The search for $0\nu\beta\beta$ decay with CUORE

Extreme cold and the slowest process ever measured

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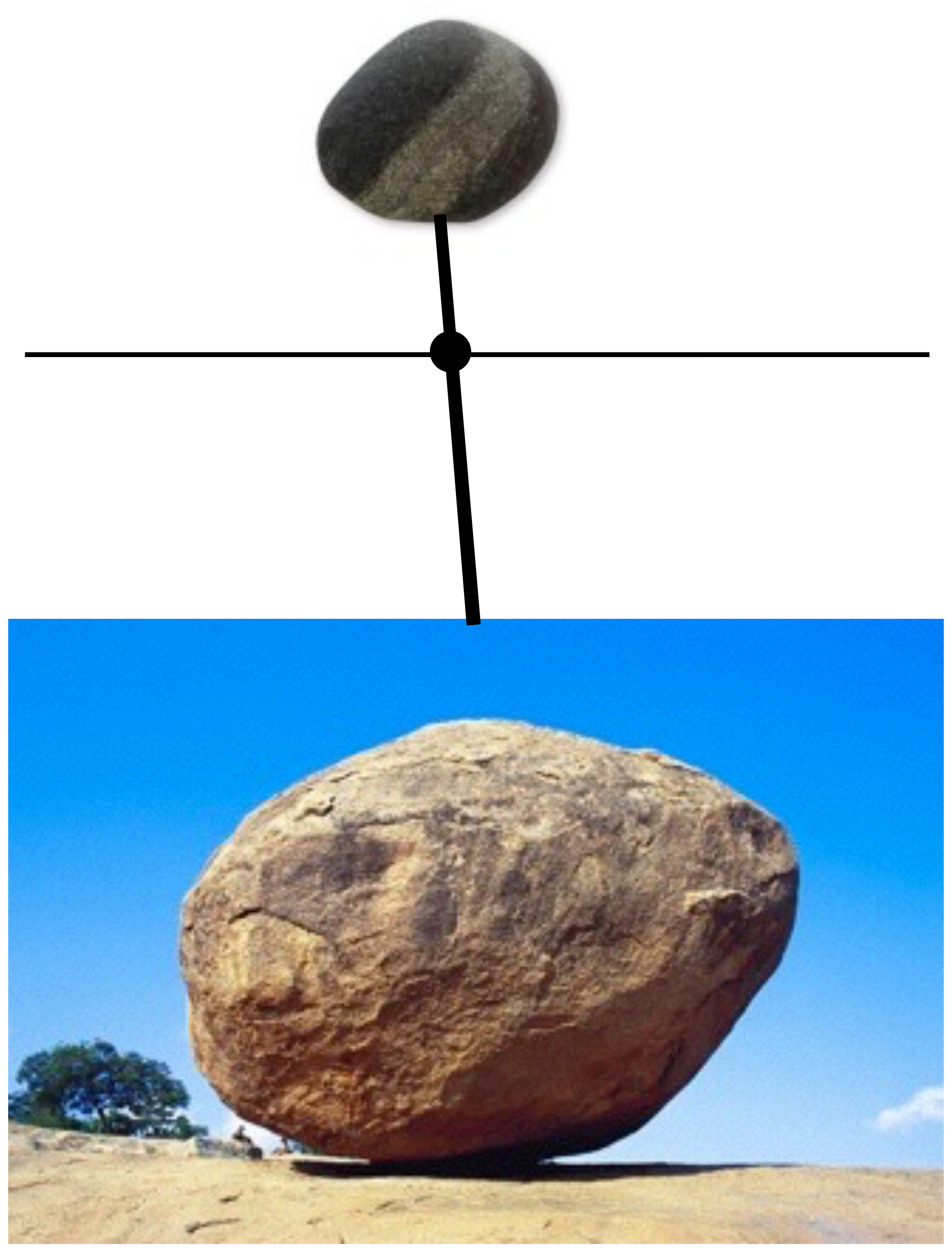
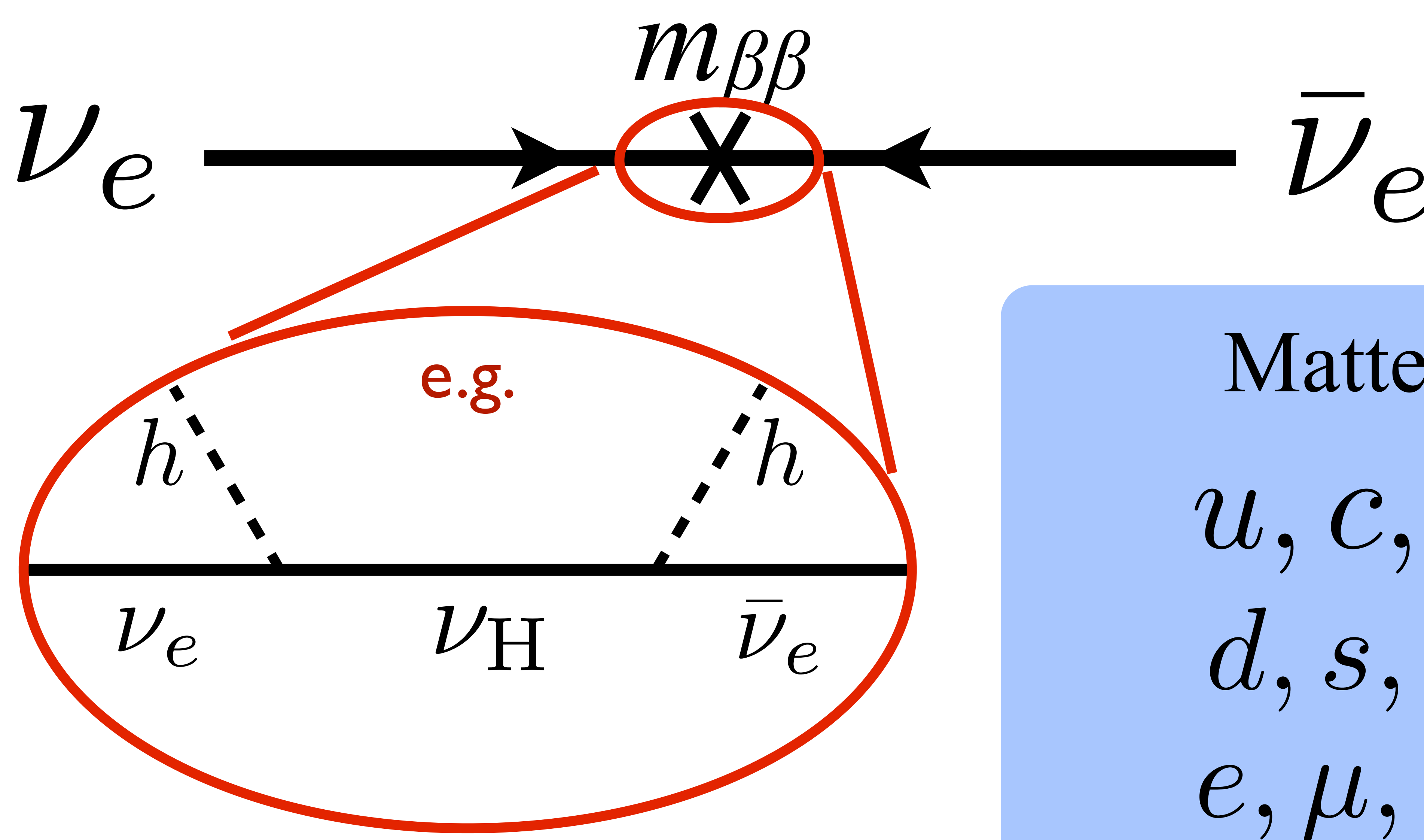
Neutrino Mass Opens Window To New Physics

- Does the neutrino have a Majorana type mass?
  - Would imply that lepton number is not a conserved quantity in nature
  - Could explain why the neutrino is so light
  - Would provide a link between matter and anti-matter and could help explain the matter/anti-matter asymmetry of the Universe.



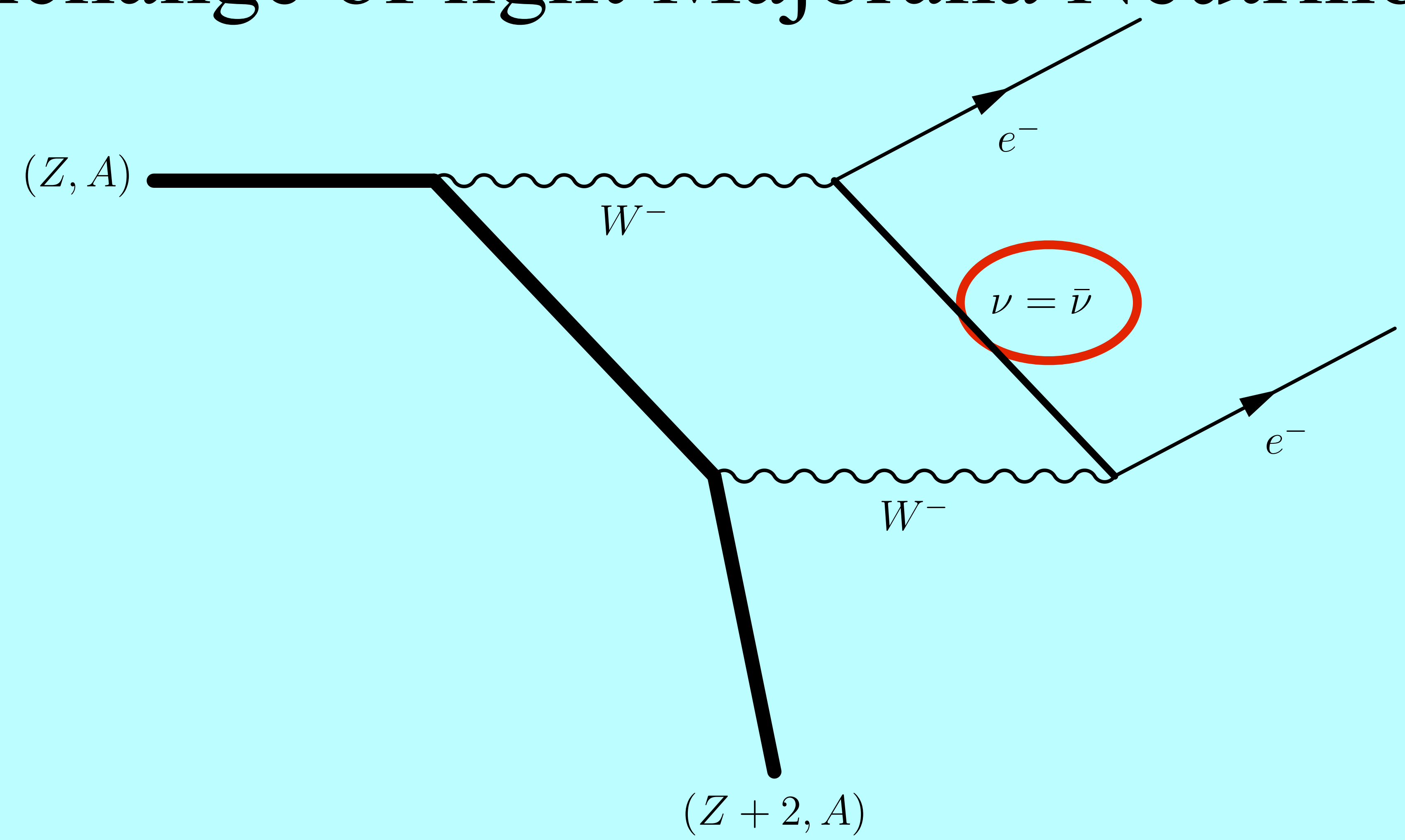


Matter	Anti-Matter
u, c, t	$\bar{u}, \bar{c}, \bar{t}$
d, s, b	$\bar{d}, \bar{s}, \bar{b}$
e, μ, τ	$\bar{e}, \bar{\mu}, \bar{\tau}$

ν_e, ν_μ, ν_τ

Neutrinoless Double Beta Decay

Exchange of light Majorana Neutrino



Decay Rate:

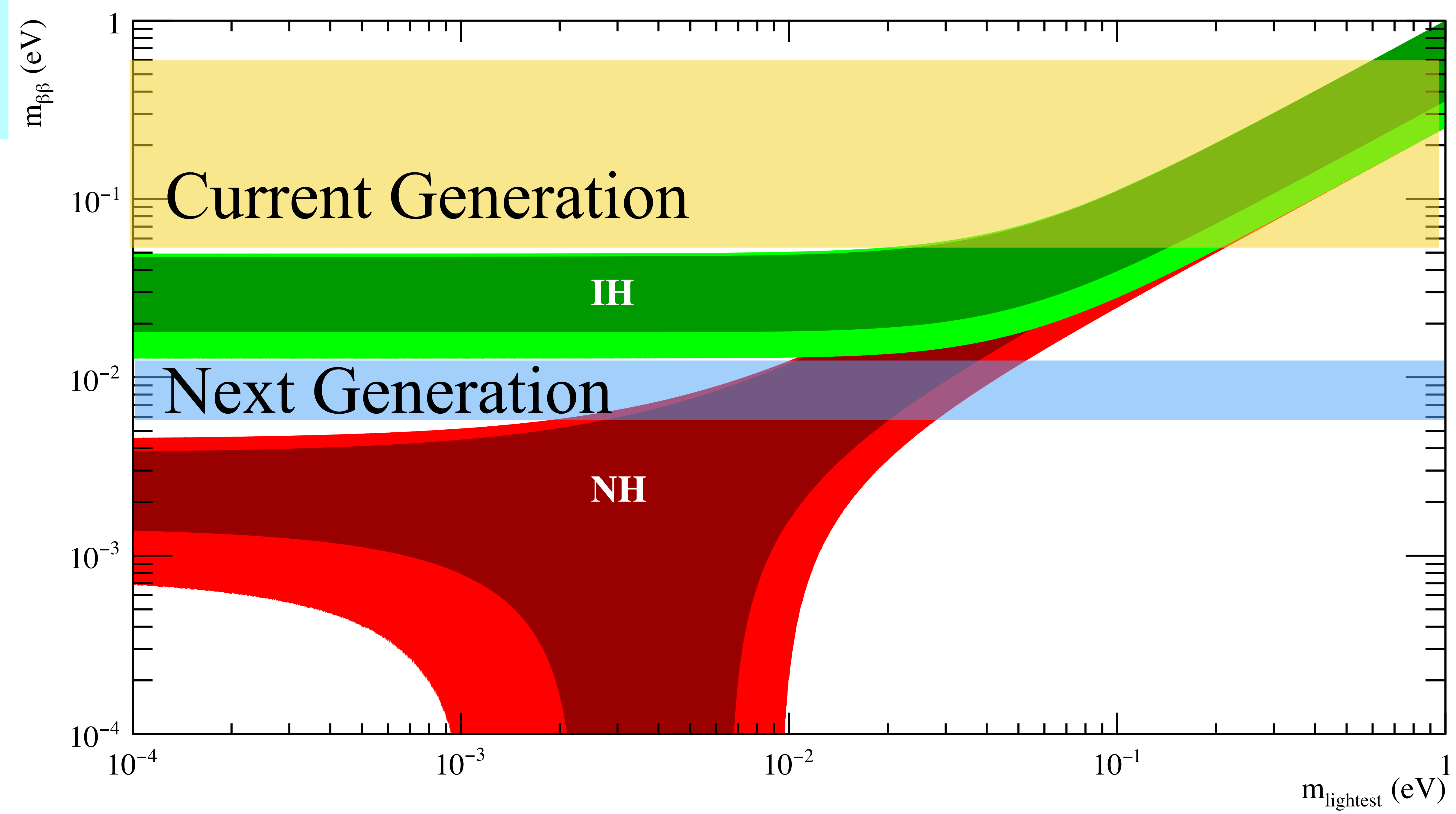
$$\Gamma_{0\nu} \propto \boxed{G_{0\nu}} \boxed{|\mathcal{M}_{0\nu}|^2} \boxed{\frac{m_{\beta\beta}^2}{m_e^2}}$$

Kinematics	Nuclear	BSM Physics

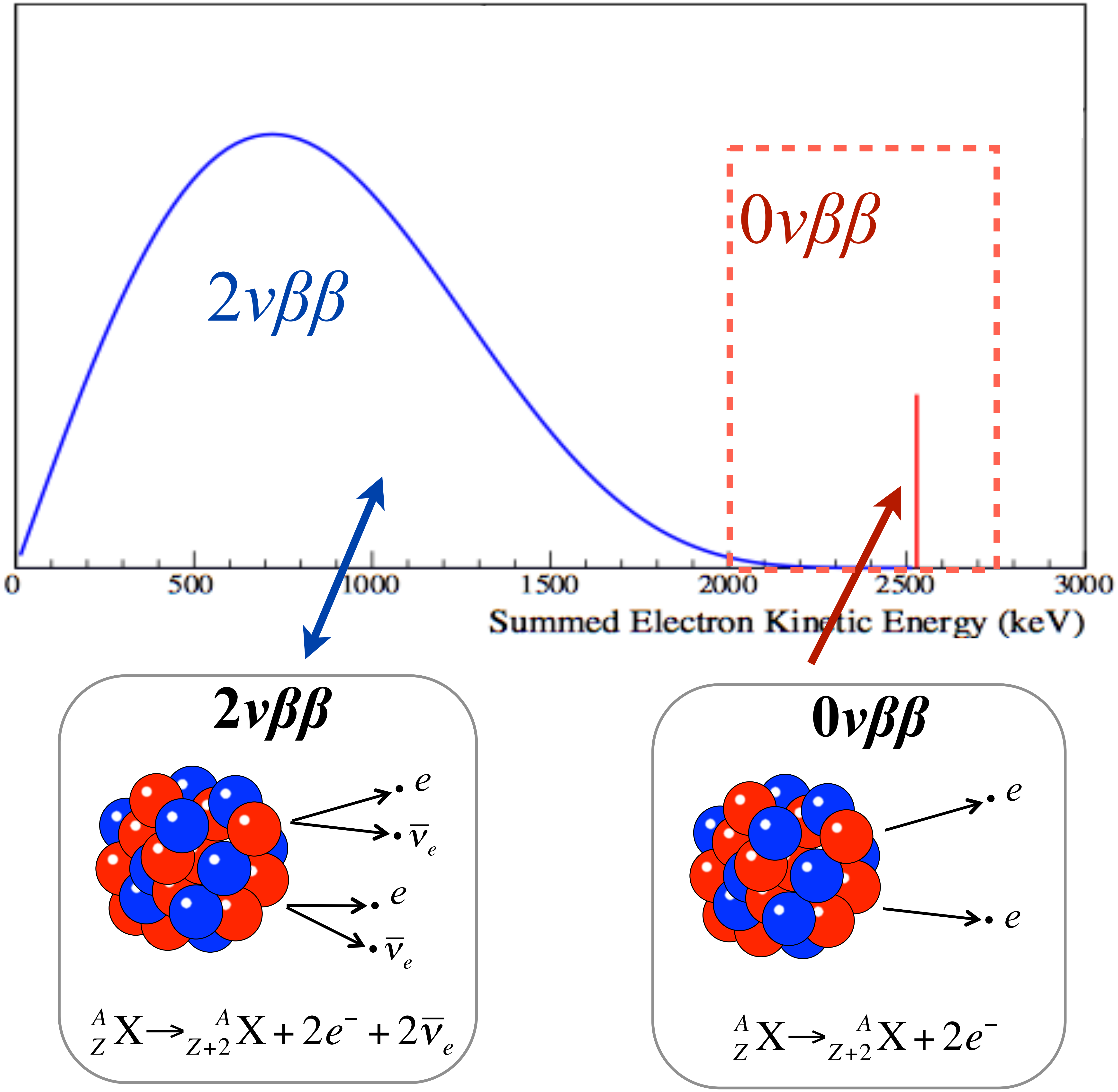
Effective Majorana Mass

$$m_{\beta\beta} \equiv \left| \sum_i U_{ei}^2 m_i \right|$$

$m_{\beta\beta}$	Effective Majorana Mass
U_{ei}	PMNS Matrix
m_i	Neutrino Masses



Double Beta Decay

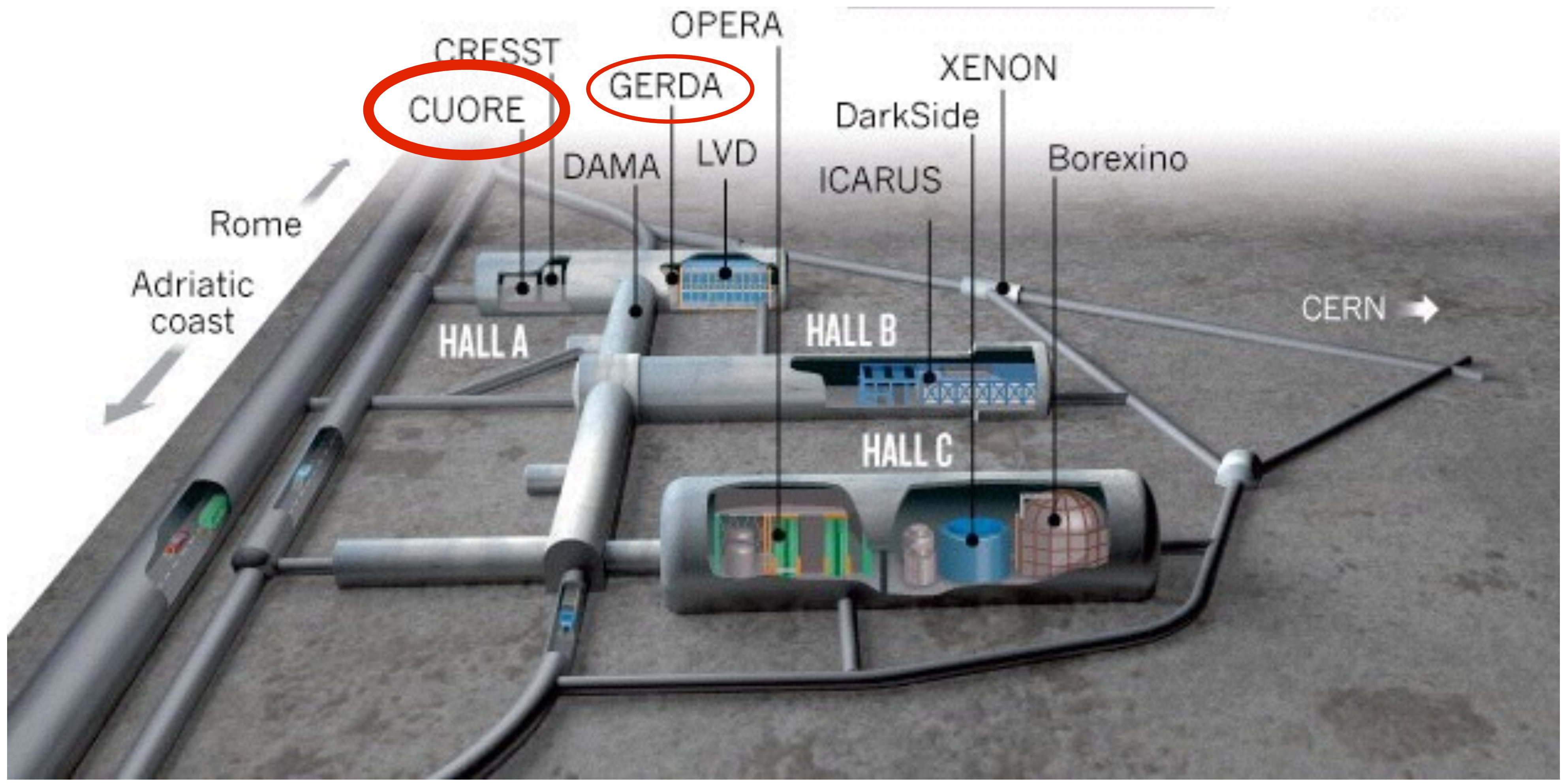


- Detectors measure the kinetic energy of the emitted electrons
- $2\nu\beta\beta$ produces a broadened spectrum
- $0\nu\beta\beta$ has no neutrinos, thus no missing energy.
- $2\nu\beta\beta$ is the *slowest* process ever measured with $T_{1/2}$~10^{19}-10^{24} yr
- $0\nu\beta\beta$ is slower still with $T_{1/2}$>10^{24}-10^{25} yr (if it occurs at all)
- We combat this by making detectors very large and very low background!

CUORE: A Ton Scale Bolometric $0\nu\beta\beta$ Decay Search

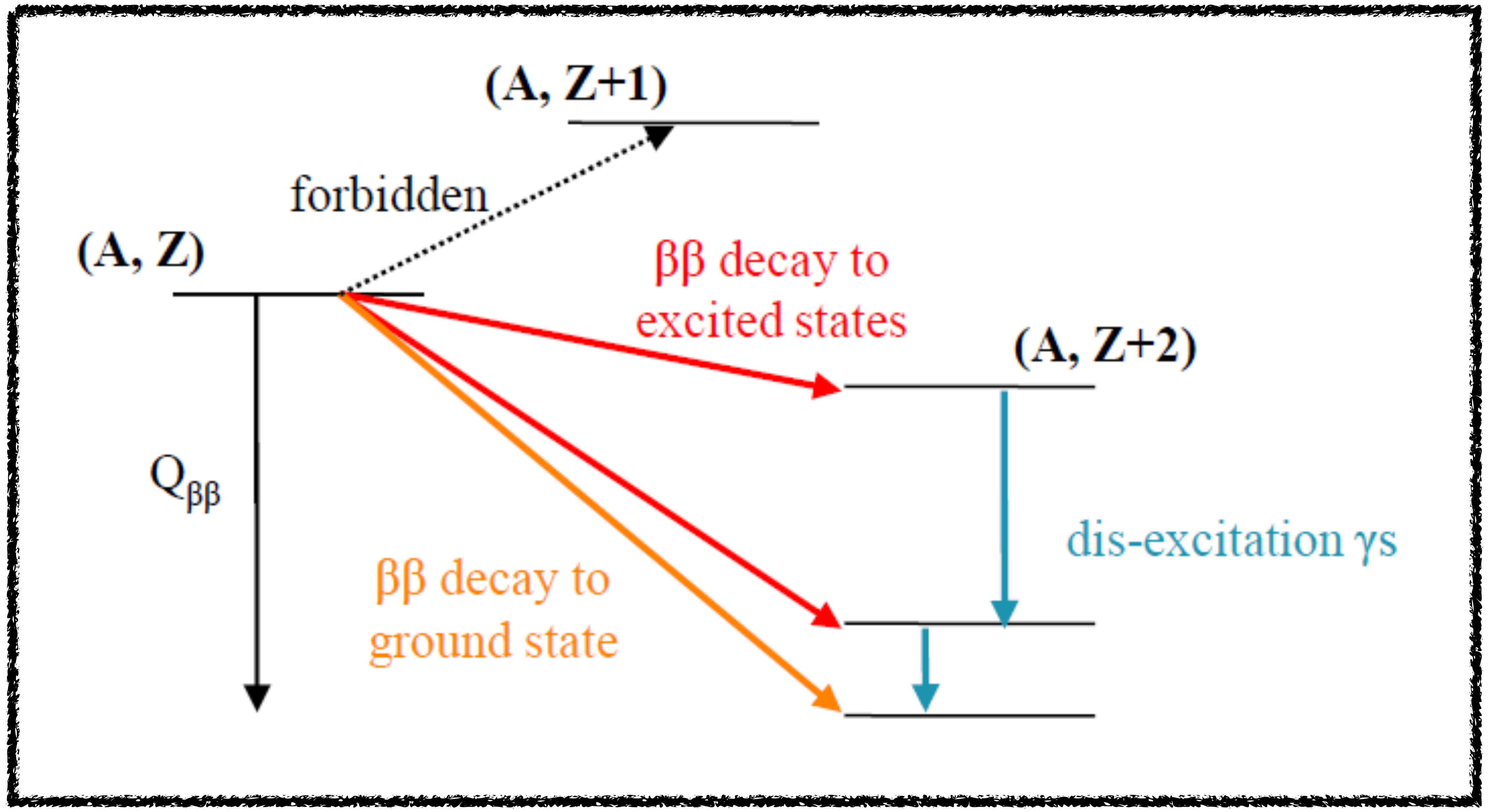
Laboratori Nazionali del Gran Sasso

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

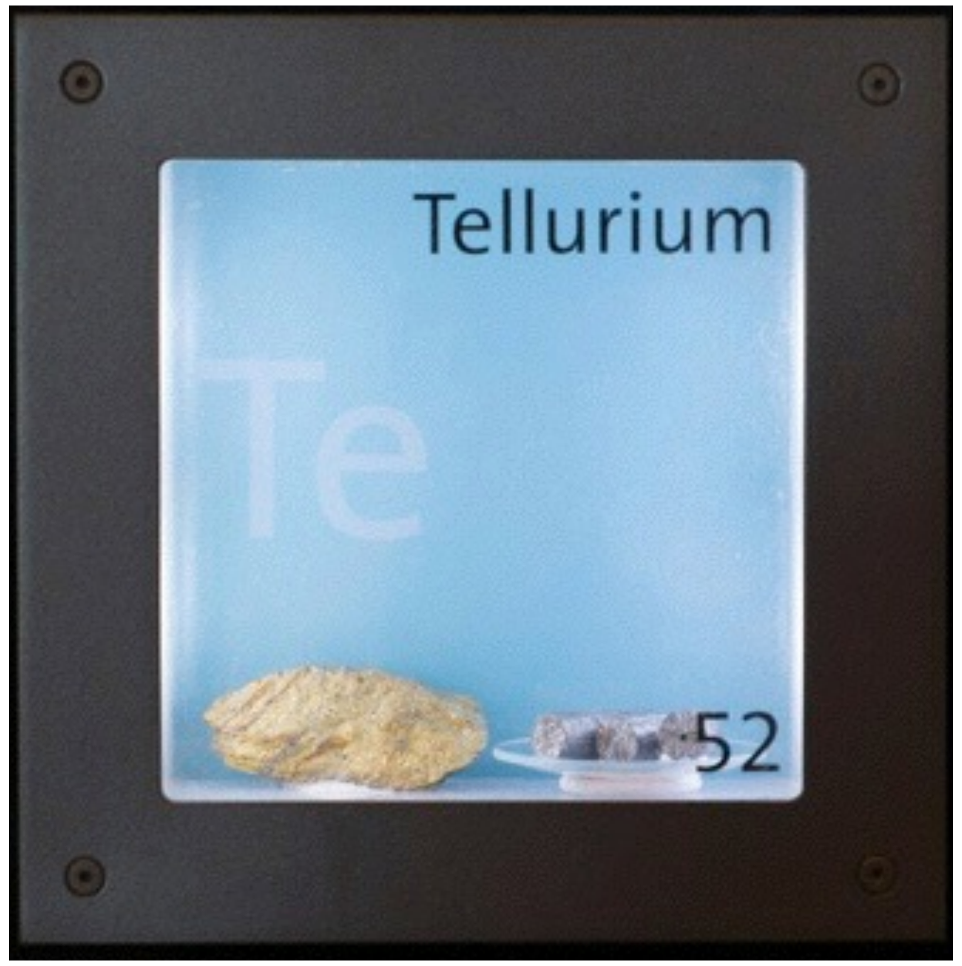


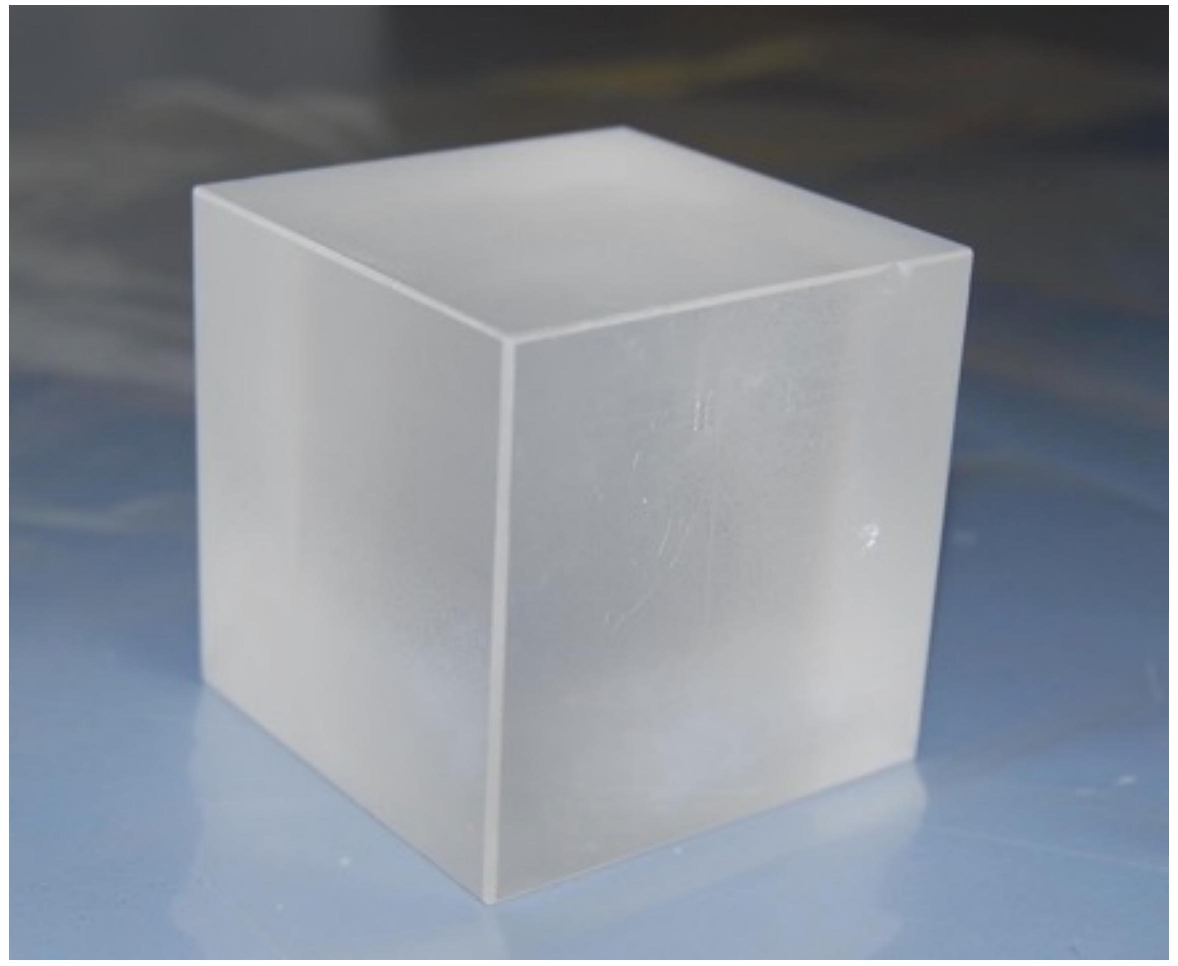
$$\Gamma_\mu \sim 2.6 \times 10^{-8} \mathrm{s}^{-1} \mathrm{cm}^{-2}$$
$$\Gamma_N \sim 4 \times 10^{-6} \mathrm{s}^{-1} \mathrm{cm}^{-2}$$

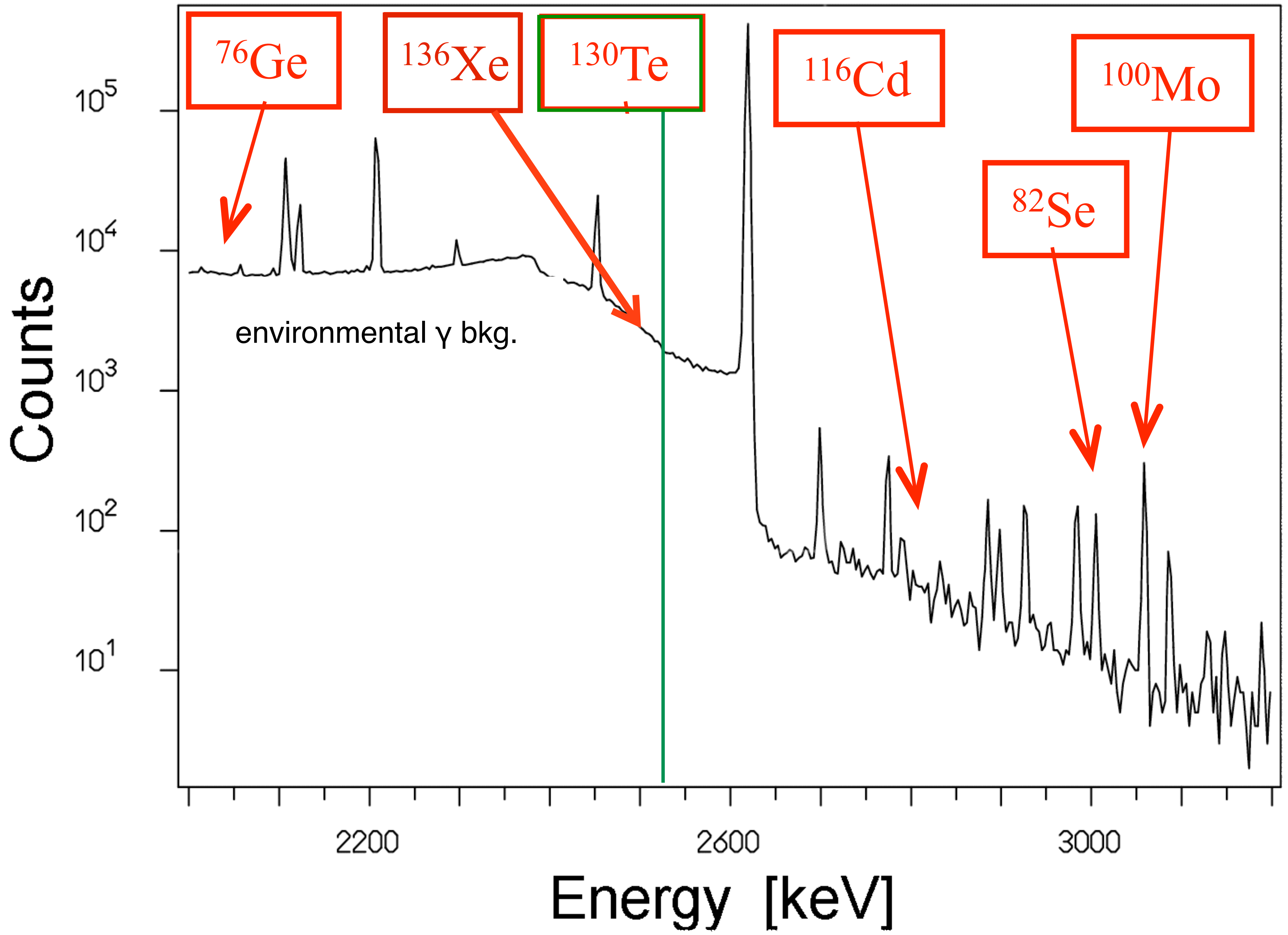
Search for $0\nu\beta\beta$ decay in ^{130}Te



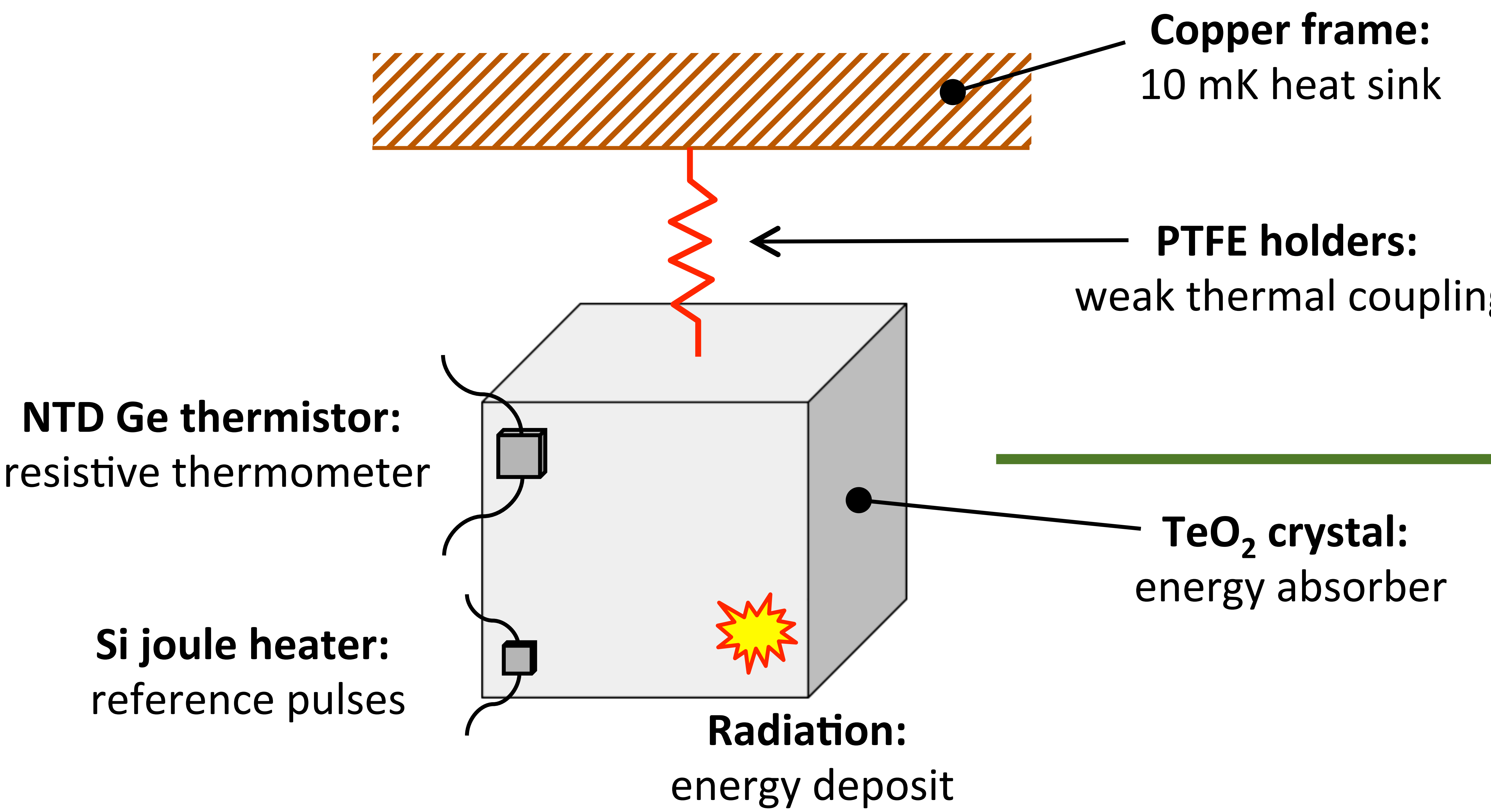
- ➡ Primary decay channel via DBD
- ➡ High natural isotopic abundance at ~34%
- ➡ Relatively high Q-value

