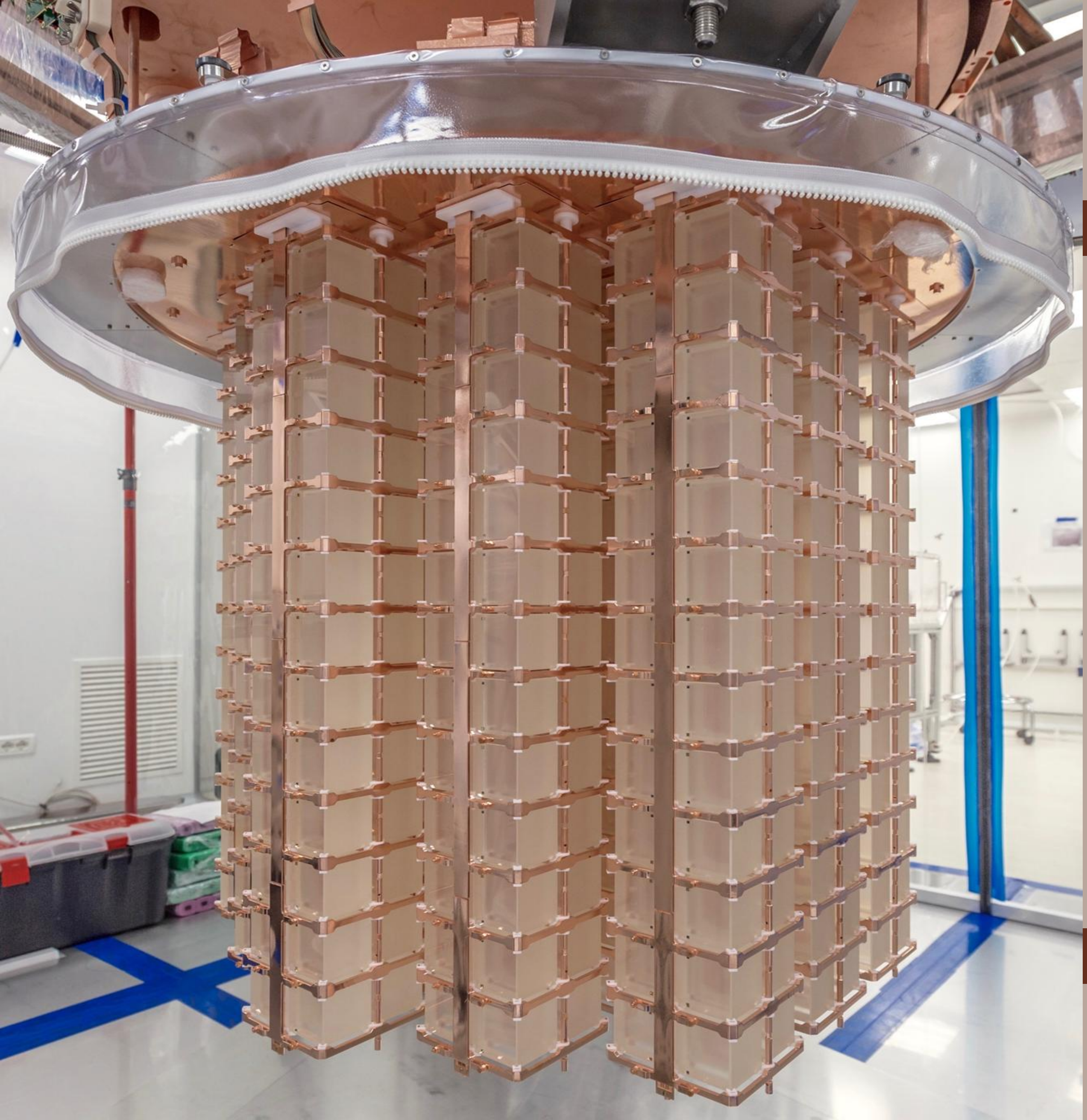


Latest Results From The CUORE Experiment

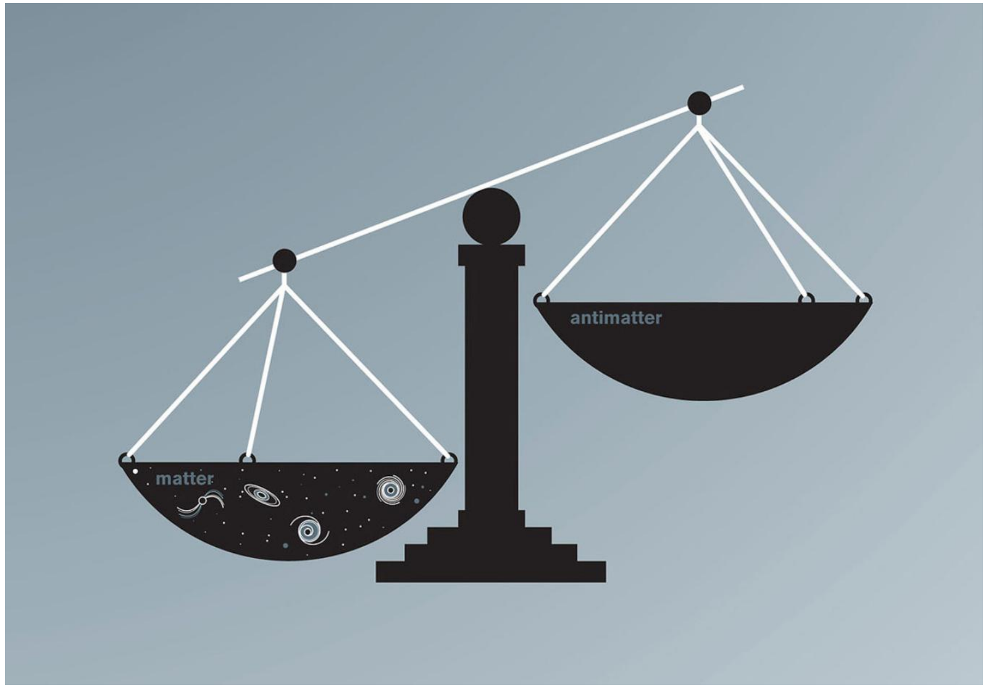
Vivek Sharma

University of Pittsburgh

PHENO 2026

Lepton Number Violation

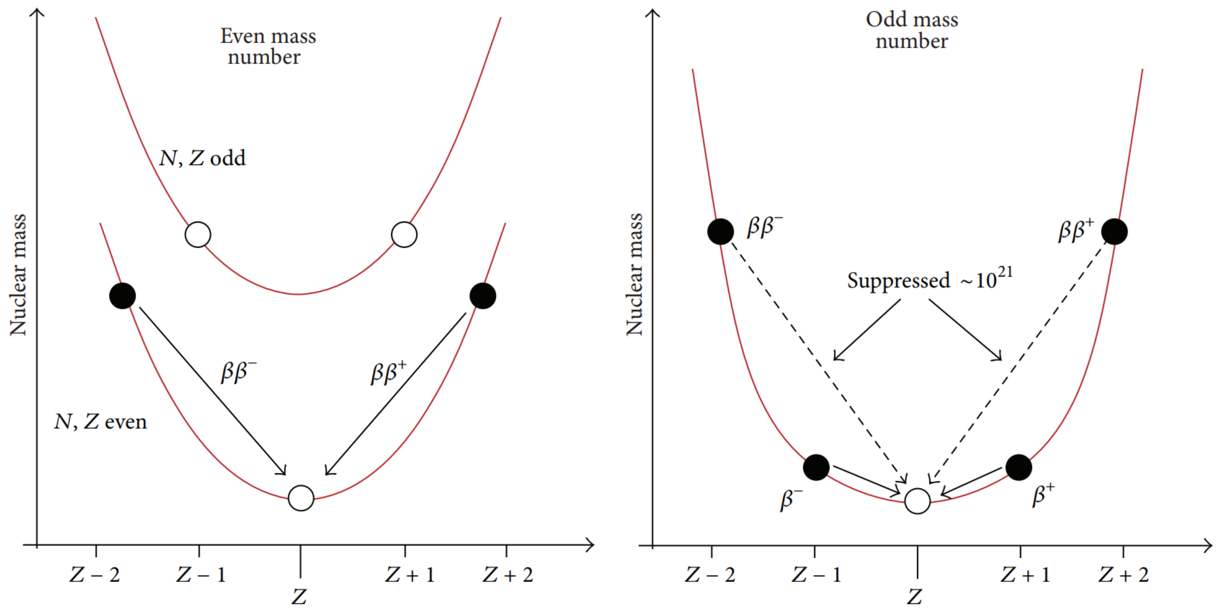
- **Lepton number** — the count of leptons minus antileptons — is conserved in all Standard Model interactions… *or is it?*
- **Leptogenesis** — in the early universe, heavy Majorana right-handed neutrinos decaying out of equilibrium can generate a lepton asymmetry
  - Can lead to baryon asymmetry through electroweak sphaleron processes
- $0\nu\beta\beta$ decay is a hypothetical process that **violates lepton number by 2 units**, indicating new physics beyond the Standard Model



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 forbidden or suppressed

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



Stefano Dell'Oro et al. "Neutrinoless Double Beta Decay: 2015 Review"

NEUTRINOLESS DOUBLE BETA DECAY

- 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**
- Limit on (mββ) can help rule out **Inverted Hierarchy** (model dependent)

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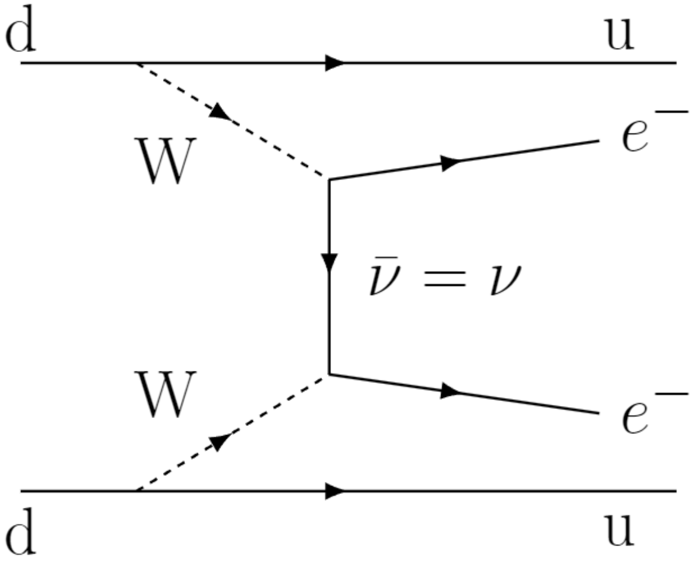

Light neutrino exchange model

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

Phase space factor

Nuclear Matrix Elements

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

Effective Majorana mass

Majorana phases

PMNS matrix

Individual neutrino masses

NEUTRINOLESS DOUBLE BETA DECAY

- Can occur if neutrinos are Majorana particles
- **Lepton number violating process**
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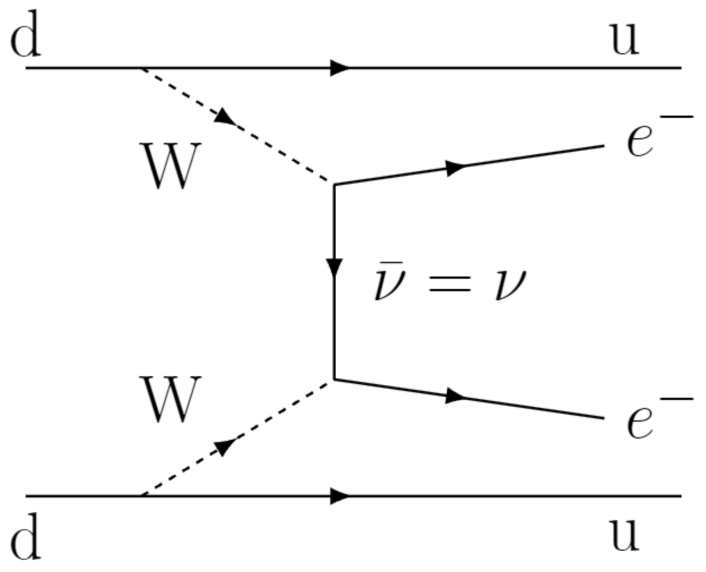

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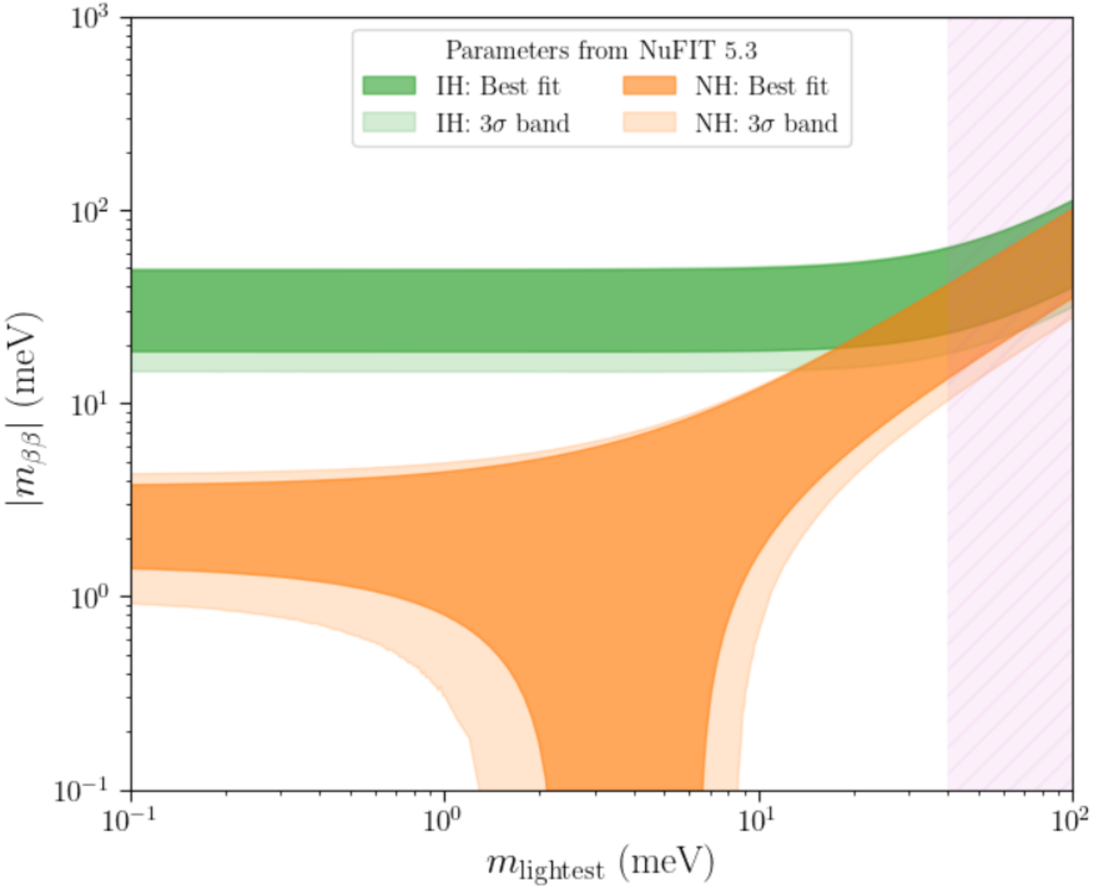
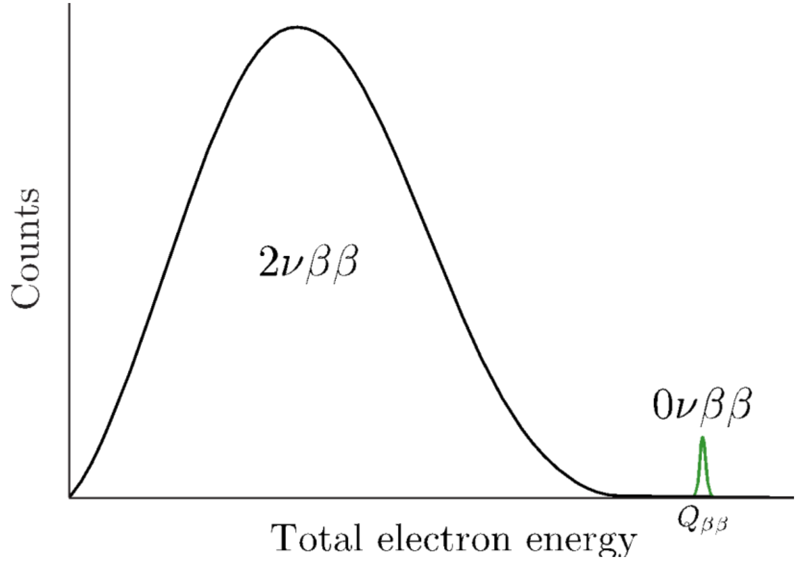


