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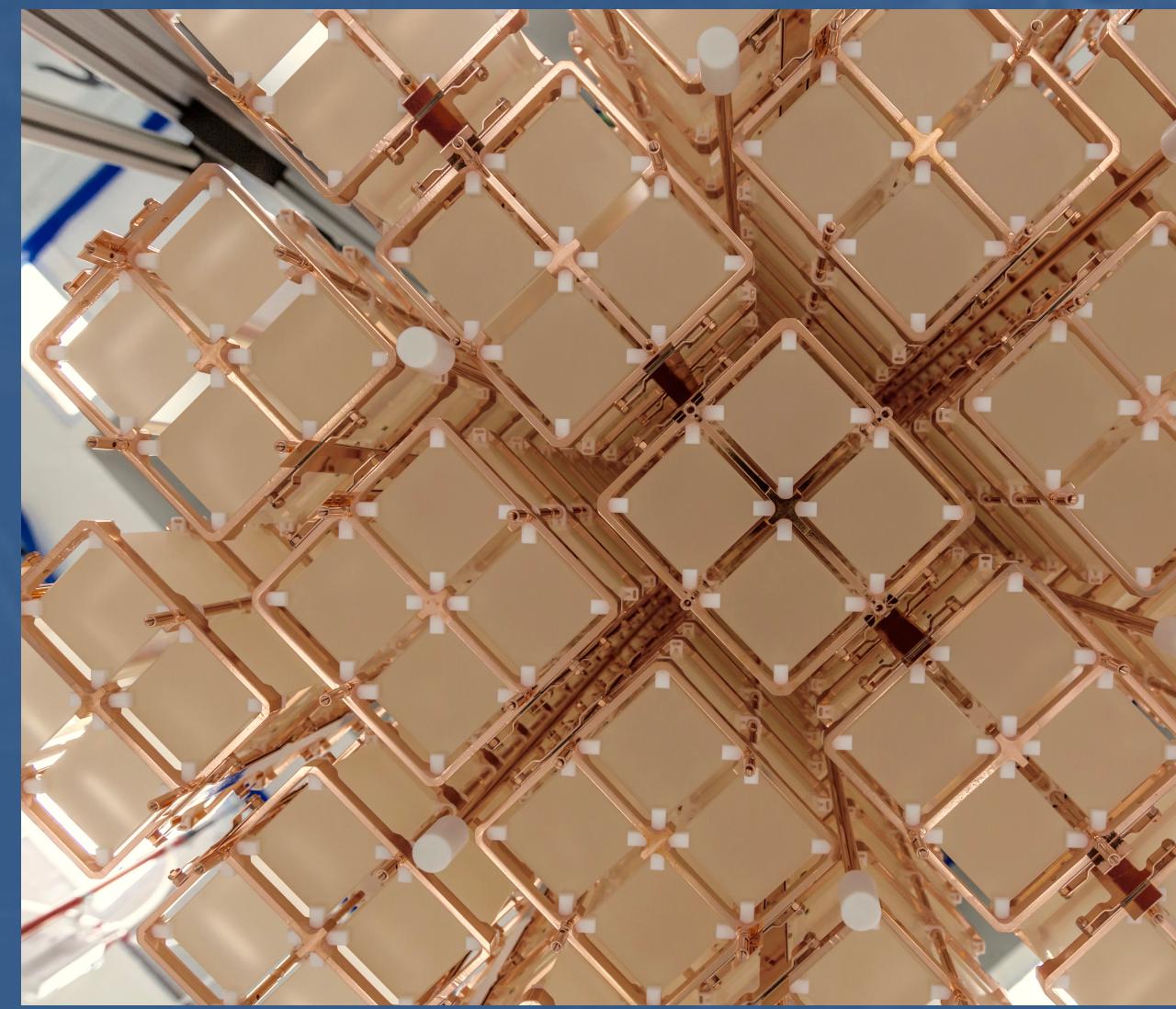


U.S. DEPARTMENT OF
ENERGY

CUORE: The First Bolometric Experiment at the Ton Scale for the Search for Neutrinoless Double Beta Decay

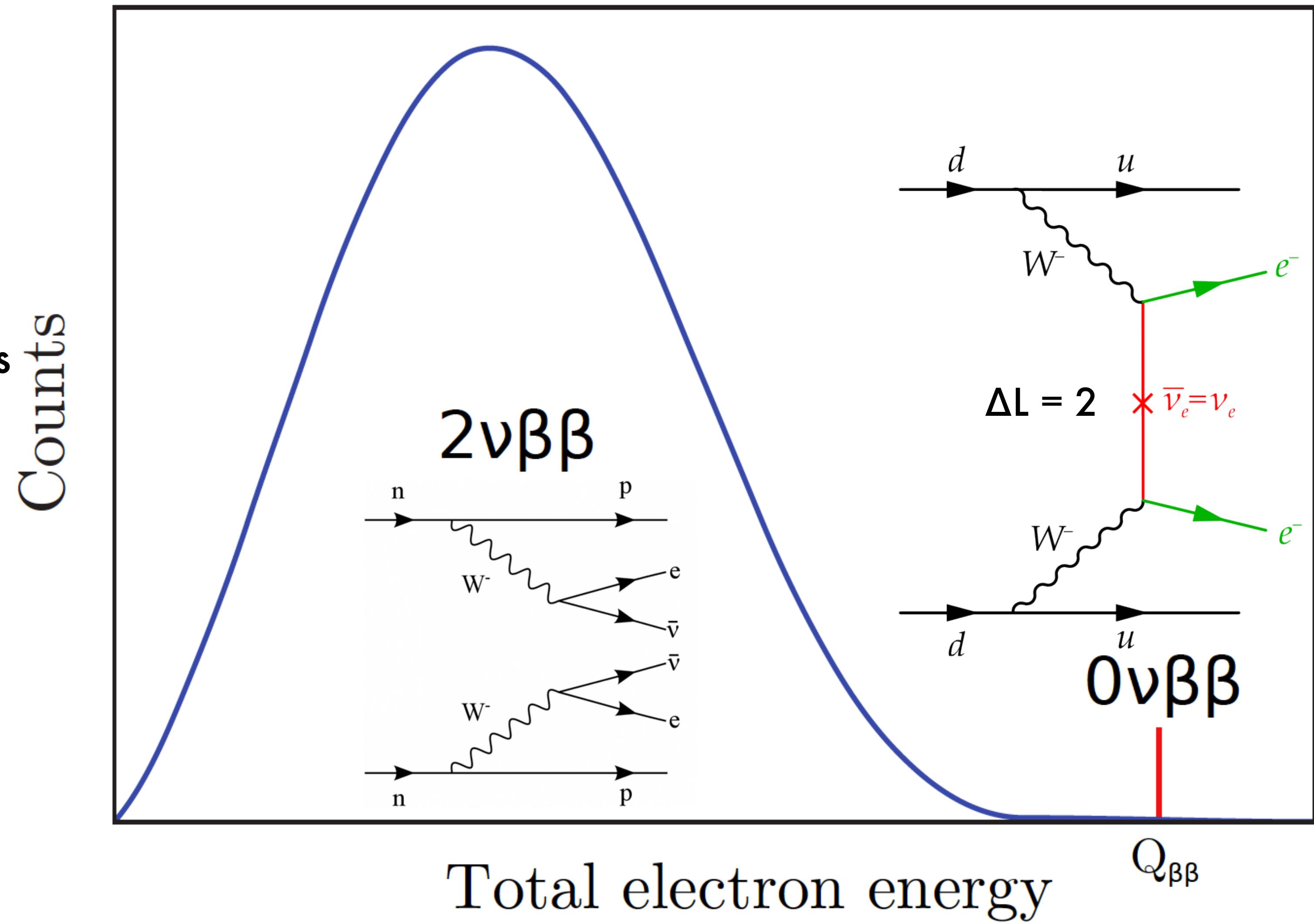


VCI 2019
B. Welliver
2019-02-22



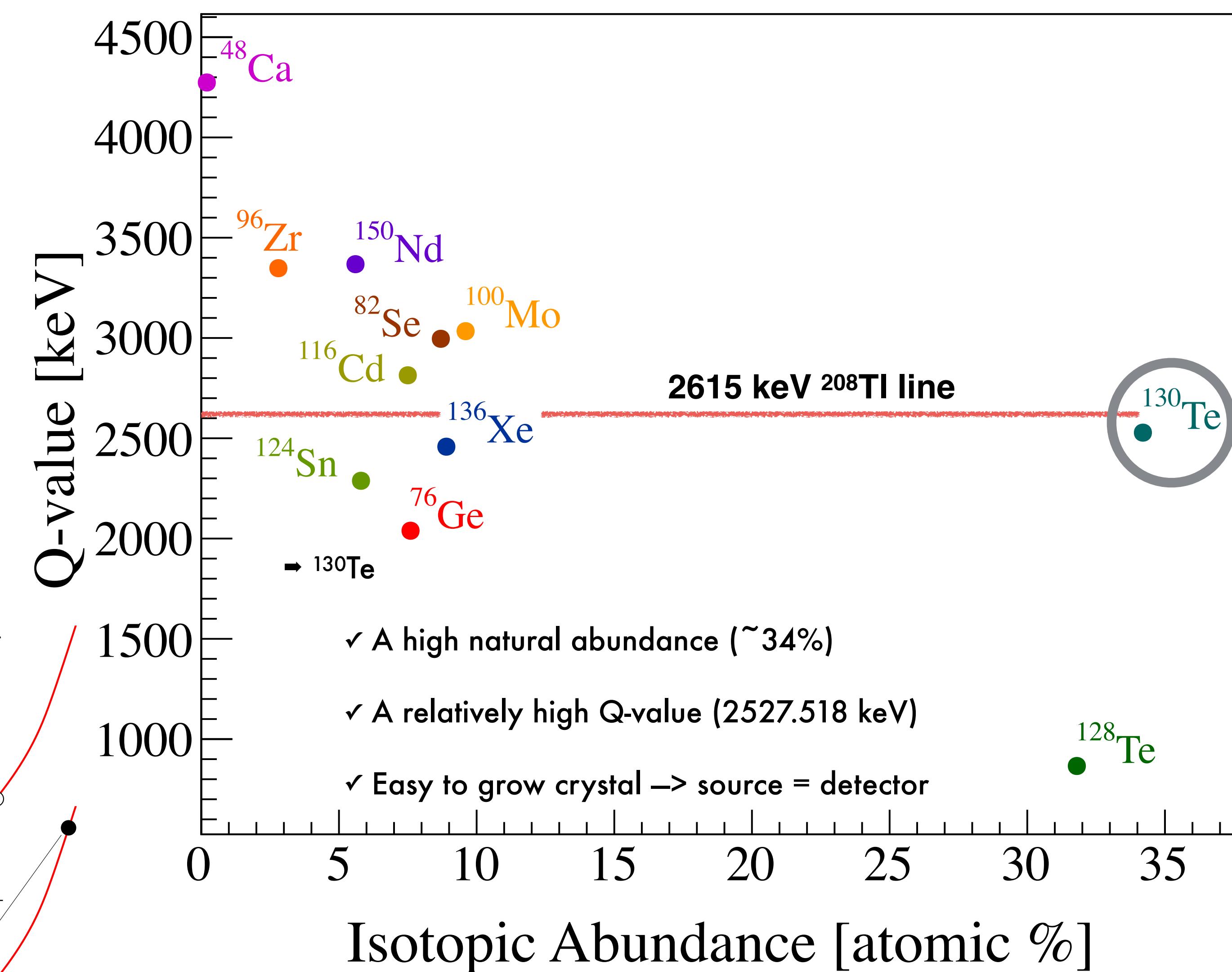
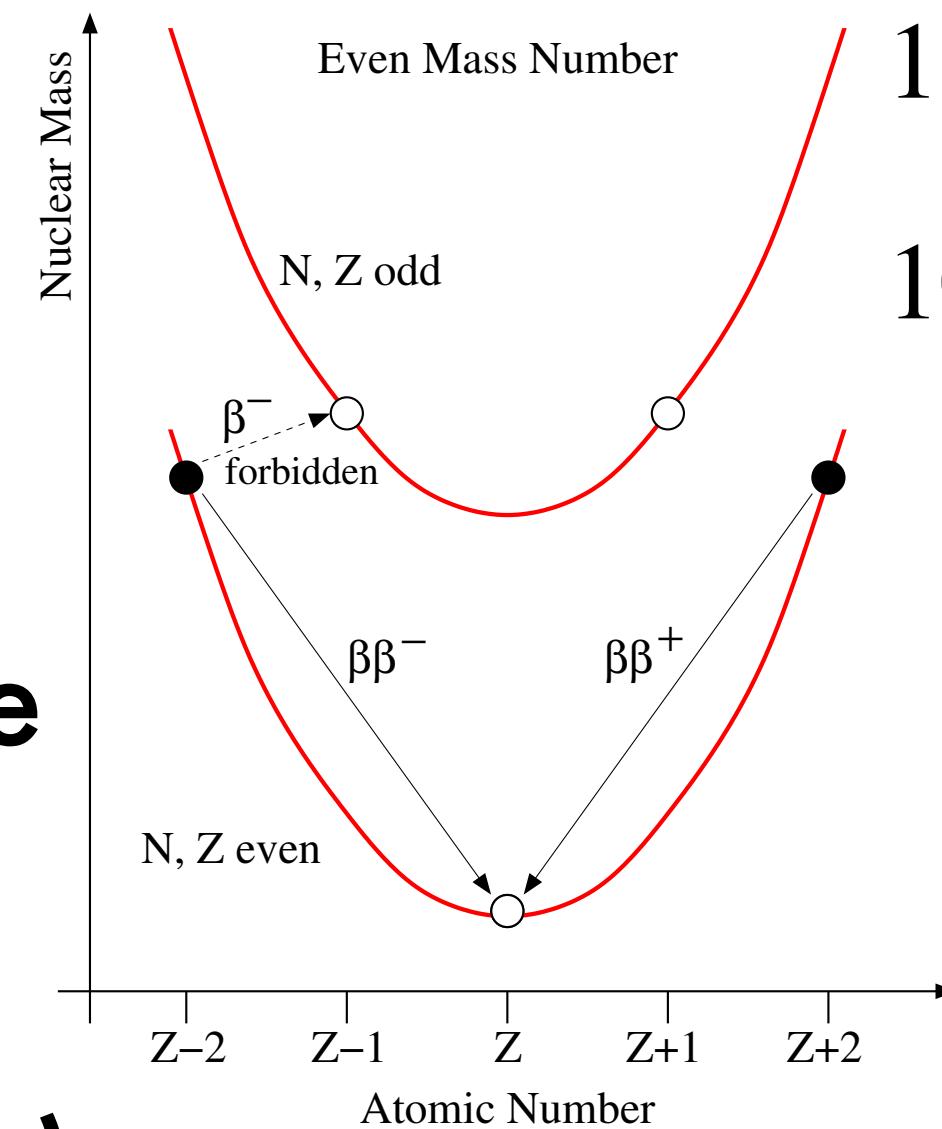
Double Beta Decay

- $2\nu\beta\beta$ is a rare standard model process
- Broad energy distribution
- Observed half-life $\tau > 10^{19}$ years
- $0\nu\beta\beta$ is a hypothetical, unobserved process
- Immediate implication of $\Delta L \neq 0$
 - Lepton number violation = new physics!
 - Can imply Majorana mass of ν
 - Possible connection to baryon asymmetry



