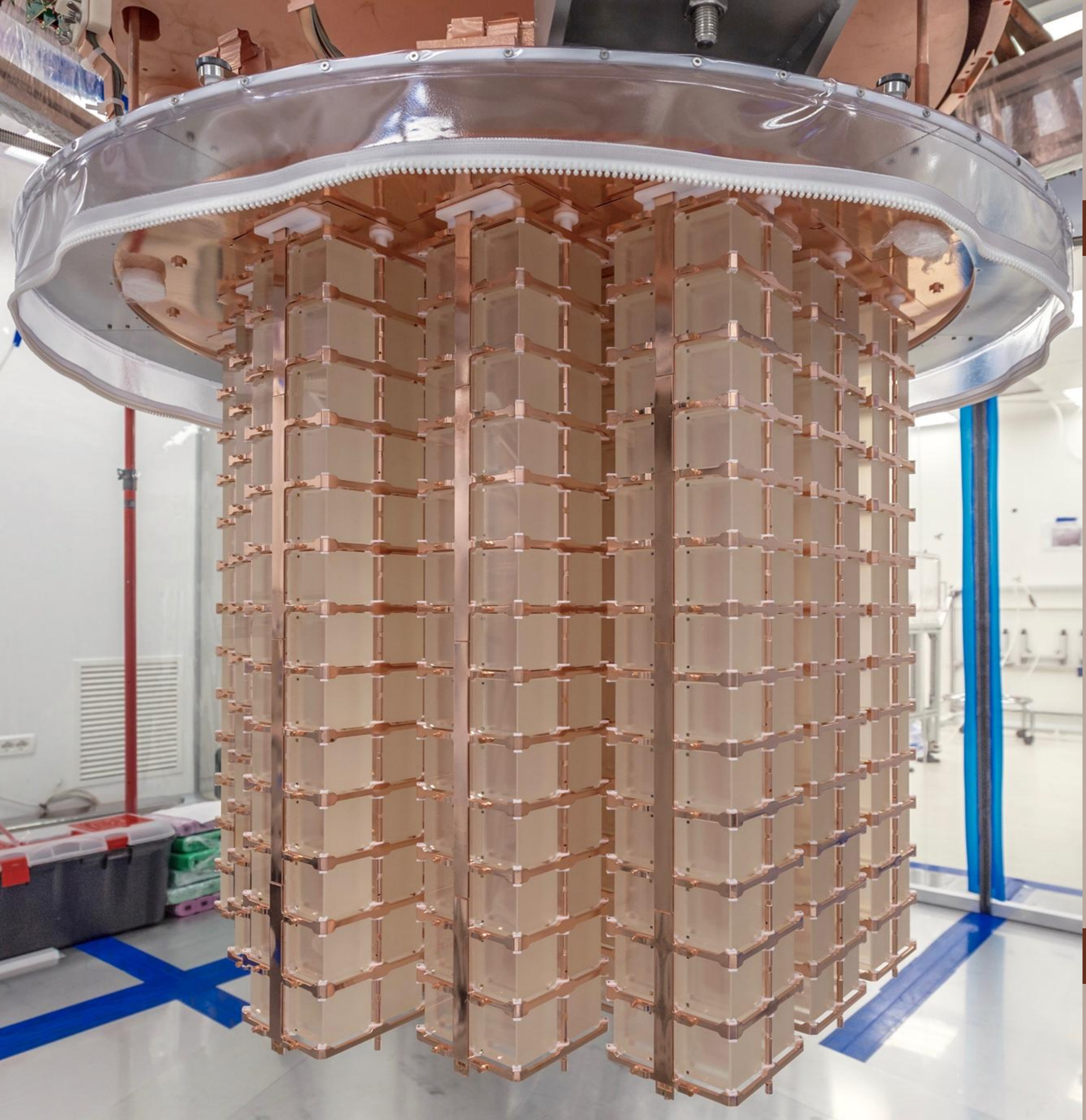


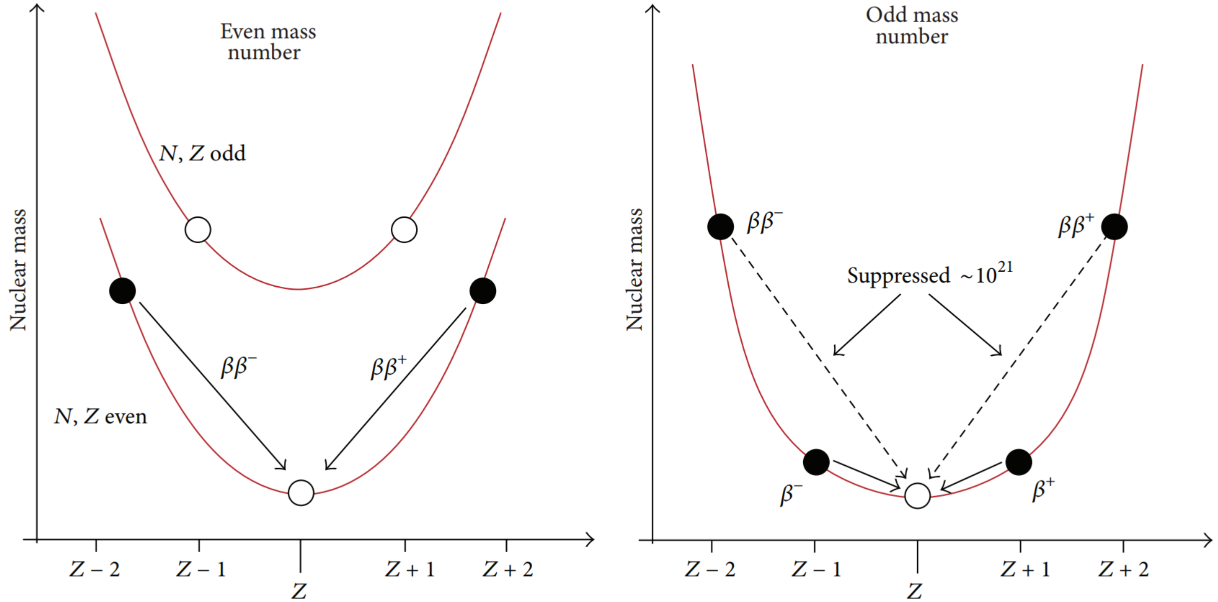
Results from CUORE and Progress towards CUPID

Vivek Sharma
University of Pittsburgh
CIPANP 2025

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

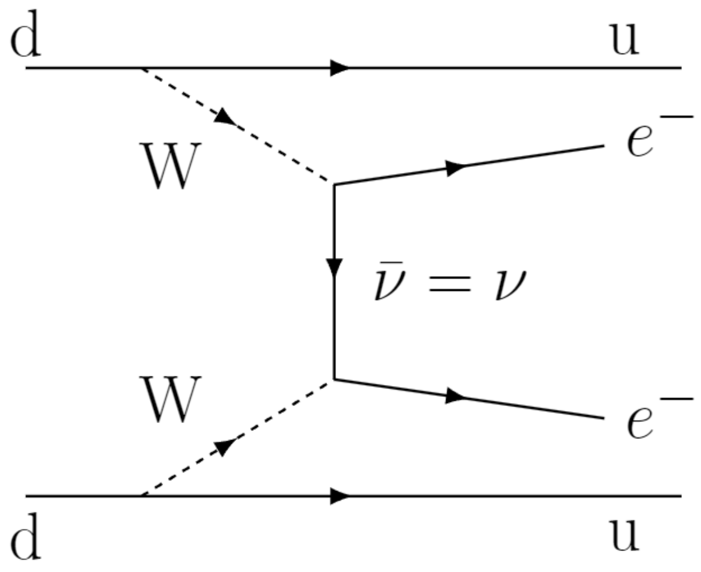
- Beyond Standard Model phenomenon, can occur if neutrinos are Majorana particles
- **Lepton number violating process**
- Potentially impact understanding of origins of matter/anti-matter asymmetry
- Constrains **neutrino mass hierarchy**, **scale** (model dependent)
- Experimental observable is **decay rate**
- Depends on **effective Majorana mass** (mββ)
- Directly related to absolute neutrino mass scale
- Limit on (mββ) 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

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



Light neutrino exchange model

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

NEUTRINOLESS DOUBLE BETA DECAY

- Beyond Standard Model phenomenon, can occur if neutrinos are Majorana particles
- **Lepton number violating process**
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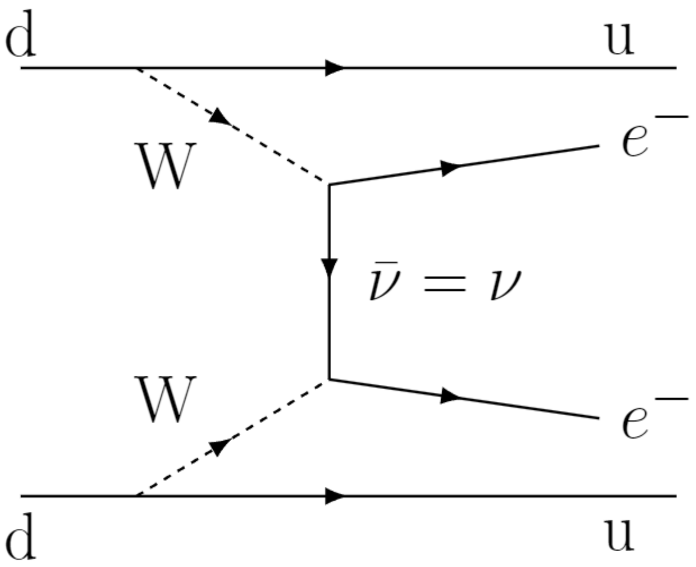
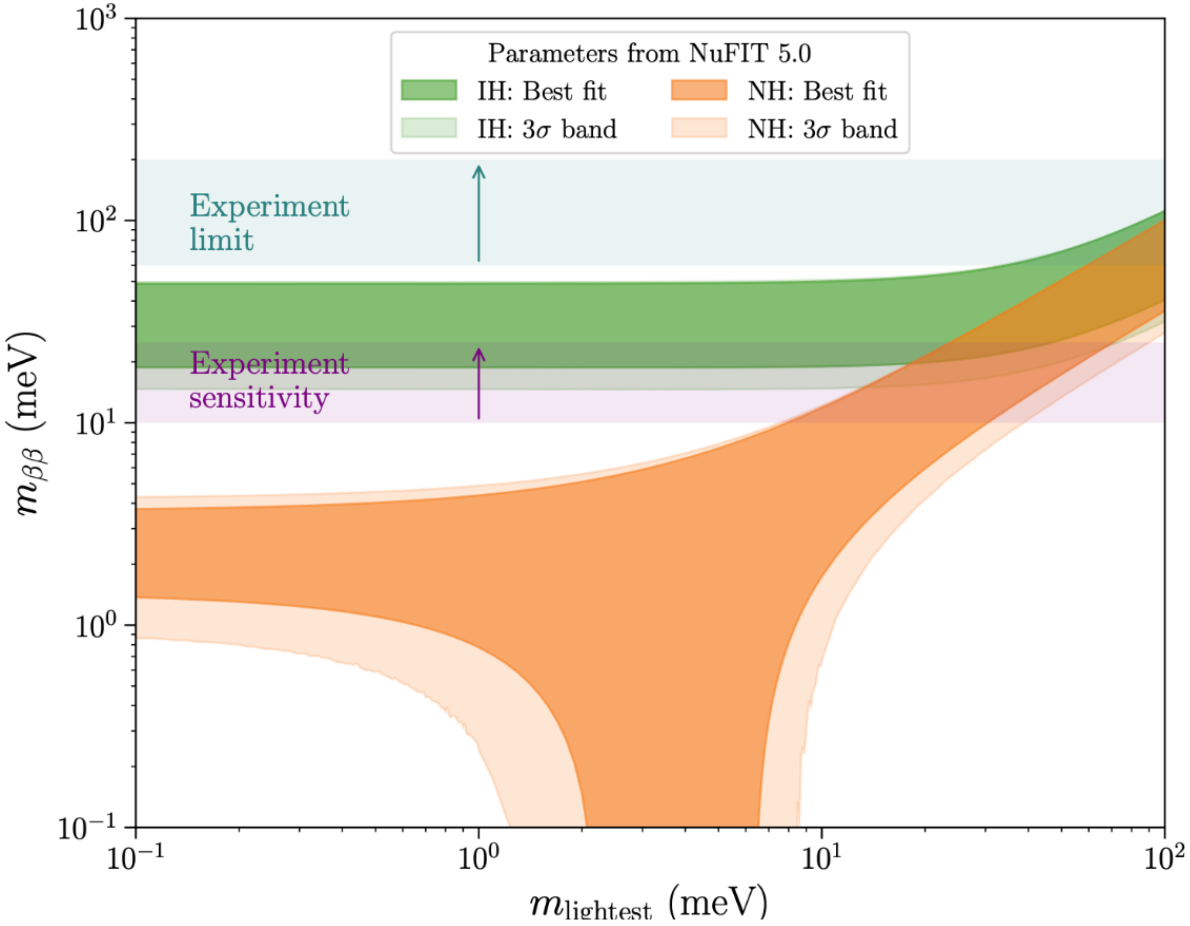
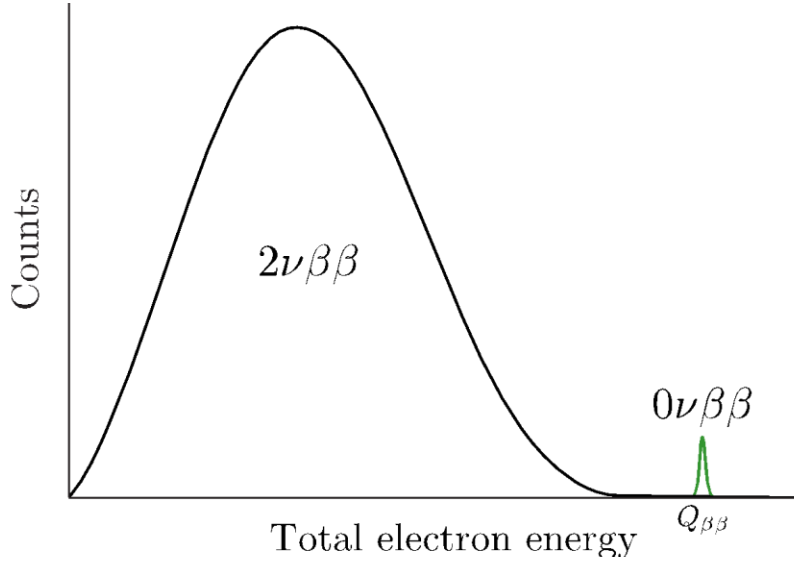


Light neutrino exchange model



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



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

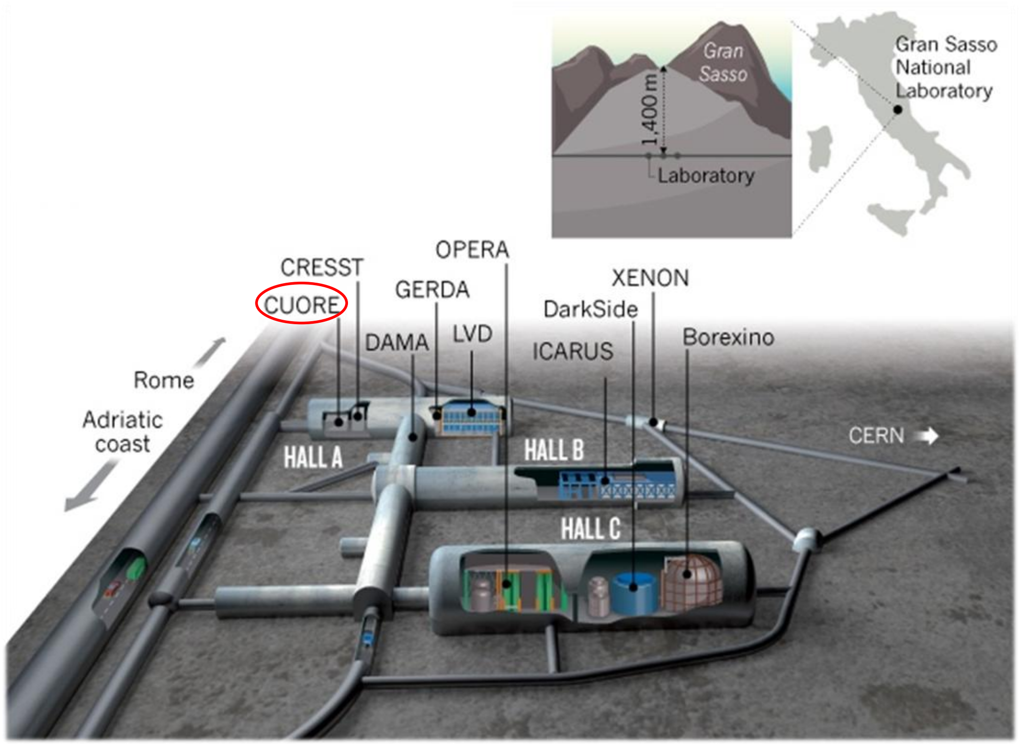
$$T^{0\nu}_{1/2}(1\sigma) = ln(2)\frac{a\epsilon N_A \eta}{W}\sqrt{\frac{mt}{b\Delta E}}$$

1-sigma sensitivity

Isotopic abundance (a), Efficiency (ϵ), Detector mass (m), Livetime (t), Bkg rate/energy/mass (b), Energy Resolution (ΔE)

CUORE

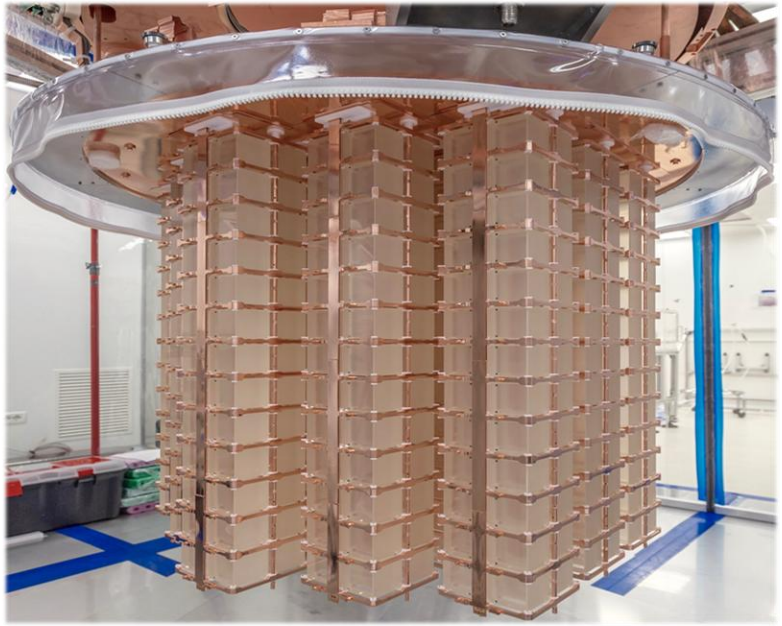
- **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents
- Located at Hall A of Gran Sasso National Laboratory
- **3600 m.w.e** of overburden, muon rate 6 orders of magnitude less than surface, extensive shielding
- ^{130}Te has a ββ Q-value of **2527.5 keV**
- **742 kg** TeO_2, **206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

