CUORE:
Cryogenic Underground Observatory for Rare Events

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CUORE Collaboration

CSNSM

Universitas Studii Paduani MCCXXII

Yale

INFN

Berkeley Lab

Cal Poly San Luis Obispo

Alma Mater Studiorum Università di Bologna A.D. 1088

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

UCLA

SINAP

University of South Carolina 1801

University of California 1868 Let there be light

Massachusetts Institute of Technology

VirginiaTech 1872 Invent the Future®

Lawrence Livermore National Laboratory

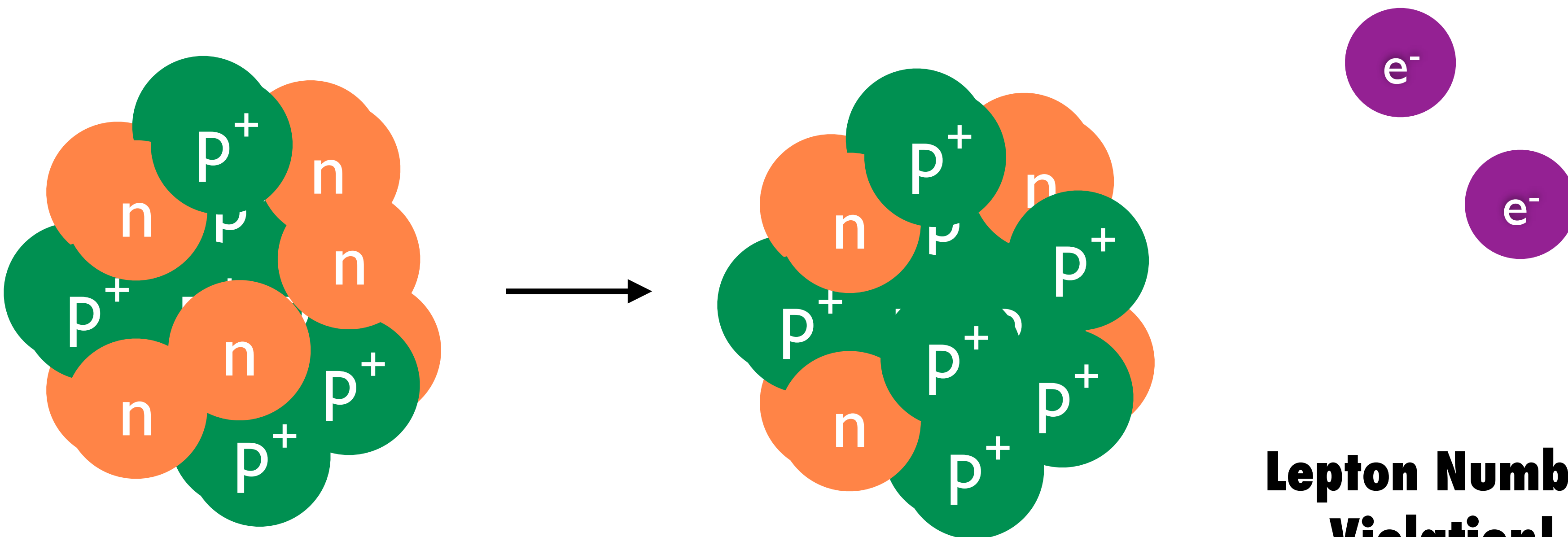
Sapienza Università di Roma

Università degli Studi di Milano Bicocca

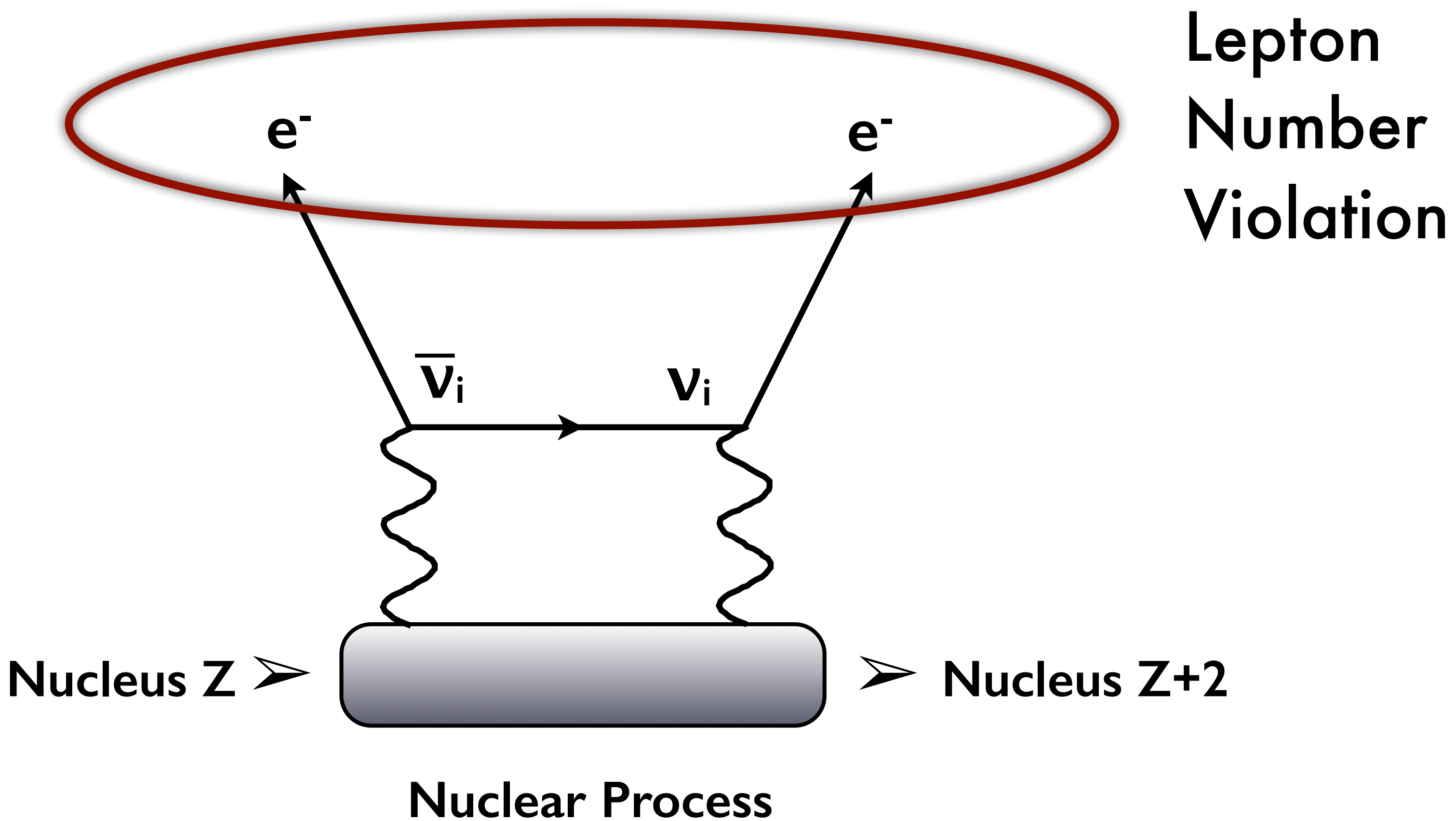
Shanghai Jiao Tong University 1896

CUORE

This is why we are all here:



Lepton Number Violation!



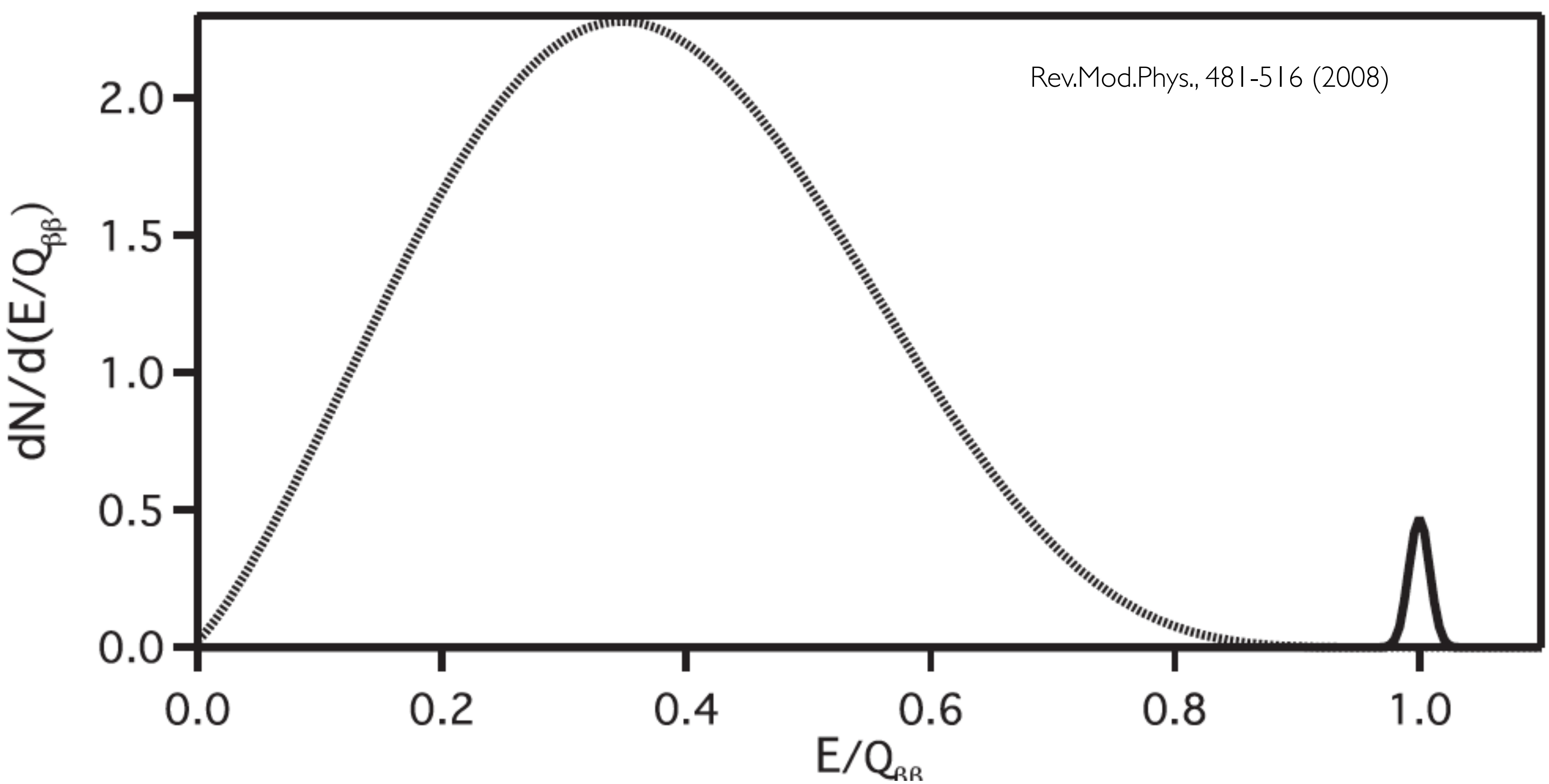
Light Majorana Neutrino Exchange (LMNE)

Common Candidate Isotopes:

Isotope	Endpoint	Abundance
^{48}Ca	4.271 MeV	0.187%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.533 MeV	34.5%
^{136}Xe	2.479 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%
^{128}Te	0.868 MeV	31.7%

See ATOMIC DATA AND NUCLEAR DATA TABLES 61, 43-90 (1995) for all 69+19!

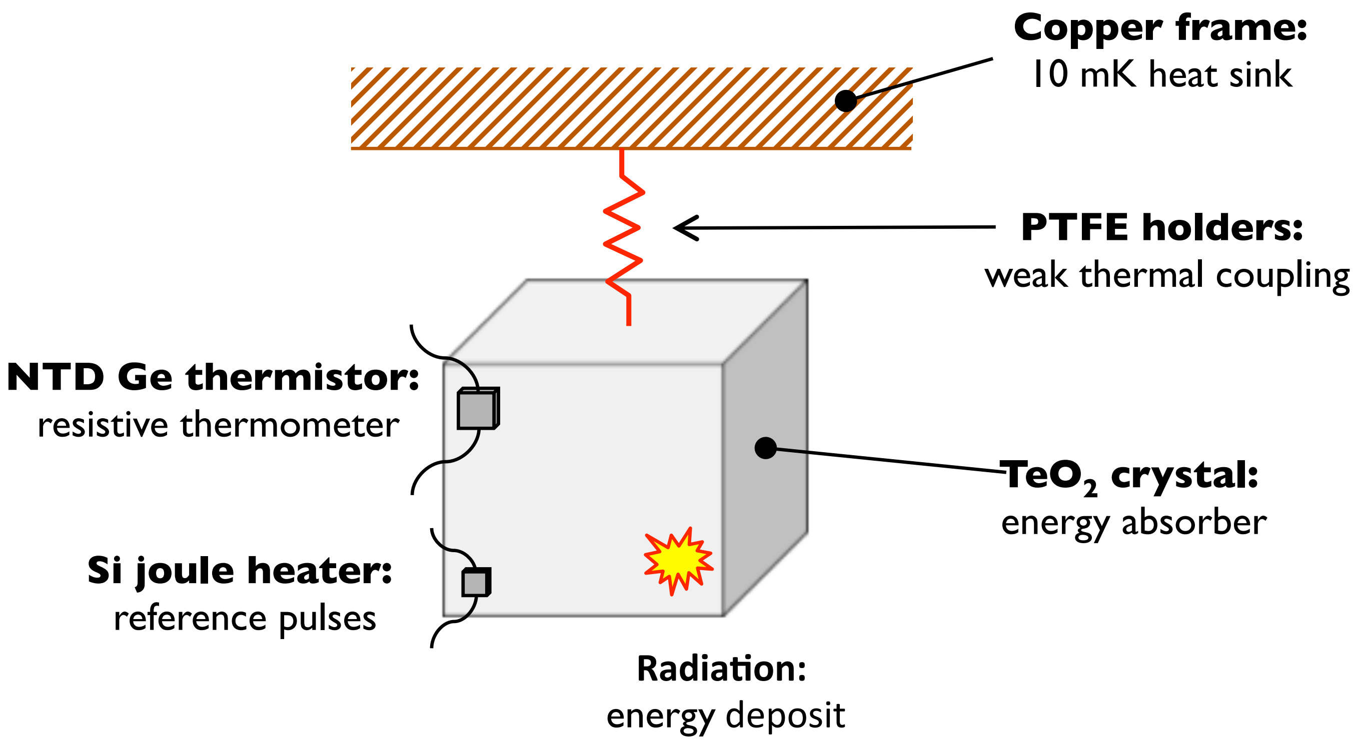
How do we measure this signal?



