First results from the CUORE $0\nu\beta\beta$ decay search

Alexey Drobizhev for the CUORE Collaboration

Lake Louise Winter Institute 2018
THU-AM: Neutrinos/LHC BSM

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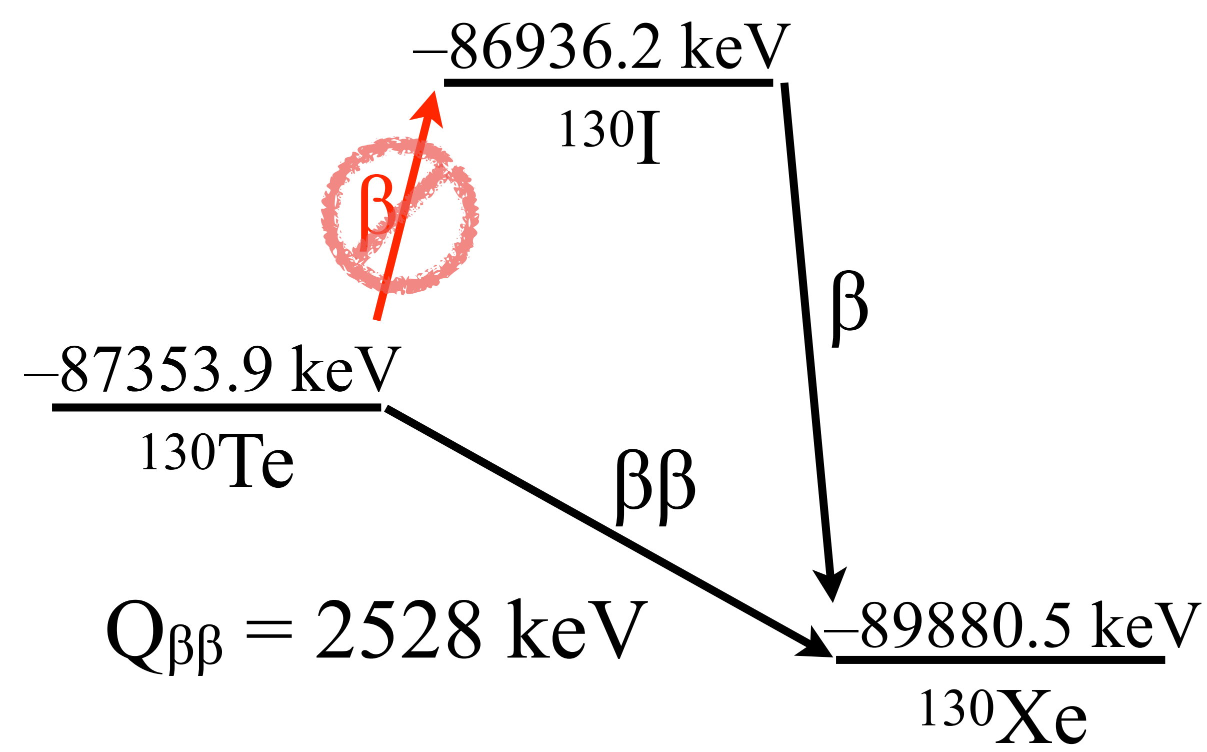
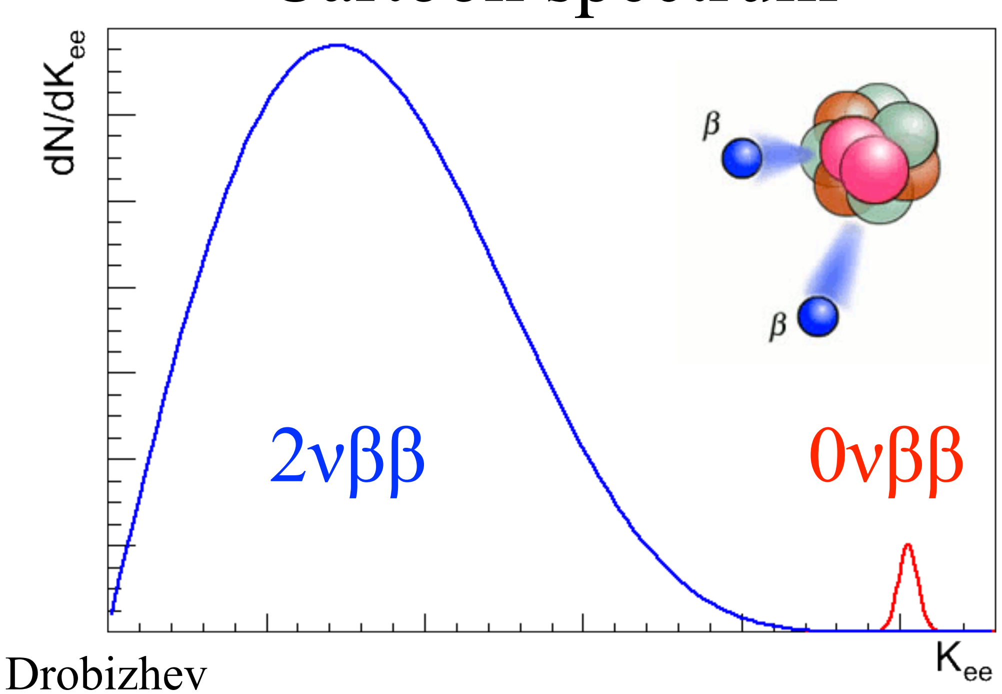
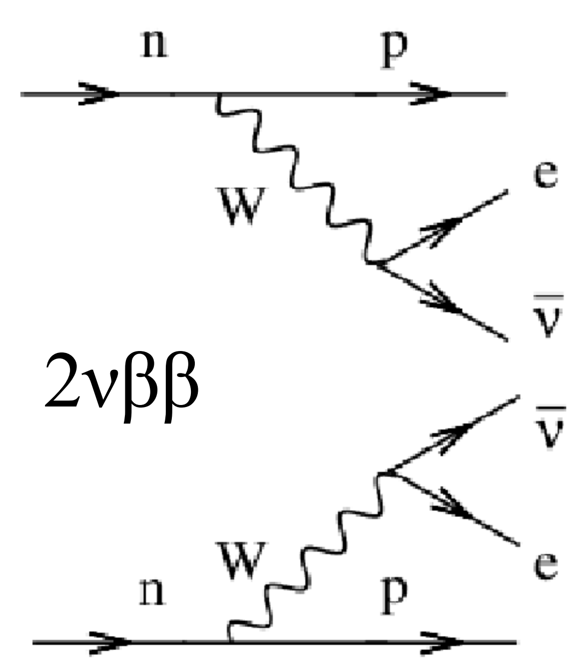
Neutrinoless Double-Beta (0νββ) Decay

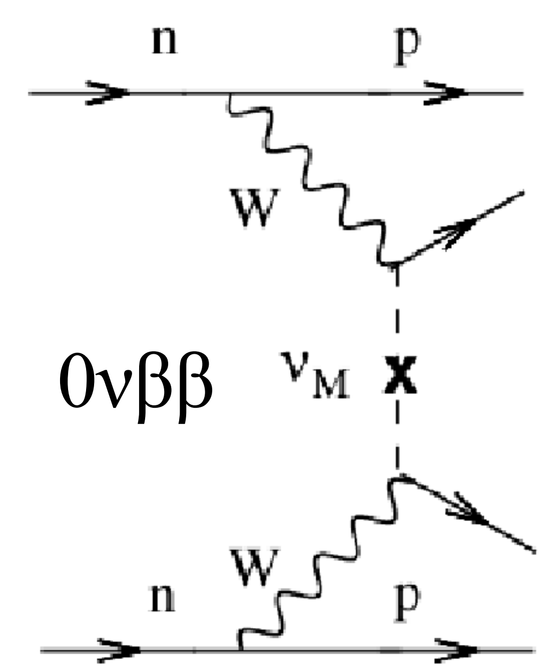
- 2νββ: $(Z, A) \to (Z+2, A) + 2e^- + 2\nu$
  - Rarest observed physical process
- 0νββ: $(Z, A) \to (Z+2, A) + 2e^-$
  - Theoretically proposed decay channel
  - Possible if the neutrino is a Majorana fermion
  - Lepton number violating process—BSM physics; potential implications for matter/antimatter asymmetry in the universe…