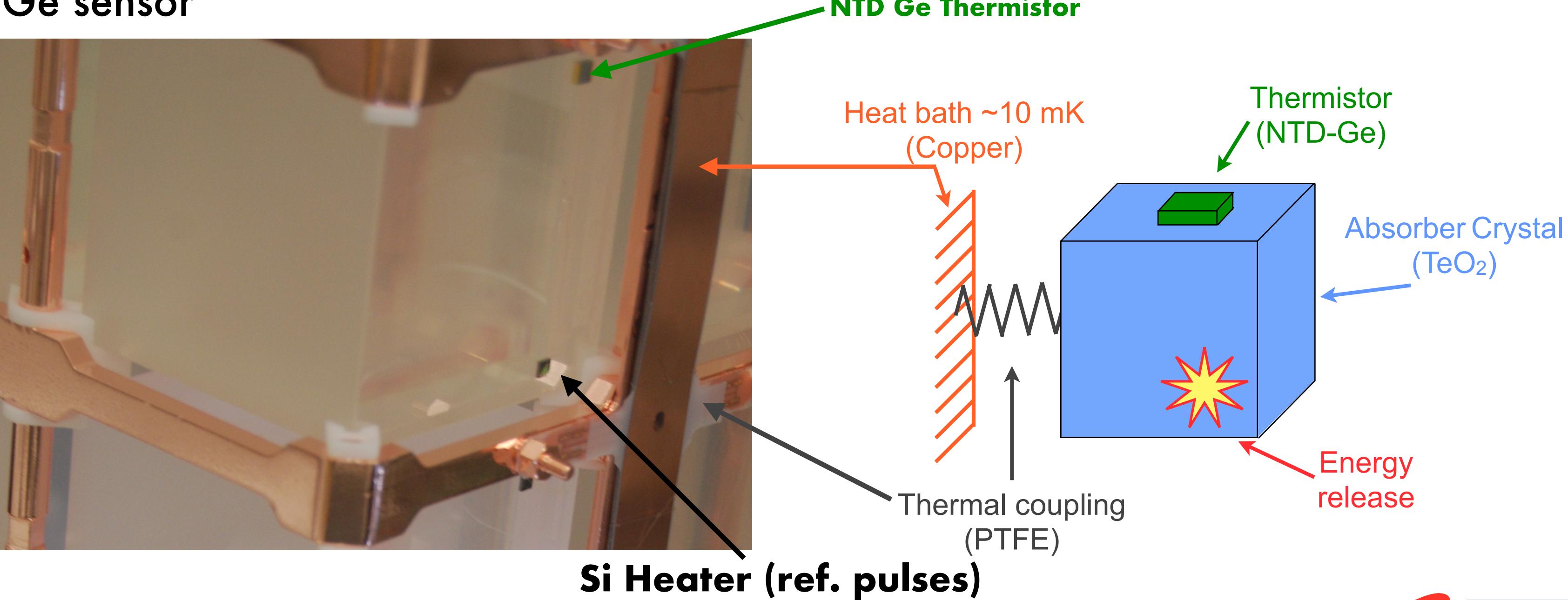
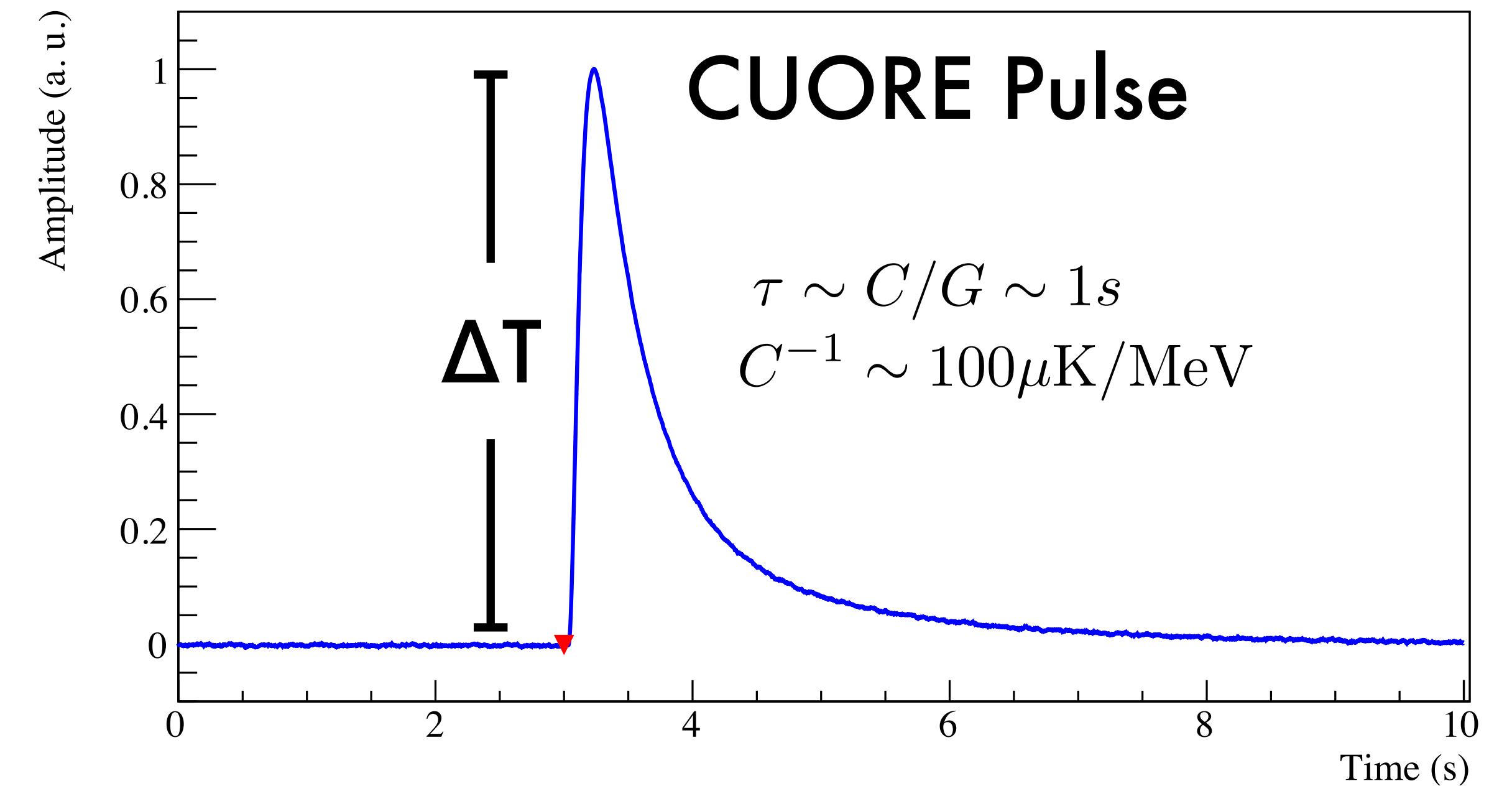
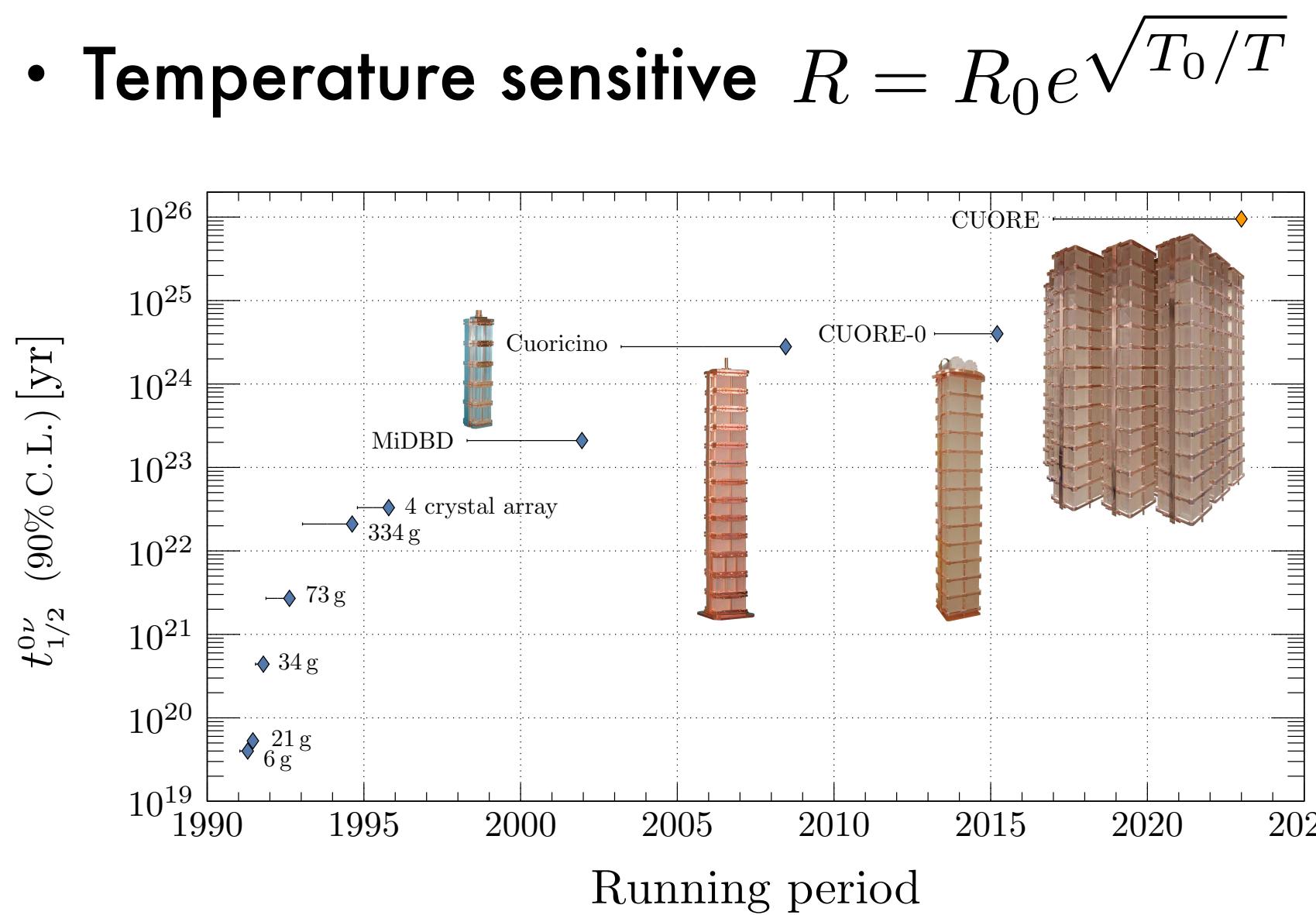
Isotope Choice

- Look at $2\nu\beta\beta$ isotopes with even-even nuclei
 - β -decay energetically forbidden
- Desired traits for $0\nu\beta\beta$ search isotope
 - High isotopic abundance (active mass)
 - High Q-value (low γ bkg)



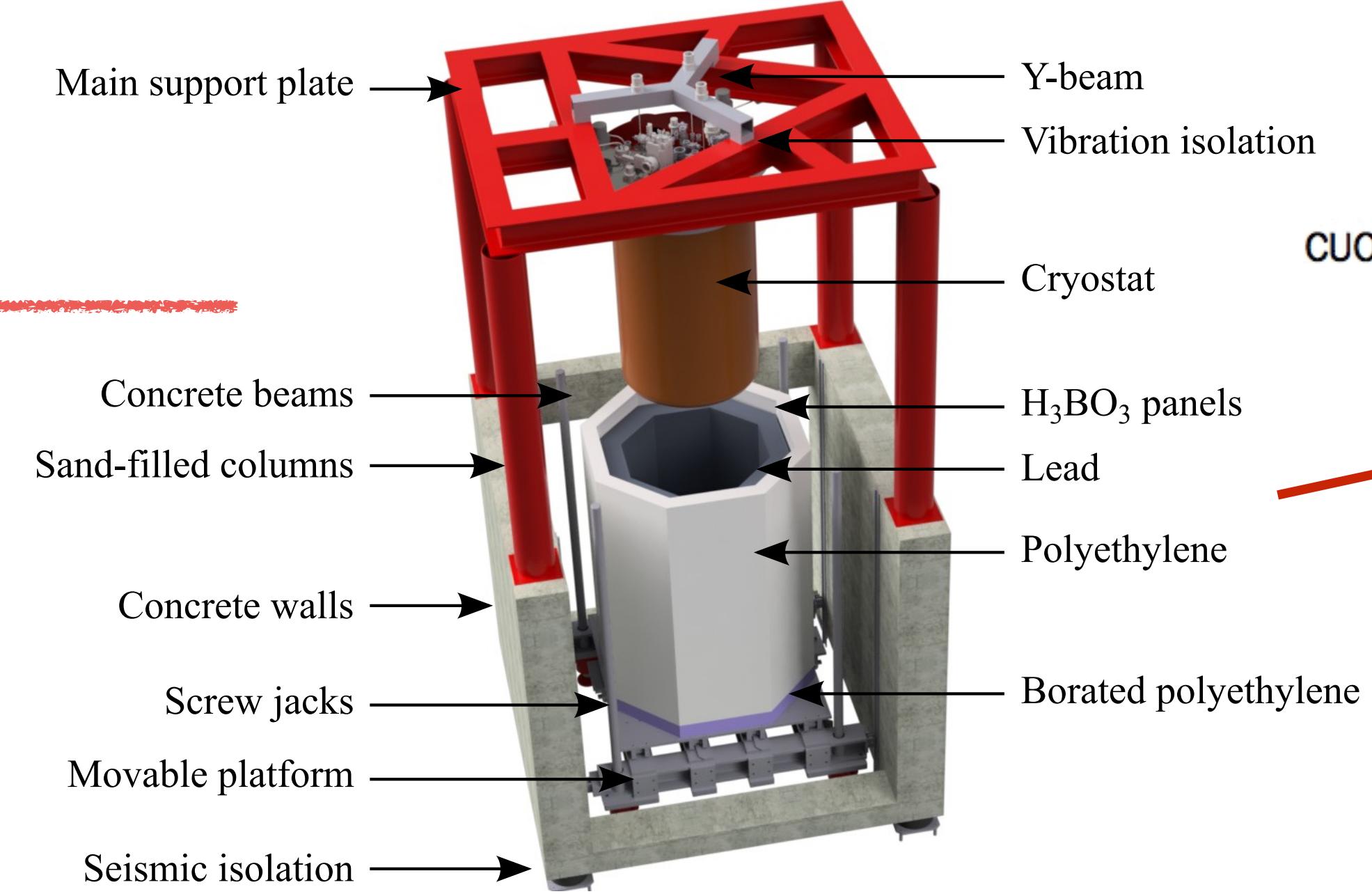
Bolometric Sensor

- Sensitive devices with good energy resolution
- Deposited energy changes temperature $\Delta T = \frac{E_{ev}}{C_{crys}}$
- CUORE TeO₂ crystals
- 5 cm x 5cm x 5cm
- Neutron transmutation doped (NTD) Ge sensor

