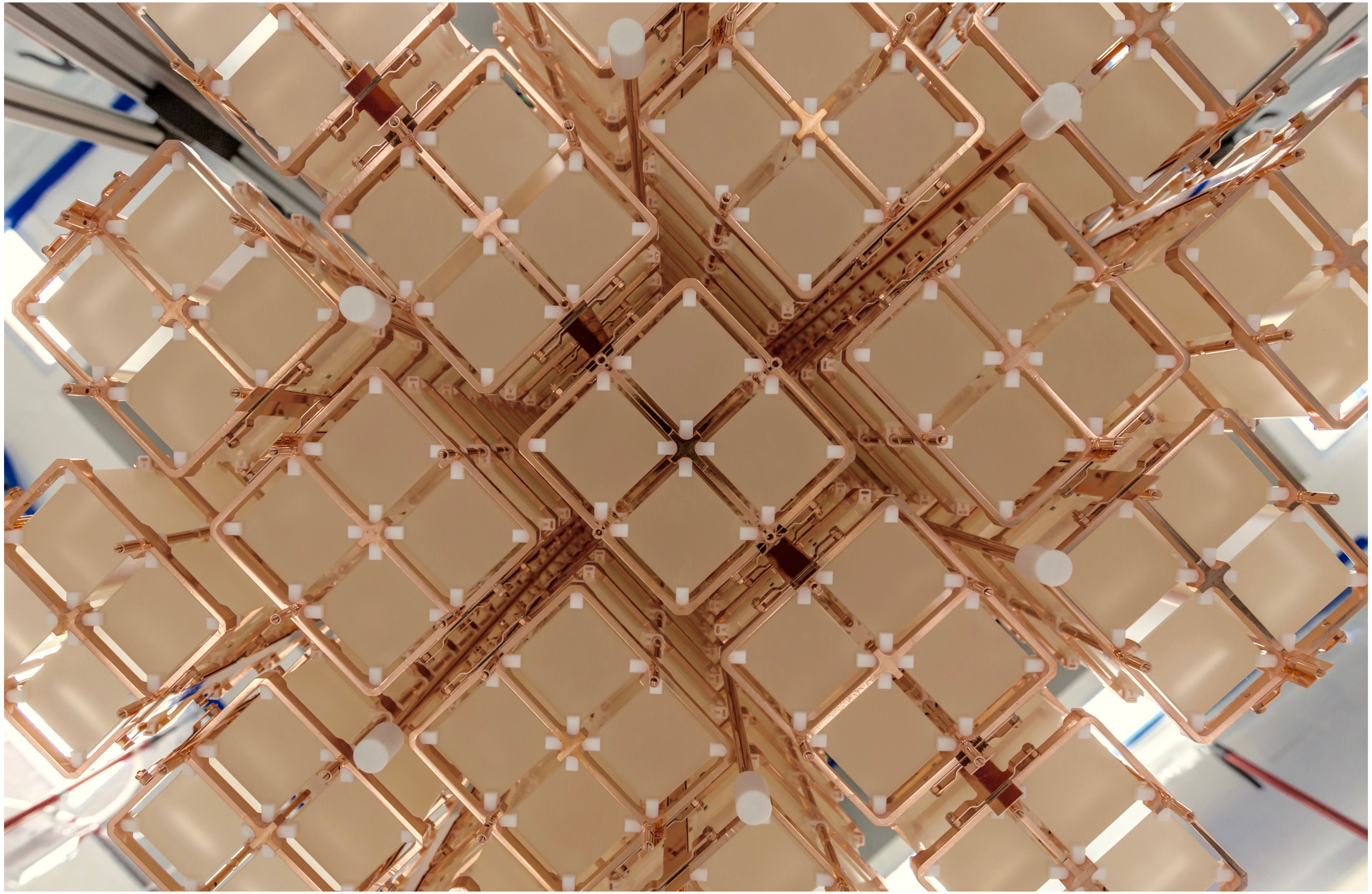


CUORE latest results and prospects

Carlo Bucci on behalf of the CUORE collaboration
INFN - LNGS

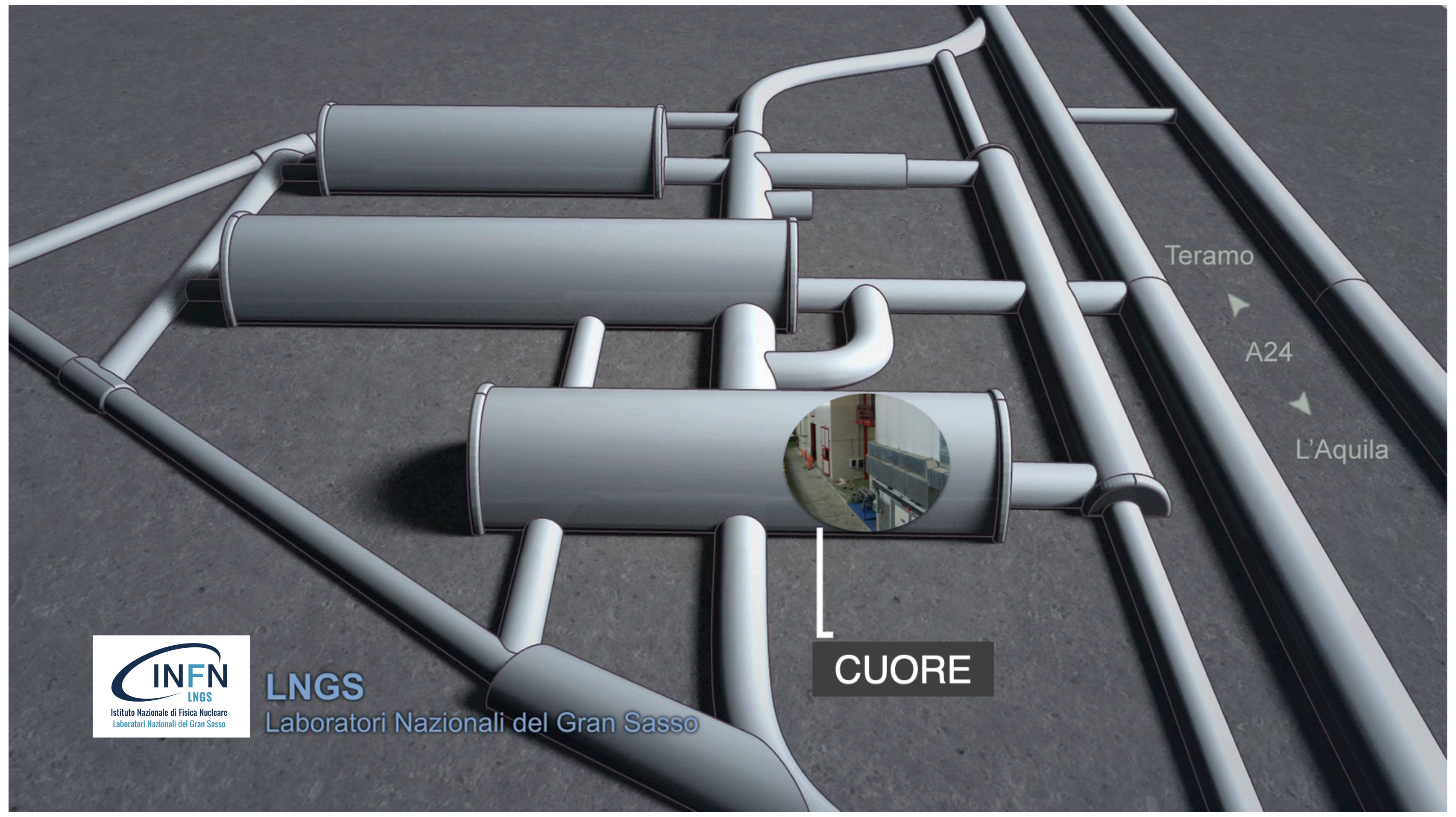
CUORE

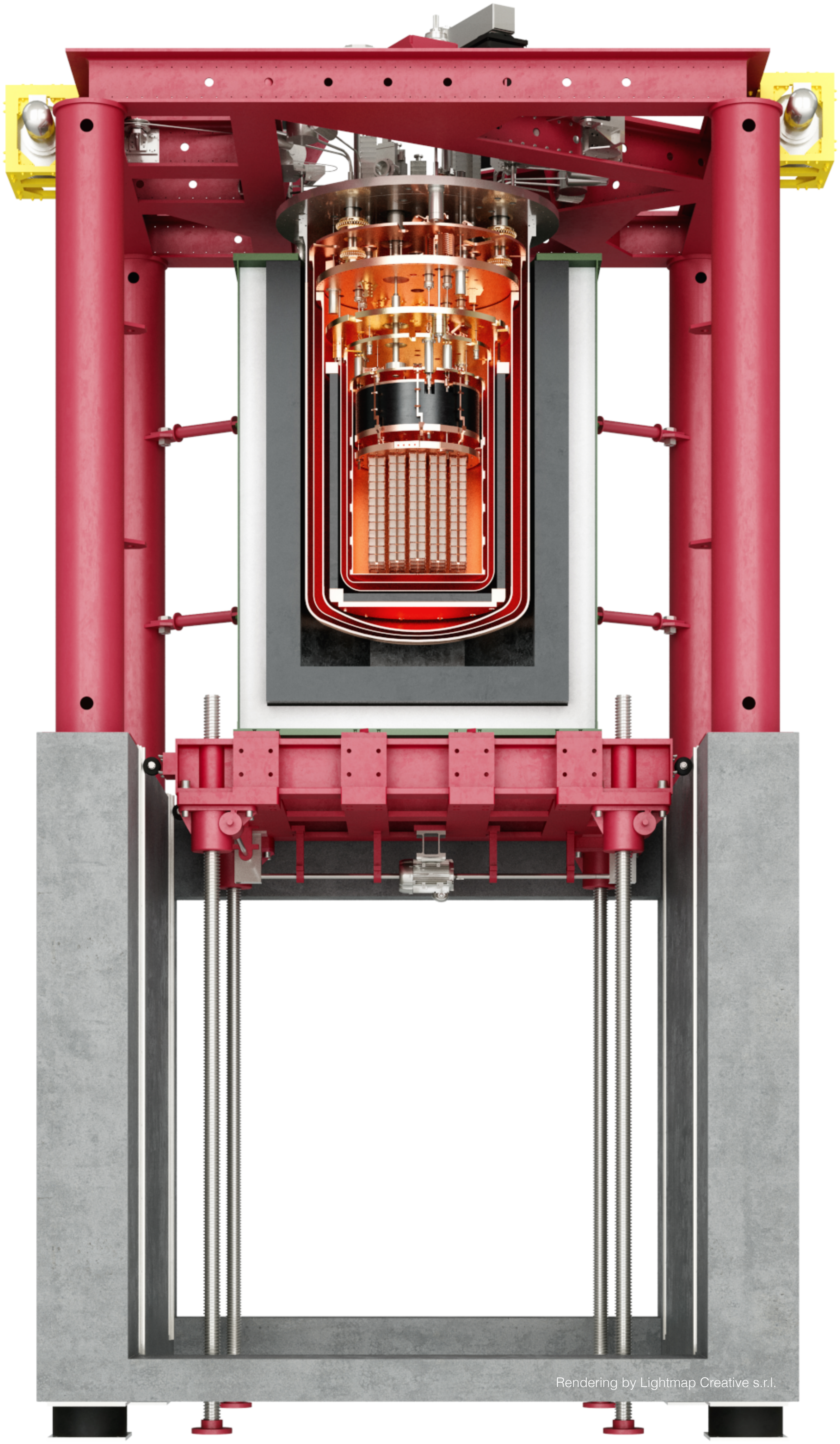
INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

CUORE @ LNGS

Cryogenic Underground Observatory for Rare Events

- Closely packed array of 988 TeO_2 crystals (750 g each) working as cryogenic calorimeters
- Total mass of TeO_2: 742 kg (~206 kg of ^{130}Te)
- Operating temperature: ~10 mK
- Main goal: assess the Majorana nature of neutrinos by searching for $0\nu\beta\beta$ in ^{130}Te

