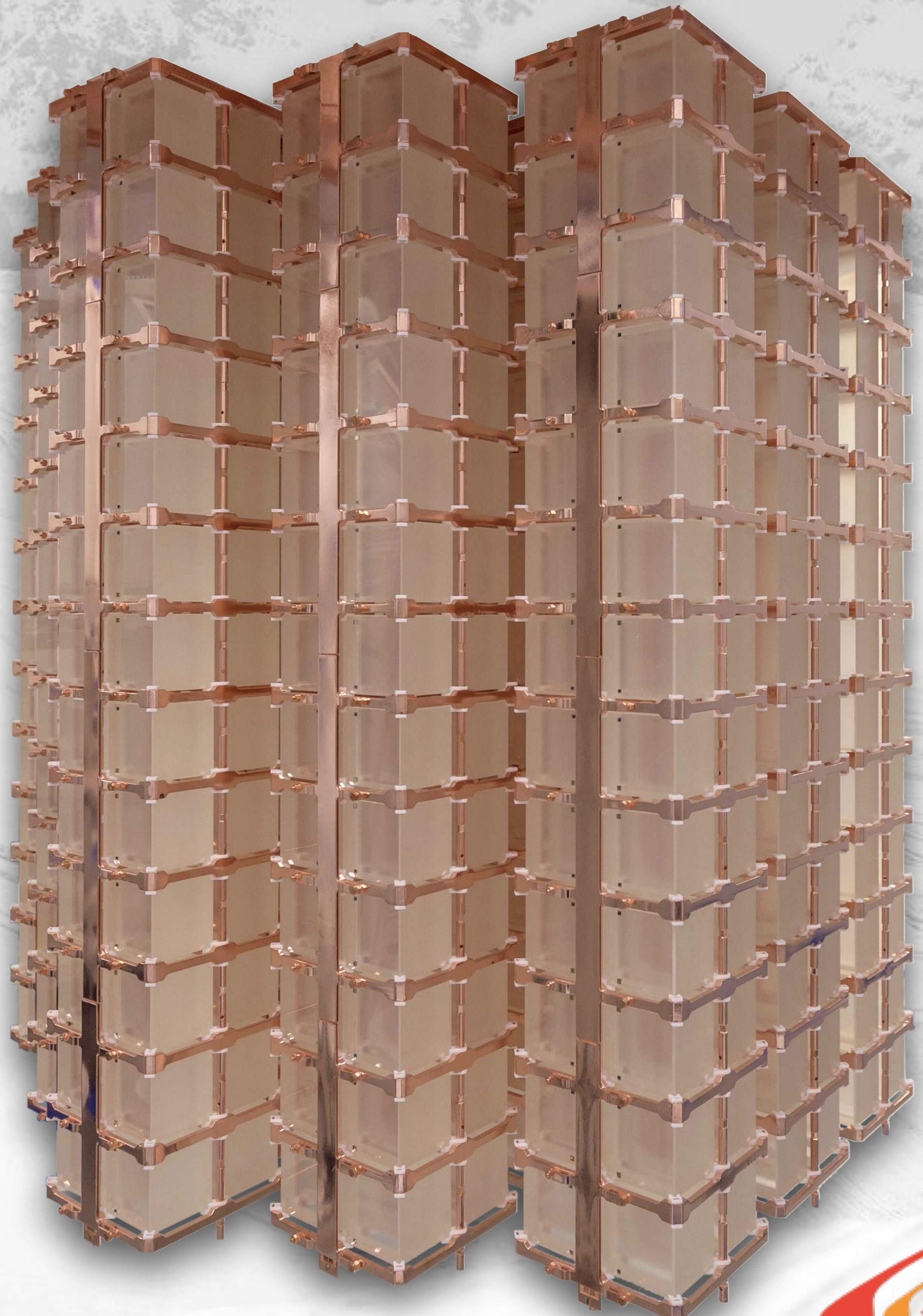
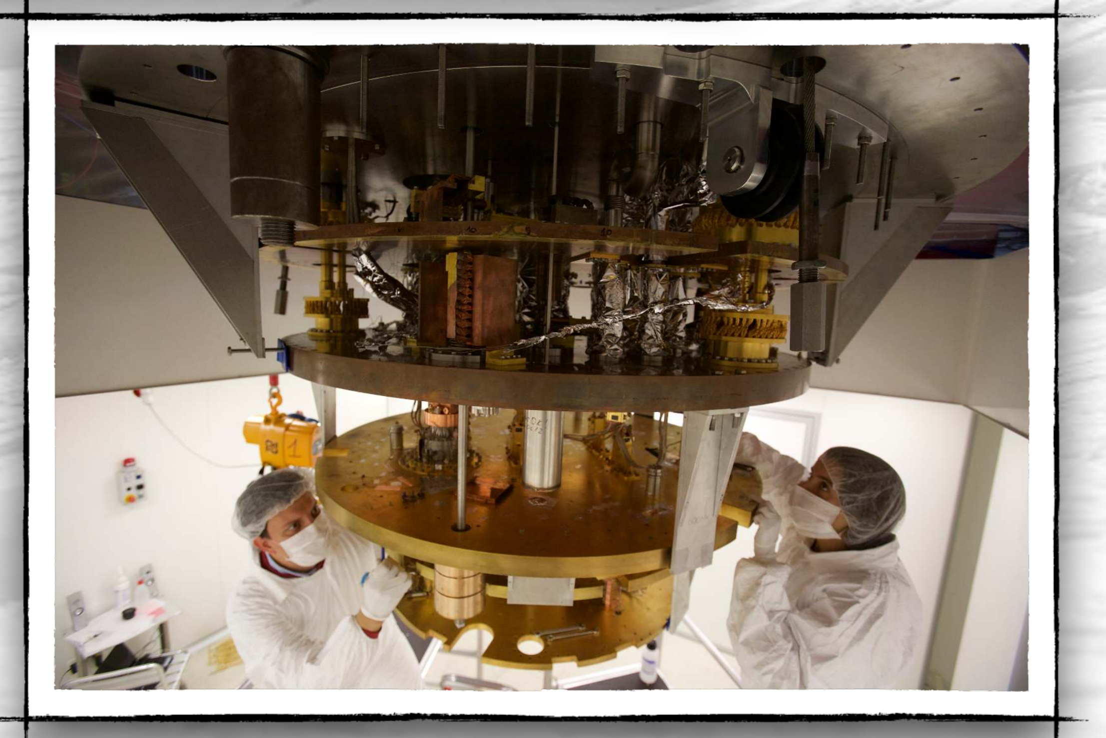
Latest results from CUORE



Alice Campani
on behalf of the CUORE collaboration
Università degli studi di Genova - INFN Genova

Rencontres de Moriond - 18 March 2026



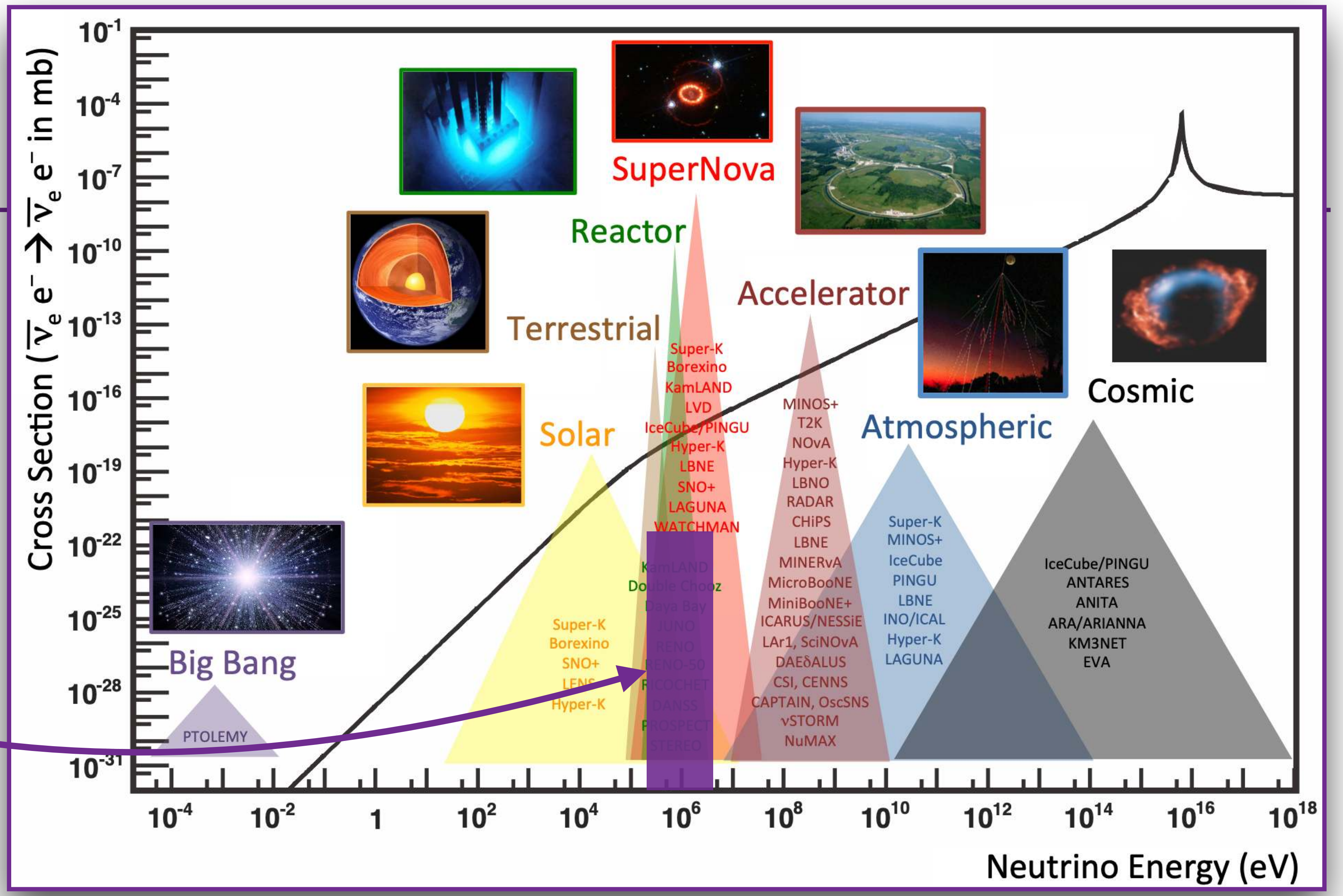
CUORE

Università di Genova

INFN
Istituto Nazionale di Fisica Nucleare

since 1966 Rencontres de Moriond

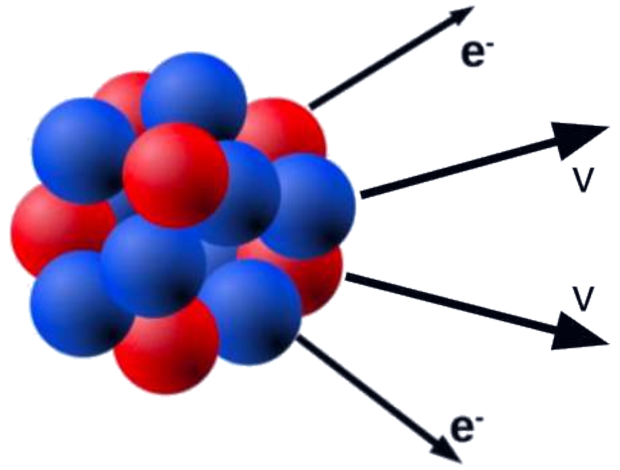
Neutrino physics & double beta decay

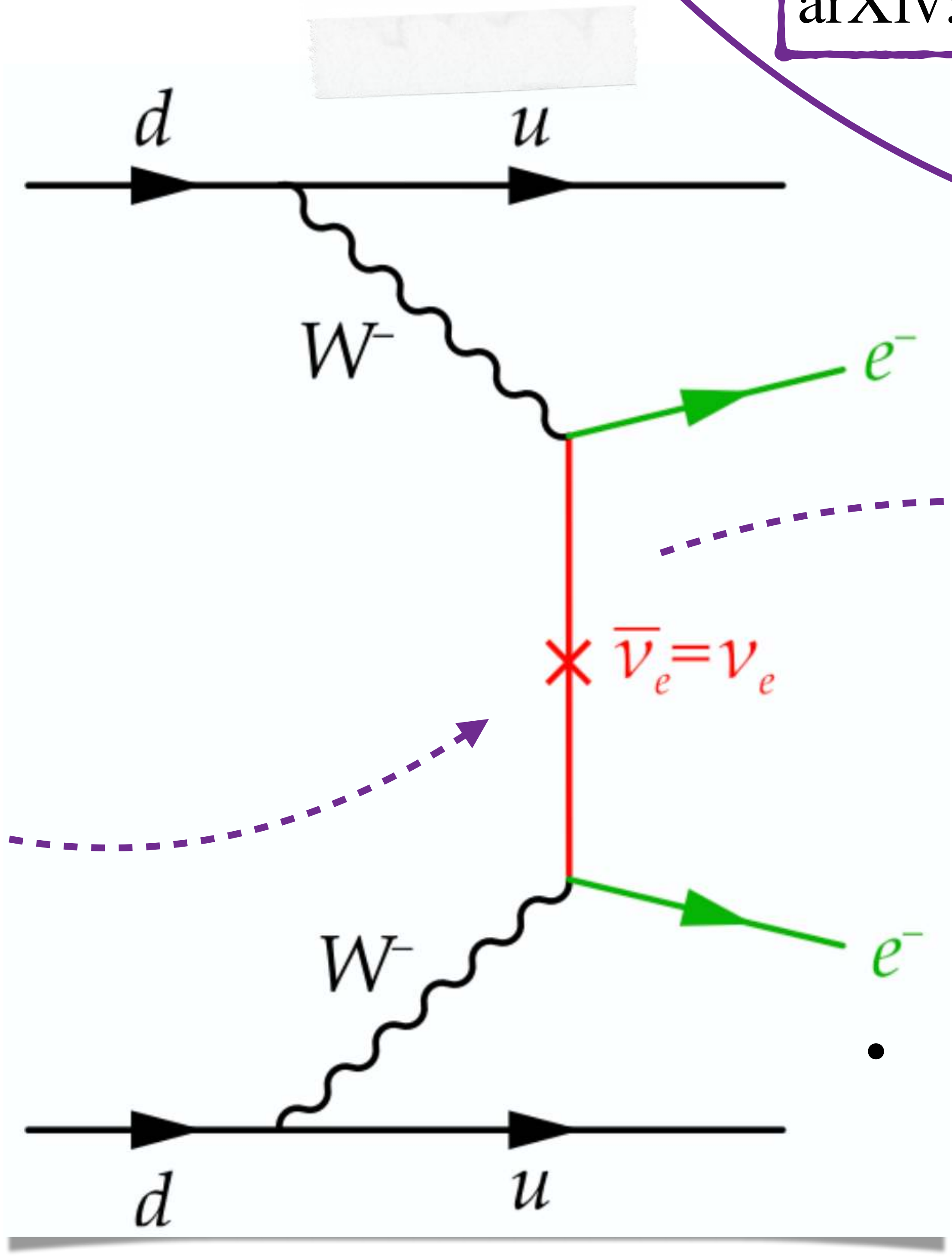


Neutrinos: elusive fundamental particles → $2\nu\beta\beta$ to probe the MeV region

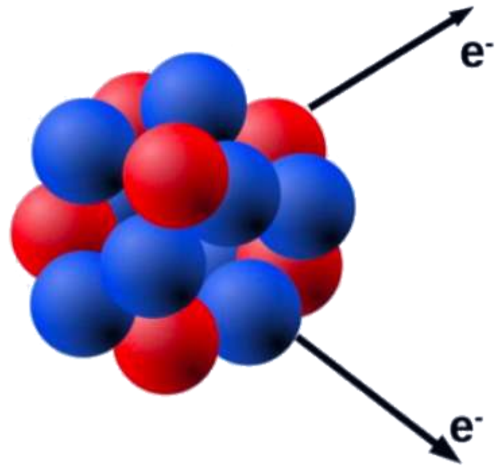
arXiv:1310.4340

$2\nu\beta\beta$





$0\nu\beta\beta$



- Allowed in the Standard Model only for ***even-even*** nuclei (**ΔL = 0**)
- Observed in several nuclei, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{136}Xe, …
- Half-life $T^{2\nu}_{1/2} \sim 10^{18} - 10^{22}$ yr

- Beyond the Standard Model: lepton number symmetry violation (**ΔL = 2**)
- Simplest model: **Majorana** ν
- No evidence observed so far
- Half-life $T^{0\nu}_{1/2} > 10^{24} - 10^{26}$ yr

What's captivating about neutrinoless double beta decay

- Assuming the exchange of a light Majorana neutrino the $0\nu\beta\beta$ decay rate is

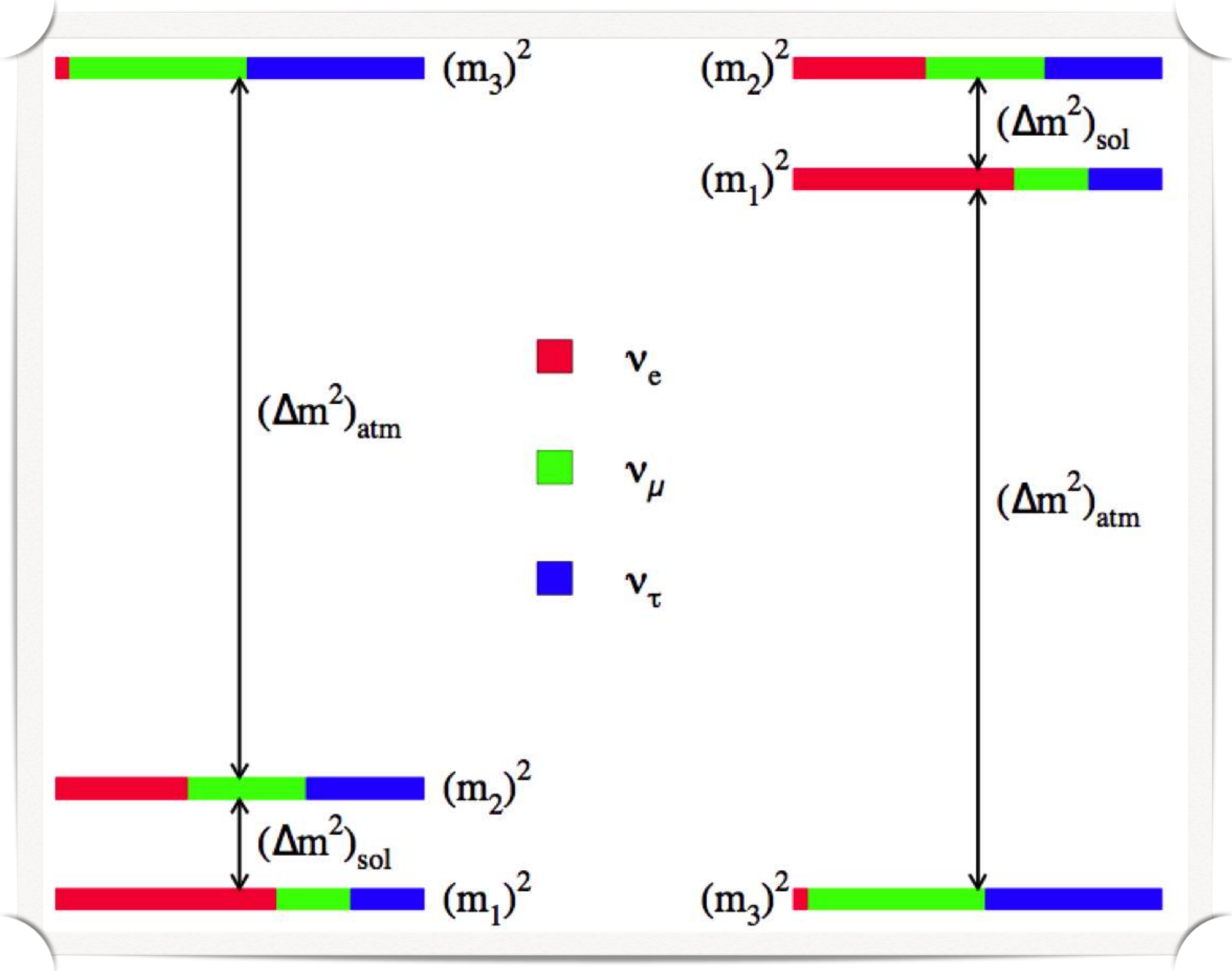
$$\Gamma_{0\nu\beta\beta} \propto G_{0\nu}(Q,Z)\left|M_{0\nu}\right|^2 \frac{\left| < m_{\beta\beta} > \right|^2}{{m_e}^2}$$

Phase space factor

Nuclear matrix element

Effective Majorana mass

$$< m_{\beta\beta} > = \left| \sum_{i=1,2,3} |U|^2_{ei} e^{i\alpha_i} m_i \right|$$



- Any observation would provide information on the neutrino ***mass scale*** and ***ordering***: unique probe of the Majorana phases that cannot be measured by oscillation experiments
- **Lepton Number Violation** could play an important role in the ***matter-antimatter asymmetry*** in the Universe

Experimental sensitivity to $0\nu\beta\beta$ decay: the case of CUORE

- Sensitivity to $0\nu\beta\beta$ scales as[†]

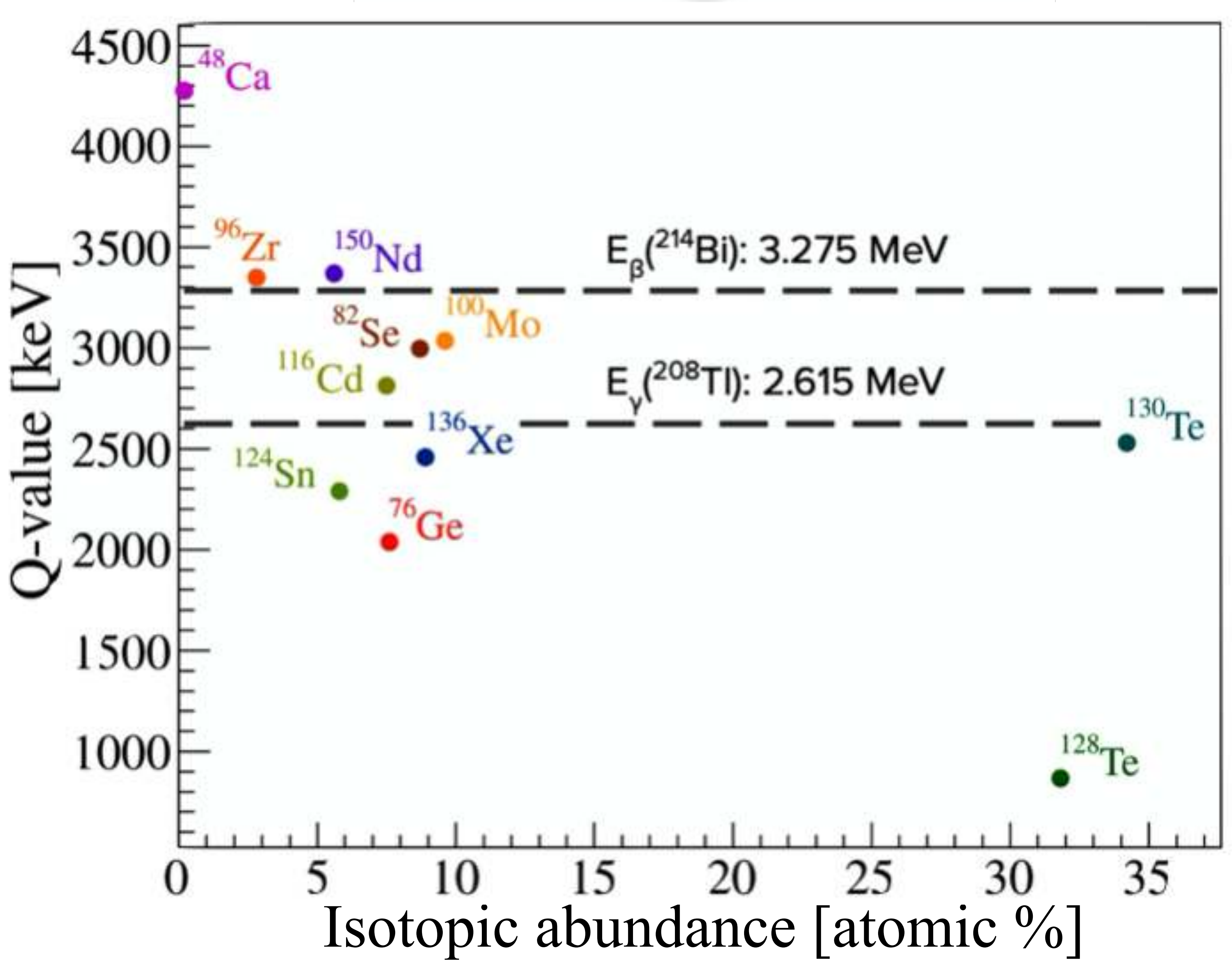
$\beta\beta$ emitter isotopic fraction
- ^{130}Te ~34%
- TeO_2 crystals with $^{(nat)}Te$

detection efficiency
- source ≡ detector
- overall (all cuts) $93.4(18)\,\%$

active mass
- tonne-scale detector: 742 (206) kg TeO_2 (^{130}Te)
- close-packed array - 988 crystals

$$S_{0\nu} \propto \eta \cdot \varepsilon \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$$

livetime
- 8 yr continuous operation
- ~50 kg · yr/month of TeO_2



background in the ROI
- $Q_{\beta\beta}$~2528 keV only Tl γ line above
- $\left(1.42^{+0.03}_{-0.02}\right) \cdot 10^{-2}$ counts/keV/kg/yr