DETECTION CHALLENGES

- $0\nu\beta\beta$ signal is the summed electron energy at Q-value
  - **Exceptional resolution** essential to differentiate between the $0\nu\beta\beta$ and $2\nu\beta\beta$ spectra
  - **High Q-value** for practically observable half-life and mitigate gamma-ray backgrounds
- **Low background** required for a detectable signal, going underground is necessary to mitigate 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



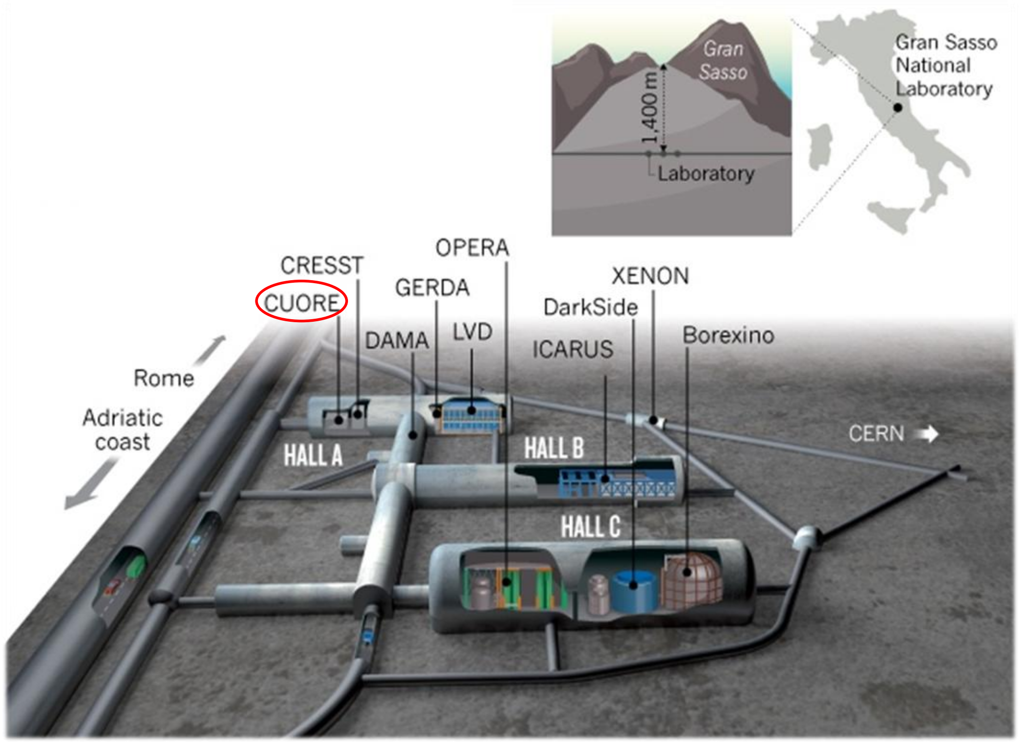
$$T^{0\nu}_{1/2} \propto Q^{-5}$$

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

1-sigma sensitivity; Isotopic abundance (a); Efficiency (ϵ); Detector mass (m); Livetime (t); Bkg rate/energy/mass (b); Energy Resolution (ΔE)

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)

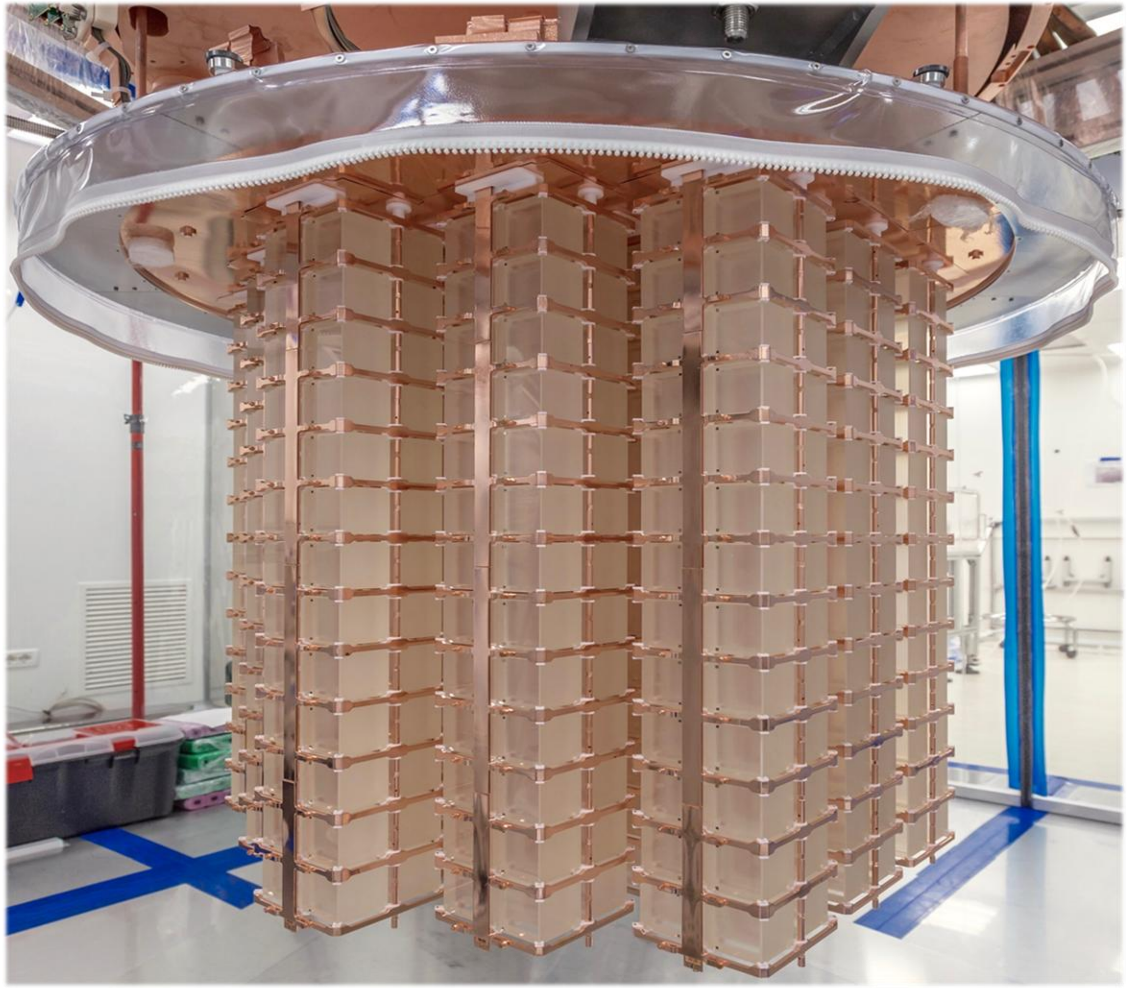


Images courtesy of LNGS: https://www.lngs.infn.it/en

DETECTOR INFRASTRUCTURE

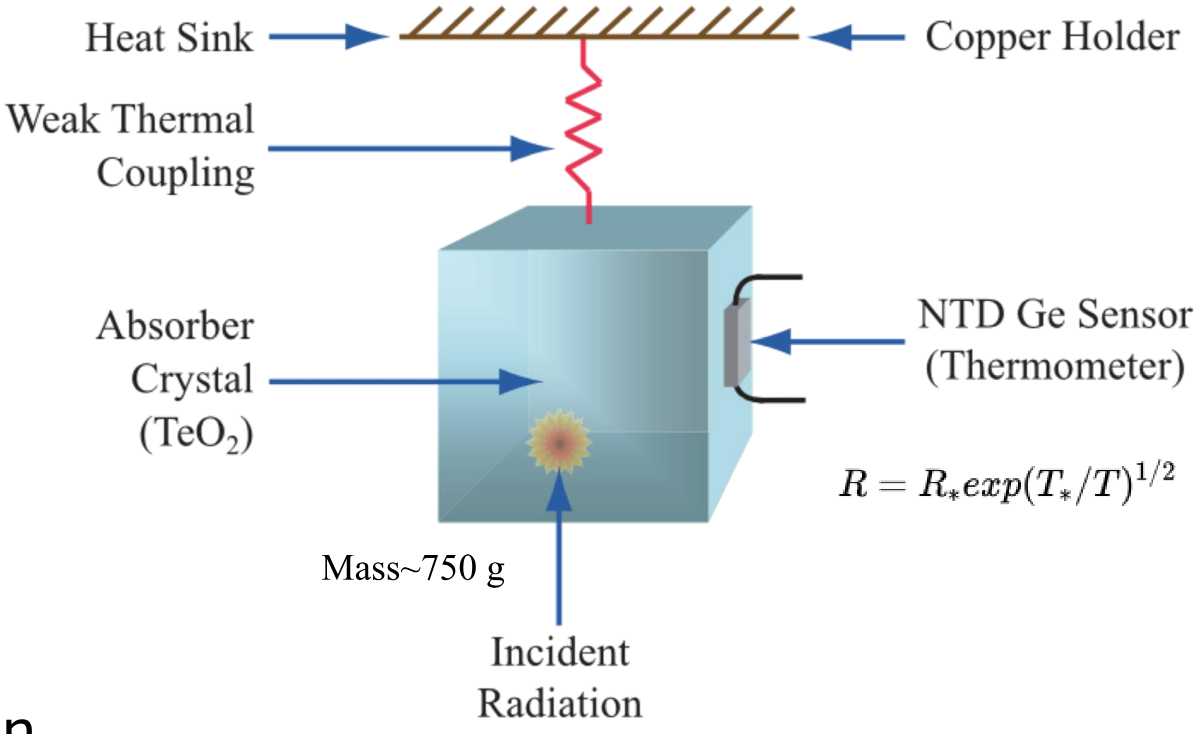
CUORE

- 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
- Tightly spaced crystals allow for coincidences to be exploited for background reduction



DETECTION PRINCIPLE - CUORE

- 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 amplitude and detector resolution depend strongly on temperature (Debye's Law)
  - $C \propto T^3$
  - Detector operated at **~15 mK**
- In CUORE, we observe an average resolution of **~7.5 keV FWHM at 2615 keV**†



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

†CUORE collaboration https://doi.org/10.48550/arXiv.2404.04453

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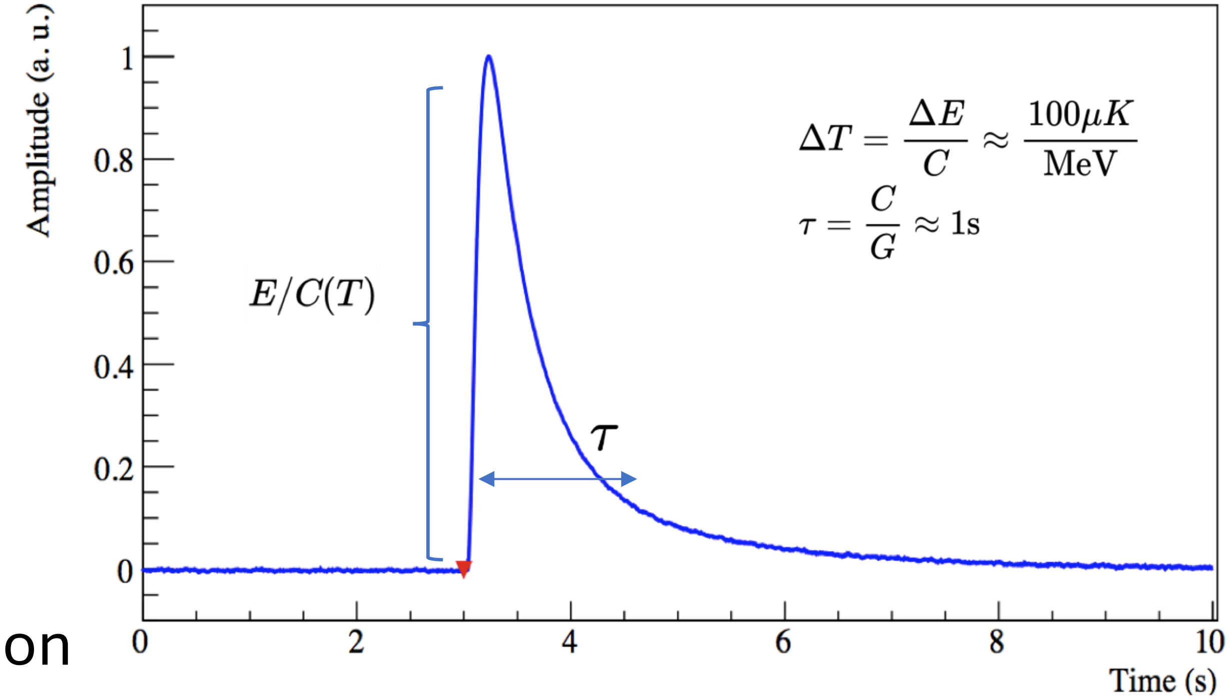
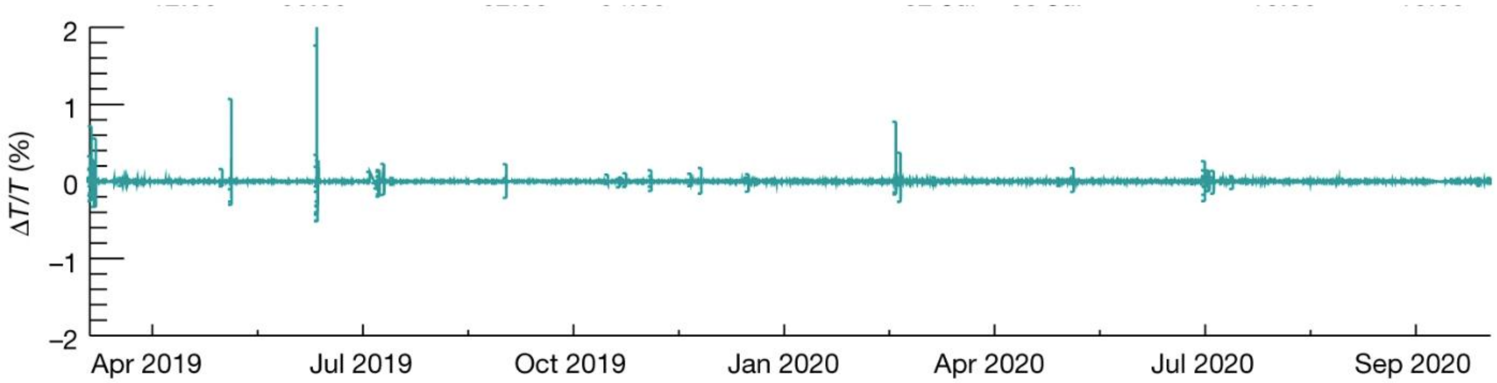


