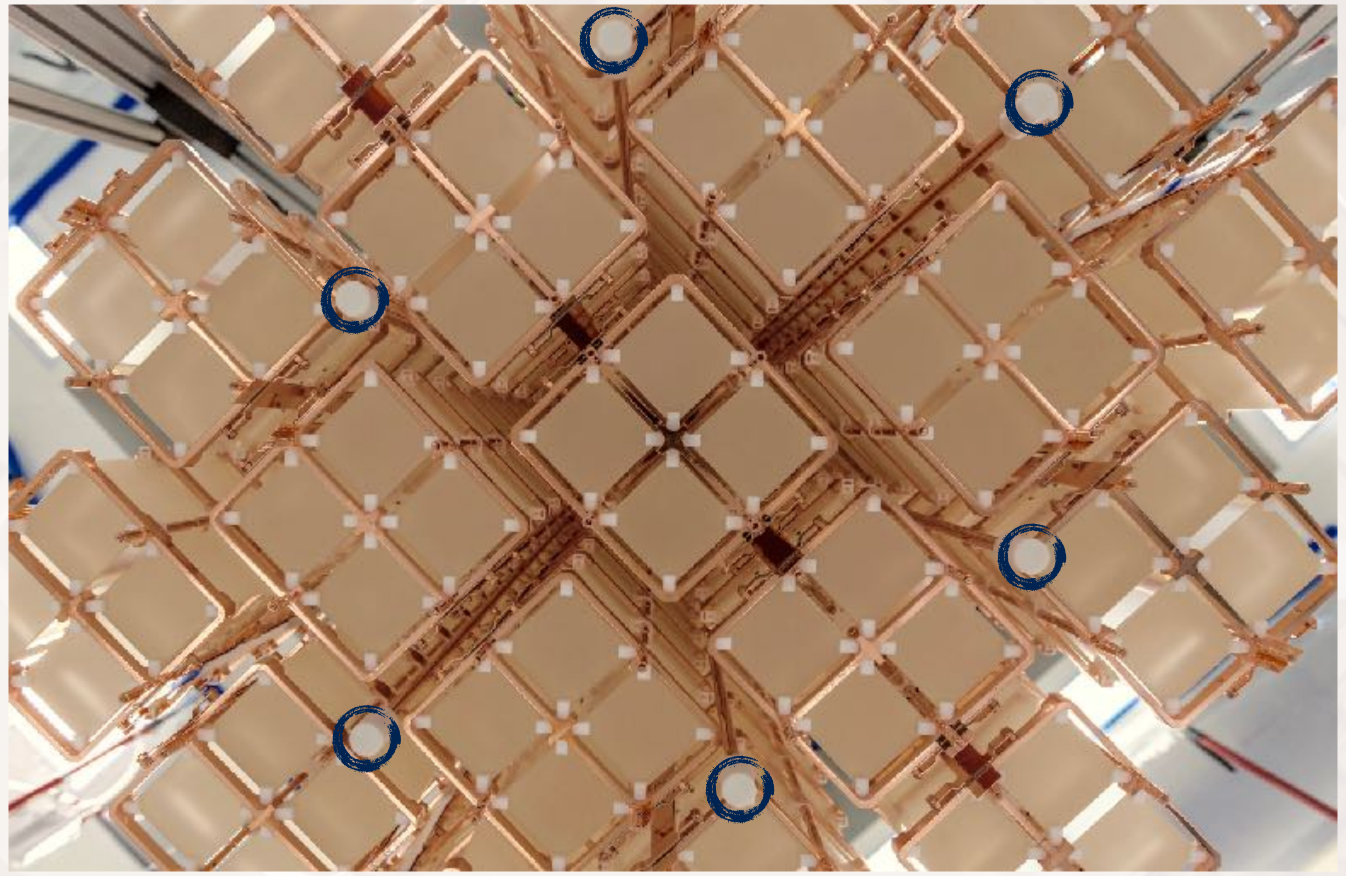
- Cryogen-free cryostat
- Fast Cooling System (^{4}He gas) down to ~50K
- 5 pulse tubes cryocooler down to ~4K
- Dilution refrigerator down to operating temperature ~10 mK
- Nominal cooling power: 3 μW @ 10mK
- Cryostat total mass ~30 tons
- Mass to be cooled < 4K: ~15 tons
- Mass to be cooled < 50 mK: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

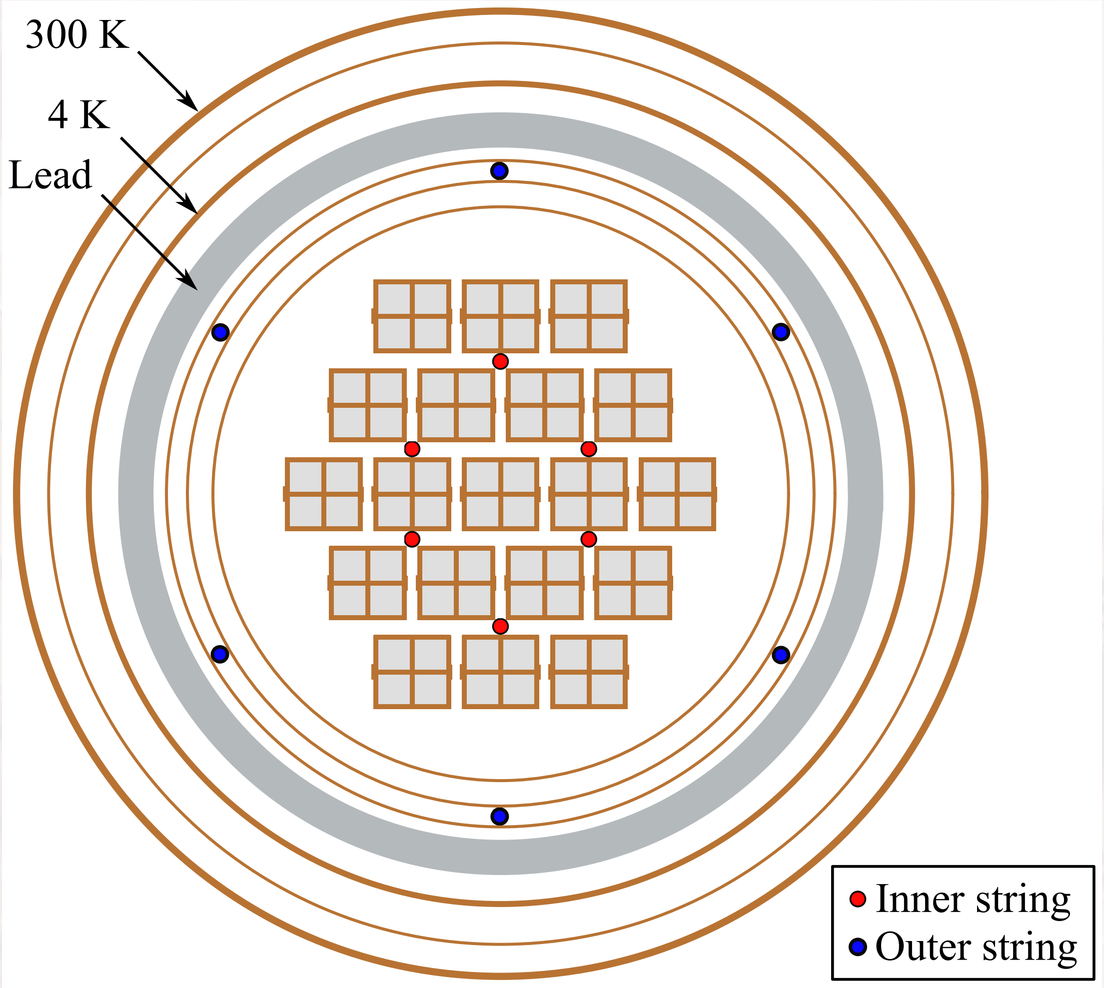


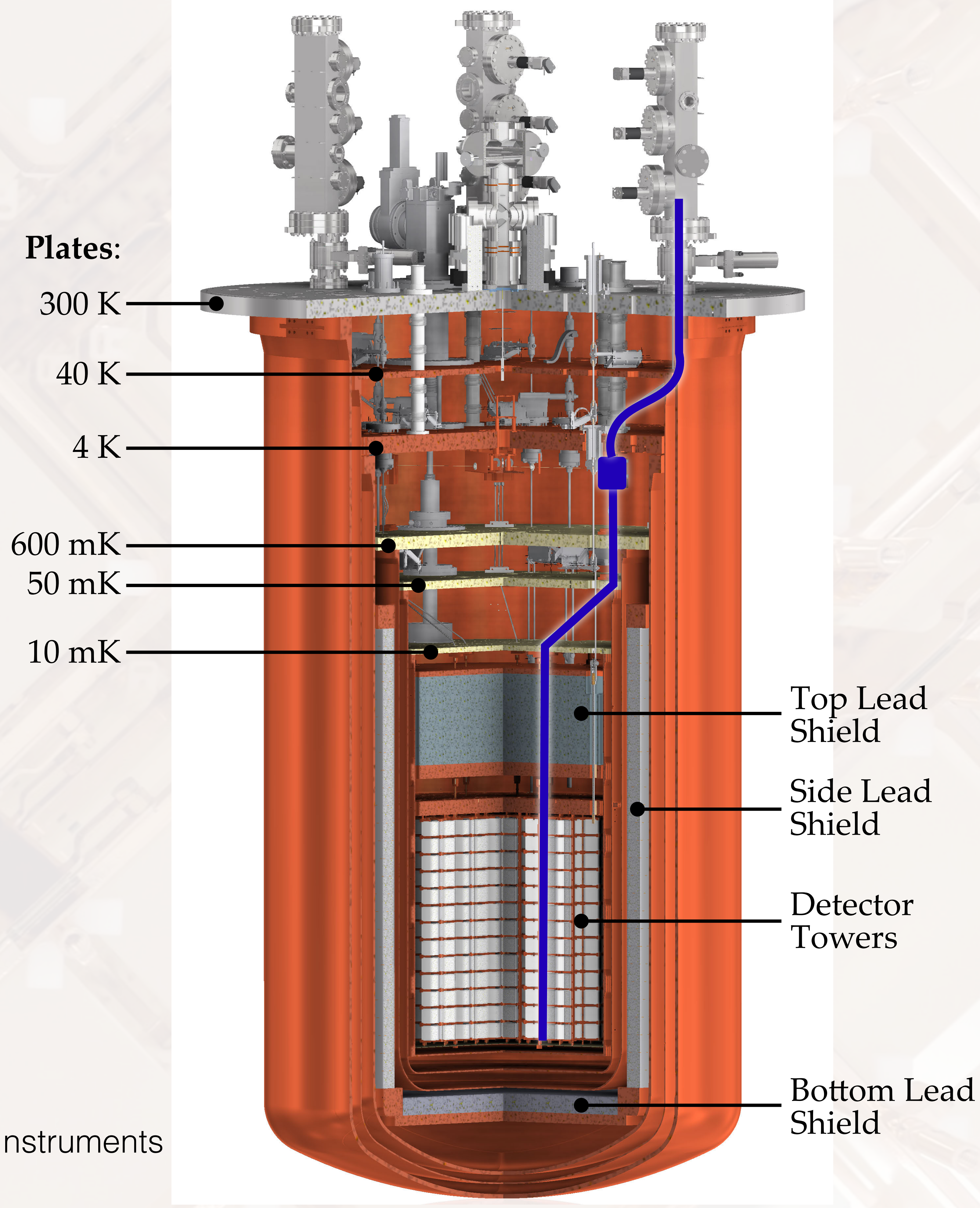
Detector calibration system

Challenges:

- Provide a uniform calibration of all the CUORE detectors
- Deployment of thoriated 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

Passive shielding

Challenges:

- Protect the detectors with a heavy shield against gamma and neutron activity from external sources (~70 tonnes lead + H_3BO_3)
- Select materials that don’t contribute themselves to the background level (ancient roman lead and selected NOSV copper)
- Cool down inner layers of the shielding to the correct temperature (2.5 tonnes @ 50mK + 5.5 tonnes @ 4K)

Cryogenic system commissioning

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

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

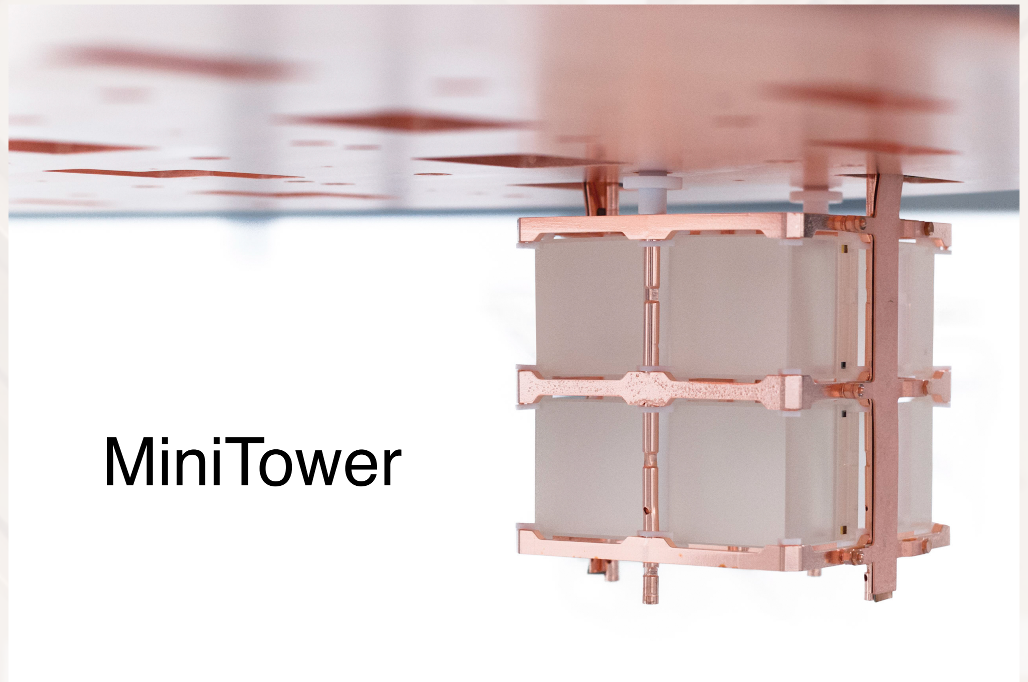
Excellent performance of the cryogenic system:

- 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 (Rn concentration < 0.1 Bq/m^3) for operators life support
- protective bags flushed with nitrogen for overnight and emergency storage
- teams composed of 3 operators spending the minimum amount of time in the cleanroom, following strict protocols developed during months of training and test with mockup components

Towers installation completed on August 26, 2016

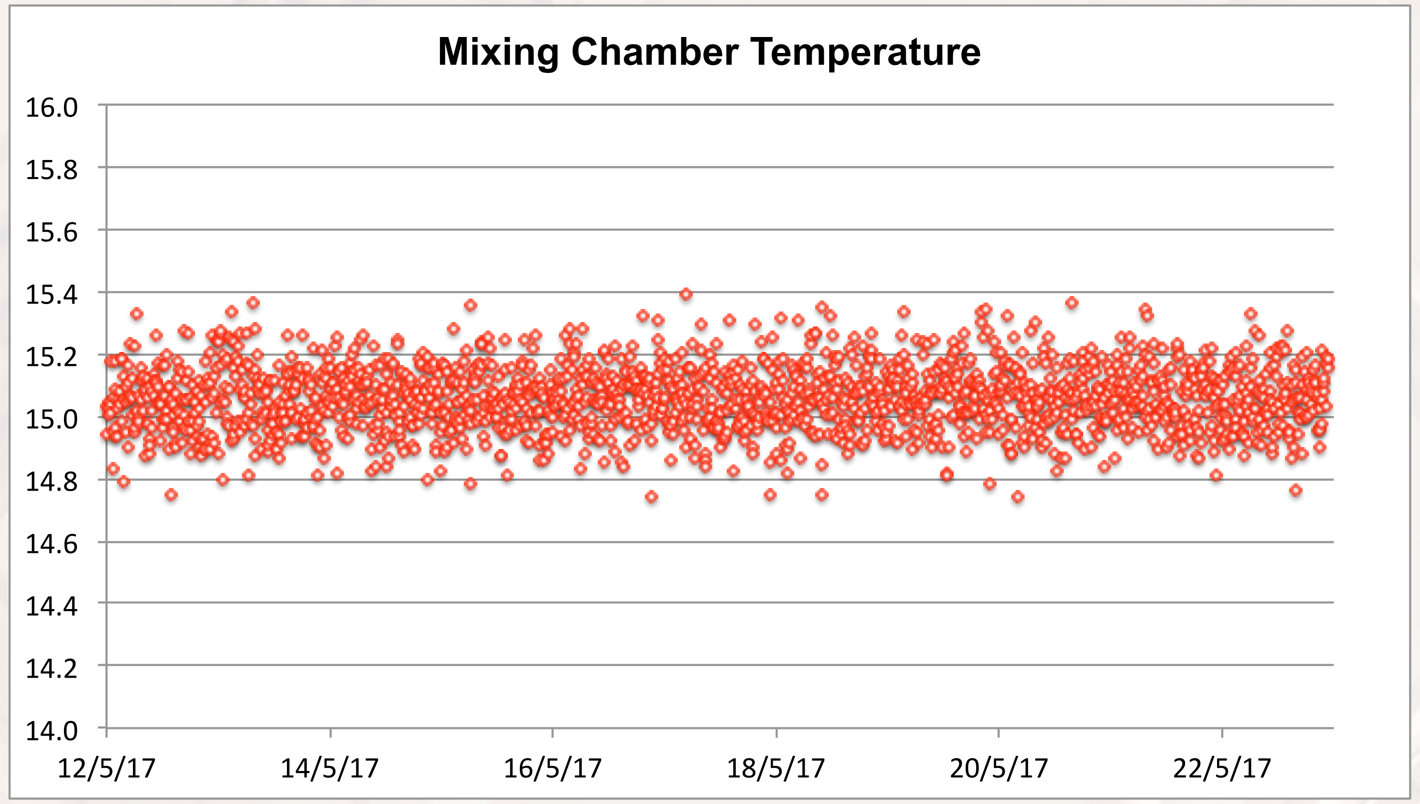
September-October 2016:

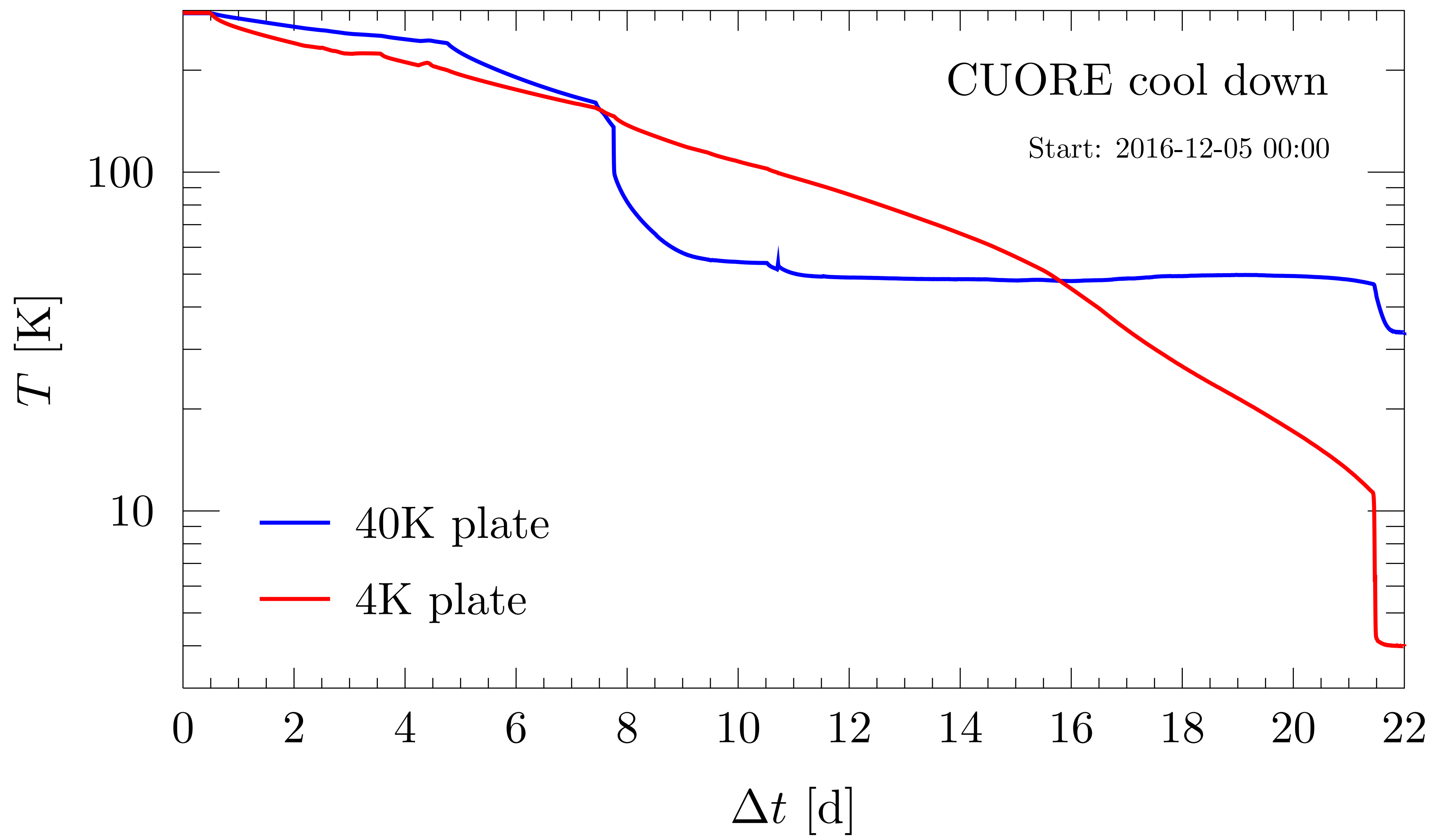
- installation of the cryostat interfaces (protective tiles) and radiation shields
- read-out tests

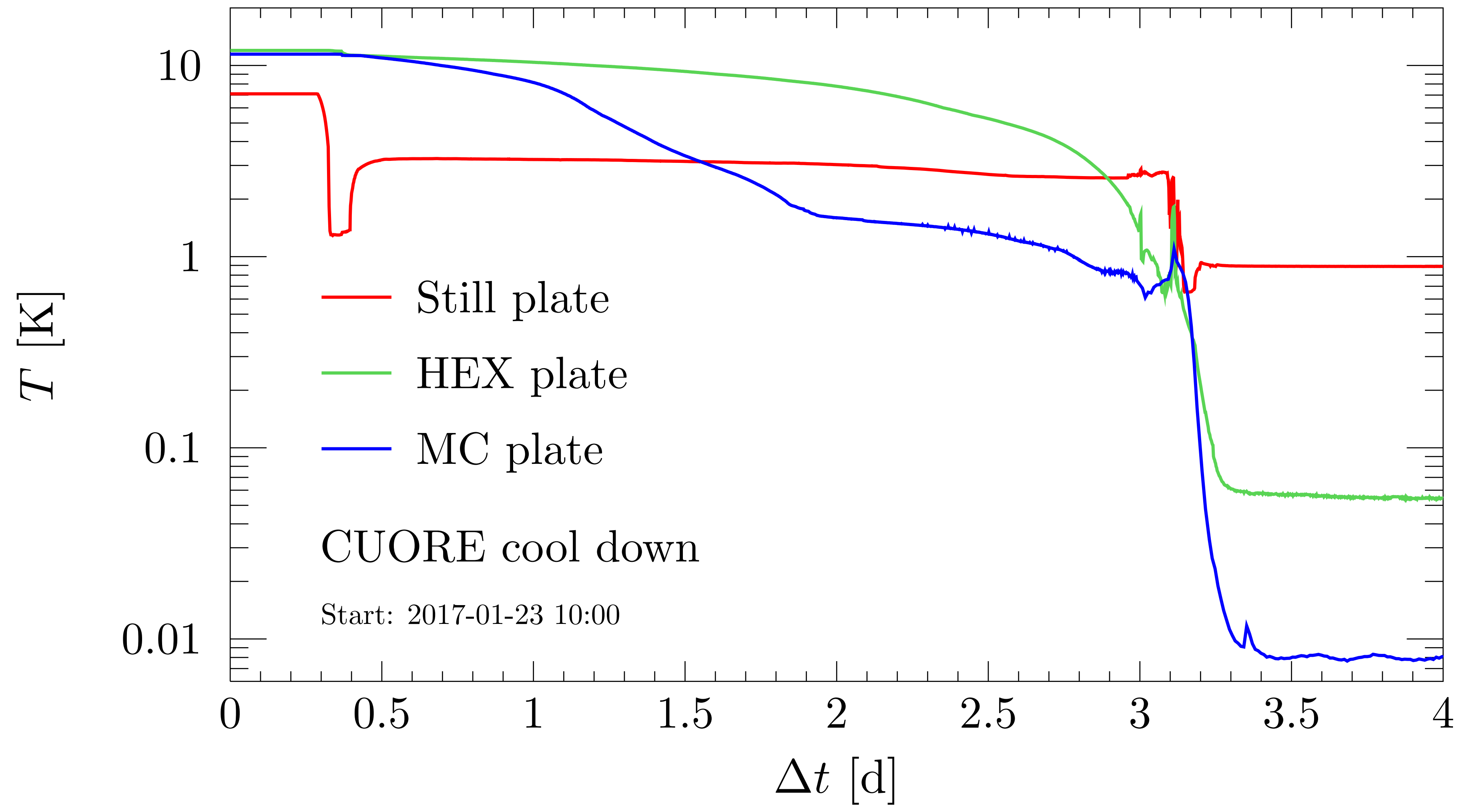
Detector cool down

Started at the beginning of December 2016:

- 300 K —> 4 K in about 22 days
- 4 K —> 7 mK in 3.5 days
- reached a stable base temperature of ~7 mK on Jan 27, 2017
- lowest observed temperature: 6.7 mK
- observed first detector pulses just after the cool down without any optimisation!







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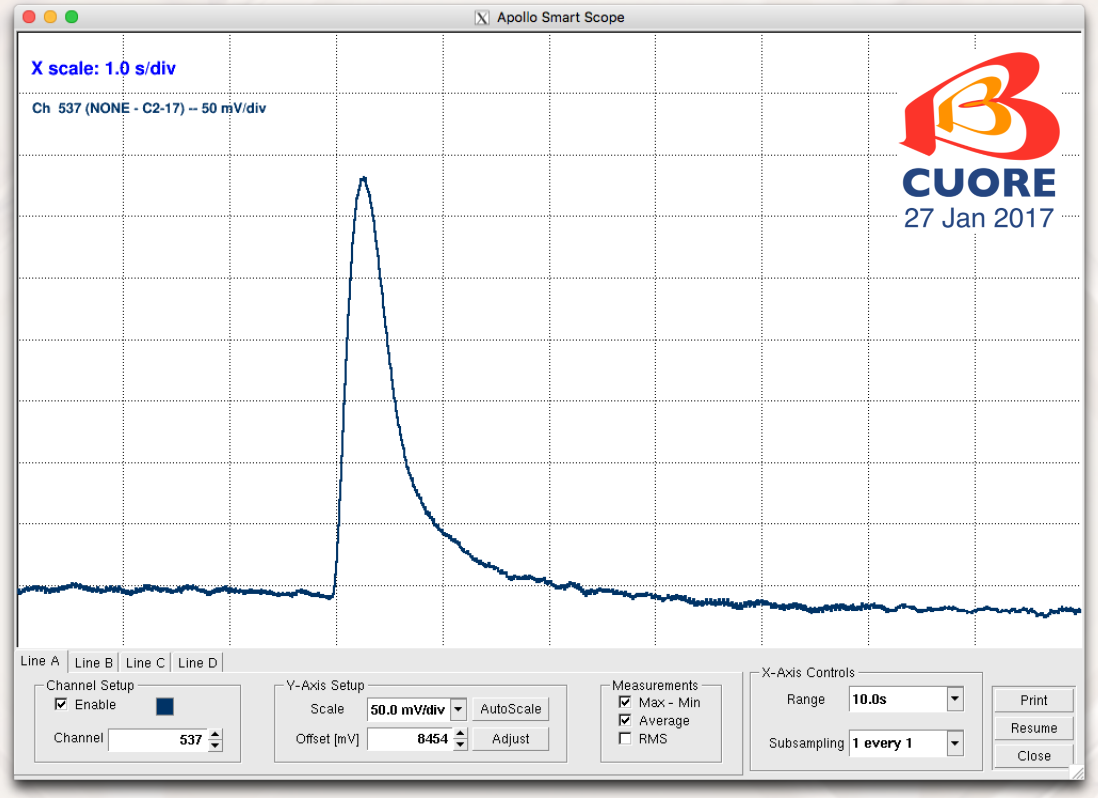


