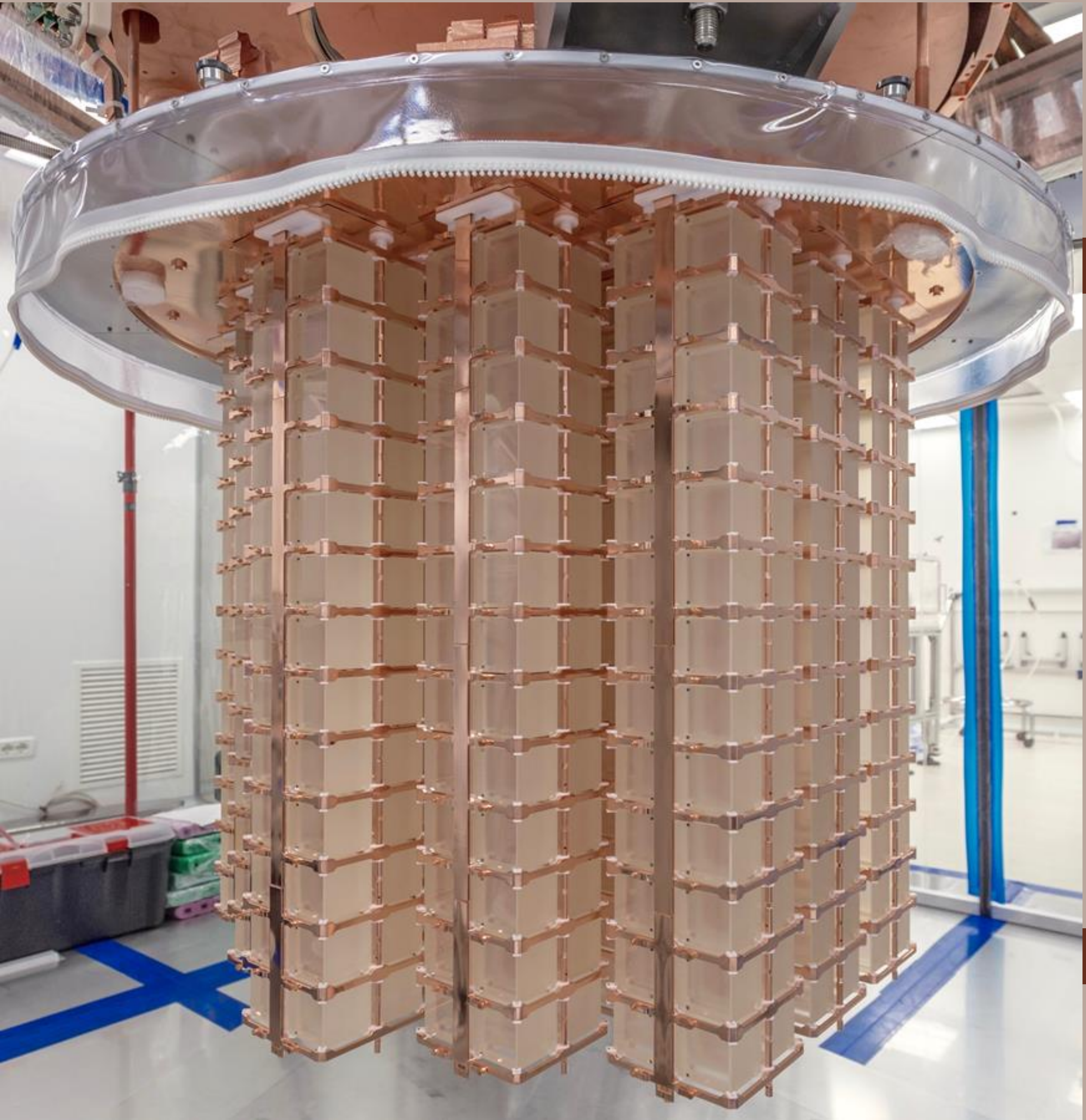


CUORE

VIRGINIA TECH

Latest Results from CUORE

Vivek Sharma

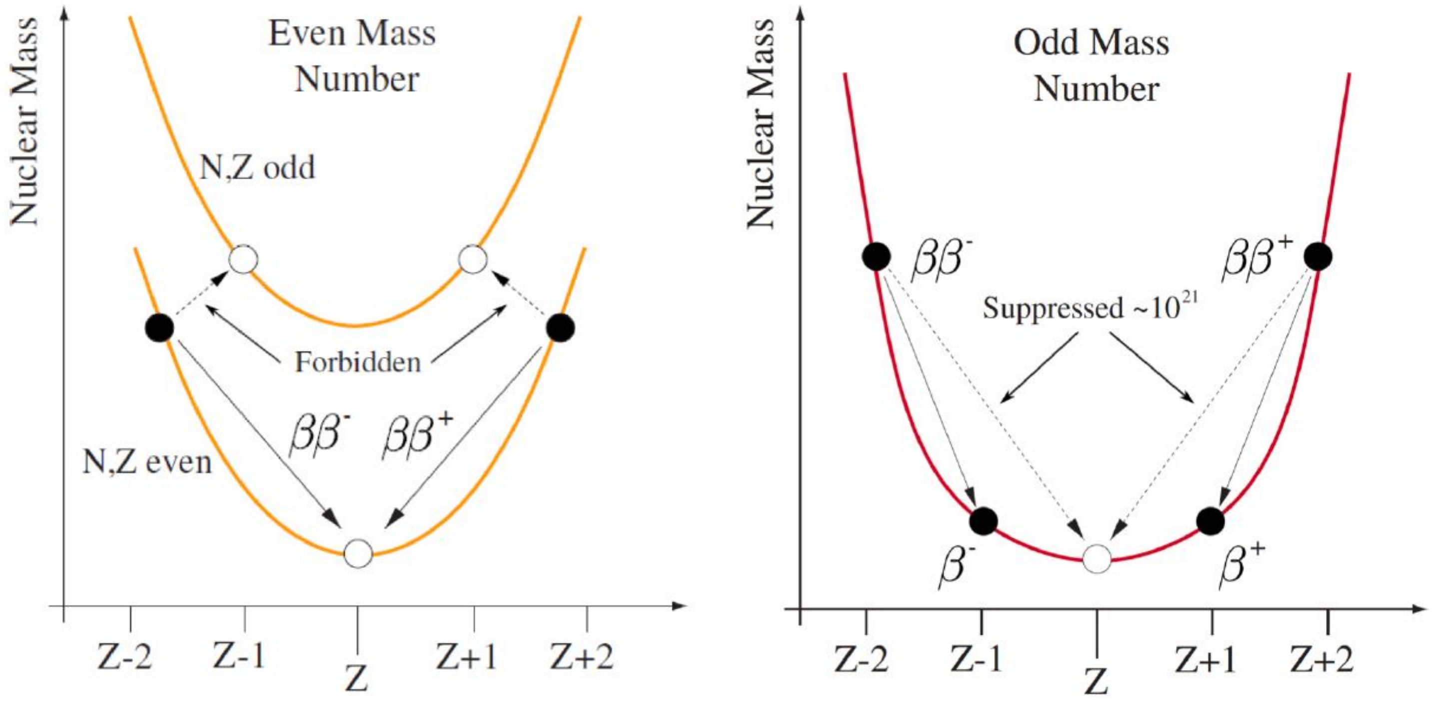
12/08/2023

CNP Research Day

2ν DOUBLE BETA DECAY

- Standard model 2nd order weak transition, extremely rare (half-life of 10^{19}-10^{22} yr)
- Observable when beta decay is kinematically forbidden

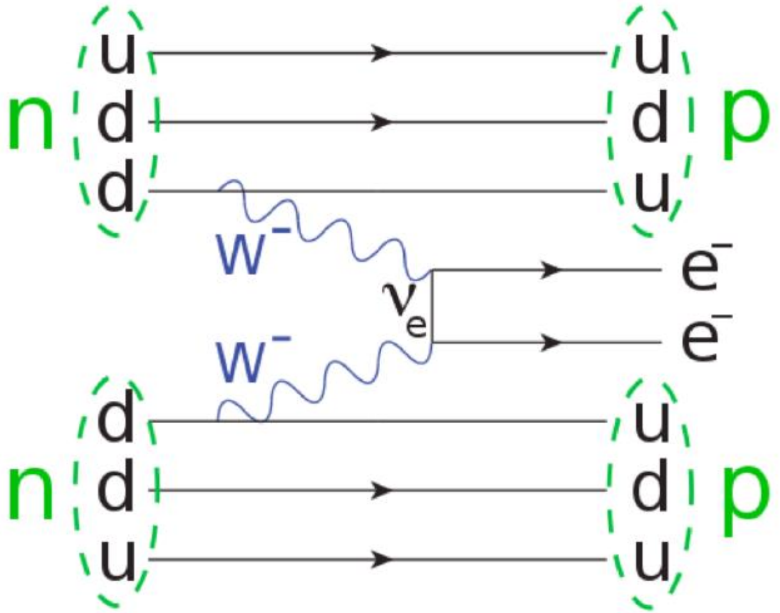
$$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\bar{\nu}_e$$



NEUTRINOLESS DOUBLE BETA DECAY

- Beyond Standard Model phenomenon, can occur if neutrinos are Majorana particles
- Lepton number violating process
- Potentially impact understanding of origins of matter/anti-matter asymmetry
- Constrains neutrino mass hierarchy, scale (model dependent)

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$



Light neutrino exchange model

NEUTRINOLESS DOUBLE BETA DECAY

CUORE

- Experimental observable is **decay rate**
  - Depends on effective Majorana mass **($m_{\beta\beta}$)**
  - Directly related to absolute neutrino mass scale
- Additional dependency on various nuclear and atomic effects.
- Limit on ($m_{\beta\beta}$) can help rule out Inverted Hierarchy (model dependent)

$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \frac{< m_{\beta\beta} >^2}{m_e^2}$$

Phase space factor

Nuclear Matrix Elements

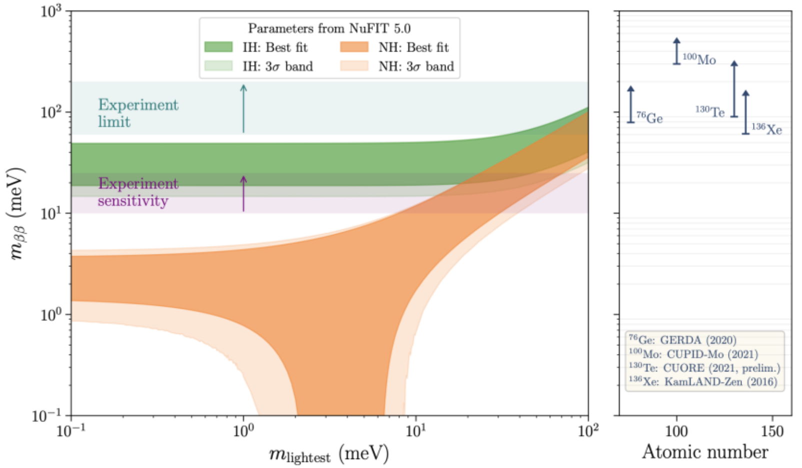
Effective Majorana mass

Majorana phases

$$m_{\beta\beta} = |\sum_{i=1}^{3} |U_{ei}|^2 m_i e^{i\alpha_i}|$$

PMNS matrix

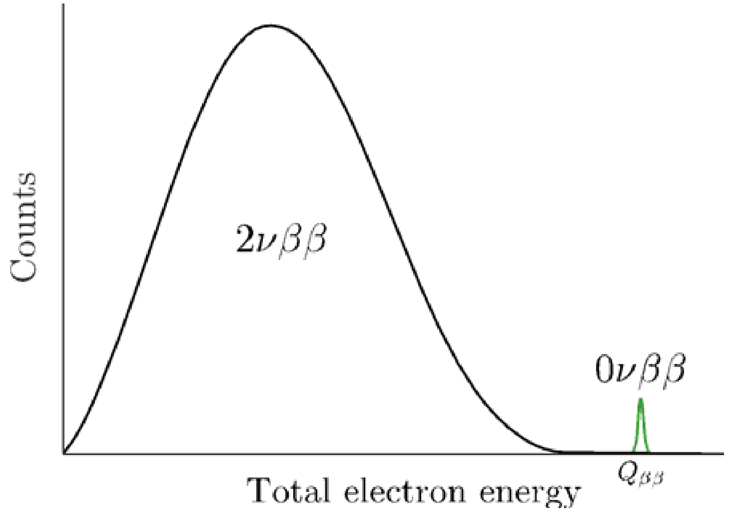
Individual neutrino masses



https://github.com/toej93/LobsterPlot

DETECTION CHALLENGES

- 0νββ signal is the summed electron energy at Q-value
  - **Exceptional resolution** essential to differentiate between the 0νββ and 2νββ spectra
  - **High Q-value** for practically observable half-life and avoiding gamma-ray backgrounds
- **Low background** required for a detectable signal, going underground is necessary to avoid cosmic ray bkg
- **Exposure** needs to be maximized
  - Large detector mass
  - Efficient duty cycle to lengthen livetime
- **Choice of isotope** should be compatible with detector technique



$$T_{1/2}^{0\nu} \propto Q^{-5}$$

$$T_{1/2}^{0\nu}(1\sigma) = ln(2)\frac{a\epsilon N_A \eta}{W}\sqrt{\frac{mt}{b\Delta E}}$$

1-sigma sensitivity

Isotopic abundance

Efficiency

Detector mass

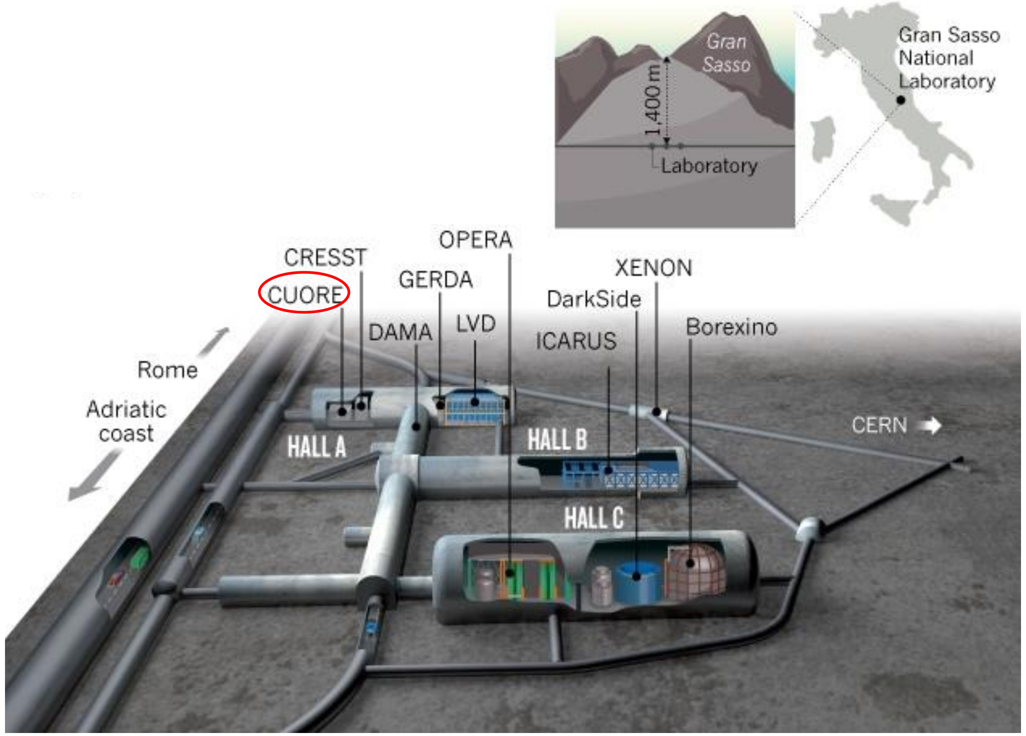
Livetime

Bkg rate/ energy/mass

Energy Resolution

CUORE

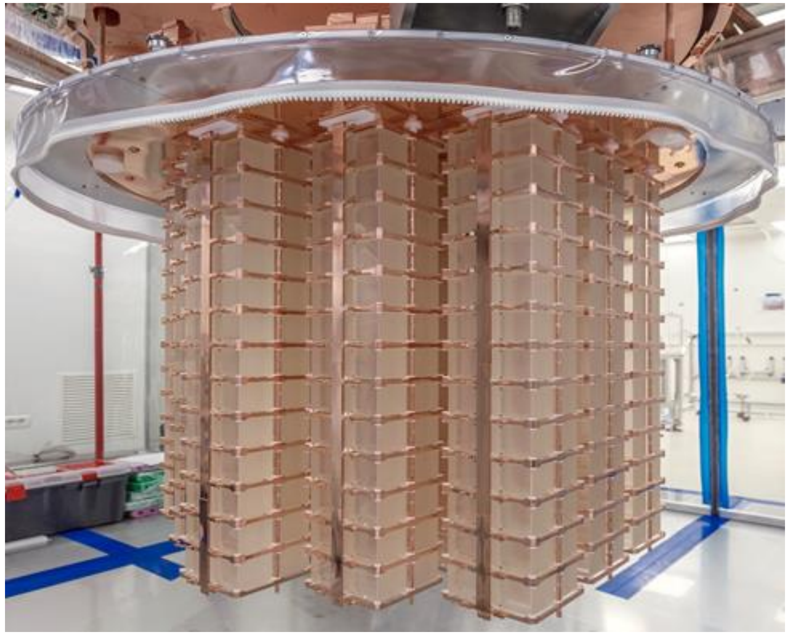
- **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents
- Located at Hall A of Gran Sasso National Laboratory
- **3600 m.w.e** of overburden, muon rate 6 orders of magnitude less than surface, extensive shielding
- ^{130}Te has a ββ Q-value of 2527.5 keV
- 742 kg TeO_2, 206 kg ^{130}Te (34% natural abundance)

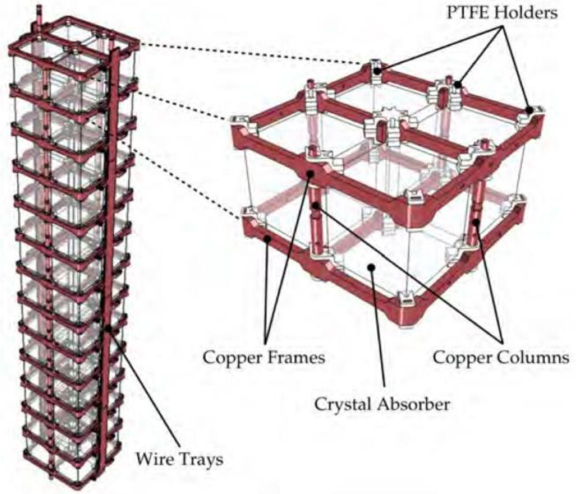


Images courtesy of LNGS: https://www.lngs.infn.it/en

DETECTOR INFRASTRUCTURE

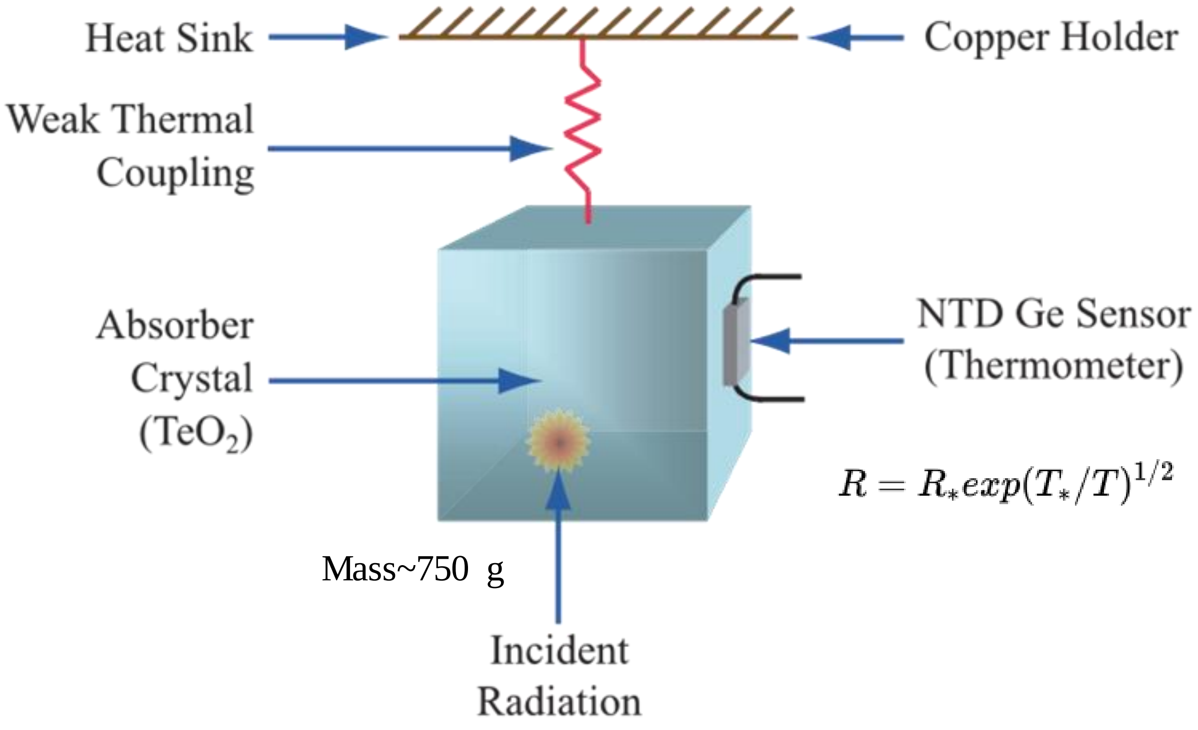
- 988 natural TeO_2 crystals
  - Total mass: 742 kg
  - ^{130}Te mass: 206 kg
  - 5x5x5 cm^3, arranged in 19 towers
- Housed in copper frame and held in place by PTFE spacers
  - Copper linked to thermal bath
  - PTFE spacers are also weak thermal links and contract more at low temperatures
- Tightly spaced crystals allow for coincidences to be exploited for background reduction





DETECTION PRINCIPLE

- 988 TeO_2 crystals operated as bolometers; energy deposited is registered as temperature change
  - Read out by a NTD (**Neutron Transmutation Doped**) Ge thermometer
- Signal strength and detector resolution depend strongly on temperature (Debye's Law)
  - $C \propto T^3$
  - Detector operated at **~11 mK**
- In CUORE, we observe an average resolution of **~8 keV FWHM at 2615 keV**†



Schematic of a CUORE bolometer.
(cuore-lngs.infn.it)

