Results from the CUORE-0 Experiment and a Status Update on CUORE

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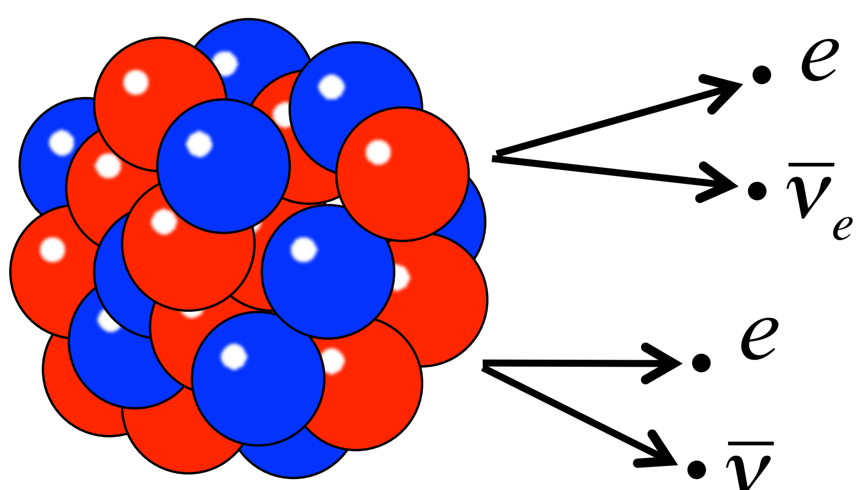
Aug 5, 2015

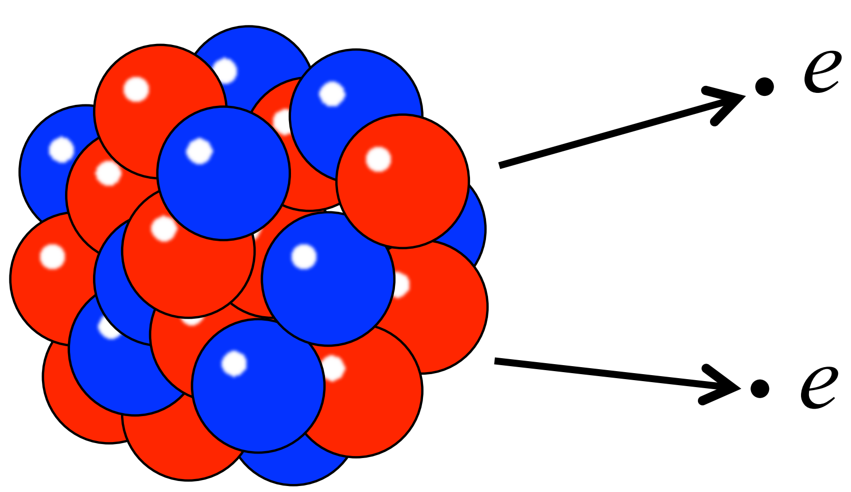
Neutrinoless Double Beta Decay

2νββ



$$^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^{-} + 2\bar{\nu}_e$$

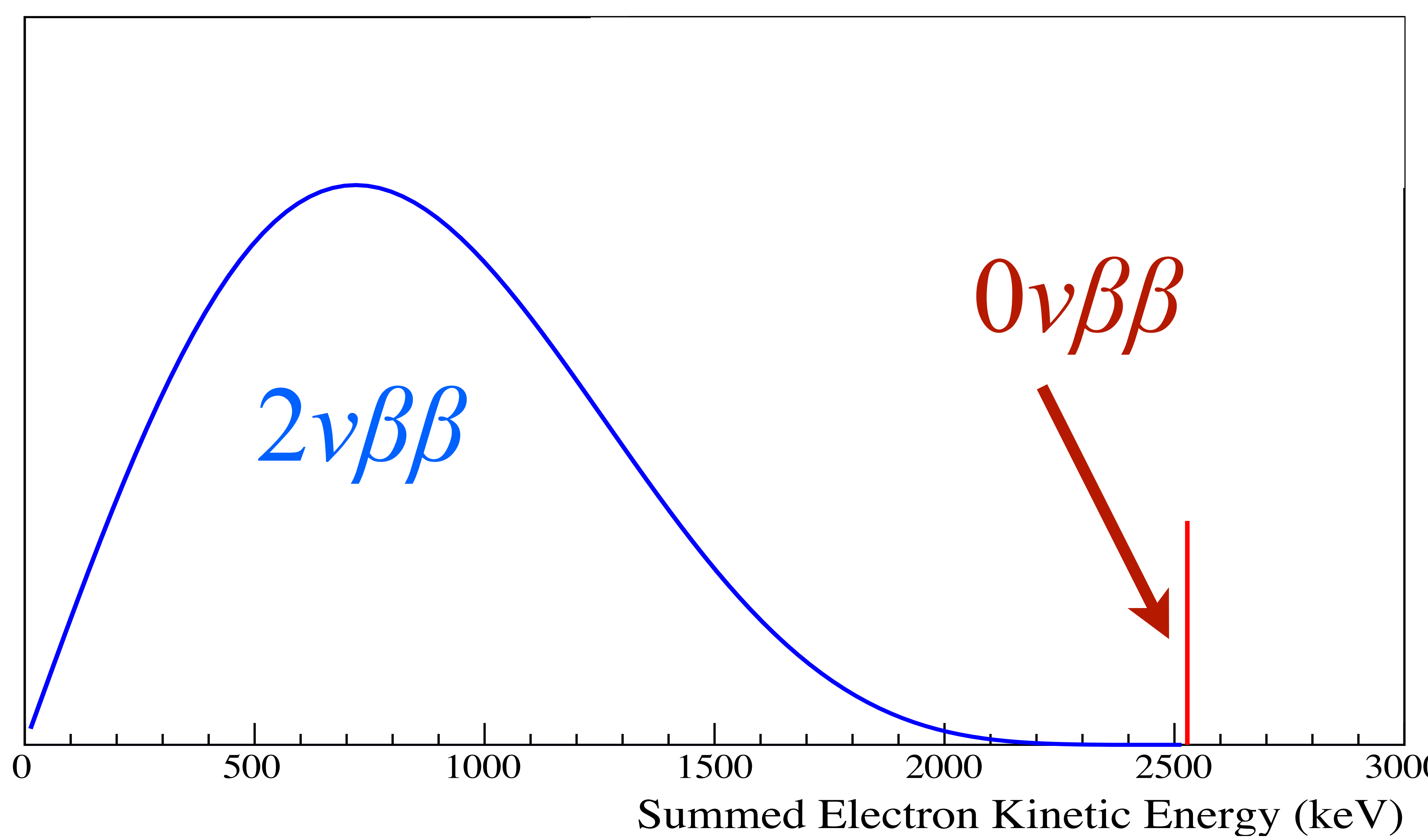
0νββ



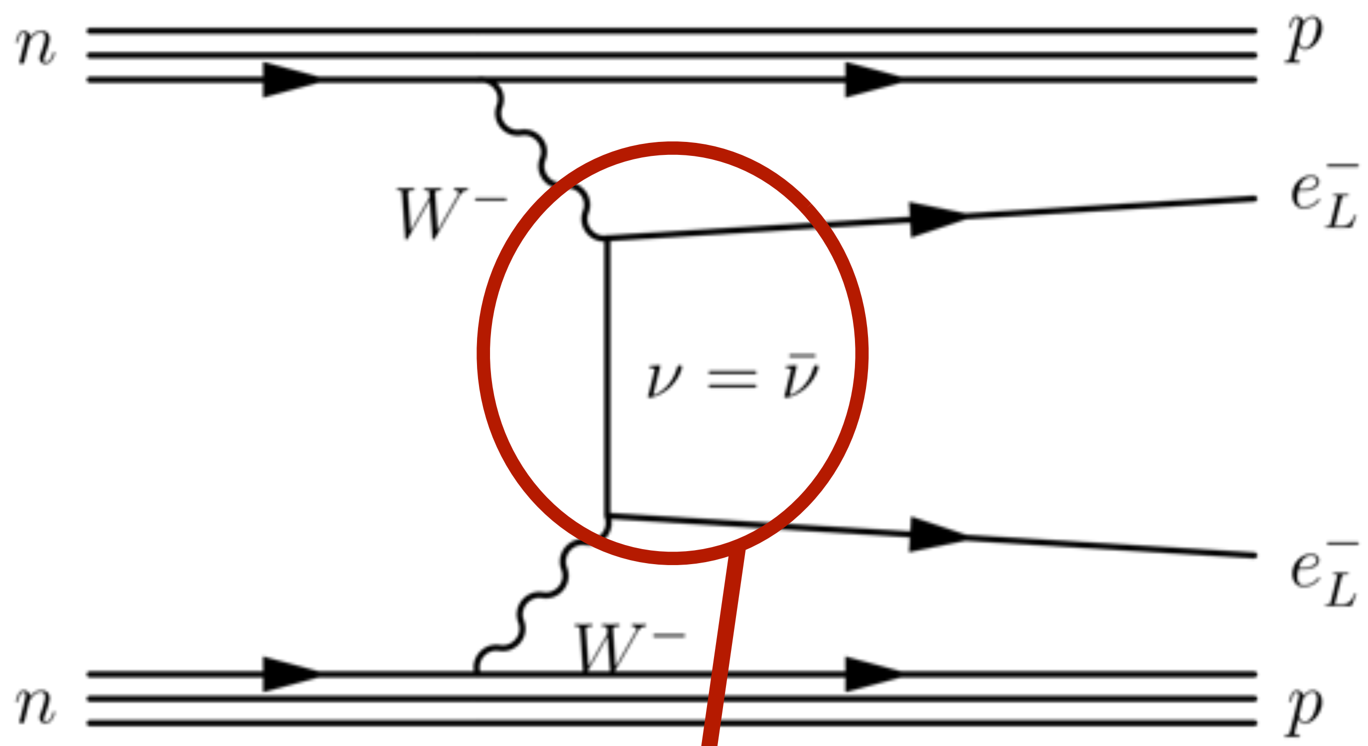
$$^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^{-}$$

$$(Z, A) \Rightarrow (Z+2, A) + 2\beta^{-}$$

- Discovery of 0νββ would indicate:
  - Lepton Number Violation
  - Indicates that neutrinos are Majorana fermions
  - Could provide insight into the neutrino mass scale and hierarchy
- Half-lives longer than ~10^{25} years



Light Majorana Neutrino Exchange Model



$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}|\mathcal{M}_{0\nu}|^2 \frac{m^2_{\beta\beta}}{m^2_e}$$

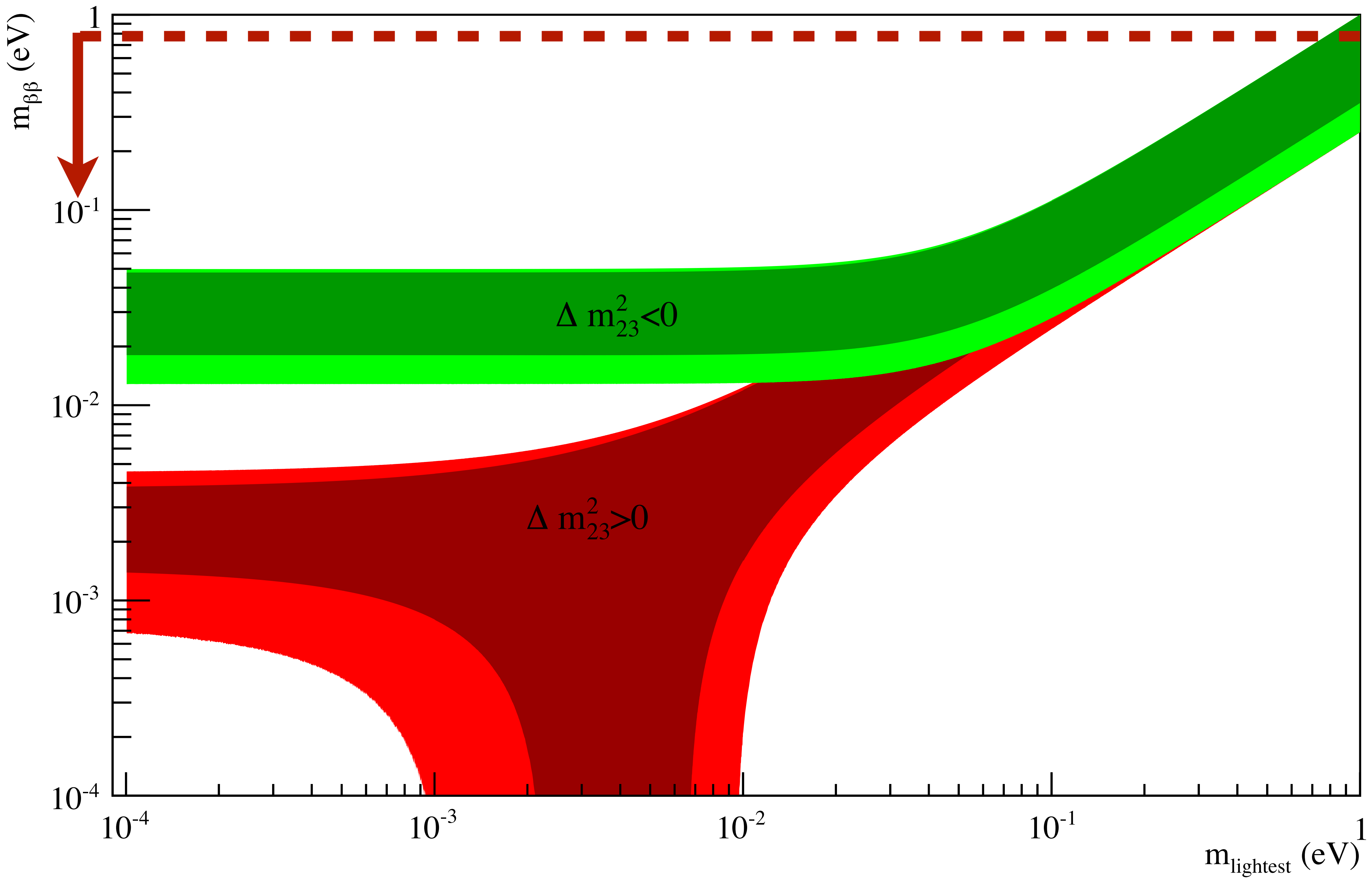
Phase space factor

Nuclear Matrix Element

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

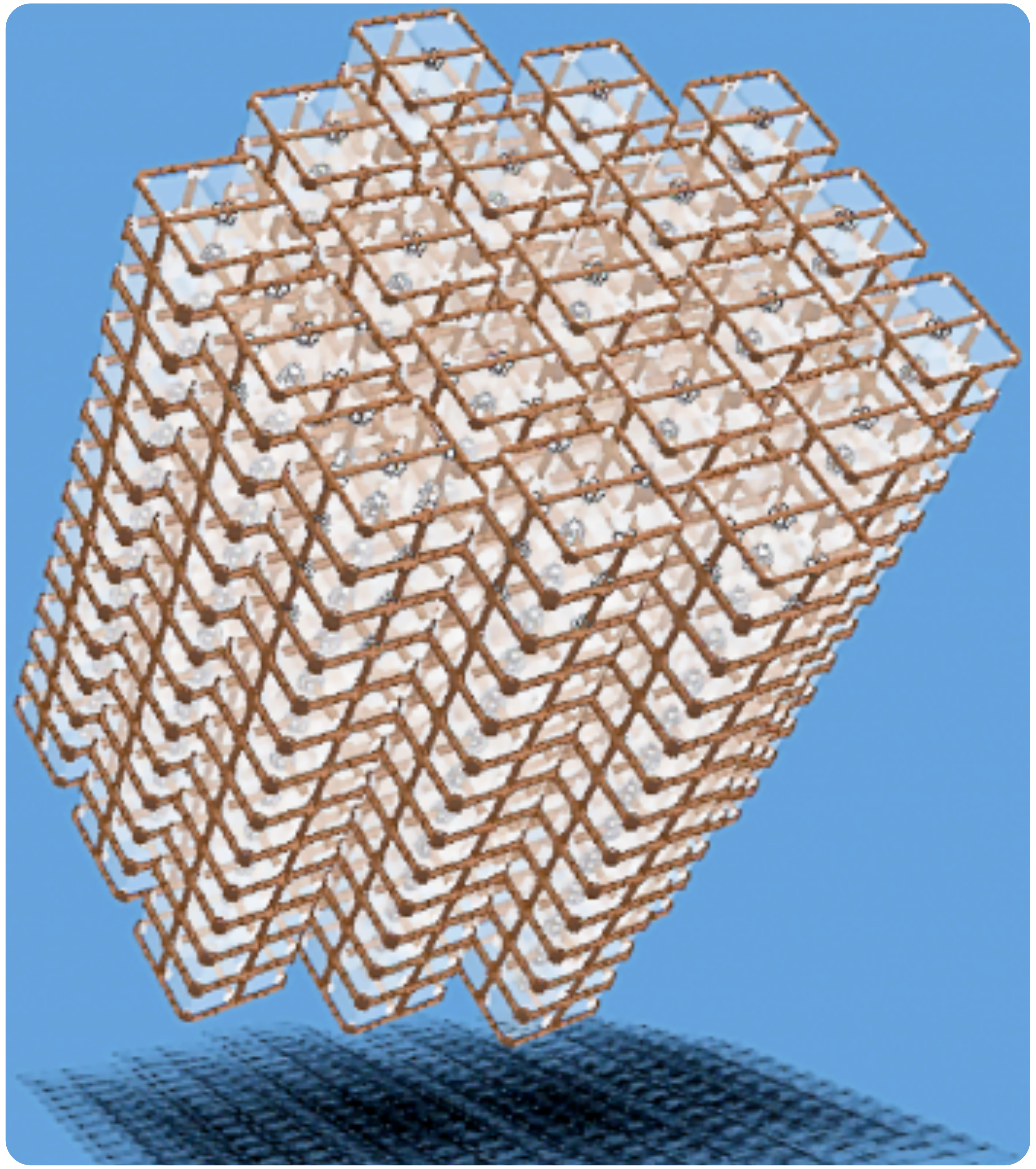
Effective Majorana Mass

$0\nu\beta\beta$ places limits on $m_{\beta\beta}$

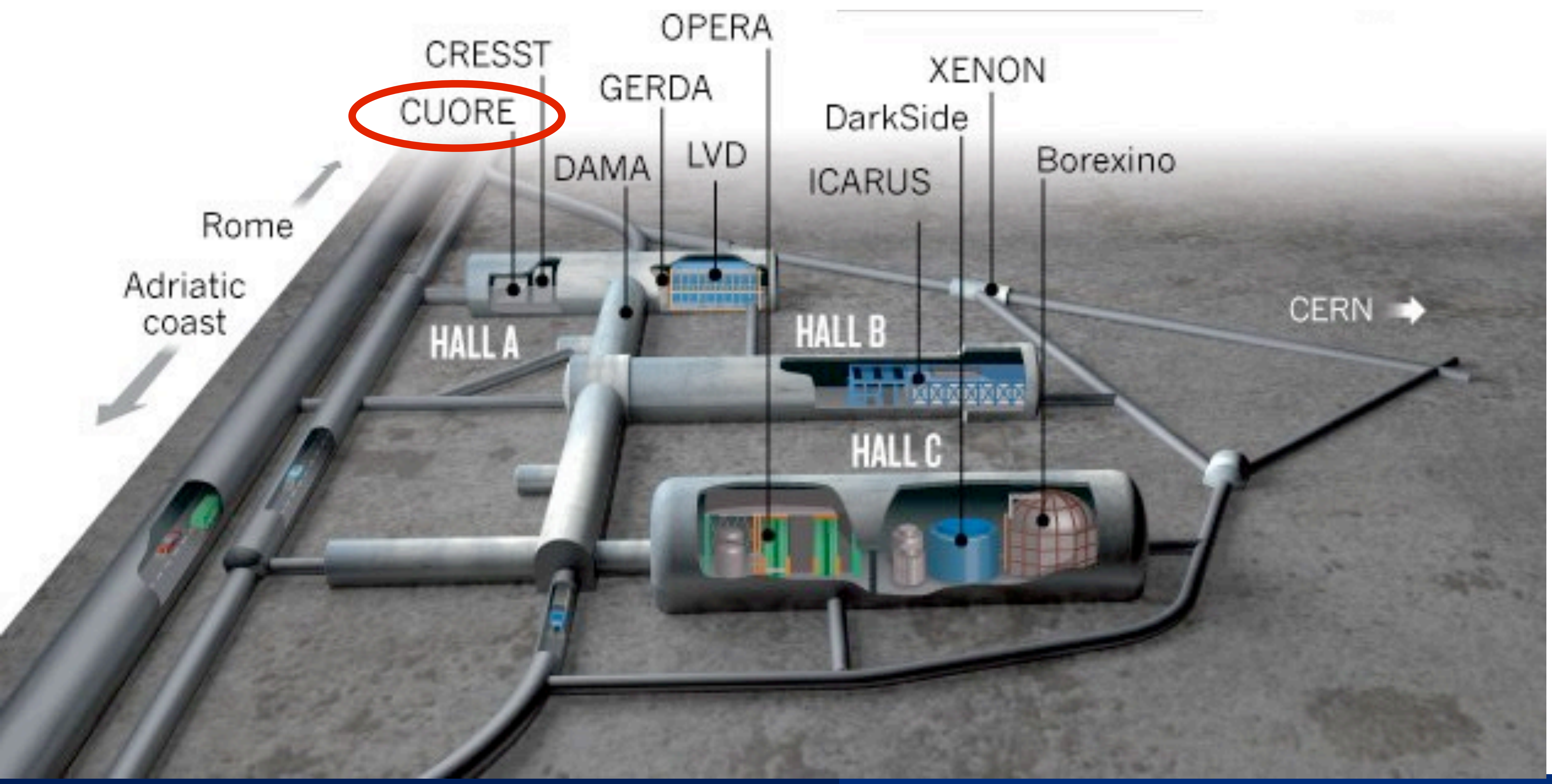


The CUORE Experiment

The Cryogenic Underground Observatory for Rare Events



Laboratori Nazionali del Gran Sasso

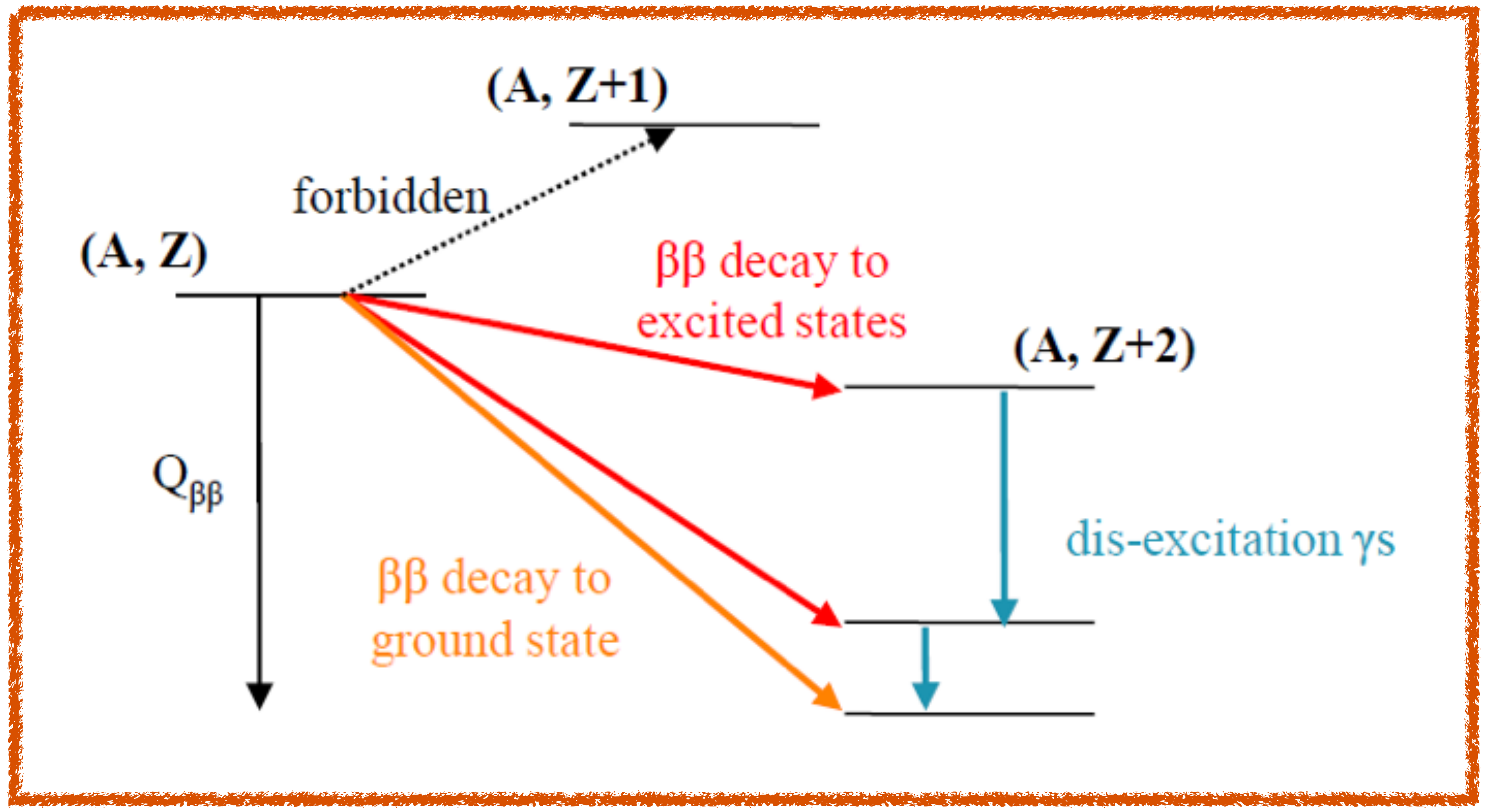


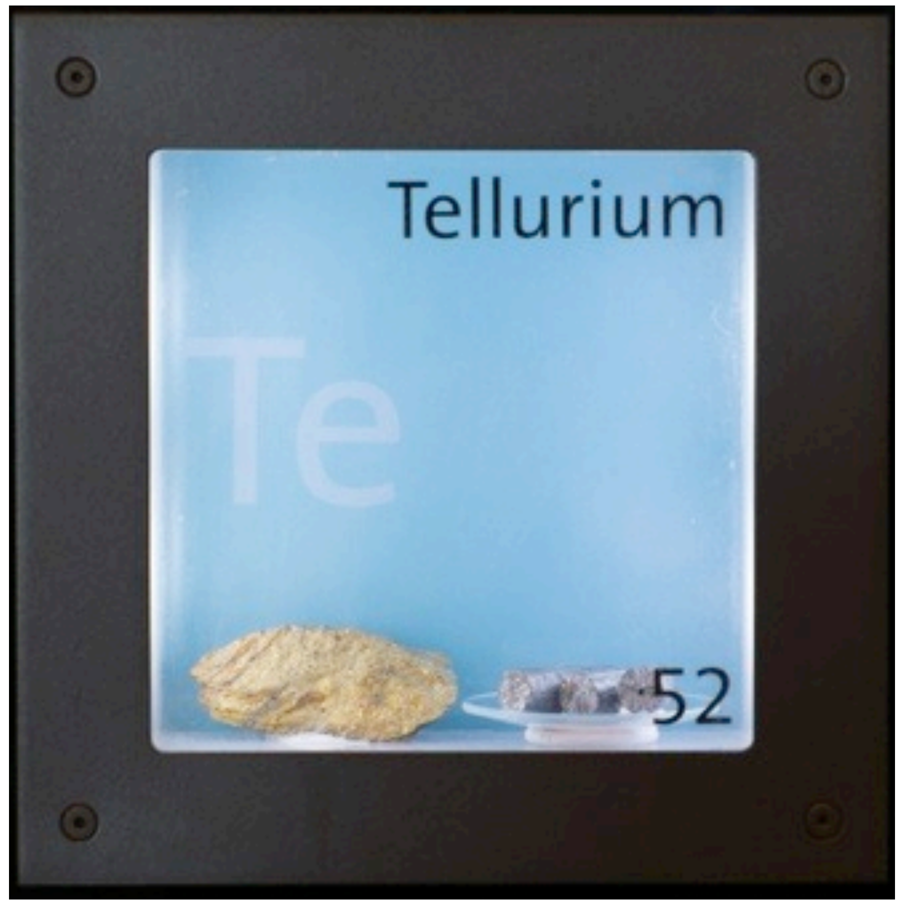
1400 m of rock overburden
➡ 3600 m.w.e. shielding

$$\Gamma_\mu \sim 3 \times 10^{-8}\ \mathrm{s}^{-1}\mathrm{cm}^{-2}$$

$$\Gamma_N \sim 4 \times 10^{-6}\mathrm{s}^{-1}\mathrm{cm}^{-2}$$

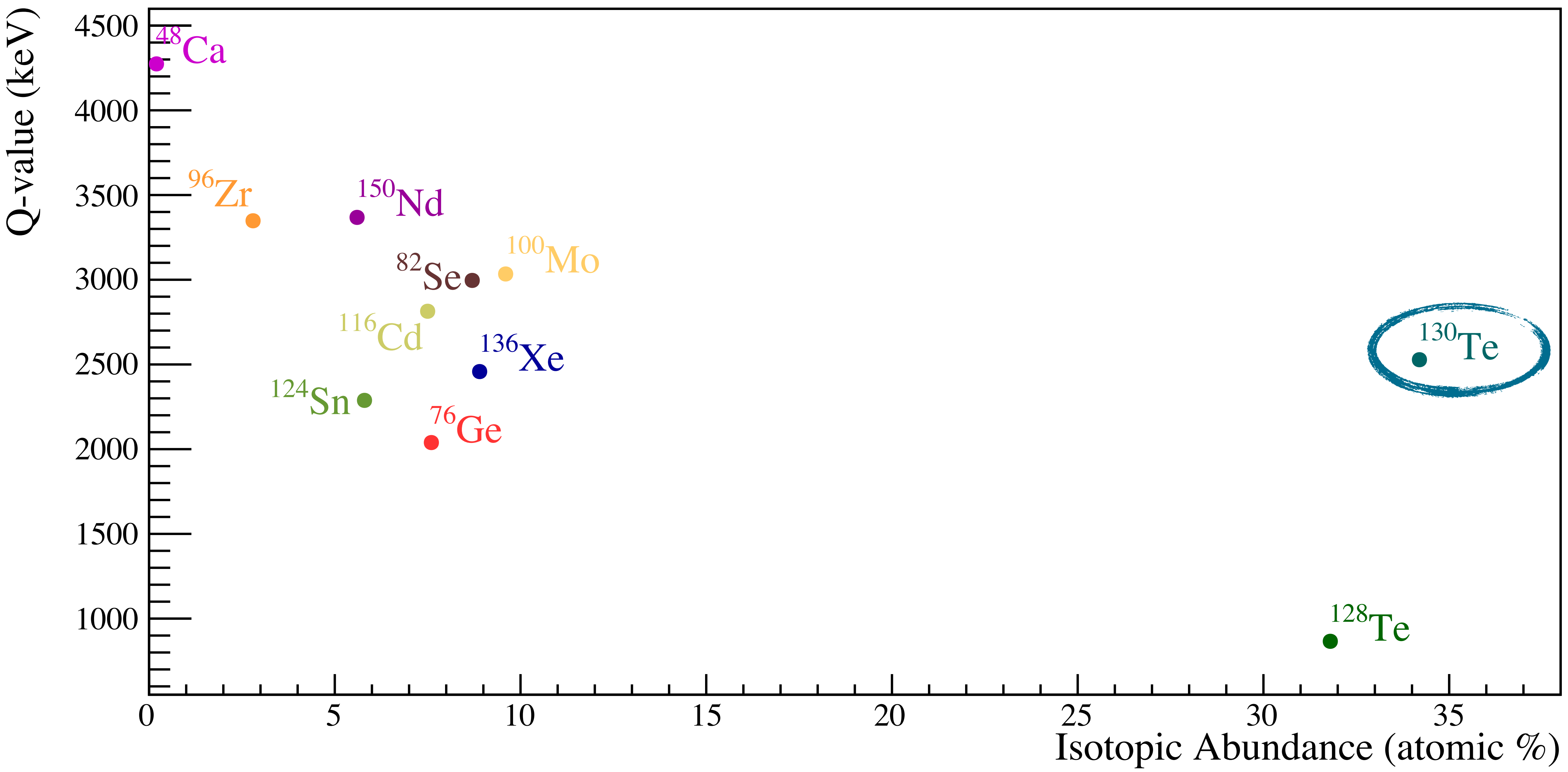
Choosing an isotope: ^{130}Te



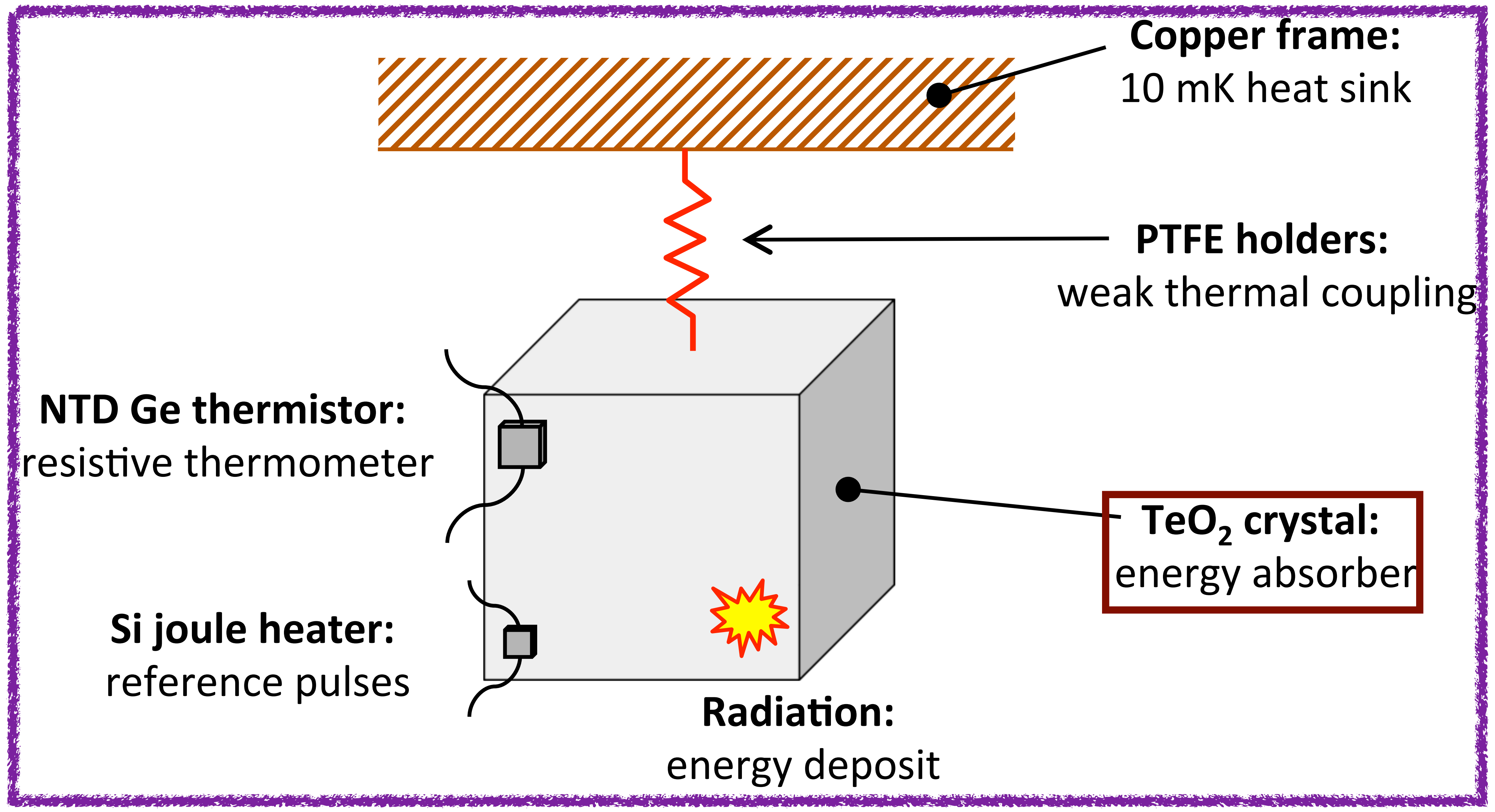


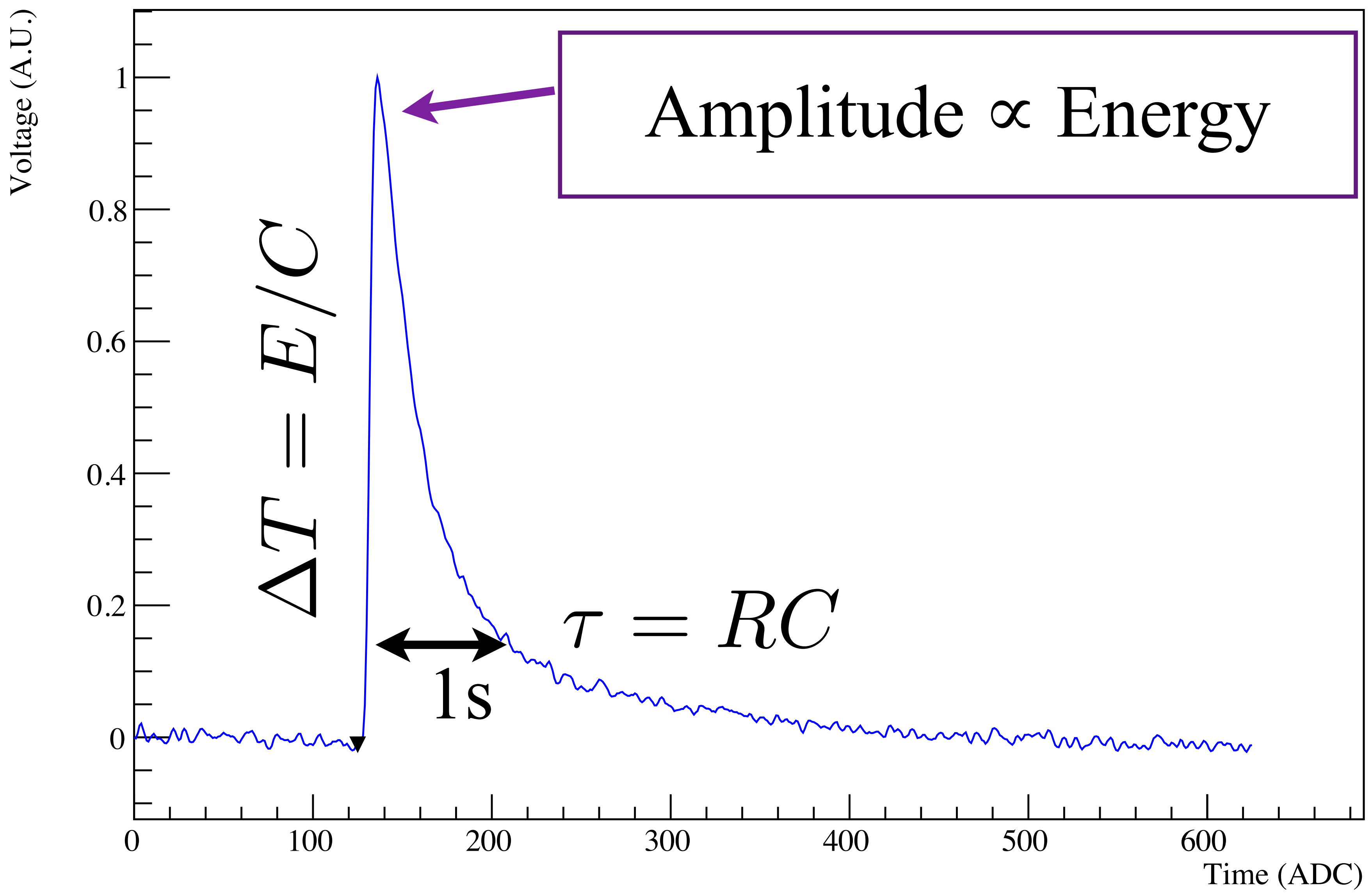
^{130}Te is a nice candidate isotope:

- ➡ High natural isotopic abundance
- ➡ Reasonably high Q-Value
- ➡ Large decay cross-section



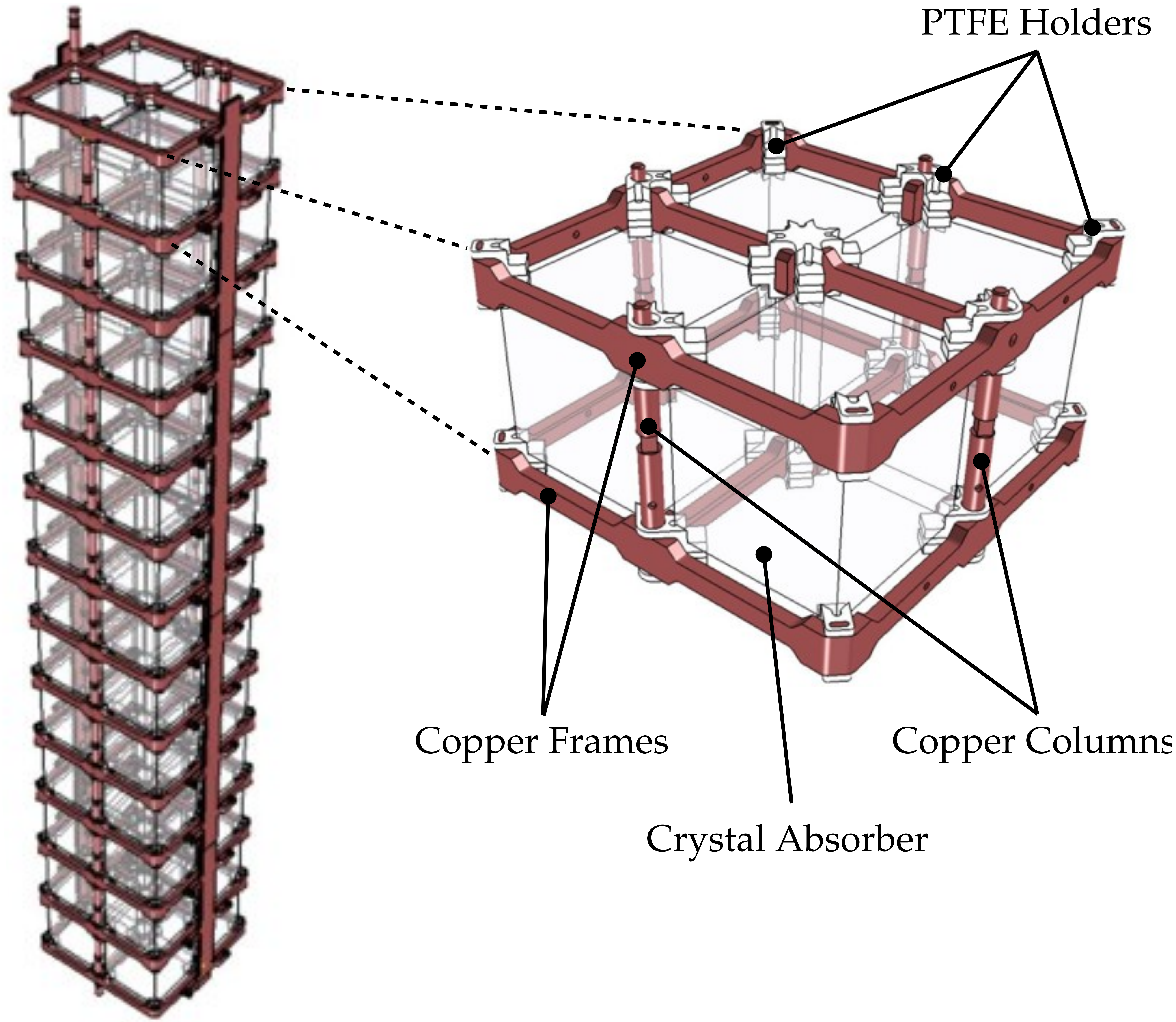
Bolometric Energy Detection



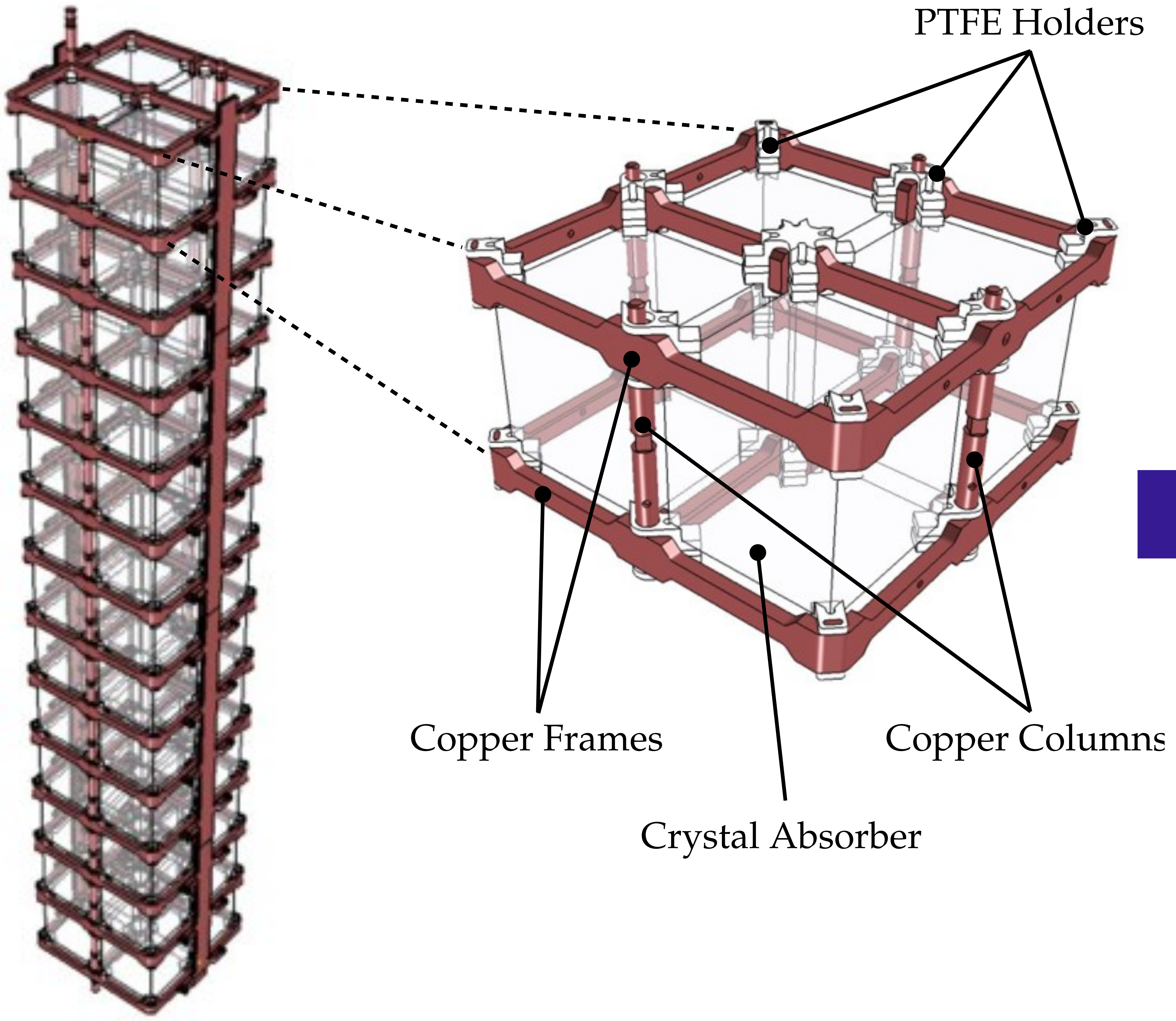


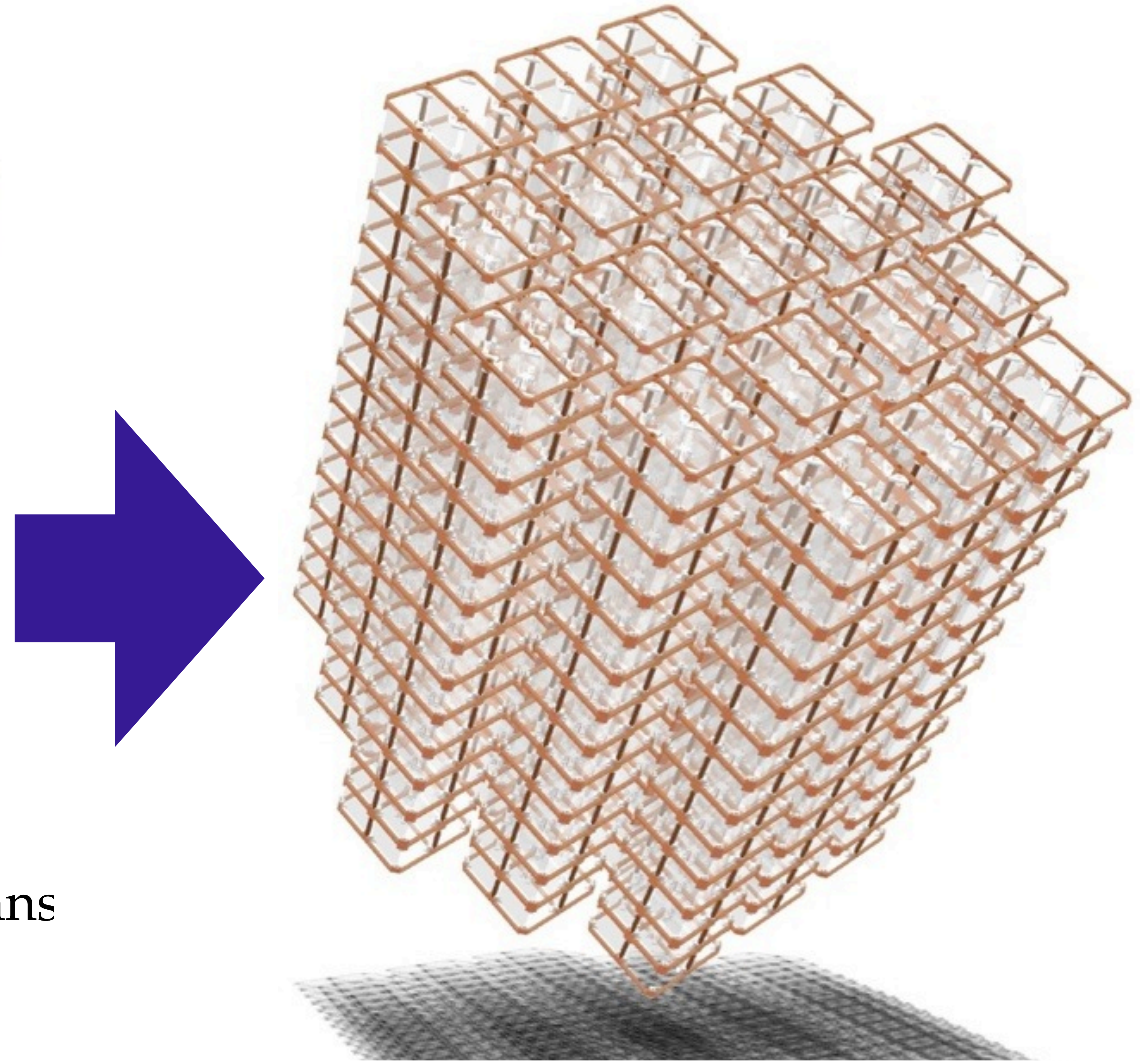
- Energy absorber is 750g 5x5x5 cm^3 $^{nat}TeO_2$ crystal
- Operated at ~10 mK
  - Heat capacity is ~10^{-9} J/K which translates to ΔT/ΔE ~100 μK/MeV
  - Pulses last ~1 second
- Temperature change read out using NTD Ge sensor
  - Exponential temperature dependence
  - Resistance change of ~3 MΩ/MeV
- Can achieve typical energy resolutions of ~5 keV FWHM at 2.5 MeV

CUORE Tower


PTFE Holders
Copper Frames
Copper Columns
Crystal Absorber

CUORE Tower

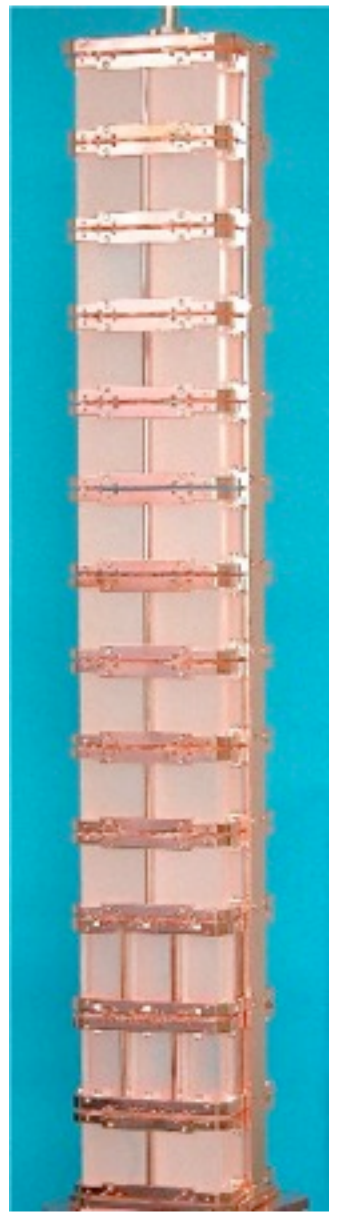




- 988 bolometers
- 206 kg of ^{130}Te

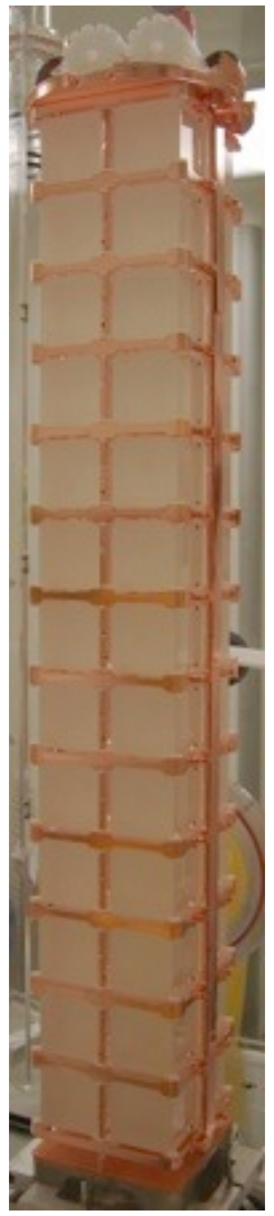
Scaling from Cuoricino to CUORE

Cuoricino



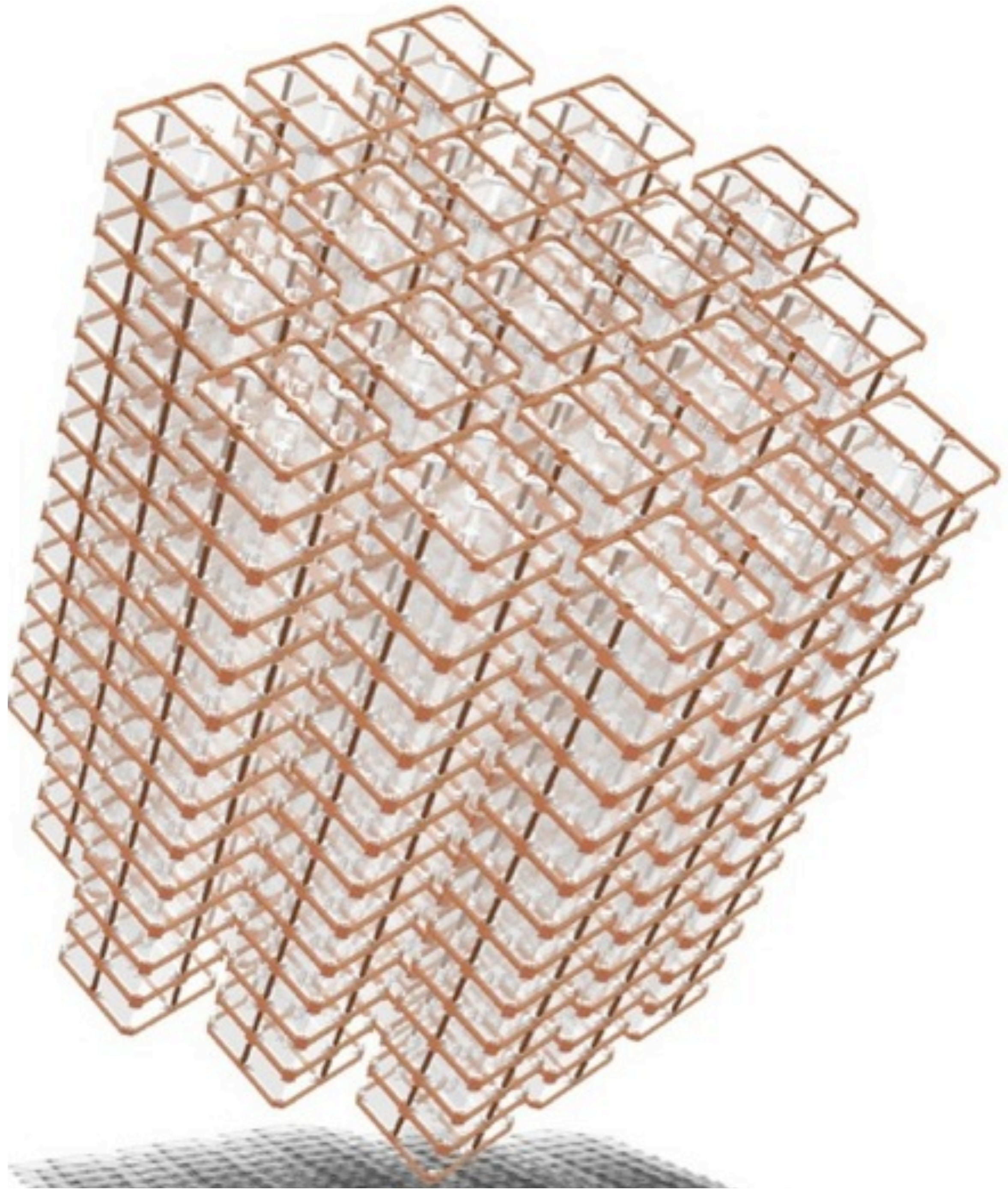
62 Bolometers
~11 kg of ^{130}Te
2003 - 2008

CUORE-0



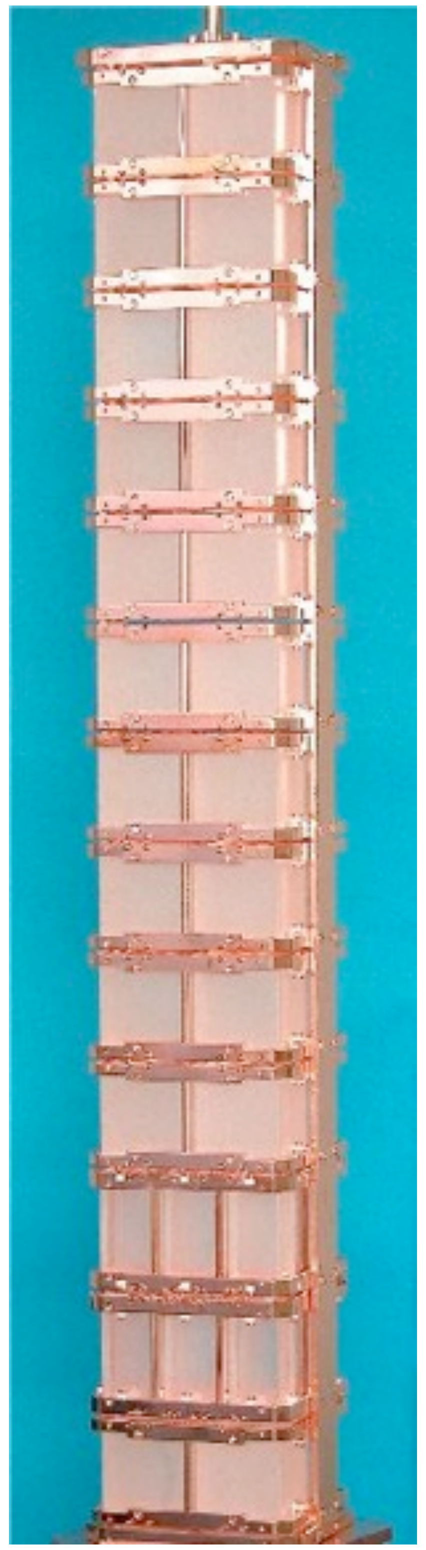
52 Bolometers
~11 kg of ^{130}Te
2013 - 2015

CUORE

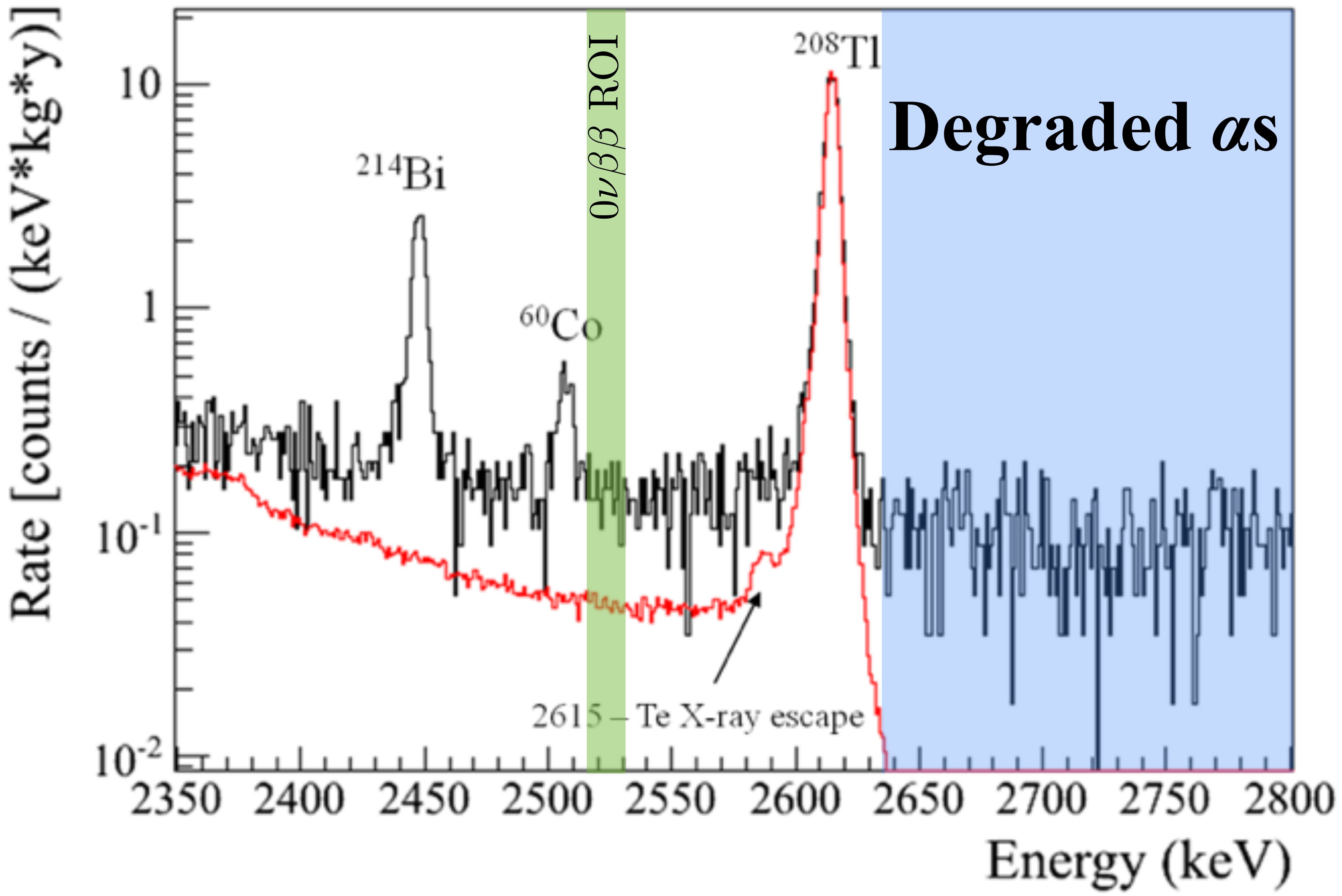


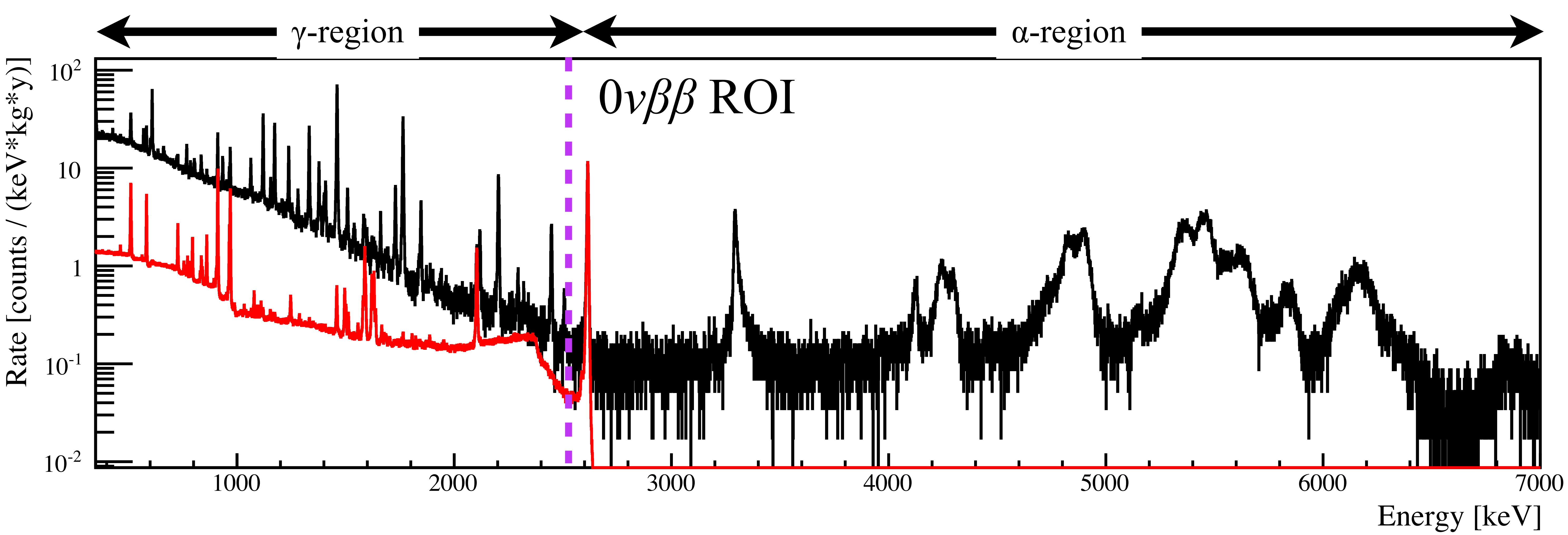
988 Bolometers
~200 kg of ^{130}Te
2015 - ?