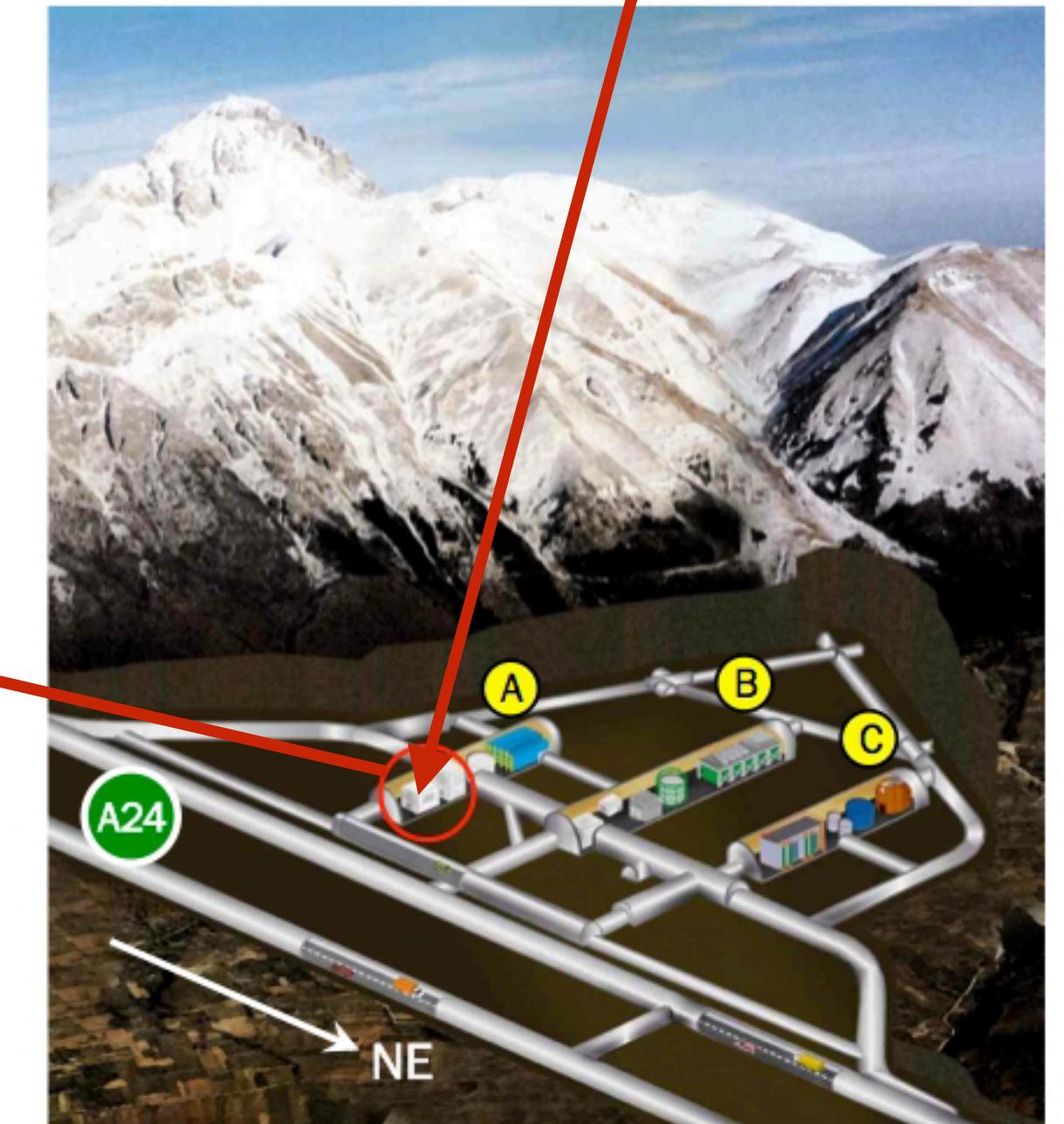
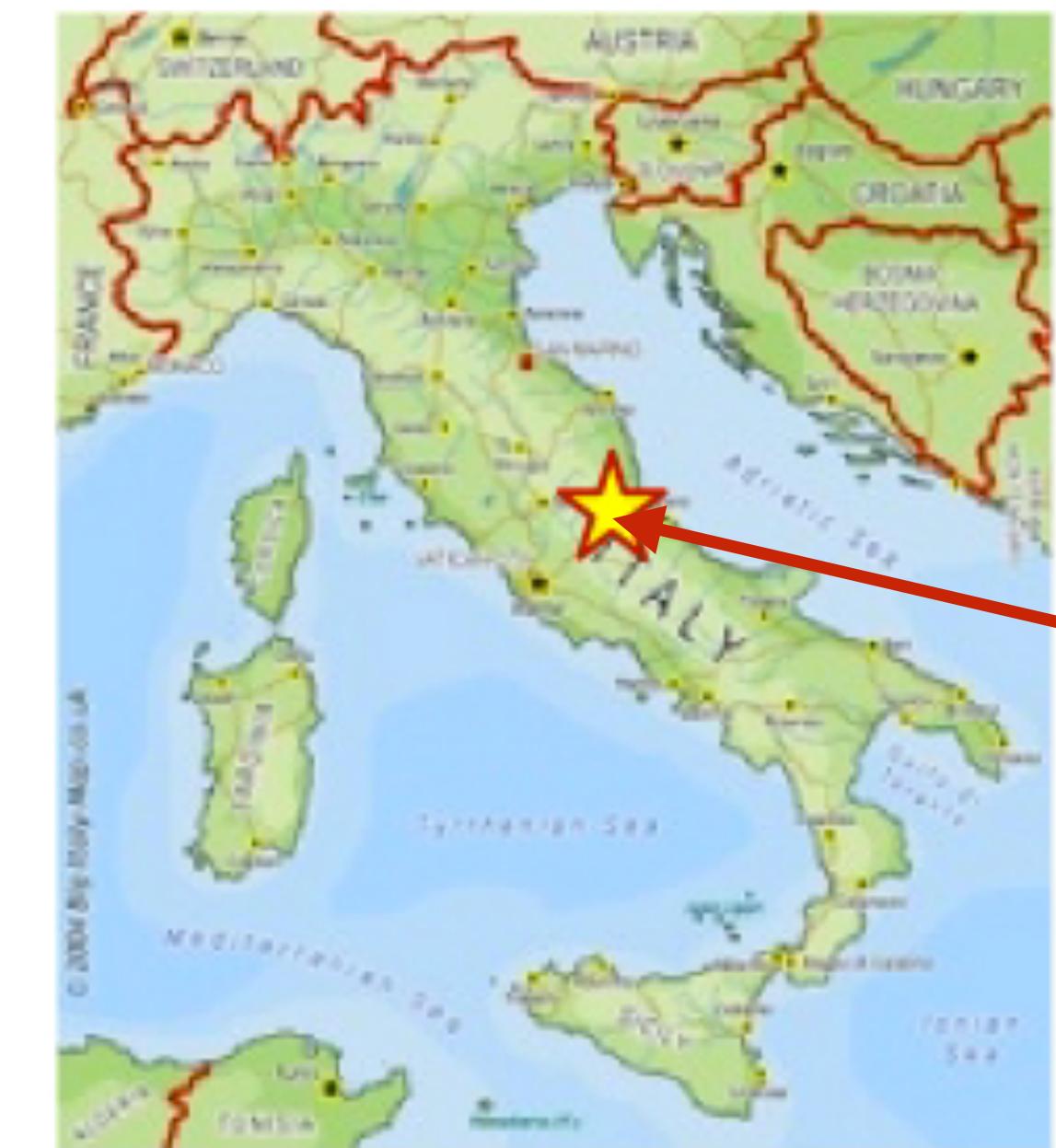


CUORE@LNGS

- **Cryogenic
Underground
Observatory for
Rare
Events**

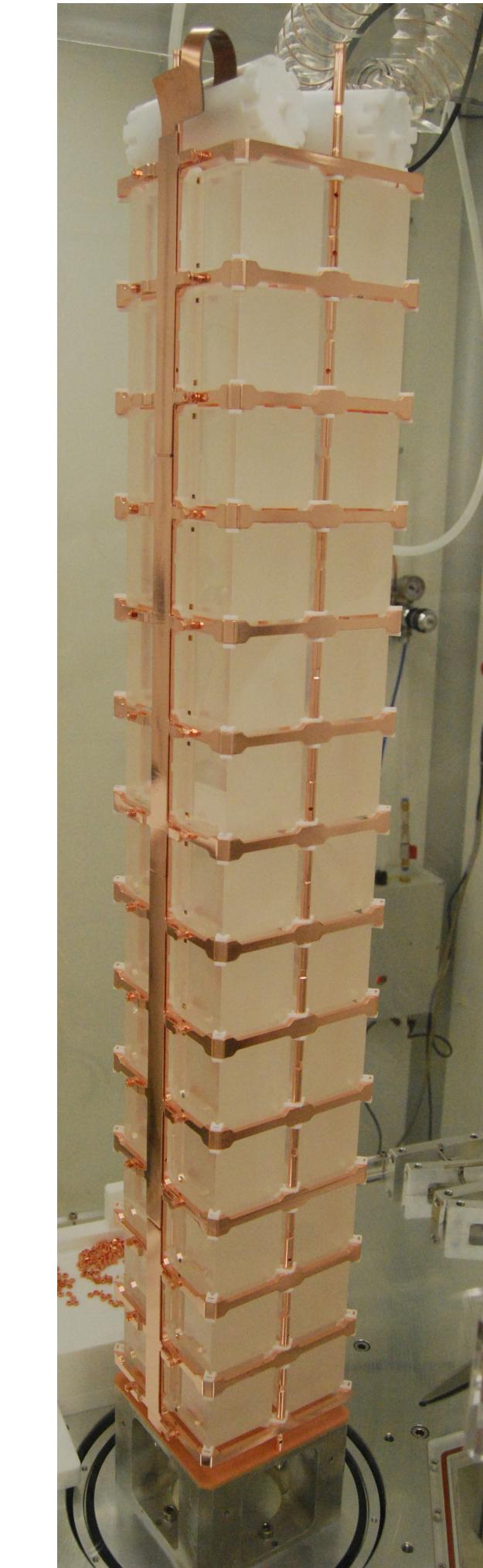


- To detect rare events:
 - sensitive detector
 - very low background
- Located at LNGS in Hall A
- 3600 m.w.e overburden

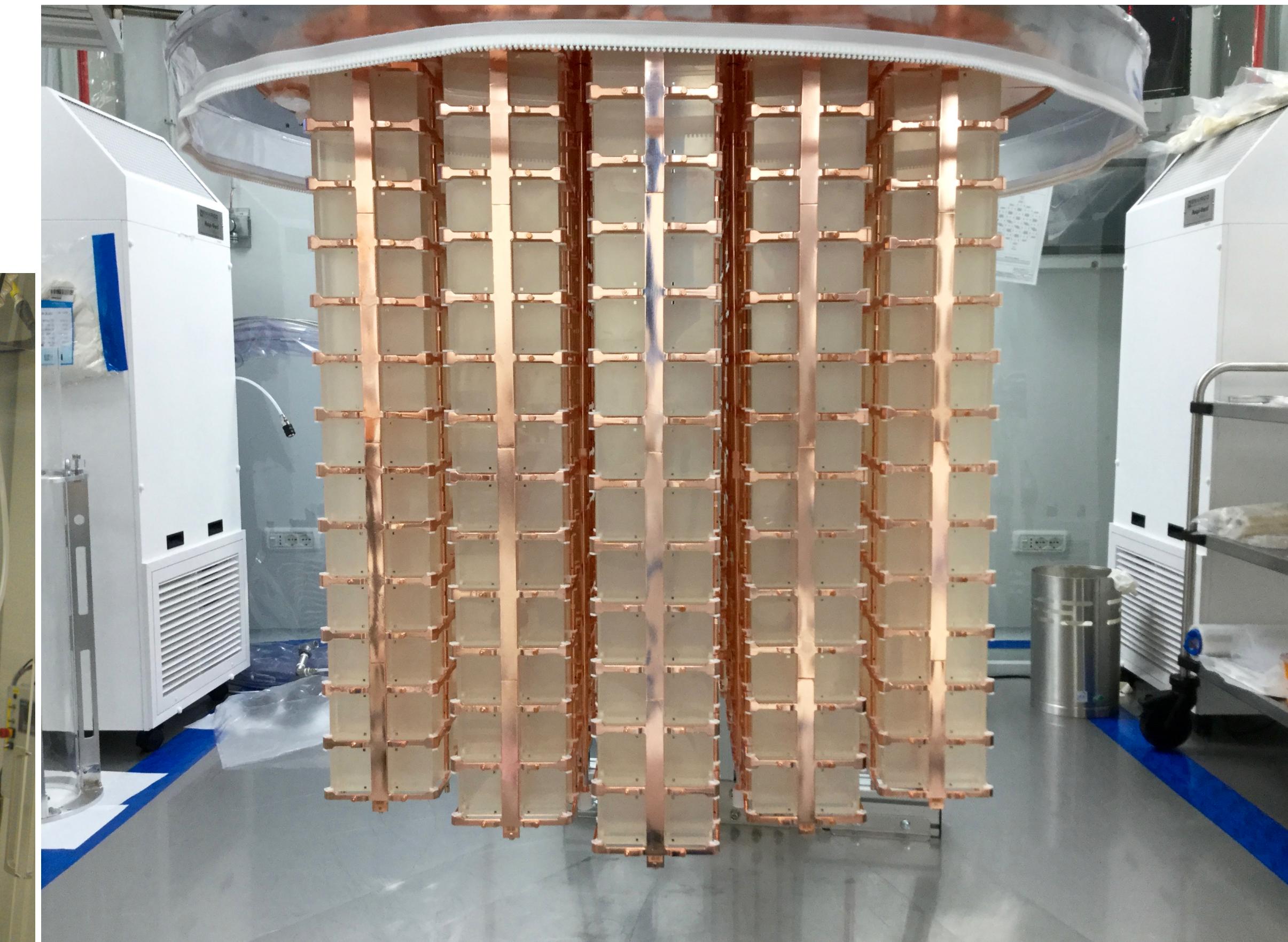


CUORE Detector

- Array of 988 $5 \times 5 \times 5$ cm³
- nat TeO₂ crystals (742 kg)
- 130 Te active isotope (206 kg)
- $Q_{\beta\beta} \sim 2527.515$ keV
- Source = detector
 - 0v $\beta\beta$ containment $\epsilon \sim 88\%$
- 984 active channels!