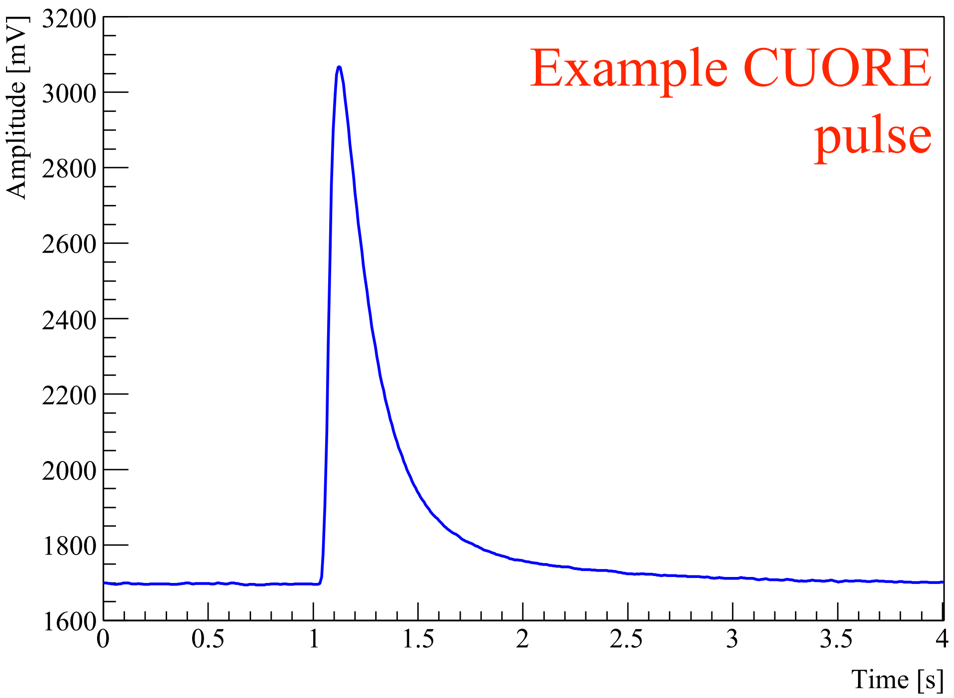
Cartoon spectrum

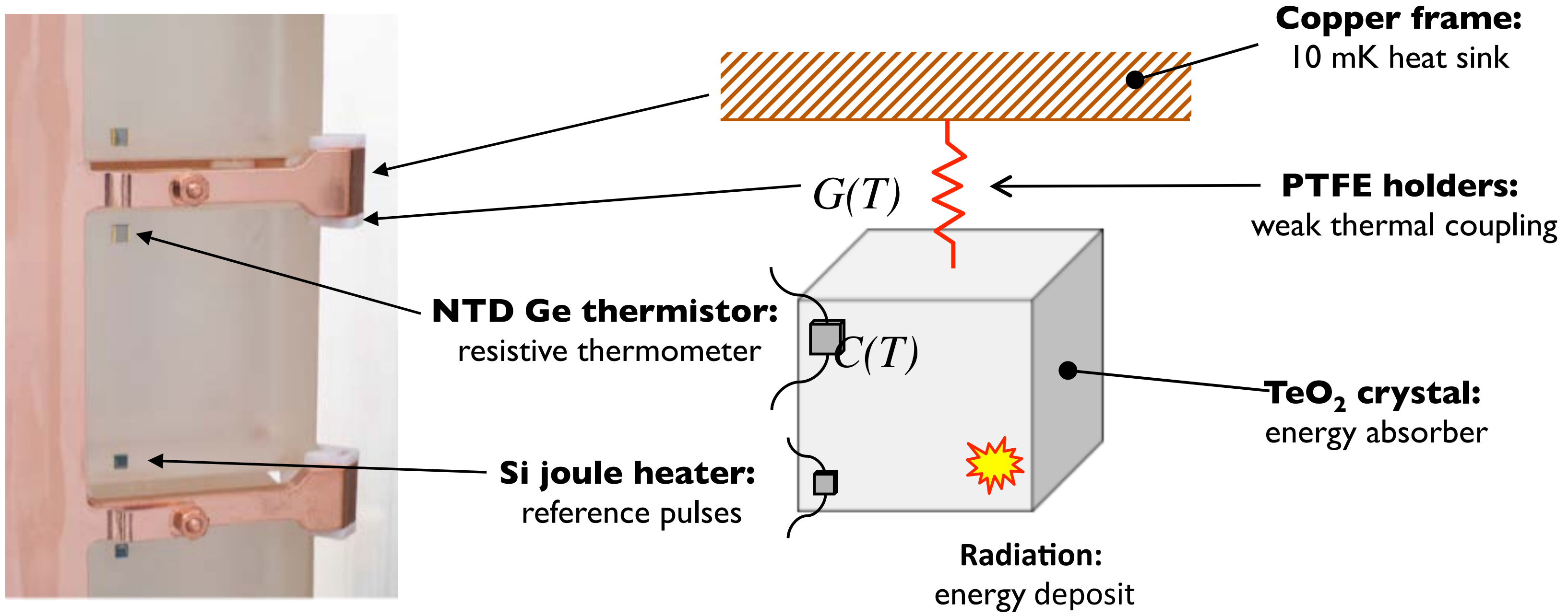


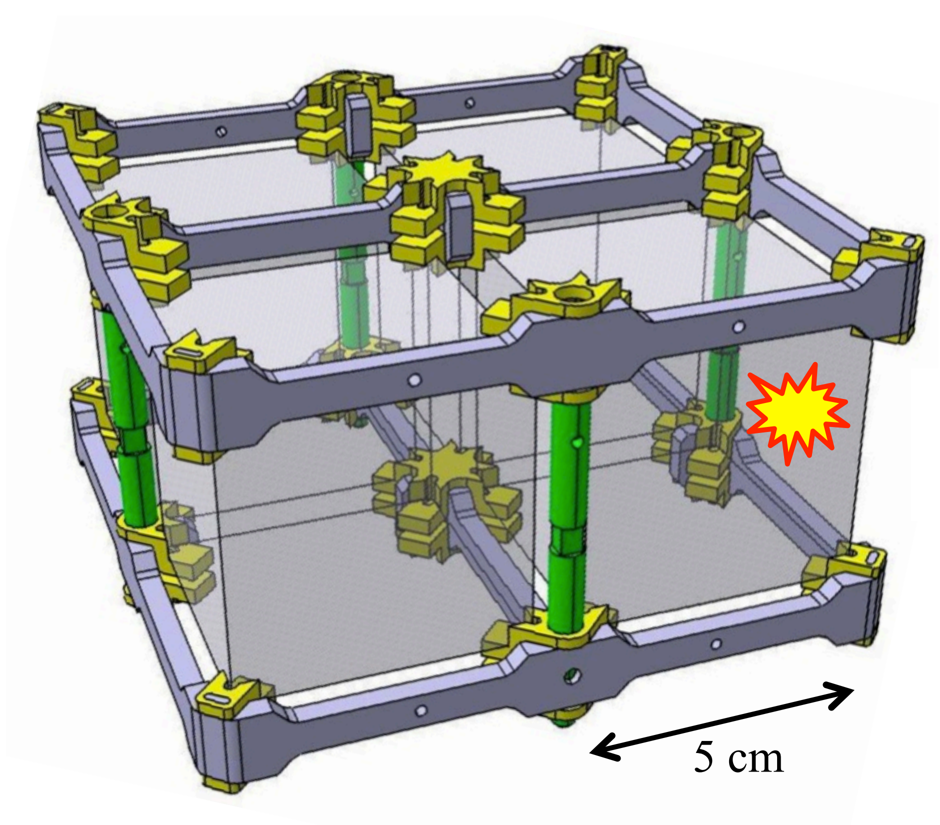




Bolometric Measurements





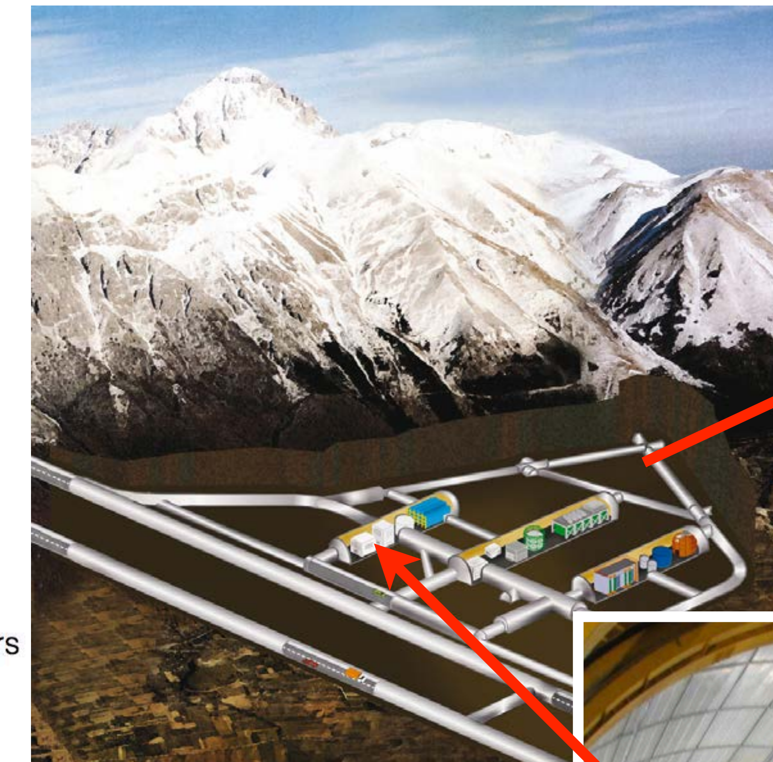


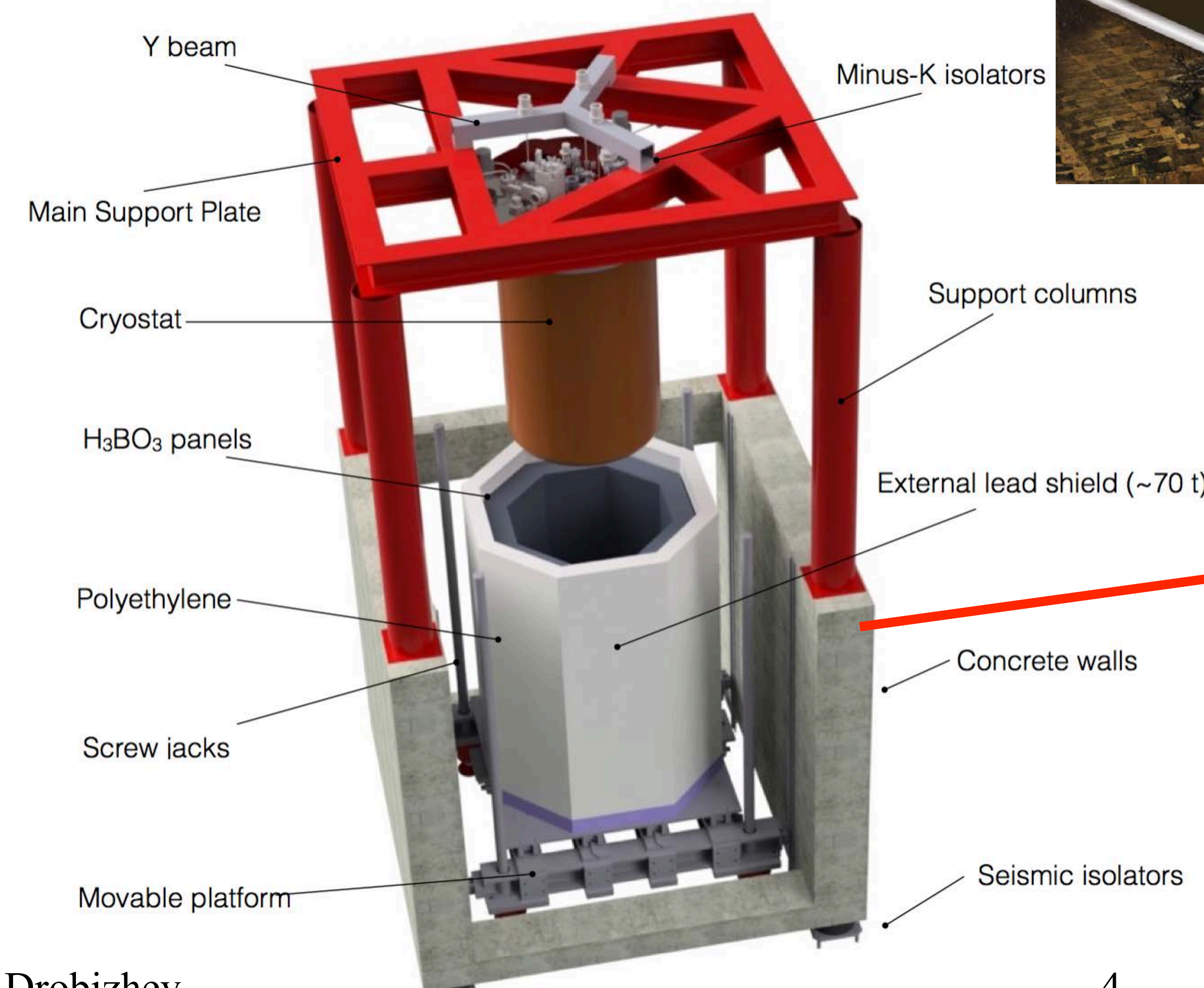
- Absorbed particle $\rightarrow \Delta T_{event} = \frac{E_{event}}{C_{crystal}}$
- Heat capacity is low at very cold temperatures:
  - In CUORE: $5\times5\times5 cm^3$ TeO_2 crystals:

    $\rightarrow C^{-1} \approx 100\mu K/MeV$
- Readout with temperature-sensitive resistive sensor (thermistor)
  - In CUORE, NTD Ge $\rightarrow R = R_0 e^{\sqrt{T_0/T}}$

