The CUORE experiment: *current status and road ahead*

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on behalf of the CUORE collaboration
Università degli studi di Genova - INFN Genova
TAUP 2025 - 25 August 2025

CUORE

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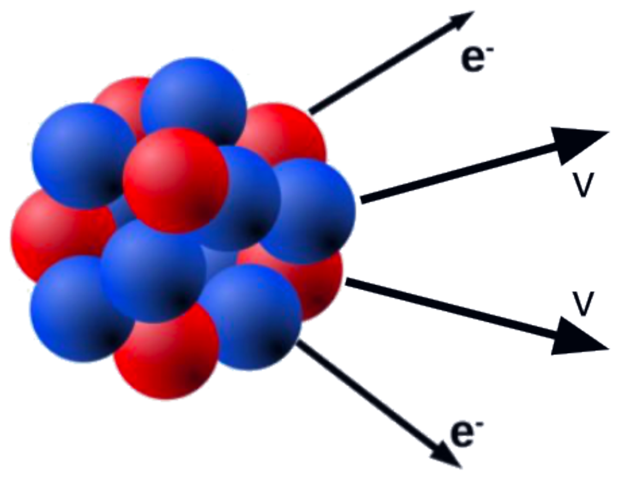
INFN Istituto Nazionale di Fisica Nucleare

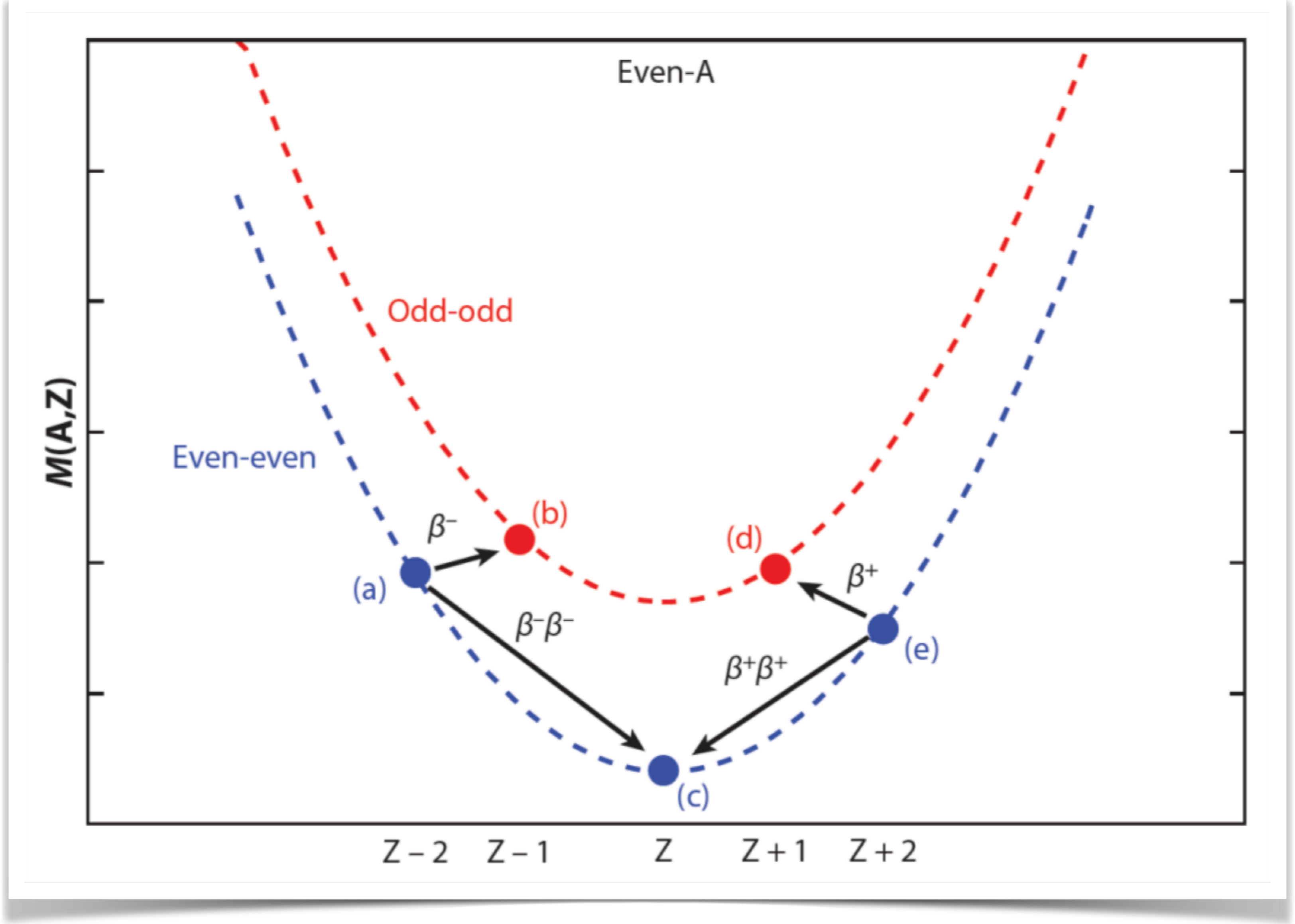
Università di Genova

Neutrino physics & double beta decay

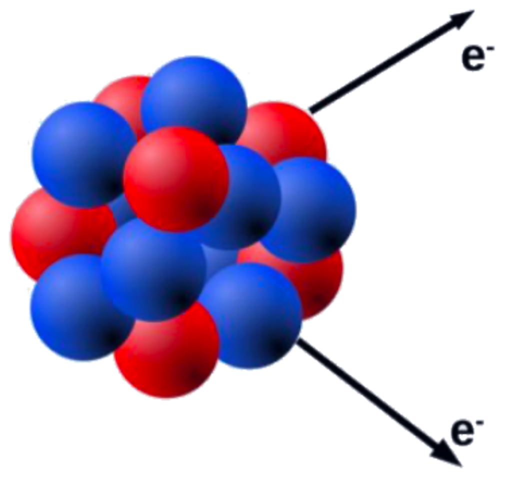
Neutrinos among the most elusive yet fundamental particles studied in a wide range of energies and experiments: double beta decay leads us to explore the MeV energy region

$2\nu\beta\beta$





$0\nu\beta\beta$



- 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

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What's captivating about neutrinoless double beta decay

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

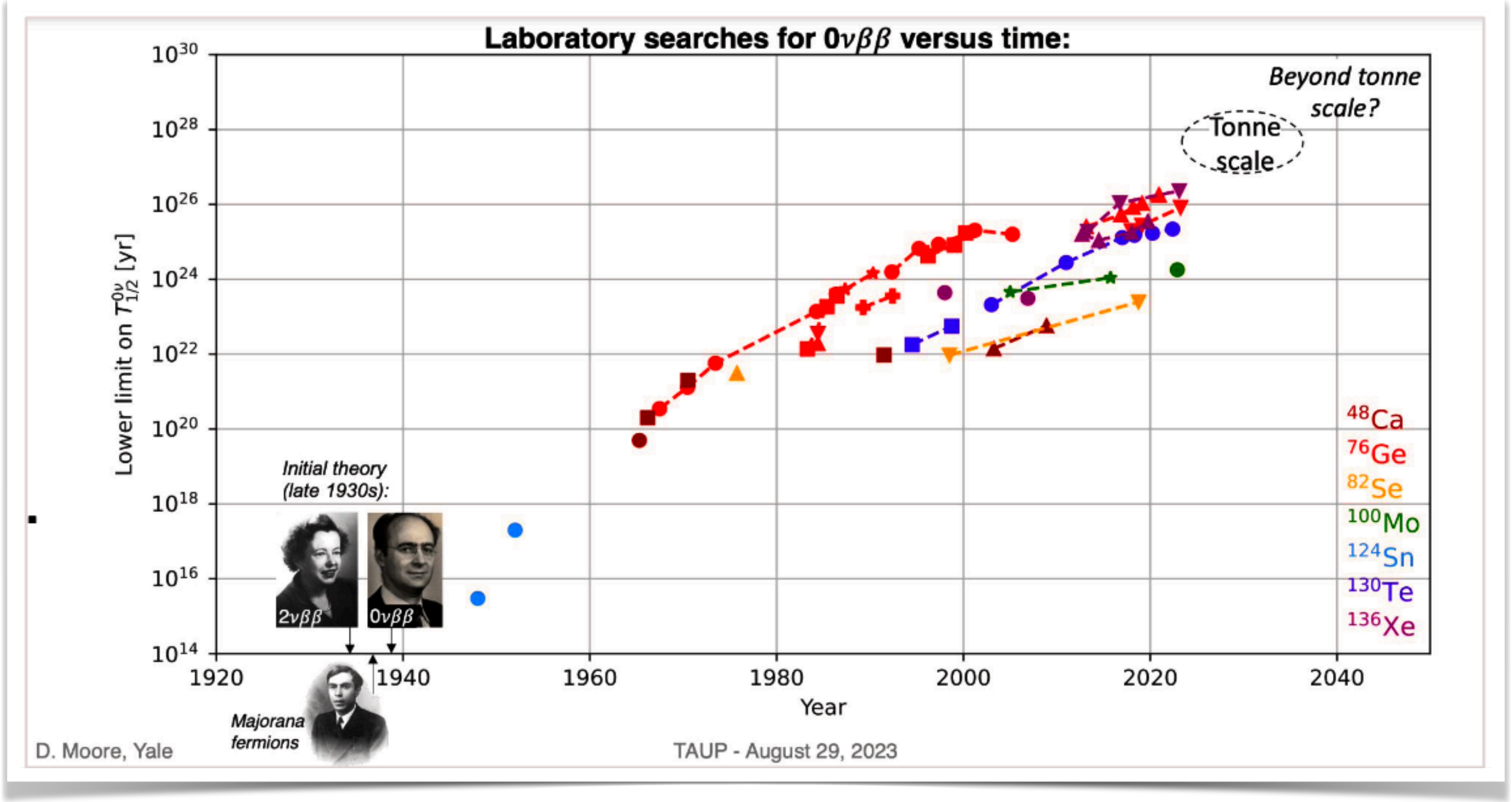
$$\Gamma_{0\nu\beta\beta} \propto G_{0\nu}(Q,Z)\left|M_{0\nu}\right|^2 \frac{\left|< m_{\beta\beta} >\right|^2}{m_e^2}$$

Phase space factor

Nuclear matrix element

Effective Majorana mass

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



D. Moore @TAUP2023

- 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

$0\nu\beta\beta$ decay: experimental search and CUORE

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

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

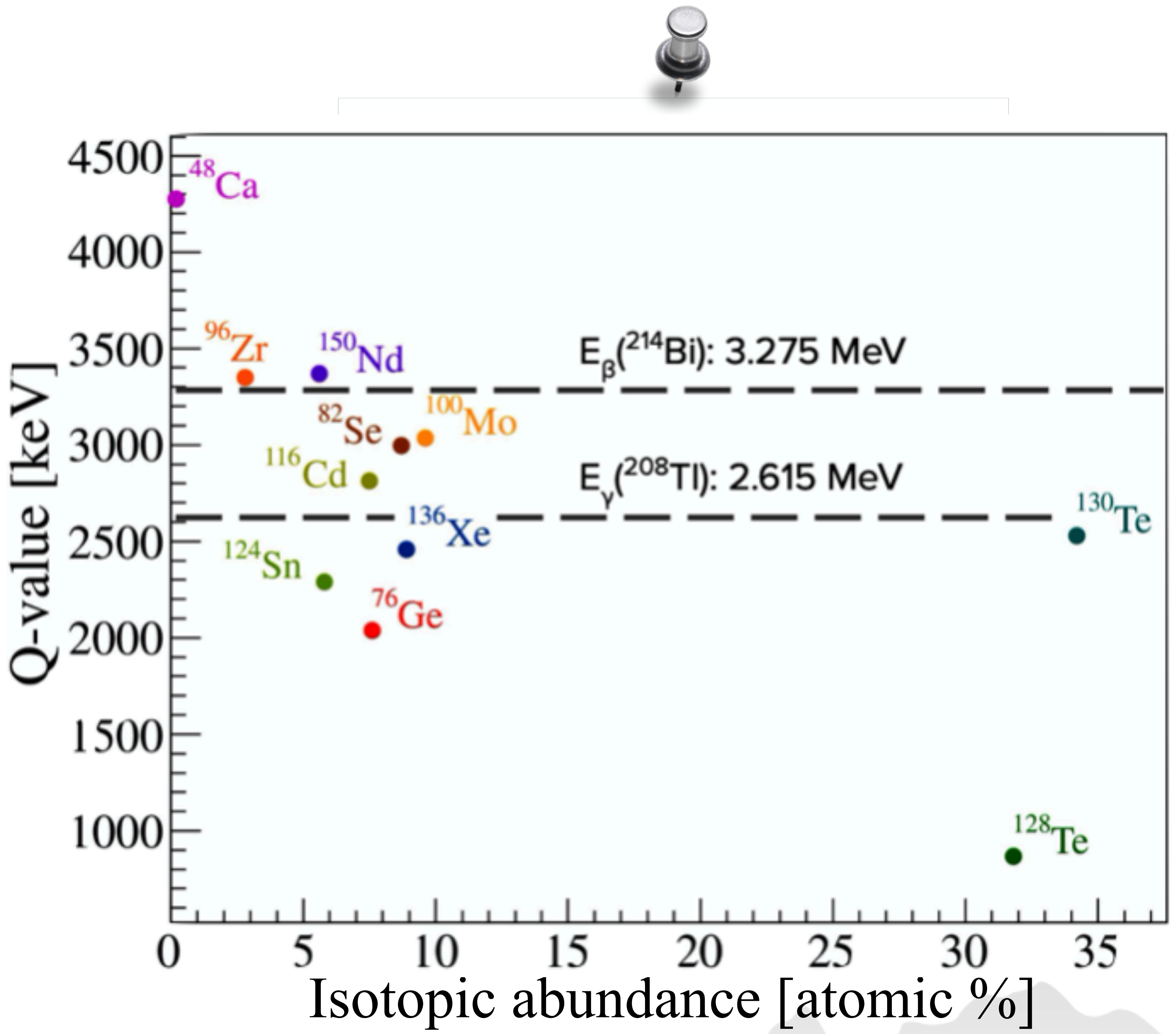
detection efficiency
- source ≡ detector
- total efficiency (all cuts) ~93%

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

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



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

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

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The CUORE experiment in a nutshell

Cryogenic Underground Observatory for Rare Events

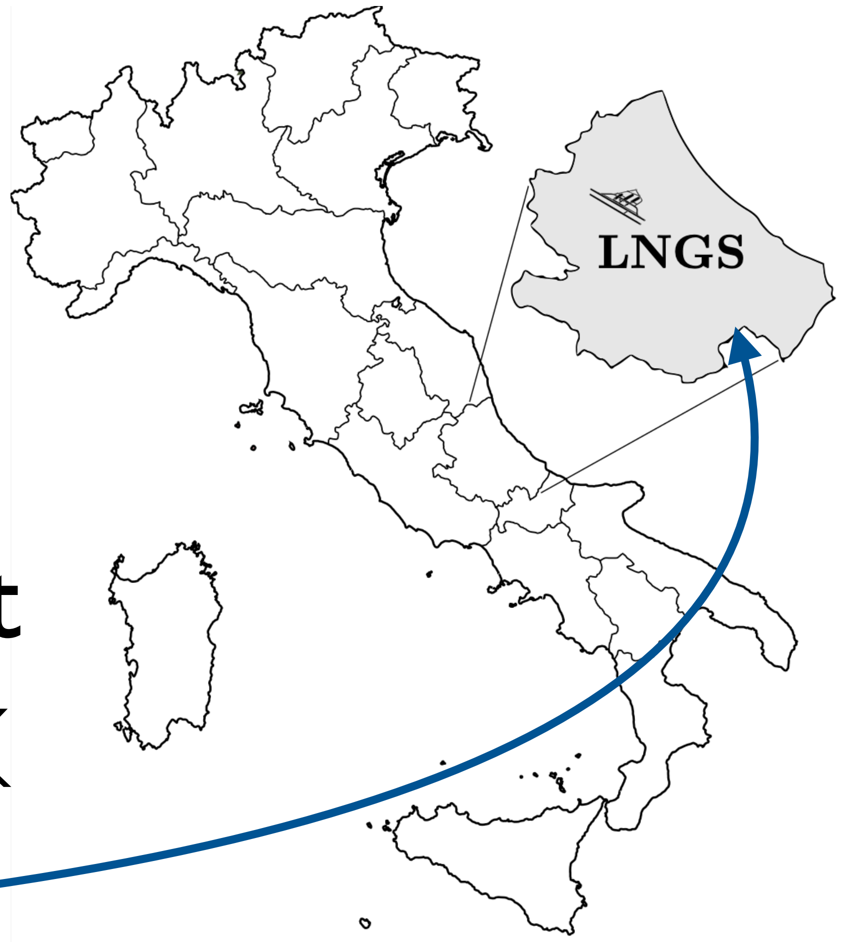
- Primary goal: search for $0\nu\beta\beta$ decay of ^{130}Te

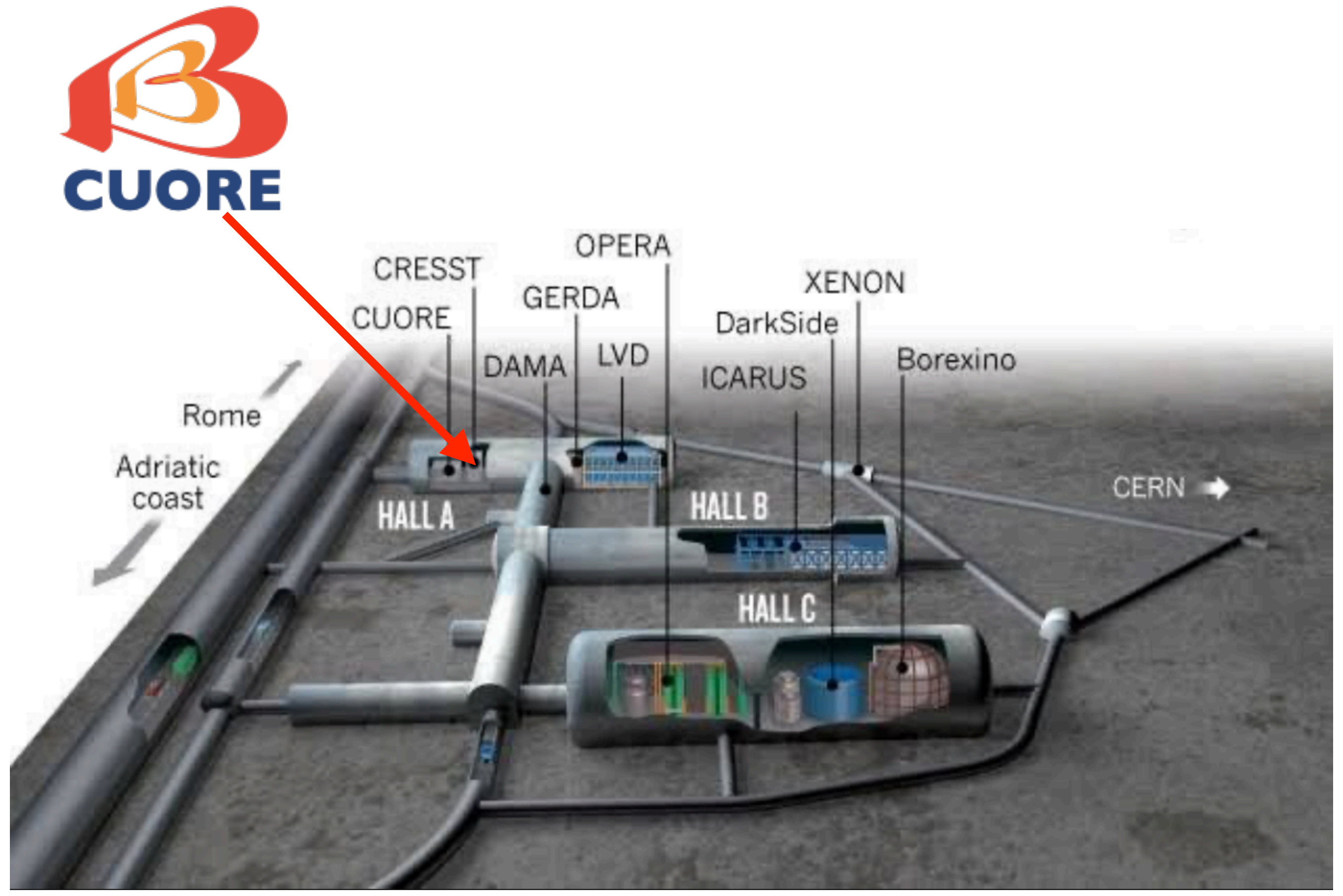
  Eur. Phys. J. C77 (2017), 532

- **Largest cryogenic-calorimeter detector ever built**

  19 towers of 13 floors of 4 crystals stably $\lesssim$20 mK

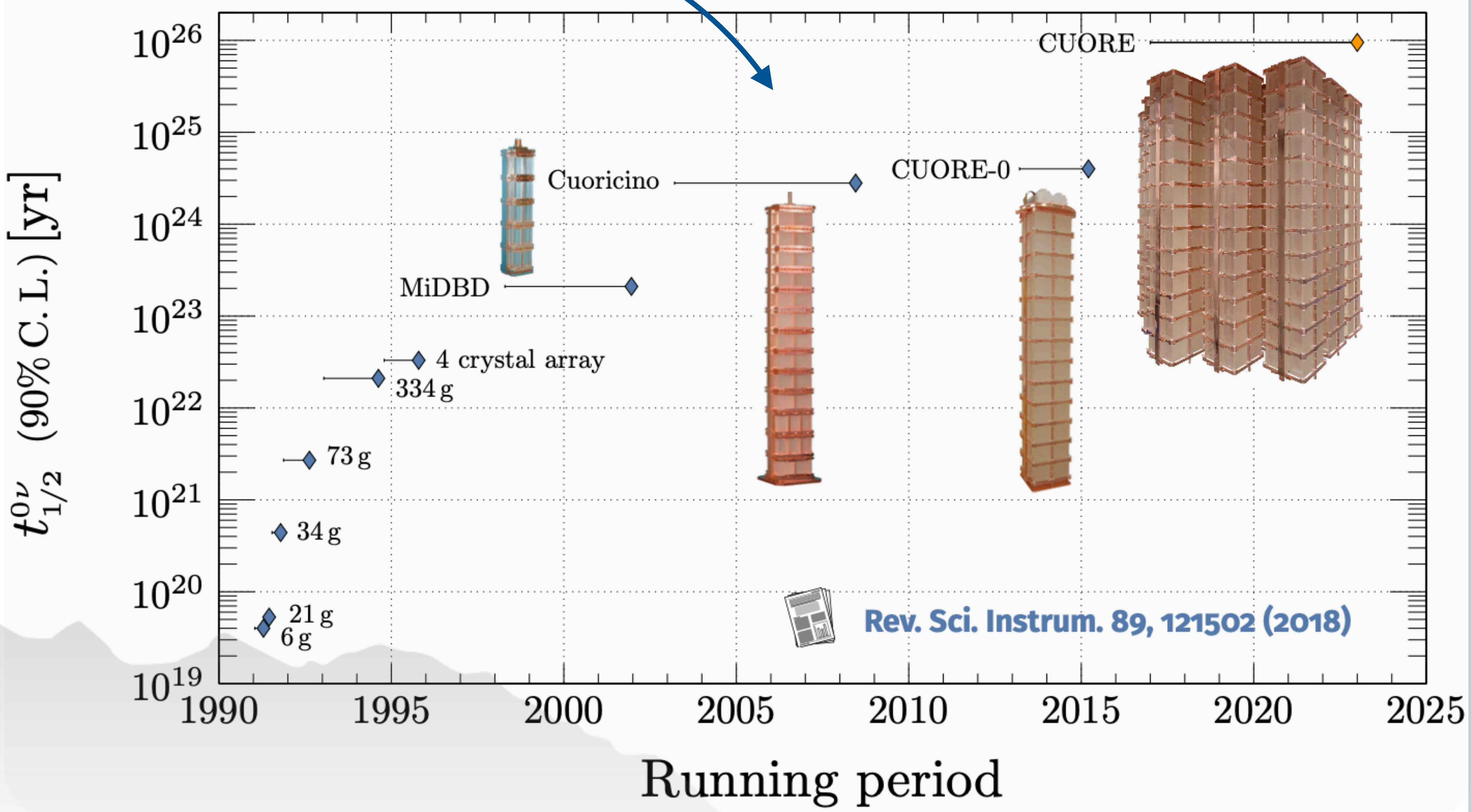
- **Underground** at the **LNGS** (Abruzzo, Italy)





