Analysis of the first data from the CUORE 0νββ decay search

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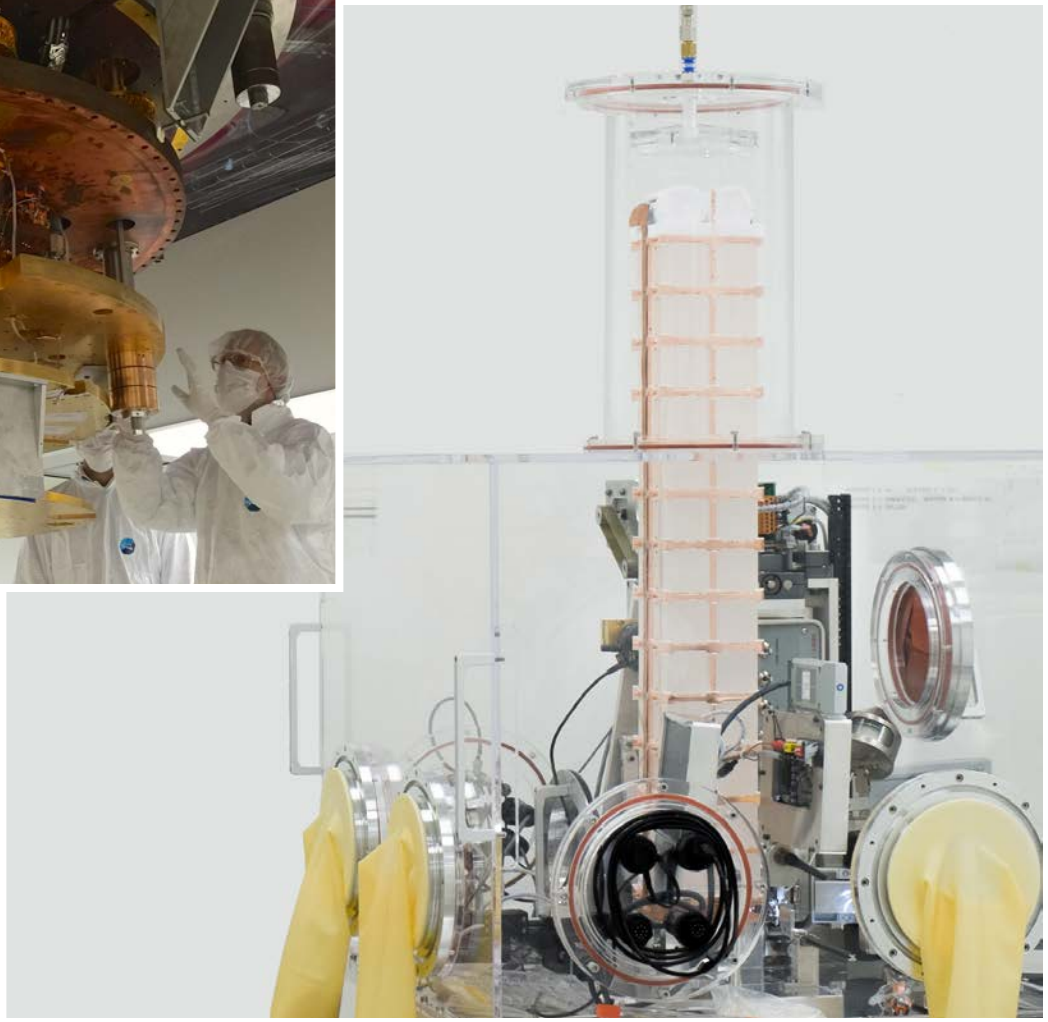
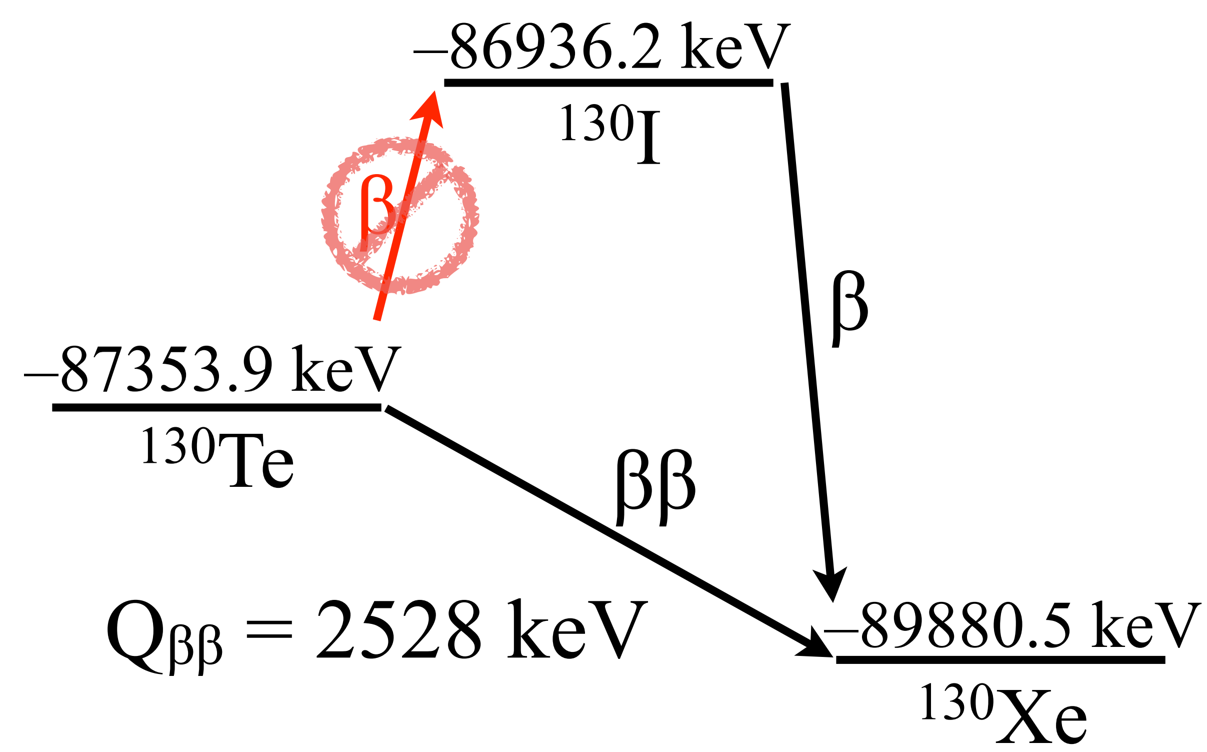
Outline

- Introduction:
  - Neutrinoless double beta (0νββ) decay
  - Bolometric detection
  - The CUORE experiment
- The first CUORE data
- Spectral line shape fit
- Resolution
- Region of interest fit
- Limits on 0νββ decay
- Fully Bayesian analysis with BAT
- Sensitivity, Toy MC, fluctuations
- Limit on effective Majorana mass
- Conclusions

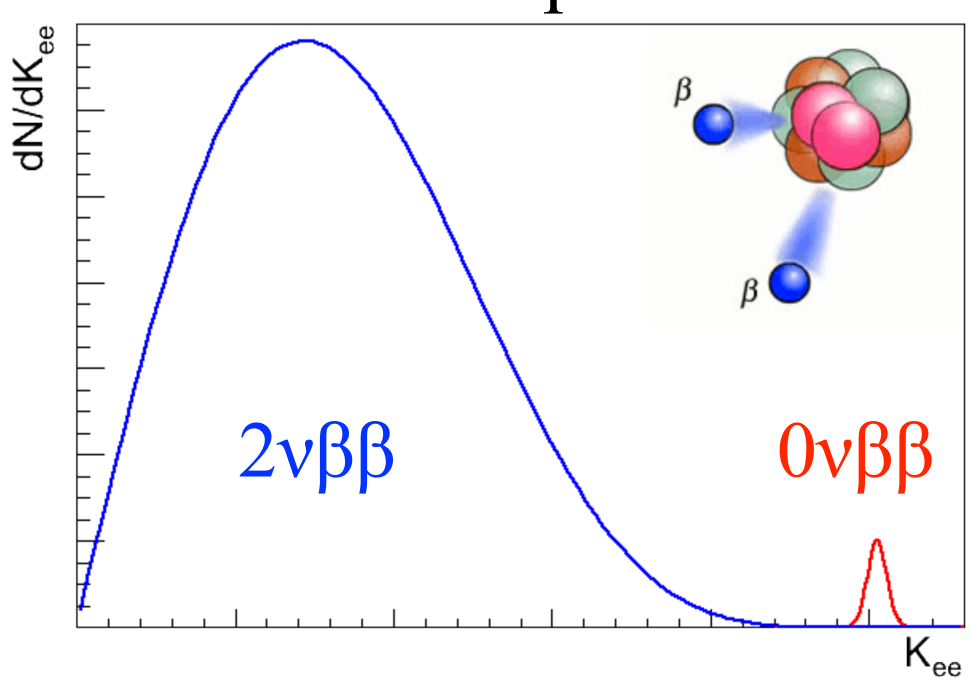


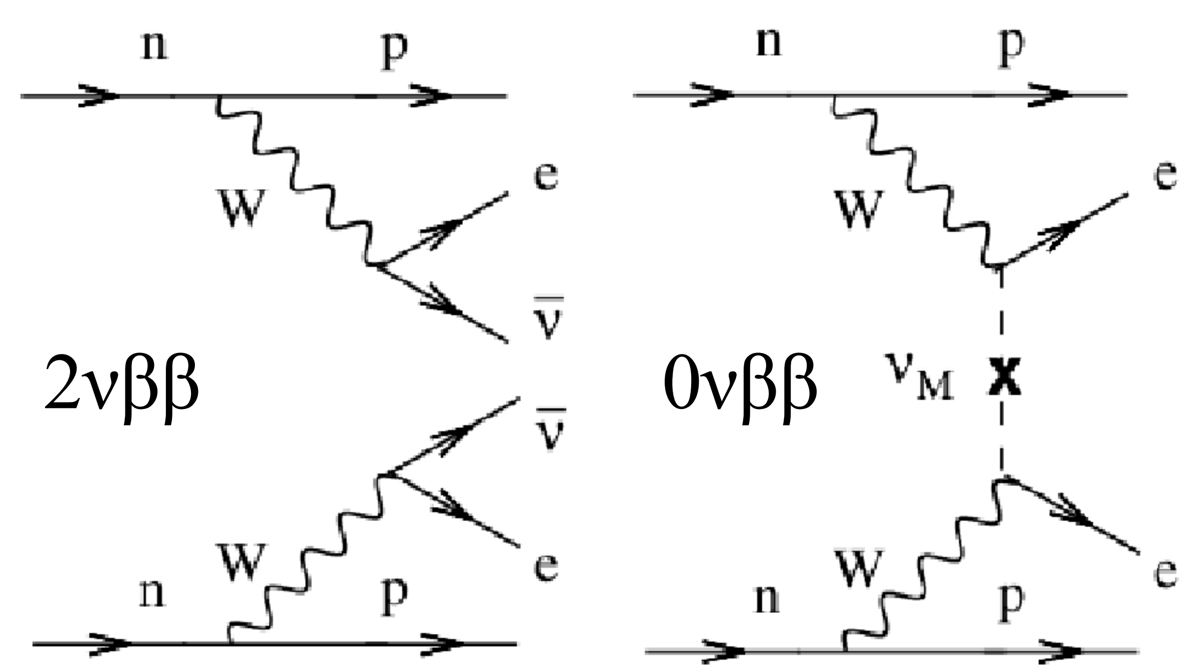
Neutrinoless Double-Beta Decay (0νββ)

- 2νββ: $(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\nu$
  - Rarest observed physical process
- 0νββ: $(Z, A) \rightarrow (Z+2, A) + 2e^-$
  - Theoretically proposed process.
  - Possible if the neutrino is a Majorana fermion—it's own antiparticle.



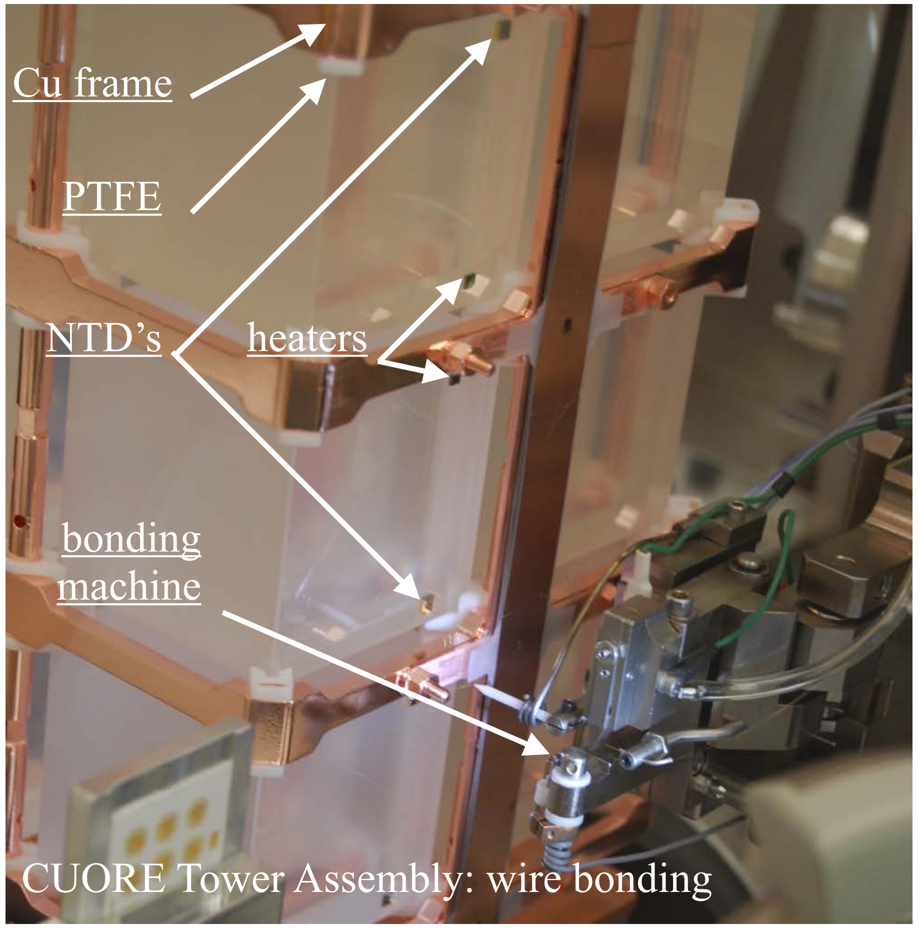
Cartoon spectrum

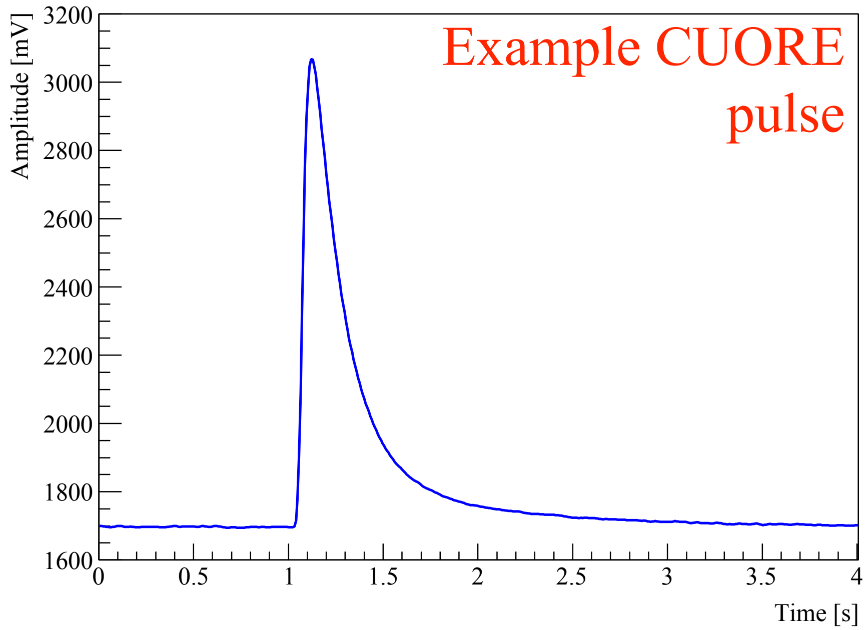


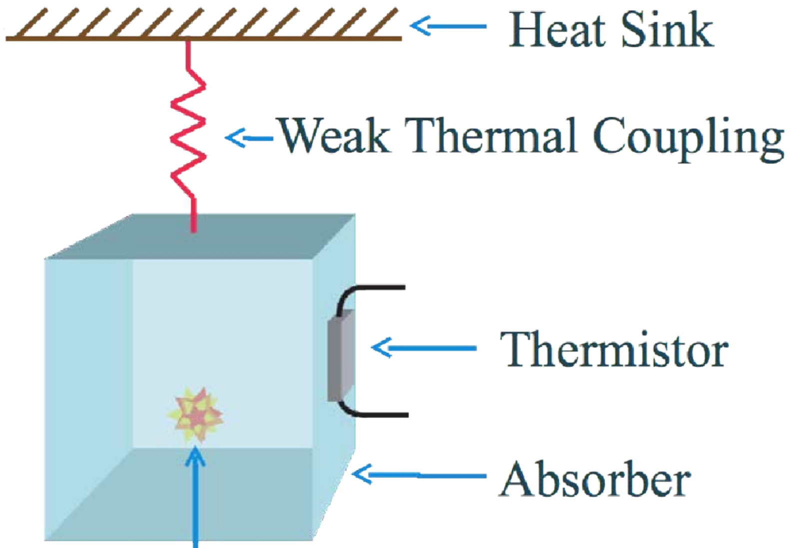


Bolometric Measurements

- Absorbed particle $\rightarrow \Delta T_{event} = \frac{E_{event}}{C_{crystal}}$
- Heat capacity is low at very cold temperatures:
  - In CUORE: 5×5×5cm^3 TeO_2 crystals: $\rightarrow C^{-1} \approx 100\mu K/MeV$
- Readout with temperature-sensitive resistive sensor (thermistor)
  - In CUORE, NTD Ge$\rightarrow R = R_0 e^{\sqrt{T_0/T}}$

