

# Latest results from the CUORE experiment



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# Cryogenic Underground Observatory for Rare Events

**Location:** LNGS, IT (3600 m.w.e)

**Primary goal:** search for  $0\nu\beta\beta$  decay in  $^{130}\text{Te}$

- active mass: 742 kg  $\text{TeO}_2$  (206 kg  $^{130}\text{Te}$ )
- close-packed array of 988 nat.  $\text{TeO}_2$  crystals

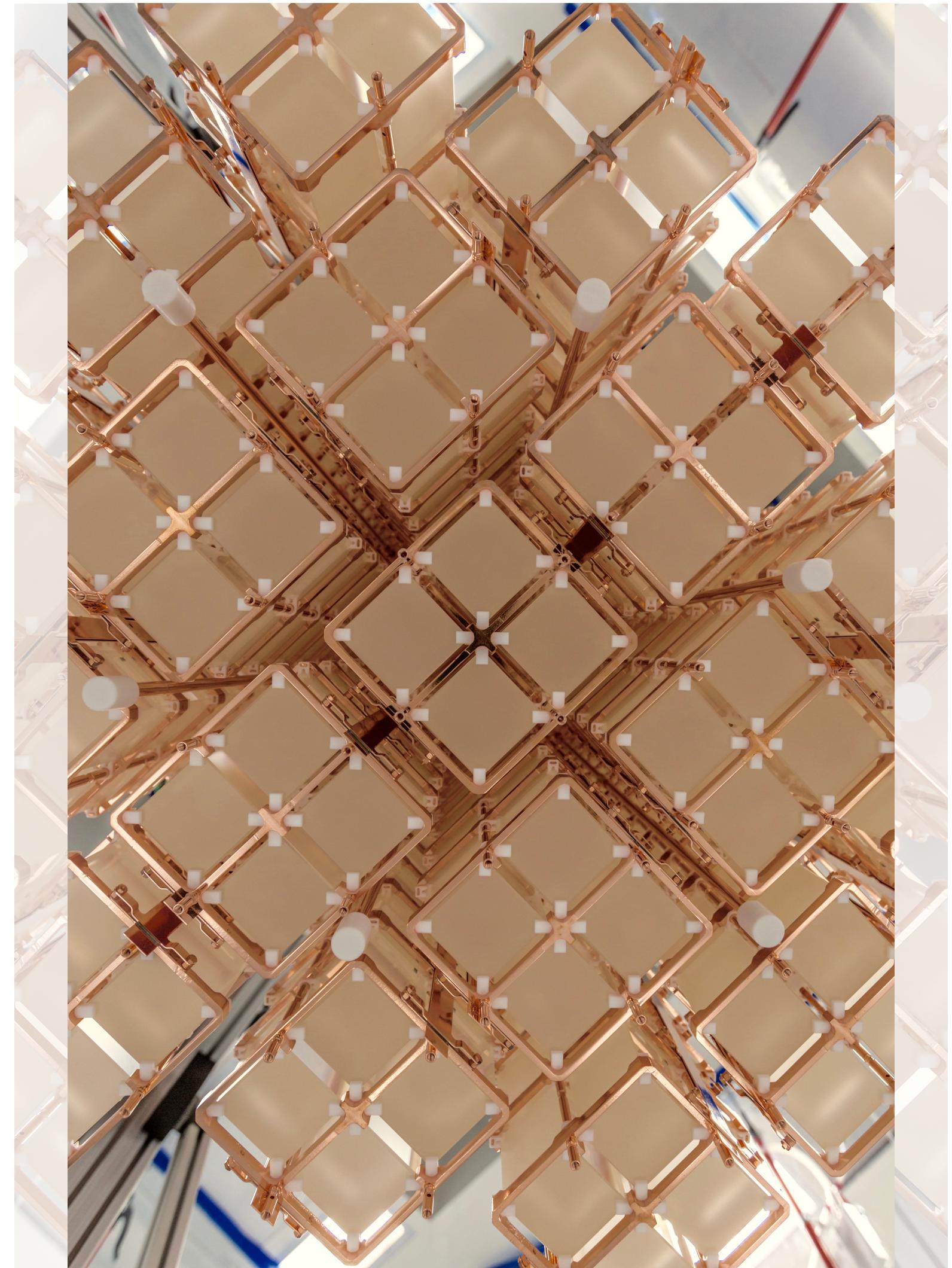
- BI:  $\sim 10^{-2}$  cky
- strict radio-purity controls on materials and assembly
- passive shielding

$$S_{0\nu} \propto \sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

- > 90% duty cycle since 2019 ( $\sim 50$  kg.yr/month exposure rate)
- custom multistage cryogen-free cryostat

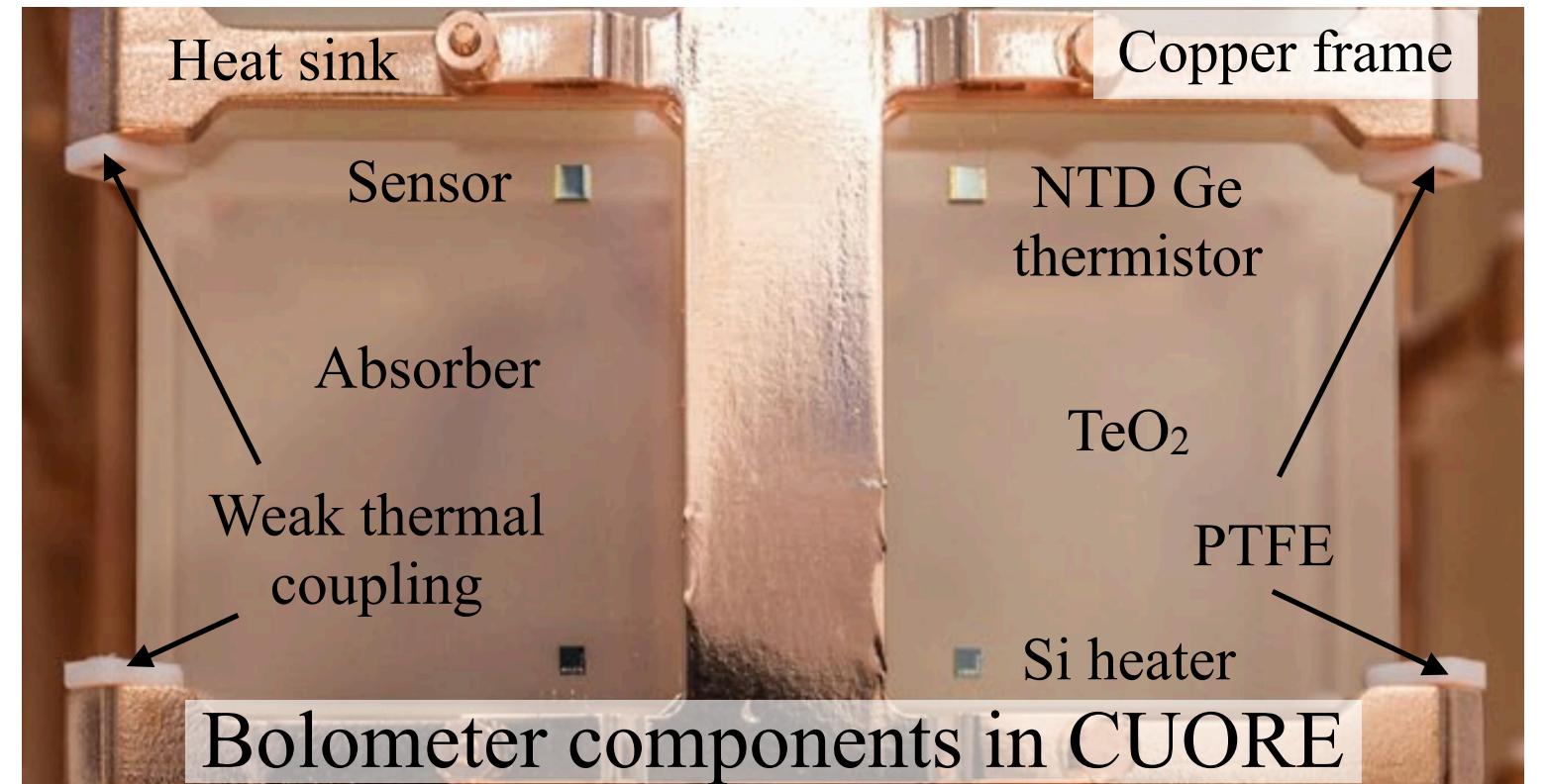
- cryogenic detection technique ( $\sim 10$  mK)
- $Q_{\beta\beta}$  energy resolution:

$$\frac{\Delta E}{E} \simeq 0.3\%$$



# Bolometric technique

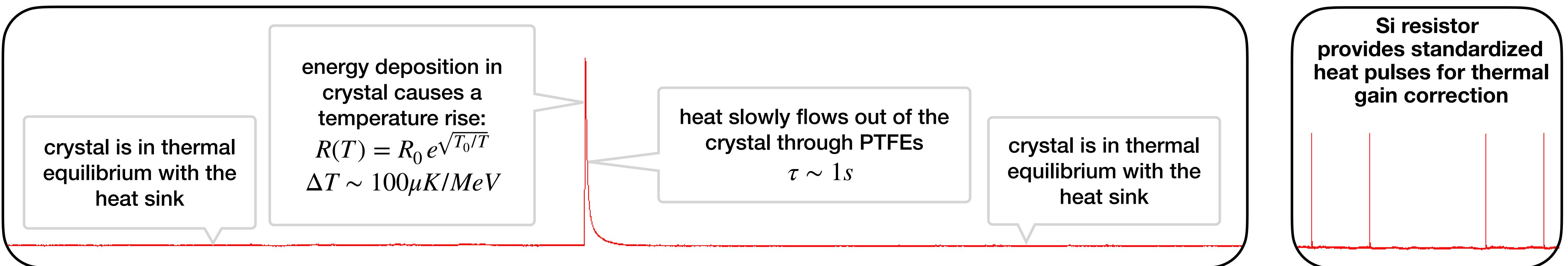
- Excellent energy resolution
  - ~0.3% FWHM @  $Q_{\beta\beta}$  (2527.5 keV)
- Flexibility in detector material ( $^{130}\text{Te}$ ,  $^{82}\text{Se}$ ,  $^{100}\text{Mo}$ )
  - $^{130}\text{Te}$  natural isotopic abundance = ~34%
  - $^{130}\text{Te}$   $Q_{\beta\beta}$  above most natural gamma ray energies



$$\Delta T = \Delta E/C$$

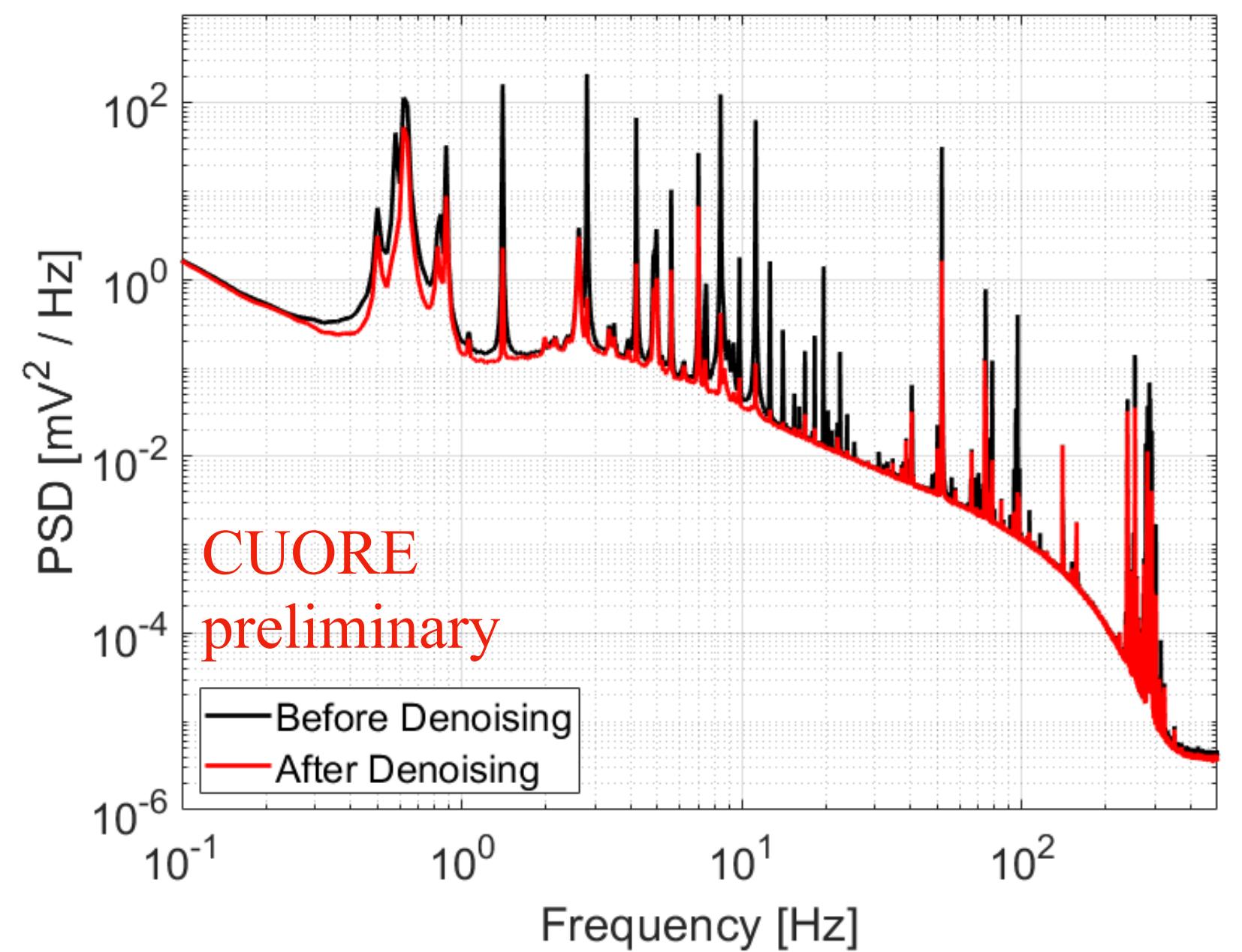
$$C(T) \propto T^3$$

Particle interactions (e.g.  $\beta\beta$  decay) in the crystal are represented by the voltage readout of the NTD Ge thermistor

