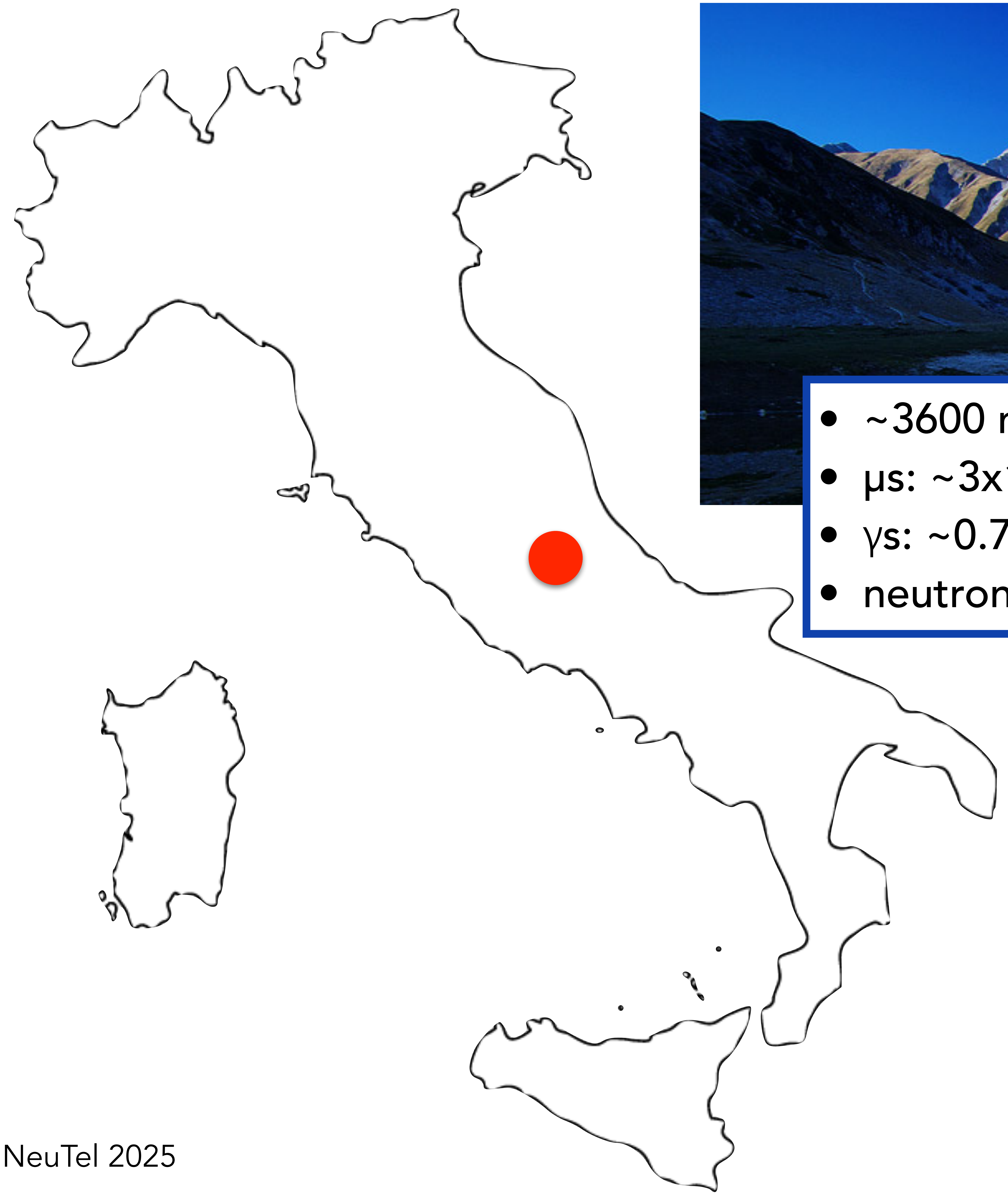
Latest results from the CUORE experiment

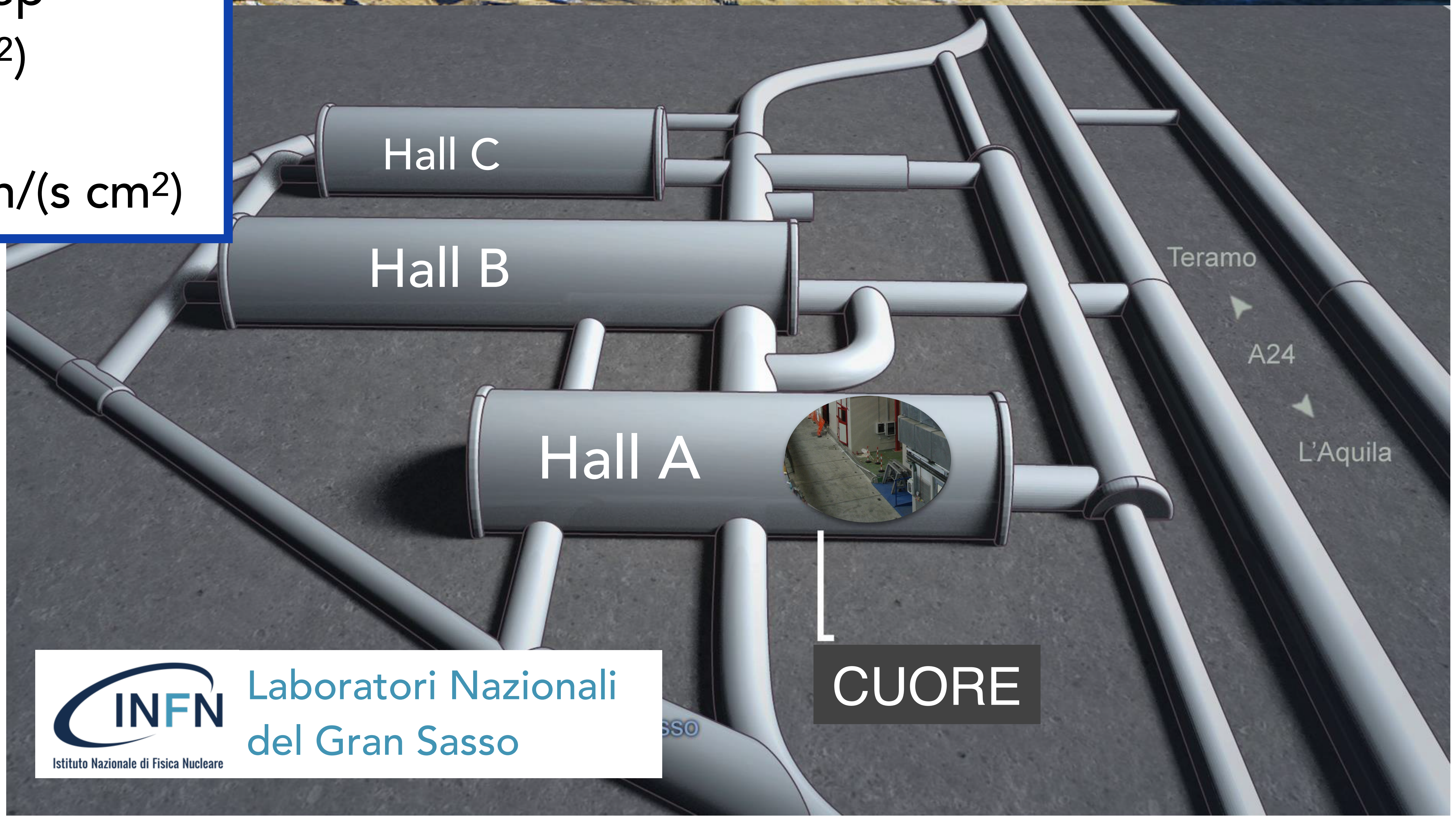
Paolo Gorla
Laboratori Nazionali del Gran Sasso
INFN

The CUORE collaboration

CUORE @ LNGS



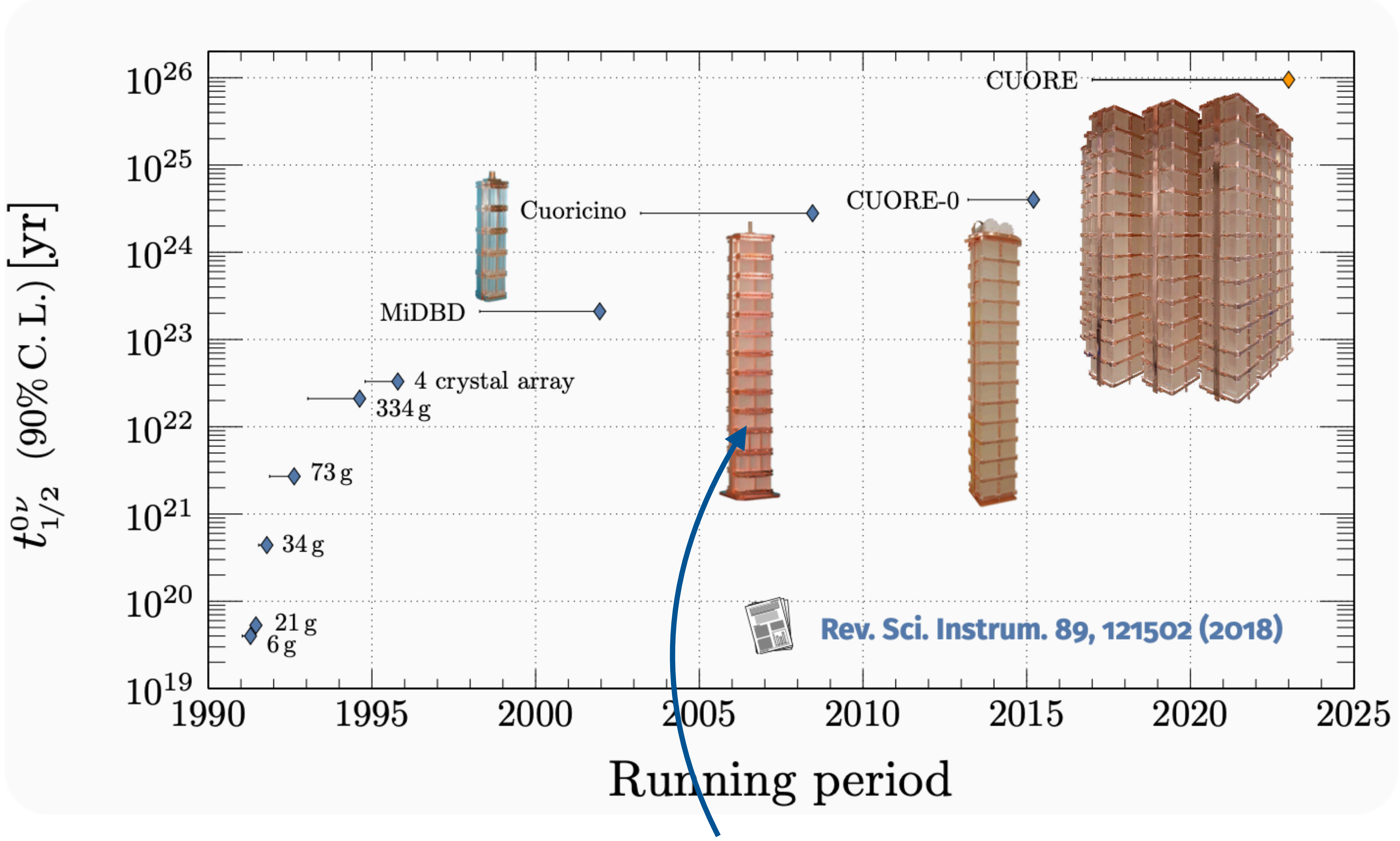
- ~3600 m.w.e. deep
- μs: ~3×10^{-8}/(s cm^2)
- γs: ~0.73/(s cm^2)
- neutrons: 4×10^{-6} n/(s cm^2)



The CUORE experiment in a nutshell

Cryogenic Underground Observatory for Rare Events

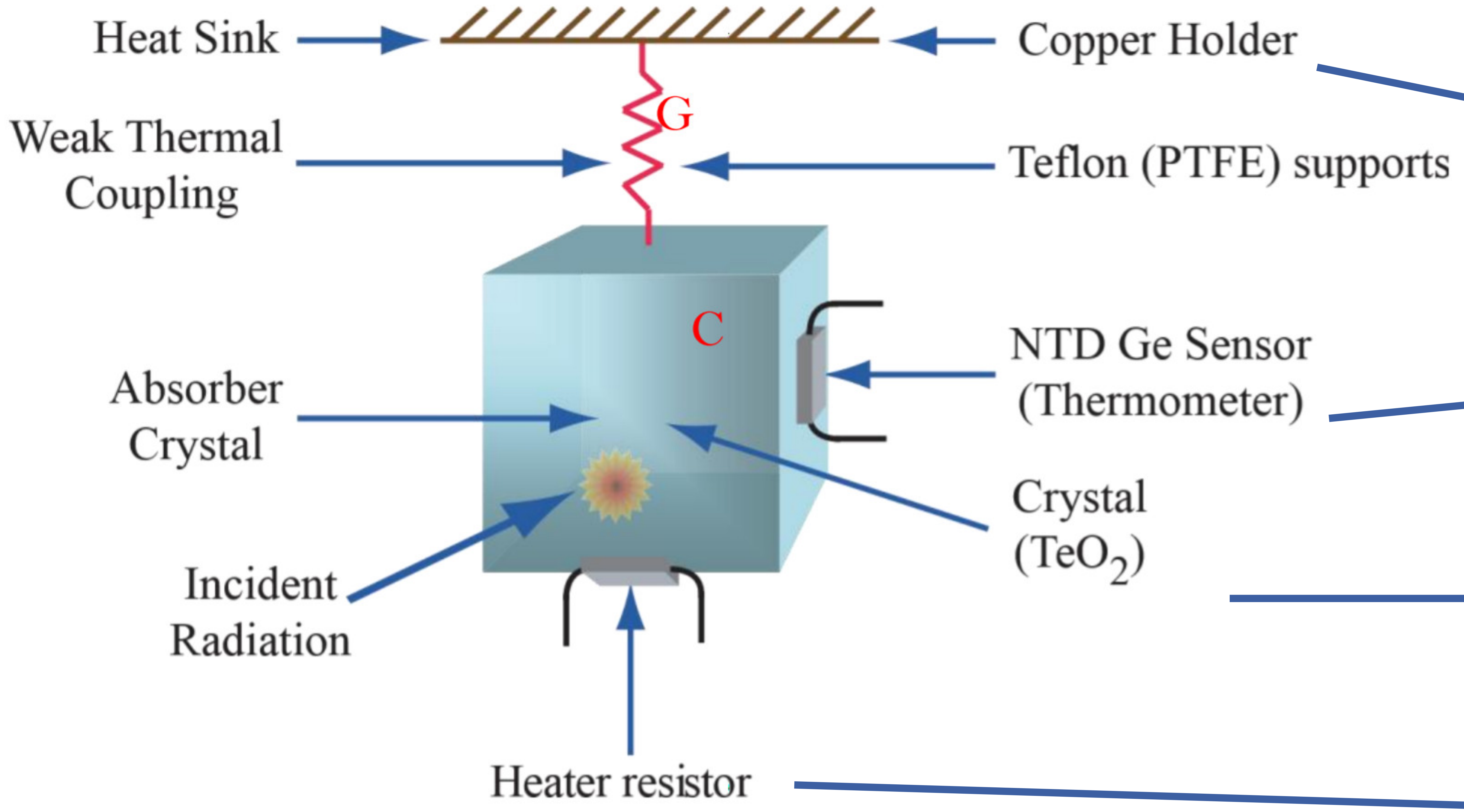
- Primary goal: search for $0\nu\beta\beta$ decay of ^{130}Te
  Eur. Phys. J. C77 (2017), 532
- **Largest cryogenic-calorimeter detector ever built**
  19 towers of 13 floors of 4 crystals = **988 detectors**
- 1 t detector mass: **327 kg Cu + 742 kg TeO_2**
  →206 kg of 130Te