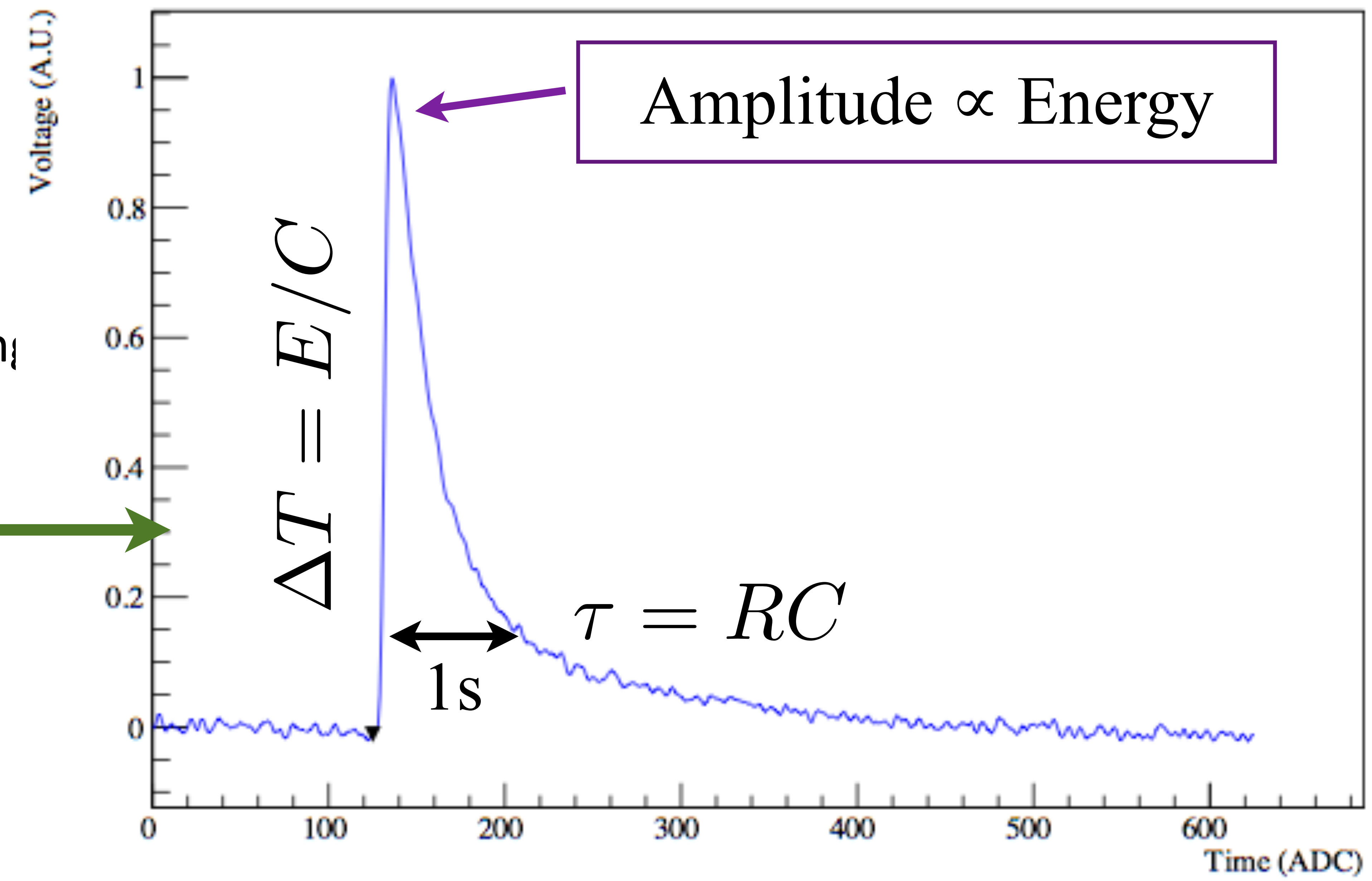






A CUORE Bolometer

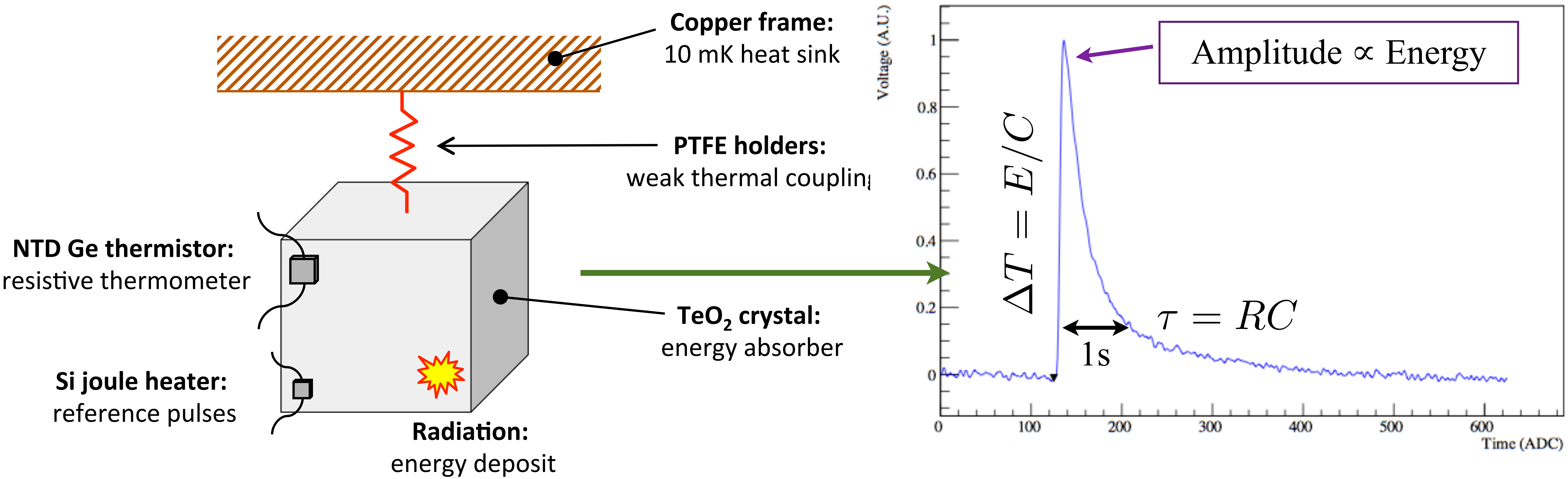




- Absorber is 750g $^{nat}TeO_2$ Crystal
  - “Source = Detector”
- Operating Temperature of 10 mK
- $\Delta T \sim 100\ \mu K$ per MeV

- Temperature change causes change in Ge-NTD resistance.
- Excellent energy resolution of 5 keV FWHM at 2615 keV (0.2% resolution FWHM)

A CUORE Bolometer



- ➡ Absorber is 750g $^{nat}TeO_2$ Crystal
  - ➡ "Source = Detector"
- ➡ Operating Temperature of 10 mK
- ➡ ΔT~100 μK per MeV

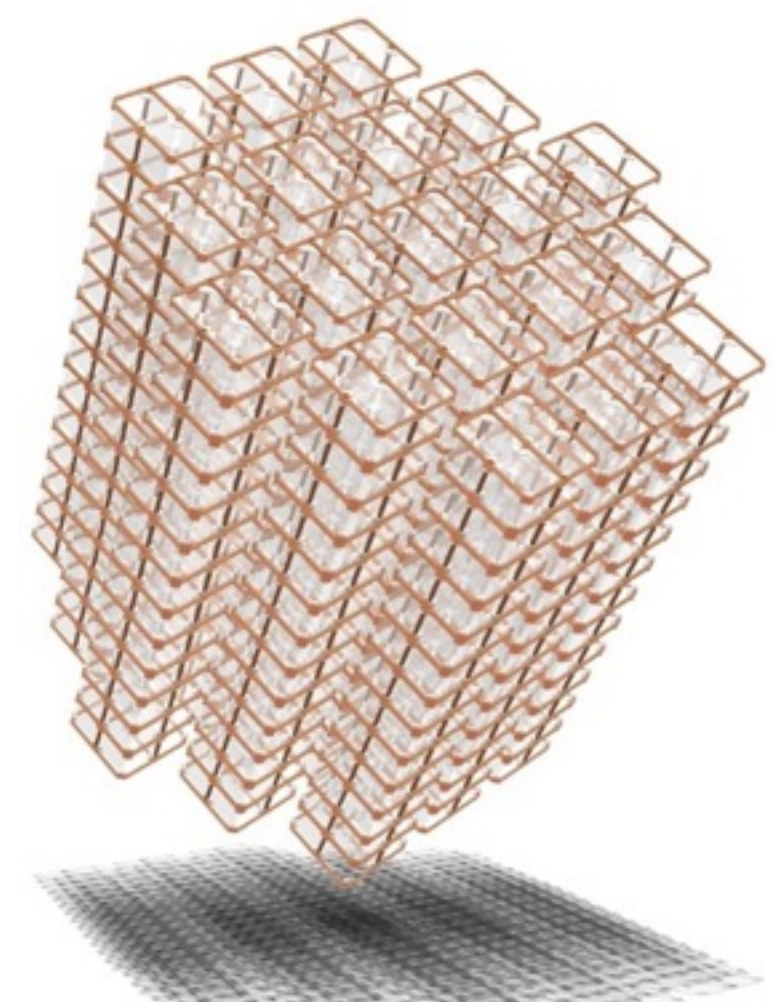
- ➡ Temperature change causes change in Ge-NTD resistance.
- ➡ Excellent energy resolution of 5 keV FWHM at 2615 keV (0.2% resolution FWHM)

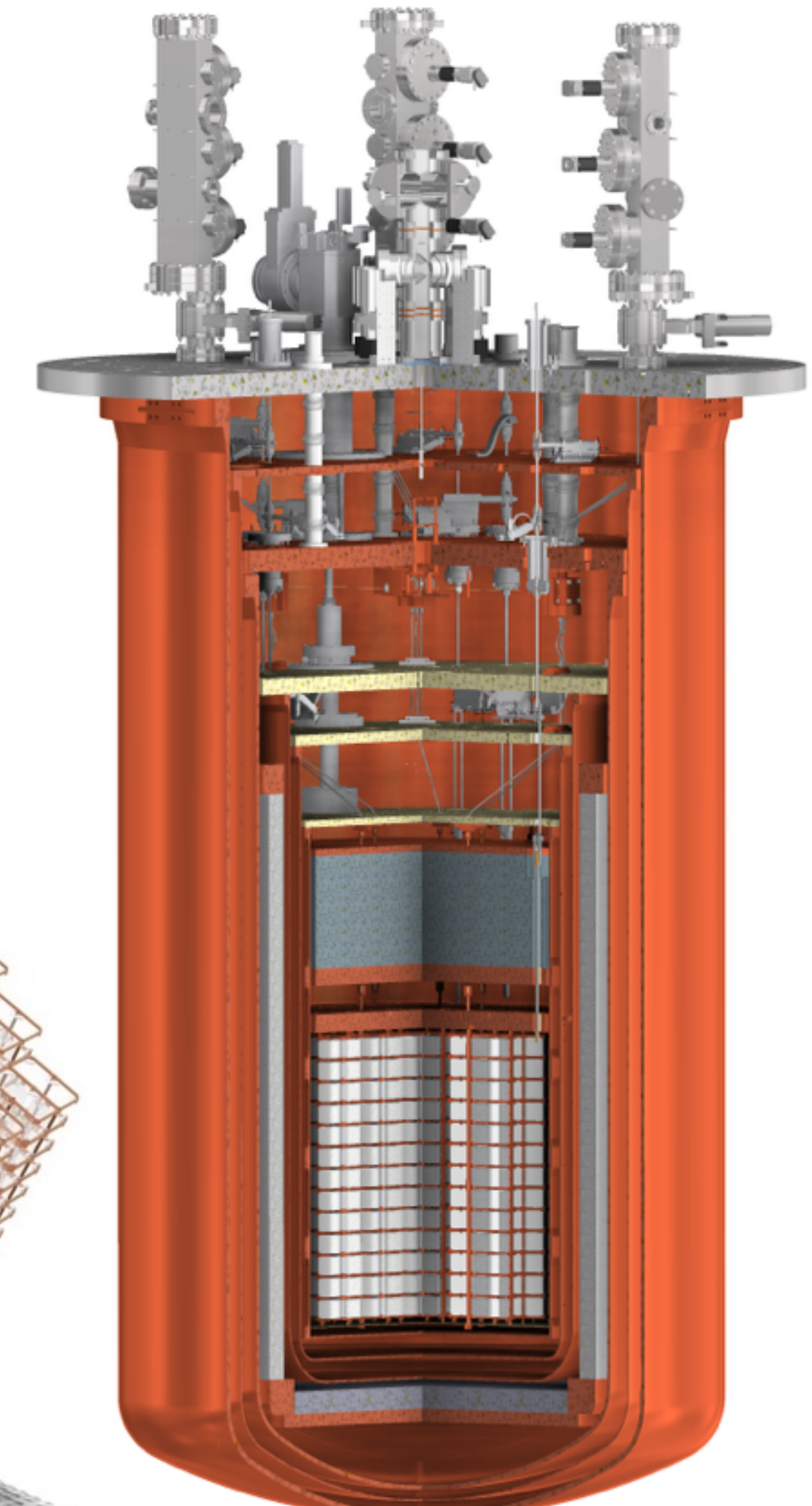
CUORE Goal

CUORE is a ~ton scale bolometric detector with the goal of detecting $0\nu\beta\beta$ down to the top of the inverted hierarchy

- Array of 988 TeO_2 bolometers
  - 19 towers of 52 750 g bolometers
- 741 kg of TeO_2 (206 kg of ^{130}Te)
- Energy resolution of ΔE = 5 keV FWHM at Q = 2615 keV
- Background goal of 0.01 cnts/keV/kg/yr
- Expected sensitivity of $T_{1/2}(0\nu) > 9.5 \times 10^{25}$ yr in 5 years of live time ($m_{\beta\beta} \lesssim 50 - 130$ meV) at 90% C.L.

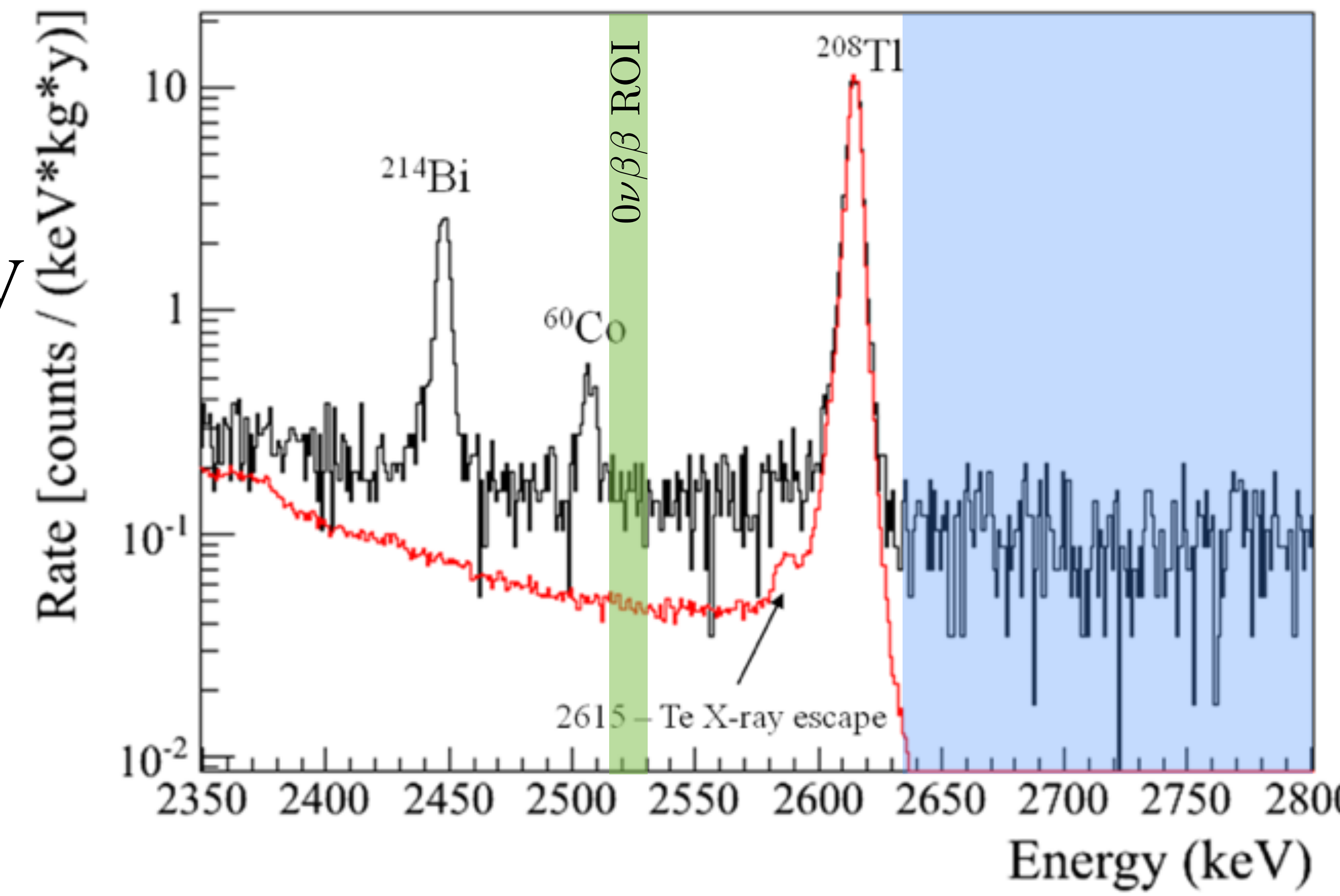
- Requires a powerful new dilution refrigerator
  - Cool 15 t of material to < 4K
  - Cool 1.5 t of material to 10mK
  - Temperature stable to <1 μK per day

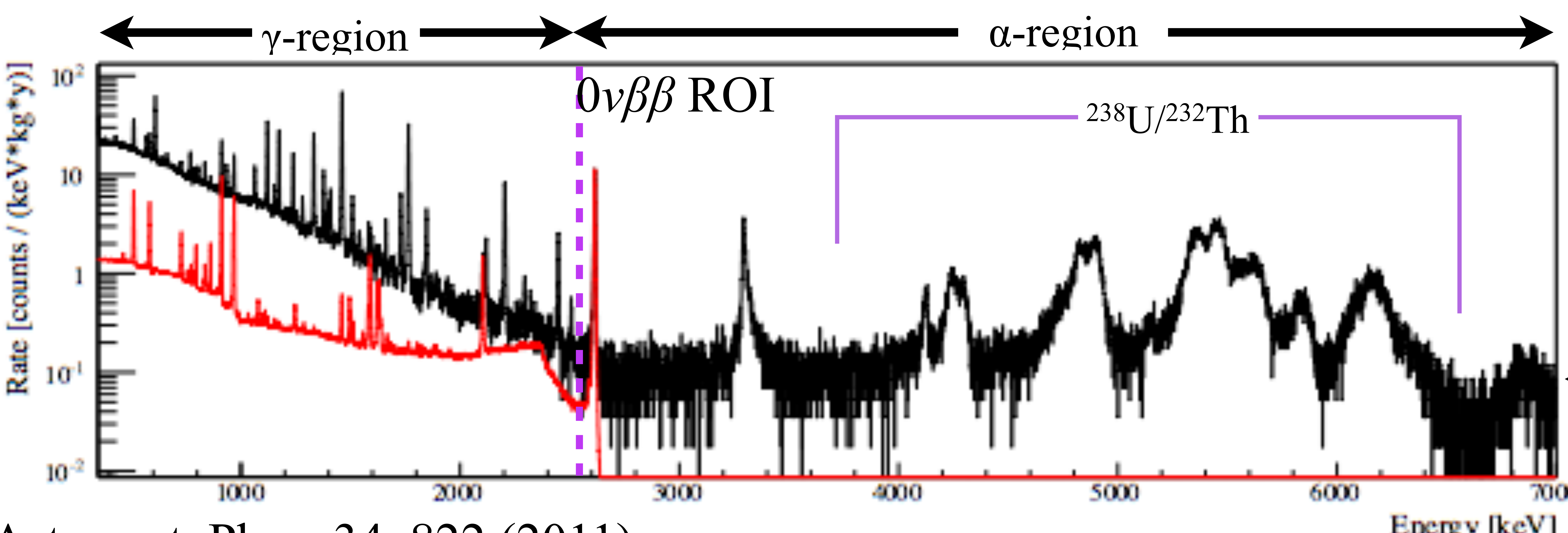


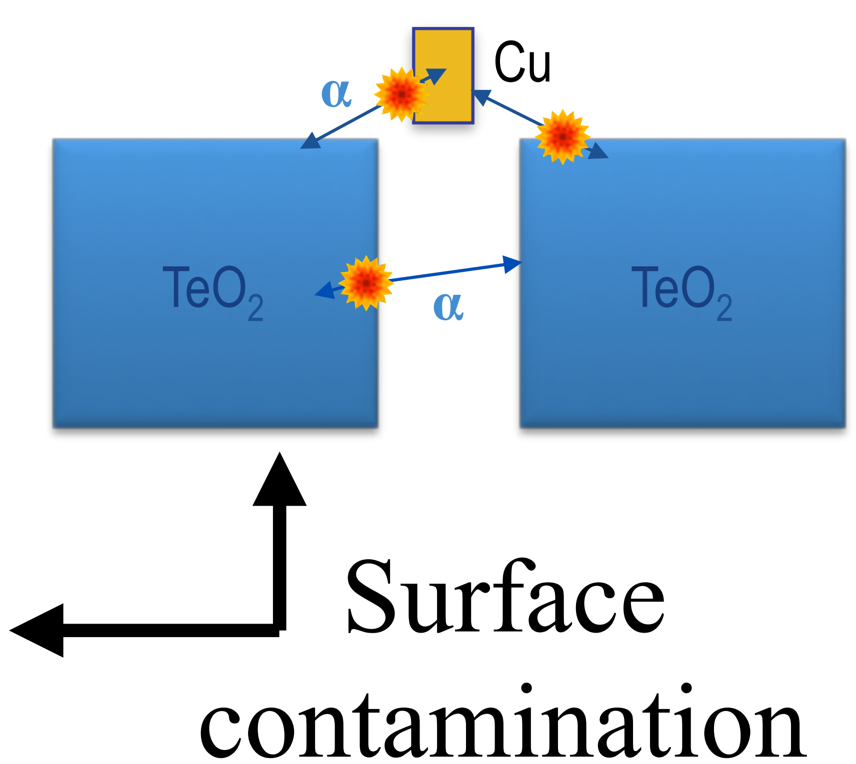


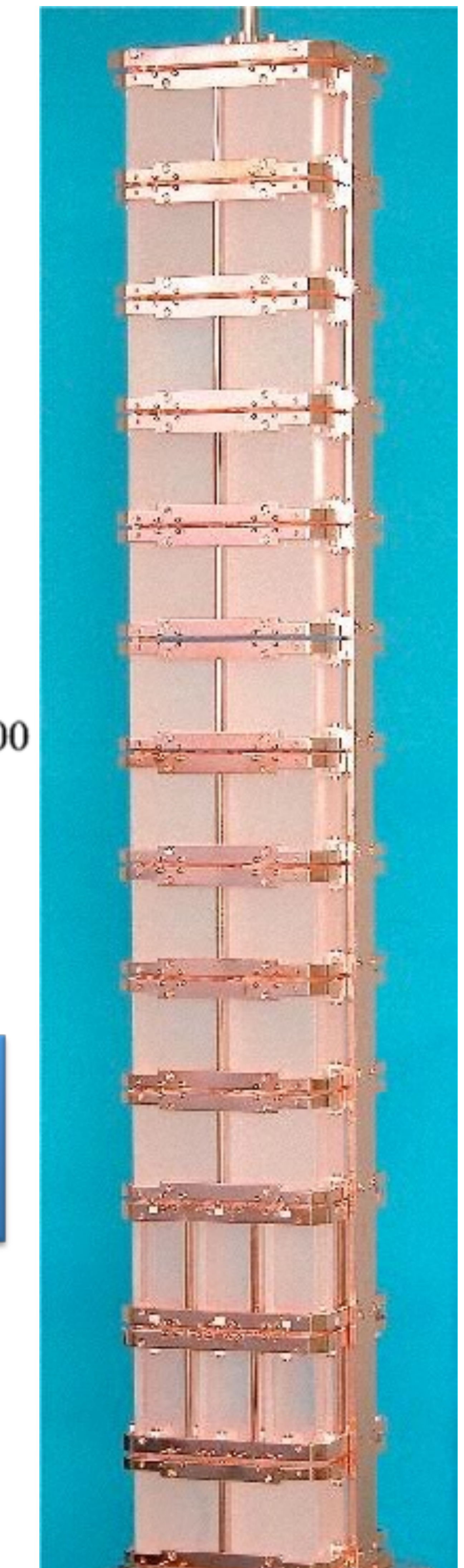
Predecessor to CUORE: Cuoricino

- 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
  - $T1/2(0\nu) > 2.8 \times 10^{24}$ yr (90% C.L.)
  - $m\beta\beta < 300\text{-}700$ meV
  - Primary background from environmental ^{238}U/ ^{232}Th surface contamination



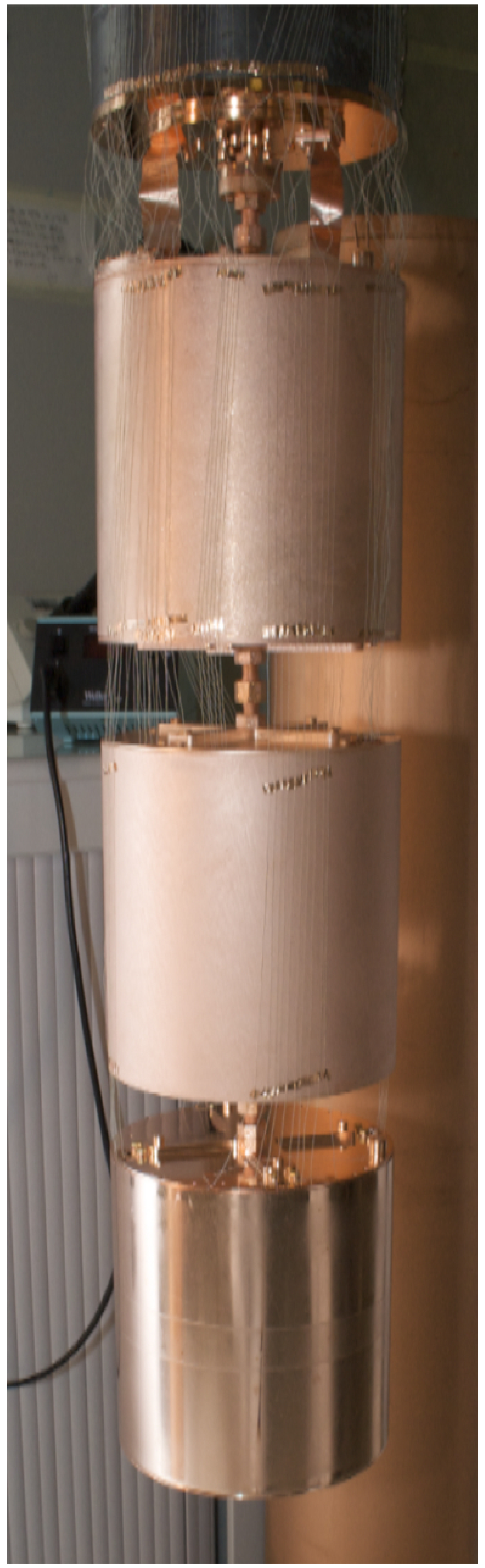






Astropart. Phys. 34, 822 (2011)

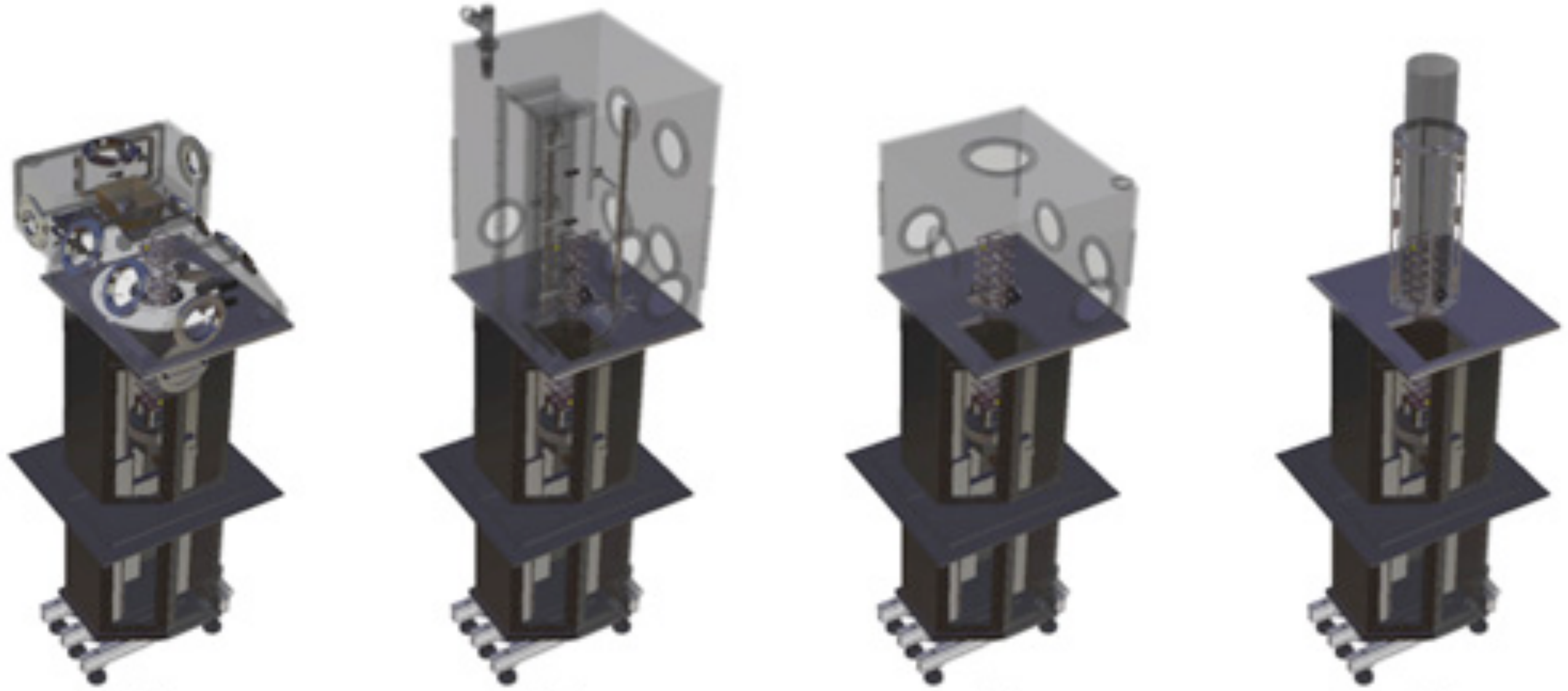
Background Reduction

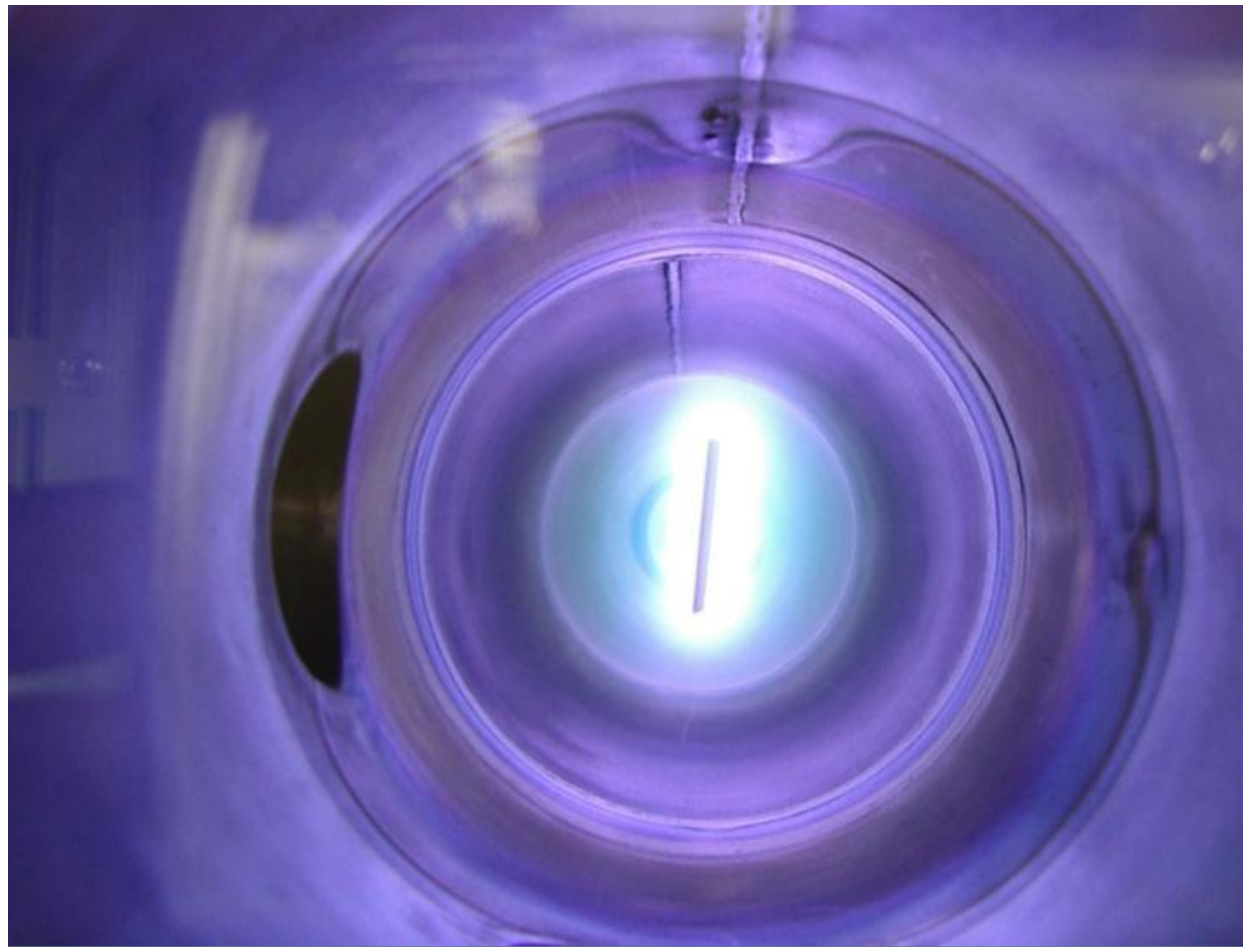


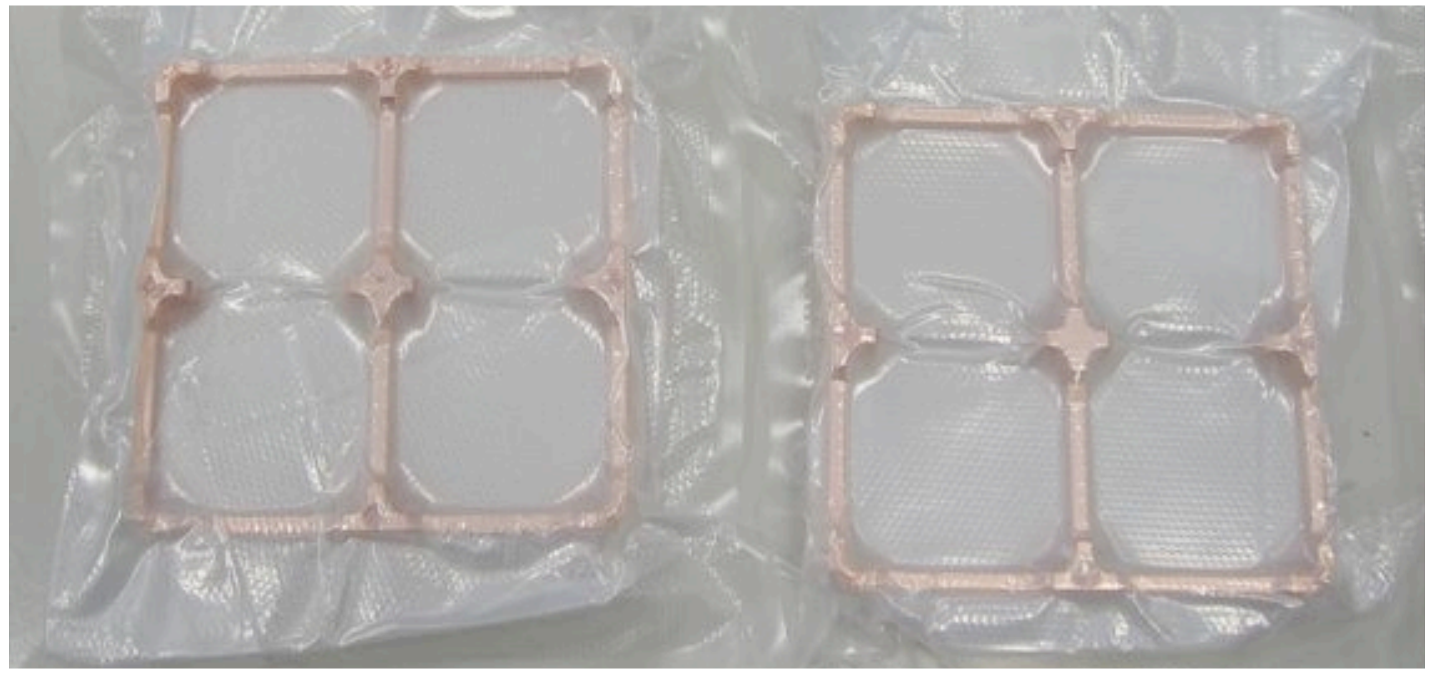
Three Towers Test

New radiopurity protocols

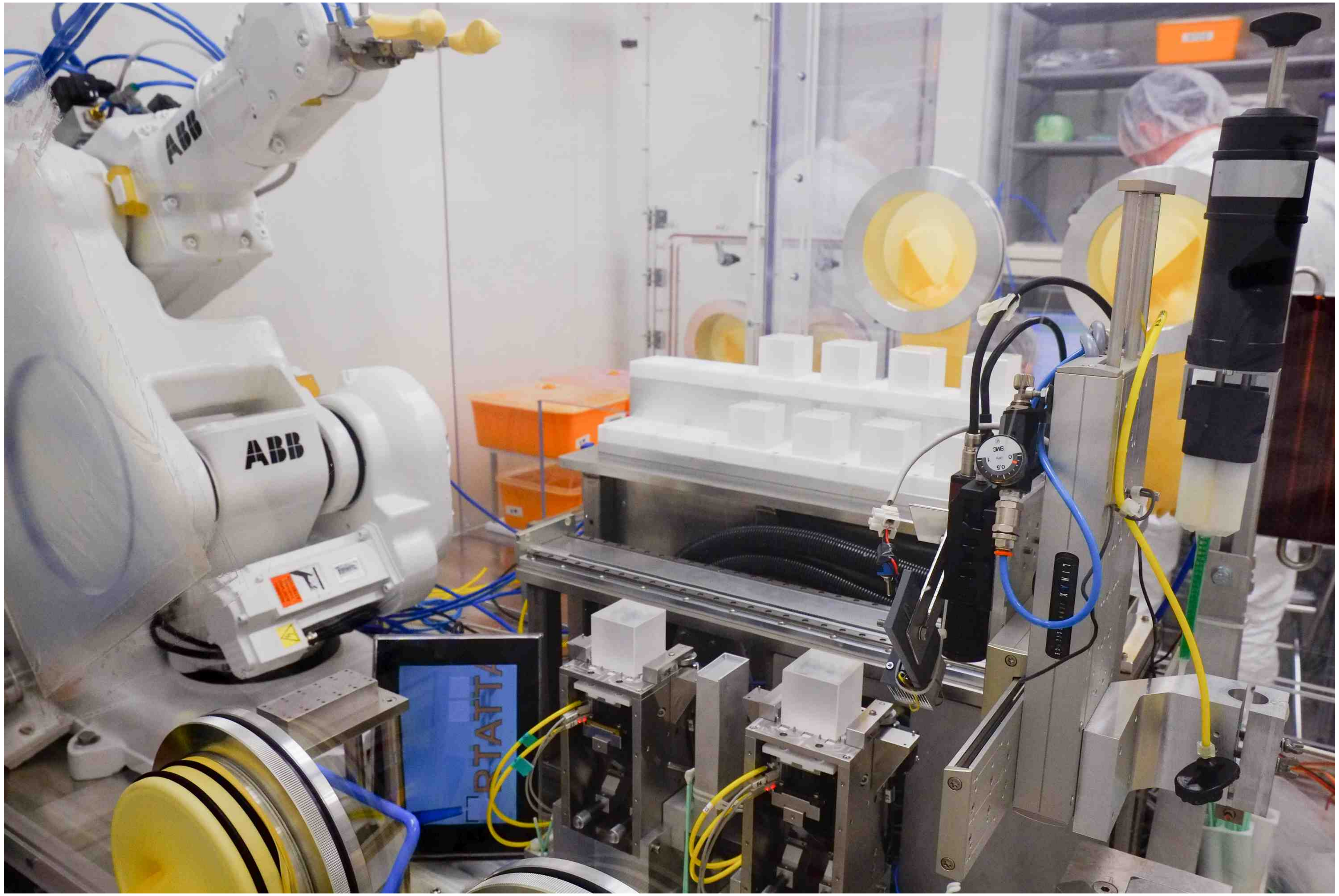
- Lighter design reduces copper surfaces facing detector
- New copper surface treatment
- Parts cleaned and stored under vacuum or N_2 flux and underground
- Custom designed assembly line for CUORE assembly
- New cryostat assembled from cleaner materials, with better shielding







