September 4 – 8, 2023

Latest Results from the CUORE Experiment

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14th MEDEX Conference **September 2023** **Prague, Czechia**

A Quick Summary of CUORE

The **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents

- Low-temperature detector with 988 TeO_2 crystals
- Detector mass of 742 kg
- Isotope of use: ^{130}Te (206 kg)
- $Q_{\beta\beta} \cong 2528$ keV
- Operating temperatures of 11–15 mK
- Located in Italy under the Apennine Mountains at Gran Sasso National Laboratory (LNGS)
- Low Backgrounds
    - Strict radio-purity controls on materials and assembly
    - Passive shielding including ancient Roman lead

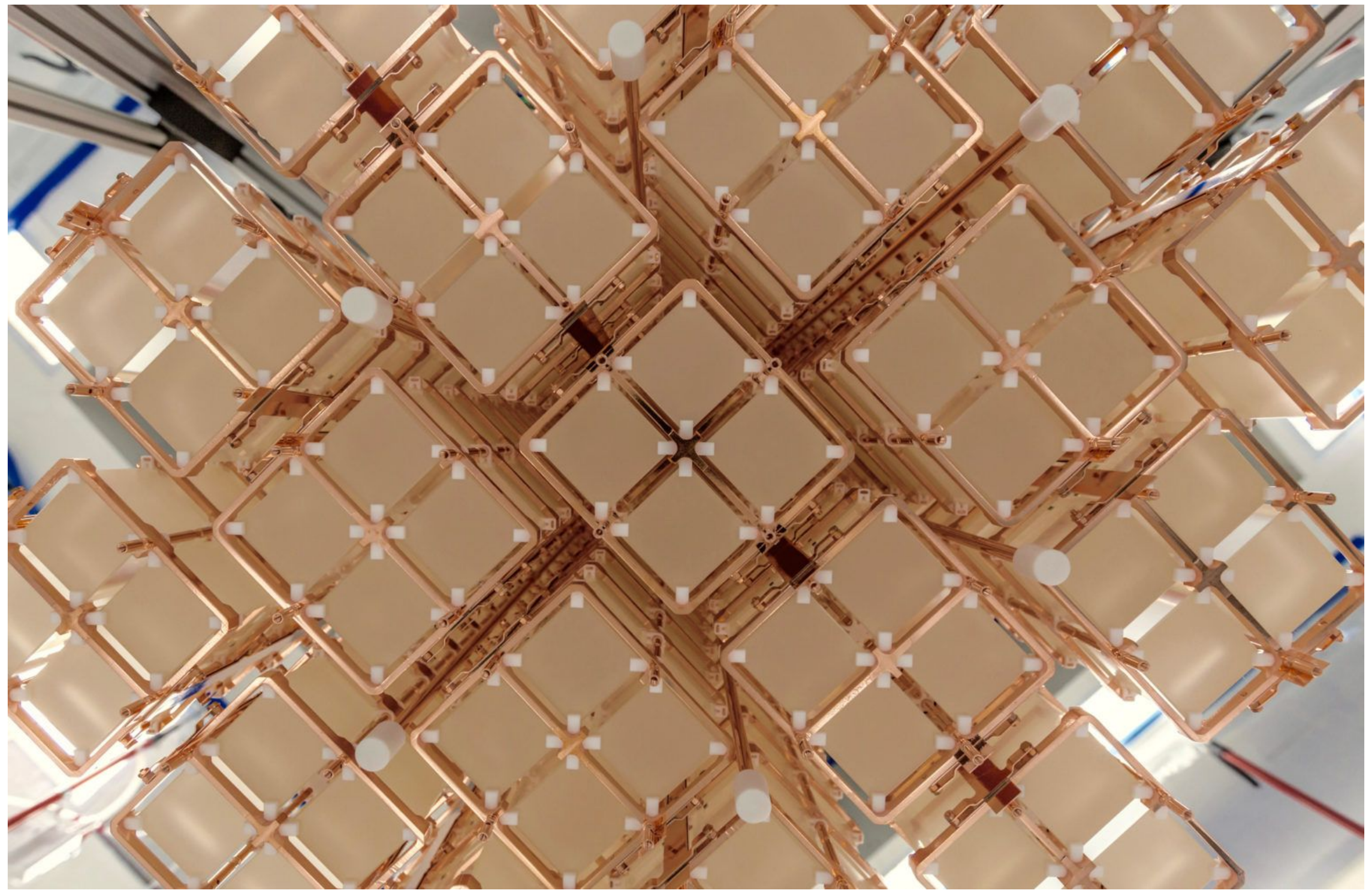
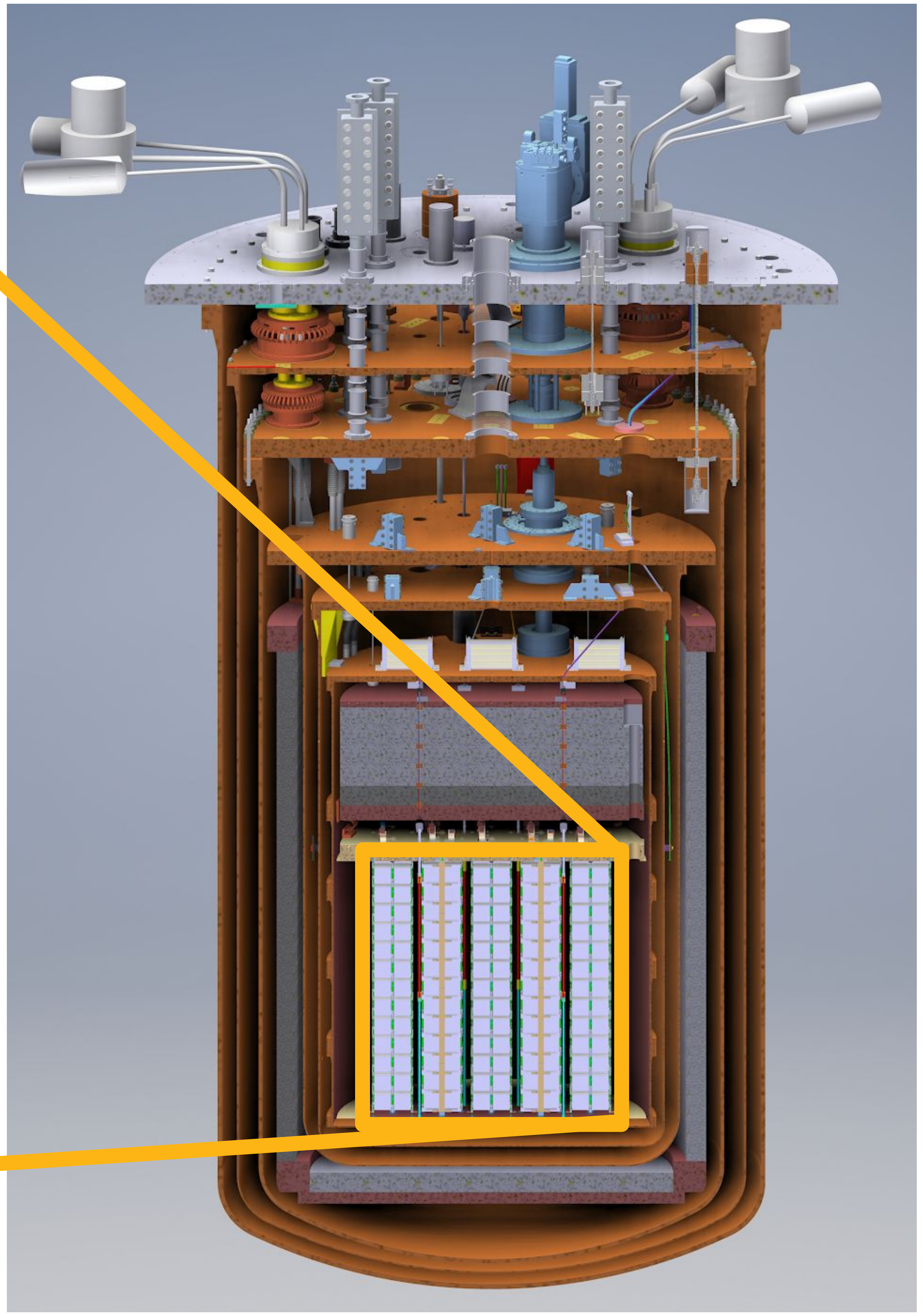


Photo courtesy of L. Marini and G. Benato

Detector Geometry

- Each TeO_2 crystal is $5x5x5\ cm^3$
- Crystals arranged in 19 towers with 13 floors
- $0\nu\beta\beta$ containment efficiency of ~88% (from Monte Carlo simulations)
- 983 active channels



The CUORE Cryostat
I. Nutini (on behalf of the CUORE collaboration) (2020) J. Phys. Conf. Ser. 1468 012112

CUORE at LNGS

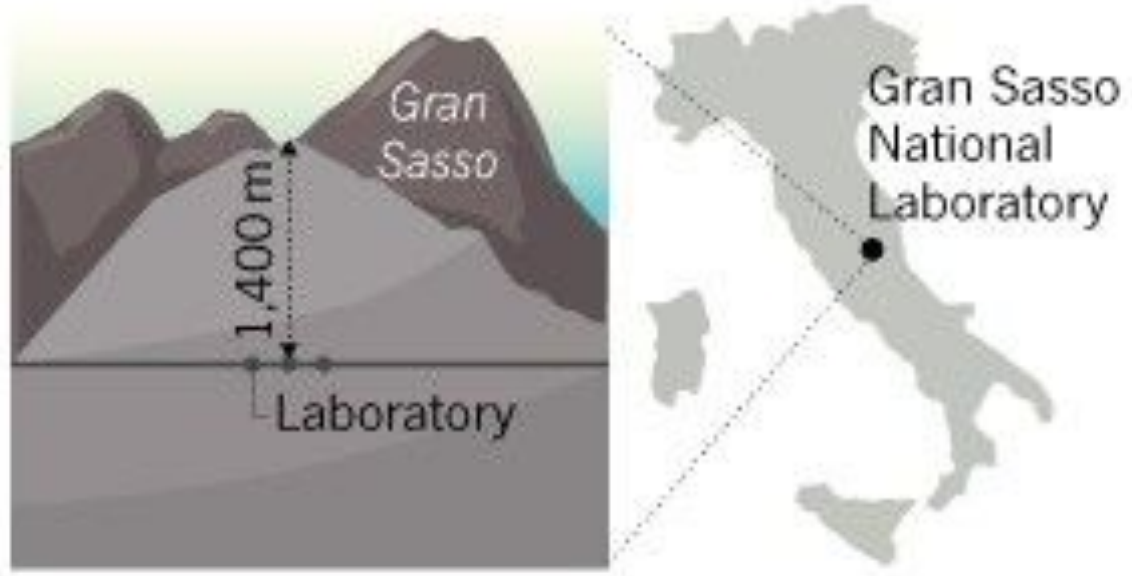
The mountain of Gran Sasso naturally protects the experiment from cosmic rays with 3600m water equivalent of shielding.

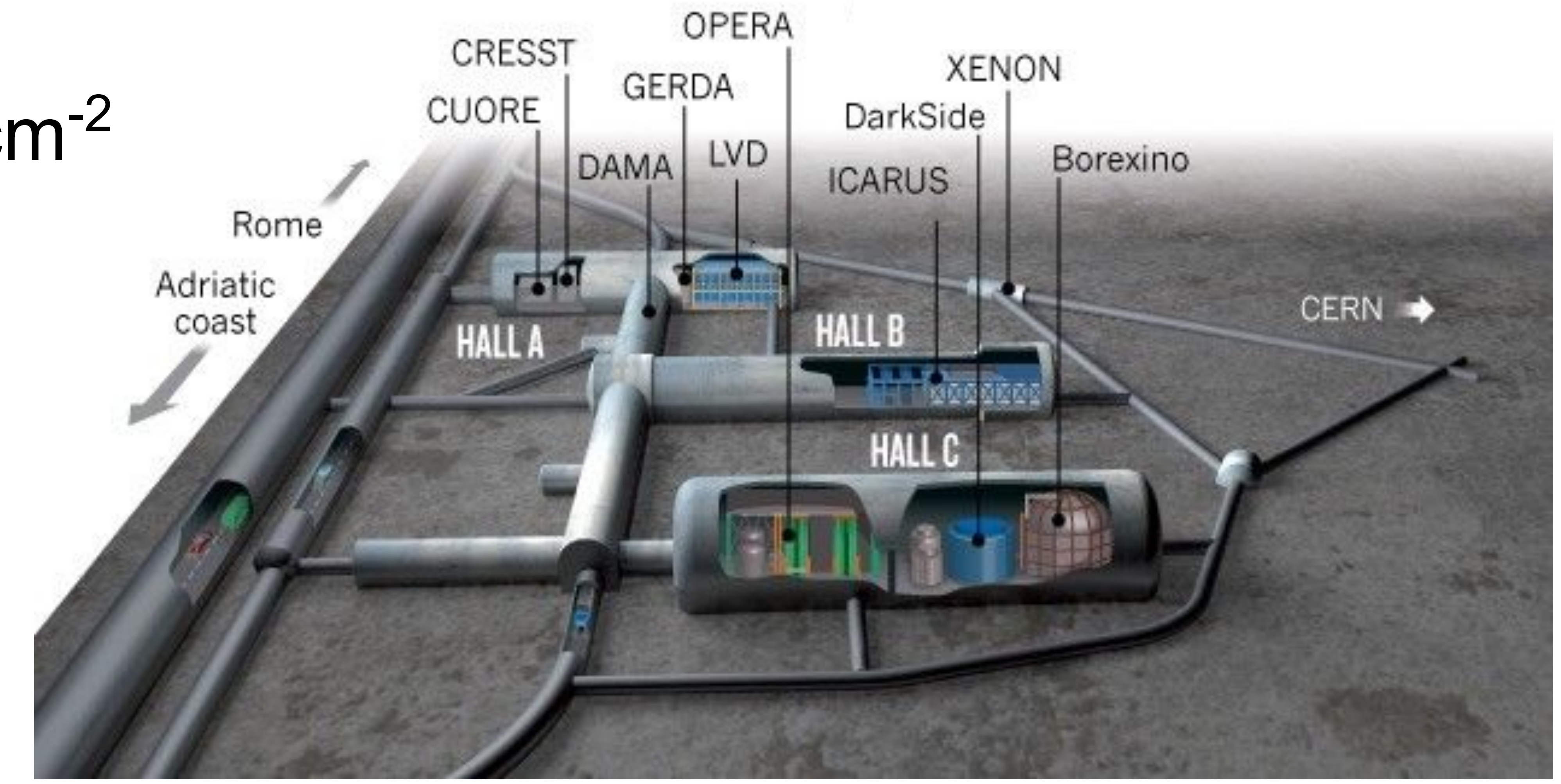
Background fluxes:

Muons: ~ $3 \times 10^{-8}\ s^{-1}\ cm^{-2}$

Neutrons: < $4 \times 10^{-6}\ s^{-1}\ cm^{-2}$

Gammas: ~ $0.73\ s^{-1}\ cm^{-2}$





Gran Sasso: Chamber of physics.
N. Nosengo. Nature 485, 435–438 (2012).

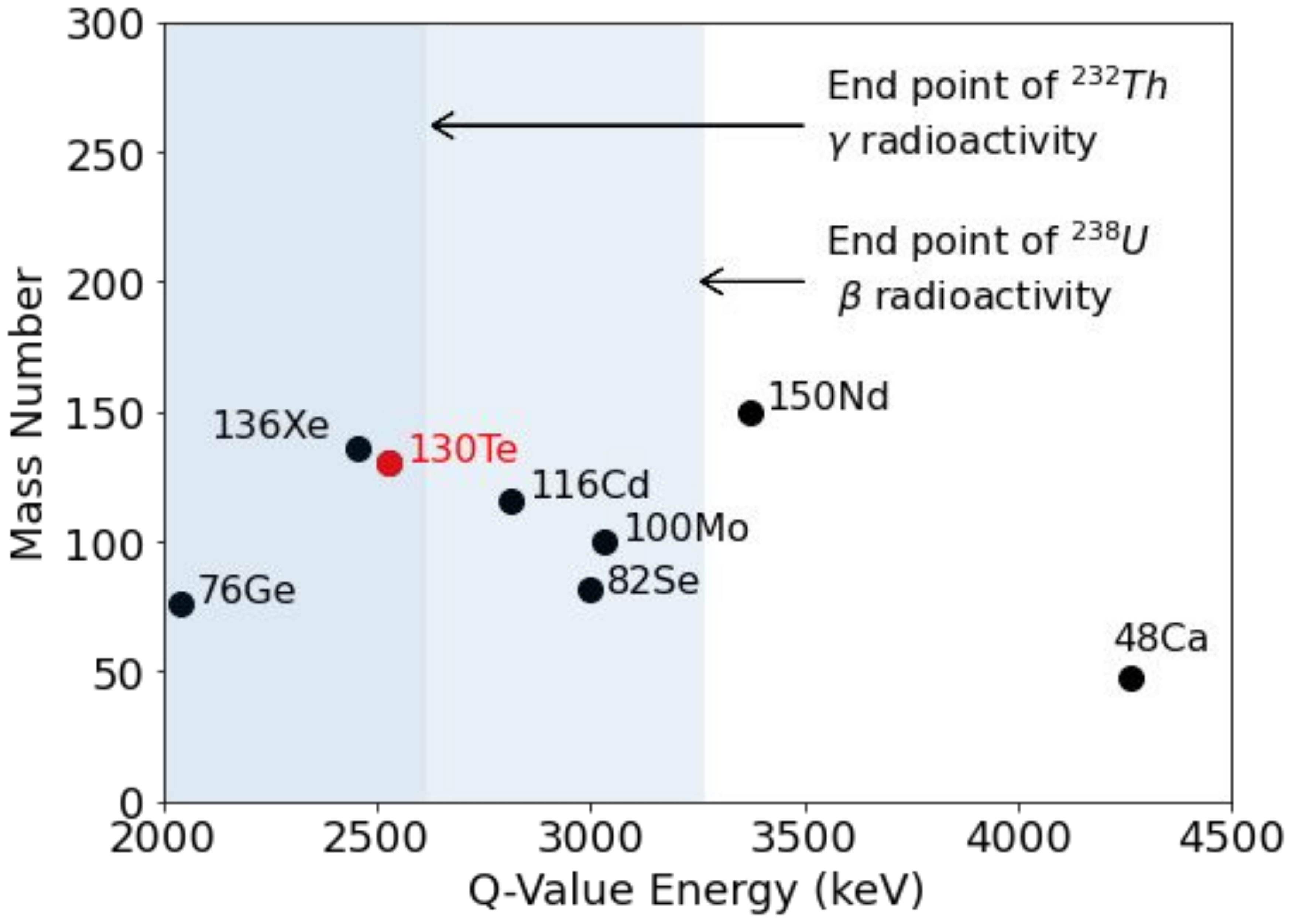
Why Tellurium-130?

