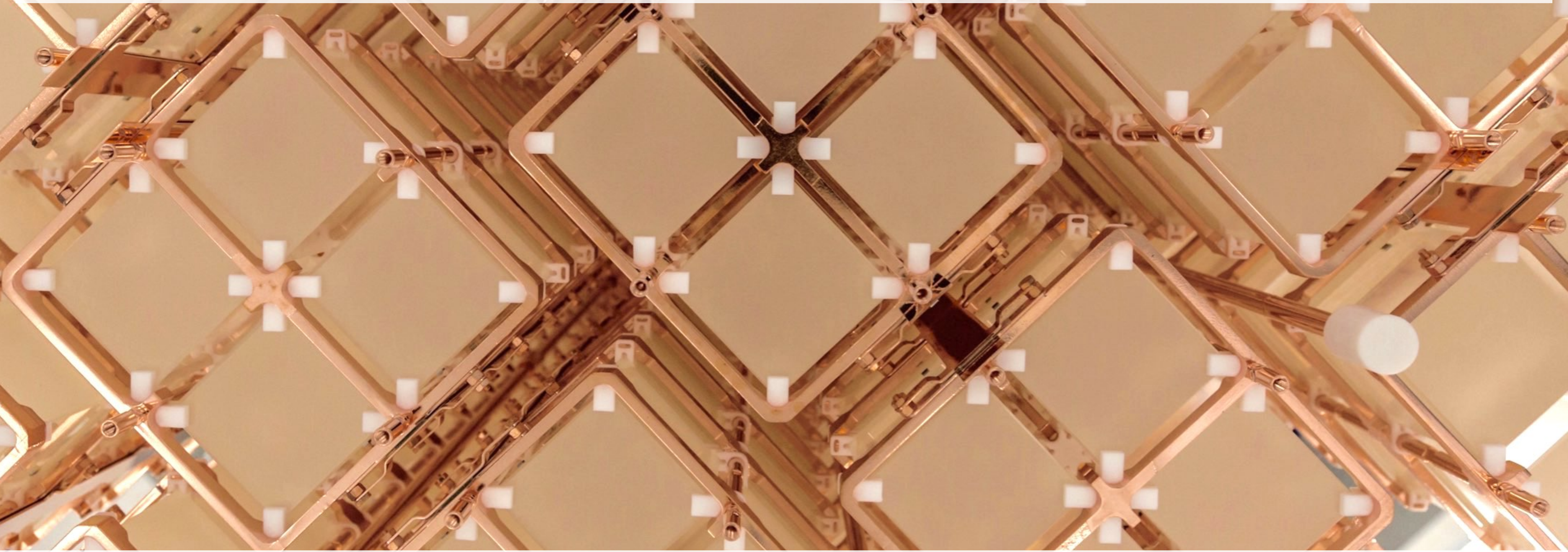
Results from the CUORE experiment

CUORE

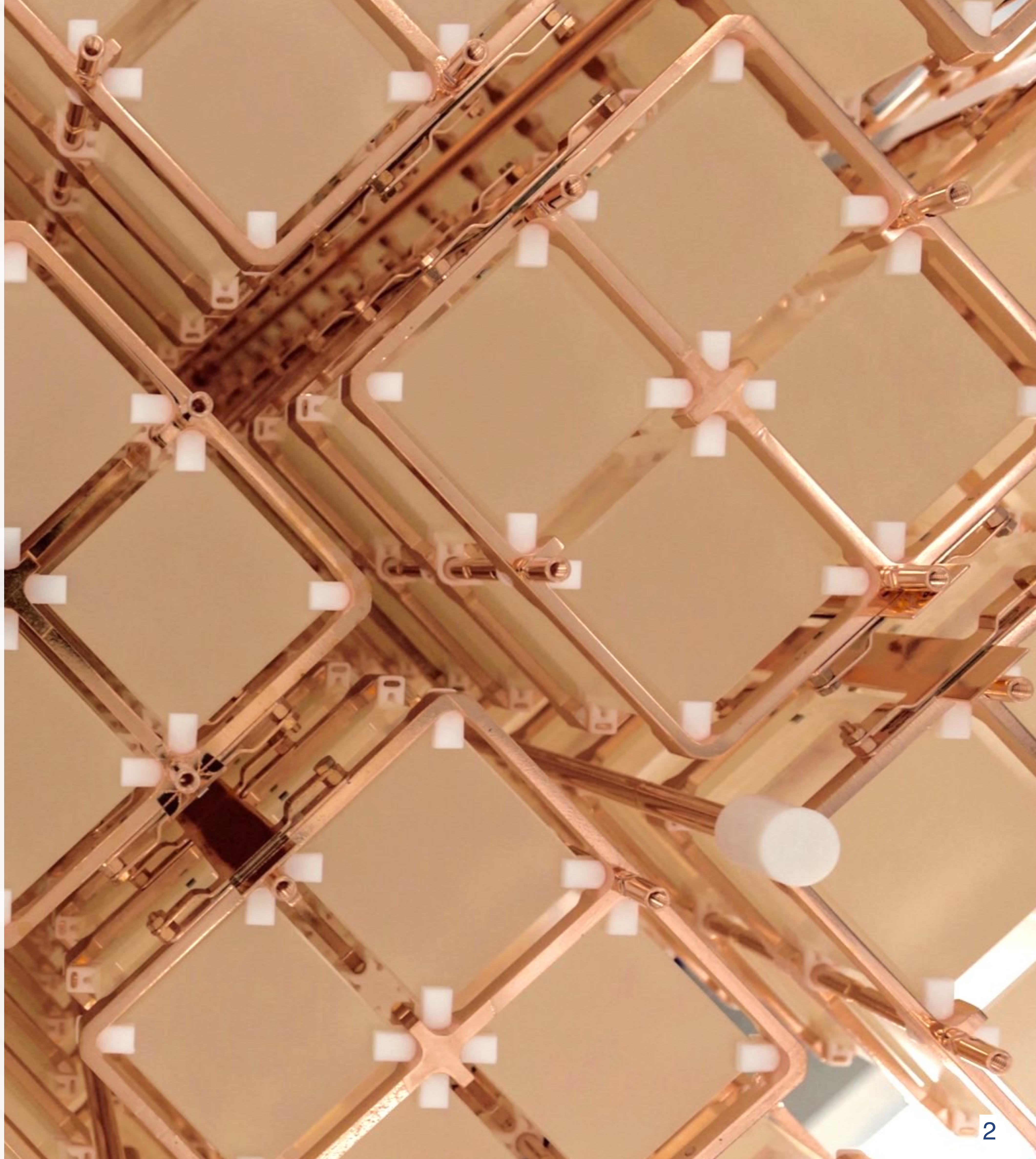
Matteo Biassoni on behalf of the **CUORE** Collaboration
INFN - Sez. Milano Bicocca

INFN 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
  - 0νββ and lepton number violation
  - background model
  - 2νββ
- Conclusions and outlook



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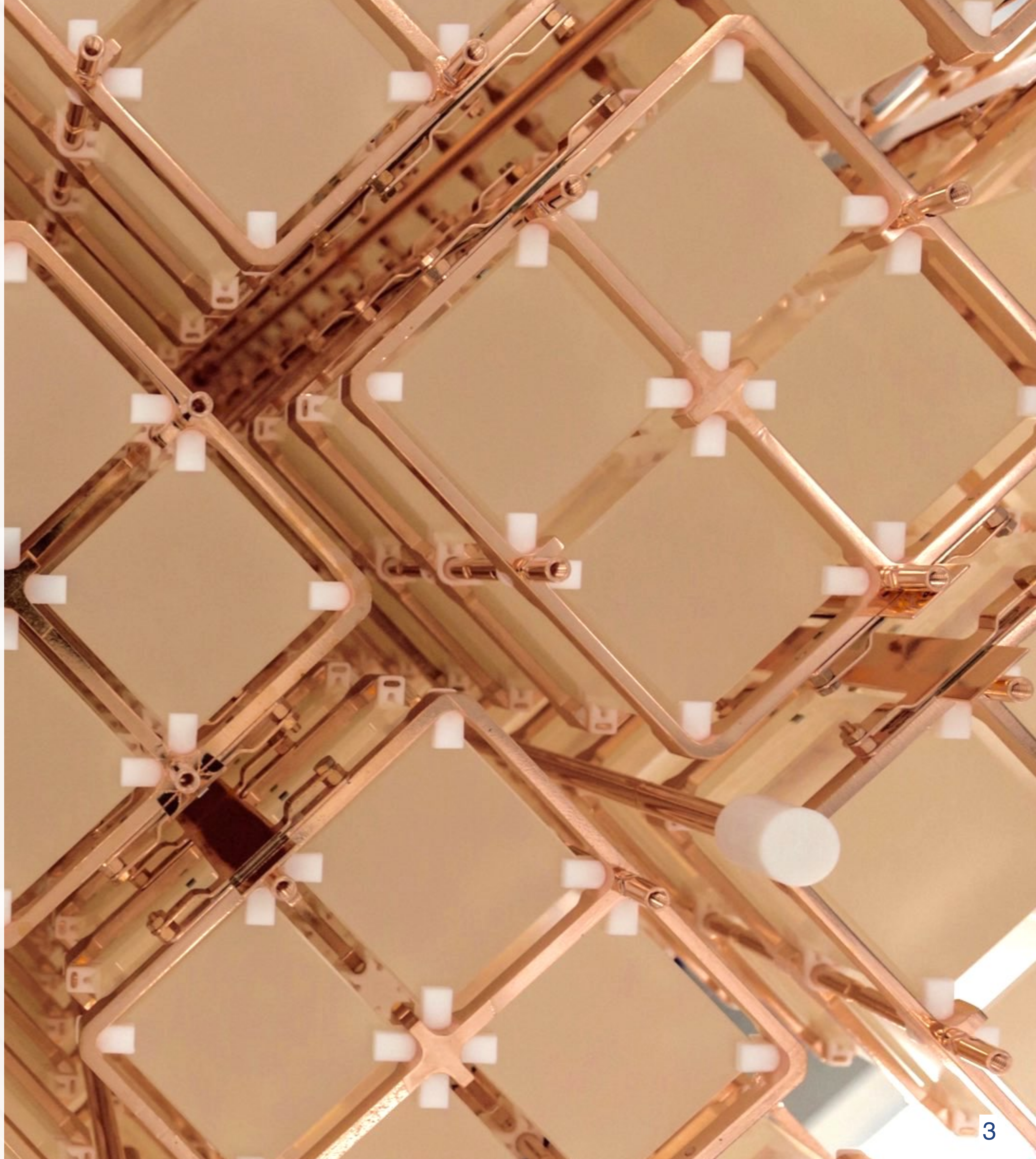


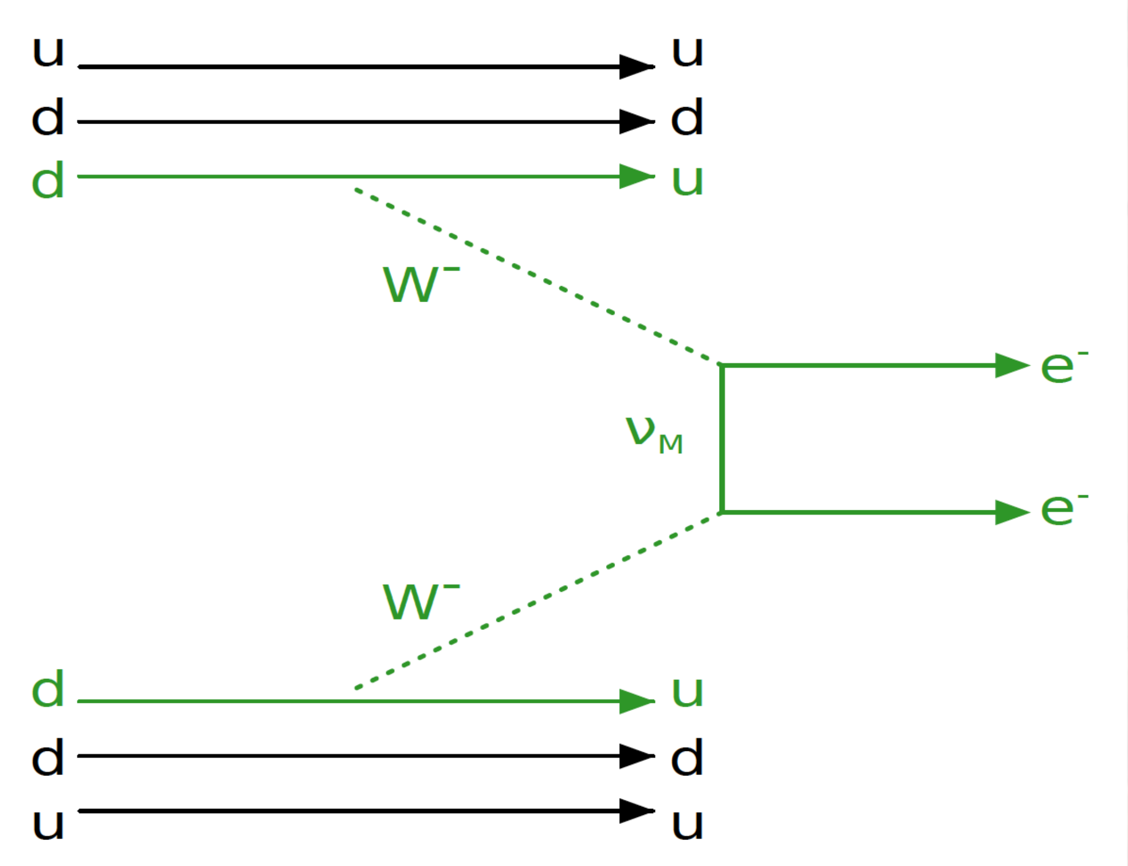
TeO_2 and thermal detectors for 0vDBD

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, $\Delta L = 2$
- **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
  - …

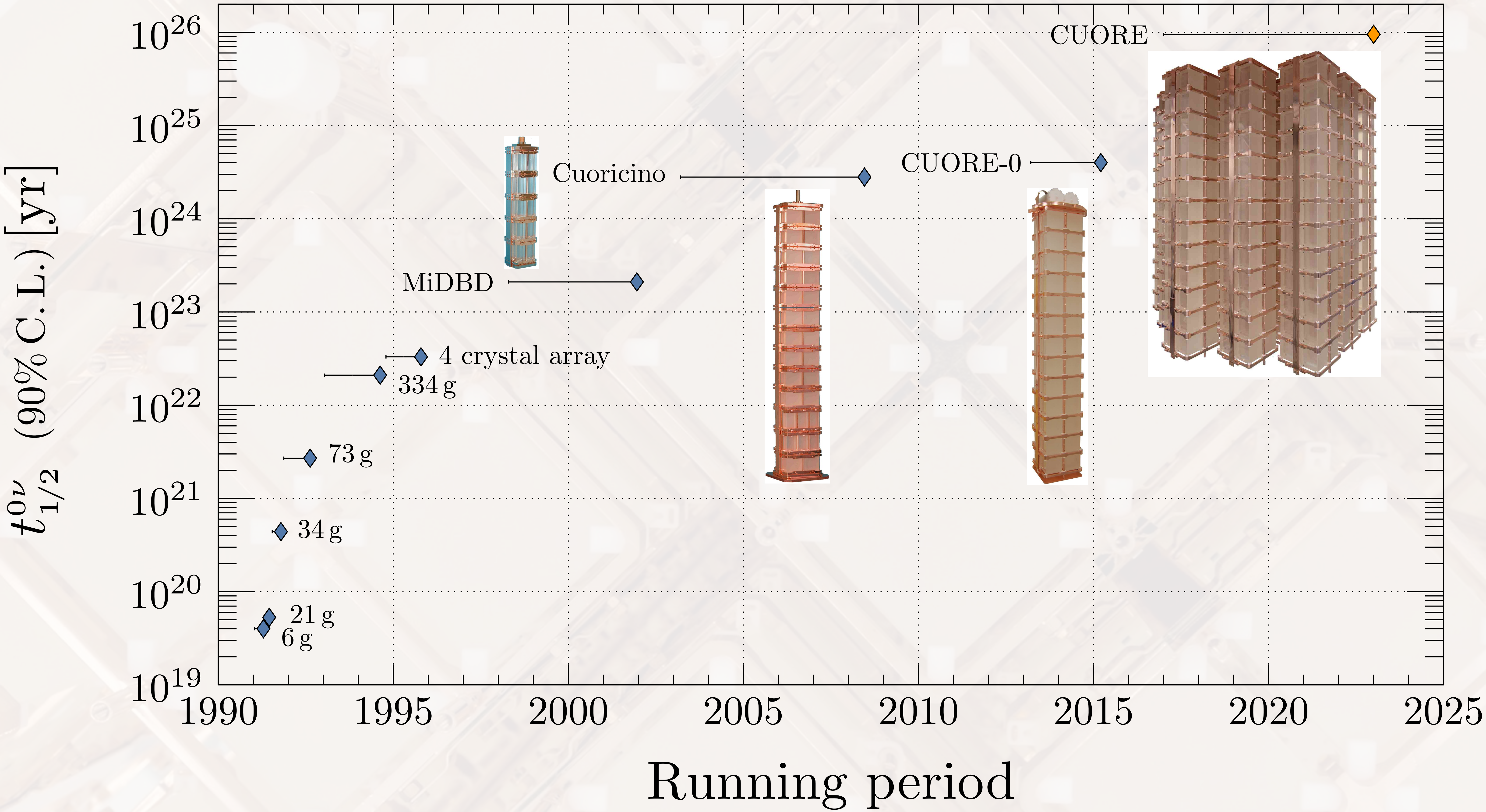
^{130}Te is a good candidate source for 0vDBD search:

- 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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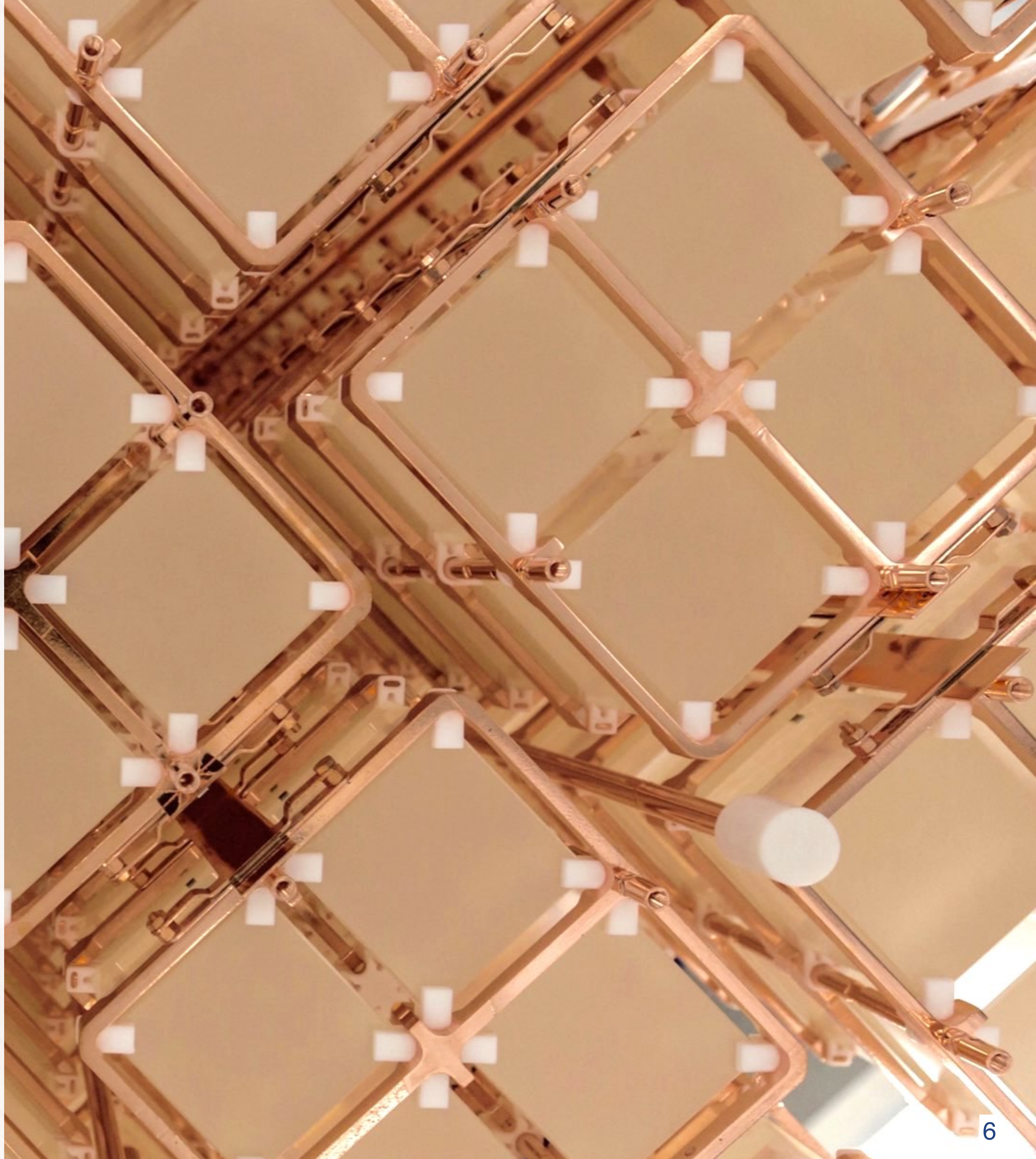


CUORE

Cryogenic Underground Observatory for Rare Events

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

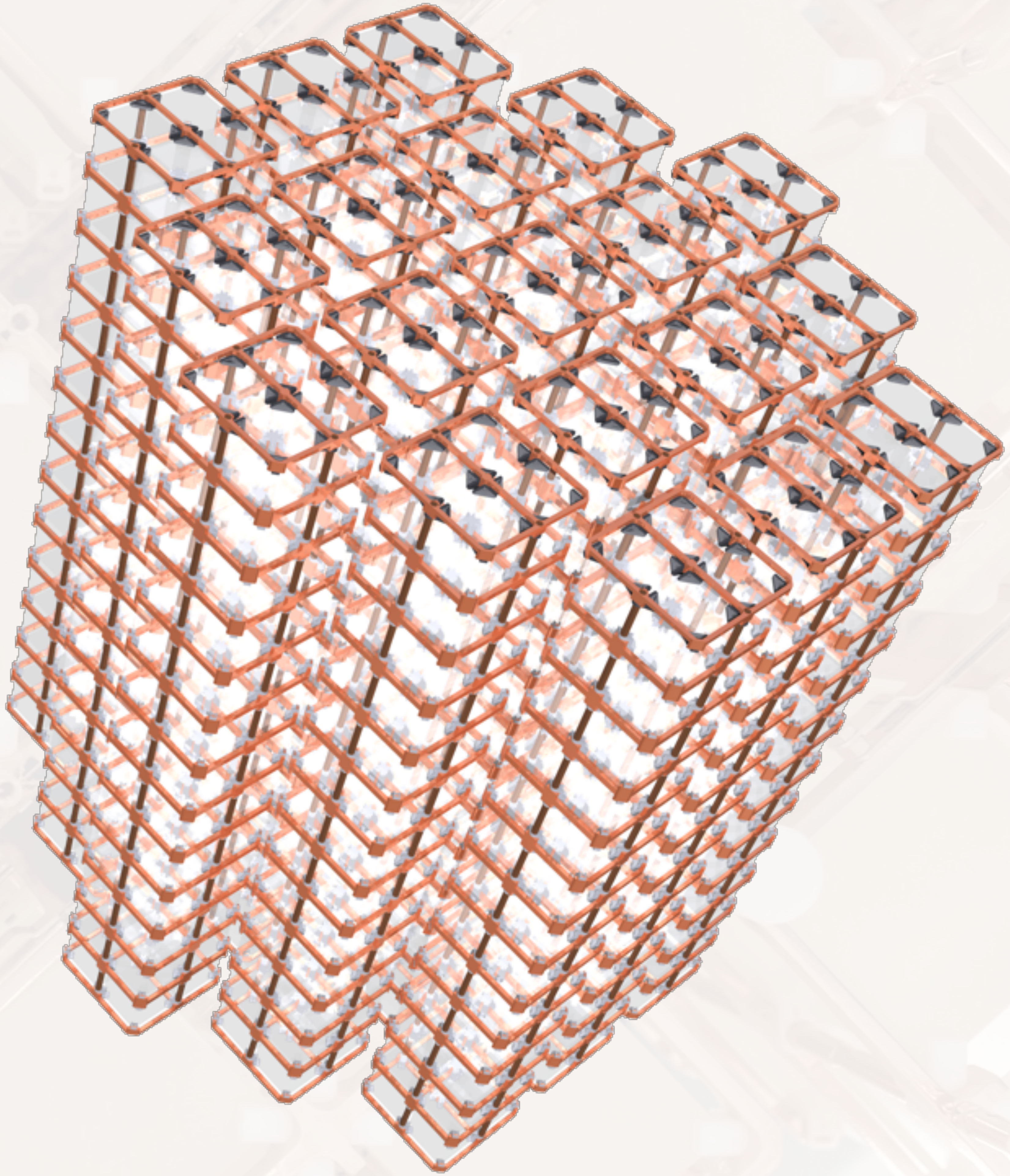
Detector design:
closely packed array of 988 TeO_2 crystals arranged in 19 towers

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

INFN LNGS

Massachusetts Institute of Technology

Università degli Studi di Padova

Università degli Studi di Cassino e del Lazio Meridionale

Università degli Studi di Milano Bicocca

Yale

University of South Carolina

Shanghai Jiao Tong University

Alma Mater Studiorum Università di Bologna

UCLA

Berkeley Lab

Lawrence Livermore National Laboratory

Cal Poly San Luis Obispo

Sapienza Università di Roma

University of California

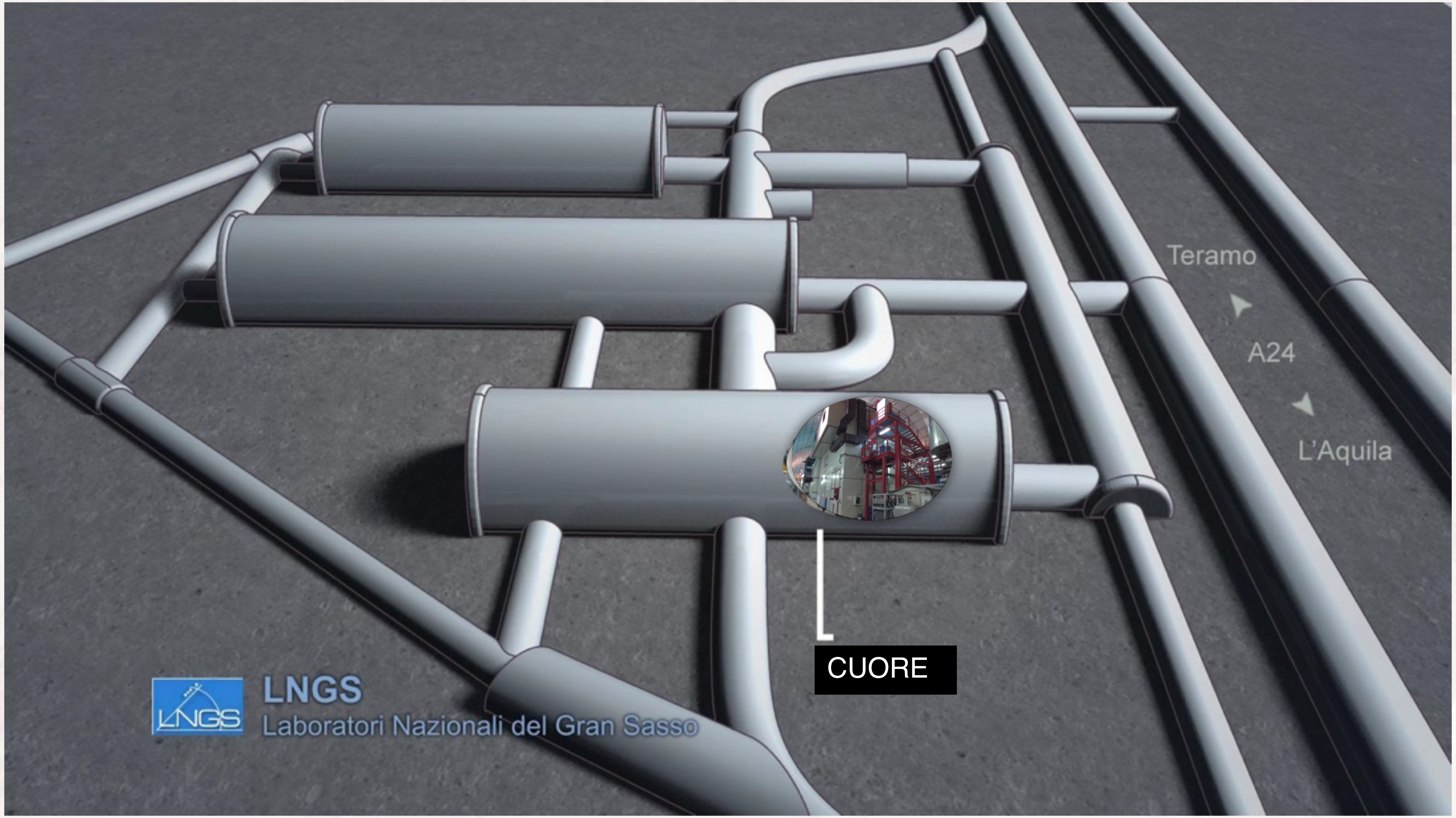
VirginiaTech Invent the Future®

CUORE @ LNGS

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

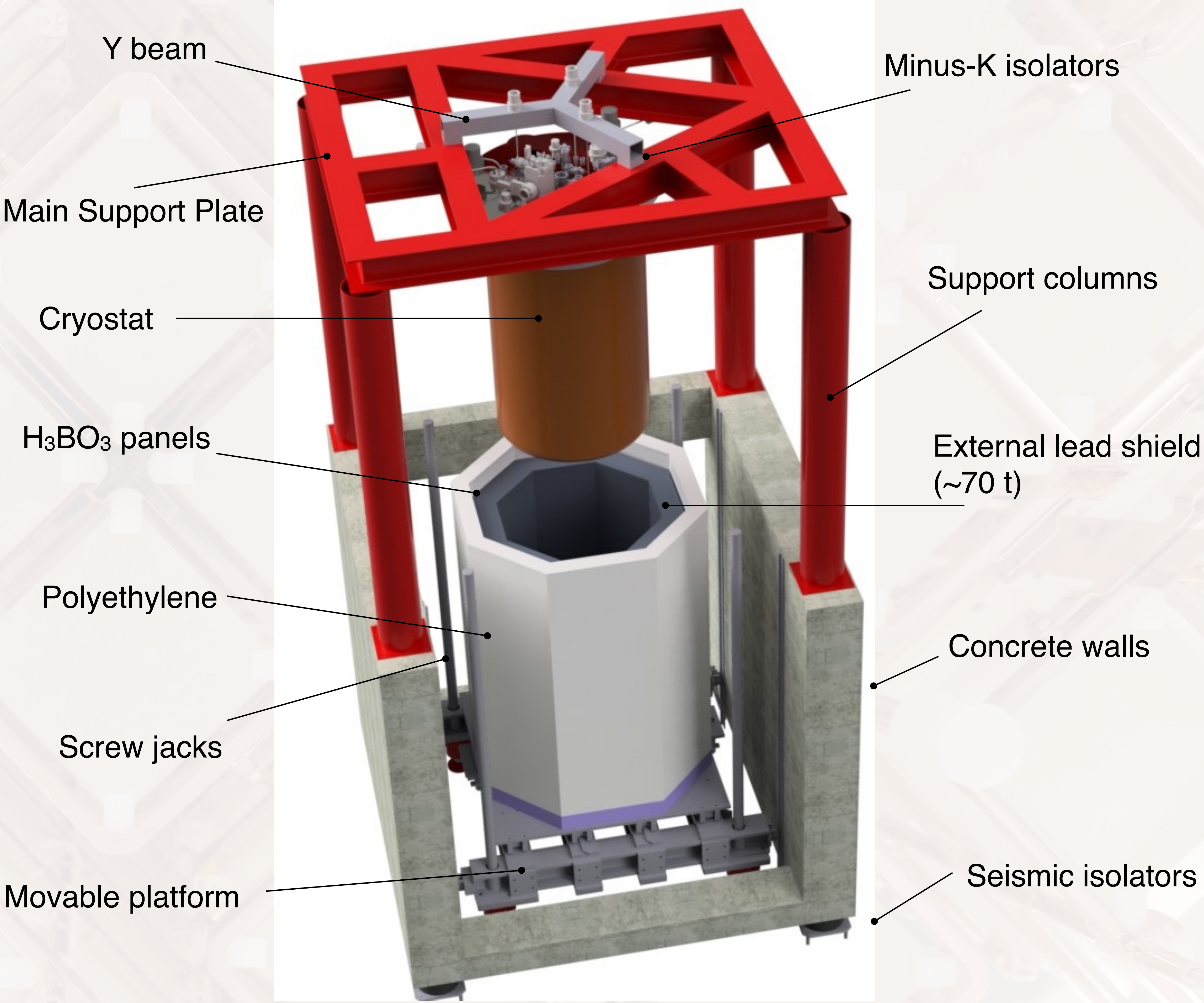
- μ's: ~3 × 10^{-8} / (s·cm^2)
- γ's: ~0.73 / (s·cm^2)
- neutrons: 4 × 10^{-6} /(s·cm^2) below 10 MeV

CUORE @ LNGS


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

Underground Laboratory

- Three-story building
- Hosting the cryostat supporting structure

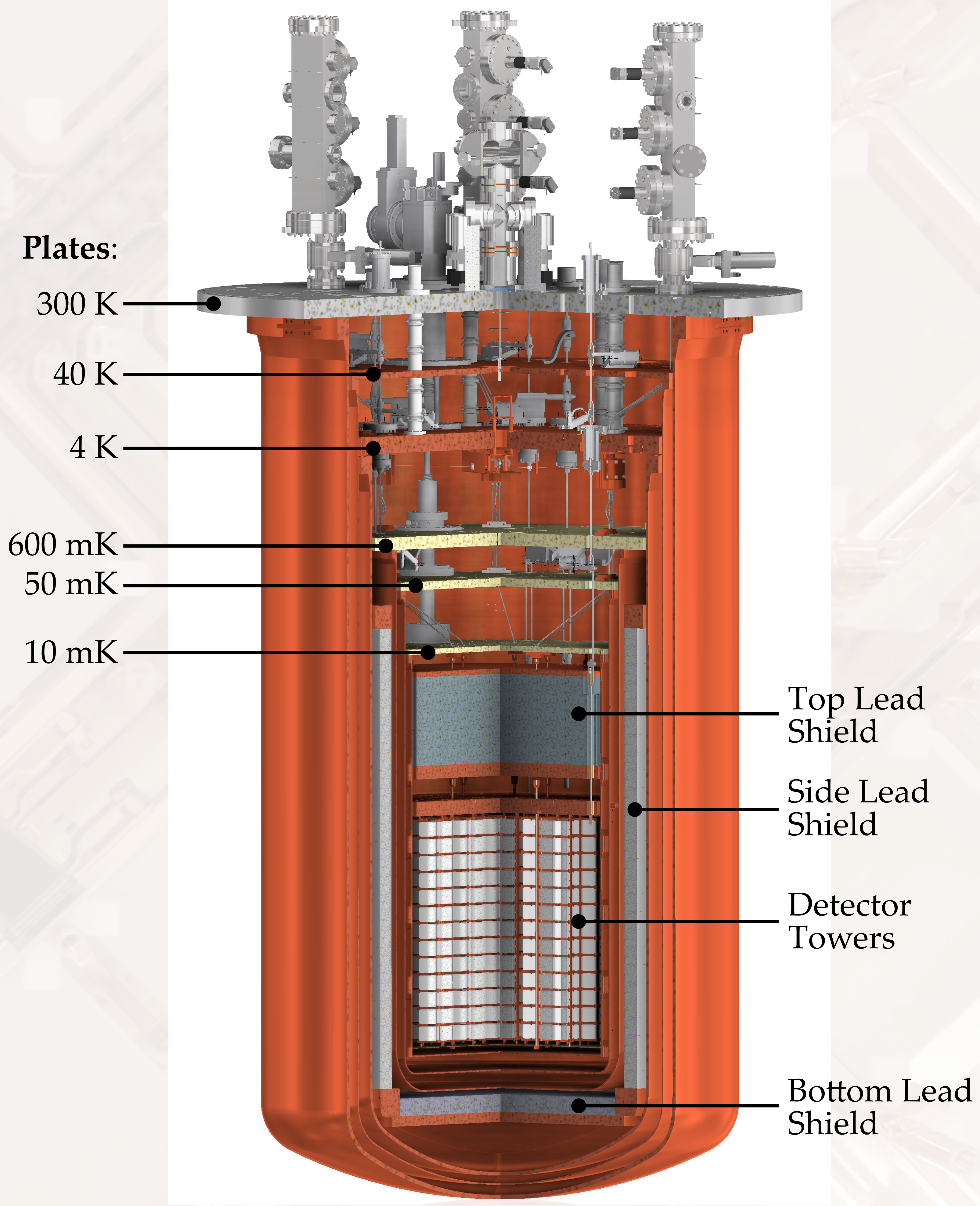


The CUORE cryostat

Challenges:

- Cool down ~1 ton detector to ~10 mK
- Mechanically decoupled for extremely low vibrations
- Low background environment
- Large duty cycle and long term stability

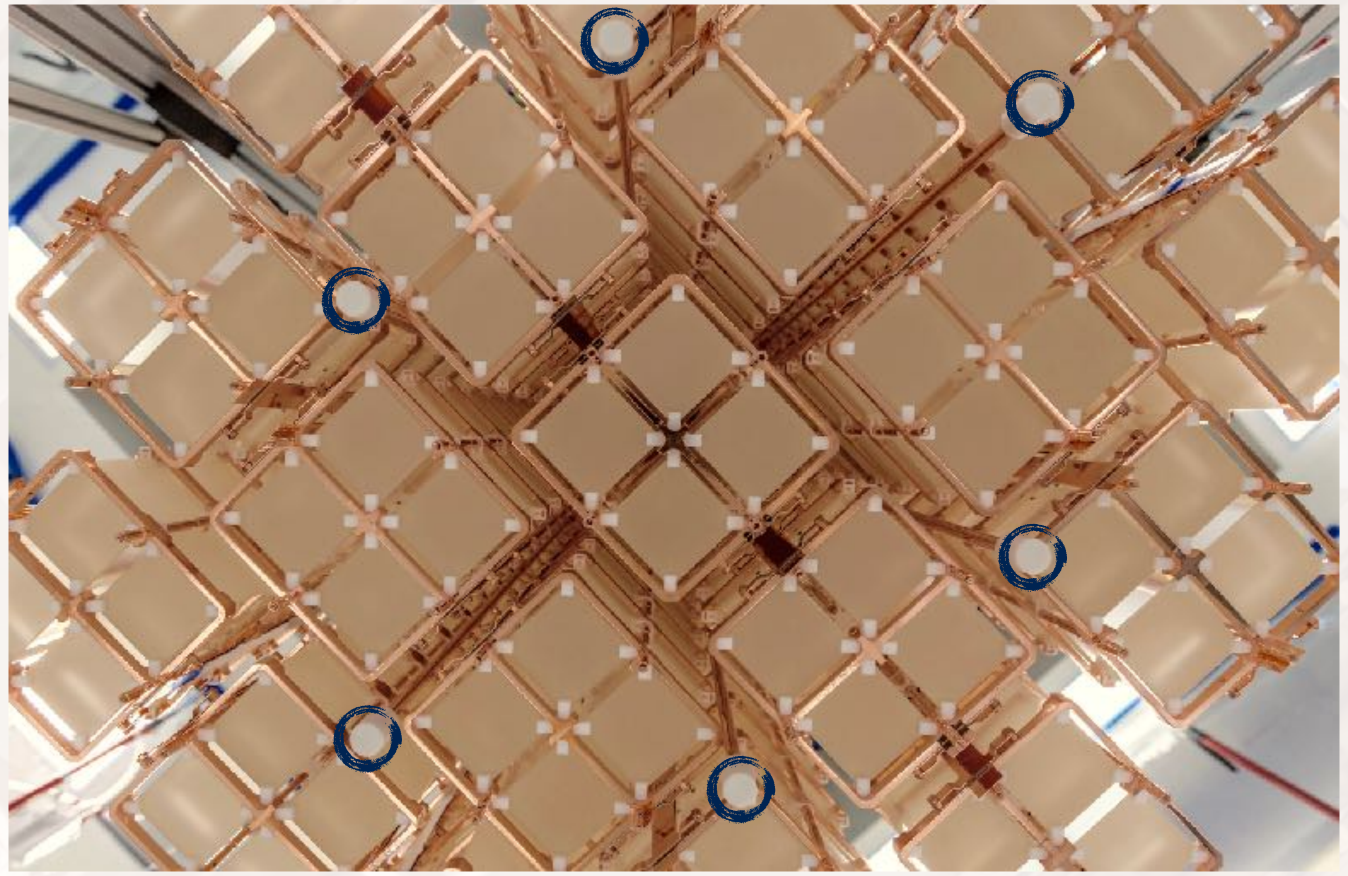
- Cryogen-free cryostat
- Fast Cooling System (^{4}He gas) down to ~50K
- 5 pulse tubes cryocooler down to ~4K
- Dilution refrigerator down to operating temperature ~10 mK
- Nominal cooling power: 3 µW @ 10mK
- Cryostat total mass ~30 tons
- Mass to be cooled < 4K: ~15 tons
- **Mass to be cooled < 50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

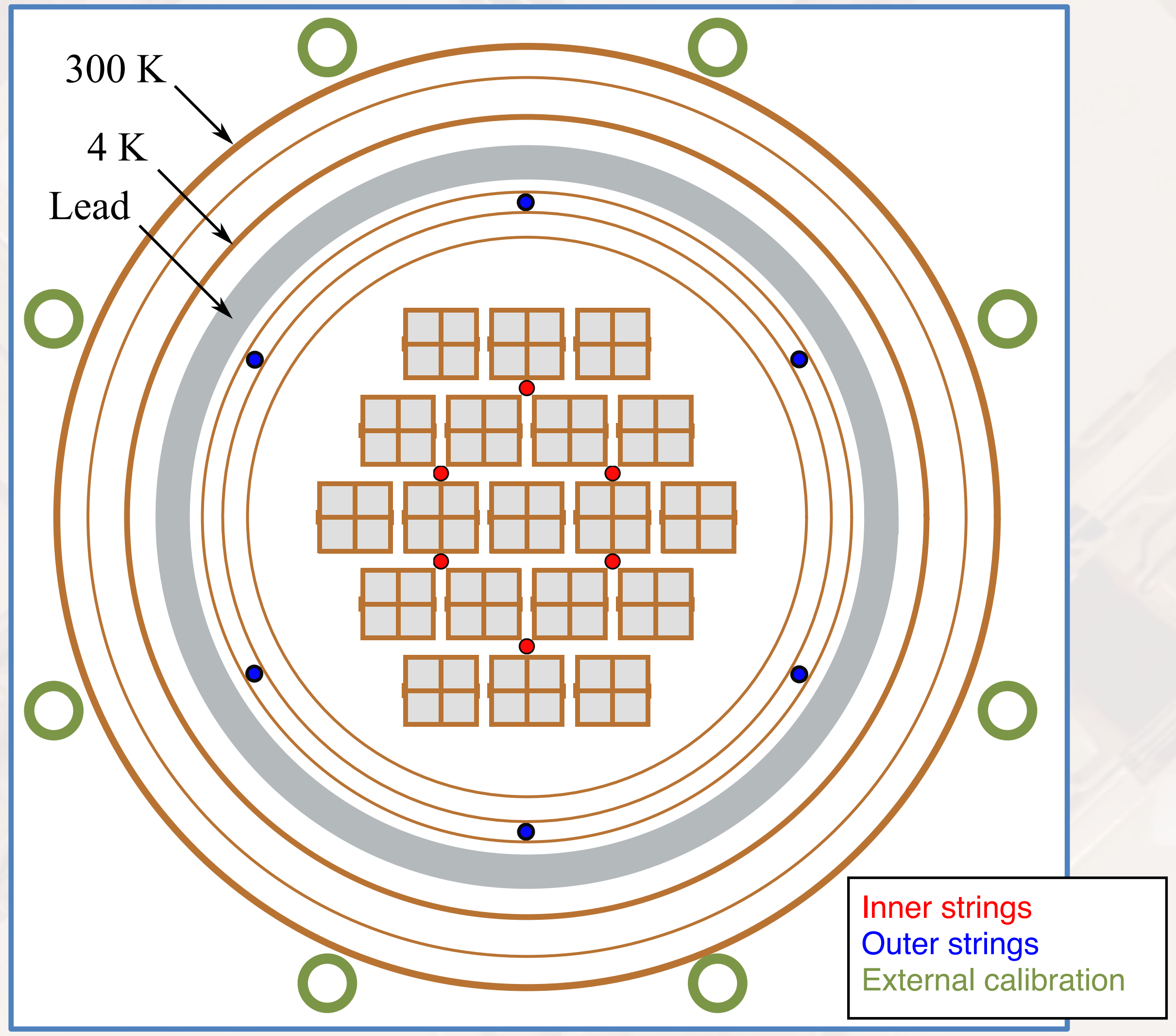


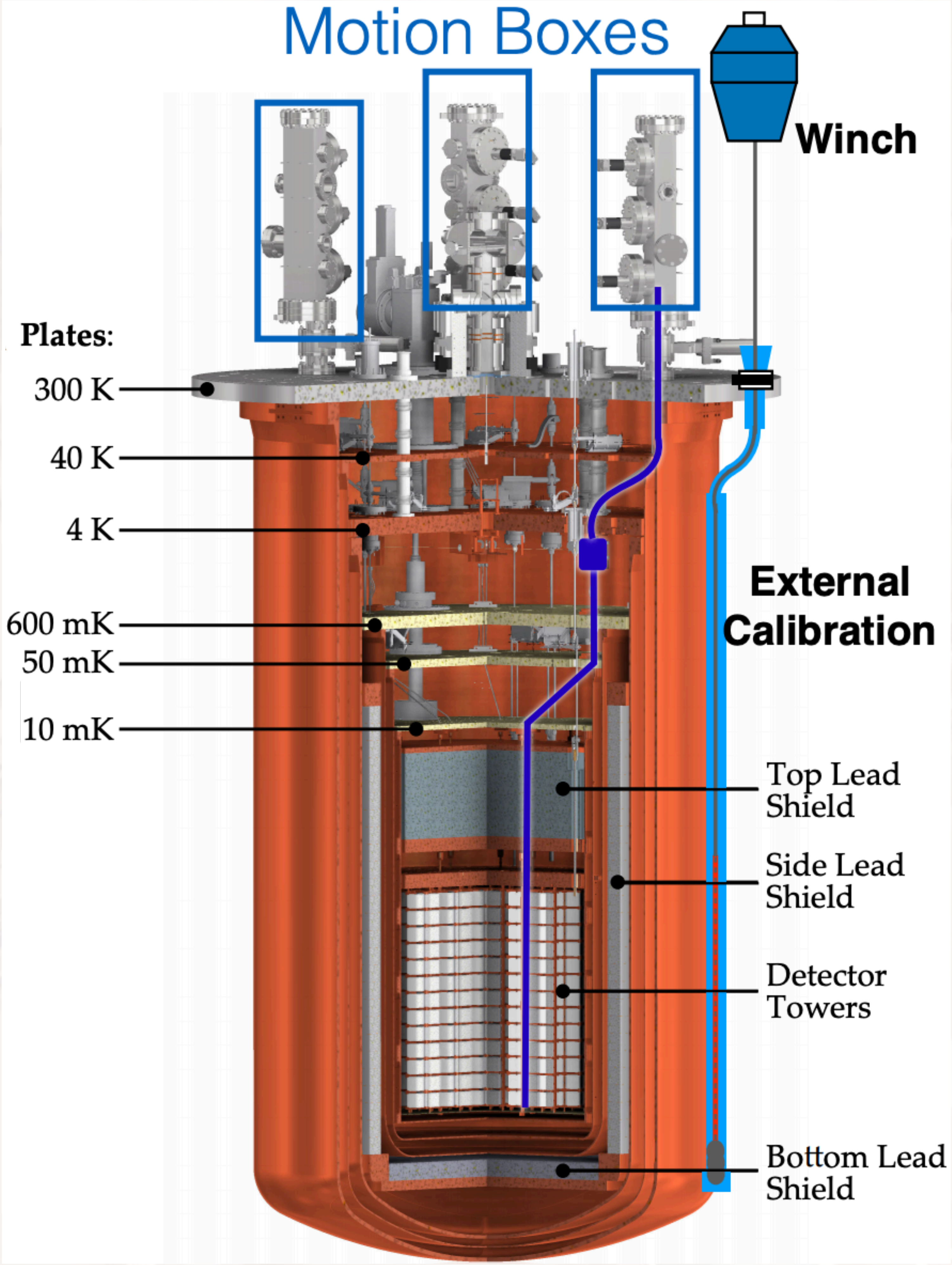
Detector calibration system

Challenges:

- Provide a uniform calibration of all the CUORE detectors
- Deployment of thoriated strings through the cryostat, from room temperature into the detector core
- 8 additional tubes can host strings outside the 300K vessel but inside the lead shielding







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)

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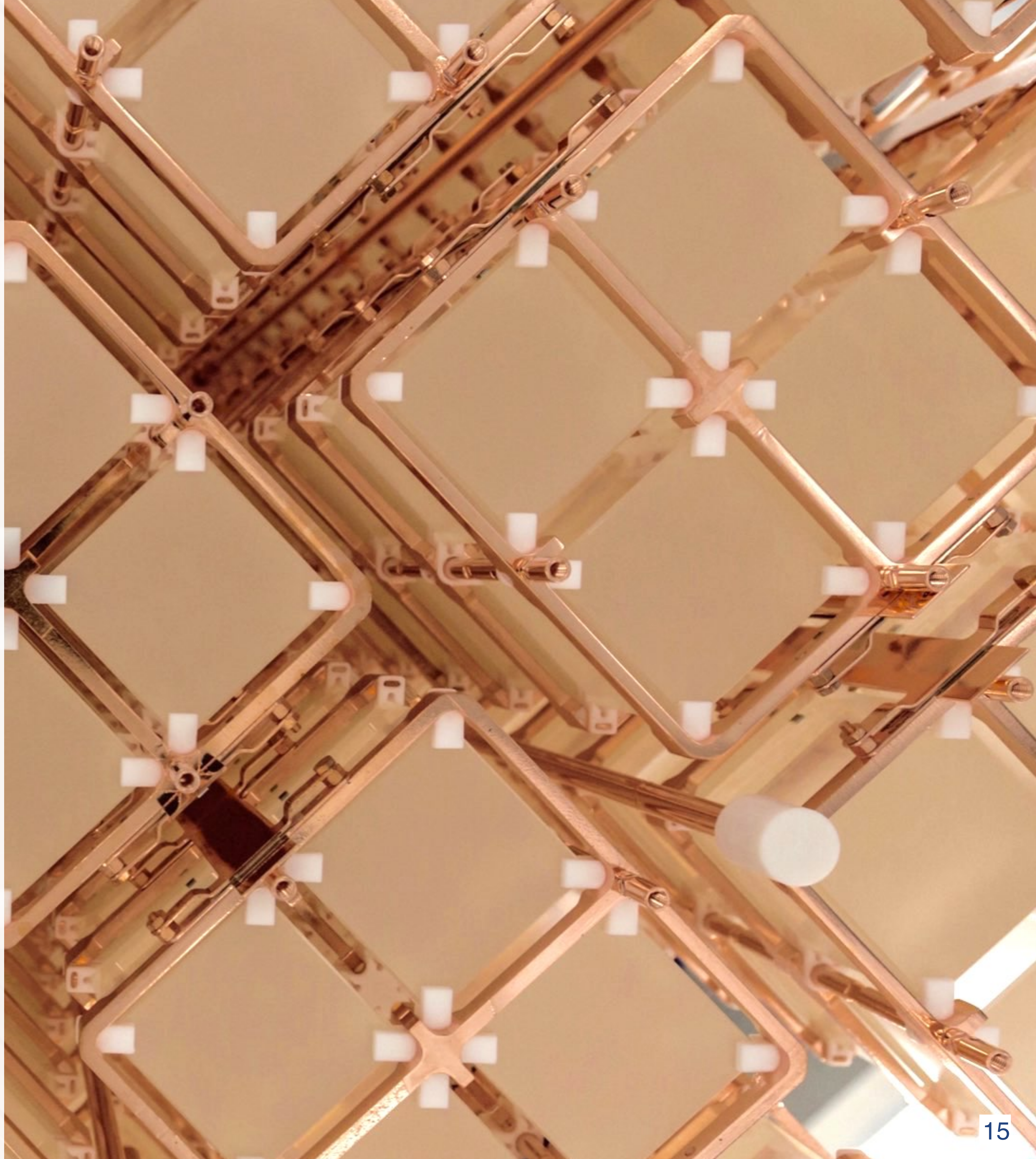
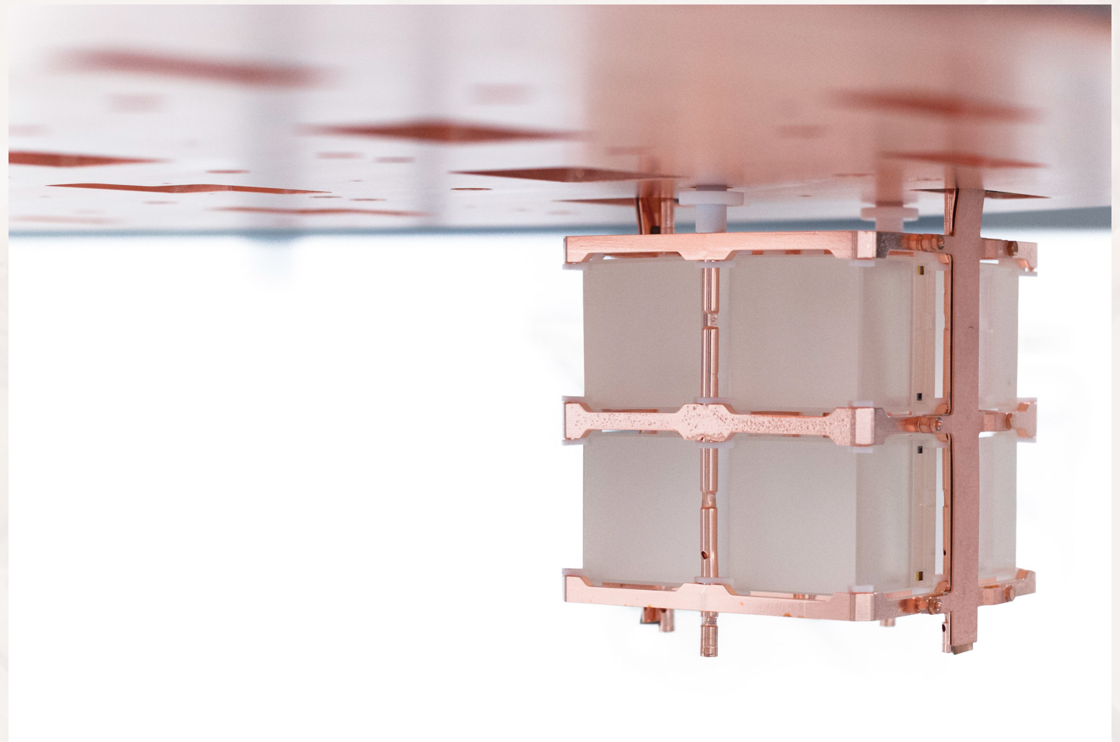


