Latest Results of the CUORE Experiment

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From Johns Hopkins University

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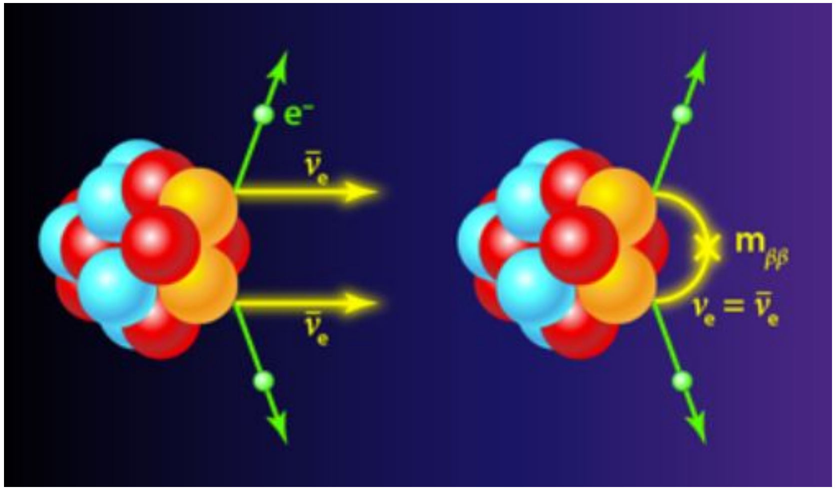
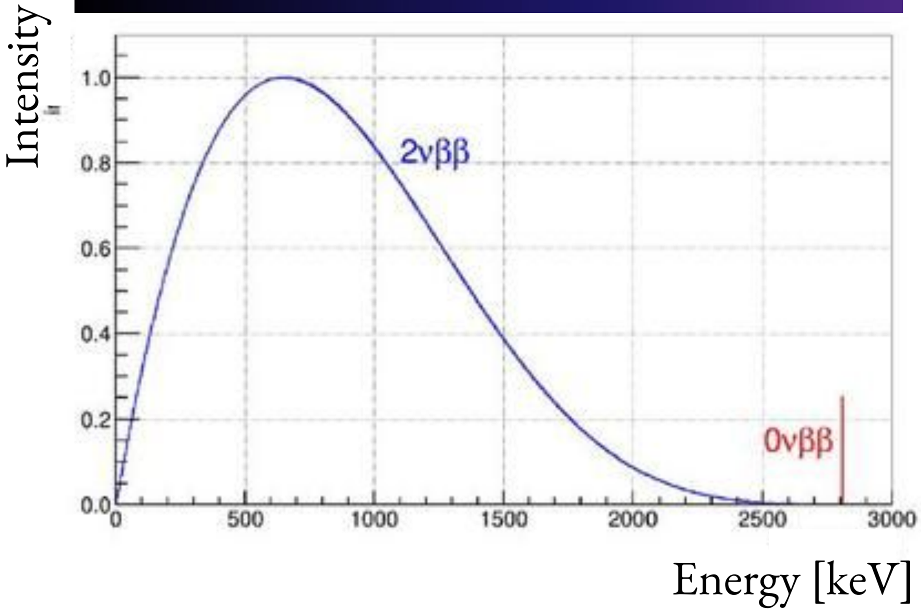
February 22, 2023

Searching for neutrinoless double beta decay

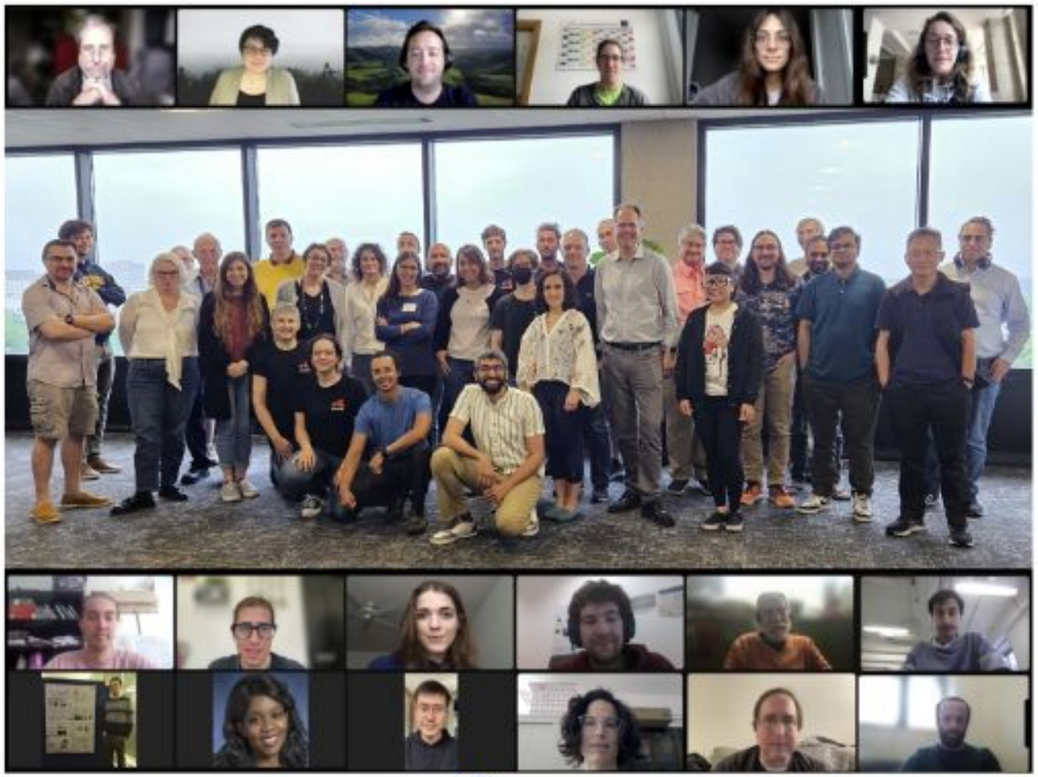
*Image courtesy of: APS Alan Stonebraker

- Double beta decay: rare second order process in even-even isotopes where single beta decay is energetically forbidden
  - Observable half life ~ 10^{18} - 10^{24} years
- Neutrinoless double beta decay
  - Lepton number violation
  - Implies majorana mass of neutrino





Meet the CUORE Collaboration



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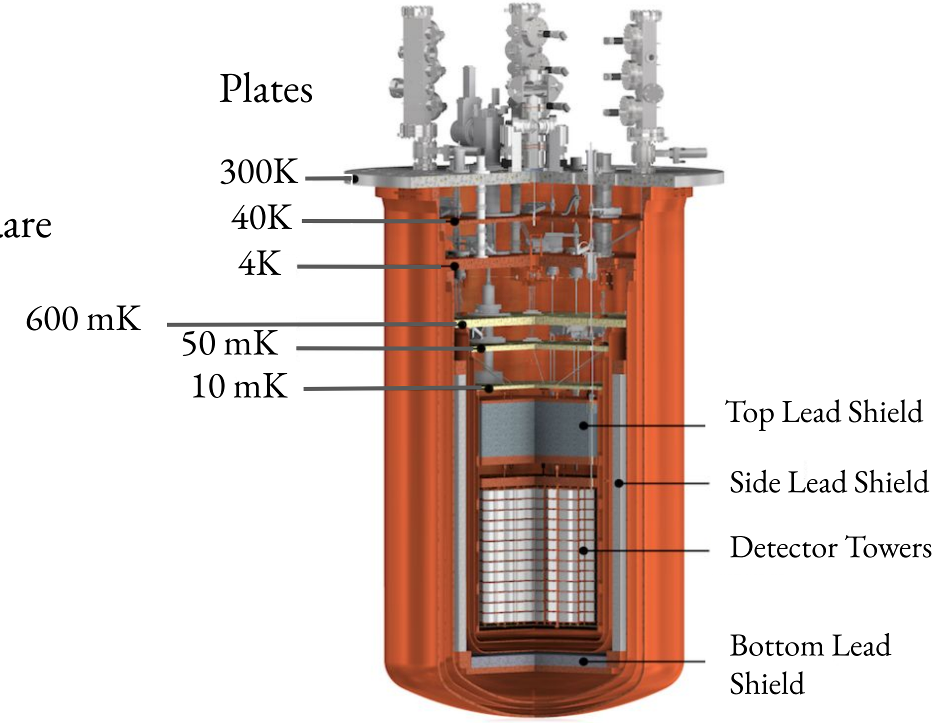
Berkeley University of California
Massachusetts Institute of Technology
Lawrence Livermore National Laboratory
University of Pittsburgh
UCLA
Virginia Tech
CUORE