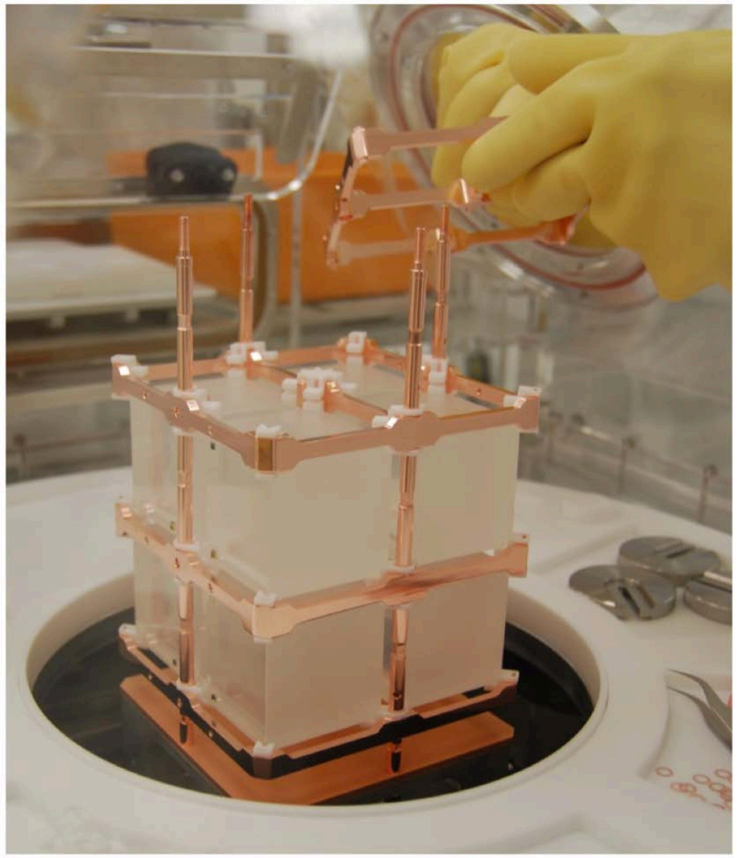
The CUORE Experiment at LNGS

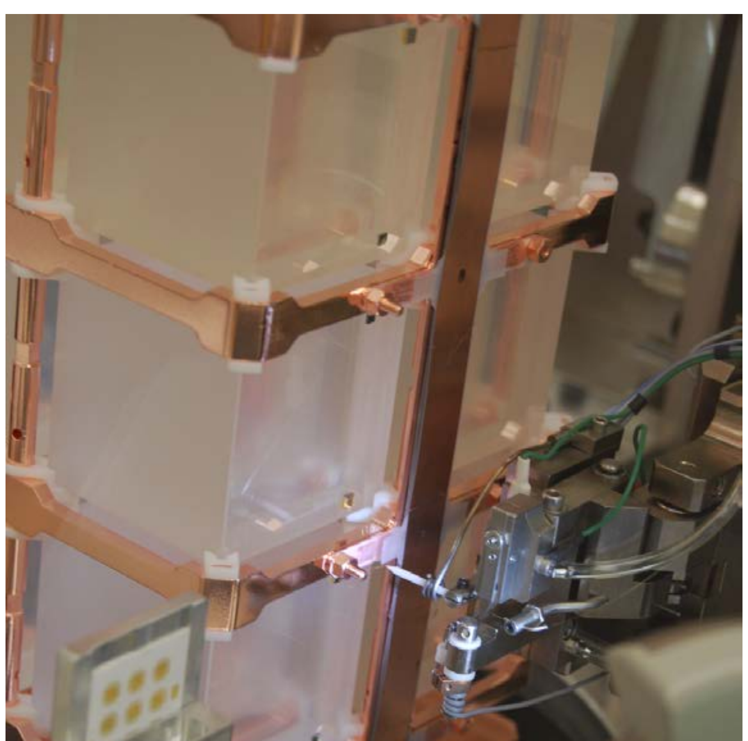
- **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents.
- Located at Gran Sasso National Laboratories (LNGS) in Italy (3650 m water equivalent overburden)





The CUORE Detector

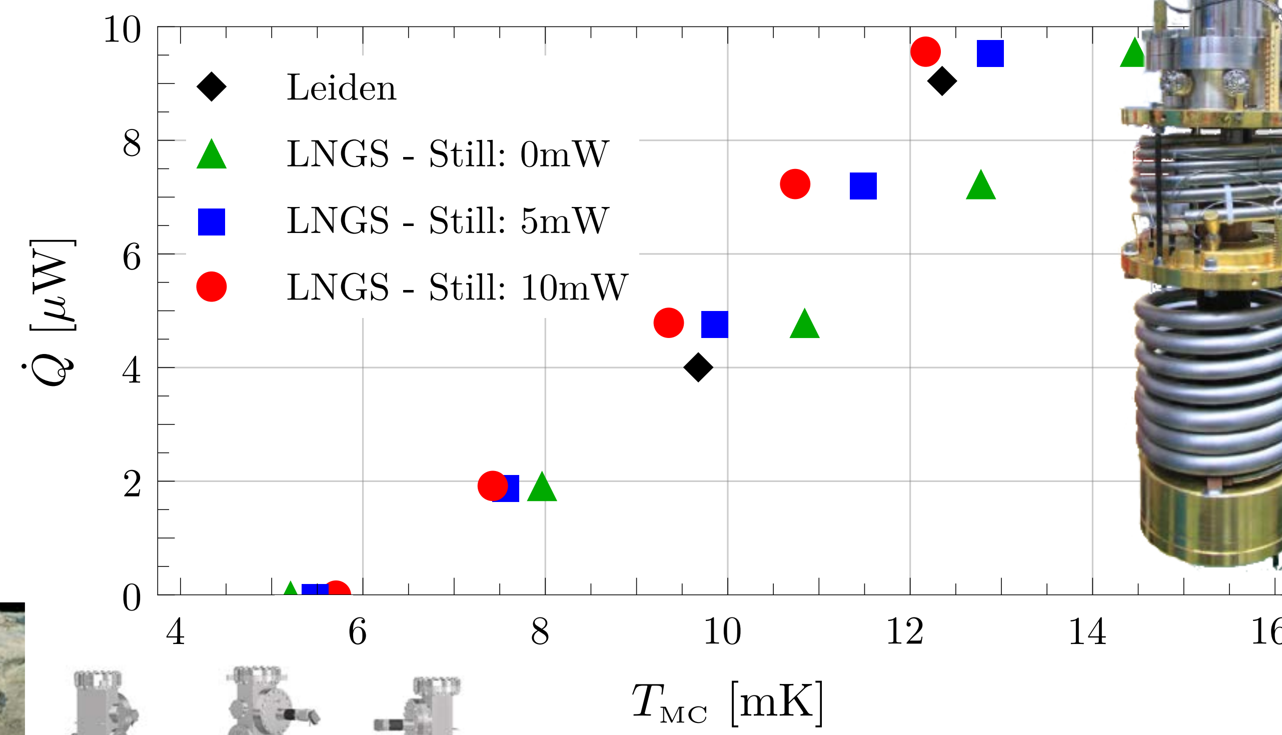


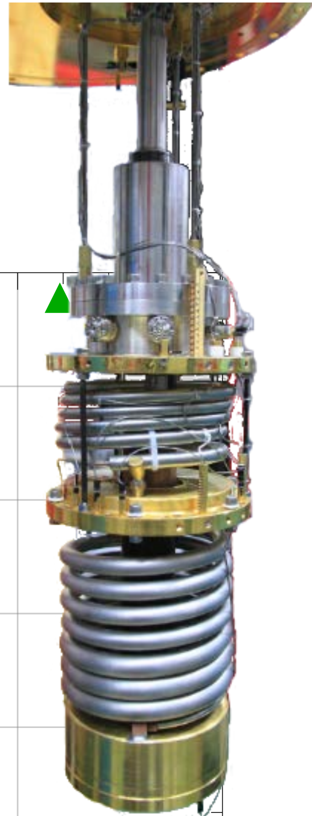


- Bolometric search for $0\nu\beta\beta$ of ^{130}Te (also topics $2\nu\beta\beta$, other isotopes, axions …)
- 988 $5\times5\times5 cm^3$ TeO_2 crystals in 19 towers of 52—source and absorber, $m_{isotope}$=206kg.
  - 984 active channels (99.6%)
- T ≲ 10 mK in the world's largest most powerful dilution refrigerator…

The CUORE Cryostat

- 5 ✕ 1.5 W Cryomech pulse tube coolers
- DU: 2 mW cooling power @ 100mK, from Leiden Cryogenics
- Radiopure materials, vibration isolation, cold Roman Pb shields.
- Coldest cubic meter in the known universe (arXiv:1410.1560).





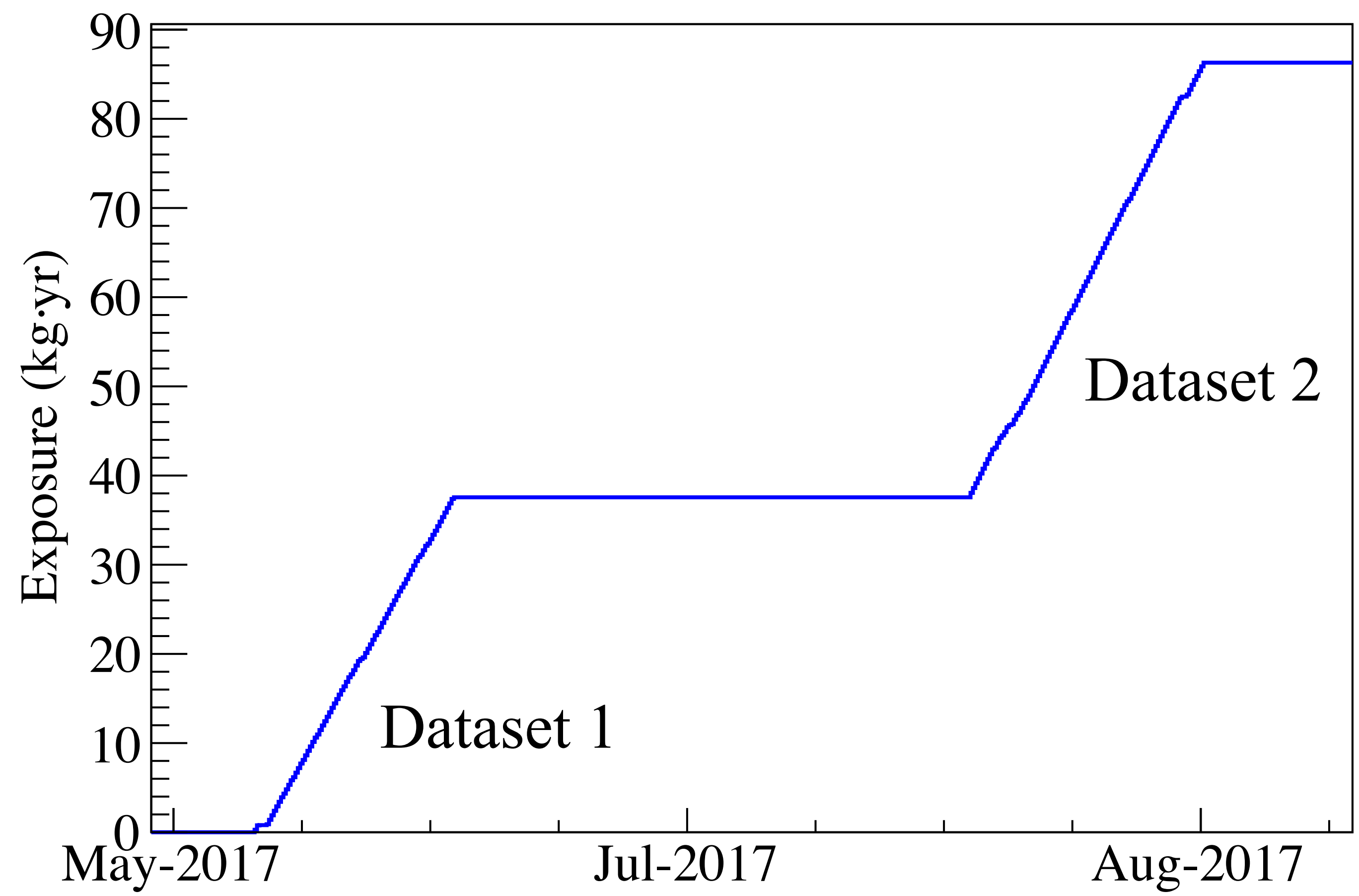
[J. Low Temp. Phys. 184, 590 – 596 (2016)]()