Experimental Considerations:

- Energy Resolution
- Scalability
- Active Background Rejection
- Flexible Isotope Choice

How Bolometers work:

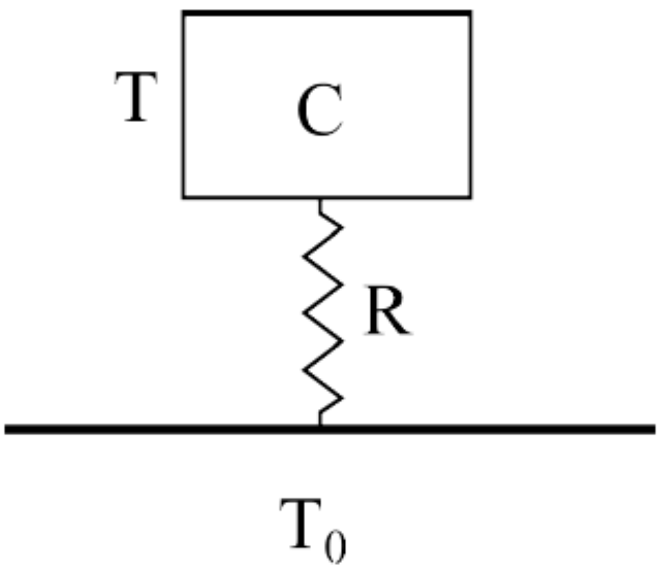


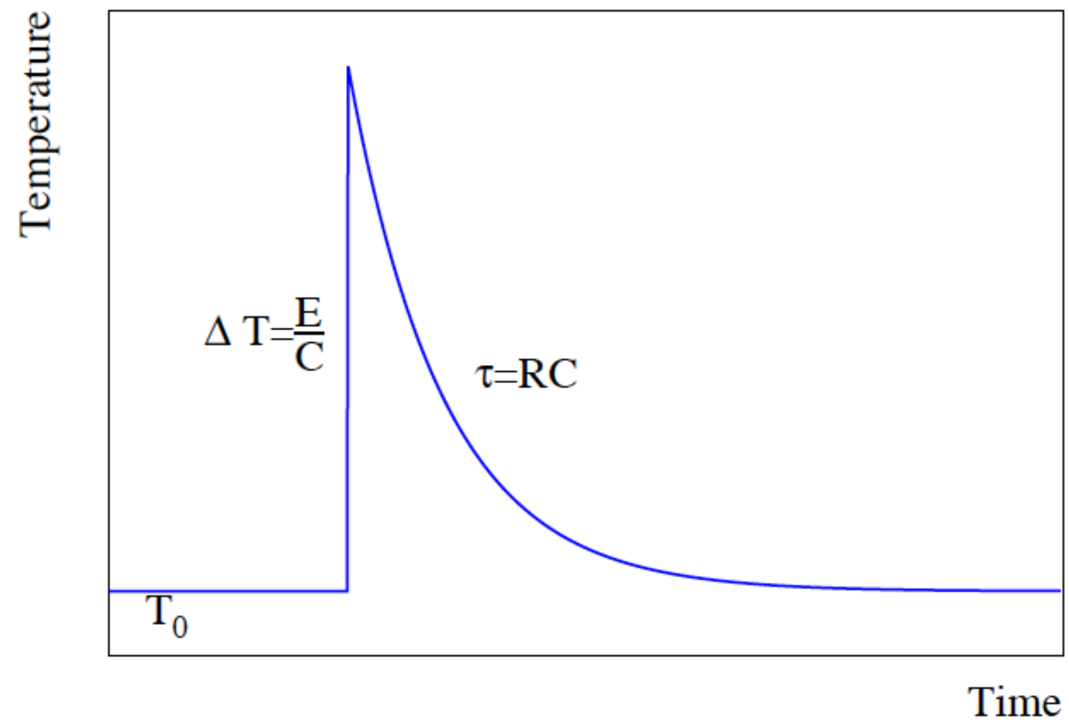
Heat Measurement: *Absorber + Thermometer*

From: J. Ouellet, Thesis 2015

How Bolometers work:

Simple Model

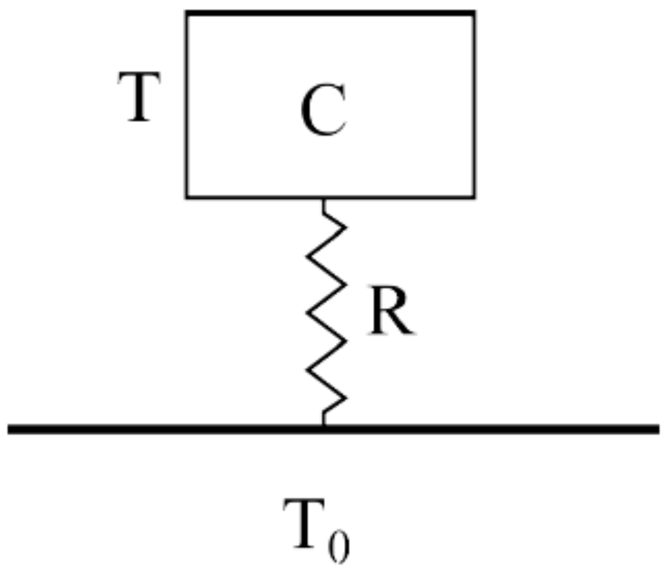


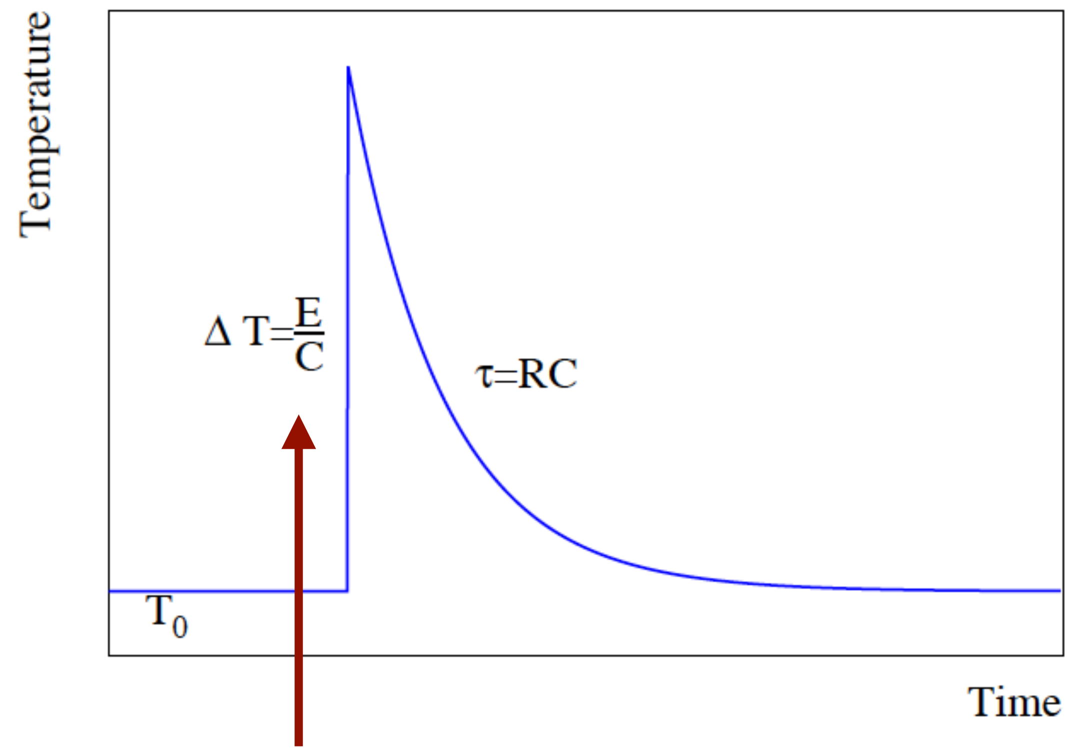


From: J. Ouellet, Thesis 2015

How Bolometers work:

Simple Model



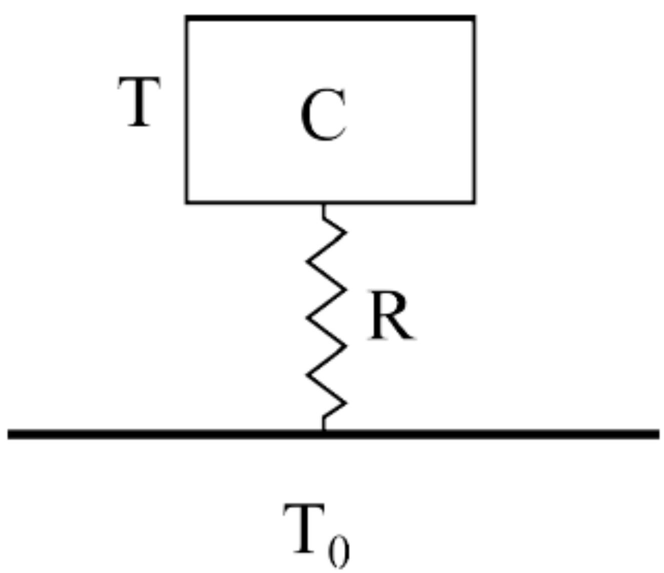


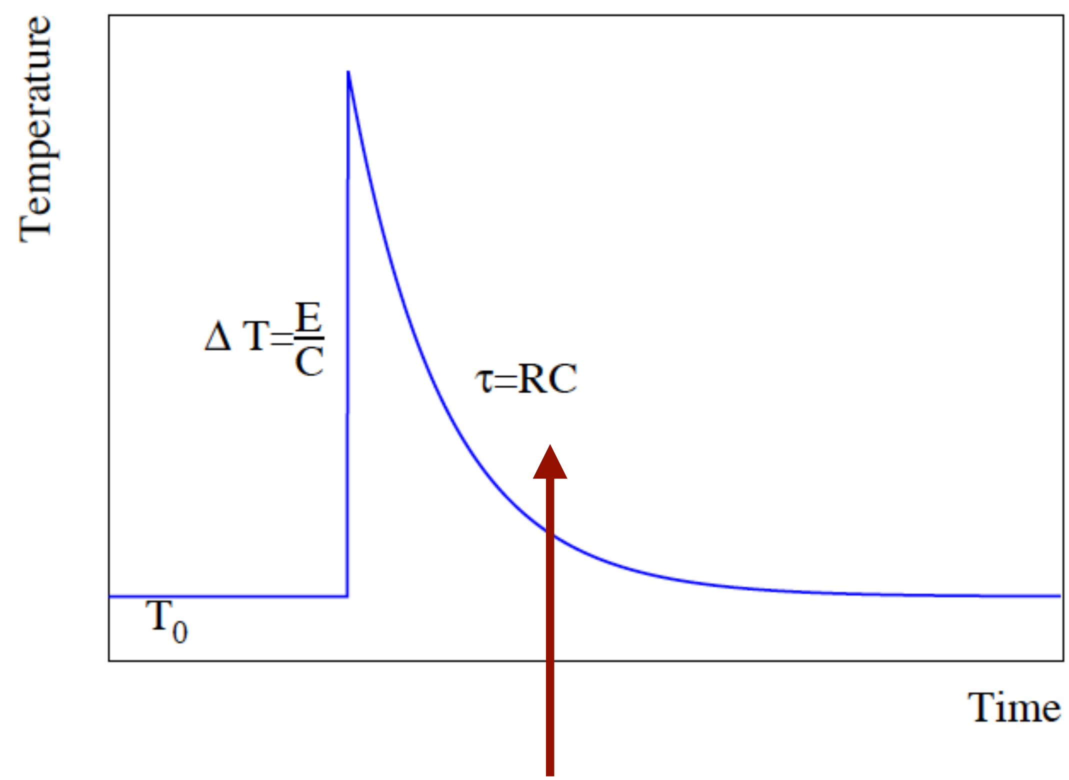
Energy Deposition causes rise in temperature inversely proportional to the heat capacity.

From: J. Ouellet, Thesis 2015

How Bolometers work:

Simple Model





The decay time of the signal is proportional to the thermal resistance.

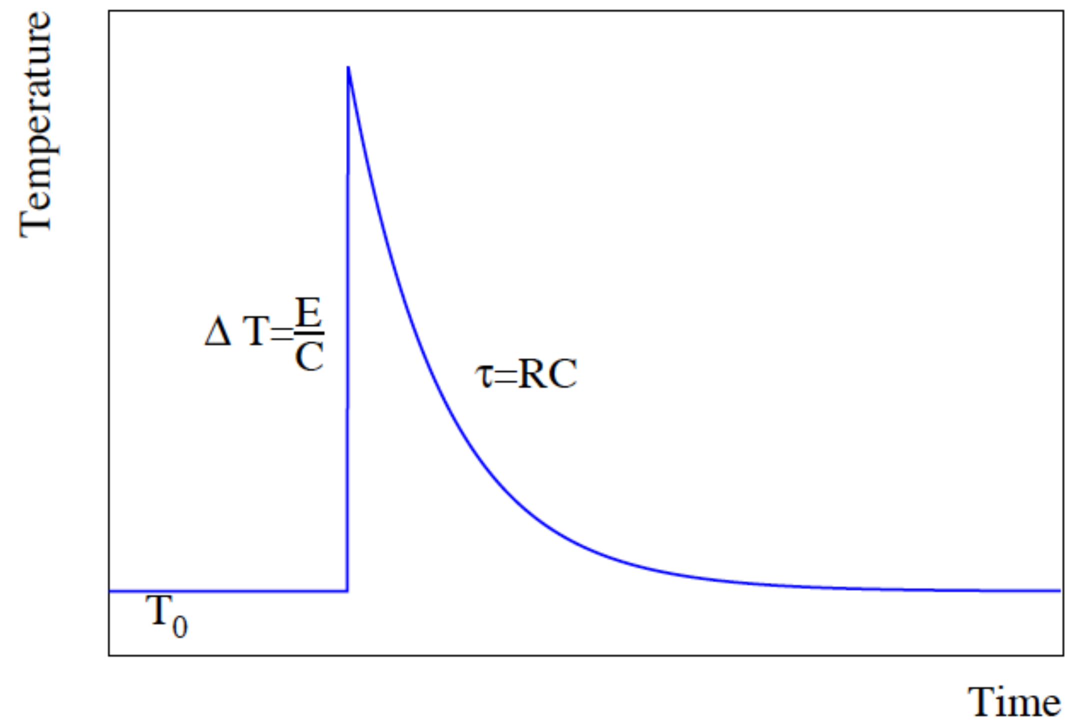
From: J. Ouellet, Thesis 2015

How Bolometers work:

Heat capacity follows Debye Law

$$C(T) \propto k_B \left(\frac{T}{\Theta_D}\right)^3$$

At 10 mK, this corresponds to a 0.1 mK rise in temperature.



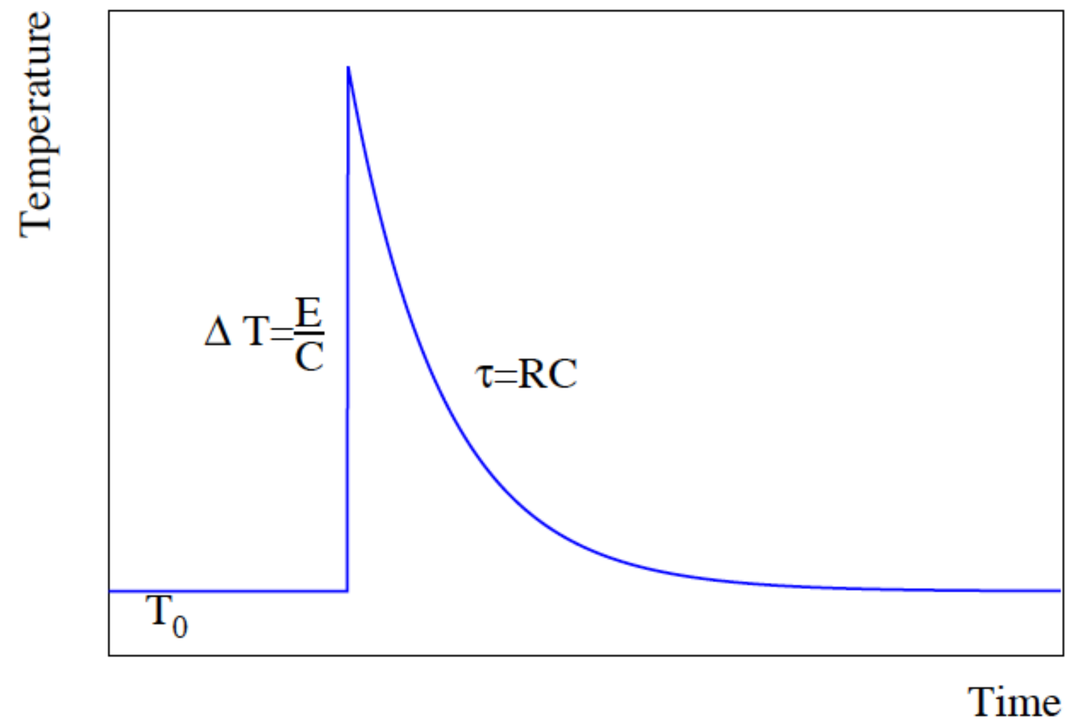
From: J. Ouellet, Thesis 2015

How Bolometers work:

Energy Resolution

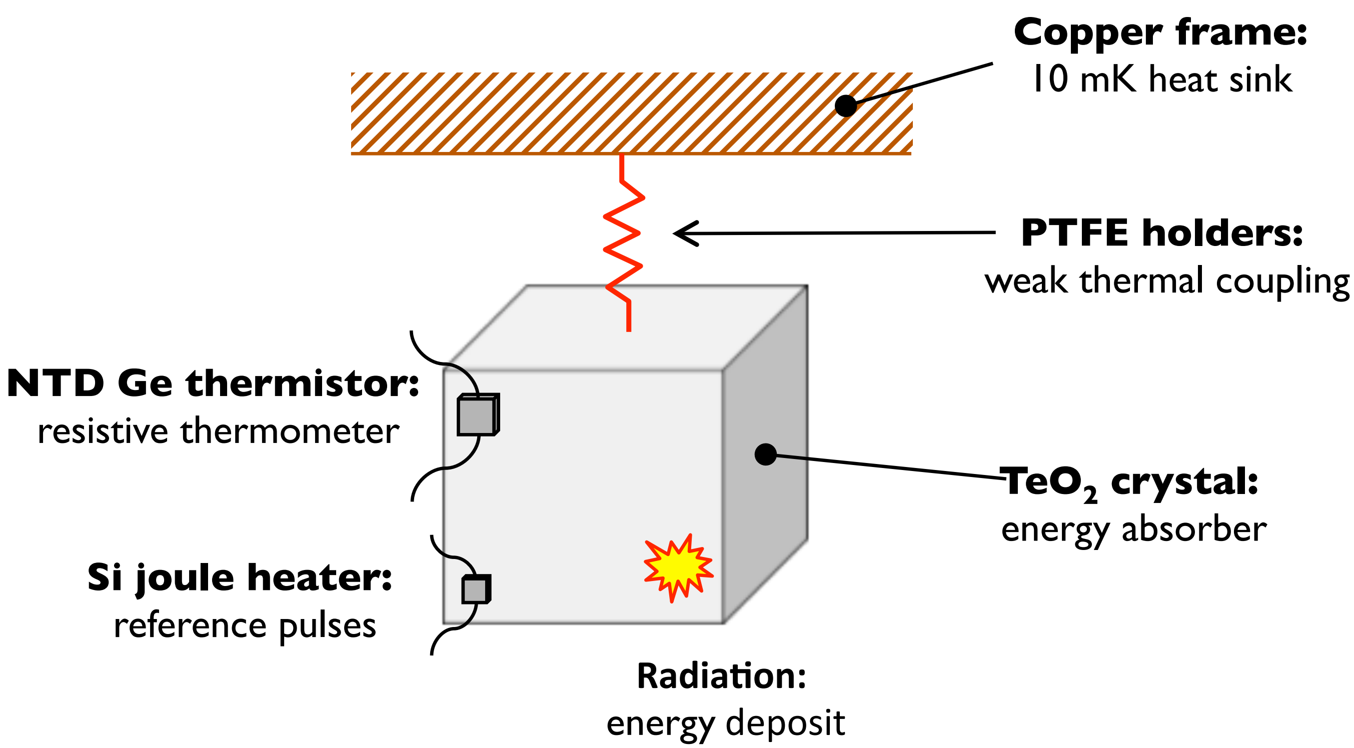
$$\sqrt{\langle \Delta E^2 \rangle} \propto k_B T \left(\frac{T}{\Theta_D} \right)^{3/2}$$

Theoretically, this could be as low as 10 eV.