Adv. in High En. Phys. 2015, 879871

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



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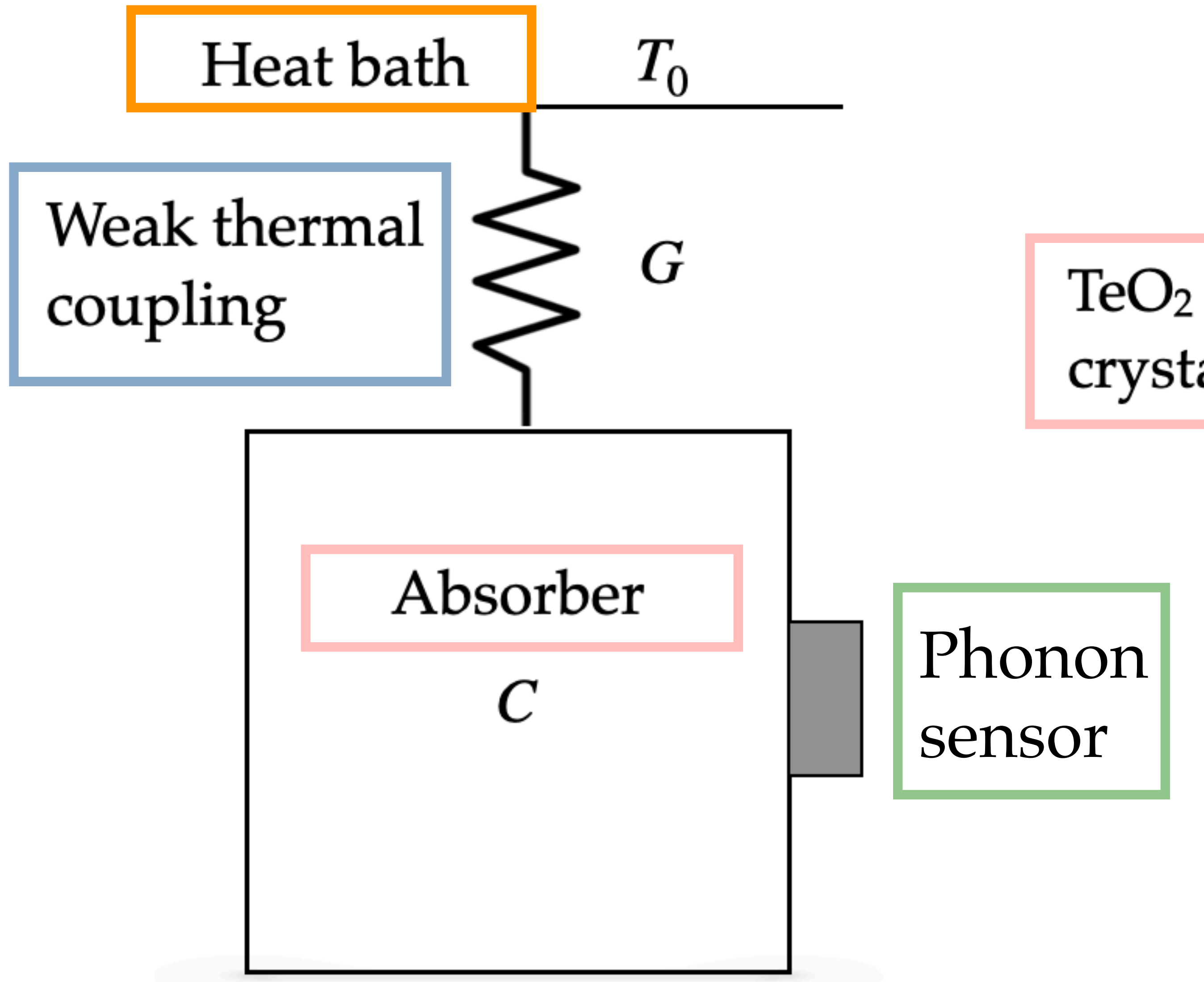
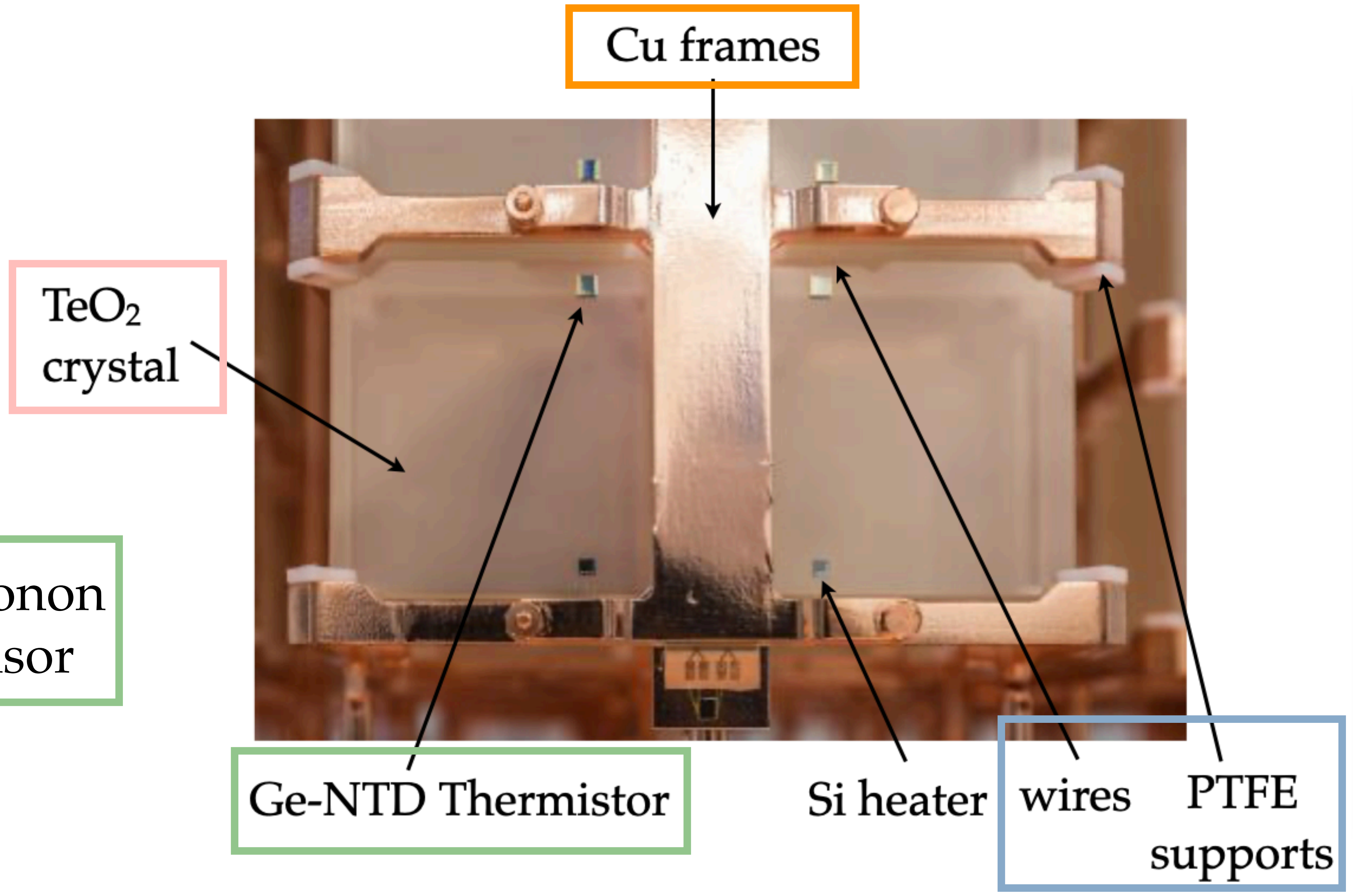
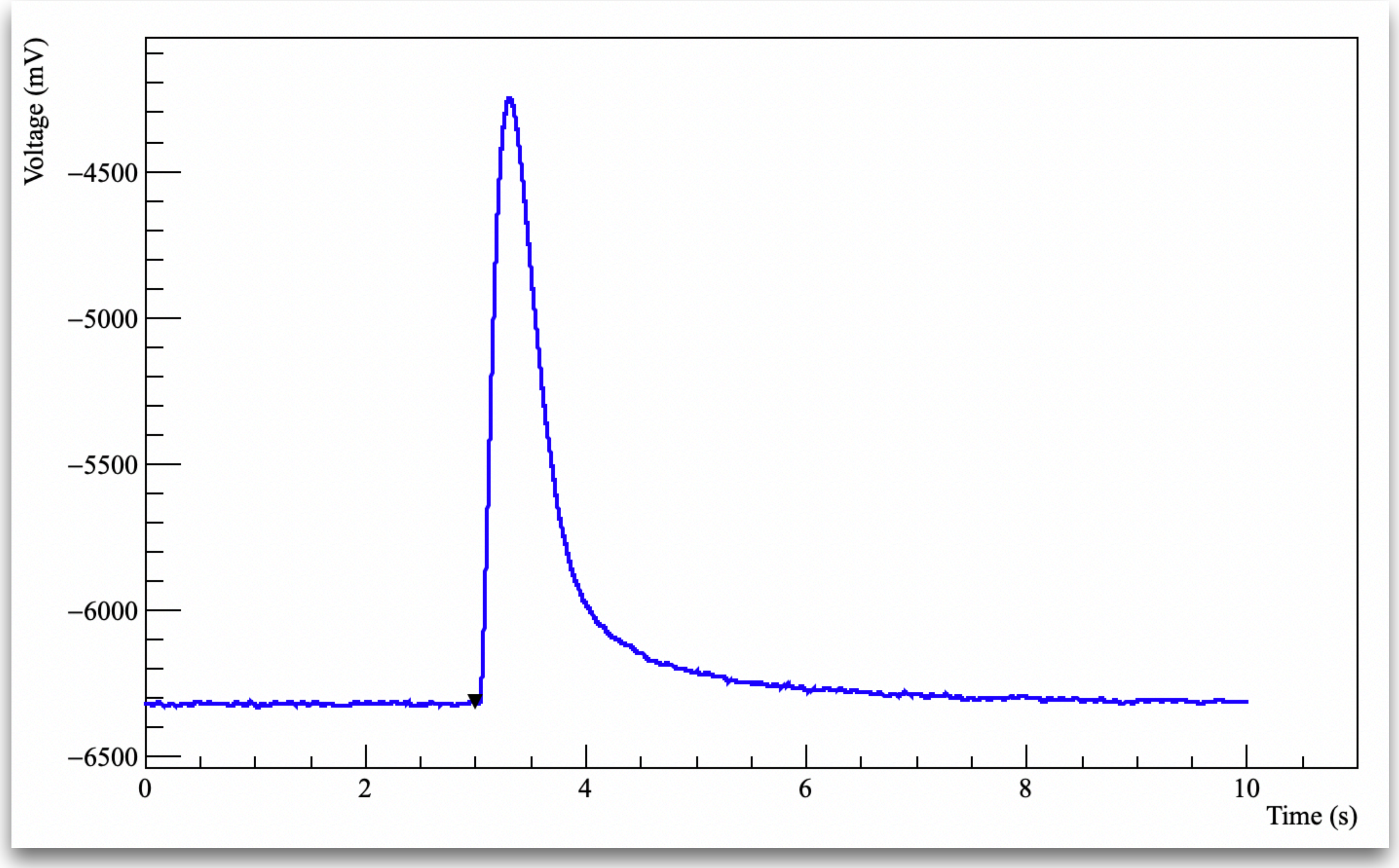
Neutrinoless double beta decay with cryogenic calorimeters

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)



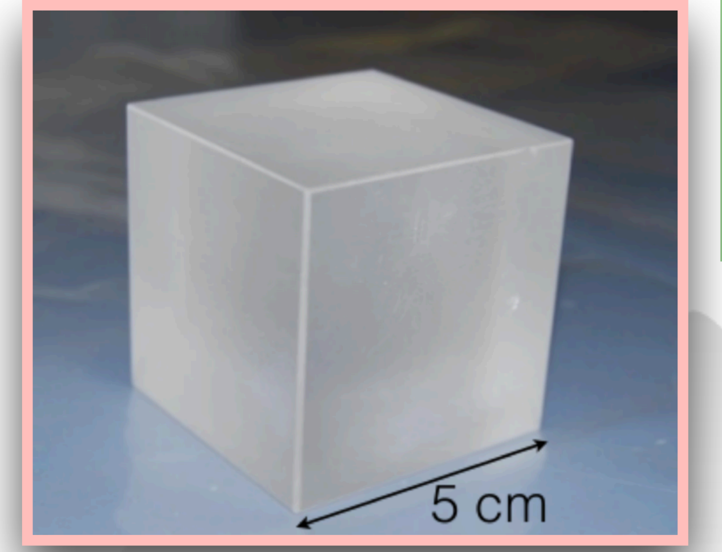




TeO_2 crystal

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

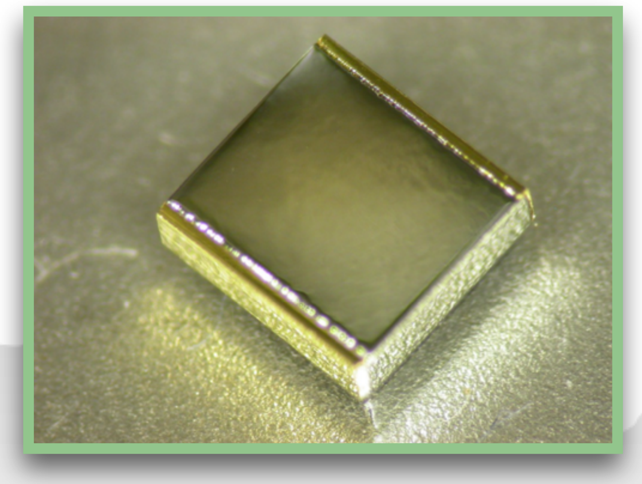
C≈ nJ/K



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**

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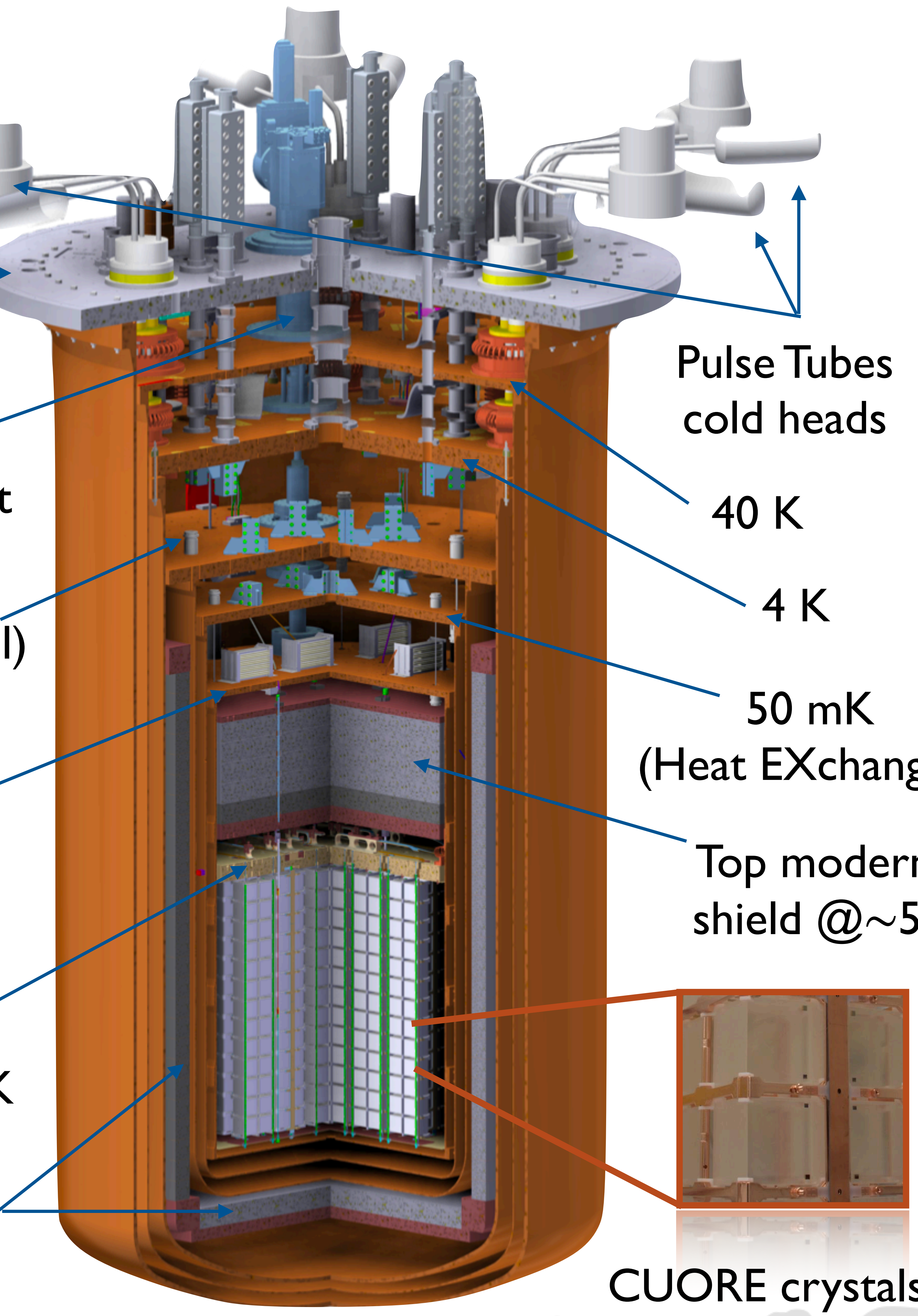
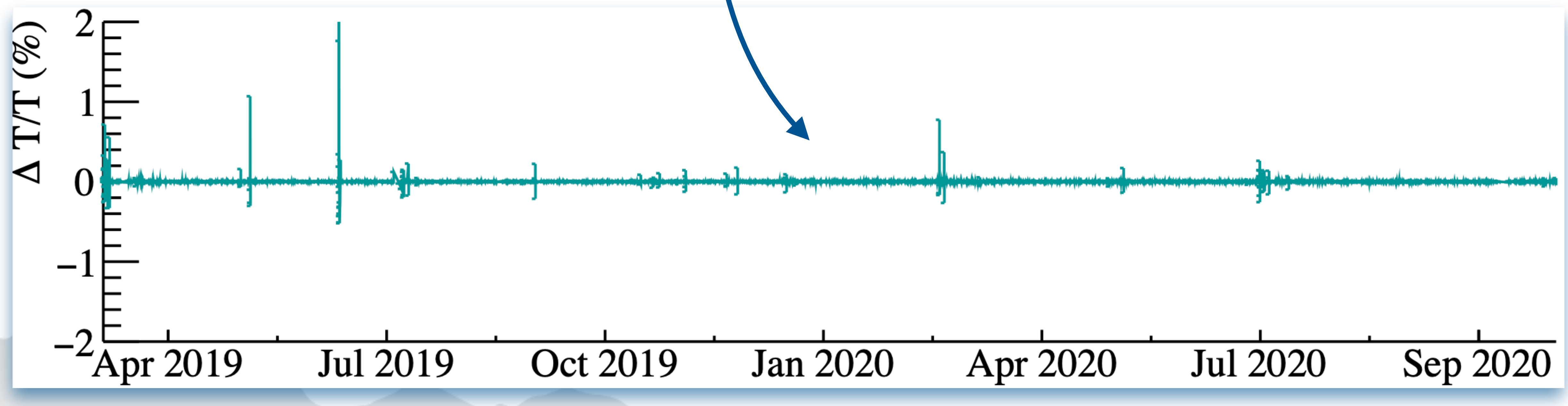
The challenges - part 1: cryogenic infrastructure



- 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**



Cryogenics 102 (2019) 9-21

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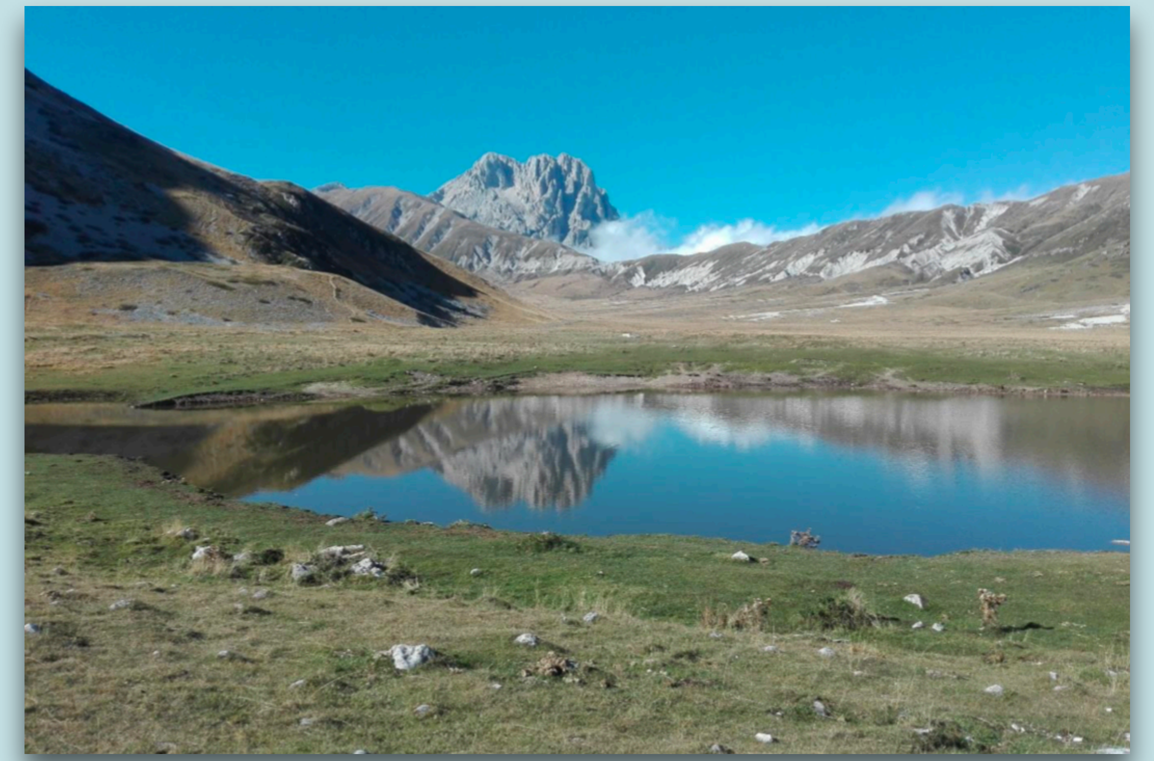
Nature 604, 53-58 (2022)