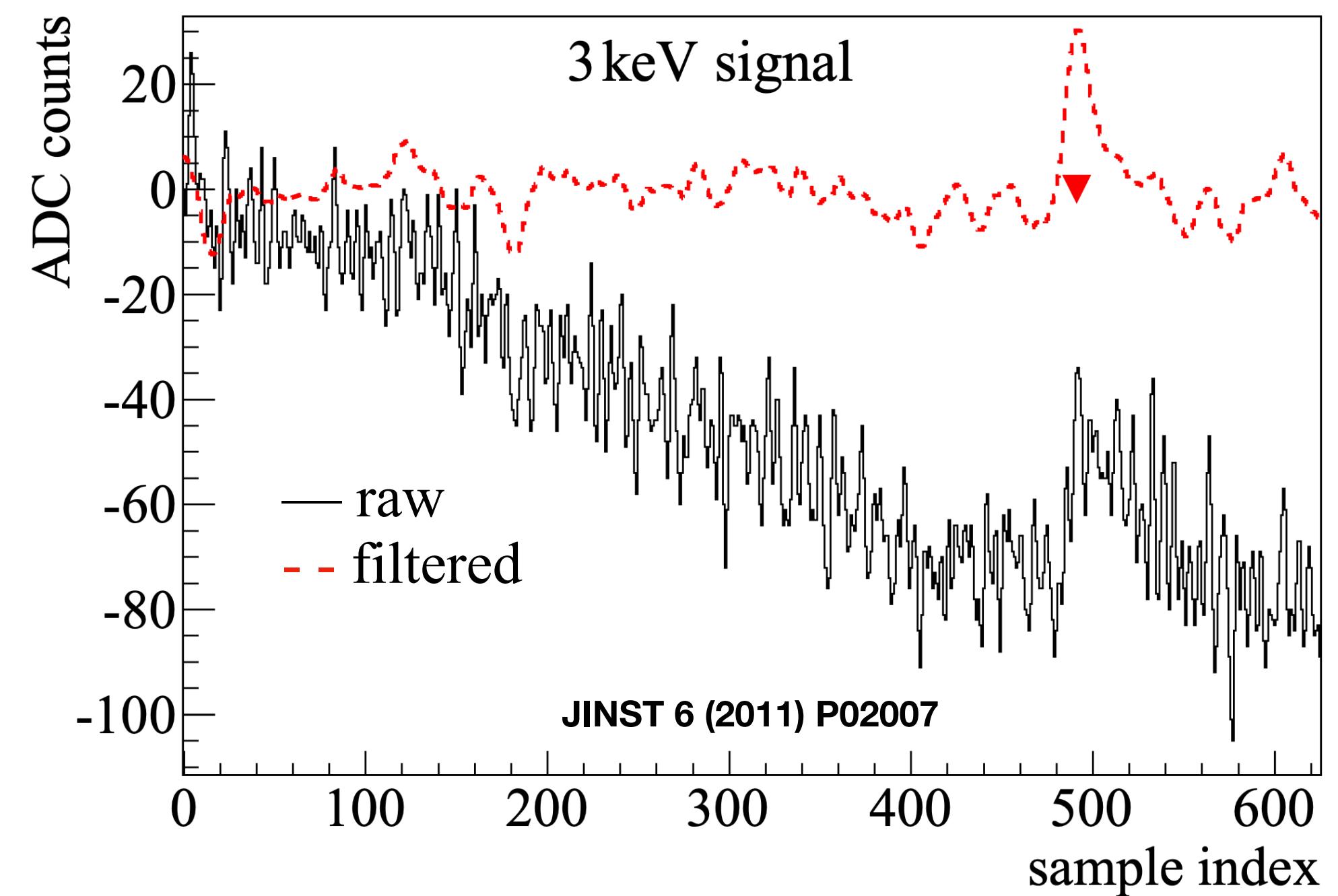


# Signal processing (offline)

- Denoising algorithm (**NEW TO ANALYSIS!**)
  - Reduces noise correlated with measured vibrations
  - Auxiliary devices: microphones, accelerometers, seismometers



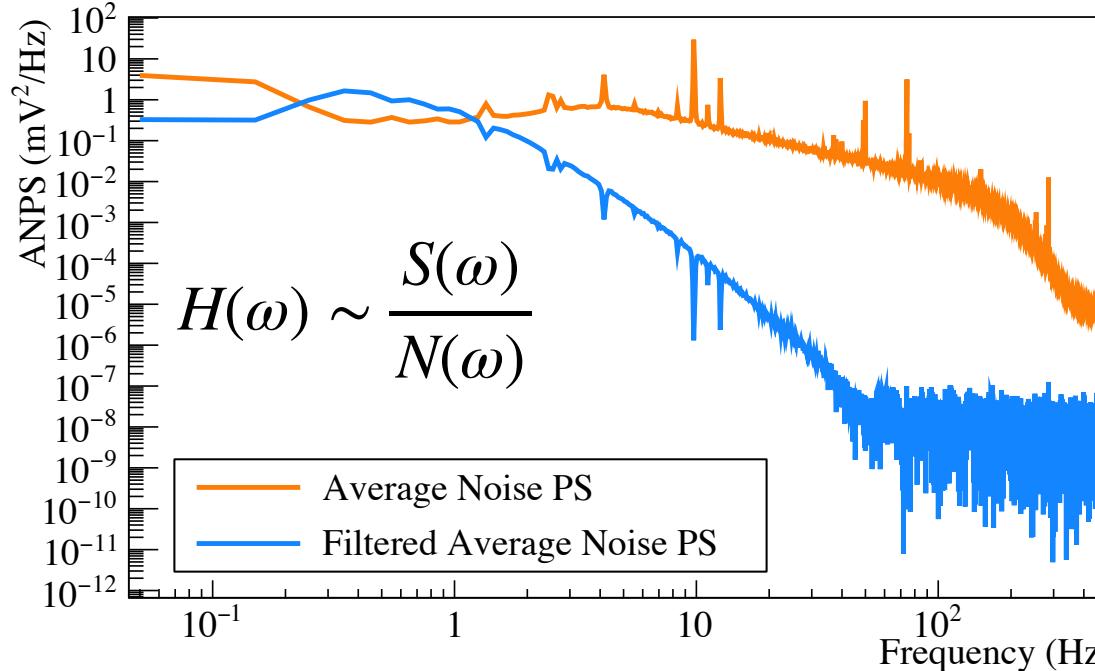
- Optimum trigger (OT) algorithm
  - Applies filter and identifies pulses
  - Lowers energy detection thresholds



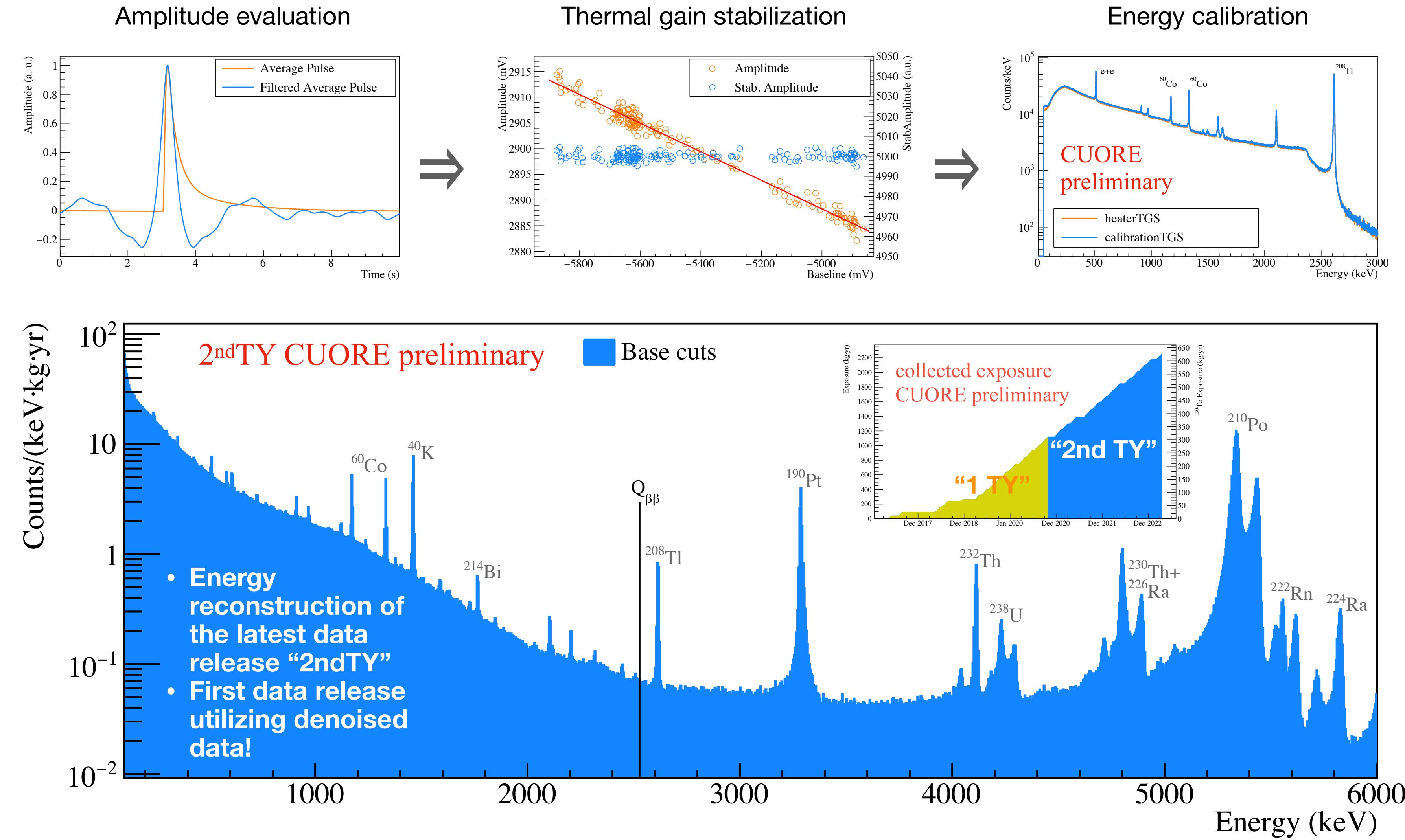
See posters: #216 (K. Vetter, denoising), #233 (S. Quitadamo, sea weather effects), and #395 (A. Ressa, dark matter)

# Energy reconstruction

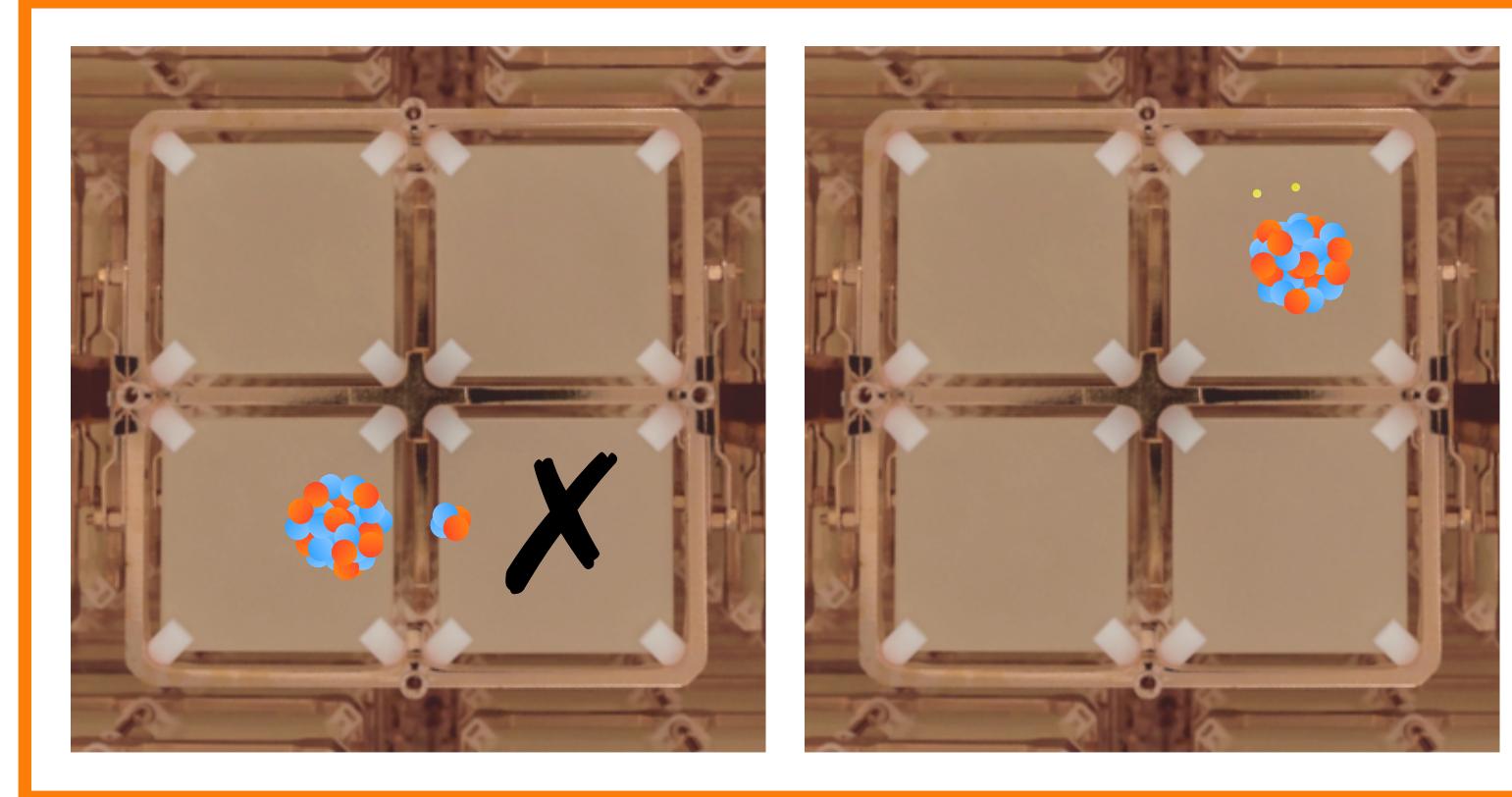
- Digital filter designed to maximize SNR is applied