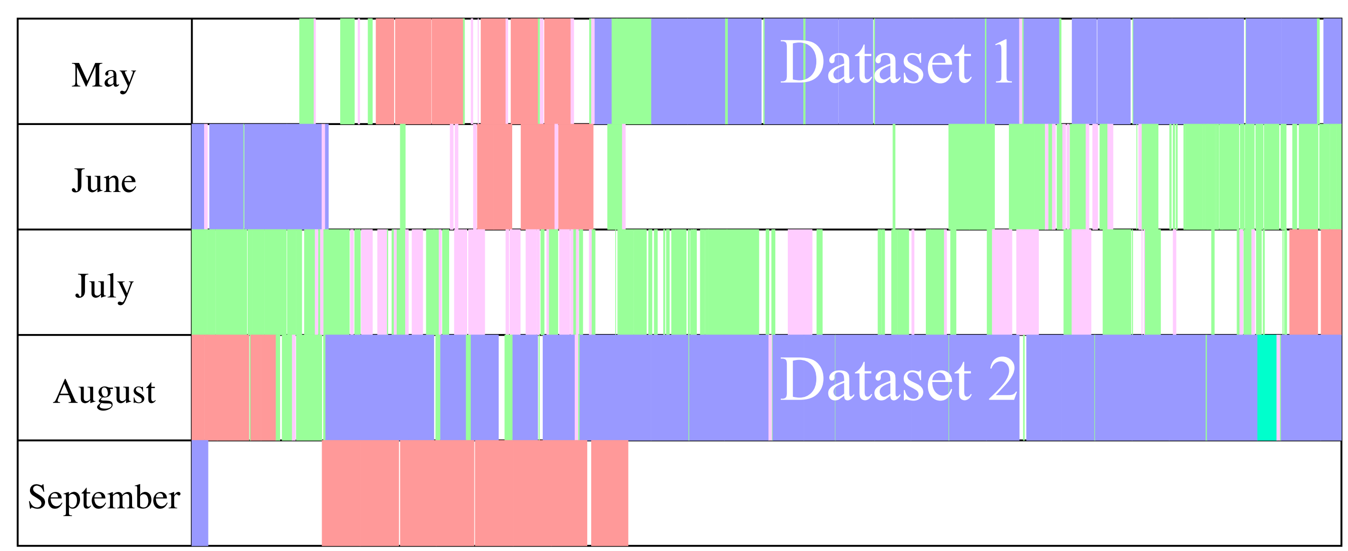
[J. Phys.: Conf. Ser 718, 062054 (2016)]()

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

[arXiv:1710.07988](https://arxiv.org/abs/1710.07988)



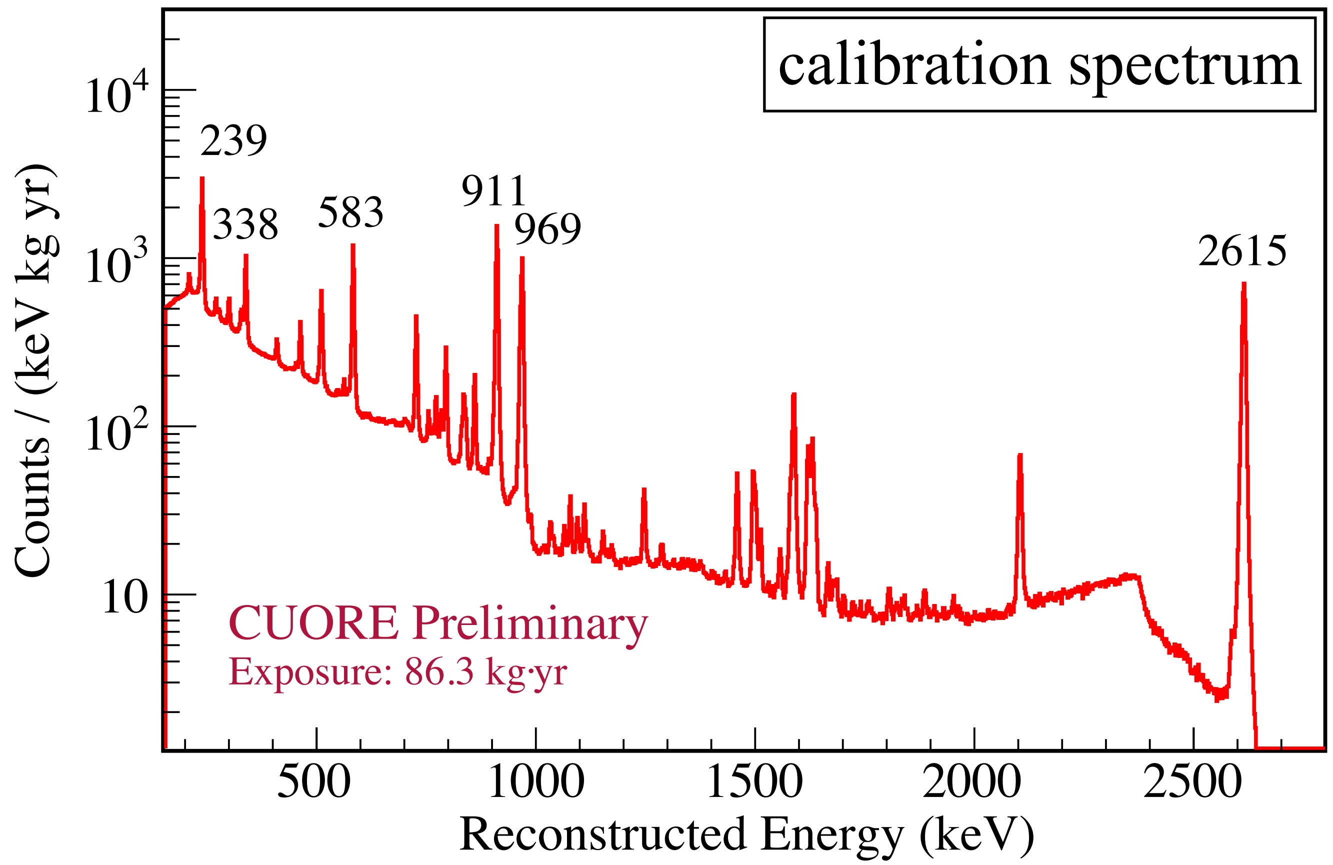


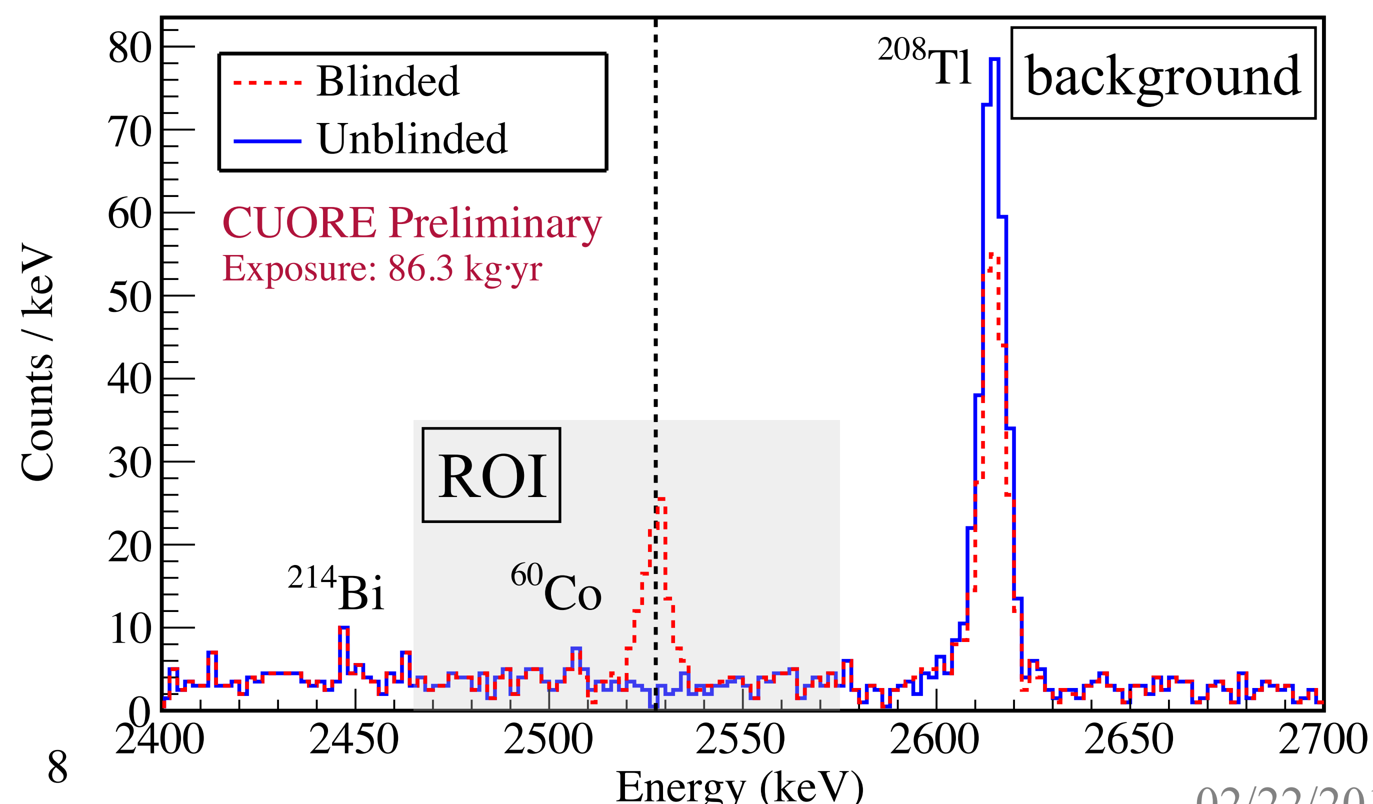
Physics, calibration, test, and configuration runs of CUORE in 2017

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

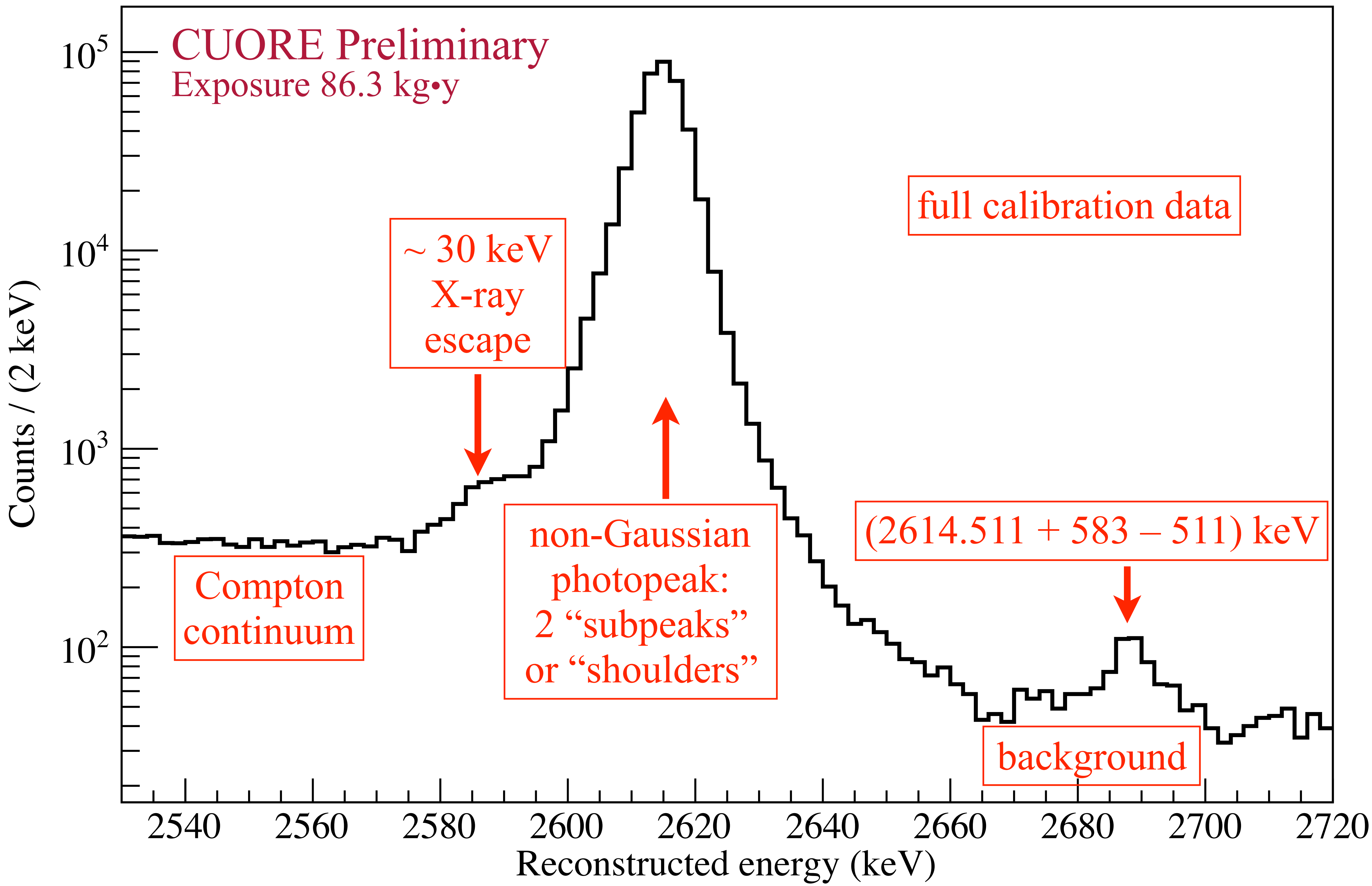
- Fit to determine the spectral line shape.
- Use the ^{208}Tl 2615 keV line:
    - Strongest peak from ^{232}Th calibration spectrum.
    - Sufficiently prominent in the background spectrum.
    - Relatively near to the ^{130}Te $0\nu\beta\beta$ decay ROI (2465 to 2575 keV, in gray at right).
- Use 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.