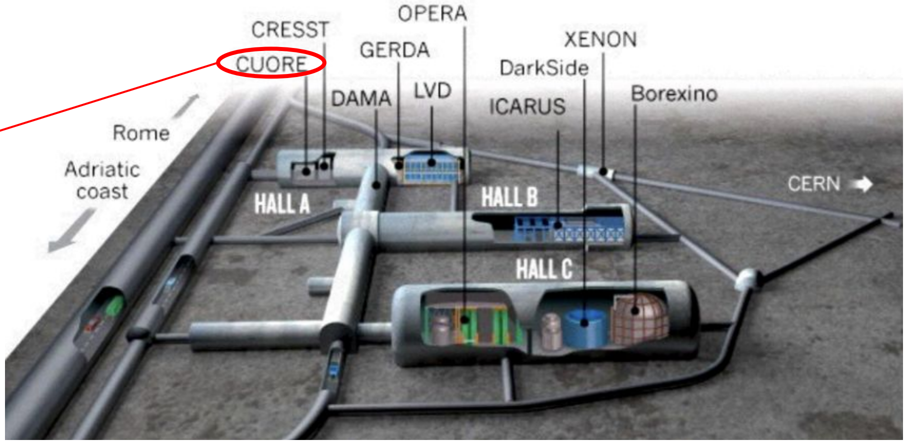
The CUORE Experiment

- The **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents
- Array of 988 natural TeO_2 crystals, 0.75 kg each
  - 206 kg ^{130}Te
- Cryogenically cooled to ~ 10 mK
  - 5 pulse tubes to 4.2 K
  - Dilution Unit from Leiden Cryogenics: 4 μW cooling at 10 mK
- **Physics goal: Search for neutrinoless double beta decay of ^{130}Te**
  - Q value of 2527.52 keV
  - Sensitivity $\propto \sqrt{\frac{MT}{B\Delta E}}$



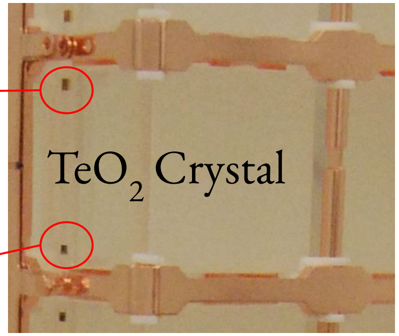
CUORE at LNGS

- Located at Gran Sasso National Laboratories in Assergi Italy
- Underneath Gran Sasso mountain
  - ~3600 w. m. e. overburden
  - Muon flux ~$3 \times 10^{-8} \mu$ / (s cm^{-2}) [1: MACRO.]