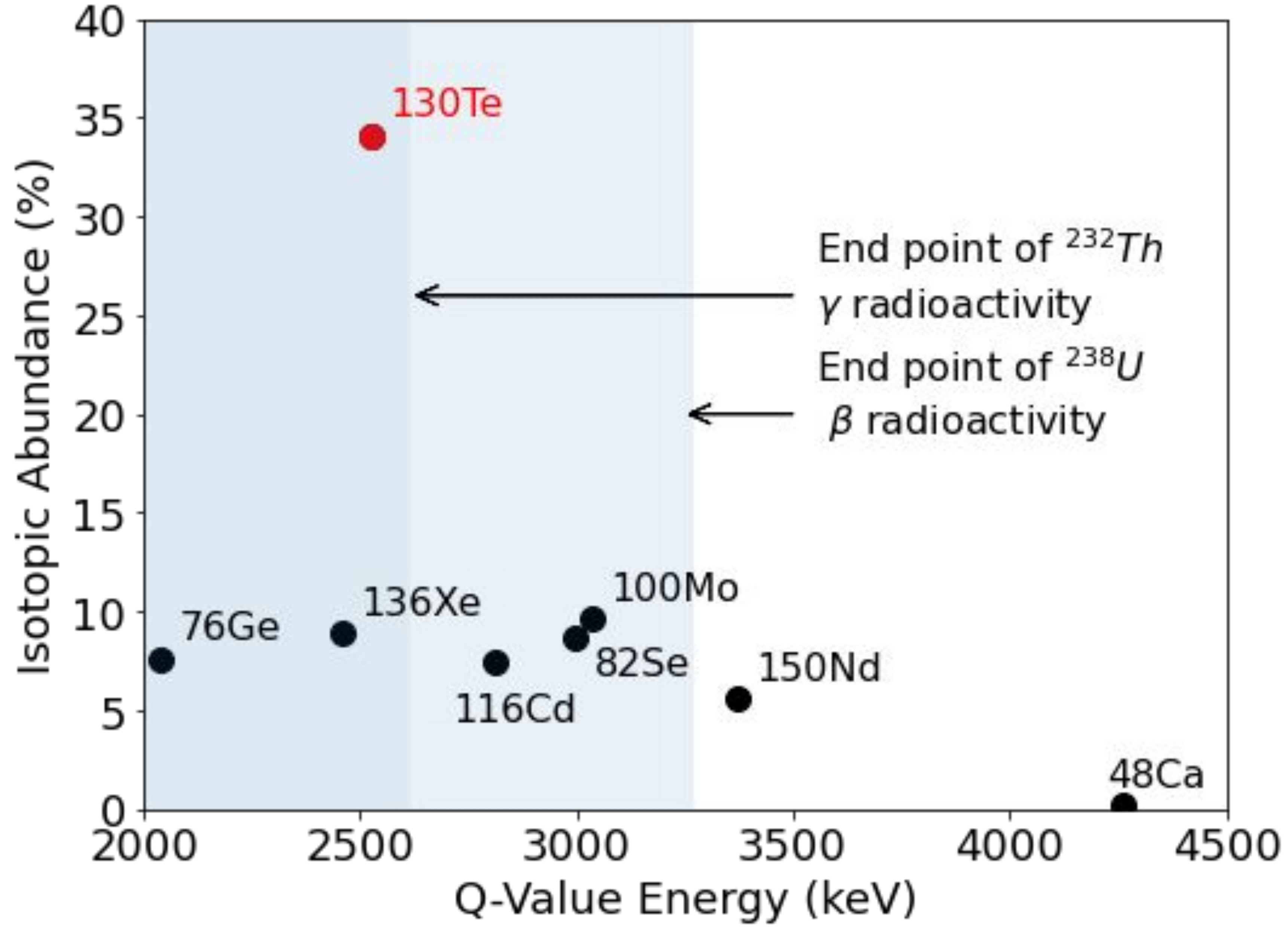
Pros:

- High natural abundance keeps enrichment costs low
- Can be made into a durable crystal (TeO_2)
- Not directly on top of a background gamma line

Cons:

- Q-value is below 2615 keV line from Tl-208 (Compton contribution to background)





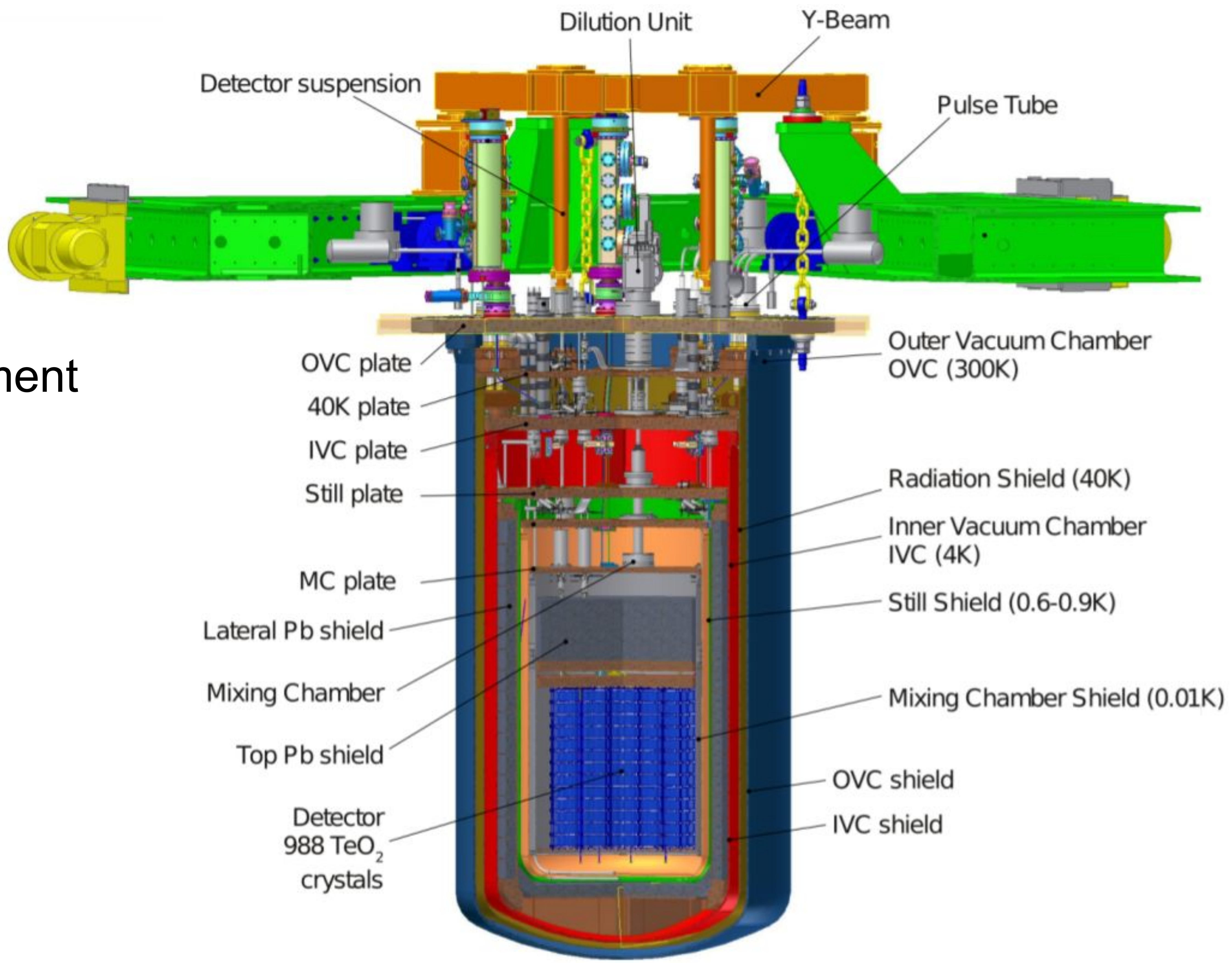
Plots made by E.V. Hansen

The CUORE Cryostat

- Cryogen-free cryostat
- Cools down ~1 ton detector to ~10 mK
- Mechanically decoupled from the environment

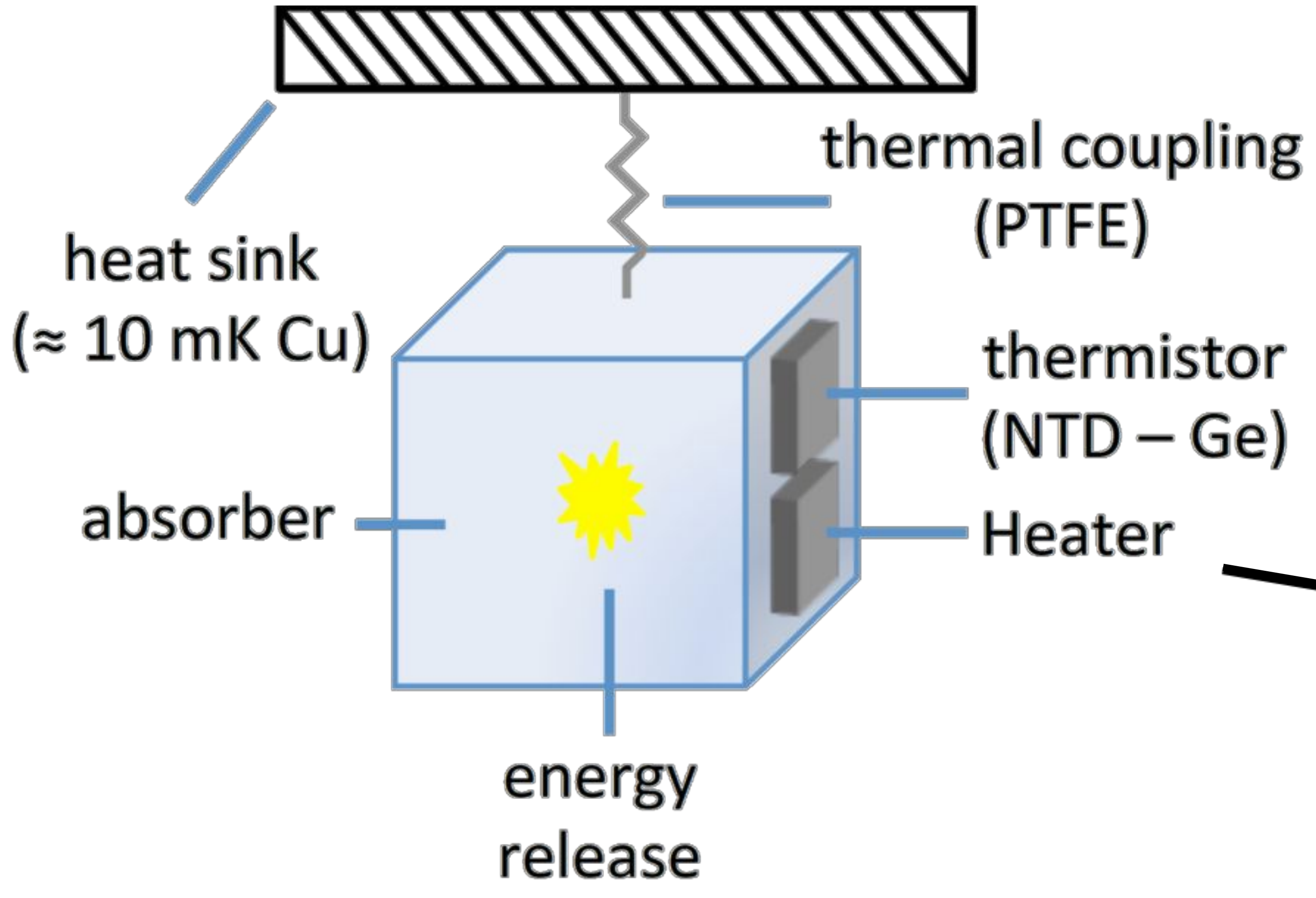
  to PT to cool down to ~4K
- Dilution refrigerator down to operating

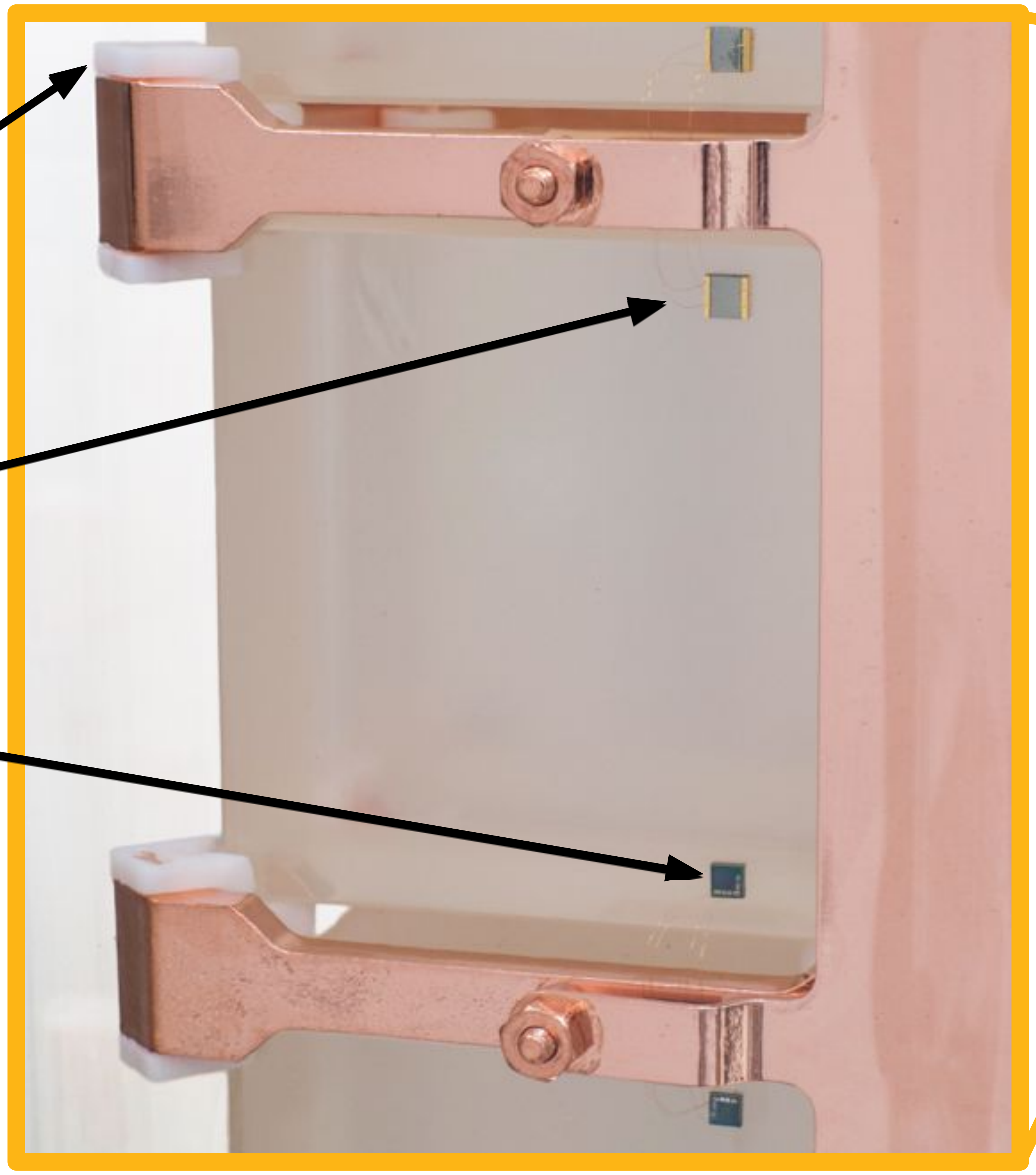
  temperature ~10 mK
- Nominal cooling power: 4 μW @ 10mK
- Cryostat total mass: ~30 tons
- Mass at T < 4K: ~15 tons
- Mass at T < 50 mK: ~3 tons (Pb, Cu and TeO_2)

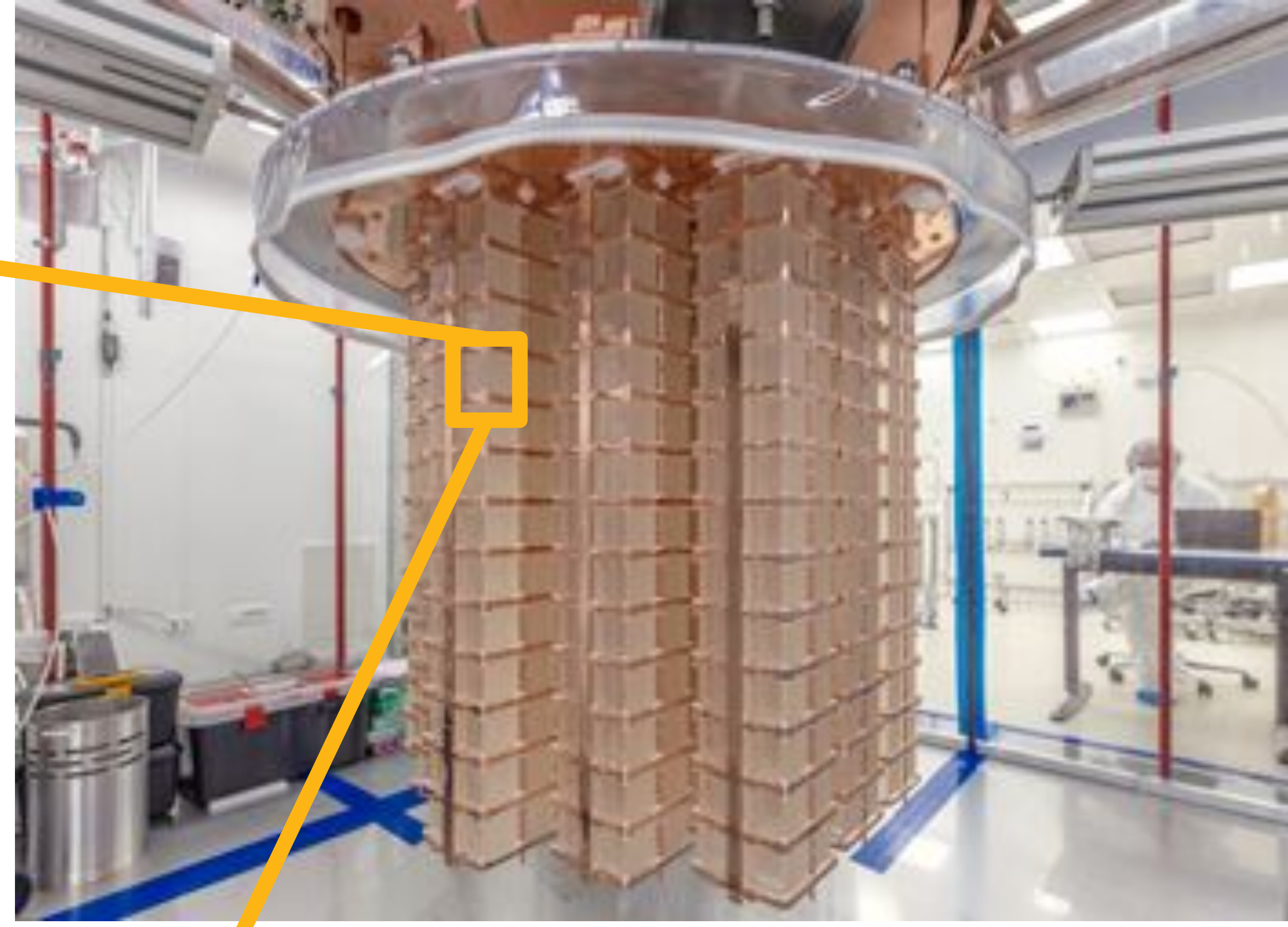


The CUORE experiment at the LNGS.
A. Branca (for the CUORE collaboration)
arXiv:1705.00005v2