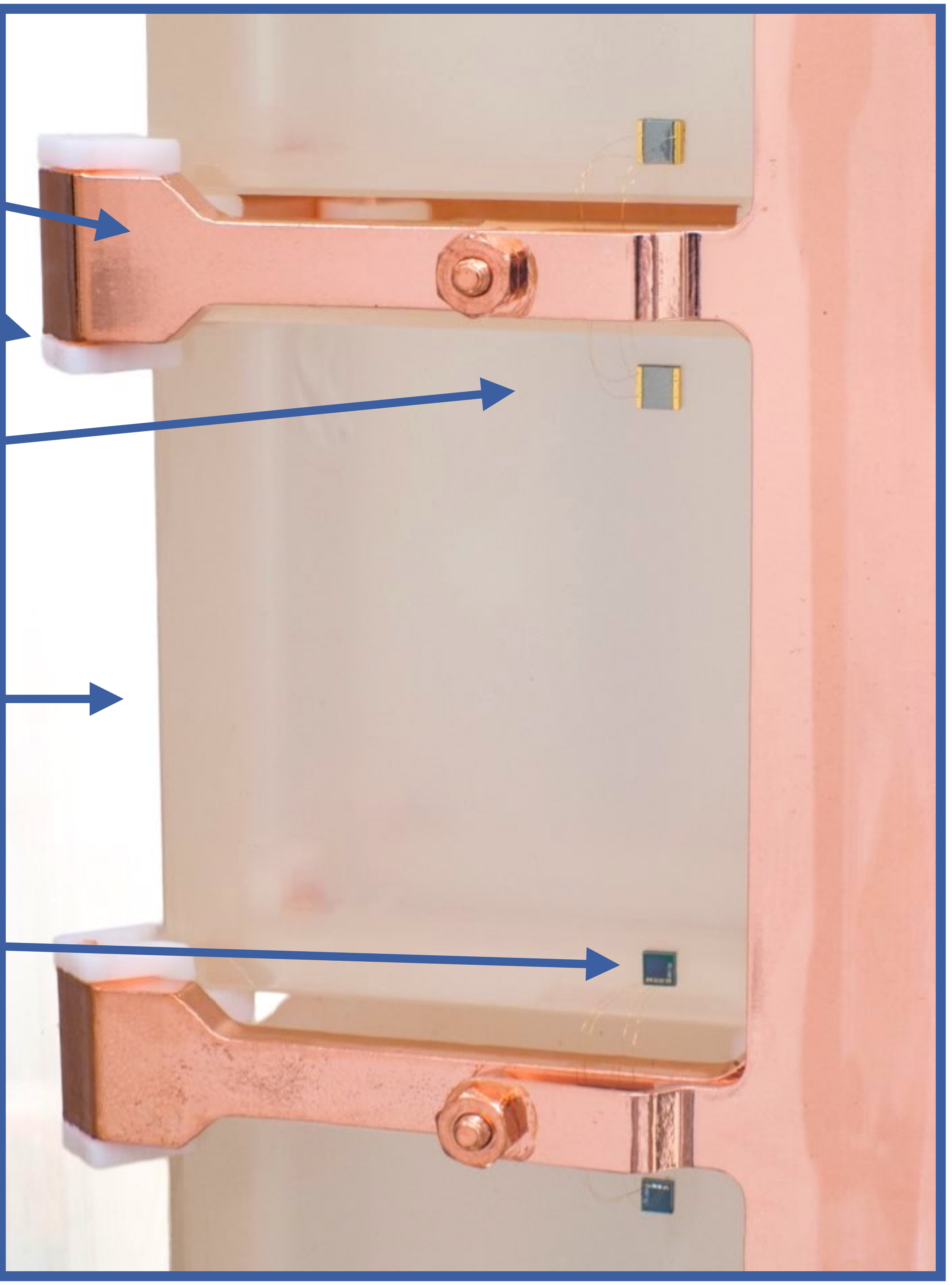


- Building on a 30-yr-long history of measurements
- Multi-year-long cryogenic stability at **T= 11−15 mK**
- FWHM resolution at $Q_{\beta\beta}$ of **7.3 keV**
- bkg in ROI **$1.4 \cdot 10^{-2}$ counts keV^{-1} kg^{-1} yr^{-1}**

Adv. in High En. Phys. 2015, 879871

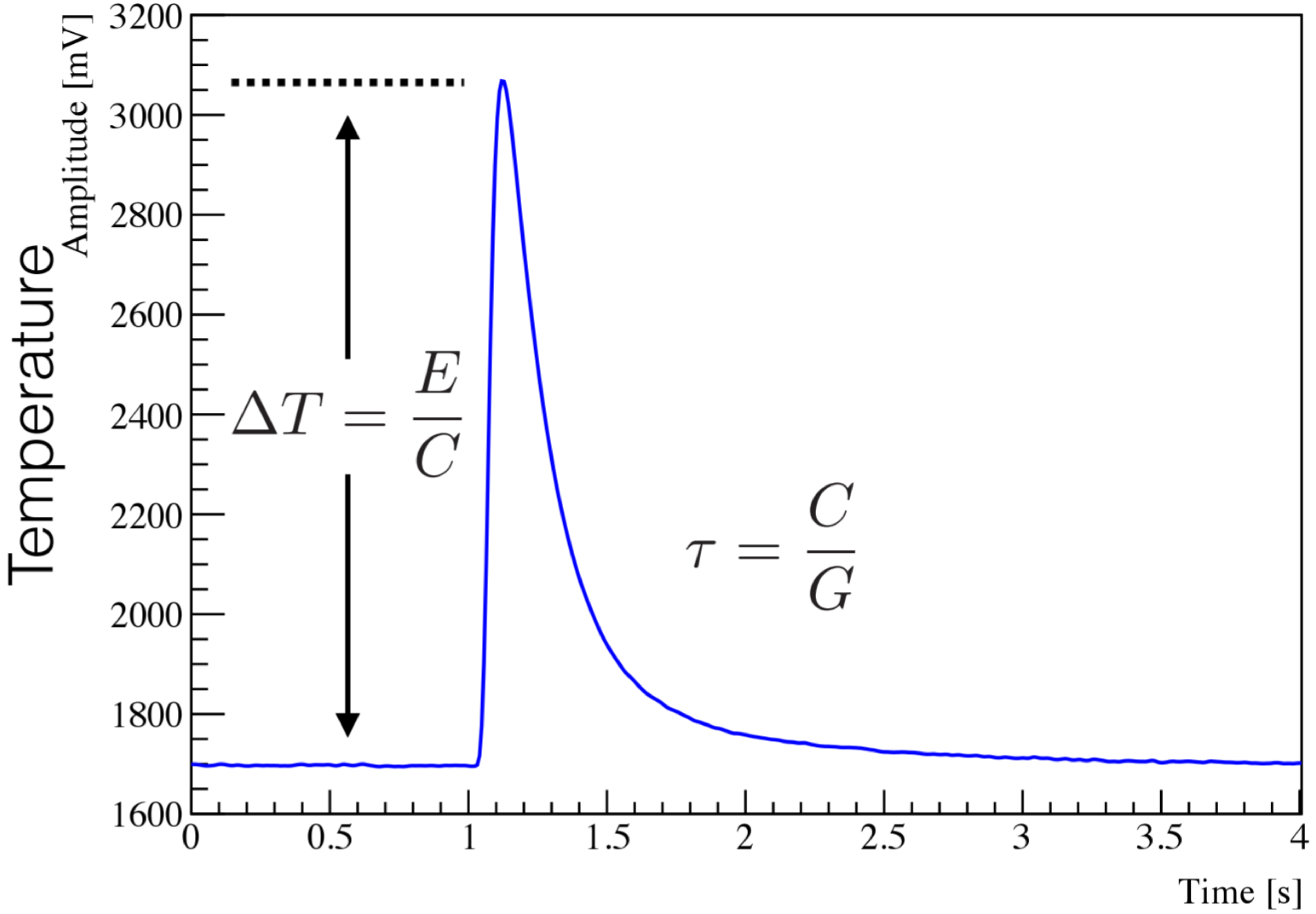
Working principle





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

Working principle



$$\Delta T = \frac{\Delta E}{C} \sim \frac{100\mu K}{MeV}$$

$$\tau = \frac{G}{C} \sim 1s$$

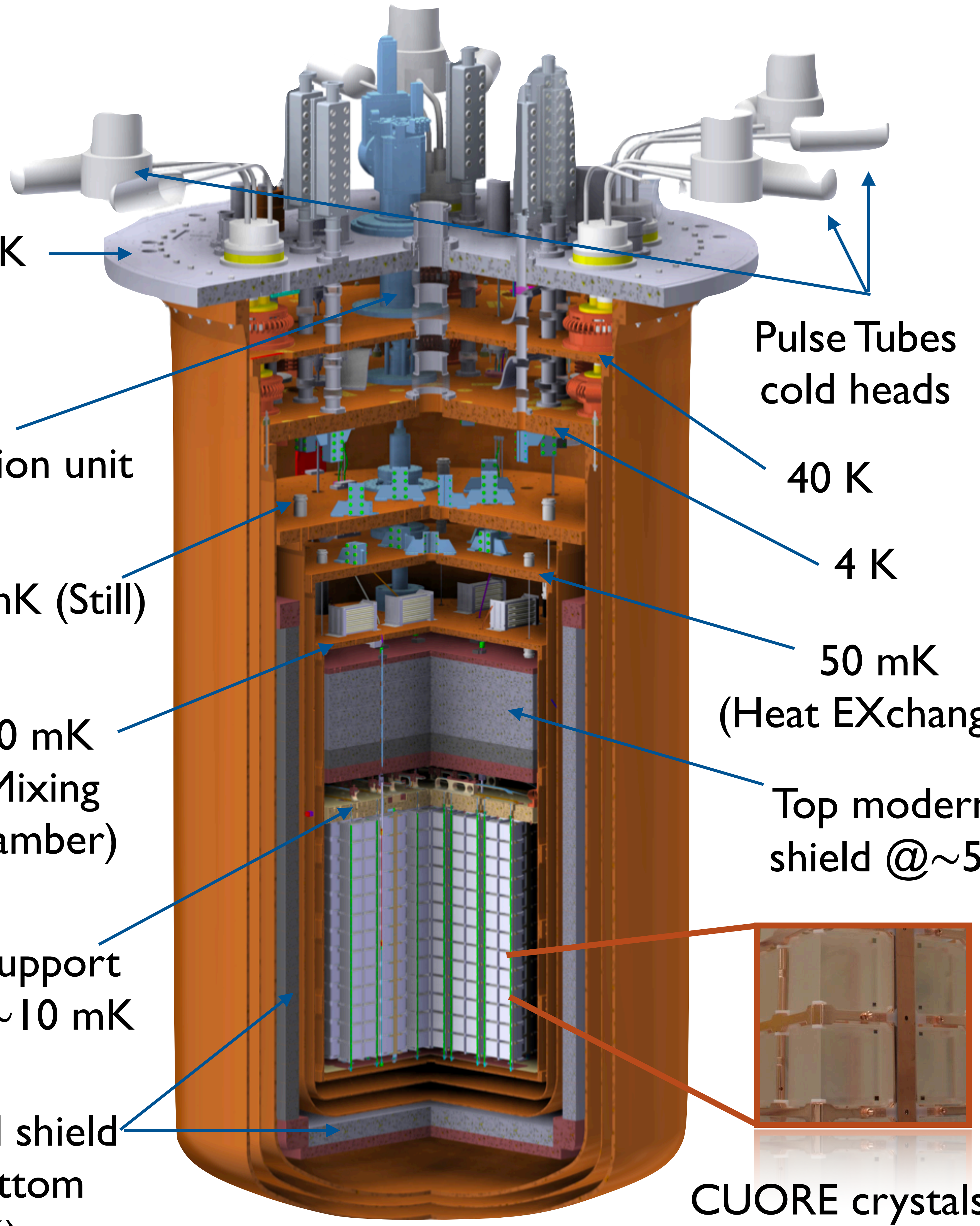
$$C(T) \propto T^3$$

$$R(T) = R_0 e^{\sqrt{T_0/T}}$$

C: absorber capacity
ΔT: temperature variation
ΔE: energy deposition
G: thermal conductance
t: signal decay time

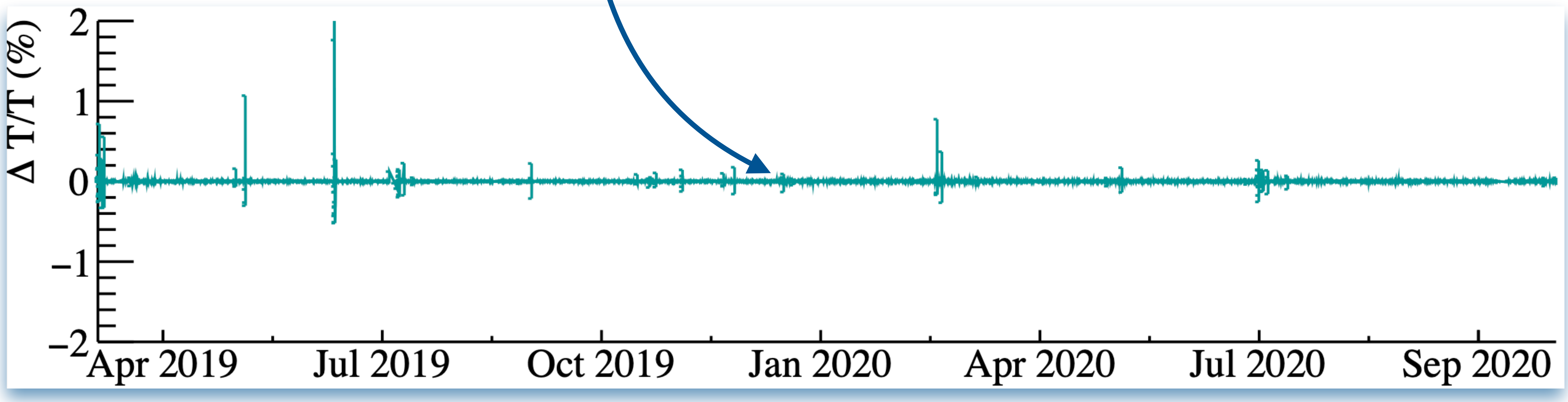
- Operating at a temperature of **10-15 mK**:
- **1 MeV** energy release causes **ΔT~100 μK (ΔR~3MΩ/MeV)**
- excellent energy resolution (few ‰ FWHM @ $Q_{\beta\beta}$)
- no radiation discrimination
- slowness (suitable for rare event searches)

The challenges - part I: cryogenic infrastructure



Cryogenics 102 (2019) 9-21

- Custom-made dry (cryogen-free) dilution cryostat
- Stringent constraints on **radiopurity** - only few materials acceptable (Cu OFE/NOSV for plates and vessels) - **mechanical reliability** and **response** to **seismic events**
- 5 **pulse-tube** cryocoolers (one/two spares)
- 6 **nested vessels** at decreasing temperature to reach base temperature ($T_{min} \simeq 7$ mK)
- Mass <4 K: 15 tons - mass @~50 mK: 3 tons
- Since 2019 they system is operating with **>90% uptime** in stable temperature conditions: **>5 yr @ <20 mK**

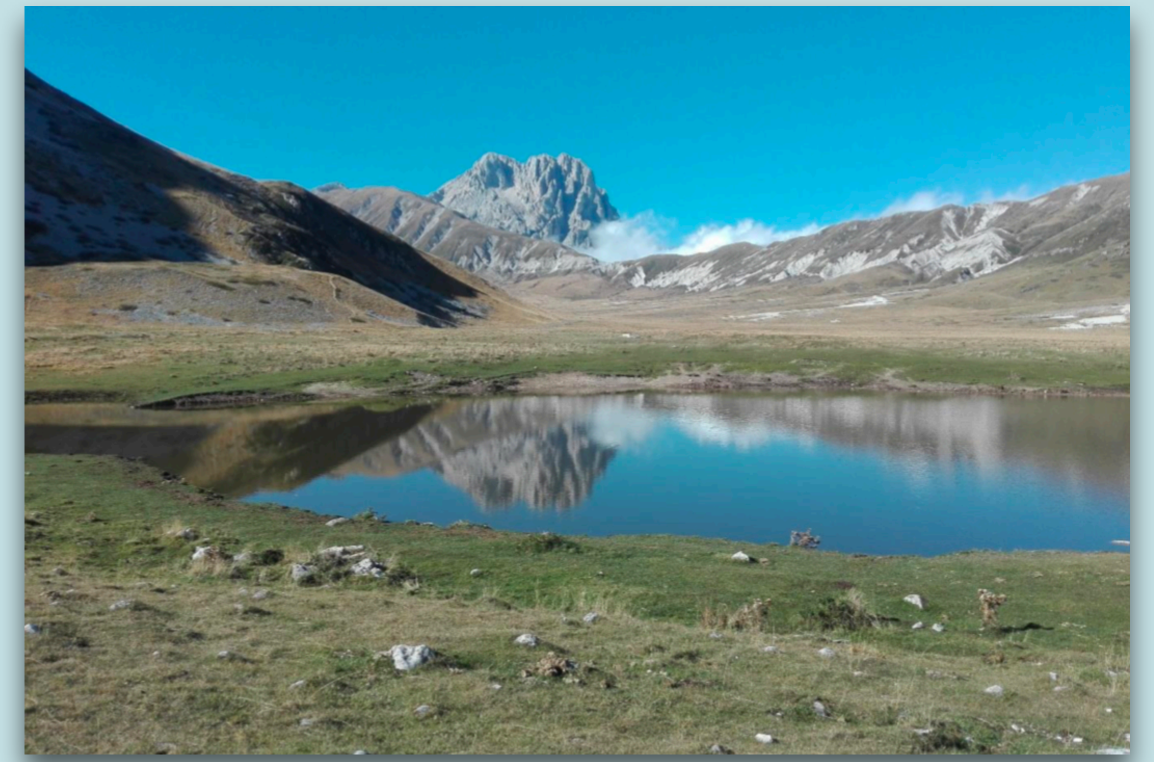


Nature 604, 53-58 (2022)

