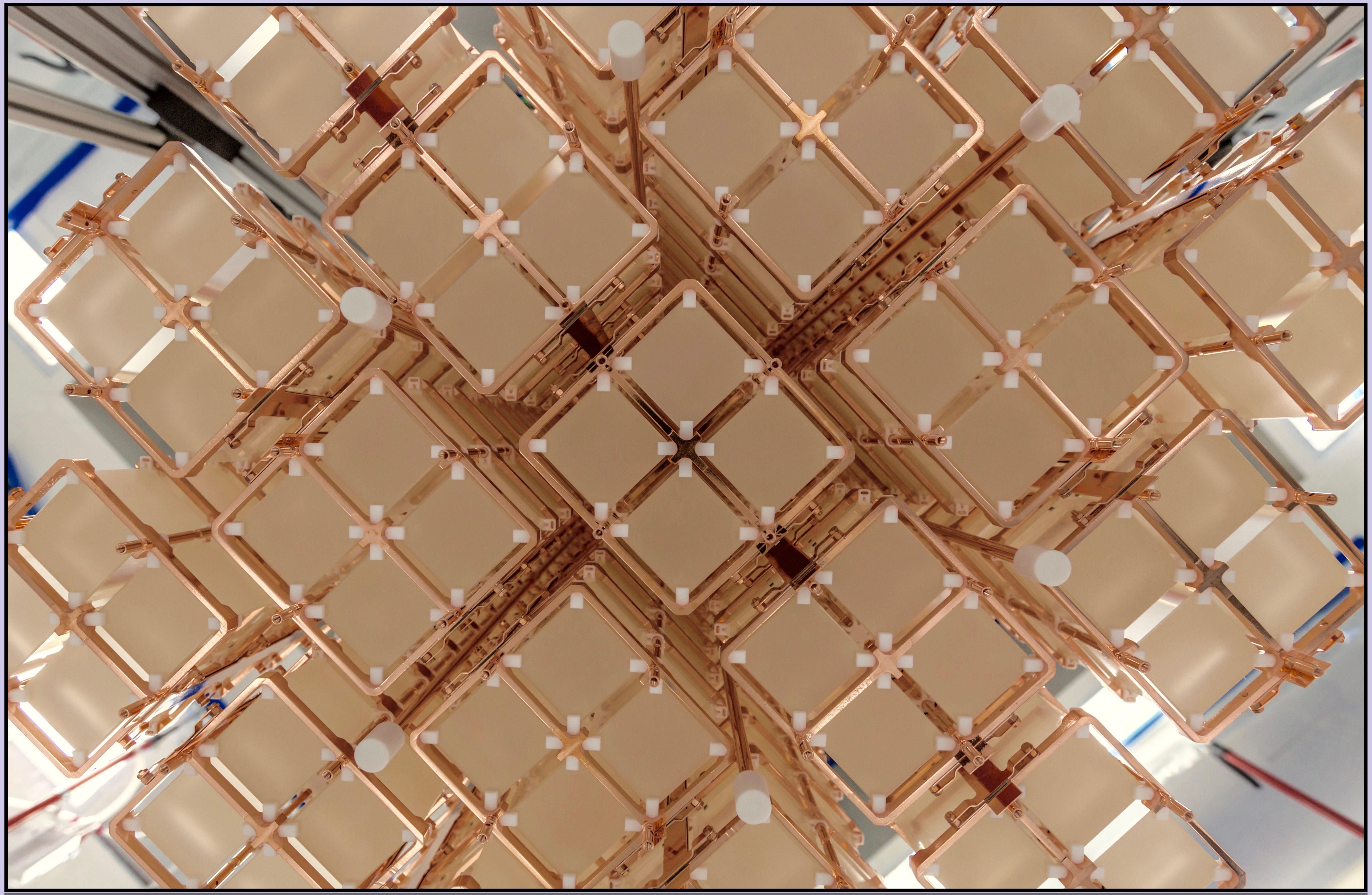


Latest results from the CUORE experiment

Alice Campani on behalf of the CUORE collaboration

Università di Genova

Prague, 19 July 2024

CUORE

INFN Istituto Nazionale di Fisica Nucleare

The importance of $0\nu\beta\beta$ for particle physics and cosmology

- Beyond Standard Model counterpart of *double beta decay* ($2\nu\beta\beta$), a rare second order nuclear process observed in **even-even nuclei** for which single beta decay is energetically forbidden
- It violates lepton number conservation ($\Delta L = 2$):
  lepton number asymmetry could explain the ***matter-antimatter asymmetry*** in the Universe
- Any observation would provide information on the neutrino ***mass scale*** and ***ordering***
- Assuming the exchange of a light Majorana neutrino (simplest scenario) the $0\nu\beta\beta$ decay rate is

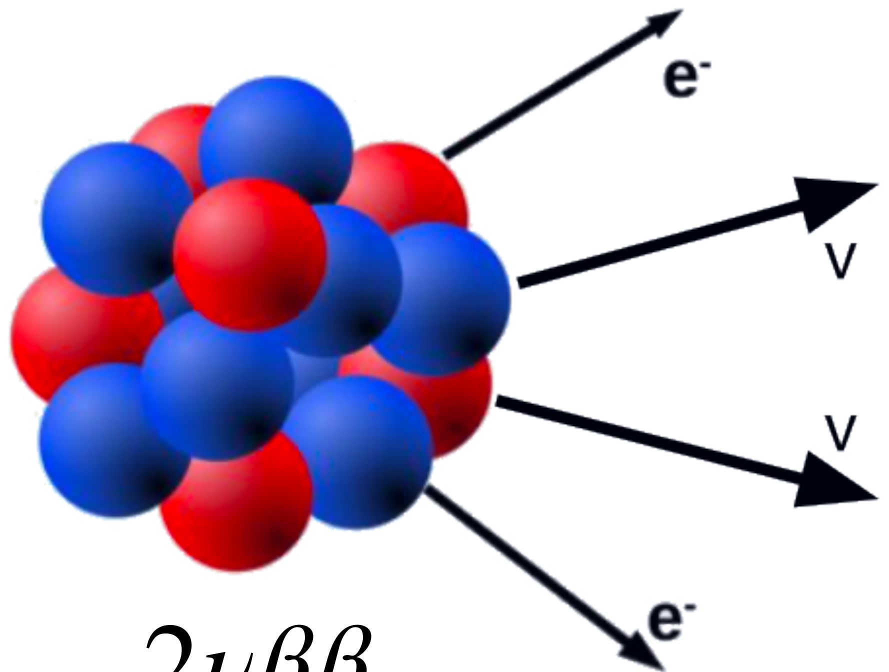
$$\Gamma_{0\nu\beta\beta} \propto G_{0\nu}(Q,Z)\left|M_{0\nu}\right|^2 \frac{\left| < m_{\beta\beta} > \right|^2}{m_e{}^2}$$

Phase space factor

Nuclear matrix element

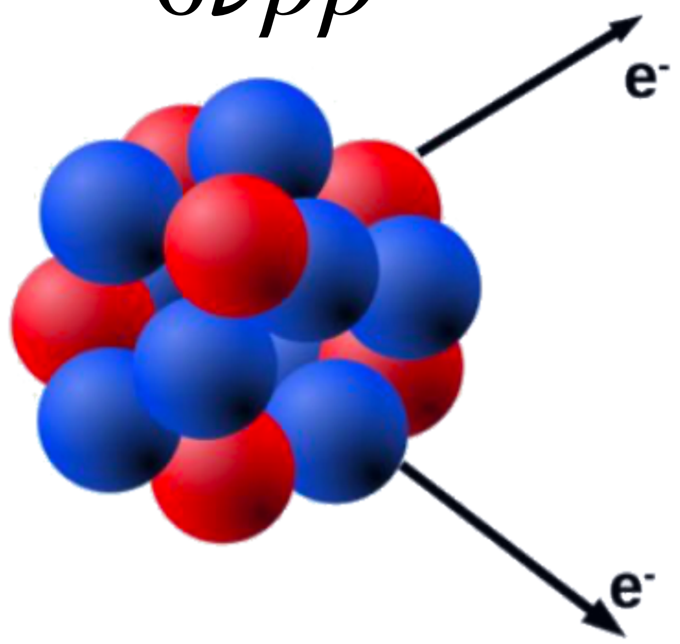
Effective Majorana mass

$$| < m_{\beta\beta} > | = \sum_{i=1,2,3} U_{ei}^2 \, m_i$$



$2\nu\beta\beta$

$0\nu\beta\beta$



CUORE & the search for $0\nu\beta\beta$: the experiment in a nutshell

Cryogenic Underground Observatory for Rare Events

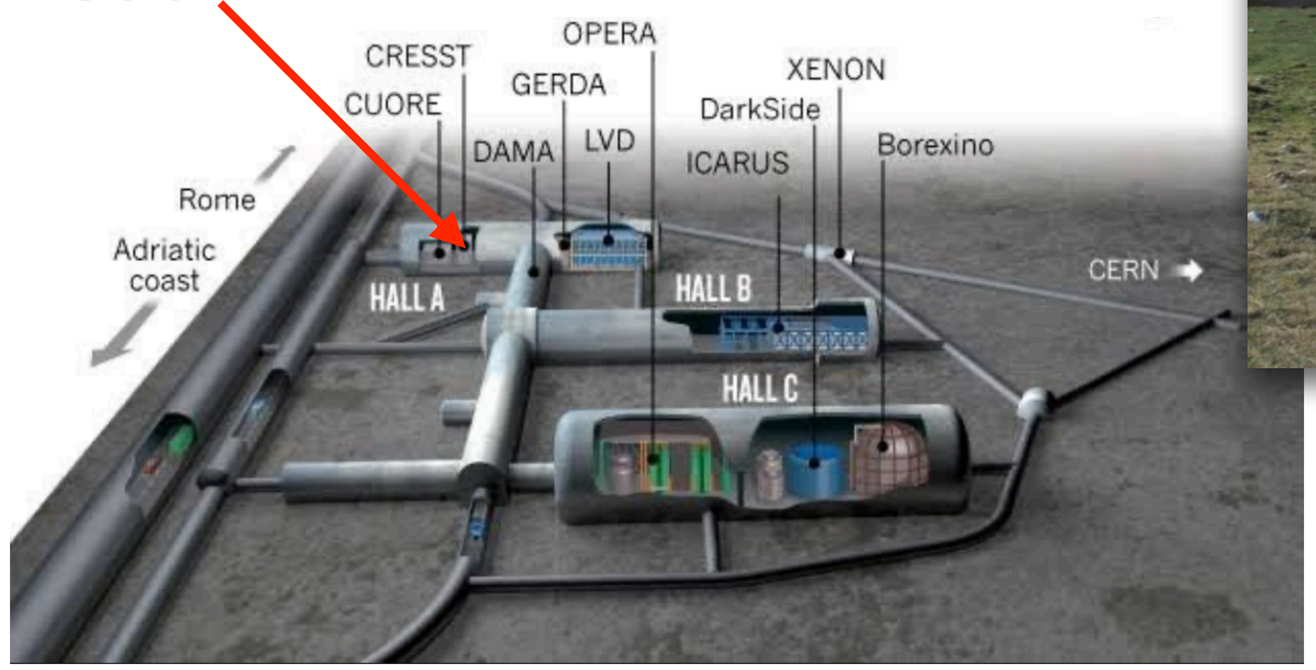
Adv. in High En. Phys. 2015, 879871
Eur. Phys. J. C77 (2017), 532

- Scientific goal: search for $0\nu\beta\beta$ decay of ^{130}**Te** (isotopic fraction ~34%, $Q_{\beta\beta}$~2528 keV, only ^{208}Tl γ line @ 2615 keV above)
- **Tonne-scale detector**: 988 $^{(nat)}TeO_2$ crystals arranged in 19 towers and operated at ~10 mK
  TeO_2 mass is 742 kg (206 kg of ^{130}Te)
- **Underground** at the **LNGS** (Abruzzo, Italy)

Scalability of the technique

Background

CUORE



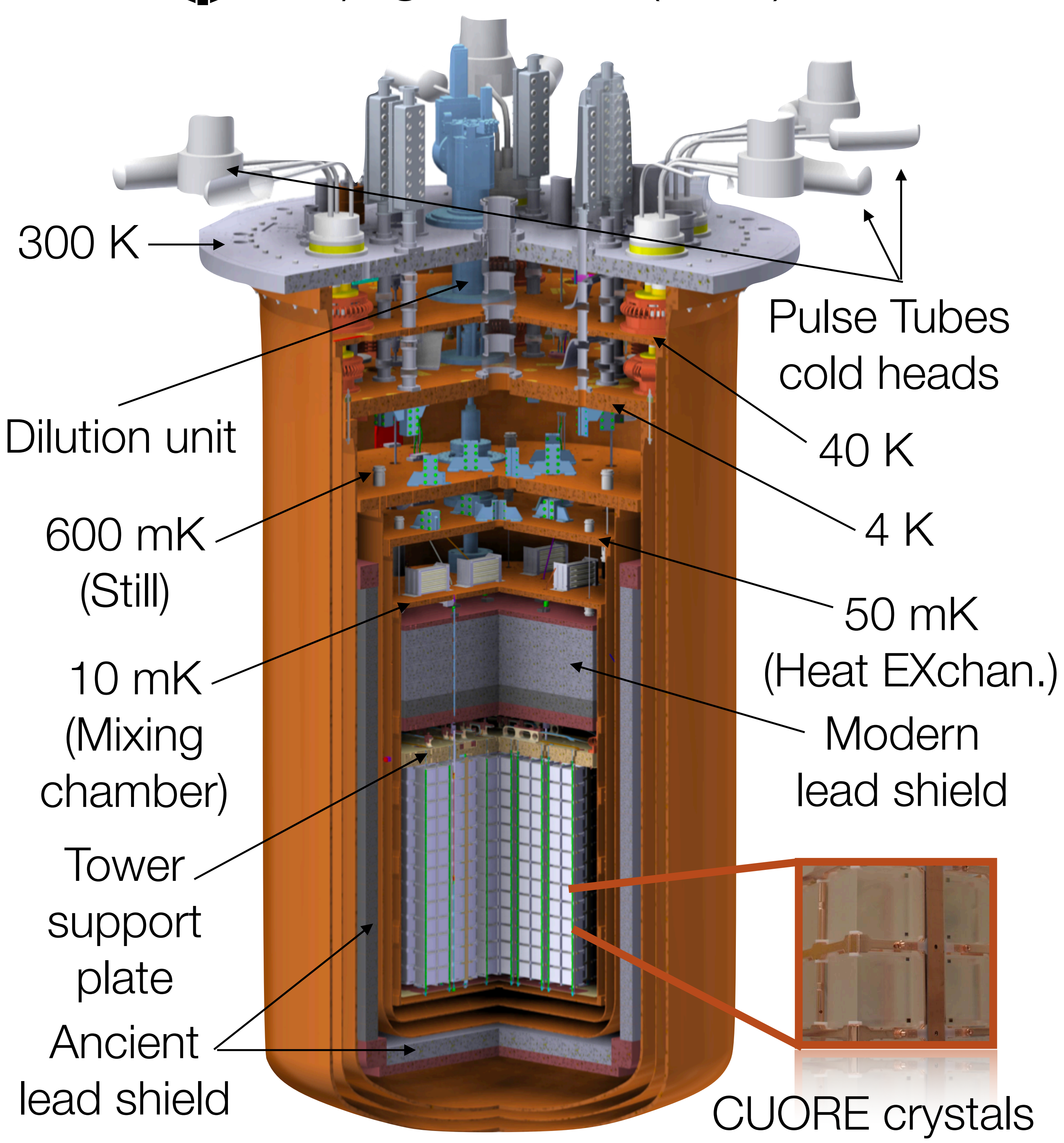
High energy resolution

Effective **FWHM** at $Q_{\beta\beta} = (7.320 \pm 0.024)\,\mathrm{keV}$

Background index in the ROI: $1.42(2)\cdot 10^{-2}$ counts/keV/kg/yr

The CUORE experiment challenge:

Cryogenics 102 (2019) 9-21



- Cryogen free dilution cryostat:
- Mass <4 K (~50 mK): 15 (3 tons)
- Operating stably (>5 yr) <20 mK

Low temperature

Low radioactivity

LNGS natural shielding

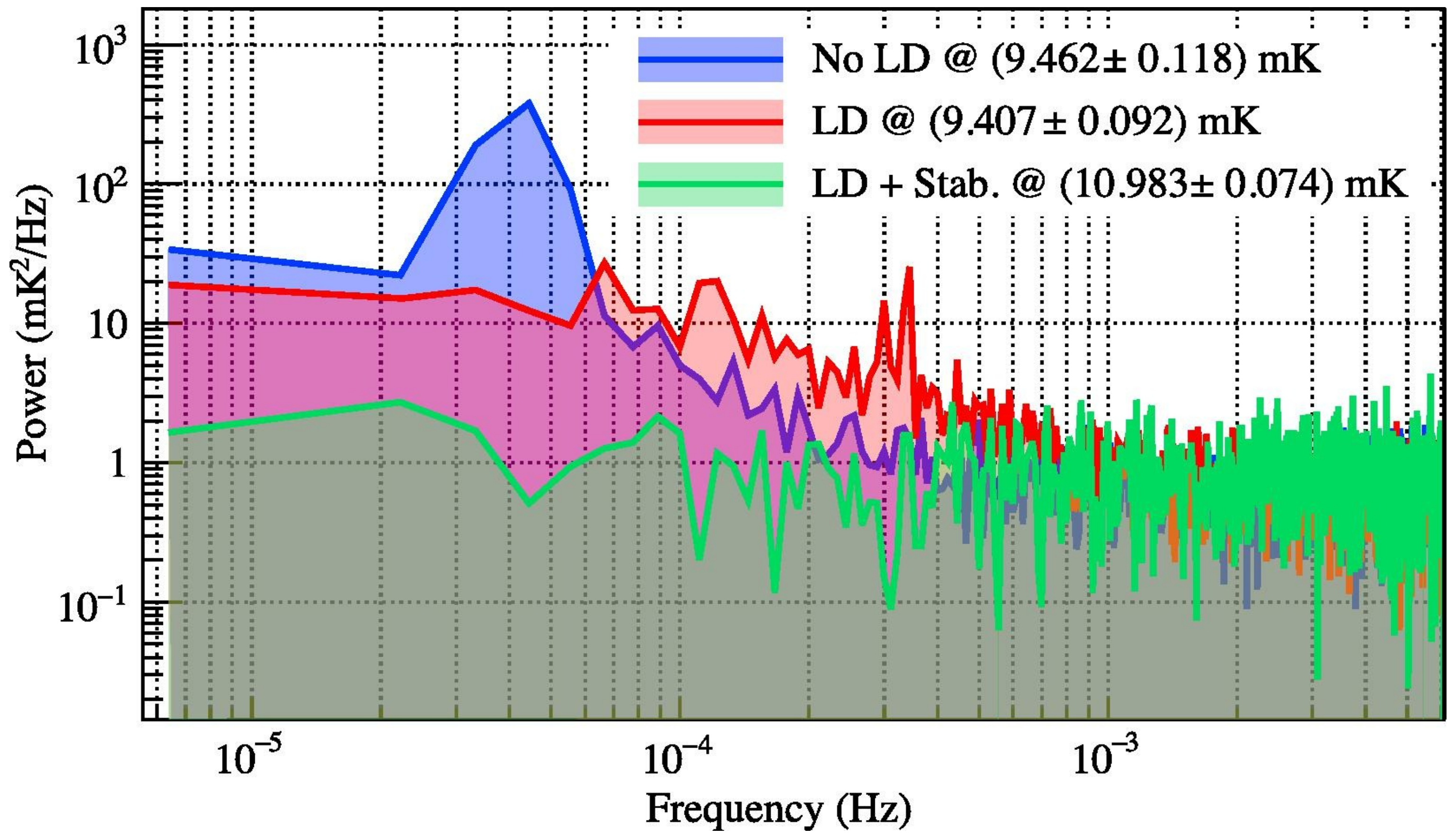
External shields:
from γs and neutrons

Internal shields:
Top: 30-cm modern lead
Side and bottom: 6-cm ancient roman Pb from a shipwreck
(^{210}Po<4 mBq/kg)