†CUORE collaboration
https://www.nature.com/articles/s41586-022-04497-4.pdf

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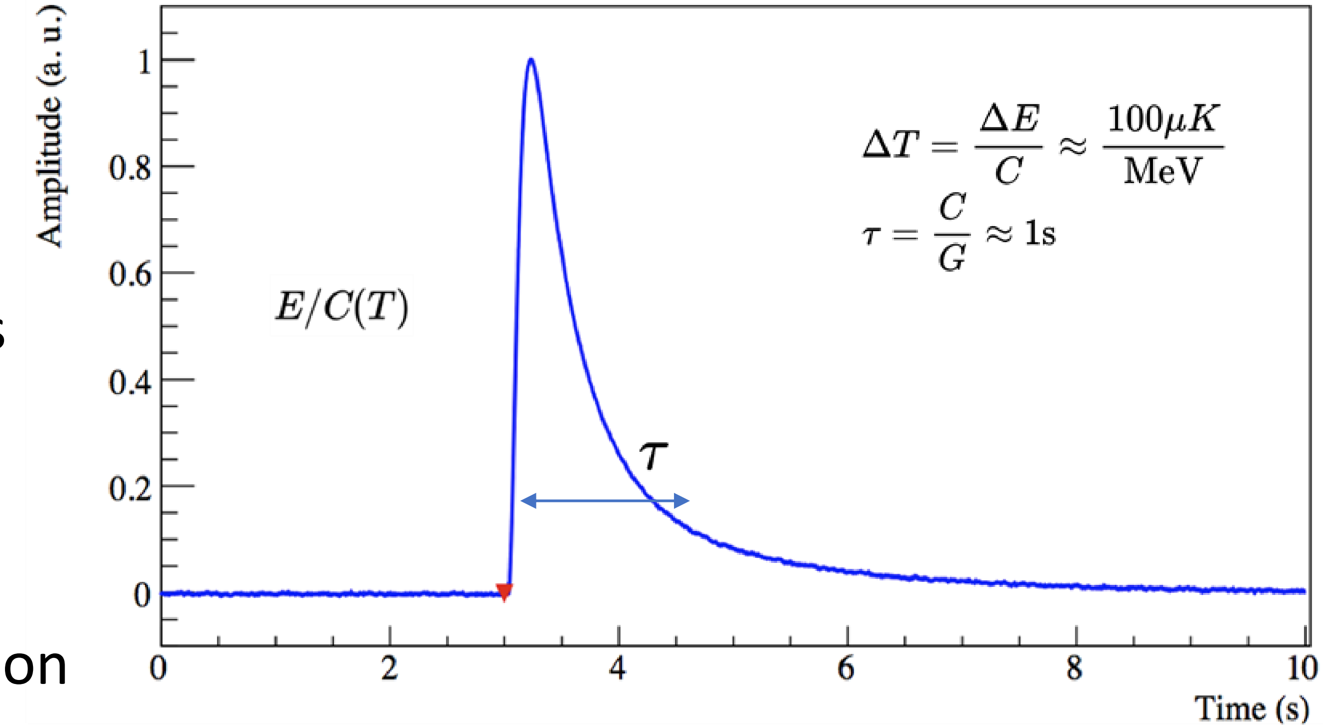
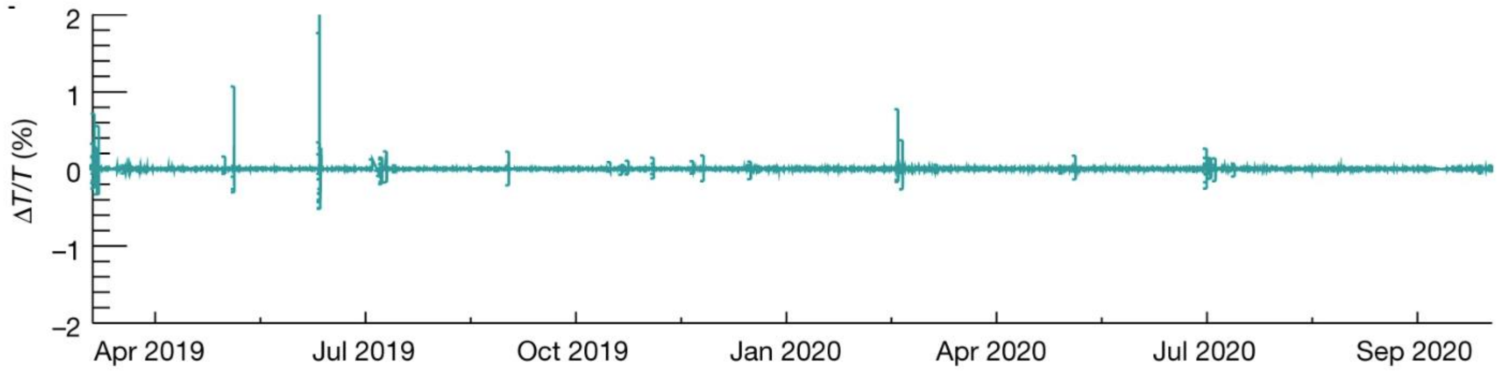


Example of a signal pulse

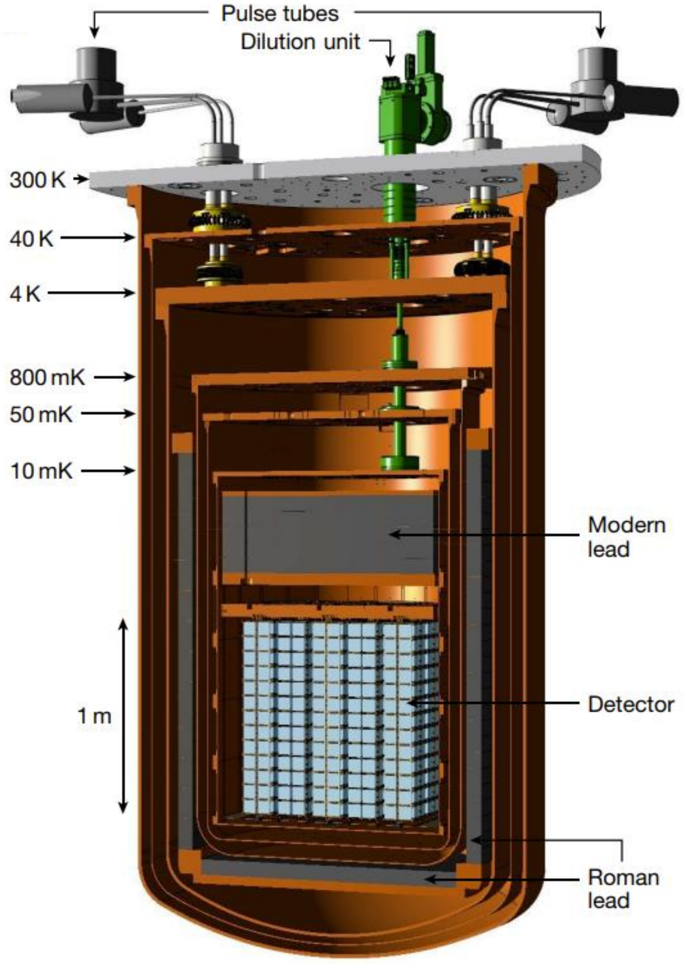
†CUORE collaboration
https://www.nature.com/articles/s41586-022-04497-4.pdf

CRYOGENICS

- Operating temperature of 15 mK is achieved via multistage cryogen-free dilution refrigerator
  - Pre-cooling performed by pulse tube cryocoolers
  - Multistage design shields from thermal radiation
- Cooling power of ~5 µW at 15 mK
  - Experimental volume of 1 m^3 and payload of 1.5 tonne
  - Demonstrated stability over years of data taking



CUORE relative temperature fluctuation over time*

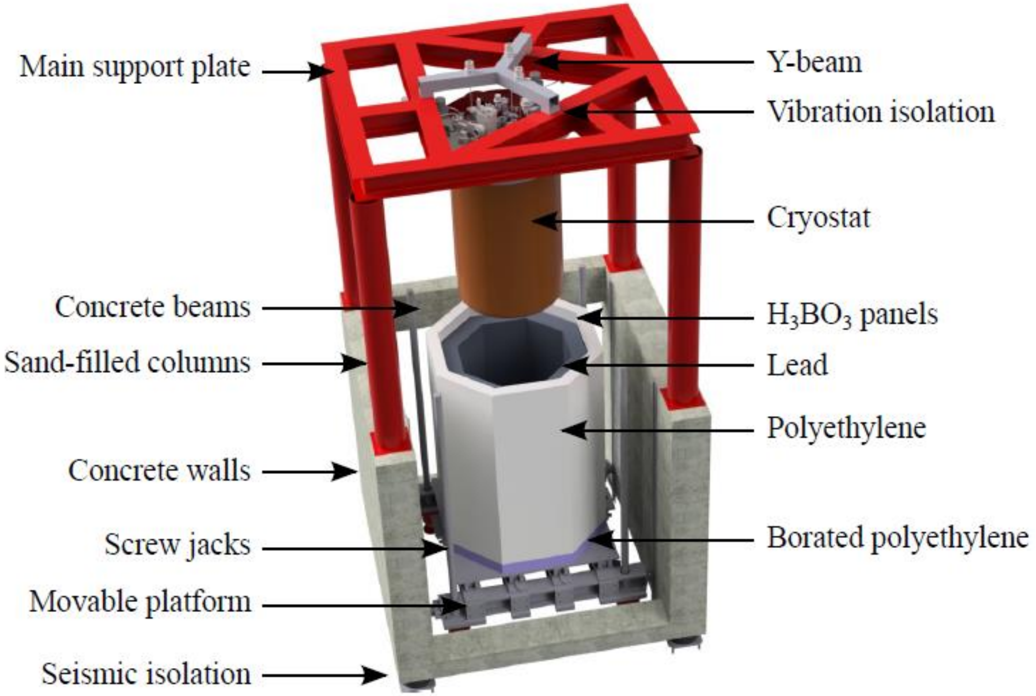


The CUORE cryostat*

*CUORE collaboration
https://www.nature.com/articles/s41586-022-04497-4.pdf

SHIELDING

- Experimental setup shielded from radiation by multiple layers
- Neutron background:
  - Lateral 18 cm polyethylene layer with 2 cm thick H_3BO_3 panels
  - 20 cm thick borated polyethylene at the bottom
- Gamma background:
  - 30 cm lead shield above the detector volume
  - 6 cm thick lead (^{210}Pb free) on the side and below the detector volume



External structure of CUORE

SHIELDING

- Experimental setup shielded from radiation by multiple layers
- Neutron background:
  - Lateral 18 cm polyethylene layer with 2 cm thick H_3BO_3 panels
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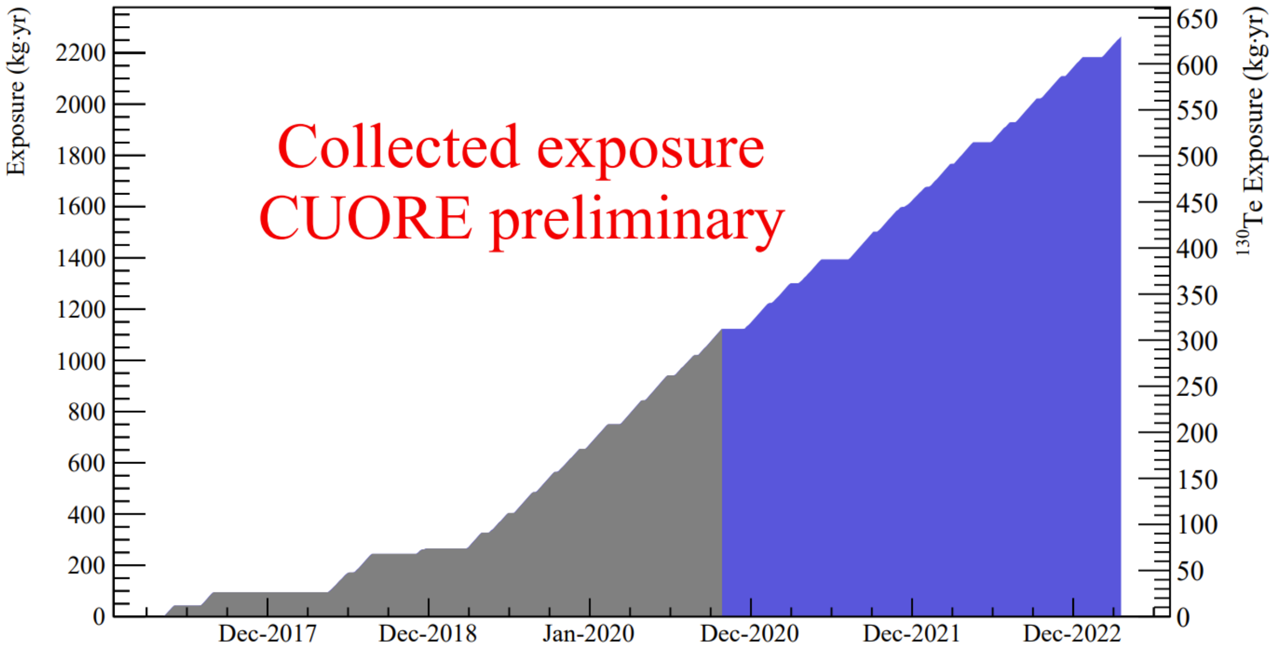
- Gamma background:
  - 30 cm lead shield above the detector volume
  - 6 cm thick lead (^{210}Pb free) on the side and below the detector volume

Image credit: Il Nuovo Saggiatore/Società Italiana di Fisica di Bologna and INFN.

CUORE DATA TAKING

- Data taking began in 2017
  - Software and hardware optimizations since have improved stability of data taking
- Steady data taking since 2019 with 90% uptime
- Smooth transition to remote detector monitoring after pandemic lockdown
- 0νββ results for 1038 kg.yr exposure reported in Nature*



*CUORE collaboration
https://www.nature.com/articles/s41586-022-04497-4.pdf

Detector mass

Isotopic abundance

$$T_{1/2}^{0\nu}(1\sigma) = ln(2)\frac{a\epsilon N_A \eta}{W}\sqrt{\frac{mt}{b\Delta E}}$$

1-sigma sensitivity

- Active Mass: 742 kg TeO_2
- Isotopic abundance: 34%, 206 kg ^{130}Te

CUORE: SUMMARY

CUORE

Livetime

$$T^{0\nu}_{1/2}(1\sigma) = ln(2)\frac{a\epsilon N_A \eta}{W}\sqrt{\frac{mt}{b\Delta E}}$$

1-sigma sensitivity

- Greater than 90% duty cycle
- Cryogen-free cryostat (No regular downtime for invasive cryogenic maintenance)

CUORE: SUMMARY

$$T^{0\nu}_{1/2}(1\sigma) = ln(2)\frac{a\epsilon N_A \eta}{W}\sqrt{\frac{mt}{b\Delta E}}$$

1-sigma sensitivity

Bkg rate

- Radiopurity controls on materials and assembly
  - 3600 m.w.e overburden
    - Extensive shielding
- BI: 10^{-2} counts keV^{-1} kg^{-1} yr^{-1}

CUORE: SUMMARY

$$T^{0\nu}_{1/2}(1\sigma) = ln(2)\frac{a\epsilon N_A \eta}{W}\sqrt{\frac{mt}{b\Delta E}}$$

1-sigma sensitivity

Energy Resolution

- Crystals operated at 15 mK
  - Denoising techniques
- $Q_{\beta\beta}$ relative energy resolution: 0.3%

CUORE: SUMMARY

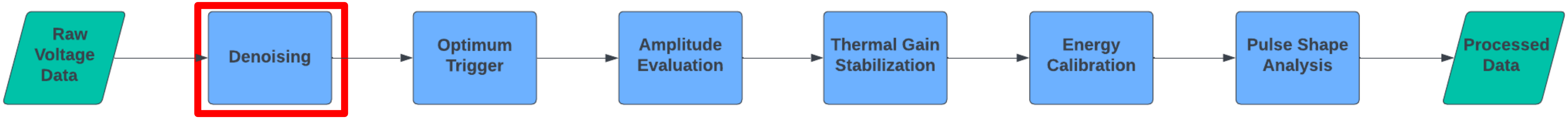
$$T^{0\nu}_{1/2}(1\sigma) = ln(2)\frac{a\epsilon N_A\eta}{W}\sqrt{\frac{mt}{b\Delta E}}$$

1-sigma sensitivity

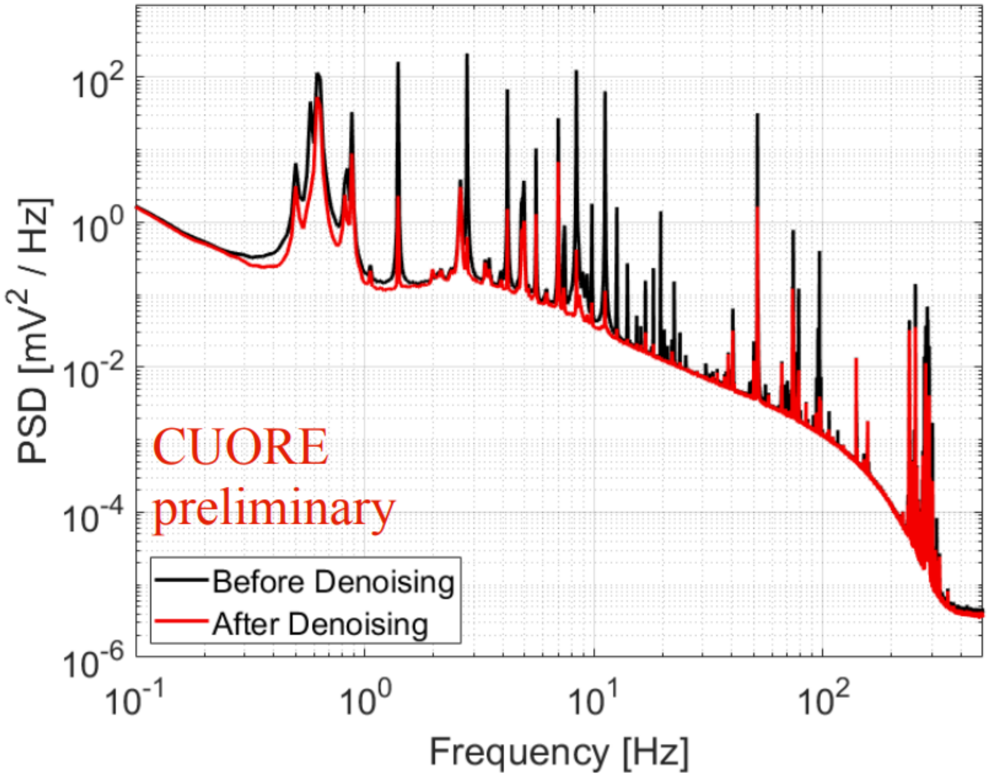
Efficiency

- Source = Detector
- Closely packed array of channels
- 88% containment efficiency
- 96% data quality cut efficiency

DATA PROCESSING

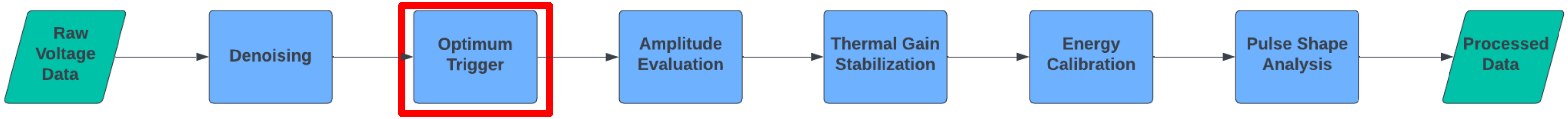


- Denoising
  - Multivariate noise cancelling algorithm to improve detector performance*
  - Uses data from auxiliary devices: Microphones, accelerometers, seismometers

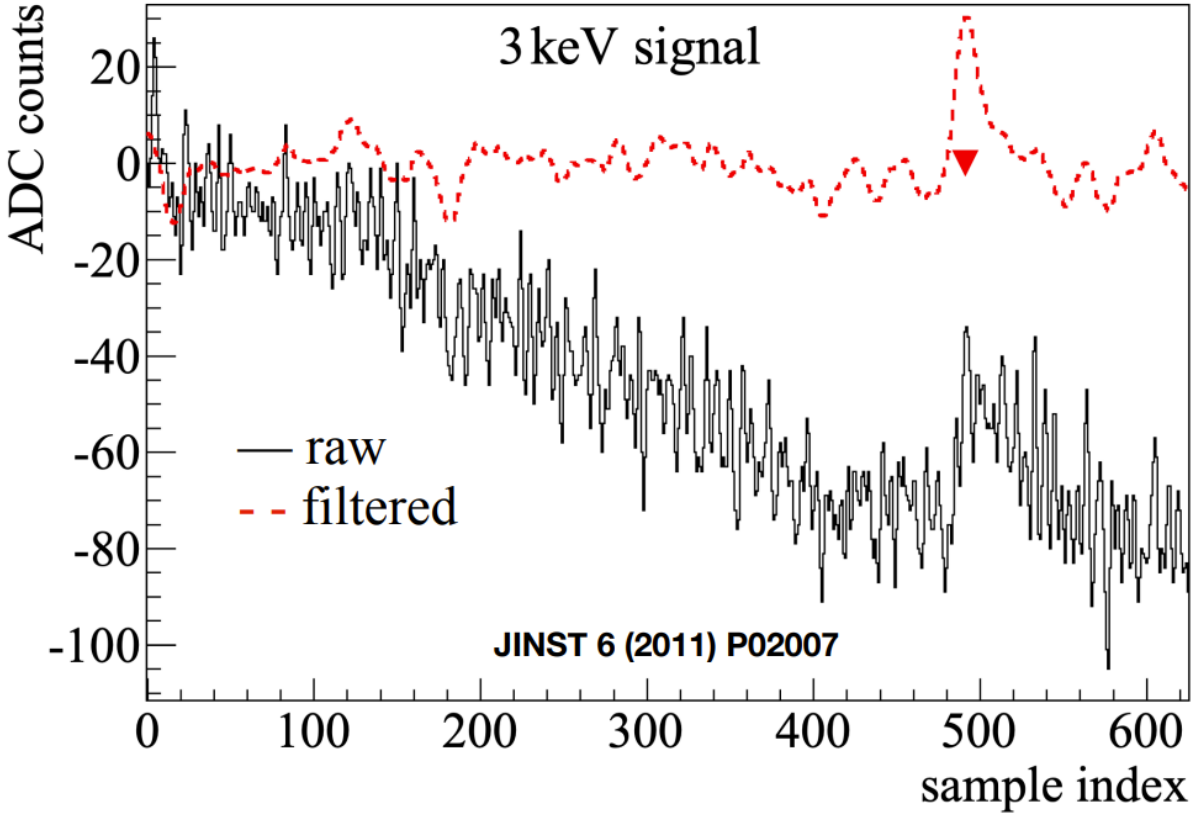


*https://arxiv.org/pdf/2311.01131.pdf

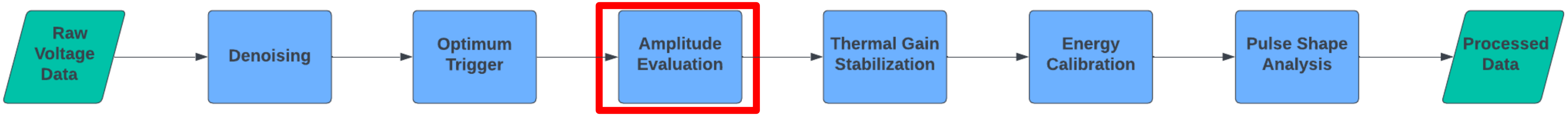
DATA PROCESSING - TRIGGER



- Optimum Trigger
  - Matched filter to maximize signal to noise
  - Adjusts for baseline drifts and noise
  - Lowers energy detection thresholds



DATA PROCESSING

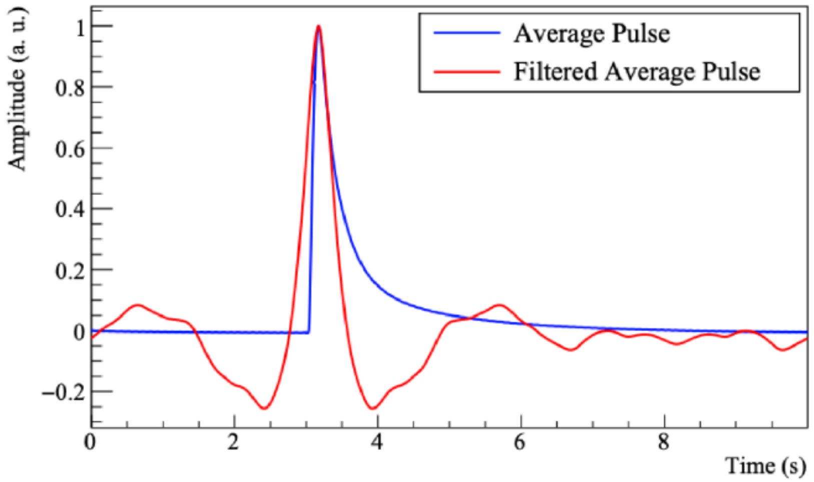


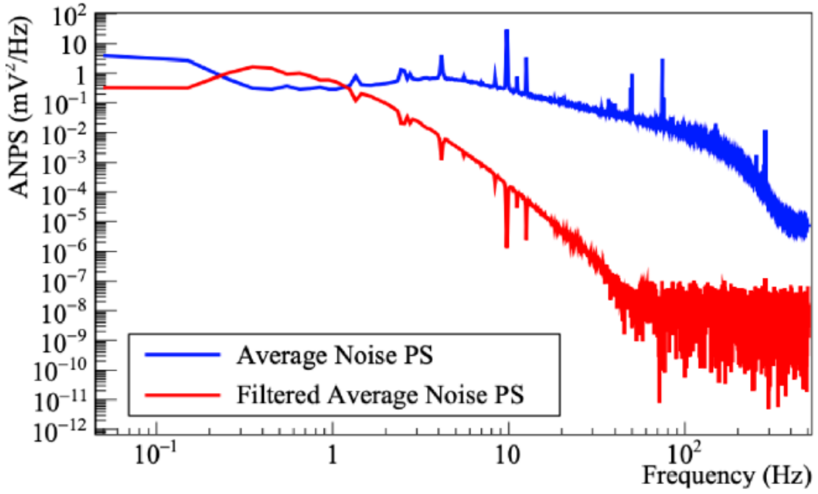
- Amplitude Evaluation
  - Using Optimum waveform filter to estimate amplitude of pulses
  - Transfer function of each channel evaluated using average pulse and average noise power spectrum