Science 390, 1029-32 (2025)

energy resolution @ $Q_{\beta\beta}$
- ΔE (FWHM)= (7.310 ± 0.024) keV
→ $\Delta E/E \simeq 0.3\,\%$

[†]For zero-background cases $S_{0\nu} \propto M \cdot T$

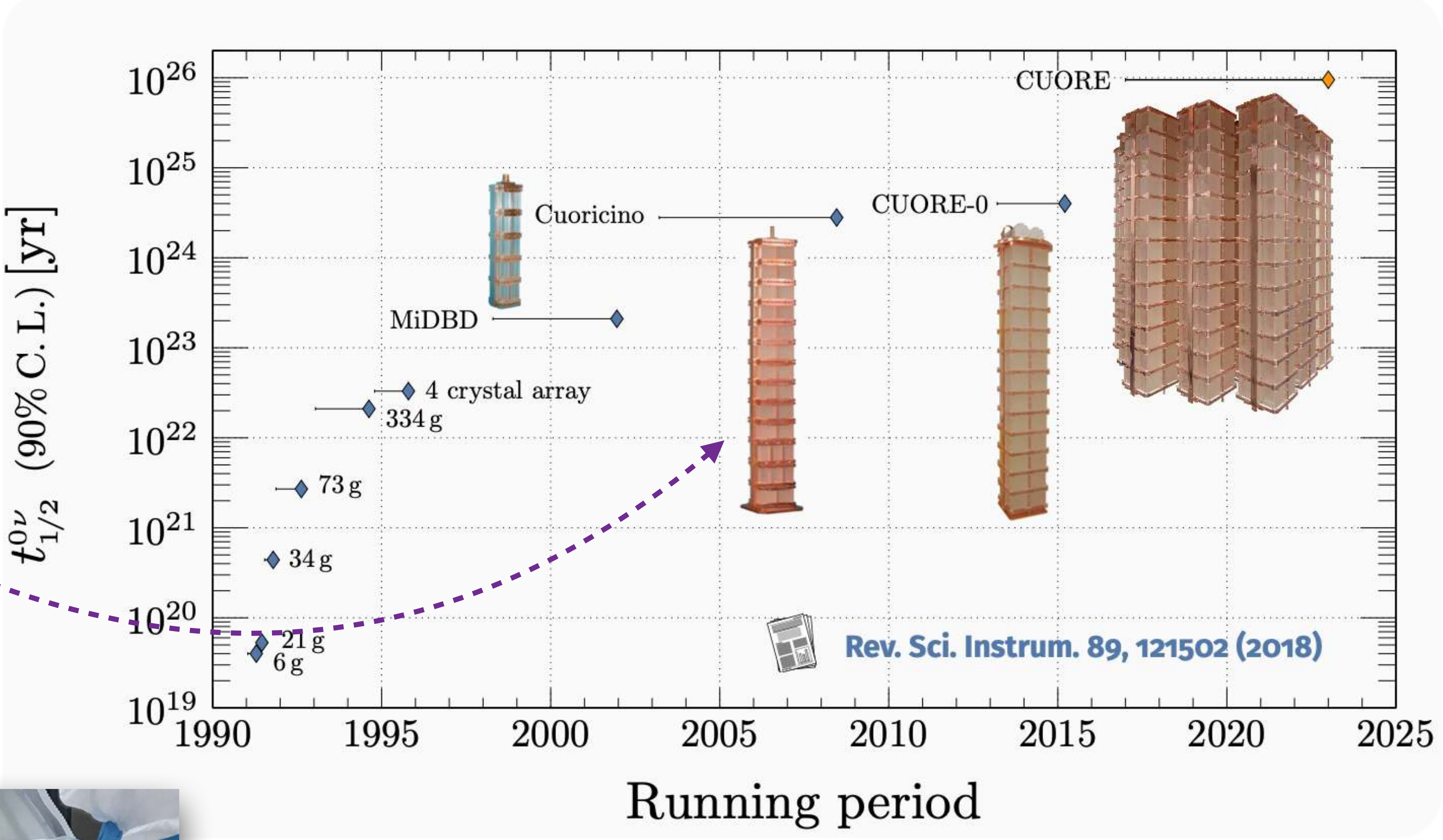
The CUORE experiment in a nutshell

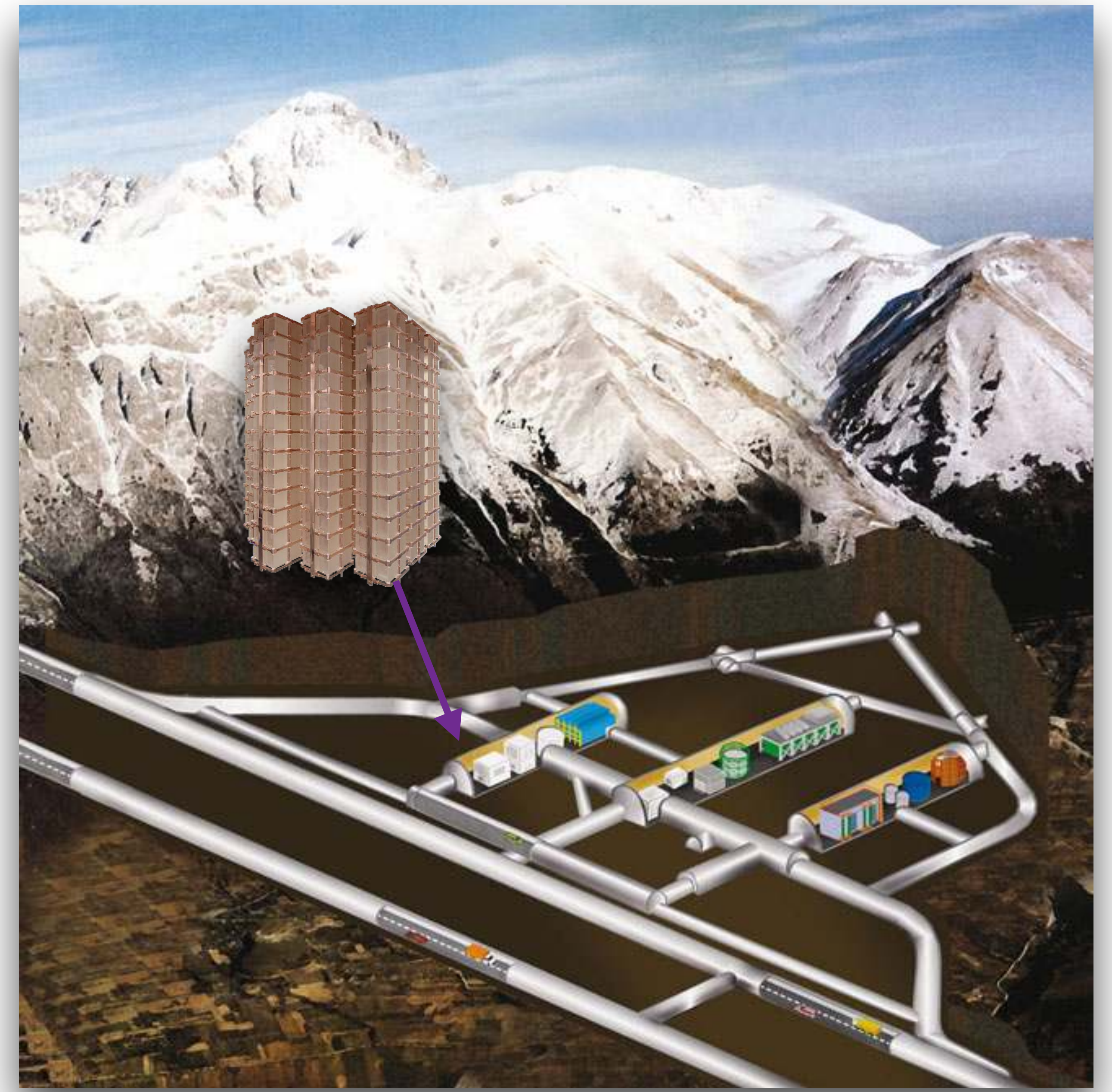
Cryogenic Underground Observatory for Rare Events

- Primary goal: search for $0\nu\beta\beta$ decay of ^{130}Te

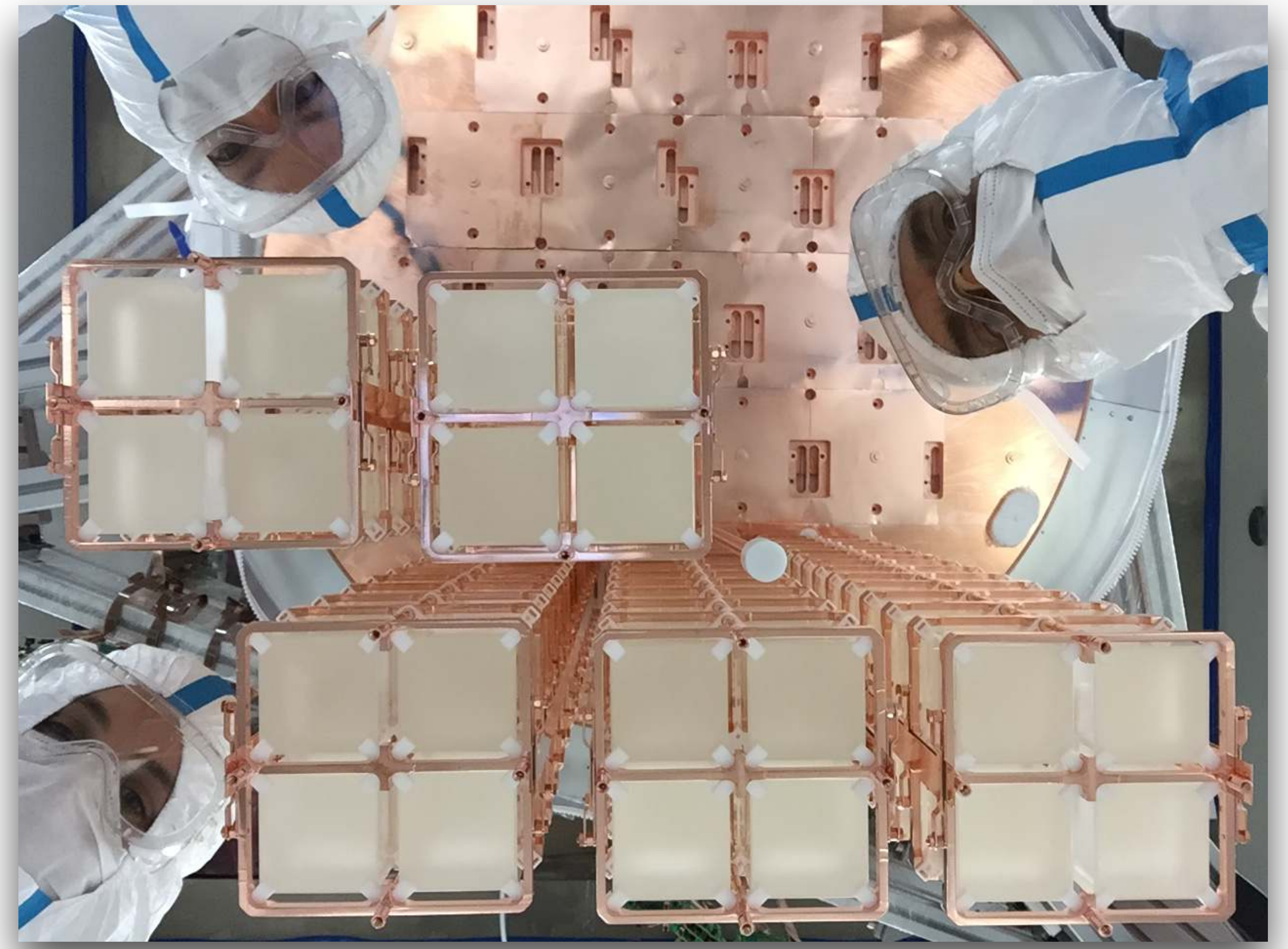
Eur. Phys. J. C77, 532 (2017)

- Building on a 30-yr-long history of measurements





- **Underground** at the **LNGS** (Abruzzo, Italy)



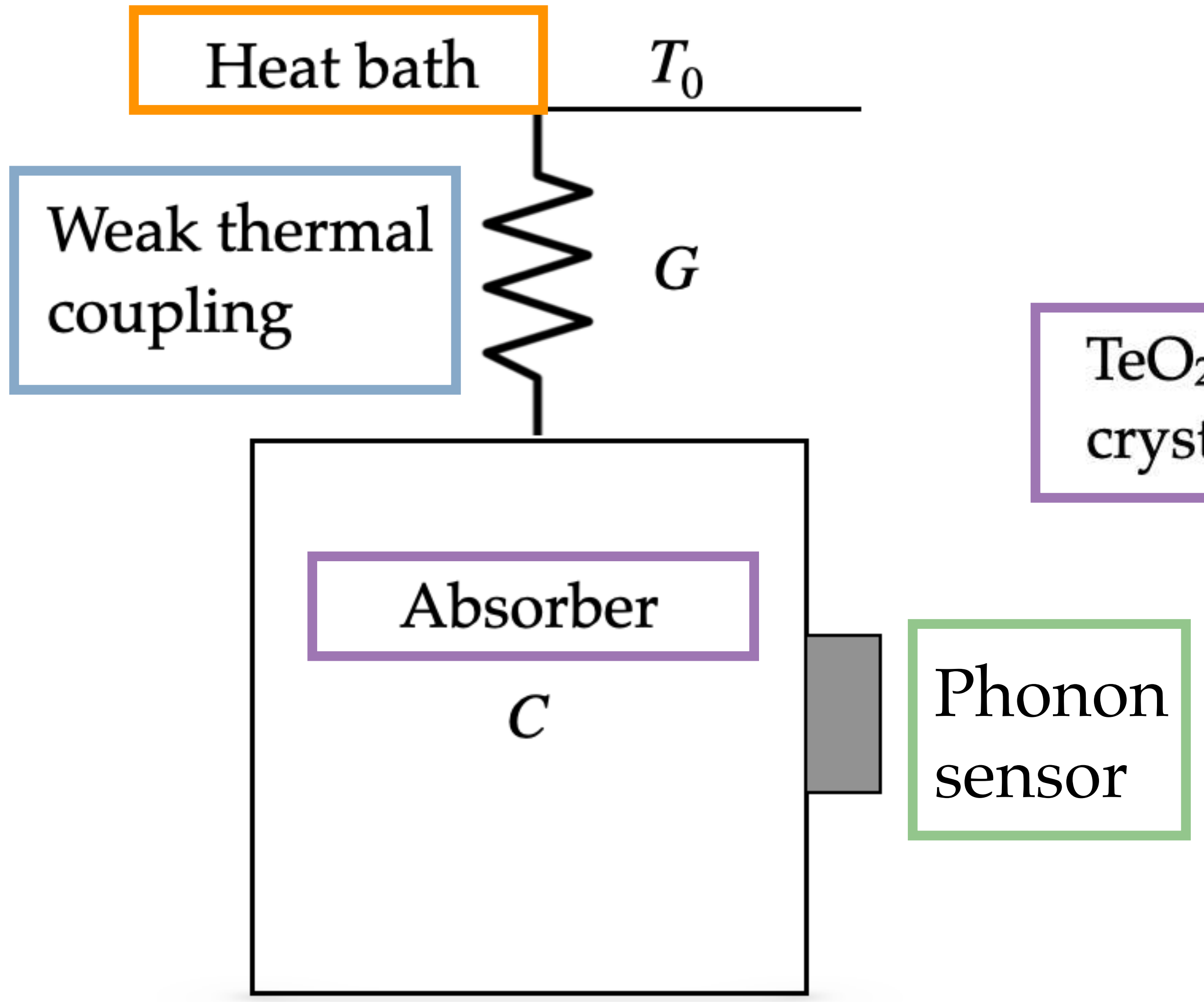
- **Largest cryogenic-calorimeter detector ever built:**
  19 towers of 13 floors of 4 crystals operated stably $\lesssim$20 mK

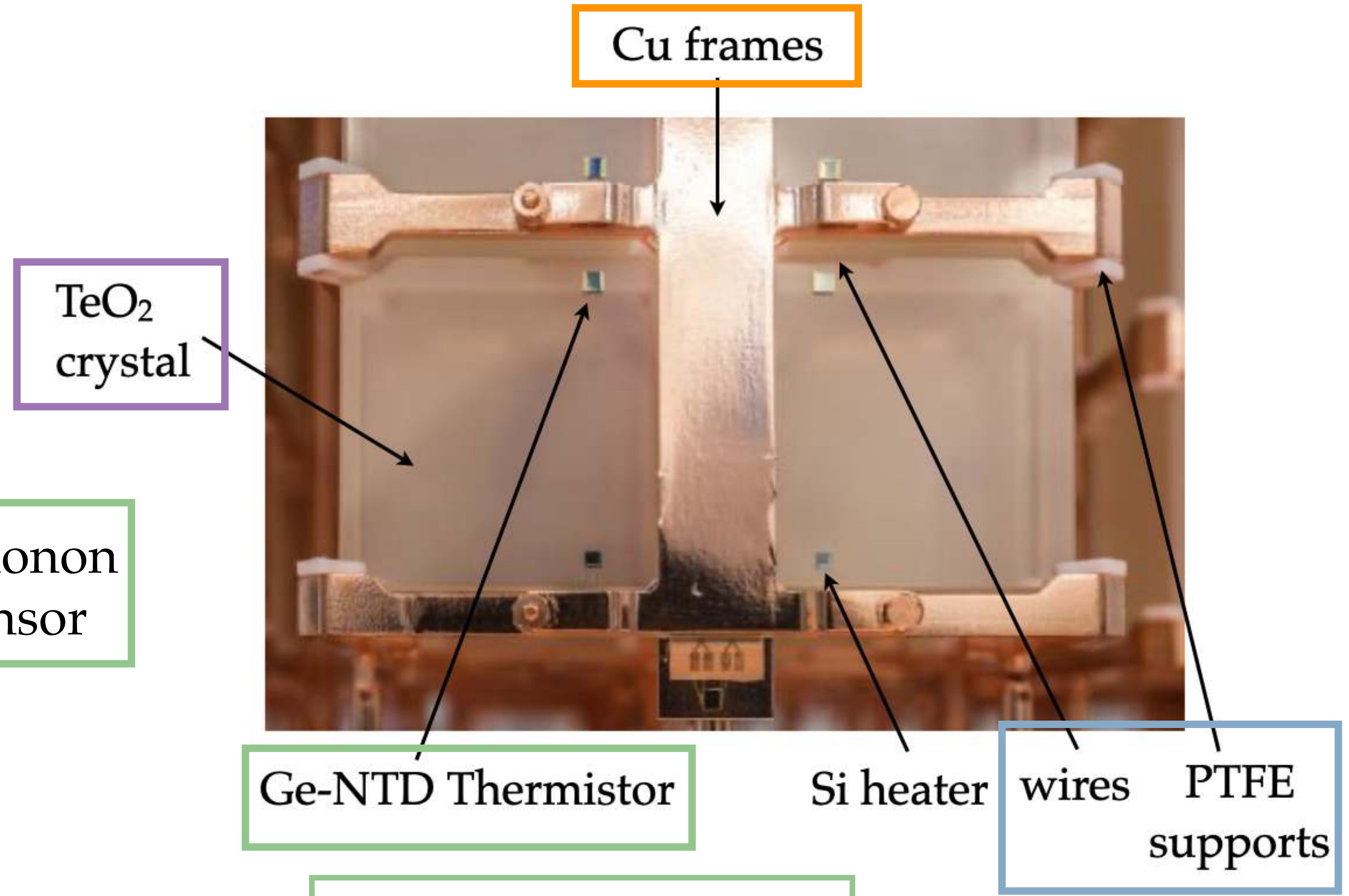
Adv. in High En. Phys. 879871 (2015)

Experimental technique: cryogenic calorimeters to detect $0\nu\beta\beta$

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

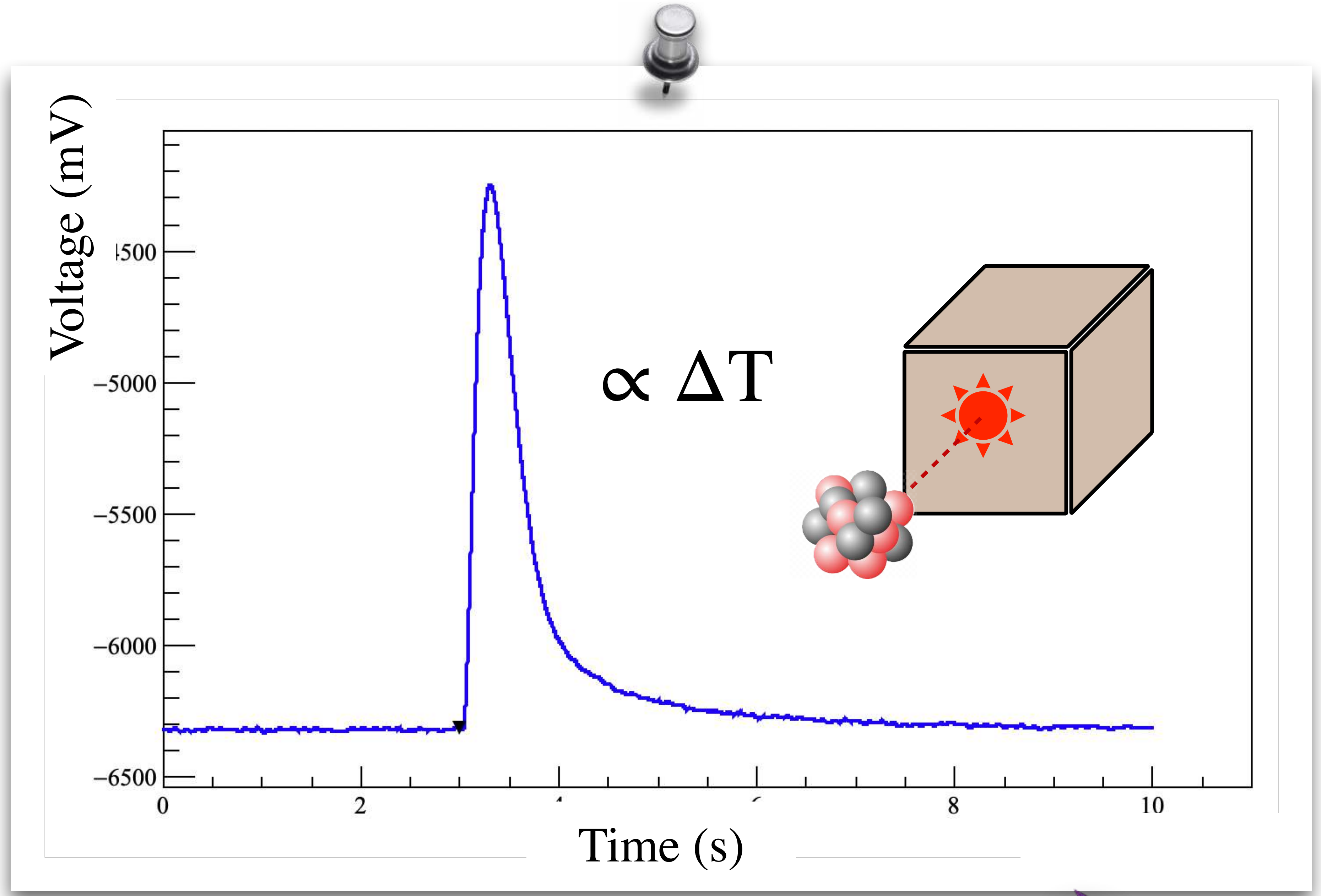
The **temperature increase** is converted into an **electrical signal** by a cryogenic sensor (e.g. a thermistor)





