CUORE

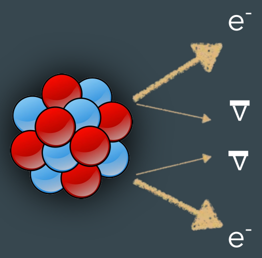
INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

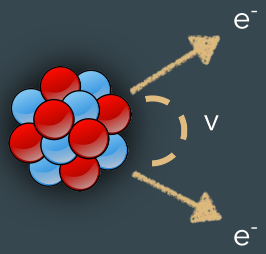
0νββ Search Results from One Tonne-Year of CUORE Data

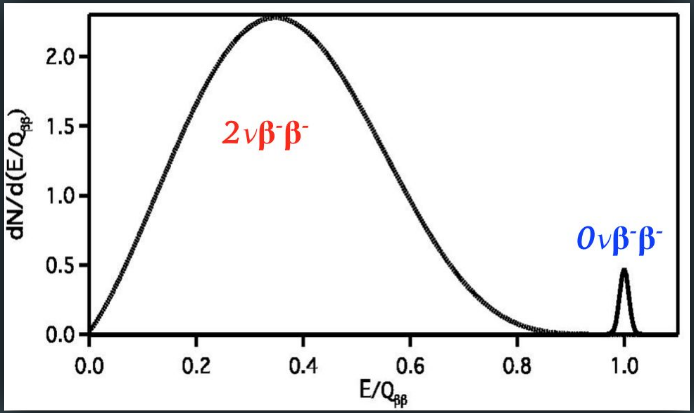
- Introduction to the CUORE Experiment
- Data Taking
- Events Reconstruction
- $0\nu\beta\beta$ Decay Analysis
- Results

Physics goal

Double Beta Decay is a second order weak interaction, only directly observable for few nuclei, for which the standard Beta Decay is suppressed or forbidden (even - even nuclei)



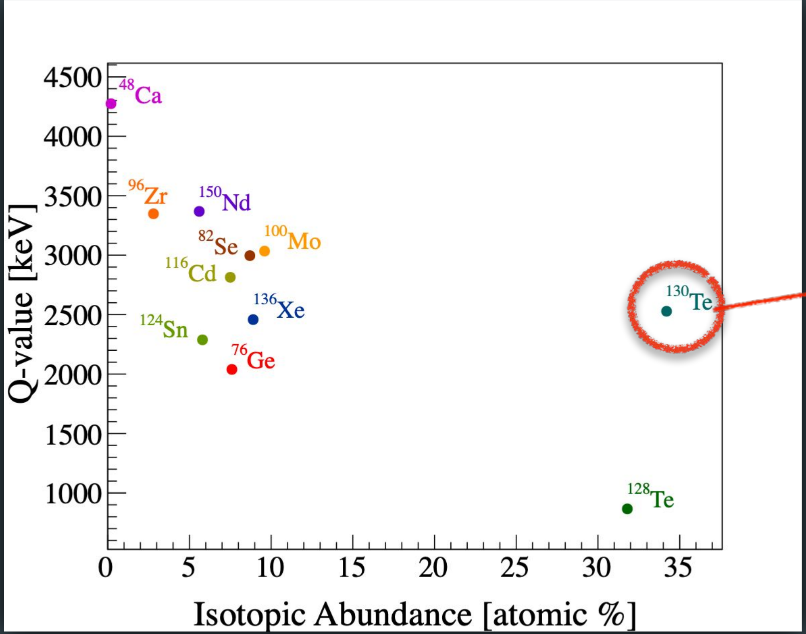




Signature:
peak at the Q-value of ßß decay spectrum

0νββ decay is a lepton-number violating process that can occur only if neutrinos are Majorana fermions.
The discovery of 0νββ decay would demonstrate that lepton number is not a symmetry of nature and that neutrinos are Majorana particles.

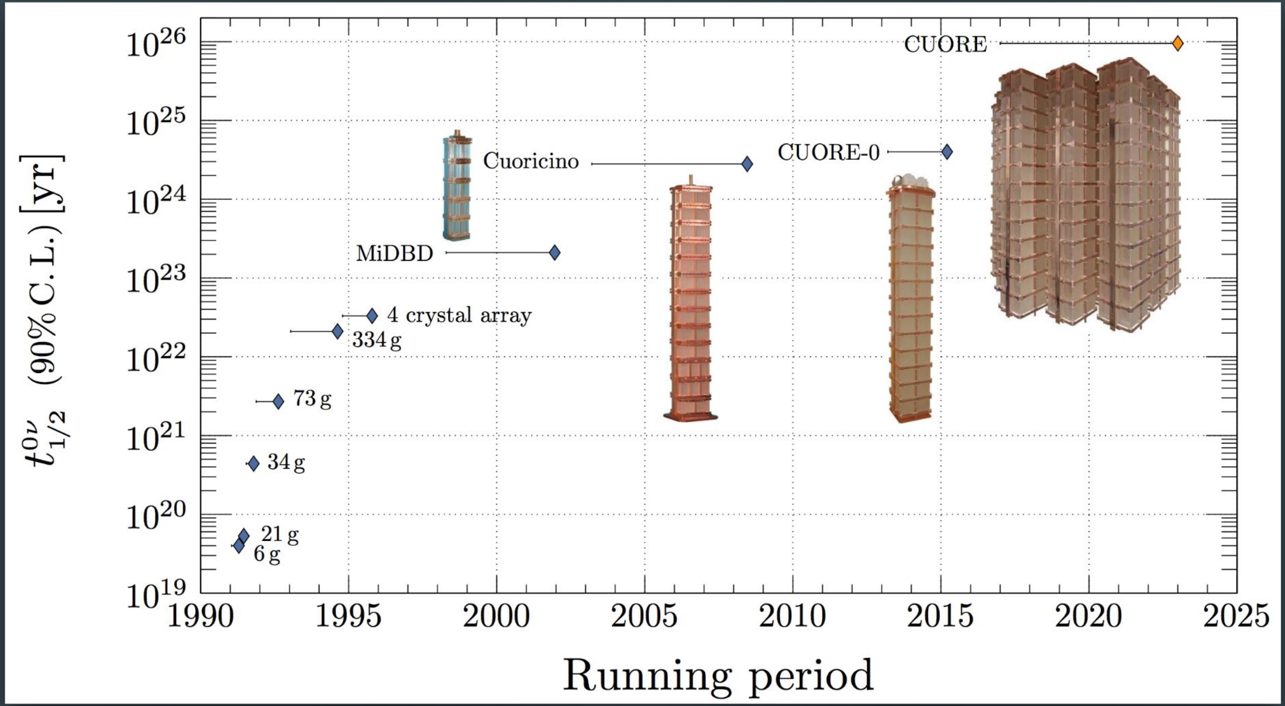
Why Tellurium?



^{130}Te is chosen for:

- high isotopic abundance (34.17%) allows the use of natural Tellurium
- ^{130}Te within the detector absorber of TeO_2 (high detection efficiency)
- Q-value of 2527.515 ± 0.013 keV in a region with low beta/gamma background
- reproducible growth of high quality crystals

SOME HISTORY



30 years of experience in searching for 0vBB decay using the bolometric technique, starting from the pioneering work of Ettore Fiorini.

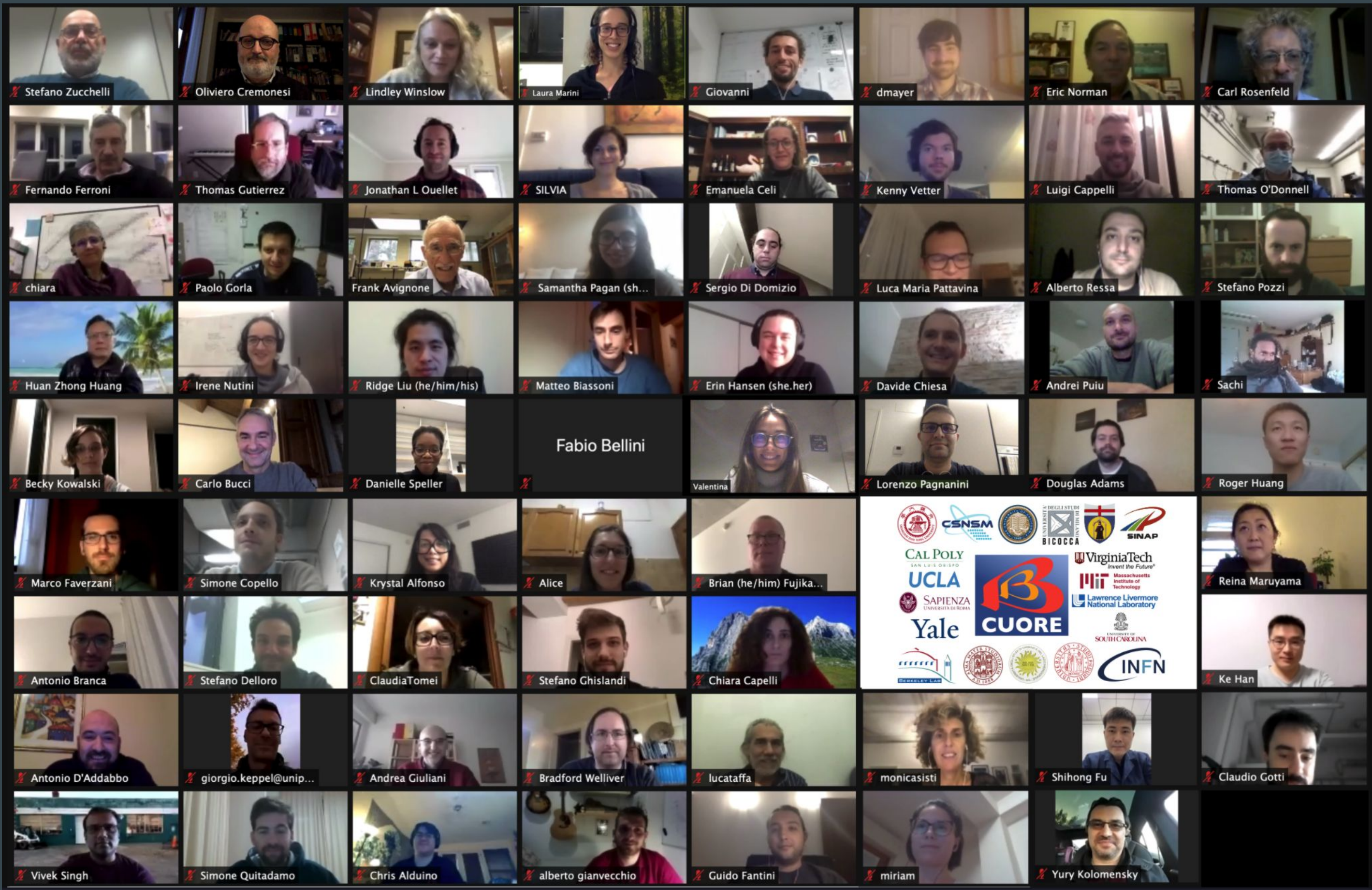
CUORE is the last of a long series of experiments, from few grams to 742 kg of detector material.

CUORE is the first tonne-scale bolometric experiment in the world.

