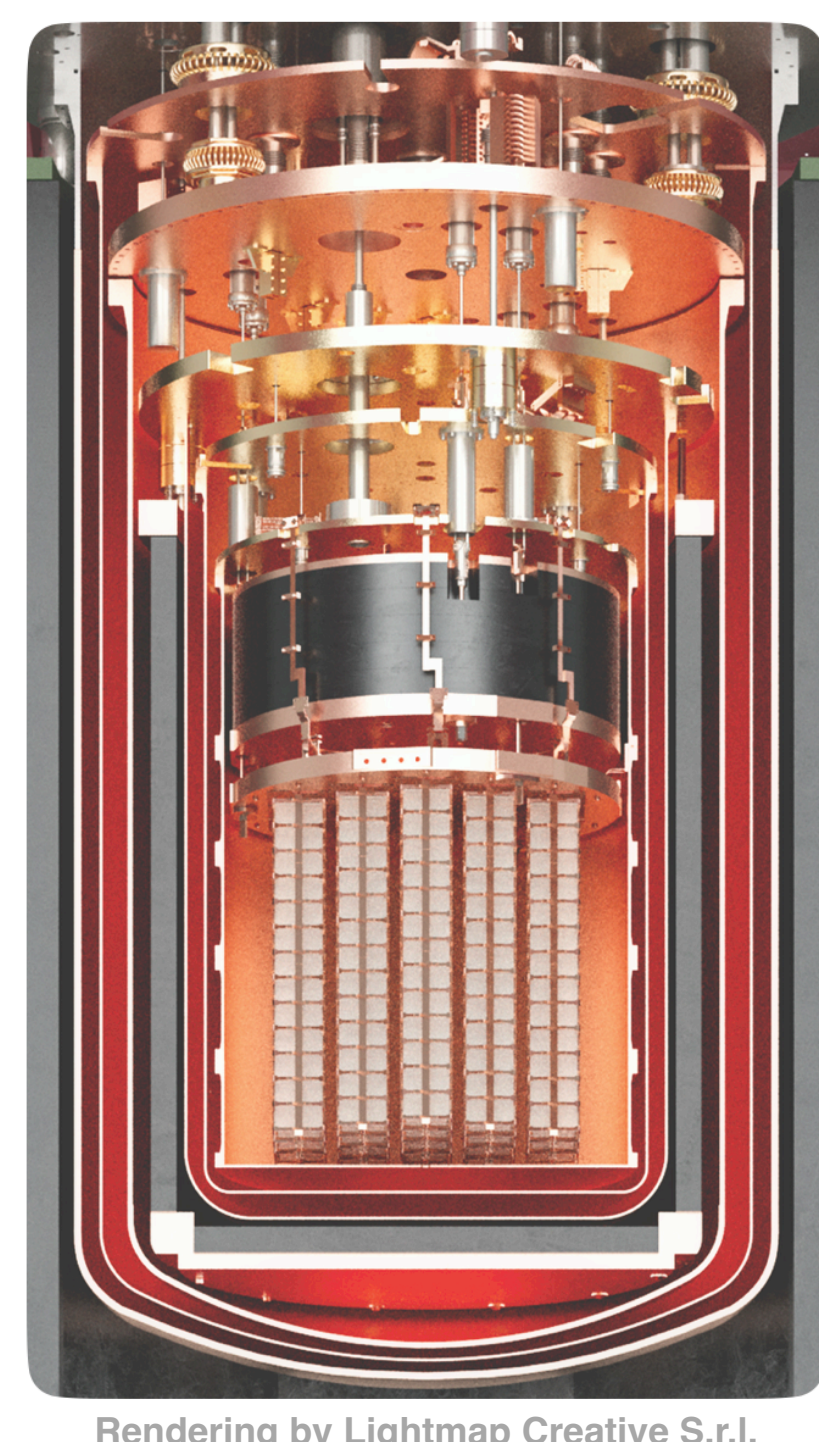


# End-to-End Data Analysis Methods for the CUORE Experiment

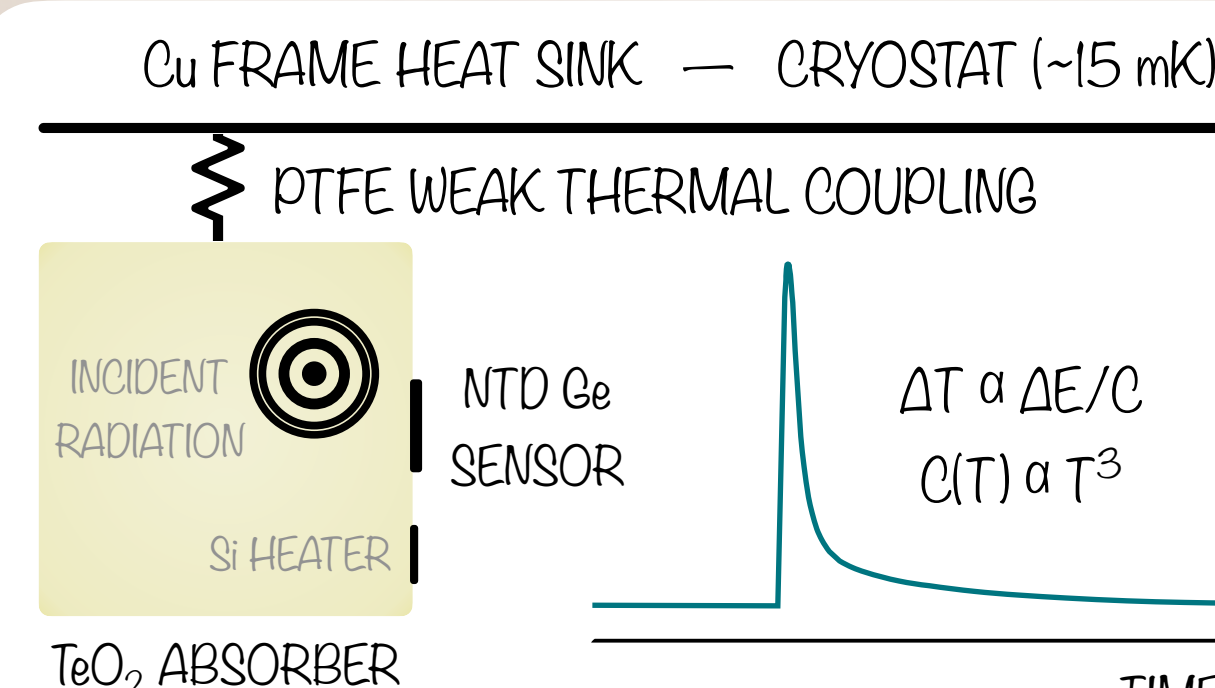
Krystal Alfonso on behalf of the CUORE (Cryogenic Underground Observatory for Rare Events) Collaboration  
Lawrence Berkeley National Laboratory, Berkeley, CA, USA

## CUORE

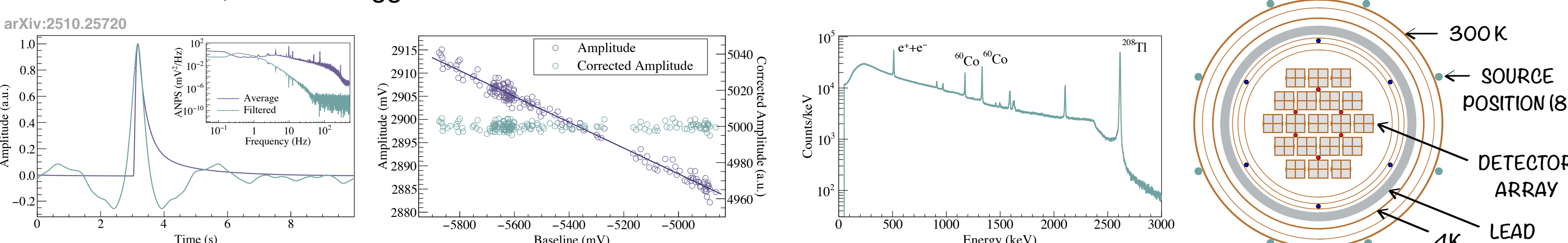
- The CUORE (Cryogenic Underground Observatory for Rare Events) experiment primarily searches for  $0\nu\beta\beta$  decay of  $^{130}\text{Te}$
- The CUORE detector is a close-packed array of 988  $\text{TeO}_2$  calorimeters
- Active mass: 742 kg  $\text{TeO}_2$  (206 kg  $^{130}\text{Te}$ )
  - Enables searches for exotic particles
- Unenriched  $\text{TeO}_2$ 
  - $^{120}\text{Te}$ ,  $^{128}\text{Te}$
- $\sim 10^{-2}$  counts/(keV·kg·yr) at  $Q_{\beta\beta}$  ( $\sim 2528$  keV)
- $Q_{\beta\beta}$  FWHM energy resolution:  $\sim 0.3\%$
- Data taking began in 2017: 3000+ kg·yr of raw  $\text{TeO}_2$  exposure
- The active mass, isotopic composition, and highly segmented geometry of the CUORE detector enables a diverse physics program