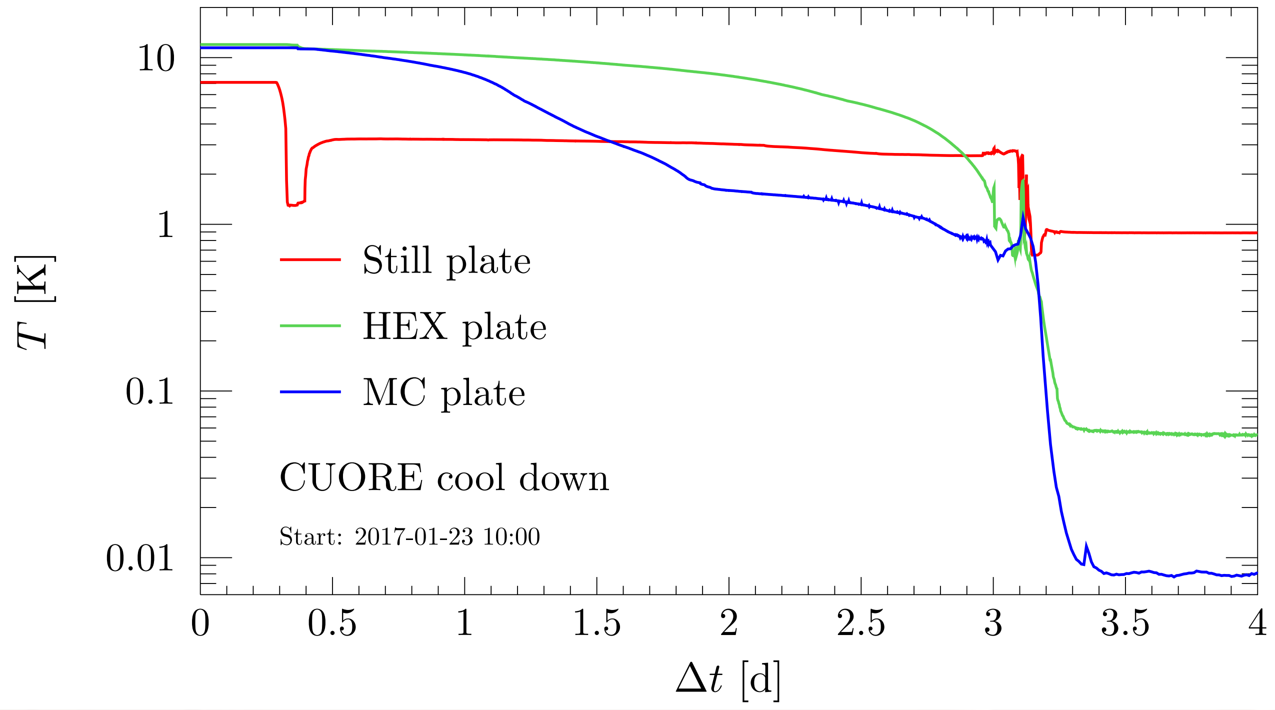
CUORE Roadmap

CUORE

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

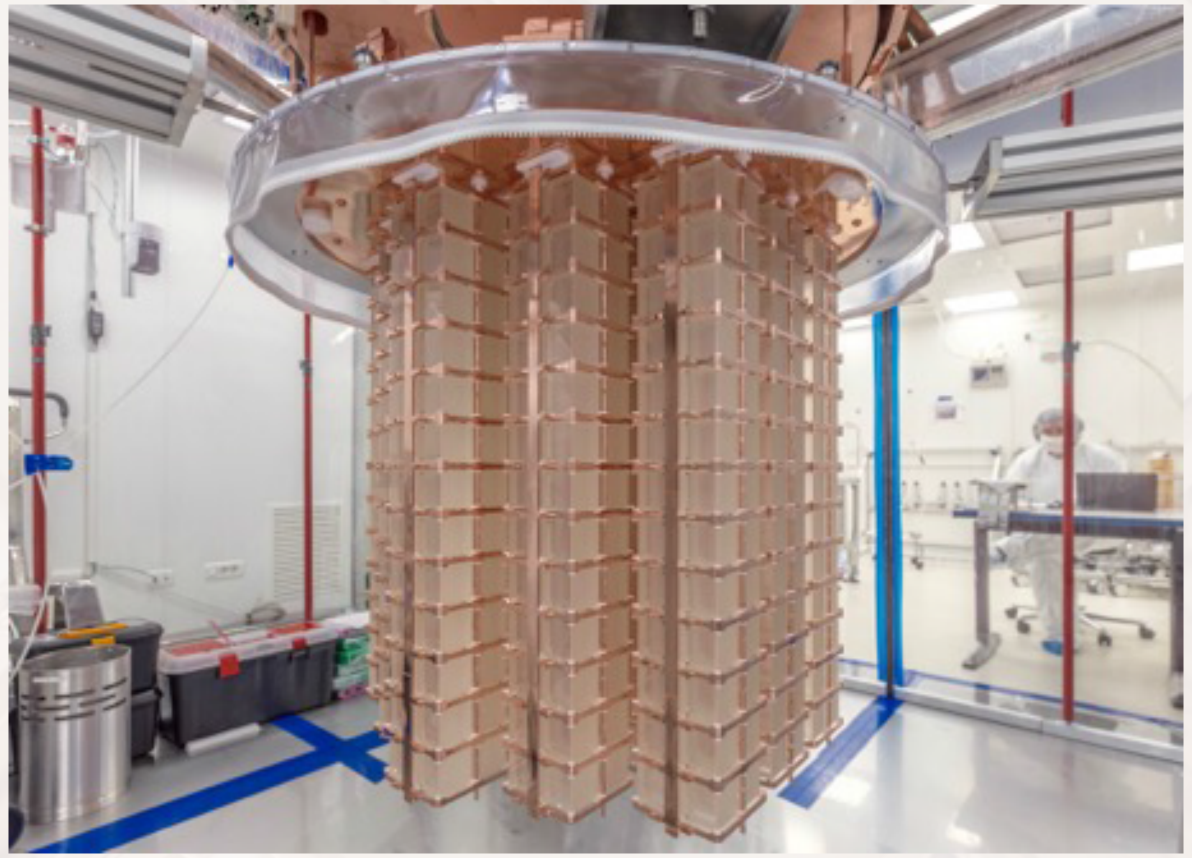


Detector Cool down
- 300 K —> 4 K in 22 days
- 4 K —> 7 mK in 3.5 days
- First pulses seen just after cool-down



Feb 2016 | Aug - Oct 2016 | Jan 2017 | Mar - Apr 2017

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



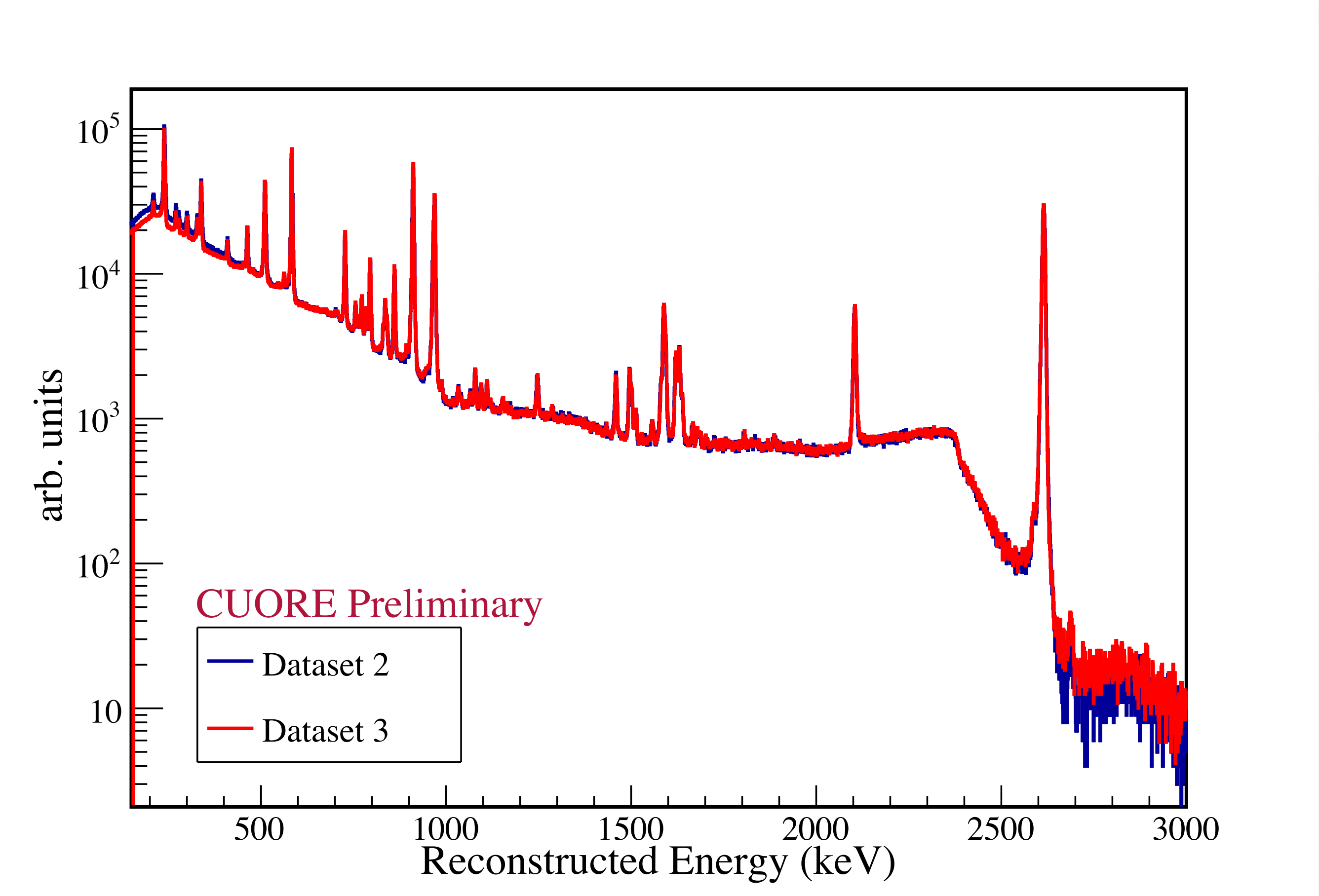
Detector pre-operation
- Optimisation of all sub-systems
- Working temperature and working point selection
- Noise reduction

CUORE Roadmap

CUORE

<u>Second period of Science Data taking</u>

- 2 Datasets
- 984/988 operational channels
- New optimised working temperature
- New working points
- PT noise reduction
- Resolution in new data unchanged
- More then doubled the statistics
- Updated physics results coming soon



<u>Third period of Science Data taking</u>

- Cool down to base temperature ongoing
- Initial calibration to begin soon
- Largely improved cryostat and detector stability
- Increased duty cycle
- Thresholds lowered with Optimum Filter-based trigger algorithm
- Refined event reconstruction algorithm to reduce correlated noise and improve energy resolution

May - Sep 2017 | Nov - Mar 2017 | Jul - Fall 2018 | Winter 2018/2019 | March 2019

<u>First period of Science Data taking</u>

- 2 Datasets
- 984/988 operational channels
- 86.3 kg*y exposure
- Most sensitive search for 0νββ in ^{130}Te to date

<u>Partial warm up</u>

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

<u>Warm up and major maintenance</u>

- Warmed up to 100 K
- Cleaned ^{3}He-^{4}He line from air that prevented stable circulation
- Improved mixture circuit to reduce leaks and increase long term stability
- Added external calibration system to reduce dead time due to strings deployment
- Fixed leaking pulse tubes to reestablish redundancy
- Ordinary maintenance of pumps

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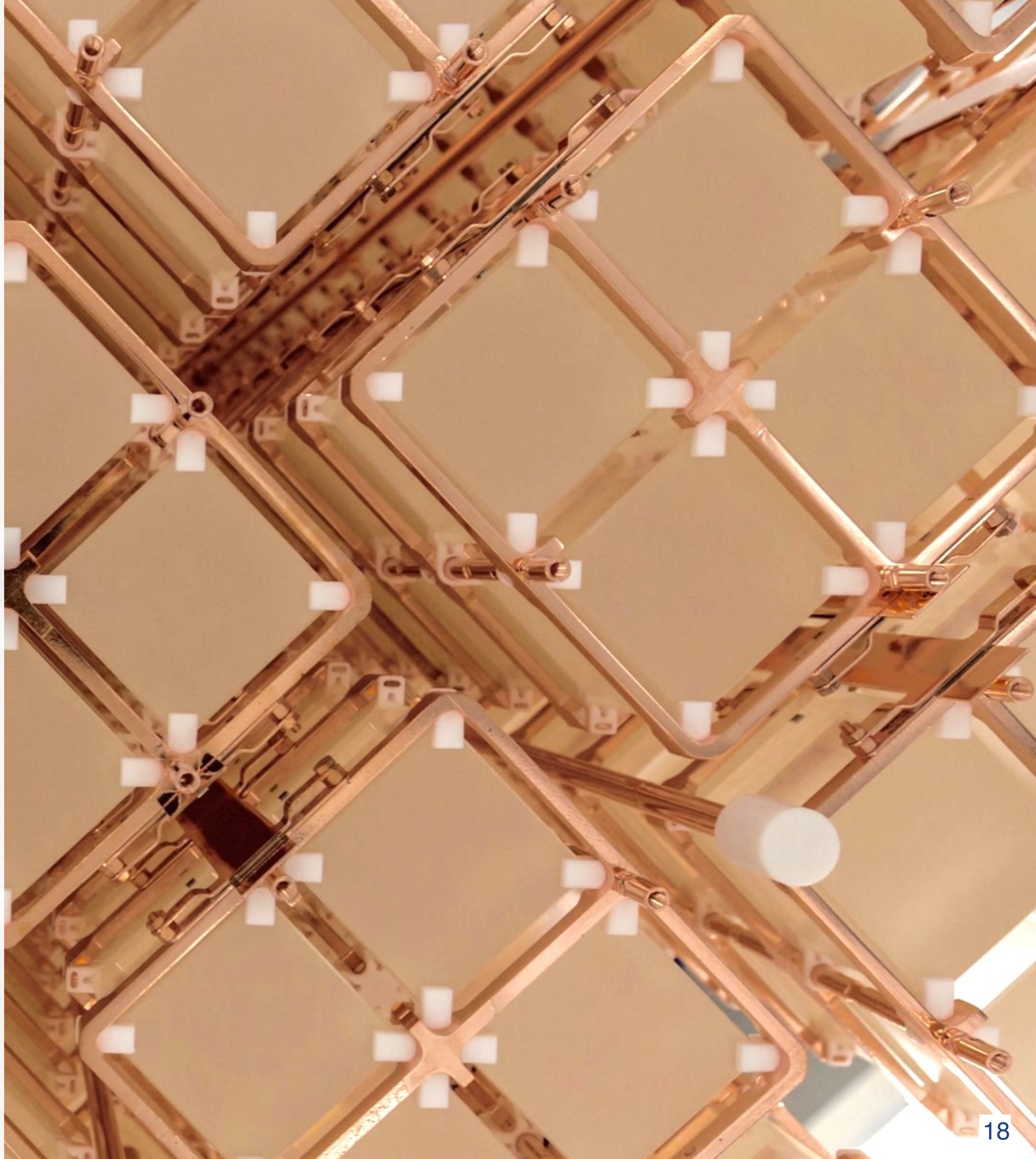
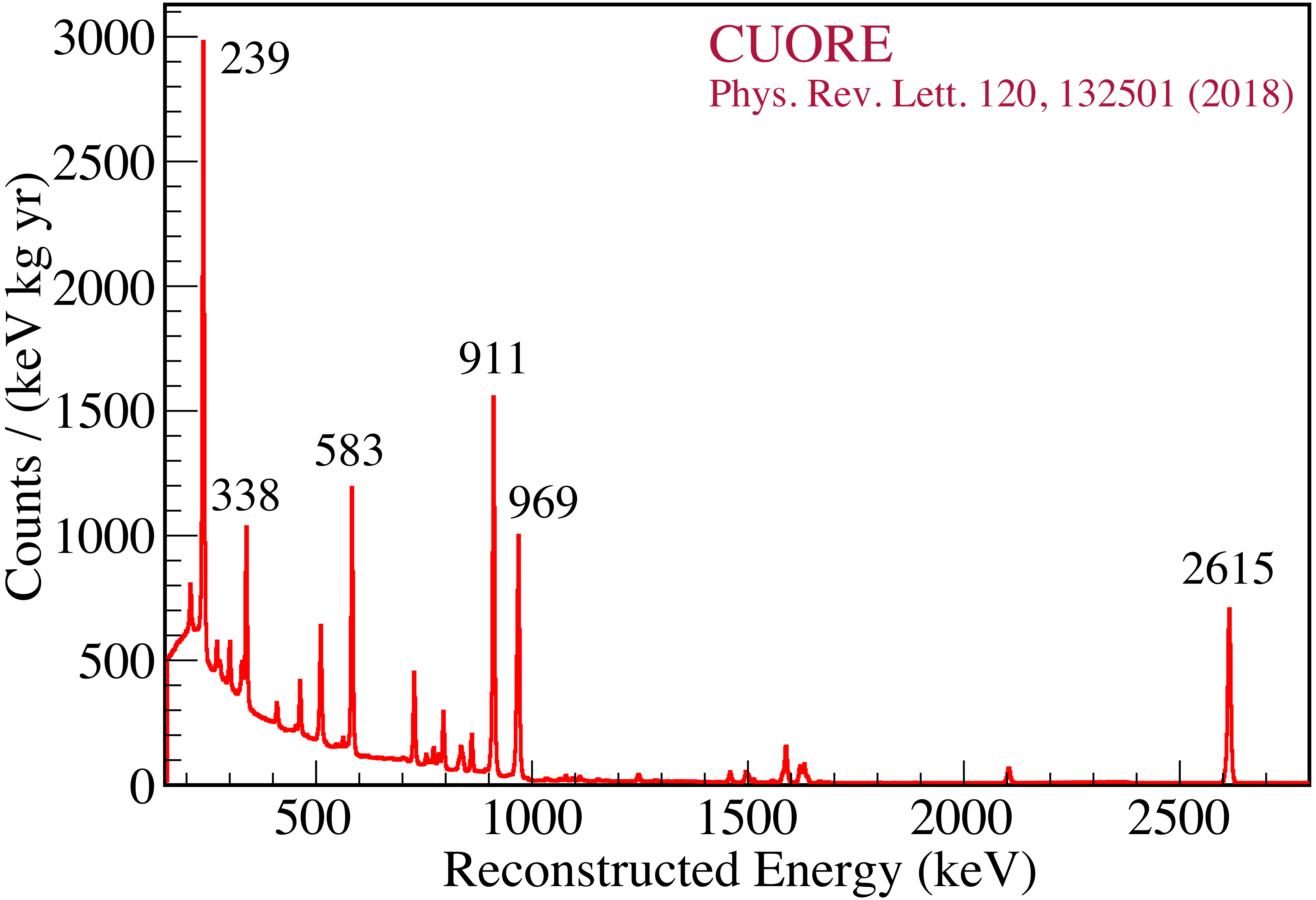