THE COLLABORATION

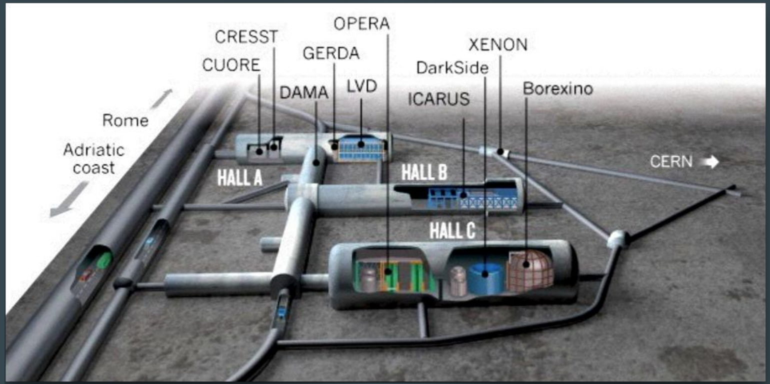
113 collaborators

from 27 institution
in 4 countries:
China
France
Italy
United States



CUORE @ LNGS - ITALY

CUORE is in Hall A



The mountain of Gran Sasso naturally protects the experiment from cosmic rays

CUORE @ LNGS - ITALY

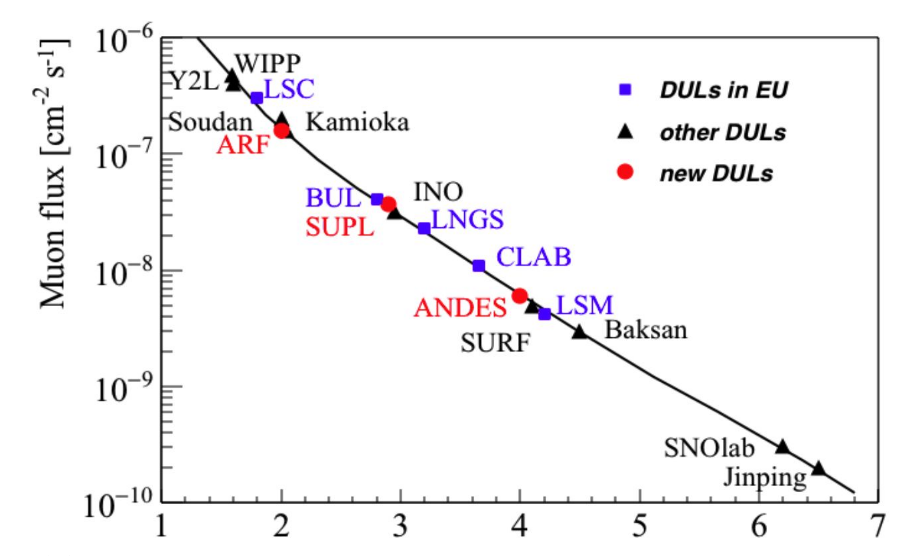
Laboratori Nazionali del Gran Sasso:

3600 m.w.e. deep

muons: ~3×10^{-8}/(s cm^2) -> 10^6 less than above ground

gammas: ~0.73/(s cm^2)

neutrons: < 4×10^{-6}/(s cm^2)



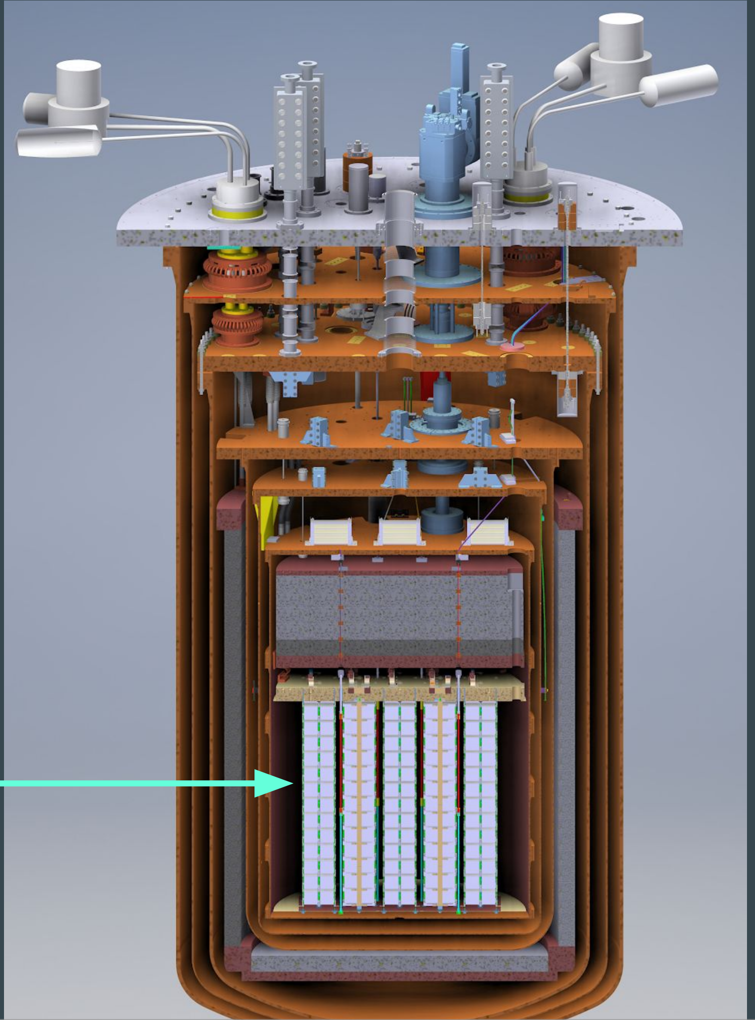
Aldo Ianni

CUORE

Cryogenic Underground Observatory for Rare Events

988 TeO_2 crystals 5x5x5 cm^3
arranged in 19 towers with 13 floors

natural TeO_2 crystals (742 kg)
130Te active isotope (206 kg)
$Q_{\beta\beta}$ ~ 2527.52 keV
Source = detector
$0\nu\beta\beta$ containment ε ~ 88%
984 active channels!

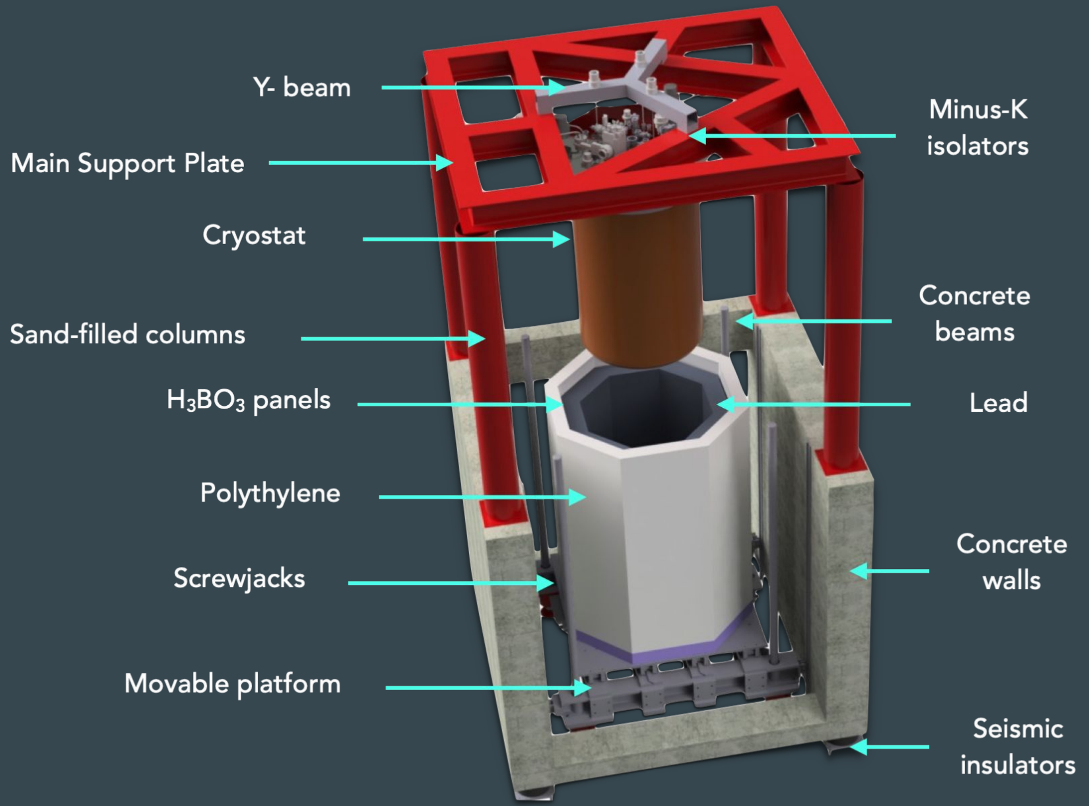


CUORE

The CUORE detector is hosted in a cryogen-free cryostat:

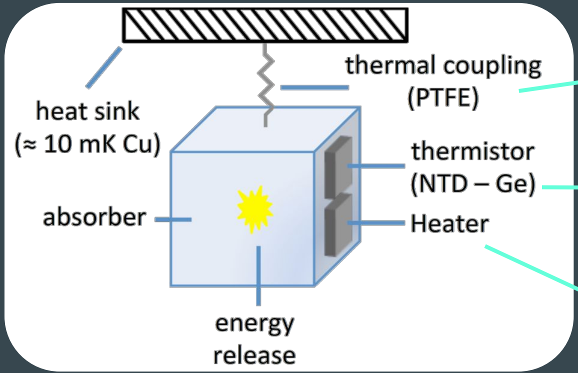
World leading cryostat in size and power

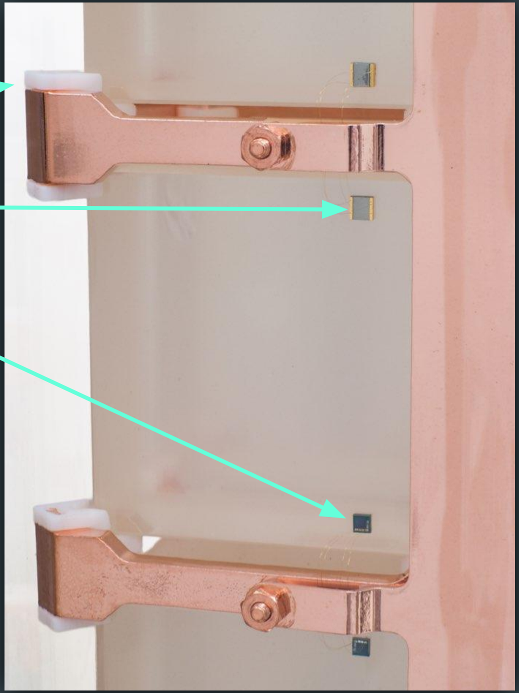
- Mass to be cooled < 4K: ~15 tonnes (Pb, Cu and TeO_2) and 3 tonnes to below 50 mK
- Five 1.2 W (@ 4.2 K) Cryomech pulse tube cryocoolers
- DU from Leiden Cryogenics (10 mK: 4 μW cooling power)
- Operating temperature ~10 mK
- Designed to guarantee extremely low radioactivity (material selection and cleaning)
- Low vibrations environment (passive and active noise mitigation techniques)

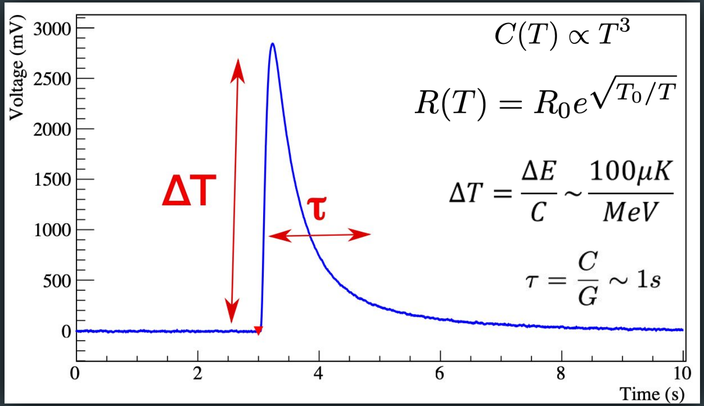


Bolometric technique

A particle interaction in the absorber causes an increase in temperature, measured by the thermistor