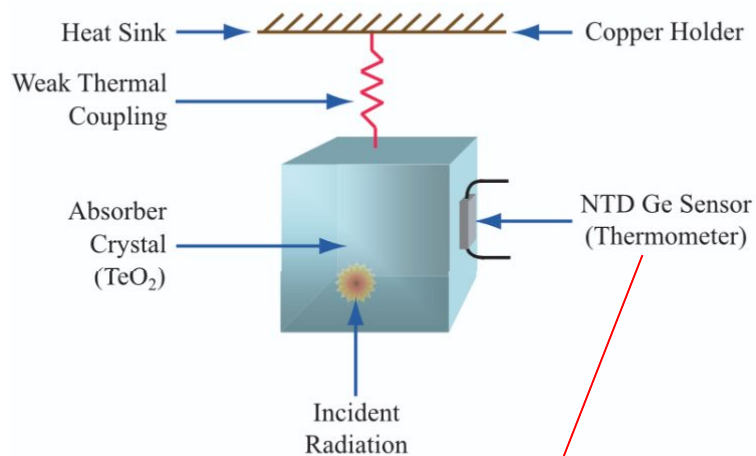


Bolometric Technique

Ge NTD

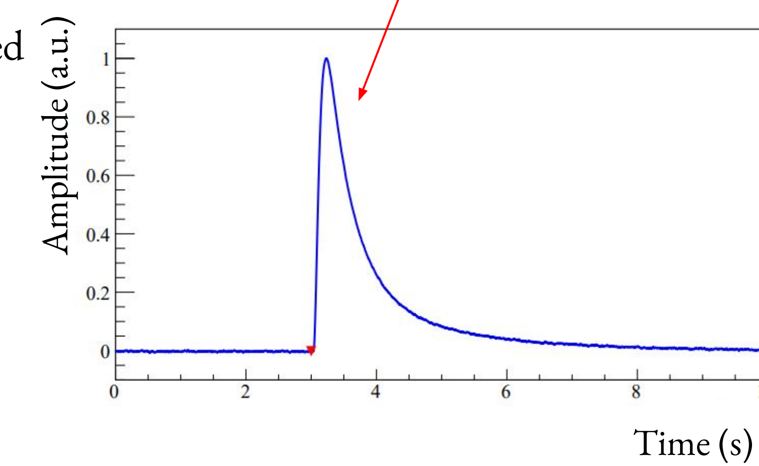


Si Heater



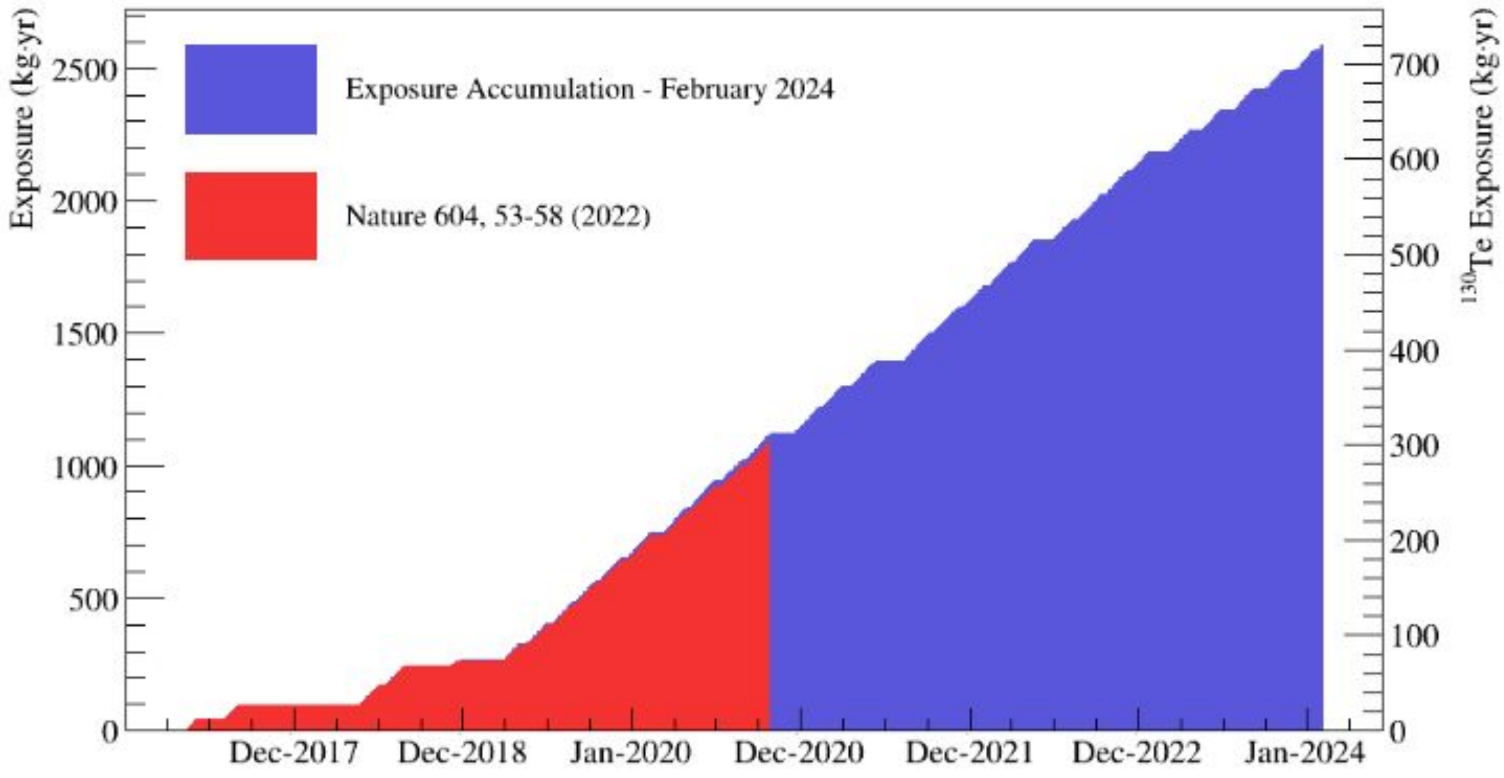
- Energetic interaction inside crystal
  - Increase of temperature caused by thermal phonons
- Electric signal read out from Neutron Transmutation Doped Ge sensor
- Temperature detected by NTD ∝ energetic interaction of event
  - $\Delta T = \Delta E / C(T) \sim 100\,\mu K$ / MeV
  - $C(T) \propto T^3$

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



Current Status of Data Collection

- Currently collected > 2 tonne-years of exposure!
- Steady data collection since early 2019
- Ongoing data collection with ~2 month long physics datasets
  - Calibration periods at the start and end of these datasets



Data Processing

1. Denoising
2. Optimum filtering
3. Offline retriggering
4. Energy reconstruction
5. Quality Cuts

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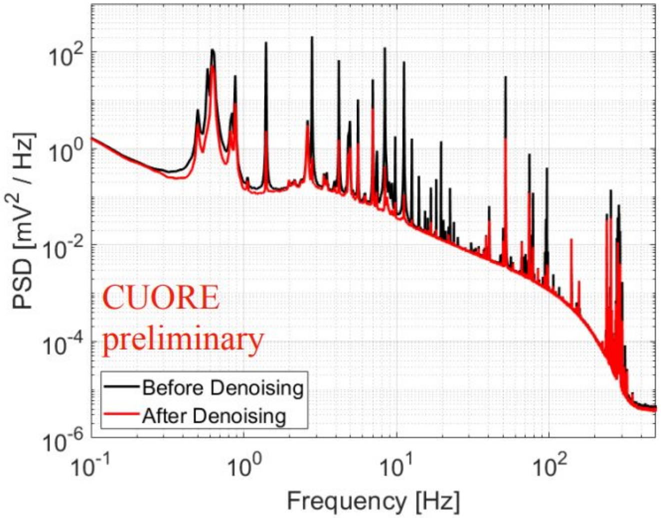
2. Optimum filtering
3. Offline retriggering
4. Energy reconstruction
5. Quality Cuts



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1. Denoising
2. **Optimum filtering**
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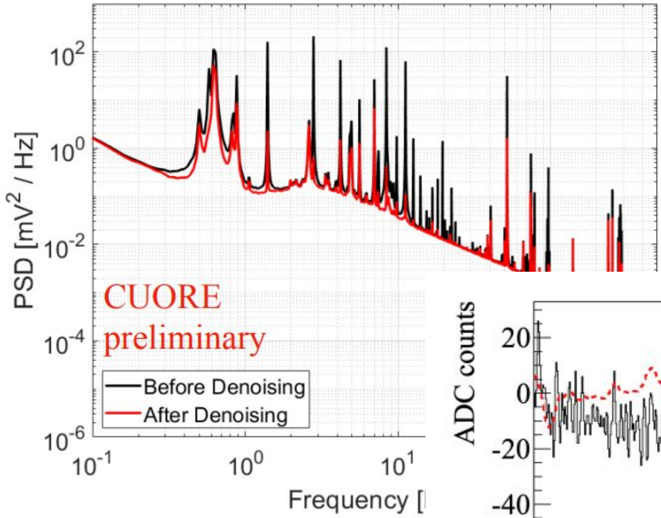

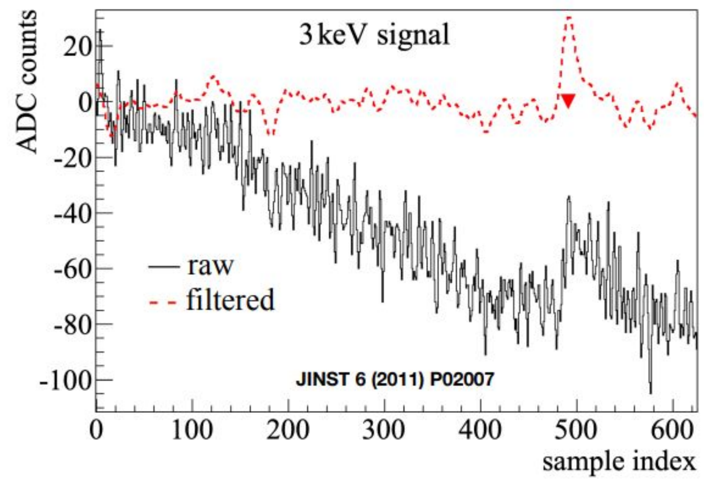

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2. Optimum filtering
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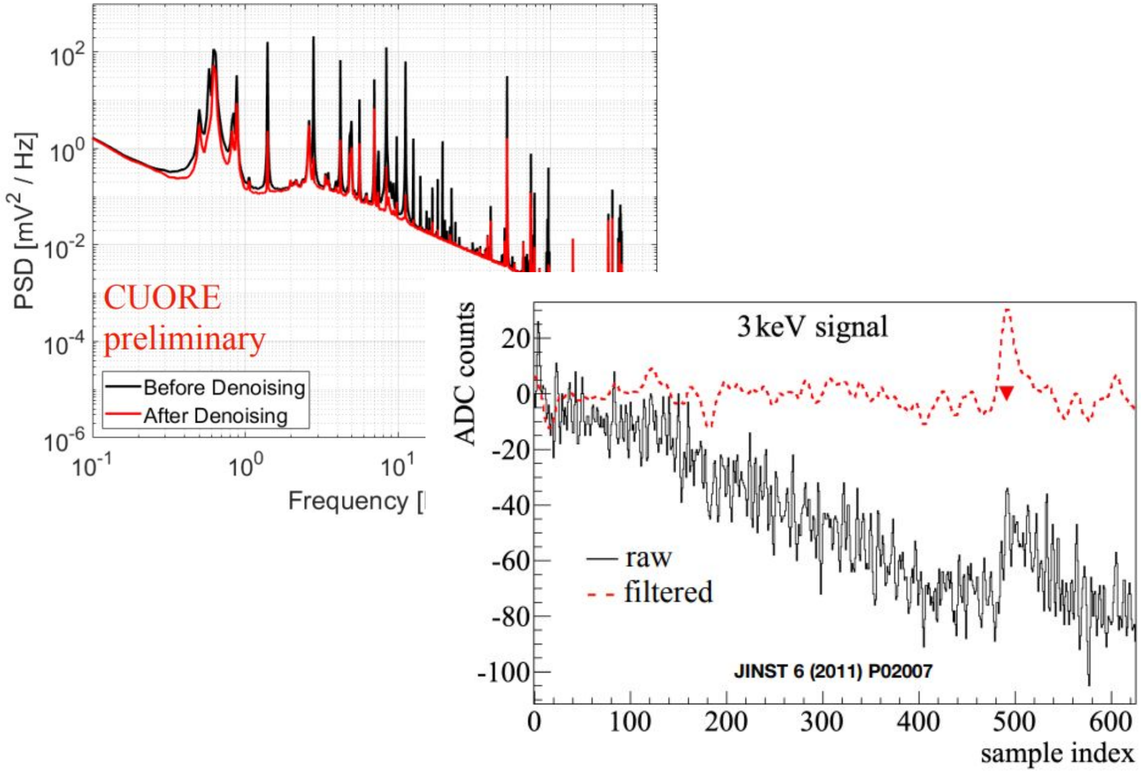
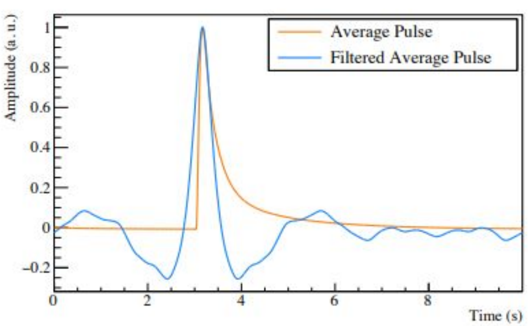