The challenges - part II: minimizing background

LNGS *natural* shielding



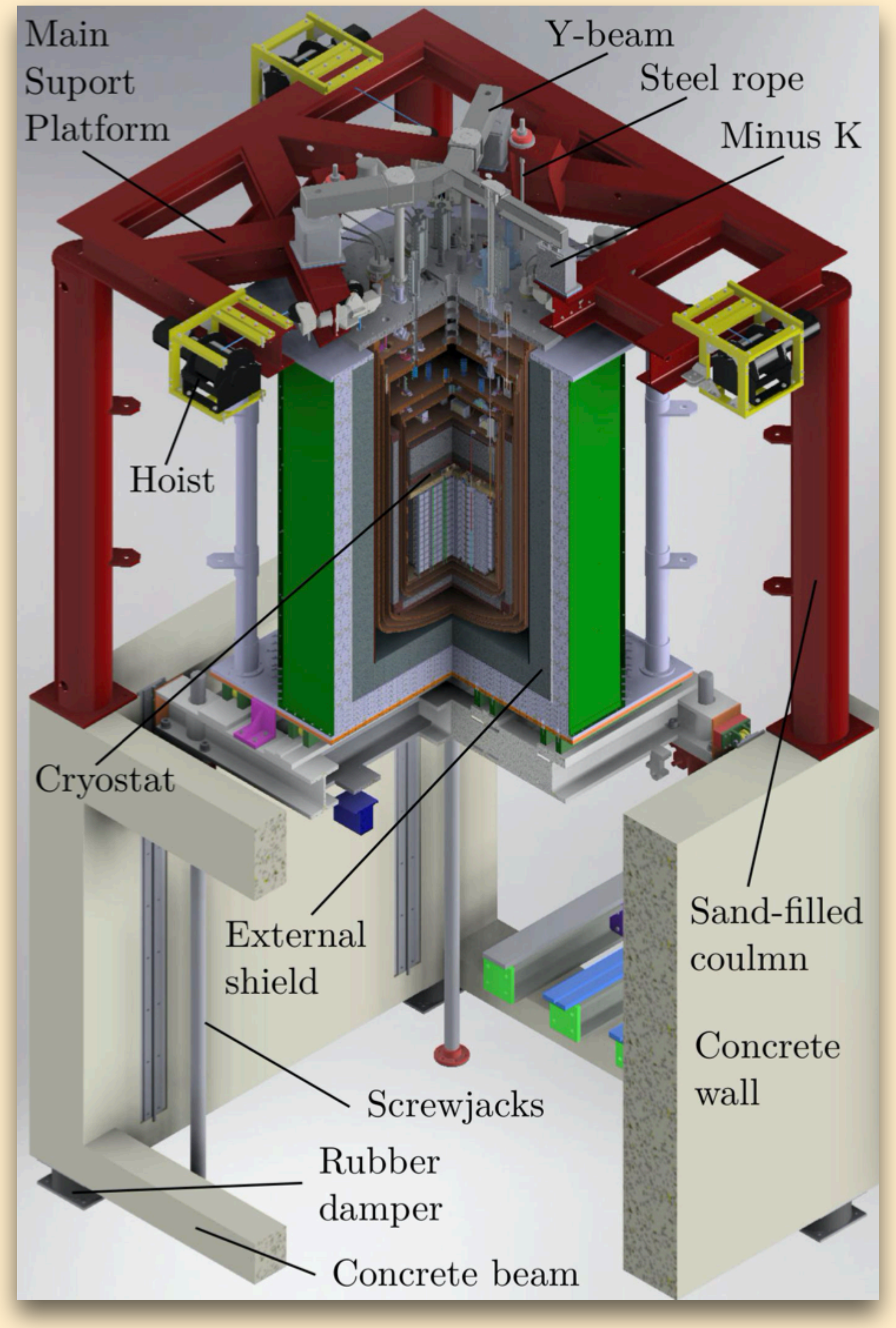
~3600 m water-equivalent rock overburden: cosmic rays flux reduced of six orders of magnitude compared to the surface

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

Astropart Phys. 34 (2010) 18-24

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

External shields



Cryogenics 102 (2019) 9-21

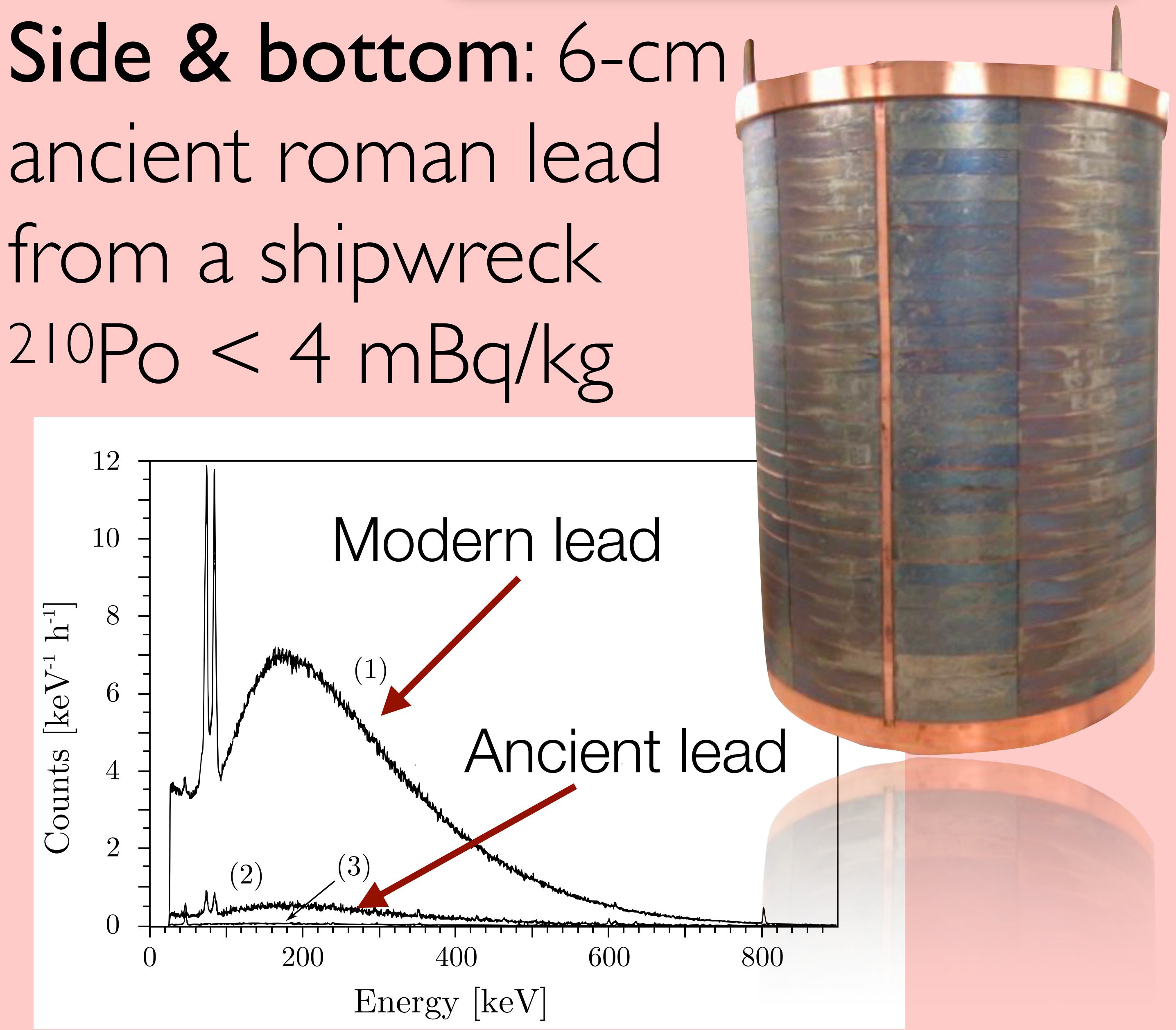
- From γs: 25-cm thick Pb layer
- From neutrons: 20-cm layer in polyethylene + H_3BO_3 panels

Internal lead shields

Top: 30-cm modern lead

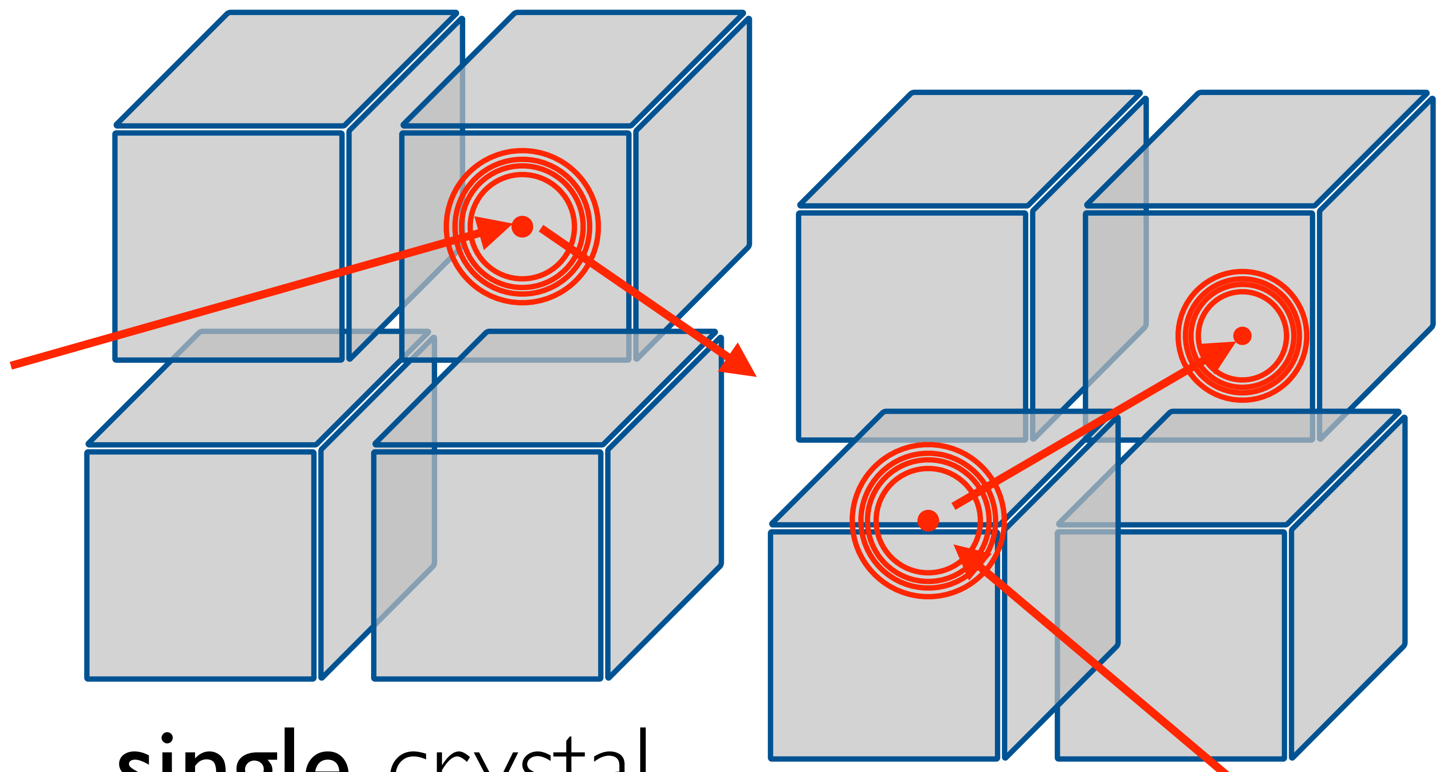
Side & bottom: 6-cm ancient roman lead from a shipwreck

^{210}Po < 4 mBq/kg



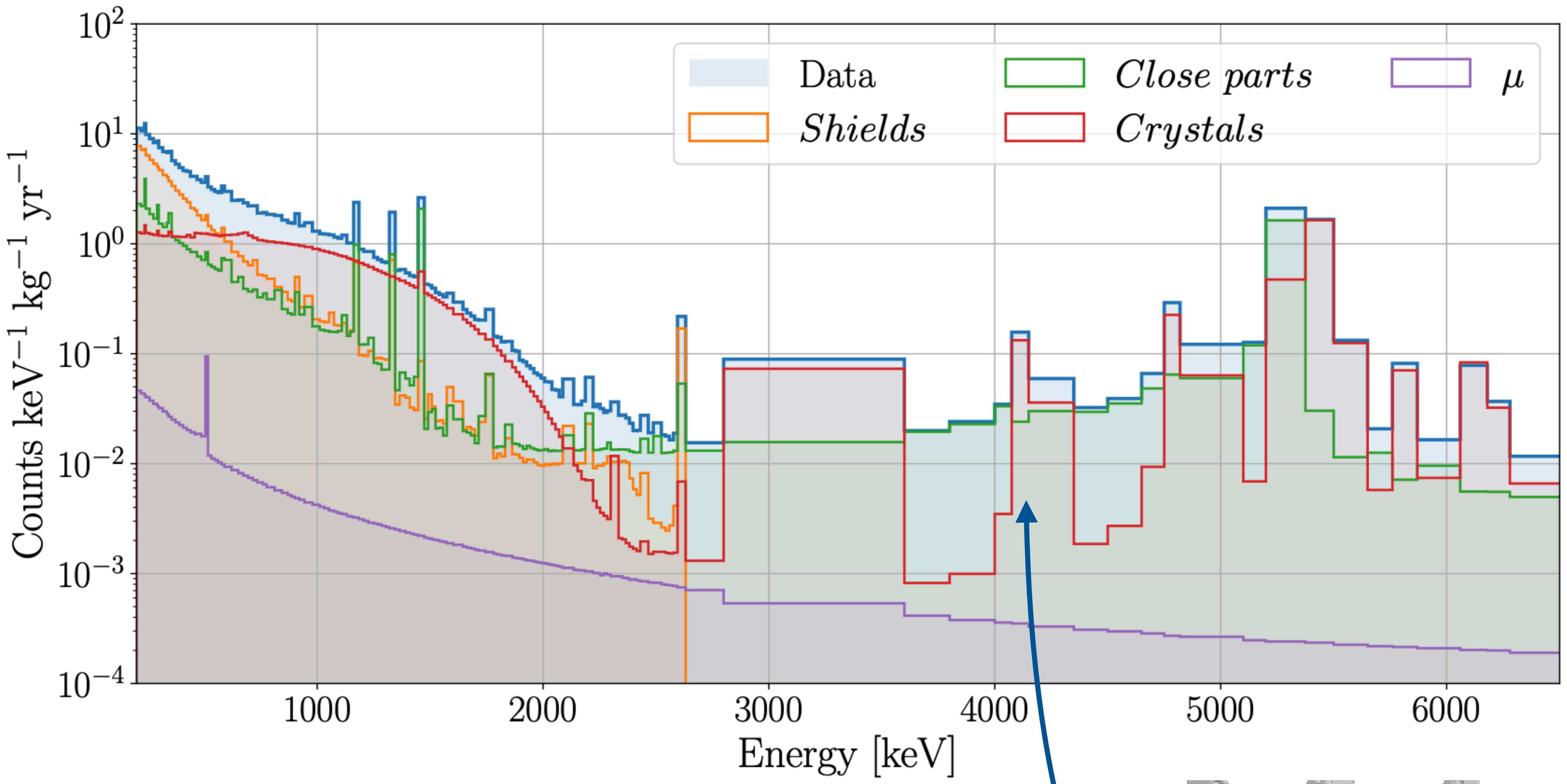
Nucl. Instrum. Meth. B 142, 163 (1998)

The challenges - part II: modeling (leftover) background

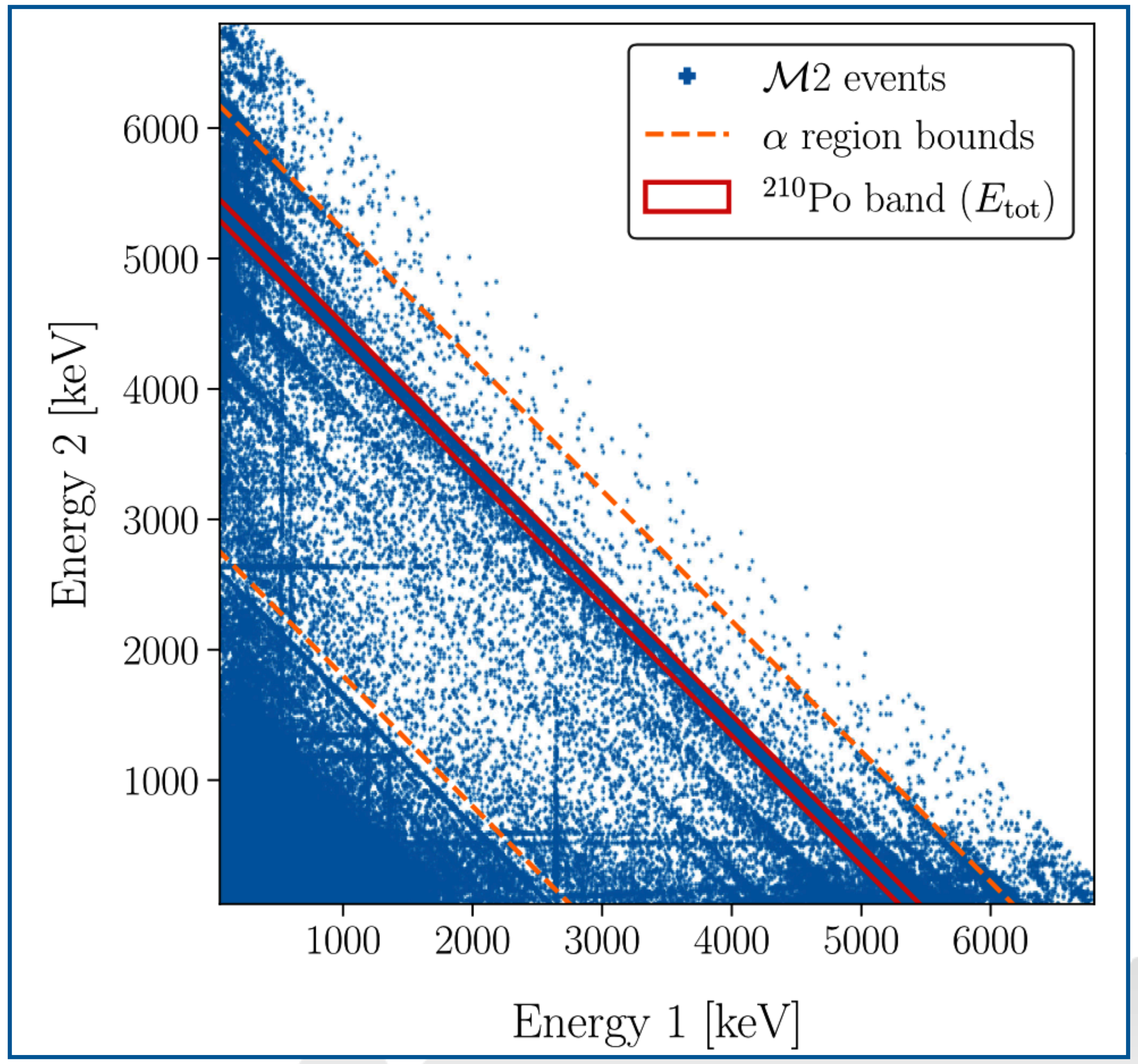


single-crystal   **double**-crystal

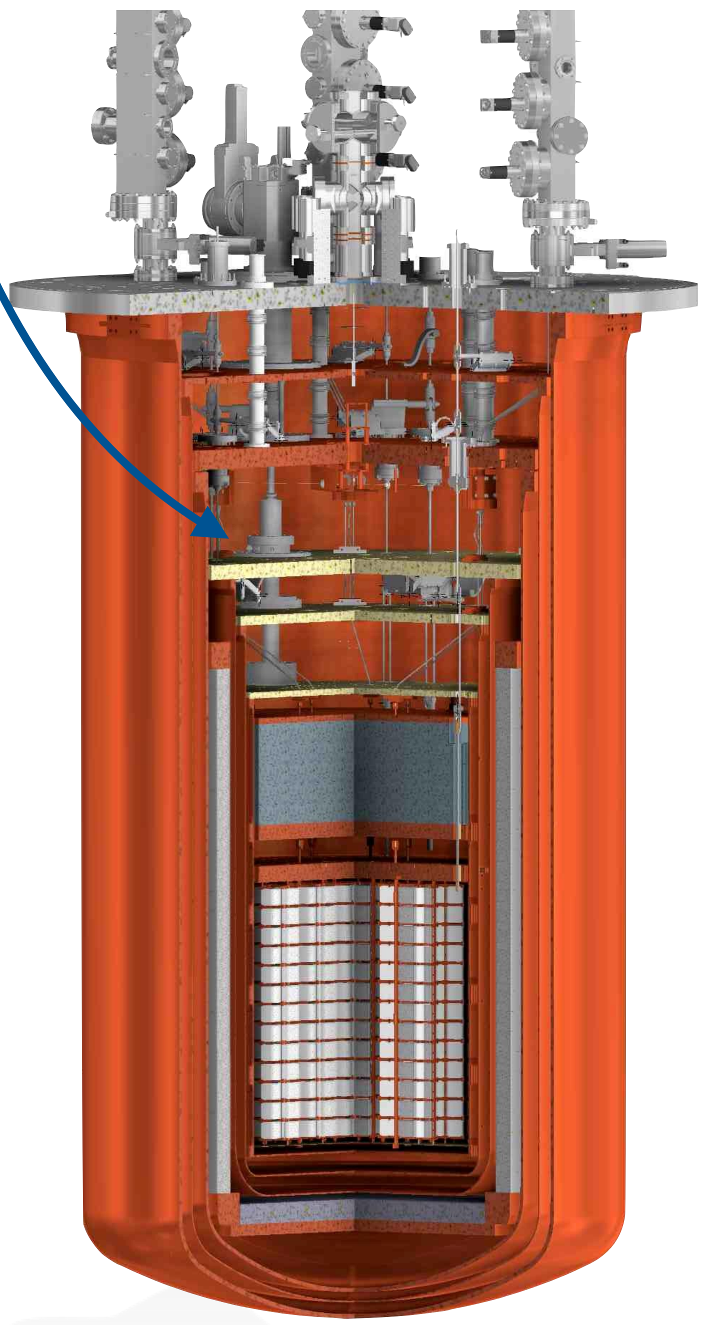
Priors extracted from radioassays and past experiments



