End-to-End Data Analysis Methods for the CUORE Experiment

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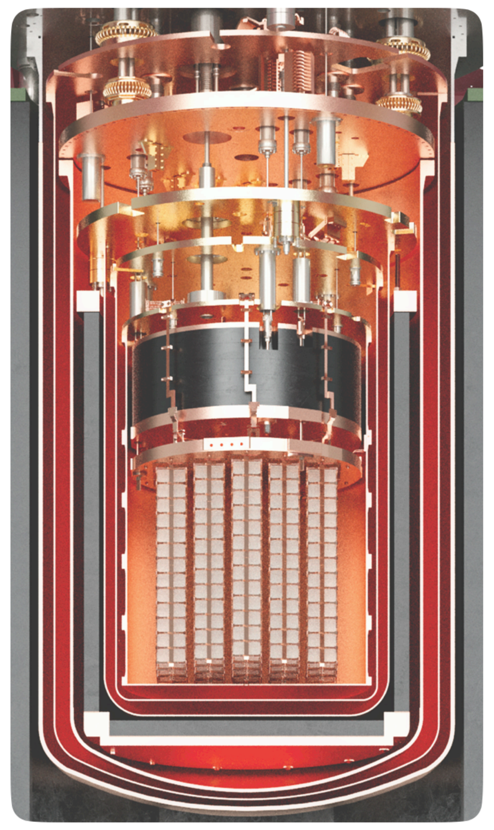
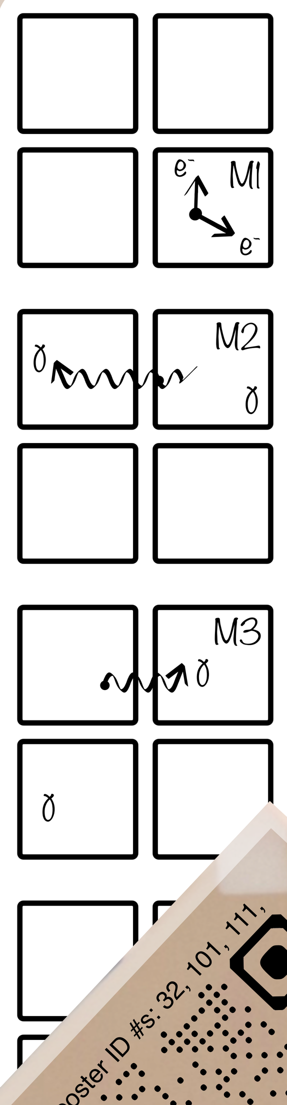
CUORE

- The CUORE (Cryogenic Underground Observatory for Rare Events) experiment primarily searches for $0\nu\beta\beta$ decay of ^{130}Te
- The CUORE detector is a close-packed array of 988 TeO_2 calorimeters
- Active mass: 742 kg TeO_2 (206 kg ^{130}Te)
  - Enables searches for exotic particles
- Unenriched TeO_2
  - ^{120}Te, ^{128}Te
- ~10^{-2} counts/(keV·kg·yr) at $Q_{\beta\beta}$ (~2528 keV)
- $Q_{\beta\beta}$ FWHM energy resolution: ~0.3%
- Data taking began in 2017: 3000+ kg·yr of raw TeO_2 exposure
- The active mass, isotopic composition, and highly segmented geometry of the CUORE detector enables a diverse physics program