Example of a signal pulse

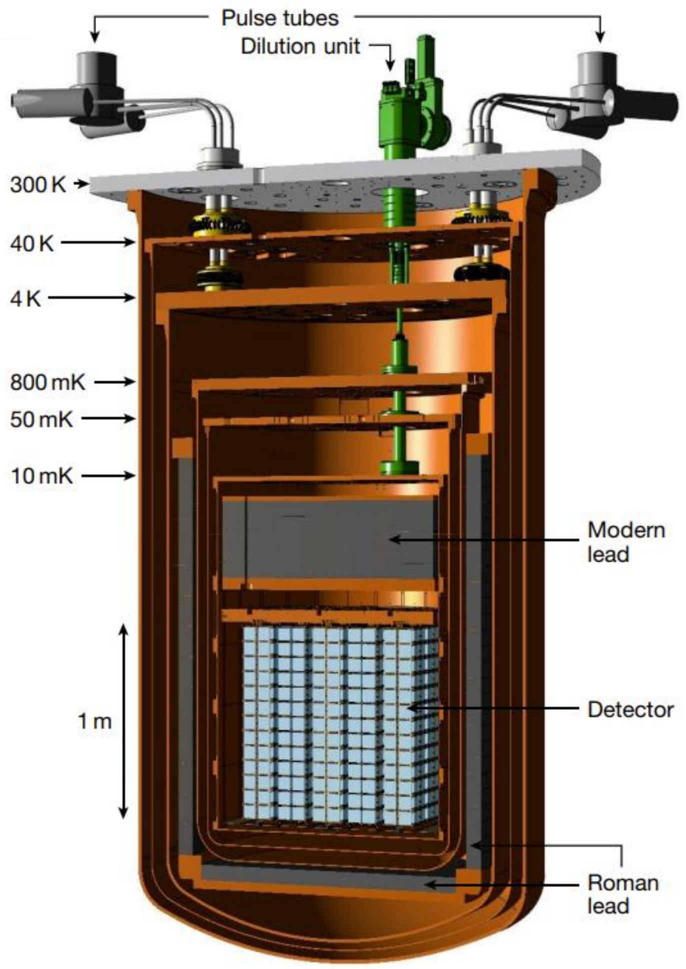
†CUORE collaboration
https://doi.org/10.48550/arXiv.2404.04453

CRYOGENICS

- Operating temperature of ~**15 mK** is achieved via multistage cryogen-free dilution refrigerator
  - Multistage design shields from thermal radiation
  - Experimental volume of ~1 m^3 and payload of ~1.5 tonne
  - Demonstrated stability over years of data taking
- Multiple layers of shielding for background mitigation



CUORE relative temperature fluctuation over time*



The CUORE cryostat*

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

CRYOGENICS

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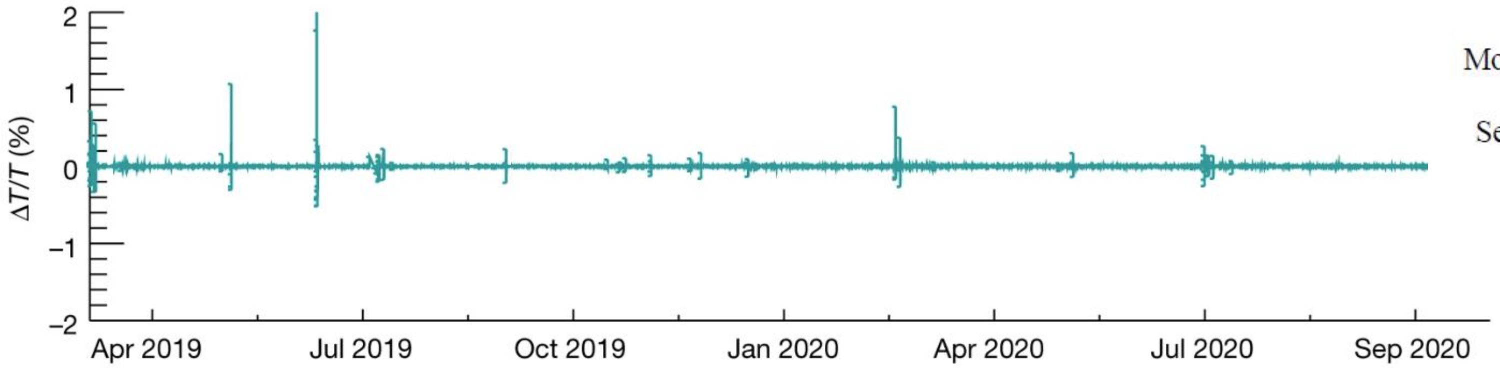

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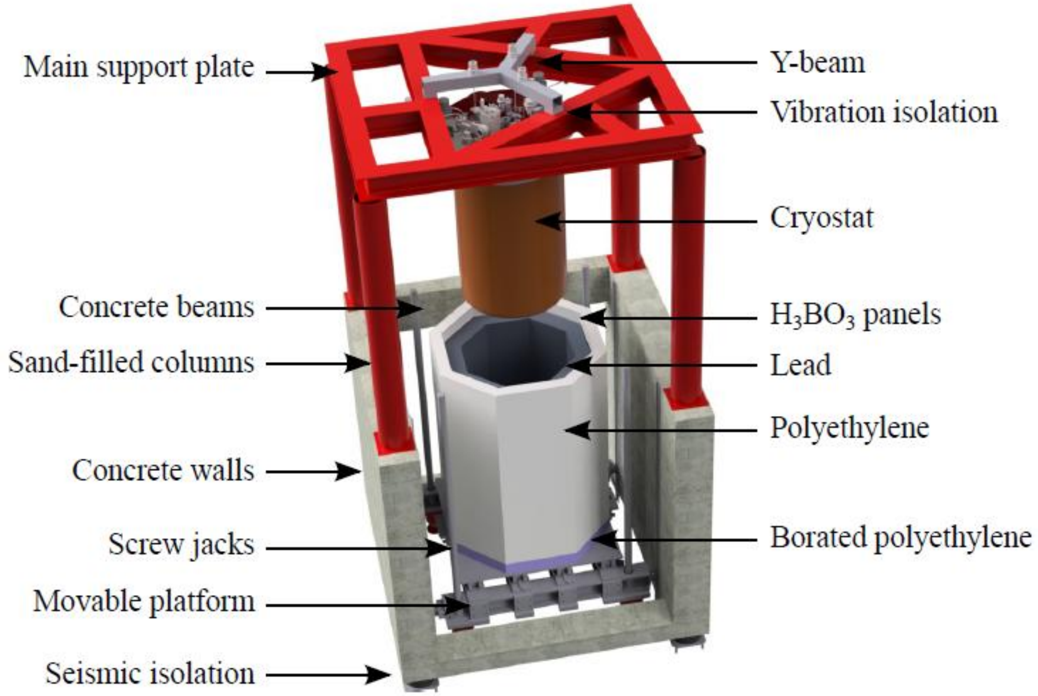
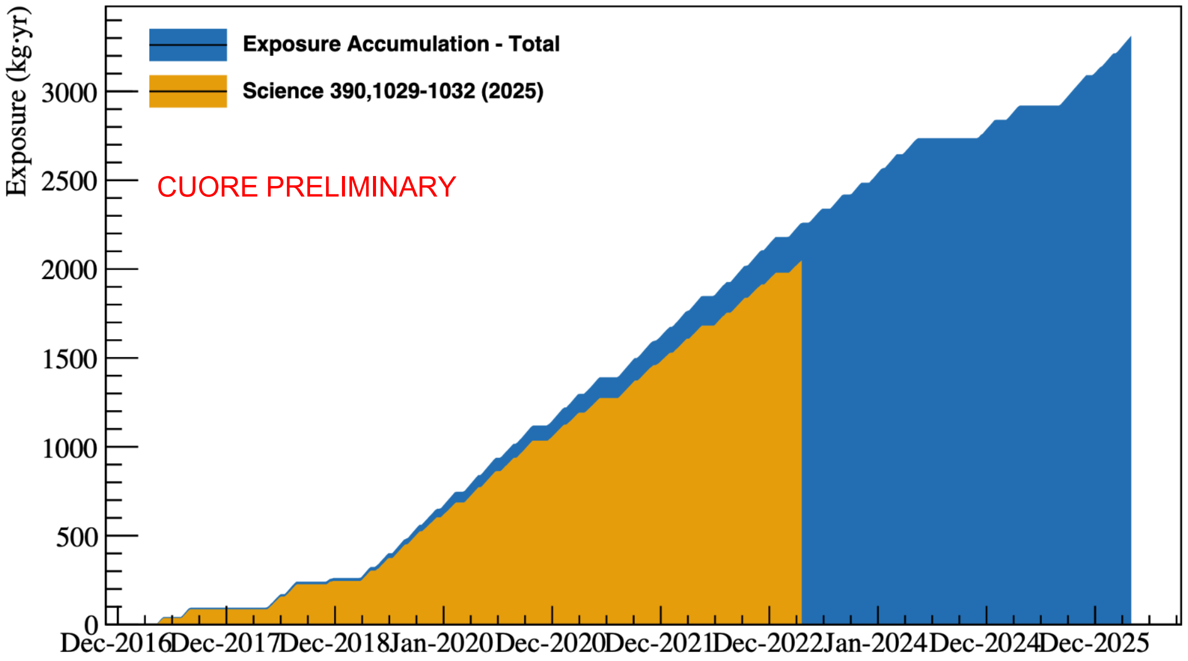


External structure of CUORE

https://doi.org/10.1016/j.cryogenics.2019.06.011

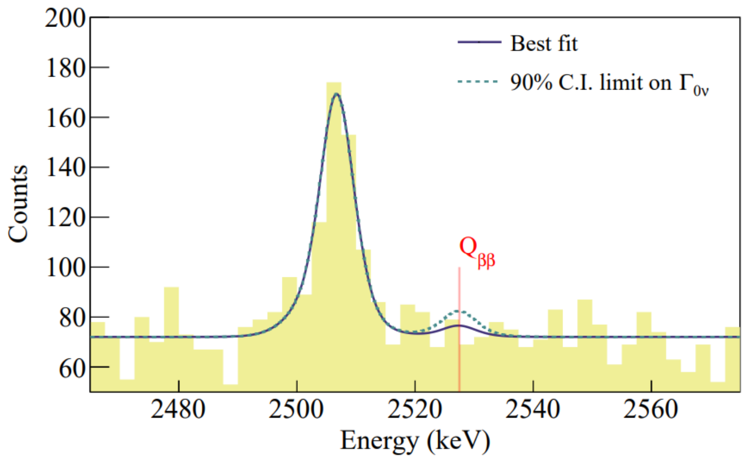
CUORE DATA TAKING

- Data taking began in 2017
  - Software and hardware optimizations since have improved stability of data taking
- Steady data taking since 2019 with >~90% uptime
- Data cycle: 1-2 months of "physics" data between ~4 days of calibration



2 TON YEAR RESULTS

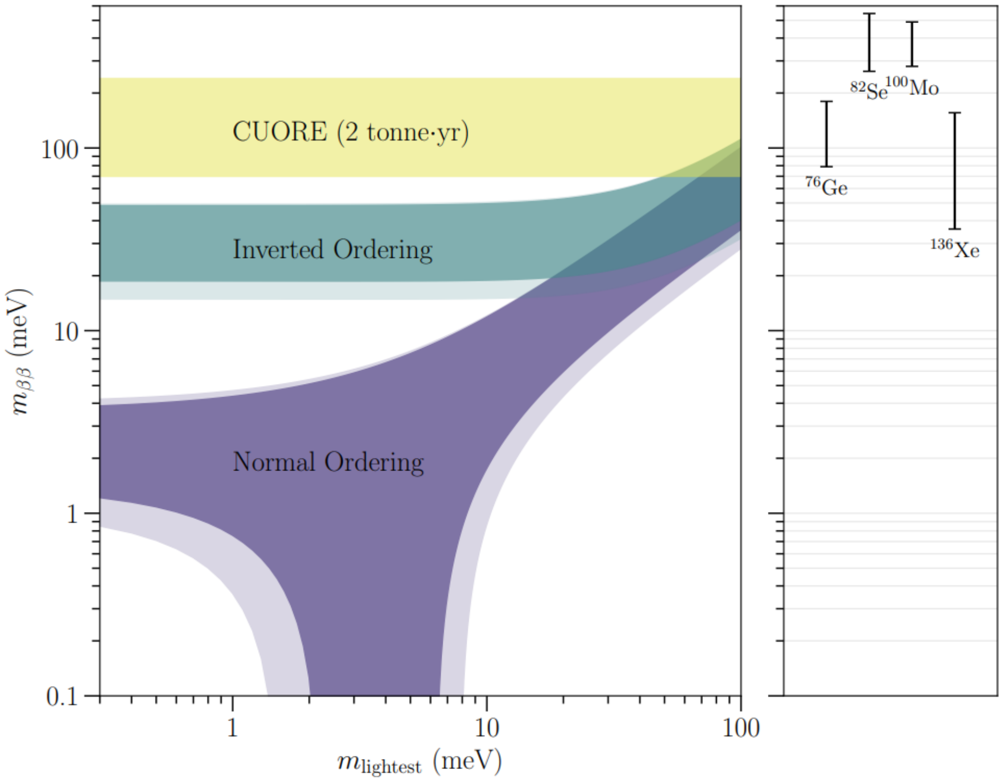
- 2nd ton.yr results:
  - Blinded analysis to prevent bias
  - ROI (2465, 2575) keV salted with ^{208}Tl 2615 keV peak
  - Fit ROI events with: ^{130}Te 0νββ peak, ^{60}Co peak, linear background
  - Finalize model parameters before unblinding
- Analyzed exposure: 2039.0 kg.yr
- Half-life limit: $T_{1/2} > 3.8 \times 10^{25}$ yr (90% C.I.)
- Median Exclusion Sensitivity: 4.4×10^{25} yr (90% C.I.)
- $m_{\beta\beta} < 70 - 250$ meV (90% C.I.)
  - Light Majorana neutrino exchange model



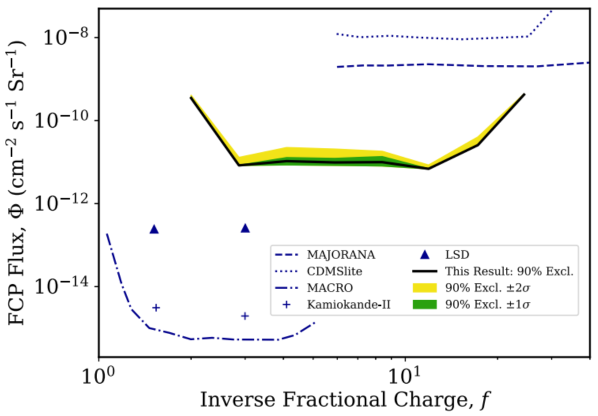
†CUORE collaboration
https://doi.org/10.48550/arXiv.2404.04453