X scale: 1.0 s/div

Ch 537 (NONE - C2-17) -- 50 mV/div

☑ Enable

Channel 537

Scale 50.0 mV/div

Offset [mV] 8454

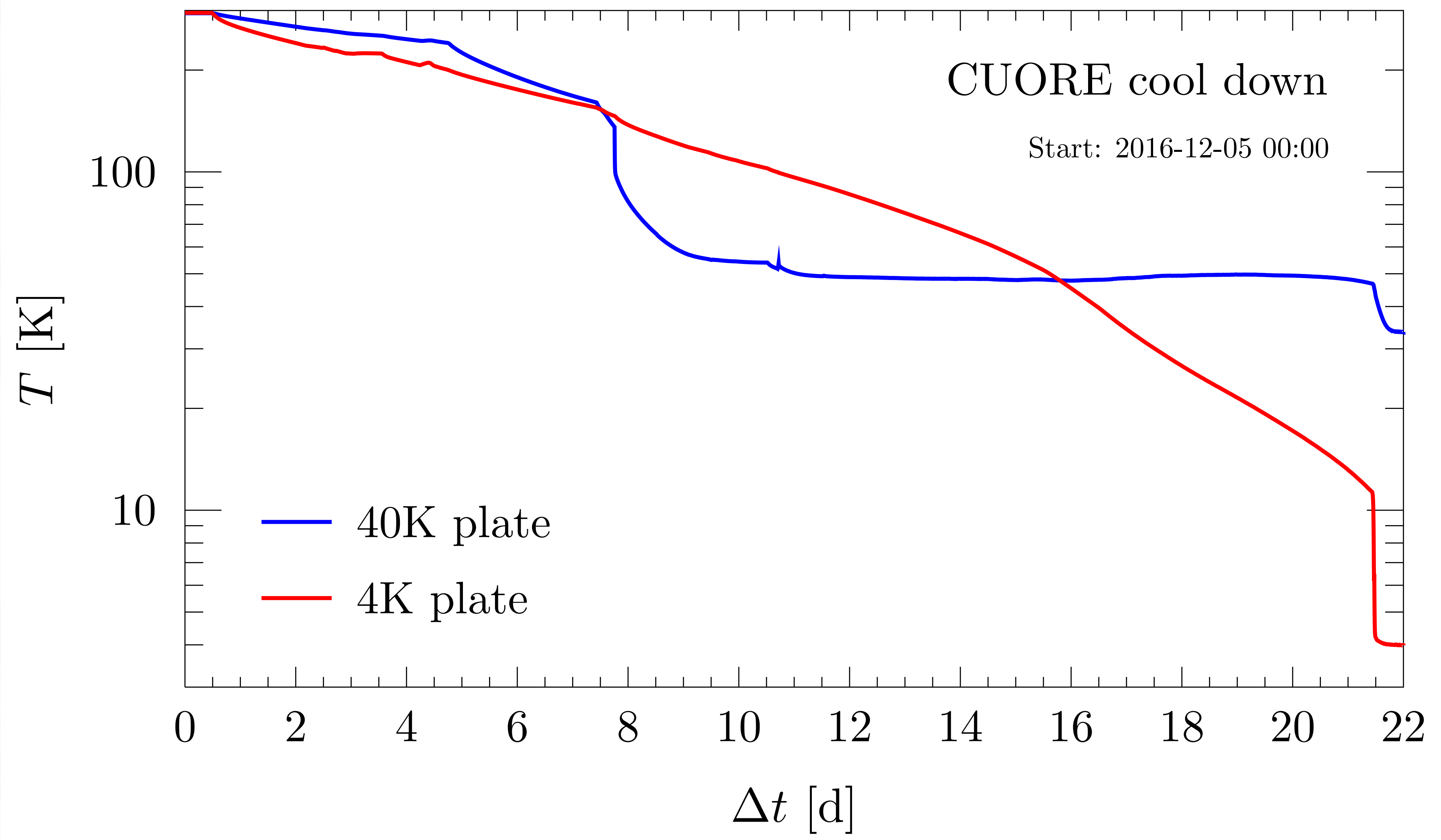
☑ Max - Min

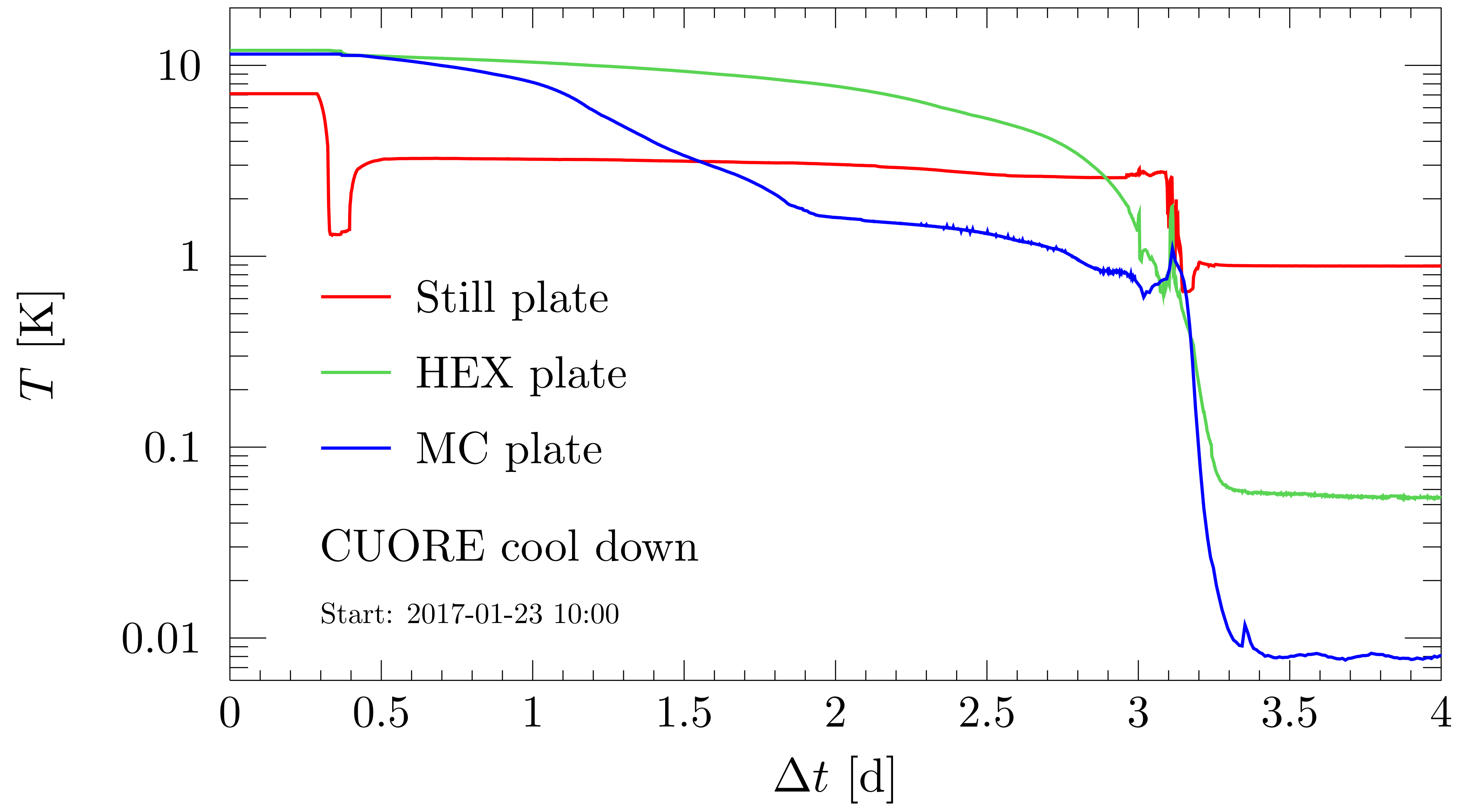
☑ Average

☐ RMS

Range 10.0s

Subsampling 1 every 1





Detector pre-operation

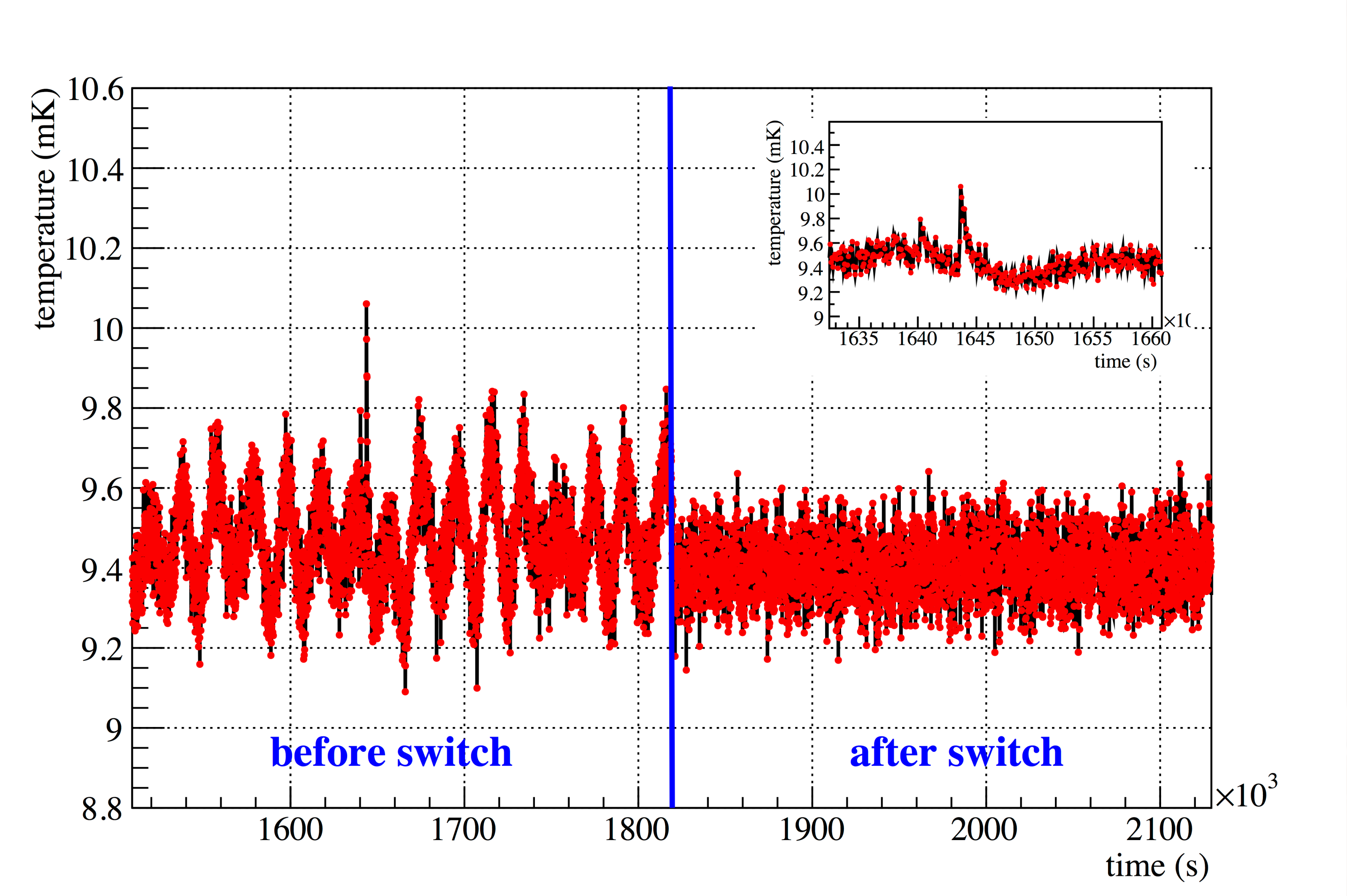
After the successful cool-down we faced the challenge to operate a thousand bolometers in a completely new system.

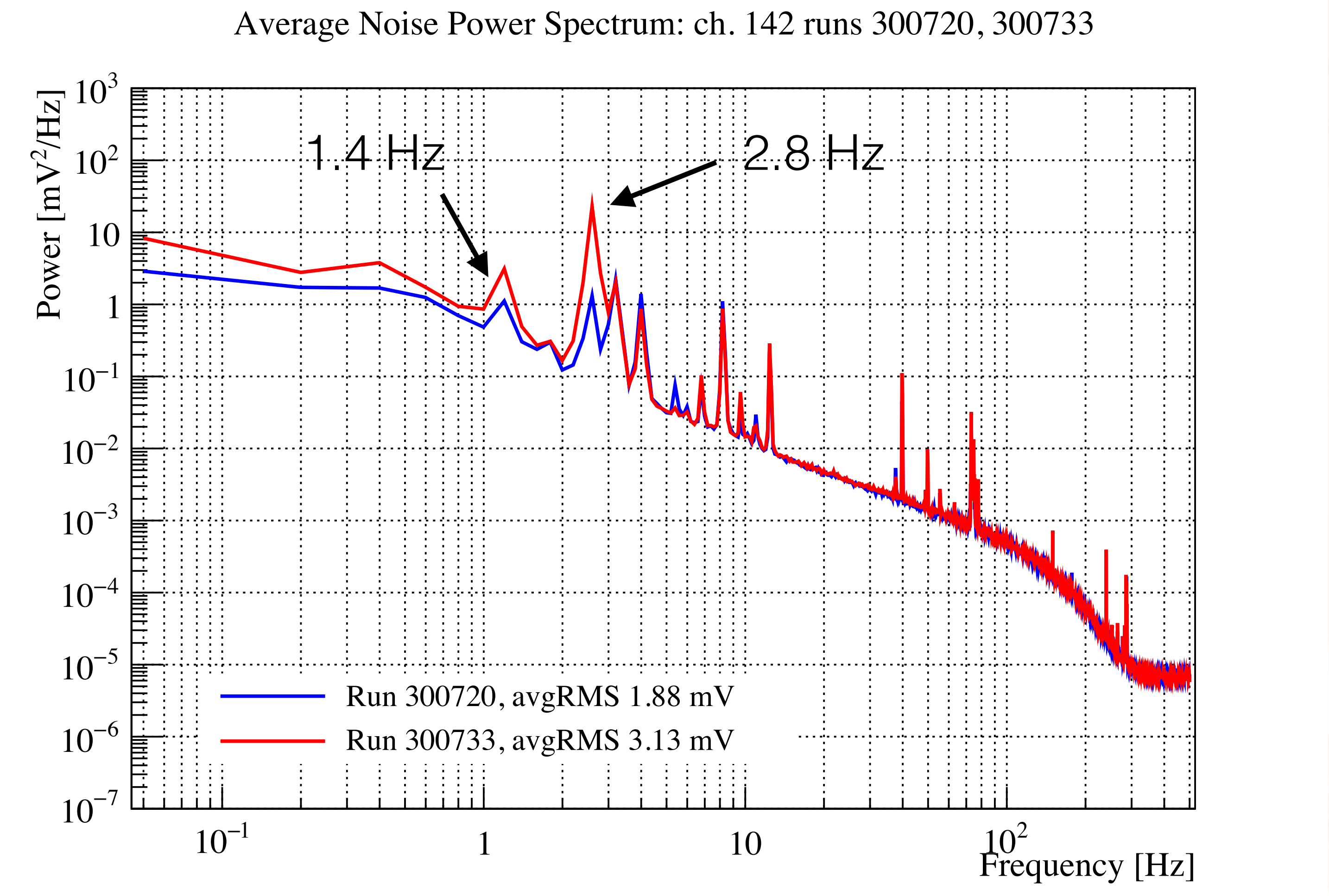
A long list of tests and activities

- 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
- 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

End of March 2017:

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



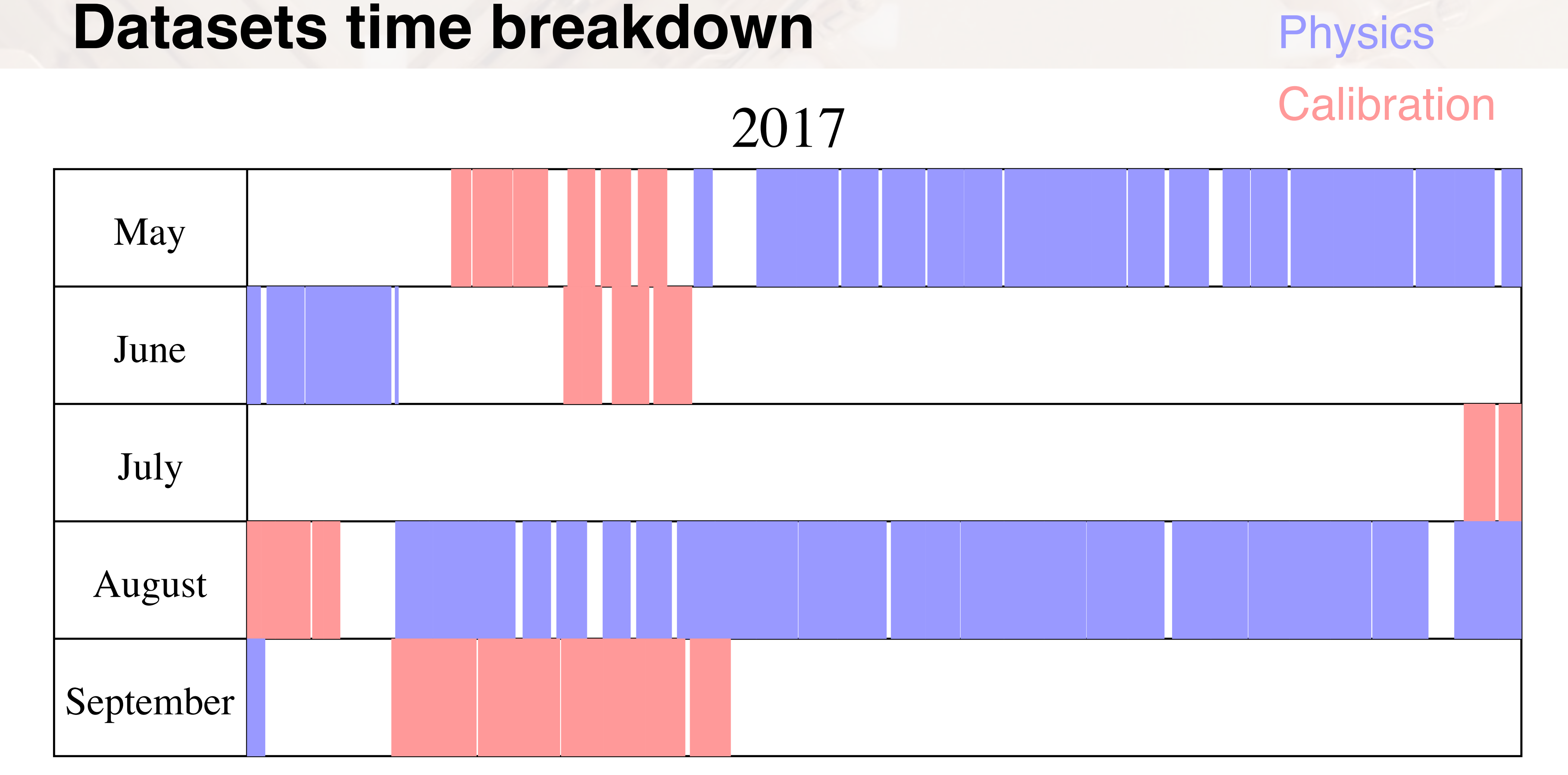


Science runs

Science operations started on April 14, 2017

- Very short commissioning run (identified issue with the thermistor bias on about 1/3 of the channels)
- First optimisation of the detector working point
- **Dataset 1**: 3 weeks of physics data bracketed by 2 calibration periods (May - June 2017)
- Second optimisation campaign
- **Dataset 2**: August - September 2017

Datasets time breakdown



Operational performance:

- **984/988 operational channels**
- Excellent data-taking efficiency when in operations
- Much improved detector stability, compared to Cuoricino/CUORE-0
- Calibrations/physics data ratio still to be optimised to maximise 0νββ sensitivity

Acquired statistics used for this 0vDBD decay search (Dataset 1 + Dataset 2):

- $^{nat}TeO_2$ exposure: **86.3 kg yr** (37.6 + 48.7)
- ^{130}Te exposure: **24.0 kg yr**

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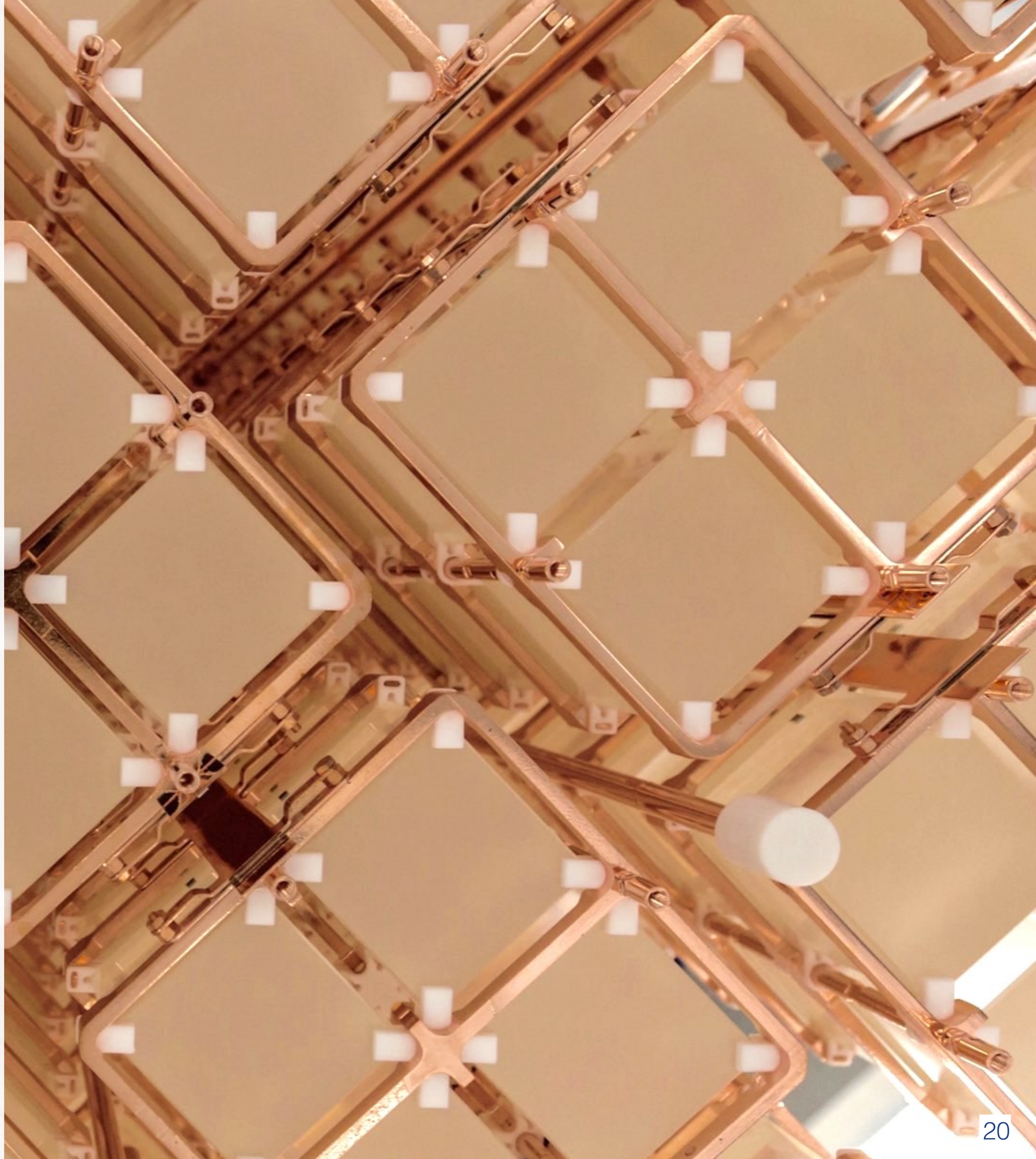
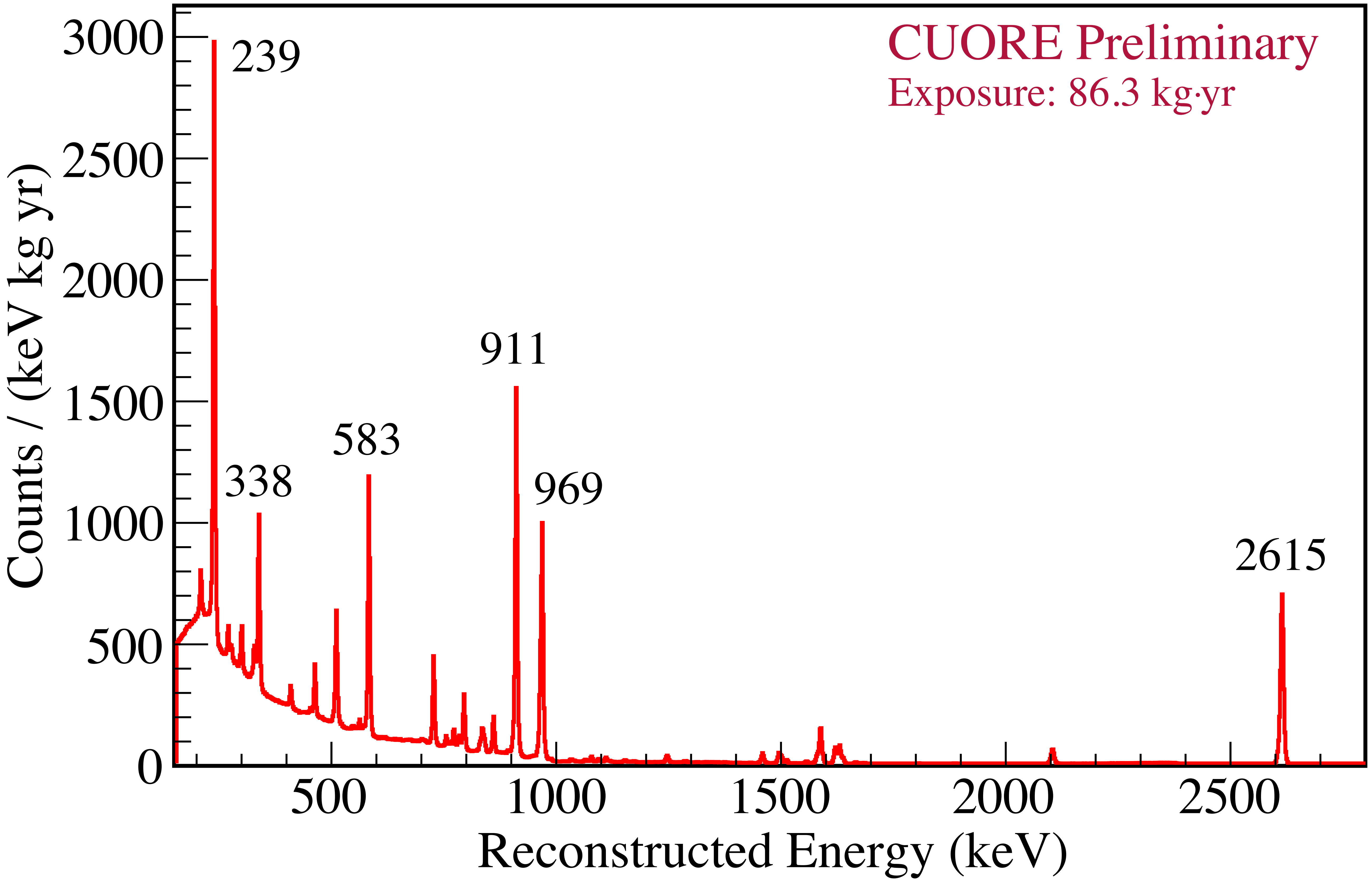