CUORE Tower

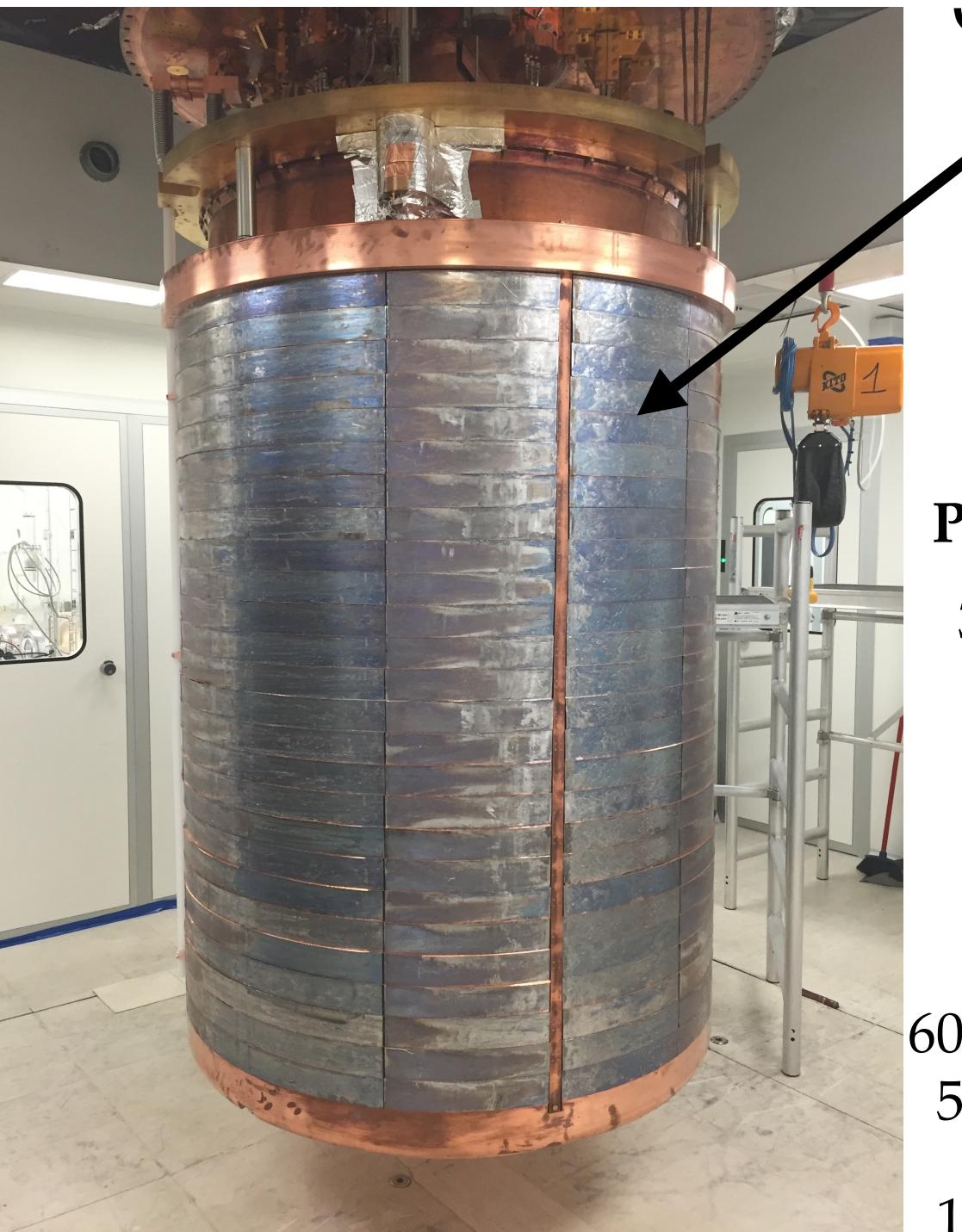


CUORE Detector Fully Assembled

19 towers, 13 floors, 4 per floor

CUORE Cryostat

- Difficult task - cool 15 tons at or below 4K and 3 tons to below 50 mK
- World leading cryostat in size and power
- Five 1.2 W (@ 4.2 K) Cryomech pulse tube coolers
- DU from Leiden Cryogenics
 - 100 mK: 2 mW cooling power
 - 10 mK: 4 μ W cooling power
- Radio-purity central to material selection
- Vibration isolation
- Cold Roman lead
- Lowest base temperature of 6.3 mK!



3920kg!

Plates:

300 K

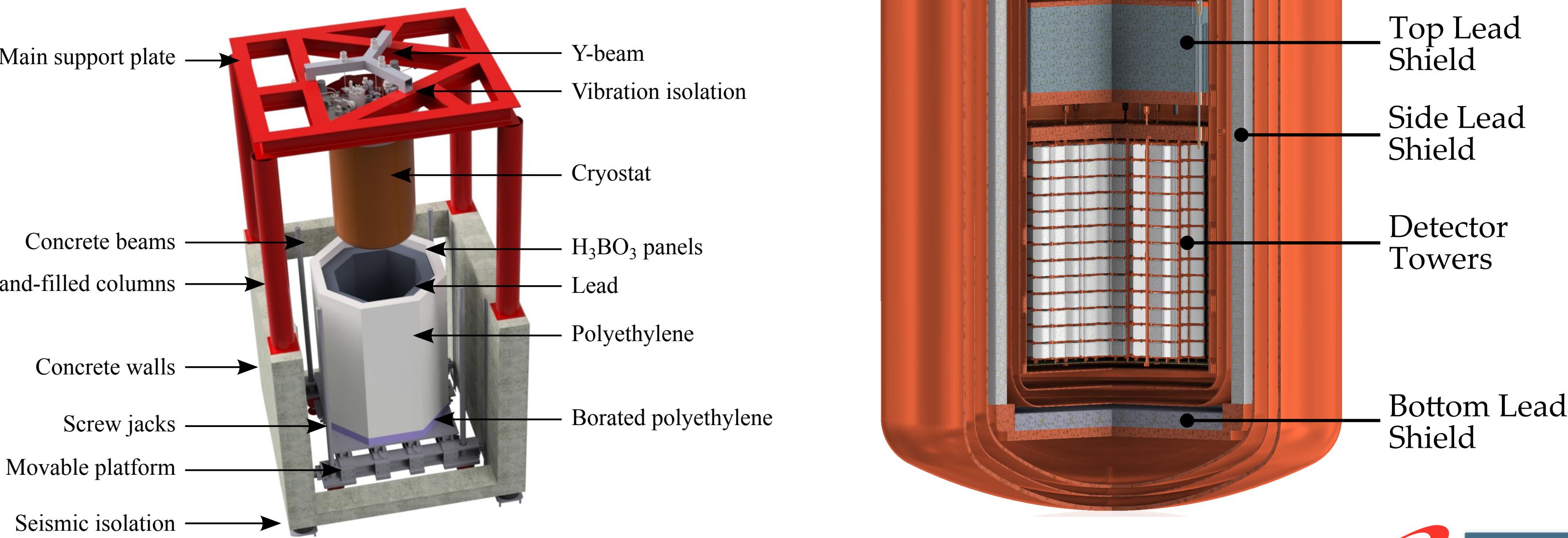
40 K

4 K

600 mK

50 mK

10 mK



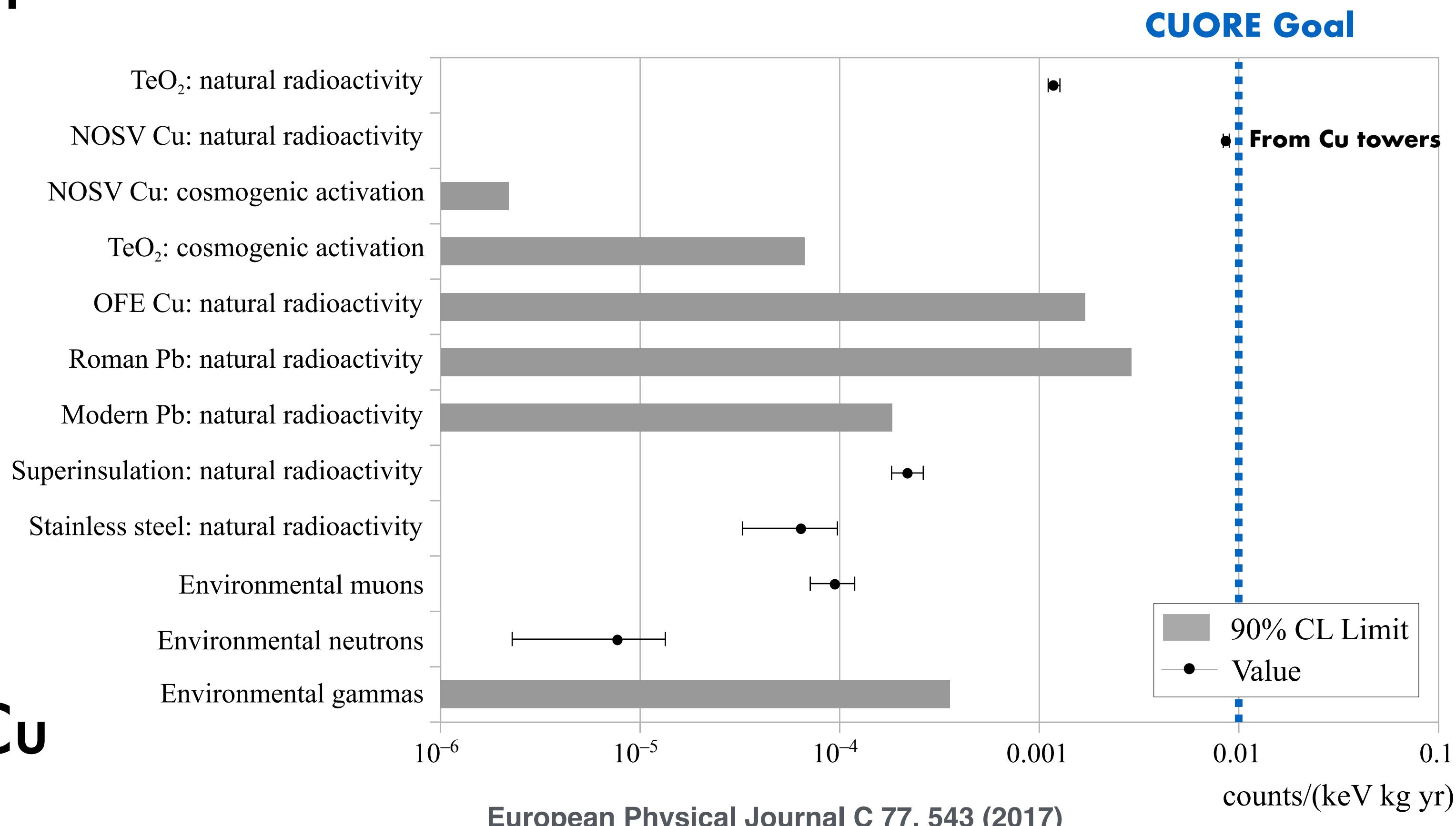
CUORE Background

- CUORE background goals met
- Degraded α 's pose problem
 - Bolometric technique provides only 1 channel
- no particle ID
- Residual contamination from Cu housing is dominant source

Background Limited Background Free

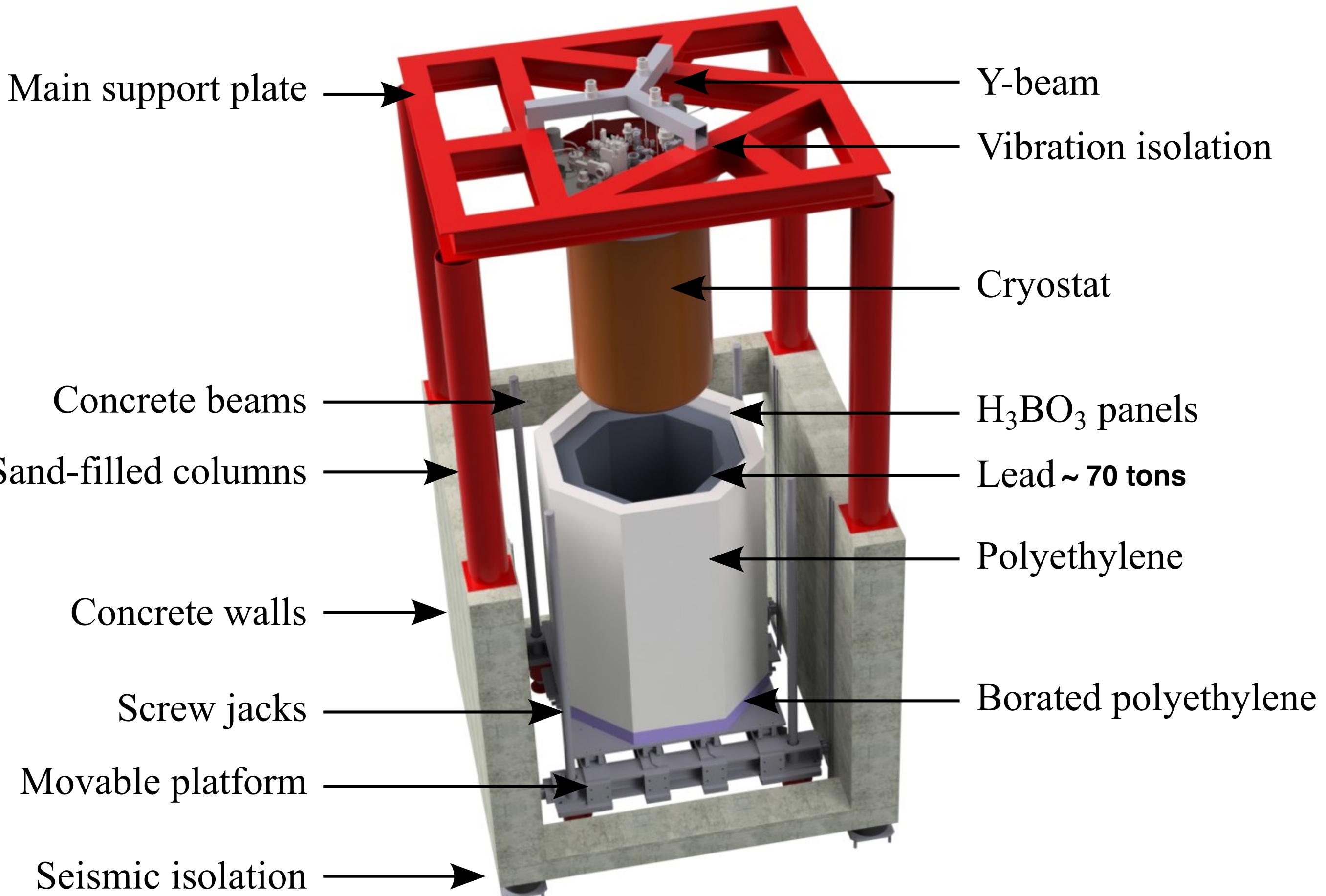
$$S \propto \frac{N_A a \eta \epsilon}{M_{mol}} \sqrt{\frac{MT}{b \Delta E}}$$