C: absorber capacity
ΔT: temperature variation
ΔE: energy deposition
G: thermal conductance
τ: signal decay time

Challenges

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{ln2}{n_\sigma}\frac{N_A i \varepsilon}{A}\sqrt{\frac{Mt}{B\Delta E}}$$

large exposure (mass x time)

- 988 TeO_2 crystal with isotopic abundance of 34.167% for a total mass 206 kg of active material
- foreseen 5 years of data taking

Achievements:

- ➢ 2 years of uninterrupted data taking
- ➢ high stability of the cryogenic apparatus
- ➢ more than 1 tonne-year of exposure accumulated

high energy resolution

- noise reduction techniques
- temperature stability
- fine tuning of detectors parameters to optimize the signal to noise ratio

Achievements:

- ➢ < 8 keV FWHM @ Qββ
- ➢ ongoing studies for vibrational and microphonic noise mitigation and decorrelation

low background

- strict radiopurity selection on materials
- low background assembly environment
- passive shields from external and cryostat radioactivity

Achievements:

- ➢ measured background index in agreement with the expectations

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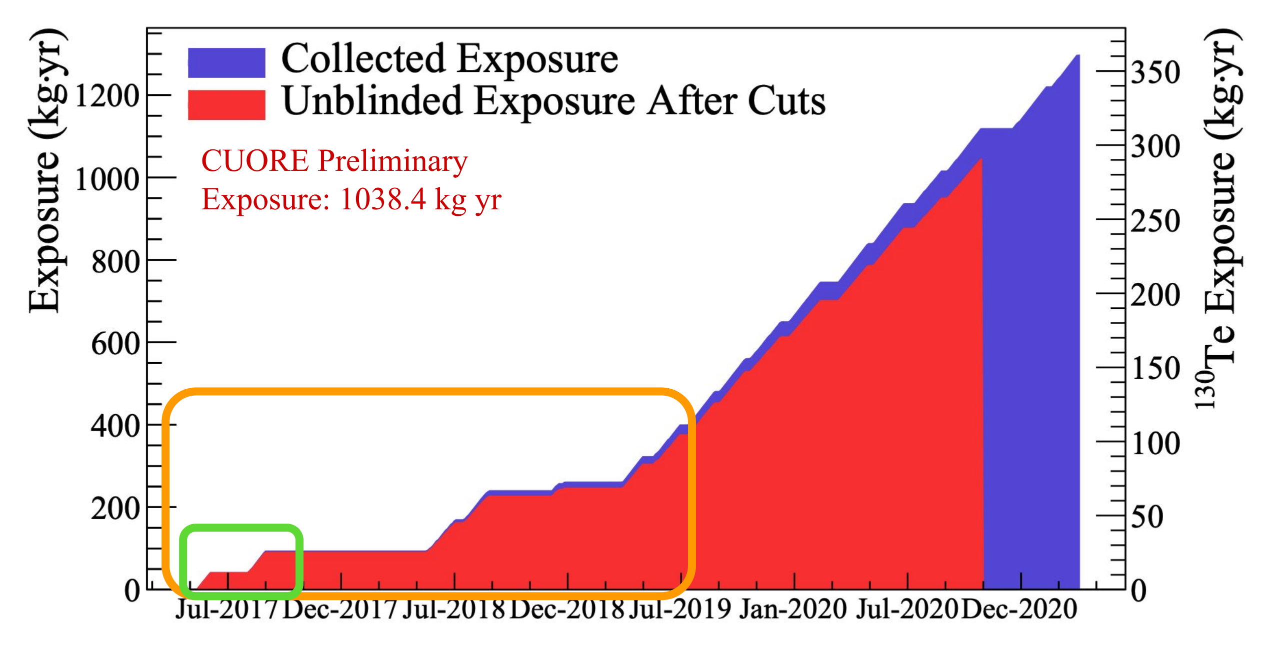
Data taking

More than 1298 kg yr of raw exposure acquired (17 datasets)

Data unblinded in 2021 - current analysis 1038.4 kg yr

Data published in PRL 124.122501 (2020) 372.5 kg yr

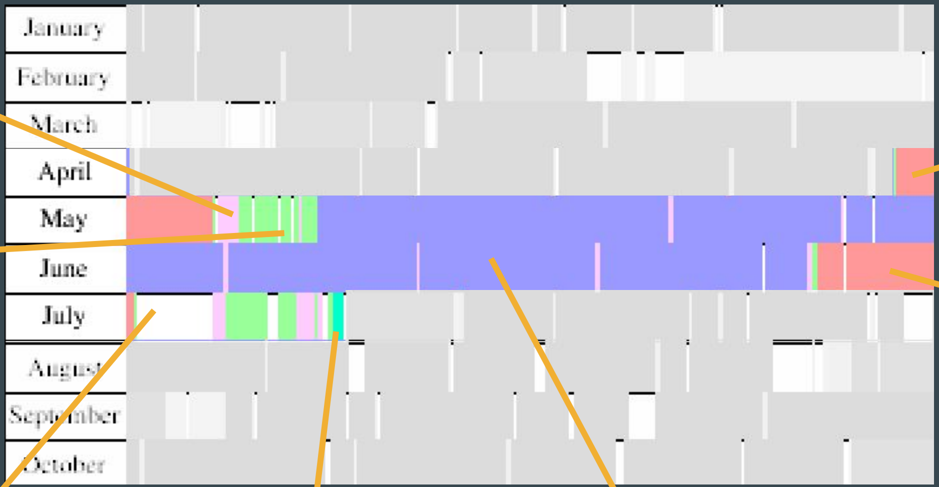
Data published in PRL 120.132501 (2018) 86.3 kg yr



Typical Dataset

setup runs / NTD resistance measurements

test runs during maintenance/ PT-induced noise optimization



initial calibration

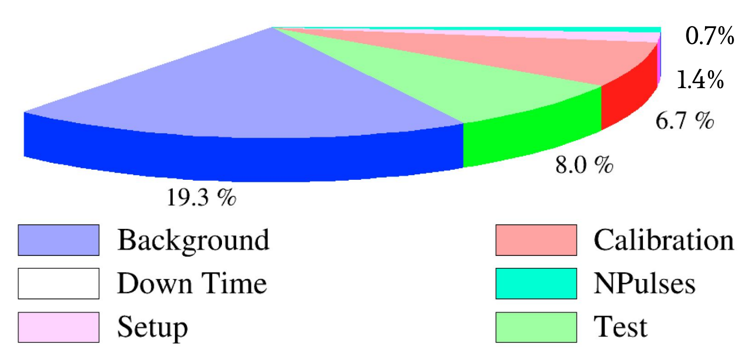
final calibration

failed runs due to earthquakes + recovering

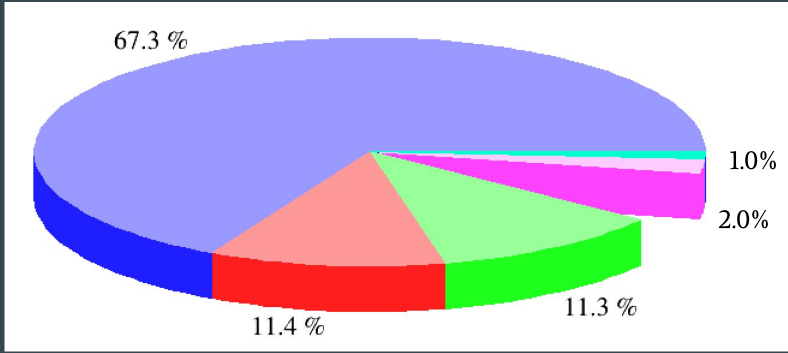
trigger thresholds evaluation run

physics data used for $0\nu\beta\beta$ decay analysis

Duty Cycle



Up to December 2018



From January 2019 up to now

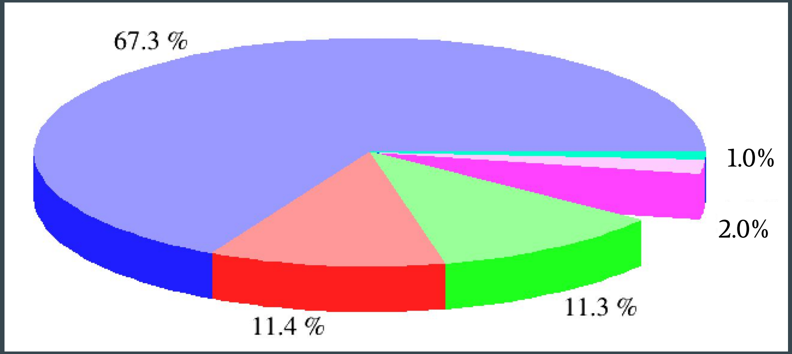
After the cryogenics interventions at the beginning of 2019 our duty cycle improved from 35.8% (19.3% physics data) to 93% (67.3% physics data)

since 2019 we accumulate an average of 69 kg yr/month

Duty Cycle

The improvement in duty cycle is mostly due to:

- **Use of an external calibration system**
  - Quick calibration string deployment
  - No interference with the cryogenic system
- **Routine maintenance to preserve the good performance of the cryogenic system**
  - Preemptively deals with potential problems before they have an effect on detector performance
  - Avoids unexpected downtime from sudden issues
- **Remote monitoring**
  - 24h / 7 days a week remote control of the system for quick response and online data quality evaluation
  - Reduced need for test runs



From January 2019 up to now

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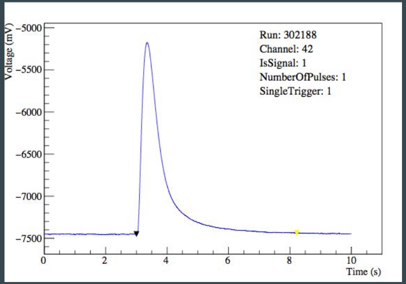
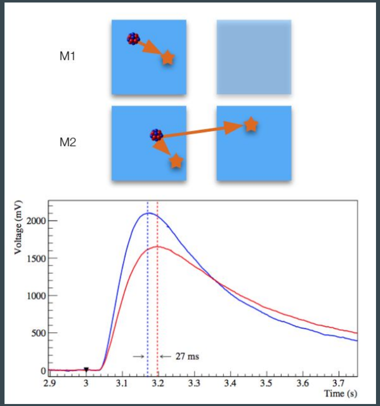
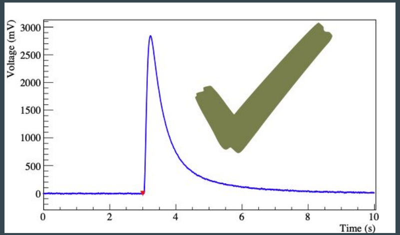
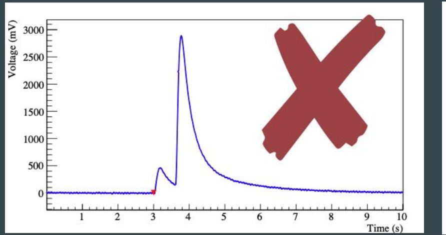
Event reconstruction

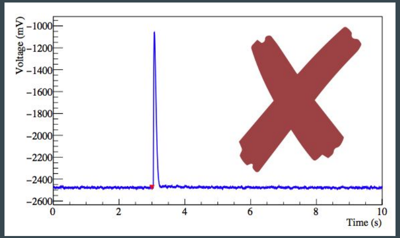


Optimum Filter → Gain Correction → Energy Calibration → Coincidences → Pulse Shape Discrimination → Blinding of the ROI → Data quality selections → Unblinding