The challenges - part II: minimizing background

CUORE

LNGS *natural* shielding



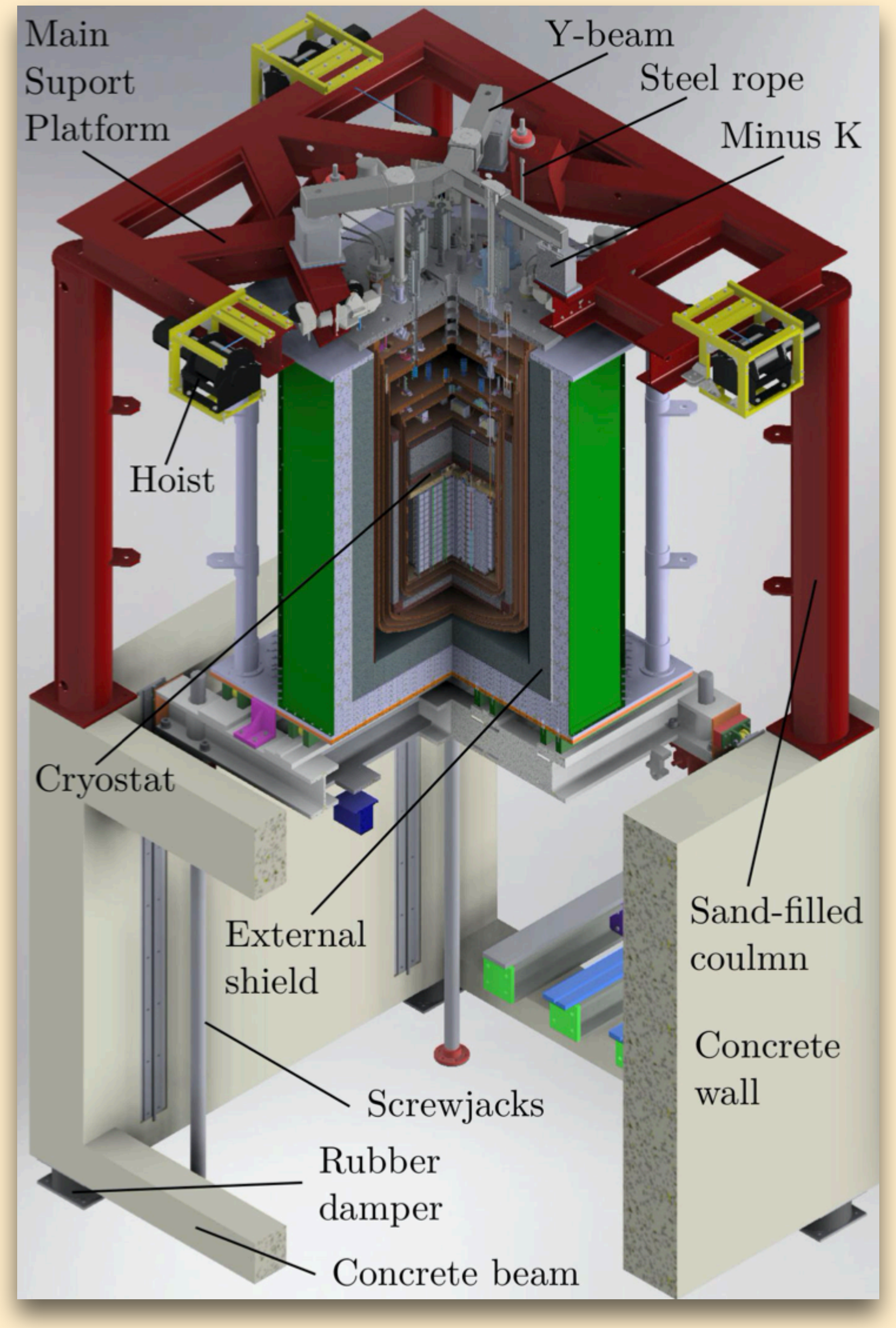
~3600 m water-equivalent rock overburden: cosmic rays flux reduced of six orders of magnitude compared to the surface

$$\Phi_\mu = 3 \cdot 10^{-8}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Astropart Phys. 34 (2010) 18-24

$$\Phi_\mathrm{n} = 4 \cdot 10^{-6}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

External shields



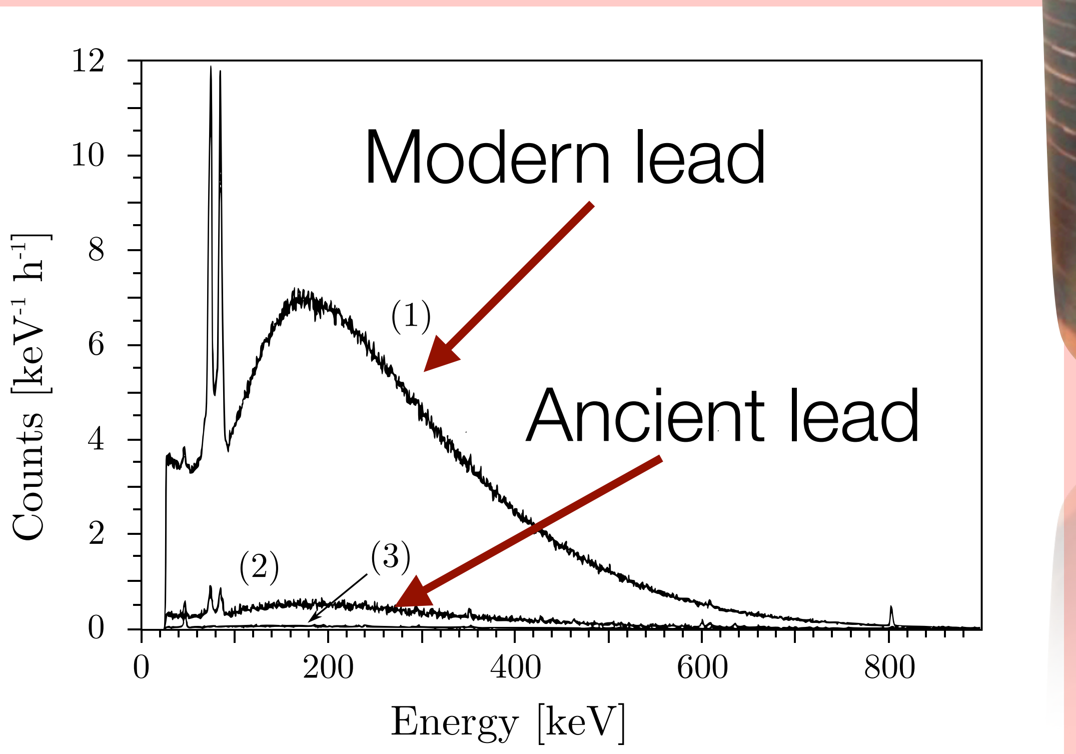
Cryogenics 102 (2019) 9-21

- From γs: 25-cm thick Pb layer
- From neutrons: 20-cm layer in polyethylene + H_3BO_3 panels

Internal lead shields

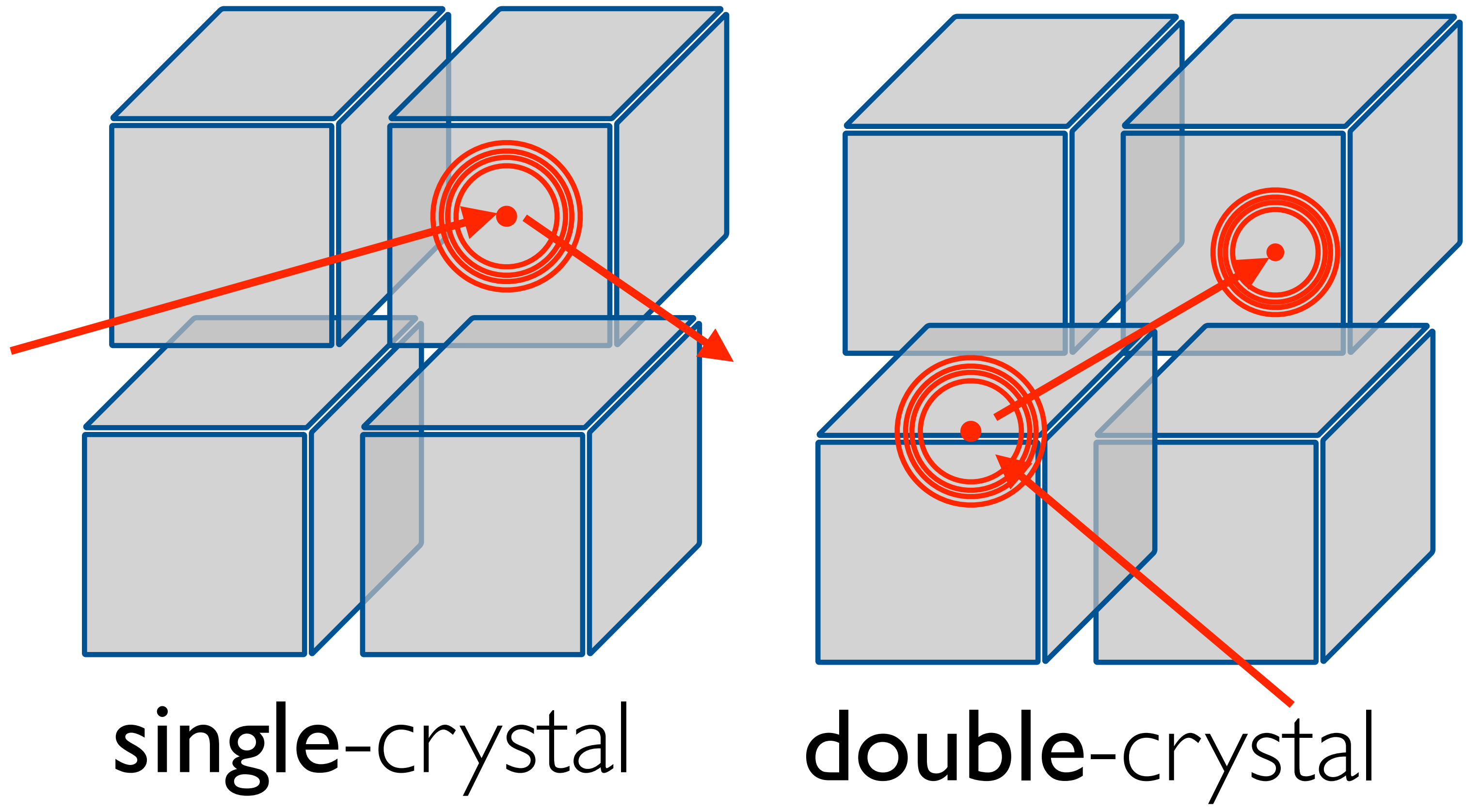
Top: 30-cm modern lead

Side & bottom: 6-cm ancient roman lead from a shipwreck ^{210}Po < 4 mBq/kg

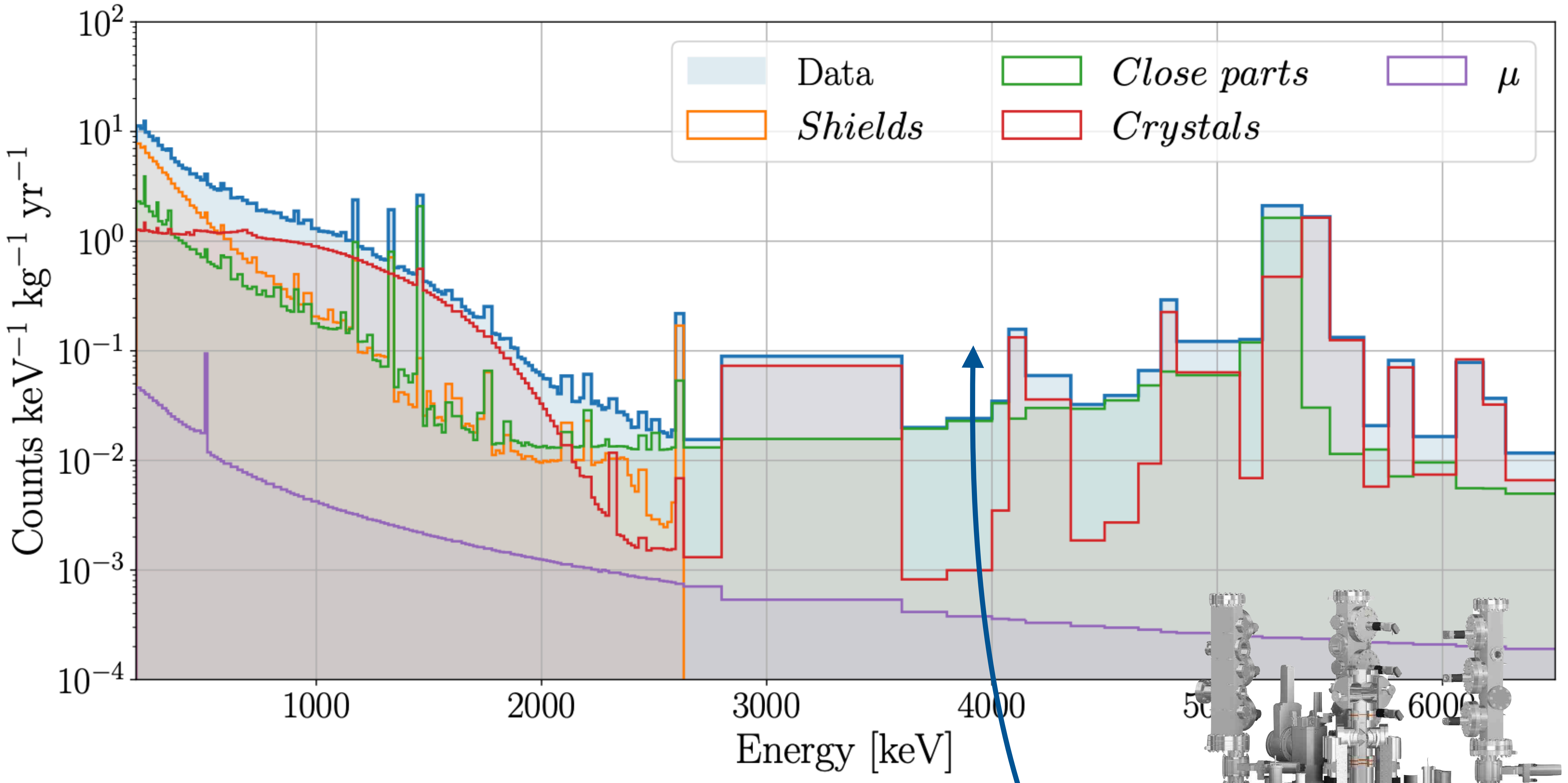


Nucl. Instrum. Meth. B 142, 163 (1998)

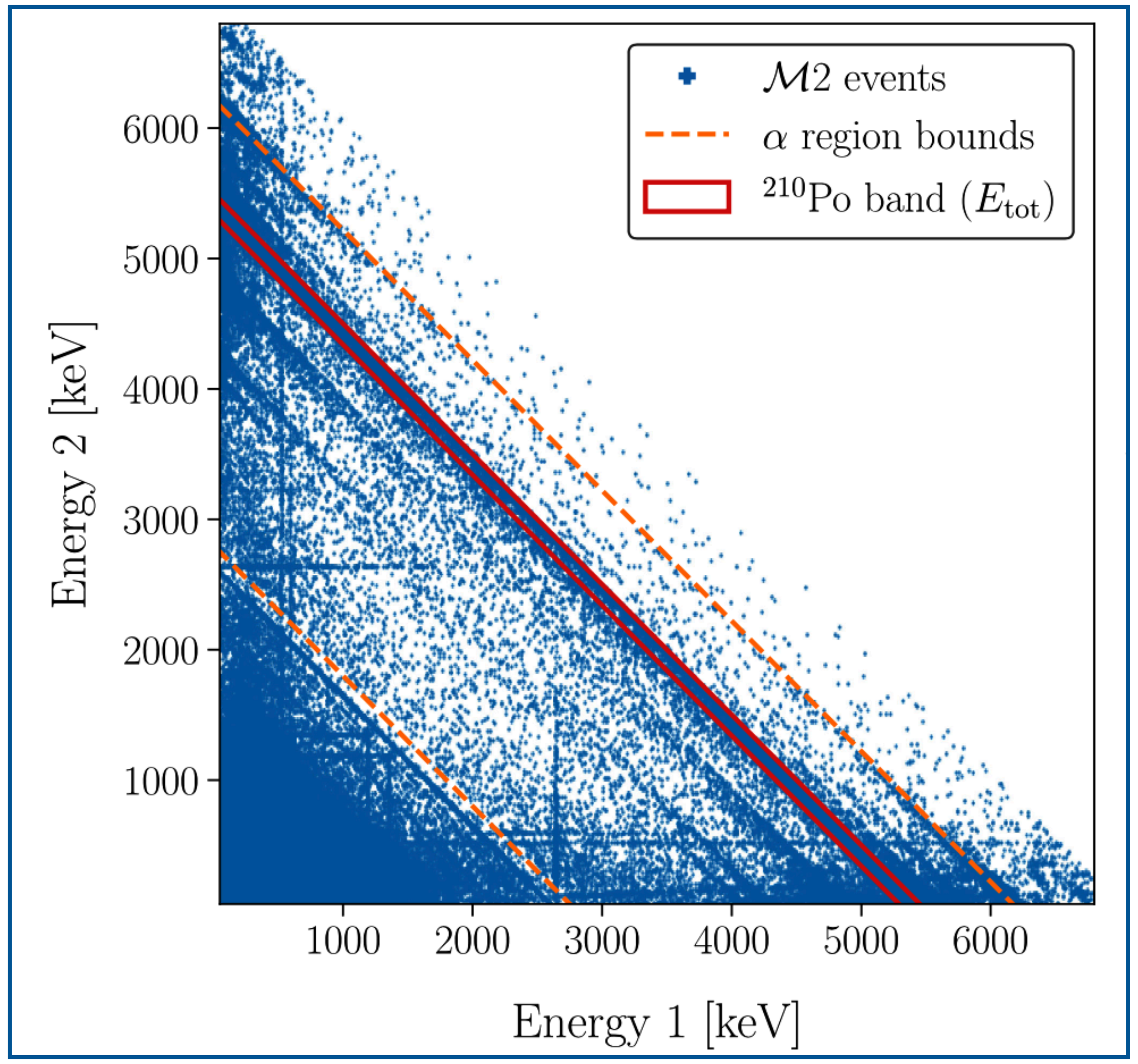
The challenges - part II: modelling (leftover) background