Amplitude Evaluation



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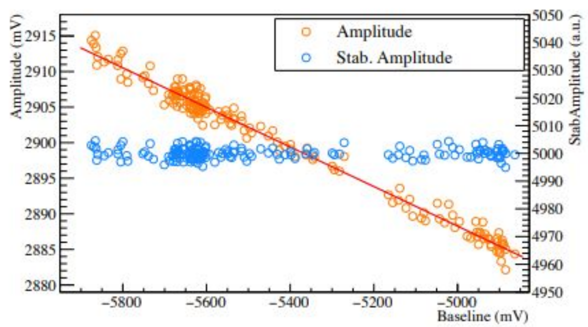
Thermal Gain Stabilization



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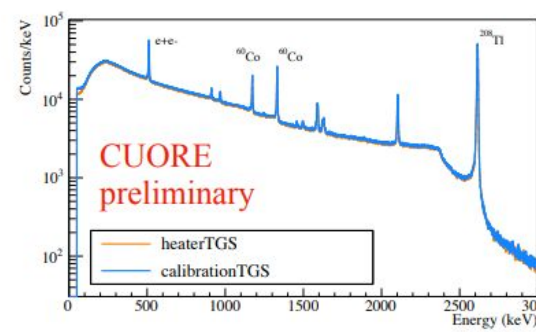
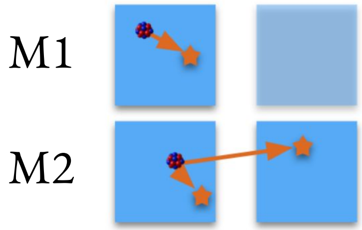
Energy Calibration

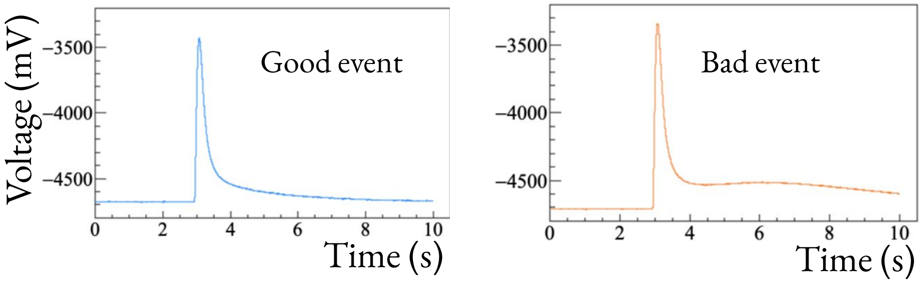


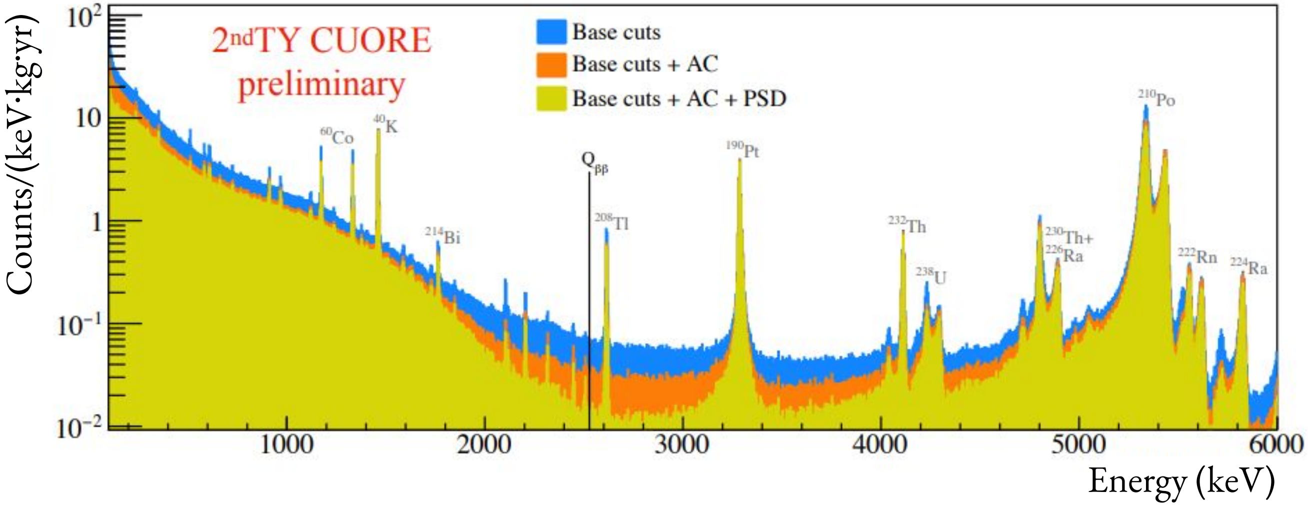
Quality Cuts

- Anti-coincidence (AC) selection
  - Expect single site (M1) events of $0\nu\beta\beta$ events ~88% containment efficiency according to MC



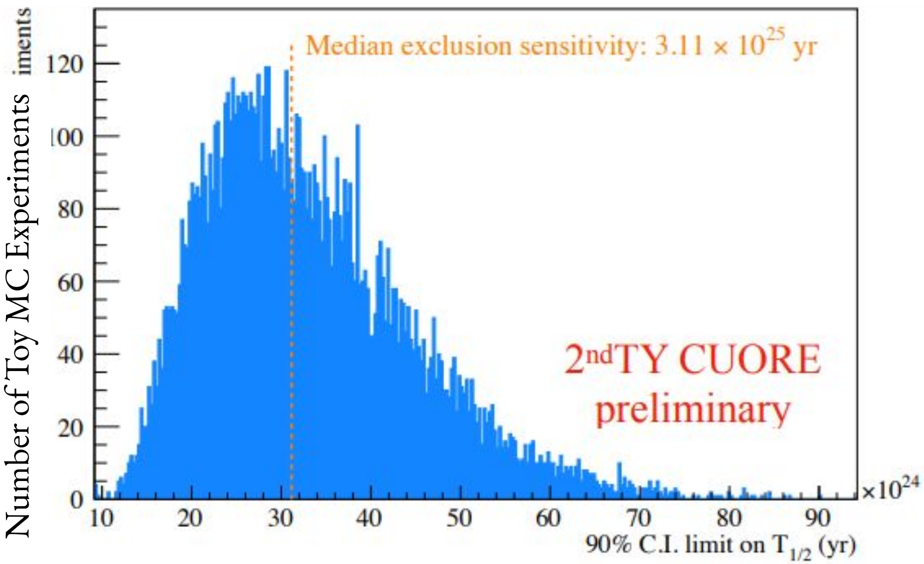
- Pulse shape discrimination (PSD)
  - Using principal component analysis techniques