Dark matter, coherent neutrino scattering, and light detectors for DBD are driving R&D here.

How Bolometers work:



For CUORE-style bolometers, the current goal is 5 keV at 2.5 MeV.

More Bolometer Talks:

Luca Pattavina - New Results on Double Beta Decay with CUPID-0

Yong-Hamb Kim - The AMoRE project

T. O'Donnell (WJB.00001) : Status of the CUORE and prospects for CUPID

A. Drobishev (DM.00007): Ultralow-Radon Environment for the Installation of the CUORE 0νββ Decay Detector

V. Singh (DM.00008): Development of cryogenic optical-photon detectors with Ir/Pt-based transition edge sensors for CUPID

R. Huang (DM.00009): Measurements of Light Emissions in TeO2 Crystals

D. Speller (EN.00007): Neutrinoless double-beta decay and other rare event searches with CUORE

B. Welliver (EN.00008): Application of Cryogenic TES based Light Detectors for CUPID

B. Schmidt (EN.00009): Li2MoO4 for $0\nu\beta\beta$ decay search in CUPID - The Physics case and current status

G. Benato (FN.00009): Background projections for CUPID

A. Leder (MN.00004): Measurement of Quenched Axial Vector Coupling Constant in In-115 Beta Decay and its Impact on Future $0\nu\beta\beta$ Searches

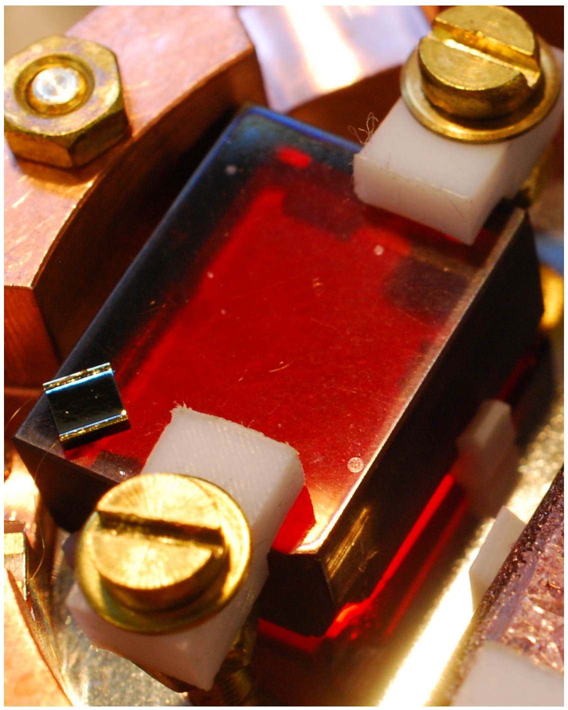
R&D Crystals: $LiInSe_2$

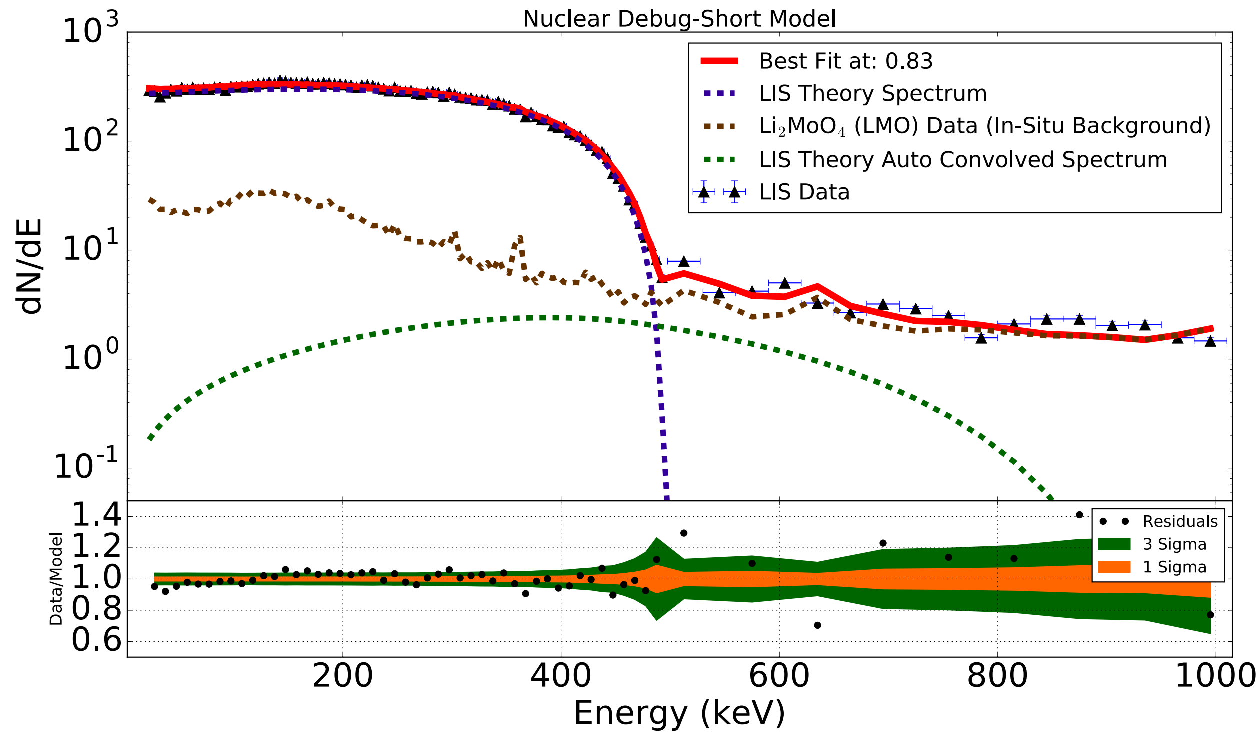
PHYSICAL REVIEW C **93**, 034308 (2016)

Forbidden nonunique β decays and effective values of weak coupling constants

M. Haaranen,[1] P. C. Srivastava,[2] and J. Suhonen[1]
[1]*University of Jyväskylä, Department of Physics, P.O. Box 35 (YFL), FI-40014, University of Jyväskylä, Finland*
[2]*Department of Physics, Indian Institute of Technology, Roorkee 247667, India*
(Received 28 October 2015; revised manuscript received 22 January 2016; published 8 March 2016)

See Talk by Dr. Alex Leder on Saturday Afternoon.





The highly forbidden ^{115}In decay prevents this crystal from being viable for CUPID, but the precision spectrum measurement can inform the nuclear matrix calculations (quenching of g_A).

Experimental Considerations:

- Energy Resolution
- Scalability
- Active Background Rejection
- Flexible Isotope Choice

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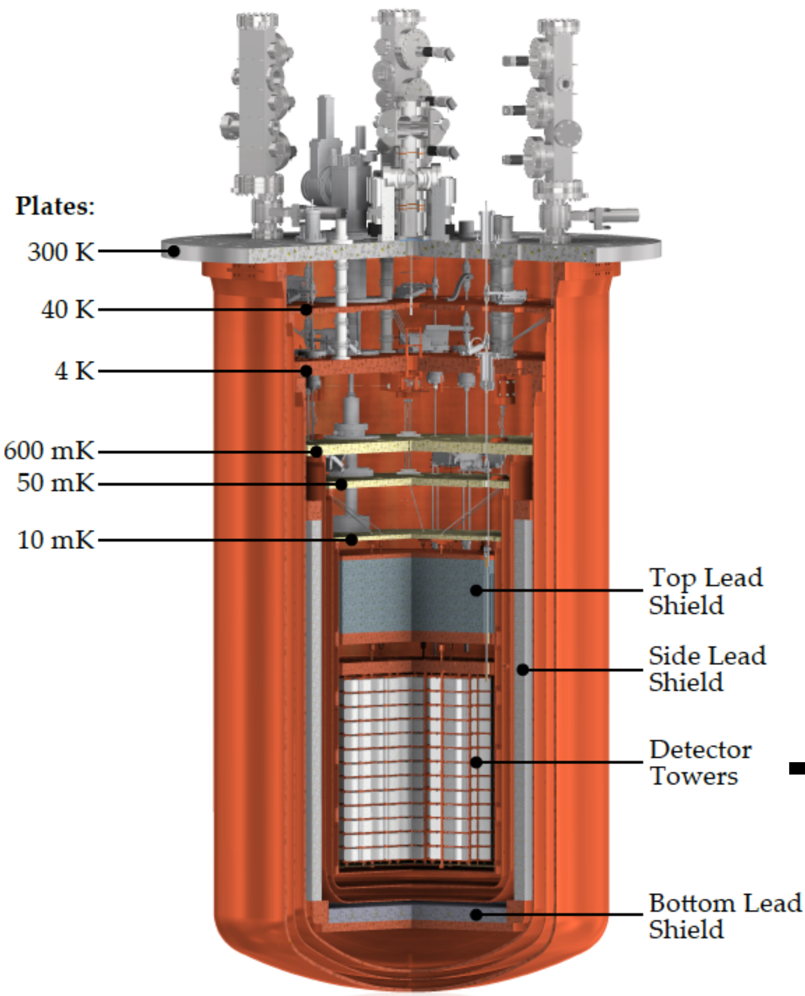
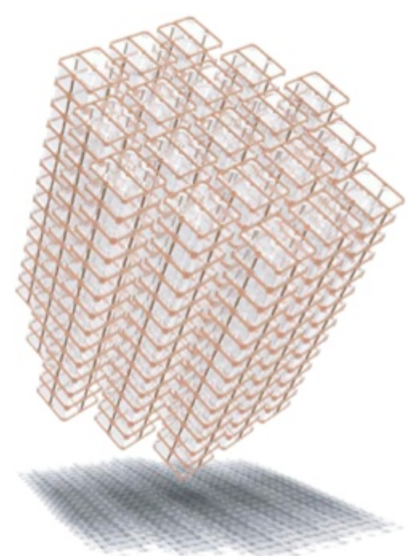
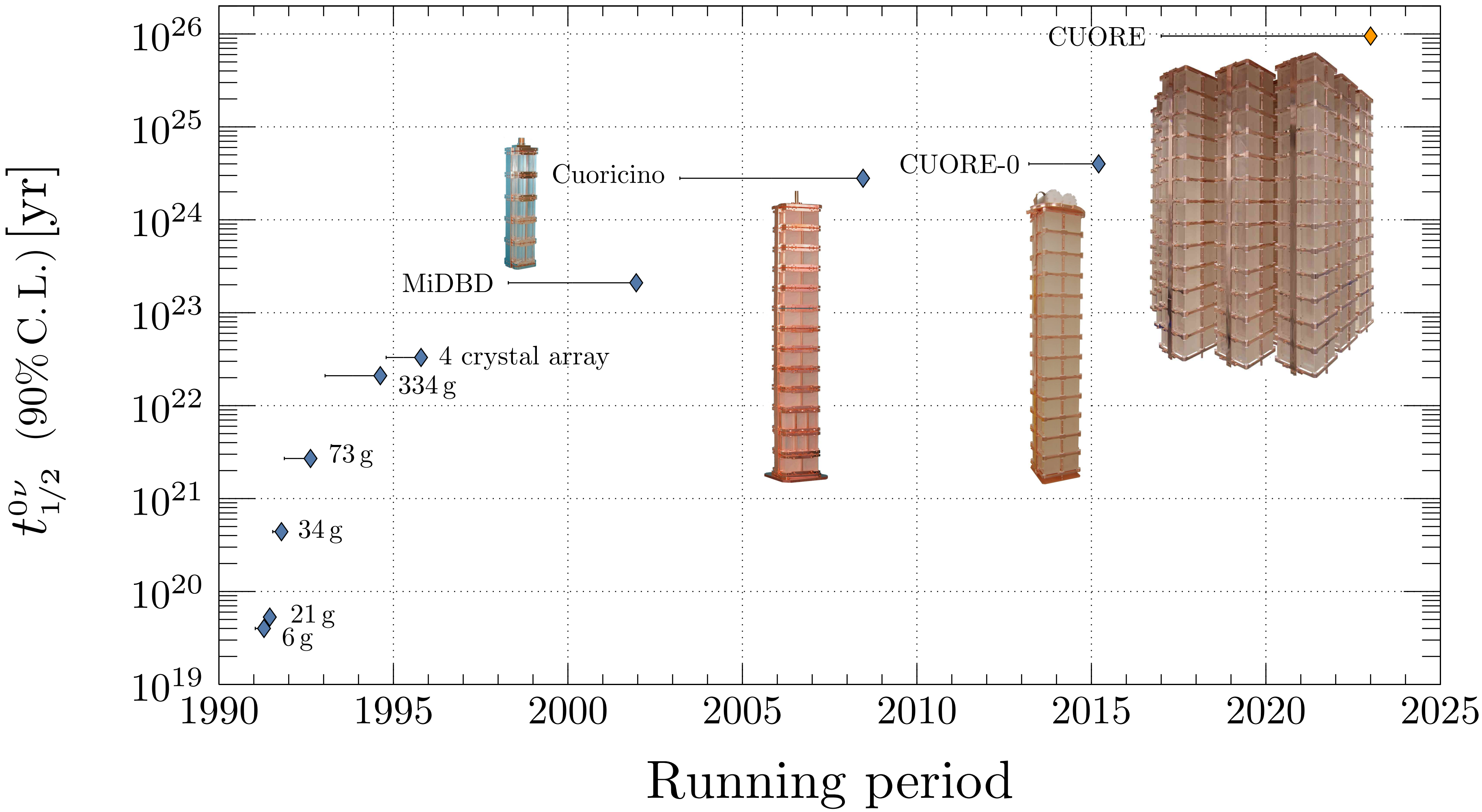


The Detector

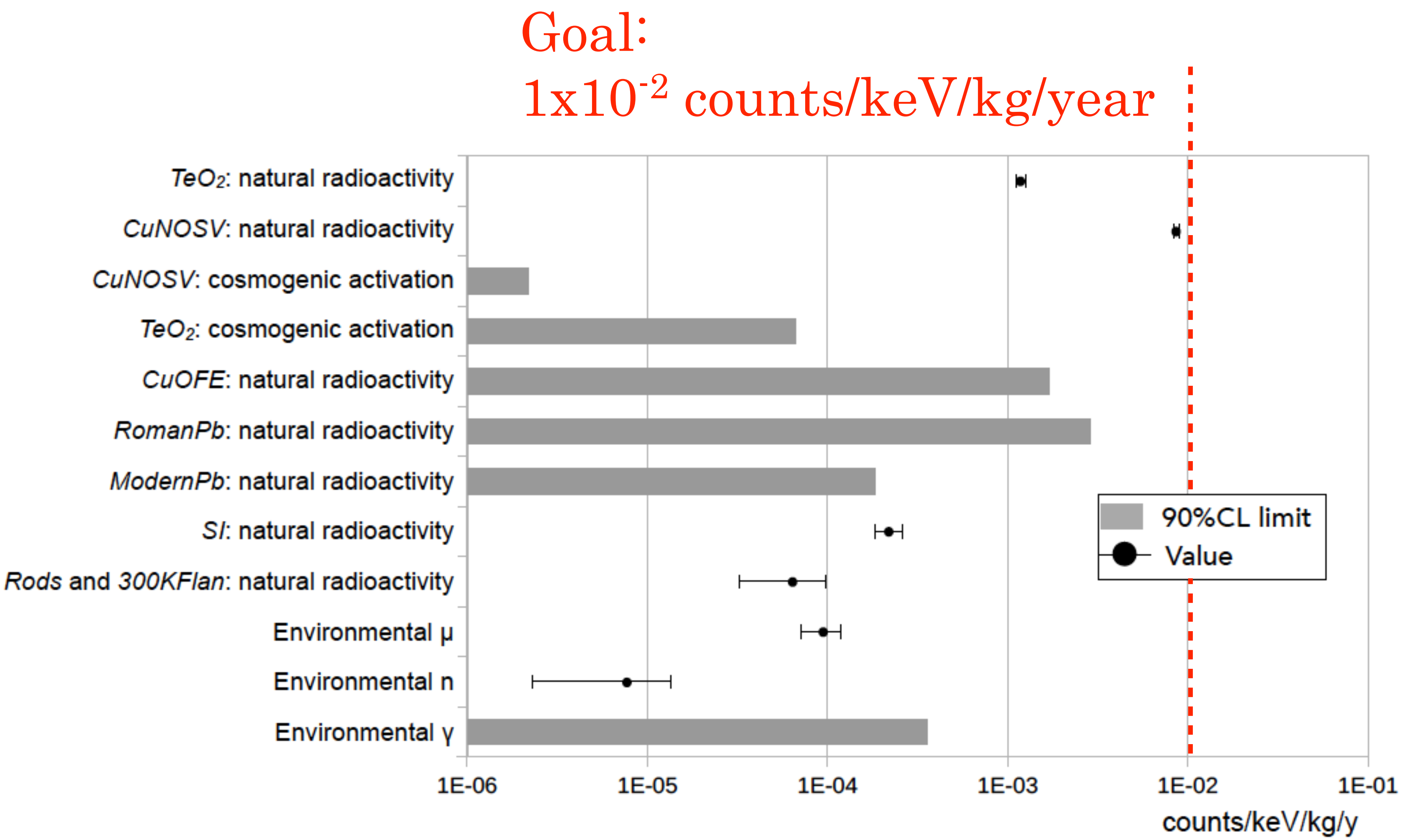
- 19 Towers, 988 TeO_2 crystals operated as bolometers.
- It is the "Coldest cubic meter in the known universe", arXiv:1410.1560