## Data Collection and Energy Reconstruction

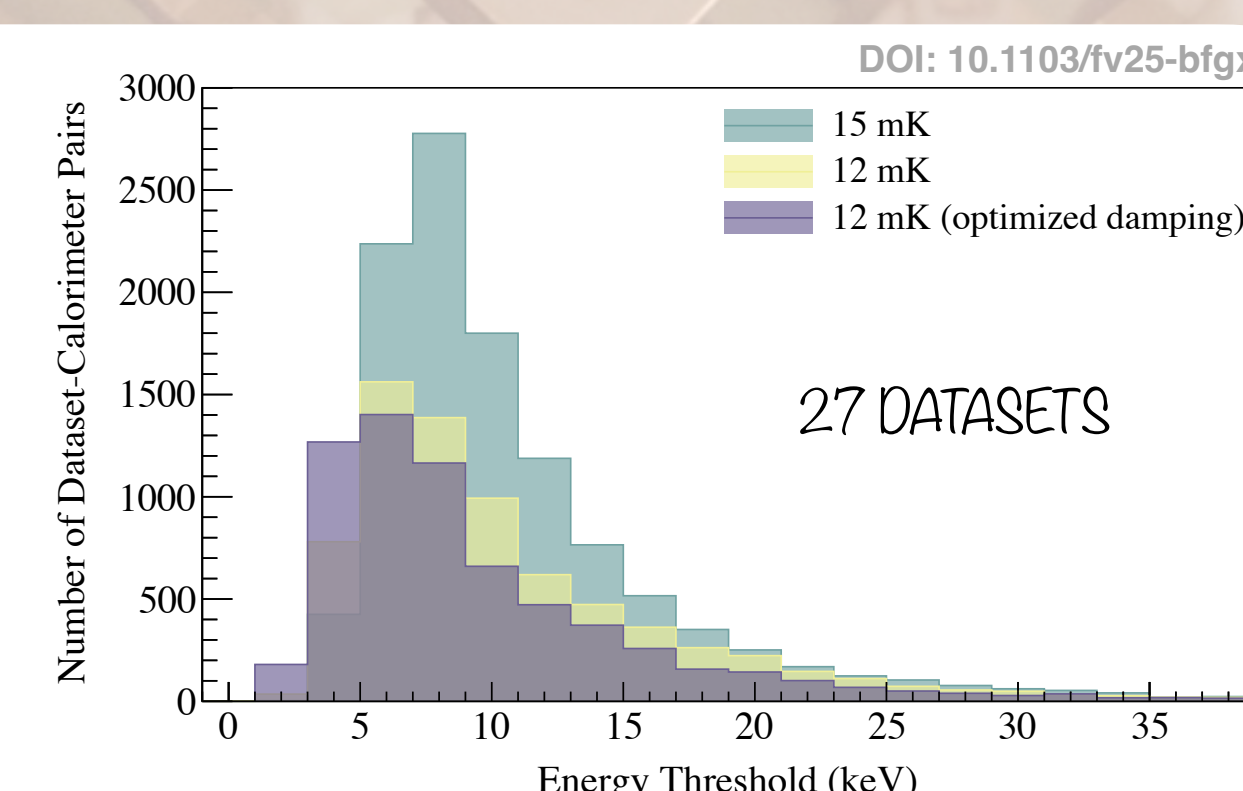


- Slight variations of the calorimeter components lead to their different intrinsic properties (e.g. rise times: 50 - 200 ms)
- Detector operating conditions also affect the detector response
- CUORE data are organized into datasets
  - Each begins and ends with  $\sim 1$  week of calibration measurements and there are  $\sim 6$  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:
  - OF + Amplitude  $\rightarrow$  Thermal Gain Correction  $\rightarrow$  Energy Calibration
- Analysis-specific, event-based quantities and flags are also embedded in the overall data production