$$S \propto \frac{N_A a \eta \epsilon}{M_{mol}} MT$$



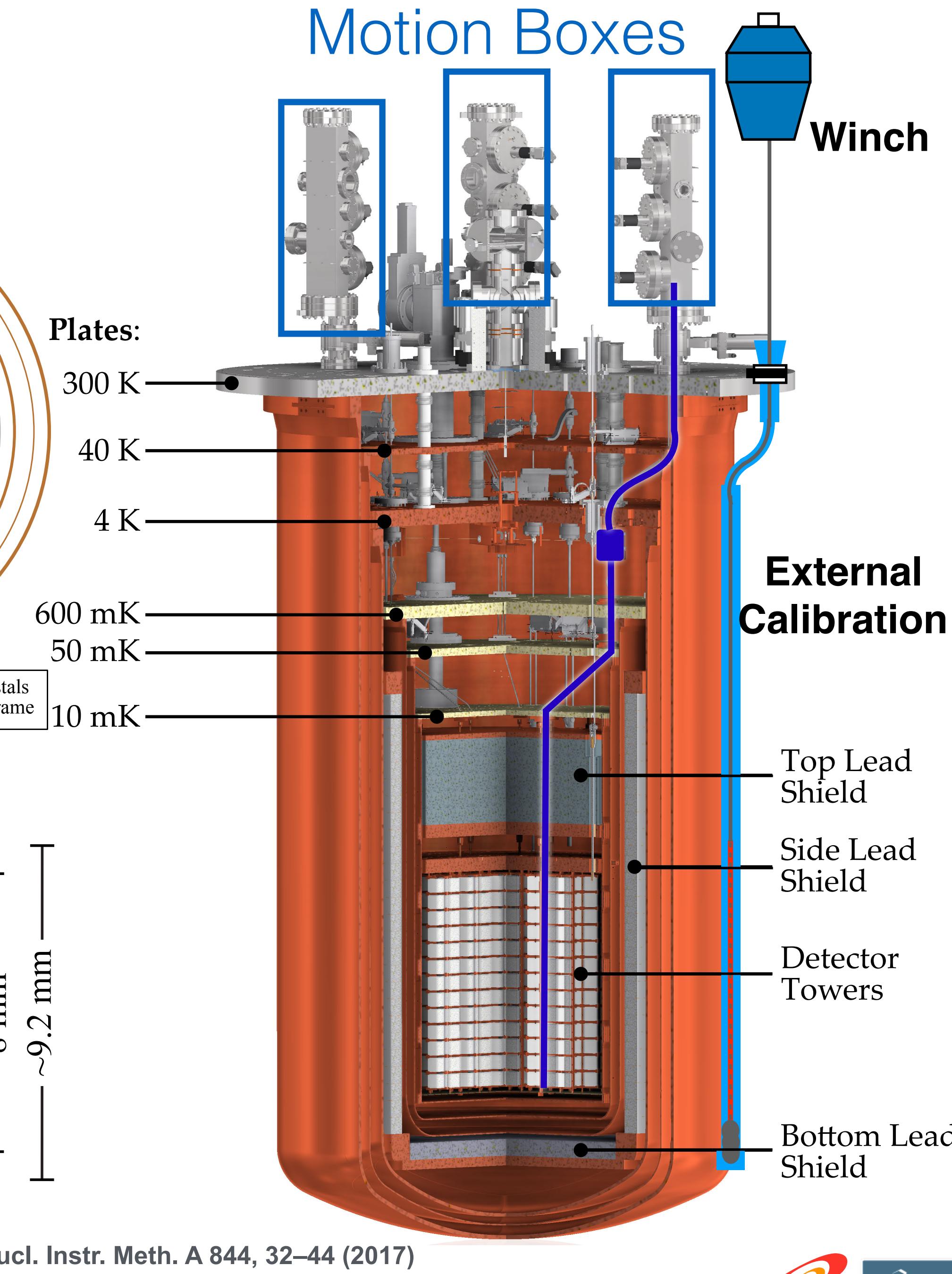
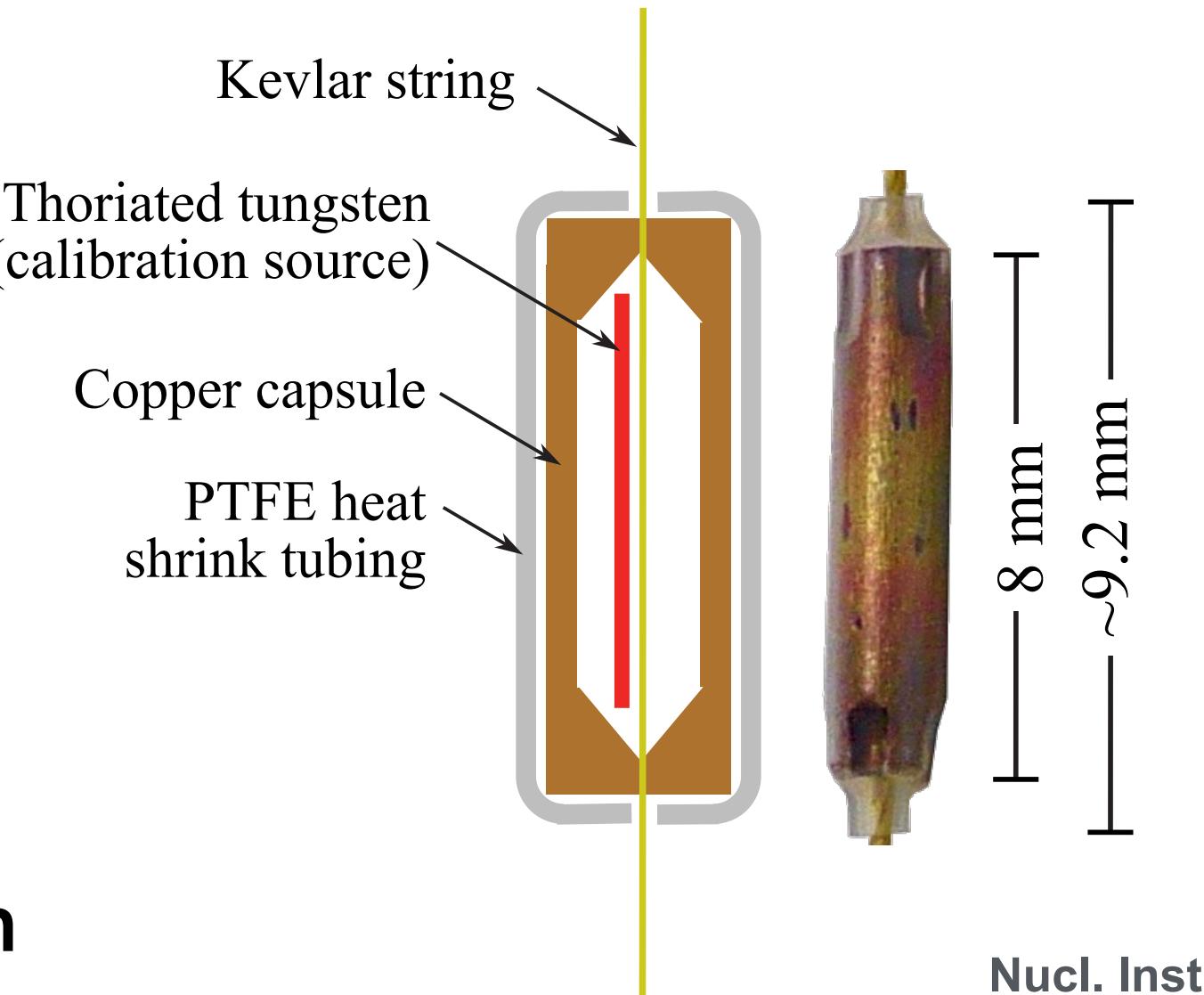
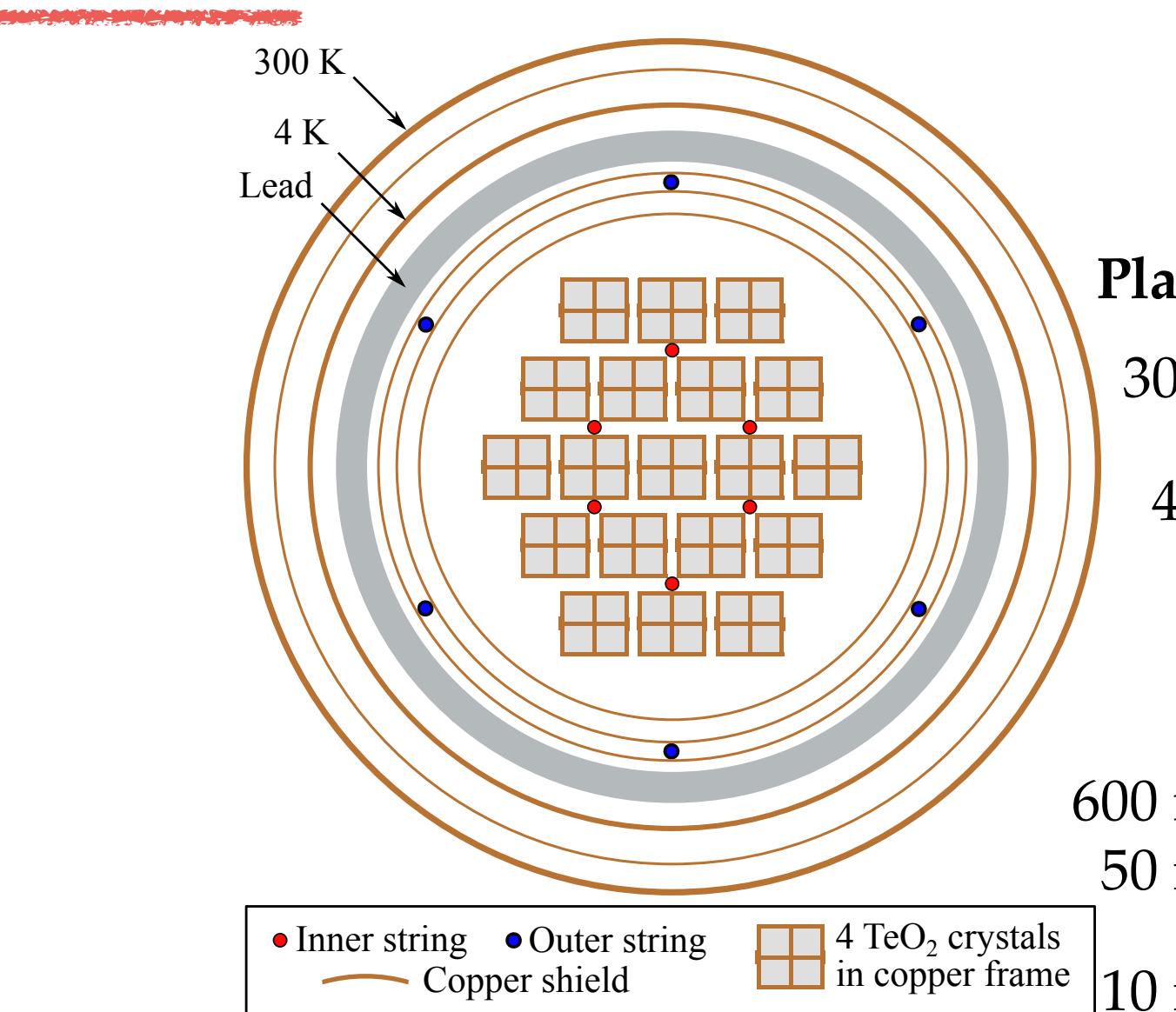
CUORE Suspension

- Detector suspension is independent of cryostat suspension
- Y-beam attached to stainless steel ties, Kevlar rope, and copper bars
 - Dampens horizontal oscillation
- 3 minus-K springs connect Y-beam to main support plate (MSP)
- Seismic isolation via elastomers



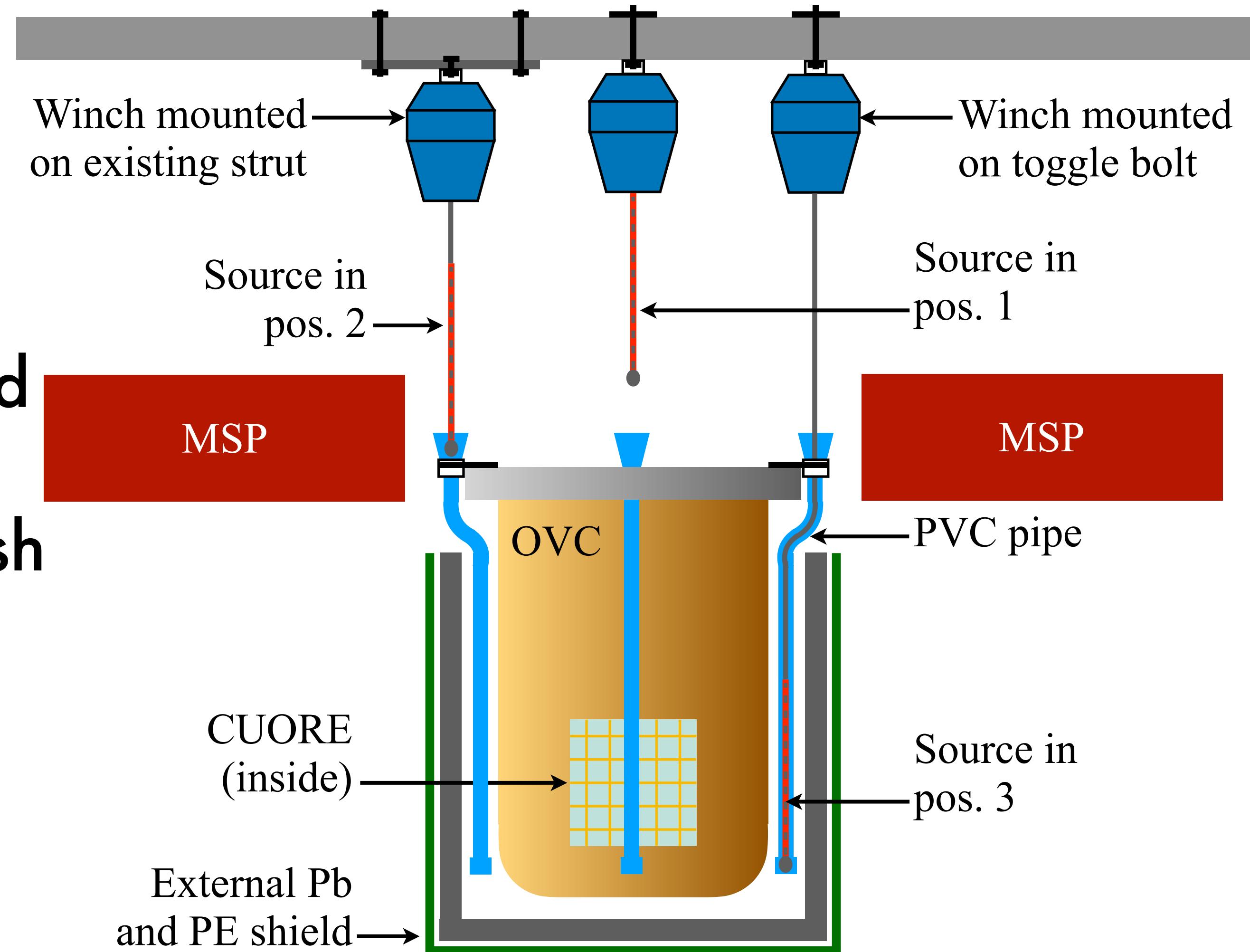
CUORE Calibration

- In-situ calibration of bolometers
- ^{232}Th γ -ray sources on strings
 - 239 keV - 2615 keV
- Motion boxes on top of cryostat contain sources when not in use
- Strings deploy into cold space
- Constant-energy pulsters
 - Generate reference pulses
 - Measure detector stability
 - Correct for variations in detector gain