The History of Bolometric Detectors

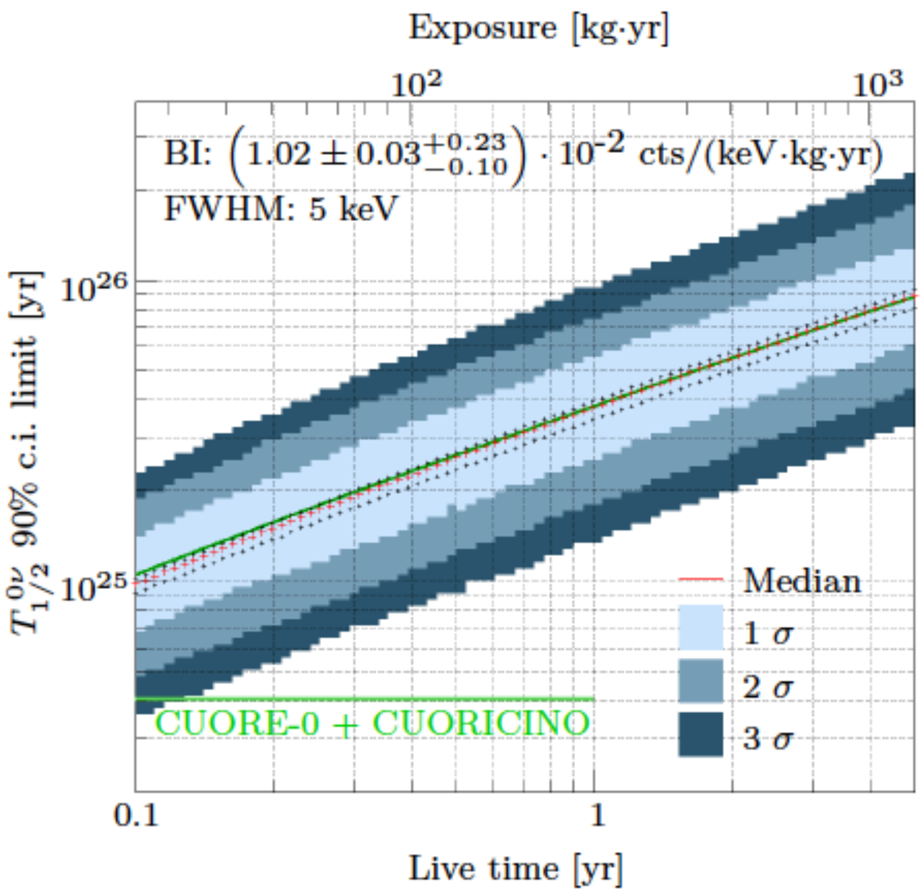


CUORE Projected Background Model



From: Eur.Phys.J. C77 (2017) no.8, 543

CUORE Projected Sensitivity



From: Eur.Phys.J. C77 (2017) no.8, 532

CUORE:
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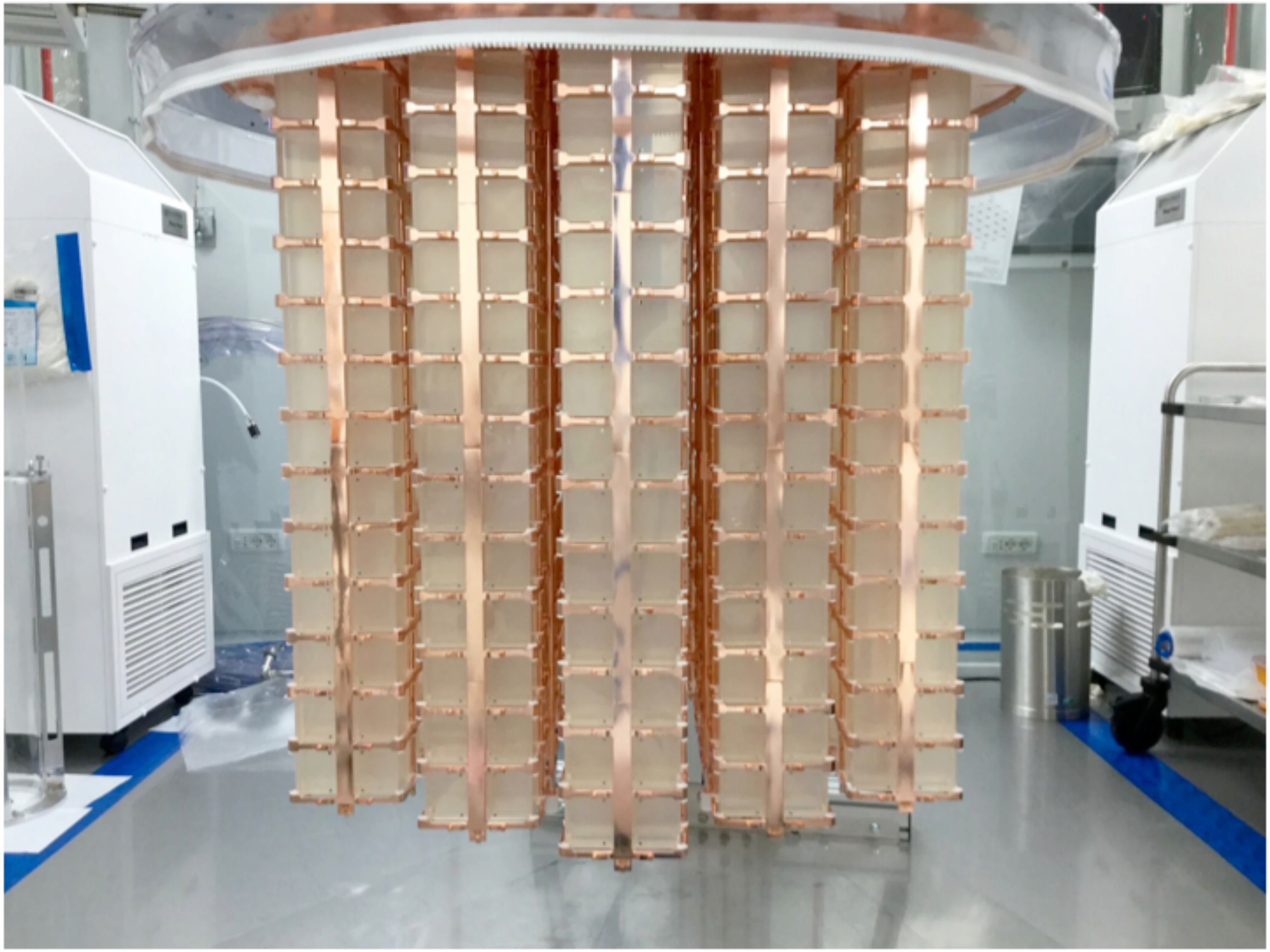
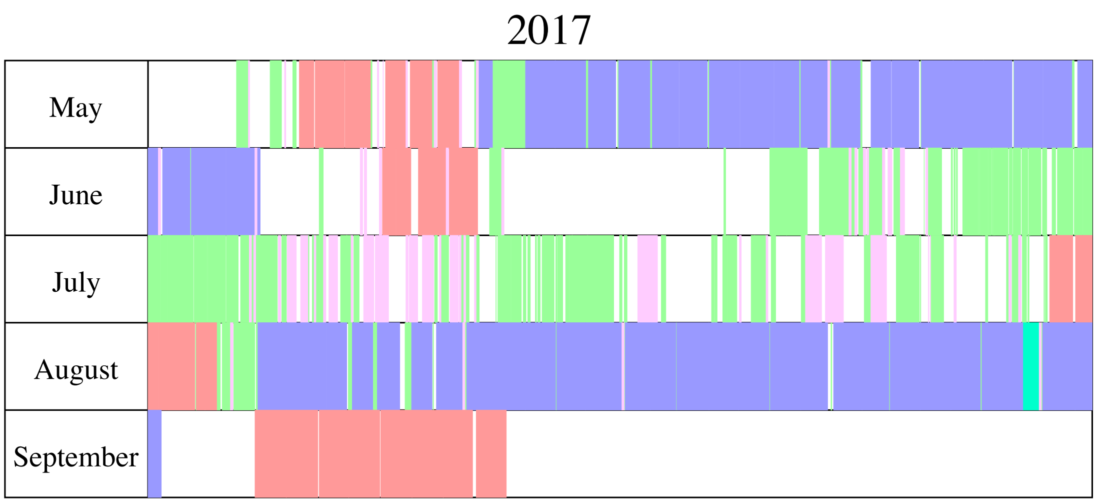


The First Data Release:



Dataset 1: May - June

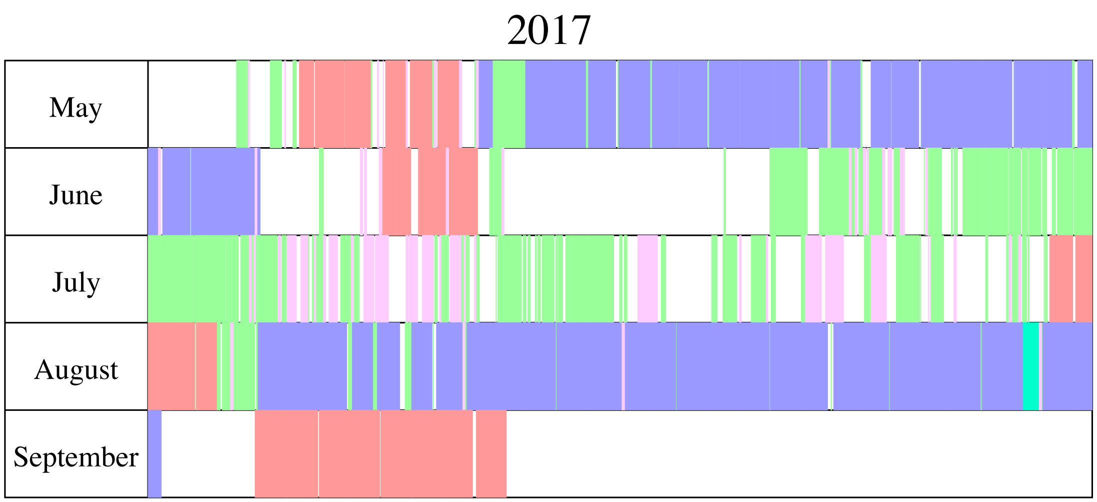
Detector Optimization Campaign

Dataset 2: August - September

Blue = Physics
Red = Calibration
Pink = Setup/Configuration
Green = Test

All physics runs bracketed by a calibration run.

The First Data Release:



Dataset 1: May - June

Detector Optimization Campaign

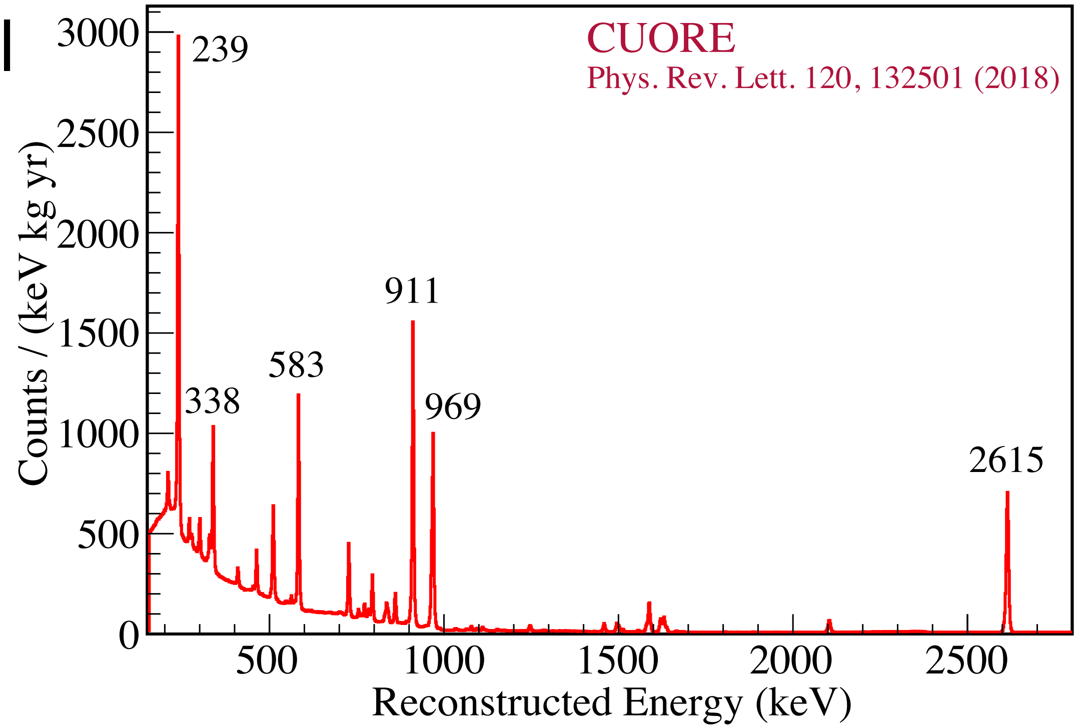
Dataset 2: August - September

Acquired statistics used for this search: (Dataset 1 + Dataset 2):

- $^{nat}TeO_2$ exposure: 86.3 kg yr (37.6 kg yr + 48.7 kg yr)
- ^{130}Te exposure: 24.0 kg yr

Calibration

- Summed energy spectrum of all the CUORE detectors-datasets
- Calibration data used for:
  - energy scale calibration
  - thermal gain stabilisation
  - detector response (line shape) study



239 keV - ^{212}Pb

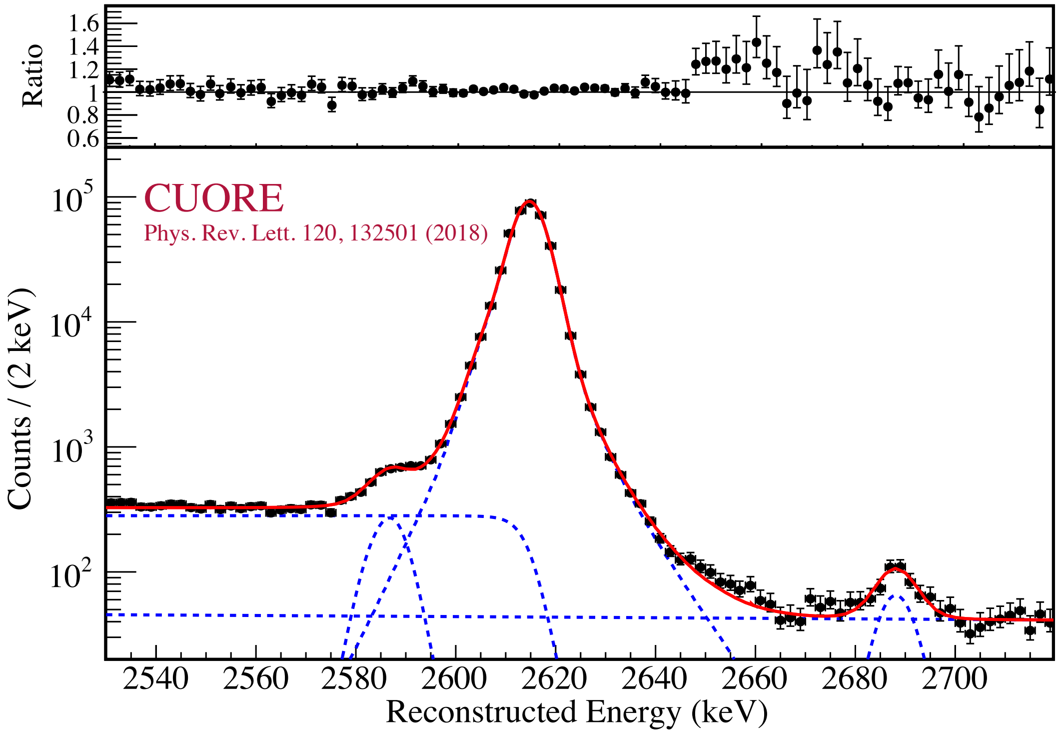
338, 911, 969 keV - ^{228}Ac

583, 2615 keV - ^{208}Tl

Detector Response: Line Shape

Fit components:

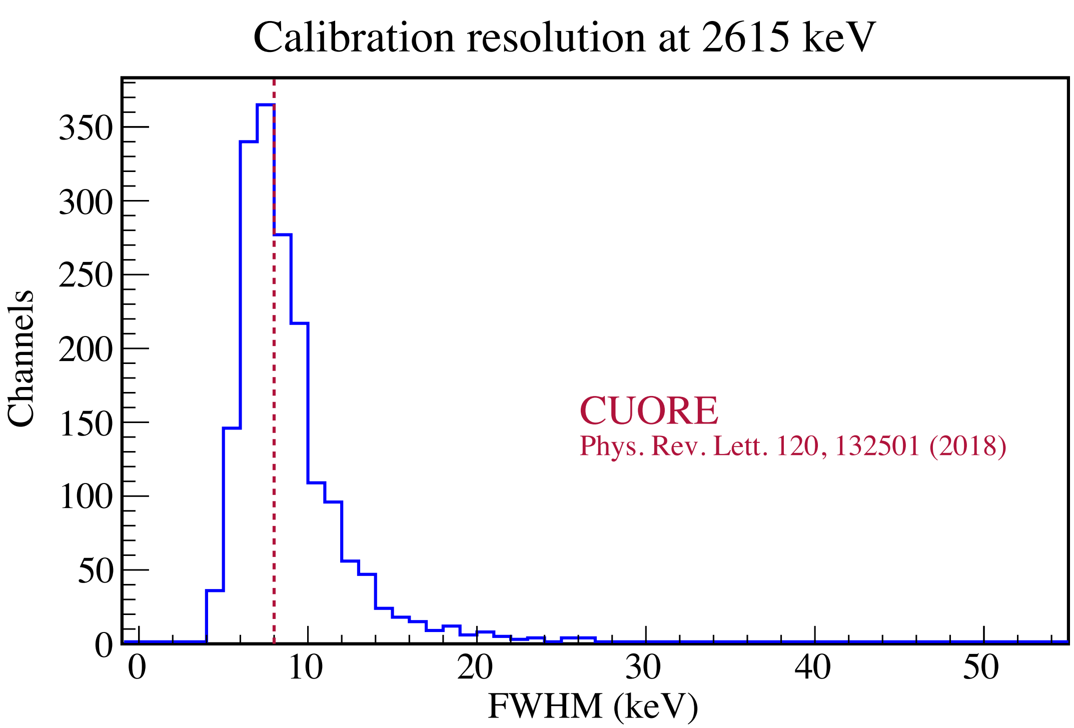
- (a) triple gaussian for the photopeak
- (b) step-wise smeared multi-compton background
- (c) combination of gaussian X-rays escape lines
- (d) linear background
- (e) single gaussian line for the coincident absorption of 2615-keV and 583-keV followed by a single escape process



The fit is done tower-by-tower.
The plot shows the sum of the result.

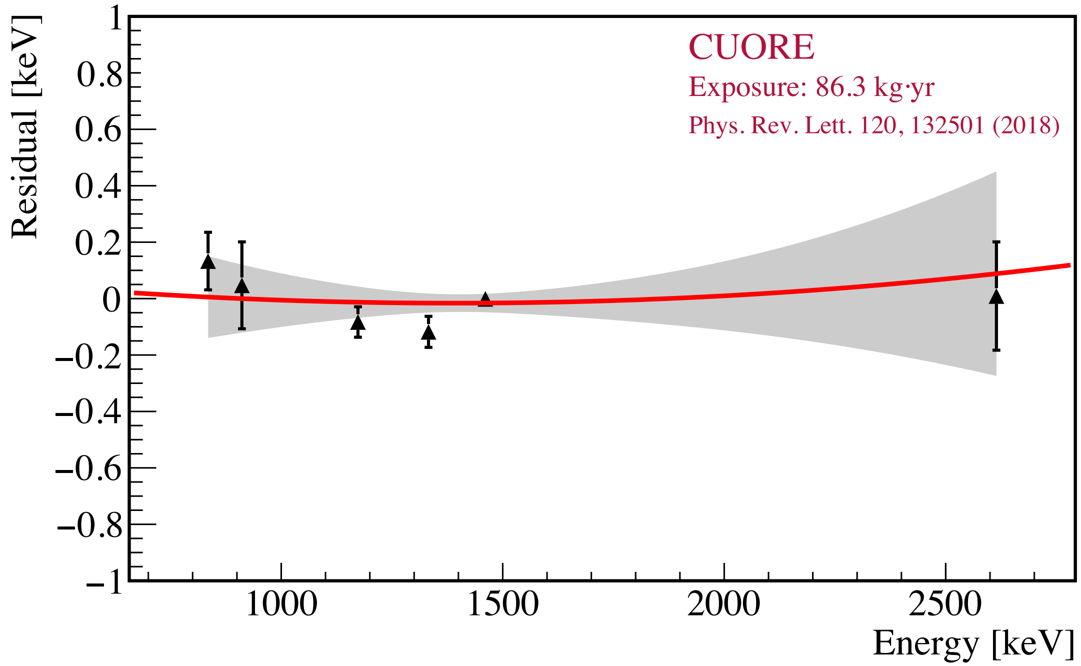
Energy Resolution

A total of 1811 (92% of live channels) channels-dataset couples were used in this analysis; discarded channels had poor line or pulse shapes, or the energy couldn't be reconstructed accurately.



@ 2615 keV
exposure-weighted
harmonic mean
8.0 keV FWHM

Energy Scale



The gamma lines in the background spectrum have been fitted with the complete detector response function (line shape) to estimate the energy scale bias.

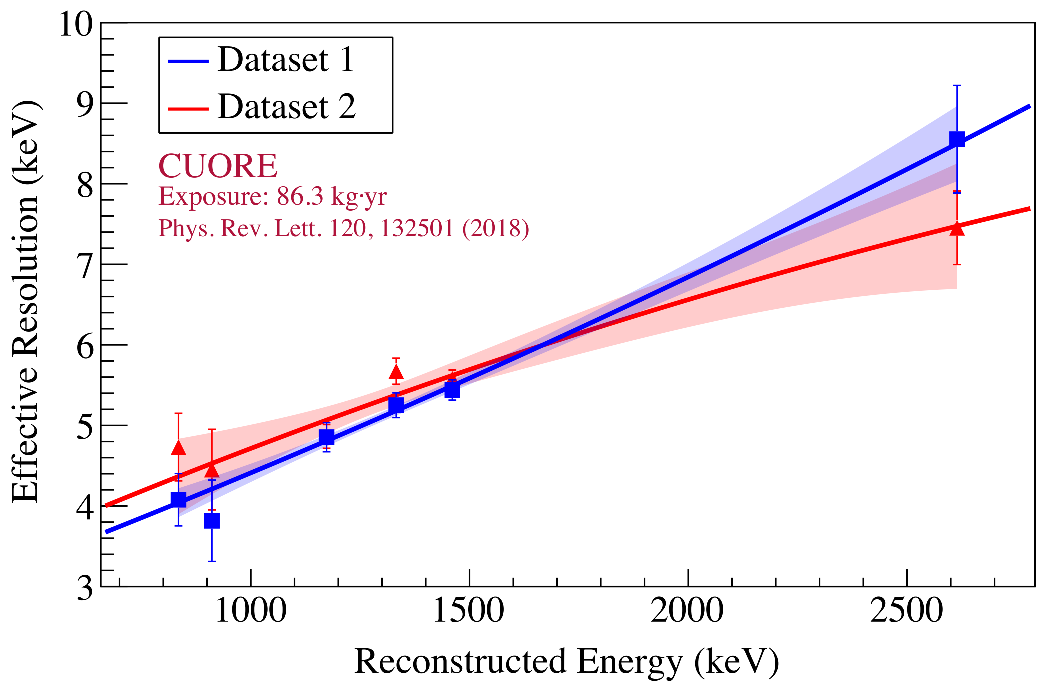
→ **(0 ± 0.5) keV**

Energy Resolution II

It is also used to scale the energy resolution down to the region of interest.

Dataset 1 (8.3 ± 0.4) keV

Dataset 2 (7.4 ± 0.7) keV



Analysis Procedure

- Acquisition of continuous waveforms
- Triggering
- Data preprocessing: estimation of raw parameters
- Pulse filtering with Optimum Filter
- Thermal Gain Stabilization (TGS): calibration and heater-based
- Energy calibration and best energy estimator selection
- Particle event selection - Pulse Shape Analysis
- Coincidence analysis w/ detector response synchronization and software threshold @ 150 keV (to prevent any spectral shape distortion due to threshold effects in the ROI)
- Energy spectrum

→ Very similar to what was developed and used for CUORE-0 (Phys. Rev. C 93, 045503 (2016))

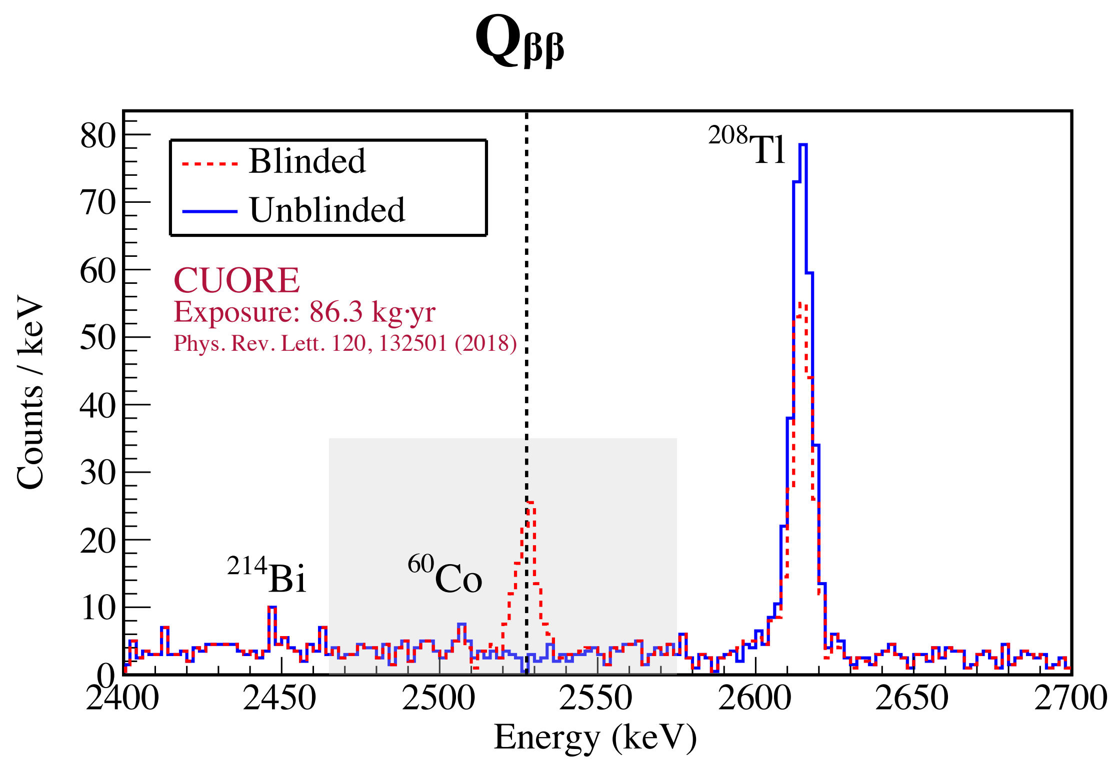
Efficiency

	Dataset 1	Dataset 2
Trigger	(99.766 ± 0.003) %	(99.735 ± 0.004) %
Energy reconstruction	(99.168 ± 0.006) %	(99.218 ± 0.006) %
Base cuts (pile-up, global data quality)	(95.63 ± 0.01) %	(96.69 ± 0.01) %
Anti-coincidence	(99.4 ± 0.5) %	(100.0 ± 0.4) %
Pulse shape analysis	(91.1 ± 3.6) %	(98.2 ± 3.0) %
All cuts except containment	(85.7 ± 3.4) %	(94.0 ± 2.9) %
$0\nu\beta\beta$ containment	(88.35 ± 0.09) %	
Total	(75.7 ± 3.0) %	(83.0 ± 2.6) %

Event selection occurs after periods of low-quality data (~1% of the total live time) are removed.

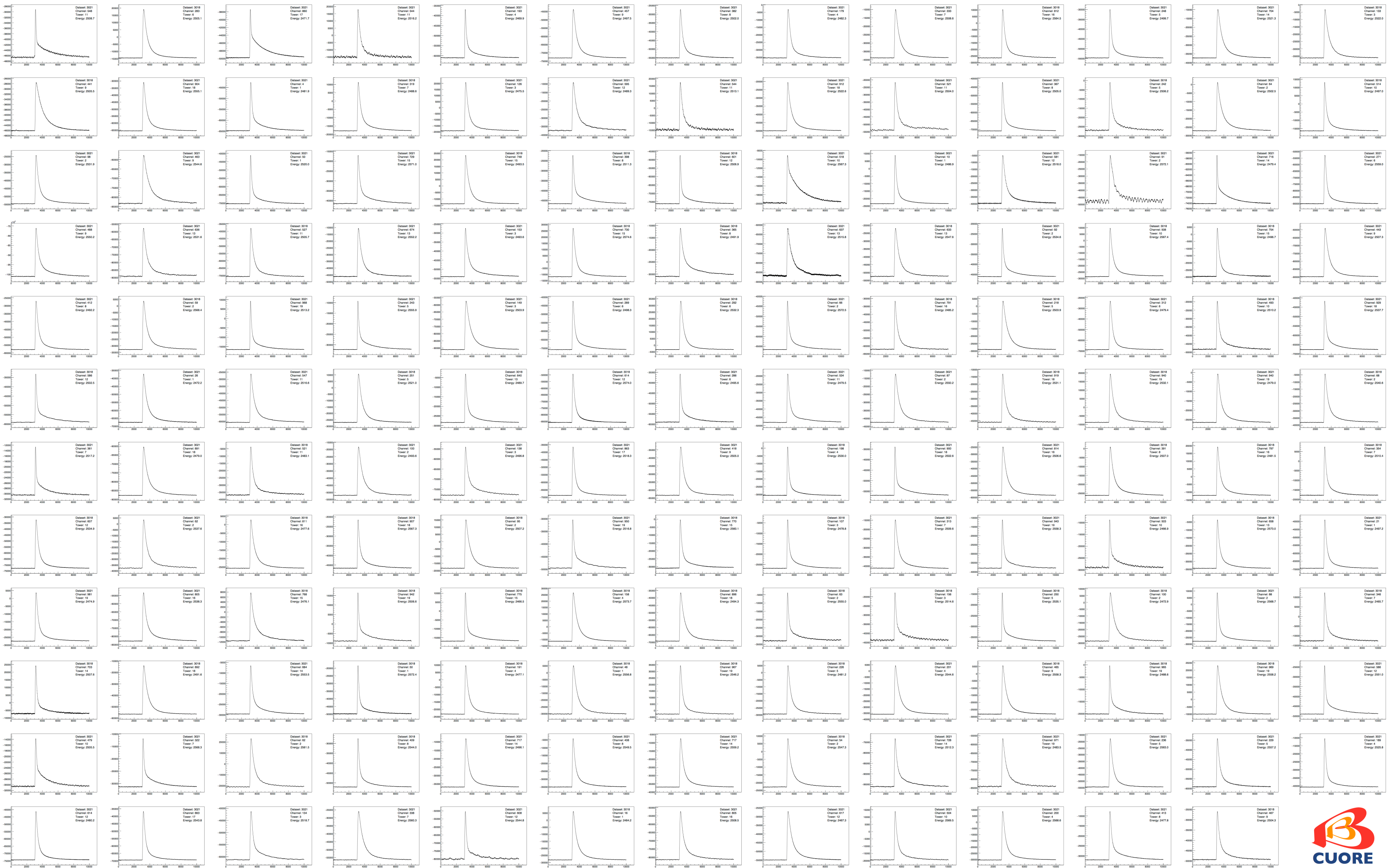
Blinding

- To blind our data we randomly move a fraction of events from +/- 20 keV of 2615 keV to the Q-value and vice versa
- The blinding algorithm produces an artificial peak around the NDBD Q-value hiding the real NDBD rate of ^{130}Te



This method of blinding the data preserves the integrity of the possible signal while maintaining the spectral characteristics with measured energy resolution and introducing no discontinuities in the spectrum.