External structure to decouple detector and the cryostat

Active noise cancellation system

Cryogenics 93, 55-56 (2018)



Denoising of the continuous data using ancillary diagnostic devices

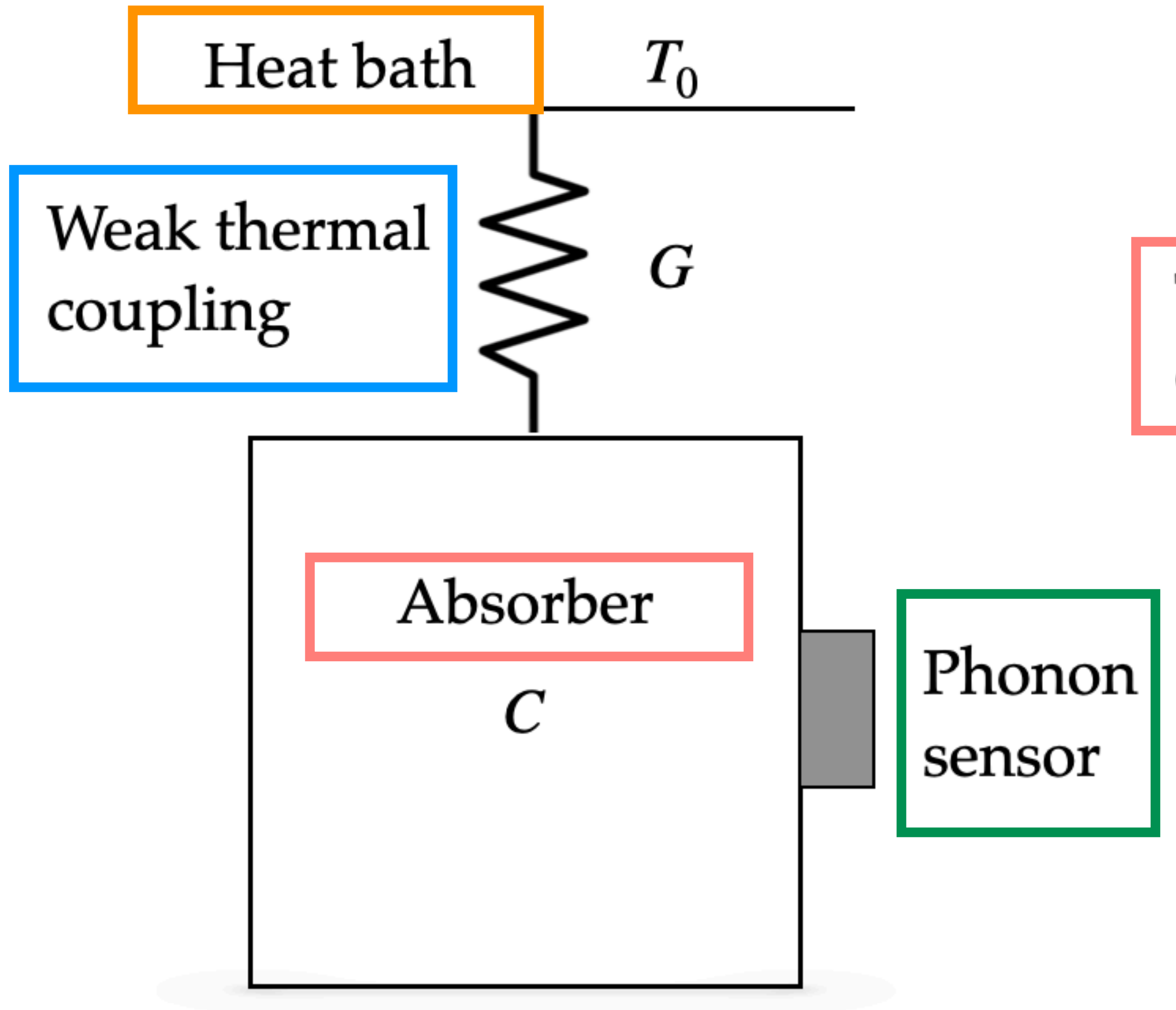
Eur. Phys. J. C 84, 243 (2024)

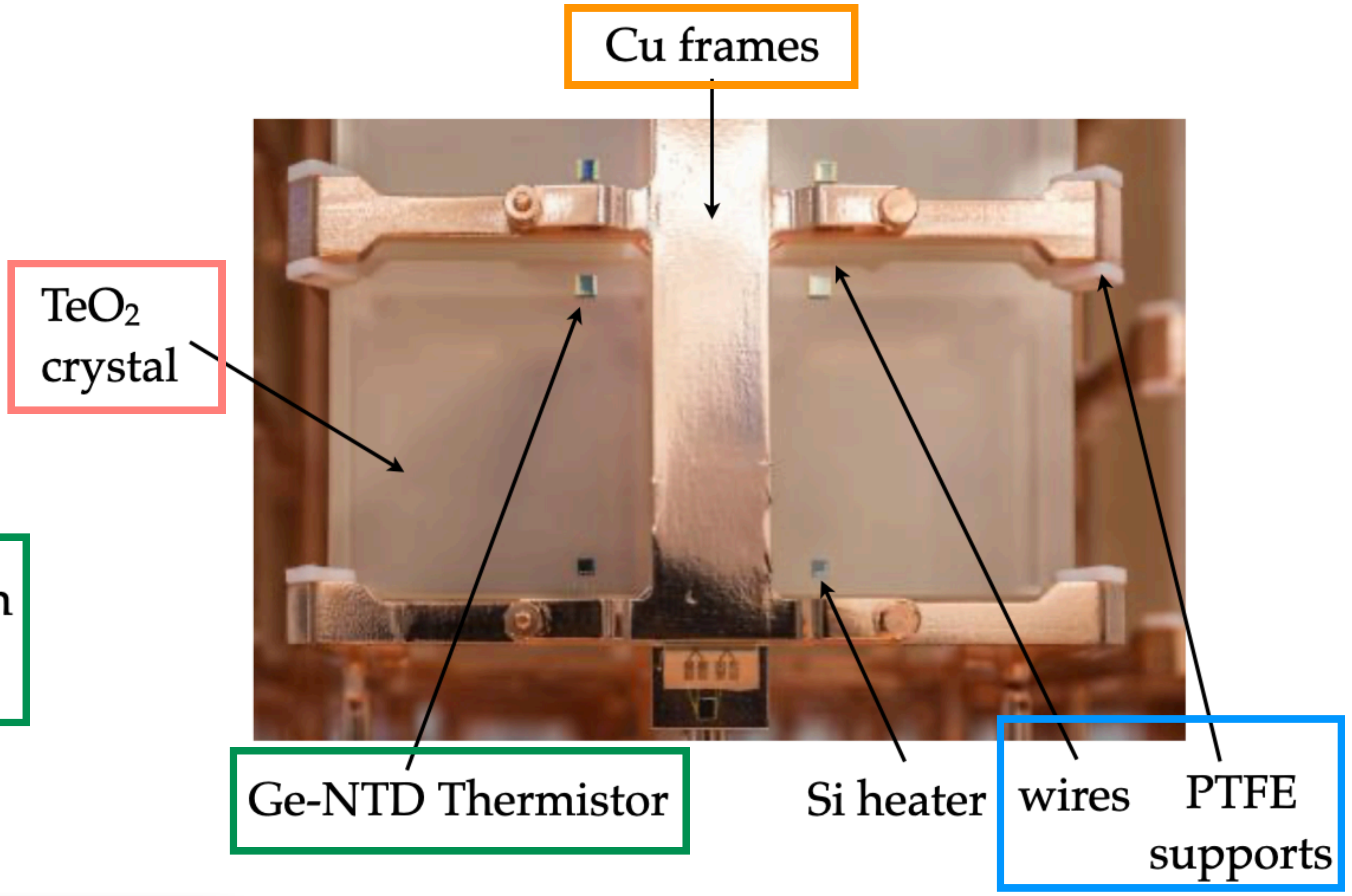
Low vibrations and noise

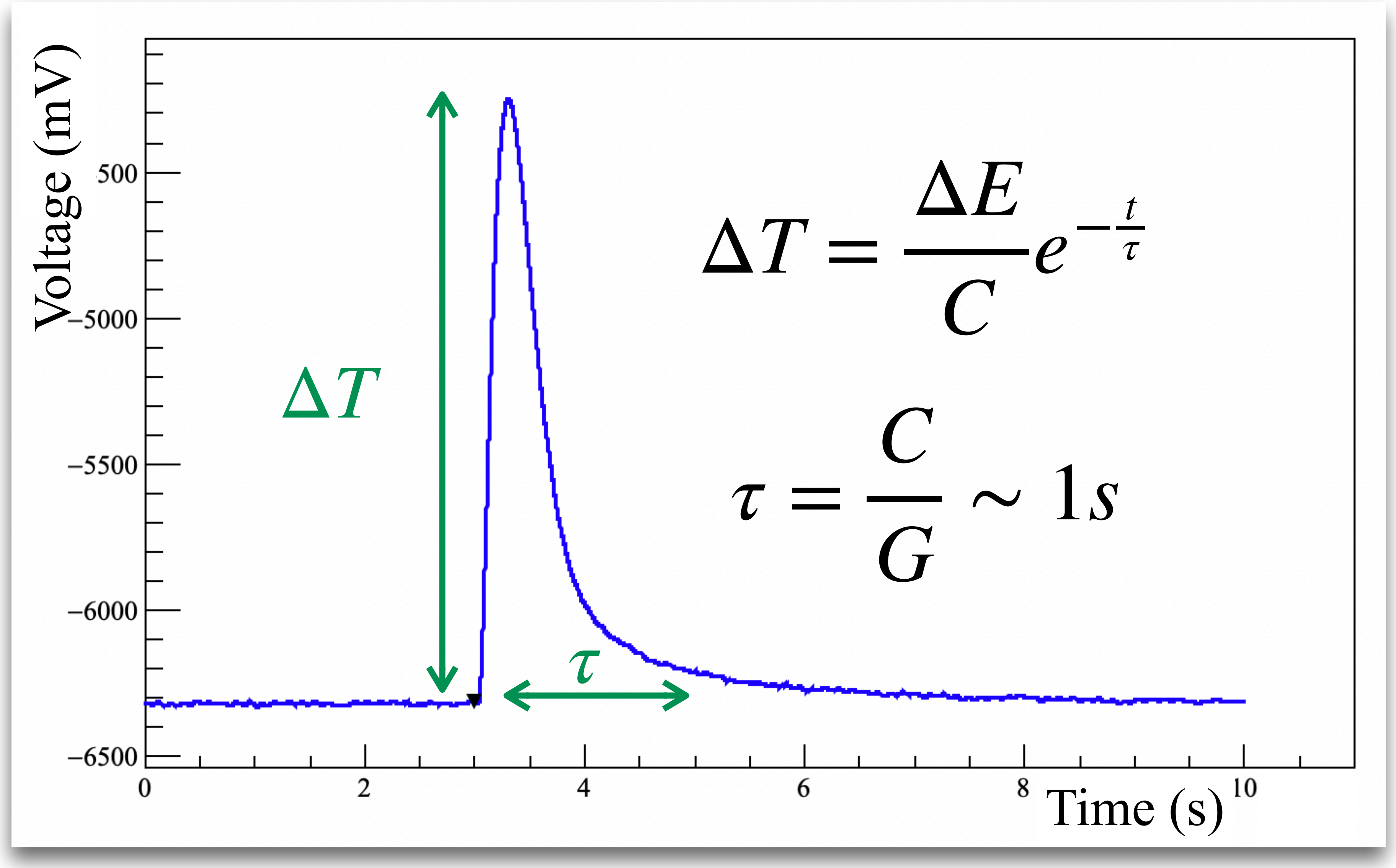
Cryogenic calorimeters for rare decays search

The **energy** released in a particle interaction is measured via **thermal excitations** (*phonons*)

The **temperature increase** is converted into an **electric signal** by a cryogenic sensor (e.g. a thermistor)



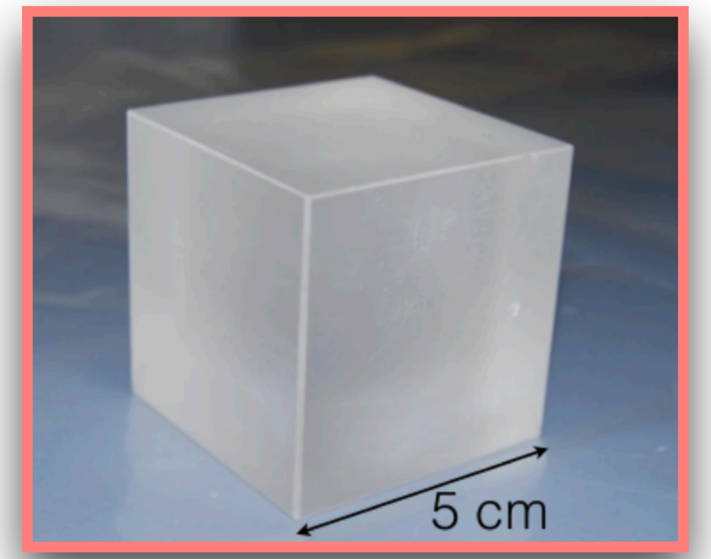




TeO_2 crystal

$C \propto T^3$ (Debye law)

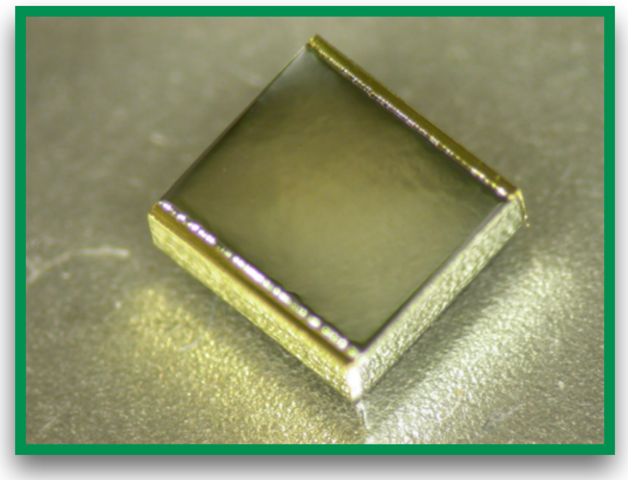
C≈ nJ/K



Ge-NTD thermistor

$R \propto e^{\sqrt{T_0/T}}$

ΔR~3MΩ/MeV



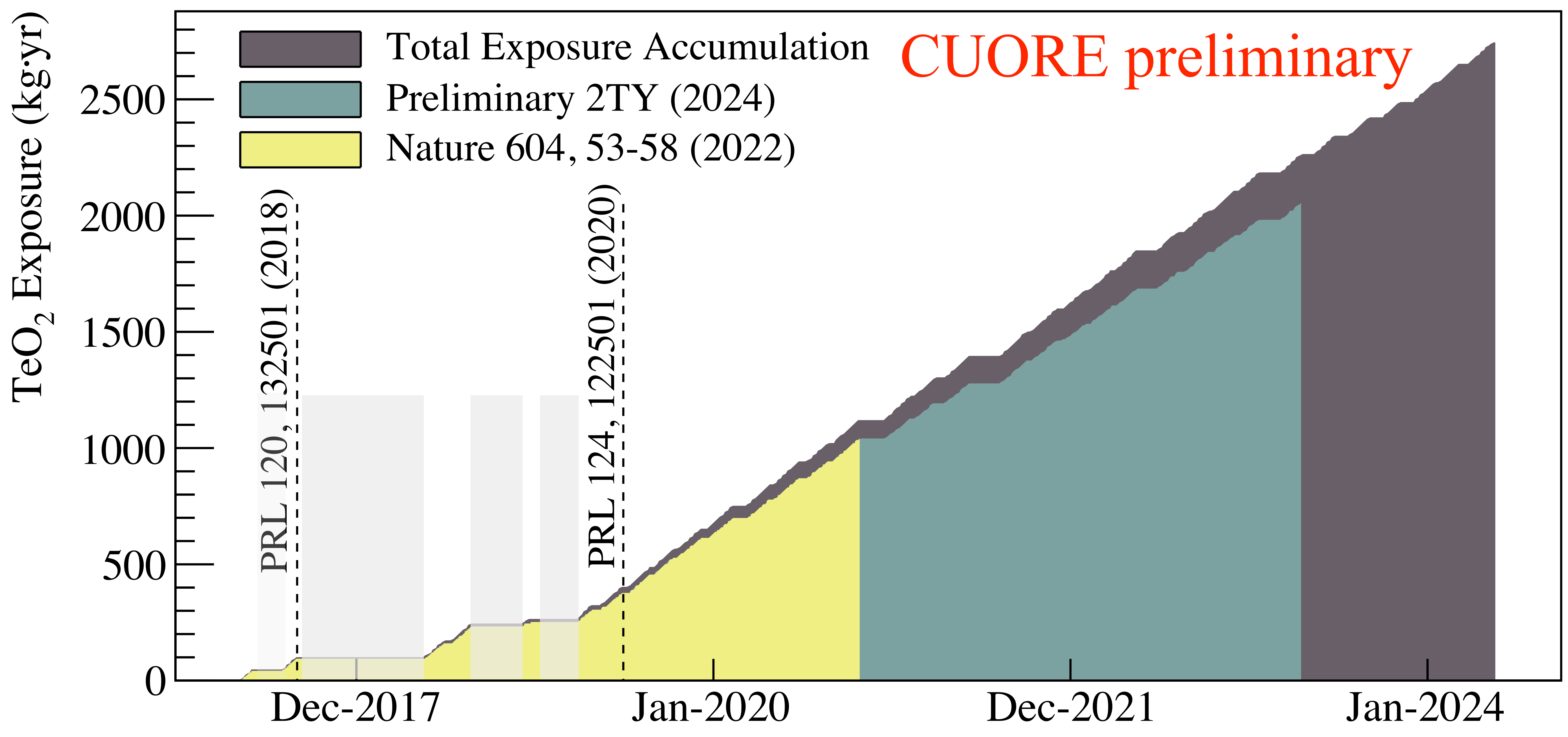
Operating at a temperature of ~10 mK:

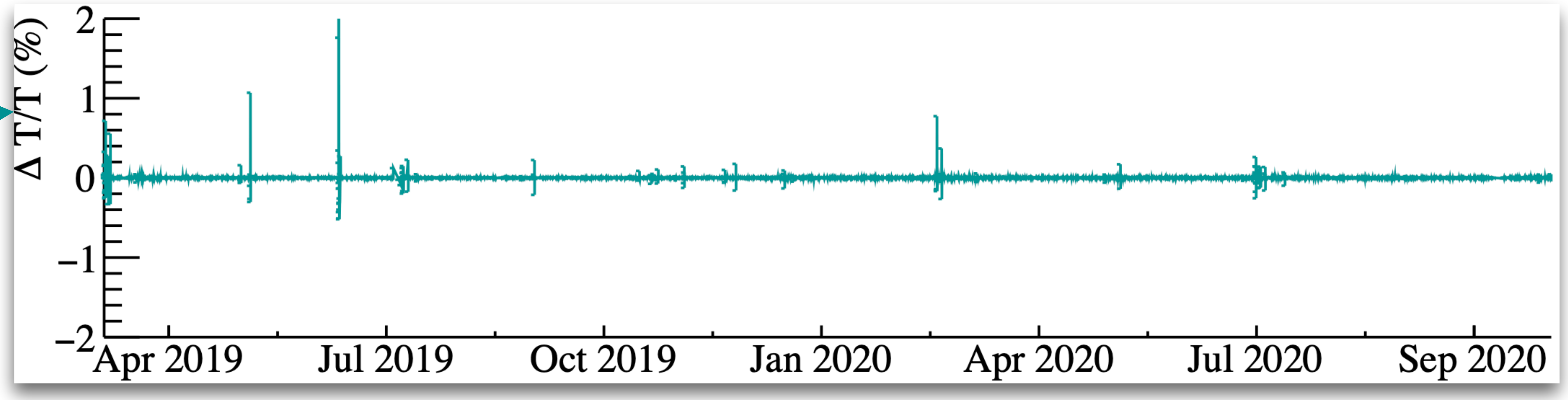
1 MeV energy release causes ΔT~100 μK

We use a **Si heater** to inject stable voltage pulses and do **thermal gain stabilization**

Data taking with CUORE

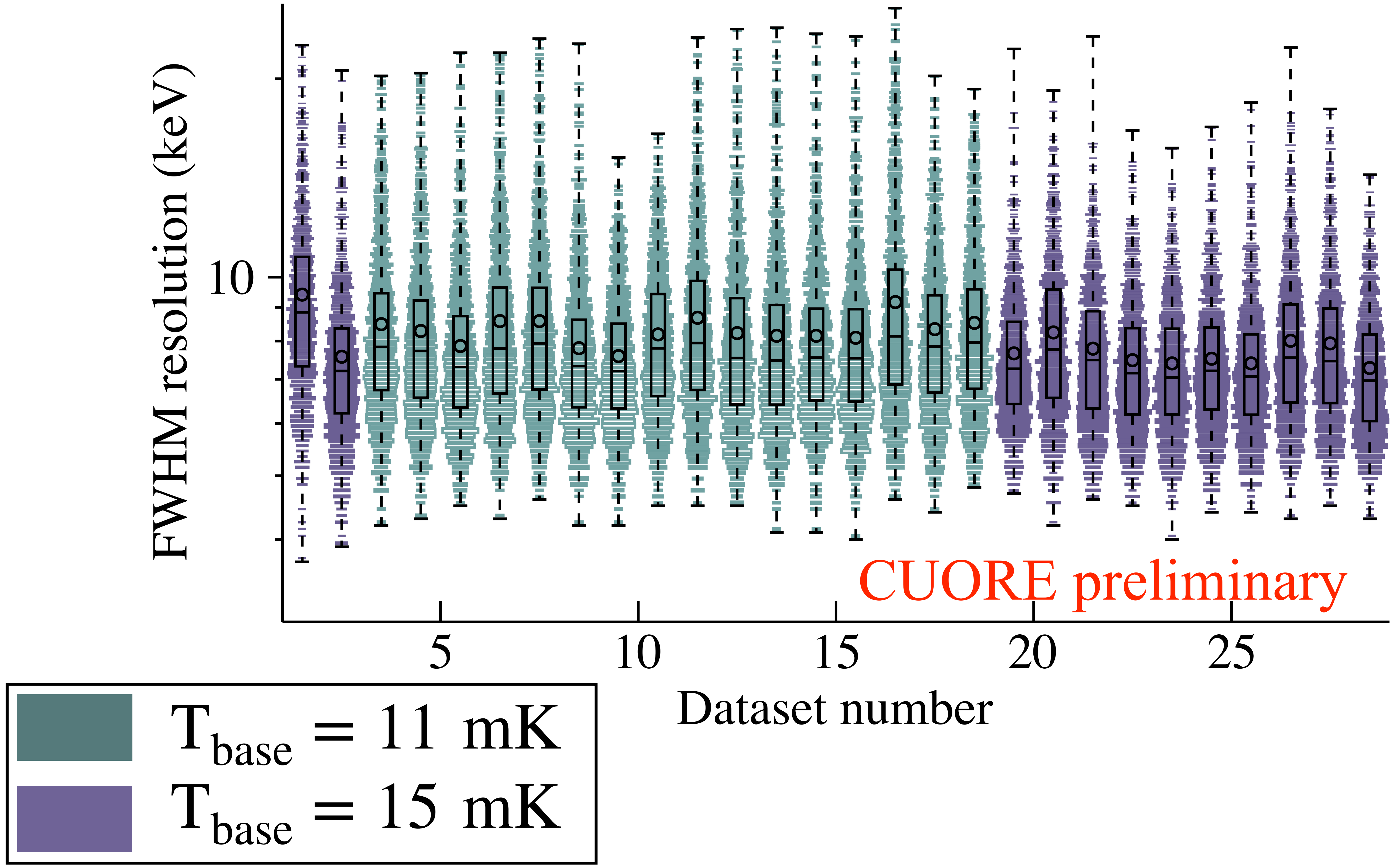
- Data split in *datasets*: 1-2 months of physics data bookended by calibration
- Typical trigger rate 50 mHz in calibration, ~6 mHz during physics runs
- Voltage across NTD Ge thermistors continuously sampled at 1kHz, a software trigger is applied offline
- Data taking started in 2017, 2017-2019: optimization campaigns
- Since march 2019 steady data taking with > 90% uptime in stable temperature conditions: more than 2.7 tonne yr of raw exposure collected so far!
- Average data taking rate of ~50 kg·yr/month





Nature 604, 53-58 (2022)

Detector performance on the 2 tonne yr data

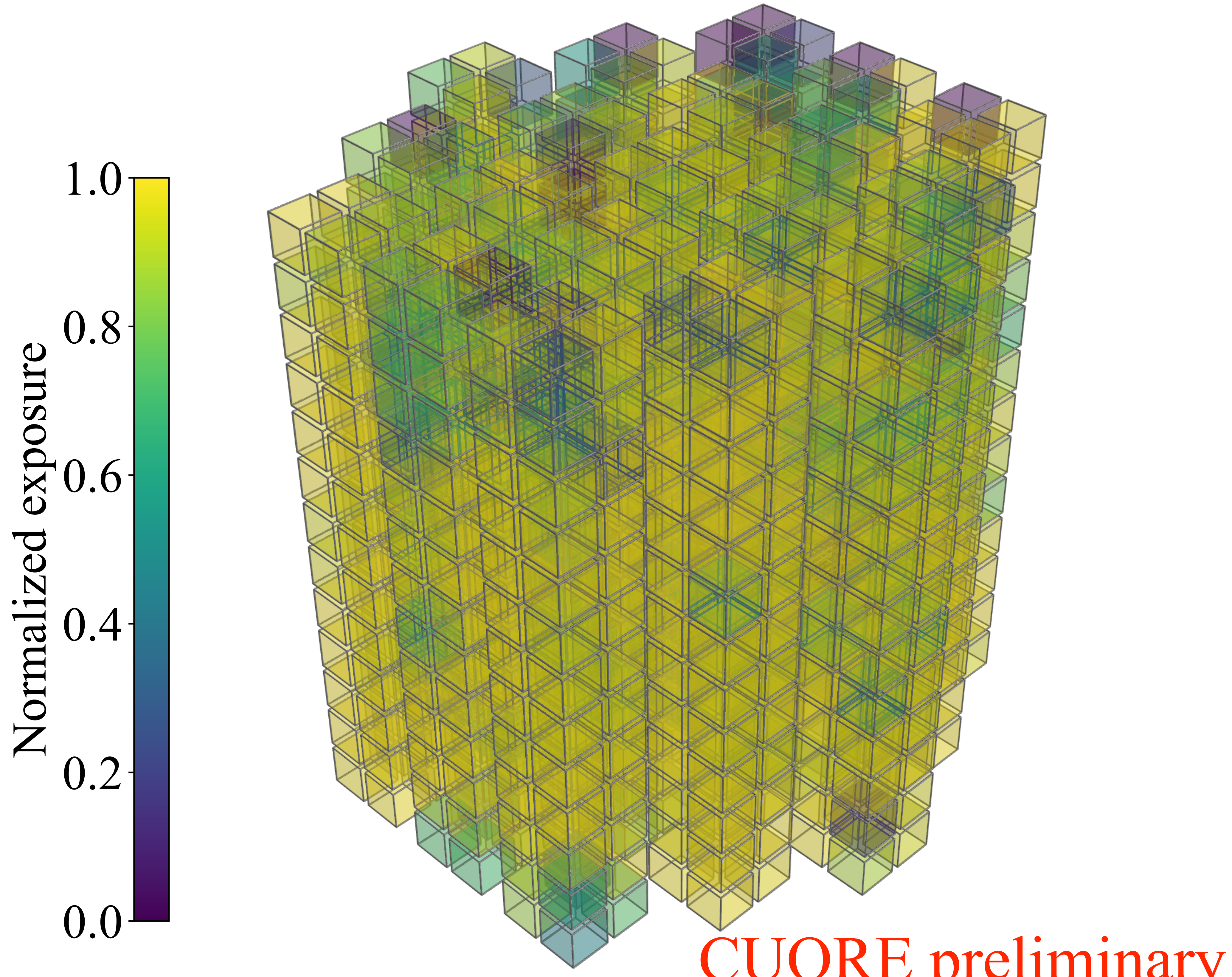


$$\mathrm{FWHM}\left({}^{208}\mathrm{Tl}\right) = (7.540 \pm 0.024)\ \mathrm{keV}$$

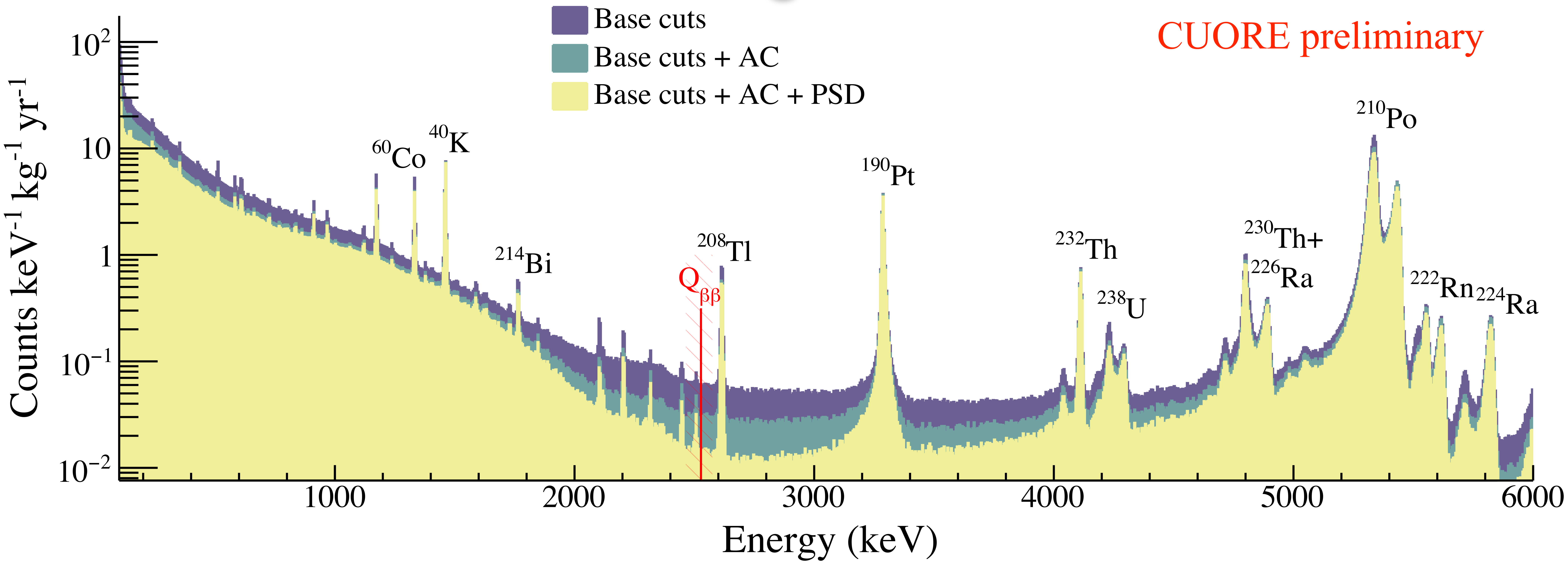
$$\mathrm{FWHM}\left(Q_{\beta\beta}\right) = (7.320 \pm 0.024)\ \mathrm{keV}$$

$$\Delta E\left(Q_{\beta\beta}\right) = 0.52^{+0.04}_{-0.30}\ \mathrm{keV}$$

- **28 datasets** (May 2017 - April 2023) for a total TeO_2 (^{130}Te) exposure of **2039.0** (**567.0**) **kg·yr** **uniformly distributed** on the detector



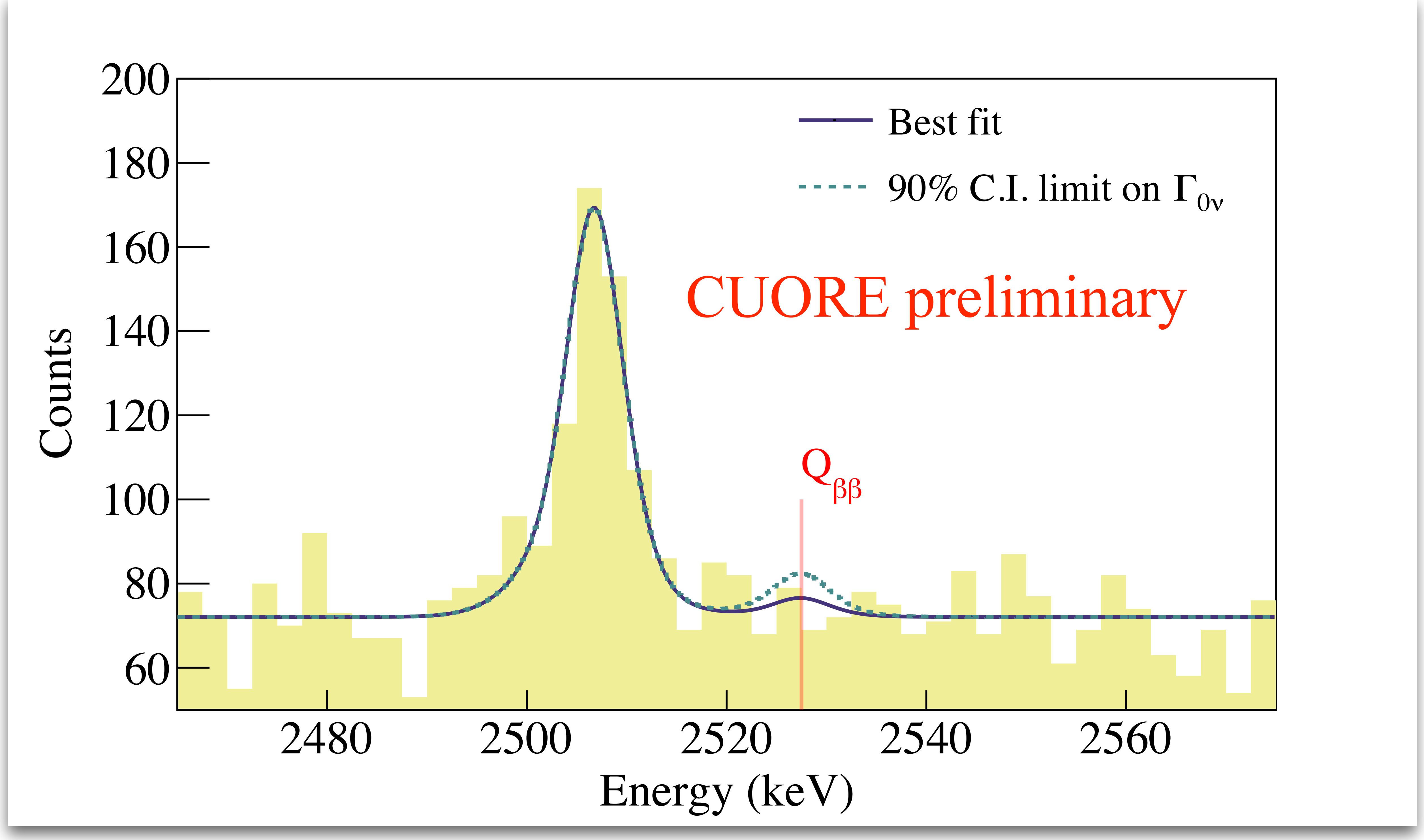
Detector performance on the 2 tonne yr data