Operating at a temperature of ~10 mK:

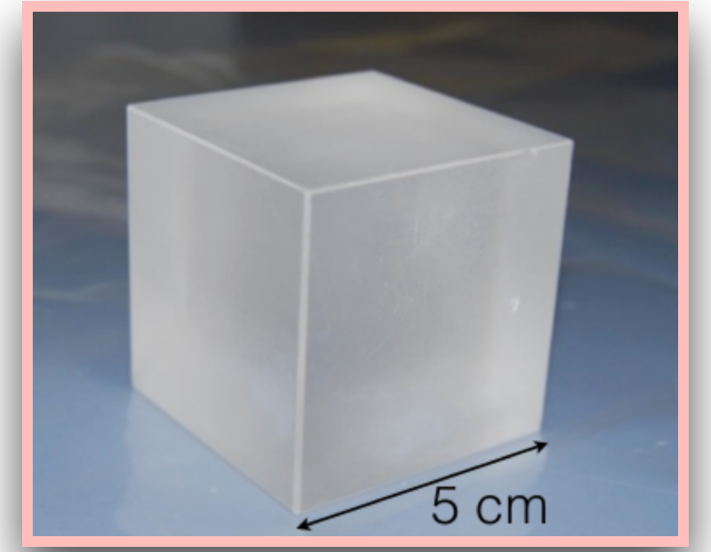
1 MeV energy release causes **ΔT~100 μK**



TeO_2 crystal

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

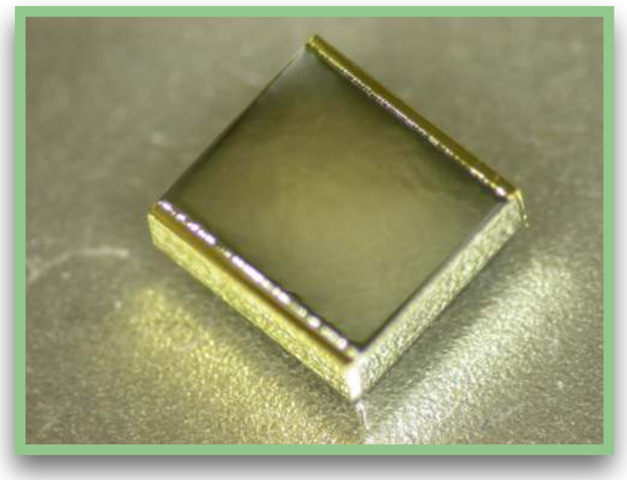
C≈ nJ/K



Ge-NTD thermistor

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

ΔR~3MΩ/MeV

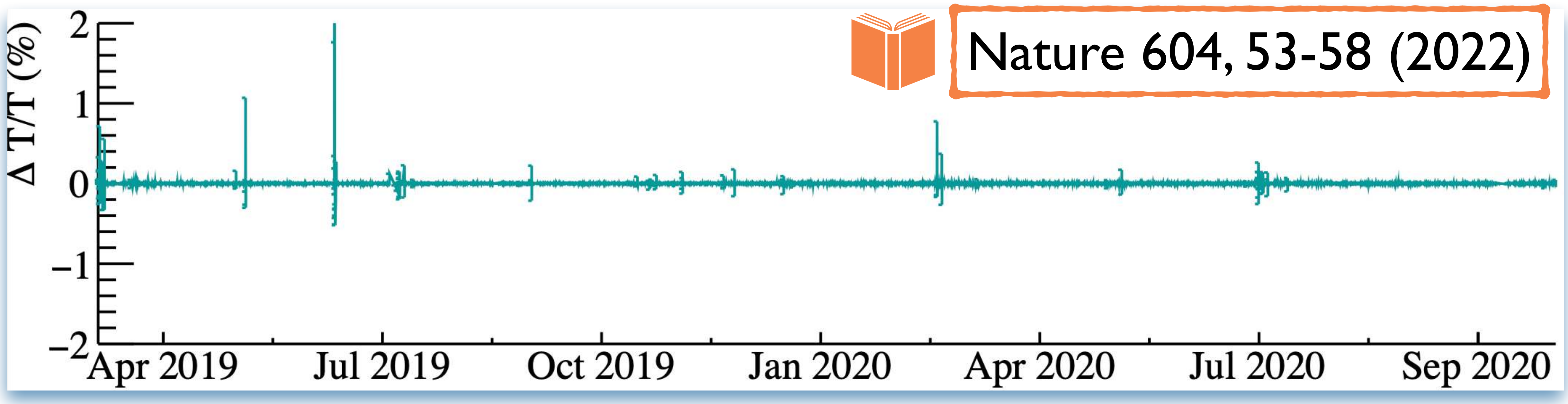


We do **thermal gain stabilization** by means of **Si heaters**

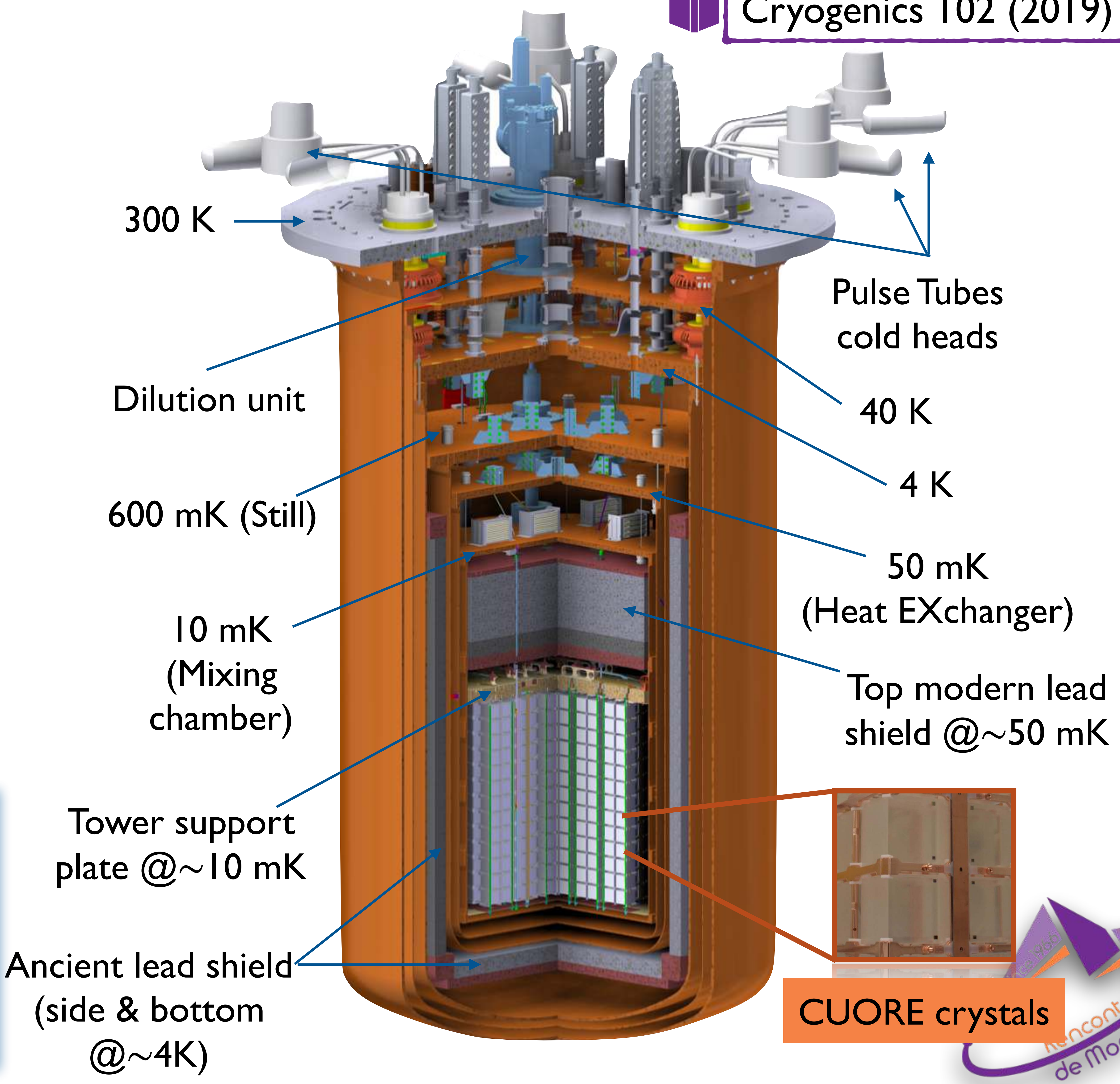
Experimental technique: the cryostat

- 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 spare)
- 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**

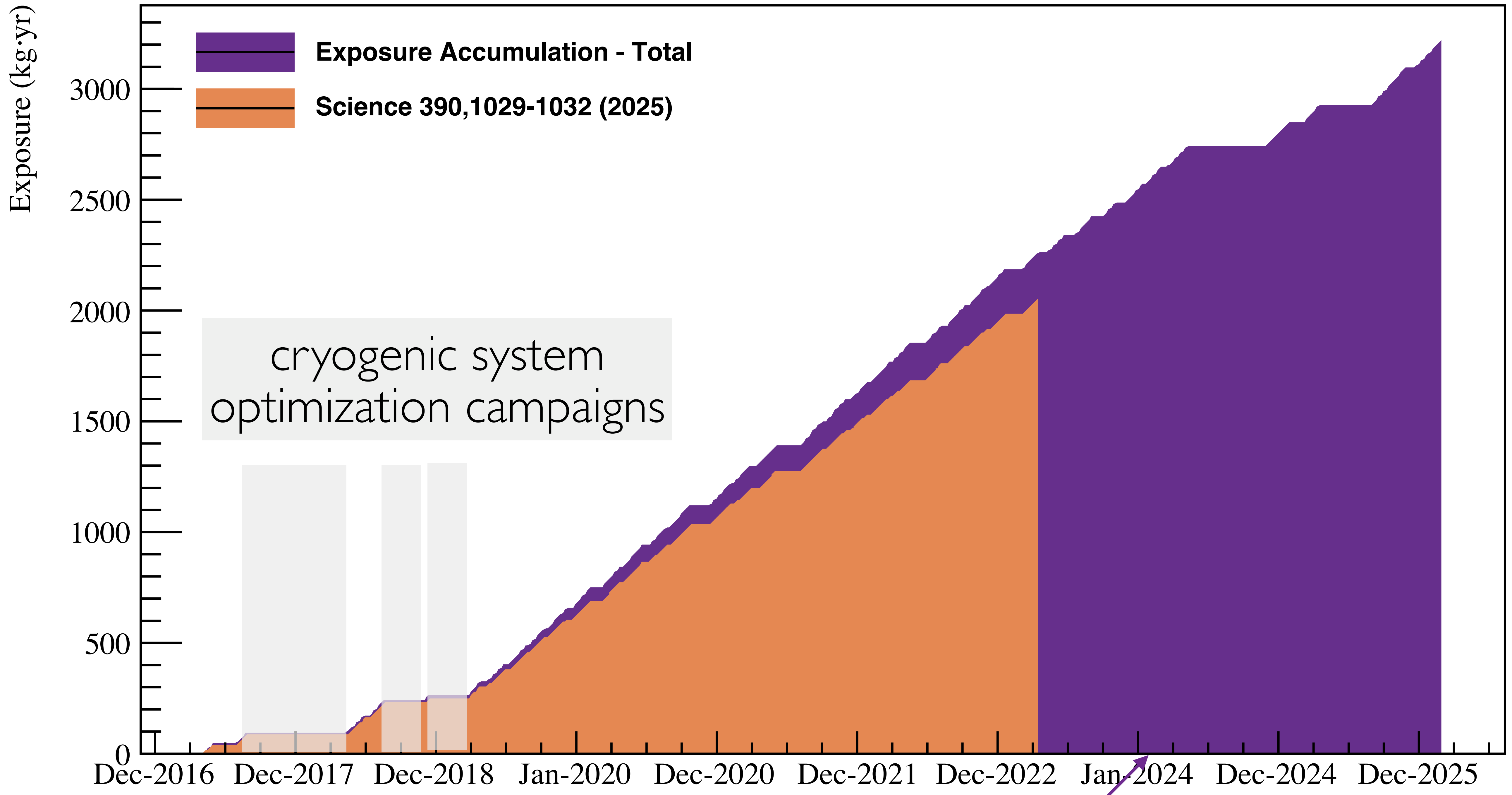
Nature 604, 53-58 (2022)



Cryogenics 102 (2019) 9-21



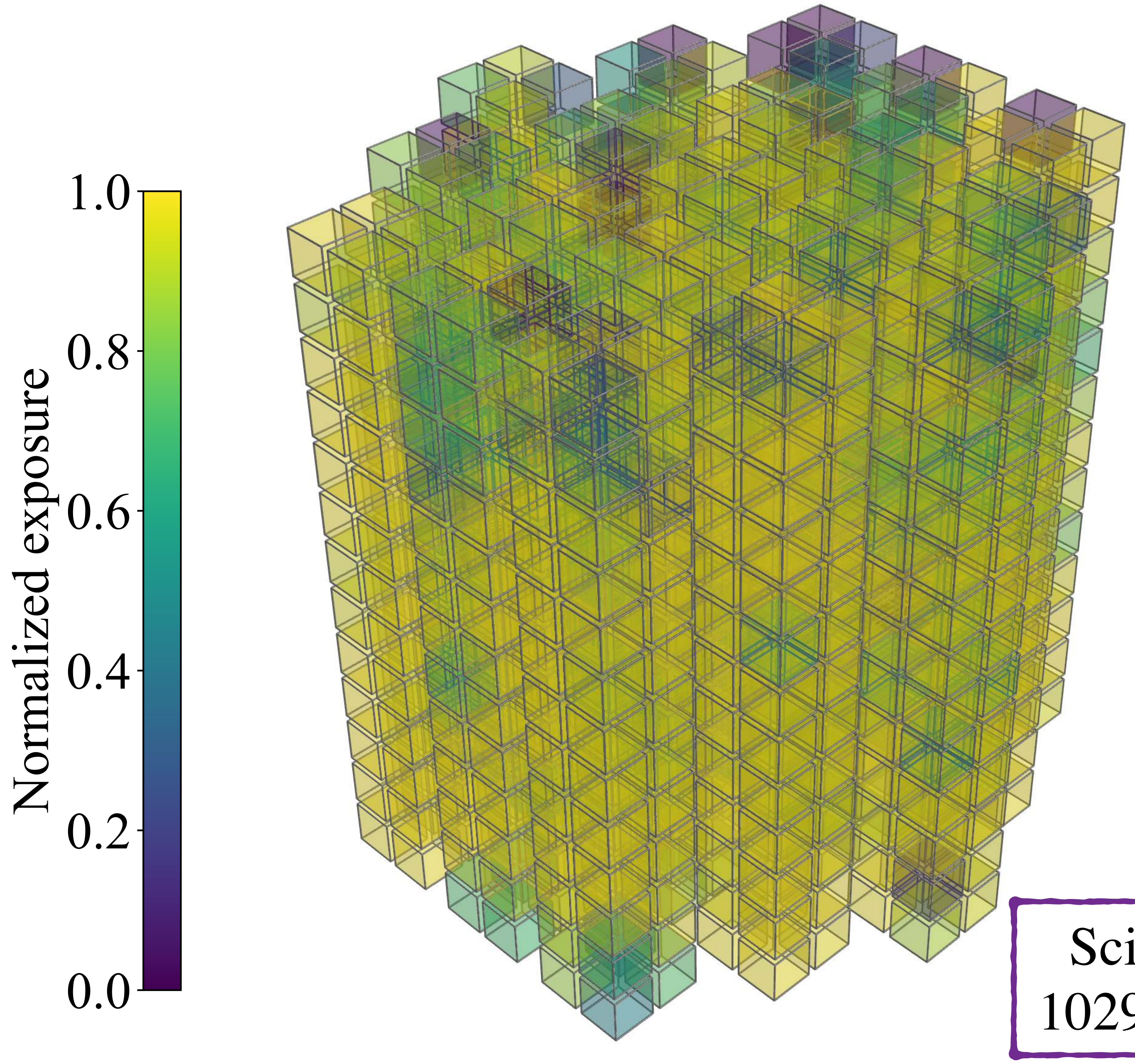
Experimental operations: our achievements



~ 3 ton·yr of raw exposure so far!

- Data taking since 2017
- Trigger rate 50 mHz (~6 mHz) in calibration (physics) run
- Voltage across NTD Ge thermistors sampled at 1kHz, a software trigger is applied offline

Analysed data (May 2017 - April 2023)



Science 390, 1029-32 (2025)

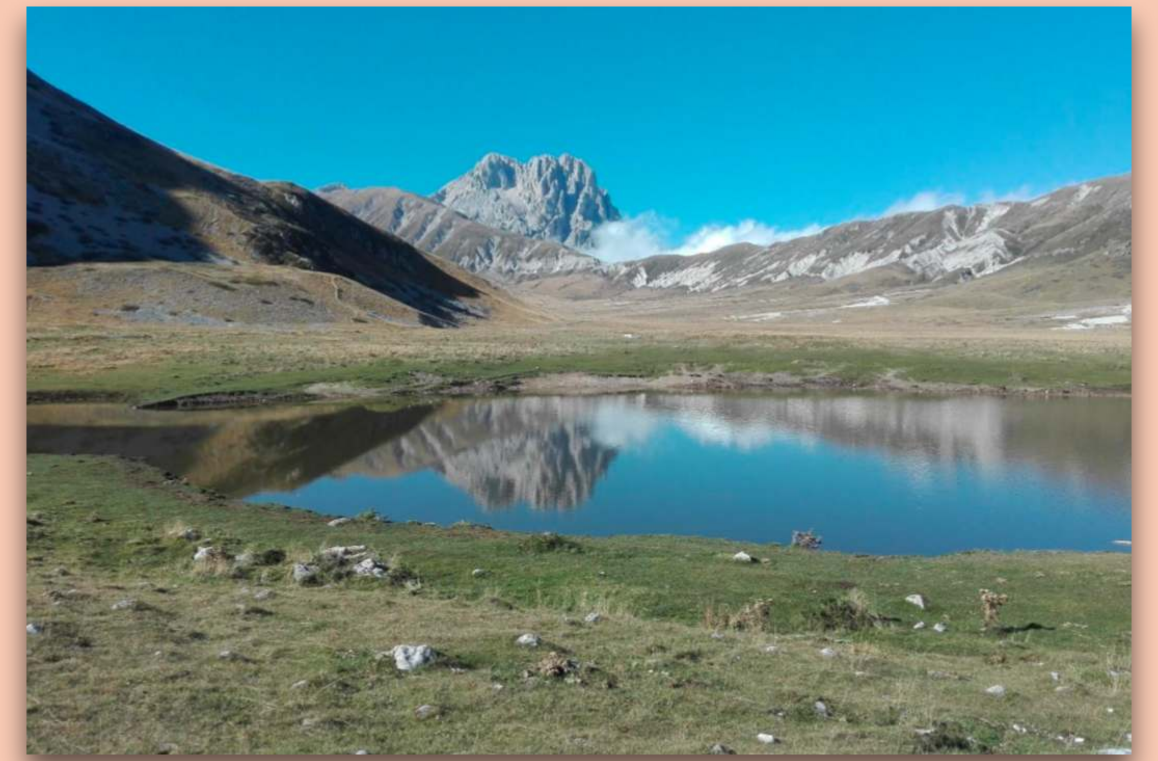
TeO_2 exposure: **2039.0 kg·yr**

^{130}Te exposure: **567.0 kg·yr**

with **uniform space distribution**

The price we paid: minimizing background

LNGS *natural* shielding



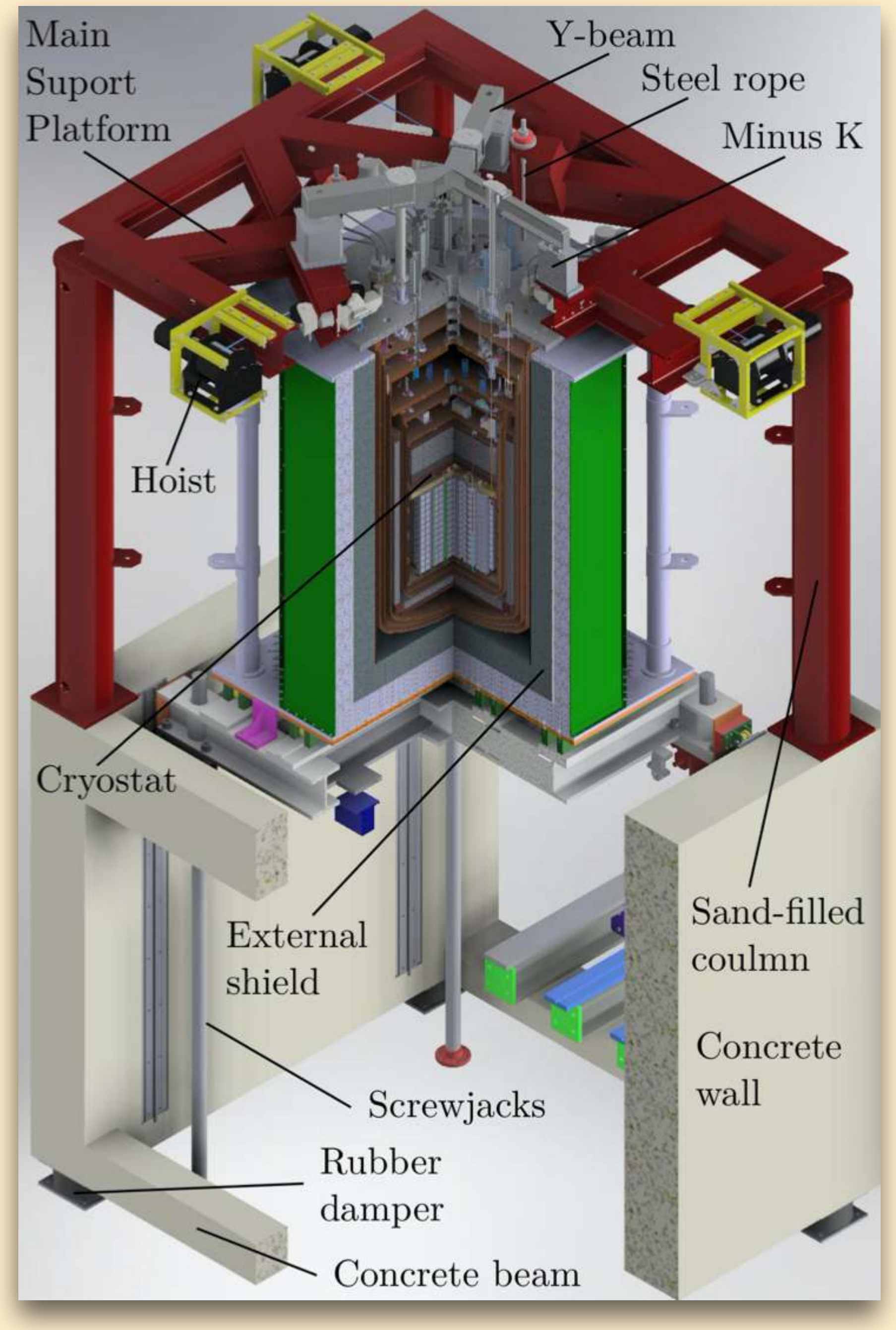
~3600 m water-equivalent rock overburden: cosmic rays flux reduced of six orders of magnitude compared to the surface

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

Astropart Phys. 34, 18-24 (2010)