arXiv:1710.07988



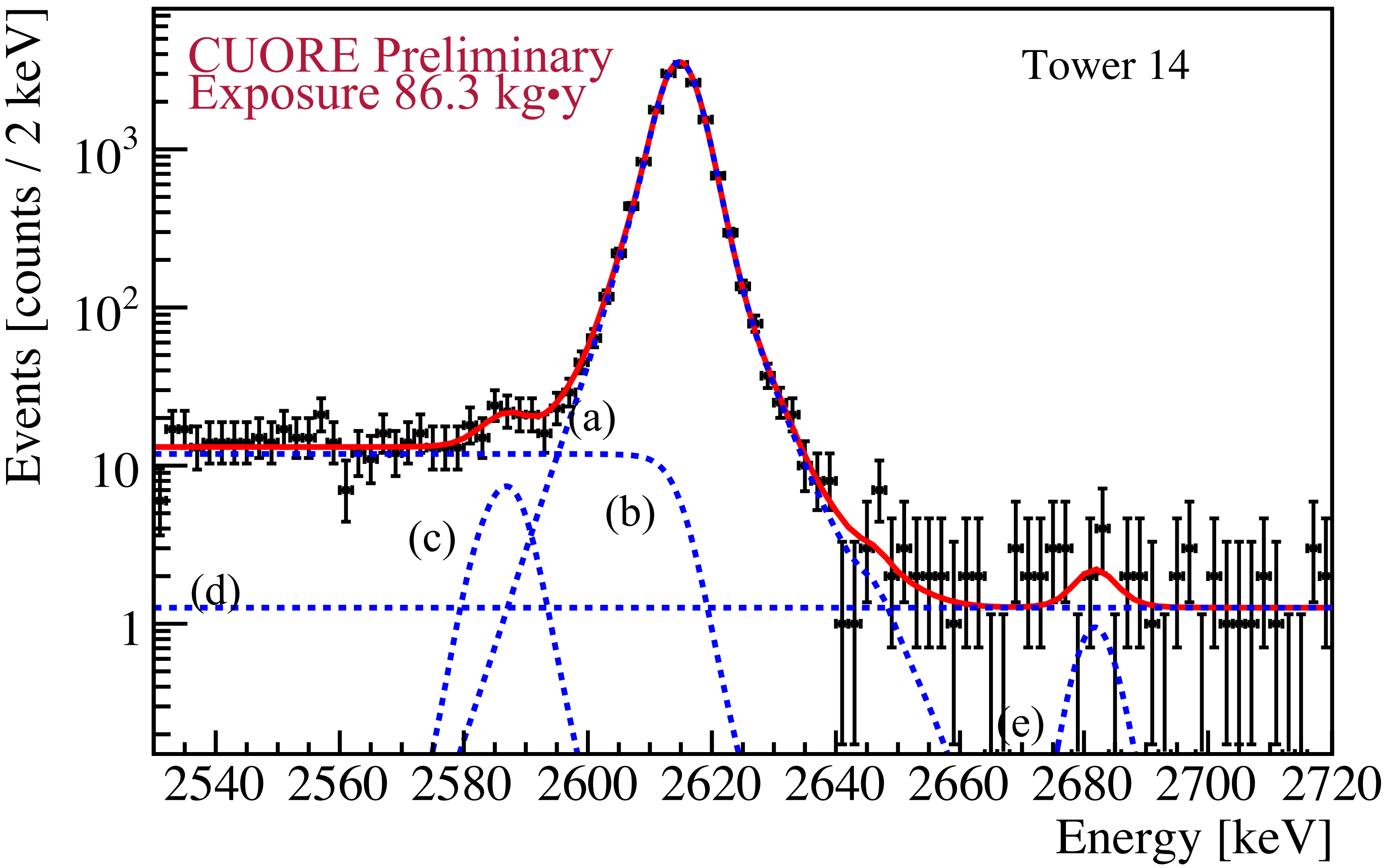


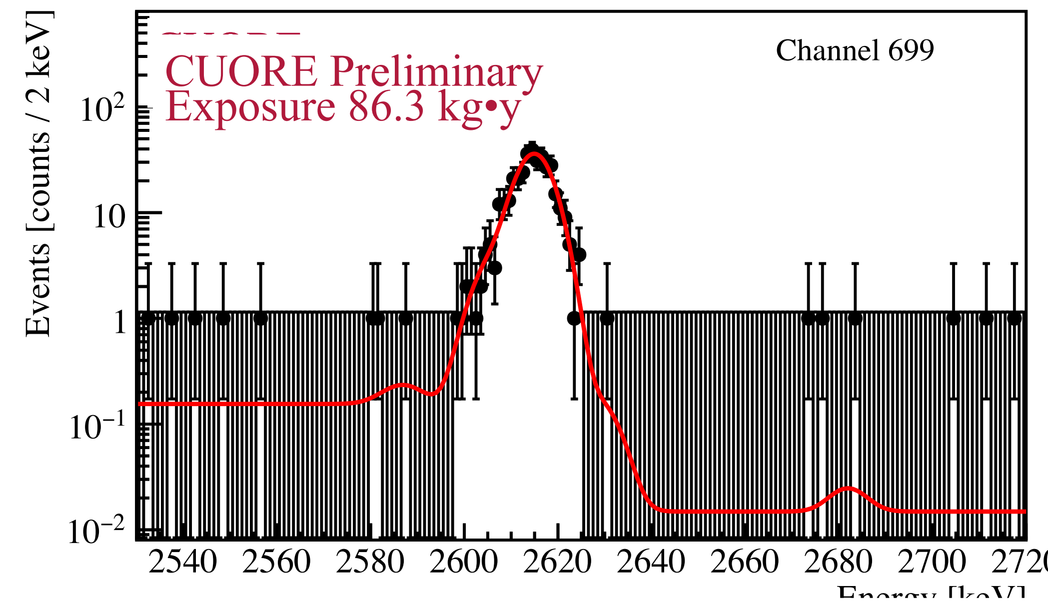
Modeling the Line Shape: 2615 keV ^{208}Tl

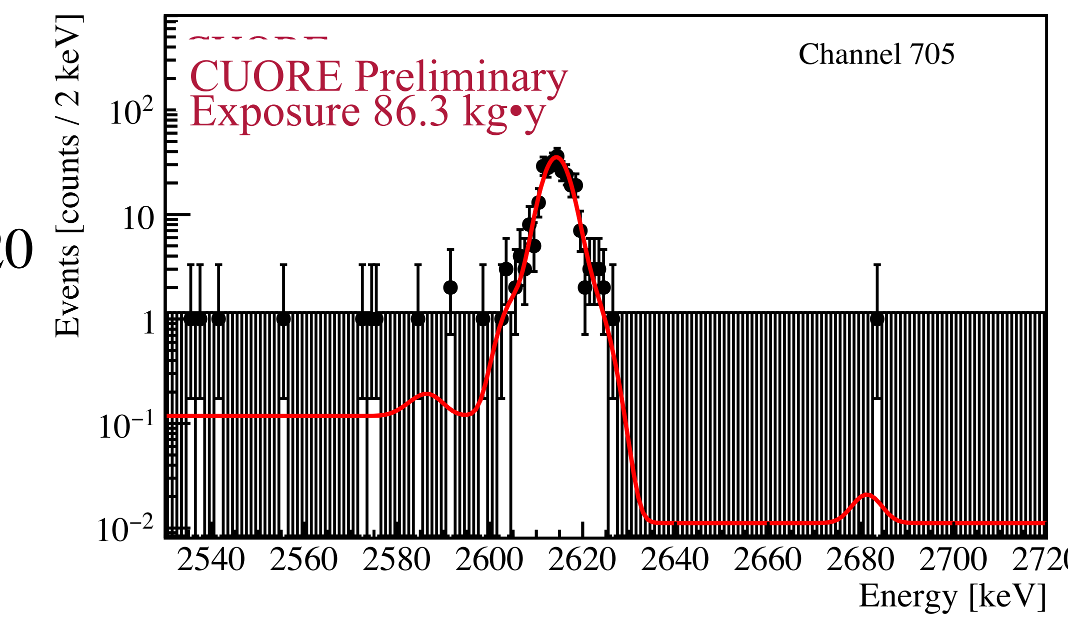


- We would like to fit the region of [2530, 2720] keV: many features to consider in and around the line.

Example Line Shape Fit Result: Tower 14





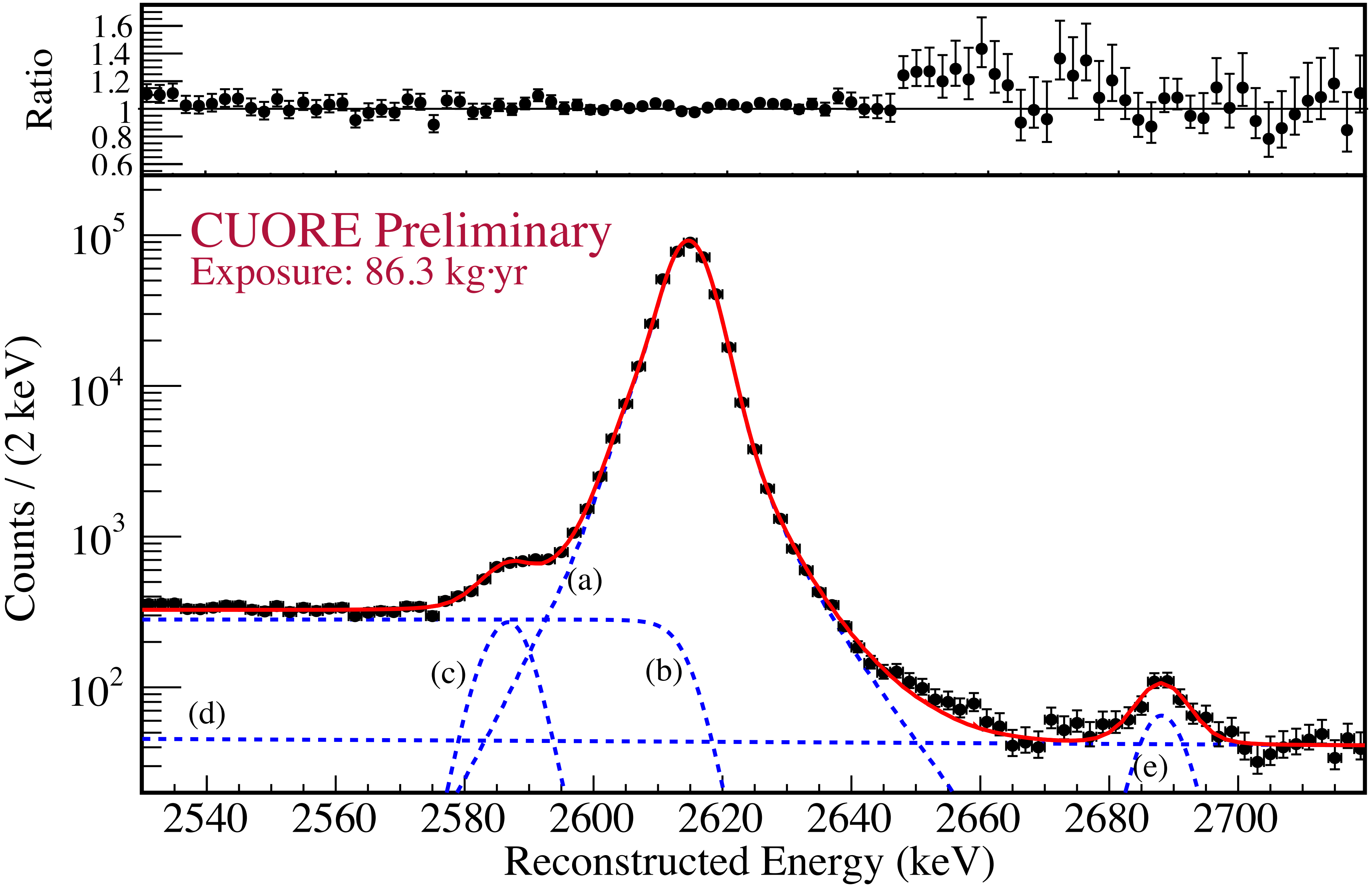


(a) - Photopeak	(b) - Compton
(c) - ~30 keV X-ray escape	(d) - Background
(e) - (2615 + 583 – 511) keV	