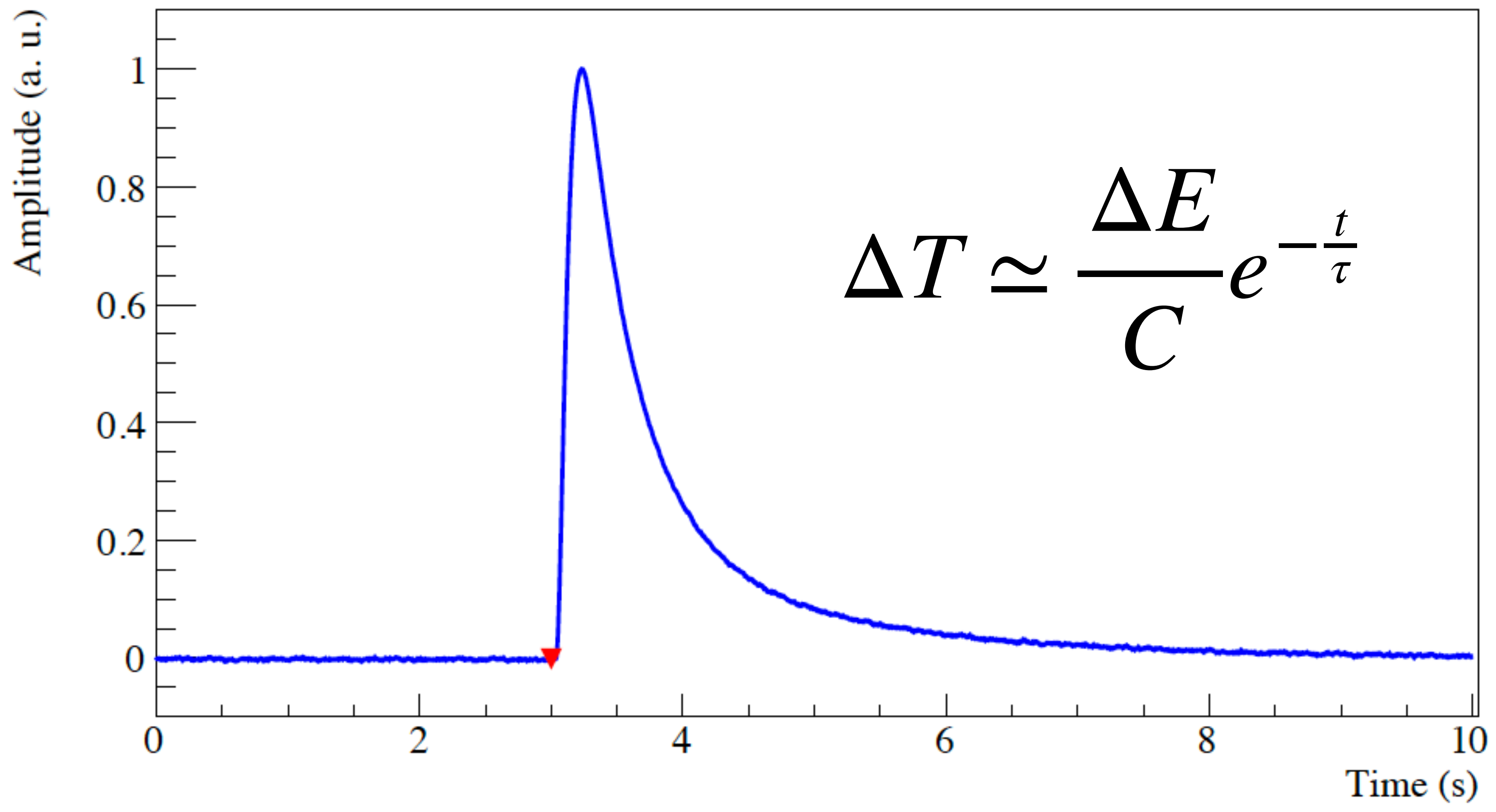




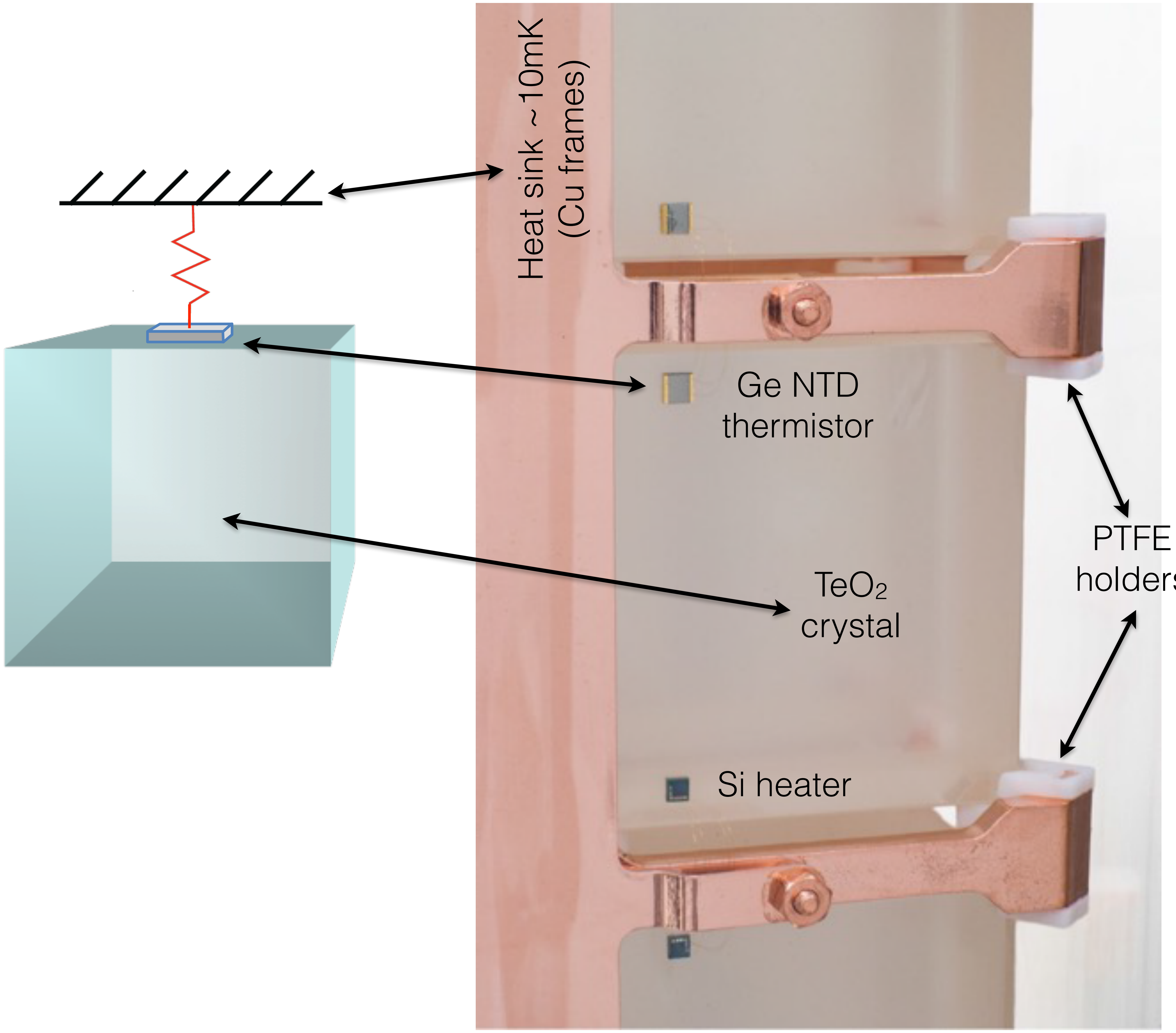
Cryogenic calorimeters

The absorbed energy is converted into a variation of the crystal temperature, measured by a thermistor

- Ample choice of detector materials
  - low heat capacity @ T_{work}
- excellent energy resolution (~0.3 % FWHM)
  - huge number of energy carriers (phonons)
- equal detector response for different particles
  - true calorimeters
- slow



$$\Delta T \simeq \frac{\Delta E}{C} e^{-\frac{t}{\tau}}$$



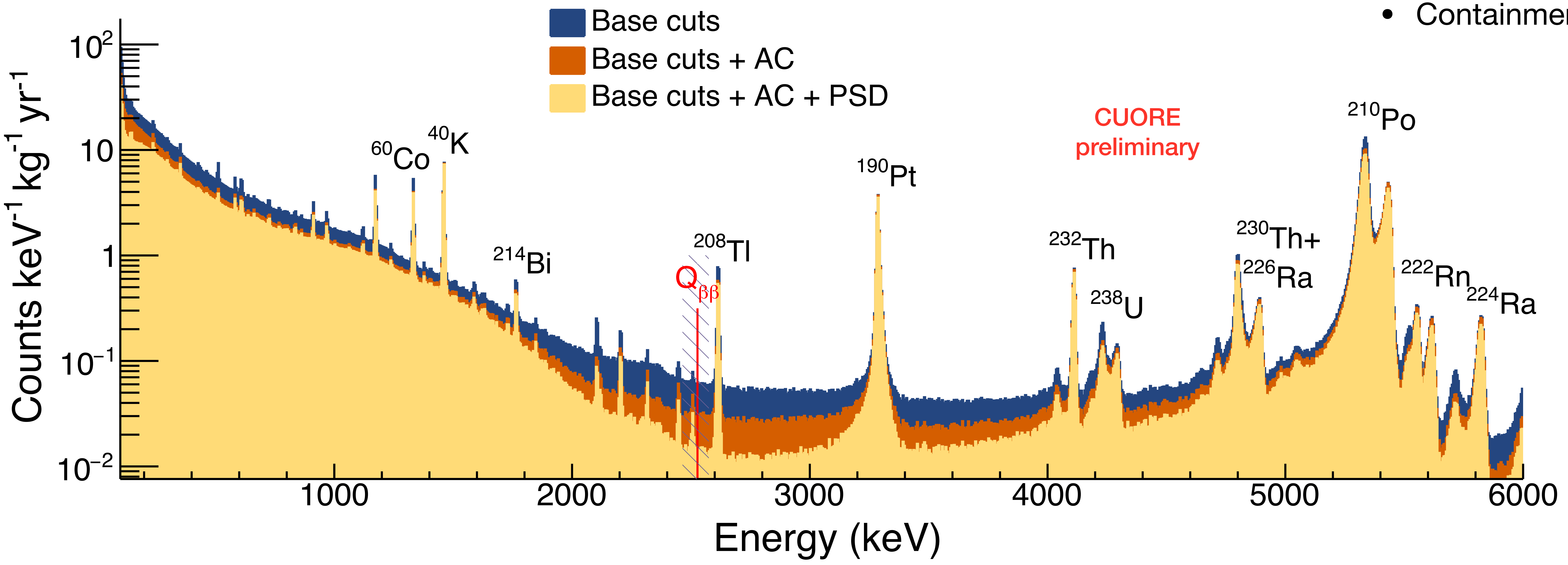
^{130}Te 0νββ search

Latest results on the ^{130}Te 0νββ search

- 28 datasets analyzed from May 2017 to April 2023
- Total analysed exposure: 2039.0 kg·yr TeO_2 (567.0 kg·yr ^{130}Te)

Efficiencies

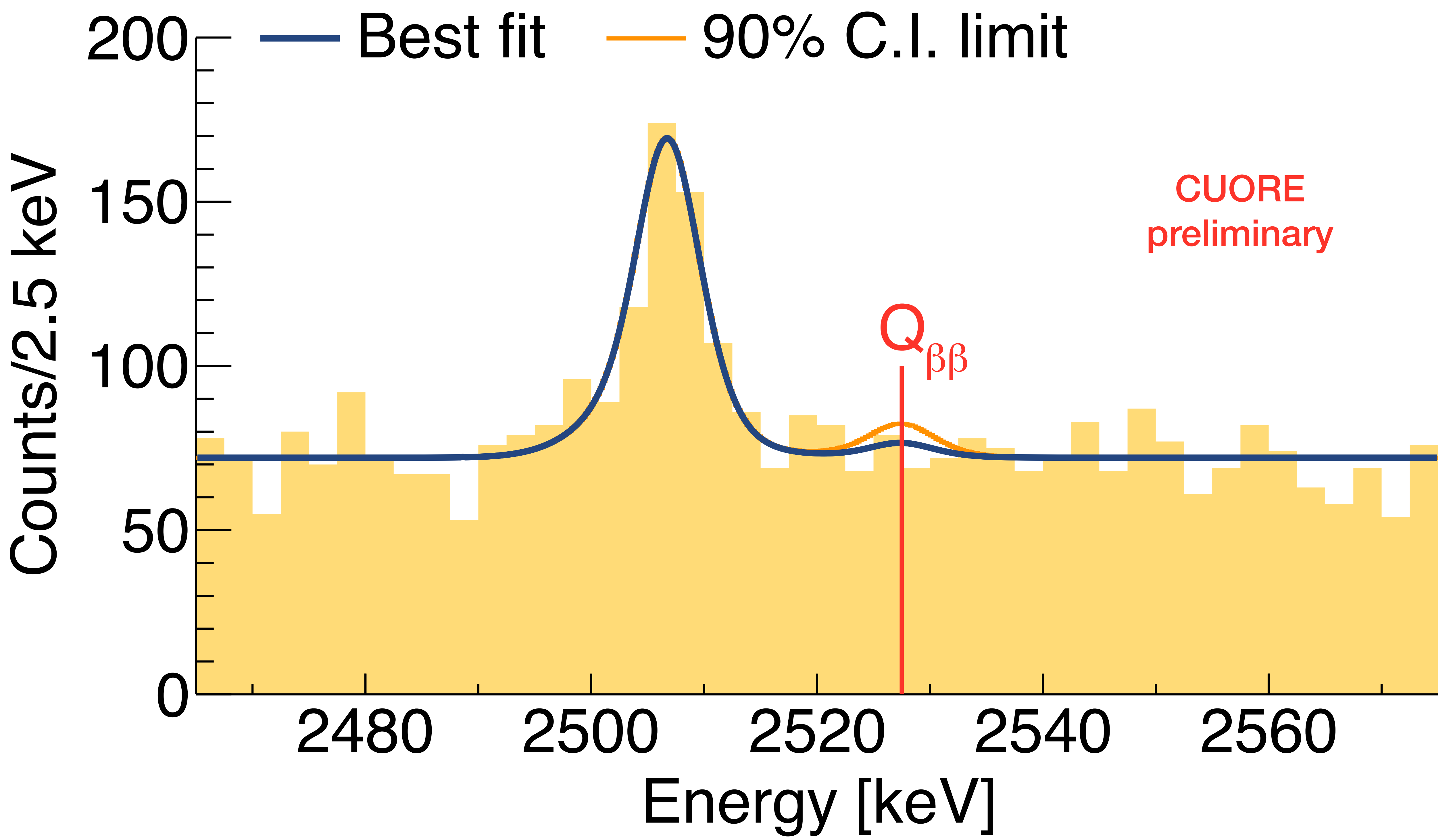
- Total analysis efficiency 93.4 %
  - Reconstruction: 95.6 %
  - Anti-coincidence (M1): 99.8 %
  - PSD: 97.9 %
- Containment efficiency: 88.4 %