Predecessor to CUORE: Cuoricino



- Similar to a single CUORE tower
- 11 kg of ^{130}Te
- Operated from 2003 - 2008
  - ^{130}Te Exposure: 19.75 kg·yr
  - Energy Resolution: 5.8 keV FWHM at 2615 keV
  - Background: 0.169 ± 0.006 cnts/keV/kg/yr





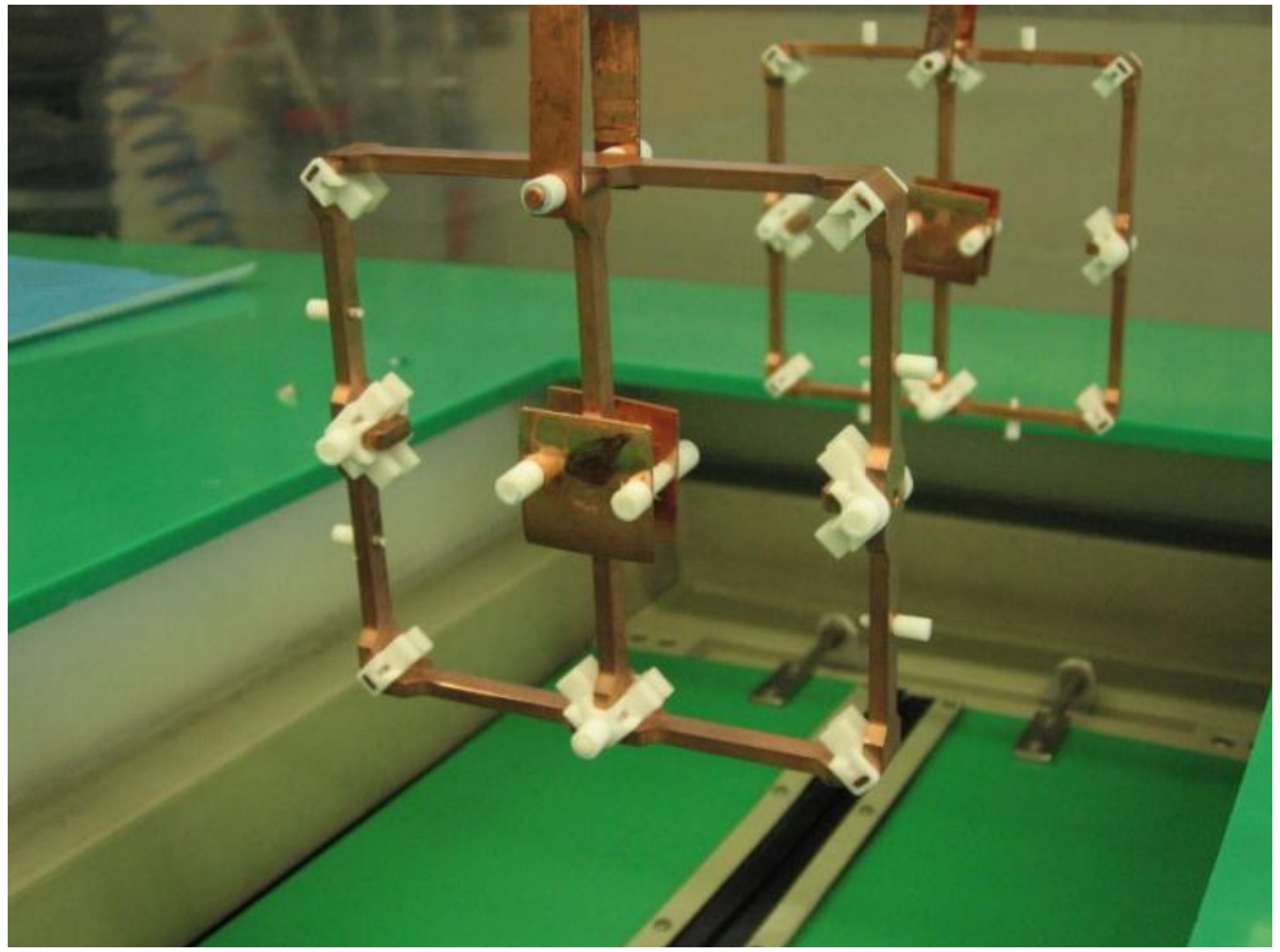
Cuoricino Result:

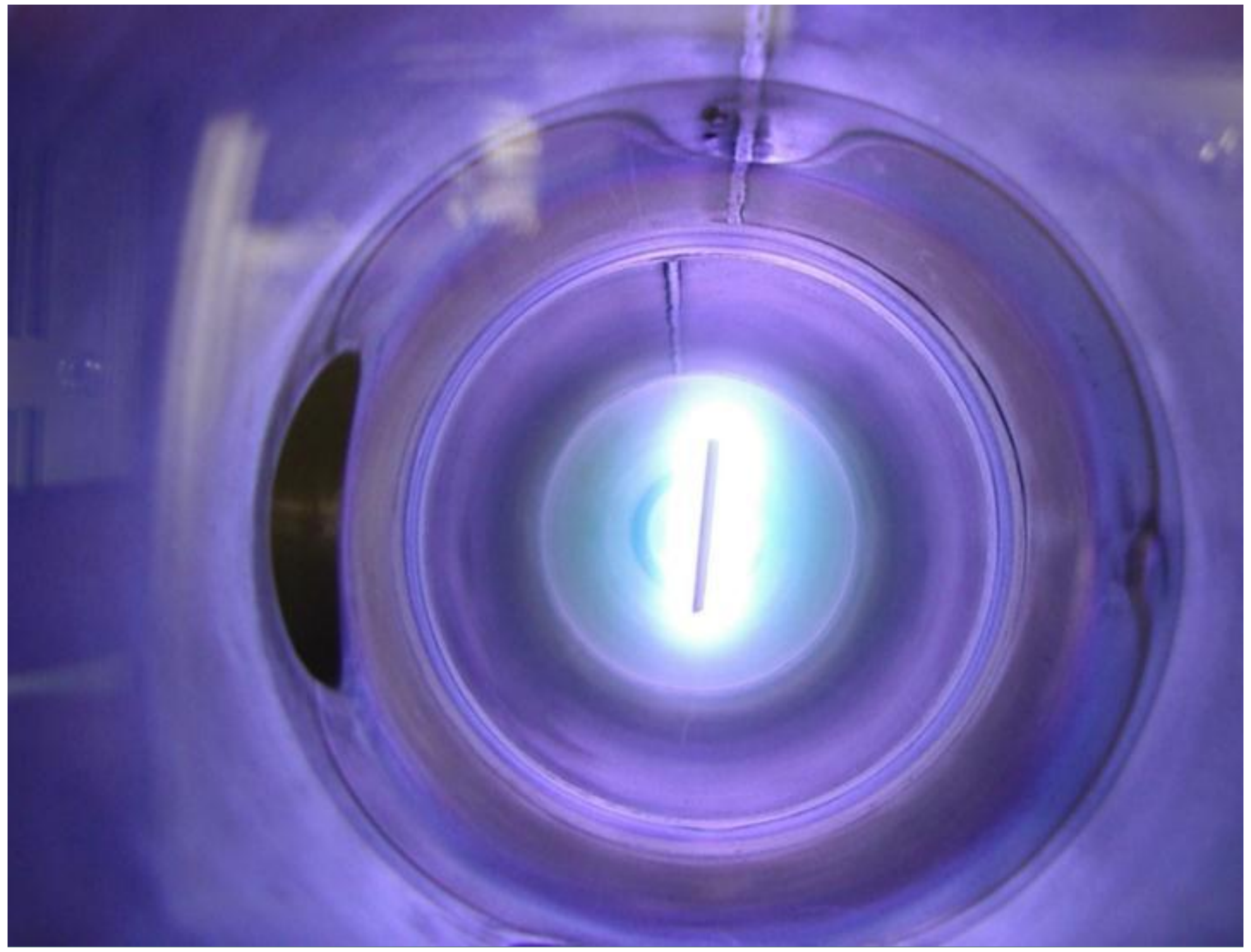
$$T^{0\nu}_{1/2} > 2.8 \times 10^{24} \text{ yr (90\% C.L.)}$$

$$m_{\beta\beta} < 300 - 700 \text{ meV}$$

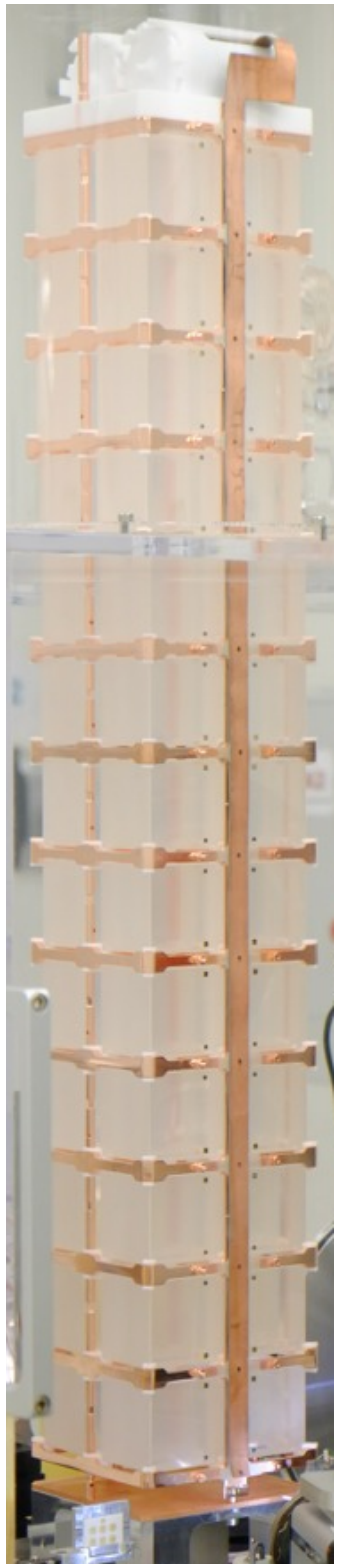
Astropart. Phys. 34, 822 (2011)

Parts Cleaning & Detector Assembly

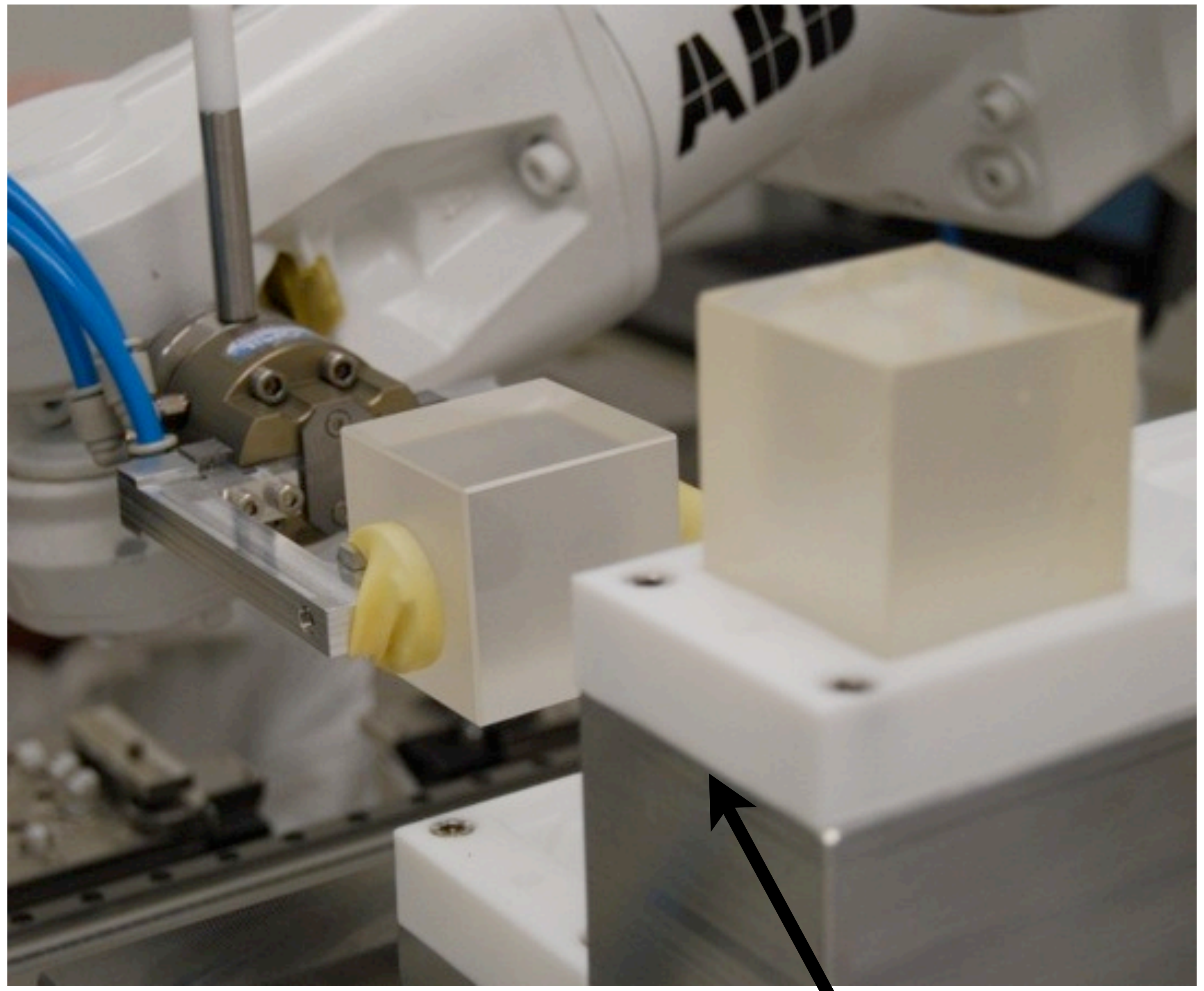


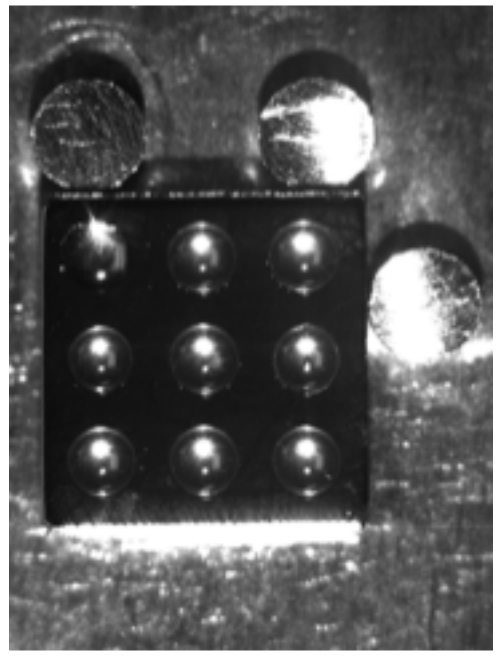


- Parts cleaned using a combination of tumbling, electropolishing, chemical etching, and plasma etching
- Parts stored under vacuum or N_2 flux to minimize recontamination
- Detector assembly in class 1000 cleanroom, in specially designed glove boxes, under constant N_2 flux
- Towers stored under constant N_2 flux in the clean room, waiting for installation



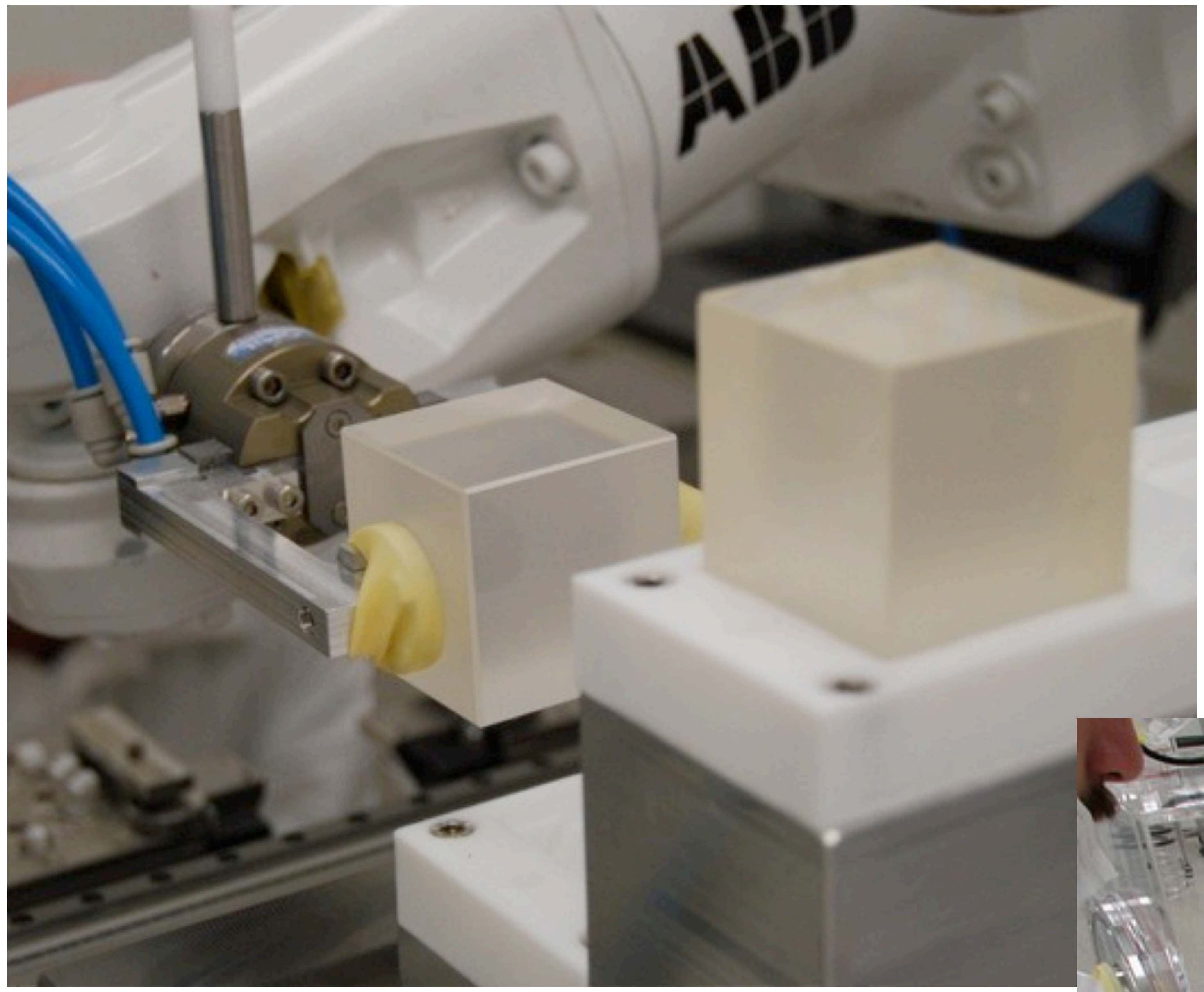
The CUORE Production Line



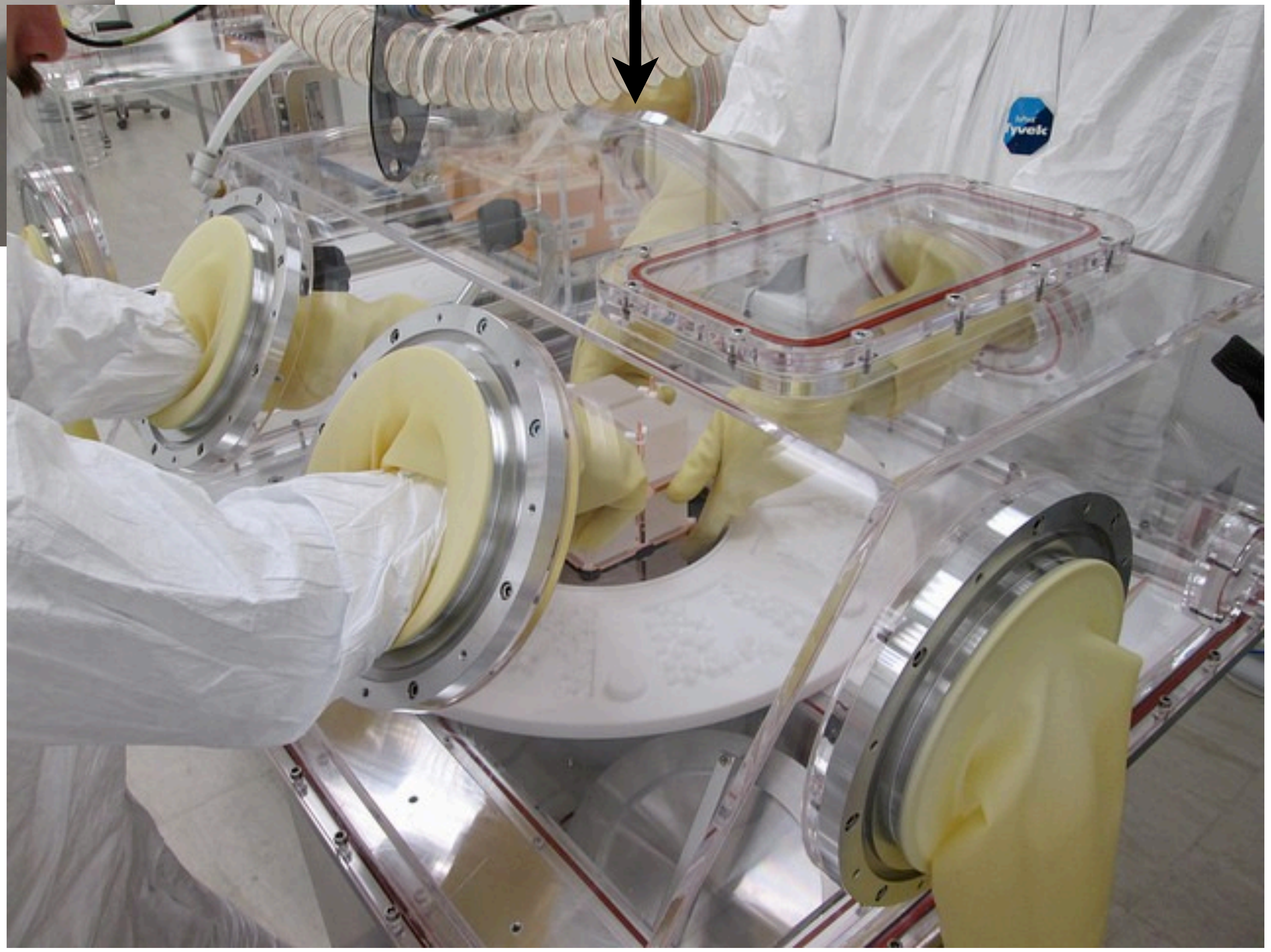


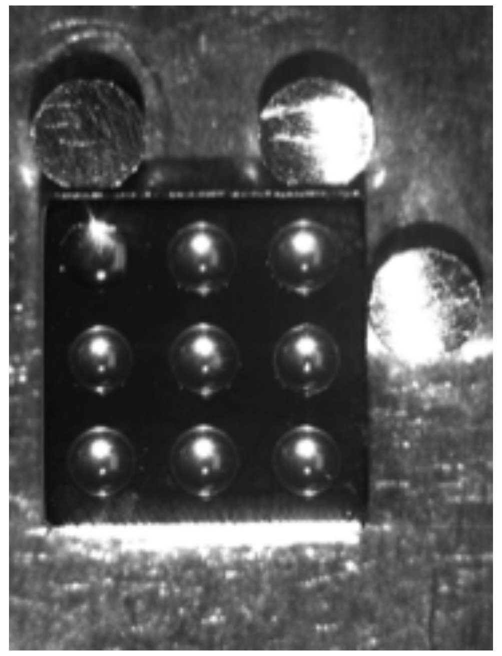
Robotic gluing system
for attaching thermistors