One tower (single simultaneous fit) with fit components and two example channels from that tower (both datasets). 19 separate fits like this are done.

arXiv:1710.07988

The Summed Line Shape Fit Result



(a) - Photopeak

(b) - Compton

(c) - ~30 keV X-ray escape

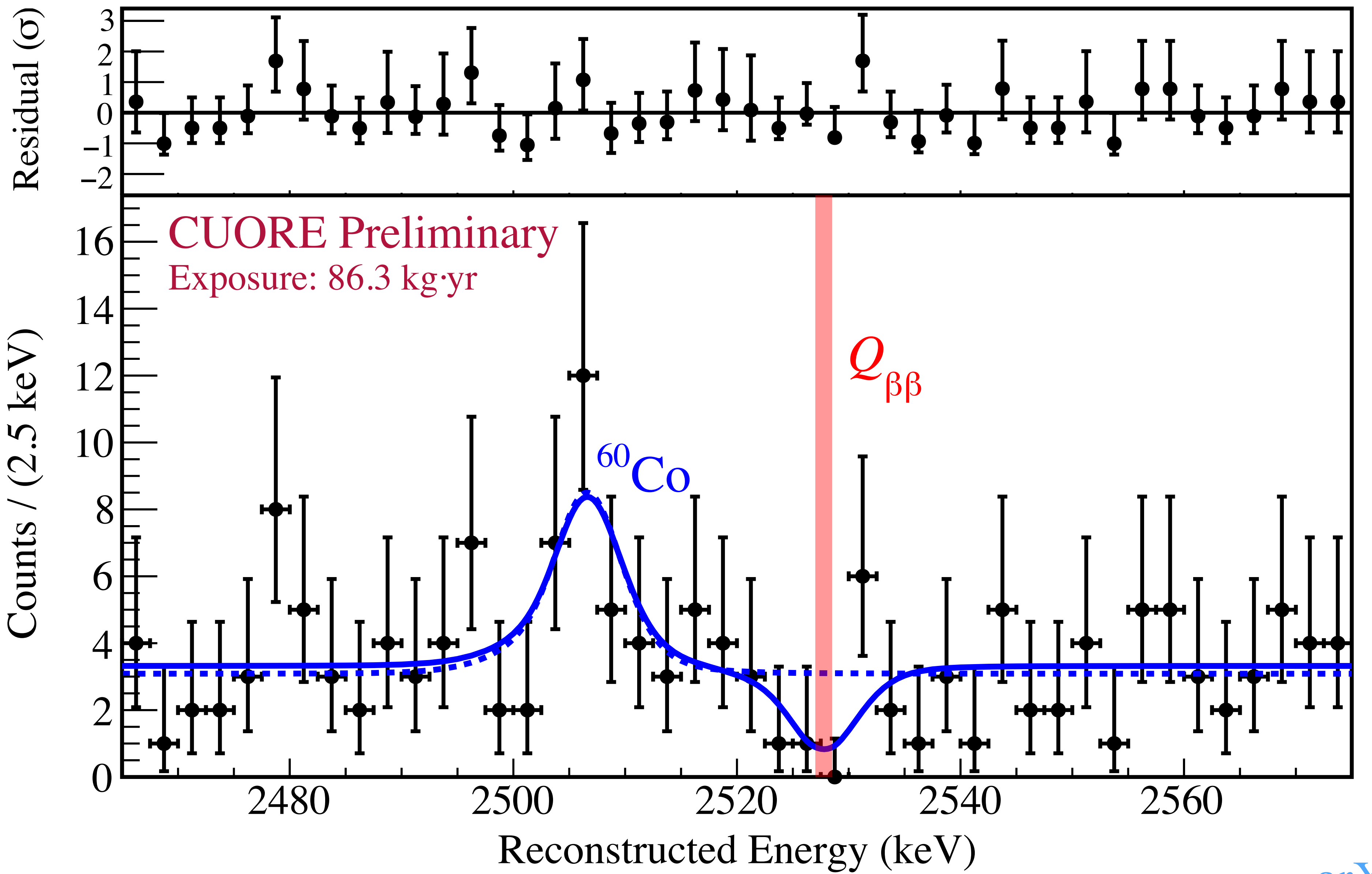
(d) - Background

(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.

arXiv:1710.07988

The ROI Fit Result

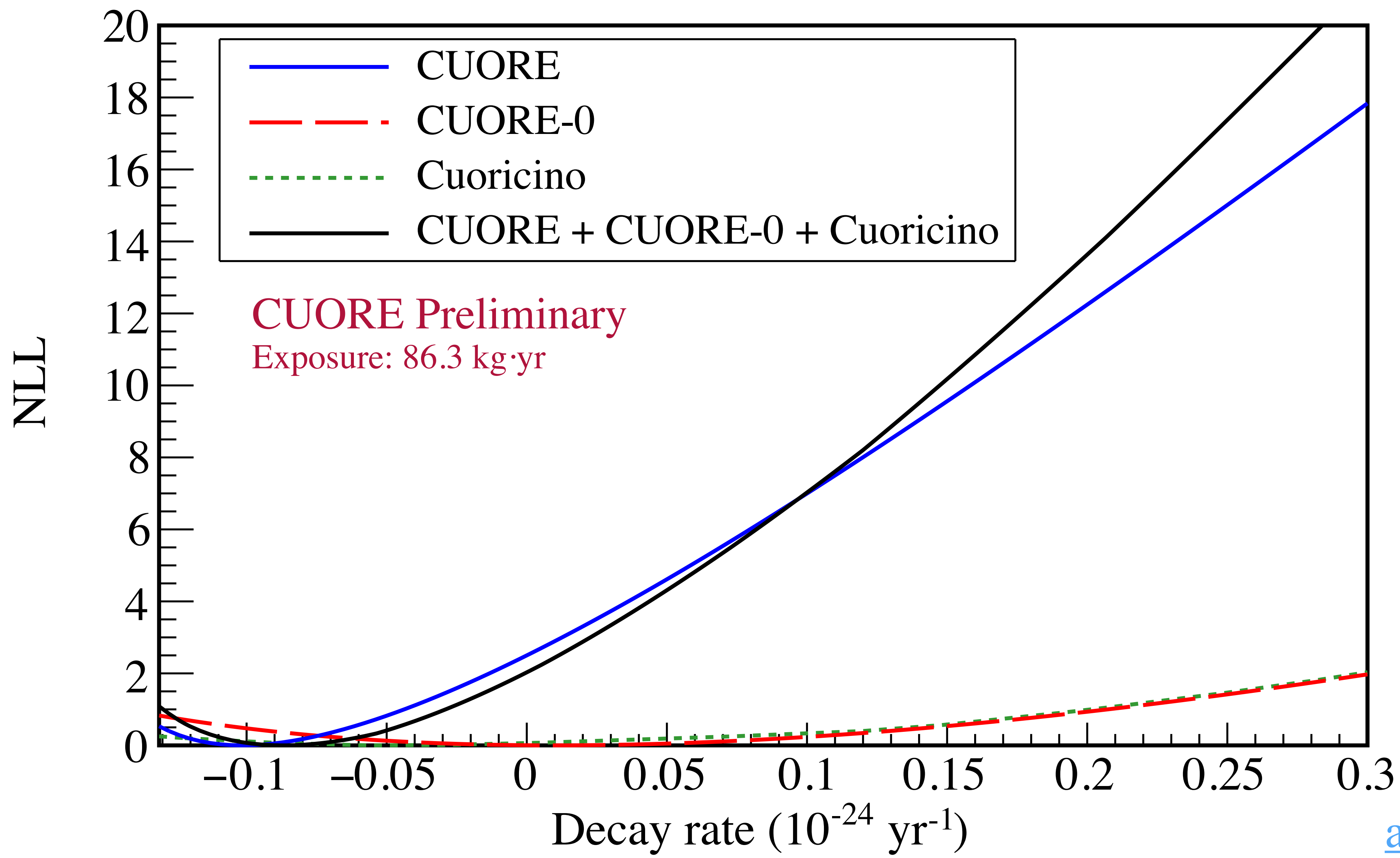


arXiv:1710.07988

- 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 ± 0.02) 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).]