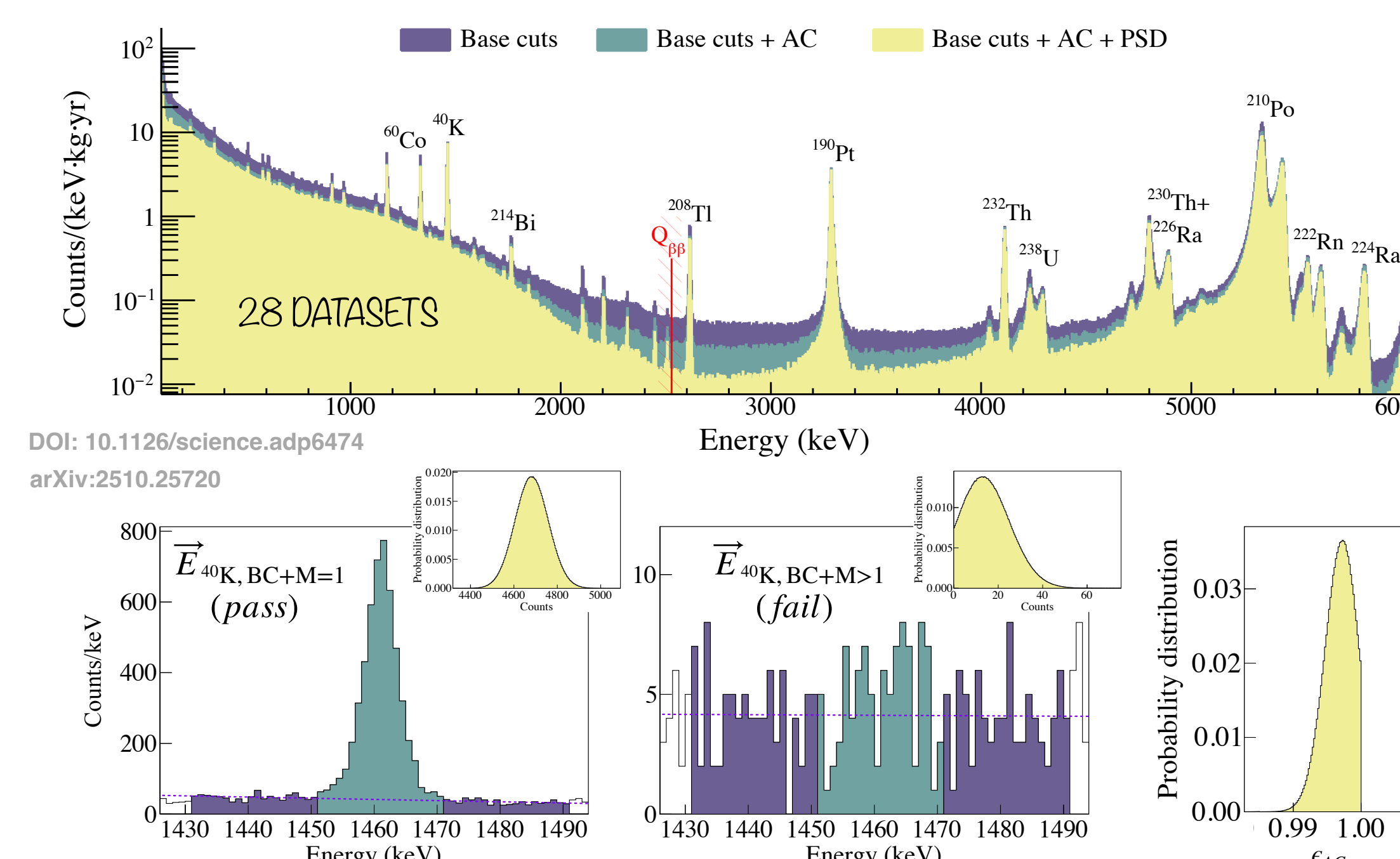
## Energy Thresholds

- 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)