CUORE Detector Assembly



CUORE Detector Assembly

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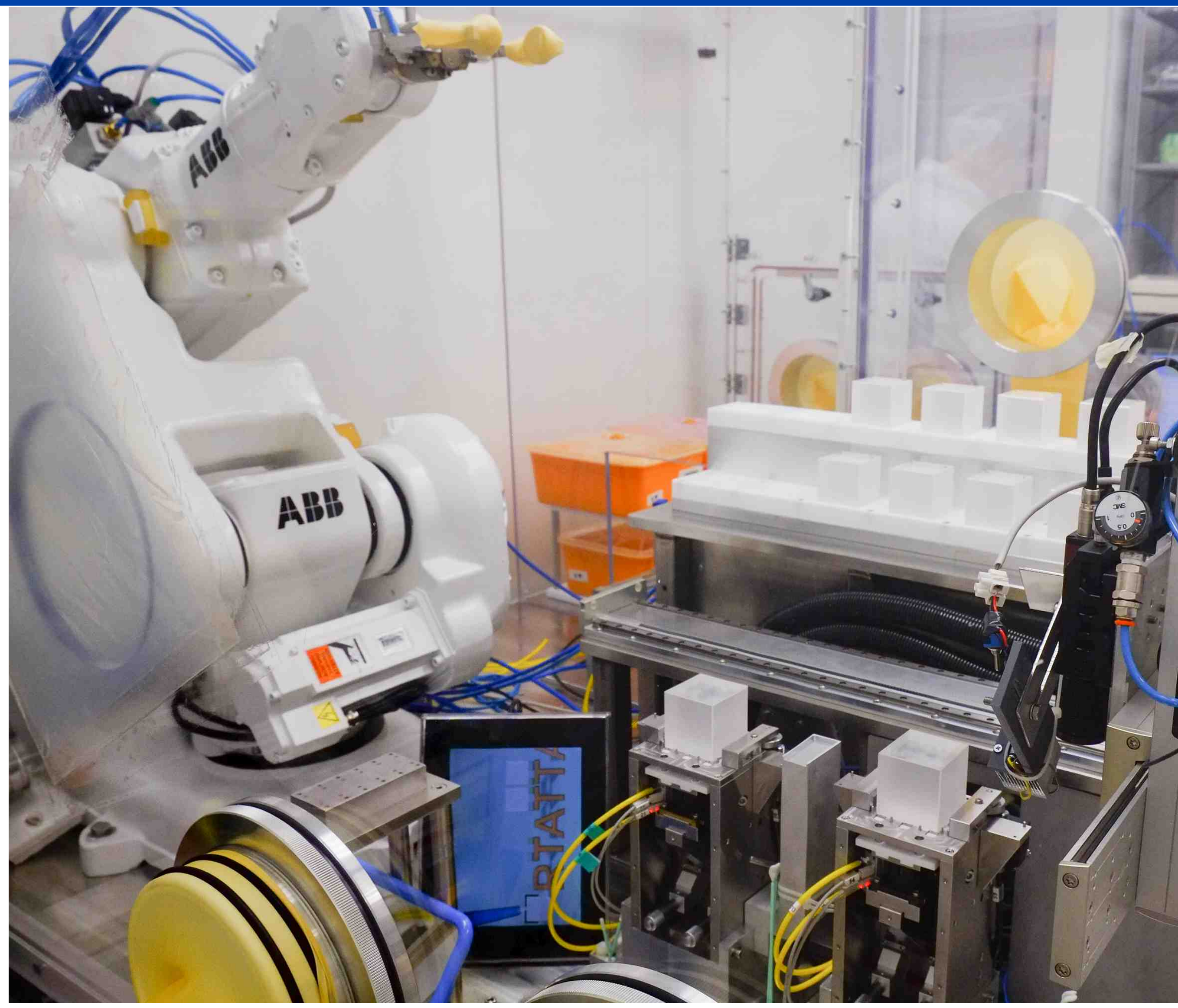

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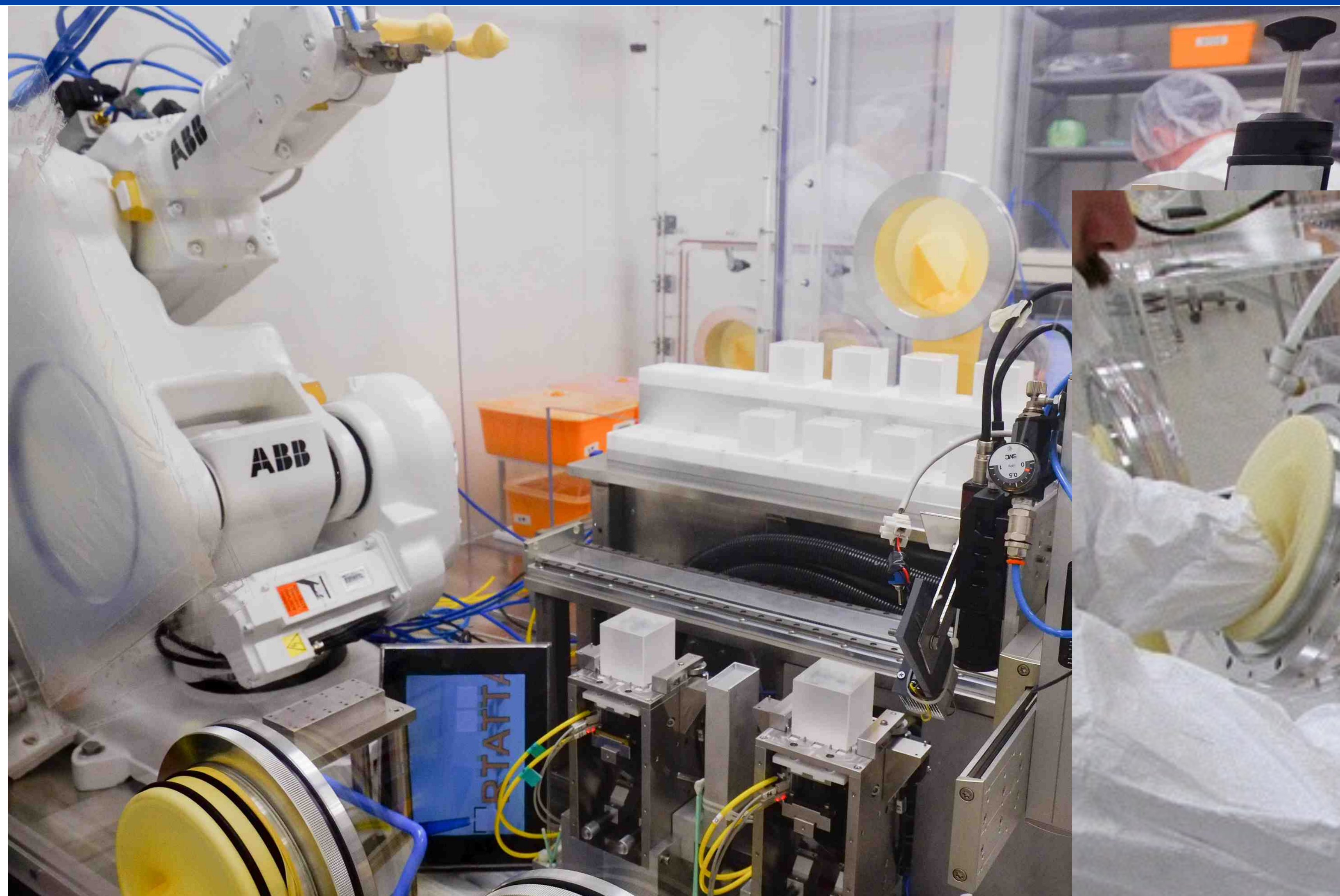
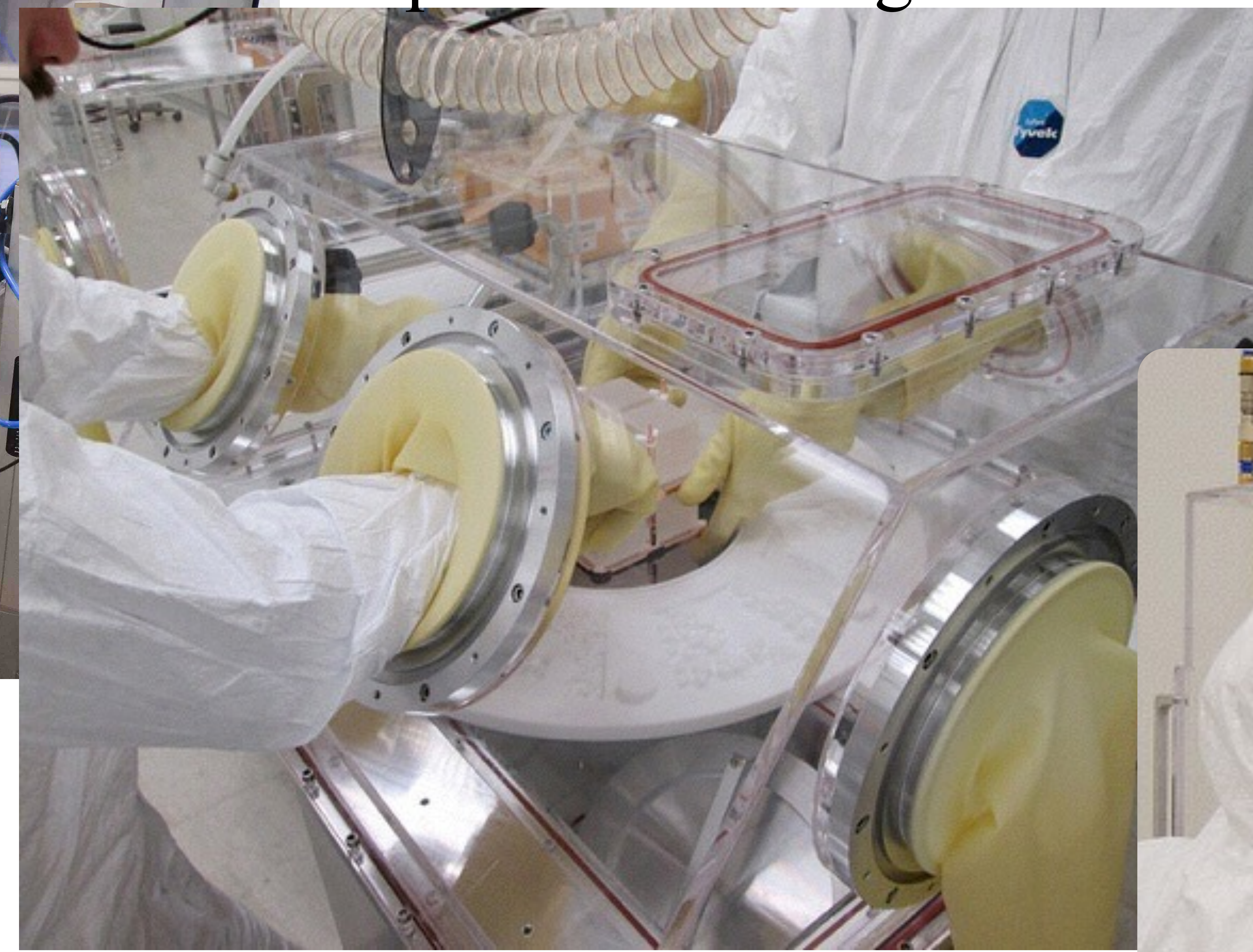


Step 1: Attaching NTDs to crystals

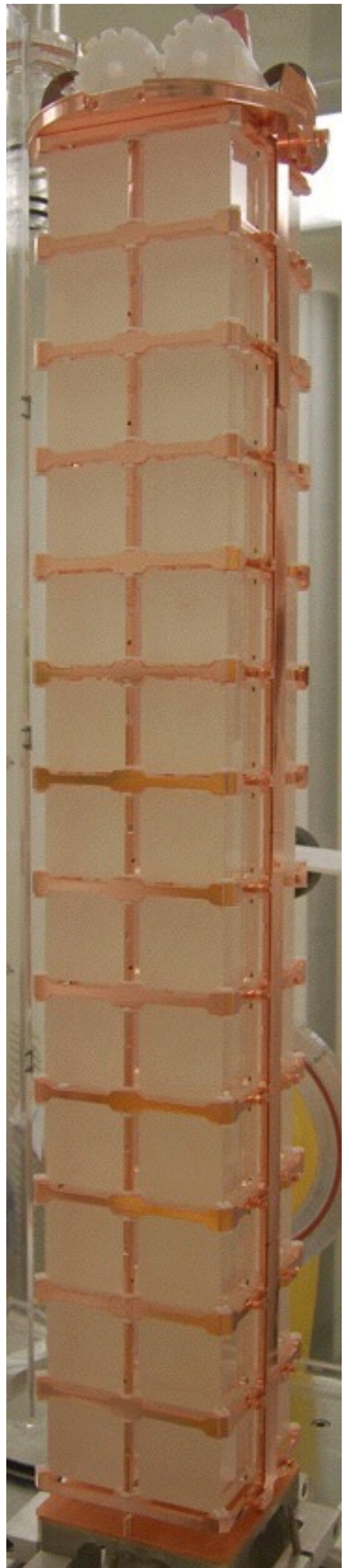
Step 2: Assembling the tower



Step 3: wiring the detectors

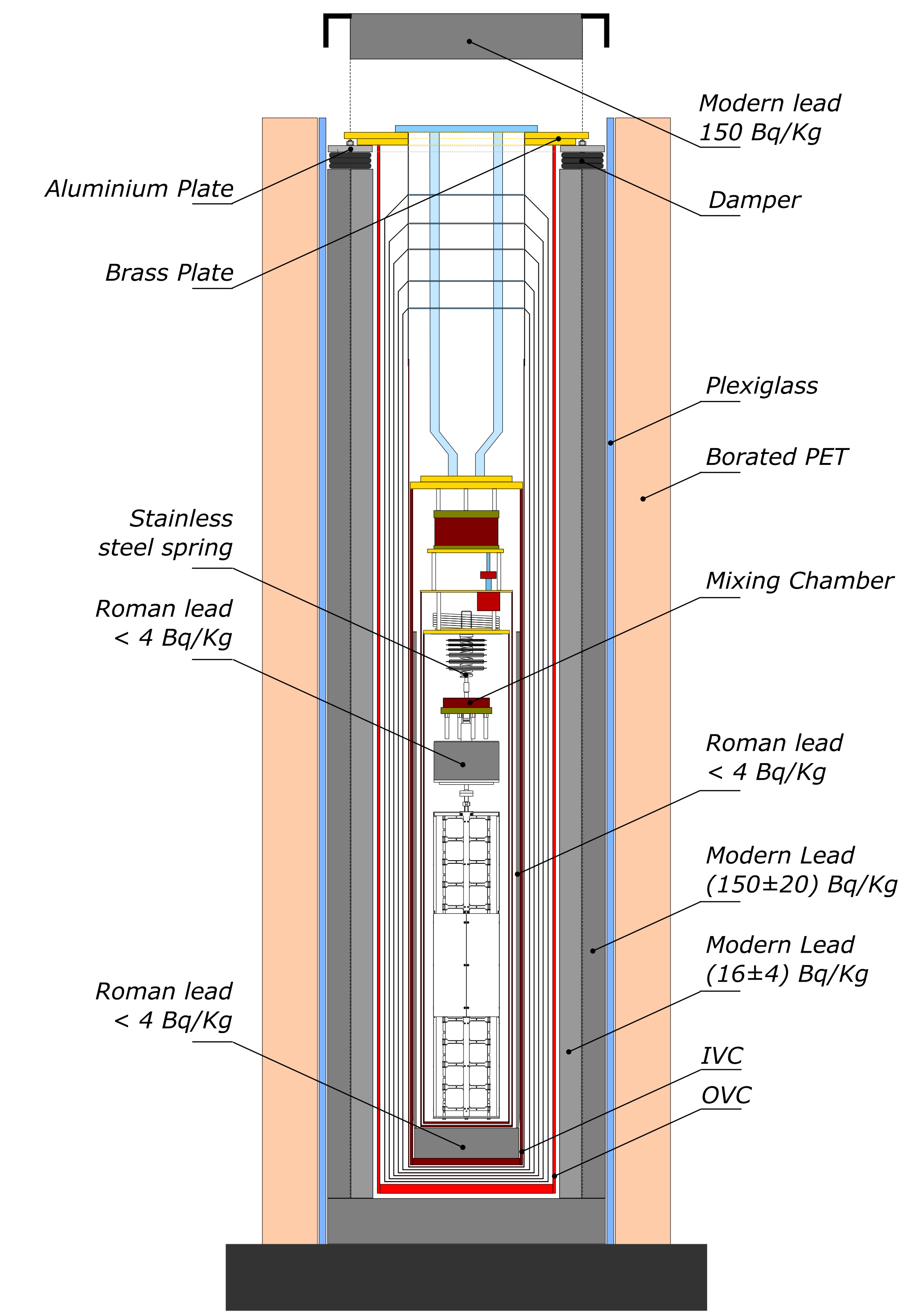
- Entire CUORE assembly takes place in N_2 flushed glove boxes in clean room underground
- Reduce radioactive contamination from Rn, environment, and even US!

The First Tower of CUORE: CUORE-0



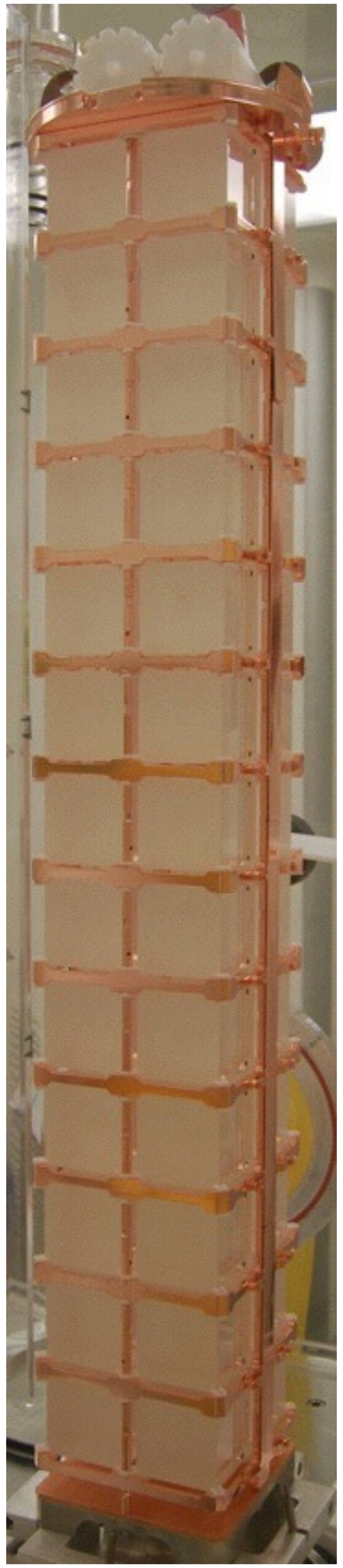
- First tower off the CUORE assembly line
  - Assembled with same materials and procedures
- Operated as a single tower in the old Cuoricino Cryostat
- CUORE-0 Objectives:
  1. Full scale debug of the CUORE assembly line
  2. Energy Resolution of 5 keV FWHM
  3. Validation of the CUORE α-background
  4. Formidable $0\nu\beta\beta$ search in its own right

◉ Detector paper arXiv:1604.05465 (submitted to JINST)



	CUORICINO	CUORE-0 (Goal)	CUORE (Goal)
^{130}Te Mass (kg)	11	11	206
Background (cnts/keV/kg/yr)	0.17	0.05	0.01
Resolution (keV)	5.8	5	5
$T_{1/2}$ Sensitivity (10^{24} yr) @ 90%C.L.	2.6	2.9	95

The First Tower of CUORE: CUORE-0



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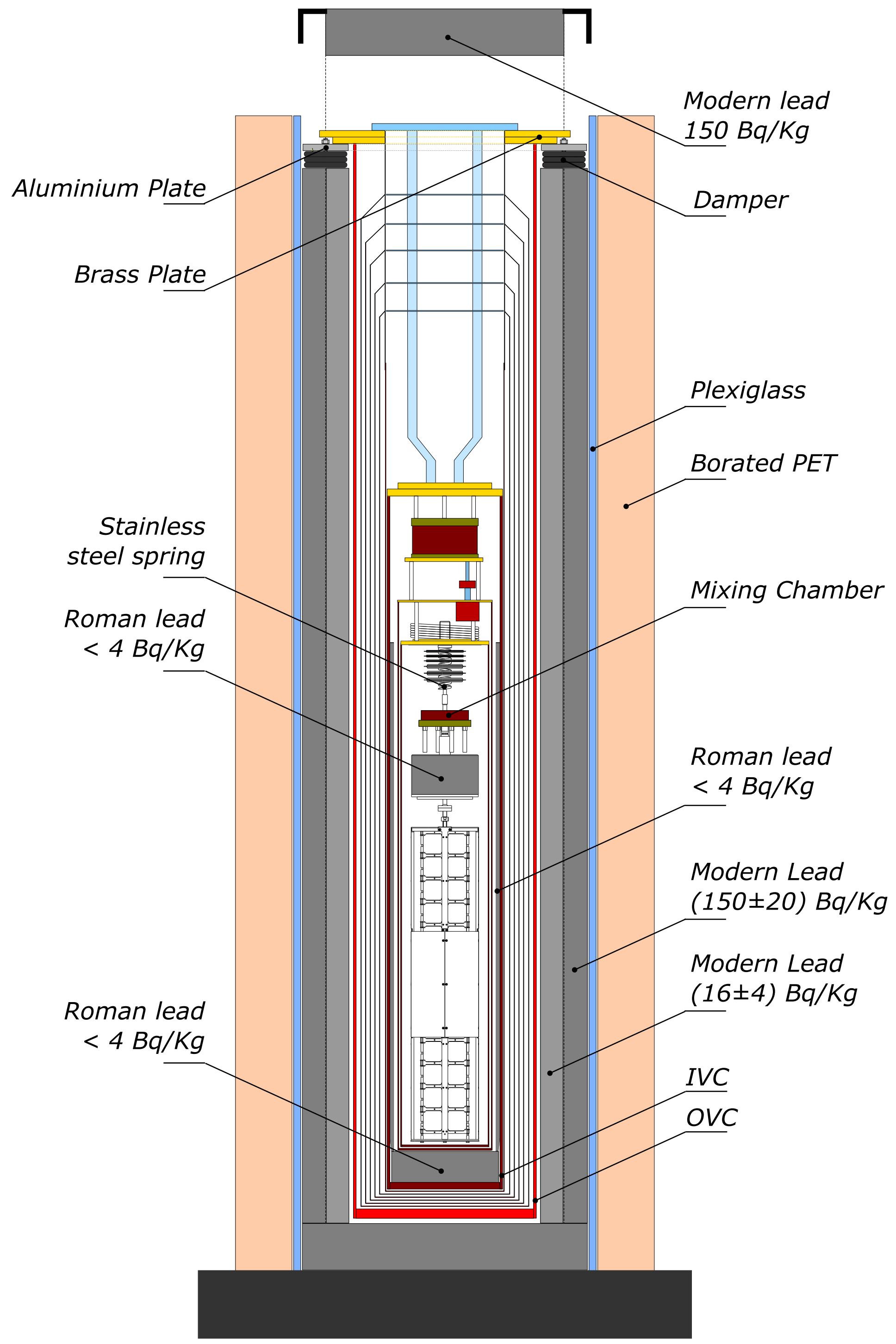

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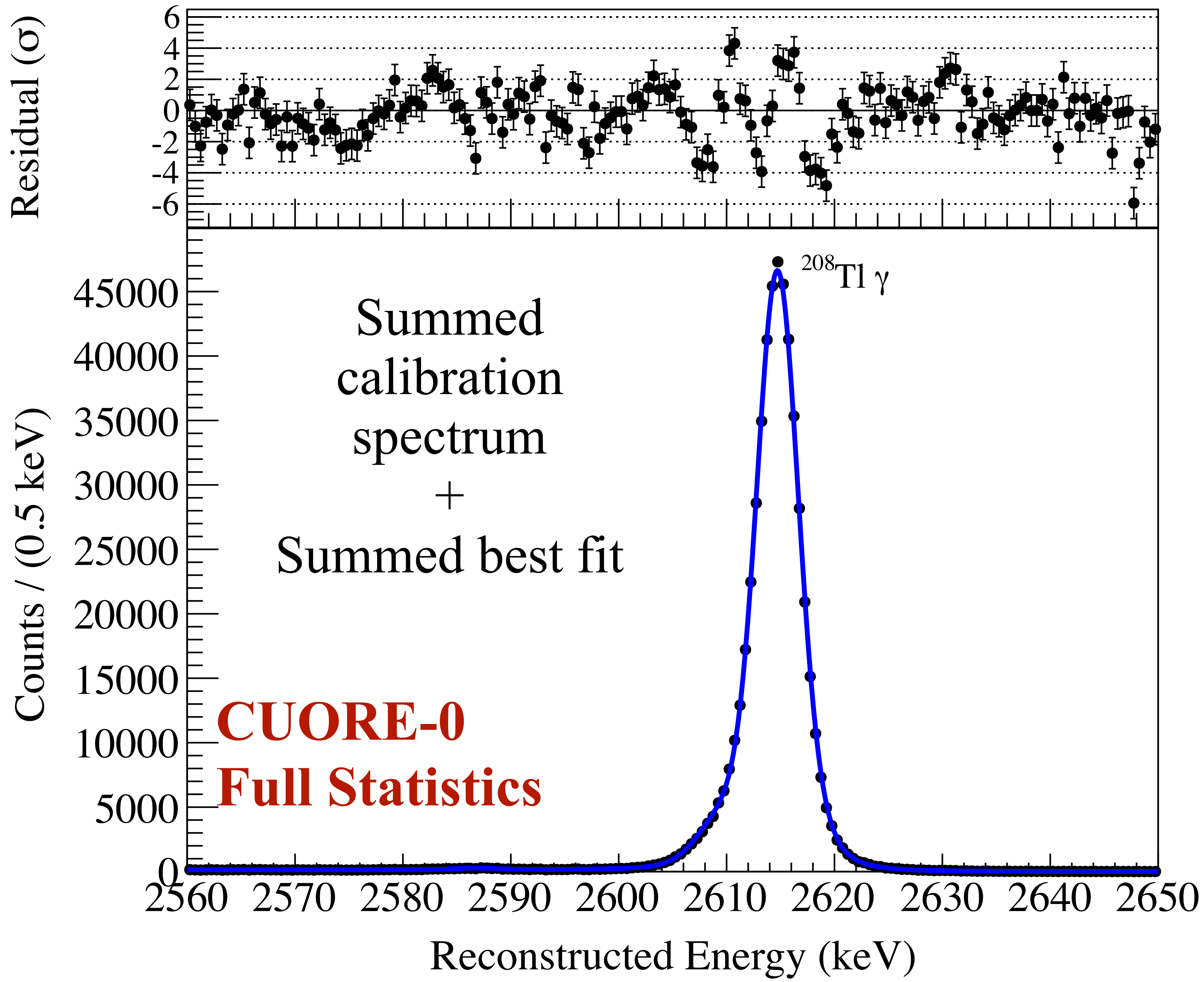
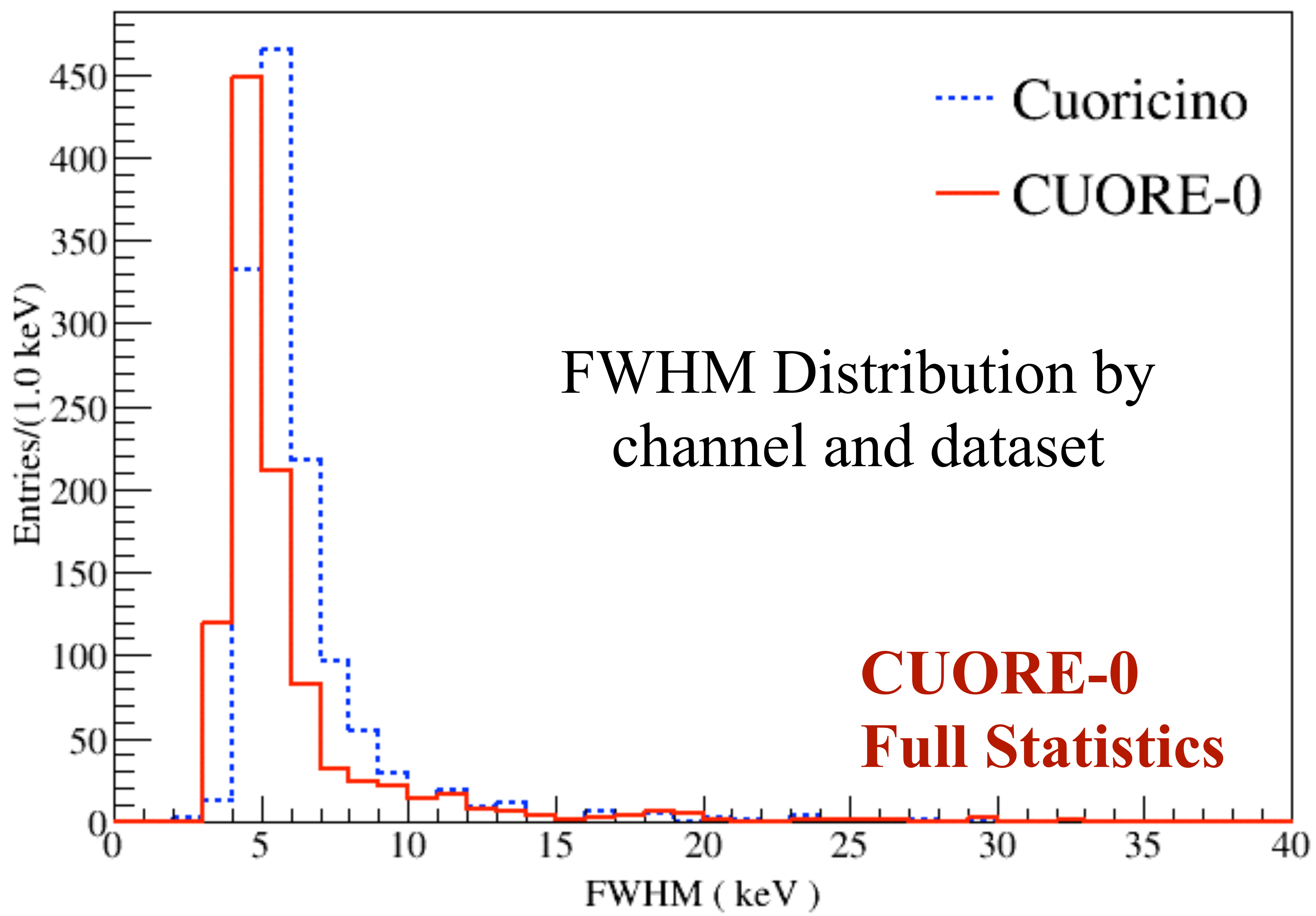
CUORE-0 Energy Resolution

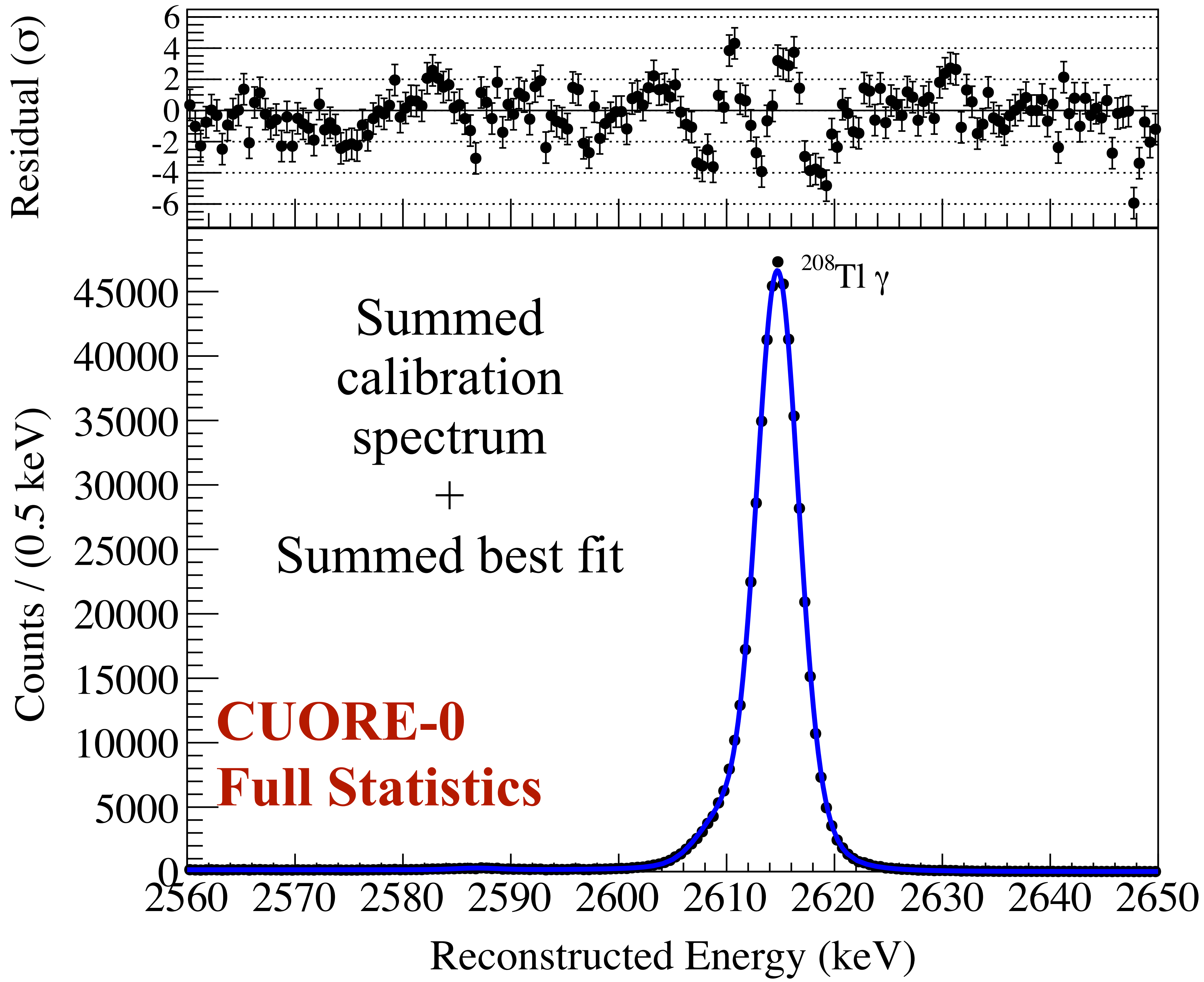


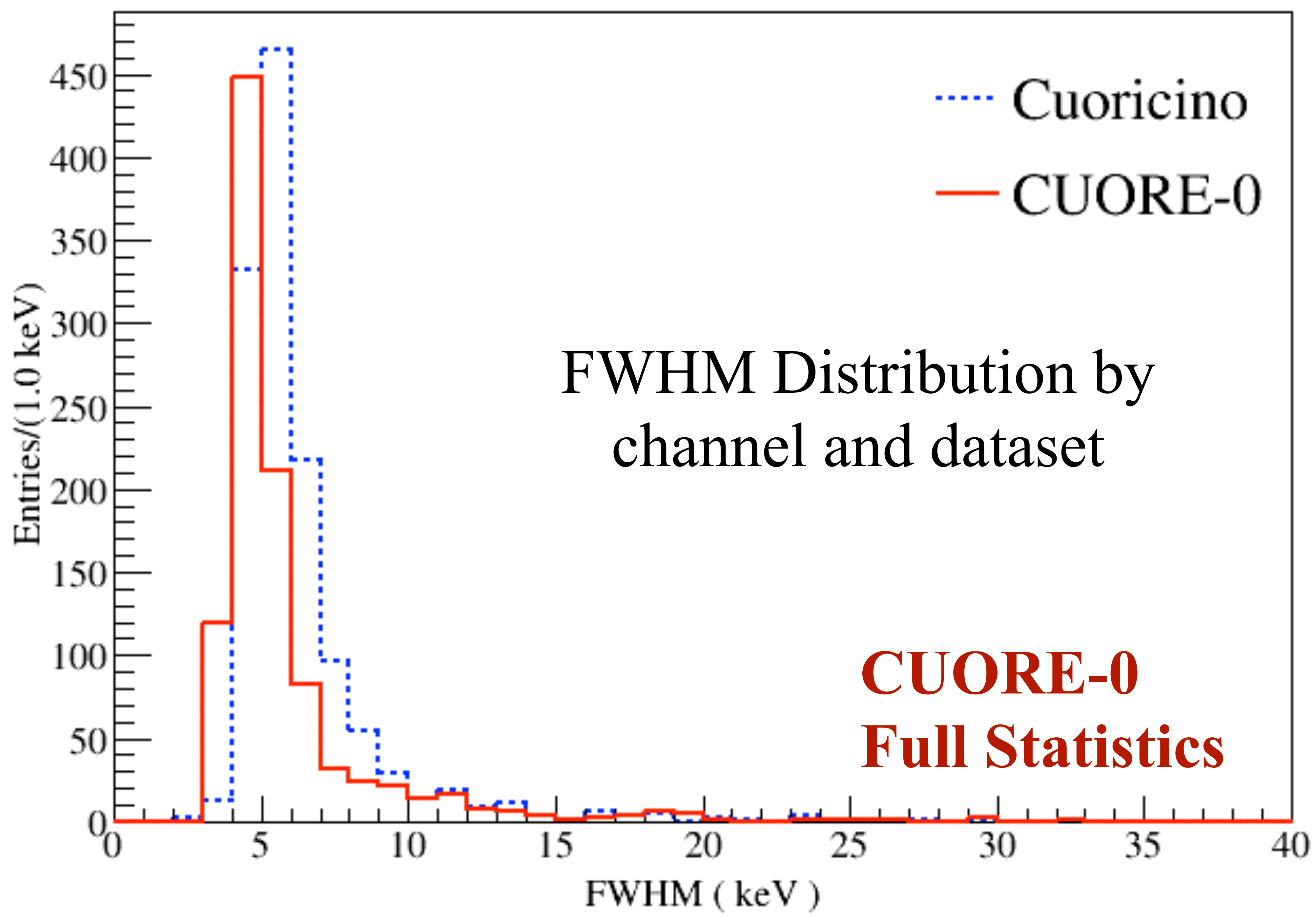


✓ CUORE-0 achieves the CUORE energy resolution goal of 5 keV FWHM at 2.6 MeV

	Effective FWHM (Harmonic Mean)	FWHM Distribution RMS
Cuoricino	5.8 keV	2.1 keV
CUORE-0	4.9 keV	2.9 keV
CUORE Goal	5.0 keV	

CUORE-0 Energy Resolution





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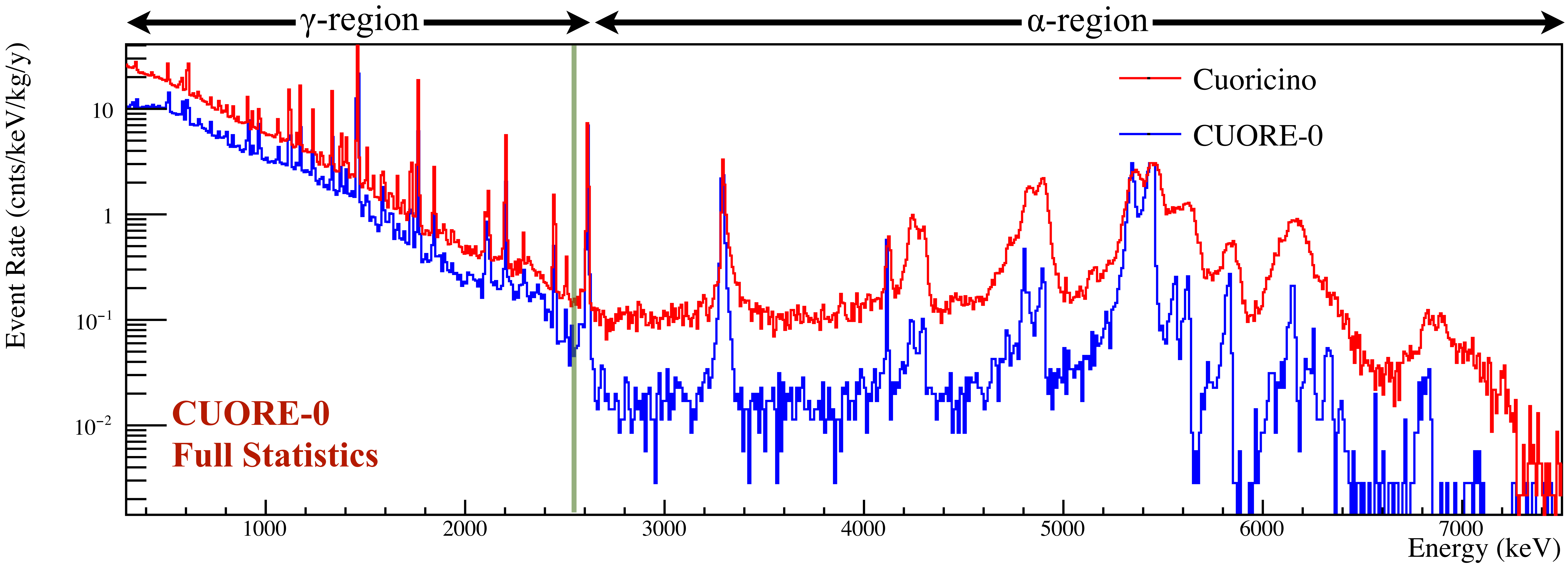
CUORE-0 α-Background