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

Average Pulse ($s^*(\omega_k)$)

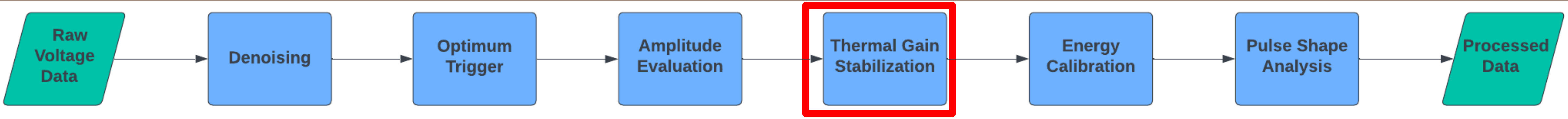
Average Noise ($N(\omega_k)$)





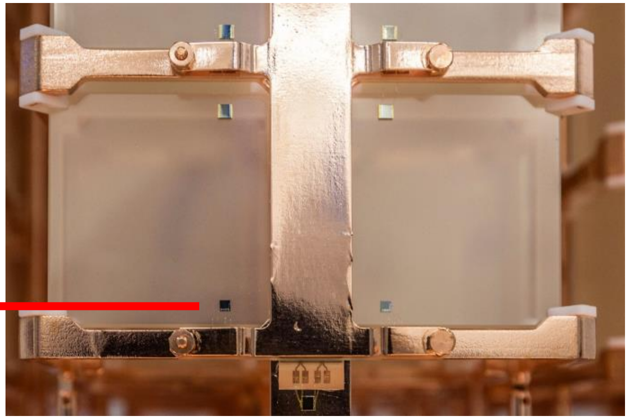
DATA PROCESSING

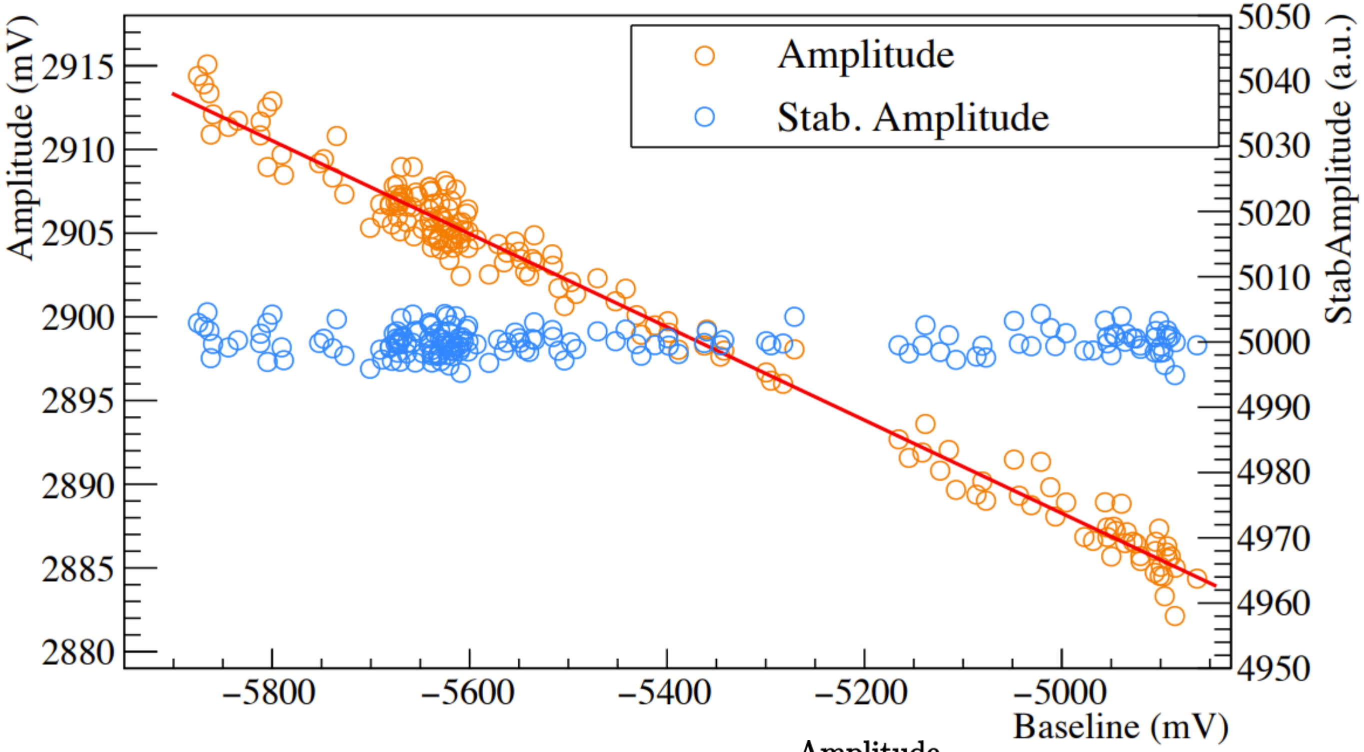
CUORE



- Gain Stabilization
  - Eliminating gain dependence on temperature using periodically injected pulses

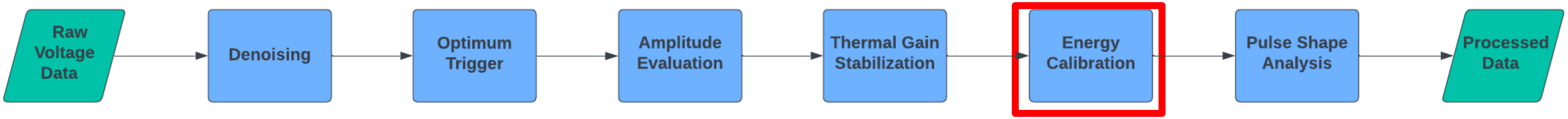
Si Heater



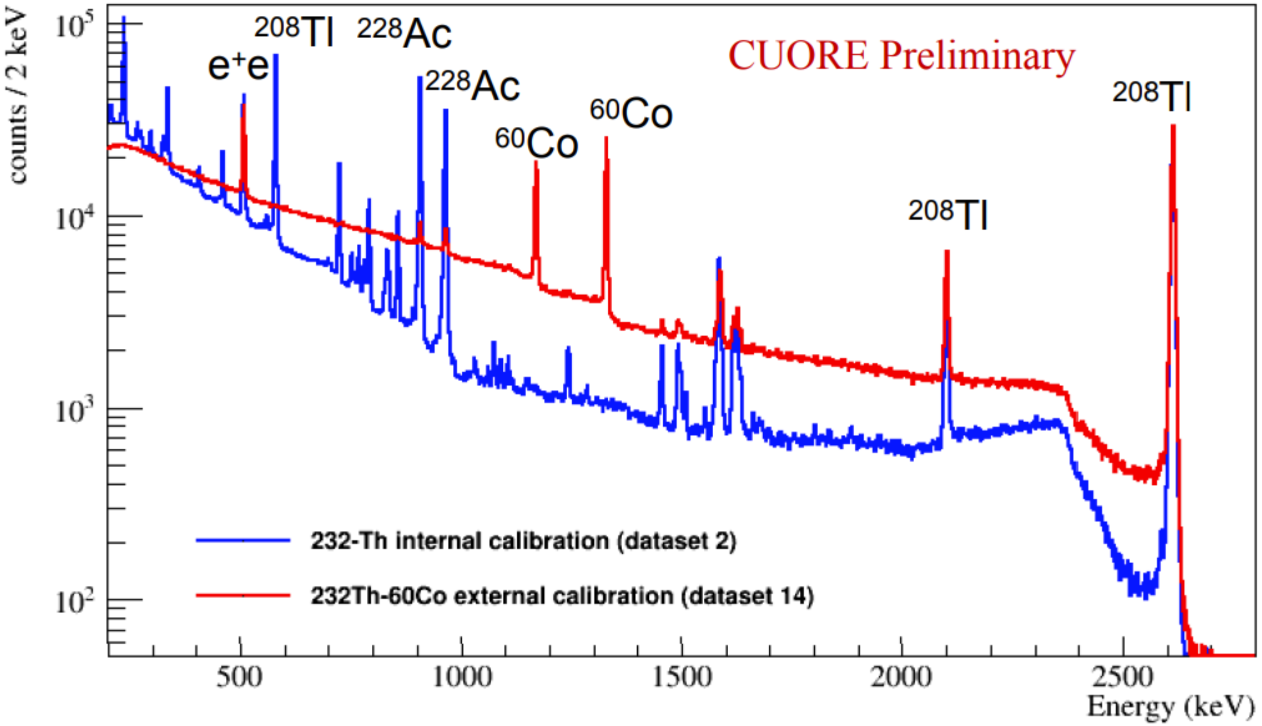


$$\text{Stabilized Amplitude} = 5000 \times \frac{\text{Amplitude}}{\text{StabPulser Amplitude}}$$

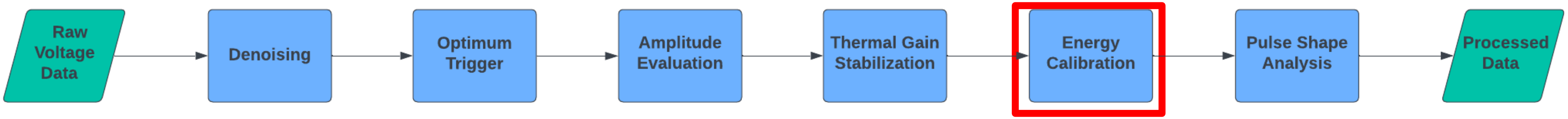
DATA PROCESSING



- Calibration
  - First 3 datasets used internal ^{232}Th source
  - Later datasets calibrated with external ^{232}Th-^{60}Co source
  - Iterative calibration algorithm
    - Iterative seeding for crystal ball fits
    - Decision between gaussian and crystal ball fits based on various fit quality metrics
    - Tools to monitor fit quality



DATA PROCESSING



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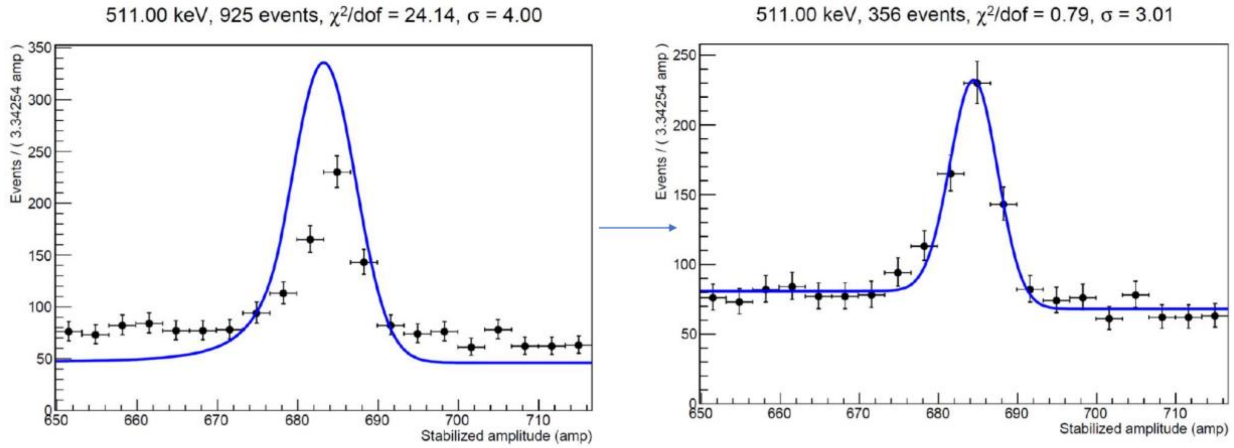
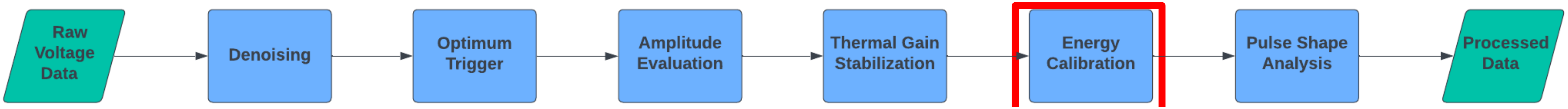


A calibration peak fit with default seeds (left), and fit with iterative algorithm (right)

DATA PROCESSING



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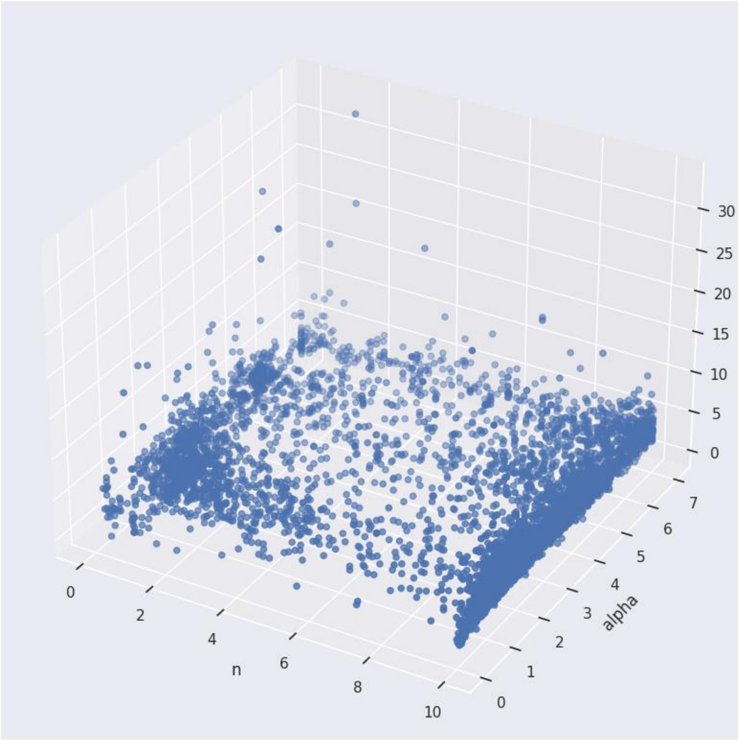
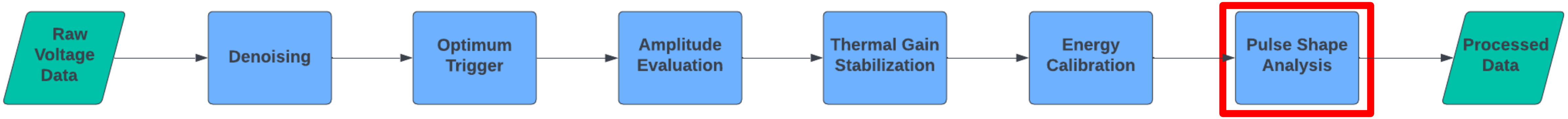
    - Decision between gaussian and crystal ball fits based on various fit quality metrics
    - Tools to monitor fit quality

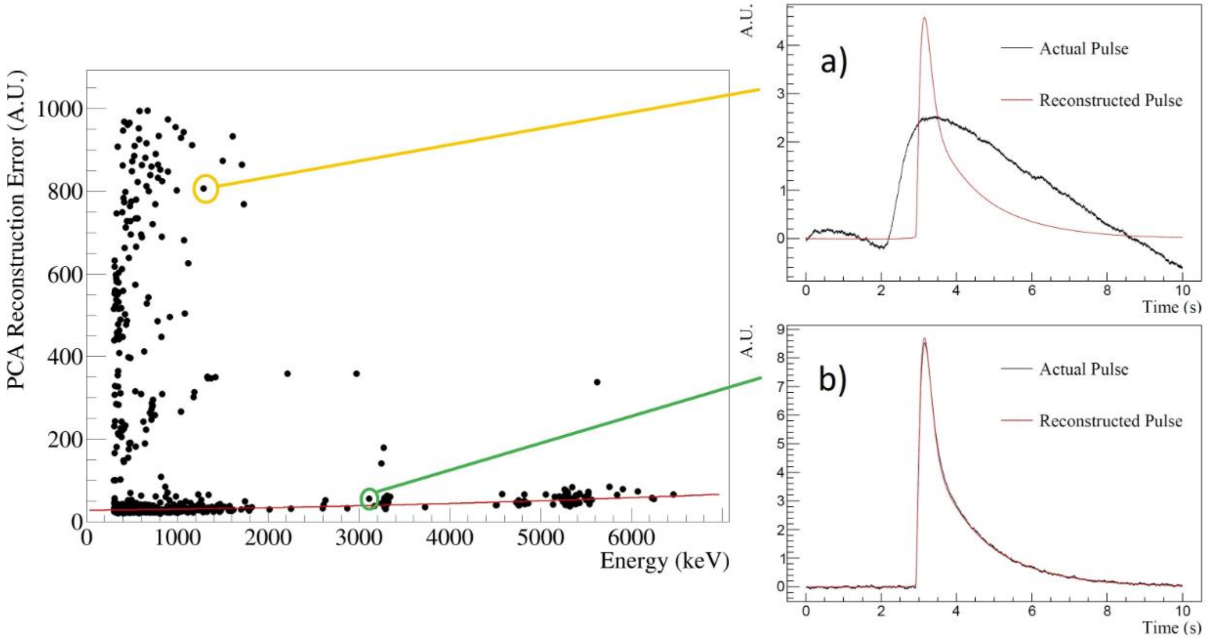


Distribution of fit parameters for a dataset

DATA PROCESSING

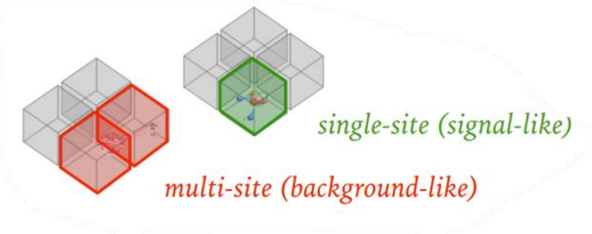


- Pulse Shape Discrimination
  - Using PCA (Principal Component Analysis) to eliminate pulses with a non-physical shape
  - Extract salient features of pulses to calculate reconstruction error for pulse shape discrimination

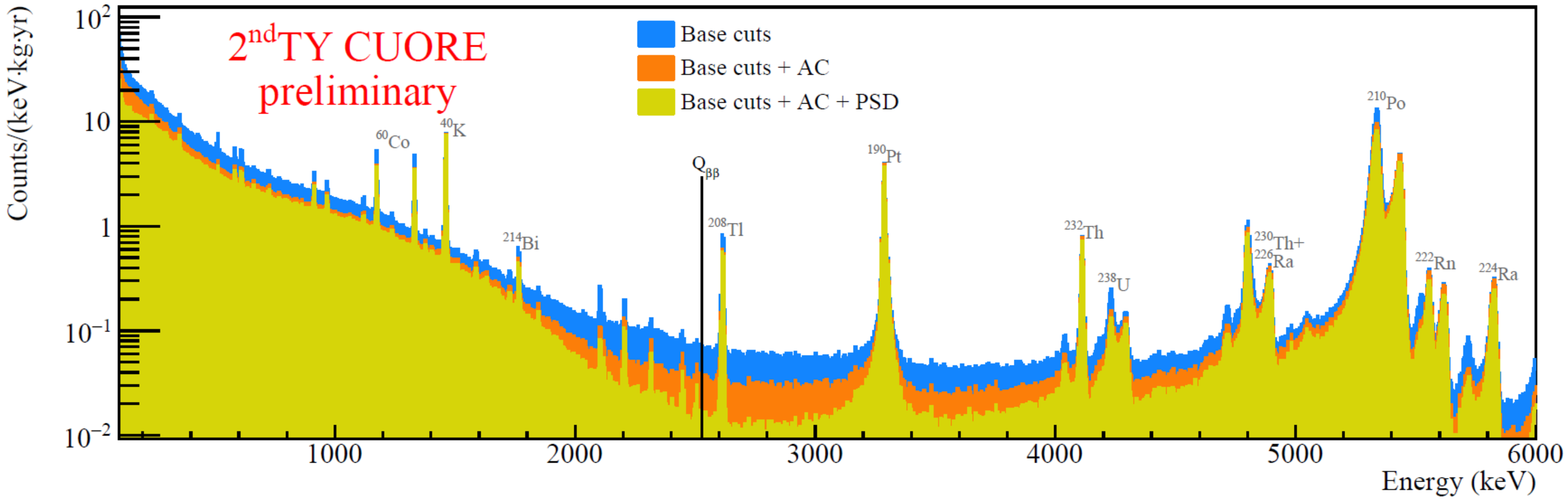


2 TONNE-YR SPECTRUM

- Blinded analysis to prevent bias
  - ROI (2465, 2575) keV salted with ^{208}Tl 2615 keV peak
  - Fit ROI events with: ^{130}Te 0νββ peak, ^{60}Co peak, linear background
  - Finalize model parameters before unblinding



88% of 0νββ events occur in a single crystal

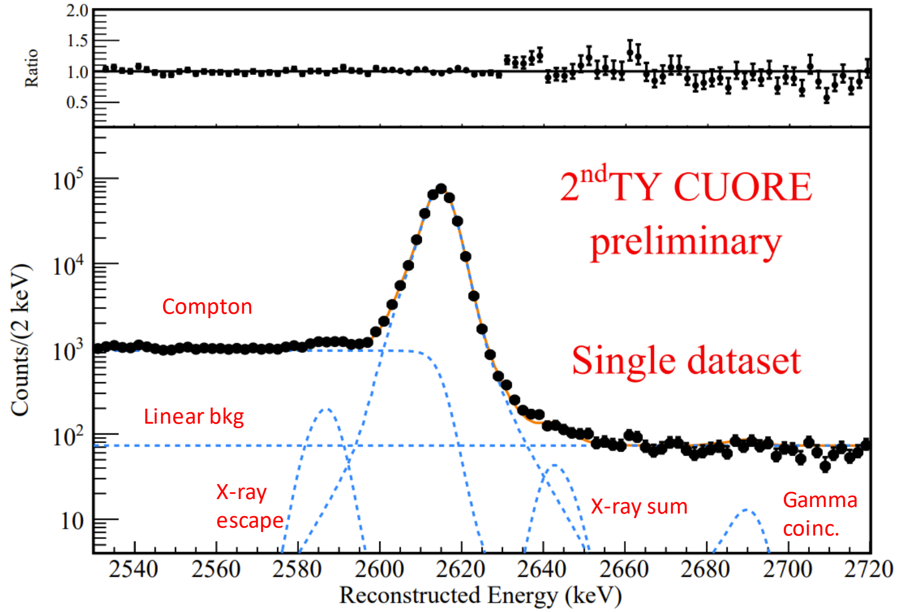


CUORE DETECTOR RESPONSE

- Fit 2615 keV calibration peak for each channel
  - 3-Gaussian signal peak + background structures

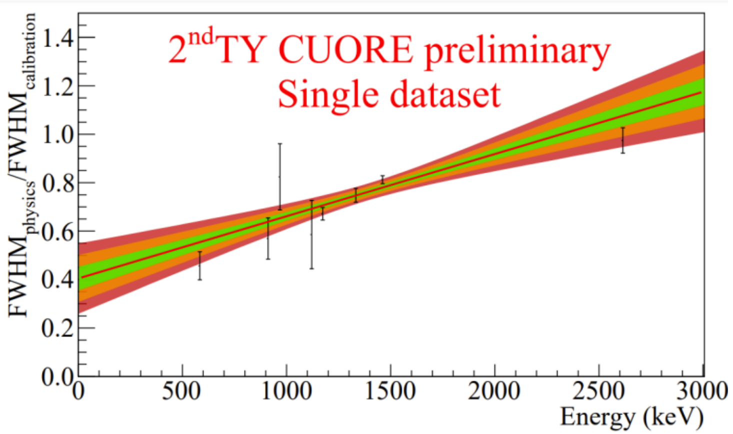
$$\Delta E_{2615keV} = 7.43 \pm 0.37\ \mathrm{keV}$$

