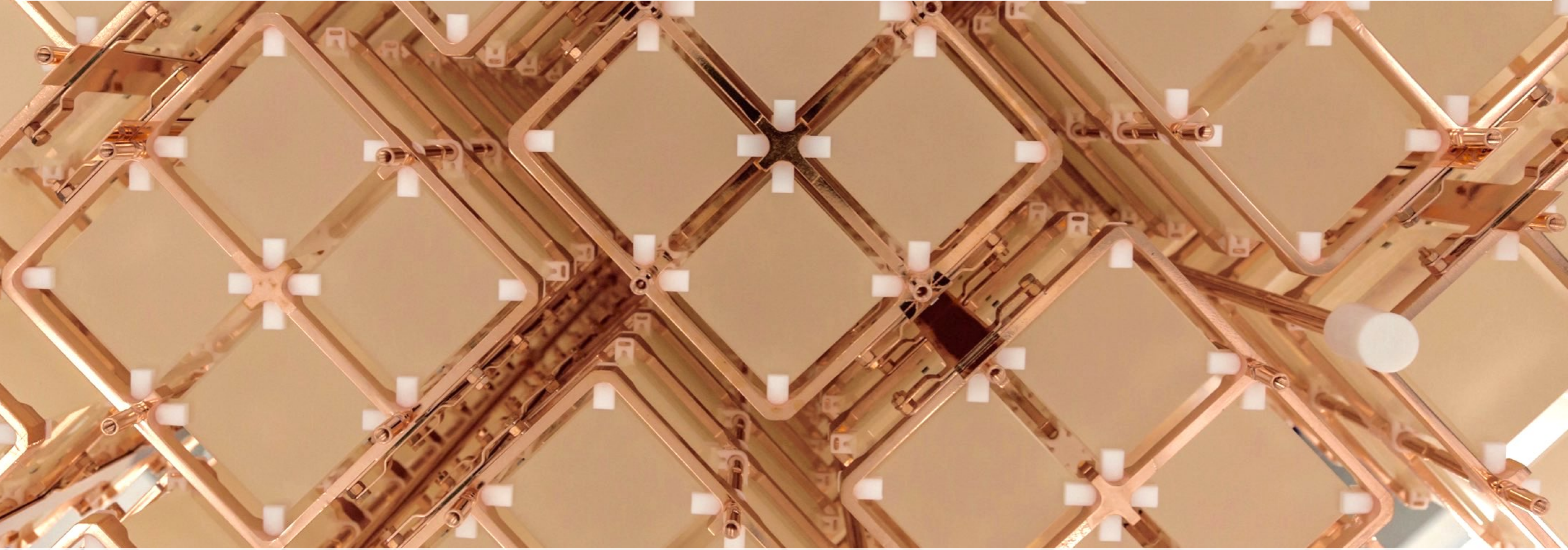
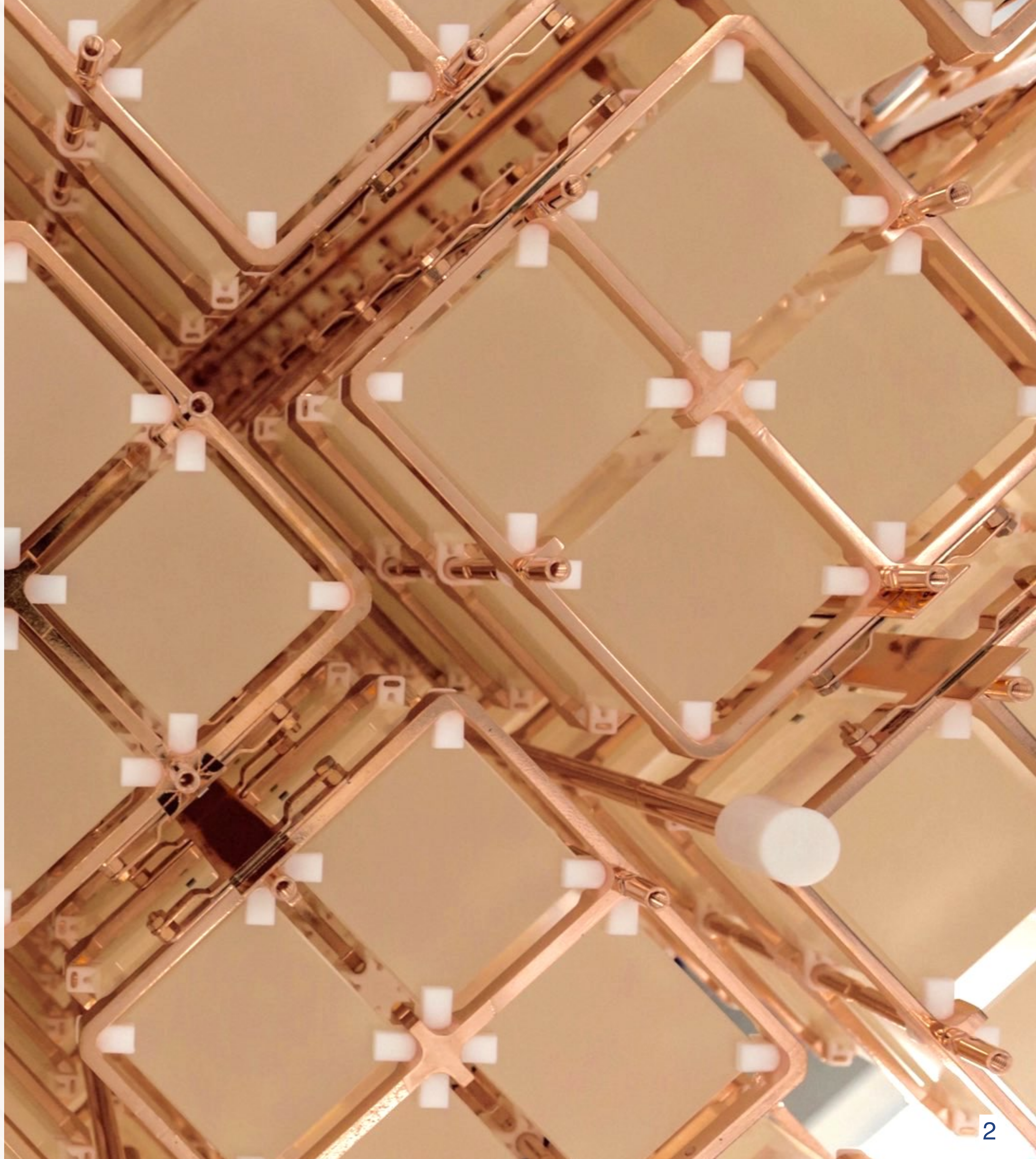
Results from the CUORE experiment

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



Outline

- TeO_2 and thermal detectors for neutrino-less DBD
- CUORE setup
  - Location
  - Cryogenic system
  - Calibration system
  - Shielding
- CUORE roadmap
- Analysis procedures
  - Calibration and detector response
  - Event selection and topology
- Physics results
  - $0\nu\beta\beta$ and lepton number violation
  - background model
  - $2\nu\beta\beta$
- Conclusions and outlook



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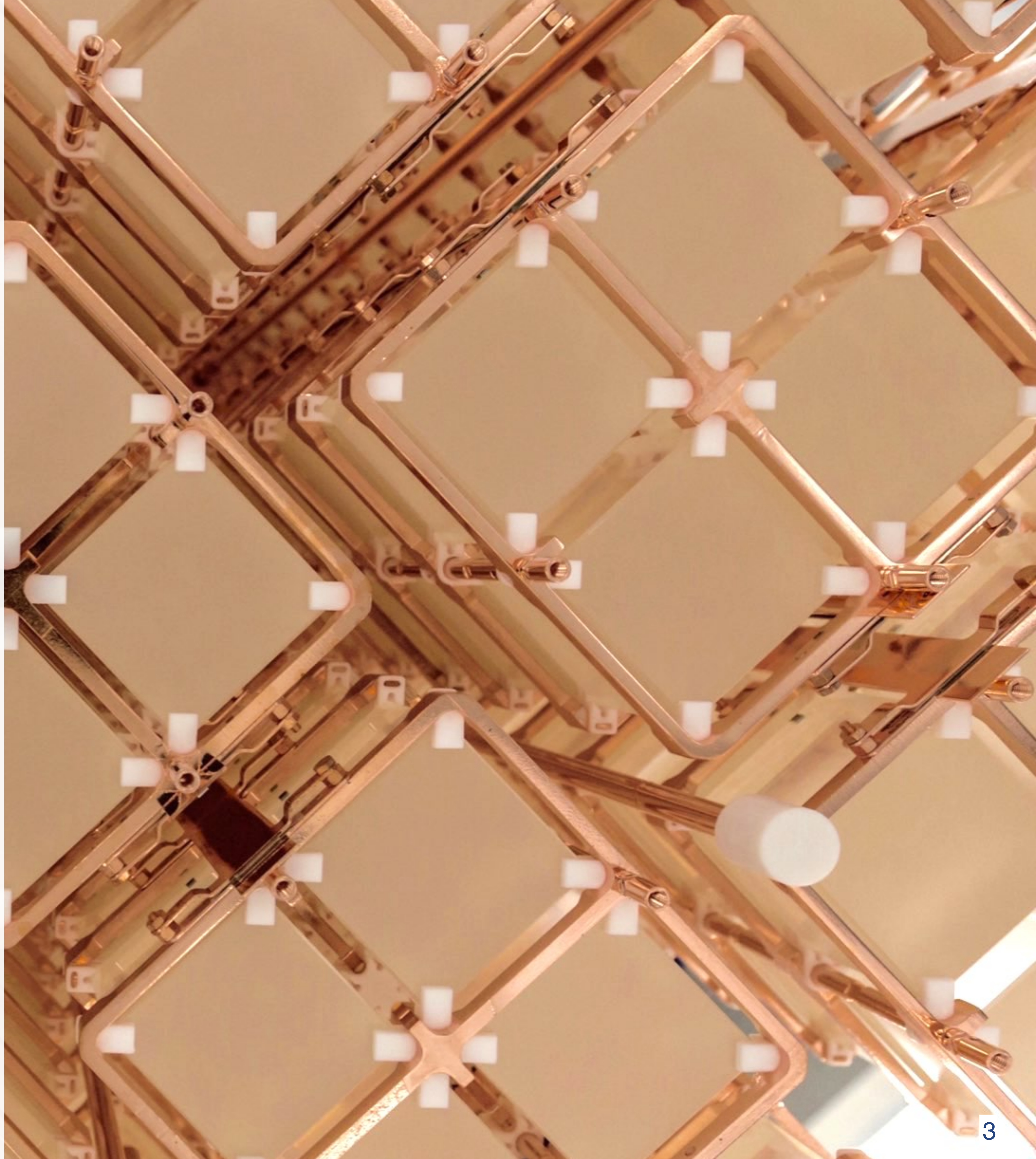


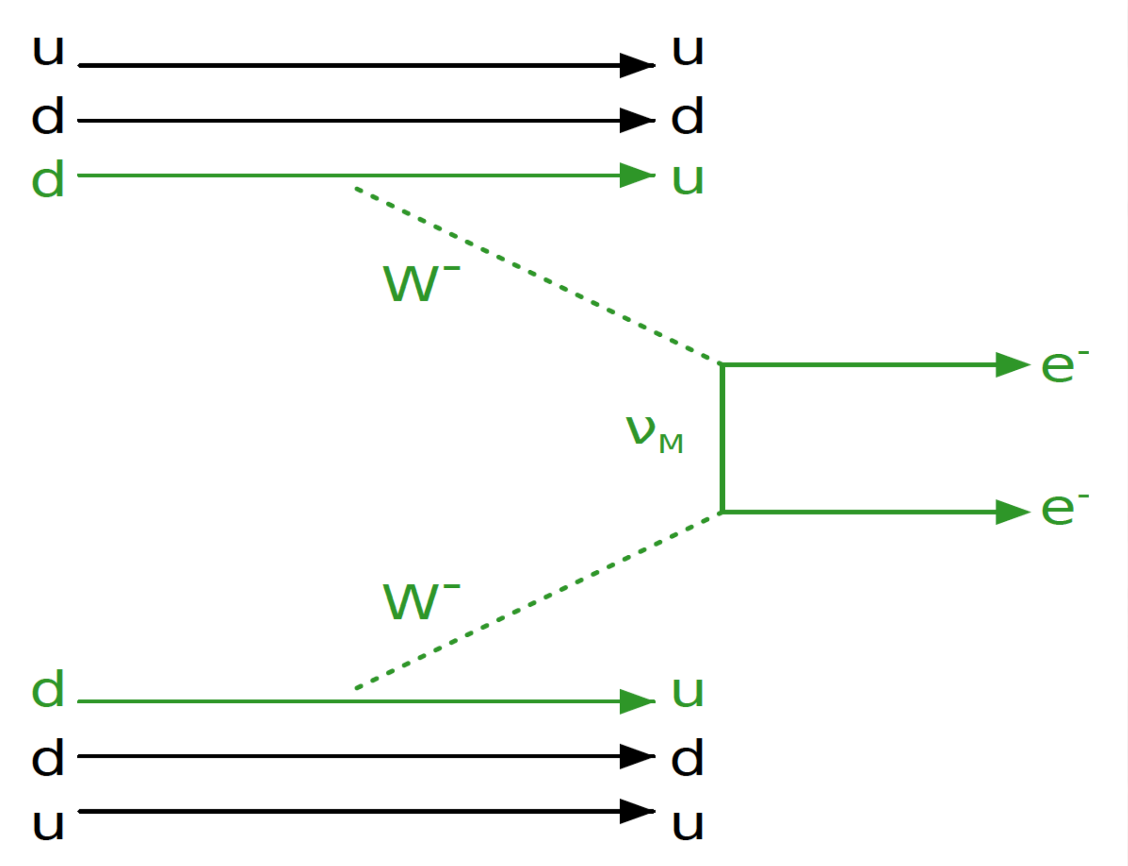
TeO_2 and thermal detectors for 0vDBD

CUORE

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
  - …

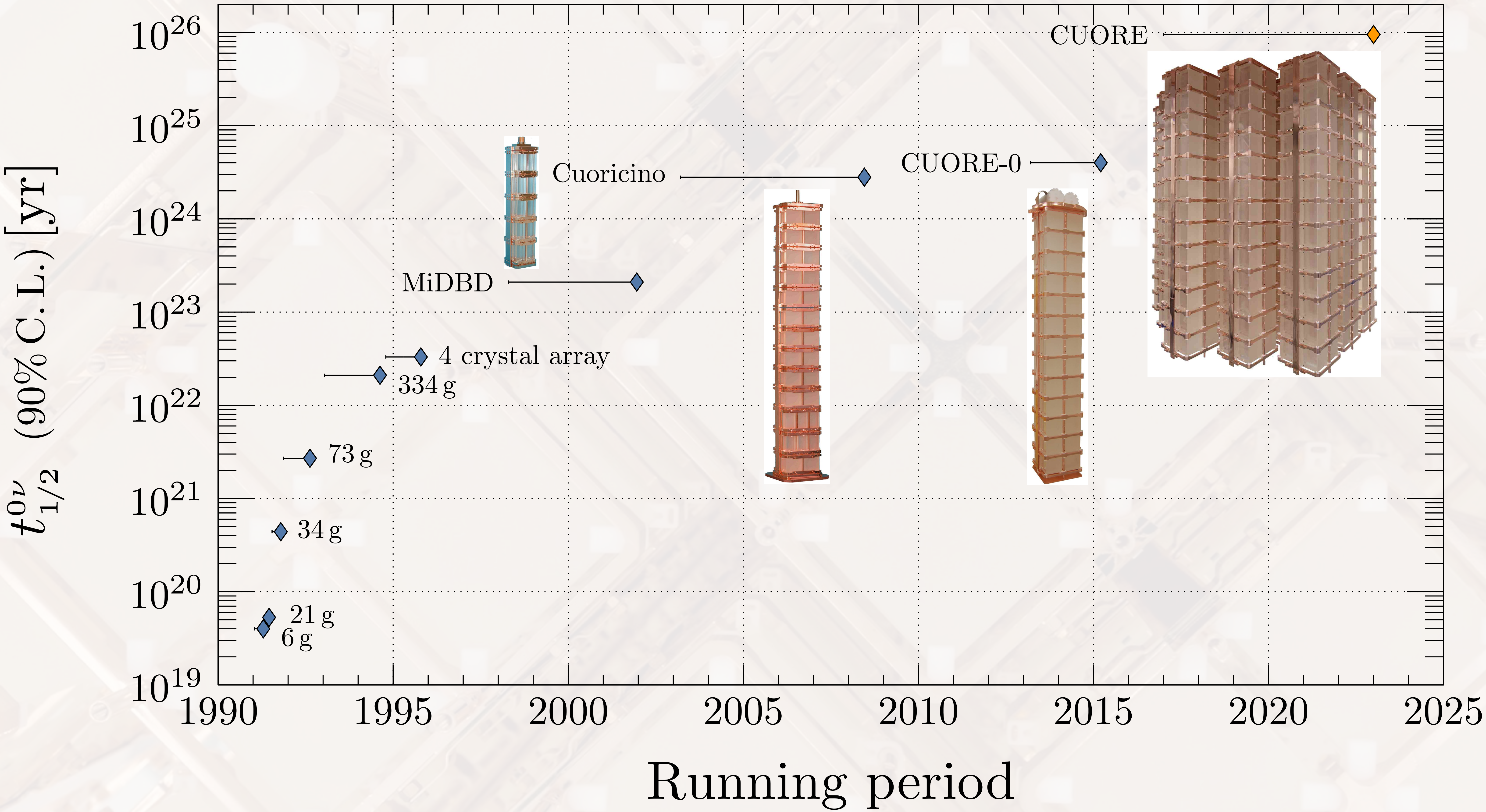
^{130}Te is a good candidate source for 0vDBD search:

- 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 ($2.8x10^{24}$ y)
- CUORE-0 ($4.0x10^{24}$ y combined)