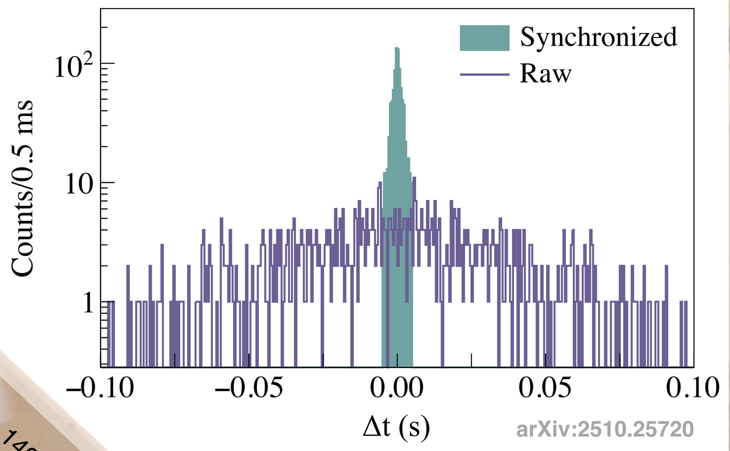


Rendering by Lightmap Creative S.r.l.

Multiplicity

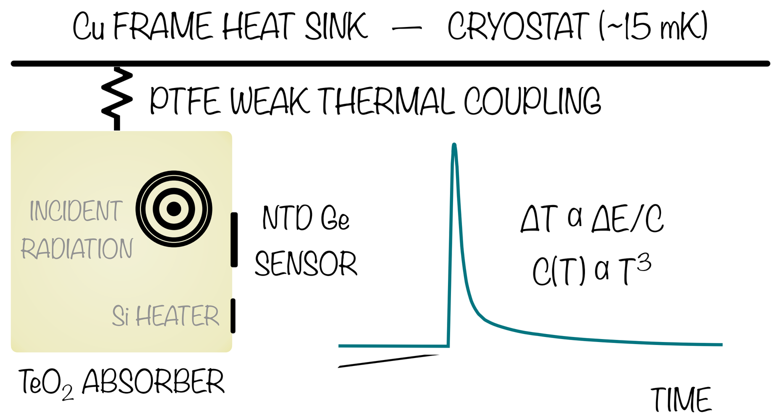


- Defined by analysis-specific coincidence parameters:
  - Minimum energy threshold
  - Maximum time window
  - Maximum radial distance
- Multiplicity number describes the amount of crystals involved



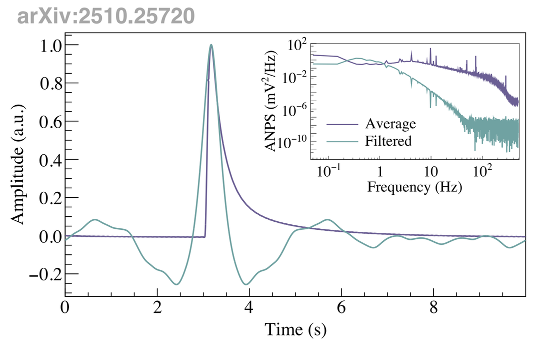
- Time synchronization corrects for difference in pulse rise times

Data Collection and Energy Reconstruction

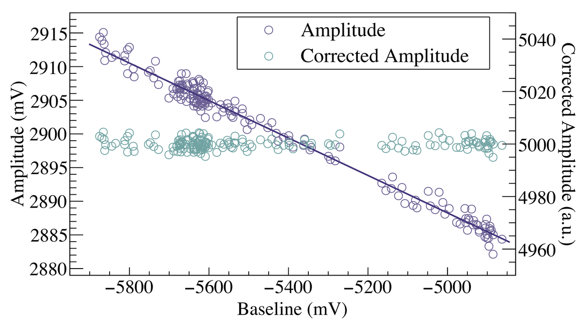


- Slight variations of the calorimeter components lead to their different intrinsic properties (e.g. rise times: 50 - 200 ms)
- Detector operating conditions also affect the detector response
- CUORE data are organized into datasets
  - Each begins and ends with ~1 week of calibration measurements and there are ~6 weeks of physics measurements between the calibrations
- Each dataset-calorimeter is analyzed independently. Denoising and triggering algorithms are applied to the continuous data stream. Then, for each triggered event:

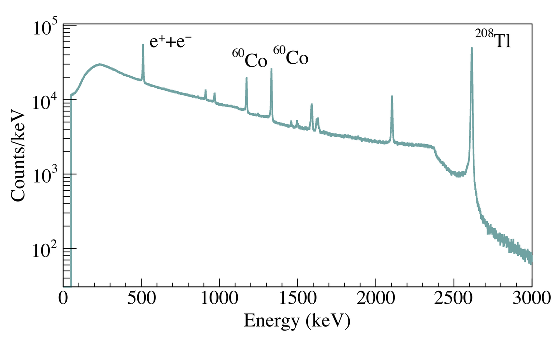
arXiv:2510.25720

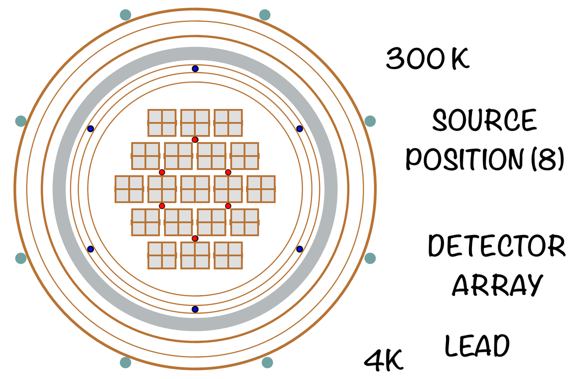


OF + Amplitude



Thermal Gain Correction

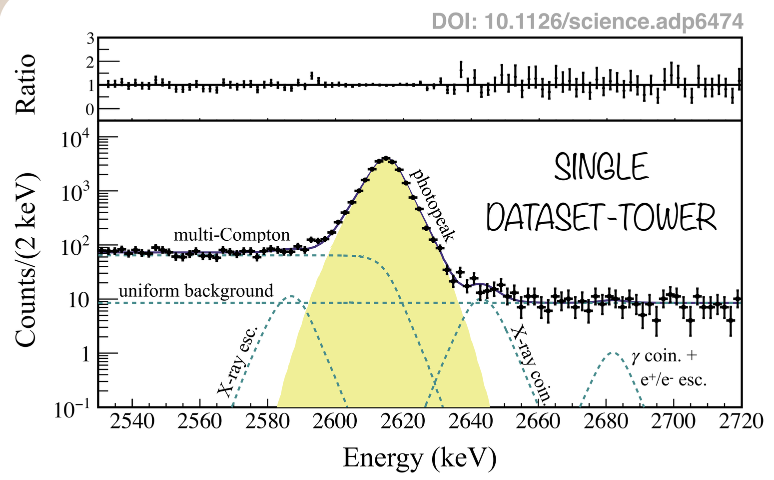


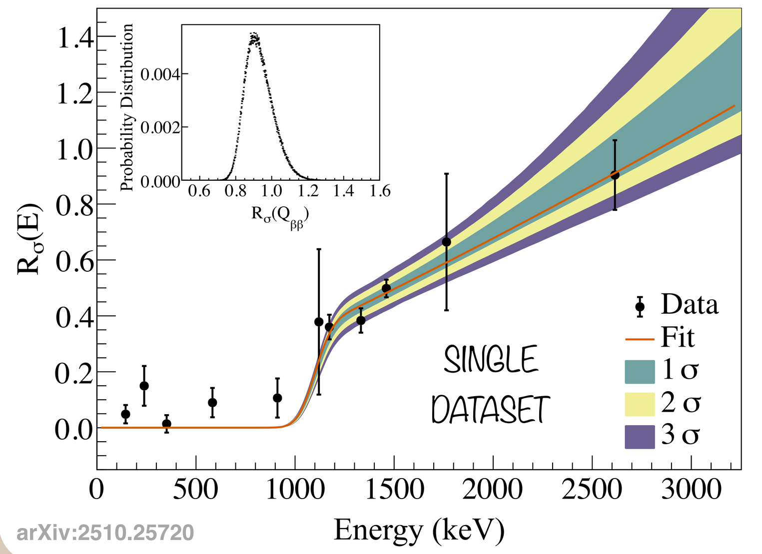


Energy Calibration

- Analysis-specific, event-based quantities and flags are also embedded in the overall data production