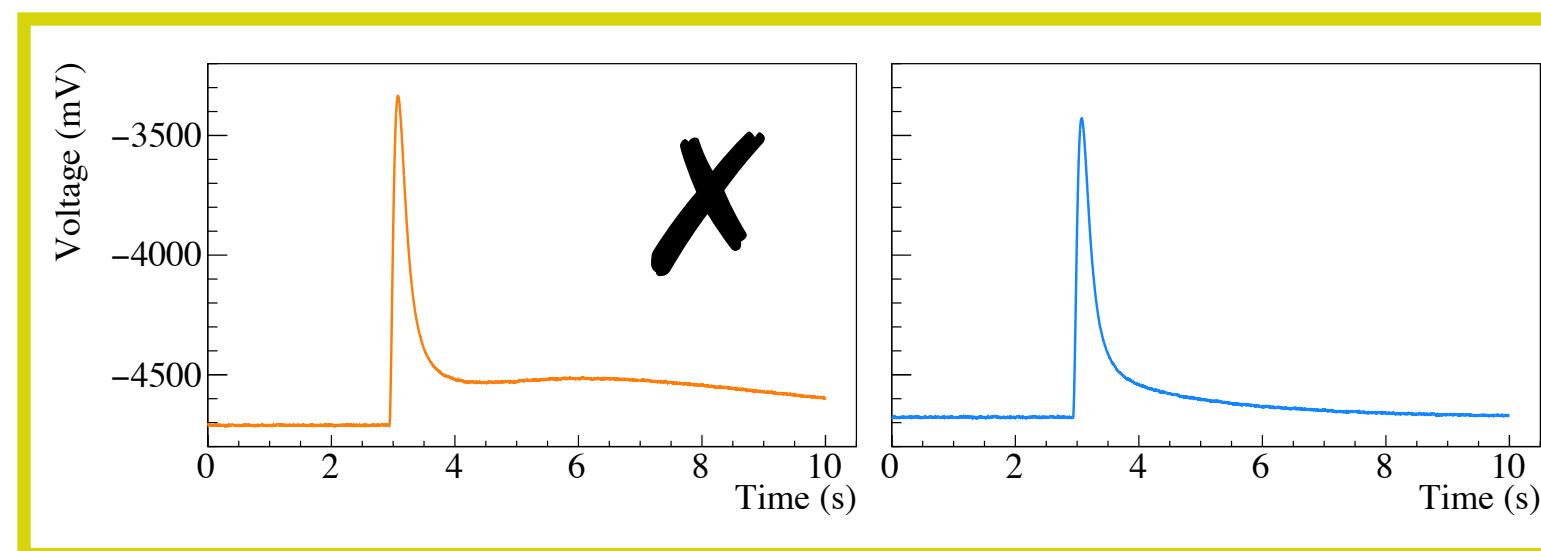
- Amplitude is evaluated from the filtered pulse peak
- Thermal gain correction based on gain observed in standardized heat and/or energy pulses
- Energy calibration is applied based on measurements taken during radioactive source deployment



# Event selection for $0\nu\beta\beta$ (M1)



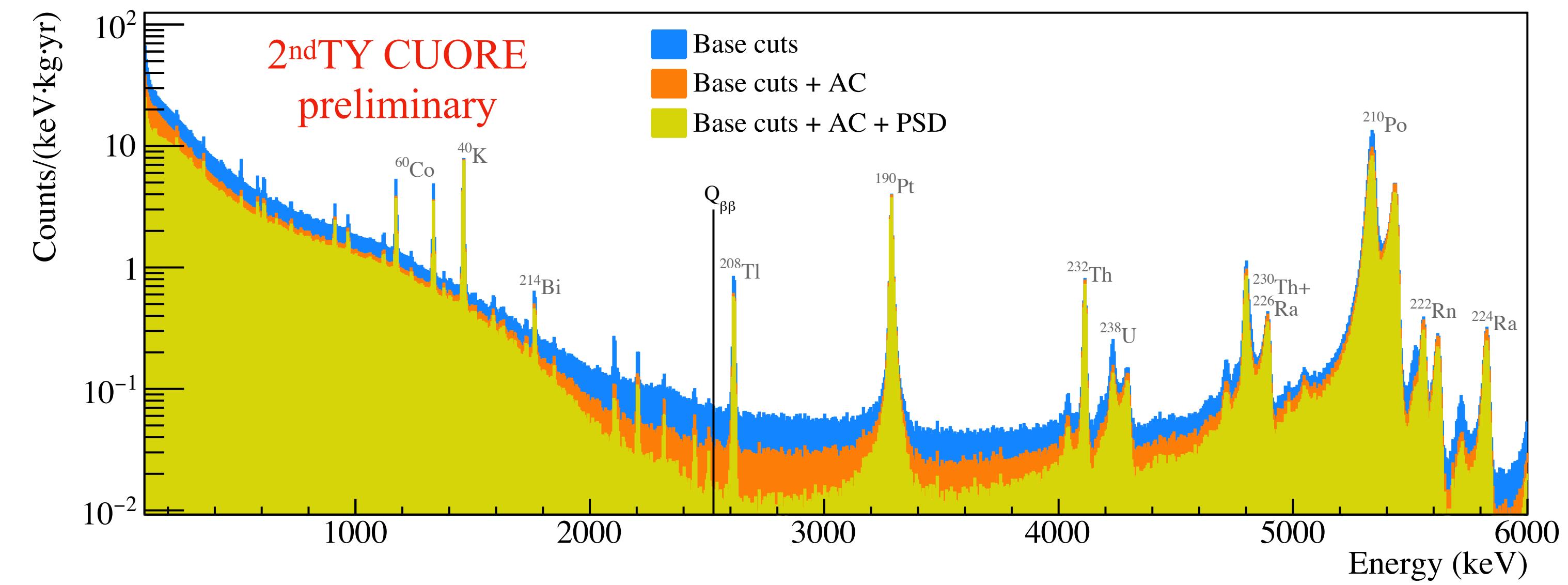
- Anti-coincidence (AC) cut selects single-site (M1) events
- ~88% containment efficiency (MC)



- Pulse shape discrimination (PSD)
- Implement principal component analysis (PCA) techniques

Blinded analysis to prevent bias

- Events exchanged between  $Q_{\beta\beta}$  and the  $^{208}\text{TI}$  2615 keV peak
- Evaluate the detector response (next slide)
- Fit model:  $^{130}\text{Te}$   $Q_{\beta\beta}$  peak +  $^{60}\text{Co}$  sum peak + flat background
- ROI: [2465, 2575] keV
- Finalize fit model parameters before running unblinded fit



# Detector response

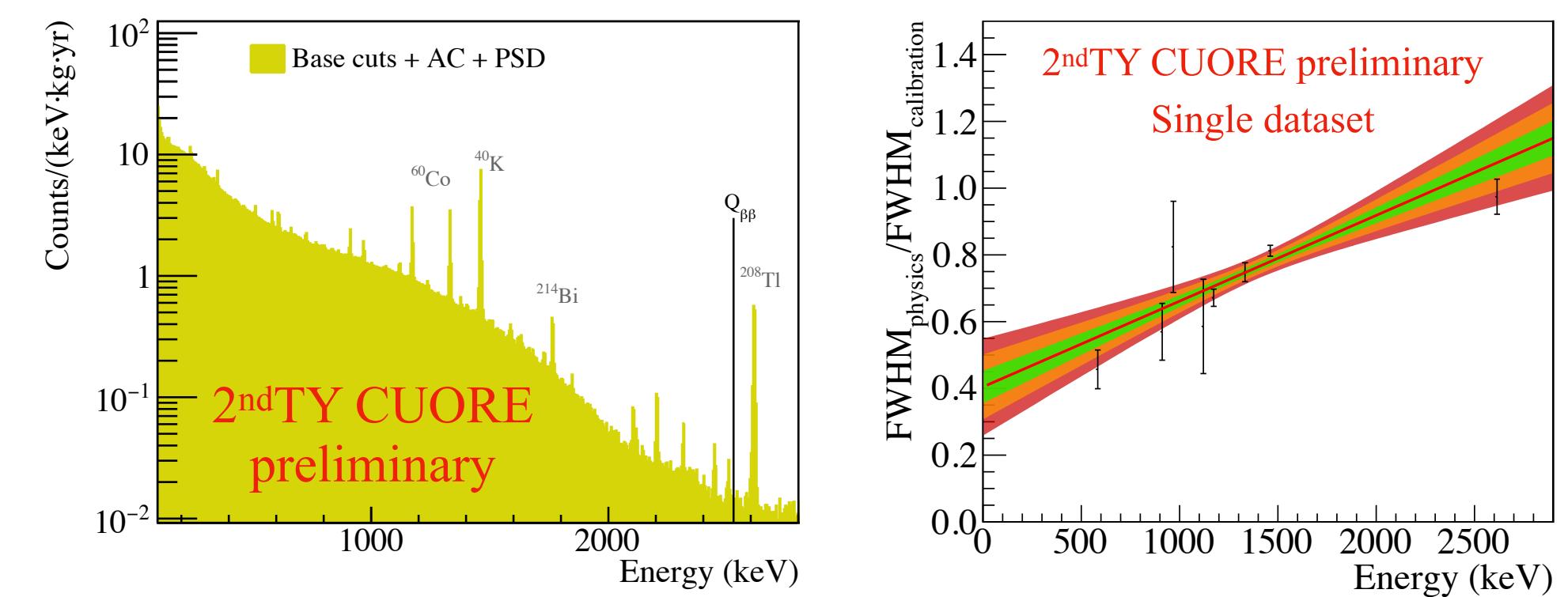
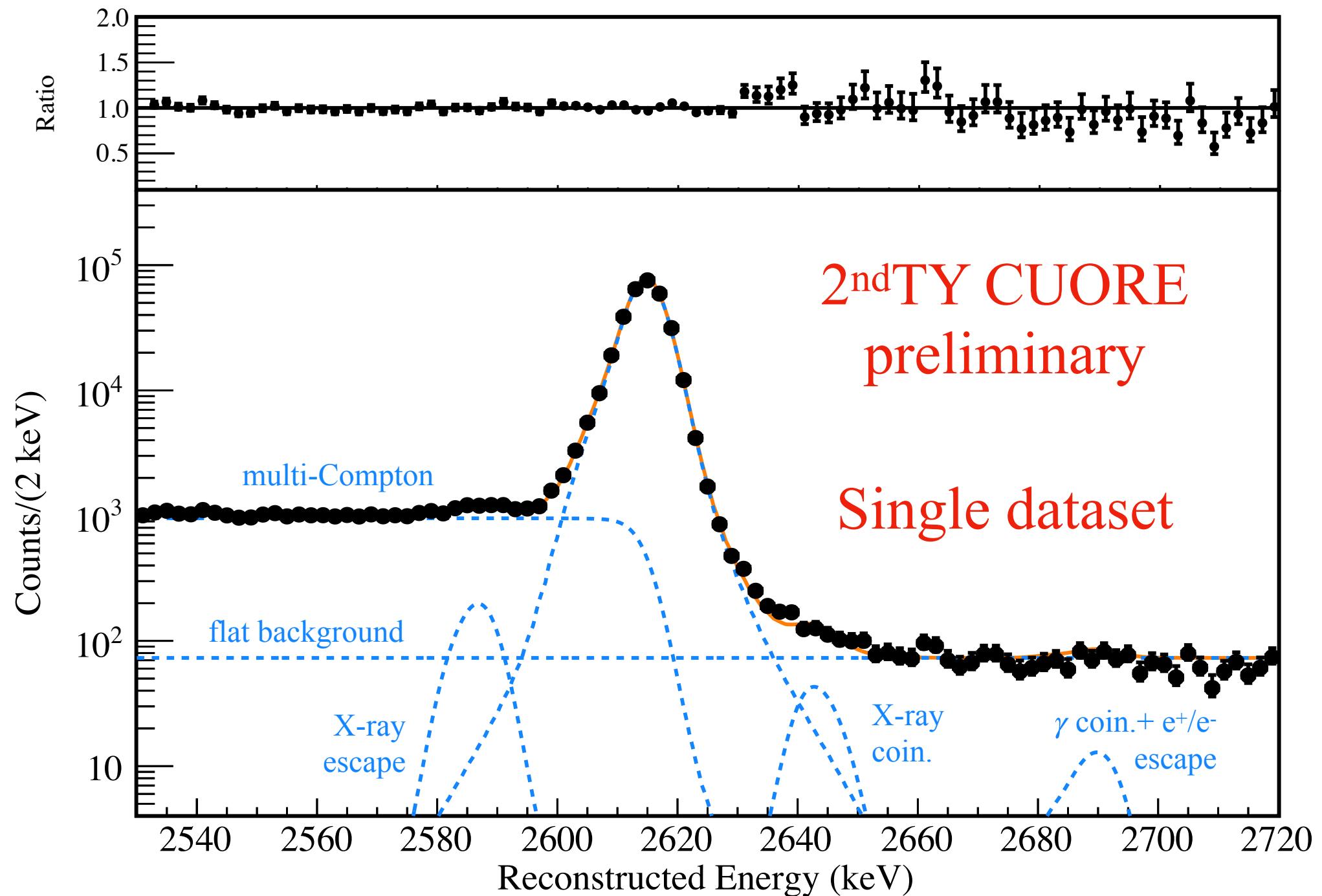
- Fit model includes peaks ↔ model detector response