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**

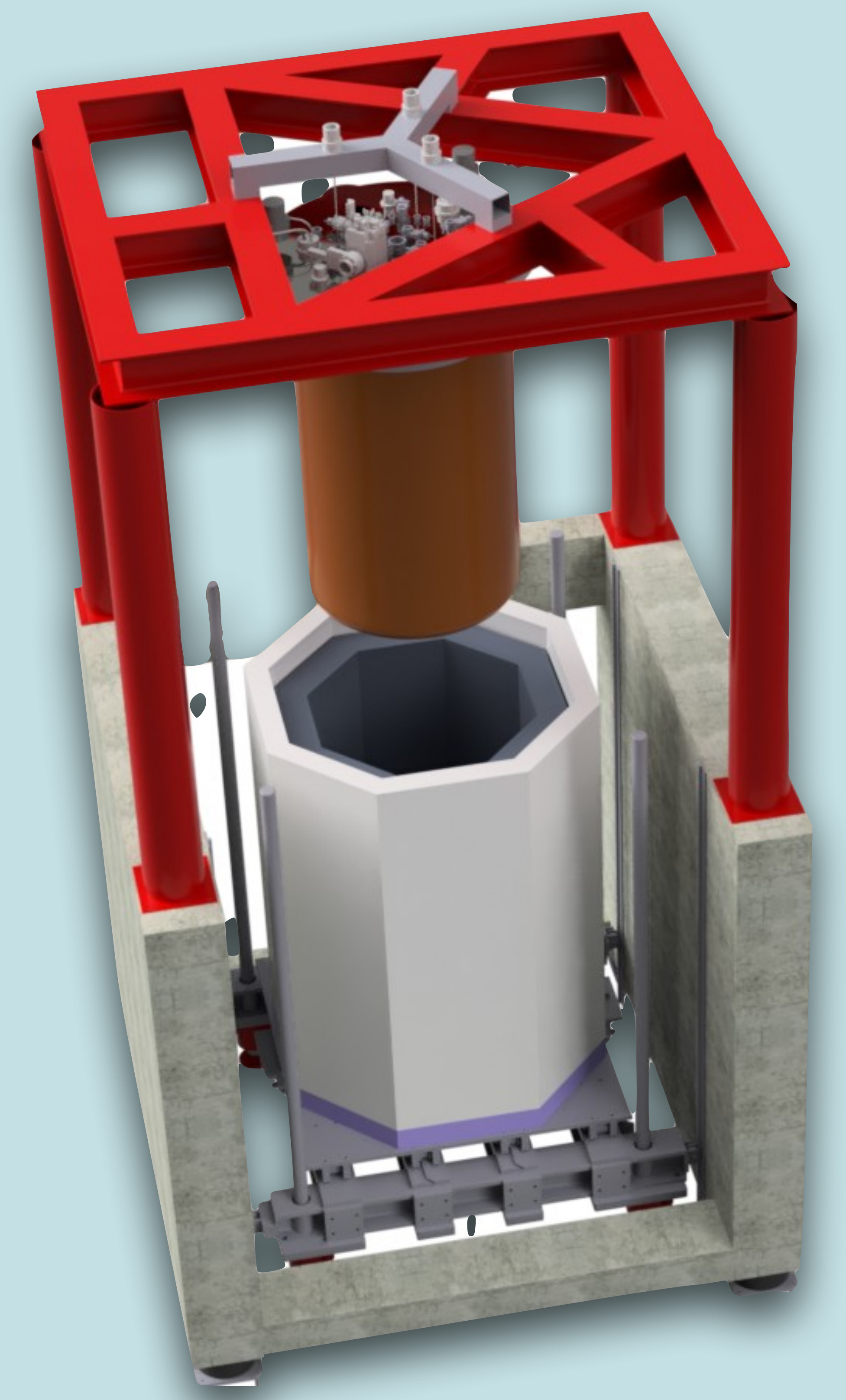


Precise measurement of ^{130}Te $2\nu\beta\beta$ decay
[S. Dell'Oro, 26/08, parallel 3A]

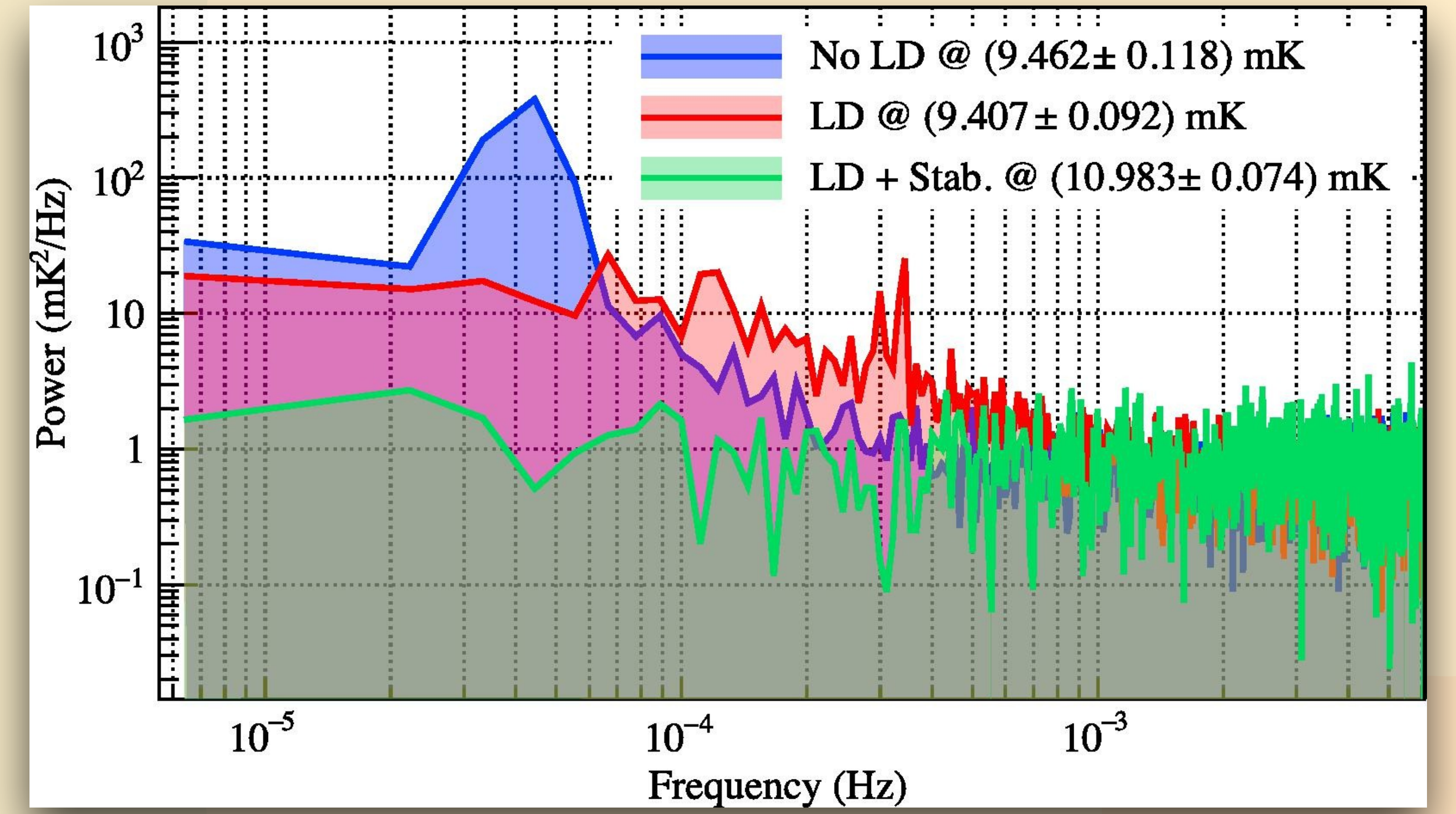
Phys. Rev. D 110, 052003   PRL 135, 082501 (2025)

The challenges - part III: suppressing noise sources

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)

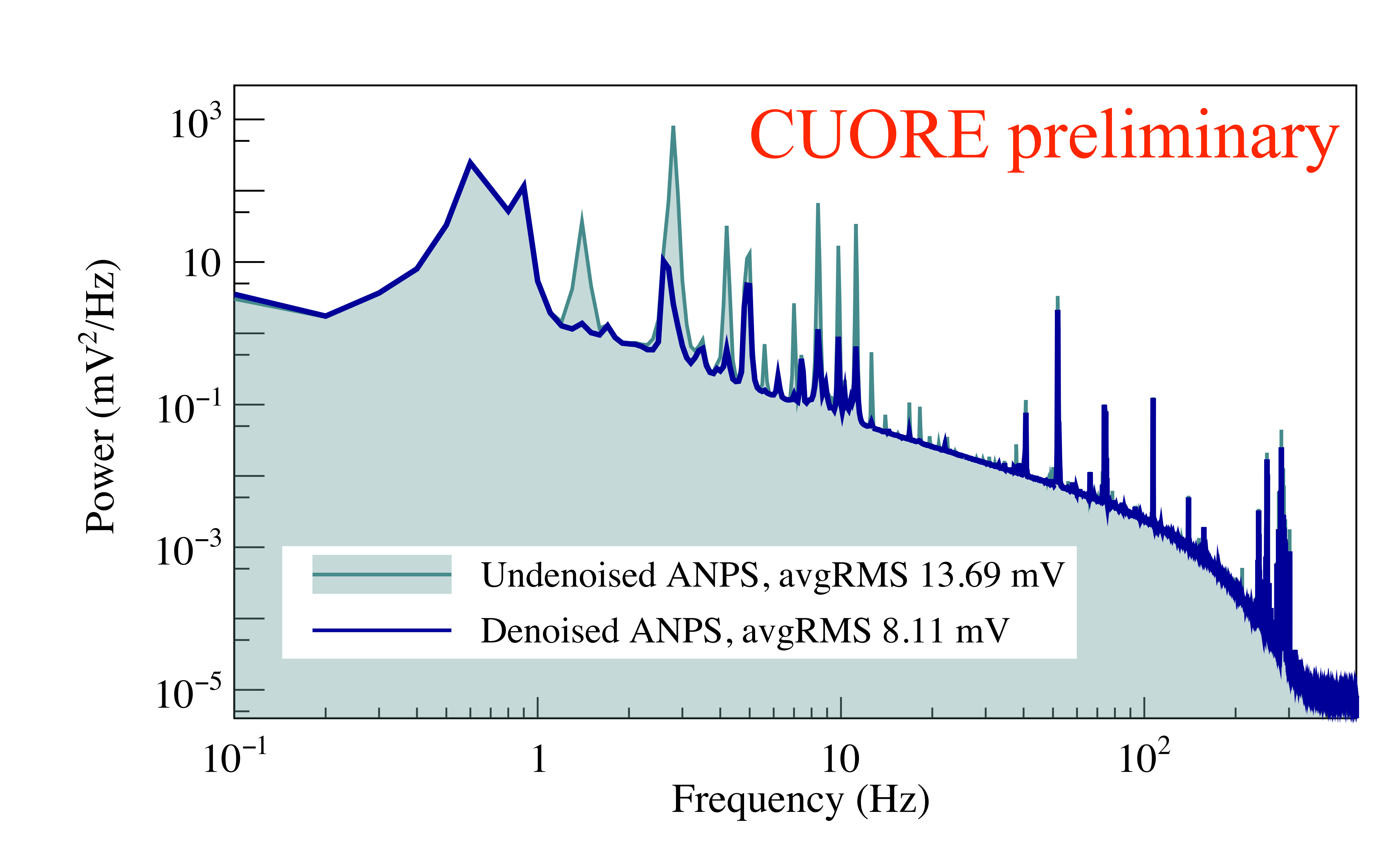
Several **ancillary devices** installed in the CUORE hut to do data denoising and enhance the quality of our data

- seismometers, antennae, microphones and accelerometers

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

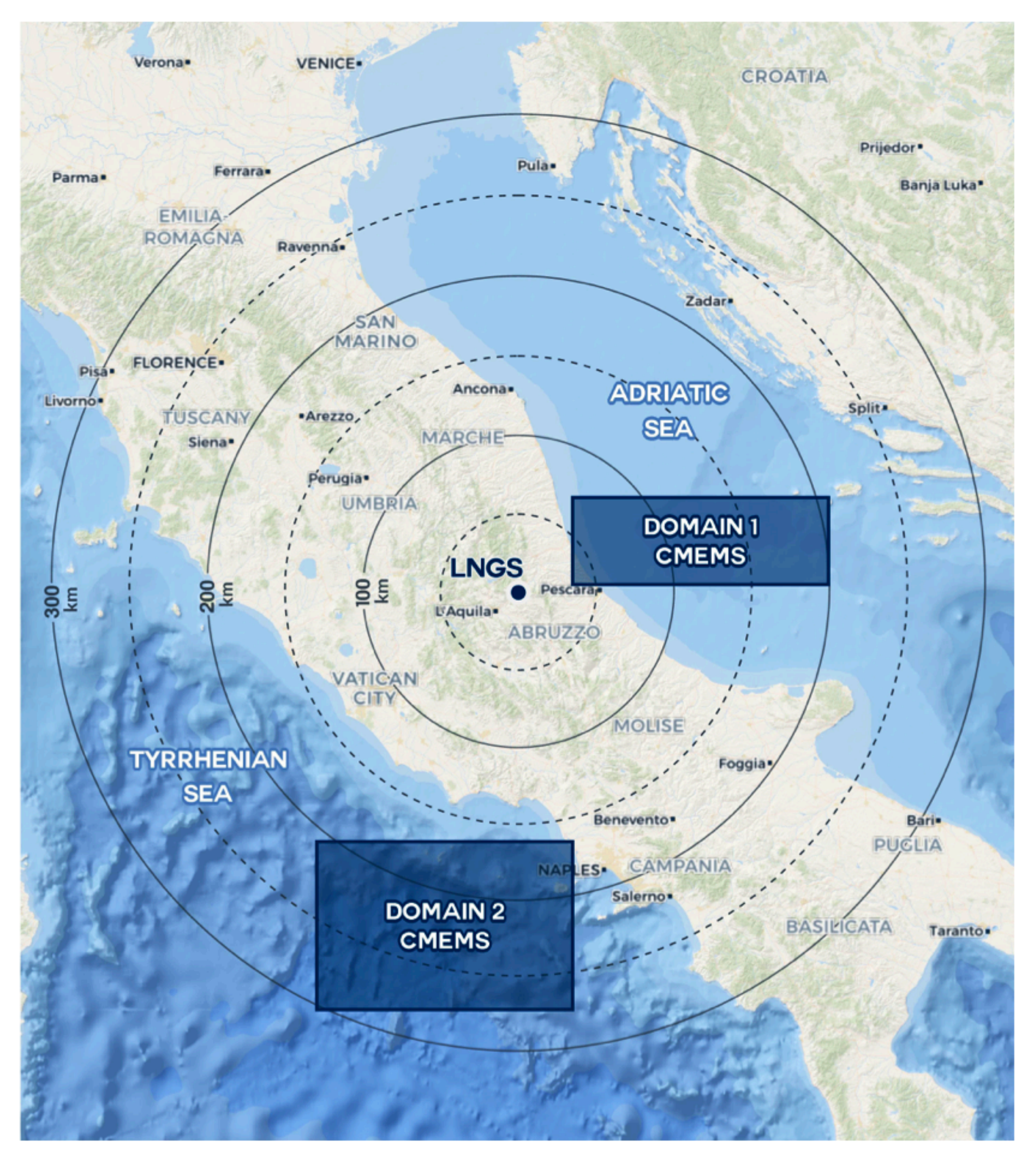
The challenges - part III: modeling (leftover) noise

- **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

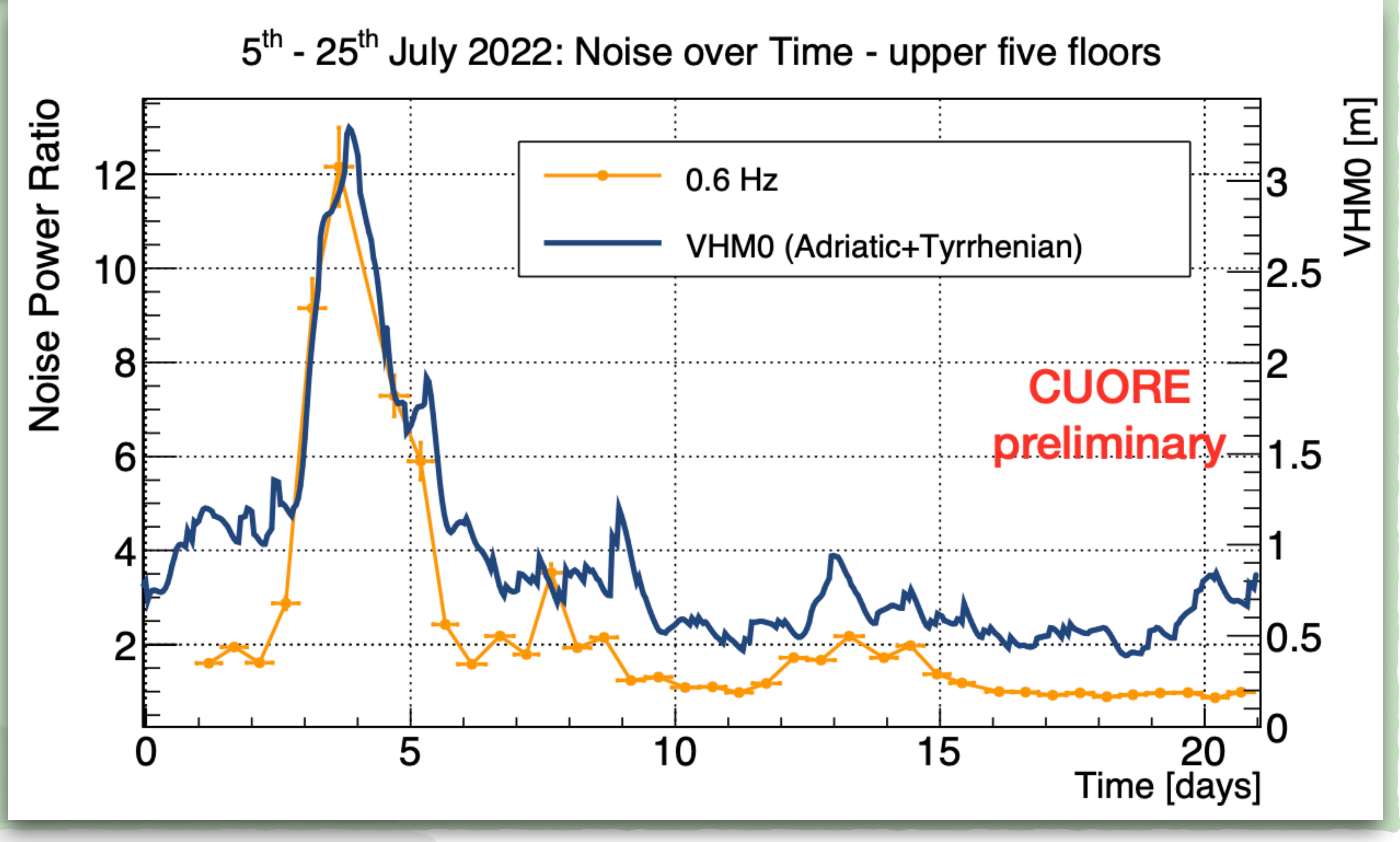
arxiv:2404.04453



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

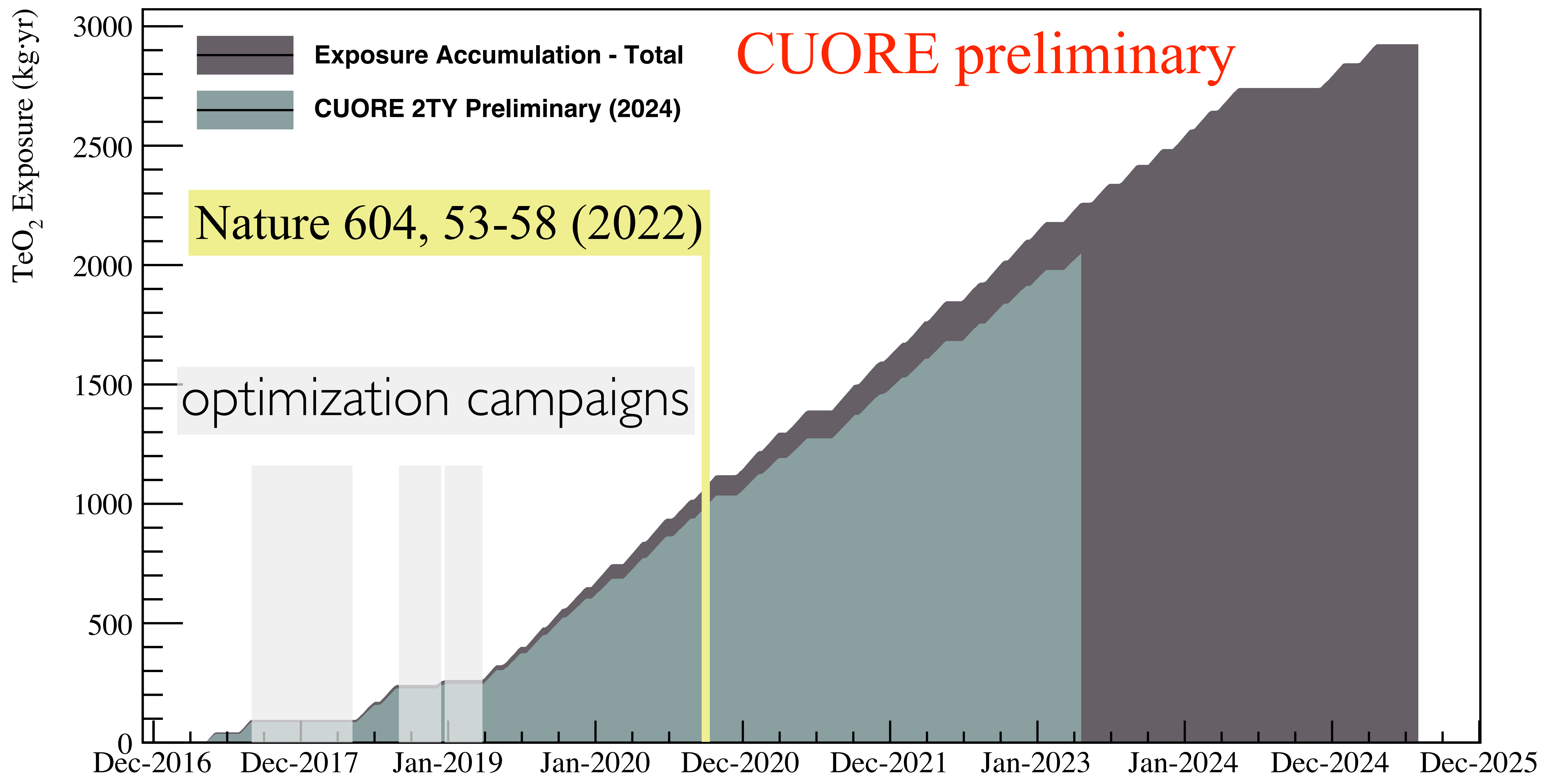
arxiv:2505.09652

- Under investigation solutions to improve cryostat decoupling



The challenges - part IV: stable operation of 1000 detectors

- Data taking started in 2017

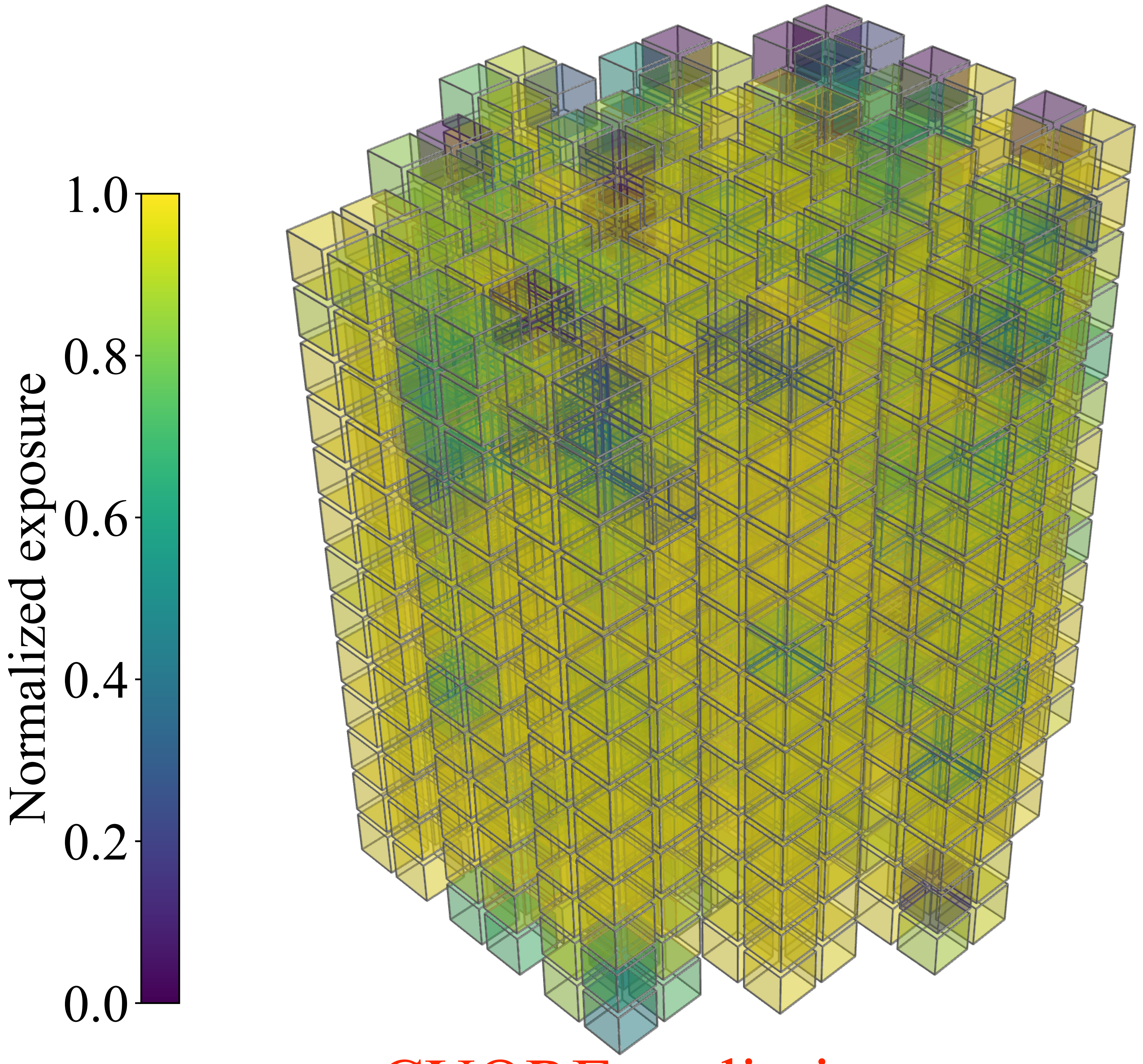


- Data split in *datasets*

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)