Calibration spectrum

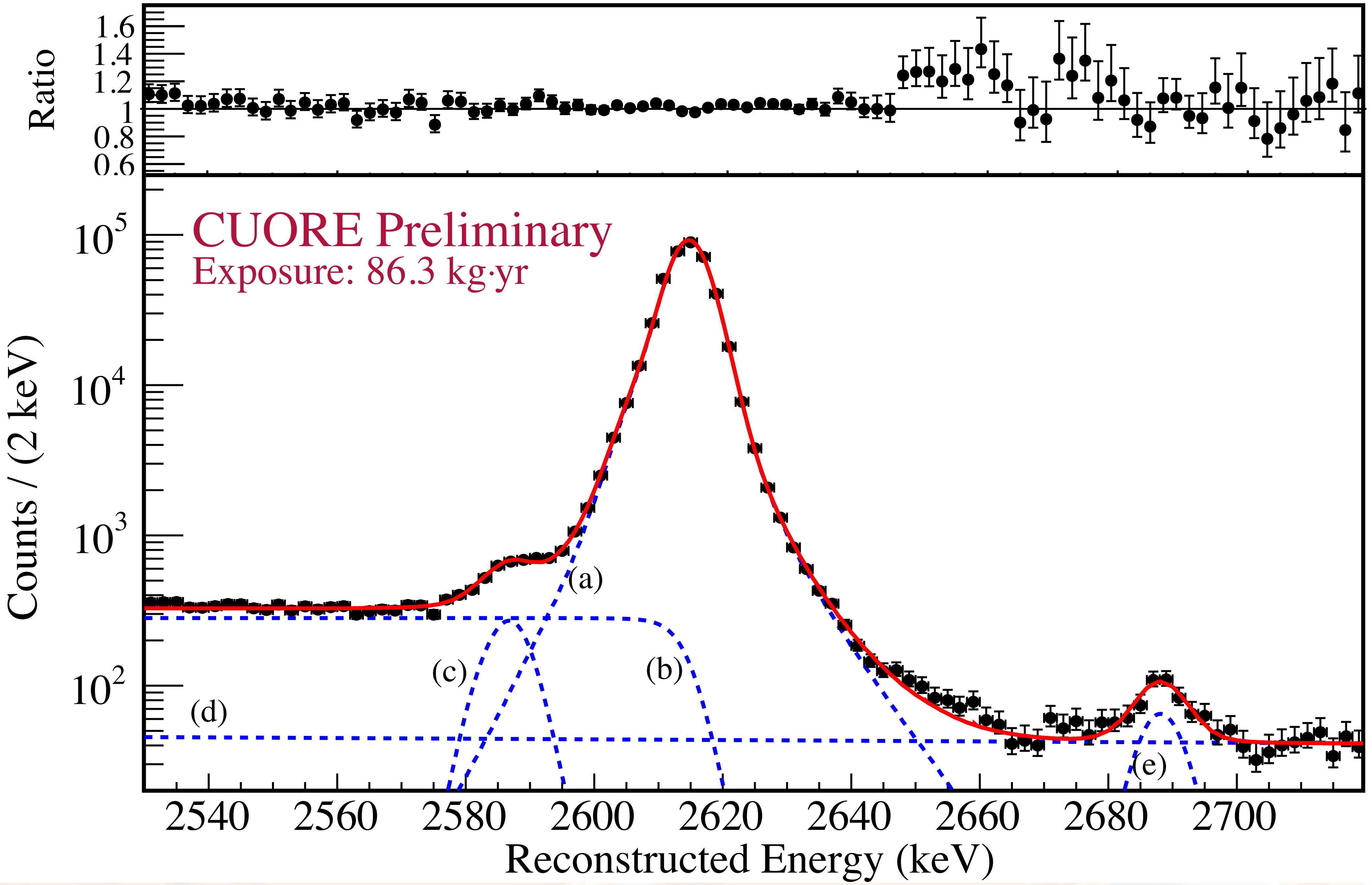
- Calibration strings deployed inside the CUORE detector
- Summed energy spectrum of all the CUORE detectors-datasets
- Calibration data used for:
    - energy scale calibration
    - thermal gain stabilisation
    - detector response (line shape) study

239 keV - ^{212}Pb
338, 911, 969 keV - ^{228}Ac
583, 2615 keV - ^{208}Tl



Detector performance: line shape

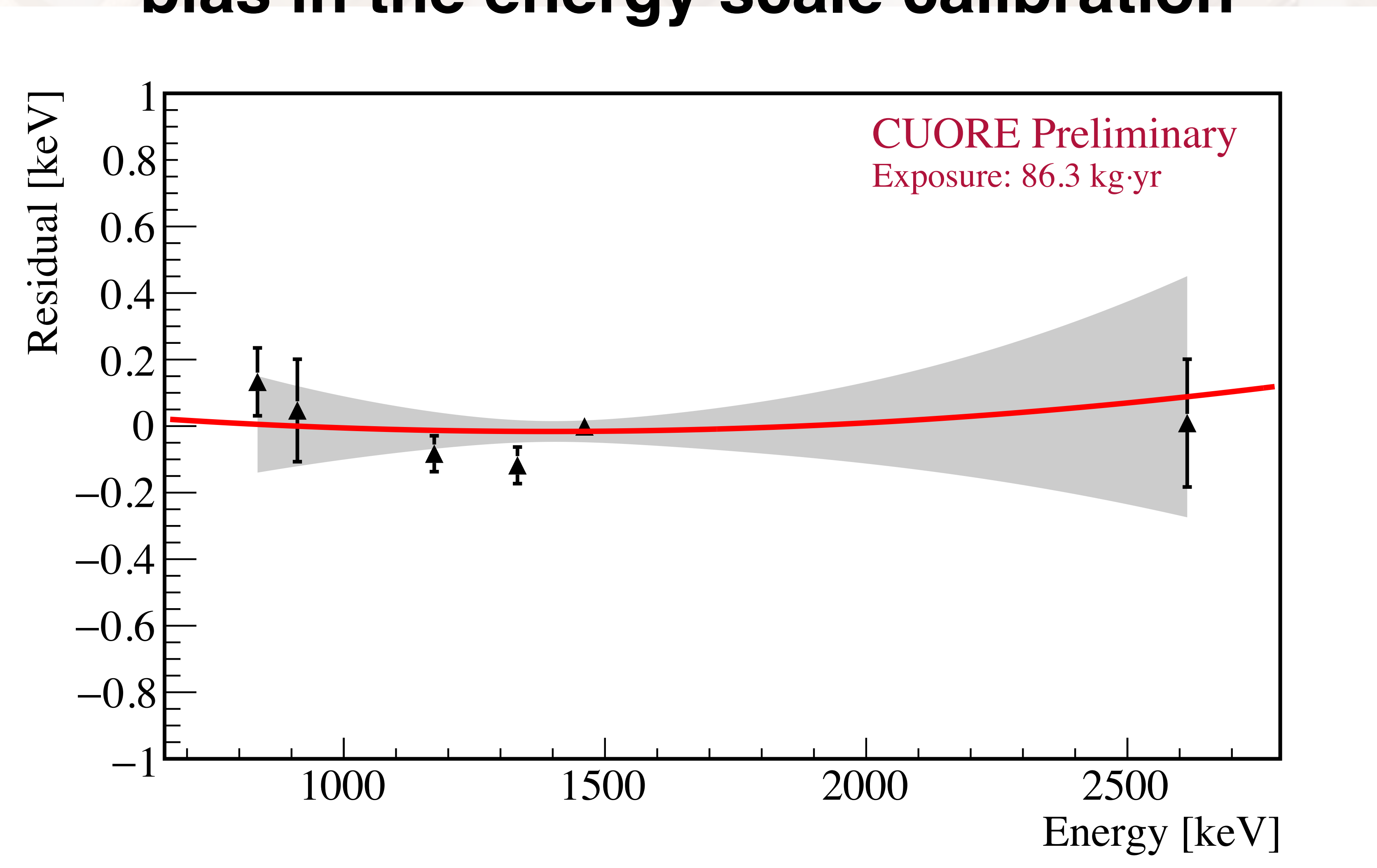
- The prominent ^{208}Tl line in the calibration spectrum was used to model the detector response to a monochromatic electron-like energy deposition
- 19 simultaneous fit on the data from all the channels of each tower, with some parameters (backgrounds) common to the whole tower and some defined channel-by-channel (resolutions, normalisations)
- Eventually only channel-dependent parameters (**signal**) will be used to build the PDF for the ROI fit
- Fit components:
  - (a) **triple gaussian for the photopeak**
  - (b) step-wise smeared multi-compton background
  - (c) combination of gaussian X-rays escape lines
  - (d) linear background
  - (e) single gaussian line for the coincident absorption of 2615-keV and 583-keV followed by a single escape process



Energy scale and resolution scaling

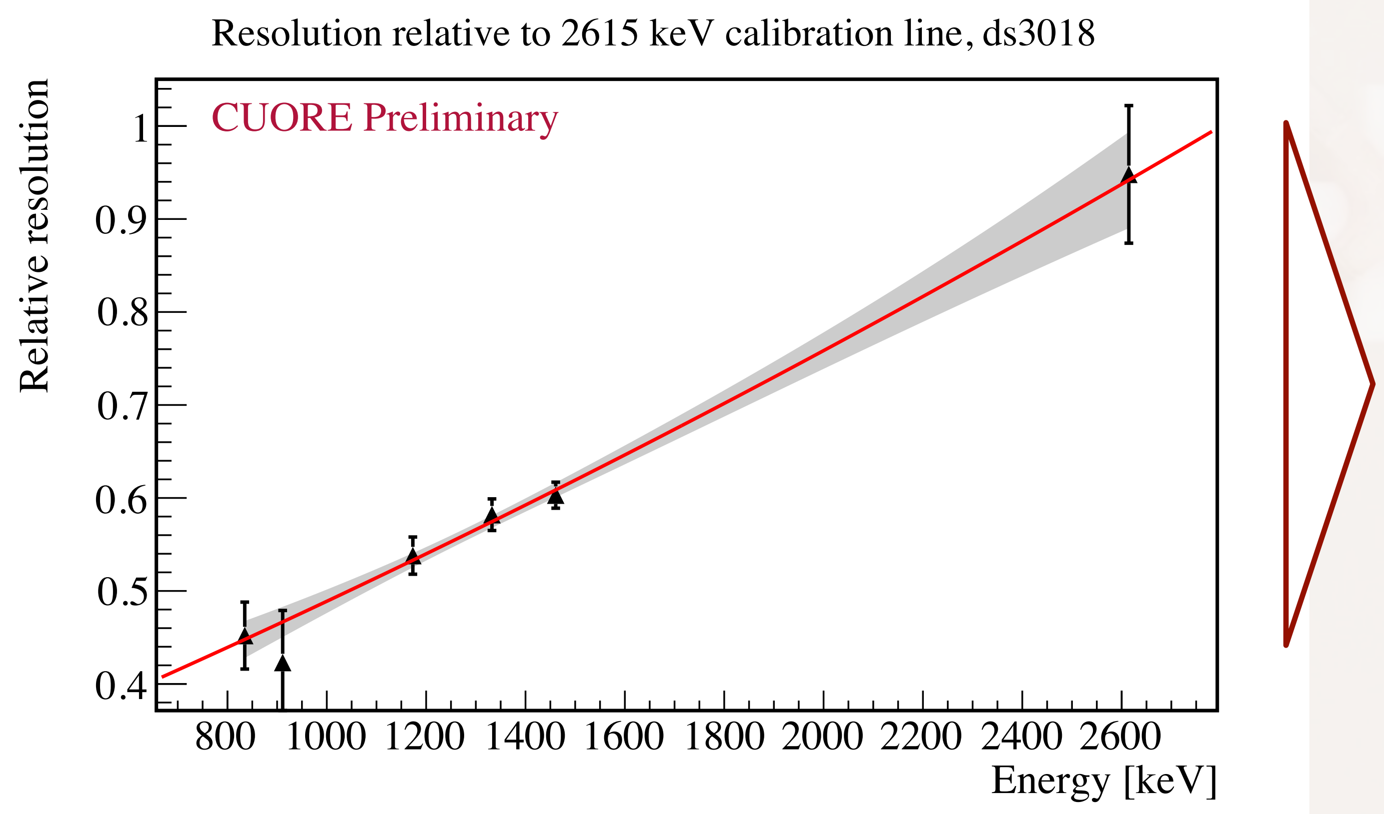
The **gamma lines in the background spectrum** have been fitted with the complete detector response function (line shape) to estimate:

bias in the energy scale calibration

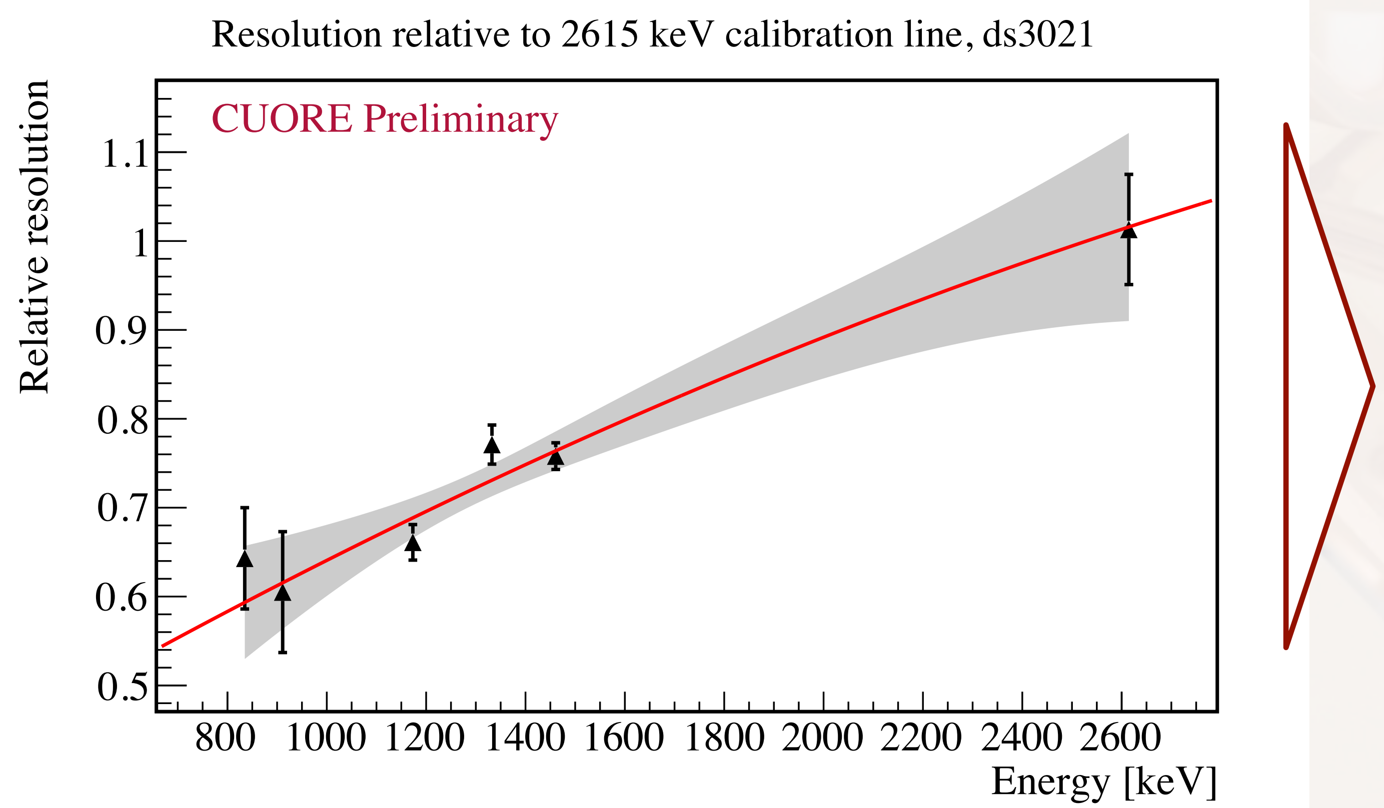


(0 ± 0.5) keV **systematics study**

dependence of resolution from energy to define a scaling factor @ Q-value



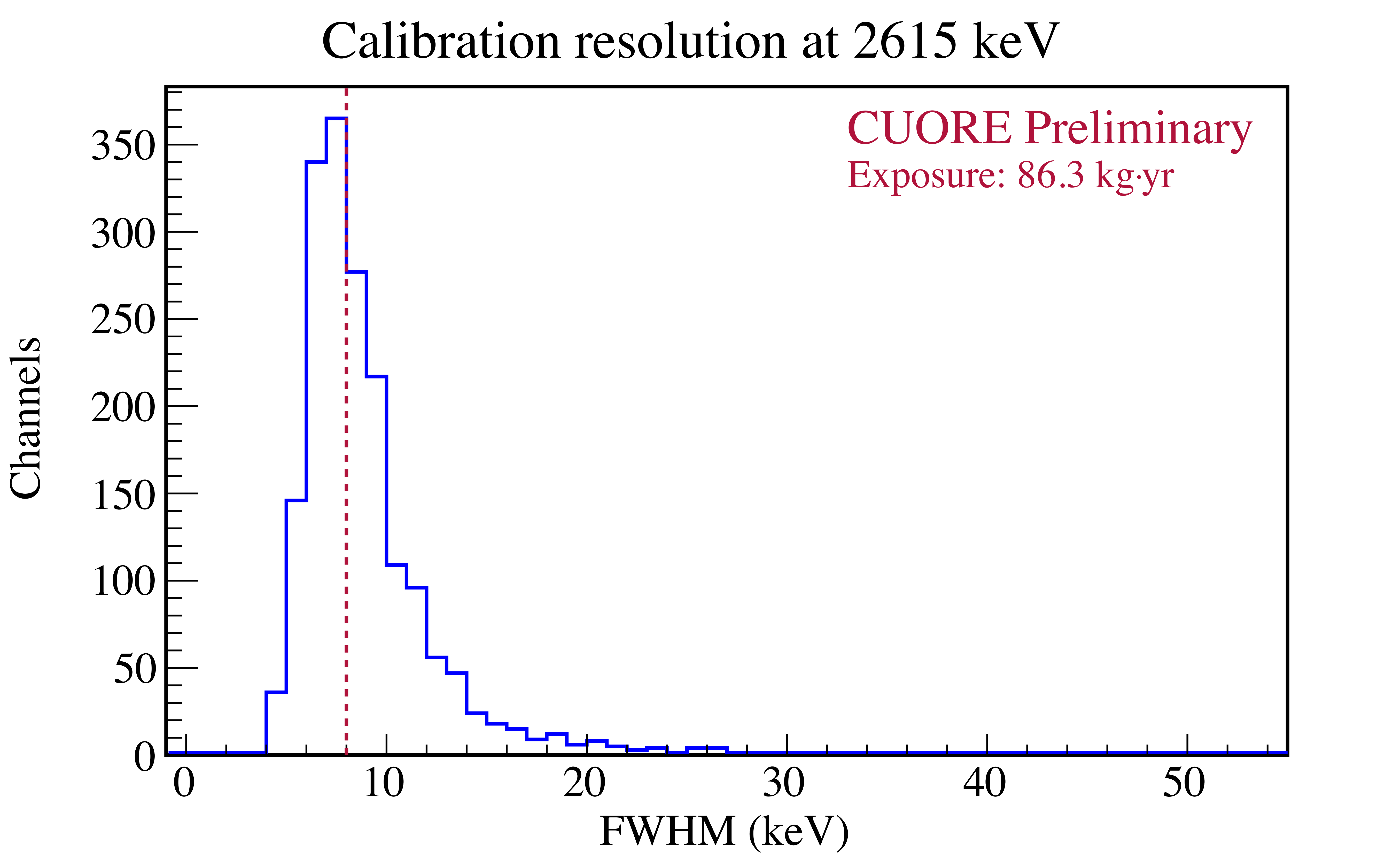
(91.5 ± 4.6)%



(100.0 ± 9.3)%

Energy resolution - Calibration runs

A total of **1811** (92% of live channels) **channels-dataset couples** were used in this analysis; **discarded channels had poor line or pulse shapes, or the energy couldn't be reconstructed accurately**