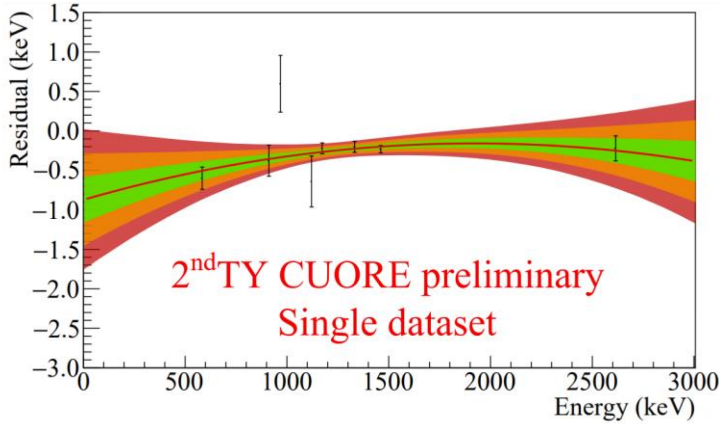
- Scale detector response from 2615 keV calibration fit to peaks in physics data
  - Calculate resolution scaling and reconstruction bias at $Q_{\beta\beta}$



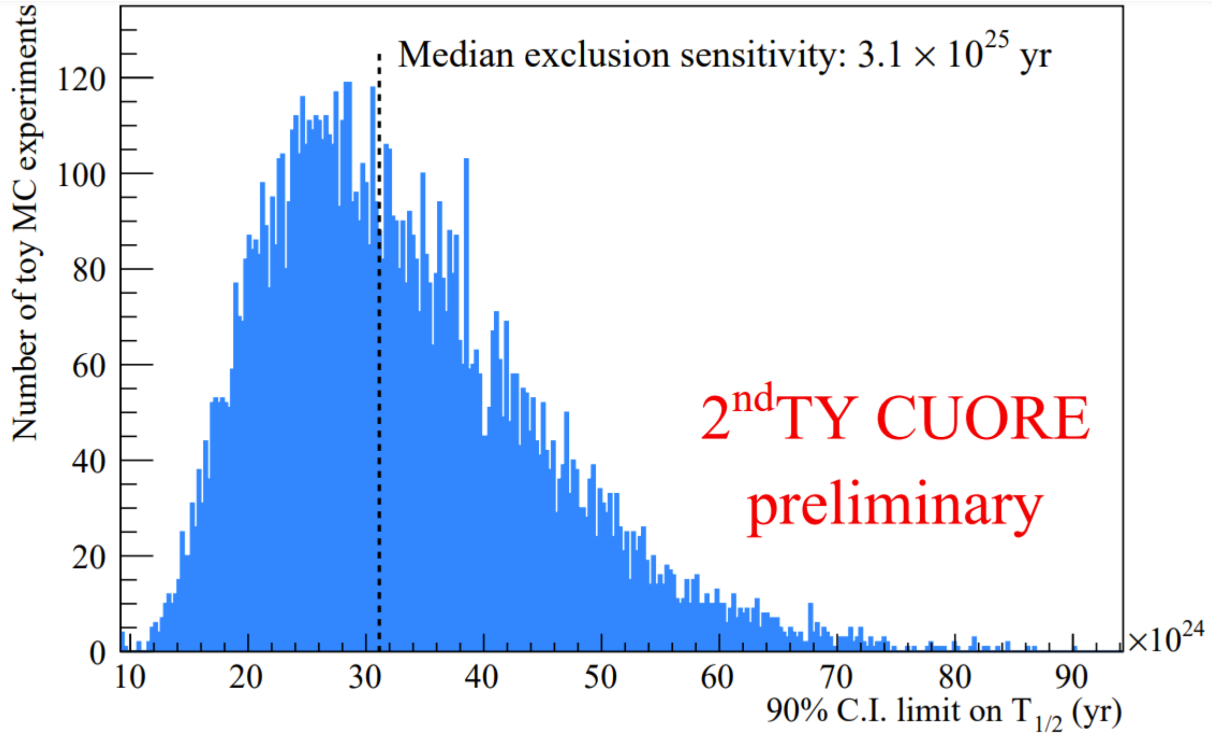
$$\Delta E_{Q_{\beta\beta}} = 7.26^{+0.43}_{-0.47}\ \mathrm{keV}$$

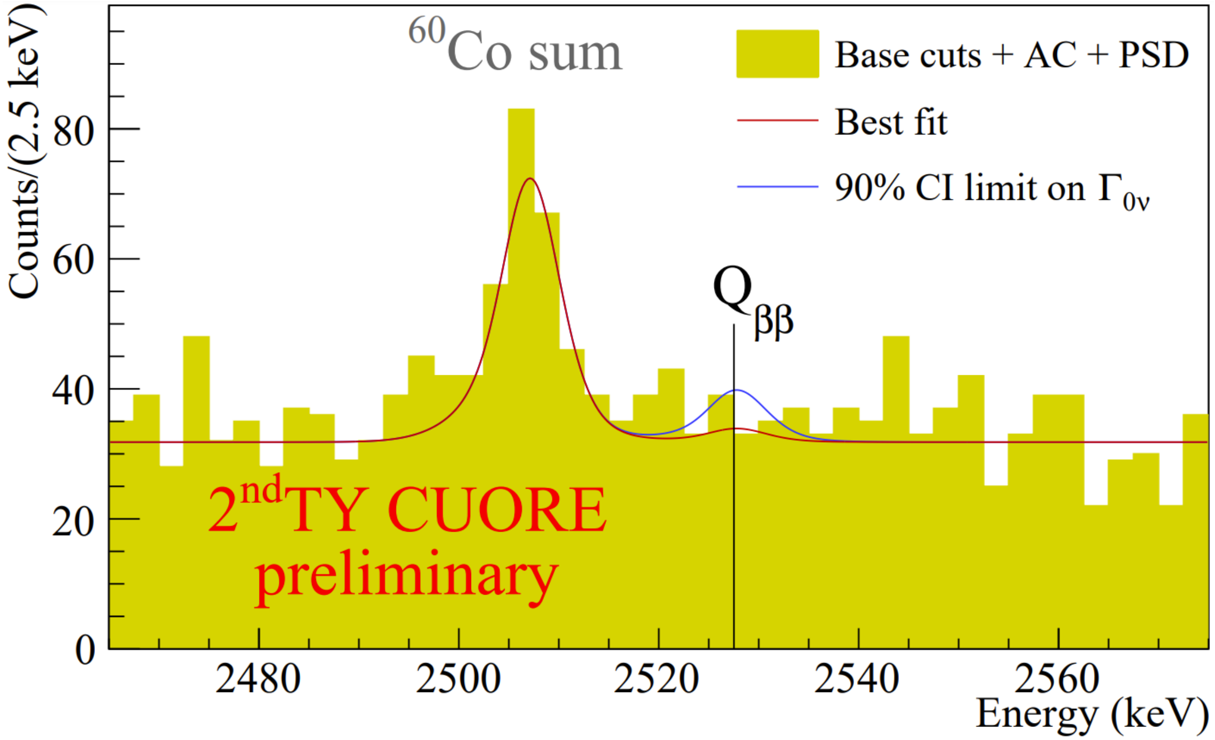
$$\Delta E_{bias} = -0.11^{+0.19}_{-0.25}\ \mathrm{keV}$$





2nd Ton Year Results





- Fit in ROI in BAT (Bayesian Analysis Toolkit) including systematics
  - Average background index: 1.3×10^{-2} counts/(keV.kg.year)
  - Decay Rate limit: $\Gamma_{0\nu} < 2.5 \times 10^{-26}$ yr^{-1} (90% C.I.)
  - Half-life limit: $T_{1/2} > 2.7 \times 10^{25}$ yr (90% C.I.)
- Median exclusion sensitivity: 3.1×10^{25} yr (90% C.I.) with MC 10^4 experiments

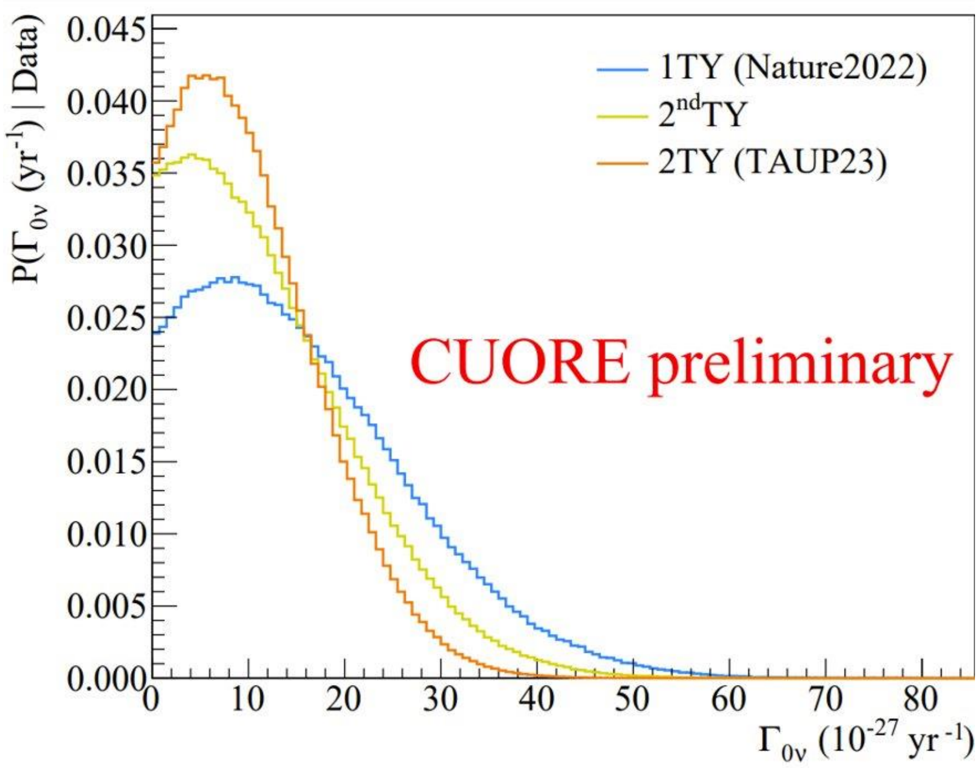
No evidence of neutrinoless double beta decay

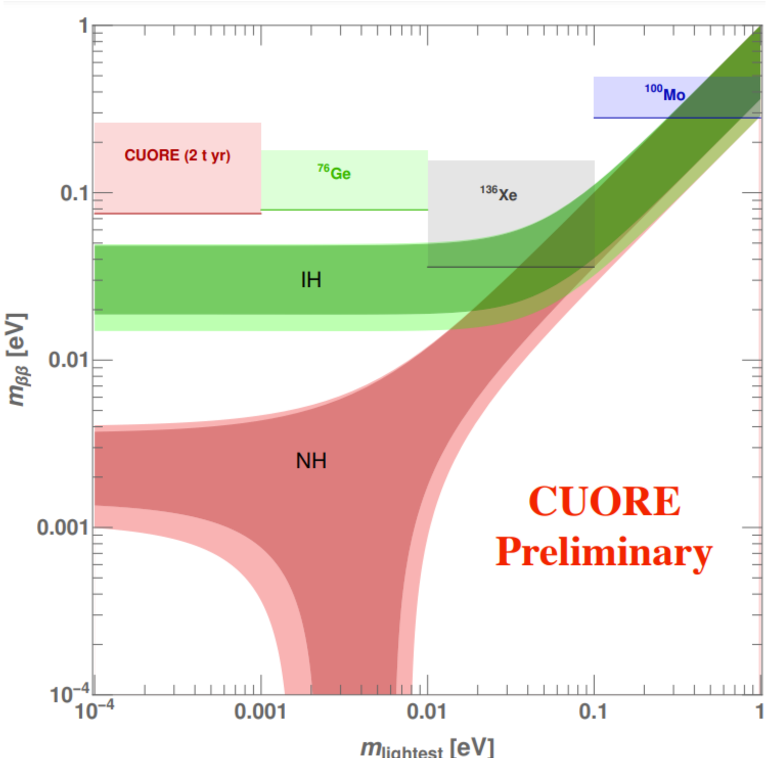
Combined Results

- Combining 2nd ton.yr results with 1 ton.yr results
  - Analyzed exposure: 2023 kg.yr
  - Half-life limit: $T_{1/2} > 3.3 \times 10^{25}$ yr (90% C.I.)
- $m_{\beta\beta} < 75 – 255$ meV
  - Light Majorana neutrino exchange model
  - Range depends on nuclear matrix elements

Limits on other isotopes:
GERDA Collaboration, Phys. Rev. Lett. 125, 252502 (2020) https://doi.org/10.1103/PhysRevLett.125.252502
CUPID-Mo Collaboration https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.181802
CUPID-0 Collaboration, Phys. Rev. Lett. 123, 032501 (2019) https://doi.org/10.1103/PhysRevLett.123.032501
KamLAND-Zen Collaboration, Phys. Rev. Lett. 117, 082503 (2016) https://doi.org/10.1103/PhysRevLett.117.082503

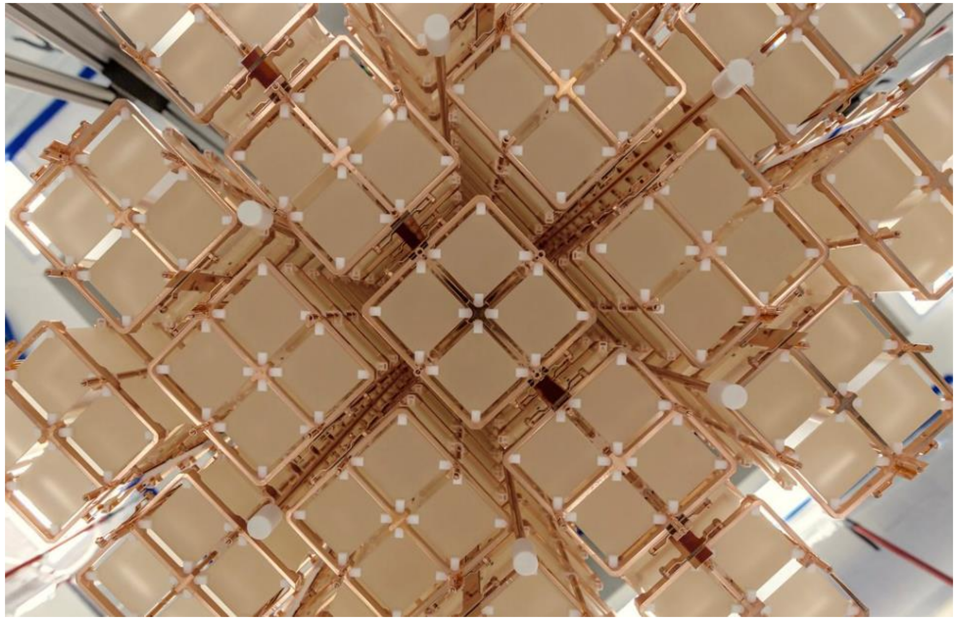
Oscillation parameters:
Esteban, I. et al., J. High En. Phys. 2020 (178) https://doi.org/10.1007/JHEP09(2020)178





SUMMARY

- CUORE has achieved 2 tonne year of exposure and continues stable data taking
- No evidence of 0νββ decay with 2023 kg.yr of data
  - Half-life limit: $T_{1/2} > 3.3 \times 10^{25}$ yr (90% C.I.)
  - Effective Majorana mass upper limit: 75-255 meV



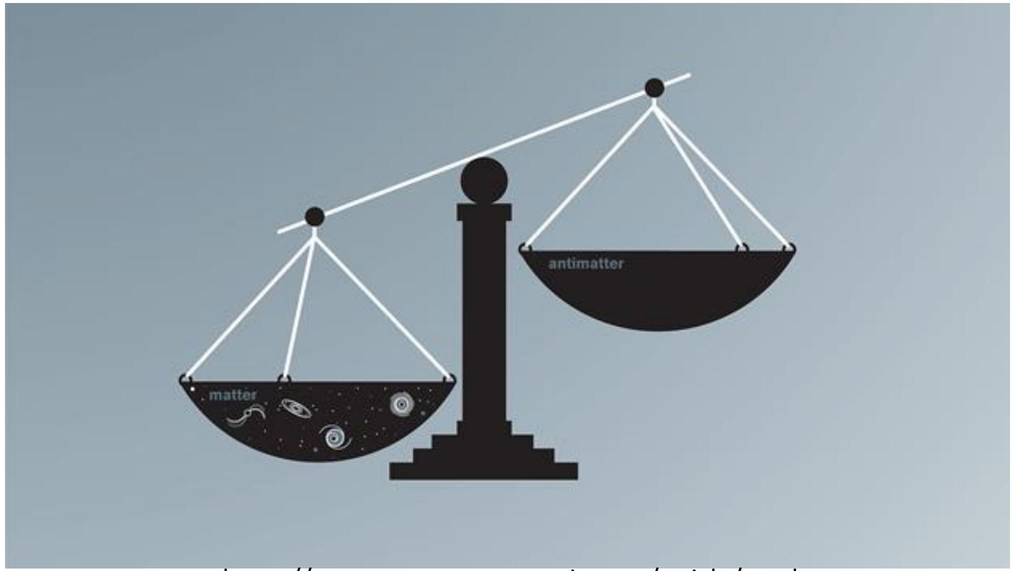
- Other avenues of research:
  - Dark matter
  - Fractionally charged particles
  - Baryon number violation

THANK YOU!

EXTRA SLIDES

Baryon Number Conservation

- Conservation of baryon number is not guaranteed by any fundamental symmetry
  - Proposed to explain the stability of matter
- Violation of baryon number conservation essential to explain matter anti-matter asymmetry (Sakharov Conditions)
- Nucleon decay modes and neutron-antineutron oscillation are two promising ways search for baryon number violation
- This work concerns tri-nucleon decay, with $\Delta B = -3$

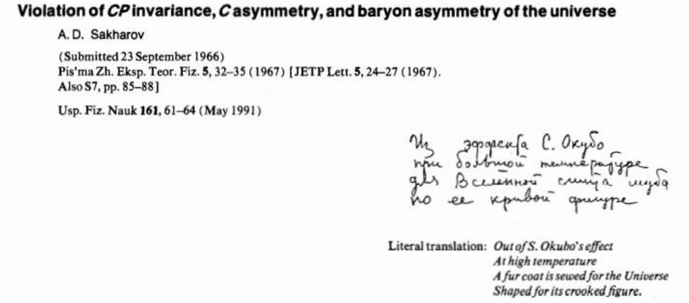


https://www.symmetrymagazine.org/article/october-2005/explain-it-in-60-seconds CP Violation

$$ppp \to e^{+}\pi^{+}\pi^{+}$$

$$ppn \to e^{+}\pi^{+} \qquad \Delta B = -3$$

$$pnn \to e^{+}\pi^{0}$$



Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

(Submitted 23 September 1966)
Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32–35 (1967) [JETP Lett. **5**, 24–27 (1967).
Also S7, pp. 85–88]

Usp. Fiz. Nauk **161**, 61–64 (May 1991)

Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

Literal translation: *Out of S. Okubo's effect*
At high temperature
A fur coat is sewed for the Universe
Shaped for its crooked figure.

*K.S. Babu et al.
https://arxiv.org/abs/1311.5285v1

Theoretical Motivation

- Model proposed by K.S. Babu* utilizes anomaly free Z_6 discrete symmetry in the SM lagrangian as gauged baryon parity with the inclusion of right-handed neutrinos
- The Z_6 symmetry has a natural embedding in the following U(1) gauge symmetry:

$$I_R^3 + L_i + L_j - 2L_k$$

$$I_R^3 = Y - (B - L)/2$$

$$L_i : i^{th} \text{ family lepton number}, i \neq j \neq k$$

- Forbids ΔB=1 and ΔB=2 nucleon decay processes
- ΔB=3 allowed with d=15 operators
- Double nucleon decay rates calculated within this framework and found to be consistent with other evaluations

*K.S. Babu et al.
https://arxiv.org/abs/1311.5285v1

Tri-proton decay in CUORE

- Tri-proton decay in ^{130}Te produces ^{127}In, and charged particles carrying 2.7 GeV
- One can search for this process in two ways:
  - Direct search: Look for decay energy deposited in the detector
  - Indirect search: Look for decay signatures of ^{127}In
- Indirect search previously implemented by MAJORANA collaboration[1] and EXO-200[2]

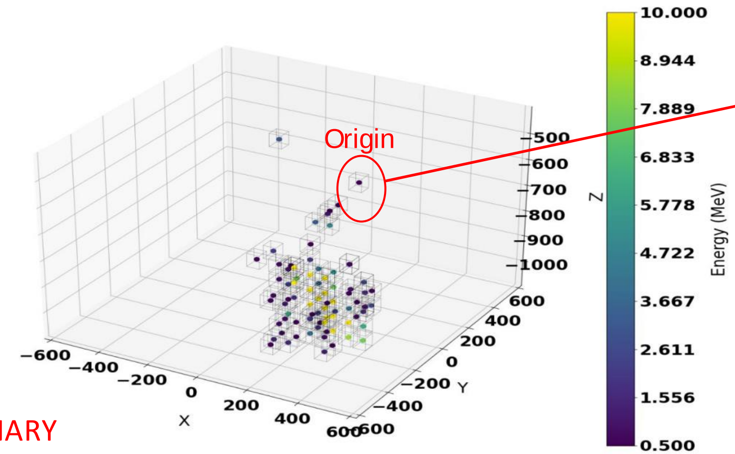
$$ppp \rightarrow e^+\pi^+\pi^+$$

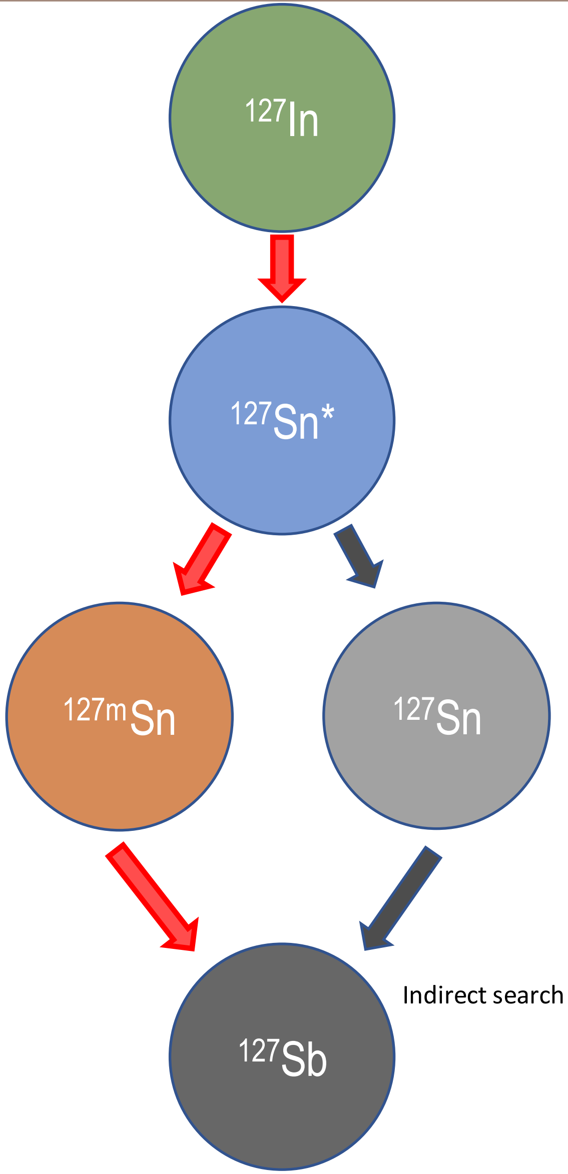
$$^{130}\mathbf{Te} \rightarrow \; ^{127}\mathbf{In} + \underbrace{e^+ + \pi^+ + \pi^+}_{2.7\ \text{GeV}}$$

1 https://journals.aps.org/prd/pdf/10.1103/PhysRevD.99.072004
2 https://journals.aps.org/prd/pdf/10.1103/PhysRevD.97.072007

Methodology

- Direct search looks for energy deposition in multiple crystals throughout the detector
  - CNN based analysis to classify these with muon events as background
- Indirect search looks for decay signatures of daughter nuclei at the origin of the tri-proton decay