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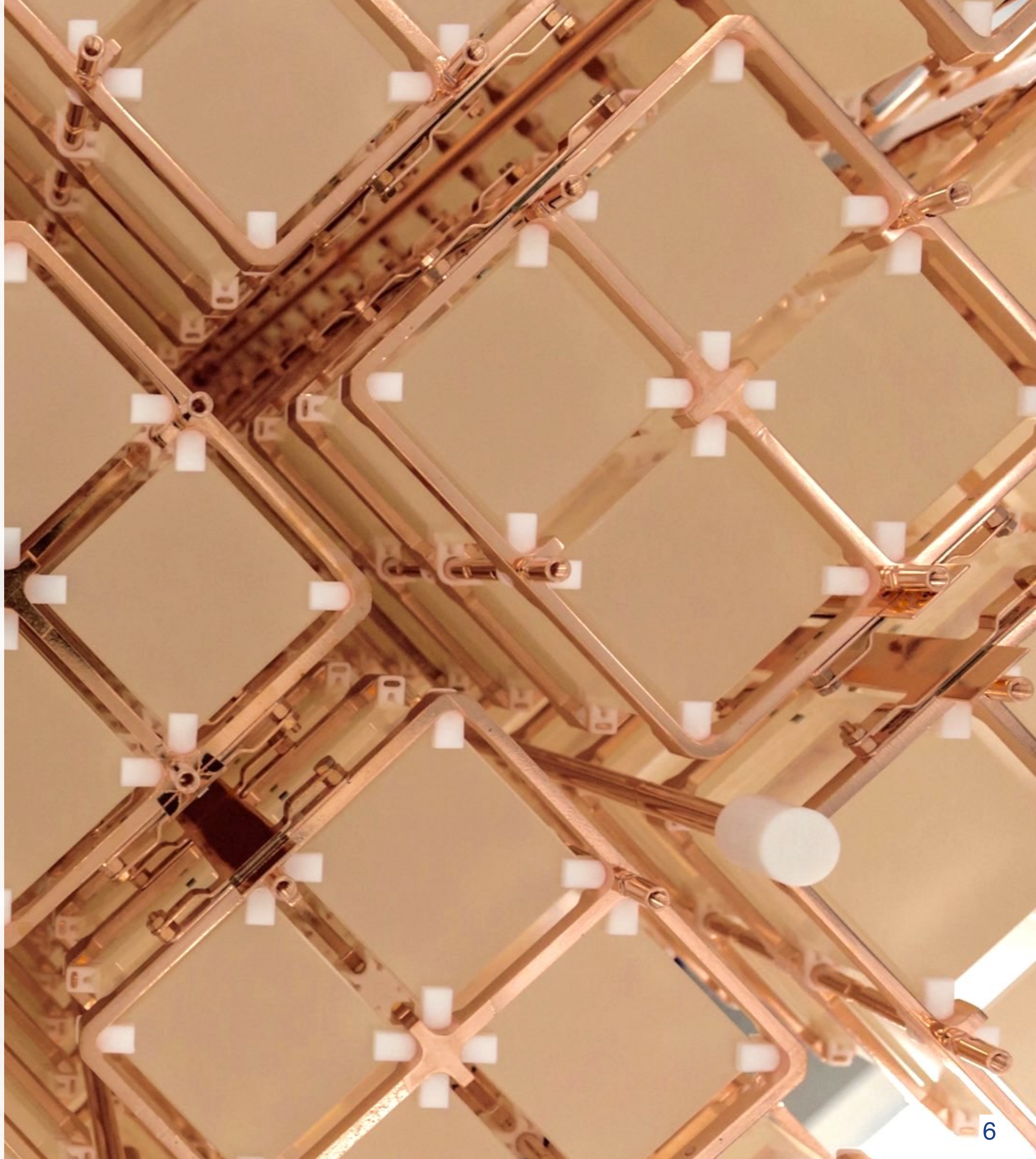


CUORE

Cryogenic Underground Observatory for Rare Events

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

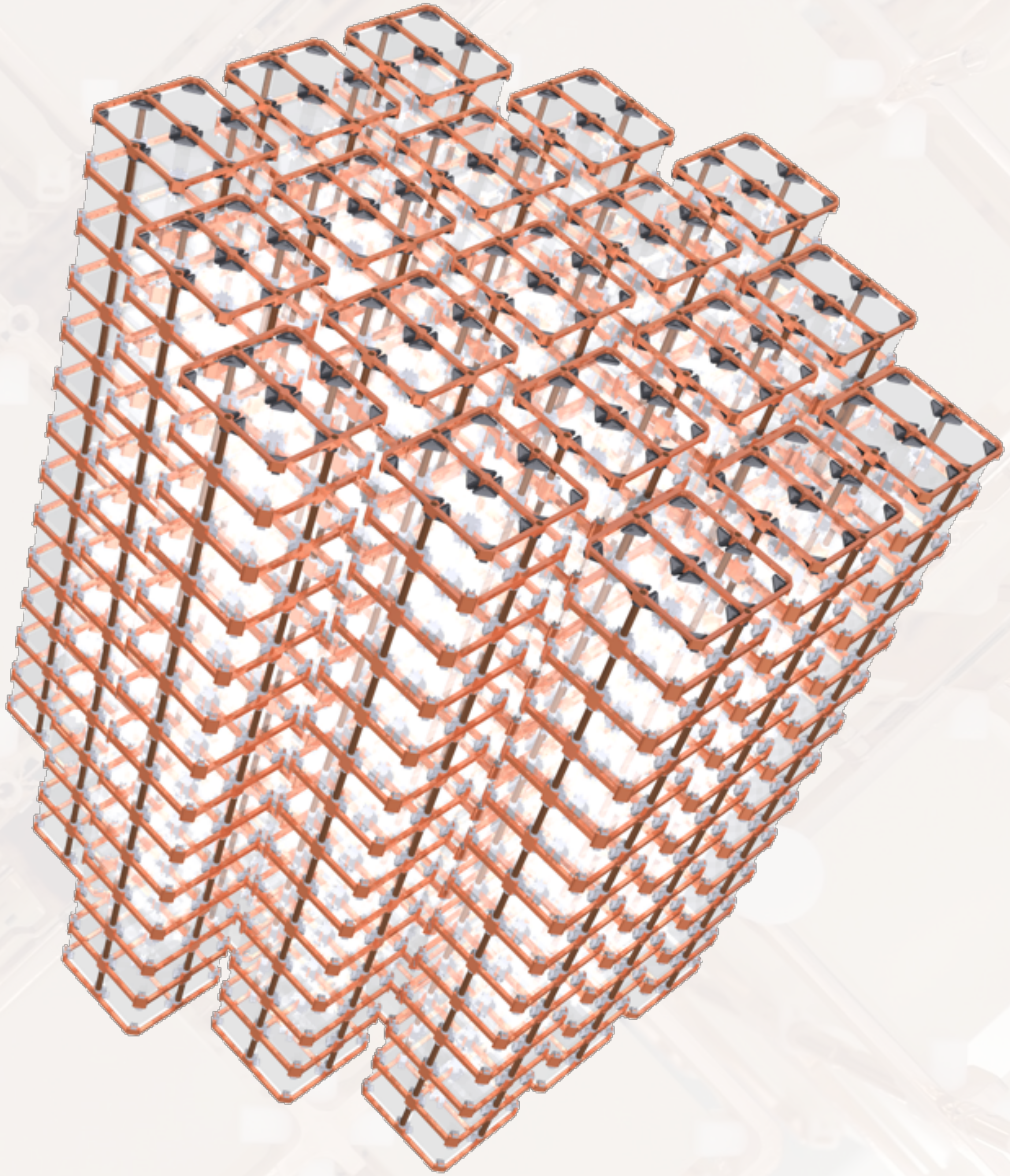
Detector design:
closely packed array of 988 TeO_2 crystals arranged in 19 towers

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

MCCXXII

Yale

INFN

Berkeley Lab

Cal Poly
San Luis Obispo

Massachusetts Institute of Technology

VirginiaTech
Invent the Future®

Lawrence Livermore National Laboratory

Sapienza
Università di Roma

Università degli Studi di Milano Bicocca

Shanghai Jiao Tong University

Alma Mater Studiorum A.D. 1088

Università degli Studi di Cassino e del Lazio Meridionale

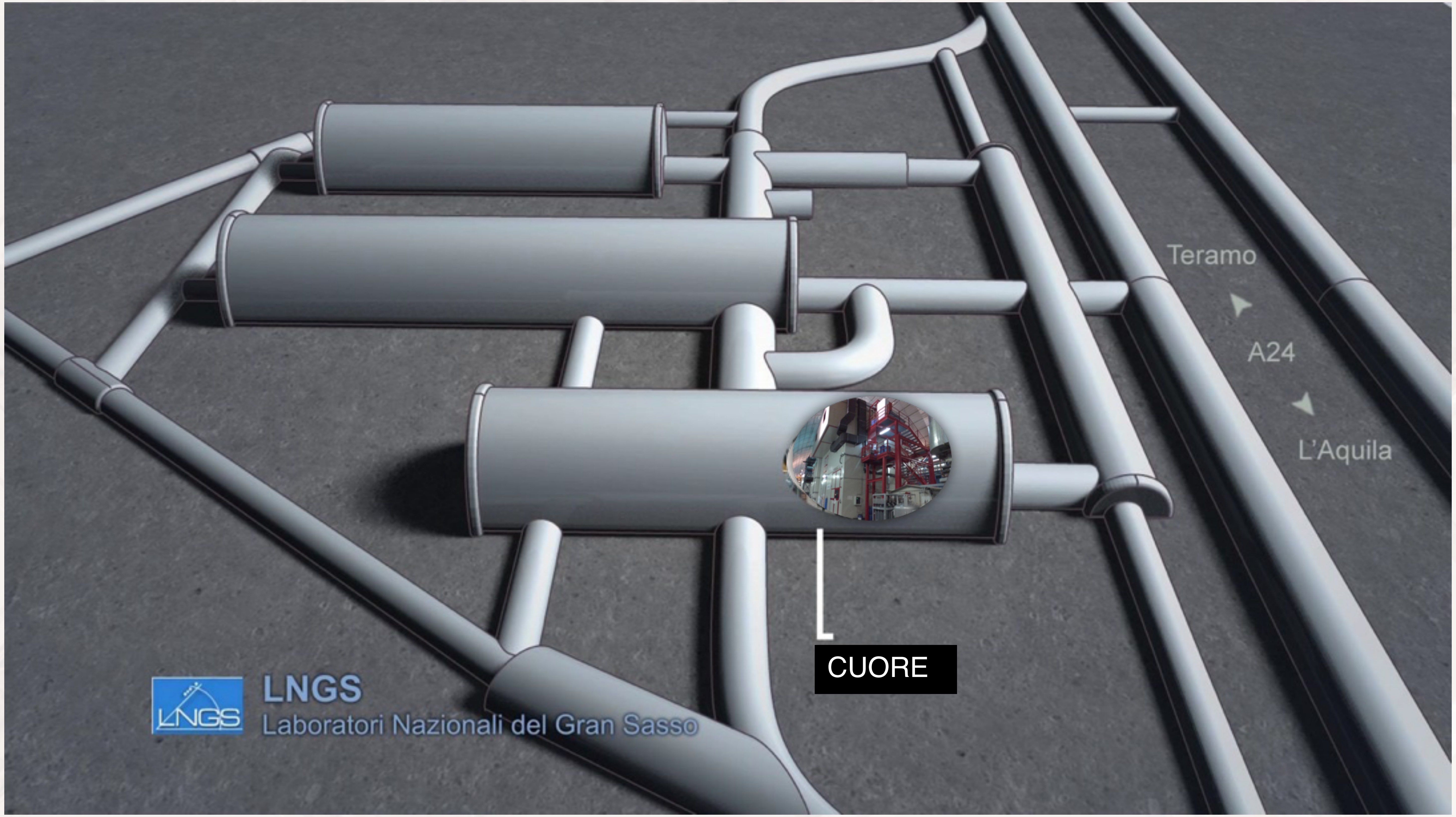
University of South Carolina

CUORE @ LNGS

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

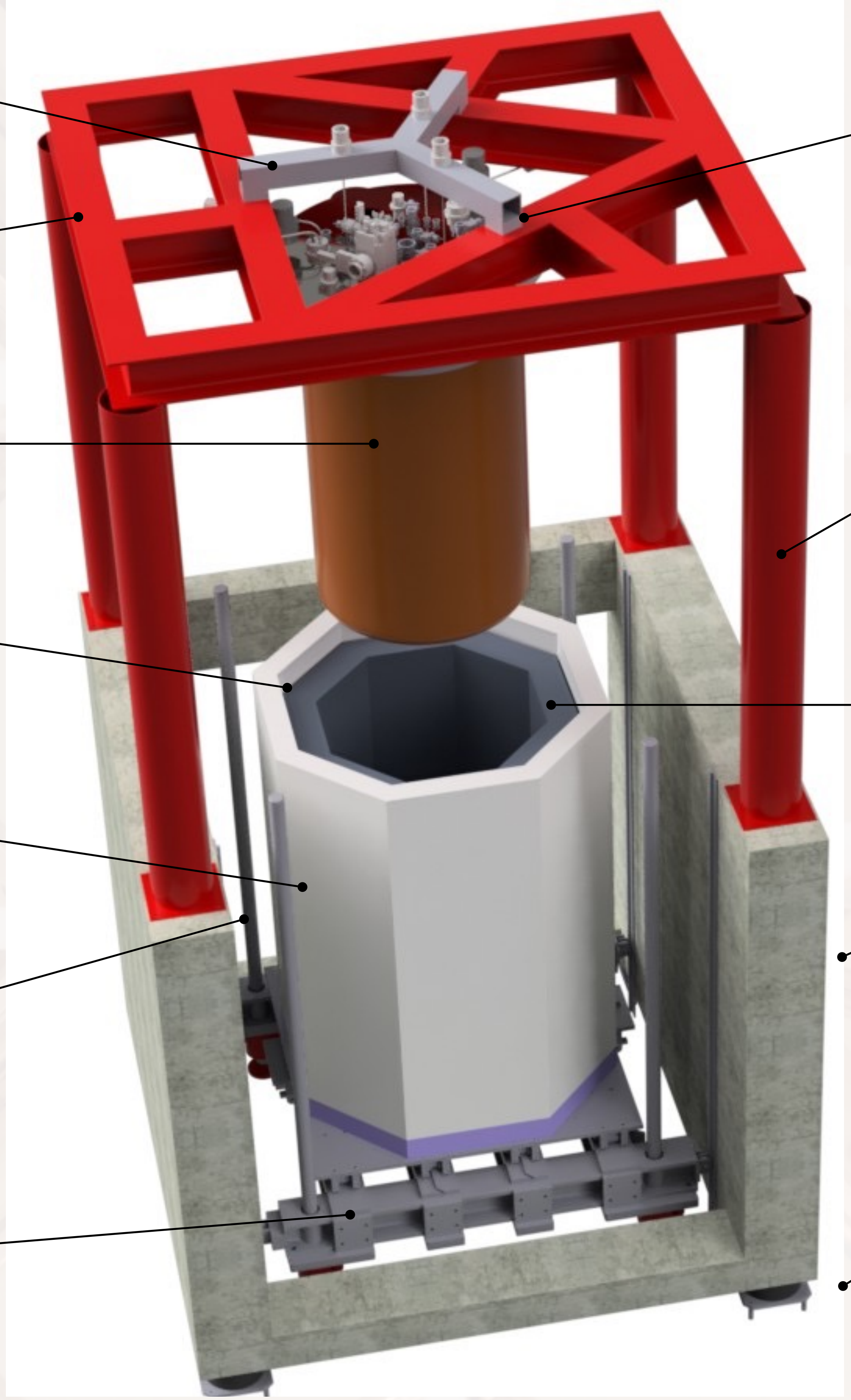
- μ's: ~3 × 10^{-8} / (s·cm^2)
- γ's: ~0.73 / (s·cm^2)
- neutrons: 4 × 10^{-6} n/(s·cm^2) below 10 MeV

CUORE @ LNGS


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

Underground Laboratory

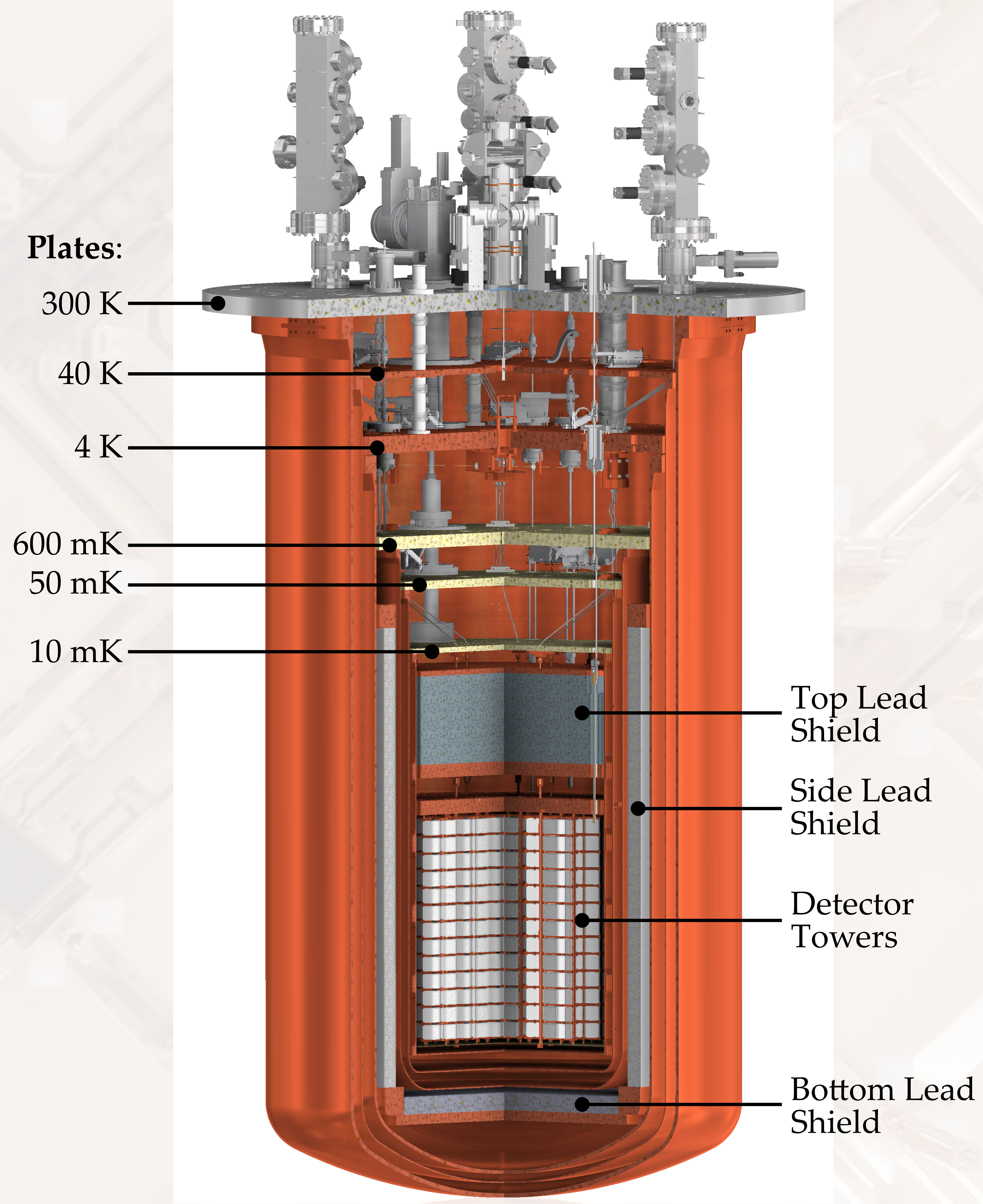
- Three-story building
- Hosting the cryostat supporting structure