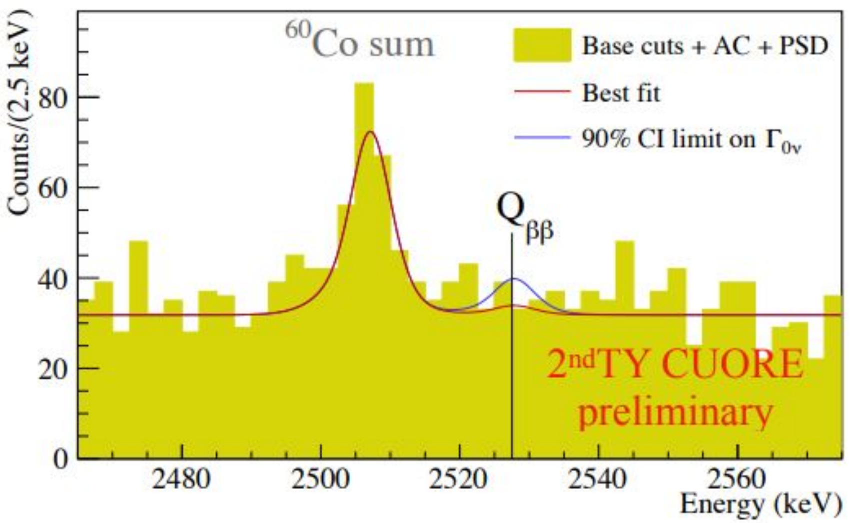




Results on 2nd Tonne Year

- Region of Interest: [2465, 2575] keV
  - $0\nu\beta\beta$ decay rate
  - ^{60}Co decay rate
  - Flat background
- Bayesian analysis using MCMC* techniques
- Exclusion sensitivity
  - 10^4 MC toy experiments on background only hypothesis
  - Median sensitivity of 3.1×10^{25} yr (90% C.I.)
- Unblinded fit:
  - **No evidence of neutrinoless double beta decay**
  - Background Index = 1.3×10^{-2} cts/keV/kg/yr
  - Best fit decay rate $\Gamma_{0\nu} < 2.5 \times 10^{-26}$ yr^{-1} (90% C.I.)
  - Half life limit $T^{0\nu}_{1/2} > 2.7 \times 10^{25}$ yr (90% C.I.)

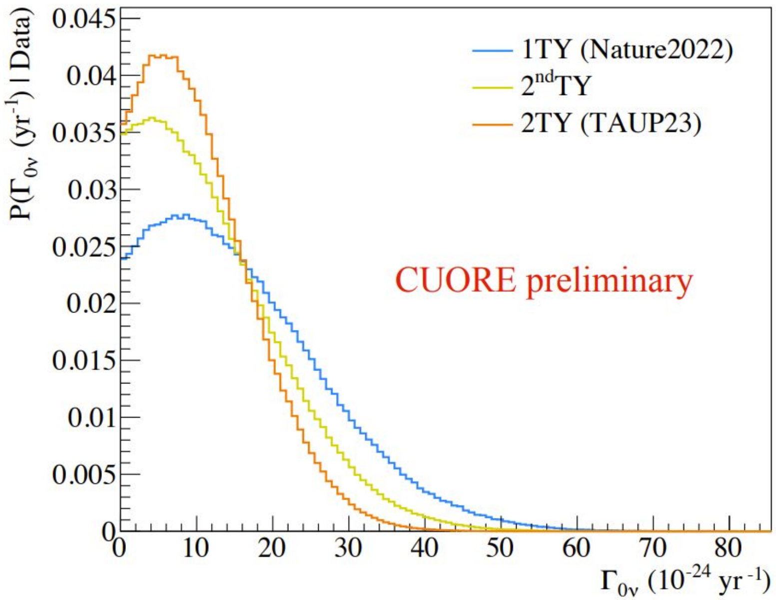




* Markov Chain Monte Carlo

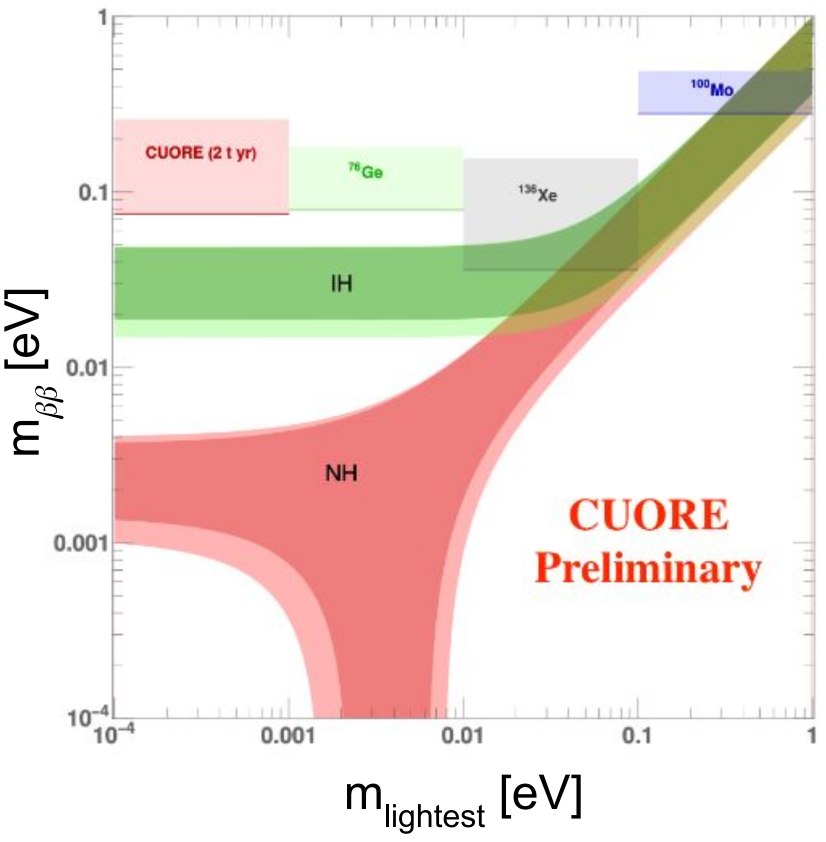
2 Tonne Year Results

- Combine 2nd TY with 1 TY results
  - Nature 604, 53-58 (2022).
- Total analyzed exposure: 2023 kg · yr
- Best fit decay rate $\Gamma_{0\nu} < 2.1 \times 10^{-26}$ yr^{-1} (90% C.I.)
- **No evidence of neutrinoless double beta decay observed**
- **Half life limit $T^{0\nu}_{1/2} > 3.3 \times 10^{25}$ yr (90% C.I.)**
- **Effective Majorana mass limit: $m_{\beta\beta} < 75\text{-}255$ meV**
- Stay tuned for full analysis!
  - Reprocess 1st TY of data with improved analysis techniques
  - Repeat fit



Conclusions

- CUORE collected > 2 tonne years exposure and is still stably collecting data
- Plan for final exposure of 3 tonne year TeO_2 by 2025
- Next generation: **C**UORE **U**pgrade with **P**article **ID**entification (CUPID)
    - See talk by J. Torres