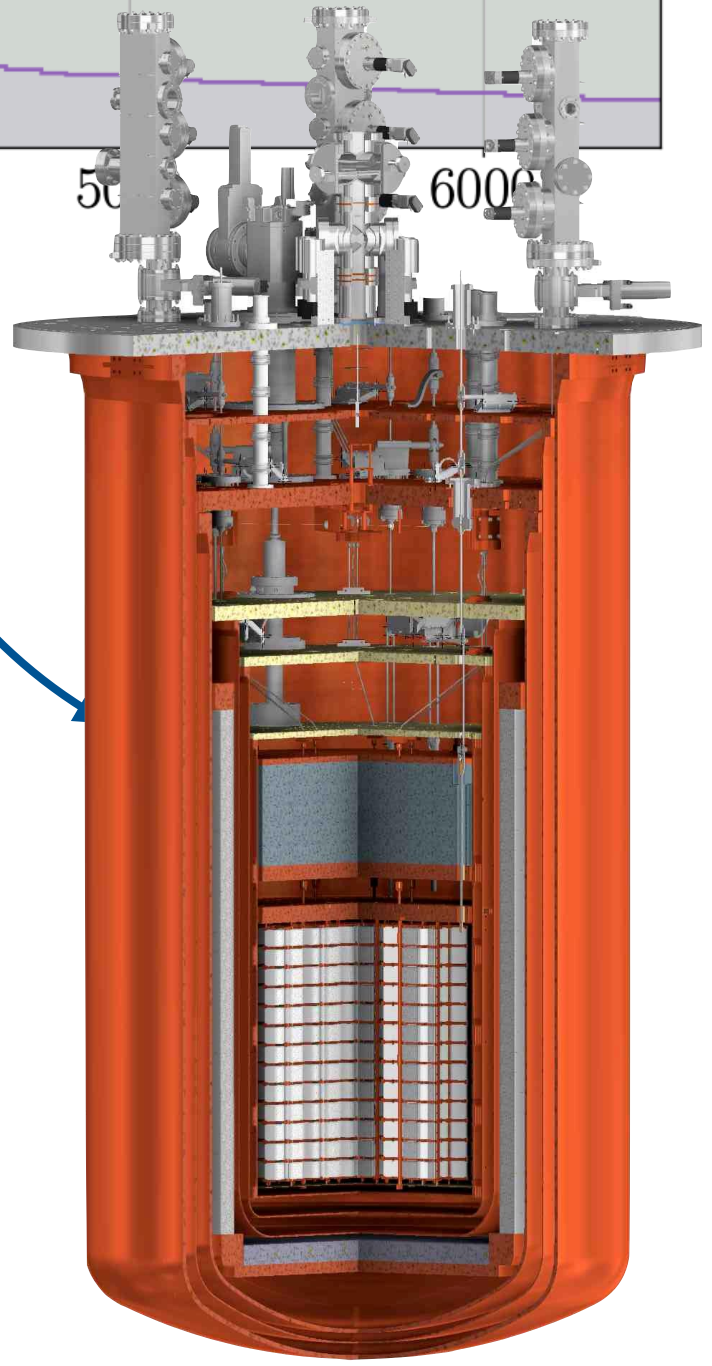
Priors extracted from radioassays and past experiments



Bayesian fit of ***single***-crystal & ***double***-crystal events



Accurate Geant-4 based background model with 80 sources thanks to high detector granularity, relating **sources** and specific **spectral contributions**



Precise measurement of ^{130}Te $2\nu\beta\beta$ decay

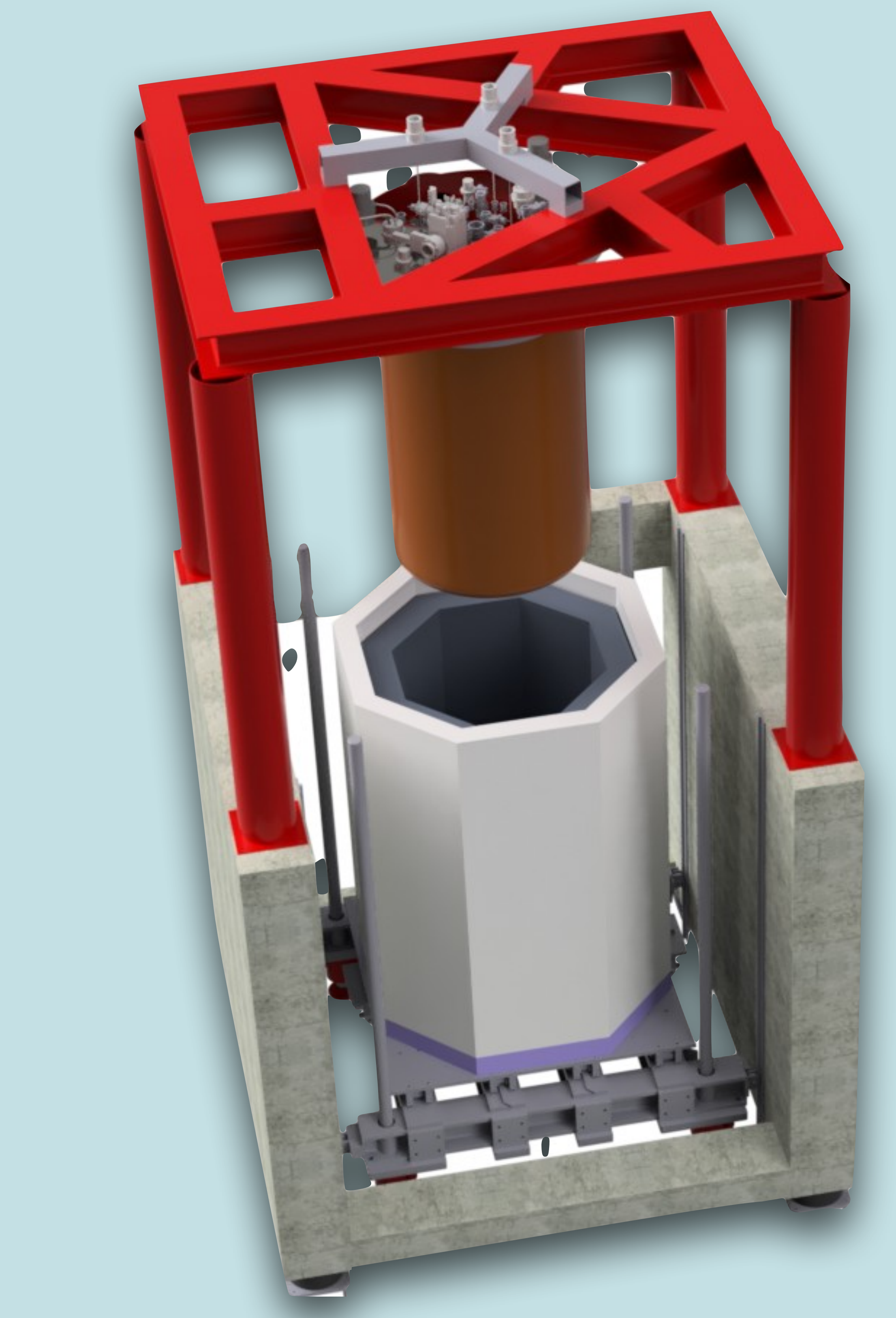
Phys. Rev. D 110, 052003

PRL 135, 082501 (2025)

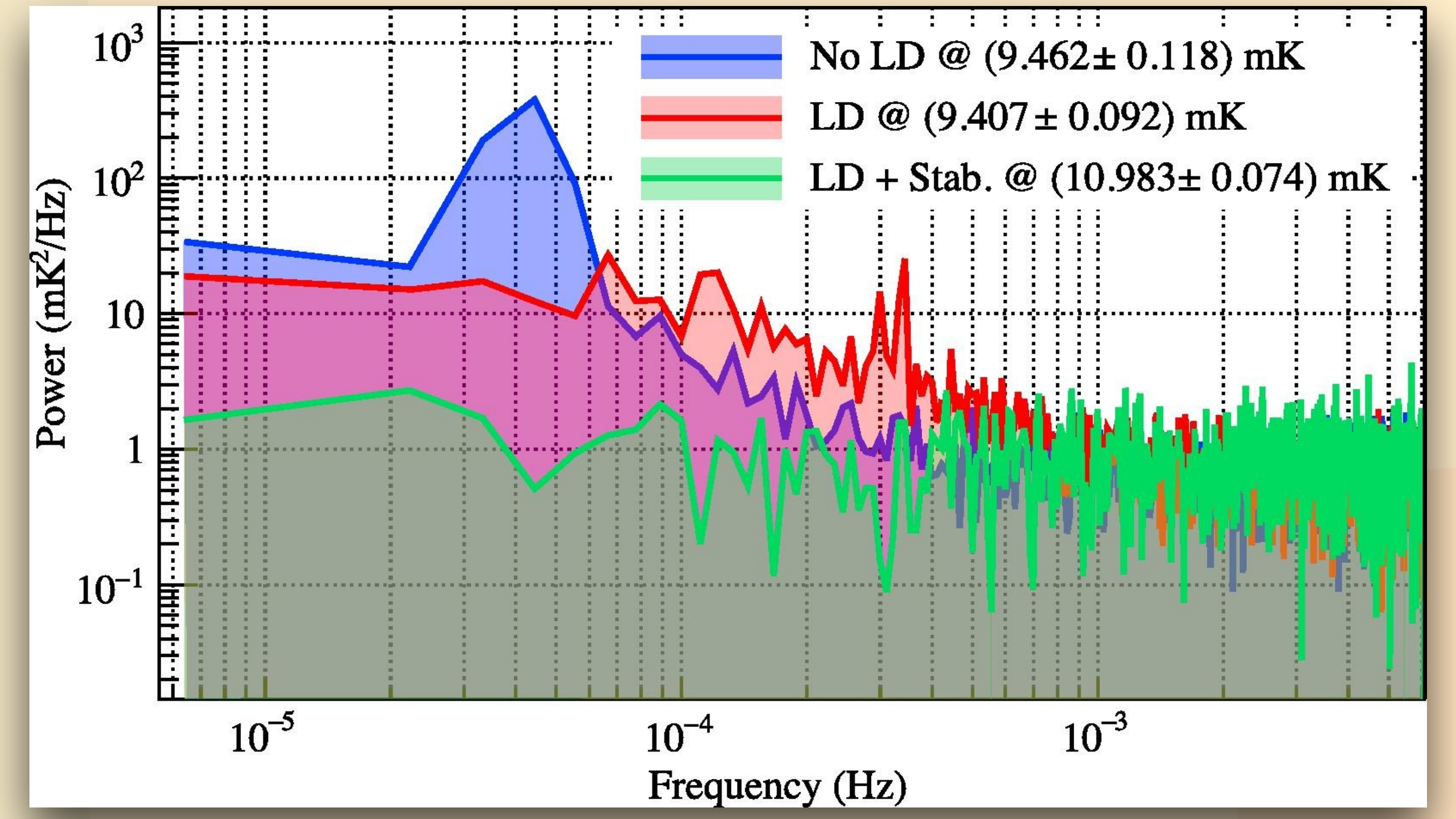
The challenges - part III: suppressing noise sources

CUORE

External structure to decouple the detector from the cryostat



Linear drives and



active noise cancellation to minimize vibrations induced by the **pulse tubes**

Cryogenics 93, 56-65 (2018)

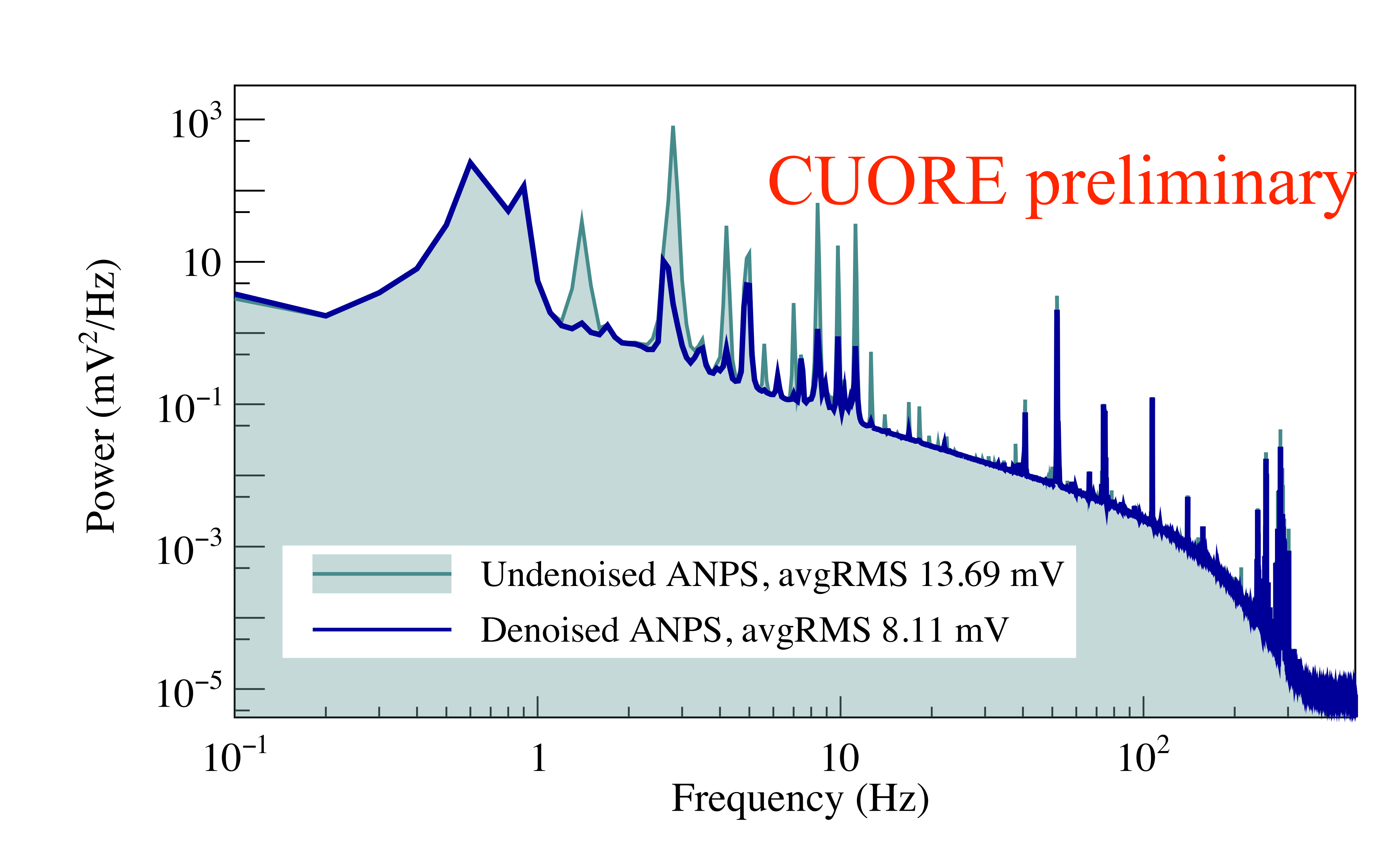
Several **ancillary devices** installed in the CUORE hut to do data denoising and enhance the quality of data

