Neutrinoless double-beta decay searches and first CUORE results

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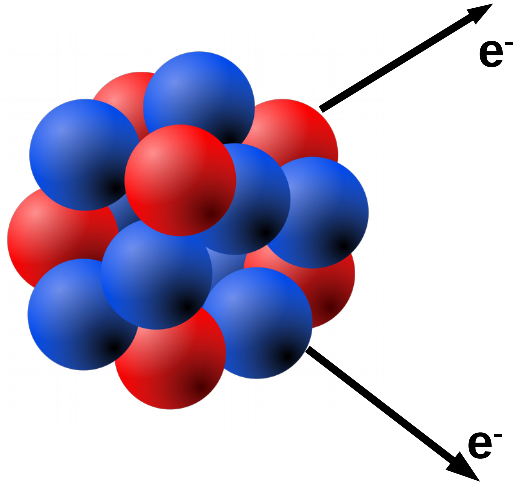
Genova University and INFN
for the CUORE collaboration

IBS Conference on Dark World – Daejeon, Korea – Nov 1 2017

Neutrinoless double-beta decay

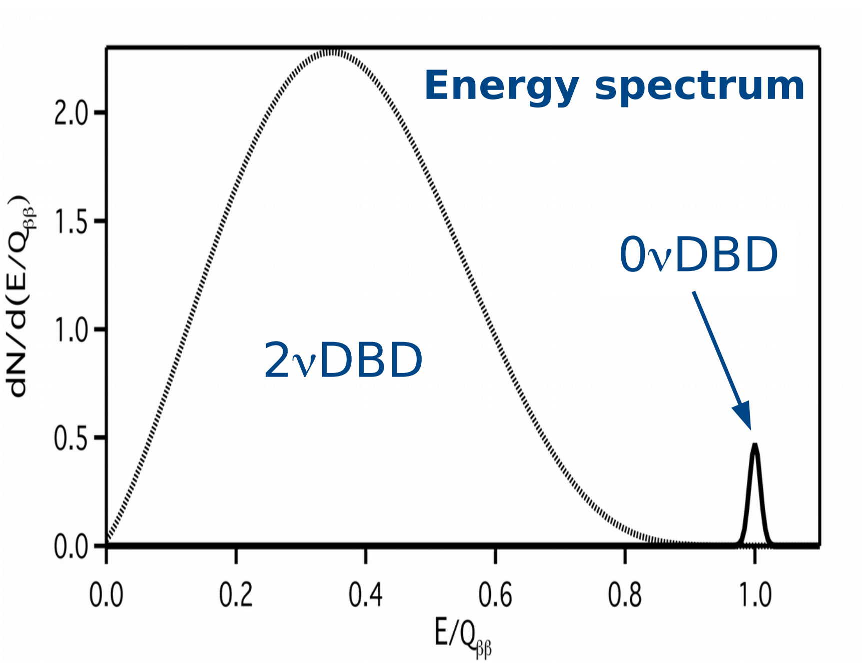


Decay: allowed on even-even nuclei

Signature: 2 electrons with fixed sum energy

Implications: ΔL=2, Majorana neutrinos

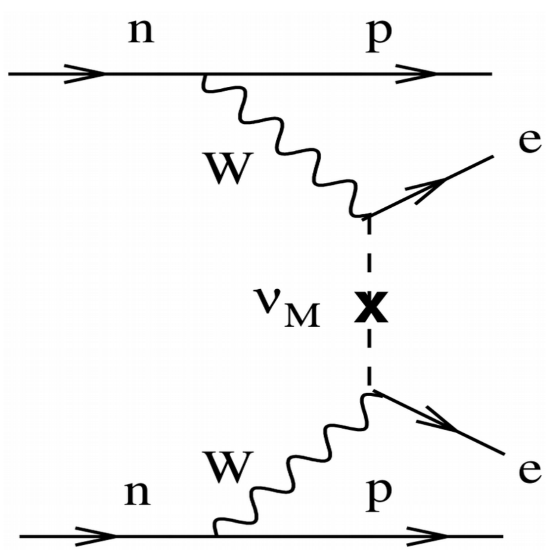
$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$



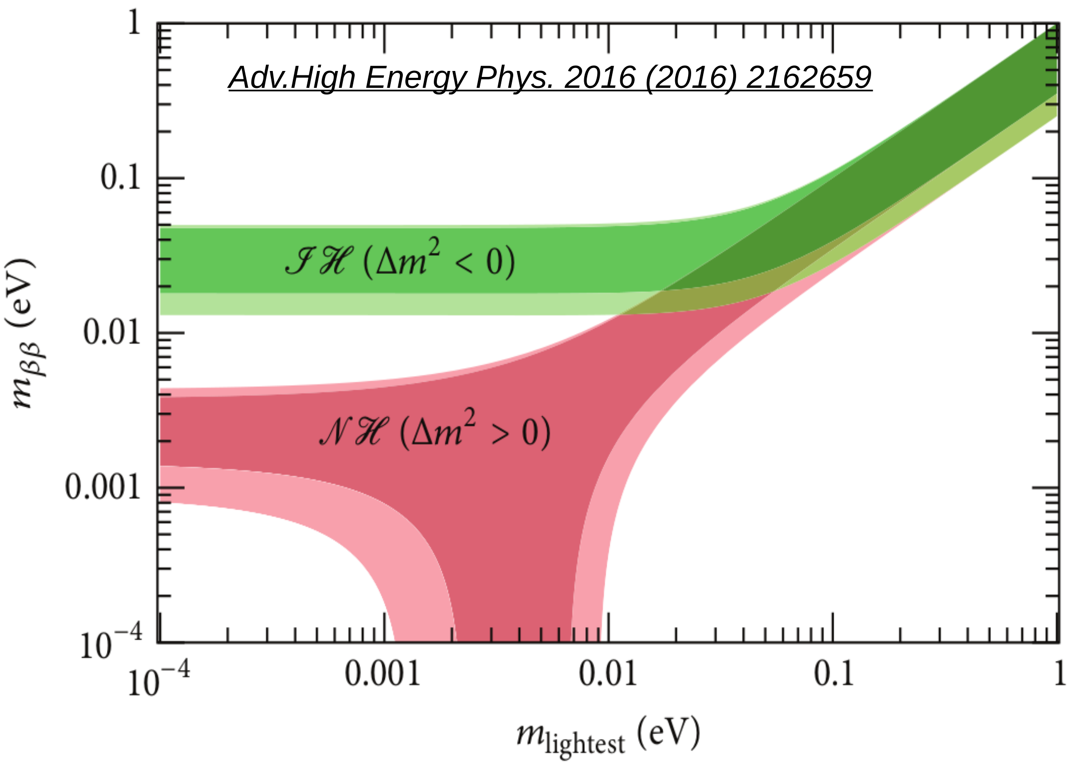
Isotope	Q [keV]	Half-life limit [10^{25} y]
^{48}Ca	4271	0.0058 (CANDLES)
^{76}Ge	2039	5.3 (GERDA)
^{82}Se	2995	0.036 (NEMO-3)
^{100}Mo	3034	0.11 (NEMO-3)
^{116}Cd	2902	0.017 (Solotvina)
^{130}Te	2528	0.40 (CUORE-0)
^{136}Xe	2479	11 (KamLAND-Zen)
^{150}Nd	3367	0.0018 (NEMO)

Light Majorana neutrino exchange

make some assumptions on the decay mechanism



exchange of a light Majorana neutrino



$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \; |M^{0\nu}|^2 \; \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

Light Majorana neutrino exchange

make some assumptions on the decay mechanism

effective Majorana mass
(neutrino physics)

$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1,2,3} U_{ei}^2 m_i\right|$$

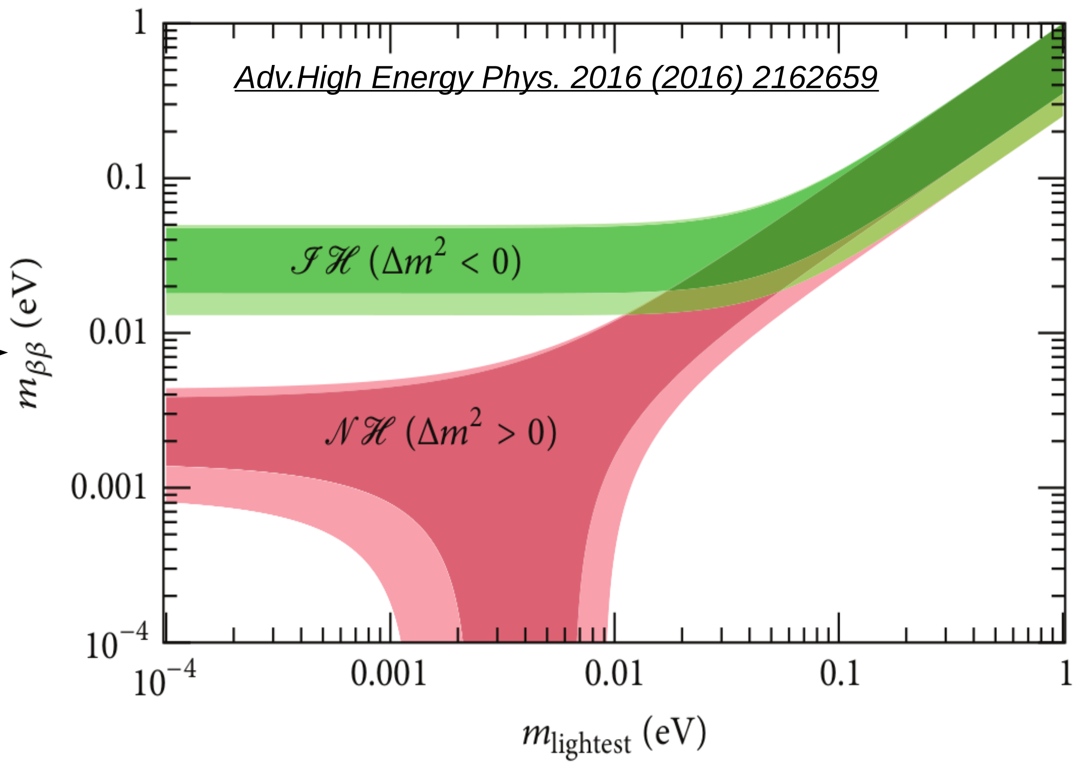
decay half life
(from experiments)

Nuclear physics
(from theory)

matrix element

phase space

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\,|M^{0\nu}|^2\,\frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$



Theoretical uncertainties come into play
Notable progresses have been made in this field in recent years

Half-life sensitivity

- In most present-generation experiments the background is not negligible, and the half-life sensitivity is given by

$$S^{0\nu} = \ln(2) N_A \frac{x}{W} \eta \cdot \varepsilon \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}$$

finite background: M · t · b · ΔE > 1

- Future generation experiments aim at a zero background condition

$$S^{0\nu} = \ln(2) N_A \frac{x}{W} \eta \cdot \varepsilon \; M \cdot t$$

zero background: M · t · b · ΔE < 1

N_A: Avogadro number
x: stoichiometric multiplicity of the element containing the DBD isotope
η: isotopic abundance of DBD isotope
ε: detection efficiency
W: molecular mass of the detector compound

M: total detector mass
t: measurement time
B: background index in counts/(keV·kg·y)
ΔE: energy resolution

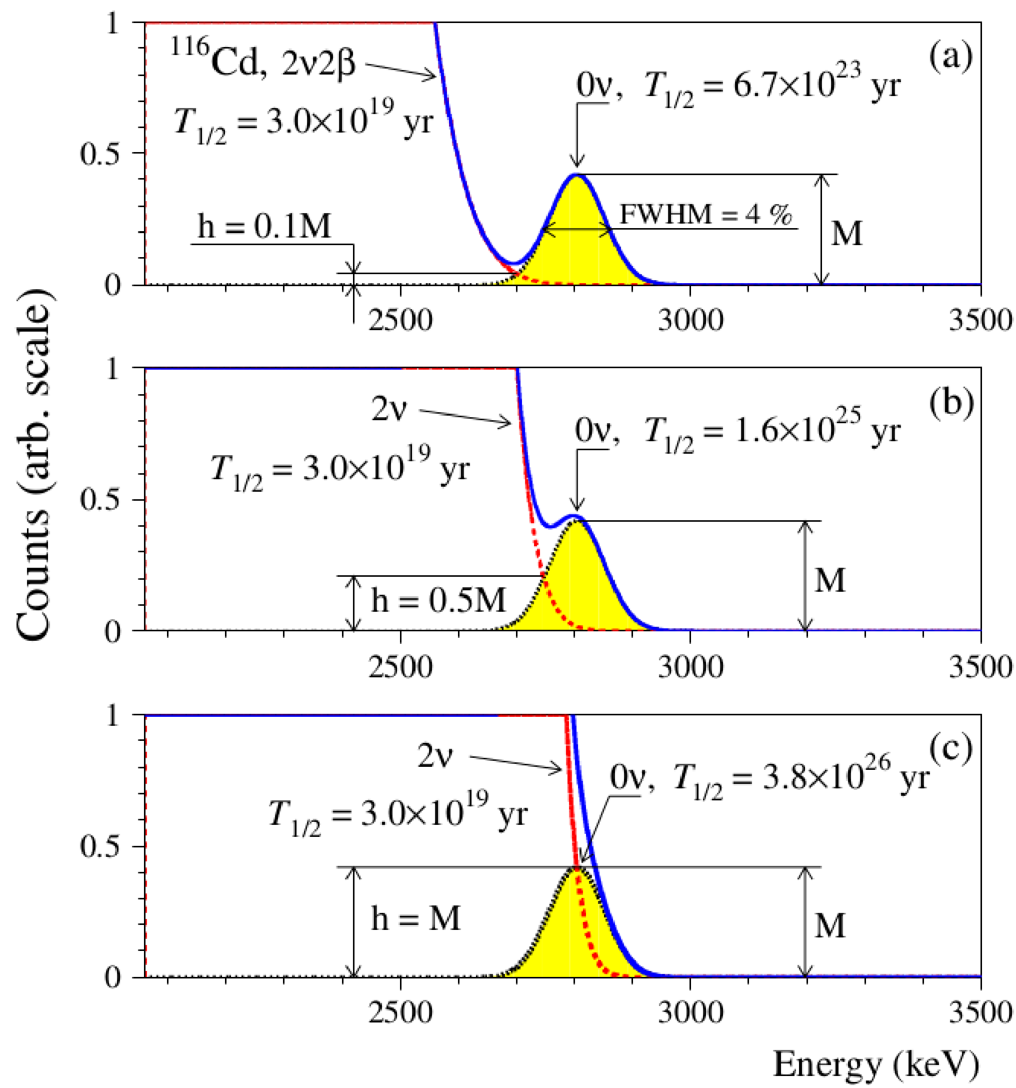
2ν irreducible background

The number $N_{2\nu}$ of 2ν-DBD events in a window of width ΔE around the Q-value of the decay scales as

$$N_{2\nu} \sim \frac{1}{T_{1/2}^{2\nu}} \frac{\Delta E^6}{Q^5}$$

Eventually energy resolution will become important also for a zero-background experiments

J. Phys. G: Nucl. Part. Phys. 30 (2004) 971-981

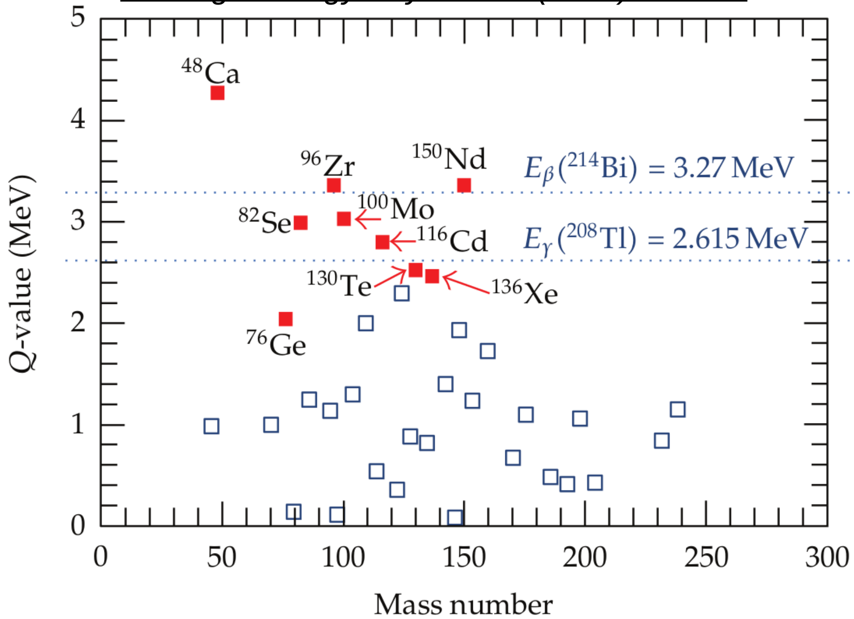


Isotope choice: Q-value

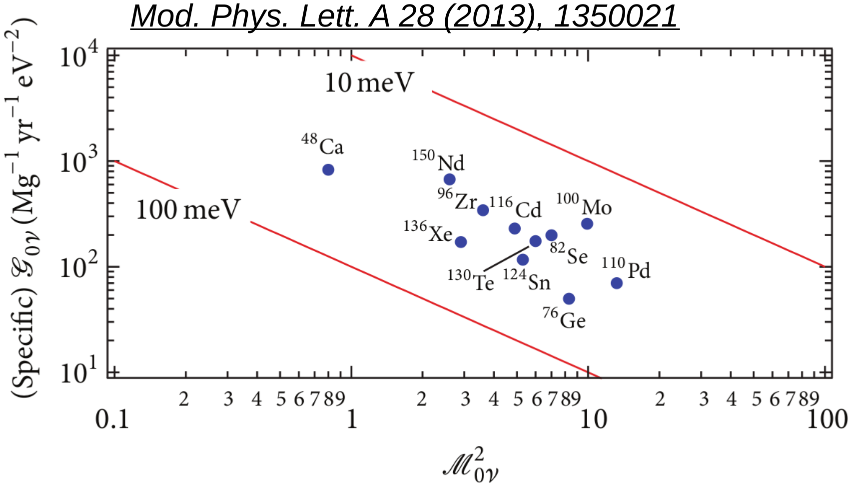
Isotopes with high Q-value are preferred