Citations

[1] MACRO Coll., M. Ambrosio et al., Phys. Rev. D 52, 3793, 1995

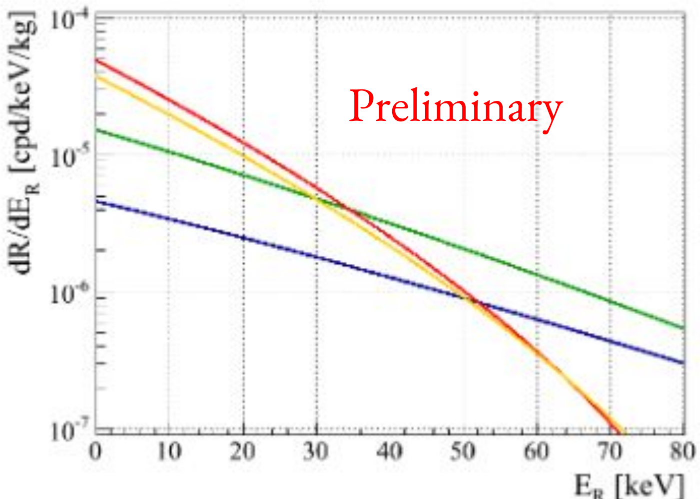
[2] Search for 14.4 kev solar axions from M1 transition of 57fe with cuore crystals. (2013). *Journal of Cosmology and Astroparticle Physics*, *2013*(05), 007–007. https://doi.org/10.1088/1475-7516/2013/05/007

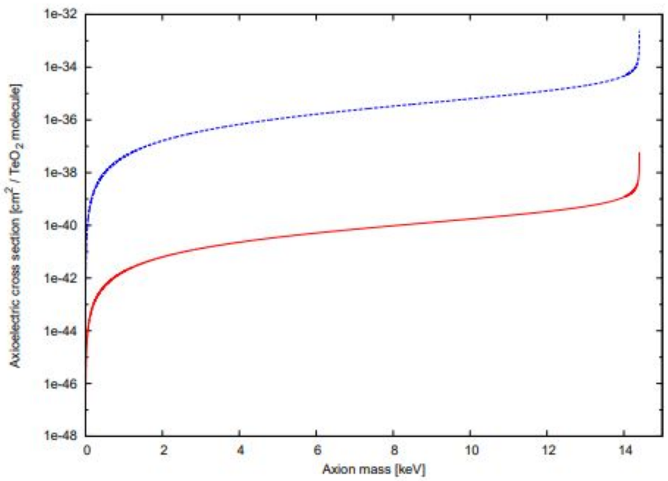
[3] D. Q. Adams *et al.* (CUORE Collaboration), Nature 604, 53-58 (2022).

BACK UP

Other Analyses with CUORE

- Low energy searches
  - **WIMP like dark matter**
  - **Solar Axions**
  - ^{123}Te Electron Capture
- High Multiplicity analyses
  - Tri-nucleon decay
  - Muon background studies
  - Etc.
- Background Model Work
  - Characterization of CUORE background model
- Other Rare Processes
  - $^{128/130}$Te $2\nu\beta\beta$ and $0\nu\beta\beta$
- Detector Response
- More!





[2]

Optimum Filter

- A matched filter algorithm
  - Takes an expected signal shape and an expected noise shape
  - Fourier transforms time series to frequency space
  - Filter suppresses non signal shapes and maintains amplitude of signal (improved signal to noise ratio)

Expected Signal

$$H(\omega_k) = h\frac{s^*(\omega_k)}{N(\omega_k)}e^{-j\,\omega_k i_M}\,.$$

Expected Noise

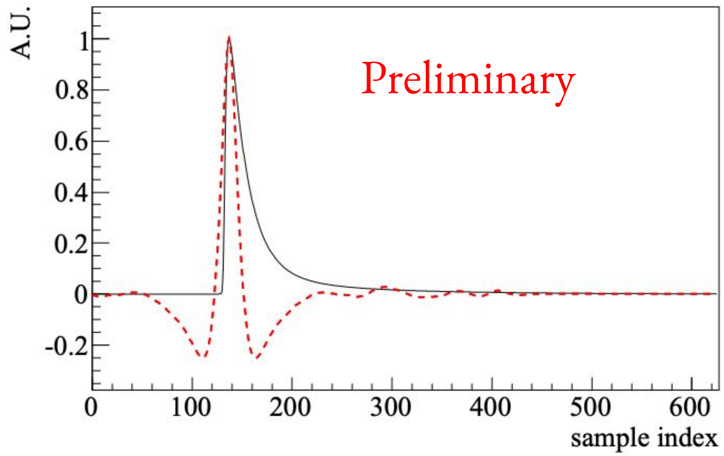
Filter Noise Power Spectrum

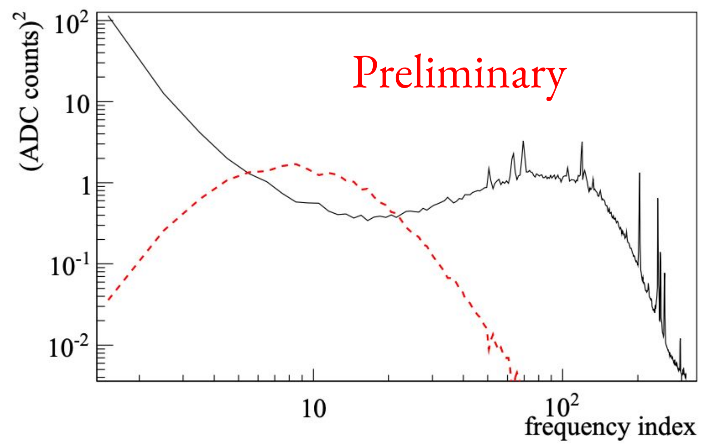
$$N_f(\omega_k) = h^2\frac{|s(\omega_k)|^2}{N(\omega_k)}\,,$$

Filter Resolution

$$\sigma_f^2 = \sum_k N_f(\omega_k) = h\,.$$

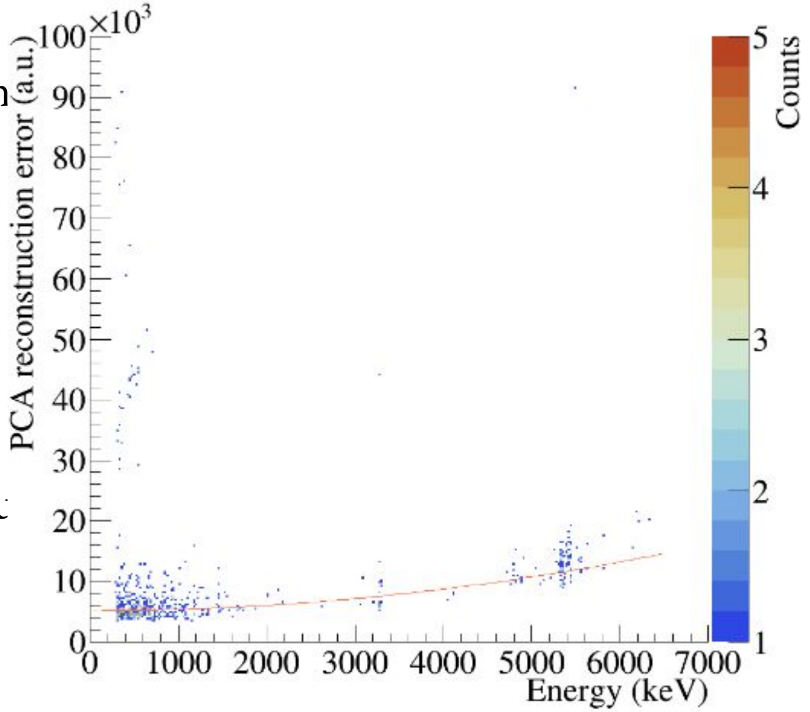
- Optimum Trigger: triggers when amplitude is $N\sigma_f$ over baseline