- seismometers, antennae, microphones and accelerometers

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

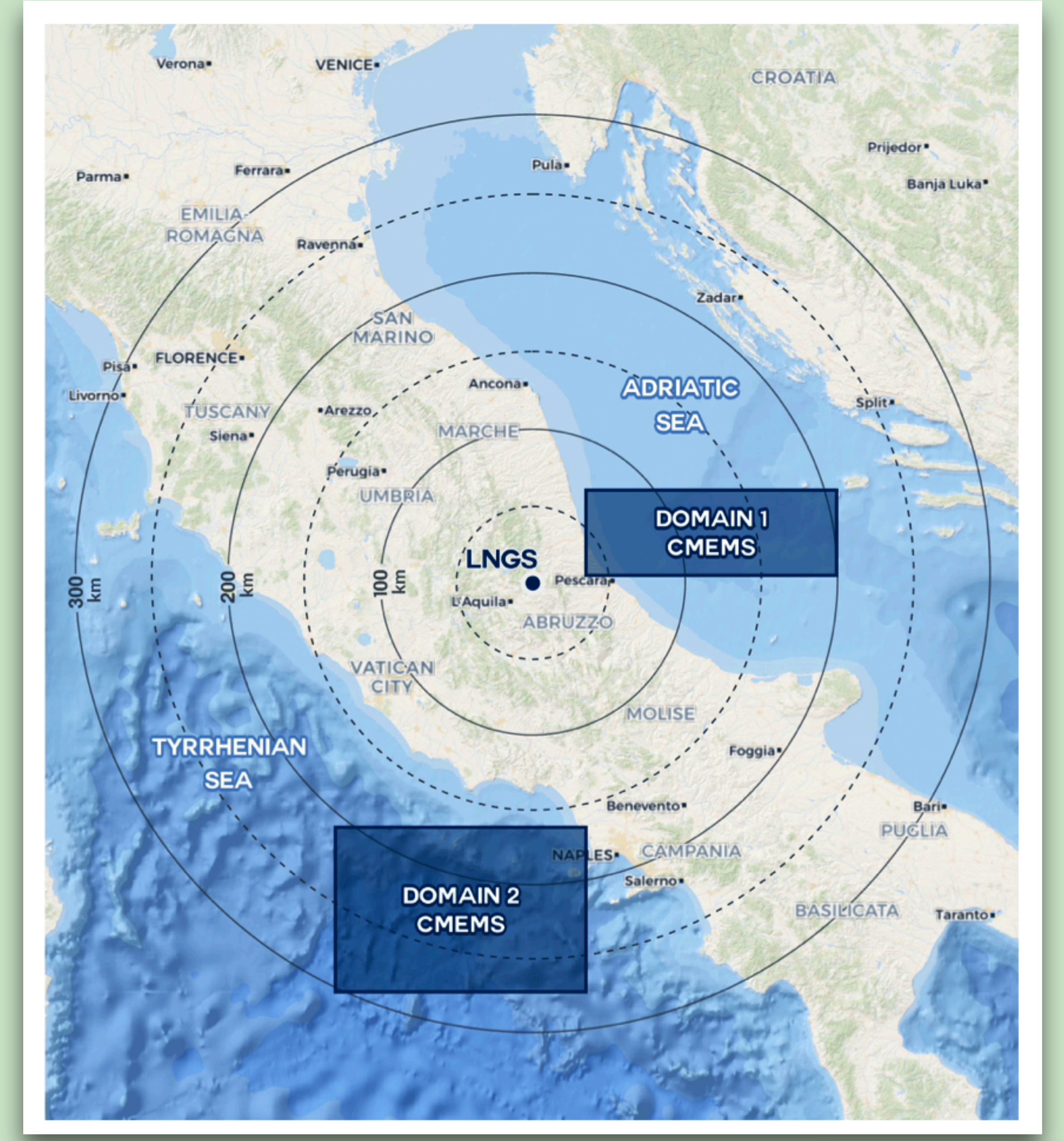
The challenges - part III: modelling (leftover) noise

- **Noise decorrelation algorithms** rely on the correlation between noise power spectra of detector channels and all diagnostic devices installed in the experimental hut:



40% total raw-RMS reduction w/ denoising

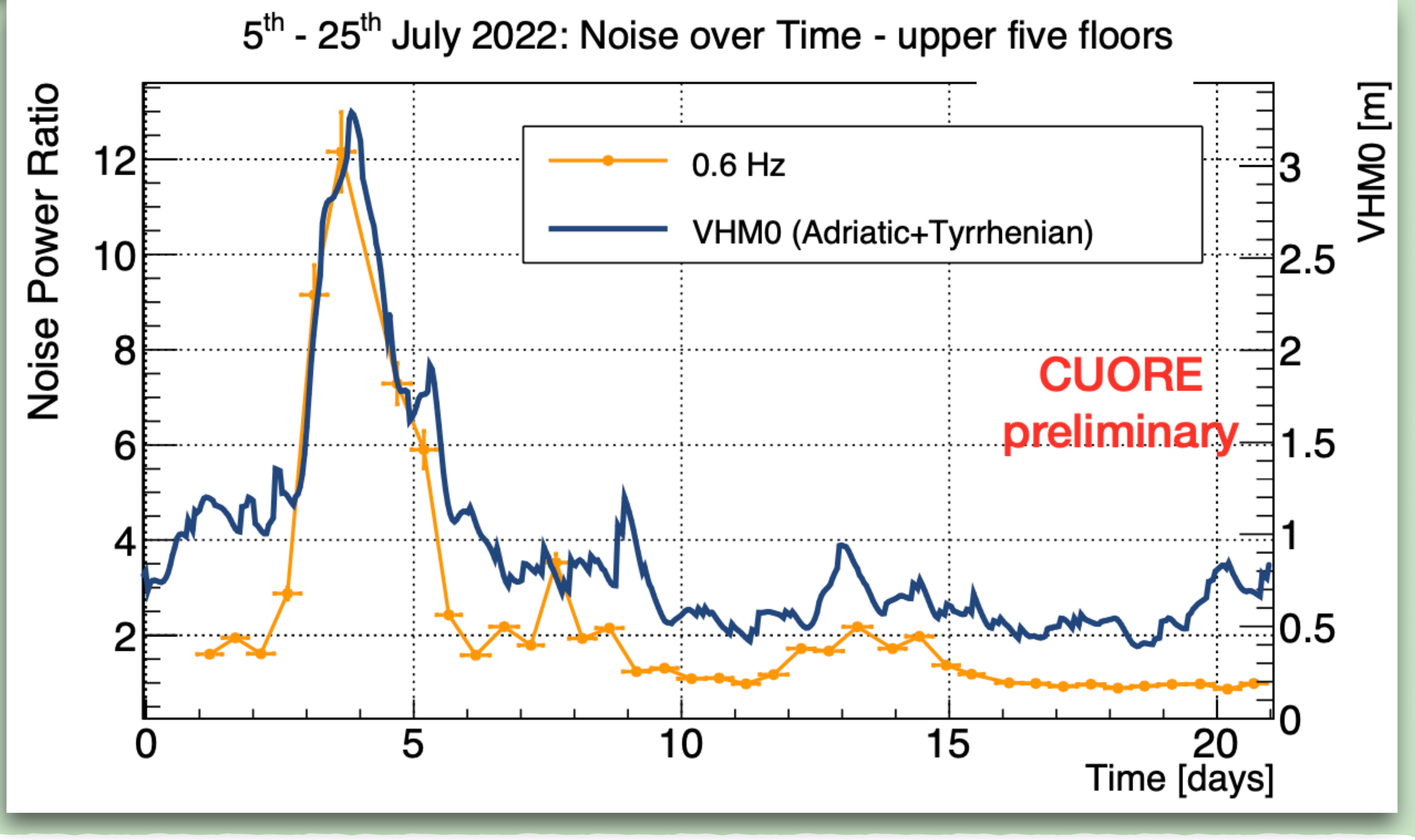
arxiv:2404.04453



- Recent discovery: CUORE is sensitive to **microseismic activity** induced by the **sea waves** (0.2 - 0.3 Hz)
- Evident correlation **storms** ↔ low frequency noise

arxiv:2505.09652

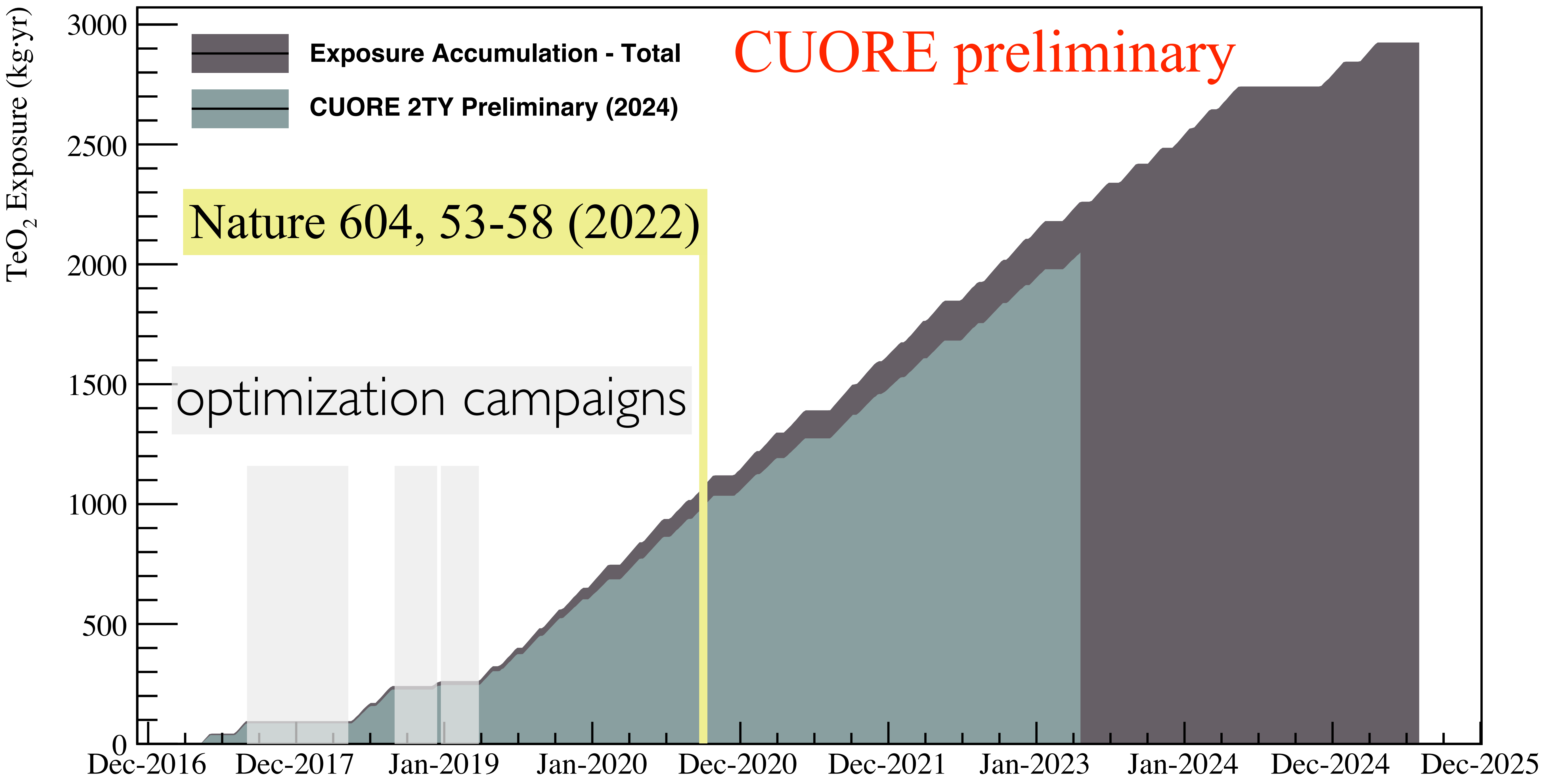
- Under investigation solutions to improve cryostat decoupling



The challenges - part IV: stable operation of 1000 detectors

CUORE

- Data taking started in 2017

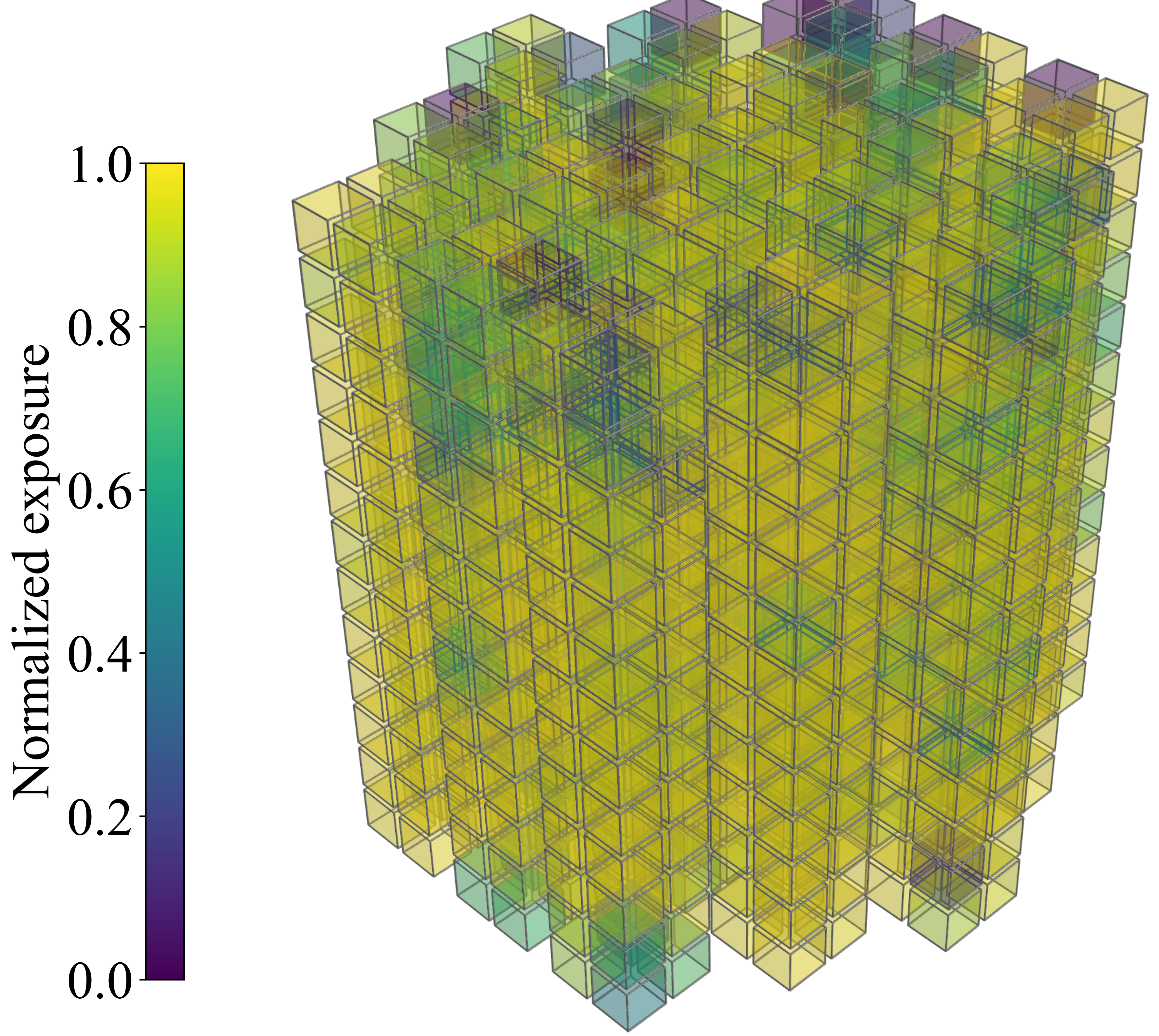


- Data split in *datasets*

calibration	physics runs	calibration

- Trigger rate 50 mHz (~6 mHz) in calibration (physics) runs
- Voltage across NTD Ge thermistors sampled at 1kHz, a software trigger is applied offline

28 datasets (May 2017 - April 2023)



