Latest Results from the CUORE Experiment

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TeVPA 2023, Napoli

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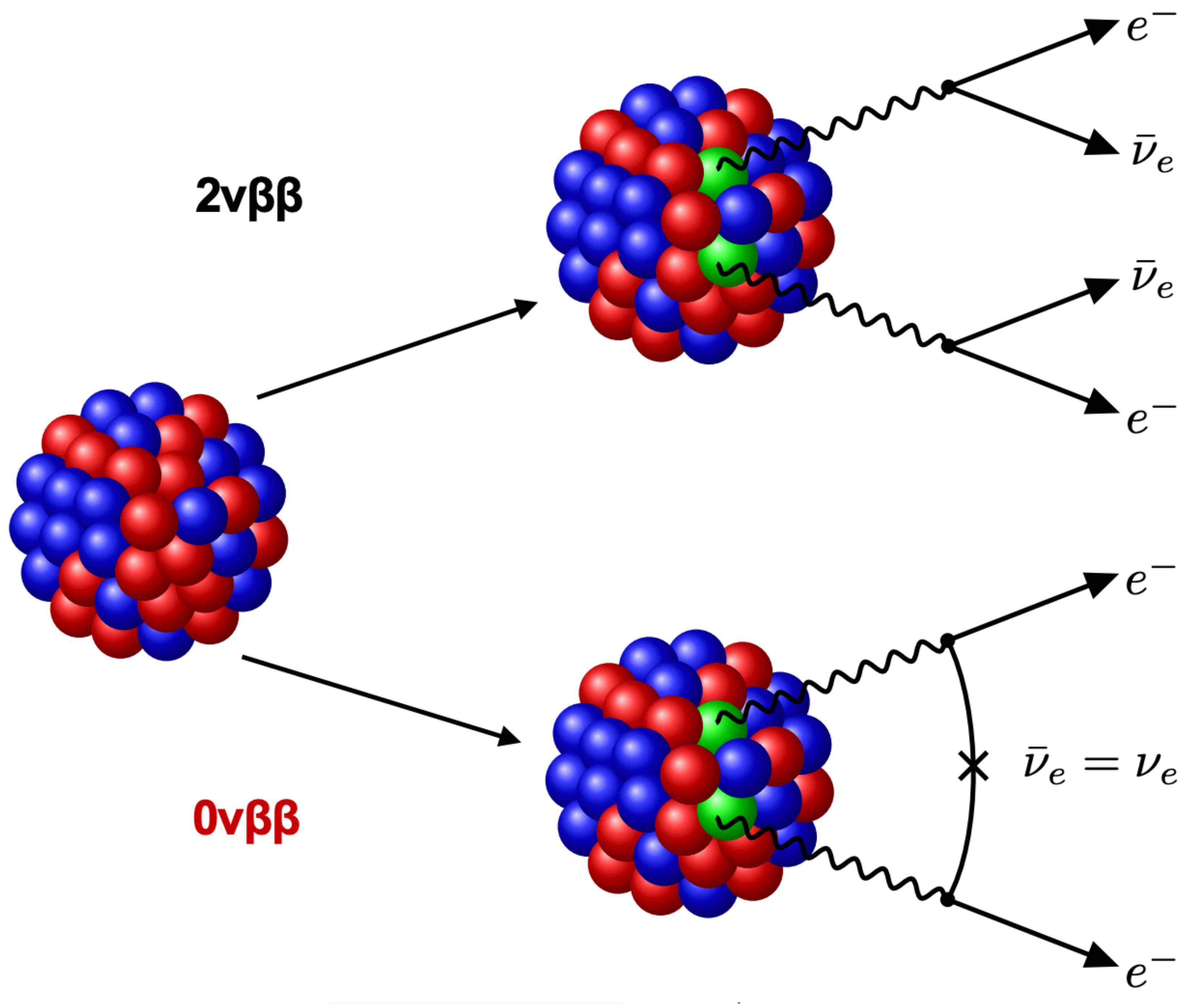
Double β Decay

CUORE



Standard Model allowed double β decay: $2\nu\beta\beta$

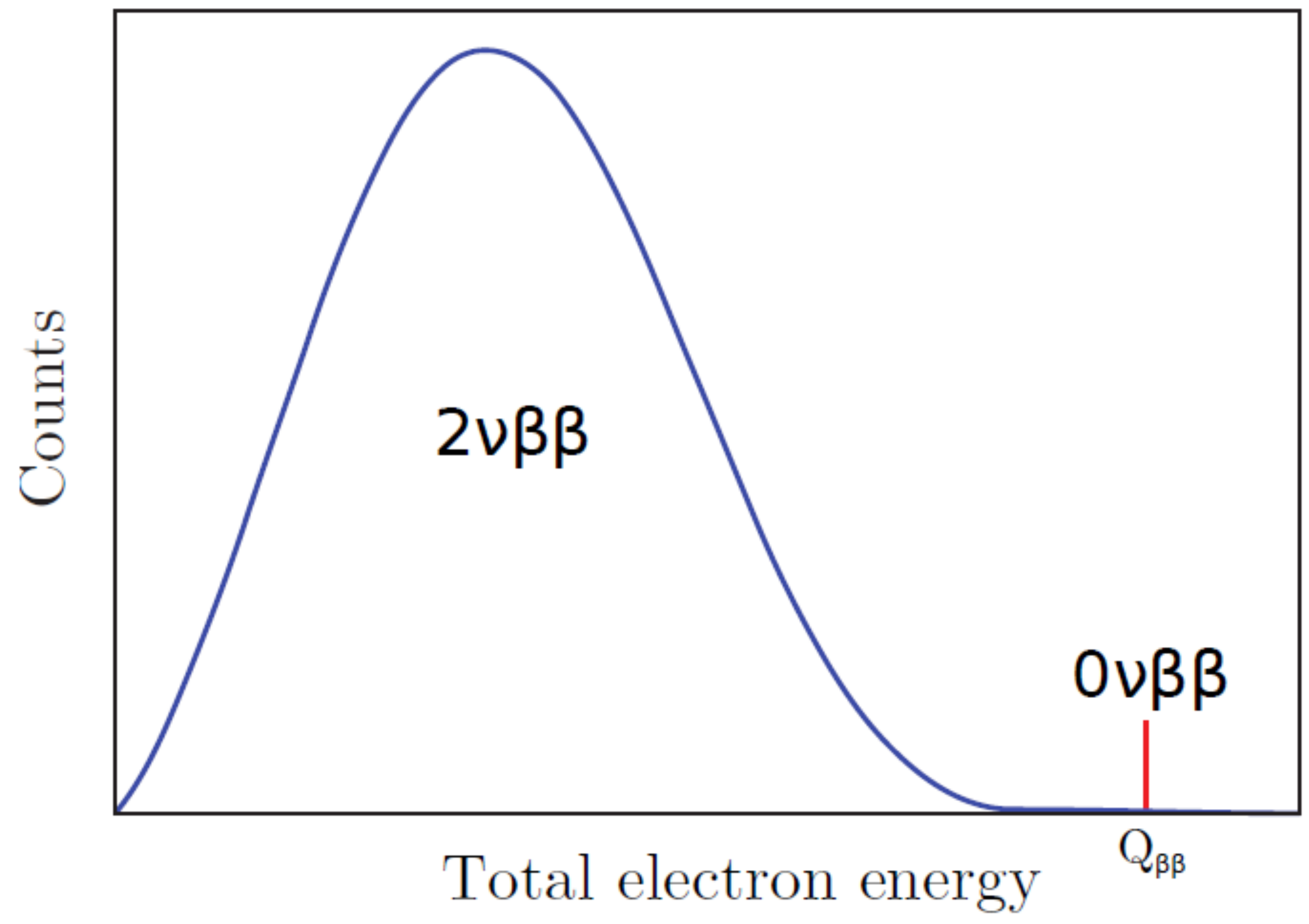
- **Observed** in 11 even-even nuclei in which single β decay is energetically forbidden
- $T_{1/2} \sim 10^{18} - 10^{24}$ years

Neutrinoless double β decay: $0\nu\beta\beta$

- **Neutrino Nature**: possible only if neutrino is a Majorana particle (coincide with its own antiparticle)
- **Total Lepton number violated of 2 units**: an ingredient to solve matter-antimatter asymmetry

Double β Decay

CUORE



Standard Model allowed double β decay: $2\nu\beta\beta$

➡ Continuous spectrum ending at the isotope Q-value

Neutrinoless double β decay: $0\nu\beta\beta$

➡ Mono-energetic peak at the isotope Q-value (a simple and clear experimental signature)