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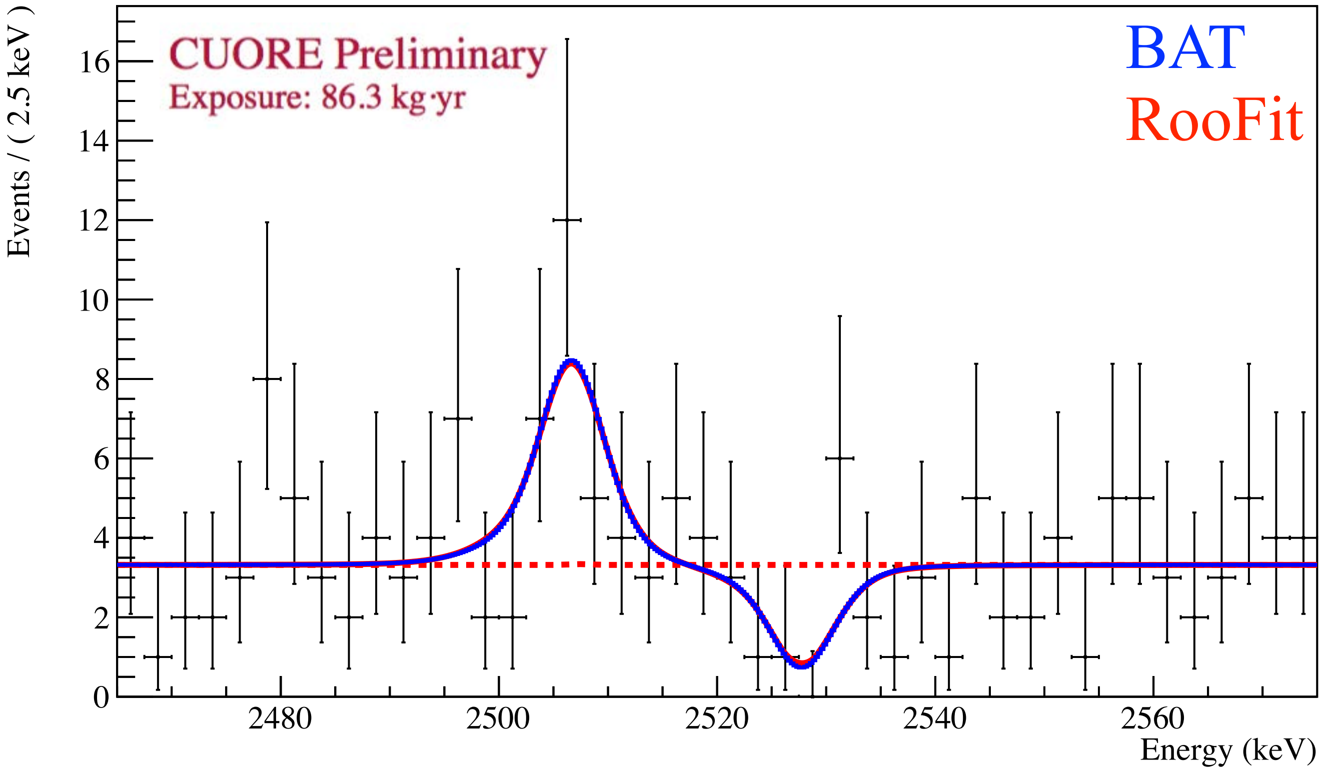
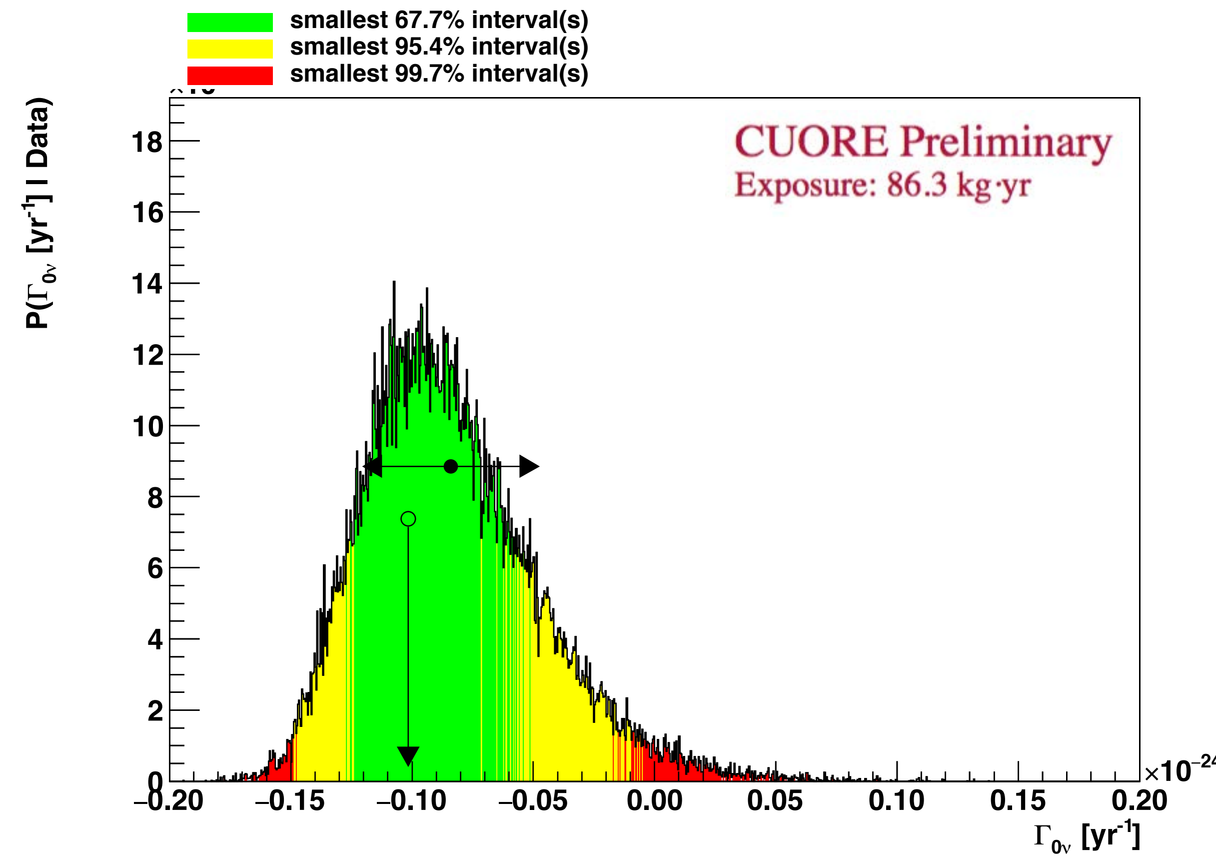
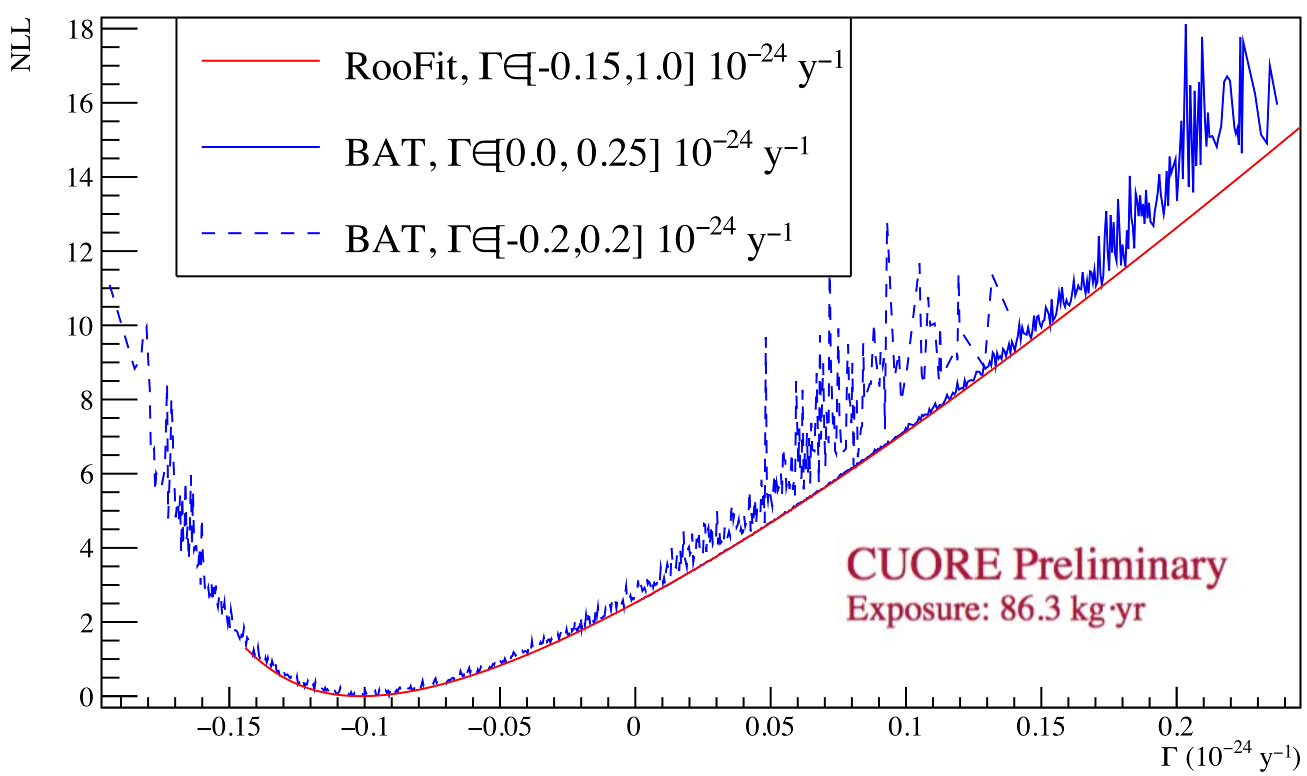
- CUORE Half-life limit (90% C.L.): $T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ y Rolke: $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$ y
- CUORE + CUORE–0 + Cuoricino: $T^{0\nu}_{1/2} > 1.5 \times 10^{25}$ y Rolke: $T^{0\nu}_{1/2} > 2.2 \times 10^{25}$ y

A Fully Bayesian Analysis with BAT





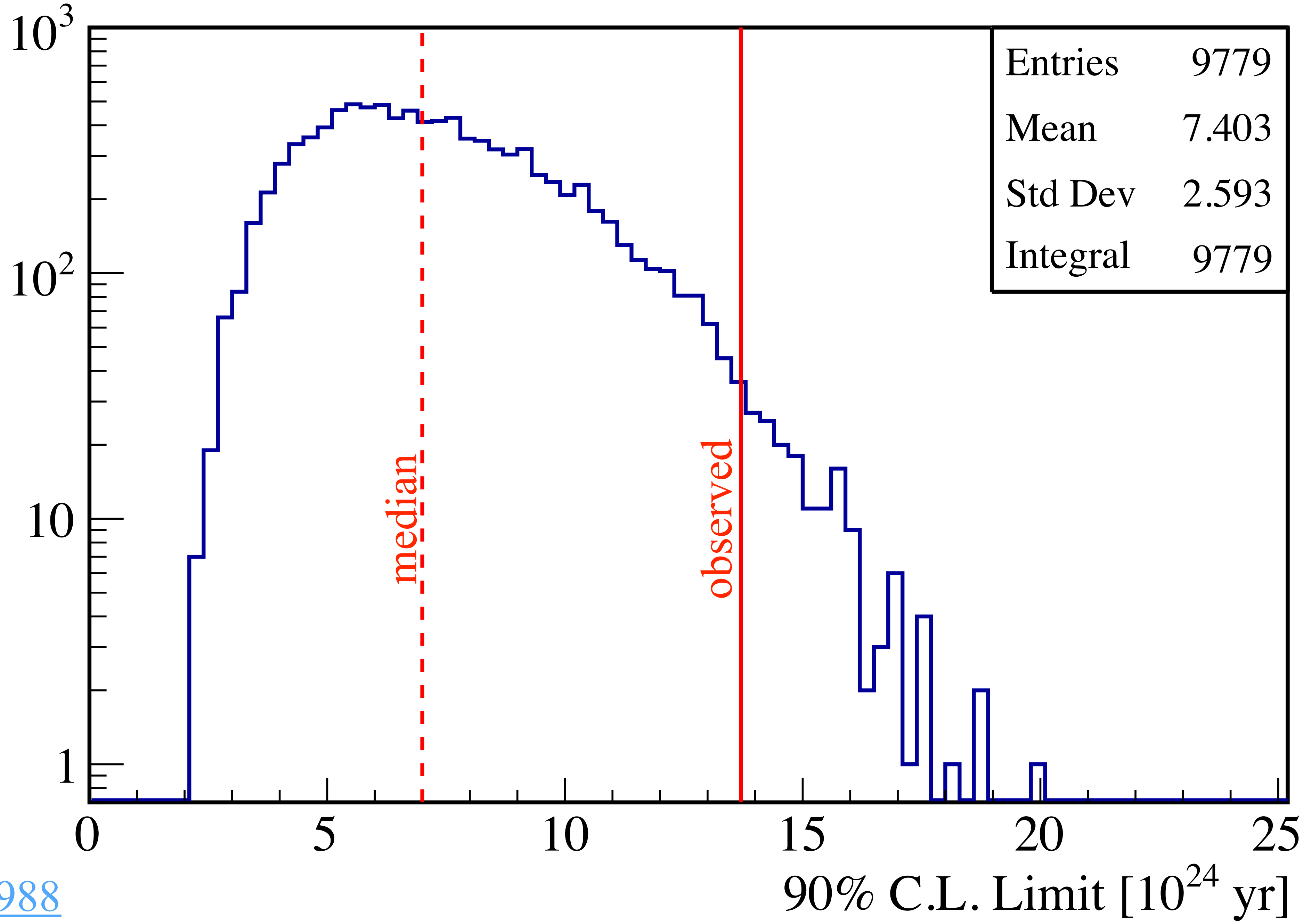


- Fit consistent with RooFit analyses at the percent level.
- Gives the same limit (both marginalized and profiled):

