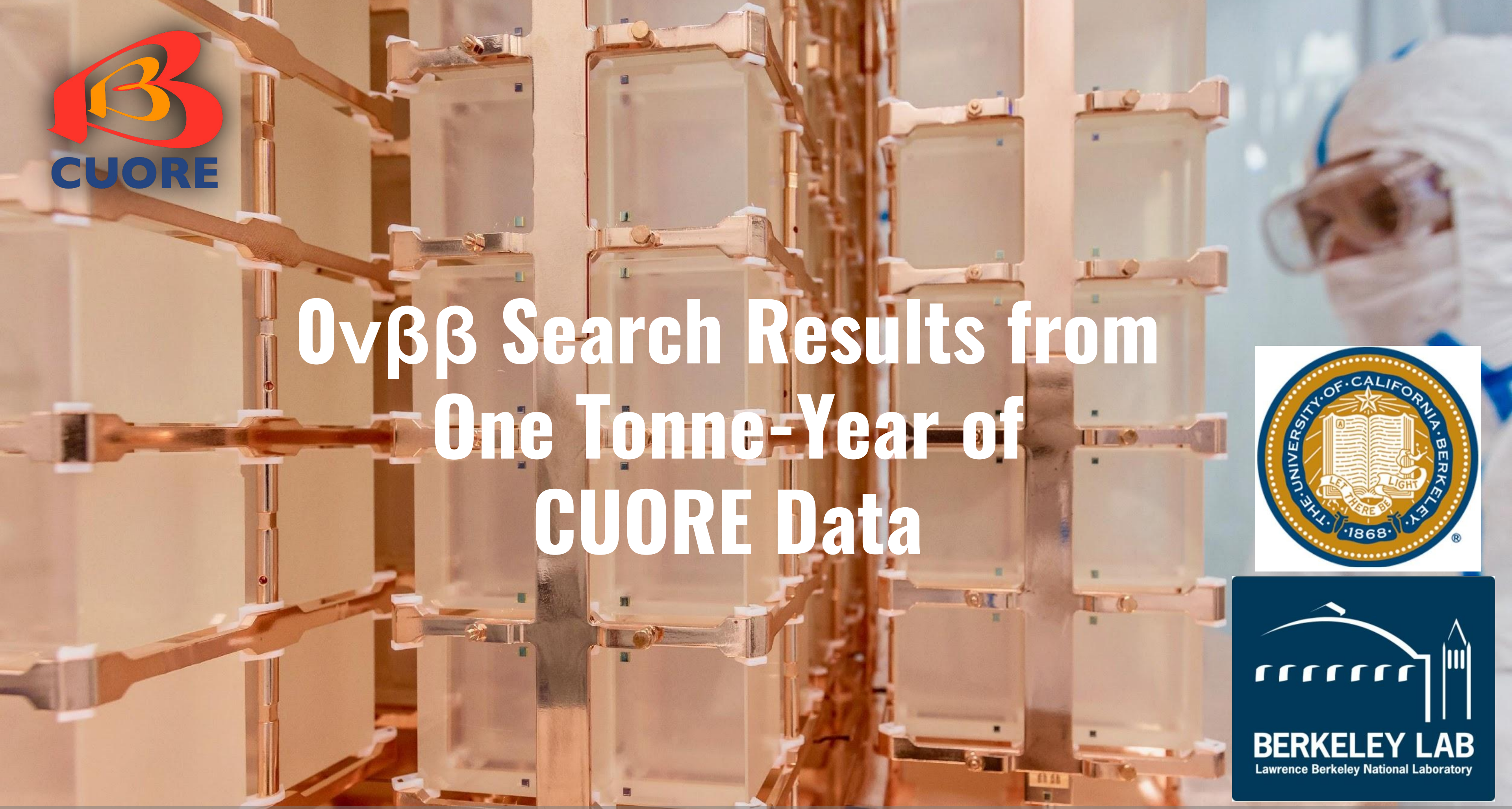


CUORE

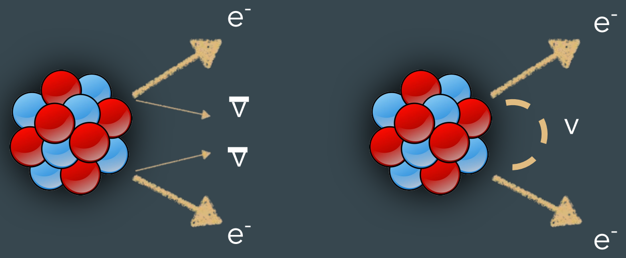
0νββ Search Results from One Tonne-Year of CUORE Data

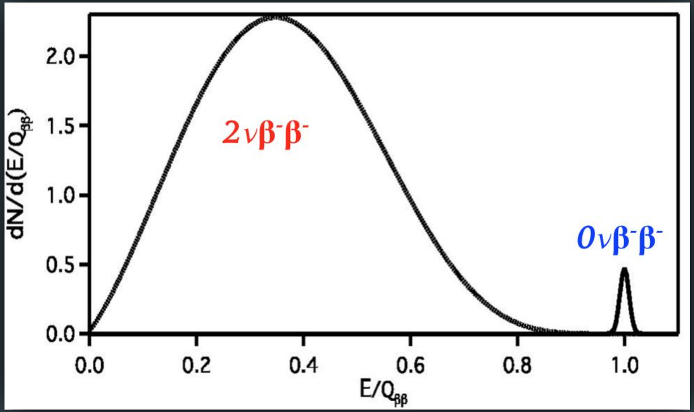
BERKELEY LAB
Lawrence Berkeley National Laboratory

- Introduction to the CUORE Experiment
- Data Taking
- Events Reconstruction
- 0νββ Decay Analysis
- Results