- **Base cut** efficiency 95.624(18) %
- **Anti-coincidence cut** efficiency 99.80(5) %
- **Pulse shape (PSD) cut** efficiency 97.9(18) %
- **Total analysis cut** efficiency **93.4(18) %**
- ~**914/984** channels surviving cuts per dataset

arxiv:2404.04453

The search for $0\nu\beta\beta$ decay with 2 tonne · yr data



No evidence of $0\nu\beta\beta$: new limit on ^{130}Te half-life

$$T^{1/2}_{0\nu\beta\beta} > 3.8 \cdot 10^{25}\ \text{yr}\ (90\,\%\,\text{C.I.})$$

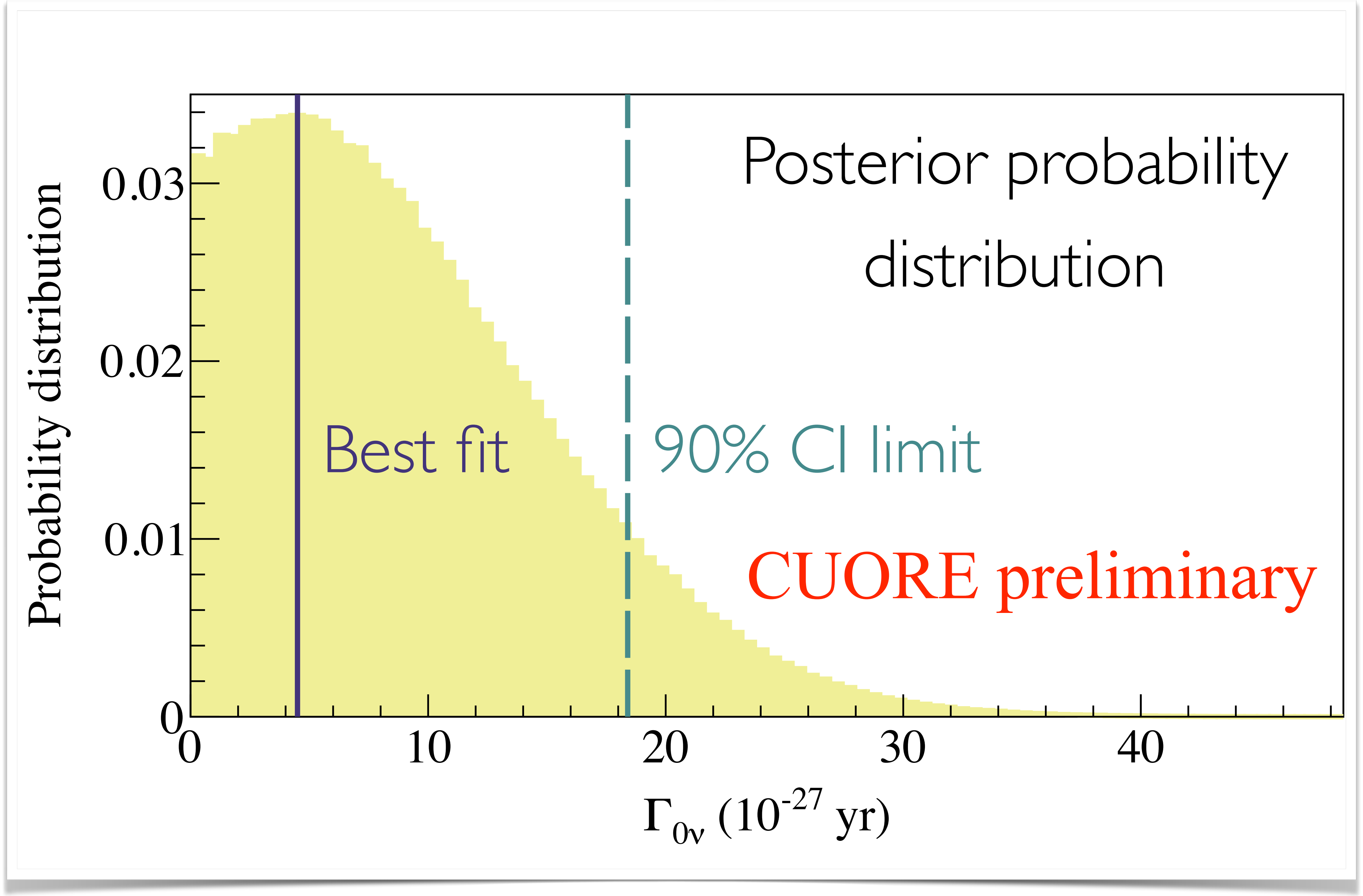
Frequentist limit $T^{1/2}_{0\nu\beta\beta} > 3.7 \cdot 10^{25}\ \text{yr}\ (90\,\%\,\text{C.L.})$

Average background index

$$b = (1.42 \pm 0.02) \cdot 10^{-2}\ (\text{counts/keV/kg/yr})$$

Region of interest (2465, 2575) keV

- flat background
- ^{60}Co sum peak at 2505.7 keV
- posited peak at 2528 keV for the signal



Unbinned Bayesian (and frequentist) fit with $\Gamma_{0\nu\beta\beta} > 0$

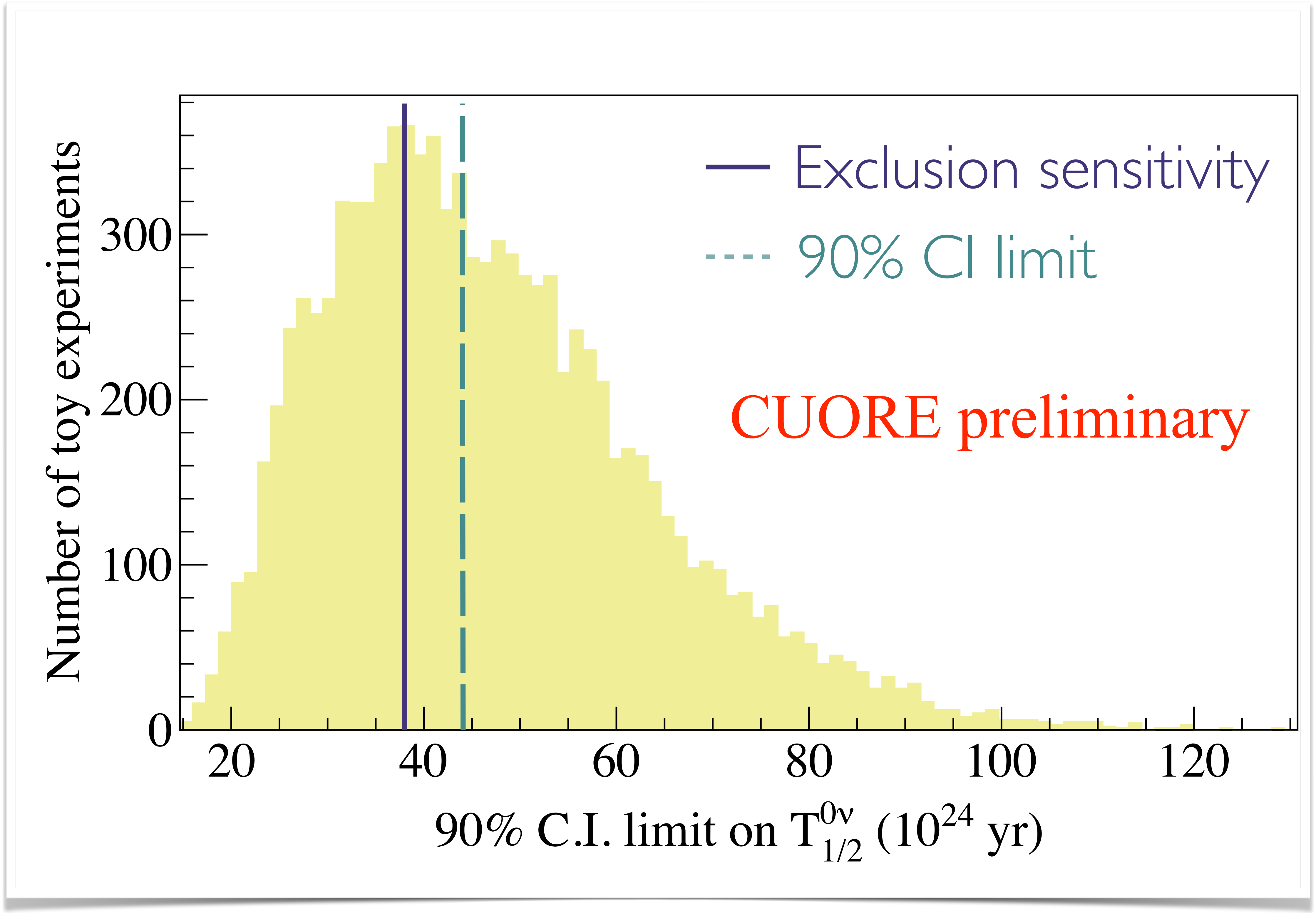
Systematics treated as nuisance parameters in the fit

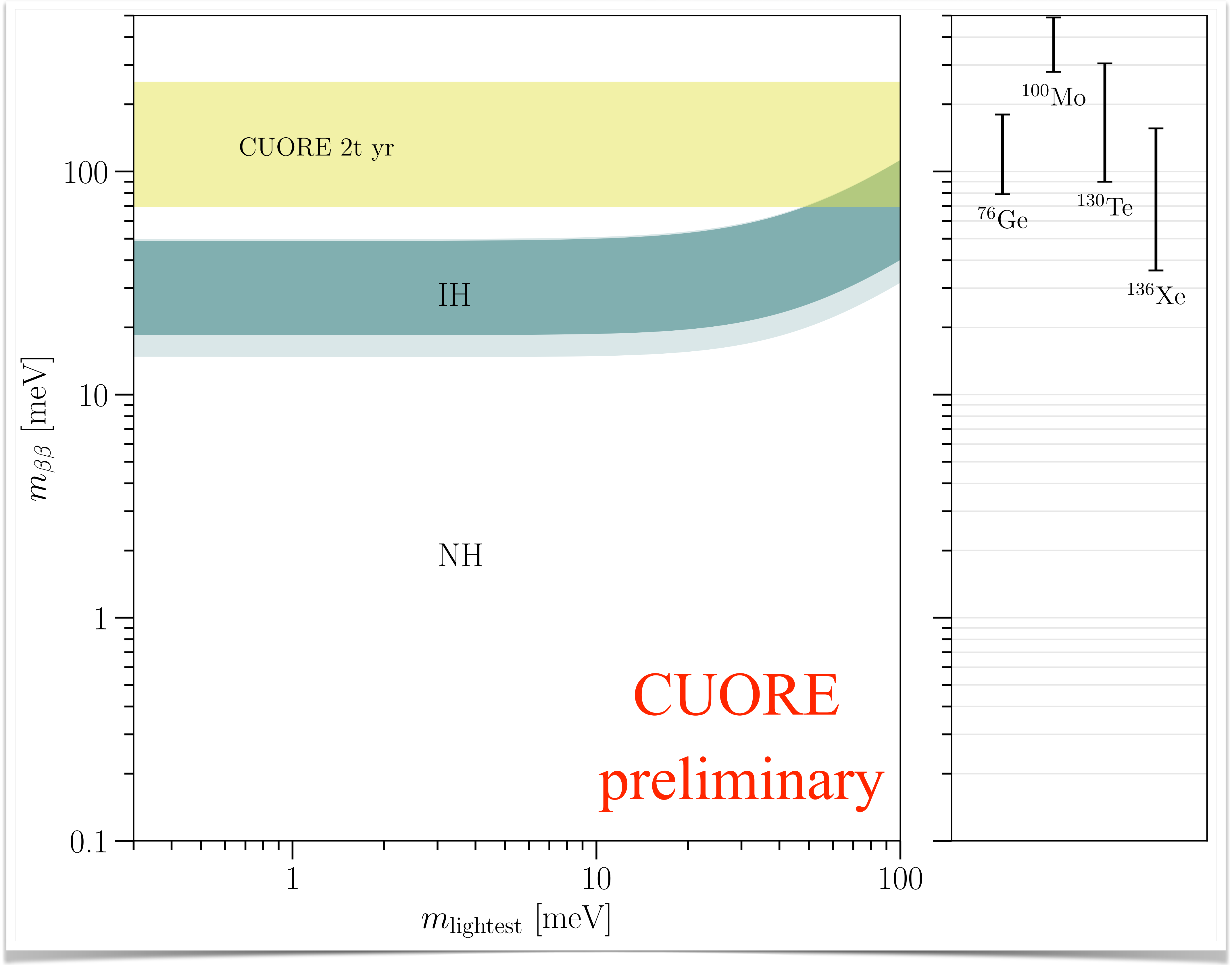
The search for $0\nu\beta\beta$ decay with 2 tonne · yr data

Median exclusion sensitivity from toy MC experiments

$$T^{1/2}_{0\nu\beta\beta} = 4.4 \cdot 10^{25}\ \mathrm{yr}\ (90\,\%\,\mathrm{C.I.})$$

The probability to obtain a more stringent limit is **67%**





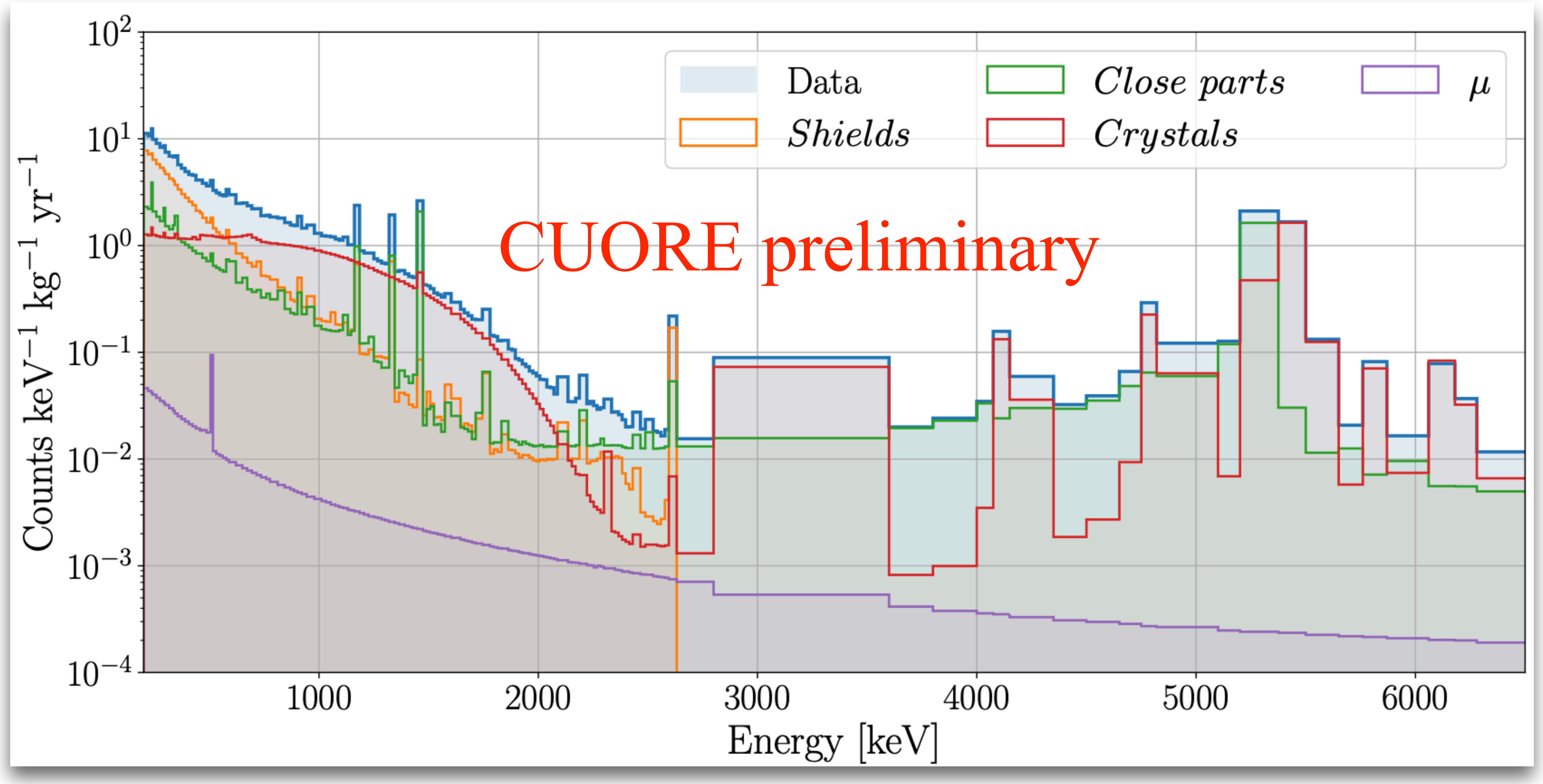
arxiv:2404.04453

Assuming the exchange of a light Majorana neutrino the limit on the effective Majorana mass is