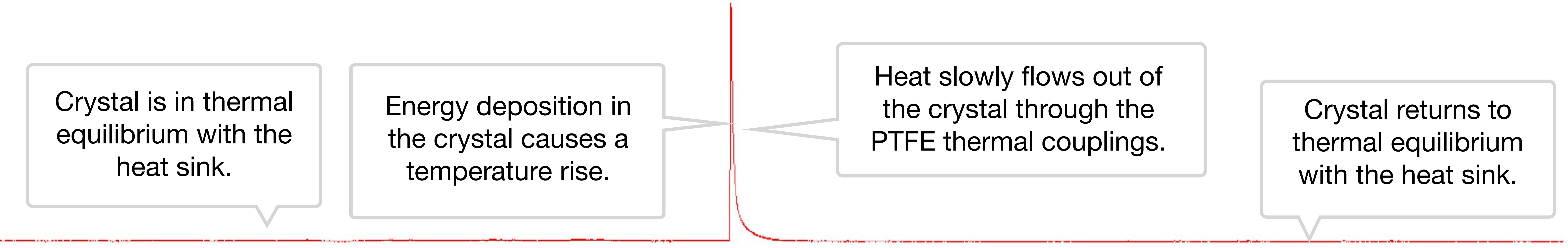
Detector Technology



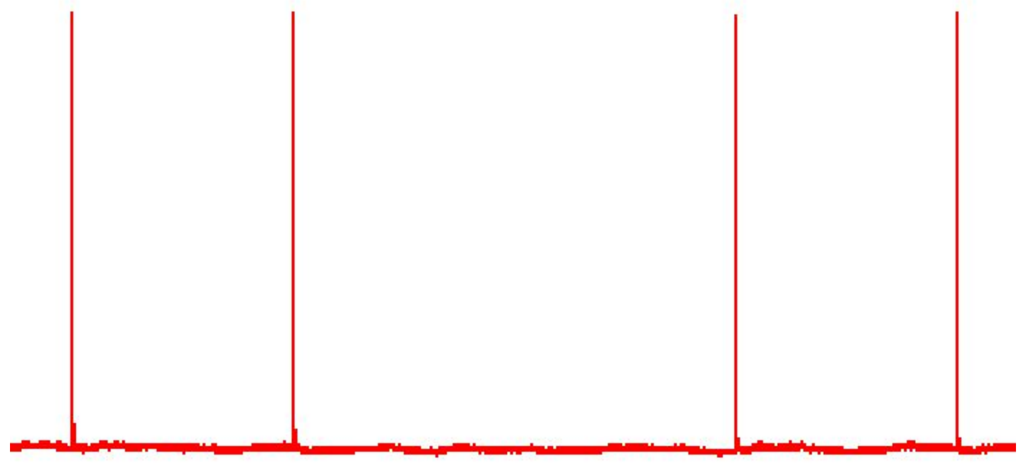




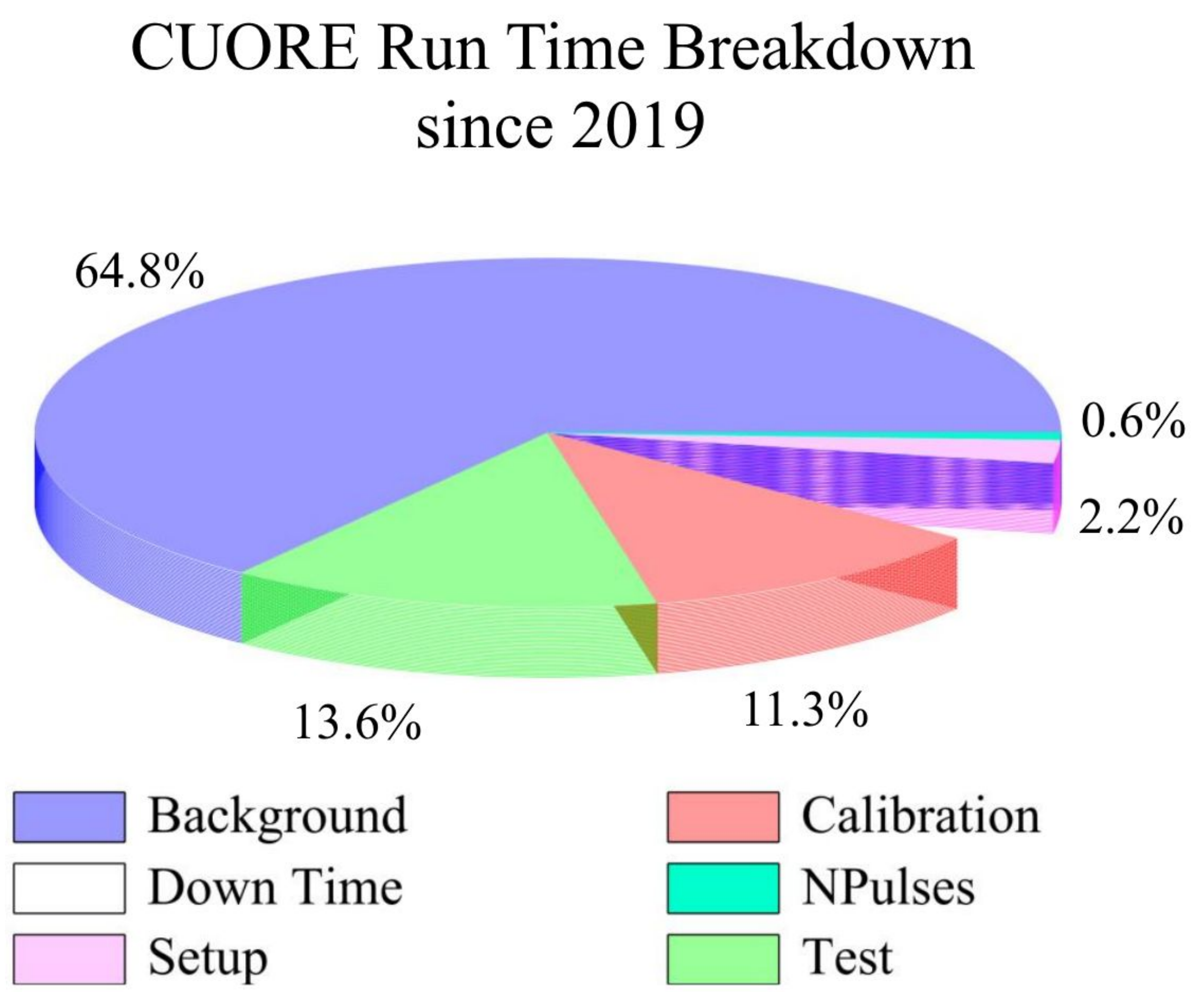
Particle interactions in the crystal are represented by the voltage readout of the NTD Ge thermistor.



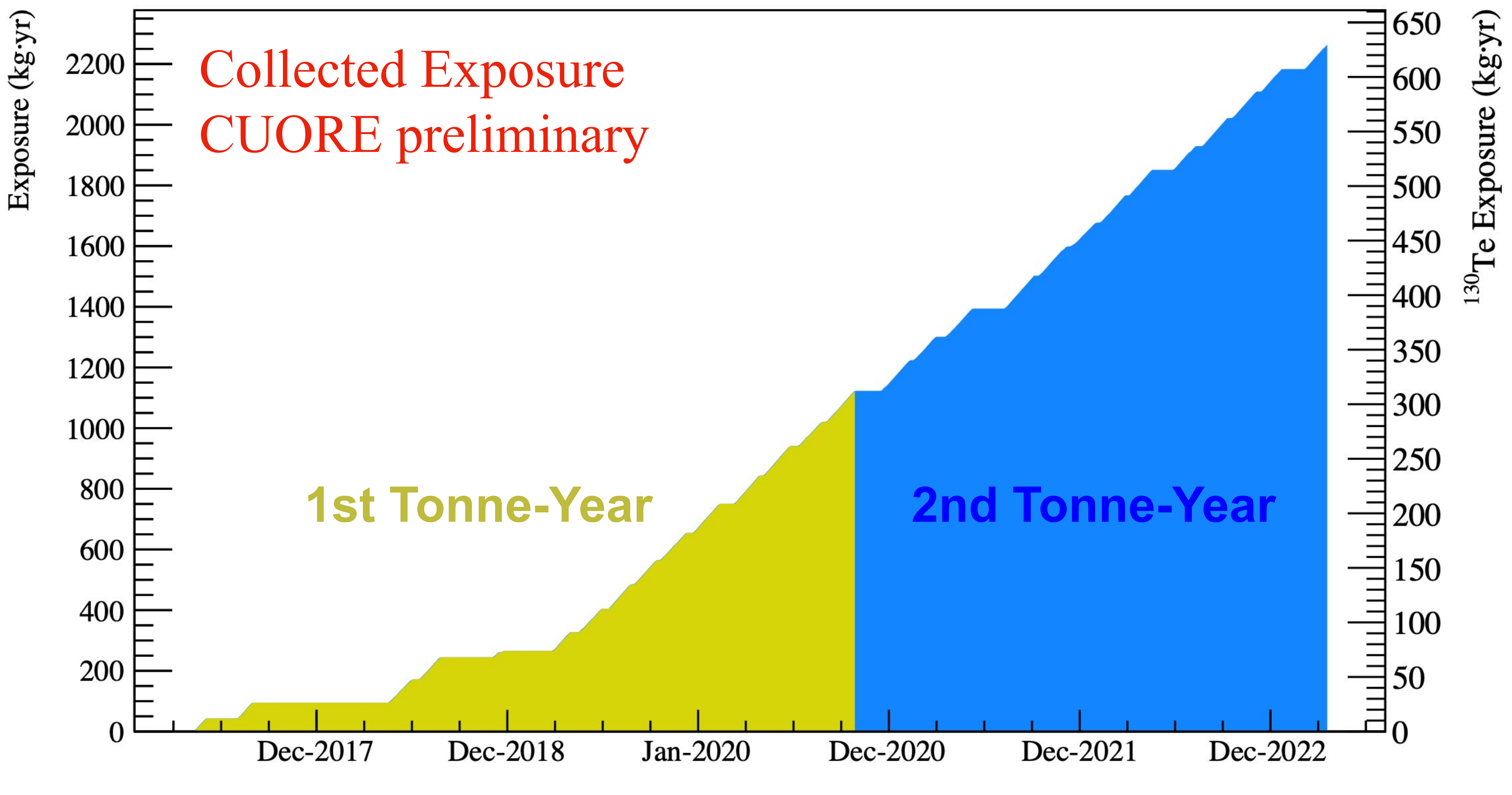
Silicon heater provides standardized heat pulses for thermal gain correction.



Data-taking



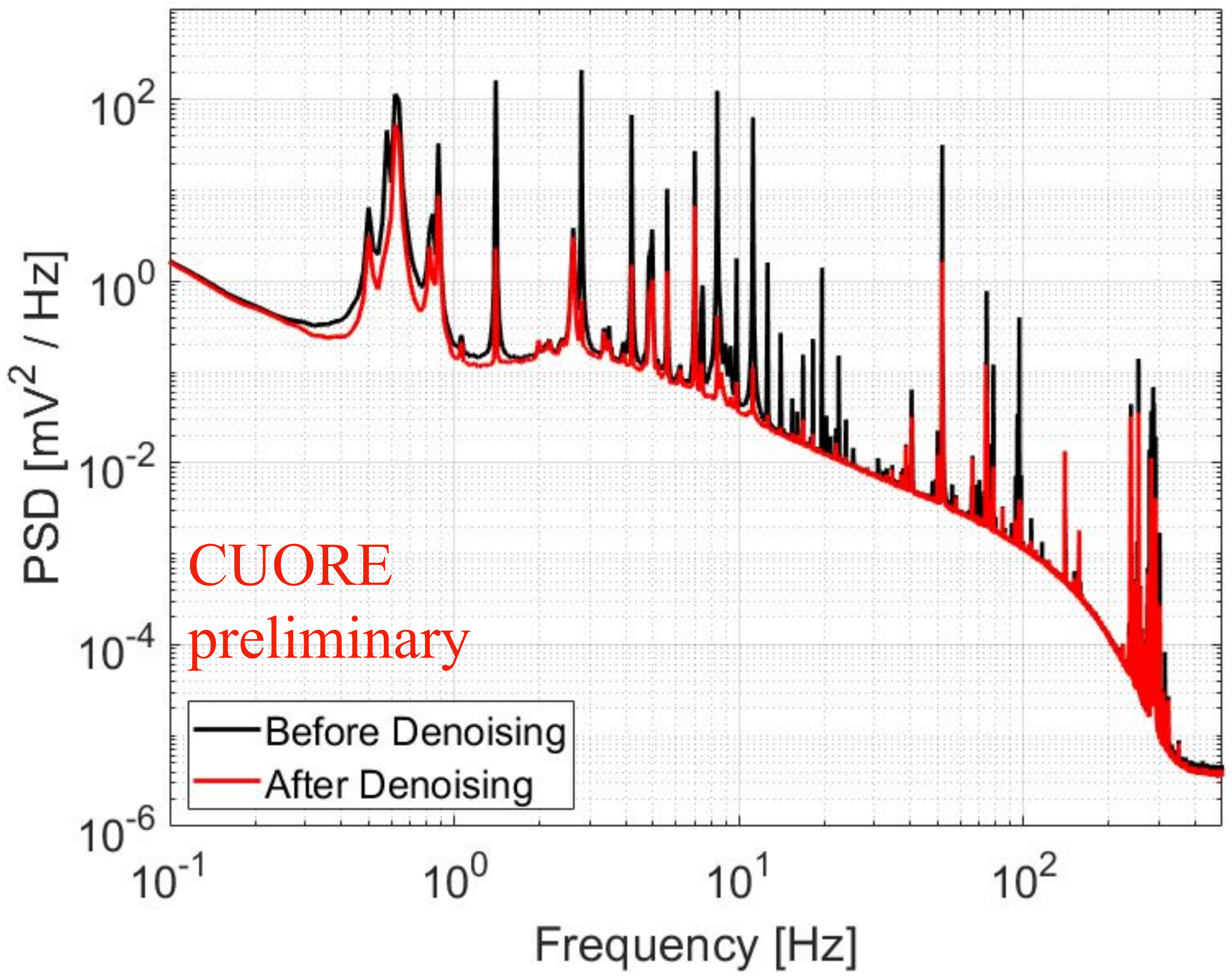
CUORE Run Time Breakdown
since 2019
64.8%
0.6%
2.2%
13.6%
11.3%
Background
Down Time
Setup
Calibration
NPulses
Test



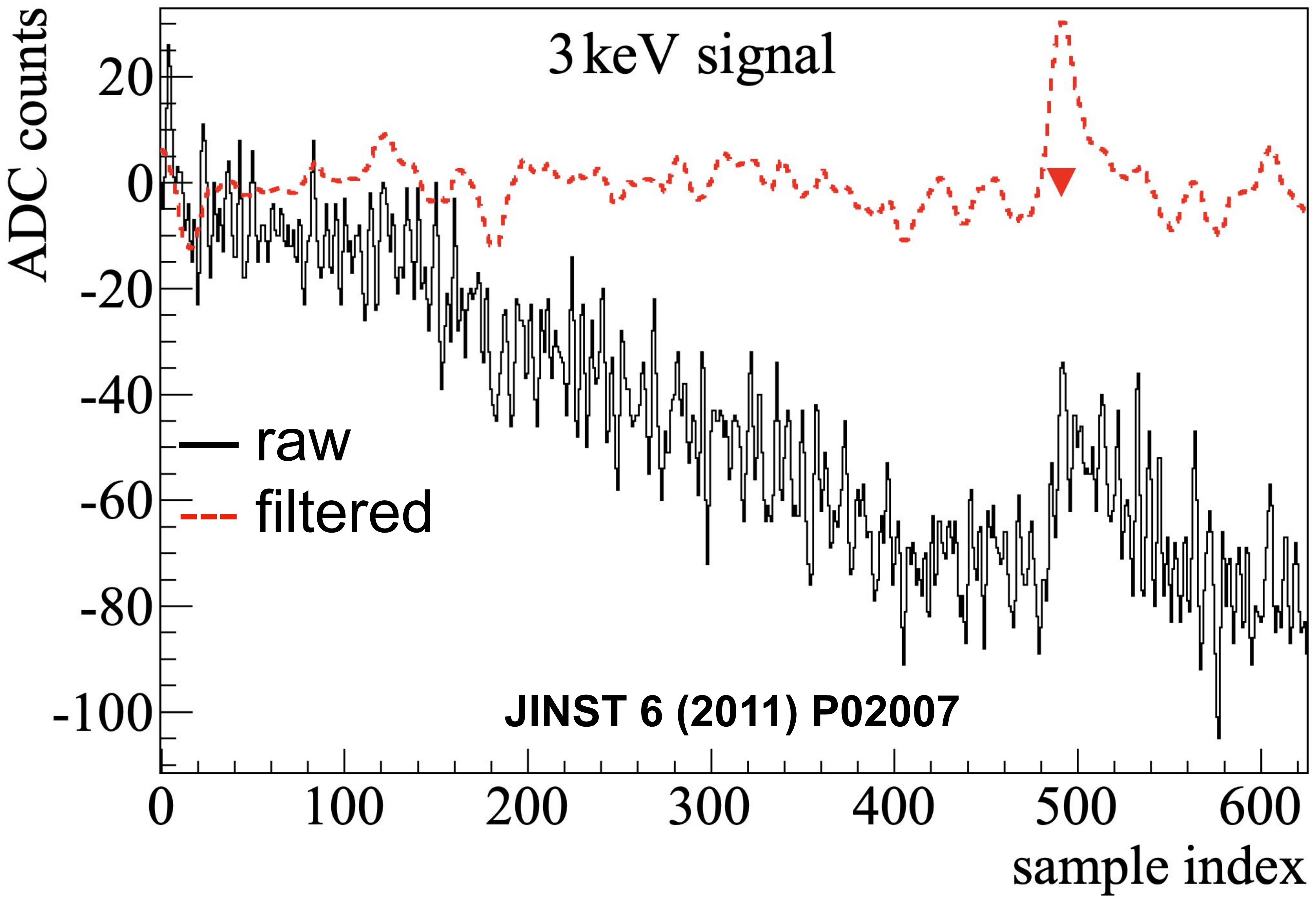
Collected Exposure
CUORE preliminary
1st Tonne-Year
2nd Tonne-Year
Exposure (kg·yr)
^{130}Te Exposure (kg·yr)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
0
50
100
150
200
250
300
350
400
450
500
550
600
650
Dec-2017
Dec-2018
Jan-2020
Dec-2020
Dec-2021
Dec-2022

Offline Signal Processing

- Denoising algorithm (new to the analysis)
- Reduces noise correlated with measured vibrations
- Auxiliary devices include microphones, accelerometers, seismometers