Physics goal

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



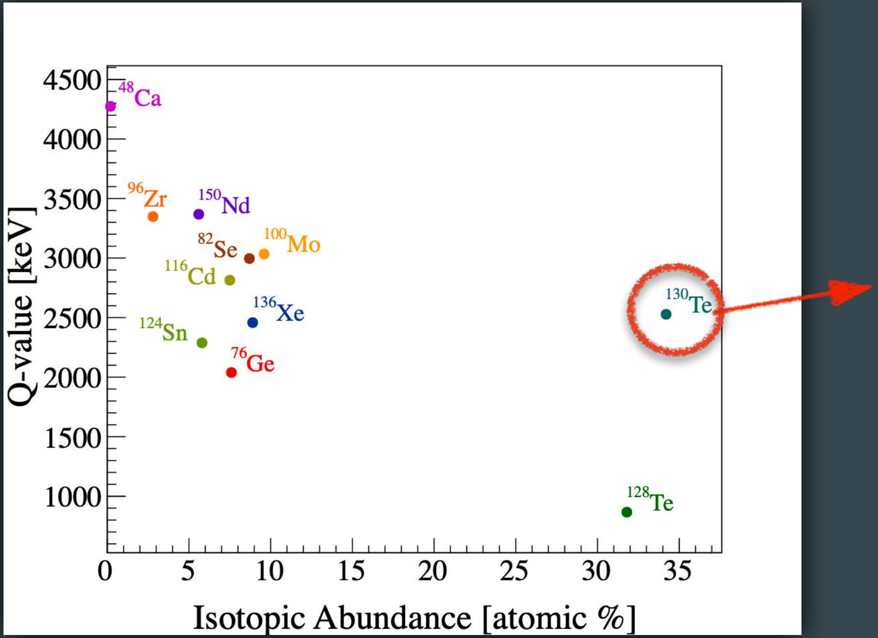


Experimental Signature:
peak at the Q-value of ßß decay spectrum

The discovery of 0νββ decay would demonstrate that lepton number is not a symmetry of nature and that neutrinos are Majorana particles.

- ➢ Currently the most practical way to address the question of Majorana neutrinos!

Why Tellurium?

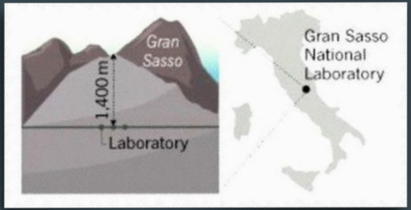


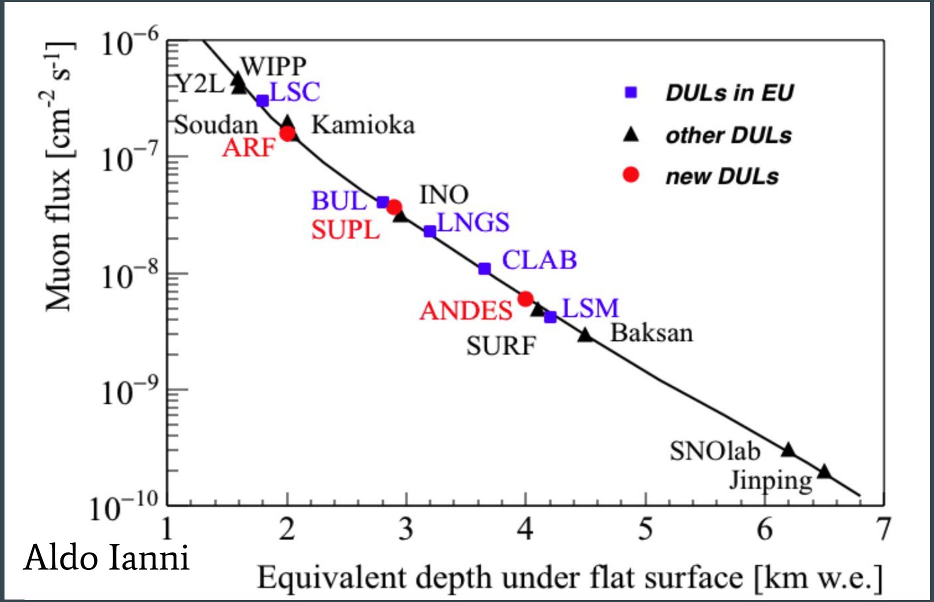
^{130}Te is chosen for:

- High isotopic abundance (34.17%) allows the use of natural Tellurium
- ^{130}Te can be incorporated into TeO_2 crystals, which also serve as the detector material (high detection efficiency)
- Reproducible growth of high quality crystals
- Q-value of 2527.515 ± 0.013 keV in a region with low beta/gamma background

CUORE @ LNGS - ITALY

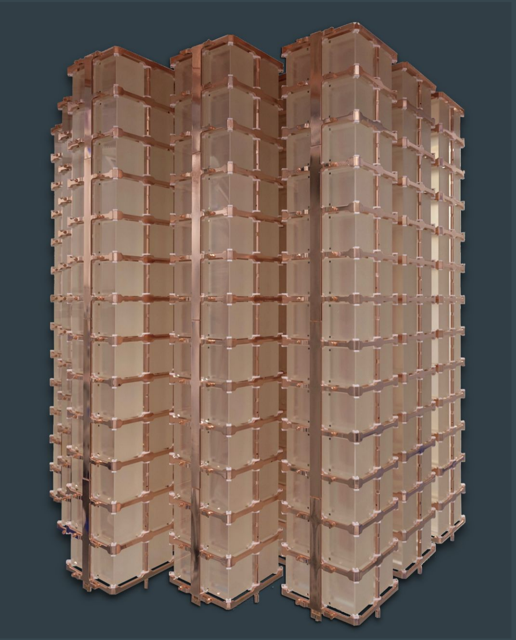
Laboratori Nazionali del Gran Sasso:
3600 meters water-equivalent deep
Muons: ~3×10^{-8}/(s cm^2) -> 10^6 less than above ground
Gammas: ~0.73/(s cm^2)
Neutrons: < 4×10^{-6}/(s cm^2)