@ 2615 keV

ds3018: 9.0 keV FWHM

ds3021: 7.4 keV FWHM

effective (exposure-weighted):

8.0 keV FWHM

Energy resolution - Physics runs

A total of **1811** (92% of live channels) **channels-dataset couples** were used in this analysis; **discarded channels had poor line or pulse shapes, or the energy couldn't be reconstructed accurately**

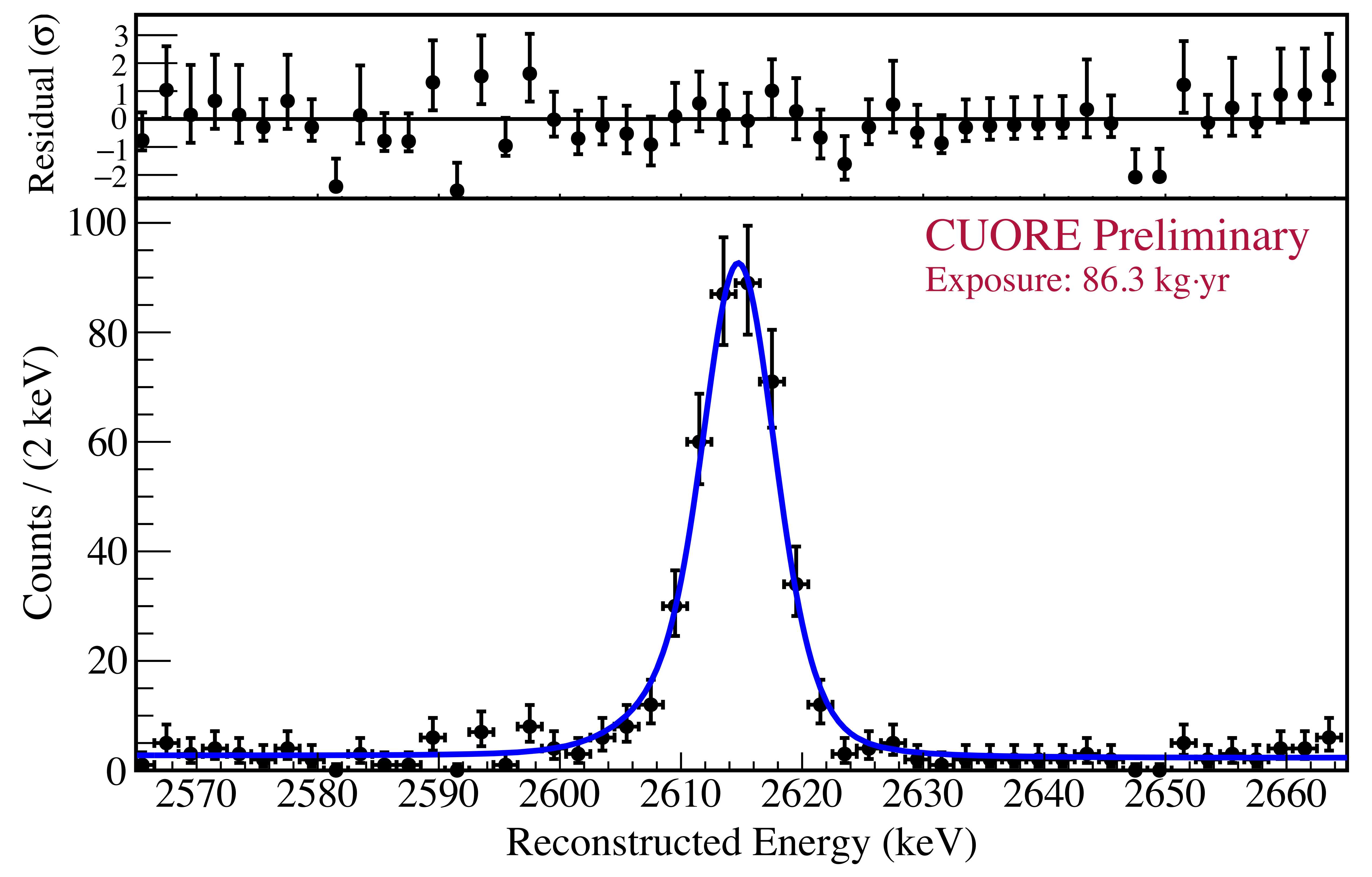
@ Q-value

ds3018: (8.3 ± 0.4) keV FWHM

ds3021: (7.4 ± 0.7) keV FWHM

effective (exposure-weighted):

(7.7 ± 0.5) keV FWHM



Analysis procedure

- Acquisition of continuous waveforms
- Triggering
- Data preprocessing: estimation of raw parameters
- Pulse filtering with Optimum Filter
- Thermal Gain Stabilization (TGS): calibration and heater-based
- Energy calibration and best energy estimator selection
- Particle event selection - Pulse Shape Analysis
- Coincidence analysis w/ detector response synchronisation and software threshold @ 150 keV (to prevent any spectral shape distortion due to threshold effects in the ROI)
- Energy spectrum

Very similar to what was developed and used for CUORE-0 (Phys. Rev. C 93, 045503 (2016))

Event selection: efficiencies

Event selection occurs after periods of low-quality data (~1% of the total live time) are removed.

- Trigger: compare the number of pulses generated by injection of power through a heater (pulser events) that were triggered as normal events
- Energy reconstruction: number of pulser-generated events reconstructed within 3 sigma from the average of their energy distribution
- Base cuts: computed on pulser events
- Anti-coincidence: calculated on ^{40}K line @ 1460 keV (no physical coincidences expected) with side-bands subtraction
- Pulse shape analysis: calculated on ^{208}Tl line @ 2615 keV (not used for optimisation) with side-bands subtraction
- Containment efficiency: calculated with Monte Carlo simulation of the detector geometry

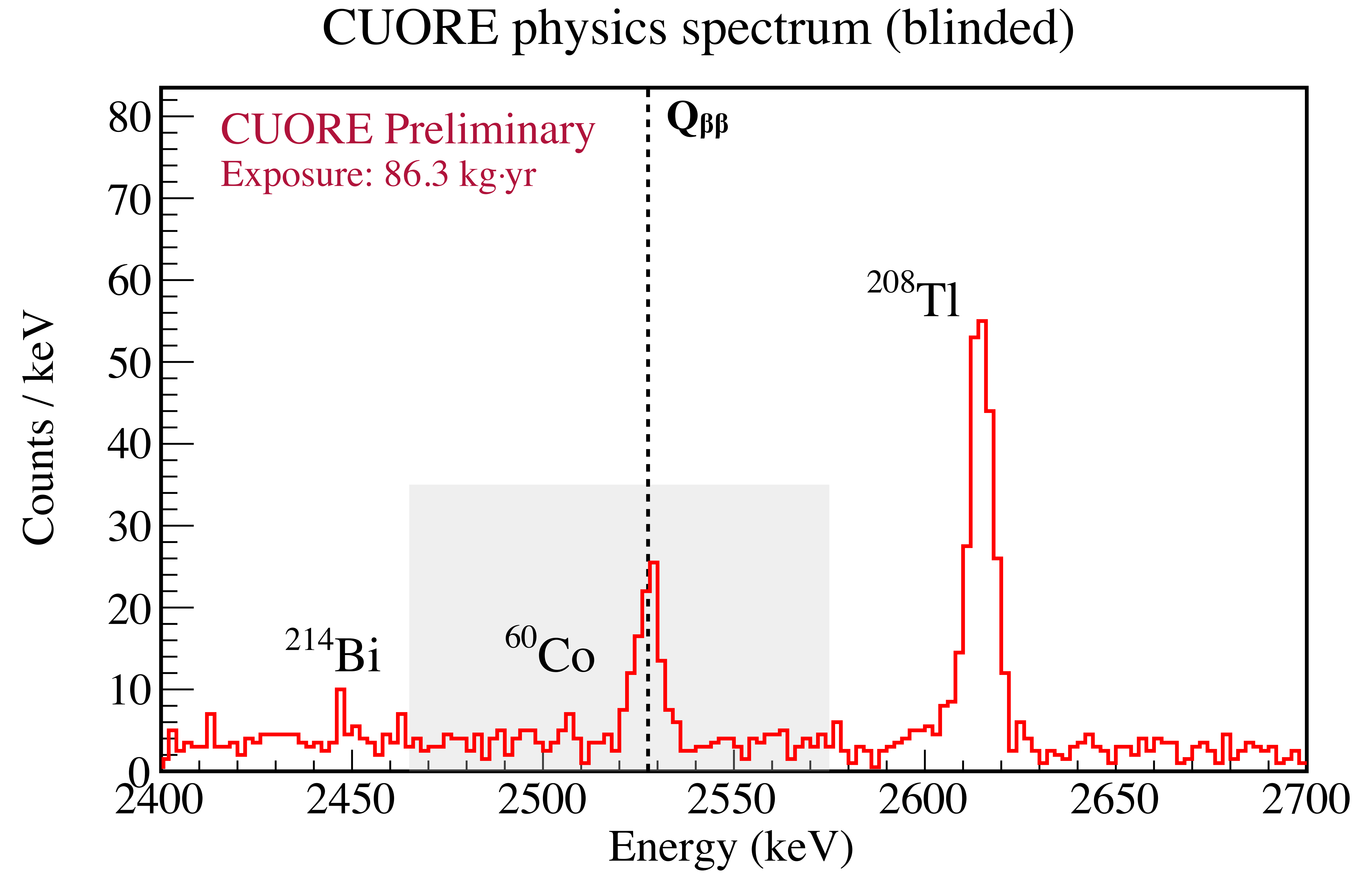
Event selection: efficiencies

Event selection occurs after periods of low-quality data (~1% of the total live time) are removed.

	Dataset 1	Dataset 2
Trigger	(99.766 ± 0.003) %	(99.735 ± 0.004) %
Energy reconstruction	(99.168 ± 0.006) %	(99.218 ± 0.006) %
Base cuts (pile-up, global data quality)	(95.63 ± 0.01) %	(96.69 ± 0.01) %
Anti-coincidence	(99.4 ± 0.5) %	(100.0 ± 0.4) %
Pulse shape analysis	(91.1 ± 3.6) %	(98.2 ± 3.0) %
All cuts except containment	**(85.7 ± 3.4) %**	**(94.0 ± 2.9) %**
$0\nu\beta\beta$ containment	(88.35 ± 0.09) %	
Total	**(75.7 ± 3.0) %**	**(83.0 ± 2.6) %**

Blinding procedure

- 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 hiding the real 0vDBD rate of ^{130}Te
- 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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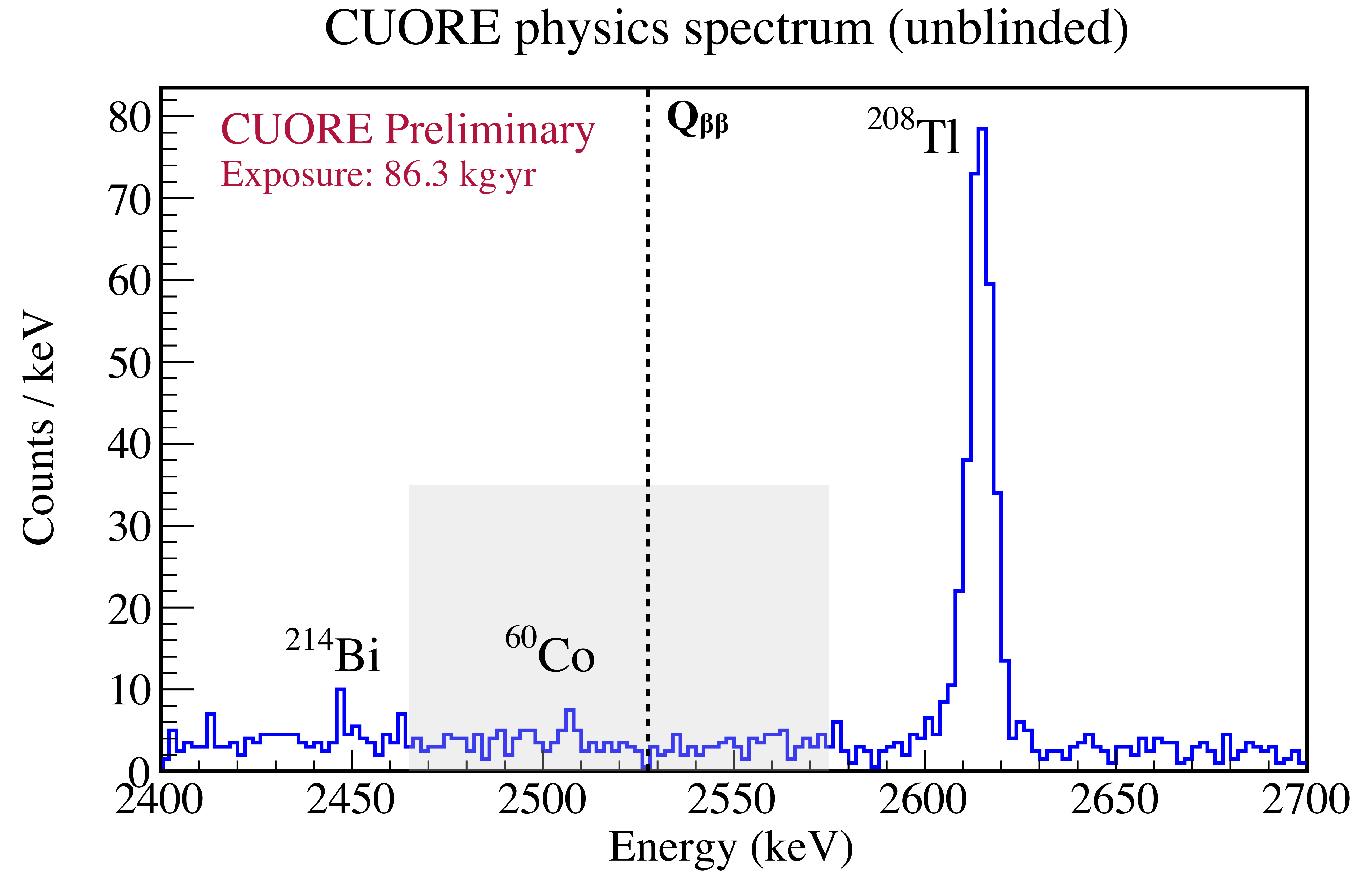

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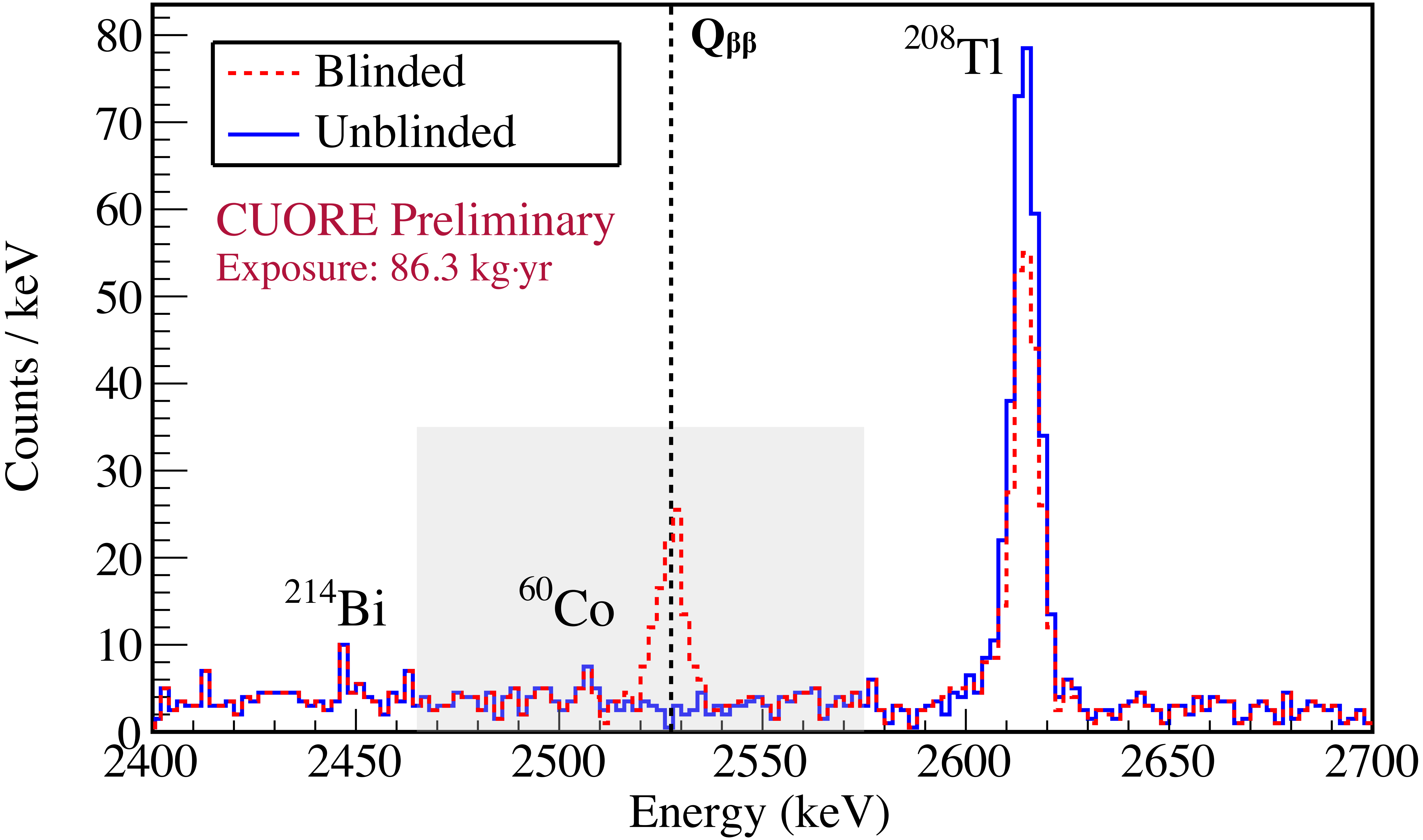