Calibration spectrum

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

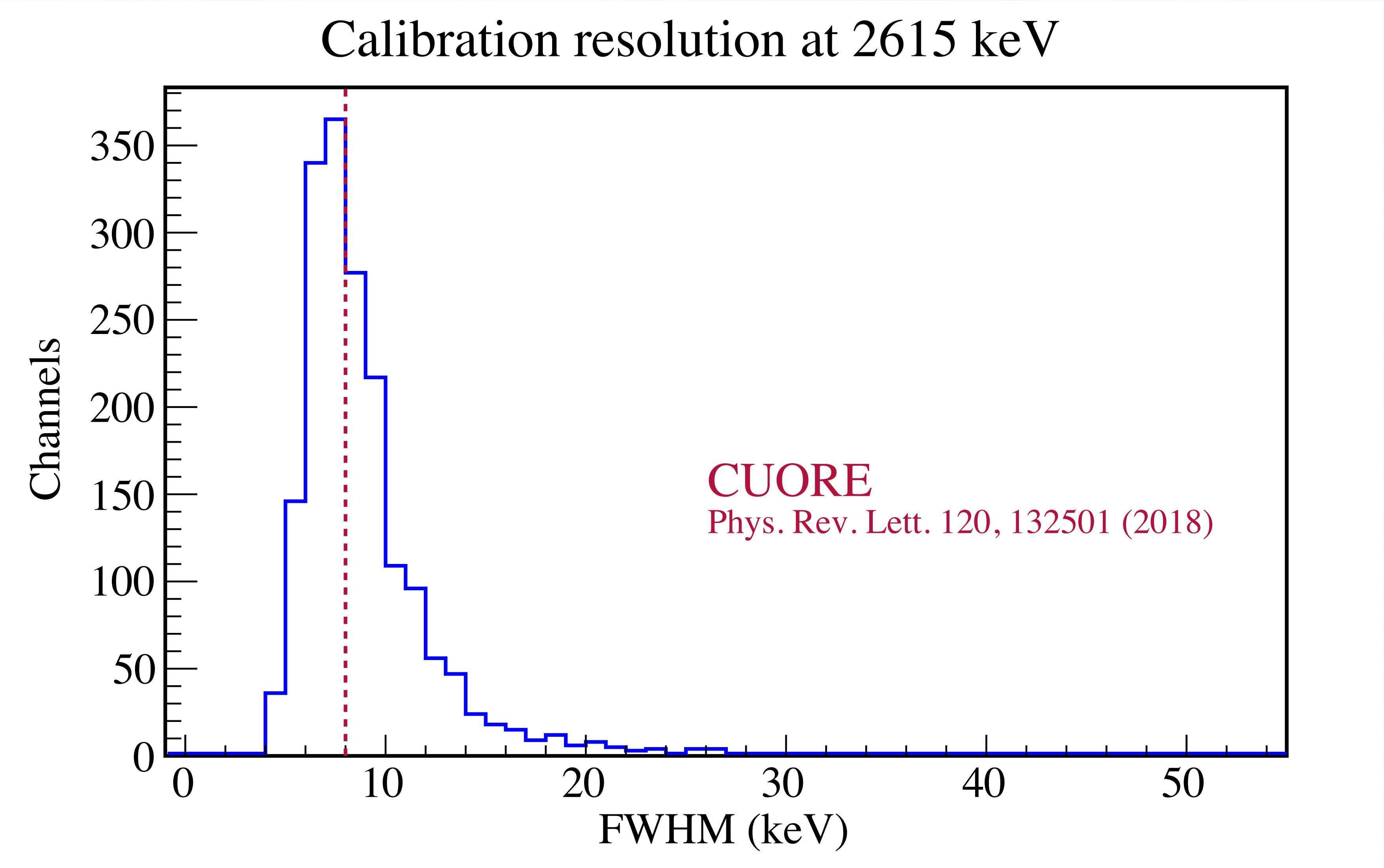
239 keV - ^{212}Pb
338, 911, 969 keV - ^{228}Ac
583, 2615 keV - ^{208}Tl

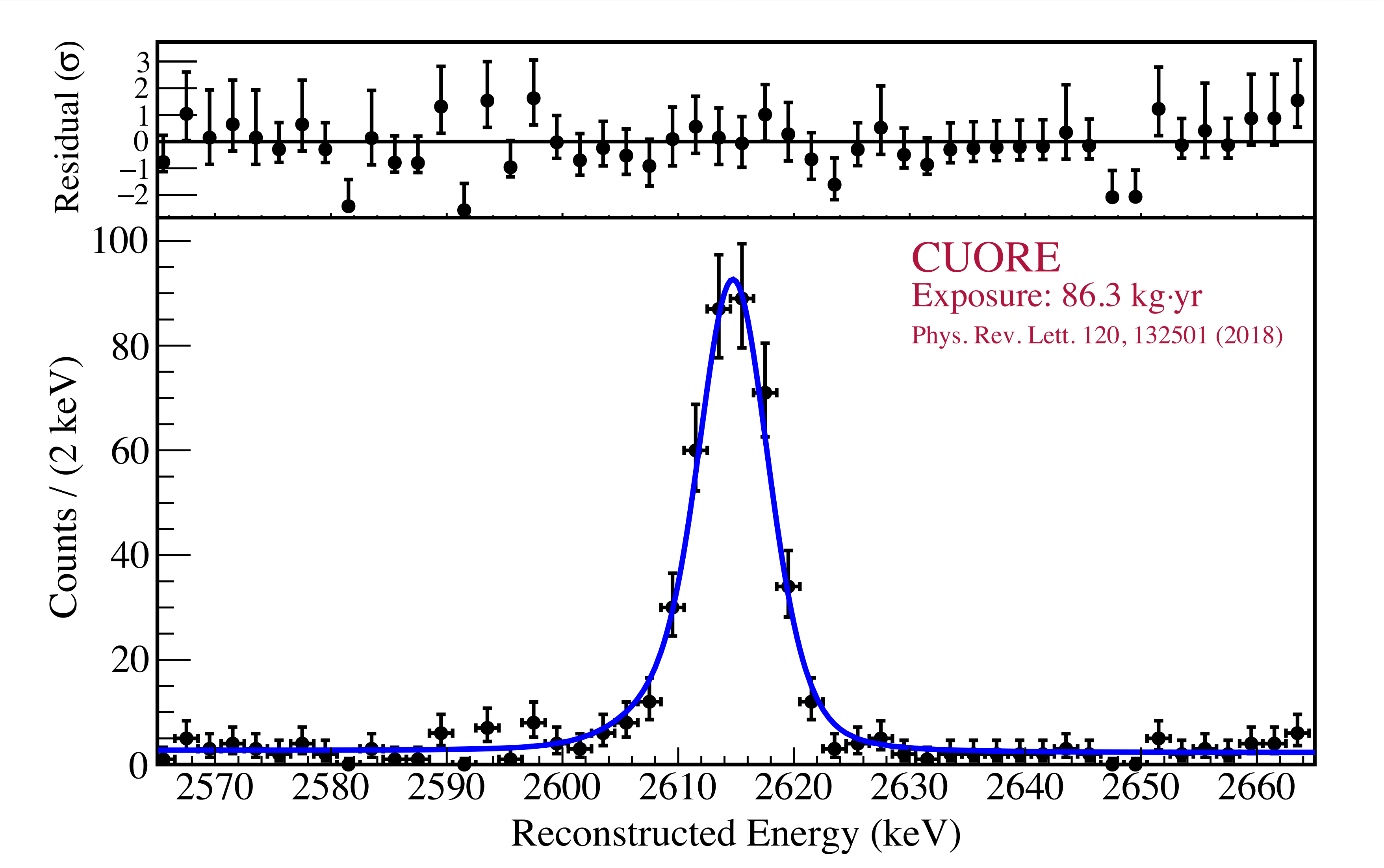


Energy resolution

@ 2615 keV
ds3018: 9.0 keV FWHM
ds3021: 7.4 keV FWHM
effective (exposure-weighted):
8.0 keV FWHM

@ 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

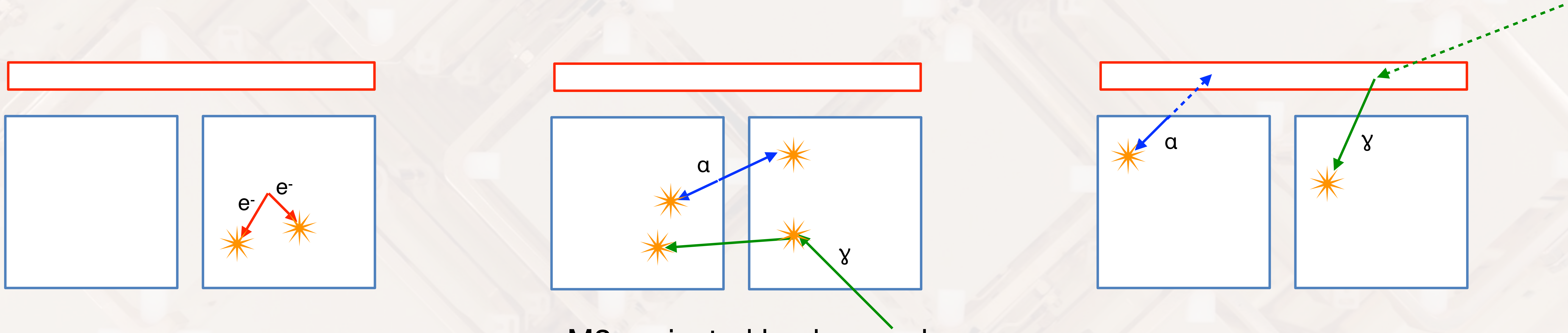




Event selection

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 - 0νββ/2νββ 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

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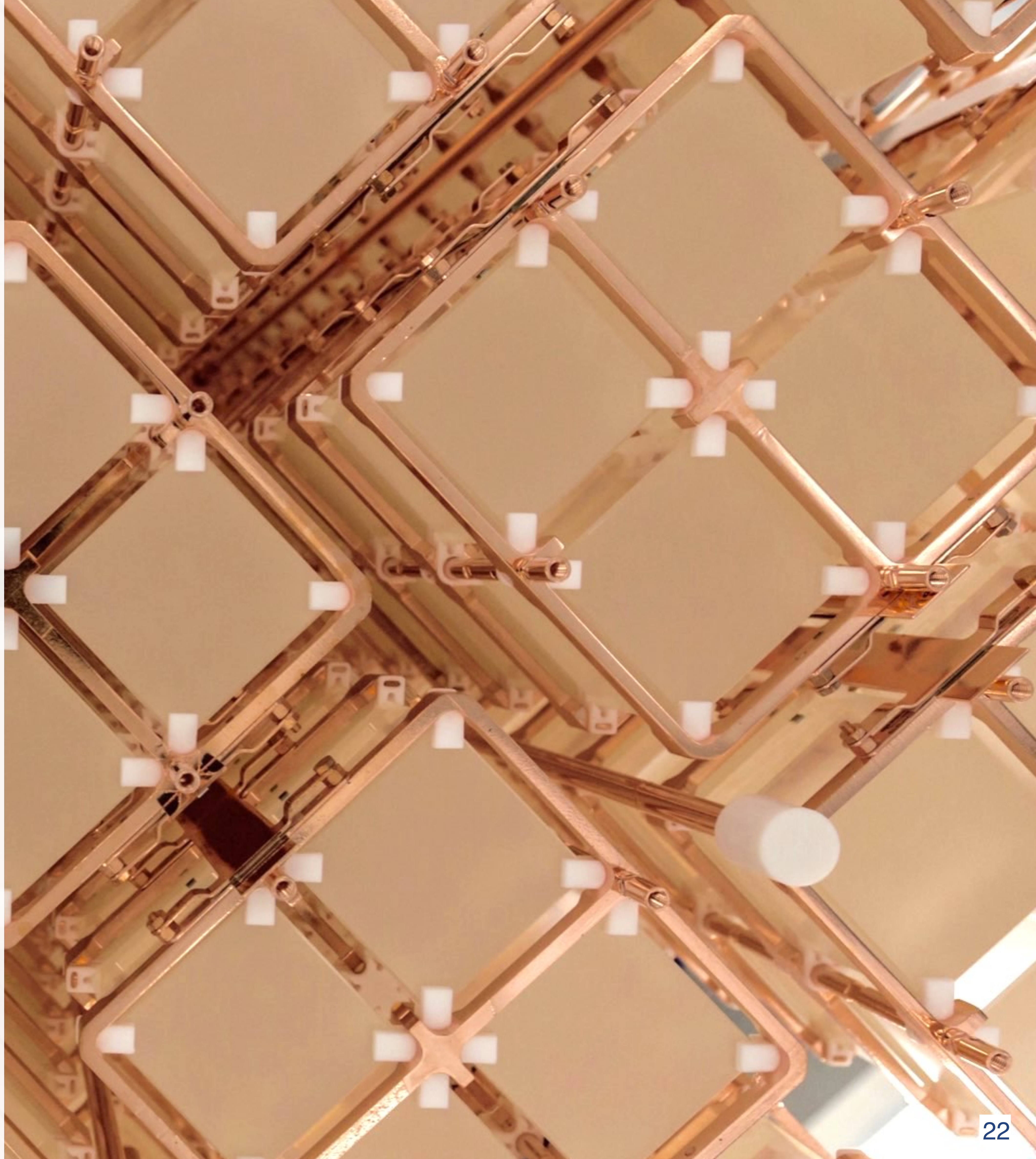


Fit in the 0vDBD ROI

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

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

(83.0 ± 2.6)% - ds3021

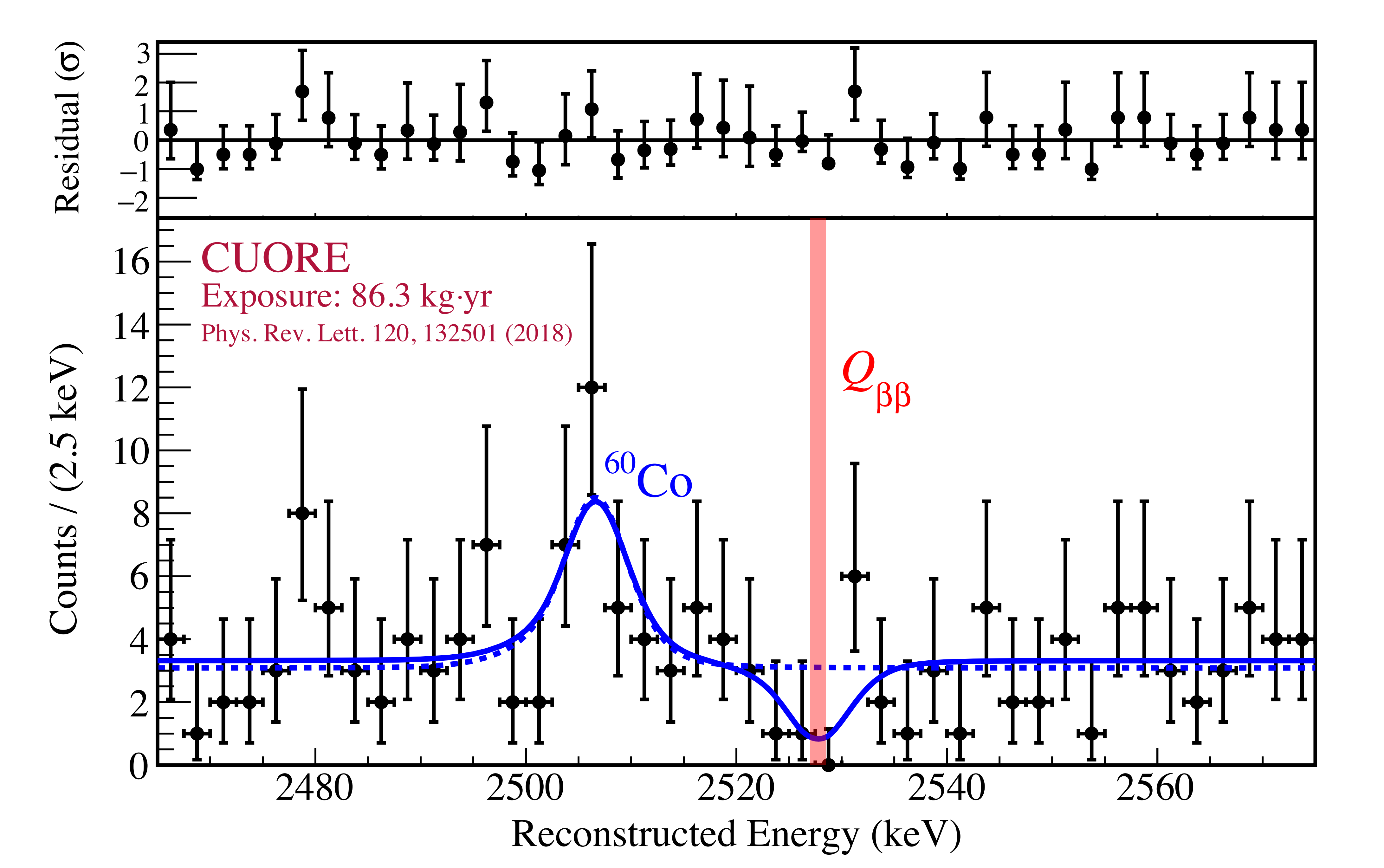
Events in the region of interest: **155**

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)