- Radioactive background is lower
  - 2615 keV: end-point of nat. γ radioactivity
  - 3272 keV: end-point of Rn-induced radioactivity
  - Background from 2ν DBD scales as ~$1/Q^5$
- No favorite isotope in terms of signal counts per unit mass

Adv.High Energy Phys. 2012 (2012) 857016



Mod. Phys. Lett. A 28 (2013), 1350021



CUORE

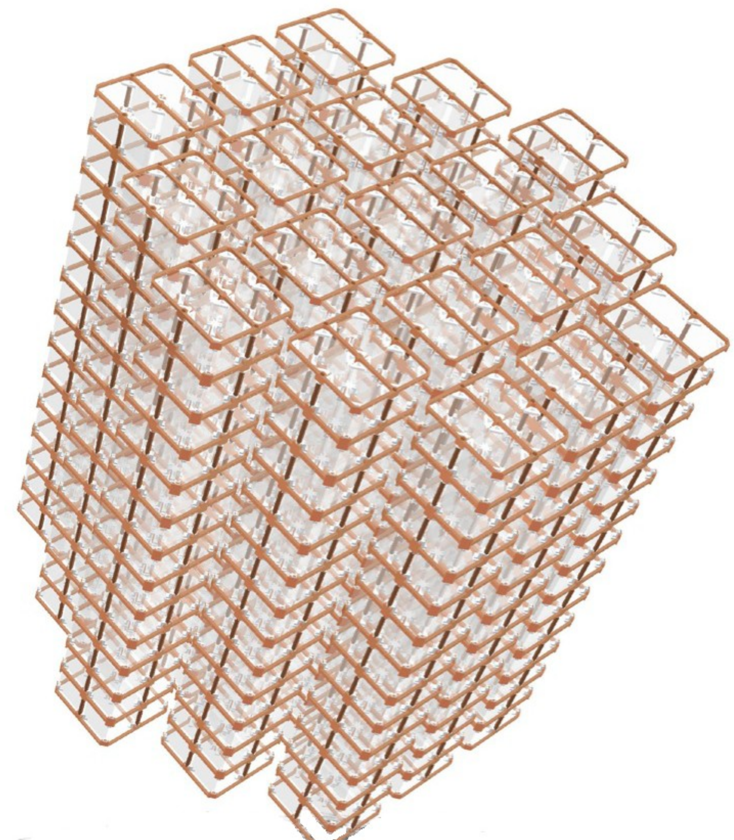
Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

- Search for $0\nu\beta\beta$ decay in ^{130}Te (Q = 2527.5 keV)
- 988 TeO_2 bolometers operated at 10 mK
- Arranged in 19 towers
- 742 kg of TeO_2 (206 kg of ^{130}Te)
- Bacgkround aim: 0.01 counts/(keV·kg·y)
- Energy resolution aim: 5 keV FWHM

half-life sensitivity in 5 y

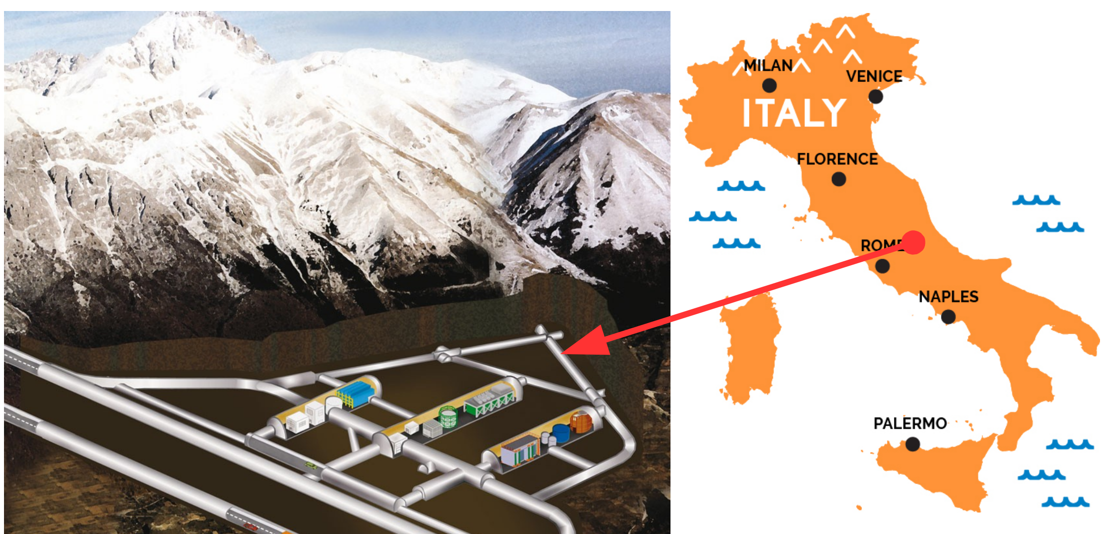
$S^{0\nu}(^{130}Te) = 9 \times 10^{25}$ y (90% CL)

Eur. Phys. J. C77 (2017), 532



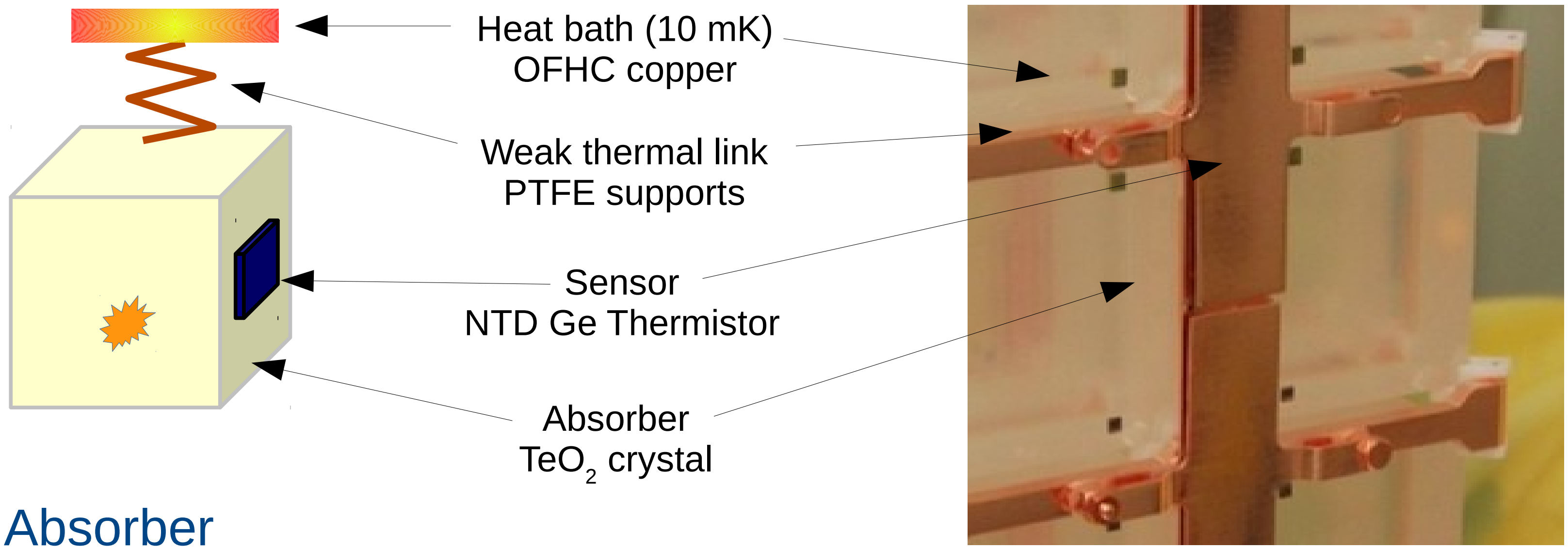
Adv. in High En. Phys. 2015 (2015), 879871

Located underground at the Laboratori Nazionali del Gran Sasso of INFN



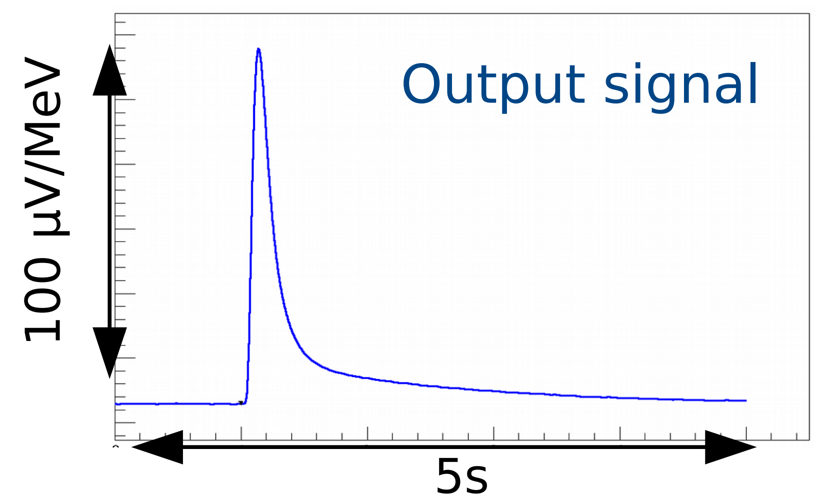
Experimental technique

Measure the temperature rise of the absorber crystal: $\Delta T = \frac{E}{C}$



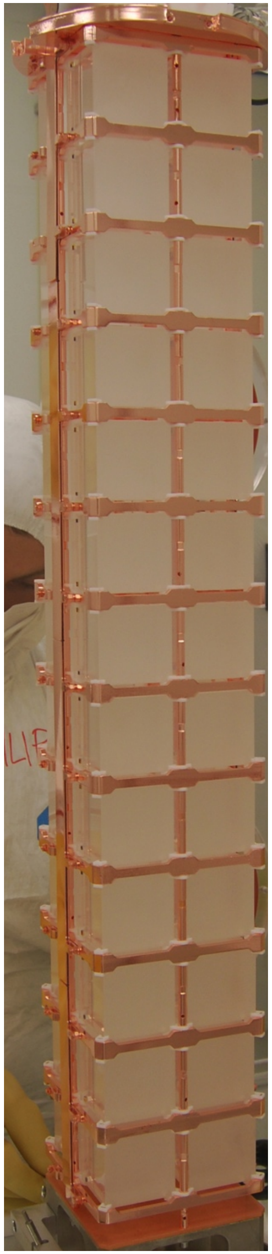
Absorber

- Dimension: 5x5x5 cm^3
- Mass: 0.75 kg
- Heat capacity: $2x10^{-9}$ J/K
- $\Delta T/\Delta E \sim 10 – 20$ μK/MeV



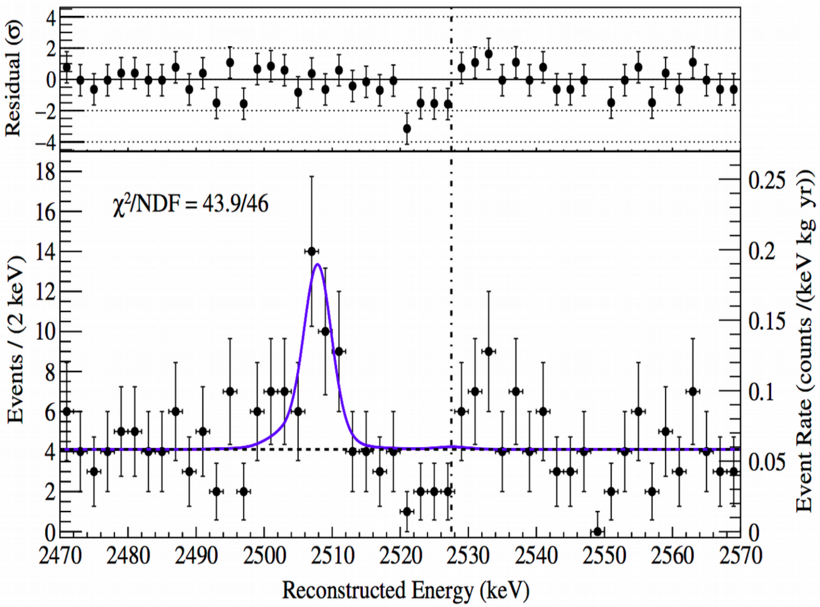
Sensor

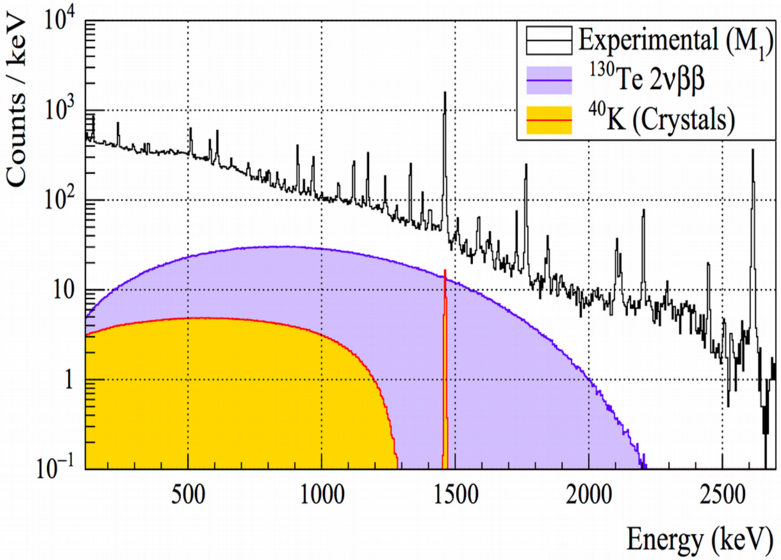
- $R = R0 \exp[(T_0/T)^{1/2}]$
- R ~ 100 MΩ
- $\Delta R/\Delta E \sim 3$ MΩ/MeV



CUORE-0

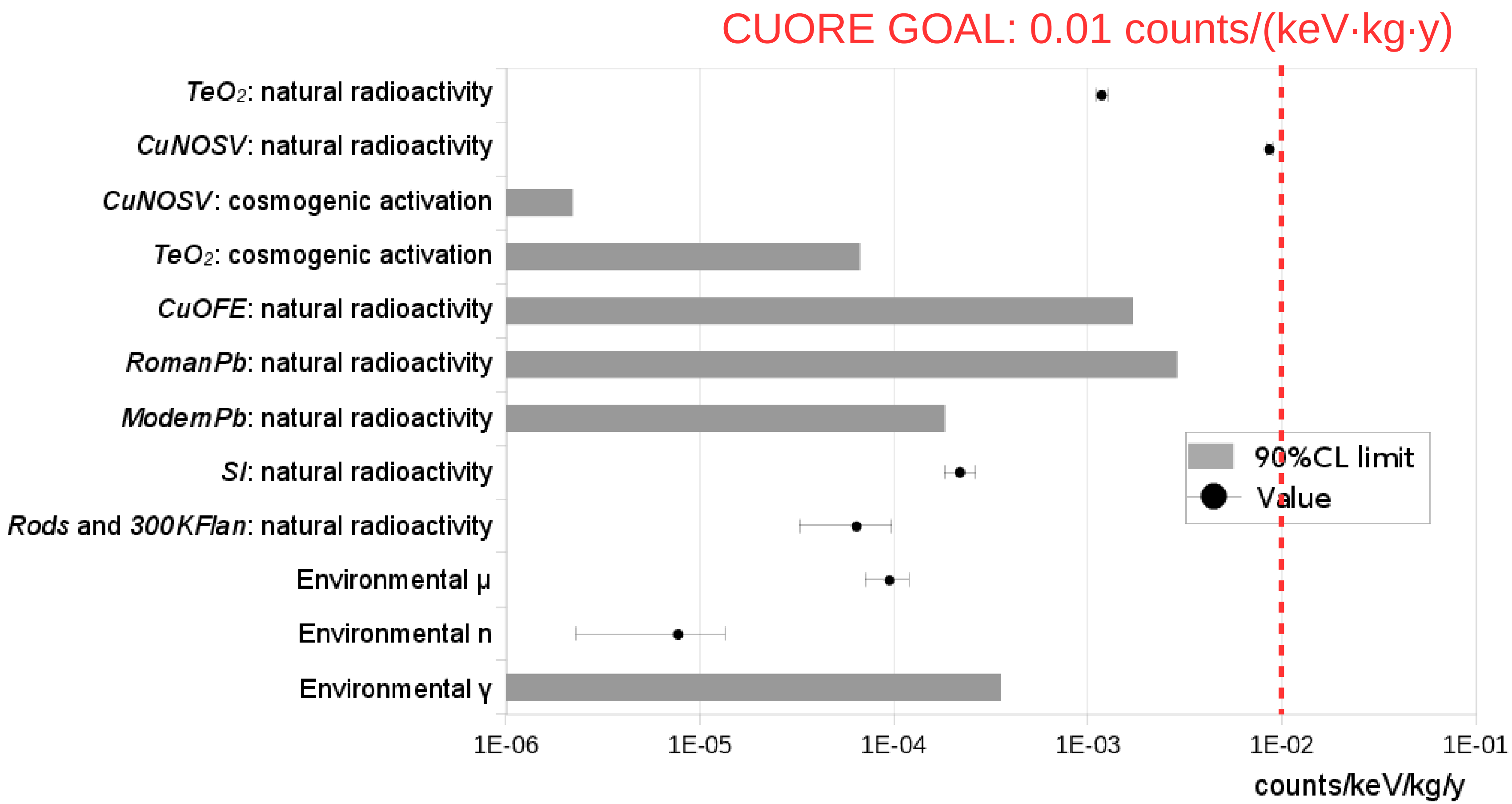
- A single CUORE-like tower
- Operated at LNGS between 2013 and 2015
- A test of the CUORE cleaning and assembling procedures
- Demonstrated that a background level as low as 0.01 counts/(keV·kg·y) in the ROI could be achieved
- Resolution: 5.0 keV FWHM at 2.6 MeV
- Also used to develop the analysis techniques for CUORE
- And scientific results





Phys. Rev. Lett. 115 (2015) 102502
Eur. Phys. J. C (2017) 77:13
Phys. Rev. C93 (2016) 045503
JINST 11 (2016) P07009
arXiv:1710.07459 (Te-120)