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

External shields



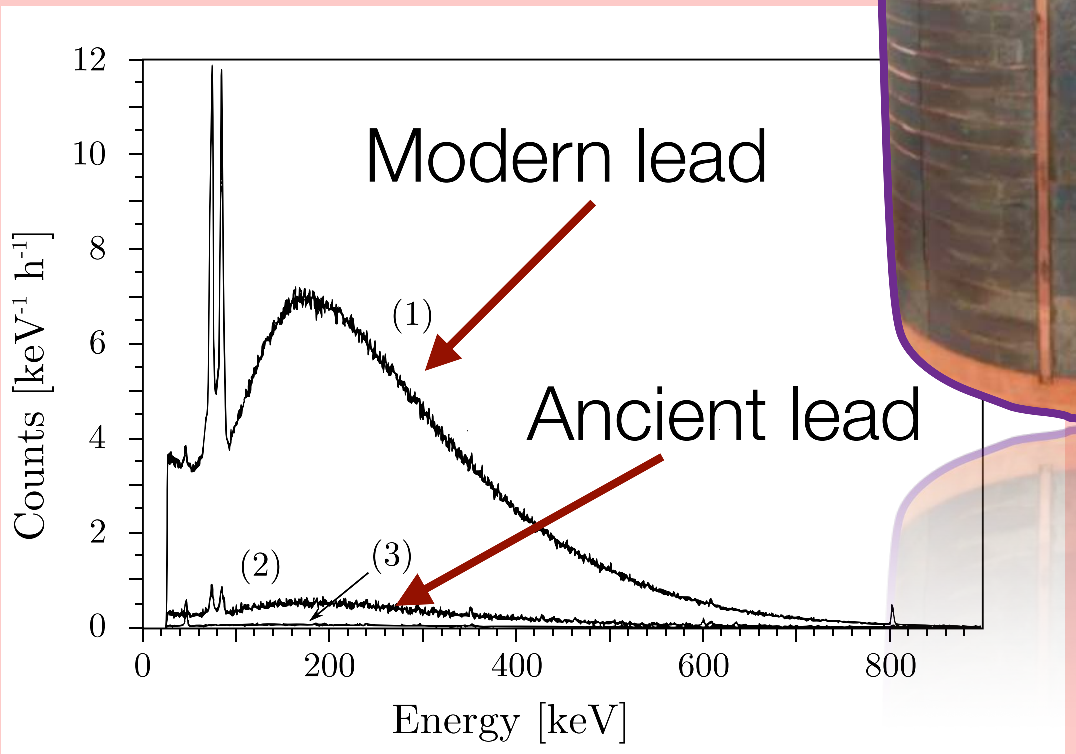
Cryogenics 102, 9-21 (2019)

- 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

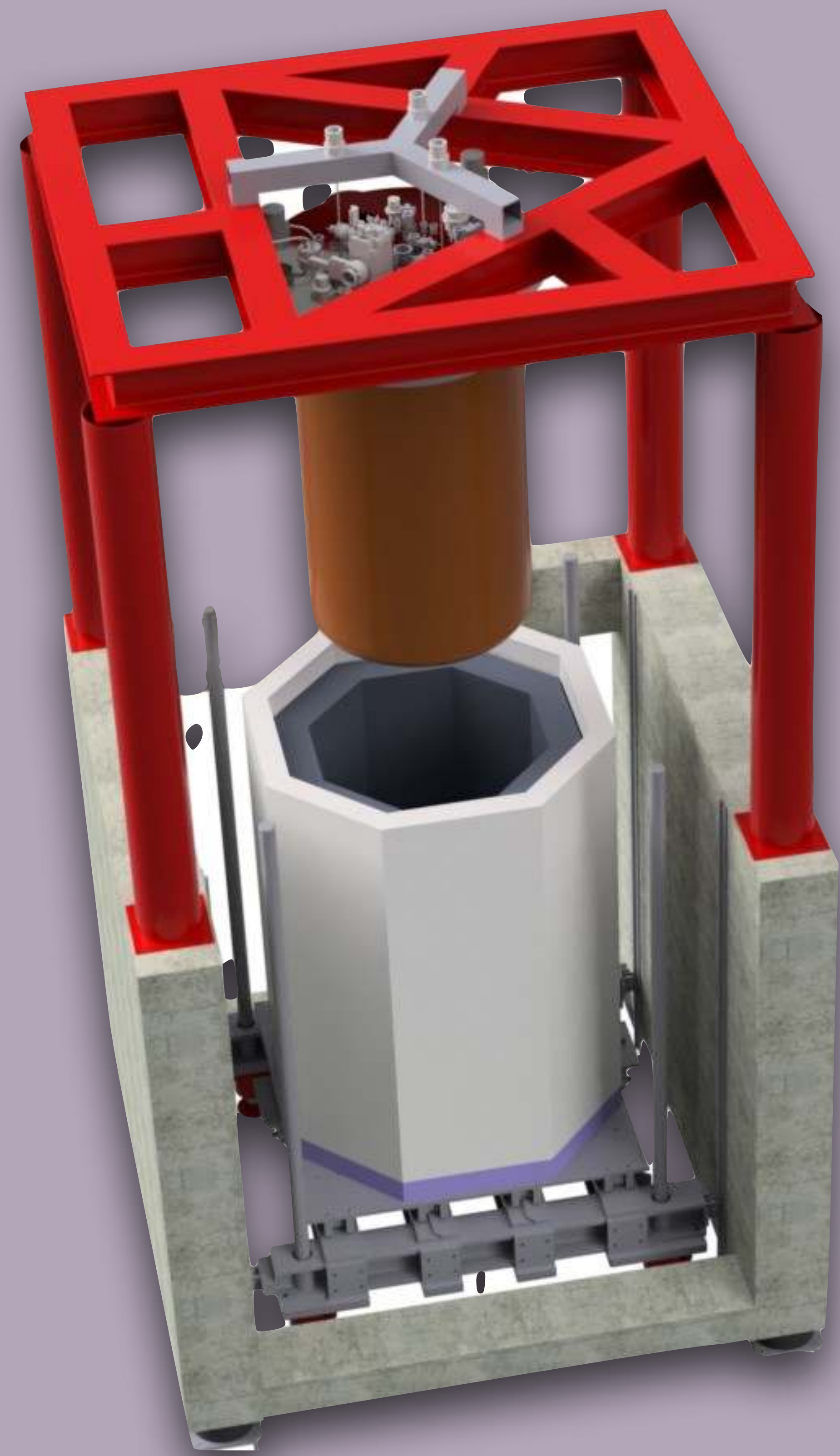
Side & bottom: 6-cm ancient roman lead from a shipwreck
^{210}Po < 4 mBq/kg



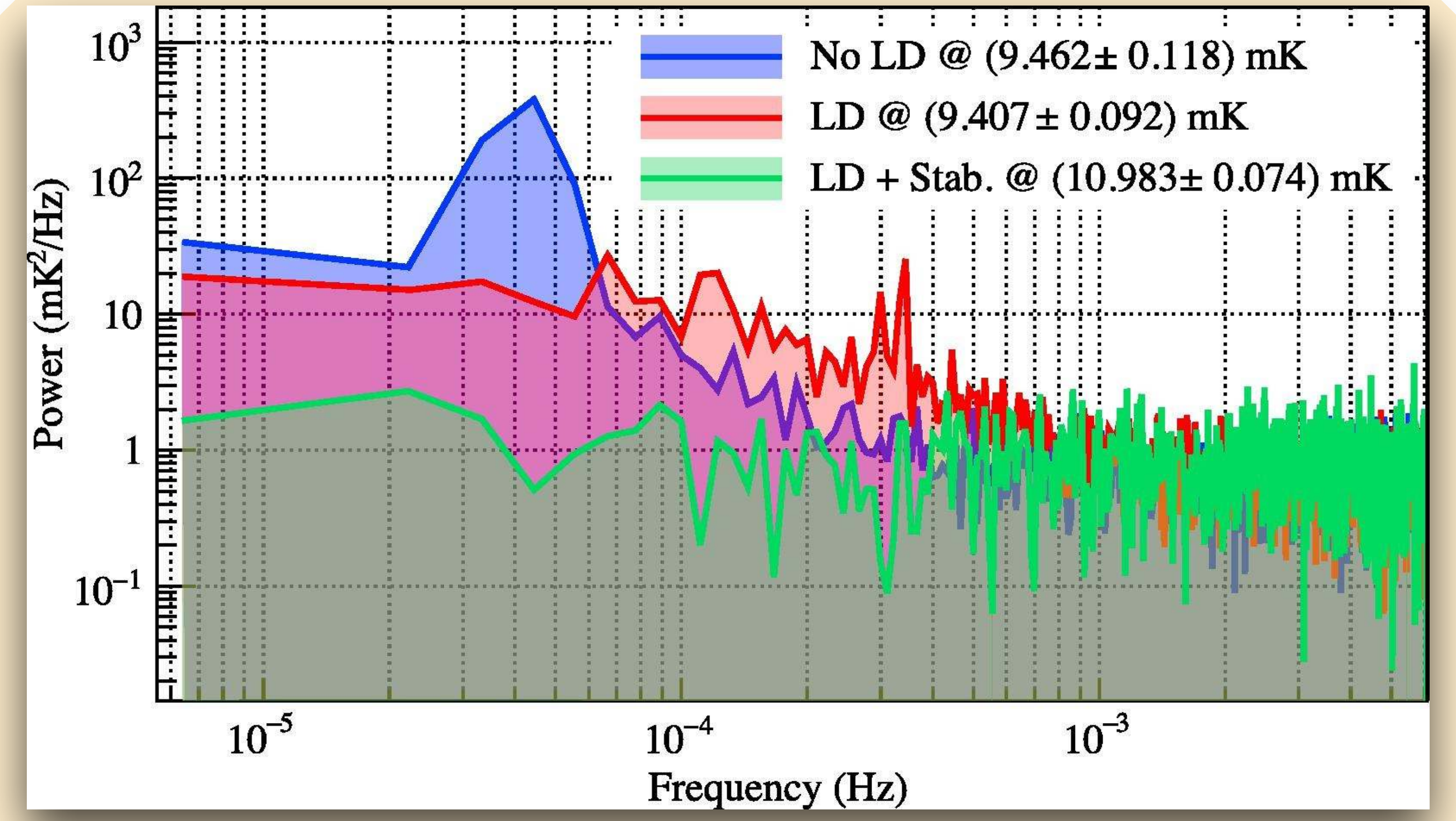
Nucl. Instrum. Meth. B 142, 163 (1998)

The price we paid: suppressing noise sources

External structure to decouple the detector from the cryostat



Linear drives



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

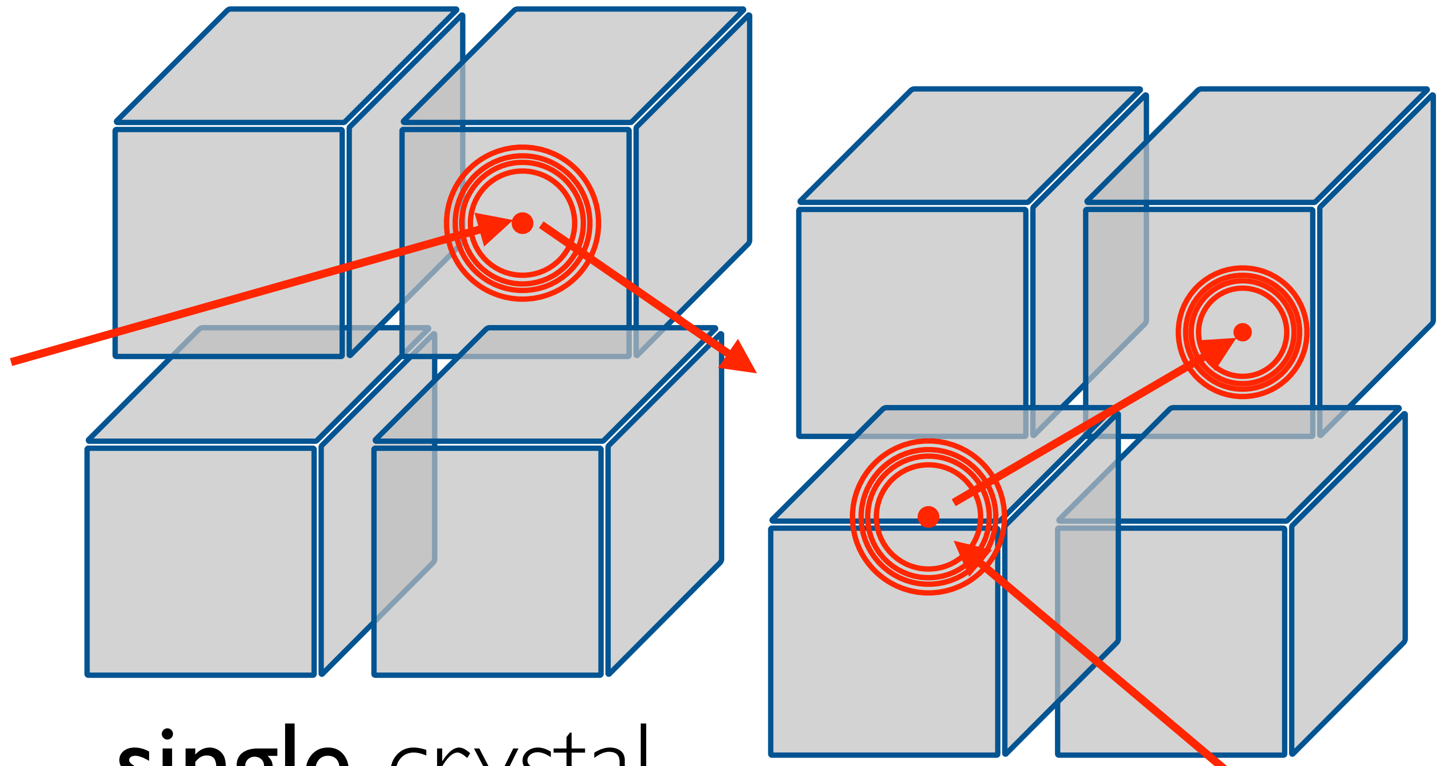
Cryogenics 93, 56-65 (2018)

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

- seismometers, antennae, microphones and accelerometers

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

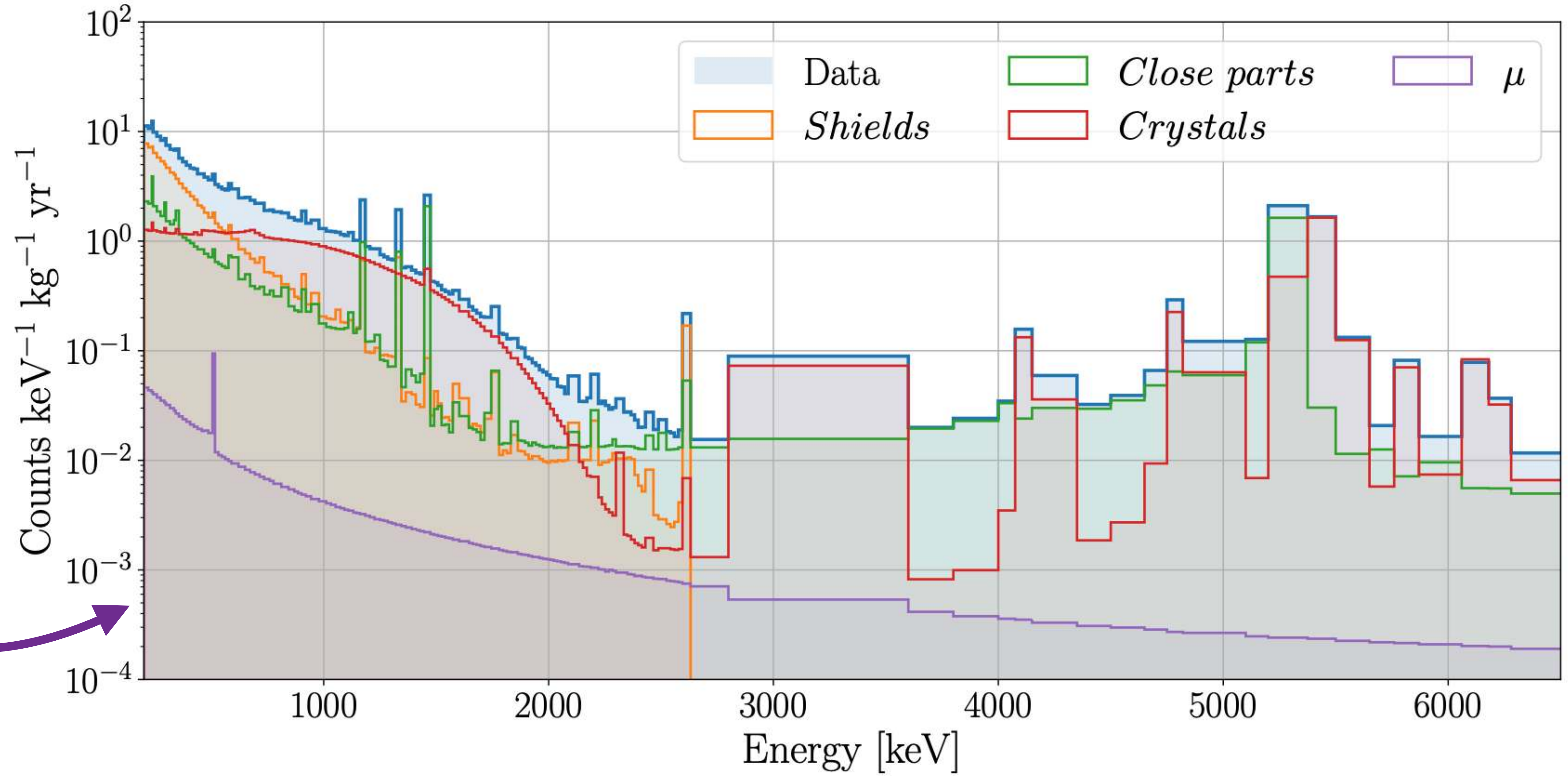
What's left to do? Modeling our background



High detector granularity

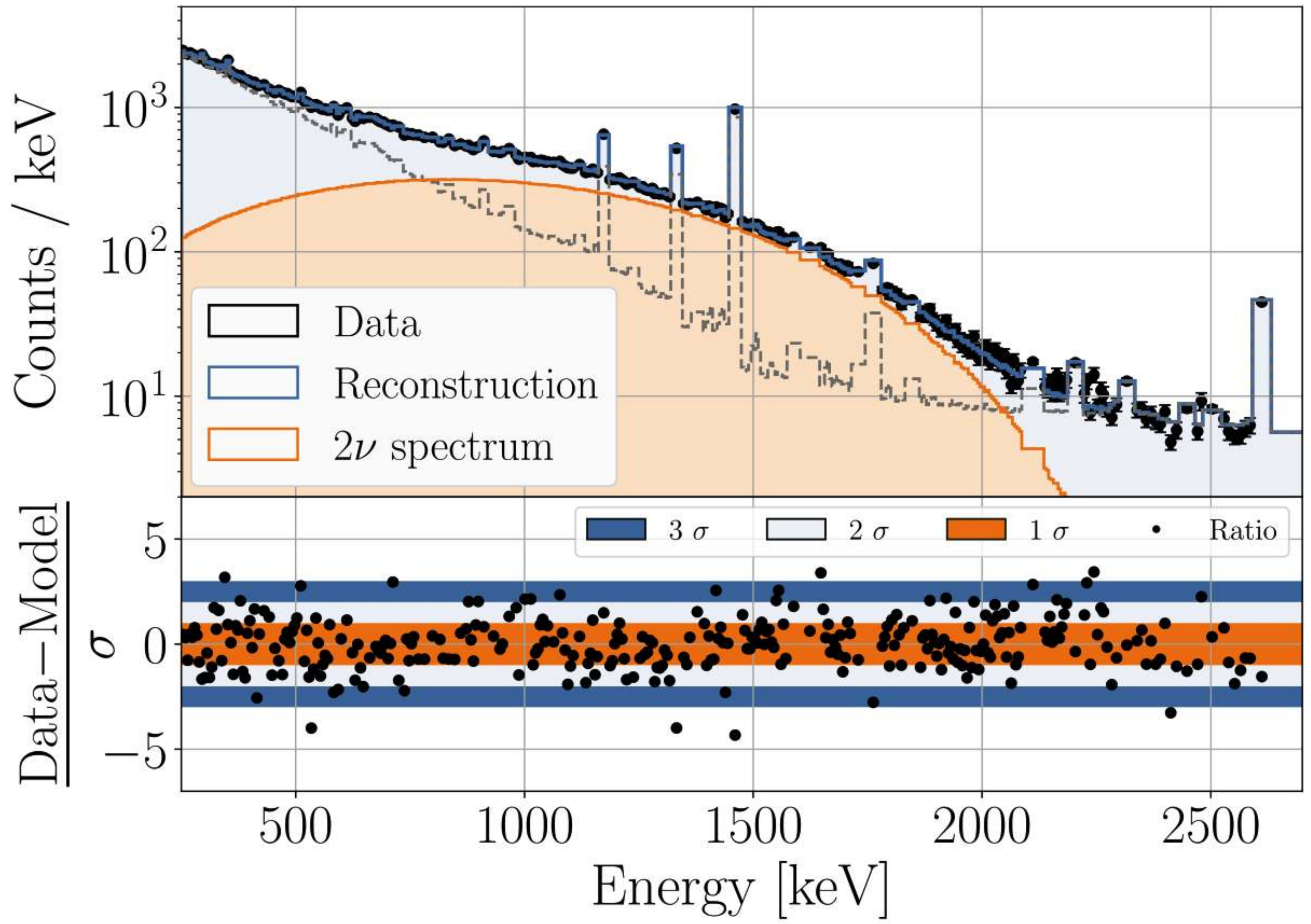
+

Priors extracted from radioassays and past experiments



Accurate Geant-4 based background model with 80 sources

Phys. Rev. D 110, 052003 (2024)



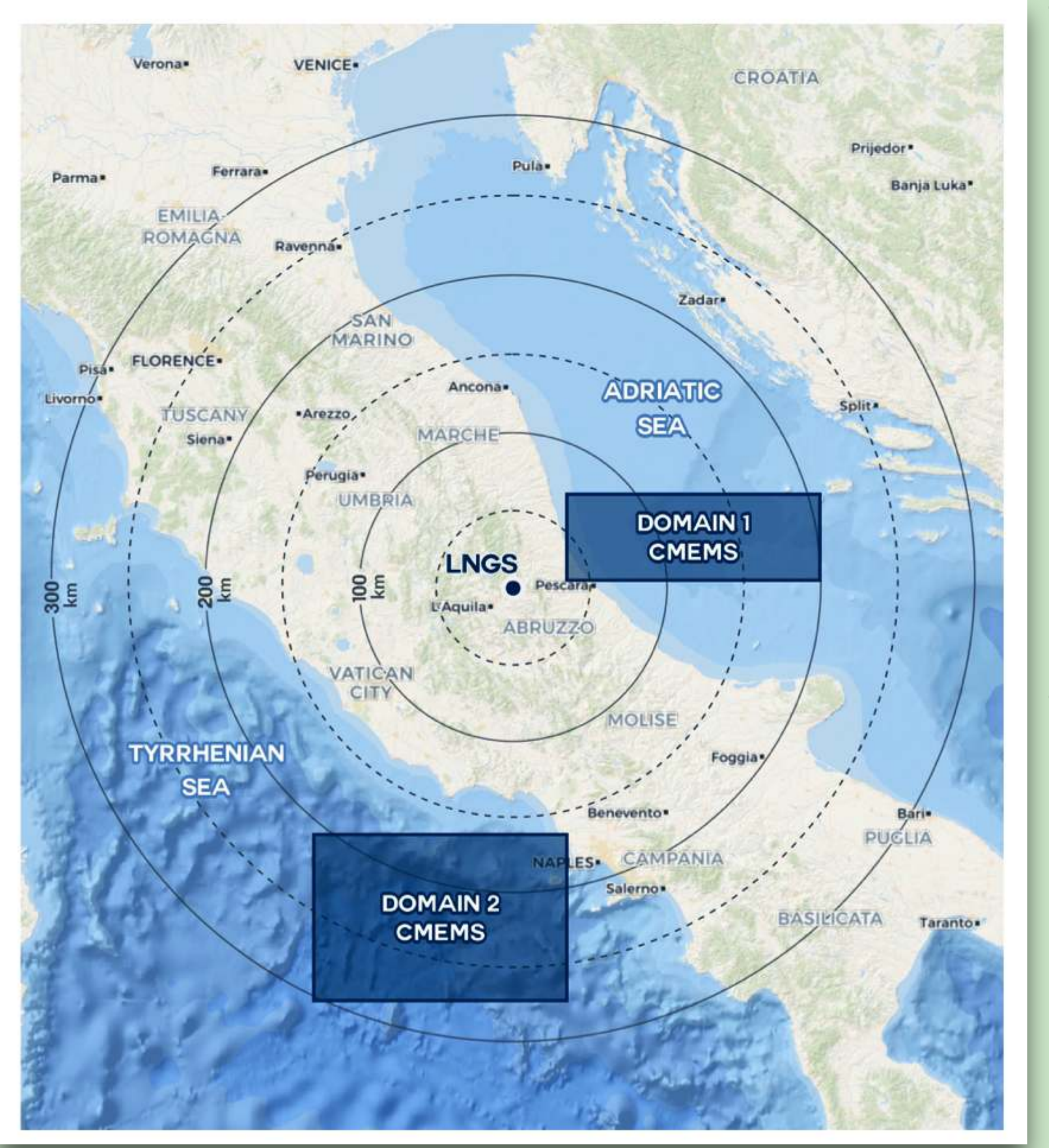
Study of $2\nu\beta\beta$ spectral shape with CUORE & twofold improvement on ^{130}Te $2\nu\beta\beta$ half-life precision:

$$T^{2\nu}_{1/2} = \left[9.32\ ^{+0.05}_{-0.04}\ (\text{stat.})\ ^{+0.07}_{-0.07}\ (\text{syst.})\right] \cdot 10^{20}\ \text{yr}$$