Event selection

Eventually 155 (65+90) events survive the selection cuts in the unblinded region of interest

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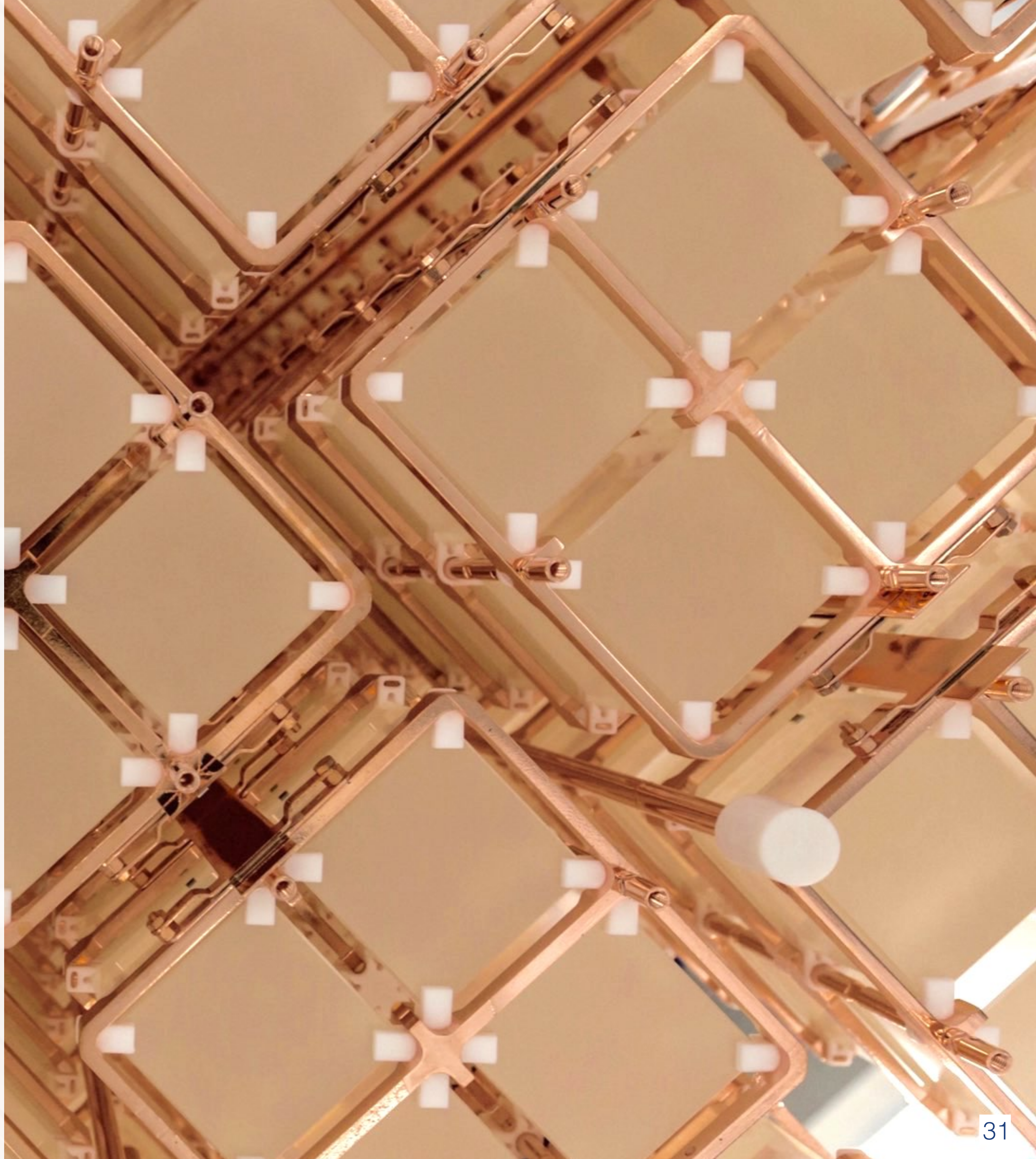
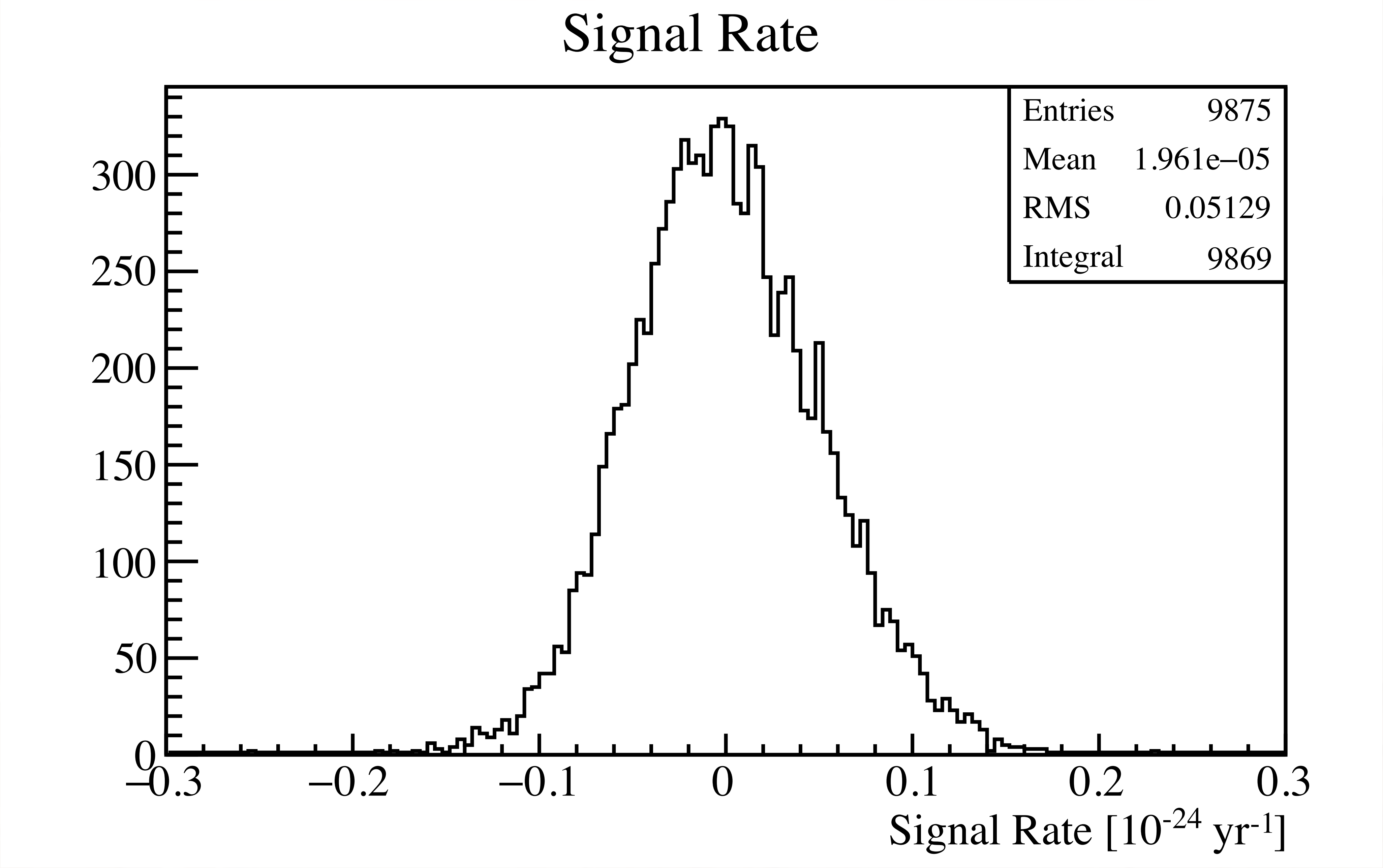


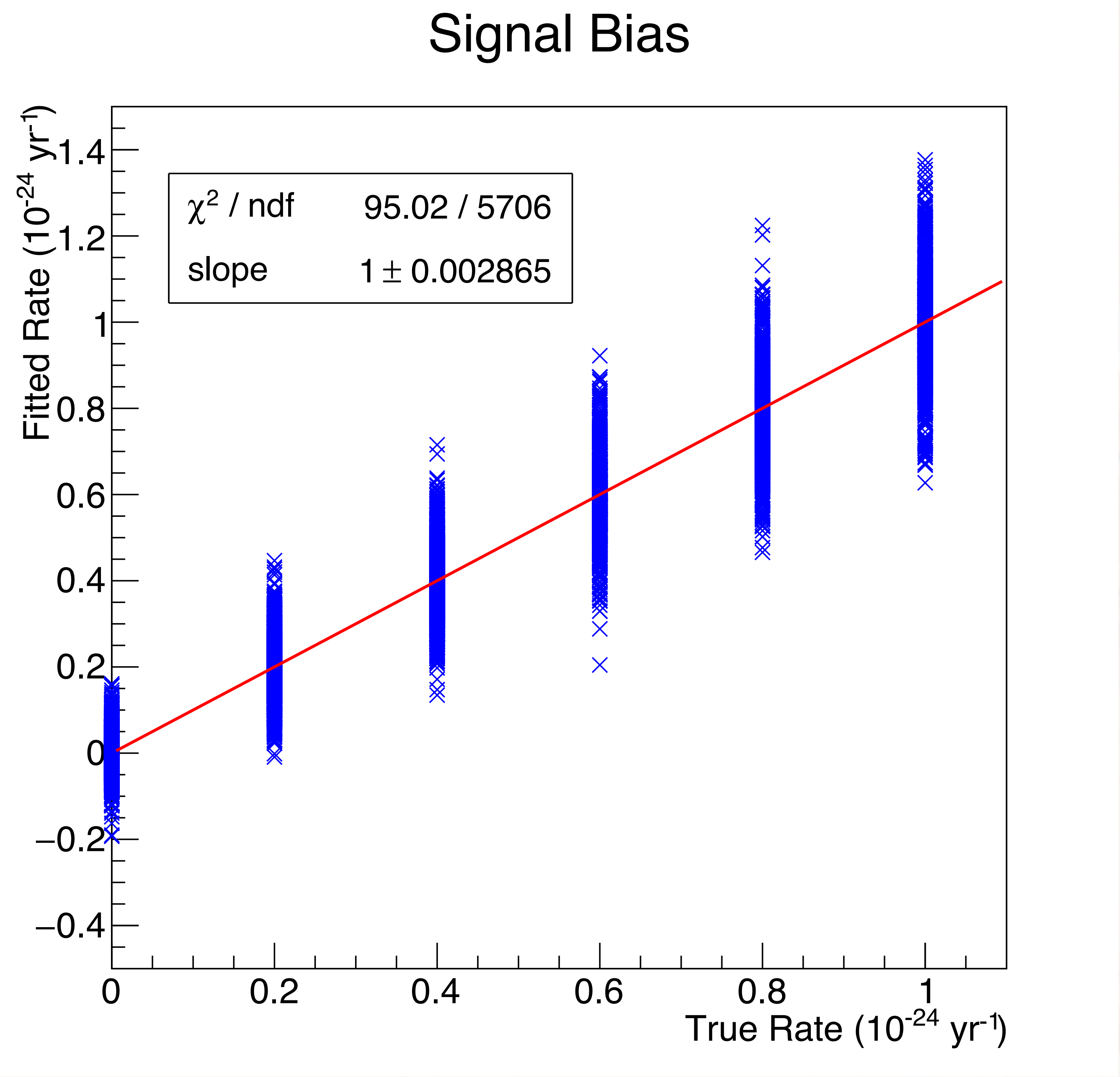
Fit in the ROI

- Simultaneous **UEML** (Unbinned Extended Maximum Likelihood) fit in the energy region **2465-2575 keV**
- The fit has 3 components:
  1. **posited peak at the Q-value** of ^{130}Te:
     - energy scale defined relative to the ^{208}Tl line in calibration data to account for residual mis-calibration between channels
     - signal normalisation common to all detectors-datasets (1 free parameter)
  2. **floating peak to account for the ^{60}Co** sum gamma line (2505 keV):
     - energy scale defined relative to the ^{208}Tl line in calibration data to account for residual mis-calibration between channels
     - rate common to all detectors-dataset, with a correction accounting for the time elapsed between the two datasets (1 free parameter)
  3. **flat background**, attributed to multi scatter Compton events from ^{208}Tl and surface alpha events:
     - common to all detectors in a single dataset, two independent parameters for the two datasets to account for differences in the background rejection efficiency (2 free parameters)
- The peaks in each channel-dataset are fitted with its own line shape (fixed from calibration data)

Bias and systematic errors

Any bias in the fitting procedure is searched for. A large number of pseudo-experiments is generated starting from a model where the signal rate $\Gamma^{0\nu}$ is changed from 0 to a large value. Each pseudo-experiment is fitted with the full model (H_1), and the distribution of the fitted signal rates are examined.





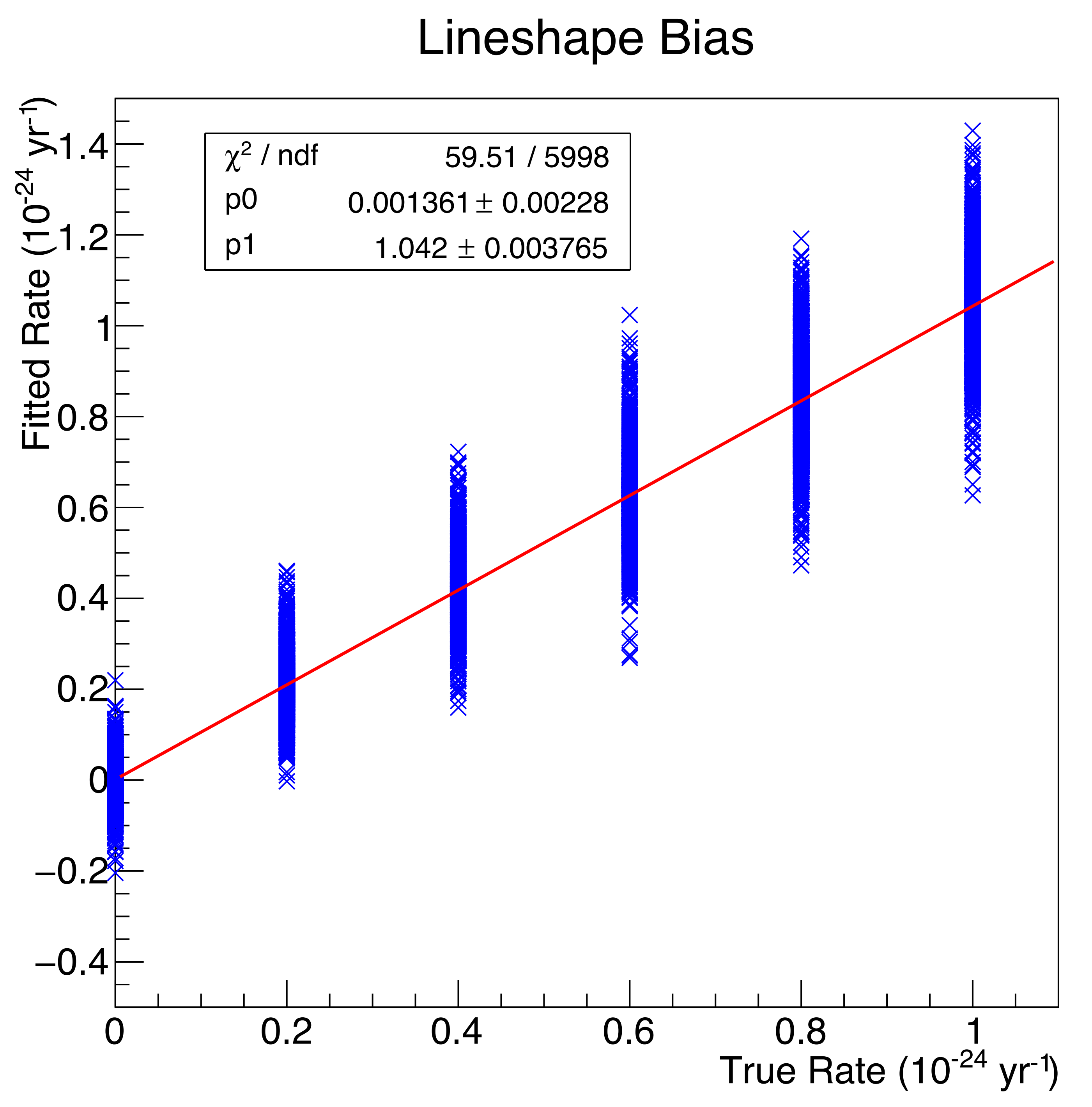
NO EVIDENCE OF ABSOLUTE BIAS is found, and a small 0.3% relative component is estimated

Bias and systematic errors

Uncertain parameters of the model that can affect the result are considered as potential source of systematic errors, and studied as nuisance parameters.