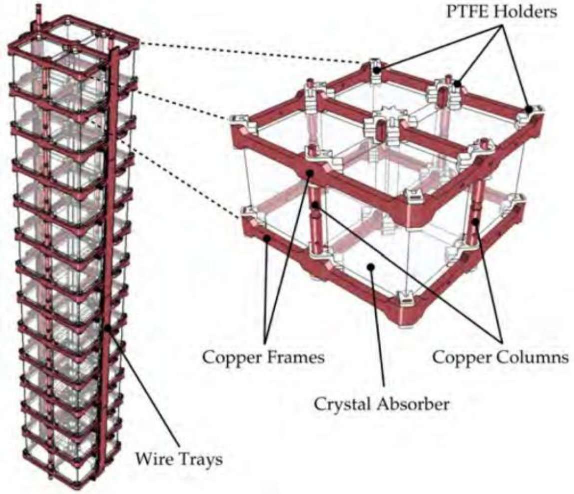


Images courtesy of LNGS: https://www.lngs.infn.it/en

DETECTOR INFRASTRUCTURE

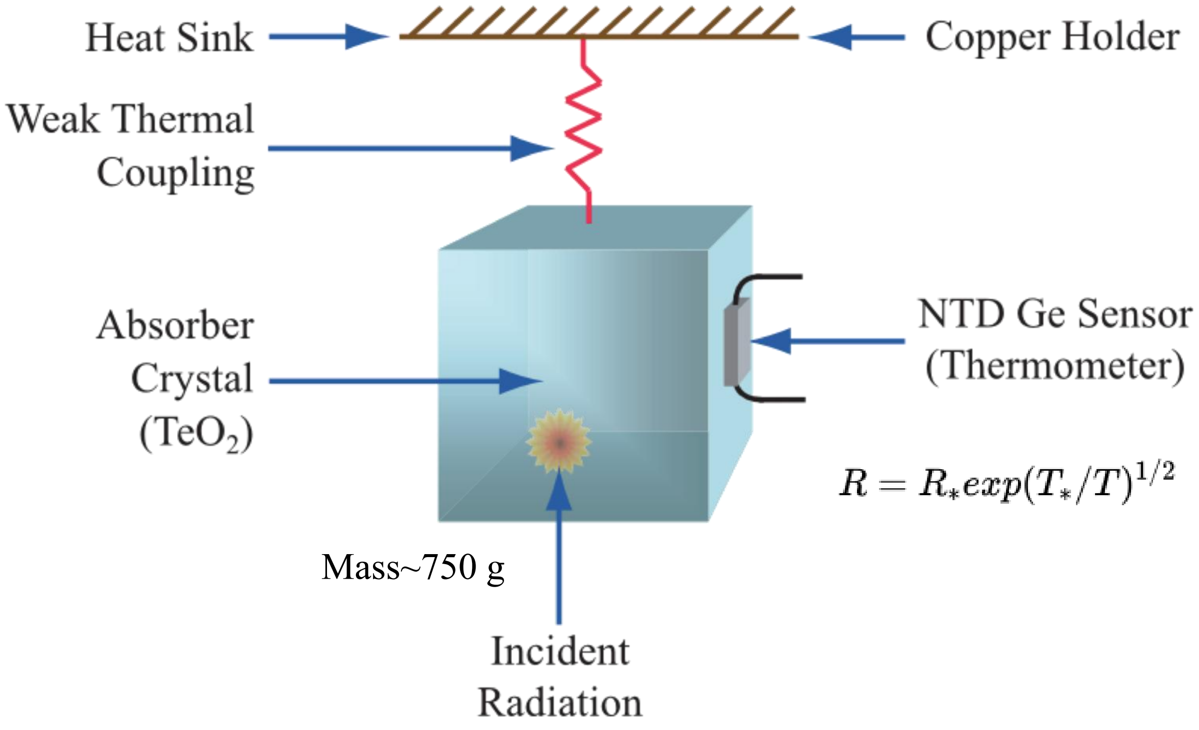
- 988 natural TeO_2 crystals
  - Total mass: 742 kg
  - ^{130}Te mass: 206 kg
  - 5x5x5 cm^3, arranged in 19 towers
- Housed in copper frame and held in place by PTFE spacers
  - Copper linked to thermal bath
  - PTFE spacers are also weak thermal links and contract more at low temperatures
- Tightly 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 **~15 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://doi.org/10.48550/arXiv.2404.04453

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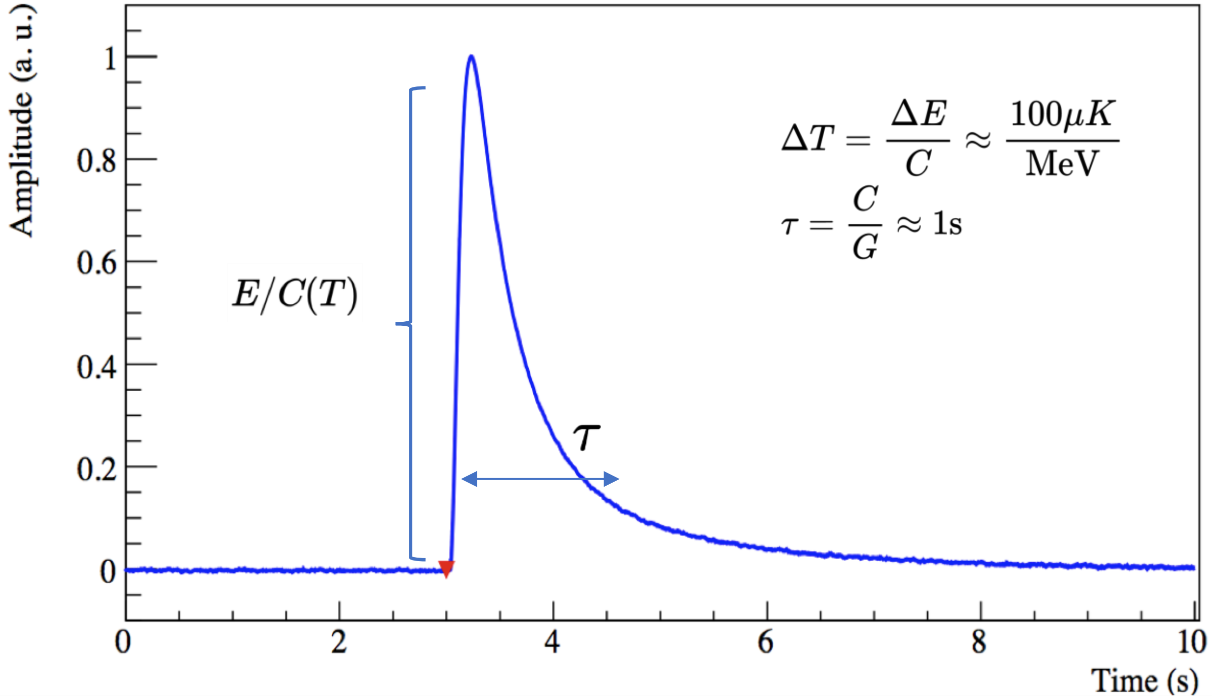
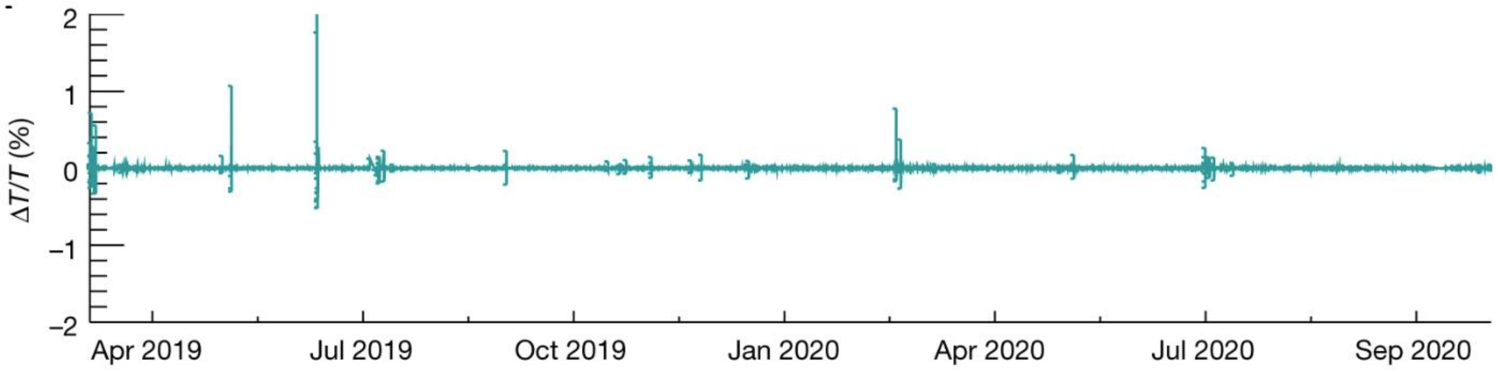


Example of a signal pulse

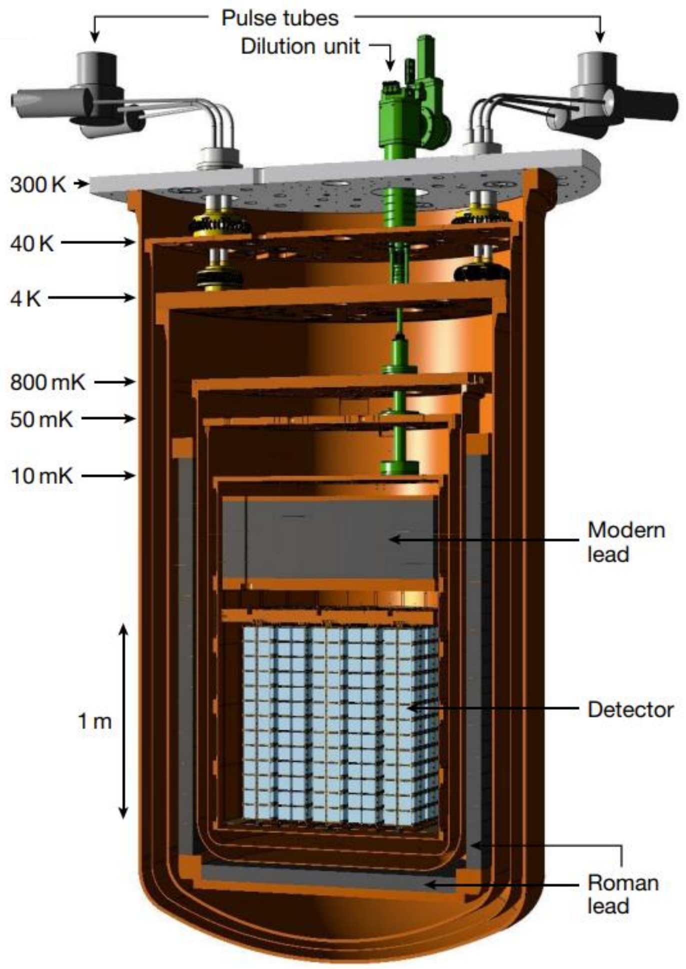
†CUORE collaboration
https://doi.org/10.48550/arXiv.2404.04453

CRYOGENICS

- Operating temperature of **15 mK** is achieved via multistage cryogen-free dilution refrigerator
  - 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*

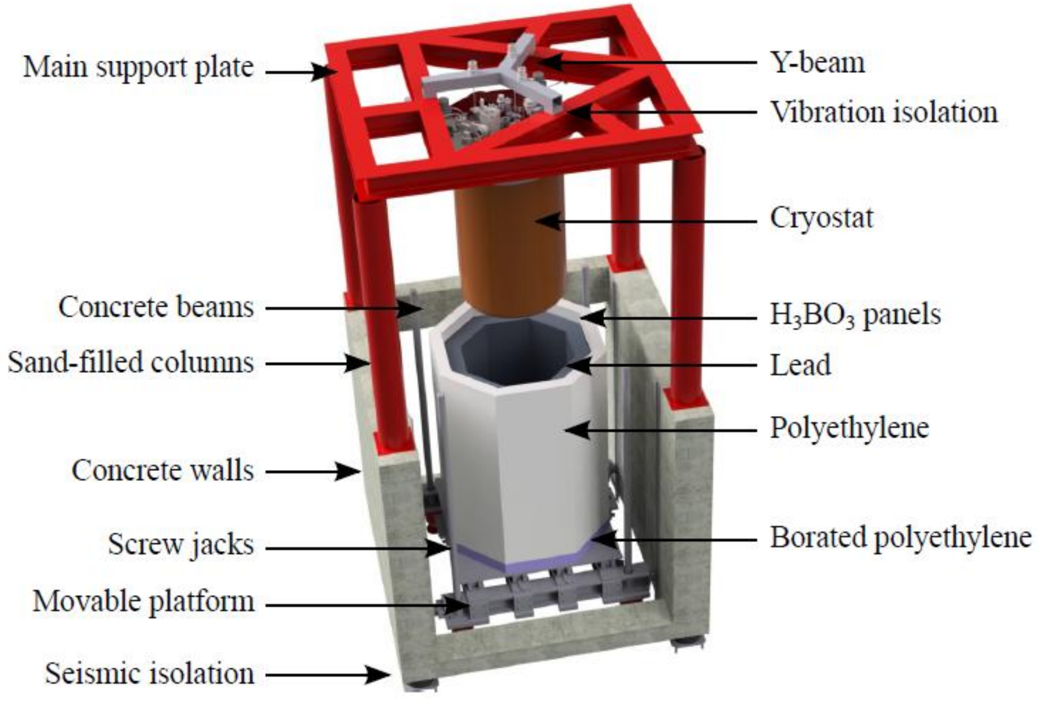


The CUORE cryostat*

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

SHIELDING

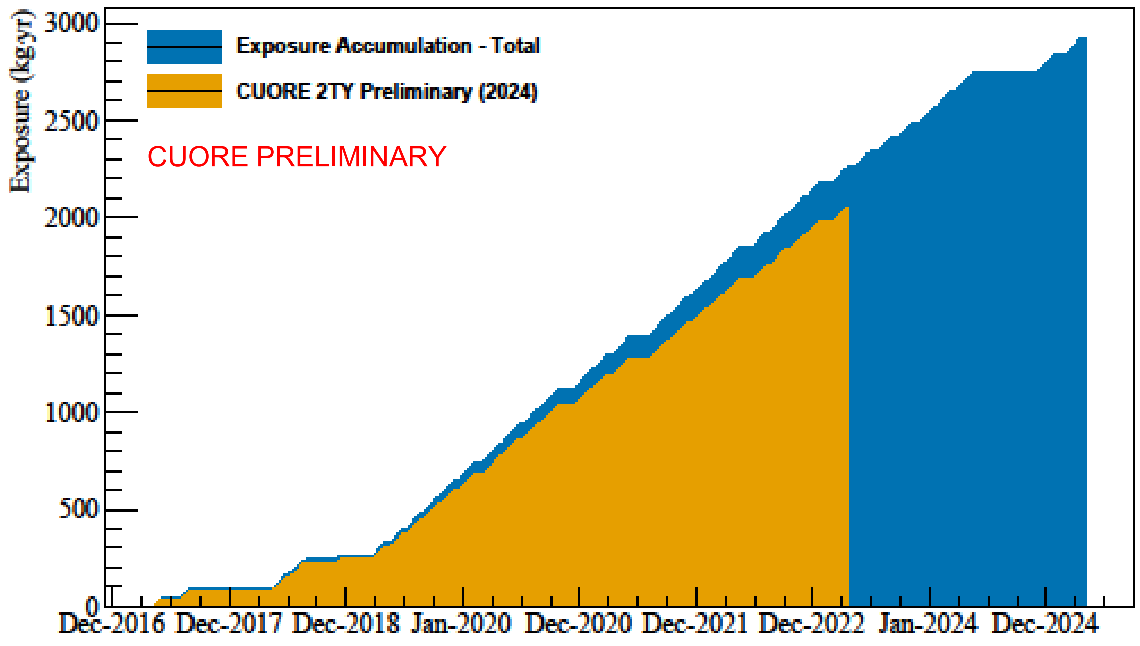
- Experimental setup shielded from radiation by multiple layers
- Neutron background:
  - Lateral 18 cm polyethylene layer with 2 cm thick H_3BO_3 panels
  - 20 cm thick borated polyethylene at the bottom
- Gamma background:
  - 30 cm external, lateral lead shield
  - 30 cm internal lead shield above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



External structure of CUORE

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



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

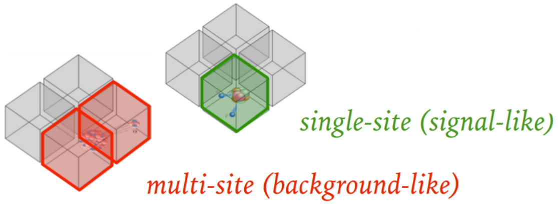
- Crystals operated at 15 mK
  - Denoising techniques
- $Q_{\beta\beta}$ relative energy resolution: 0.3%

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

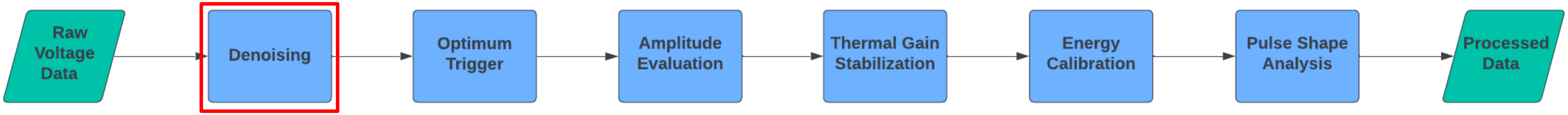
Efficiency



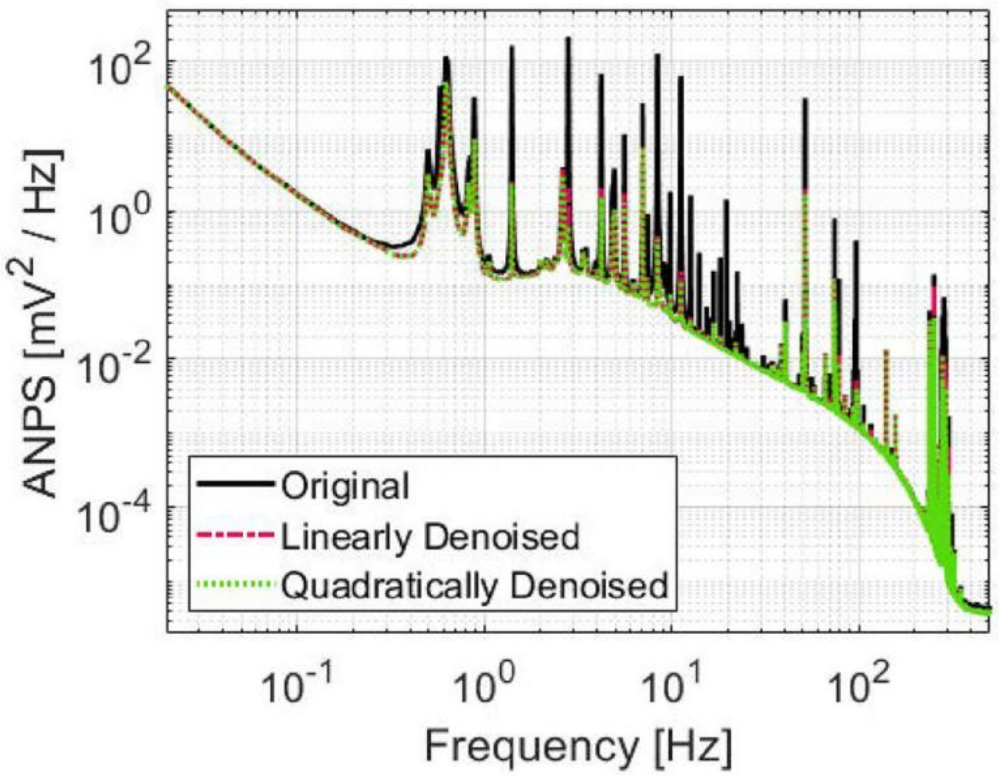
88% of 0νββ events occur in a single crystal