Phys. Rev. Lett. 135, 082501 (2025)

What's left to do? Modeling noise → study low energies

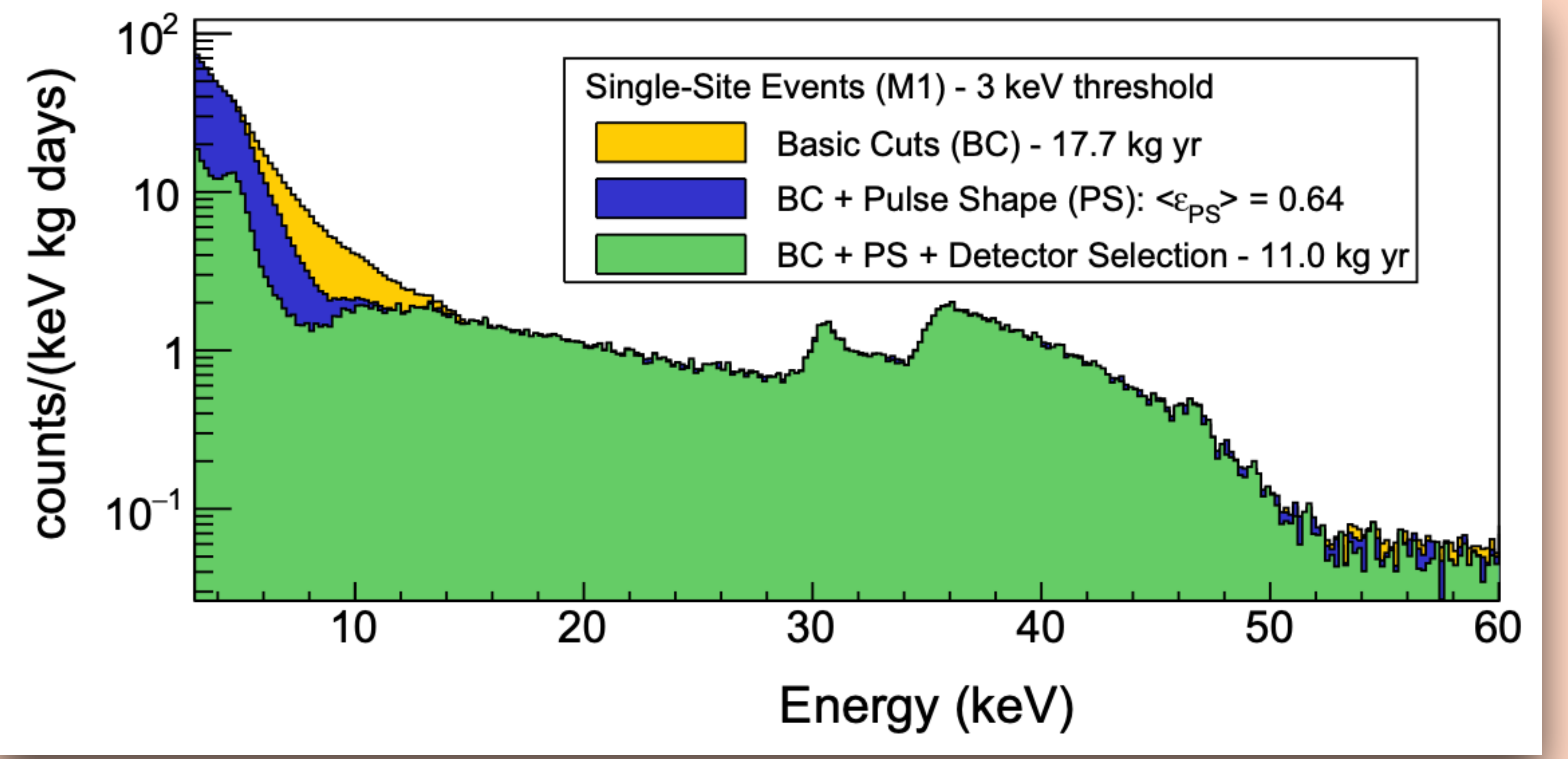
- **Noise decorrelation algorithms** to reduce noise relating channels noise & diagnostic devices signal Science 390, 1029-32 (2025)



arxiv:2505.09652

- CUORE is sensitive to **microseismic activity** induced by the **sea waves** (0.2 - 0.3 Hz)
- Correlation **storms** ↔ low frequency noise
- Under investigation solutions to improve cryostat decoupling

- **Low energy studies**: specific low-energy variables and event-level cuts to optimise sensitivity at keV-scale targeting Phys. Rev. D 113, 012012 (2026)
  - spectral studies potentially related to ^{121}Te, ^{123}Te, ^{125m}Te decays (not measured yet)



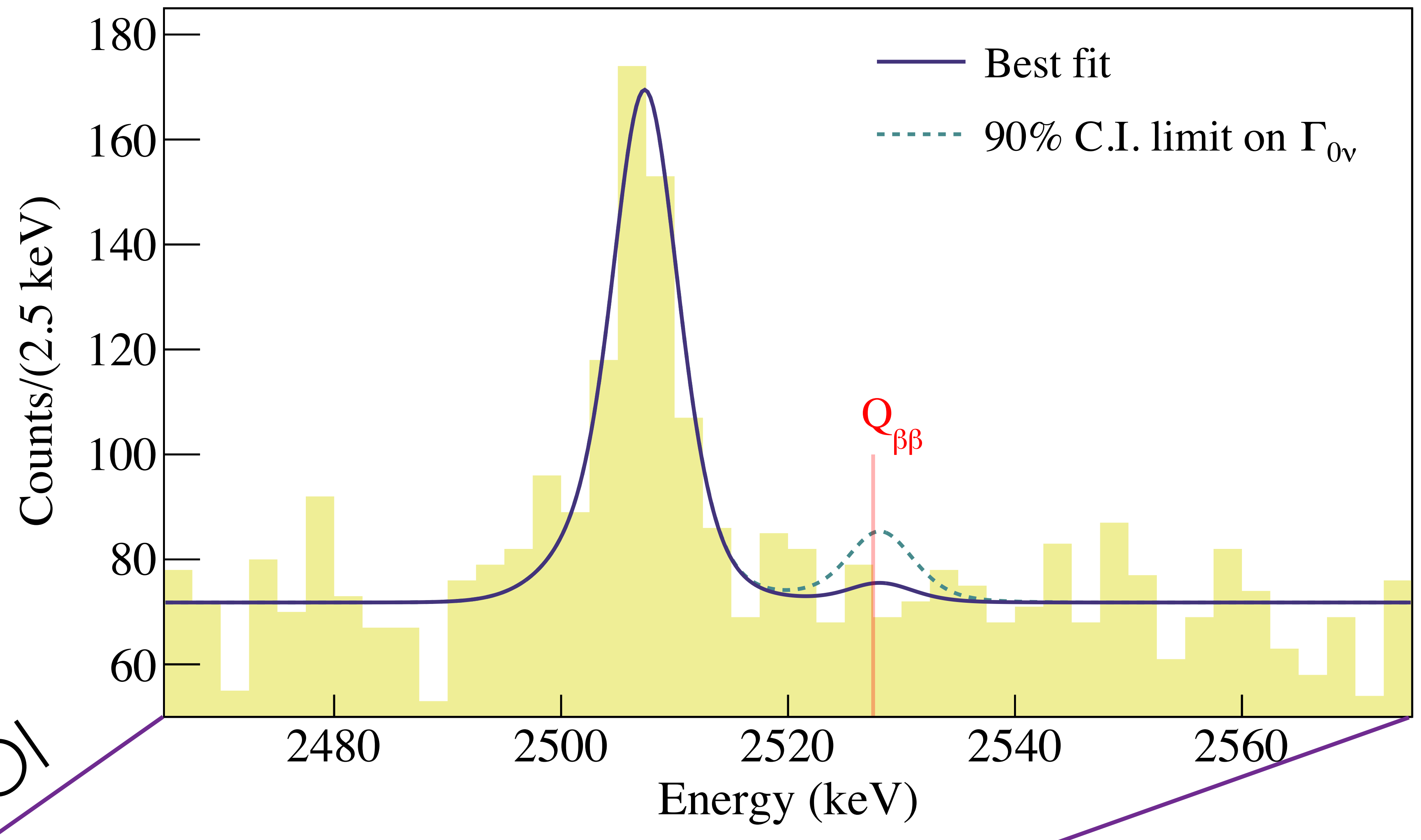
- Increased sensitivity for BSM searches including solar axions, WIMPs

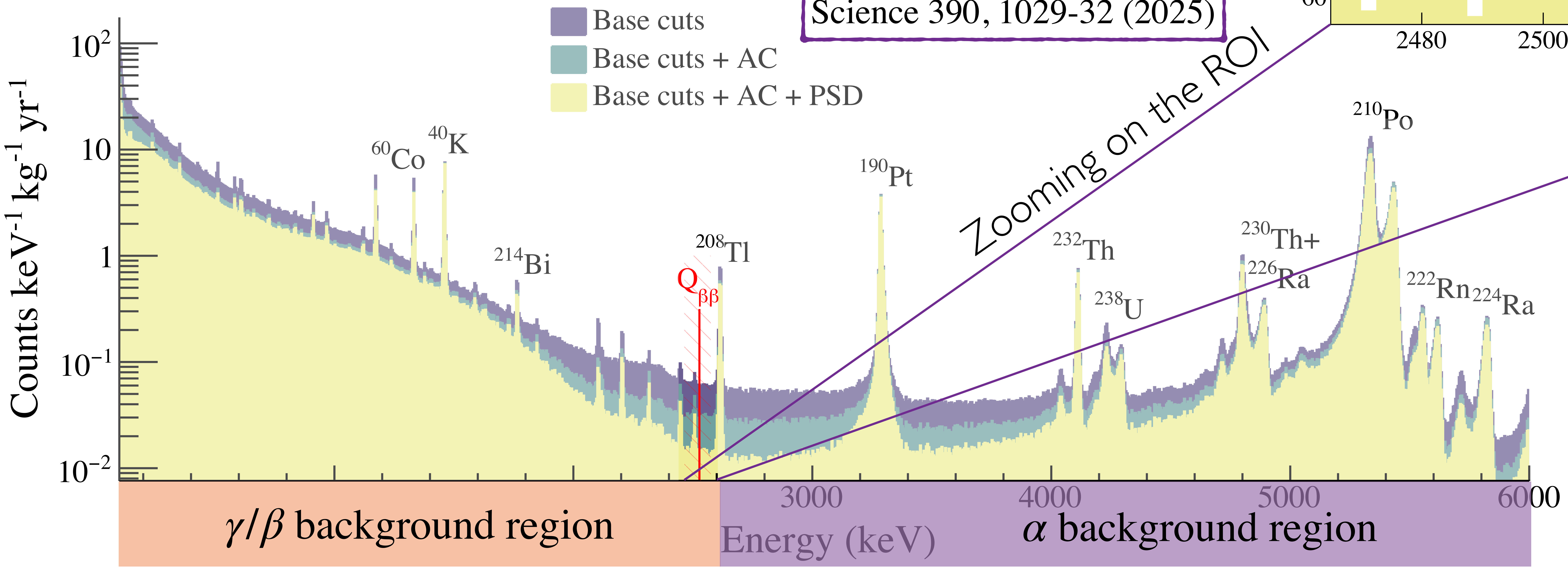
Unveiling the truth: the 2 tonne-yr data spectrum

- 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) %**

Science 390, 1029-32 (2025)

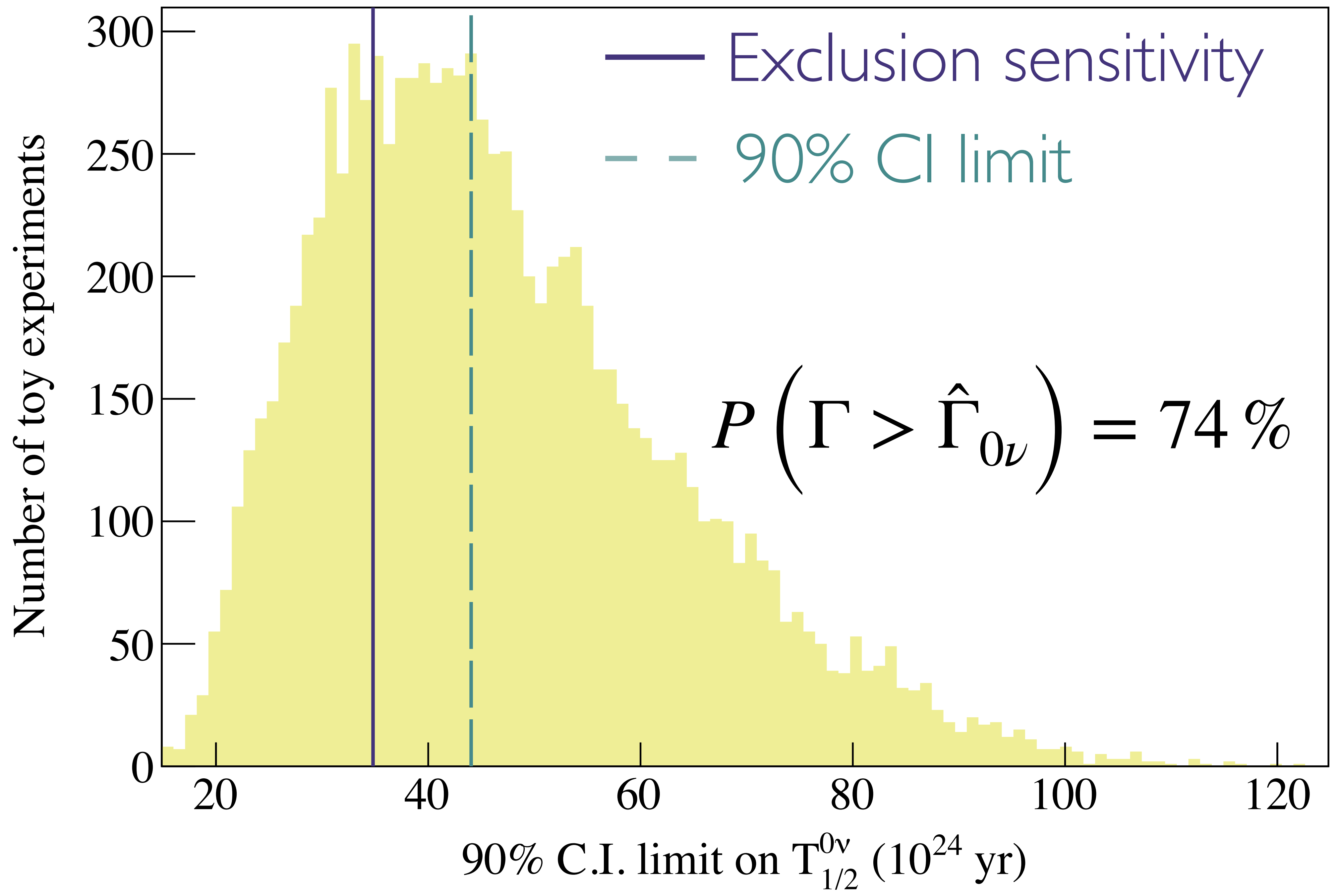




Average background index in the ROI

$$b = \left(1.42^{+0.03}_{-0.02}\right) \cdot 10^{-2}$$
$$\left(\text{counts/keV/kg/yr}\right)$$

Unblinding and fitting our data to extract $\Gamma_{0\nu\beta\beta}$

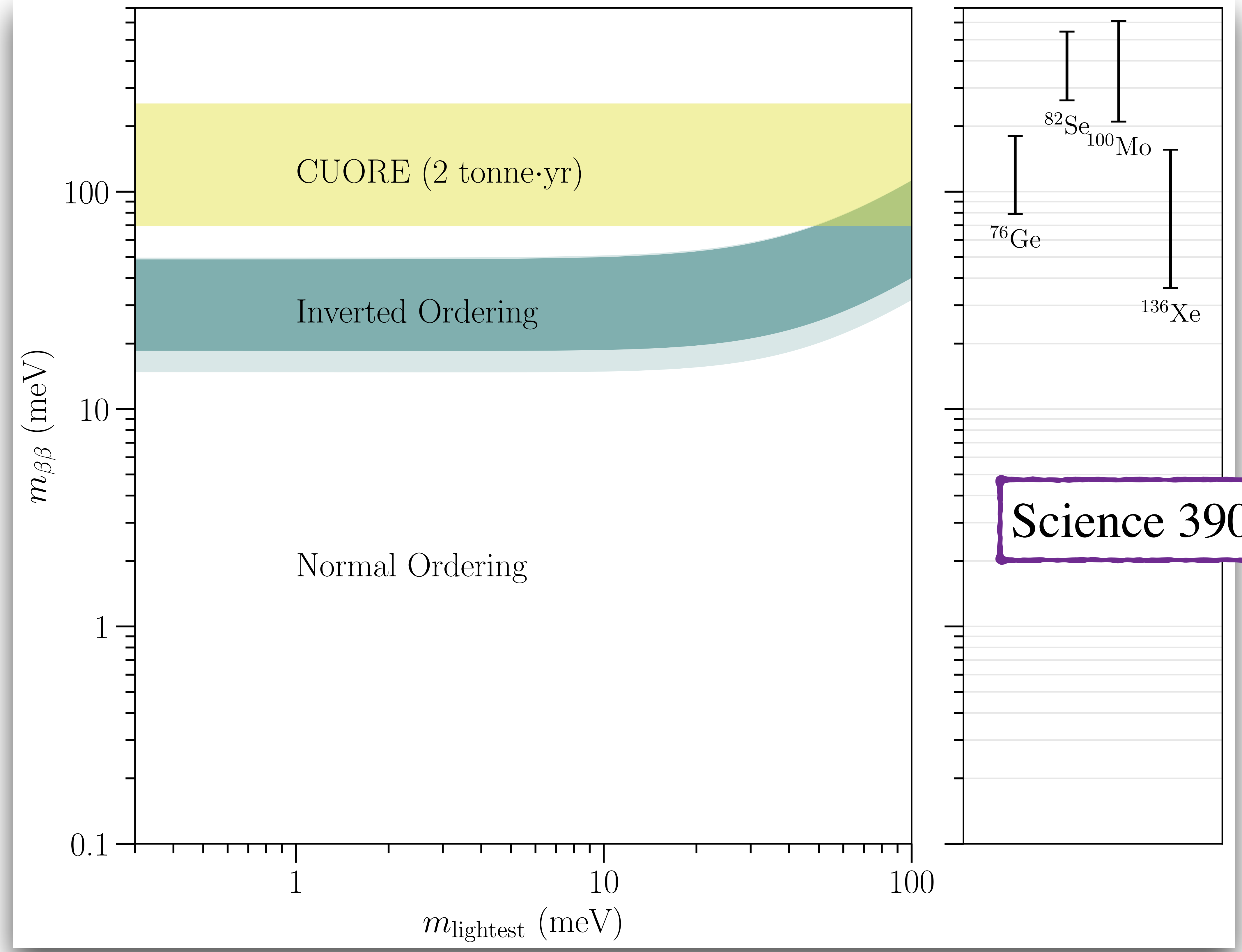


- Median exclusion sensitivity from toy MC experiments $T^{1/2}_{0\nu\beta\beta} = 4.4 \cdot 10^{25}$ yr (90 % C.I.)
- Unbinned Bayesian fit with $\Gamma_{0\nu\beta\beta} > 0$
- No evidence of $0\nu\beta\beta$ and new limit on ^{130}Te half-life $T^{1/2}_{0\nu\beta\beta} > 3.5 \cdot 10^{25}$ yr (90 %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



Science 390, 1029-32 (2025)

Present and future: CUORE & CUPID

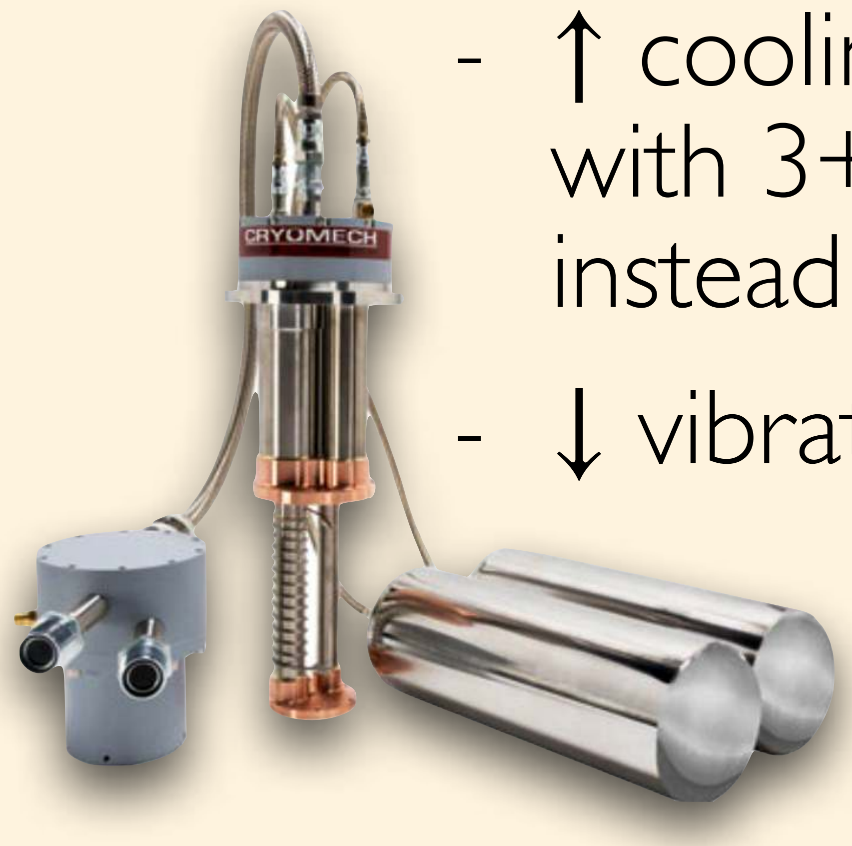
CUORE

- 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, …)

Where we are now…

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, …)

…CUORE after CUORE…

CUPID

CUORE Upgrade with Particle IDentification

- Scintillating cryogenic calorimeters to overcome CUORE main background: αs
- ^{130}Te → ^{100}Mo
  2528 → 3034 keV
- 10^{-4} cts/keV/kg/yr target background
- Same cryogenic infrastructure as CUORE

CUPID

…Our next target!