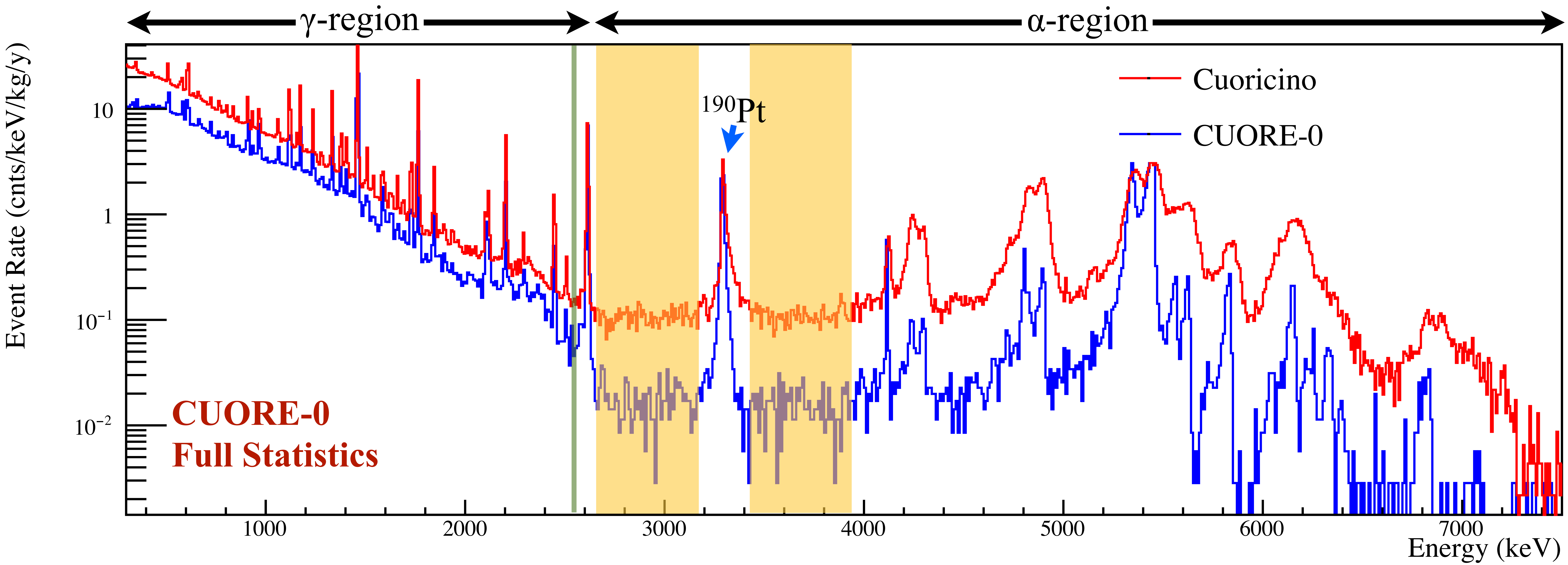


✓ CUORE-0 validates the α-background reduction procedures for CUORE

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
CUORE Goal	0.01	<0.01

CUORE-0 α-Background



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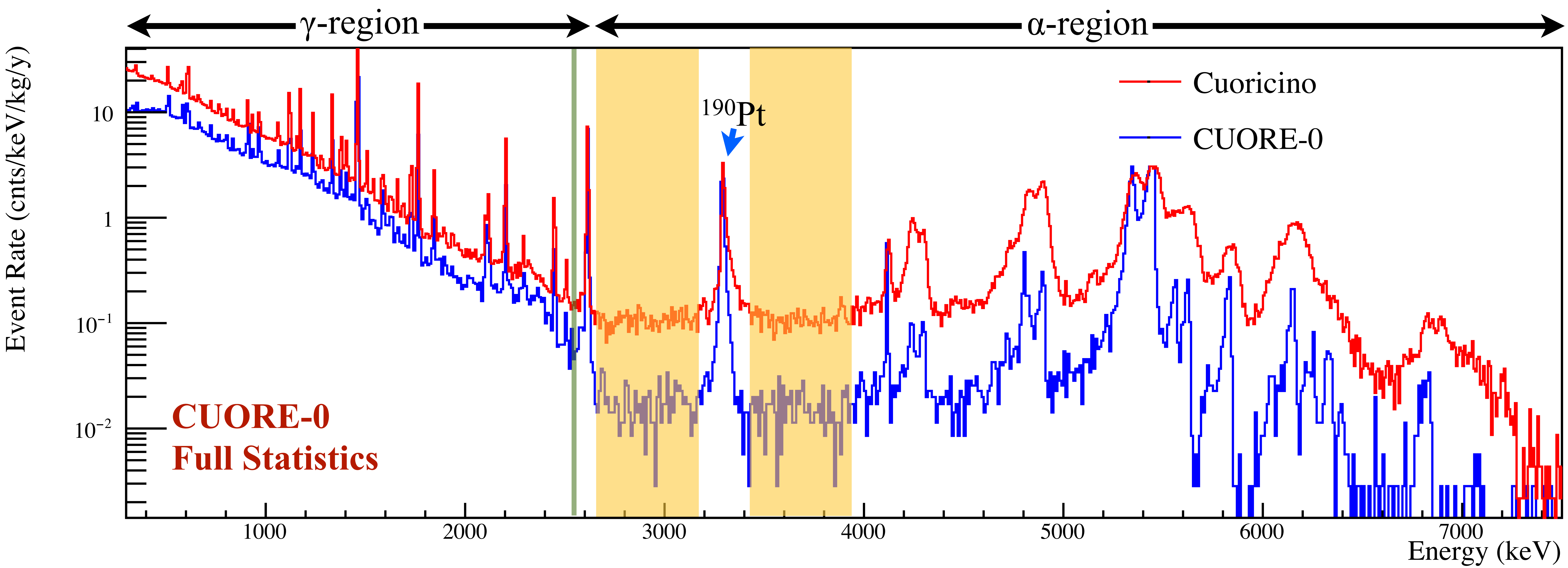

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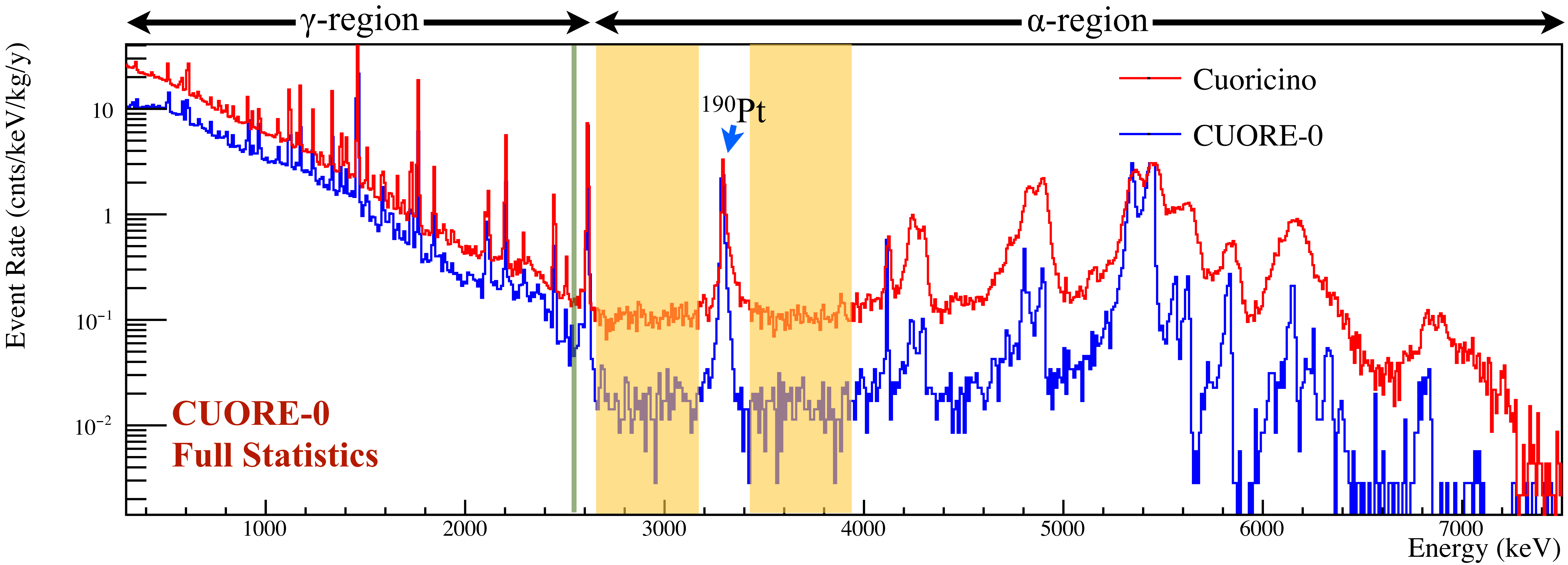

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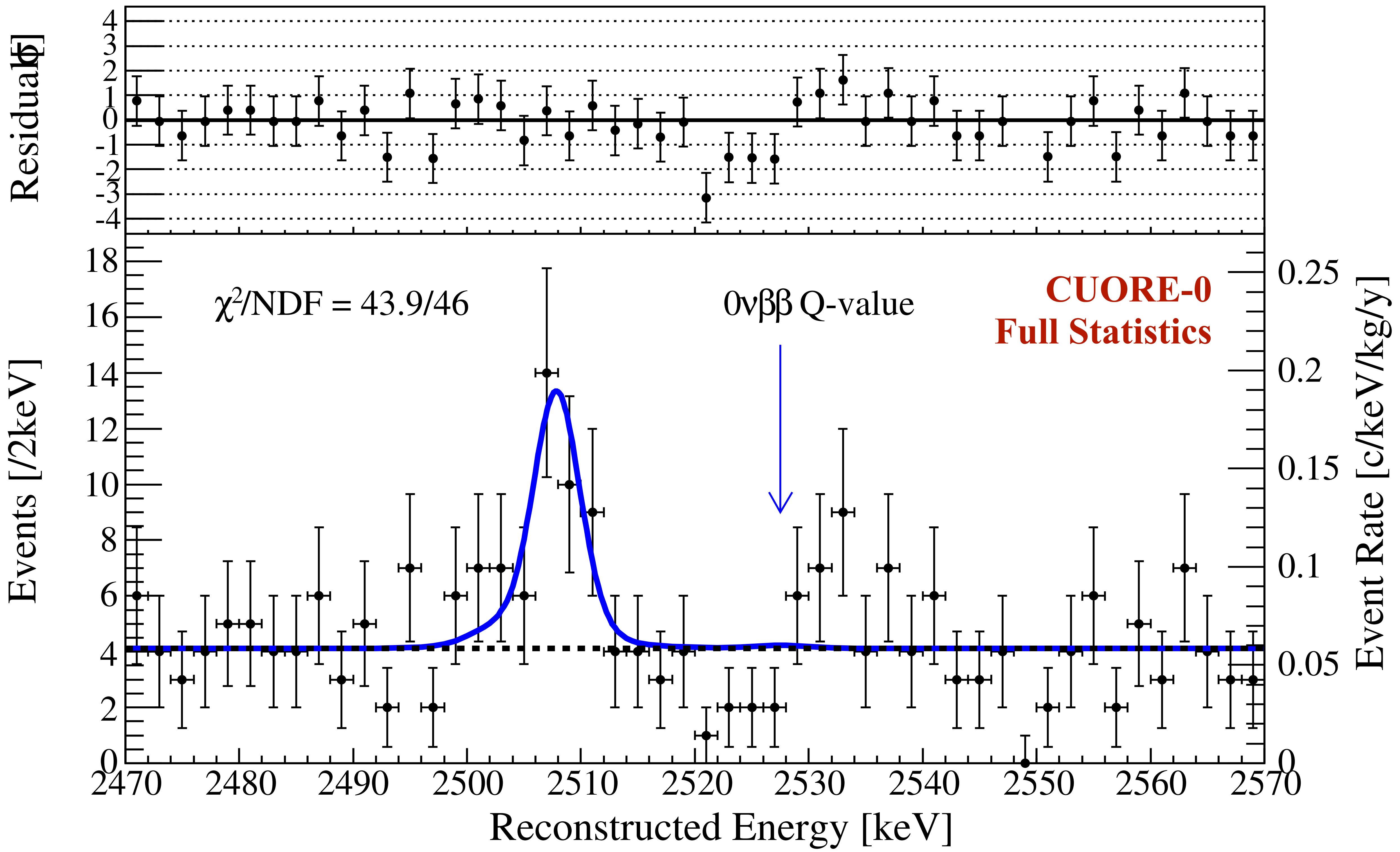
Final CUORE-0 Result



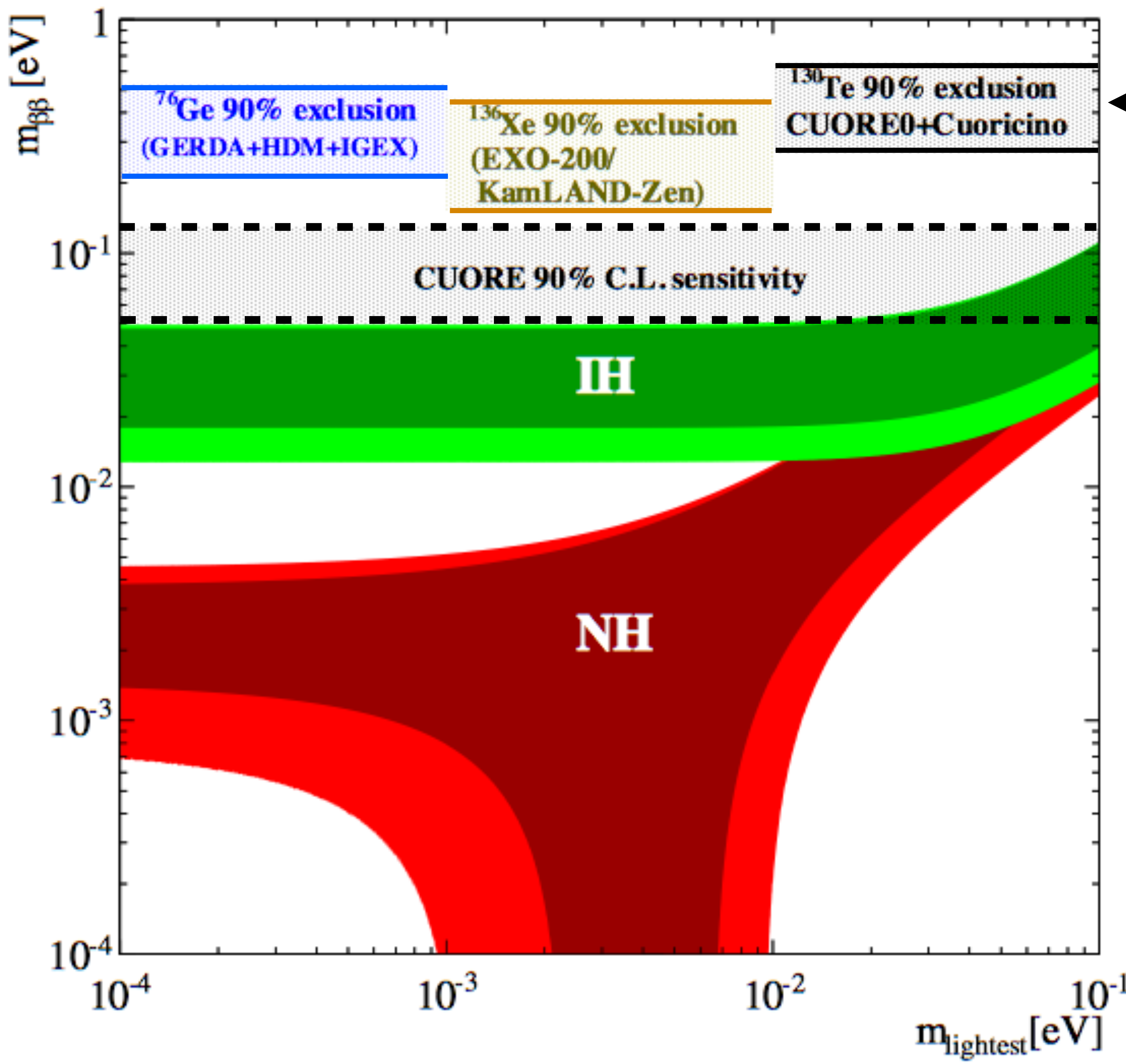
CUORE-0 + Cuoricino combined Limit:

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

- 233 candidate events in the ROI from 2470 - 2570 keV
- Simultaneous UEML fit over all channels and datasets
- Background in the ROI of 0.058±0.004 cnts/keV/kg/yr
- Signal detection efficiency of 81.3 ± 0.6 %
- Projected position uncertainty at $Q_{\beta\beta}$ of ~100 eV
- Projected energy resolution at $Q_{\beta\beta}$ of 5.1 ± 0.2 keV
- Expected 90% sensitivity of $T_{1/2} > 2.9 \times 10^{24}$ yr

Phys.Rev.Lett. 115 (2015) 10, 102502
Phys.Rev.C 93, 045503 (2016)

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))
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Status of CUORE

feature

April 23, 2015

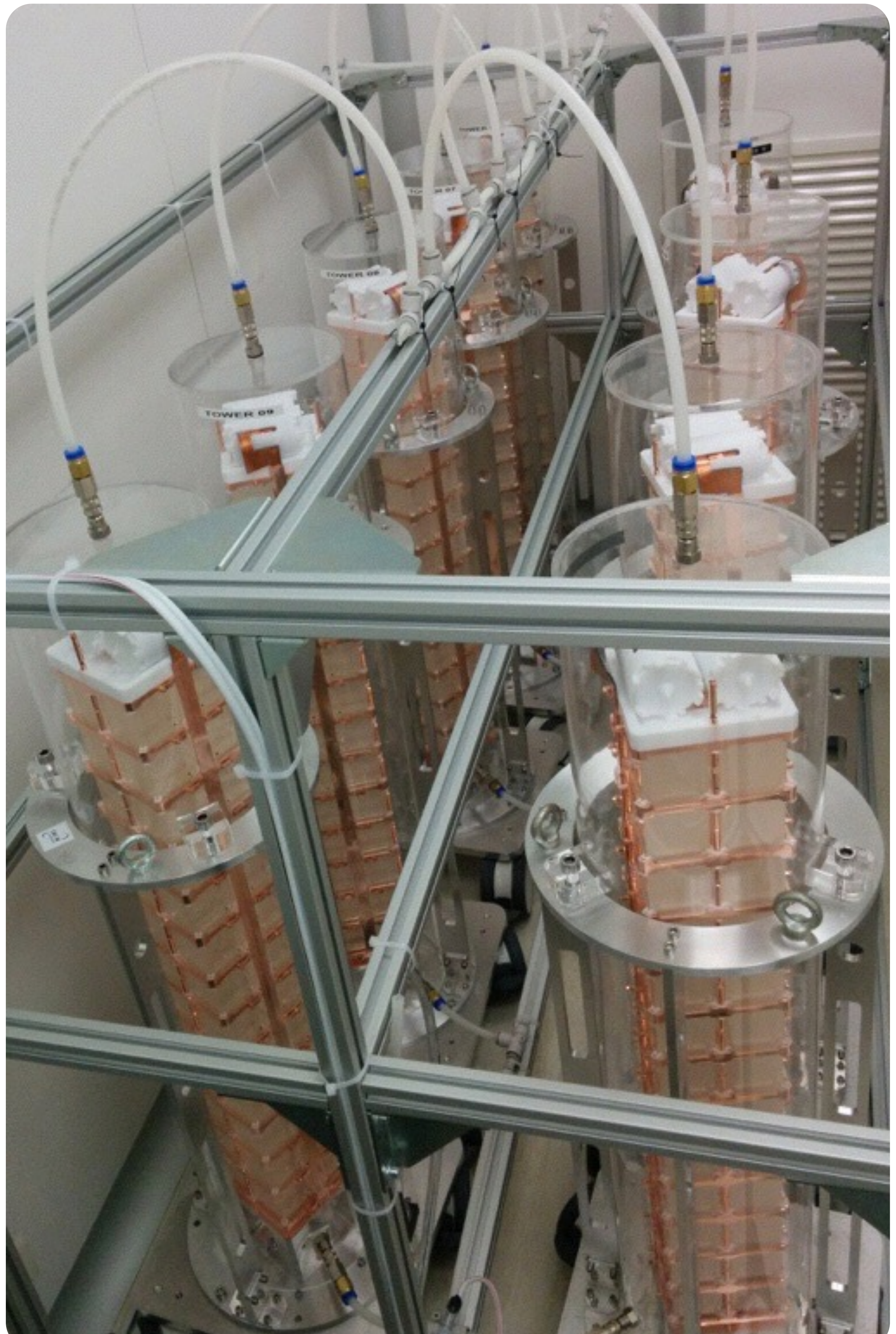
Extreme cold and shipwreck lead

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

CUORE Detector Assembly

CUORE



1-9

Detector Construction Completed June 2014

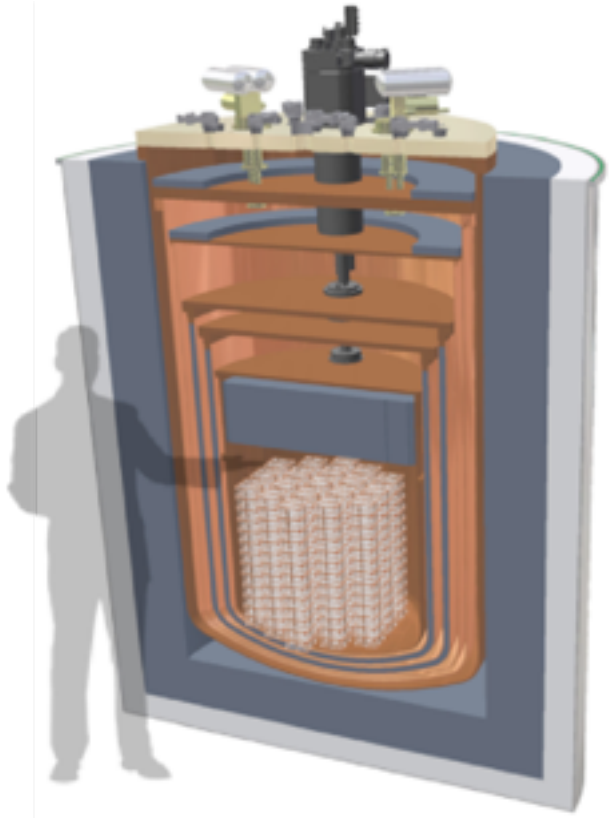
- Total detector assembly time: ~18 Months
- Detectors stored in clean room under constant N_2 flux
- Currently awaiting cryostat completion

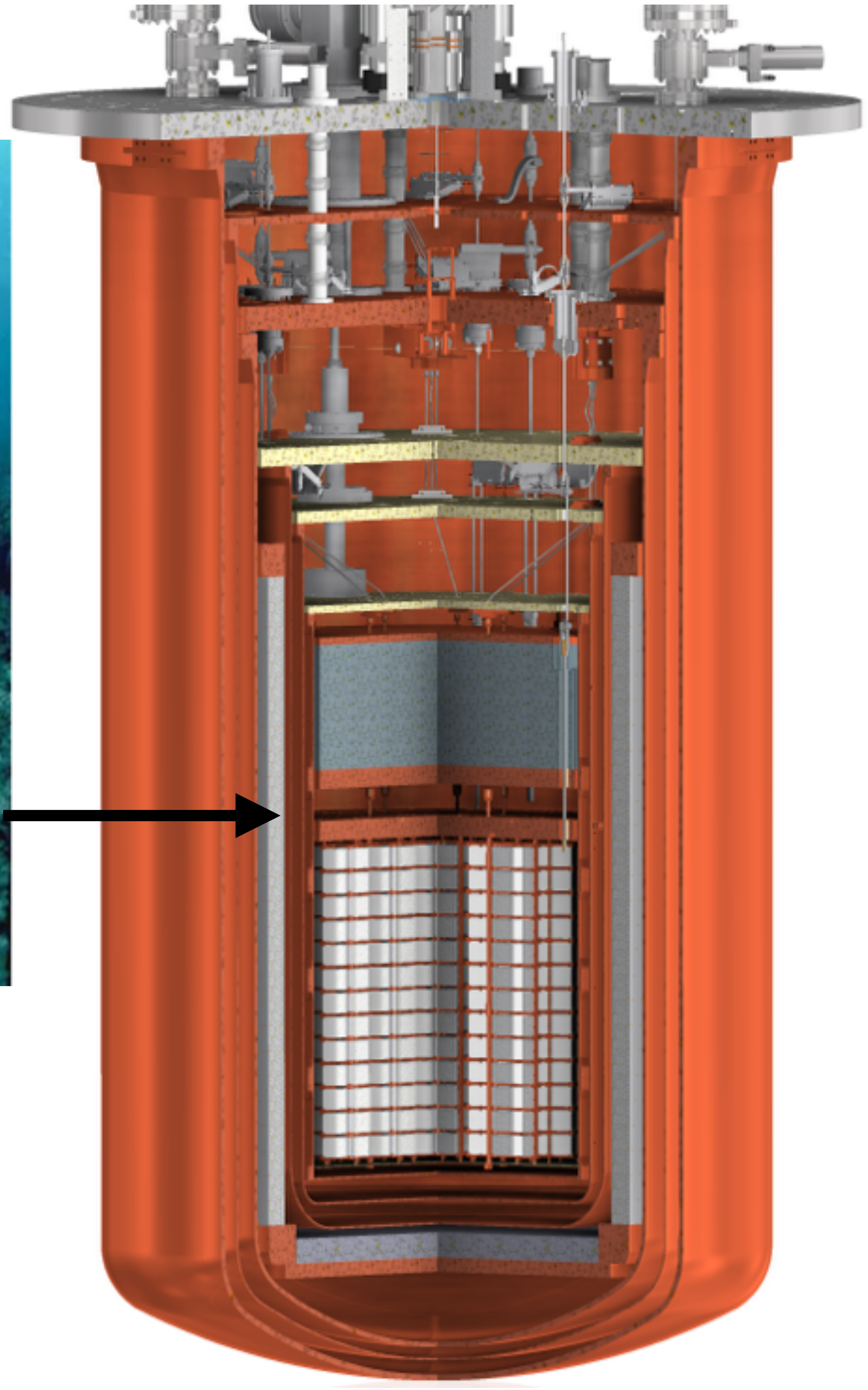
10-16

17-19

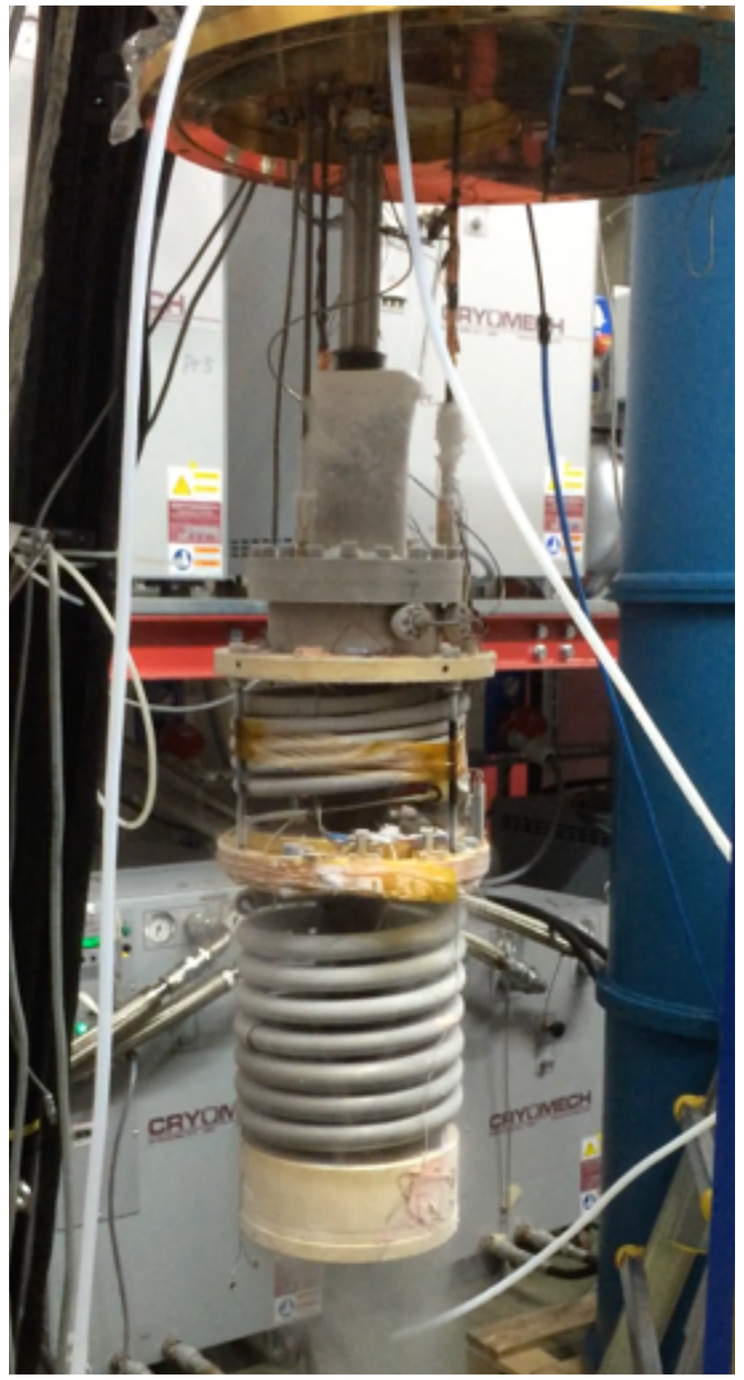
The CUORE Cryostat

- Brand new state of the art dilution refrigerator
  - Cool 15 t of material to < 4 K
  - Cool 1.5 t of material to < 10mK
- Built using low radioactivity materials
  - Clean copper
  - 30 cm of shielding in every direction
  - Lateral lead shielding made from ultra low radioactivity ancient Roman lead
- Cryostat commissioned in 4 cool down runs between 2014 and 2016

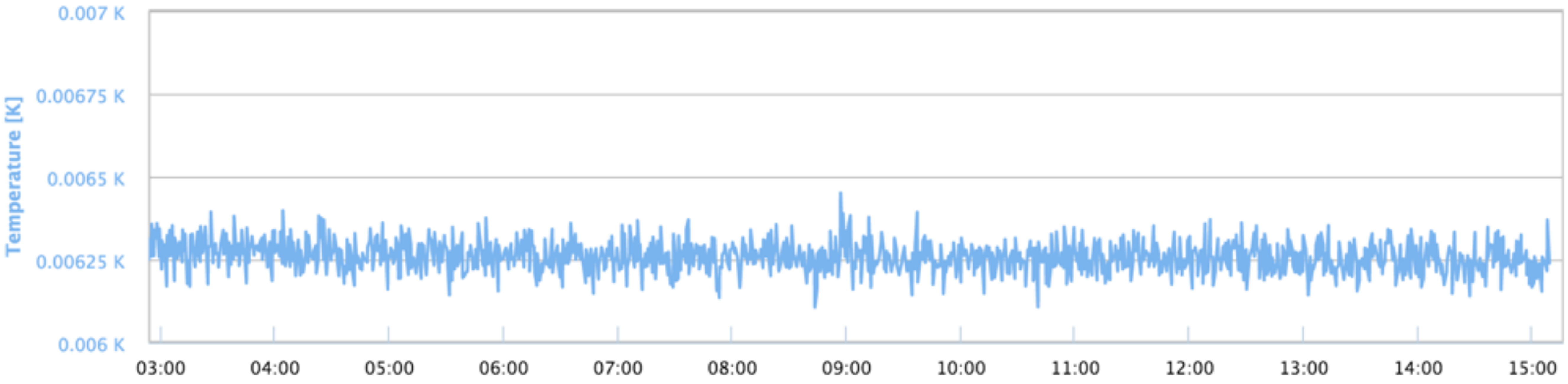




Cryostat Commissioning Run 1



- First commissioning cool down of the cryostat.
  - Cool down to base with no load
- Achieved a base temperature of 5.9 mK
- Cooling power of 3 μW at 10 mK



Cryostat Commissioning Run 1

CUORE

NEWS CENTER

known

Creating the Coldest Cubic Meter in the Universe

A forthcoming neutrino detector will require temperatures approaching absolute zero.

Feature Story Kate Greene 510-486-4404 • OCTOBER 28, 2014

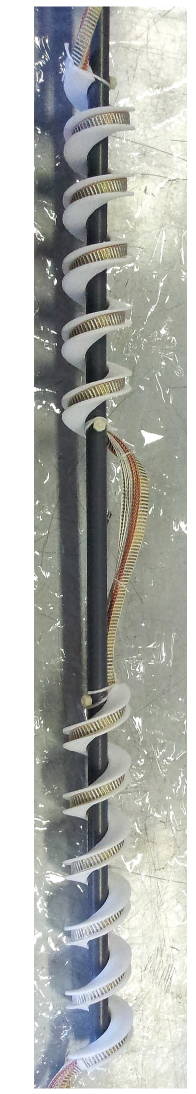
In an underground laboratory in Italy, an international team of scientists has created the coldest cubic meter in the universe. The cooled chamber—roughly the size of a vending machine—was chilled to 6 milliKelvin or -273.144 degrees Celsius in preparation for a forthcoming experiment that will study neutrinos, ghostlike particles that could hold the key to the existence of matter around us.

The collaboration responsible for the record-setting refrigeration is called the Cryogenic Underground Observatory for Rare Events (CUORE), supported jointly by the Istituto Nazionale di Fisica Nucleare (INFN) in Italy, and the Department of Energy's Office of Science and National Science Foundation in the US. Lawrence Berkeley National Lab (Berkeley Lab) manages the CUORE project in the US. The CUORE collaboration is made of 157 scientists from the U.S., Italy, China, Spain, and France, and is based in the underground Italian facility called Laboratori Nazionali del Gran Sasso (LNGS) of the INFN.

"We've been building this experiment for almost ten years," says Yury Kolomensky, senior faculty scientist in the Physics

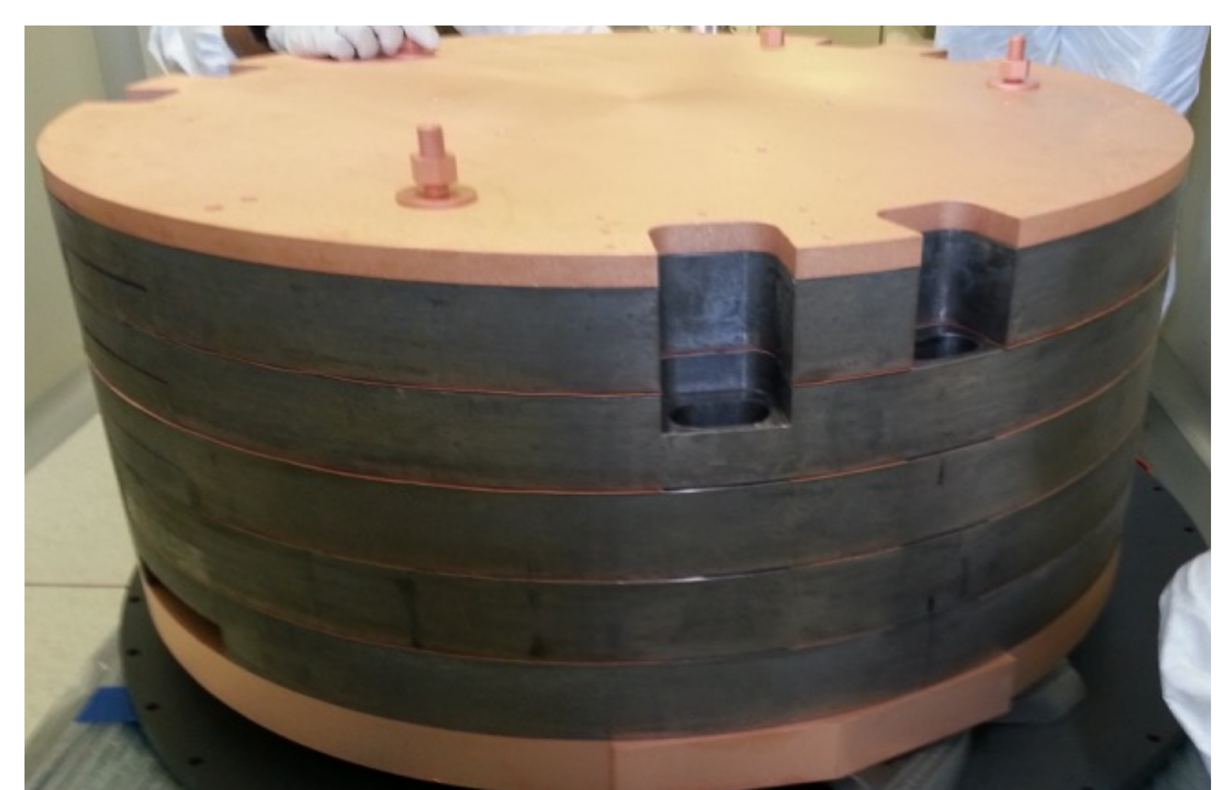
arXiv:1410.1560

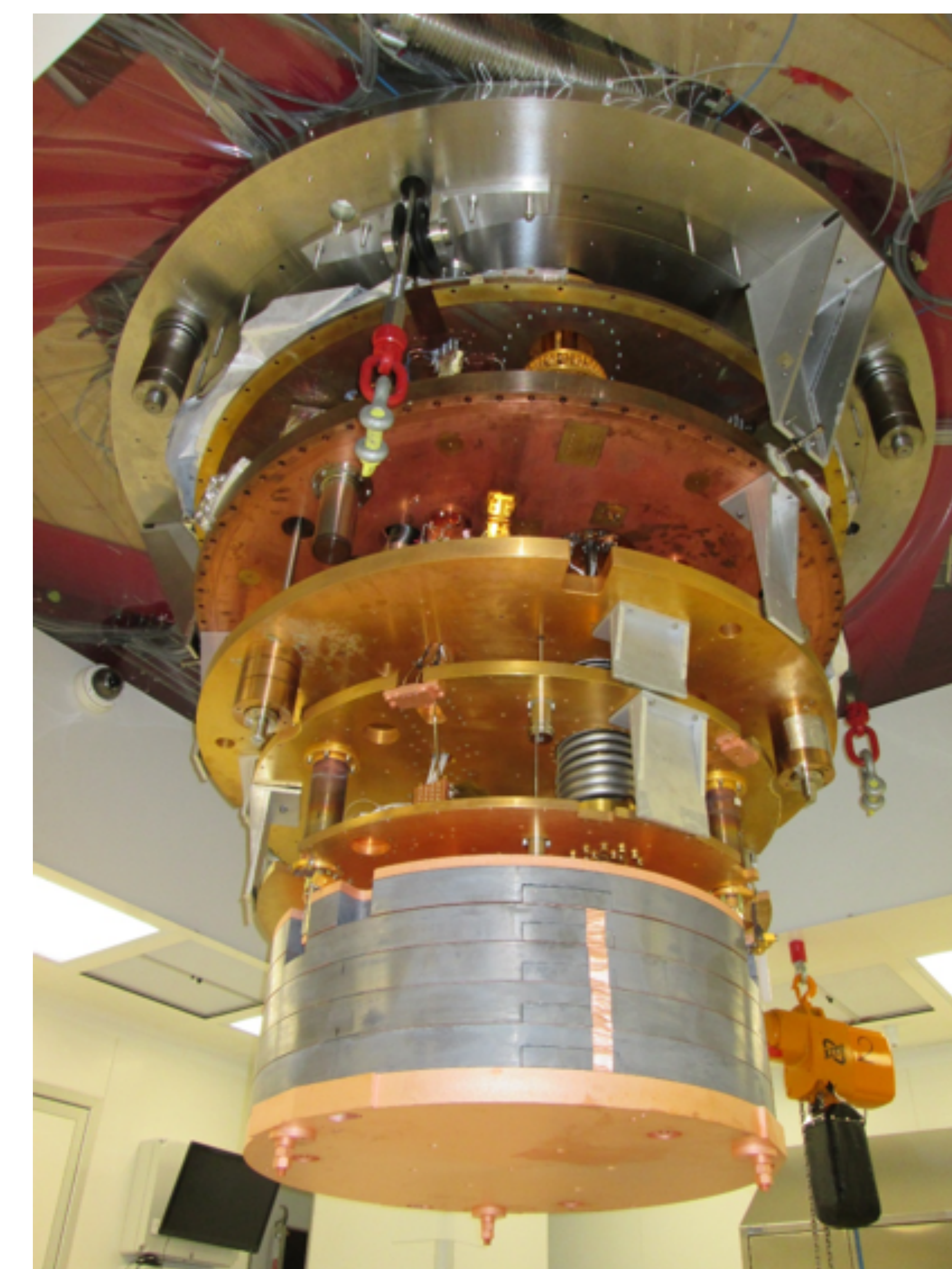
Cryostat Commissioning Run 2 & 3



Run 2: Test of the cryostat wiring

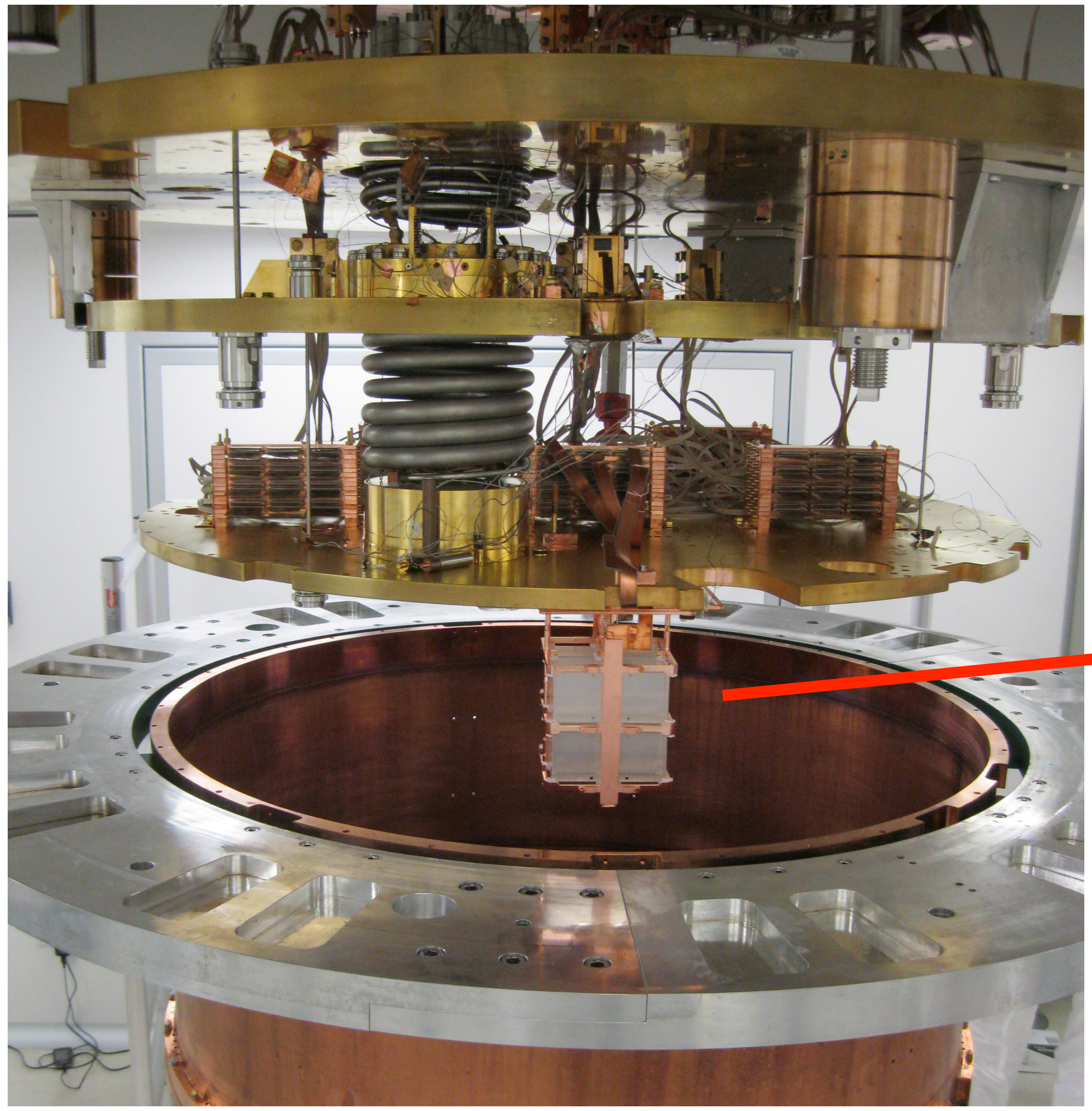
Run 3: Test of the top Pb shielding, fast cooling system, calibration system