Pulse Shape Discrimination

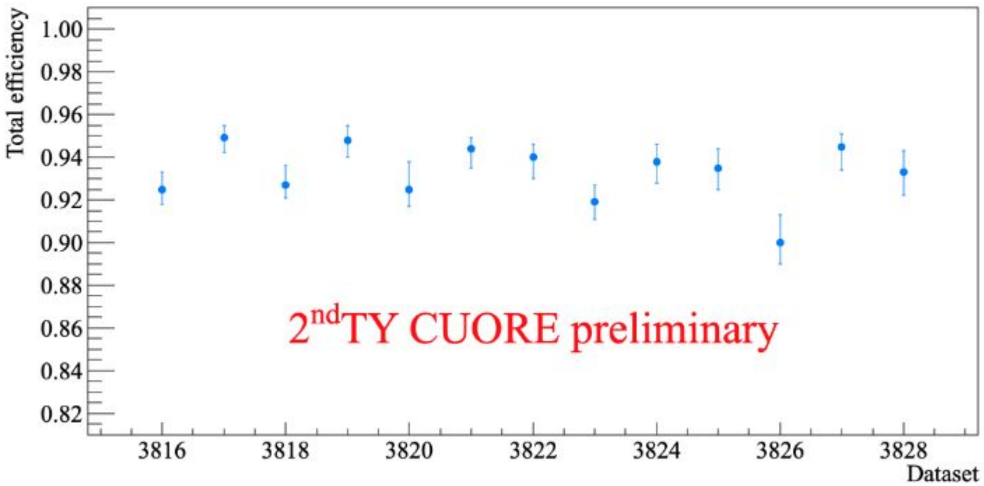
- Principal Component Analysis method
- Treat each channel's average pulse like it is a leadin
  principle component
- Define "reconstruction error" for each event x
  using principle component w
  - $RE = \sqrt{\sum_{i=1}^{n} (x_i - (x \cdot w) w_i)^2}$
- Normalize reconstruction error vs energy to get cu



[3]

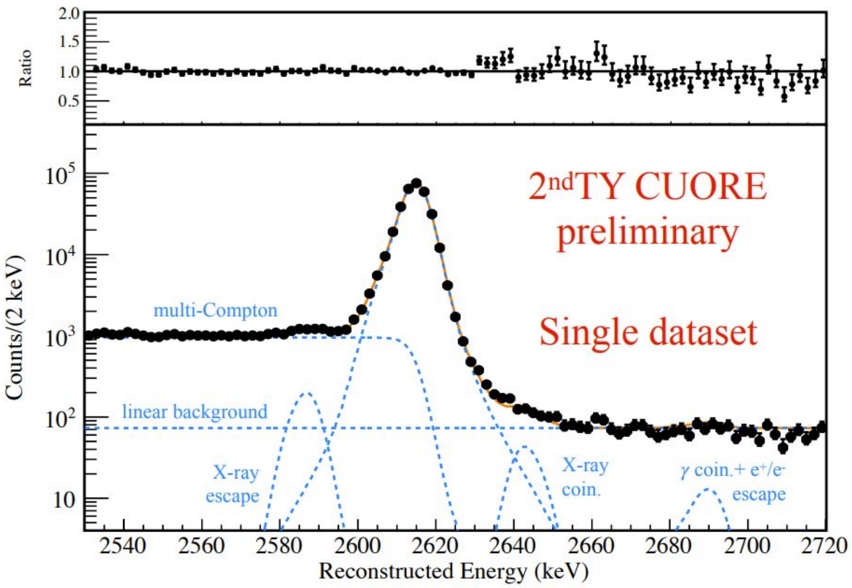
Efficiencies

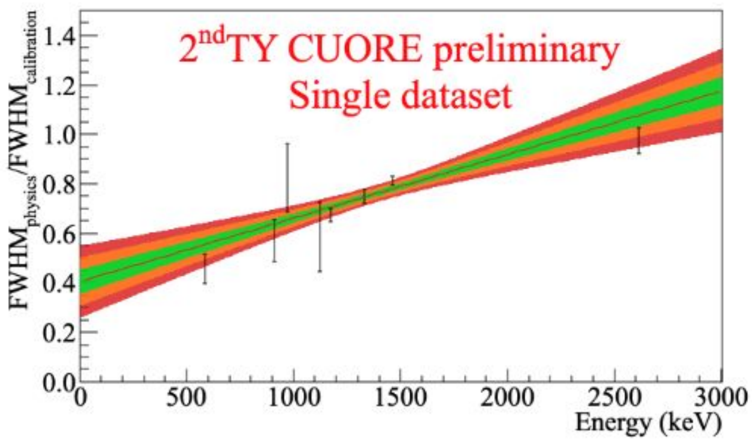
- Evaluated using heater pulses
  - Trigger efficiency
  - Pile up efficiency
  - Energy reconstruction efficiency
- PSA Efficiency
- Anti Coincidence Efficiency
- Containment efficiency (from simulation)

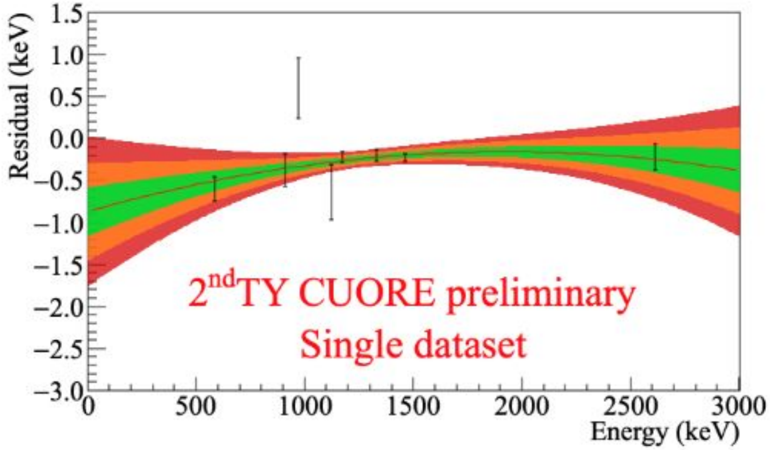


Detector Response Model

- Sum of three Gaussians at 2615 keV line in calibration data
  - Fit simultaneously with nearby structures
  - $\Delta E_{2615} = 7.43 \pm 0.37$ keV
- Fit peaks in physics data
- Scale resolution and bias to $Q_{\beta\beta}$
  - $\Delta E_{Q_{\beta\beta}} = 7.26^{+0.43}_{-0.47}\,\mathrm{keV}$
  - $E_{\mathrm{bias}Q_{\beta\beta}} = -0.11^{+0.19}_{-0.25}\,\mathrm{keV}$