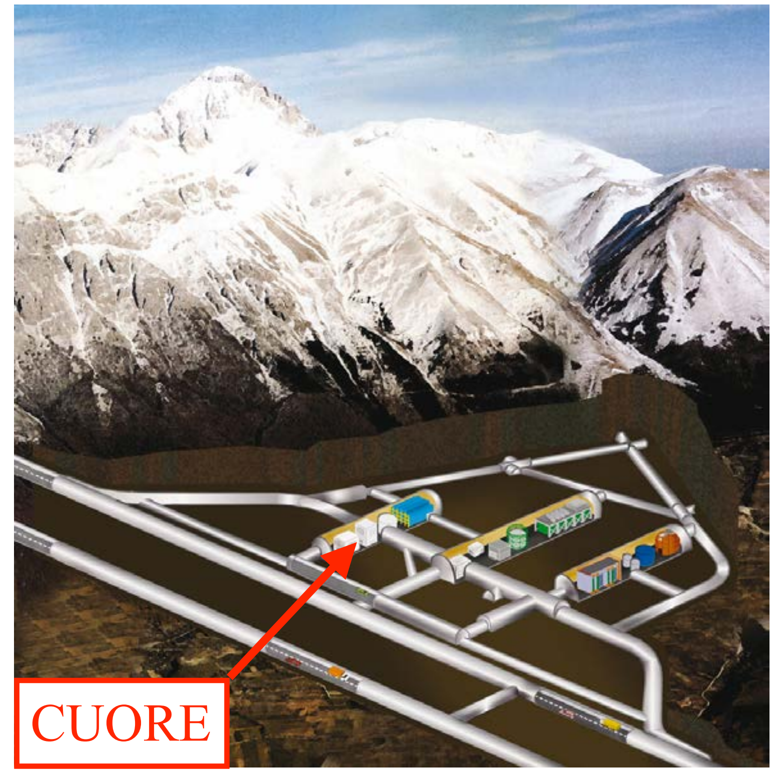


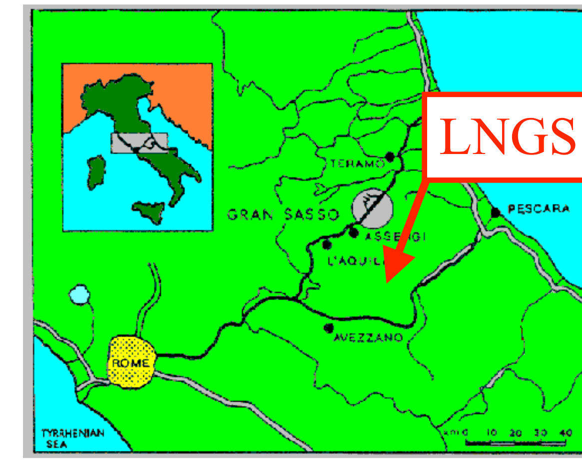


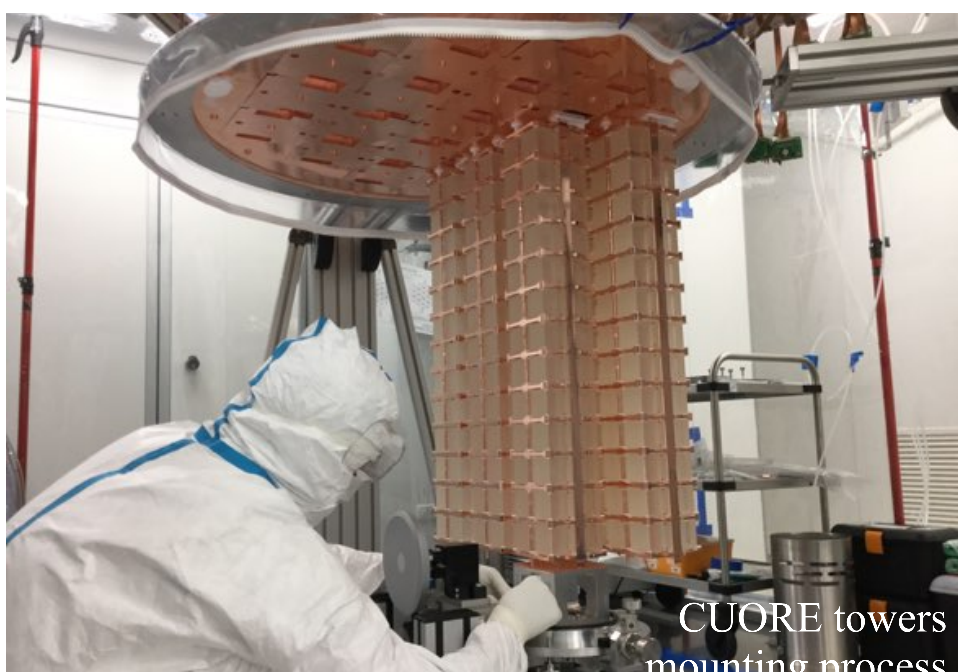


The CUORE Detector

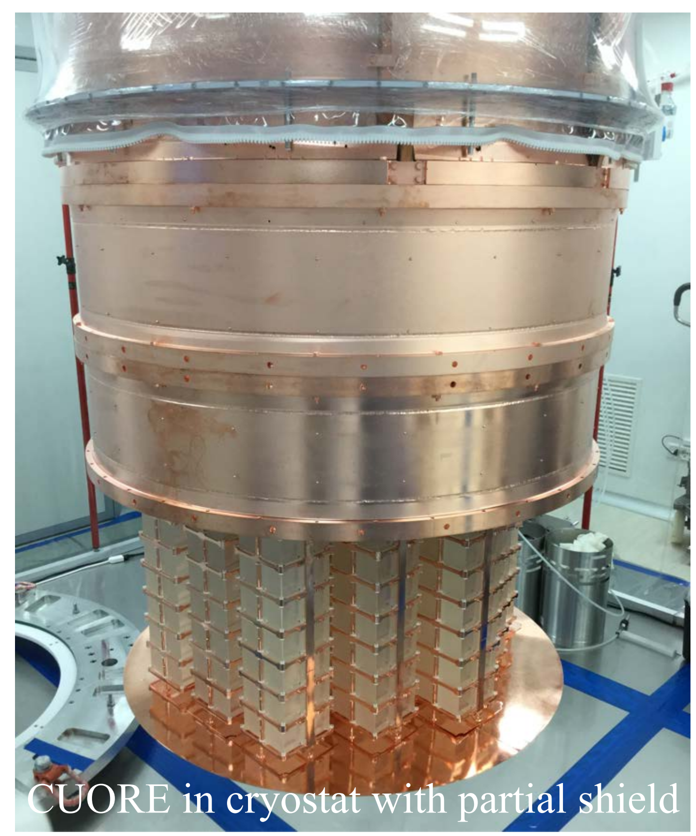
- **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents.
- Located at Gran Sasso National Laboratories in Italy (3650 m water equivalent overburden)
- Bolometric search for $0\nu\beta\beta$ of ^{130}Te (with secondary topics $2\nu\beta\beta$, other isotopes, axions …)
- 988 $5\times5\times5$cm^3 TeO_2 crystals in 19 towers of 52—source and absorber, $m_{isotope}$=206kg.
  - 984 active channels (99.6%)
- T_{base} ~ 10mK in world's largest dilution refrigerator.



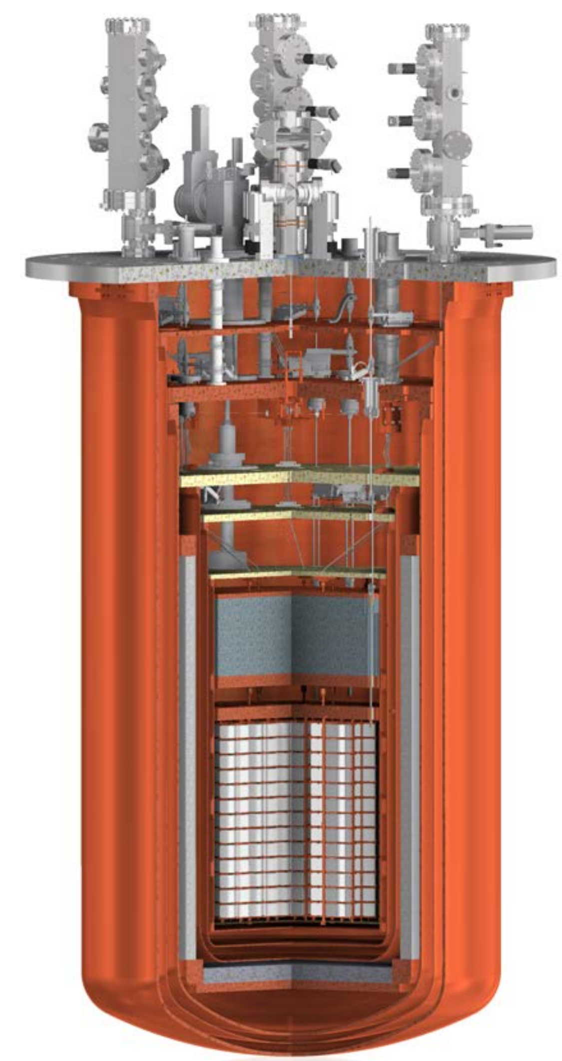




CUORE towers mounting process

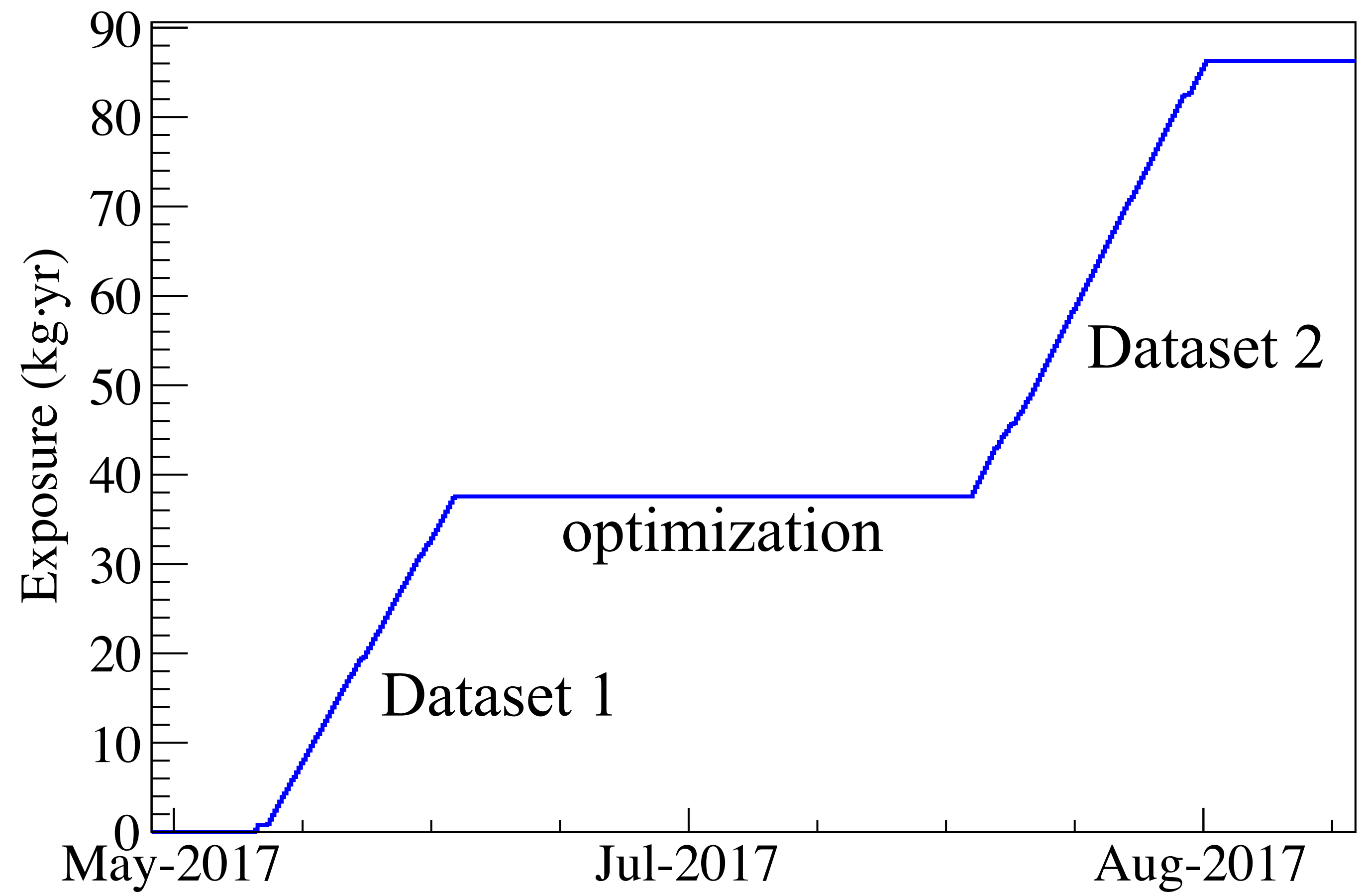


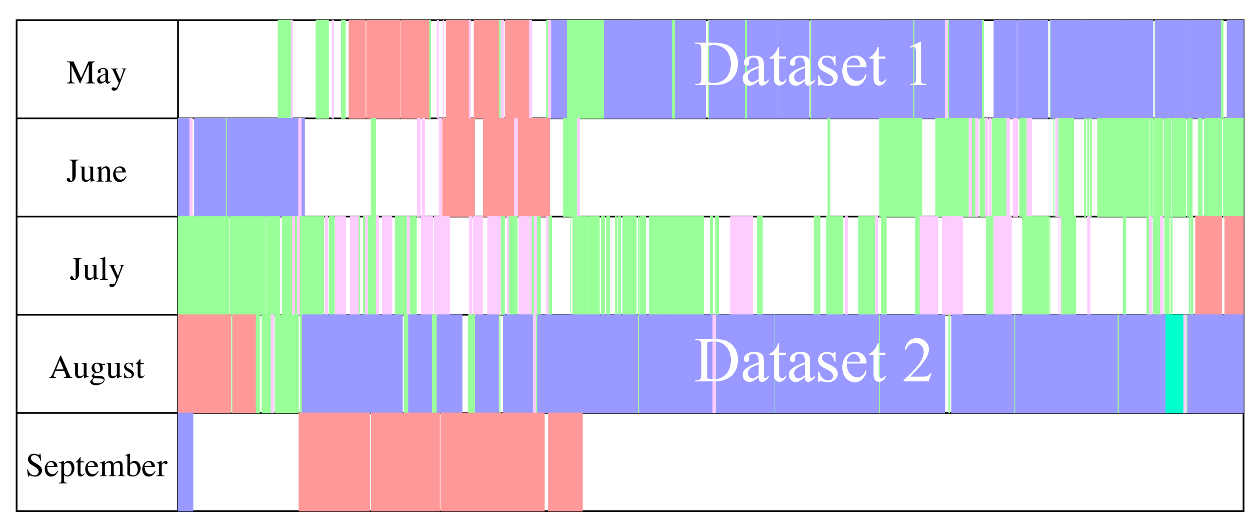
CUORE in cryostat with partial shield



The First Data from CUORE

- Active channels: 984/988 (99.6%)
- 2 physics datasets (right) separated by optimization period
- Channel-dataset pairs used in analysis: 1811 (92% of live channels)
- TeO_2 exposure: 86.3 kg yr (37.6 kg yr in Dataset 1 + 48.7 kg yr in Dataset 2)
- ^{130}Te exposure: 24.0 kg yr