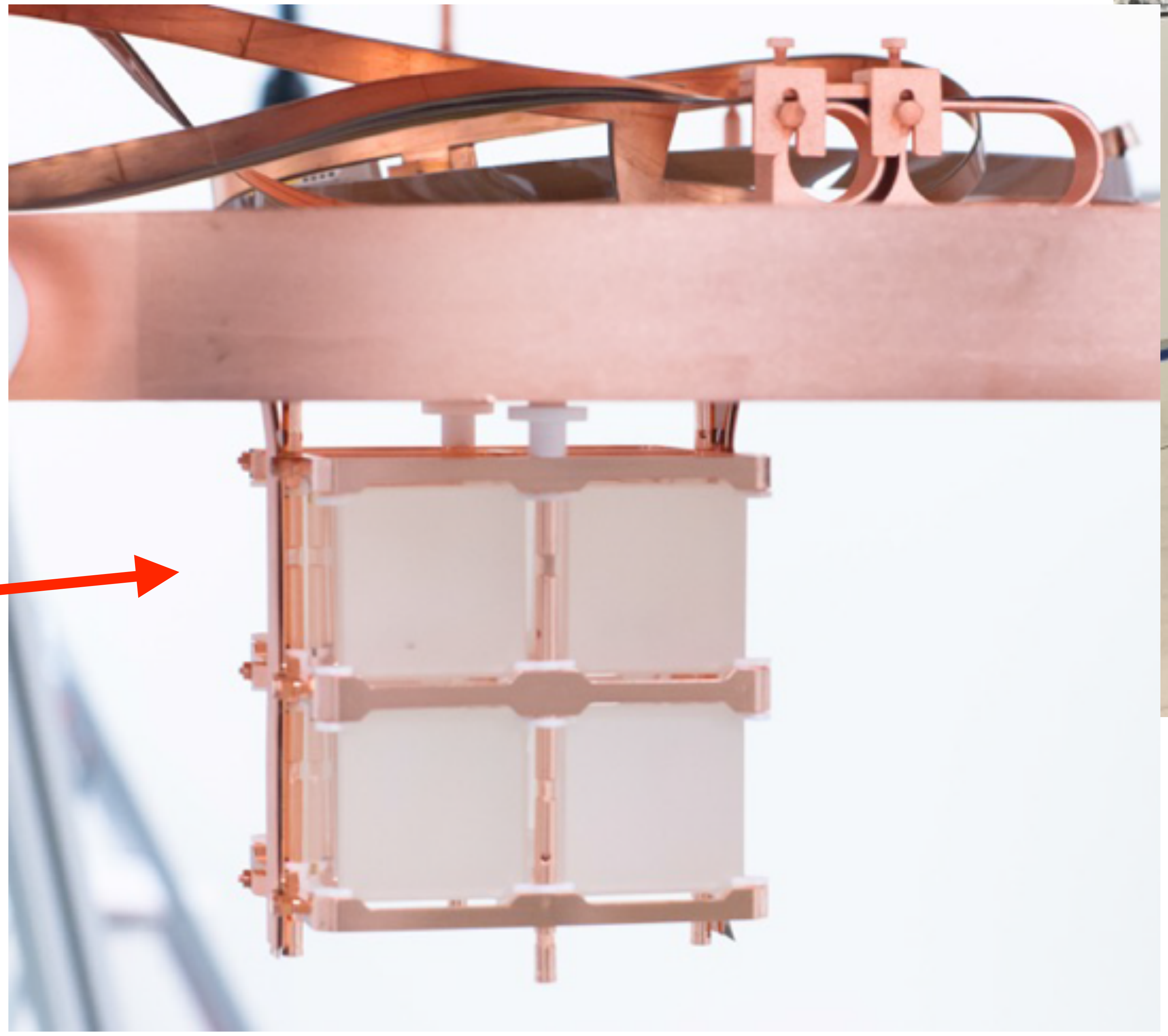


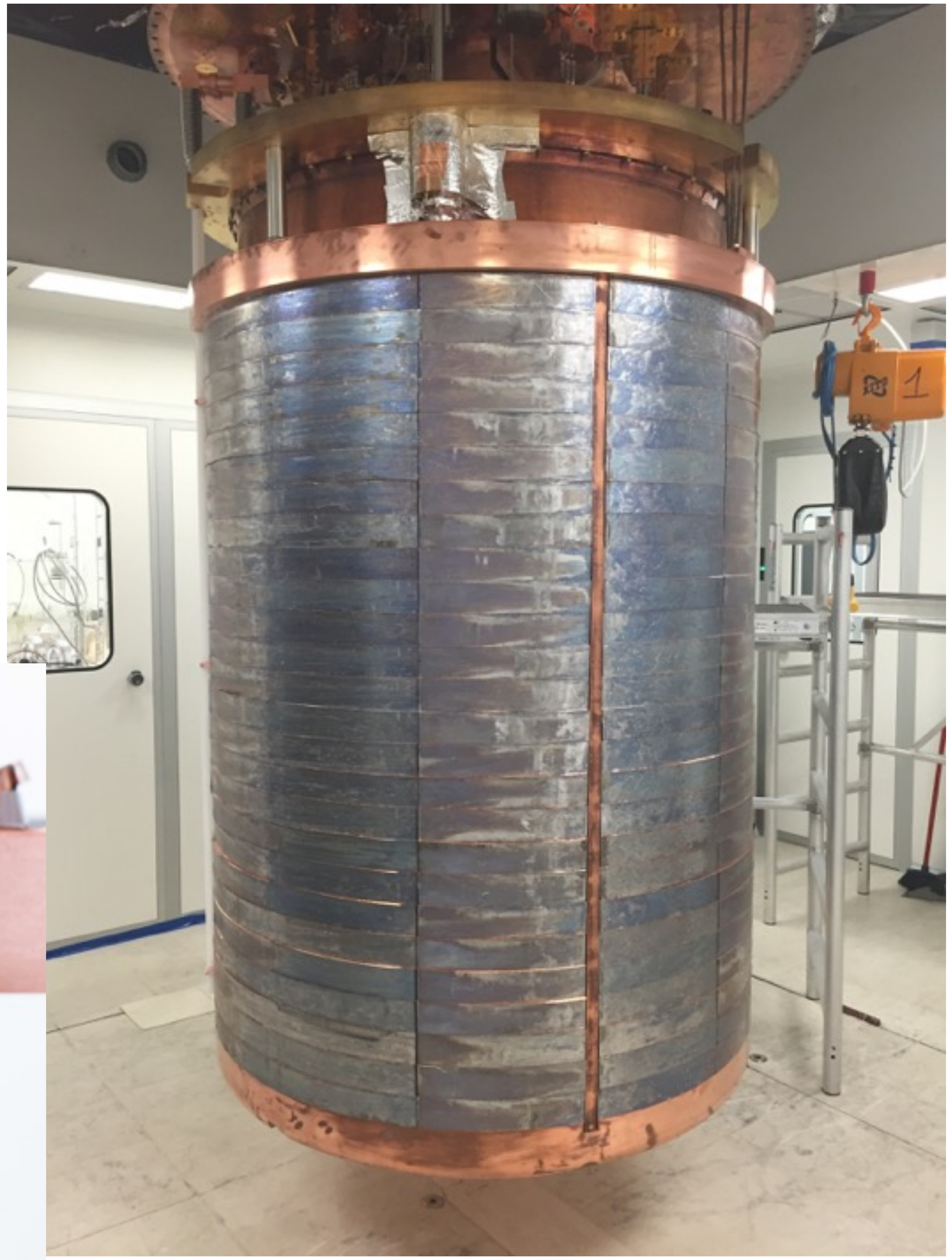


Cryostat Commissioning Run 4

- Test cool down with lateral Roman lead shielding
  - Full load excluding the detector itself
- Mounted small 8 channel bolometric array
  - Commissioned electronics, DAQ, temperature stabilization, calibration system







In Summary...

CUORE-0

- ✓ Collected 9.8 kg·yr of ^{130}Te exposure from March 2013 - March 2015
- ✓ 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
- ✓ Achieved the CUORE energy resolution goal of 5 keV FWHM at 2615 keV
- ✓ Validated the background reduction protocols for CUORE
- ✓ CUORE-0 gives confidence that our background goal is within reach

CUORE

- ✓ 19 towers built and stored under N_2 flux
- ✓ Cryostat achieved 5.9 mK in first commissioning run
- ✓ Auxiliary cryostat systems installed and tested
- ✓ Completed test cool down with bolometers
- ✓ Cryostat commissioning completed March 2016
- ➡ Detector commissioning beginning in summer 2016

Stay tuned!

Connect with CUORE!

Like us on Facebook : "CUORE Experiment"

On the web : http://cuore.lngs.infn.it/

Follow us on Twitter : (Not yet)

Università degli Studi di Milano Bicocca

Università degli Studi di Cassino e del Lazio Meridionale

SINAP

Lux et Veritas

INFN Istituto Nazionale di Fisica Nucleare

Cal Poly San Luis Obispo

Lawrence Livermore National Laboratory

Alma Mater Studiorum Università di Bologna A.D. 1088

Massachusetts Institute of Technology

CSNSM

Shanghai Jiao Tong University 1896

Sapienza Università di Roma

Berkeley Lab

University of South Carolina

UCLA

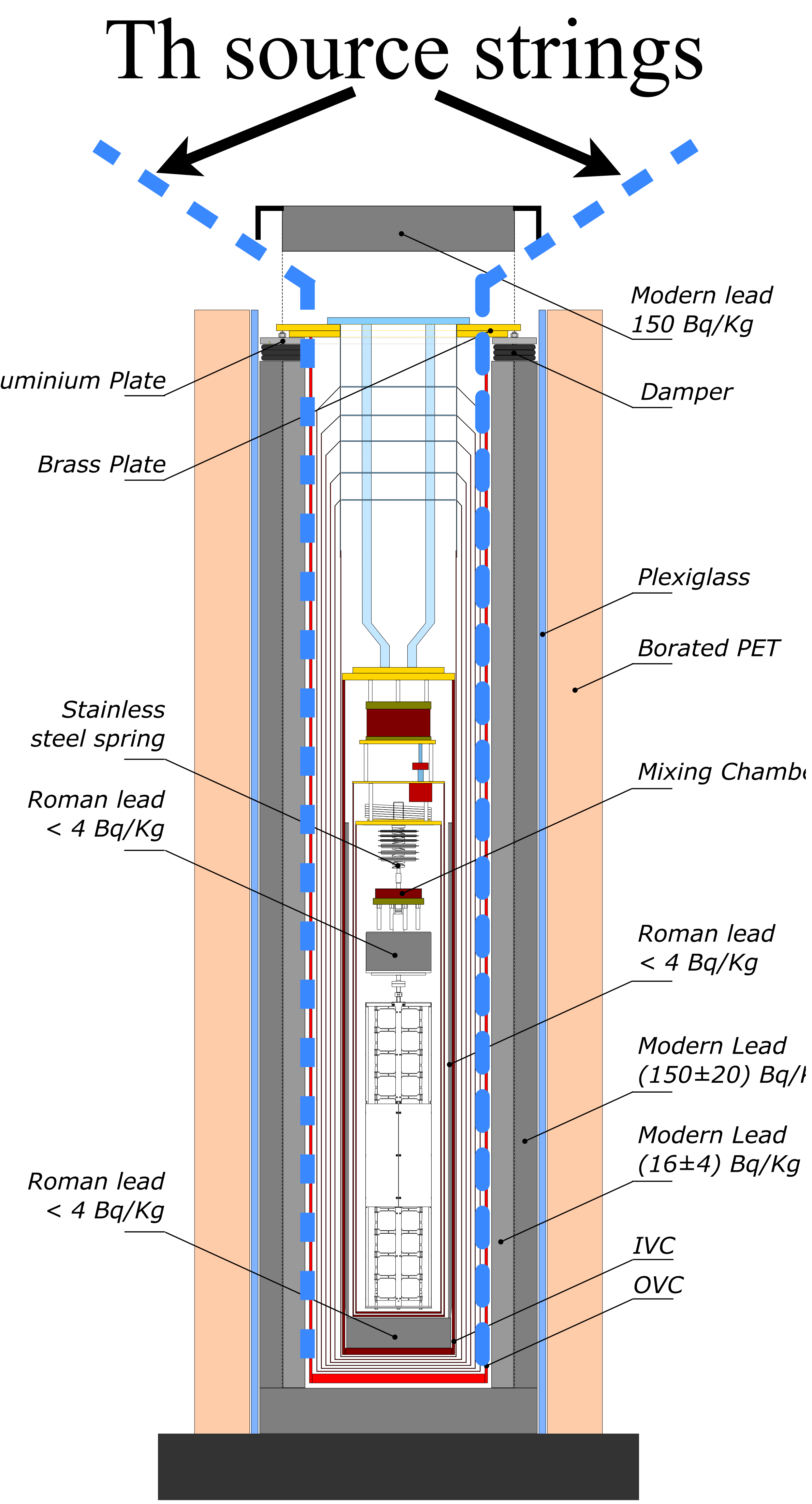
Universitas Studii Paduani MCCXXII

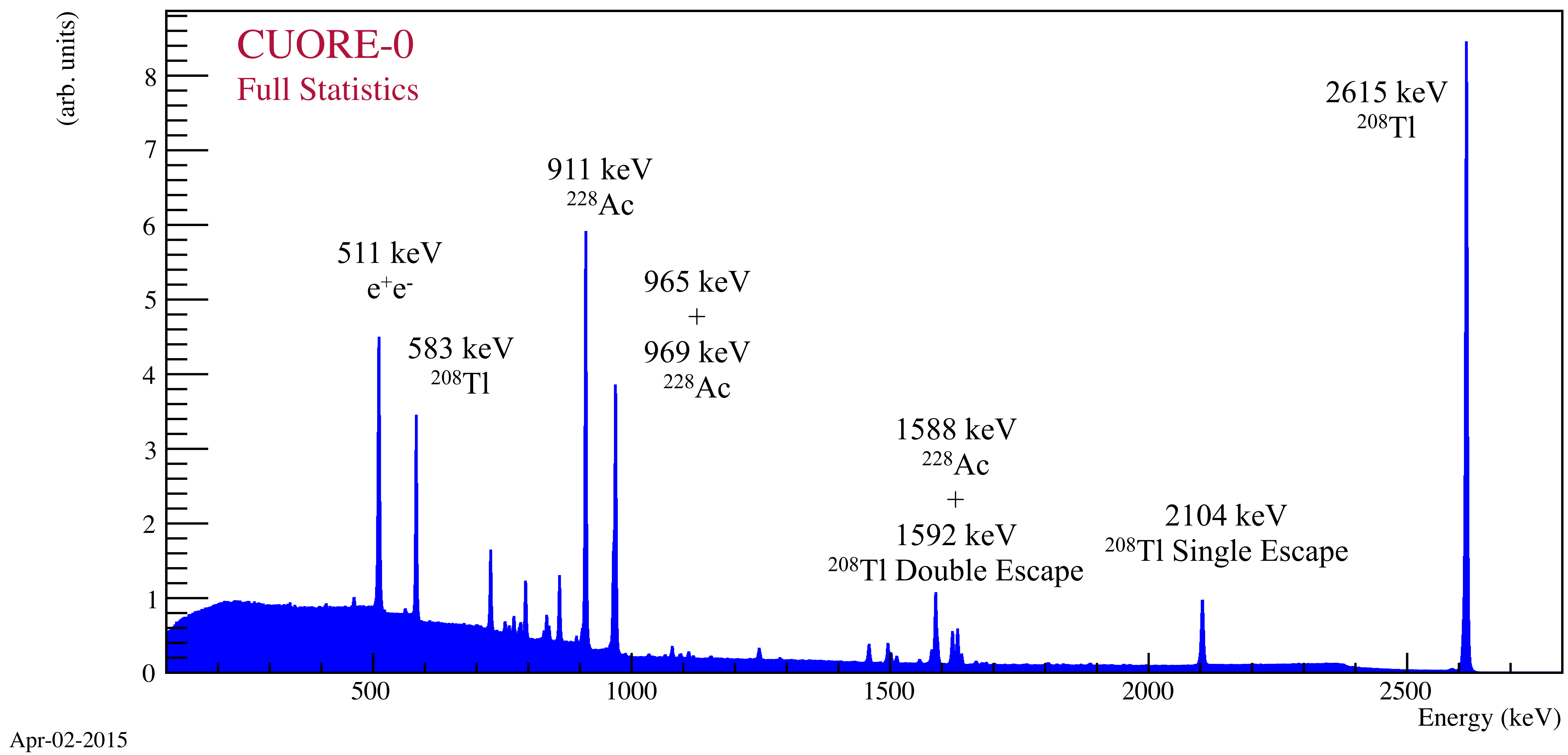
The University of California 1868

CUORE

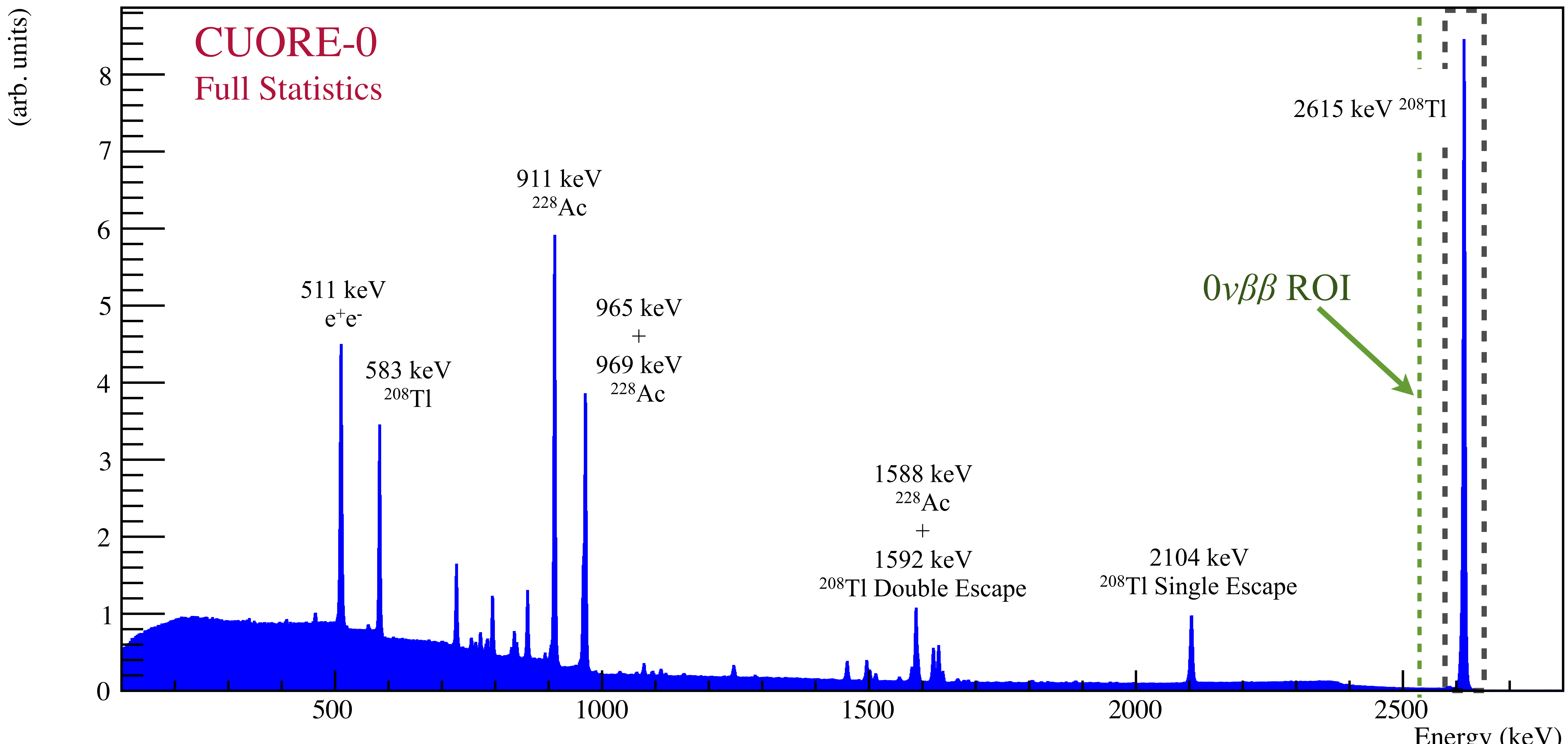
Backup Slides

Detector Energy Calibration





Energy Resolution



Apr-02-2015

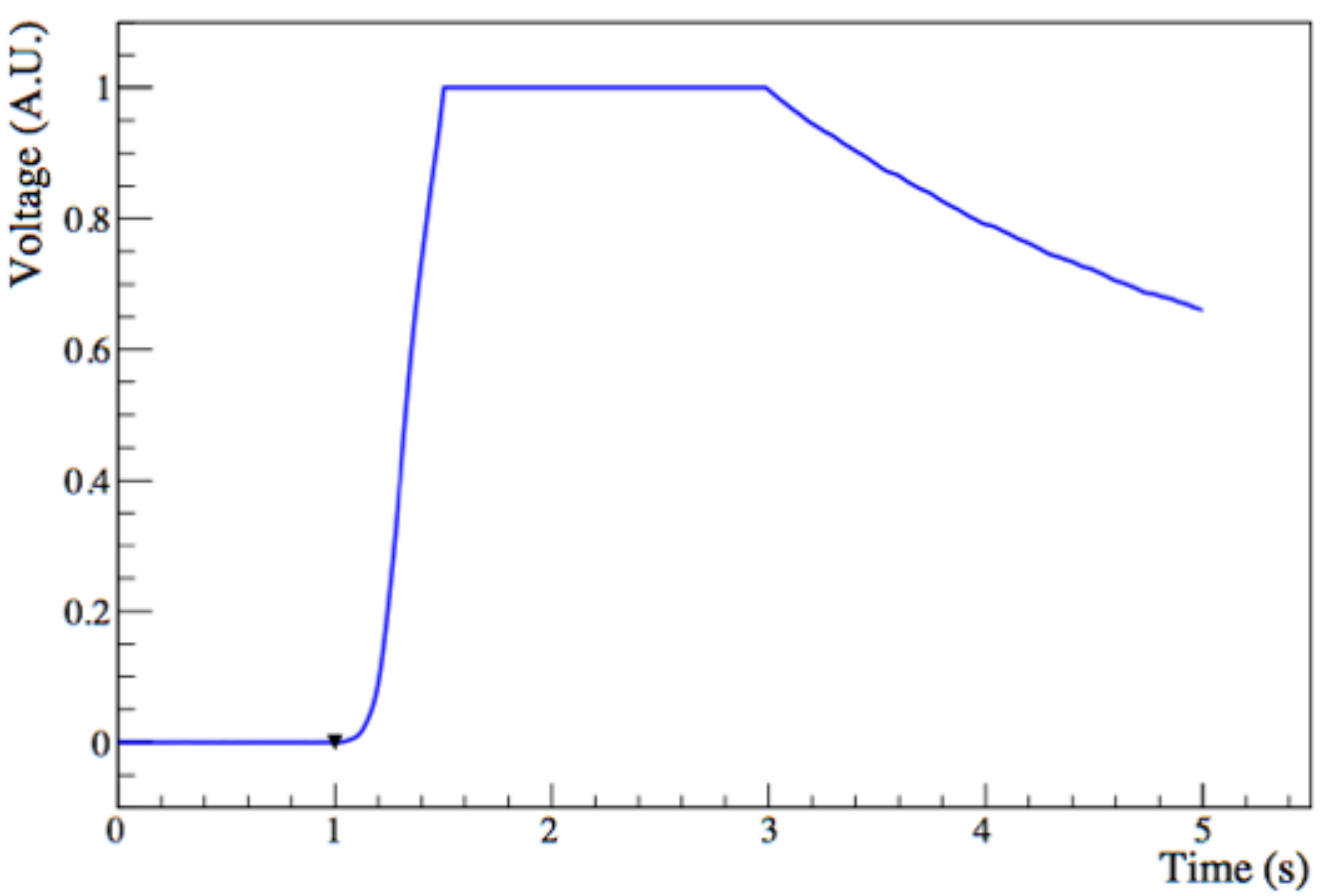
- Use the resolution of the ^{208}Tl line as the benchmark

Event Cuts

... or how we try to get rid of any non-signal-like events

Event Cuts

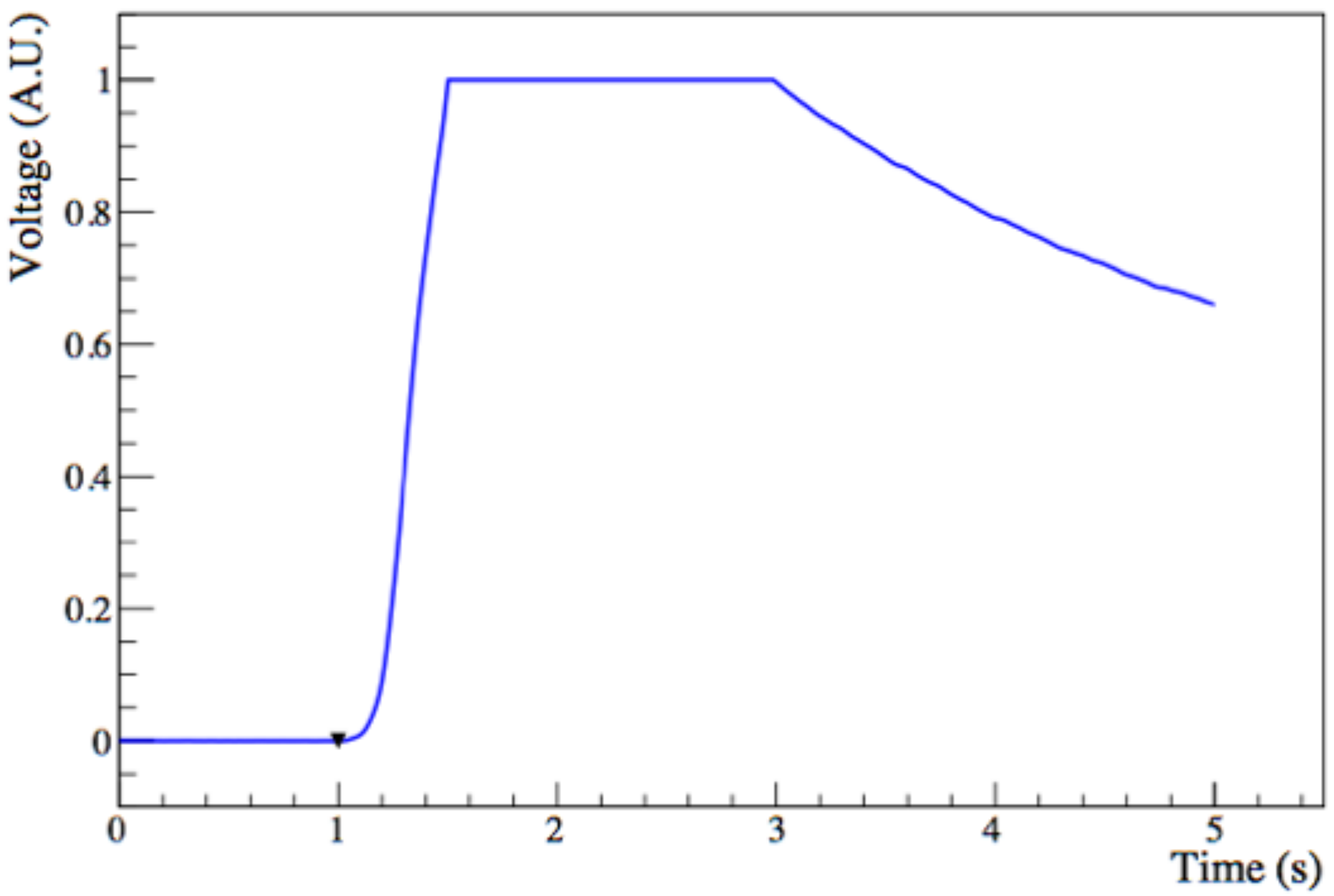
... or how we try to get rid of any non-signal-like events

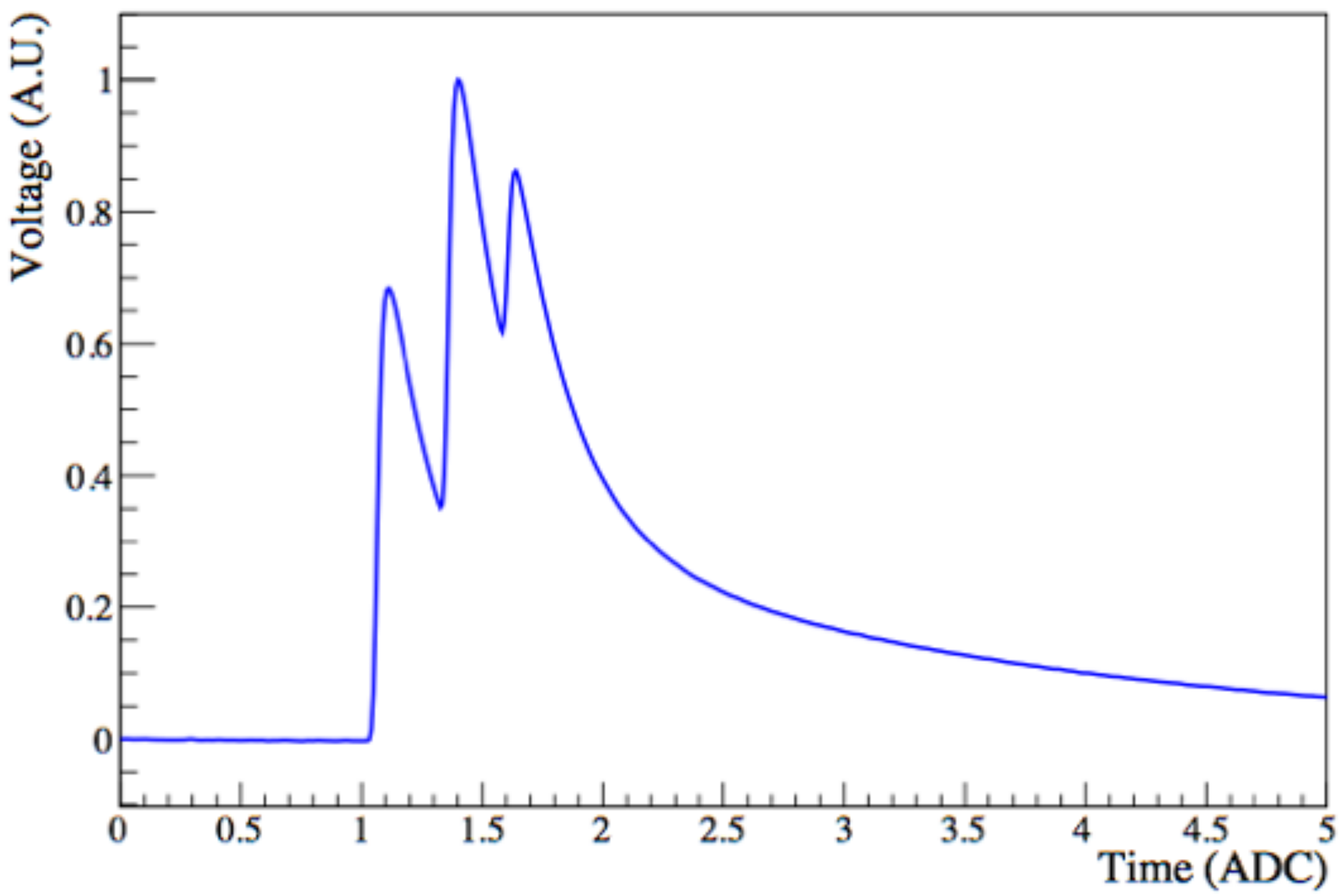


- Basic Quality Cuts
  - Saturated pulses
  - Multiple triggers or pulses in a single window

Event Cuts

... or how we try to get rid of any non-signal-like events





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

Event Cuts

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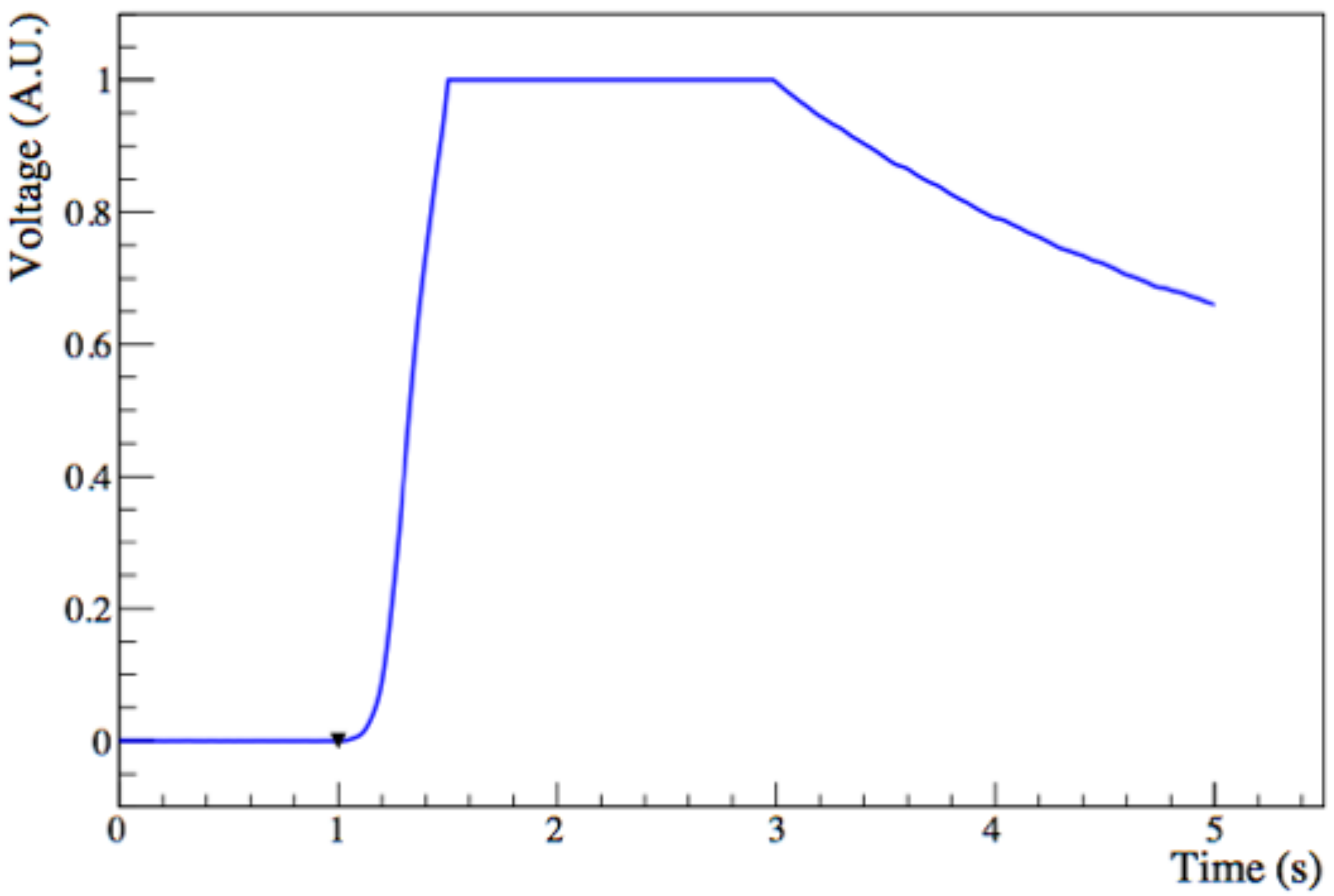

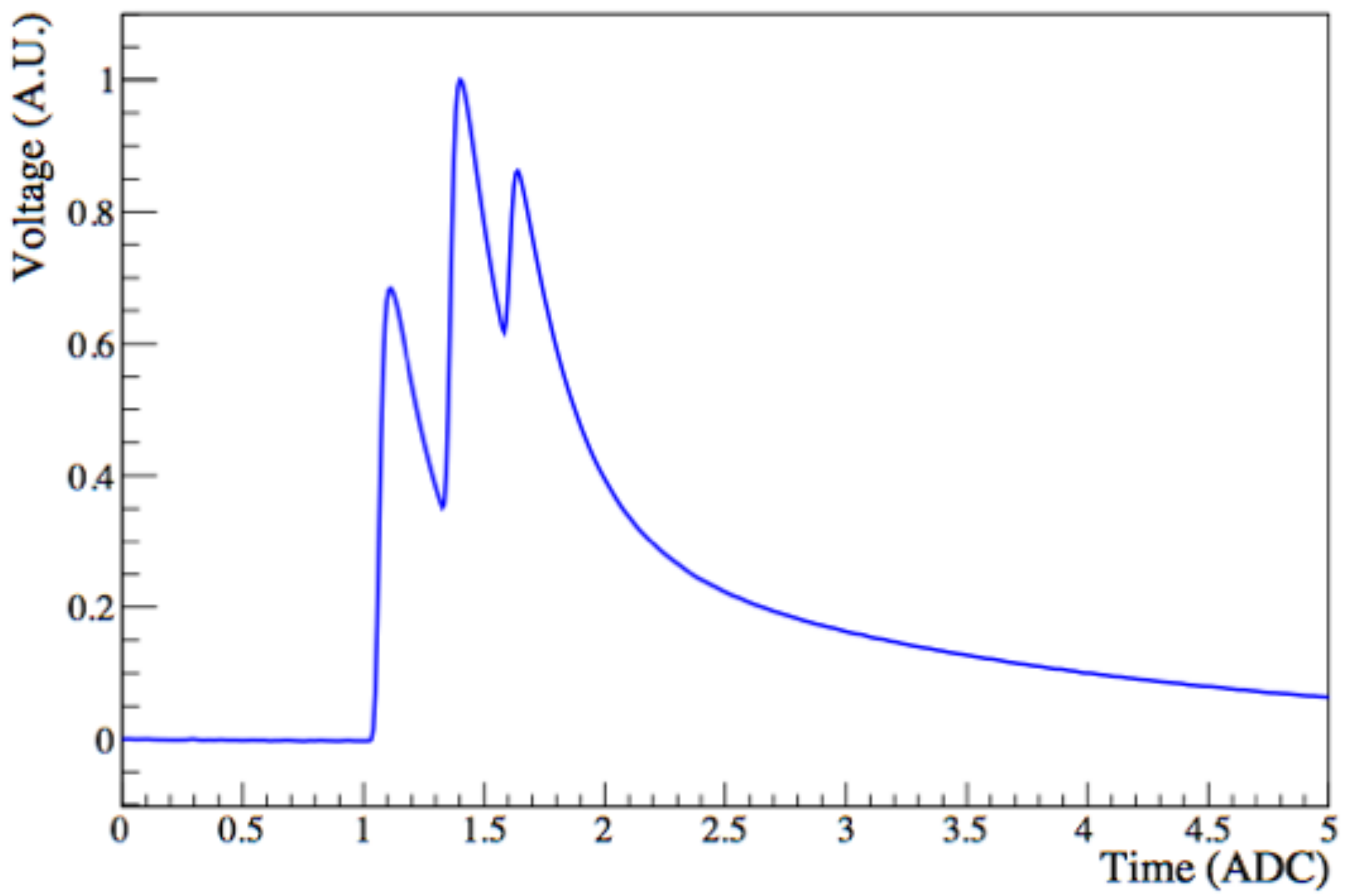

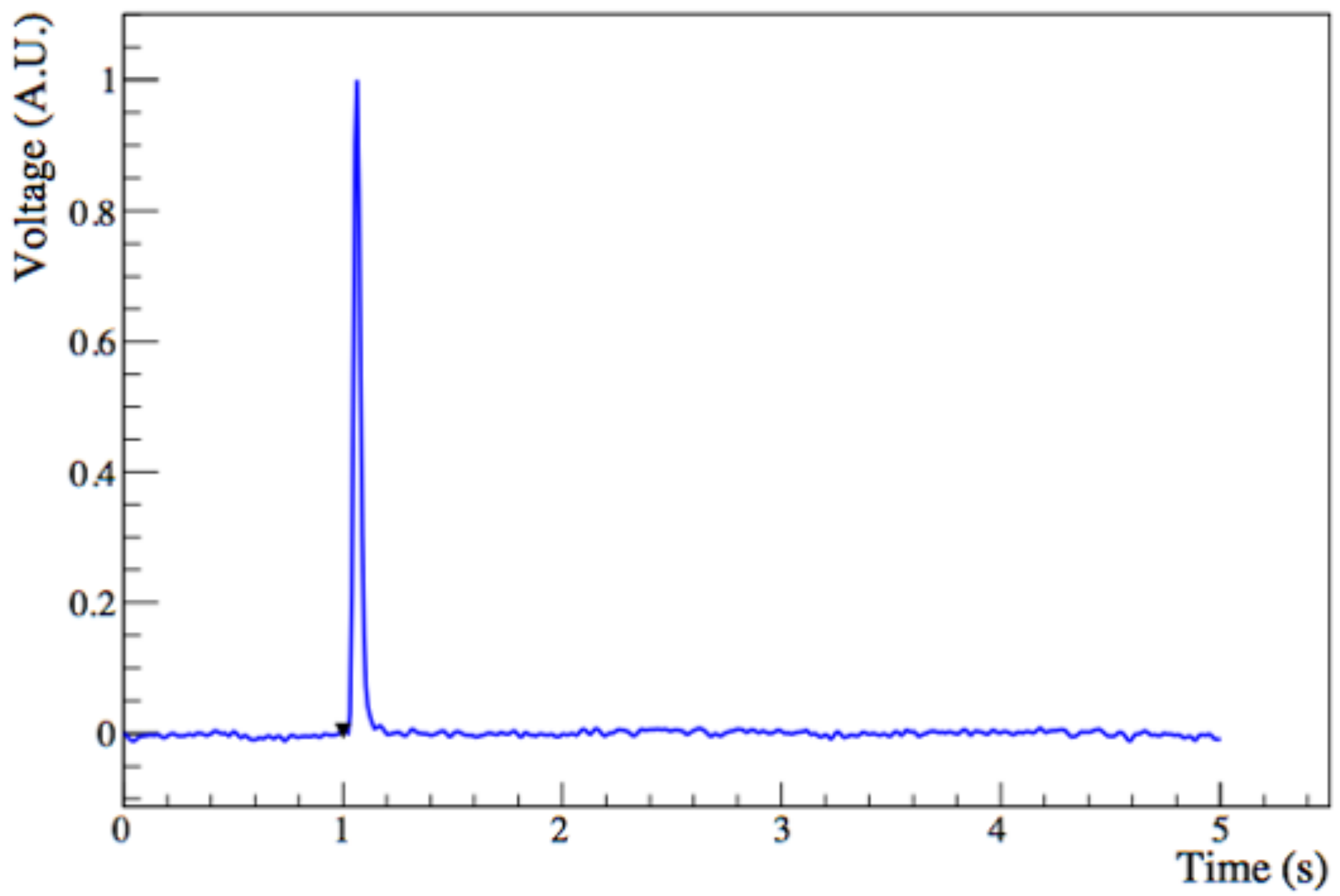

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- Pile-up Cuts
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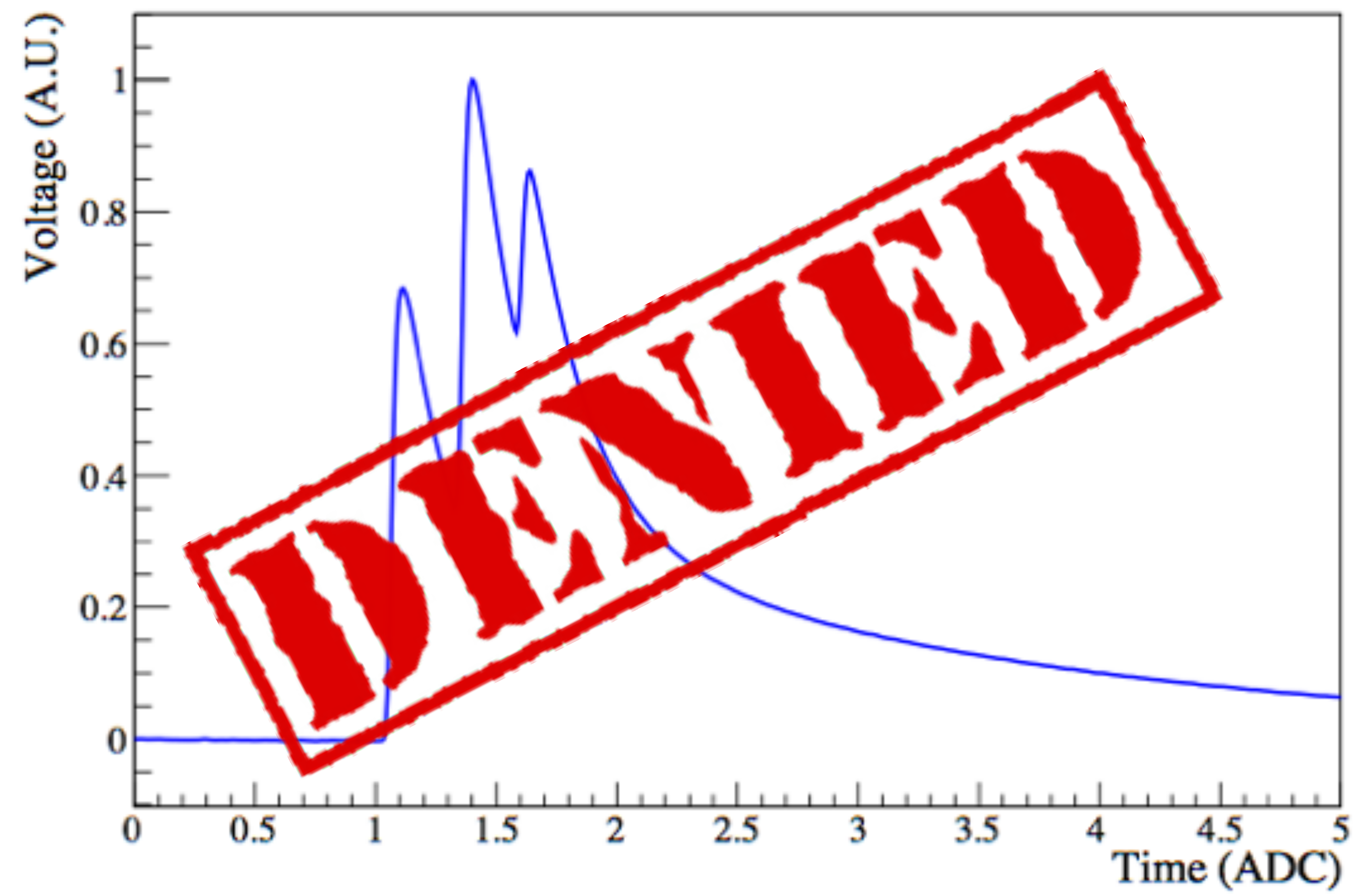
- Pulse Shape Cuts
  - Remove "spike" events
  - Remove electronic noise