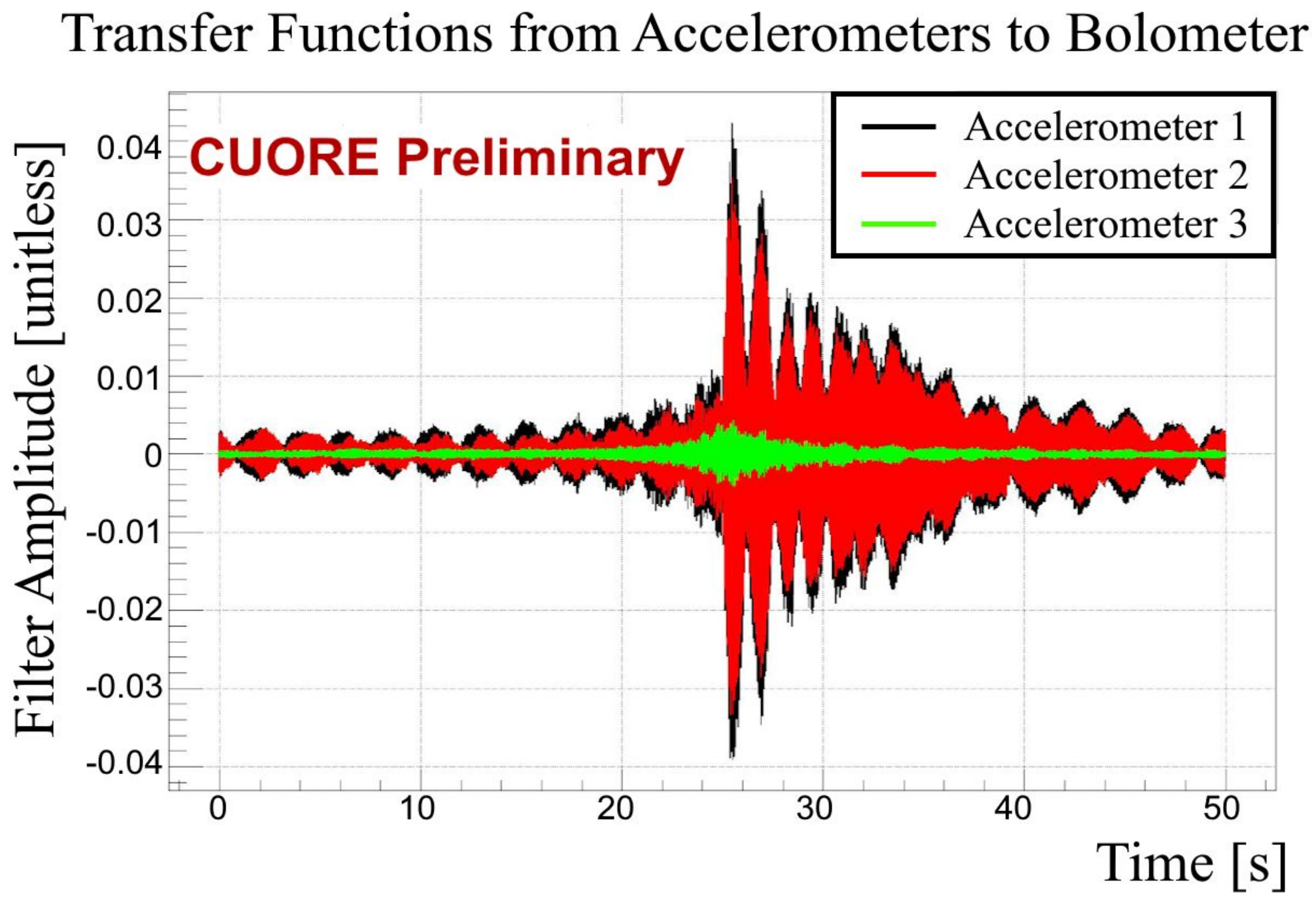


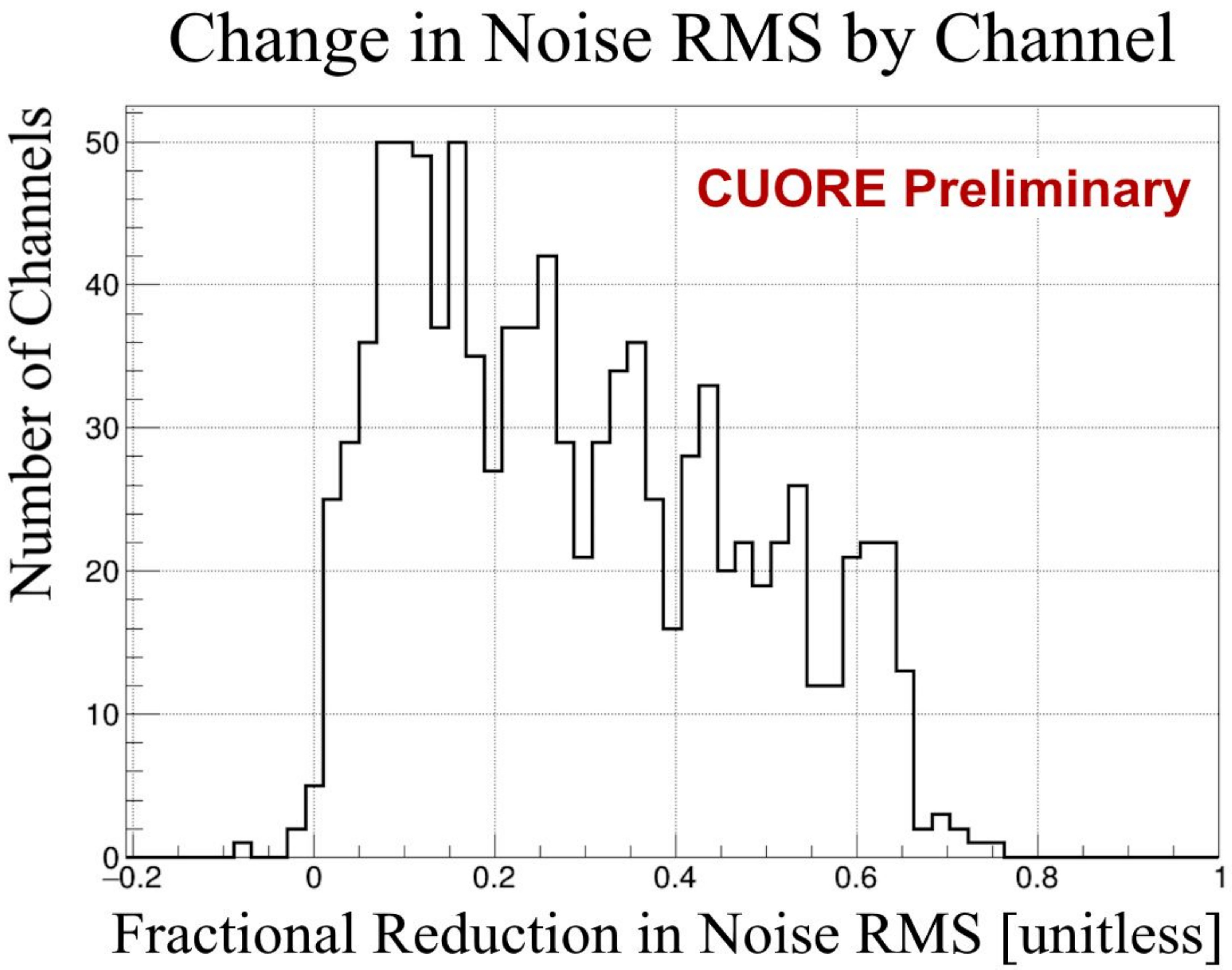
- Optimum trigger (OT) algorithm
- Applies filter and identifies pulses
- Lowers energy detection thresholds

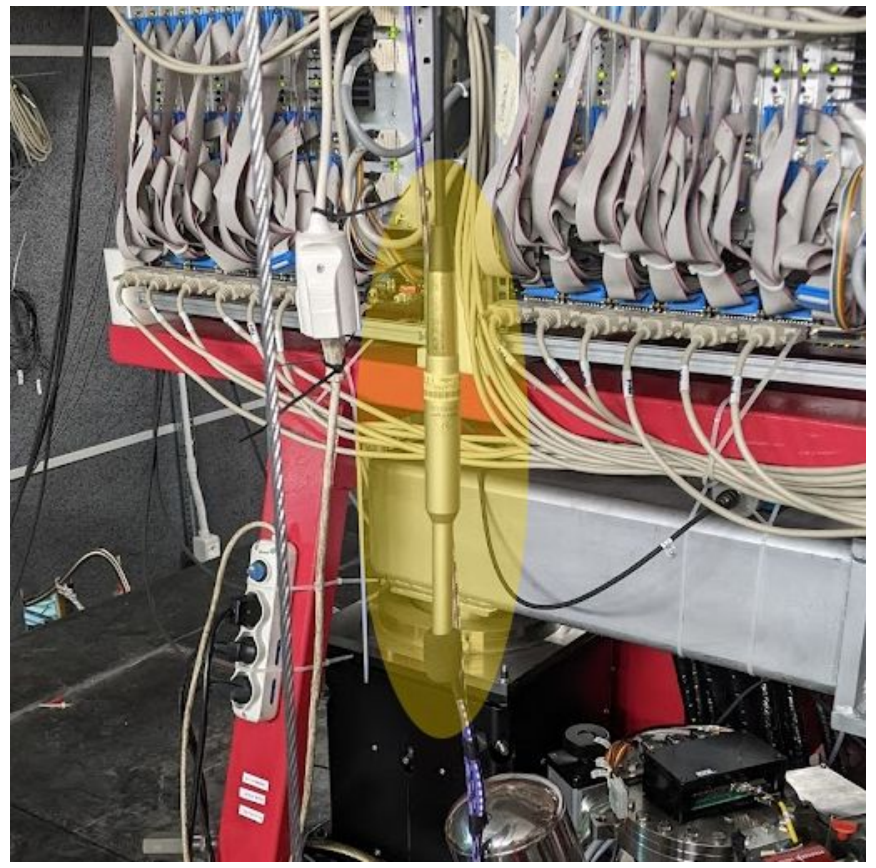


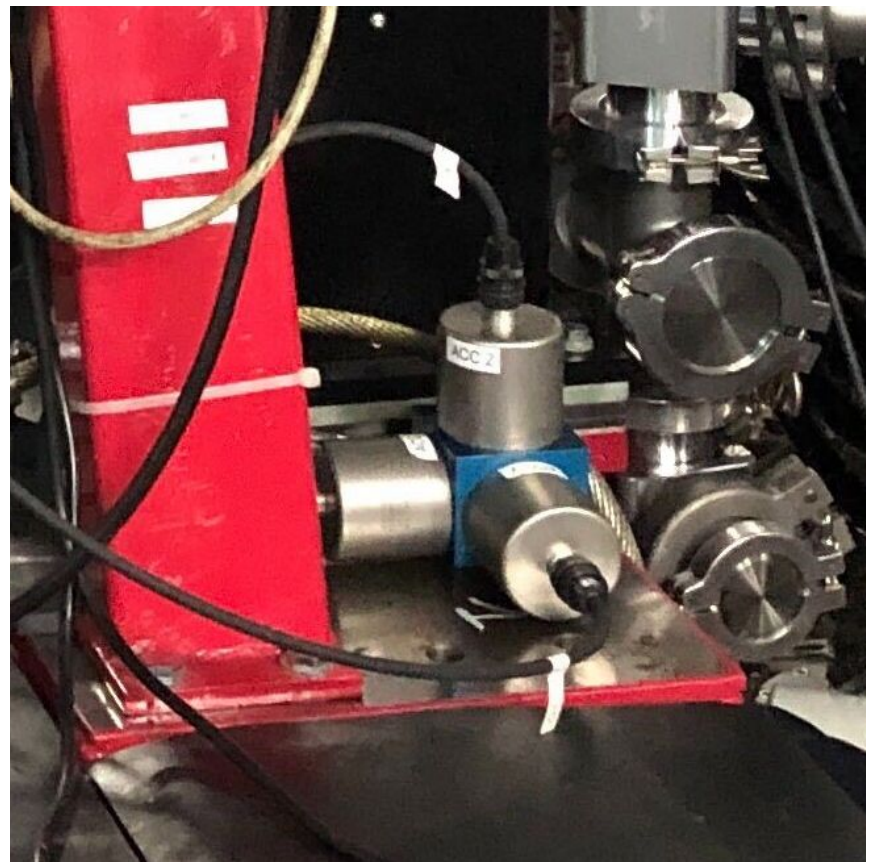
Denoising Algorithm

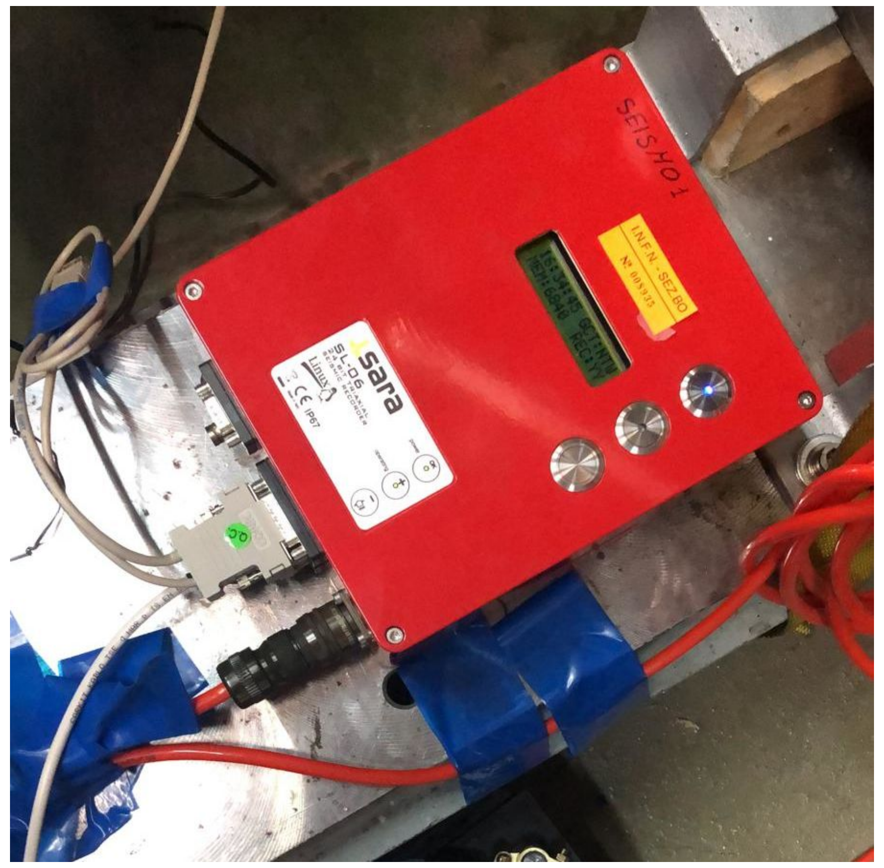
- Denoising uses a combination of microphones, accelerometers, and seismometers to remove vibrational noise from the CUORE data.
- Before applying the optimal filter, an average of ~40% of the detector noise is removed by the algorithm.
  - The median reduction in noise RMS by channel is ~25%.











Optimal Filter

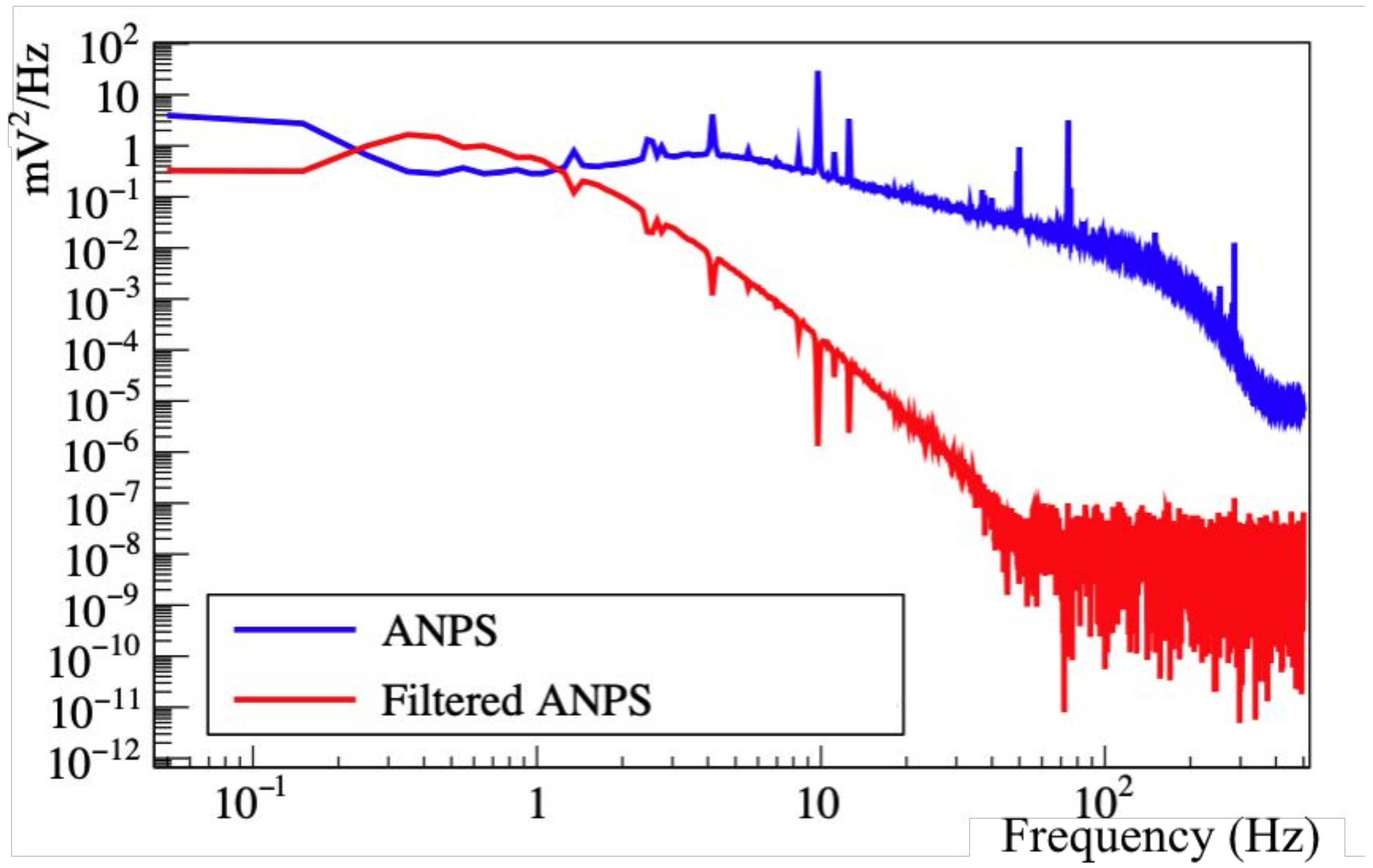
$$H(\omega_k) = h\frac{s^*(\omega_k)}{N(\omega_k)}e^{j\omega_k i_{max}}$$

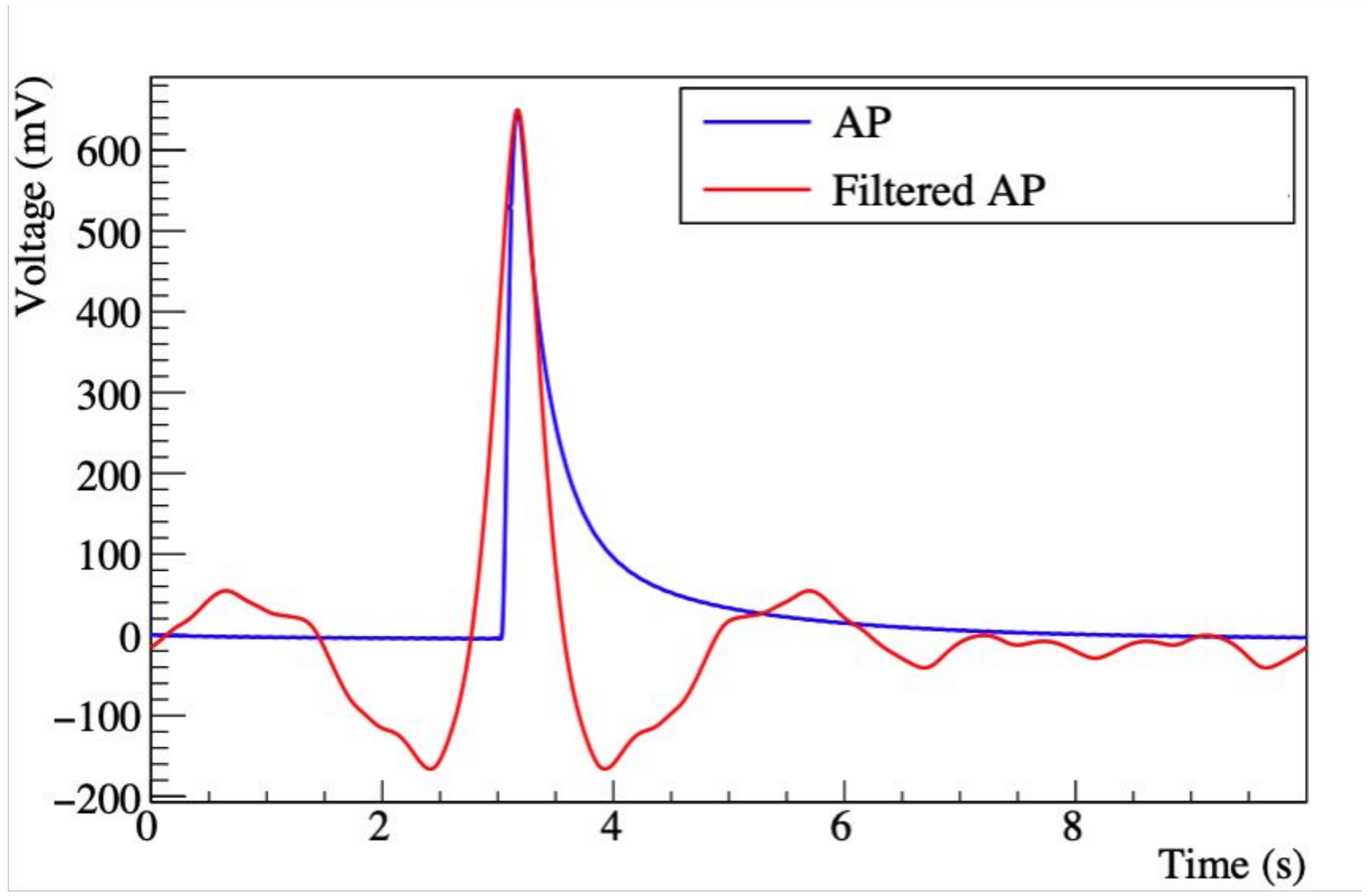
Signal template for each channel-dataset

Typical noise for each channel-dataset

Transfer function directly proportional to the signal to noise ratio

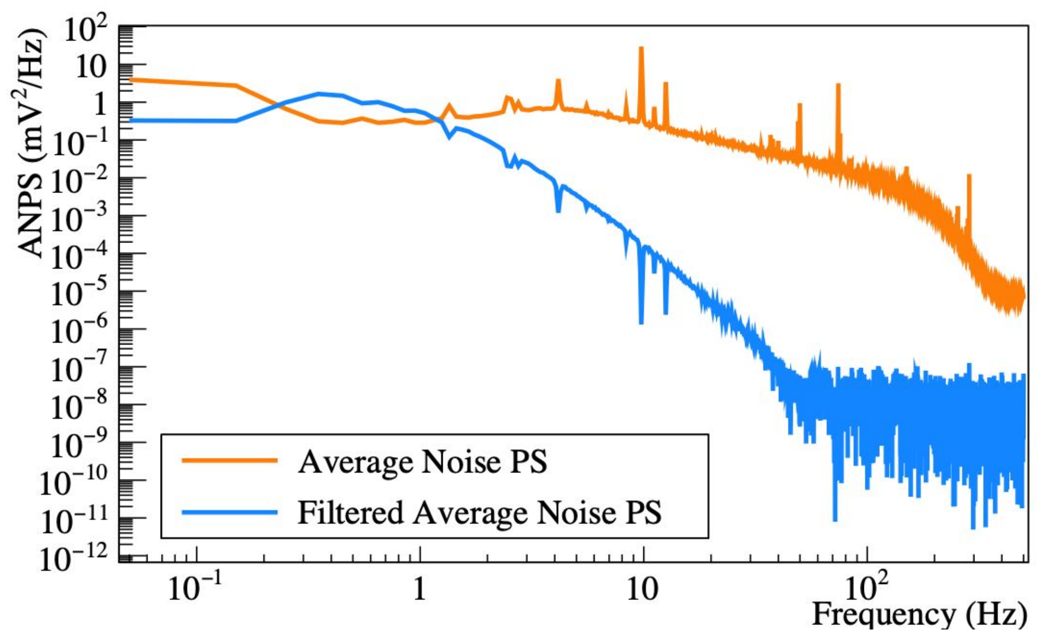
We trigger our continuous waveforms and we evaluate the pulse amplitude on the Optimum Filtered data.