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

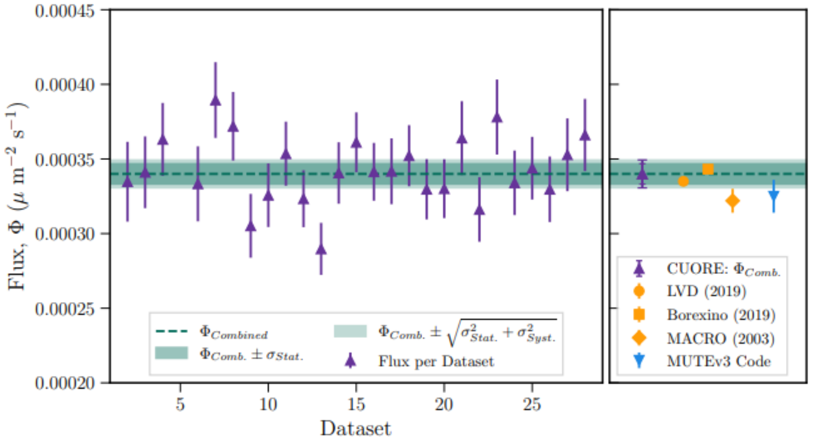


Secondary Physics Studies



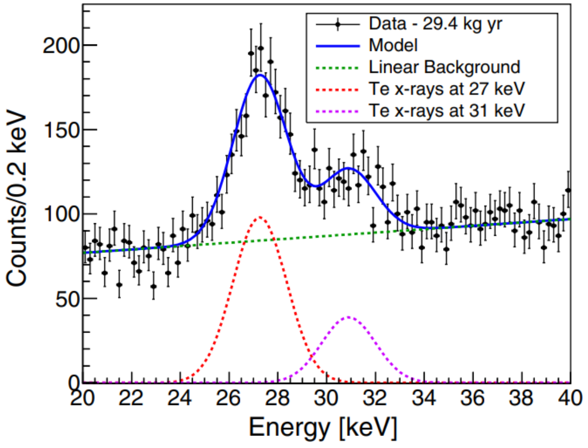
Multi-spectral search for fractionally charged particles

Phys. Rev. Lett. 133, 241801



Muon Event Reconstruction

arxiv:2509.05528

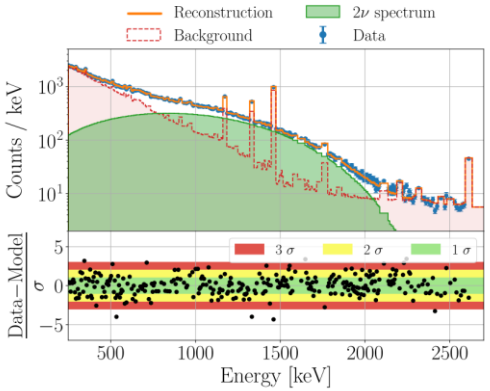


Low energy analyses to optimize sensitivity for solar axions, WIMP searches

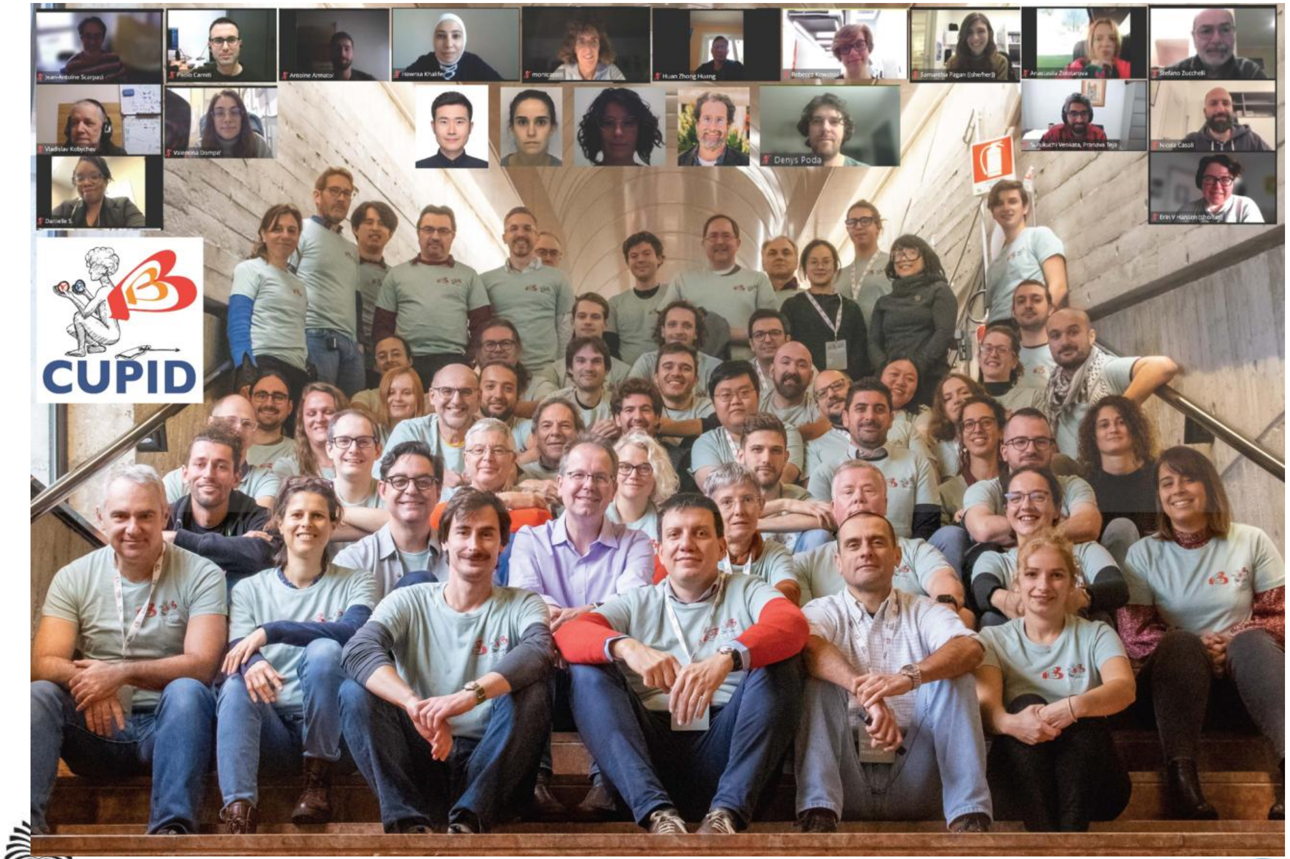
Phys. Rev. D 113, 012012

Other ββ searches

- 130Te SM-allowed 2νββ (**arXiv:2503.24137v1**)
- 130Te decay to 1st excited state (**Eur. Phys. J. C 81, 567**)
- 128Te 0νββ decay to ground state (**Phys. Rev. Lett. 129, 222501**)
- 120Te 0νβ+ EC decay to ground state (**Phys. Rev. C 105, 065504**)

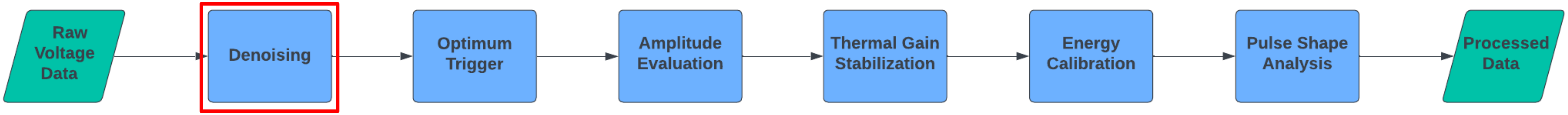


THANK YOU!

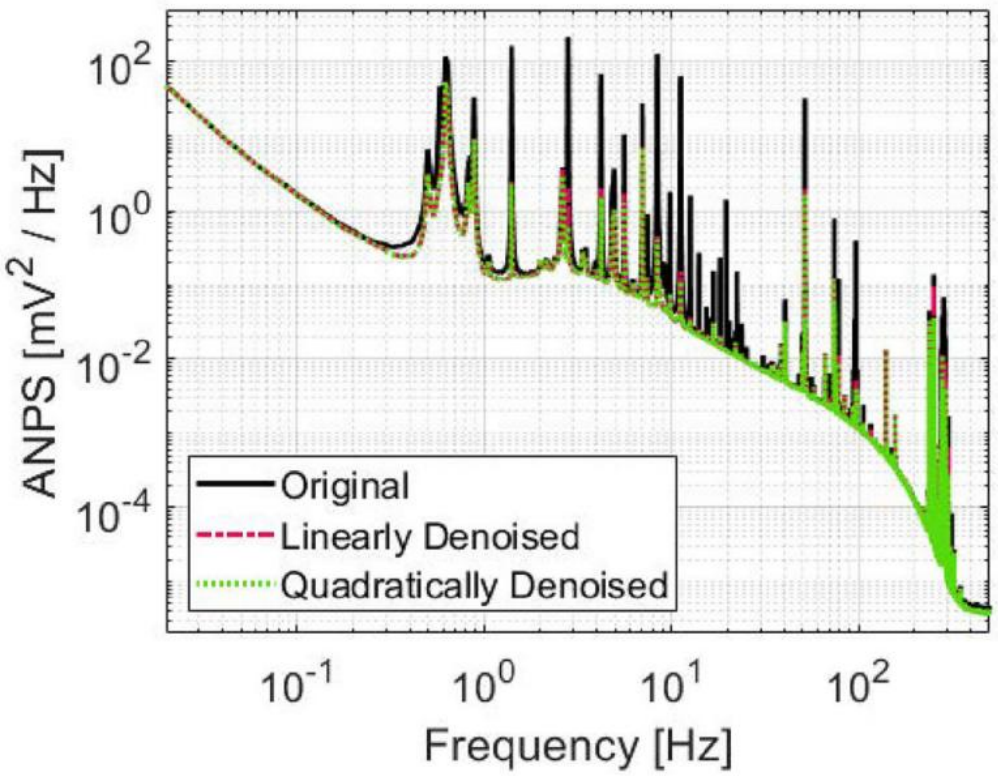


EXTRA SLIDES

DATA PROCESSING

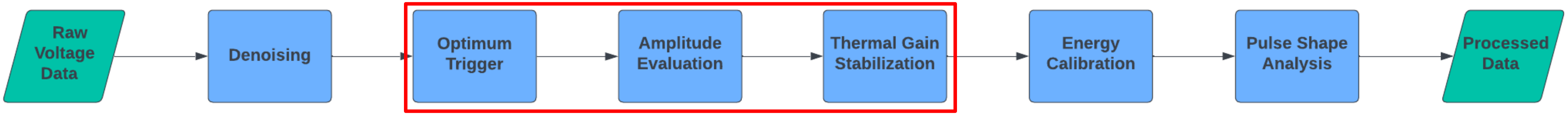


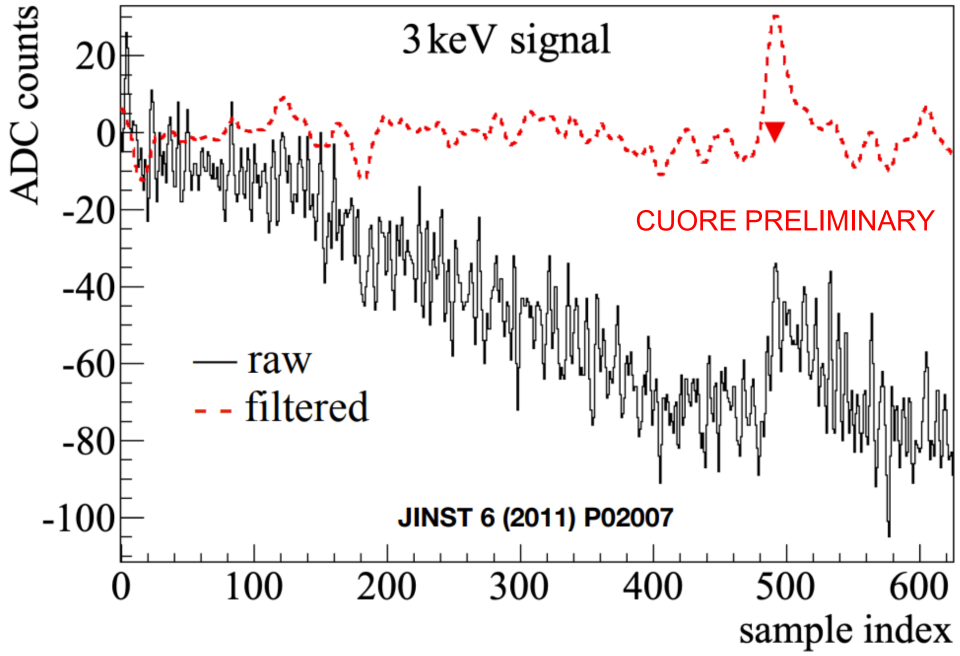
- Predict noise contribution by correlating noise between auxiliary devices and correlating with calorimeter noise
  - Produce less noisy data with improved resolution

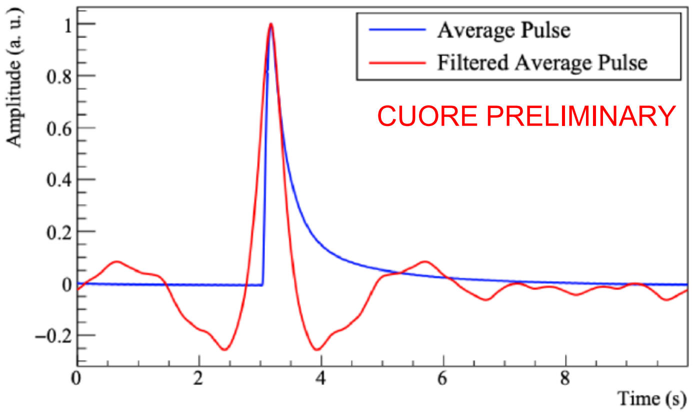


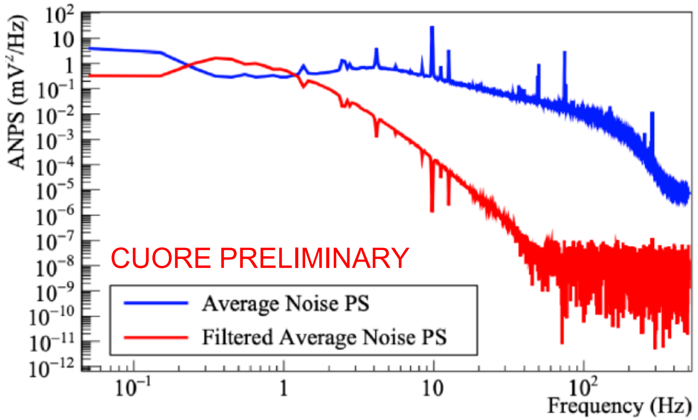
https://doi.org/10.1140/epjc/s10052-024-12595-y

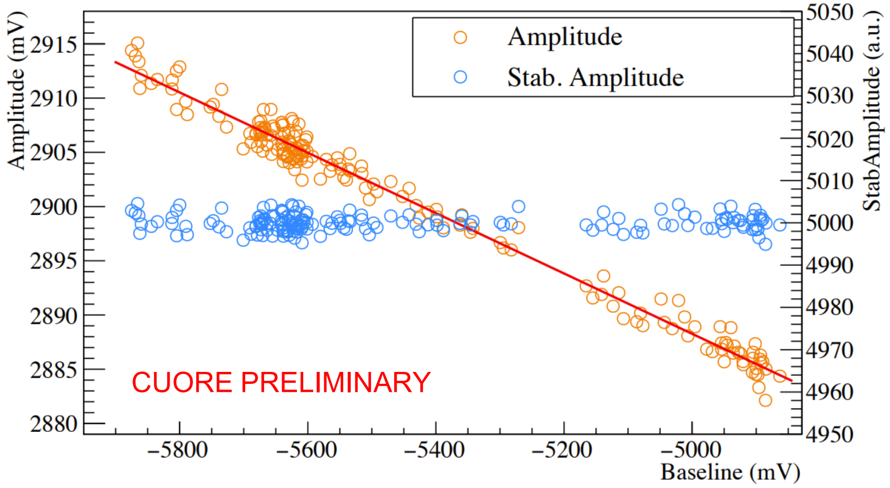
DATA PROCESSING











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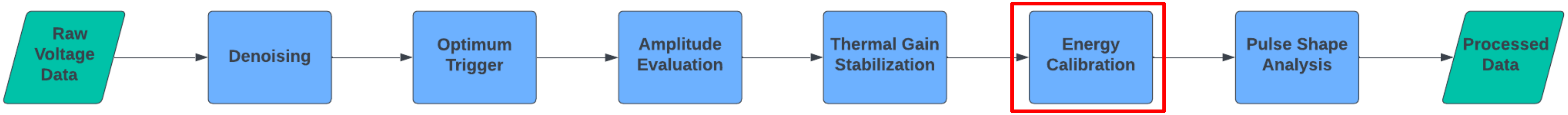