Experimental search for $0\nu\beta\beta$

$$S_{0\nu} \propto \epsilon \sqrt{\frac{MT}{B\Delta}}$$

High Exposure

High Efficiency

Low Background

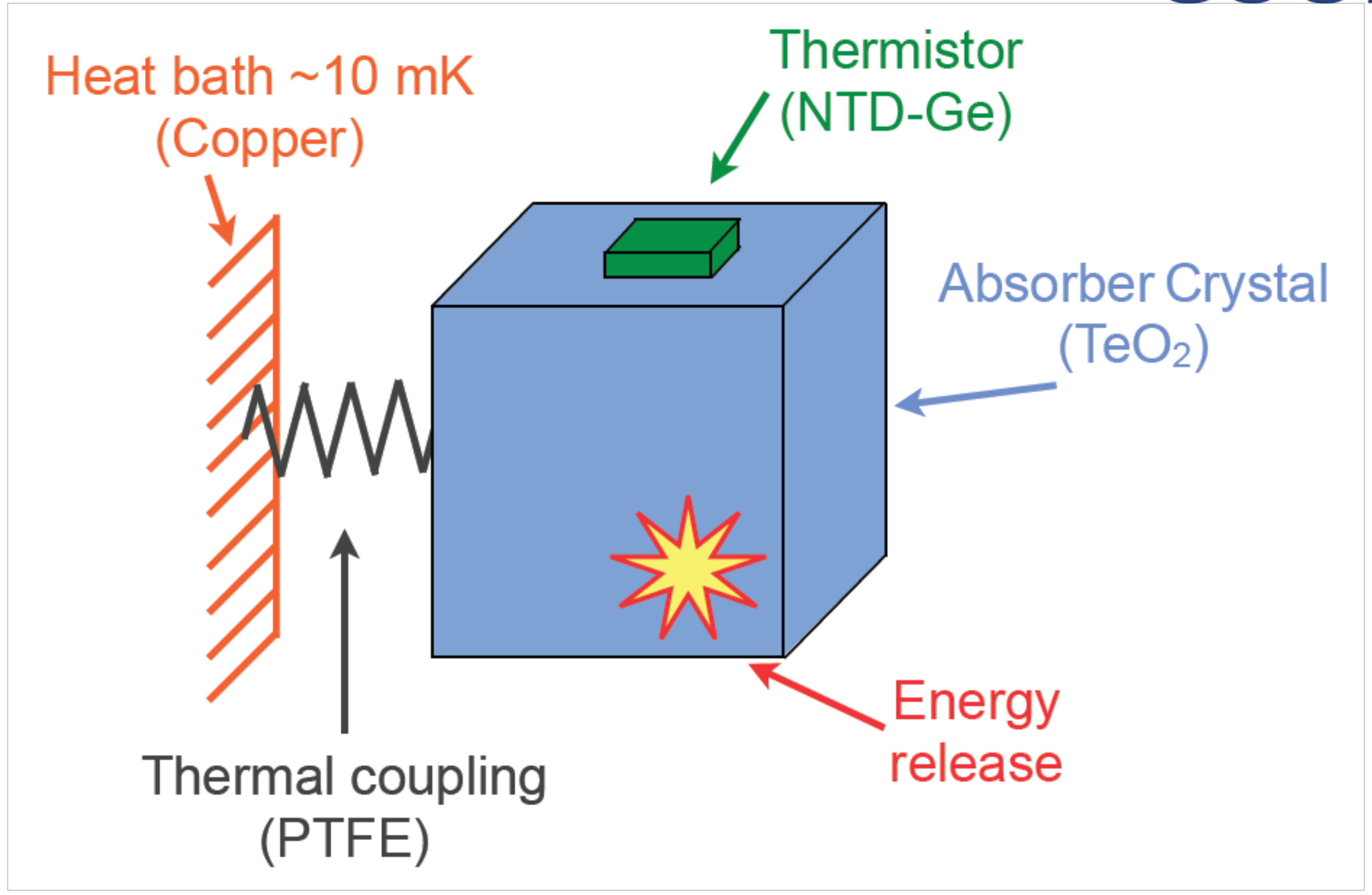
Good Energy Resolution

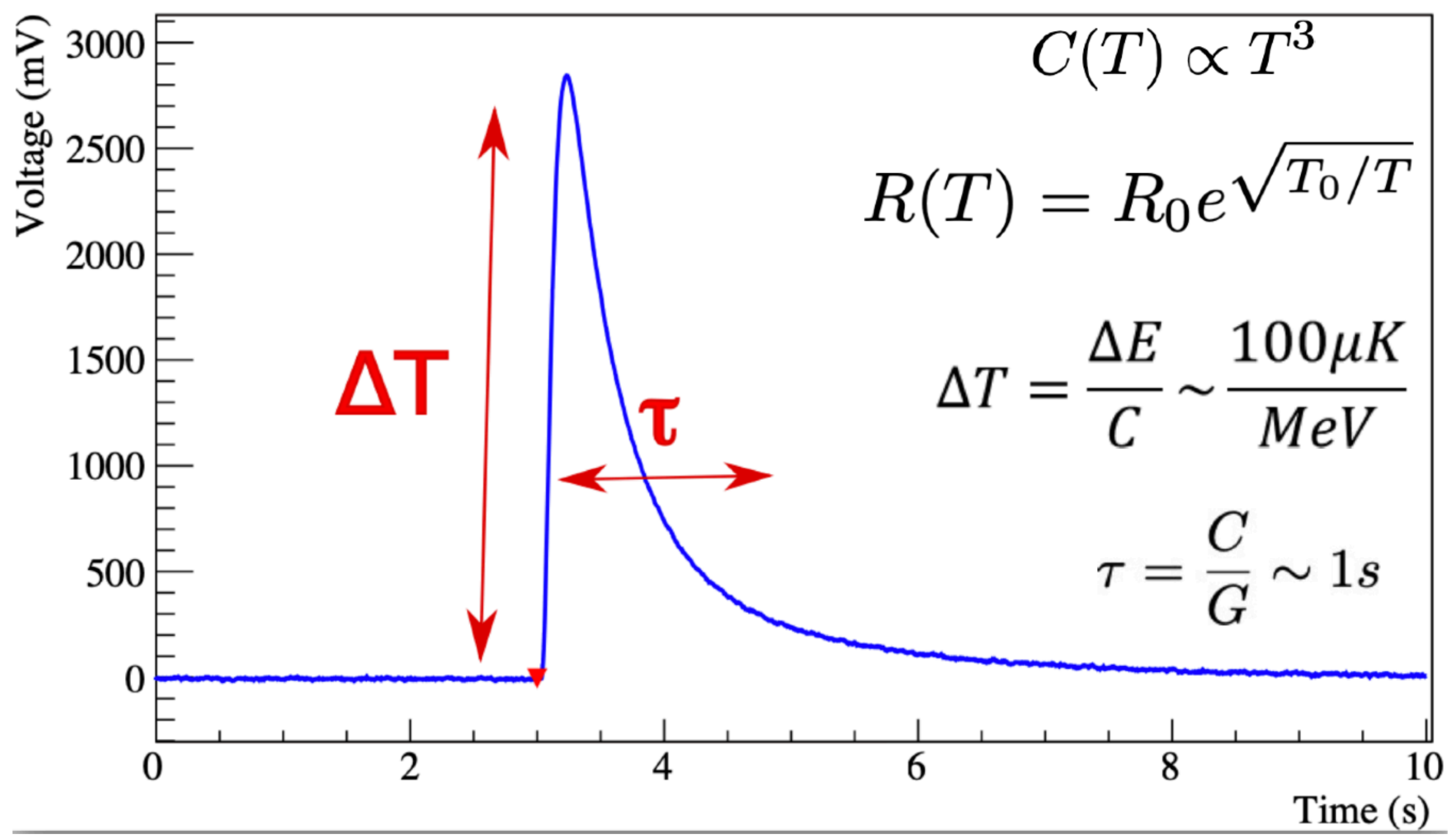
Cryogenic Calorimeters:

- A mature technology as demonstrated by several experiment in the $0\nu\beta\beta$ field (CUORE, CUPID-0, CUPID-Mo, AMoRE)
- A mature technology able to explore competitive regions for the $0\nu\beta\beta$ parameter space

Cryogenic Calorimeters

1. Interacting particles deposit energy in the crystal
2. The energy release heats up the crystal via thermal phonons
3. The temperature increase is converted into an electric signal by a cryogenic sensor (e.g. a thermistor)





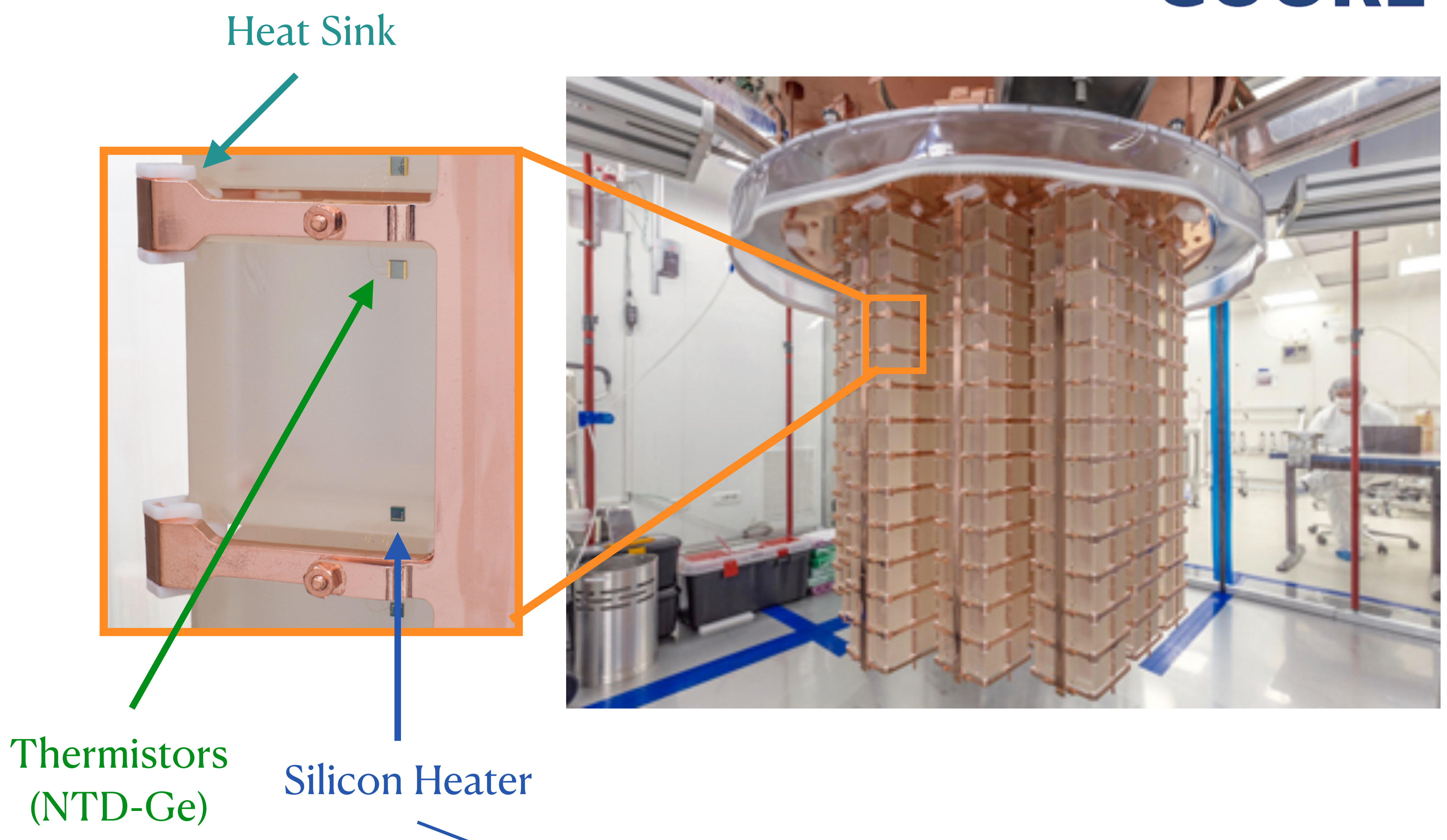
➡ Cryogenic temperatures (about 10 mK) make possible to turn the energy deposit into a readable temperature increase

CUORE Experiment

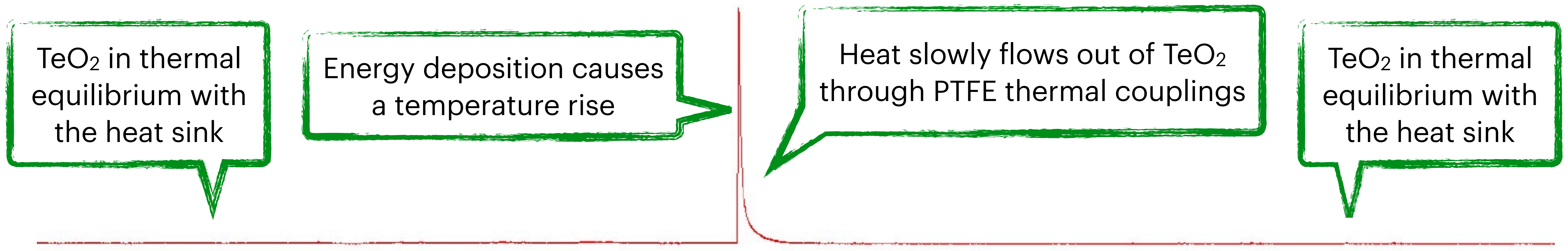
CUORE

Cryogenic **U**nderground **O**bservatory for **R**are **E**vents:

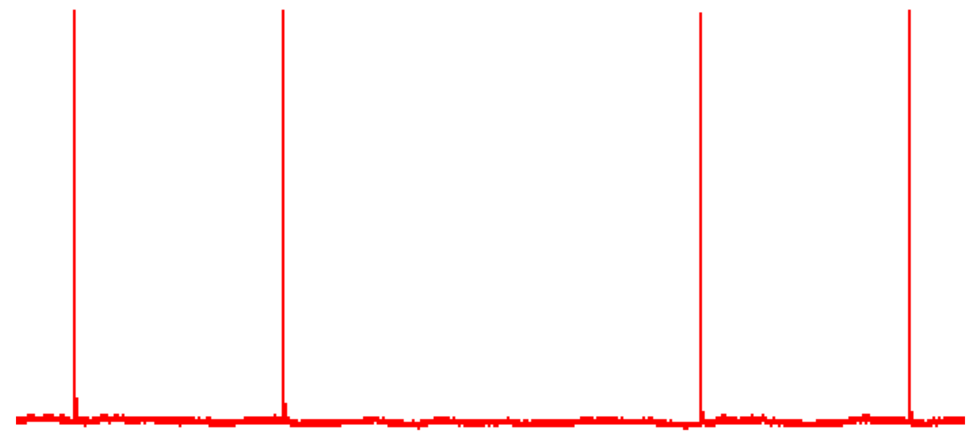
- Searching for $0\nu\beta\beta$ of ^{130}Te at 2528 keV
- Located at the Laboratori Nazionali del Gran Sasso in Italy
- 988 natural TeO2 5x5x5 cm3 cubic crystals arranged in 19 towers of 13 floors
- 742 kg of TeO2 (i.e. 206 kg of ^{130}Te)
- Taking data for over 4 years with >90% duty cycle



Example of CUORE data stream



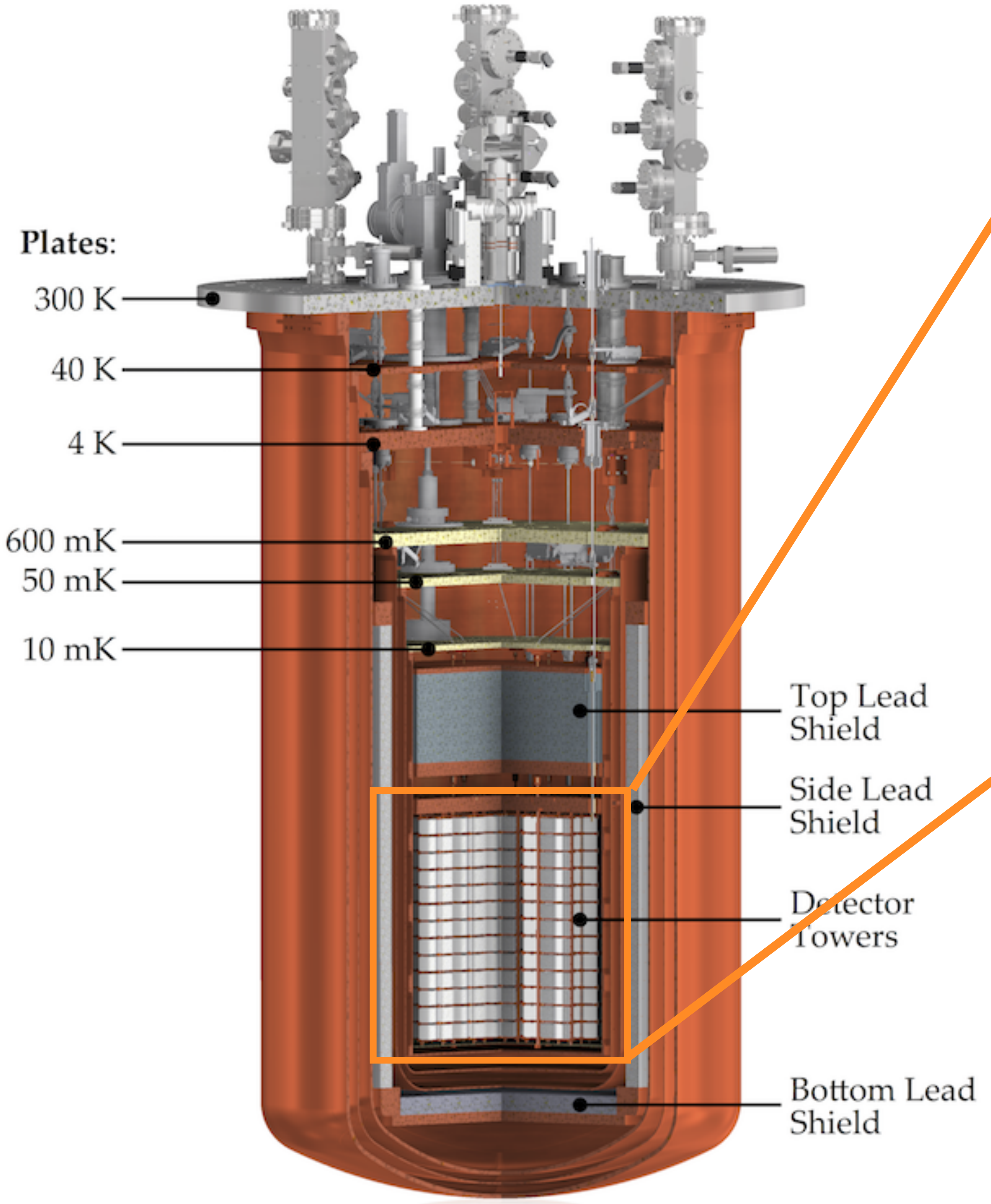
Silicon heaters provide standardized heat pulses for thermal gain correction