Optimum Filter

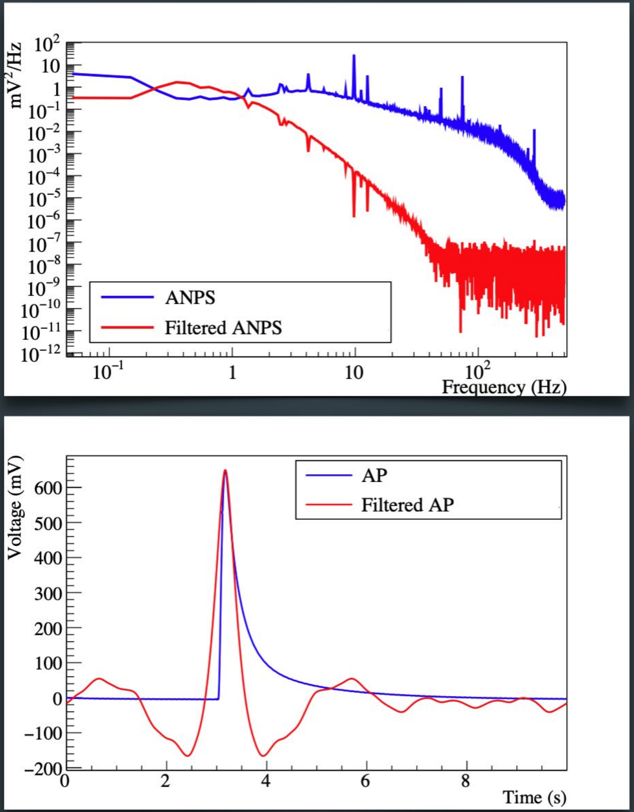
OF is a matched filter that maximizes the signal to-noise ratio.

$$H(\omega_k) = h\frac{s^*(\omega_k)}{N(\omega_k)}e^{-j\omega_k i_{max}}$$

transfer function directly proportional to the signal to noise ratio

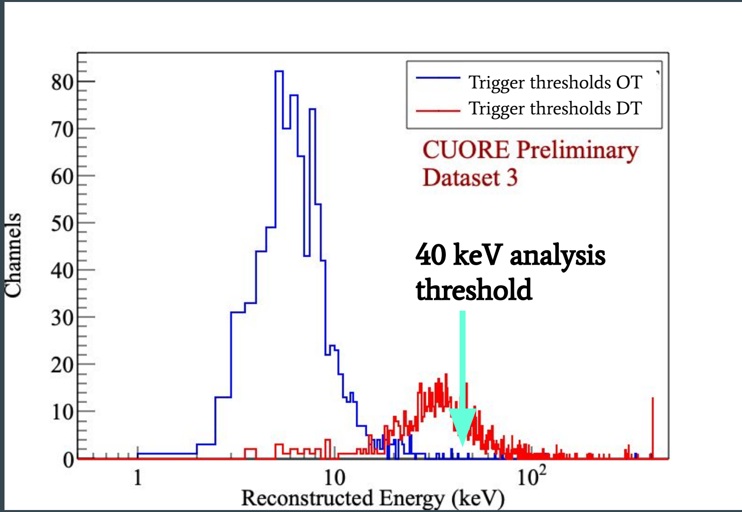
typical noise for each channel-dataset

ideal signal for each channel-dataset



We trigger our continuous waveforms and we evaluate the pulses amplitude on the Optimum Filtered data.

Retriggering with OT



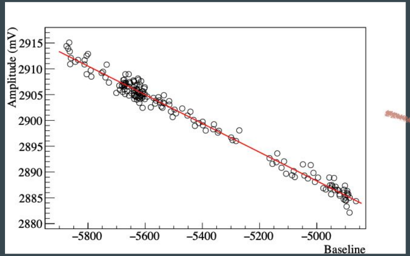
After an online analysis for a quick turn-around on the data quality, the continuous stream of data acquired is re-triggered using the Optimum Trigger (OT) technique.

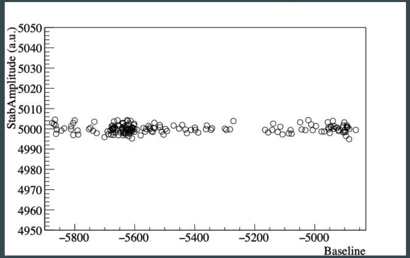
OT allows to disentangle low energy signals from fake signals produced by noise, lowering the detectors trigger thresholds

- OT algorithm: identifies a signal when the amplitude of the filtered signal waveform exceeds a configurable threshold
- trigger thresholds can be as low are few keV
- 40 keV analysis threshold guarantees that 97% of the channels have a trigger efficiency above 90%
- 40 keV analysis threshold minimizes ROI events contributions from multi-Compton scattered 2615 keV γ events

Thermal gain stabilization

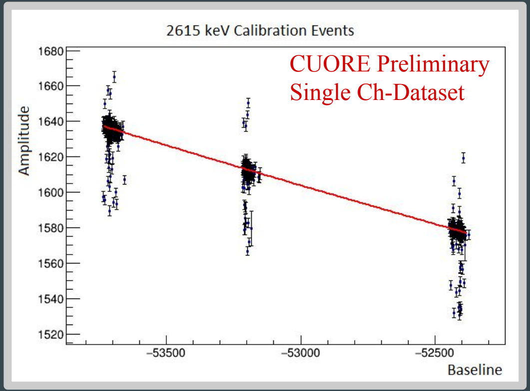
HEATER THERMAL GAIN STABILIZATION:
We use heater events at a fixed energy to study the amplitude dependence for small variations of
the operating temperature.
Then we correct the amplitude gain variations.





CALIBRATION THERMAL GAIN STABILIZATION:
We stabilize the 2615 keV γ peak from the opening and closing calibrations, interpolating from the baseline values we have data at

- Used for <10% of channels, with non-functional or underperforming heaters



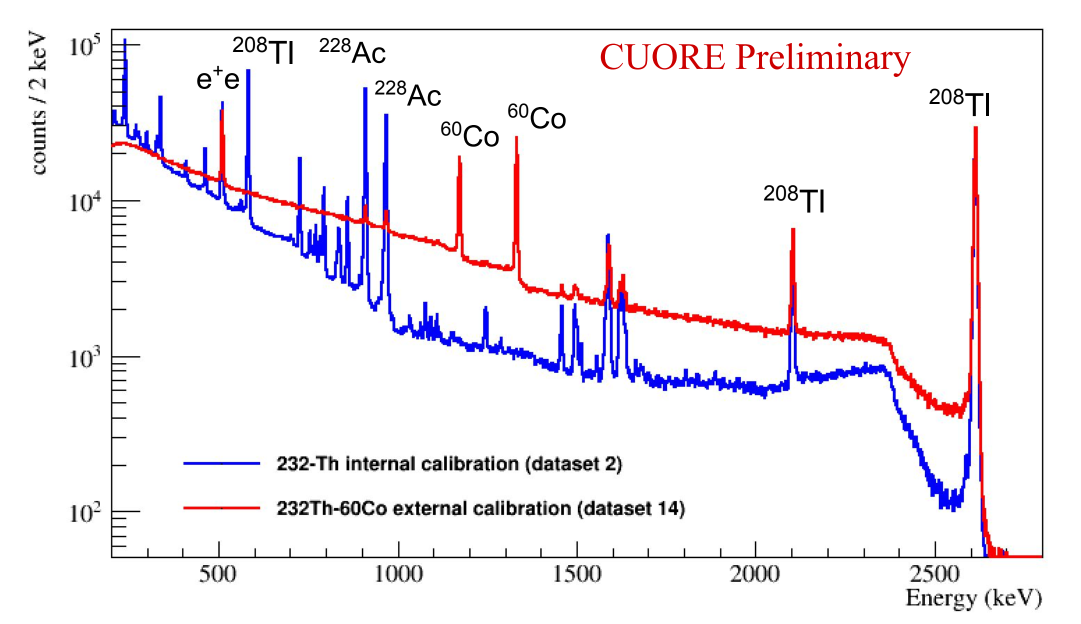
Calibration

First 3 datasets were calibrated with an internal ^{232}Th source

- This internal calibration system was phased out for a simpler external calibration system in the later datasets

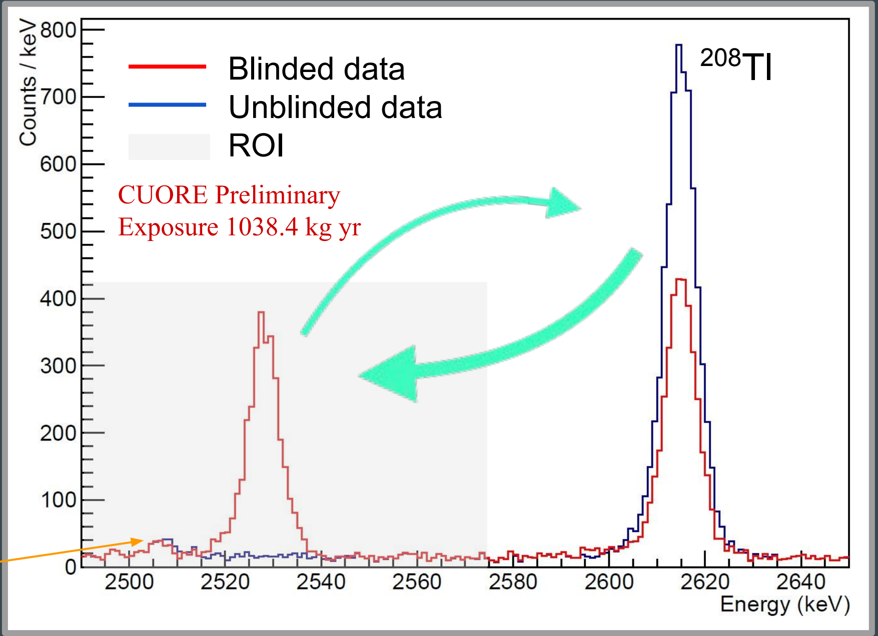
Data is now calibrated with an external ^{232}Th-^{60}Co source

- 2nd order polynomial calibration function with 0 intercept to fit to the 511, 1173, 1333, and 2615 keV calibration lines



Blinding

The blinding algorithm takes a random fraction of the events from the ^{208}Tl line and shift them around the $Q_{\beta\beta}$ and vice versa. The original energies remain encrypted until unblinding.
The unblinding occurs only after the full analysis procedure has been fixed.



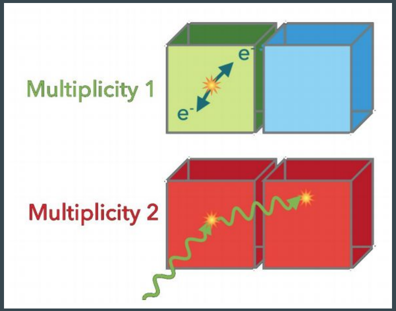
^{60}Co Sum Peak

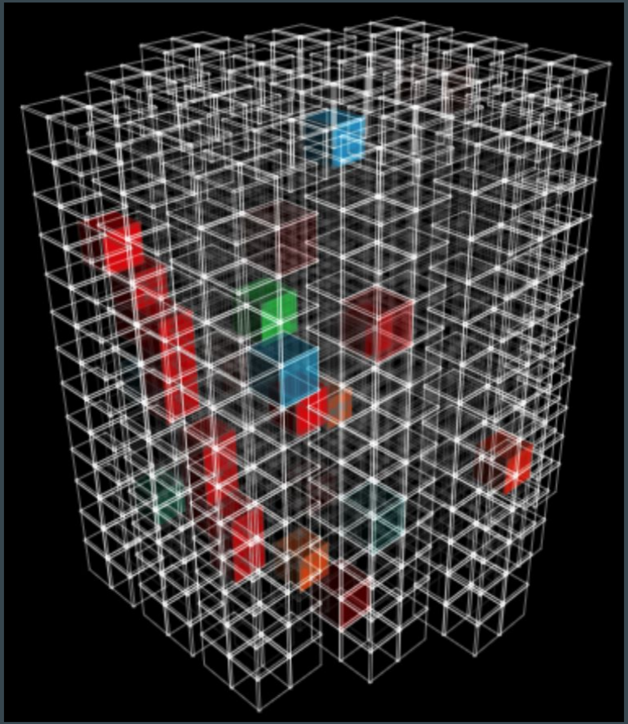
Coincidences

88% of $0\nu\beta\beta$ decay events deposit all of their energy in one crystal

When more than one bolometer fires in a small time window, the event is likely to be due to radioactive contaminations or muon-induced events.