The CUORE Production Line

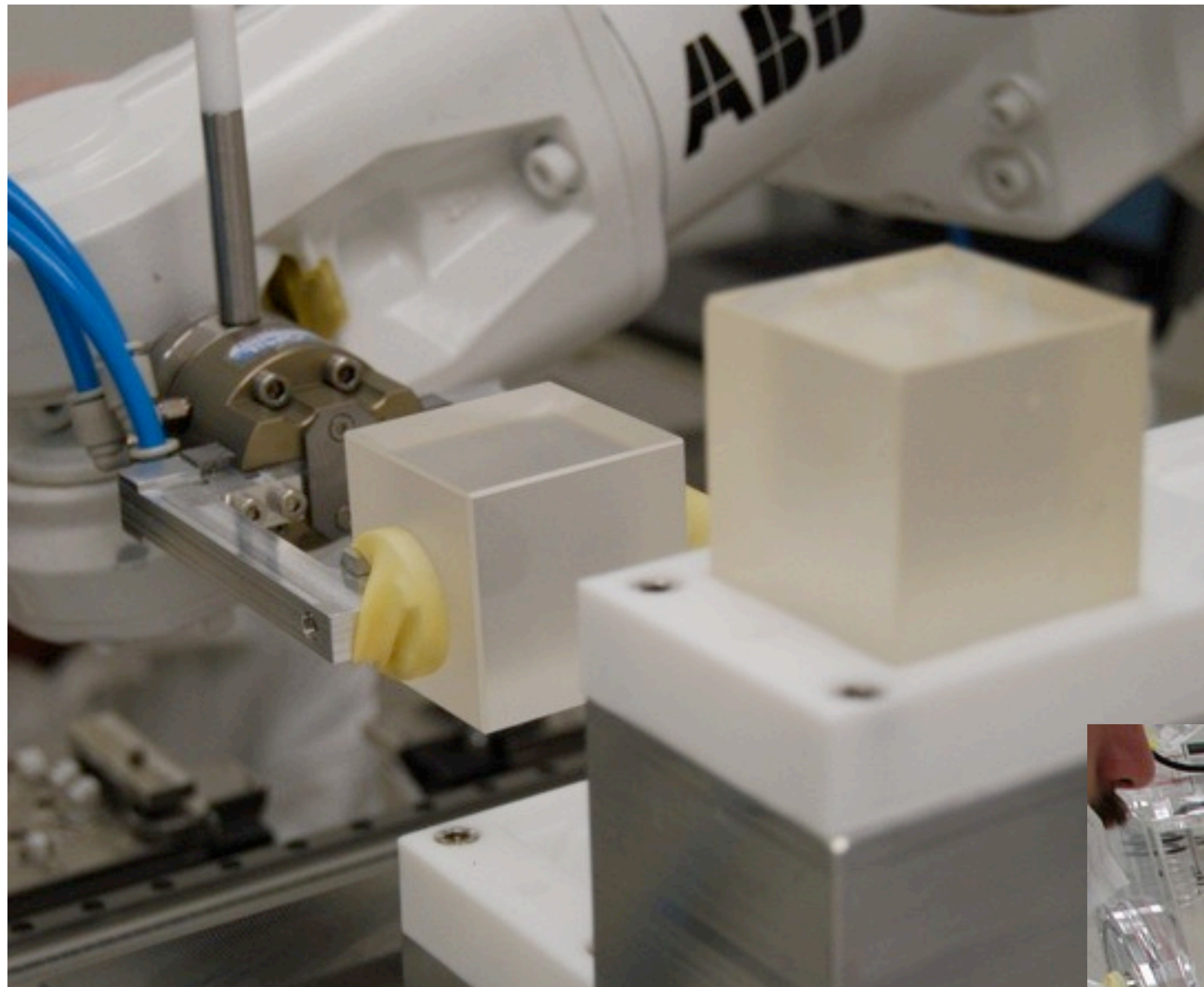


Assembly into a tower

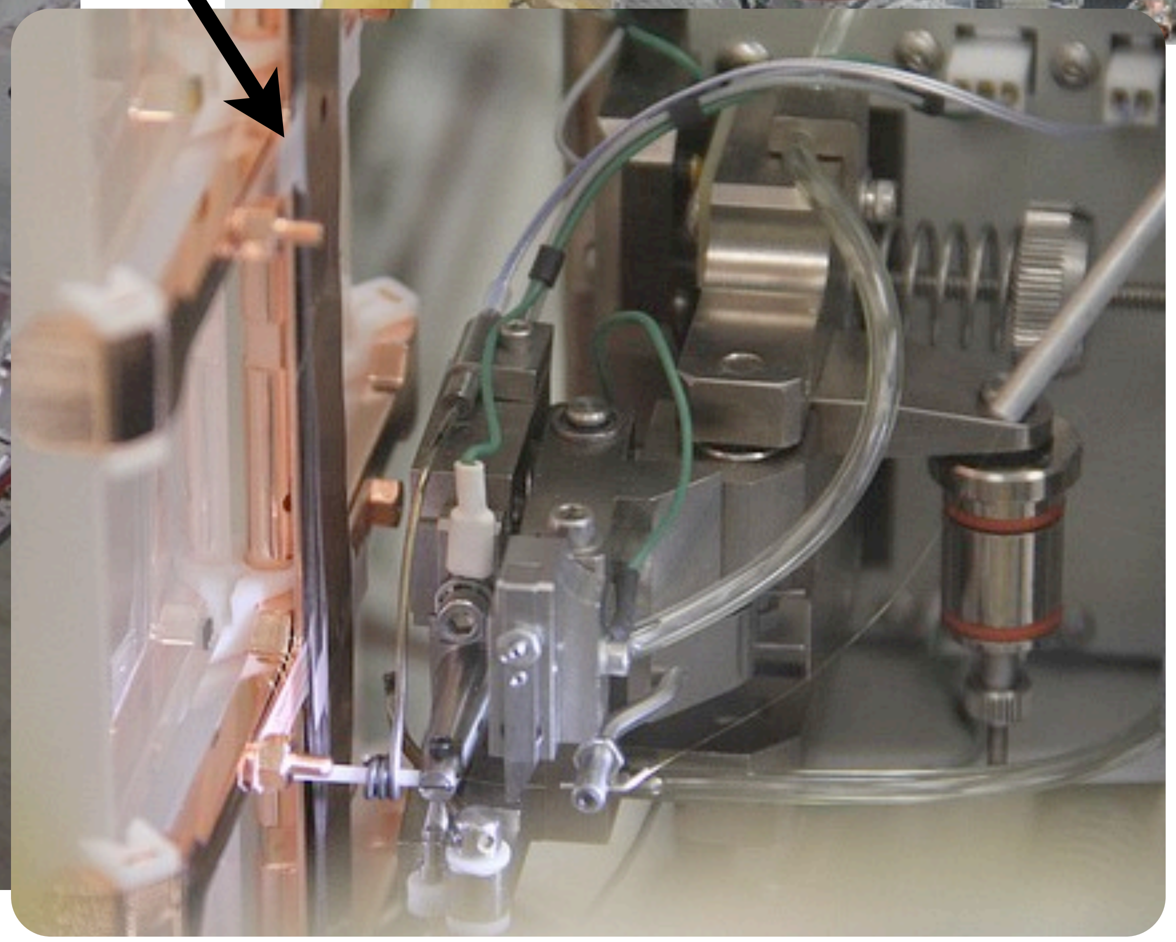




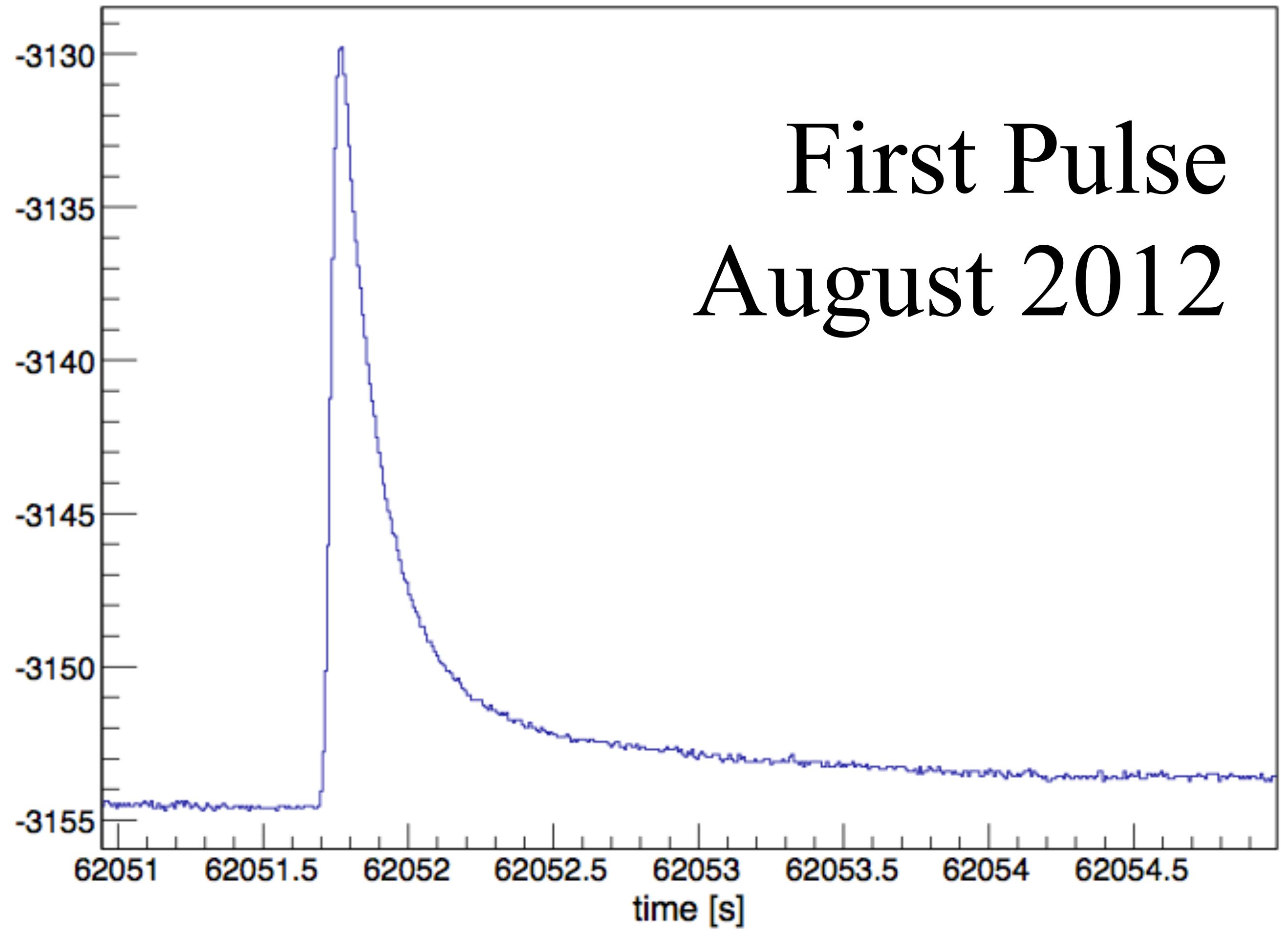
The CUORE Production Line



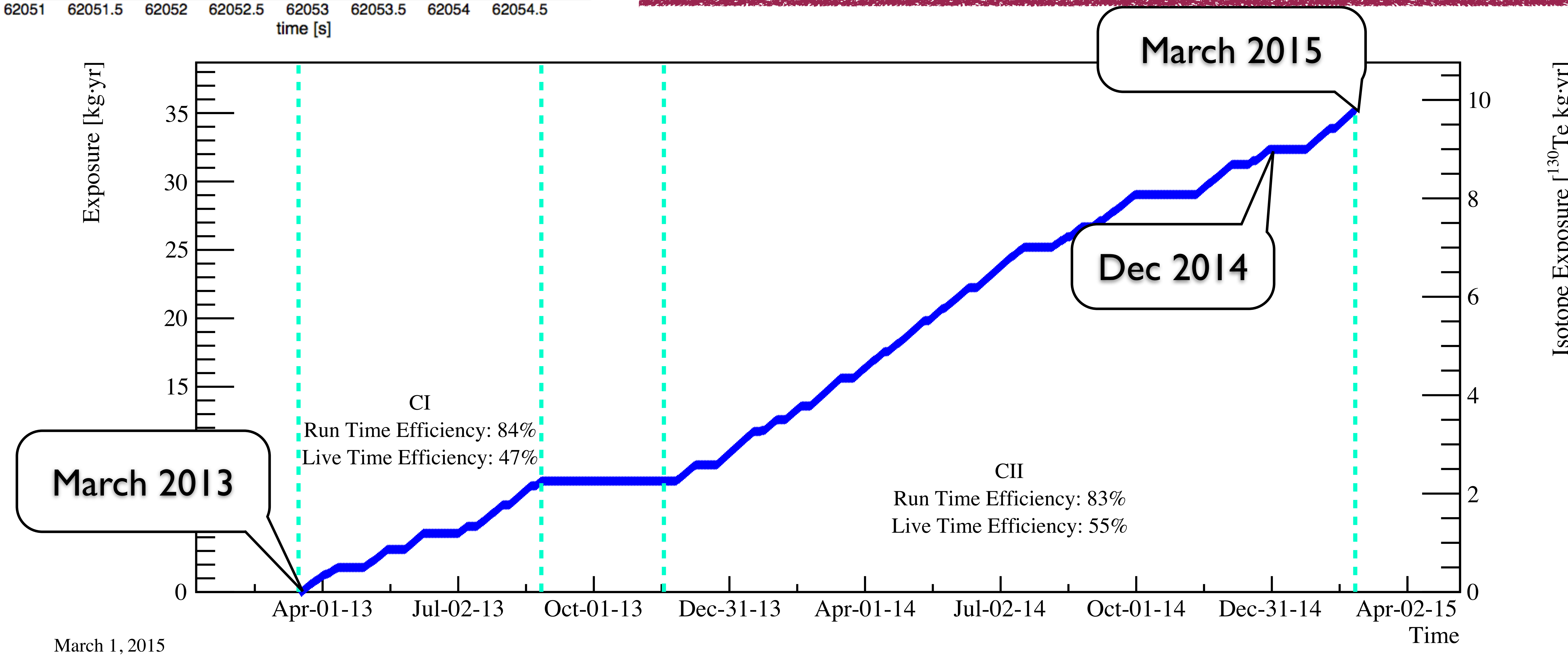
Wire bonding electrical connections



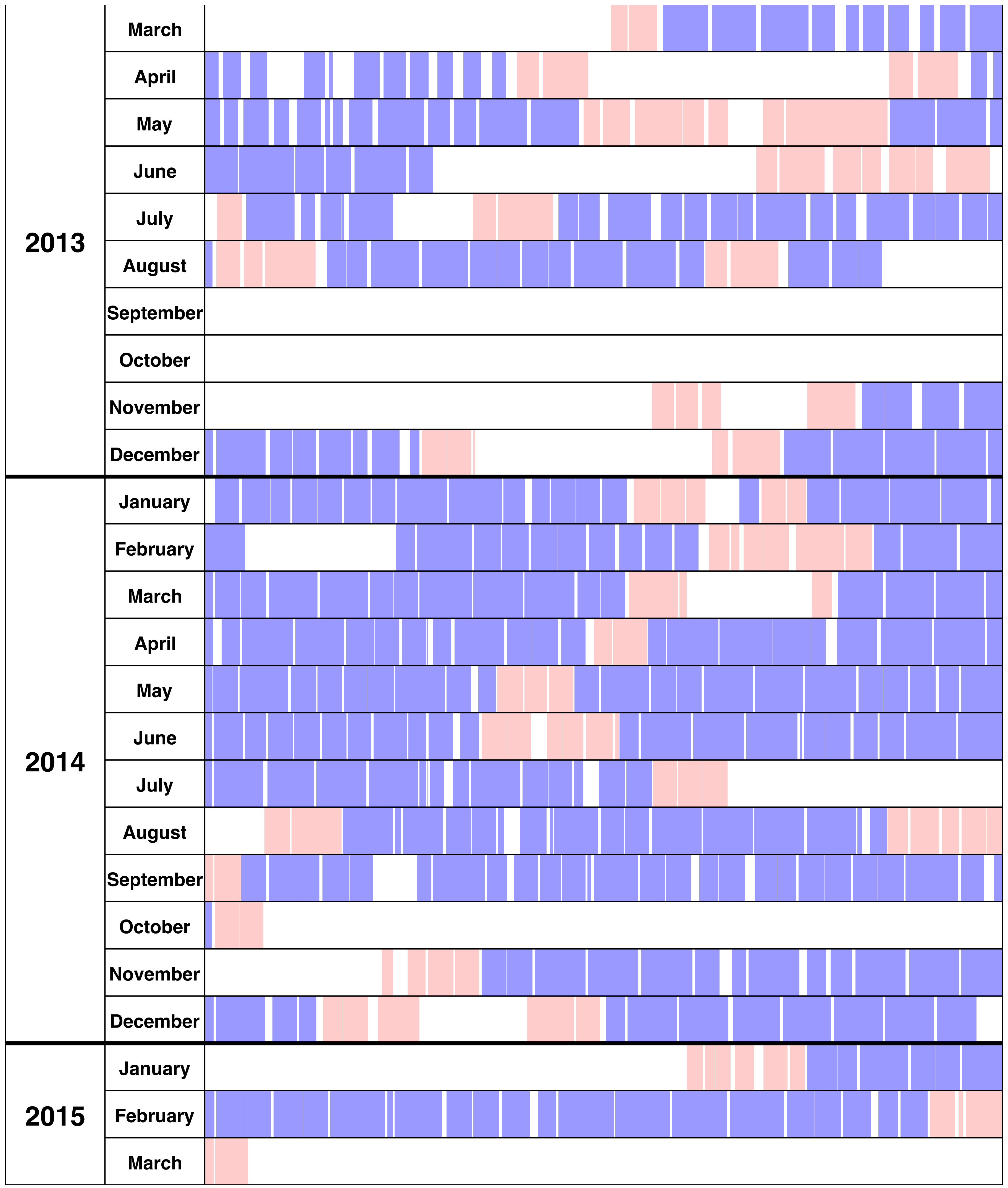
CUORE-0

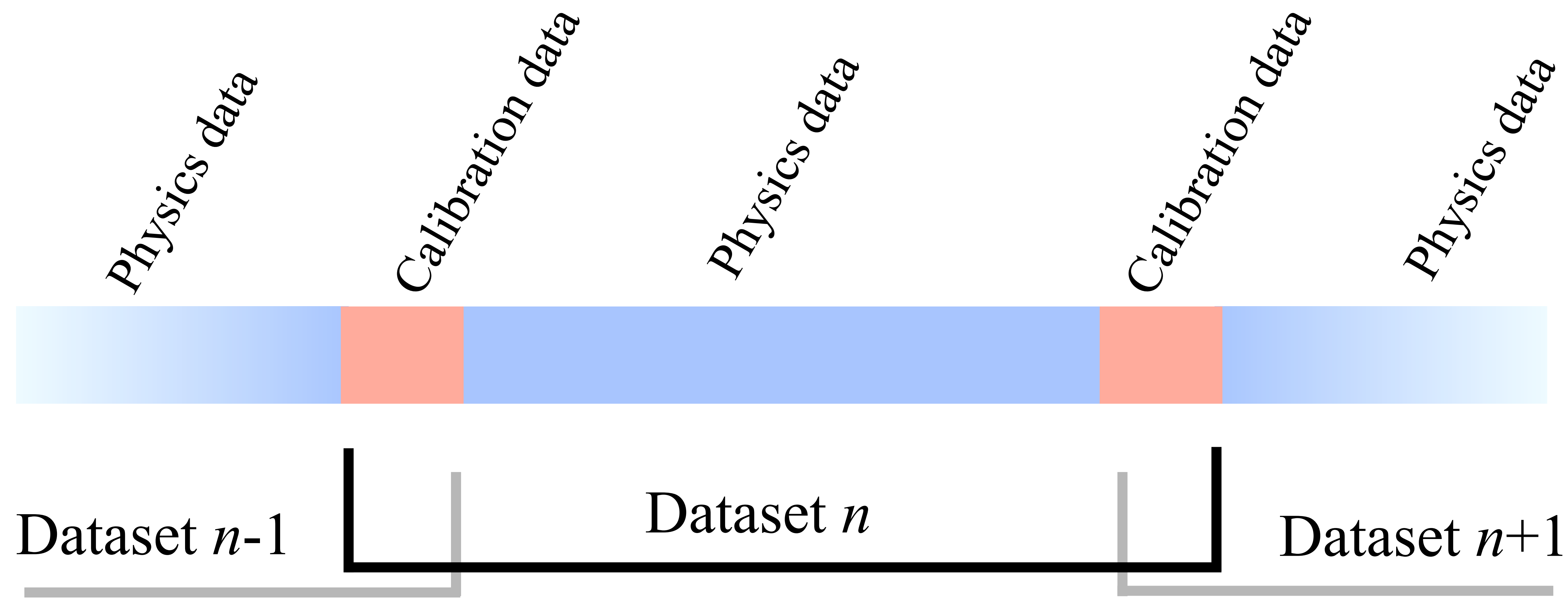


- First tower off the CUORE assembly line
- Ran from March 2013 - March 2015
- Collected 9.8 kg·yr of ^{130}Te exposure
- Surpassed the Cuoricino sensitivity in less than half the run time



Data Collection

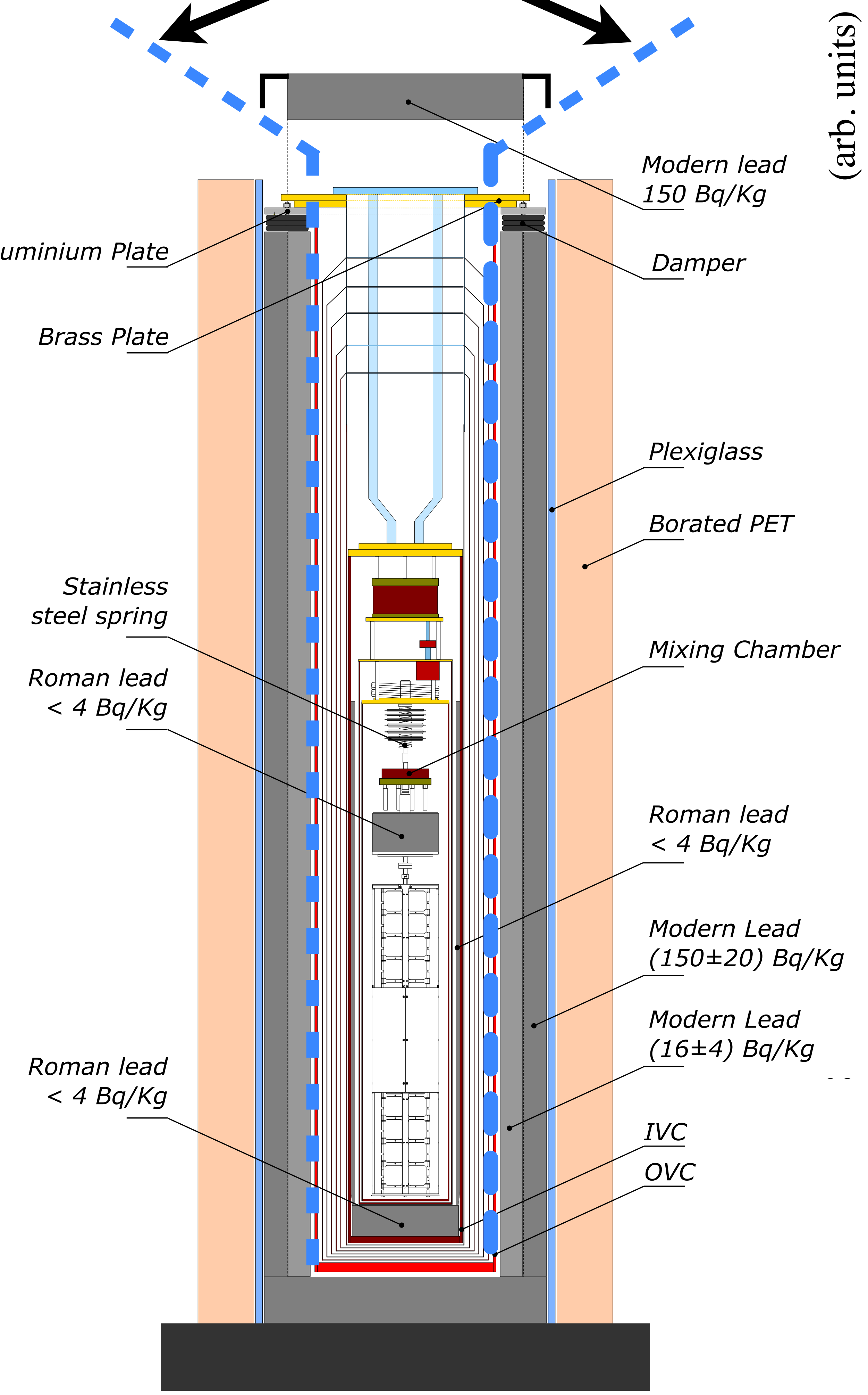


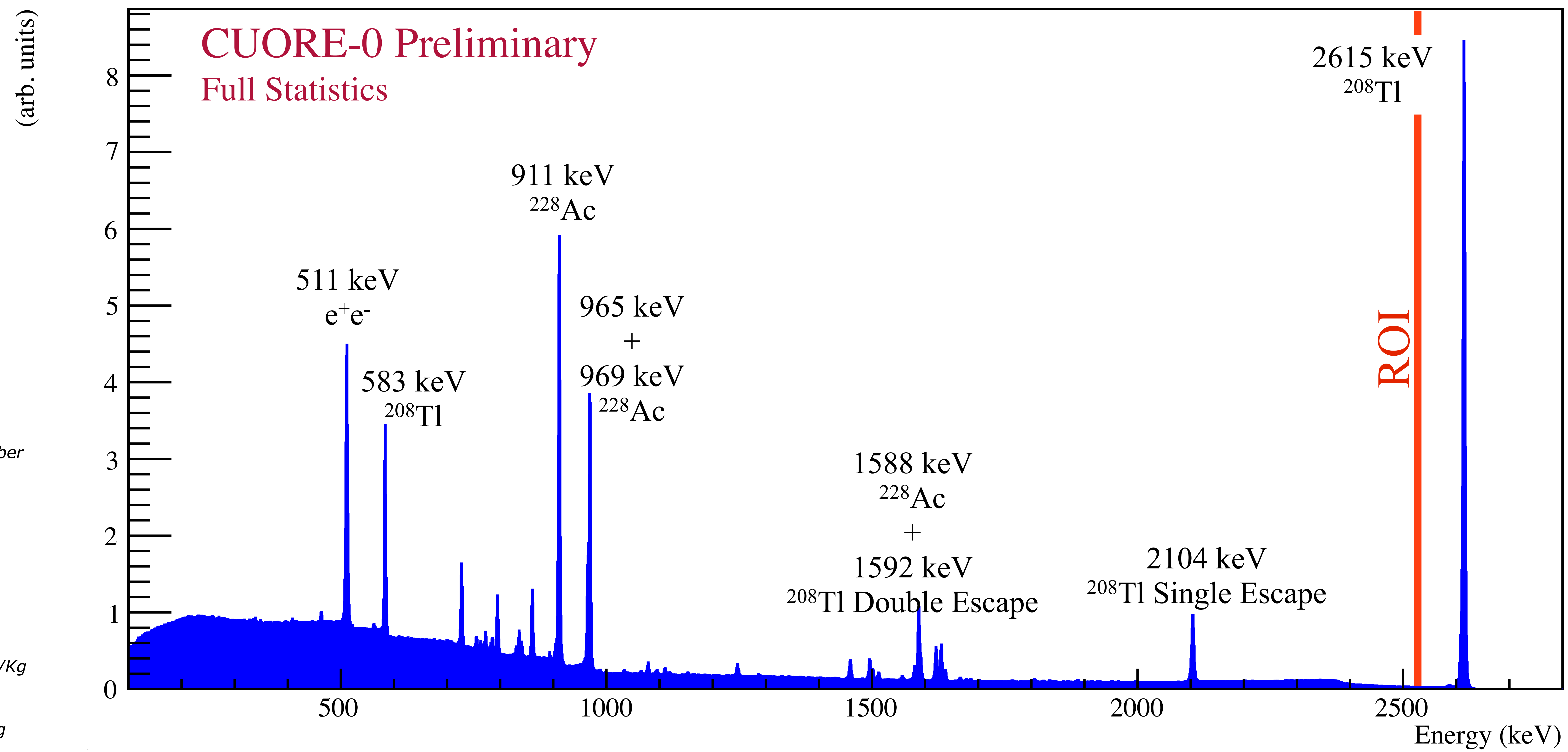


- Collect data in ~1 day runs
- Combined into ~month long datasets
- Each dataset is flanked by a set of calibration runs
- Dataset has ~3 weeks of physics data and ~6 days of calibration data
- Occasional down time for cryostat maintenance

Detector Calibration

Th source strings





Detector Calibration

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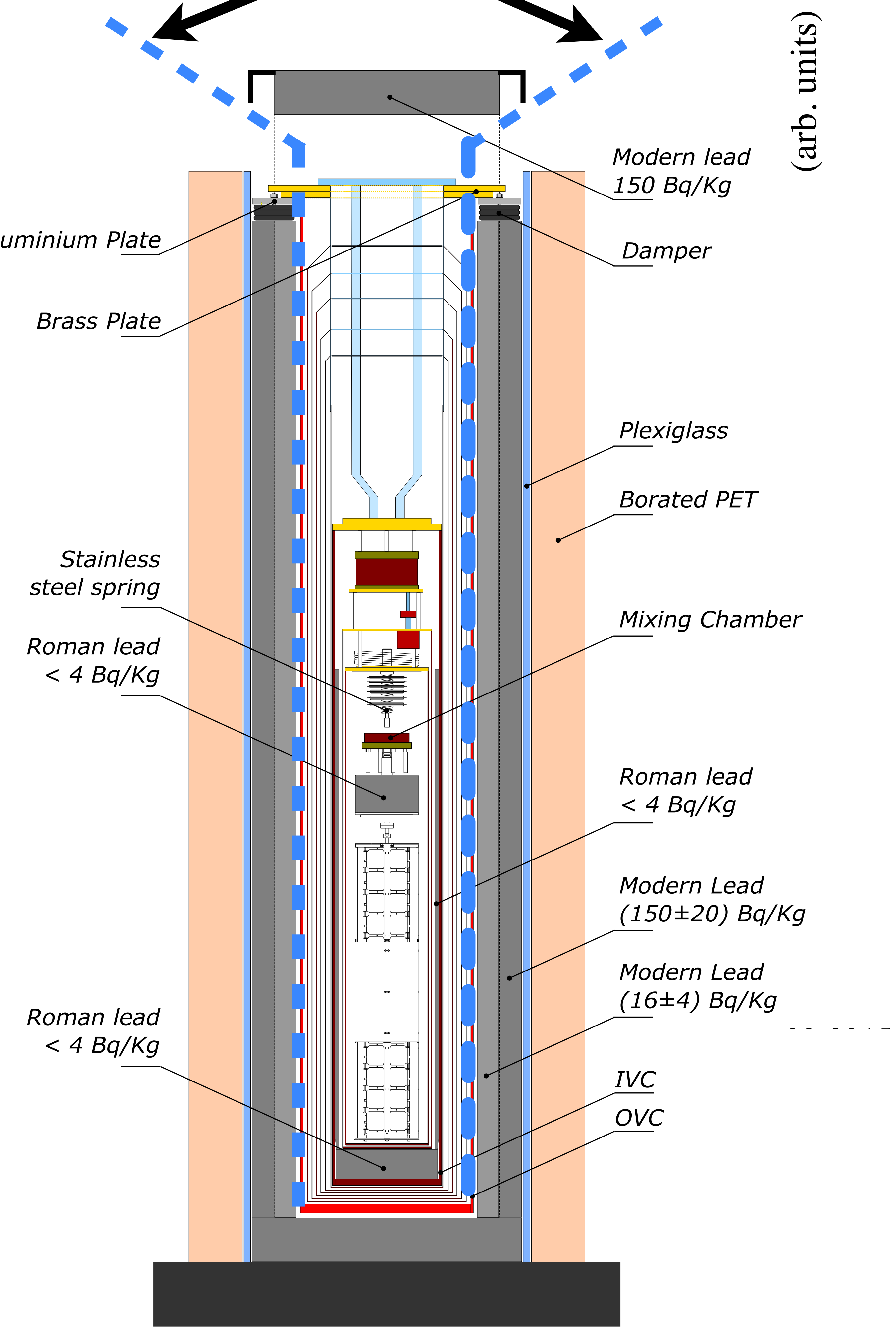
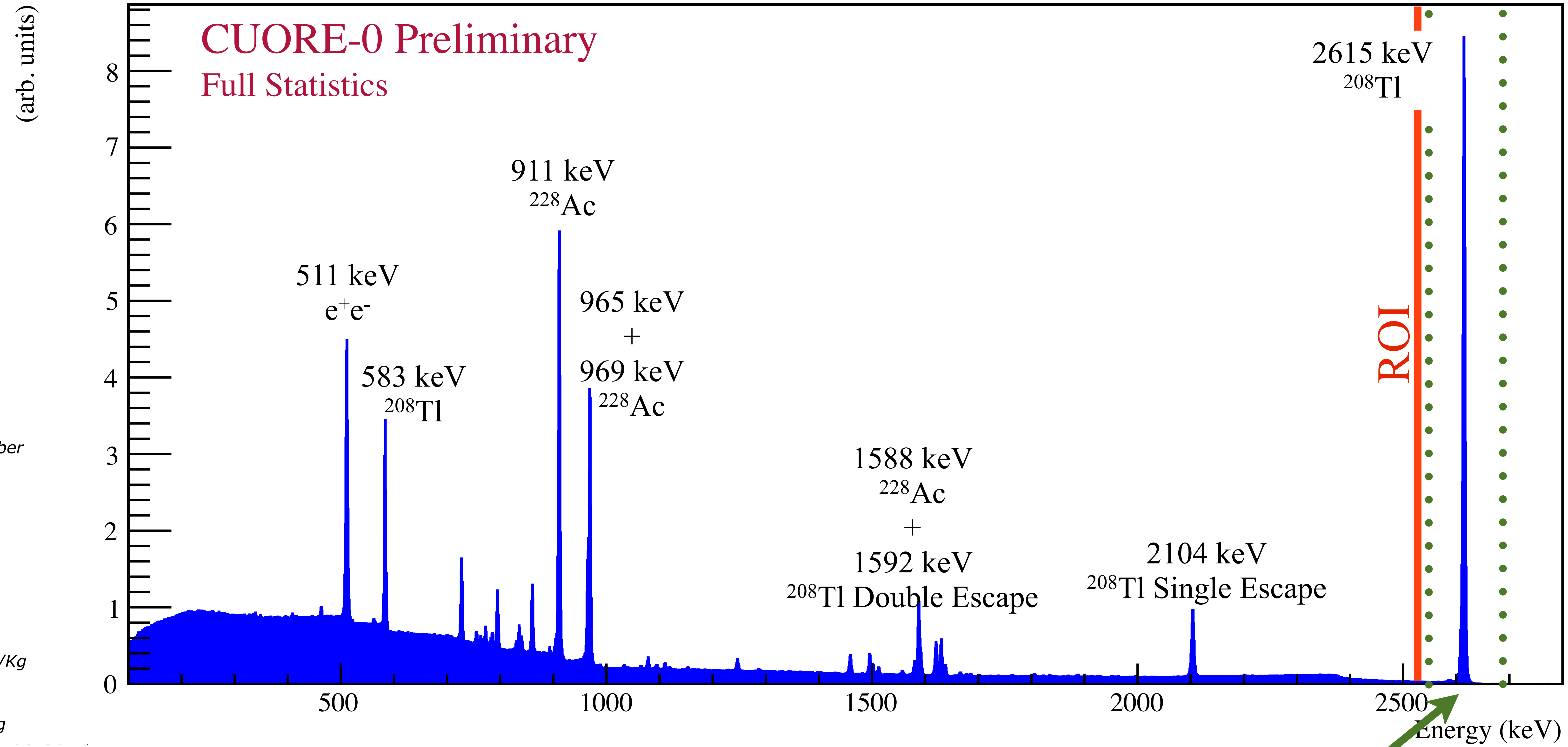
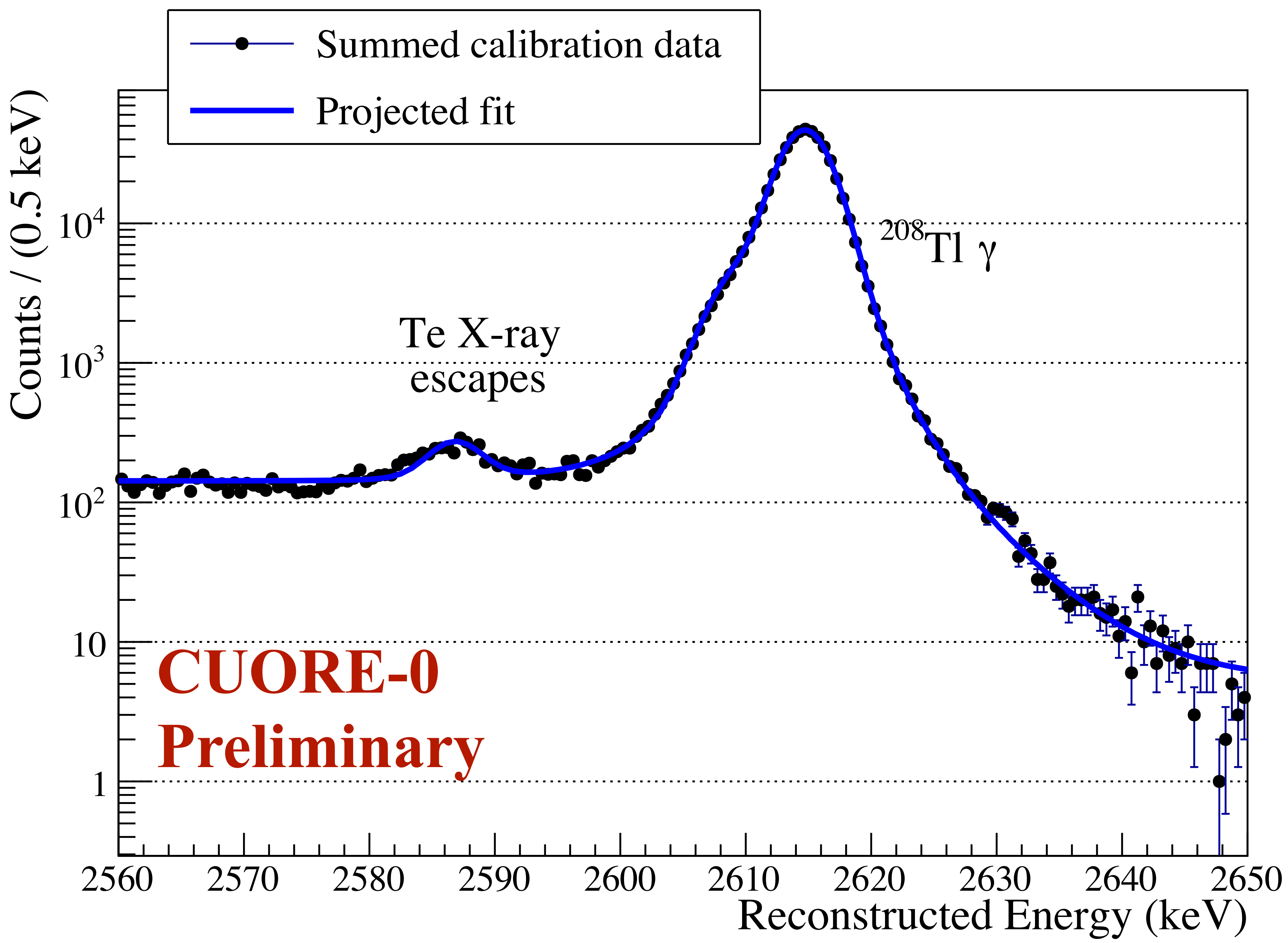
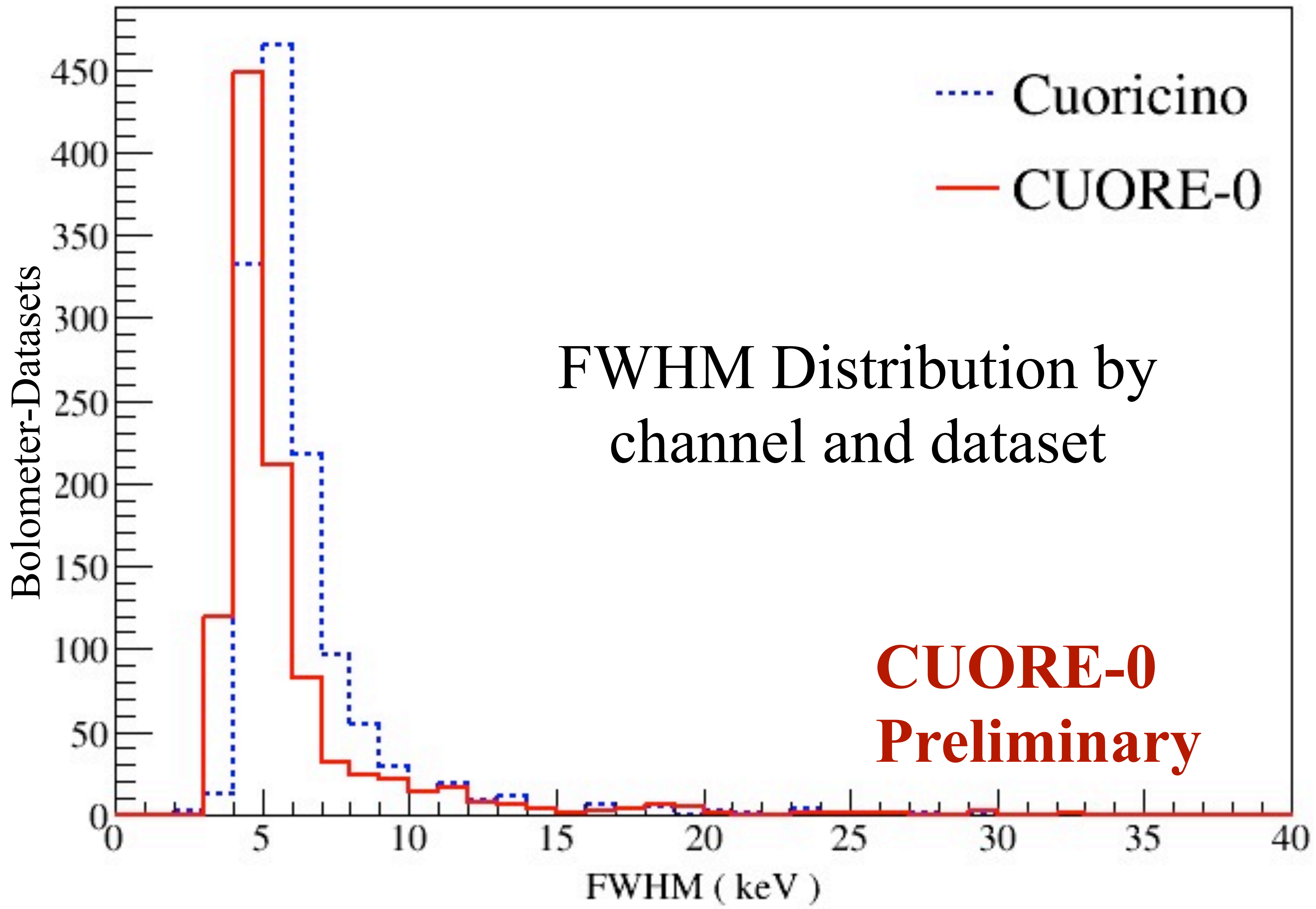




Use 2615 keV ^{208}Tl peak for evaluating the energy resolution

CUORE-0 Energy Resolution

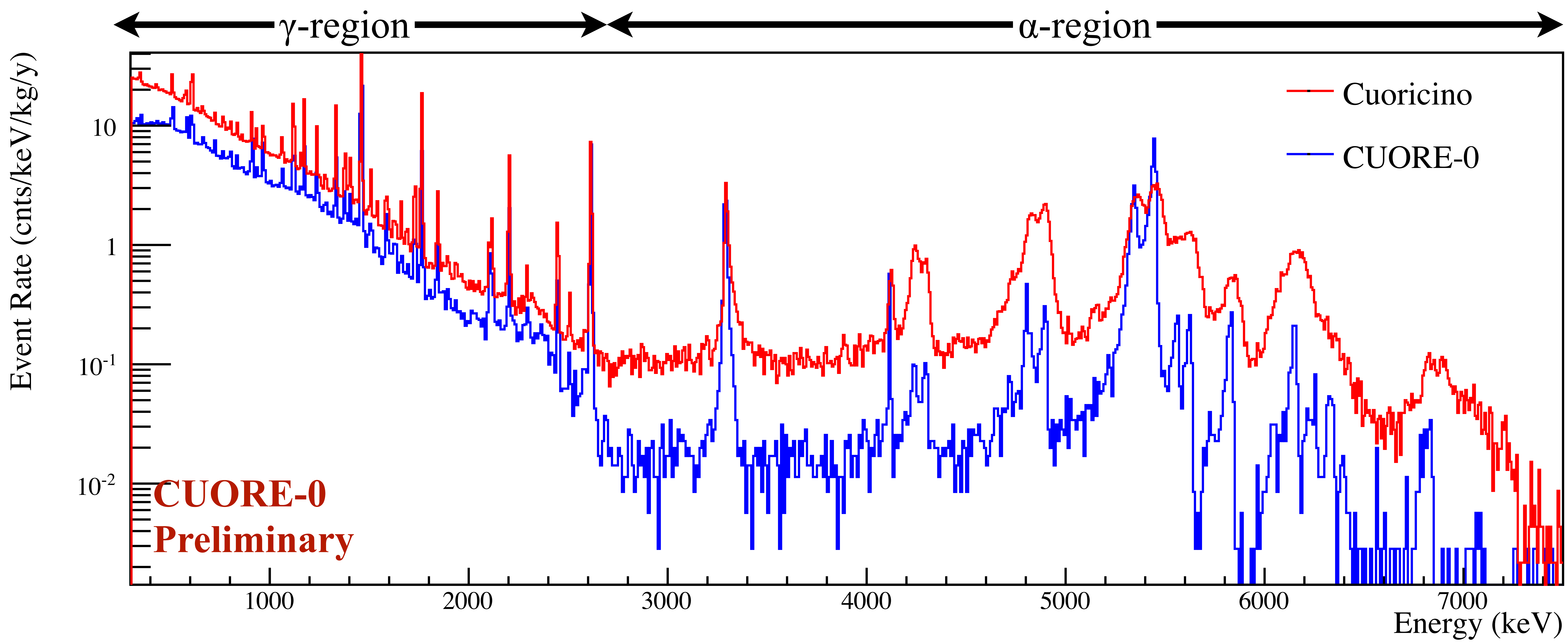




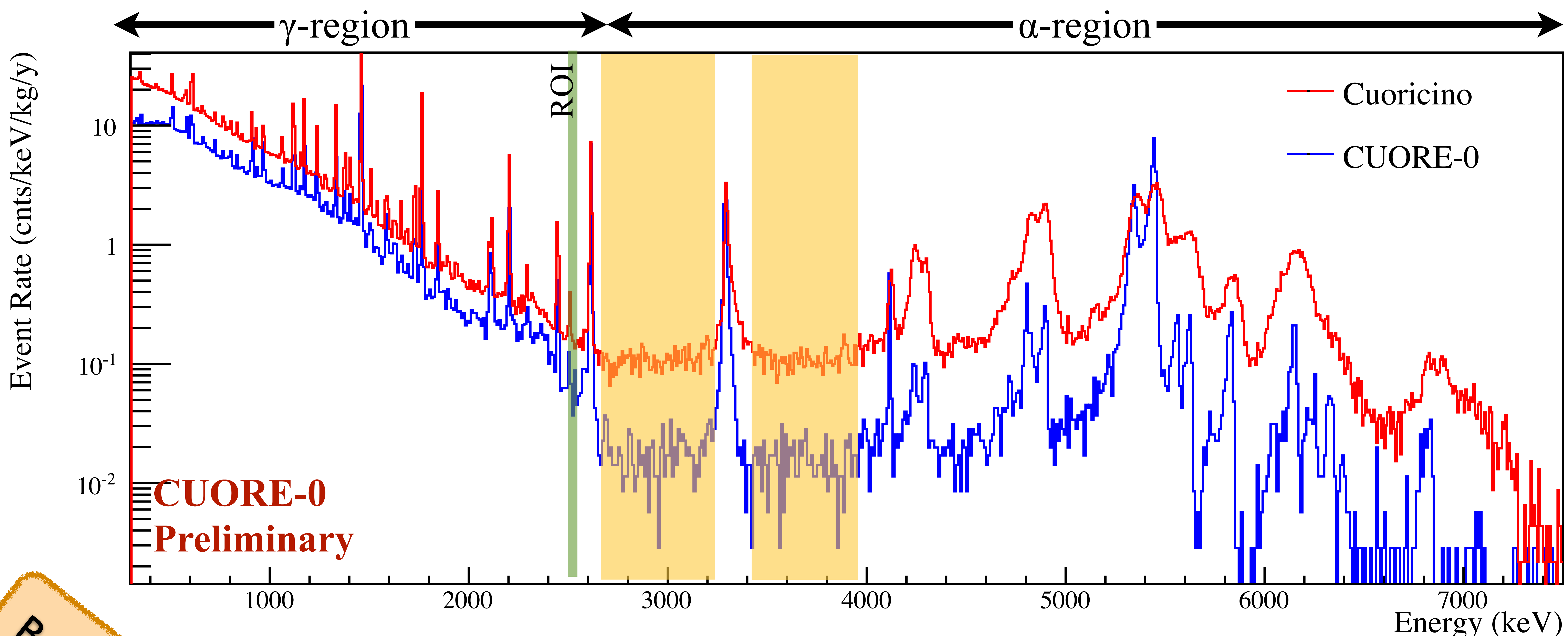
- Fit the ^{208}Tl calibration peak for each channel-dataset pair
- Evaluate the FWHM for each from the fit
- "Effective FWHM" is analogous to averaging the experimental sensitivities

	Effective FWHM (Harmonic Mean)	FWHM Distribution RMS
Cuoricino	5.8 keV	2.1 keV
CUORE-0	4.9 keV	2.9 keV