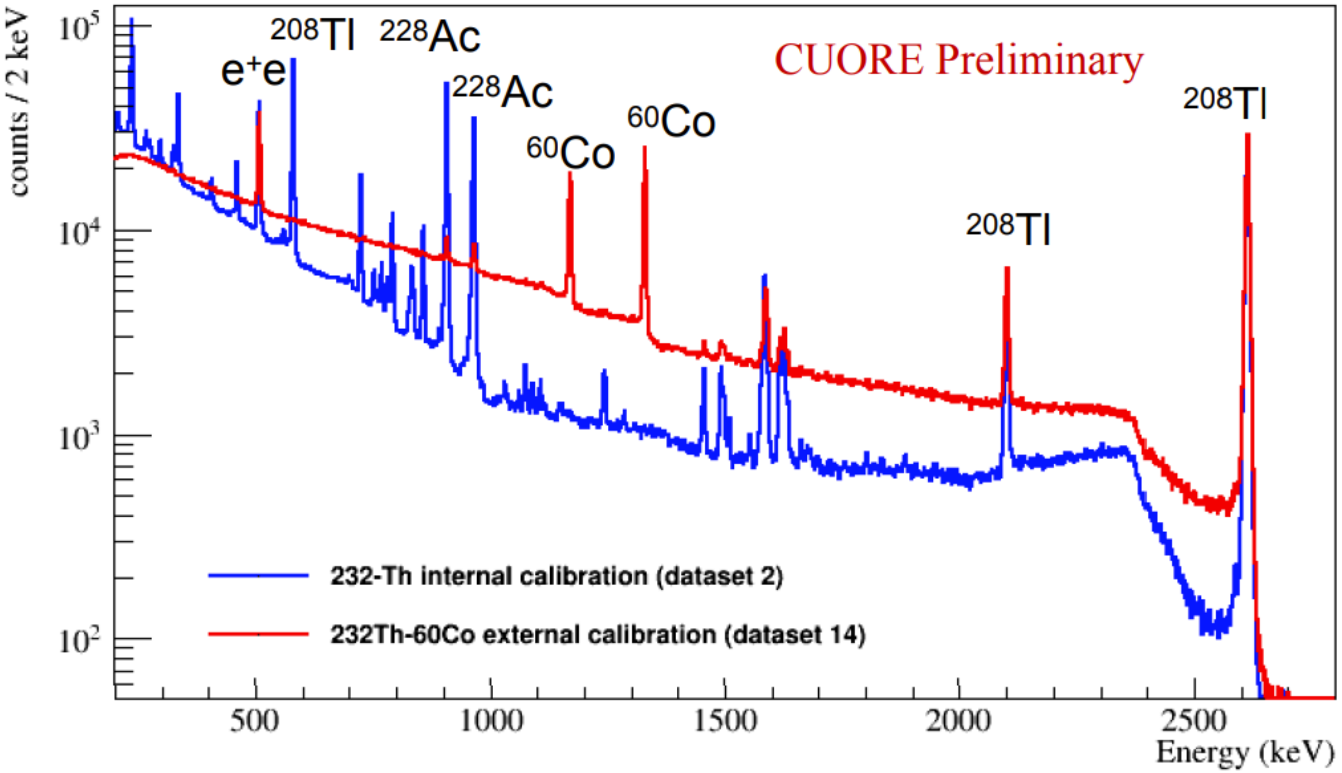

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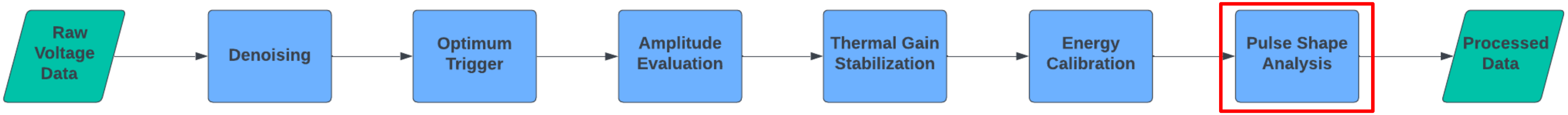
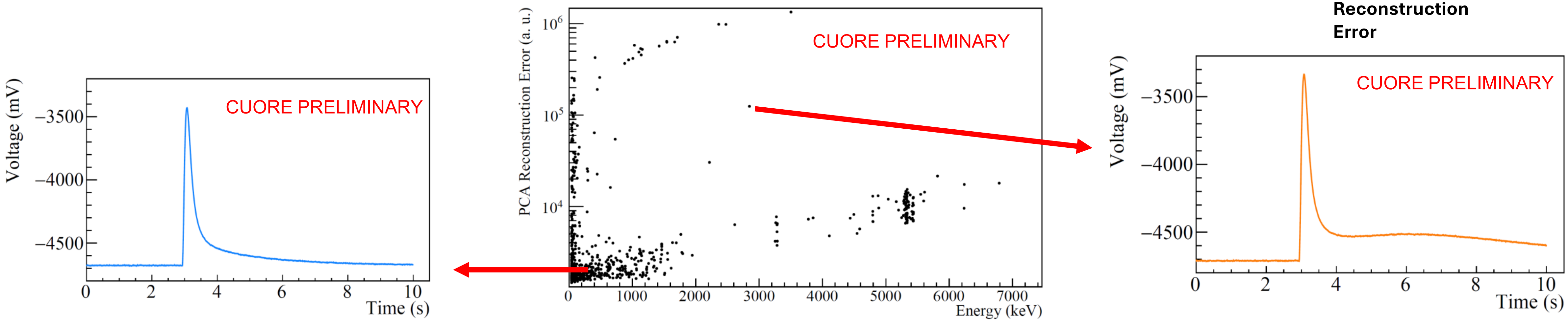


$$RE = \sqrt{\sum_{d=1}^{D} [x_d - (\boldsymbol{x} \cdot \boldsymbol{u}_{AP}) u_d]^2}$$

Reconstruction Error



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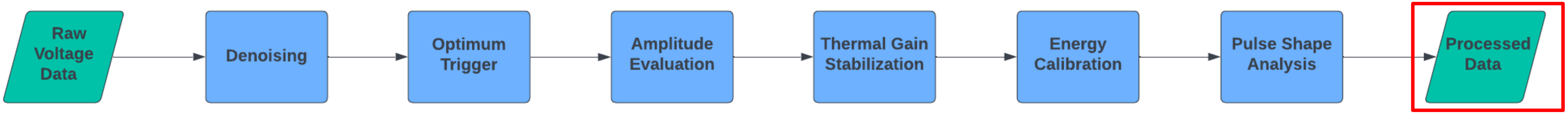

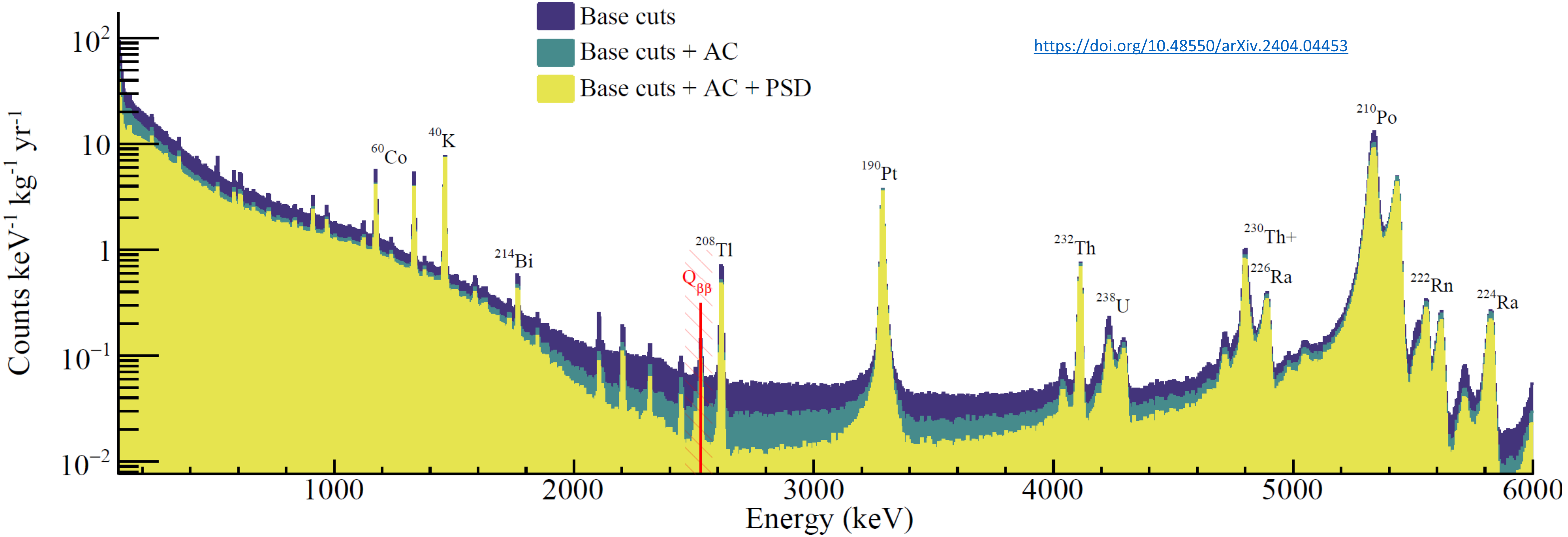

https://doi.org/10.48550/arXiv.2404.04453

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

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

PMNS matrix

Individual neutrino masses

https://github.com/toej93/LobsterPlot

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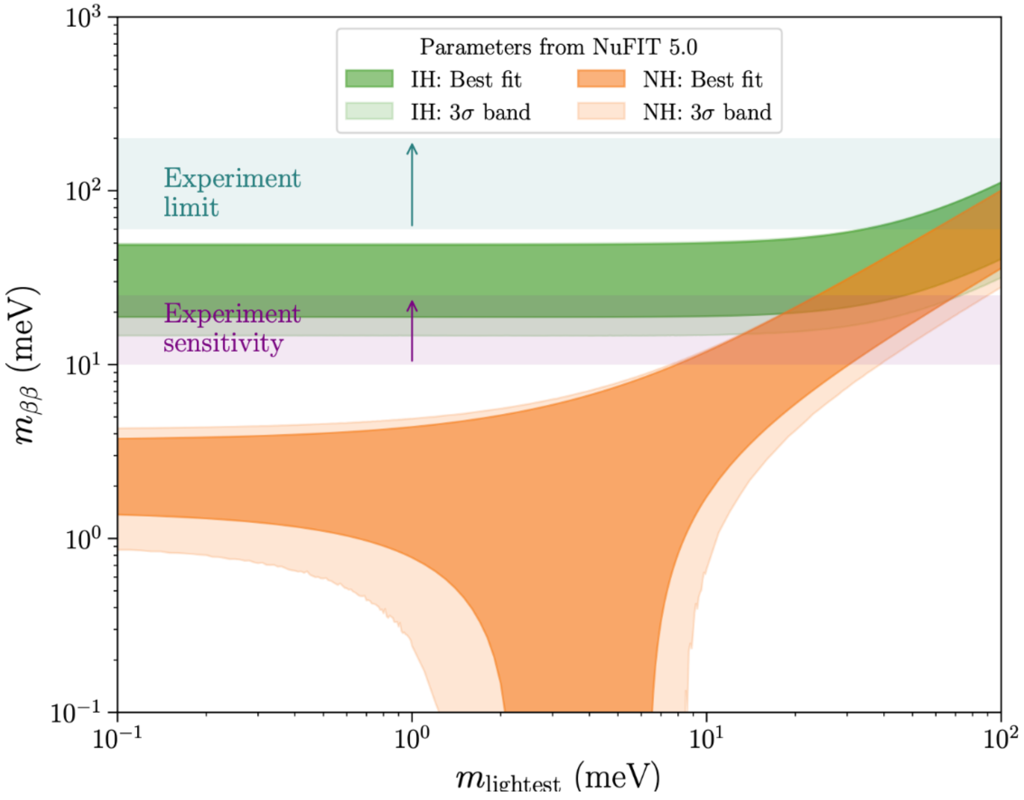


https://github.com/toej93/LobsterPlot

CUORE: SUMMARY

Detector mass

Isotopic abundance

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

1-sigma sensitivity

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

CUORE: SUMMARY

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/energy/mass

- 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

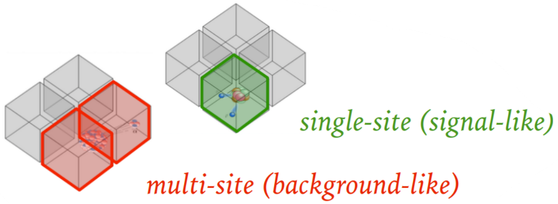
- Crystals operated at ~15 mK
- Denoising techniques
- $Q_{\beta\beta}$ relative energy resolution: 0.3%

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

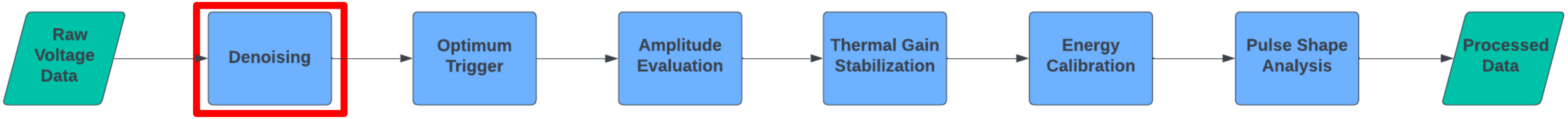


88% of 0νββ events occur in a single crystal

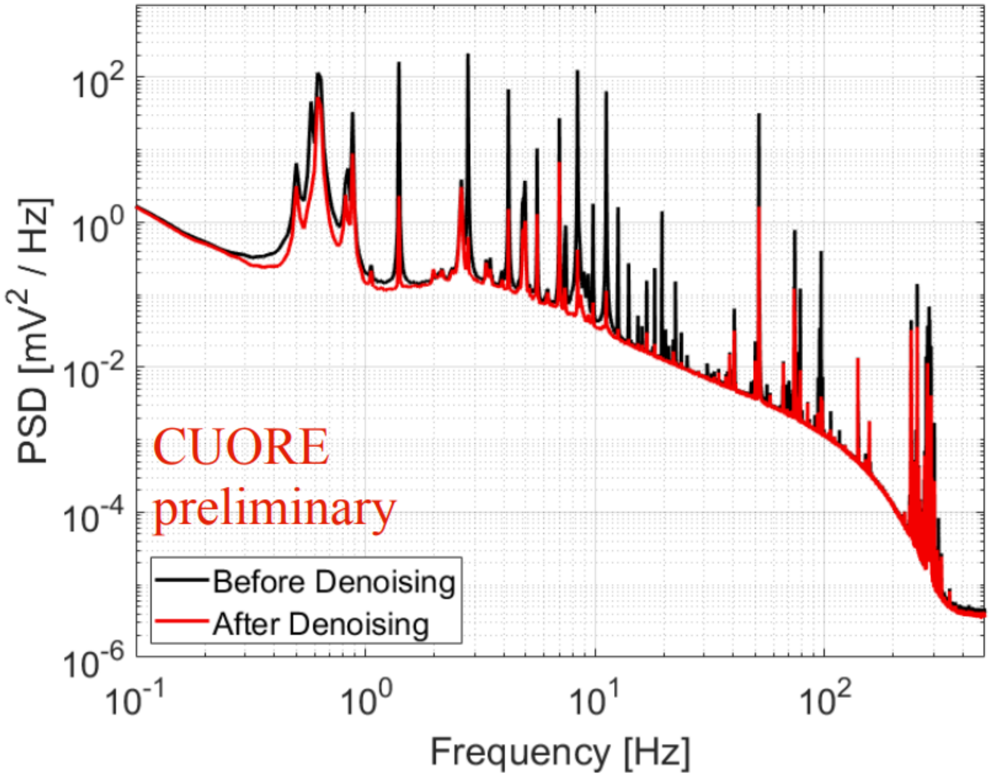
- Source = Detector
- ~88% containment efficiency
- ~93% data quality cut efficiency

https://doi.org/10.48550/arXiv.2404.04453

DATA PROCESSING

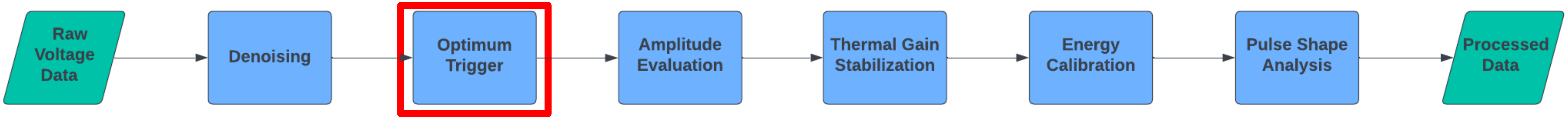


- Denoising
  - Multivariate noise cancelling algorithm to improve detector performance*
  - Uses data from auxiliary devices: Microphones, accelerometers, seismometers