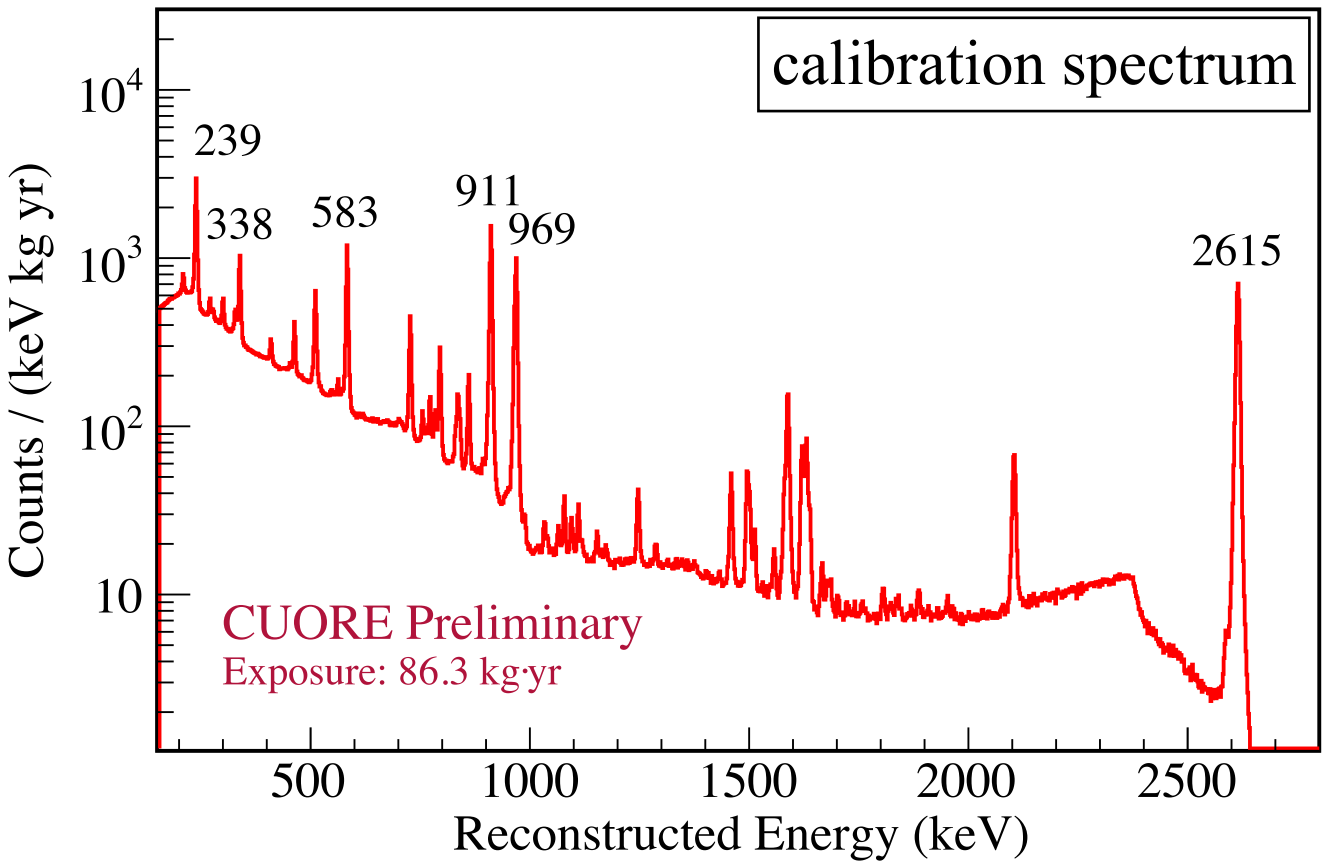


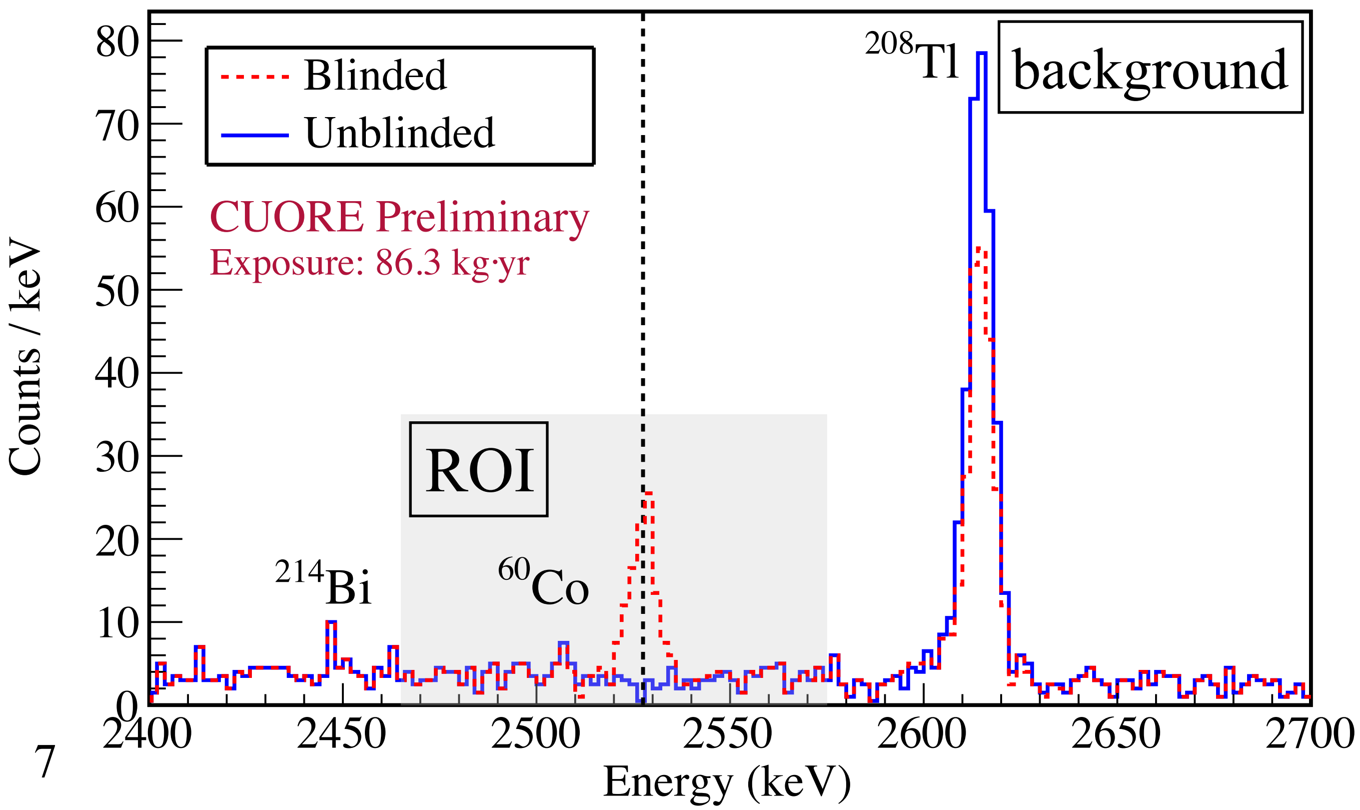


Physics, calibration, test, and configuration runs of CUORE in 2017

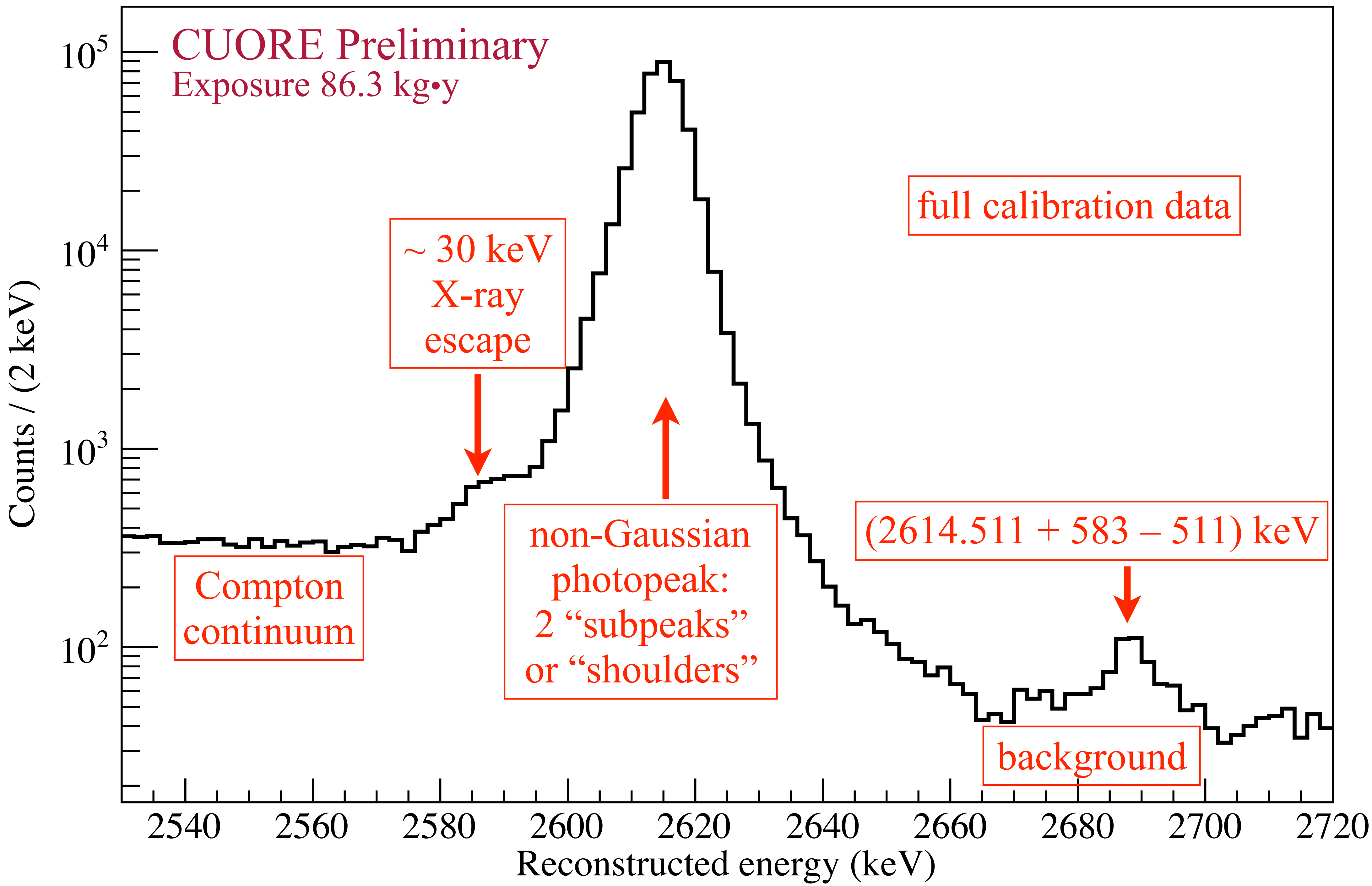
Modeling the Line Shape: 2615 keV ^{208}Tl

- Fit to determine the spectral line shape.
- Use the ^{208}Tl 2615 keV line:
  - Strongest peak from ^{232}Th calibration spectrum.
  - Sufficiently prominent in the background spectrum.
  - Relatively near to the ^{130}Te $0\nu\beta\beta$ decay ROI (2465 to 2575 keV, in gray at right).
- Use this fit result as the PDF for fits to spectral lines, particularly for the ^{60}Co 2γ line and ^{130}Te $0\nu\beta\beta$ decay in the main analysis.





Modeling the Line Shape: 2615 keV ^{208}Tl



- We would like to fit the region of [2530, 2720] keV: many features to consider in and around the line.

Simultaneous Fit by Tower

One PDF for each Channel-Dataset in the energy range [2530-2720] keV:

- Channel-Dataset-dependent parameters:
  - Q-value of the photopeak
  - Sigma (same for all Gaussians)
  - Total signal rate in main peak
    - Exposure (kg $\times$ y) from database
- Channel–dependent parameters:
  - 2 $\times$ Subpeak Energy Ratios: positions of the left and right shoulders w.r.t. Q-value
  - 2 $\times$ Subpeak Ratios: events in the 2 shoulders w.r.t. the main peak

- Global parameters:
  - Compton Ratio: events in the Compton shoulder w.r.t. main peak
  - Background Ratio: events in linear background w.r.t. main peak
  - Linear Background Coefficient
  - X-Ray Ratio: events in the ~ 30keV X-Ray escape peak w.r.t. main peak
  - 2687 keV Peak Ratio: ratio of events in the peak at (2615 – 511 + 538) keV
  - 2687 keV Peak Energy Ratio: position of peak at (2615 – 511 + 538) keV w.r.t. Q-value

Perform simultaneous fit with RooFit on the tower level: 19 independent fits of up to 52 channels (104 channel-datasets) in each.

Simultaneous Fit by Tower

- Each PDF has 5 components:

$$\text{ModelPDF}_{ChDs} = N_{bkg}\times\ \text{Pol}_1 + N_{Compton} \times ComptonFunc + N_{Signal} \times PhotoPeak + N_{Xray} \times XRayFunc + N_{2687keV} \times Gauss$$

$$ComptonFunc = \frac{1}{2} \cdot Erfc\left(\frac{x-\mu}{\sqrt{2}/\sigma}\right)$$

$$PhotoPeak = \frac{1}{\sigma\sqrt{2\pi}} \times e^{-\frac{(x-\mu)^2}{2\sigma^2}} + Ratio \times e^{-\frac{(E.Ratio-\mu)^2}{2\sigma^2}} + Ratio2 \times e^{-\frac{(E.Ratio2-\mu)^2}{2\sigma^2}}$$

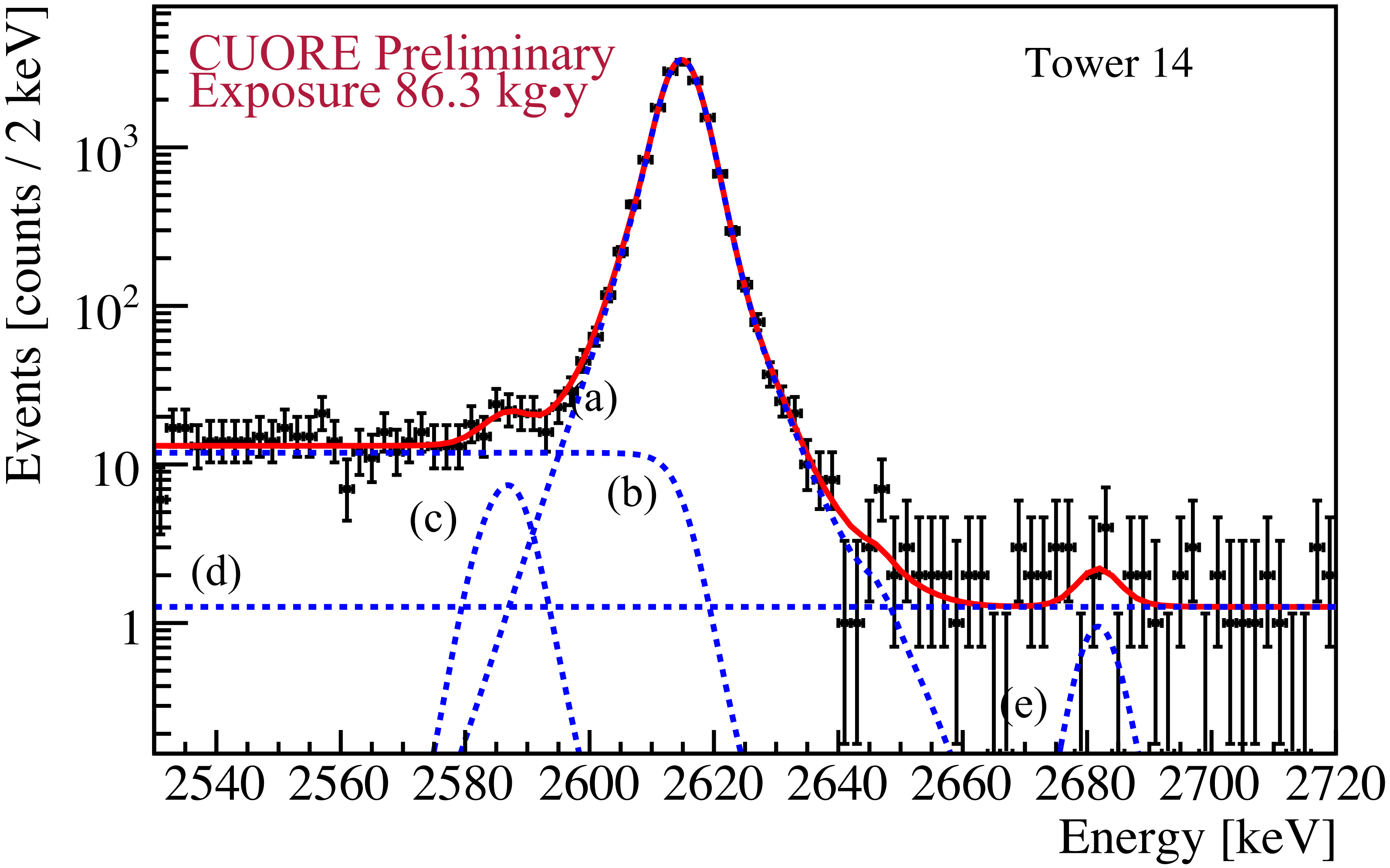
$$XRayFunc = \frac{1}{\sigma\cdot\sqrt{2\pi}\cdot\text{TotalWeight}} \cdot \sum_{i=1}^{n=6} R_i \cdot e^{-\frac{(x-\mu+Ediff_i)^2}{2\sigma^2}}$$

- Perform simultaneous fit with RooFit on the tower level:

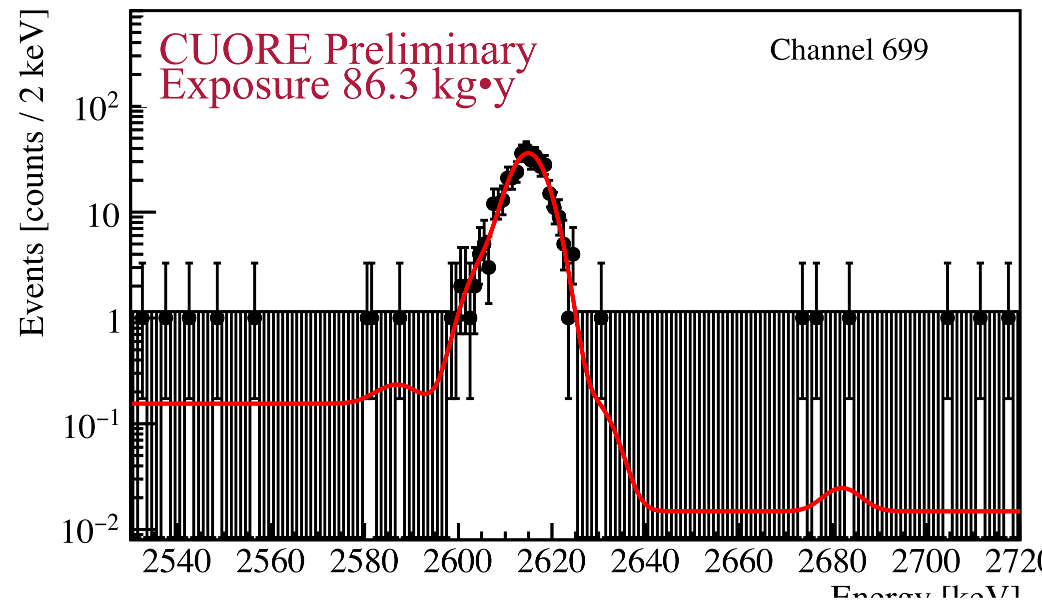
➡ 19 independent fits of up to 52 channels (104 channel-datasets) in each.

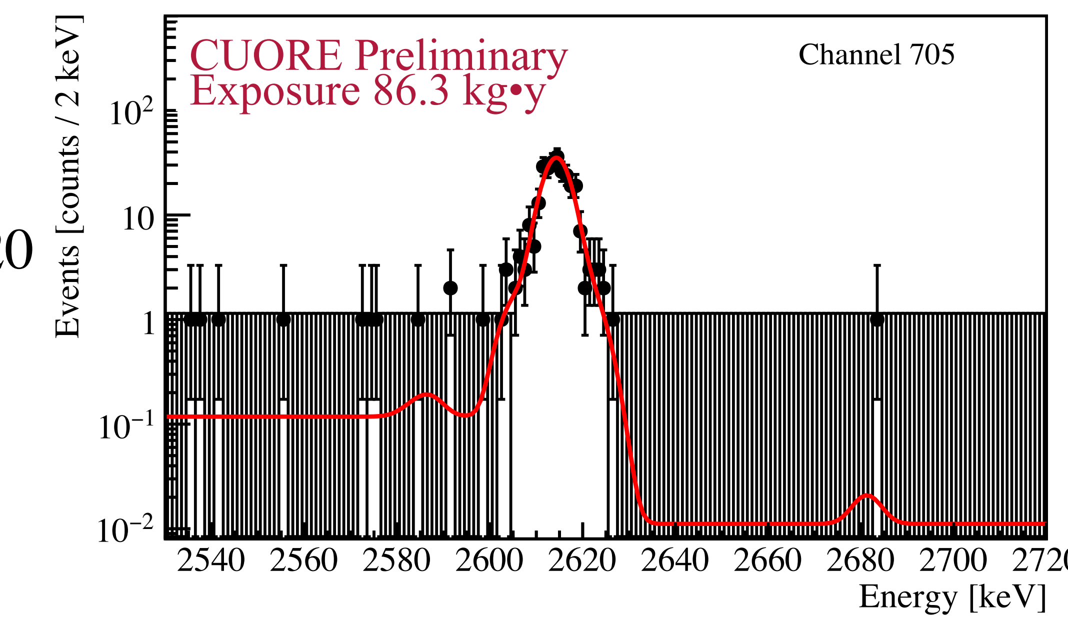
➡ Balance between good statistics and converging fits while grouping channels by similar background performance.