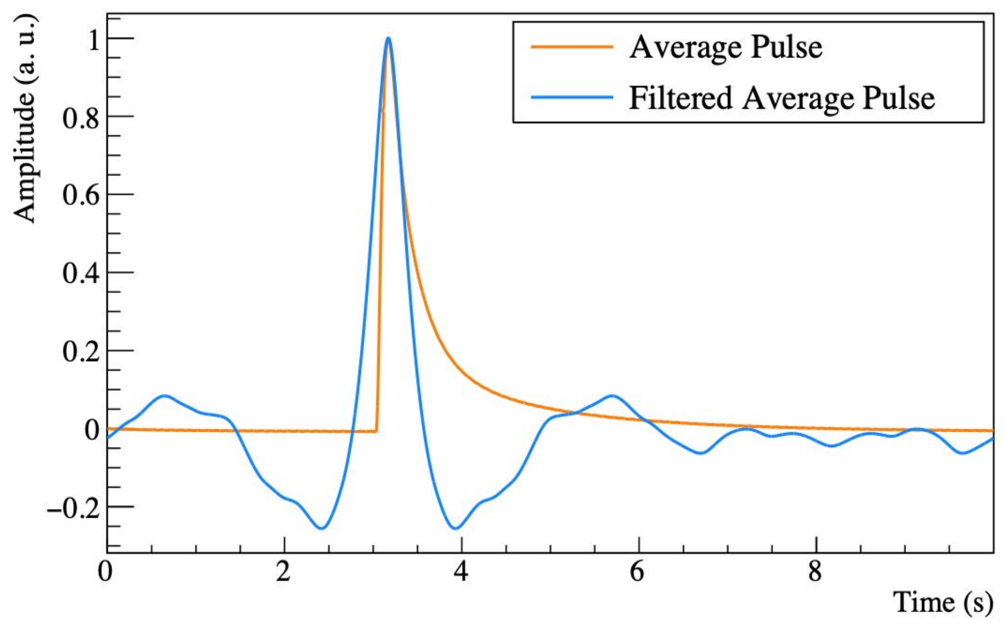


Energy Reconstruction

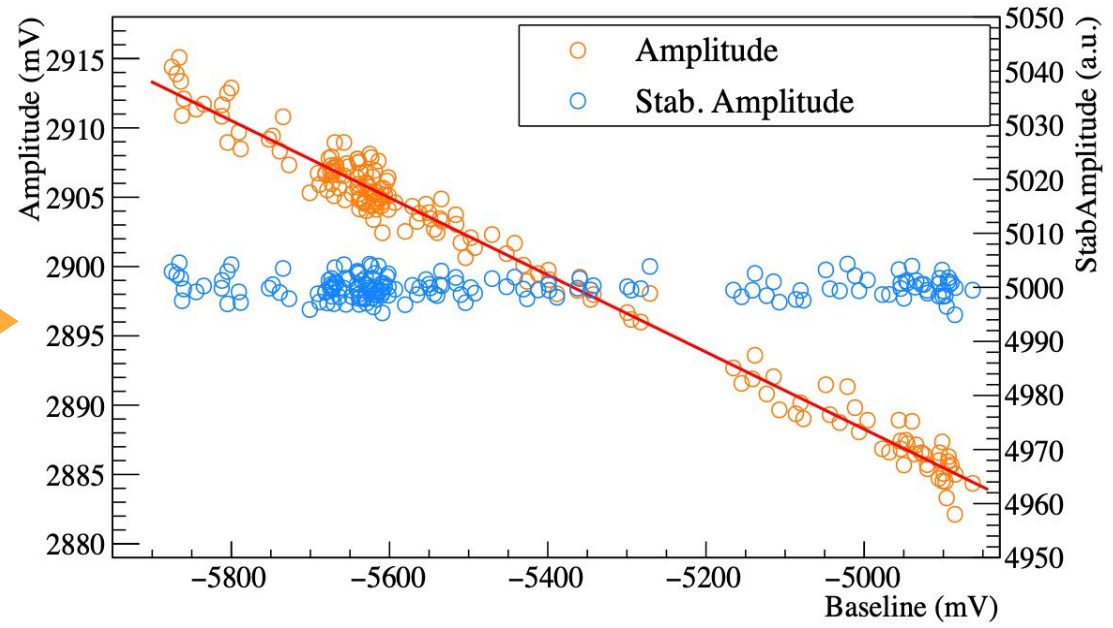
Signal Processing



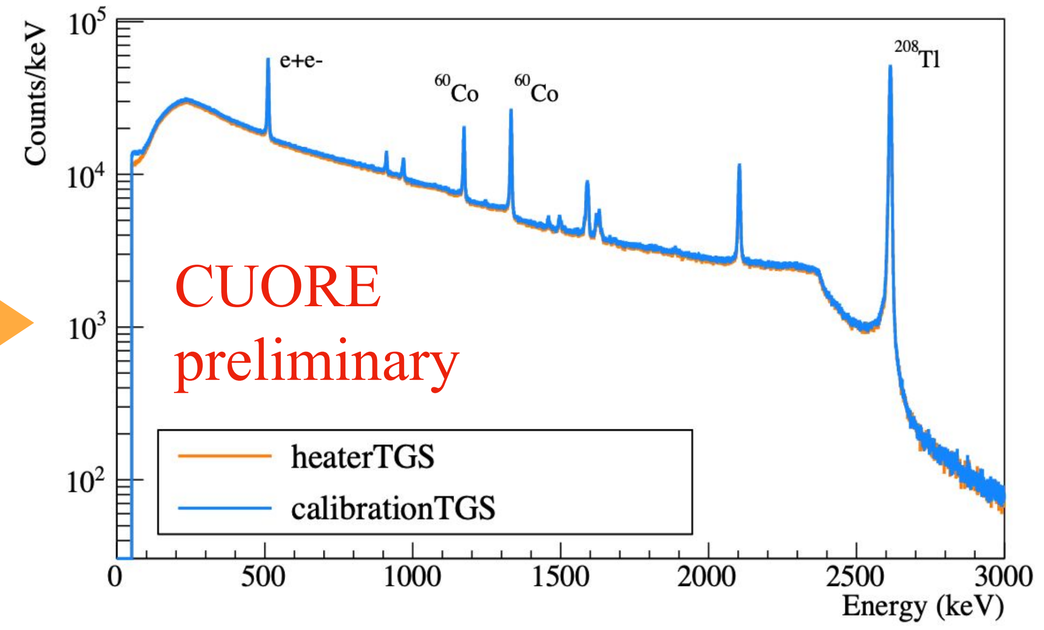
Amplitude evaluation



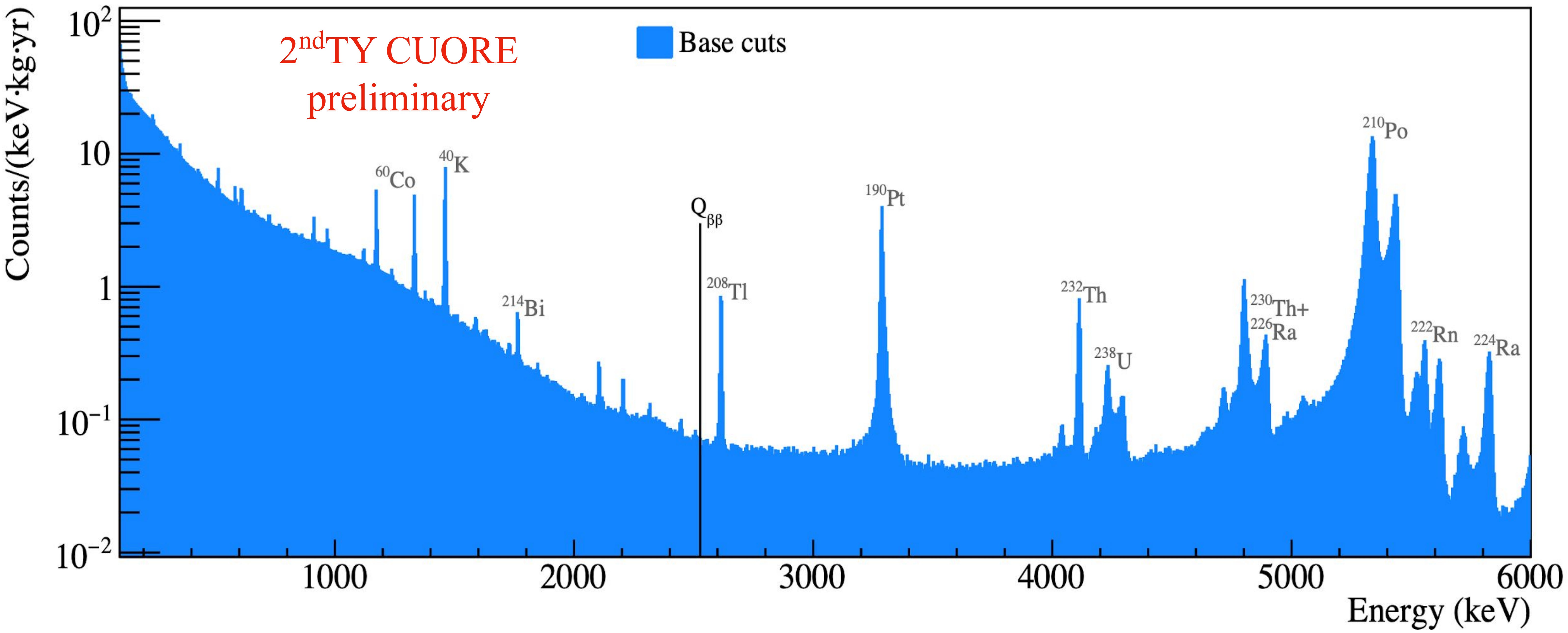
Thermal gain stabilization



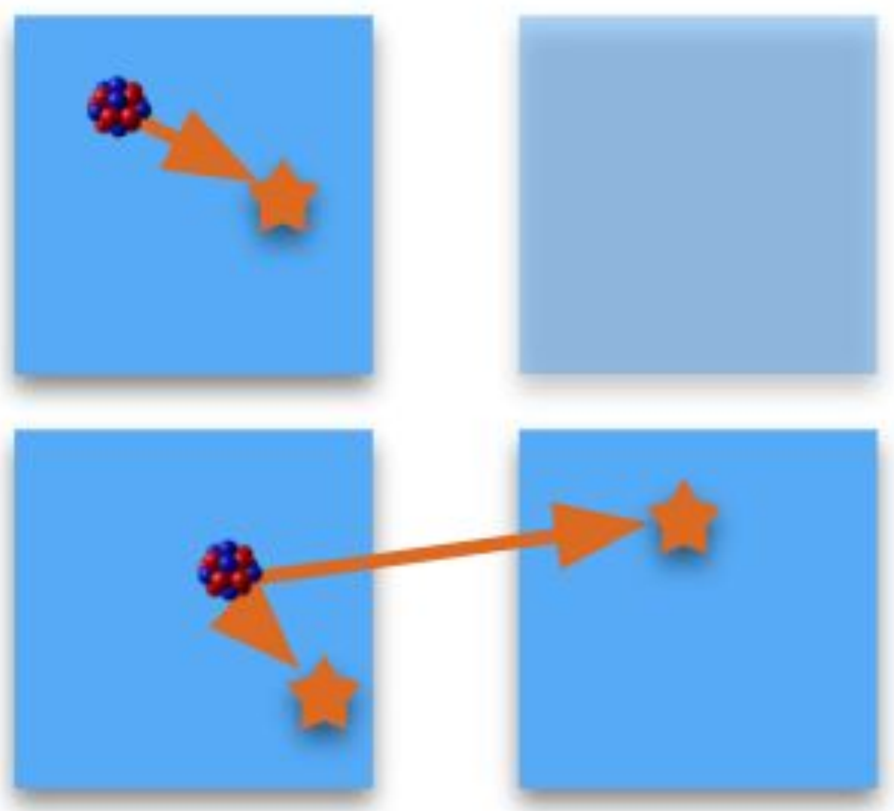
Energy calibration



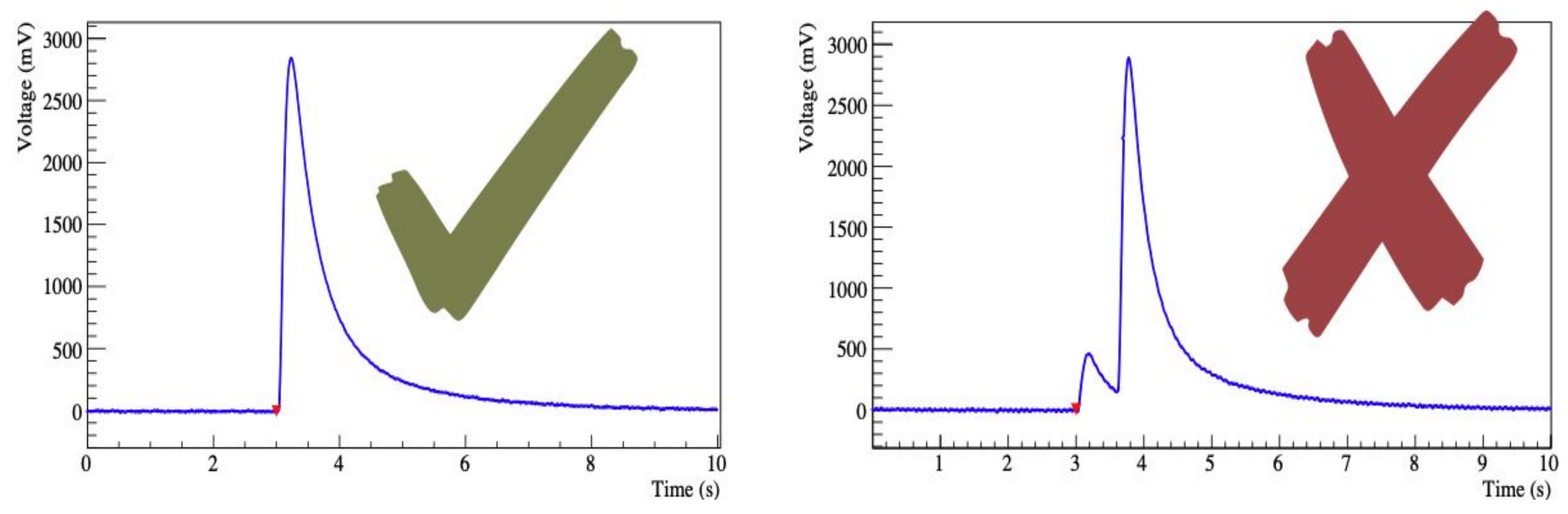
- Digital filter designed to maximize SNR is applied
- Amplitude is evaluated from the filtered pulse peak
- Thermal gain correction based on gain observed in standardized heat and/or energy pulses
- Energy calibration is applied based on measurements taken during radioactive source deployment



Event Selection and Methods for 0νββ search



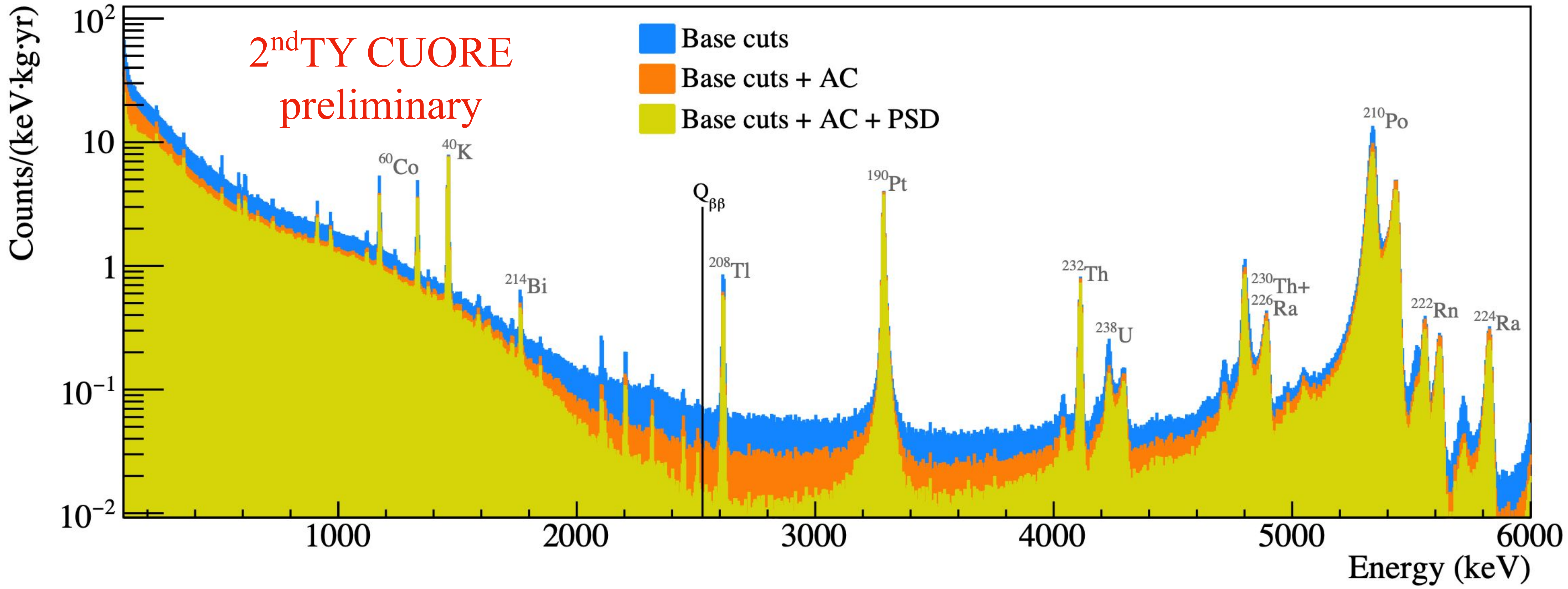
- Anti-coincidence (AC) cut selects single-site (M1) events