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

arXiv:1710.07988

Sensitivity and Negative Fluctuation



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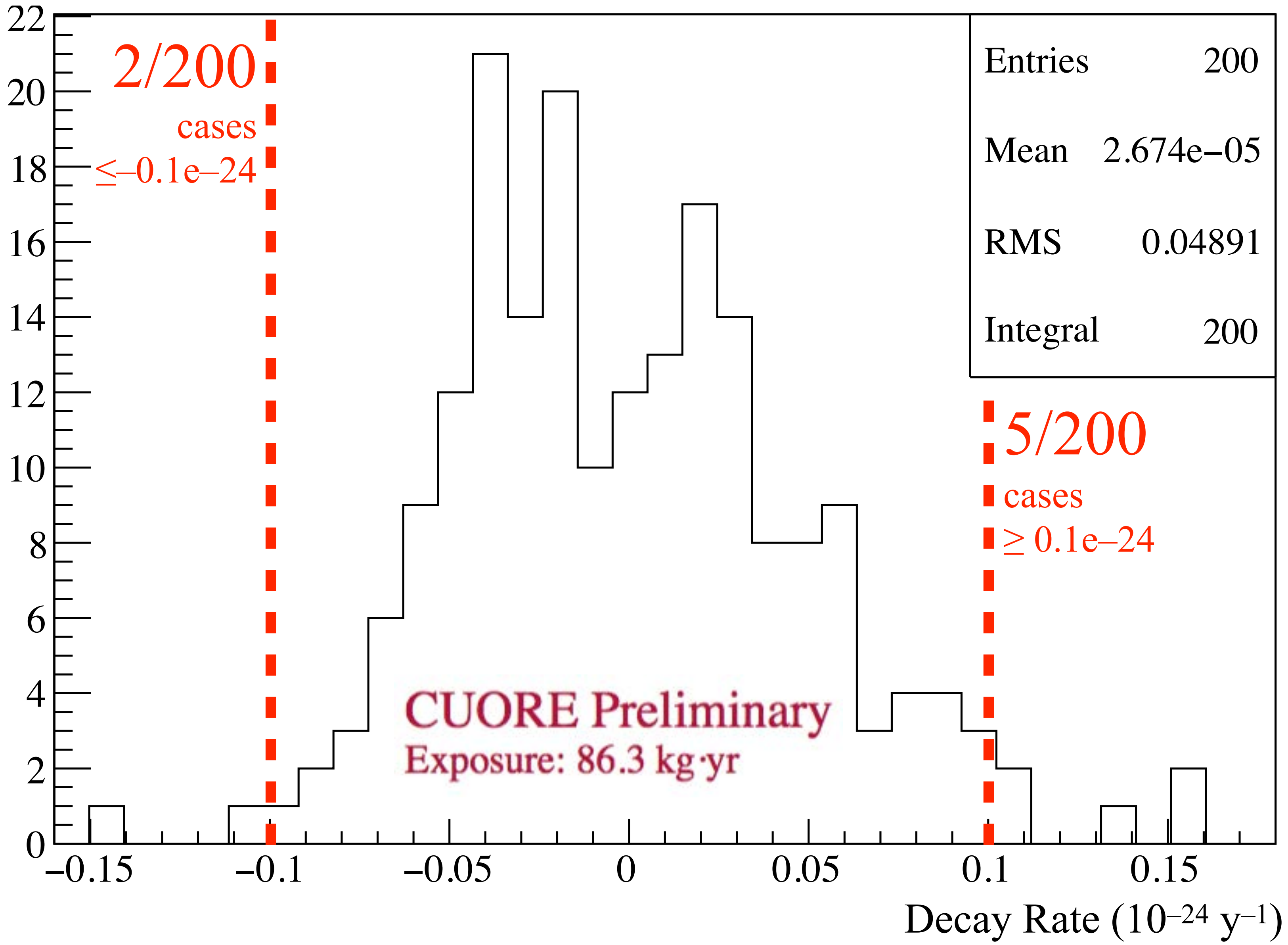
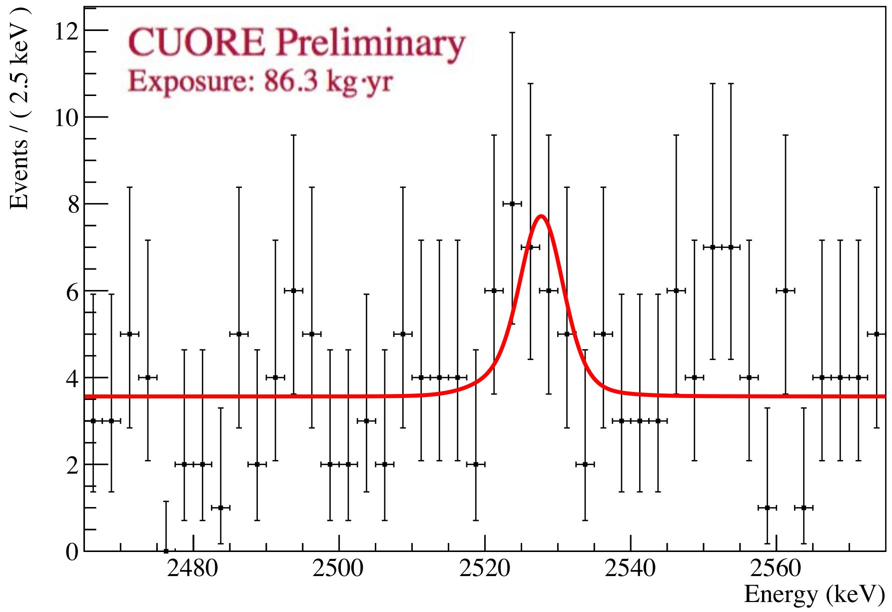
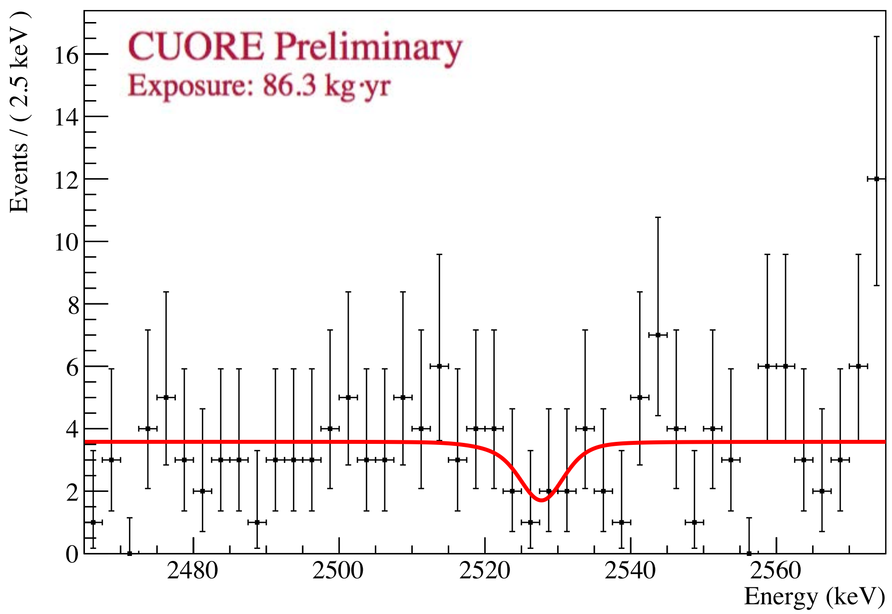
Toy MC study with null hypothesis:

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

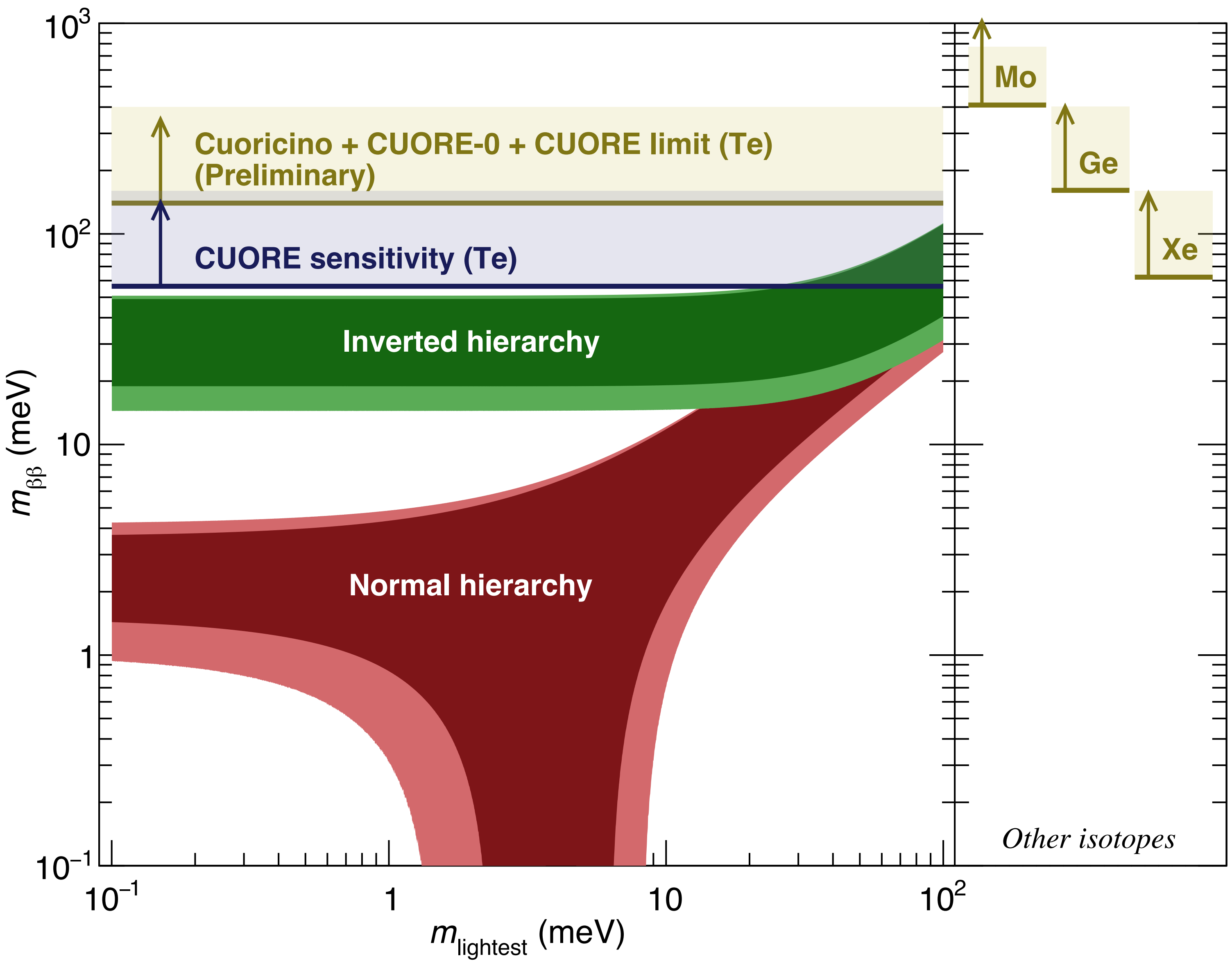






- ROI-style fits to 200 overlapping pieces of degraded α region avoiding ^{210}Po: [2650, 3150] keV and [3400, 4000] keV.
- Results appear to be consistent with the ROI Toy MC study.

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)

arXiv:1710.07988

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

Conclusions

- The first result from the CUORE experiment
- On the arXiv: [arXiv:1710.07988 [nucl-ex]]
- Accepted by PRL 10/20/2018 (two days ago)!
- Scientific:
  - 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 bolometer
  - custom construction and operation of the world's largest and most powerful dilution refrigerator
- The future:
  - 5 years of live time planned → 9×10^{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):
    - active discrimination with optical channel
    - enriched crystals for more isotope mass
    - probe entire inverted hierarchy parameter space

Acknowledgements

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Backup slides

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%

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 × y) from database
- Channel–dependent parameters:
  - 2 × Subpeak Energy Ratios: positions of the left and right shoulders w.r.t. Q-value
  - 2 × 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.

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.

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**

arXiv:1710.07988