Detector Response (0νββ Decay)





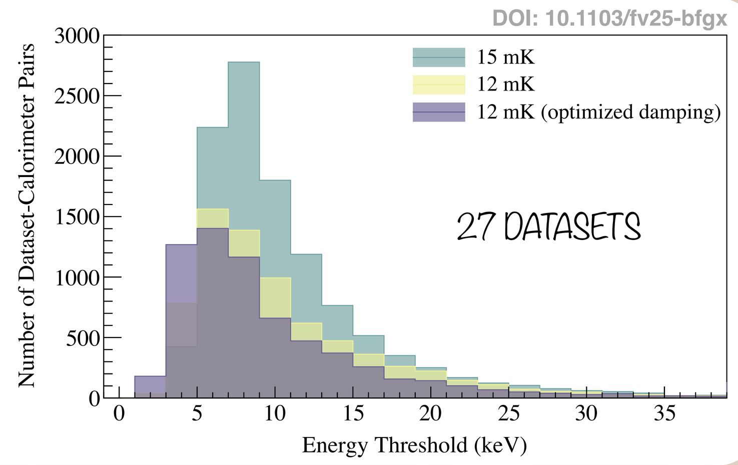
- Foundational, peak shape model (filled) is a multi-Gaussian function
- Model parameters include the position of the main peak, a common width (σ_{cal}), and the relative amplitudes and positions of the subpeaks
- Calorimeter-dependent parameters are evaluated from fitting the high-statistics 2615 keV ^{208}Tl peak in calibration data
- Calorimeter-dependent energy resolutions at $Q_{\beta\beta}$ are determined from physics data
- Fit the peak shape model to individual dataset-peaks over all calorimeters with

$$\sigma_{phys}(E) = \sqrt{\sigma^2_{\circ,phys} + R_\sigma(E)\cdot(\sigma^2_{cal} - \sigma^2_{\circ,cal})}$$

- Then, fit the dataset-level scaling parameter $R_\sigma(E)$ and extrapolate to $Q_{\beta\beta}$