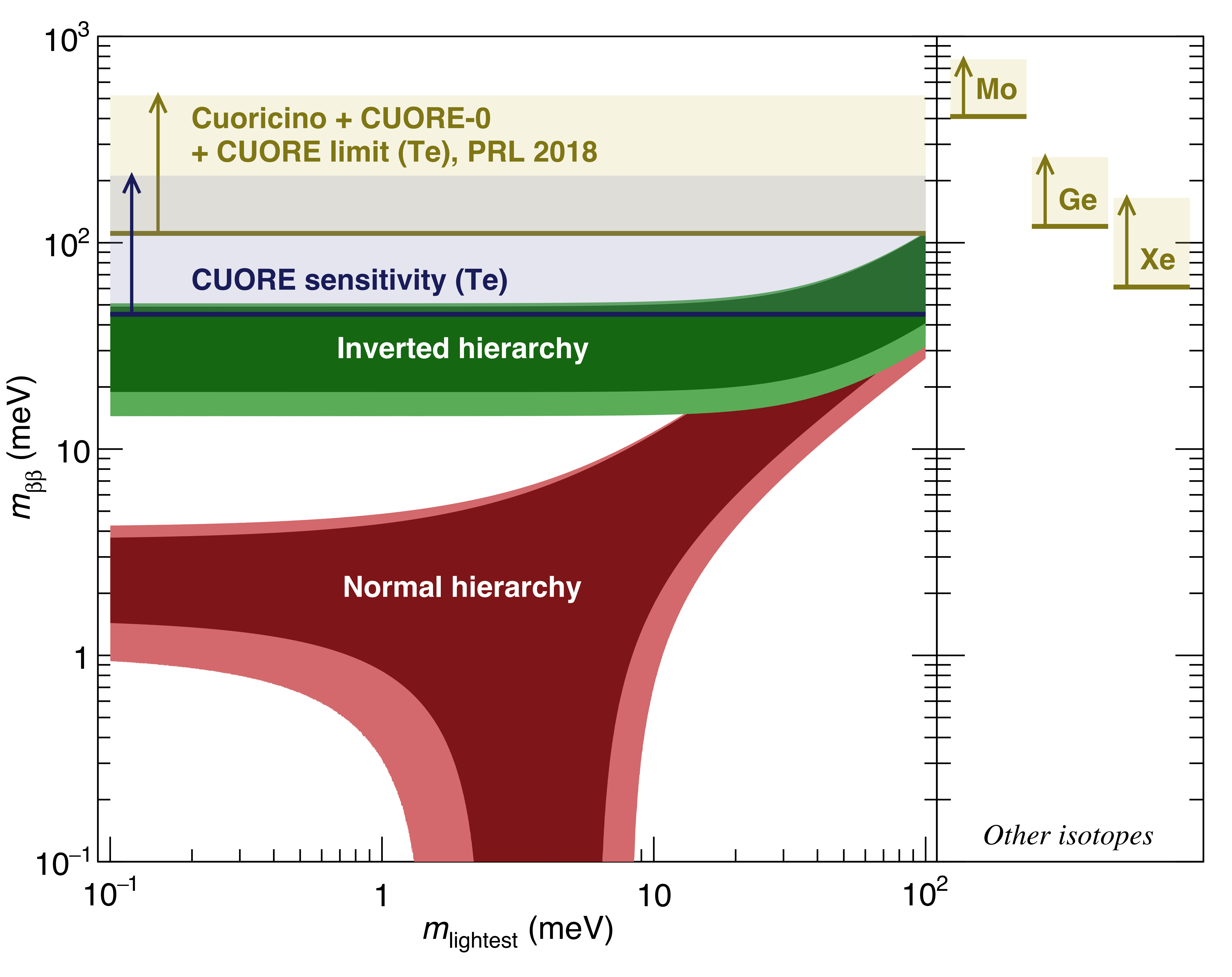
Combination with previous 0vDBD results

- 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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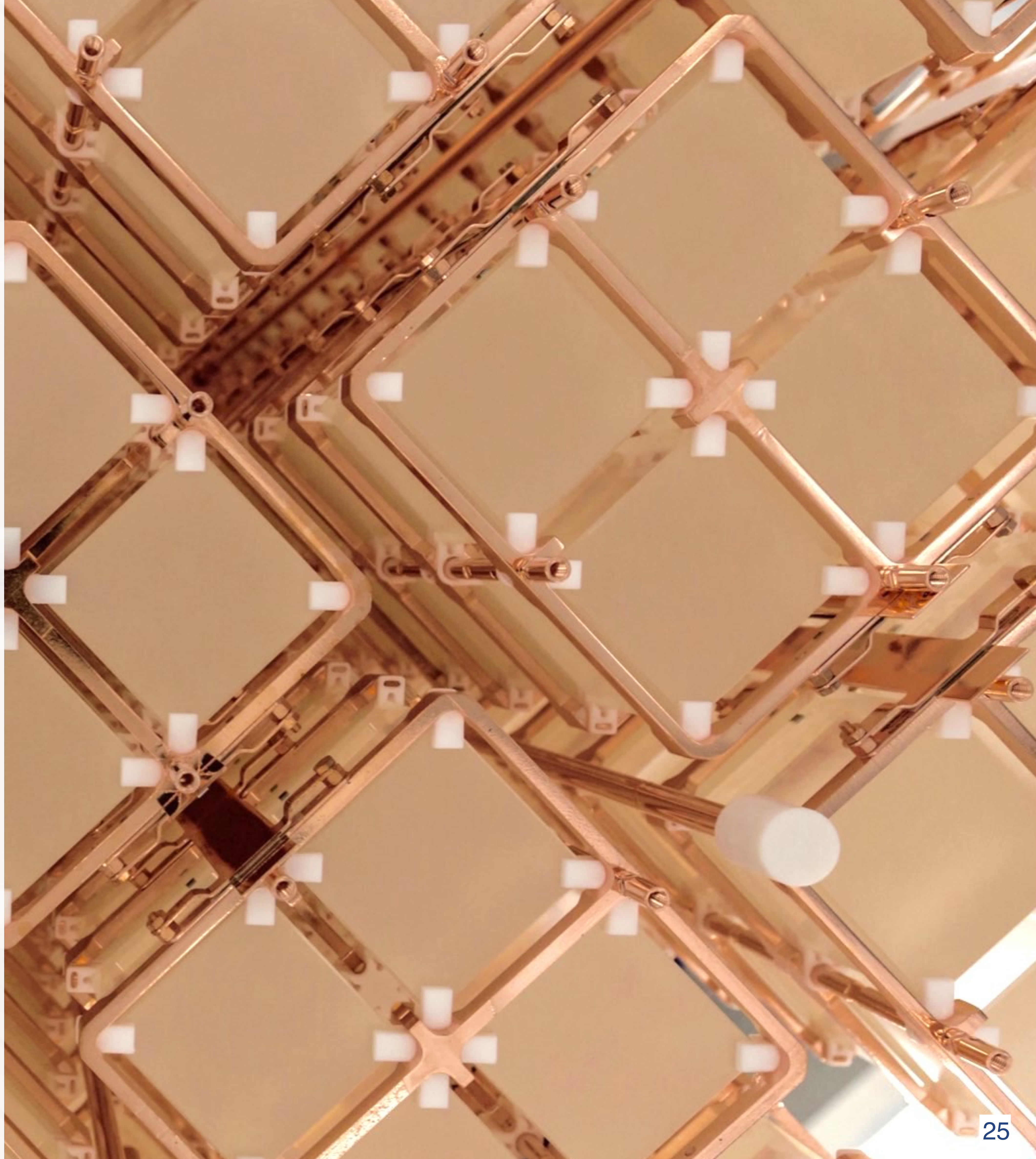
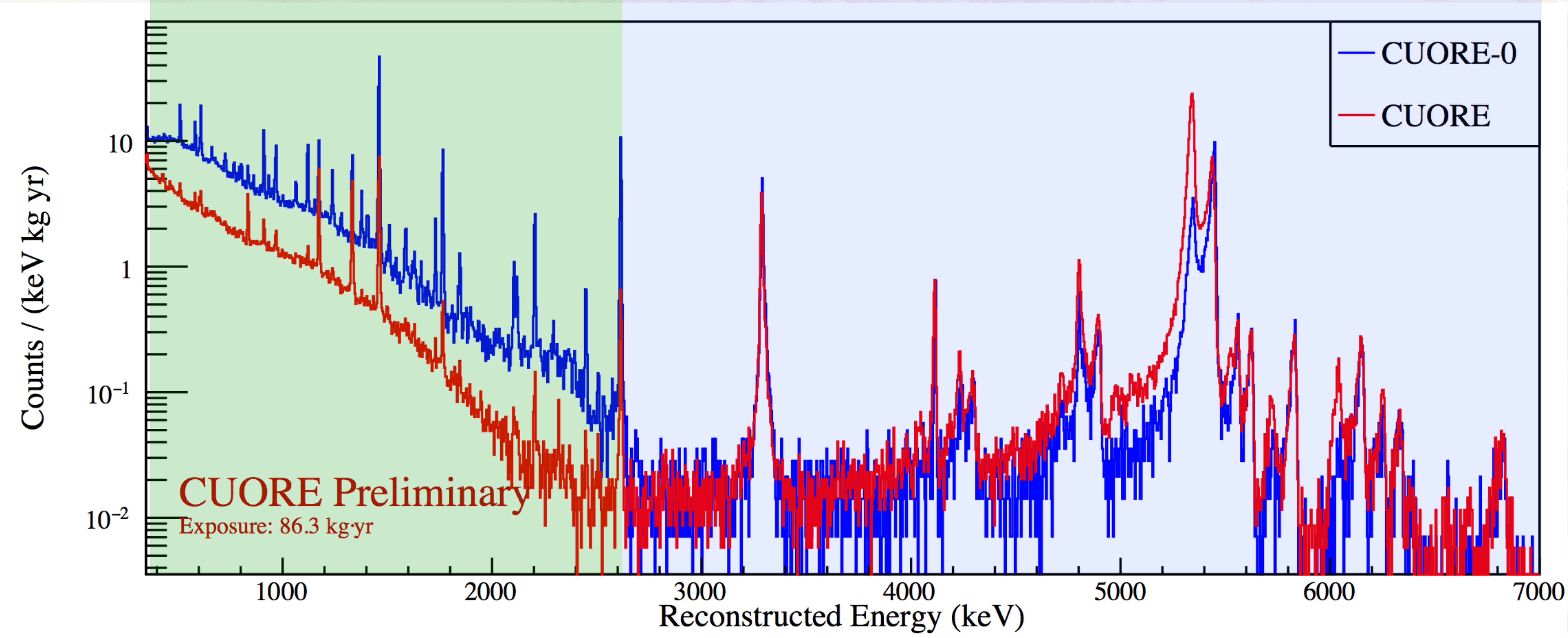


CUORE Background Model

CUORE

ɣ background significantly reduced

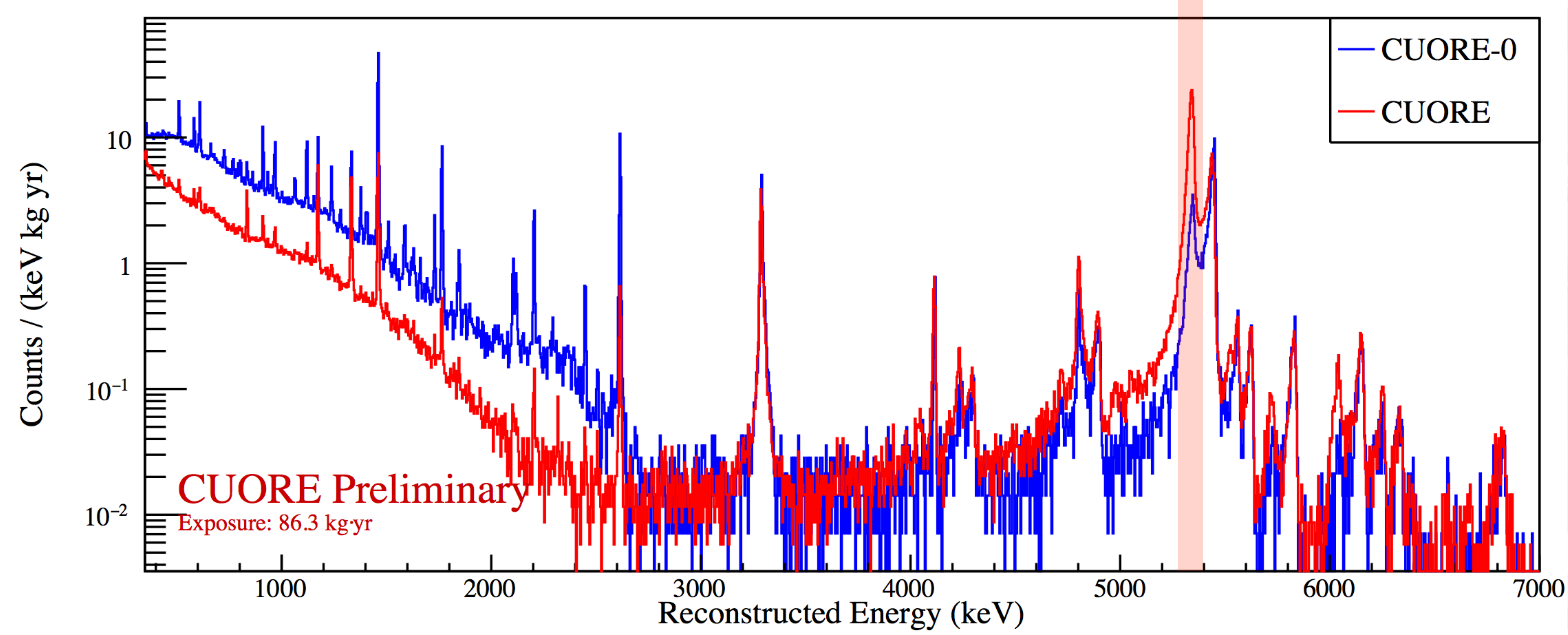
α background mostly consistent with CUORE-0 (as expected)



CUORE Background Model

^{210}Po excess still under investigation:

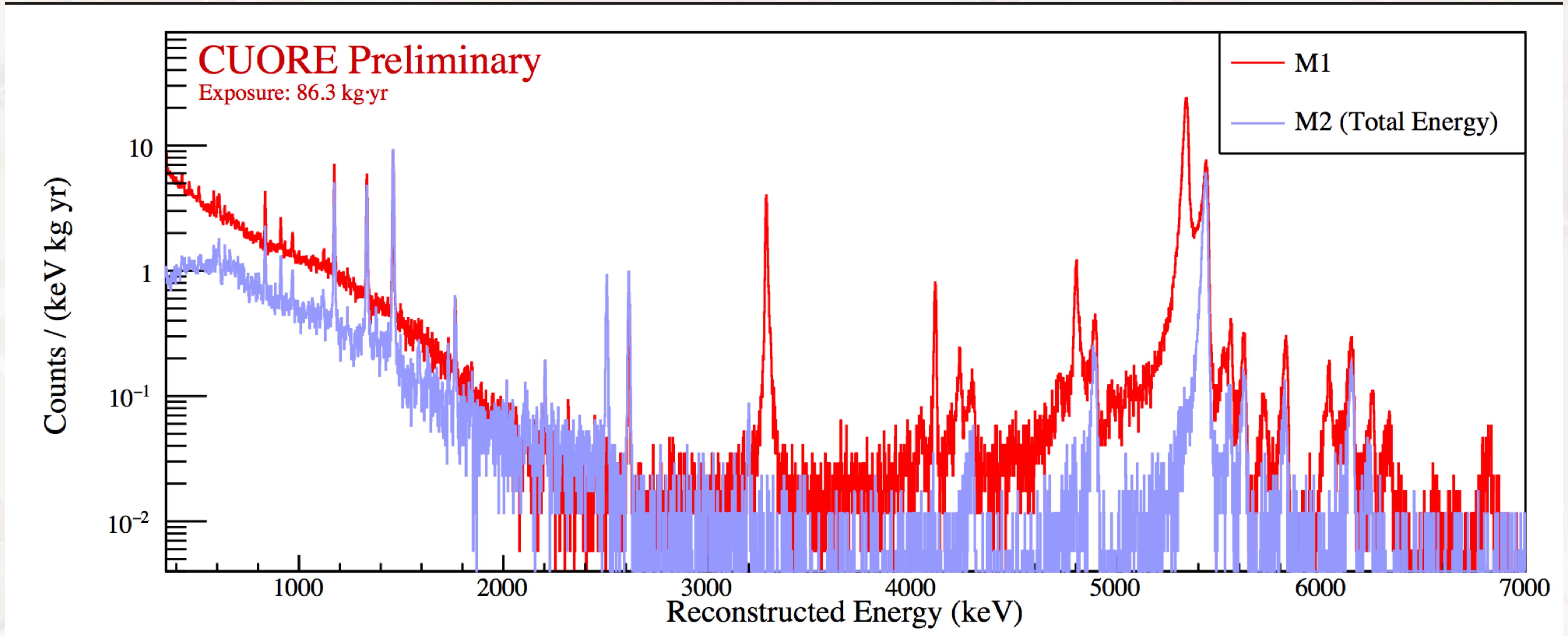
- appears to be from surface contamination in copper around the detector
- estimated contribution to ROI ~ 10^{-4} ckky (~1%)