The CUORE cryostat

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

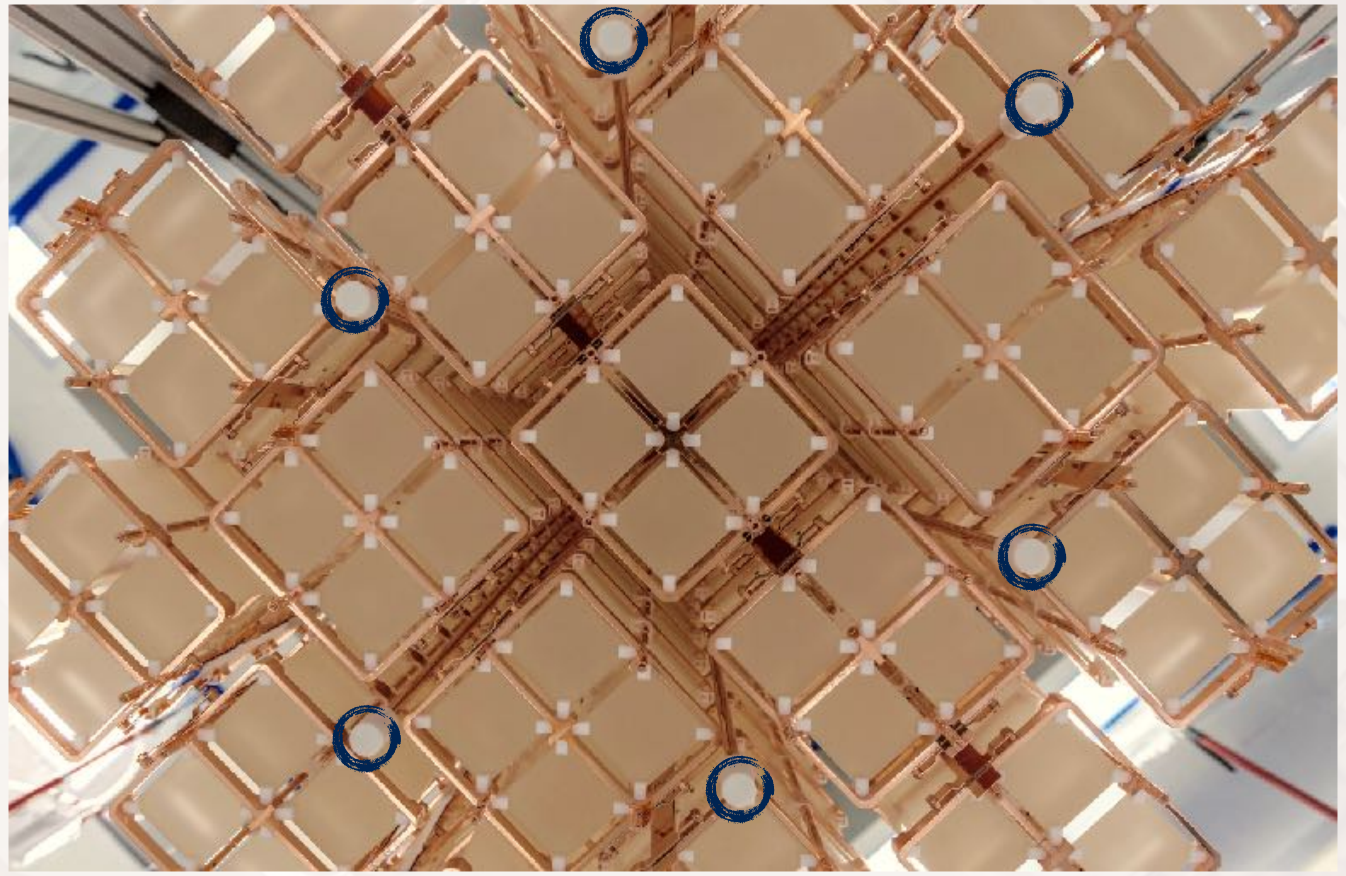
- Cryogen-free cryostat
- Fast Cooling System (^4He gas) down to ~50K
- 5 pulse tubes cryocooler down to ~4K
- Dilution refrigerator down to operating temperature ~10 mK
- Nominal cooling power: 3 µW @ 10mK
- Cryostat total mass ~30 tons
- Mass to be cooled < 4K: ~15 tons
- Mass to be cooled < 50 mK: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

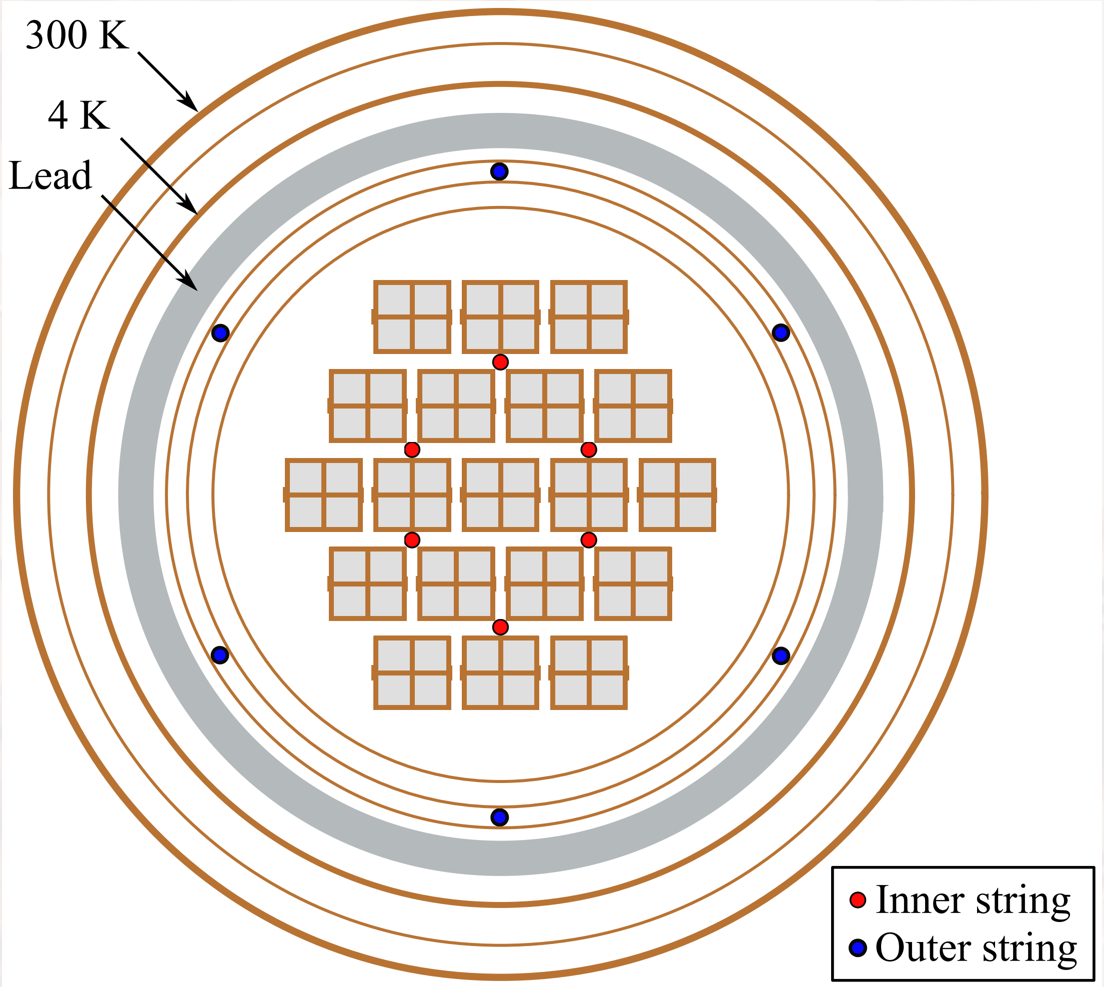


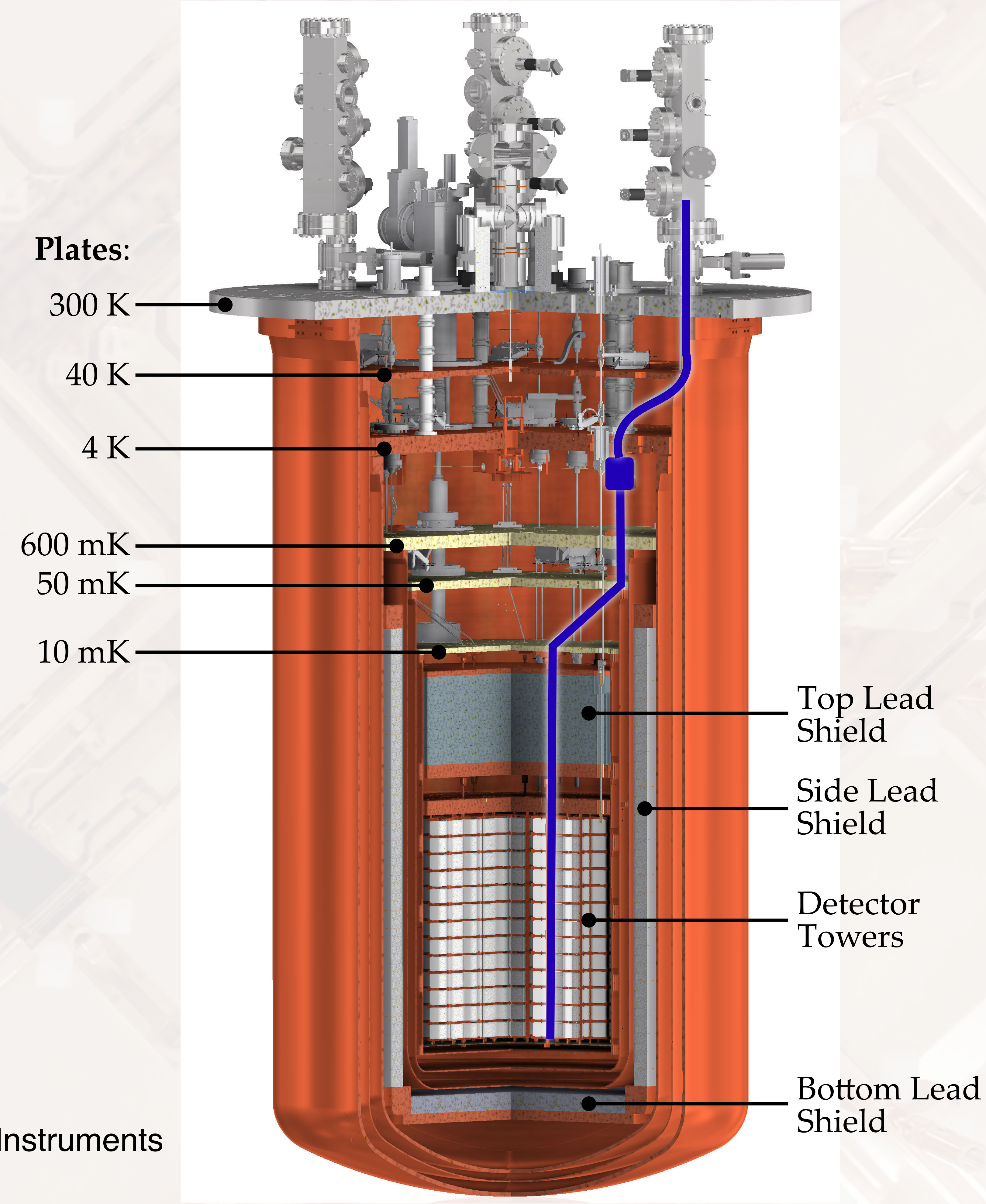
Detector calibration system

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

CUORE

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)

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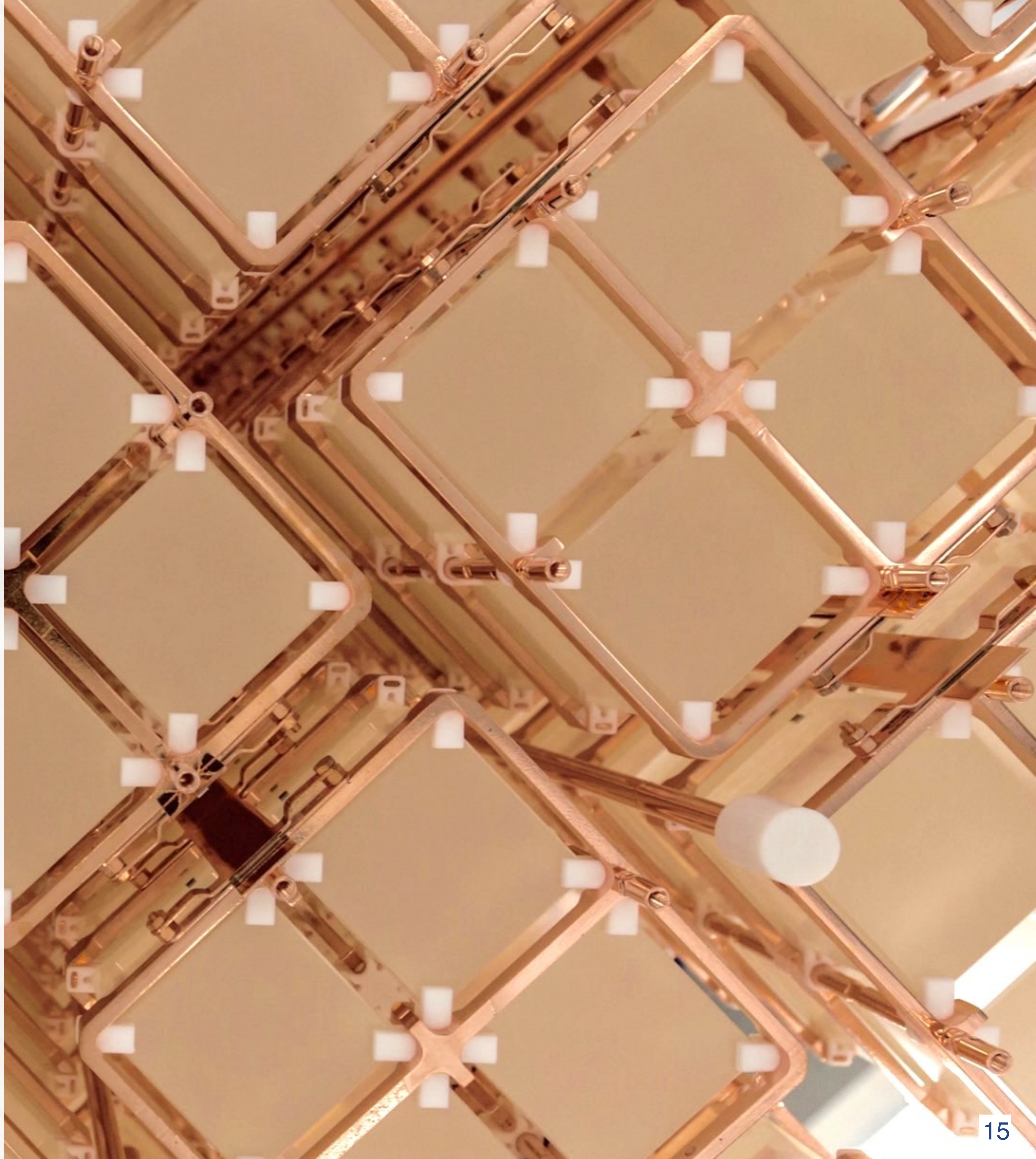
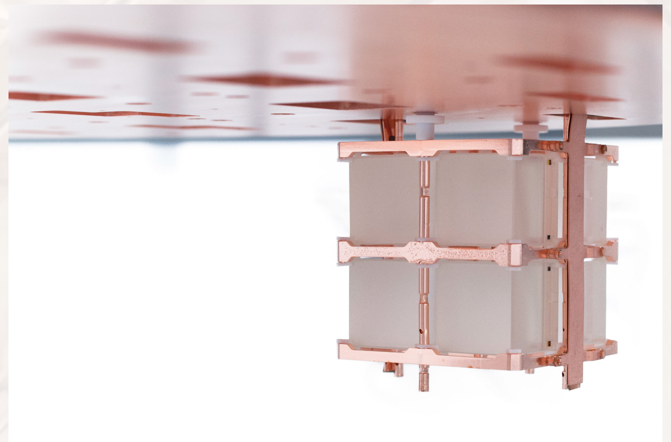


CUORE Roadmap

CUORE

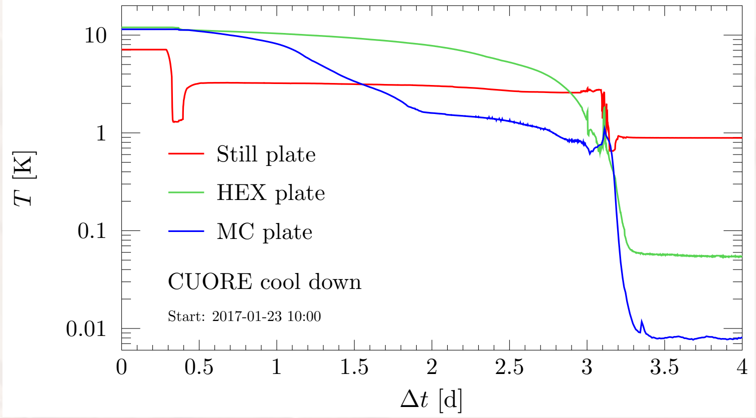
Cryostat Commissioning

- 8-channels functioning mock-up detector
- Noise study and mitigation
- Stable base temperature < 7 mK
- Calibration sources deployment