CUORE preliminary

TeO_2 exposure: **2039.0 kg·yr**

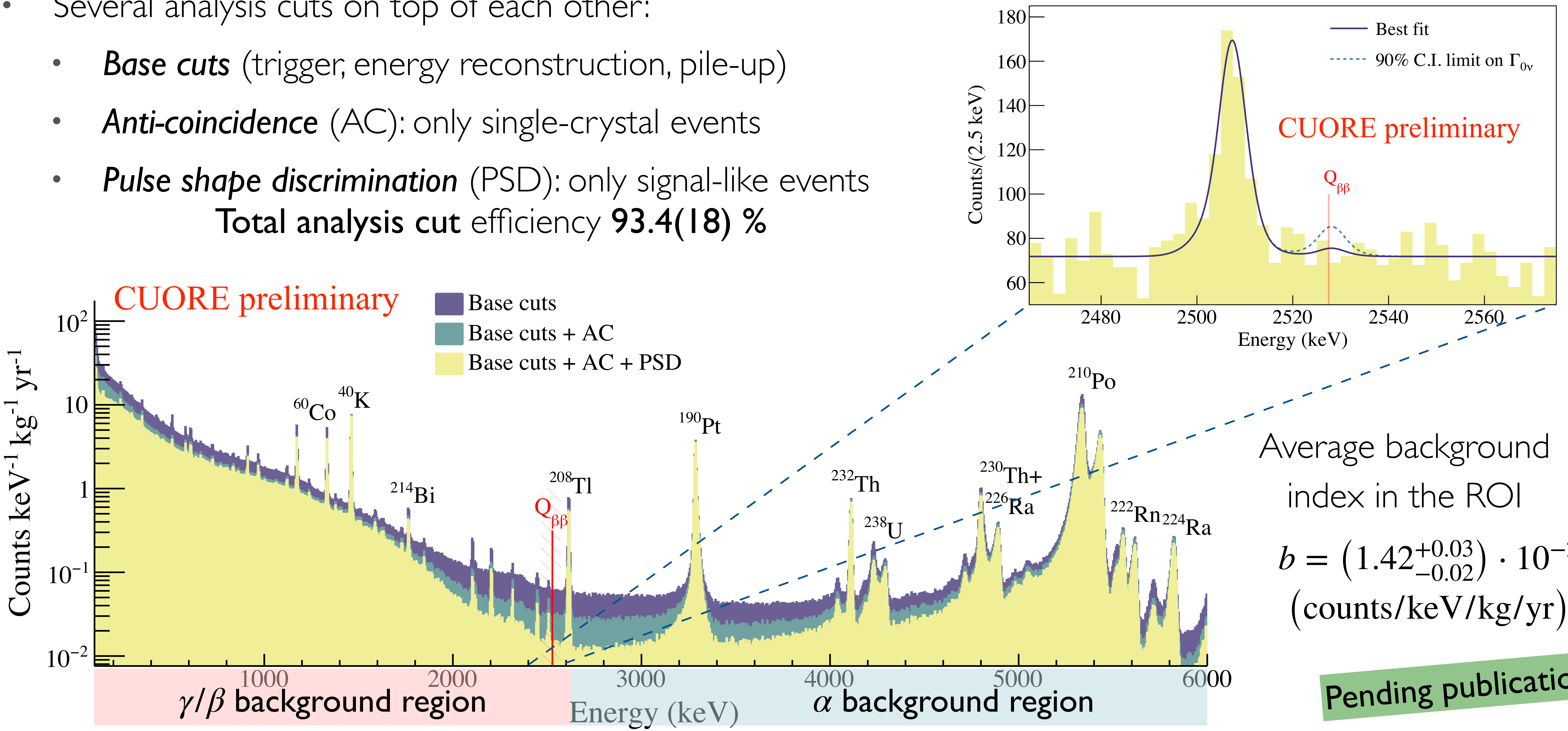
^{130}Te exposure: **567.0 kg·yr**

uniformly distributed on the detector

The 2 tonne-yr data spectrum

- Several analysis cuts on top of each other:
  - ***Base cuts*** (trigger, energy reconstruction, pile-up)
  - ***Anti-coincidence*** (AC): only single-crystal events
  - ***Pulse shape discrimination*** (PSD): only signal-like events

Total analysis cut efficiency **93.4(18) %**



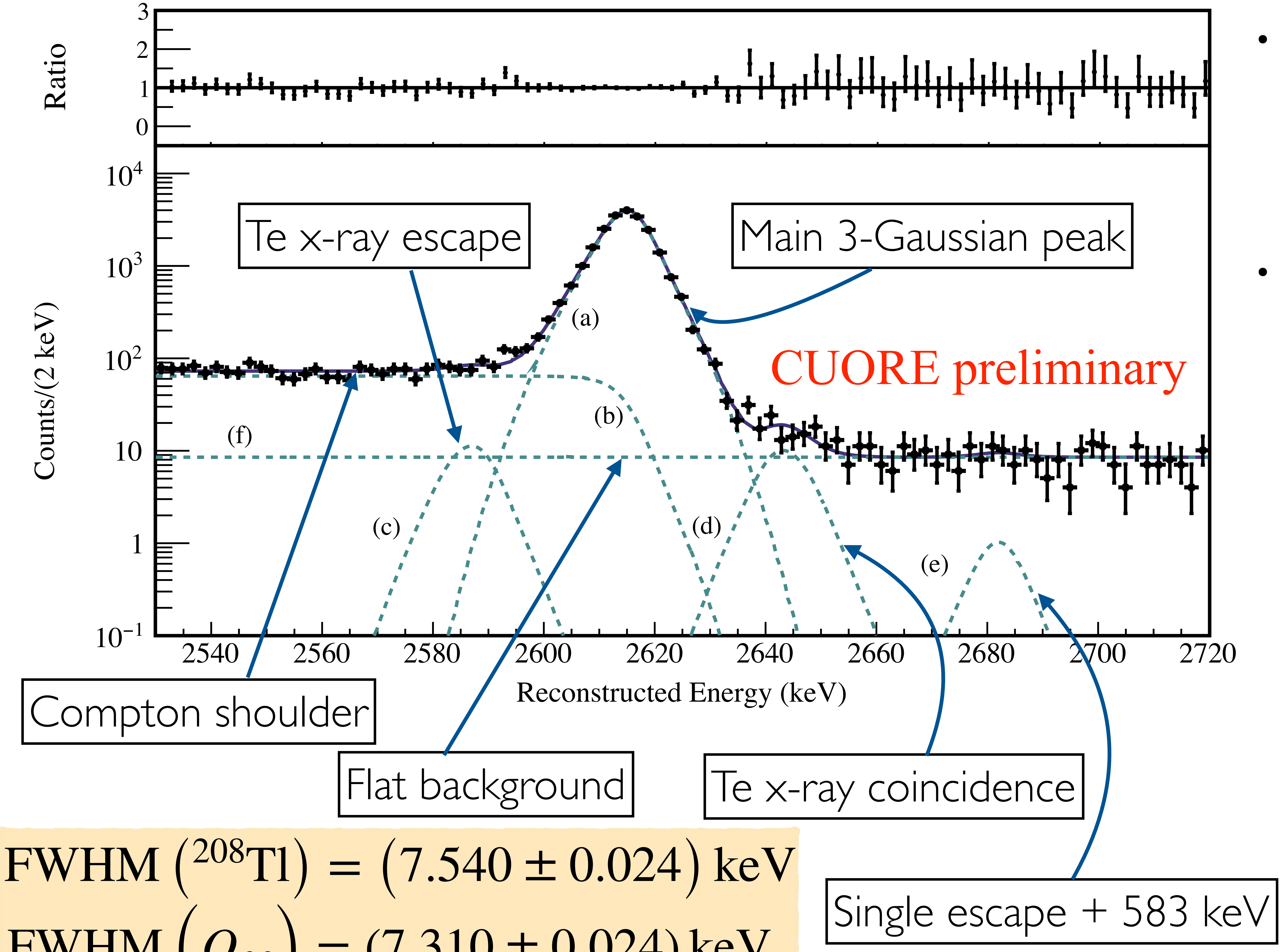
Average background index in the ROI

$$b = \left(1.42^{+0.03}_{-0.02}\right) \cdot 10^{-2}$$

(counts/keV/kg/yr)

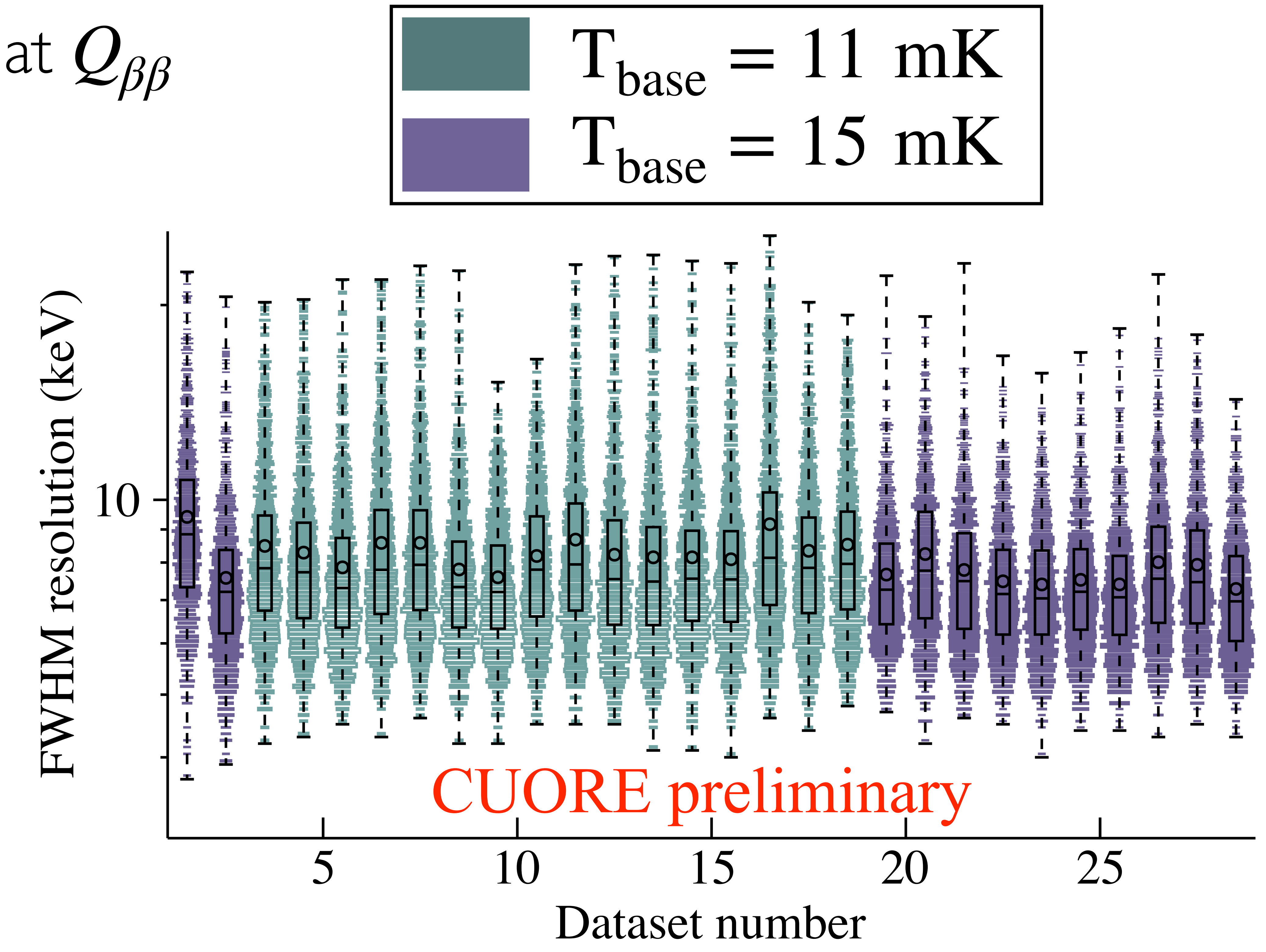
Pending publication

Modeling detector response



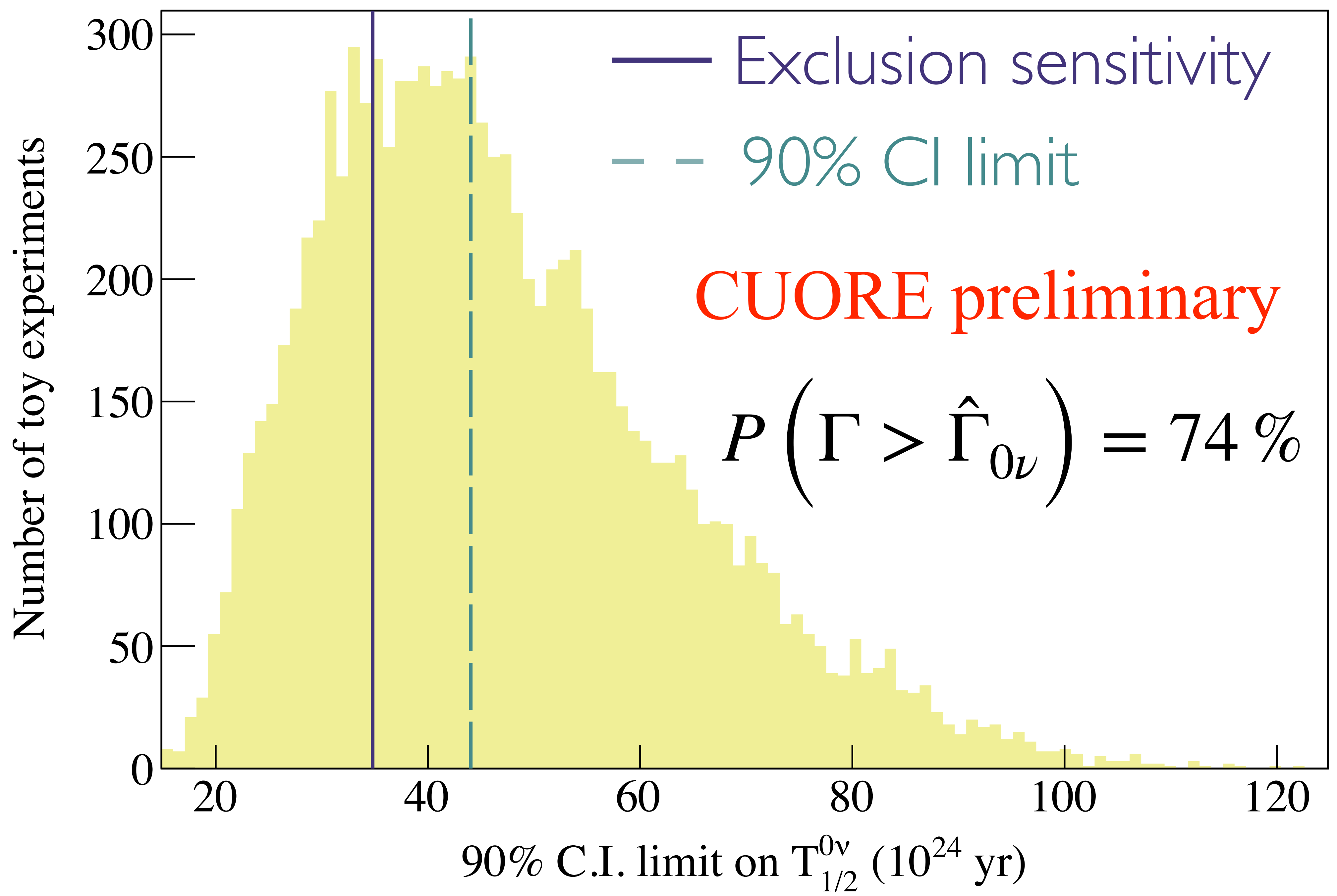
$$\mathrm{FWHM}\left({}^{208}\mathrm{Tl}\right) = (7.540 \pm 0.024)\ \mathrm{keV}$$
$$\mathrm{FWHM}\left(Q_{\beta\beta}\right) = (7.310 \pm 0.024)\ \mathrm{keV}$$
$$\Delta E\left(Q_{\beta\beta}\right) = \left(0.40^{+0.21}_{-0.44}\right)\ \mathrm{keV}$$

- Detector response extracted on events from the ^{208}Tl line at 2615 keV in calibration data separately for each bolometer and dataset
- Fit of the most prominent γ lines in physics data to scale the energy resolution and calibration bias at $Q_{\beta\beta}$



Fitting our data to extract $\Gamma_{0\nu\beta\beta}$

CUORE

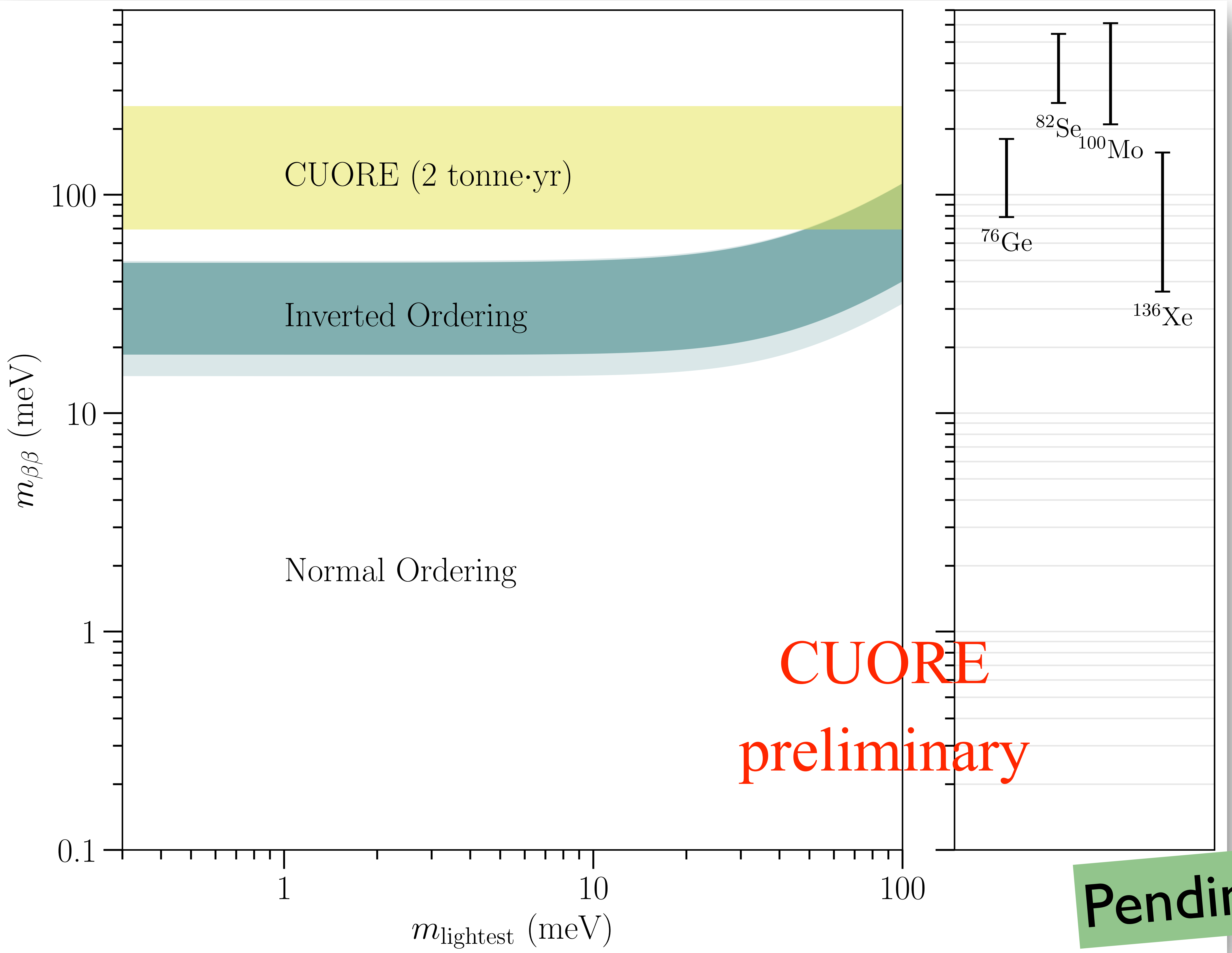


- Median exclusion sensitivity from toy MC experiments $T^{1/2}_{0\nu\beta\beta} = 4.4 \cdot 10^{25}$ yr (90 % C . I.)
- Unbinned Bayesian fit with $\Gamma_{0\nu\beta\beta} > 0$
- No evidence of $0\nu\beta\beta$ and new limit on ^{130}Te half-life $T^{1/2}_{0\nu\beta\beta} > 3.5 \cdot 10^{25}$ yr (90 % C . I.)