Example Line Shape Fit Result: Tower 14



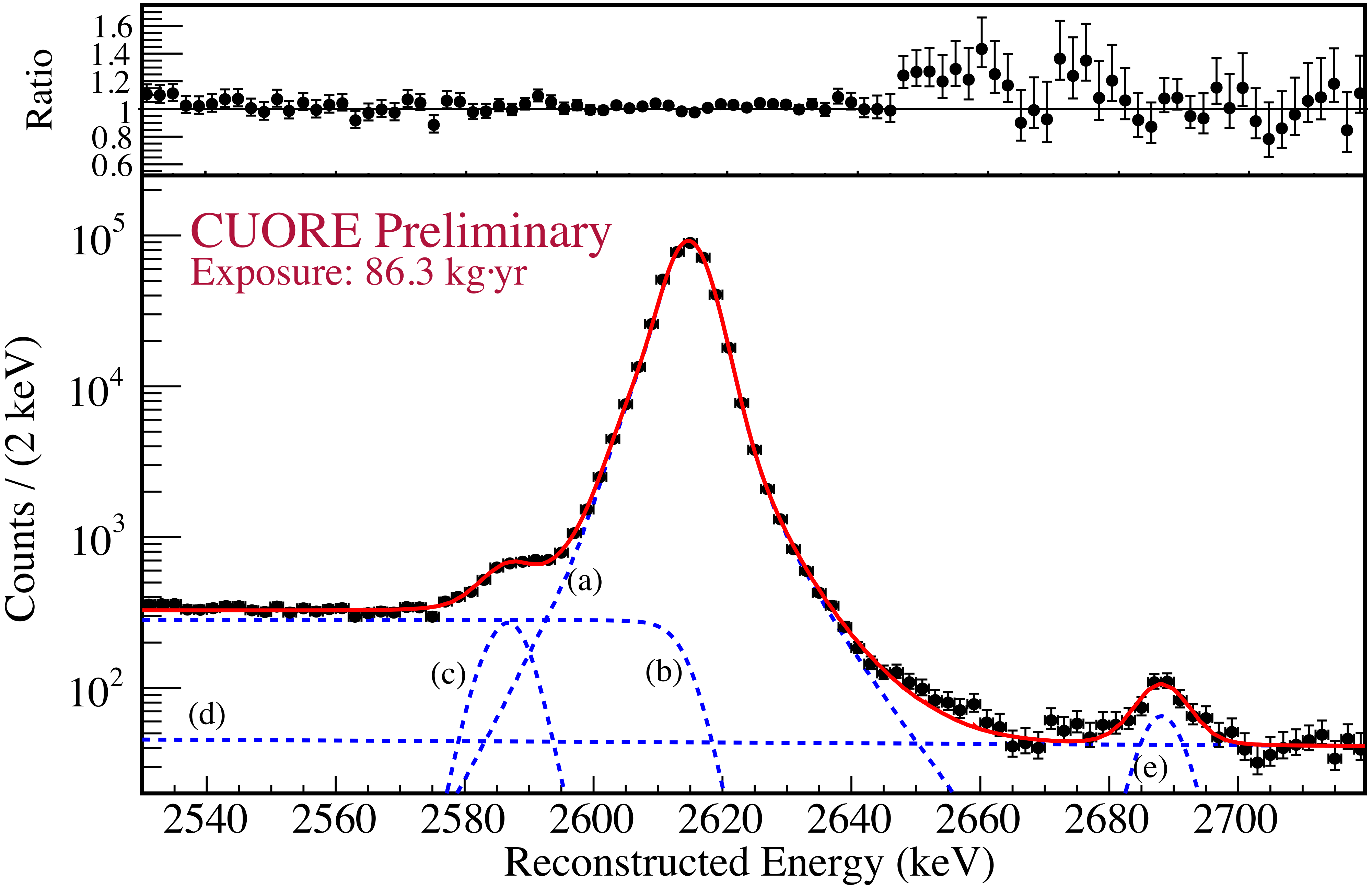
(a) - Photopeak
(b) - Compton
(c) - ~30 keV X-ray escape
(d) - Background
(e) - (2615 + 583 – 511) keV





One tower (single simultaneous fit) with fit components and two example channels from that tower (both datasets).

The Summed Line Shape Fit Result



(a) - Photopeak

(b) - Compton

(c) - ~30 keV X-ray escape

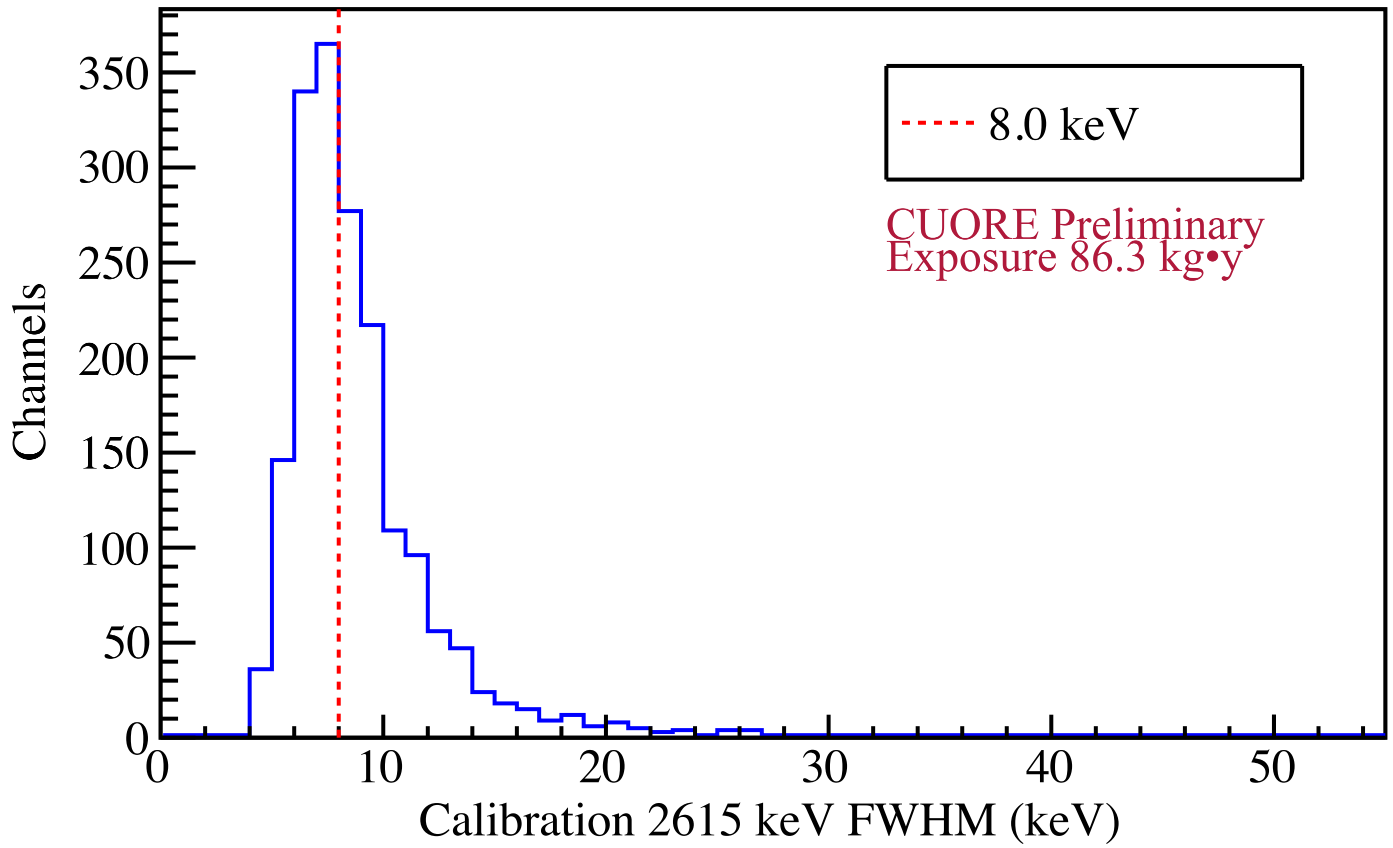
(d) - Background

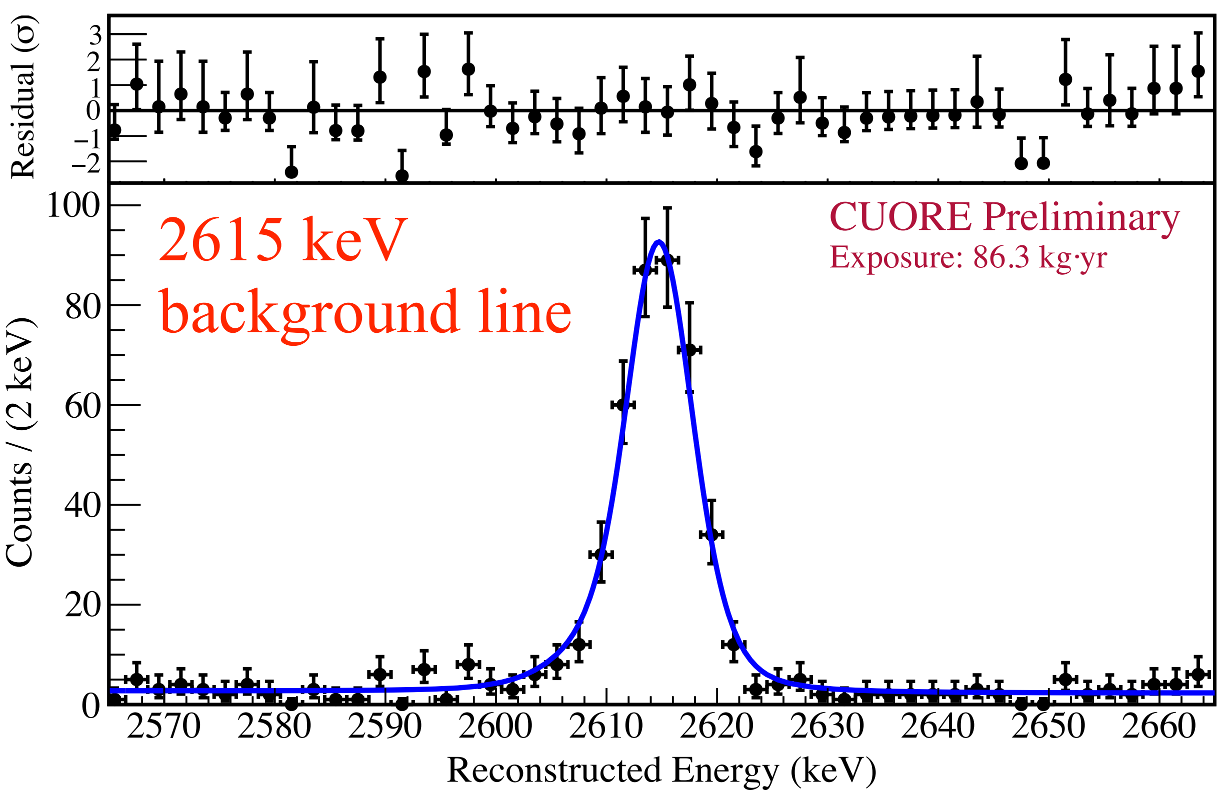
(e) - (2615 + 583 – 511) keV

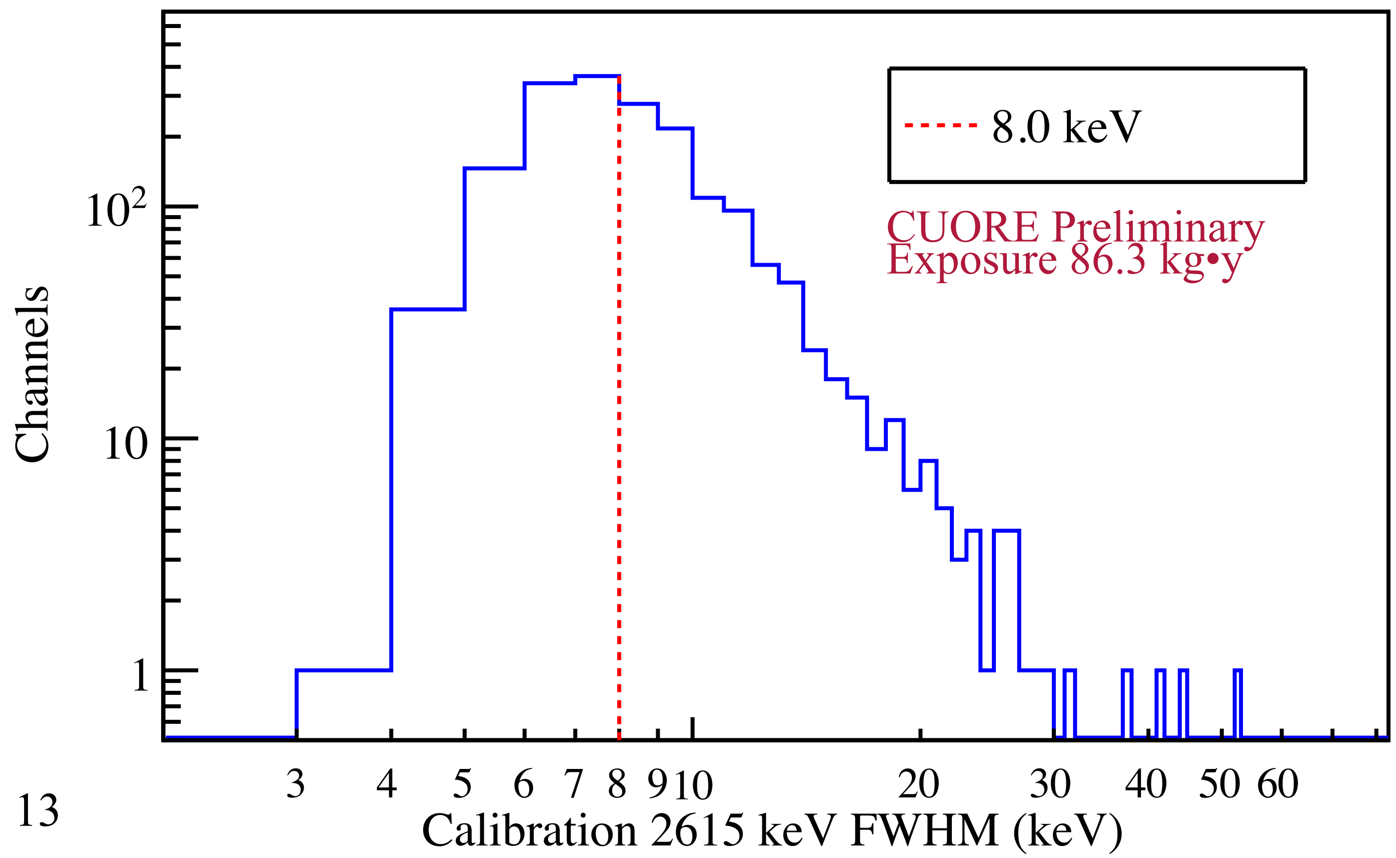
As an illustration, the sum of 19 tower-level simultaneous fits, with components, overlaid on full-detector data with the ratio of the histogram to curve plotted above.

Resolution

- Effective FWHM (exposure-weighted harmonic mean) of 2615 keV calibration fits: 8.0 keV (right).
- FWHM in physics data at Q-value:
  - Dataset 1: (8.3 ± 0.4) keV
  - Dataset 2: (7.4 ± 0.7) keV
  - Exposure-weighted: **(7.7 ± 0.5) keV**







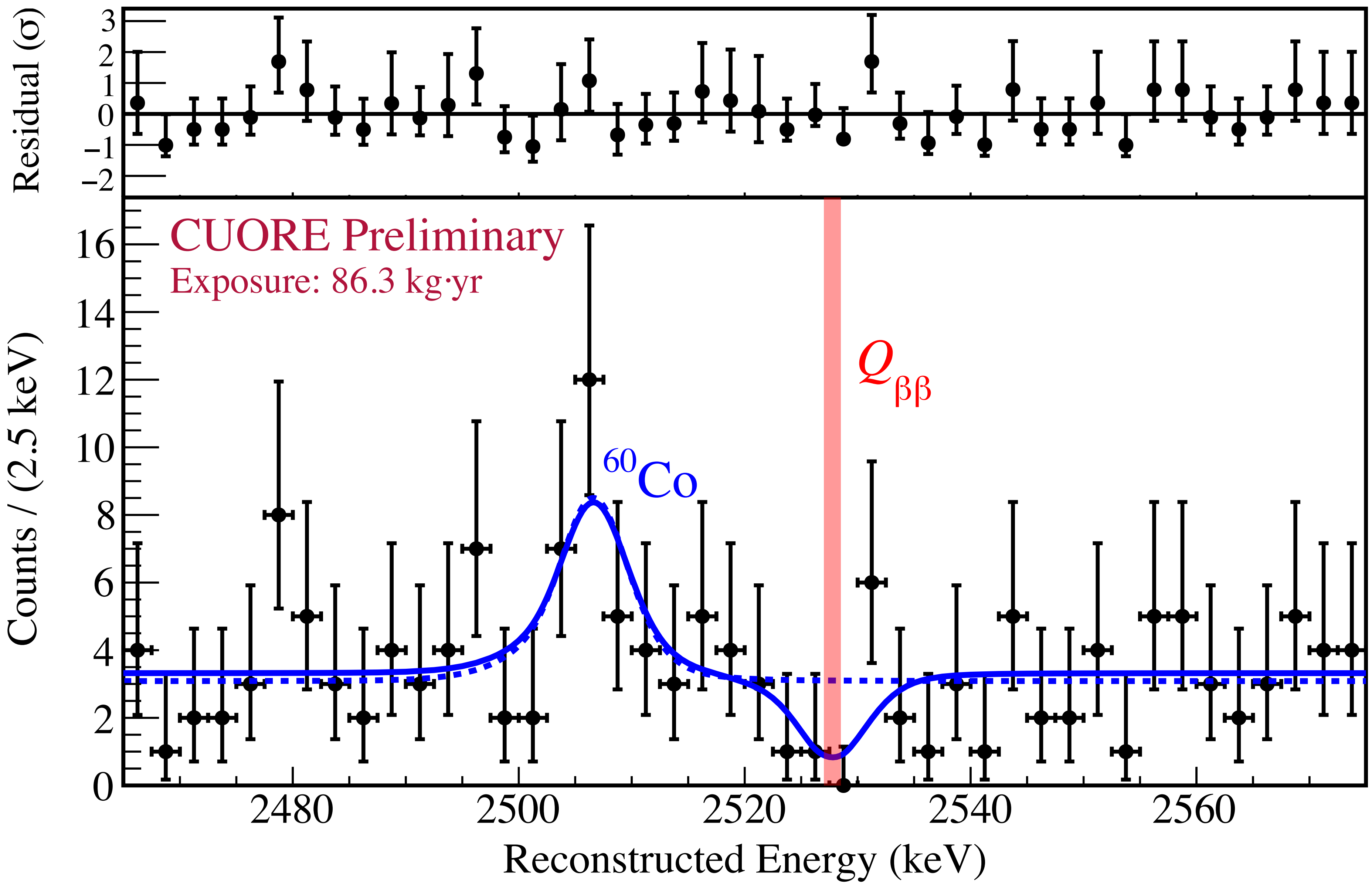
The ROI Fit Approach

- The model:
  - 2 peaks (2-photon ^{60}Co and 0νββ decay) + flat background.
  - Peak shape from ^{208}Tl 2615 keV line shape fit results (by channel-dataset pair), as well as Q-values:

$$Q_{\mathrm{NDBD}} = \frac{2527.518\ \mathrm{keV}}{2614.511\ \mathrm{keV}} \times Q_{2615\ \mathrm{from\ L.S.\ fit}}$$

  - ^{60}Co Q-value allowed to additionally float with a multiplicative quenching factor.
- The parameters:
  - 2 background rates for 2 datasets.
  - Global ^{60}Co rate taking into account decay.
  - Global 0νββ decay rate as the parameter of interest.
- Unbinned likelihood fit with RooFit for whole detector.
  - Two independent RooFit-based analyses (plus one fully Bayesian analysis with BAT) done for robustness.