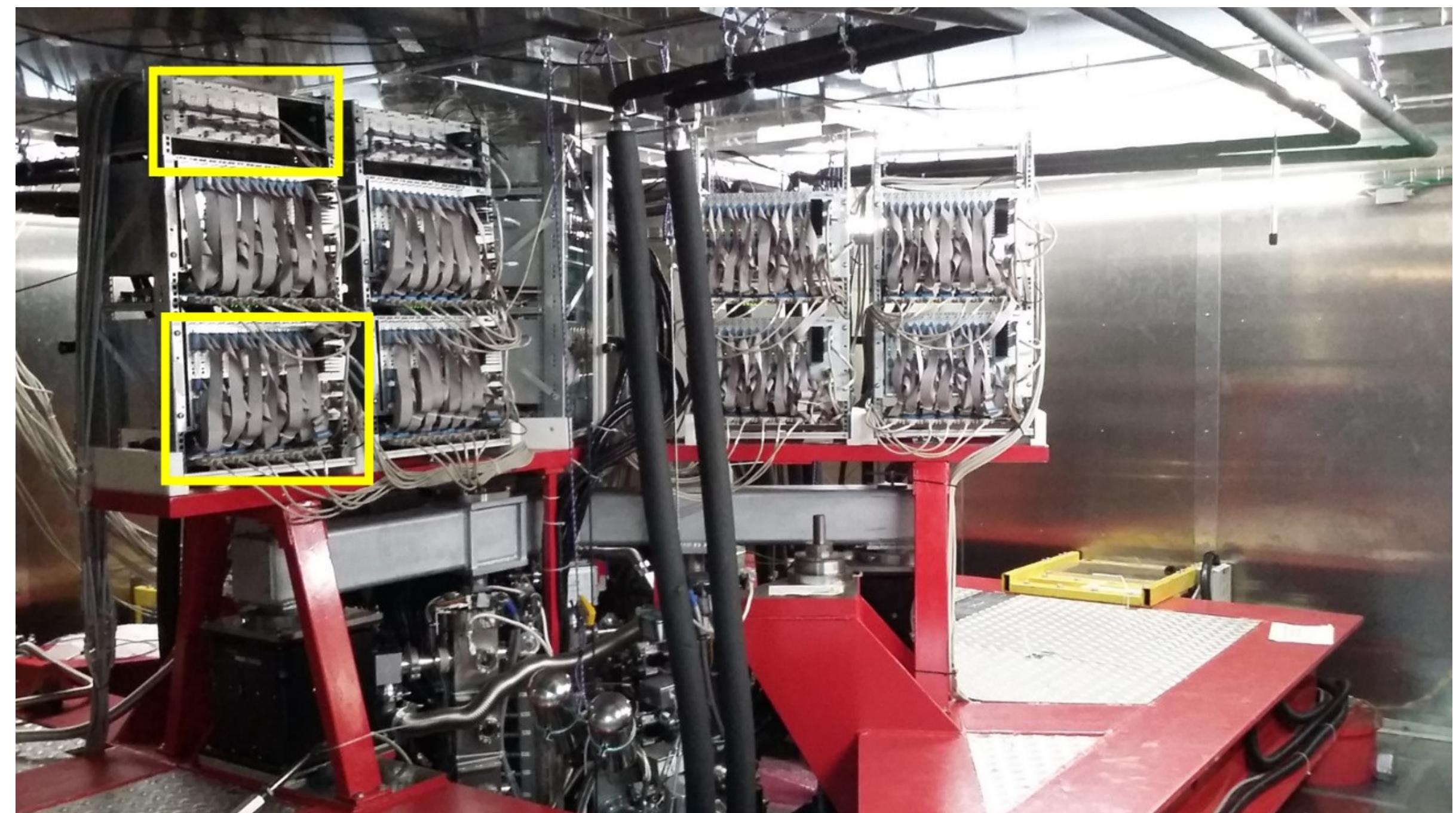
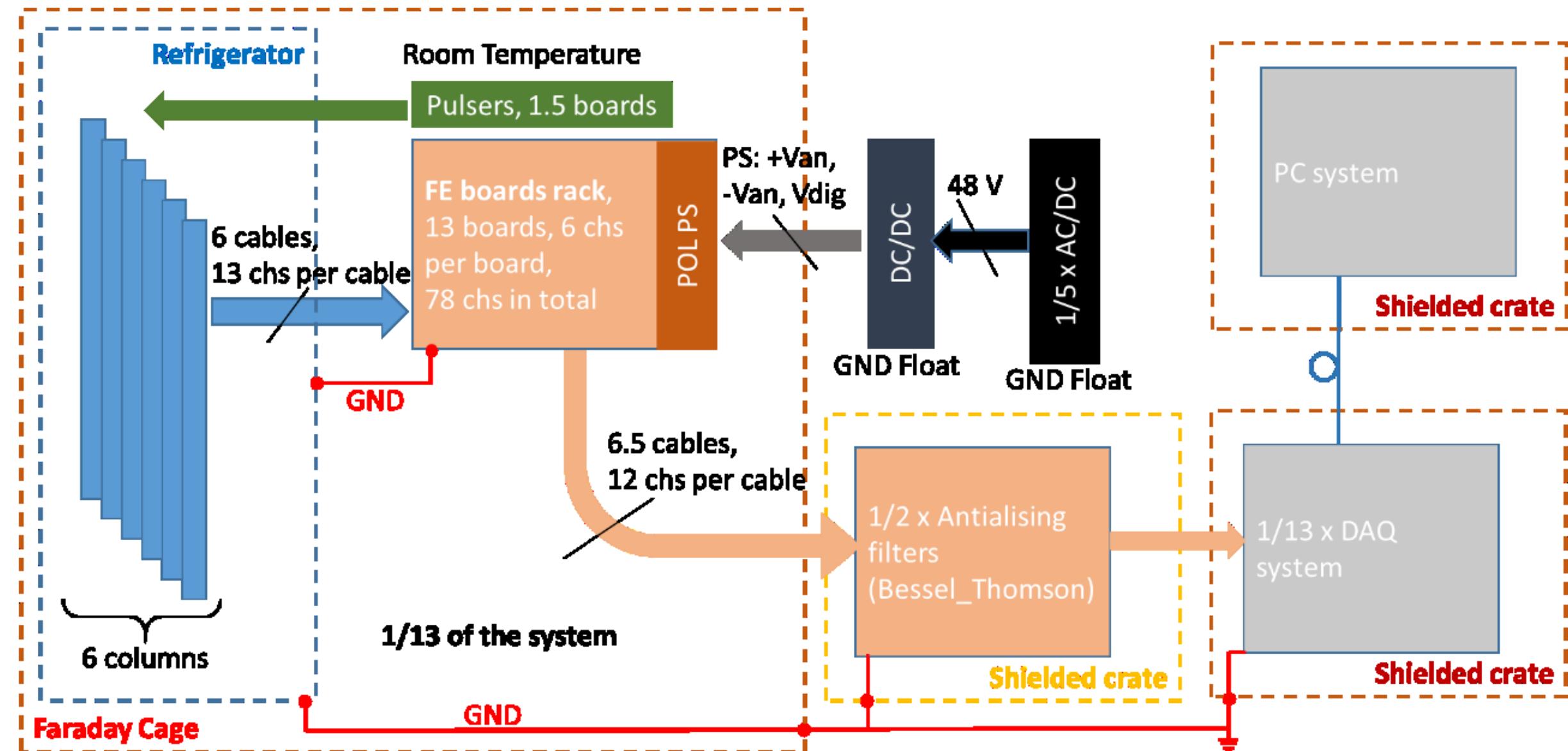
External DCS

- Provides another calibration method
- Thoriated welding rod in fabric mesh
- Eight sources
- Total ~ 70 kBq activity



Front End Electronics

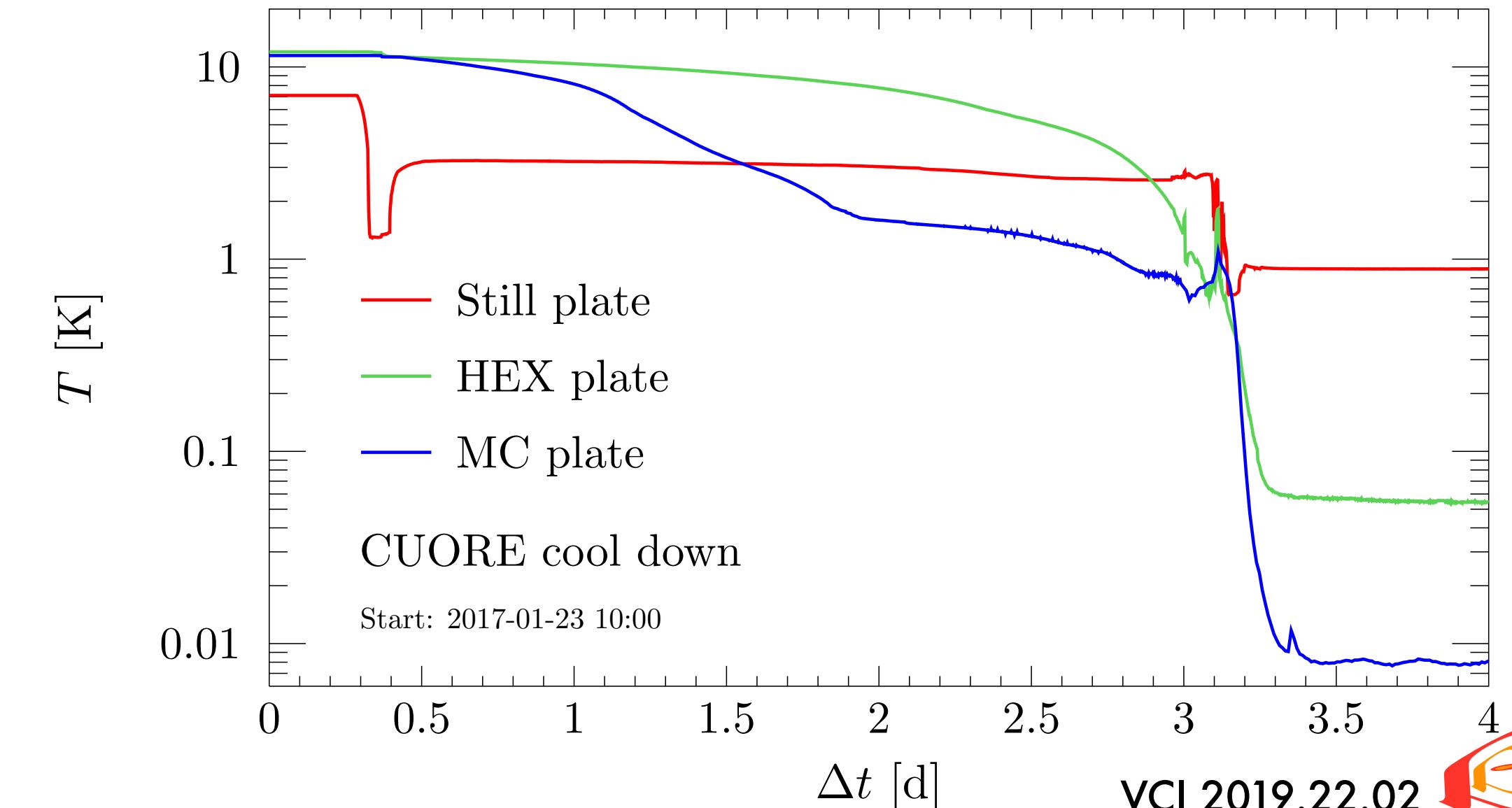
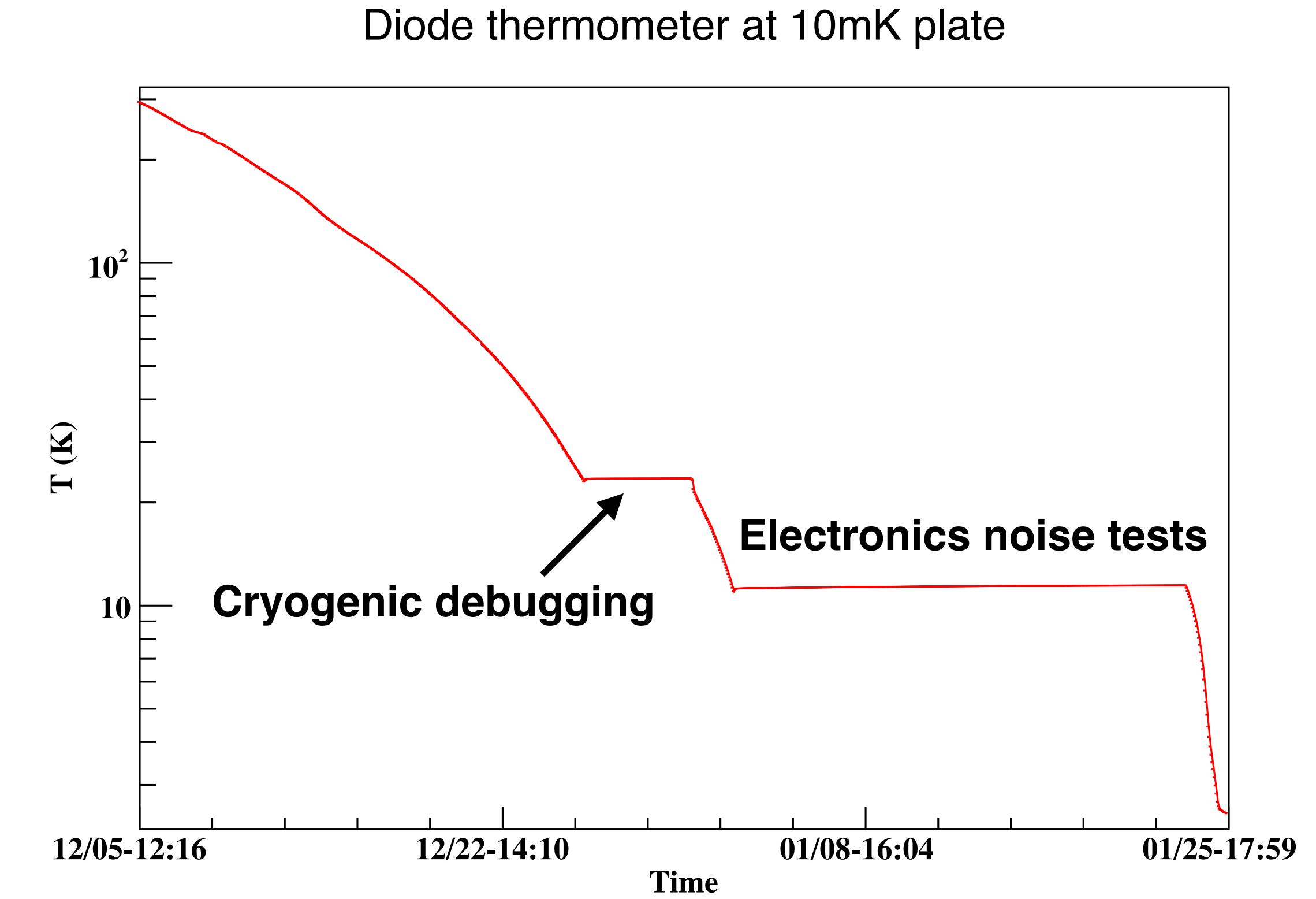
- Readout of ~ 1000 bolometers is nontrivial
- Front end electronics system custom made
- Differential voltage preamp at room temperature (JFET)
 - Low noise at low frequency
- Mainboards: 6 preamps with programmable gain, detector bias, offset, drift, and provides common-mode noise rejection
- A 6-pole active Bessel-Thomson antialiasing filter suppresses high frequency noise
- 18-bit DAQ
- Optical fibers are used for communication with control computers