Aldo Ianni

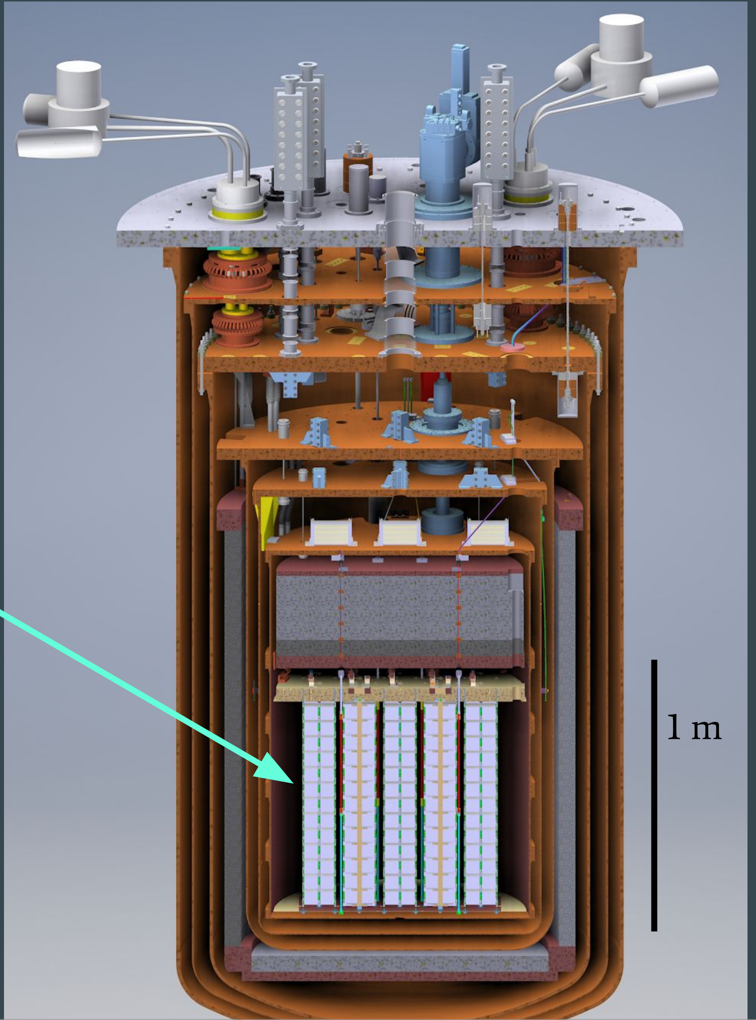
Cryogenic Underground Observatory for Rare Events



988 high purity $^{Nat}TeO_2$ 5x5x5 cm^3 crystals arranged in 19 towers with 13 floors with a total mass of 742 kg
984 active channels!

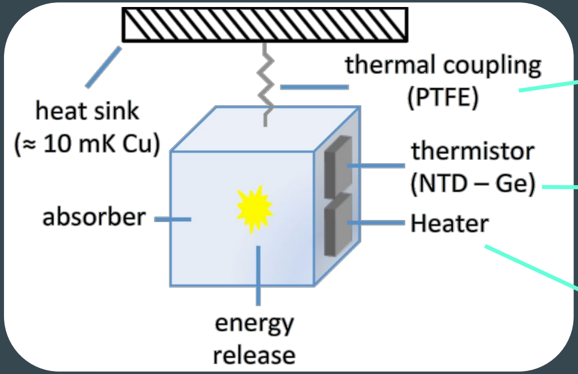
World-leading cryostat in size and power:

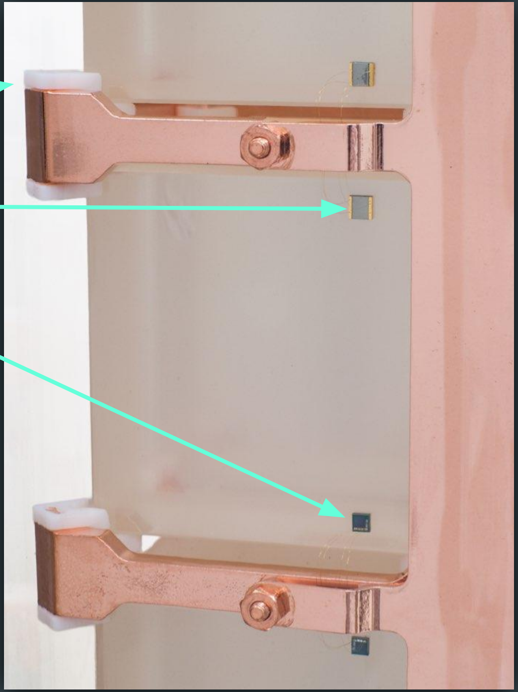
- ~15 tonnes (Pb, Cu and TeO_2) below 4 K, and 3 tonnes cooled to below 50 mK
- 4 μW cooling power at operating temperature of ~10 mK

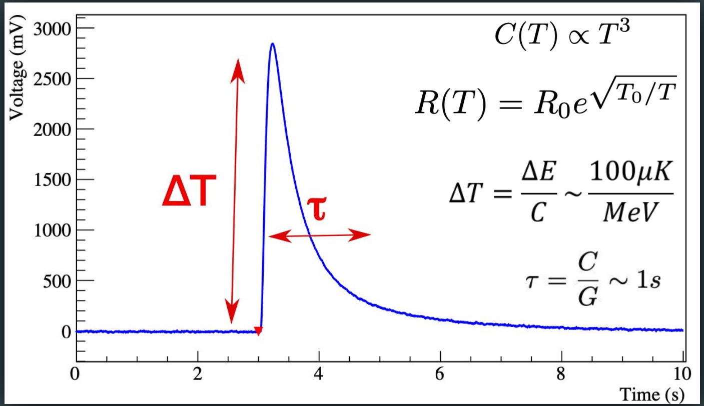


Bolometric technique

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







$$C(T) \propto T^3$$

$$R(T) = R_0 e^{\sqrt{T_0/T}}$$

$$\Delta T = \frac{\Delta E}{C} \sim \frac{100 \mu K}{MeV}$$

$$\tau = \frac{C}{G} \sim 1s$$

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

Challenges

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

Large exposure (mass x time)