We assign multiplicity and total energy to such events and select only the ones that do NOT have other signals in coincidence



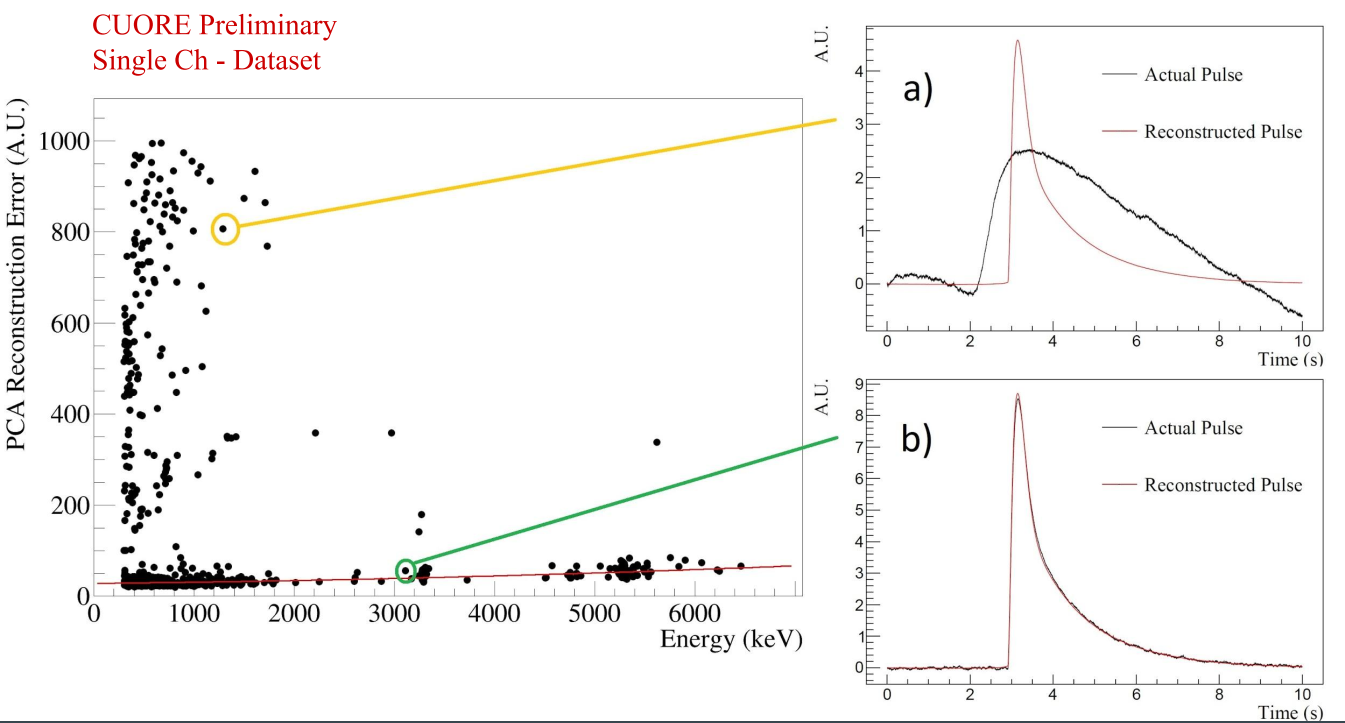


PULSE SHAPE DISCRIMINATION: PCA

- We adopt a new pulse shape discrimination method based on principal component analysis (PCA)
- For each channel in a dataset, treat the average pulse like it's a leading principal component
- Define a *reconstruction error* for each event **x** using this principal component **w**:

$$RE = \sqrt{\sum_{i=1}^{n} (\mathbf{x}_i - (\mathbf{x} \cdot \mathbf{w})\mathbf{w}_i)^2}$$

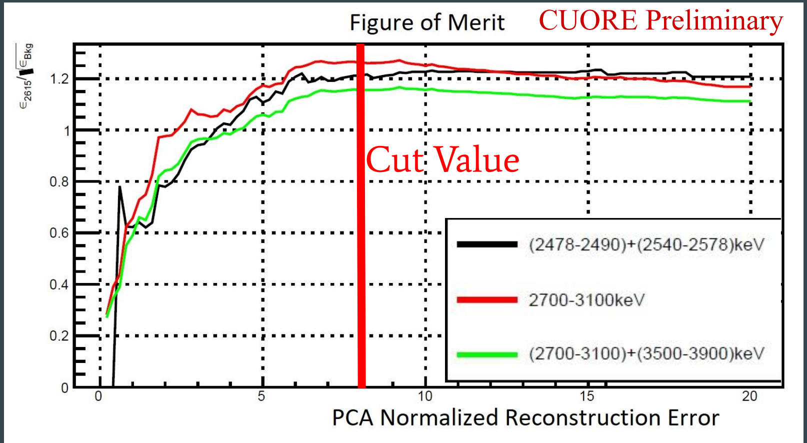
- Normalize the RE vs energy to obtain a cut

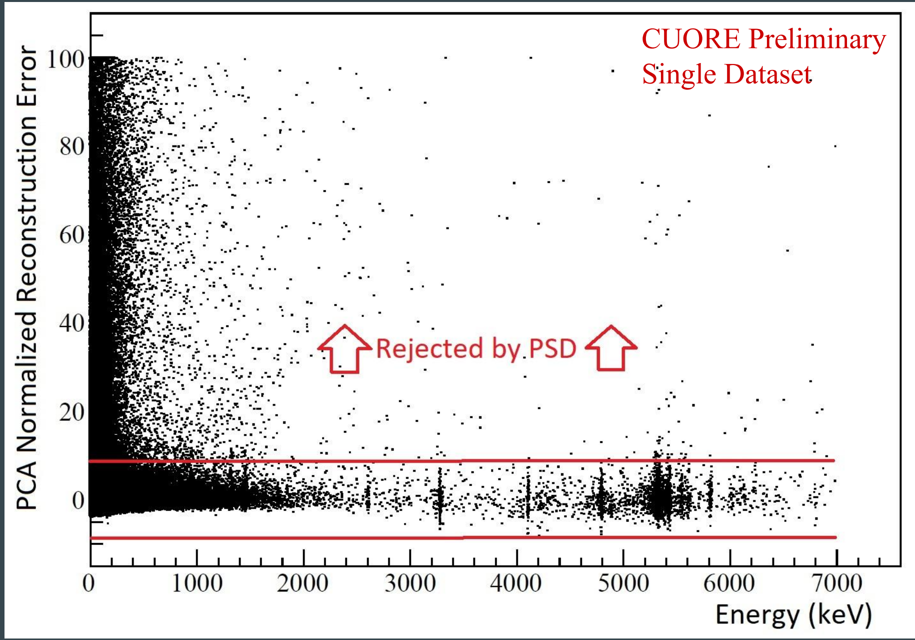


PULSE SHAPE DISCRIMINATION: PCA

Tune a S/√B figure of merit to find a cut on the PCA normalized reconstruction error for each dataset

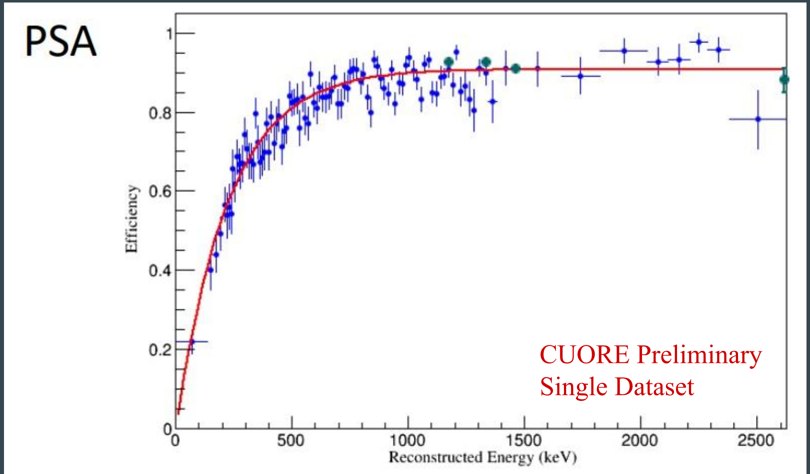
- Use gamma peaks for signal efficiency
- Use alpha region as background proxy

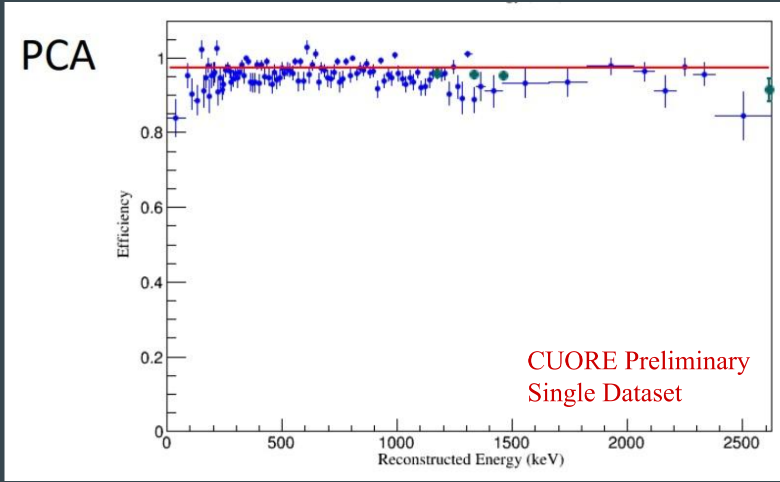




PSA vs PCA

- PCA based method shows an increase in efficiency across all energies compared to our previous pulse shape analysis (PSA)
- Efficiency gain is most pronounced at lower energies
- Similar background rejection capability





CUTS

BASE CUTS:

- manually removed periods of data in coincidence with external events (earthquakes) and periods presenting excessive noise
- removed channels-dataset failing one of the reconstruction steps
- removed events having other pulses in the same time window
- removed channels-datasets performing poorly (energy resolution FWHM > 19keV)

~5% loss in exposure

~3% loss in exposure

ANTICOINCIDENCE CUT (AC): selecting only single hit events

- 40 keV energy threshold, 5 ms time window

PULSE SHAPE DISCRIMINATION (PSD): method based on principal component analysis (PCA) to cut events with anomalous pulse shapes

- Cuts pileup and other detector noise that slips through the previous cuts

Efficiencies

Reconstruction Efficiency:
96.4%

Probability that a good event is triggered, reconstructed properly, and not rejected by basic pile-up cuts

- Evaluated on heater events

Anti-coincidence efficiency:
99.3%

Quantifies the probability that an event is not erroneously cut by being in accidental coincidence with an unrelated event