CUORE projected background

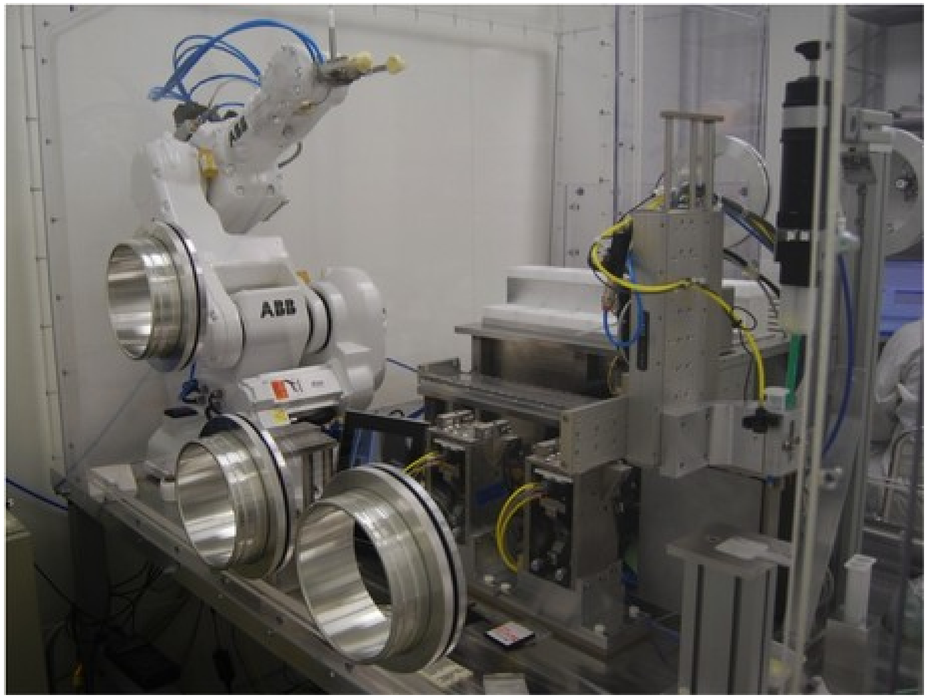


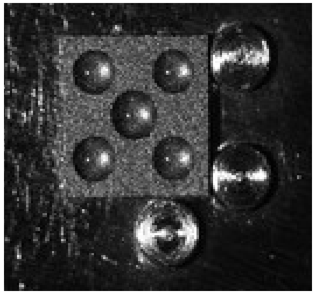
Eur.Phys.J. C77 (2017), 543

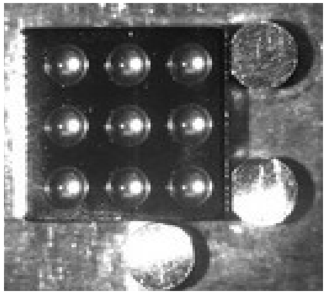
Consisted of 3 steps

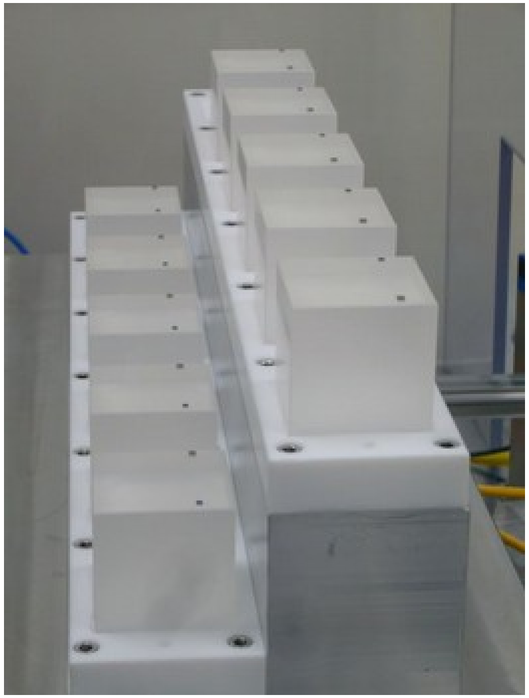
1. Gluing

Semi-automatic absorber-sensor coupling system
- NTD sensors
- Joule heaters for thermal gain calibration







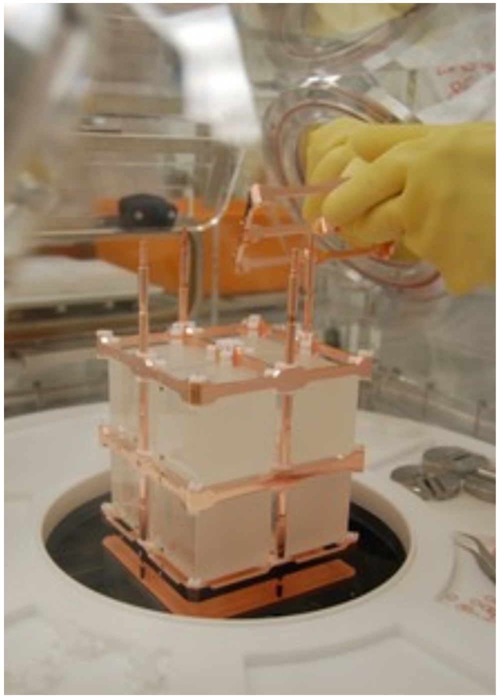


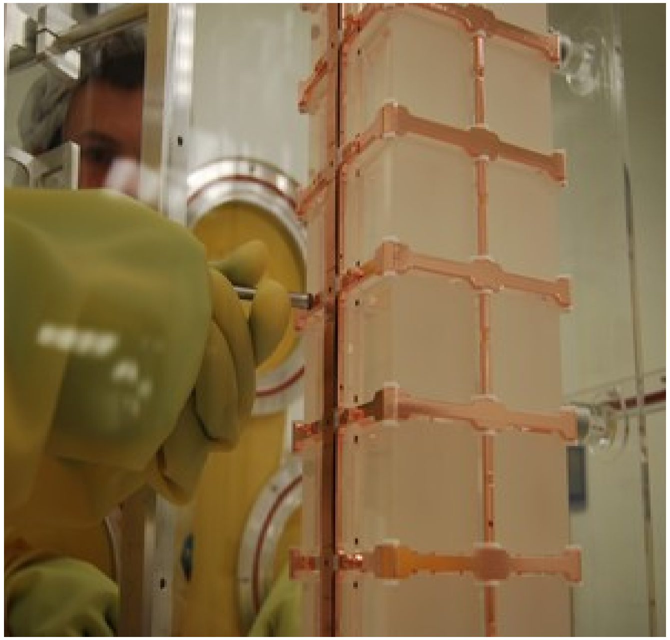
All operations performed in glove boxes to avoid radon recontamination

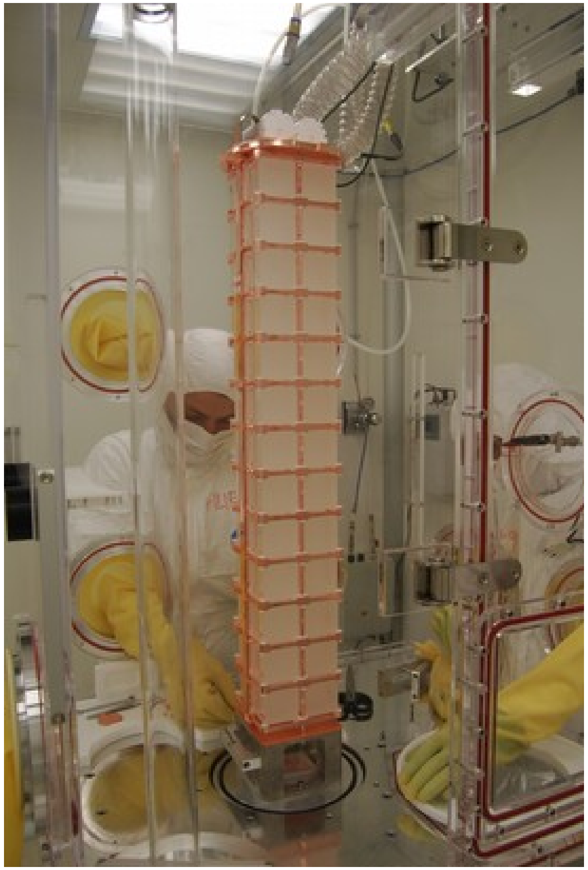
CUORE towers construction

Consisted of 3 steps

1. Gluing
2. Tower assembly







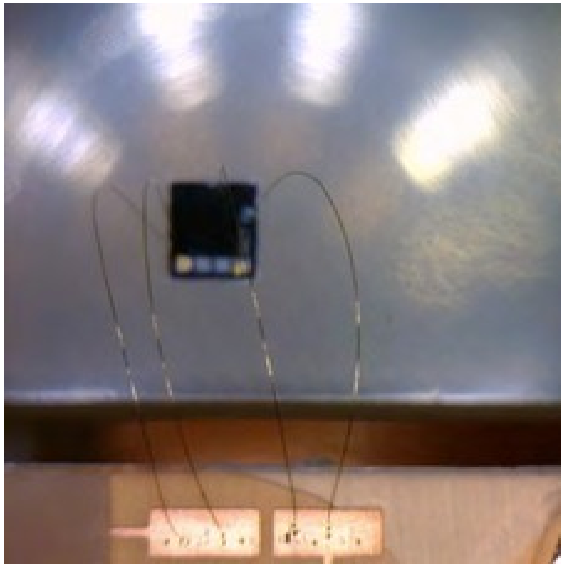
- Copper support structure
- Teflon supports
- Crystals
- tapes for signal readout

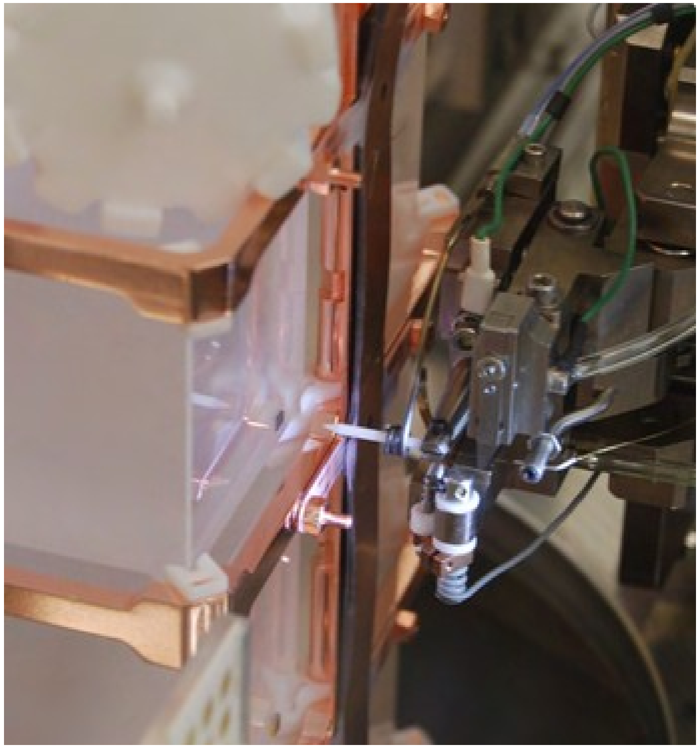
All operations performed in glove boxes to avoid radon recontamination

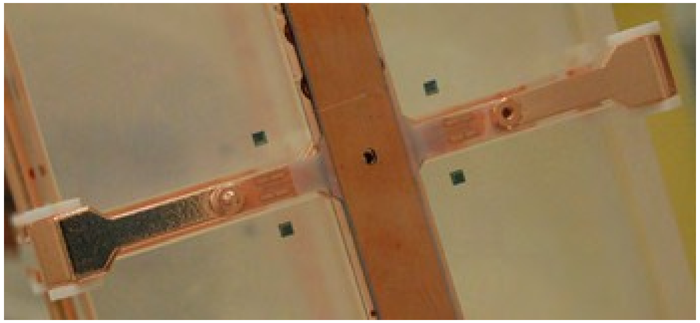
CUORE towers construction

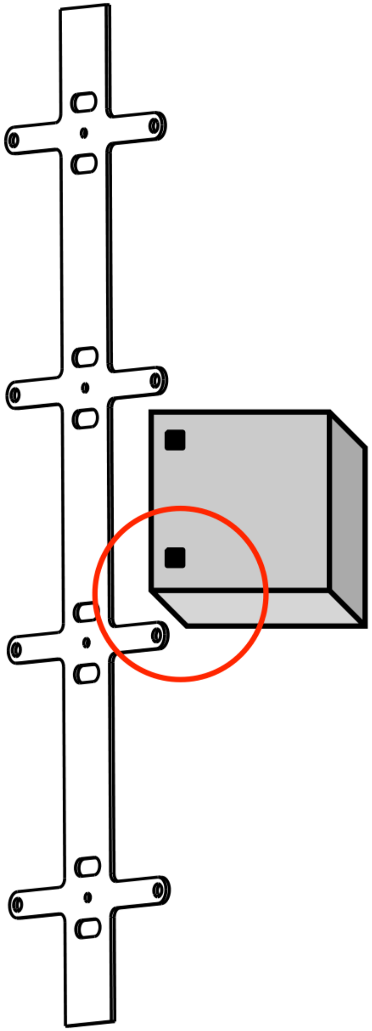
Consisted of 3 steps

1. Gluing
2. Tower assembly
3. Sensor bonding









All operations performed in glove boxes to avoid radon recontamination

CUORE towers construction

Tower construction completed in June 2014

Towers stored nitrogen atmosphere,
waiting to be installed in the cryostat

CUORE cryostat

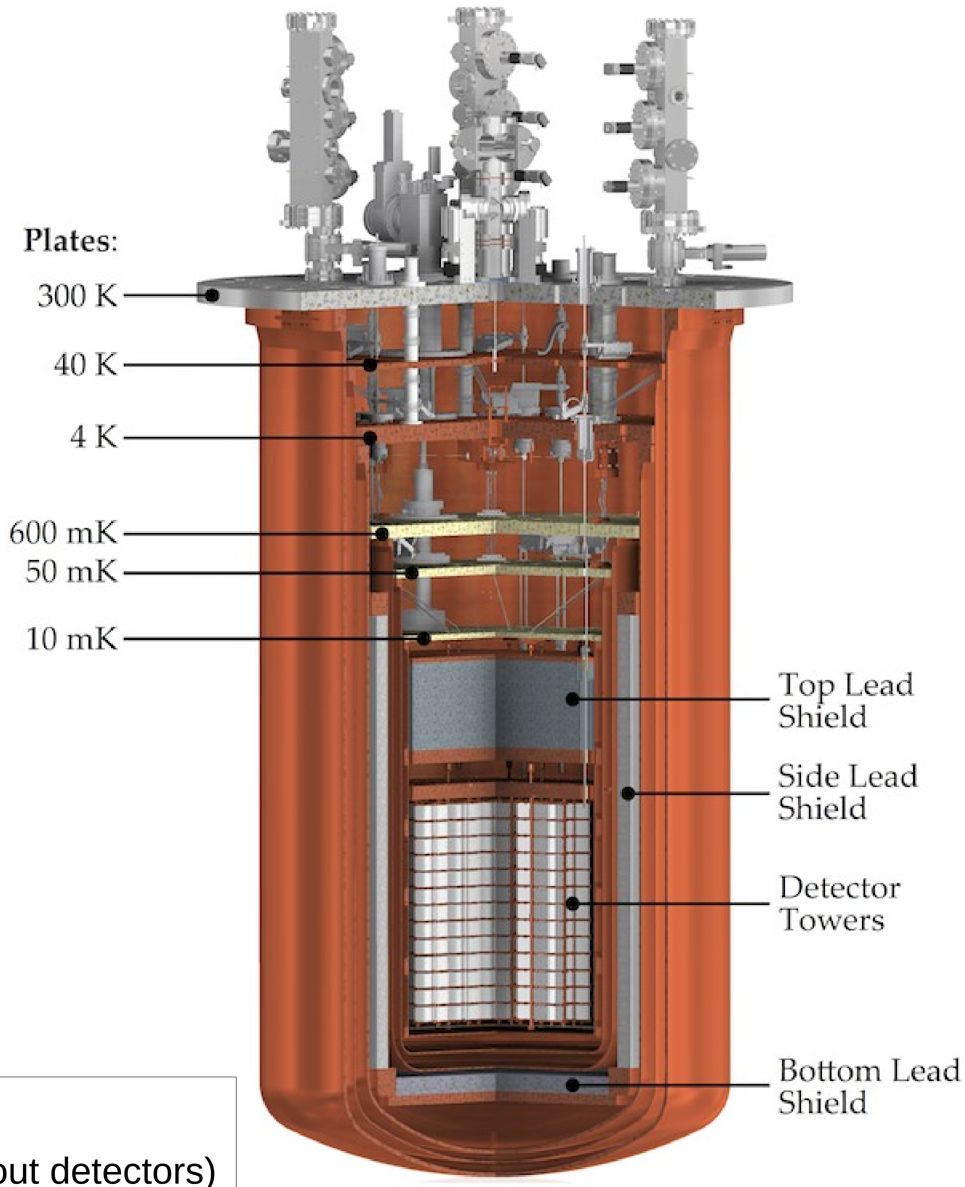
Cool a ton-scale detector at 10 mK in a radiopure, low noise environment

- Total cryostat mass: 30 t
- Mass below 4K: 15 t
- Mass below 50 mK: 3 t

Nominal cooling power: 3μW at 10 mK

- Cryogen-free apparatus
- Fast cooling system: gas exchange down to 50K
- 5 pulse tubes down to 4K
- Dilution unit: down to ~10mK
- Suspension system: detectors are mechanically isolated from the cryostat vibrations