155 Events in the ROI



Fit in the ROI

Simultaneous UEML (Unbinned Extended Maximum Likelihood) fit

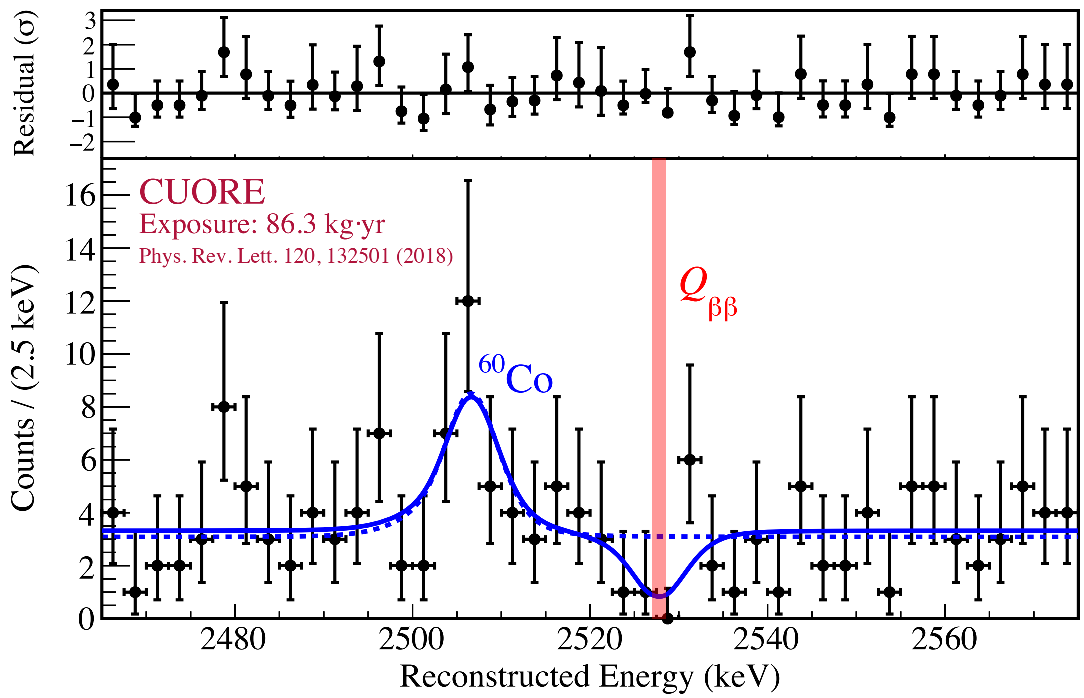
Energy region 2465-2575 keV

- **The fit has 3 components:**
  1. Posited peak at the **Q-value of ^{130}Te**:
     - energy scale defined relative to the ^{208}Tl line in calibration data to account for residual mis-calibration between channels
     - signal normalization common to all detectors-datasets (1 free parameter)
  2. Floating peak to account for the **^{60}Co sum gamma line** (2505 keV):
     - energy scale defined relative to the ^{208}Tl line in calibration data to account for residual mis-calibration between channels
     - rate common to all detectors-dataset, with a correction accounting for the time elapsed between the two datasets (1 free parameter)
  3. **Flat background**, attributed to multi scatter Compton events from ^{208}Tl and surface alpha events:
     - common to all detectors in a single dataset, two independent parameters for the two datasets to account for differences in the background rejection efficiency (2 free parameters)
- **The peaks in each channel-dataset are fitted with its own line shape** (fixed from calibration data)

Systematic Uncertainties

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

The Result

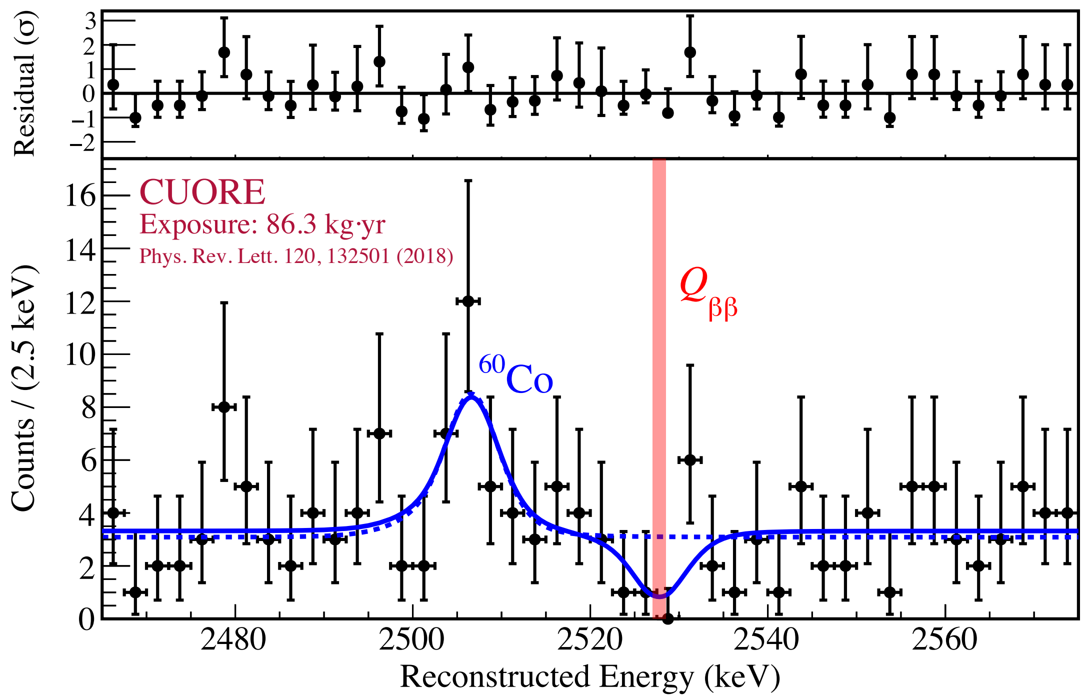


ROI background index: $(1.49_{-0.17}^{+0.18}) \times 10^{-2}$ c/(keV·kg·yr)

$(1.35_{-0.18}^{+0.20}) \times 10^{-2}$ c/(keV·kg·yr)

Best fit for ^{60}Co mean: (2506.4 ± 1.2) keV

The Result



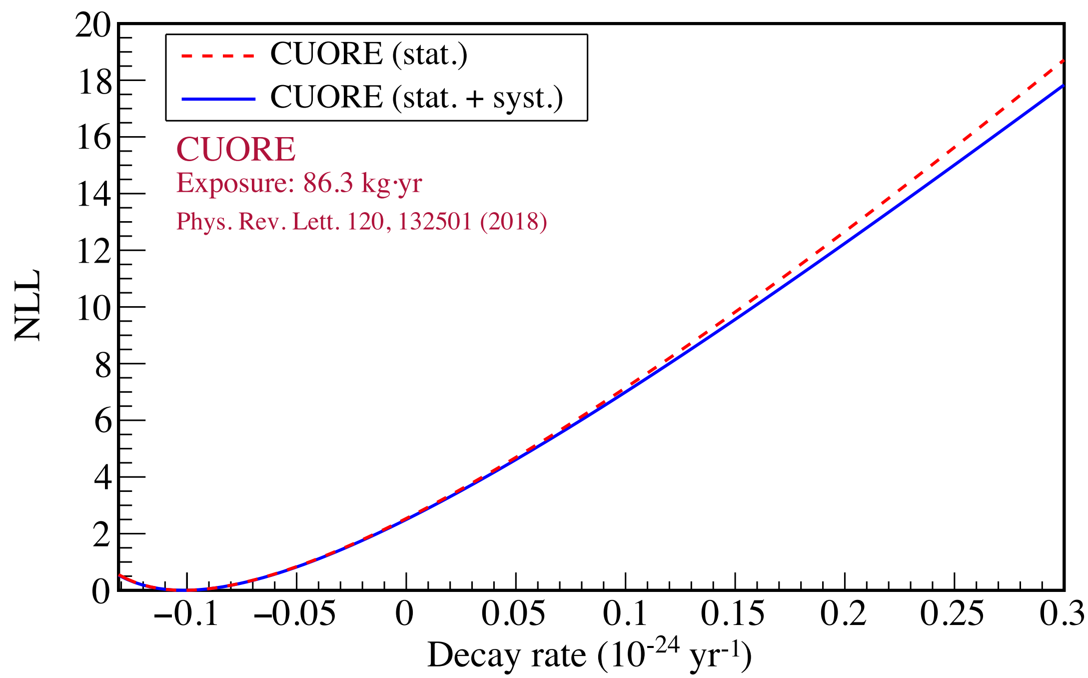
Best fit decay rate: $(-1.0_{-0.3}^{+0.4}$ (stat.) $\pm$ 0.1 (syst.)$)\times10^{-25}$ / yr

The Result

No evidence of signal

Profile likelihood integrated on the physical region

($\Gamma^{0\nu} > 0$)



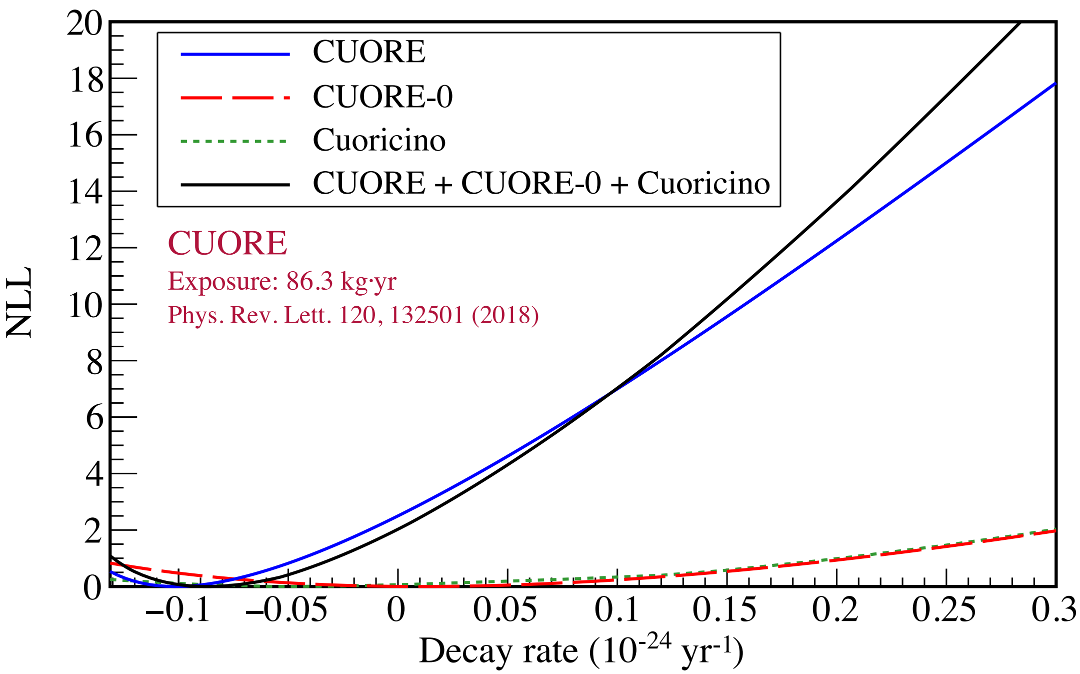
Decay rate limit (90% CL, including systematics): 0.51×10^{-25} / yr

Half-life limit (90% CL, including systematics): 1.3×10^{25} yr

Median expected sensitivity: 7.0×10^{24} yr

Combination with Previous Results

We combined the CUORE result with the existing ^{130}Te:
19.75 kg·yr of Cuoricino and 9.8 kg·yr of CUORE-0

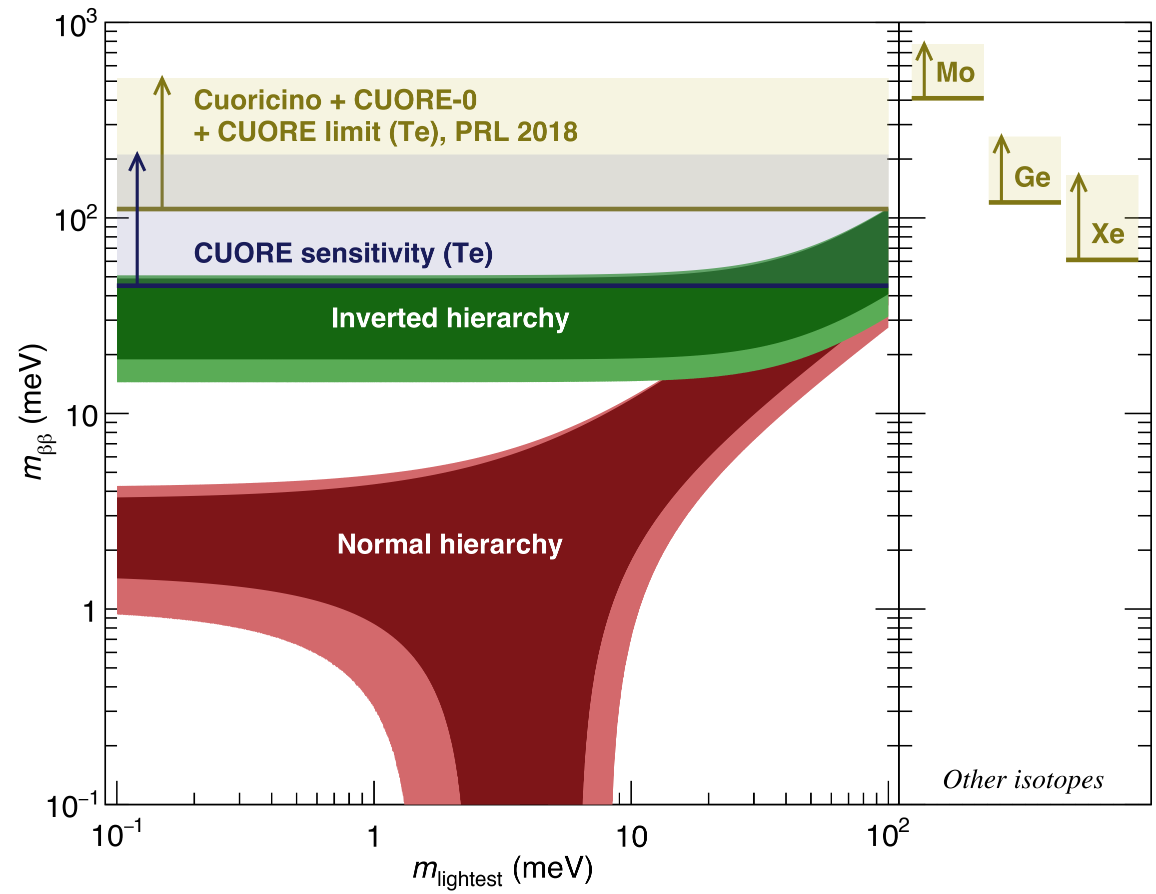


The combined 90% C.L. limit is $T_{0\nu} > 1.5 \times 10^{25}$ yr

In terms of the Majorana Mass:

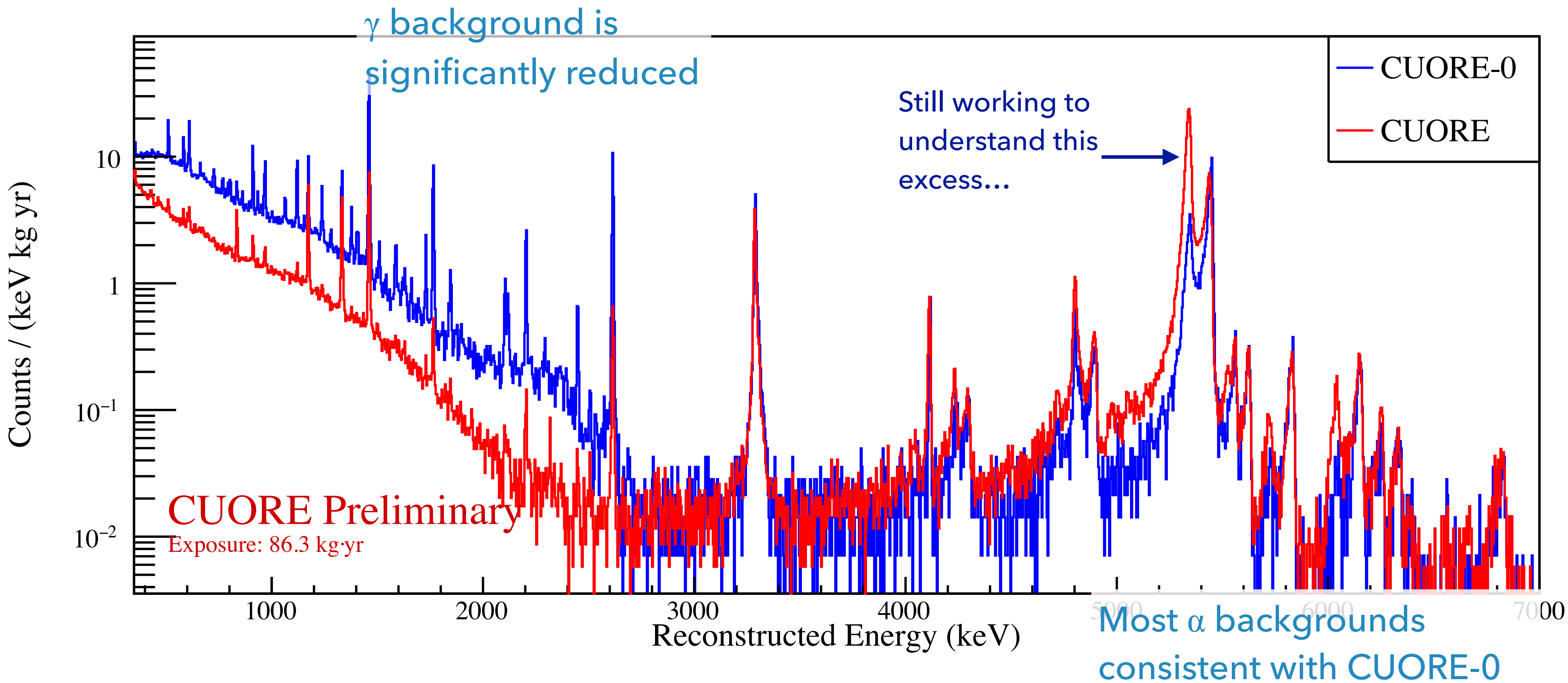
NME:
JHEP02 (2013) 025
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 87, 064302 (2014)
Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 91, 024613 (2015)
Phys. Rev. C 91, 024309 (2015)
Phys. Rev. C 91, 024316 (2015)
Phys. Rev. Lett. 105, 252503 (2010)
Phys. Rev. Lett. 111, 142501 (2013)