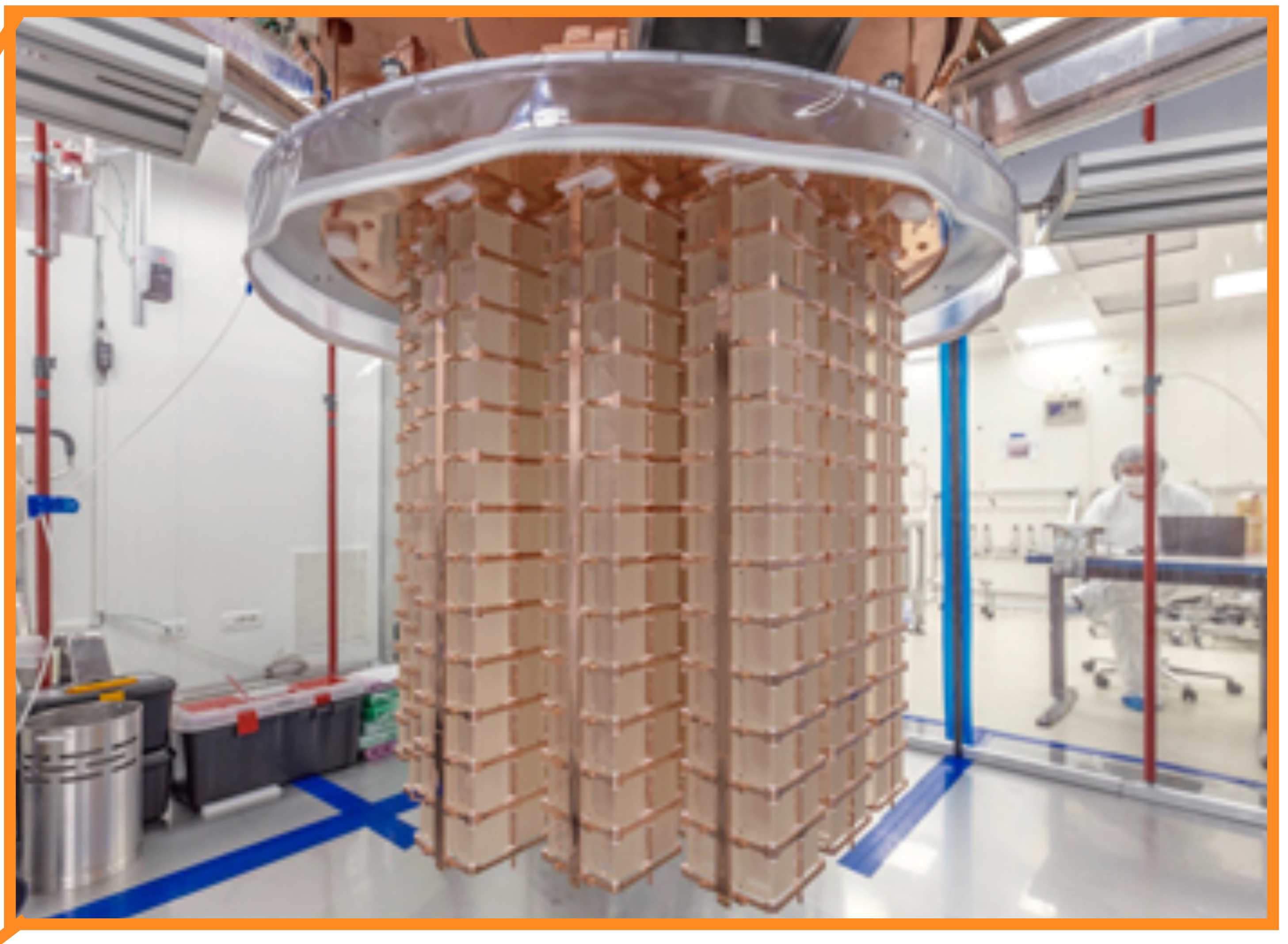


CUORE Experiment

Cryogenic **U**nderground **O**bservatory for **R**are **E**vents:

- Operated in a world leading dilution refrigerator in terms of power and size
- Equipped with 4 Pulse Tubes for cooling to 4K
- Nested co-axial copper vessels at decreasing temperatures
- 15 tons cooled blow 4 K and 3 tons below 50 mK
- TeO_2 crystals kept at 11-15 mK





$0\nu\beta\beta$ with CUORE

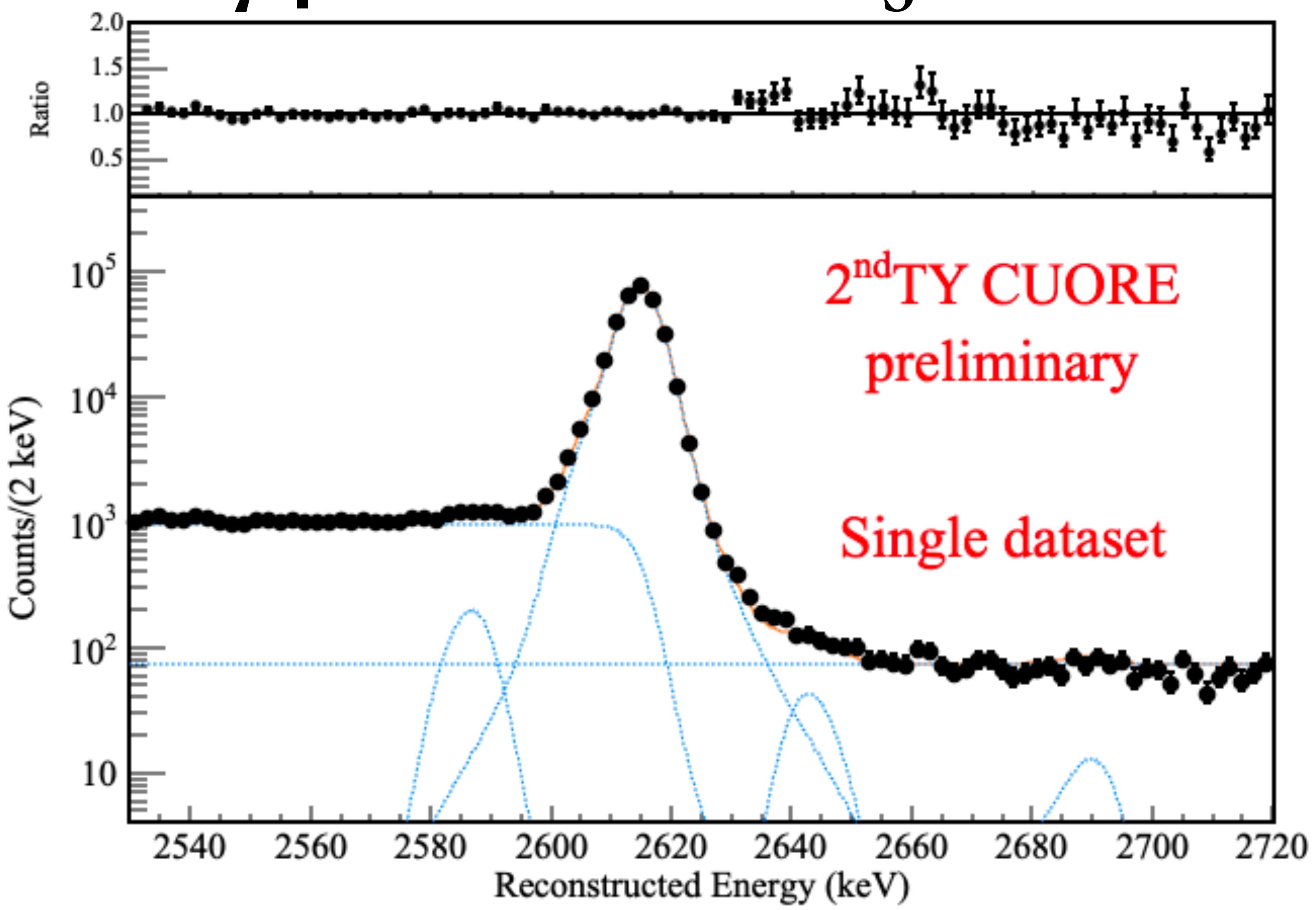
CUORE

The source of the decay coincide with the absorber, implying an very high detection efficiency (**88.4%**)

$$S_{0\nu} \propto \epsilon \sqrt{\frac{MT}{B\Delta}}$$

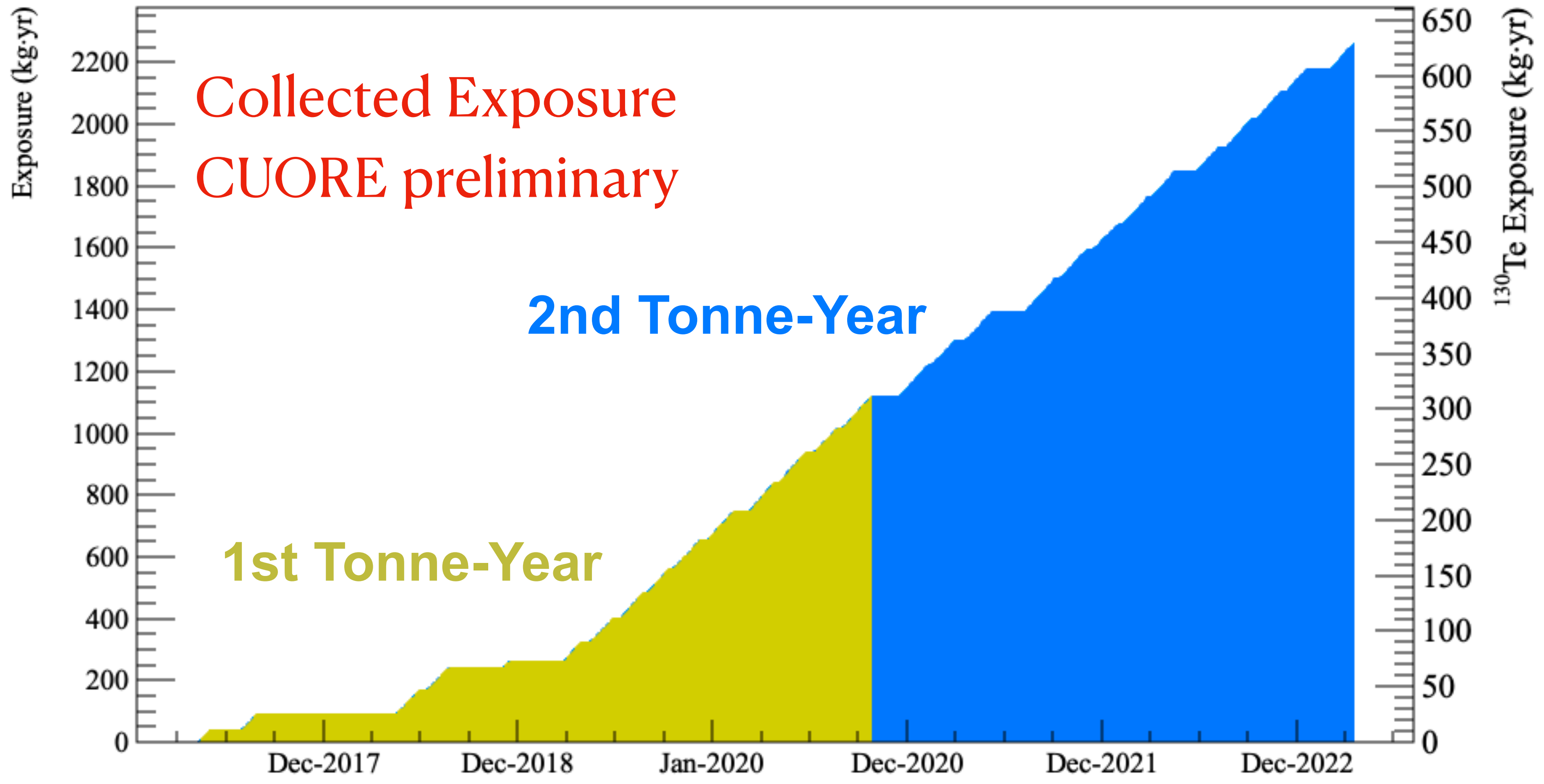
Large scalability for ton-scale experiments (only limited by the cryogenics)

7.4 keV FWHM at 2615 keV



Thermal phonon detection allows for an excellent energy resolution (0.3 %)

> 2 ton yr of TeO2 exposure collected (so far!)