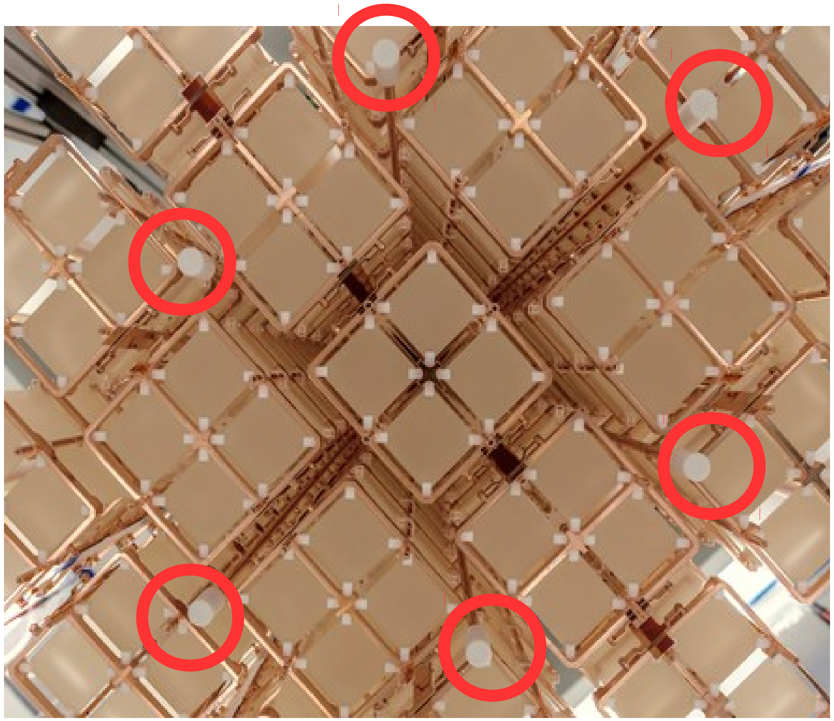
Cryostat commissioning completed in 2016
Reached a stable base temperature < 6 mK (without detectors)

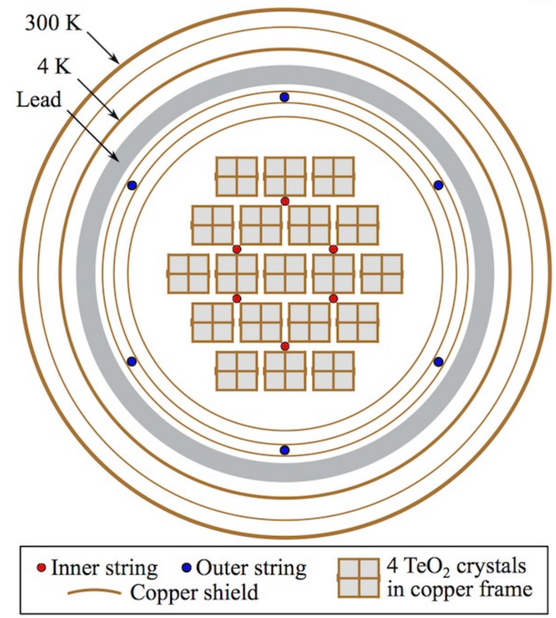


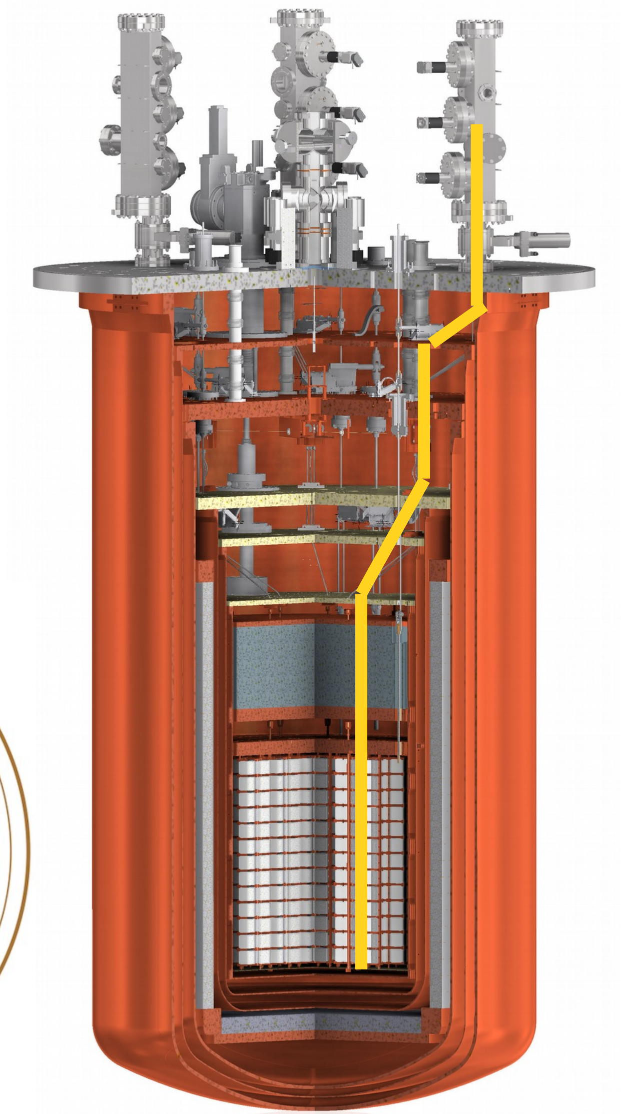
Calibration system

Expose the detectors to a ^{232}Th source for absolute energy calibration

Periodically deploy thoriated tungsten wires around and among the CUORE towers, for uniform illumination

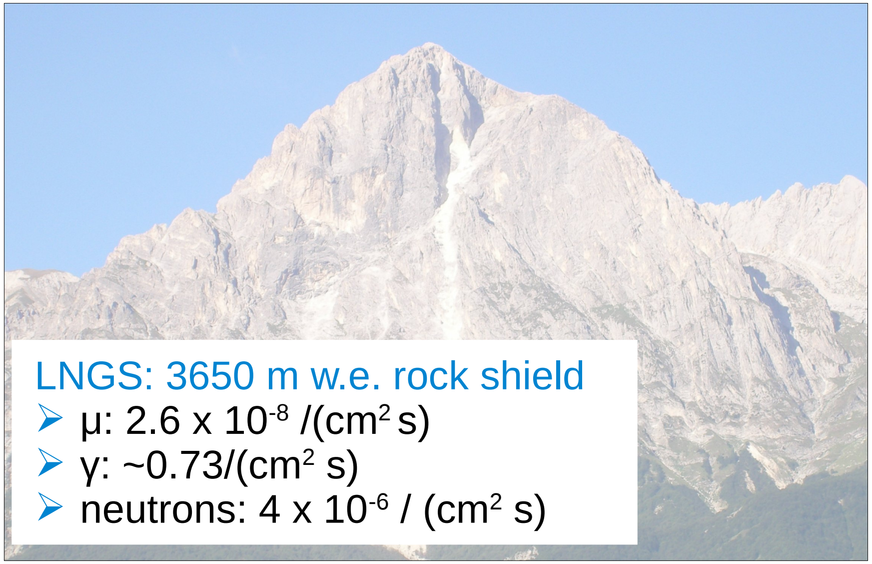






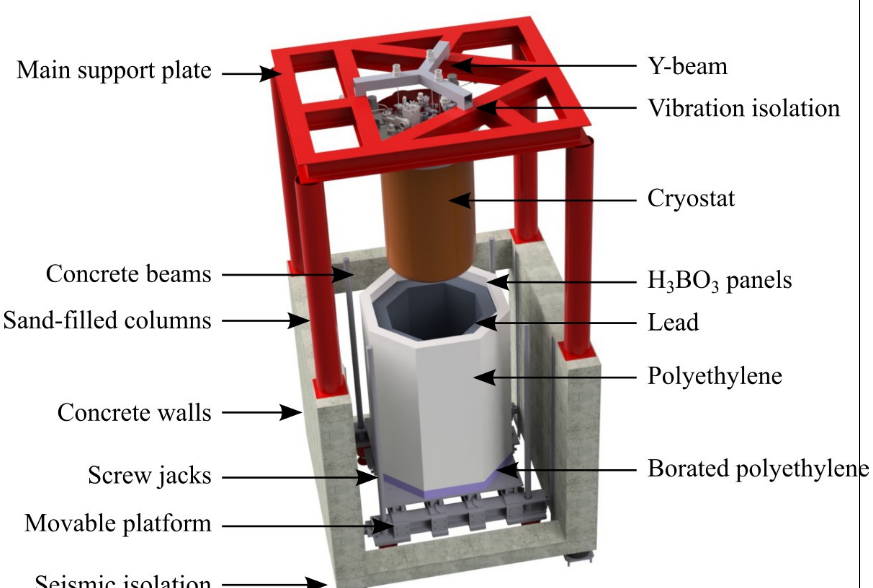
NIM A 844, (2017) 32-44

Radiation shields



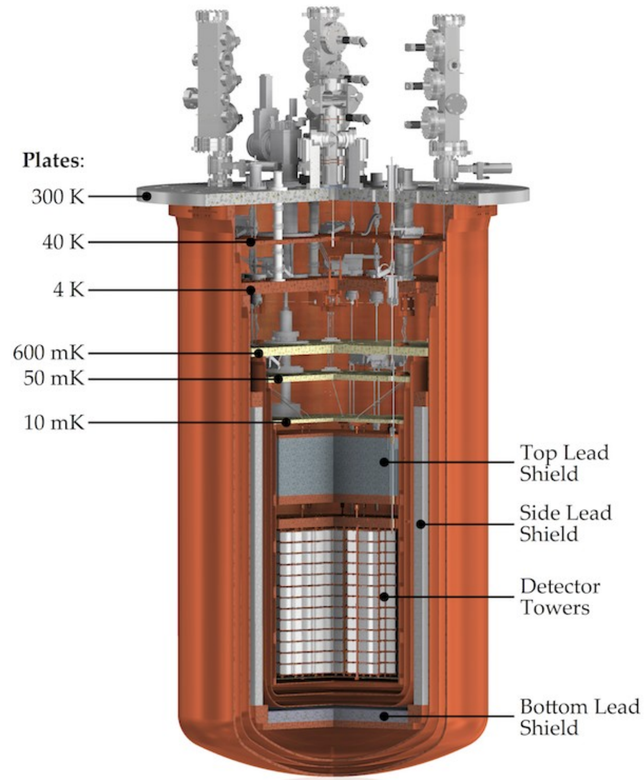
LNGS: 3650 m w.e. rock shield
- μ: 2.6×10^{-8} /(cm^2 s)
- γ: ~0.73/(cm^2 s)
- neutrons: 4×10^{-6} / (cm^2 s)

External shields: H_3BO_3 and lead



Inner (cold) shields

- Top: low ^{210}Pb activity lead
- Side and bottom: ancient roman lead



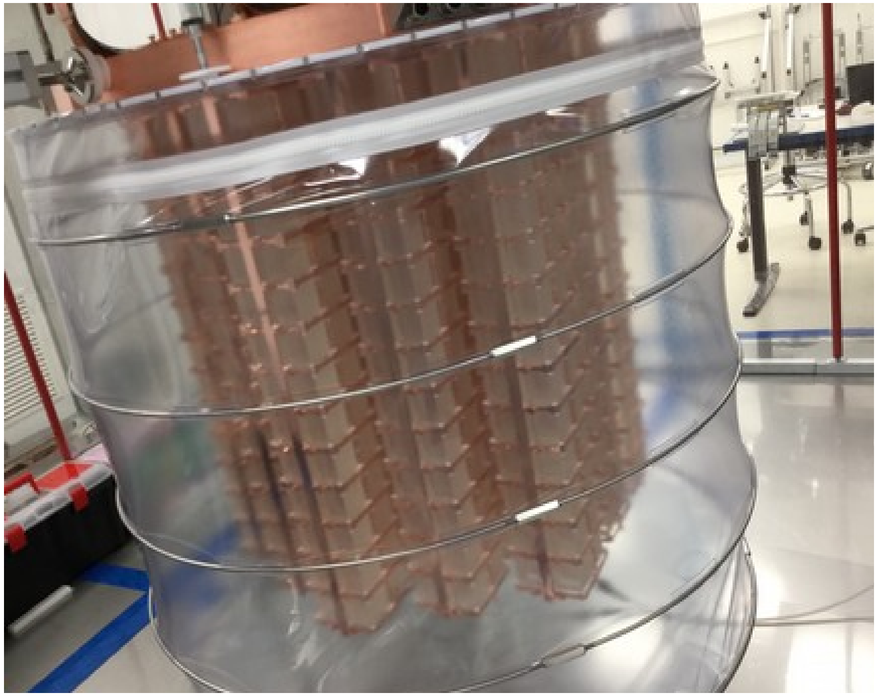
Towers installation

Jul 27, 2016 → Aug 26, 2016

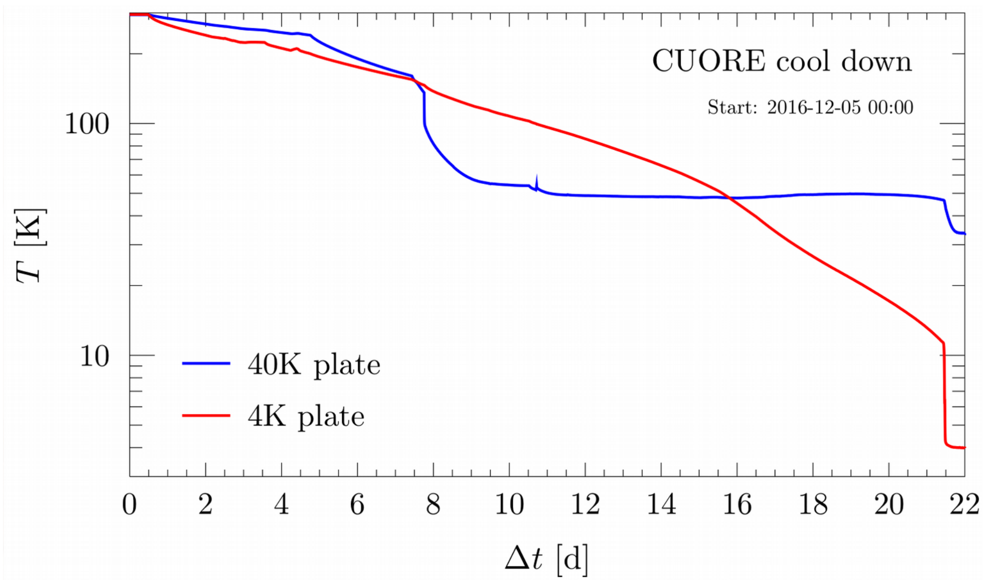
Performed in Rn-free air (< $1 Bq/m^3$)

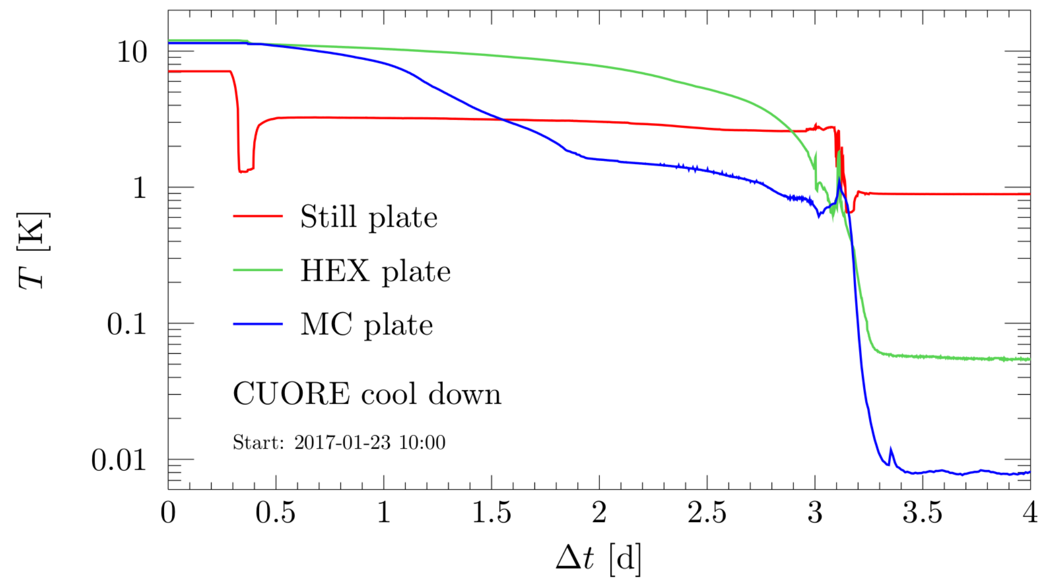
Towers enclosed in nitrogen-flushed protective bag over night

First and only time when the towers were exposed to air

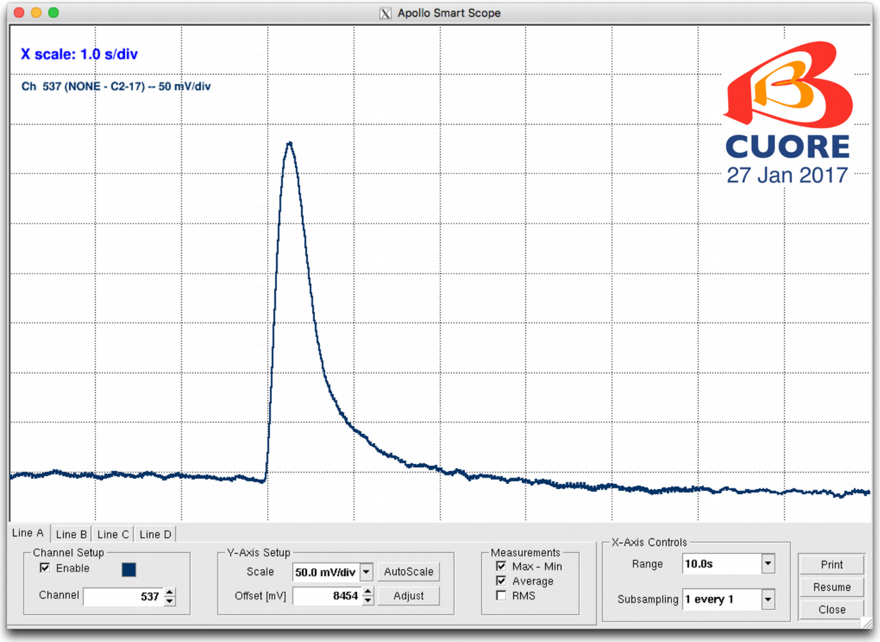


Cool down





- Sep – Nov 2016: cryostat closing
- Cool down started in December 2016
- 4K reached in 22 days
- Base temperature reached in 3.5 days
- First pulse observed the same day