Final remarks and future outlook

- ✓ 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 final **goal** of **3 tonne · yr TeO_2 exposure** (~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 studies in progress** including rare event searches beyond $0\nu\beta\beta$: background-related studies in view of CUPID, several multi-spectral searches (i.e. based on multiple-crystal events) and low energy analyses
- ✓ Important feedback for **CUPID**, both for the cryogenic setup and background budget
- ✓ Between interventions on the cryogenics and the CUPID detector installation, a CUORE phase II focused on **low energy studies** (dark matter searches, including WIMPs, solar axions, …) is planned

Stay tuned

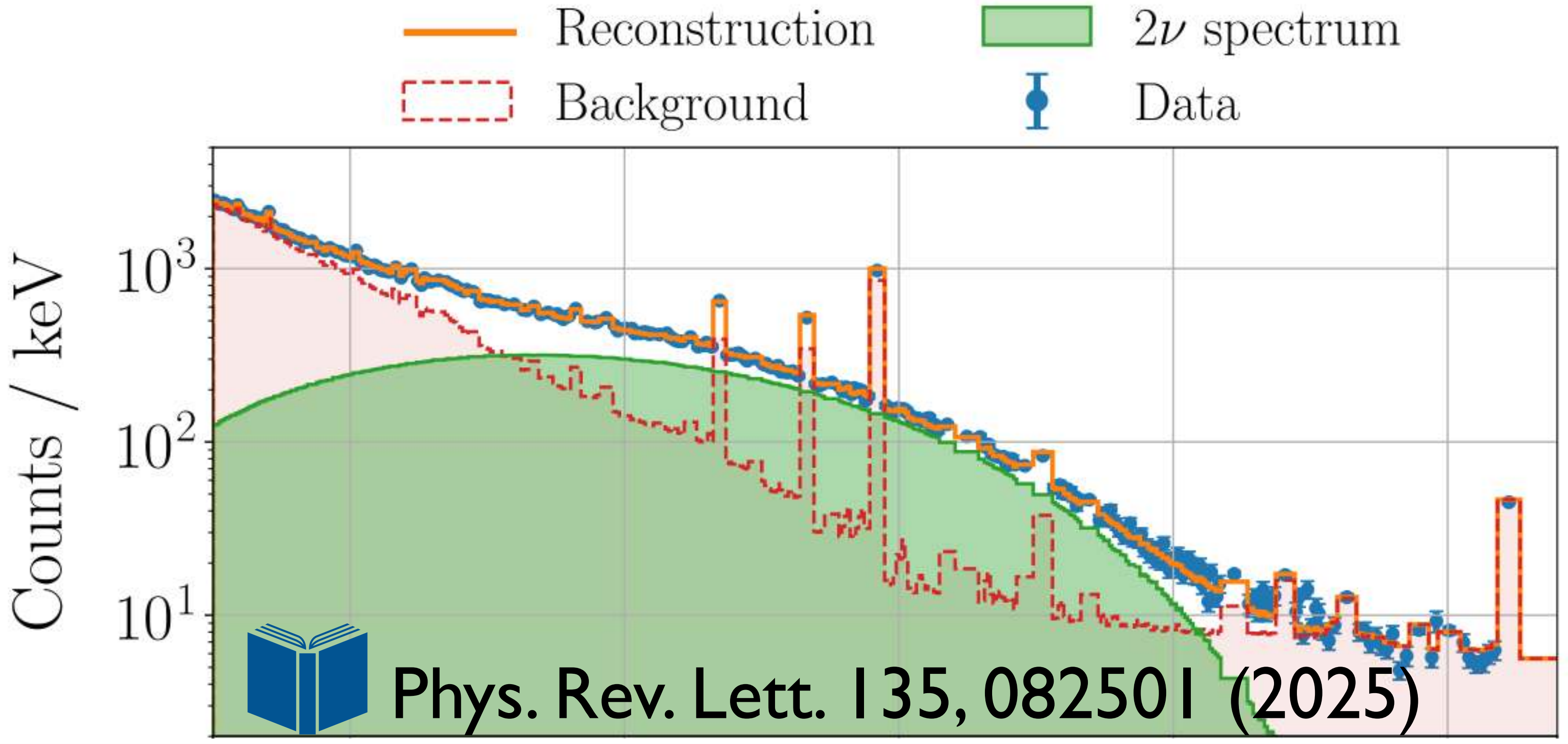
Thank you for your attention

Back-up slides

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

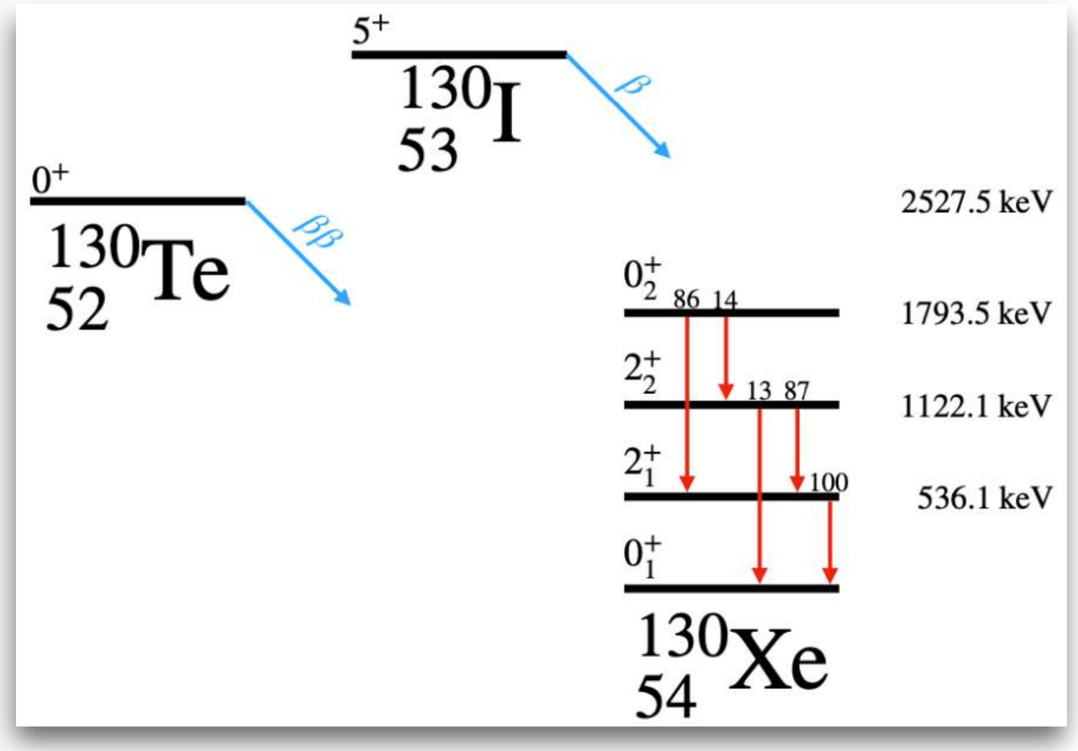
Analysis with 2 ton · yr in progress!

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



Phys. Rev. Lett. 135, 082501 (2025)

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

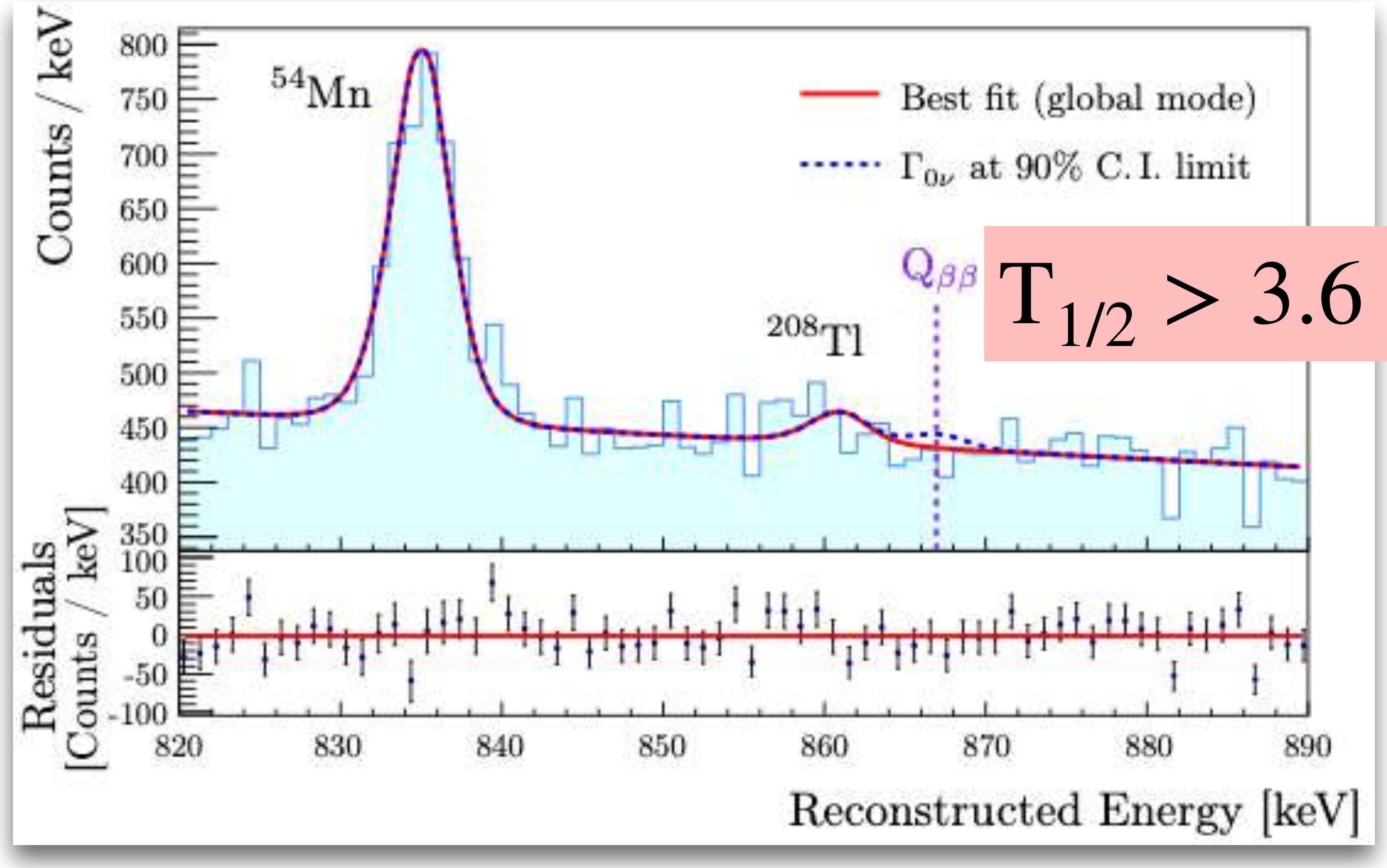


$T^{1/2}_{0\nu} > 5.9 \cdot 10^{24}$ yr (90 % C.I.)

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

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

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

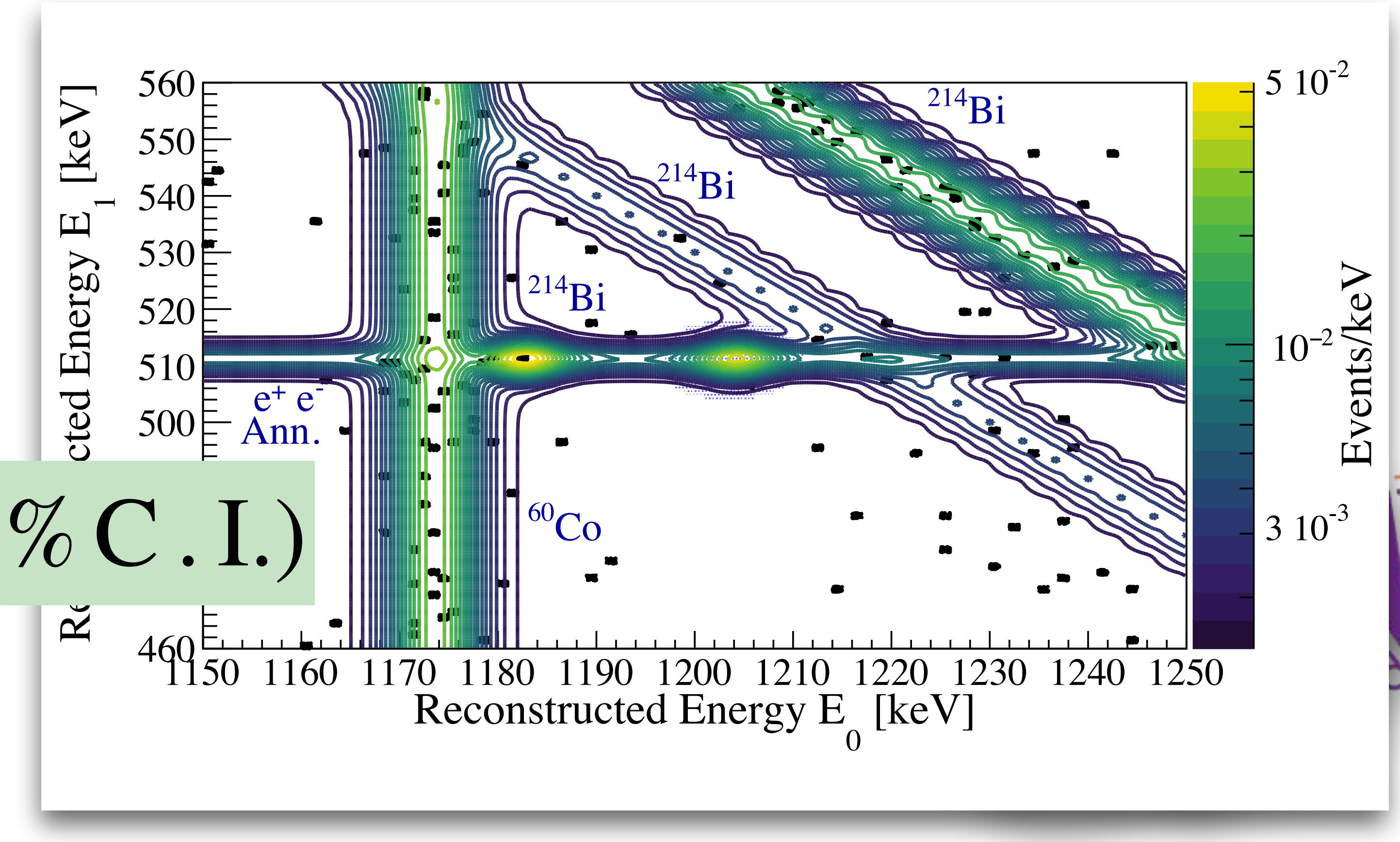


$T_{1/2} > 3.6 \cdot 10^{24}$ yr (90 % C.I.)

Phys. Rev. Lett. 129, 222501 (2022)

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

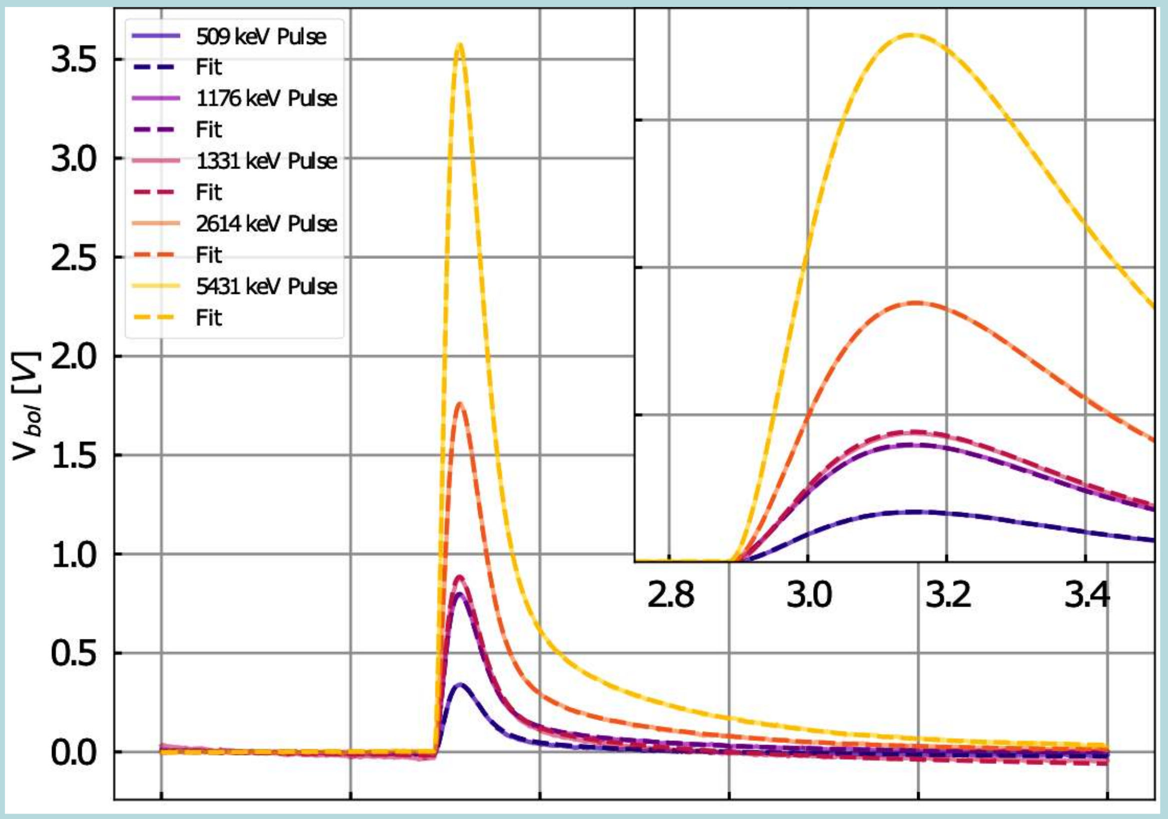
Phys. Rev. C, 105 065504 (2022)



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

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

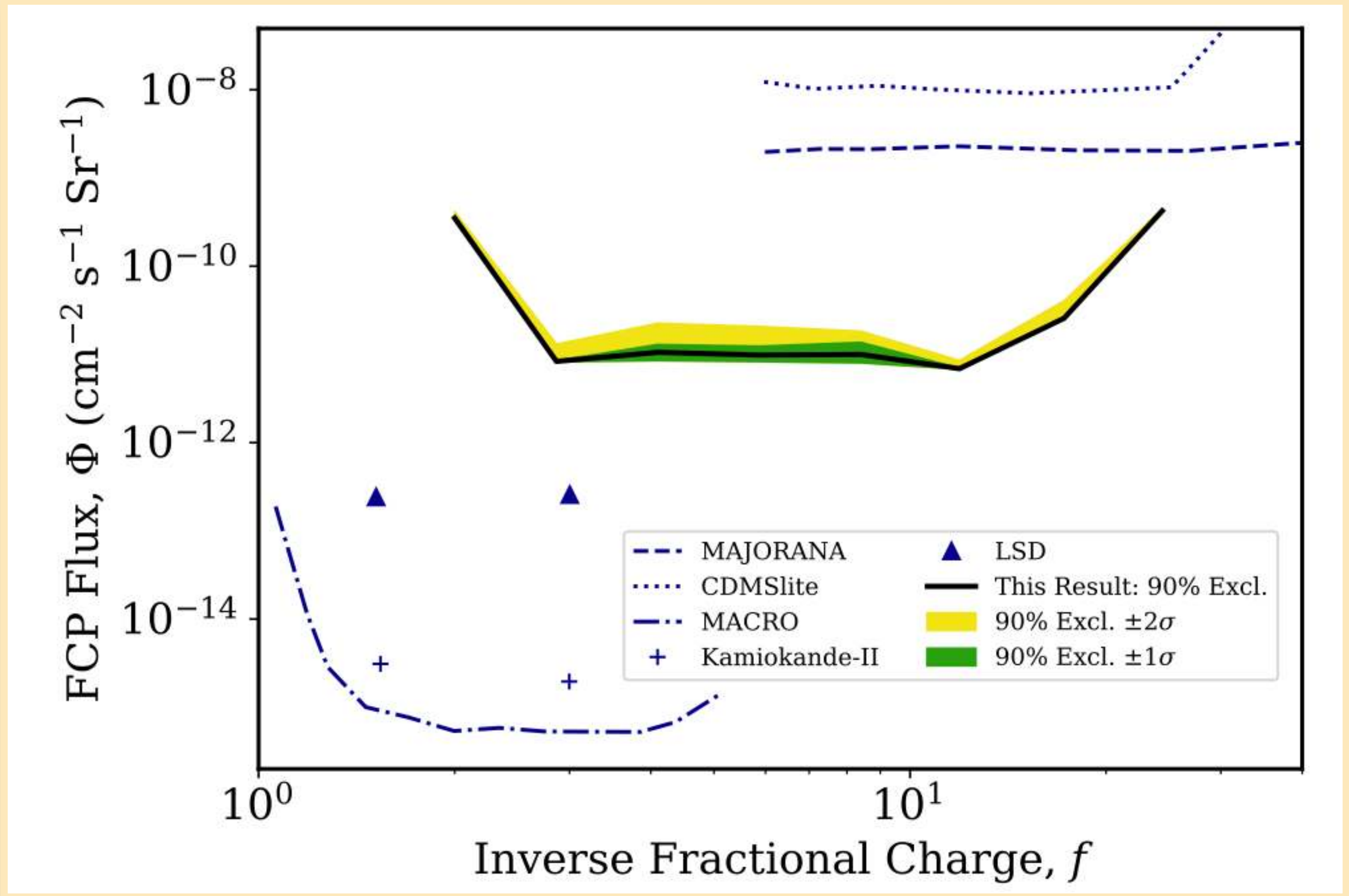
Thermal model of CUORE calorimeters



Dedicated study of environmental and antropic vibrational sources

JINST 17, 11, P11023 (2022)

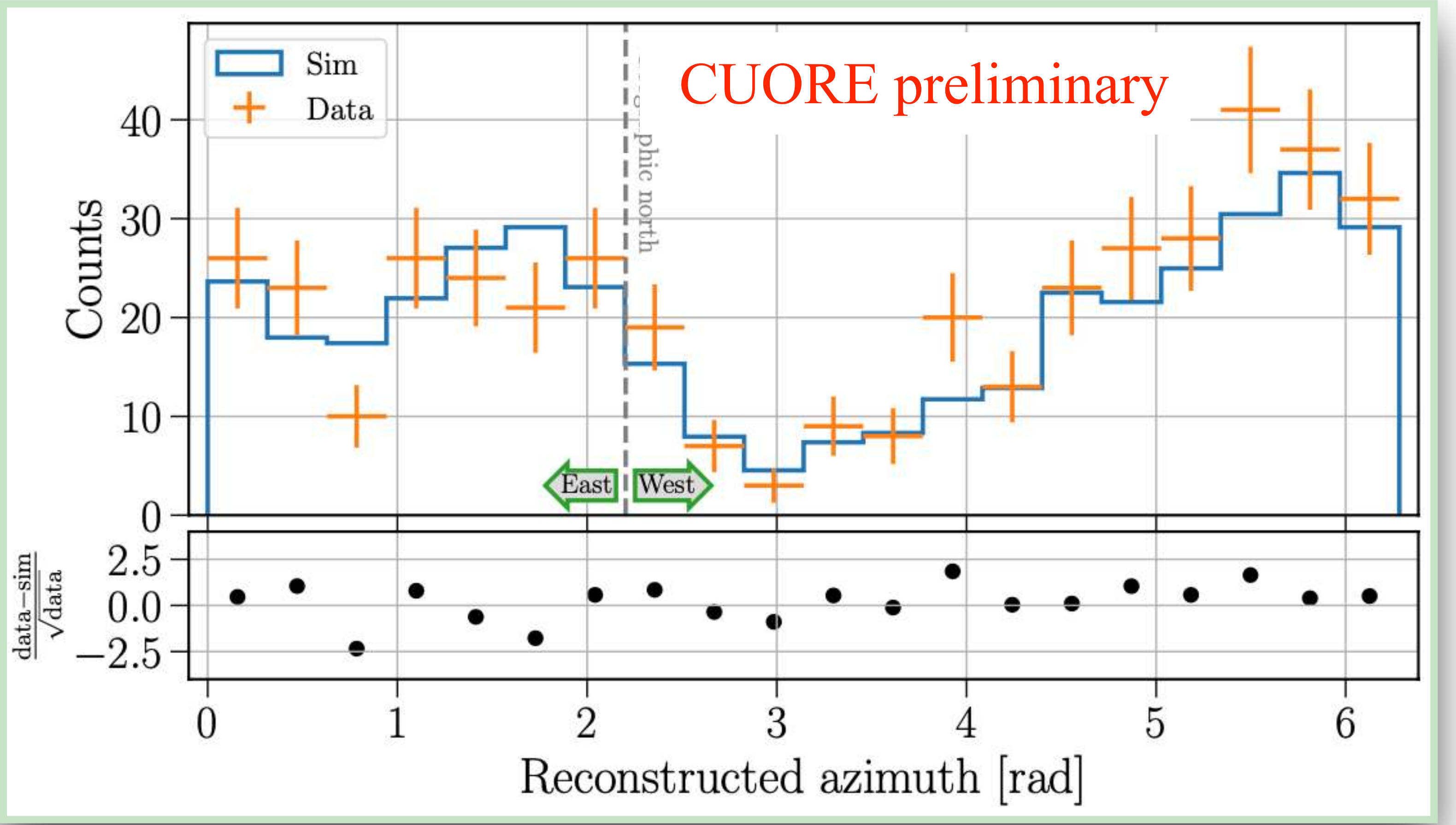
Search for fractionally charged particles



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

Phys. Rev. Lett. 133, 241801 (2024)

Muon event reconstruction (in progress)