- Pulse shape discrimination (PSD) implemented using principal component analysis (PCA)

Analysis procedure for the final fit:

- Blind the analysis to prevent bias by *salting* the data, i.e. exchanging events between $Q_{\beta\beta}$ and the ^{208}Tl 2615 keV peak
- Evaluate the detector response from calibration data and scale the response to match that of physics data
- Finalize fit model parameters before unblinding and re-fitting



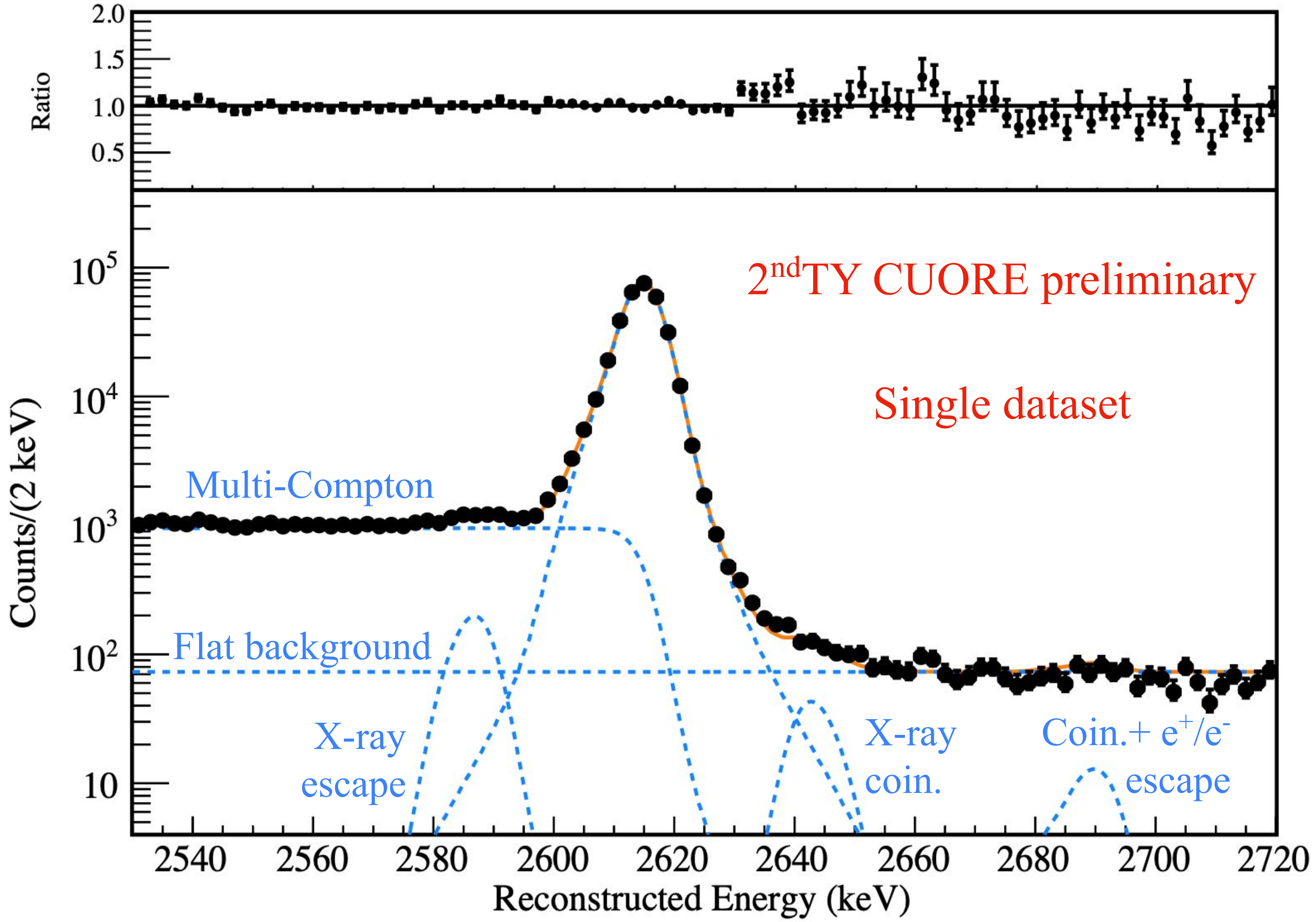
Evaluating Detector Response

Gamma peak at 2615 keV from calibration data provides a sufficient number of events to fit the detector response in an energy region close to $Q_{\beta\beta}$.

Fit model includes several structures:

- 3-Gaussian response function
- Multi-compton background
- Flat background
- (2615 – 30) keV X-ray escape peak
- (2615 + 30) keV X-ray coincidence peak
- (2615 + 583 – 511) keV gamma coincidence with e^+/e^- escape peak

$$\Delta E_{2615\,keV,\,2^{nd}TY} = 7.43 \pm 0.37\,keV$$



Scaling the Detector Response to Physics Data

In physics data, we expect the resolution of the detector to be different than during calibration:

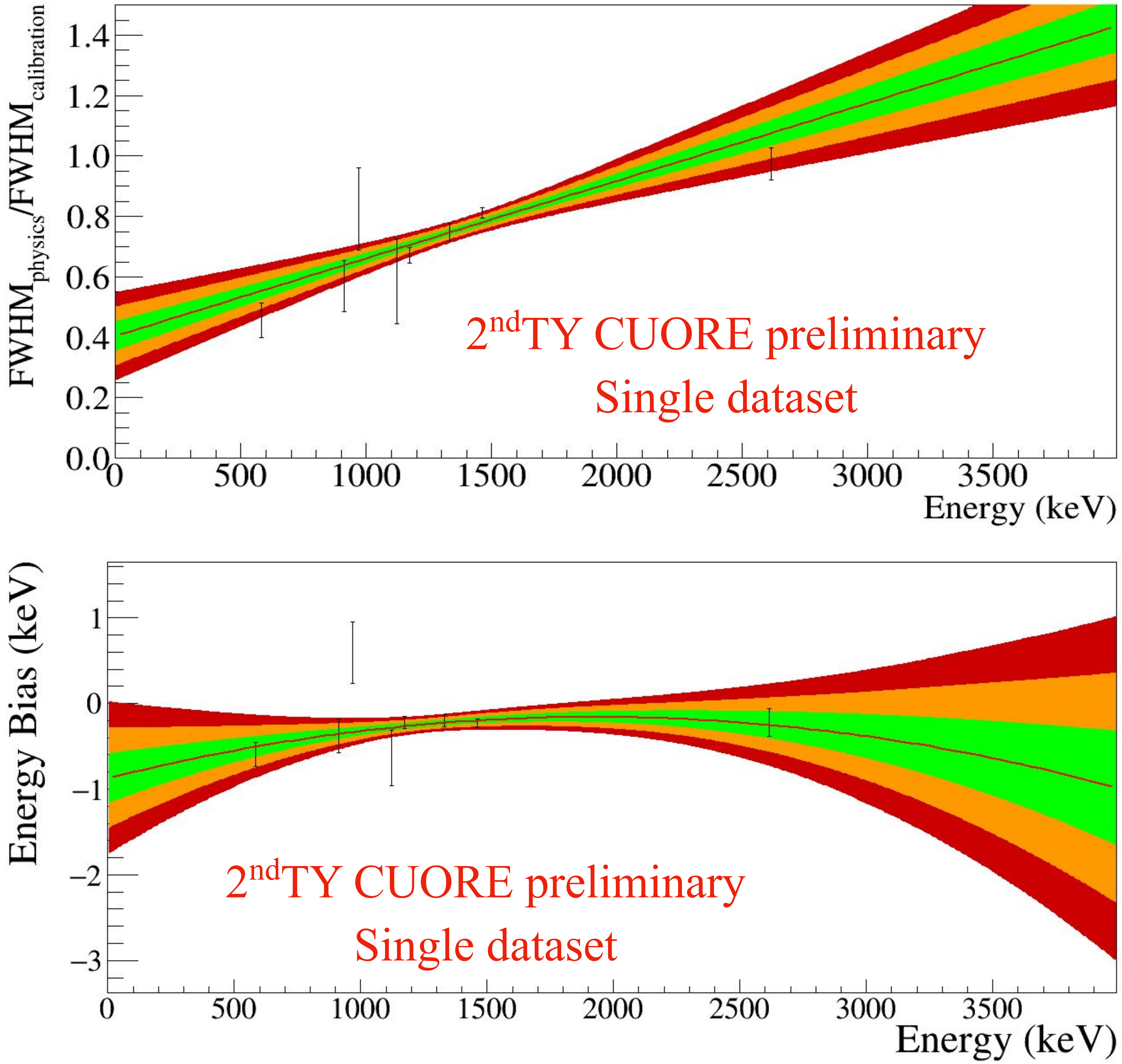
- Average noise power spectrum is built from physics data and noise can change during calibration
- Pile-up rate is lower in physics data than in calibration

We determine the detector response at $Q_{\beta\beta}$ by:

- Taking peak shape parameters from calibration
- Fitting peaks in the physics data spectrum
- Evaluating the resolution and energy bias at each peak, then scaling each to $Q_{\beta\beta}$

$$\Delta E_{Q_{\beta\beta},\,2^{nd}TY} = 7.26^{+0.43}_{-0.47}\,keV,$$

$$E_{bias,\,2^{nd}TY} = -0.11^{+0.19}_{-0.25}\,keV$$

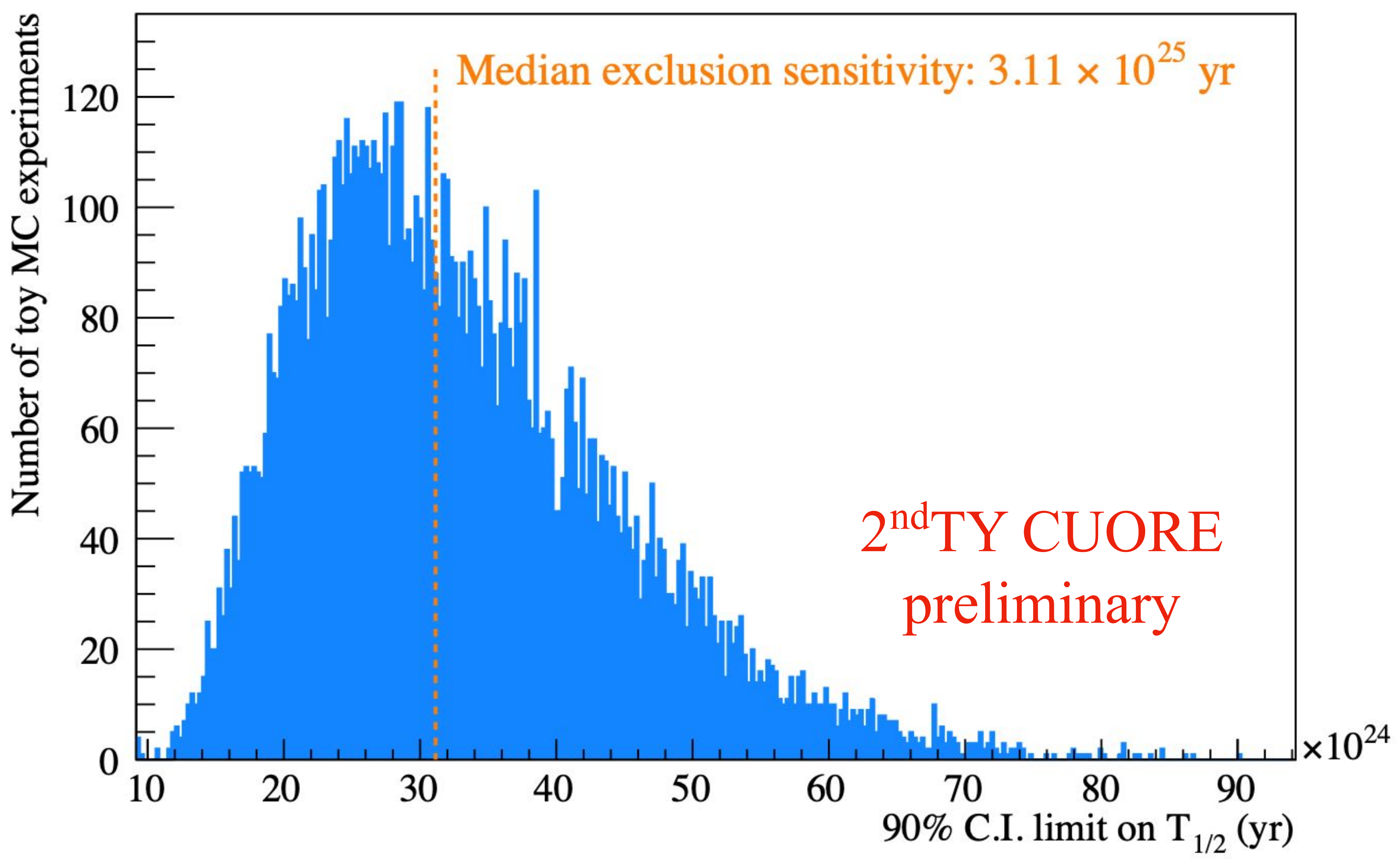


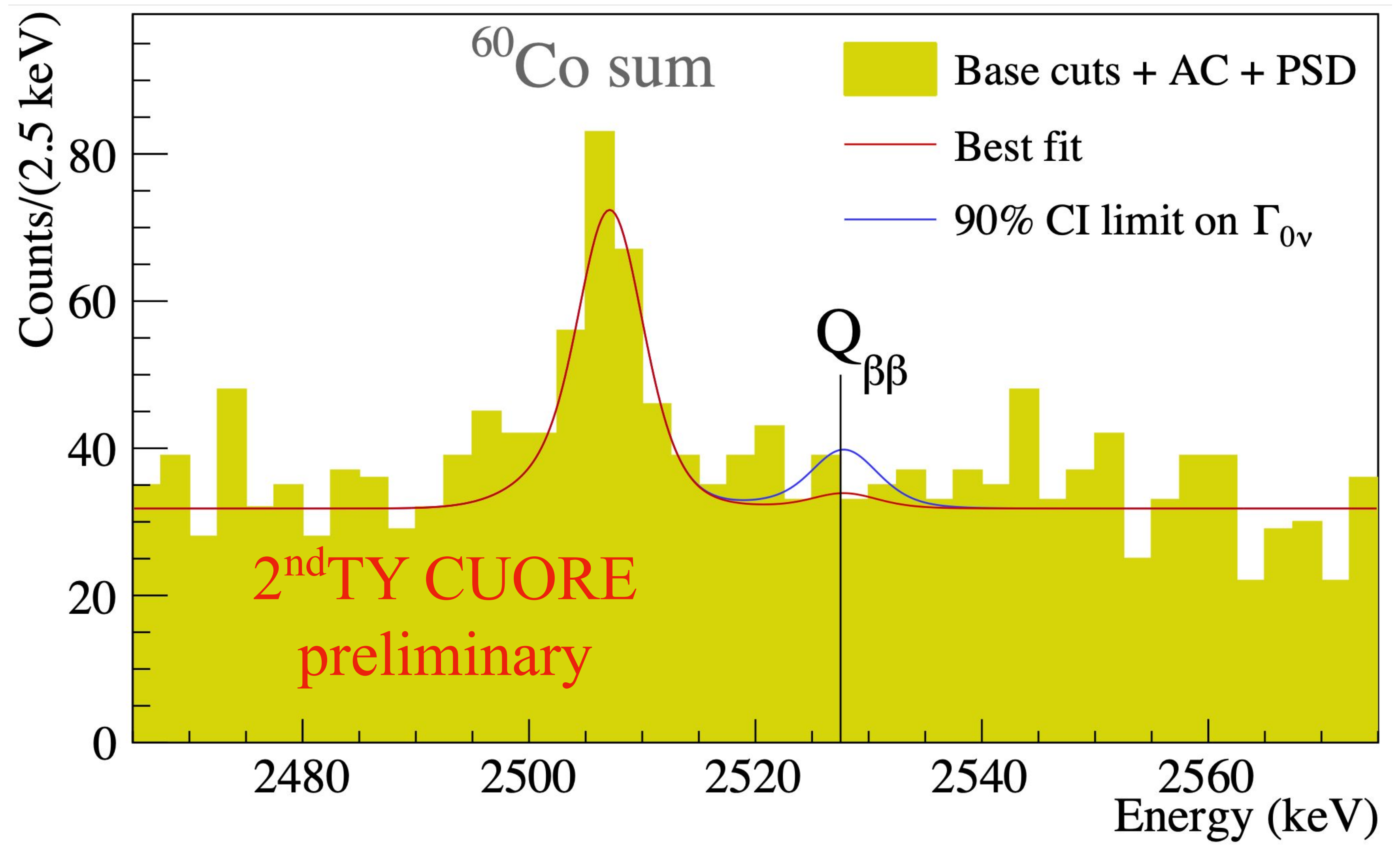
Results from the 2nd Tonne-Year of Data

Fit in ROI: [2465,2575] keV using BAT (Bayesian Analysis Toolkit) including systematics

- Median exclusion sensitivity: **3.11 x 10^{25} years** (90% C.I.)
  - We calculate the sensitivity by generating 10^4 toy experiments with no 0νββ signal and determining the median of all best fit values to $T_{1/2}$
- Background index (BI): **1.3 x 10^{-2} counts / (keV·kg·year)**
- 0νββ decay rate limit: **2.53 x 10^{-26} / year** (90% C.I.)
- 0νββ half-life limit: **$T_{1/2}$ > 2.74 x 10^{25} years** (90% C.I.)

No evidence of 0νββ decay





Combining Results

- CUORE results from 1 tonne-year of exposure found a limit on the half-life of 0νββ (90% C.I.):
  $T_{1/2}$ > 2.2 x 10^{25} years.