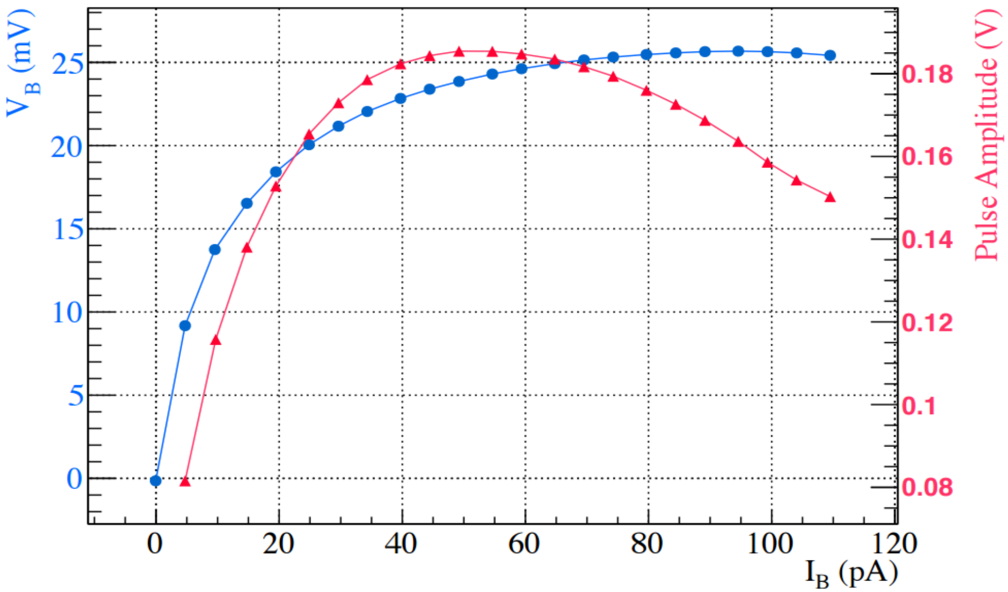


Detector optimization

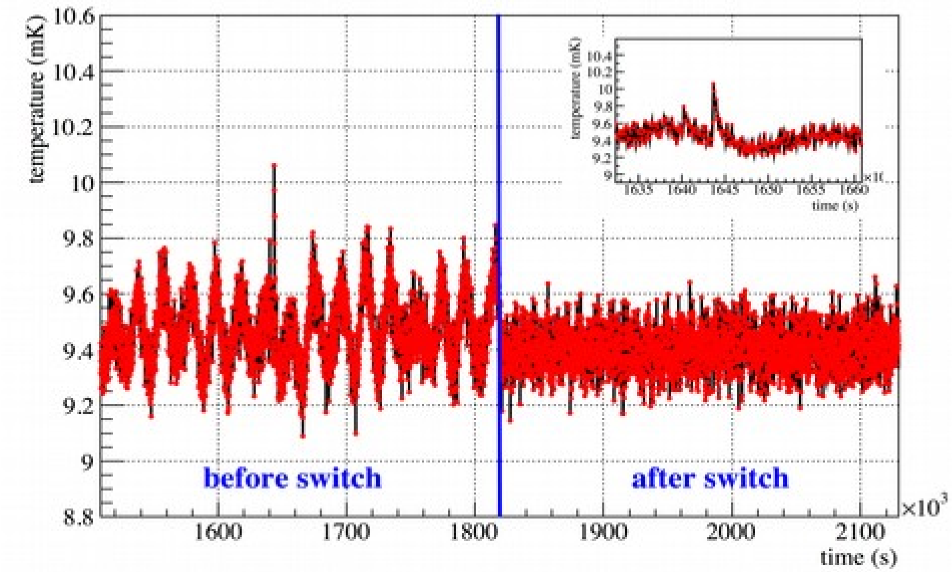
First optimization campaign: Feb-Mar 2017

- Elctronics and DAQ debugging
- Noise and vibrations optimization
- Pulse tubes phase scan
- Working temperature scan
- Load curves
- Optimization of trigger thresholds

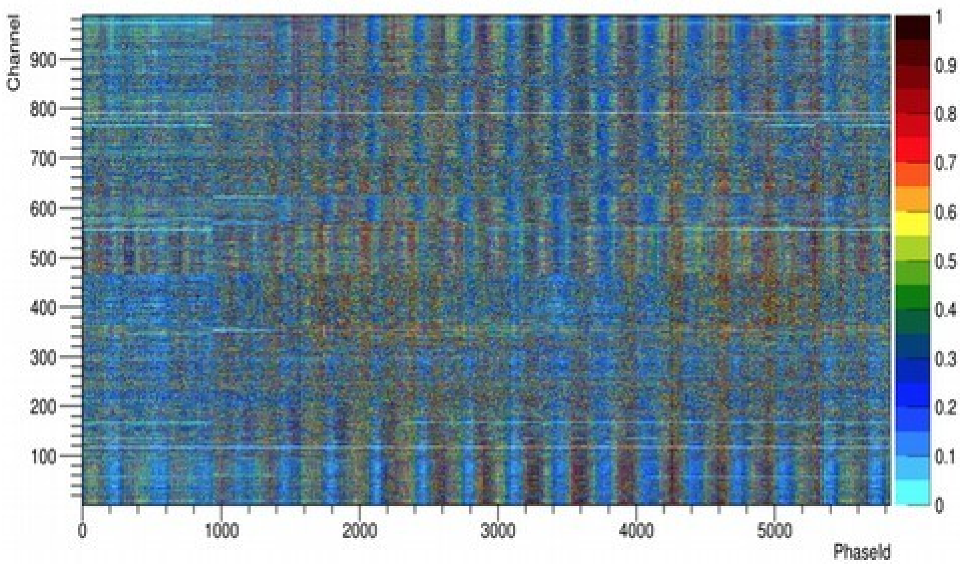
Load curve



Pulse tubes linear drives

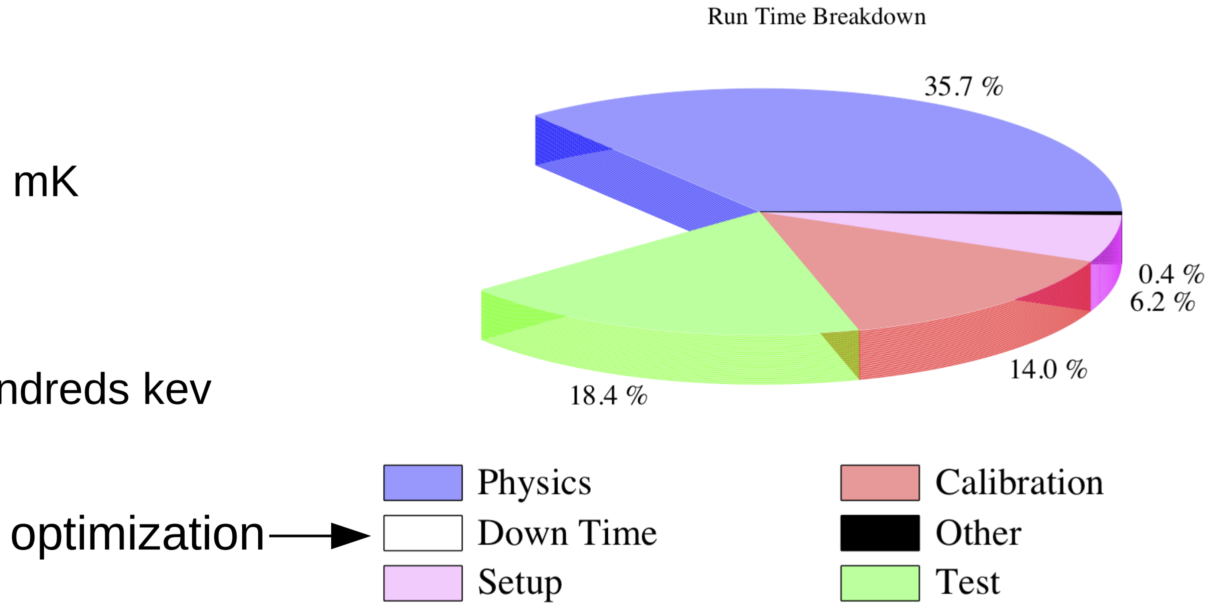


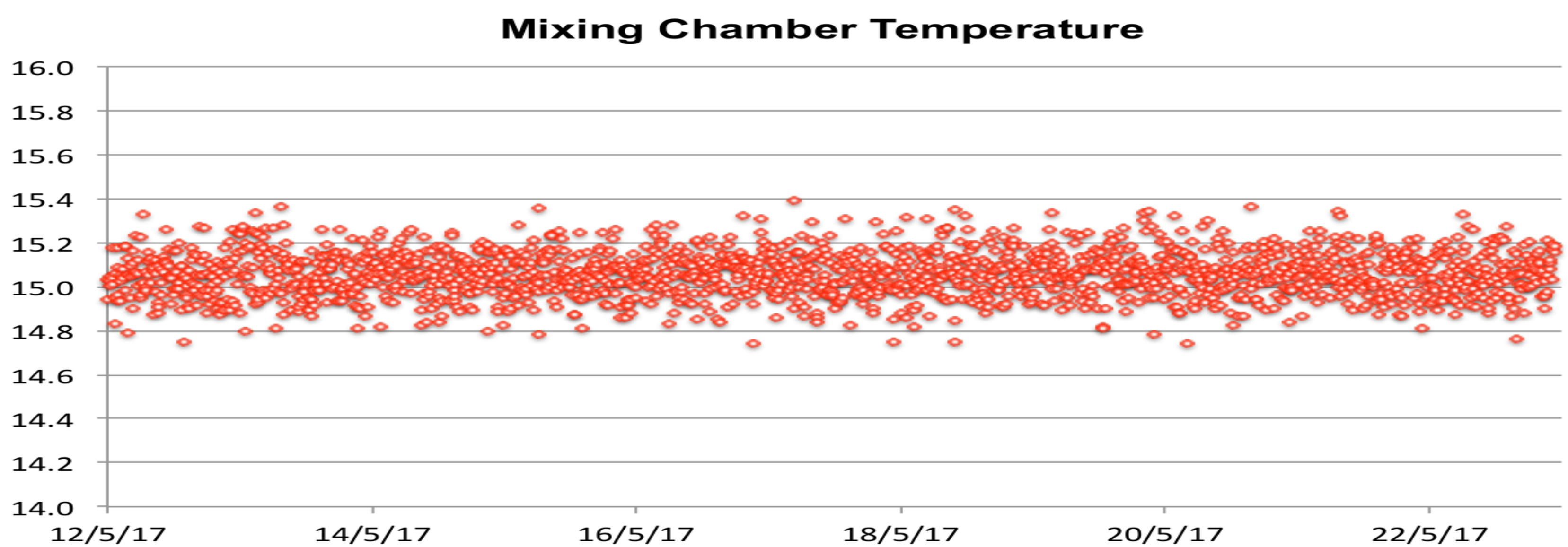
Pulse tubes phases scan



Data taking and performance

- 984 out of 988 working bolometers
- Selected operating temperature: 15 mK
- Excellent system stability
- High duty cycle when in operation
- Thresholds: from ~20keV to few hundreds kev
- Trigger rate per bolometer
  - Calibration: 50 mHz
  - physics runs: 6 mHz

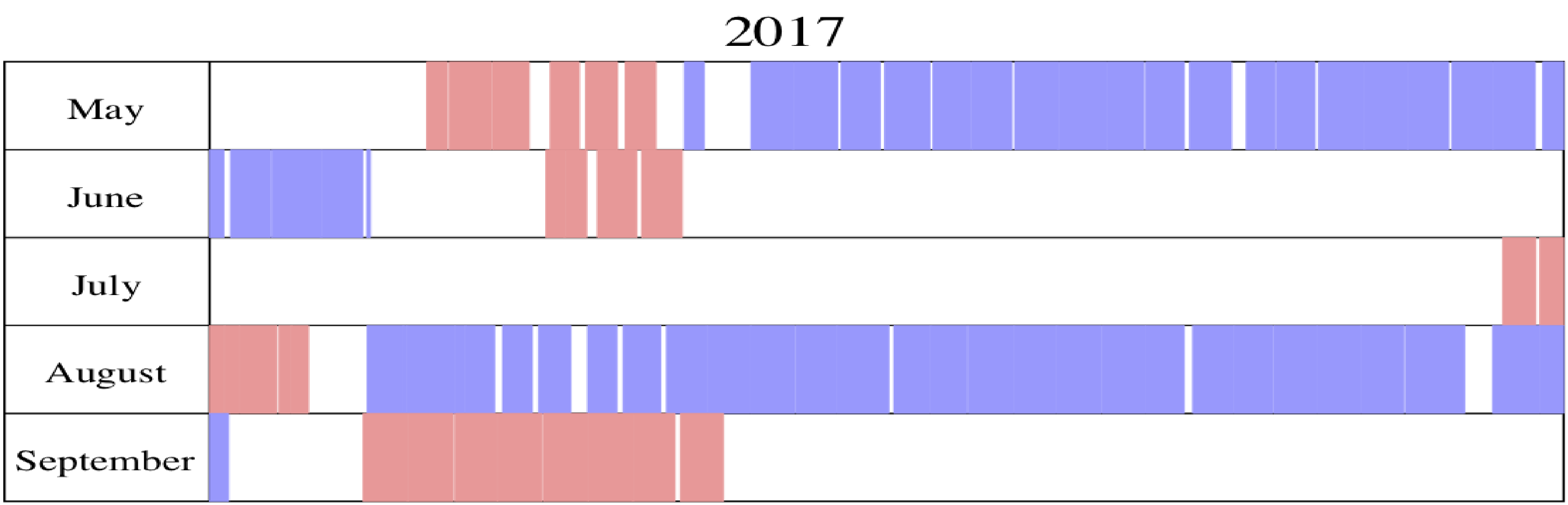




Science runs

- 2 periods of physics data
  - Dataset 1: May – Jun 2017 → 37.6 kg·y of TeO_2
  - Dataset 2: Aug – Sep 2017 → 48.7 kg·y of TeO_2
- Each dataset enclosed between two calibrations
- Another optimization campaign took place in July 2017
- TeO_2 exposure: 86.3 kg·y
- ^{130}Te exposure: 24.0 kg·y

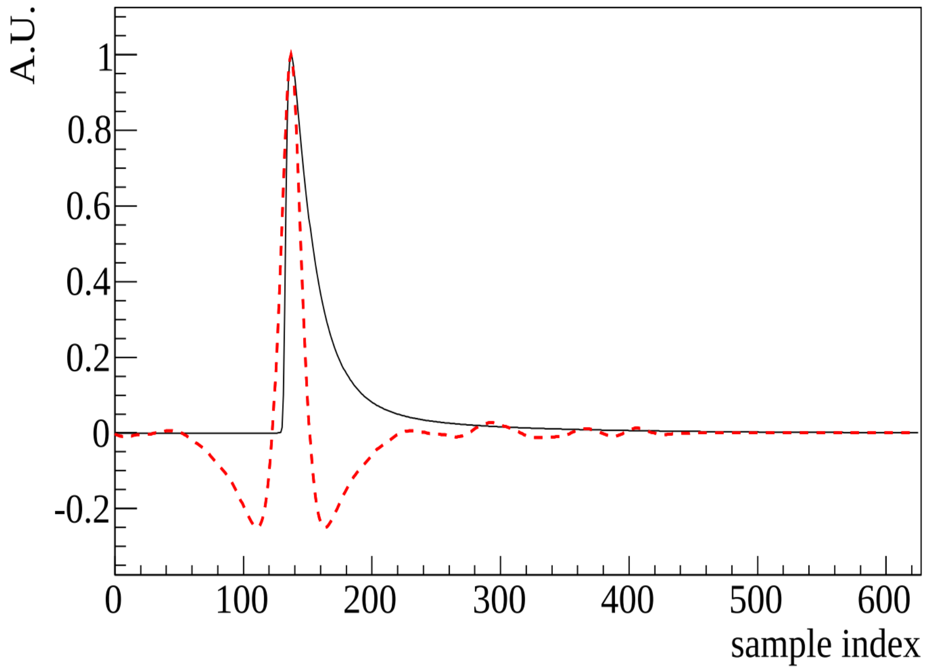
surpassed the CUORE-0 exposure in ~3 weeks



Analysis chain

First level anlysis

- Amplitude estimation

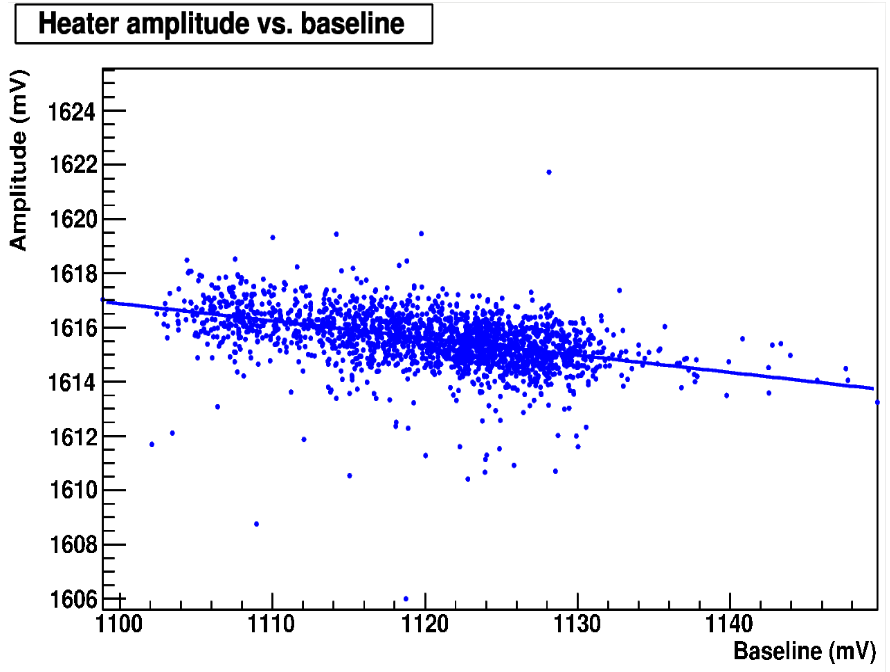


Evaluate the amplitude of pulses using a matched filter that maximizes the signal-to-noise ratio