TeO$_2$ exposure: **2039.0 kg·yr**

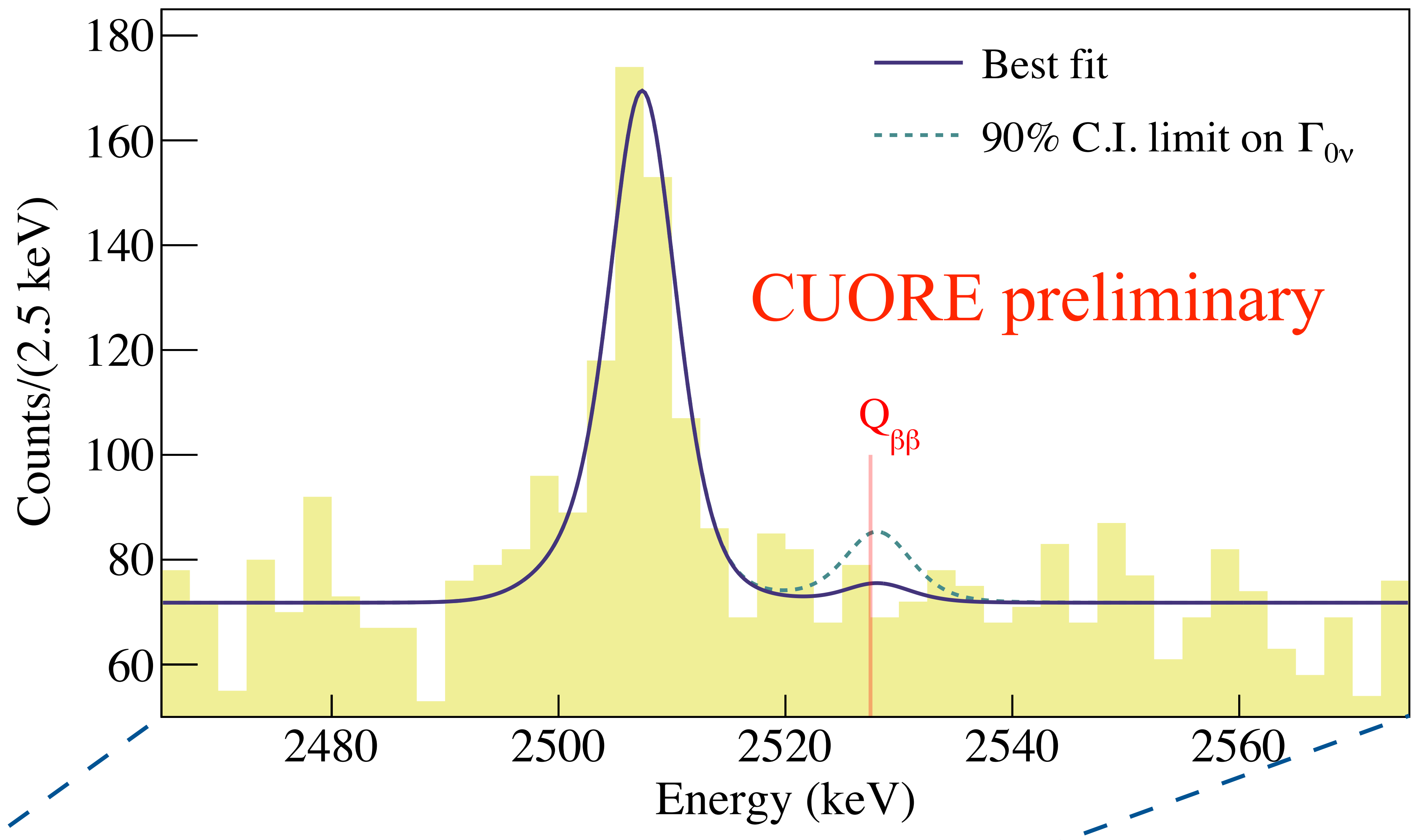
^{130}Te exposure: **567.0 kg·yr**

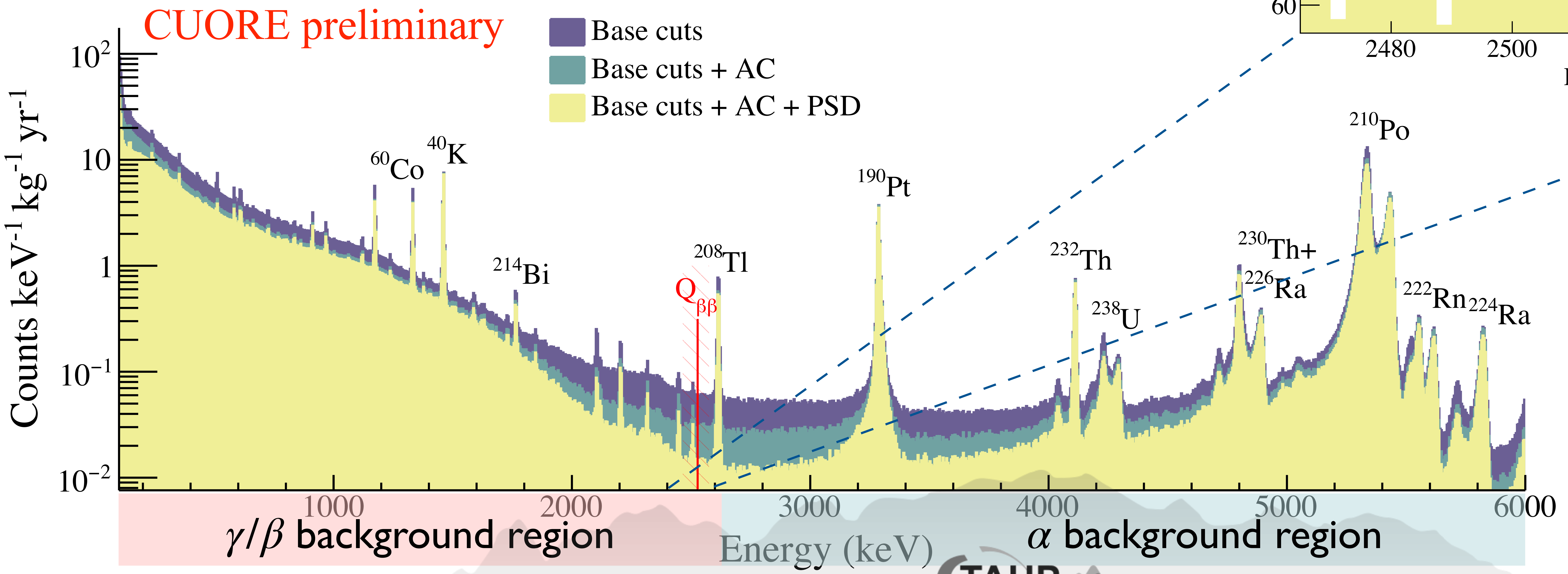
uniformly distributed on the detector

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) %**





Average background index in the ROI

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

$$\left(\text{counts/keV/kg/yr}\right)$$

Pending publication

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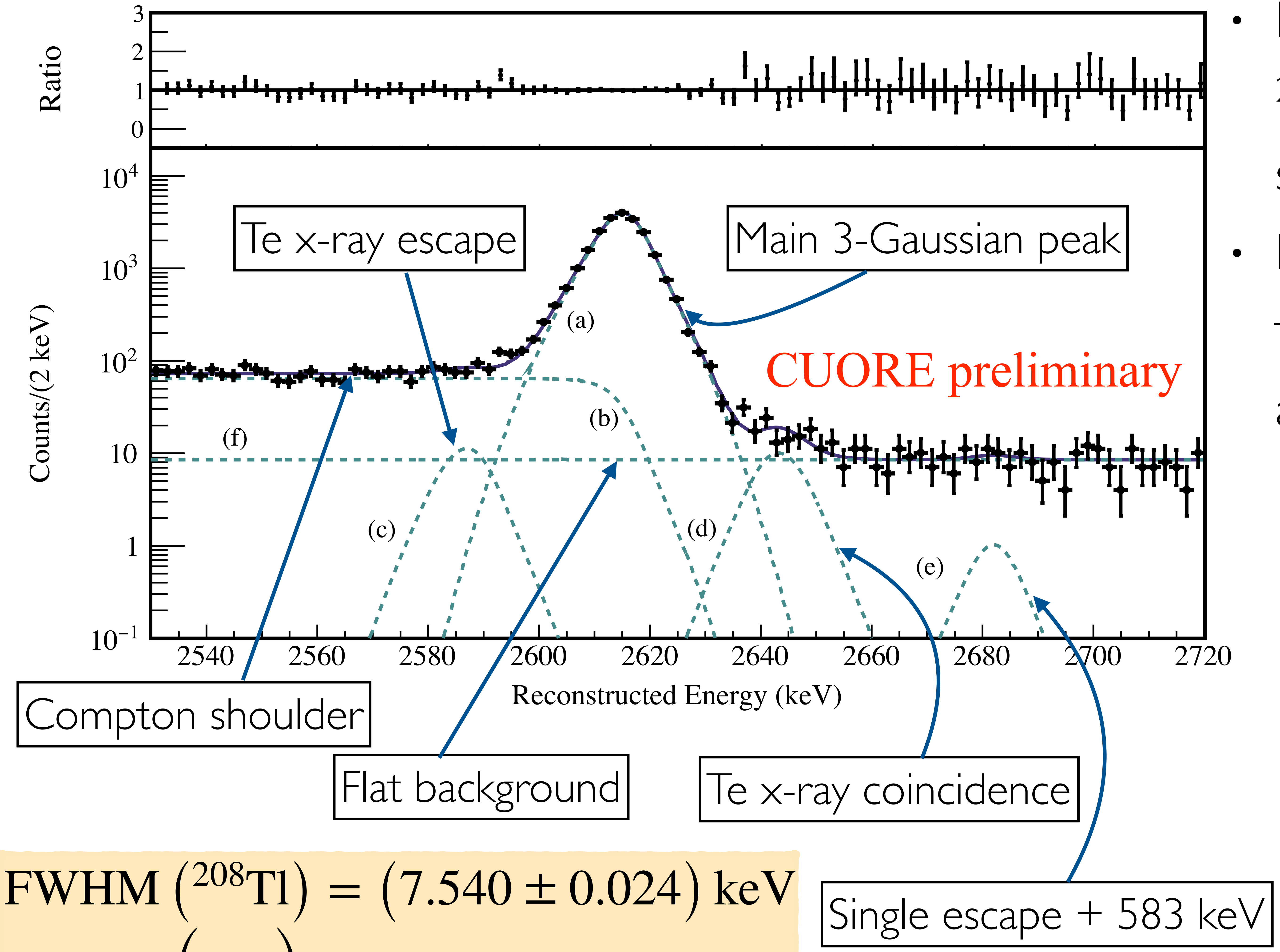
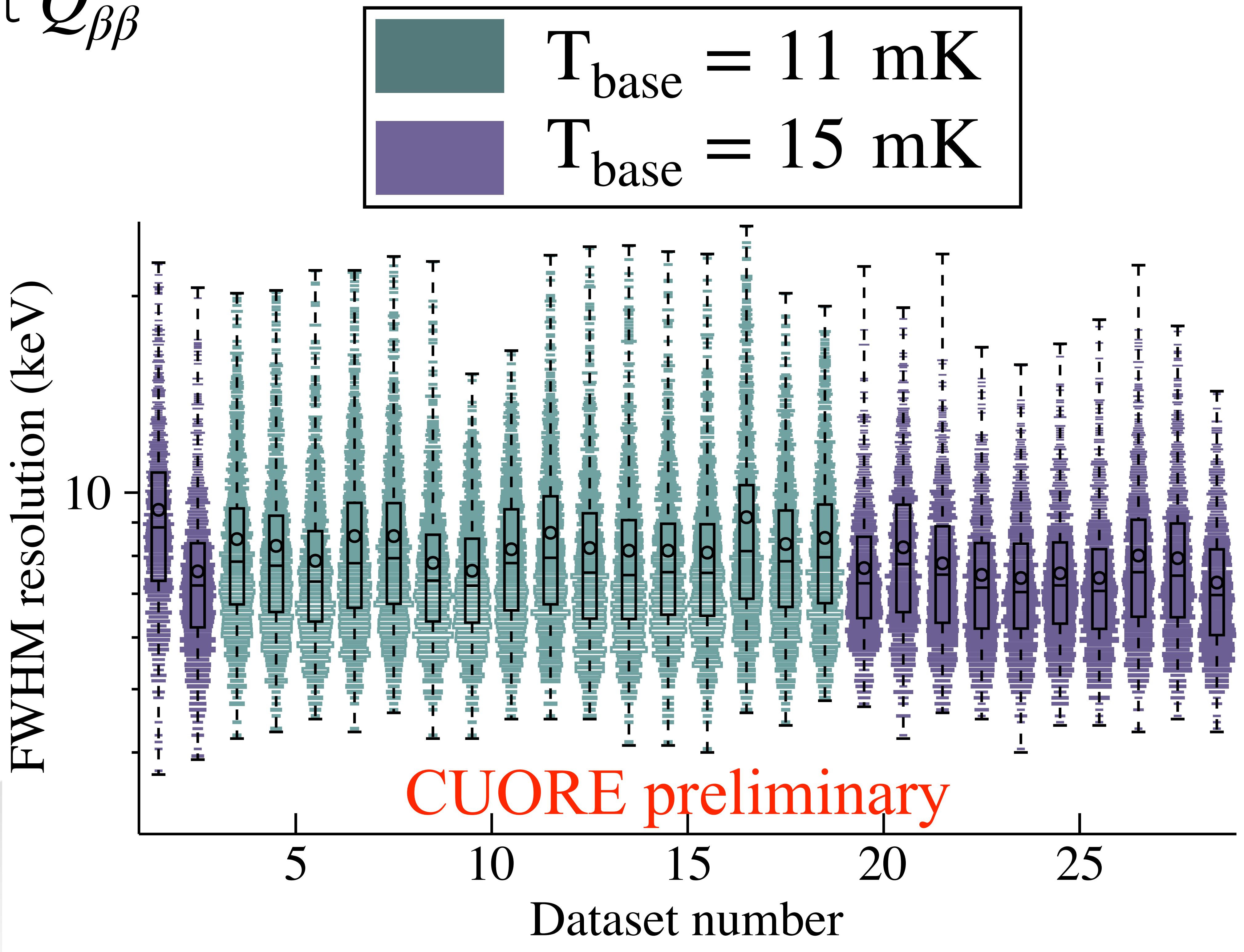
Unveiling the truth: modeling detector response

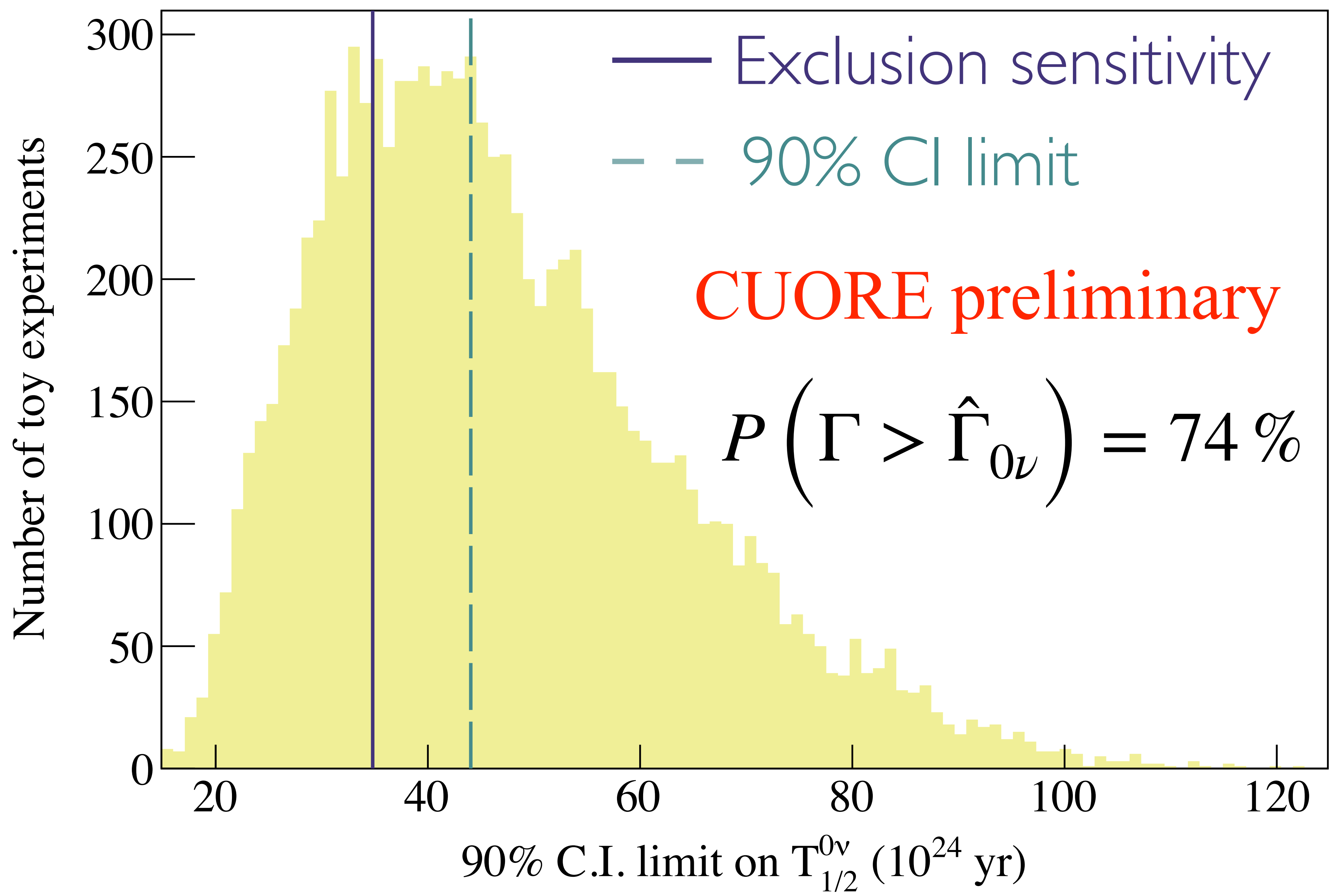


$$\mathrm{FWHM}\left({}^{208}\mathrm{Tl}\right) = (7.540 \pm 0.024)\ \mathrm{keV}$$
$$\mathrm{FWHM}\left(Q_{\beta\beta}\right) = (7.310 \pm 0.024)\ \mathrm{keV}$$
$$\Delta E\left(Q_{\beta\beta}\right) = \left(0.40^{+0.21}_{-0.44}\right)\ \mathrm{keV}$$

- 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 $Q_{\beta\beta}$



Unveiling the truth: fitting our data to extract $\Gamma_{0\nu\beta\beta}$

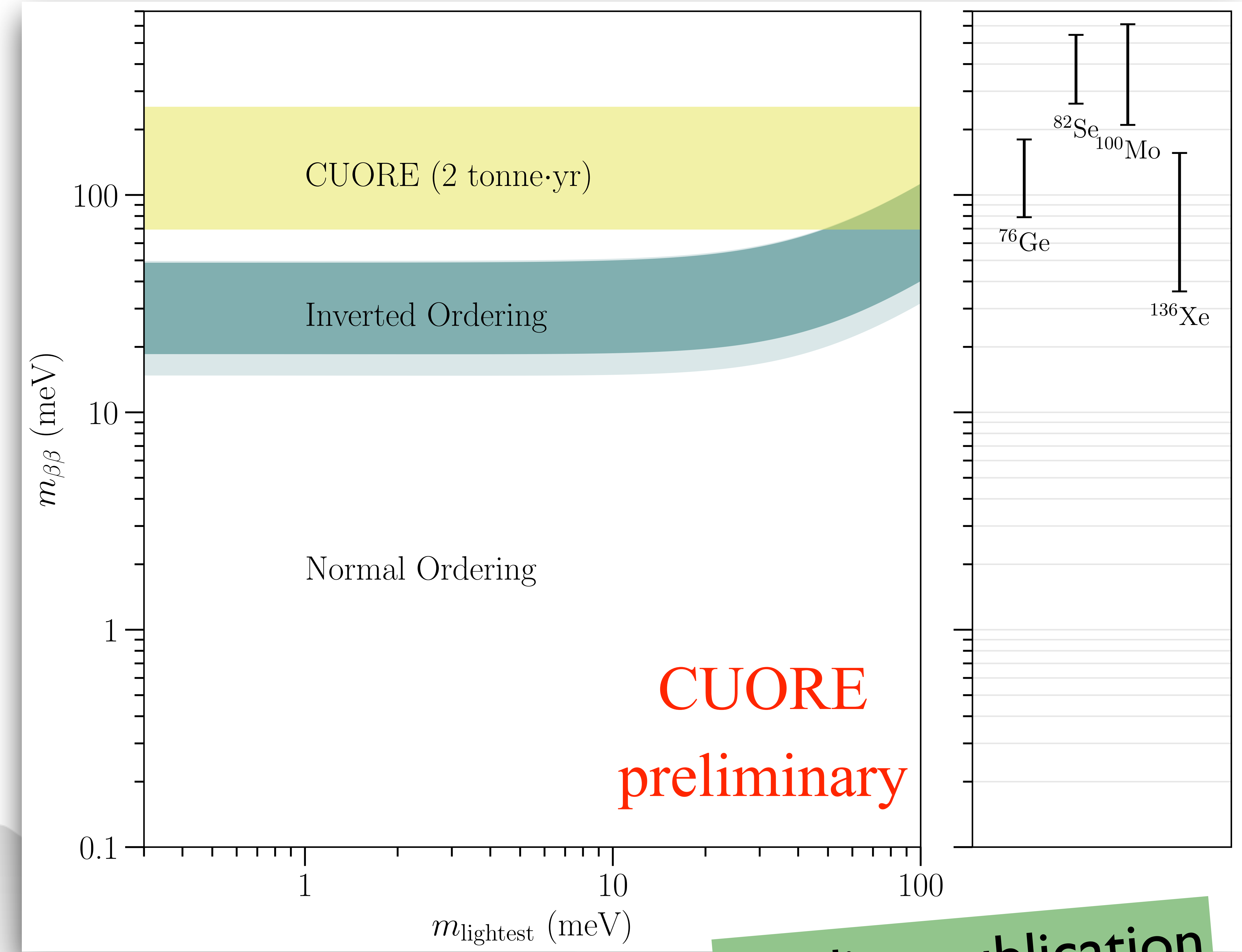


- Median exclusion sensitivity from toy MC experiments $T^{1/2}_{0\nu\beta\beta} = 4.4 \cdot 10^{25}$ yr (90 % C.I.)
- Unbinned Bayesian fit with $\Gamma_{0\nu\beta\beta} > 0$
- No evidence of $0\nu\beta\beta$ and new limit on ^{130}Te half-life $T^{1/2}_{0\nu\beta\beta} > 3.5 \cdot 10^{25}$ yr (90 %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