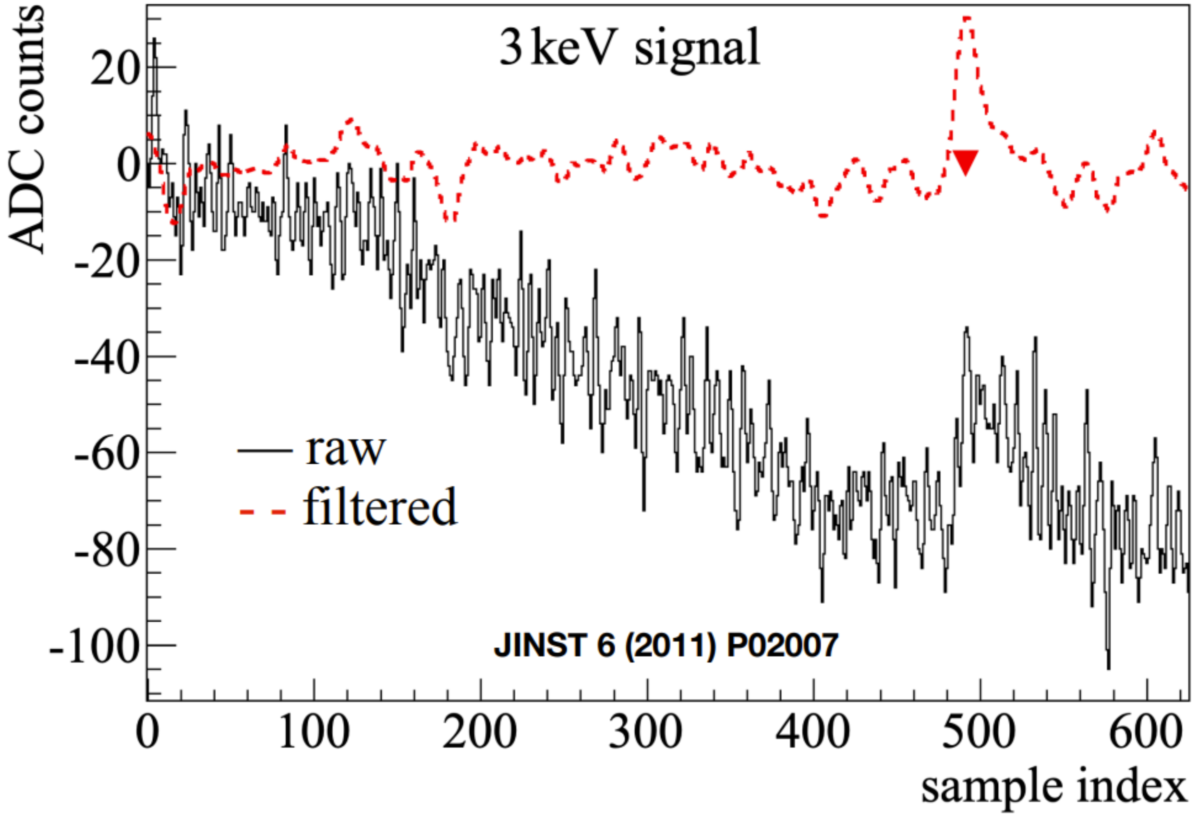


*https://arxiv.org/pdf/2311.01131.pdf

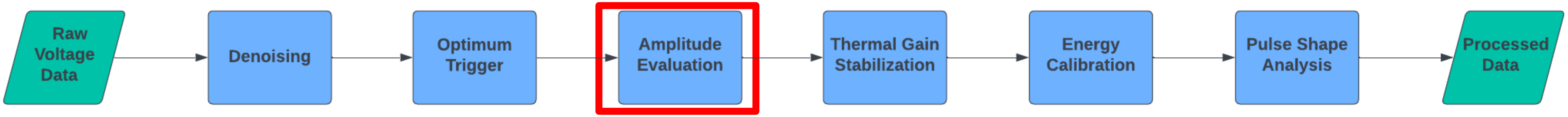
DATA PROCESSING - TRIGGER



- Optimum Trigger
  - Triggers on pulses after filtering waveform
  - Matched filter to maximize signal to noise
  - Matched filter to adjust for baseline drifts and noise
  - Lowers energy detection thresholds



DATA PROCESSING

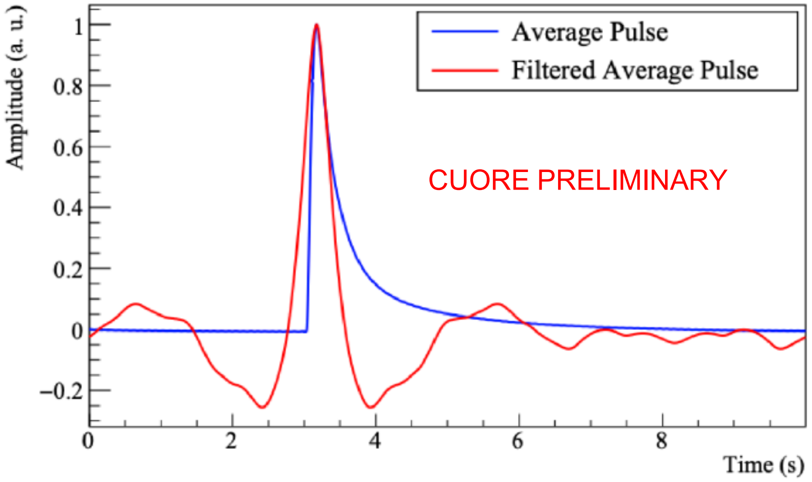


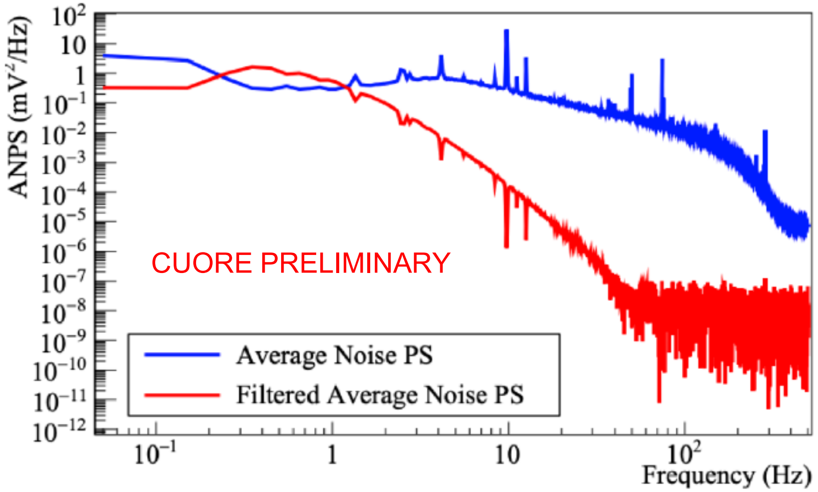
- Amplitude Evaluation
  - Using optimum waveform filter to estimate amplitude of pulses
  - Transfer function of each channel evaluated using average pulse and average noise power spectrum

$$H(\omega_k) \propto e^{i\omega_k t_{max}} \frac{s^*(\omega_k)}{N(\omega_k)} h(\omega_k)$$

Average Pulse

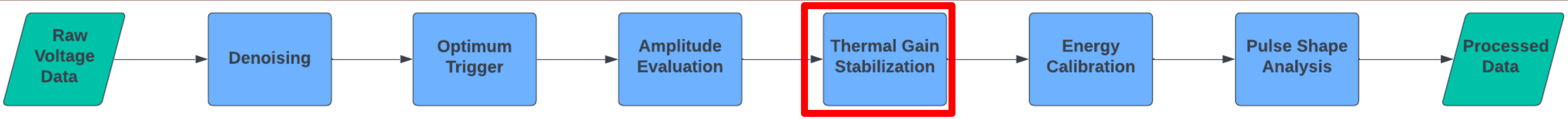
Average Noise Power Spectrum



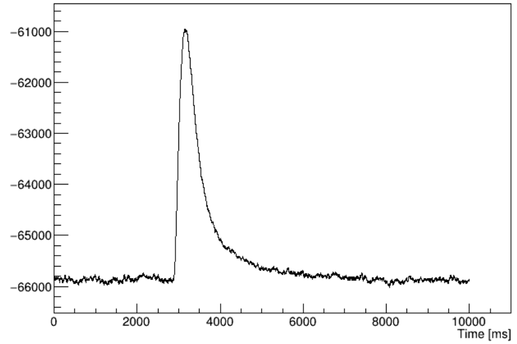


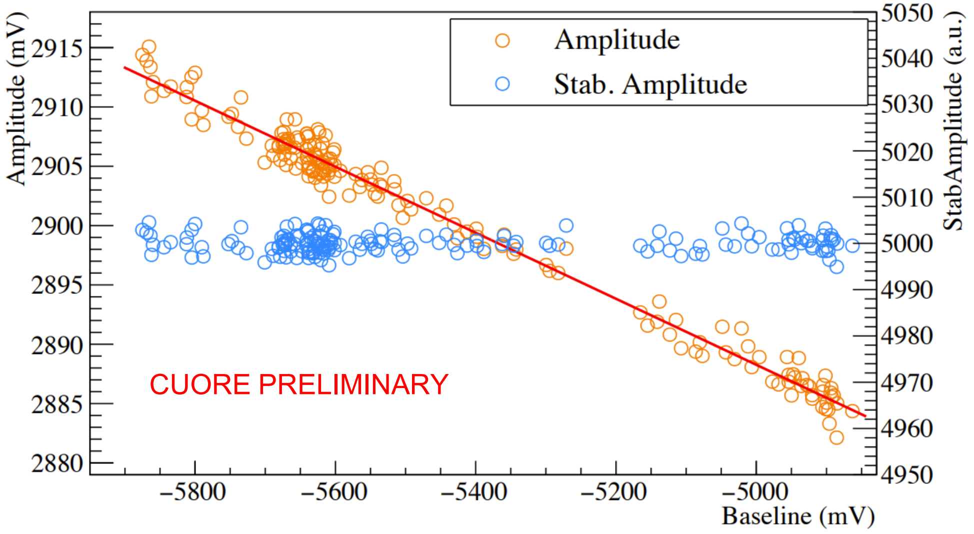
DATA PROCESSING

CUORE

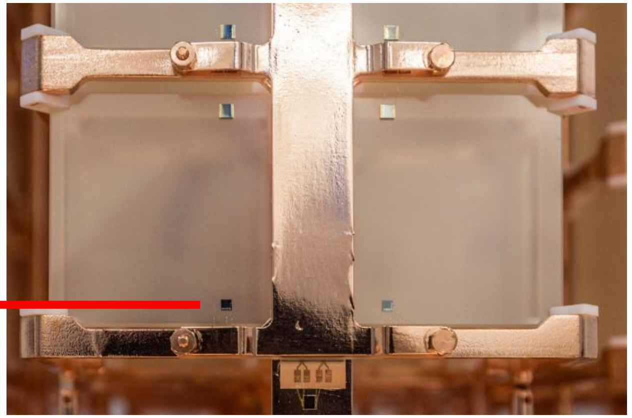


- Gain Stabilization
  - Minimizing gain dependence on temperature using periodically injected pulses



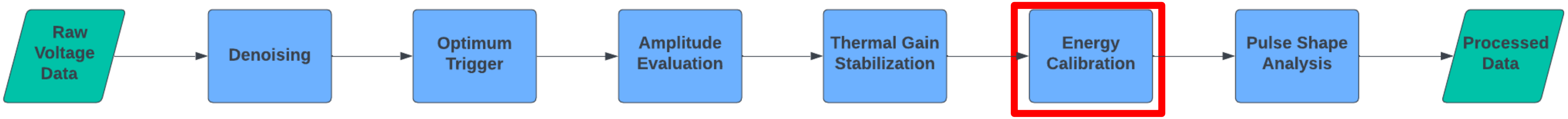


$$\text{Stabilized Amplitude} = 5000 \times \frac{\text{Amplitude}}{\text{StabPulser Amplitude}}$$