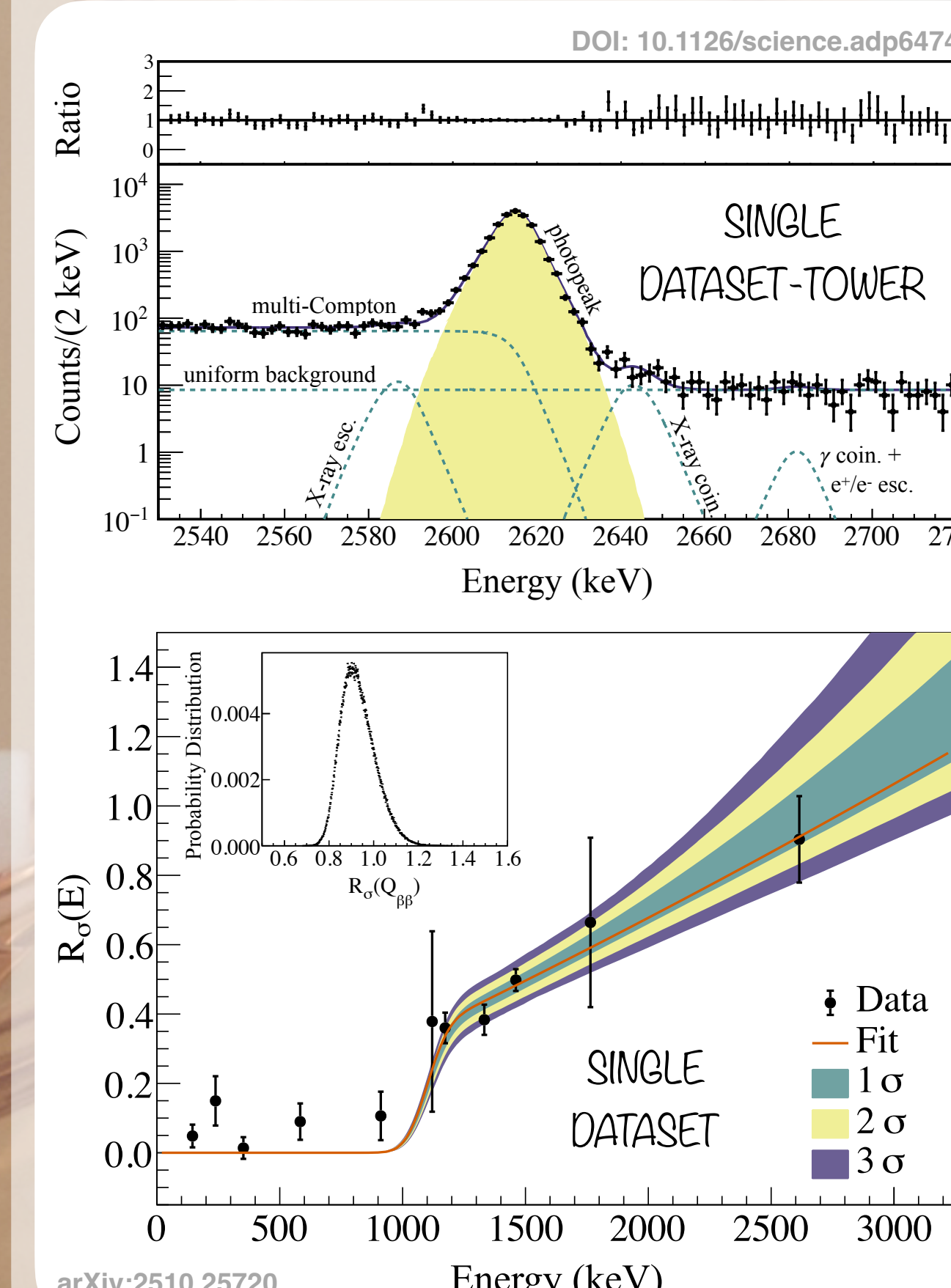


## Event Selection and Efficiencies ( $0\nu\beta\beta$ Decay)

- 