Pending publication

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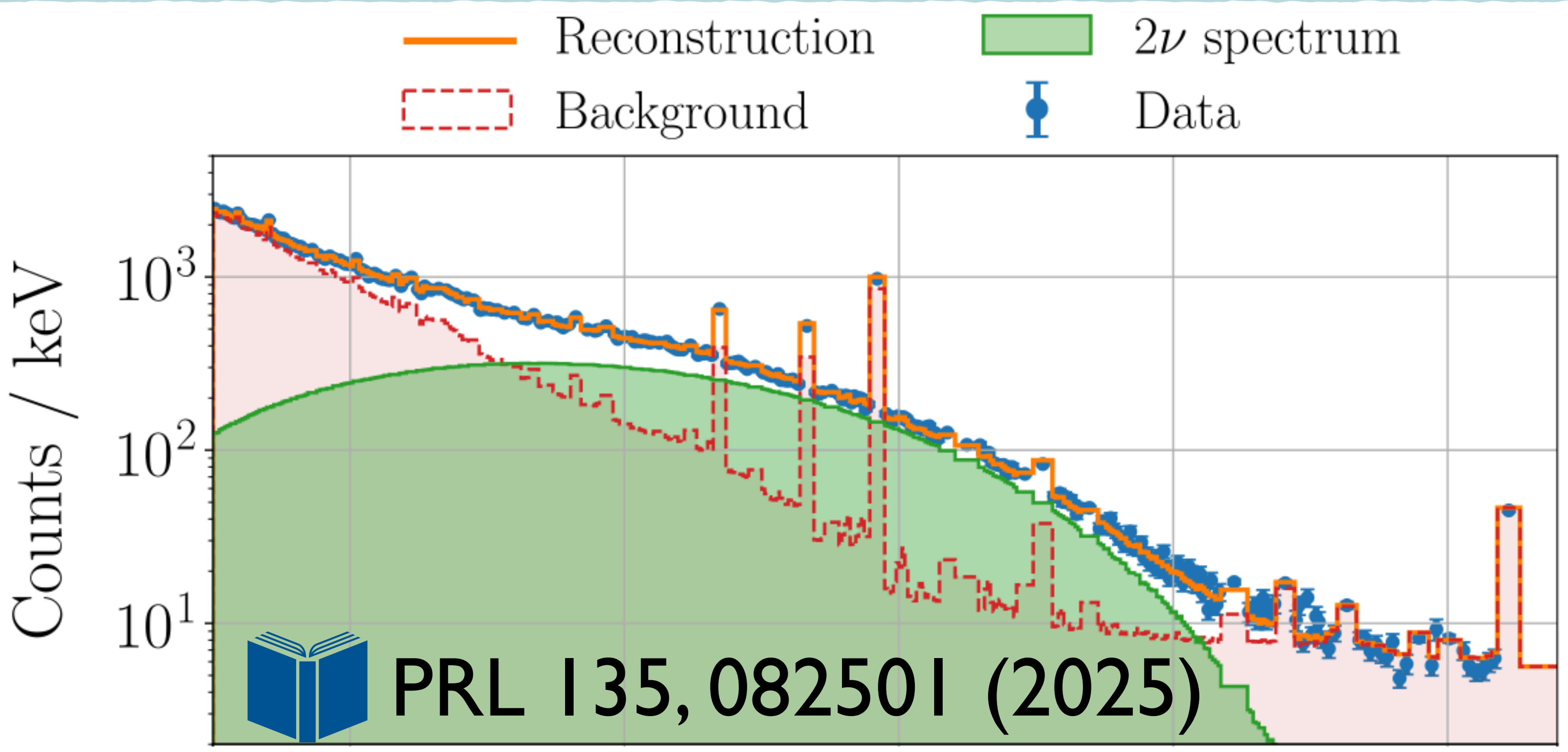
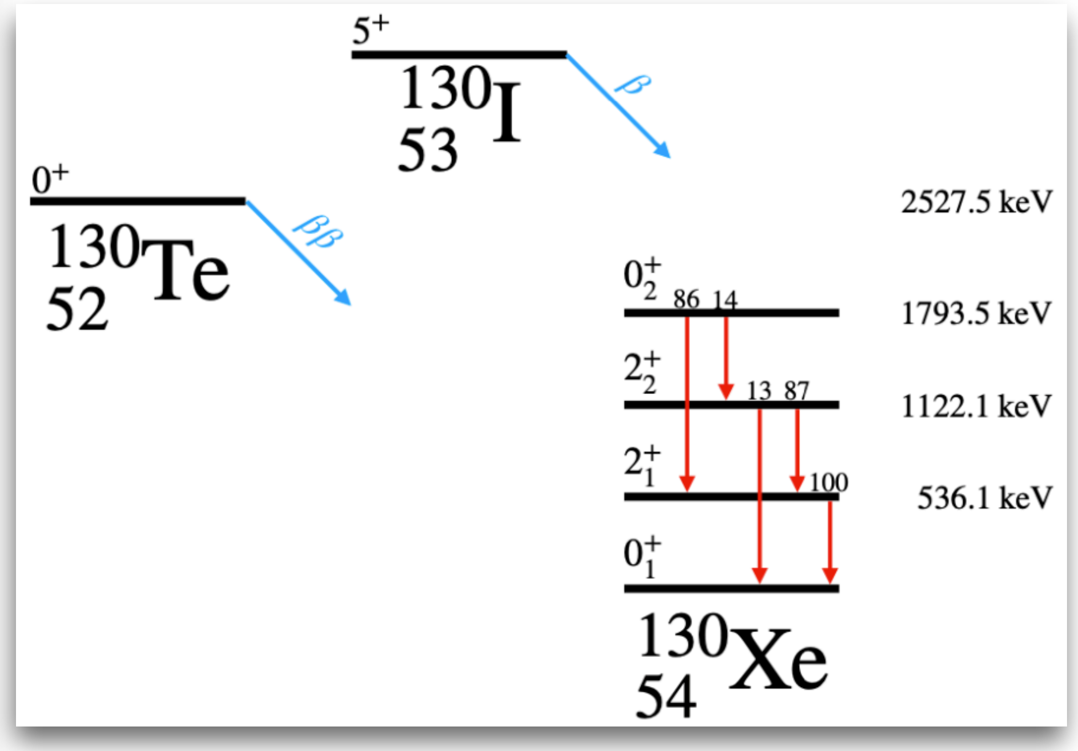
Not only ^{130}Te $0\nu\beta\beta$: other $\beta\beta$ searches

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



PRL 135, 082501 (2025)

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

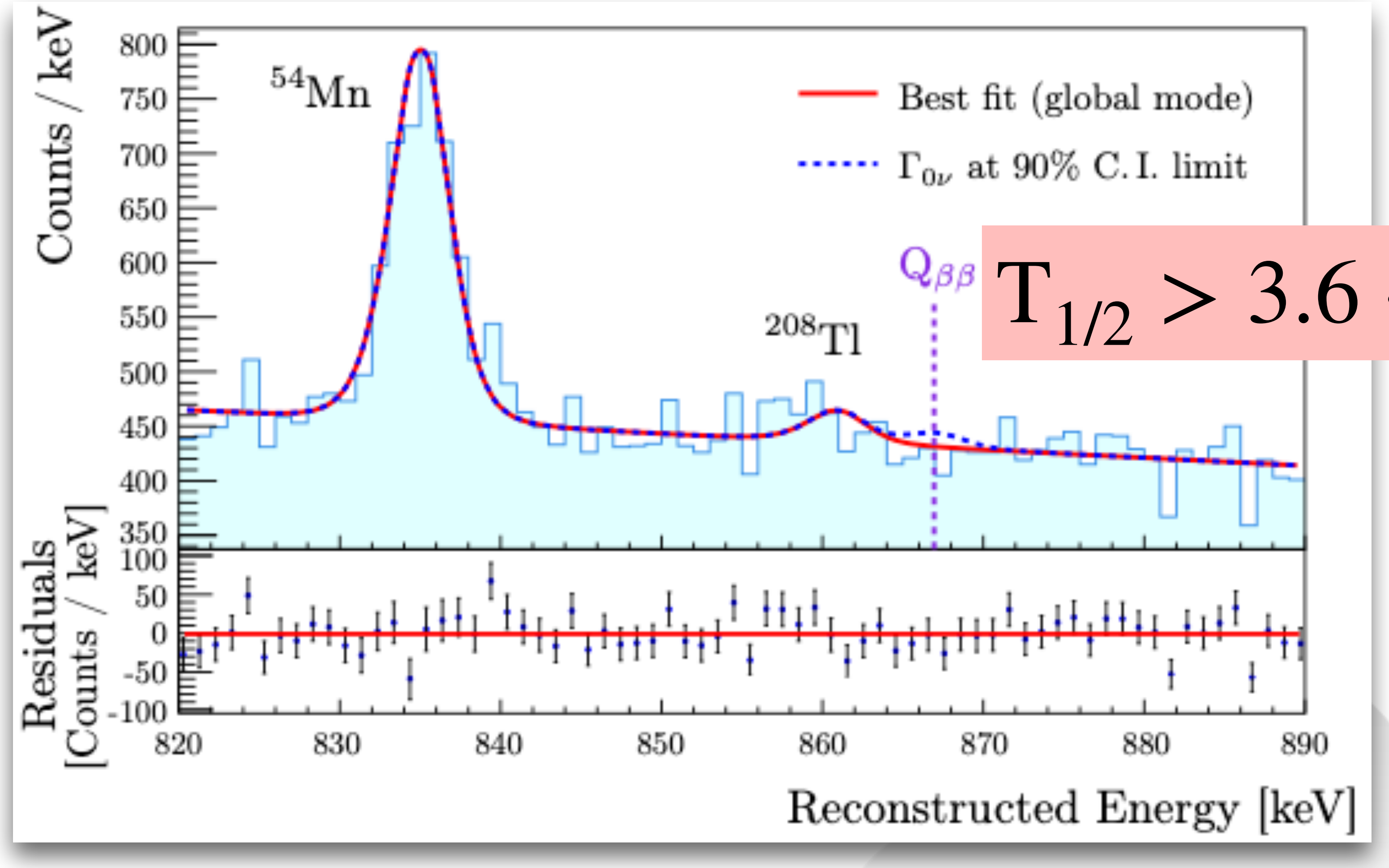


$T^{1/2}_{0\nu} > 5.9 \cdot 10^{24}$ yr (90 % C.I.)

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

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

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

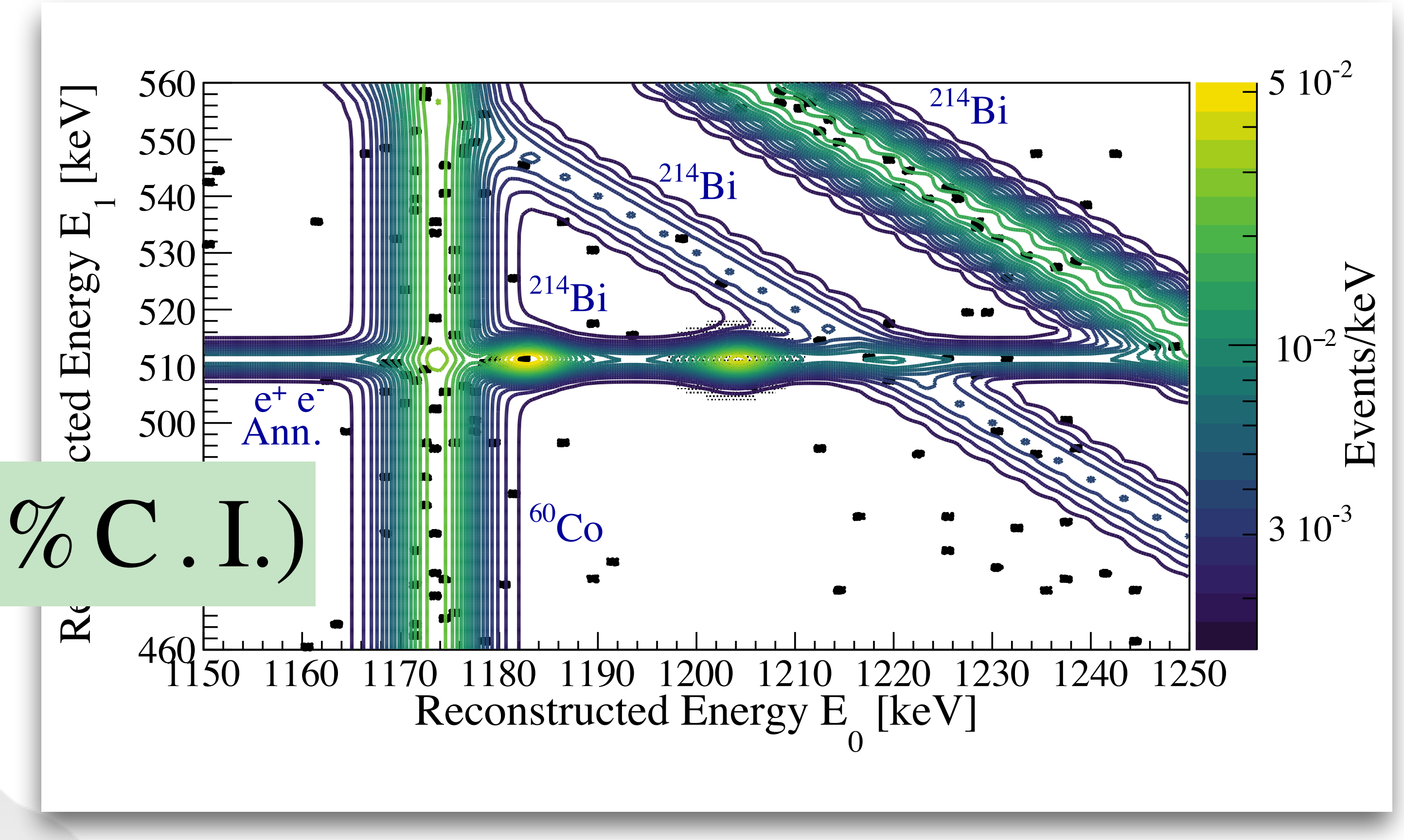


$T_{1/2} > 3.6 \cdot 10^{24}$ yr (90 % C.I.)

PRL 129, 222501 (2022)

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

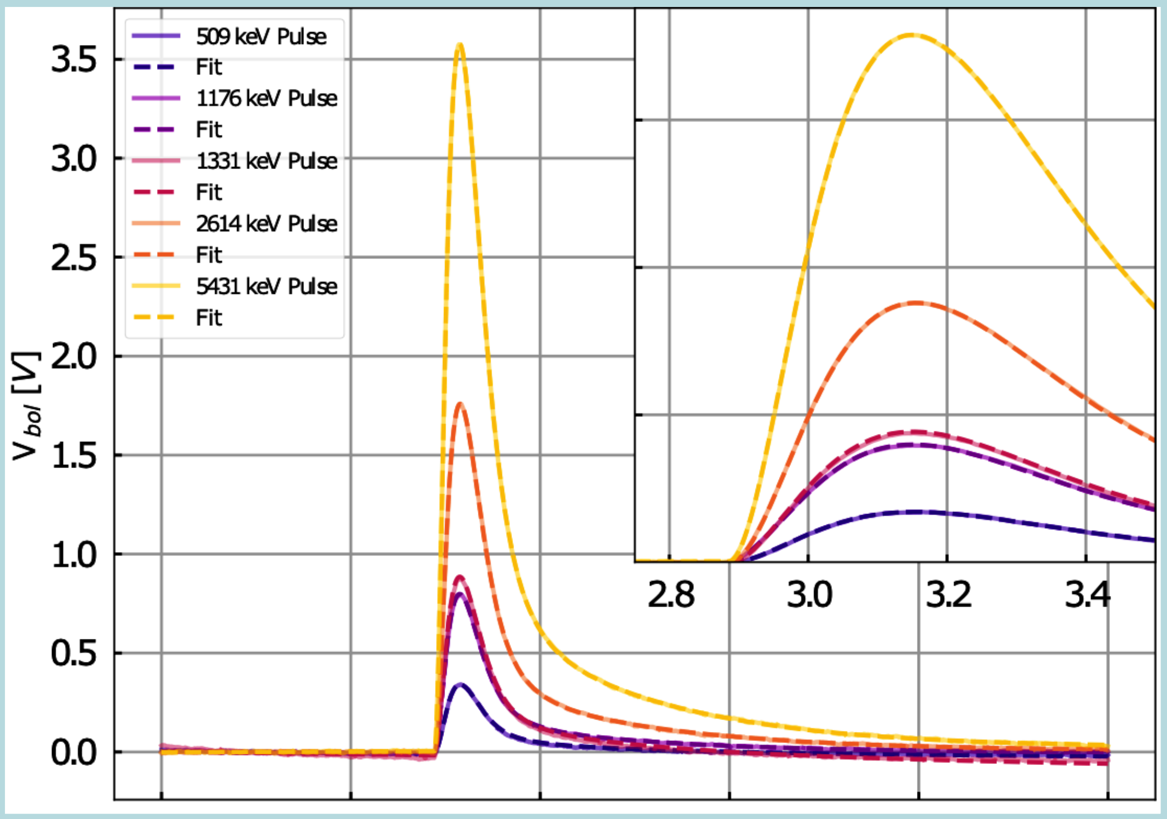
Phys. Rev. C, 105 065504 (2022)



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

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

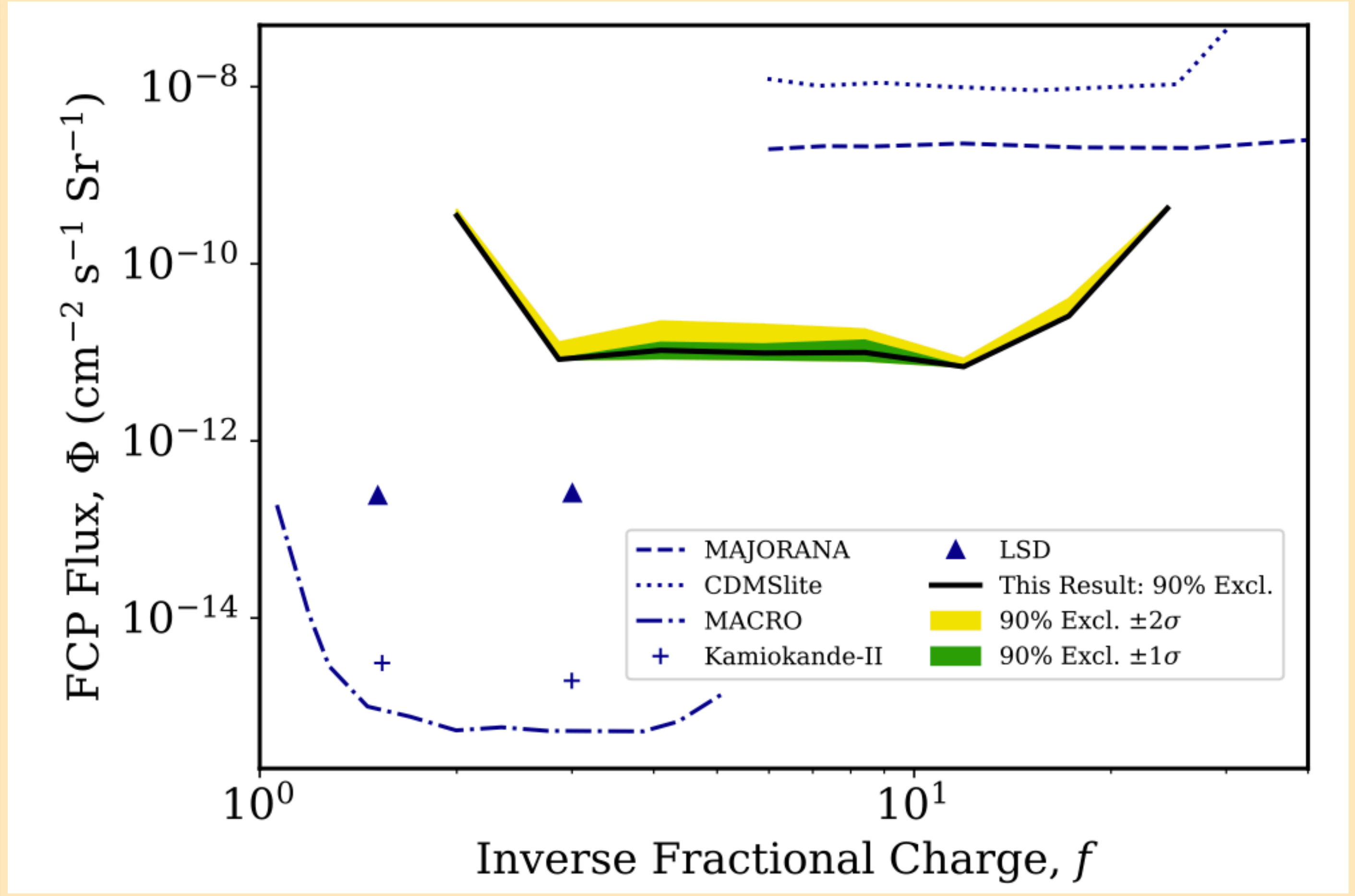
Thermal model of CUORE calorimeters



Dedicated study of environmental and antropic vibrational sources

JINST 17 (2022) 11, P11023

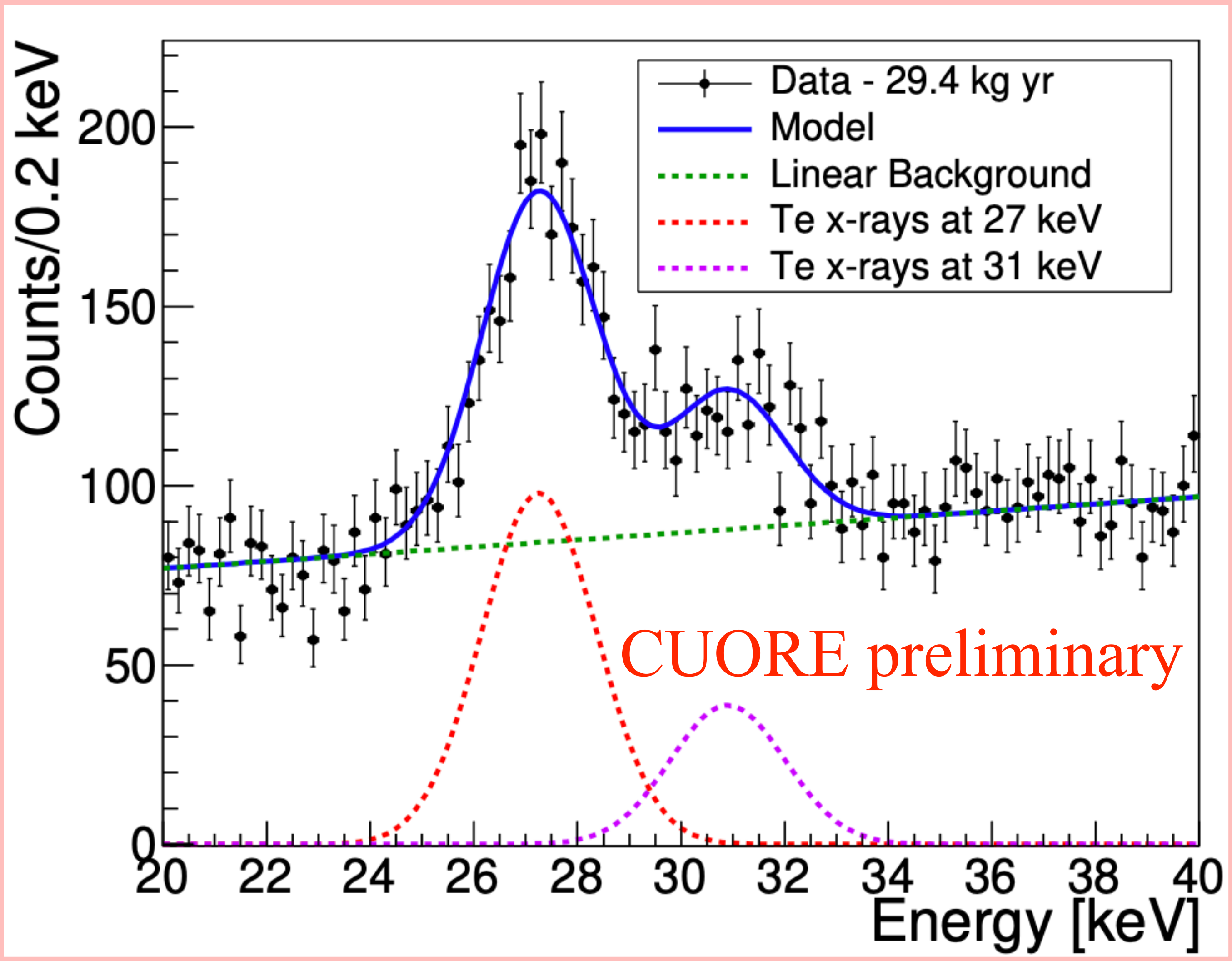
Search for fractionally charged particles