$0\nu\beta\beta$ with CUORE

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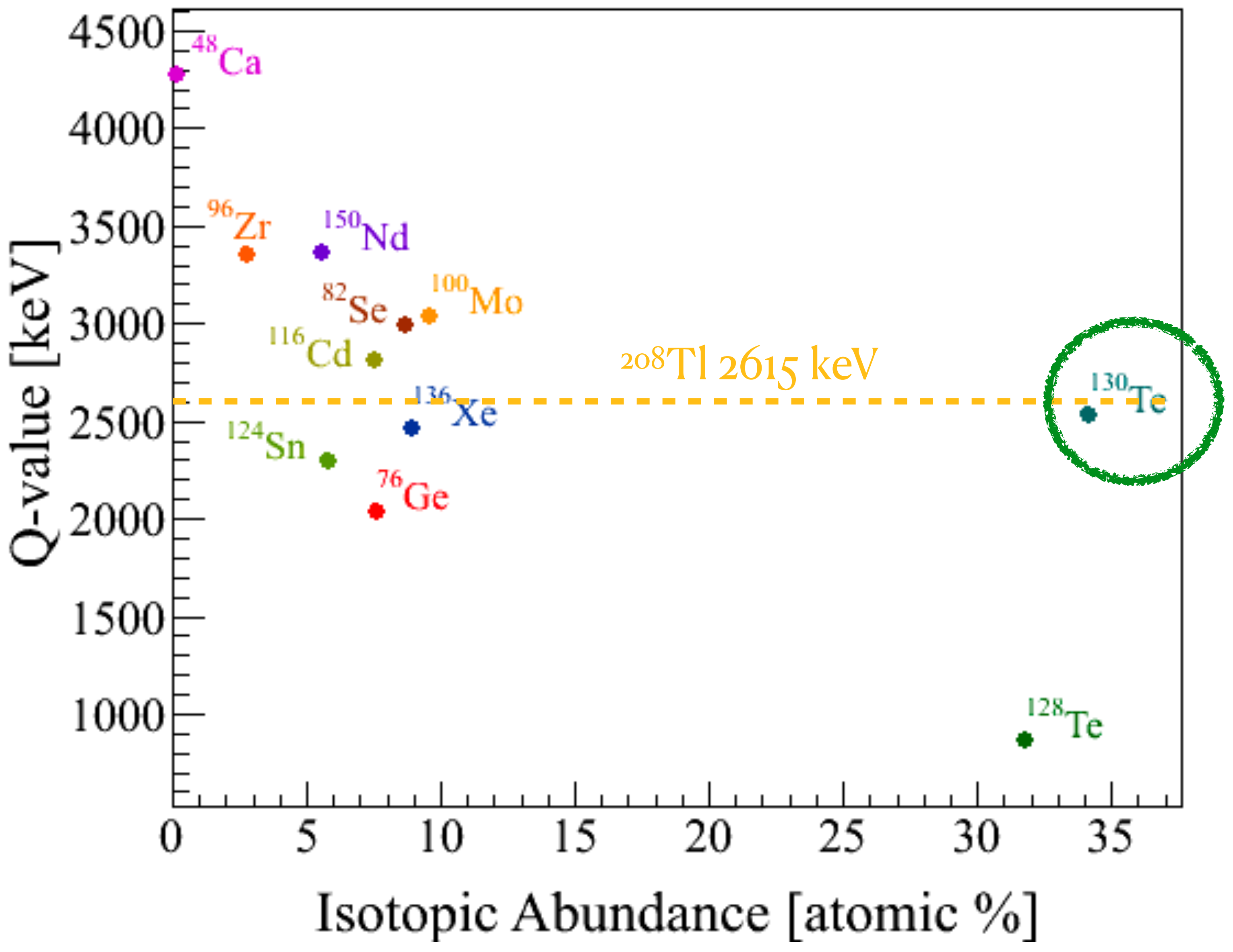
^{130}Te:

Large natural abundance (34%), no need for enrichment

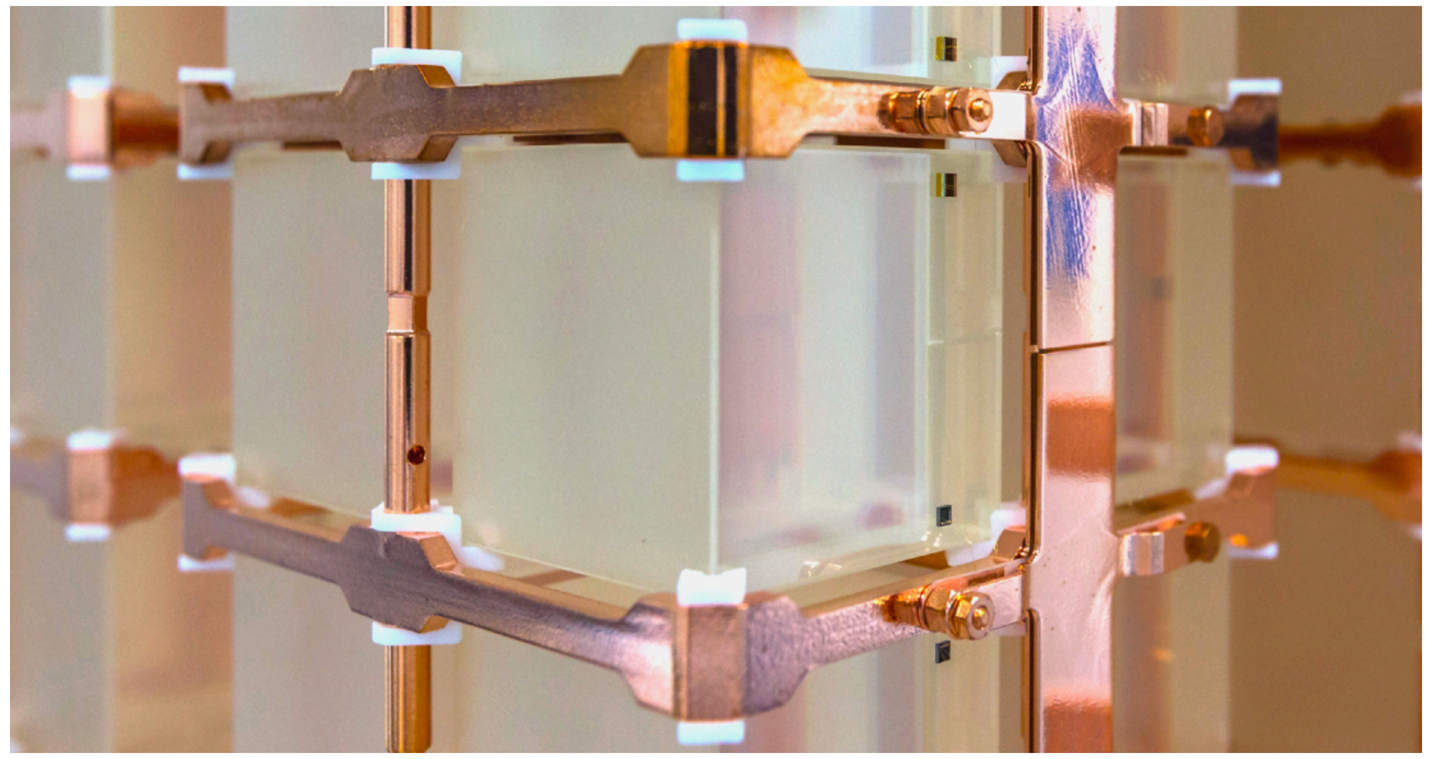
Close to the endpoint of gamma natural radioactivity



$$S_{0\nu} \propto \epsilon \sqrt{\frac{MT}{B\Delta}}$$

Cryogenic calorimeters technology presents a large flexibility in the materials choice

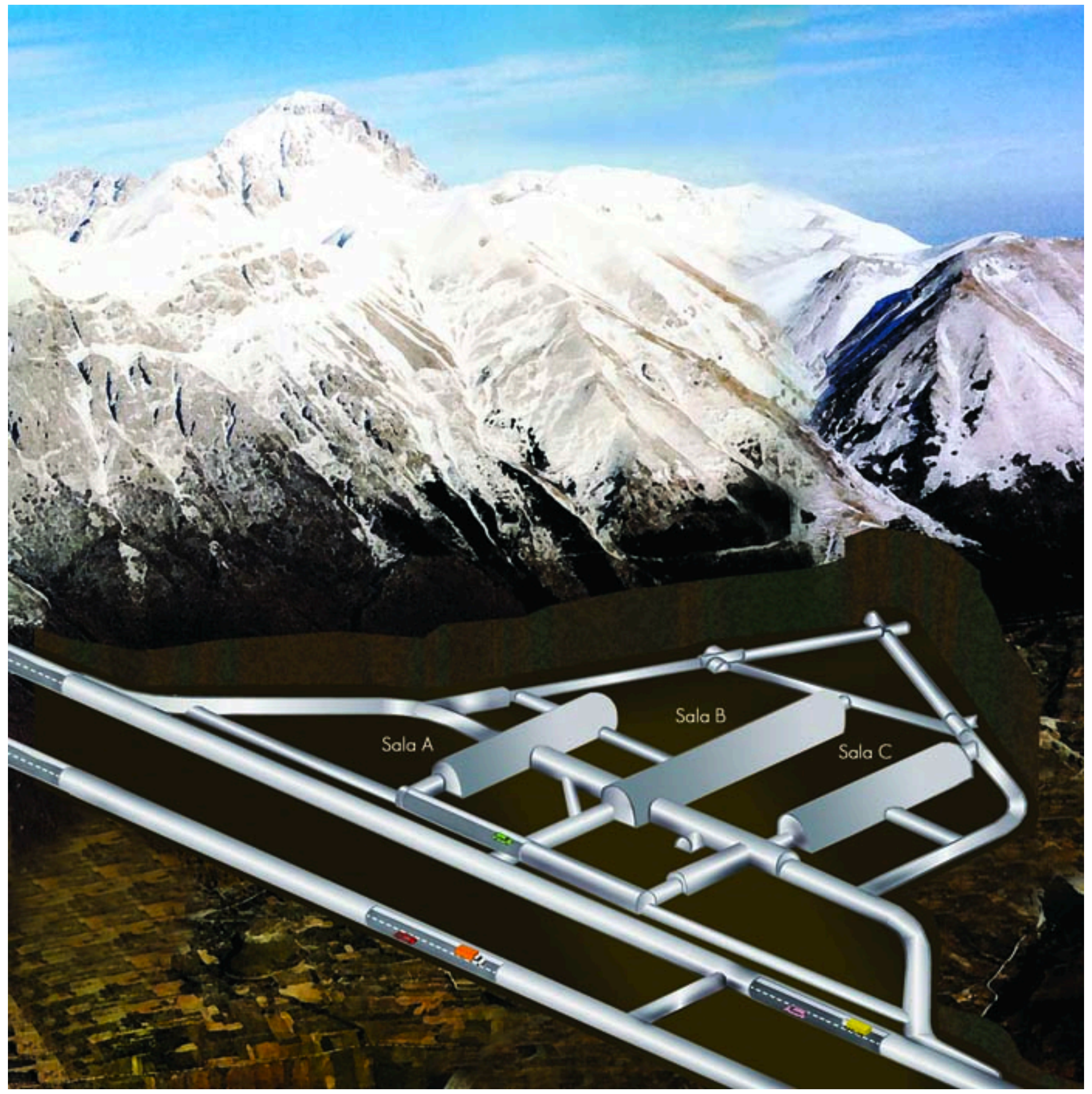
- Detector structure and components
- Crystal compounds



Select radiopure materials and perform strict cleaning procedures

$0\nu\beta\beta$ with CUORE

CUORE



Muons: ~ 3x10^{-8} s^{-1} cm^{-2}

Neutrons: < 4x10^{-6} s^{-1} cm^{-2}

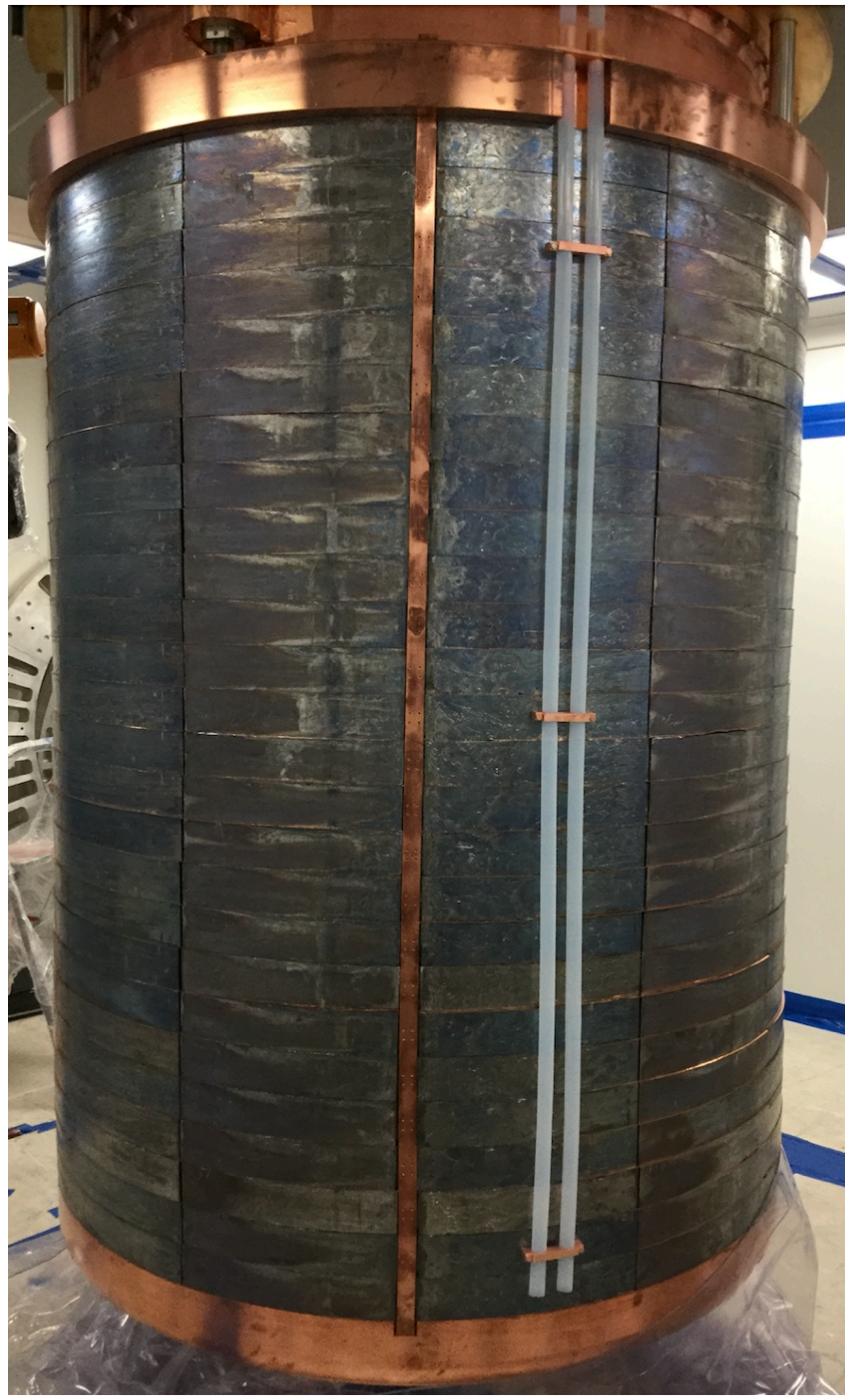
Gammas: ~ 0.73 s^{-1} cm^{-2}

$$S_{0\nu} \propto \epsilon \sqrt{\frac{MT}{B\Delta}}$$

Operated Underground at LNGS with 3600 meters of water equivalent to shield against cosmic rays