- 988 TeO_2 crystals 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

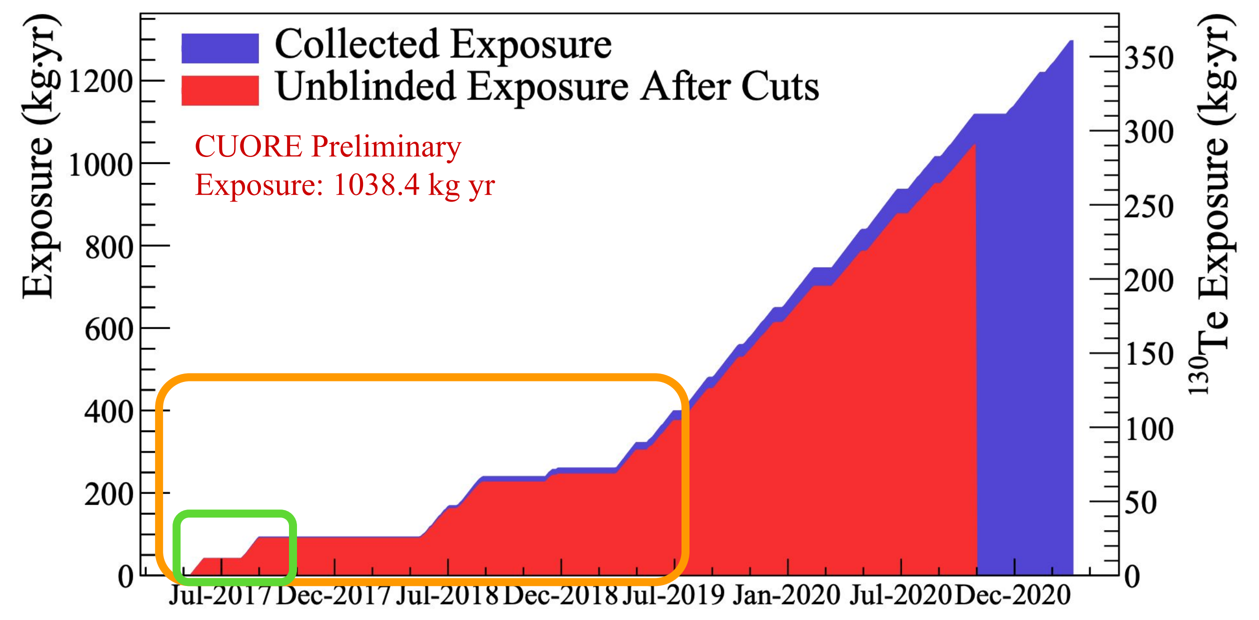
Data taking

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

Data unblinded in 2021 - arXiv:2104.06906
1038.4 kg yr

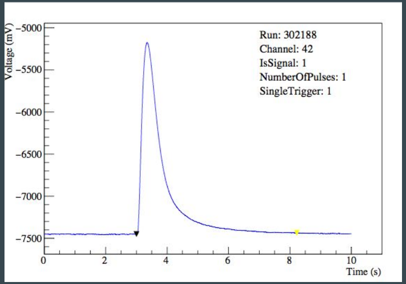
Data published in PRL 124.122501 (2020)
372.5 kg yr

Data published in PRL 120.132501 (2018)
86.3 kg yr

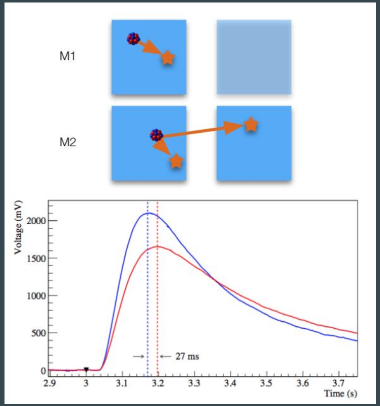


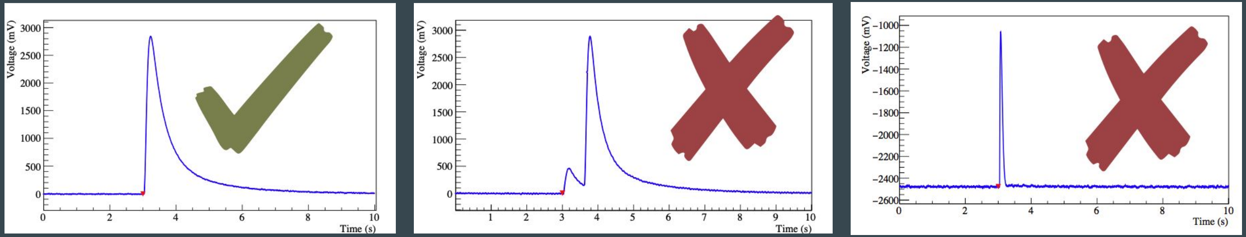
Since 2019 we have been accumulating an average of 69 kg yr/month

Event reconstruction



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



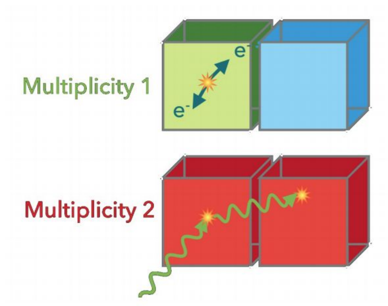


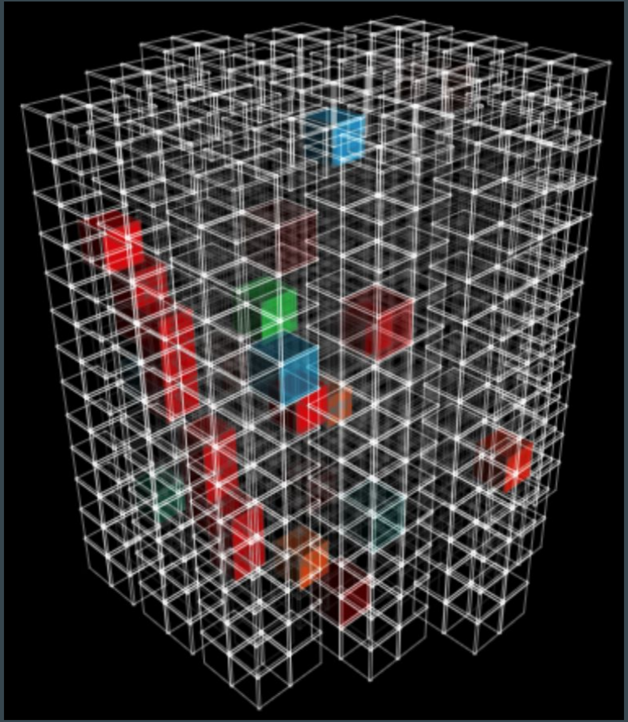
Coincidences

88% of $0\nu\beta\beta$ decay events deposit all of their energy in one crystal (source = detector)