- Peak shape model
  - Sum of 3 Gaussians
  - Fit the 2615 keV line shape from calibration
  - Simultaneously fit with nearby structures

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

- Detector response parameters in the ROI
  - Use peak shape parameters from calibration
  - Fit peaks in the corresponding background spectrum
  - Scale resolution and bias to  $Q_{\beta\beta}$

$$\Delta E_{Q_{\beta\beta}, 2^{\text{nd}}\text{TY}} = 7.26^{+0.43}_{-0.47} \text{ keV}, E_{bias, 2^{\text{nd}}\text{TY}} = -0.11^{+0.19}_{-0.25} \text{ keV}$$



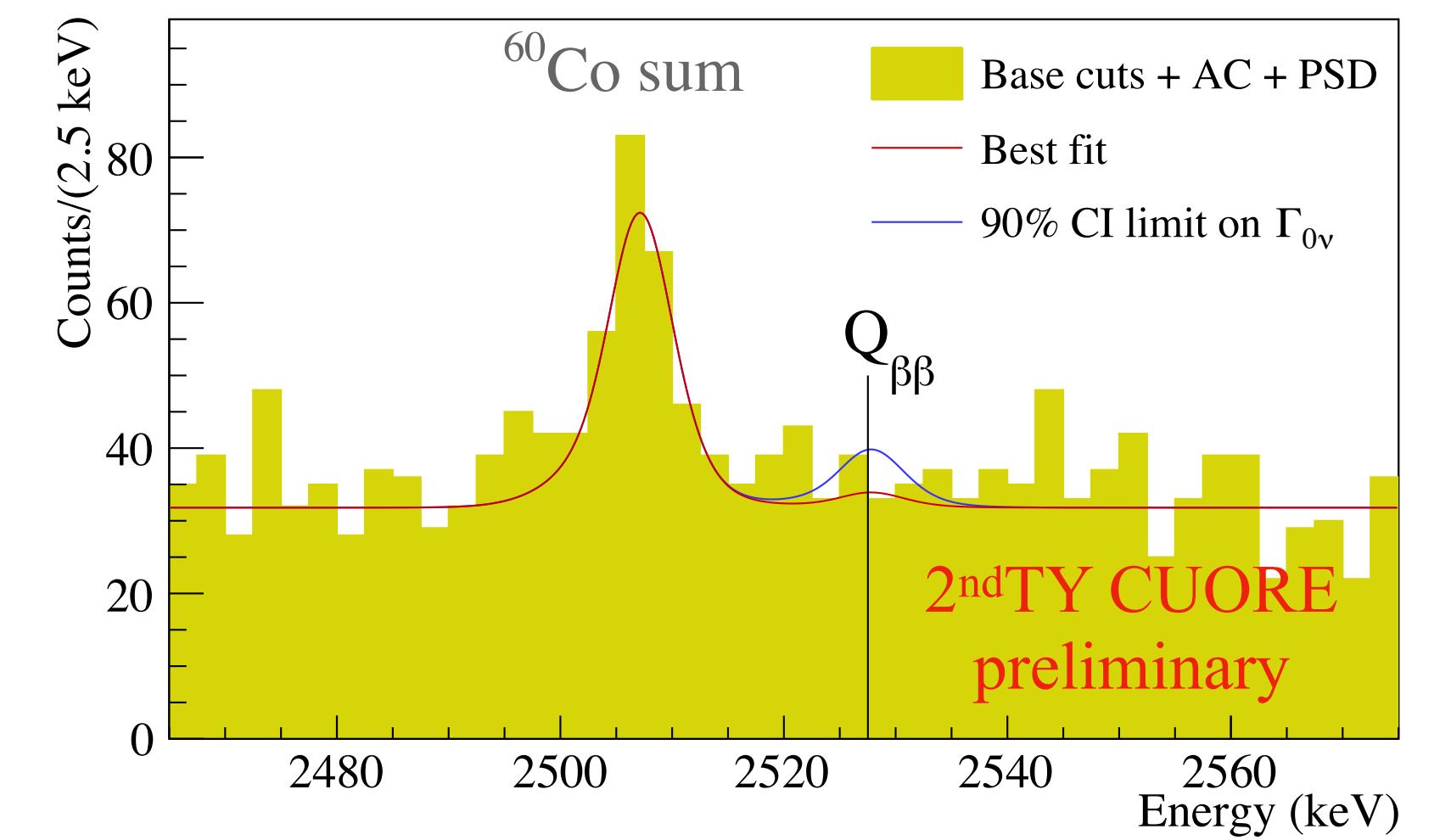
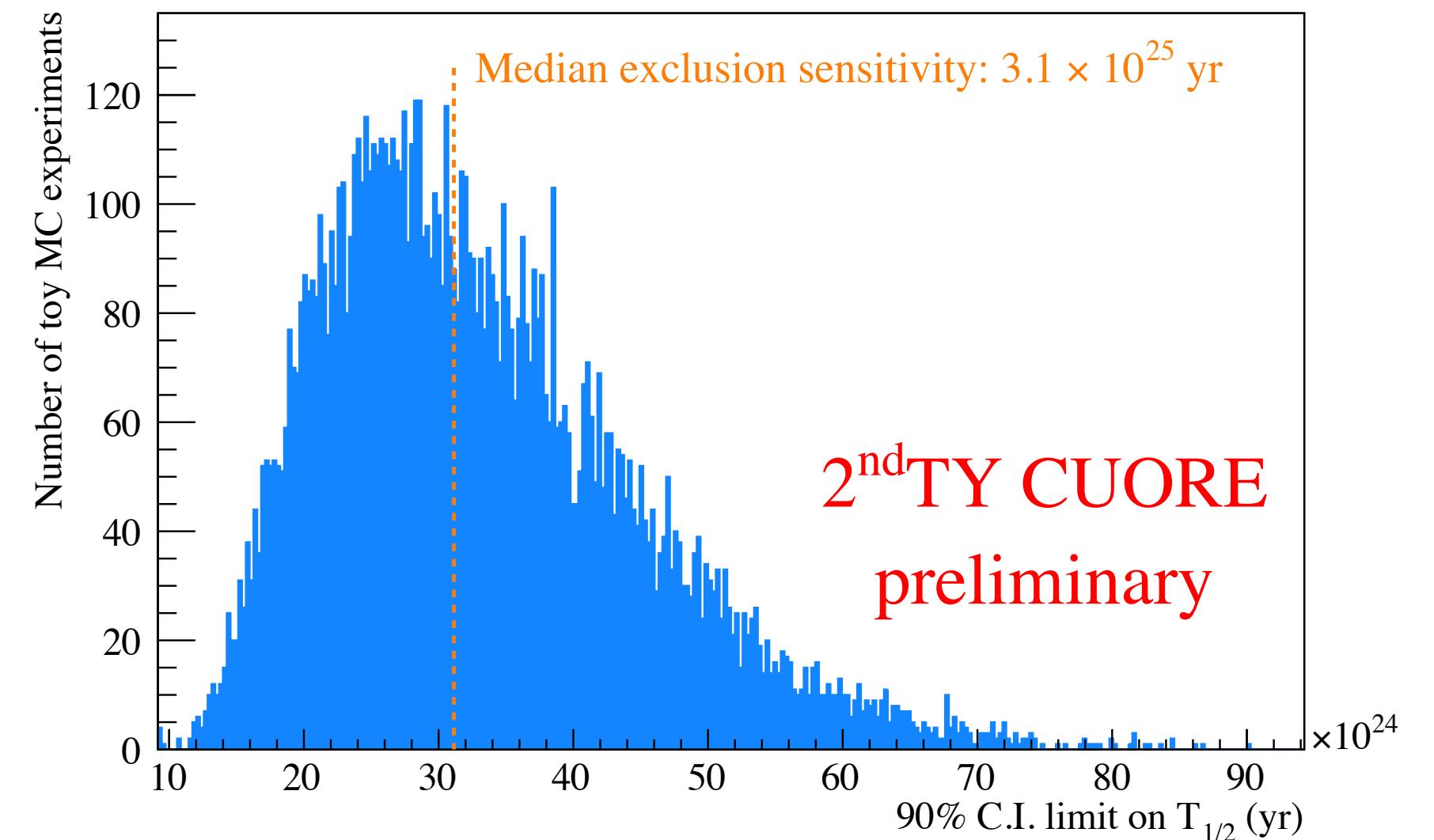
# 2ndTY (tonne·year) results

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

- Median exclusion sensitivity:  $3.1 \times 10^{25} \text{ yr}$  (90% C.I.)
- $10^4$  toy MC experiments
- Average background index (BI):  $1.30(3) \times 10^{-2} \text{ counts/(kev}\cdot\text{kg}\cdot\text{yr)}$
- Decay rate limit:  $\Gamma_{0\nu} < 2.5 \times 10^{-26} \text{ yr}^{-1}$  (90% C.I.)

Half-life limit:  $T_{1/2}^{0\nu} > 2.7 \times 10^{25} \text{ yr}$  (90% C.I.)

**No evidence of  $0\nu\beta\beta$  decay**



# 2TY (tonne·year) results!

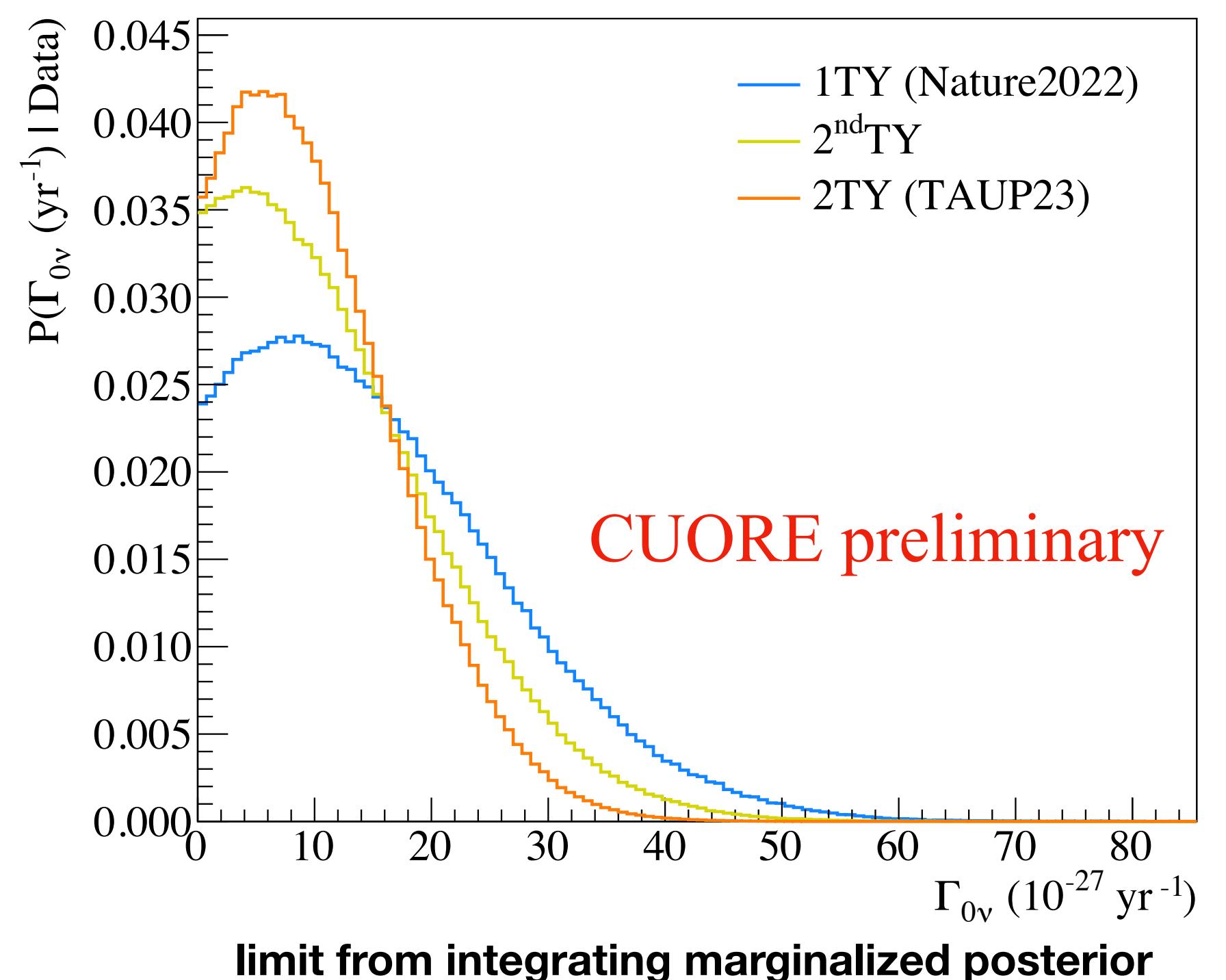
Combining 2ndTY with 1TY results – Nature **604**, 53-58 (2022).