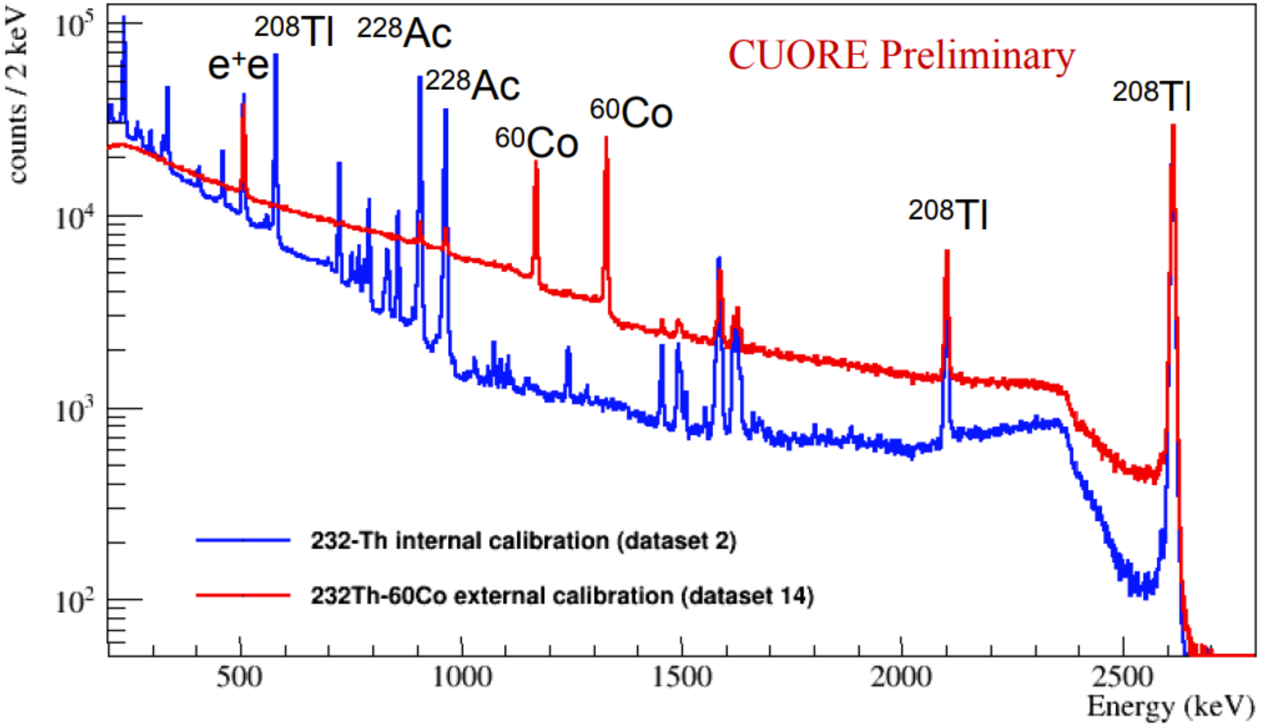


Si Heater

DATA PROCESSING

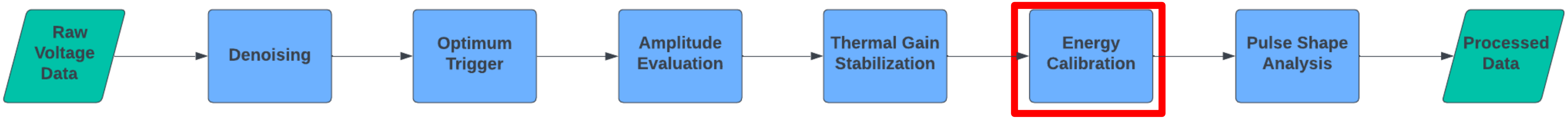


- Calibration
  - First 3 datasets used internal **^{232}Th** source
  - Later datasets calibrated with external **^{232}Th-^{60}Co** source
  - Iterative calibration algorithm
    - Iterative seeding for crystal ball fits
    - Decision between gaussian and crystal ball fits based on various fit quality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



DATA PROCESSING

CUORE



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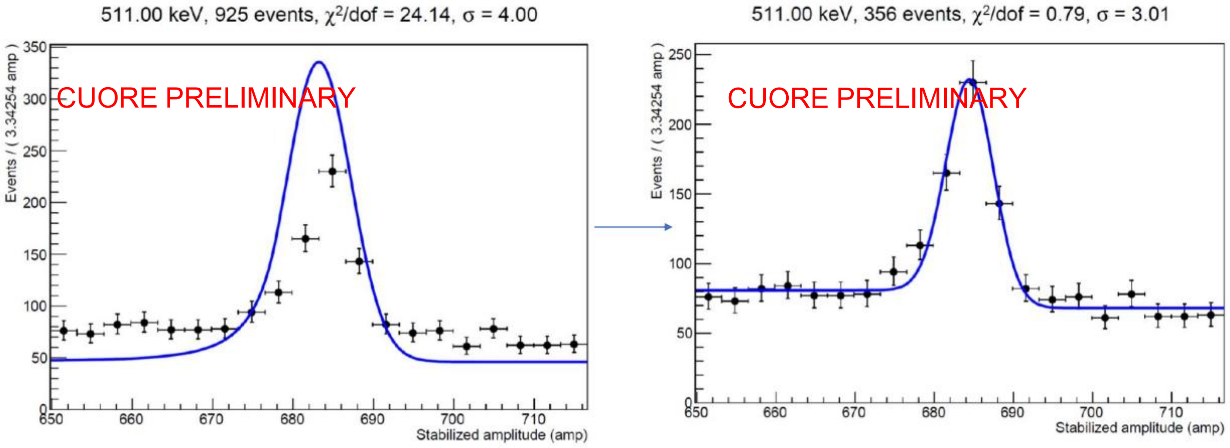
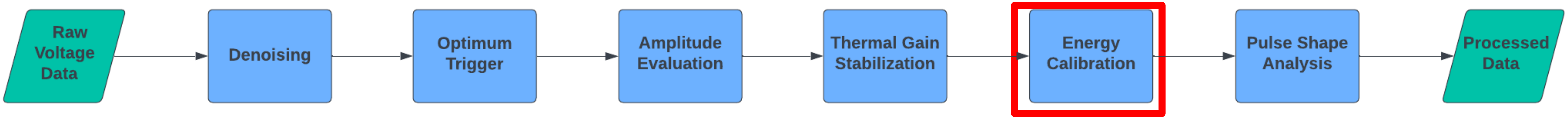


A calibration peak fit with default seeds (left), and fit with iterative algorithm (right)

DATA PROCESSING



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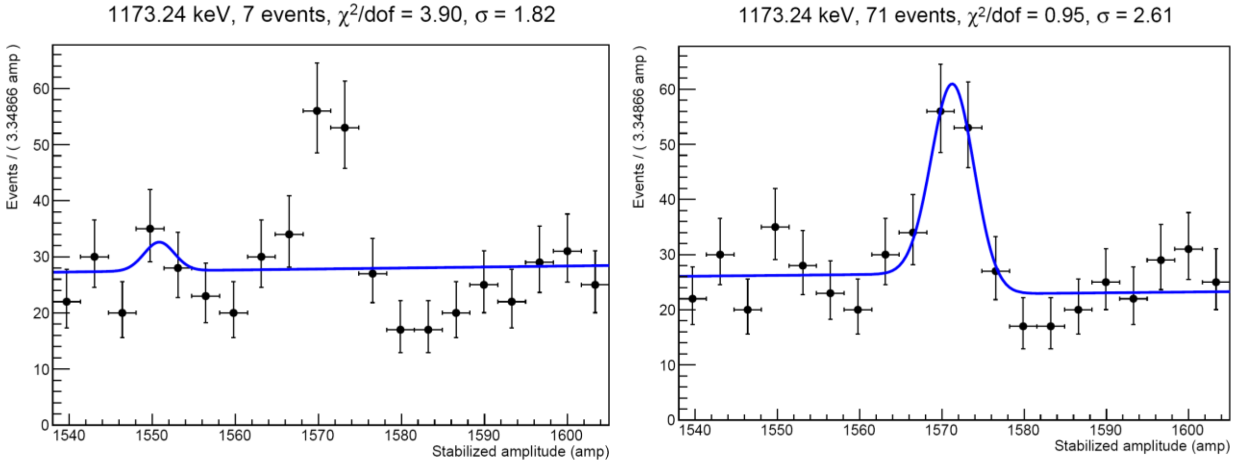
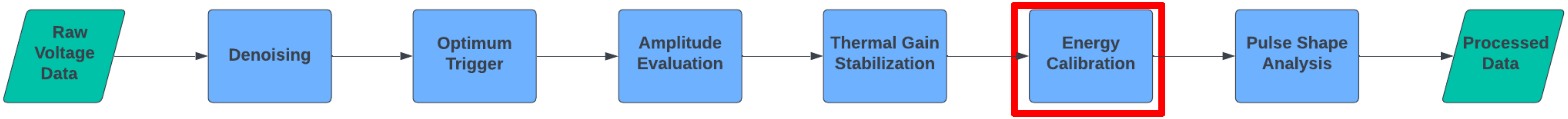


A calibration peak fit by crystal ball function (left), and gaussian (right); algorithm chose the gaussian as the better fit

DATA PROCESSING



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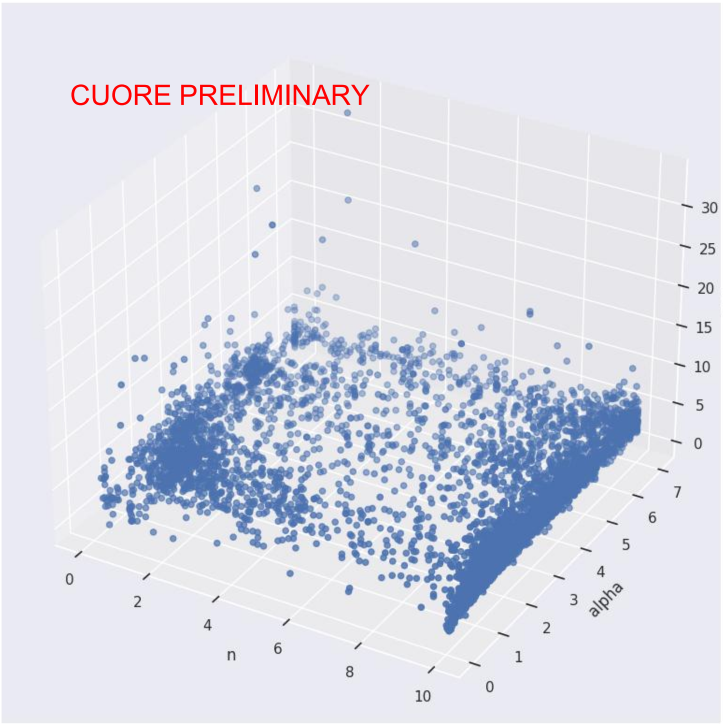
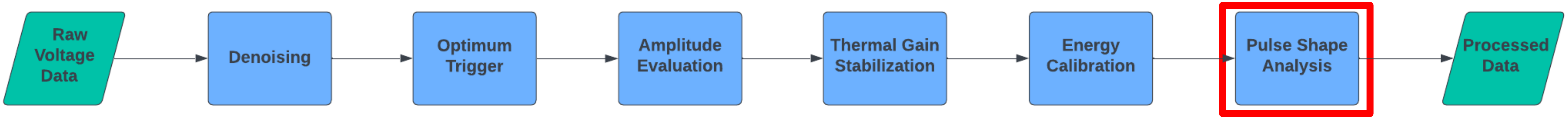


Distribution of fit parameters for a dataset

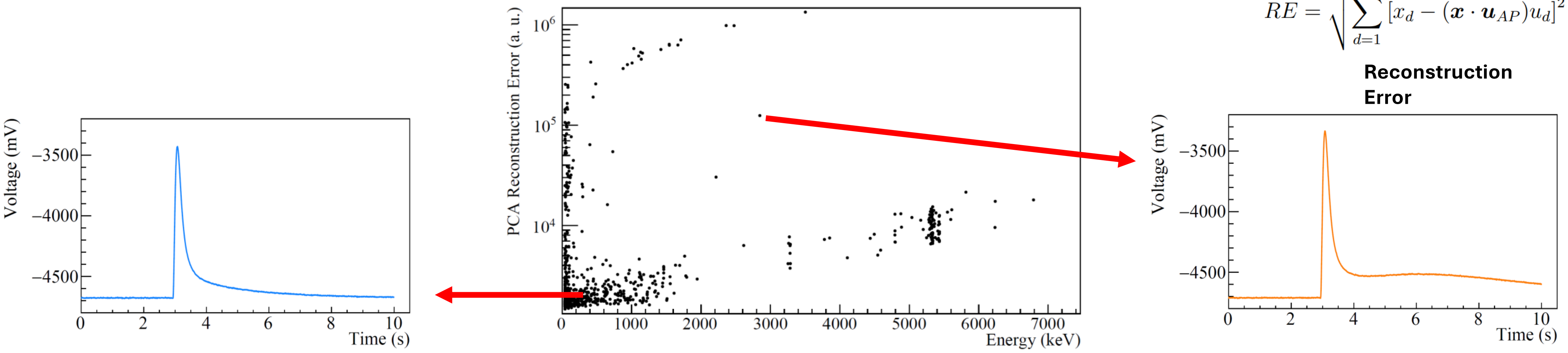
DATA PROCESSING



- 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

$$RE = \sqrt{\sum_{d=1}^{D} \left[x_d - (\boldsymbol{x} \cdot \boldsymbol{u}_{AP}) u_d\right]^2}$$

Reconstruction Error

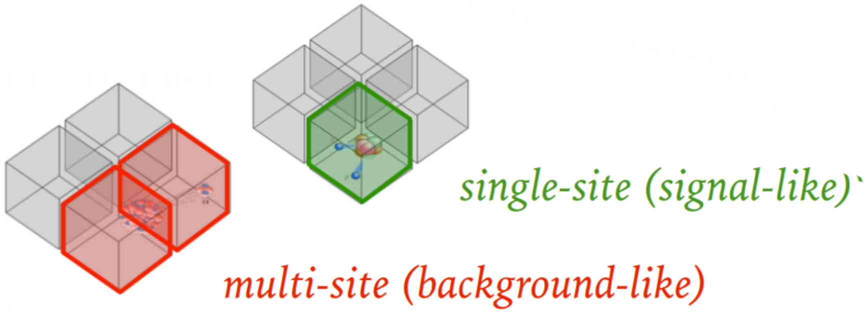


$0\nu\beta\beta$ Analysis Systematics

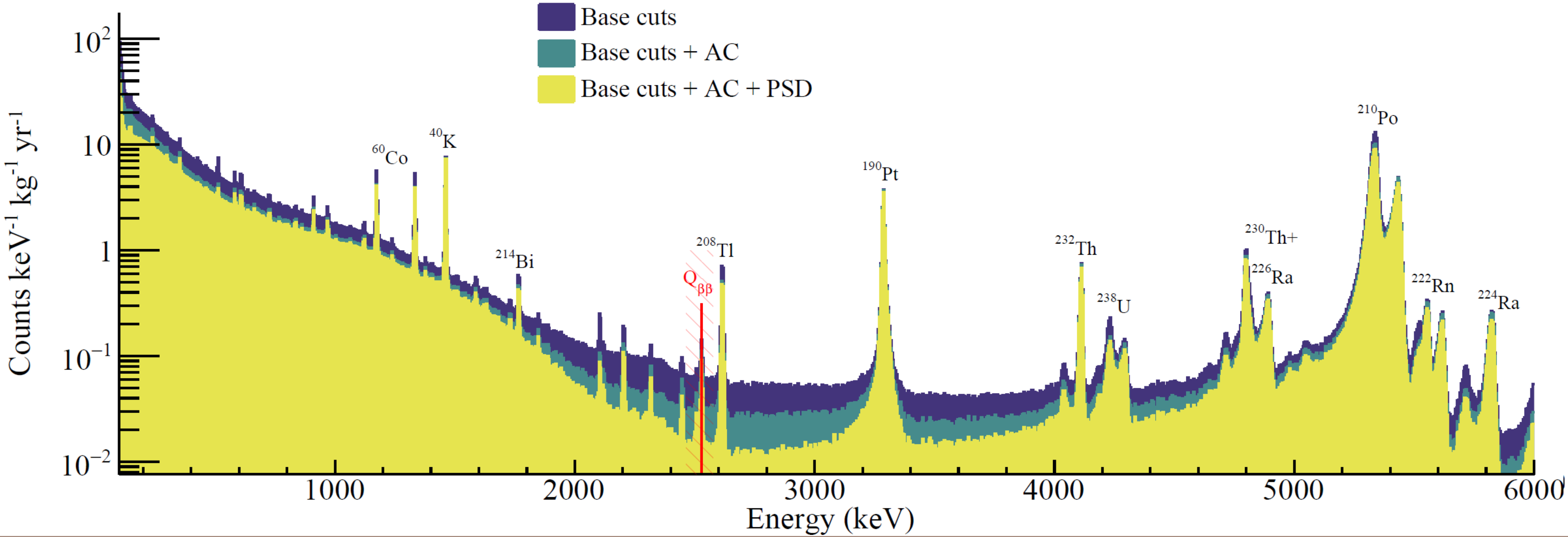
- Uncertainty in the total analysis efficiency. (93.4(2)%)
- Uncertainty in the PCA efficiency. (98.1(2)%)
- Uncertainty in the containment efficiency (88.35 ± 0.090)%
- Uncertainty in the $Q_{\beta\beta}$ (2575.5 ± 0.013) keV
- Tellurium natural isotopic abundance (34.167 ± 0.002)%
- Uncertainties in the bias and resolution scaling