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

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





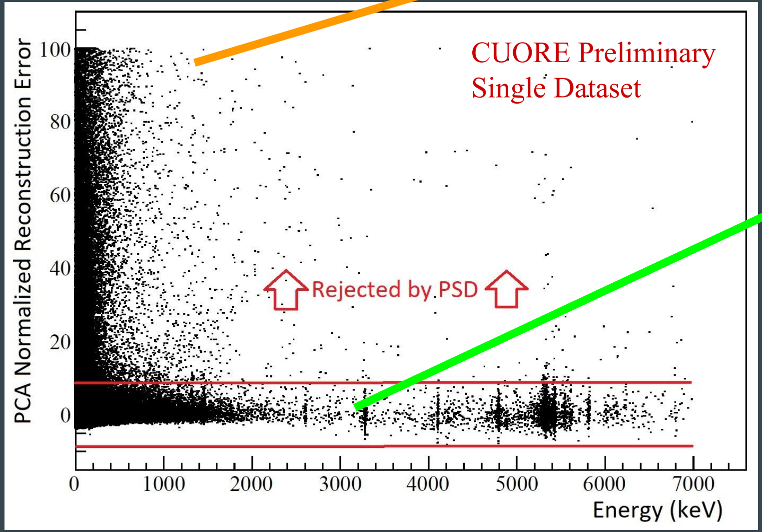
PULSE SHAPE DISCRIMINATION: PCA

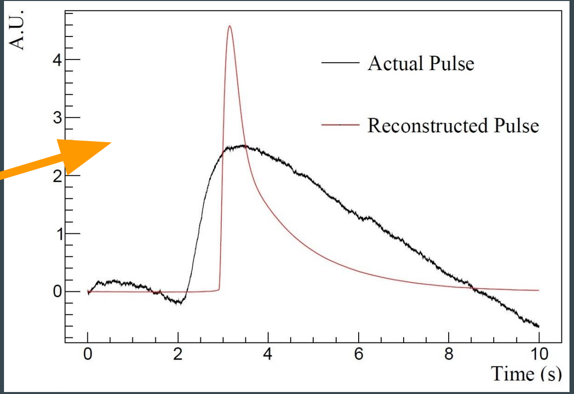
- We adopt a new pulse shape discrimination method based on principal component analysis (PCA)
- For each channel in a dataset, treat the average pulse like it's a leading principal component and calculate a *reconstruction error*

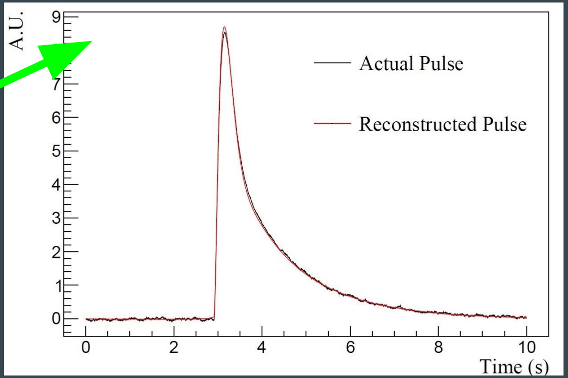
- Define a *reconstruction error* for each event **x** using this principal component **w**:

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

- Normalize the RE vs energy and optimize a S/√B metric to obtain a cut





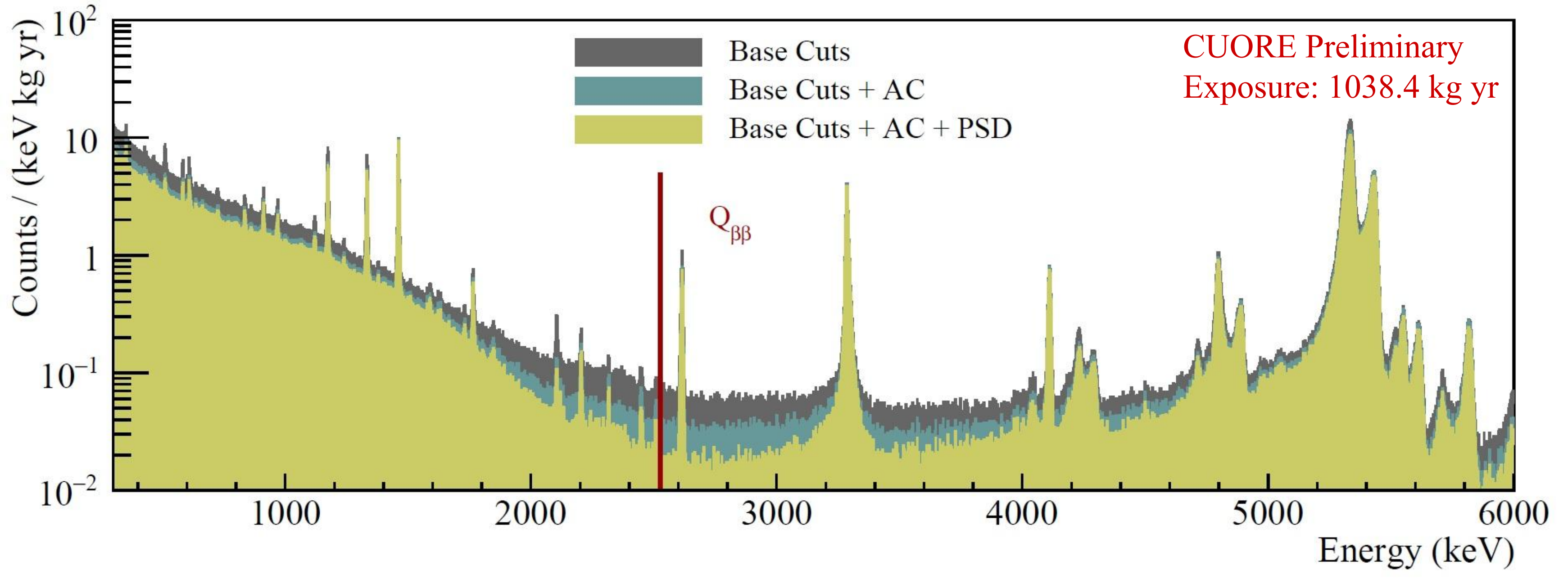


Spectrum after selection

BASE CUTS: remove periods with excessive noise, events with multiple pulses, and channels failing processing