- Analyzed exposure:  $2023 \text{ kg} \cdot \text{yr}$
- Decay rate limit:  $\Gamma_{0\nu} < 2.1 \times 10^{-26} \text{ yr}^{-1}$  (90% C.I.)

**No evidence of  $0\nu\beta\beta$  decay**

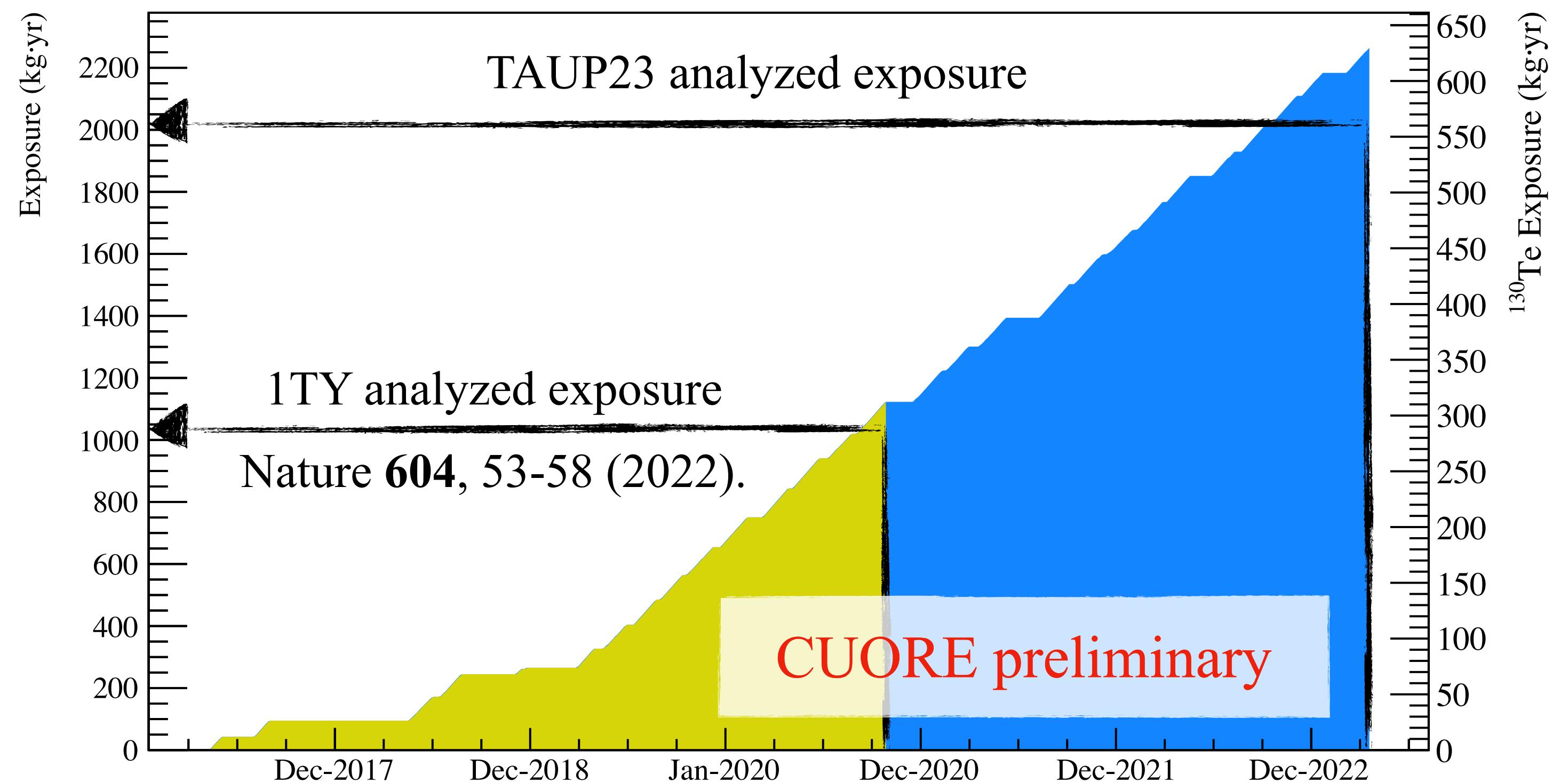
Half-life limit:  $T_{1/2}^{0\nu} > 3.3 \times 10^{25} \text{ yr}$  (90% C.I.)

Effective Majorana mass limit:  $m_{\beta\beta} < 75 - 255 \text{ meV}$



# Next steps

- Reprocess and analyze recently denoised 1TY data
  - Denoising algorithm is performed on raw, continuous data
- 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 stable data taking
- No evidence of  $0\nu\beta\beta$  decay with 2023 kg.yr exposure

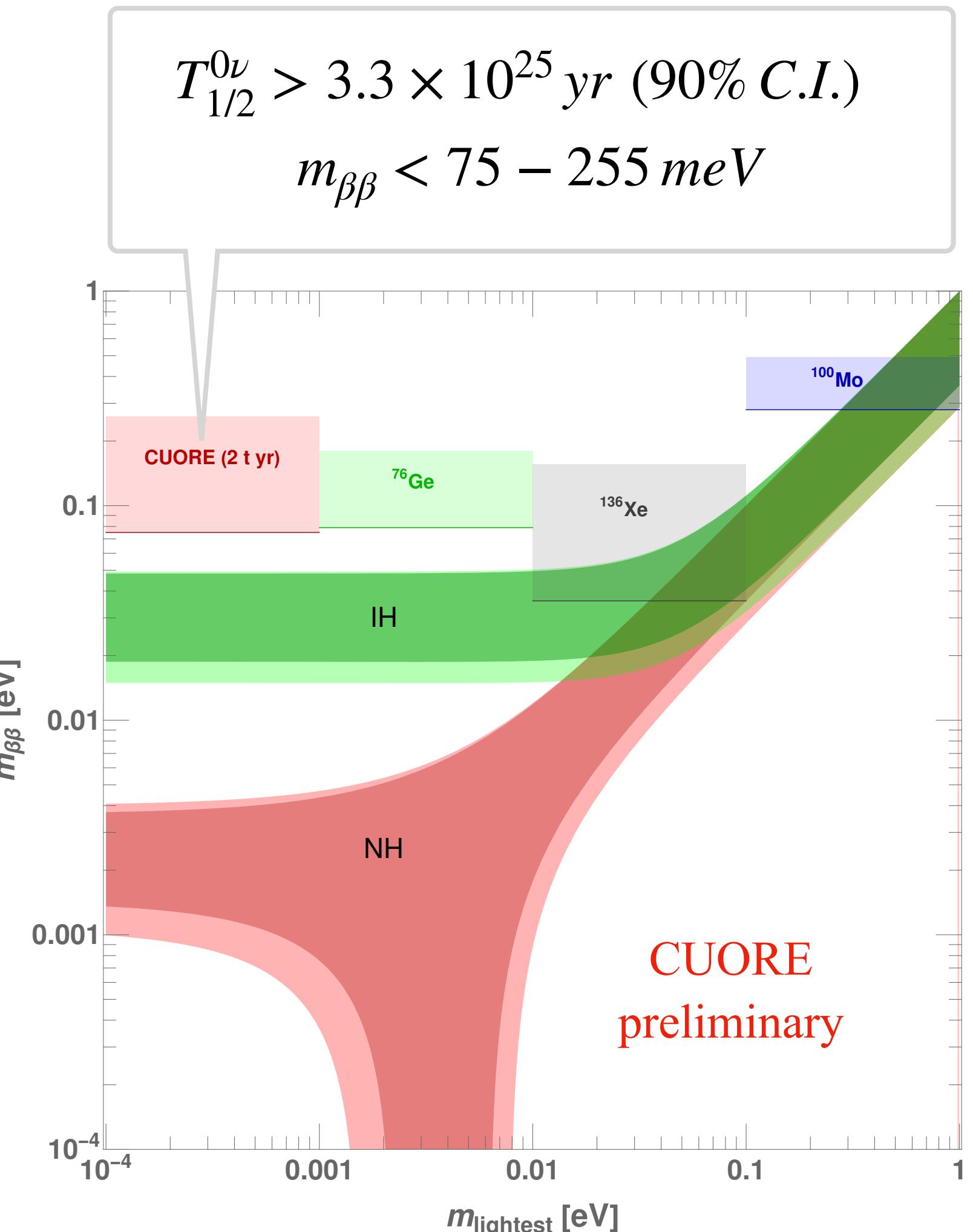
$$T_{1/2}^{0\nu} > 3.3 \times 10^{25} \text{ yr (90\% C.I.)}$$
$$m_{\beta\beta} < 75 - 255 \text{ meV}$$

## FORTHCOMING ANALYSES

- CUORE background model (see talk by S. Ghislandi)
- Search for  $0\nu\beta\beta$  decay in M2 spectrum (events involving two crystals)

## OUTLOOK

- 2025: Planned final exposure for CUORE: 3TY TeO<sub>2</sub> (1TY <sup>130</sup>Te)
- Next-generation CUPID experiment (see talk by C. Nones)



# Thank you!



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# Related posters/talks

## Recent progress on BSM and dark matter searches in CUORE

Alberto Ressa

Aug 28, 2023, 6:30 PM (#395)

## First results from the CUORE background model

Stefano Ghislandi

Aug 29, 2023, 4:45 PM (Audimax)

## Denoising Algorithms for the CUORE Experiment

Kenny Vetter

Aug 30, 2023, 3:30 PM (#216)

## Impact of marine macroseisms on the response of the CUORE cryogenic calorimeters

Simone Quitadamo

Aug 30, 2023, 3:30 PM (#233)

## Analysis techniques for the search of neutrinoless double-beta decay of Te-130 with CUORE

Krystal Alfonso

Aug 30, 2023, 3:30 PM (#557)

## Related (CUPID/CUPID-Mo/CUPID-0/R&D)

### Final results of the CUPID-Mo $0\nu\beta\beta$ experiment

Léonard Imbert

Aug 29, 2023, 2:00 PM (Audimax)

### CUPID the next generation $0\nu\beta\beta$ bolometric experiment

Claudia Nones

Aug 30, 2023, 2:30 PM (Audimax)

### Backgrounds and sensitivity of the CUPID experiment

Pia Loaiza

Aug 30, 2023, 3:30 PM (#183)

### Development of enhanced light detectors for CUPID experiment

Vladyslav Berest, Anastasiia Zolotarova

Aug 30, 2023, 3:30 PM (#372)

### Novel techniques for thermal detectors and applications for rare events physics

Irene Nutini

Aug 30, 2023, 3:30 PM (#396)

### BINGO: investigation of the Majorana nature of neutrinos at a few meV level of the neutrino mass scale

Vladyslav Berest

Aug 30, 2023, 5:45 PM (Audimax)

### Final results of the CUPID-0 combined background model

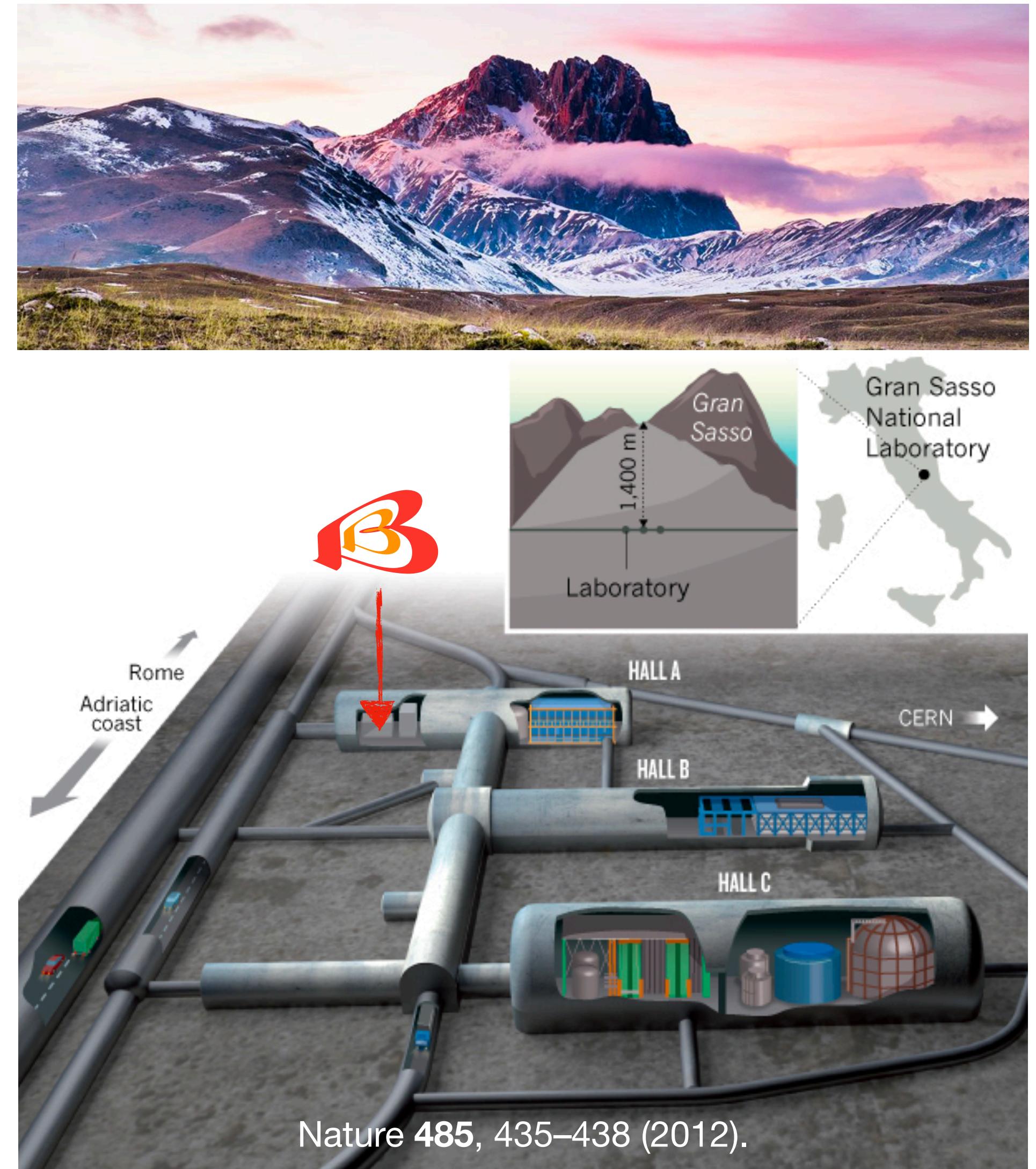
Emanuela Celi and Lorenzo Pagnanini

Aug 30, 2023, 6:15 PM (Audimax)