- Source = Detector
- 88% containment efficiency
- 96% data quality cut efficiency

DATA PROCESSING

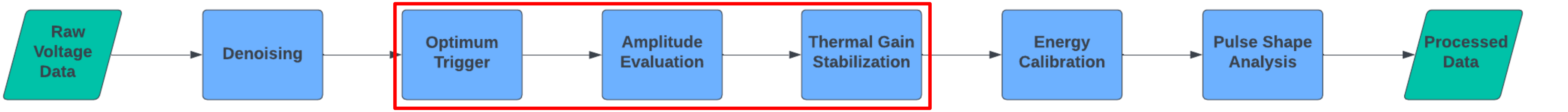


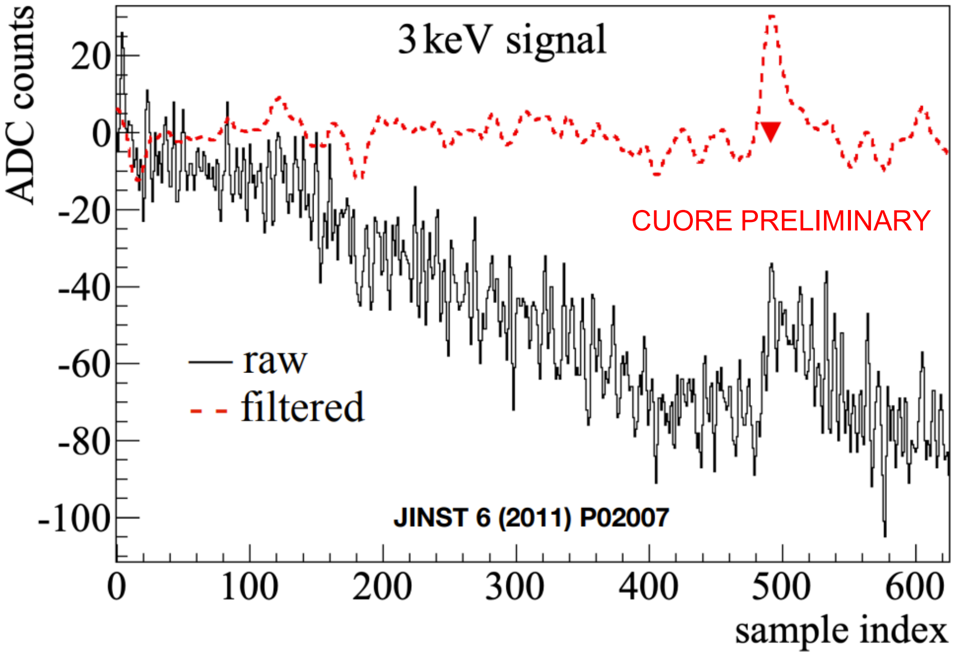
- Predict noise contribution by correlating noise between auxiliary devices and correlating with calorimeter noise
  - Produce less noisy data with improved resolution

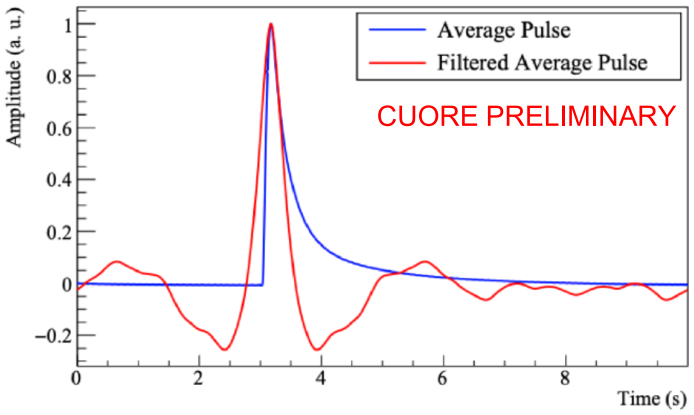


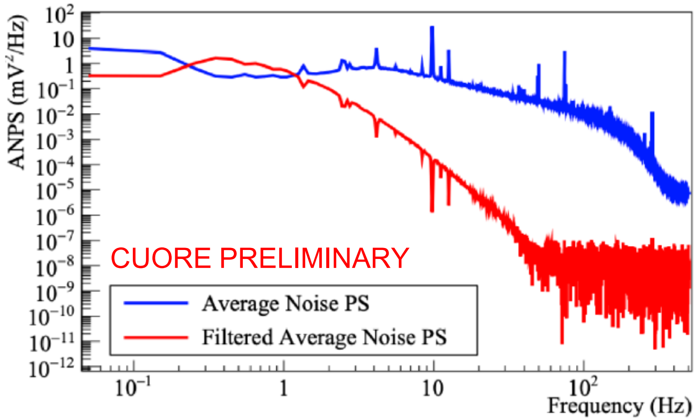
https://doi.org/10.1140/epjc/s10052-024-12595-y

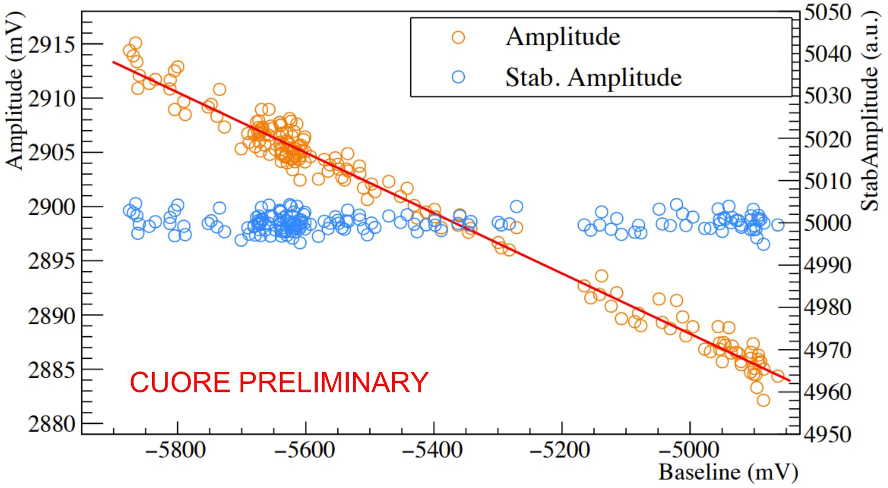
DATA PROCESSING











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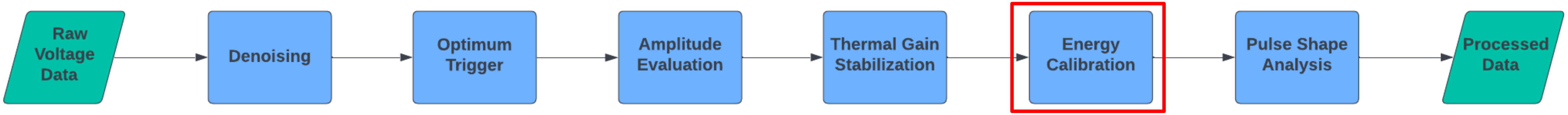
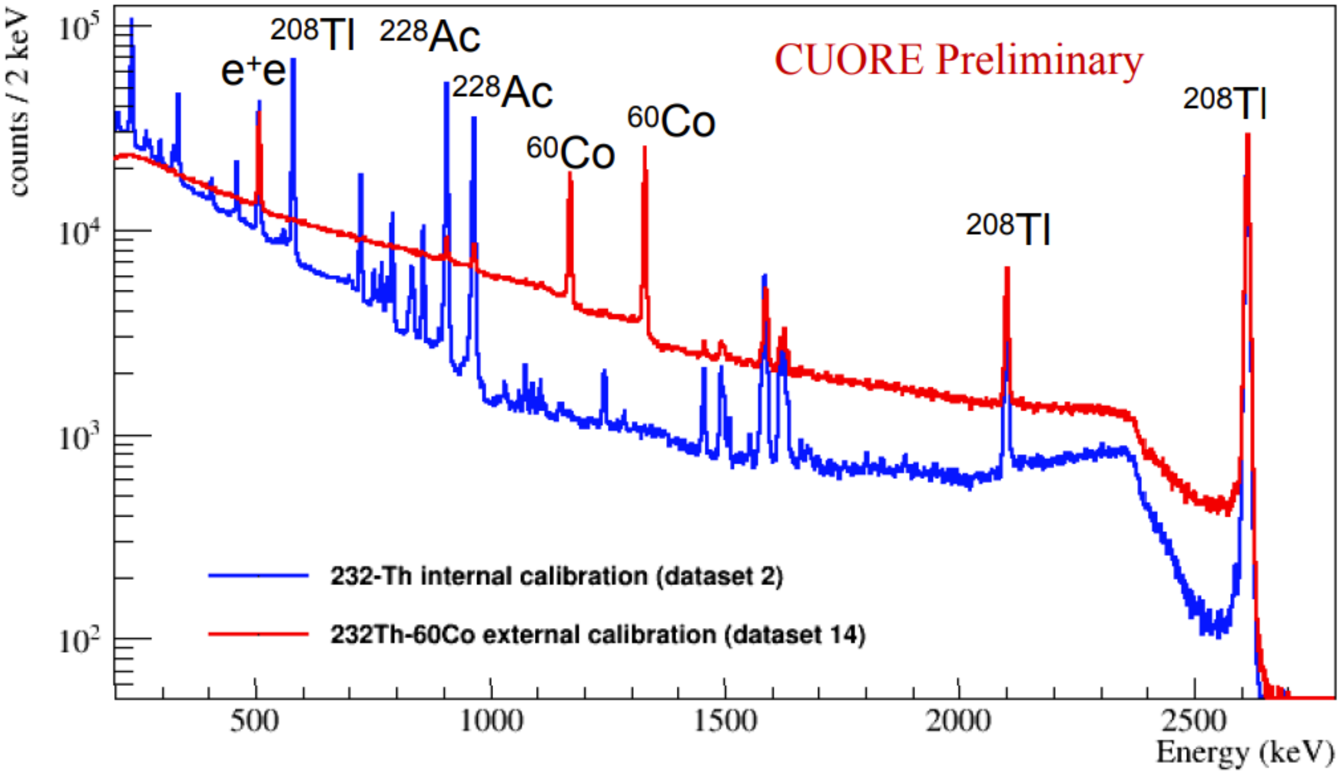
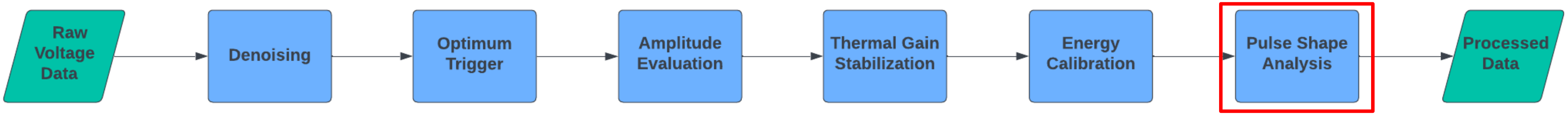


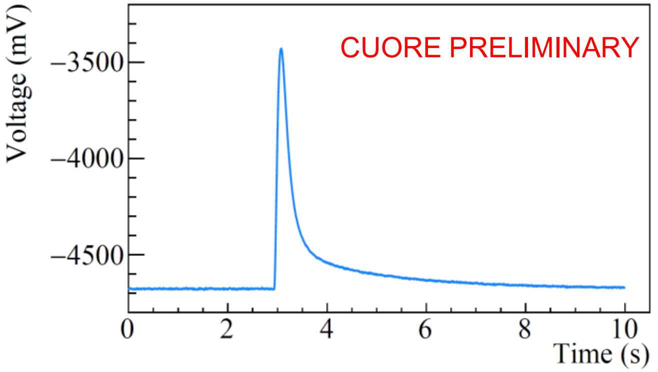


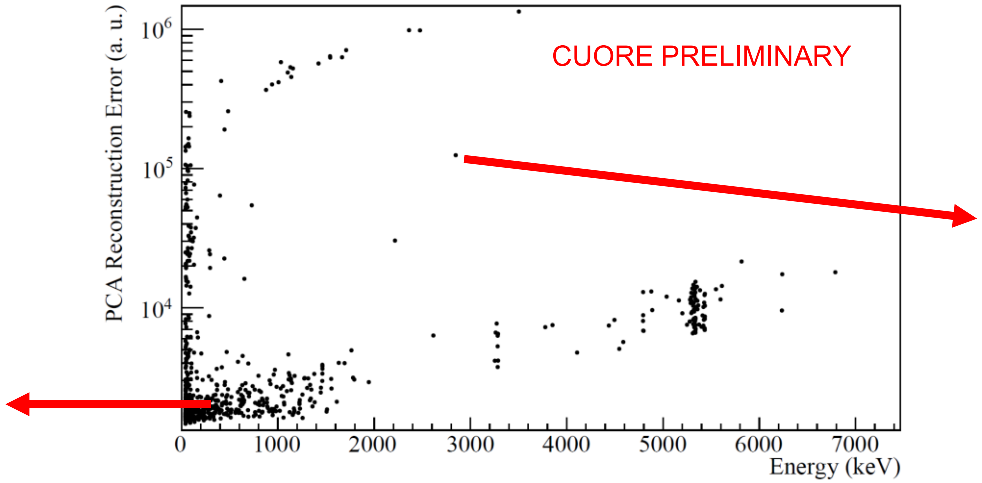
DATA PROCESSING

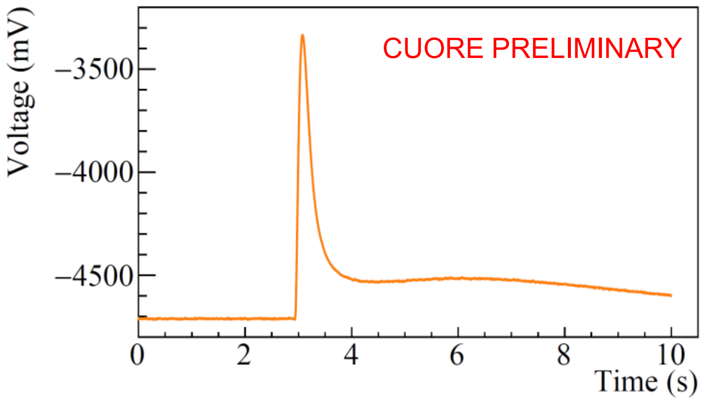


$$RE = \sqrt{\sum_{d=1}^{D} [x_d - (\boldsymbol{x} \cdot \boldsymbol{u}_{AP})u_d]^2}$$

Reconstruction Error







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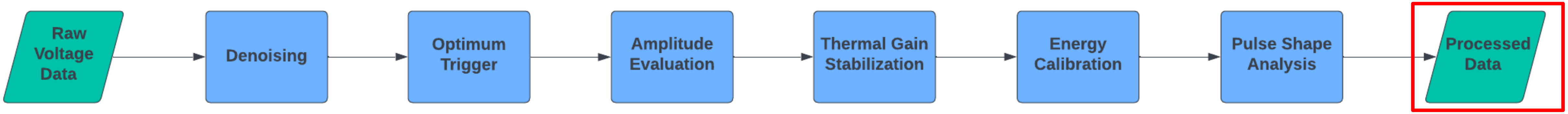
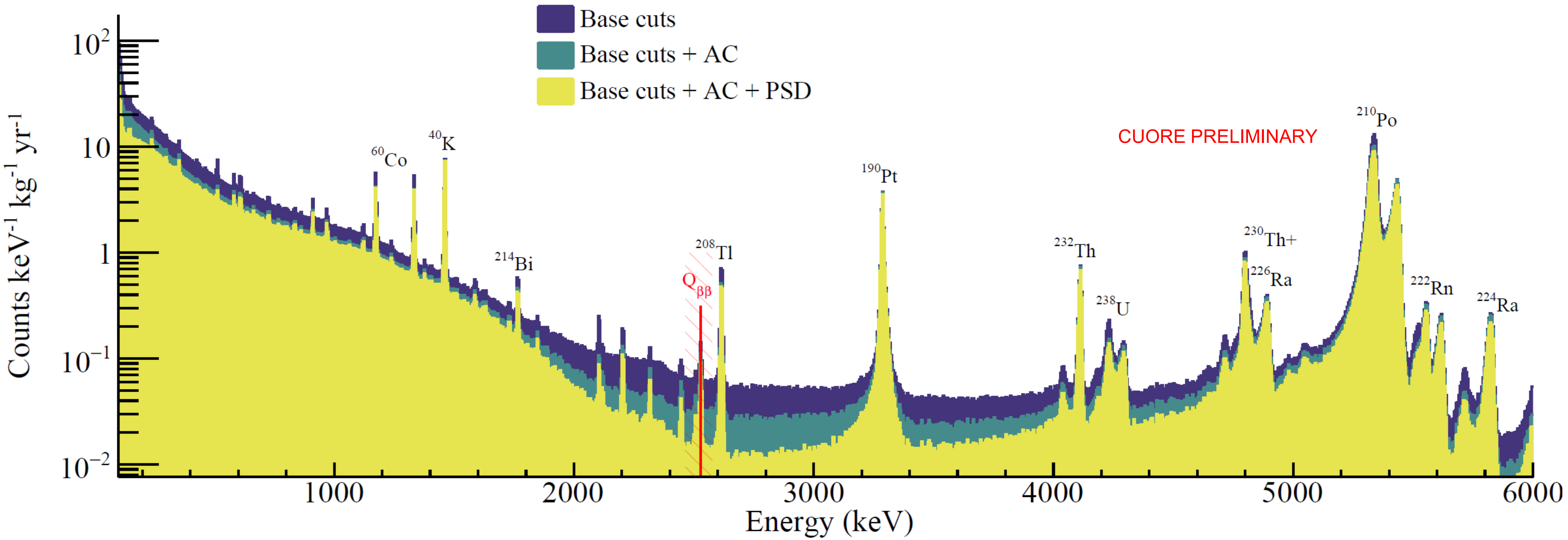