^{130}Te 0νββ decay search

Bayesian and Frequentist Analysis

- Unbinned fit in ROI: [2465, 2575] keV
- Flat-background dataset-dependent
- 0νββ posited peak
- time-dependent ^{60}Co-sum peak
- Energy resolution channel and dataset dependent



Average background index: $1.42(2) \times 10^{-2}$ count/ keV kg yr

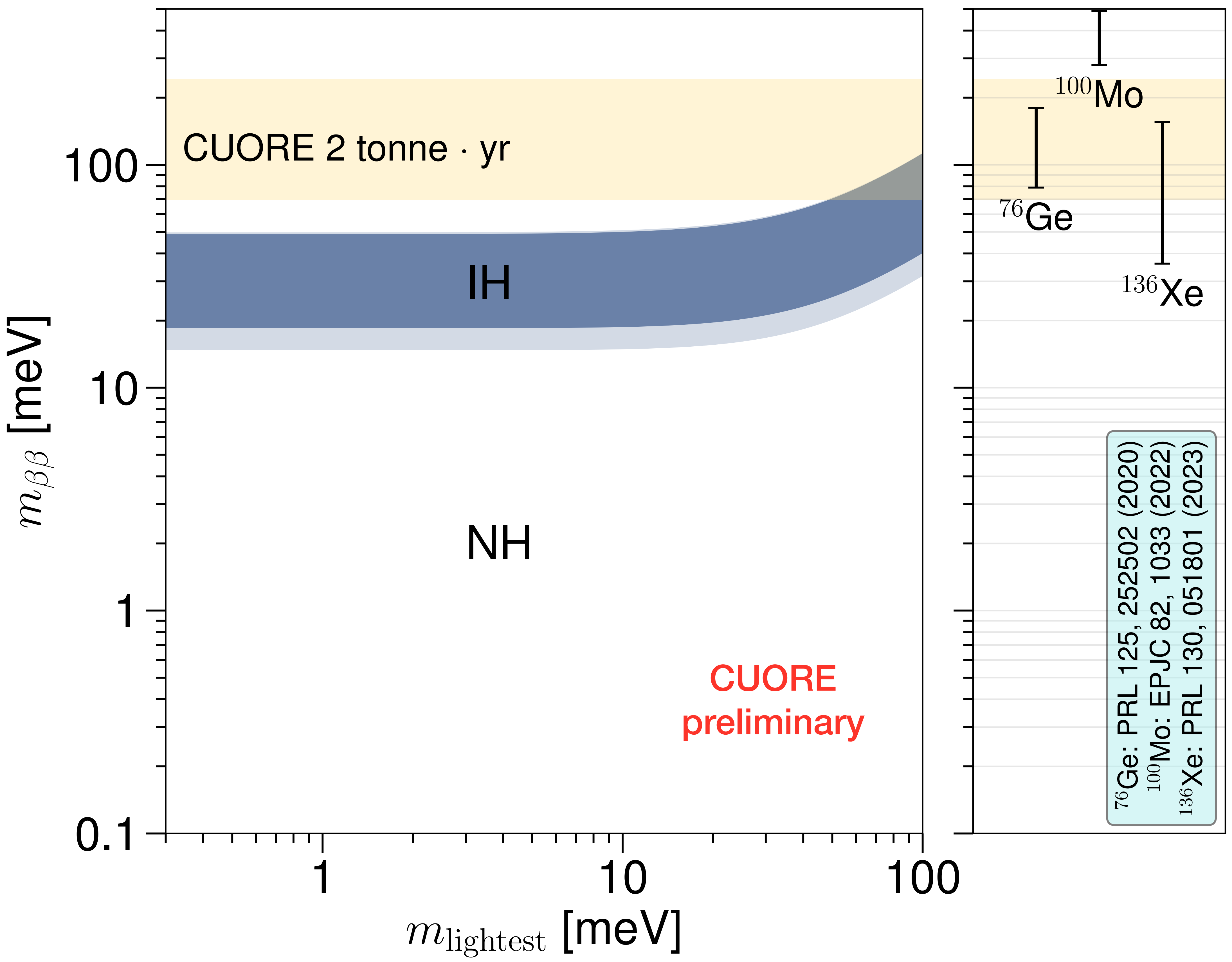
Half-life limit: $T^{0\nu}_{1/2} > 3.8 \times 10^{25}$ yr (90% C.I.)

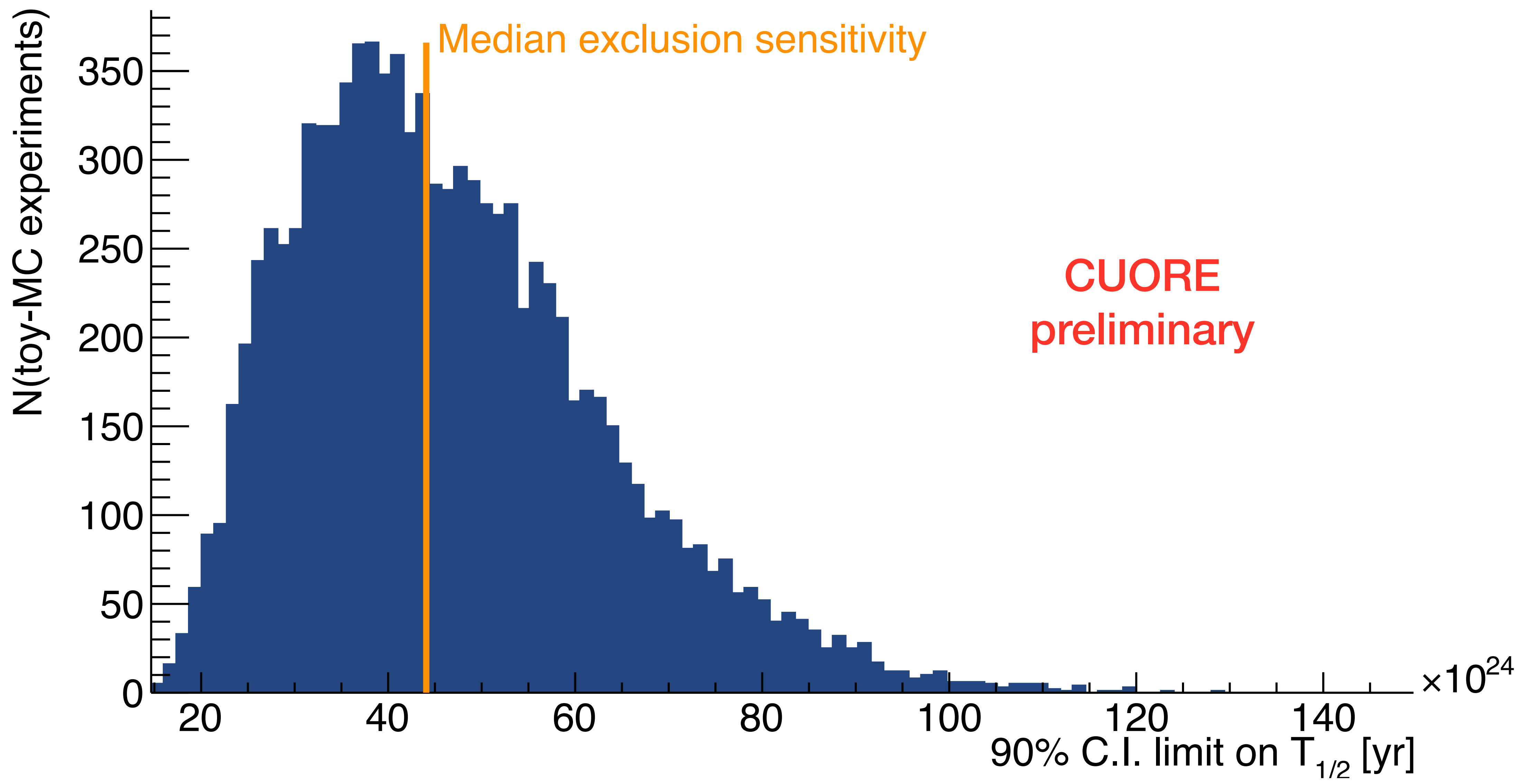
Frequentist limit: $T^{0\nu}_{1/2} > 3.7 \times 10^{25}$ yr (90% C.L.)

^{130}Te 0νββ decay search

Median exclusion sensitivity: 4.4×10^{25} yr (90% C.I.)

- 67% probability to get a more stringent limit given the current sensitivity





Limit on the effective Majorana mass (assuming light Majorana neutrino exchange)

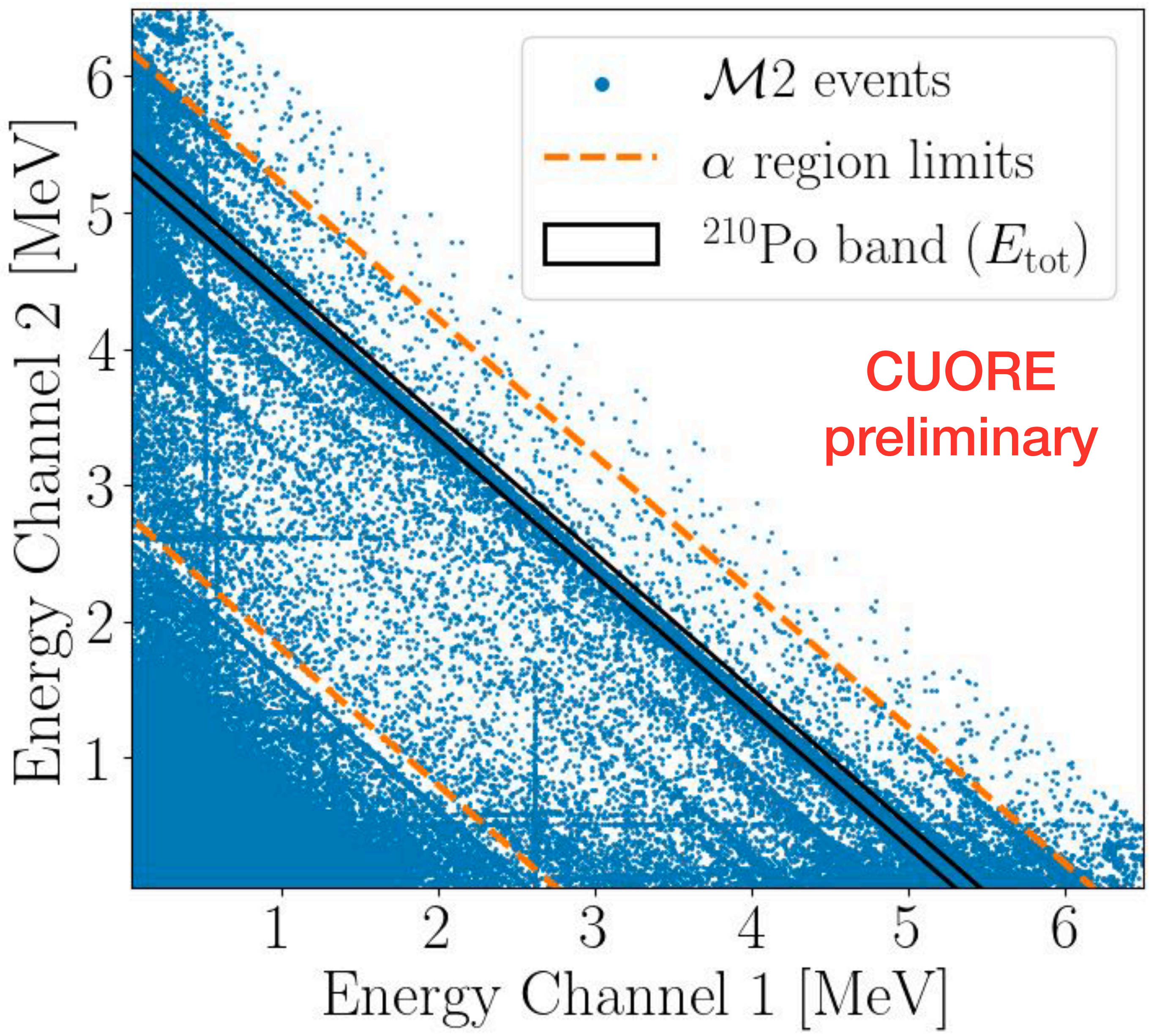
$$m_{\beta\beta} < 70 - 240 \text{ meV}$$