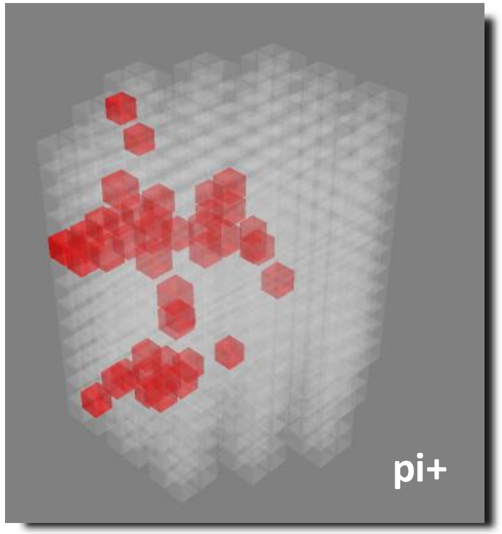


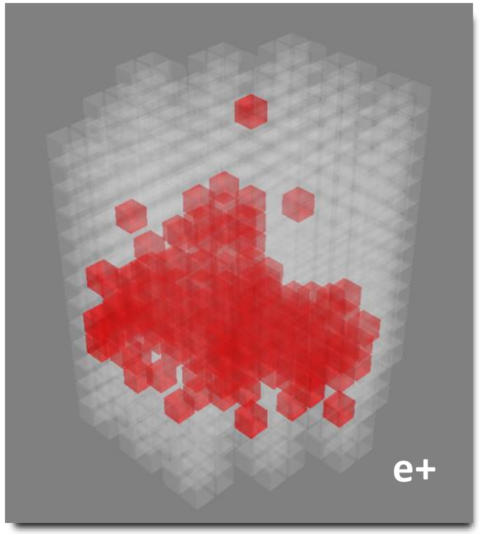
Indirect search of tri-proton decay via 127In

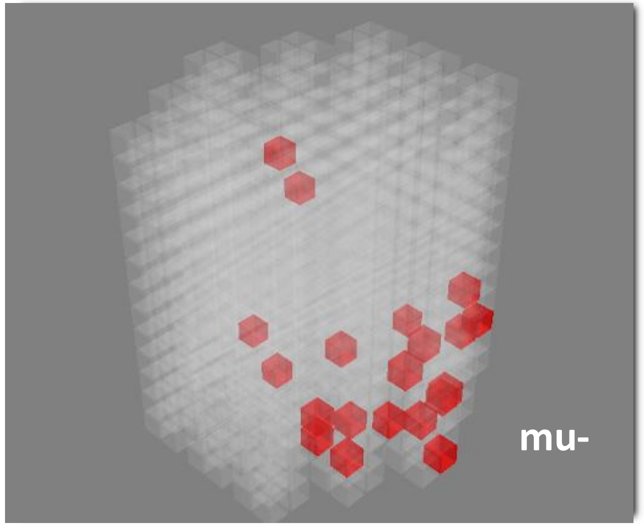
Direct Search

CUORE

- PPP decay events characterized by diffuse showers
  - High multiplicity, high energy events
- Muon events show tracks with relatively lower multiplicity secondary events
- Potential to discriminate between events based on energy distribution and event topology
- Convolutional Neural Network good candidate for classification algorithm
  - Excellent at extracting spatial information with translational invariance



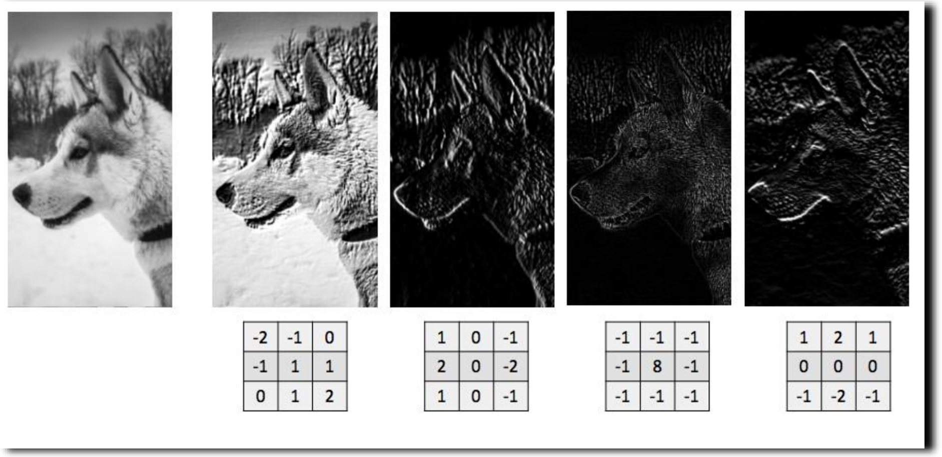


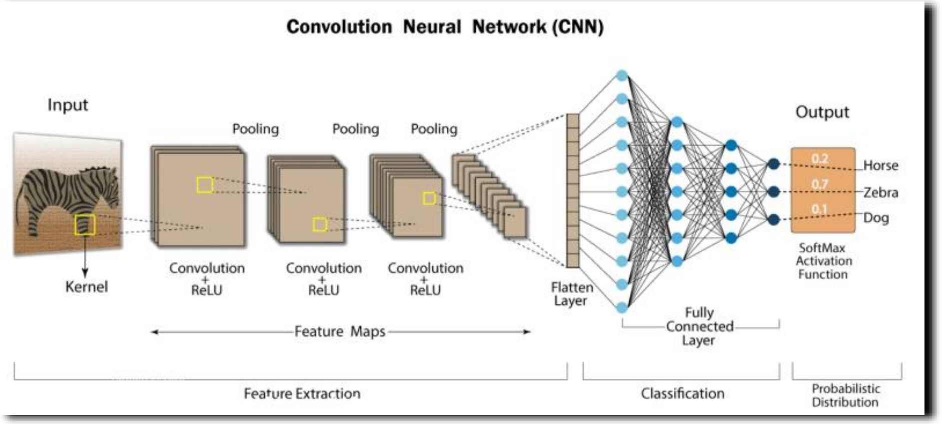


PRELIMINARY

Convolutional Neural Networks

- Artificial neural networks commonly used to classify visual data
- Involves convolution of the input array with filters to abstract distinguishing features
  - Elements of filters are trainable parameters
- Commonly followed by fully connected neural network to perform classification
- Commonly used layers
  - Convolution: Generating feature maps
  - Pooling: Downsampling feature maps, introduces translational invariance, increase receptive field





https://nafizshahriar.medium.com/what-is-convolutional-neural-network-cnn-deep-learning-b3921bdd82d5

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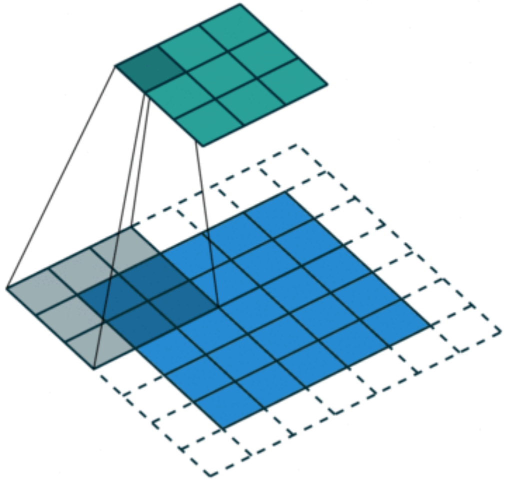
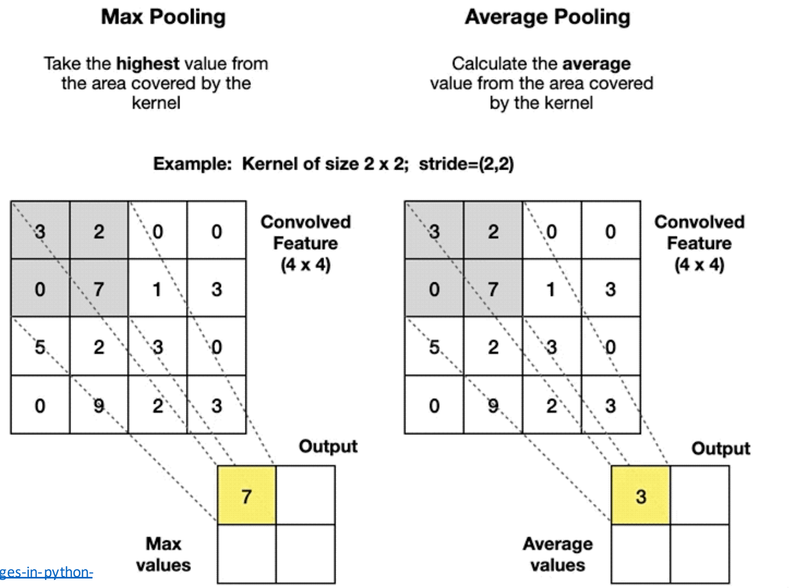
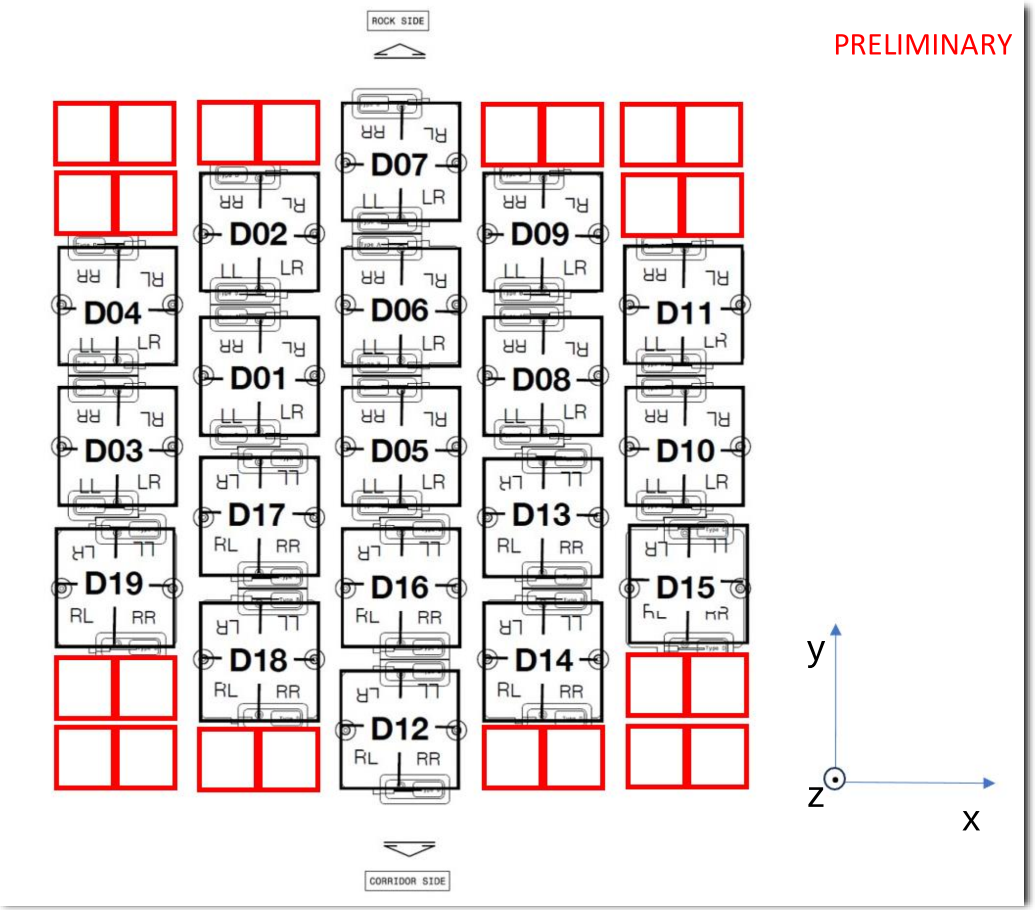




https://towardsdatascience.com/convolutional-neural-networks-explained-how-to-successfully-classify-images-in-python-df829d4ba761

Training data

- Simulated ppp decays and muon events in CUORE geometry
  - Randomly split 2.7 GeV among the decay products
  - Processed events with CUORE detector response
- Mapped events to 3D arrays (10x10x13)
- Pre-processing
  - Energies capped to 12 MeV to simulate saturation
  - Individual energy threshold: 350 keV
  - Events with number of depositions > 10
  - Energies scaled to [0,1] range to facilitate efficient backpropagation
  - Accounted for data quality cuts (~96% efficiency)



CNN Implementation

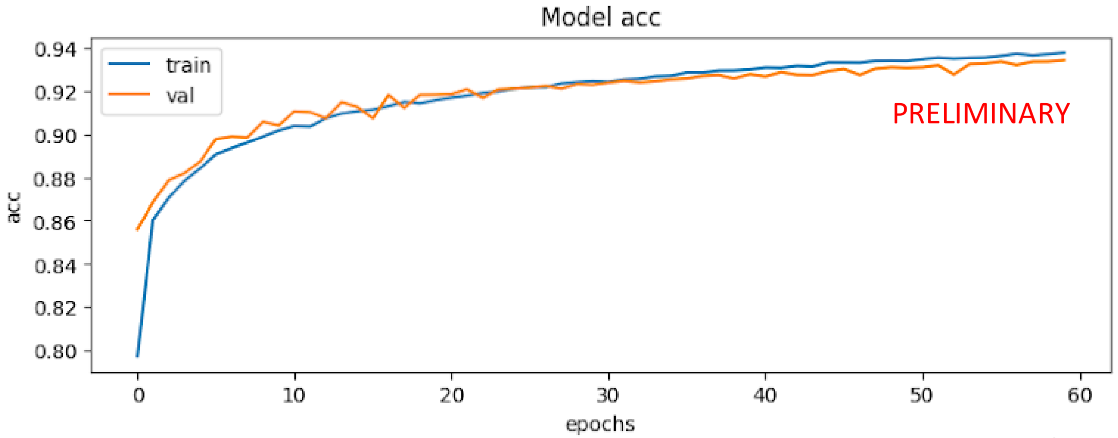
CUORE

- 2 blocks of Conv3D + MaxPool3D
  - 1st block: 16 filters, kernel size: 3x3x3
  - 2nd block: 32 filters, kernel size: 3x3x3
  - MaxPool kernel size: 2x2x2
- 2 layers of FC layers
  - Dropout: 0.3
  - ReLU activation
- Output Layer: Sigmoid
- Loss function: Binary cross entropy
- Optimizer: Adam
- Early stopping, validation accuracy as monitor

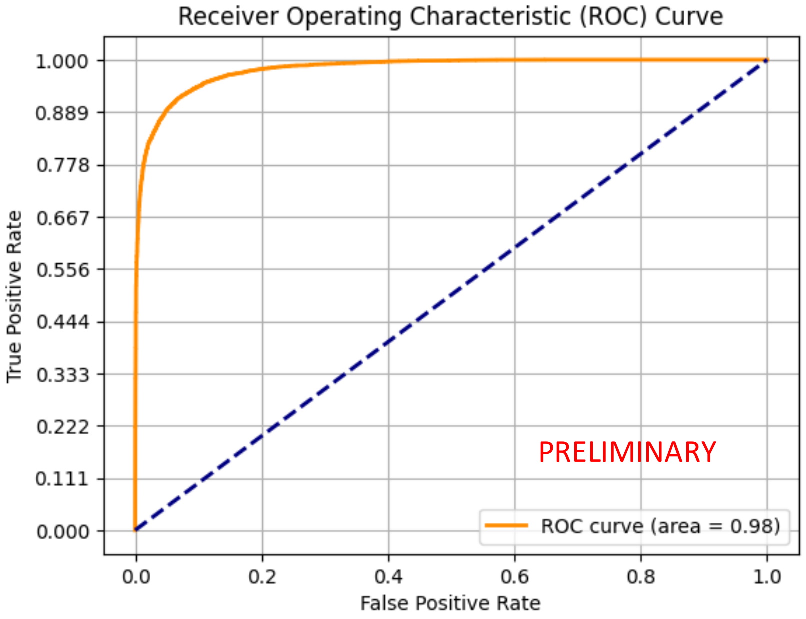
Layer (type)	Output Shape	Param #
input_1 (InputLayer)	[(None, 10, 10, 13, 1)]	0
conv3d (Conv3D)	(None, 10, 10, 13, 16)	448
conv3d_1 (Conv3D)	(None, 10, 10, 13, 16)	6928
max_pooling3d (MaxPooling3D)	(None, 5, 5, 6, 16)	0
conv3d_2 (Conv3D)	(None, 5, 5, 6, 32)	13856
conv3d_3 (Conv3D)	(None, 5, 5, 6, 32)	27680
max_pooling3d_1 (MaxPooling 3D)	(None, 2, 2, 3, 32)	0
global_average_pooling3d (G lobalAveragePooling3D)	(None, 32)	0
dense (Dense)	(None, 32)	1056
dropout (Dropout)	(None, 32)	0
dense_1 (Dense)	(None, 16)	528
dense_2 (Dense)	(None, 1)	17

Total params: 50,513
Trainable params: 50,513
Non-trainable params: 0

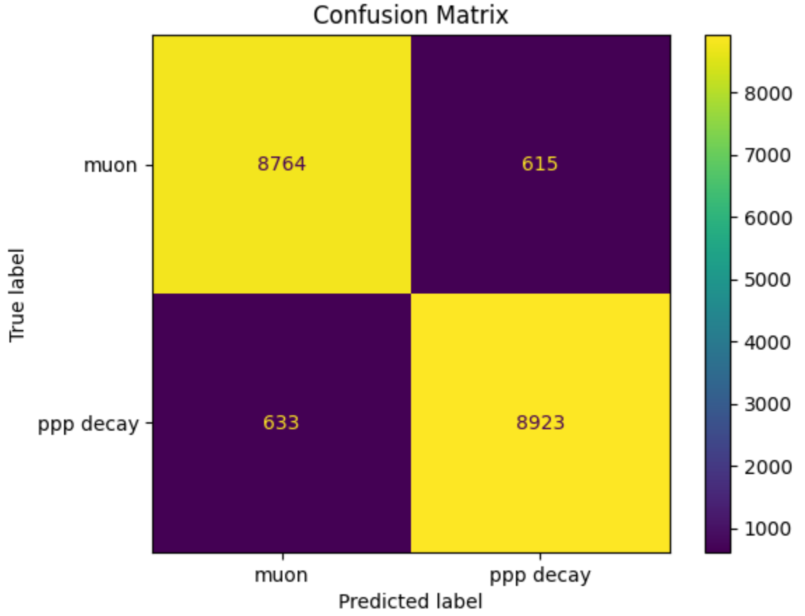
CNN Performance



80%-20% split for training and validation data



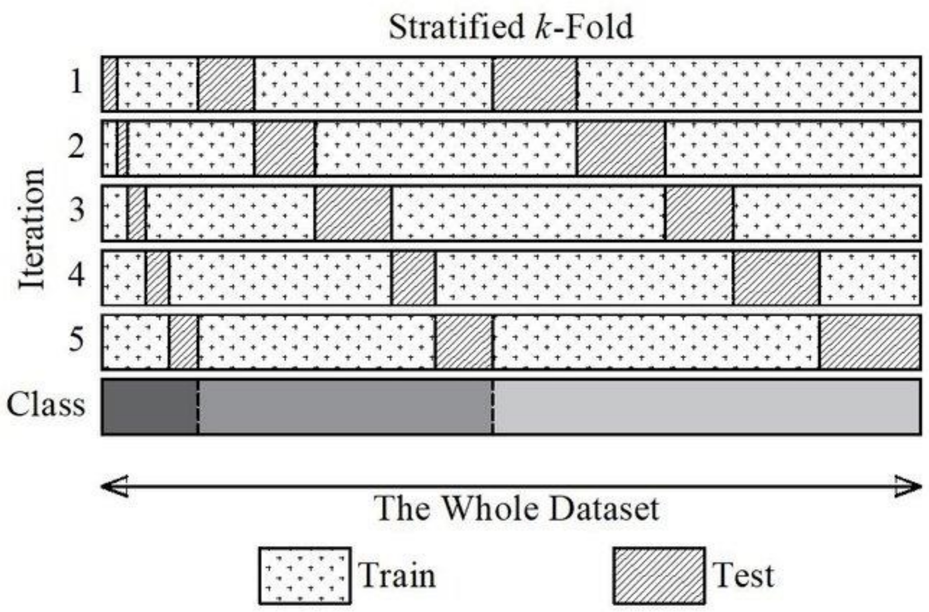
Signal efficiency: 93.3%
Bkg efficiency: 93.4%



PRELIMINARY

Stratified Kfold Cross Validation

- Splits the dataset into k subsets, or folds, while maintaining the same proportion of classes in each fold as the original dataset.
- Each fold serves as a validation set while the remaining k-1 folds are used for training.
  - This process is repeated k times, allowing every data point to be part of the validation set exactly once.
- Final evaluation is an average of the results obtained from all k folds, helping to detect potential overfitting.
- Robust technique for evaluating the performance of machine learning models.
  - Ensures an unbiased assessment, avoids over-optimistic estimates



https://doi.org/10.1111/mice.12517

Stratified Kfold Cross Validation

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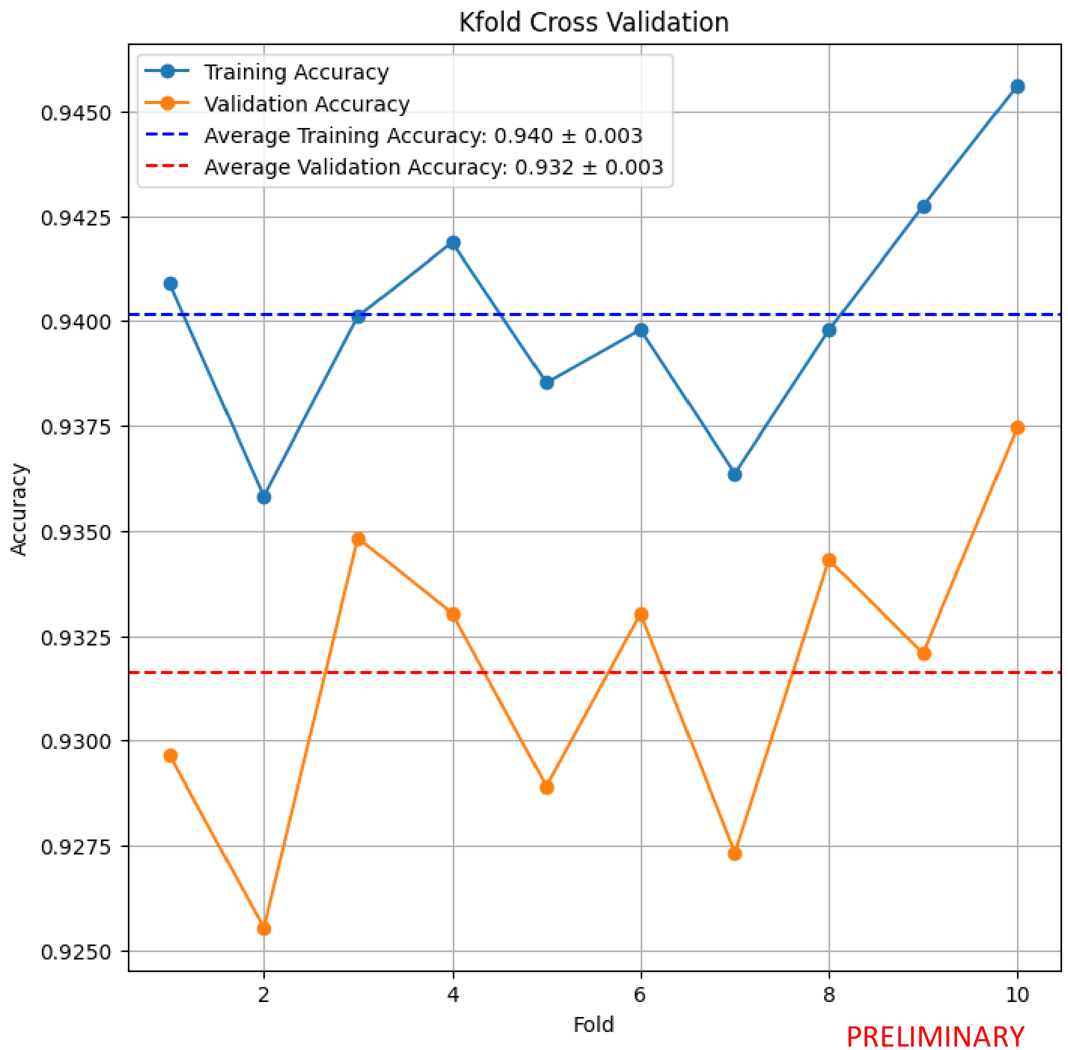
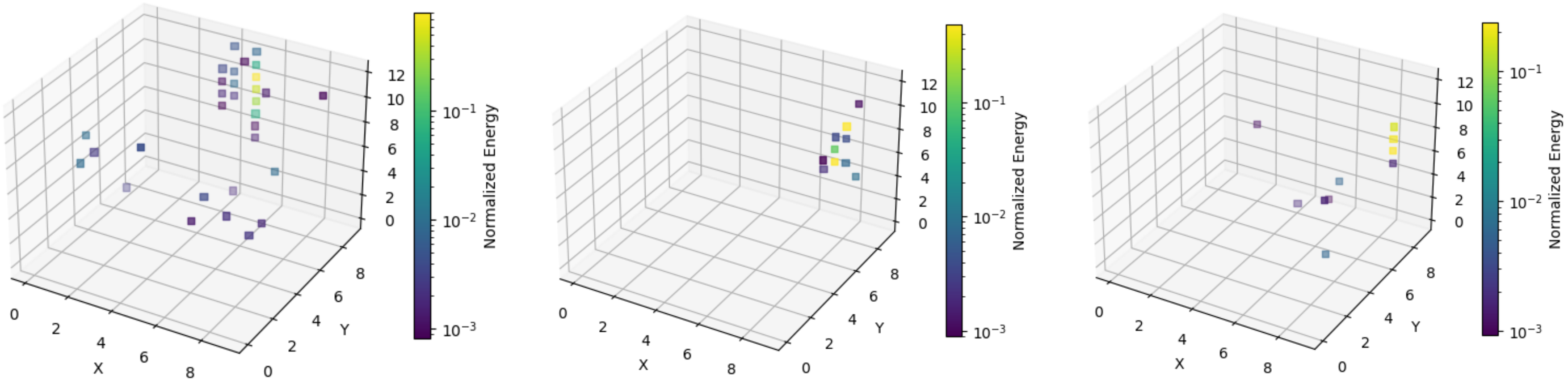