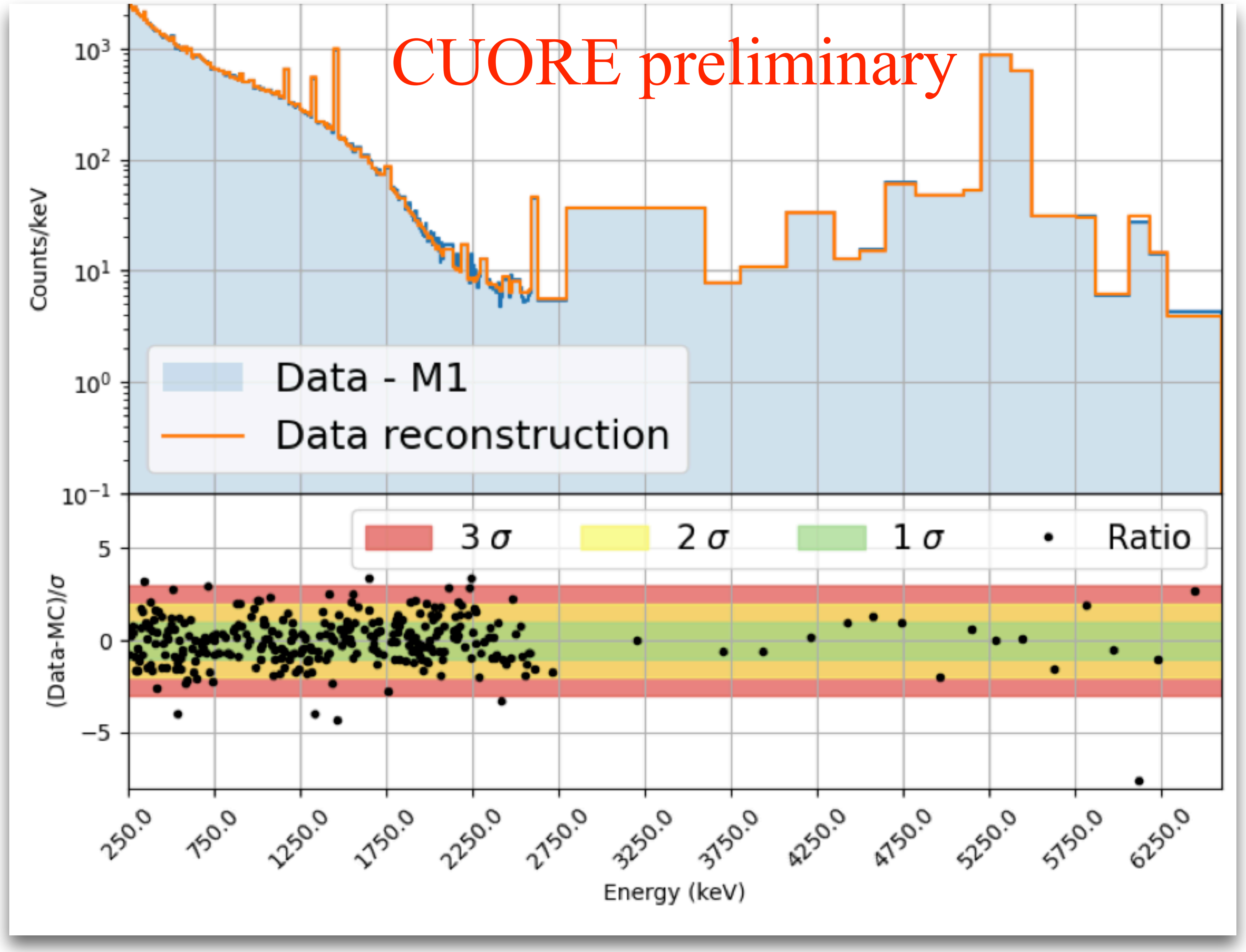
$$m_{\beta\beta} < 70 - 240\ \mathrm{meV}$$

CUORE background model and ^{130}Te $2\nu\beta\beta$ decay

- Accurate Geant-4 based background model profiting of the high detector granularity
- ~80 sources simulated, Bayesian fit of the *single-* and *double-*calorimeter events with priors obtained from radioassays and past experiments



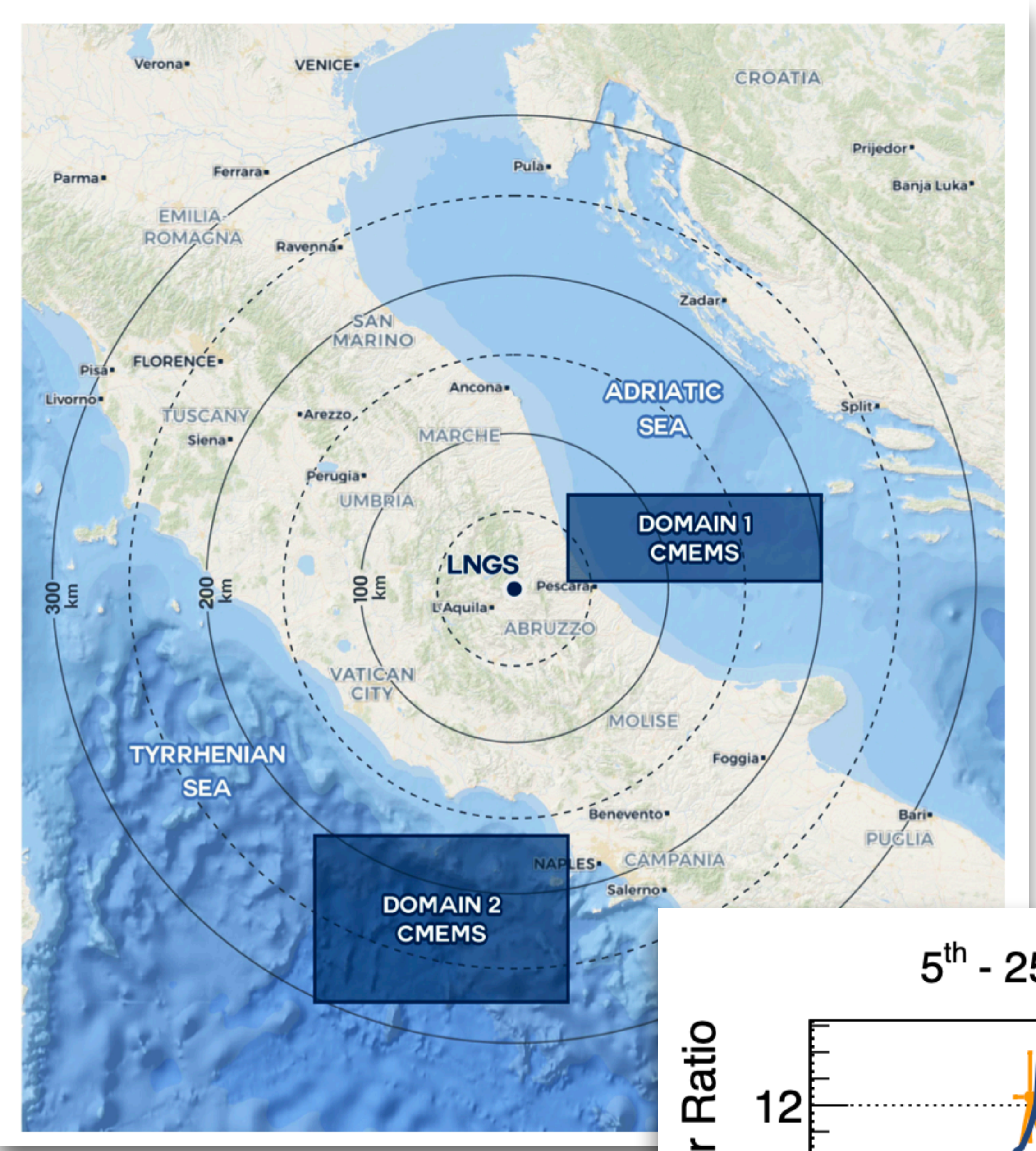
1038.4 kg·yr TeO_2 exposure arxiv:2405.17937



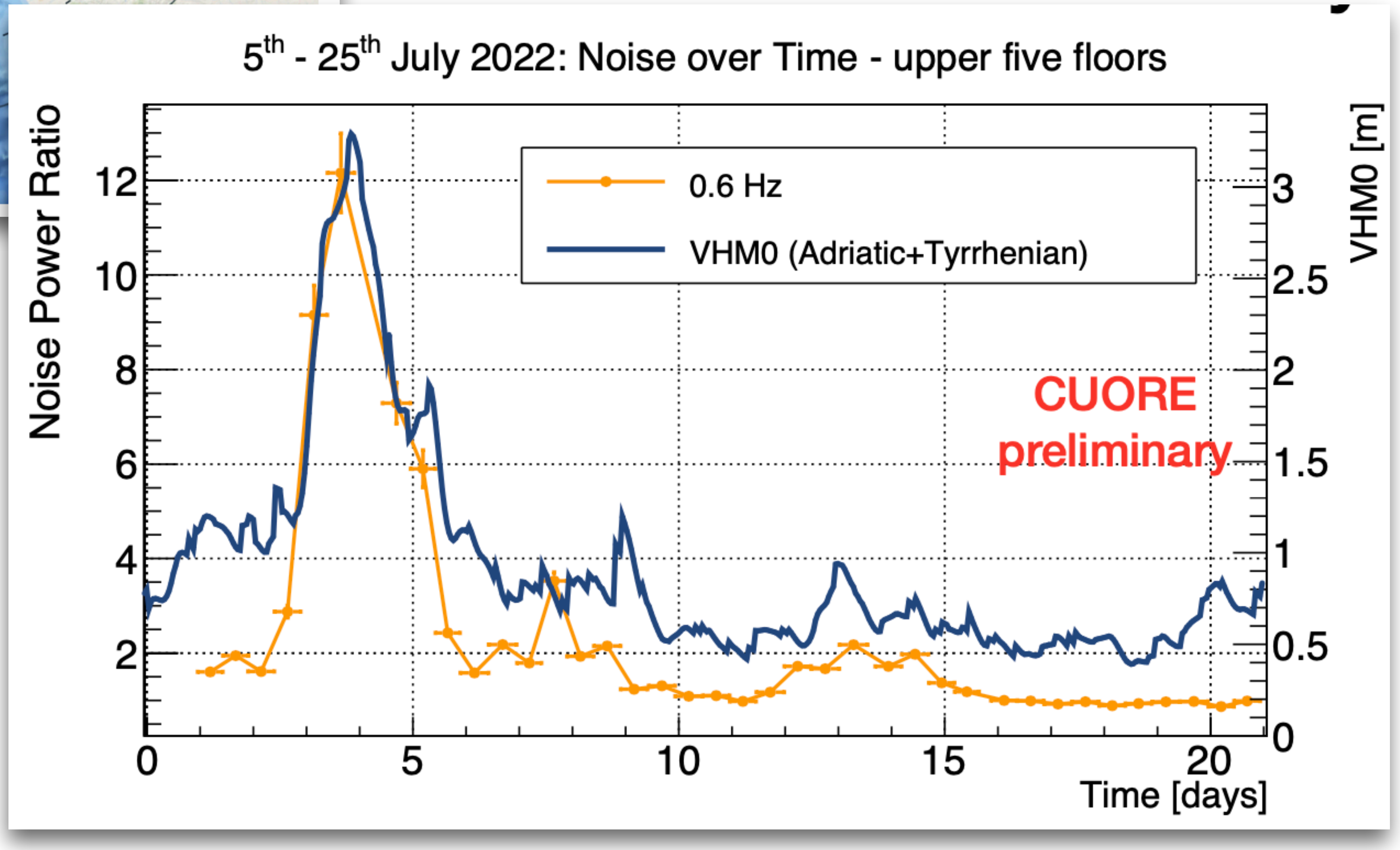
- Precise measurement of ^{130}Te $2\nu\beta\beta$ decay with the background reconstruction improvements (energy range, binning, systematics treatment)

$$T_{1/2}\left(^{130}\mathrm{Te}\right) = \left[9.321^{+0.055}_{-0.034}\ (\mathrm{stat})\ ^{+0.069}_{-0.013}\ (\mathrm{syst})\right] \cdot 10^{20}\ \mathrm{yr}$$

Noise studies



- We recently discovered that CUORE is sensitive to microseismic activity induced by the sea waves
- Storms ↔low frequency noise: strong correlation

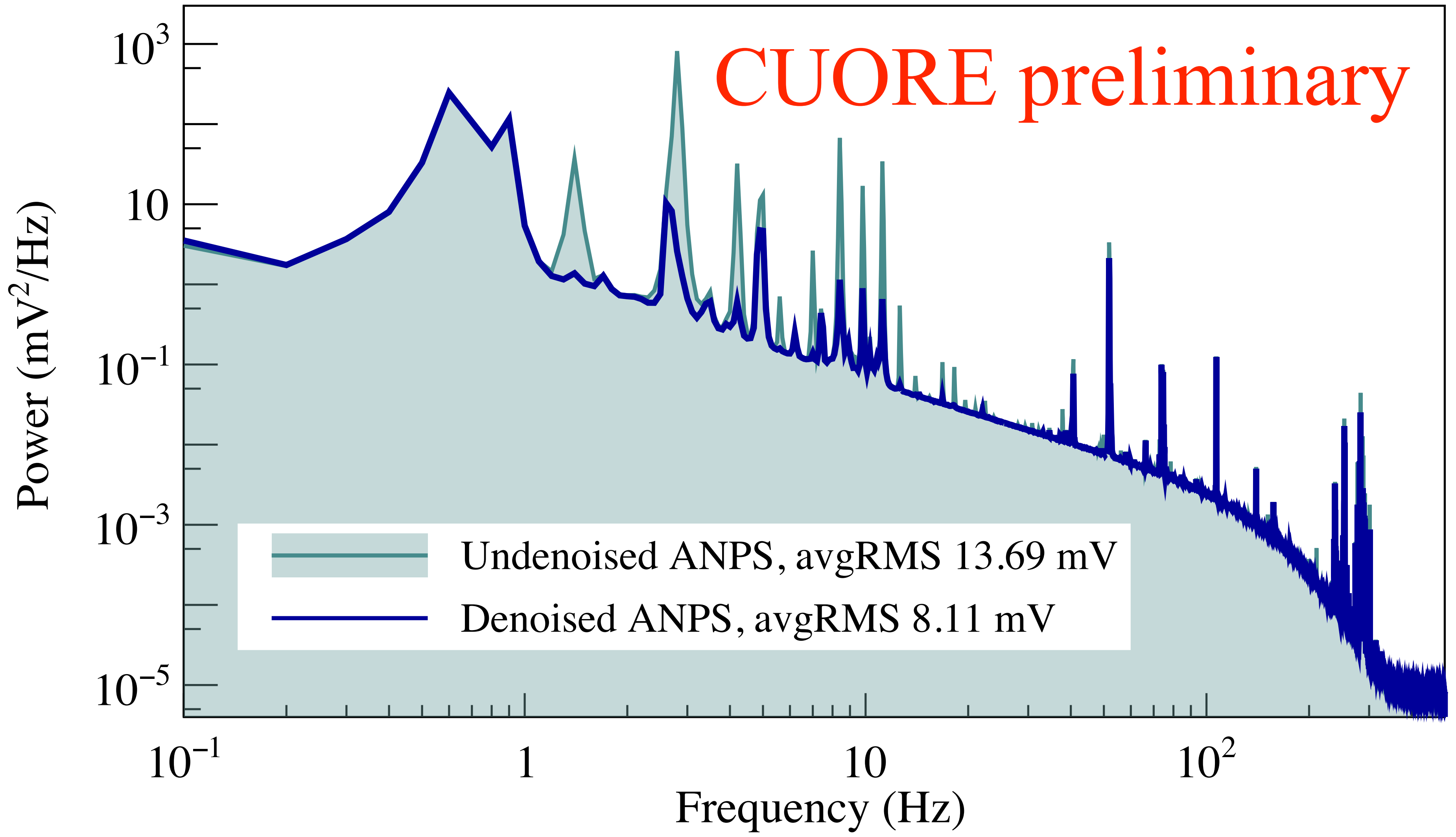


- Solutions to improve decoupling are under investigation

arxiv:2405.13602

- Continuous data *denoising* exploiting the correlation between noise power spectra of detector channels and ancillary diagnostic devices (seismometers, accelerometers, antennae and microphones) installed in the experimental hut:

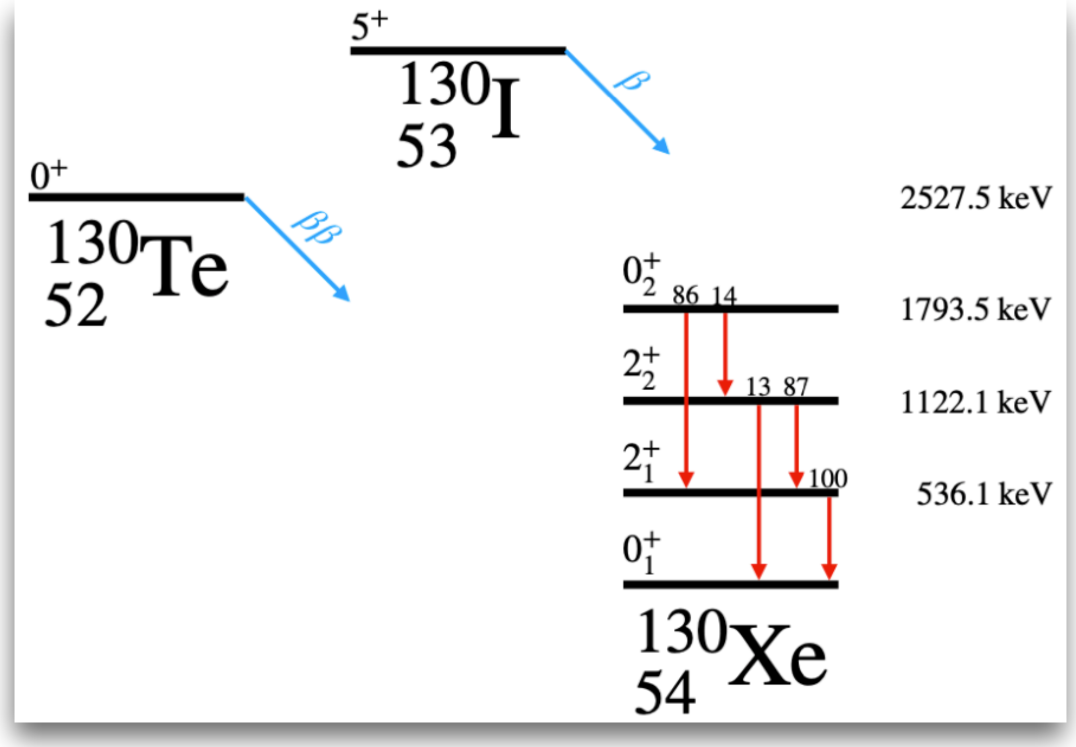
  40% raw-RMS reduction



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

Other searches and analyses with CUORE

^{130}Te $\beta\beta$ decay to the 1st 0^+ excited state



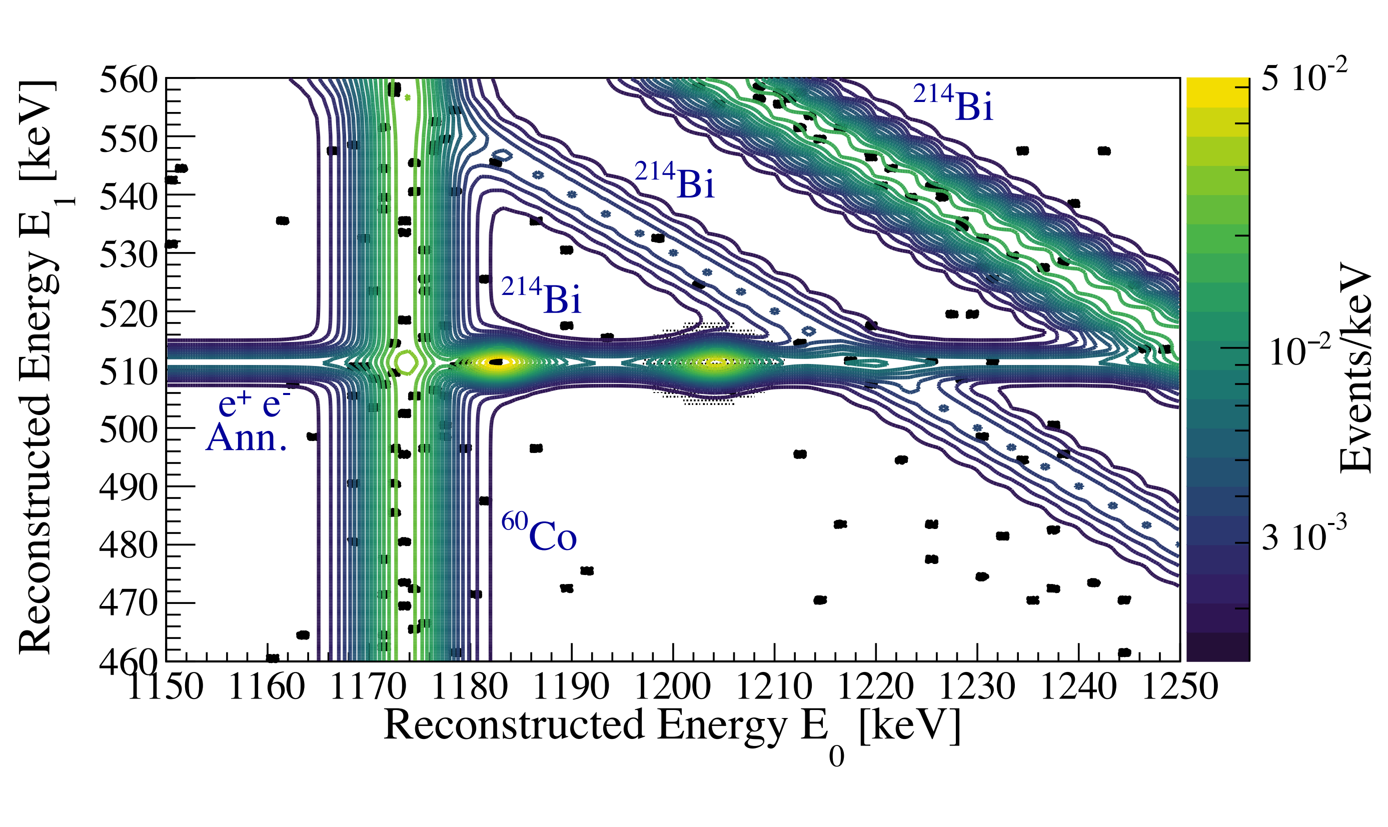
$$T^{0\nu}_{1/2} > 5.9 \times 10^{24}\ \mathrm{yr}\ (90\,\%\ \mathrm{C.I.})$$

$$T^{2\nu}_{1/2} > 1.3 \times 10^{24}\ \mathrm{yr}\ (90\,\%\ \mathrm{C.I.})$$

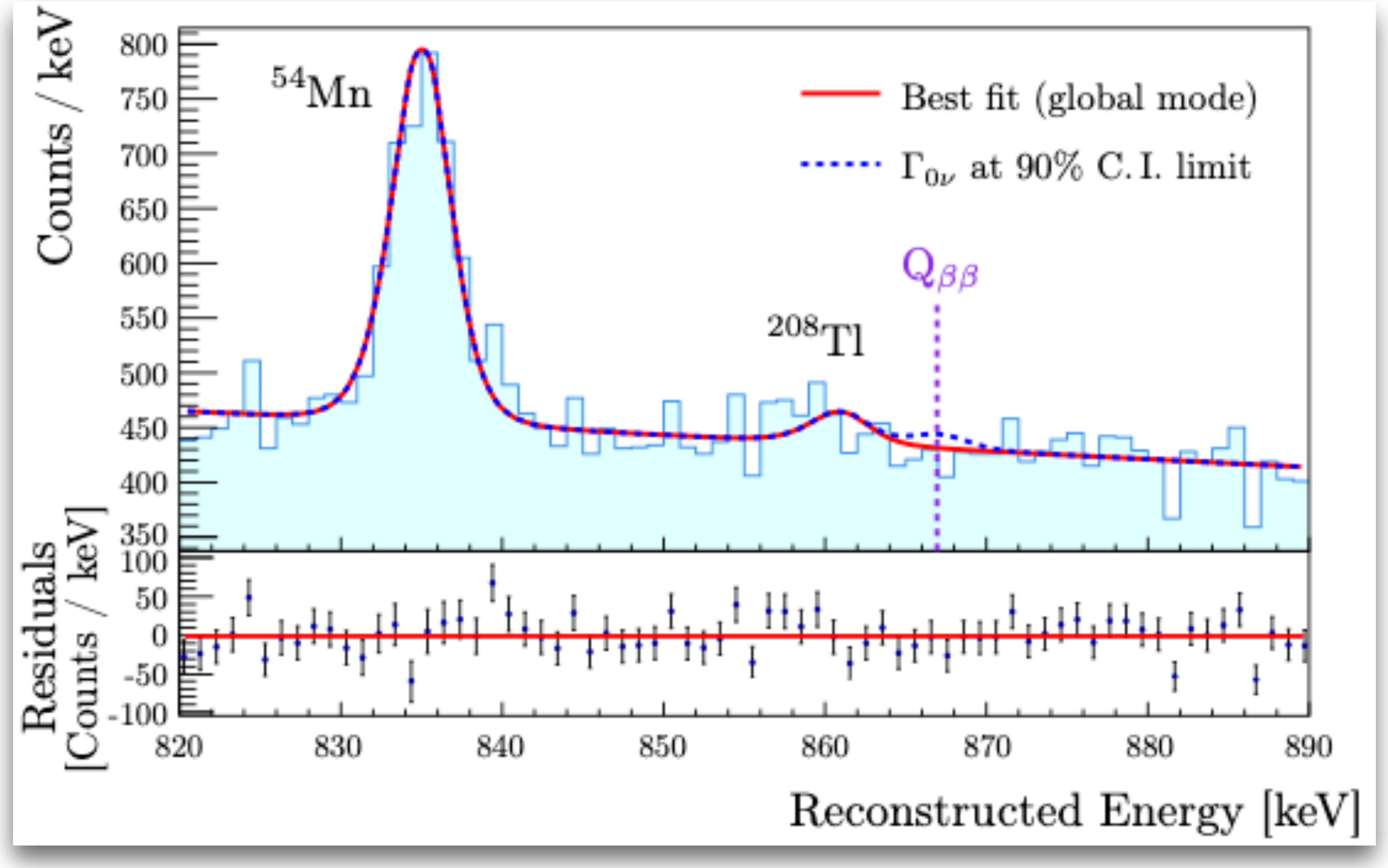
Eur. Phys. J. C, 81 57 (2021)

^{120}Te $0\nu\beta^+$EC decay to the ground state

Phys. Rev. C, 105 065504 (2022)



$$T^{0\nu}_{1/2} > 2.9 \cdot 10^{22}\ \mathrm{yr}\ \ (90\,\%\ \mathrm{C.I.})$$



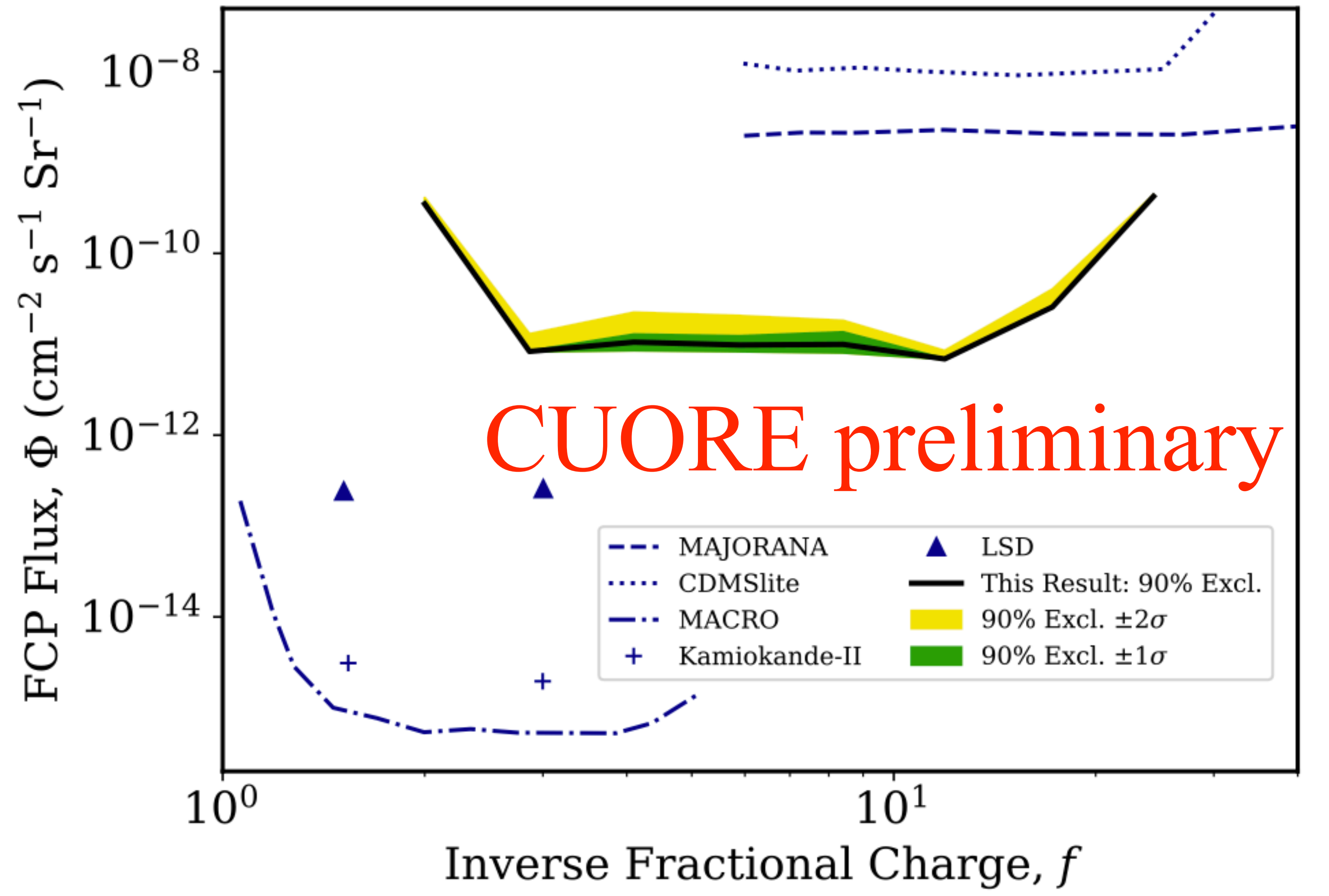
^{128}Te $0\nu\beta\beta$ to the ground state

PRL 129, 222501 (2022)

$$T^{1/2}_{0\nu\beta\beta} > 3.6 \cdot 10^{24}\ \mathrm{yr}\ (90\,\%\ \mathrm{C.I.})$$

Search for fractionally charged particles

arxiv:2406.12380



Conclusions and future perspectives

- CUORE proved the **scalability of the cryogenic calorimeters** technique to tonne-scale detectors thereby paving the way to **rare decay searches with cryogenic calorimeters**

- We exceeded 2 tonne · yr TeO_2 analyzed exposure and data collection is proceeding smoothly towards our **goal** (2025) of a final **3 tonne · yr TeO_2 exposure** (corresponding to ~1 tonne · yr ^{130}Te)

- We found no evidence of $0\nu\beta\beta$ decay with 2039 kg · yr TeO_2 exposure

- **Many interesting analyses ongoing** on and beyond $\beta\beta$ decay searches: background-related studies (e.g. muon tracks reconstruction), multispectral analyses (search for $0\nu\beta\beta$ decay in double-crystal events) and low energy studies

- Important feedback for the CUPID project that will come after CUORE, both for the cryogenics and background budget

- After interventions on the cryogenics and before the CUPID (CUORE upgrade) detector installation, a CUORE phase II dedicated to **low energy studies** (dark matter searches, e.g. WIMPs, axions, …) is planned (2026)

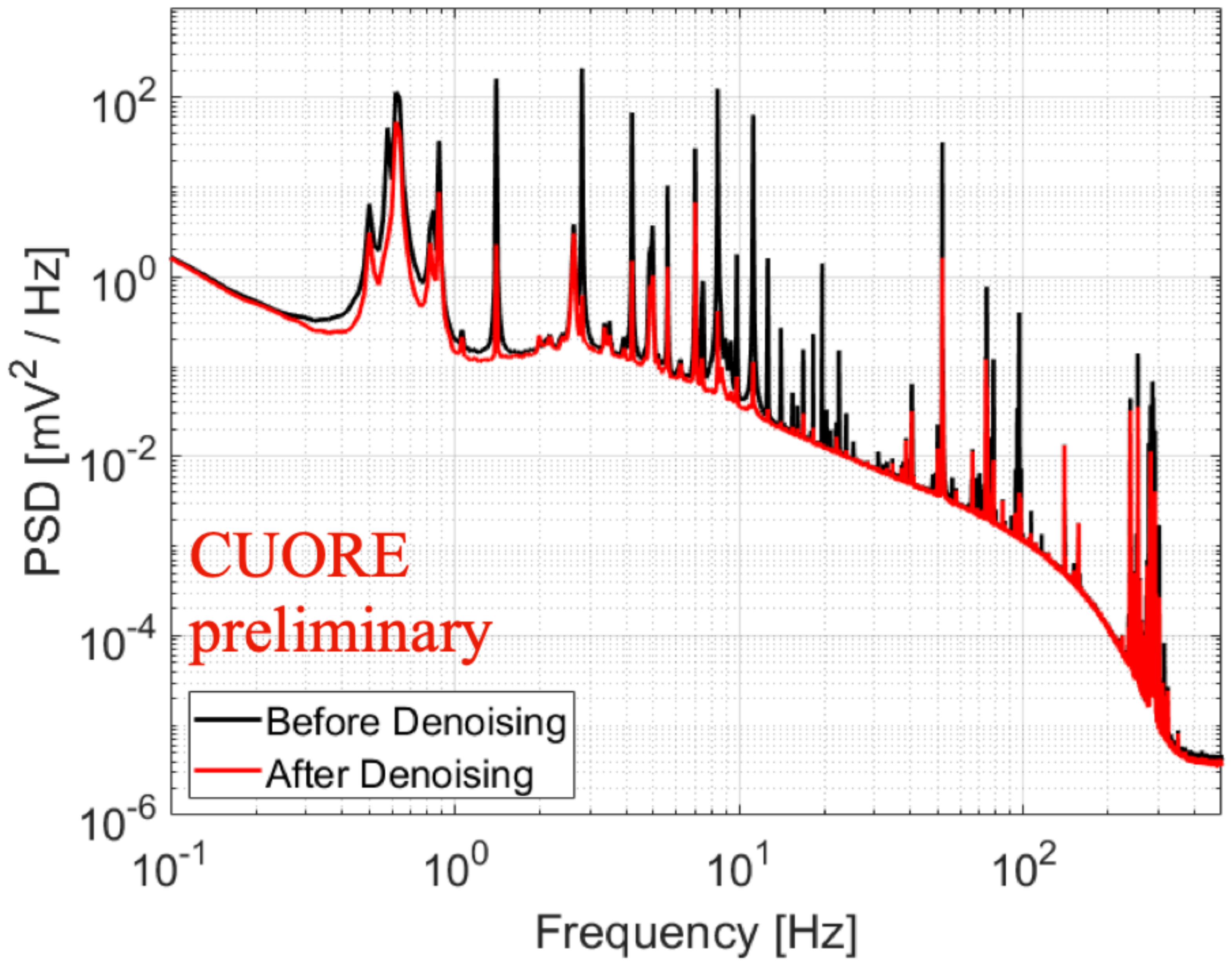
New results soon: stay tuned!