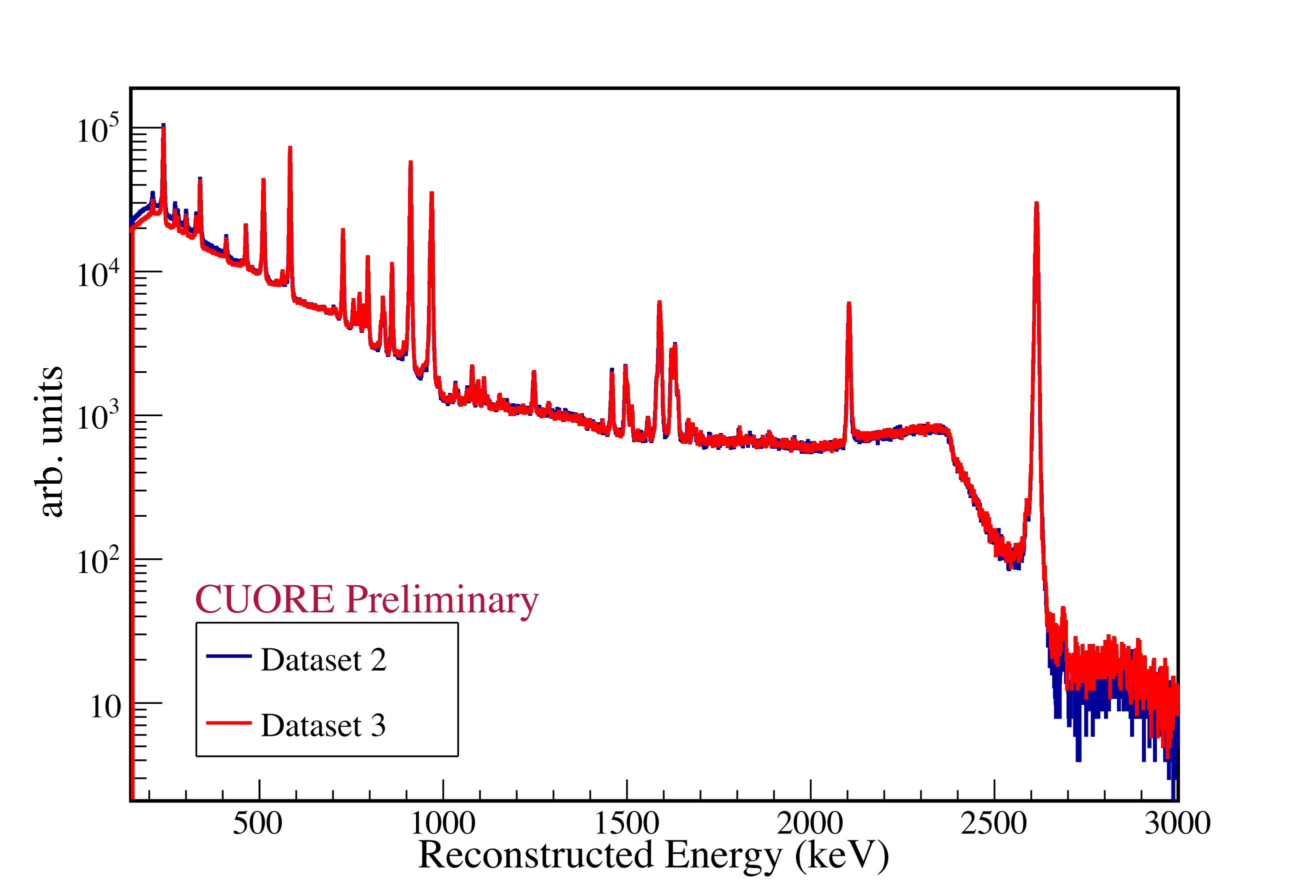
Detector Cool down

- 300 K —> 4 K in 22 days
- 4 K —> 7 mK in 3.5 days
- First pulses seen just after cool-down



Second period of Science Data taking

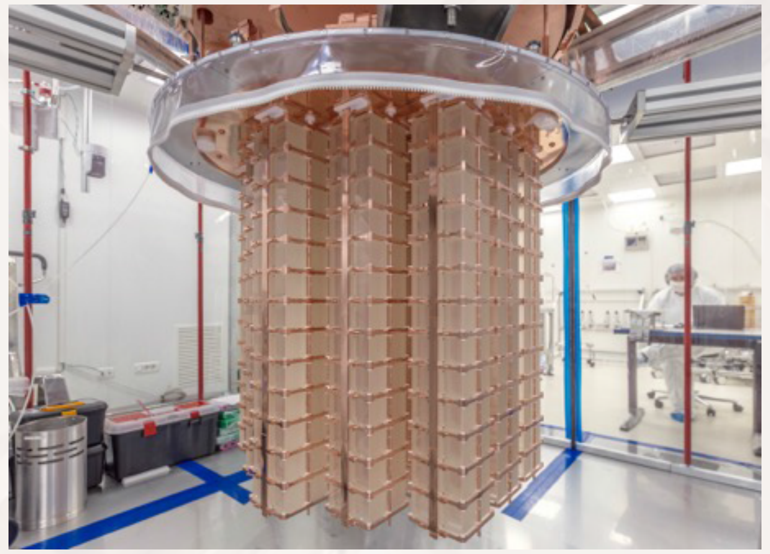
- New optimised working temperature
- New working points
- PT noise reduction
- Back to stable data taking:
  - calibration runs completed
  - physics runs ongoing
- Resolution in new data unchanged after maintenance



Feb 2016 | Aug - Oct 2016 | Jan 2017 | Mar - Apr 2017 | May - Sep 2017 | Nov - Mar 2017 | Mar 2018

Detector Installation

- Radon-free environment
- 1 tower/day, 3 operators
- Read-out testing
- Cryostat interfaces
- Inner radiation shields



Detector pre-operation

- Optimisation of all sub-systems
- Working temperature and working point selection
- Noise reduction

First period of Science Data taking

- **Dataset 1**: physics data bracketed by calibrations (May - Jun 2017)
- Short optimisation campaign
- **Dataset 2**: Aug - Sep 2017
- 984/988 operational channels
- 86.3 kg*y exposure

Partial warm up

- Fix small leak in the cryostat region
- Warmed up to 100 K

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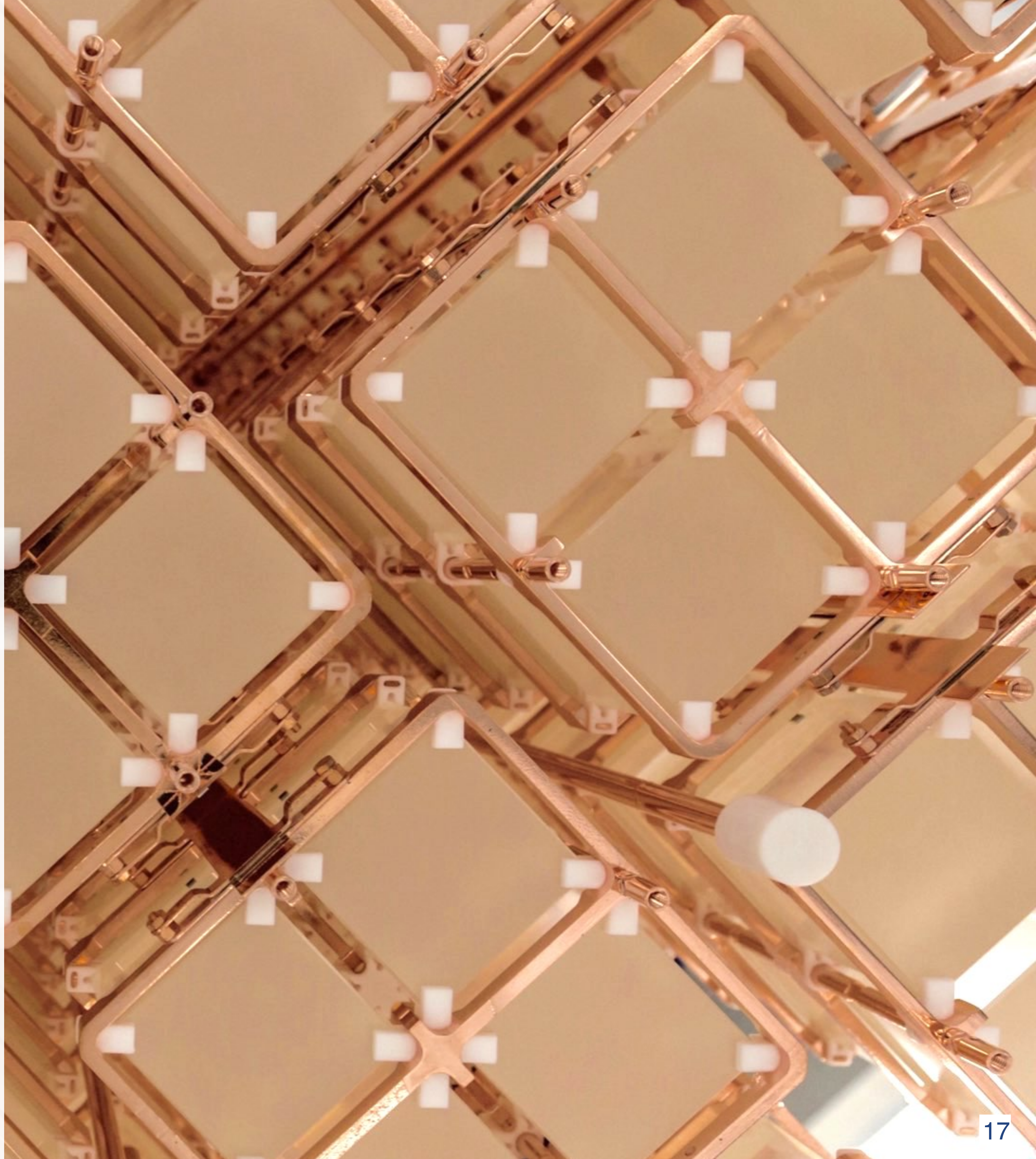
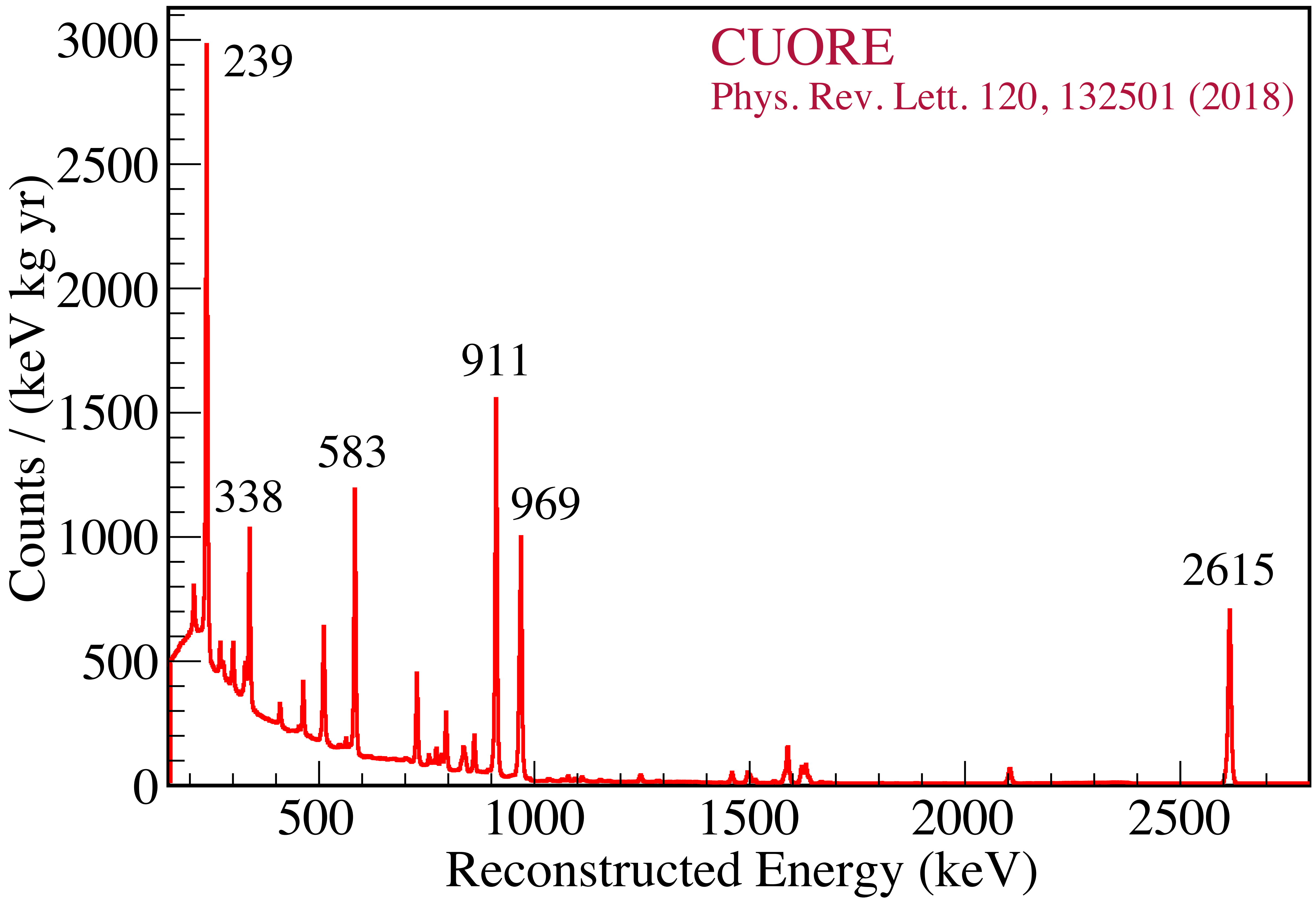


Calibration spectrum

- 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



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**

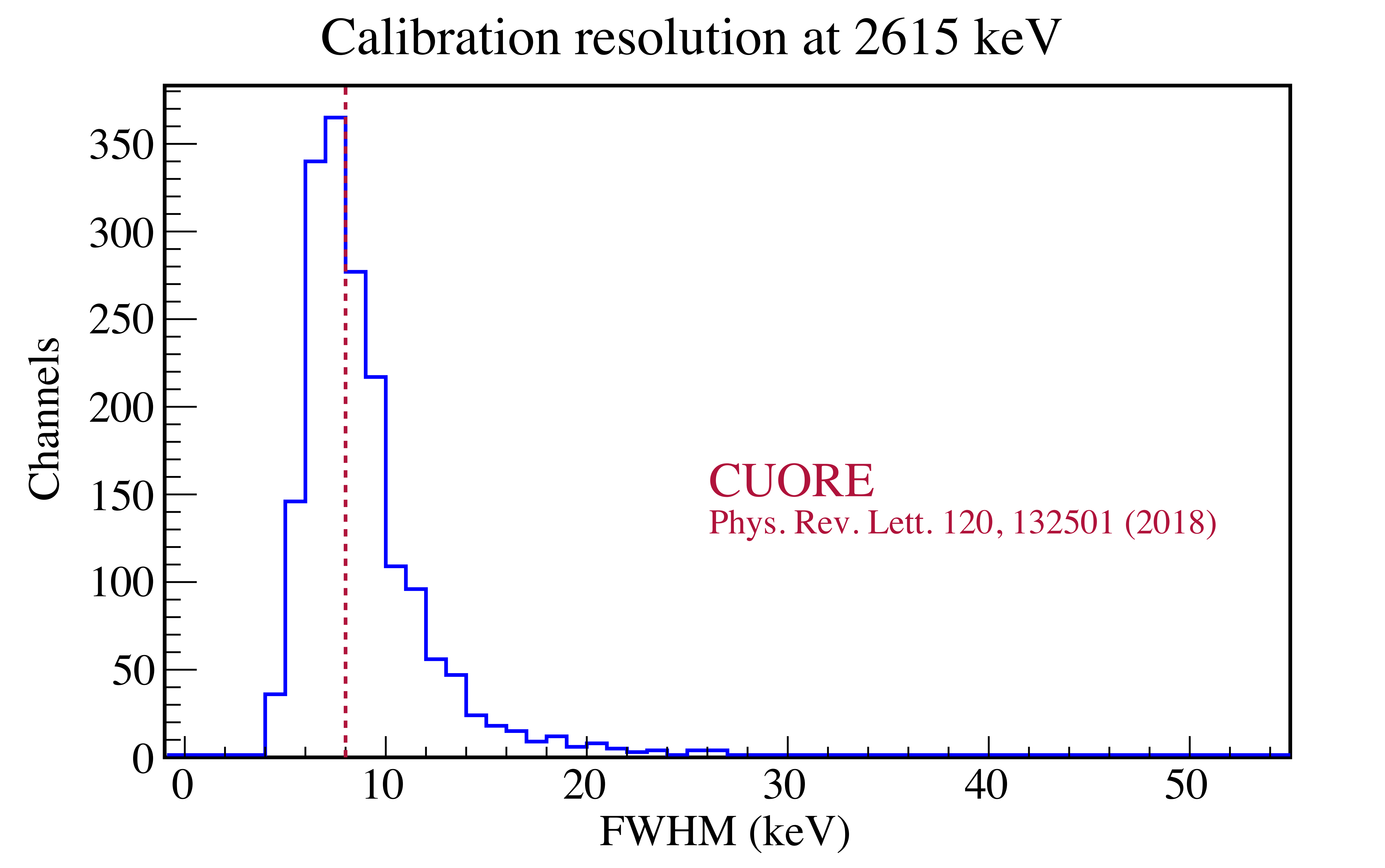
@ 2615 keV

ds3018: 9.0 keV FWHM

ds3021: 7.4 keV FWHM

effective (exposure-weighted):