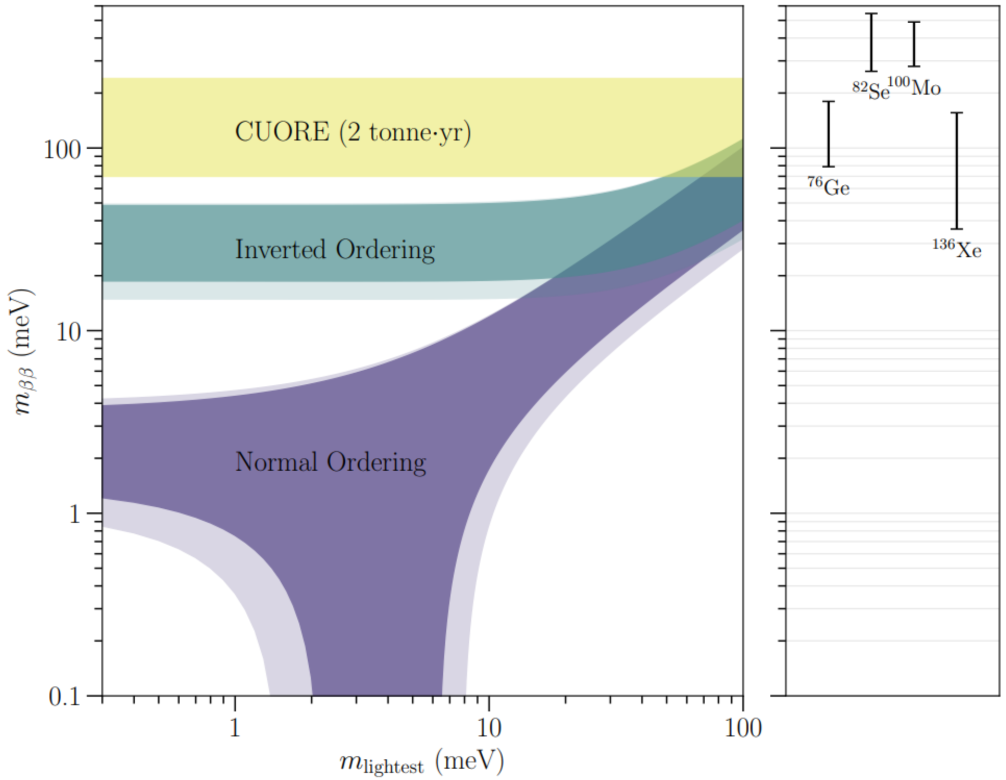


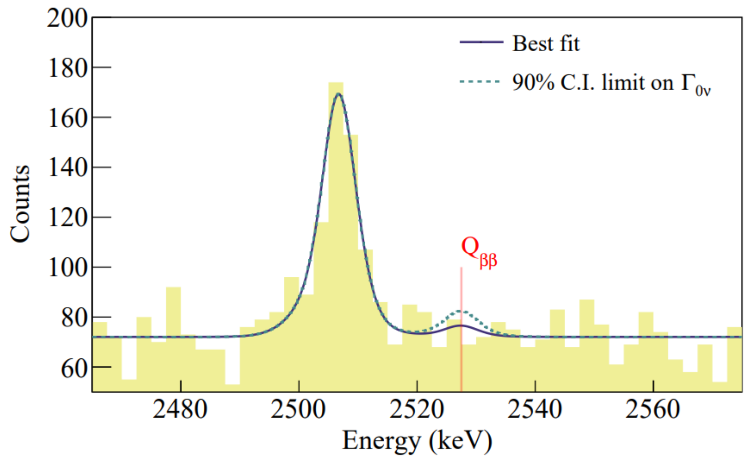
2 TON YEAR RESULTS

- 2nd ton.yr results:
  - Blinded analysis to prevent bias
  - ROI (2465, 2575) keV salted with 208Tl 2615 keV peak
  - Fit ROI events with: 130Te 0νββ peak, 60Co peak, linear background
  - Finalize model parameters before unblinding
- Analyzed exposure: 2039.0 kg.yr
- Half-life limit: $T_{1/2}$ > 3.8 x 10^{25} yr (90% C.I.)
- Median Exclusion Sensitivity: 4.4 x 10^{25} yr (90% C.I.)
- $m_{\beta\beta}$ < 70 - 240 meV (90% C.I.)
  - Light Majorana neutrino exchange model

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

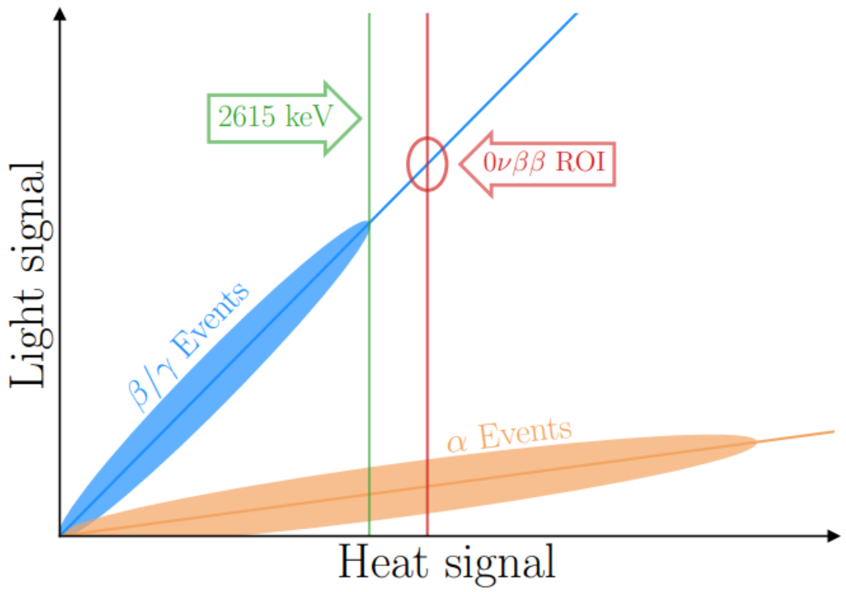


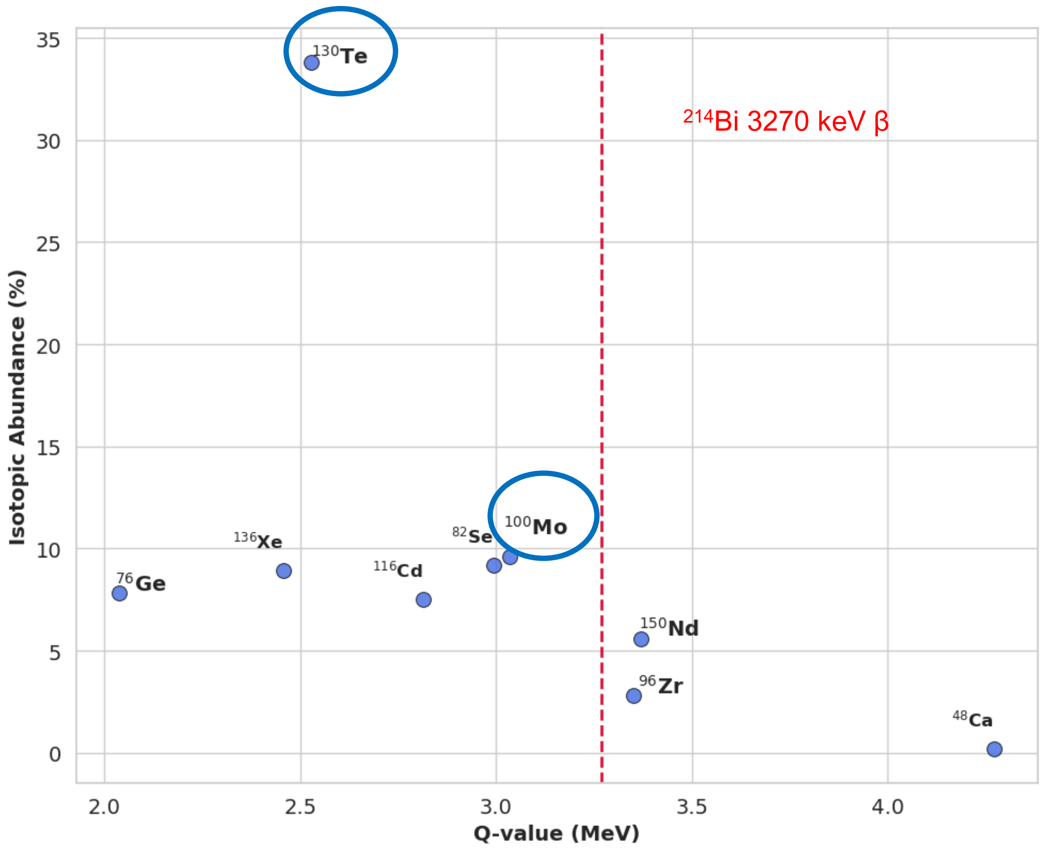


†CUORE collaboration
https://doi.org/10.48550/arXiv.2404.04453

CUORE to CUPID

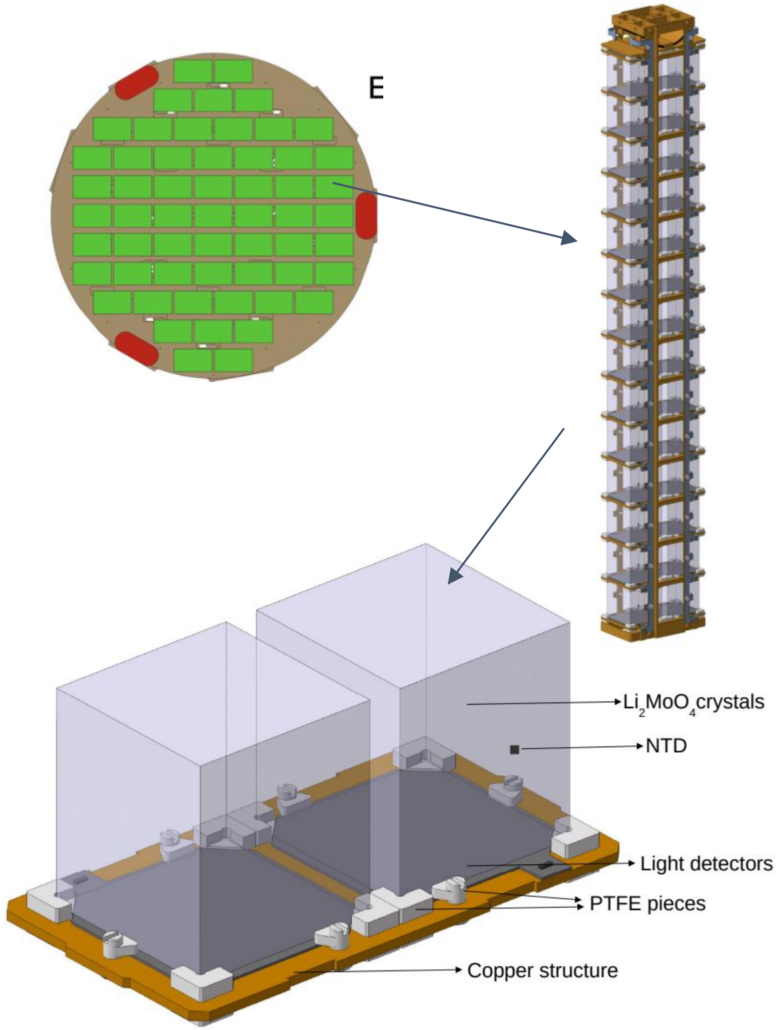
- Degraded alpha's biggest background component
- Use scintillating calorimeters – Li_2MoO_4
  - Use light signal to distinguish between alphas and beta/gamma events
- 100Mo Q value: 3034 MeV
  - Lower background region





CUPID BASELINE DESIGN

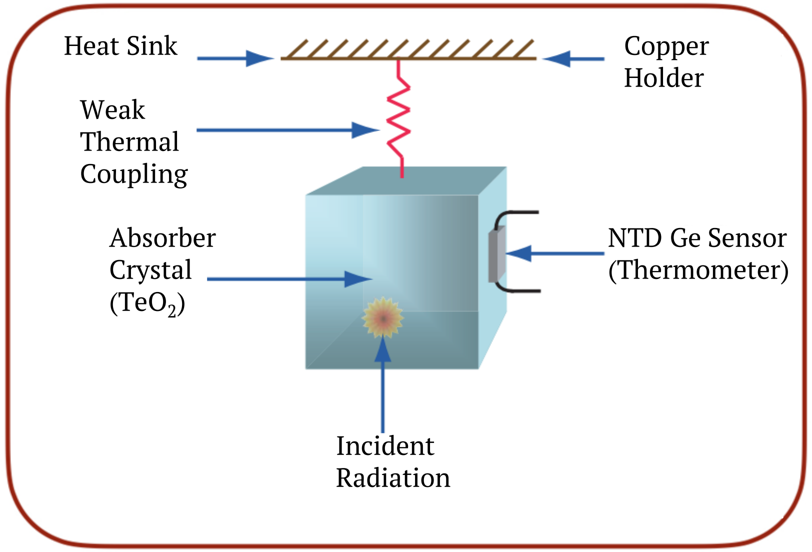
- 45 x 45 x 45 mm3 $Li_2{}^{100}MoO_4$ crystals
  - Crystal mass: 280 g
- 1596 total crystals
  - 450 kg of $Li_2{}^{100}MoO_4$
  - 95% enrichment in 100Mo: 240 kg of 100Mo
  - 57 towers of 28 crystals. 14-floors of 2x1 crystal pairs. Gravity-assisted design
- Ge light detectors with SiO anti-reflective coating
  - Each crystal has top and bottom light detectors
- Muon veto for muon-induced background suppression
- Planned to be housed in the CUORE cryostat



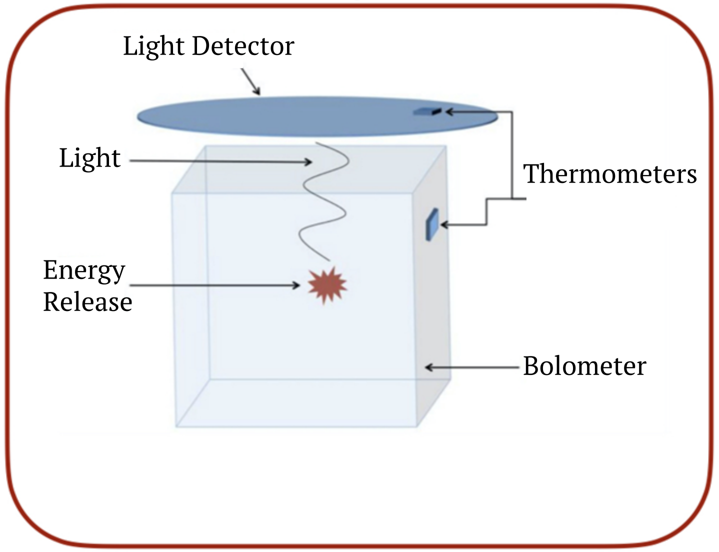
arXiv:2503.04481

CUPID DETECTION PRINCIPLE

CUORE ^{130}Te Bolometer



CUPID ^{100}Mo Scintillating Bolometer



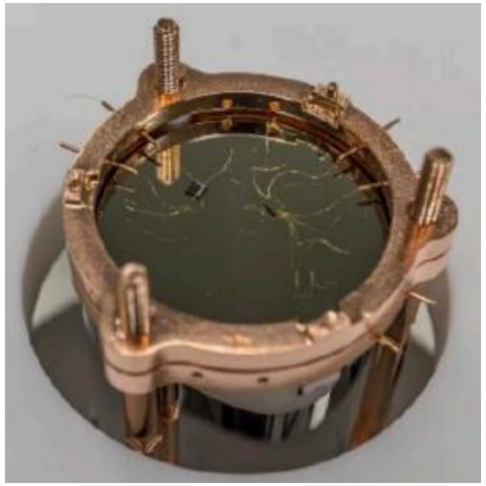
$Q_{\beta\beta}$ = 2527 keV < 2615 keV peak
Measure only heat
No particle ID

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

PROTOTYPE DEMONSTRATORS

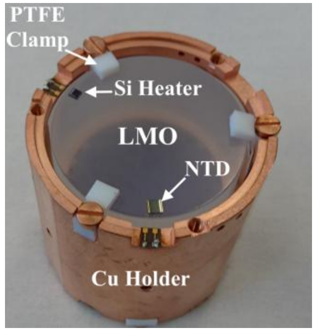
CUPID-0

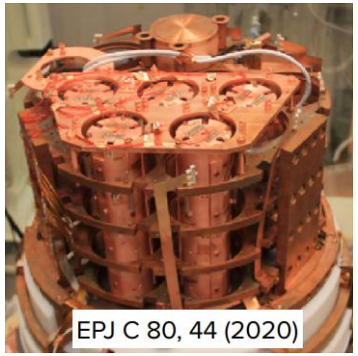
- CUORE-0 cryostat at LNGS, Italy
- 24 $Zn^{82}Se$ (95% enrichment) + 2 $Zn^{nat}Se$ crystals
- 5.17 kg of ^{82}Se
- Ge light detectors and NTD thermistors



CUPID-Mo

- Located in the LSM, France
- 20 enriched $Li_2{}^{100}MoO_4$ (97% enrichment) crystals
- 2.26 kg of ^{100}Mo
- Ge light detectors and NTD thermistors

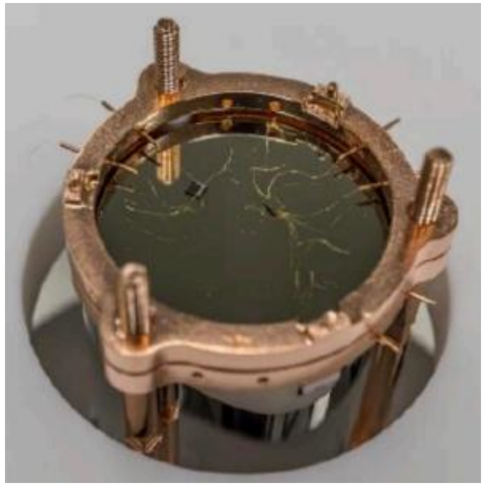




PROTOTYPE DEMONSTRATORS

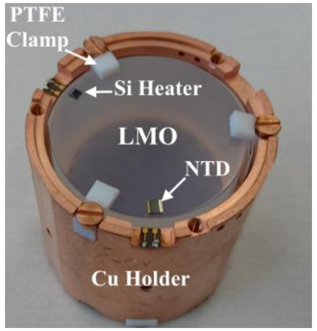
CUPID-0

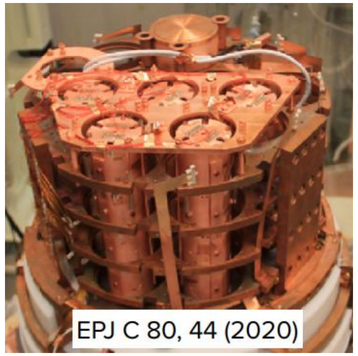
- Resolution of Qββ 23 keV FWHM
- Background in ROI: 3.5×10 −3 cts/(keV.kg .yr)