For each parameter θ_i in the model H_1:

- take H_1 best fit and change by +(-)1σ (worst case for the line shape) the value of θ_i
- generate a large number of pseudo-experiments from the obtained PDF
- fit each pseudo-experiment with H_1 with the original value of θ_i and extract $\Gamma^{0\nu}_{fit}$
- repeat the procedure with different values of the signal $\Gamma^{0\nu}_{true}$, from 0 to a large value
- plot $\Gamma^{0\nu}_{fit}$ vs $\Gamma^{0\nu}_{true}$
- parametrise the bias as p0 (additive) +p1· $\Gamma^{0\nu}$ (scaling)



Only deviations from 0 in p0 and from 1 in p1 that are statistically significant are considered as systematic errors and added in quadrature and propagated to the limit

Systematic errors

The following nuisance parameters are considered:

- energy resolution (higher and lower by 1σ)
- Q-value (higher and lower by 0.5 keV from energy scale uncertainty)
- no sub-peak in the detector response (simple gaussian lineshape)
- linear background (higher and lower by 1σ)

The systematic error associated to efficiency is computed directly from the statistical uncertainty on the efficiency

Systematic	Absolute uncertainty [10^{-24} yr]	Relative uncertainty
Resolution	-	1.5%
Q-value location	-	0.2%
No subpeaks	0.002	2.4%
Efficiency	-	2.4%
Linear fit	0.005	0.8%

Fit in the ROI

Region of interest: **2465 to 2575 keV**

Overall signal efficiency: **(75.7 ± 3.0)% - ds3018**

(83.0 ± 2.6)% - ds3021

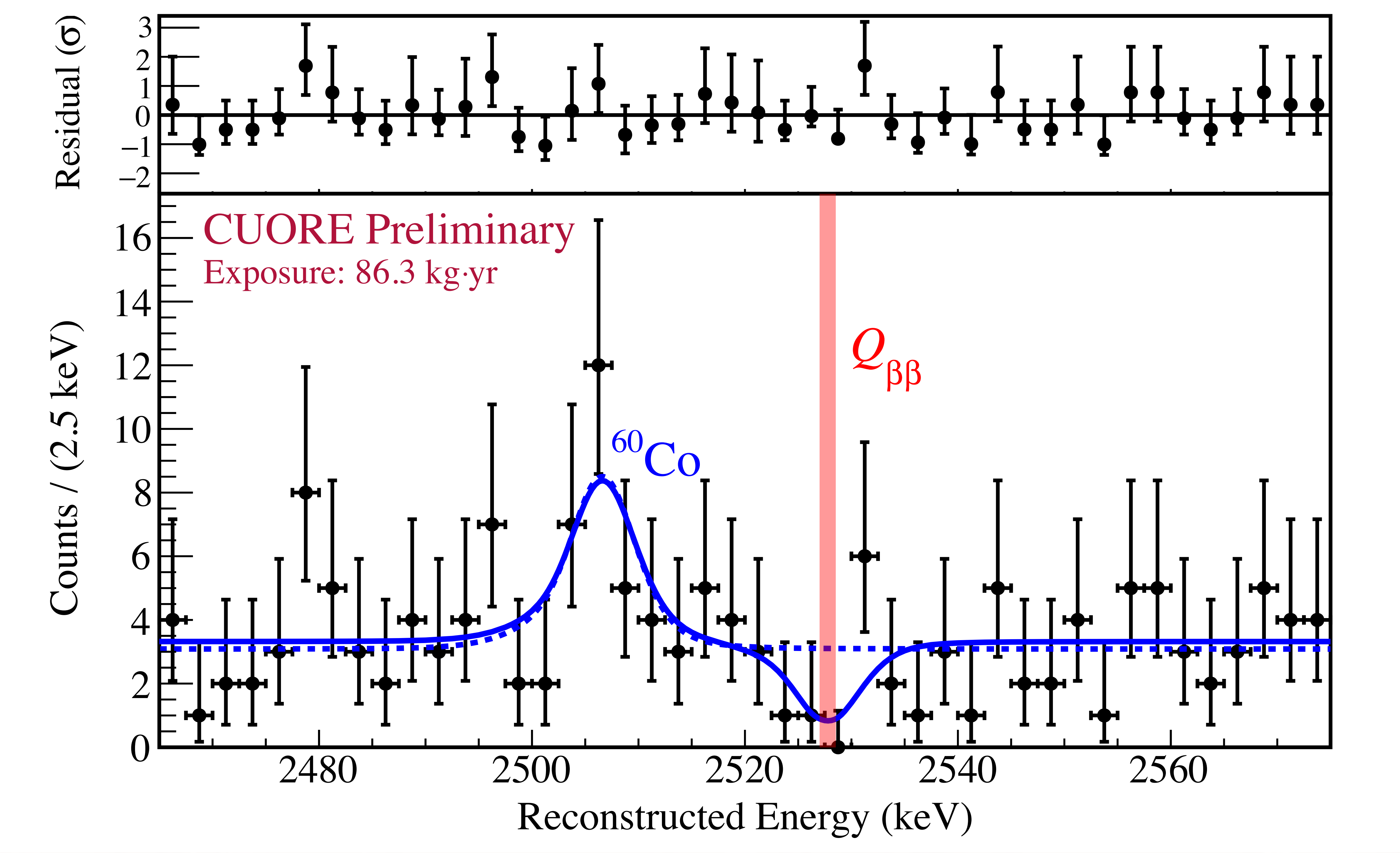
Events in the region of interest: **155**

ROI background index: **$(1.49_{-0.17}^{+0.18}) \times 10^{-2}$ c/(keV·kg·yr)**

$(1.35_{-0.18}^{+0.20}) \times 10^{-2}$ c/(keV·kg·yr)

Best fit for ^{60}Co mean: **(2506.4 ± 1.2) keV**

Best fit decay rate: **$(-1.0_{-0.3}^{+0.4}$ (stat.) ± 0.1 (syst.))$\times 10^{-25}$ / yr**

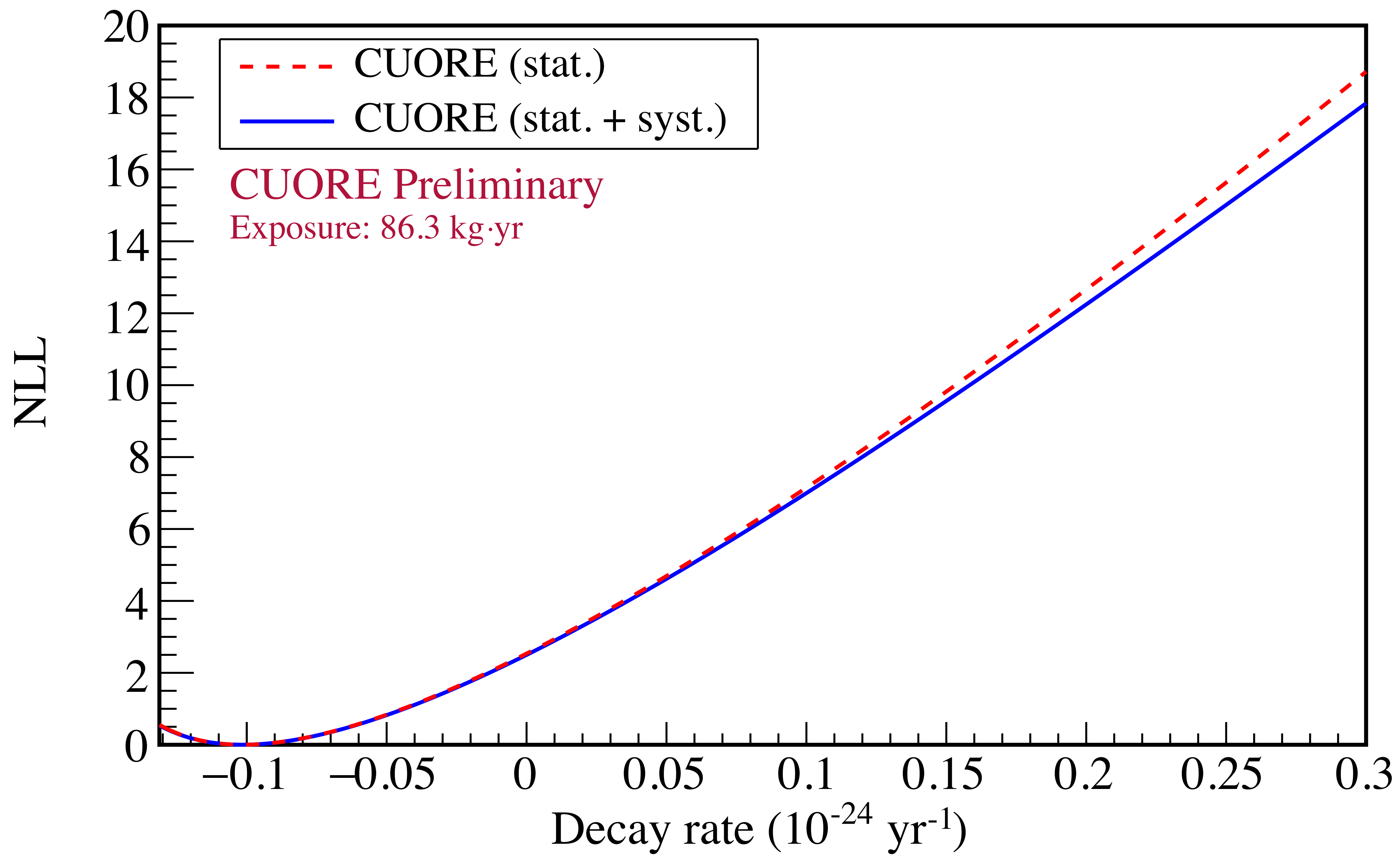


Fit in the ROI

Best fit decay rate:

$(-1.0_{-0.3}^{+0.4}$ (stat.) ± 0.1 (syst.))$\times 10^{-25}$ / yr

No evidence of signal
Limit calculation
Profile likelihood integrated on the physical region ($\Gamma^{0\nu} > 0$)



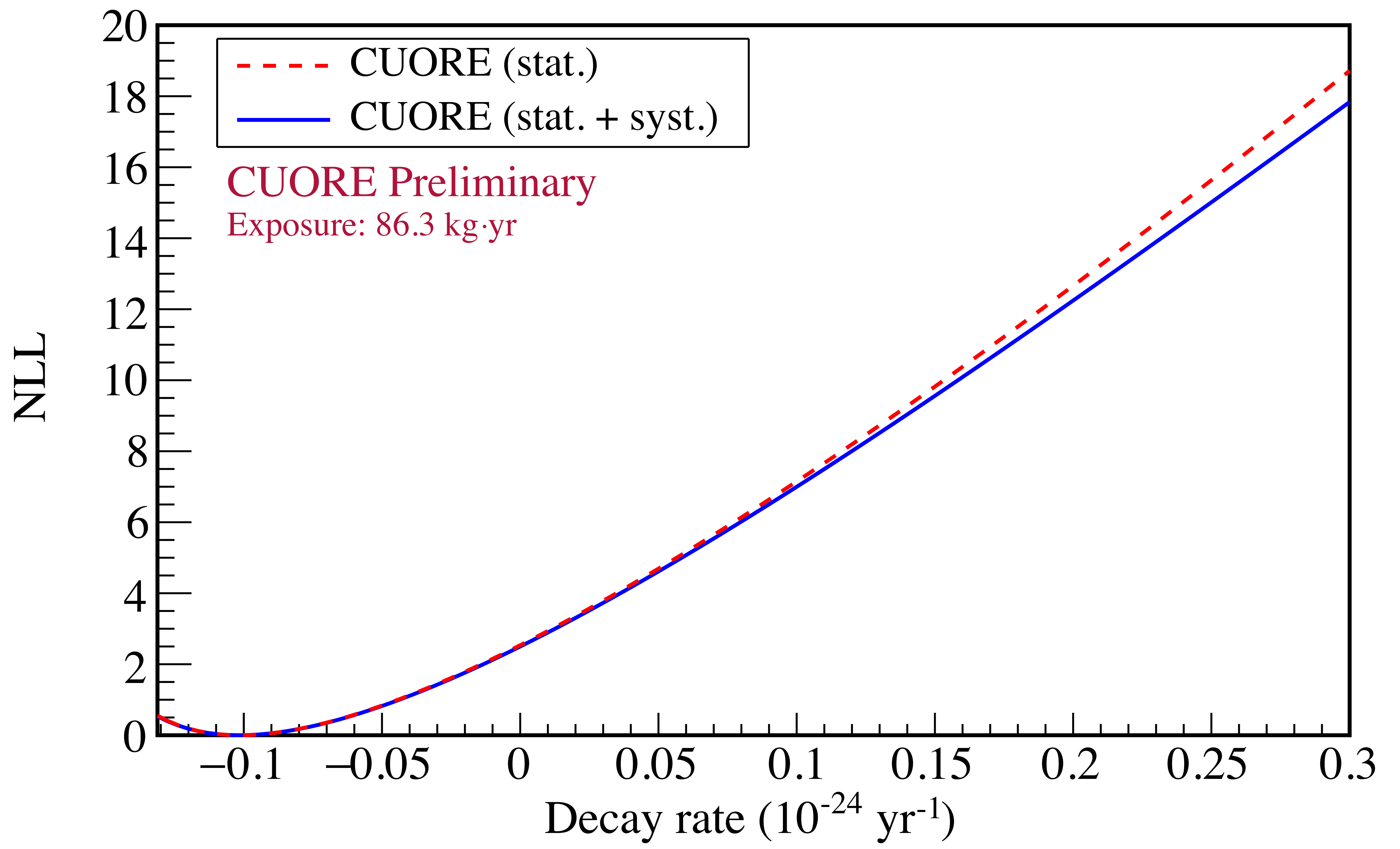
Fit in the ROI

Best fit decay rate:

$(-1.0_{-0.3}^{+0.4}$ (stat.) ± 0.1 (syst.)$)\times 10^{-25}$ / yr

No evidence of signal
Limit calculation
Profile likelihood integrated on the physical region ($\Gamma^{0\nu} > 0$)

Decay rate limit (90% CL, including systematics):
0.51×10^{-25} / yr
Half-life limit (90% CL, including systematics):
1.3×10^{25} yr
Median expected sensitivity:
7.0×10^{24} yr



Fit in the ROI

We also perform an independent, **fully-bayesian** analysis based on the MCMC Gibbs sampler implemented in BAT.

We put a flat positive prior on the signal rate and compute the limit on the signal rate by integrating the marginalised posterior.

The result is compatible with the one obtained by integration of the profile likelihood.

Fit in the ROI

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We put a flat positive prior on the signal rate and compute the limit on the signal rate by integrating the marginalised posterior.

The result is compatible with the one obtained by integration of the profile likelihood.

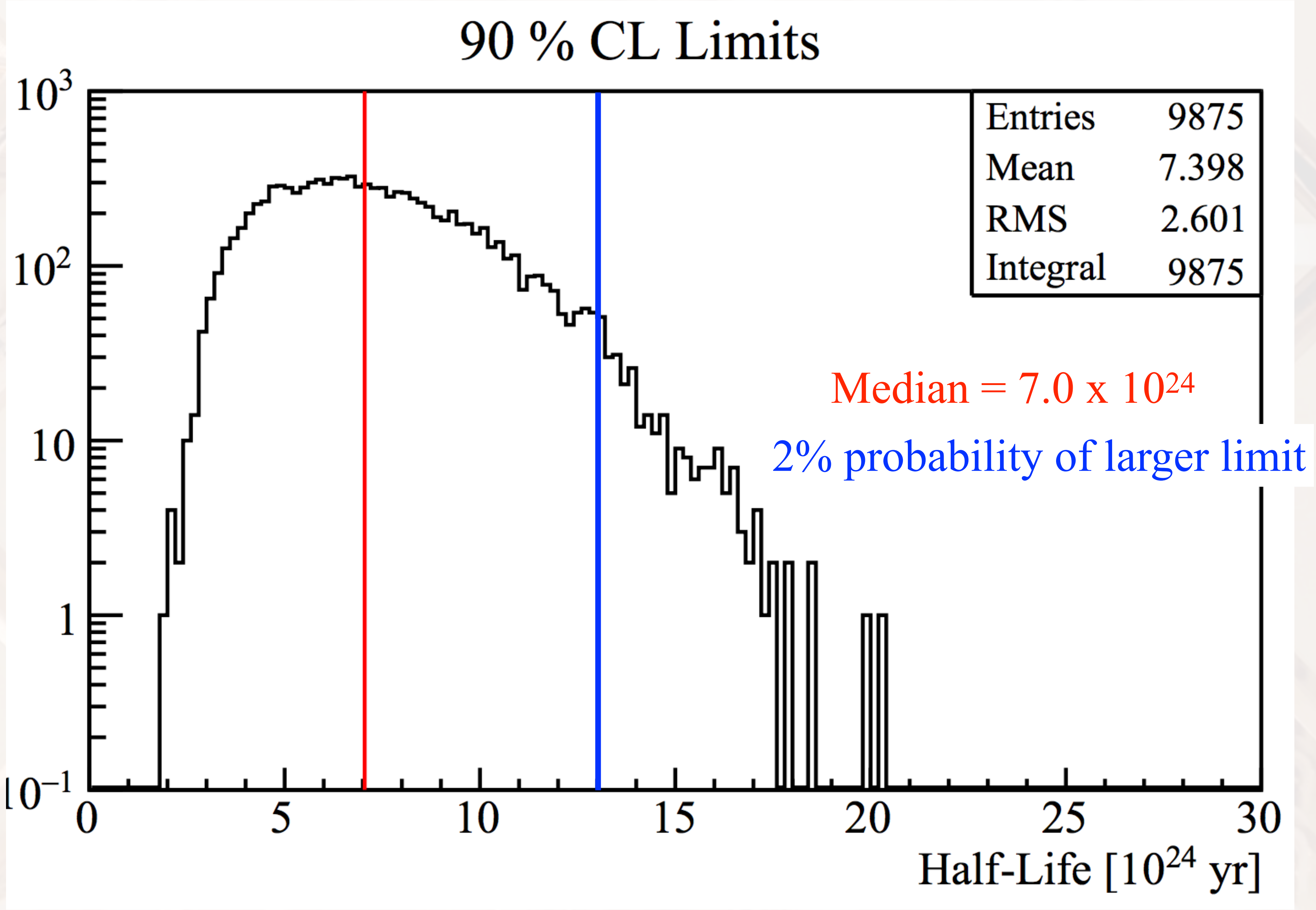
We have also evaluated **frequentist limits** according to “W. Rolke et al., Nucl. Instrum. Meth. A 551, 493-503 (2005)”:

- Decay rate limit (90% CL, including systematics): 0.33×10^{-25} / yr
- Half-life limit (90% CL, including systematics): 2.1×10^{25} yr

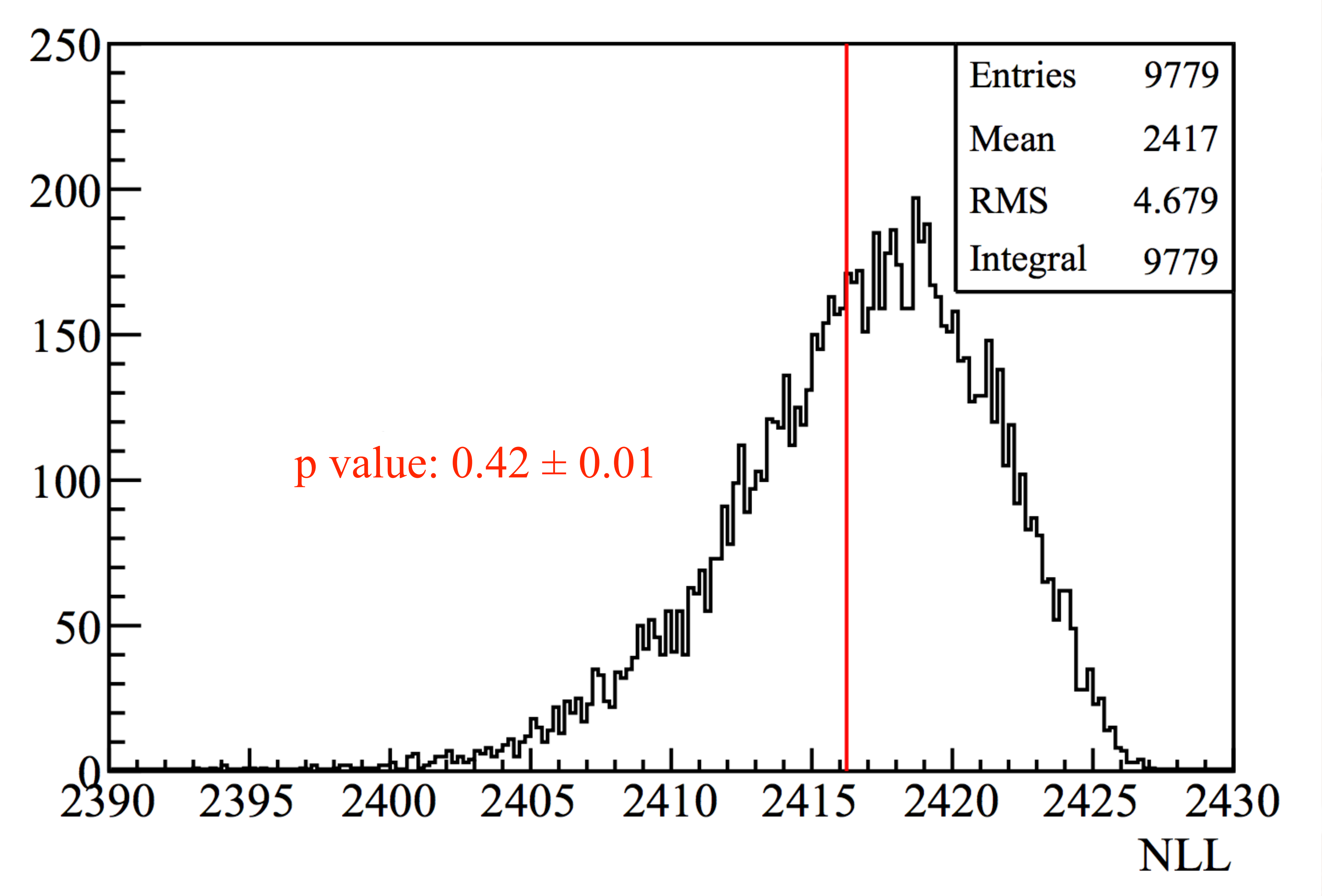
Statistical considerations

We perform a number of tests to establish the statistical significance of the result and the goodness of fit.