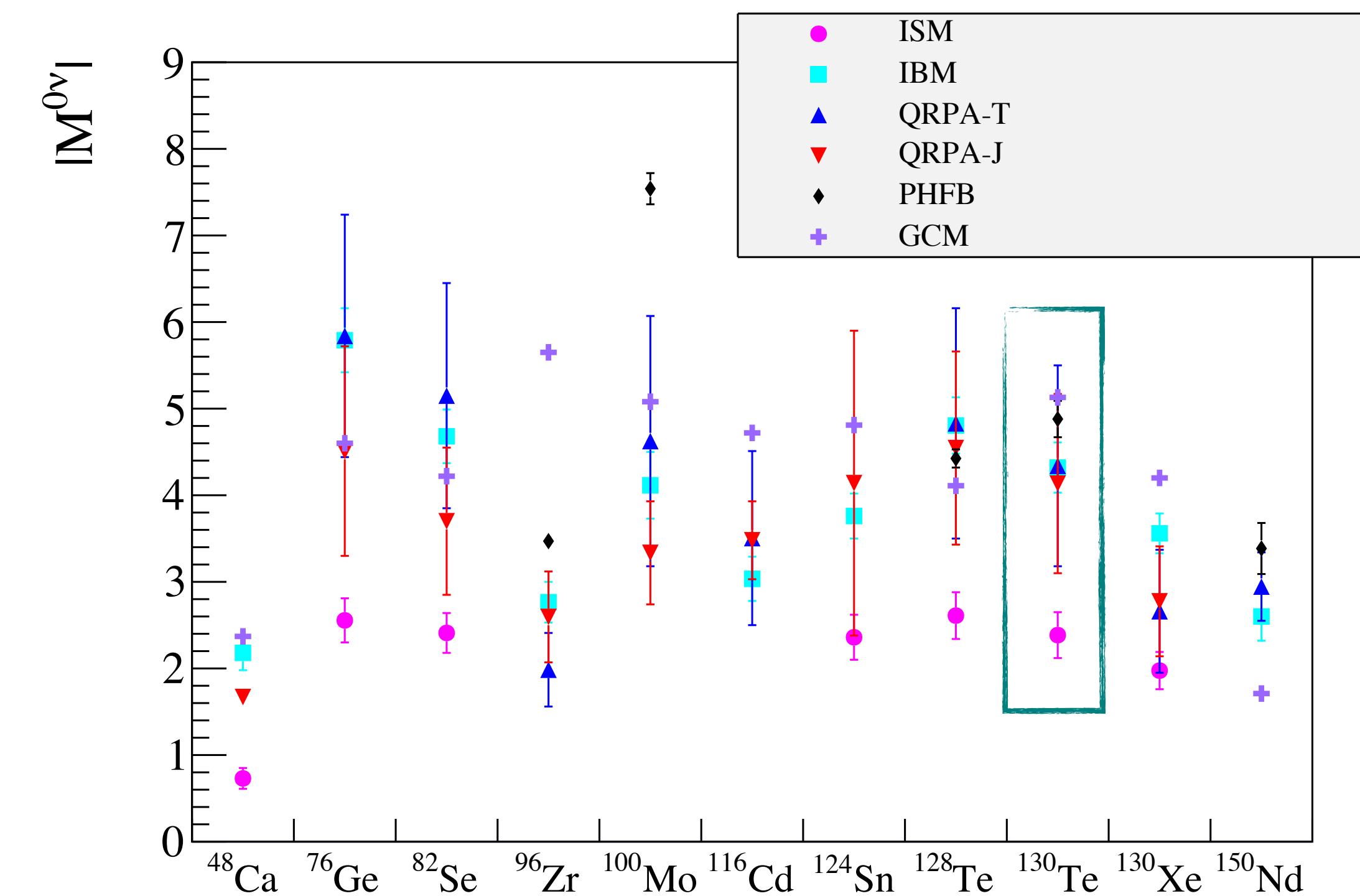
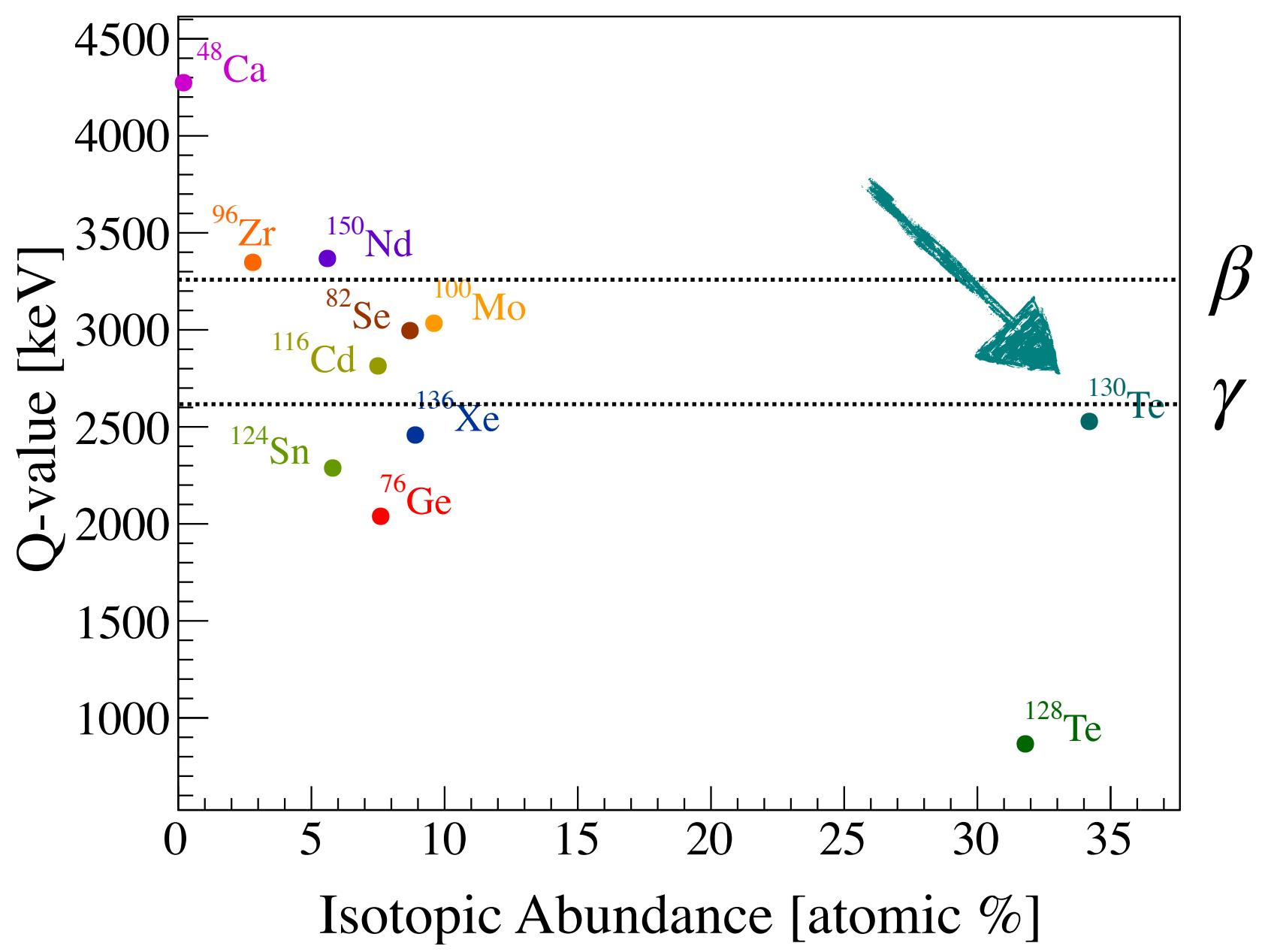


# LNGS

- Gran Sasso National Laboratory
  - ~ 3600 m.w.e. deep
  - ~  $3 \times 10^{-8}$  muons / (s cm<sup>2</sup>)
  - ~ 0.73 gammas / (s cm<sup>2</sup>)
  - ~  $4 \times 10^{-6}$  neutrons / (s cm<sup>2</sup>) below 10 MeV



# Isotope choice / NME



- High natural isotopic abundance
- Relatively low  $\beta/\gamma$  background
- Reproducible growth of high quality crystals

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q, Z) |M_{0\nu}|^2 \frac{|\langle m_{\beta\beta} \rangle|^2}{m_e^2}$$

# CUORE (1TY)

- 19 towers
  - 13 floors with 4 crystals on each floor
- 988 TeO<sub>2</sub> crystal bolometers
  - <sup>130</sup>Te isotopic abundance ~34%
  - 280 g (742 kg TeO<sub>2</sub>, 206 kg <sup>130</sup>Te)
  - cubic (5x5x5 cm<sup>3</sup>)
- cryostat (CUORE)
  - ~10 mK

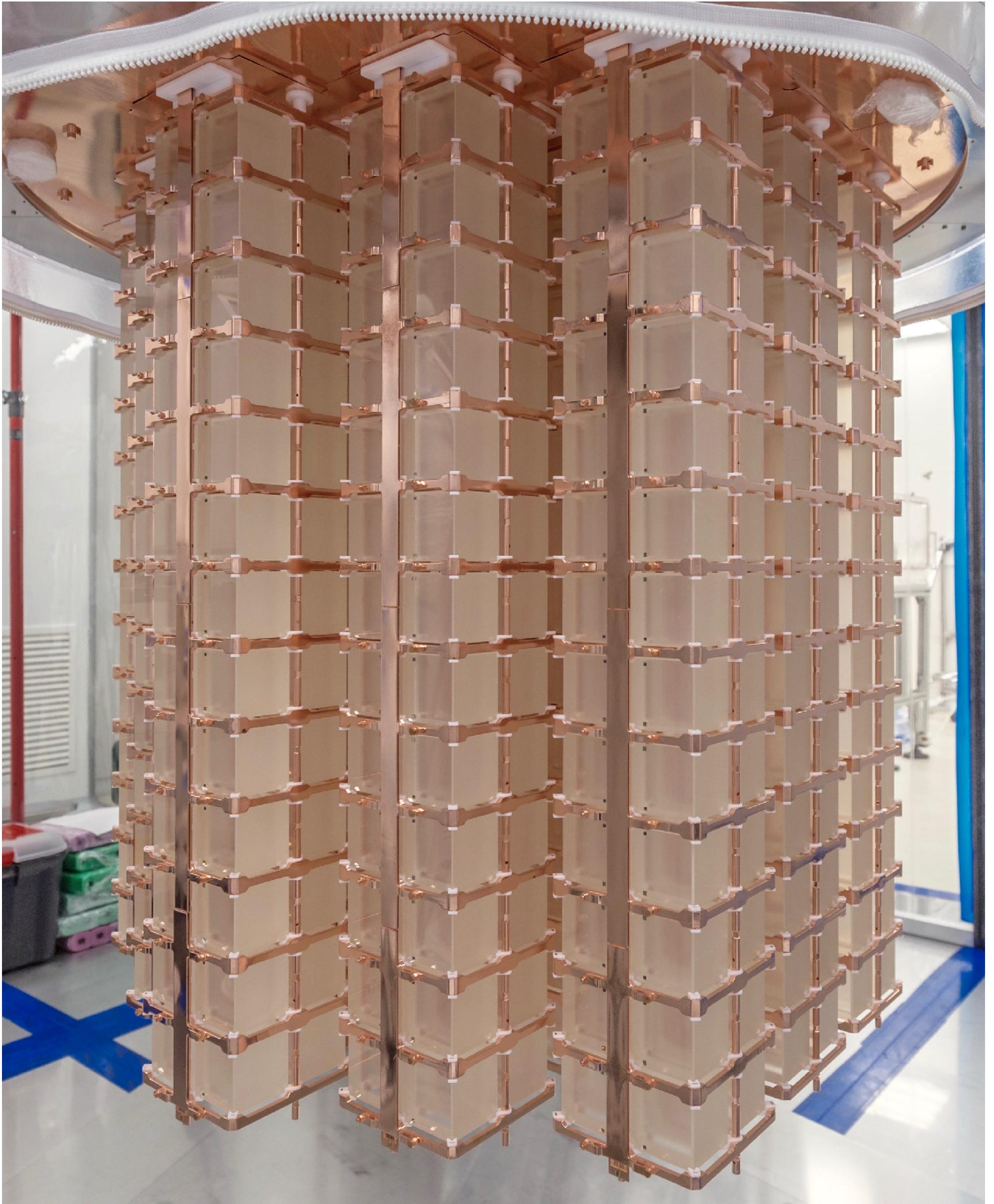
exposure: 1038.4 kg·yr TeO<sub>2</sub> (288 kg·yr <sup>130</sup>Te)