CUPID-Mo

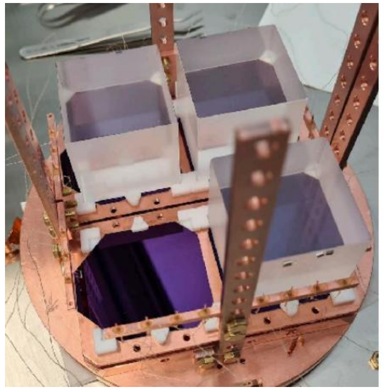
- Resolution of Qββ 5-7 keV FWHM
- No background events in ROI

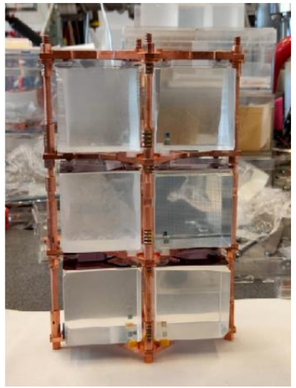


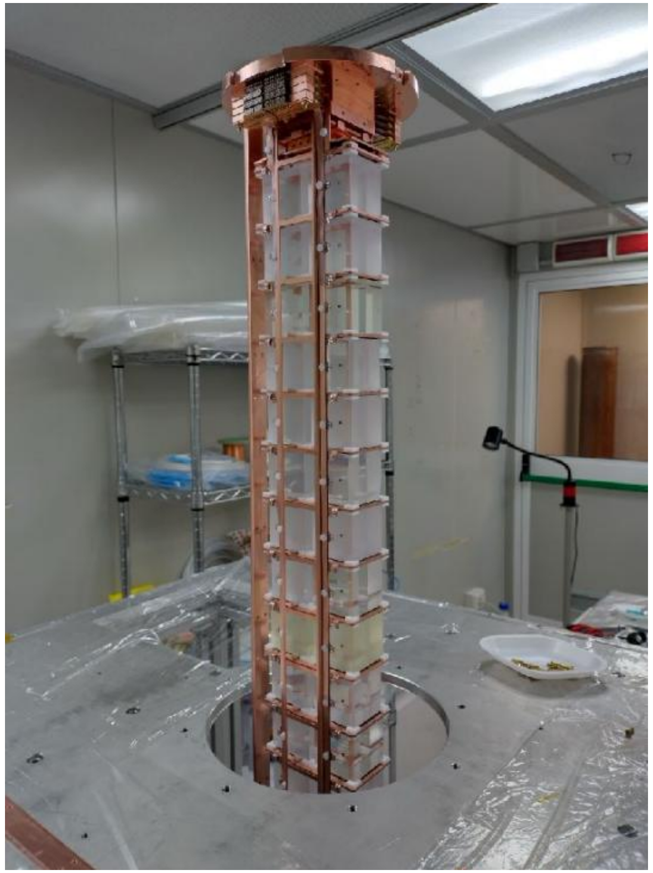


CUPID R&D TESTS

- Many ongoing R&D efforts
- Test runs for tower optimization
  - Assembly procedure
  - Thermalization
  - LMO and LDs performance
  - Vibrational studies
- 1 tower (14 floors, 28 LMO, 30 LDs)

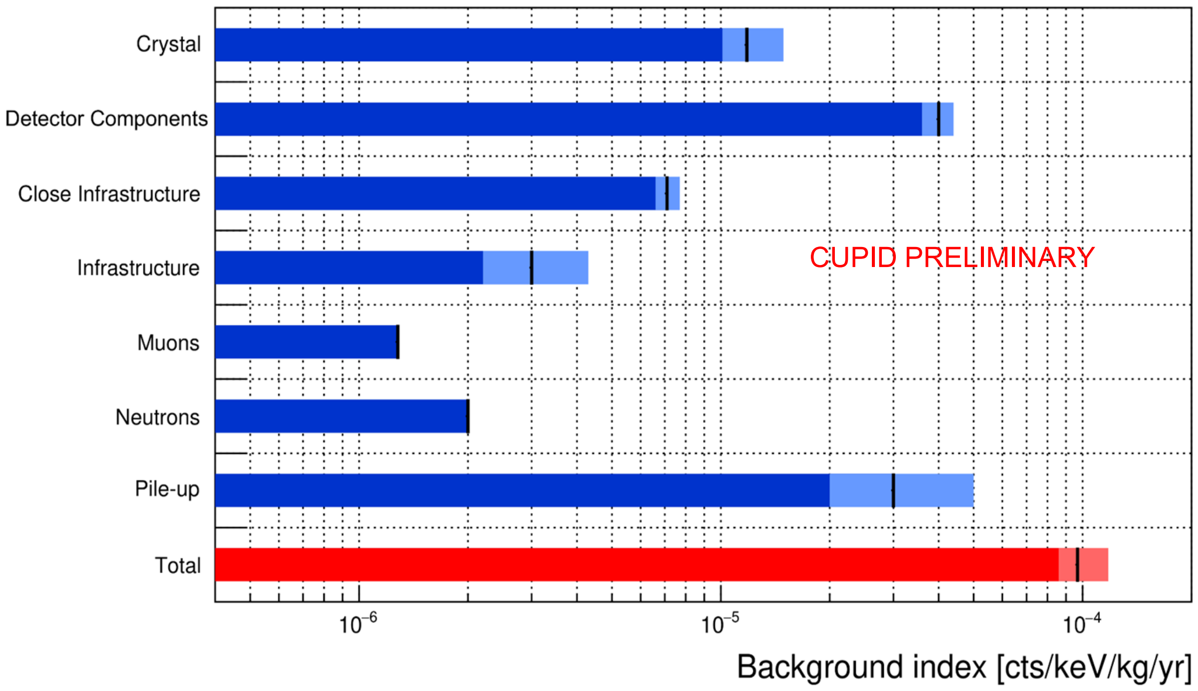




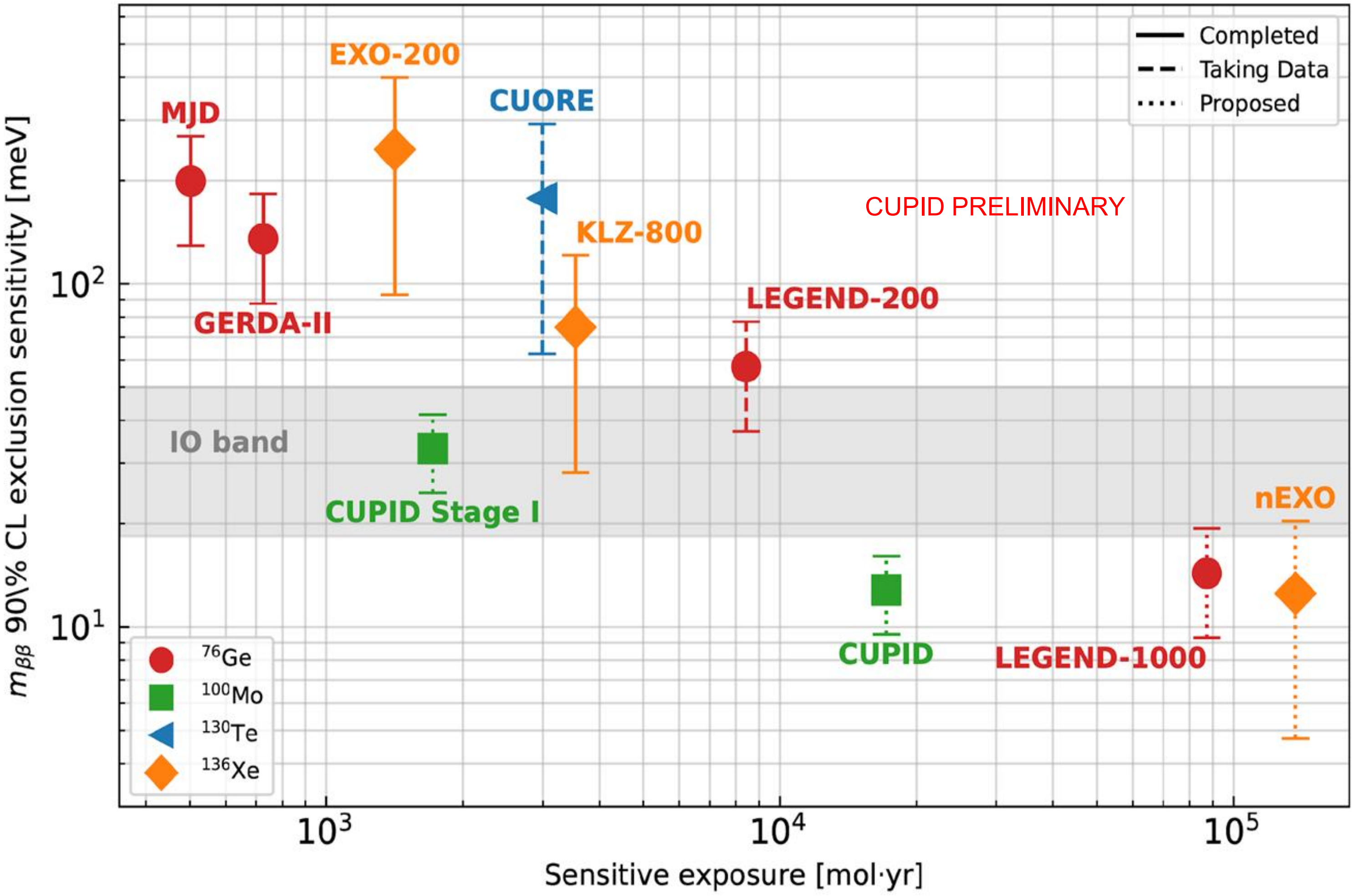


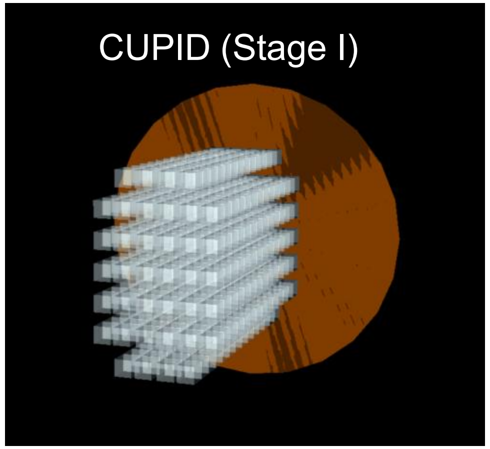
BACKGROUND ESTIMATIONS

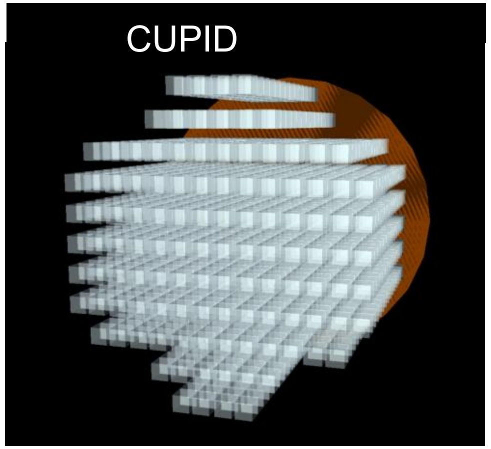
- CUPID background estimates are based on measured contaminations in CUORE and CUPID-Mo
- LMO 100Mo pile-up:
  - Extrapolated from measured performances of NTL light detectors
- Detector components:
  - Holders. Surface driven.
- LMO crystal contaminants:
  - Surface driven. Includes bulk and cosmogenic
- Cryostat & shields:
  - Bulk
- Neutrons and muons:
  - Based on initial design and MC simulation



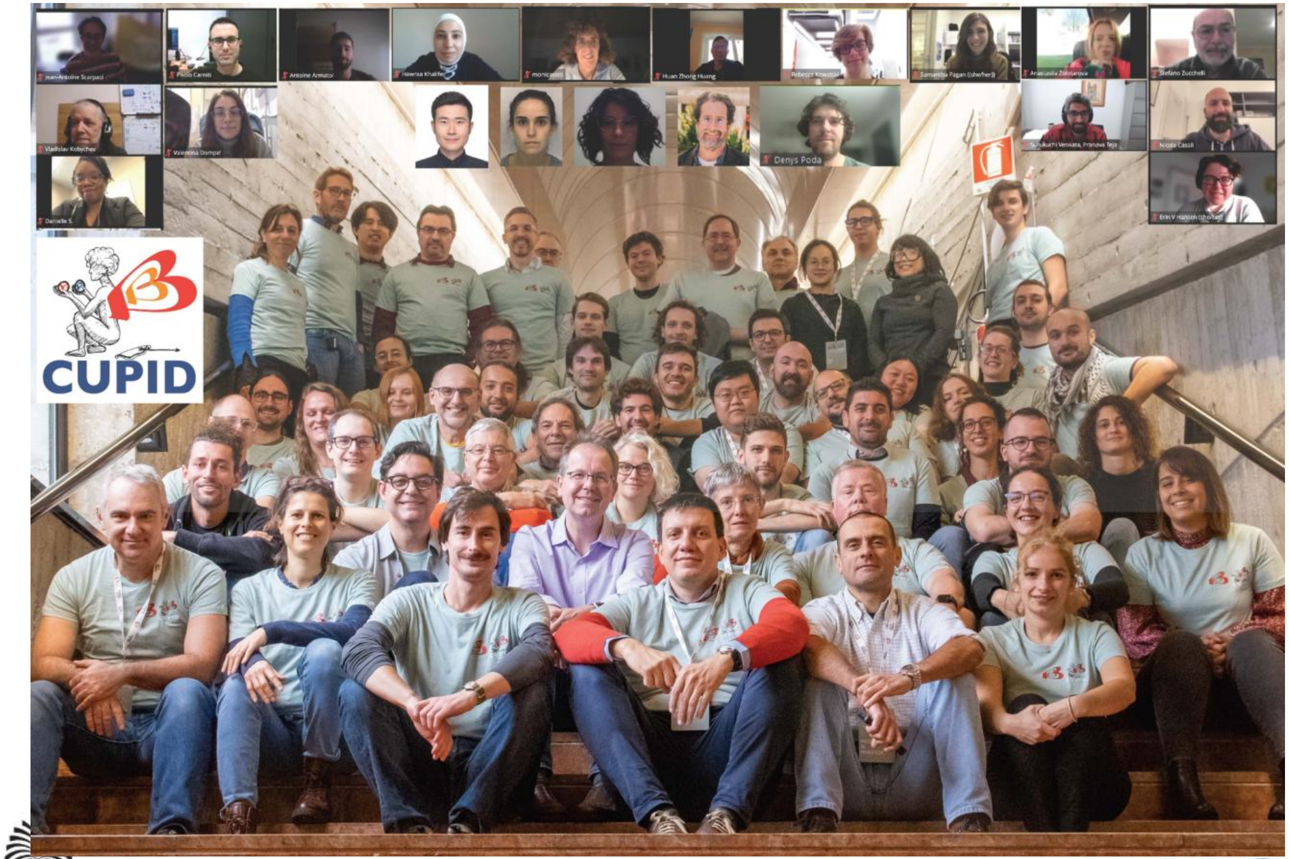
CUPID SENSITIVITY







THANK YOU!



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THE UNIVERSITY OF CALIFORNIA 1868

UCLA

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University of Science and Technology of China 1958

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Argonne NATIONAL LABORATORY

SHANGHAI JIAO TONG UNIVERSITY 1896

Yale

GSSI

EXTRA SLIDES

NEUTRINOLESS DOUBLE BETA DECAY

CUPID 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

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

Effective Majorana mass

Majorana phases

PMNS matrix

Individual neutrino masses

https://github.com/toej93/LobsterPlot

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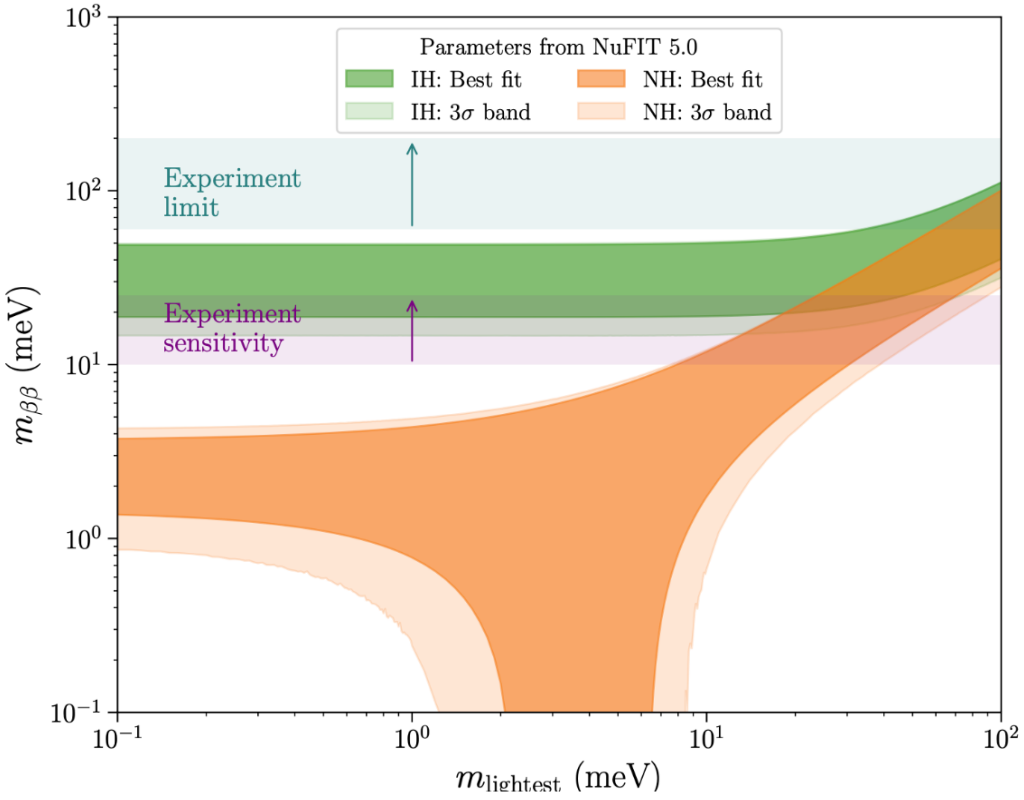