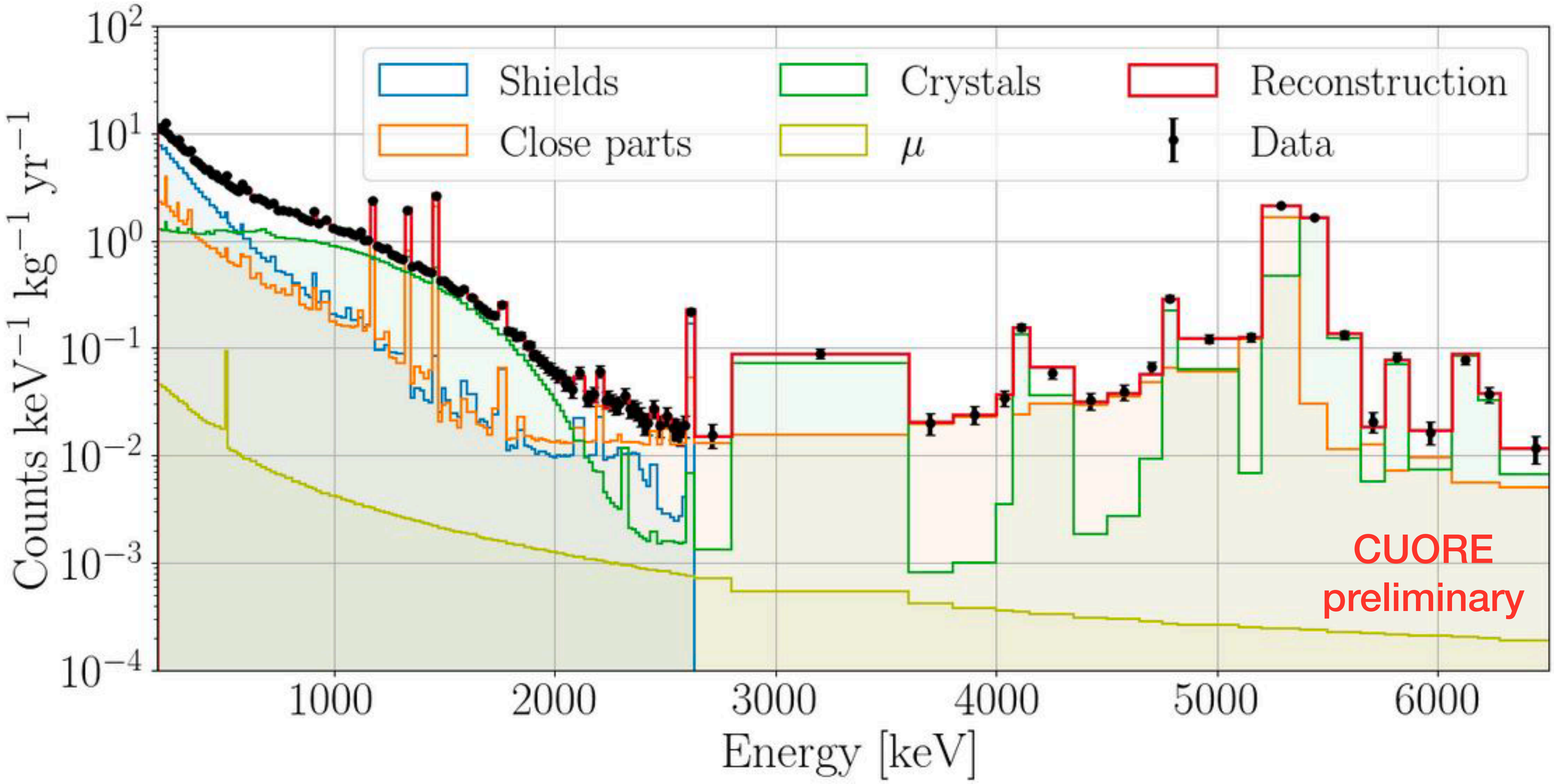
ArXiv:2404.04453

Background Model

Accurate Geant4-based background model

- Detailed geometry
- Simulation of ~80 different sources
- Takes advantage of the high granularity of the detector
- Bayesian simultaneous fit of M1 and M2 spectra with a linear combination of the background sources
- Priors given by radioassays and previous experiments





ArXiv:2405.17937

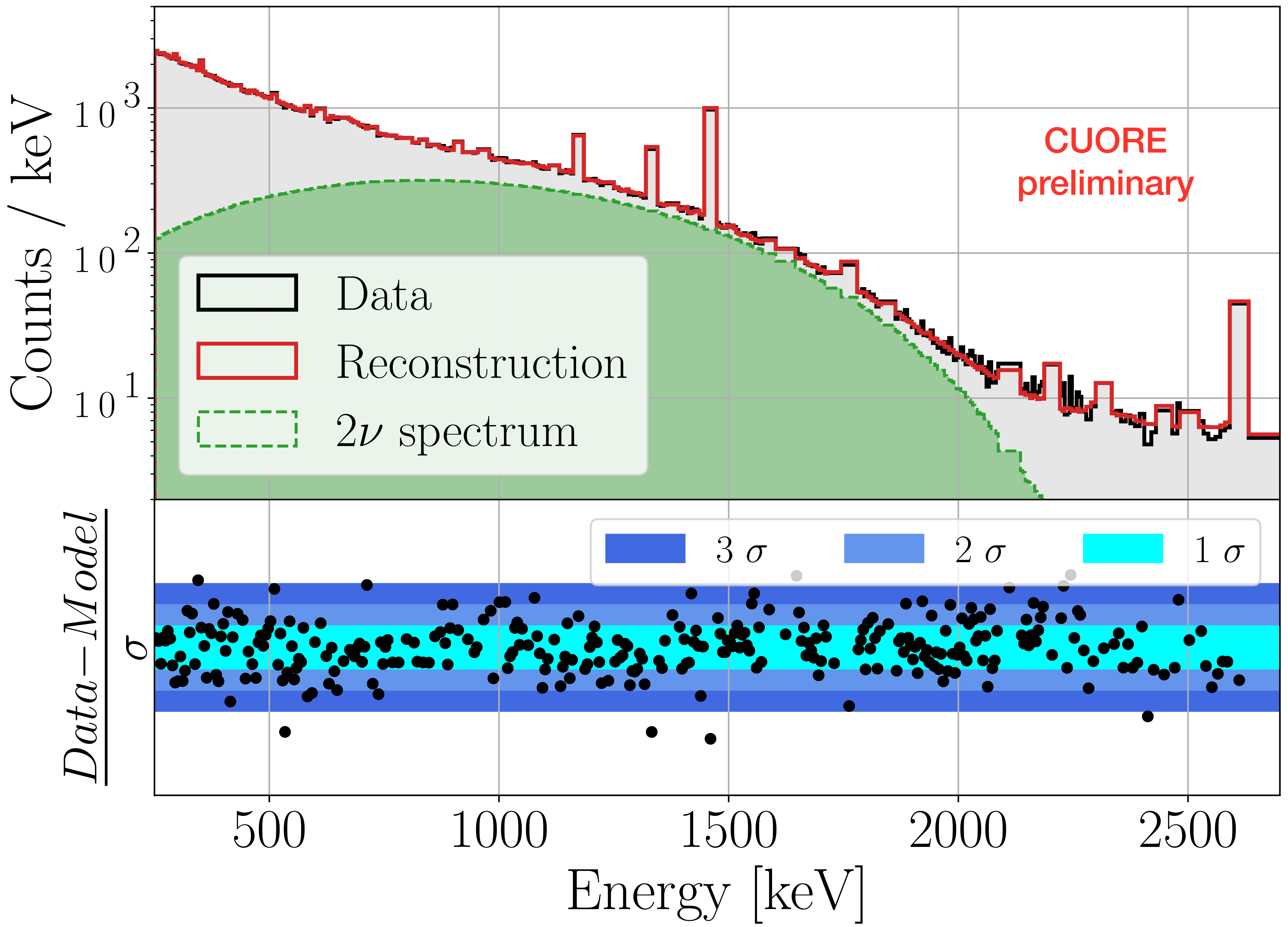
^{130}Te 2νββ decay

Our background reconstruction allows for precise measurement of the ^{130}Te 2νββ half-life

- Subset of channels with lower background (innermost towers)
- Optimisation of fit energy range and binning
- SSD model assumed
- Improved accuracy respect to the previous result

$$T^{2\nu}_{1/2} = 9.323^{+0.052}_{-0.037}\ (stat.)\ \times 10^{20}\ yr$$

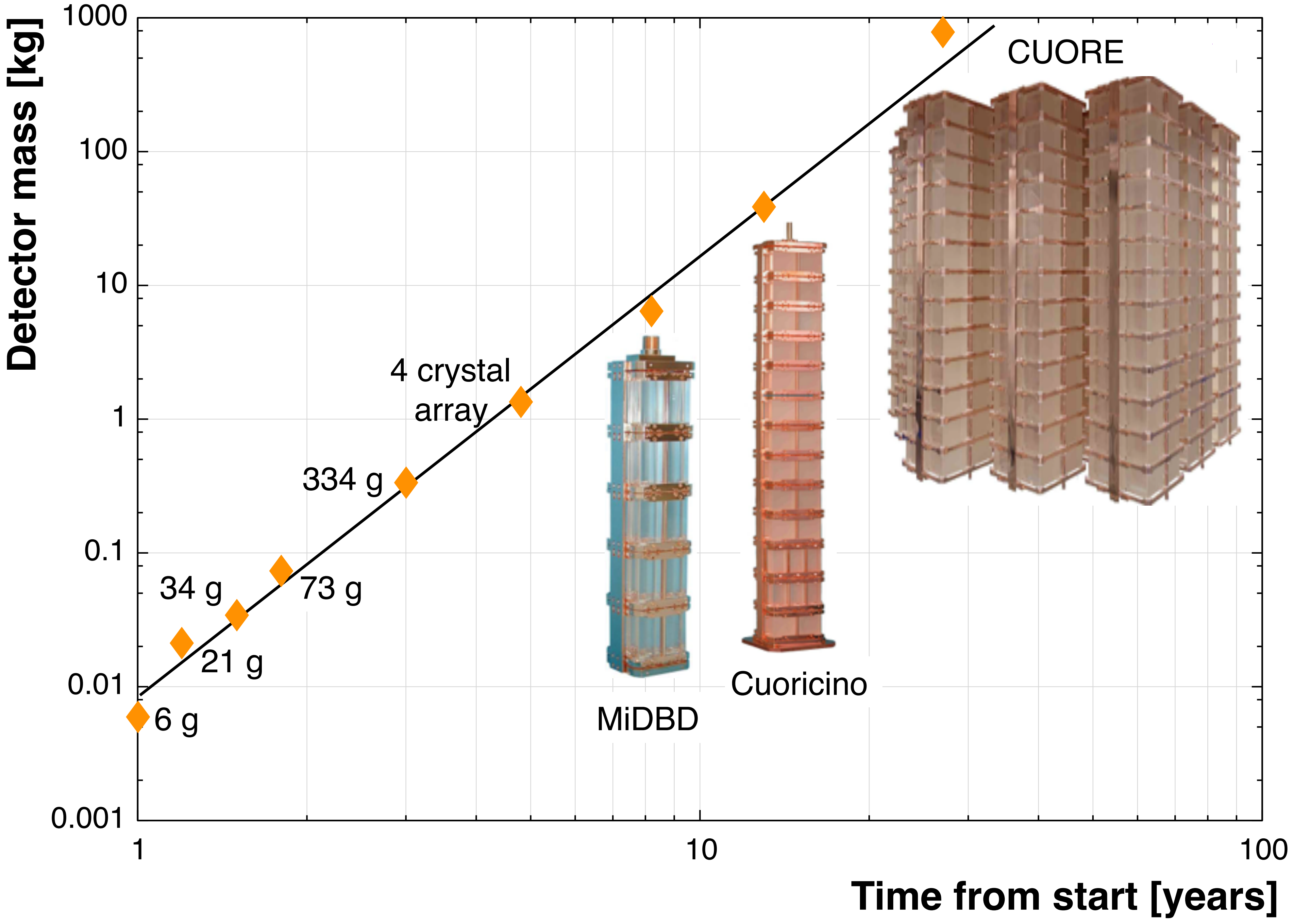
- Systematics under finalisation (~ 1%)



Ettore Fiorini and CUORE

CUORE would not have been possible without the vision, determination, and enthusiasm of Ettore

- In about 30 years from the original paper of E. Fiorini and T. Niinikoski cryogenic detectors moved from a smart idea to a ton-scale project.



Nuclear Instruments and Methods in Physics Research 224 (1984) 83–88
North-Holland, Amsterdam

LOW-TEMPERATURE CALORIMETRY FOR RARE DECAYS

E. FIORINI
Dipartimento di Fisica dell'Università and INFN, Milano, Italy

T.O. NIINIKOSKI
CERN, Geneva, Switzerland

Received 27 December 1983

The recent developments in underground low-counting experiments give limits to rare decays which are hard to improve since scaling the size and the resolution of the combined source–detector is difficult with the existing techniques. We explore here the possibility of low-temperature calorimetry to improve the limits on processes such as neutrinoless double-beta decay and electron decay.