Bl: 1.49(4) × 10<sup>-2</sup> counts/(keV·kg·yr)

resolution: 7.8(5) keV (FWHM)

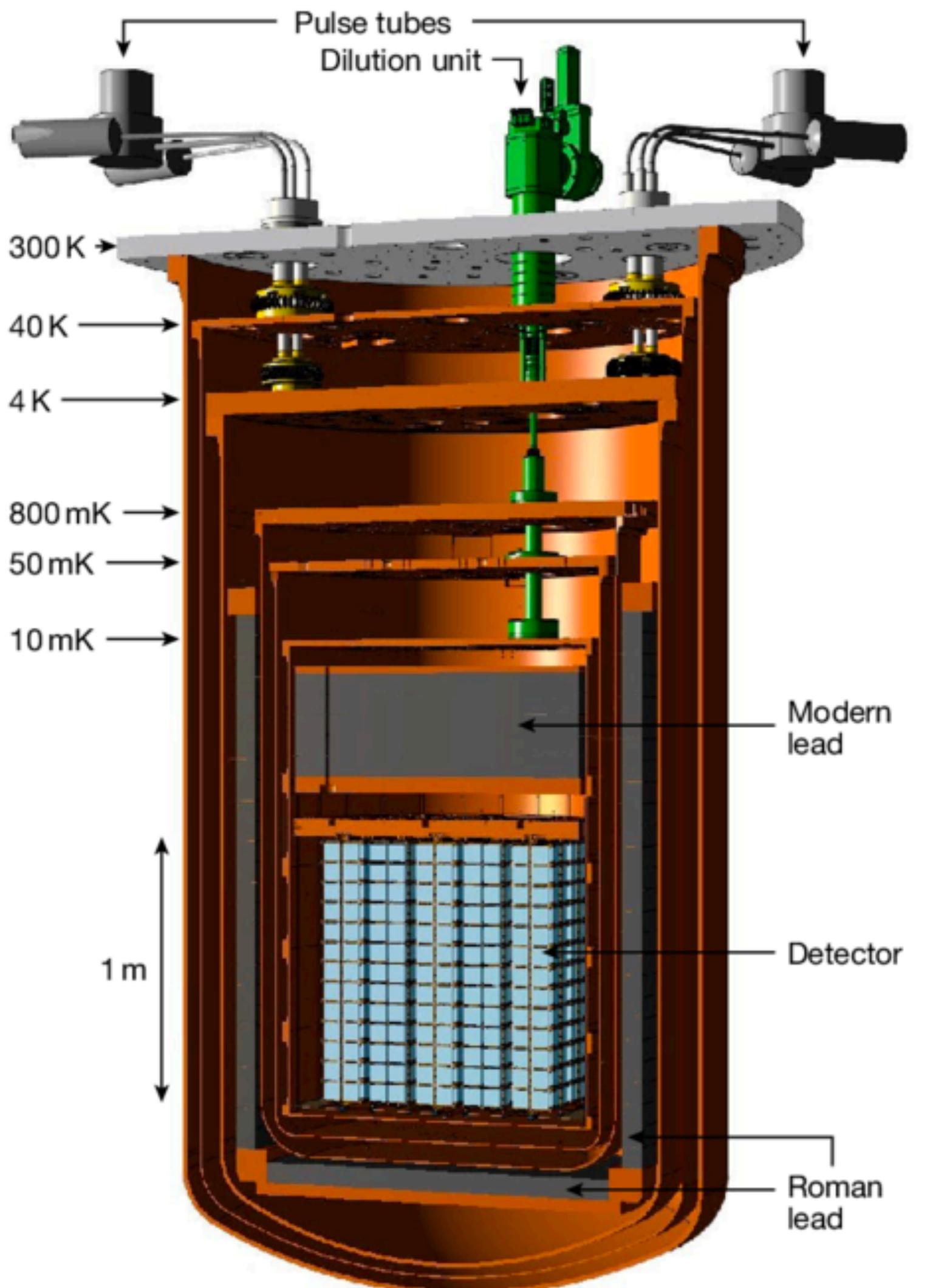
$T_{1/2}^{0\nu} > 2.2 \times 10^{25}$  years (90% C.I.)

$\langle m_{\beta\beta} \rangle < 90 - 305$  meV



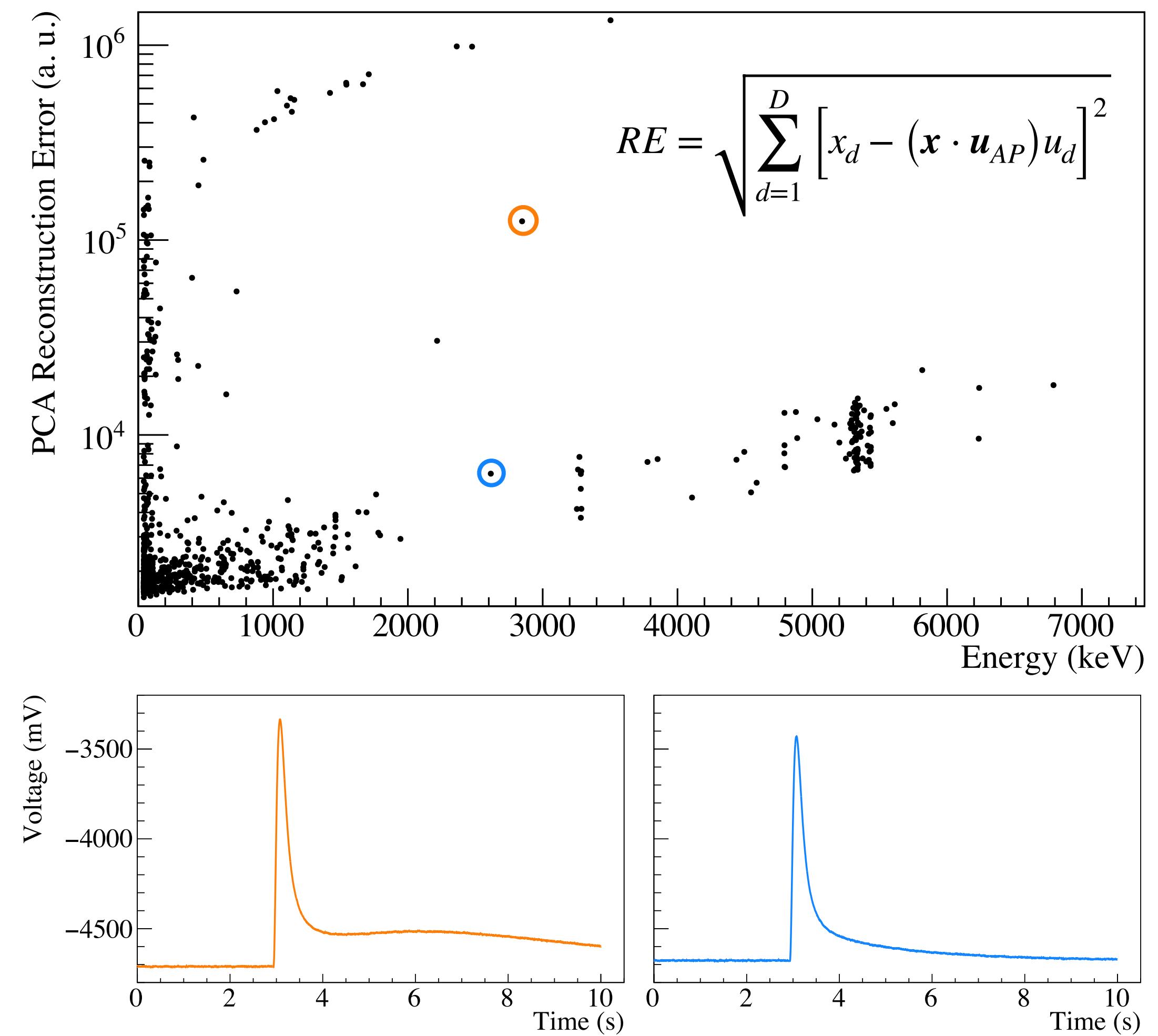
# Cryostat

- Cryogen-free cryostat
- Cools down ~1 ton detector to ~10 mK
- Mechanically decoupled for extremely low vibrations
- PT to cool down to ~4K
- Dilution refrigerator down to operating temperature ~10 mK
- Nominal cooling power: 4  $\mu\text{W}$  @ 10mK
- Cryostat total mass ~30 tons
- Mass at  $T < 4\text{K}$ : ~15 tons
- Mass at  $T < 50 \text{ mK}$ : ~3 tons (Pb, Cu and TeO<sub>2</sub>)

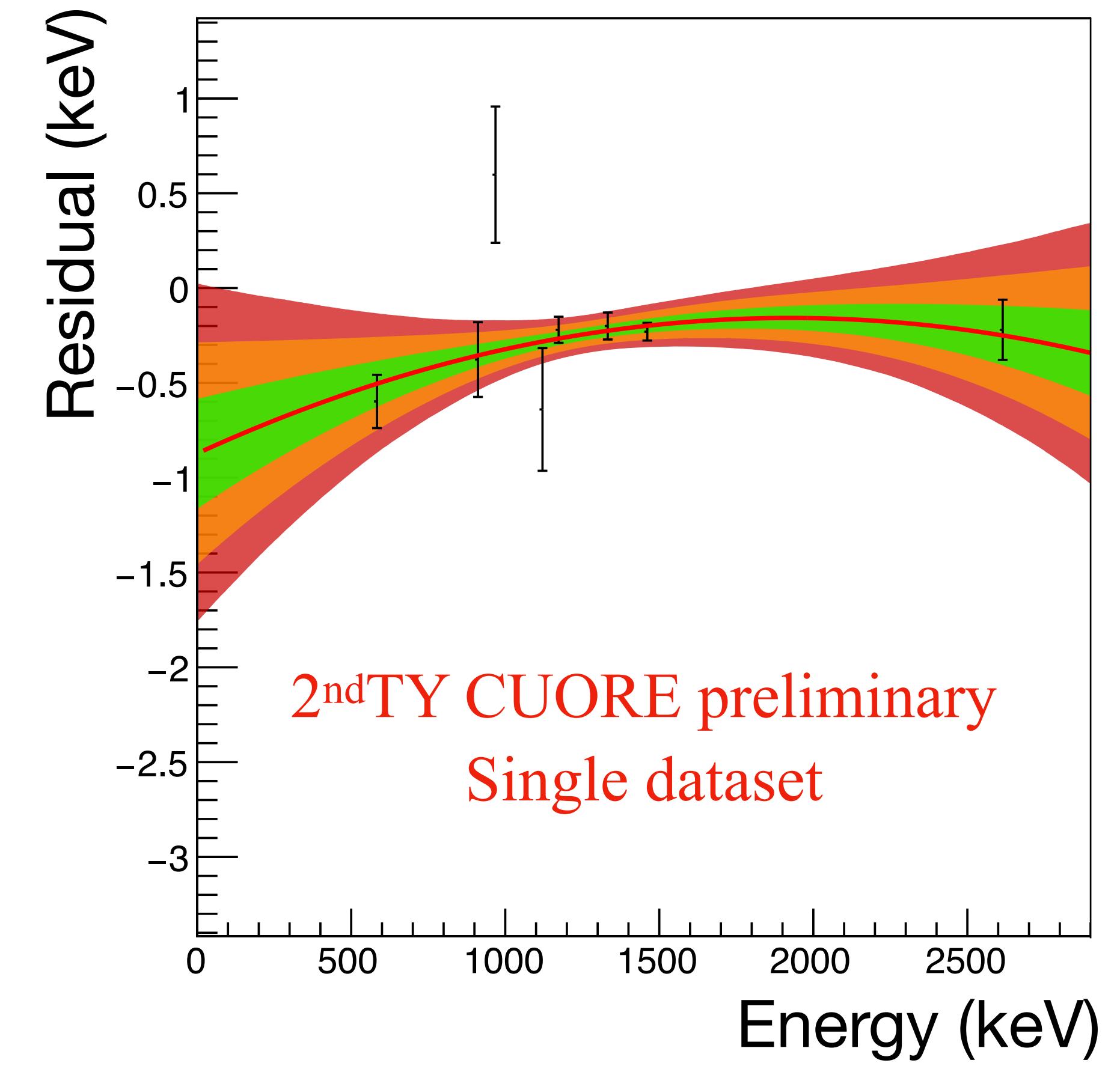
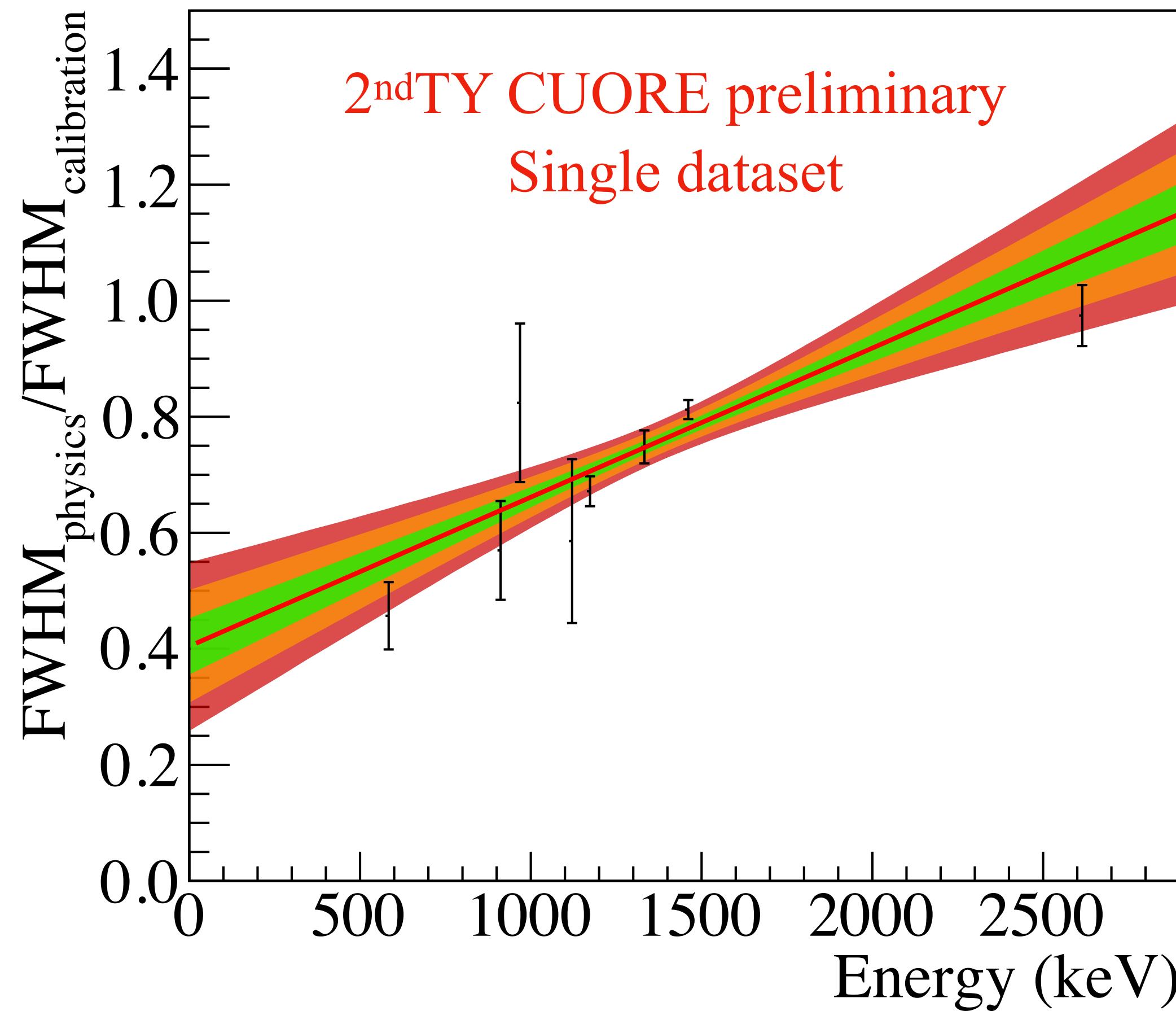