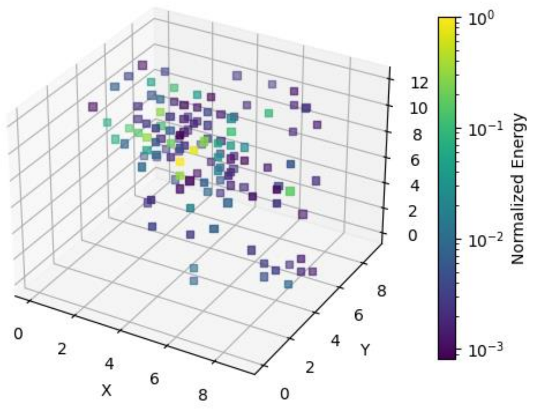
PRELIMINARY

Error Analysis

False negatives

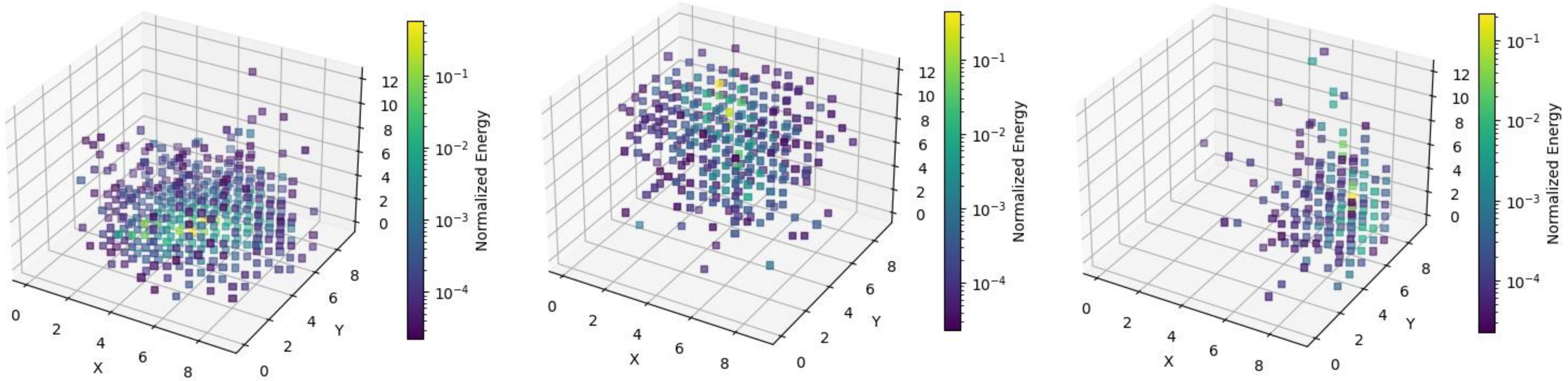


True positive

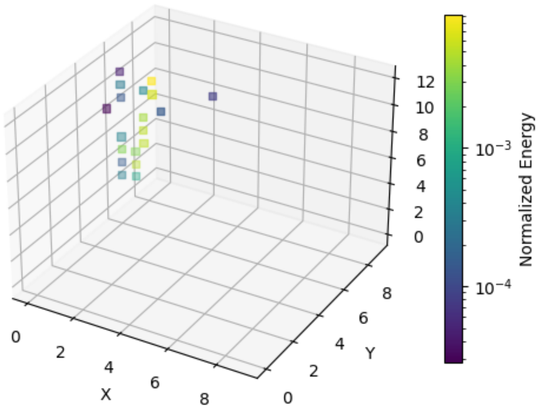


PRELIMINARY

False positives

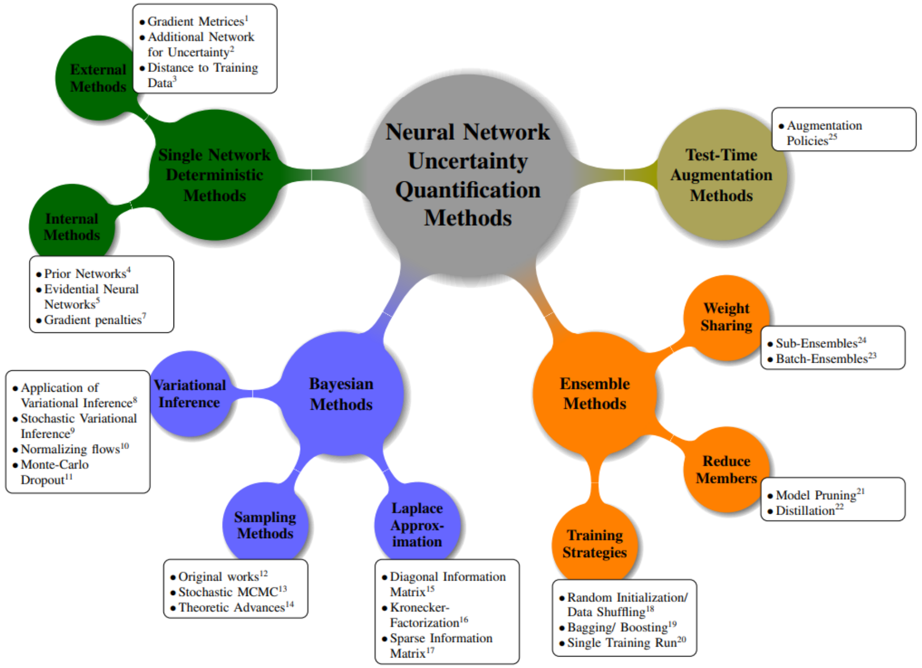


True negatives



CNN Uncertainty estimation

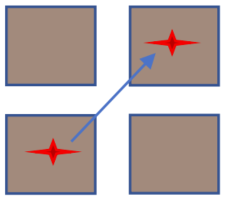
- Monte Carlo dropout
  - Employ dropout for both training and inference
  - Generate distribution of accuracies
- Bootstrap aggregation and boosting
  - Extension of kfold cross validation
  - Average performance of multiple independent

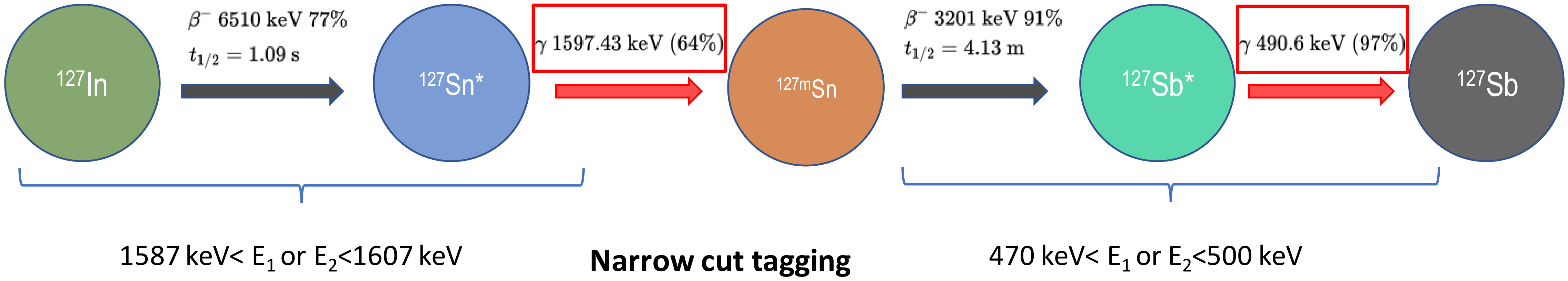


https://arxiv.org/abs/2107.03342

Delayed Signal

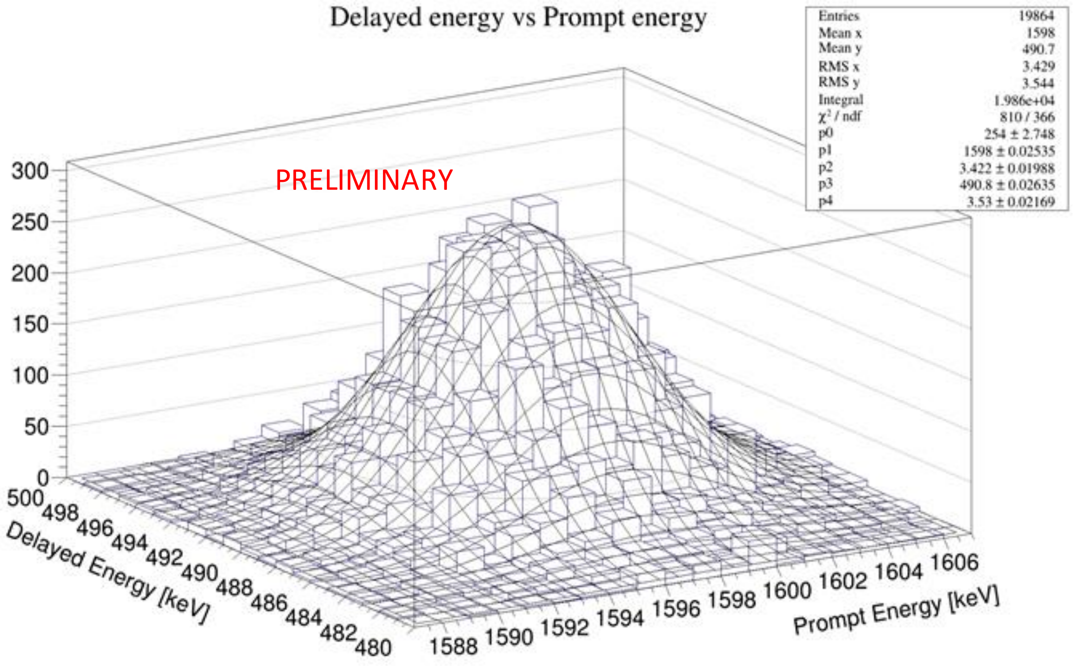
- Simulated 10^6 ^{127}In nuclei in a Geant4-based CUORE geometry and detector response simulation
- Tagged ^{127}In-^{127}Sb coincidences:
  - Tag M2 events with a tight cut to only account for gamma peaks

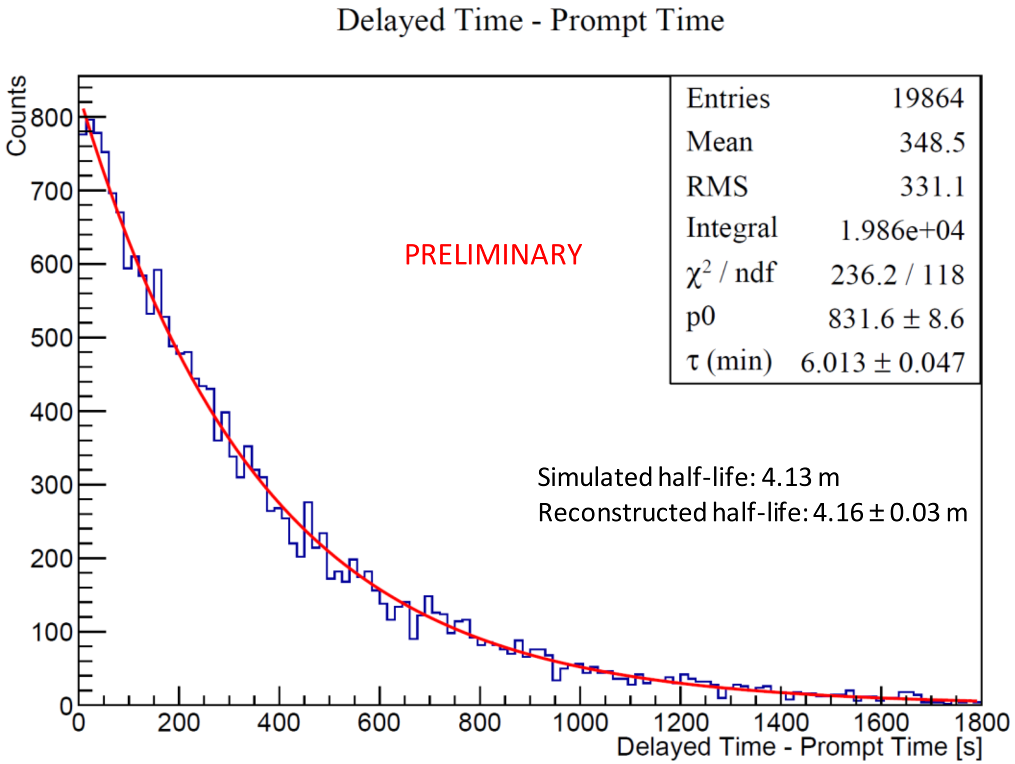




Delayed Signal

- Prompt-Delayed energy and time distribution consistent with literature input

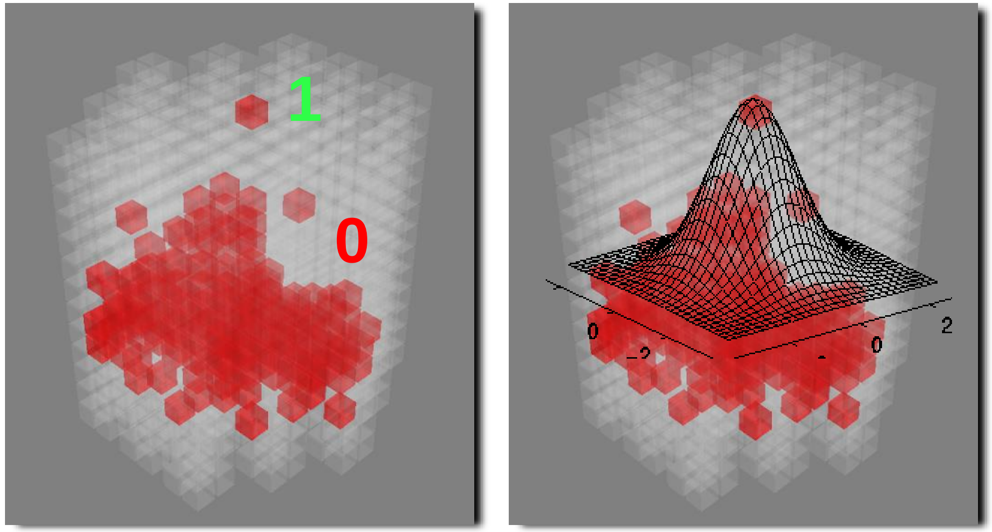


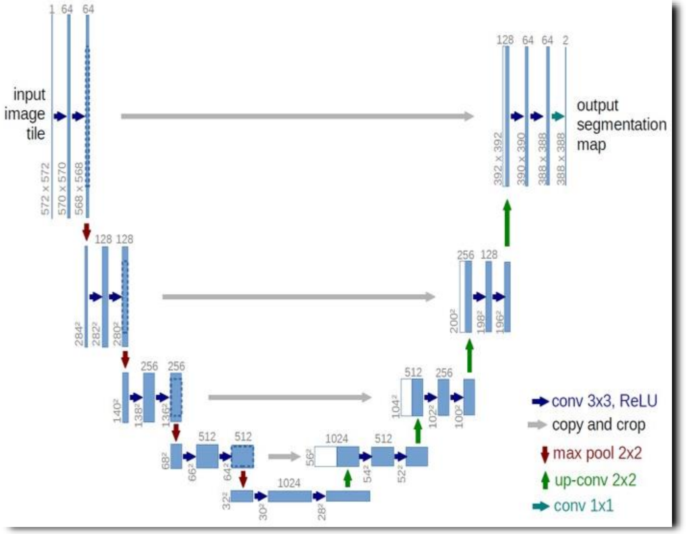


$Time_{delayed} - Time_{Prompt} < 7*t_{(1/2)}$

Integration with delayed signal

- Once candidate ppp decays are tagged, important to identify decay origin to minimize background
  - High multiplicity -> More channels to search -> Higher background
- Model can help narrow down candidate origin channels for 127In decay tagging
  - Pixel(Crystal) level classification
  - Currently testing UNet-like architectures to perform semantic segmentation
    - Classification with discrete labels
    - Regression with Gaussian scoring





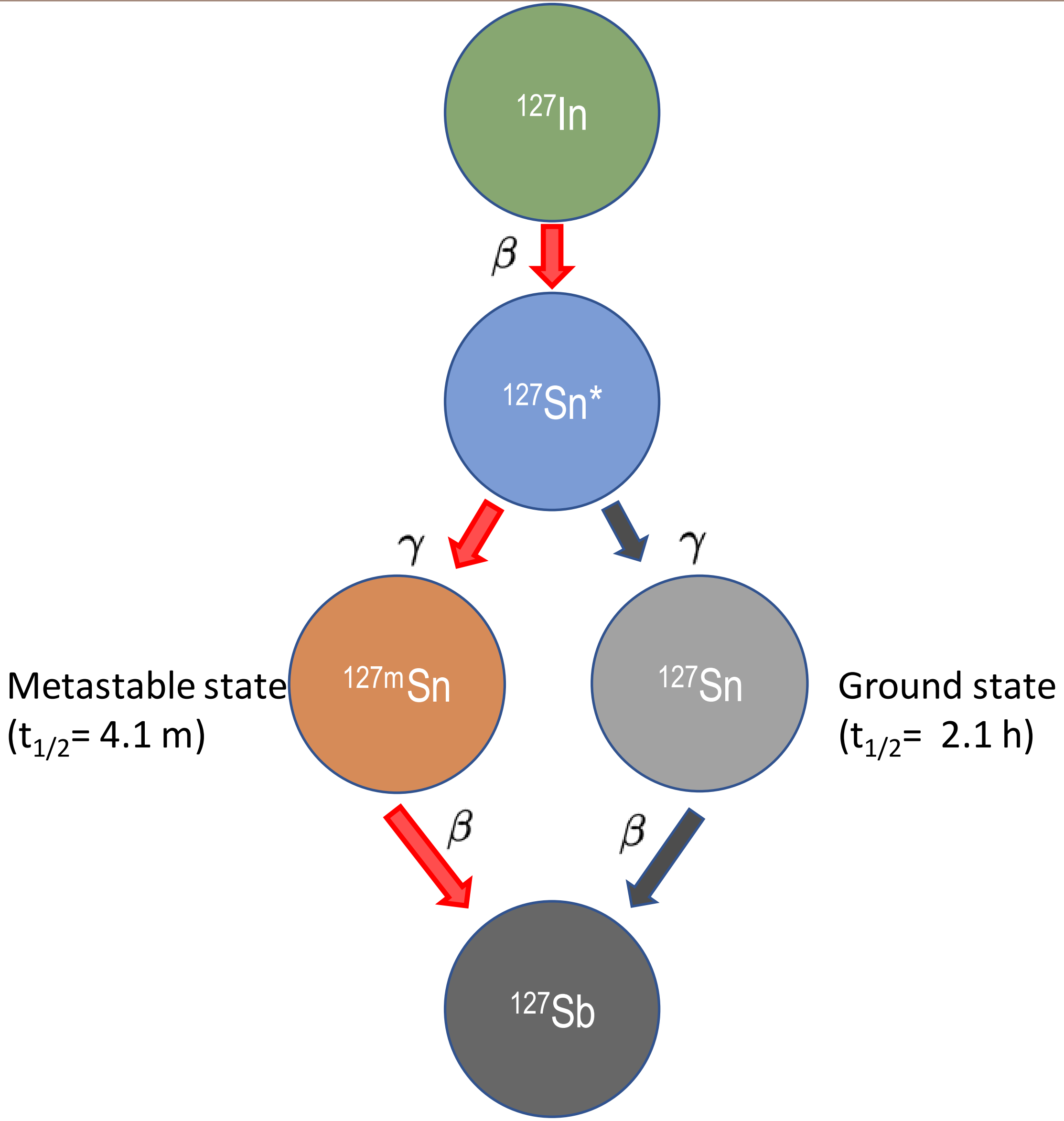
http://dx.doi.org/10.1007/978-3-319-24574-4_28

Roadmap

- Currently developing Bayesian framework to calculate MC limit with preliminary systematics on muon rate and CNN classification accuracies
- Final round of CNN tuning
  - Larger training dataset
  - Training data augmentation by rotations of muon and ppp events about the vertical axis
  - Developed tools to perform error analysis more efficiently
  - Hidden layer analysis
- Testing segmentation models to control delayed coincidence backgrounds
- Investigating systematics
  - MC physics list
  - Data event extraction
  - Muon rate

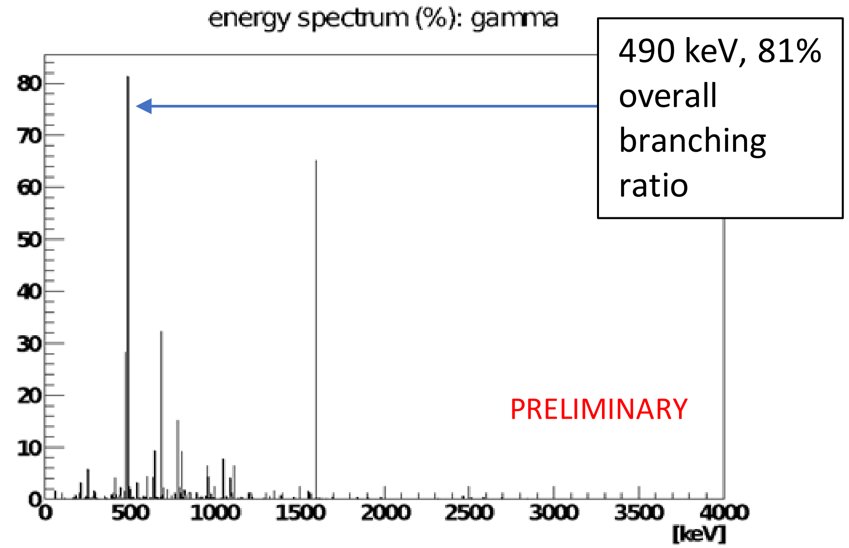
^{127}In decay chain

- ^{127}In is a short-lived nuclei ($t_{1/2}$= 1.1 s)
- Decays to an excited state of ^{127}Sn which decays to ^{127}Sb via two decay pathways
  - One of them involves a metastable state which decays with a half-life of 4.1 m
- The metastable route is well suited for a delayed coincidence search
  - Half-life short enough to control accidental backgrounds, and long enough to work with CUORE timing resolution

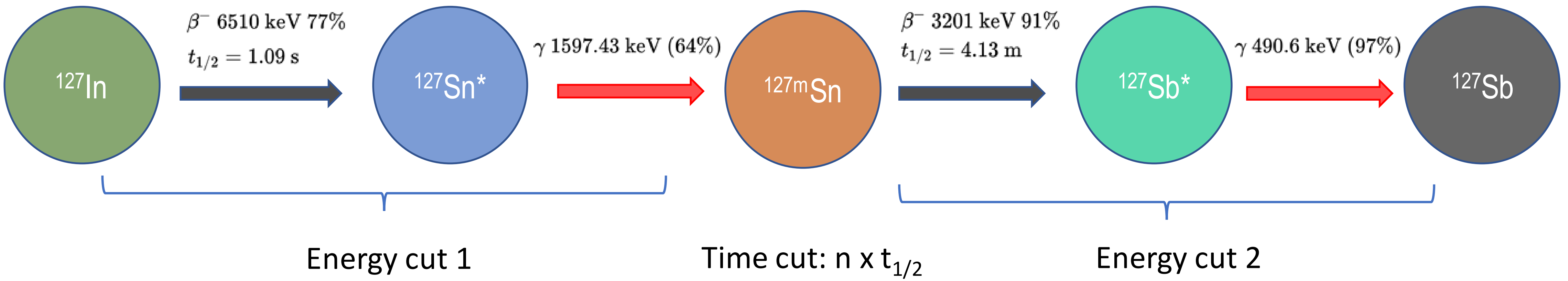


Delayed coincidence search

- Probability of occupying metastable state 81% as calculated in a Geant4 simulation
- The primary signal for this search would be a time coincidence between the prompt and delayed events with energy cuts