CUORE

Event Cuts

... or how we try to get rid of any non-signal-like events



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  - Remove “spike” events
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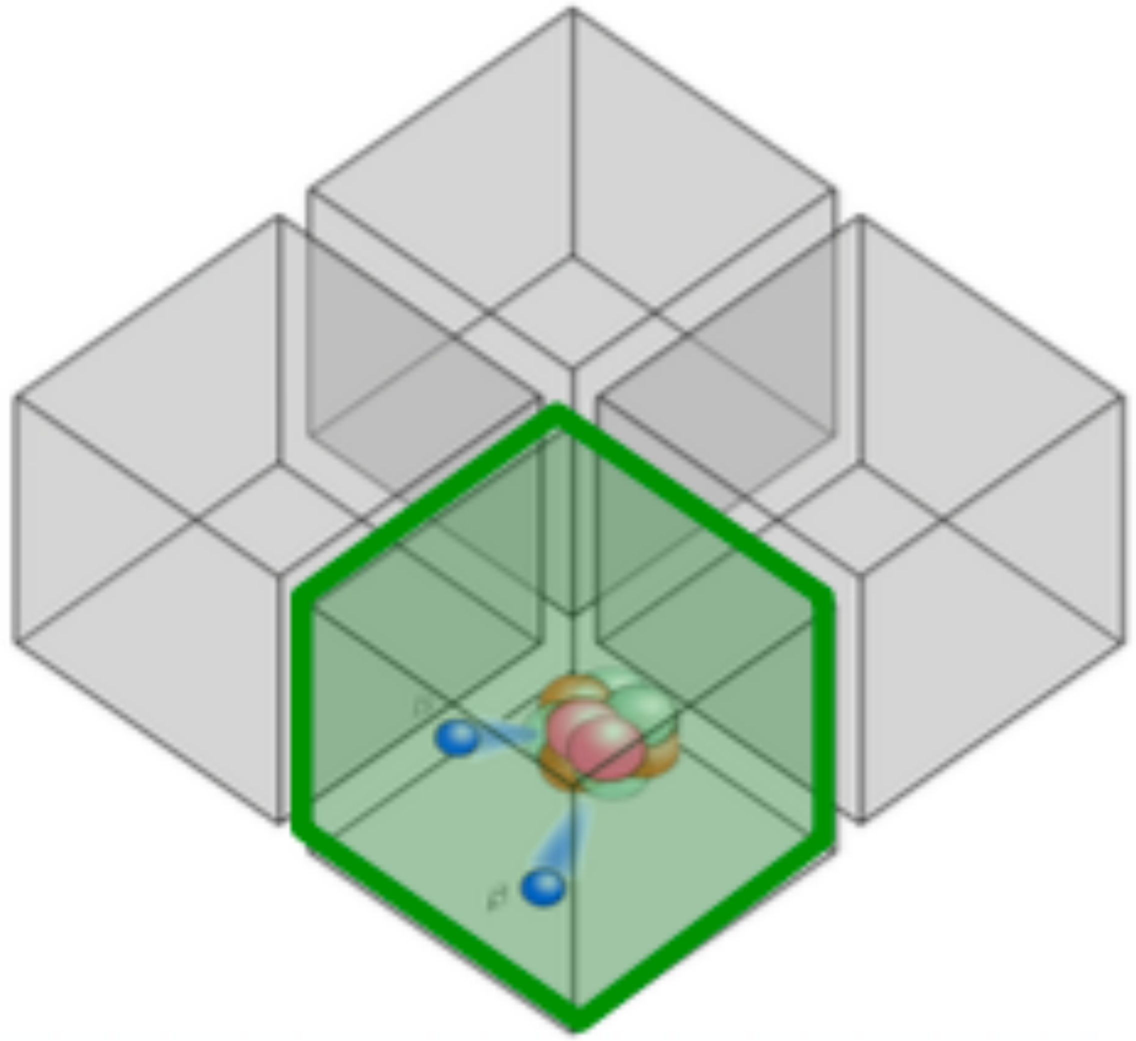
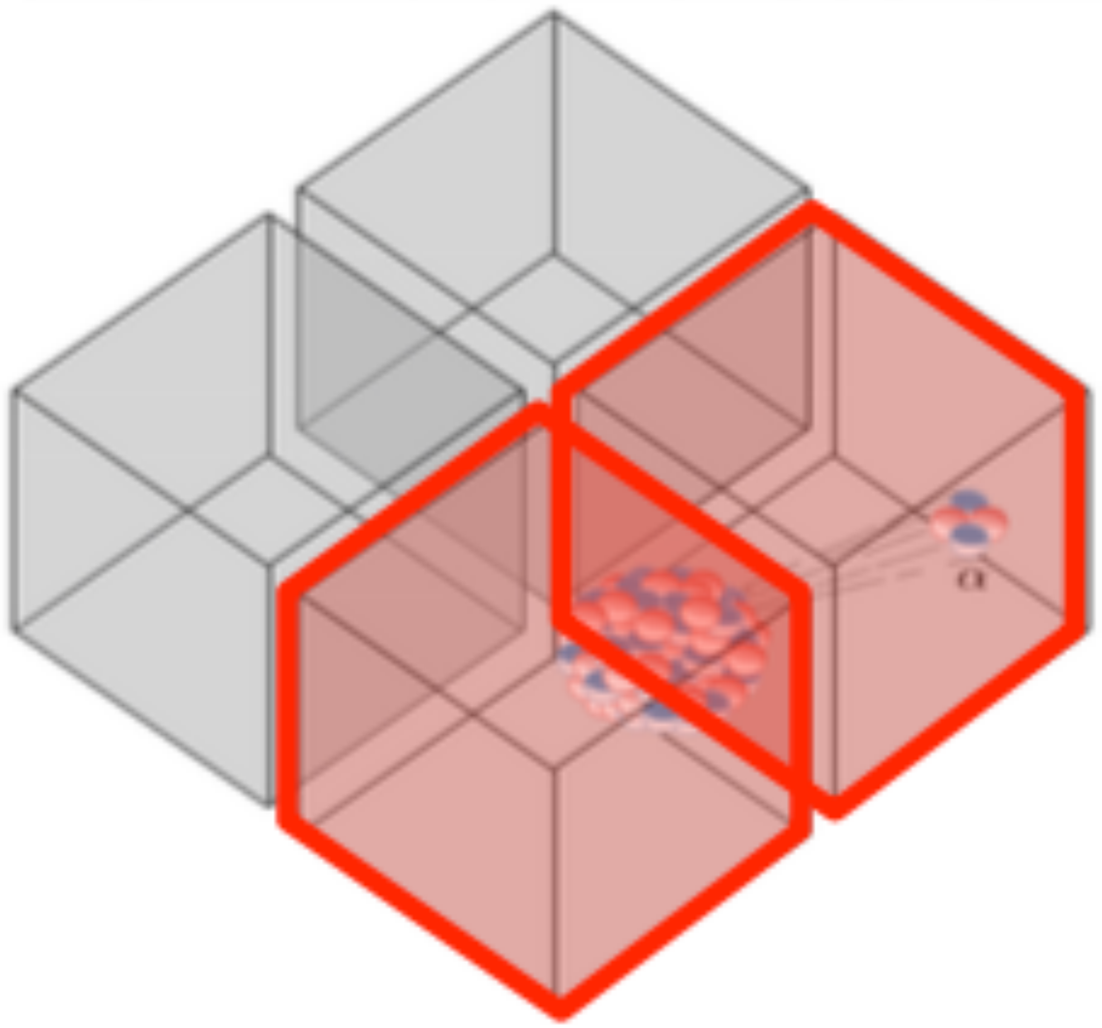
Anti-Coincidence Cut

- We expect that ~88% of $0\nu\beta\beta$ events will be contained in a single crystal.
- Anti-coincidence window of ±5 ms.
- Removes:
  - α decays on the bolometer surface
  - Compton scattered γ-rays
  - Cascade decays
  - Muons





Event Selection Efficiencies

CUORE

Cut	Efficiency
Single Crystal Containment	88.4±0.09
Trigger & Energy Reconstruction	98.529±0.004
Pileup & Pulse shape	93.7±0.7
Accidental Coincidence	99.6±0.1
Total Signal Efficiency	**81.3±0.6**

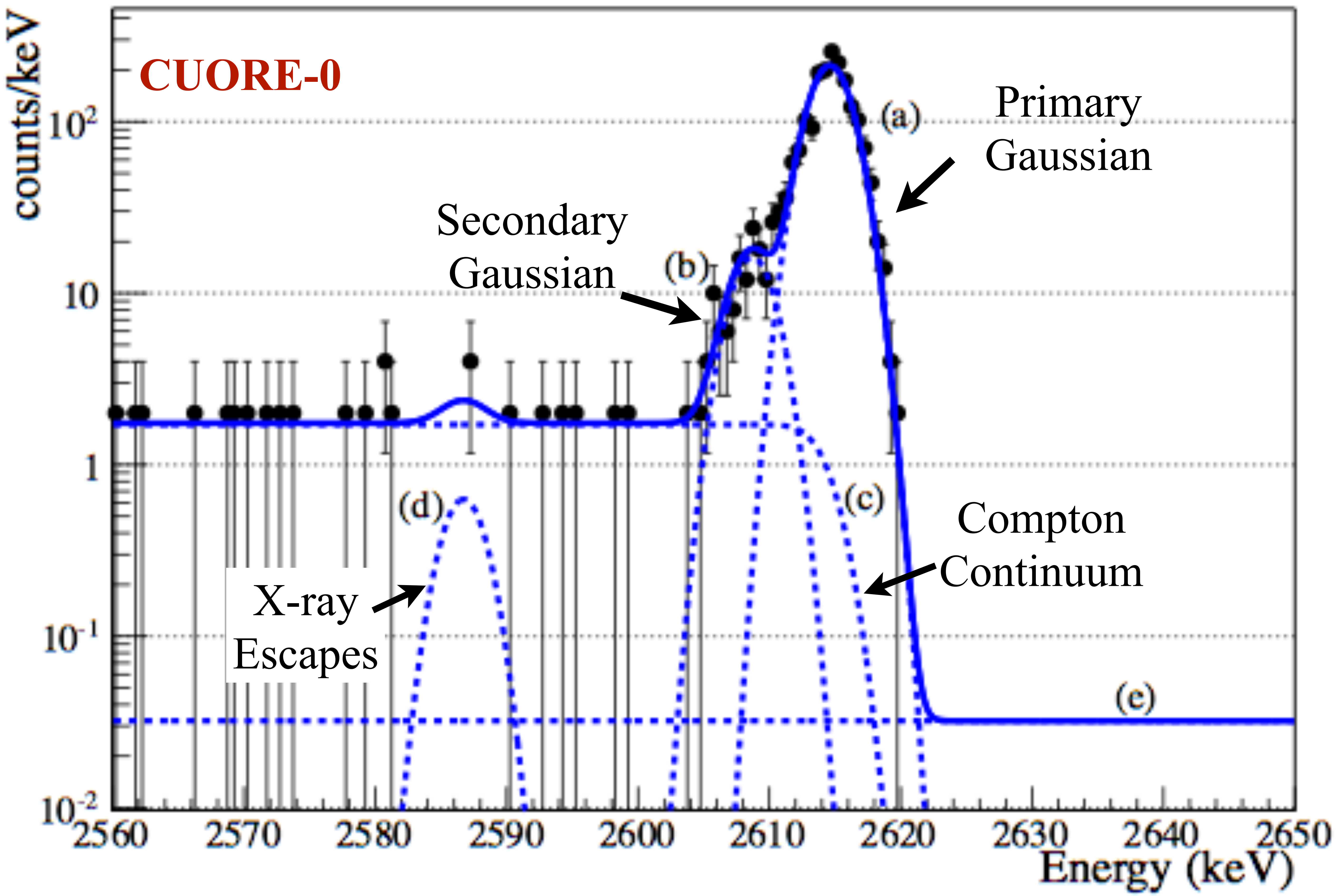
Measured using MC

$\Big\}$ Measured directly on data

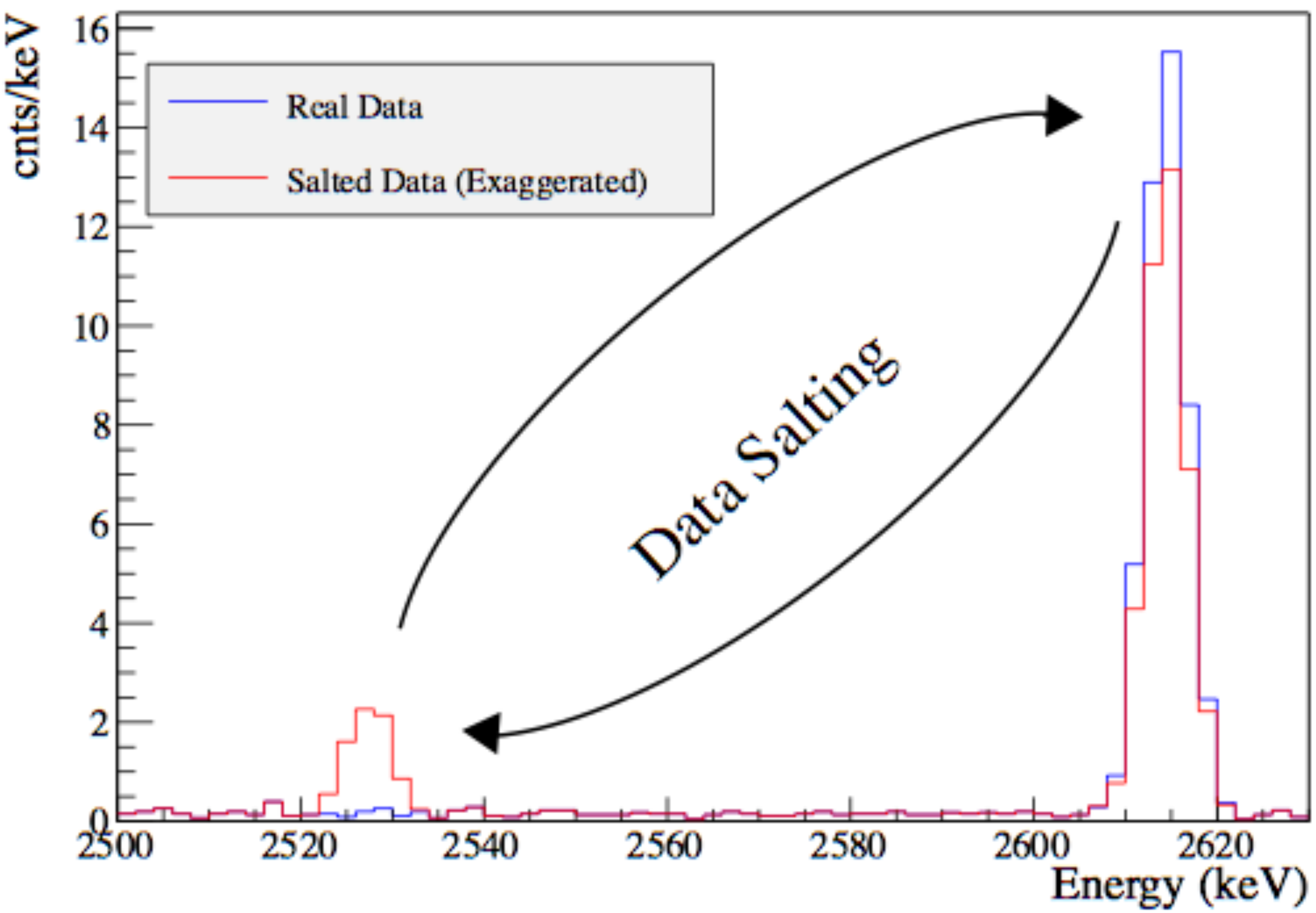
With the cuts, we maintain a signal efficiency of 81%.

Building the Detector Response

➡ Each bolometer gets its own detector response shape for each dataset

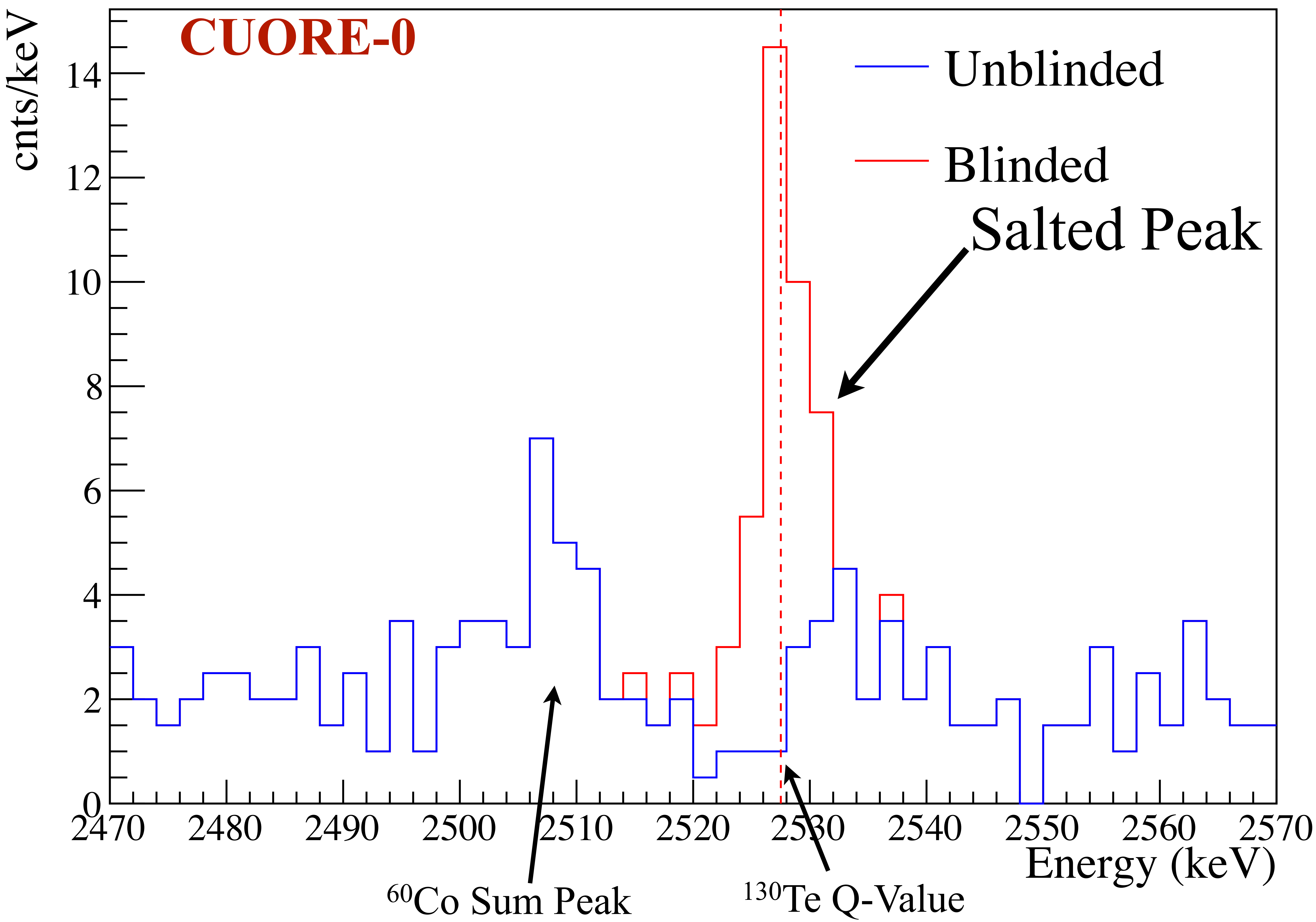


CUORE-0 Blinding

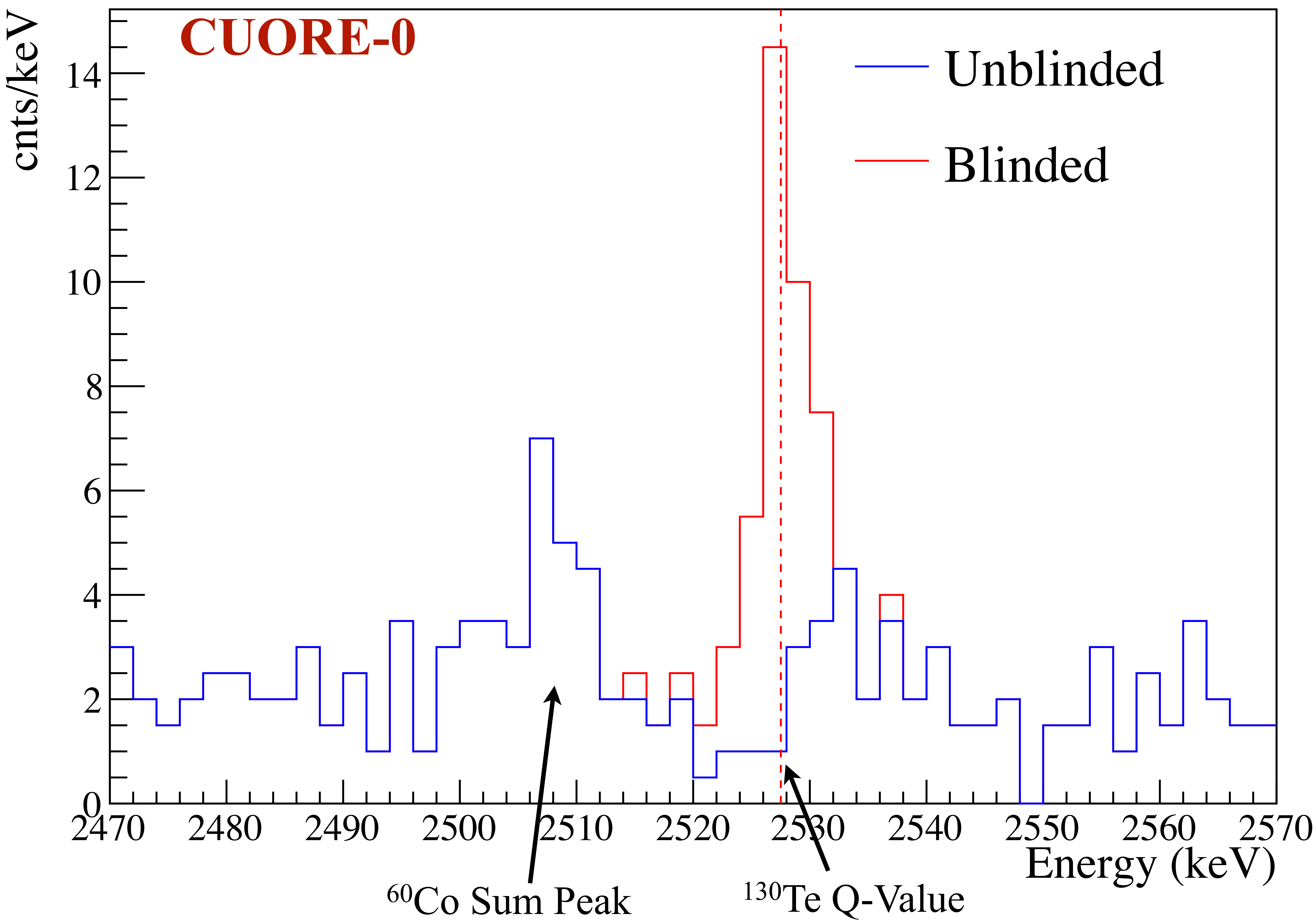


- Randomly move a fraction of events from the 2615 keV line to the ROI and vice versa
- Fraction of events is random
- Creates an unrealistically large peak at the $0\nu\beta\beta$ value

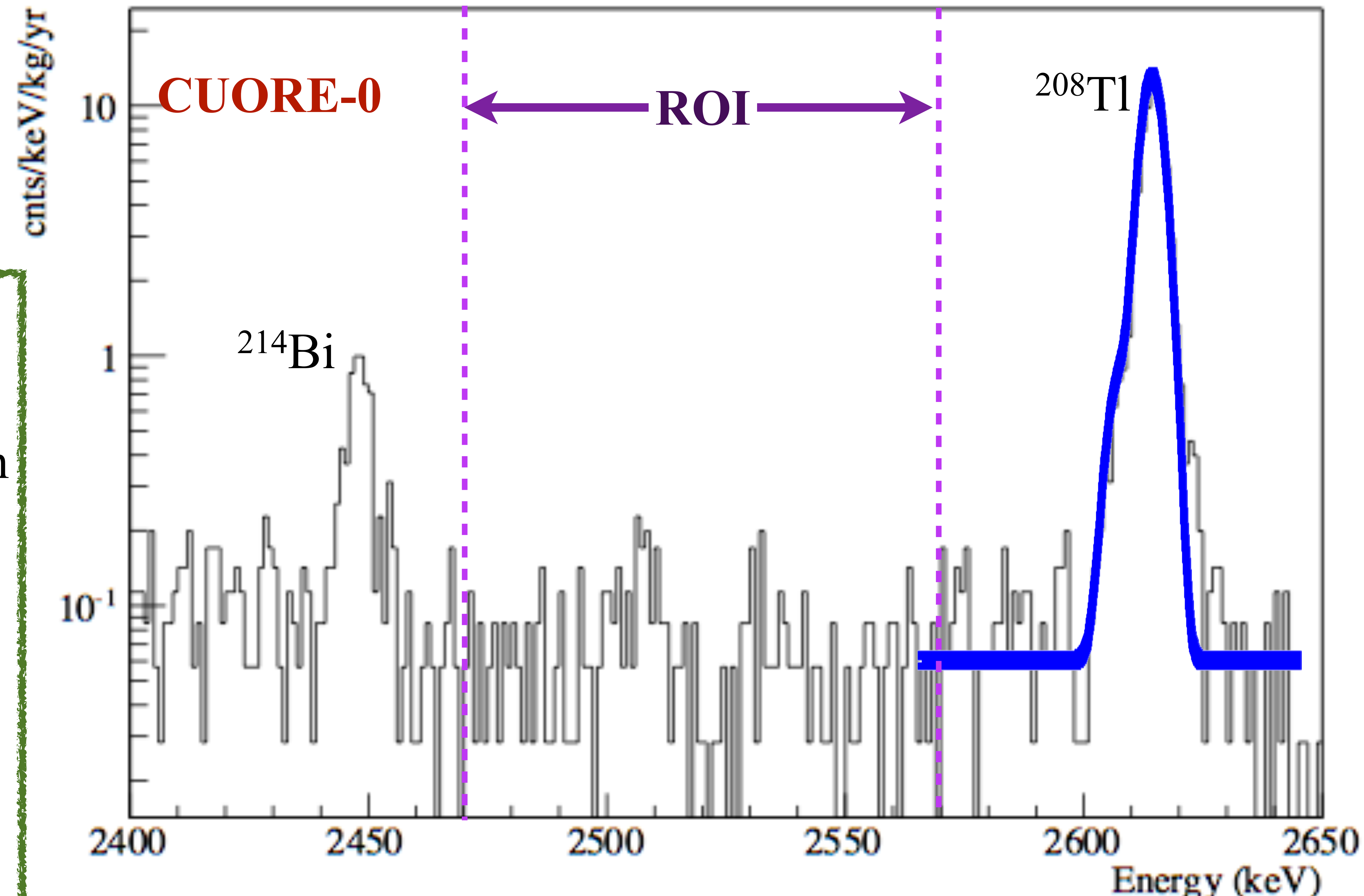
CUORE-0 Unblinding the ROI



CUORE-0 Unblinding the ROI



Fitting The ROI



- Simultaneously fit each bolometer and dataset using an UEML fit
- Use the lineshape derived on the calibration ^{208}Tl
- Scale detector response down to 0νββ position
  - Position fixed *relative* to ^{208}Tl position
- Scale second line to ^{60}Co position
- Scale bias and resolutions from ^{208}Tl value
- Flat background

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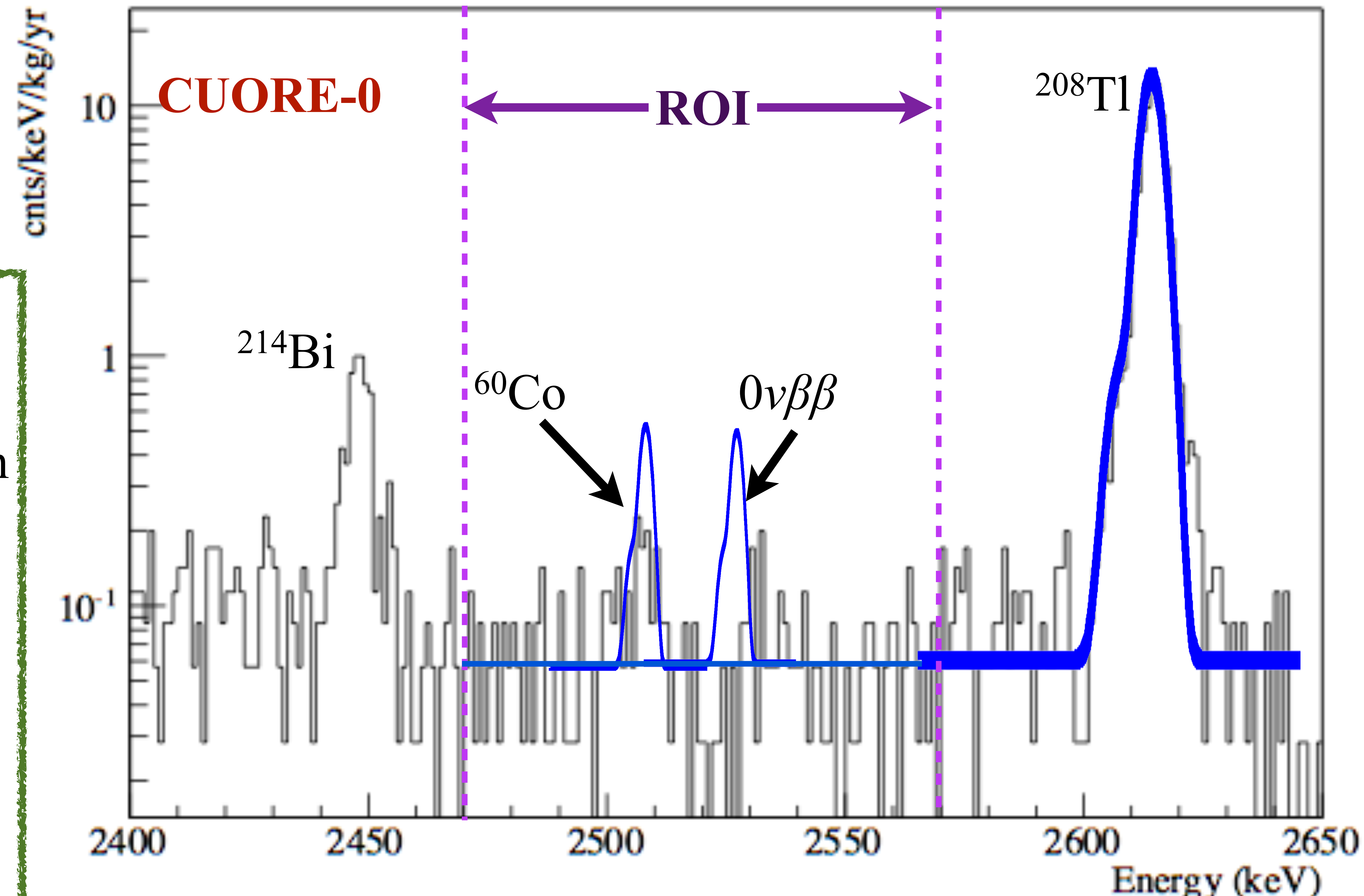
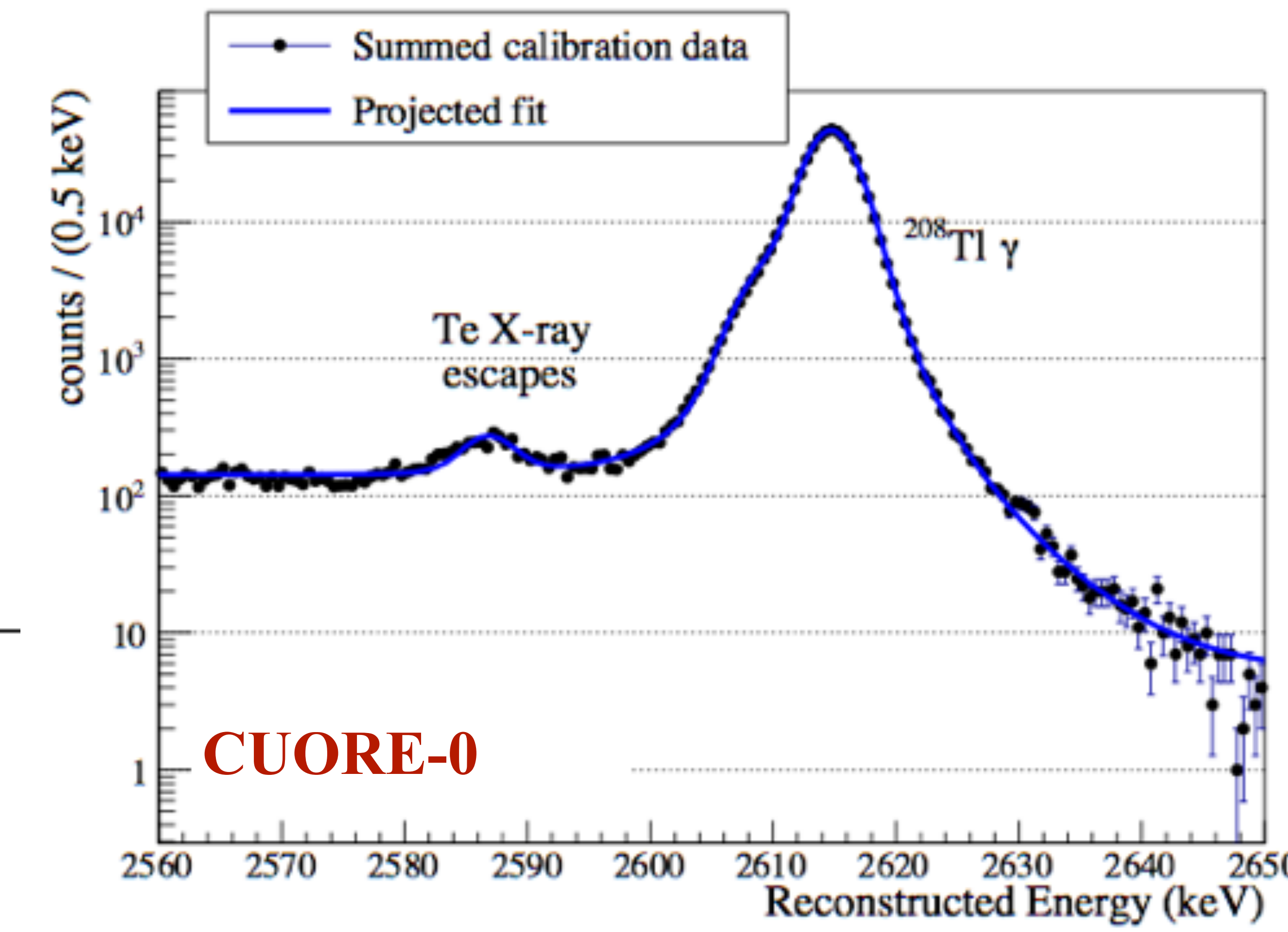
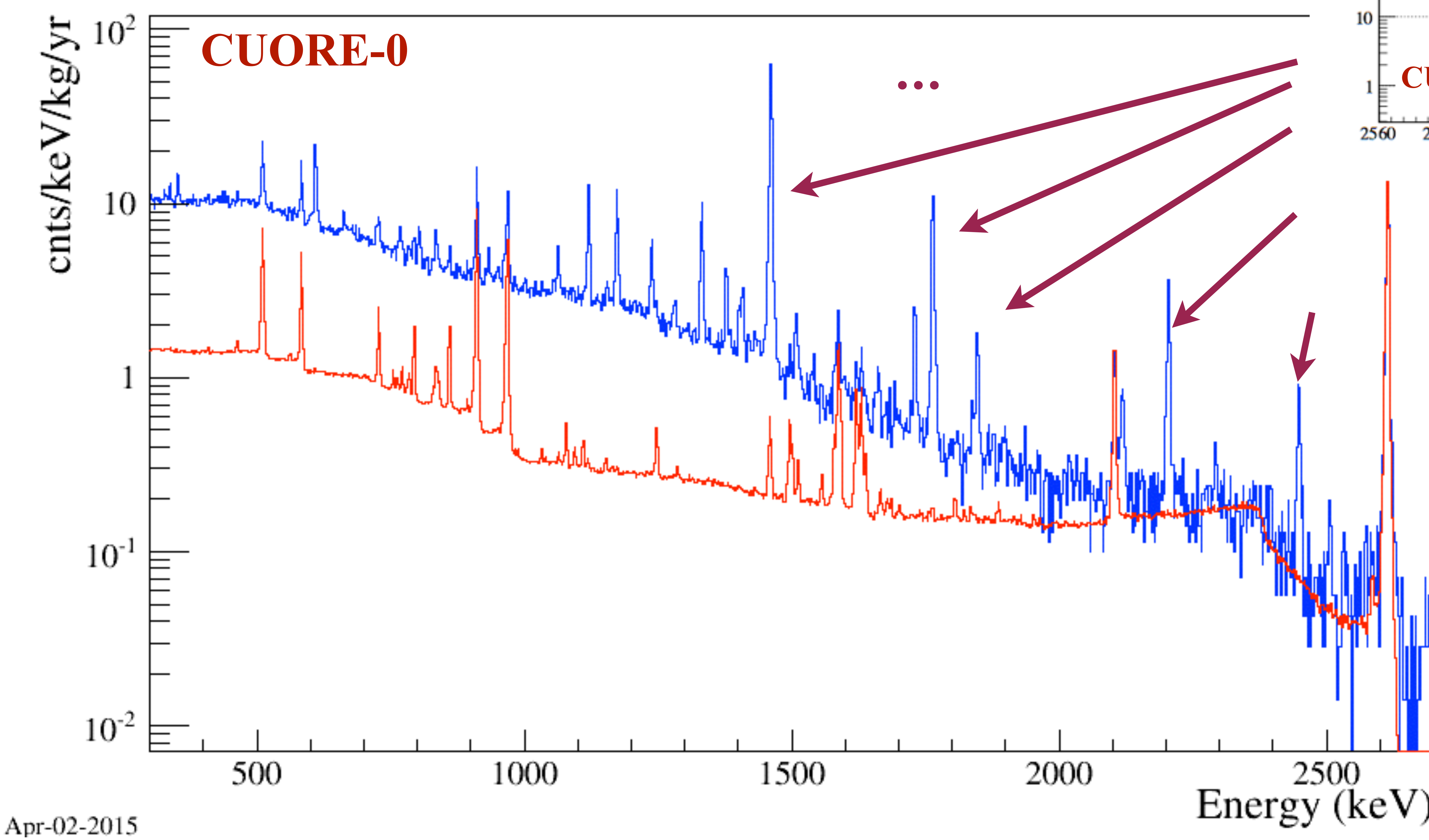