# Pulse shape discrimination (PSD)

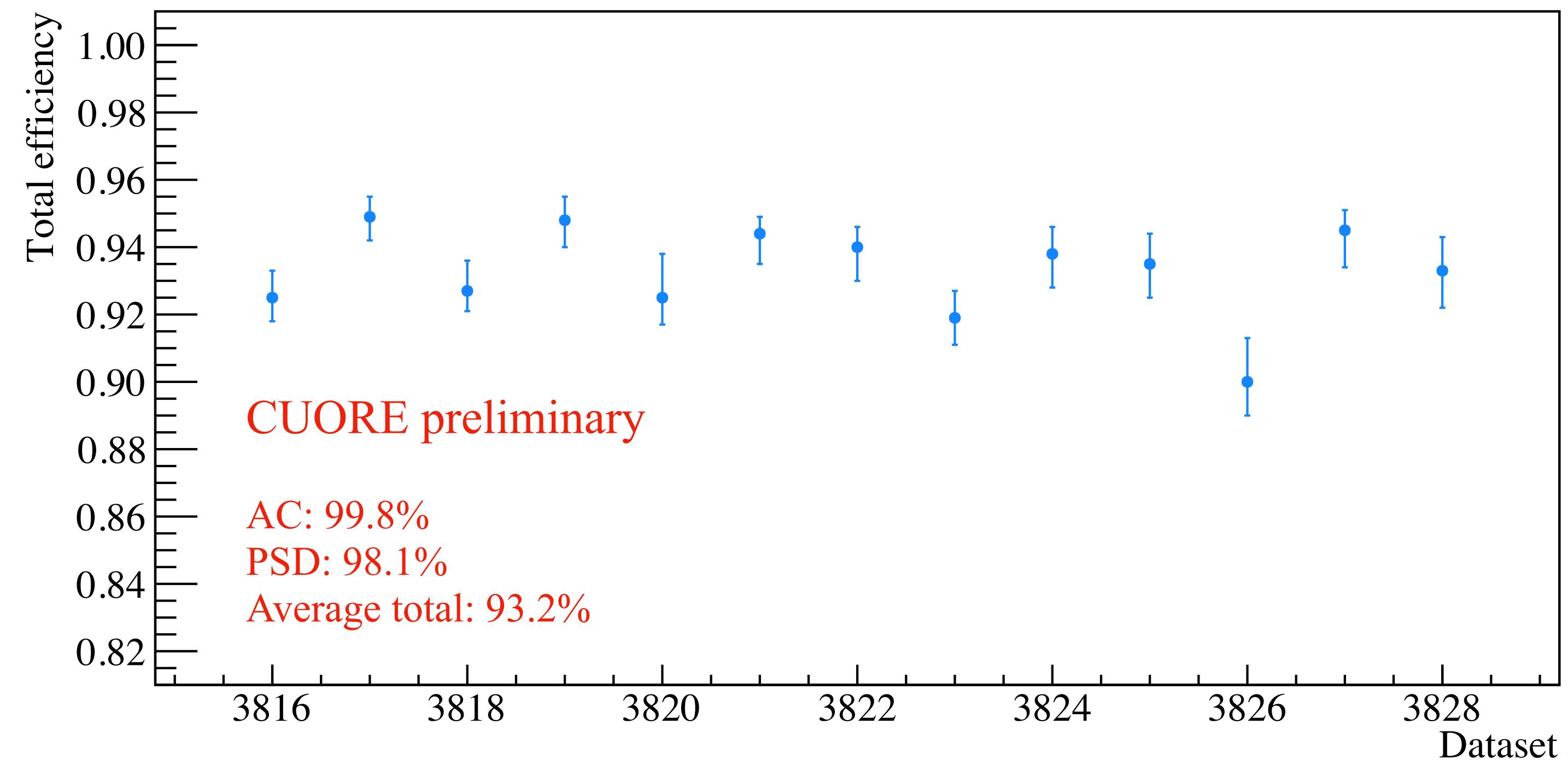
- principal component analysis (PCA) is sensitive to outliers in data
- the average pulse is used as a proxy for the leading principal component that reflects physical pulse shape
- PCA reconstruction error is used to discriminate physical and nonphysical (pileup, noise, etc.) events
- event selection is based on the figure-of-merit:  $\frac{\epsilon_{2615keV}}{\sqrt{\epsilon_{bkg}}}$  that reflects the experimental sensitivity



# line shape scaling



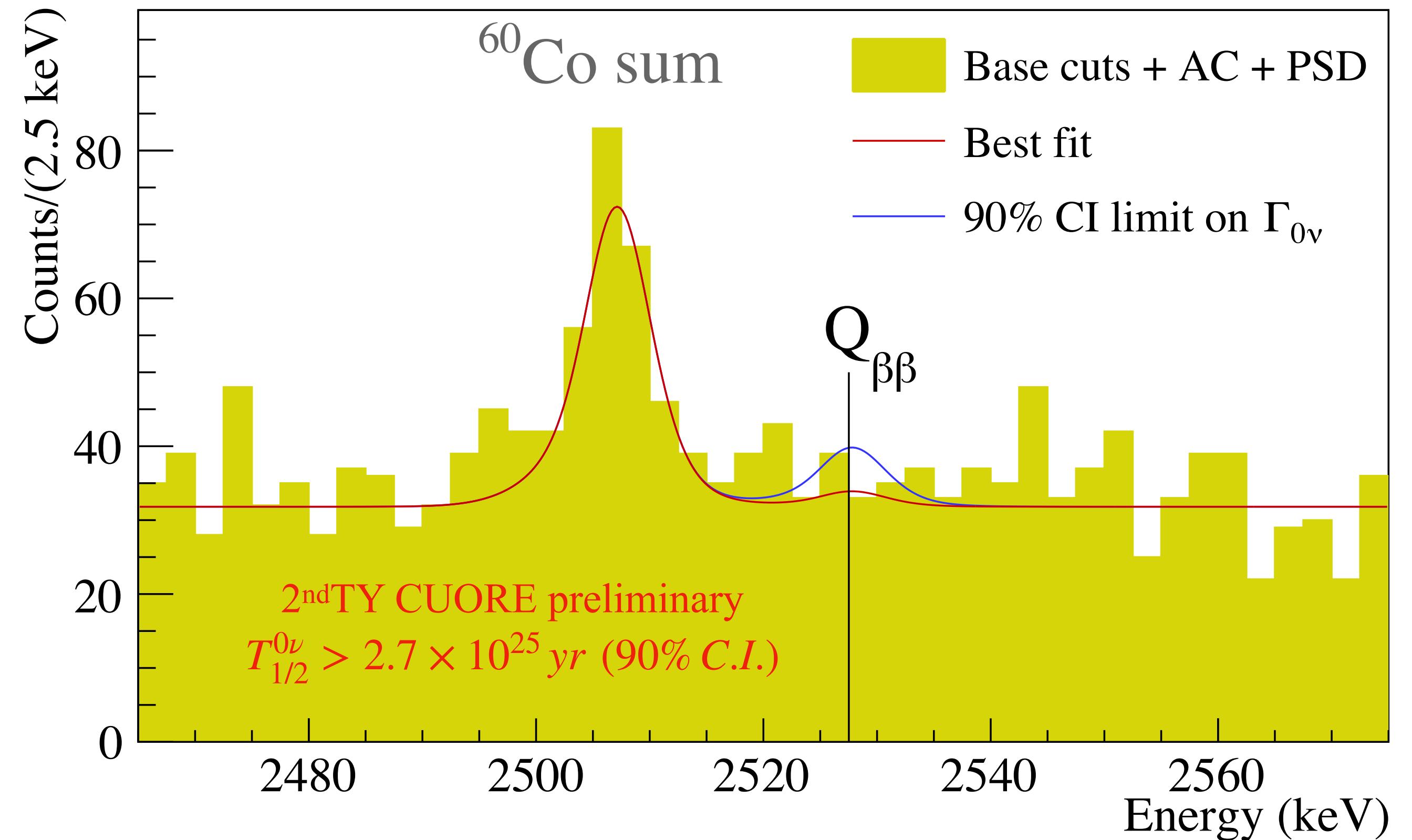
## Efficiencies



- Base Cuts: probabilities of accurate detection, energy reconstruction, and pile-up rejection (heater pulses)
- AC: probability of identifying single crystal event ( $^{40}\text{K}$ )
- PSD: probability of keeping a physical event ( $\gamma_{i,BG}$ )

## ROI fit

- UEML fit in ROI: [2465,2575] keV
- likelihood model:  $^{130}\text{Te}$   $Q_{\beta\beta}$  peak ( $\Gamma_{0\nu}$ ) +  $^{60}\text{Co}$  sum peak ( $\Gamma_{Co}$ ) + flat background (BI)
- flat priors on BI and  $\Gamma_{0\nu}$
- informative priors for efficiencies, energy bias, resolution,  $Q_{\beta\beta}$ , and isotopic abundance
- fit procedure determined using blinded data, where events are exchanged between posited  $Q_{\beta\beta}$  and the  $^{208}\text{Tl}$  2615 keV peak



- Bayesian Analysis Toolkit (BAT) - MCMC based evaluation of posteriors
  - UEML fit in ROI: [2465,2575] keV
  - likelihood model:  $^{130}\text{Te}$  Q $_{\beta\beta}$  peak ( $\Gamma_{0\nu}$ ) +  $^{60}\text{Co}$  sum peak ( $\Gamma_{Co}$ ) + flat background (BI)
- Dataset-dependent parameters:
  - Background Index (BI)
  - Efficiencies
  - Resolution and bias scaling
- Global parameters:
  - $\Gamma_{Co}$  : one activity rate with a time-dependent correction for each DS
  - Q $_{\beta\beta}$
  - Isotopic abundance of  $^{130}\text{Te}$
  - Containment Efficiency
  - $\underline{\Gamma_{0\nu}}$