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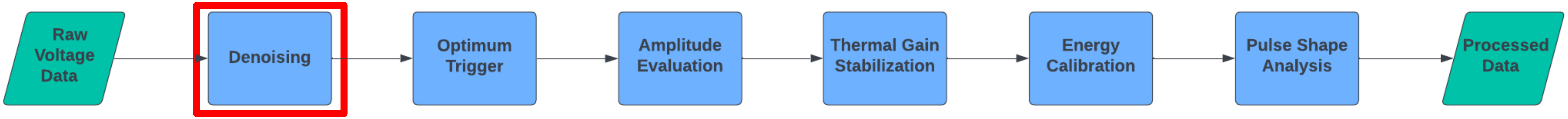
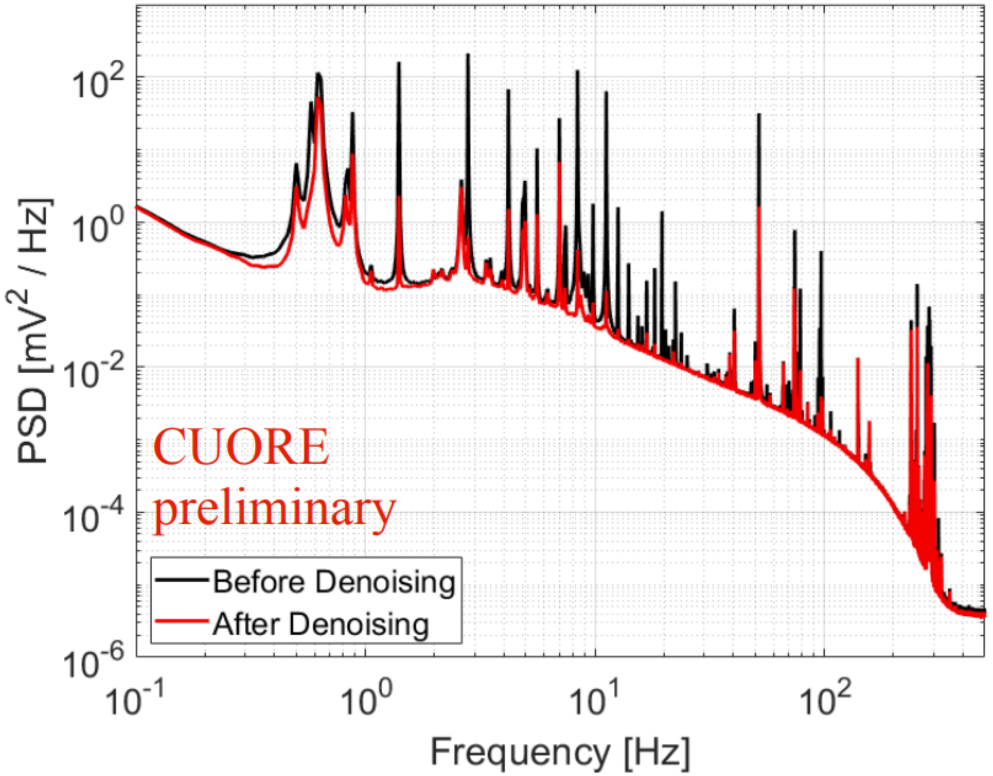
DATA PROCESSING

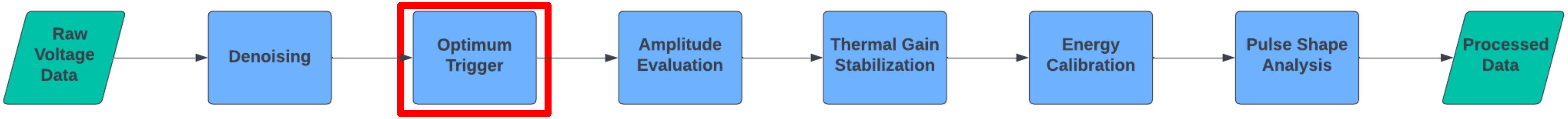


- Denoising
  - Multivariate noise cancelling algorithm to improve detector performance*
  - Uses data from auxiliary devices: Microphones, accelerometers, seismometers

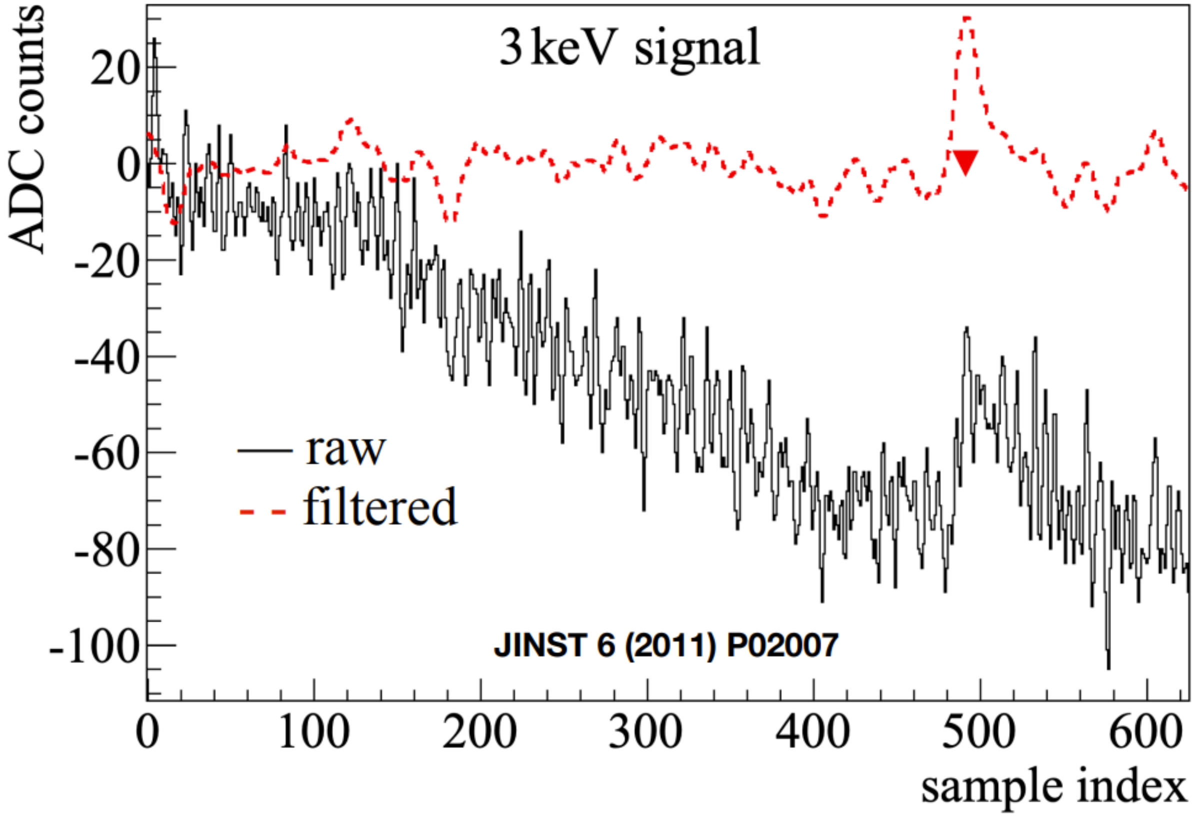


*https://arxiv.org/pdf/2311.01131.pdf

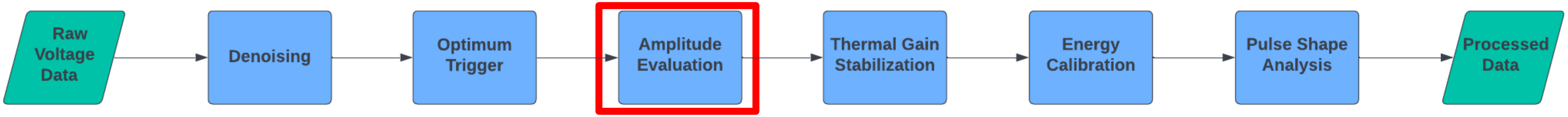
DATA PROCESSING - TRIGGER



- 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

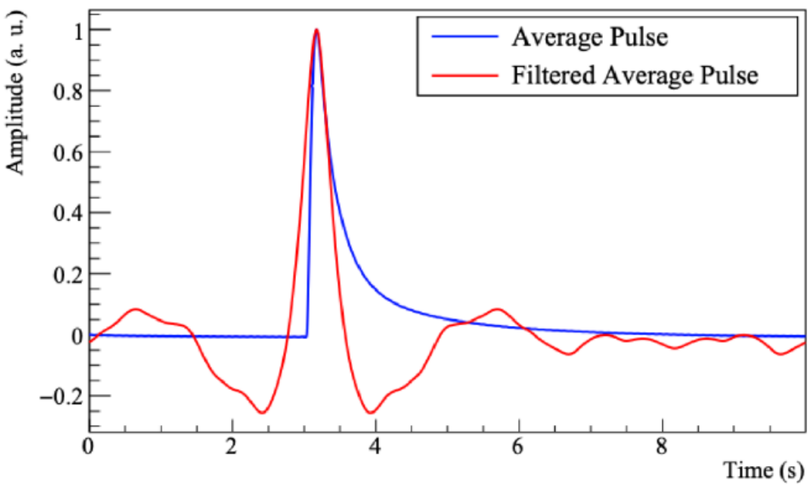


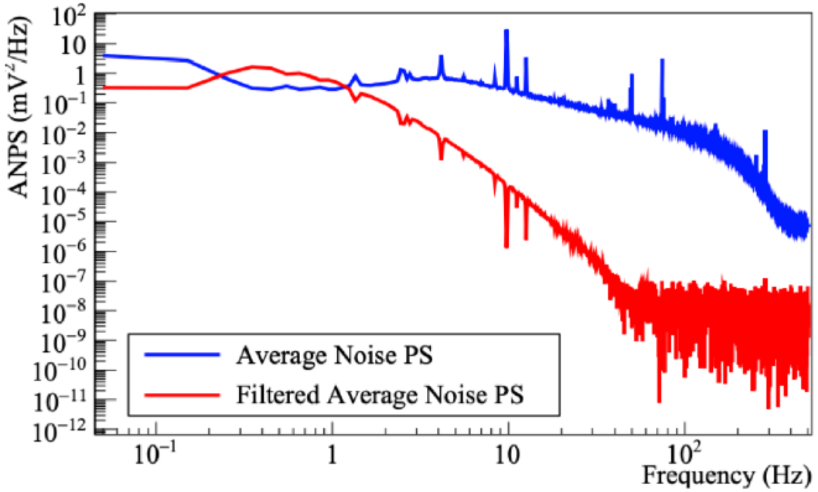
- Amplitude Evaluation
  - Using optimum waveform filter to estimate amplitude of pulses
  - Transfer function of each channel evaluated using average pulse and average noise power spectrum

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

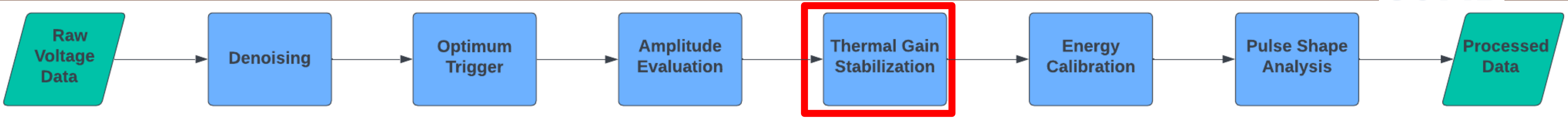
Average Pulse

Average Noise Power Spectrum

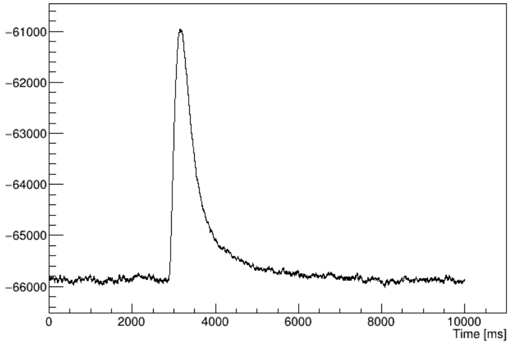


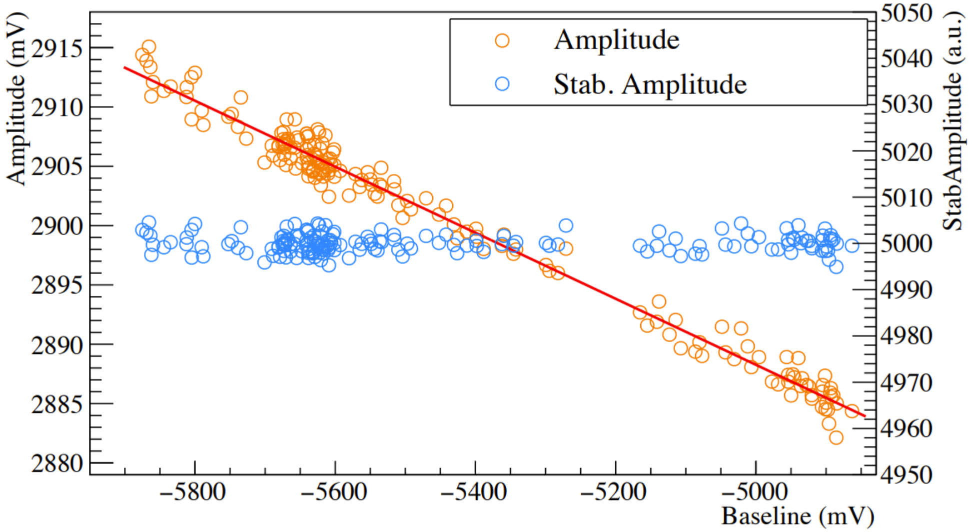


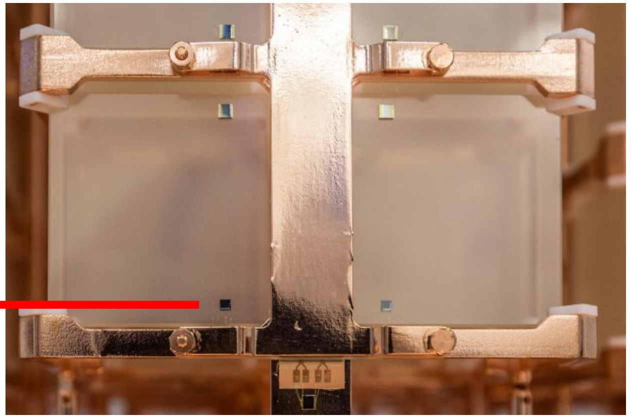
DATA PROCESSING



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



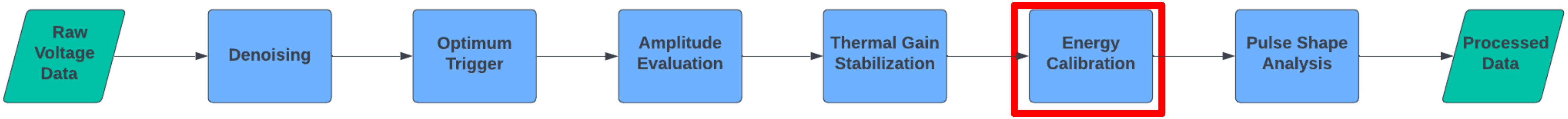




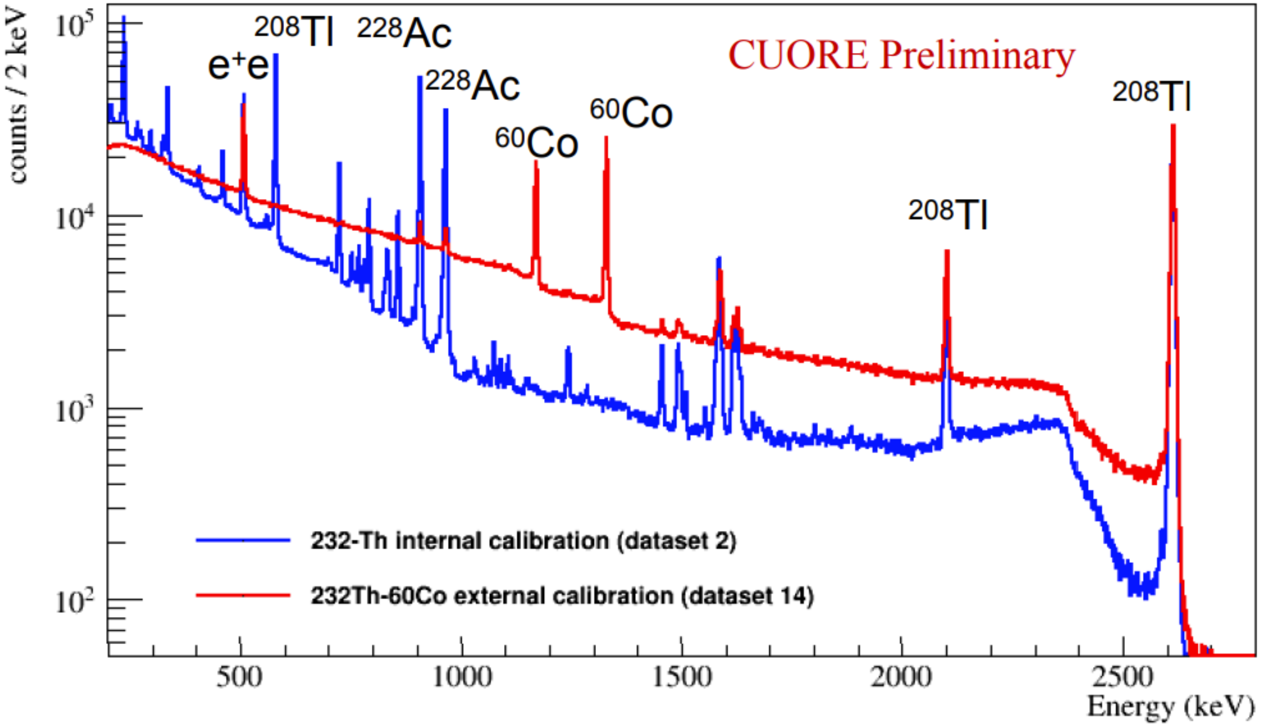
Si Heater

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

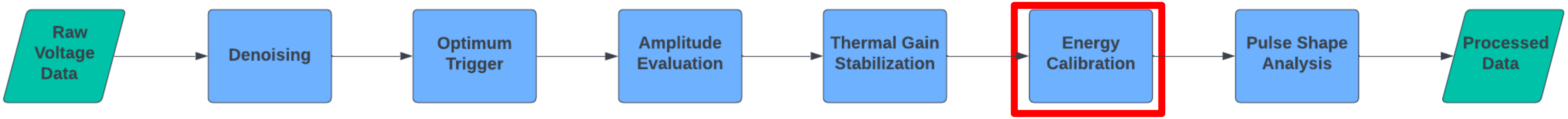
DATA PROCESSING



- 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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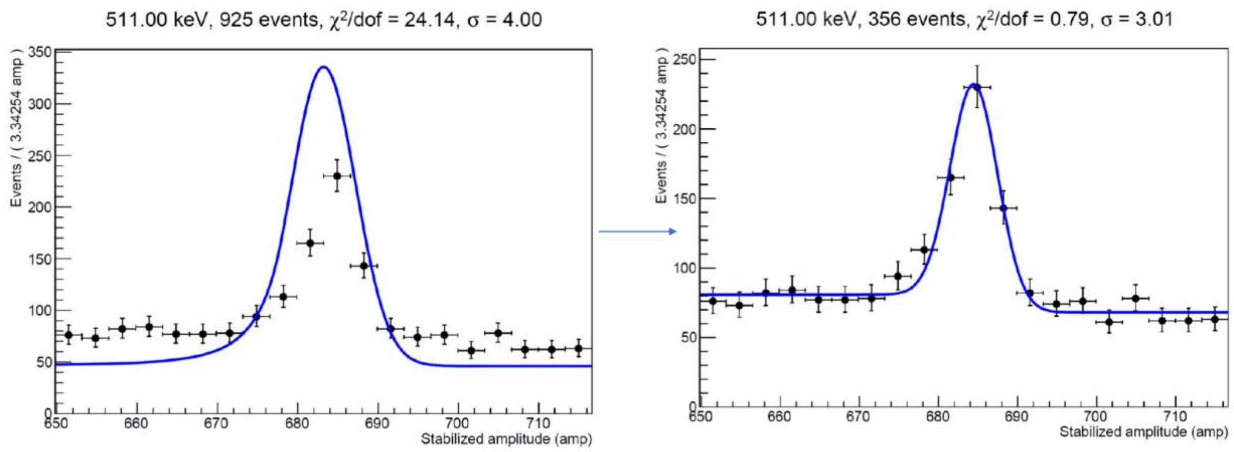
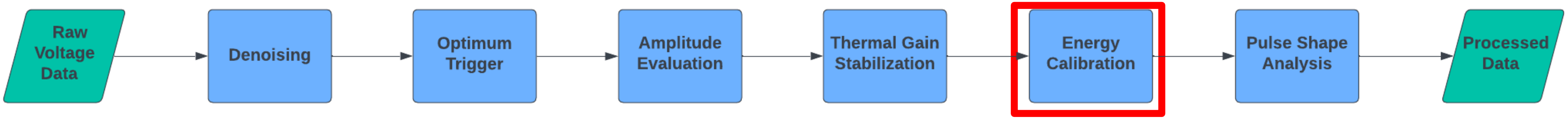