CUORE-0 α-Background



CUORE-0 α-Background

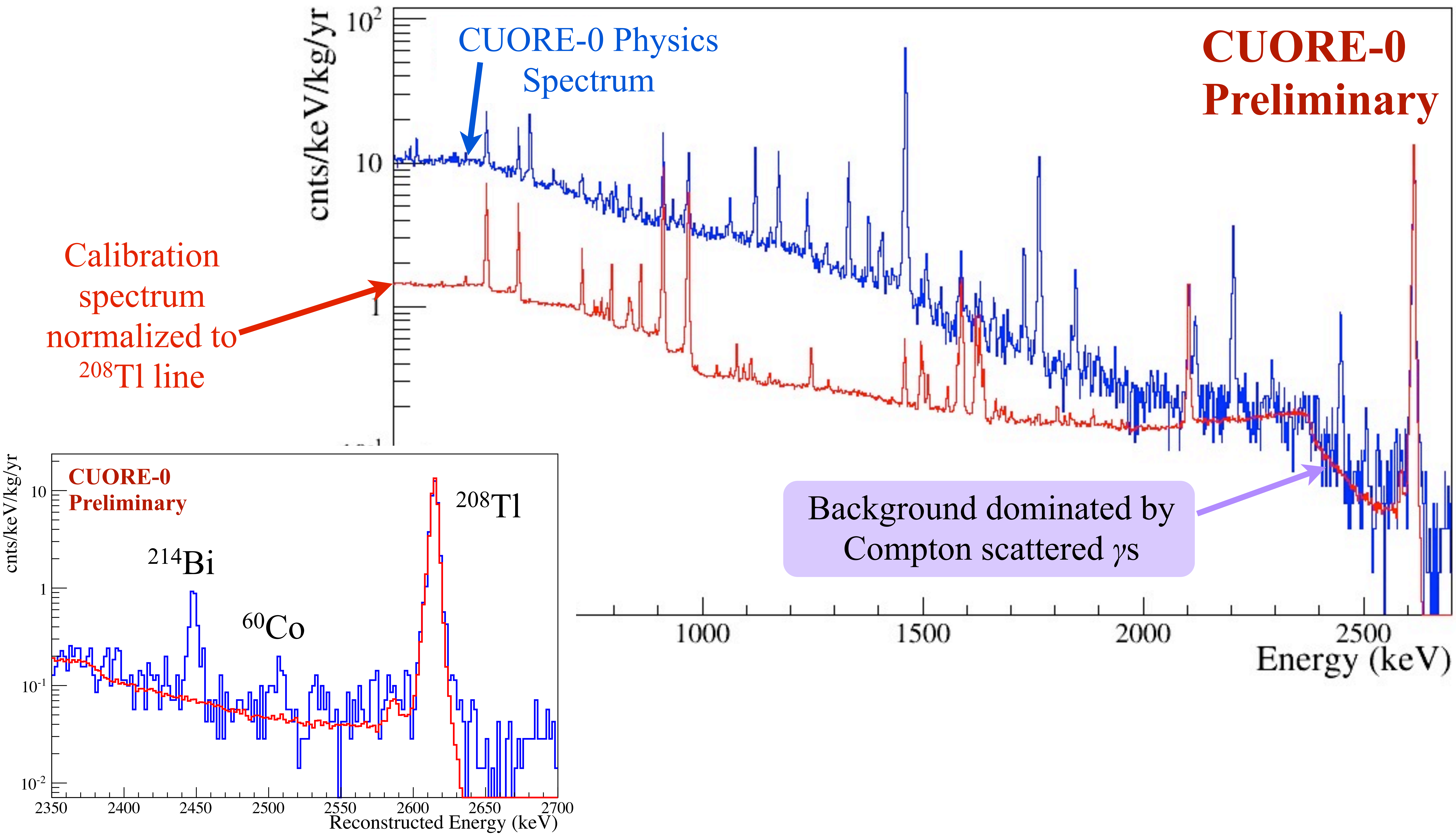


Background Model paper in preparation

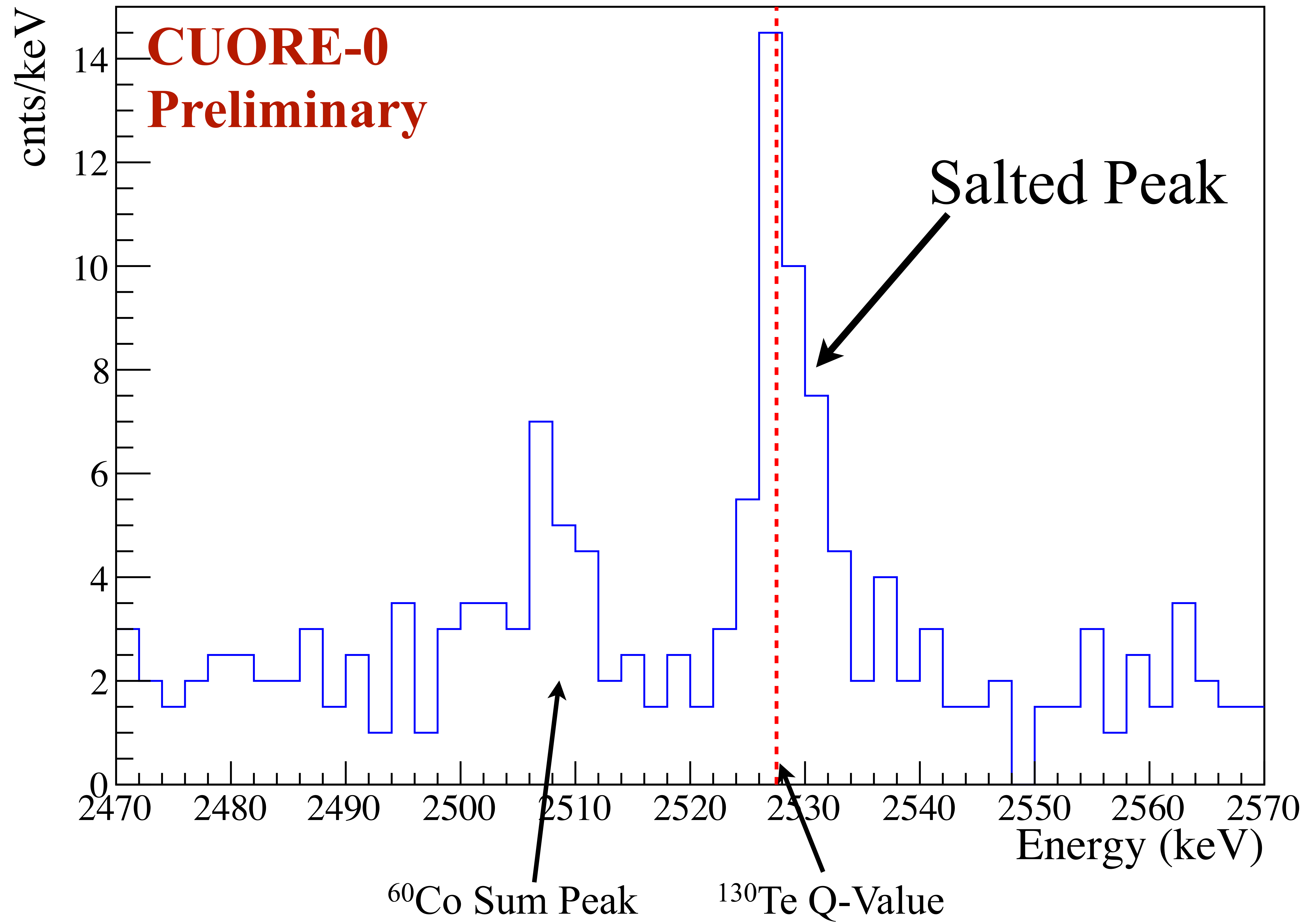
	Background Rate (cnts/keV/kg/yr)	
	0νββ Region	α Region
Cuoricino	0.169 ± 0.006	0.110 ± 0.001
CUORE-0	0.058 ± 0.004	0.016 ± 0.001

Factor of 7 improvement in α-background

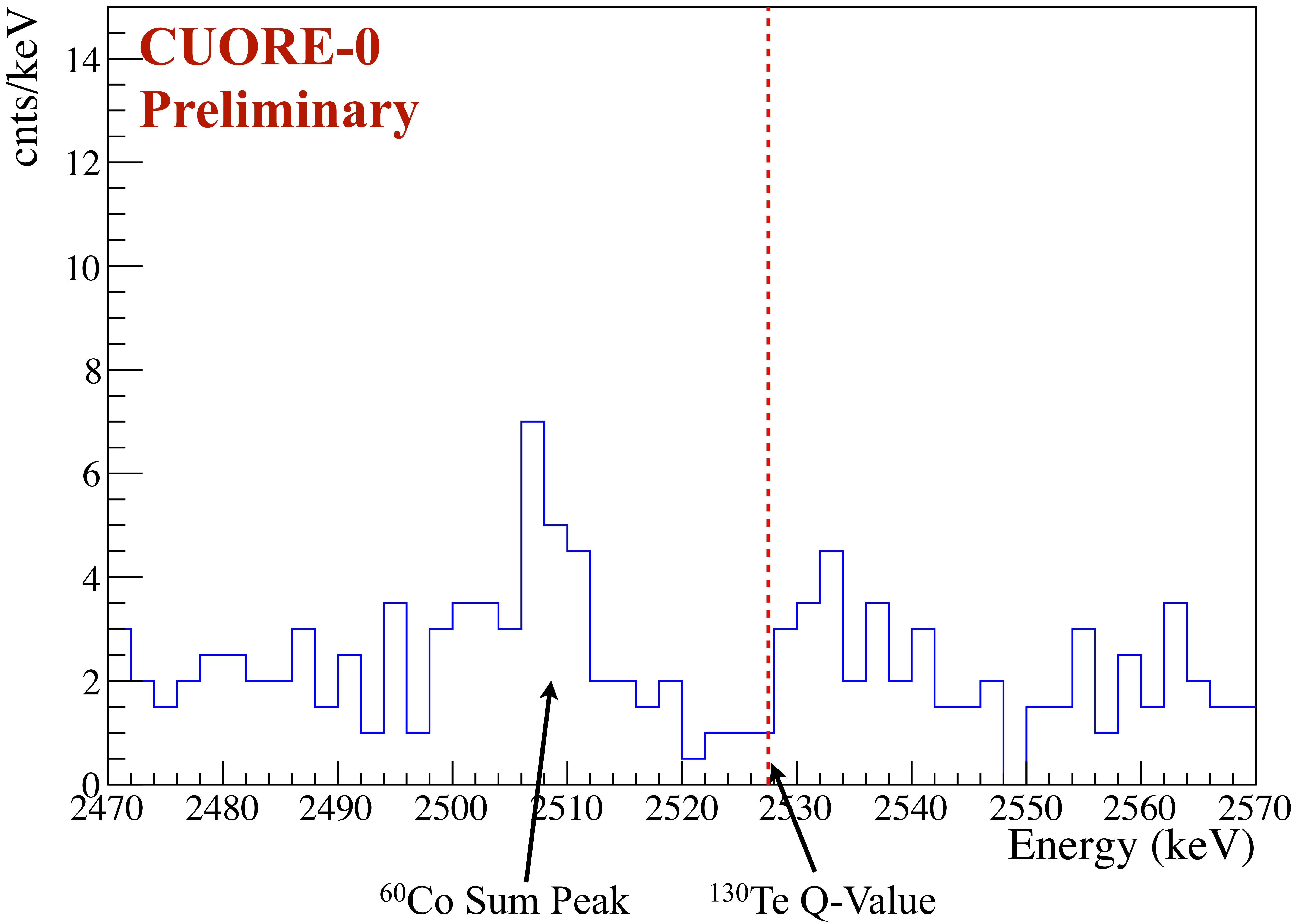
CUORE-0 γ-Background



CUORE-0 Unblinded ROI

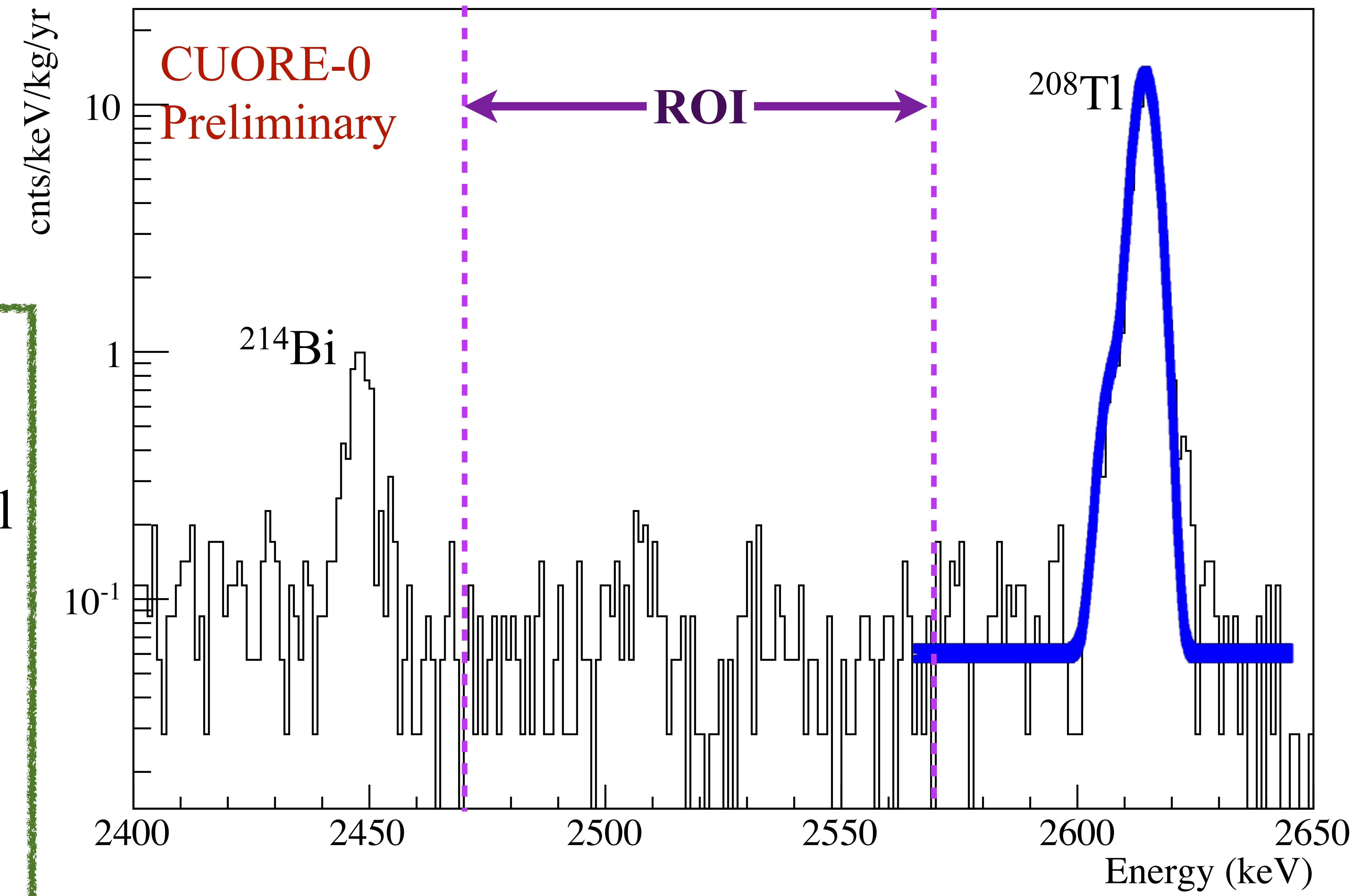


CUORE-0 Unblinded ROI



Fitting The ROI

- Simultaneously fit all 1008 channel-dataset "experiments"
- Use the lineshape from calibration ^{208}Tl
- Scale one line to $0\nu\beta\beta$ position
  - Position fixed *relative* to ^{208}Tl position
- Scale one line to ^{60}Co position
  - Leave position floating
- Scale resolutions from ^{208}Tl value
- Flat background



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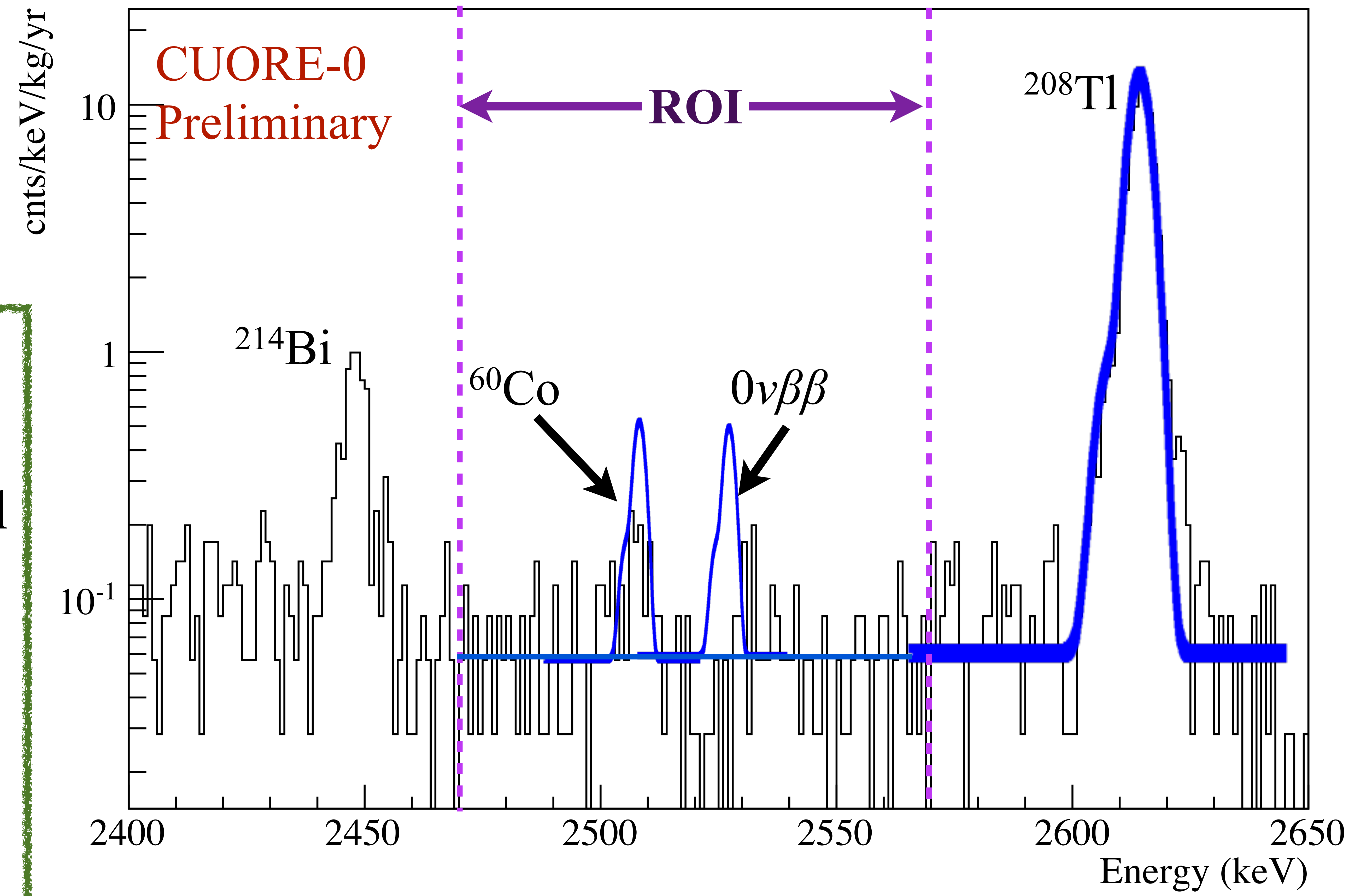

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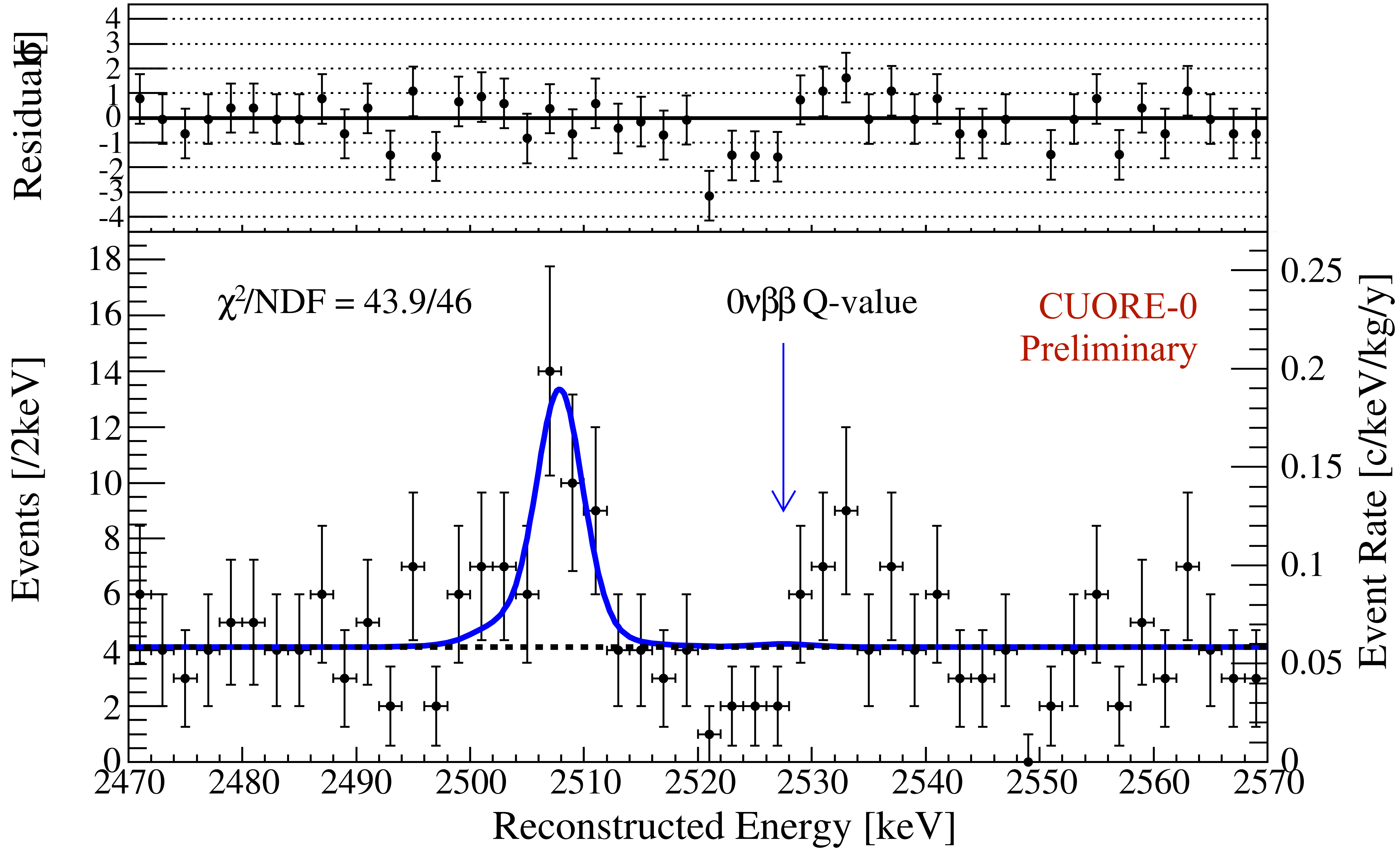
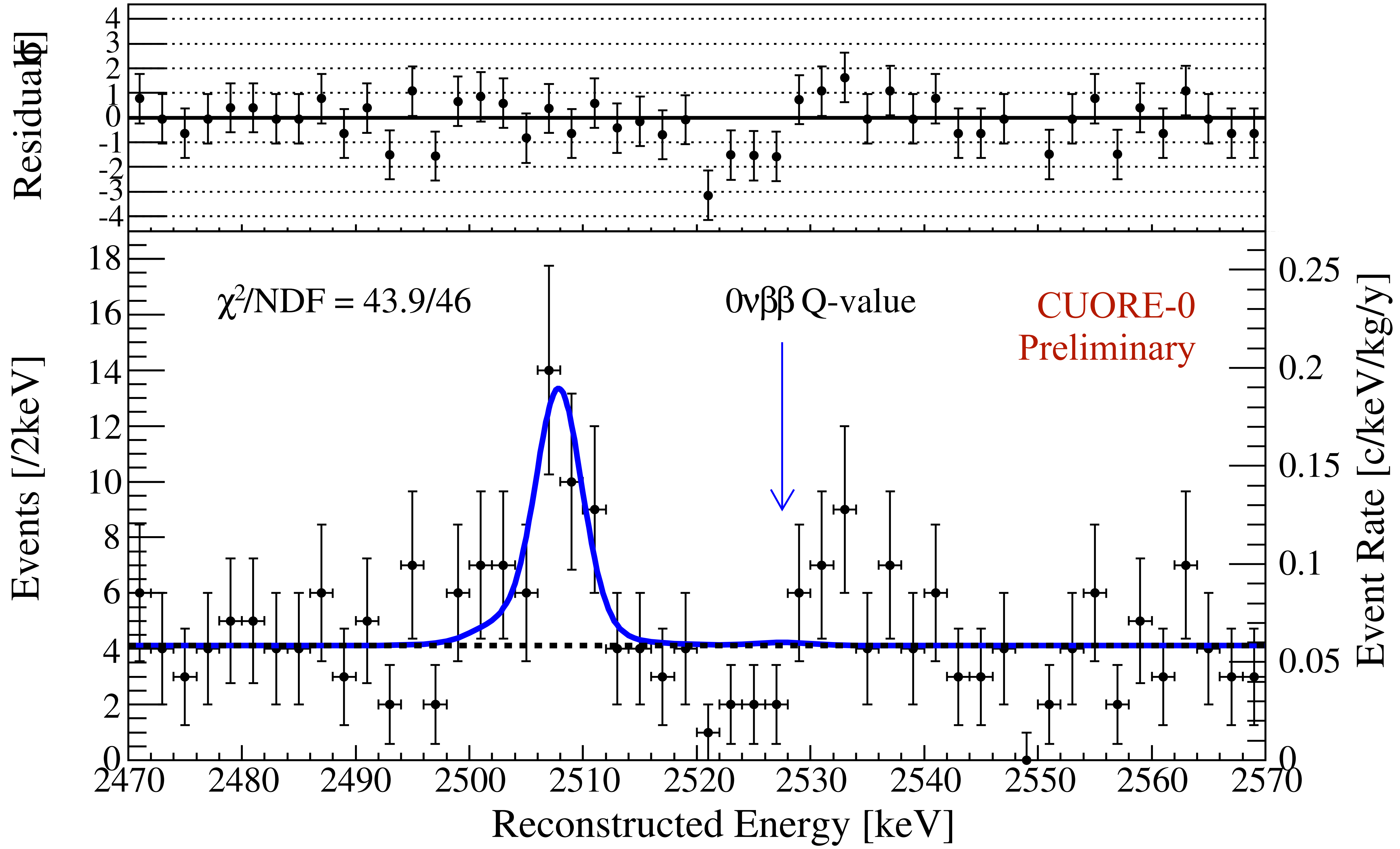
Final ROI Fit



Best fit rate:

$$\Gamma_{0\nu} = 0.007 \pm 0.123 \pm 0.012 \times 10^{-24} \text{yr}^{-1}$$

Final ROI Fit

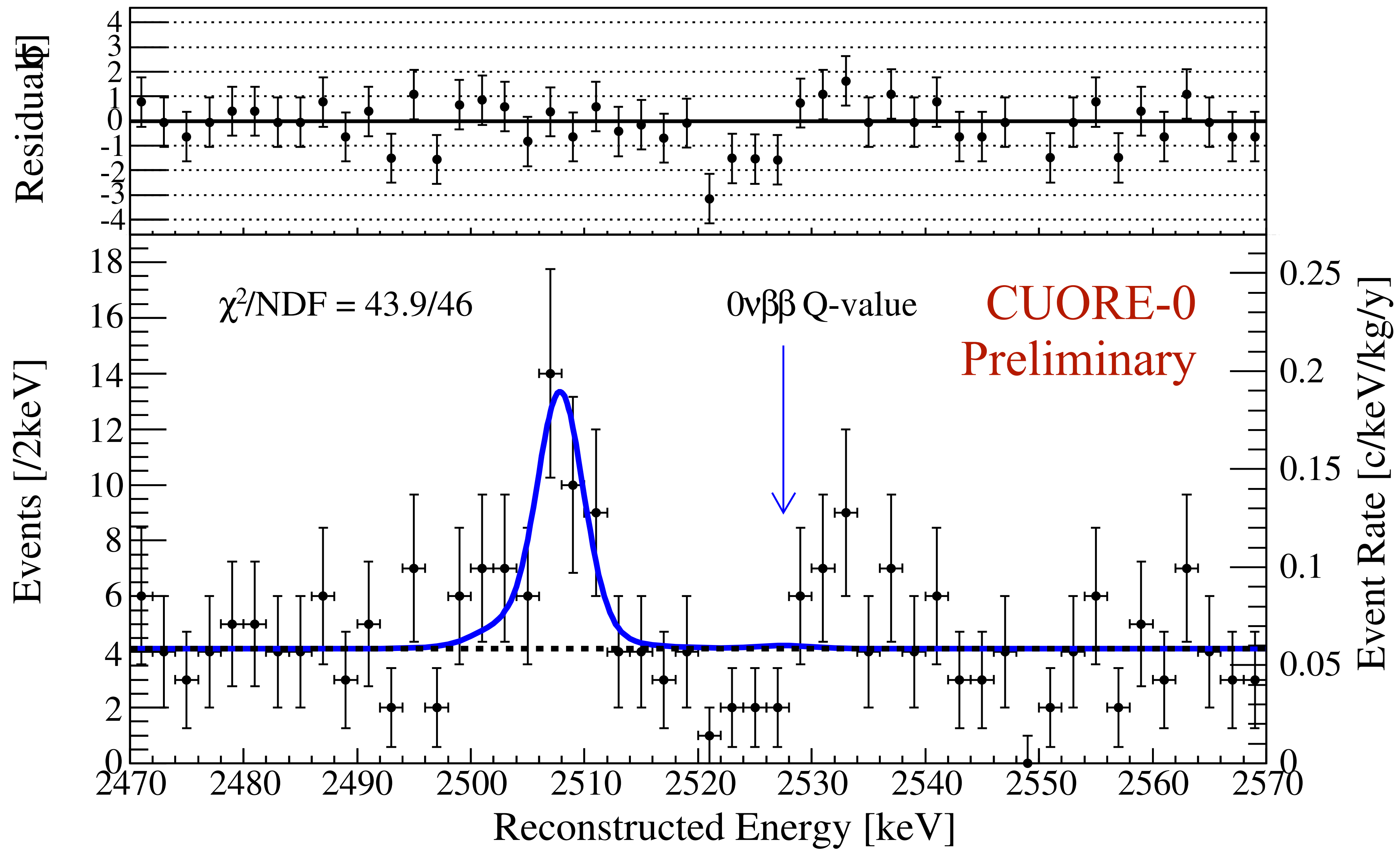


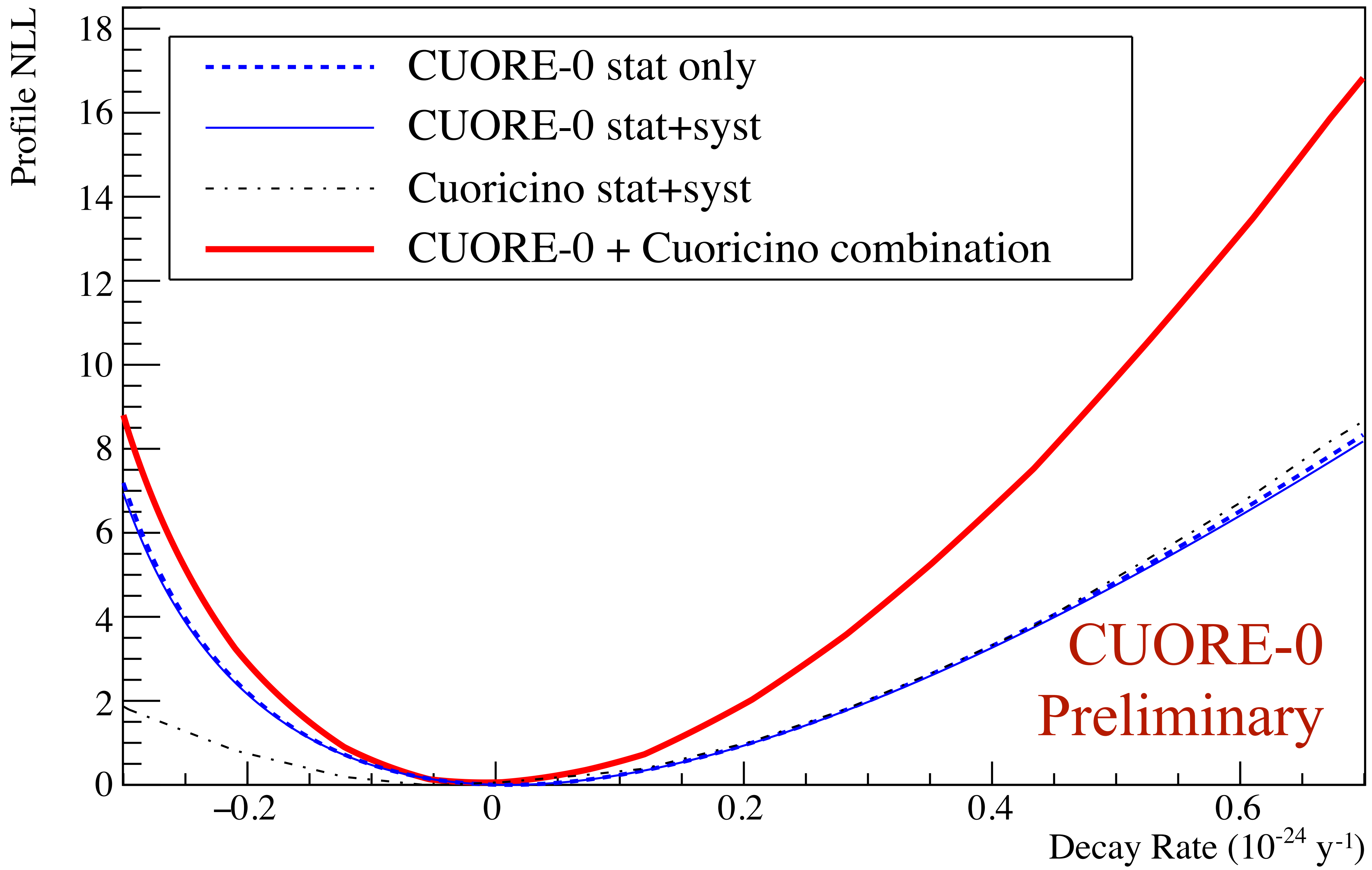
CUORE-0 Limit (90% C.L.)

$$\Gamma_{0\nu} < 0.25 \times 10^{-24} \ \mathrm{yr}^{-1}$$

$$T_{1/2}^{0\nu} > 2.7 \times 10^{24} \ \mathrm{yr}$$

Final ROI Fit





9.8 kg·yr ^{130}Te exposure from CUORE-0

+

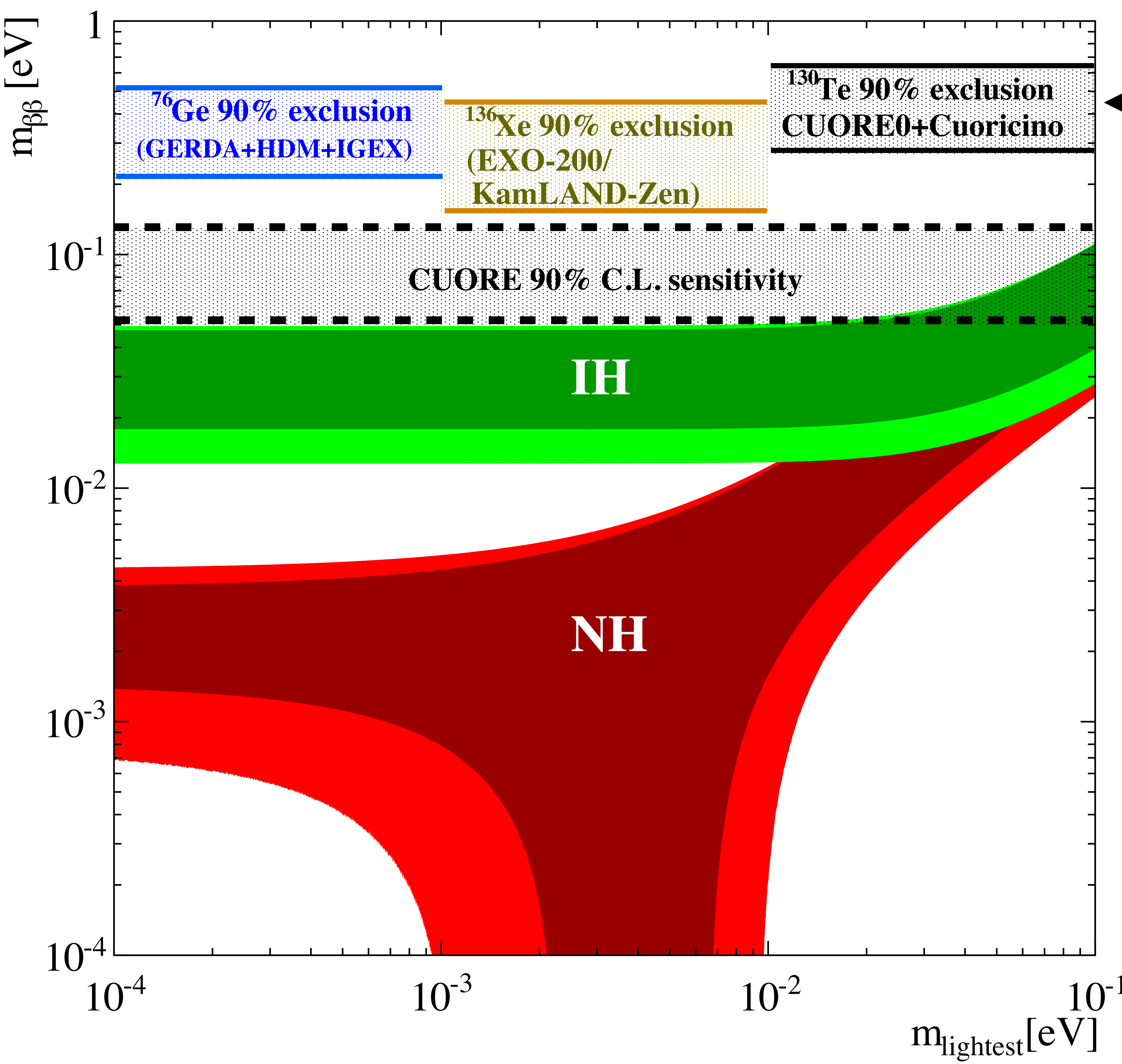
19.75 kg·yr ^{130}Te exposure from Cuoricino

New combined ^{130}Te Limit:

$$T_{1/2}^{0\nu} > 4.0 \times 10^{24} \text{ yr (90\% C.L.)}$$

ArXiv: 1504.02454. (Accepted to PRL.)