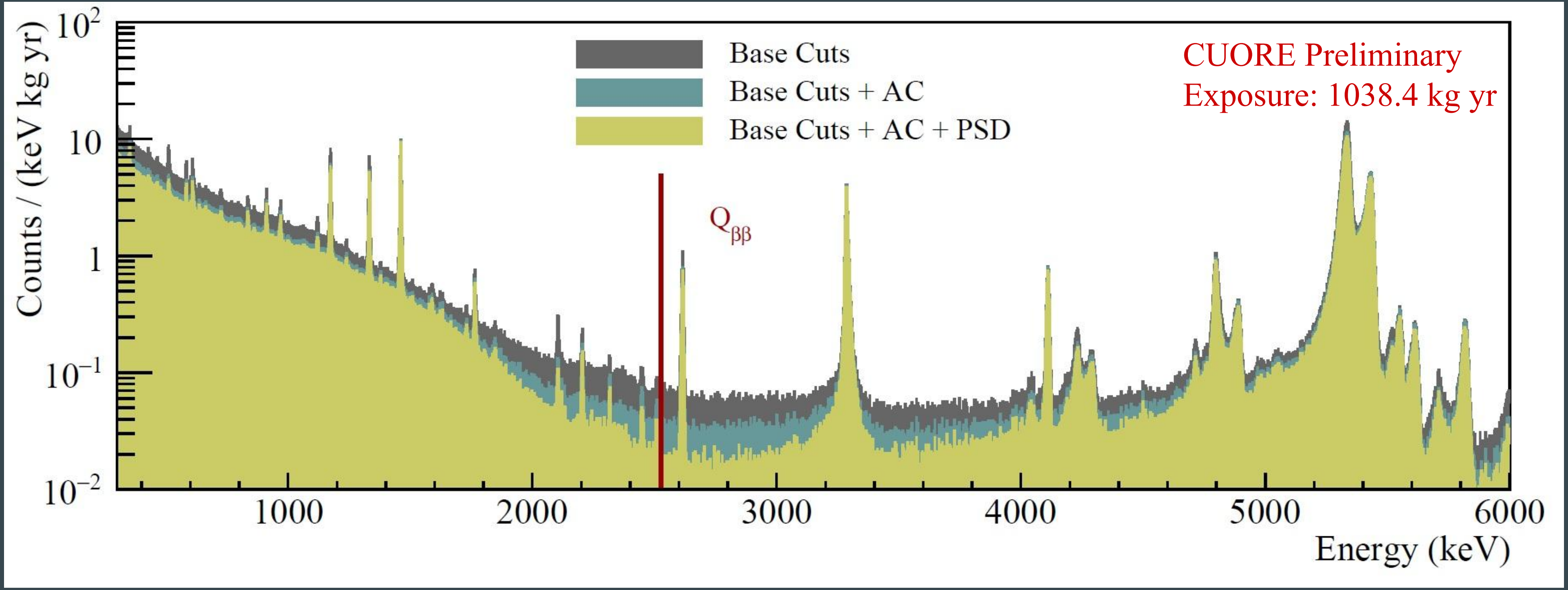
- Calculated on 1460 keV ^{40}K peak

Pulse Shape Discrimination efficiency:
96.4%

Fraction of signal-like events passing the PCA-based PSD

- Calculated on events in the ^{60}Co, ^{40}K, and ^{208}Tl γ peaks that passed the anti-coincidence cut

Spectrum after selection



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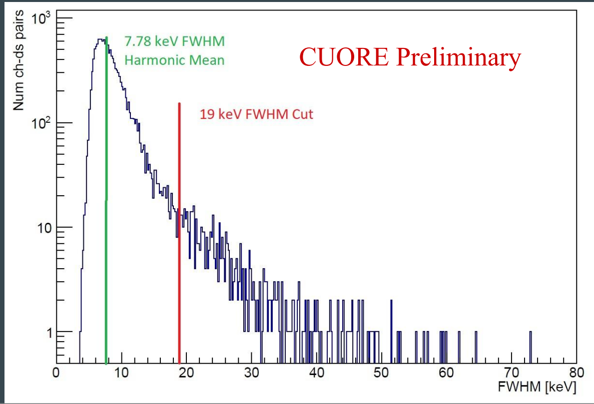
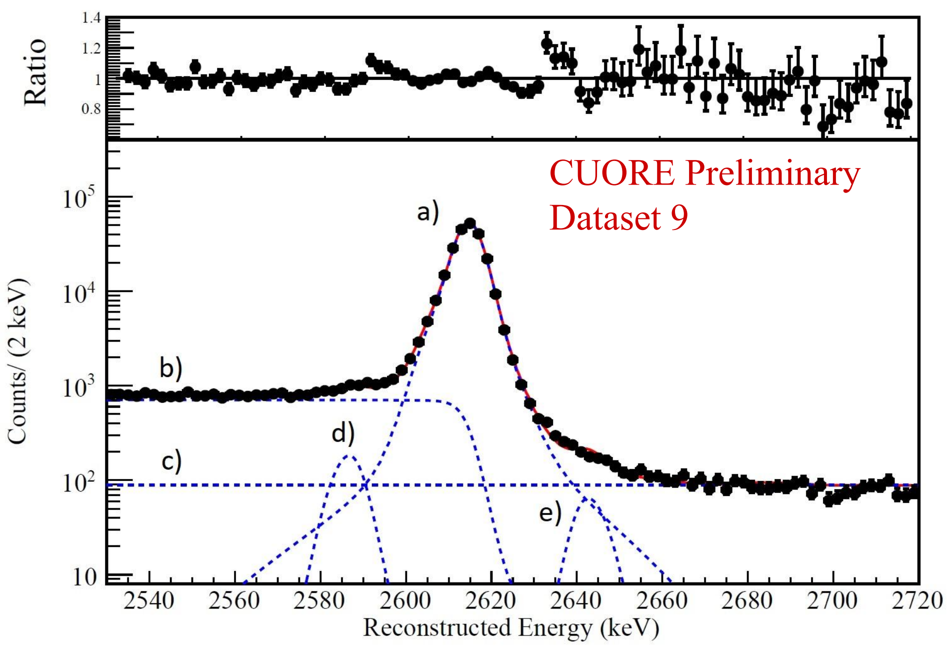
Detector response and energy resolution

We fit the 2615 keV calibration peak for each channel with

a) 3-Gaussian response function
b) Multi-compton background
c) Flat background
d) 30 keV X-ray escape peak
e) 30 keV X-ray coincidence peak

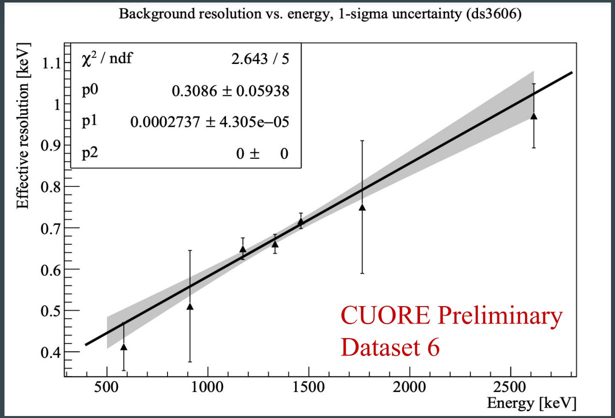
We exclude channels with FWHM > 19 keV from this analysis

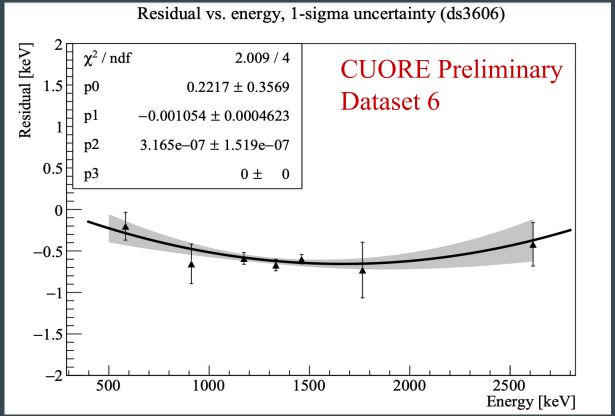




FWHM harmonic mean @ 2615keV (calibration) -> 7.78 keV

Detector Response Scaling

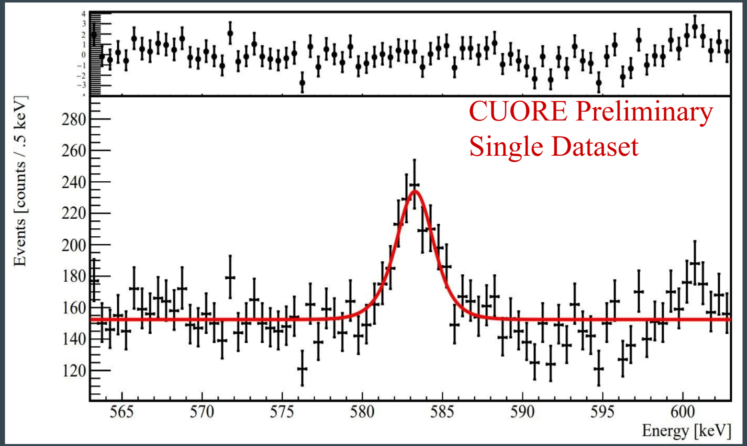




We scale the detector response fit from the 2615 keV calibration line to multiple background peaks in the physics data to determine any energy bias and resolution scaling

- Bias is a pol2 function of energy and resolution is a pol1 function of energy
- Depending on dataset, energy bias at $Q_{\beta\beta}$ is < 0.7 keV, and resolution at $Q_{\beta\beta}$ in physics data is similar to the 2615 keV calibration resolution

FWHM harmonic mean @ Qββ (physics) -> 7.8 keV



1 Ton-Year Analysis: Numbers

Parameters	Values
Number of datasets	15
Number of channels	~934 average per dataset
TeO_2 exposure	1038.4 kg yr
^{130}Te exposure	288 kg yr
FWHM at 2615 keV in calibration	(7.78 ± 0.03) keV
FWHM at $Q_{\beta\beta}$ in physics data	(7.8 ± 0.5) keV
Total analysis efficiency	(92.4 ± 0.2)%
Reconstruction efficiency	(96.418 ± 0.002)%
Anticoincidence efficiency	(99.3 ± 0.1)%
PSD efficiency	(96.4 ± 0.2)%
Containment efficiency	(88.35 ± 0.09)%

$0\nu\beta\beta$ Fit Method

- Bayesian analysis based on MCMC method (BAT)
- Results on $\Gamma_{0\nu}$ obtained from a flat prior on non-negative rates
- Input parameters from analysis:
  - Detector response function for each channel in each dataset
  - Resolution and energy bias scaling from calibration to physics data
  - Efficiency numbers
- Free parameters:
  - $\Gamma_{0\nu}$ rate
  - ^{60}Co peak rate, scaled for each dataset by the ^{60}Co lifetime
  - Background rate for each dataset, and a shared linear slope to the background
- Repeat fit with additional nuisance parameters to account for systematics
  - Systematics have a 0.8% effect on our limit and best-fit value for $\Gamma_{0\nu}$

$0\nu\beta\beta$ Fit Systematics

Fit parameter systematics			
Systematic	Prior	Effect on the Marginalized $\Gamma_{0\nu}$ Limit	Effect on $\hat{\Gamma}_{0\nu}$
Total analysis efficiency I	Gaussian	0.2%	$< 0.1\%$
Analysis efficiency II	Gaussian	0.3%	$< 0.1\%$
Containment efficiency	Gaussian	0.2%	$< 0.1\%$
Isotopic abundance	Gaussian	0.2%	$< 0.1\%$
$Q_{\beta\beta}$	Gaussian	$< 0.1 \cdot 10^{-27}\ \mathrm{yr}^{-1}$	$< 0.1 \cdot 10^{-27}\ \mathrm{yr}^{-1}$
Energy bias and Resolution scaling	Multivariate	$0.2 \cdot 10^{-27}\ \mathrm{yr}^{-1}$	$0.1 \cdot 10^{-27}\ \mathrm{yr}^{-1}$