A calibration peak fit with default seeds (left), and fit with iterative algorithm (right)

DATA PROCESSING



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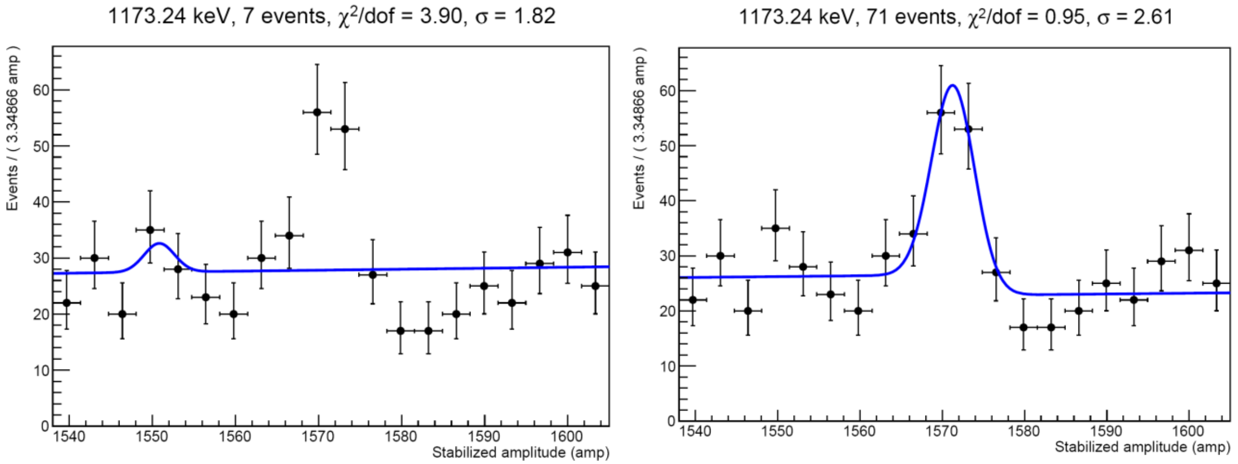
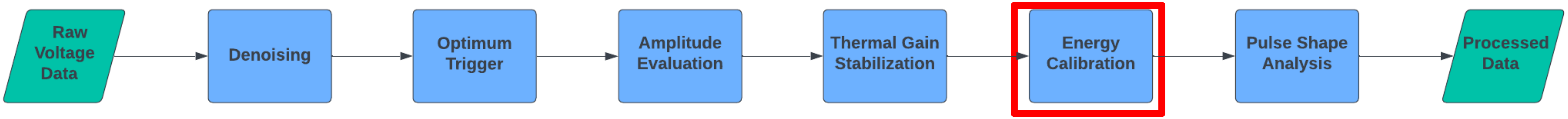


A calibration peak fit by crystal ball function (left), and gaussian (right); algorithm chose the gaussian as the better fit

DATA PROCESSING



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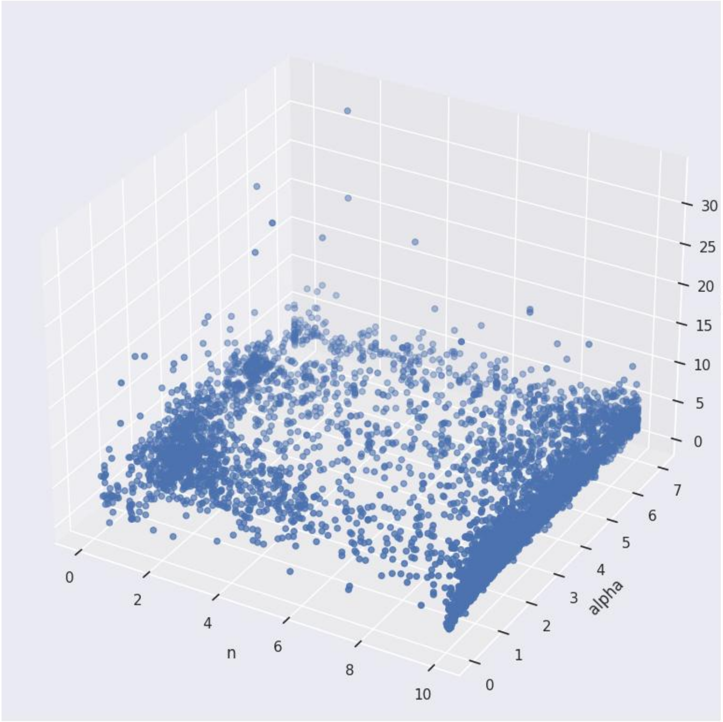
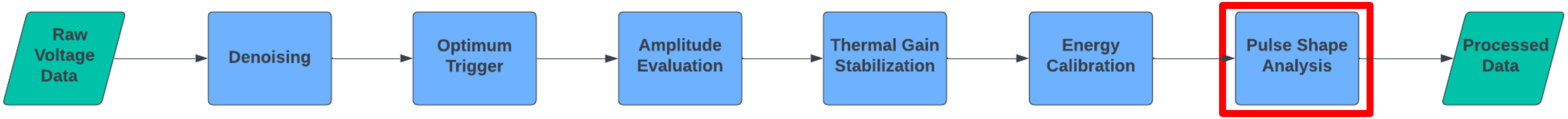


Distribution of fit parameters for a dataset

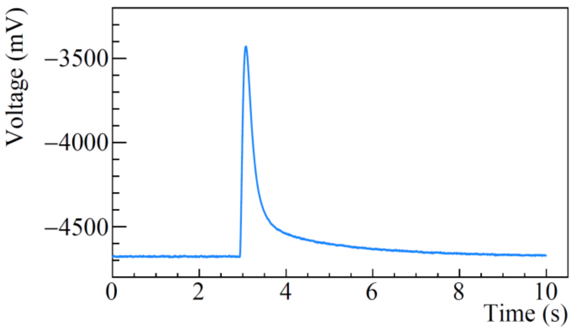
DATA PROCESSING

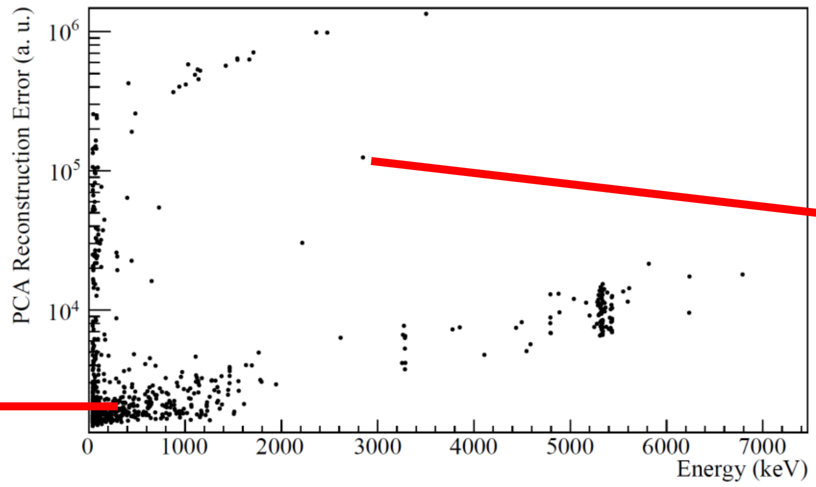


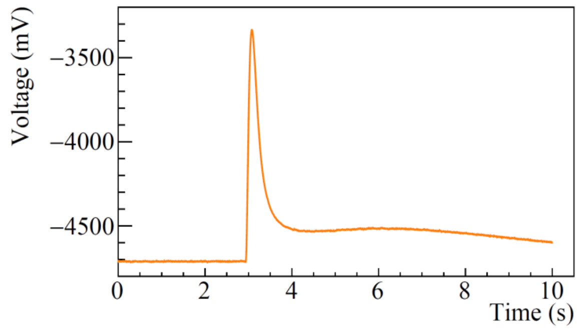
- Pulse Shape Discrimination
  - Using PCA (Principal Component Analysis) to eliminate pulses with a non-physical shape
  - Extract salient features of pulses to calculate reconstruction error for pulse shape discrimination

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

Reconstruction Error







$0\nu\beta\beta$ Analysis Systematics

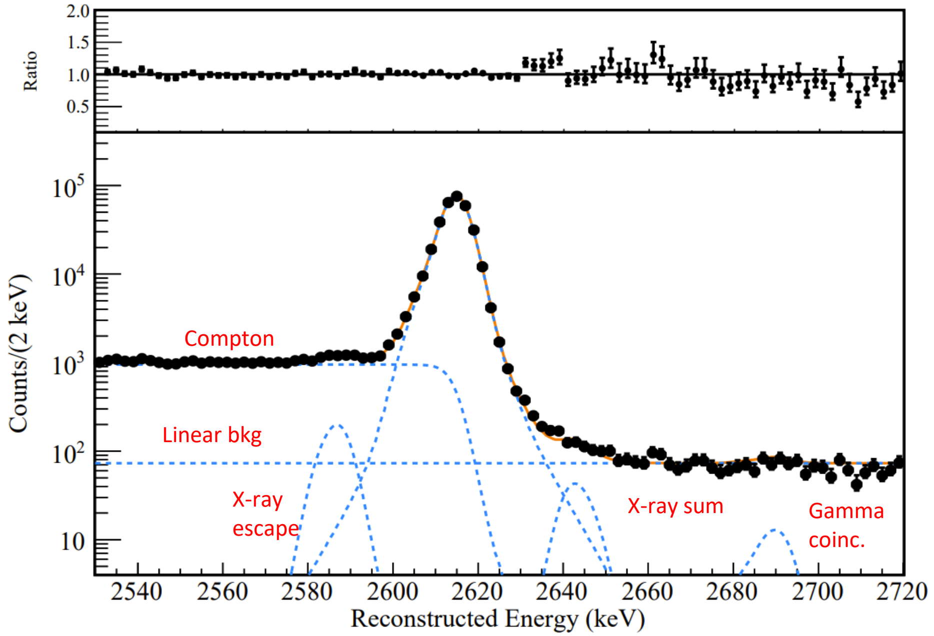
- Uncertainty in the total analysis efficiency. (92.4(2)%)
- Uncertainty in the PCA efficiency. (98.1(2)%)
- Uncertainty in the containment efficiency (88.35 ± 0.090)%
- Uncertainty in the $Q_{\beta\beta}$ (2575.5 ± 0.013) keV
- Tellurium natural isotopic abundance (34.167 ± 0.002)%
- Uncertainties in the bias and resolution scaling

CUORE DETECTOR RESPONSE

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

$$\Delta E_{2615keV} = 7.32 \pm 0.024\ \mathrm{keV}$$

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

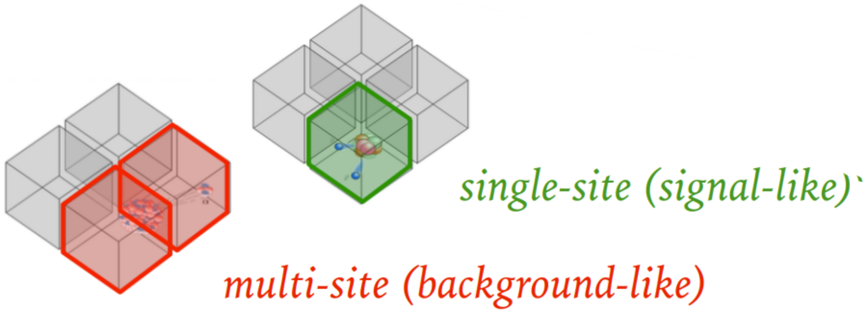


$$\Delta E_{Q_{\beta\beta}} = 7.26^{+0.43}_{-0.47}\ \mathrm{keV}$$

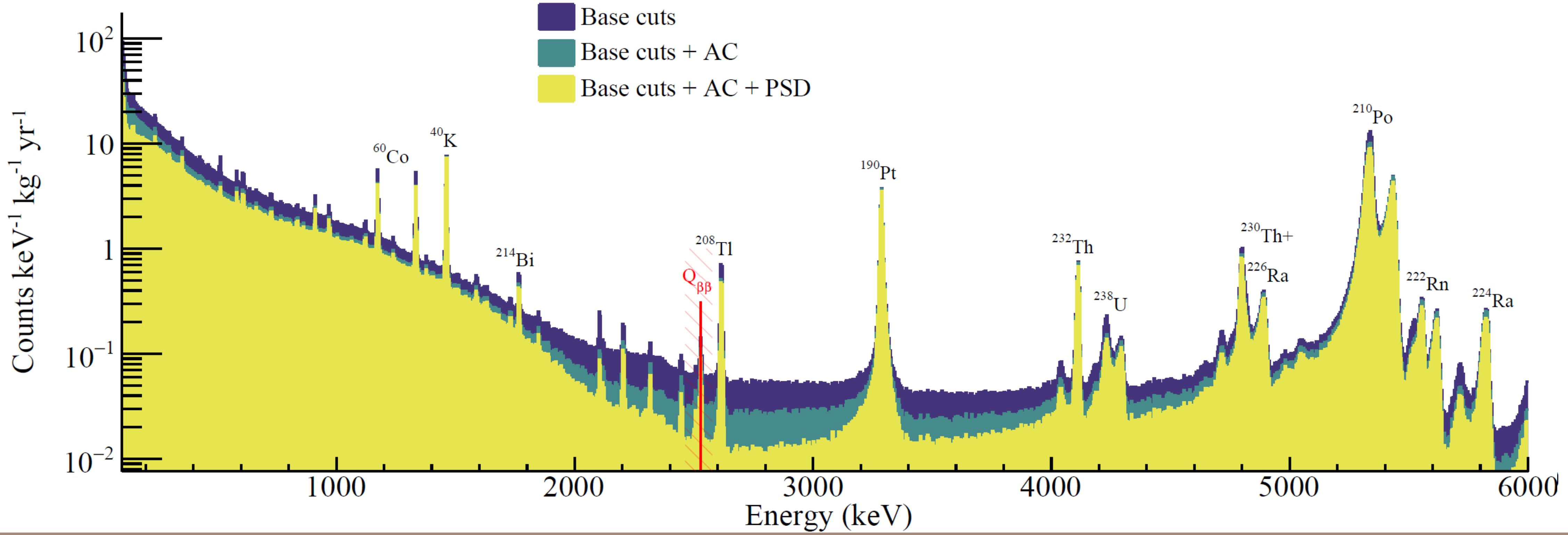
$$E_{bias} = -0.52^{+0.04}_{-0.30}\ \mathrm{keV}$$