Sensitivity: for each pseudo-experiment generated from H_0 compute 90% CI limit. Compute quantile of measured limit

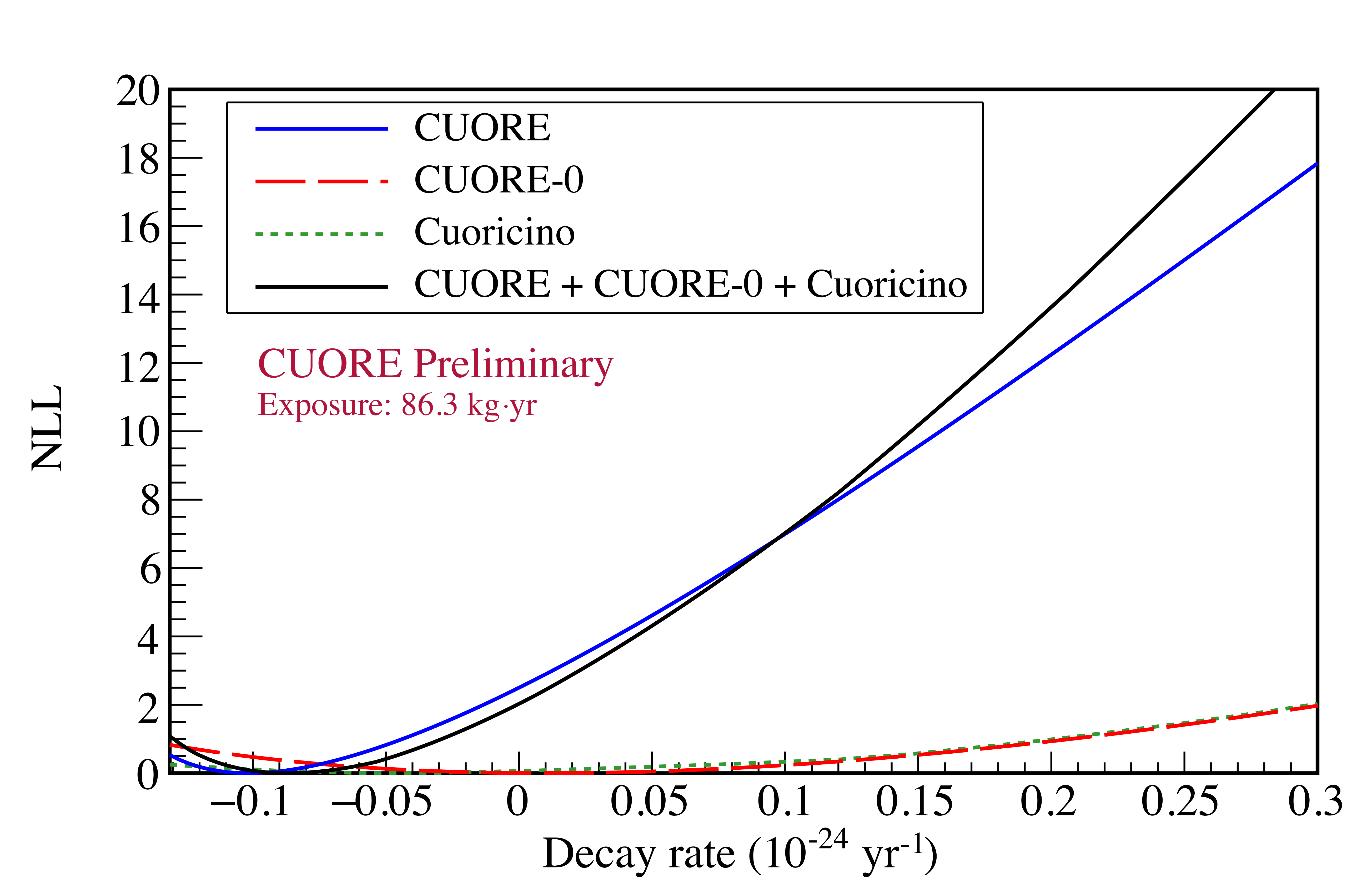


NLL test: for each pseudo-experiment generate from H_0 fit and compute NLL. Compute quantile corresponding to NLL of real data



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
  $T_{0v} > 1.5 \times 10^{25}$ yr



Combined "Rolke" limit: 2.2×10^{25} 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

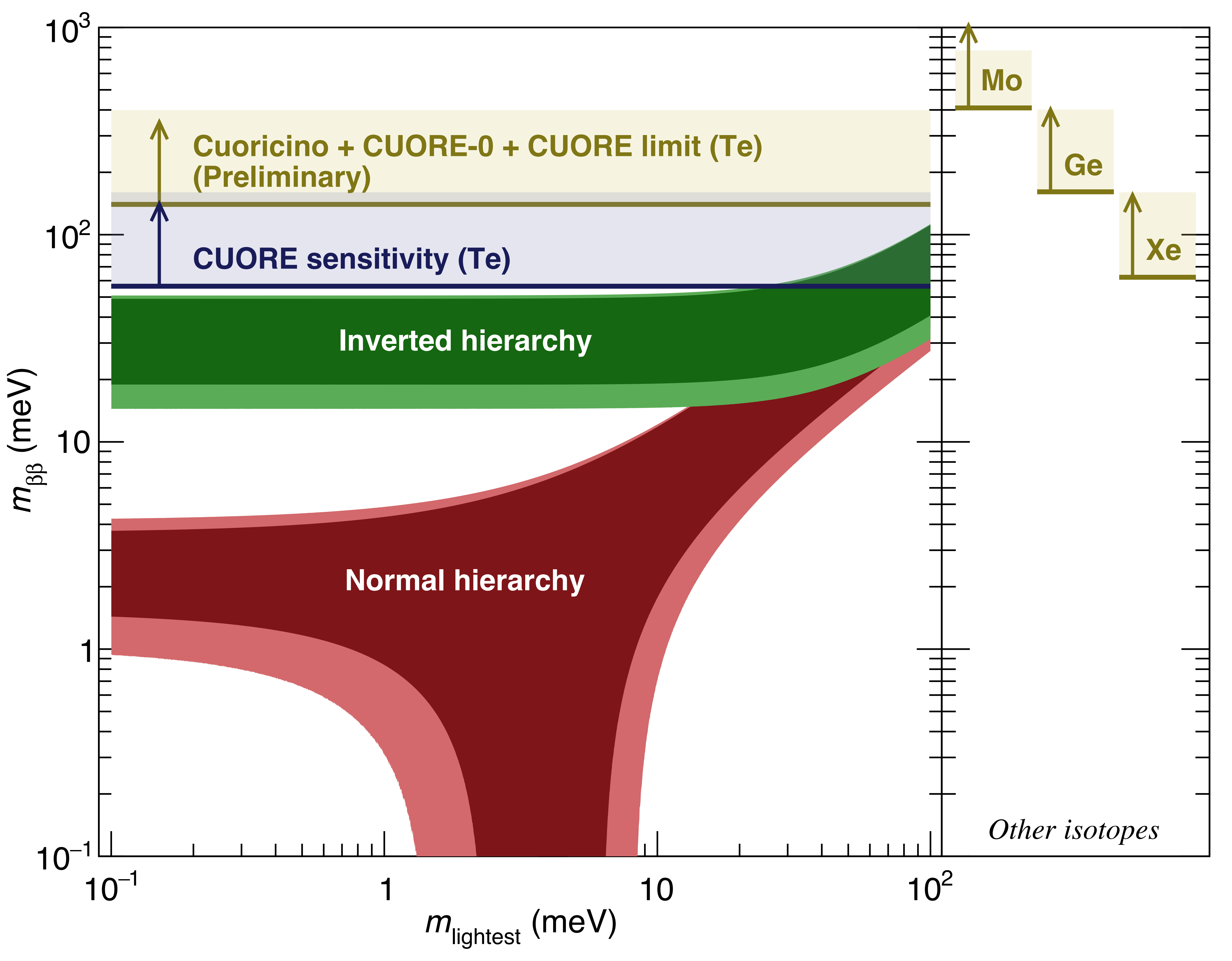
- The combined 90% C.L. limit is

$T_{0\nu} > 1.5 \times 10^{25}$ yr

$m_{\beta\beta} <$ 140–400 meV

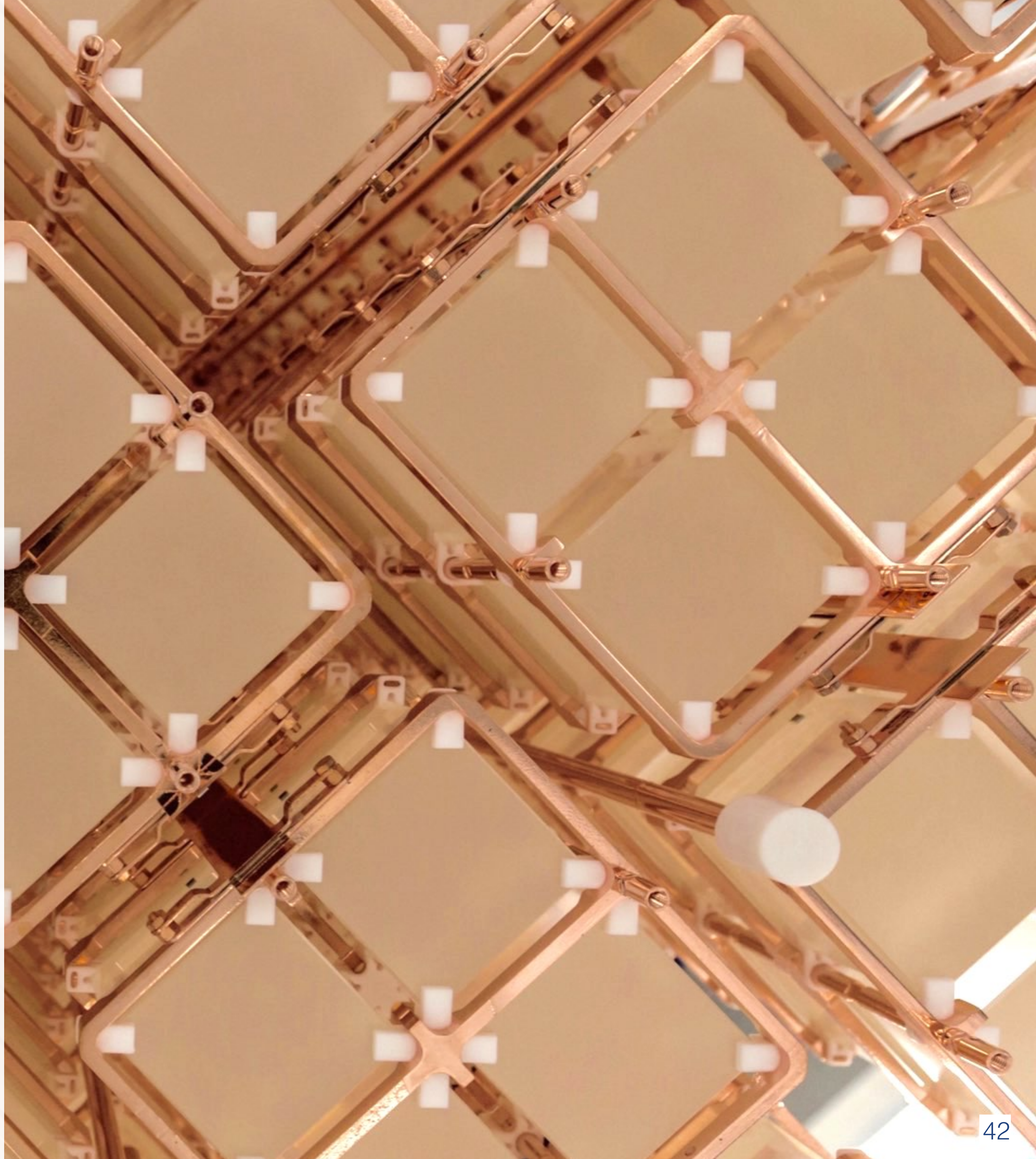
NME:
Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 91, 024613 (2015)
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. Lett. 105, 252503 (2010)

Experiments:
^{130}Te: 1.5×10^{25} 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



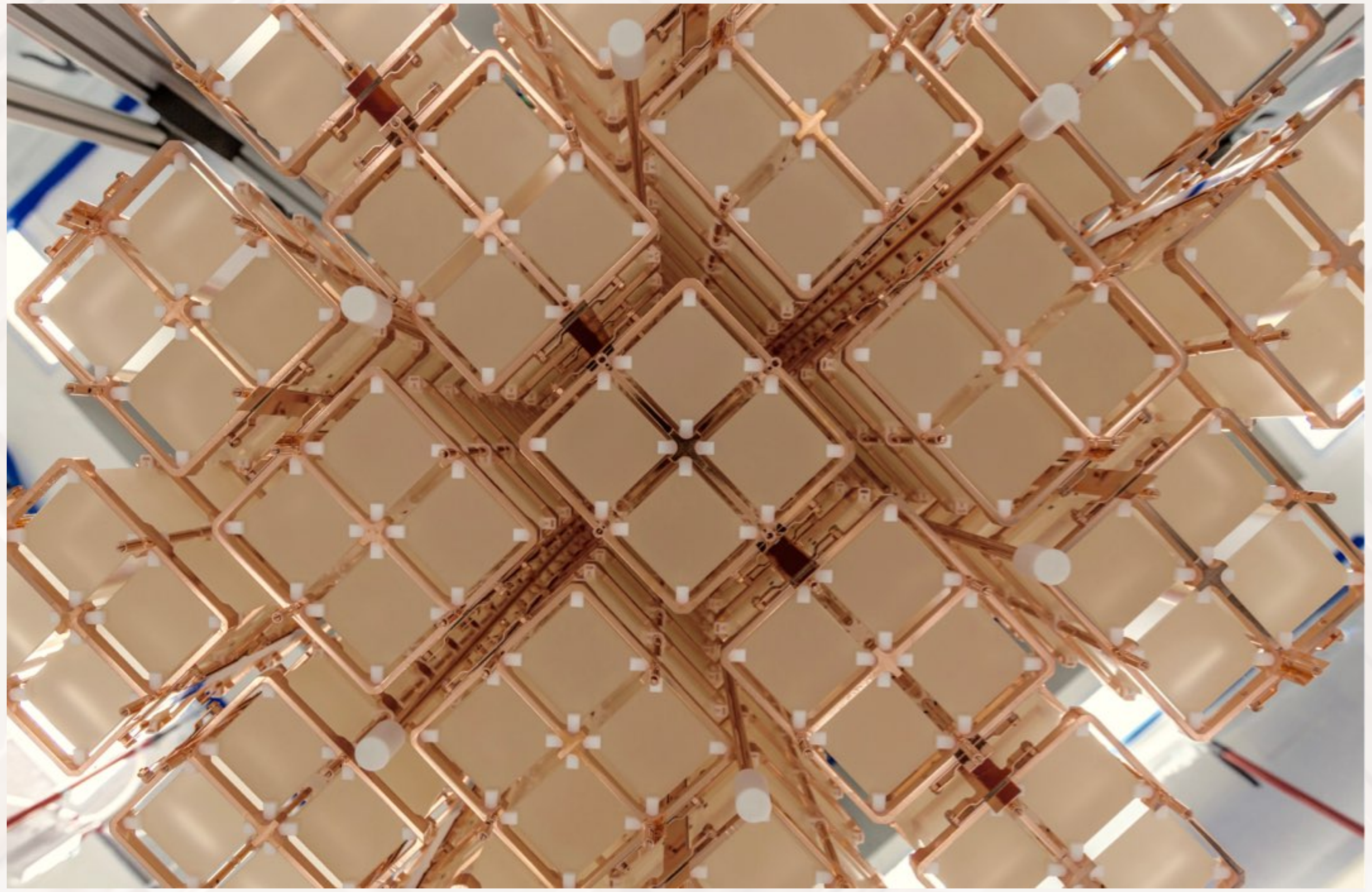
Outline

- TeO_2 and thermal detectors for neutrino-less DBD
- CUORE setup
    - Cryogenics
    - Installation
    - Pre-operation
    - Science data taking
- Analysis procedures
    - Calibration and detector response
    - Event selection
    - Blinding
- Physics results
    - Fit
    - Systematics
    - Combination with other experiments
- Conclusions and outlook



Conclusions

- With the first two datasets CUORE have:
  - accumulated a total exposure of almost 100 kg·y
  - Invaluable operational experience
  - collected important information on detector performance, noise, resolutions, background levels
  - pushed for the first time the limit on neutrino-less double beta decay half life of ^{130}Te beyond 10^{25} years



- CUORE cryogenic system is working spectacularly well
- The largest and most complex cryogenic experiment is taking physics data
- The first analysis efforts were focused on the neutrino-less double beta decay
- Physics results on more processes are on their way
- With an unprecedented amount of data, CUORE is the best tool to study and model the backgrounds for the next generation experiments
- Paper will appear on arXiv tomorrow, to be submitted to PRL