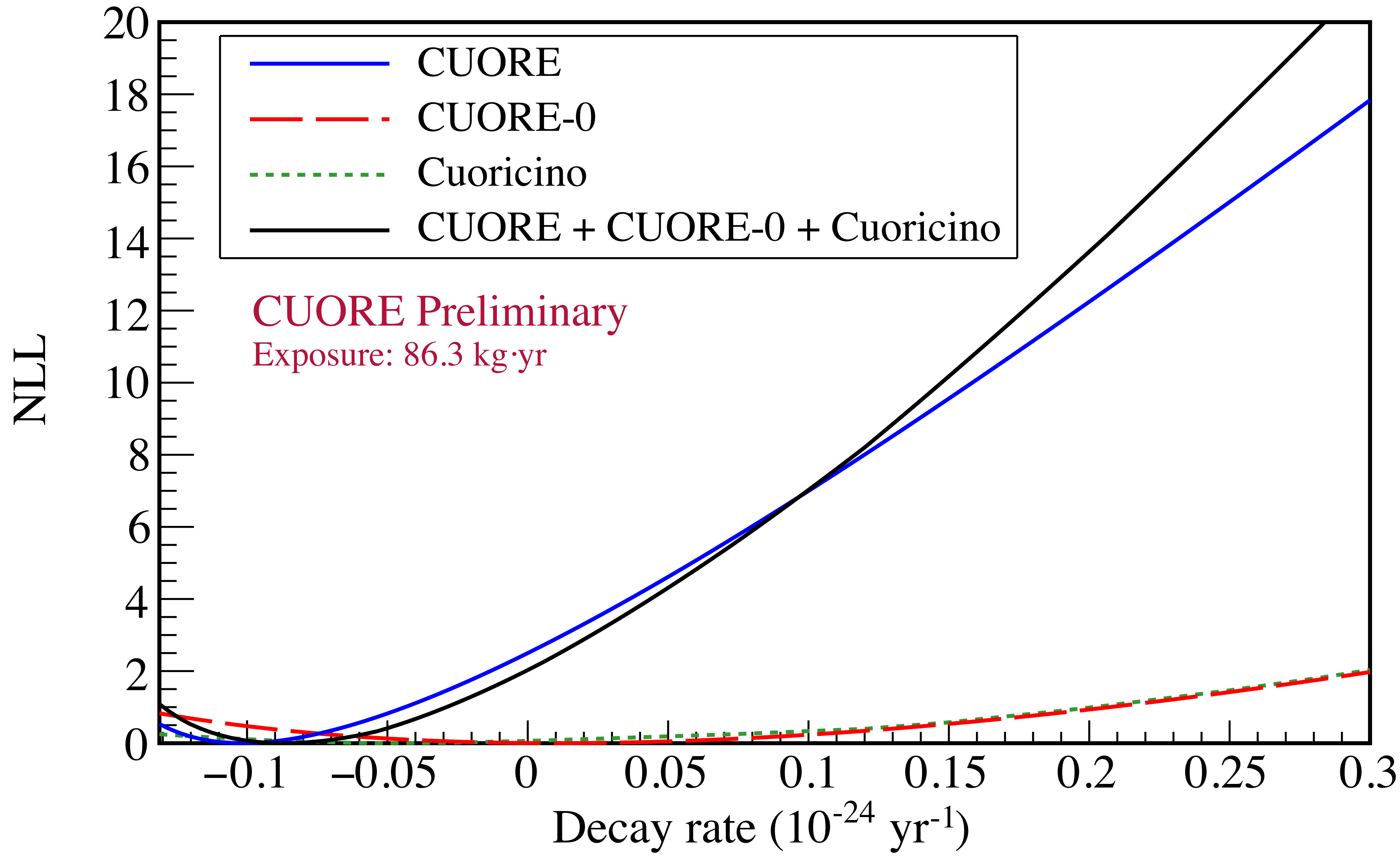
The ROI Fit Result



- Best fit 0νββ decay rate (signal model): $(-1.0^{+0.4}_{-0.3}\ (\text{stat.}) \pm 0.1(\text{syst.})) \times 10^{-25}\ \text{y}^{-1}$
- Background index (no-signal model) : $(0.014 \pm 0.02)\ \text{counts/keV/kg/y}$

The ROI Fit 0νββ Decay Limit

- Integrate positive part of negative log likelihood (NLL) curve (shifted to zero) to set Bayesian limit on 0νββ decay rate.
- Use the same NLL to set Rolke-type frequentist limit as in [W. A. Rolke et al., Nucl. Instrum. Meth. A 551, 493 (2005).]



- CUORE Half-life limit (90% C.L.): $T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ y Rolke: $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$ y
- CUORE + CUORE–0 + Cuoricino: $T^{0\nu}_{1/2} > 1.5 \times 10^{25}$ y Rolke: $T^{0\nu}_{1/2} > 2.2 \times 10^{25}$ y

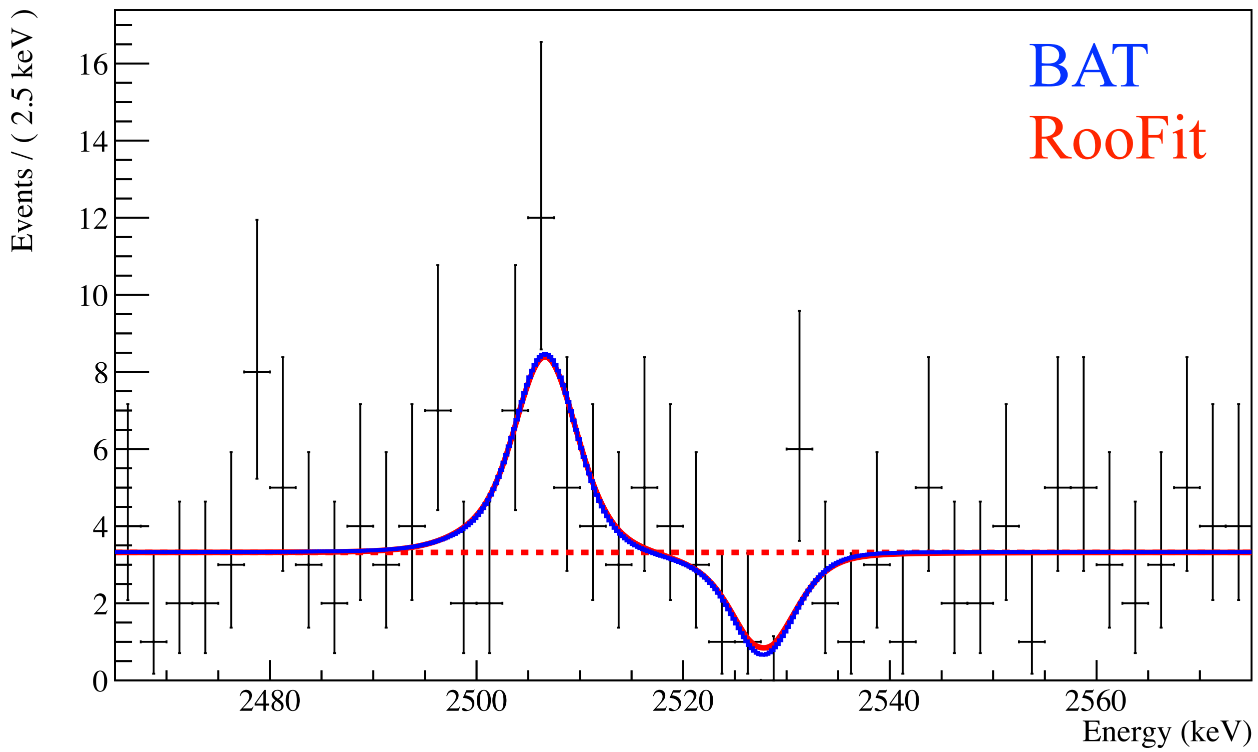
A Fully Bayesian 0νββ Analysis with BAT

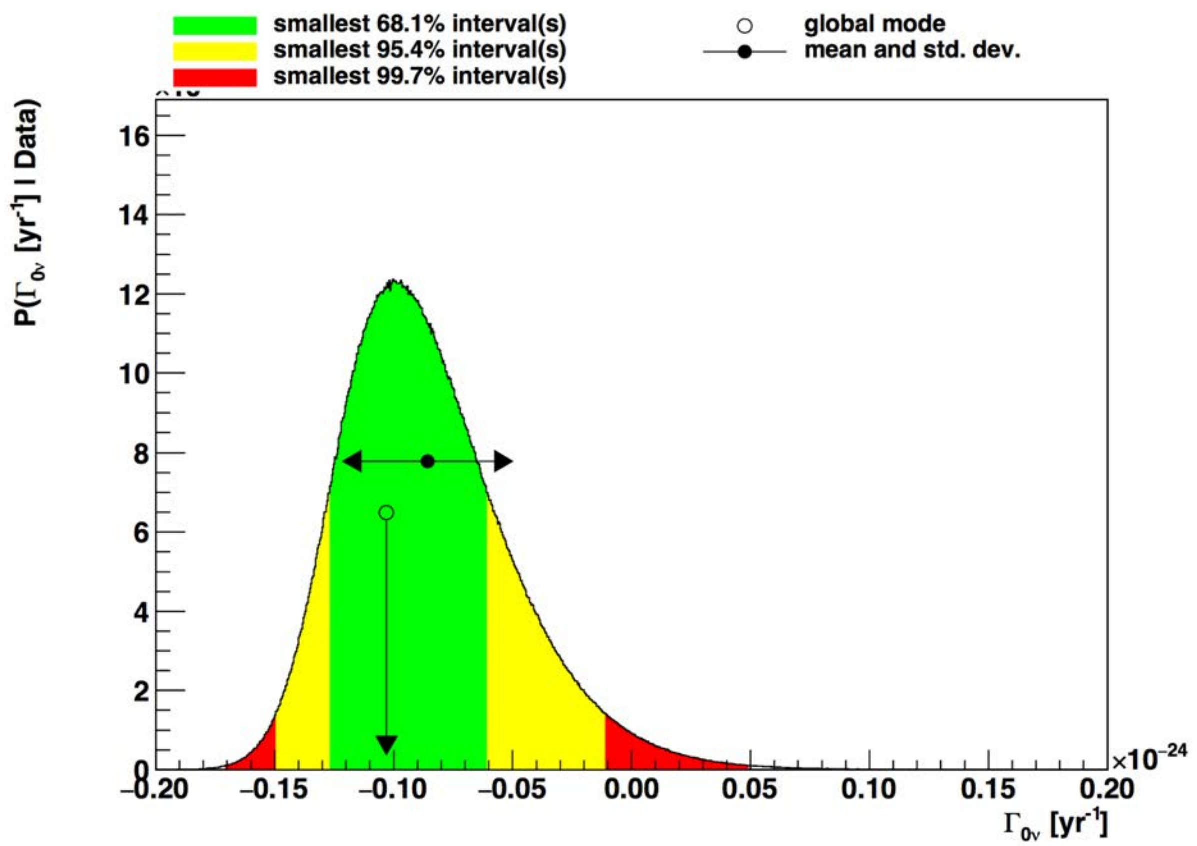
- BAT: Bayesian Analysis Toolkit [website; arXiv:0808.2552].
- Analyze the same data with the same fit model, parameters, constraints, etc., but…
  - Markov Chain Mote Carlo (MCMC) fit.
    - 8 chains of 10^7 samples each.
  - Limit from marginalization (more natural)
    - Fix parameters besides the one of interest (0νββ rate) and integrate:

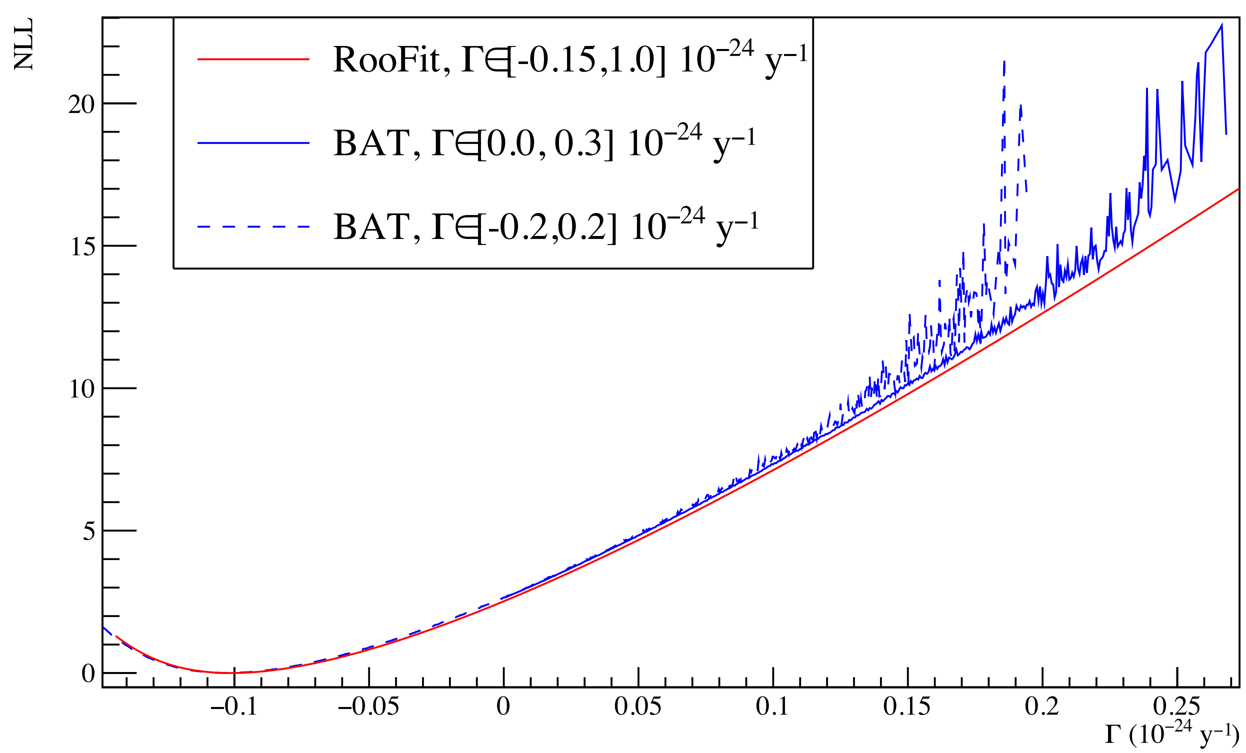
$$p(\mathbb{X}|\alpha) = \int_\theta p(\mathbb{X}|\theta)\, p(\theta|\alpha)\ \mathrm{d}\theta$$

  - Also evaluate profiled limit as a check.
    - Same as the RooFit analysis—scan over fixed rate values in a range; BAT is less well suited for this.

A Fully Bayesian 0νββ Analysis with BAT



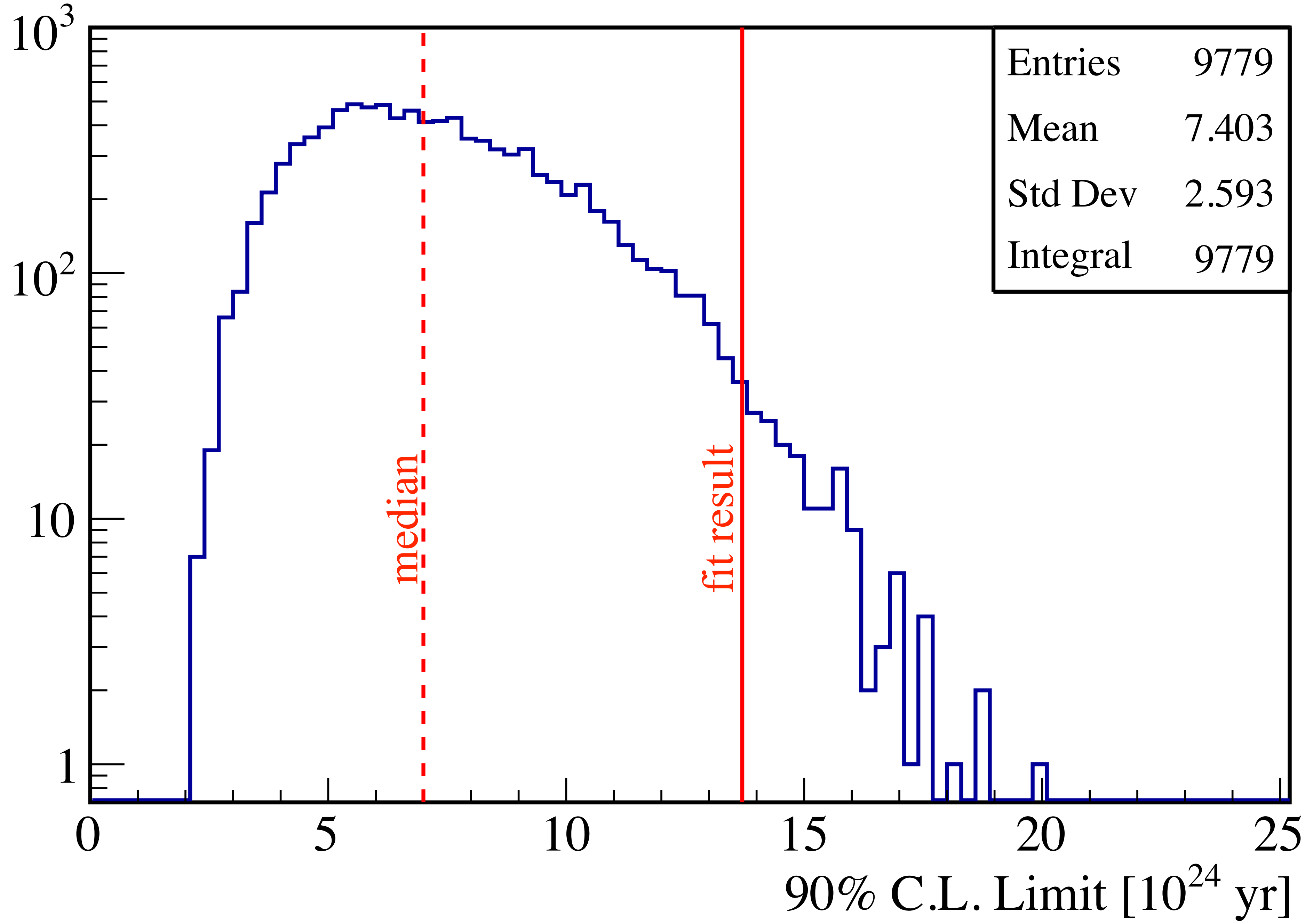




- Fit consistent with RooFit analyses at the percent level.
- Gives the same limit (both marginalized and profiled):

$$T^{0\nu}_{1/2} > 1.4 \times 10^{25}\ \mathrm{y}$$
$$(90\%\ \mathrm{C.I.,\ stat.\ only})$$