C. Arnaboldi et al. JINST 13 2018 Feb

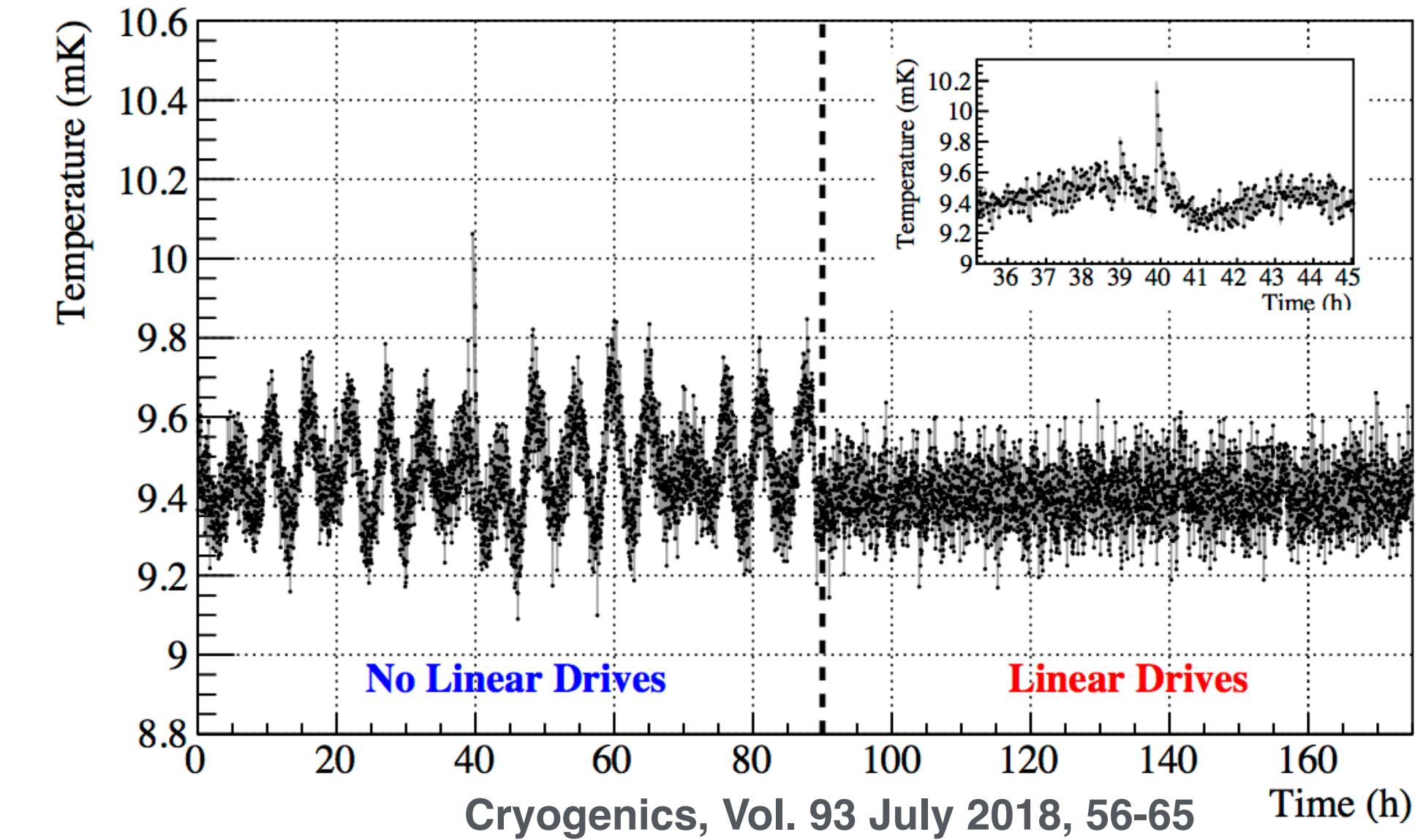
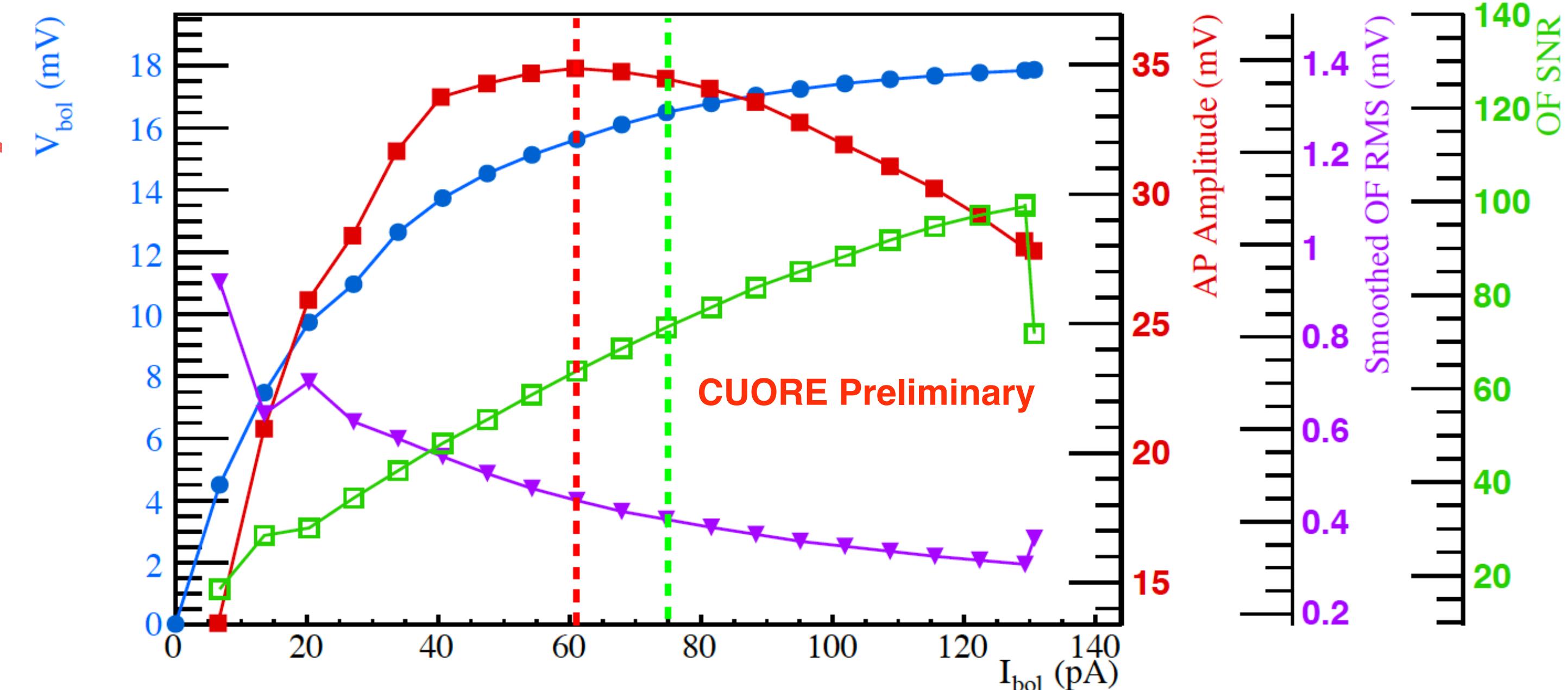
CUORE Cooldown

- Fast cooling system (${}^4\text{He}$ gas) allows quick (3 wk) cool down to ~ 40 K
- All 5 PT coolers activated to bring cryostat to ~ 4 K
- DU temp down to ~ 8 mK in 4 days
- 10 mK: 3 μW residual cooling power with full payload



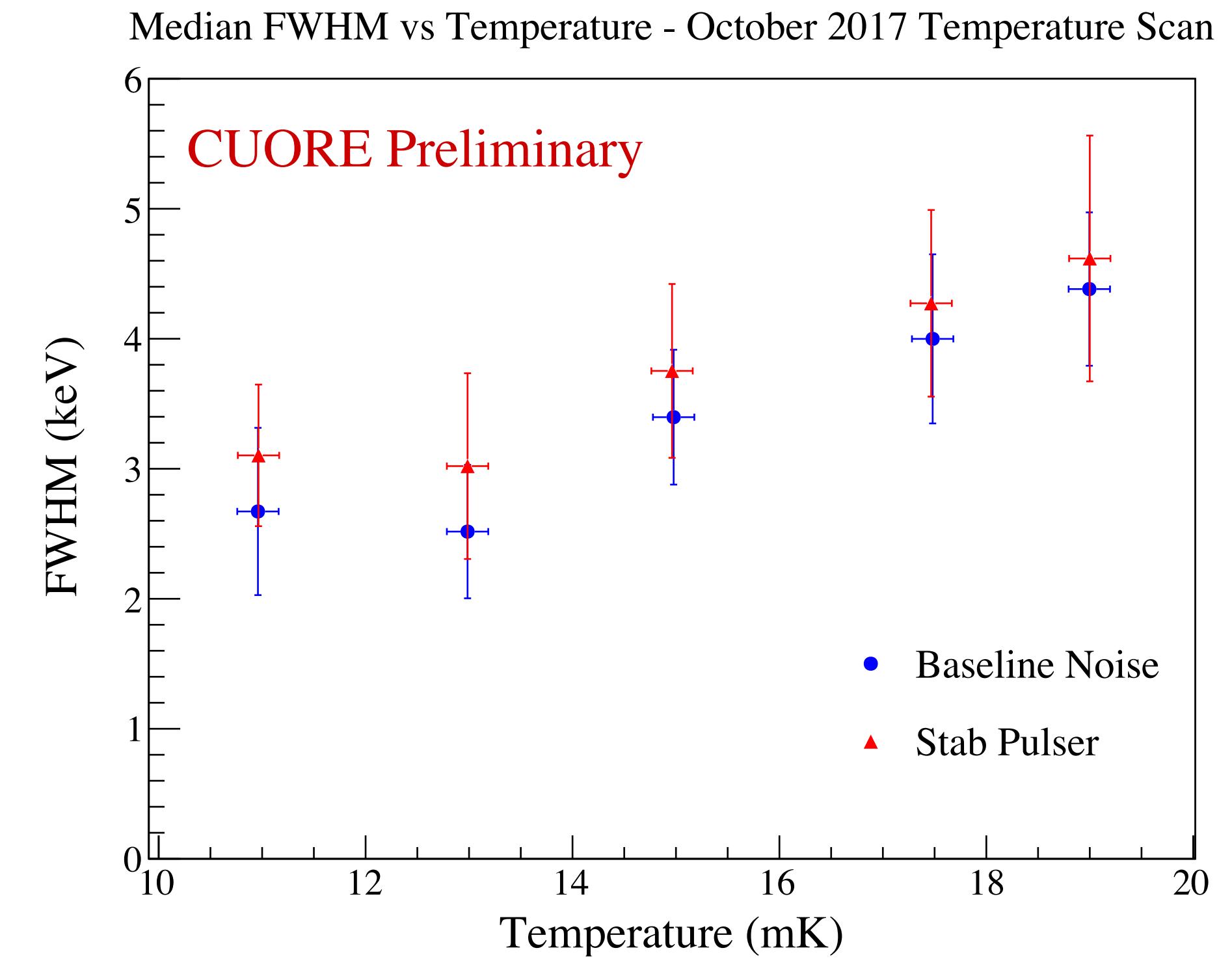
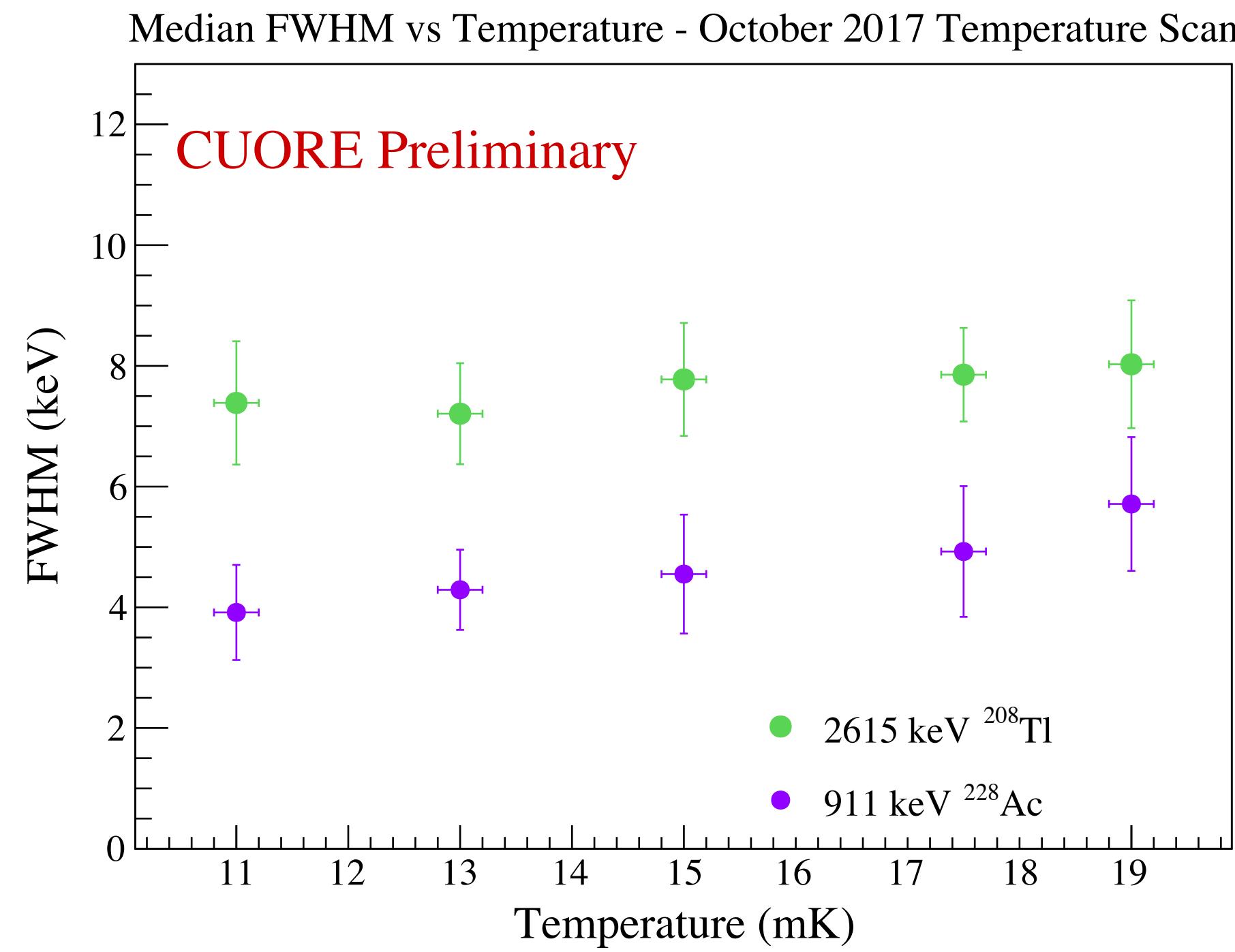
Detector Optimization

- Temperature Scan
 - Optimize signal to noise ratio, resolution, and electronics performance
 - 15 mK operation \rightarrow 11 mK operation
- Working point
 - Maximize signal to noise ratio
 - Optimize pulse amplitude
- Noise optimization
 - Electronic noise attenuation
 - Vibration reduction
 - Pulse tube active noise mitigation