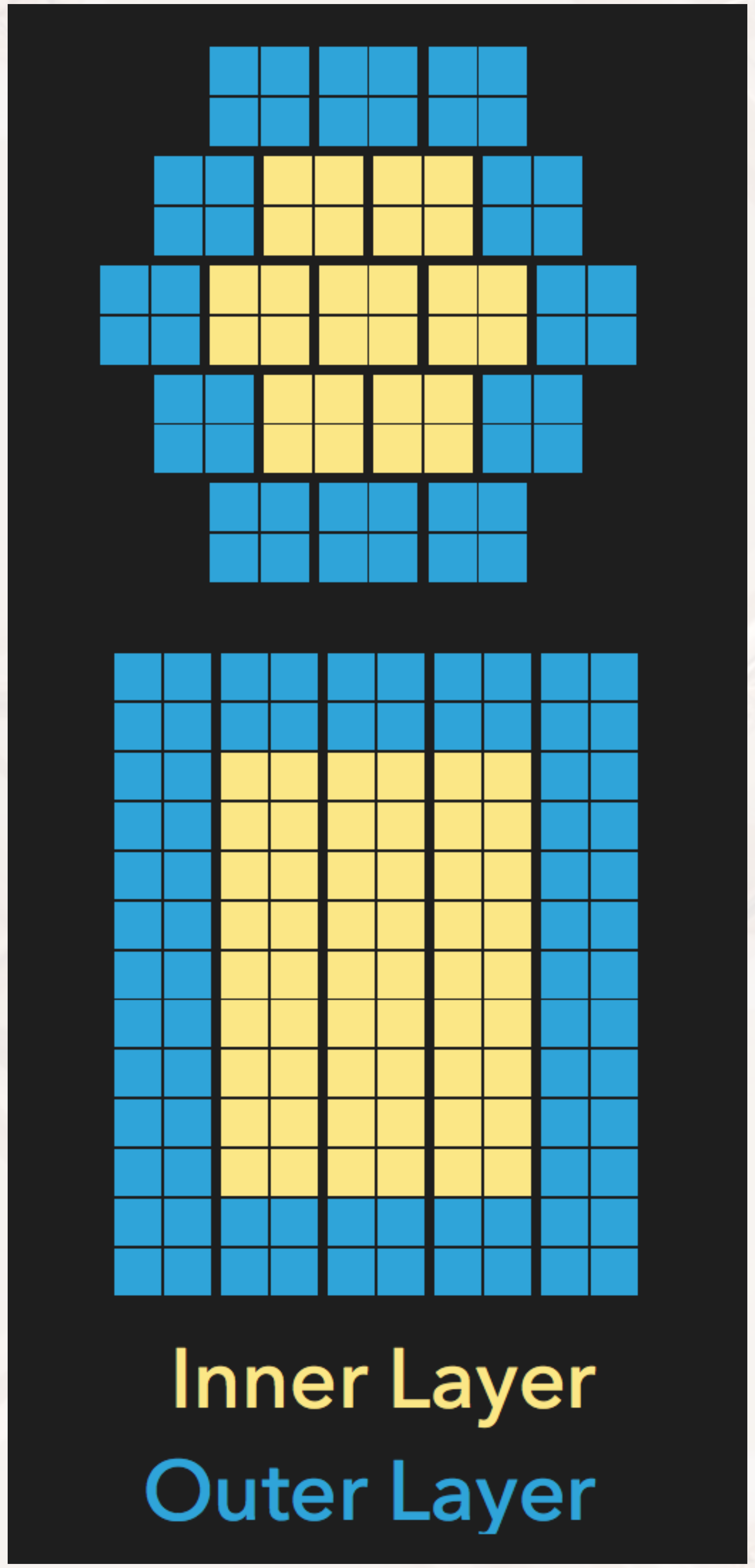


CUORE Background Model

DATA

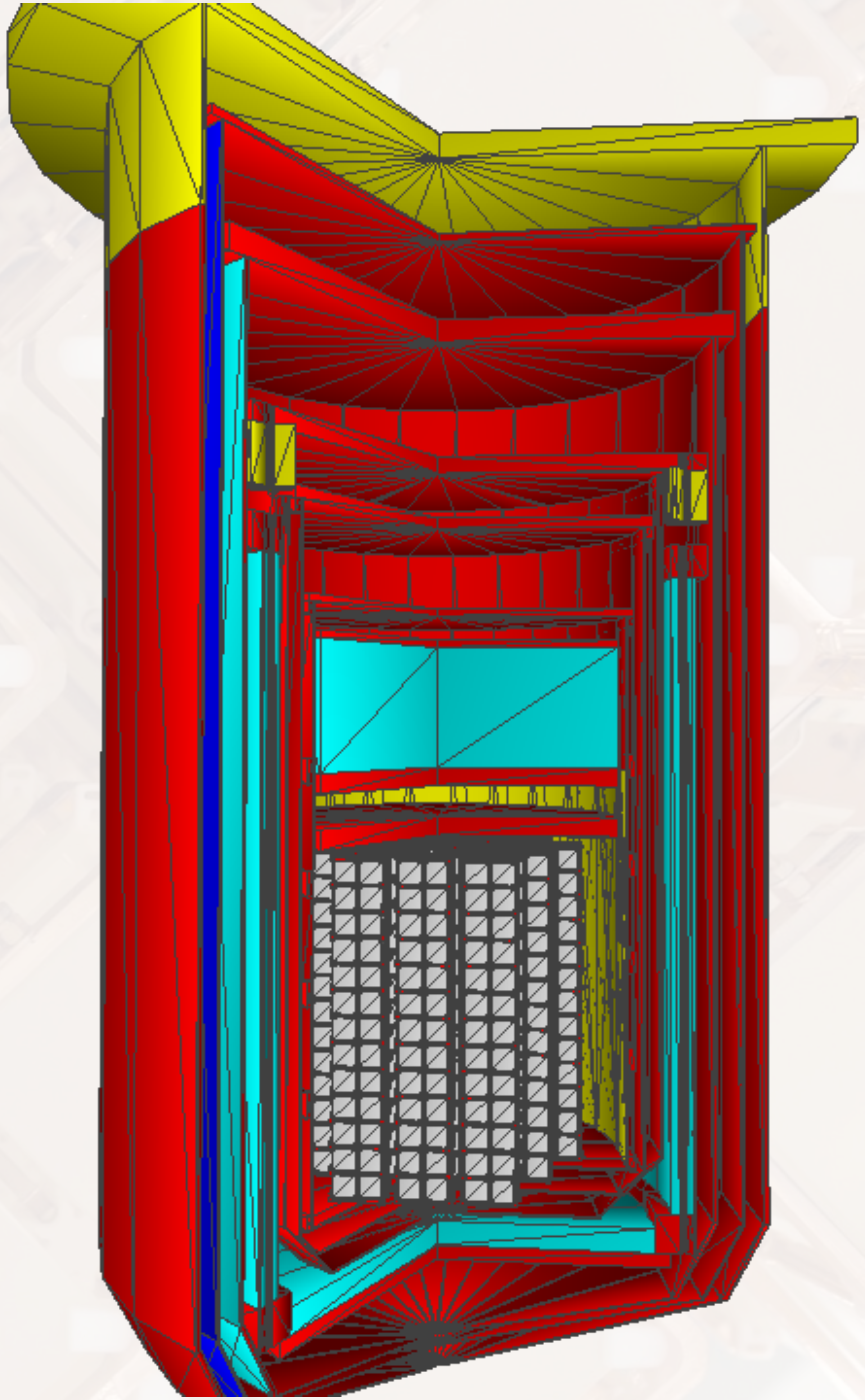
- 86.3 kg yr of TeO_2, same data used for 0vDBD analysis
- split data into inner and outer (2 crystals thick) layers
  - outer layers more sensitive to external backgrounds
- split data into Multiplicity 1, Multiplicity 2 and Multiplicity 2 Sum
  - different multiplicities are sensitive to different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

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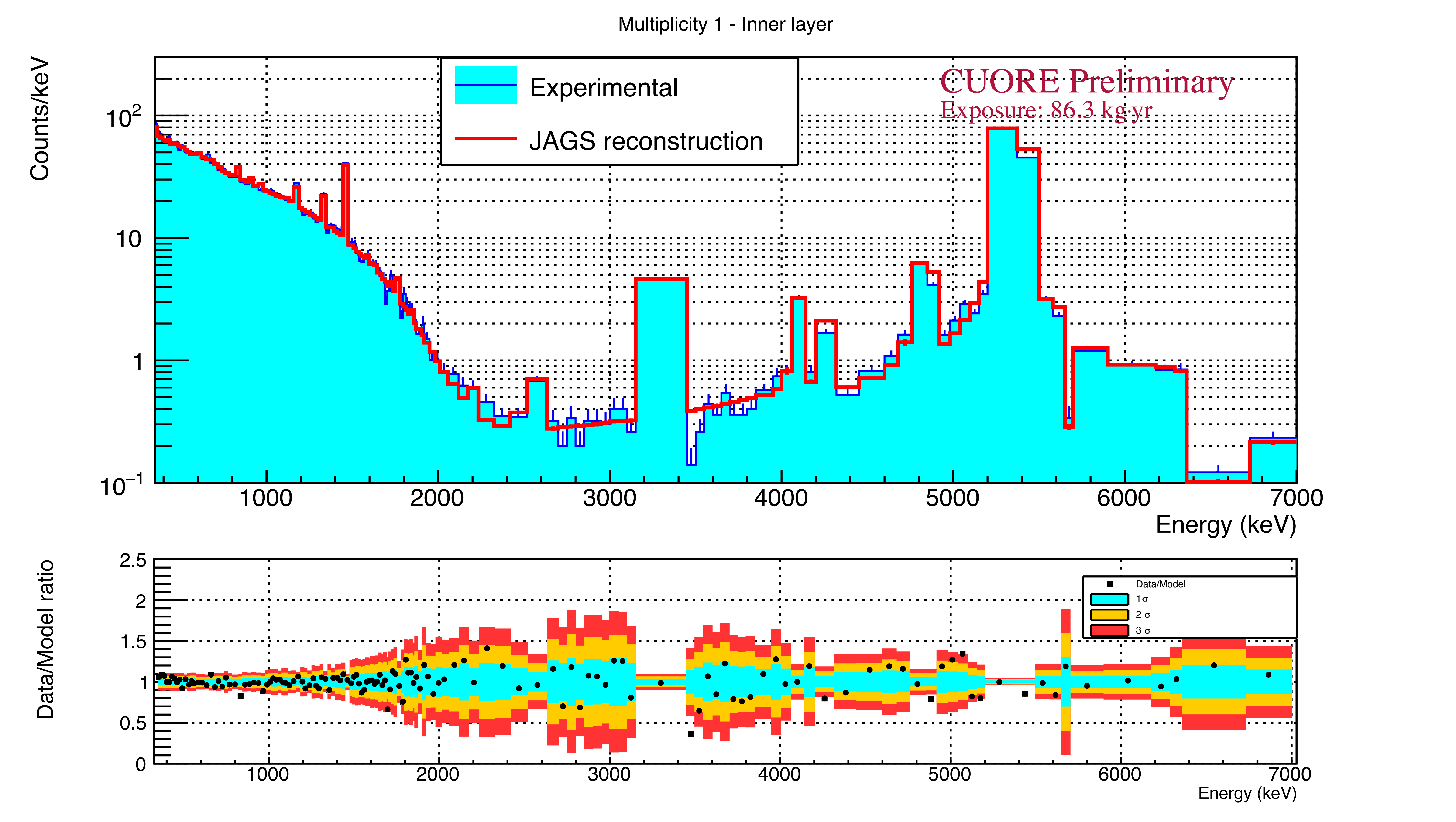

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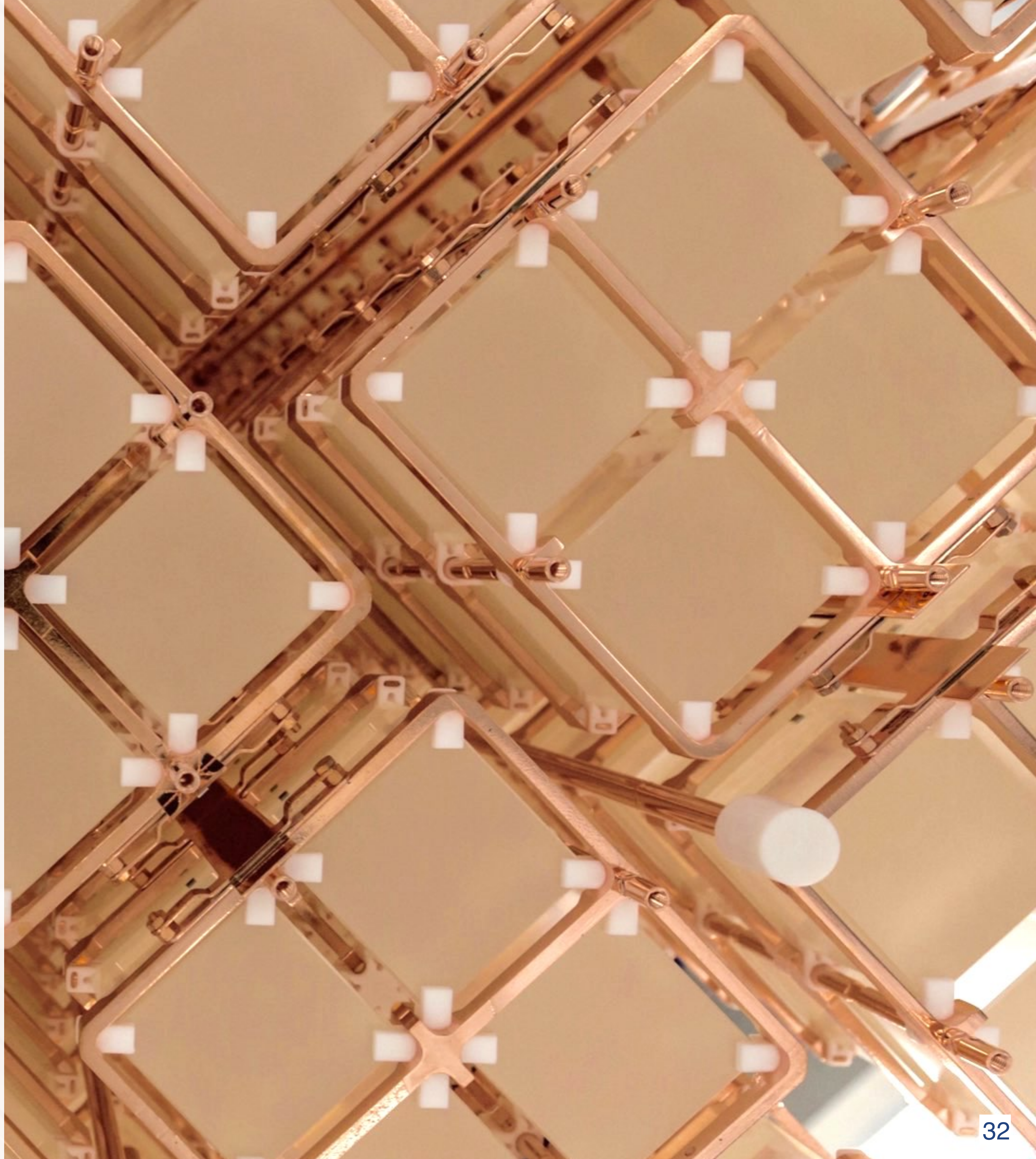
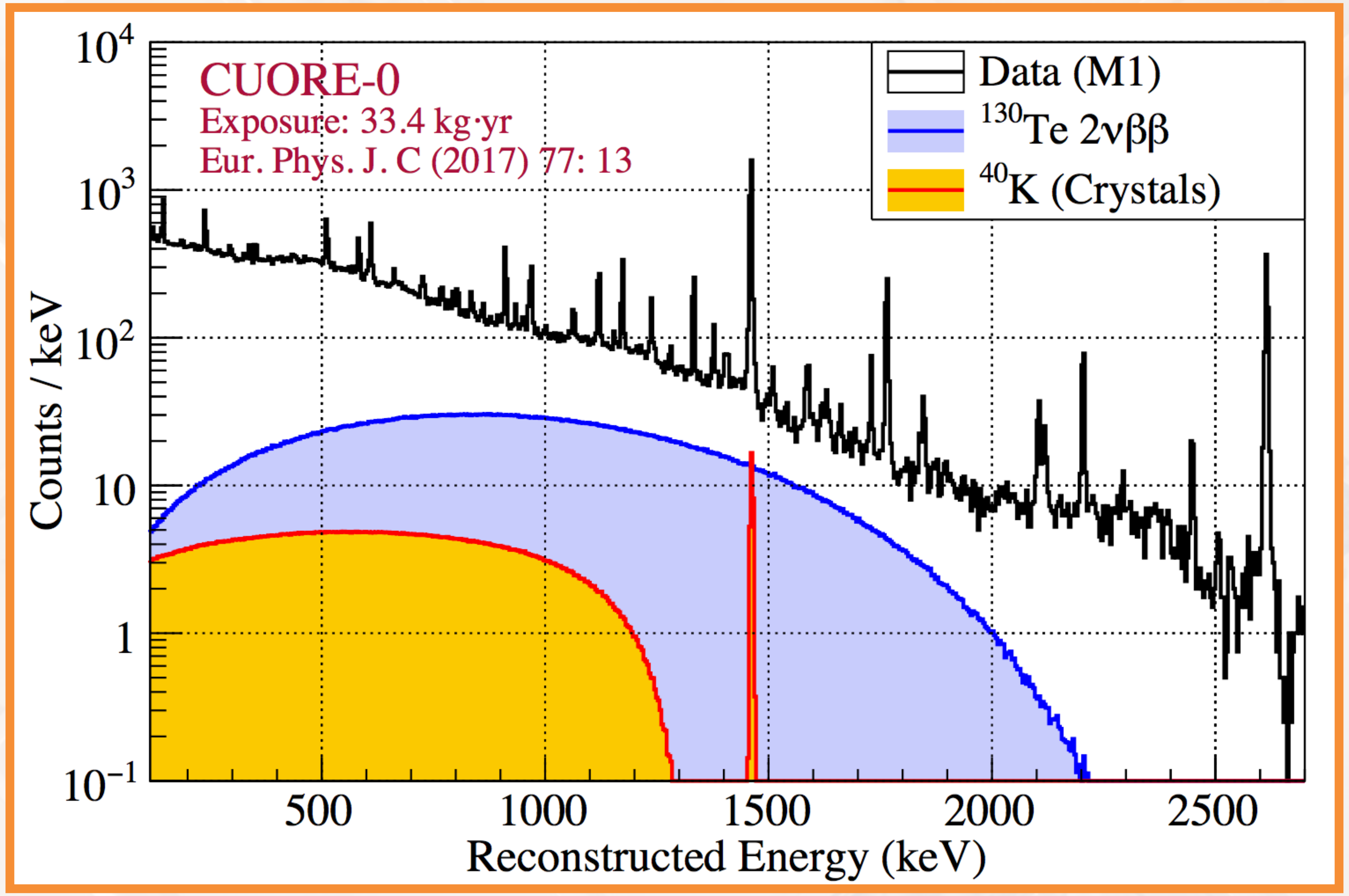
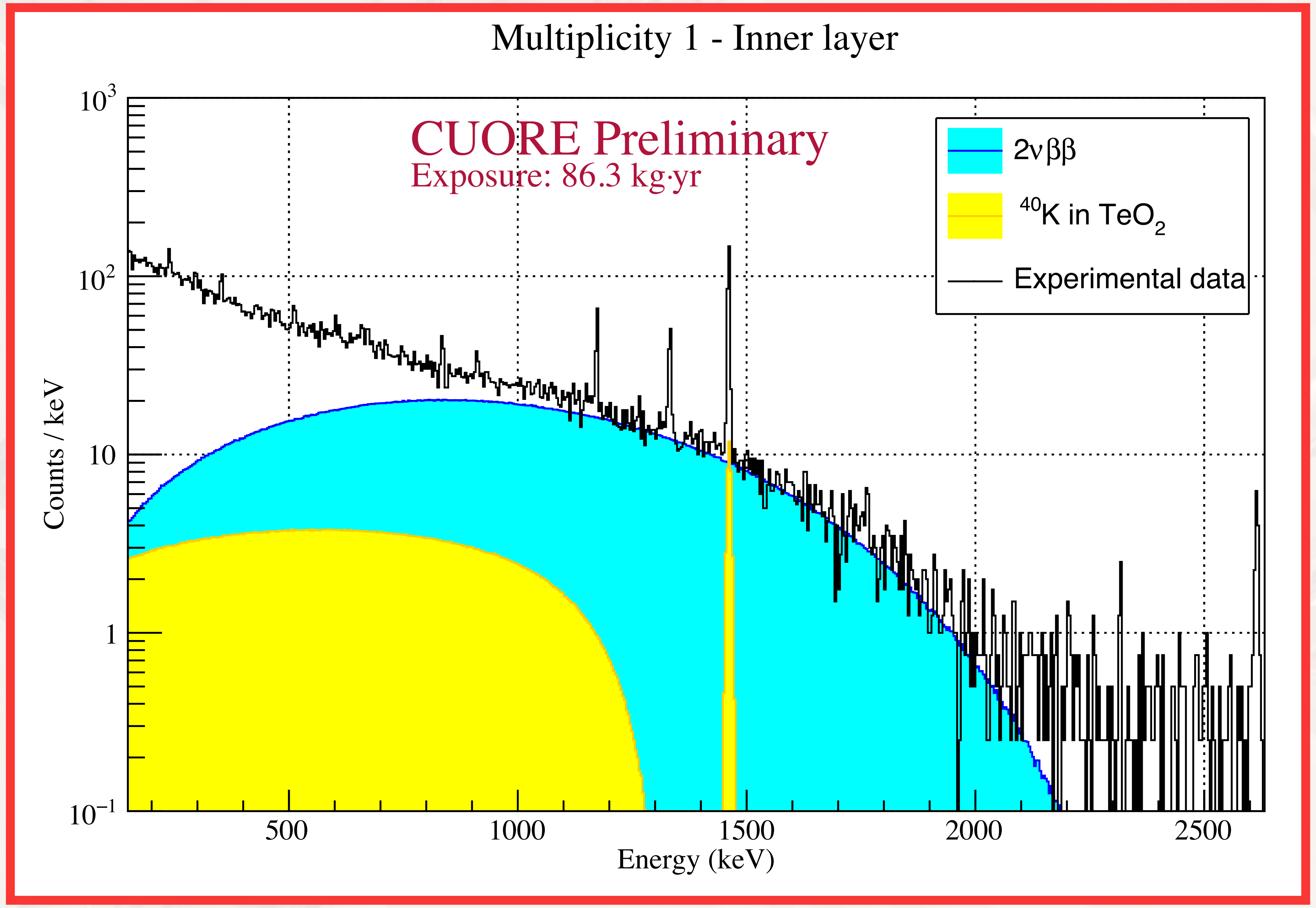
- CUORE roadmap
- Analysis procedures
  - Calibration and detector response
  - Event selection and topology
- Physics results
  - 0νββ and lepton number violation
  - background model
  - 2νββ
- Conclusions and outlook