Fit Method

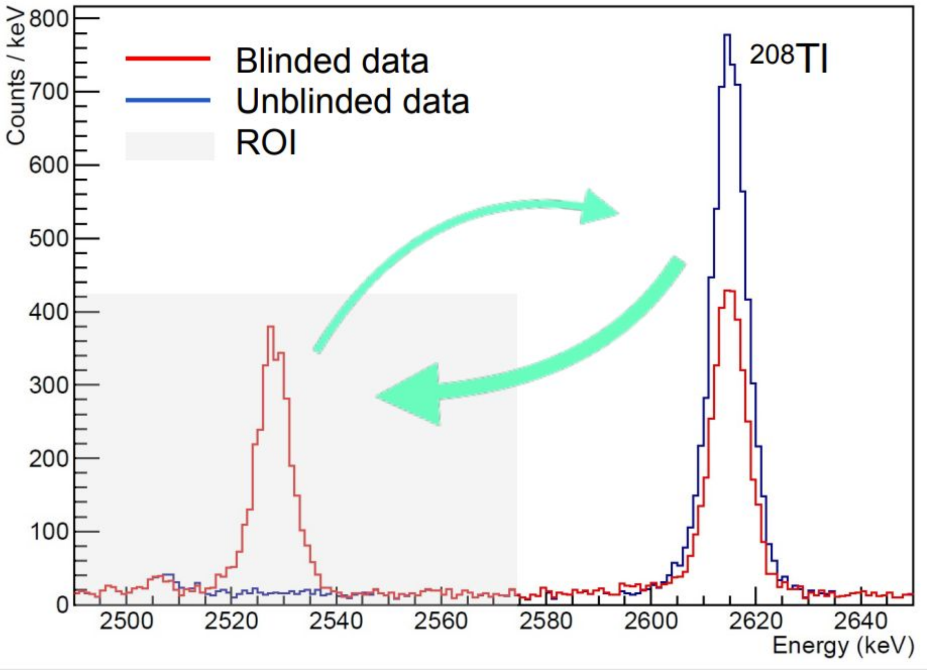
- Bayesian method
  - $P(\overrightarrow{\theta}, \alpha|D) = \frac{\mathcal{L}(D|\overrightarrow{\theta},\alpha)\pi(\overrightarrow{\theta},\alpha)}{\int d\overrightarrow{\theta} d\alpha\pi(\overrightarrow{\theta},\alpha)\mathcal{L}(D|\overrightarrow{\theta},\alpha)}$
- Likelihood model:
  - $\mathcal{L}(E_i|\overrightarrow{\theta}) = \prod_{Ds}\prod_{Ch}[\frac{e^{-\lambda}\lambda^n}{n!}\prod_i(\frac{s}{\lambda}\mathrm{pdf}_{0\nu}(E_i|\overrightarrow{\theta}) + \frac{c}{\lambda}\mathrm{pdf}_{^{60}\mathrm{Co}}(E|\overrightarrow{\theta}) + \frac{b}{\lambda}\frac{1}{\Delta E})]$
  - Expectation count: $\lambda = s + c + b$

Background Index

- Predominantly degraded α interactions from copper structures and surface of crystals
  - Fit flat background in [2650, 3100] keV region
- Flat region in $Q_{\beta\beta}$ region
  - Fit flat background + ^{60}Co in [2490, 2575] keV region

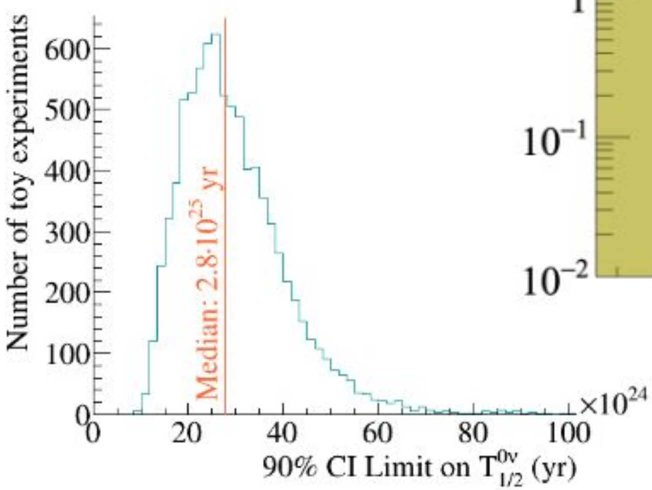
Blinding Procedure

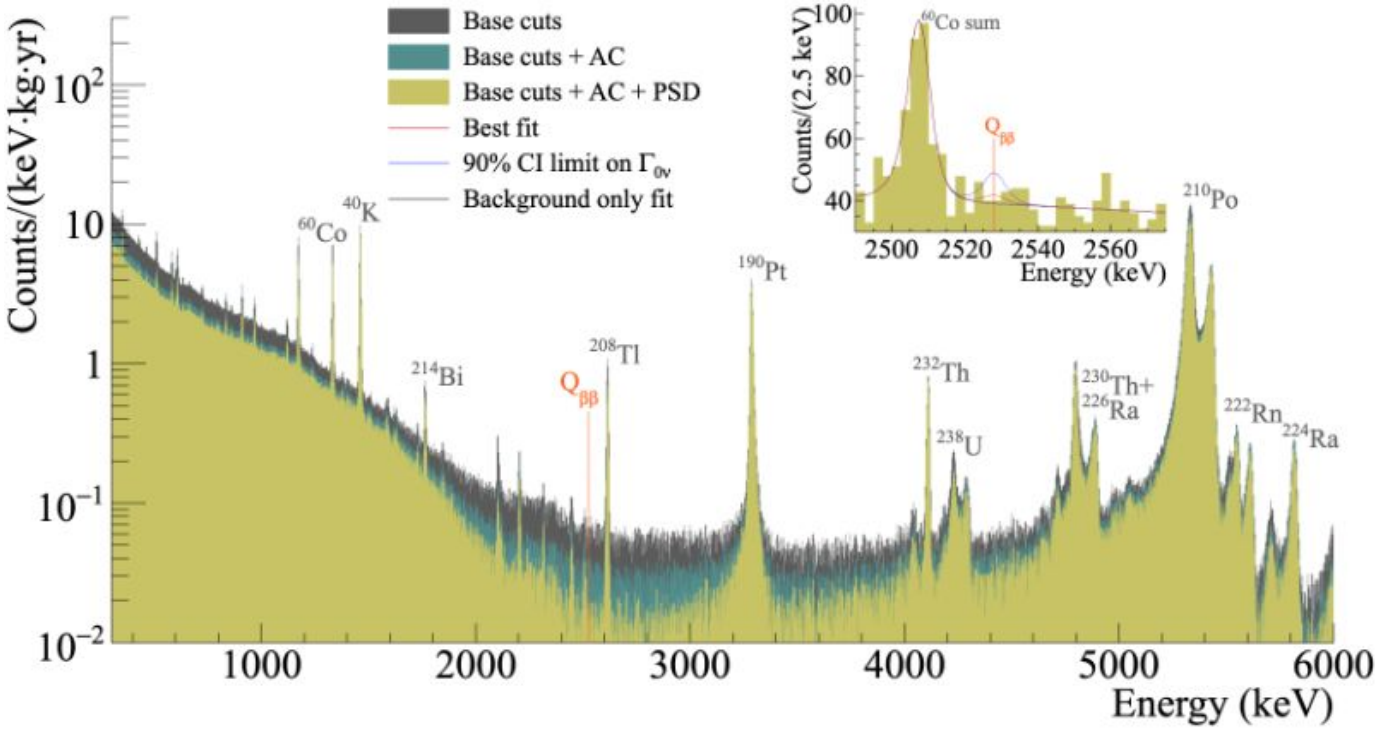
- Shift a fraction of events from ^{208}Tl 2615 keV line to $Q_{\beta\beta}$ line and vise versa
- Keep original energies encrypted until unblinded
- Unblind once full analysis procedure is fixed



1st Tonne Year Results

- Results: Nature 604, 53-58 (2022))
- Median exclusion sensitivity: 2.8×10^{25} yr (90% C.I.)
- $T_{1/2} > 2.2 \times 10^{25}$ yr (90% C.I.)





2nd TY Analysis Numbers

Parameter	Value
FWHM at 2615 keV (calibration data)	7.43 ± 0.37 keV
FWHM at $Q_{\beta\beta}$ (physics data)	$7.26^{+0.43}_{-0.47}$ keV
Total Analysis Efficiency	93.2%
Average Background Index at $Q_{\beta\beta}$	1.3×10^{-2} cts/keV/kg/yr

CUPID

- New Li_2MoO_4 towers to be installed after decommissioning of CUORE
    - Same cryostat used with upgraded pulse tubes
- Additional scintillating bolometer coupled to crystal
    - Light escapes crystal to induce a phonon signal in the Germanium wafer