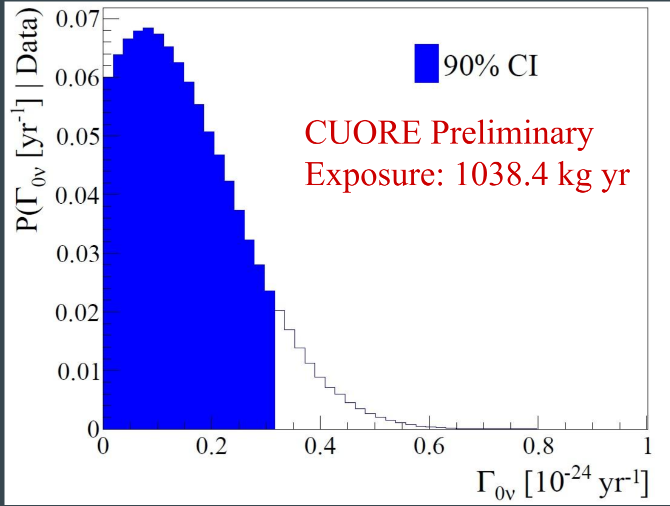
Total effect of systematics on rate is 0.8%

ROI fit

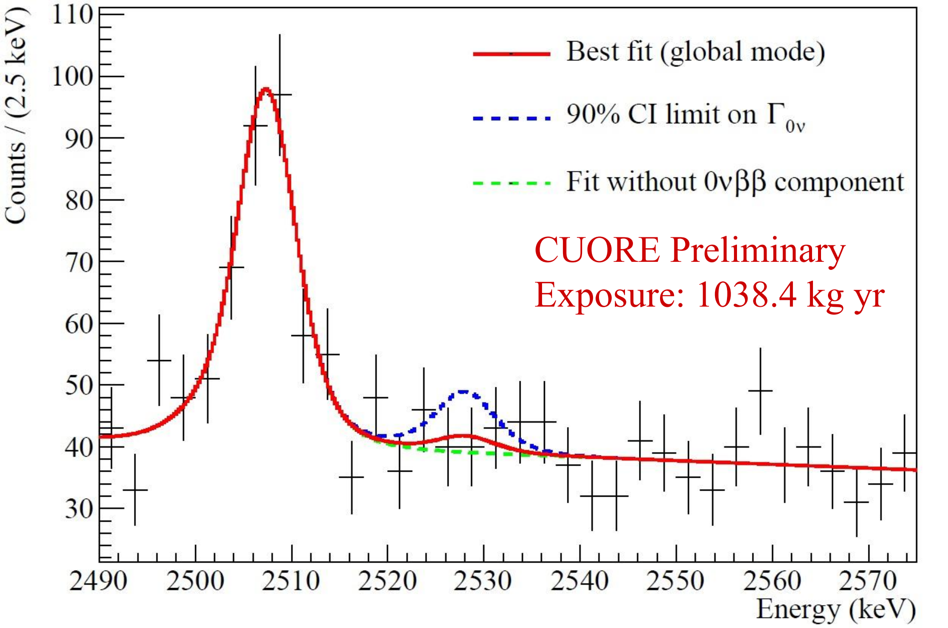
Best Fit Value: $\Gamma_{0\nu} = (0.9 \pm 1.4) \times 10^{-26}\ yr^{-1}$

Bayesian 90% CI Limit: $T_{1/2} > 2.2 \times 10^{25}$ yr

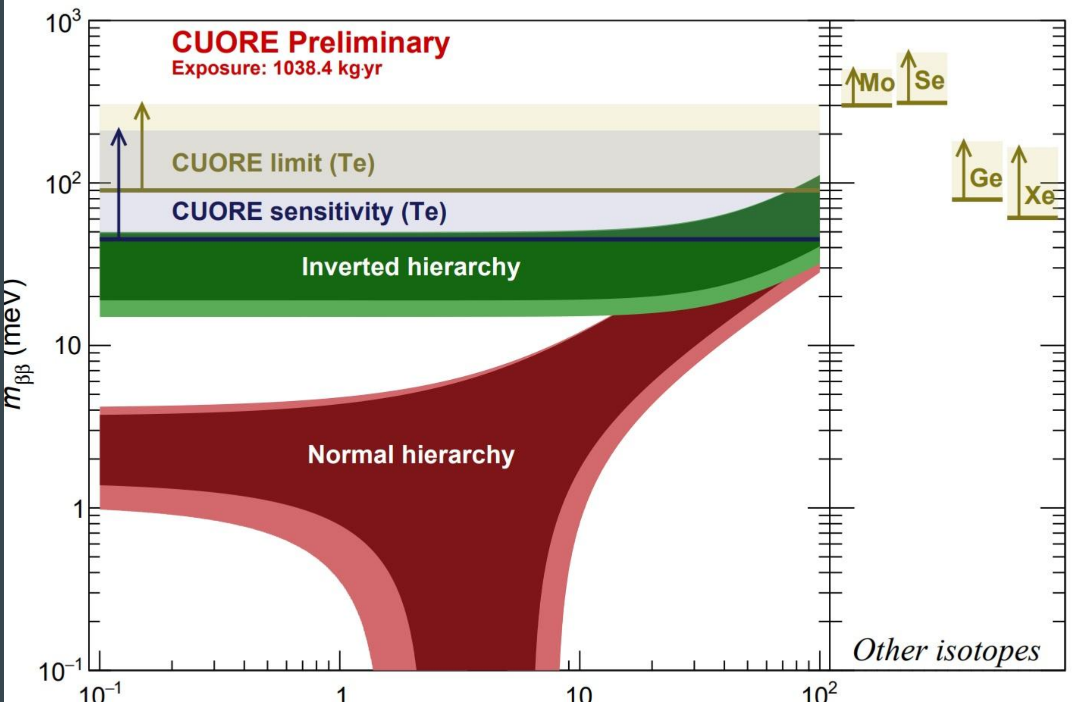
Frequentist 90% CI limit: $T_{1/2} > 2.6 \times 10^{25}$ yr



Region Of Interest [2490,2575] keV



$m_{\beta\beta}$ Limit



Representation of $m_{\beta\beta}$ from F. Vissani JHEP06(1999)022

From the Bayesian 90% limit of $T_{1/2} > 2.2 \times 10^{25}$ yr Using a current range of NME calculations, this correspond to a limit on the neutrino effective Majorana mass of

$m_{\beta\beta}$ < (90-305) meV

Oscillation parameters from NUFIT 2020 are used. All limits are at 90% C.L. and 3σ uncertainty is shown on the inverted and normal hierarchy bands.

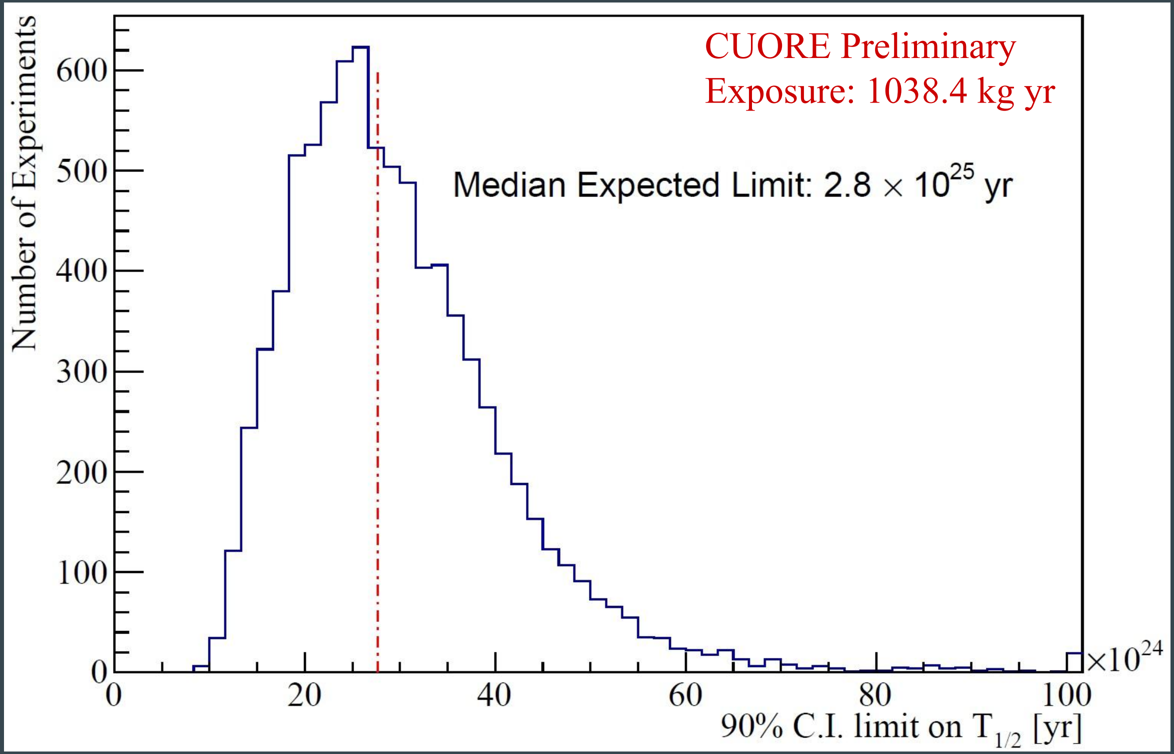
The sensitivity line corresponds to the one quoted in the CUORE 2017 EPJC sensitivity paper. The limits on Ge, Mo, Se and Xe come from Gerda (2020), CUPID-Mo (2021), CUPID-0 (2019) and KamLAND-Zen (2016) respectively.

SENSITIVITY

Median 90% Exclusion Sensitivity:

2.8×10^{25} yr

- Sensitivity calculated by generating 10^4 toy experiments assuming no $0\nu\beta\beta$ signal
  - Poisson-fluctuate background events and ^{60}Co events, with rates taken from the actual fit to data
  - Fit each toy using the same $0\nu\beta\beta$ signal + background model we use on actual data
- 72% chance of obtaining a stronger limit than our actual result



Results Publication

High sensitivity neutrinoless double-beta decay search with one tonne-year of CUORE data

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(CUORE Collaboration)

On Arxiv in a few hours!!!