ANTICOINCIDENCE CUT (AC): selecting only single hit events, with a 40 keV energy threshold, 5 ms time window

PULSE SHAPE DISCRIMINATION (PSD): PCA-based method to cut remaining events with anomalous pulse shapes

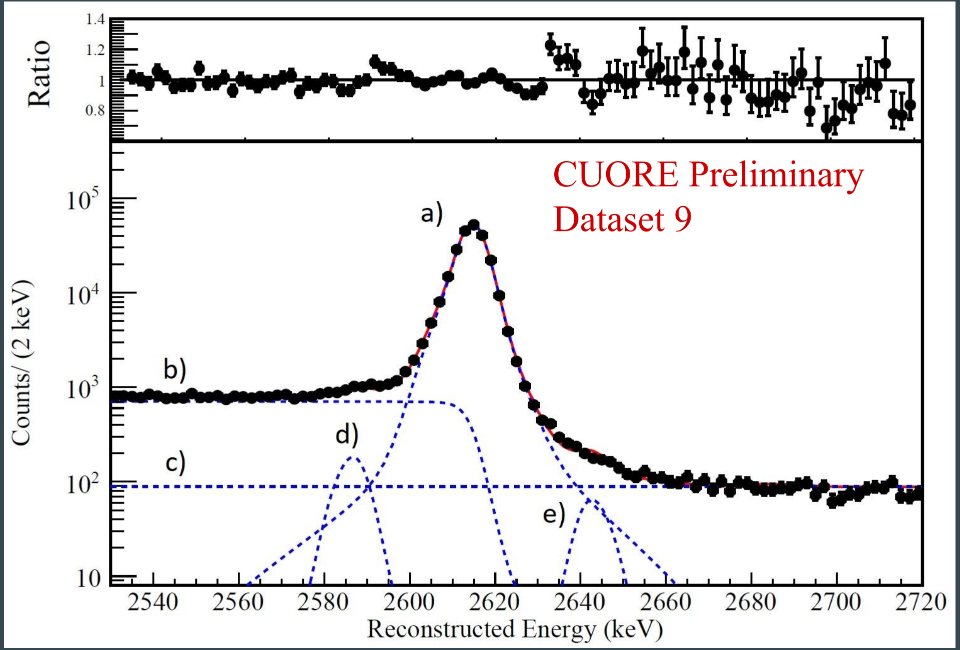


Detector response and energy resolution

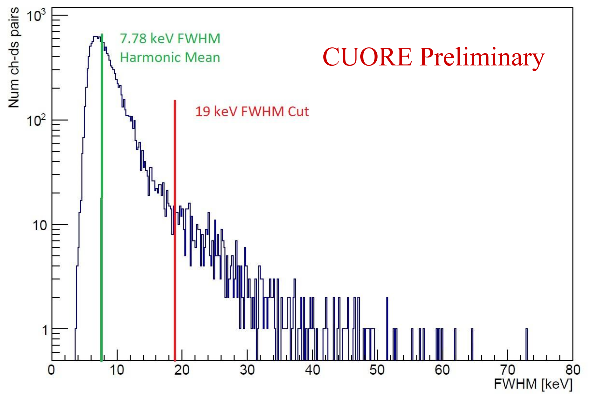
We fit the 2615 keV calibration peak for each channel with

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

Results are scaled to background peaks to account for possible differences in response between calibration and physics data



We exclude channels with FWHM > 19 keV from this analysis



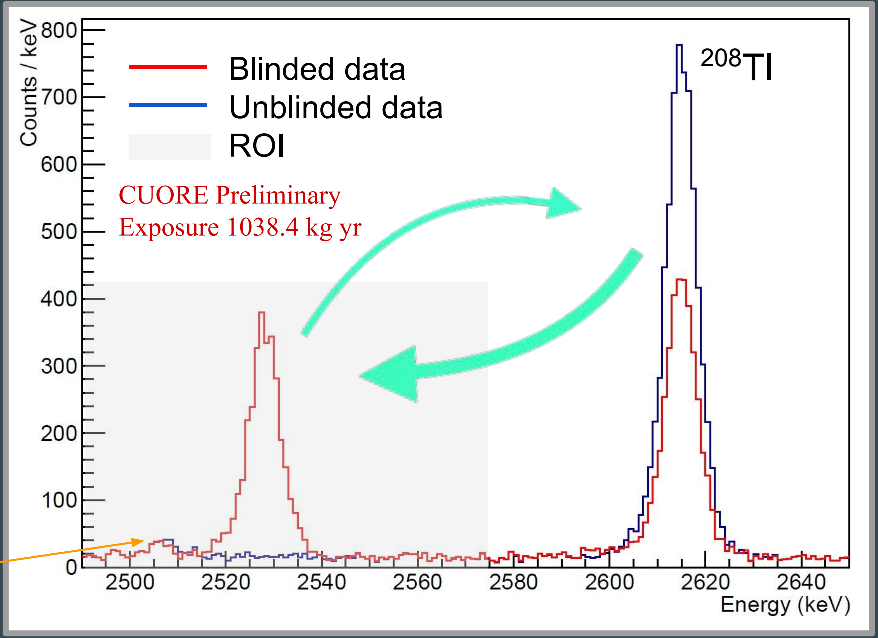
FWHM harmonic mean @ 2615keV (calibration) -> 7.78 keV

1 Tonne-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)%

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

0νββ Fit Method

- Bayesian analysis based on MCMC method (BAT)