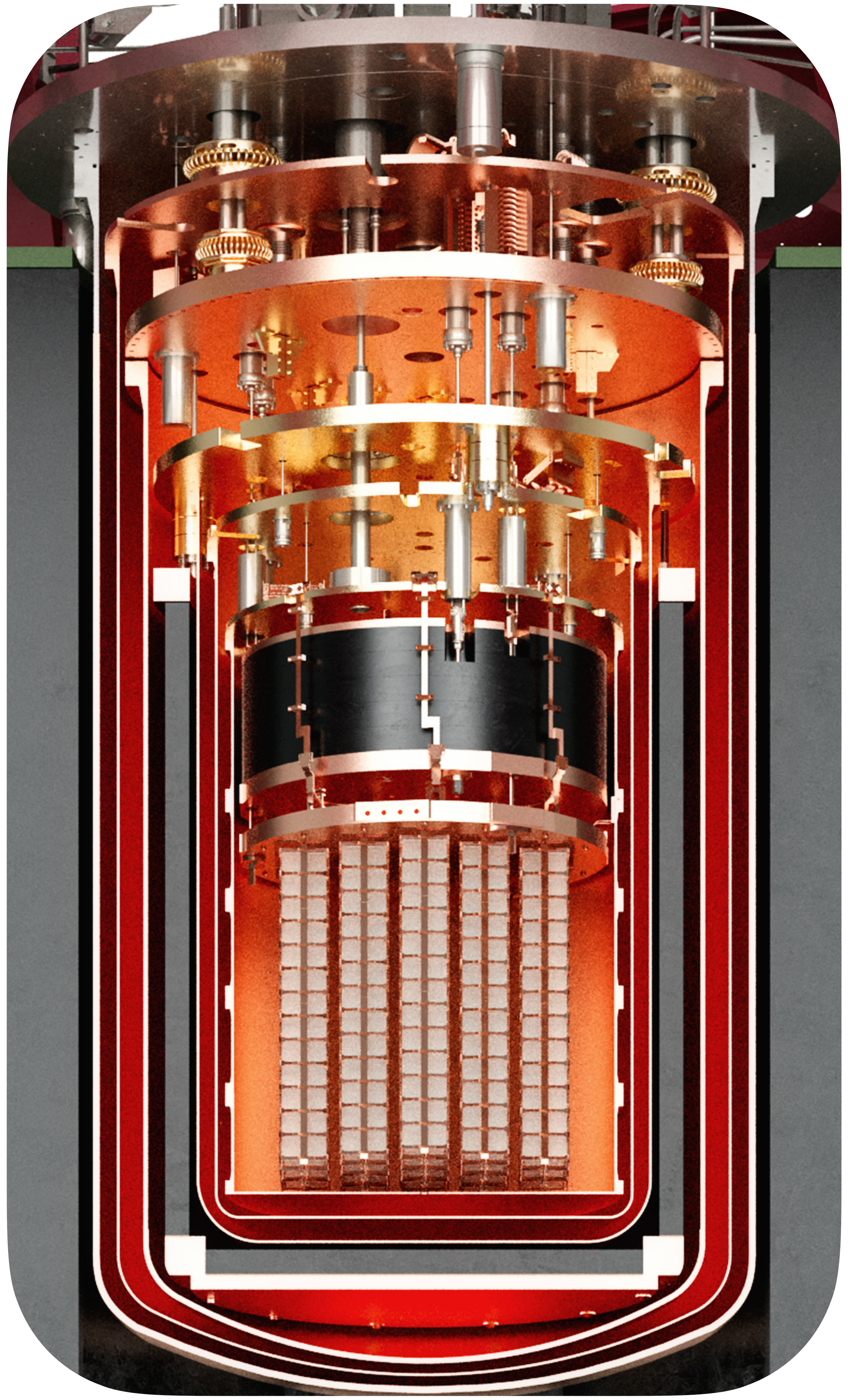
Challenge

Build a cryogenic system with an experimental volume of ~1 m^3 in which to operate for several years a huge Low Temperature Detector array in a low-radioactivity and low-vibrations environment

- Cryogenics
  - Mass cooled below 4K : ~ 15 tons
  - Mass cooled below 50 mK : ~ 3 tons
  - Lowest operating temperature: 7 mK
  - Continuously operating at mK temperature: > 5 years

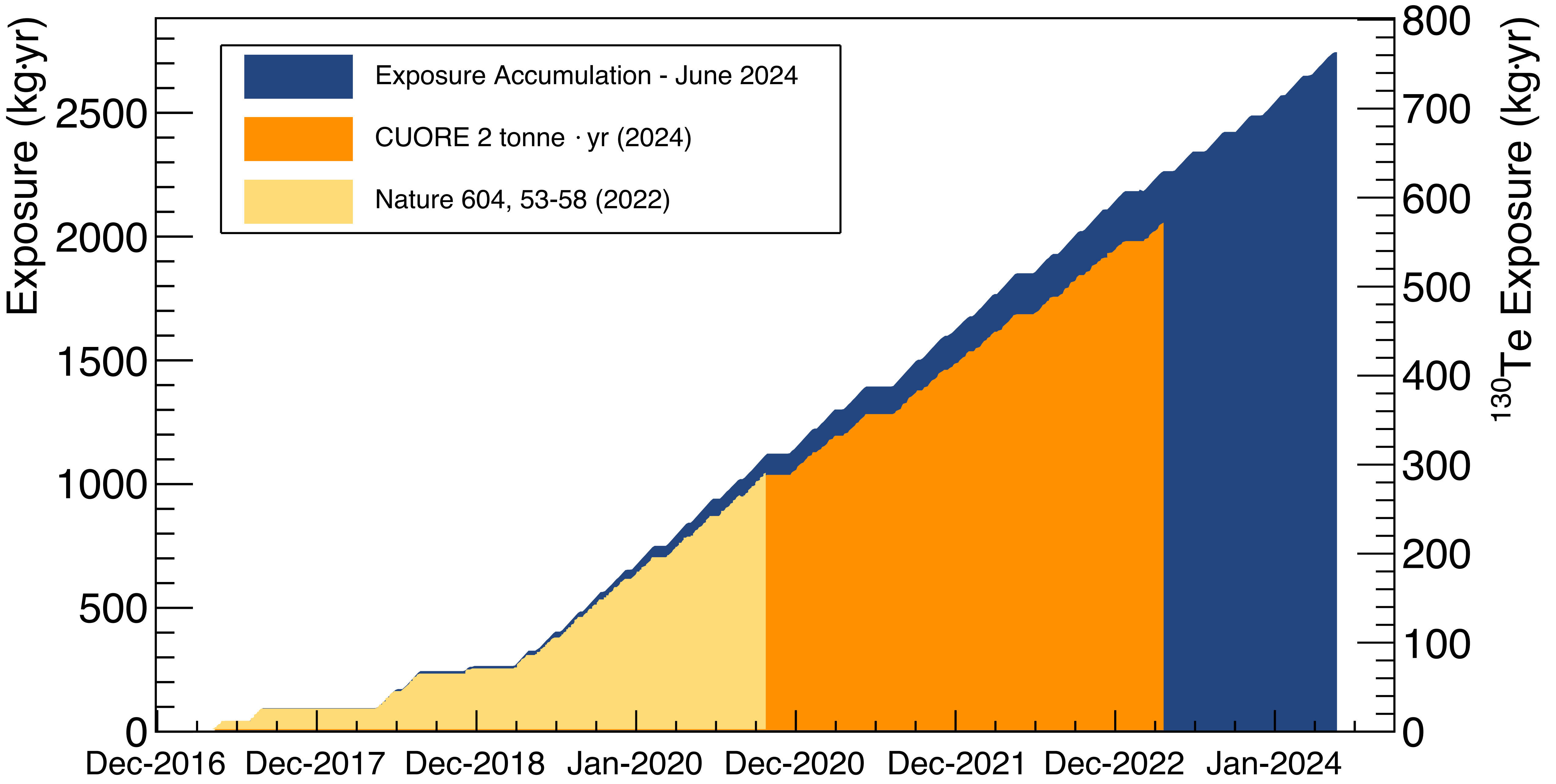
- Low-background
  - Deep underground location
  - Strict radio-purity controls on materials and assembly
  - Passive shields outside and inside the cryostat

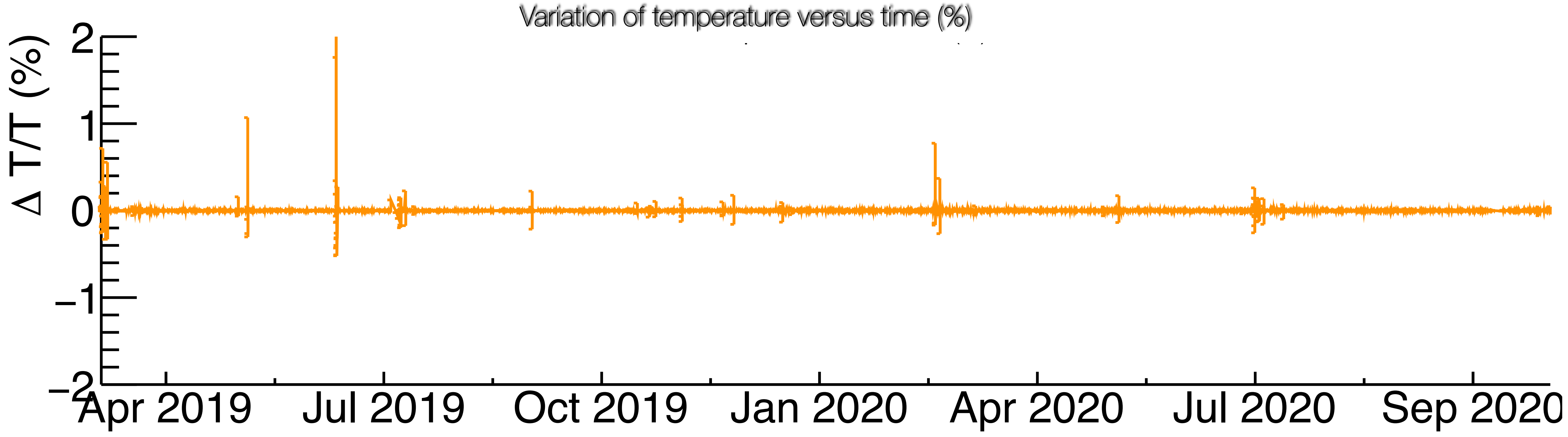
Ancient roman lead

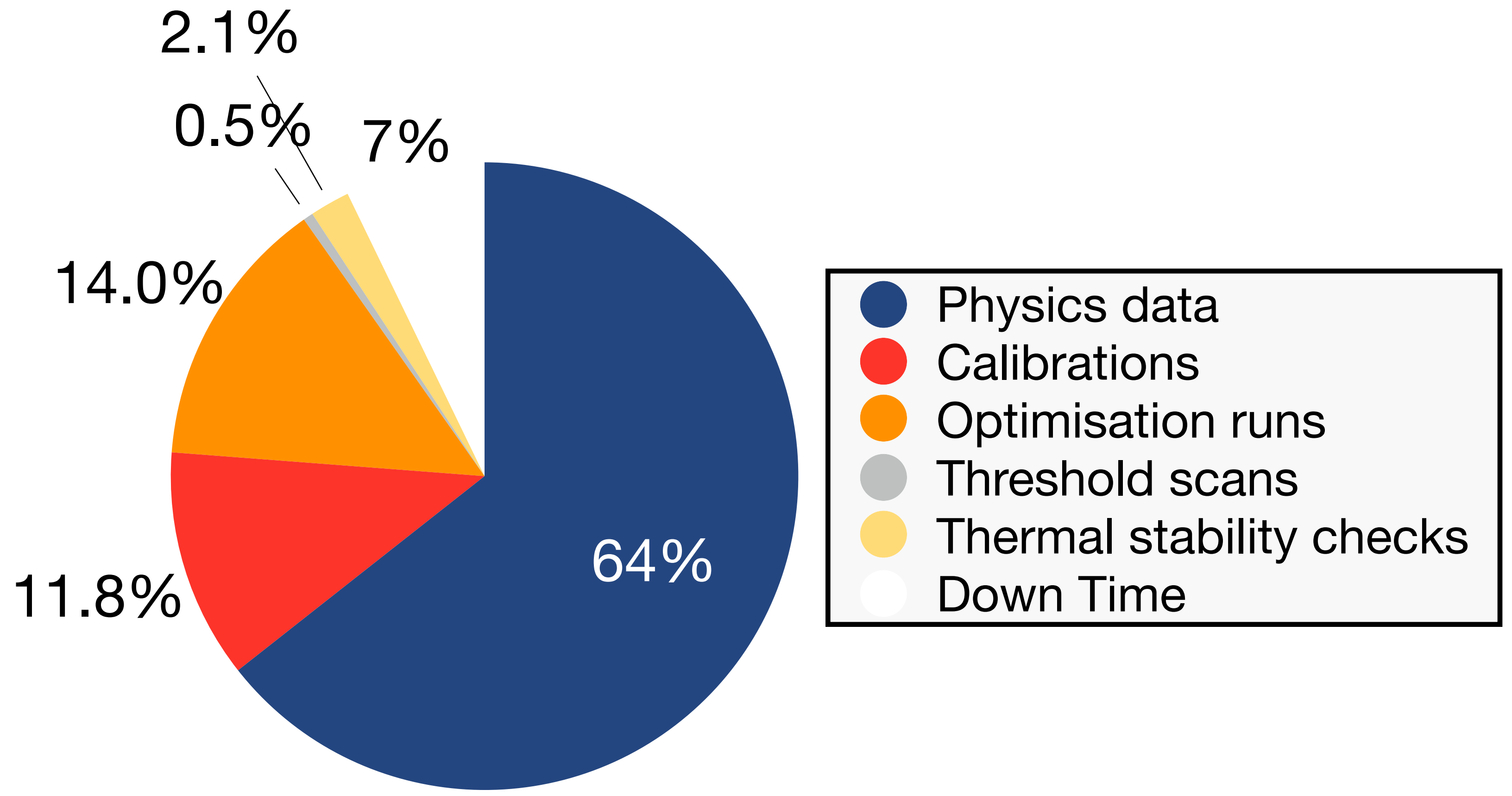


Exposure

- Data taking started in Spring 2017
  - In the first two years we learned how to operate the cryogenic system at its best and optimised the performances
  - Datasets (~ 2 months long) interleaved by routine maintenances
- Continuous physics data taking at mK temperature since March 2019
  - Uptime > 90%
  - Data taking rate ~ 50 kg·yr/month