Characterizing the Detector Response

CUORE

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



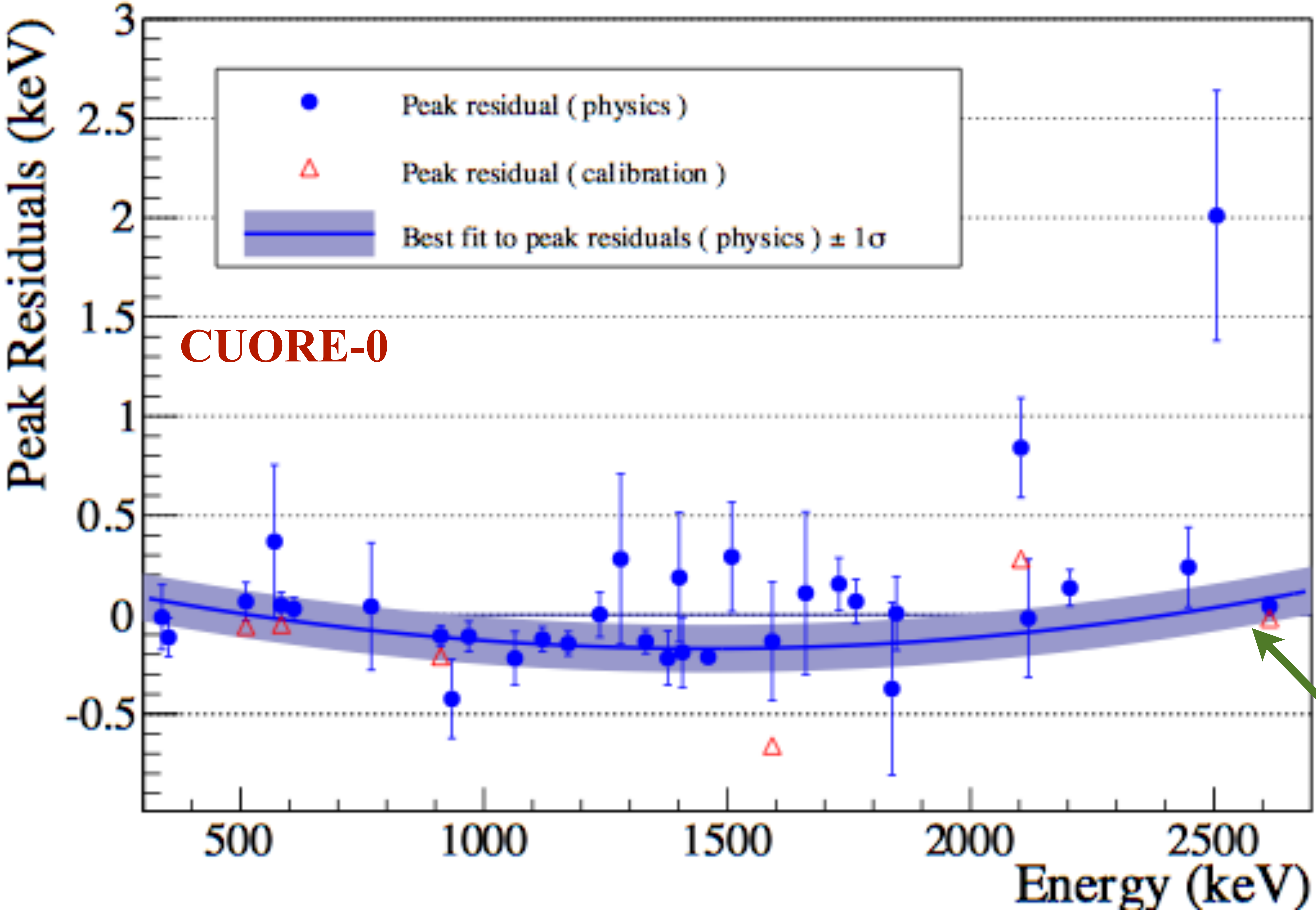


Want to know:

- Bias vs Energy
- Resolution vs Energy

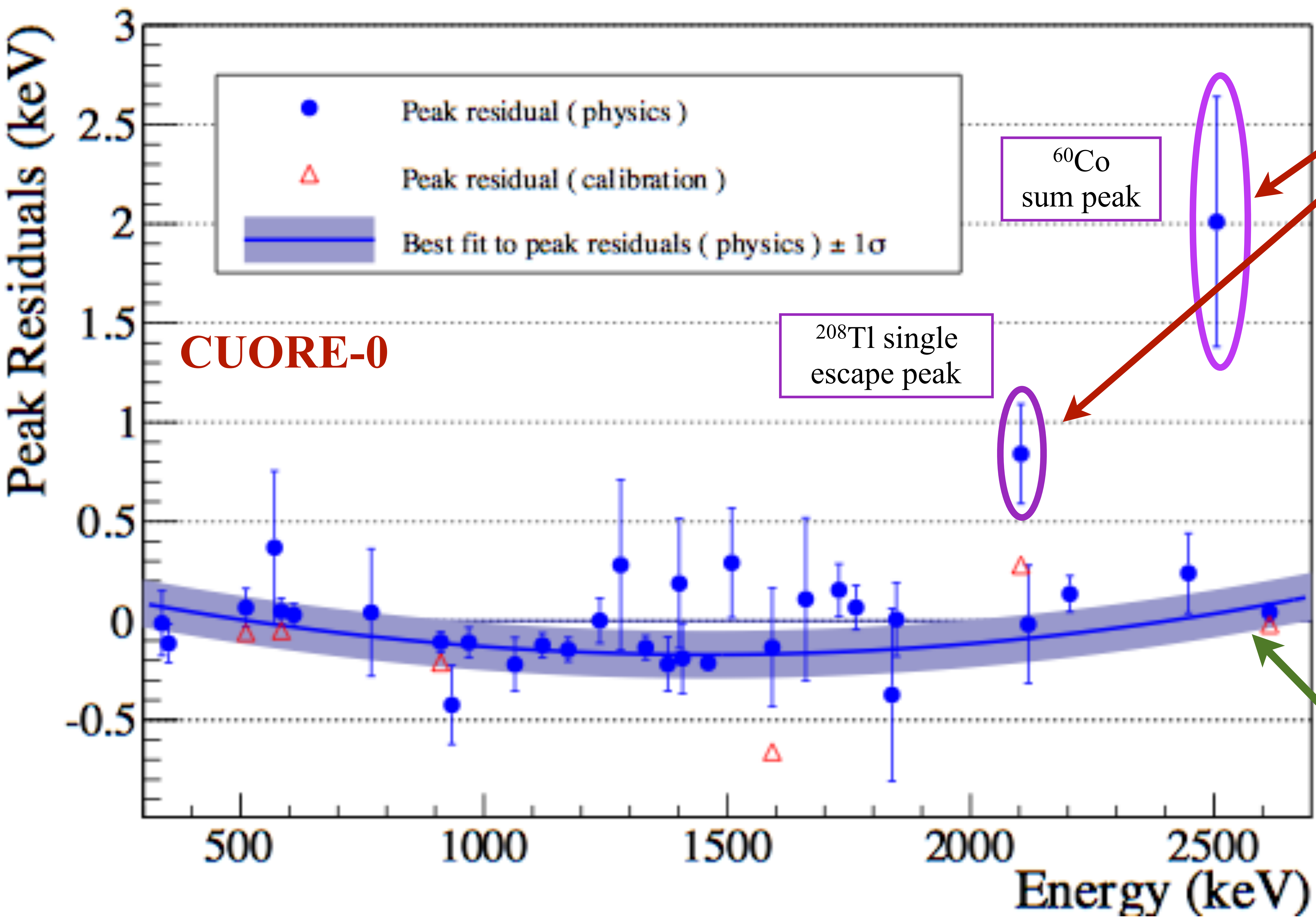
Projecting the Detector Response

CUORE



- 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

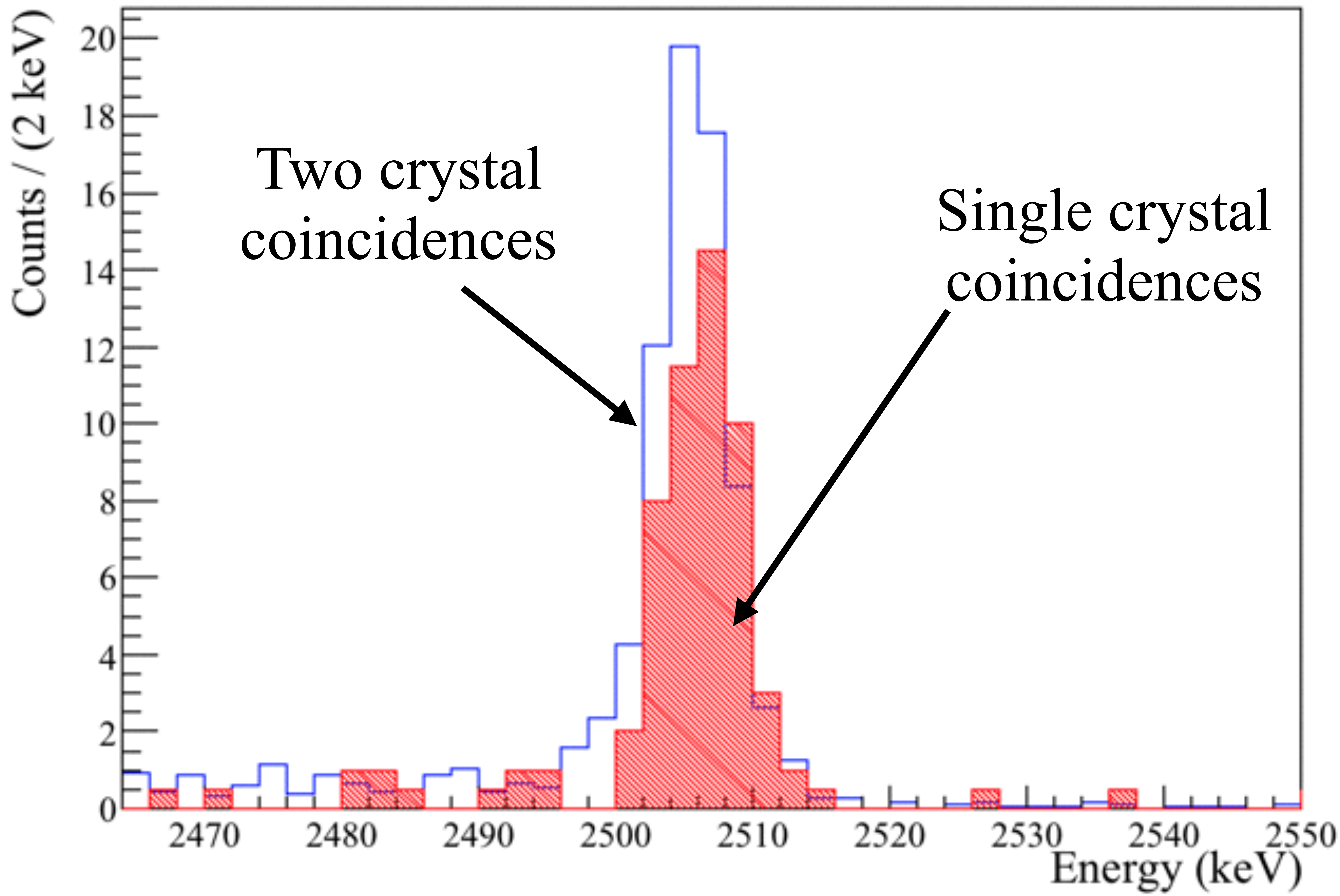
Projecting the Detector Response



- 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

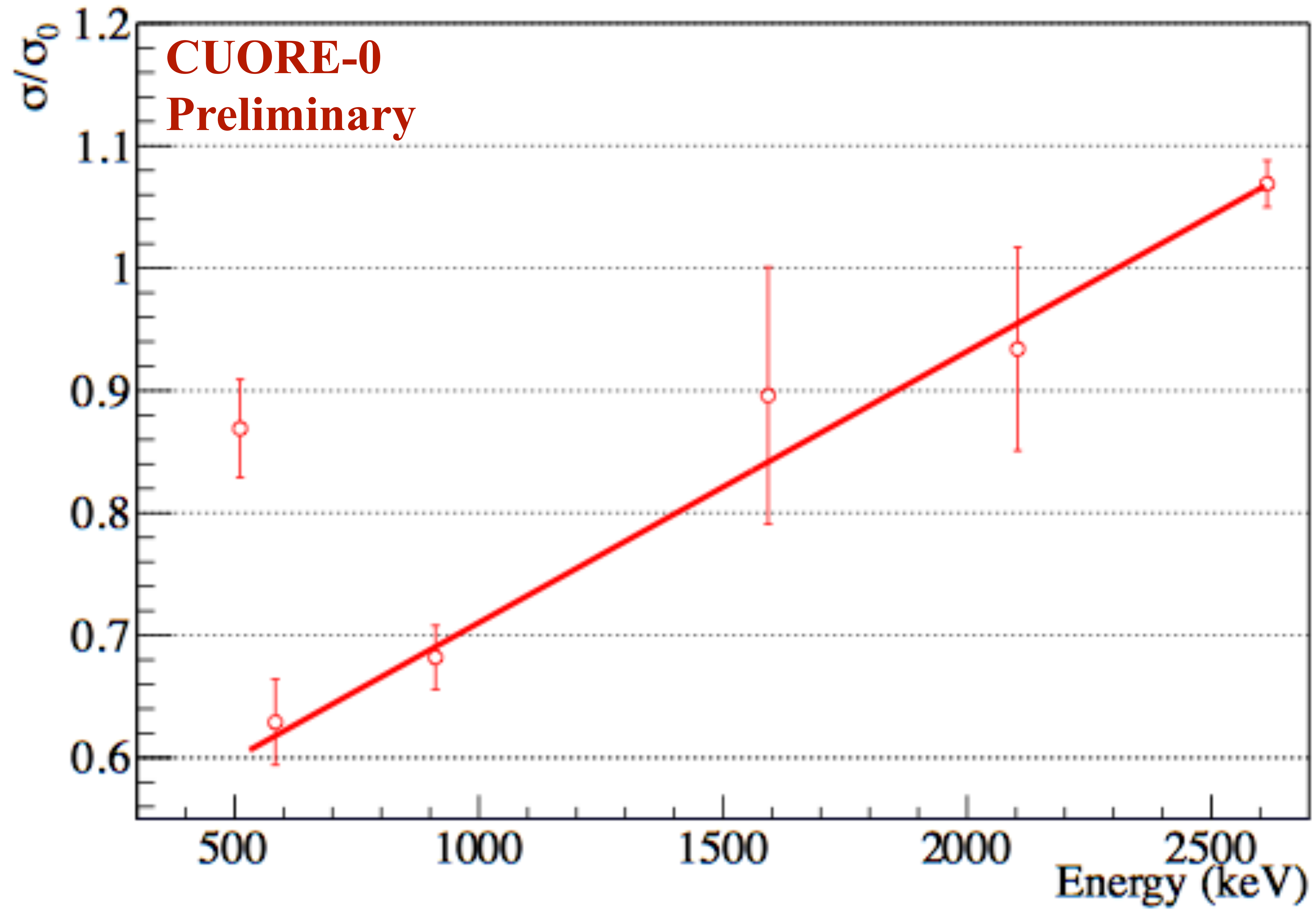
Single vs Multi Crystal ^{60}Co Coincidences



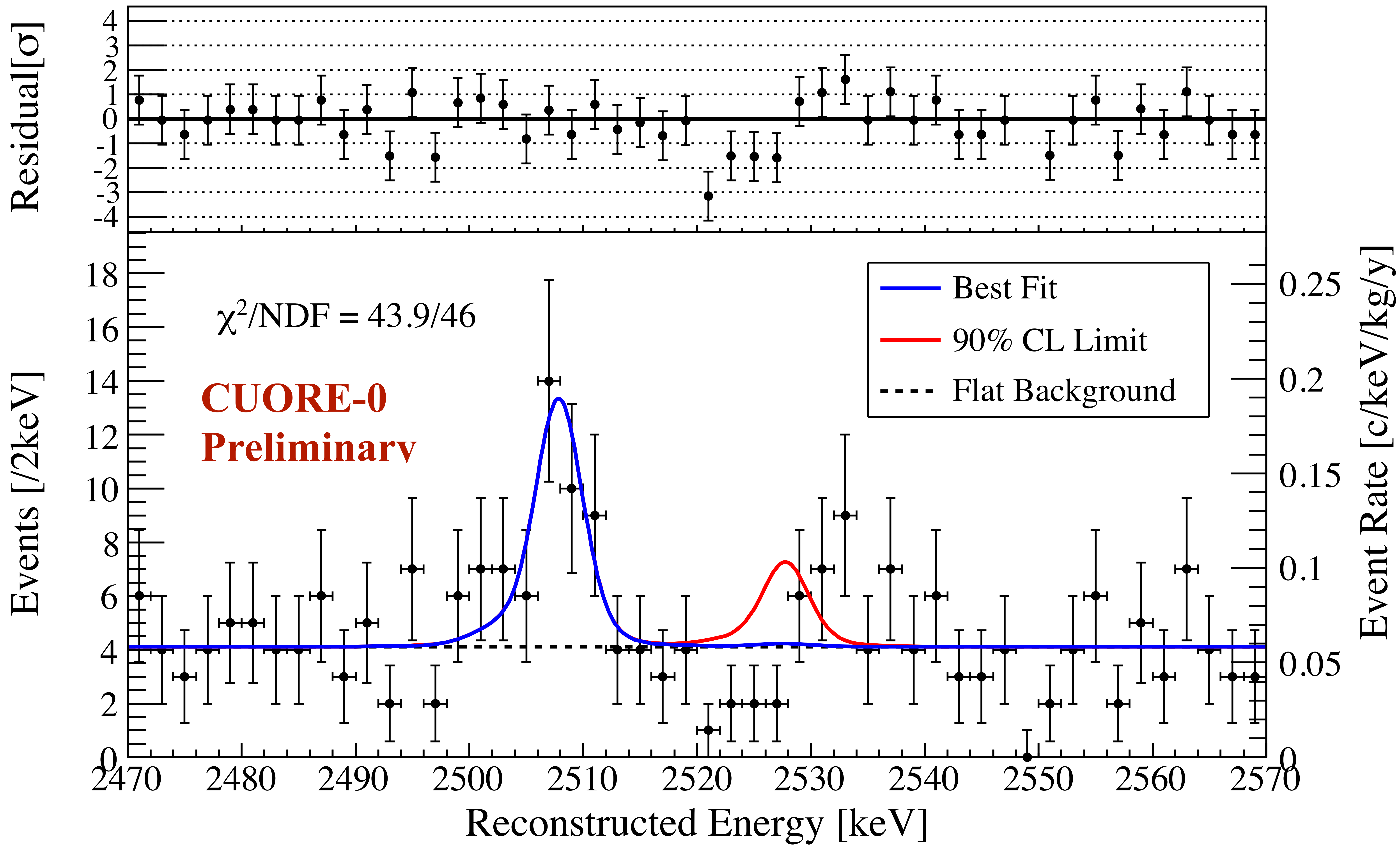
Scaling the Energy Resolution

CUORE

- Energy resolution scaling includes ratio of energy resolutions at Q to 2615 and difference between calibration and physics run performance
- Scaling at ROI is given by $\alpha_\sigma(Q_{\beta\beta})$=1.05±0.05
- This corresponds to an energy resolution of $\Delta E(Q_{\beta\beta})$=5.1±0.3 keV (FWHM)

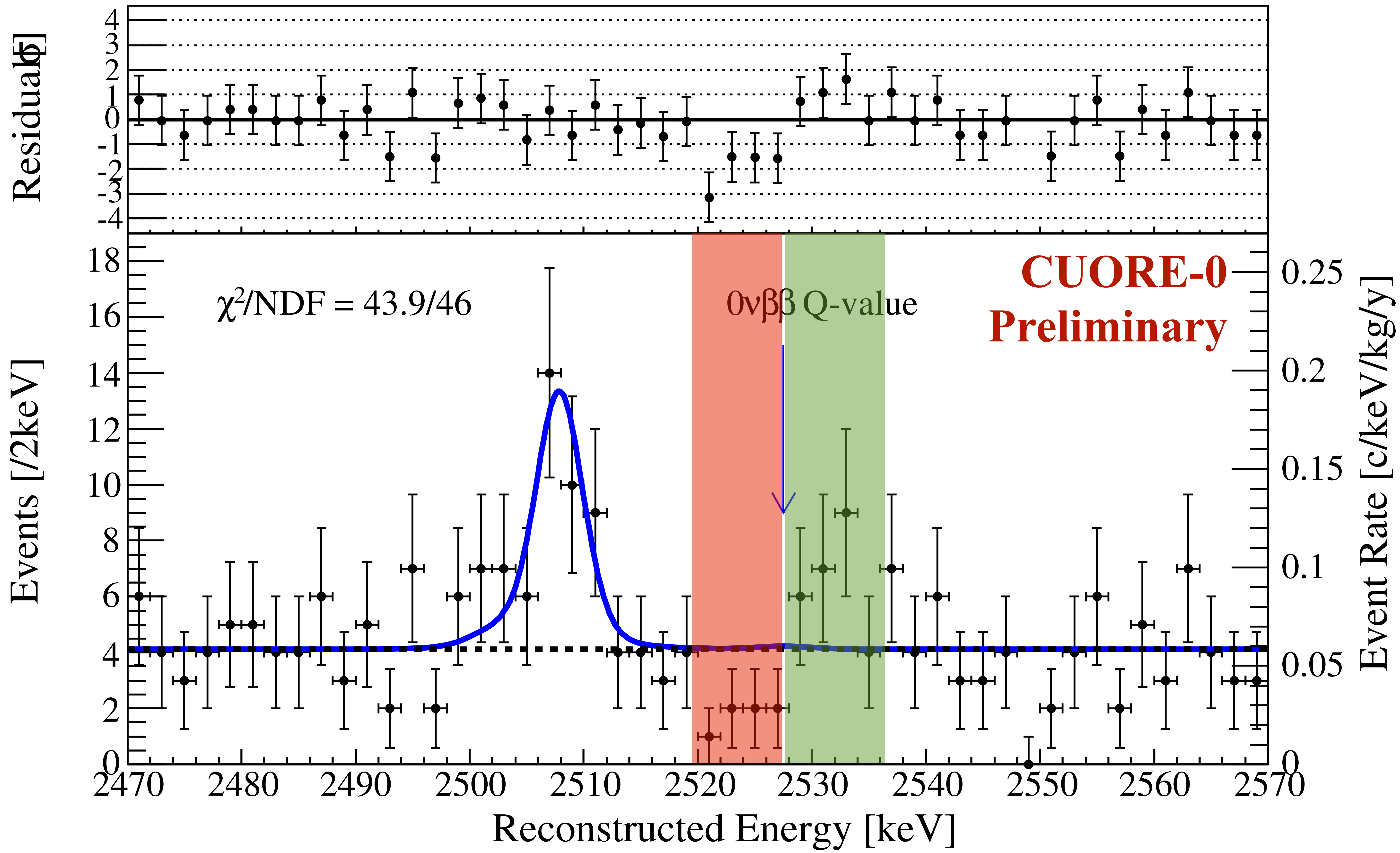


CUORE-0 90% C.L.



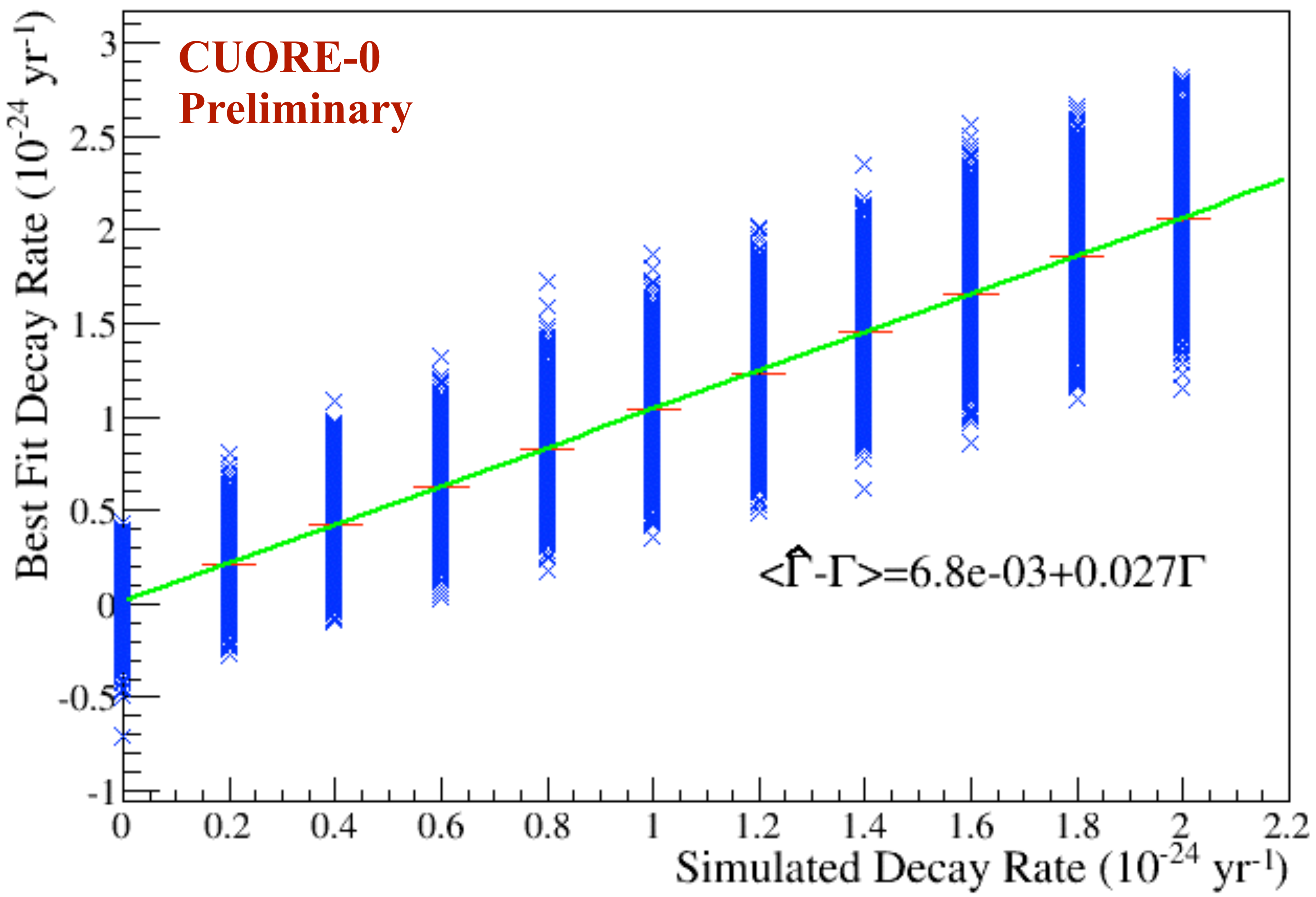
Residual[σ]
Events [/2keV]
Event Rate [c/keV/kg/y]
Reconstructed Energy [keV]
χ^2/NDF = 43.9/46
CUORE-0
Preliminary
Best Fit
90% CL Limit
Flat Background

Consistency Of The Model



- 90% of pseudo-experiments had a larger χ^2
- Probability of the largest peak (including the "look elsewhere" effect) is ~40%
- Both KS and AD tests were consistent with the model

CUORE-0 Official Systematic Uncertainties



Toy MC simulation with best fit decay rate vs simulated decay rate

Combining Systematics:

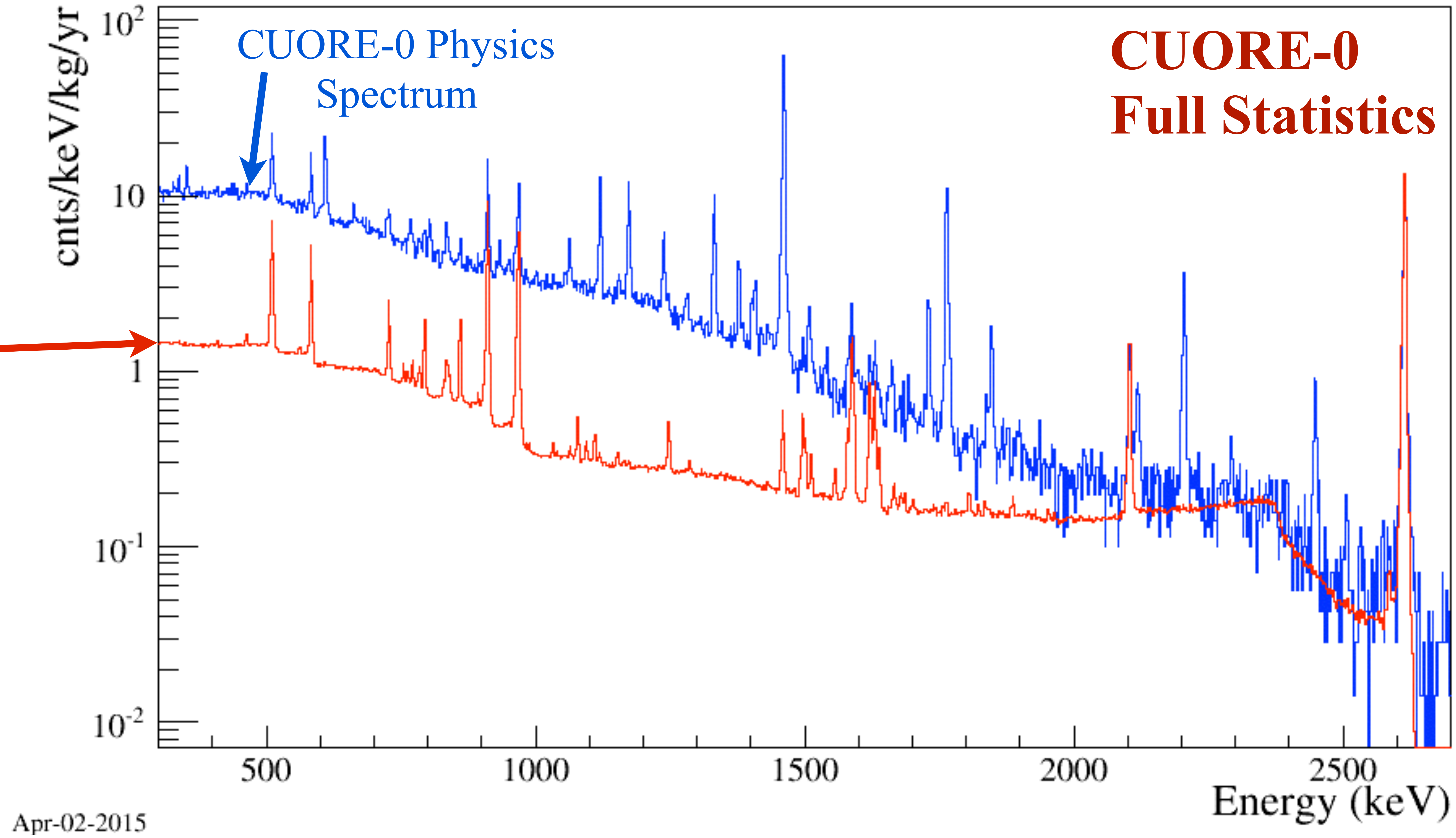
$$\sigma^2_{\text{syst}}(\Gamma) = \sum_i \sigma^2_{\text{add},i} + \sigma^2_{\text{rel},i}\Gamma^2$$

$$\frac{1}{\chi^2_{\text{Tot}}(\Gamma)} = \frac{1}{\chi^2_{\text{Stat}}(\Gamma)} + \frac{1}{\chi^2_{\text{Syst}}(\Gamma)}$$

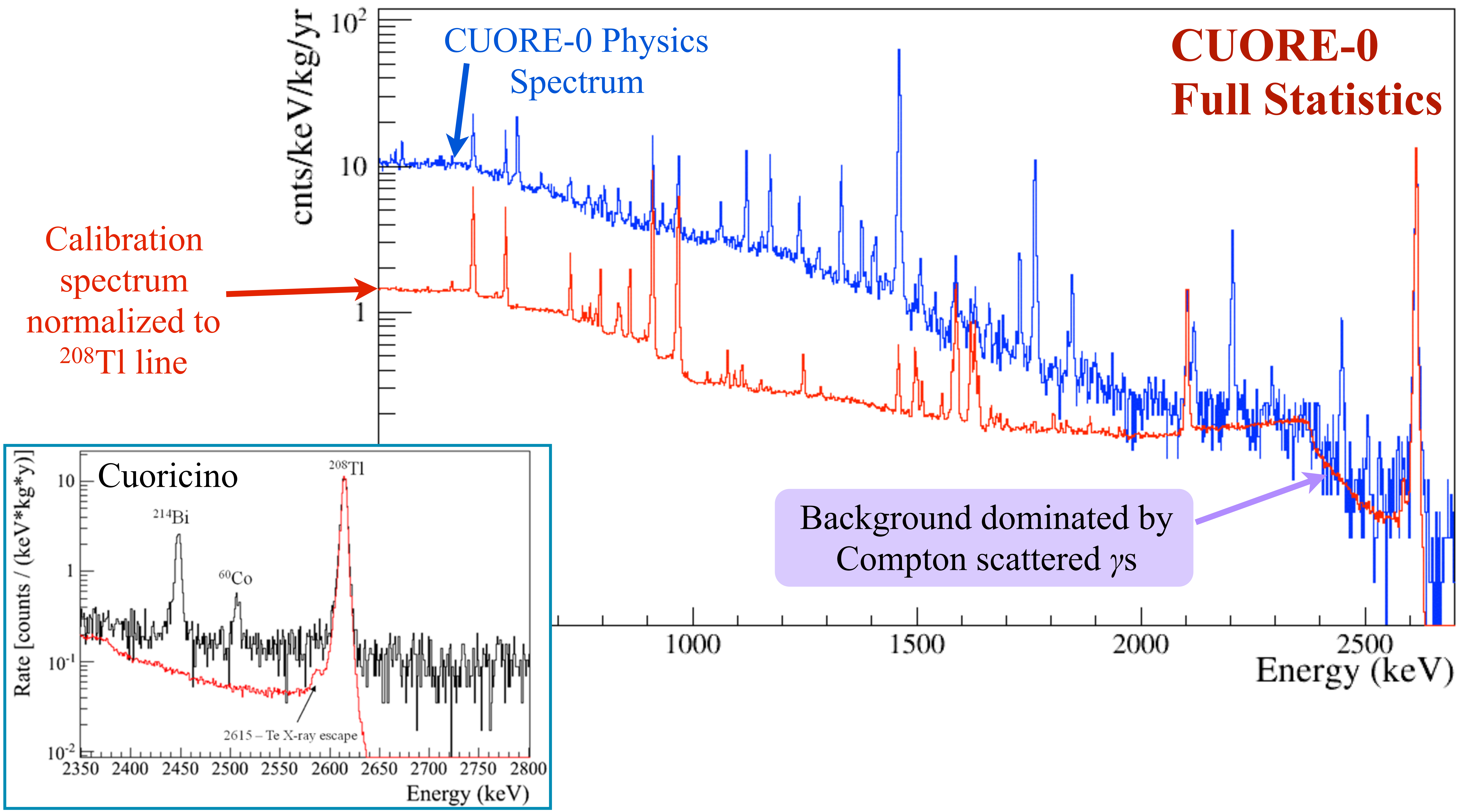
	CUORE-0 Official	
	Additive (10^{-24} yr^{-1})	**Relative (%)**
Lineshape	0.007	1.3
Energy Resolution	0.006	2.3
Background Shape	0.004	0.8
Efficiency	-	0.7
Energy Scale	0.005	0.4
Fit Bias	0.006	0.15
Total	0.012	2.9

CUORE-0 γ-Background

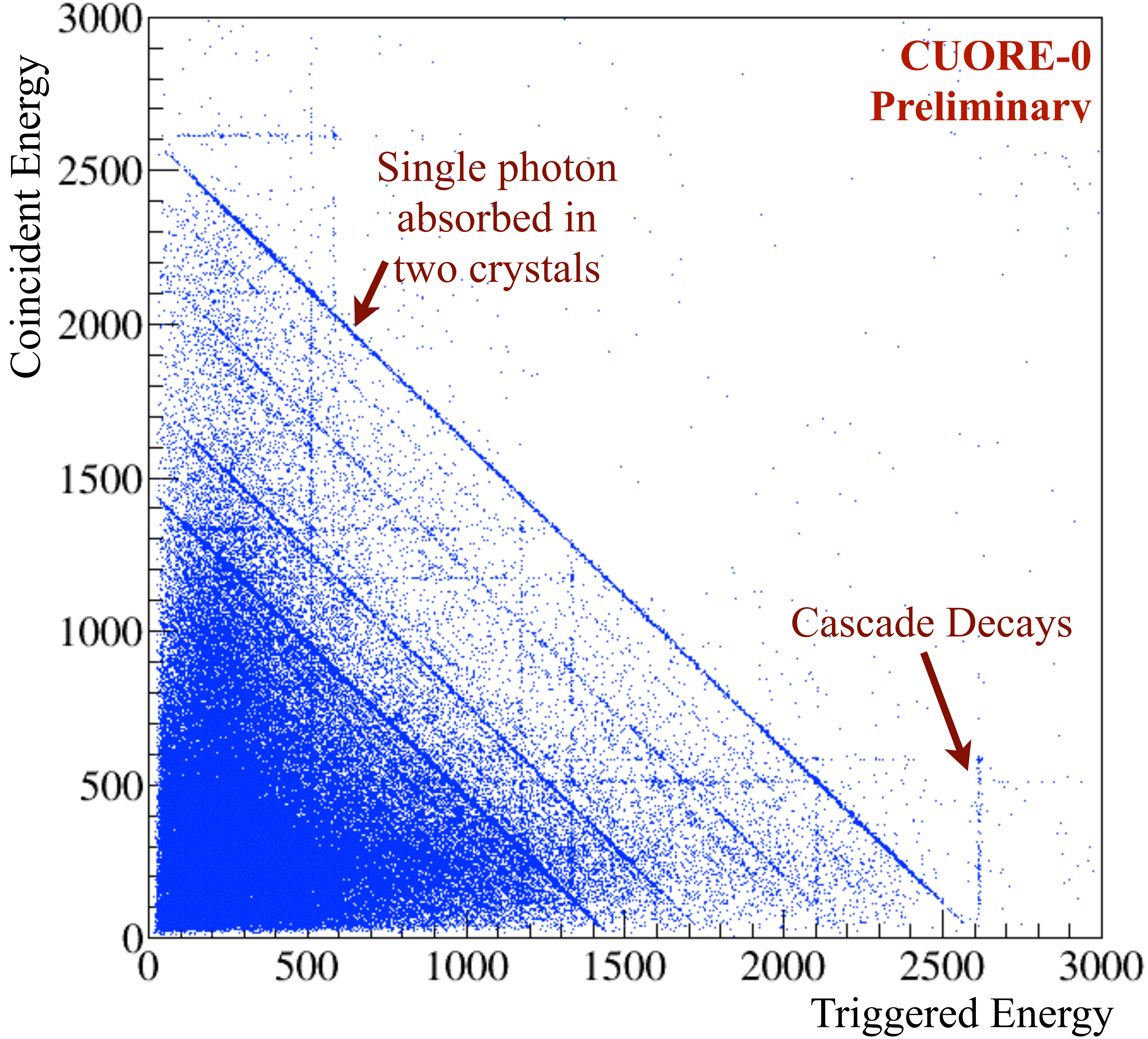
Calibration spectrum normalized to ^{208}Tl line