CUORE-0 Limit on $m_{\beta\beta}$



This Result

$$m_{\beta\beta} < 270 - 650 \text{ meV}$$

1) IBM-2 (PRC 91, 03404 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015))
4) ISM (NPA 818, 139 (2009))
5) EDF (PRL 105, 252503 (2010))

$$m_{\beta\beta} < 270 - 760 \text{ meV}$$

1) IBM-2 (PRC 91, 03404 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015))
4) Shell Model (PRC 91, 024309 (2015))
5) ISM (NPA 818, 139 (2009))
6) EDF (PRL 105, 252503 (2010))

Status of CUORE

feature

April 23, 2015

Extreme cold and shipwreck lead

Scientists have proven the concept of the CUORE experiment, which will study neutrinos with the world's coldest detector and ancient lead.

By Lauren Biron

Update on CUORE

1-9

10-16

17-19

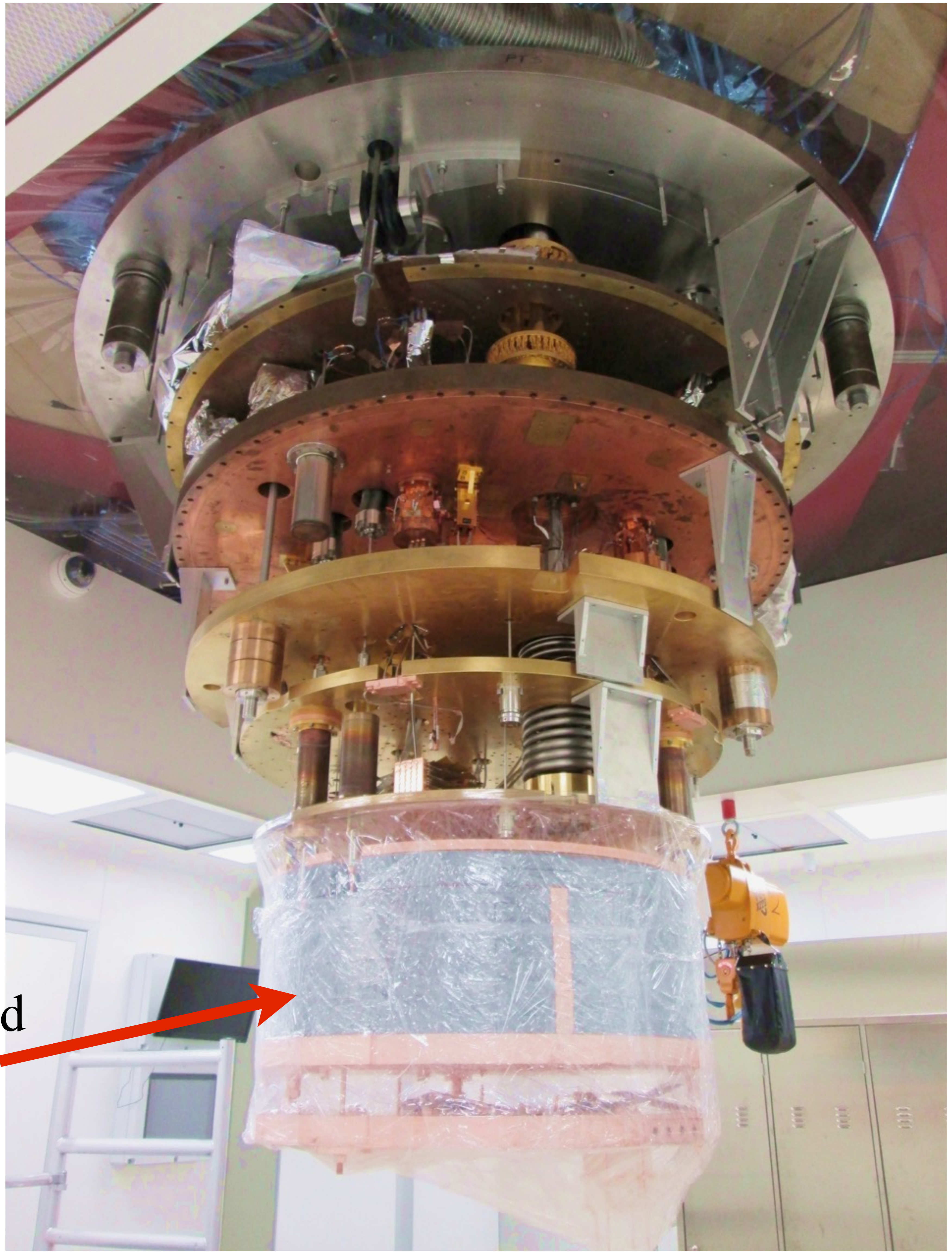
Detector Construction Completed June 2014

- Total detector assembly time: ~18 Months
- Detectors stored in clean room under constant N_2 flux
- Currently awaiting cryostat completion

Update on CUORE

Cryostat Construction

- In September 2014 achieved base temperature of 5.9 mK and became the coldest cubic meter in the known universe!
- Began installation of the lead shielding and full-scale test scheduled for late summer
- Expect to install detector in the fall and begin detector operation before the end of 2015!



Low-activity lead shielding

In Summary...

CUORE-0

- ✓ Collected 9.8 kg·yr of ^{130}Te exposure from March 2013 - March 2015
- ✓ Achieved the CUORE energy resolution goal of 5 keV FWHM at 2615 keV
- ✓ Demonstrated a factor of 7 reduction in the α-background
- ✓ Validated the background reduction protocols for CUORE
- ✓ Surpassed the Cuoricino sensitivity in less than half the run time
- ✓ Set a new combined limit of the $0\nu\beta\beta$ half-life of $T^{0\nu}_{1/2} > 4.0 \times 10^{24}$ yr

CUORE

- ✓ CUORE-0 gives confidence that our background goal is within reach
- ✓ 19 towers built and stored under N_2 flux
- ✓ Cryostat achieved 5.9 mK in first commissioning run
- ➡ Auxiliary cryostat systems currently being installed and tested
- ➡ Aiming for detector turn-on by the end of 2015

Stay tuned!

Università degli Studi di Milano Bicocca

Università degli Studi di Cassino e del Lazio Meridionale — Sol per noctem — 1979

SINAP

אור ותמים — Lux et Veritas

INFN Istituto Nazionale di Fisica Nucleare

Cal Poly San Luis Obispo

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Massachusetts Institute of Technology

UCLA

Studium Urbis

Sapienza Università di Roma

CSNSM

CUORE

Berkeley Lab

University of South Carolina 1801

The University of California 1868 — Let there be light

Universitas Studii Paduani MCCXXII

BACK UP SLIDES

Sensitivity by the Numbers

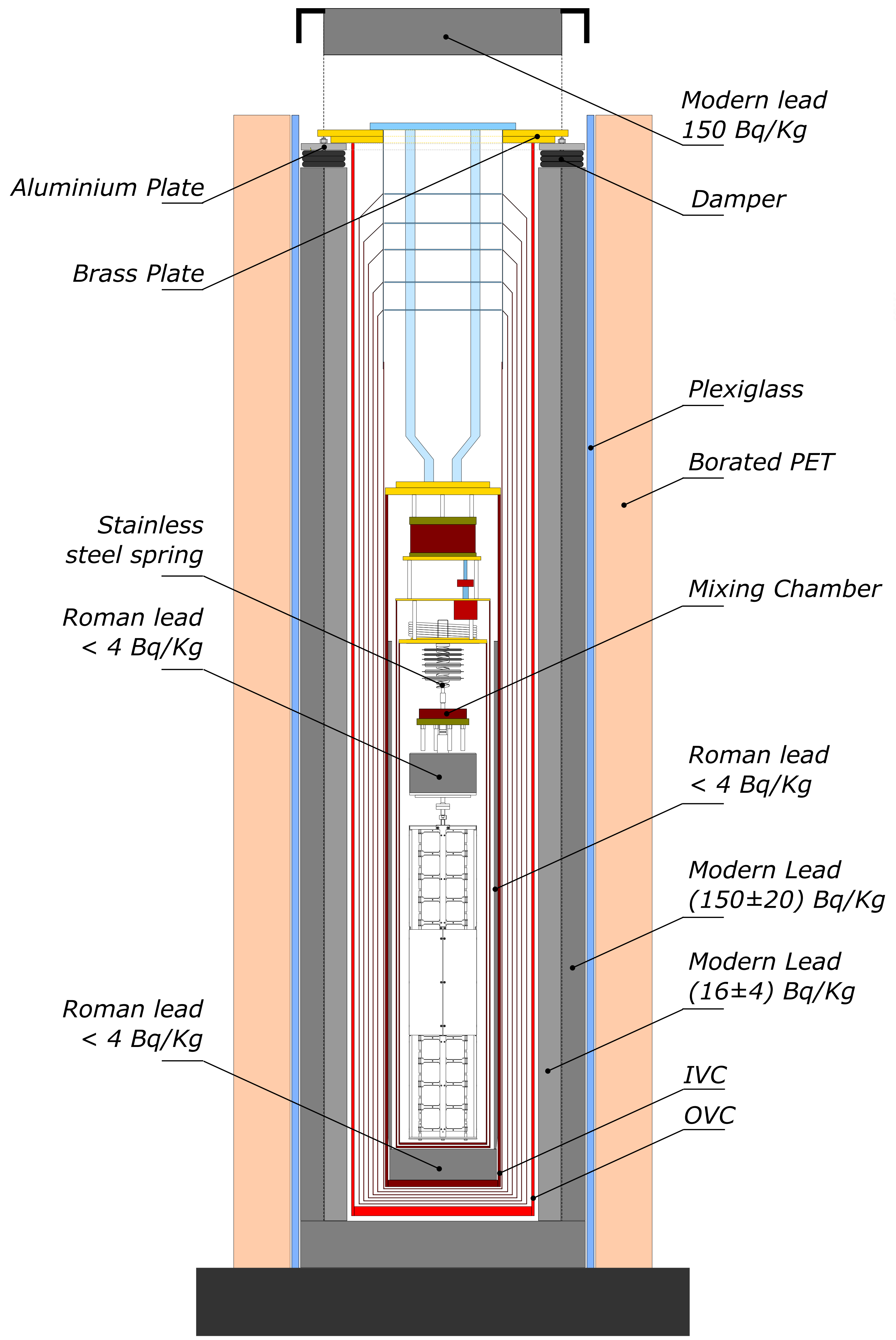
Half-life Sensitivity:

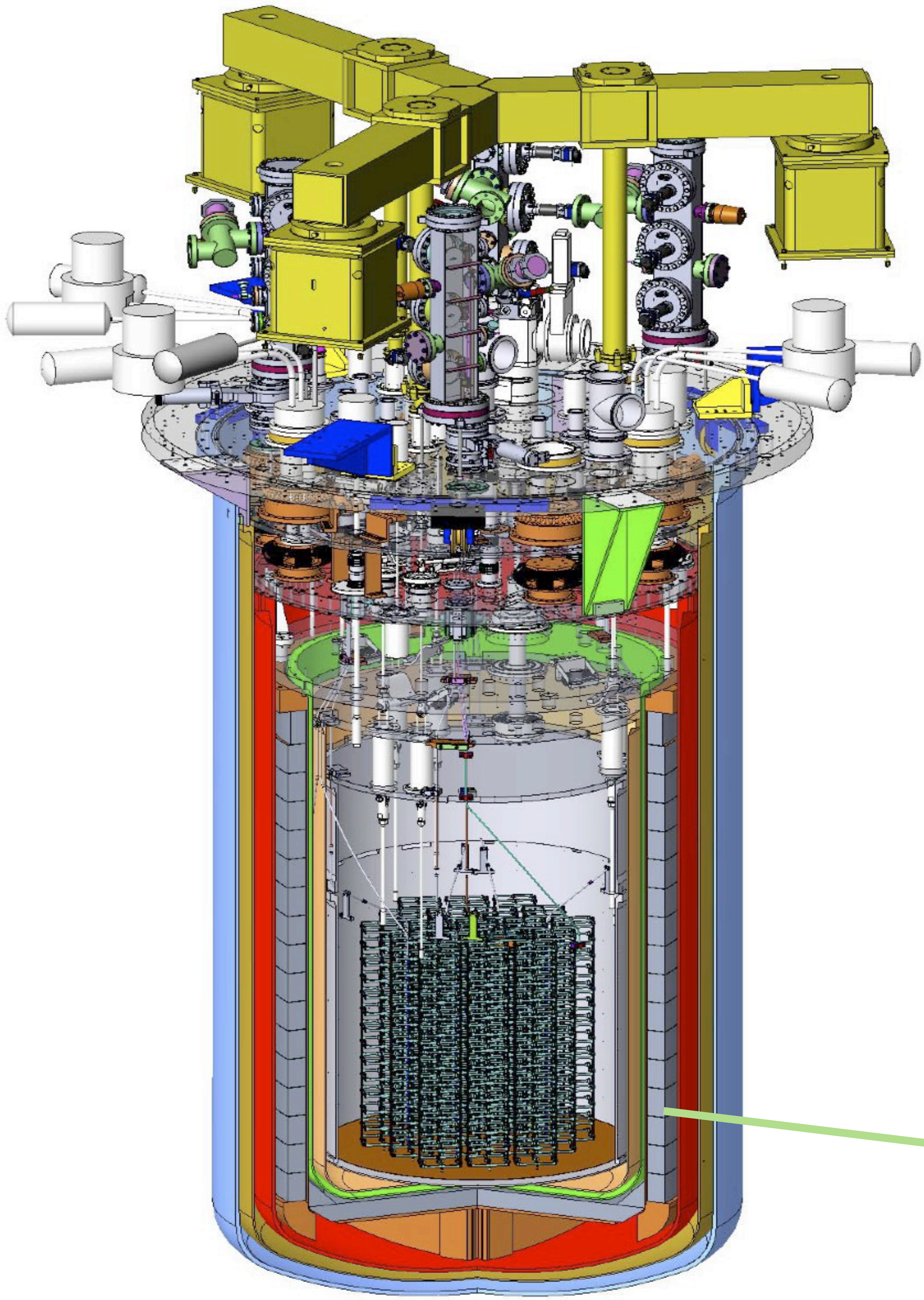
$$T_{1/2}^{0\nu} \sim \varepsilon \frac{a_I \eta}{W} \sqrt{\frac{Mt}{b \Delta E}}$$

M	:	Total detector mass
t	:	Livetime
b	:	Background rate, per keV, per unit detector mass
ΔE	:	Energy resolution
a_I	:	Isotopic abundance
ε	:	Signal efficiency

	Cuoricino	CUORE-0	CUORE (Goal)
Background Rate (cnts/keV/kg/yr)	0.169	0.058	0.01
Energy Resolution (keV)	5.8	4.9	5.0

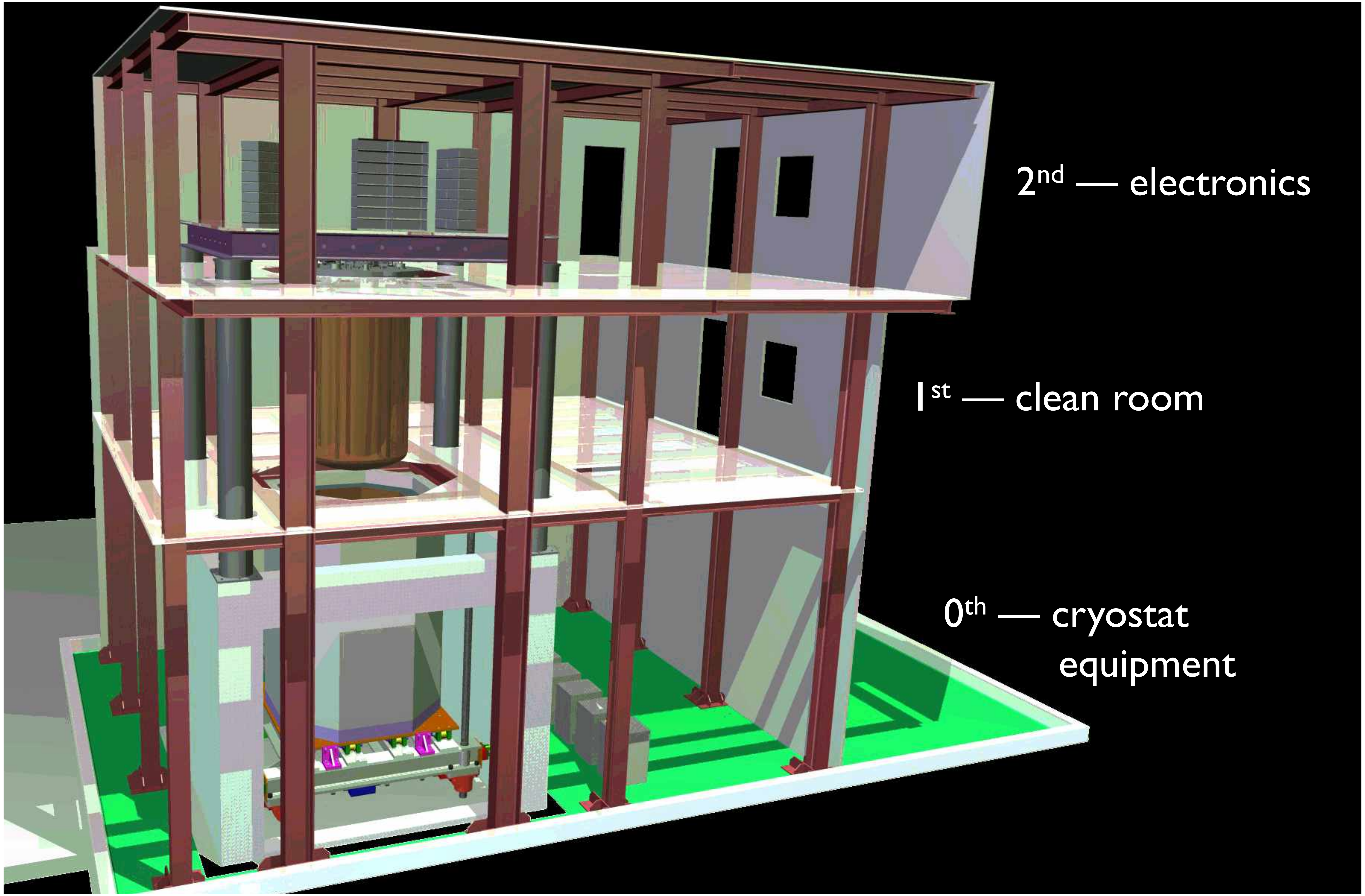
Cryostats





- Pulse-tube cooled "dry" dilution refrigerator
- Base temperature of ~10 mK
- Must cool ~1 t of material to base
- An additional ~10 t of shielding to <4 K
- Must have cooldown time ~two weeks
- >30 cm of shielding in every direction
  - Made from clean copper and Roman lead (<4 Bq/kg)

CUORE Hut

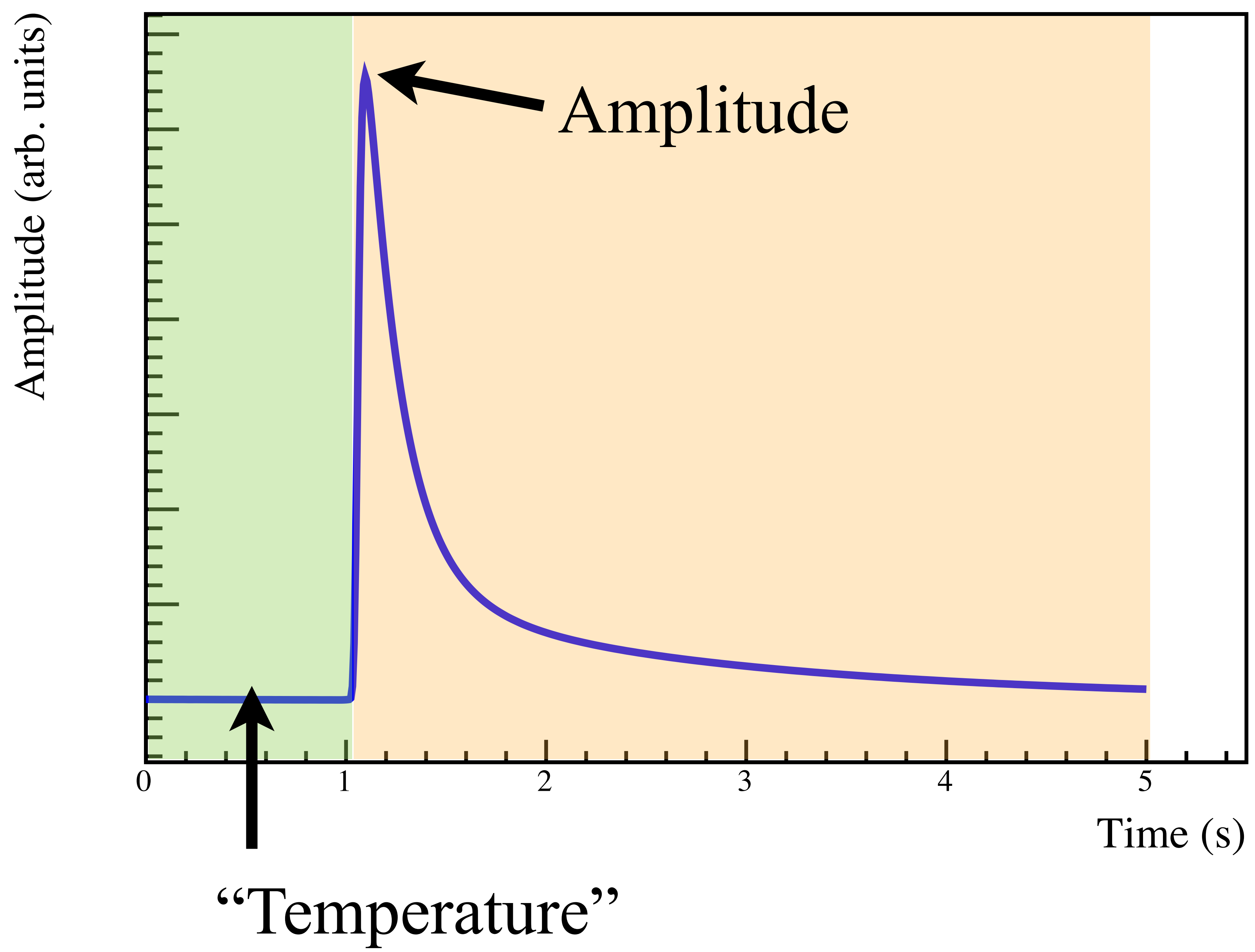


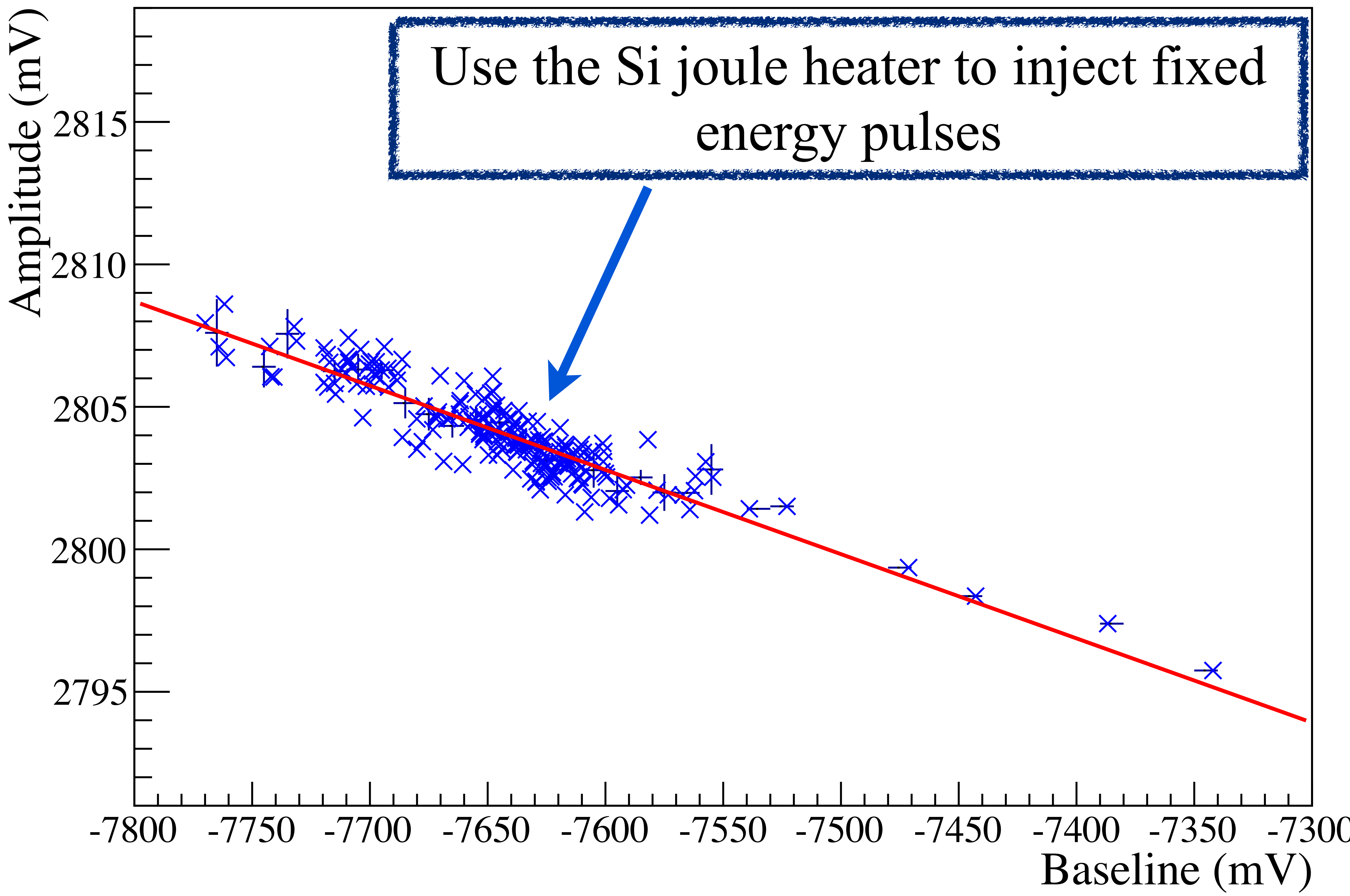
2nd — electronics

1st — clean room

0th — cryostat equipment

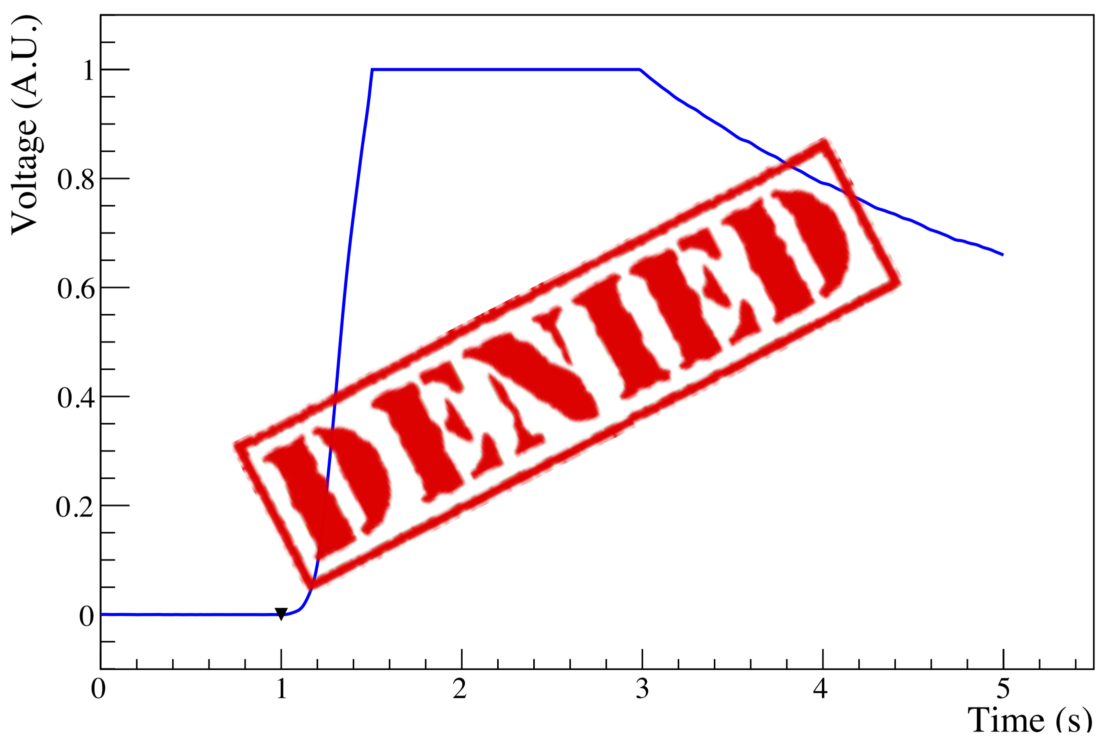
Heater-Based Thermal Gain Stabilization

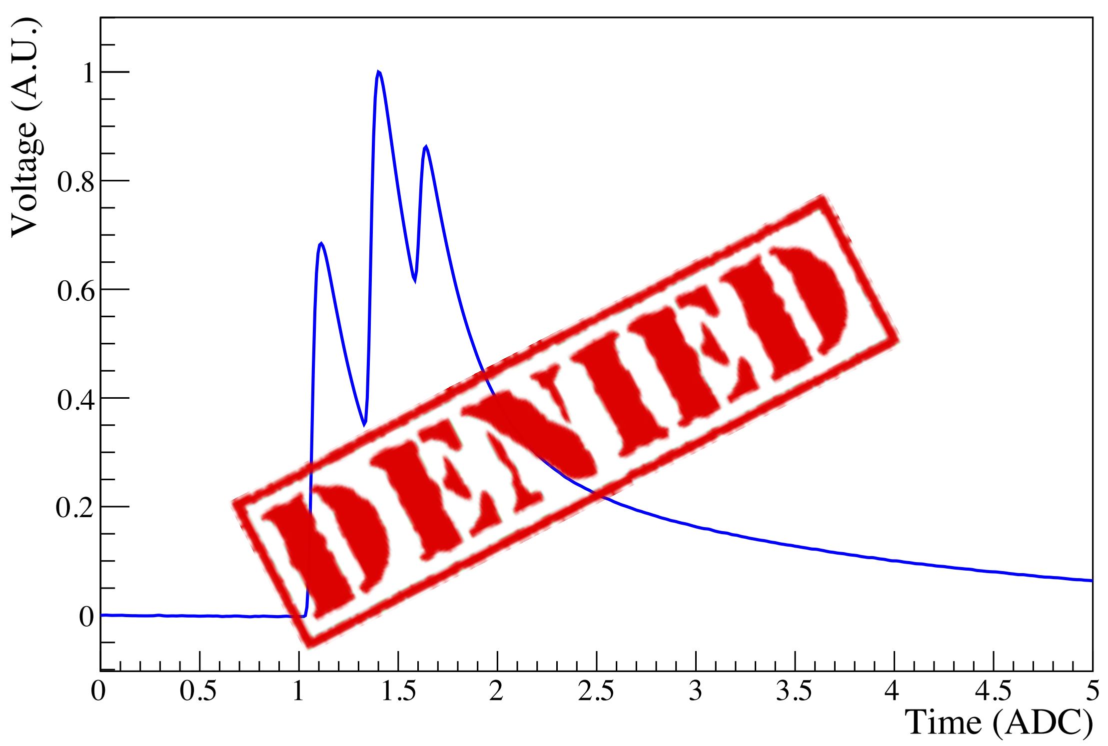


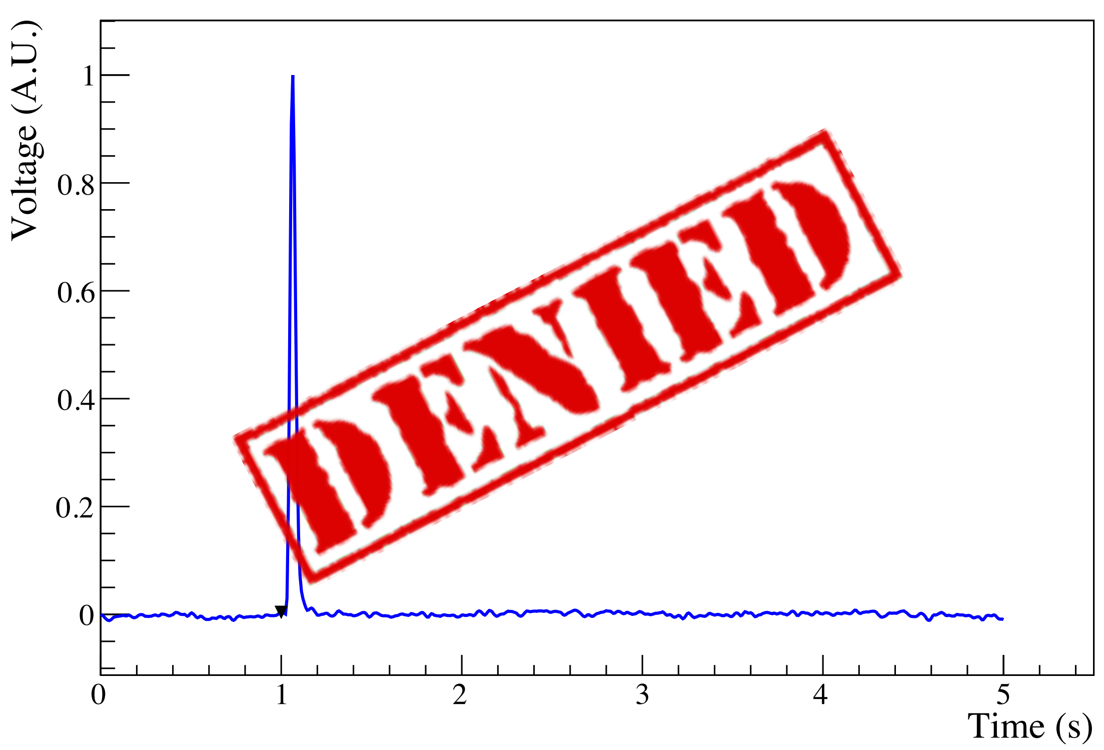


By measuring the amplitude of fixed energy heater pulses vs "temperature" we can map the gain dependence on temperature and correct the particle pulses for this variation.