Experiment:
130Te: 1.5 × 1025 yr from this analysis PRL 120, 132501 (2018)
76Ge: 8.0 × 1025 yr from PRL 120, 132503 (2018)
136Xe: 1.1 × 1026 yr from Phys. Rev. Lett. 117, 082503 (2016)
100Mo: 1.1 × 1024 yr from Phys. Rev. D 89, 111101 (2014)
82Se: 2.4 × 1024 yr from Phys. Rev. Lett 120, 232502 (2018)
CUORE sensitivity: 9.0 × 1025 yr



The limit corresponds to $m_{\beta\beta} <$ 140–400 meV

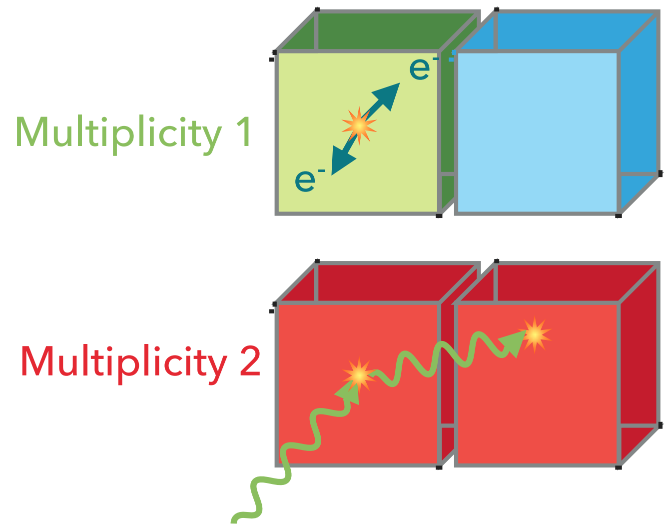
Understanding the Background

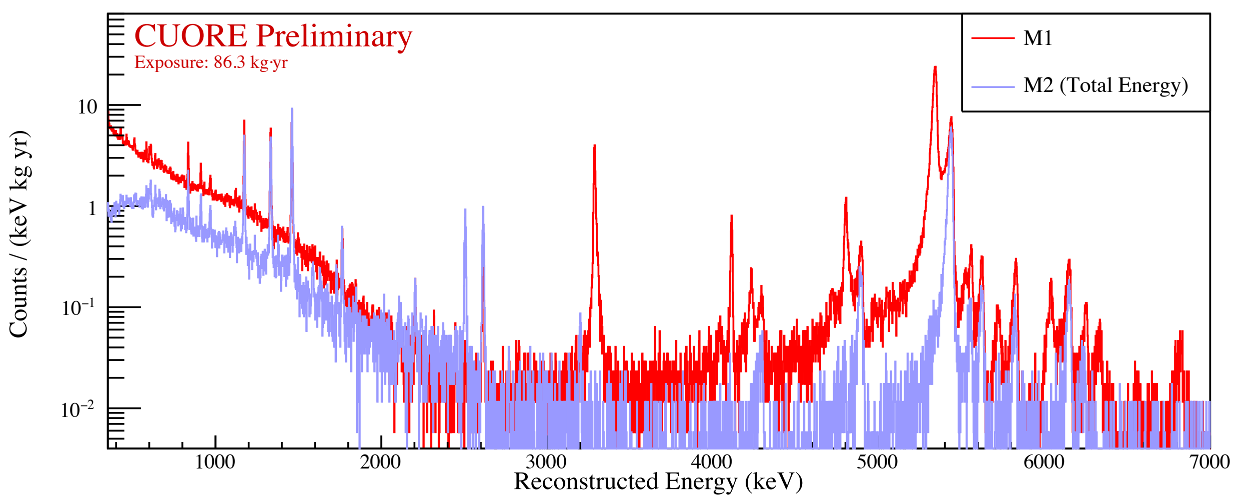


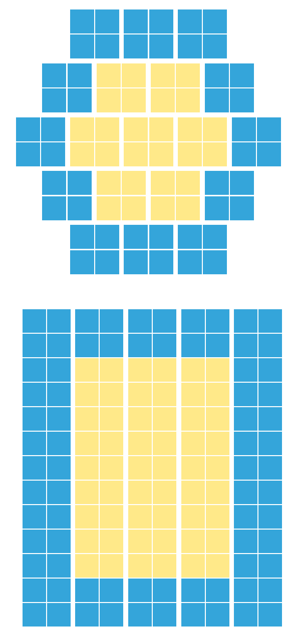
- Backgrounds generally consistent with expectations
- ^{210}Po excess appears to be from shallow contamination in copper around the detectors
    - Current estimated contribution to ROI at the level of 10^{-4} cnts/(keV kg yr)

Building the Model

- 86.3 kg·yr of TeO_2 from summer 2017
- Split data into inner and outer layers
- Split data into Multiplicity 1 (M1), Multiplicity 2 (M2), and Multiplicity 2 Sum (Σ2) spectra
  - Higher multiplicity spectra sensitive to backgrounds

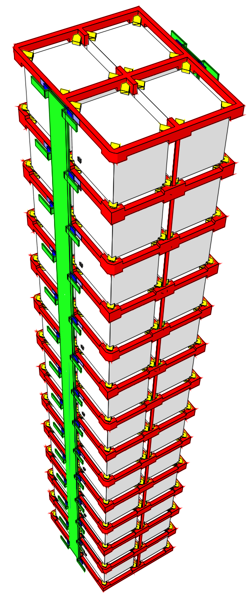


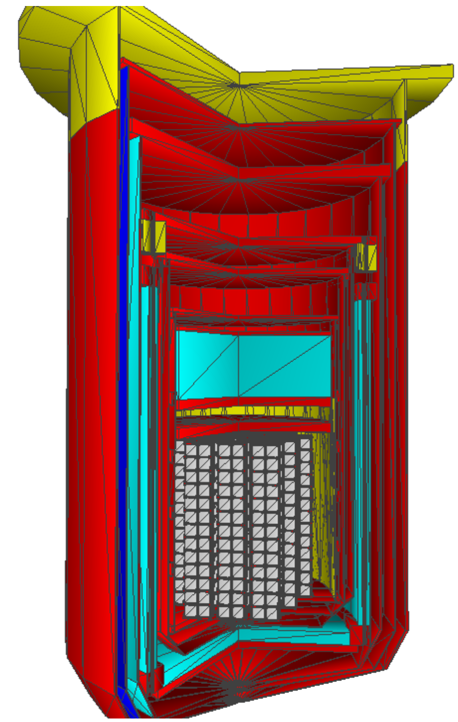




Details of the Model

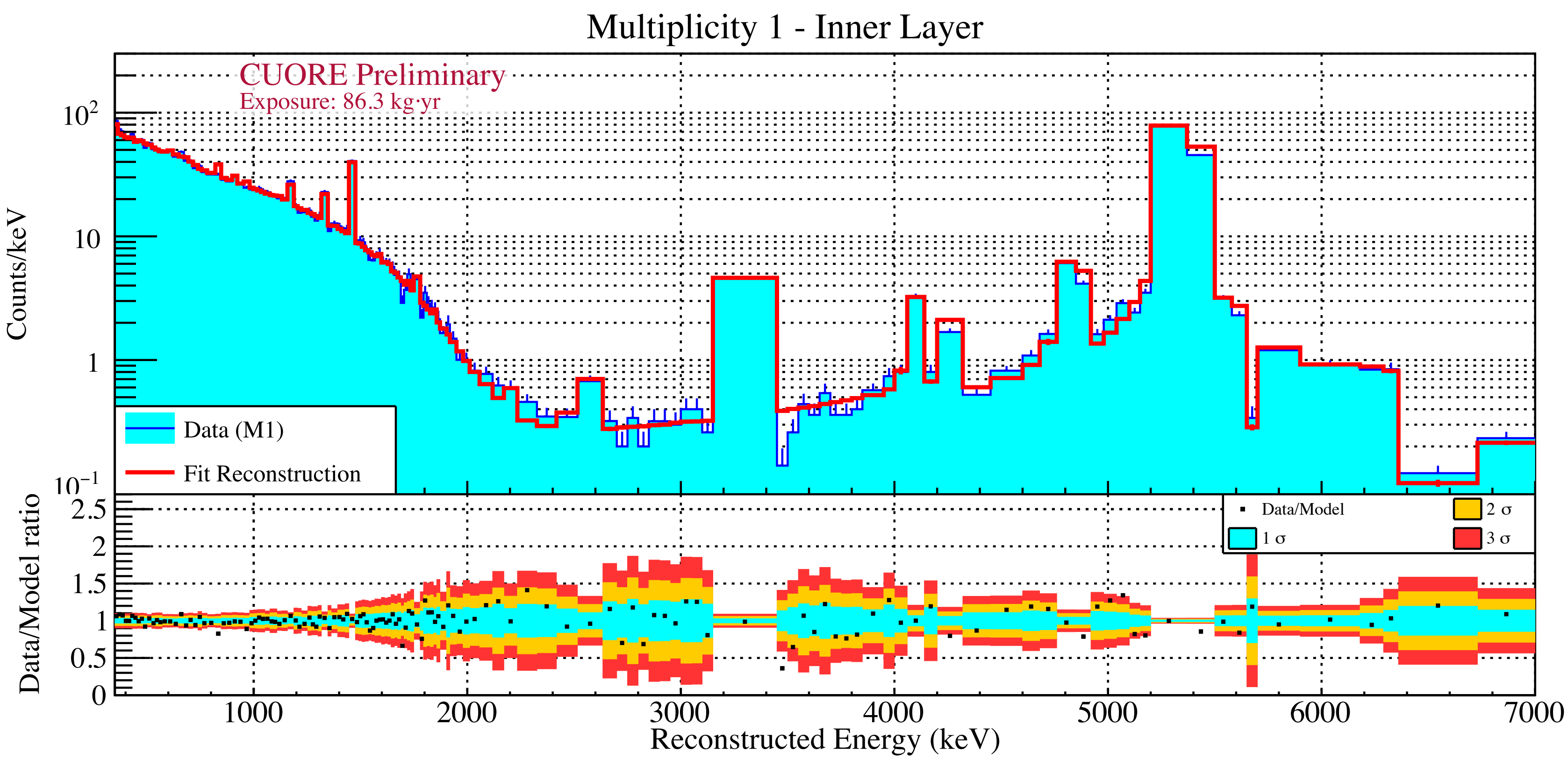
- Simulate the contaminations coming from different cryostat components using a detailed Geant4 MC simulation
- About 60 independent parameters representing various contaminations that could contribute to the CUORE background model
- Perform a large Bayesian fit to the data using a MCMC Gibbs sampler
- Flat priors on all parameters except muons which come from a cosmogenic analysis





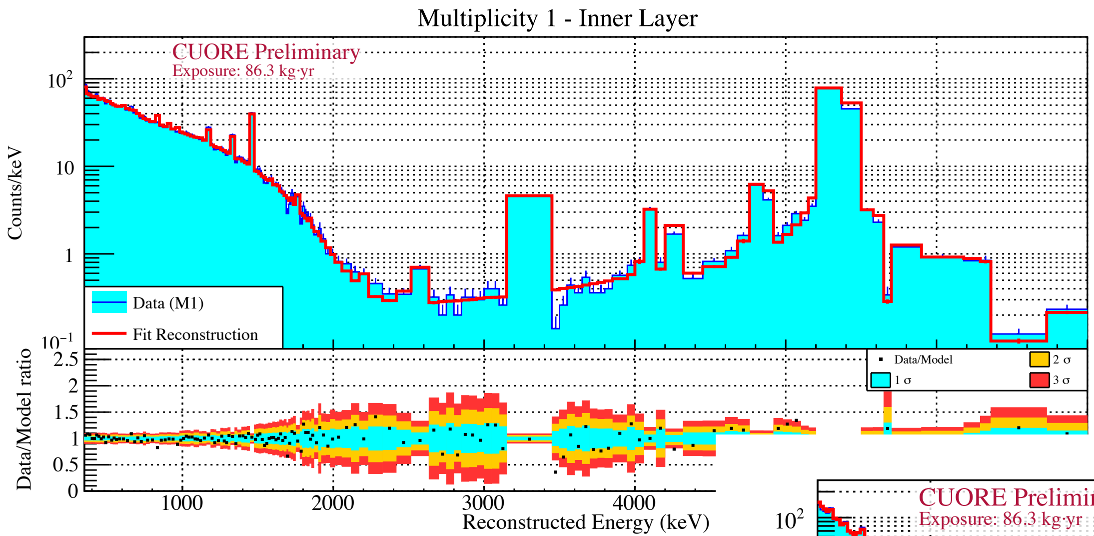
Volume	Type	Components
TeO_2	Bulk	$2\nu\beta\beta$, ^{210}Pb, ^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{230}Th ^{226}Ra-^{210}Pb, ^{40}K, ^{60}Co, ^{125}Sb, ^{190}Pt
TeO_2	Surface (0.01 μm)	^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{226}Ra-^{210}Pb, ^{210}Pb
TeO_2	Surface (1 μm)	^{210}Pb
TeO_2	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Bulk	^{232}Th, ^{238}U, ^{40}K, ^{60}Co, ^{54}Mn
CuNOSV	Surface (0.01 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (1 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
Roman lead	Bulk	^{232}Th, ^{238}U, ^{108m}Ag
Top lead	Bulk	^{232}Th, ^{238}U, ^{210}Bi
Ext. lead	Bulk	^{210}Bi
CuOFE	Bulk	^{232}Th, ^{238}U, ^{60}Co
External	-	Cosmic muons