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

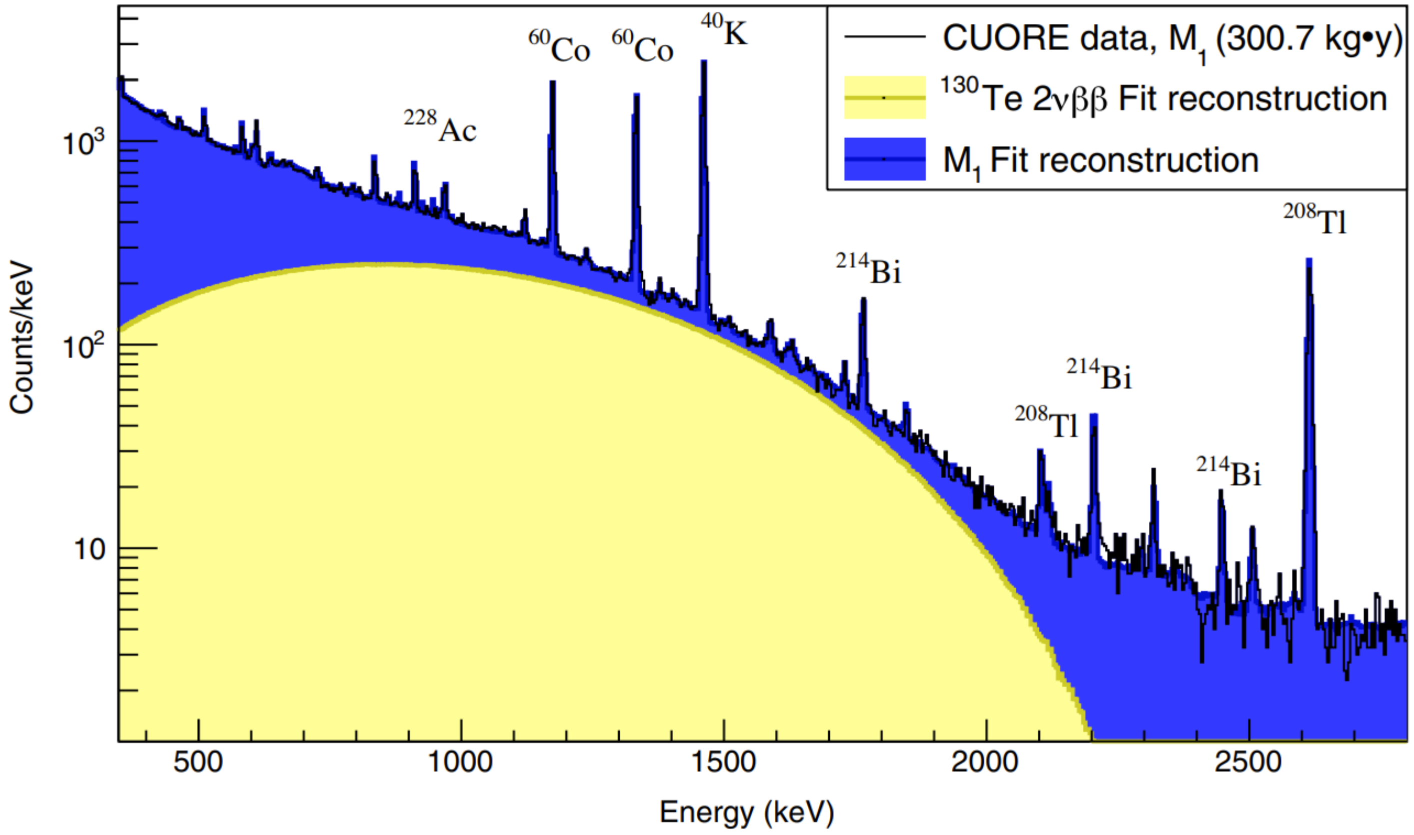


88% of 0νββ events occur in a single crystal



DOUBLE BETA DECAY RESULTS

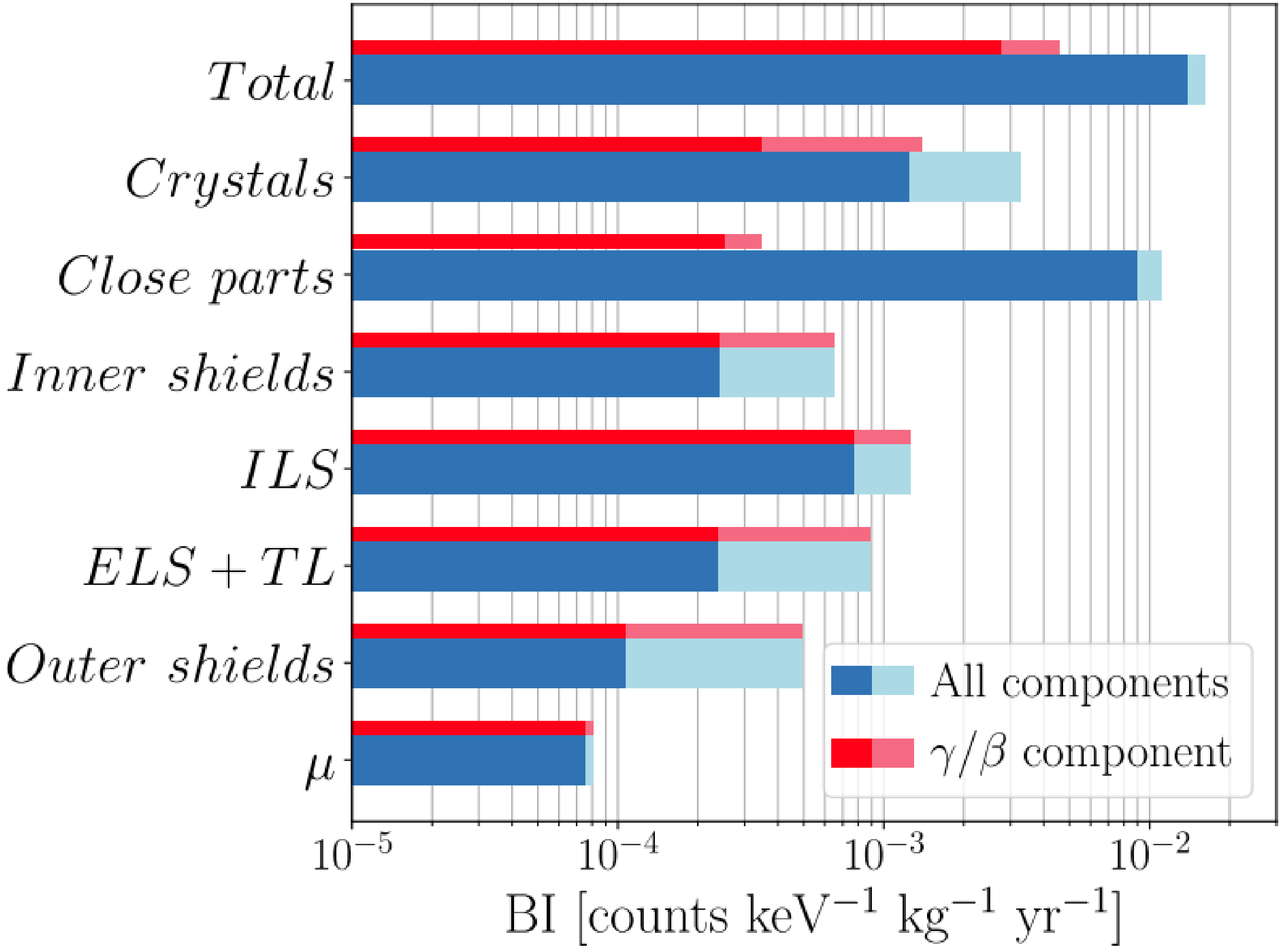
- Double beta decay simulated in Geant4 with CUORE geometry and detector response
- Spectrum reconstructed by simultaneous fit of data with 62 MC simulated sources (2νββ + surface and bulk contaminations + muons)
  - MCMC Bayesian approach
  - Uniform prior for sources except muons
- For 900-2000 keV,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

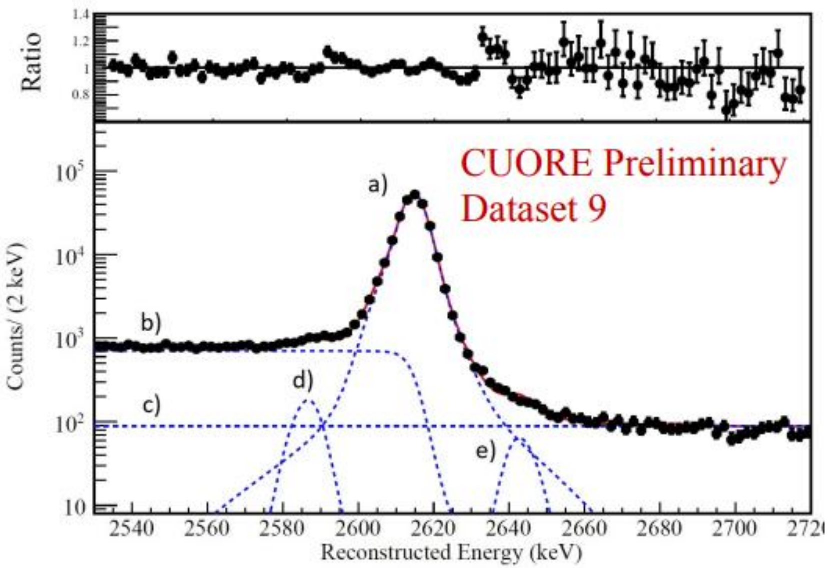
BACKGROUND BUDGET

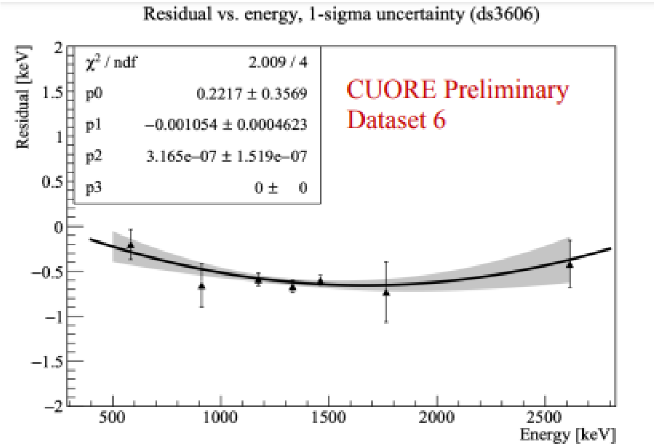


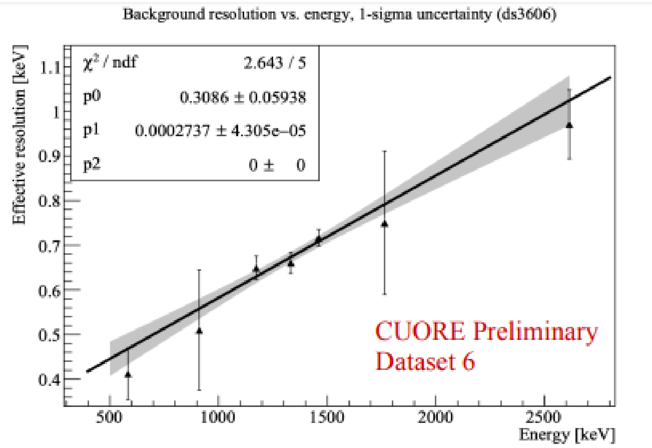
*CUORE collaboration
Phys. Rev. D 110, 052003

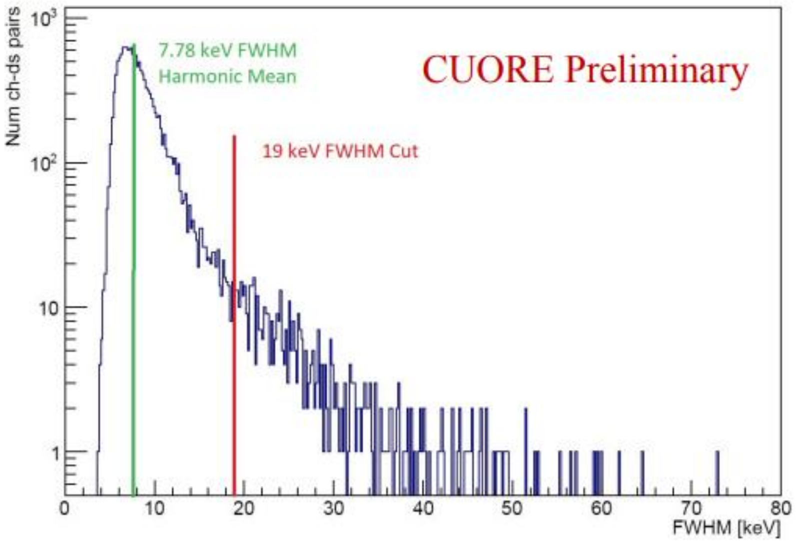
DETECTOR RESPONSE

- 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



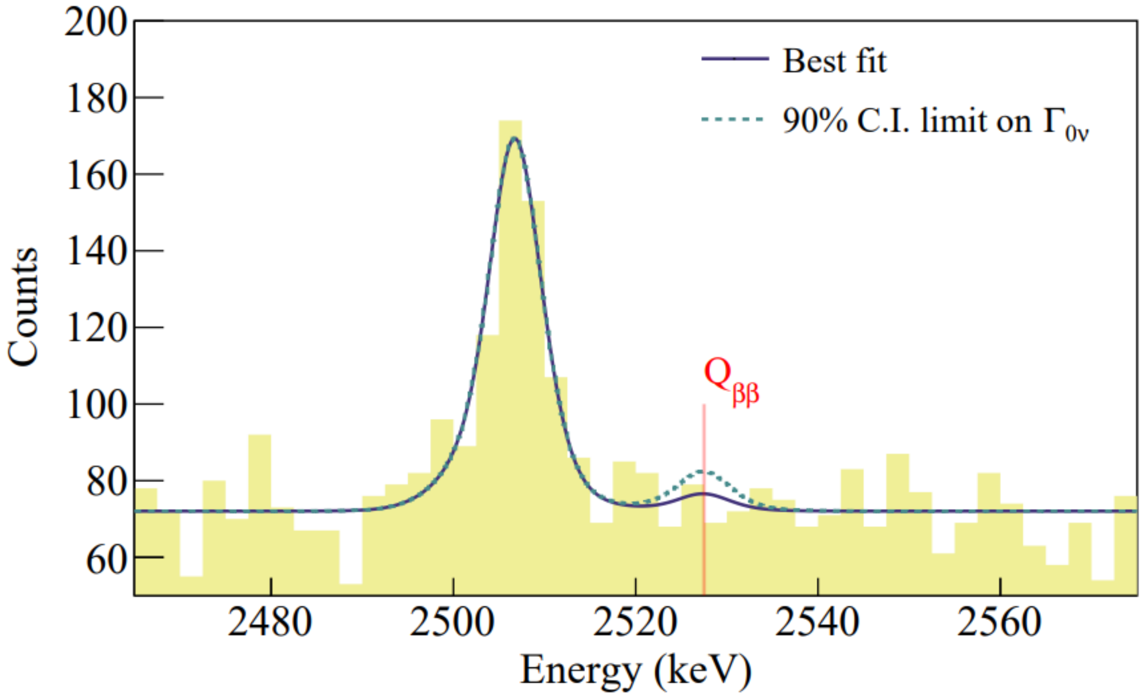






BACKGROUND IN ROI

- 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