Event Cuts





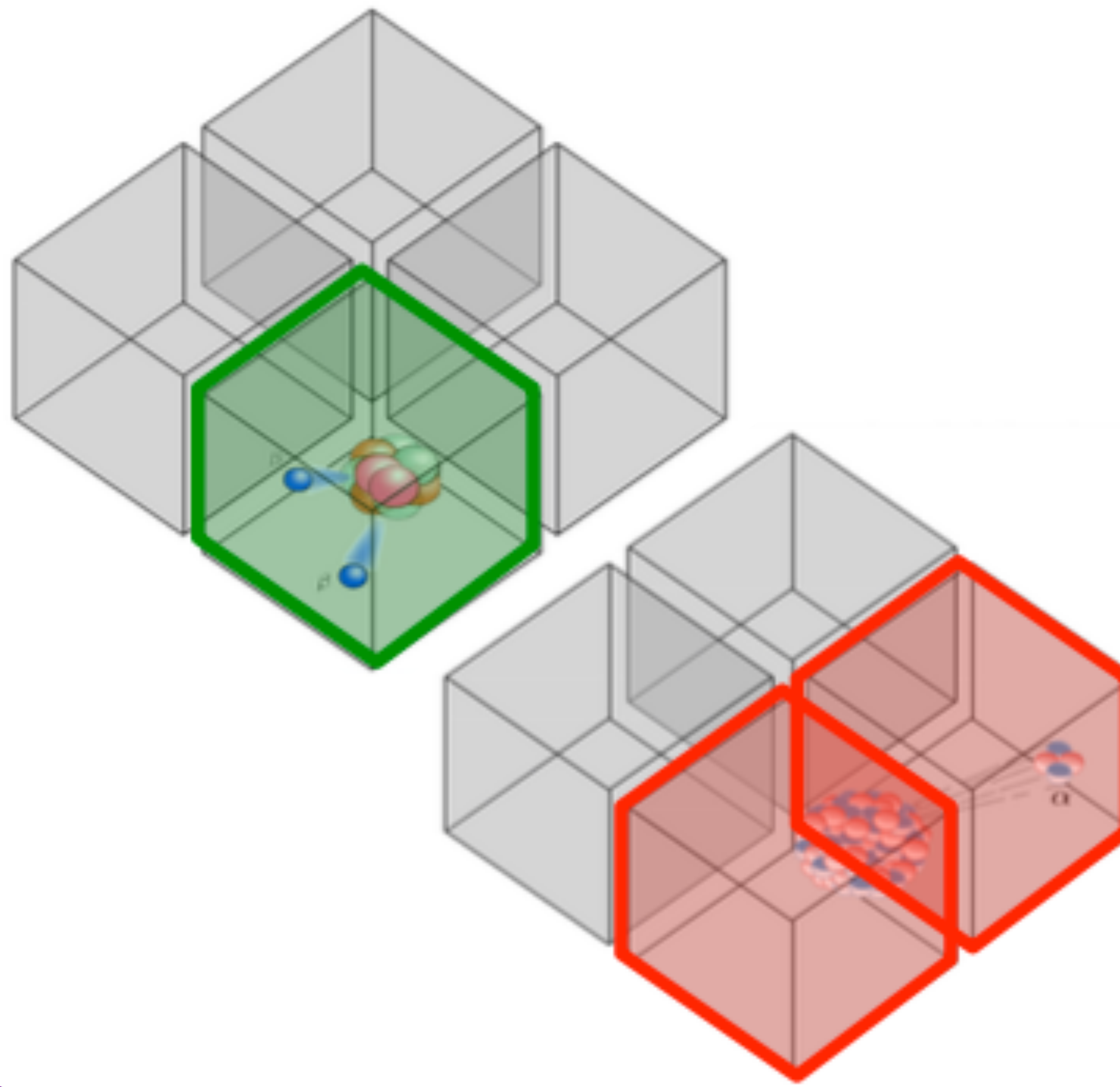


- Basic Quality Cuts
  - Saturated pulses
  - Multiple triggers or pulses in a single window

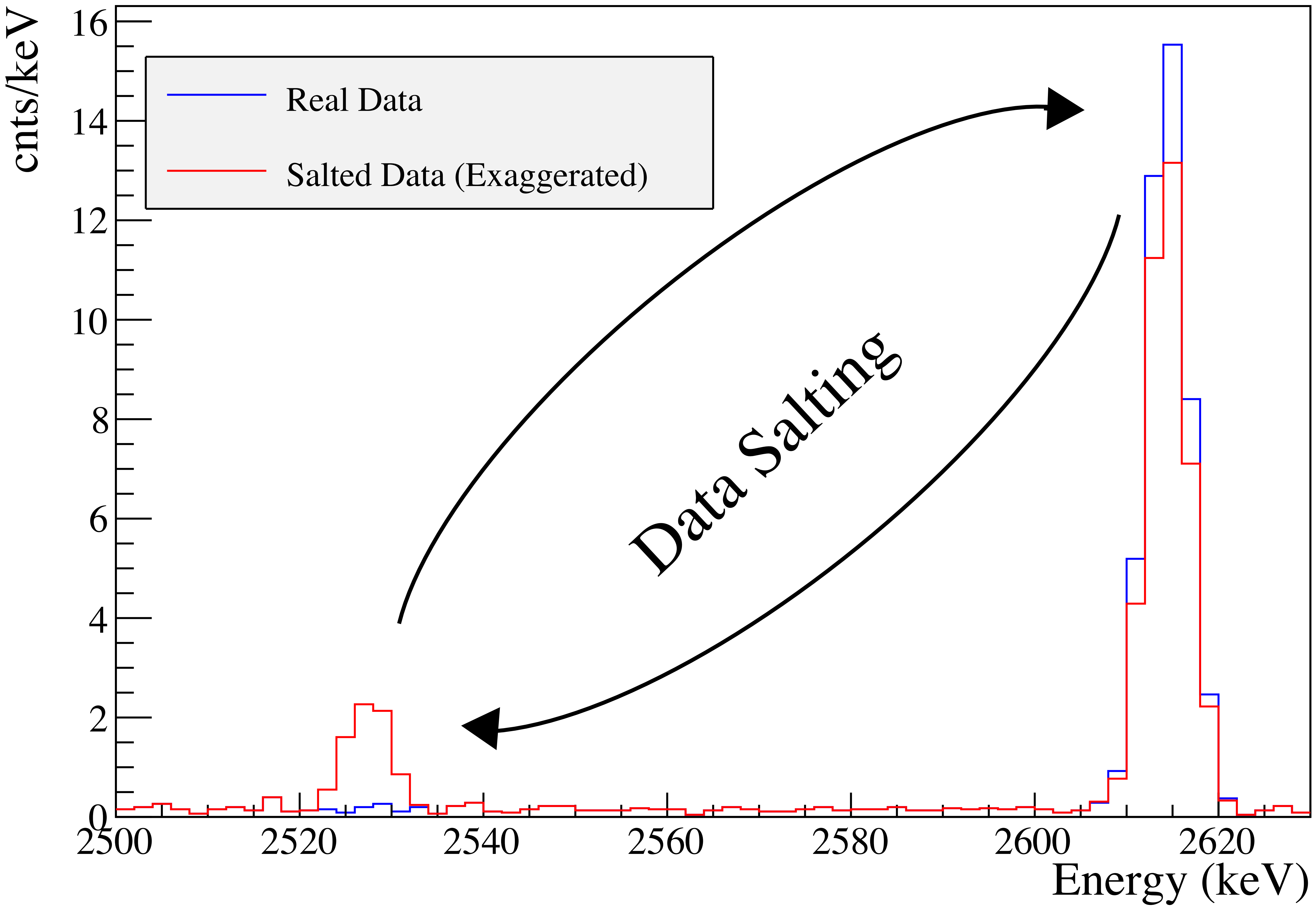
- Pile-up Cuts
  - 7.1 second dead window around each pulse

- Pulse Shape Cuts
  - Remove "spike" events
  - Remove electronic noise

- Anti-coincidence Cuts
  - 5 ms anti-coincidence window

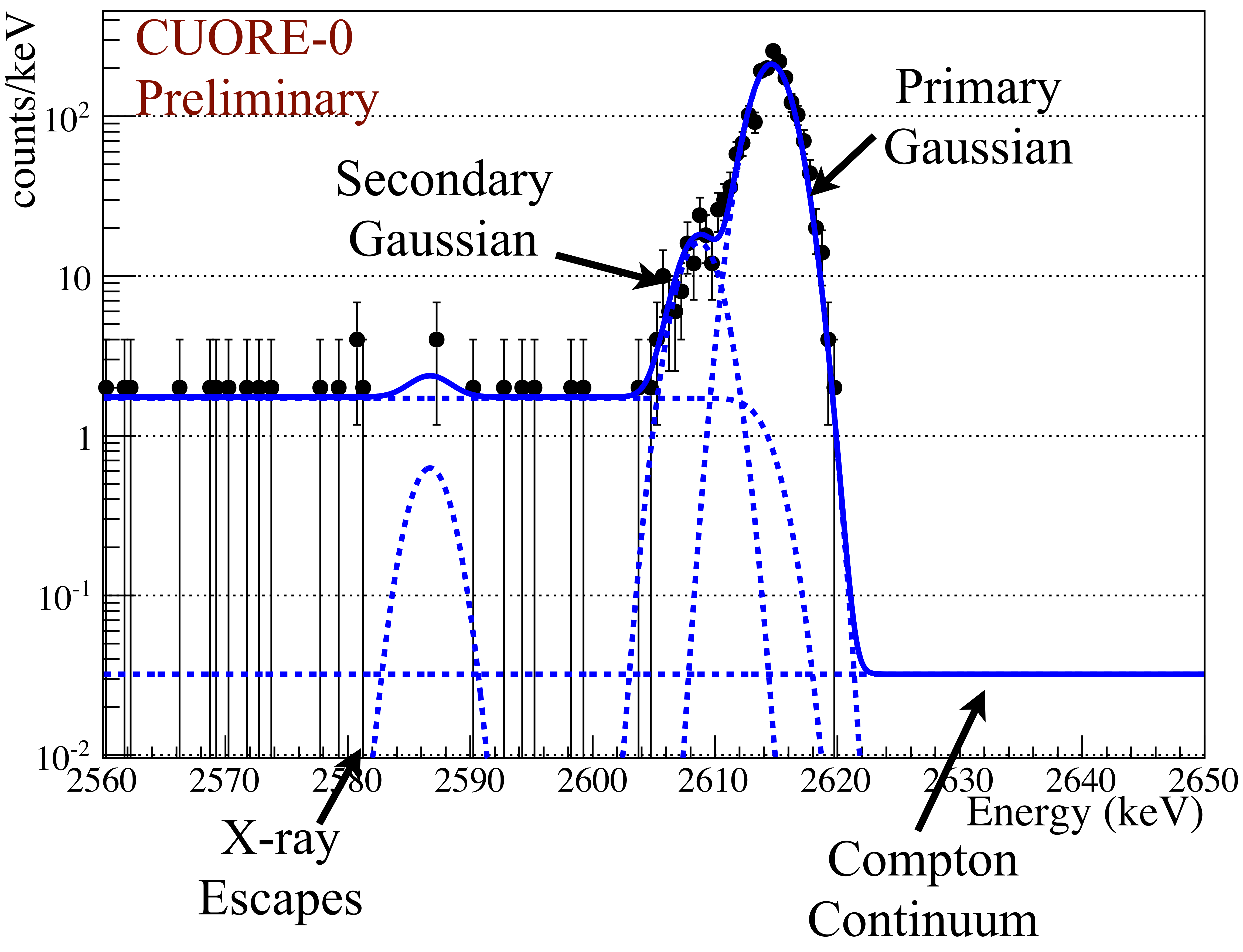


CUORE-0 Blinding Procedure



- Randomly move a fraction of events from the 2615 keV line to the ROI and vice versa
- Fraction of events is random
- Creates an unrealistically large peak at the $0\nu\beta\beta$ value

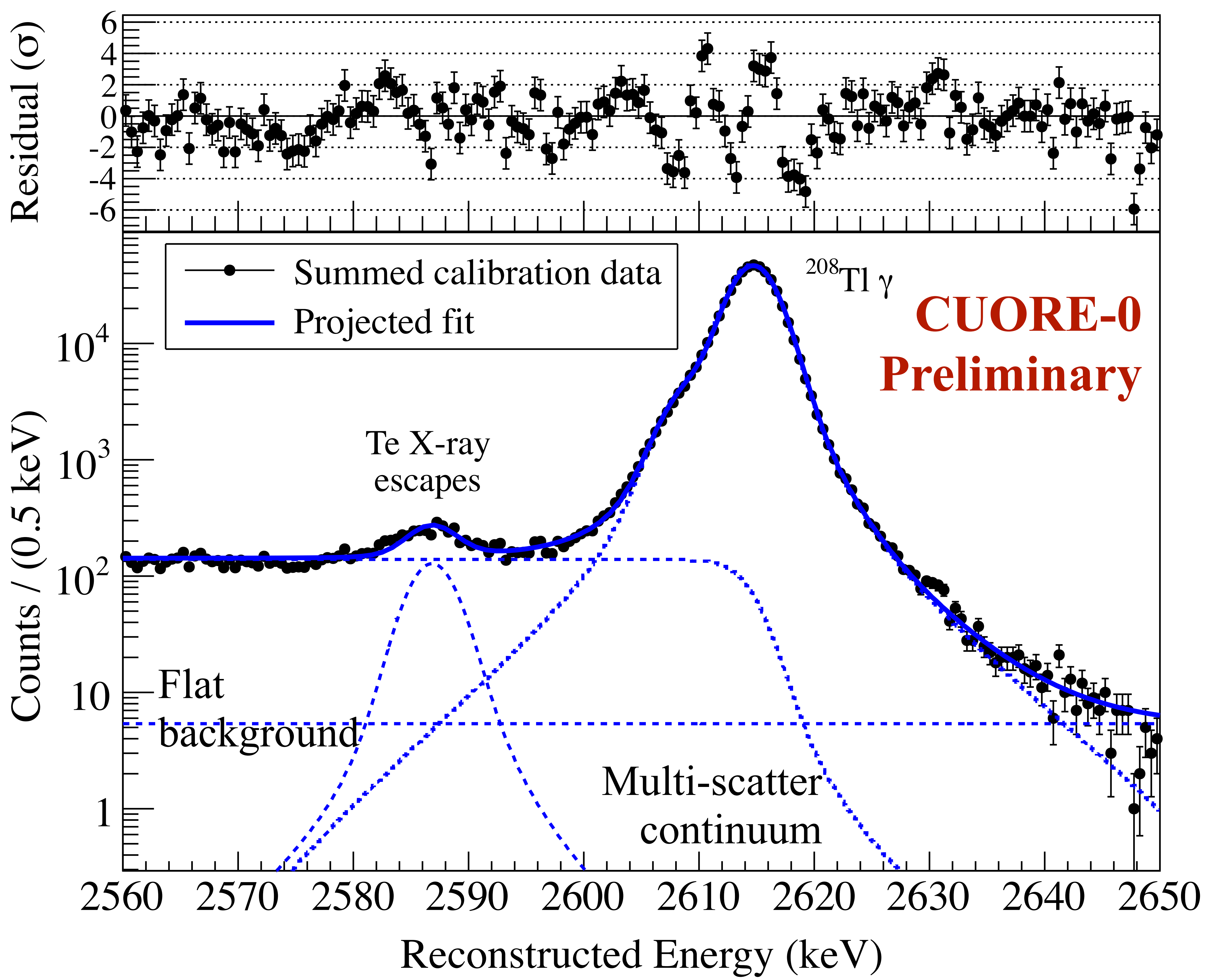
Building the Detector Response

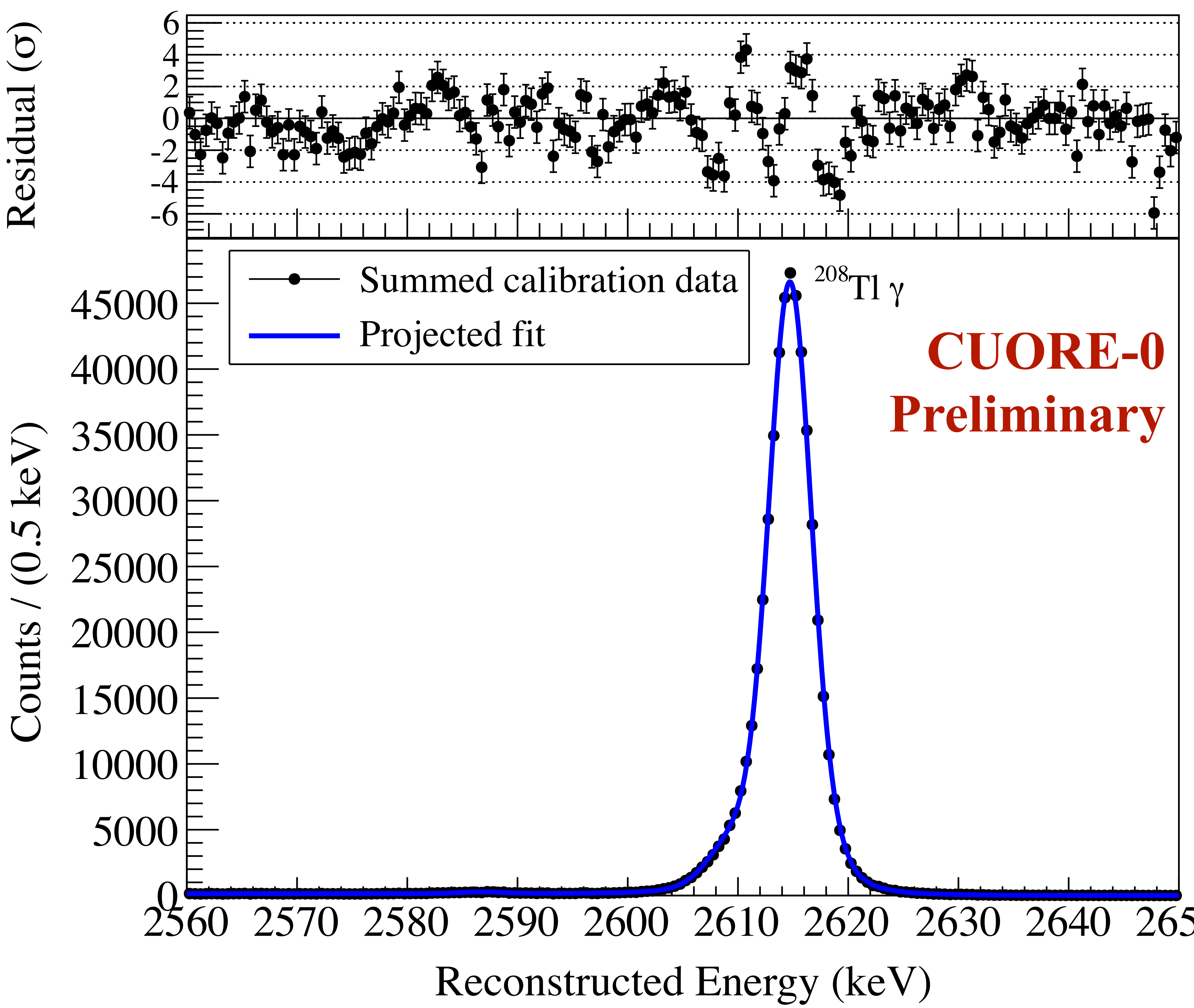


$$f^C_{\mathrm{Det}}(\mu,\sigma;E) = (1-\eta(C))\mathrm{Gauss}(E;\mu,\sigma) + \eta(C)\mathrm{Gauss}(E;\delta(C)\mu,\sigma)$$

- We model the detector response as sum of two gaussian shapes:
  - A peak which accounts for ~95% of events
  - A subpeak about 0.3% lower (6 keV at 2615) which accounts for ~5% of events
- Each bolometer-dataset pair has the same shape but its own set of position and resolution parameters
- Shape parameters vary by channel only
- Compton continuum, background, and X-ray escapes common to all bolometer-datasets
- Perform a simultaneous unbinned maximum likelihood fit to all bolometer-dataset pairs

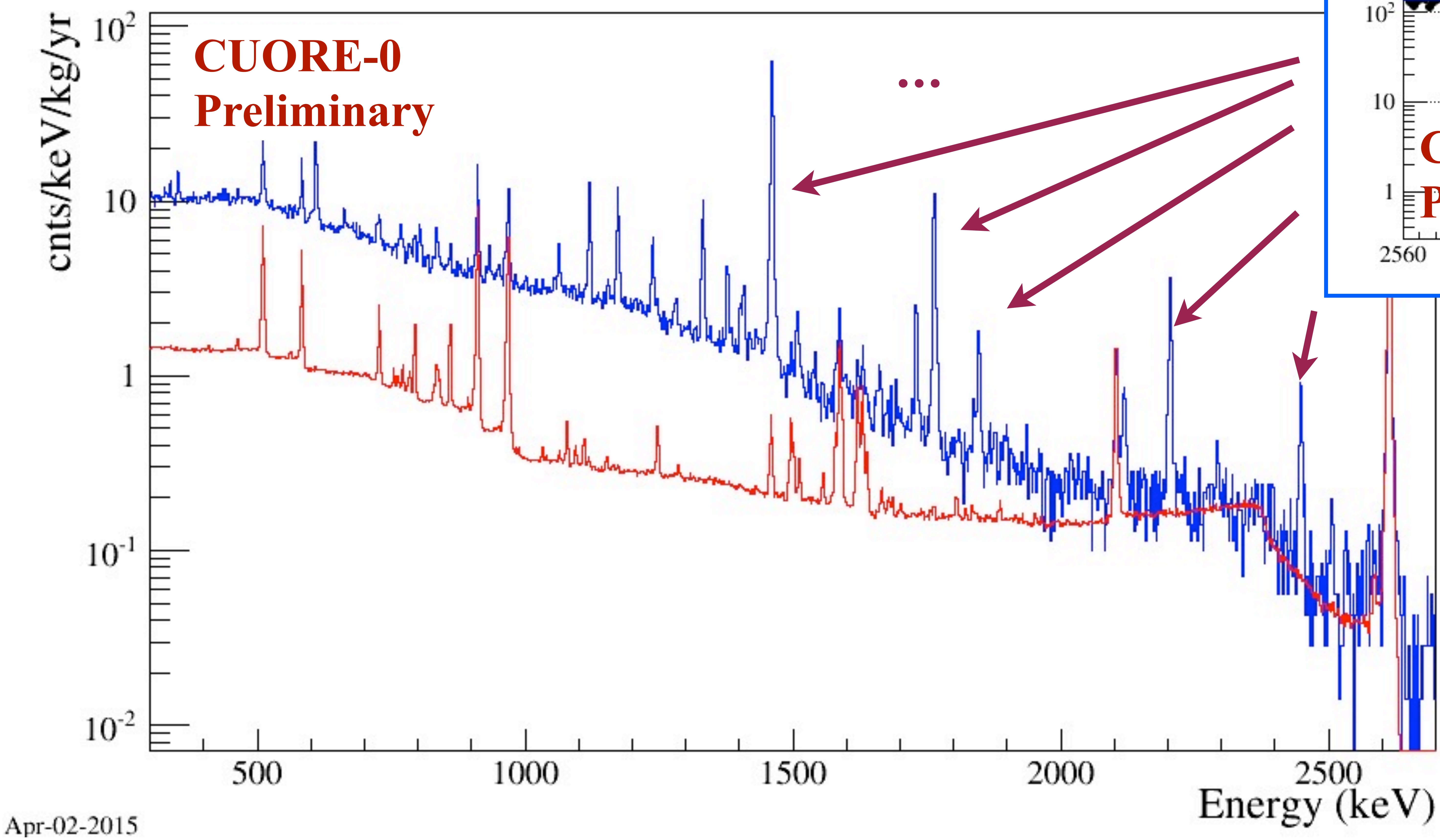
Fitting the Calibration ^{208}Tl Line

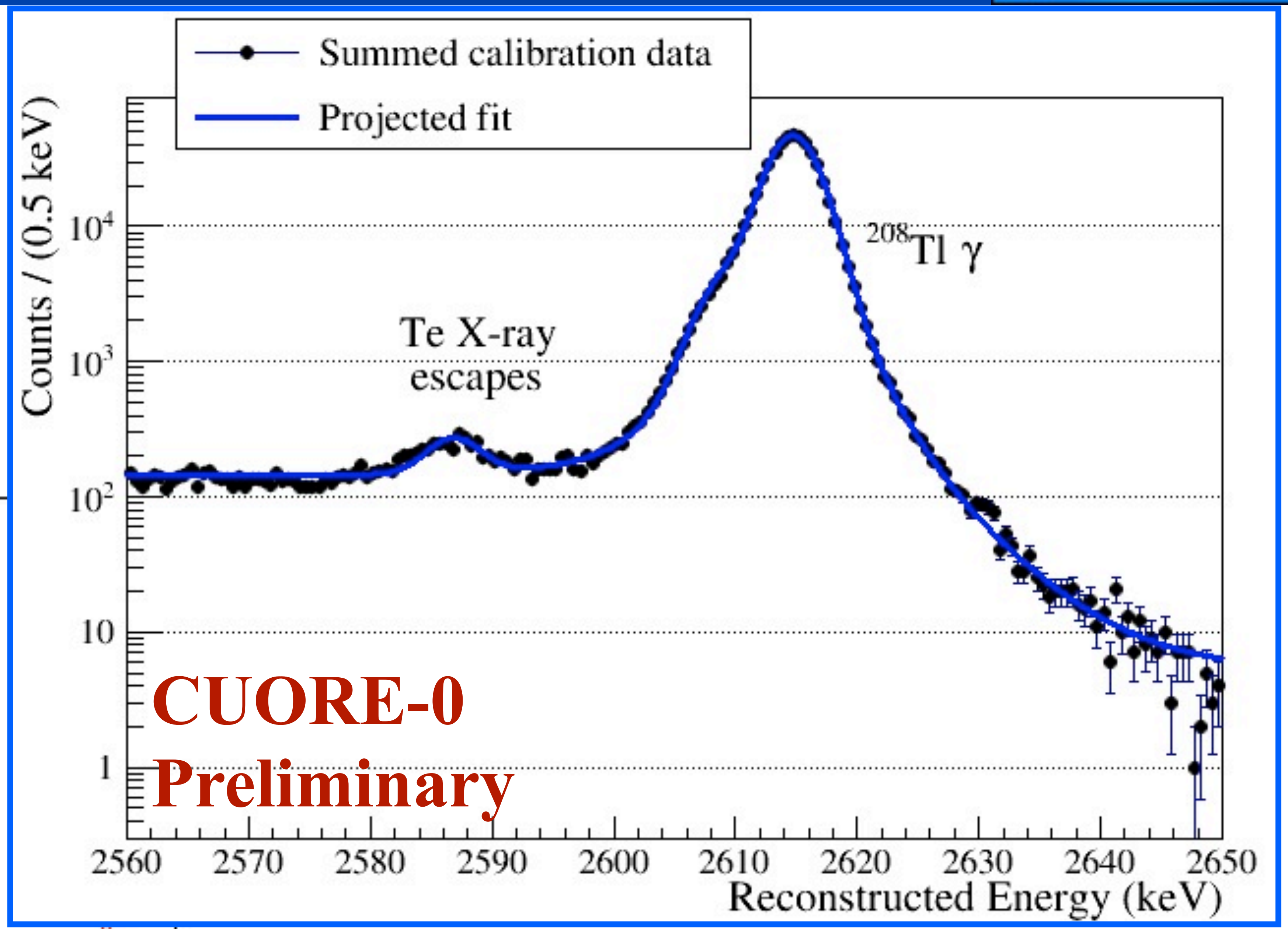




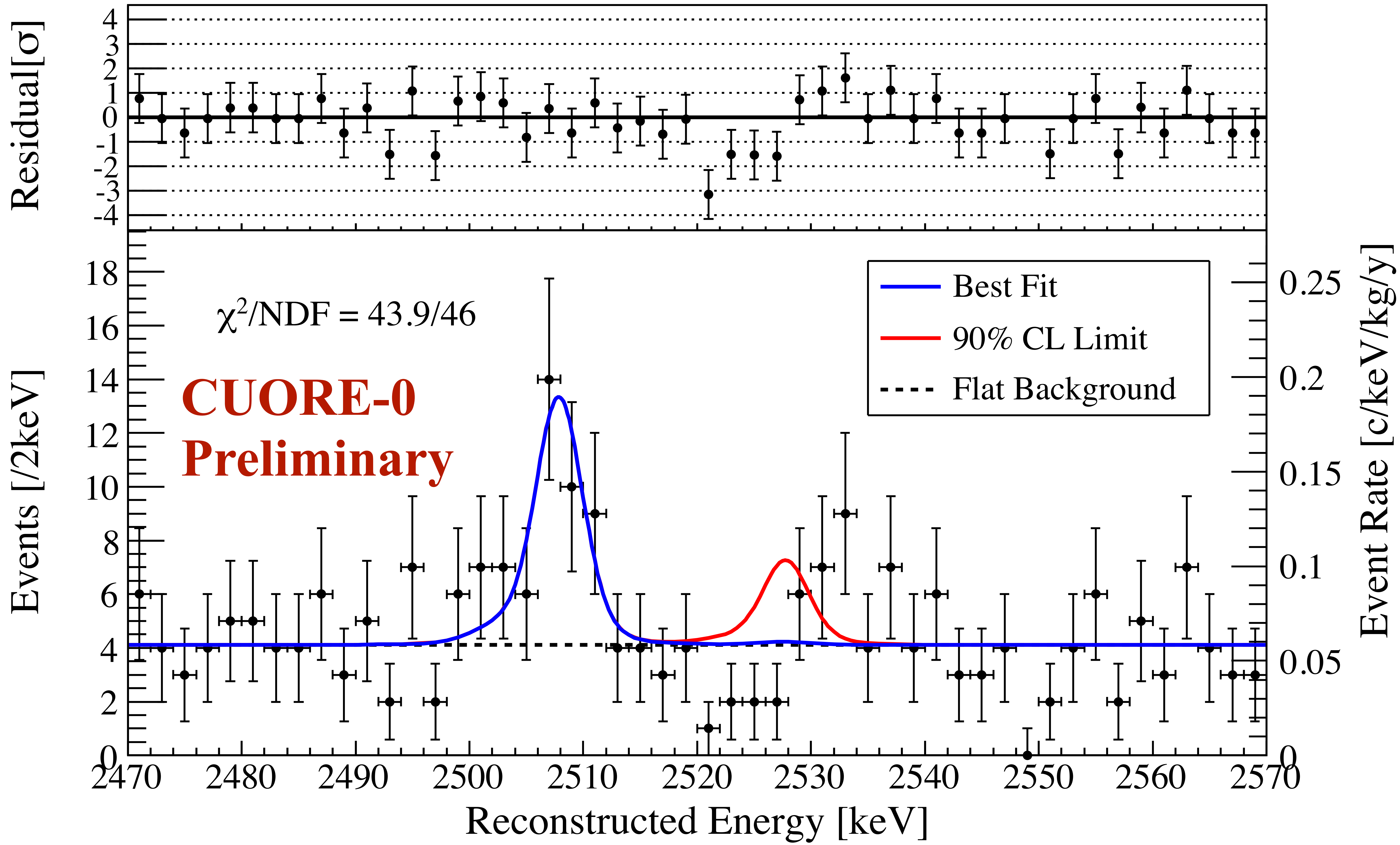
Characterizing the Detector Response

- Project the ^{208}Tl lineshape onto other lines in the physics and calibration spectra
- Bolometer-dataset dependent projection