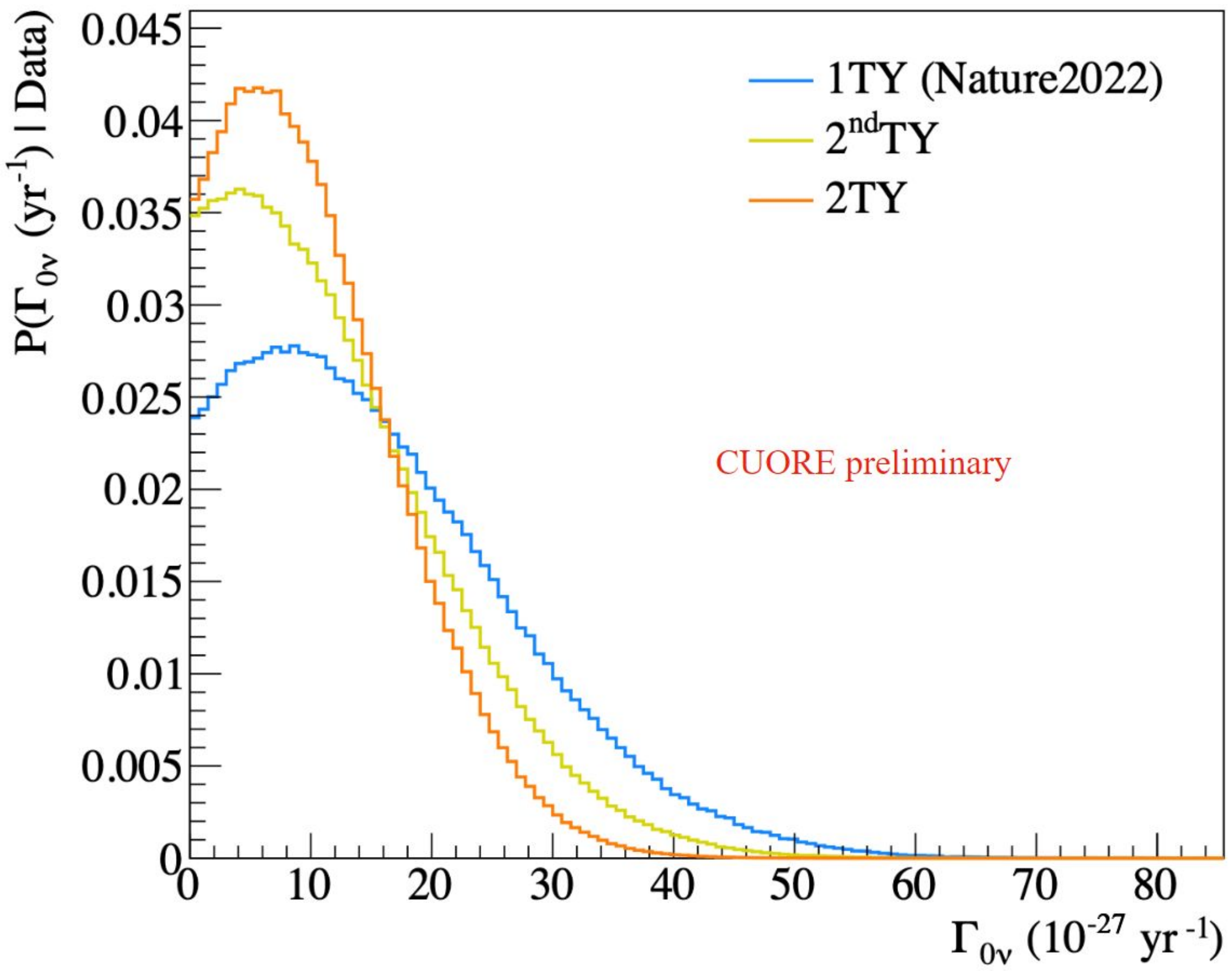
  → Result in Nature **604**, 53-58 (2022)

- Each tonne-year of data has a posterior on the 0νββ rate. We combine these posteriors to give us the posterior of the full 2TY exposure.

- Analyzed exposure: **2023 kg·years**

- Decay rate limit: **2.08 x 10^{-26} / year** (90% C.I.)

- Half-life limit: **$T_{1/2}$ > 3.33 x 10^{25} years** (90% C.I.)



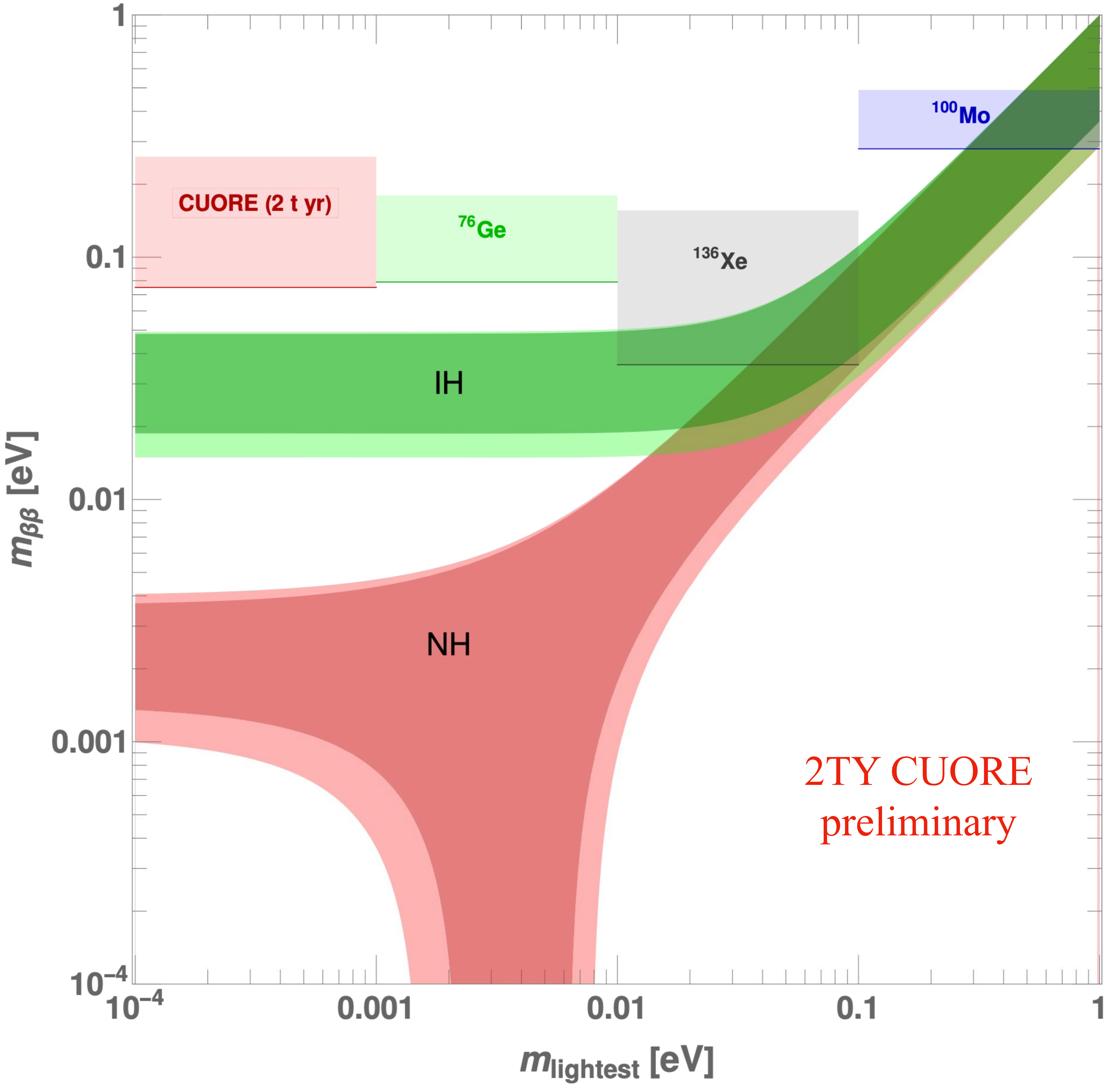
(Still) no evidence of 0νββ decay

Effective Majorana Mass Limit

CUORE's limit on $T_{1/2}$ for $0\nu\beta\beta$ decay in ^{130}Te gives us a limit on the effective Majorana mass:

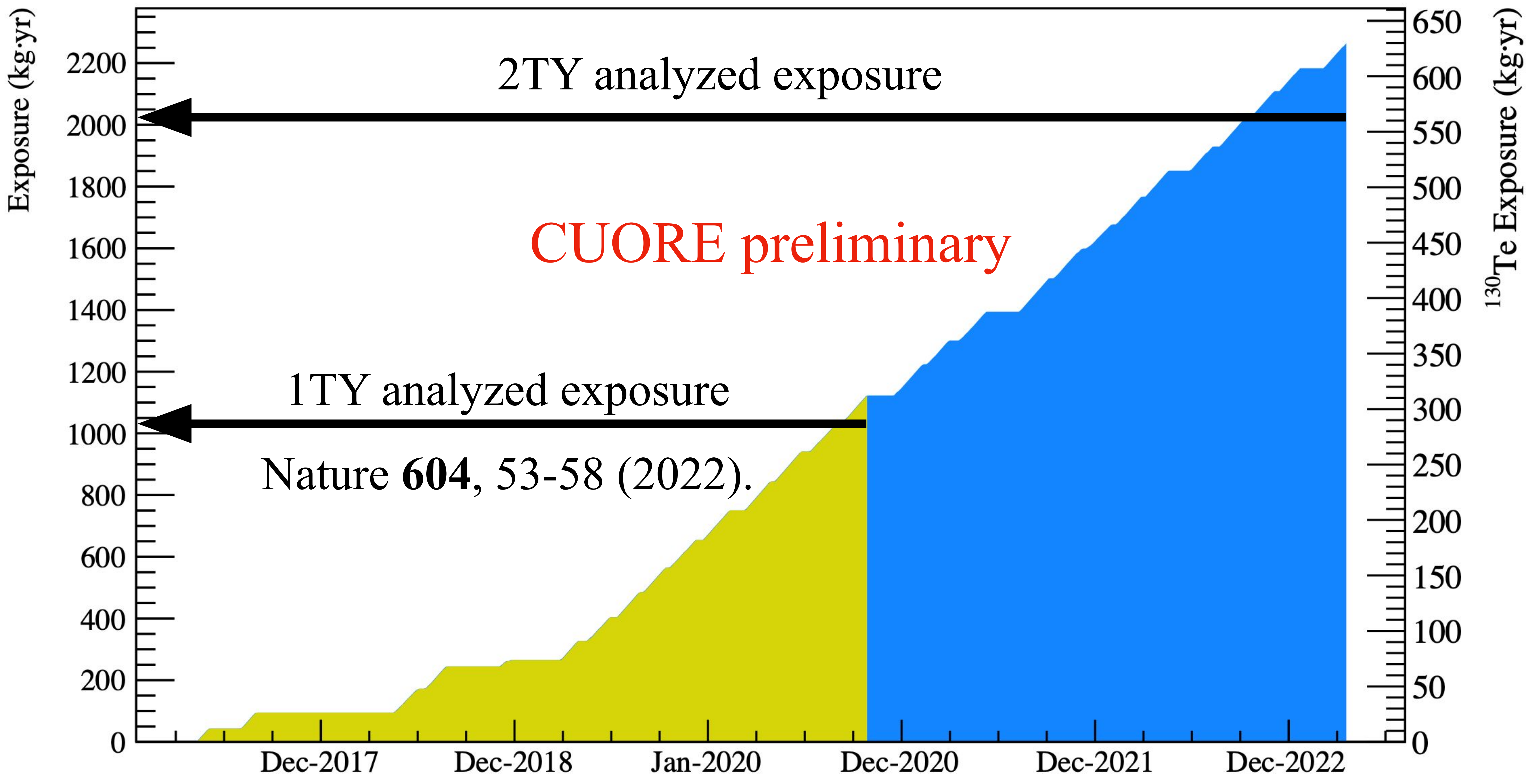
$$\mathbf{m_{\beta\beta} < 75 - 255\ meV}$$

This assumes the light Majorana neutrino-exchange mechanism and $g_A^{eff} = 1.27$



Ongoing Work for the Full 2TY Release

- Reprocess and analyze recently denoised 1TY data
  - Denoising algorithm is performed on raw, continuous data, so data must be re-analyzed
- Re-run fit on the full analysis statistics
- Finalize systematics studies
- Release final 2TY result



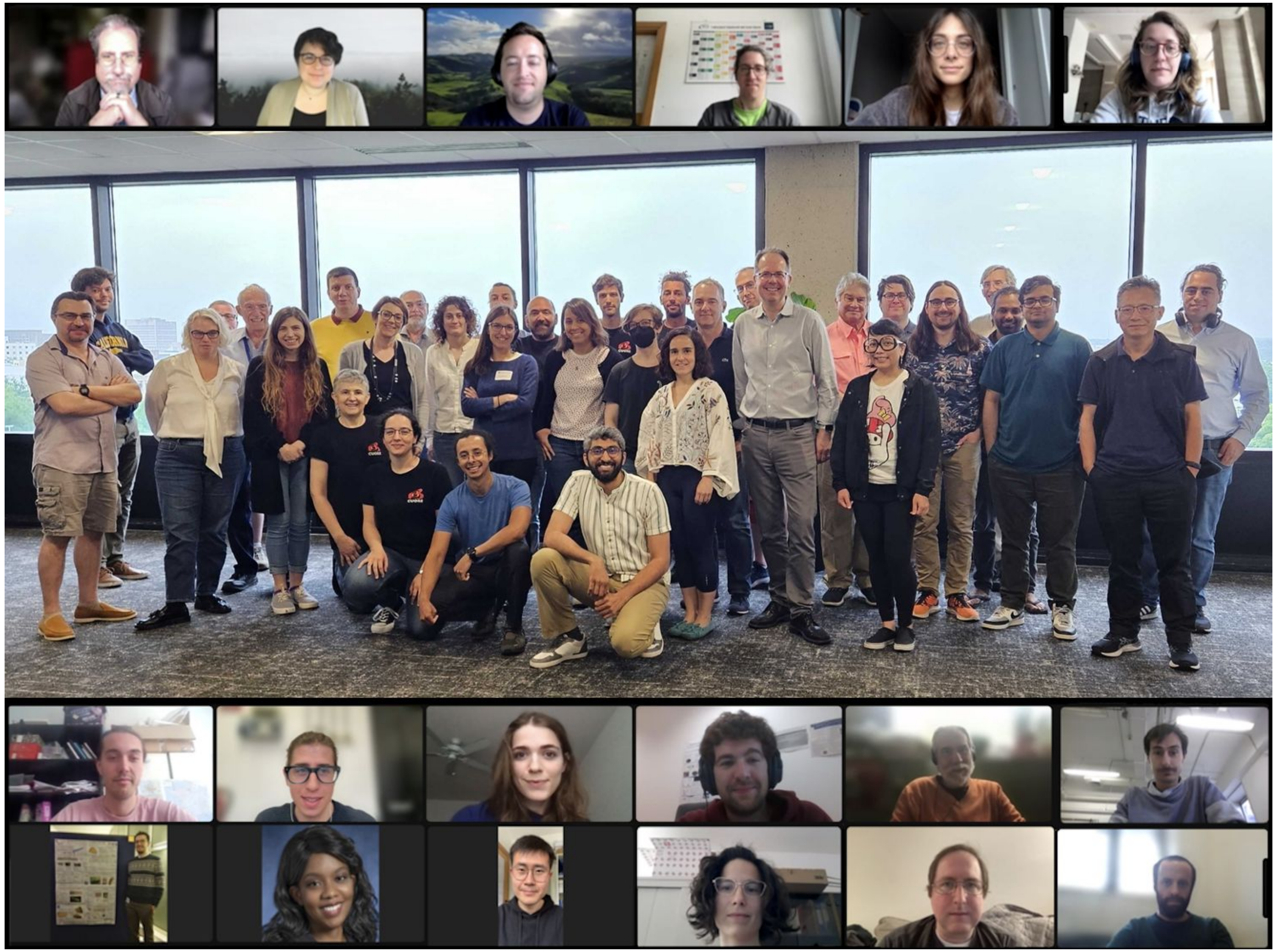
Summary

- CUORE has exceeded 2 tonne years of exposure and is in a stable data-taking condition.
- No evidence of 0νββ decay with 2023 kg yr exposure
- New limit on $\mathbf{m_{\beta\beta} < 75 – 255\ meV}$

Future Analyses & Experiments

- Background model and 2νββ half-life measurement
- Search for 0νββ decay in M2 spectrum
- 2025: Planned final exposure for CUORE
  - 3TY of TeO_2 exposure (1TY of ^{130}Te)
- Next-generation CUPID experiment
  - See talk by Pia Loaiza on Wednesday

Thank you for the attention!



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CUORE

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Backup Slides

0νββ Formulae and Experimental Parameters

$$S^{0\nu} \propto \eta\sqrt{\frac{Mt}{b\Delta E}}$$

$$|m_{\beta\beta}| = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

η : isotopic abundance

M : detector mass

t : live time

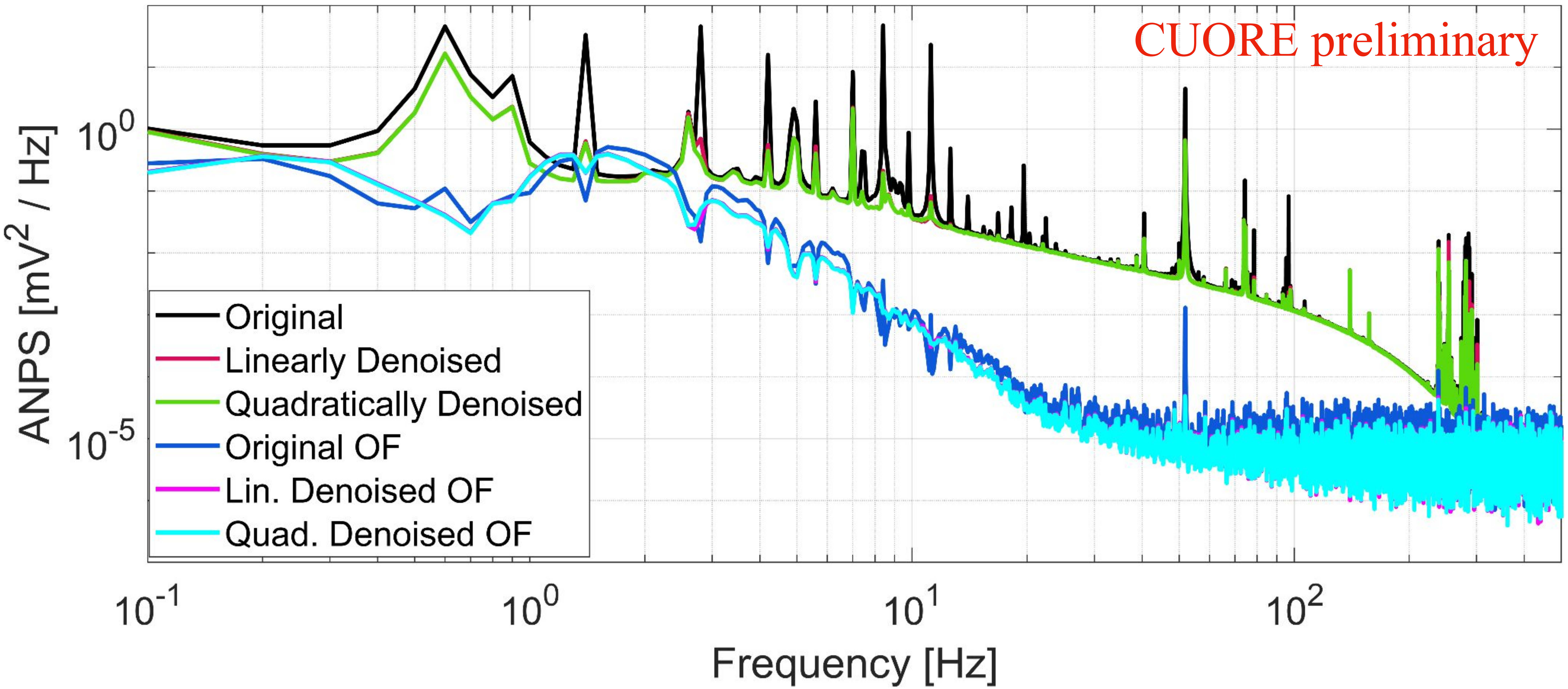
b : background index

ΔE : energy resolution

$$\Gamma_{0\nu} = \frac{1}{\ln 2} G^{0\nu}\, g_A^4 \,|M_{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

See also:
Effective Majorana mass and neutrinoless double beta decay.
G. Benato. Eur. Phys. J. C 75, 563 (2015).