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



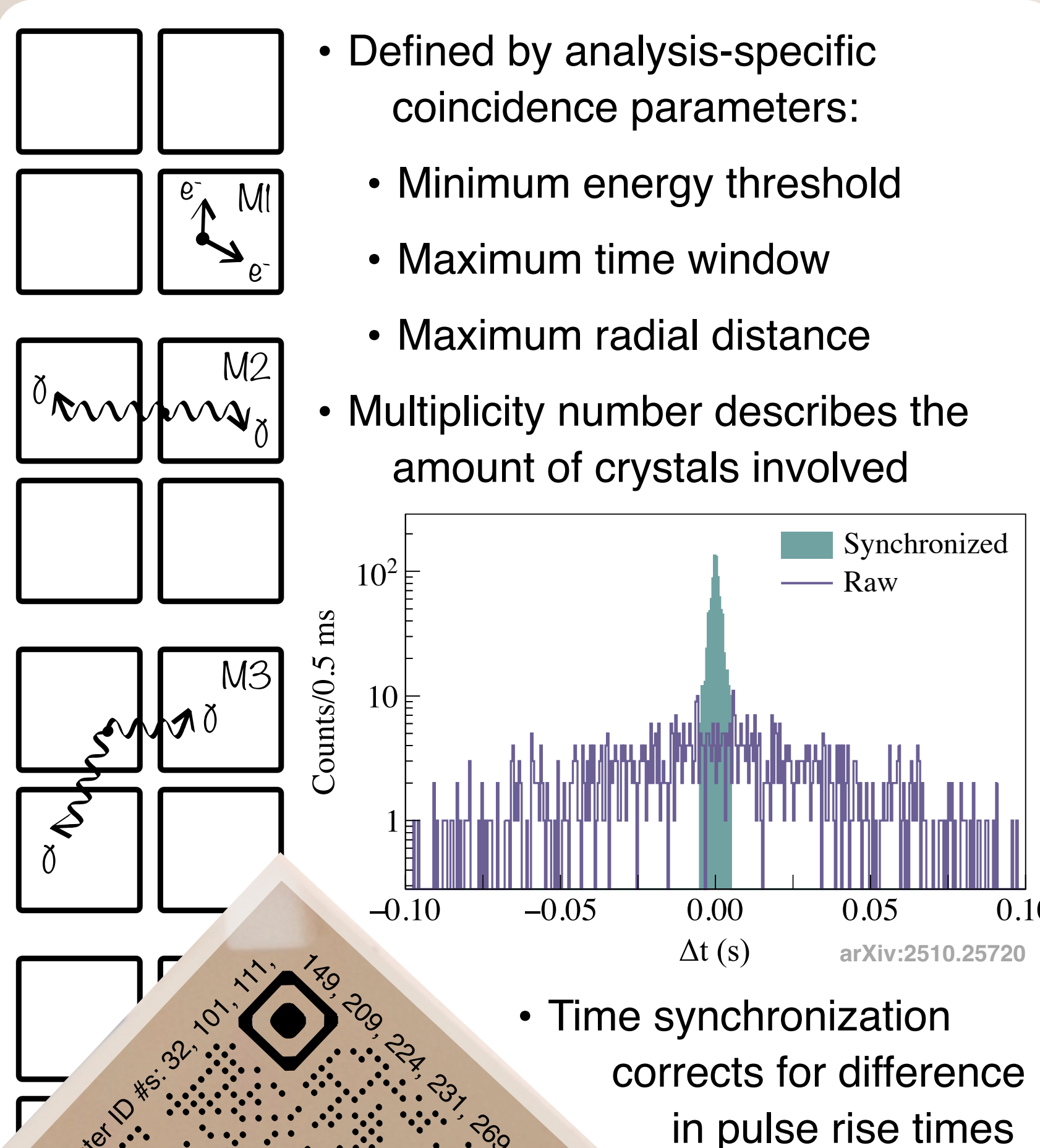
## Detector Response ( $0\nu\beta\beta$ Decay)