Analysis chain

First level anlysis

- Amplitude estimation
- Thermal gain correction

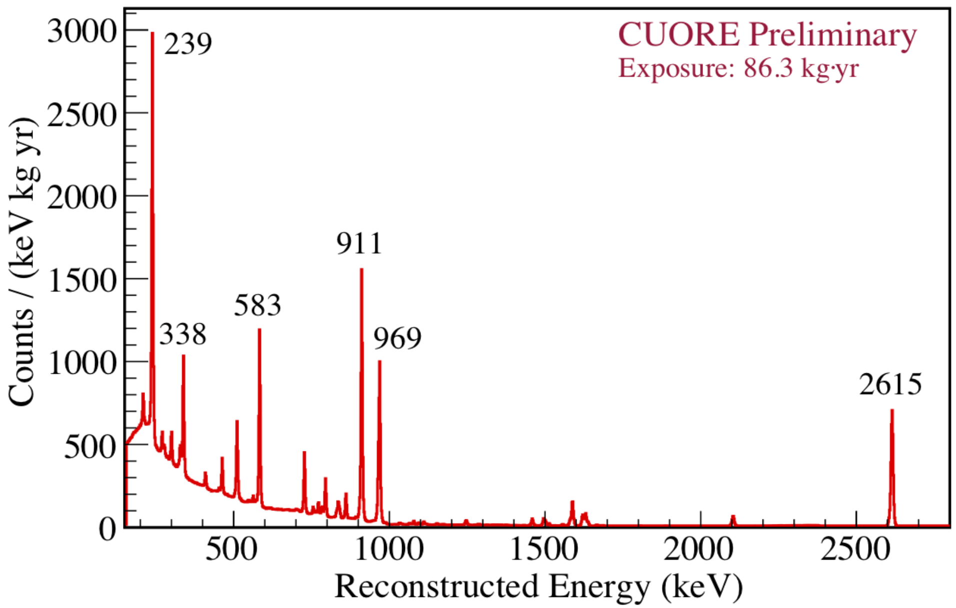


Correct for thermal gain instabilities using the amplitude of a fixed-energy reference pulse

Analysis chain

First level anlysis

- Amplitude estimation
- Thermal gain correction
- Energy calibration

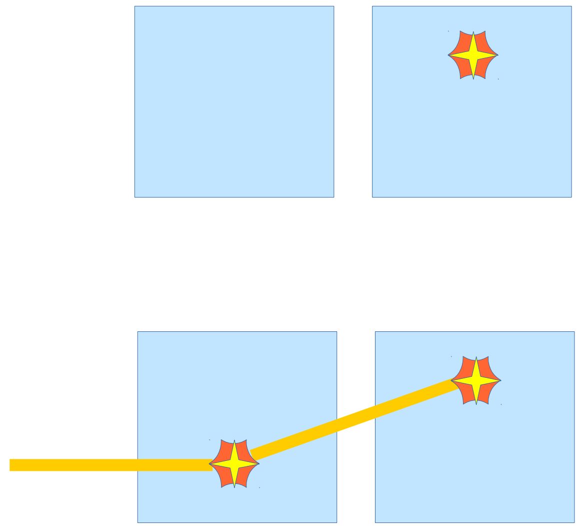


Apply amplitude-to-energy conversion using a calibration function built on known gamma lines

Analysis chain

First level anlysis

- Amplitude estimation
- Thermal gain correction
- Energy calibration
- Event multiplicity



single-hit (signal-like)

double-hit (bkg-like)

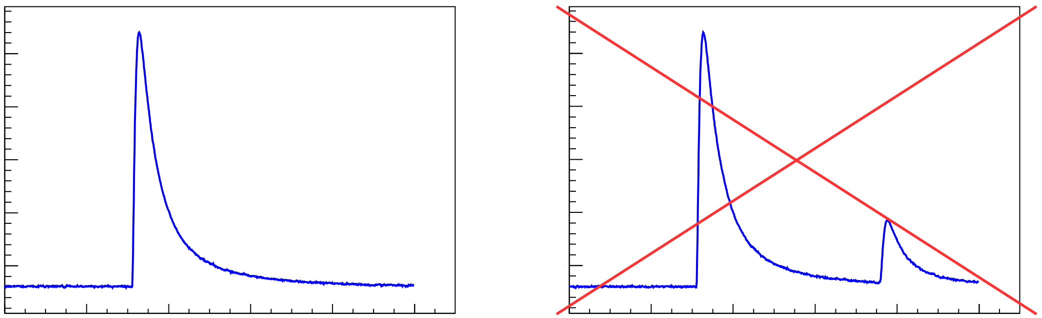
Assign multiplicity and a total energy to each group of events occurred at the same time

An analysis threshold of 150 keV was applied for building coincident events

Analysis chain

First level anlysis

- Amplitude estimation
- Thermal gain correction
- Energy calibration
- Event multiplicity
- Pulse shape analysis



Define pulse-shape parameters that are used to identify and discard non-physical pulses and pile-up

NOTE: no physical background rejection based on pulse-shape is possible in CUORE

Define a distance in the multi-dimensional pulse-shape parameter space

Accept or discard events based on their distance from the centroid of the distribution

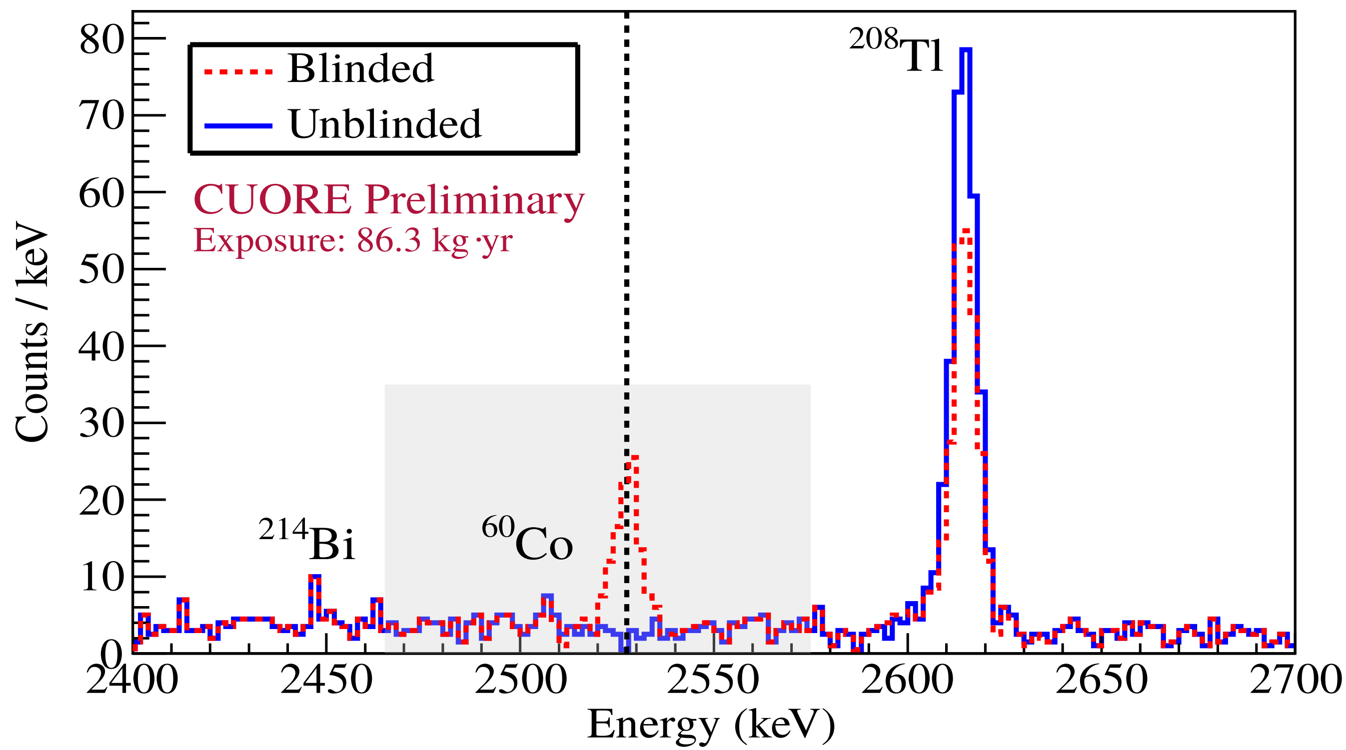
The threshold distance is chosen to maximize the experimental sensitivity

Analysis chain

First level anlysis

- Amplitude estimation
- Thermal gain correction
- Energy calibration
- Event multiplicity
- Pulse shape analysis
- Data blinding

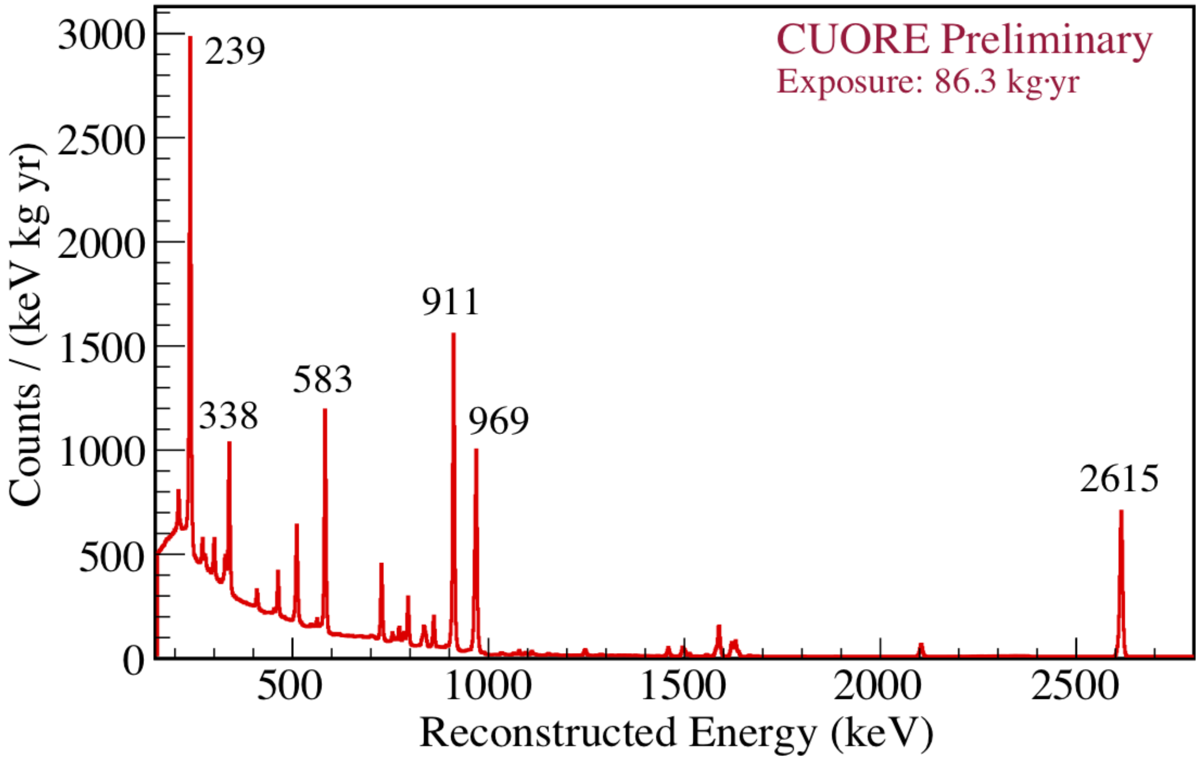
Shift the energy of a “blinded” fraction of events within ±20 keV around 2615 keV down to the energy of $Q_{\beta\beta}$, and vice-versa



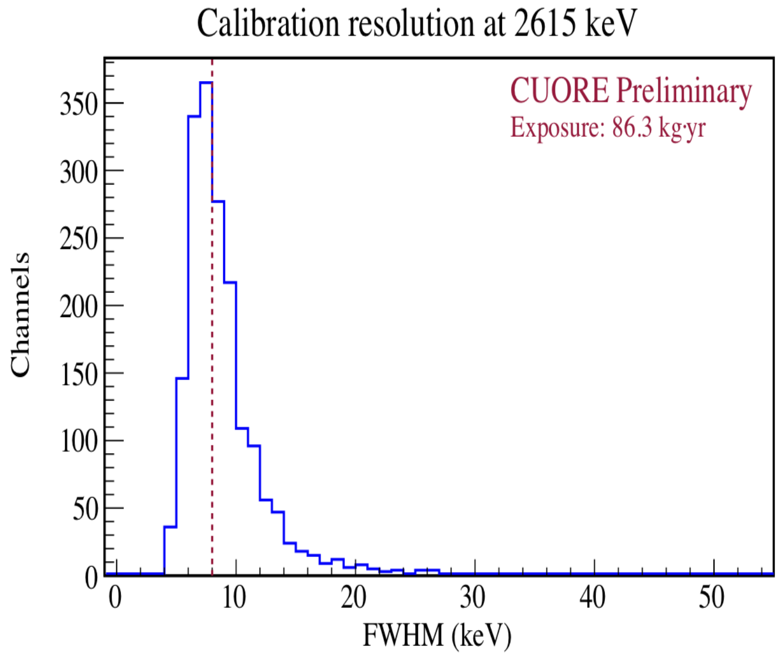
Data are unblinded only when the analysis procedure is fixed

Calibration

Performed on the most intense gamma-lines in the calibration spectrum



239 keV: ^{212}Pb
338, 911, 969 keV: ^{228}Ac
583, 2615 keV: ^{208}Tl

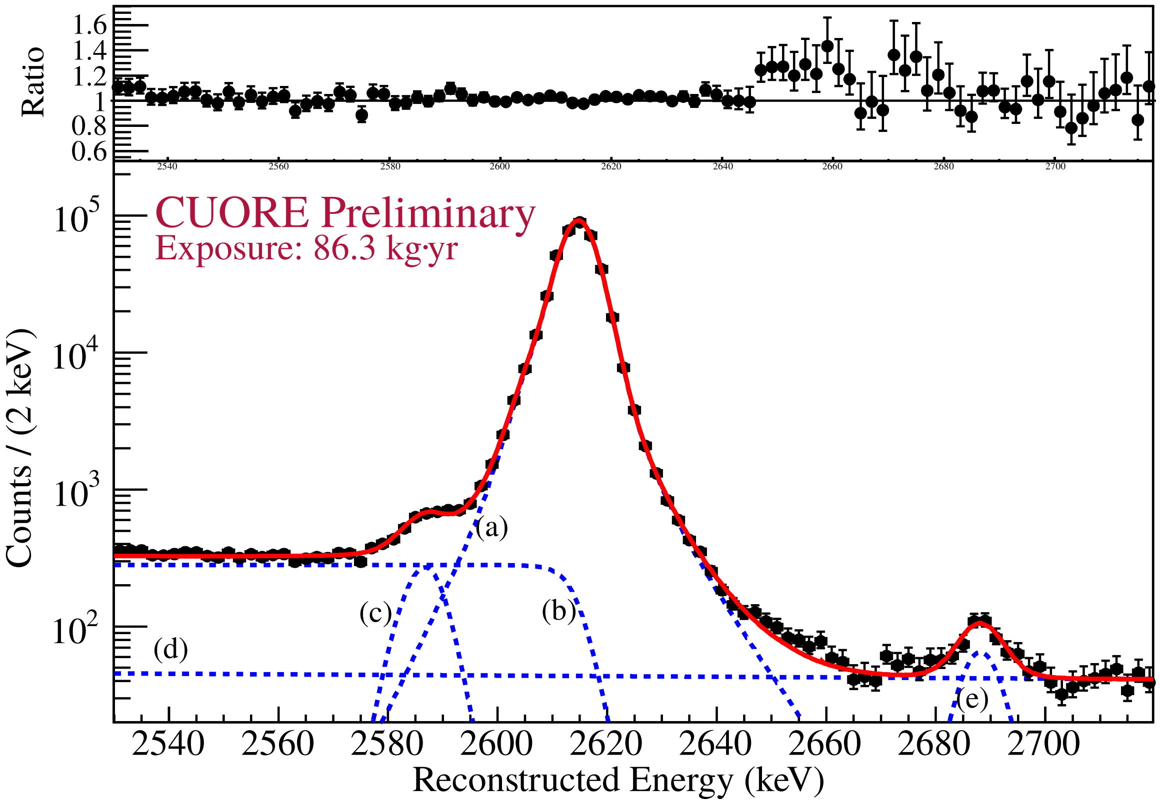


Energy resolution at 2615 keV in calibration

Dataset 1: 9.0 keV FWHM
Dataset 2: 7.4 keV FWHM
Average (exposure weighted): 8.0 keV FWHM

Line shape

The detector response function is evaluated in the high statistics ^{208}Tl peak in calibration runs