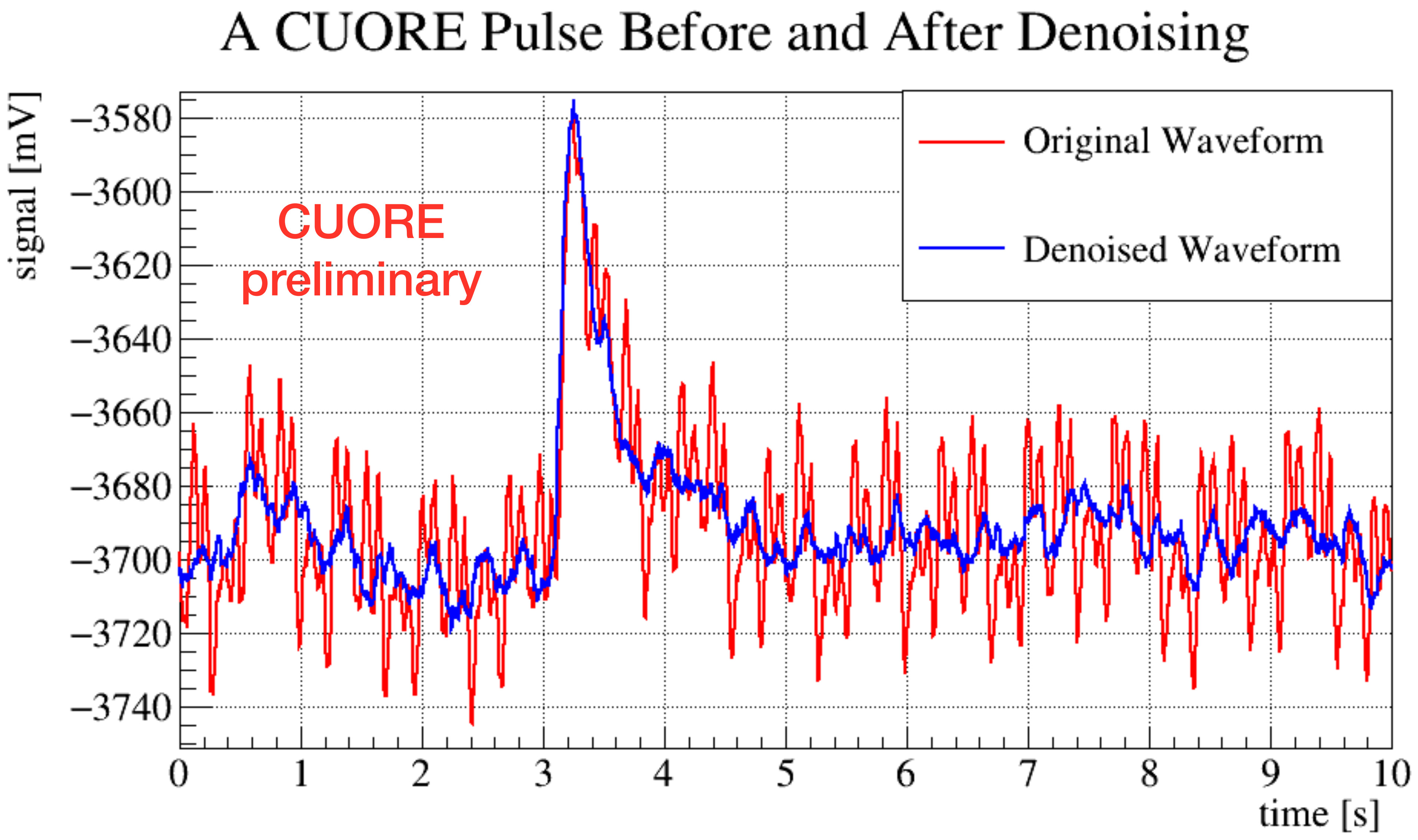


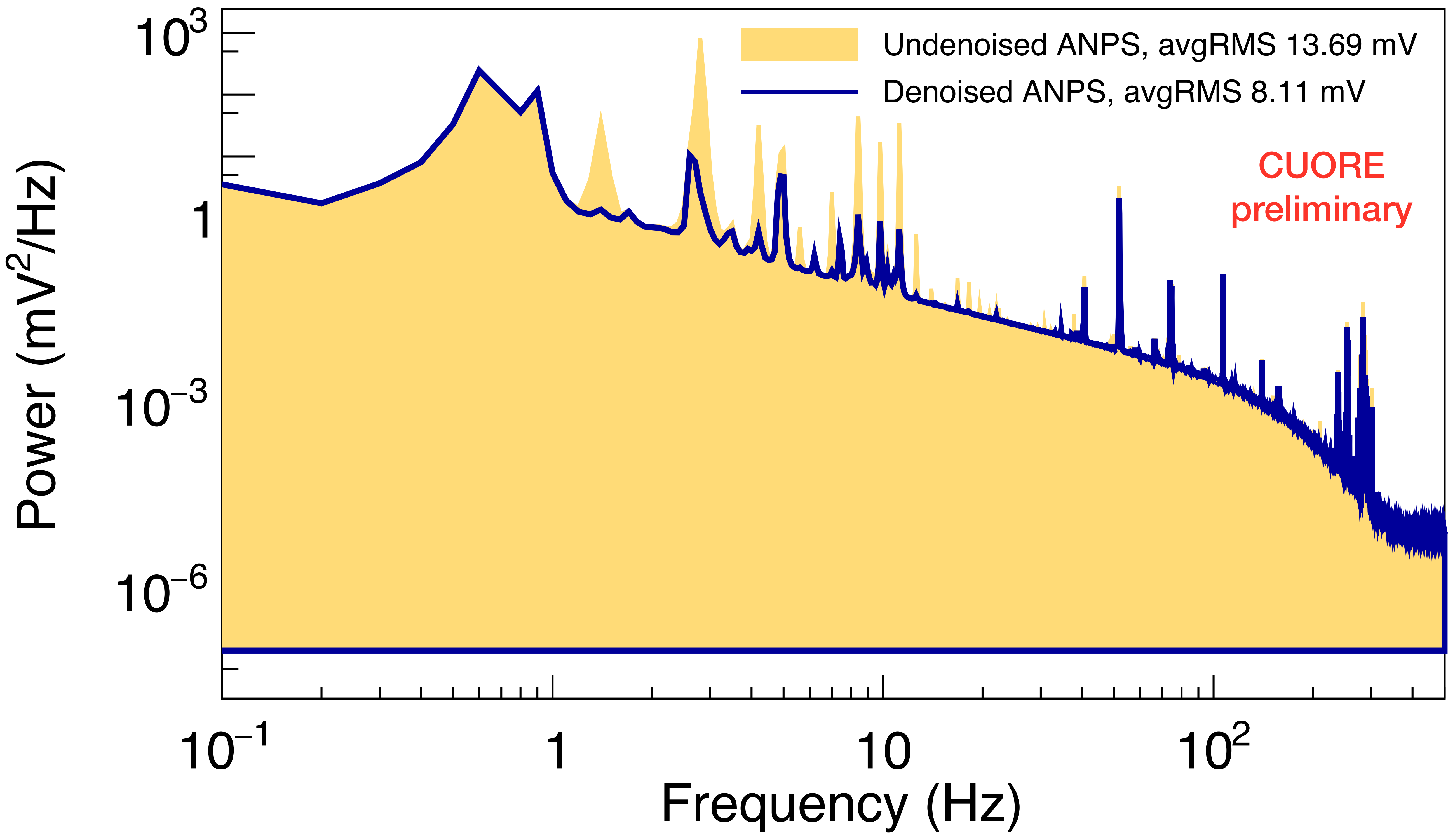
Noise reduction

We developed noise decorrelation algorithms utilizing auxiliary devices to enhance the quality of CUORE data

Auxiliary devices:

- Microphones
- Accelerometers
- Seismometers
- Antennas





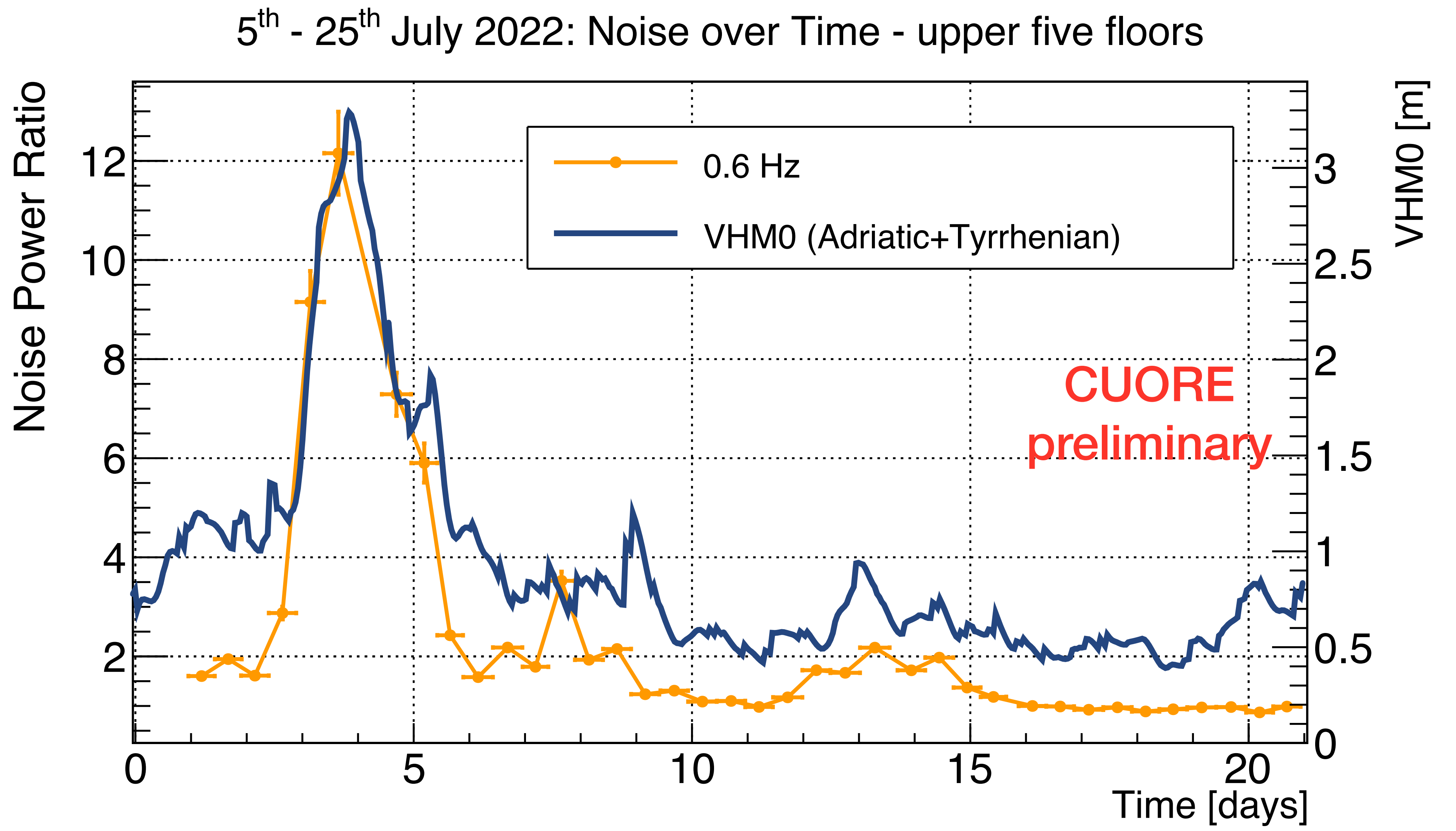
- The total RMS noise of the CUORE detector is reduced by ~ 40%

Eur. Phys. J. C 84, 243 (2024)