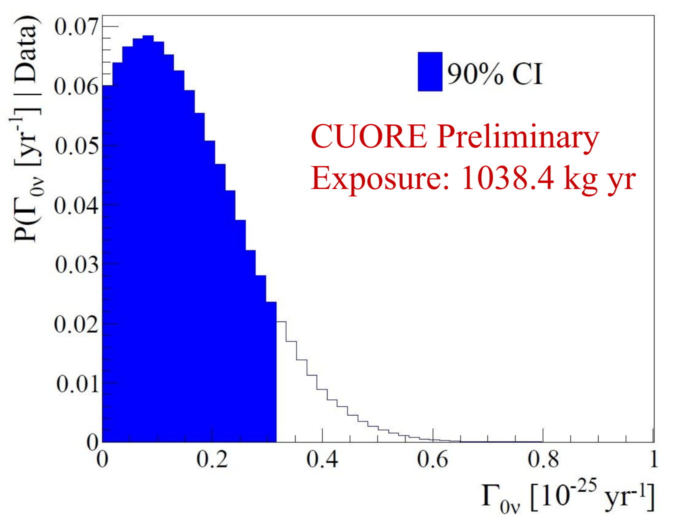
- Results on $\Gamma_{0\nu}$ obtained from a flat prior on non-negative rates
- Input parameters from analysis:
    - Detector response function for each channel in each dataset
    - Resolution and energy bias scaling from calibration to physics data
    - Efficiency numbers
- Free parameters:
    - **$\Gamma_{0\nu}$ 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 $\Gamma_{0\nu}$

ROI fit

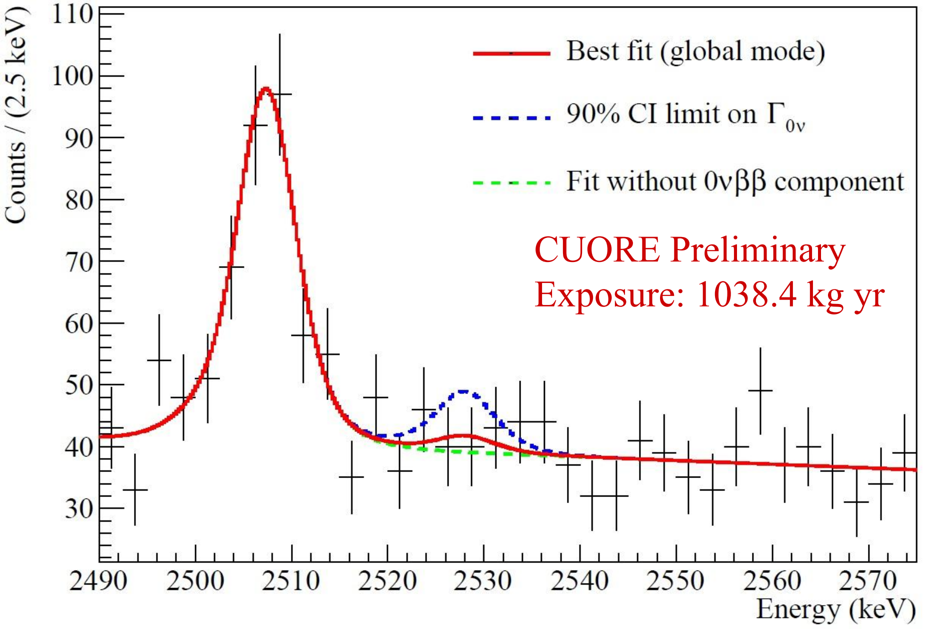
Best Fit Value: $\Gamma_{0\nu} = (0.9 \pm 1.4) \times 10^{-26}\ \mathrm{yr}^{-1}$

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

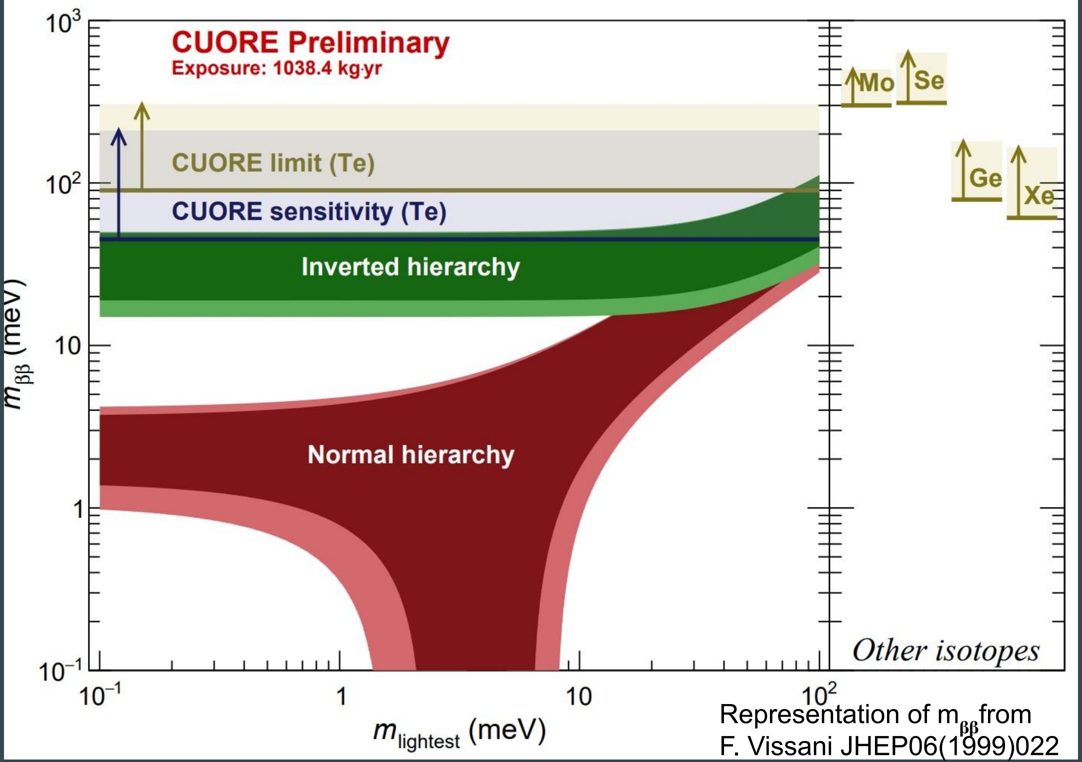
Frequentist 90% CI limit: $T_{1/2} > 2.6 \times 10^{25}$ yr



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 corresponds 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.