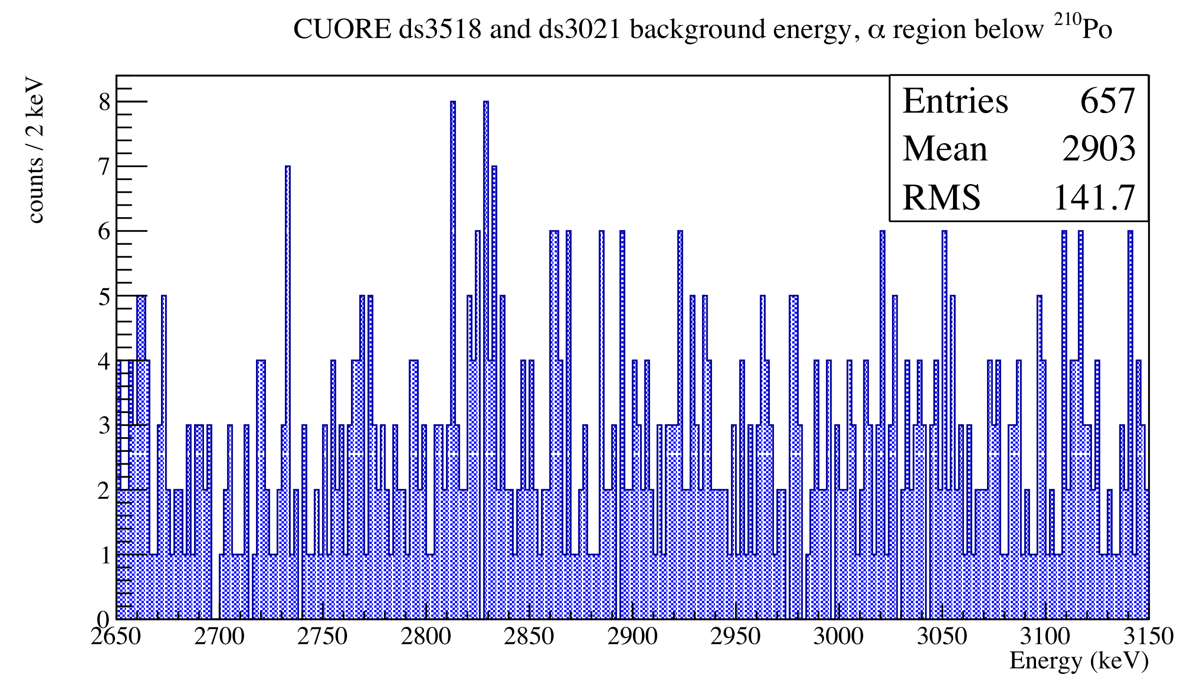
Sensitivity and Negative Fluctuation

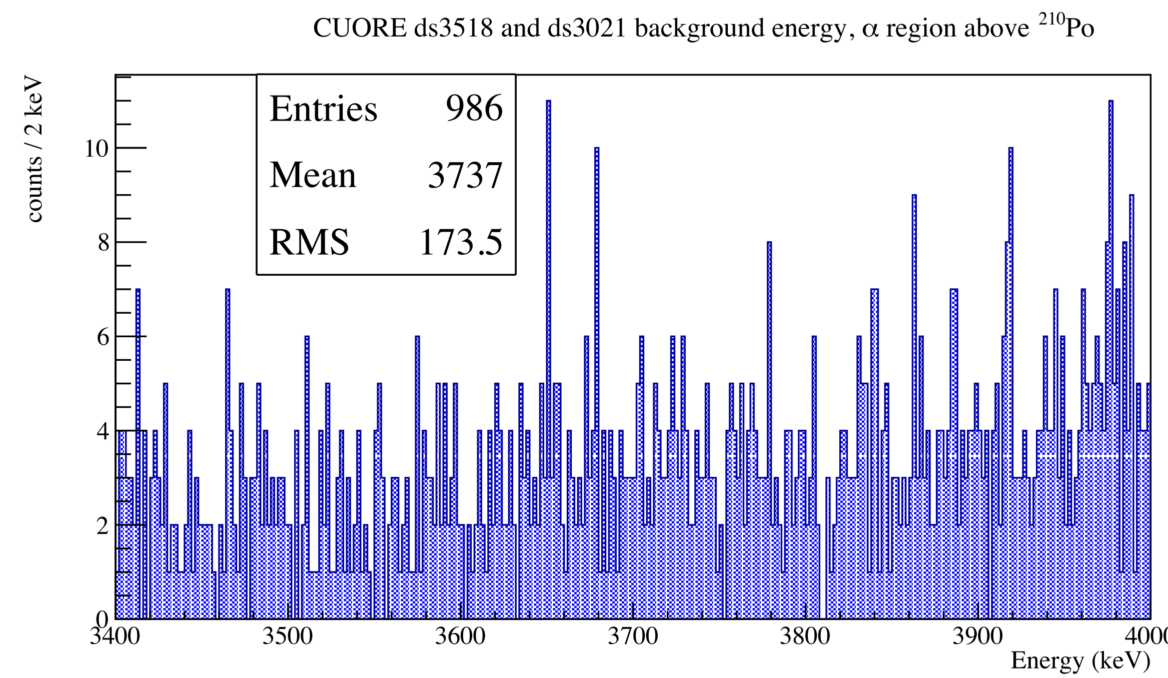


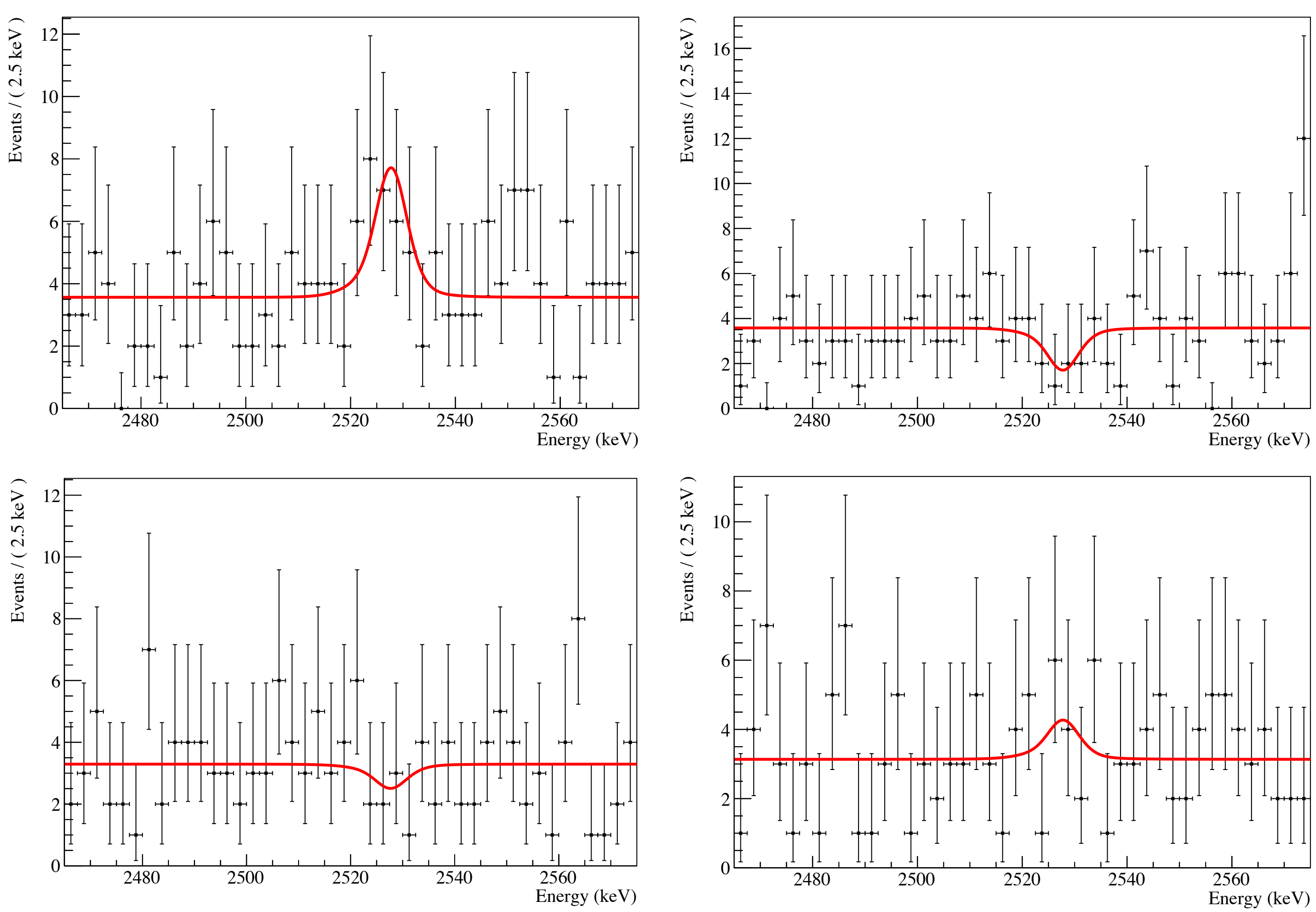
Toy MC study with null hypothesis:

Median sensitivity (90% C.L.) is 7.0×10^{24} y , 2% probability of obtaining a greater negative fluctuation than observed.

Alternative fluctuation study with data

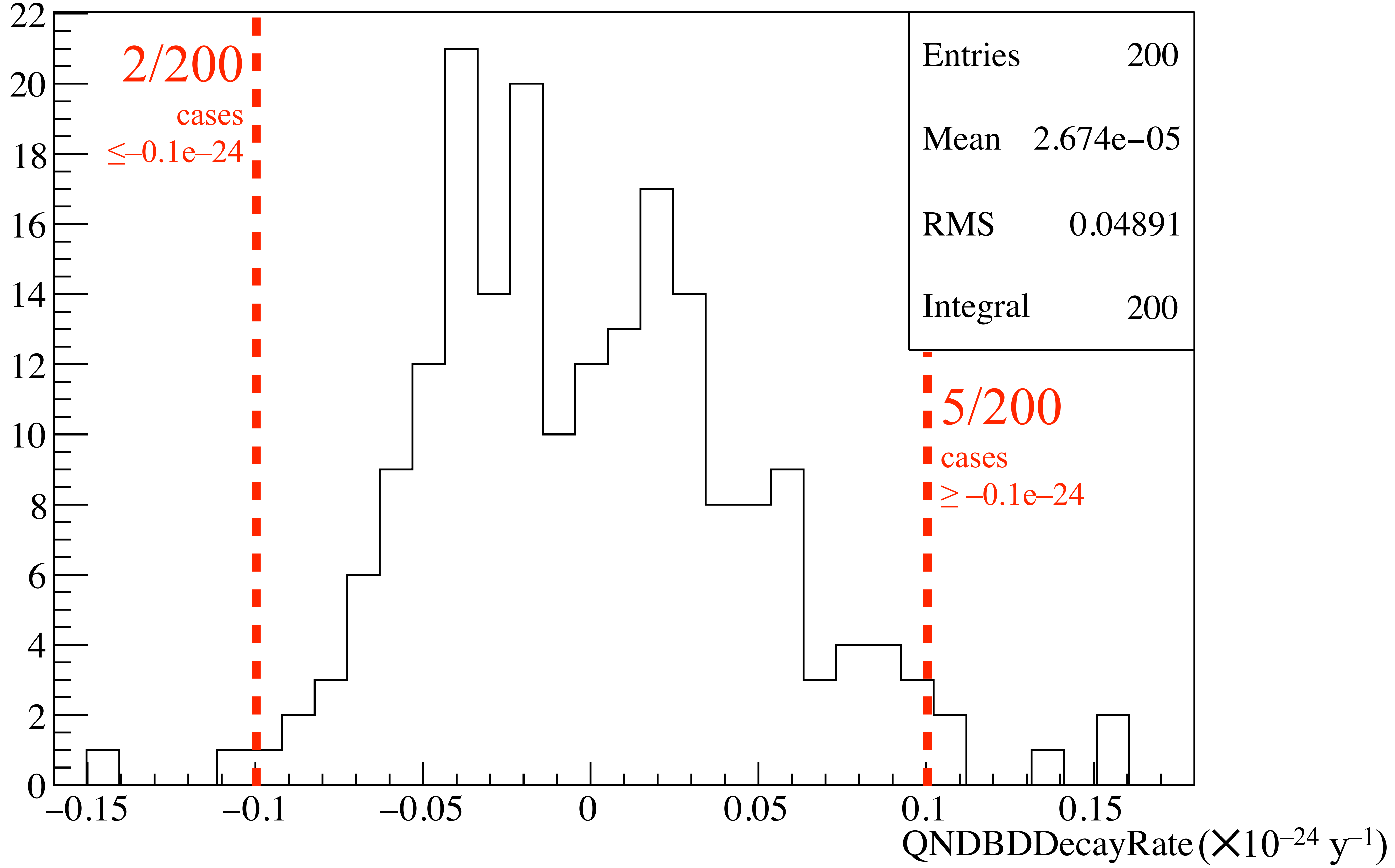






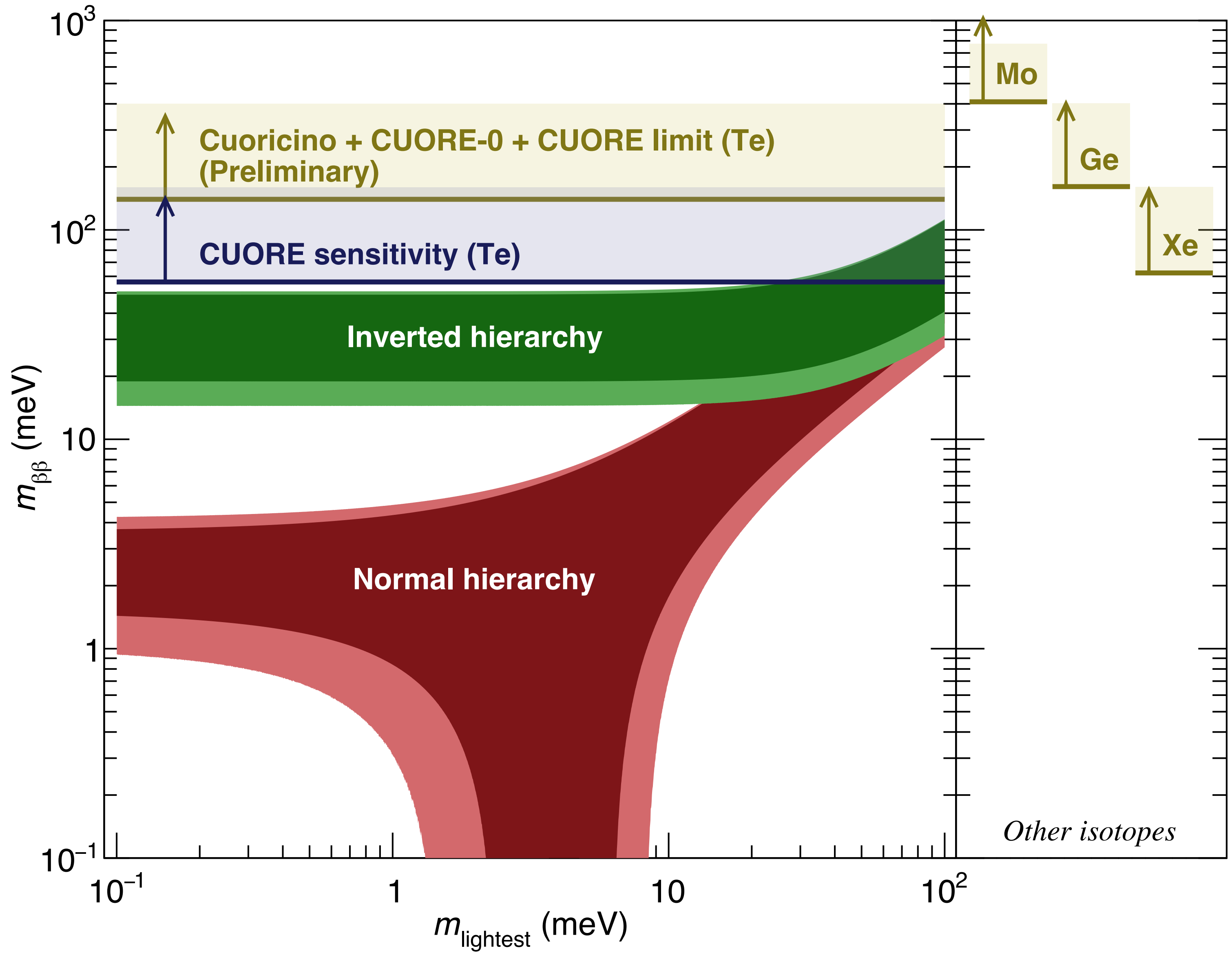
- Flat background: 2 intervals in α region avoiding ^{210}Po: [2650, 3150] keV and [3400, 4000] keV.
- Evenly divide each span into 100 overlapping 110-keV wide pieces, and shift them into the [2465, 2575] keV domain.
- Fit each one with ROI fit (minus ^{60}Co line) to check for fluctuations.

Alternative fluctuation study with data



Statistics are quite low to quote a fluctuation probability with high precision, but we appear to be consistent with the ROI Toy MC study.

Effective Majorana Mass $m_{\beta\beta}$



Half-life limits:

- ^{130}Te: 1.5 × 10^{25} yr from this analysis
- ^{76}Ge: 5.3 × 10^{25} yr from Nature 544, 47–52 (2017)
- ^{136}Xe: 1.1 × 10^{26} yr from Phys. Rev. Lett. 117, 082503 (2016)
- ^{100}Mo: 1.1 × 10^{24} yr from Phys. Rev. D 89, 111101 (2014)
- CUORE sensitivity: 9.0 × 10^{25} yr

Nuclear matrix elements:

- Phys. Rev. C 91, 034304 (2015)
- Phys. Rev. C 87, 045501 (2013)
- Phys. Rev. C 91, 024613 (2015)
- Nucl. Phys. A 818, 139 (2009)
- Phys. Rev. Lett. 105, 252503 (2010)

$m_{\beta\beta} < 140 – 400$ meV , depending on nuclear matrix elements model.