- Foundational, peak shape model (filled) is a multi-Gaussian function
- Model parameters include the position of the main peak, a common width ( $\sigma_{\text{cal}}$ ), and the relative amplitudes and positions of the subpeaks
- Calorimeter-dependent parameters are evaluated from fitting the high-statistics 2615 keV  $^{208}\text{Tl}$  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
 
$$\sigma_{\text{phys}}(E) = \sqrt{\sigma_{\text{phys}}^2 + R_o(E) \cdot (\sigma_{\text{cal}}^2 - \sigma_{\text{cal}}^2)}$$
- Then, fit the dataset-level scaling parameter  $R_o(E)$  and extrapolate to  $Q_{\beta\beta}$

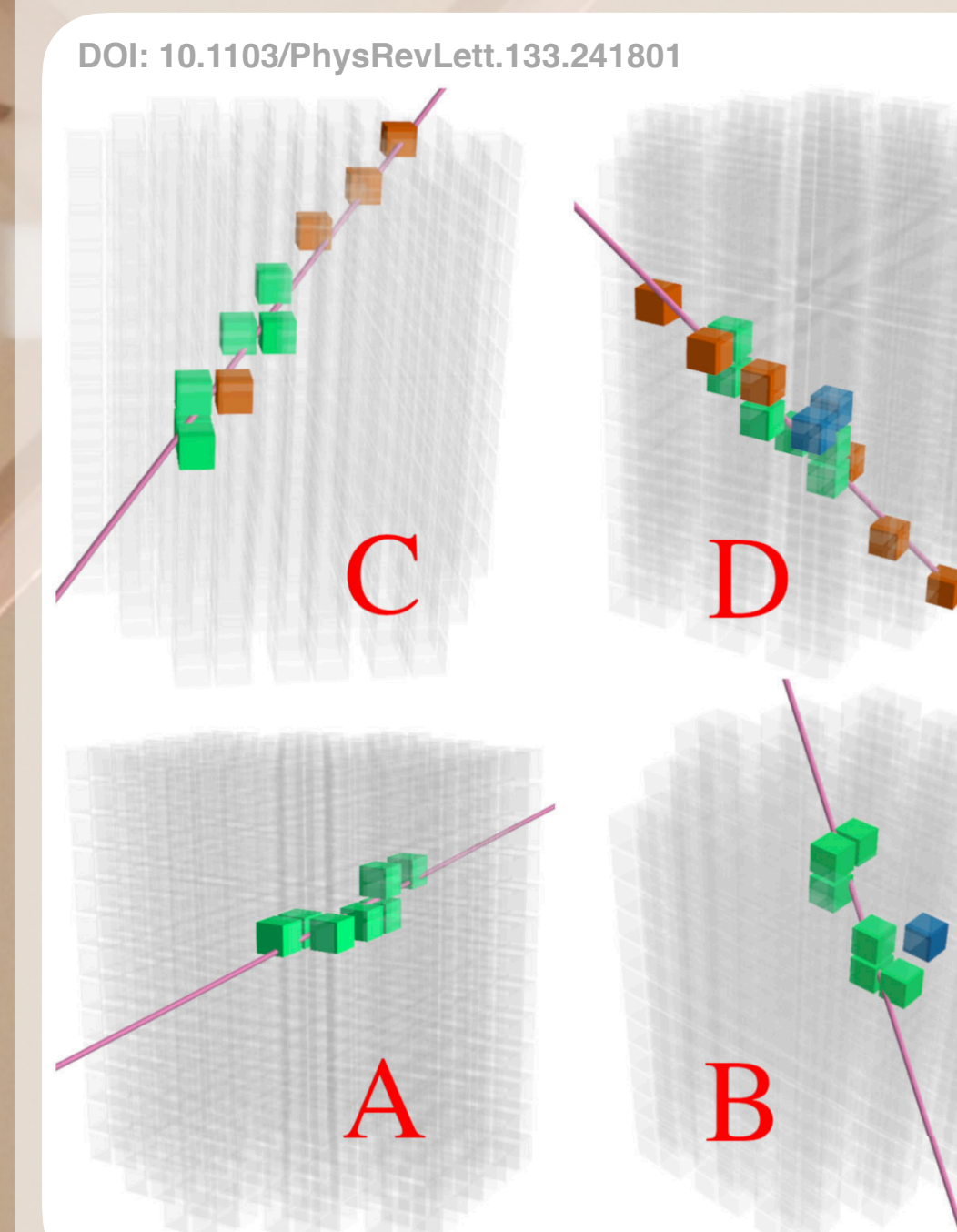
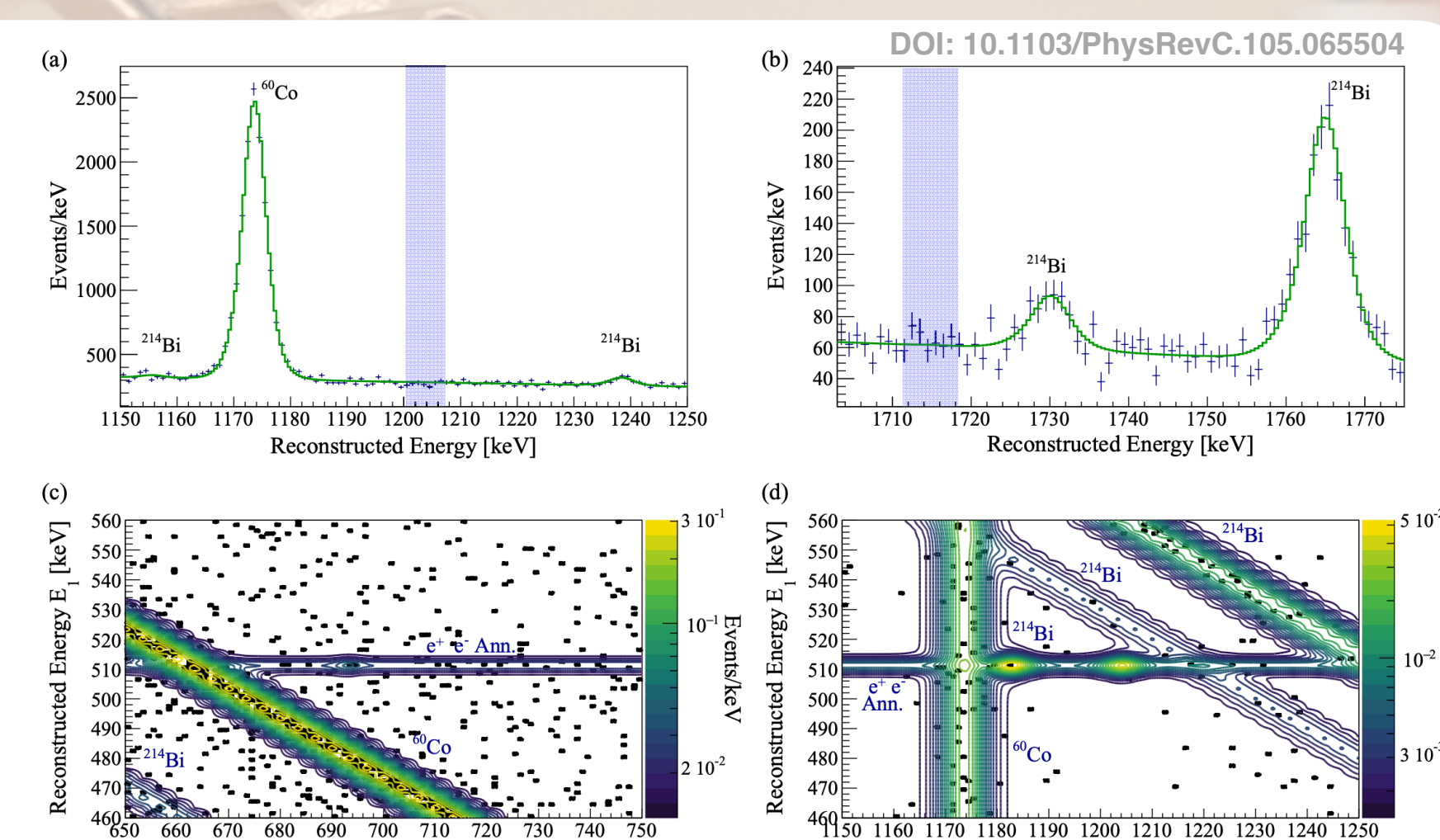
## Multiplicity

- 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



## Examples of Physics Breadth

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



- 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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