8.0 keV FWHM



Energy resolution - Physics runs

CUORE

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**

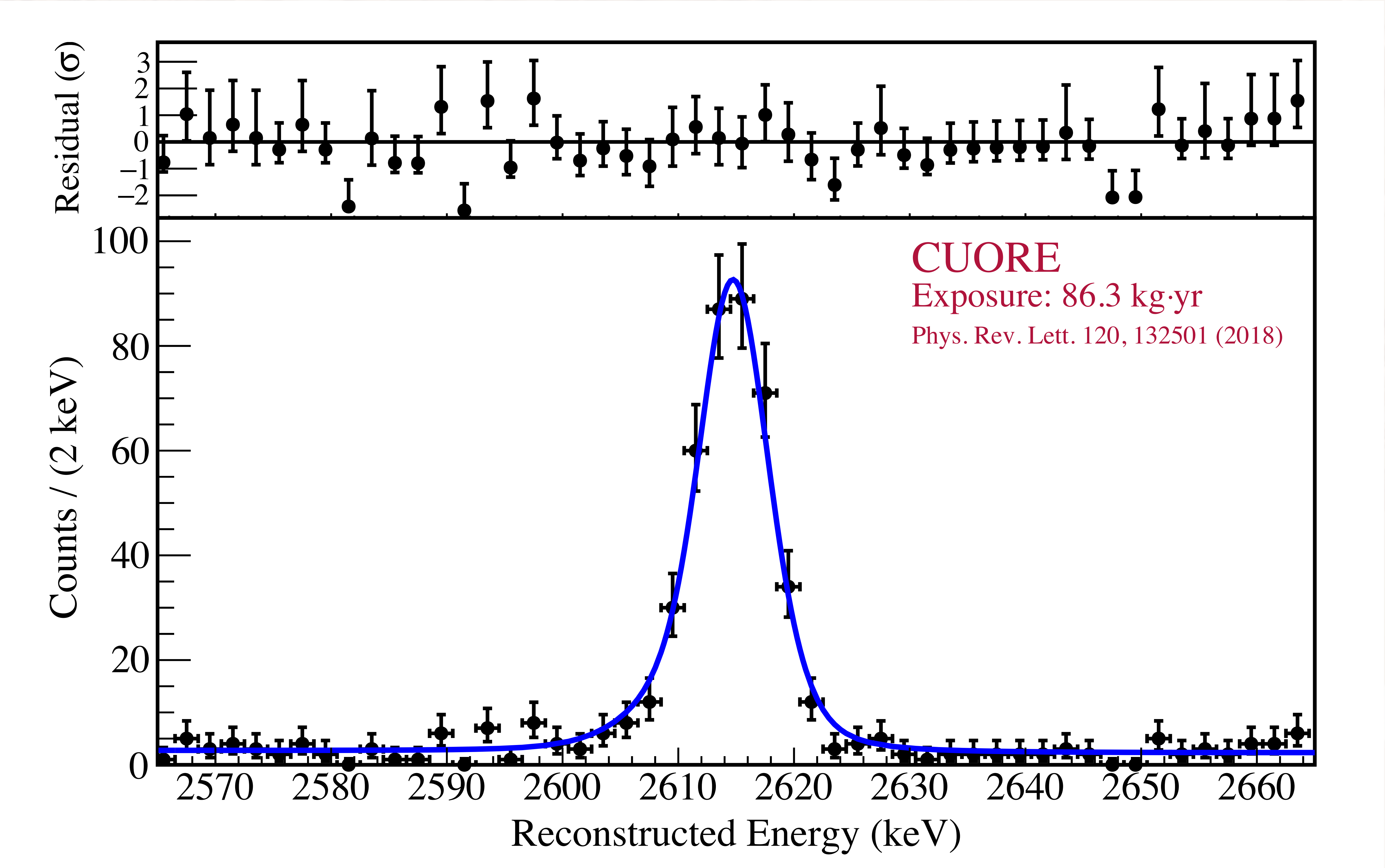
@ Q-value

ds3018: (8.3 ± 0.4) keV FWHM

ds3021: (7.4 ± 0.7) keV FWHM

effective (exposure-weighted):

(7.7 ± 0.5) keV FWHM

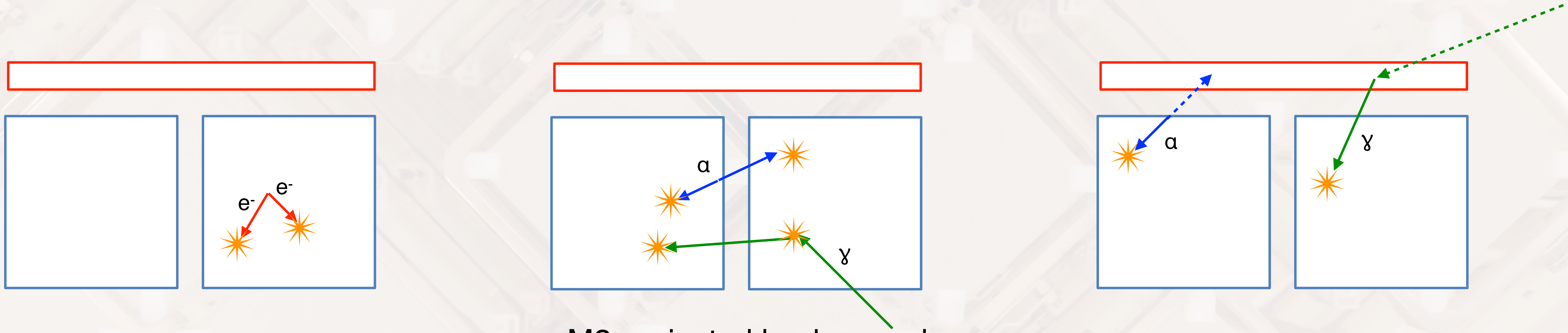


Event selection

CUORE

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

- Base quality cuts (number of pulses in the window, baseline stability, etc…)
- Anti-coincidence



M1 - signal like

M2 - rejected background and important information for bkg studies

M1 - dangerous background

- Pulse shape analysis: deformed events are not used to build the final spectra to avoid spectral shape distortions (but are still used fo anti-coincidence)

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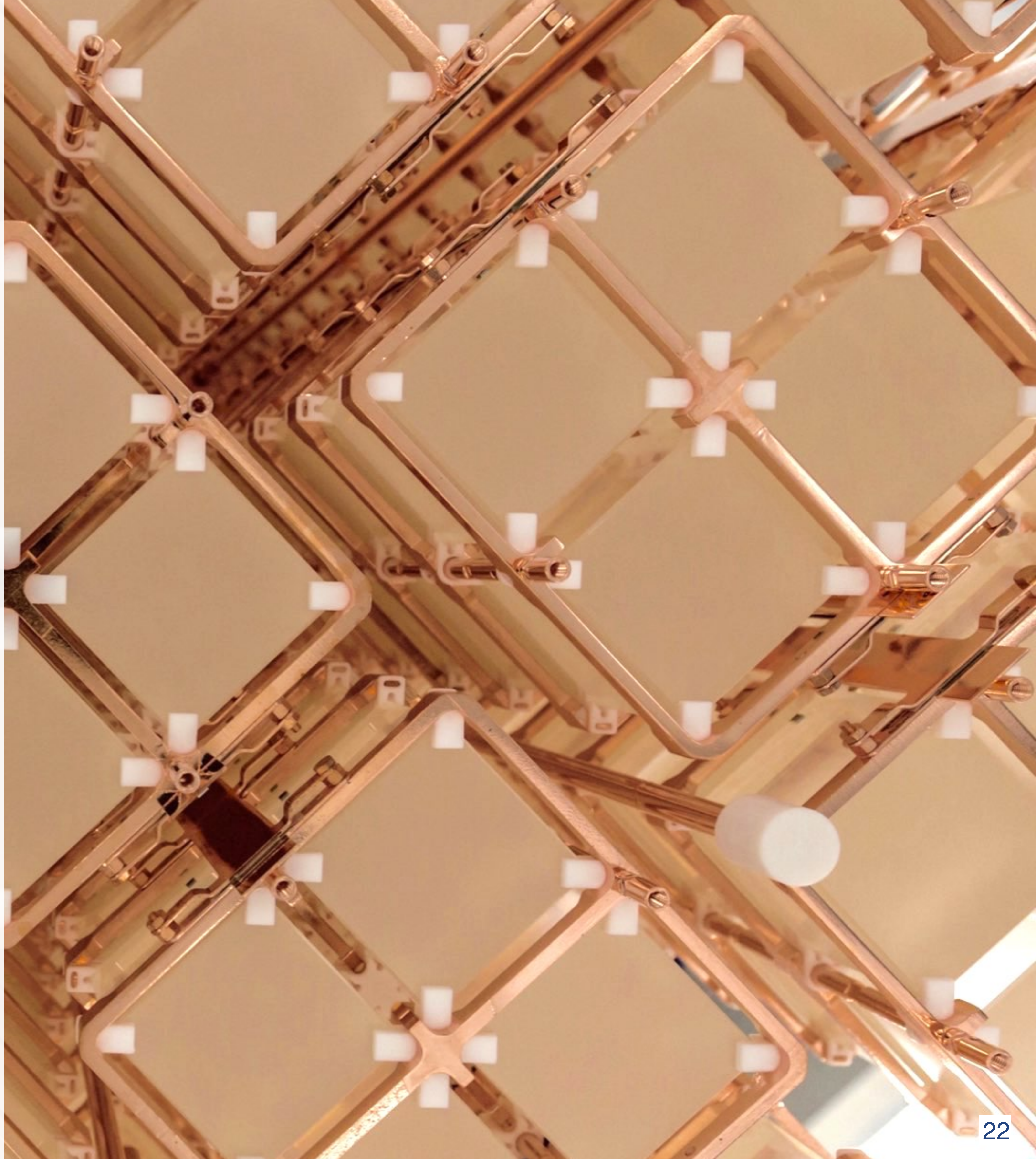


Fit in the 0vDBD ROI

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

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

(83.0 ± 2.6)% - ds3021

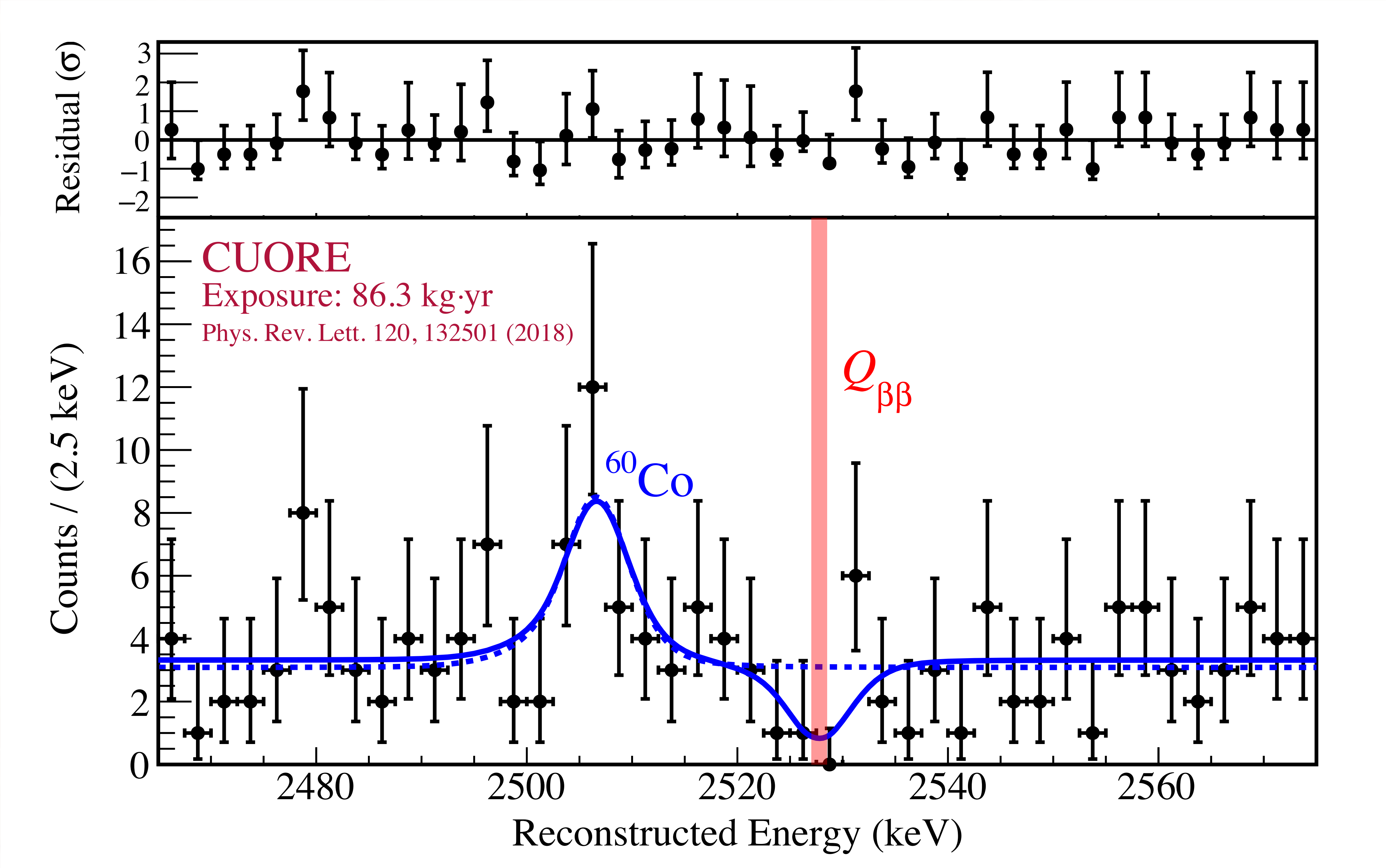
Events in the region of interest: **155**

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**



No evidence of signal

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

CUORE, CUORE-0 and CUORICINO combined 90% C.L. limit is

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

Phys. Rev. Lett. 120, 132501 (2018)

Combination with previous 0vDBD results

CUORE

- Total ^{130}Te exposure
  - 86.3 kg·yr of CUORE
  - 19.75 kg·yr of Cuoricino
  - 9.8 kg·yr of CUORE-0

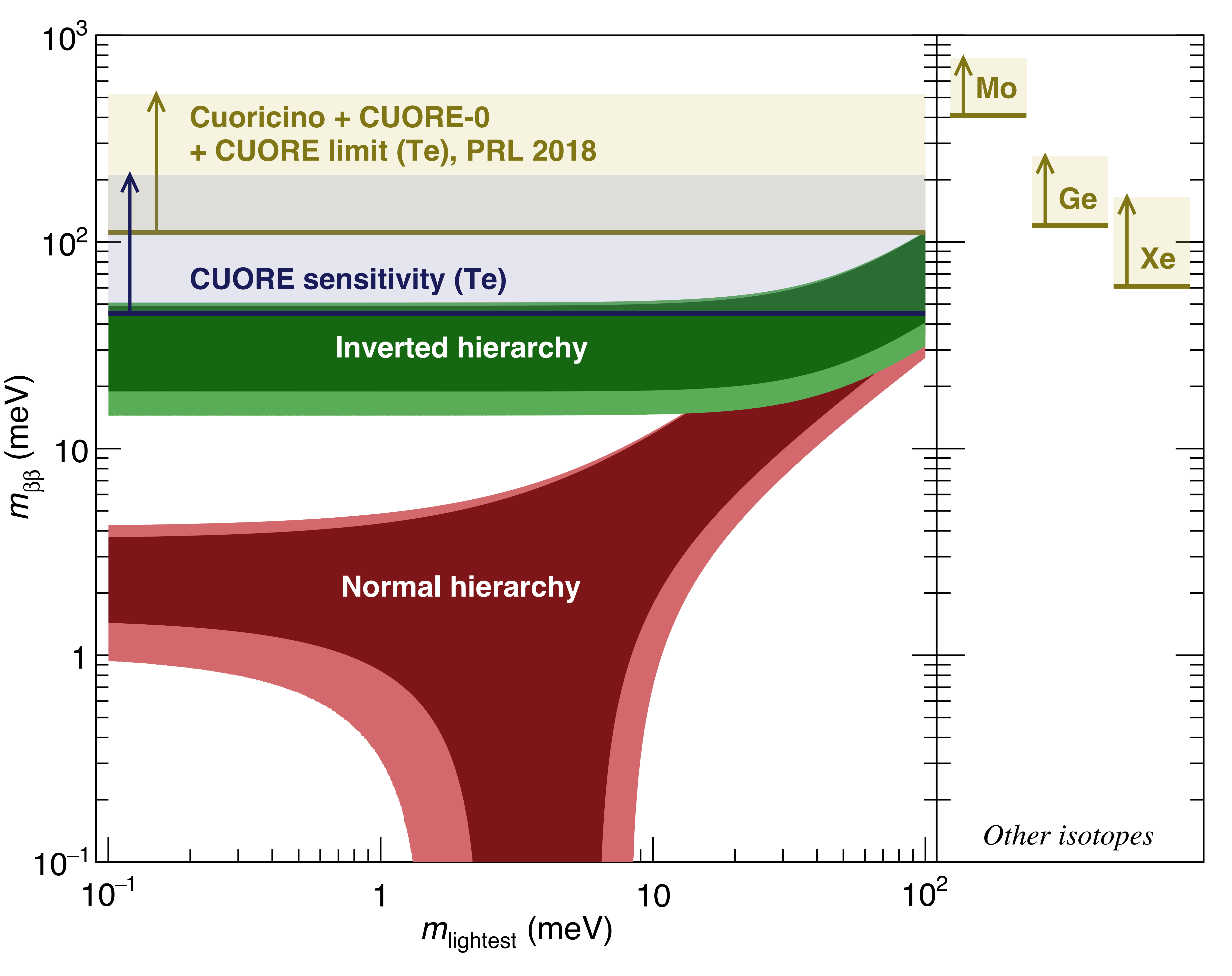
- The combined 90% C.L. limit is

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

  $m_{\beta\beta} <$ 110-520 meV

NME:
JHEP02 (2013) 025
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 87, 064302 (2014)
Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 91, 024613 (2015)
Phys. Rev. C 91, 024309 (2015)
Phys. Rev. C 91, 024316 (2015)
Phys. Rev. Lett. 105, 252503 (2010)
Phys. Rev. Lett. 111, 142501 (2013)

Experiments:
^{130}Te: 1.5 × 10^{25} yr from PRL 120, 132501 (2018)
^{76}Ge: 8.0 × 10^{25} yr from PRL 120, 132503 (2018)
^{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