Thank you on behalf of the CUORE collaboration

Back-up slides

Data processing in CUORE

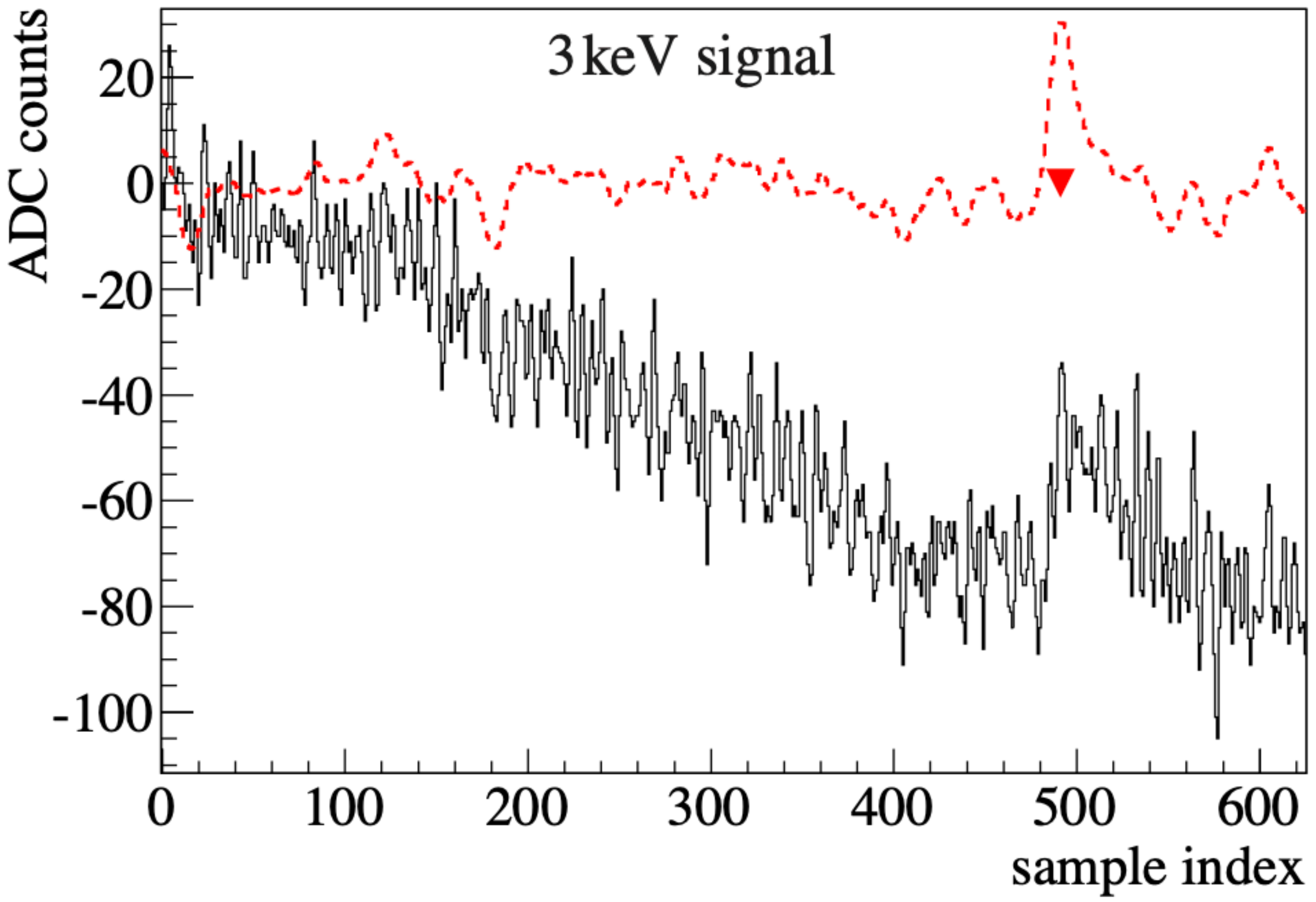
1 Denoising (New!)



Noise is mitigated correlating *vibrations* with measurements obtained with *auxiliary devices*, i.e. microphones, antennae, accelerometers, seismometers

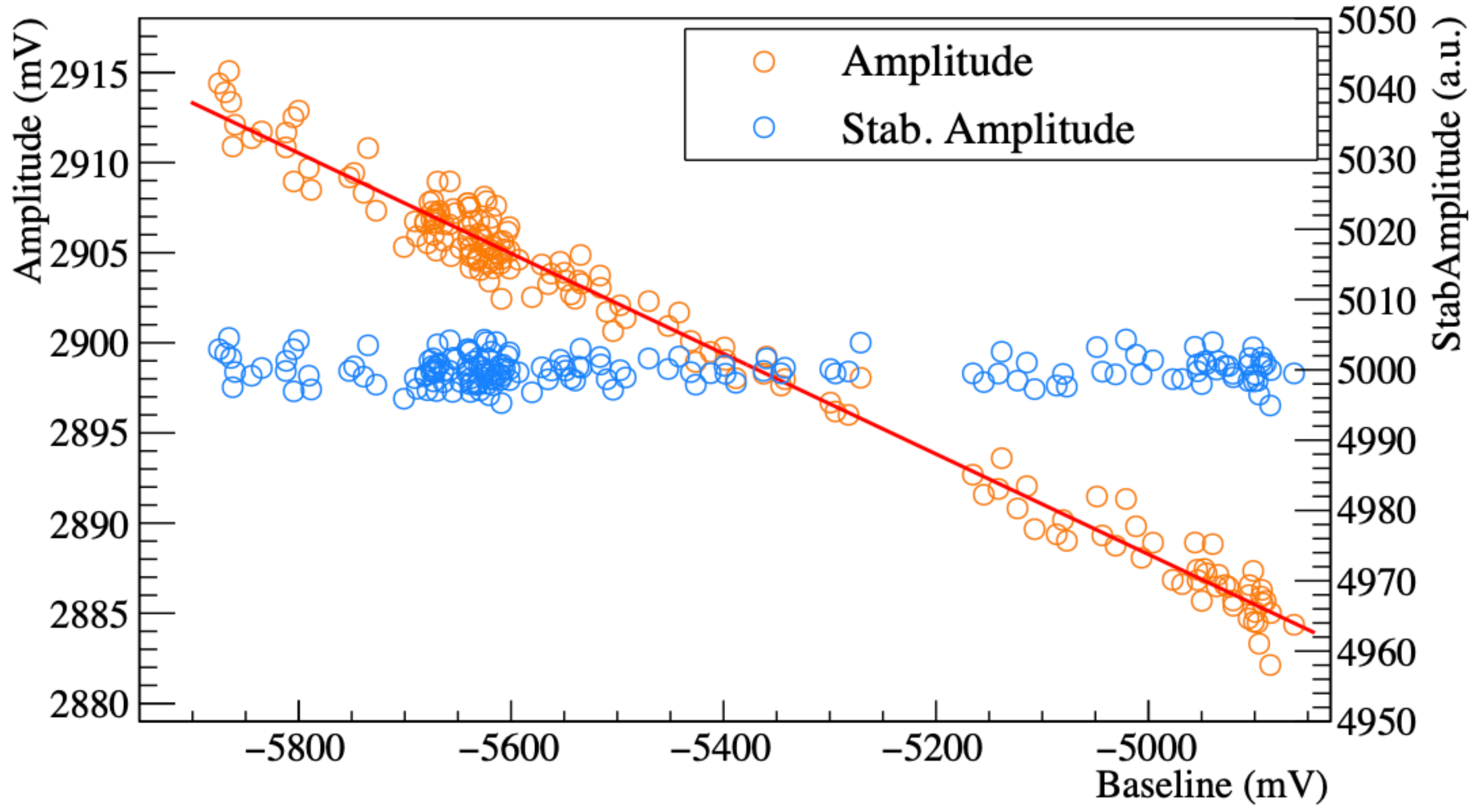
2 Optimum trigger (OT)

Offline retrigger to maximize SNR using power spectra of particle induced and noise waveforms.



3 Optimum Filter technique

4 Thermal gain stabilization (TGS)



Filtered signal amplitude is corrected against T drifts with fixed E pulses

5 Energy calibration

^{232}Th + ^{60}Co external strings

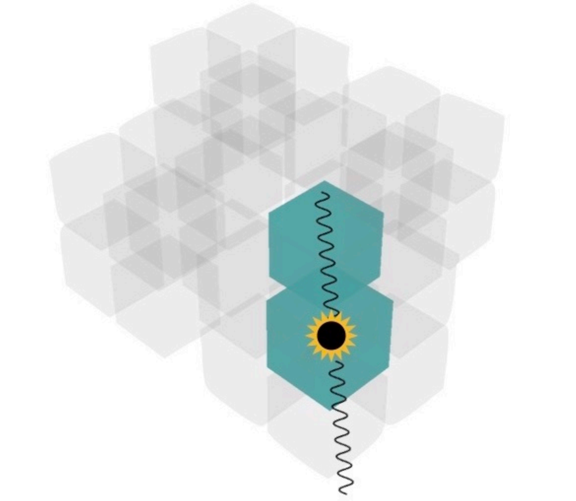
2nd order polynomial fit

to extract our calibration coefficients

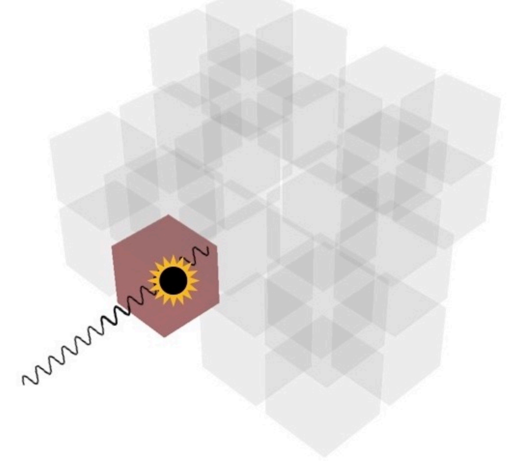
Event selection for the $0\nu\beta\beta$ decay search

6 Anti-coincidence (AC) selection

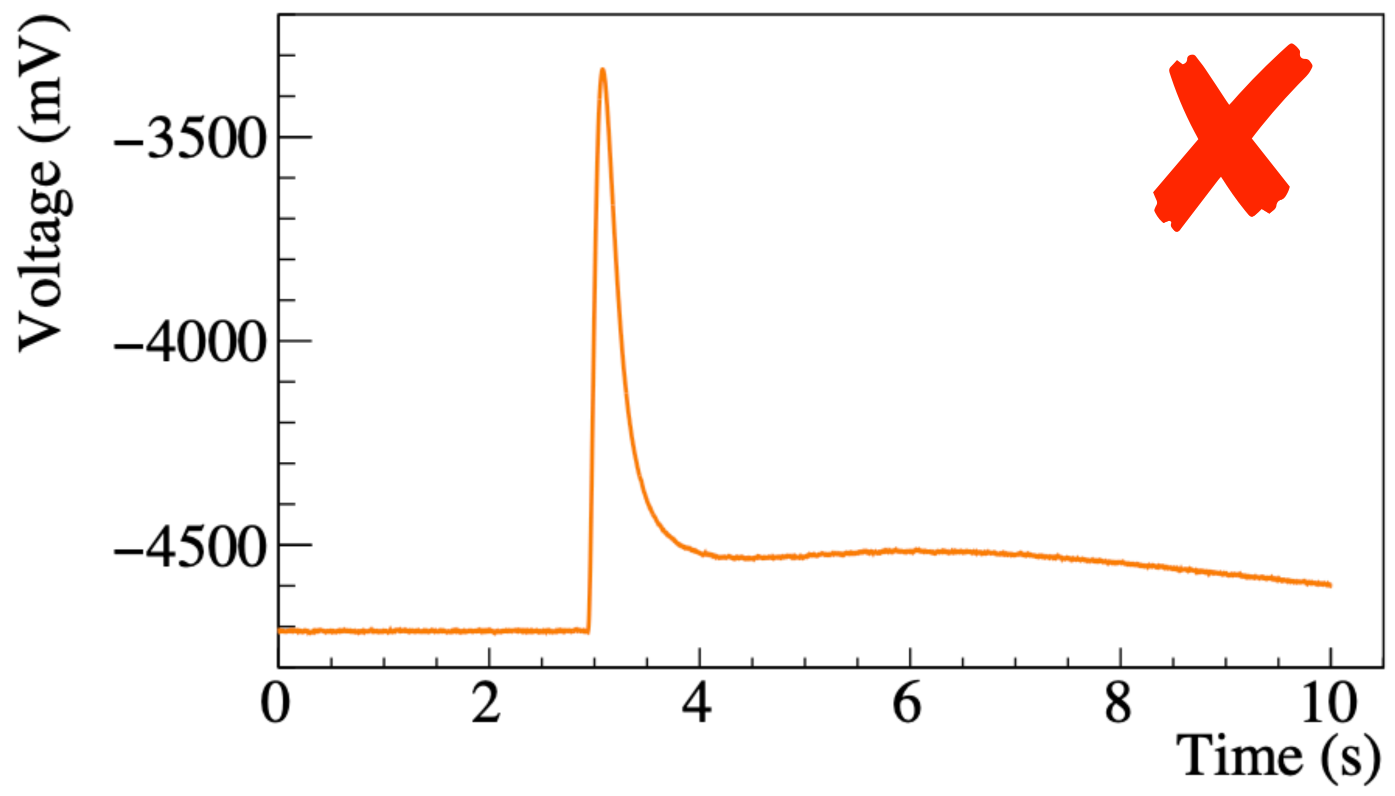
~88% $0\nu\beta\beta$ events release all energy in a single crystal: multi-site events are rejected

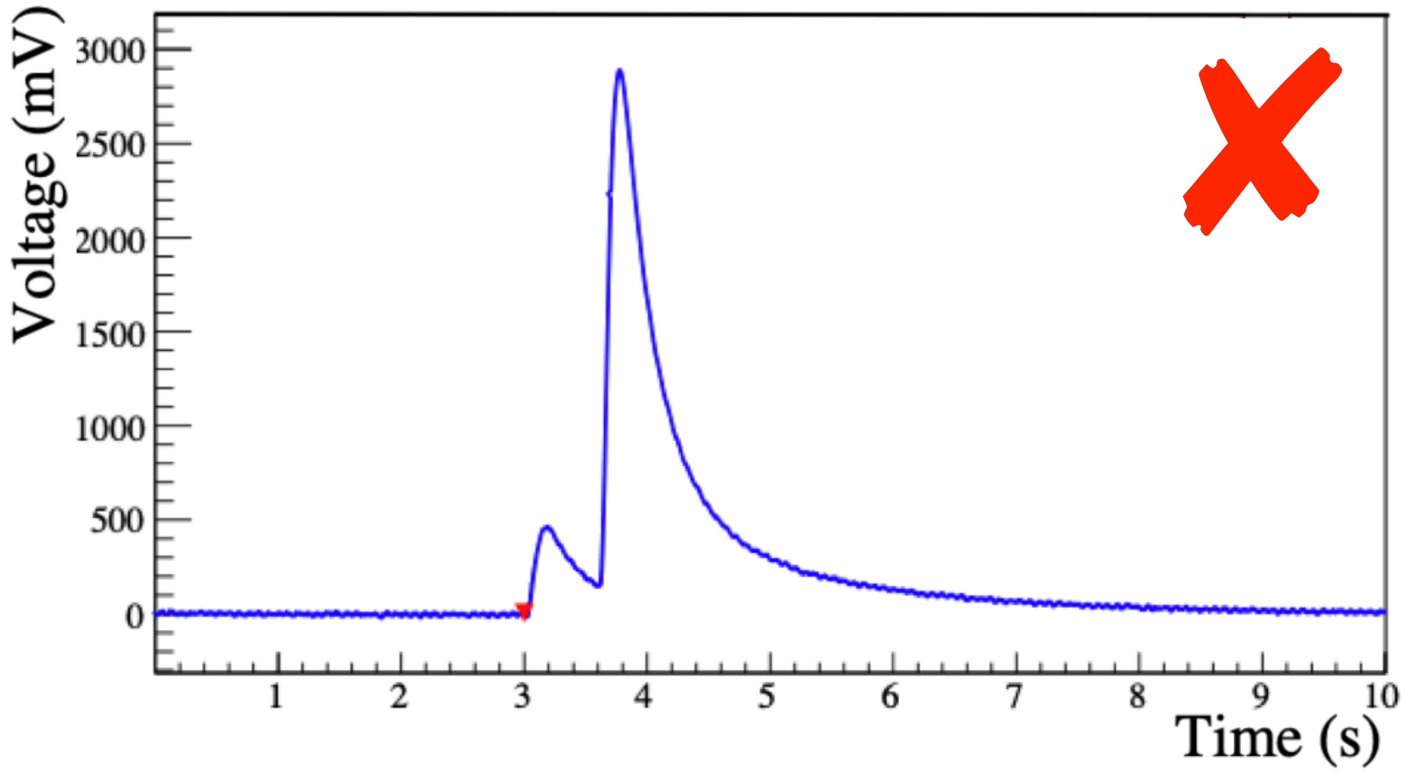


multi-site event (M=2)



single-site event (M=1)





7 Pulse shape discrimination (PSD)

We use Principal Component Analysis (PCA) to reject non-signal like and noisy events

8 ROI blinding

Exchange events from ^{208}Tl line at 2615 keV with events at the ^{130}Te $0\nu\beta\beta$ Q-value

9 Efficiency of selection cuts

10 Detector response evaluation

On a calorimeter-dataset basis using ^{208}Tl line at 2615 keV in calibration data