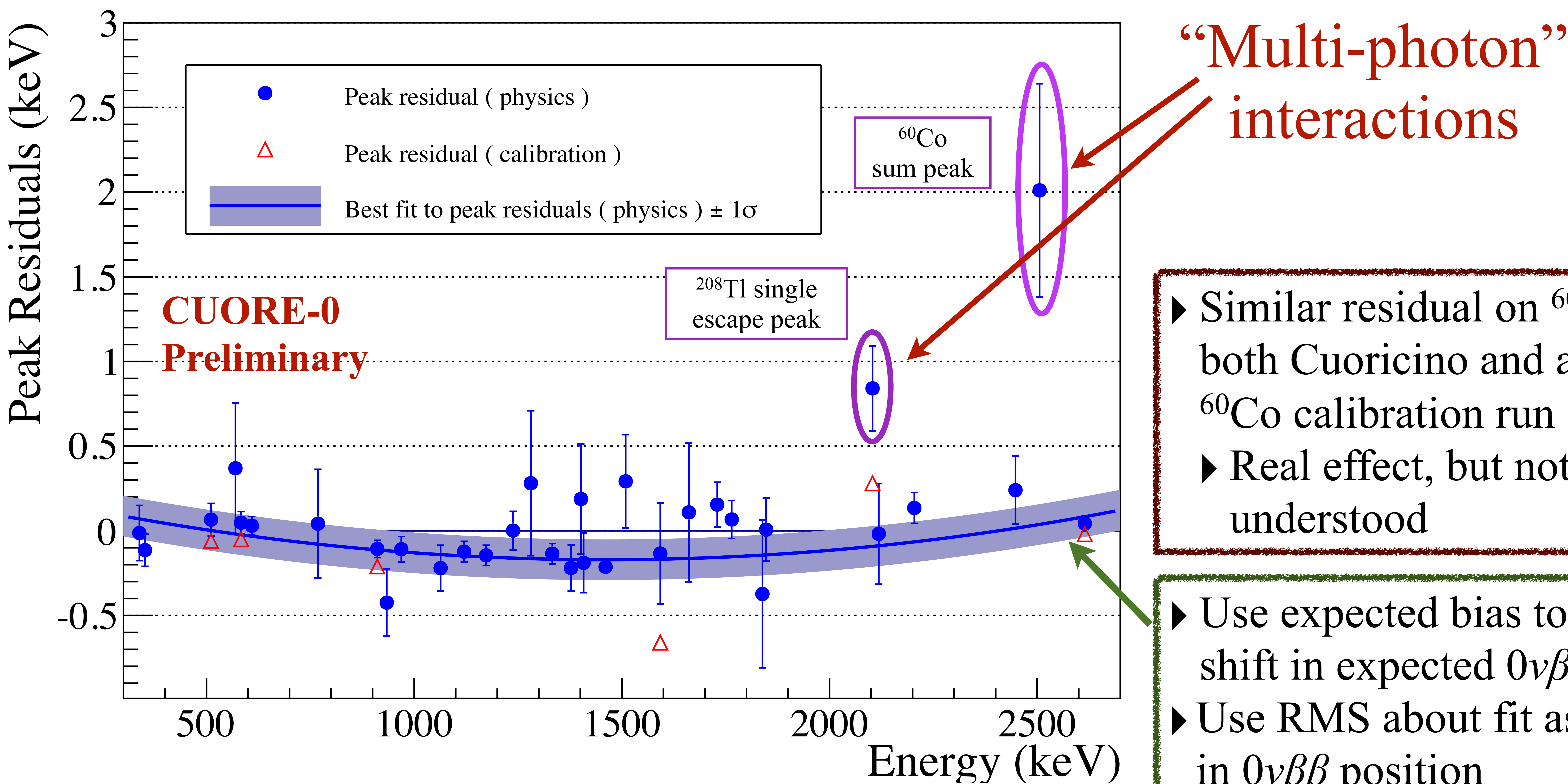




ROI With 90% Limit



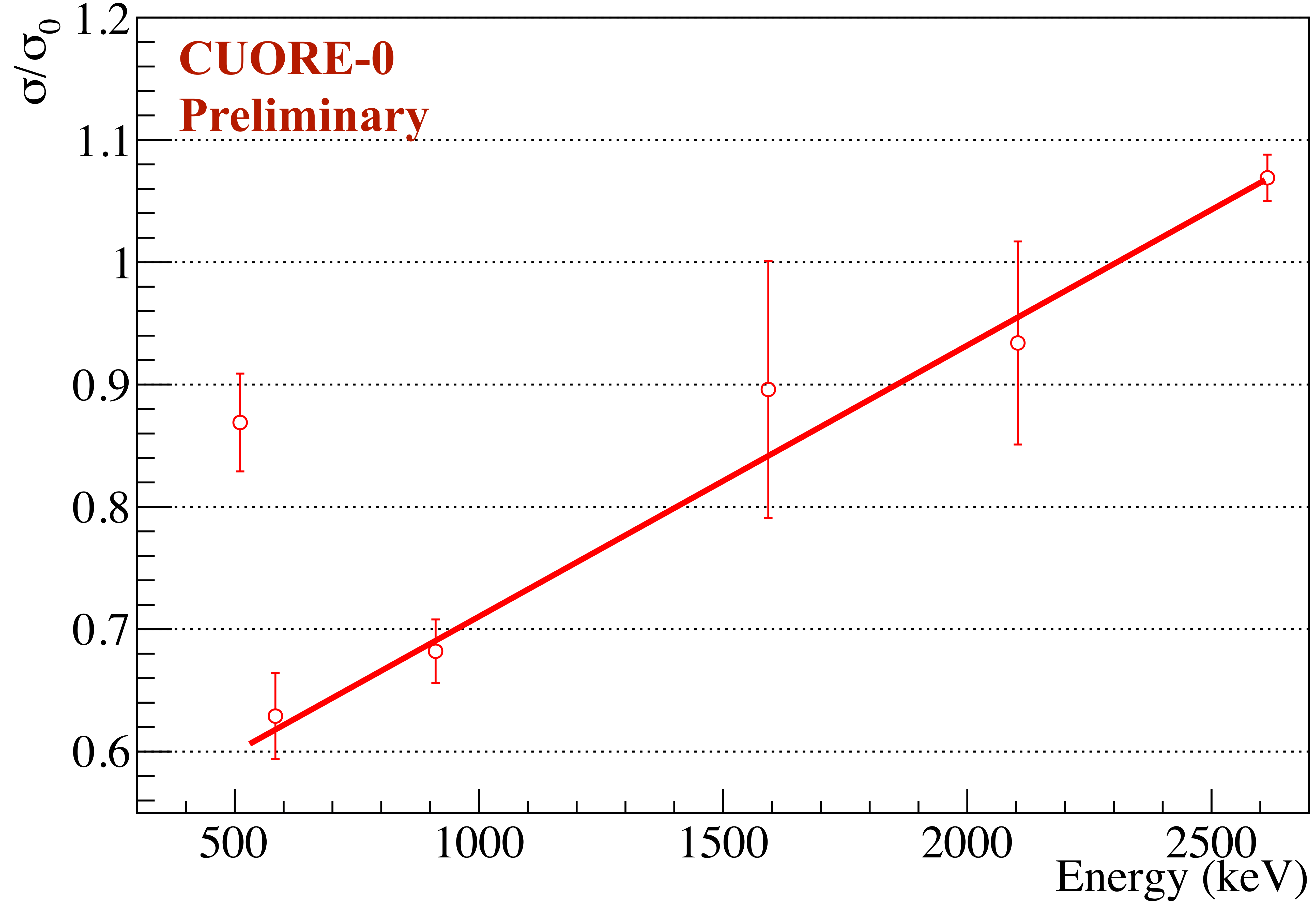
Projecting the Detector Response



- Similar residual on ^{60}Co seen in both Cuoricino and a dedicated ^{60}Co calibration run
  - Real effect, but not presently understood

- Use expected bias to understand shift in expected $0\nu\beta\beta$ position
- Use RMS about fit as uncertainty in $0\nu\beta\beta$ position
- Bias at $0\nu\beta\beta$: 0.05±0.05±0.09 keV

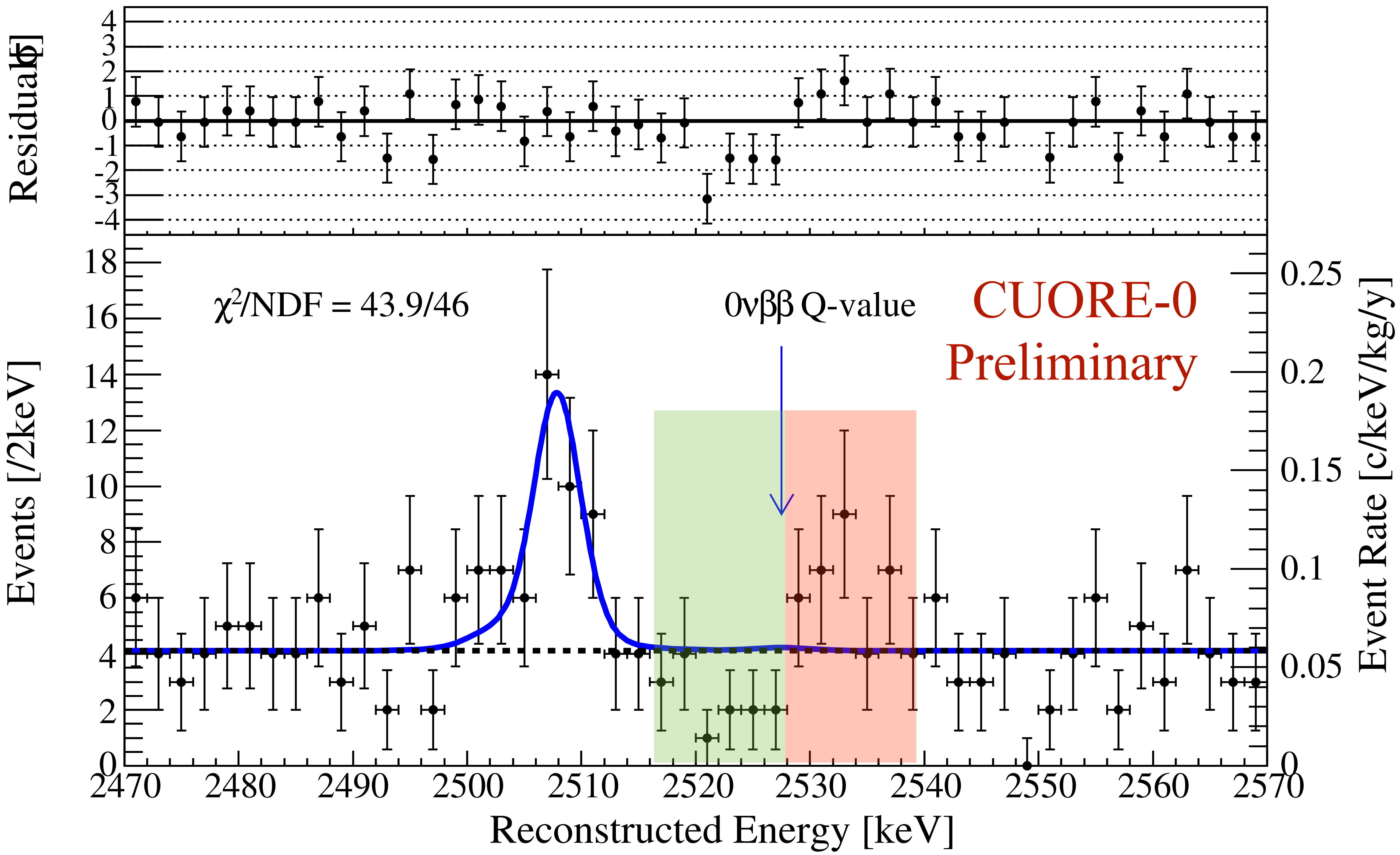
Scaling the Energy Resolution

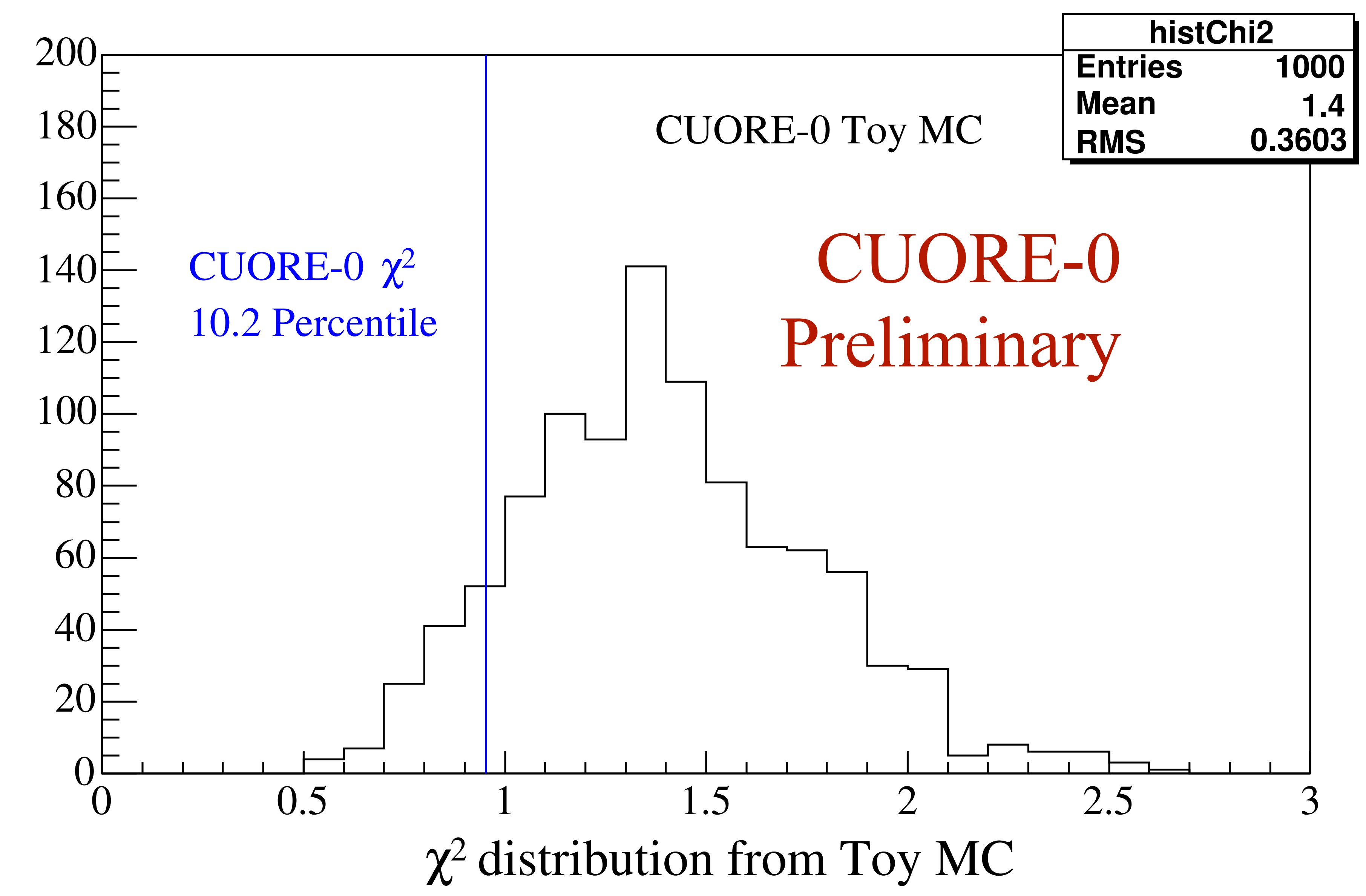


- Energy resolution scaling includes ratio of energy resolutions at Q to 2615 and difference between calibration and physics run performance

$$\alpha_\sigma(Q_{\beta\beta})=1.05\pm0.05$$

Fluctuations near the ROI





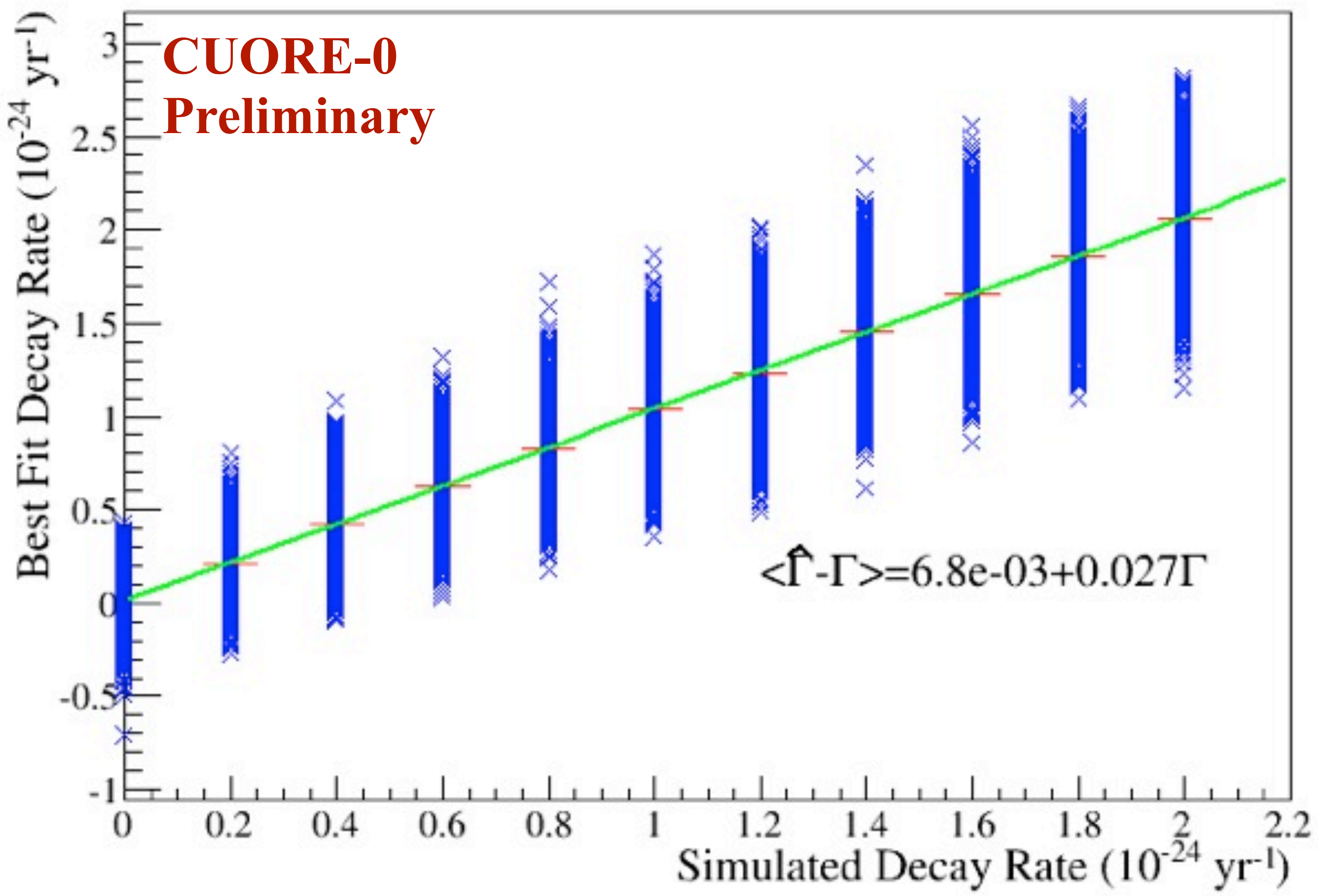
- Probability of this fluctuation p~0.5%. But including the “look elsewhere” effect is p~12%
- χ^2 statistic is in the 10th percentile
- Kolmogorov-Smirnov tests show no statistical significance

Systematic Uncertainties

Approach:

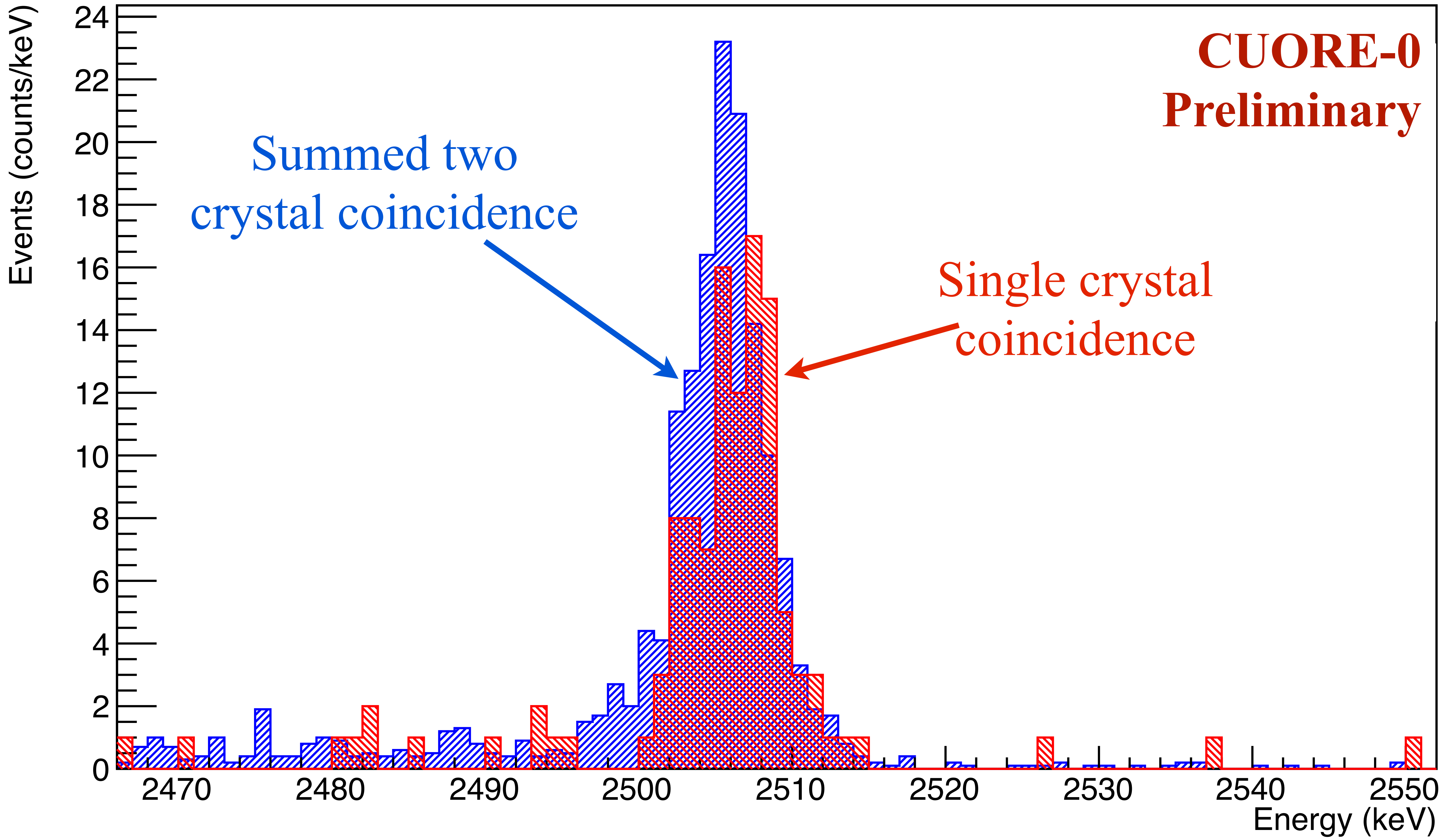
- Simulate many toy MC experiments with "true" rate in the range $[0,2]\times10^{-24}$ yr^{-1}, modifying one nuisance parameter at a time
- Fit each with our "standard" ROI model.
- Fit $(\Gamma_{Fit}-\Gamma_{True})$ vs Γ_{True} to determine an additive and relative bias.
- Modify the profile likelihood curve and re-evaluate our limit.
- Combine systematics:

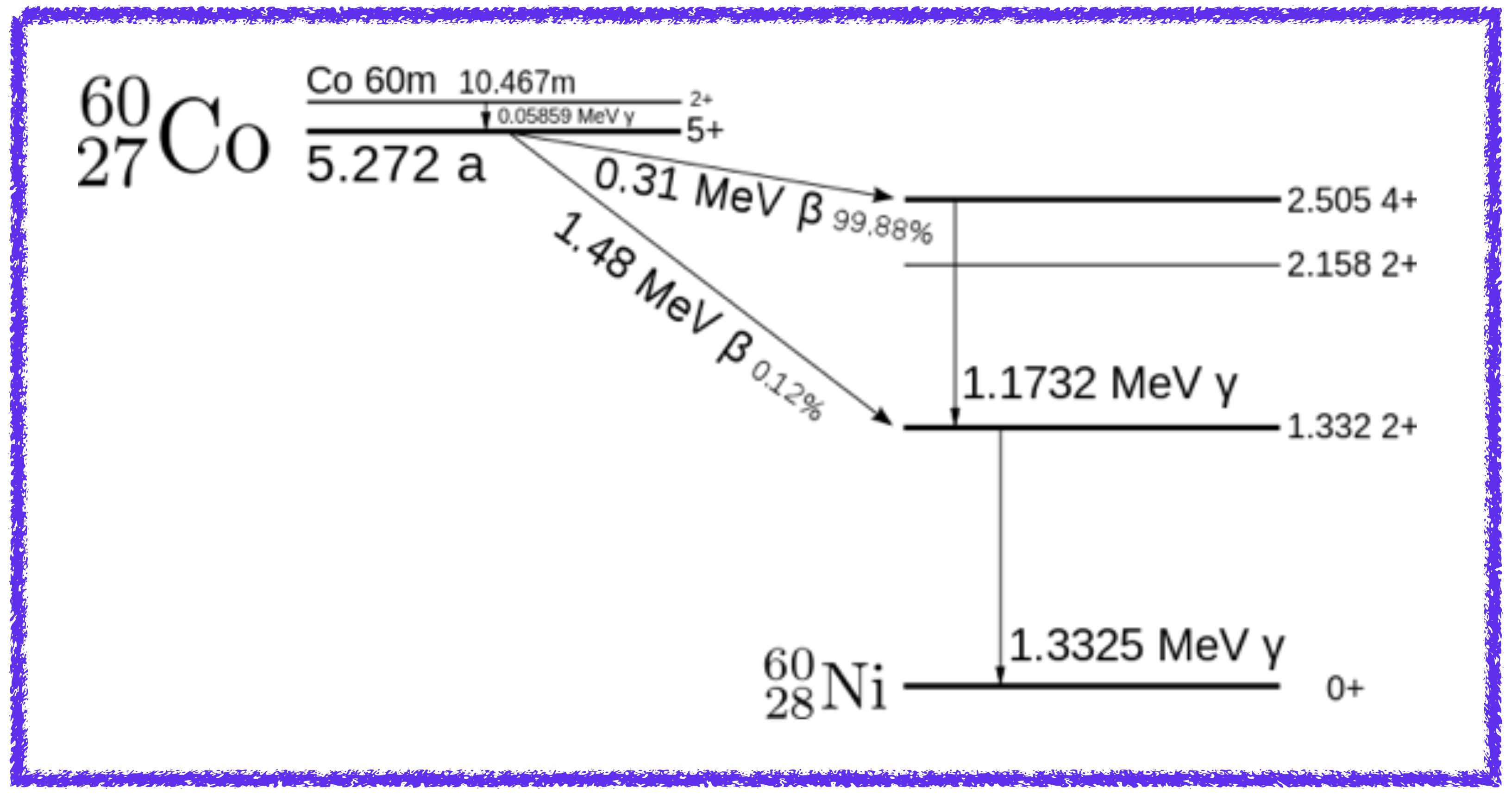
$$\sigma^2_{\mathrm{syst}}(\Gamma) = \sum_i \sigma^2_{\mathrm{add},i} + \sigma^2_{\mathrm{rel},i}\Gamma^2$$



	Additive (10^{-24} yr^{-1})	Relative (%)
Lineshape	0.007	1.3
Energy Resolution	0.006	2.3
Fit Bias	0.006	0.15
Energy Scale	0.005	0.4
Bkg Function	0.004	0.8
Signal Efficiency	-	0.7

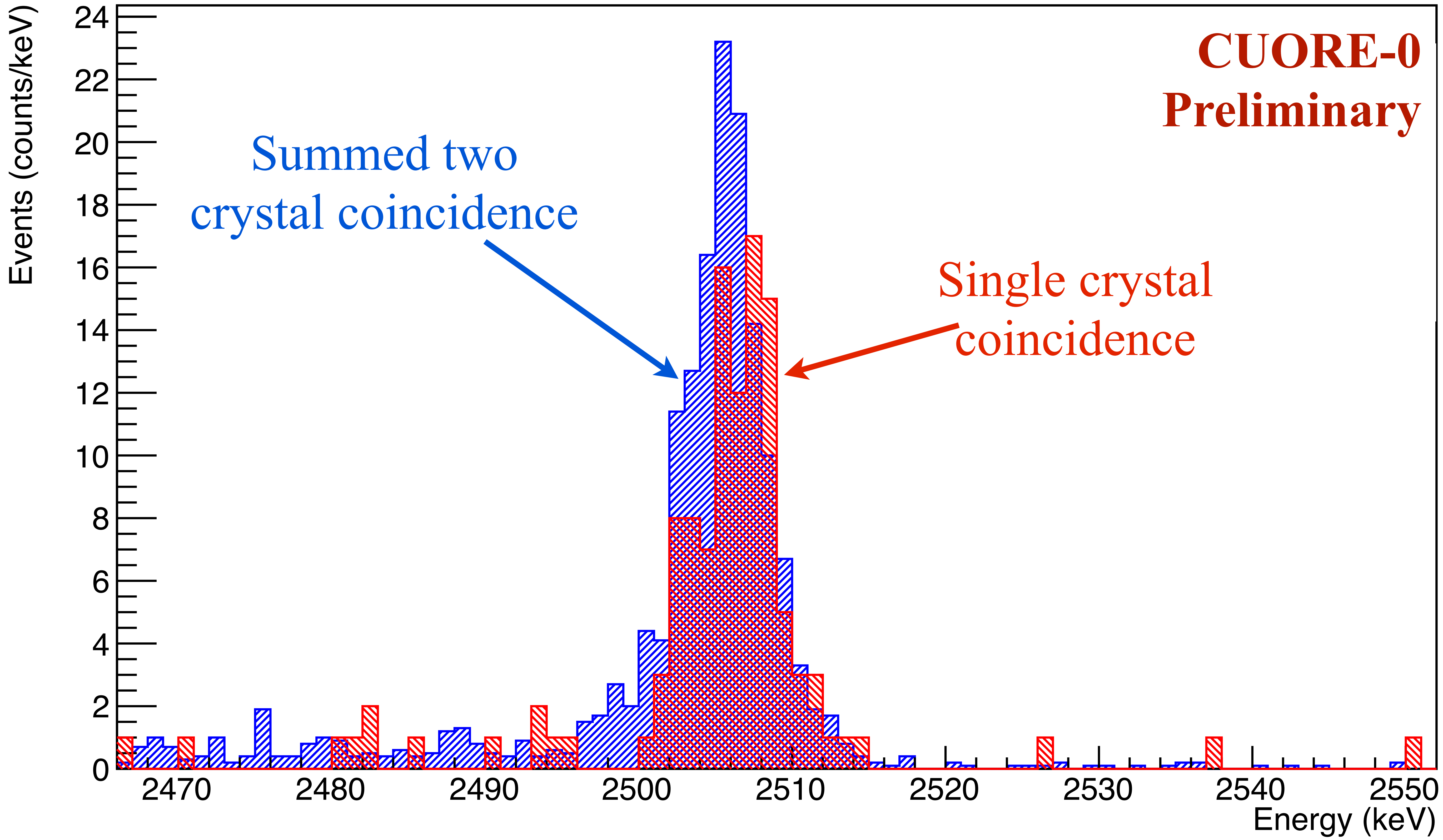
Results of a ^{60}Co Run

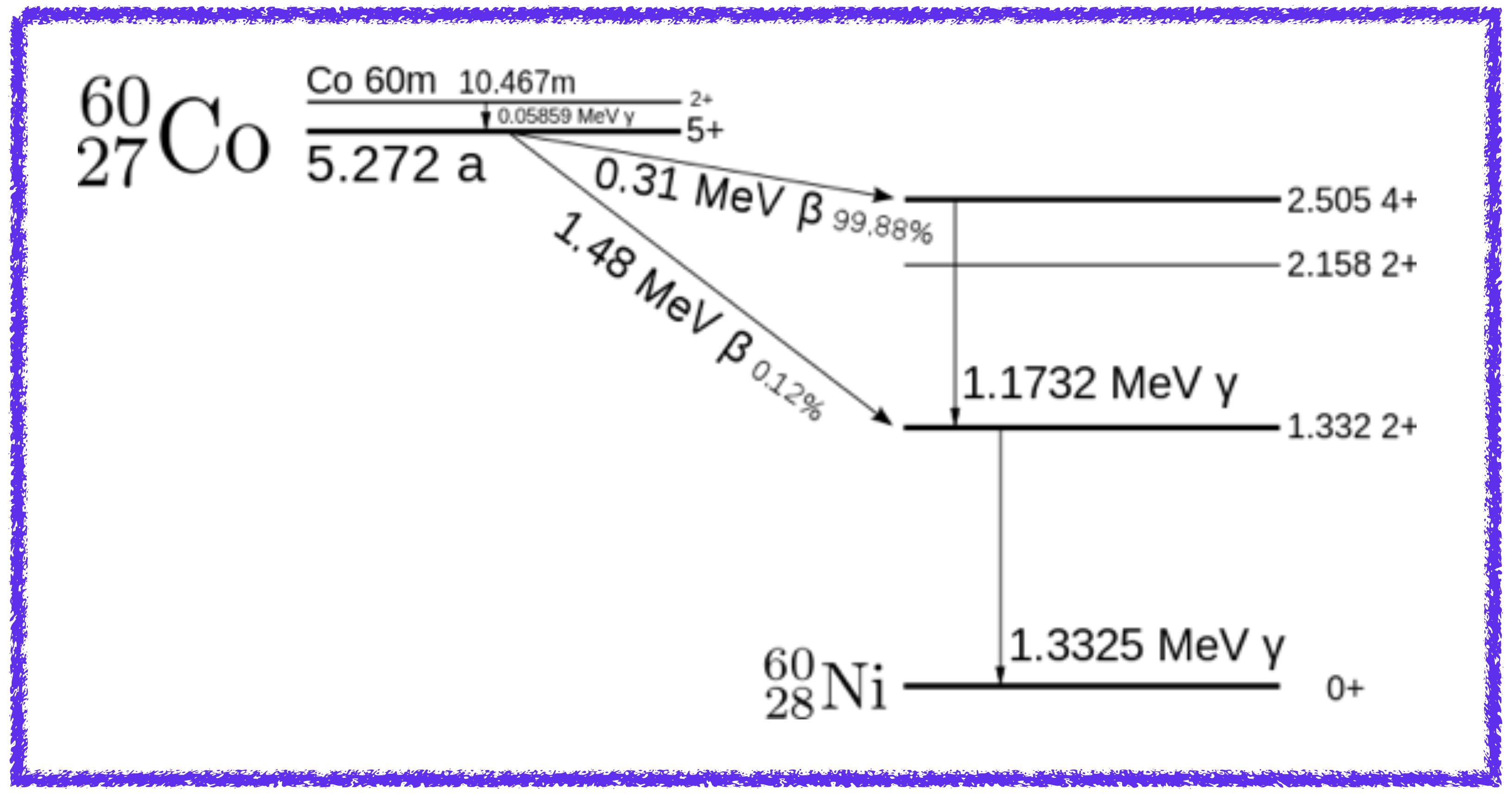




- ^{60}Co single crystal coincidence peak at 2505.720 keV reconstructs ~2 keV too high
- Similar effect seen in Cuoricino

Results of a ^{60}Co Run





^{60}Co Sum Peak

1173.228
+ 1332.492
2505.720

- ^{60}Co single crystal coincidence peak at 2505.720 keV reconstructs ~2 keV too high
- Similar effect seen in Cuoricino

Official CUORE-0 Limit Summary

	Bayesian Limits		Rolke Limits	
	Rate (10^{-24} yr^{-1})	Half-life (10^{24} yr)	Rate (10^{-24} yr^{-1})	Half-life (10^{24} yr)
CUORE-0 stat. only	0.25	2.7	0.24	2.9
CUORE-0 stat. + syst.	0.26	**2.7**	0.24	2.8
Cuoricino stat. + syst.	0.27	2.6	0.24	2.8
CUORE-0 + Cuoricino	0.17	**4.0**	0.17	4.1