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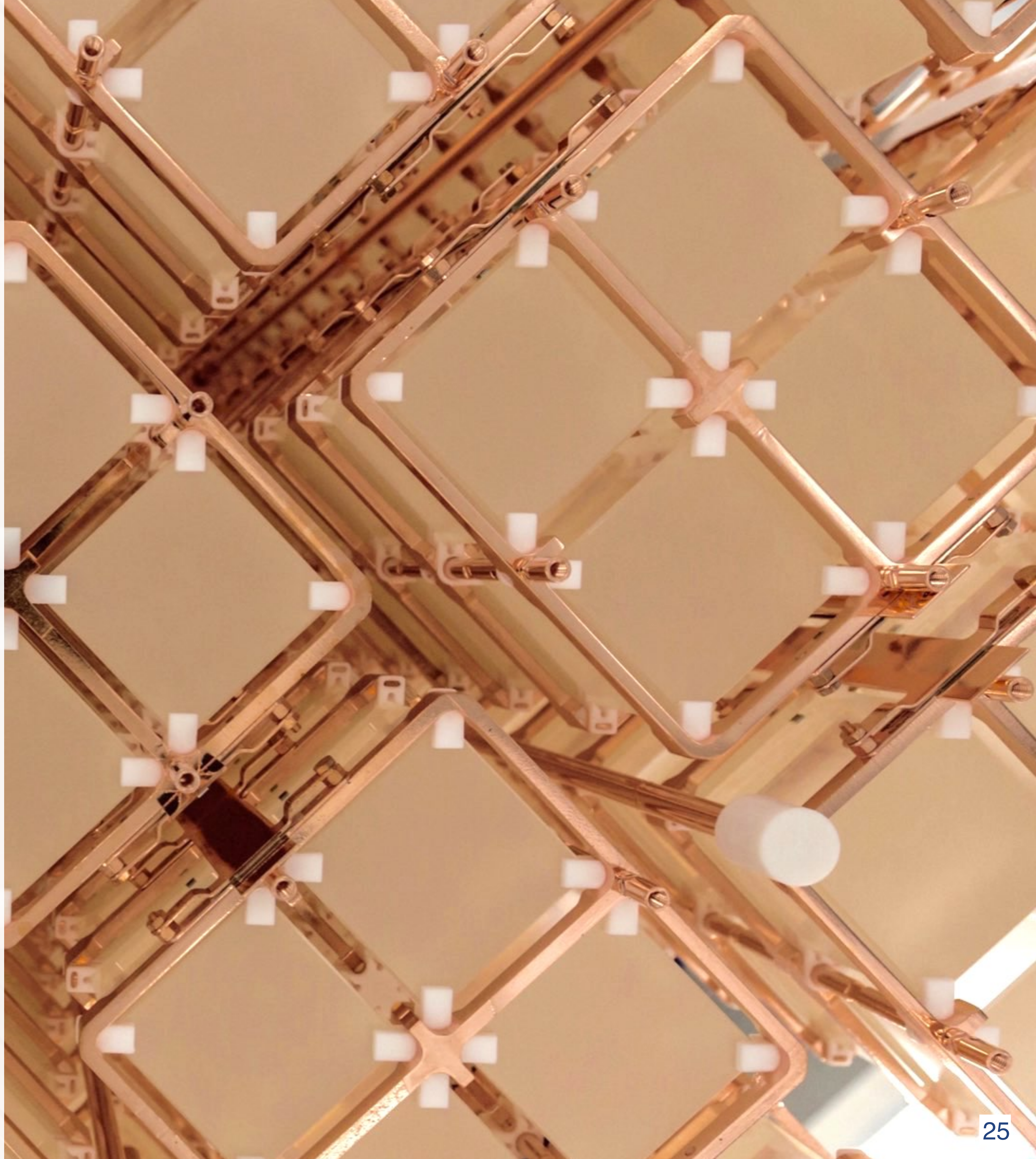
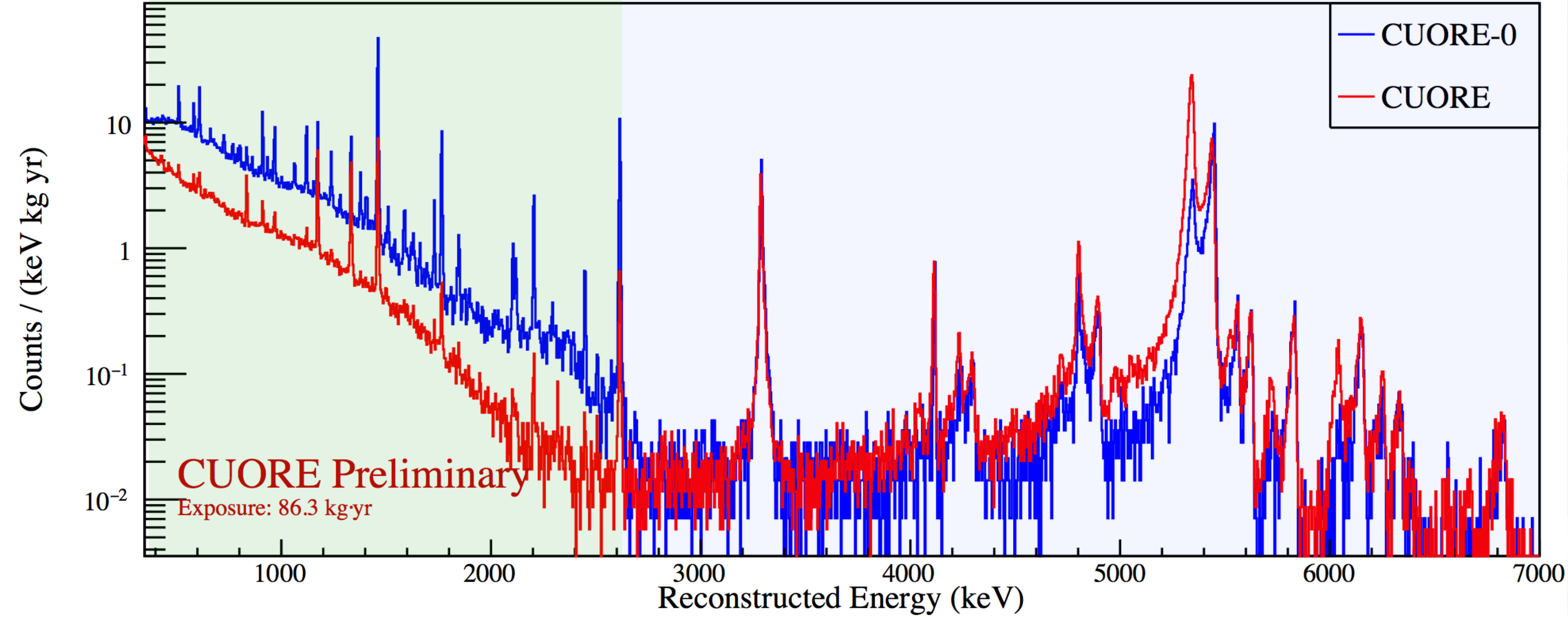


CUORE Background Model

ɣ background significantly reduced

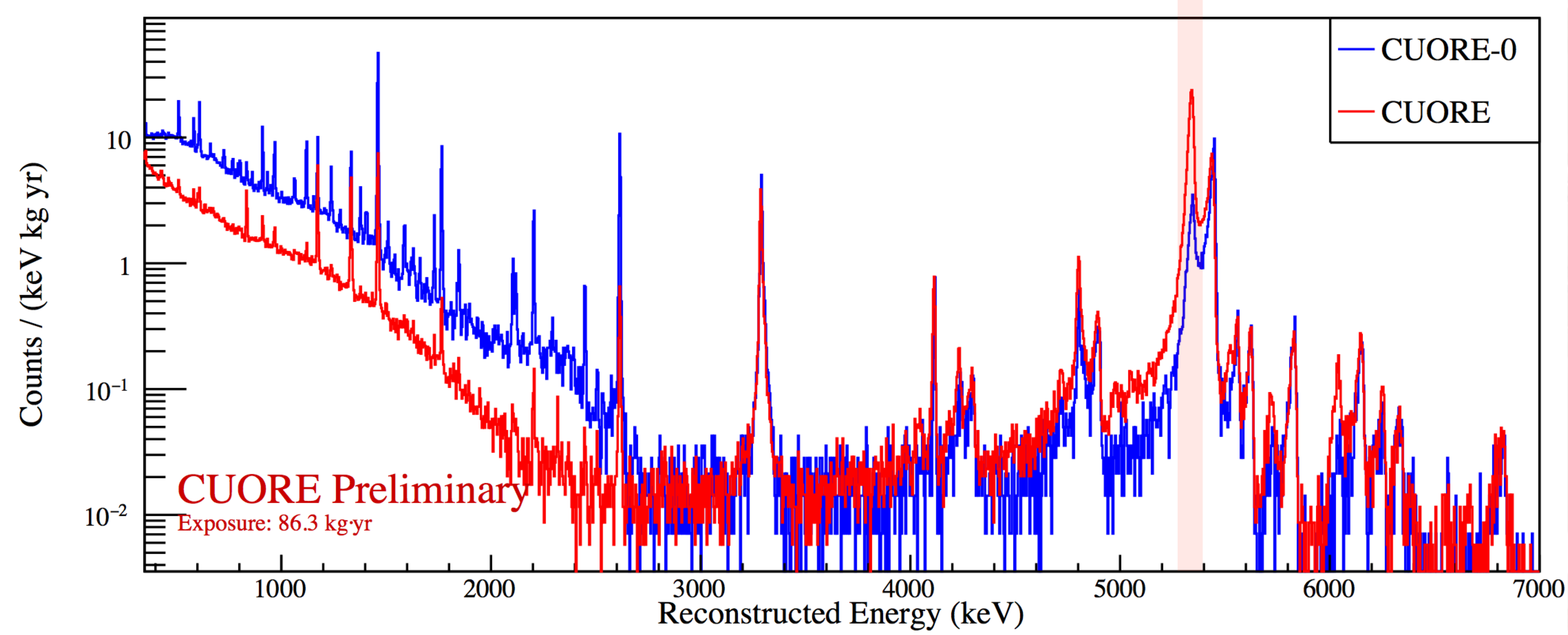
α background mostly consistent with CUORE-0 (as expected)



CUORE Background Model

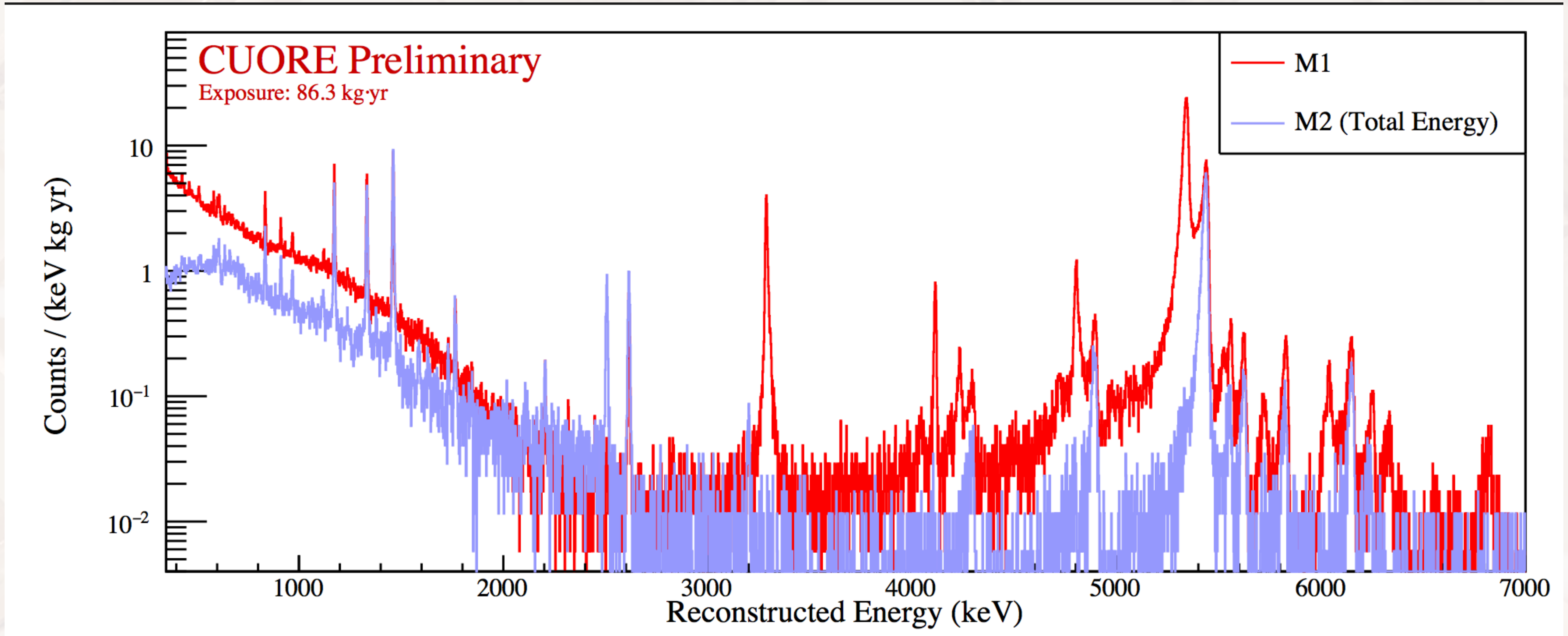
^{210}Po excess still under investigation:

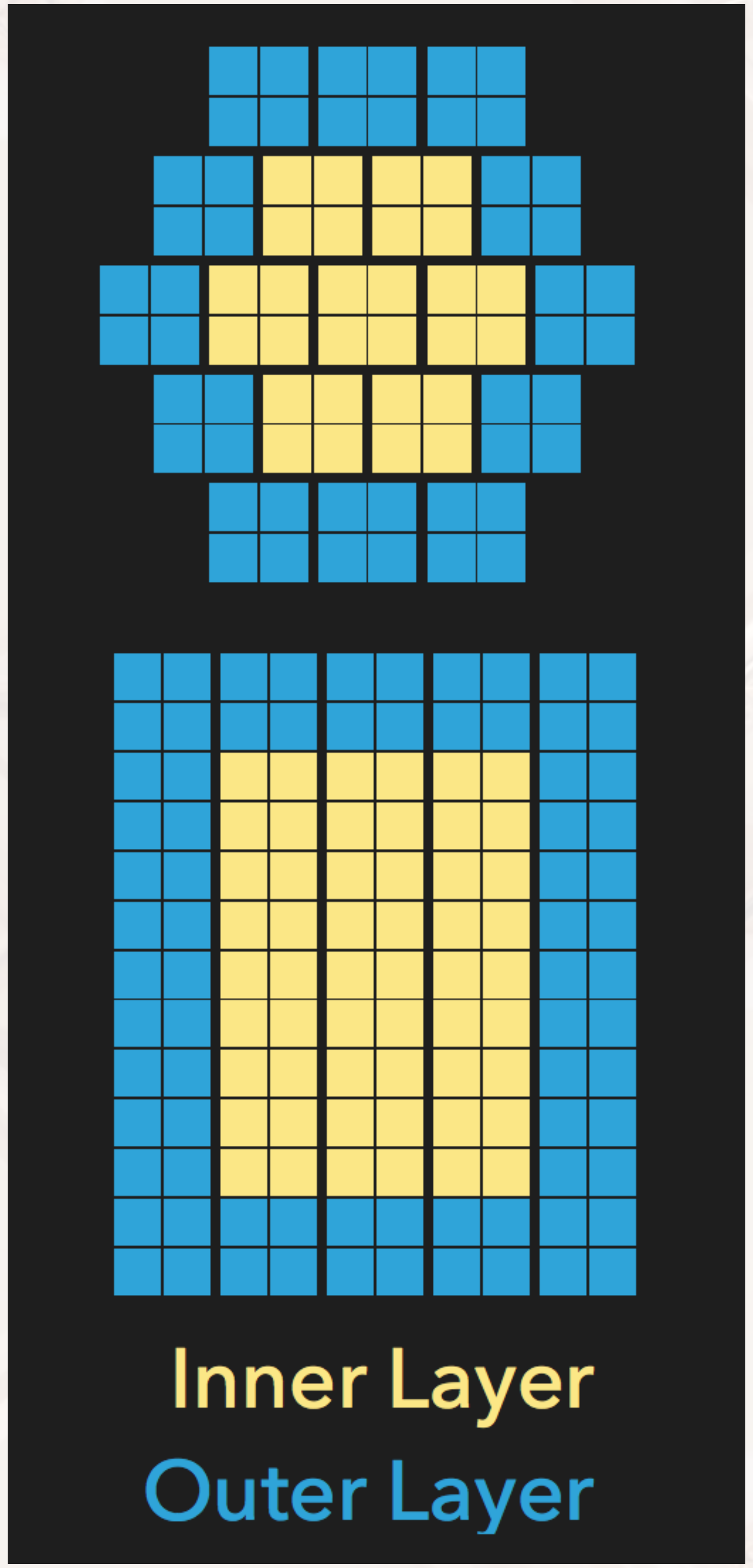
- appears to be from surface contamination in copper around the detector
- estimated contribution to ROI ~ 10^{-4} ckky (~1%)