Conclusions

- The first result from the CUORE experiment
- On the arXiv: [arXiv:1710.07988 [nucl-ex]]
- Submitted to PRL
- Scientific:
  - the strongest limit on $0\nu\beta\beta$ decay half-life of ^{130}Te to date
  - the first such limit $\geq 10^{25}$ years.
- Technical:
  - operation of the world's first ton-scale bolometric detector.
  - custom construction and operation of the world's largest and most powerful dilution refrigerator
- The future:
  - 5 years of live time planned $\rightarrow 9\times10^{25}$ year sensitivity
  - Further detector performance optimization
  - New analyses (other isotopes, dark matter, $2\nu\beta\beta$…)
  - CUPID (**C**UORE **U**pgrade with **P**article **Id**entification)

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BERKELEY LAB
CUORE

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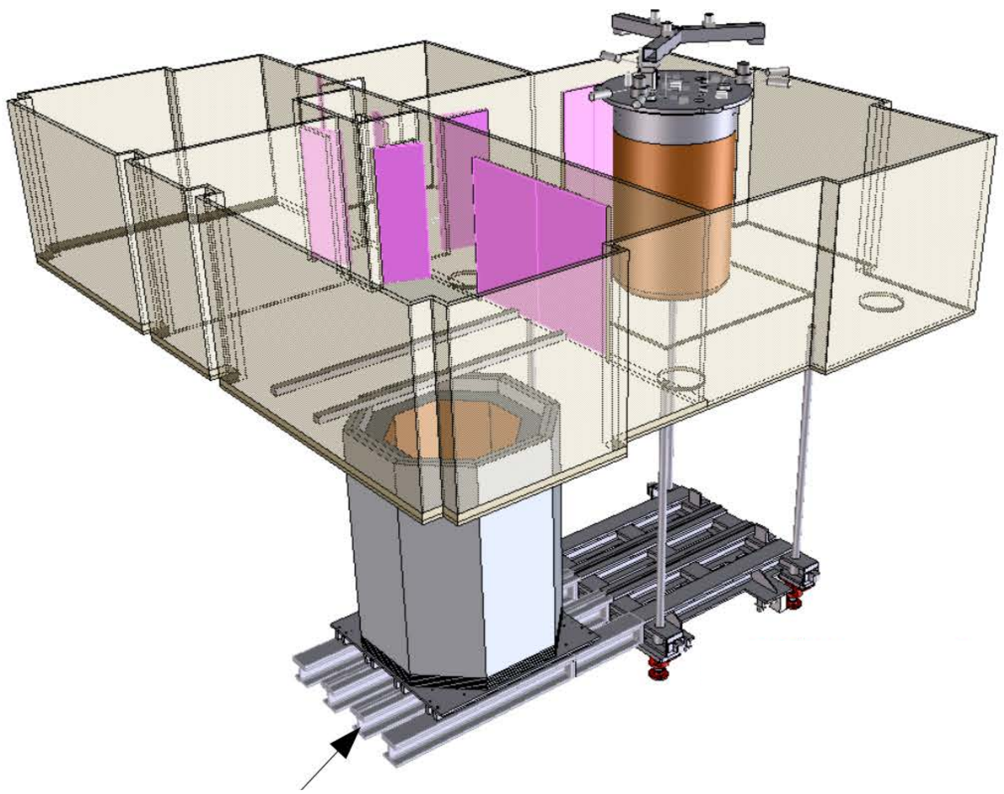
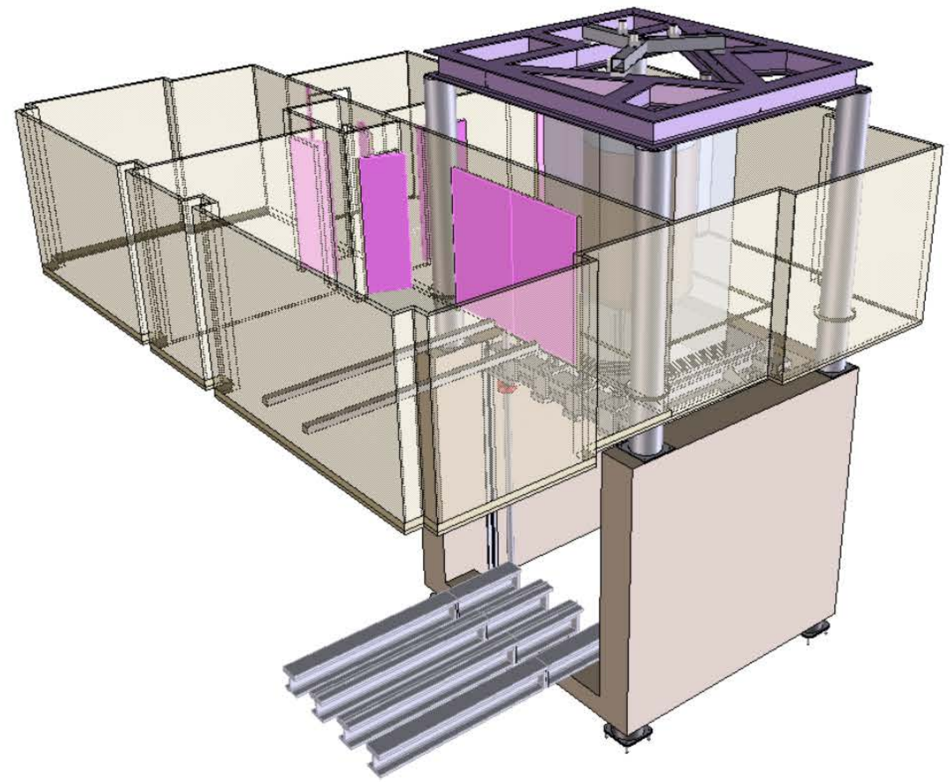
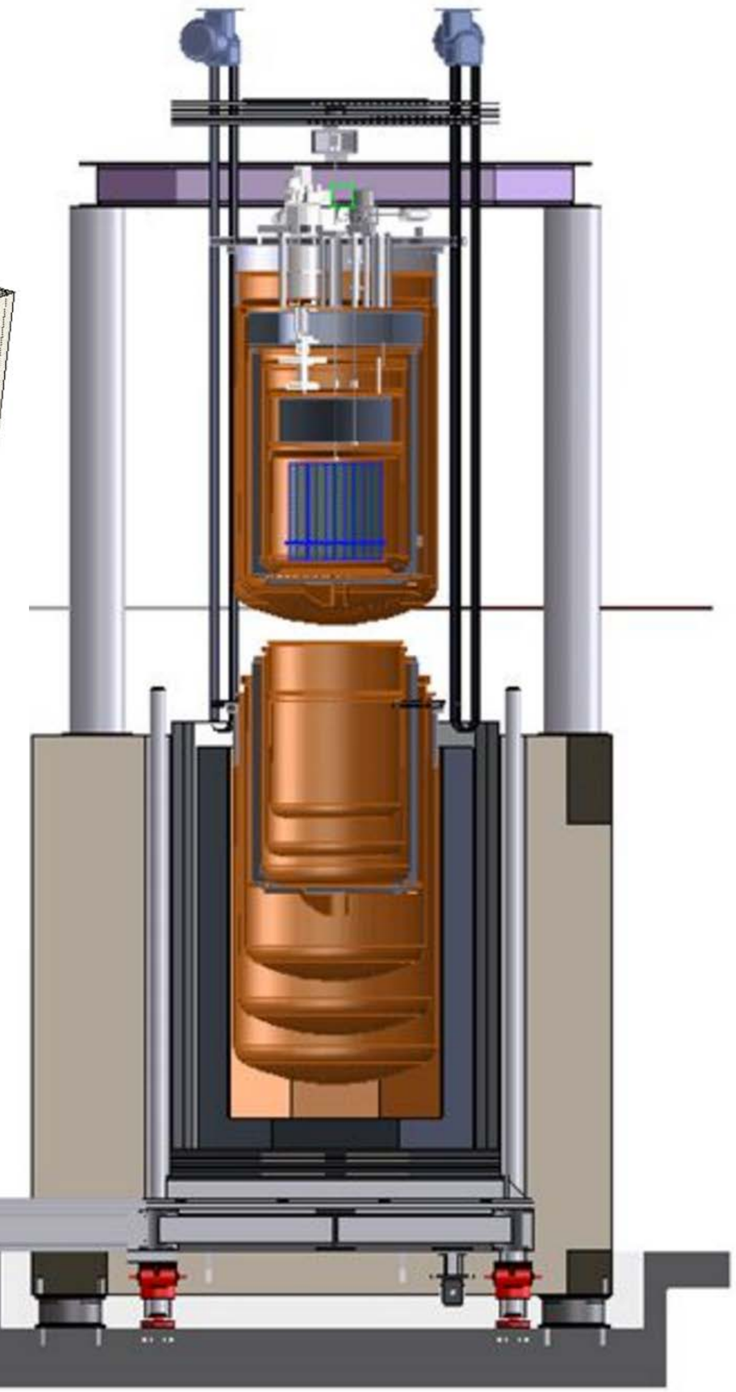
Backup slides

General arrangement

- Top floor: cryostat roof, calibration system, electronics, DAQ, fast cooling system, computers, etc.



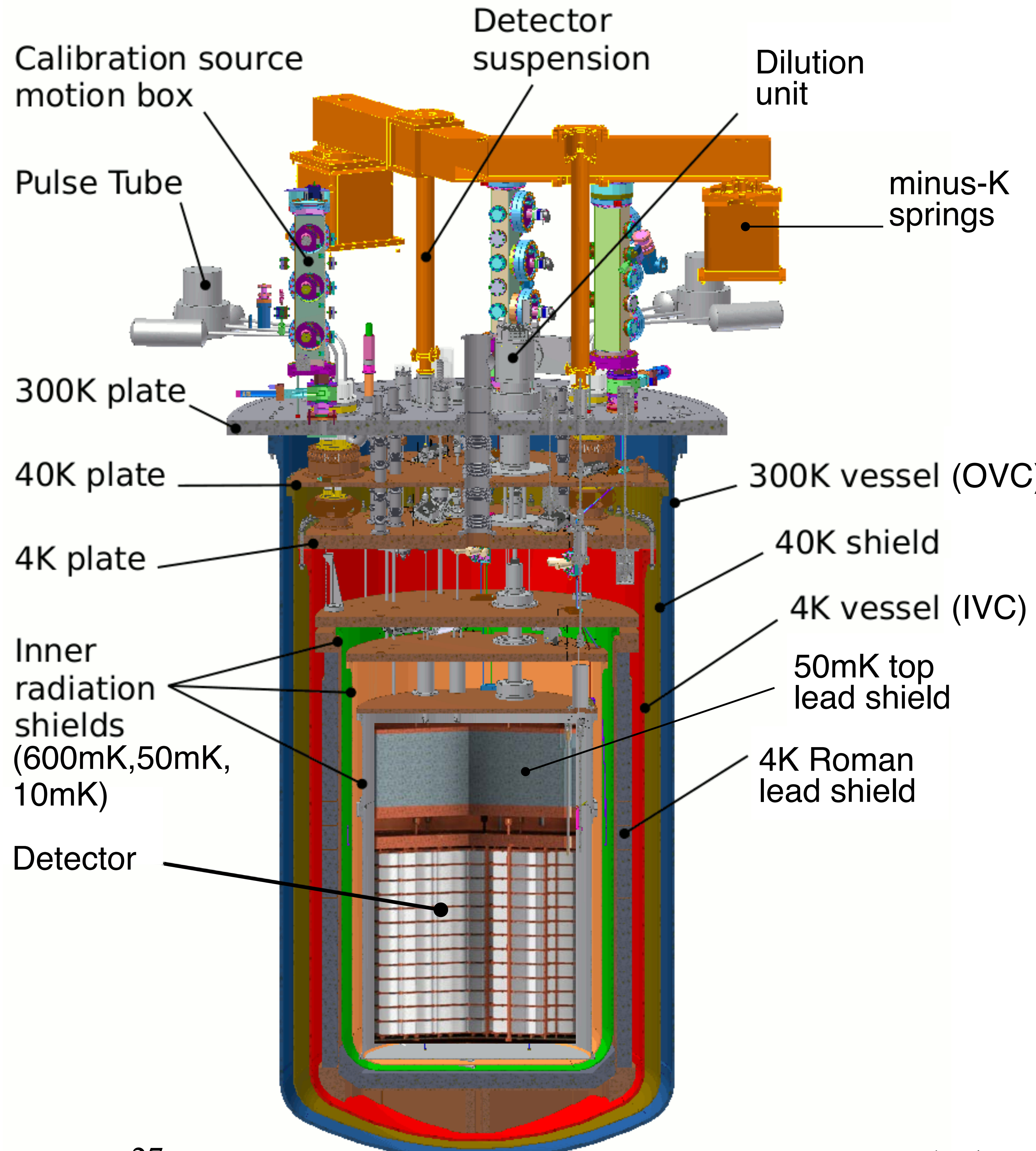




- Middle floor (clean room): tower assembly, storage, and cryostat access.
- Ground floor: services, pumps, shield storage.

The CUORE cryostat: overview

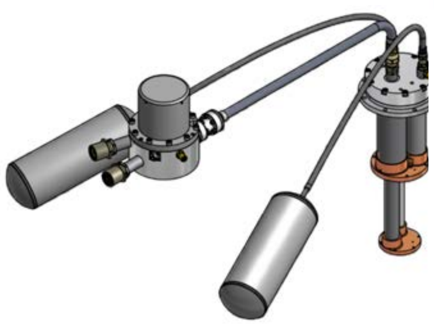
- Pulse tube precool.
- DU from Leiden Cryogenics.
- Custom detector suspension.
- Cold Roman lead shields.
- High purity NOSV Cu used.
- Cryogenic calibration system.
- Empty test run: stable over more than 70 days at 6.3 ± 0.2 mK.
- As low as 7 mK with detector.

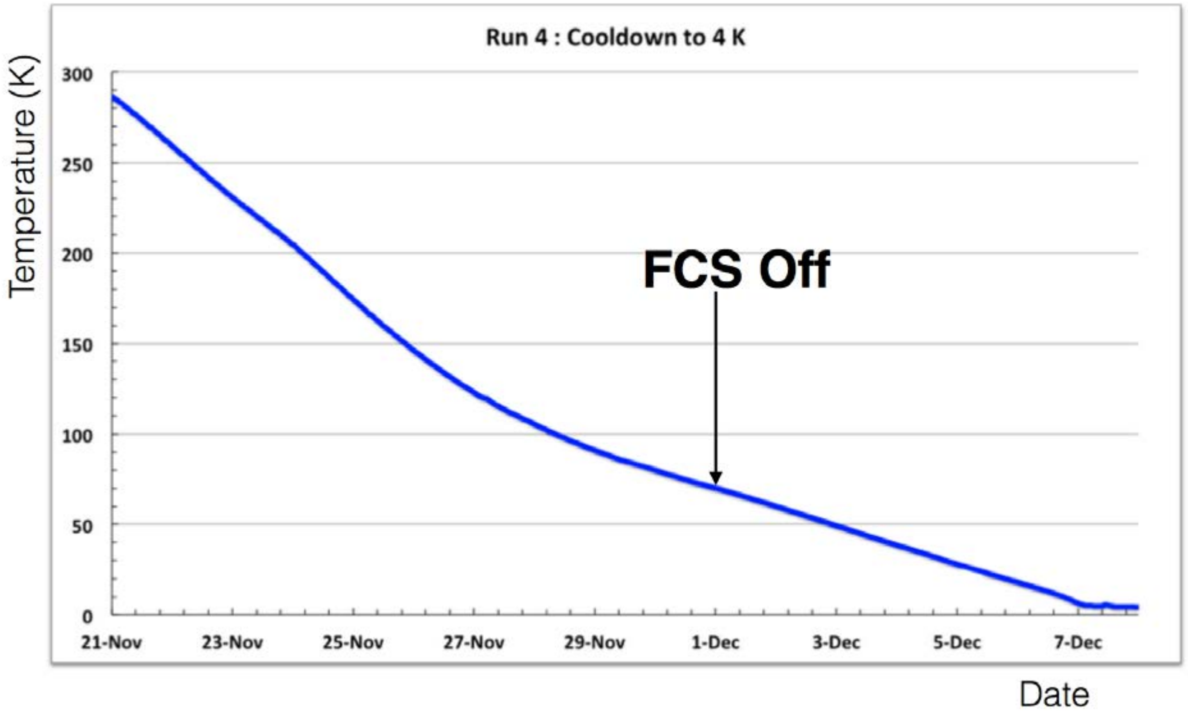


The CUORE cryostat: precooling

- 5 Cryomech PT415–RM pulse tube coolers (4 + 1 redundant).
  - 2-stage 4K pulse tube.
  - remote motor.
  - 1.5W @ 4K (each)
  - 2 of 5 with mixture line thermalizers.
  - Linear drives for motors with phase alignment control.
- Inner vacuum chamber (IVC) at 4K level filled with He exchange gas for precool.
- Fast Cooling System (FCS) circulates He pre-cooled to 20–40K by GM coolers.
- **~14 tons to 4K in ~16 days.**

PT415–RM



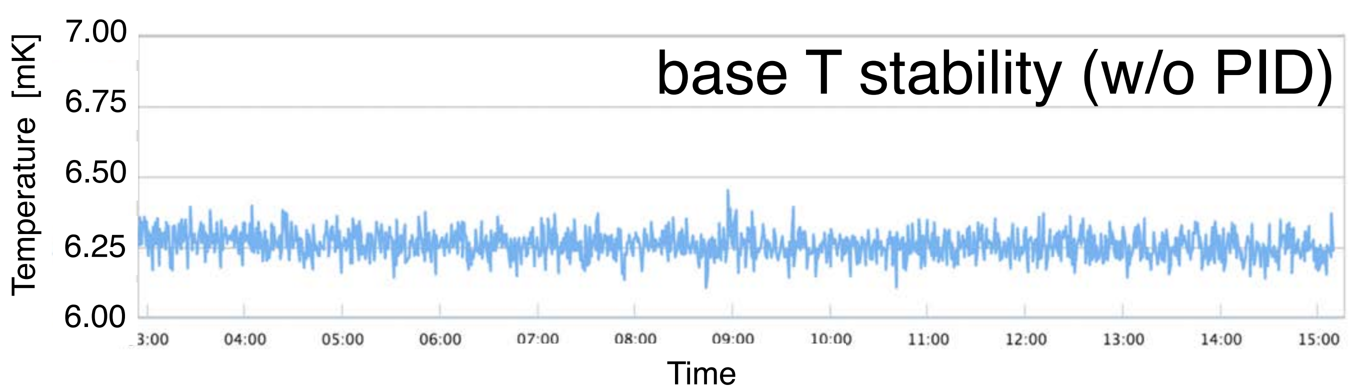


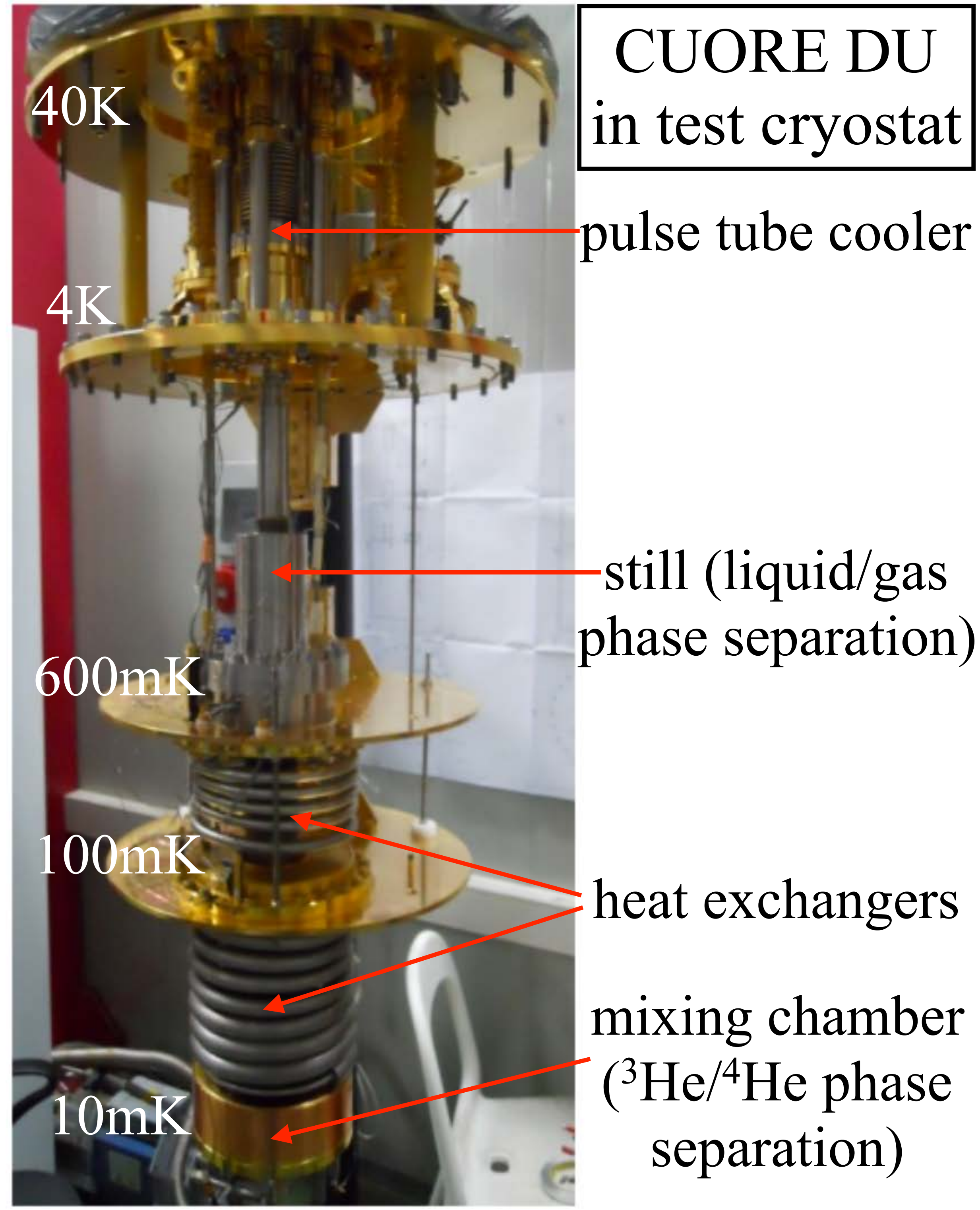
above: CUORE pulse tube and copper thermalization at 40K and 4K stages.