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

Phys. Rev. Lett. 133, 241801

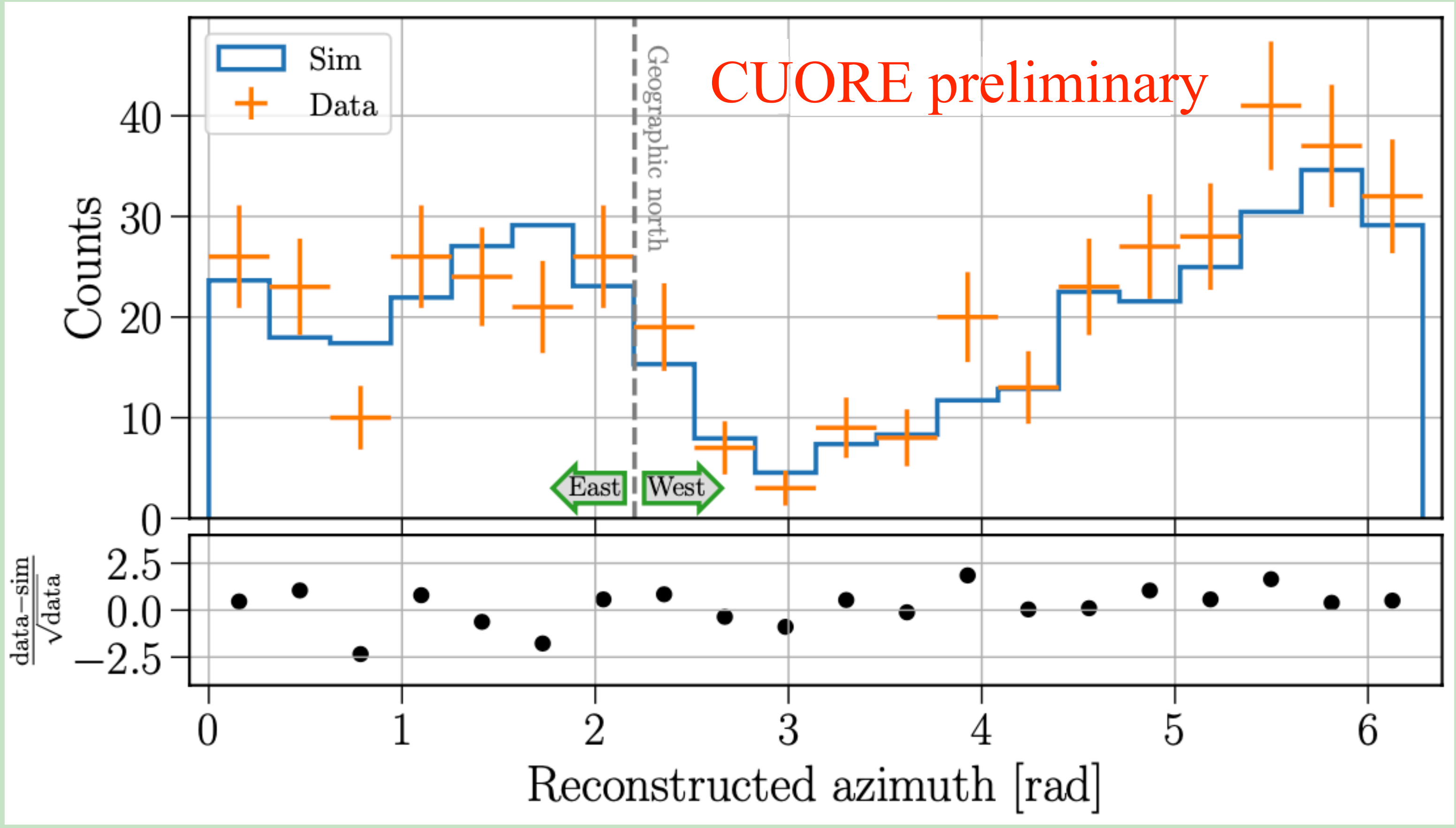
Low energy studies



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

poster@Neutrino2024

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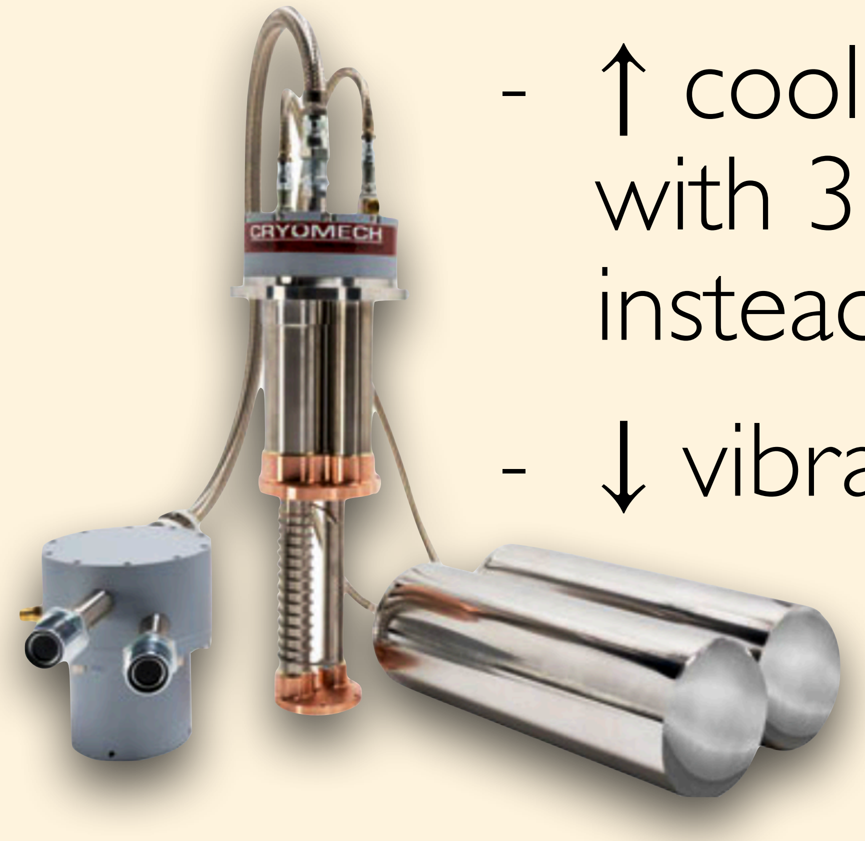
CUORE: what's next? Our path towards CUPID

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

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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

[I. Nutini, 25/08, par. 1A]

Conclusions and 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 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

Stay tuned

Thank you for your attention 感谢您的聆听!

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Related posters/talks: CUORE, CUPID…

CUORE

- ✓ *High precision study of $2\nu\beta\beta$ of ^{130}Te from the CUORE experiment*
  S. Dell'oro, 26/08/25 - parallel 3A (#2421)
- ✓ *Unlocking the keV frontier: low energy physics with the CUORE experiment*
  A. Ressa, 27/08/25 (poster) (#2510)
- ✓ *Sensitivity of search for double beta decay of ^{130}Te to excited daughter state in CUORE*
  R. Liu, 27/08/25 (poster) (#2269)

Stay tuned

CUPID

- ✓ *The CUPID neutrinoless double-beta decay experiment*
  I. Nutini, 25/08/25 - parallel 1A (#2274)
- ✓ *Sensitivity of the CUPID experiment to $0\nu\beta\beta$ decay of ^{100}Mo*
  P. Loaiza, 26/08/25 - parallel 4A (#2403)
- ✓ *CUPID-CJPL: a cryogenic bolometer tested*
  H. Chen, L. Ma, 26/08/25 - parallel 4A (#2314)
- ✓ *Validation of LMO crystals for the CUPID experiment*
  M. Girola, 27/08/25 - parallel 5 (#2487)
- ✓ *Performance validation of the VSTT: An Upgraded CUPID Prototype Tower with Neganov-Luke Enhanced Light Detectors*
  I. Nutini, 27/08/25 (poster) (#2220)

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Related posters/talks: … $0\nu\beta\beta$ with cryogenic calorimeters

- ✓ Toward a background-free ton-scale $0\nu\beta\beta$ *bolometric experiment: status and prospects of BINGO*, C. Nones, 25/08/25 - parallel 2A (#2455)
- ✓ Detector response study of cryogenic scintillating Li_2MoO_4 detectors for next generation $0\nu\beta\beta$ search, B. Schmidt, 26/08/25 - parallel 3A (#2400)

- ✓ *Opossum - Optimal Particle Identification Of Single Site events with Underground MKIDs detectors*, A. Puiu, 27/08/25 - parallel 6B (#2397)
- ✓ *CERES: Cryogenic Experiment to Reconstruct Energy Systematics in TeO_2 bolometers* T. Zhu, 27/08/25 (poster) (#2147)

Stay tuned

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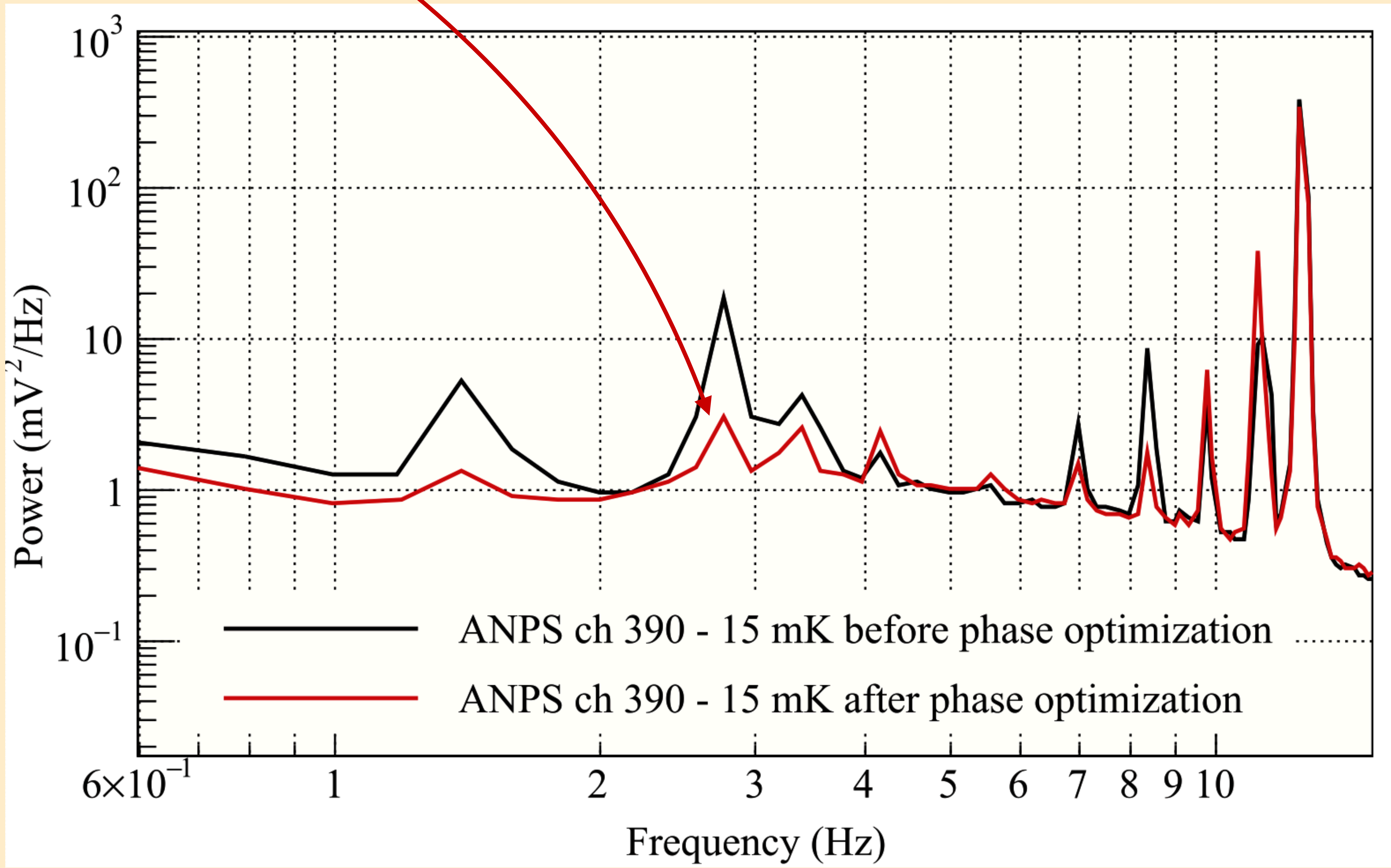
Back -up slides

The challenges - part III: suppressing noise sources

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



Cryogenics 93, 56-65 (2018)

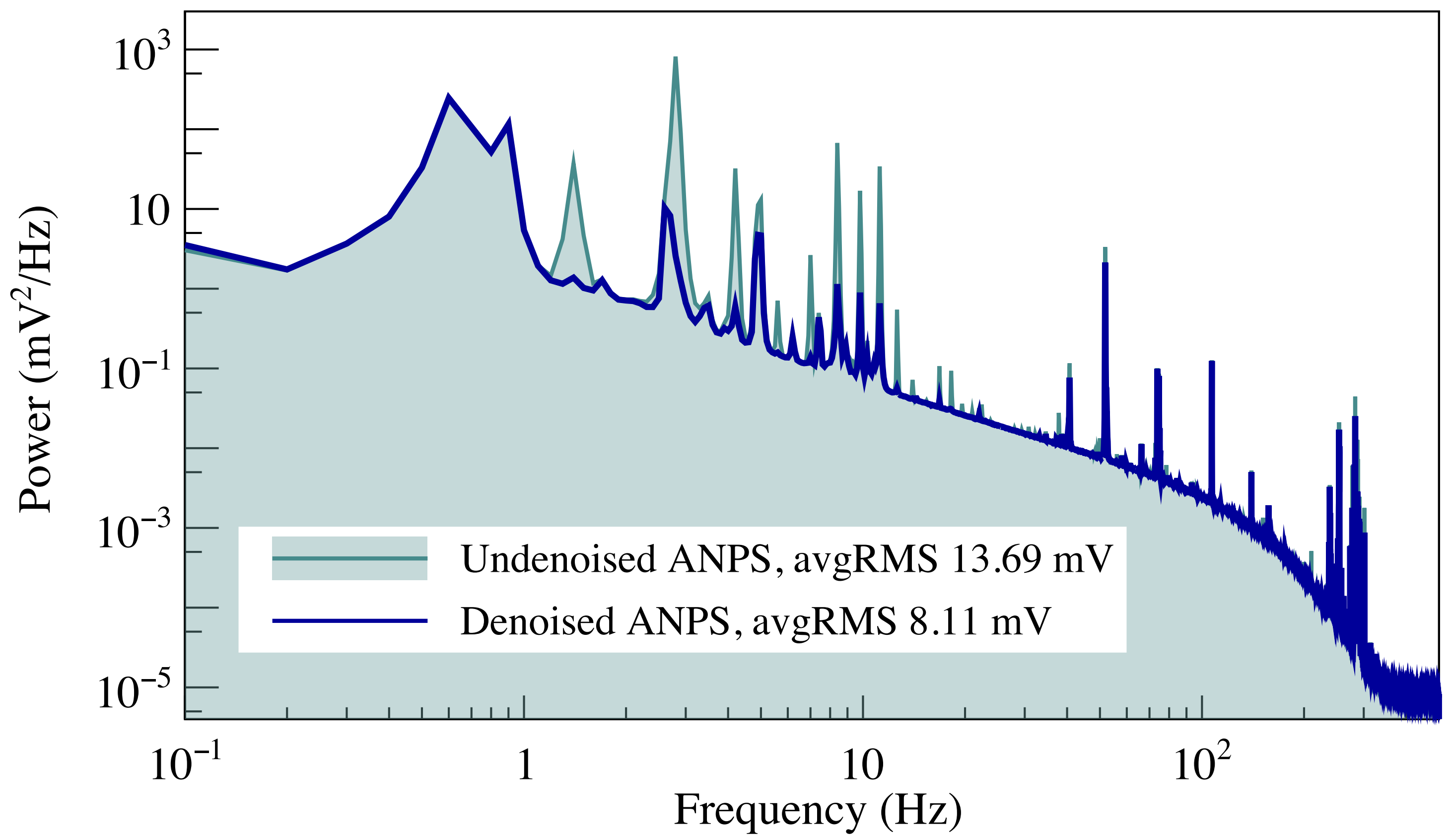
2 tonne·yr data: analysis & $0\nu\beta\beta$ fit parameters

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}

Data processing chain to extract a spectrum of events

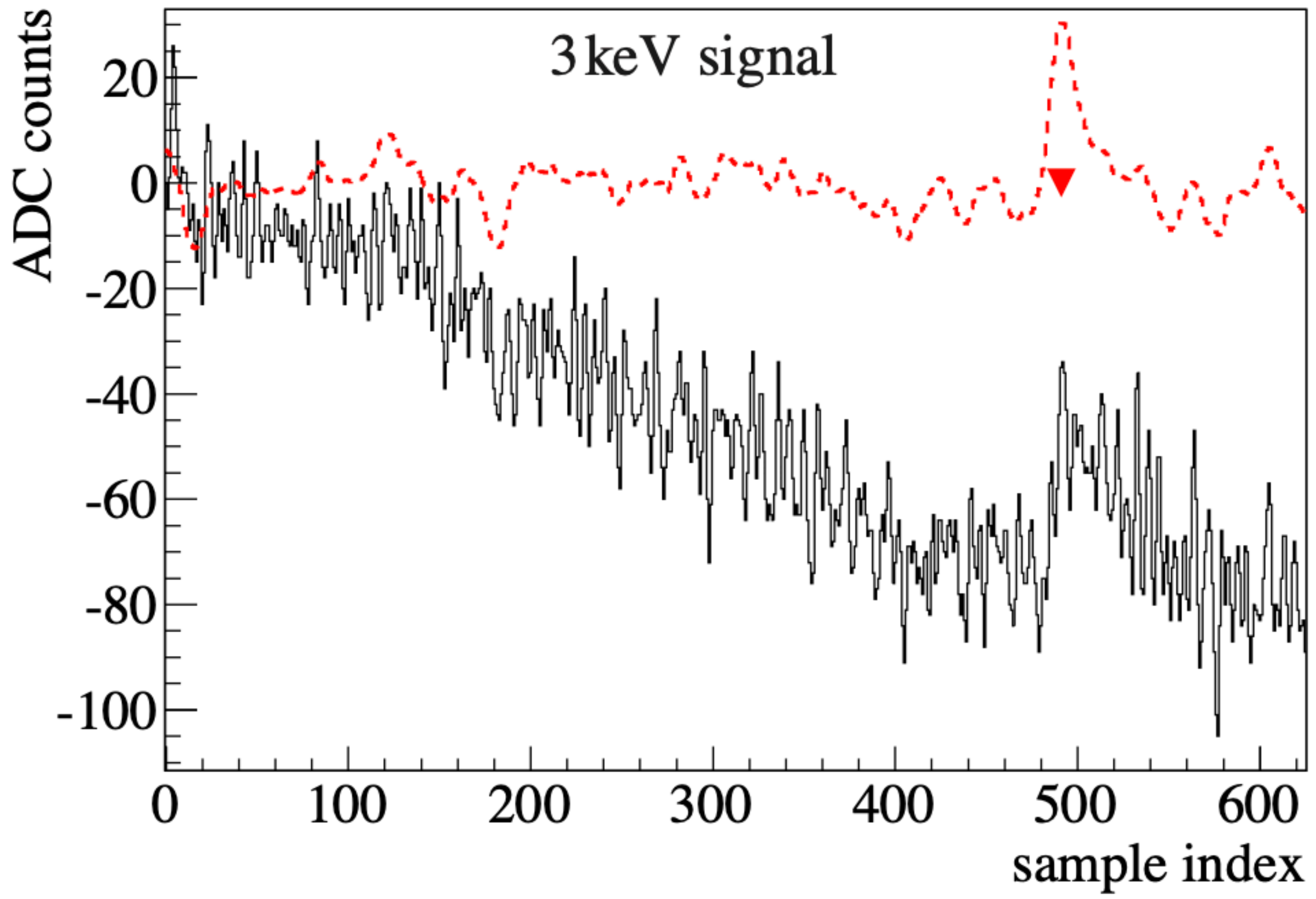
Denoising (New!)