2vDBD

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





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

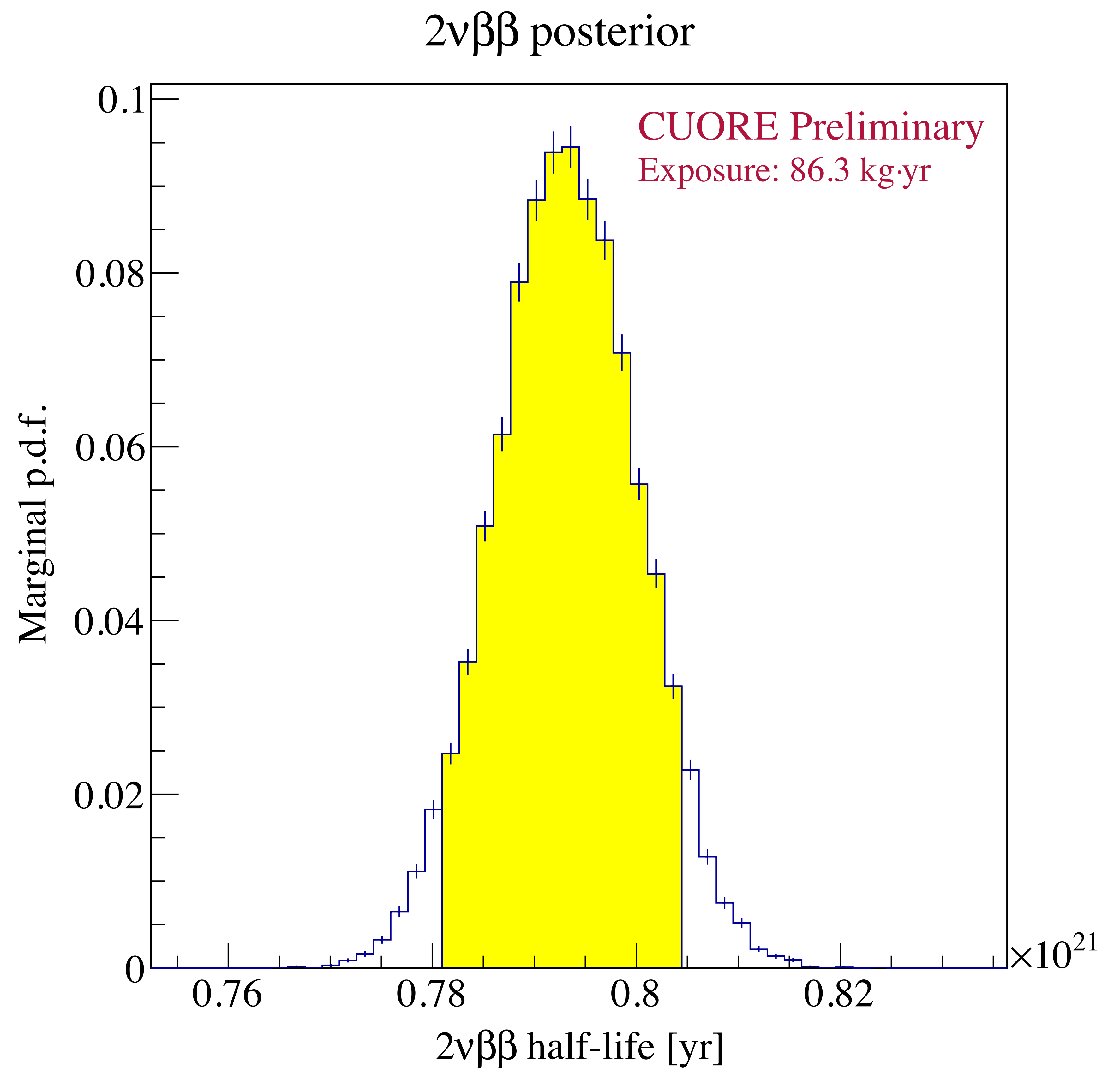
- lower background
- self-shielding
- anti-coincidence efficiency

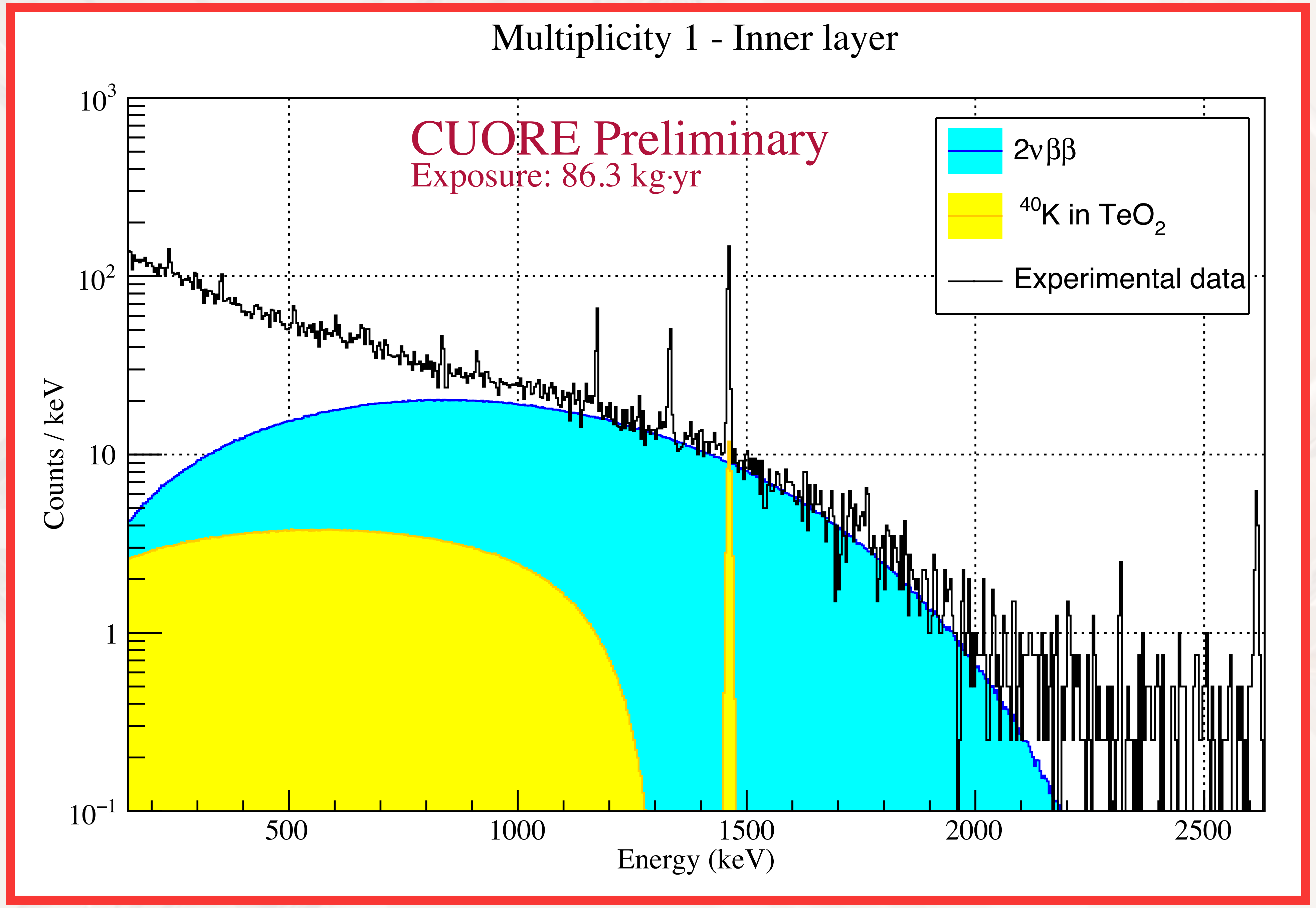
CUORE:
~ 100% of counts in 1-2 MeV region

2vDBD

CUORE

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





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

2vDBD

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

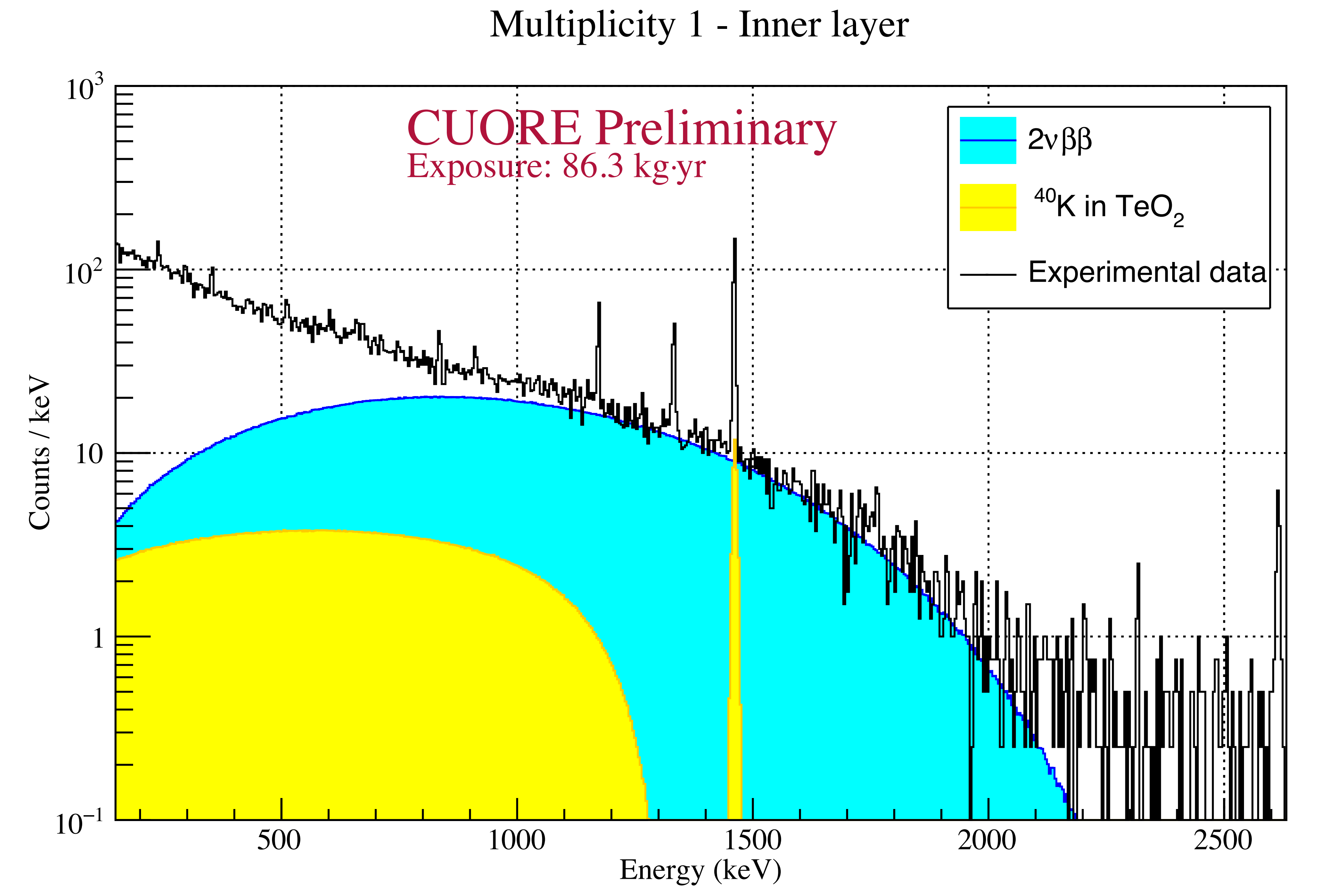
$$\Gamma^{2\nu}_{1/2} = [8.7 \pm 0.1(\text{stat.}) \pm 0.2(\text{syst.})] \times 10^{-22}\text{yr}^{-1}$$

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

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

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

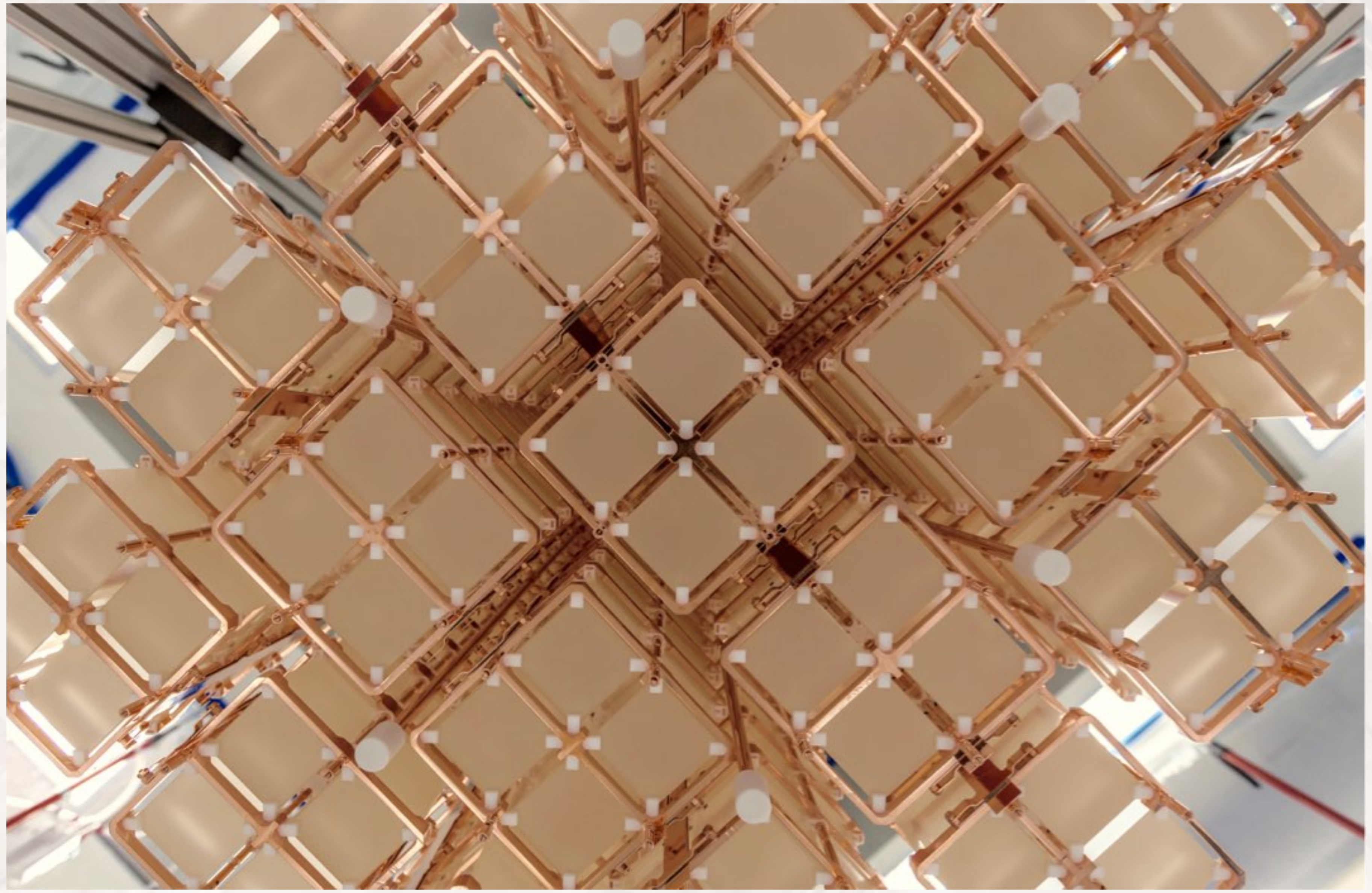
- Systematic uncertainty dominated by uncertainty on contaminant location and uniformity
  - studied by repeating the fit with different geometric splitting of the data
  - more data —> finer geometric splitting of the array —> reduce this component
- Fit is independent of energy threshold over the range 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
  - $\beta\beta$ 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
- Data release and physics results with more then doubled statistics coming soon