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

arxiv:2509.05528

Several additional analyses *in progress*

- Multi-spectral studies exploting the high CUORE detector granularity to study detector response
- Low energy studies profiting of the improved analysis tools and energy thresholds
- Background model related studies
- Rare event searches with larger statistics

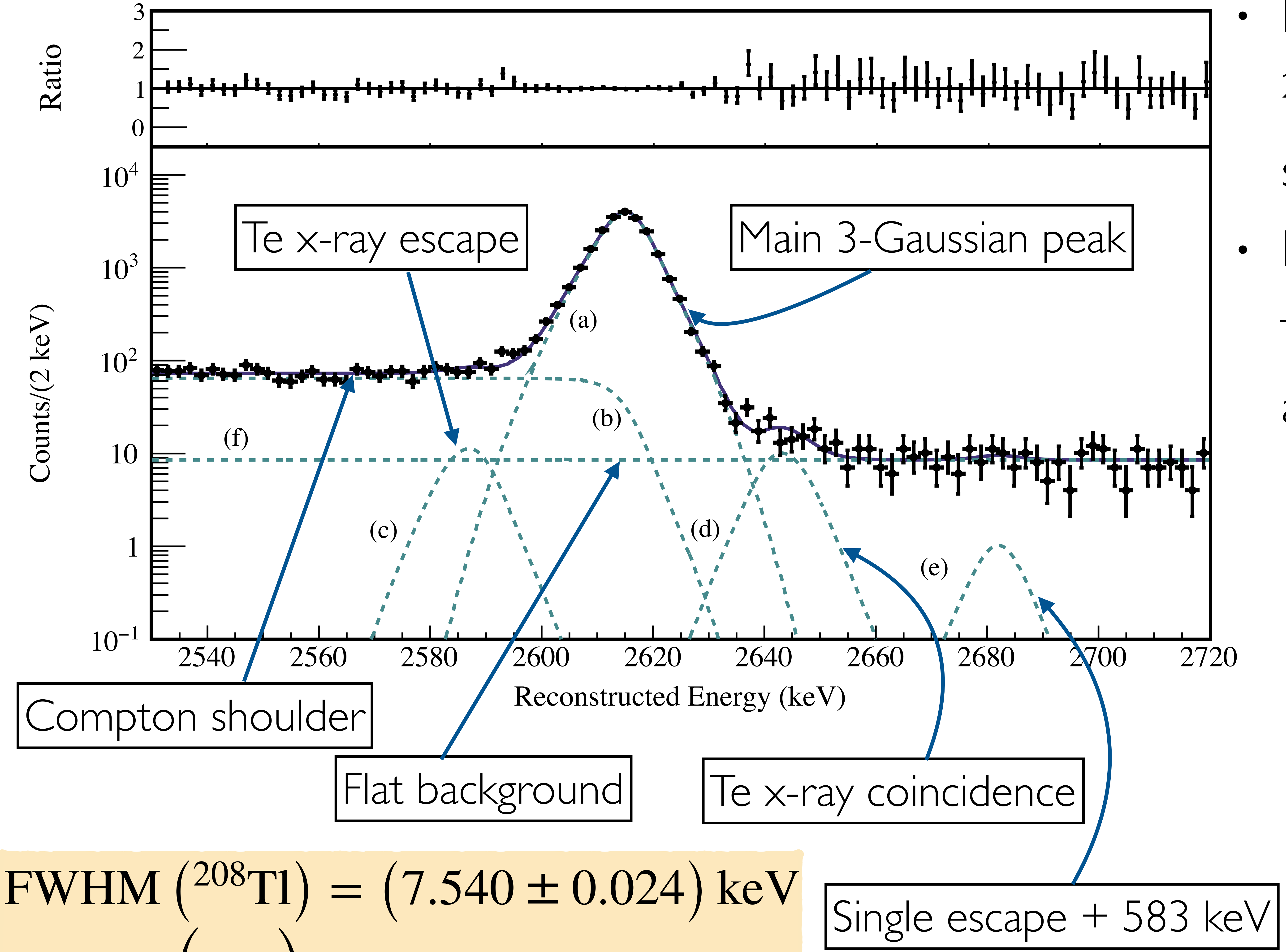
2 tonne·yr data: analysis & $0\nu\beta\beta$ fit parameters

Table I: Relevant parameters for the 2 tonne yr $0\nu\beta\beta$ analysis		
Operational detectors	Functioning detectors	984/988
	Active detectors (average)	914/988
Amount of data	# Datasets	28
	TeO_2 exposure	2039.0 kg yr
	^{130}Te exposure	567.0 kg yr
Energy calibration	2615 keV (^{208}Tl) FWHM (calibration)	7.540(24) keV
	$Q_{\beta\beta}$ (2528 keV) FWHM (physics)	7.310(24) keV
	Bias @ $Q_{\beta\beta}$ (2528 keV) (physics)	$0.40^{+0.21}_{-0.44}$ keV
Data selection efficiency	Reconstruction (base cuts) efficiency	95.624(16)%
	Anti-coincidence (AC) efficiency	99.80(5)%
	Pulse Shape Discrimination (PSD) efficiency	97.9(18)%
	Total analysis efficiency	93.4(18)%
	Containment efficiency (Monte Carlo)	88.35(9)%

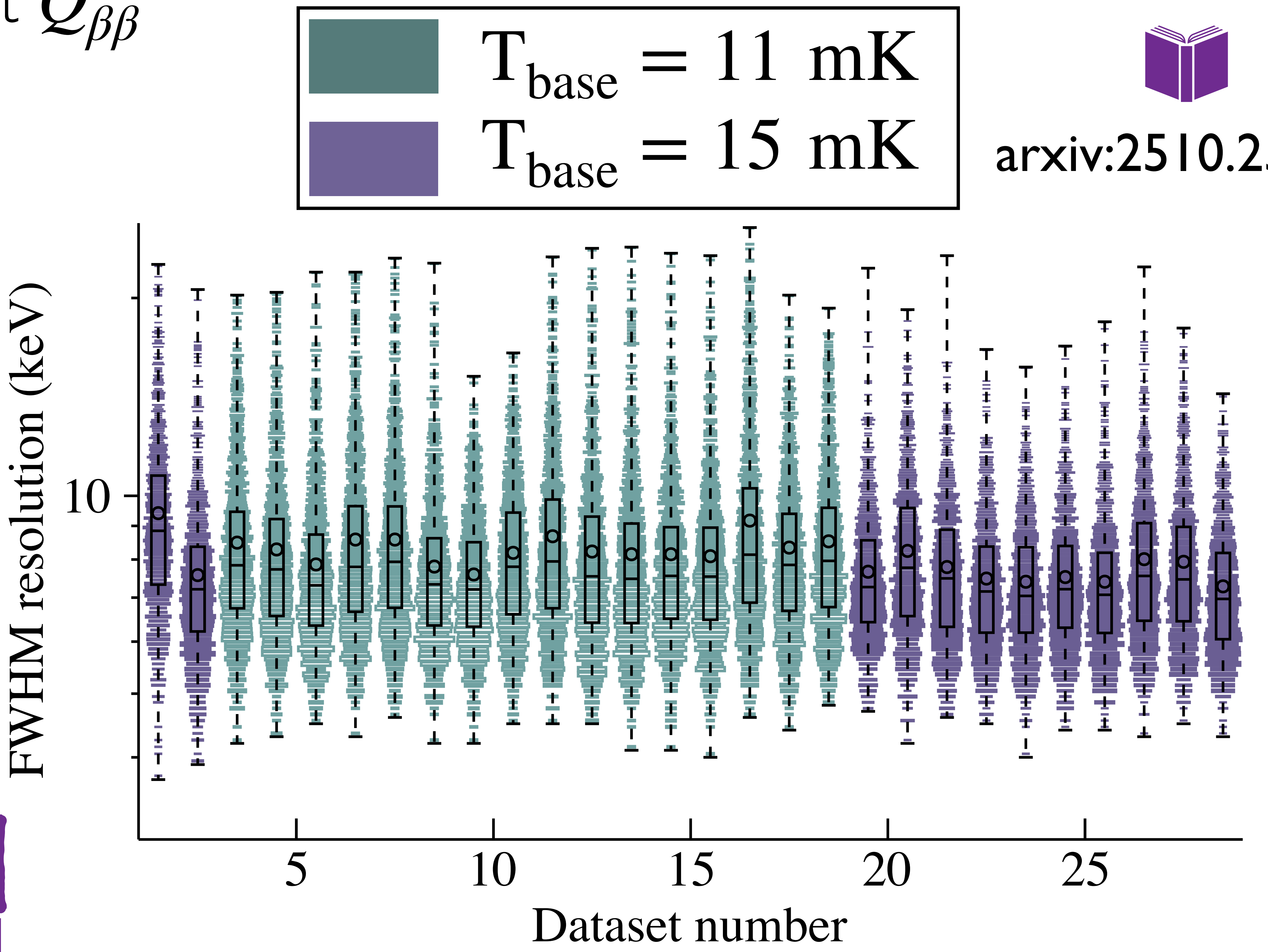
Table II: $0\nu\beta\beta$ fit parameters of the 2 tonne yr data	
Limit setting sensitivity	
90% C.I. limit on $T^{1/2}_{0\nu\beta\beta}$	4.4 10^{25} yr
Bayesian fit	
Best-fit $\Gamma_{0\nu\beta\beta}$	$5.5^{+7.3}_{-5.5}$ 10^{-27} yr^{-1} (stat.+syst.)
90% C.I. limit on $\Gamma_{0\nu\beta\beta}$	2.0 10^{-26} yr^{-1}
90% C.I. limit on $T^{1/2}_{0\nu\beta\beta}$	3.5 10^{25} yr
$P(T^{1/2} > T^{1/2}_{0\nu\beta\beta})$	74%
Frequentist fit	
90% C.L. limit on $\Gamma_{0\nu\beta\beta}$	2.0 10^{-26} yr^{-1}
90% C.L. limit on $T^{1/2}_{0\nu\beta\beta}$	3.4 10^{25} yr
Effective Majorana mass	
$m_{\beta\beta}$	70 - 250 meV
Residual background in the ROI	
BI (counts/keV/kg/yr)	$1.42^{+0.03}_{-0.02}$ 10^{-2}

Science 390, 1029-32 (2025)

Unveiling the truth: modeling detector response



- 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 $Q_{\beta\beta}$



arxiv:2510.25720

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

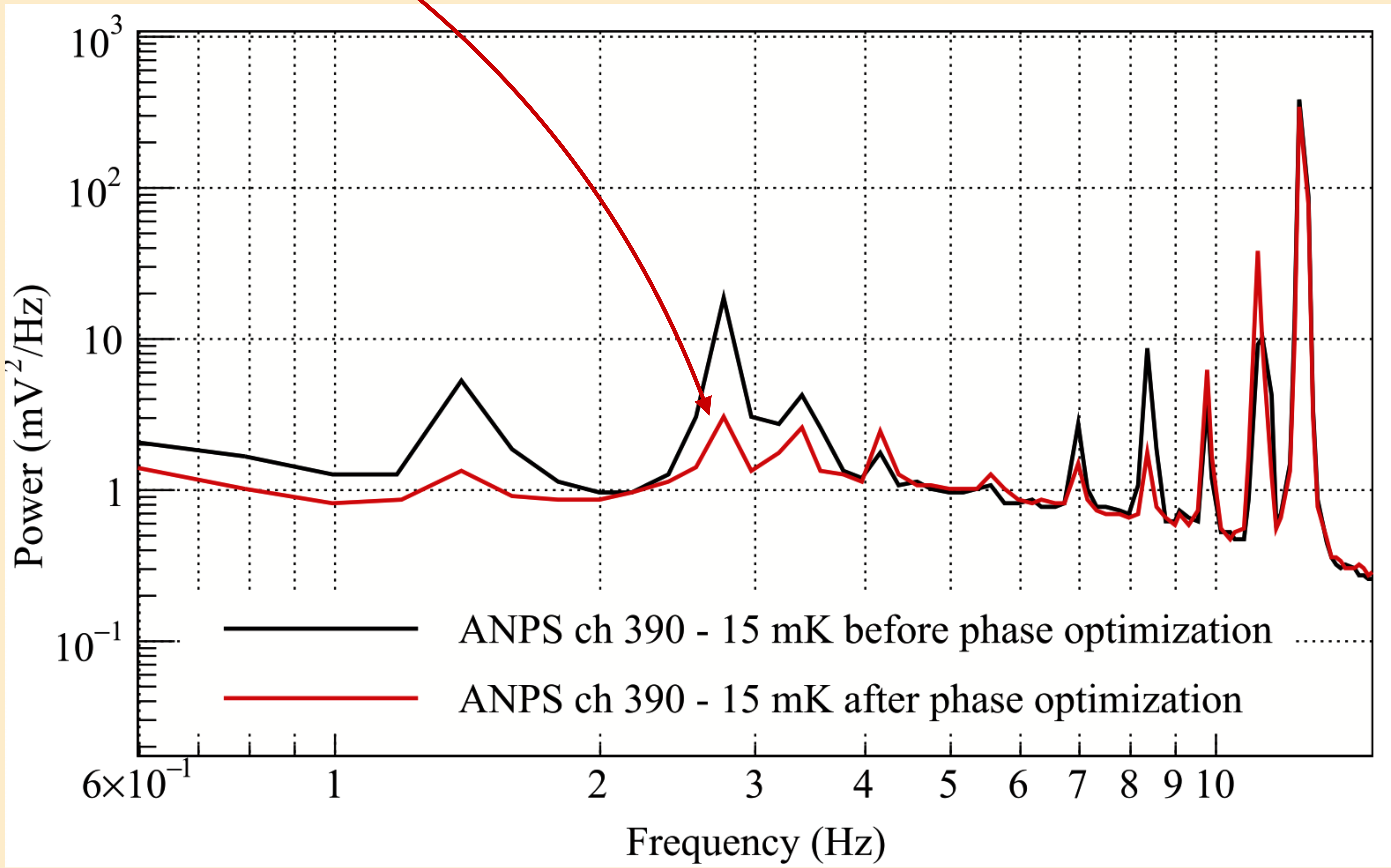
$$\mathrm{FWHM}\left(Q_{\beta\beta}\right) = (7.310 \pm 0.024)\ \mathrm{keV}$$

$$\Delta E\left(Q_{\beta\beta}\right) = \left(0.40^{+0.21}_{-0.44}\right)\ \mathrm{keV}$$

Science 390, 1029-32 (2025)

The price we paid… suppressing noise sources

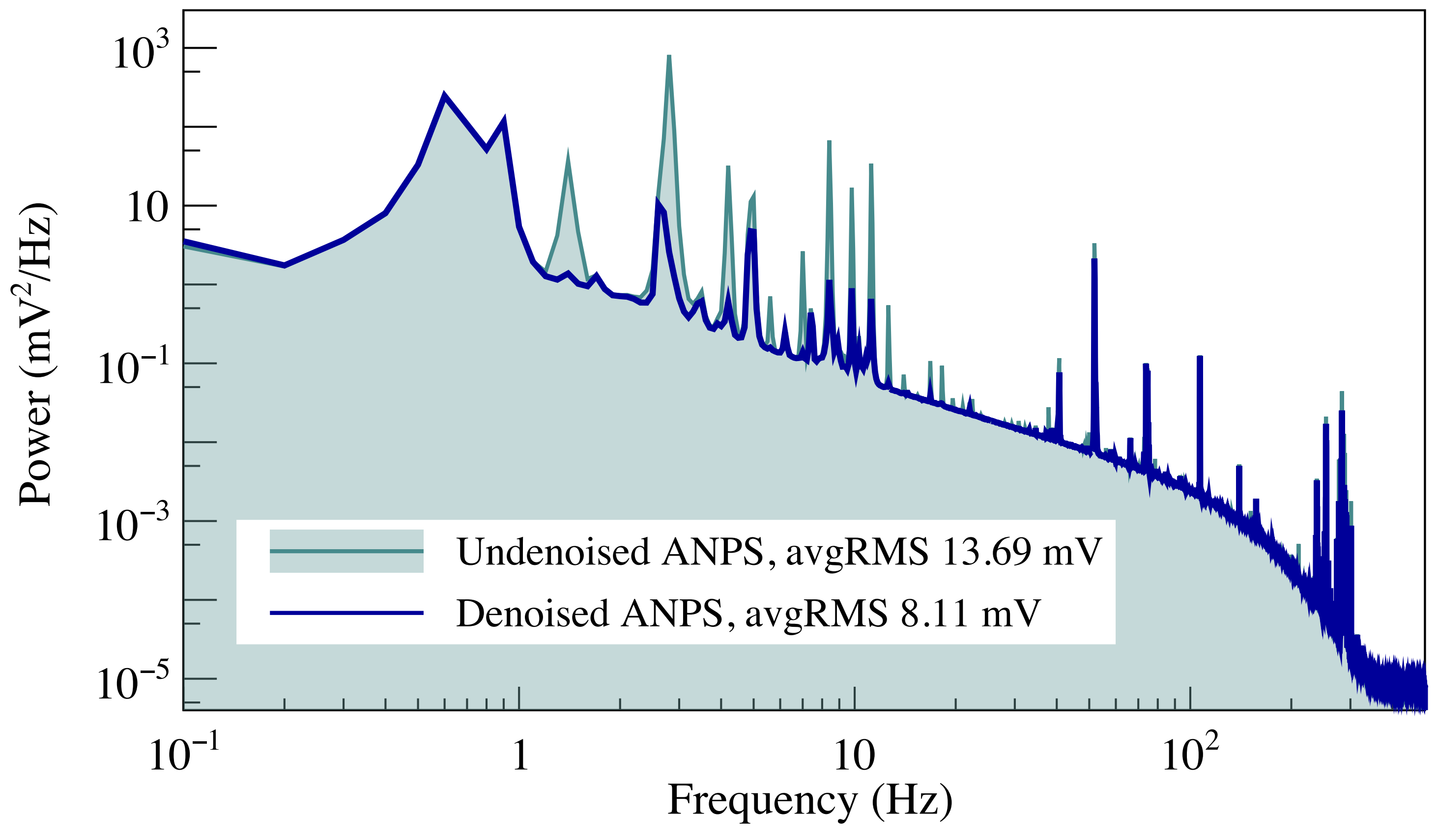
Linear drives and active noise cancellation to minimize vibrations induced by the **pulse tubes**



Cryogenics 93, 56-65 (2018)

Data processing chain to extract a spectrum of events

Denoising (New!)

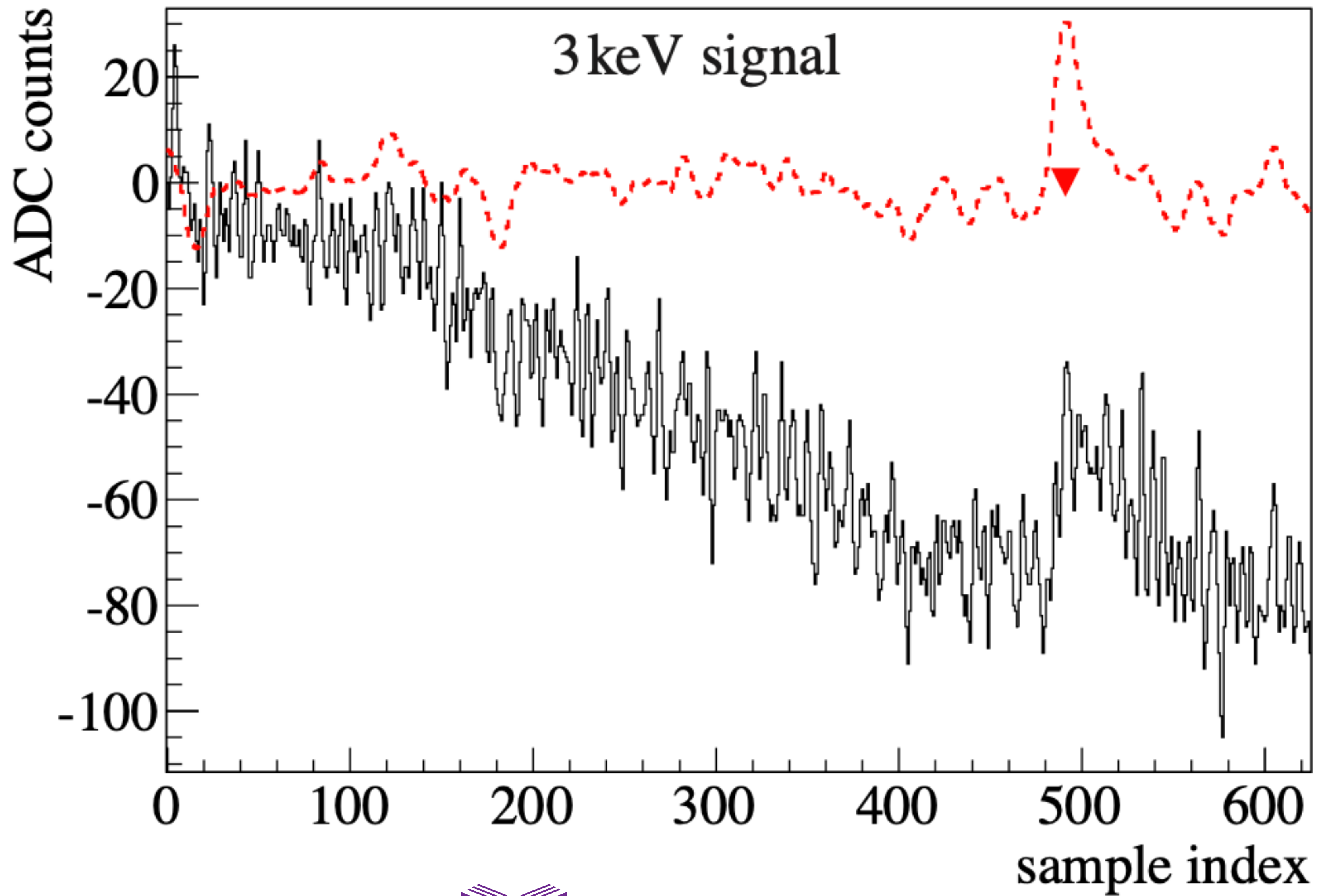


Science 390, 1029-32 (2025)

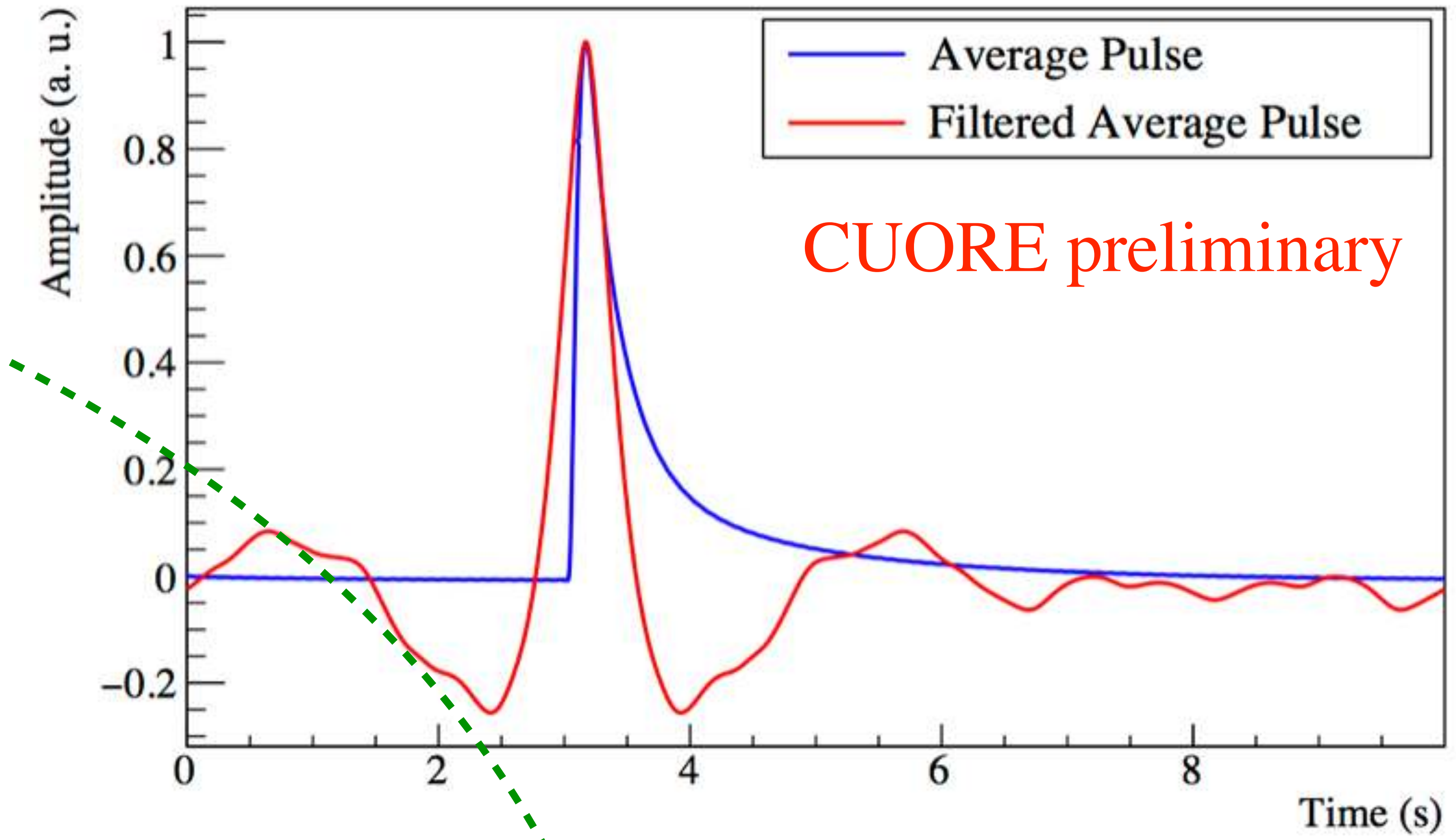
Noise is mitigated correlating *vibrations* with measurements obtained with *auxiliary devices*, i.e. microphones, accelerometers, seismometers