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

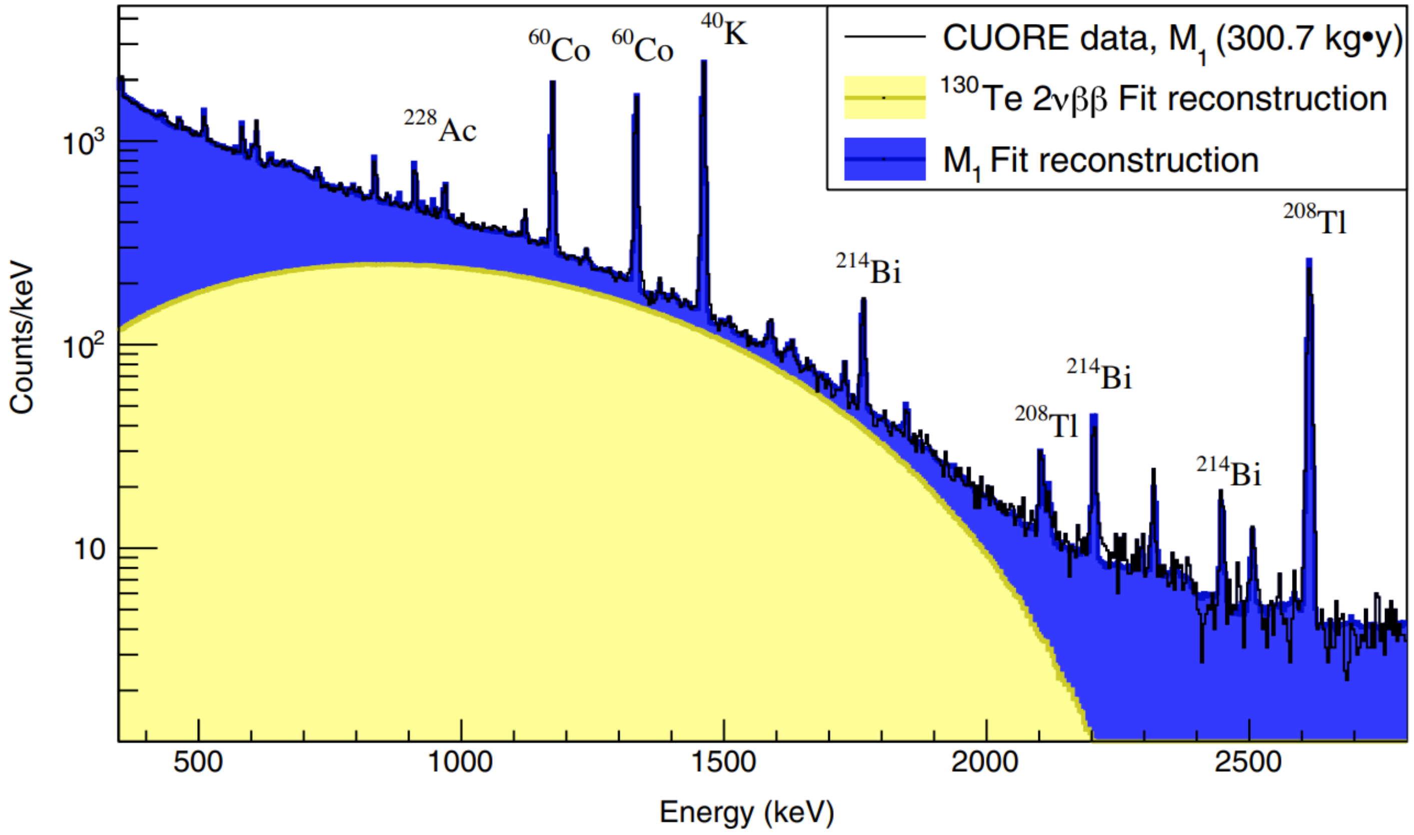


88% of 0νββ events occur in a single crystal



DOUBLE BETA DECAY RESULTS

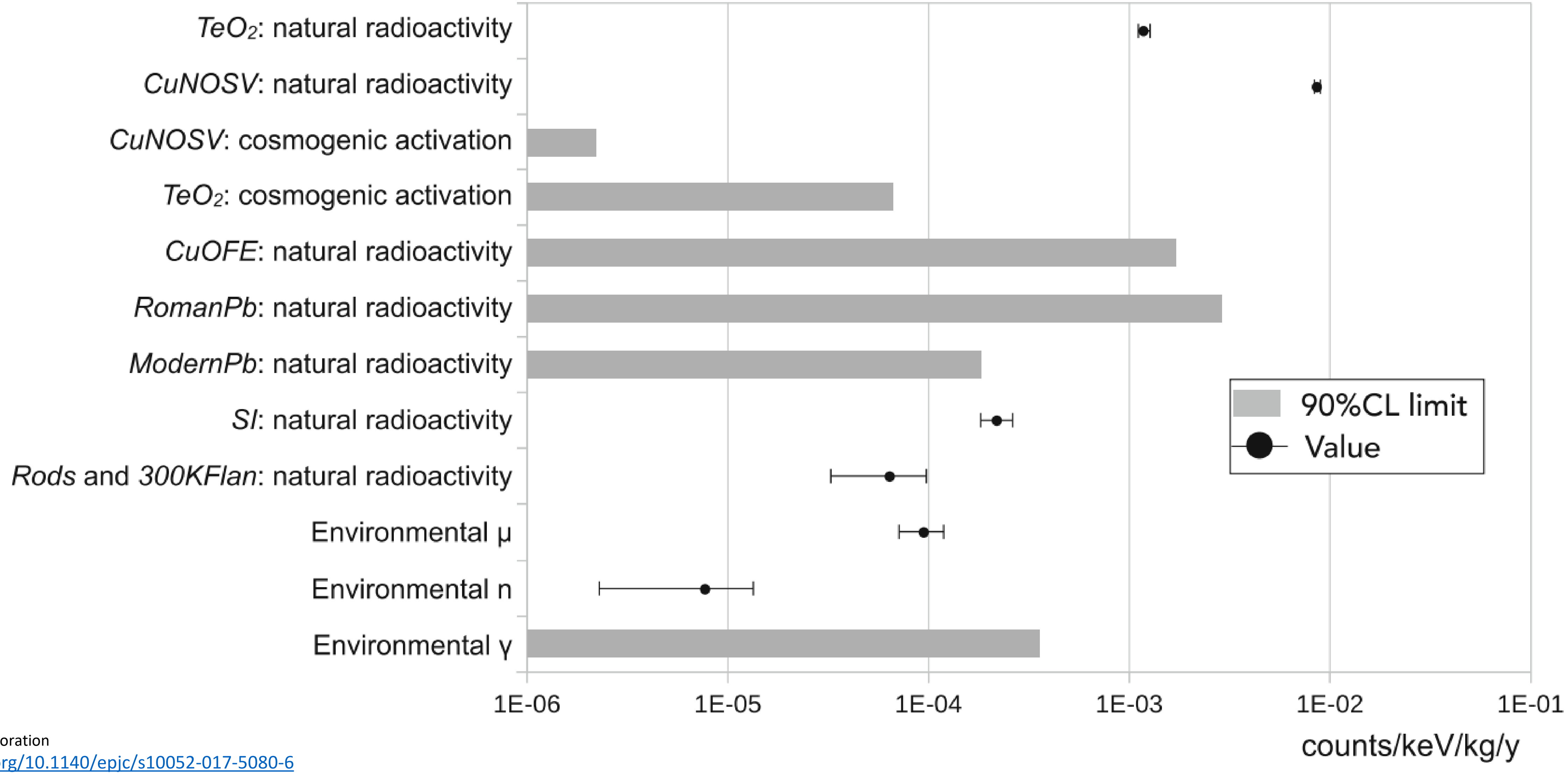
- Double beta decay simulated in Geant4 with CUORE geometry and detector response
- Spectrum reconstructed by simultaneous fit of data with 62 MC simulated sources (2νββ + surface and bulk contaminations + muons)
  - MCMC Bayesian approach
  - Uniform prior for sources except muons
- For 900-2000 keV,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

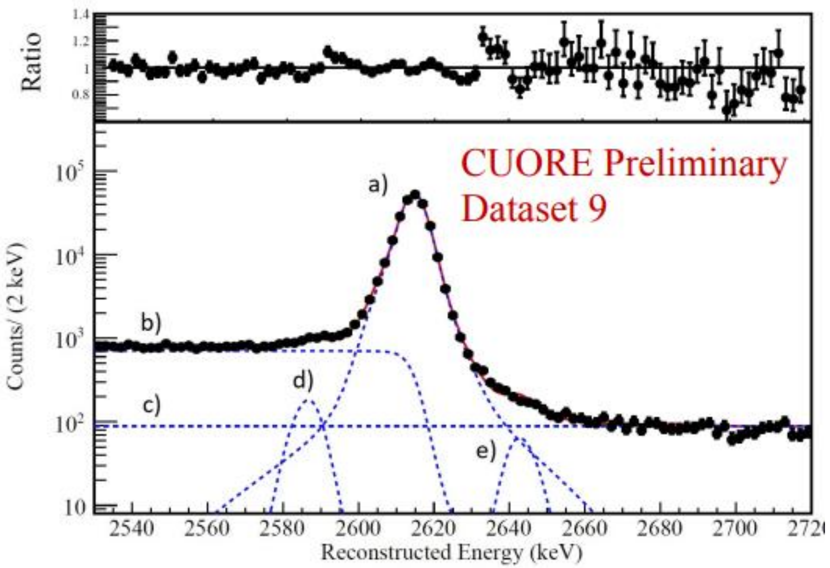
BACKGROUND BUDGET

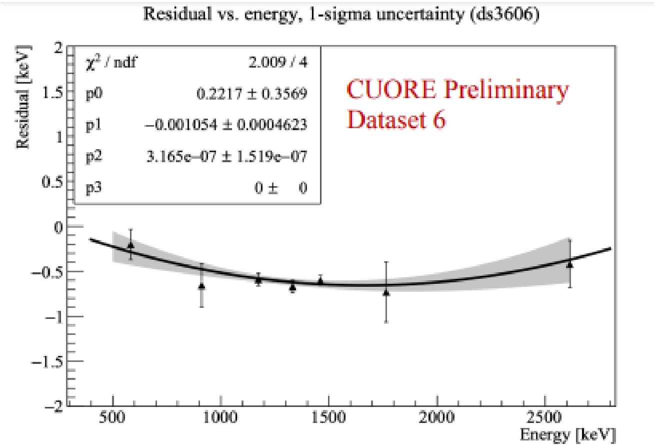


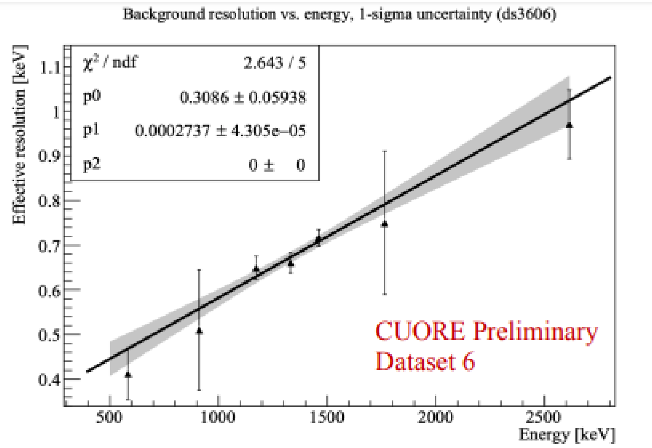
*CUORE collaboration
https://doi.org/10.1140/epjc/s10052-017-5080-6

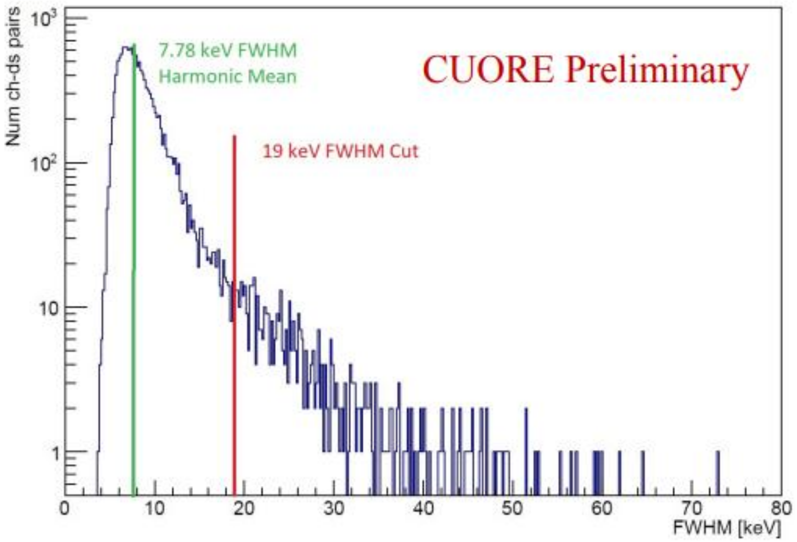
DETECTOR RESPONSE

- 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



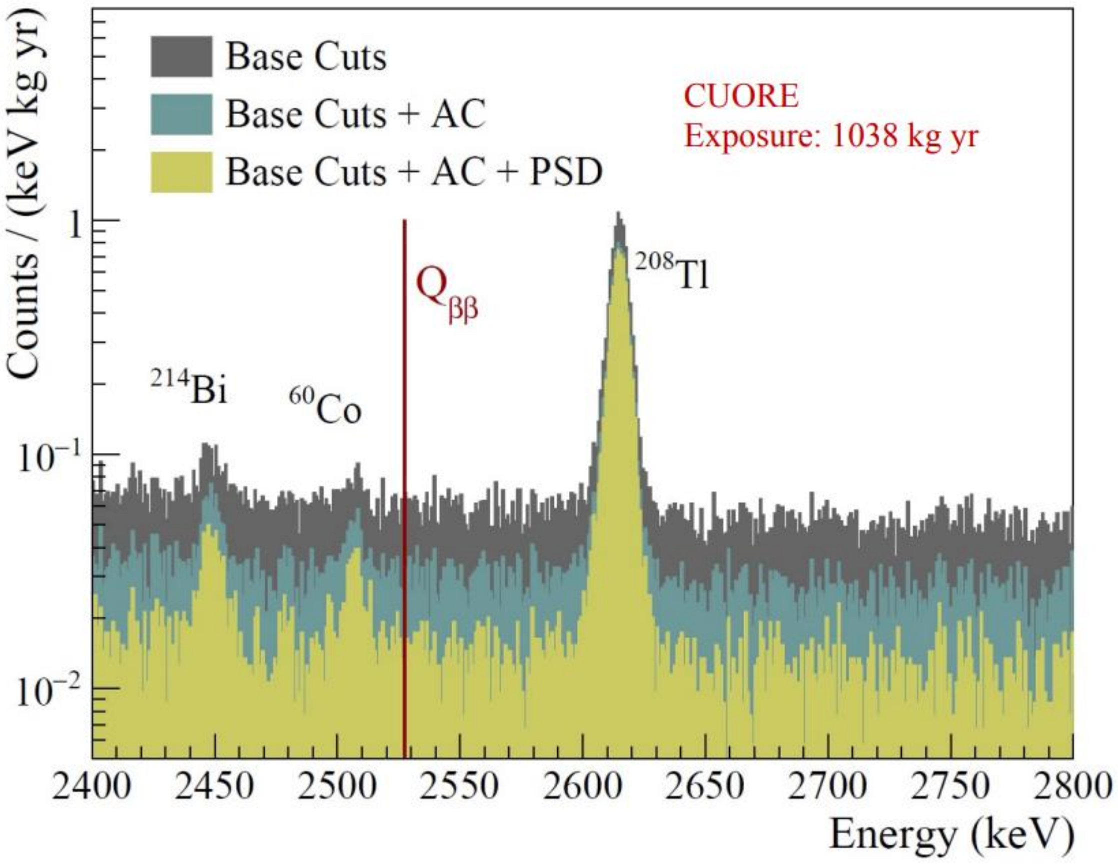






BACKGROUND IN ROI

- 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

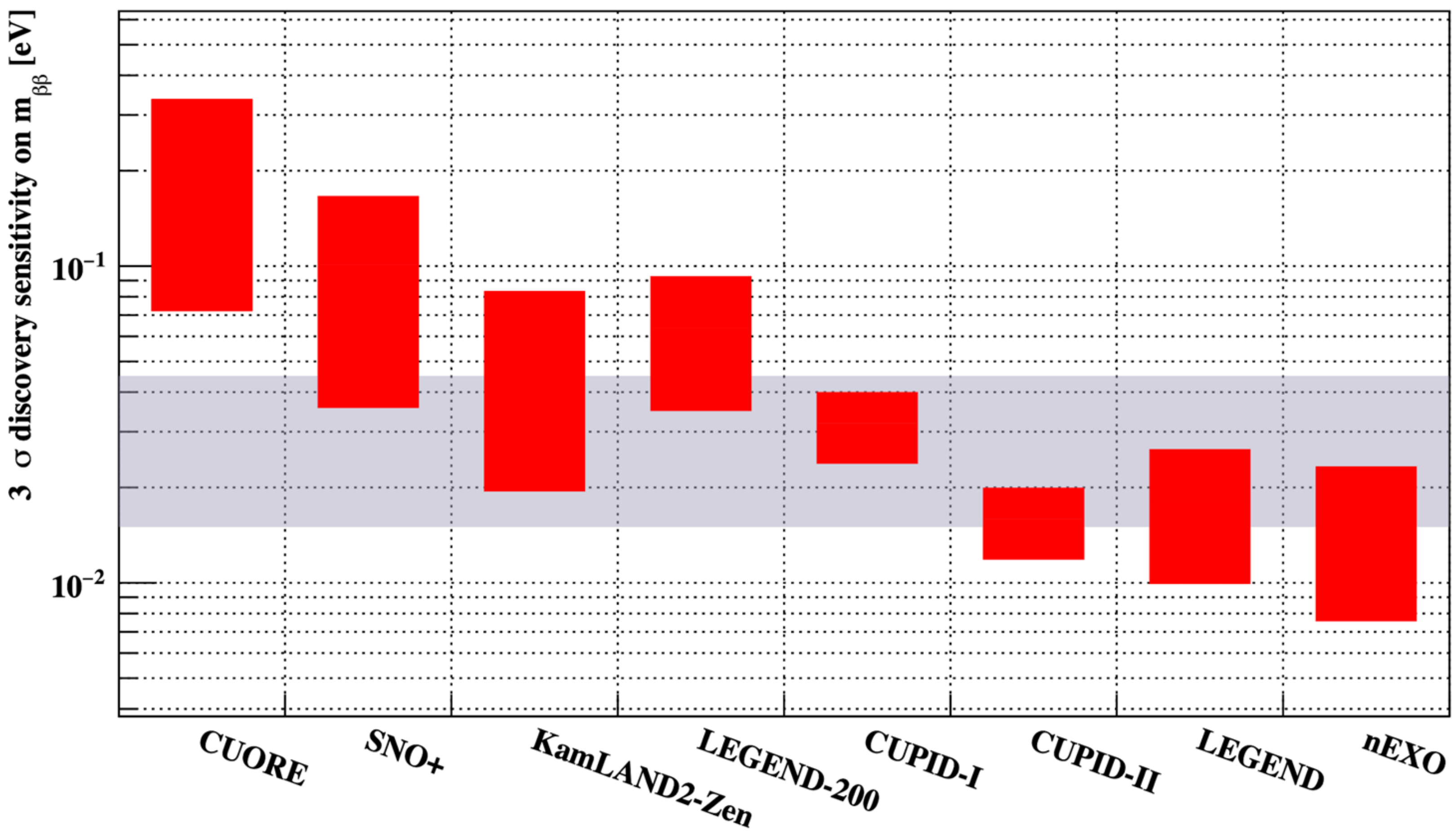
CUORE UPGRADE WITH PARTICLE IDENTIFICATION

- Next generation 0νββ 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

CUPID Discovery Sensitivity

Sensitivity

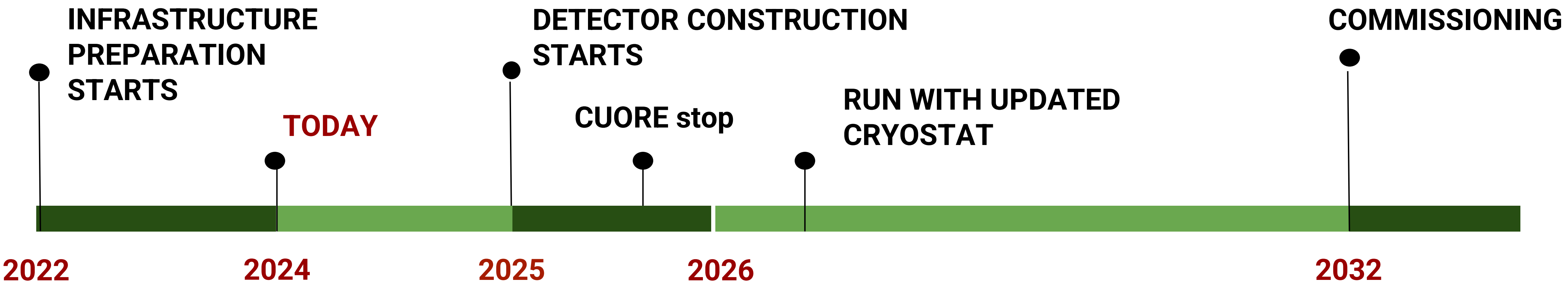


CUPID is critical to the discovery program at LNGS.

Staged deployment enables first science data by 2030 with CUPID Stage I

Ton-scale experiment with competitive sensitivity

CUPID Timeline



★ $Li_2{}^{100}MoO_4$ pre-production

★ $Li_2{}^{100}MoO_4$ production

★ detector design prototype and test
★ infrastructure preparation (clean-room, assembly line, cryogenic test facilities at LNGS …)

★ cryostat upgrade and commissioning

★ detector assembly