Detector response function

- Triple-gaussian shape

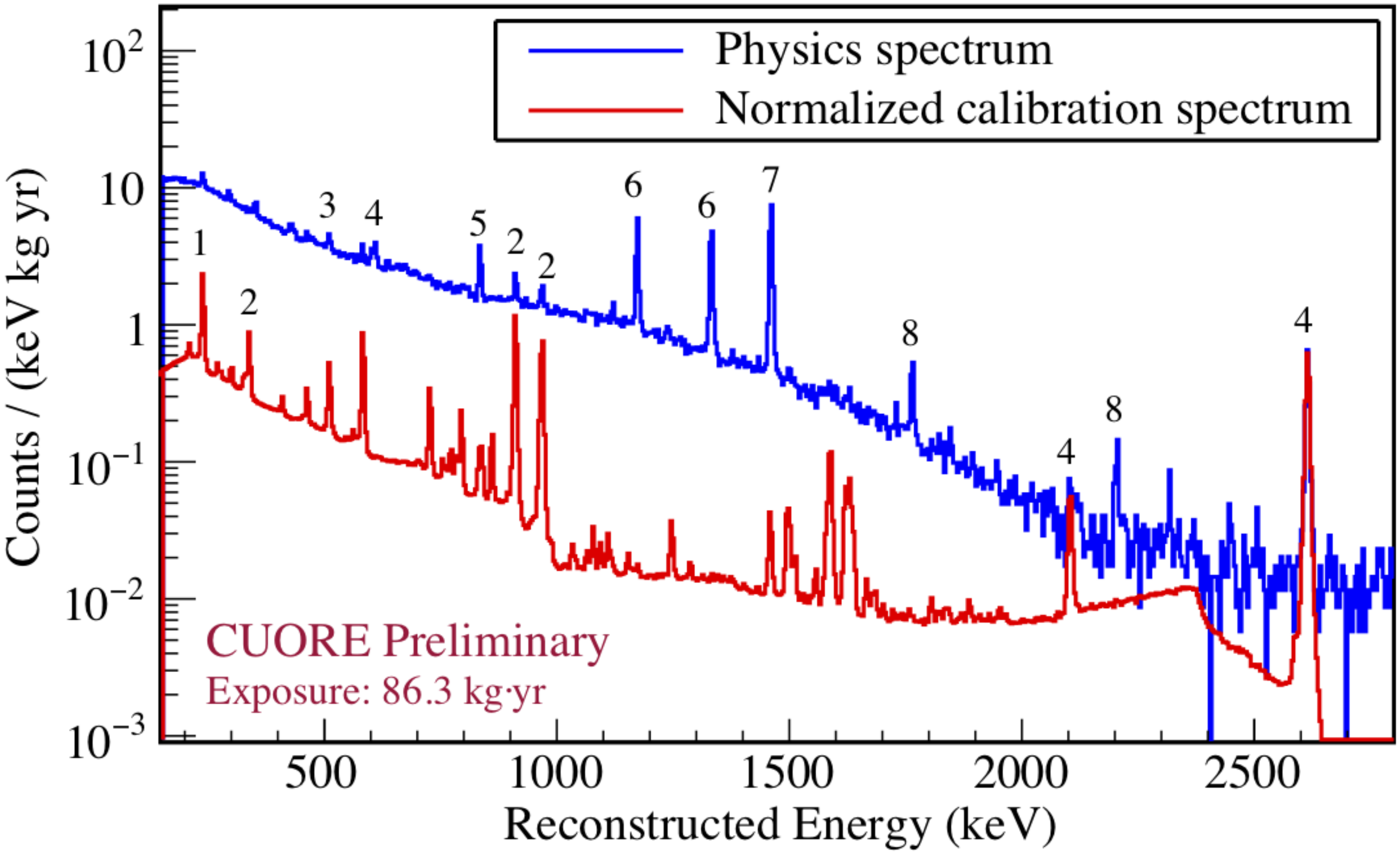
Other fit components

- Step-wise multi-compton background
- linear background
- Te X-rays escape peak
- (2615+583-511) keV peak

Fit performed on a tower-by-tower basis for computational reasons

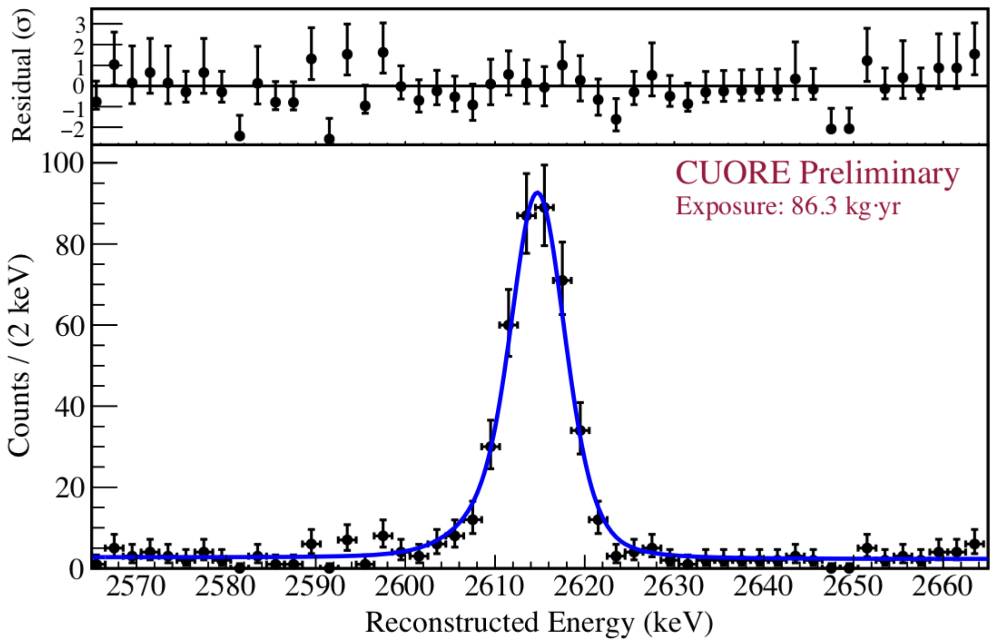
An independent response function is obtained for each channel

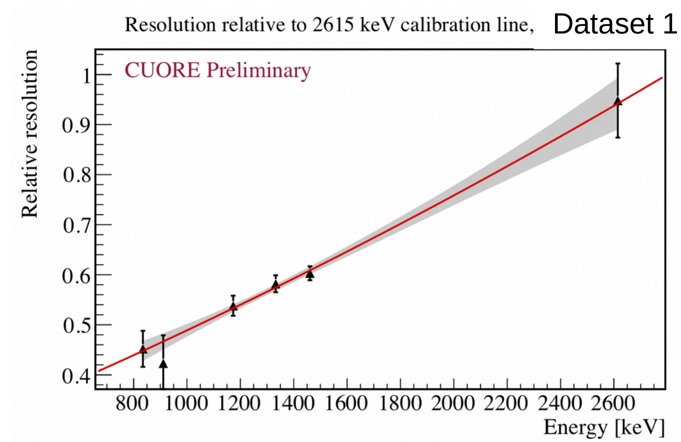
Physics data energy spectrum

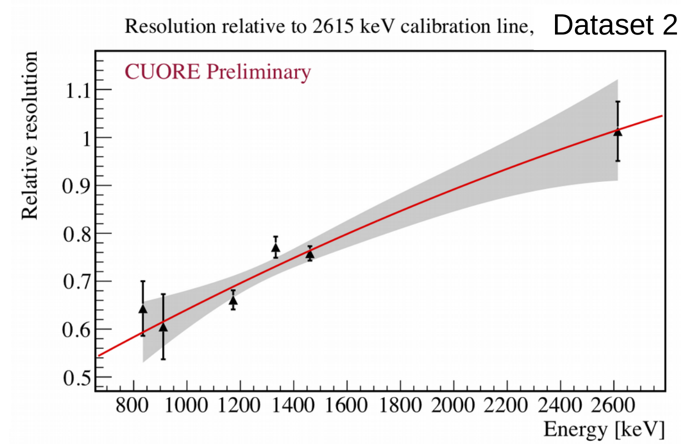


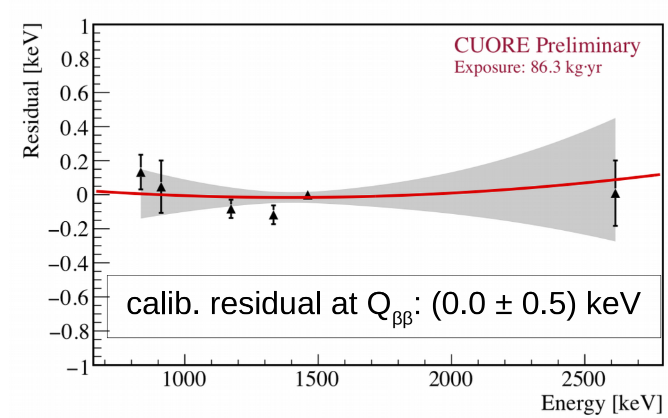
Energy resolution in physics runs

Energy resolution is better in physics runs









Apply a scaling factor to the energy resolution evaluated in calibration runs to obtain the correct energy resolution at $Q_{\beta\beta}$

FWHM in physics runs, at $Q_{\beta\beta}$

dataset 1: (8.3 ± 0.4) keV

dataset 2: (7.4 ± 0.7) keV

average: (7.7 ± 0.5) keV – exposure weighted

Efficiency evaluation

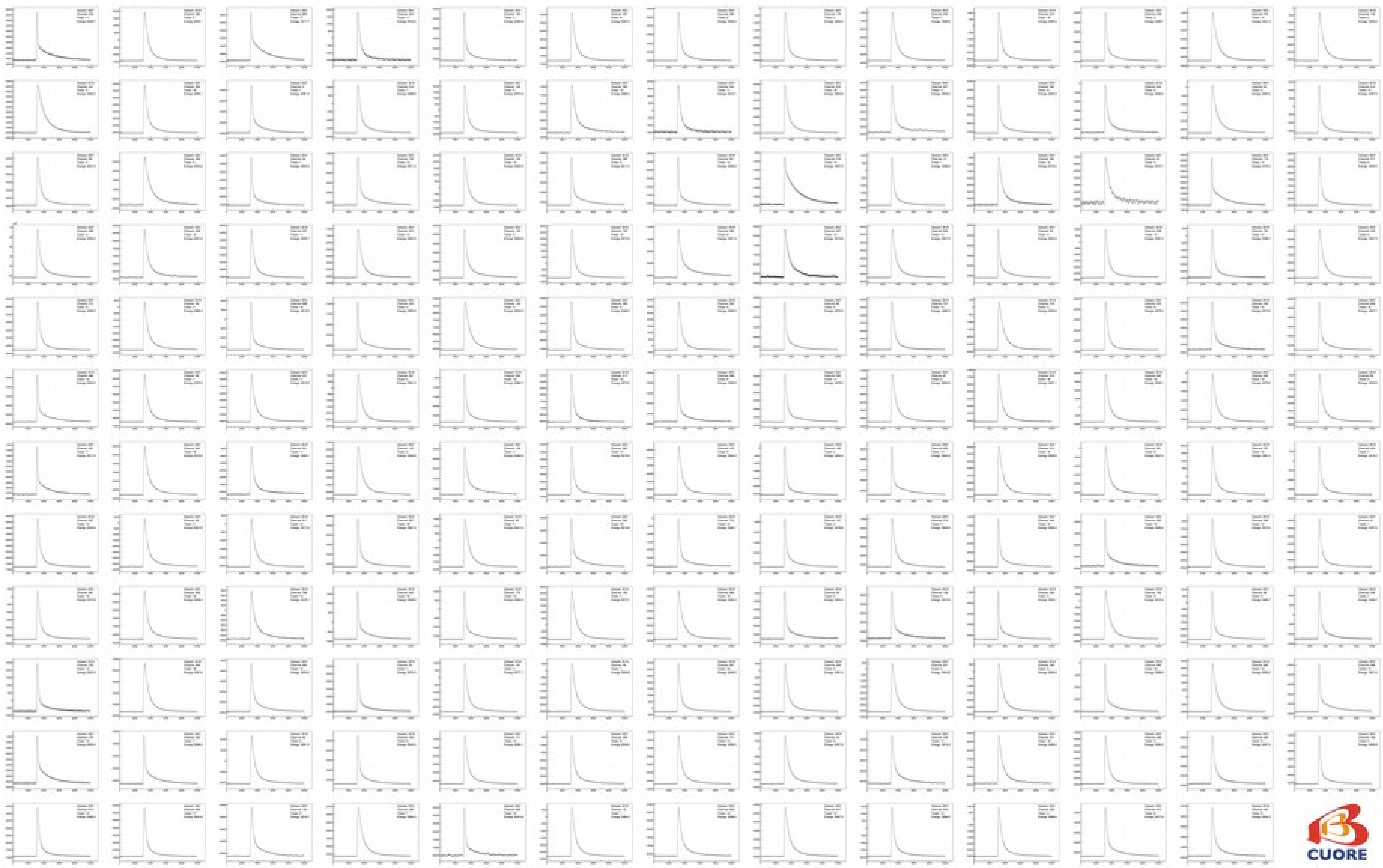
	Dataset 1	Dataset 2
Trigger	(99.766 ± 0.003) %	(99.735 ± 0.004) %
Energy reconstruction	(99.168 ± 0.006) %	(99.218 ± 0.006) %
Base cuts (pile-up, global data quality)	(95.63 ± 0.01) %	(96.69 ±0.01) %
Anti-coincidence	(99.4 ± 0.5) %	(100.0 ± 0.4) %
Pulse shape analysis	(91.1 ± 3.6) %	(98.2 ± 3.0) %
All 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 is performed after discarding periods of low quality data (about 1% of live time)

The $0\nu\beta\beta$ containment efficiency is evaluated from Monte Carlo simulations

All other efficiencies are evaluated on data

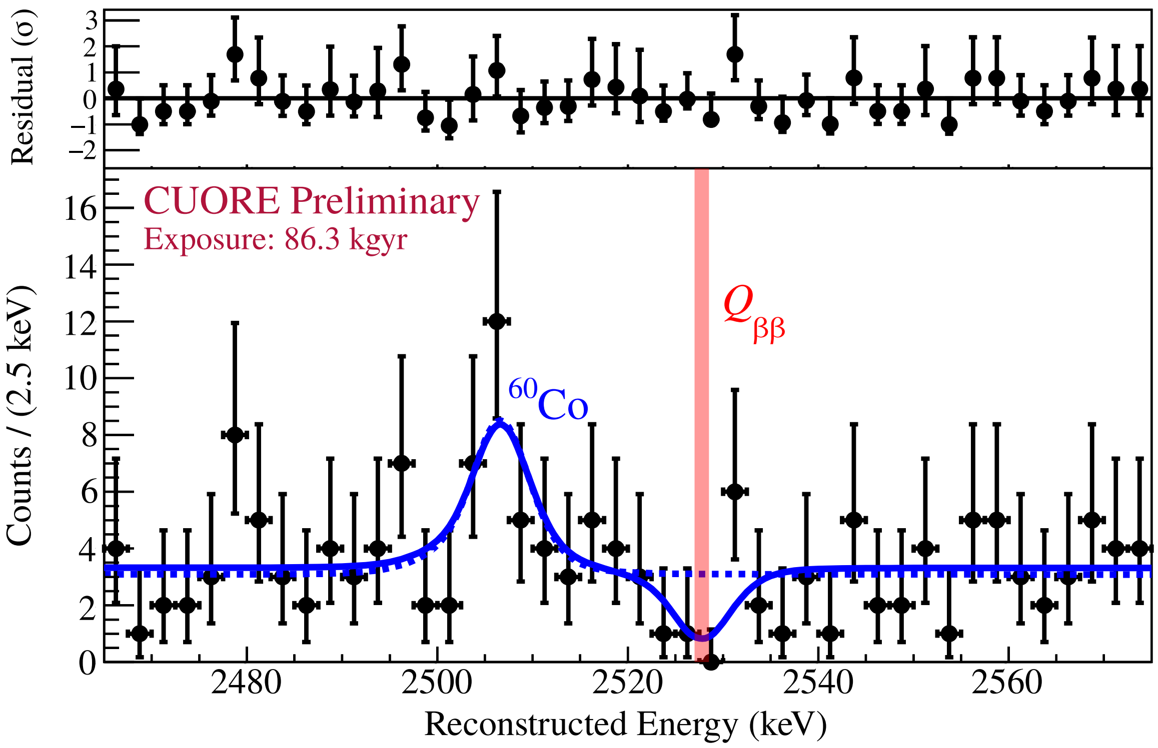
155 Pulses in the ROI



ROI fit

Unbinned extended maximum-likelihood (UEML) fit based on RooFit

Region of interest: (2465 – 2575) keV



Flat background

- common to all channels, but dataset-dependent

^{60}Co sum peak

- floating peak position and rate
- rate common to all channel-dataset pairs

Peak at $Q_{\beta\beta}$

- Fixed position: 2527.518 keV
- floating rate, common to all channel-dataset pairs

signal decay rate best fit: $\Gamma^{0\nu} = (-1.0^{+0.4}_{-0.3}\,(\text{stat}) \pm 0.1\,(\text{syst}))\ 10^{-25}\ y^{-1}$

background index (dataset 1): $(1.49^{+0.18}_{-0.17})\ 10^{-2}$ counts/(keV·kg·y) [efficiency: (75.7 ± 3.0)%]

background index (dataset 2): $(1.35^{+0.20}_{-0.18})\ 10^{-2}$ counts/(keV·kg·y) [efficiency: (83.0 ± 2.6)%]

^{60}Co peak position: (2506.4 ± 1.2) keV

arXiv:1710.07988 (submitted to PRL)

Fit bias and systematics

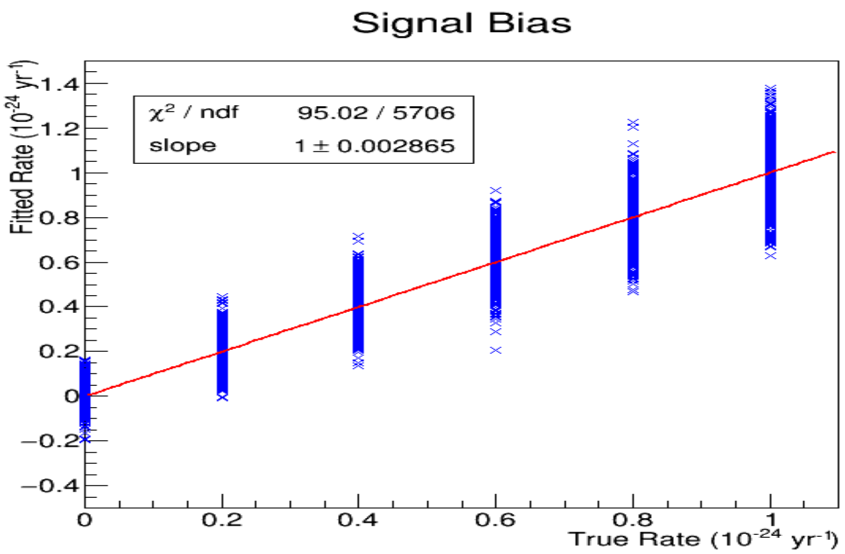
We evaluate the fit bias and systematic uncertainty using toy Monte Carlo