Fitting the Background

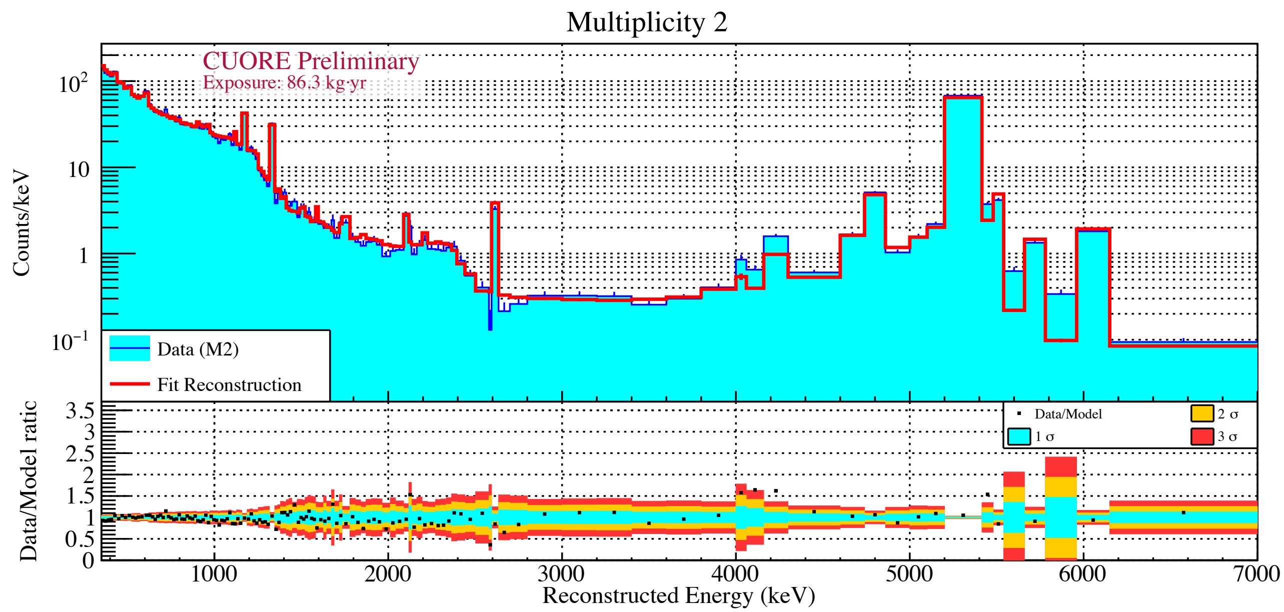


➡Able to reconstruct the major features of the observed spectrum in CUORE

Fitting the Background

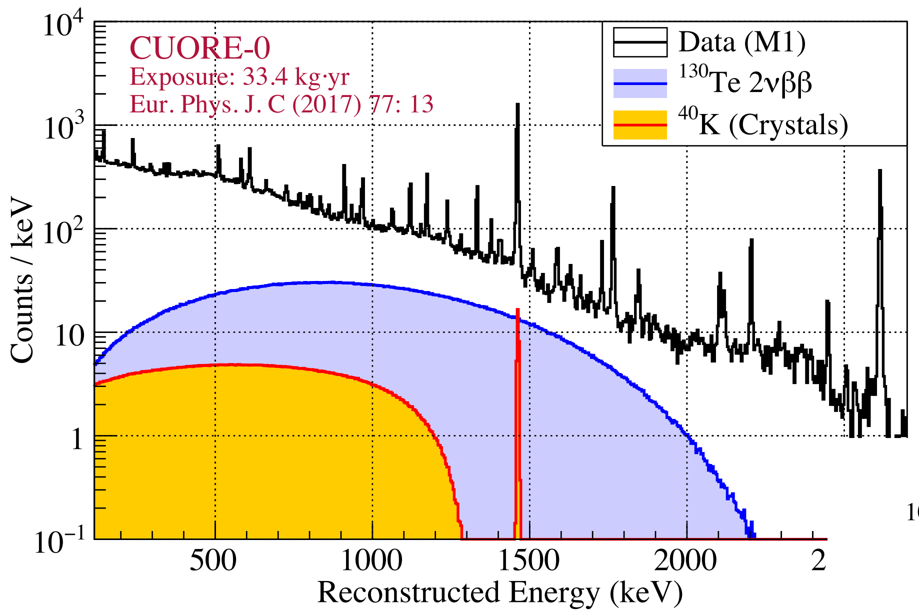


Multiplicity 1 spectra very sensitive to signal events



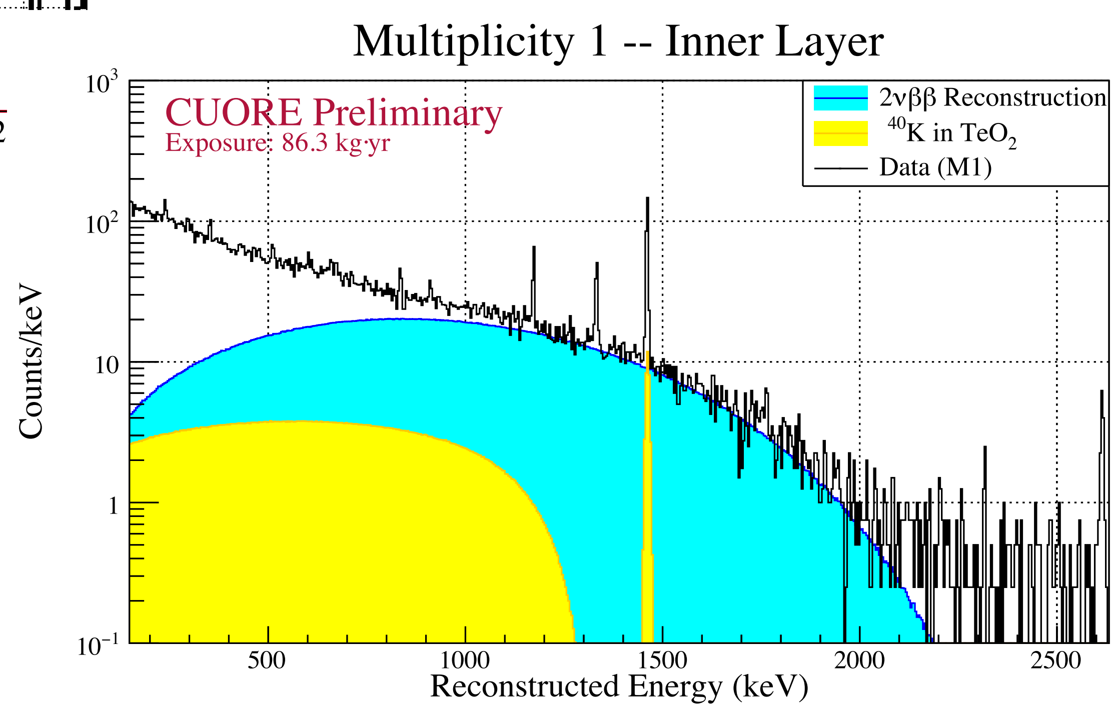
Many contaminations constrained by the higher multiplicity spectra

Measuring the $2\nu\beta\beta$ Half-life



In CUORE-0, $2\nu\beta\beta$ decay spectrum accounts for ~20% of the signal in the range 1 - 2 MeV

In CUORE, $2\nu\beta\beta$ decay spectrum accounts for nearly all of the signal in the range 1 - 2 MeV



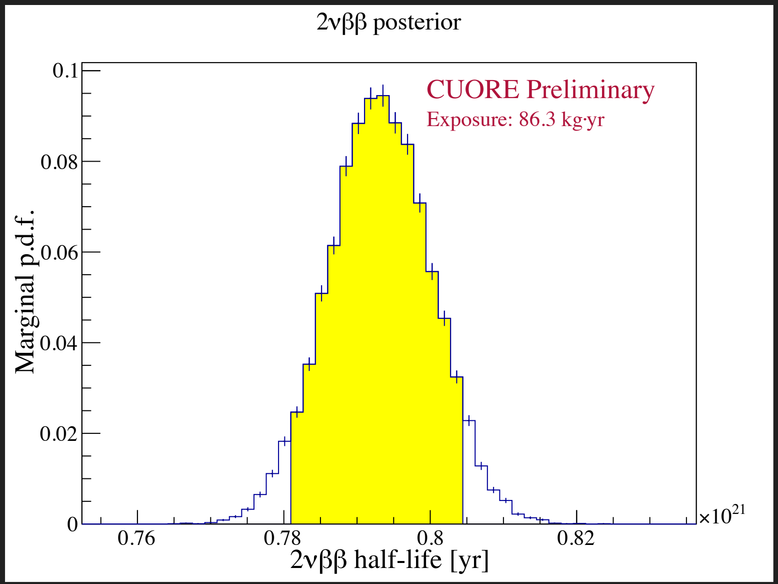
Measuring the 2νββ Half-Life

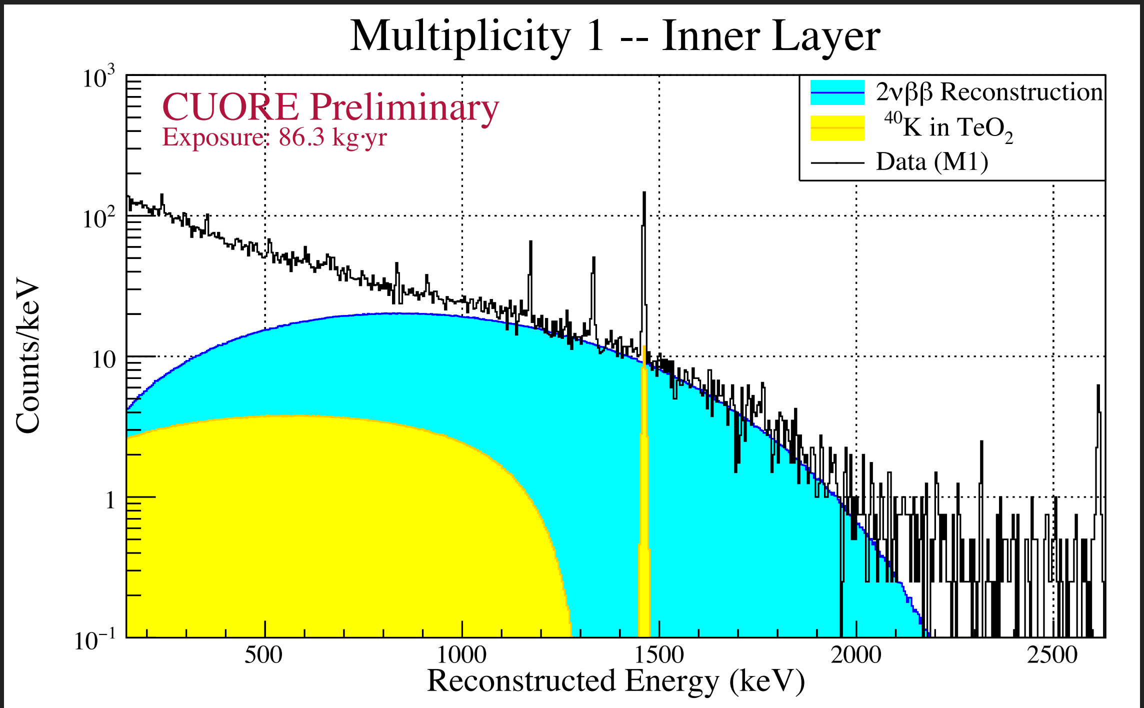
$$\Gamma^{2\nu}_{1/2} = [8.7 \pm 0.1\,(\text{stat.}) \pm 0.2\,(\text{syst.})] \times 10^{-22}\ \text{yr}^{-1}$$
$$T^{2\nu}_{1/2} = [7.9 \pm 0.1\,(\text{stat.}) \pm 0.2\,(\text{syst.})] \times 10^{20}\ \text{yr}$$

(Preliminary)

(For Reference)

$$\text{CUORE-0}: T^{2\nu}_{1/2} = [8.2 \pm 0.2\,(\text{stat.}) \pm 0.6\,(\text{syst.})] \times 10^{20}\ \text{yr}$$
$$\text{NEMO-3}: T^{2\nu}_{1/2} = [7.0 \pm 0.9\,(\text{stat.}) \pm 1.1\,(\text{syst.})] \times 10^{20}\ \text{yr}$$

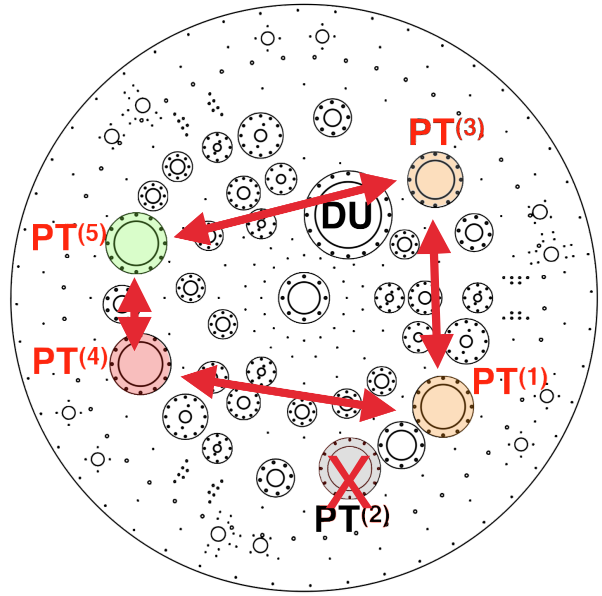




Detector Optimization

- October - December 2017: Scan of detector performance vs temperatures
  - Selecting a new operating temperature of 11mK
- January - March 2018: Warmed the cryostat to 100K to upgrade a set of gate valves
- Returned to base temperature in early March
- March 2018, performed Pulse Tube Phase Scan

Top of the Cryostat



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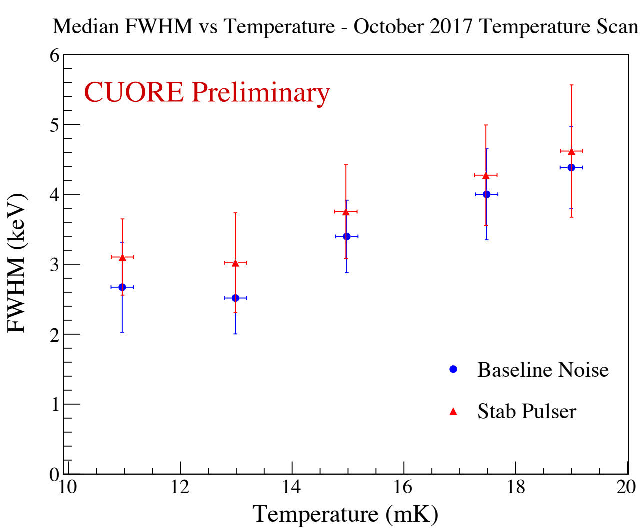
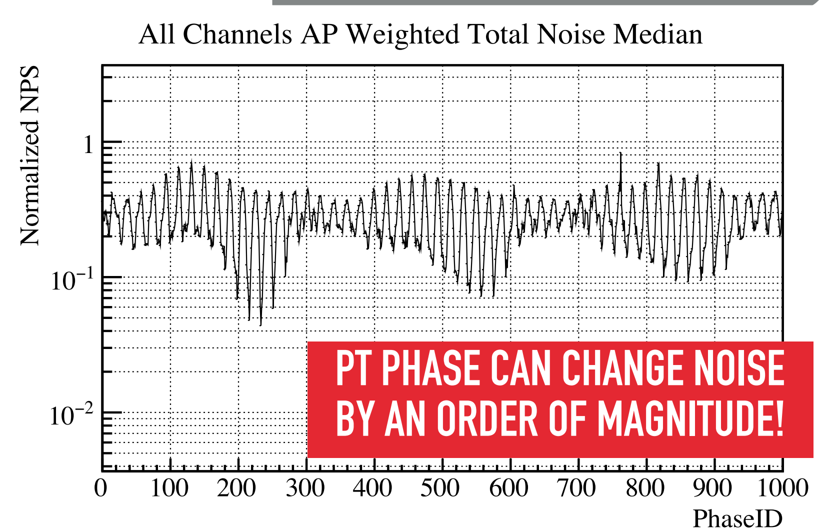
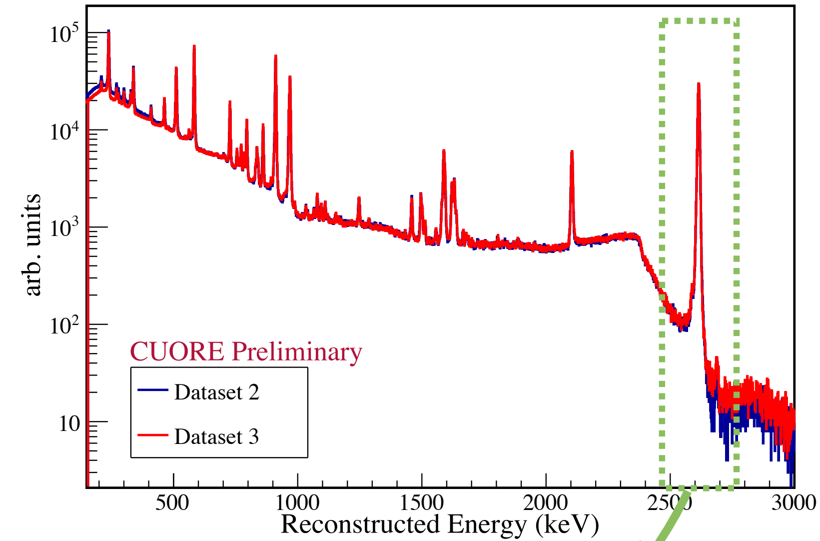
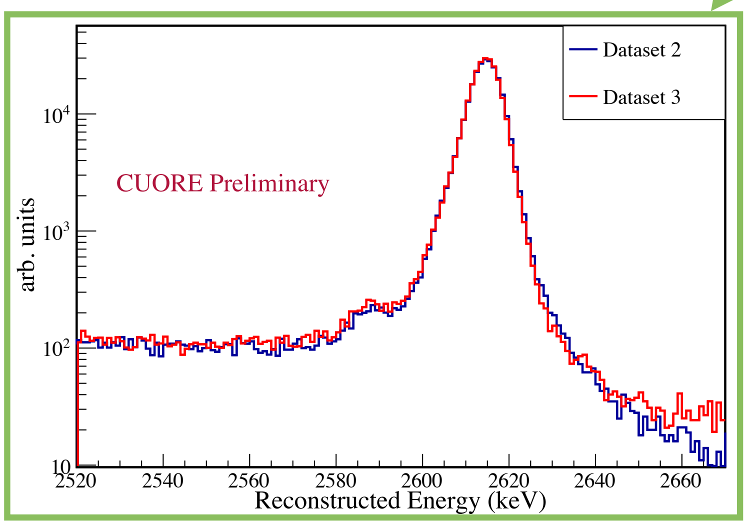




Current Status

- April calibration data characterized by energy resolution of 7.6 keV FWHM with 93% of channels passing cuts (using same processing procedures)
- Still working to achieve the energy resolution goal of 5 keV FWHM
- Back to stable physics data taking in May 2018
- Many potential physics searches:
  - Symmetry violation searches: 0ν, Majoron emission, CPTV
  - Low energy searches: Dark Matter, axions
  - Nuclear physics measurements: other ββ decays and decays to excited states, β^+/E.C. decays





Future Outlook

- With 7 weeks of data, set the most stringent limit on the 0νββ half-life of ^{130}Te to date
- Made the most precise measurement of the 2νββ half-life of ^{130}Te to date
- We have restarted physics data taking
- CUORE will continue to be one of the most sensitive searches for 0νββ over the coming years
  - Ultimate 90% sensitivity to 0νββ half-life of $T_{1/2} = 9\times10^{25}$ yr