Frequentist result $T^{1/2}_{0\nu\beta\beta} > 3.4 \cdot 10^{25}$ yr (90 % C . L.)

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

$m_{\beta\beta} < 70 - 250$ meV

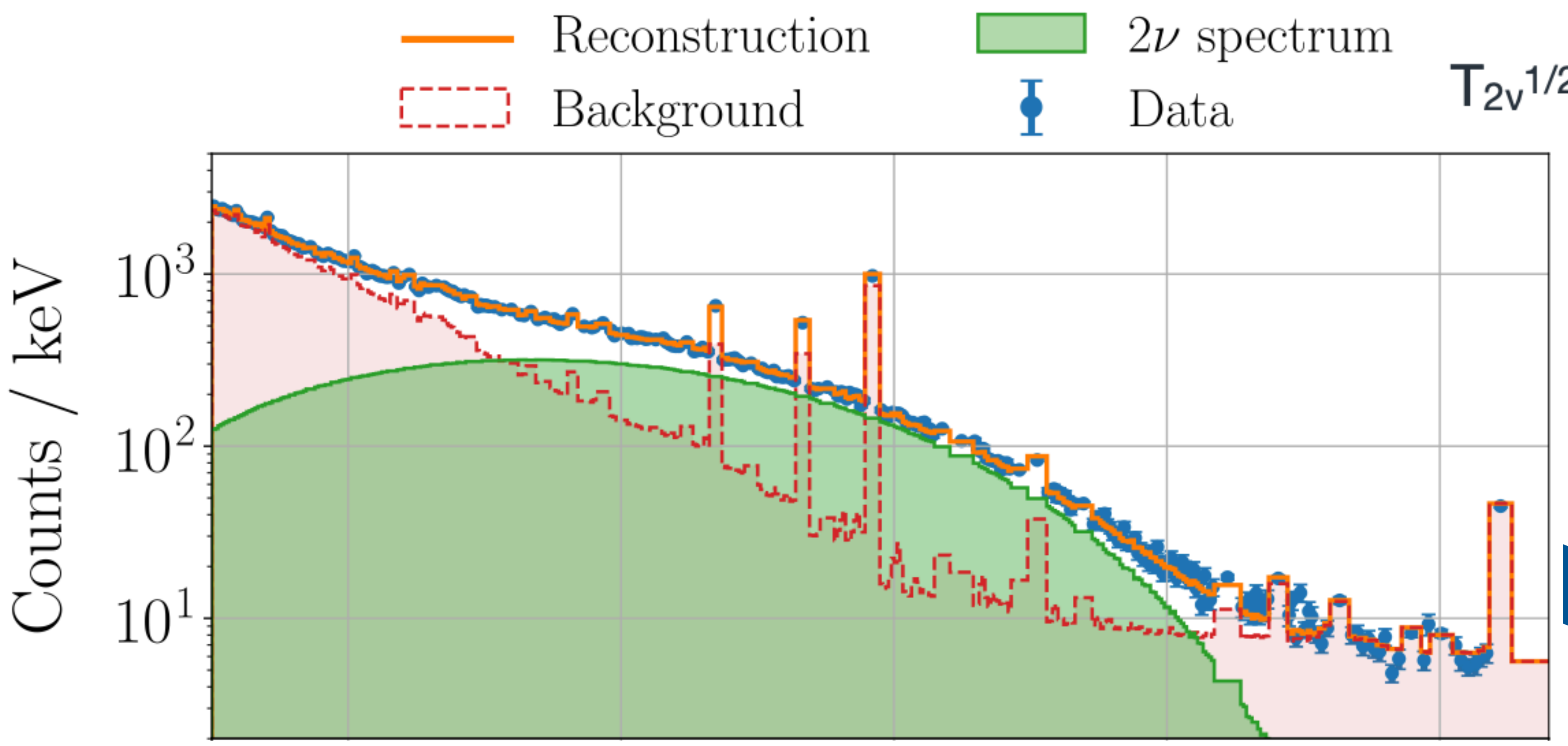


Pending publication

Not only 130Te $0\nu\beta\beta$: other $\beta\beta$ searches

CUORE

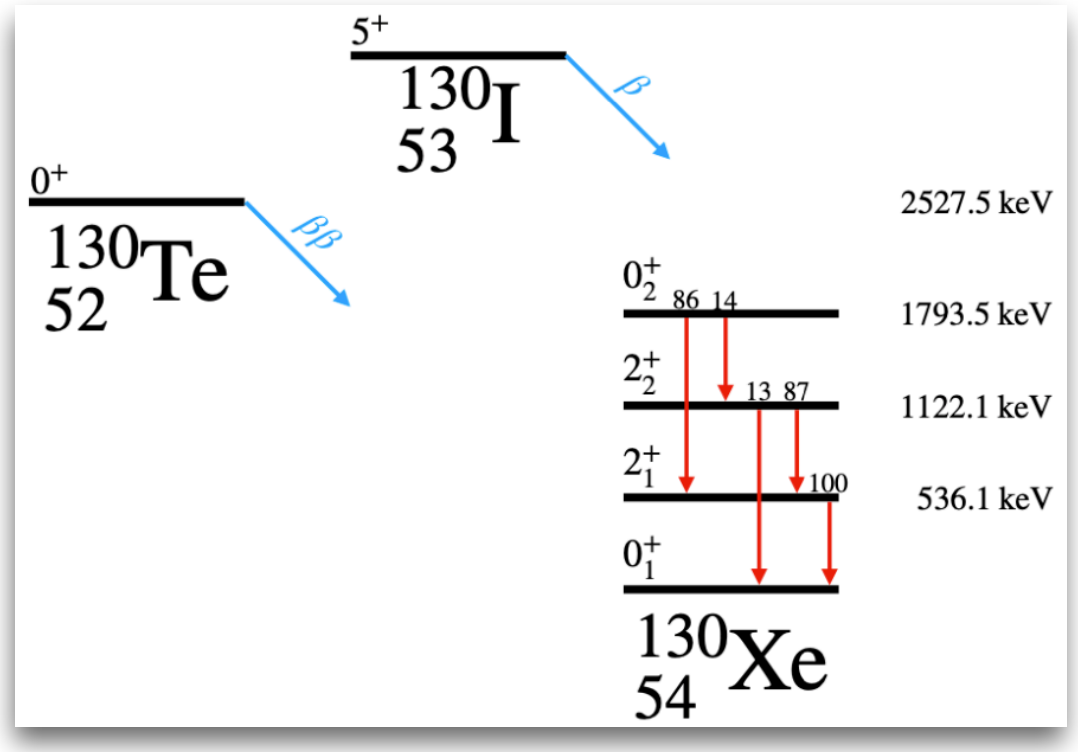
^{130}Te SM-allowed $2\nu\beta\beta$ decay



$T_{2\nu}^{1/2}$ (^{130}Te) = [9.32 $^{+0.05}_{-0.04}$(stat) $^{+0.07}_{-0.07}$(syst)] x 10^{20} yr

PRL 135, 082501 (2025)

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

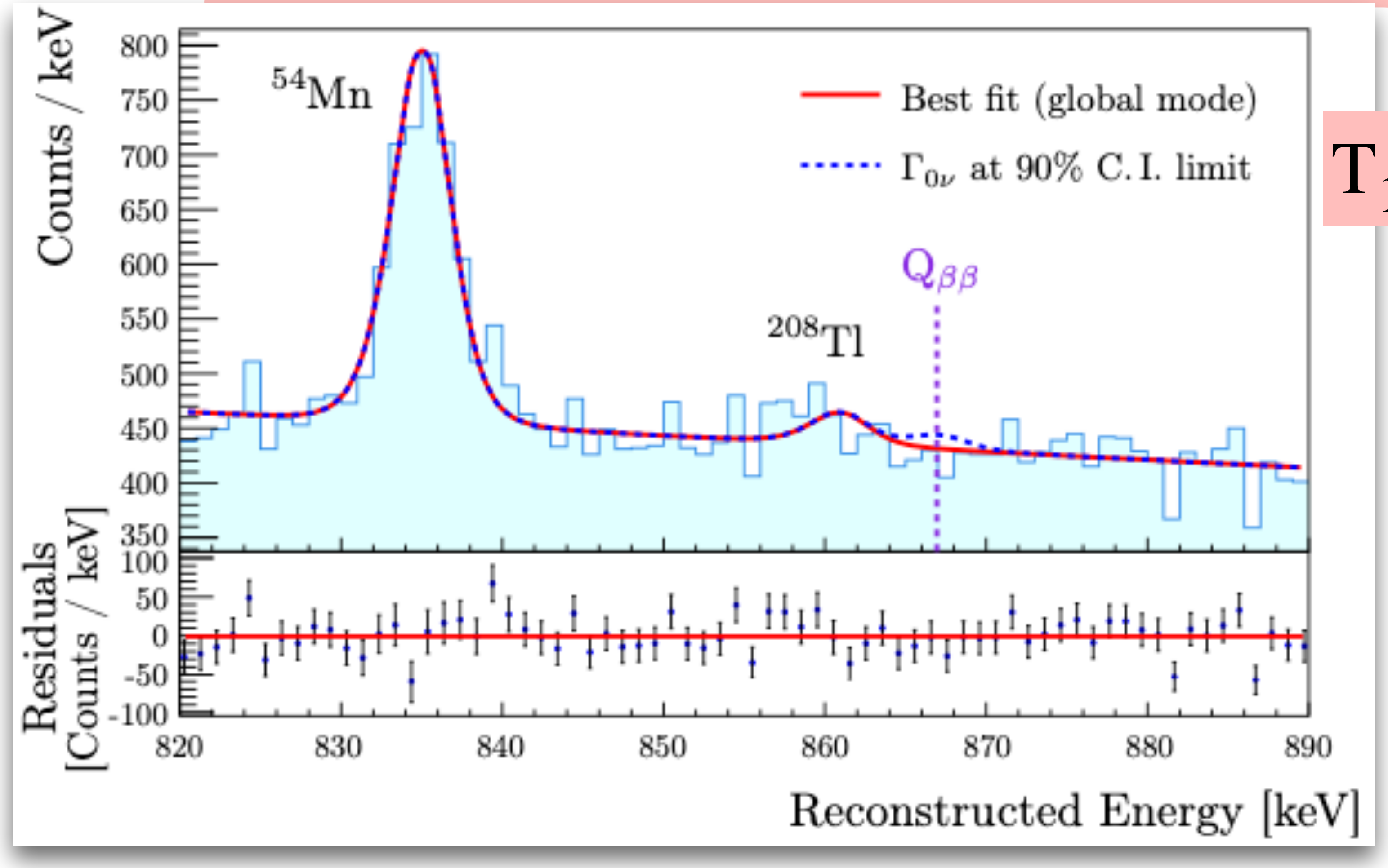


$T^{1/2}_{0\nu} > 5.9 \cdot 10^{24}$ yr (90 % C.I.)

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

Eur. Phys. J. C 81, 567 (2021)

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

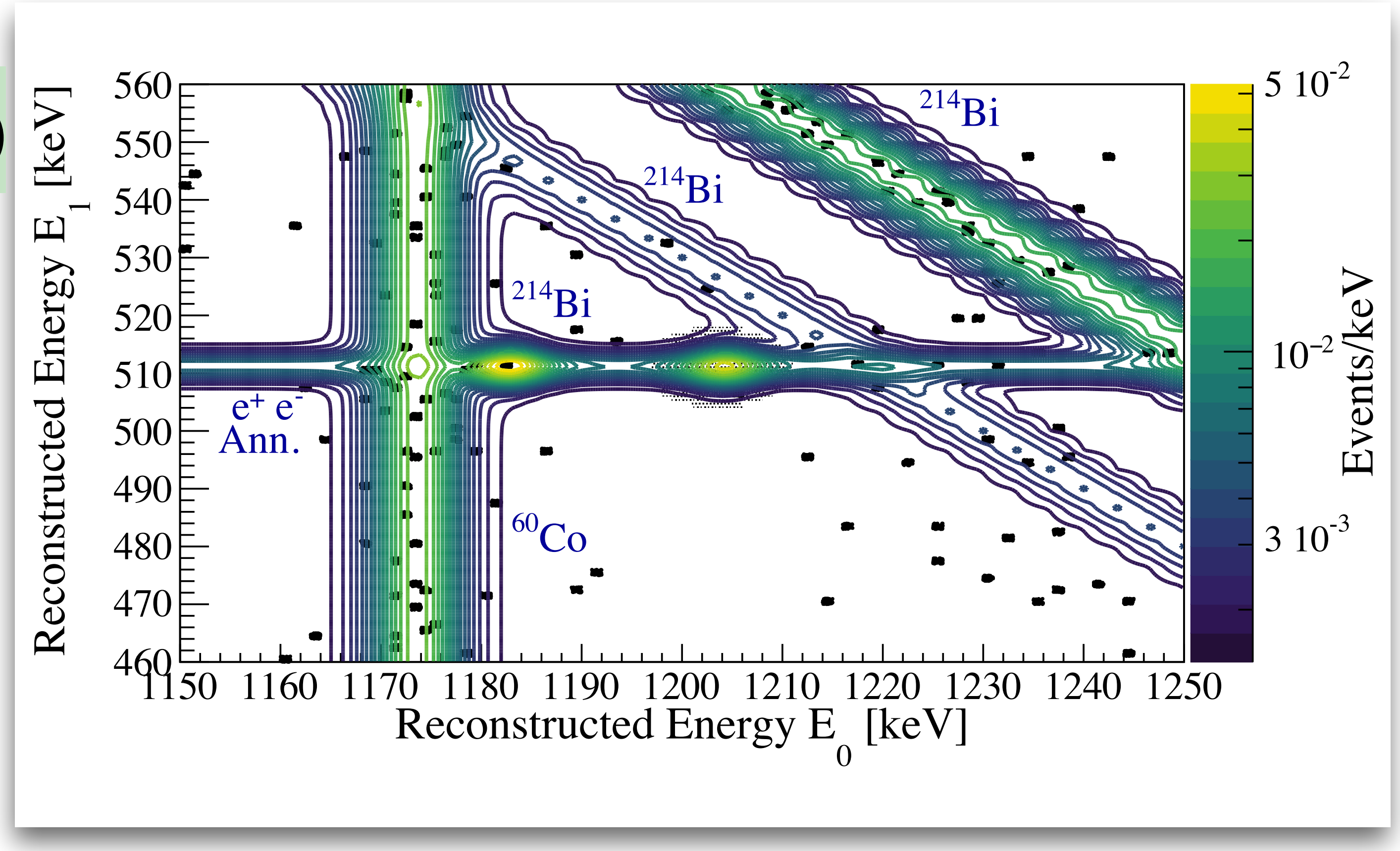


$T_{1/2} > 3.6 \cdot 10^{24}$ yr (90 % C.I.)

PRL 129, 222501 (2022)

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

$T_{1/2} > 2.9 \cdot 10^{22}$ yr (90 % C.I.)