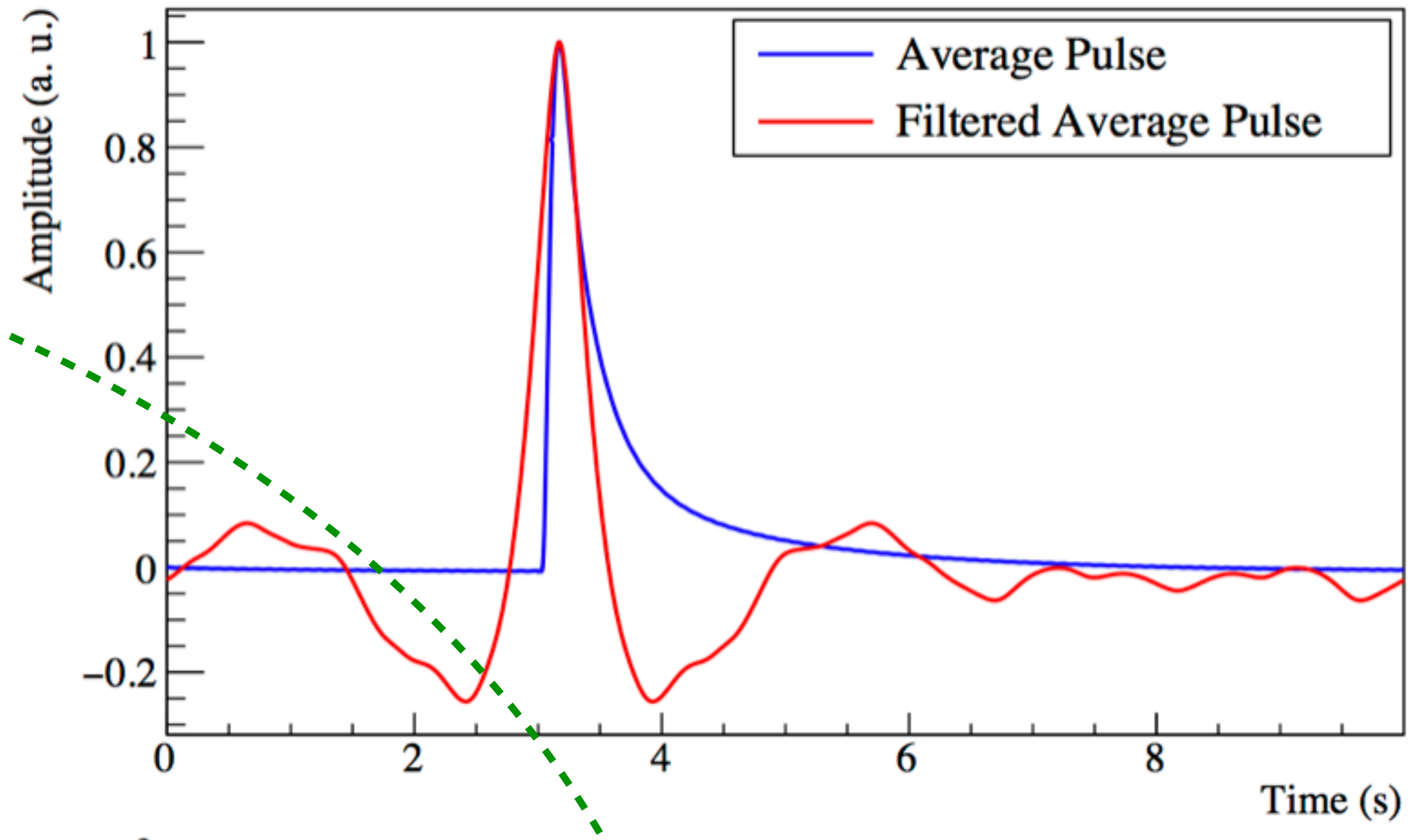


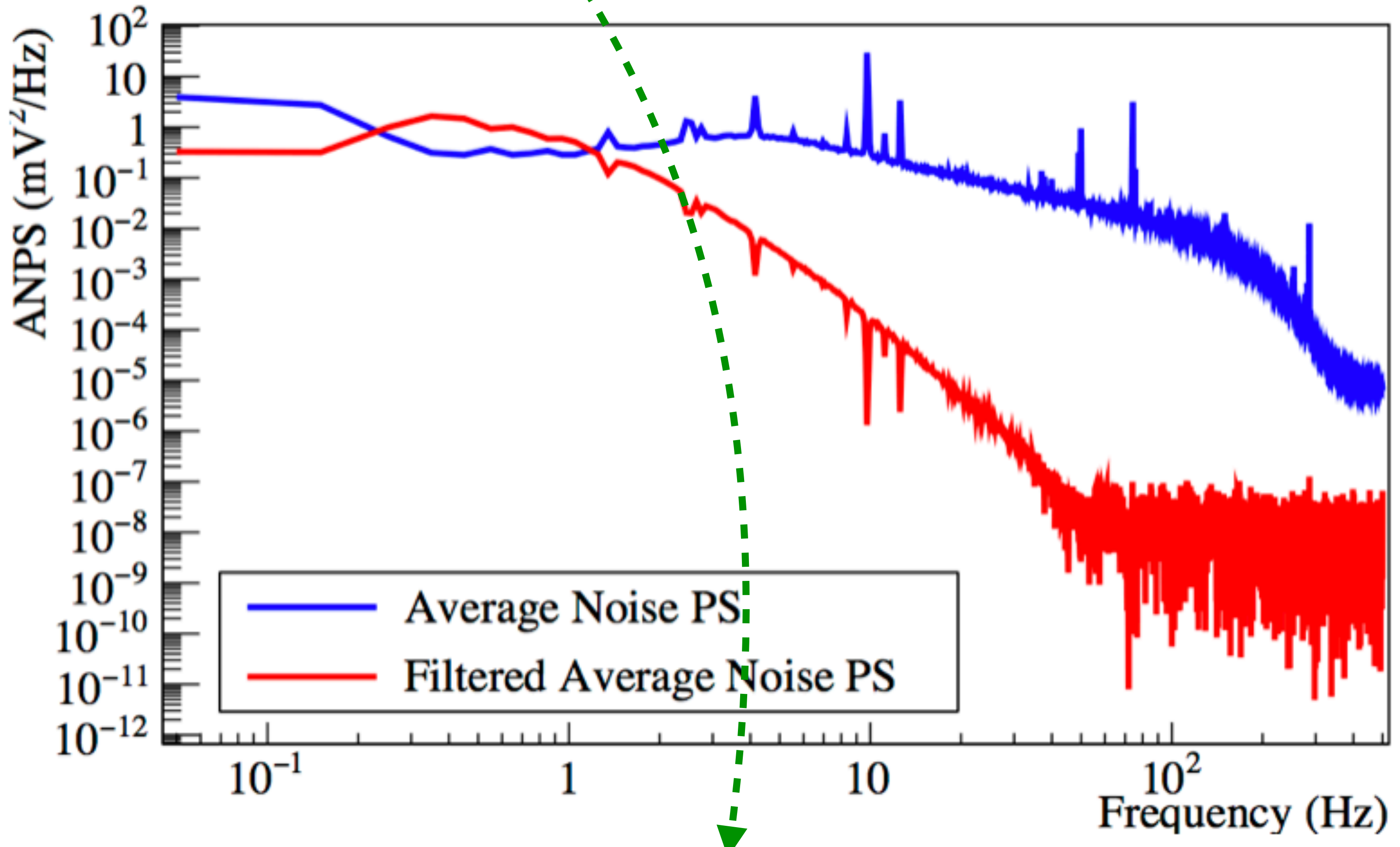
Noise is mitigated correlating *vibrations* with measurements obtained with *auxiliary devices*, i.e. microphones, accelerometers, seismometers

Optimum trigger (OT)

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





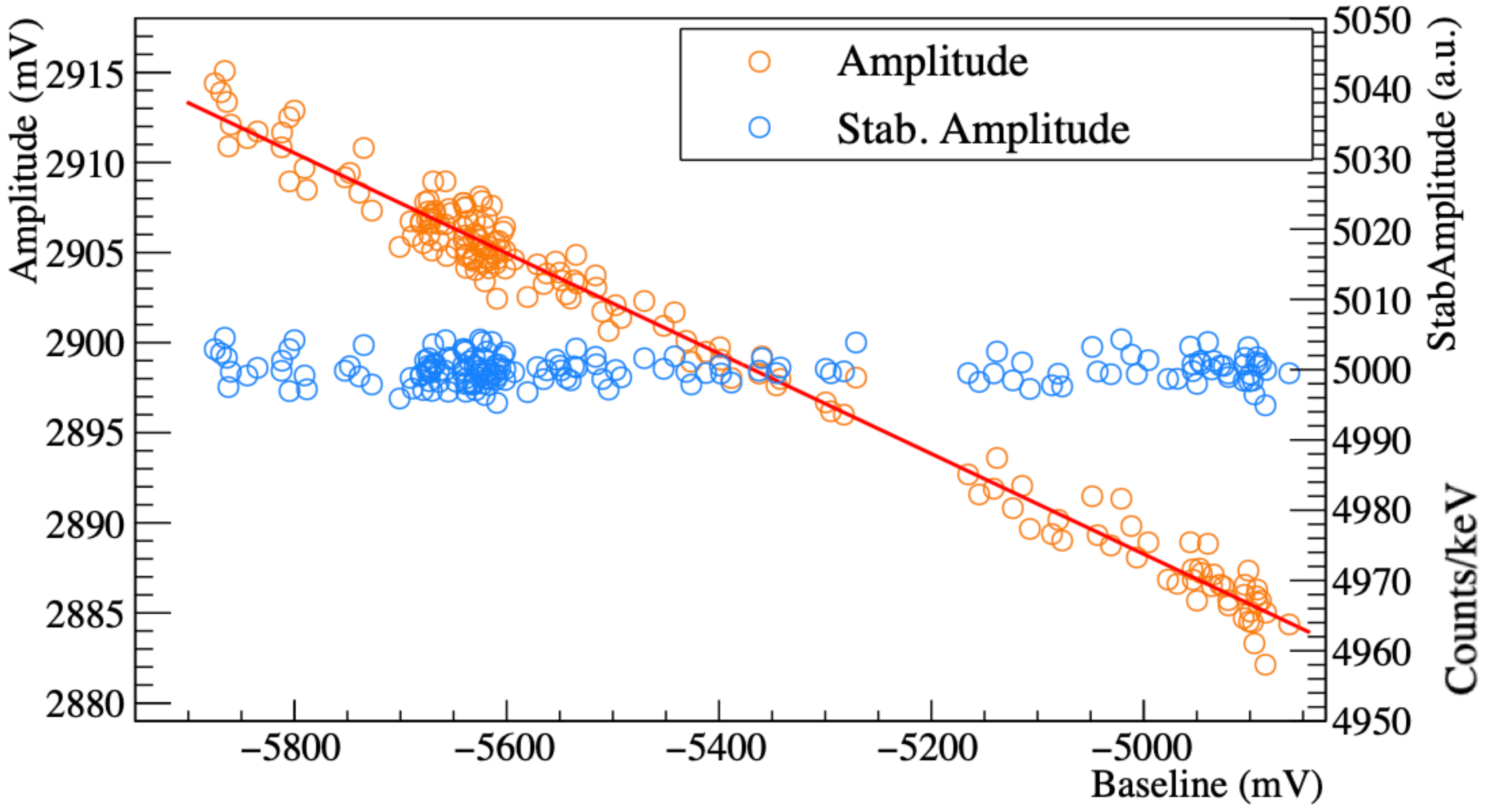


Optimum Filter technique

We evaluate *filtered* signal amplitude

Data processing chain to extract a spectrum of events

Thermal gain stabilization (TGS)

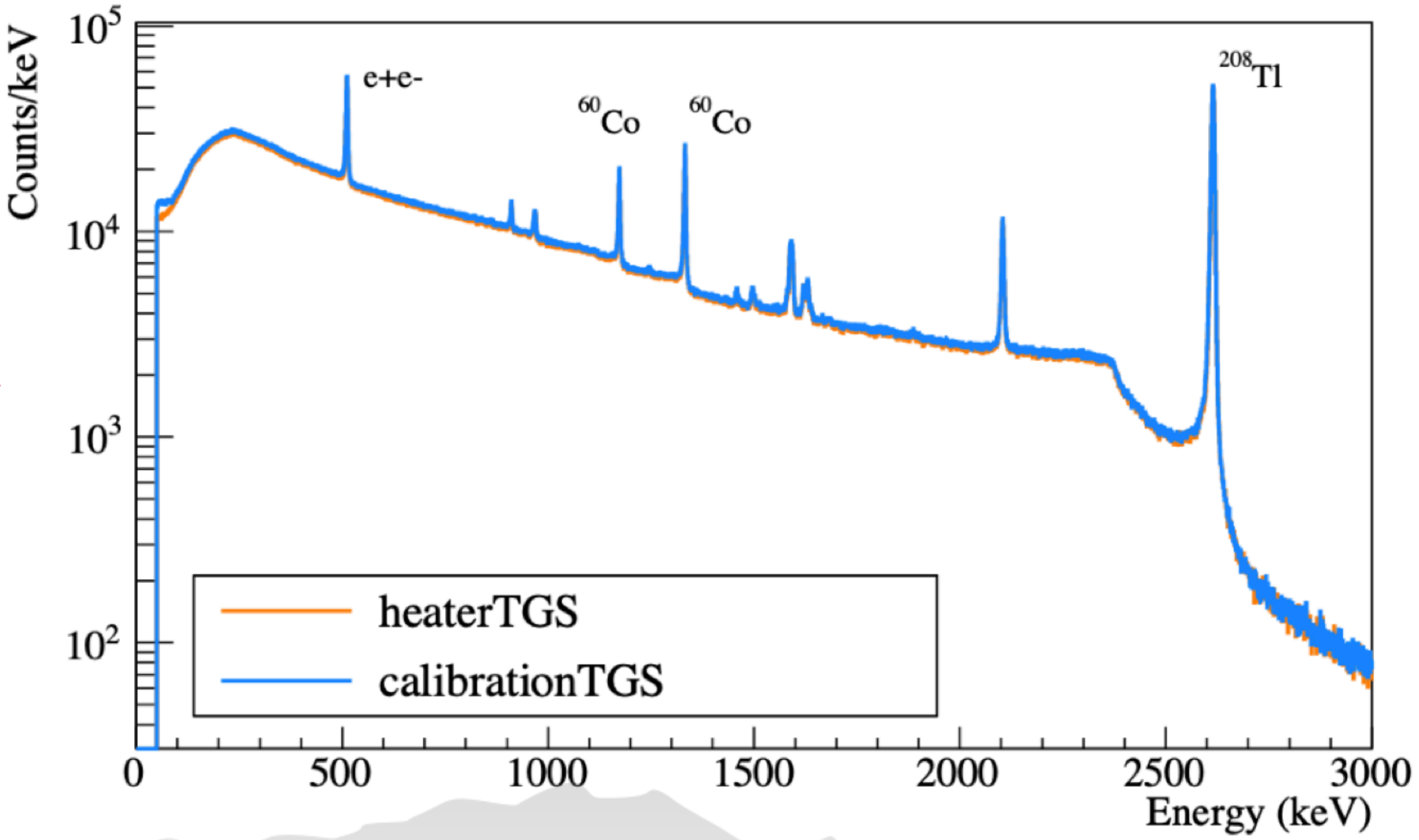


We employ fixed energy pulses to correct for drifts in the thermal gain

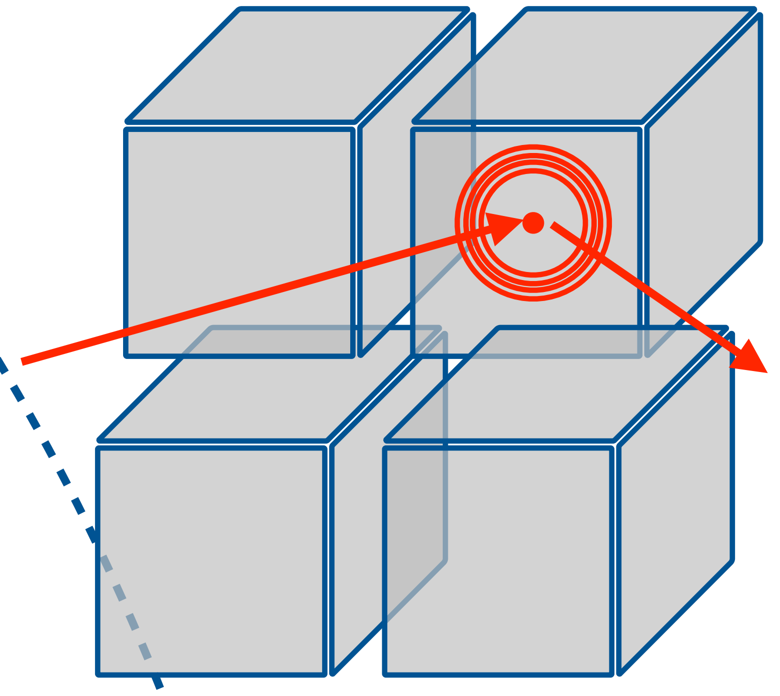
Energy calibration

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

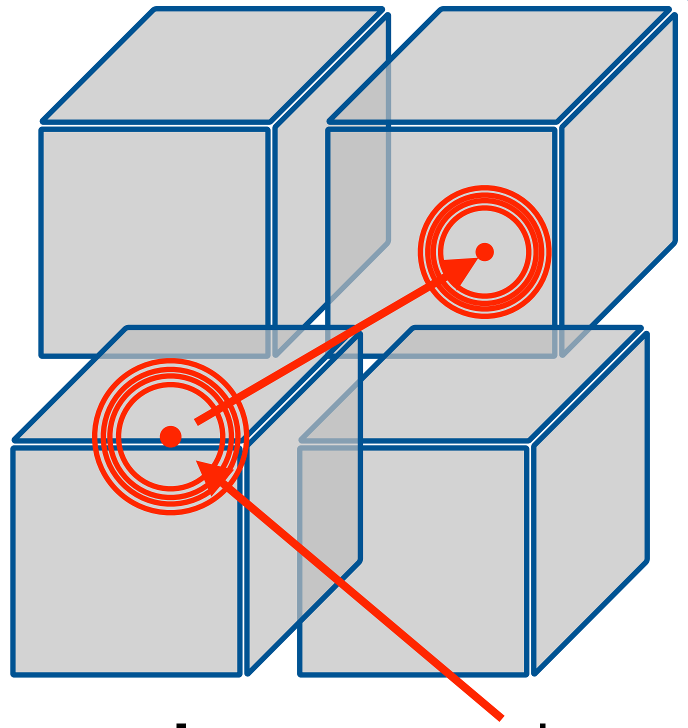
We use a 2nd order polynomial fit to extract our calibration coefficients



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



single-crystal



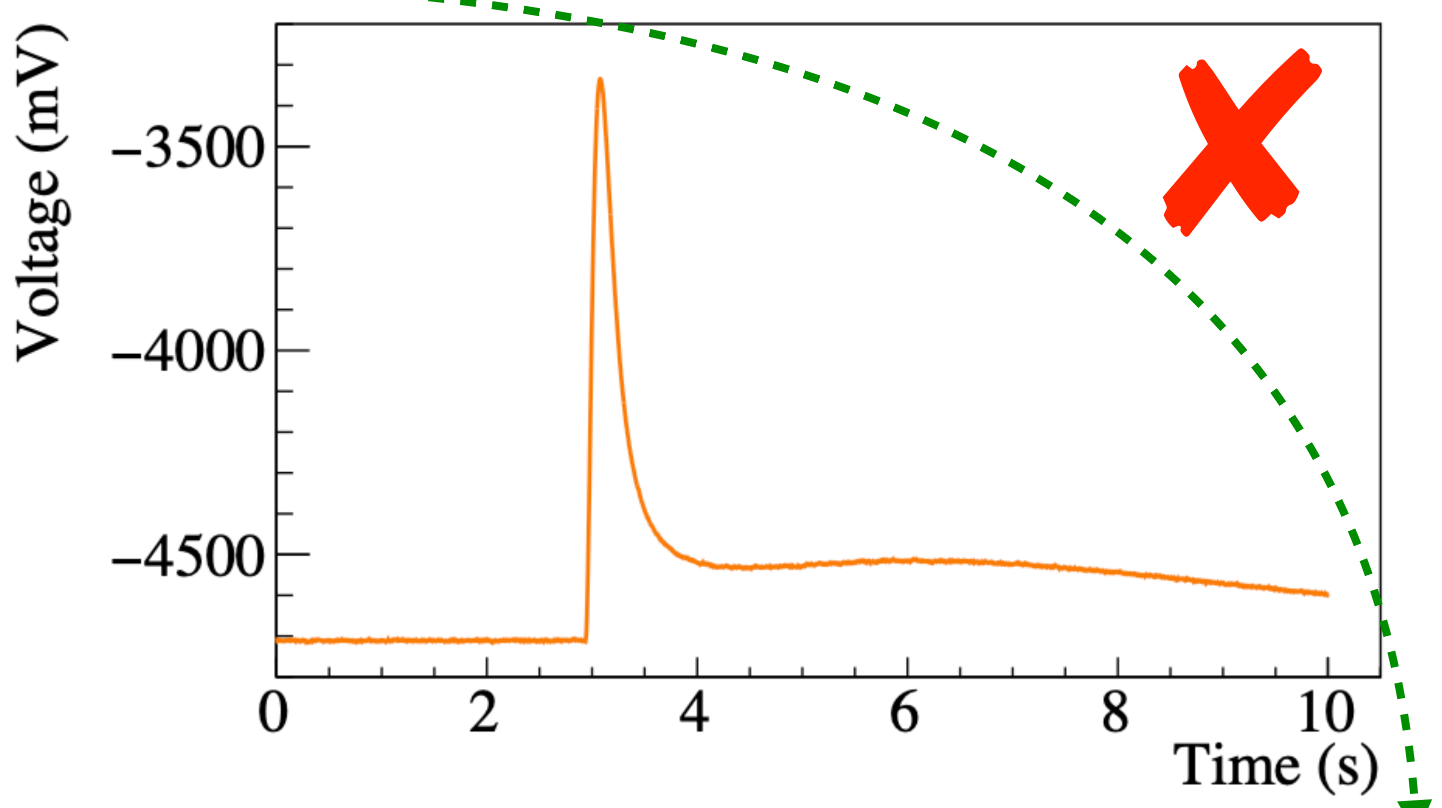
multi-crystal

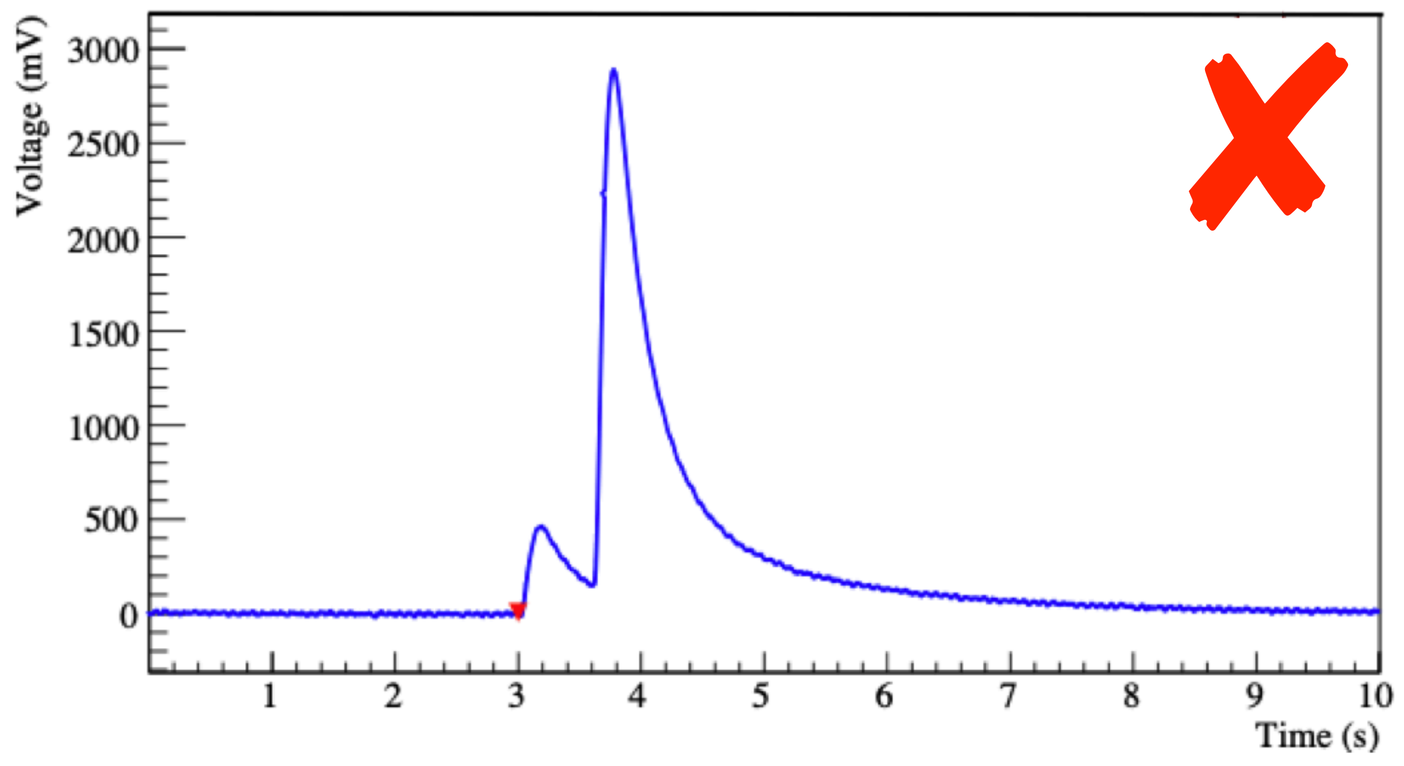
Coincidences

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





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

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