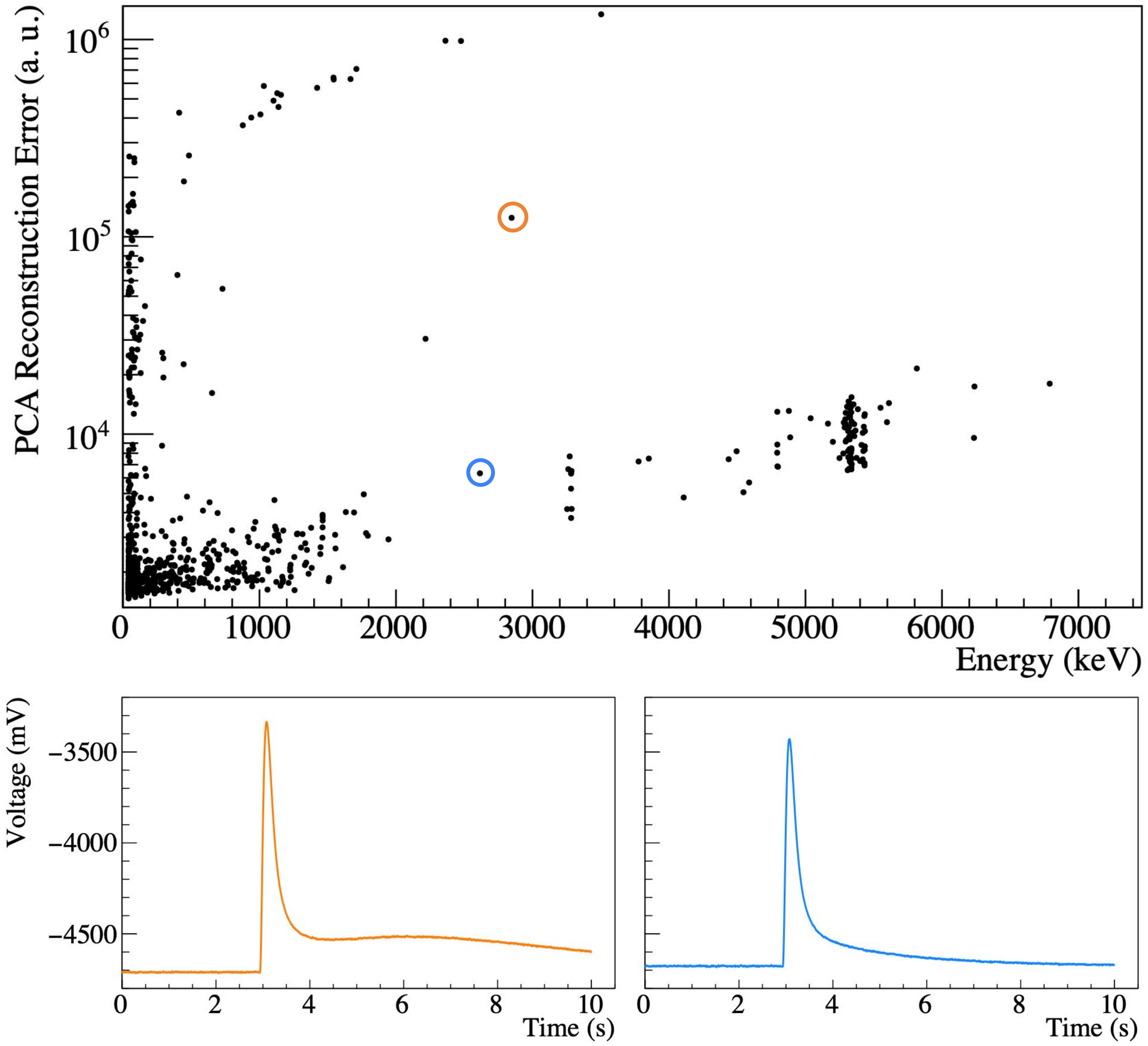
Effects of Denoising on the OF ANPS



Pulse Shape Discrimination

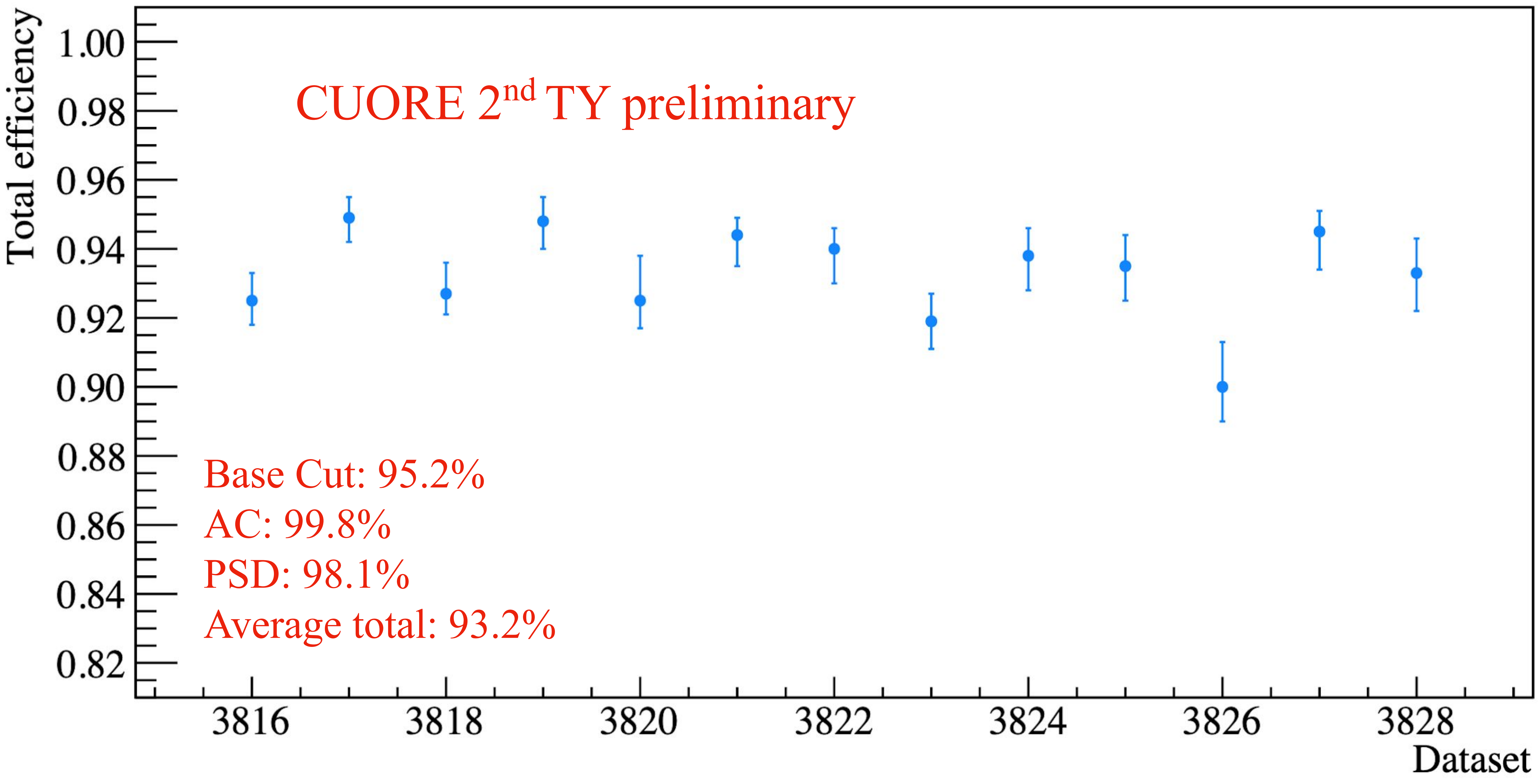
- Principal component analysis (PCA) is sensitive to outliers in data
- The average pulse is used as a proxy for the leading principal component that reflects physical pulse shape
- PCA reconstruction error is used to discriminate physical and nonphysical (pileup, noise, etc.) events
- Event selection is based on optimizing the figure-of-merit that reflects the experimental sensitivity:

$$\frac{\epsilon_{2615keV}}{\sqrt{\epsilon_{bkg}}}$$



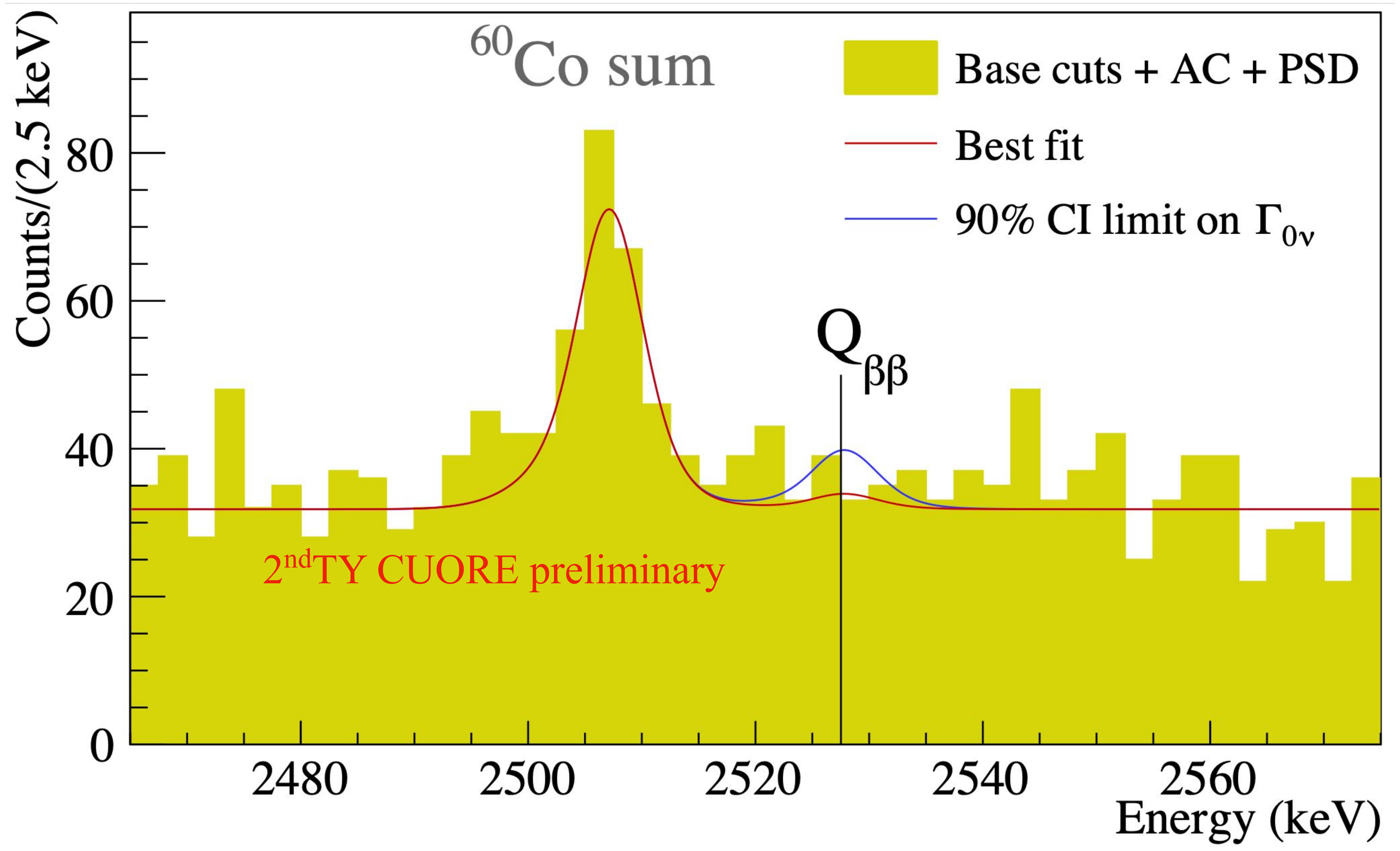
Efficiencies

- Base Cuts: probabilities of accurate detection, energy reconstruction, and pile-up rejection (heater pulses)
- AC: probability of identifying single crystal event (^{40}K)
- PSD: probability of keeping a physical event after applying PCA



0νββ Fit in Region of Interest

- Unbinned extended maximum likelihood fit in ROI: [2465,2575] keV
- Likelihood model has 3 terms:
  - ^{130}Te $Q_{\beta\beta}$ peak
  - ^{60}Co sum peak
  - Flat background index (BI)
- Flat priors on BI and the 0νββ rate
- Informative priors for efficiencies, energy bias, resolution scaling, $Q_{\beta\beta}$, and isotopic abundance
- Fit procedure determined using the salted data, where events are exchanged between posited $Q_{\beta\beta}$ and the ^{208}Tl 2615 keV peak

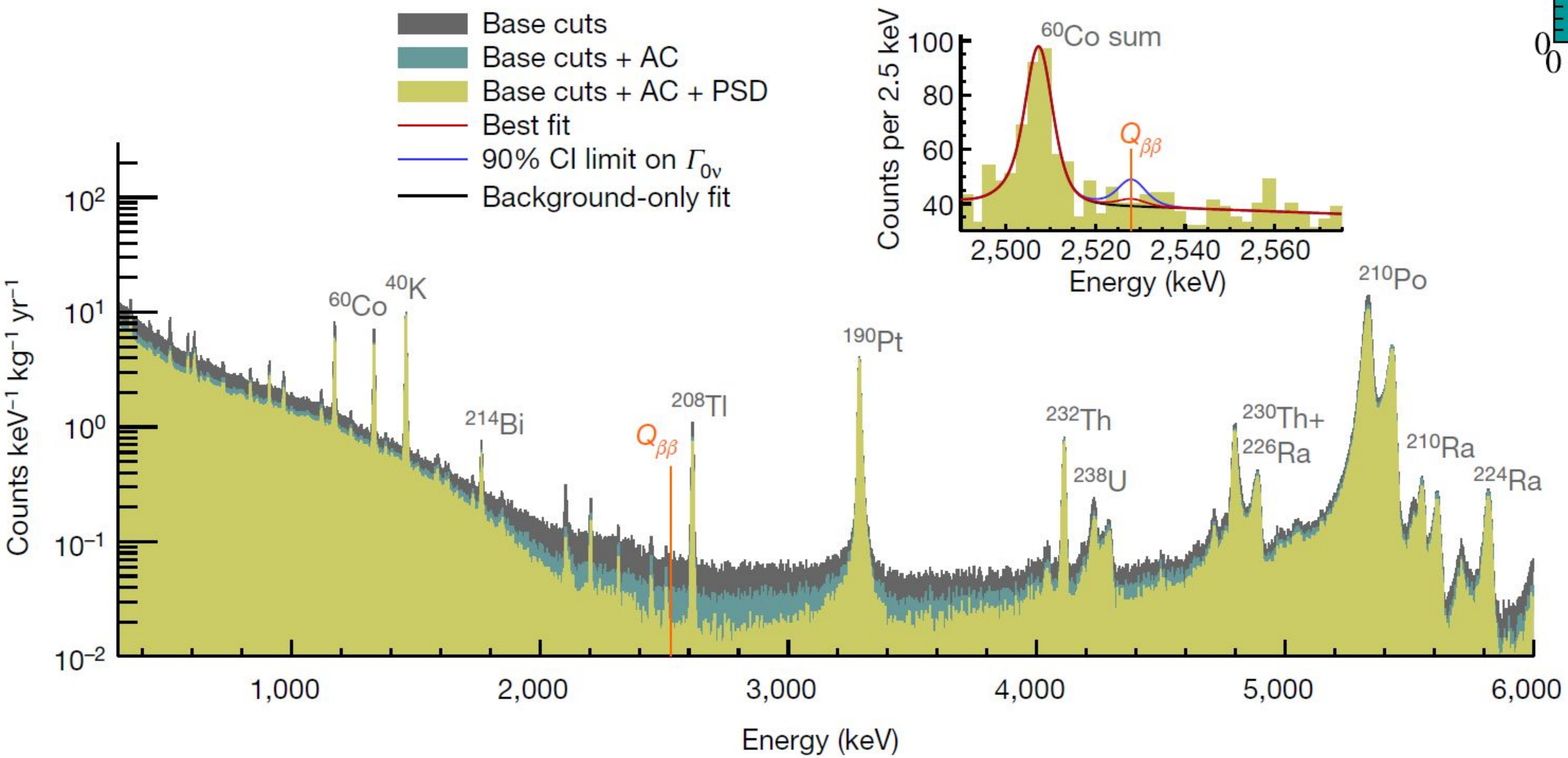


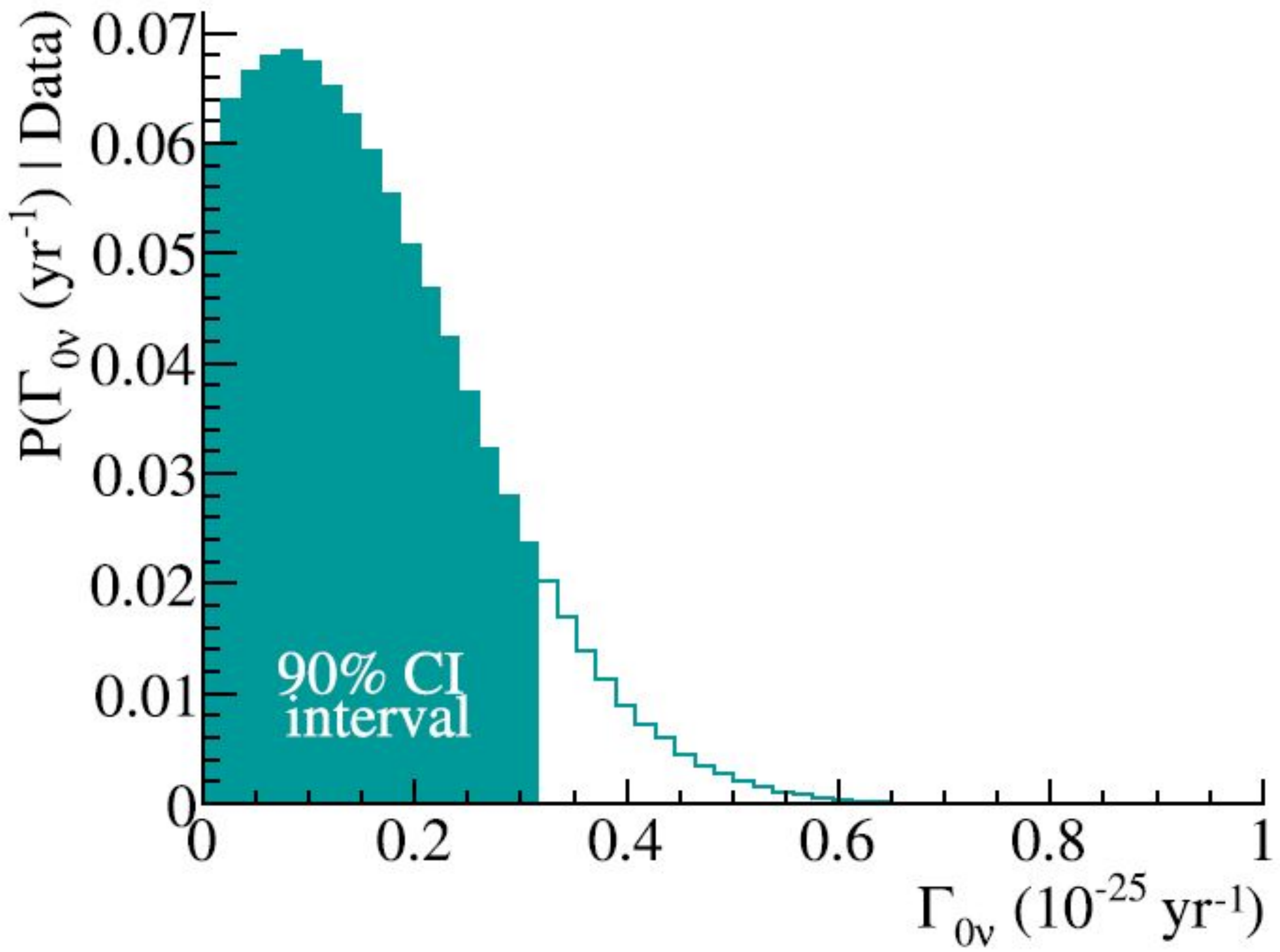
$0\nu\beta\beta$ Fit Nuisance Parameters

- Dataset-dependent parameters:
  - Background Index (BI)
  - Efficiencies
  - Resolution and bias scaling
- Global parameters:
  - ^{60}Co activity rate (with a time-dependent correction for each dataset)
  - $Q_{\beta\beta}$
  - Isotopic abundance of ^{130}Te
  - Containment Efficiency

The CUORE 1TY Result

See: *Nature* **604,** 53–58 (2022)





Best Fit Value:

Γ_{0v}= (0.9 ± 1.4) x 10^{-26} / yr

Bayesian 90% CI Limit:

$T_{1/2}$ > 2.2 x 10^{25} yr

Frequentist 90% CI Limit:

$T_{1/2}$ > 2.6 x 10^{25} yr