External layers against radioactivity (e.g. Ancient Roman Lead)

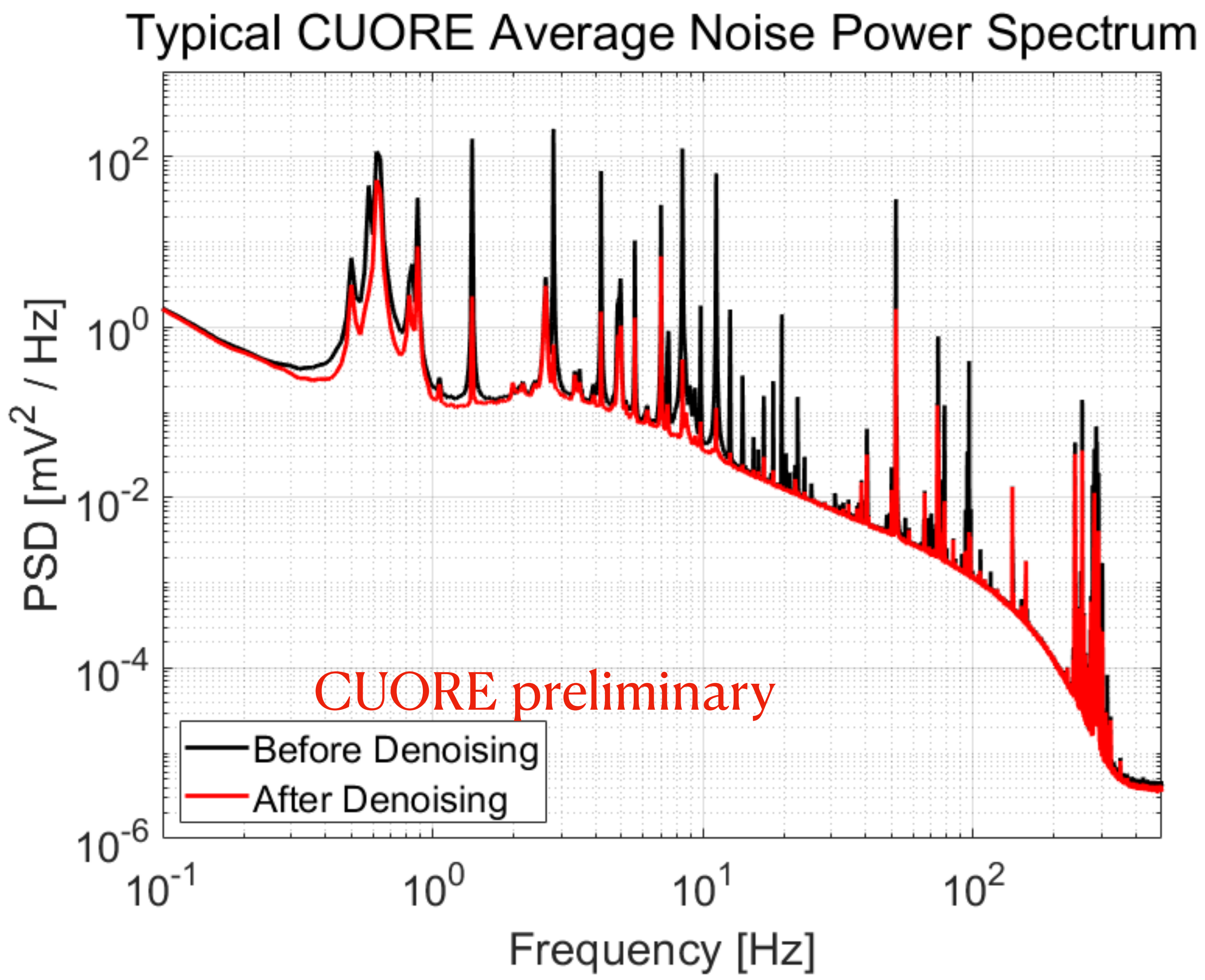
1.3×10^{-2} counts/(keV kg yr) at 2528 keV



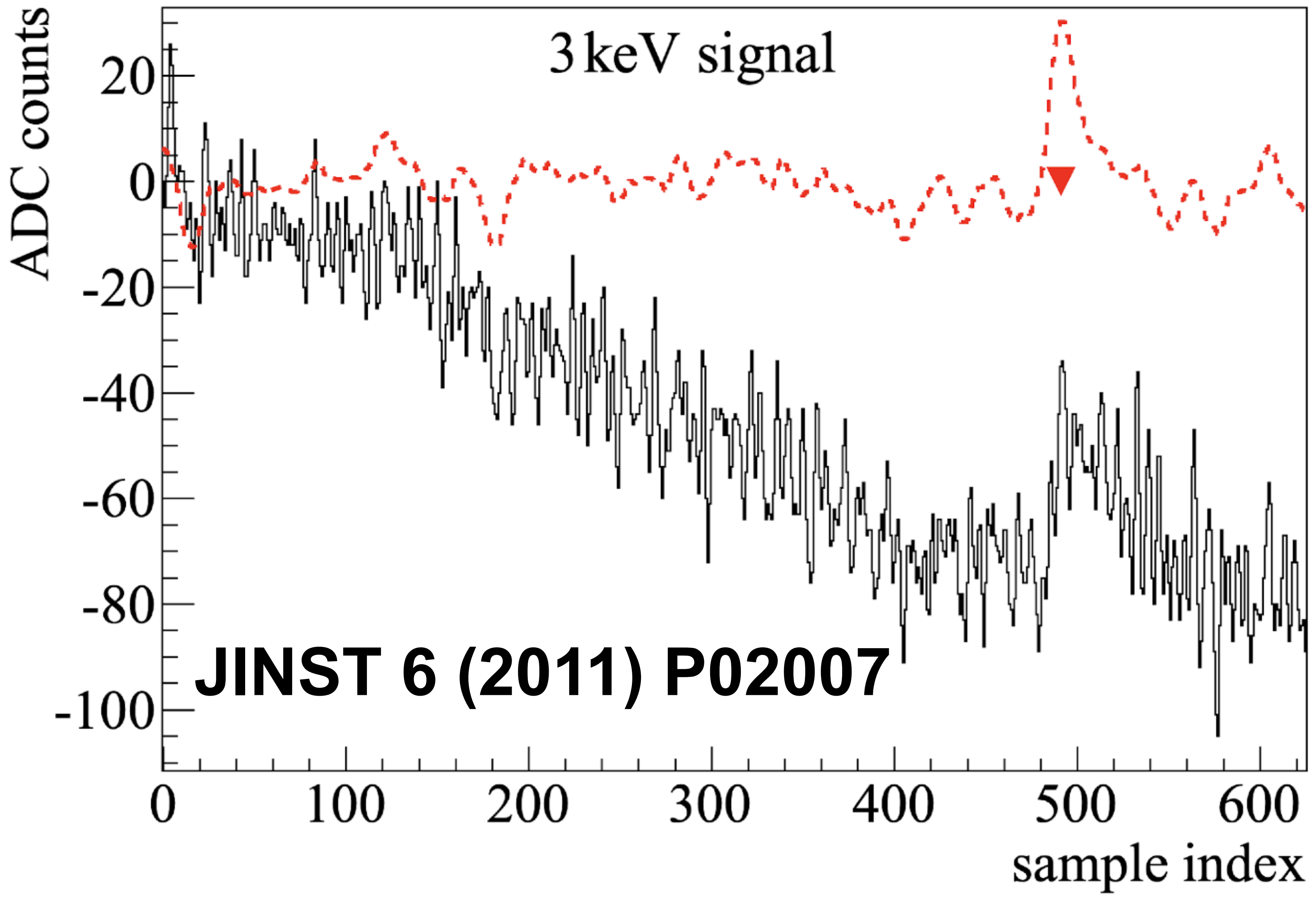
Analysis Methods

Signal Processing:

- **Denoising:** mitigate the noise by correlating it with auxiliary devices (microphones, accelerometers, seismometers)

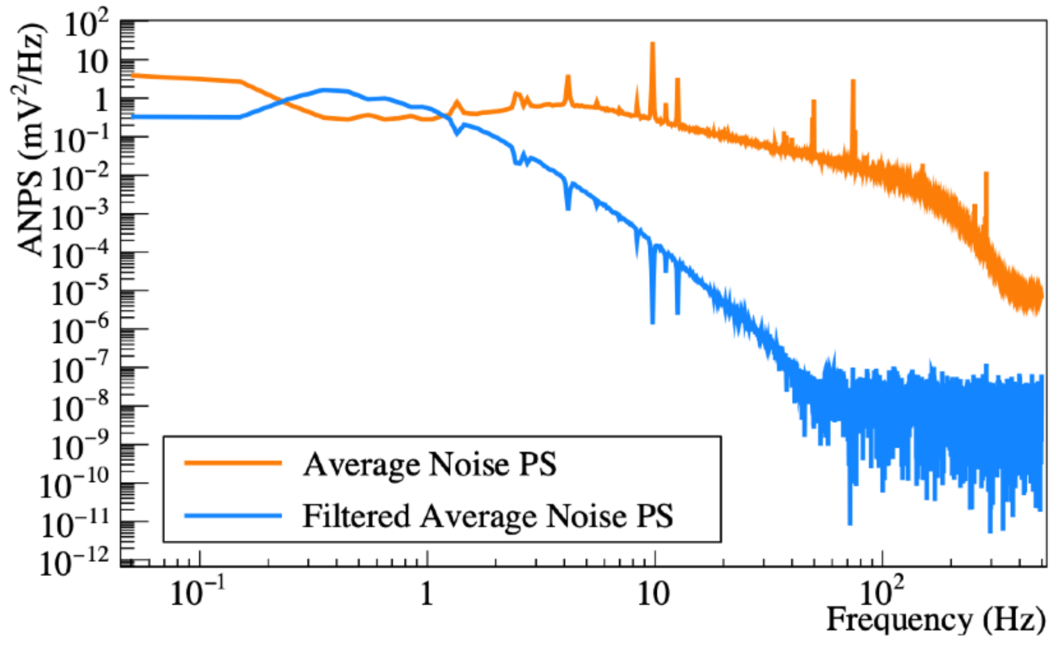


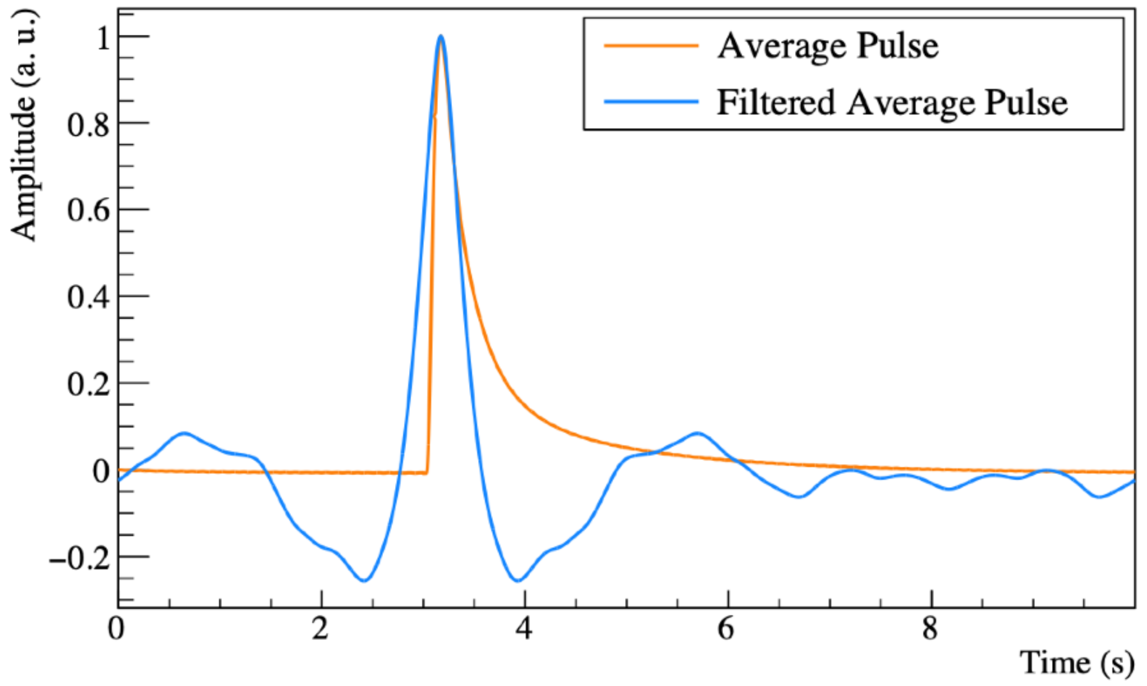
- **Optimum Trigger**: apply an offline trigger on filtered waveforms to lower the energy threshold