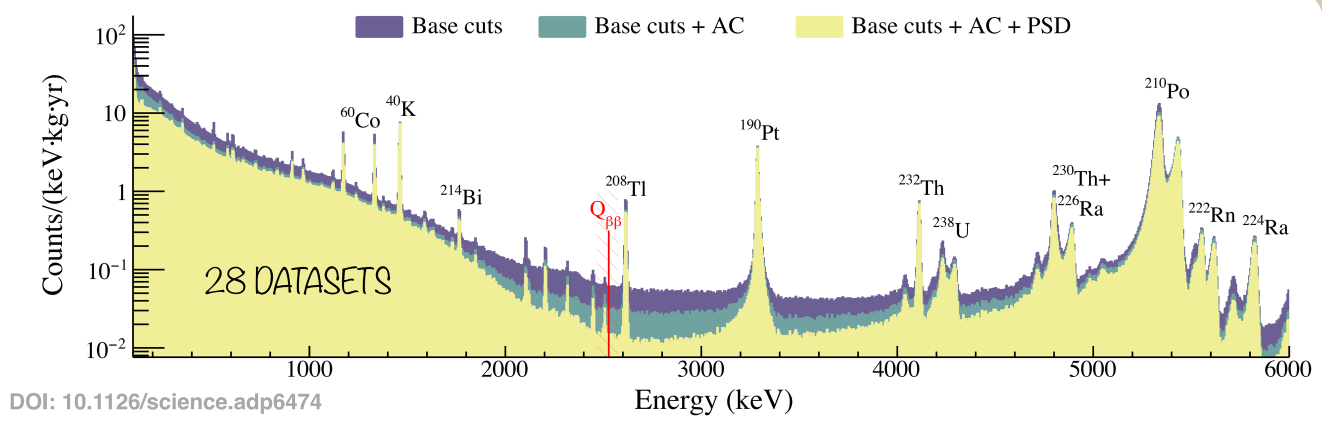
Energy Thresholds

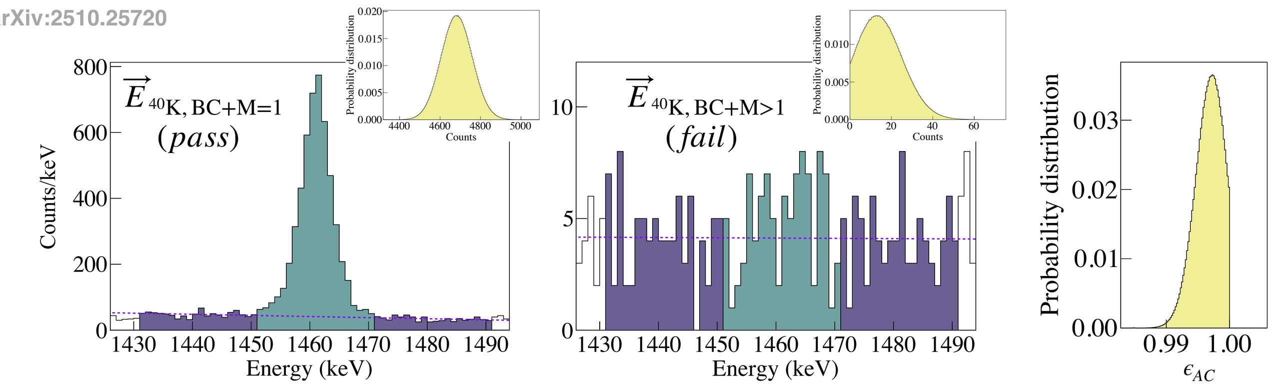
- The energy threshold of a calorimeter corresponds to the 90% trigger efficiency
- > 95% of dataset-calorimeter pairs have a threshold below 40 keV ($0\nu\beta\beta$ decay coincidence energy threshold)
- 59% of dataset-calorimeter pairs have an energy threshold below 10 keV
- 0.9% of dataset-calorimeter pairs have an energy threshold lower than 3 keV
- CUORE is capable of searching for dark matter candidates (e.g. axions, WIMPs)



Event Selection and Efficiencies (0νββ Decay)

- Base cuts reject baseline instabilities and pileup
  - Heater-induced pulses are used to evaluate the efficiencies (accurate detection, energy reconstruction, and pileup rejection)
- Anticoincidence (AC) cut rejects multi-crystal events
- Pulse shape discrimination (PSD) cut rejects pulses with uncharacteristic features
- Bayesian counting analysis on peak regions in the physics spectrum is performed to evaluate the AC and PSD efficiencies
- $0\nu\beta\beta$ decay results and methods are readily applicable for other analyses and searches