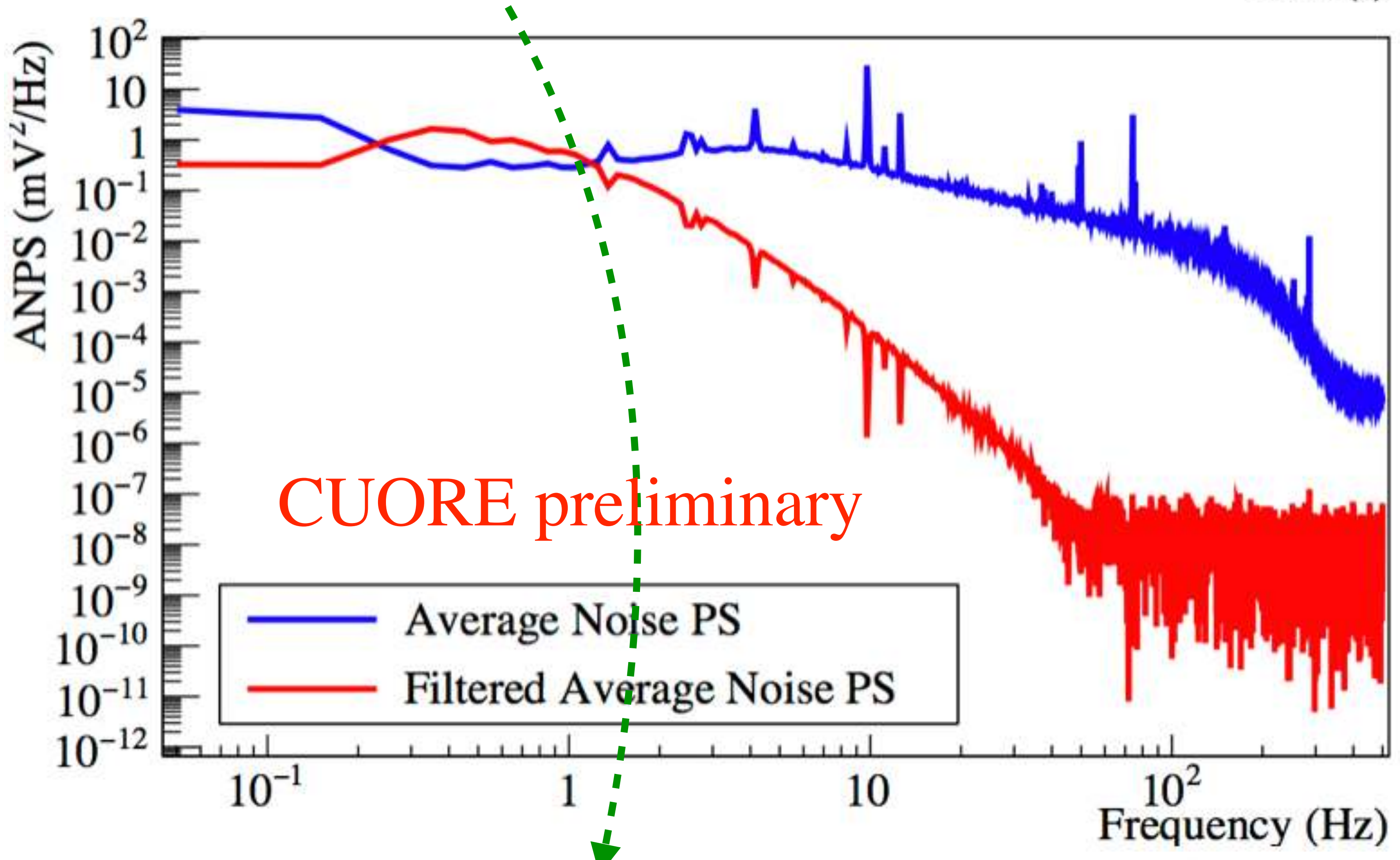
Optimum trigger (OT)

Offline data retrigger with OT to maximize SNR exploiting the distinct power spectra of particle induced and noise waveforms.



JINST 6, P02007 (2011)



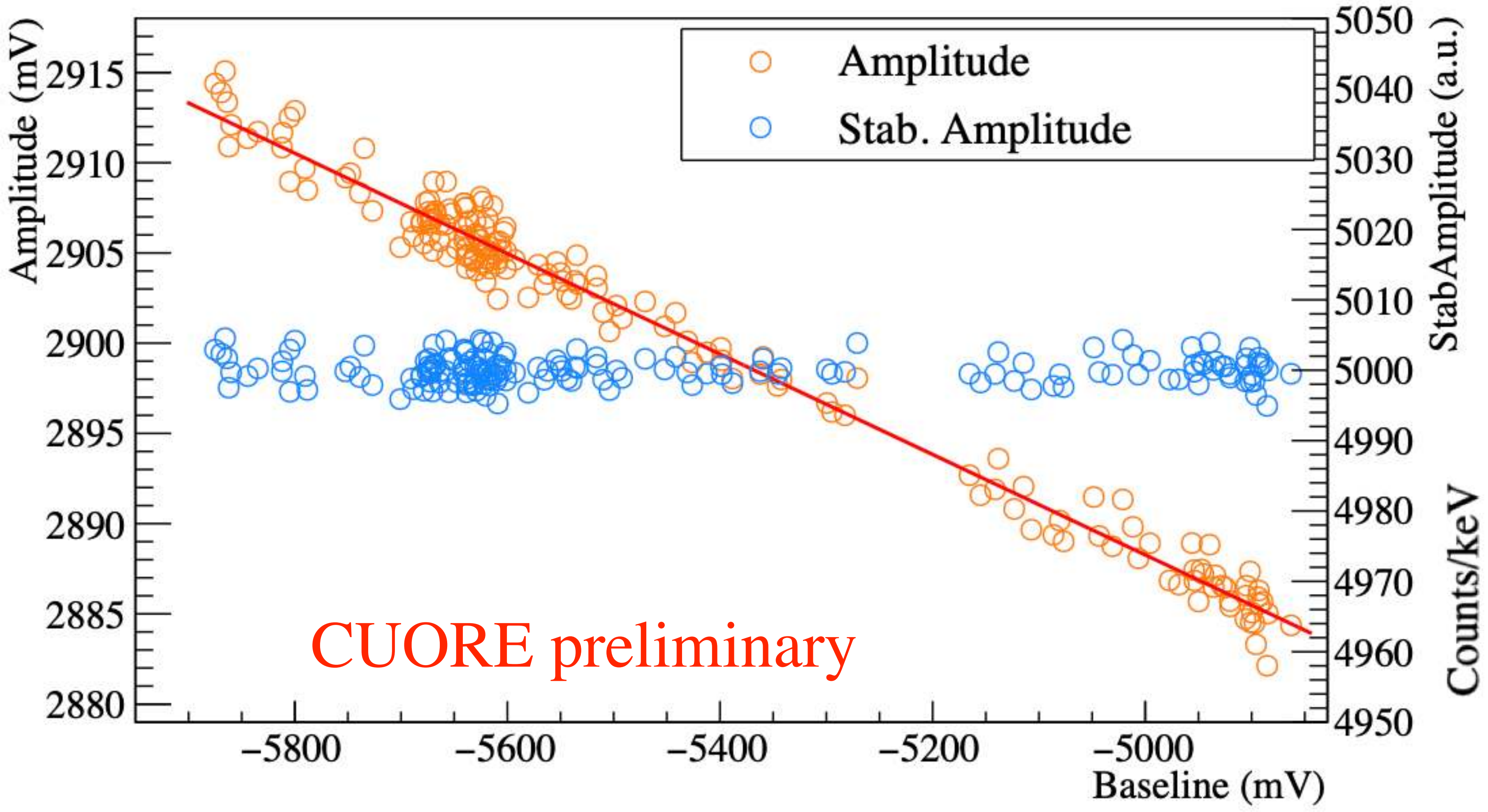


Optimum Filter technique

We evaluate *filtered* signal amplitude

Data processing chain to extract a spectrum of events

Thermal gain stabilization (TGS)



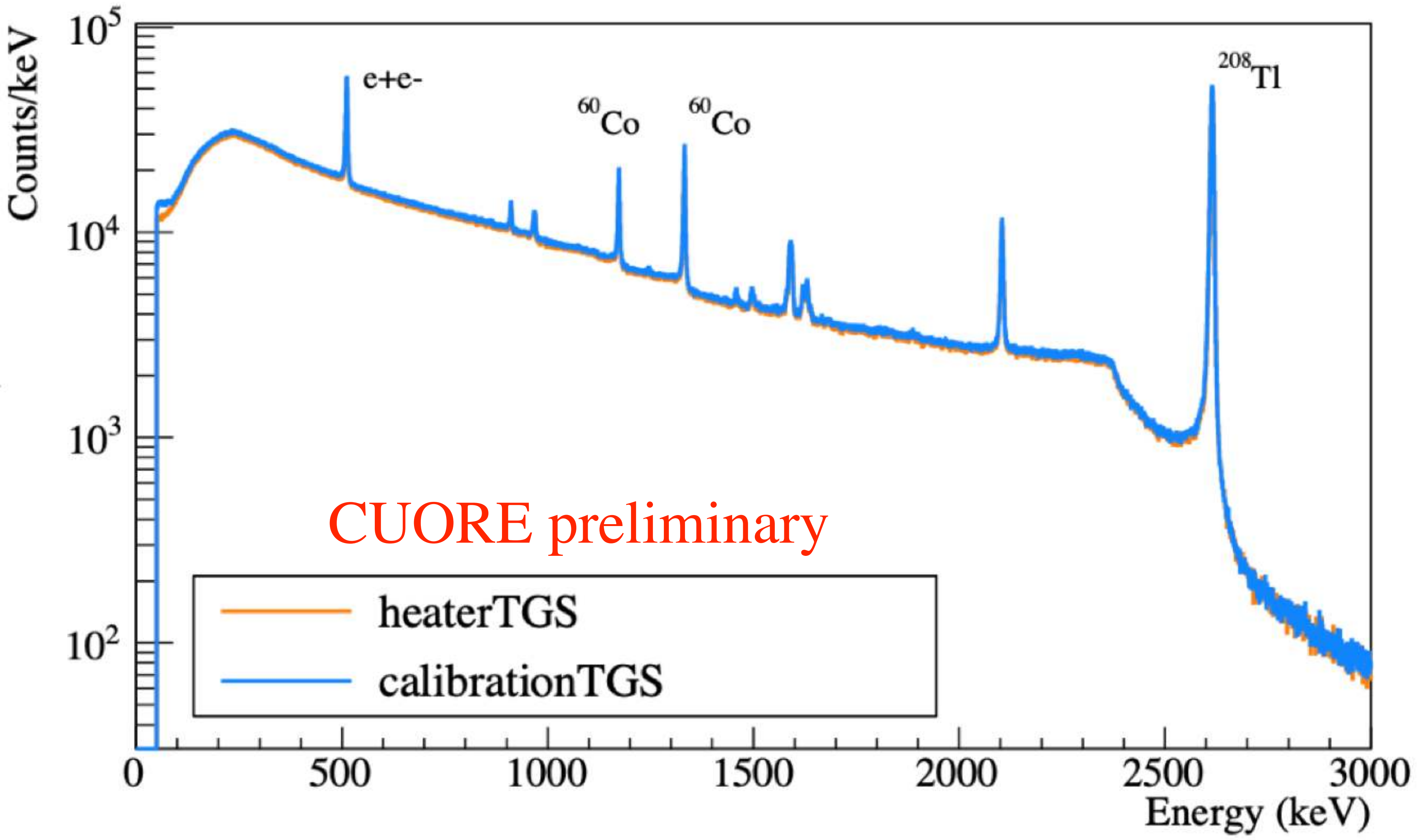
We employ fixed energy pulses to correct for drifts in the thermal gain

arxiv:2510.25720

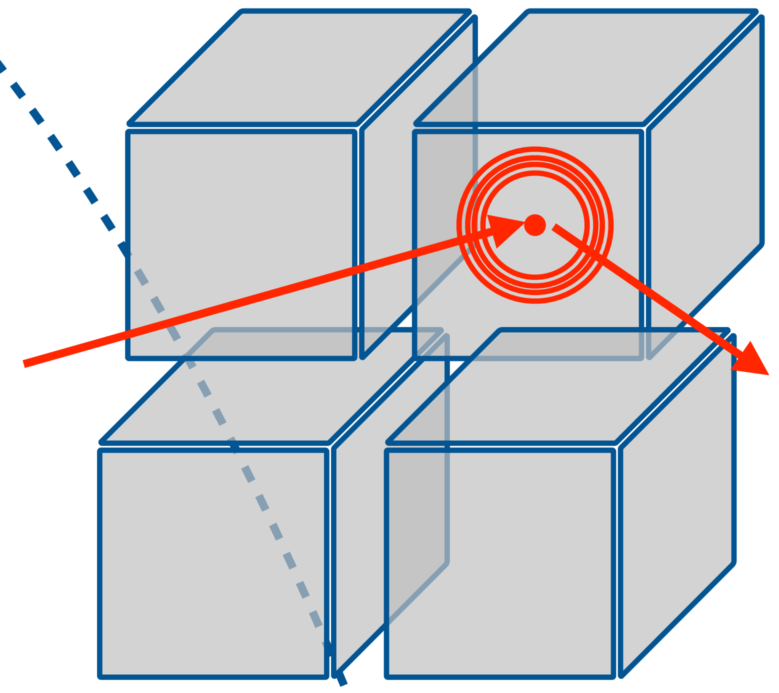
Energy calibration

This is based on measurements with ^{232}Th + ^{60}Co external strings, periodically deployed in the detector

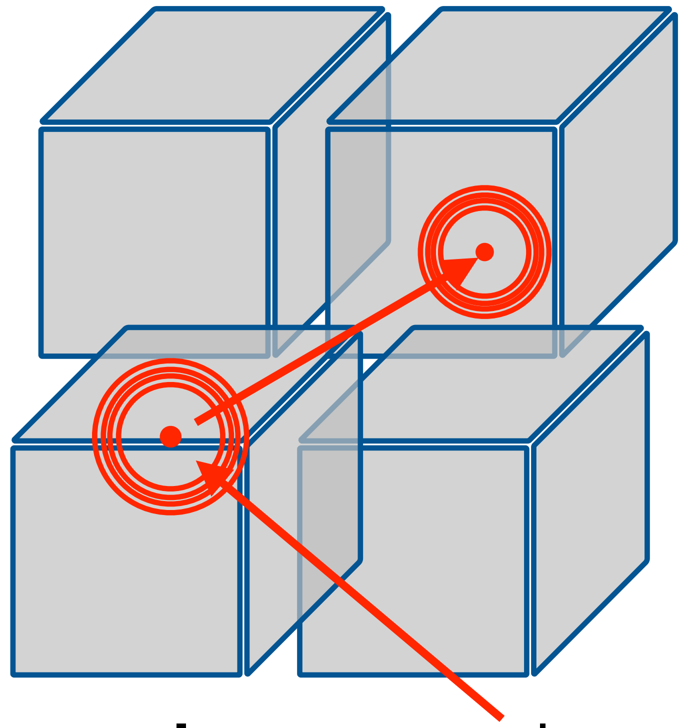
We use a 2nd order polynomial fit to extract our calibration coefficients



We identify *simultaneous* (±5 ms) particle events on multiple crystals



single-crystal



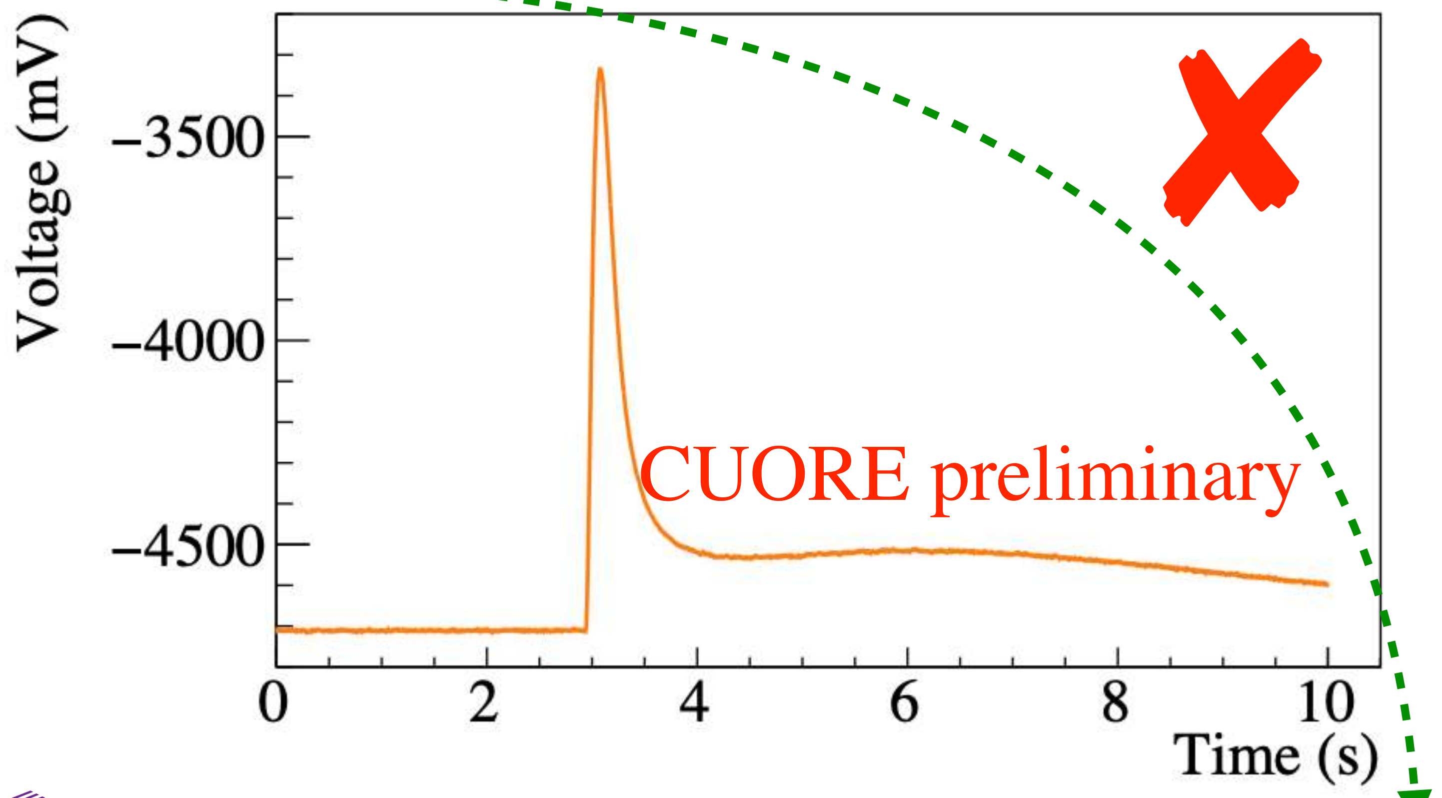
multi-crystal

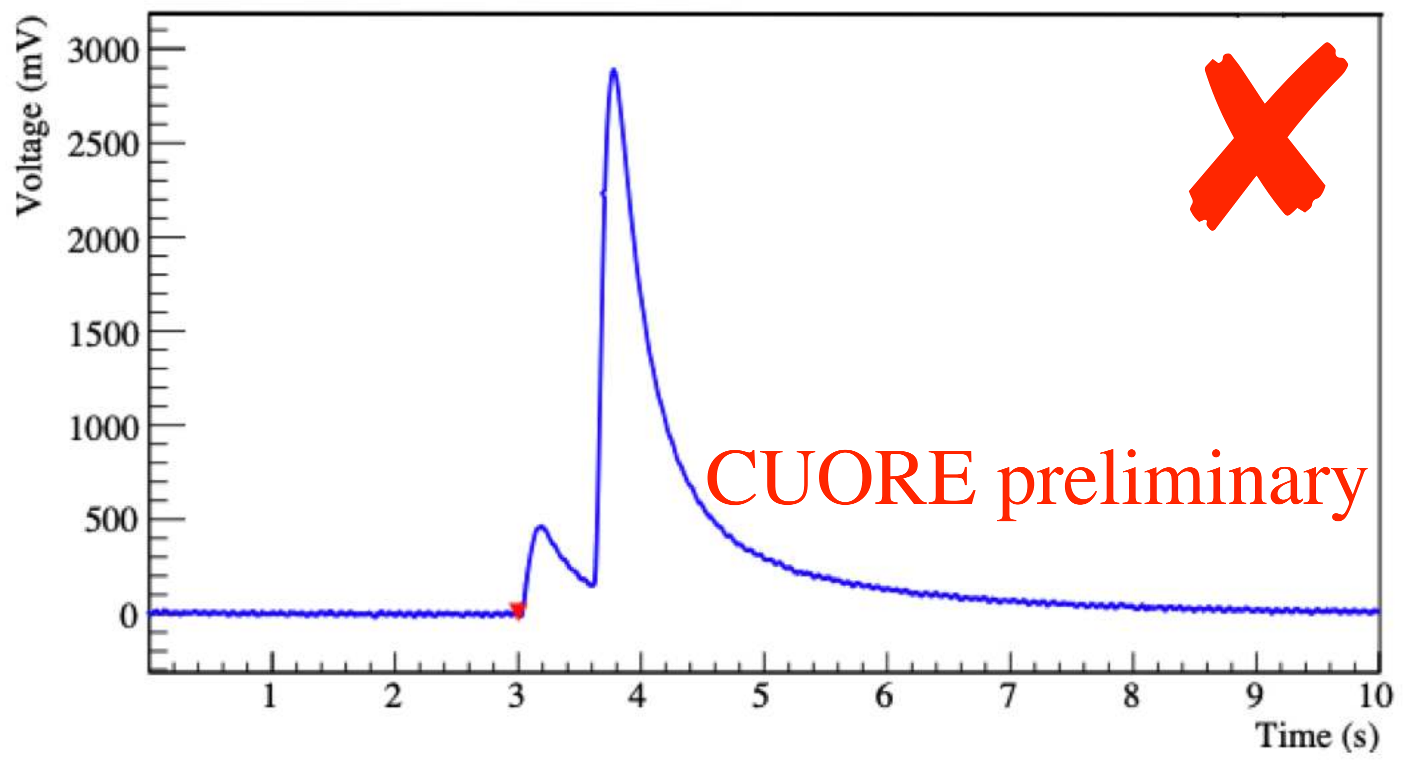
Coincidences

Data selection to detect $0\nu\beta\beta$

Anti-coincidence (AC) selection

From MC simulations, we expect ~88% of $0\nu\beta\beta$ events to release all the energy in the same crystal in which the decay occurred. Thus, we reject multi-site events, i.e. events with *Multiplicity* > 1





arxiv:2510.25720

Pulse shape discrimination (PSD)

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

ROI blinding

To avoid biasing our result, we exchange events from ^{208}Tl line at 2615 keV with events at the ^{130}Te $0\nu\beta\beta$ Q-value

Analysis efficiency evaluation

This is the strategy we adopted for the 2nd tonne · yr (**2nd TY**) data

Detector response

ROI model and blinded fit

Data unblinding and fit