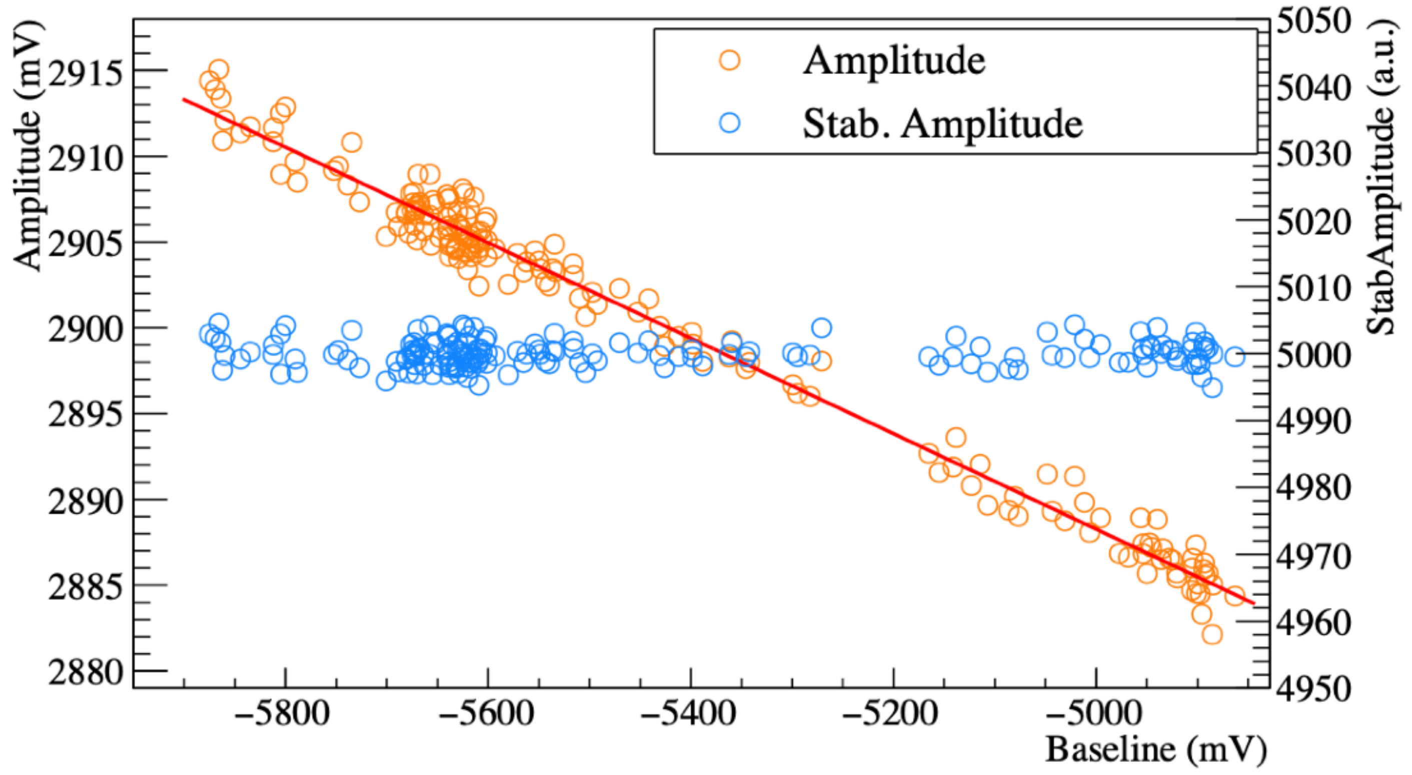
https://indico.cern.ch/event/1199289/contributions/5447391/

Analysis Methods

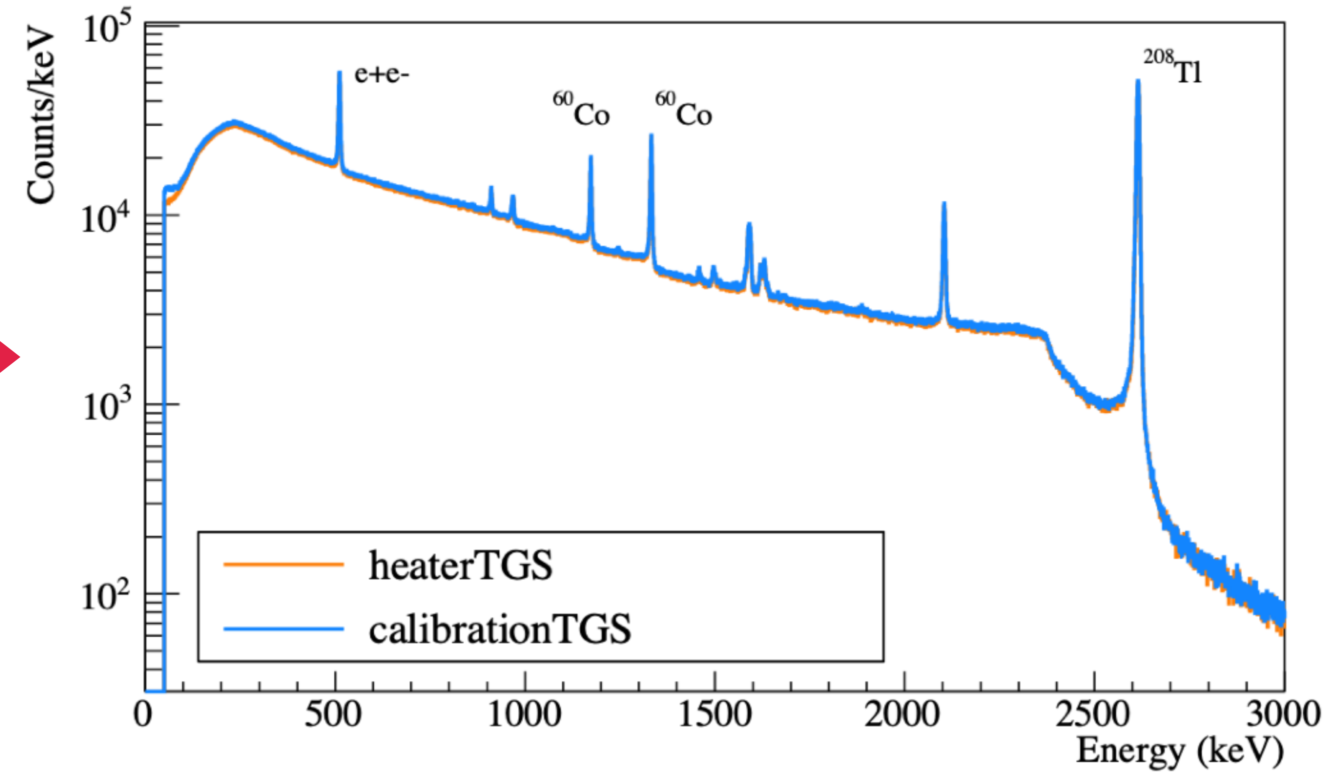




Optimum Filter: suppress the frequencies most affected by the noise relying with ideal pulse and noise spectrum



Thermal Gain Correction: correct amplitude dependence on the operating temperature (~ baseline) drift by using the injected thermal pulses



Energy Calibration: based on measurements with external ^{232}Th-^{60}Co source deployment

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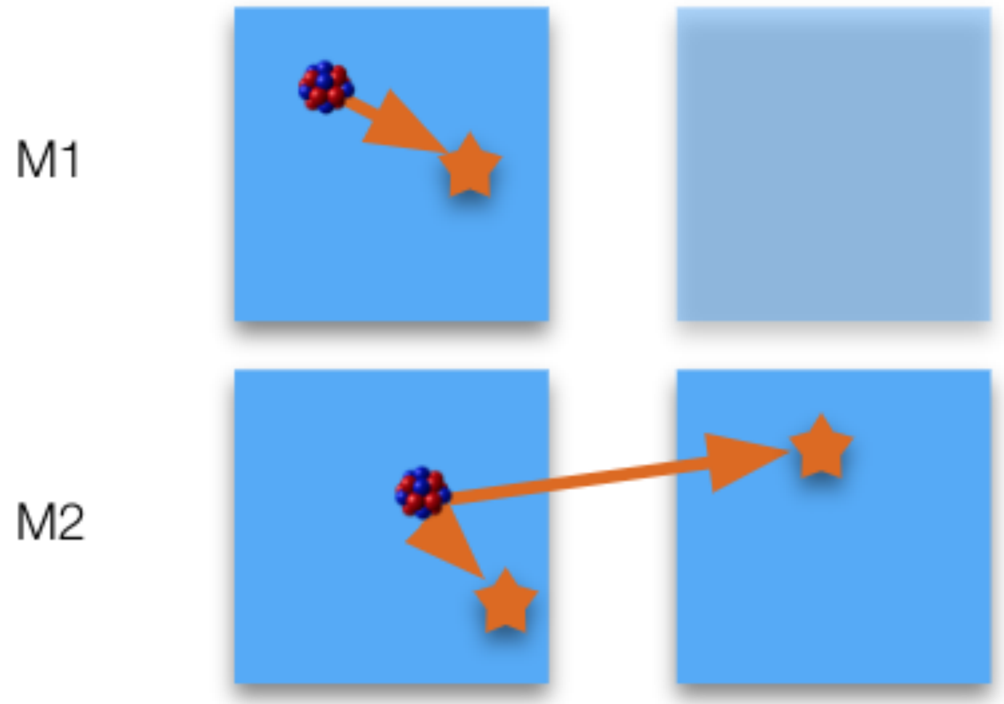
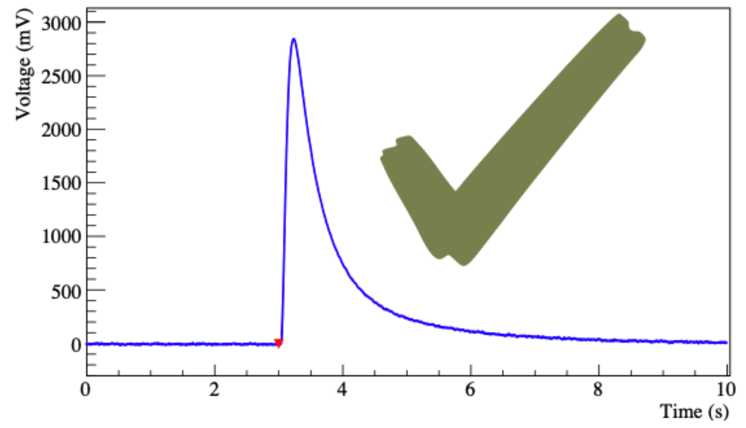
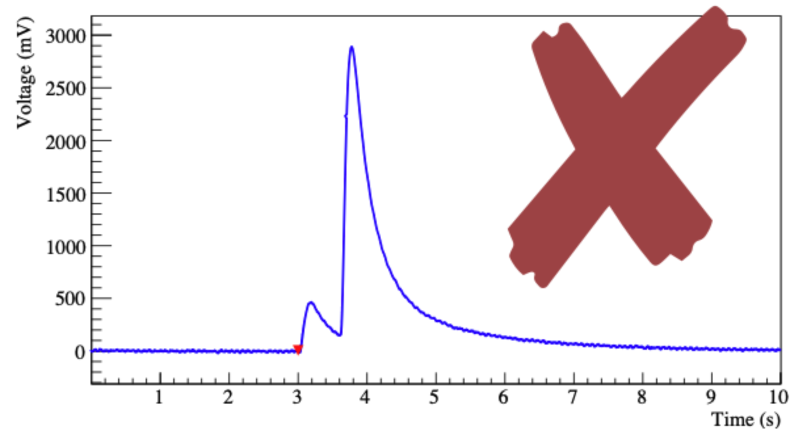
Analysis Methods

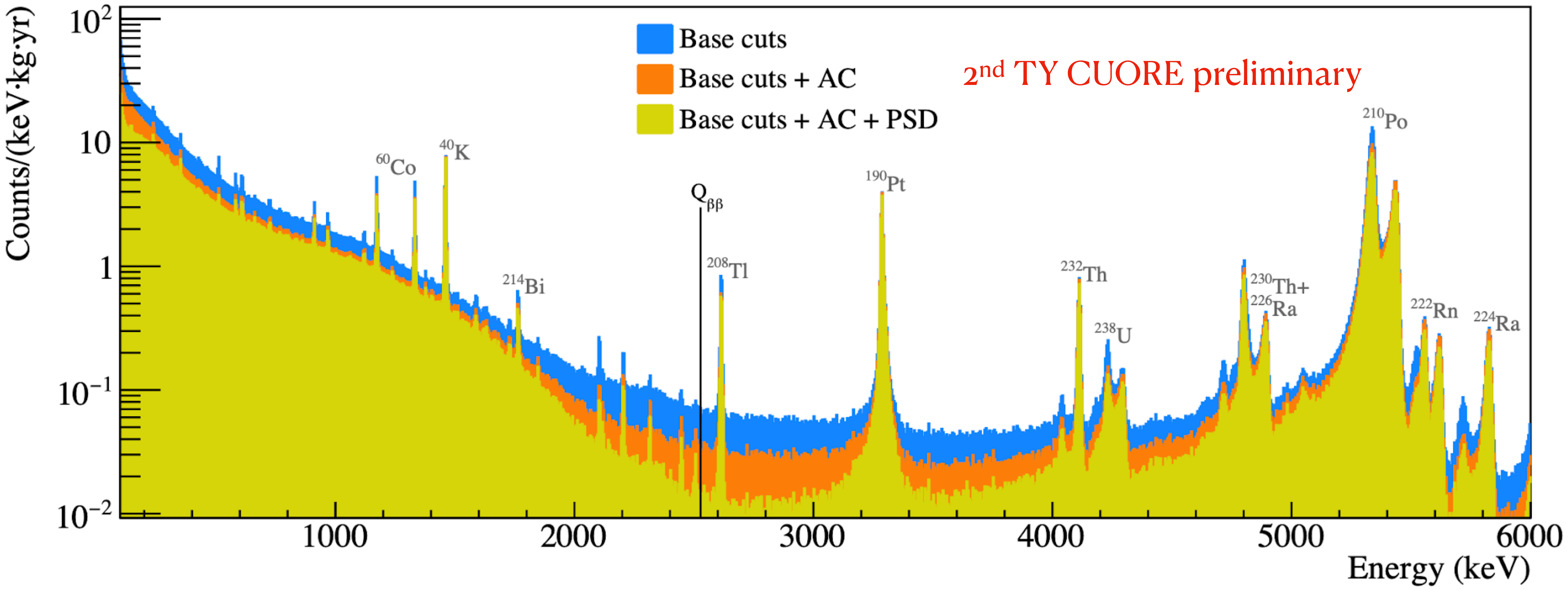
- **Anti-Coincidence:** reject events depositing energy in multiple crystals