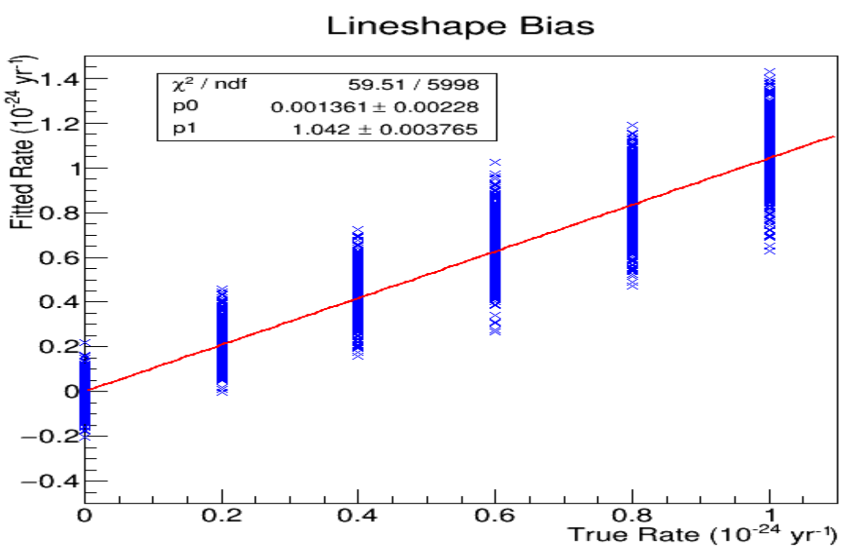
We also include among the systematics the uncertainty on the signal efficiency

No evidence for absolute bias, a 0.3% relative component is present

Systematic uncertainties are treated as uncorrelated and added in quadrature

Parameter	Abs. uncertainty [10^{-24} y^{-1}]	Rel. uncertainty
Energy resolution	–	1.5%
Energy scale	–	0.2%
Fit bias	–	0.3%
Line shape	0.002	2.4%
Efficiency	–	2.4%
Background shape	0.005	0.8%

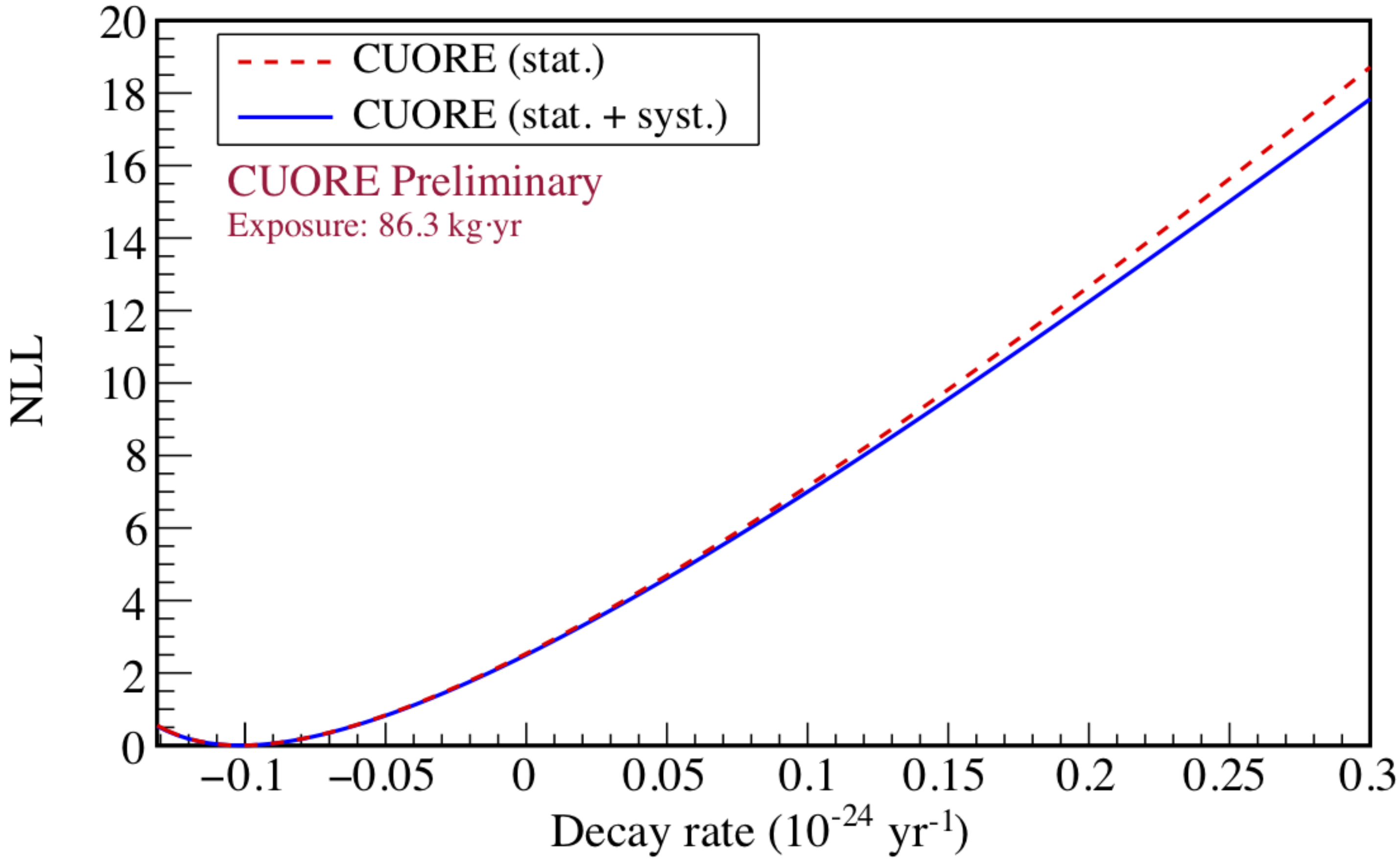




arXiv:1710.07988 (submitted to PRL)

Half-life limit

Profile likelihood integrated in the physical region (decay rate > 0)



$T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ y (90% CL, syst. included)

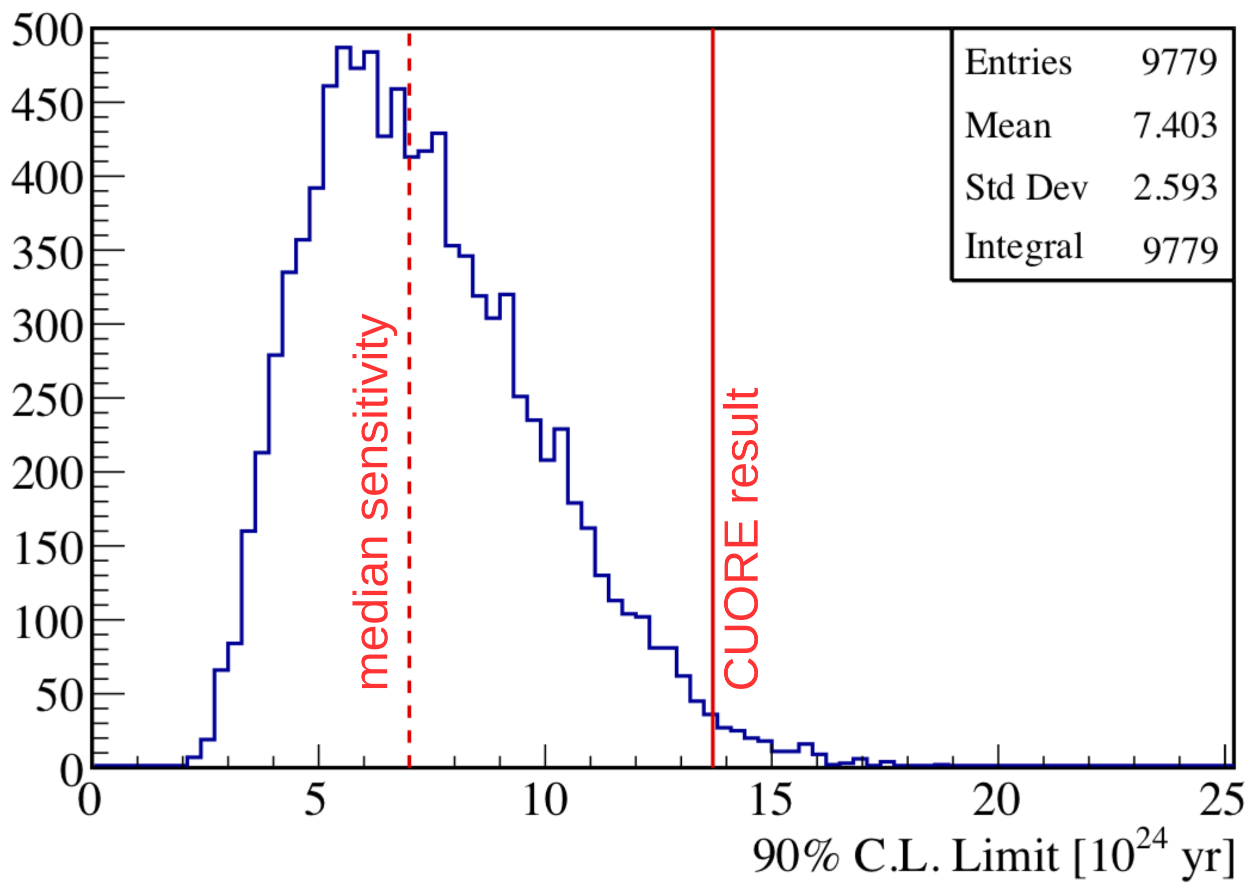
Frequentist "Rolke" limit
(from *NIM A 551 (2005) 493-503)*

stat. + syst: $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$ y (90% CL, syst. included)

arXiv:1710.07988 (submitted to PRL)

Expected half-life sensitivity

Expected sensitivity evaluated with 10000 toy MC with zero signal and background level from best fit

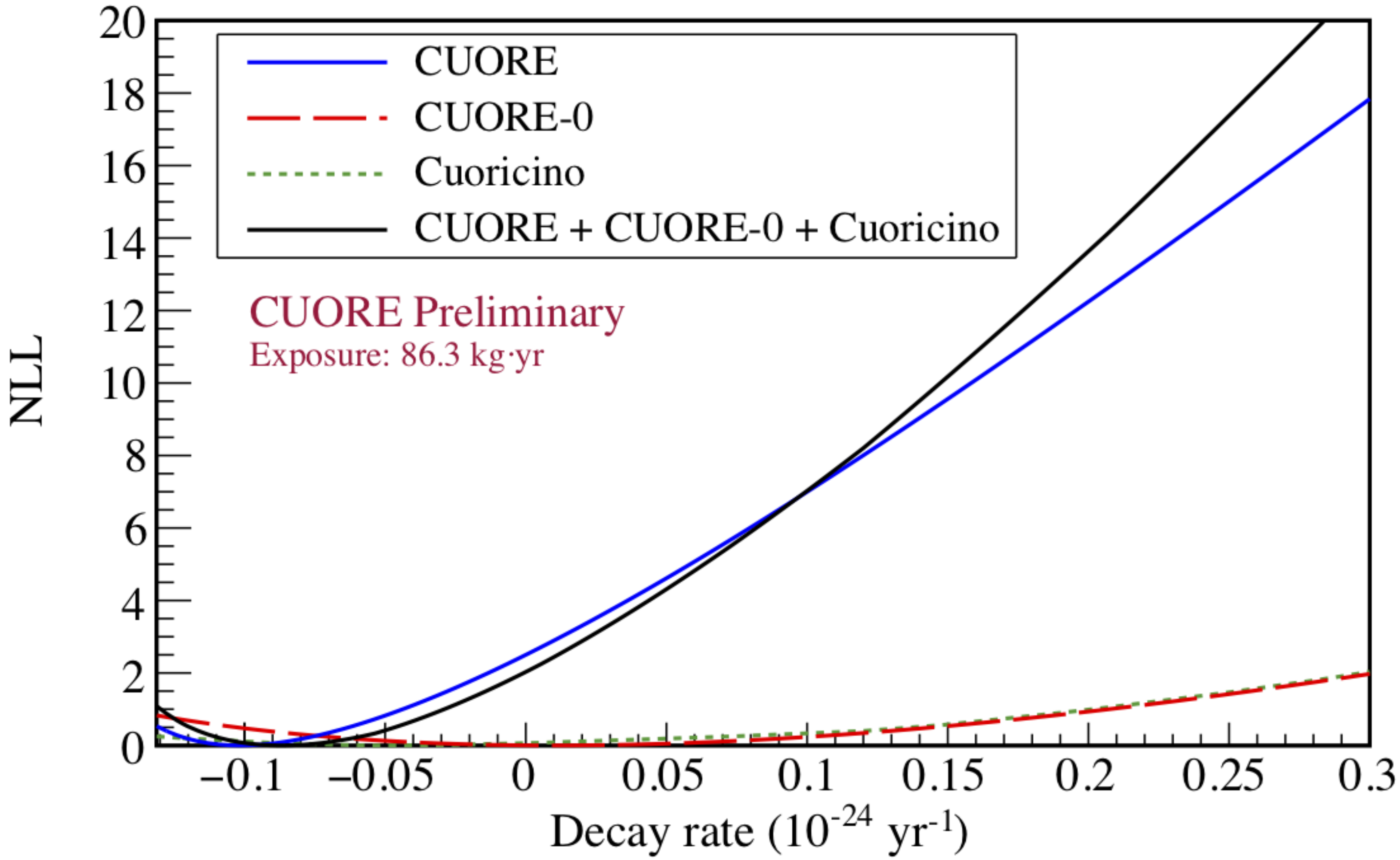


arXiv:1710.07988 (submitted to PRL)

2% probability to get a better limit

Combined limit

Combine CUORE result with CUORE-0 and Cuoricino



CUORE
+ CUORE-0
+ Cuoricino

$T^{0\nu}_{1/2} > 1.5 \times 10^{25}$ y (90% CL, syst. included)

Frequentist "Rolke" limit
(from *NIM A 551 (2005) 493-503)*

stat. + syst: $T^{0\nu}_{1/2} > 2.2 \times 10^{25}$ y (90% CL, syst. included)

arXiv:1710.07988 (submitted to PRL)

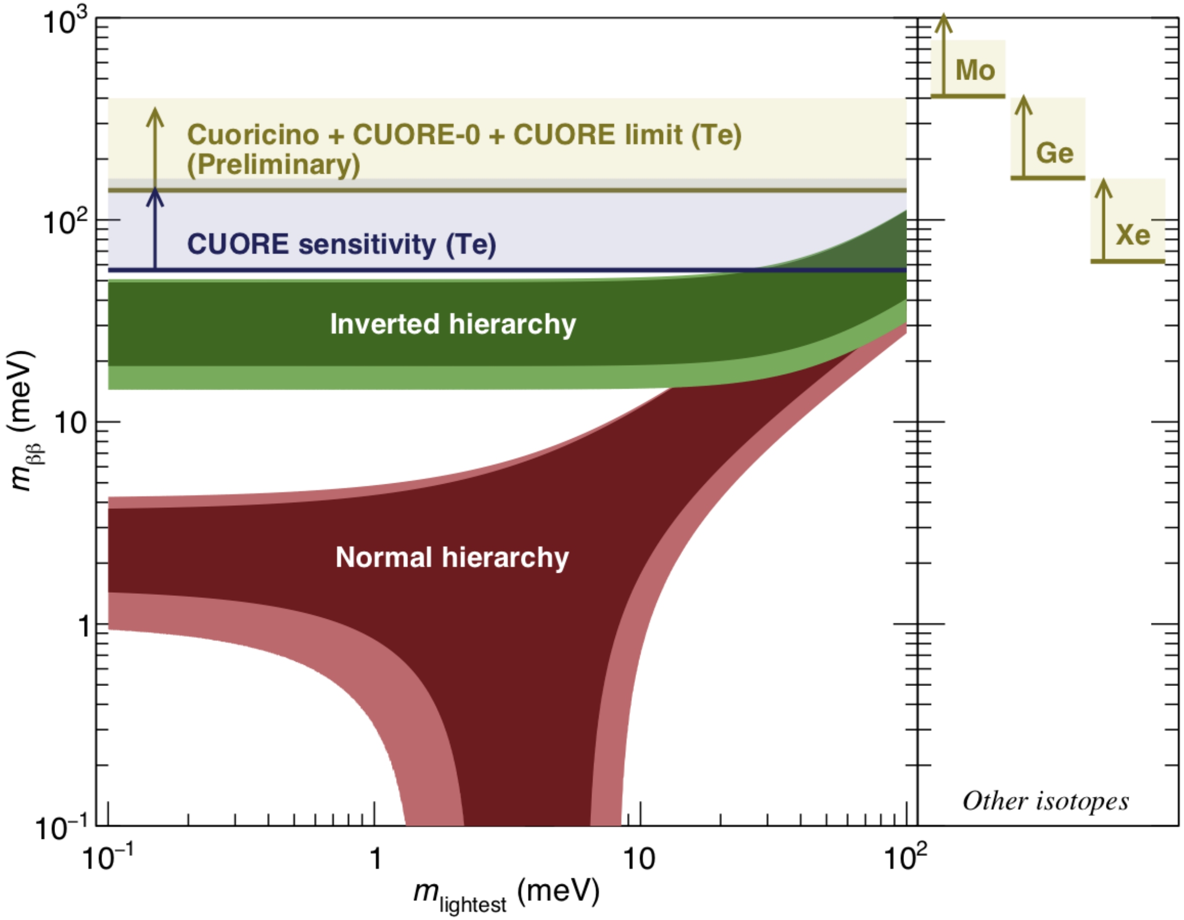
Constraint on $m_{\beta\beta}$

half-life limits

^{130}Te: 1.3 × 10^{25} yr – this analysis
^{76}Ge: 5.3 × 10^{25} yr – *Nature 544 (2017), 47-52*
^{136}Xe: 1.1 × 10^{26} yr – *Phys. Rev. Lett. 117 (2016), 082503*
^{100}Mo: 1.1 × 10^{24} yr – *Phys. Rev. D 89 (2014) , 111101*

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)



this result

$T_{1/2} > 1.5 \times 10^{25}$ y

$m_{\beta\beta} < 140 – 400$ meV

CUORE sensitivity in 5y

$T_{1/2} > 9.0 \times 10^{25}$ y

$m_{\beta\beta} < 50 – 130$ meV

Conclusion

- CUORE started data taking at LNGS in April 2017
- The detector is working well and there is still room for improvement
- We discussed the first CUORE results on neutrinoless double-beta decay

  Exposure: 86.4 kg·y

  Background index: $(1.4 \pm 0.2) \times 10^{-2}$ counts/(keV·kg·y)

  Energy resolution at $Q_{\beta\beta}$: (7.7 ± 0.2) keV

  Half-life limit: $T_{1/2} > 1.5 \times 10^{25}$ y at 90% CL

- Results on other processes are on their way