CUORE Background Model

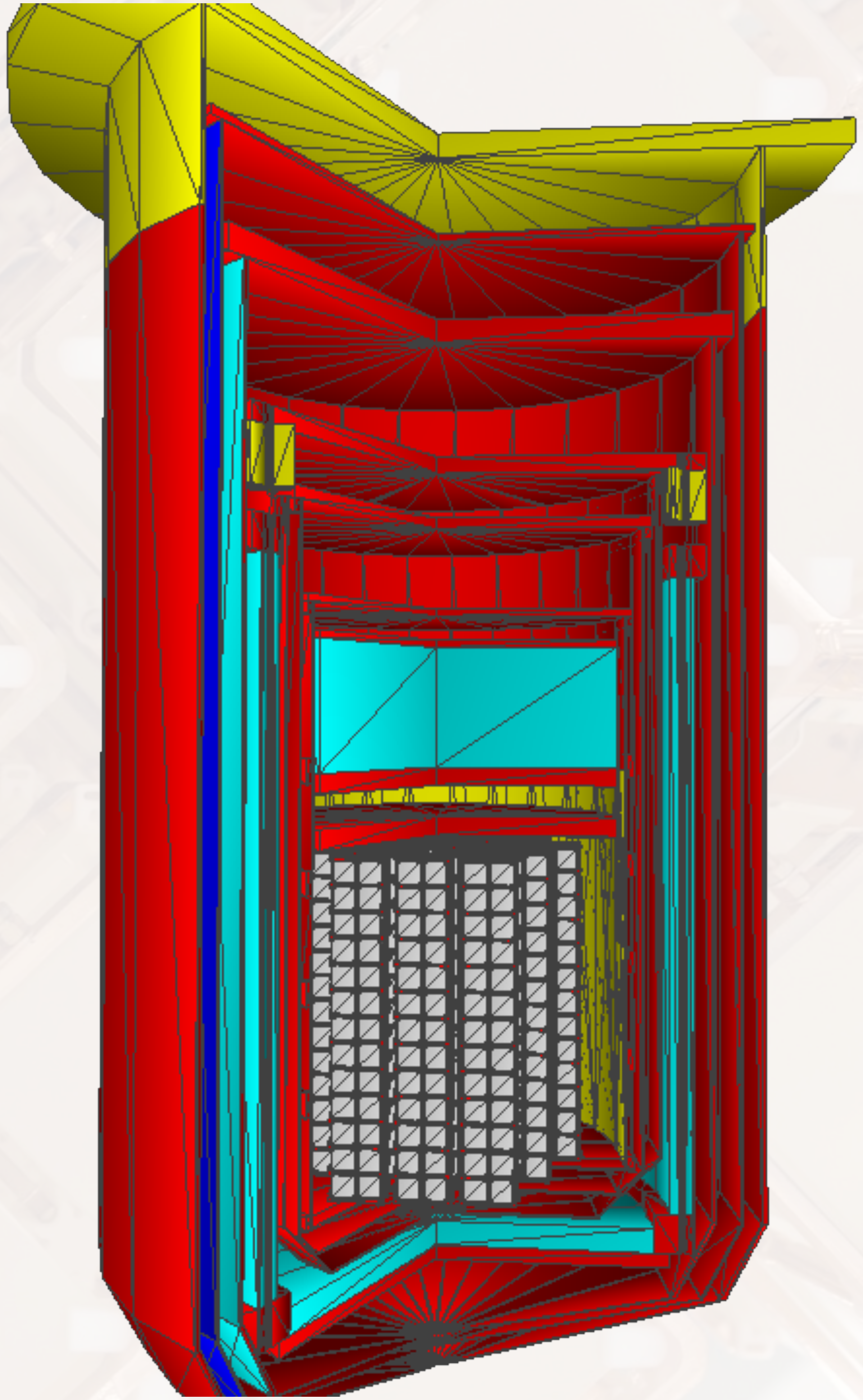
DATA
- 86.3 kg yr of TeO_2, same data used for 0vDBD analysis
- split data into inner and outer (2 crystals thick) layers
  - outer layers more sensitive to external backgrounds
- split data into Multiplicity 1, Multiplicity 2 and Multiplicity 2 Sum
  - different multiplicities are sensitive to different types of backgrounds





CUORE Background Model

Volume	Type	Components
TeO_2	Bulk	$2\nu\beta\beta$, ^{210}Pb, ^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{230}Th ^{226}Ra-^{210}Pb, ^{40}K, ^{60}Co, ^{125}Sb, ^{190}Pt
TeO_2	Surface (0.01 μm)	^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{226}Ra-^{210}Pb, ^{210}Pb
TeO_2	Surface (1 μm)	^{210}Pb
TeO_2	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Bulk	^{232}Th, ^{238}U, ^{40}K, ^{60}Co, ^{54}Mn
CuNOSV	Surface (0.01 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (1 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
Roman lead	Bulk	^{232}Th, ^{238}U, ^{108m}Ag
Top lead	Bulk	^{232}Th, ^{238}U, ^{210}Bi
Ext. lead	Bulk	^{210}Bi
CuOFE	Bulk	^{232}Th, ^{238}U, ^{60}Co
External	-	Cosmic muons



MONTE CARLO

- ~60 independent simulations of sources/location in the setup
- full radioactive chains and single iotopes
- the different energy spectra (inner/outer, M1/M2,M2sum) of each source/location are generated with Geant4 based simulation implementing a detailed geometry of the setup (detector, cryostat, shields)

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  - different multiplicities are sensitive to different types of backgrounds

BAYESIAN FIT

- Assign to each ingredient (source/location) a normalisation factor
- Assign a prior to each normalisation factor from material screening, assays and cosmogenic analysis
- Fit the model to the data and sample the posteriors with MCMC Gibbs sampler

MONTE CARLO

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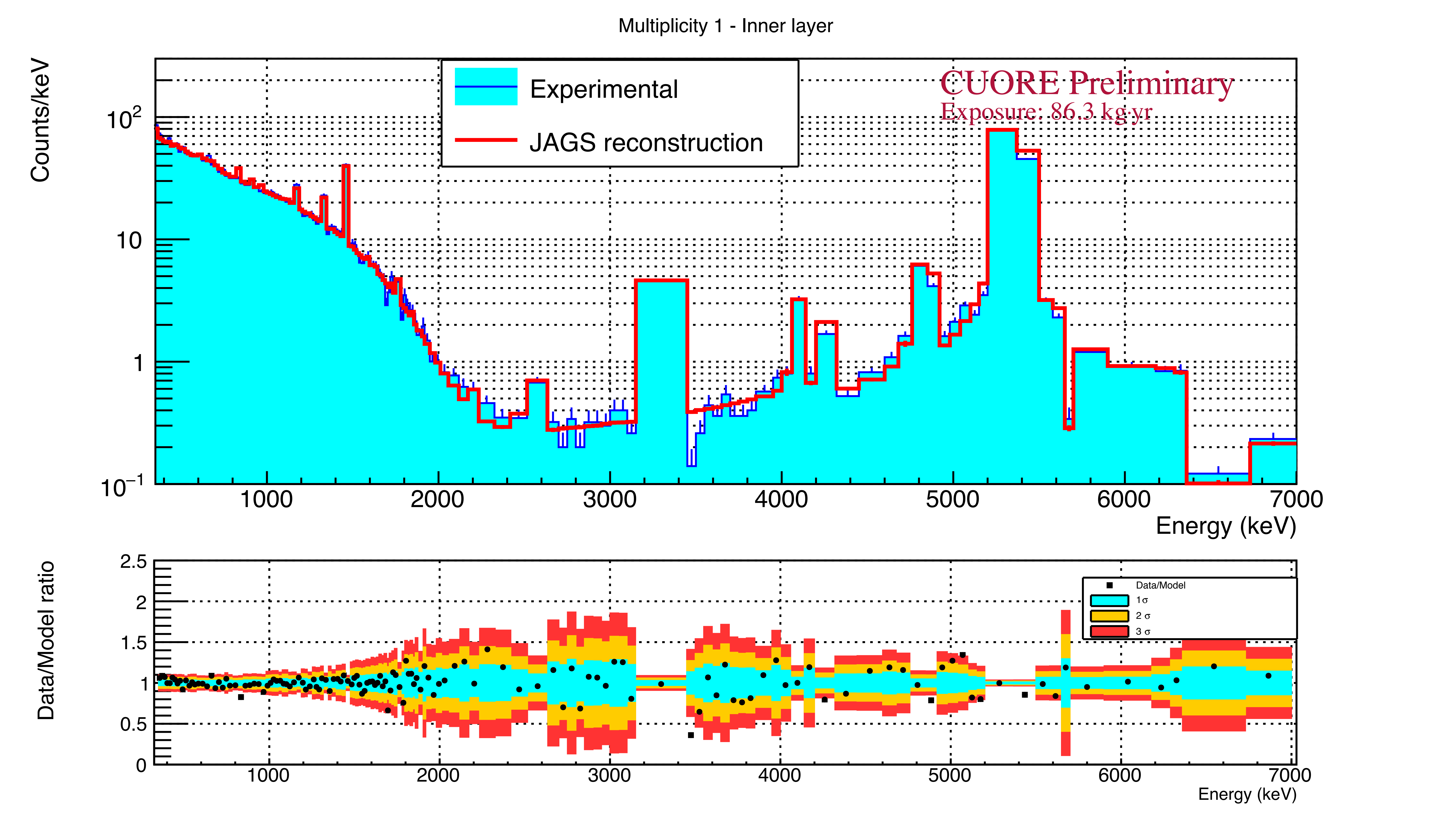

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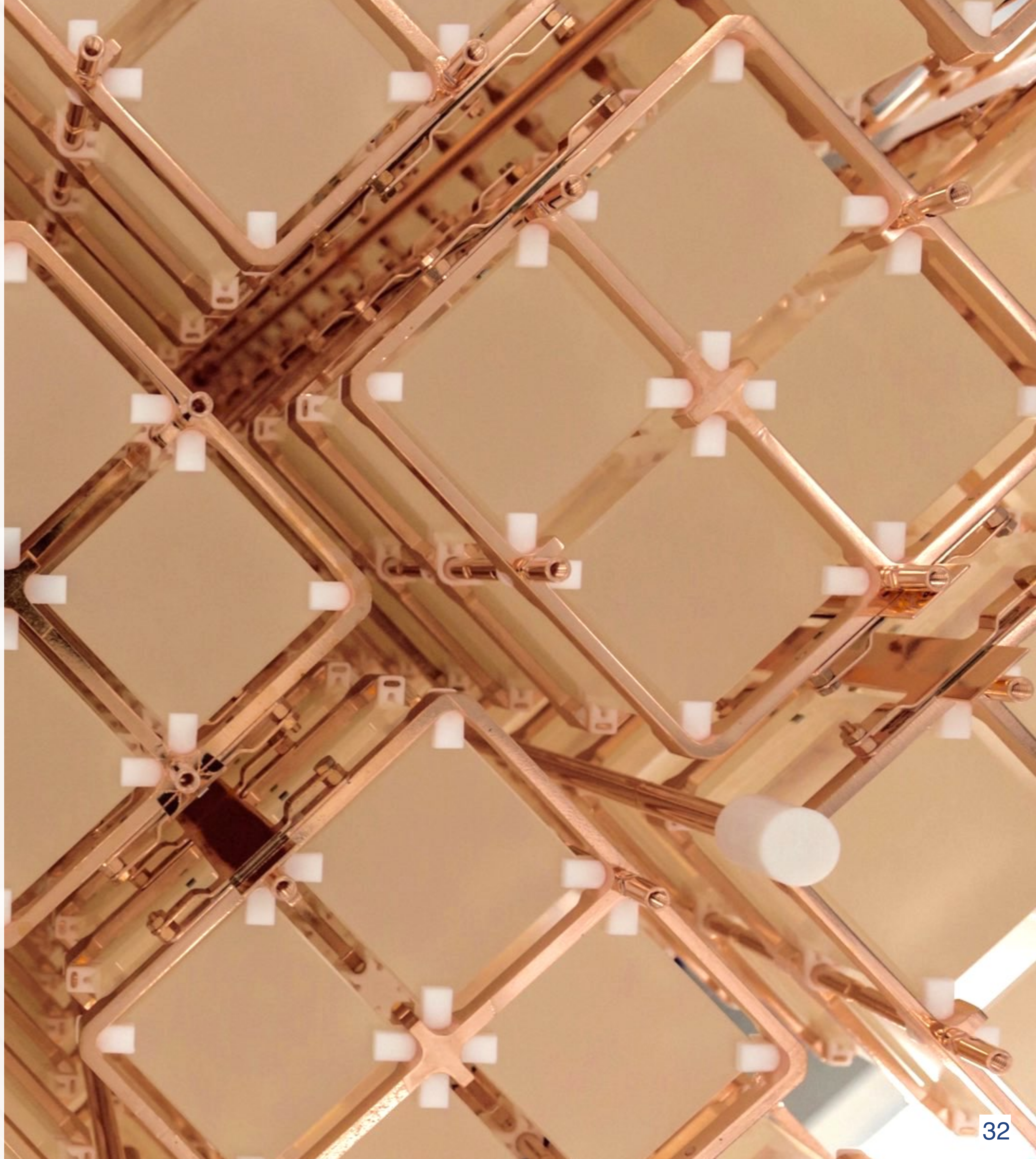
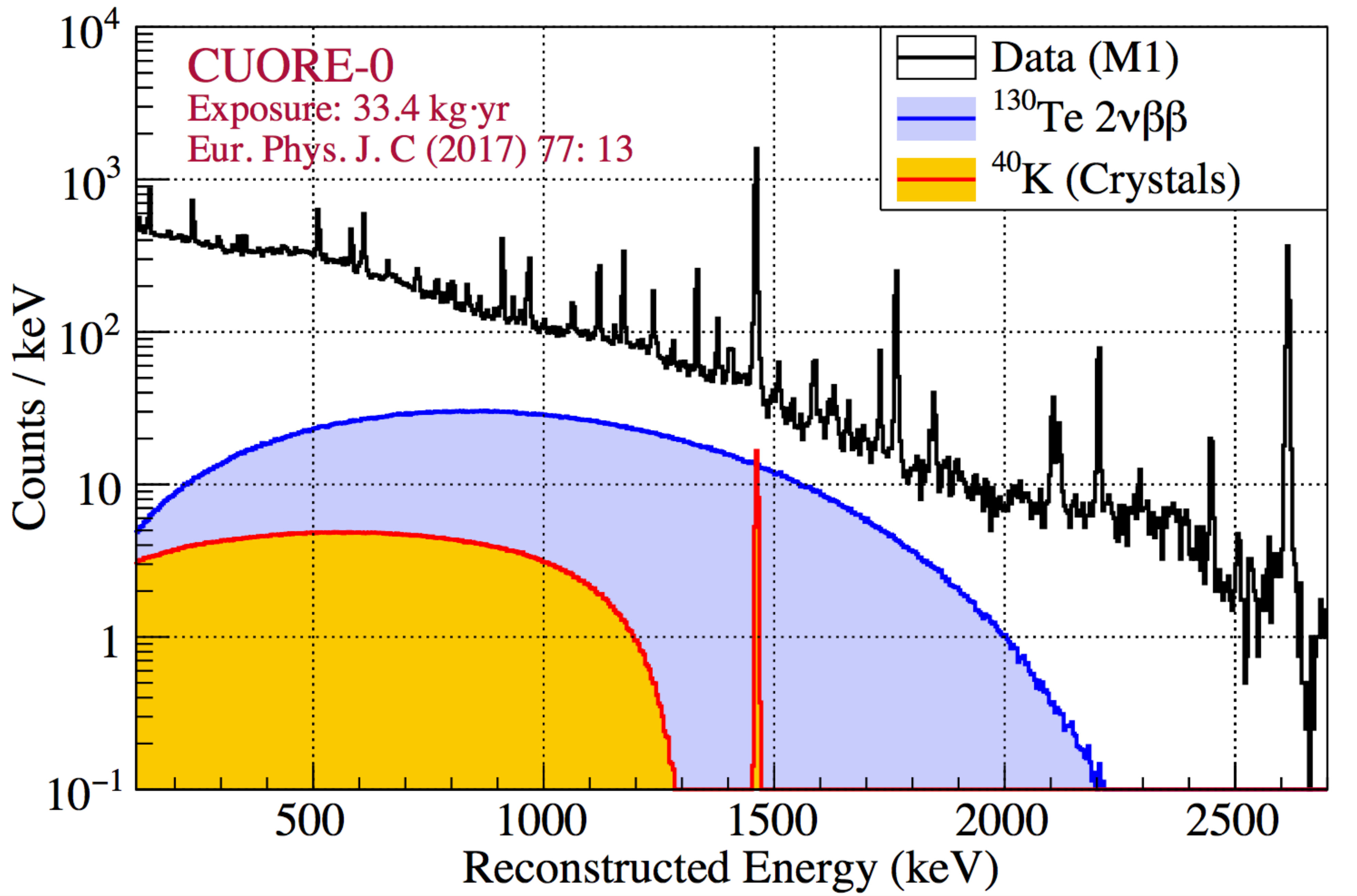
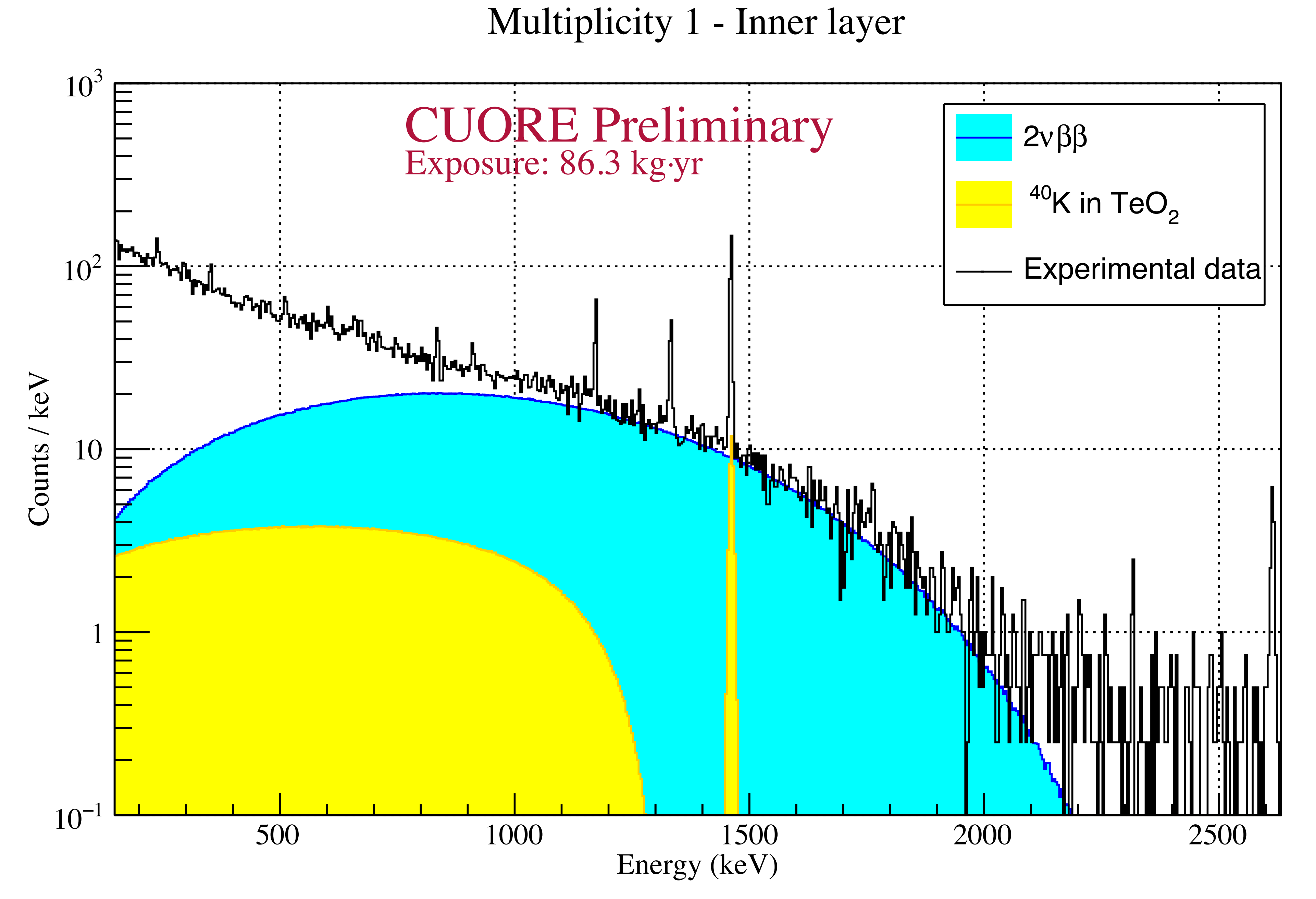