right: Fast Cooling System

The CUORE cryostat: dilution unit

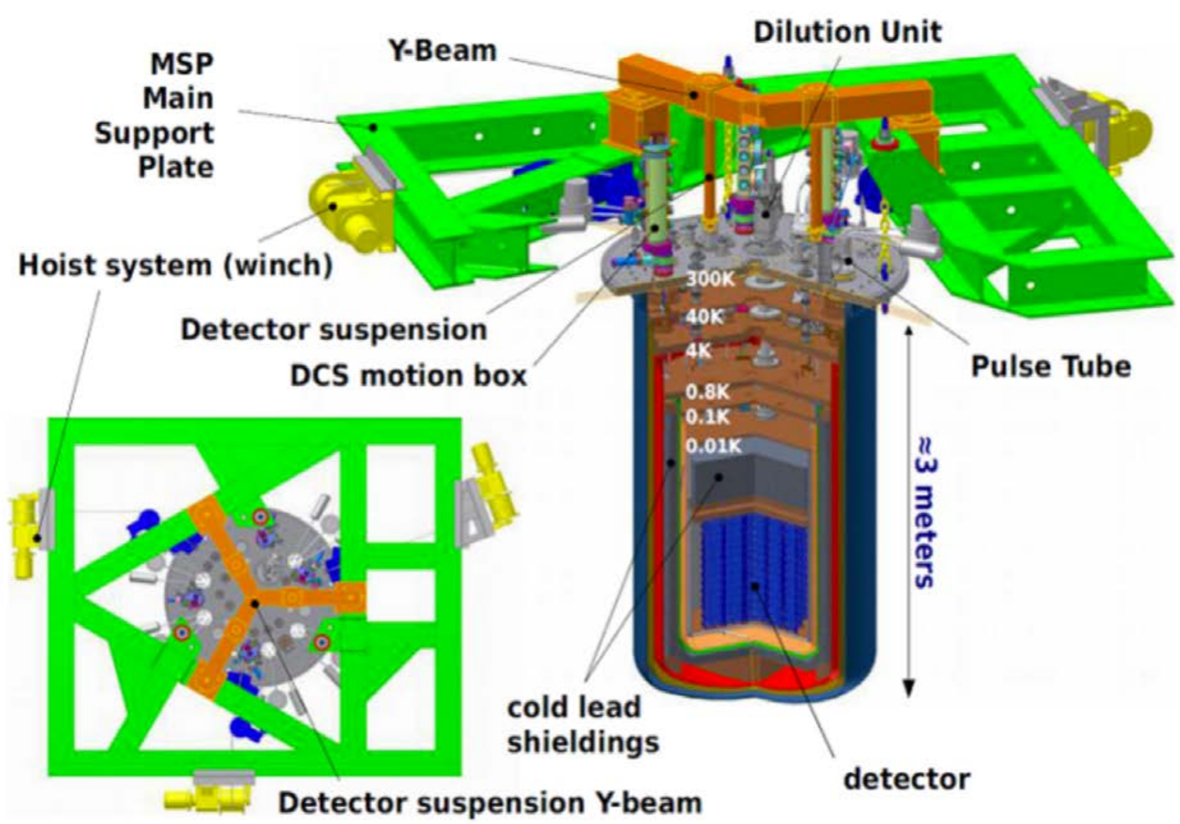
- Custom (modified DRS-CF2000) high-power Joule-Thompson unit from Leiden Cryogenics.
- 2mW @ 100mK, 3μW @ 10mK.
- 120L of ^{3}He.
- No 1K pot due to pulse tube design (still at 600mK behaves as one).
- 2 (redundant) primary impedances w/valves:
  - high-circulation cooldown mode: 8 mmol/s for high cooling power.
  - lower circulation base-temperature operation mode: 1 mmol/s to minimize heat load from incoming mixture.

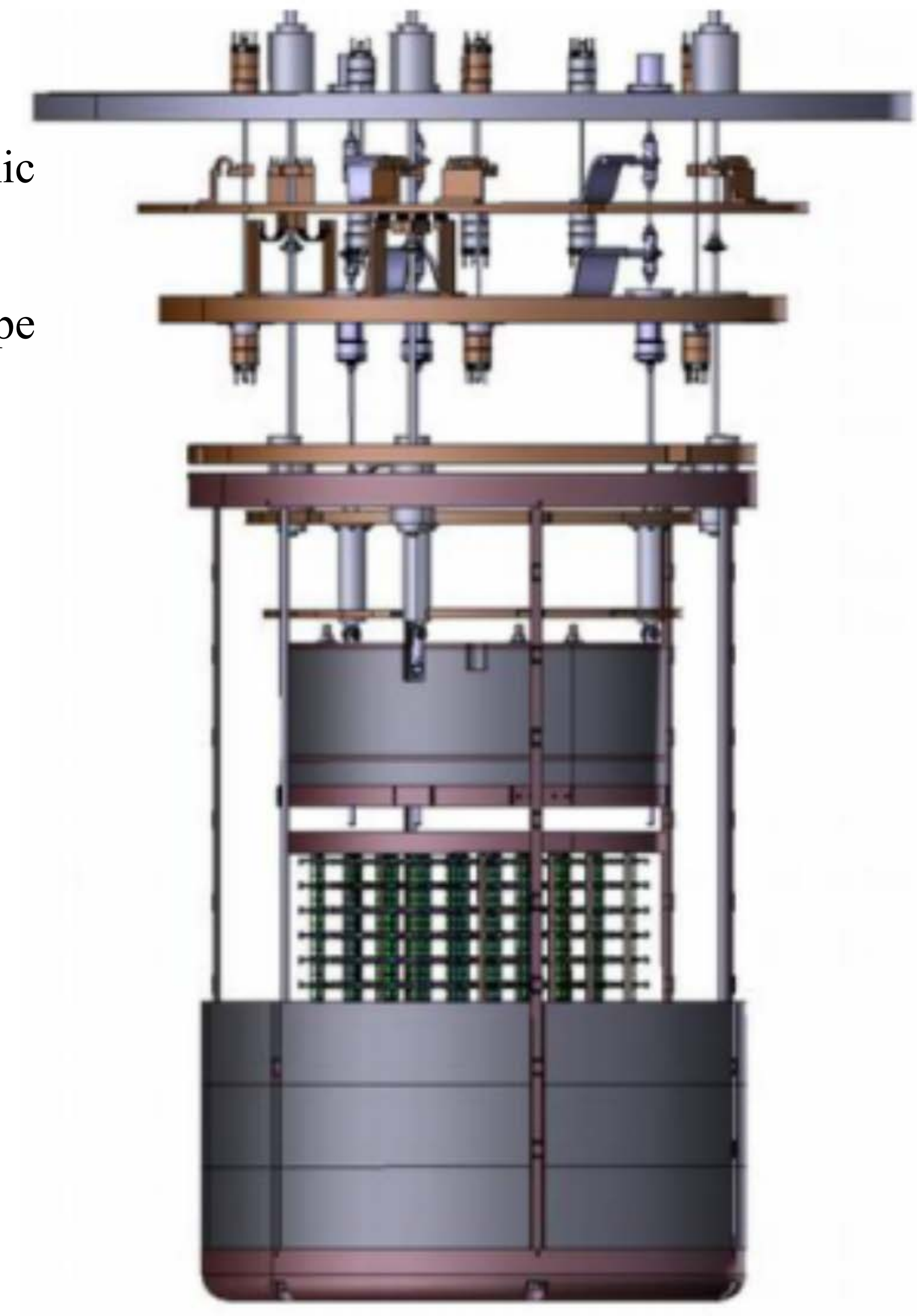




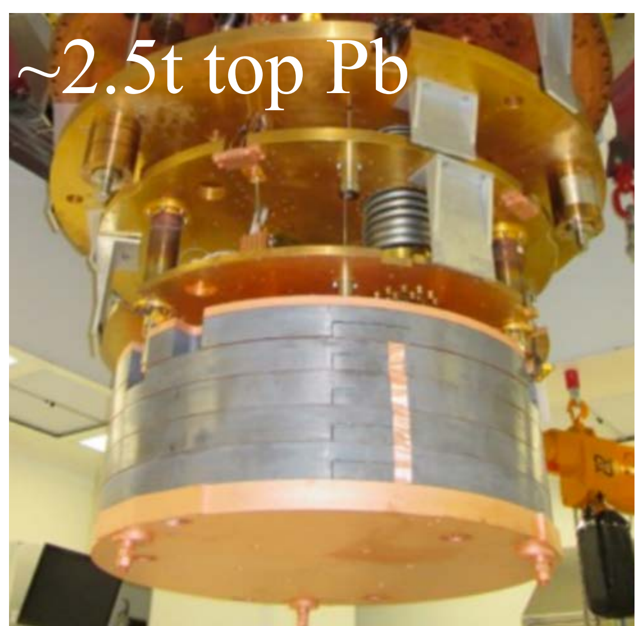
The CUORE cryostat: suspension

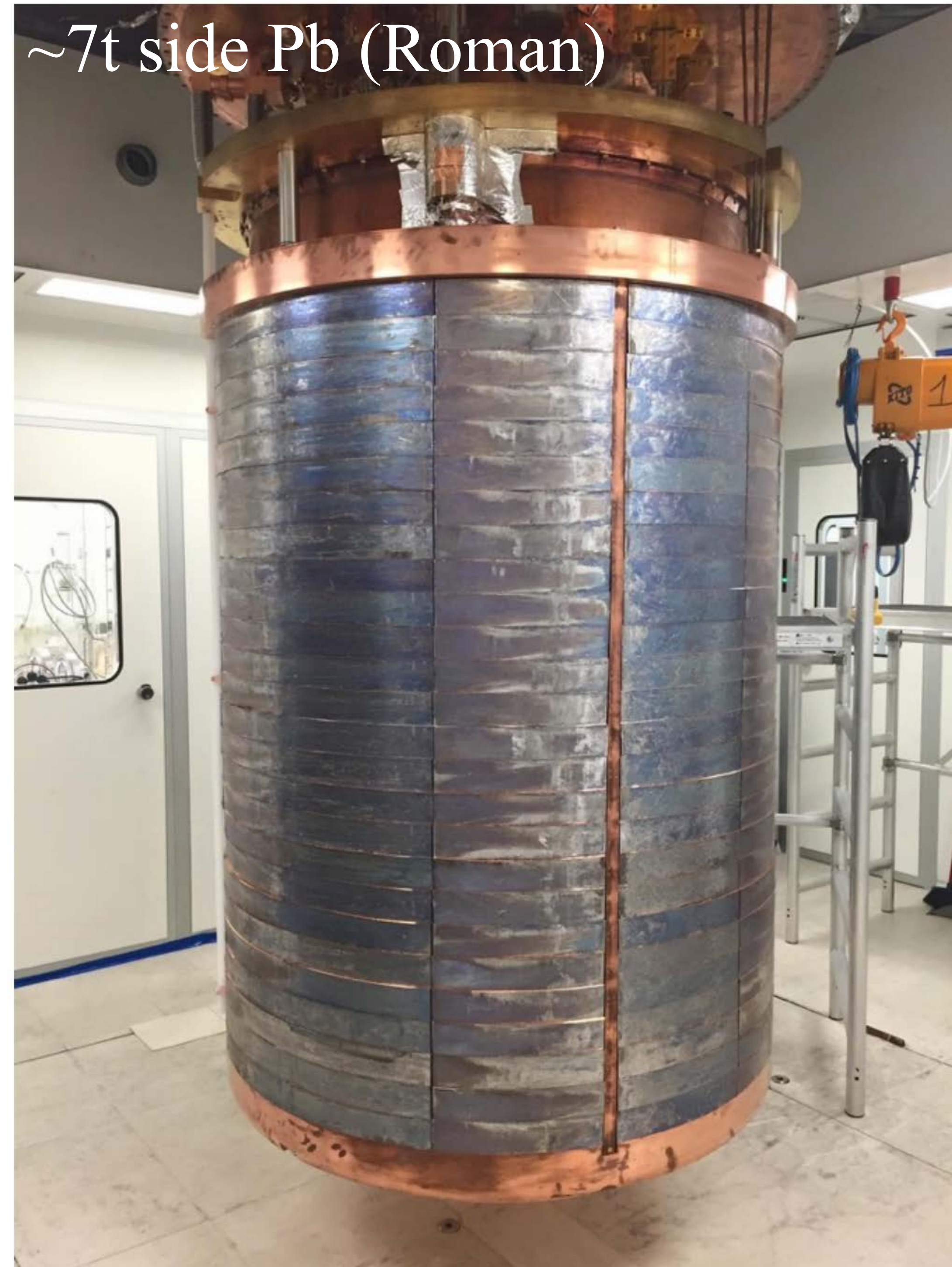
- Main support plate on pneumatic pads.
- All cryostat plates mounted on flexible suspensions (rods with cardanic joints); can be stiffened with PTFE braces.
- Top lead shield (50mK) on independent suspension with Kevlar rope loops.
- Detector coupled to external Y-beam, on minus-K springs.
- High frequency vibrational noise reduction; seismic safety.





The CUORE cryostat: cold shields





Numbers: Detector Performance

Active channels	984 (99.6%)
Dead channels	4
Channel-dataset pairs used in analysis	1811 (92% of live channels)
TeO_2 exposure	86.3 kg yr (37.6 kg yr in ds3518 + 48.7 kg yr in ds3021)
Te-130 exposure	24.0 kg yr
FWHM at 2615 keV in calibration data, ds3518	9.0 keV
FWHM at 2615 keV in calibration data, ds3021	7.4 keV
FWHM at 2615 keV in calibration data, exposure-weighted	8.0 keV
Trigger thresholds	
Analysis threshold	150 keV
Energy bias at Q-value	(0 ± 0.5) keV
Resolution scaling at 2615, ds3518	(95 ± 7)%
Resolution scaling at 2615, ds3021	(101 ± 6)%
FWHM in physics data at Q-value, ds3518	(8.3 ± 0.4) keV
FWHM in physics data at Q-value, ds3021	(7.4 ± 0.7) keV
FWHM in physics data at Q-value, exposure-weighted	(7.7 ± 0.5) keV

Numbers: 0νββ Decay Analysis

Region of interest	2465 to 2575 keV
Overall 0vBB signal efficiency, ds3518	(75.69 ± 3.02)%
Overall 0vBB signal efficiency, ds3021	(83.01 ± 2.56)%
Overall 0vBB signal efficiency, effective	(±)%
Resolution scaling at Q-value, ds3518	(91.5 ± 4.6)%
Resolution scaling at Q-value, ds3021	(100.0 ± 9.3)%
Events in the region of interest	155
Best fit for ^{60}Co mean	(2506.4 ± 1.2) keV
ROI background index, ds3518	$(1.49_{-0.17}^{+0.18}) \times 10^{-2}$ ckky
ROI background index, ds3021	$(1.35_{-0.18}^{+0.20}) \times 10^{-2}$ ckky
ROI background index, exposure weighted	$(1.4 \pm 0.2) \times 10^{-2}$ ckky
Median expected sensitivity	7.0×10^{24} yr (Bayesian)
	7.6×10^{24} yr (Rolke)
Best fit decay rate	$(-1.0_{-0.3}^{+0.4}$ (stat.) ± 0.1 (syst.)) $\times 10^{-25}$ / yr
Bayesian half-life limit (90% CL, including systematics)	1.3×10^{25} yr
Bayesian decay rate limit (90% CL, including systematics)	0.051×10^{-24} / yr
Bayesian half-life limit (90% CL, combination with Q0 + Qino)	1.5×10^{25} yr
Corresponding limit on $m_{\beta\beta}$	$m_{\beta\beta}$ < 140–400 meV
Rolke half-life limit (90% CL, including systematics)	2.1×10^{25} yr
Rolke decay rate limit (90% CL, including systematics)	0.033×10^{-24} / yr
Rolke half-life limit (90% CL, combination with Q0 + Qino)	2.2×10^{25} yr

Cut efficiencies:

	ds3518	ds3021
0vBB containment	(88.345 ± 0.085)%	(88.345 ± 0.085)%
Pulser detection	(99.7663± 0.0034)%	(99.7349 ± 0.0035)%
Pulser energy	(99.1677 ± 0.0064)%	(99.218 ± 0.006)%
Base cuts on pulser	(95.6288 ± 0.0088)%	(96.6907 ± 0.0084)%
Multiplicity	(99.4 ± 0.5)%	(100.0 ± 0.4)%
PSA	(91.1± 3.6)%	(98.2 ± 3.0)%
All cuts except containment	(85.67 ± 3.42)%	(93.96 ± 2.89)%

Systematic uncertainties:

Systematic	Absolute uncertainty [10^{-24} yr]	Relative uncertainty
Resolution	0	1.5%
Q-value location	0	0.2%
No subpeaks	0.002	2.4%
Efficiency	0	2.4%
Linear Fit	0.005	0.8%
Fit Bias	0	0.3%