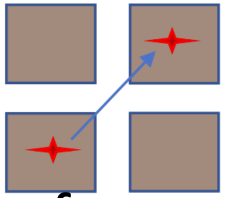


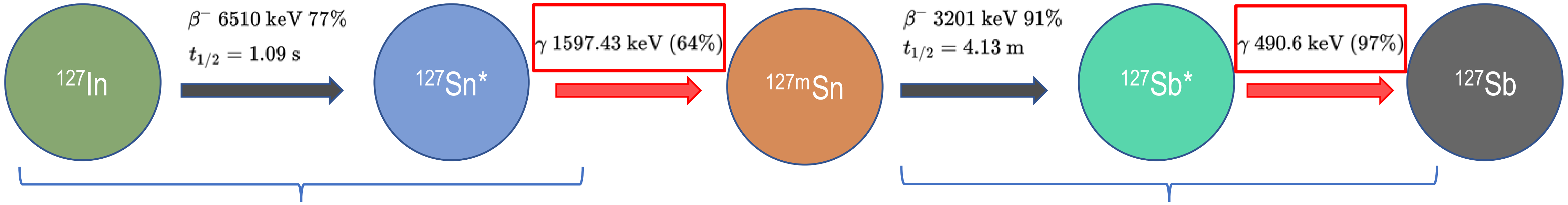
Geant4 simulation of the ^{127}In decay chain



Signal Efficiency in CUORE

- Simulated 10^6 ^{127}In nuclei in a Geant4-based CUORE geometry and detector response simulation
- Tagged ^{127}In-^{127}Sb coincidences in two ways:
  - Narrow cut approach: Tag M2 events with a tight cut to only account for gamma peaks
  - Broad cut approach: Tag M2 events for prompt and delayed events with cuts accounting for both gamma and beta decays





1587 keV< E_1 or E_2<1607 keV

Narrow cut tagging

470 keV< E_1 or E_2<500 keV

Signal Efficiency in CUORE

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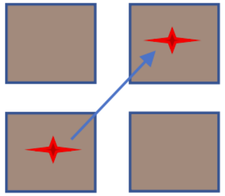
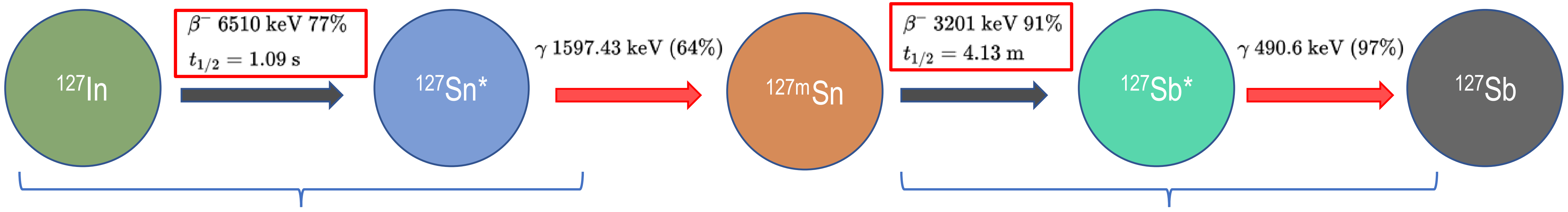
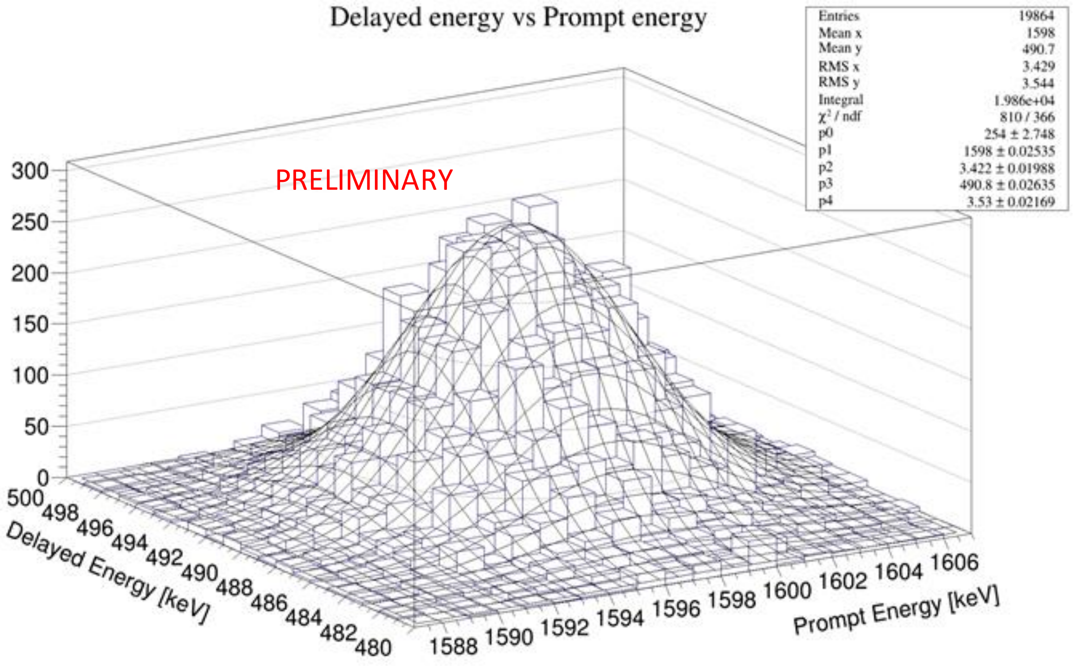
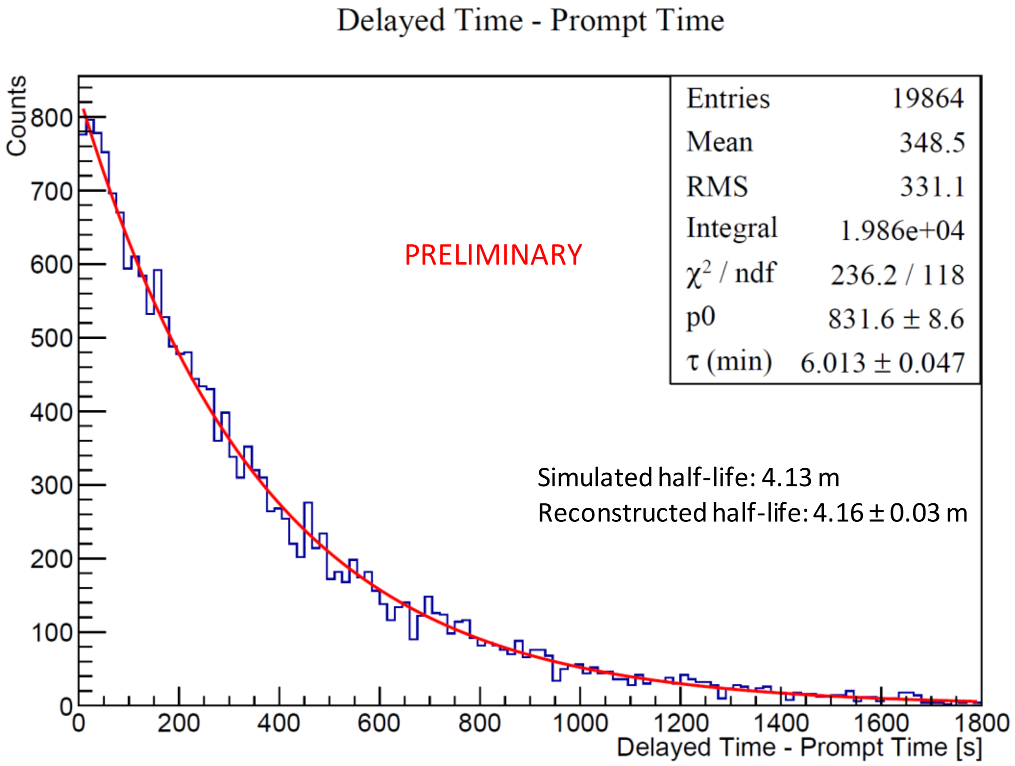




Signal Efficiency in CUORE (Narrow cut)

- Tagged 2% of ^{127}In primaries (10^6) in CUORE geometry
- Sanity Checks:
  - Prompt-Delayed energy and time distribution consistent with literature input

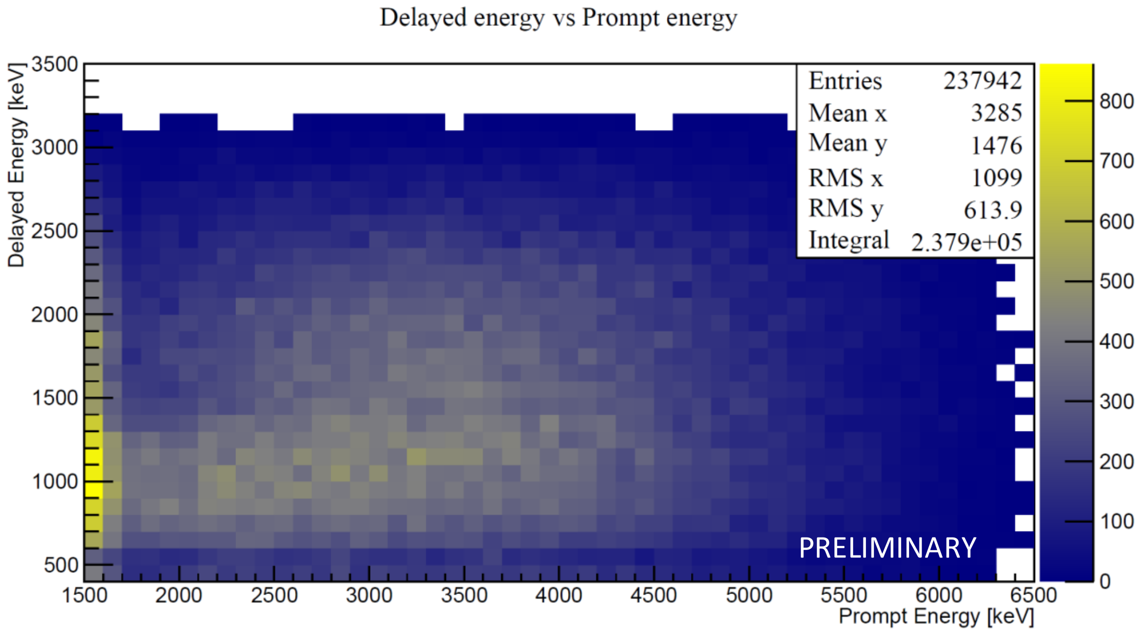


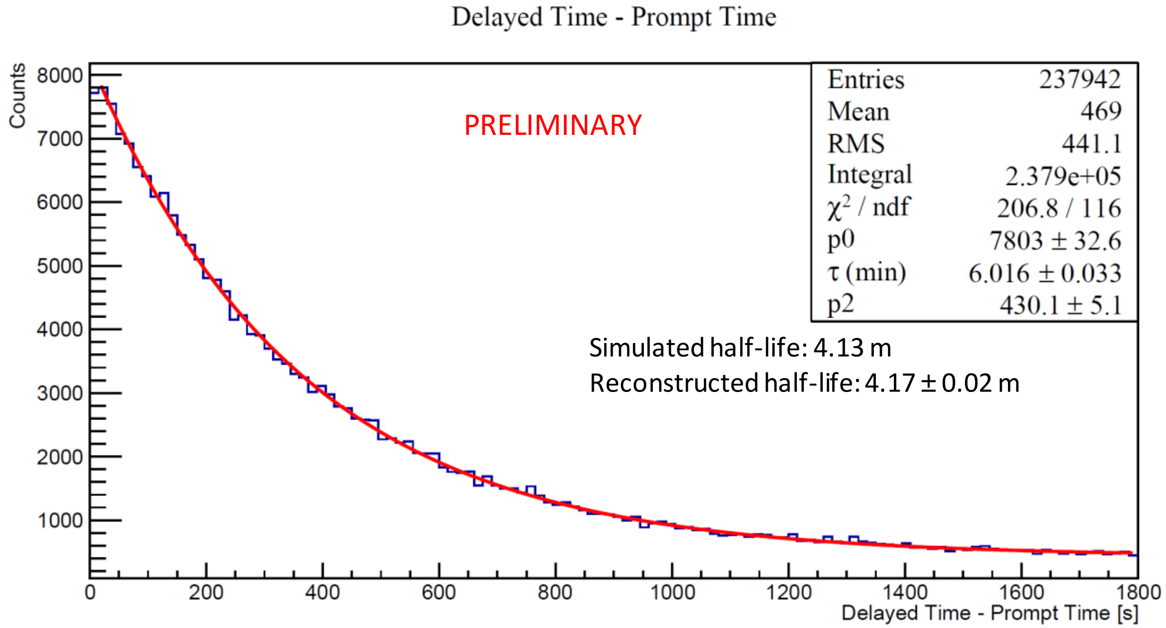


$Time_{delayed} - Time_{Prompt} < 7*t_{(1/2)}$

Signal Efficiency in CUORE (Broad cut)

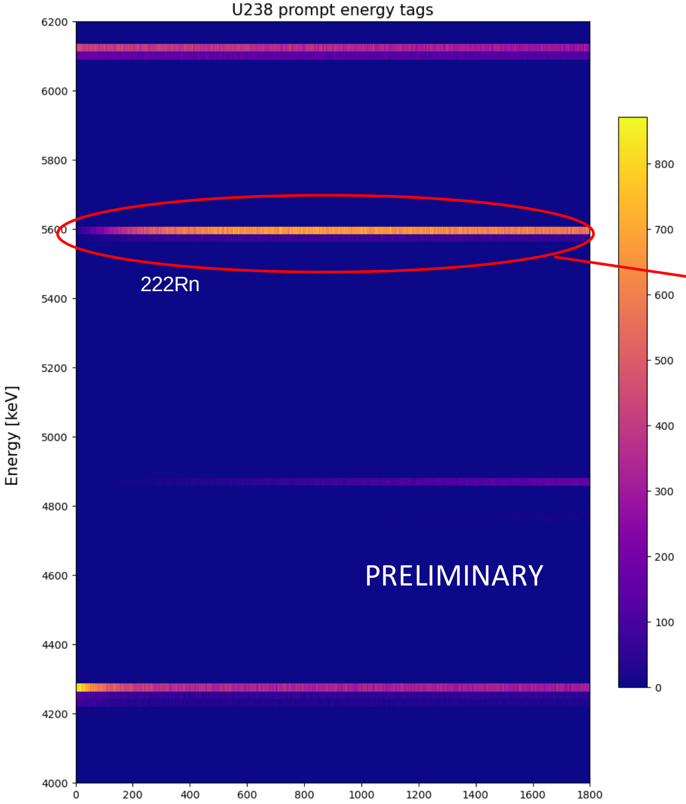
- Tagging efficiency increases significantly (18%), but backgrounds increase as well
- This approach lets us leverage prompt/delayed energy distributions for a likelihood analysis to optimize sensitivity

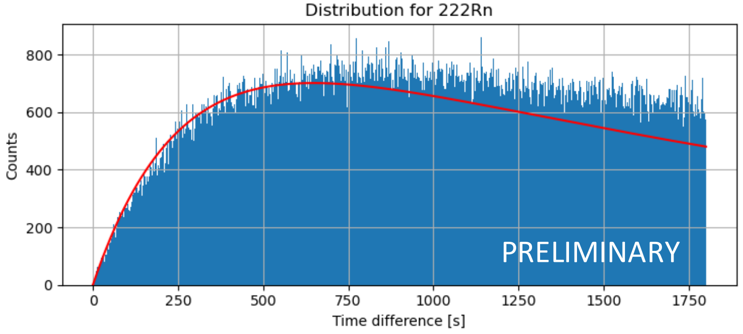




Background Estimates

- Removing tags associated with known decays significantly reduces background
  - Negligible effect on signal efficiency (2%)
- Currently investigating distribution of these tags to better understand background



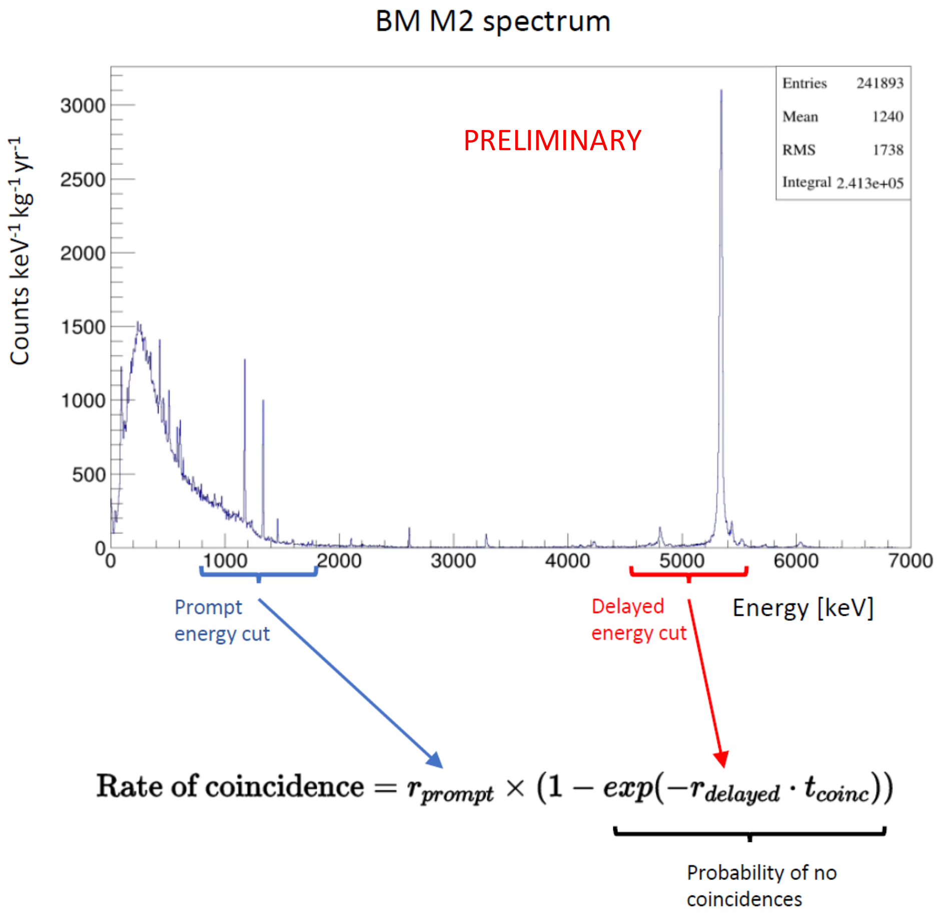


$$f(x) = \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2}(e^{-x\lambda_2} - e^{-x\lambda_1})$$

Background type	Narrow cut	Broad Cut	Broad cut (with additional cuts)	Broad cut reduction
238U-Bulk	22	13381	4018	70%
232Th-Bulk	0	22985	3568	85%
238U-Surface	39	4623267	237043	95%
232Th-Surface	0	716266	254029	65%

Background Estimates

- Potential backgrounds comprise of:
  - Accidental coincidences
  - Coincidences correlated in time from major background sources
- Uncorrelated background can be estimated from the CUORE background model*
  - Probability of coincidence calculated assuming prompt and delayed events are independent
  - With an exposure of 1038.4 kg.yr:
    - Narrow cut accidental bkg events: 55
    - Broad cut accidental bkg events: 56×10^3

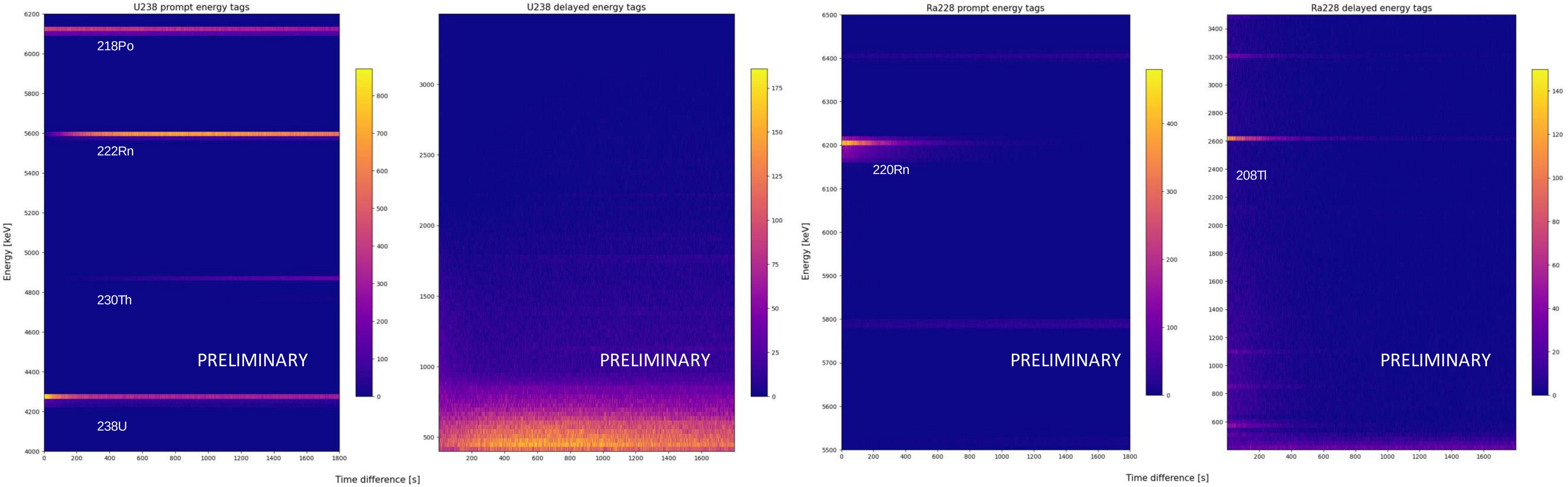


$$\text{Rate of coincidence} = r_{prompt} \times (1 - exp(-r_{delayed} \cdot t_{coinc}))$$

*D. Q. Adams et al. https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.126.171801

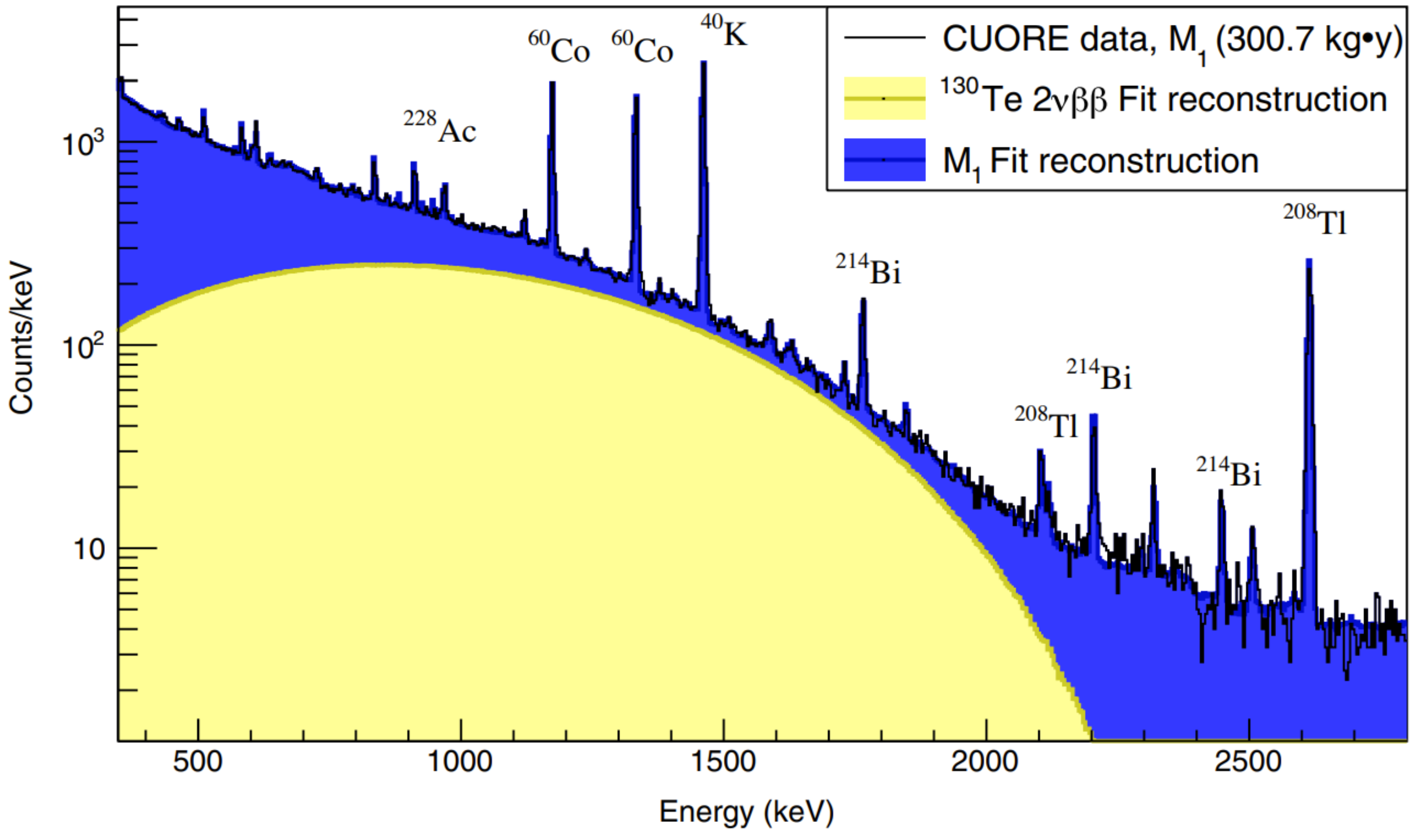
Background Estimates

- Correlated backgrounds are estimated by tagging on background model output with same energy and time cuts