2vDBD

2vDBD spectrum is one of the ingredients in the background model





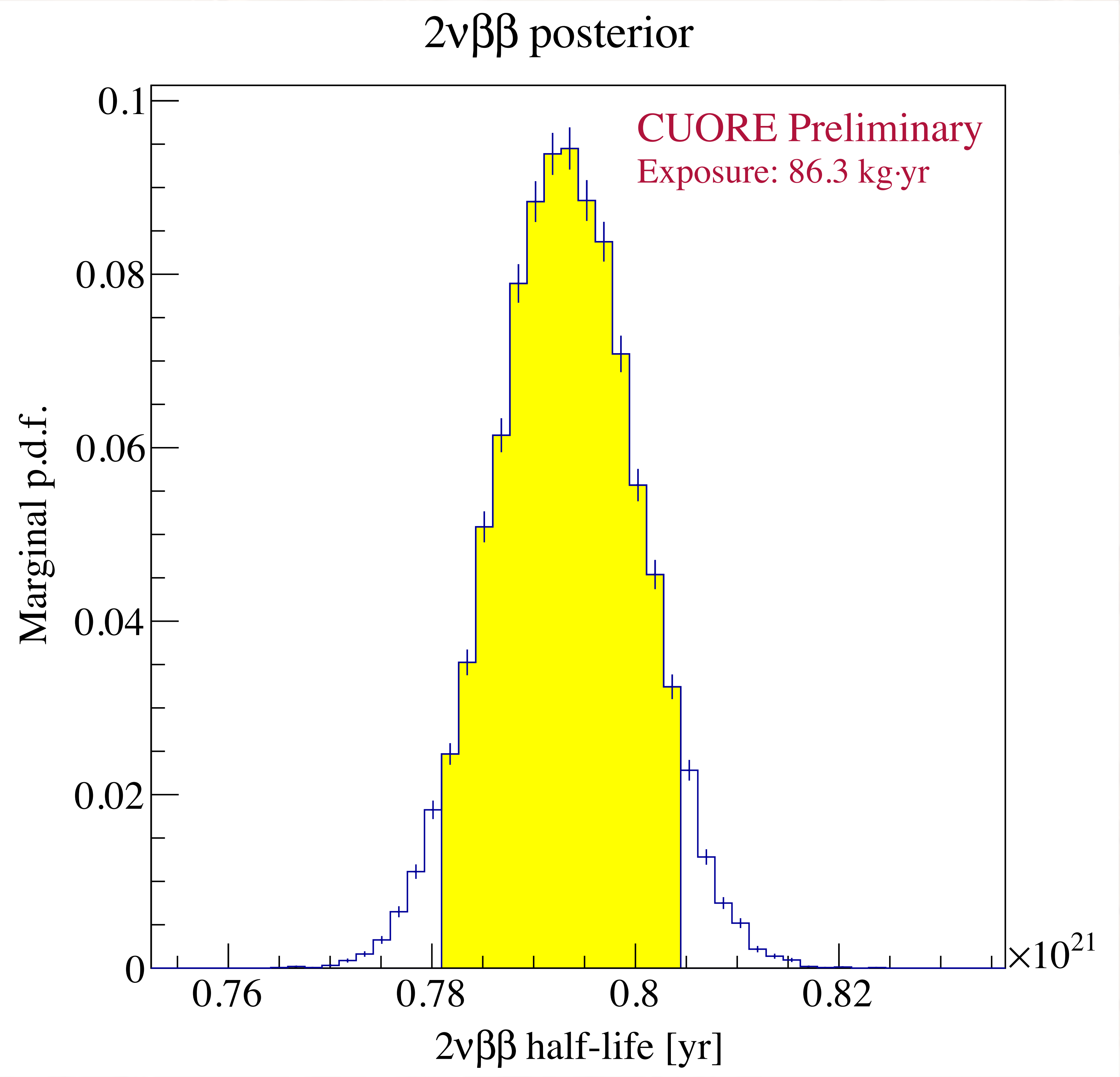
CUORE-0:
~ 20% of counts in 1-2 MeV region

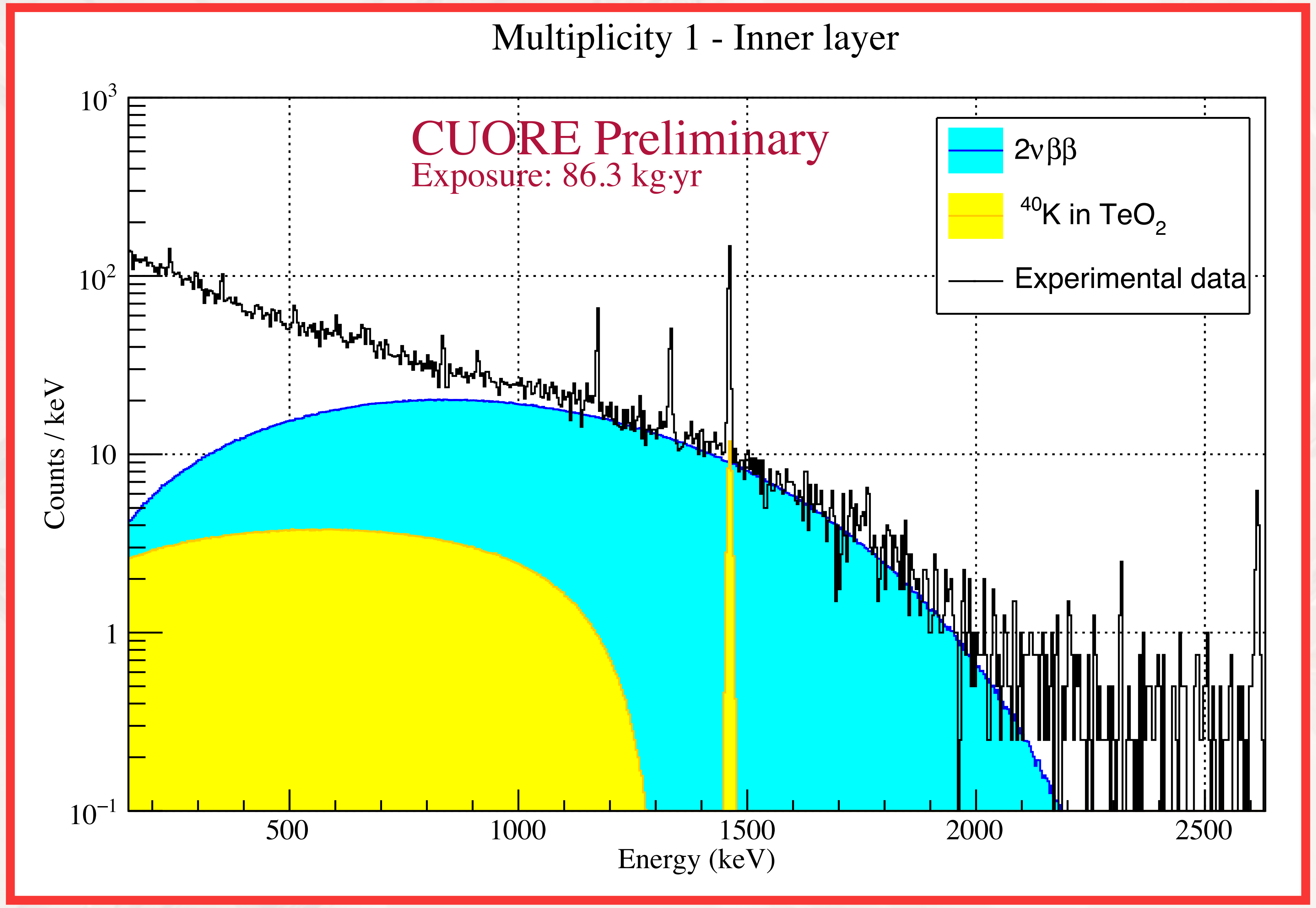
- lower background
- self-shielding
- anti-coincidence efficiency

CUORE:
~ 100% of counts in 1-2 MeV region

2vDBD

2vDBD spectrum is one of the ingredients in the background model





CUORE:
~ 100% of counts in 1-2 MeV region

2vDBD

CUORE

2vDBD spectrum is one of the ingredients in the background model

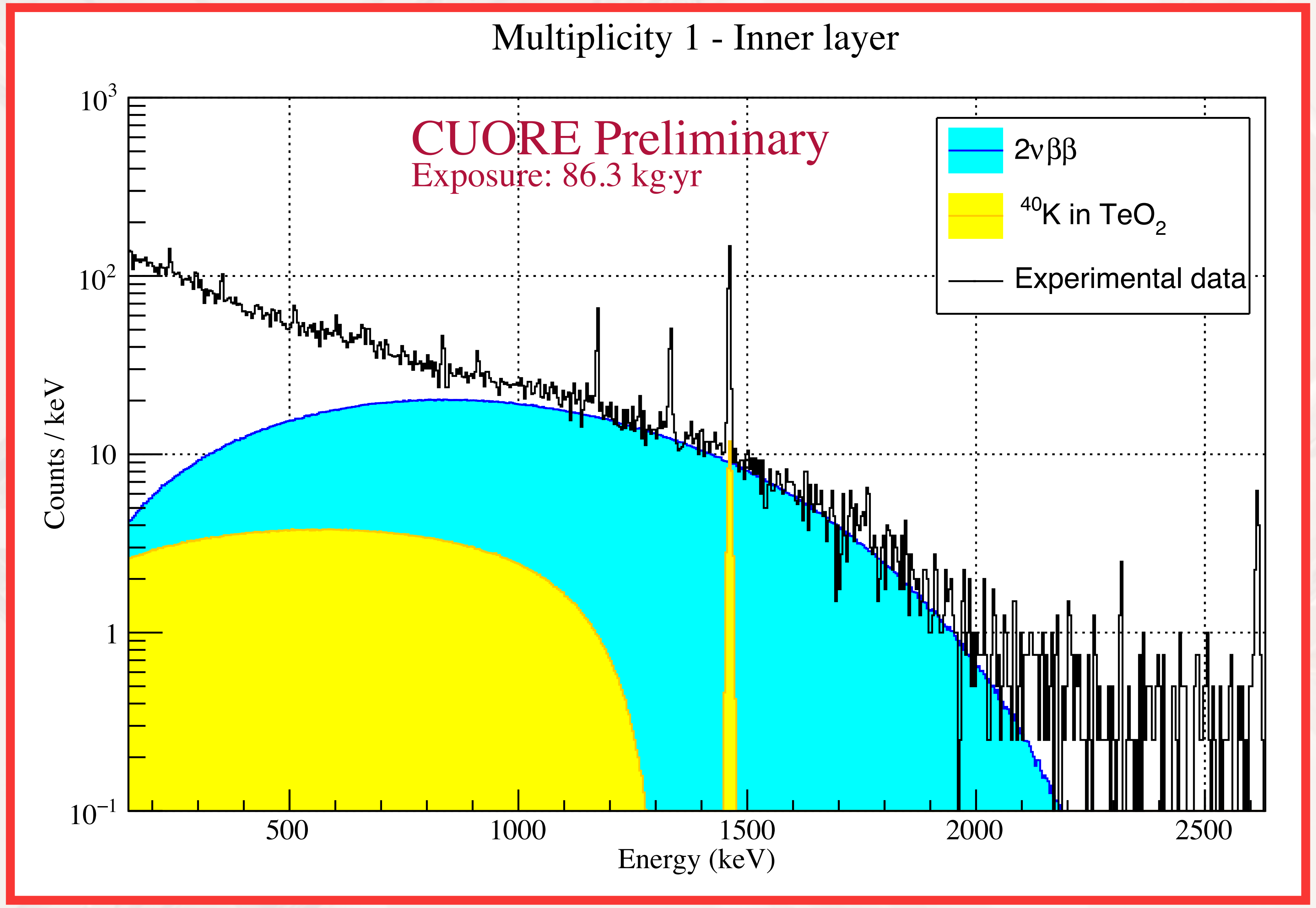
$$\Gamma^{2\nu}_{1/2} = [8.7 \pm 0.1(\mathrm{stat.}) \pm 0.2(\mathrm{syst.})] \times 10^{-22}\mathrm{yr}^{-1}$$

$$T^{2\nu}_{1/2} = [7.9 \pm 0.1(\mathrm{stat.}) \pm 0.2(\mathrm{syst.})] \times 10^{20}\mathrm{yr}$$

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

$$\mathrm{NEMO-3}: \; T^{2\nu}_{1/2} = [7.0 \pm 0.9(\mathrm{stat.}) \pm 1.1(\mathrm{syst.})] \times 10^{20}\mathrm{yr}$$

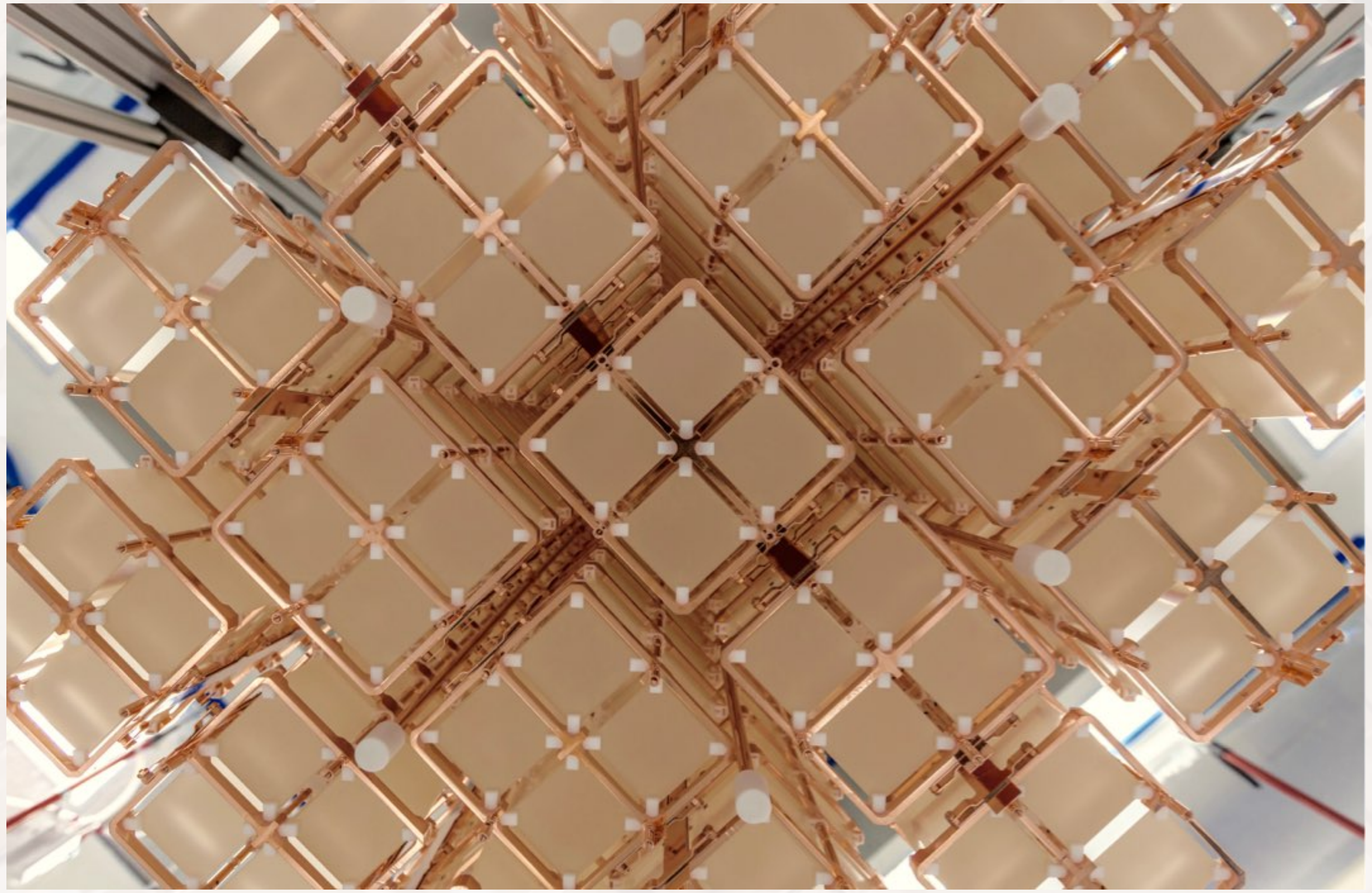
- Systematic uncertainty dominated by uncertainty on contaminant location and uniformity
  - studied by repeating the fit with different geometric splitting of the data
  - more data —> finer geometric splitting of the array —> reduce this component
- Fit is independent of energy threshold over the range 100 - 750 keV
- Used M2 data (purer sample of particle events) to improve the systematic uncertainty on the selection efficiency by one order of magnitude w.r.t. PRL 2018 data release



CUORE:
~ 100% of counts in 1-2 MeV region

Conclusions and Outlook

- 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
  - performed the most precise measure of two-neutrino half life to date



- The largest and most complex cryogenic experiment is taking physics data
- The first analysis efforts were focused on the neutrino-less and two-neutrino double beta decay of ^{130}Te to GS
- Physics results on more processes are on their way:
  - Majoron emission, CPTV
  - Dark matter, axions
  - ββ to excited states, β^+/EC decays
- With an unprecedented amount of data, CUORE is the best tool to study and model the backgrounds for the next generation experiments