- **Pulse Shape Discrimination:** implemented using Principal Component Analysis (PCA)







- **Blinding:** exchange events from ^{208}Tl 2615 keV line to the ^{130}Te Q-value

Analysis Methods

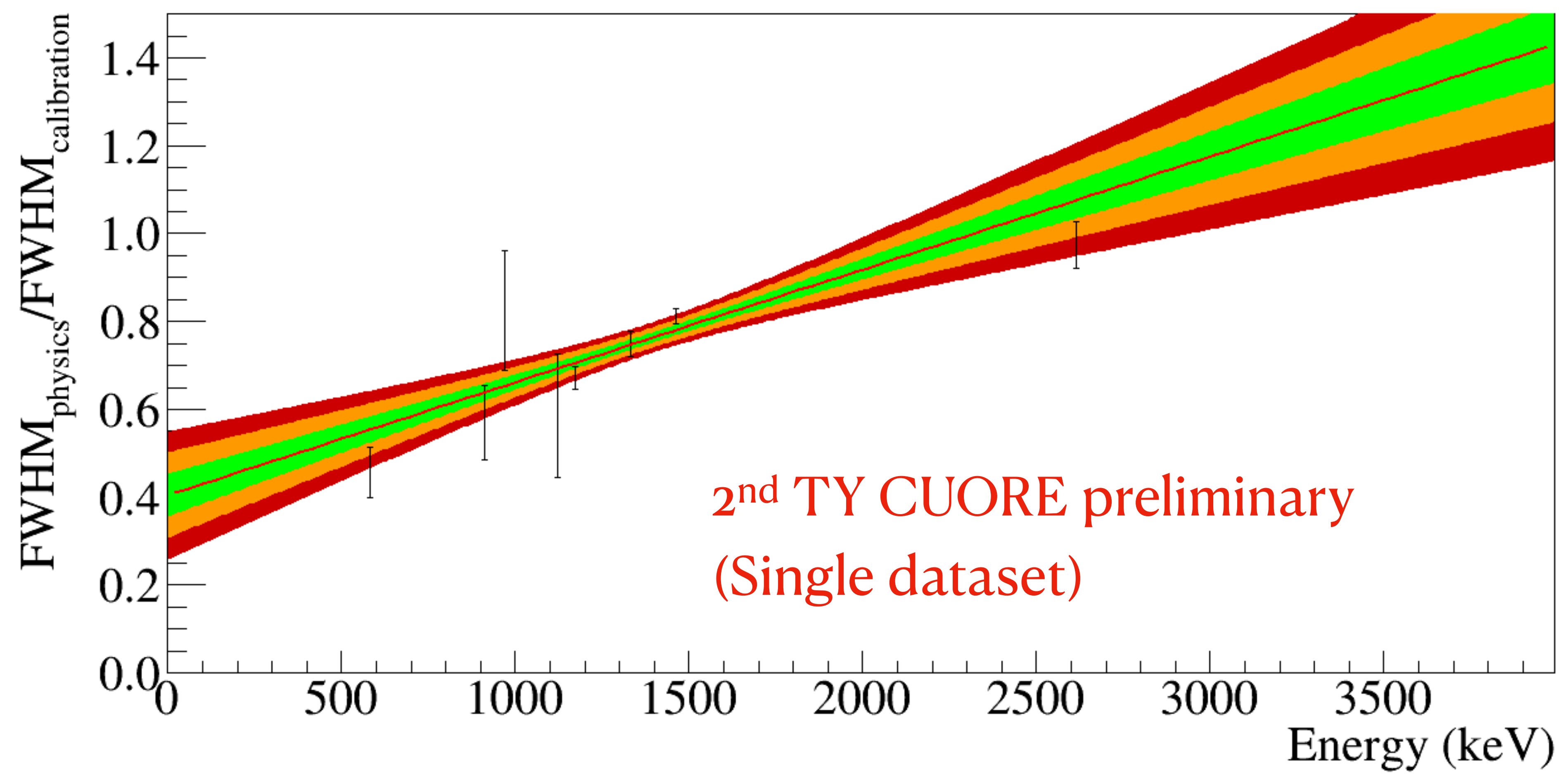
Physics peaks modeled on ^{208}Tl 2615 keV line (calibration data):

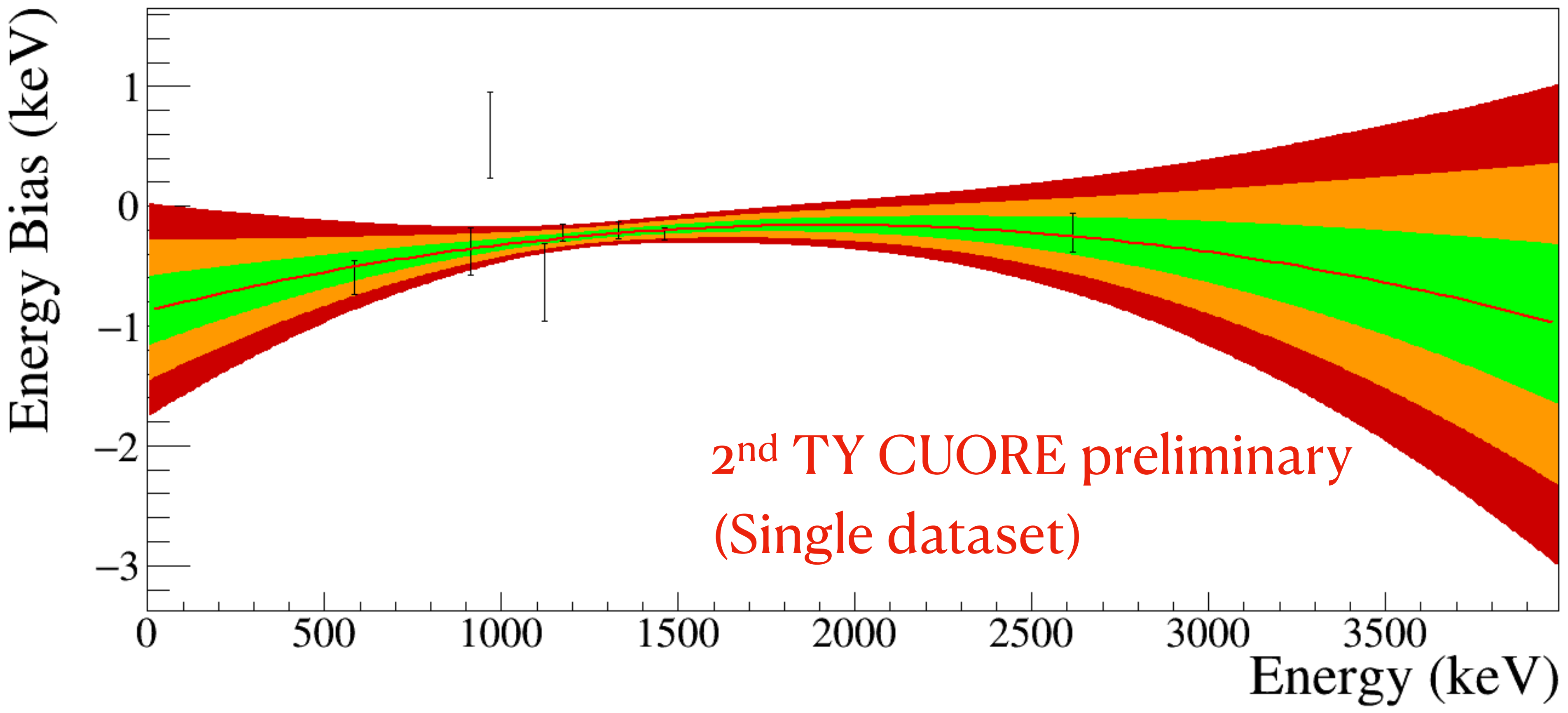
- 3 Gaussians
- Te x-rays (escape + coincident)
- 583 keV gamma line coincident with annihilation escape peak
- multi-Compton and flat background

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

Scale the results at the Q-value of ^{130}Te fitting peaks in physics data (noise and pile-up improved)