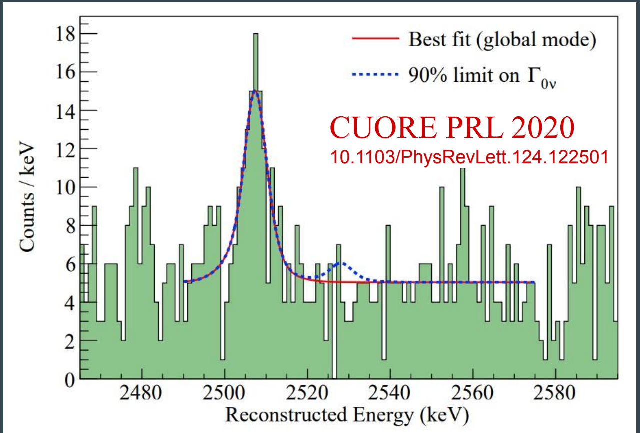
Read our publications @ https://cuore.lngs.infn.it/

Comparison to Previous Result

Our last result published a 90% CI limit of

$T_{1/2} > 3.2 * 10^{25}$ yr

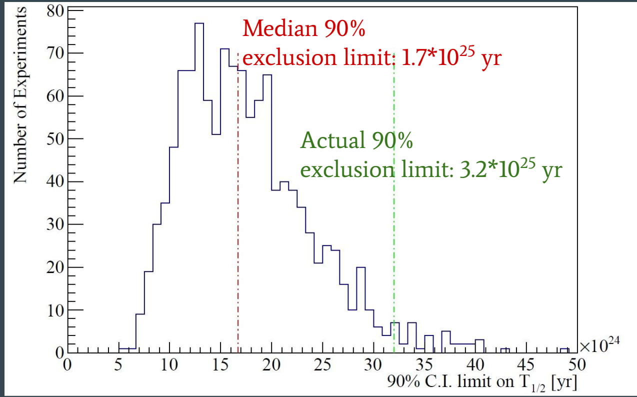
- This was determined to be in the top 3% of possible expected results

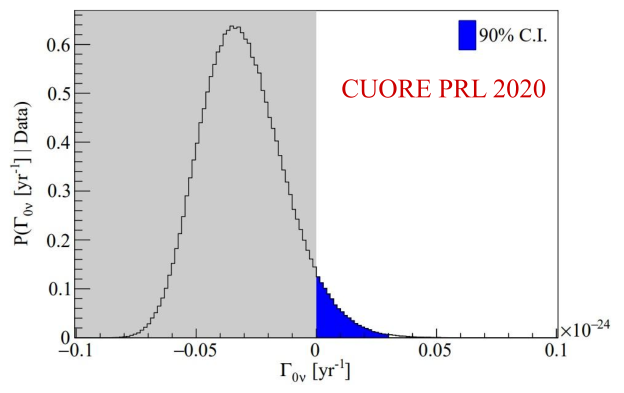


Our new limit of

$T_{1/2} > 2.2 * 10^{25}$ yr

is weaker due to normal statistical fluctuations around $Q_{\beta\beta}$, stemming from the re-analysis and the new data





Background in the ROI

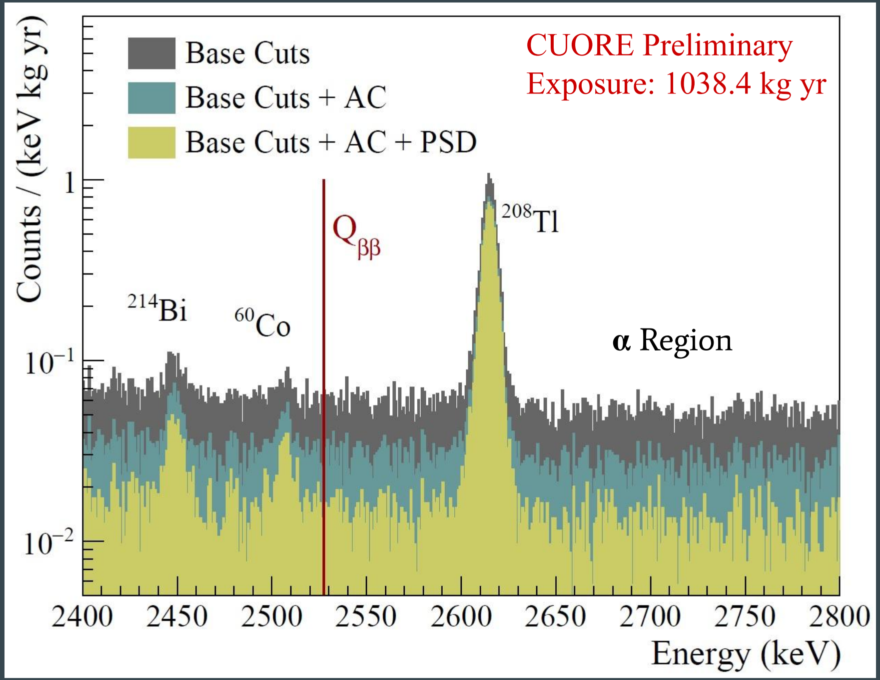
α region

Fit flat background in [2650,3100] keV region
Average α background: **$1.40(2)\cdot10^{-2}$ cts/keV/kg/yr**

$Q_{\beta\beta}$ region

Fit with background + ^{60}Co peak in [2490,2575] keV region
Average BI: **$1.49(4)\cdot10^{-2}$ cts/keV/kg/yr**

~90% of the background in the ROI is given by degraded alpha interactions



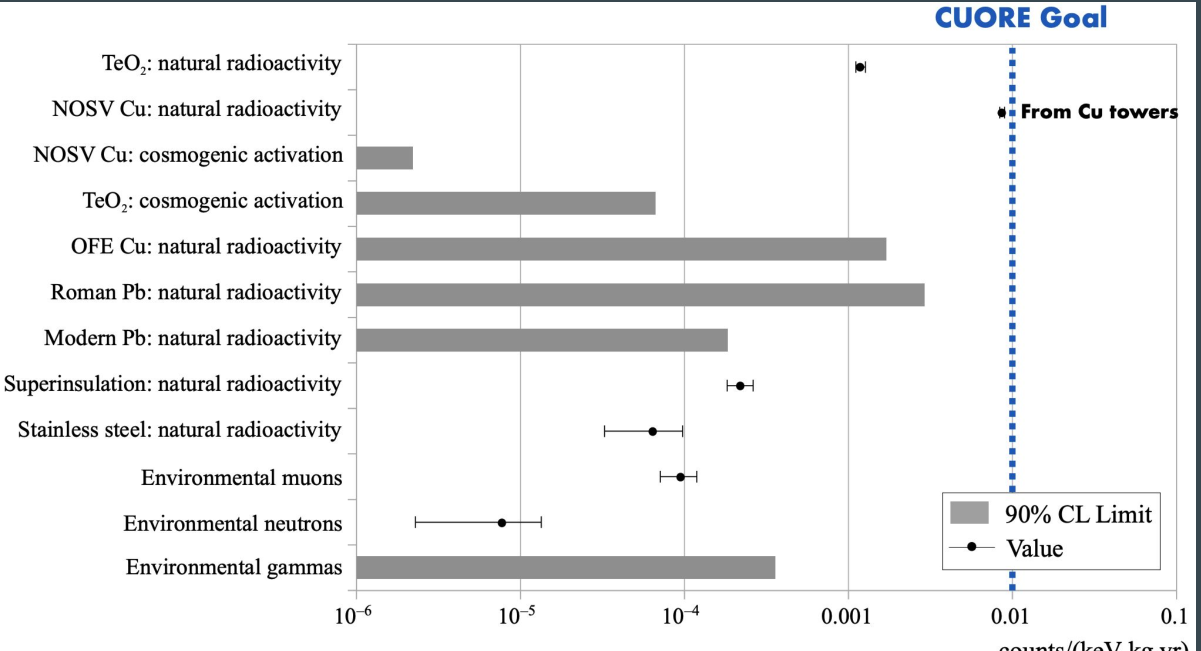
Background budget

Background index from the the ROI fit:
BI = 1.49 x 10^{-2} counts/keV/kg/yr

CUORE background goals met

- Degraded α's pose problem
- Bolometric technique provides only 1 channel
- No particle ID

To be solved with CUPID!



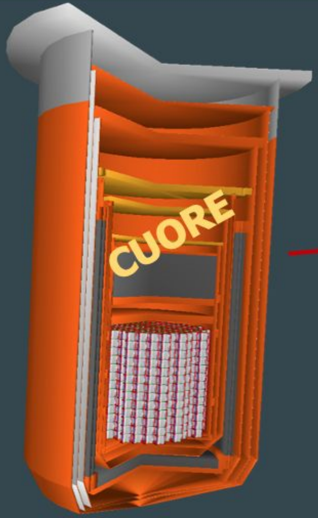
European Physical Journal C 77, 543 (2017)

Foreseen publication of the background model in the near future

CUPID: CUORE Upgrade with Particle IDentification

~1600 $Li_2{}^{100}MoO_4$ scintillating bolometers (240 kg of ^{100}Mo):

- high energy resolution (<10 keV)
- excellent radiopurity
- enrichment > 95%



Best world limit on ^{130}Te
$T^{1/2}_{0\nu} > 2.2 * 10^{25}$ y @90% CI

7 countries
~180 members

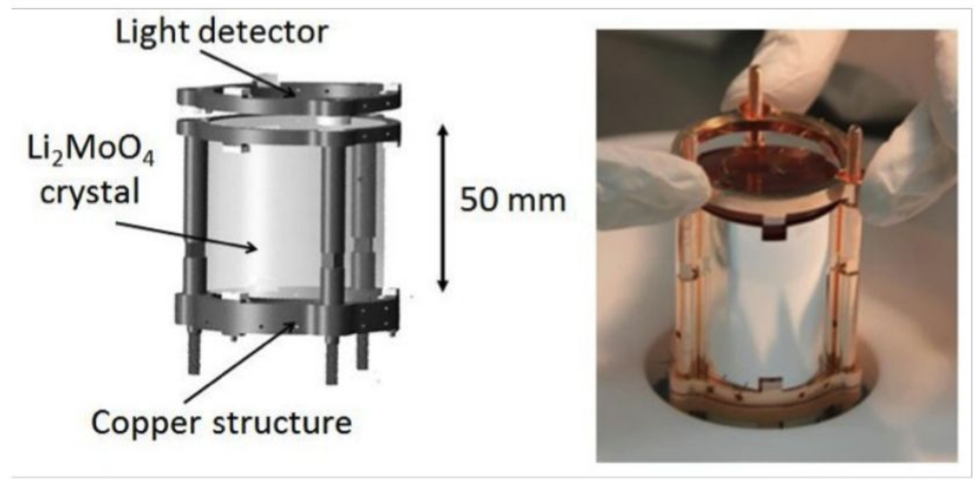
Best world limit on ^{82}Se
$T^{1/2}_{0\nu} > 3.5\ 10^{24}$y @90% CI

Best world limit on ^{100}Mo
$T^{1/2}_{0\nu} > 1.5\ 10^{24}$y @90% CI

FRESH FORCES!

CUPID

- β/γ background significantly reduced because of higher ^{100}Mo Q-value (3034 keV)
- Particle ID from scintillation to reduce α background
- β/γ versus α discrimination technique robustly demonstrated by CUPID-0 and CUPID-Mo
- Reuse proven CUORE cryogenic infrastructure @LNGS
- Expansion to 1-ton scale (CUPID-1T) technically possible



Future of CUORE

With the ultimate goal of accumulating a total of 3 tonne-years of exposure, CUORE will run until the beginning of CUPID commissioning phase.

While waiting for more data, we are performing other rare events searches and studies on our spectrum:

- $2\nu\beta\beta$ of ^{130}Te
- $0\nu\beta\beta$ and $2\nu\beta\beta$ of ^{130}Te on excited states of ^{130}Xe
- **low energy analysis (dark matter, axions, supernovae neutrinos, etc)**
- $0\nu\beta^+\beta^+$, $0\nu\beta^+$EC, 0νECEC of ^{120}Te
- ...

We are also investigating the origin of our sources of noise and are working on its mitigation and decorrelation techniques:

- **use of diagnostic devices (accelerometers, microphones, seismometers)**
- **dedicated measurements**
- ...

Summary

- CUORE has now exceeded 1 tonne year of exposure and continues to stably collect data
- We observe no evidence of $0\nu\beta\beta$ decay of ^{130}Te with an analysis of **1038.4 kg yr** of data
  - Bayesian 90% CI exclusion limit: $T_{1/2} > 2.2 \times 10^{25}$ yr
  - Frequentist 90% CI exclusion limit: $T_{1/2} > 2.6 \times 10^{25}$ yr
  - Effective Majorana mass limit: $m_{\beta\beta} < (90\text{-}305)$ meV
- This is the highest sensitivity search for $0\nu\beta\beta$ decay of ^{130}Te to date
  - Median 90% exclusion sensitivity: $T_{1/2} > 2.8 \times 10^{25}$ yr
- Look forward to other analyses from this data in the future!