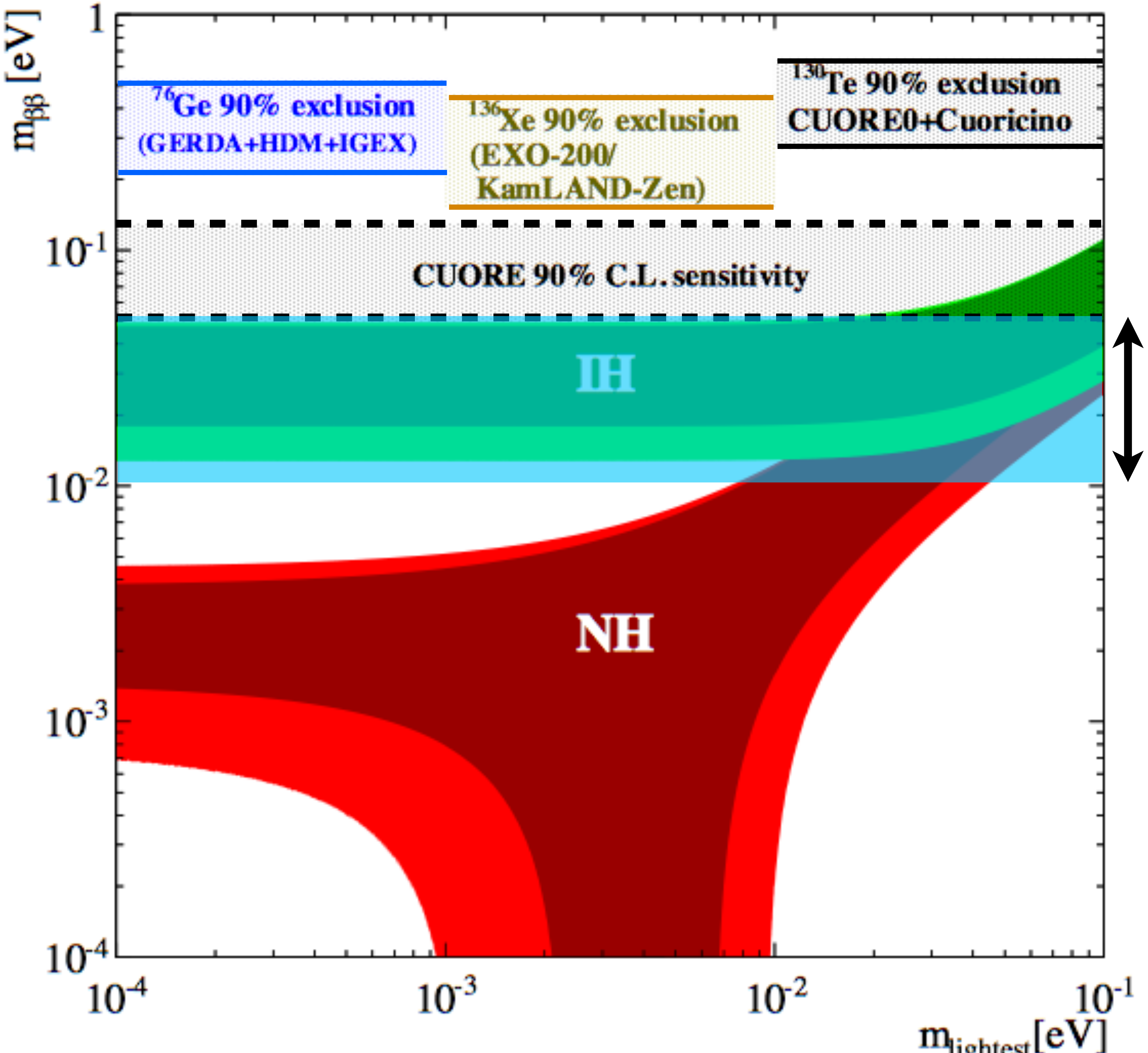
CUORE-0 γ-Background



Anti-Coincidence Rejection



Probing the Inverted Hierarchy



Fully probe the 'inverted hierarchy' region

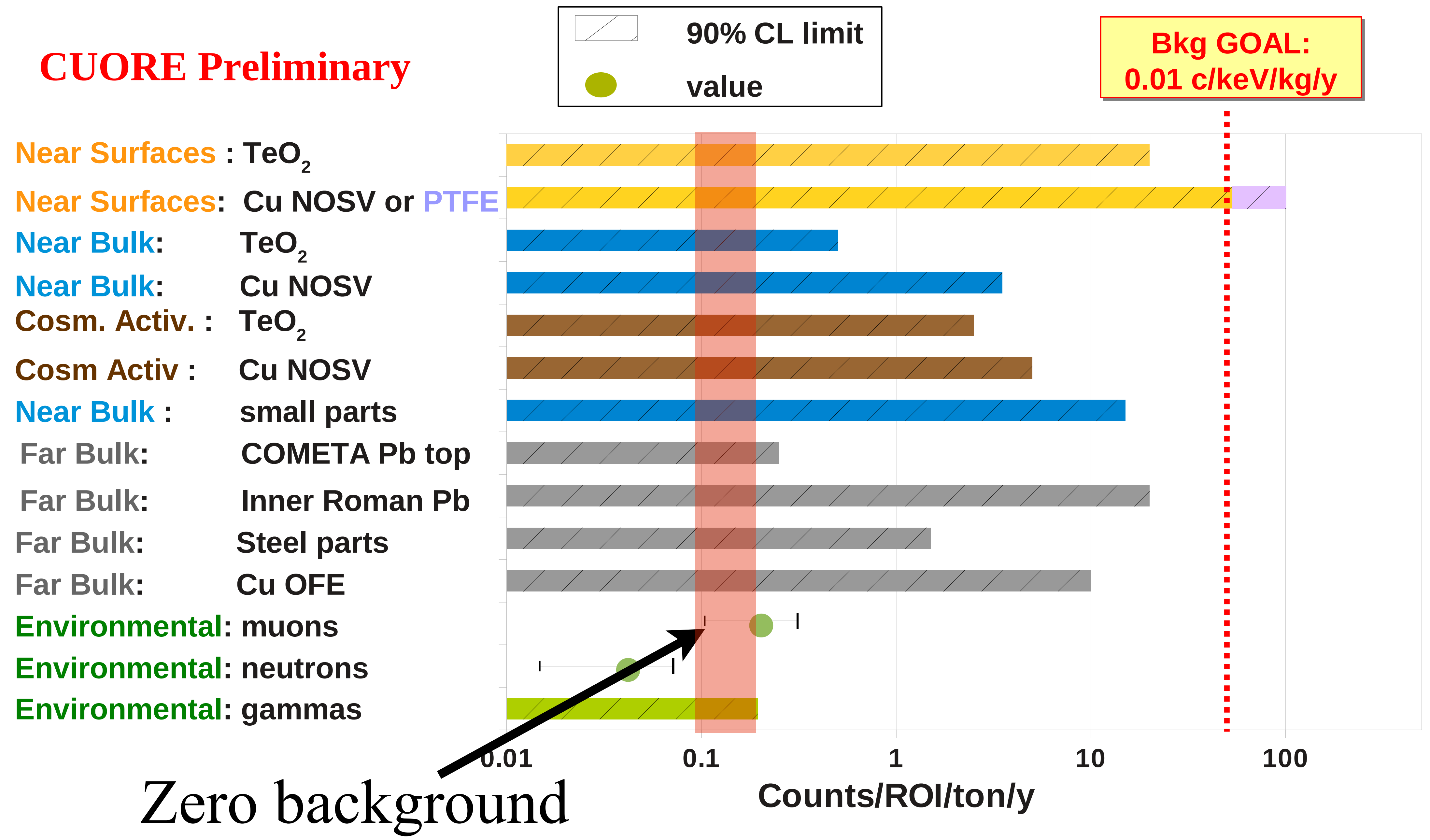
Requirements:

- ~ 1 ton of instrumented isotope
- Isotopic enrichment
- Essentially zero background
- 5-10 year run time

A Future Bolometric Detector

The next generation detector will require:

- Isotopic enrichment to increase the amount of ^{130}Te
  - On going tests to grow high enrichment low background detectors
- Particle Identification to reject background event by event



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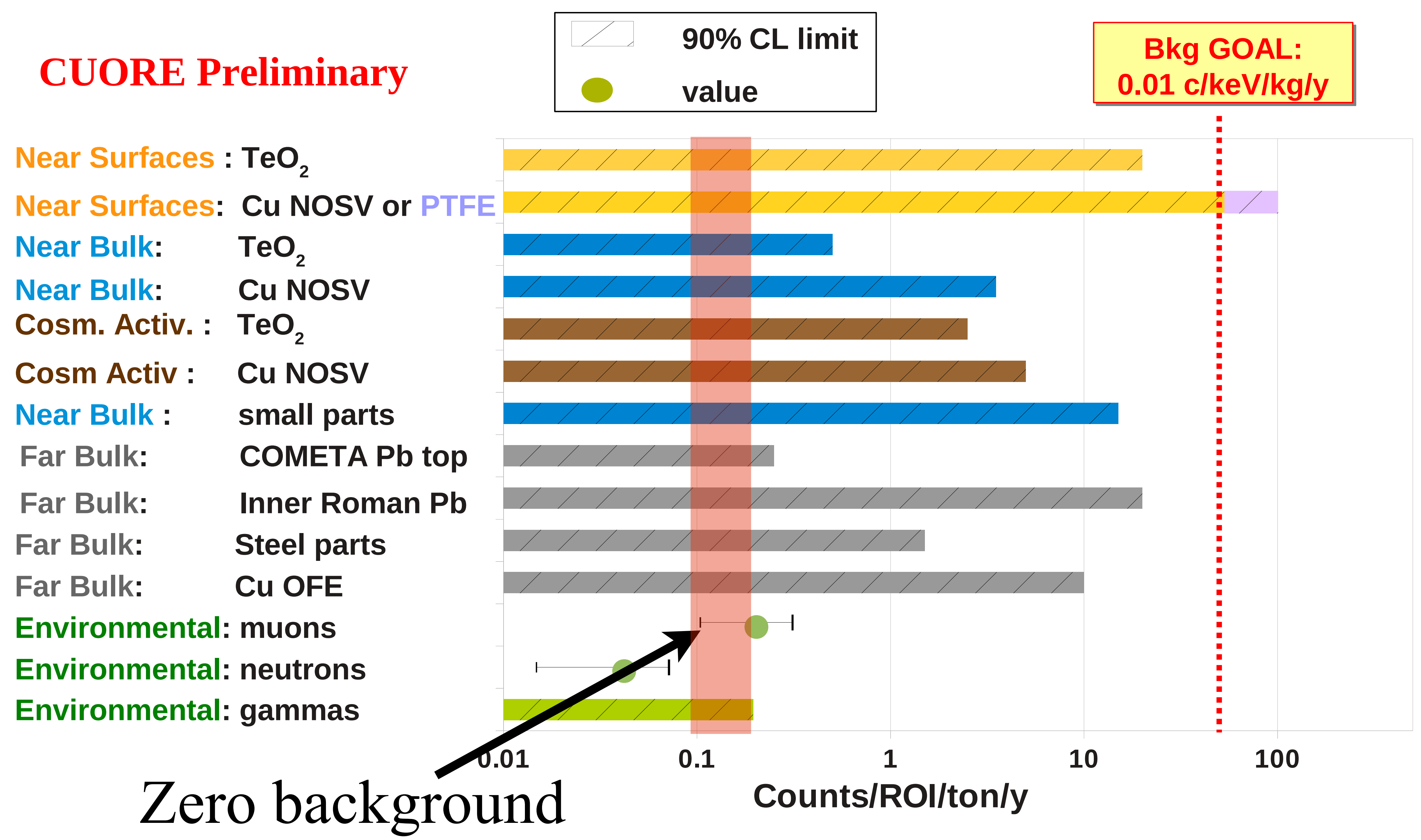
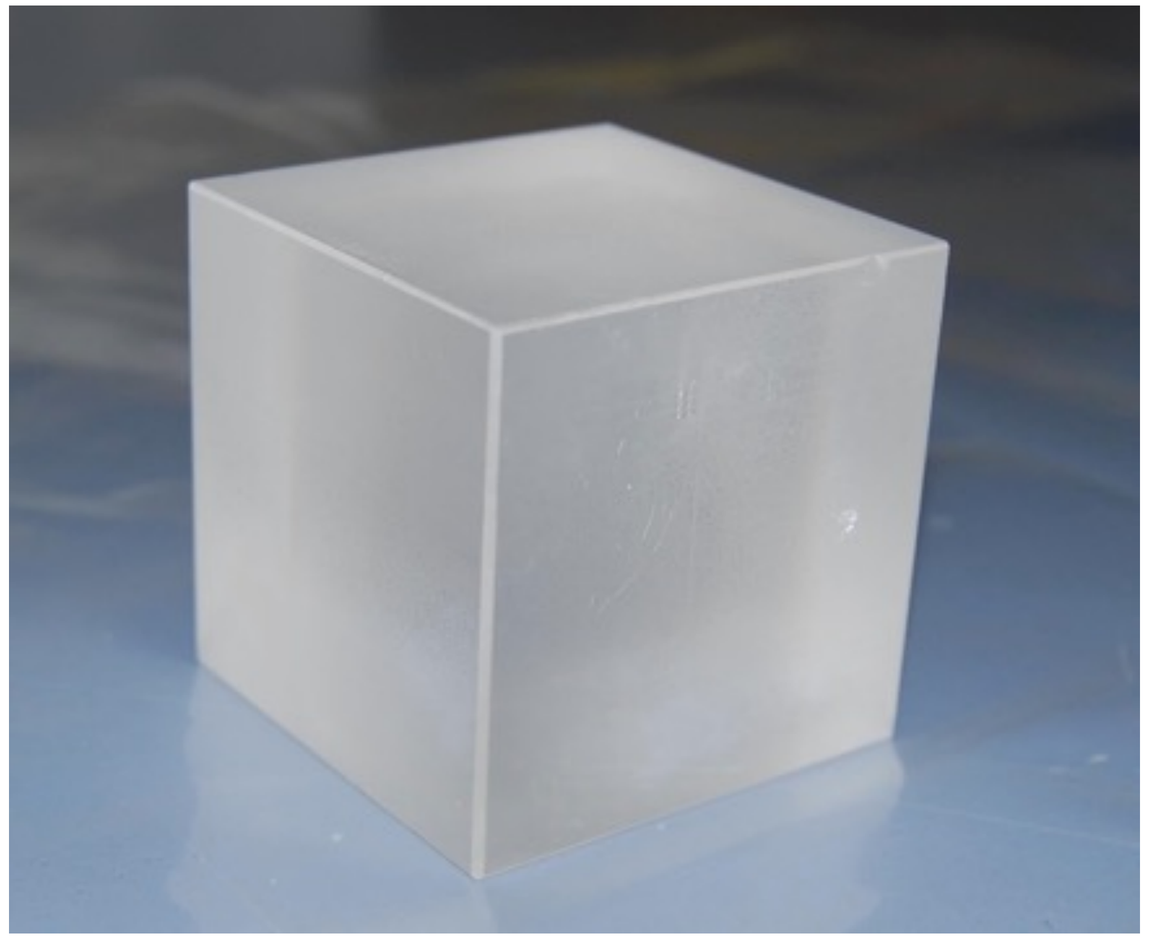


Multiple Channel Readout



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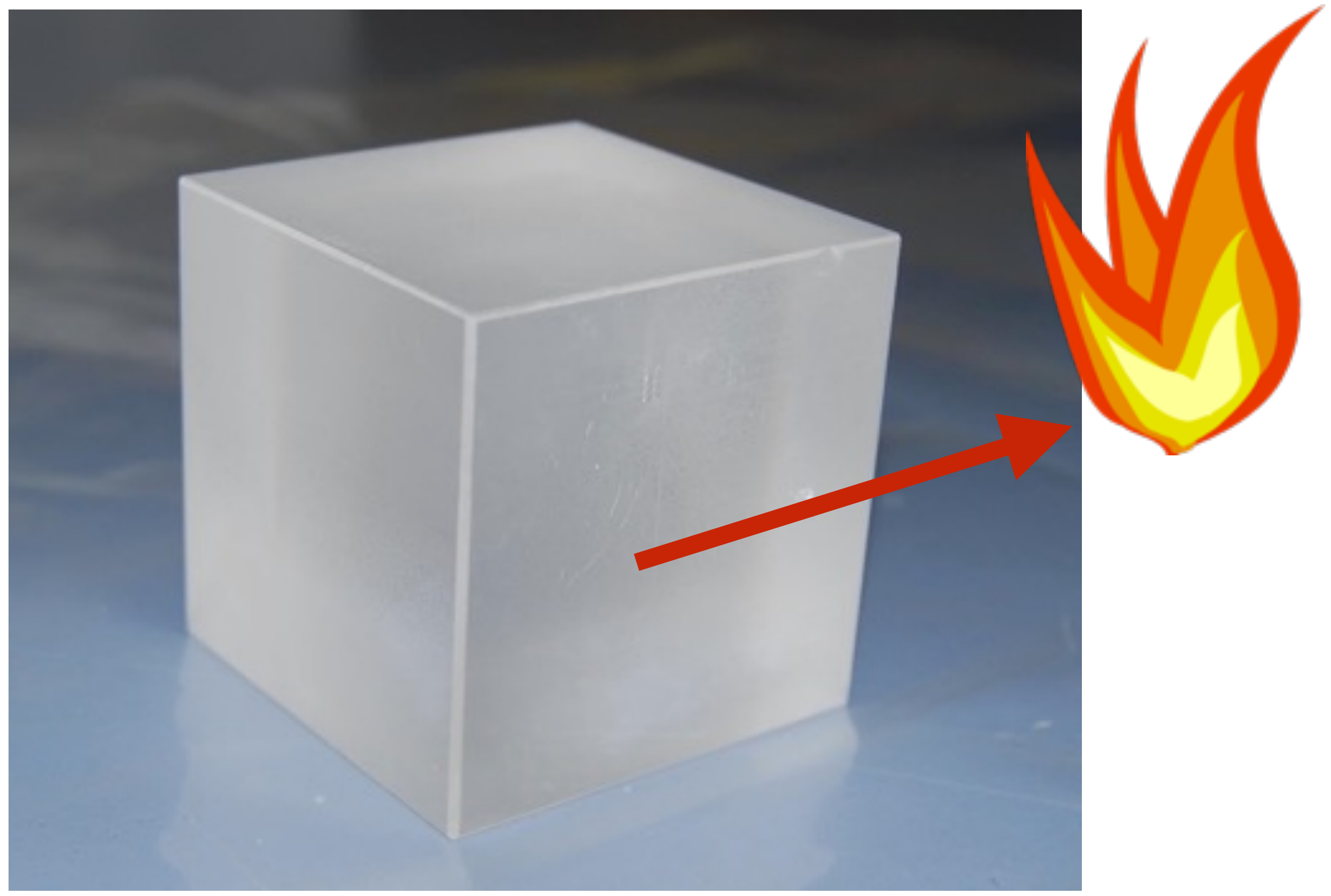
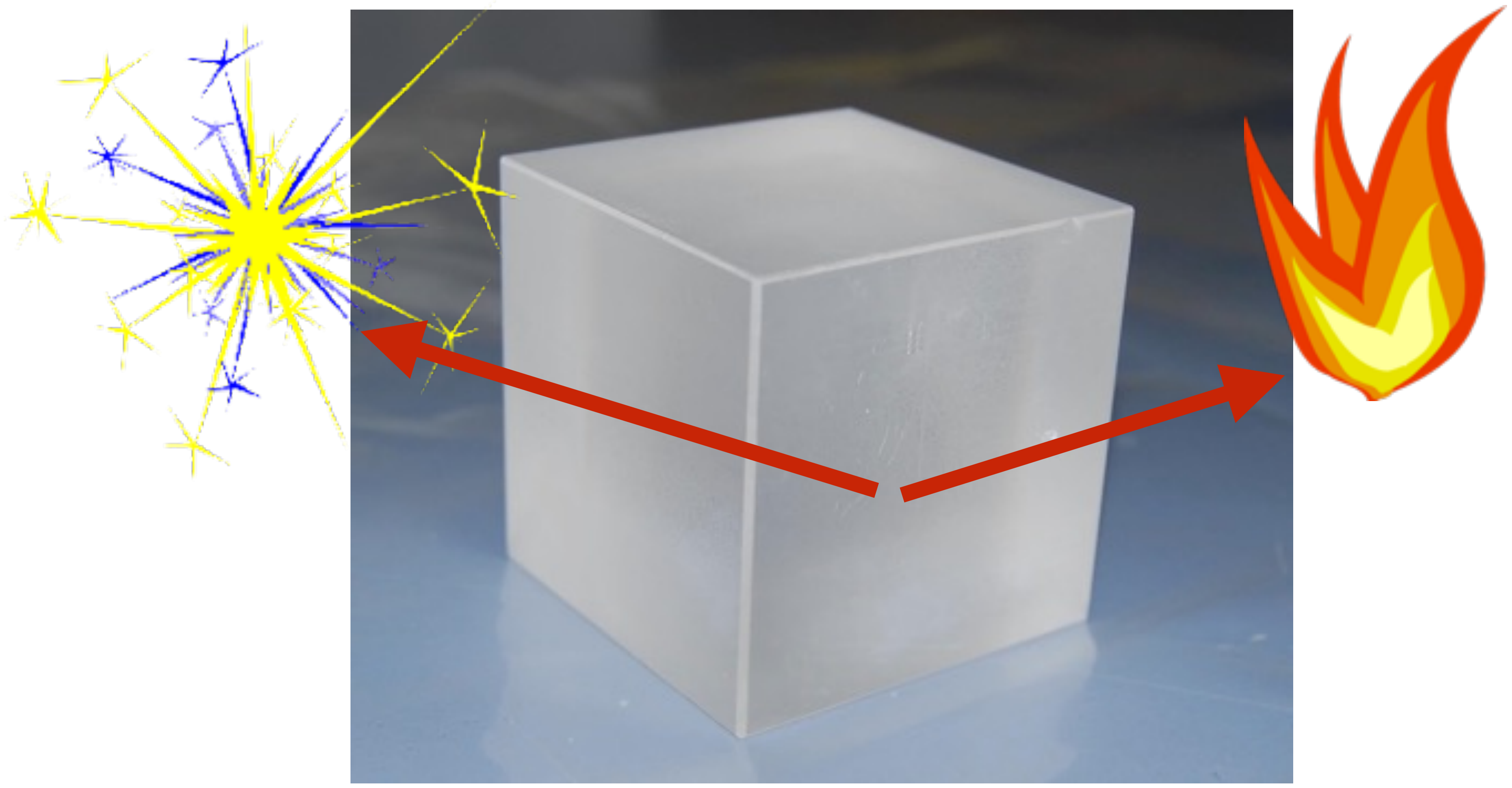


Multiple Channel Readout



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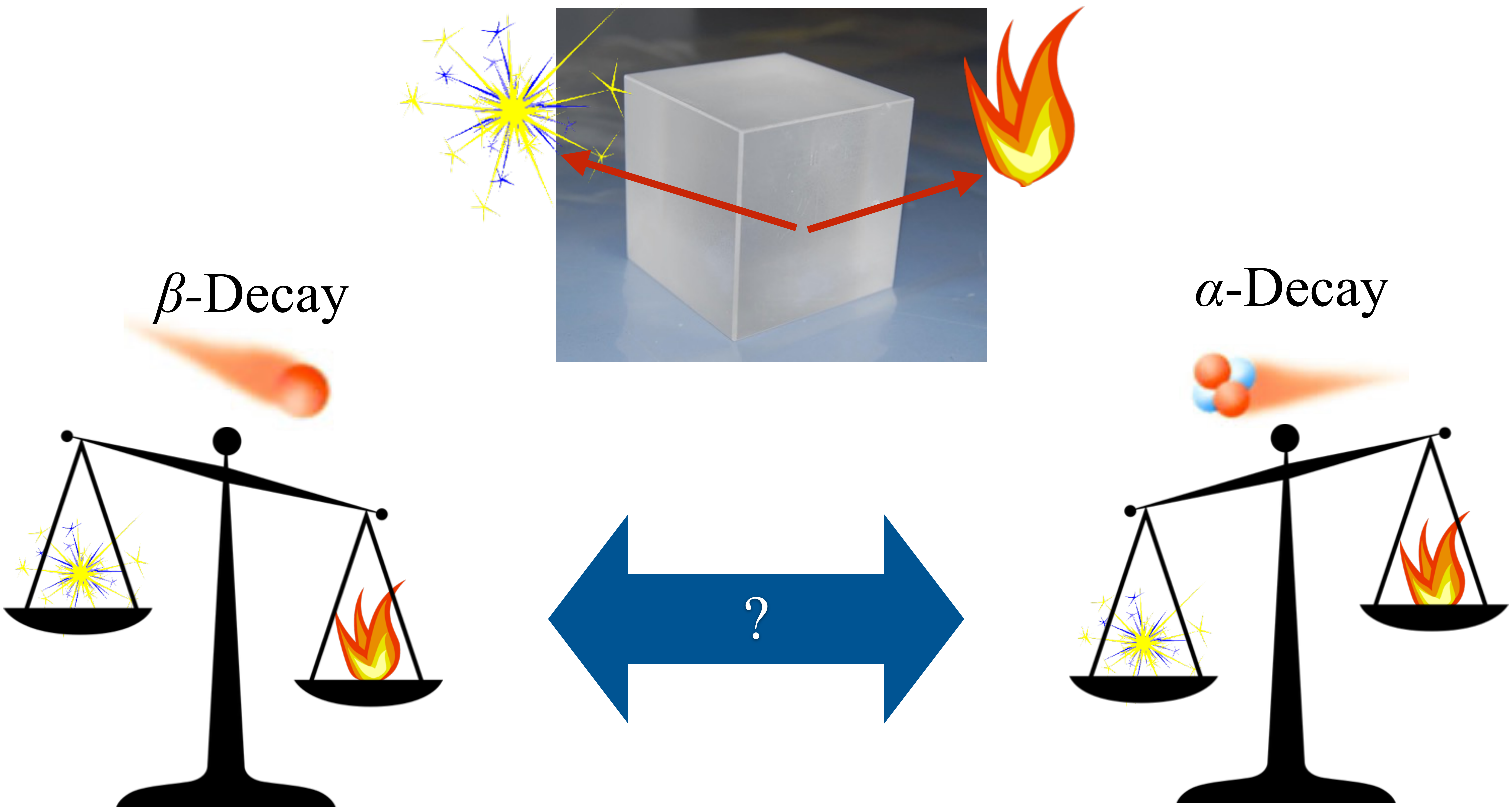
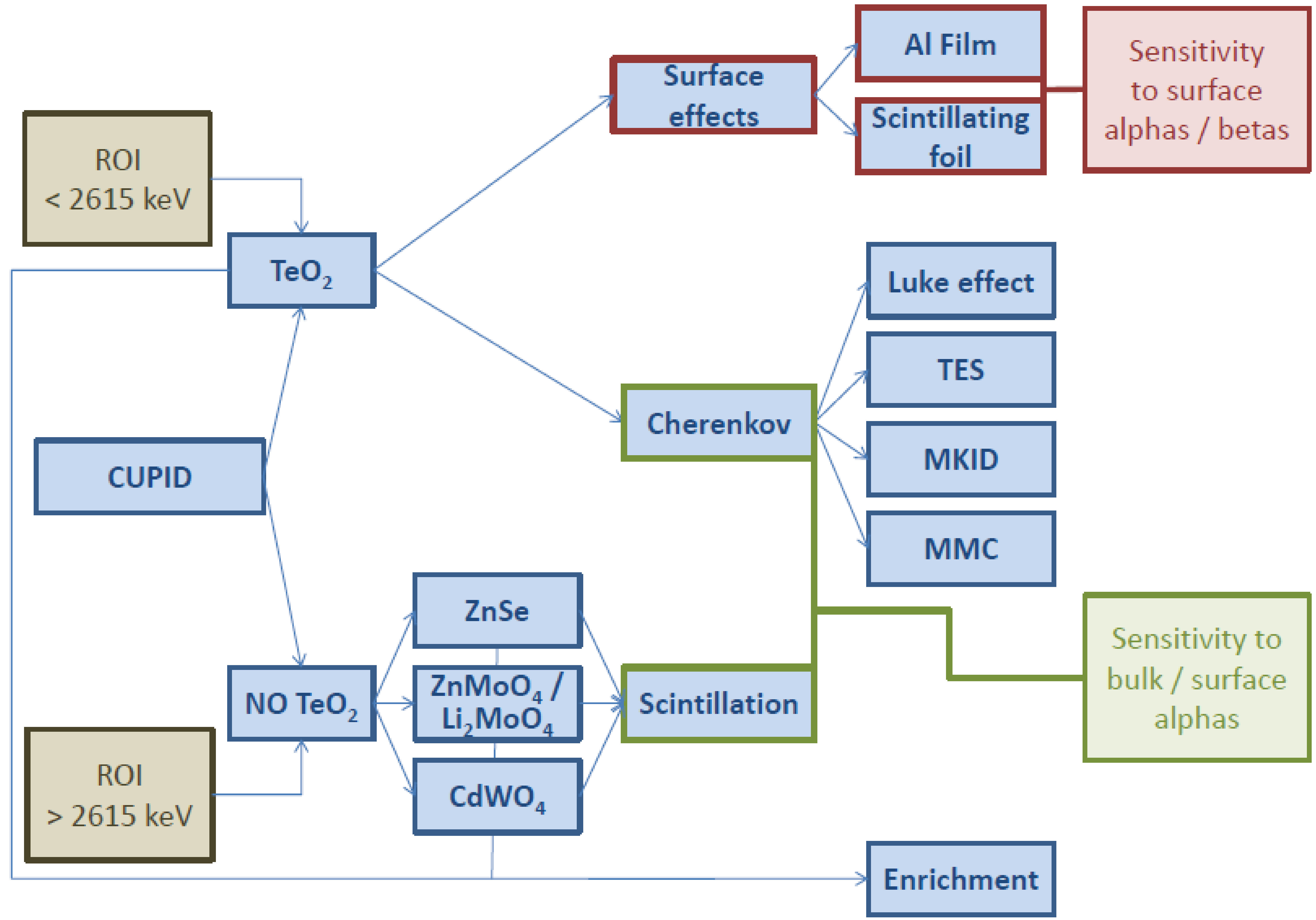


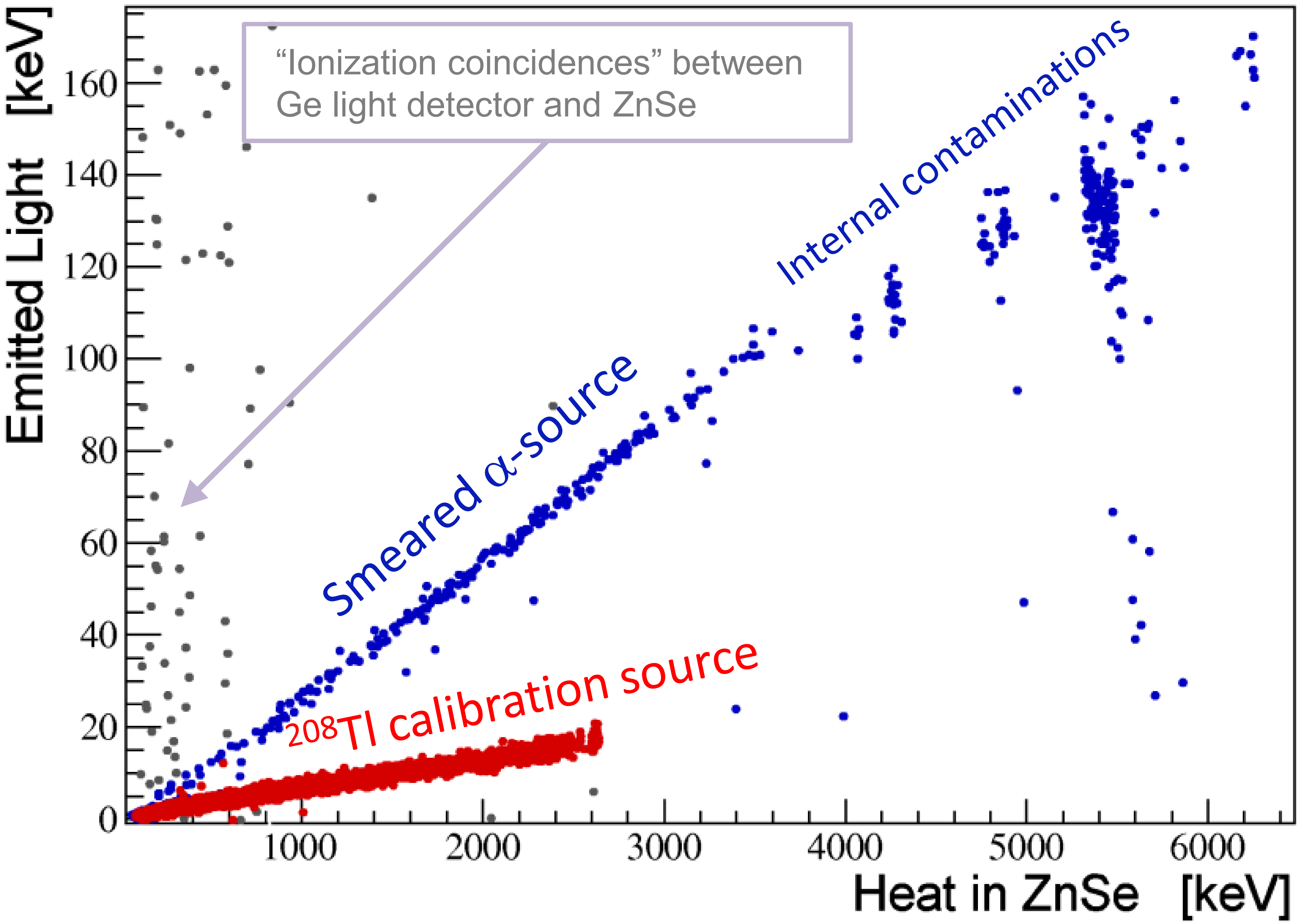
CUPID: CUORE Upgrade with Particle ID

Many Options Being Investigated:

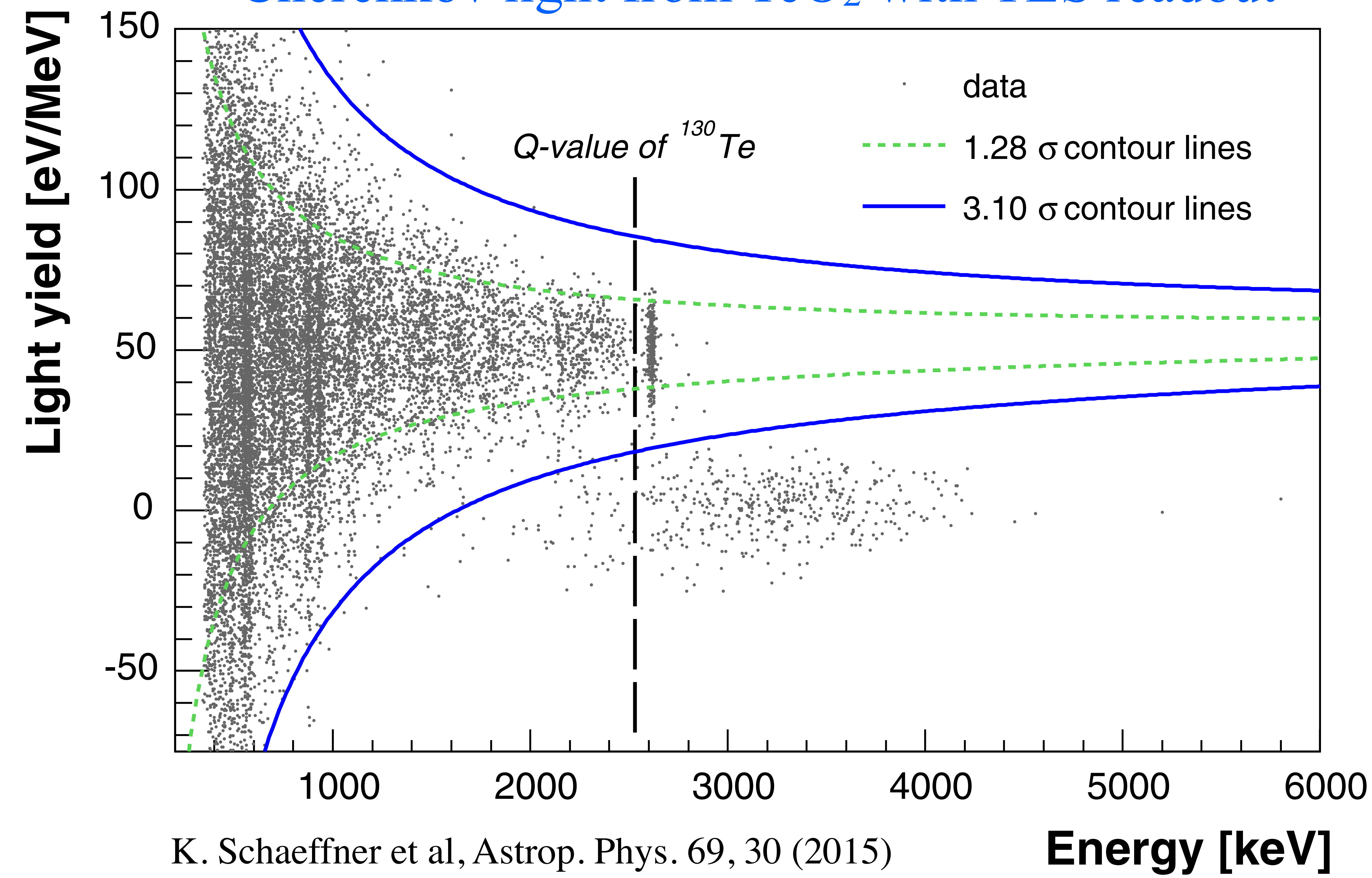


Combining Light Measurements

Scintillation light from $Zn^{82}Se$ with NTD readout

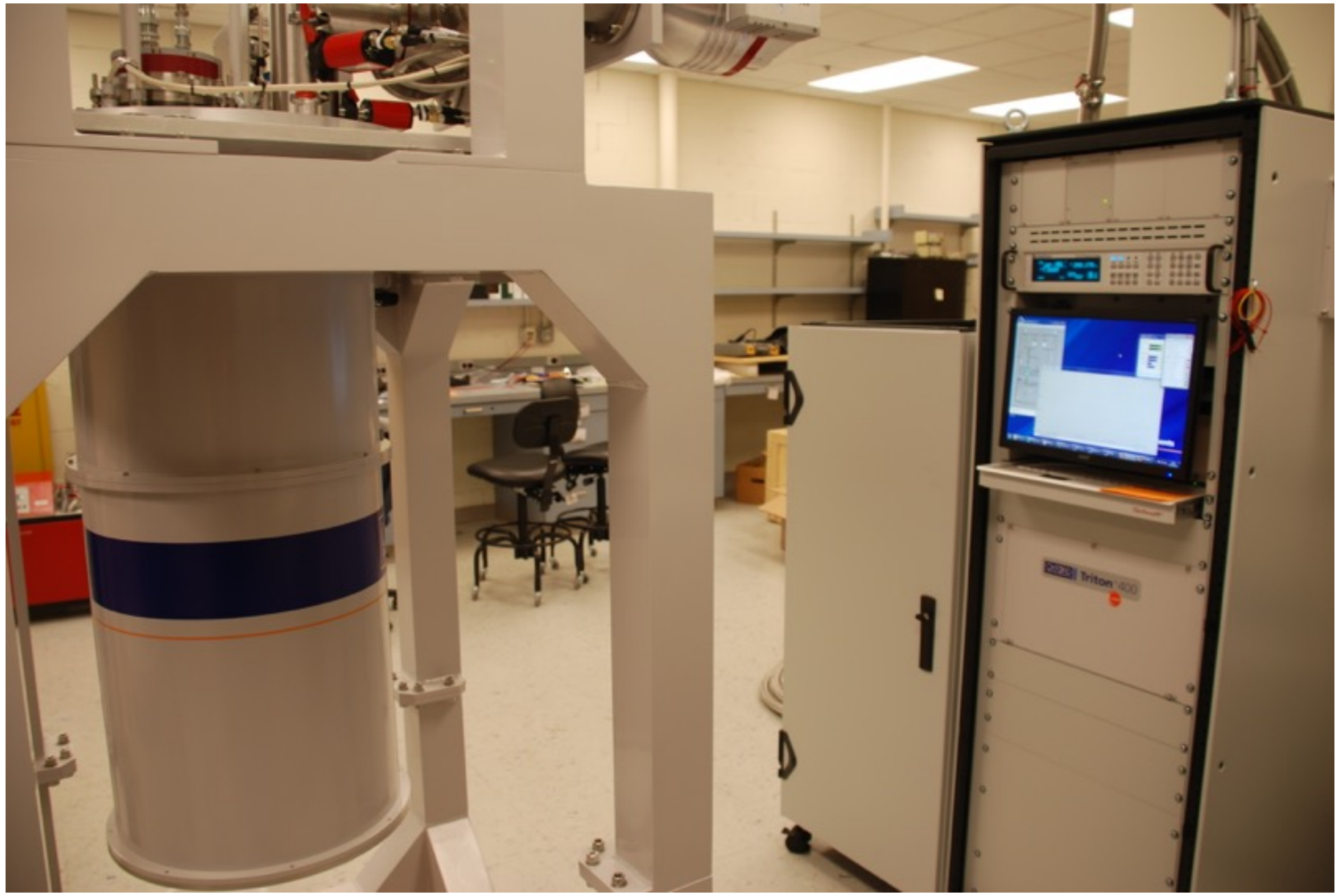


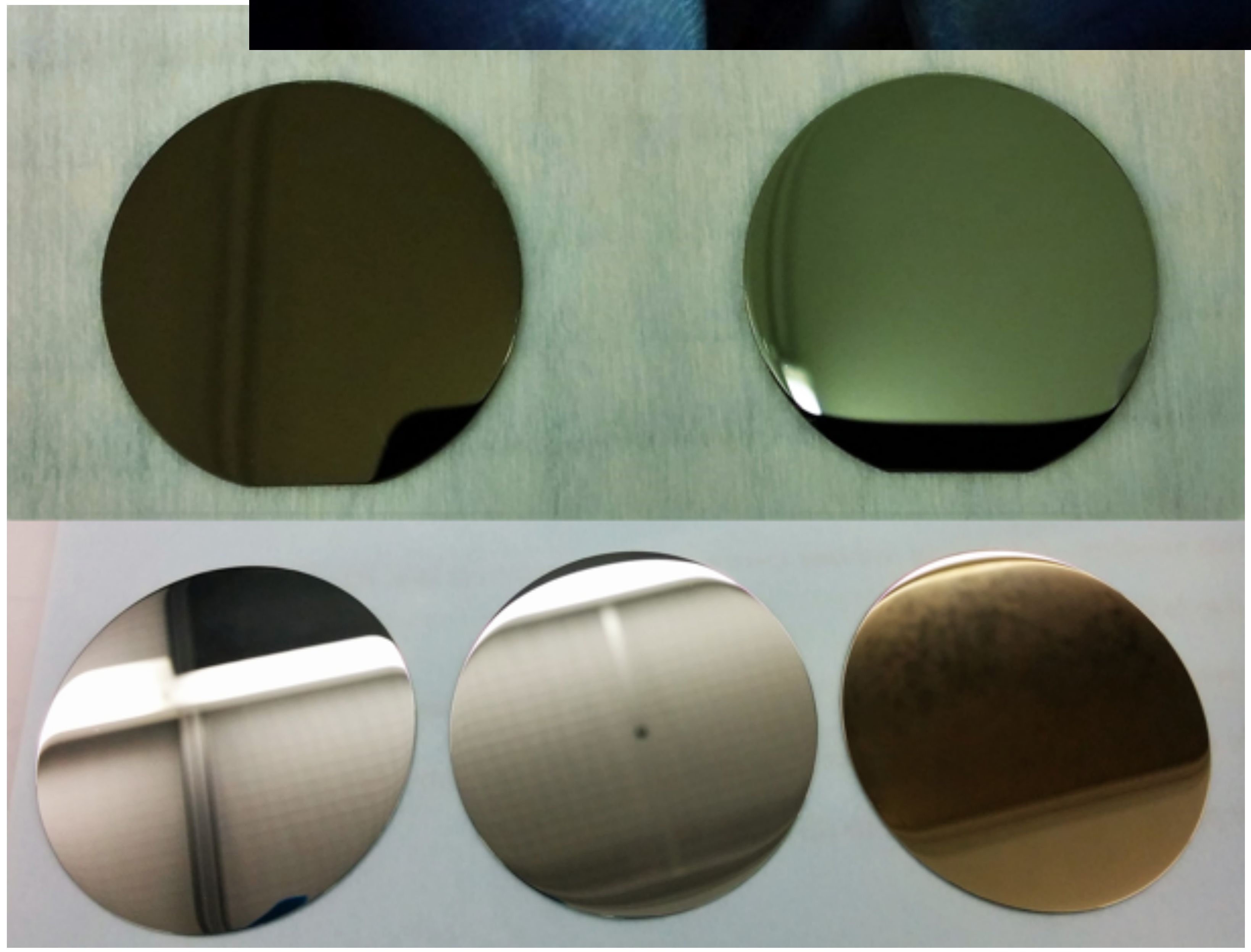
Cherenkov light from TeO_2 with TES readout



K. Schaeffner et al, Astrop. Phys. 69, 30 (2015)

R&D Effort at MIT





- Brand new dilution refrigerator
  - NTD and TES readout
  - Studying anti-reflective coatings for light absorbers
  - Developing new scintillating crystals