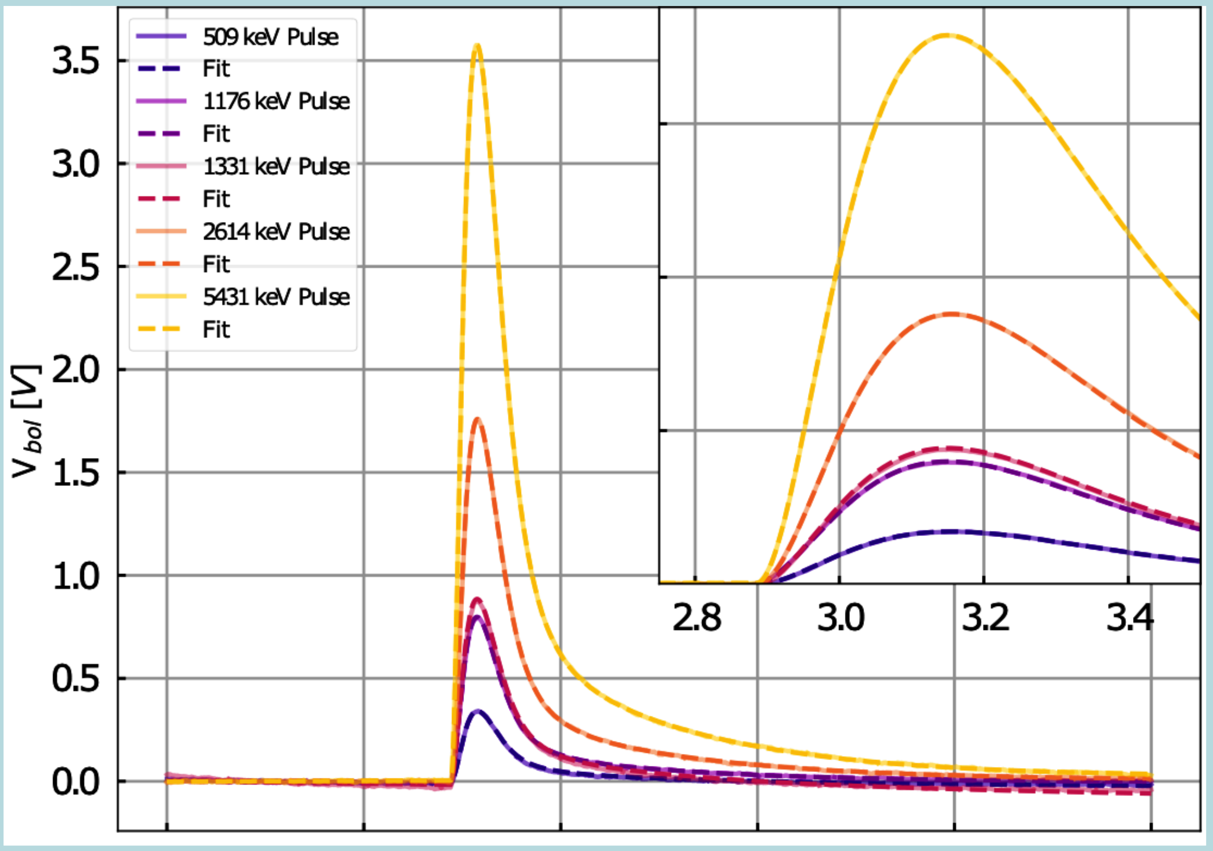


Phys. Rev. C, 105 065504 (2022)

Not only 130Te $0\nu\beta\beta$: other physics cases

CUORE

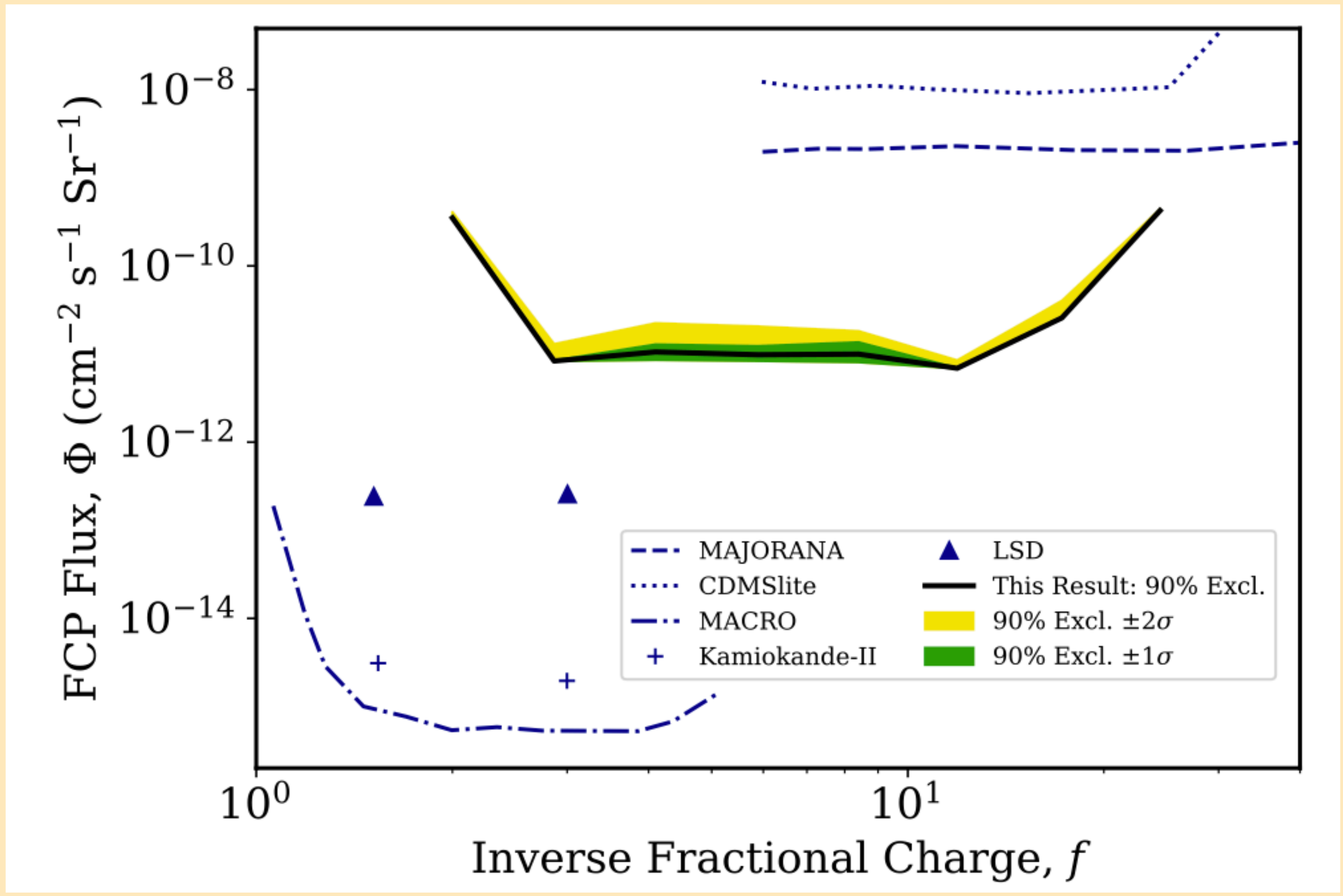
Thermal model of CUORE calorimeters



Dedicated study of environmental and antropic vibrational sources

JINST 17 (2022) 11, P11023

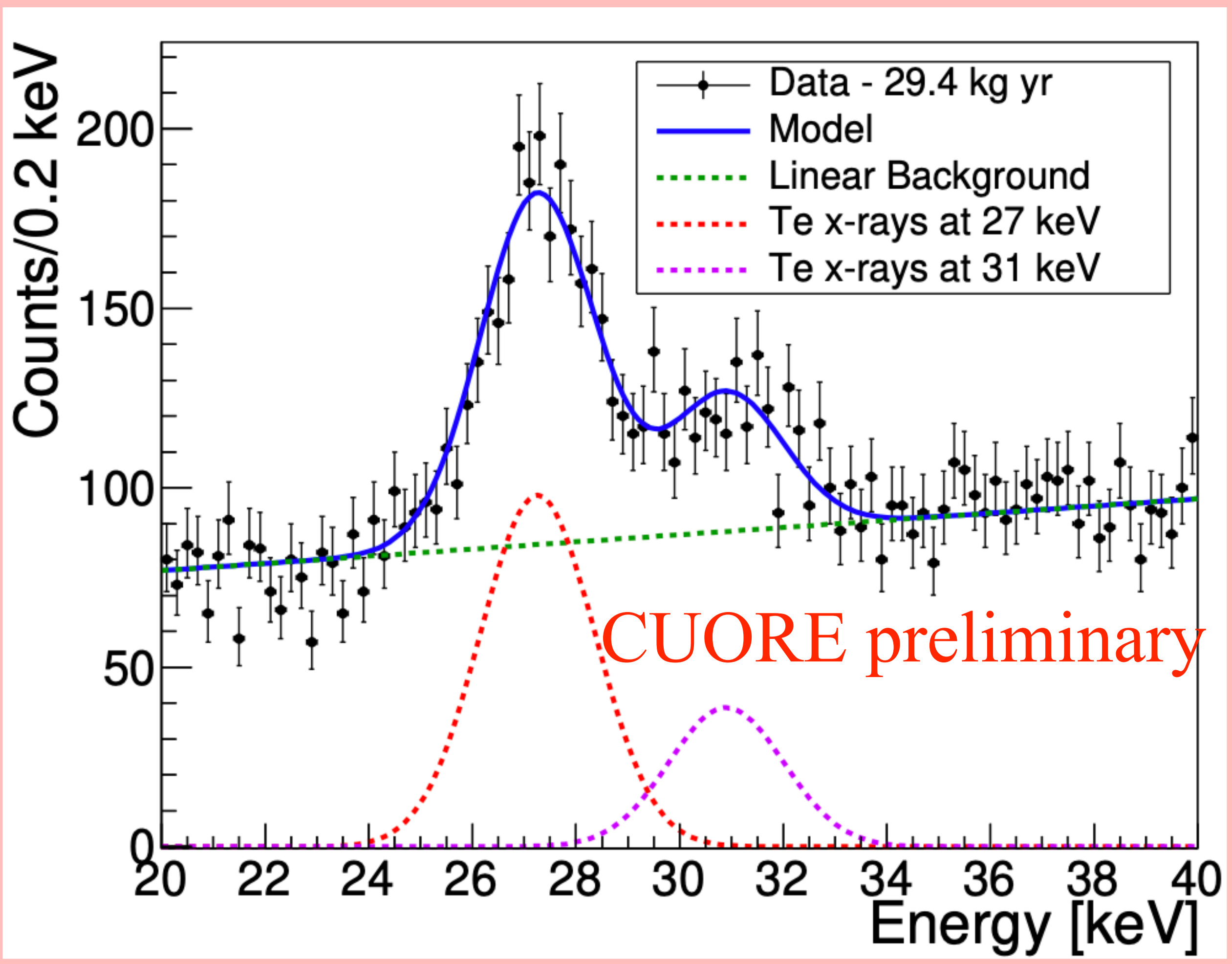
Search for fractionally charged particles



Multi-spectral search for rare events based on multi-crystal track-like topologies

Phys. Rev. Lett. 133, 241801

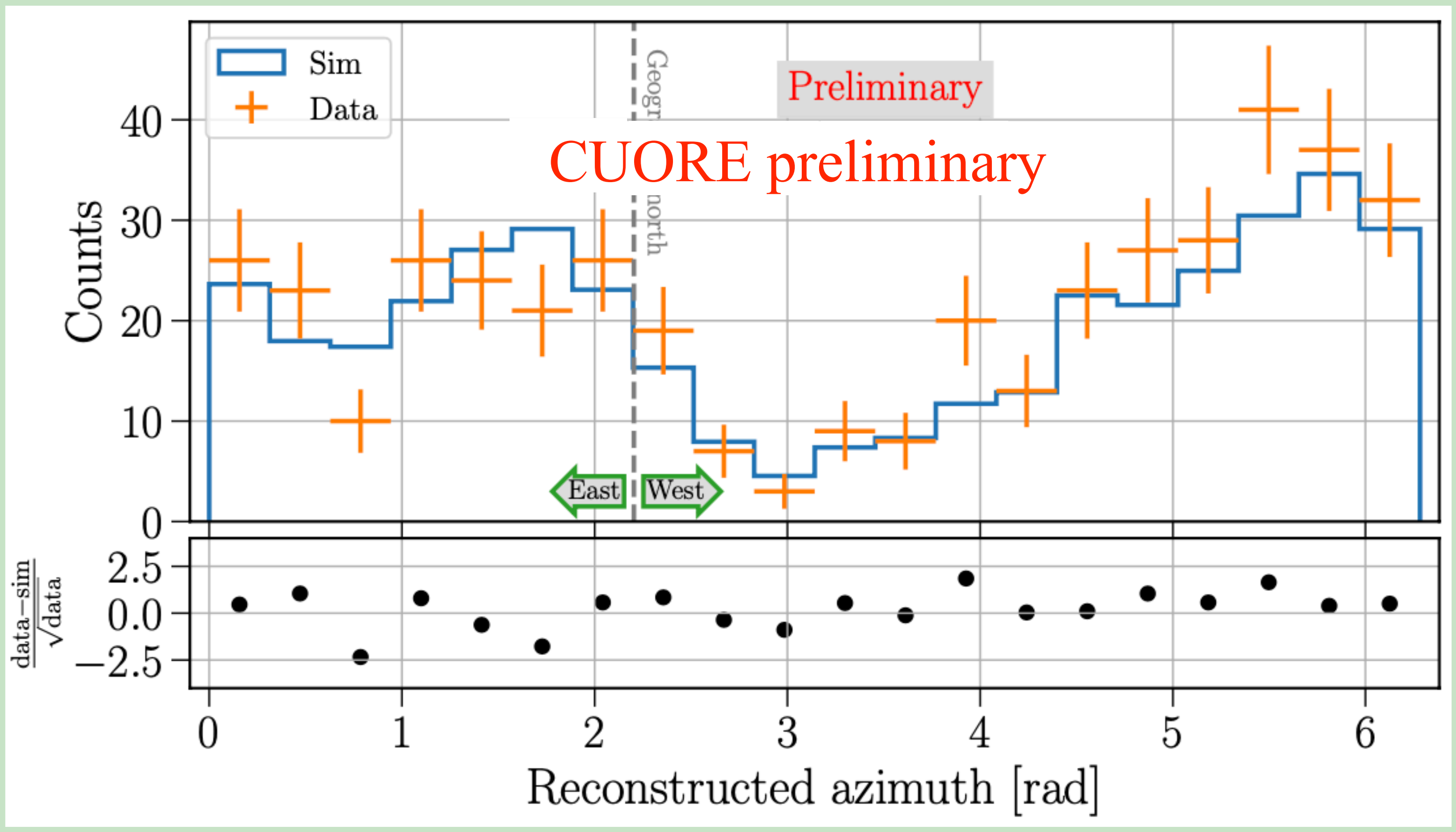
Low energy studies



Specific low-energy variables & event-level cuts to optimise sensitivity for solar axions, WIMP searches

arxiv:2505.23955

Muon event reconstruction (ongoing)



Track-like events ($N_{crystals} \geq 5$ & Edep≥ 9 MeV) to study μ-induced background

CUORE: what's next? Our path towards CUPID

CUORE (now)

- Continue data taking until meeting our goal:
  3 tonne · yr TeO_2 exposure
  (~1 tonne · yr of ^{130}Te)
- Estimate: end up data taking by mid 2026
- Large statistics to perform high sensitivity searches in several channels ($\beta\beta$ decay, dark matter, exotic phenomena, …)

CUORE-phase II

- Upgrade of the **cryogenic system** to improve **Pulse Tubes** performance and coupling to the cryostat

  - ↑ cooling power with 3+1 setting instead of 4+1
  - ↓ vibrations
- Lower thresholds → high sensitivity low energy studies (axions, WIMPS, …)

CUPID

CUORE Upgrade with Particle IDentification

- Scintillating cryogenic calorimeters to overcome CUORE-sensitivity-limiting α background
- $^{130}Te \rightarrow {}^{100}Mo$
  2528 → 3034 keV
- 10^{-4} cts/keV/kg/yr target background
- Same cryogenic infrastructure

{See S.Fu talk in this session}

Conclusions and perspectives

CUORE

- 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 progressing towards our goal 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 2039.0 kg · yr TeO_2 exposure and set a new limit on the half life for such decay of $T^{1/2}_{0\nu\beta\beta} > 3.5 \cdot 10^{25}$ yr $(90\,\%\,C.I.)$
  - ✓ Many interesting analyses ongoing also beyond $\beta\beta$ decay: background-related studies (e.g. muon reconstruction), multispectral (search for decays in multiple-crystal events) and low energy studies
  - ✓ Important feedback for CUPID, both for the cryogenics and background budget
  - ✓ After interventions on the cryogenics and before the CUPID detector installation, a CUORE phase II dedicated to low energy studies (dark matter searches, e.g. WIMPs, axions, …) is planned