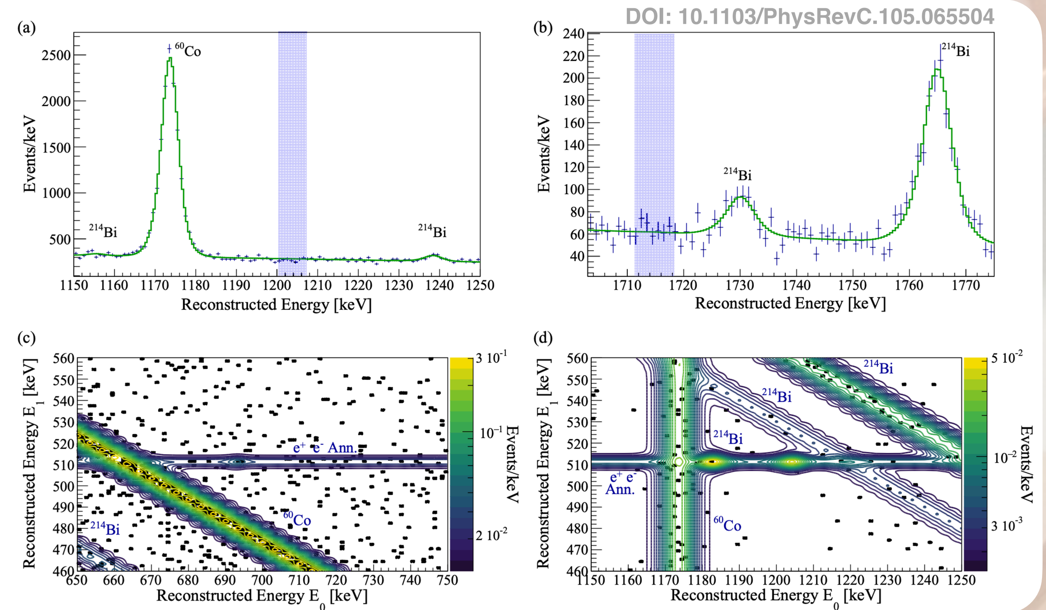




Examples of Physics Breadth

Search for neutrinoless positron-emitting electron capture decay of ^{120}Te

- Two back-to-back 511 keV gamma rays from positron annihilation provide a clear topological decay signature
- Energy spectra of all signatures are fit simultaneously



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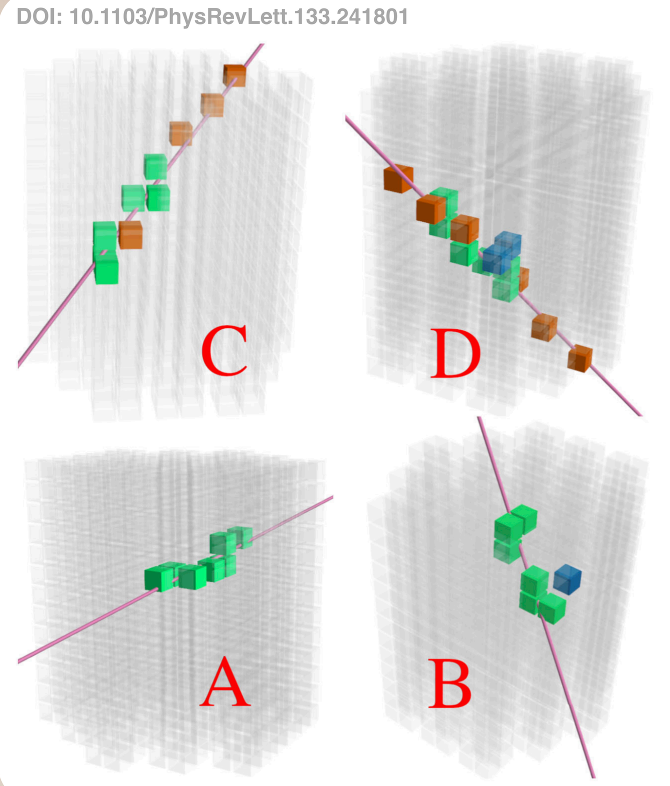

Search for relativistic fractionally charged particles (FCPs)

- Linear track across multiple crystals (ionization energy loss of FCPs)
- High-multiplicity (M6+) events are used to reconstruct through-going particle tracks
- Assuming minimally-ionizing FCPs, for each multiplet, an inverse fractional charge is estimated using the observed pattern of energy deposition along the best-fit track
- Demonstrates an unprecedented capability of cryogenic calorimeters to search for detectorwide signatures of new physics

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