Noise reduction

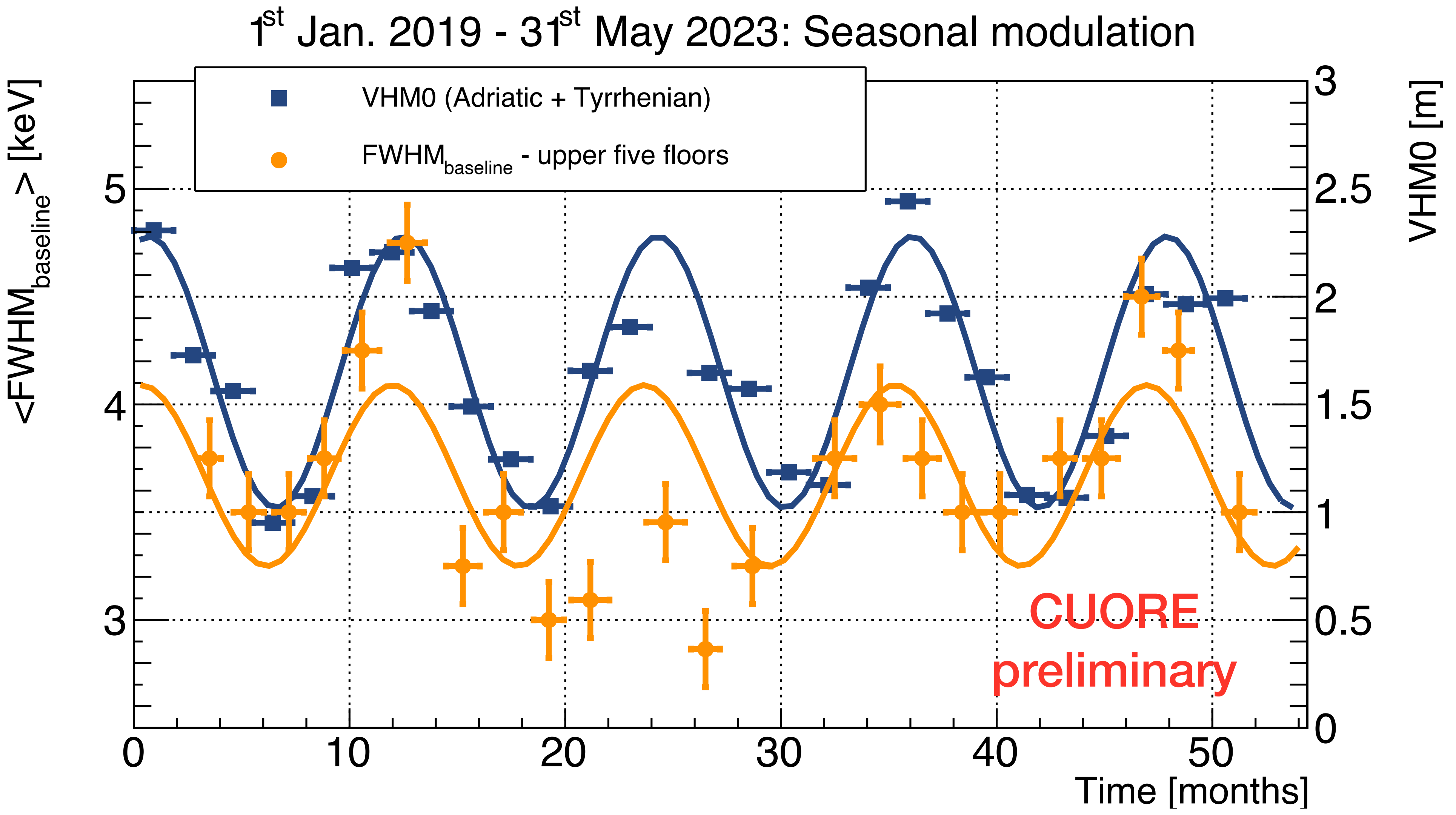
Quite unexpectedly we discovered that CUORE is sensitive to the faint microseismic activity induced by the sea waves

- Strong correlation between storms and low frequency noise in CUORE
- Sea waves characteristic frequency: 0.2 - 0.3 Hz
- Resonance frequency in the cryogenic apparatus



Copernicus
Europe's eyes on Earth

- Seasonal modulation of detectors energy resolution
- Solutions under study to improve cryostat seismic decoupling



ArXiv:2404.13602

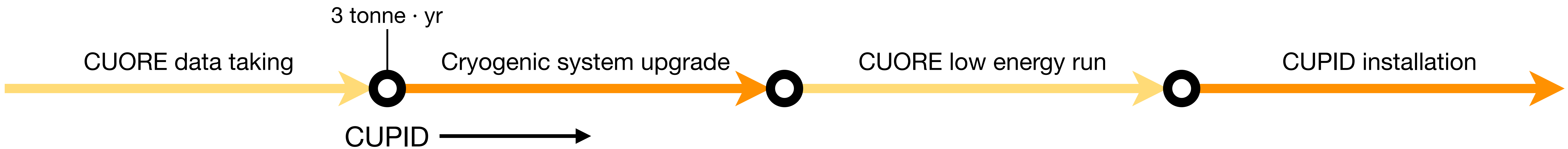
Future plans

We will continue collecting data until reaching 3 tonne·yr of analysed TeO_2 exposure (around end of 2025) after which we will proceed toward CUPID

Upgrade of the cryogenic system in view of CUPID

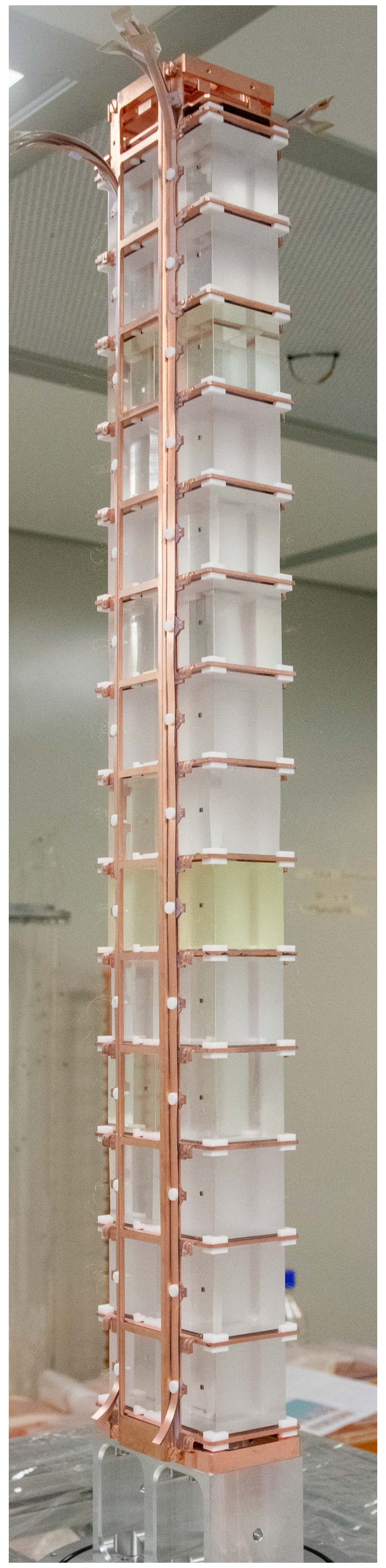
- The CUORE cryogenic system is working spectacularly well
- It is capable of cooling detector payload (~1 ton) down to 7 mK
- The only needed upgrade regards the Pulse Tubes and their coupling to the cryostat
  - Substantial decrease of the vibrational induced noise on the detectors

- The effectiveness of the cryogenic upgrade will be tested with the CUORE detector
  - 2nd CUORE run with improved vibrational noise ➡ lower threshold ➡ low energy studies
  - Axions, WIMPs, etc.

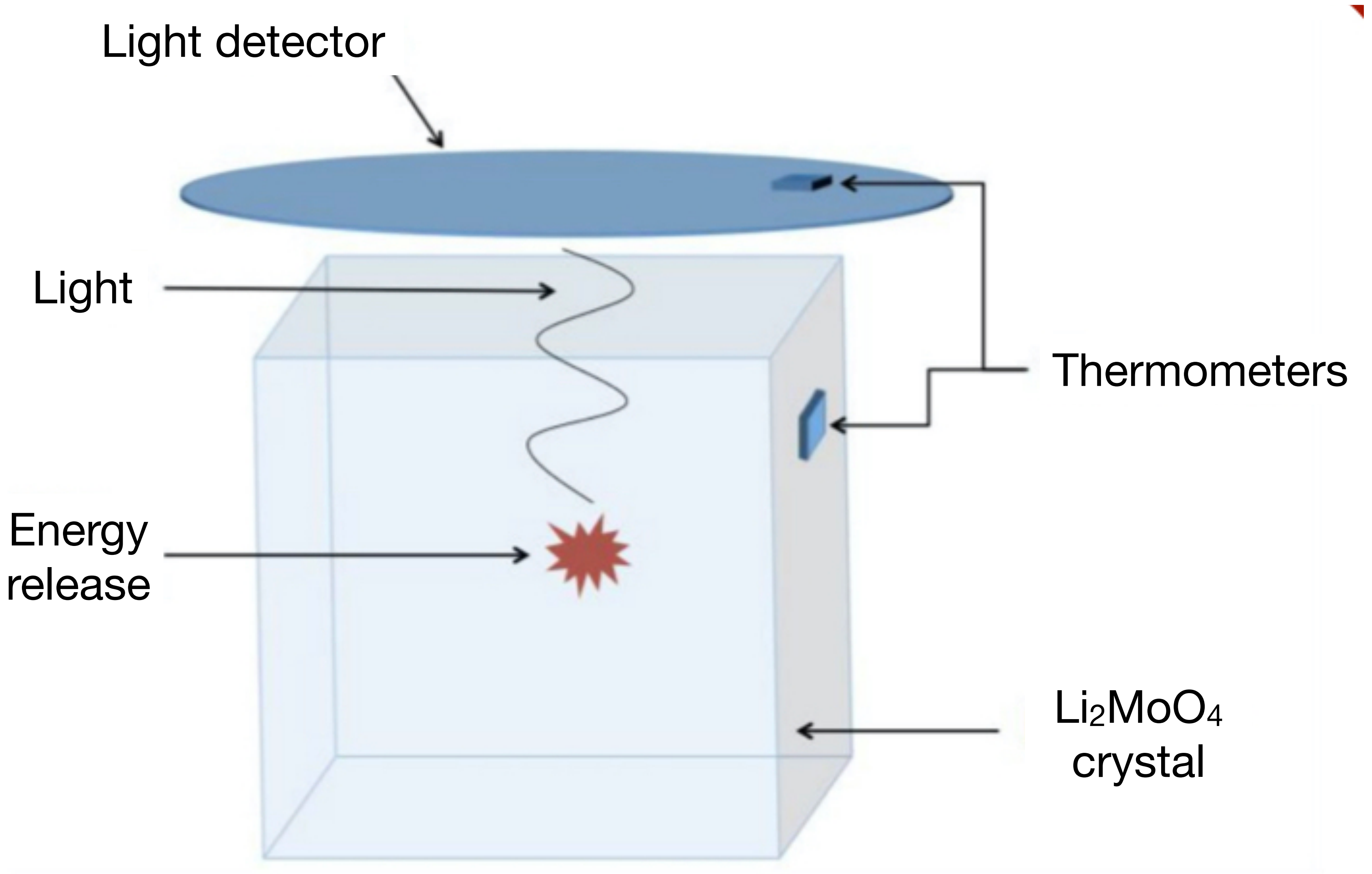


CUPID

CUPID (CUORE Upgrade with Particle IDentification) is conceived to overcome the CUORE limitations



- TeO_2 → Li_2MoO_4: double readout for particle identification
  - 1596 Li_2MoO_4 crystals arranged in 57 towers
  - Each crystal has top and bottom Ge light detectors with Neganov-Luke amplification
- ^{130}Te → ^{100}Mo: higher $Q_{\beta\beta}$ for reduced γ/β backgrounds
  - 95% enrichment in ^{100}Mo
  - 450 kg total mass: 240 kg of ^{100}Mo
- Muon veto



Thanks to those characteristics CUPID aims at a background level of 10^{-4} count/keV kg yr

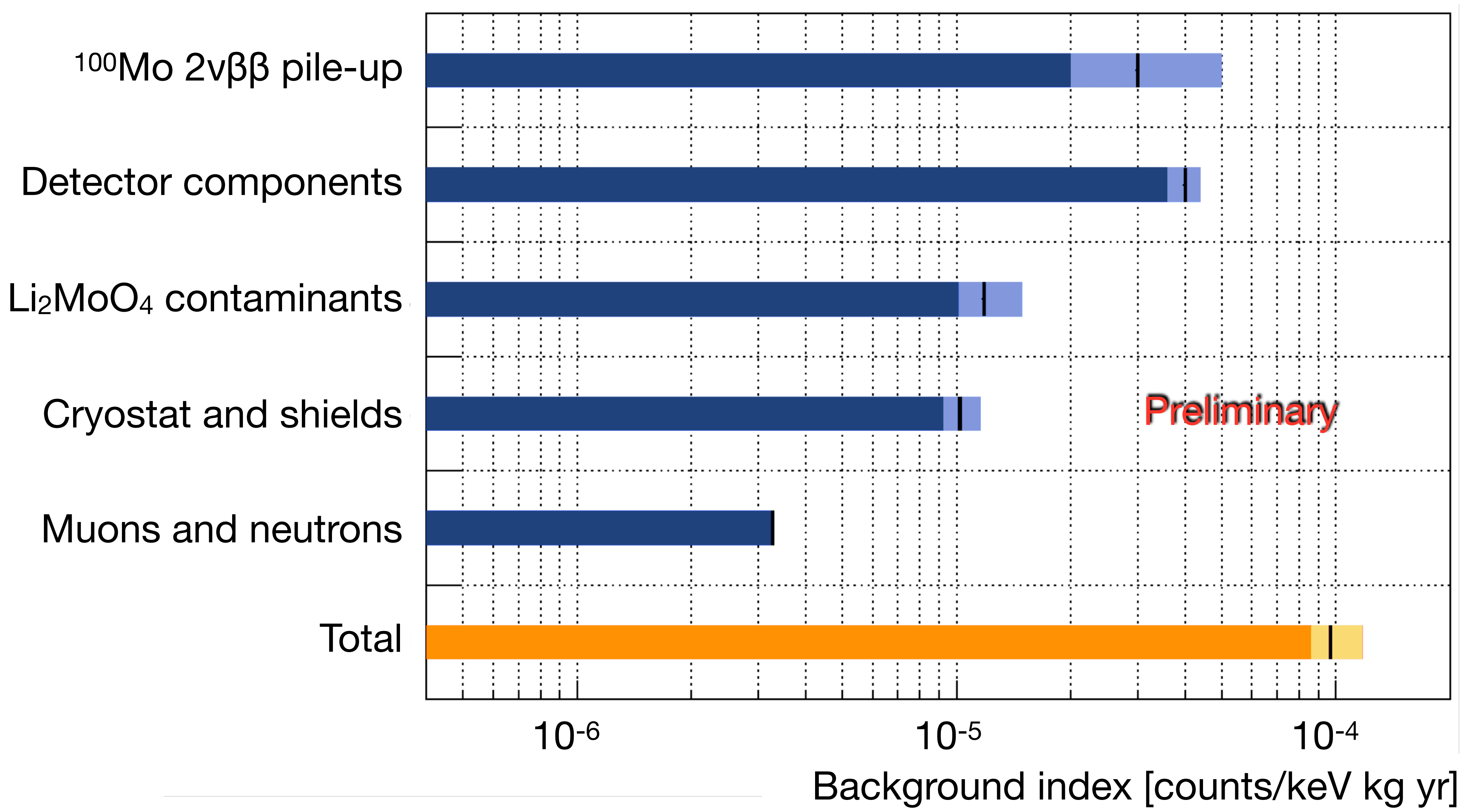
Improve sensitivity to $m_{\beta\beta}$ by factor of ~5 relative to CUORE