DOUBLE BETA DECAY RESULTS

- Double beta decay simulated in Geant4 with CUORE geometry and detector response
- Spectrum reconstructed by simultaneous fit of data with 62 MC simulated sources (2νββ + surface and bulk contaminations + muons)
  - MCMC Bayesian approach
  - Uniform prior for sources except muons
- For 900-2000 keV, more than 50% counts are 2νββ events

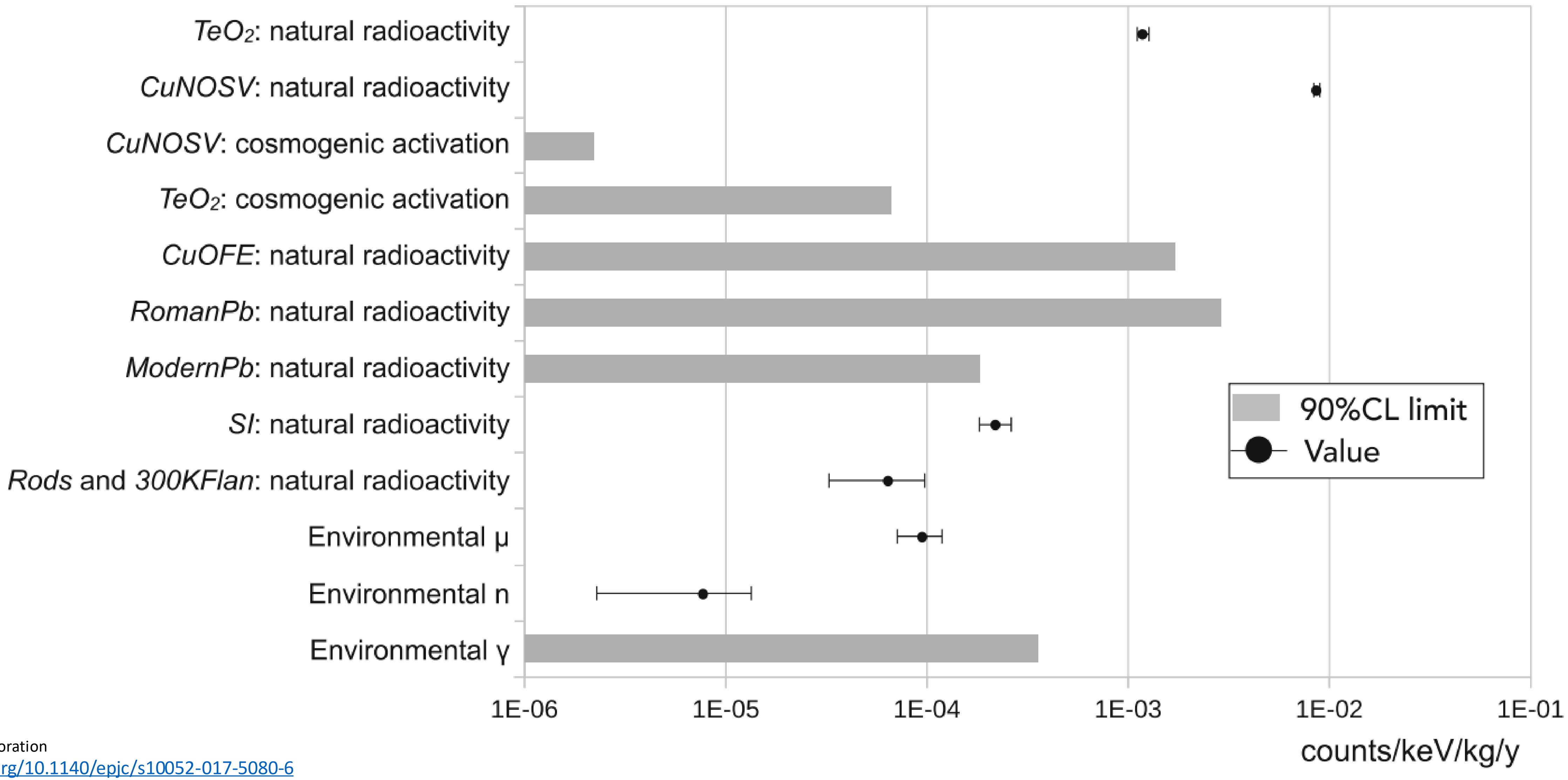


$$T^{2\nu}_{1/2} = 7.71^{+0.08}_{-0.06}(\text{stat.})^{+0.12}_{-0.15}(\text{syst.}) \times 10^{20} yr$$

D. Q. Adams et al.
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.171801

HPGe Work

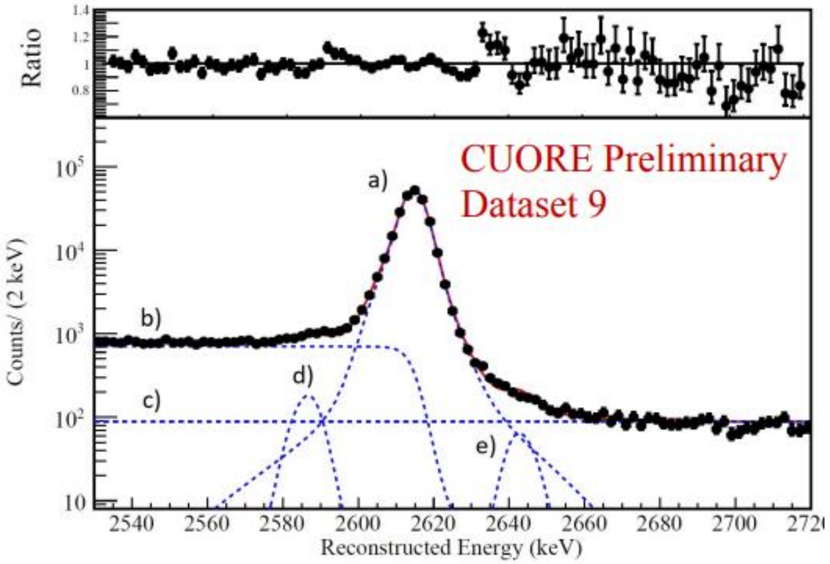
BACKGROUND BUDGET

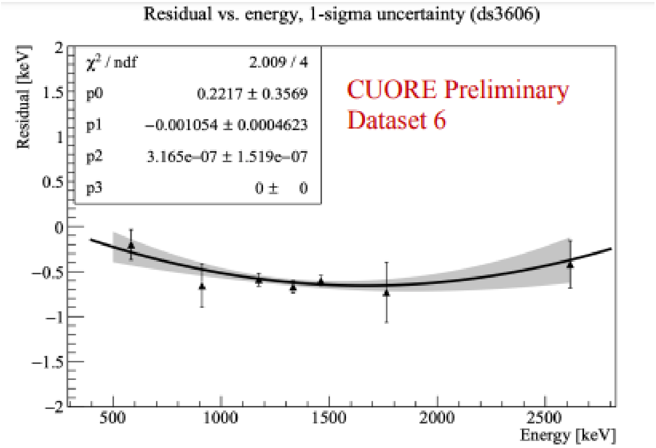


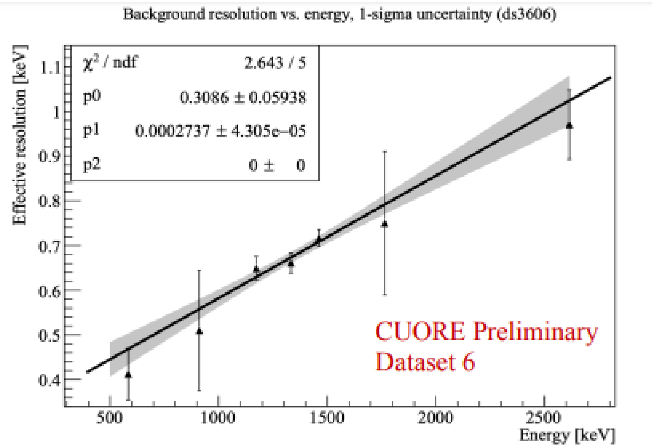
*CUORE collaboration
https://doi.org/10.1140/epjc/s10052-017-5080-6

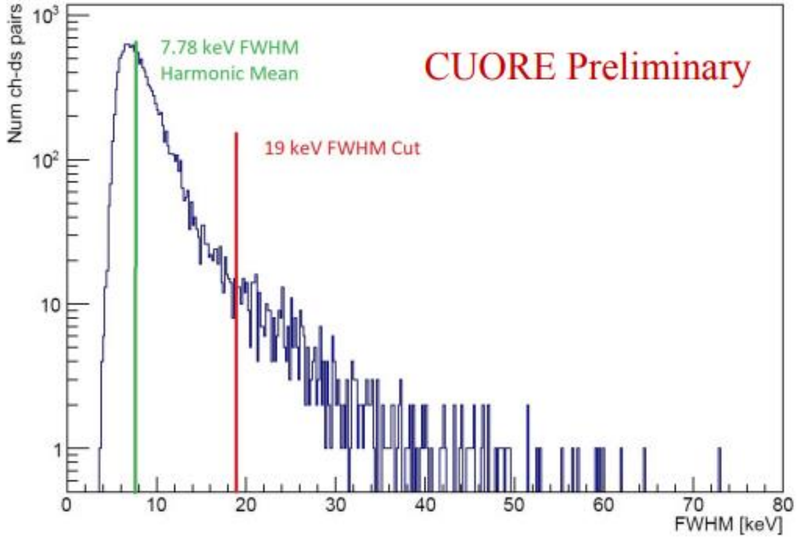
DETECTOR RESPONSE

- Fit 2615 keV calibration peak for each channel
  - 3-Gaussian signal peak
  - Compton background
  - Flat background
  - 30 keV X-ray escape peak
  - 30 keV X-ray sum peak
- Scale detector response from 2615 keV calibration fit to peaks in physics data



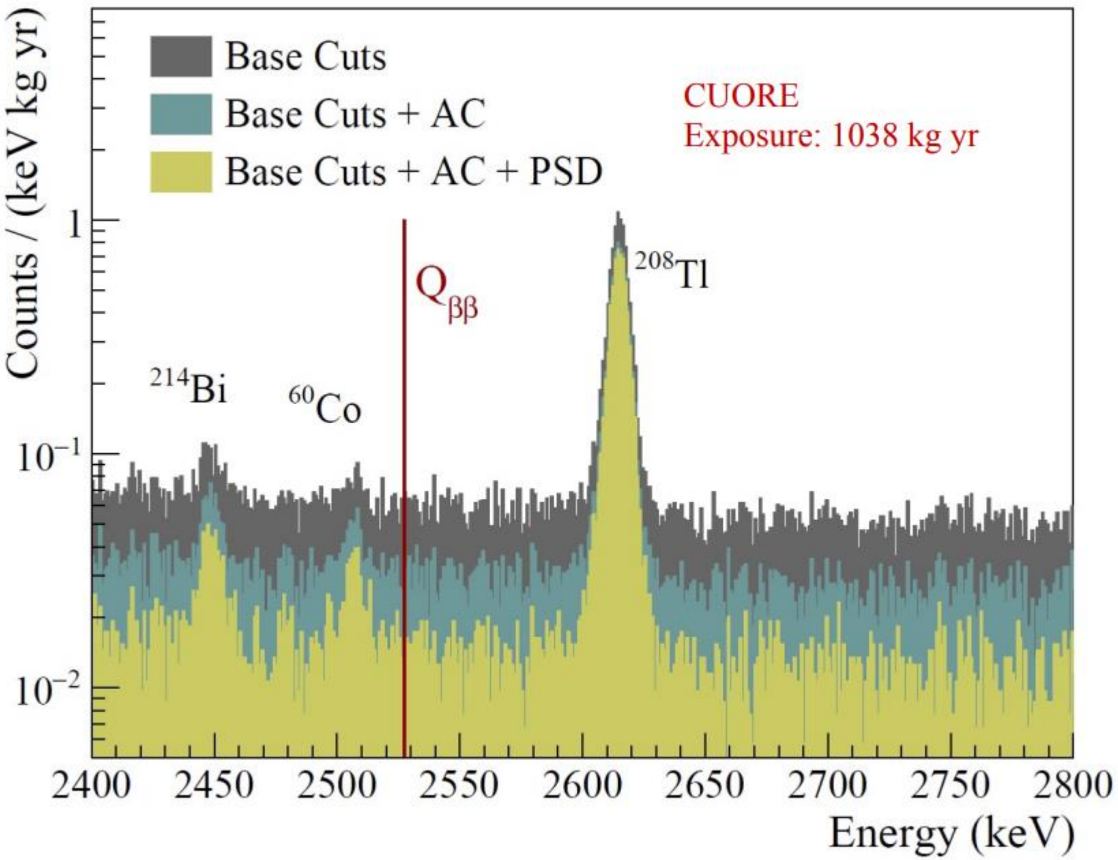






BACKGROUND IN ROI

- Alpha region:
  - Flat background in [2650, 3100] keV
  - 1.40(2) x 10^{-2} counts/(keV kg yr)*
- $Q_{\beta\beta}$ region
  - Flat background + ^{60}Co peak in [2490, 2575] keV
  - 1.49(4) x 10^{-2} counts/(keV kg yr)*
- Background dominated by degraded alpha energy depositions (90%)



*CUORE collaboration
https://www.nature.com/articles/s41586-022-04497-4.pdf

CUORE UPGRADE WITH PARTICLE IDENTIFICATION

- Next generation $0\nu\beta\beta$ decay search.
  - Scintillating bolometer technology.
  - Extremely good energy resolution, flexible choice of isotope.
- CUPID builds on CUORE, the largest bolometric array ever built.
  - Established and well understood infrastructure and environment.
  - CUORE has demonstrated stable and reliable operation over multiple years of exposure.
- Particle identification with scintillating Li_2MoO_4 bolometers has been demonstrated in the CUPID-Mo pilot experiment.*
  - Isotopic enrichment and crystals growth has been demonstrated and can be done at scale.*
- Background index goal of $<10^{-4}$ counts/(keV·kg·yr).
  - Data driven based on CUORE, CUPID-0, and CUPID-Mo experiments.*
- Probe the full Inverted Hierarchy region down to $m_{\beta\beta}<12$ meV (3σ, favorable NME).
  - Using only 240 kg of ^{100}Mo.
- Next-next generation CUPID-1T capable of probing into Normal Hierarchy, or multiple isotope precision measurements in Inverted Hierarchy.

*https://cupid.lngs.infn.it/doku.php?id=cupid_pub:start, arXiv:1907.09376

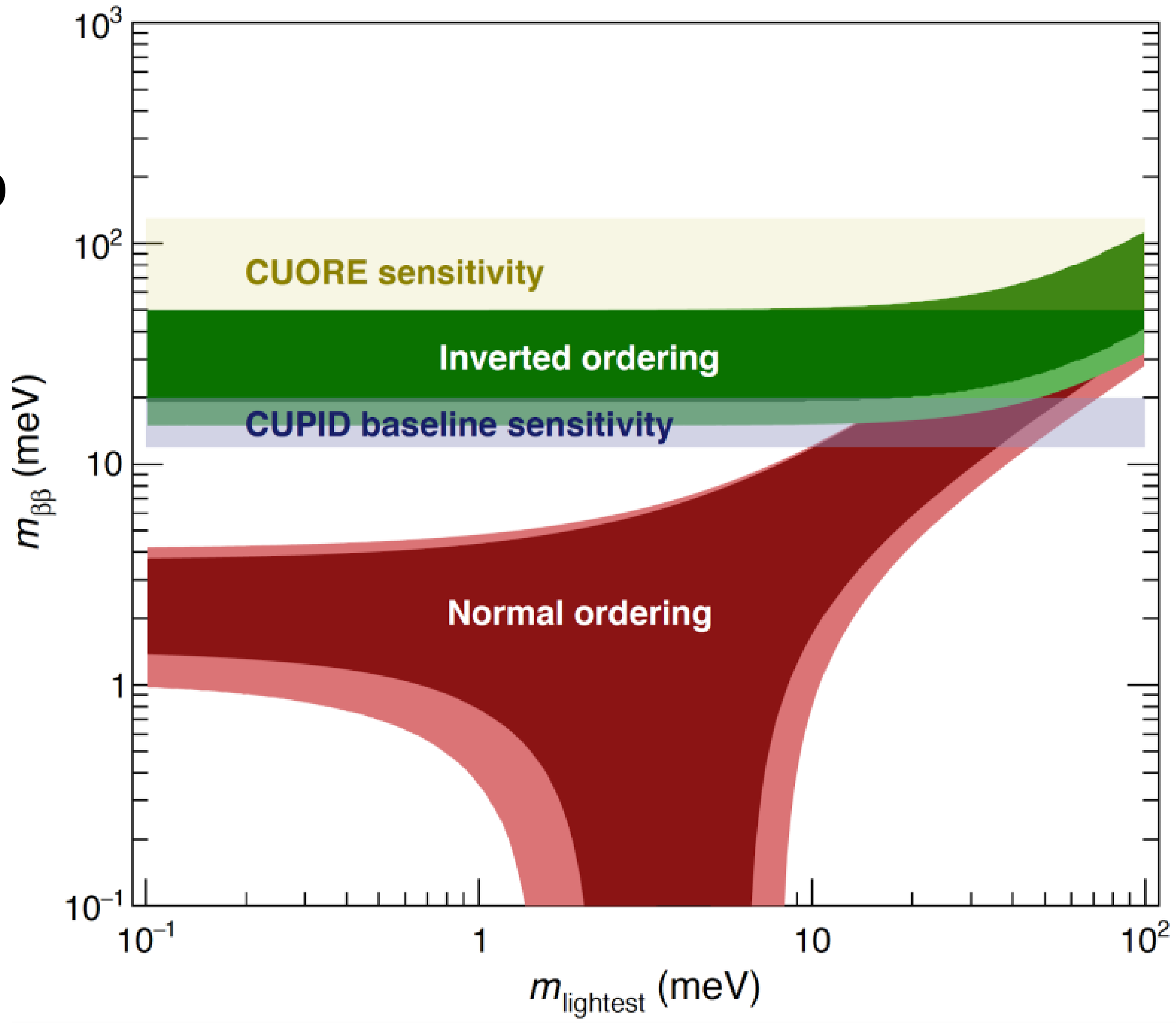
CUORE UPGRADE WITH PARTICLE IDENTIFICATION

- Will operate in the same cryostat that currently houses CUORE
- Goal: Fully probe the "Inverted Hierarchy" region. Improve sensitivity to $m_{\beta\beta}$ by factor of ~5 relative to CUORE

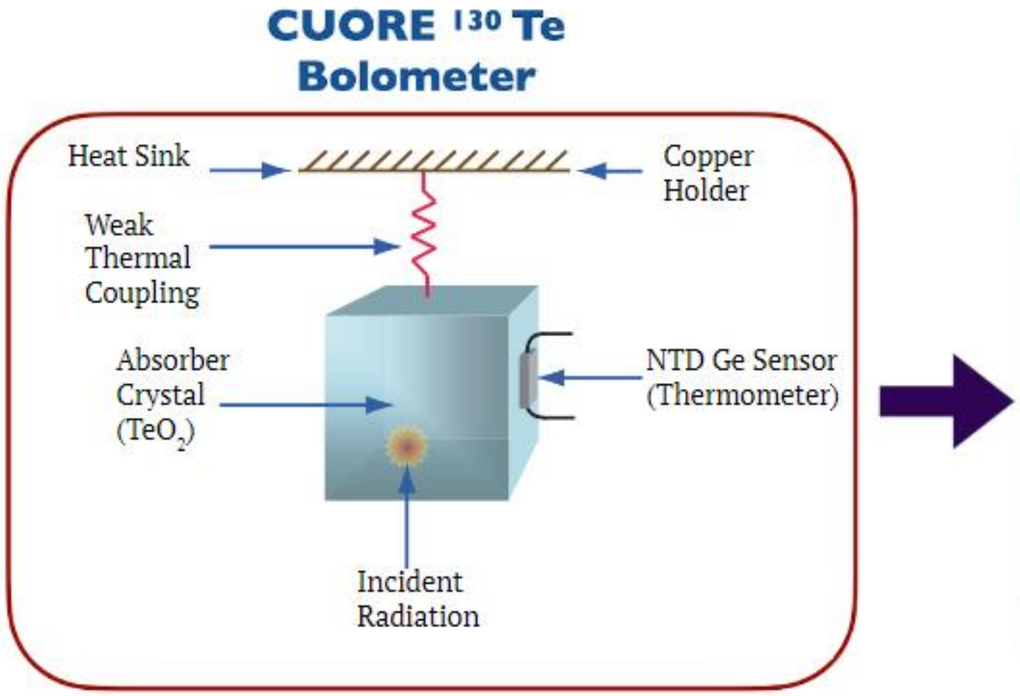
Improved Sensitivity from Background Reduction

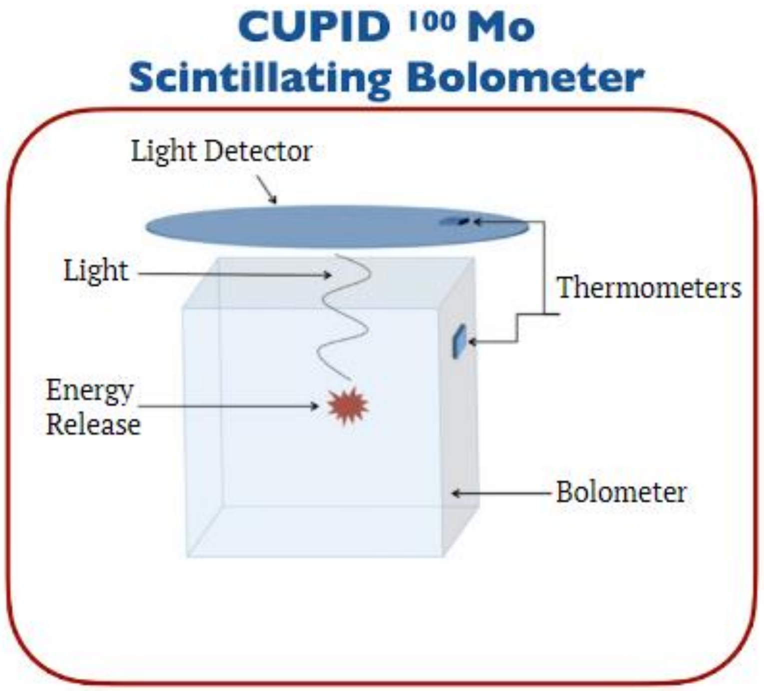
Particle identification

- Muon veto
- Increased Q value for reduced γ/β backgrounds



CUPID Technology





- $Q_{\beta\beta}$ = 2527 keV < 2615 keV peak
- Measure only heat
- No particle ID

- $Q_{\beta\beta}$= 3034 keV: Most β/γ backgrounds reduced
- Measure both heat + light
- Particle ID to actively discriminate **α** particles