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





Search for $0\nu\beta\beta$ with 2nd ton yr only

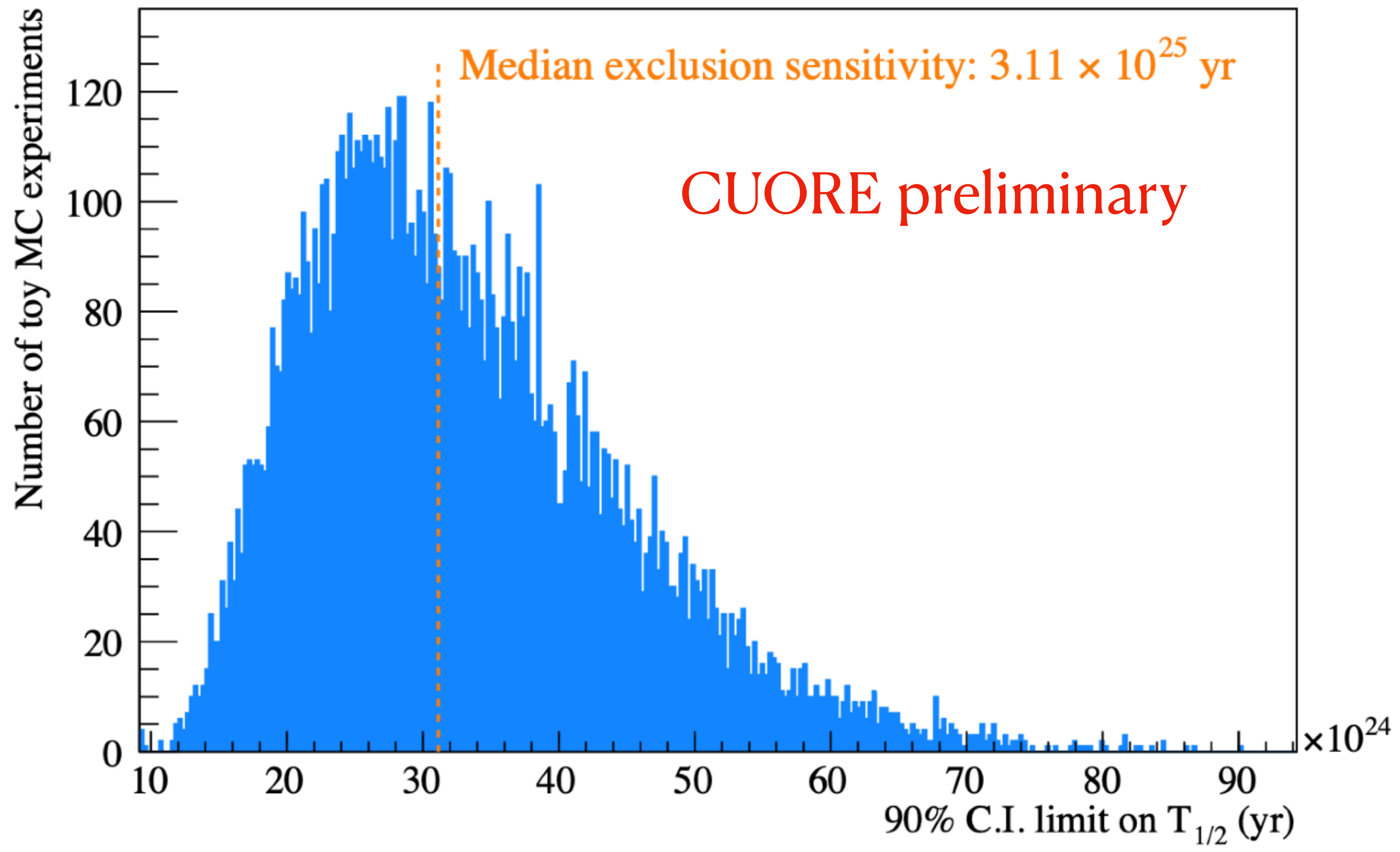
Region of Interest [2465, 2575] keV

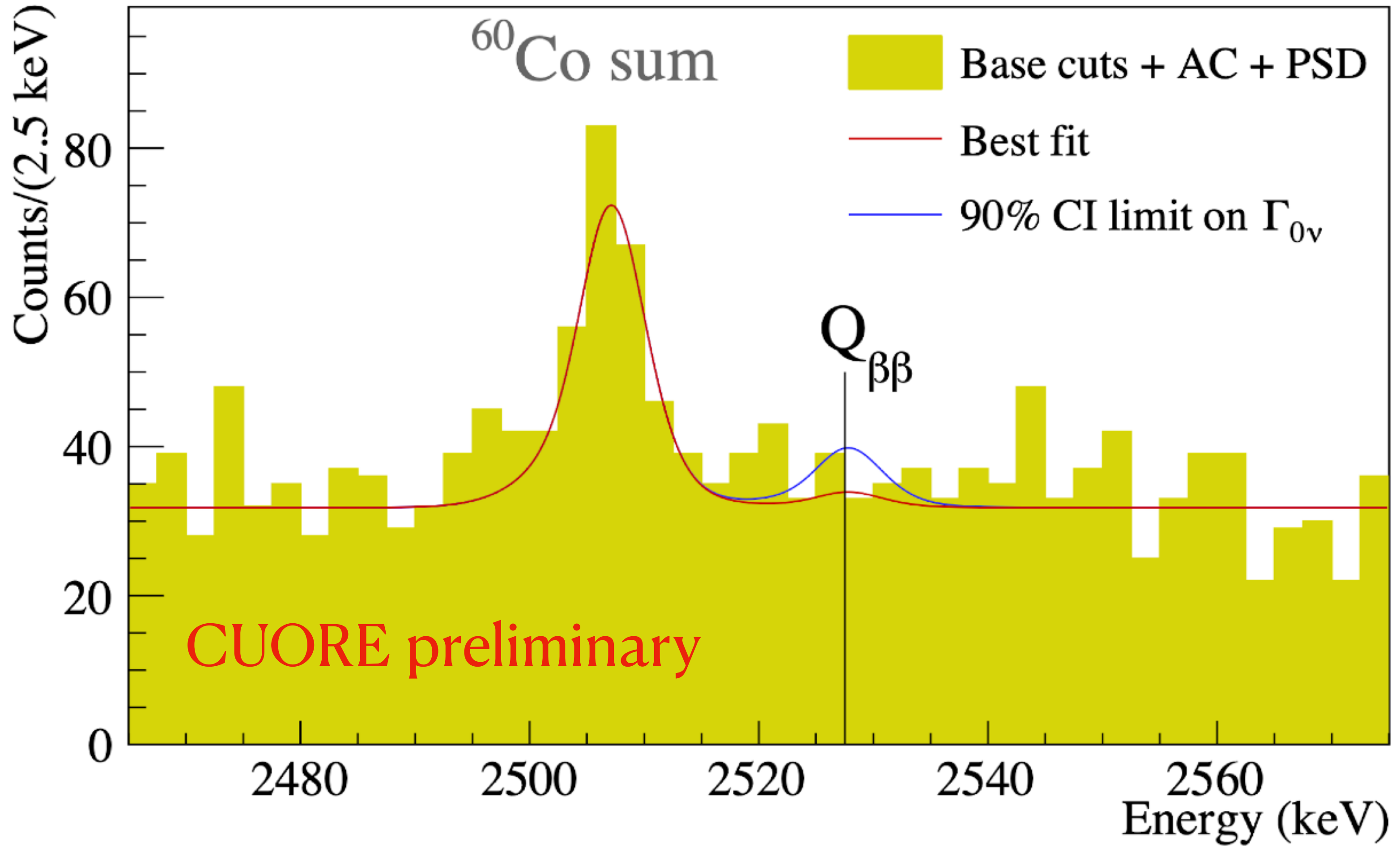
- Peak at 2528 keV ($0\nu\beta\beta$ signal)
- ^{60}Co peak
- Linear background

➡ Rates and background index and slope as free parameters

➡ Systematics treated as nuisance parameters

➡ Sensitivity evaluated from toy experiments in background only hypothesis





Background Index = 1.3×10^{-2} counts/(keV kg yr)

No evidence for $0\nu\beta\beta$

Decay Rate at 90% C.I. $\Gamma_{0\nu} < 2.53 \times 10^{-26}$ /yr

Half-life at 90% C.I. $T_{1/2} > 2.74 \times 10^{25}$ yr

Combine 1st and 2nd ton yr of data

CUORE

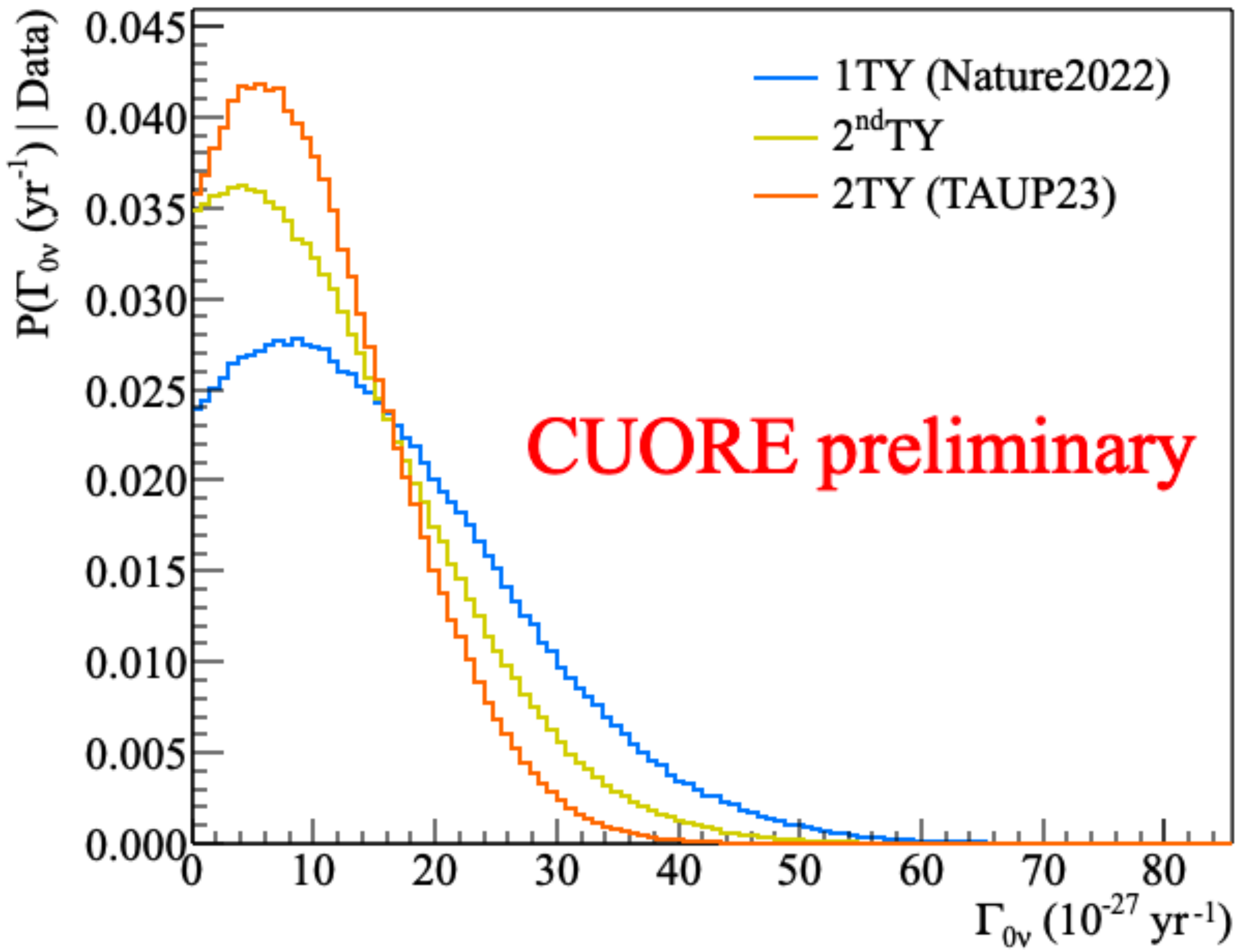
We combined the posteriors on $0\nu\beta\beta$ half-life resulting from the analysis of the 1^{st} ($T_{1/2} > 2.2 \times 10^{25}$ yr, Nature 604, 53-58 (2022)) and 2^{nd} ton yr

➡ **Overall exposure 2023 kg yr**

(Still) No evidence for $0\nu\beta\beta$

Decay Rate at 90% C.I. $\Gamma_{0\nu} < 2.08 \times 10^{-26}$ /yr

Half-life at 90% C.I. $T_{1/2} > 3.33 \times 10^{25}$ yr



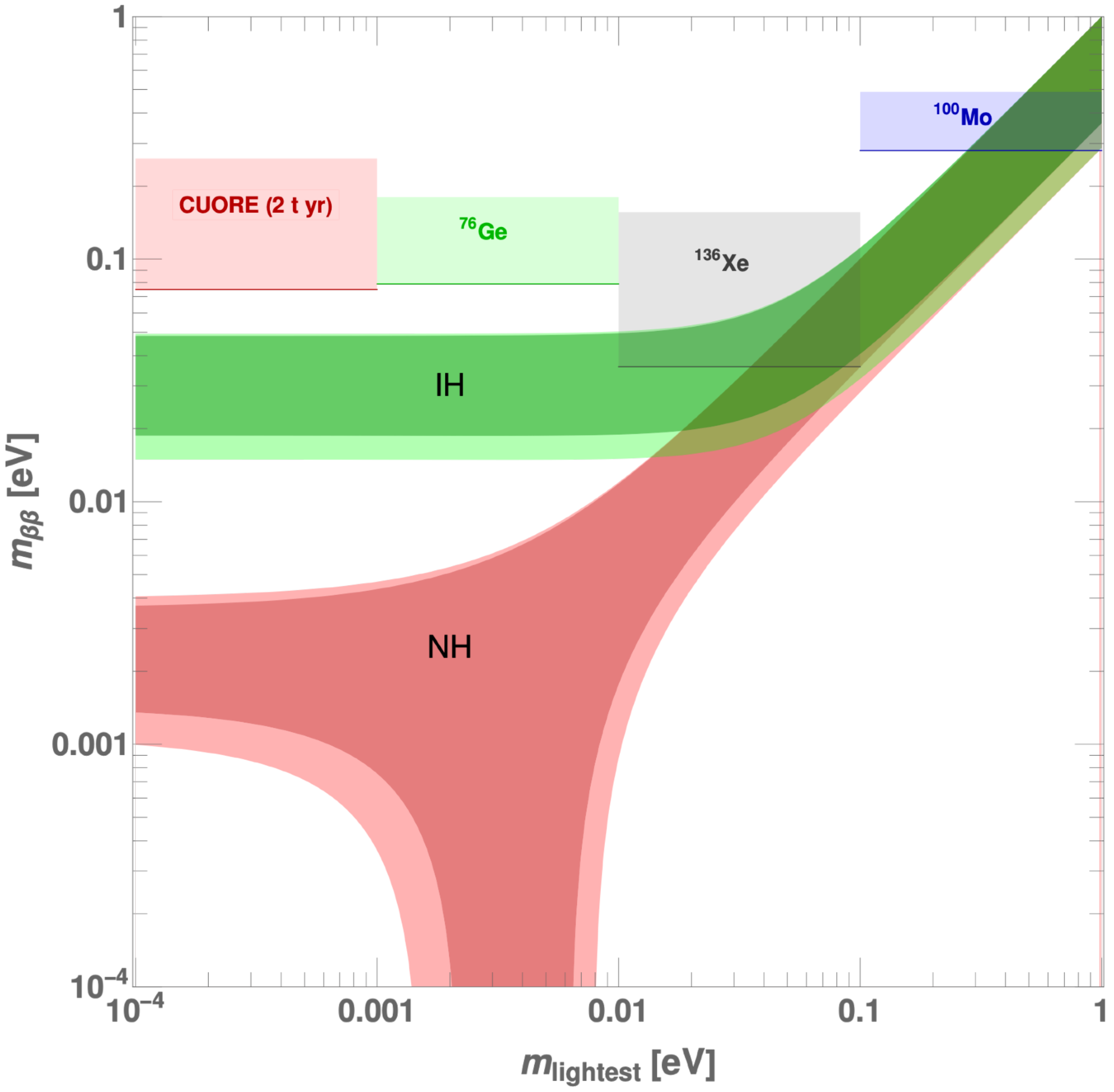
Stay tuned for the full analysis!

- Reprocess the 1st ton yr of data with the updated analysis techniques
- Repeat the $0\nu\beta\beta$ fit
- Finalize systematics

https://indico.cern.ch/event/1199289/contributions/5447112/

Limit on Majorana Mass

CUORE



We converted half-life limit into an upper limit on the Majorana mass

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Phase Space Factor

Nuclear Matrix Elements from several possible models (ISM, IBM, QRPA, ...)
here assuming $g_A = 1.27$

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

What's next in CUORE

Published results

- $2\nu\beta\beta$ measurement: $T_{1/2} = 7.71^{+0.08}_{-0.06}(stat.)^{+0.12}_{-0.15}(syst.) \times 10^{20} yr$
  https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.171801
- $0\nu\beta\beta$ and $2\nu\beta\beta$ to the first 0+ excited state of ^{130}Te
  https://link.springer.com/article/10.1140/epjc/s10052-021-09317-z
  - $T^{0\nu}_{1/2} > 5.9 \times 10^{24}$ yr
  - $T^{2\nu}_{1/2} > 1.3 \times 10^{24}$ yr
- $0\nu\beta\beta$ of 128Te (867 keV - 188 kg): $T_{1/2} > 3.6 \times 10^{24}$ yr
  https://journals.aps.org/prc/abstract/10.1103/PhysRevC.105.065504
- $0\nu\beta^{+}EC$ of 120Te: $T_{1/2} > 2.9 \times 10^{22} yr$
  https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.129.222501
- Detailed thermal model of the detector response
  https://iopscience.iop.org/article/10.1088/1748-0221/17/11/P11023/meta

Work in Progress

- Denoising Techniques (already in the analysis!)
  https://indico.cern.ch/event/1199289/contributions/5447124/
- Background Model
  https://indico.cern.ch/event/1199289/contributions/5447161/
- Impact of marine microseism on detector response
  https://indico.cern.ch/event/1199289/contributions/5445886/
- Dark matter search at low energies (Solar Axions, WIMPs…)
  https://indico.cern.ch/event/1199289/contributions/5445882/

Stay Tuned!

Thank You!

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Berkeley University of California

CUORE

1st ton yr results

- $T_{1/2} > 2.2 \times 10^{25} yr$
- Median Expected Sensitivity $= 2.8 \times 10^{25} yr$
- Background Index $= 1.5 \times 10^{-2}$ counts/(keV kg yr)
- $\Delta E = 7.8(5) keV$