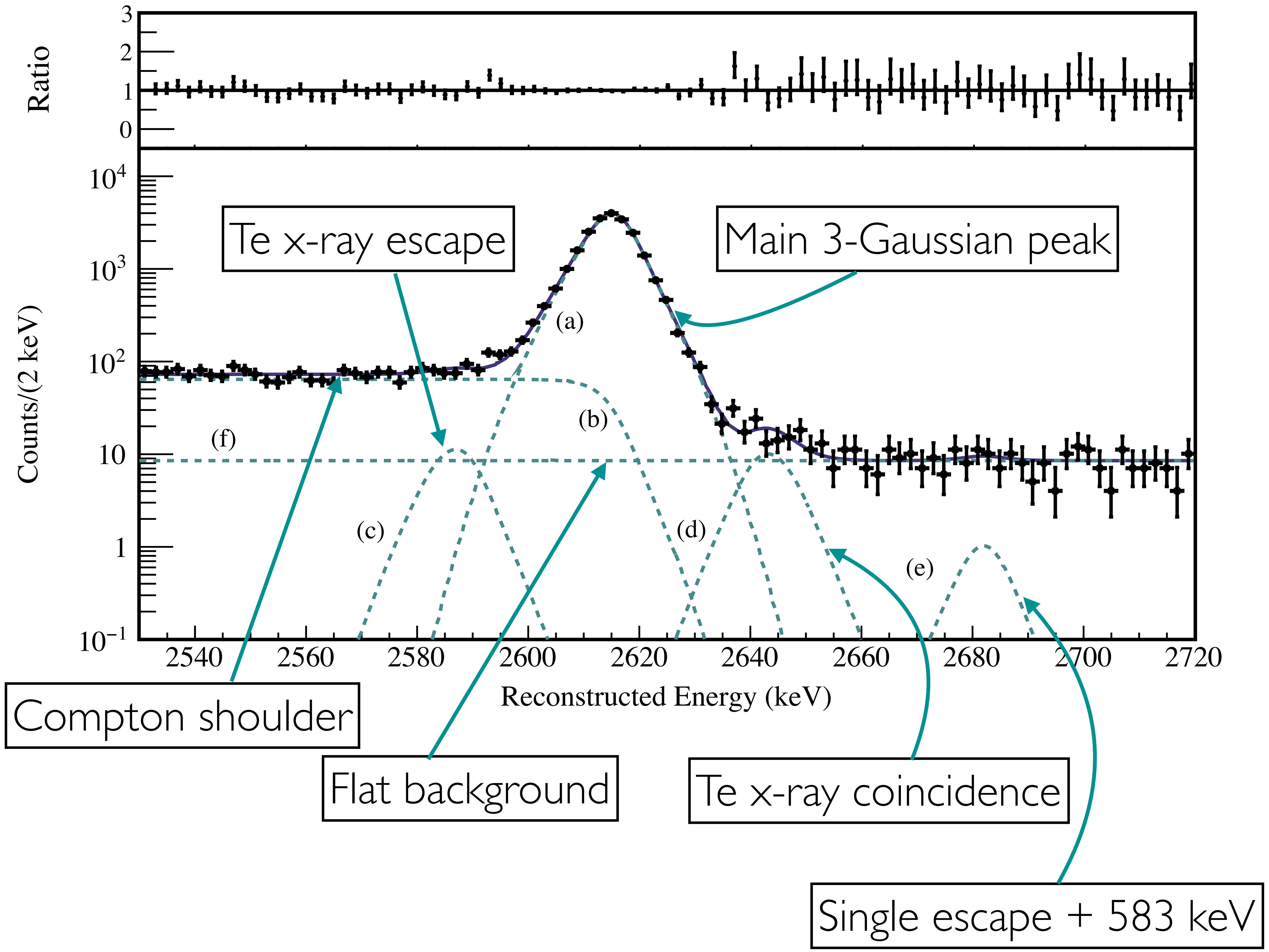
11 ROI model and blinded fit

12 Data unblinding and fit

Detector response evaluation

- We extract the detector response on events from the ^{208}Tl line at 2615 keV in calibration data separately for each bolometer and dataset
- The signal peak is modeled as a sum of 3 Gaussians, recent updates to deal with cases where a single/double-Gaussian model is sufficient to speed up the fitting procedure
- We fit the most prominent γ lines in physics data to scale the energy resolution and calibration bias at $Q_{\beta\beta}$

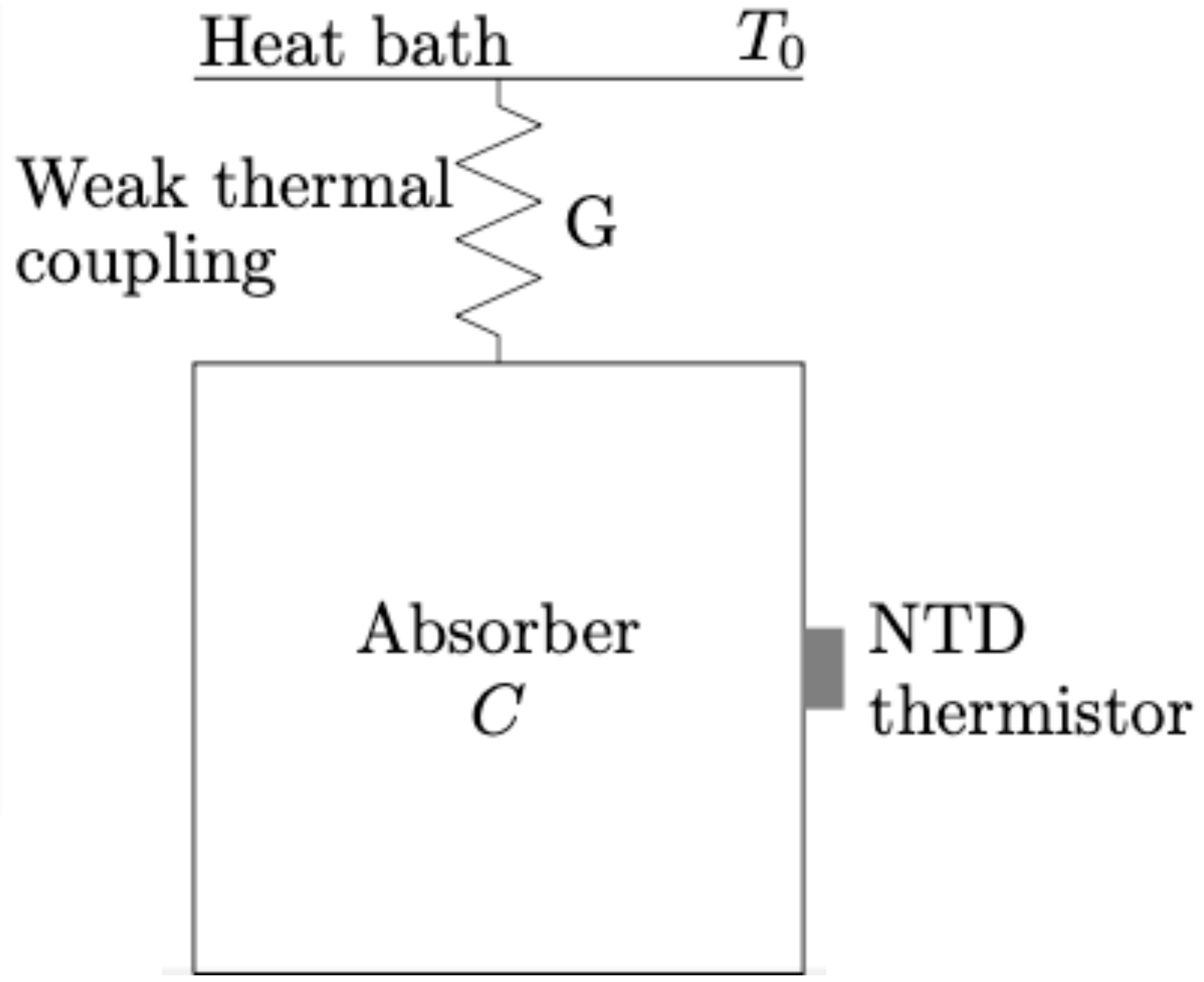
$$\text{FWHM}\left(^{208}\text{Tl}\right) = \left(7.540 \pm 0.024\right)\,\text{keV}$$
$$\text{FWHM}\left(Q_{\beta\beta}\right) = (7.320 \pm 0.024)\,\text{keV}$$
$$\Delta\text{E}\left(Q_{\beta\beta}\right) = 0.52^{+0.04}_{-0.30}\ \text{keV}$$



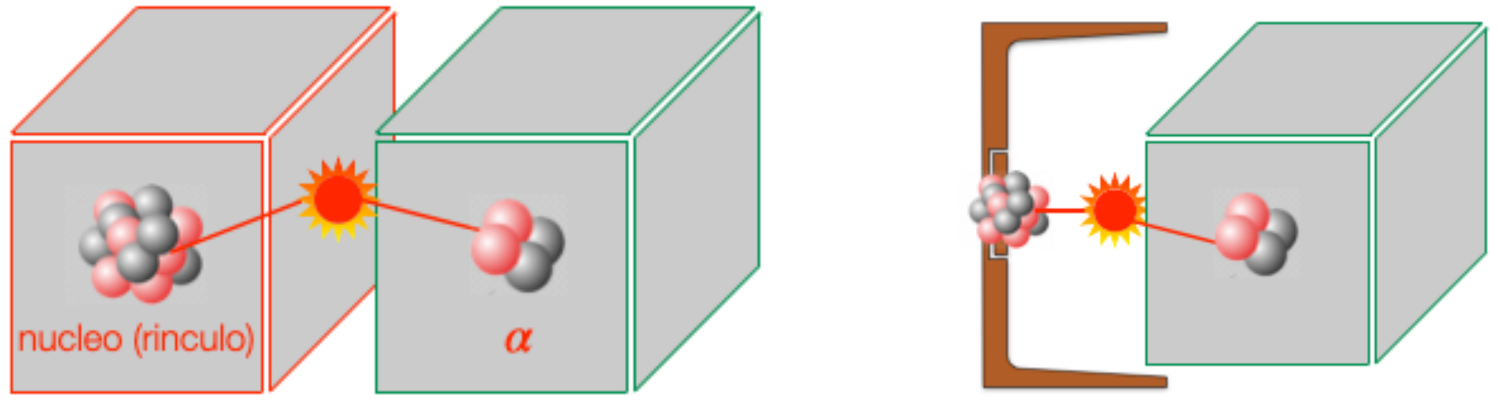
What's next: from CUORE to CUPID

CUORE

^{130}Te

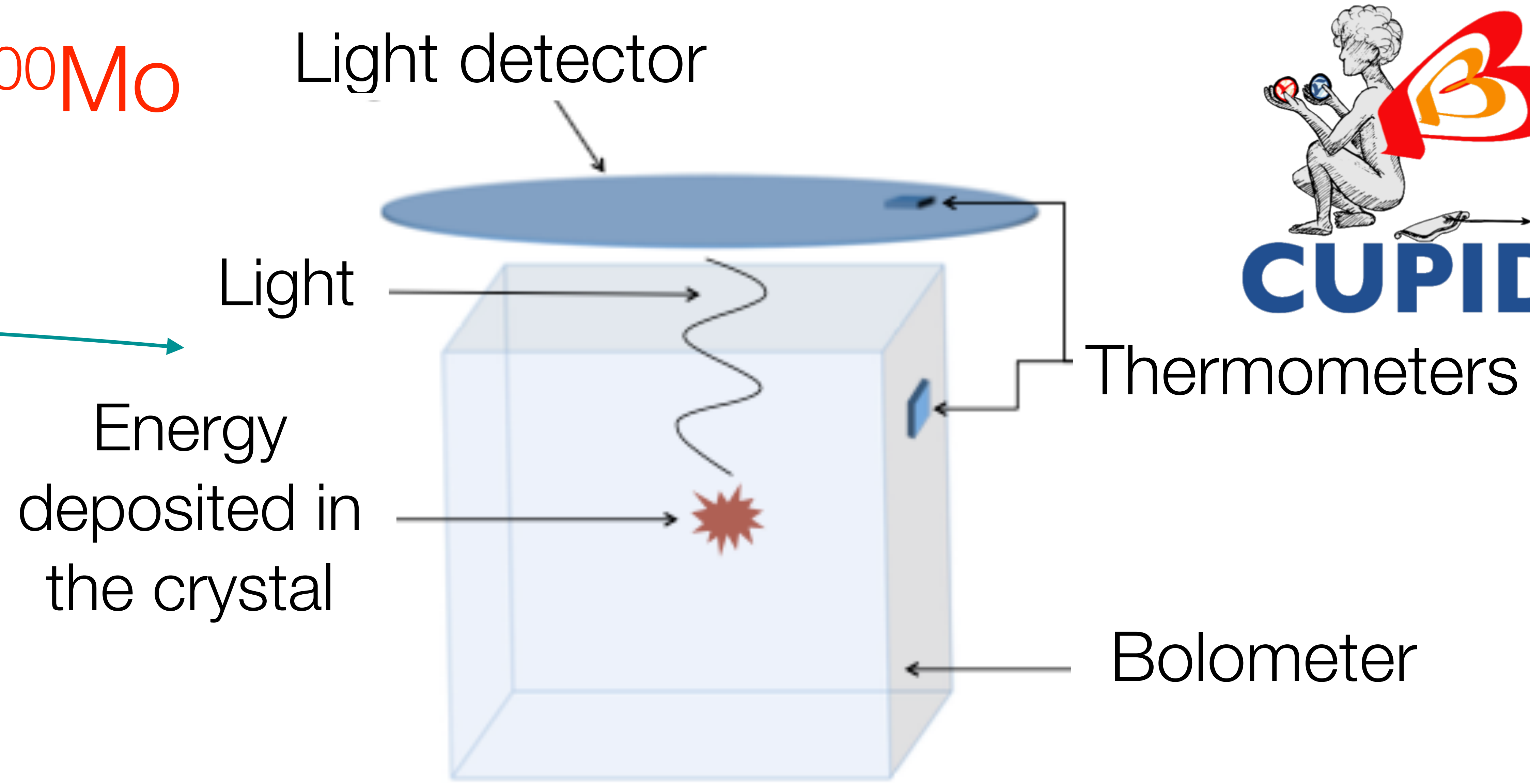


- **Pure thermal detector** w/o particle identification capability
- **Main background** contribution: α decays (surface contaminations)



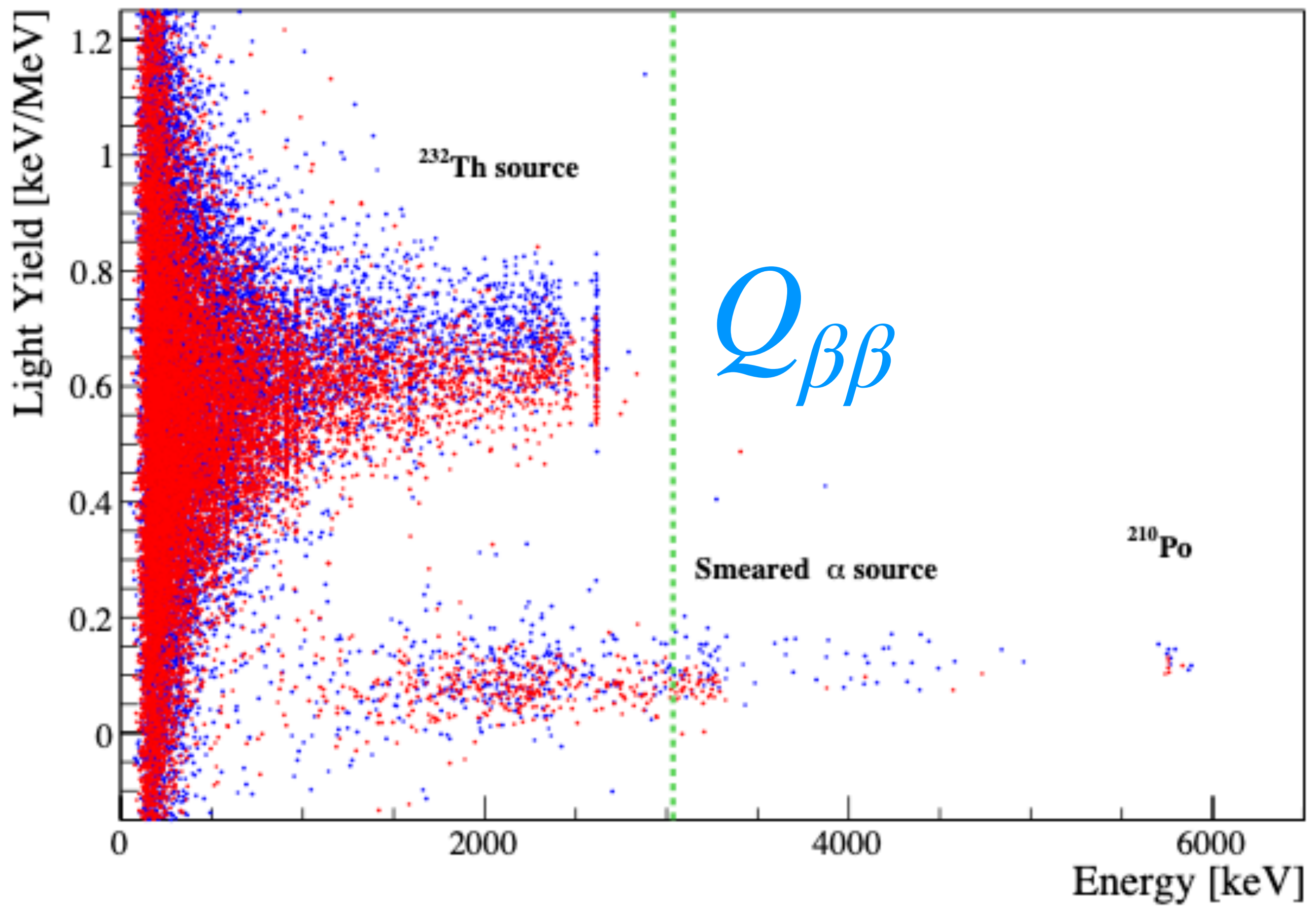
CUPID

^{100}Mo



Simultaneous measurement of light and heat signal to distinguish β, γ from α

PID (α) + ^{100}Mo (β, γ) bkg reduction ~1/150



CUPID: **C**UORE **U**pgrade with **P**article **ID**entification

- CUPID to overcome CUORE limitations and continue the $0\nu\beta\beta$ decay search with cryogenic calorimeters - solid bases from CUORE, CUPID-0, CUPID-Mo

- *Isotope:* ^{130}Te, ^{nat}Te (i.a. ~34%) → ^{100}Mo, enrichment necessary (95%)
  $Q_{\beta\beta}$ ~2528 keV → ~3034 keV (larger phase space, lower bkg)
  Absorber: TeO_2 → Li_2MoO_4
  Mass: 742 kg (206 kg) TeO_2 (^{130}Te) → 450 kg (240 kg) Li_2MoO_4 (^{100}Mo)
  988 crystals (19 towers) → 1596 crystals (57 towers)

- Single channel (heat) readout → double (light & heat) readout for PID
  Top & Bottom Ge light detectors with Neganov-Luke amplification

- Same cryostat with an additional muon veto to achieve a background level of 10^{-4} counts/keV/kg/yr and a factor ~5 improvement in the sensitivity