CUPID

CUPID has established a supply chain for producing all the Li_2MoO_4 crystals grown with ~95% enriched ^{100}Mo

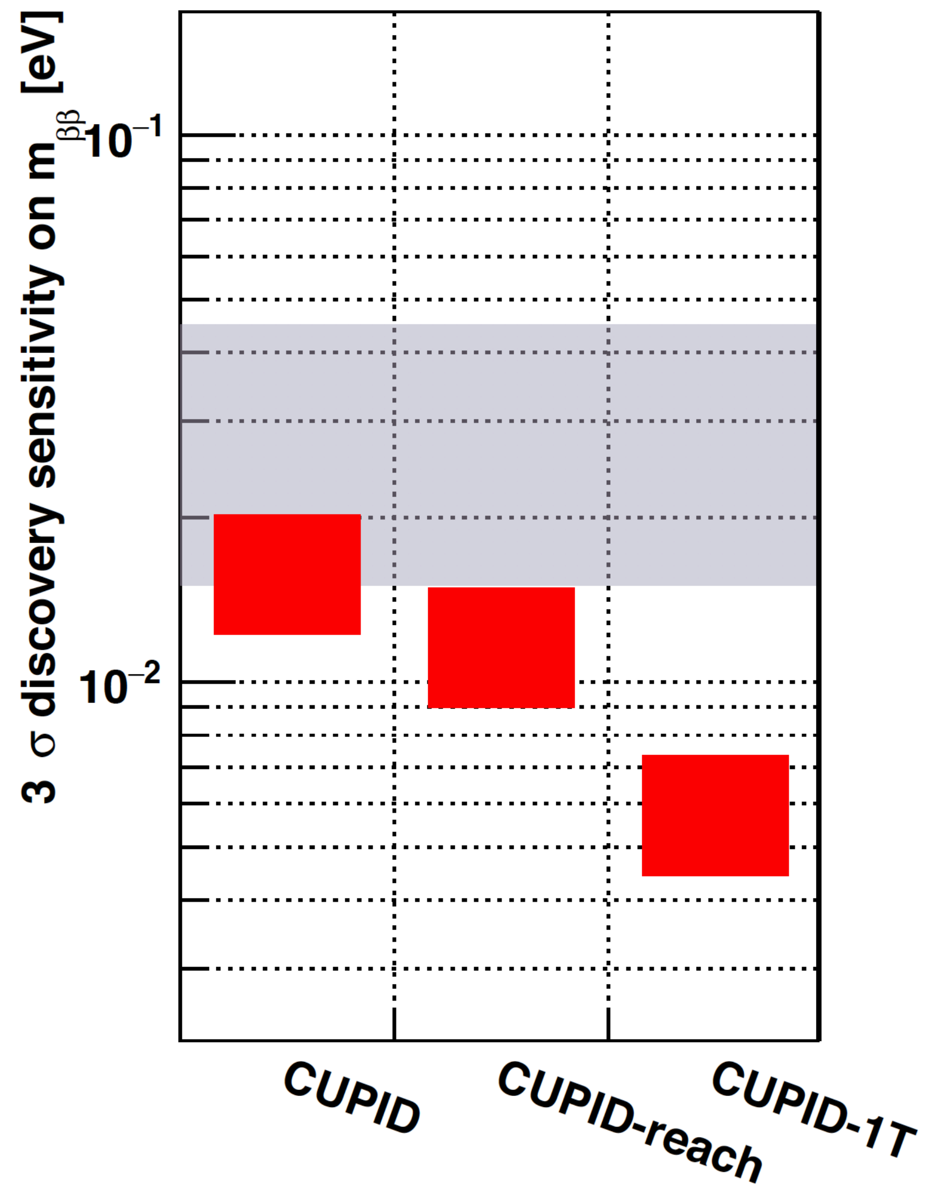
- SICCAS (Shanghai, China) has the capability to produce the enriched Li_2MoO_4 crystals, procuring the isotope from a Chinese manufacturer.
- SICCAS is the same company that produced all the CUORE TeO_2 crystals with radiopurity similar to CUPID requirements for Li_2MoO_4
- Pre-production is on-going

Solid CUPID background estimates based on CUORE and R&Ds



CUPID pros

- Existing infrastructure
- Known background
- Cost effective project
- Scalable

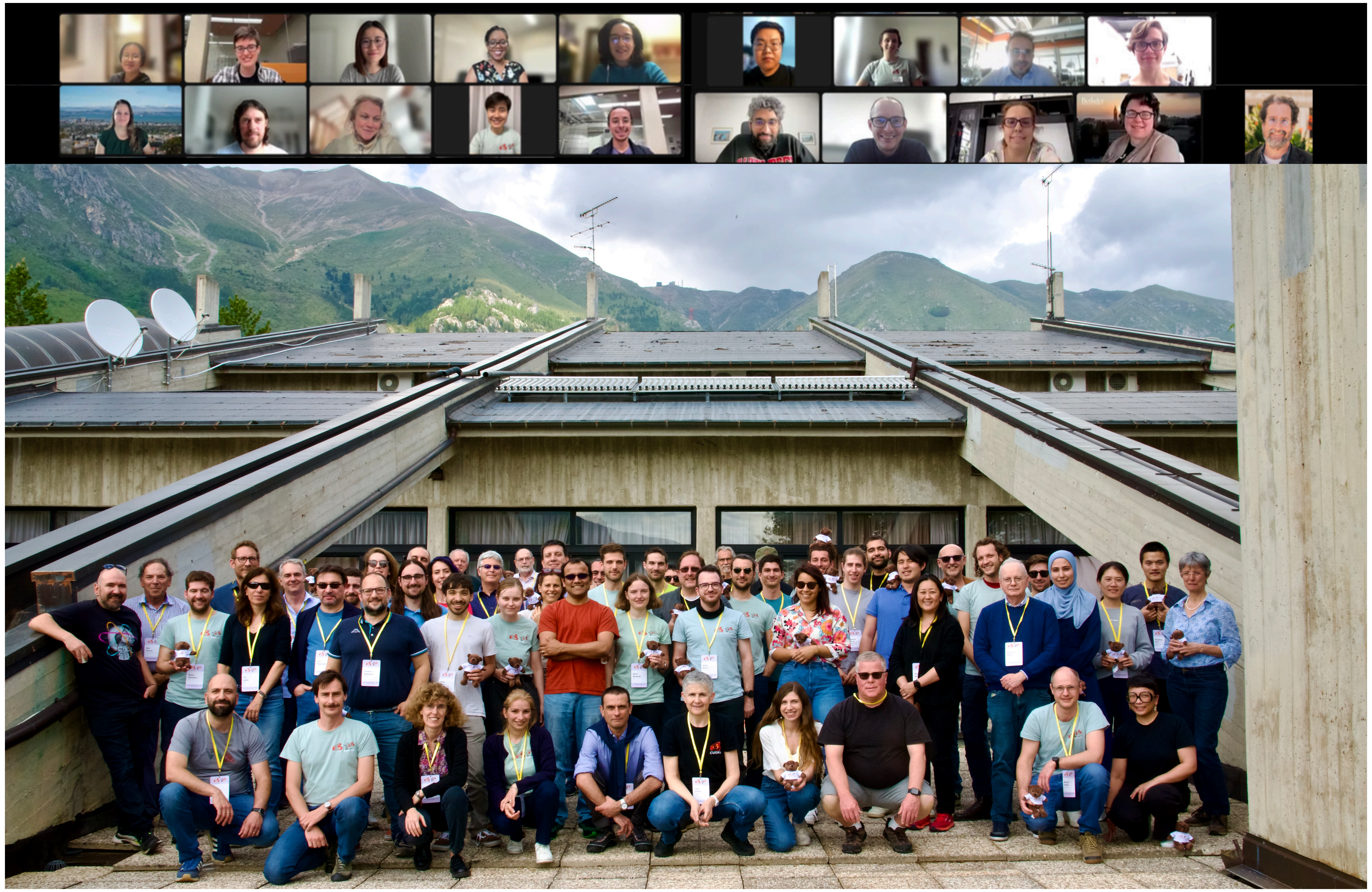


CUORE/CUPID Posters

Wide spectrum of physics results and developments

- K. Alfonso - CUORE analysis framework for 988 cryogenic calorimeters: Searching for $0\nu\beta\beta$ of ^{130}Te
- S. Ghislandi - Background decomposition of the CUORE experiment and measurement of the $2\nu\beta\beta$ half-life of ^{130}Te
- D. Mayer - Search for Fractionally-Charged Particles with CUORE
- S. Pagan - Low Energy Analyses with CUORE and a Search for Solar Axions
- S. Quitadamo - Exploring the impact of the Mediterranean Sea activity on the performance of CUORE mK-calorimetric experiment
- J. Torres - Reconstruction of muon events with the CUORE experiment
- K. J. Vetter - Enhancing CUORE Data Quality with Denoising Techniques
- S. Wagaarachchi - $0\nu\beta\beta$ search using CUORE dual-Site events

- A. Armatol - Development of NTL light detectors for the CUPID $0\nu\beta\beta$ experiment
- A. Armatol - Multiplexed TES Based Light Detectors using transition edge sensors for CUPID and beyond
- V. Berest - The CUPID $0\nu\beta\beta$ experiment
- M. Buchynska - The CROSS demonstrator: structure, performance and physics reach
- D. Cintas Gonzales - Background simulations for CROSS experiment
- S. Ghislandi, S. Quitadamo - Evaluation of the CUPID First Tower Prototype performance
- P. Loaiza - Backgrounds of the CUPID experiment
- P. Loaiza - Results from the CUPID-Mo Experiment
- B. Schmidt - BINGO: Investigation of the Majorana nature of neutrinos at the few meV level of the neutrino mass scale
- A. Zolotarova - TINY experiment: search for $0\nu\beta\beta$ decay with ^{96}Zr and ^{150}Nd



INFN
Istituto Nazionale di Fisica Nucleare

CSNSM
CENTRE DE SCIENCES NUCLÉAIRES ET DE SCIENCES DE LA MATIÈRE

SINAP

Yale

BERKELEY LAB

VIRGINIA TECH

Berkeley
UNIVERSITY OF CALIFORNIA

SAPIENZA
UNIVERSITÀ DI ROMA

CAL POLY
SAN LUIS OBISPO

UNIVERSITY OF South Carolina

GSSI

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

UNIVERSITÀ DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE

ALMA MATER STUDIORUM A.D. 1088

UNIVERSITAS STUDII PADUANI

SHANGHAI JIAO TONG UNIVERSITY 1896

CUORE

JOHNS HOPKINS UNIVERSITY

Massachusetts Institute of Technology

UCLA

University of Pittsburgh

Acknowledgements

The CUORE Collaboration thanks the directors and staff of the Laboratori Nazionali del Gran Sasso and the technical staff of our laboratories.

This work was supported by the Istituto Nazionale di Fisica Nucleare (INFN); the National Science Foundation under Grant Nos. NSF-PHY-0605119, NSF-PHY-0500337, NSF-PHY-0855314, NSF-PHY-0902171, NSF-PHY-0969852, NSF-PHY-1307204, NSF-PHY-1314881, NSF-PHY-1401832, and NSF-PHY-1913374; Yale University, Johns Hopkins University, and University of Pittsburgh.

This material is also based upon work supported by the US Department of Energy (DOE) Office of Science under Contract Nos. DE-AC02-05CH11231 and DE-AC52-07NA27344; by the DOE Office of Science, Office of Nuclear Physics under Contract Nos. DE-FG02-08ER41551, DE-FG03-00ER41138, DE- SC0012654, DE-SC0020423, DE-SC0019316.

This research used resources of the National Energy Research Scientific Computing Center (NERSC). This work makes use of both the DIANA data analysis and APOLLO data acquisition software packages, which were developed by the CUORICINO, CUORE, LUCIFER, and CUPID-0 Collaborations.