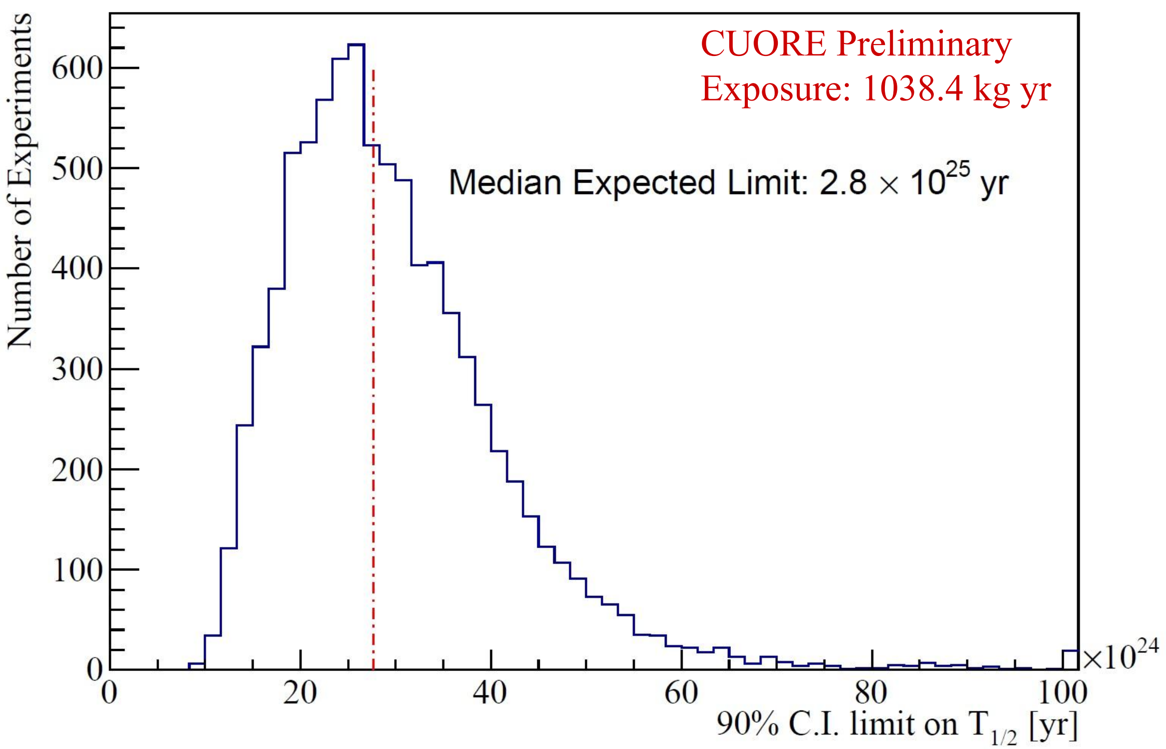
The sensitivity line corresponds to the one quoted in the CUORE 2017 EPJC sensitivity paper. The limits on Ge, Mo, Se and Xe come from Gerda (2020), CUPID-Mo (2021), CUPID-0 (2019) and KamLAND-Zen (2016) respectively.

SENSITIVITY

Median 90% Exclusion Sensitivity:

2.8×10^{25} yr

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

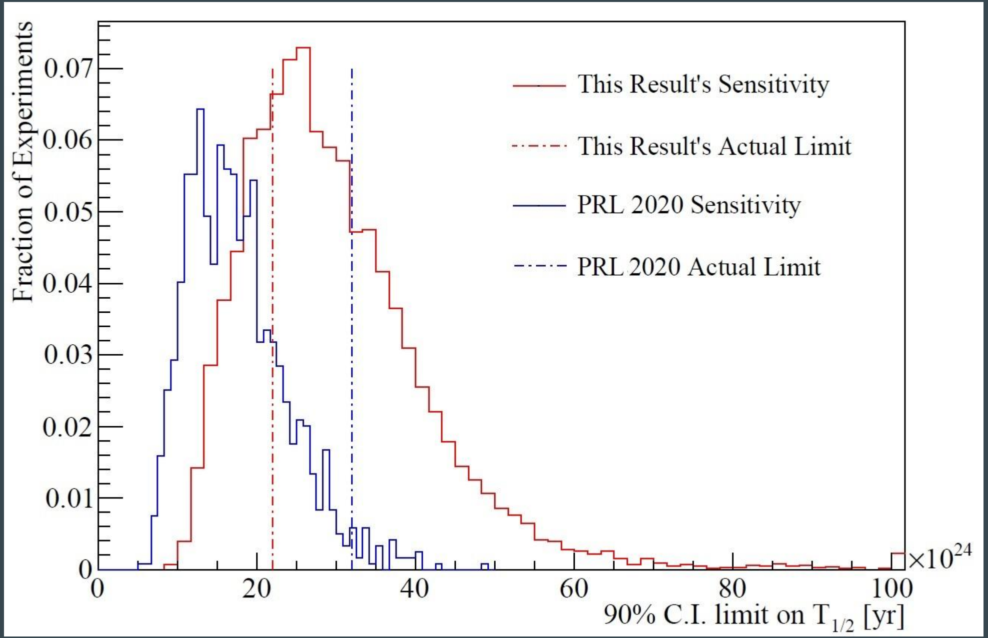


Comparison to Previous Result

	Actual Limit	Median Exclusion Sensitivity
Previous Result	$T_{1/2} > 3.2 * 10^{25}$ yr	$T_{1/2} > 1.7 * 10^{25}$ yr
This Result	$T_{1/2} > 2.2 * 10^{25}$ yr	$T_{1/2} > 2.8 * 10^{25}$ yr

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

Our median exclusion sensitivity shows a notable improvement with the new exposure



Summary

- CUORE has now exceeded 1 tonne year of exposure and continues to stably collect data, with an ultimate goal of 3 tonne-years of exposure before CUPID commissioning begins
- We observe no evidence of 0νββ 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: $m_{\beta\beta} <$ (90-305) meV
- This is the highest sensitivity search for 0νββ decay of ^{130}Te to date
  - Median 90% exclusion sensitivity: $T_{1/2} > 2.8 \times 10^{25}$ yr
- Preprint of these results can be found at arXiv:2104.06906
- Look forward to other analyses from this data in the future!