Temperature Scan

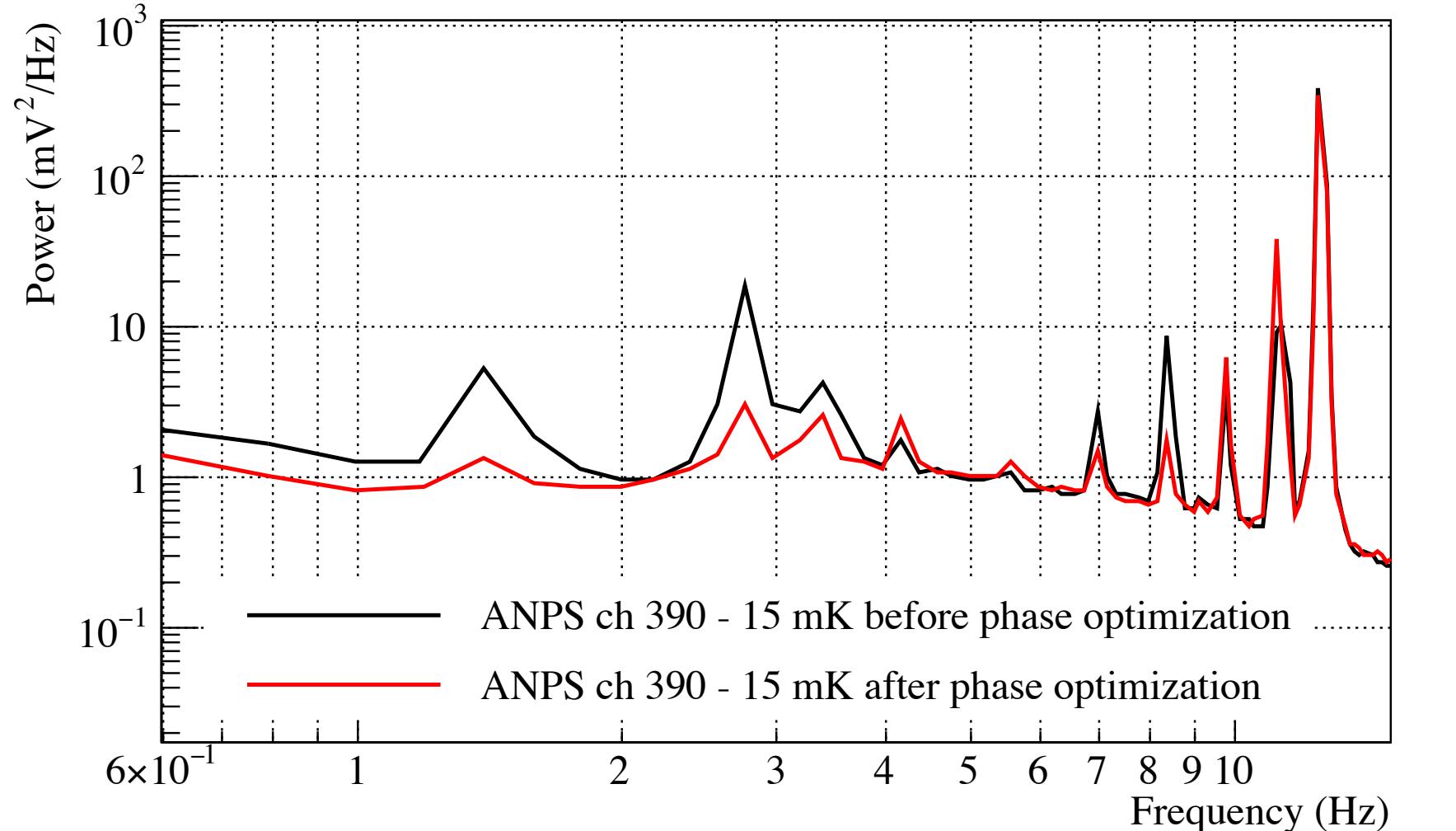
- Temperature scan performed around base temperature
- Aimed to optimize detector energy resolution and NTD resistance
- Scan 1 - March 2017 - 15 mK identified as best operating temperature
- Scan 2 - July 2017 - Check of previous scan settings



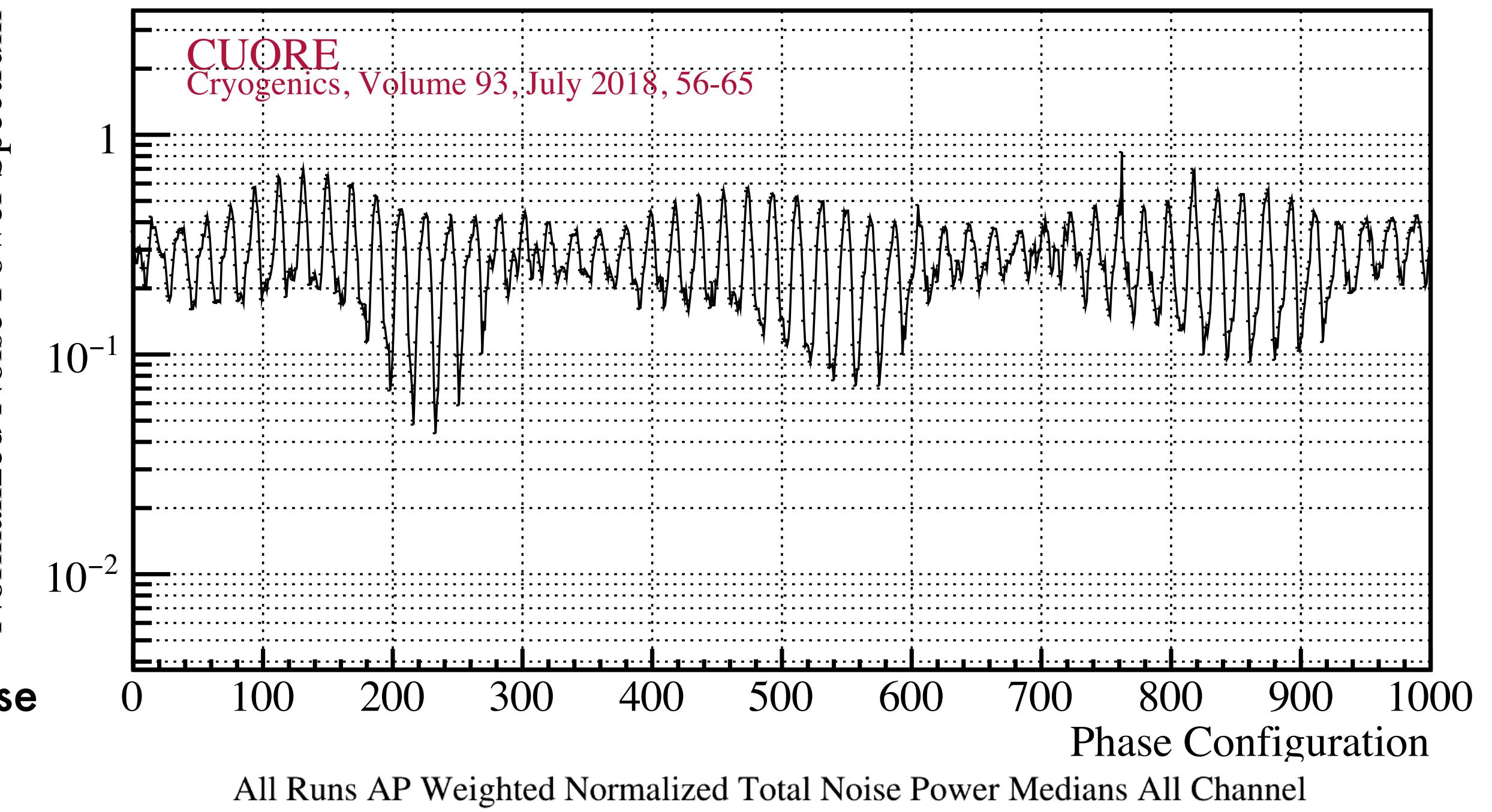
- Scan 3 - September/October 2017
- Performed with calibration sources deployed
- Confirmed better resolution at lower T
- 11 mK was set as new operating temperature

Pulse Tube Vibrations

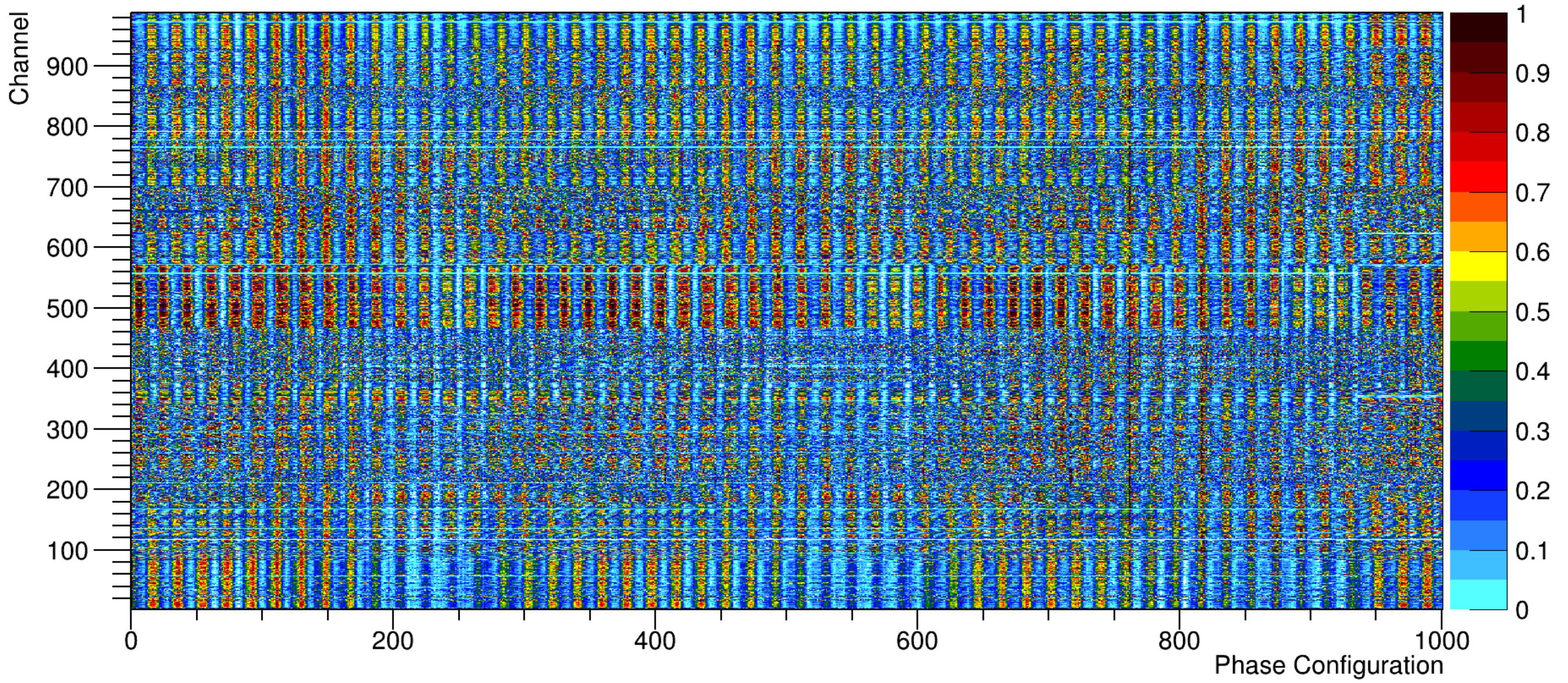
- Passive vibration dampening is implemented
 - Suspended rotary valves, soft bellows, Cu braids
- Active vibration dampening possible
 - Relative phases of PT rotary valves measured
 - Discretize space of all possible relative phases into distinct phase configurations and scan
 - Tune relative phase of vibrations to cause maximal destructive interference



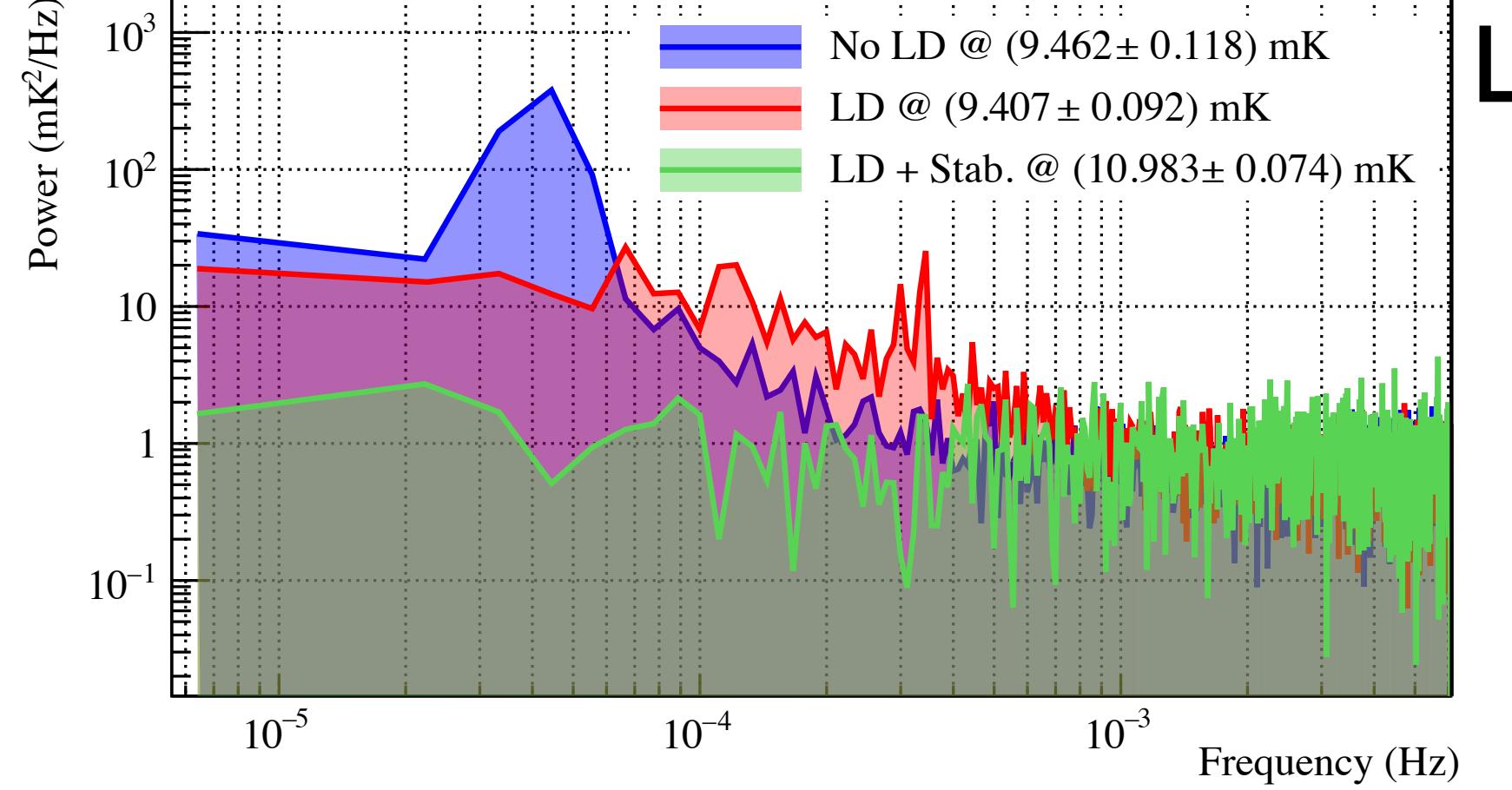
All Channels AP Weighted Total Noise Median



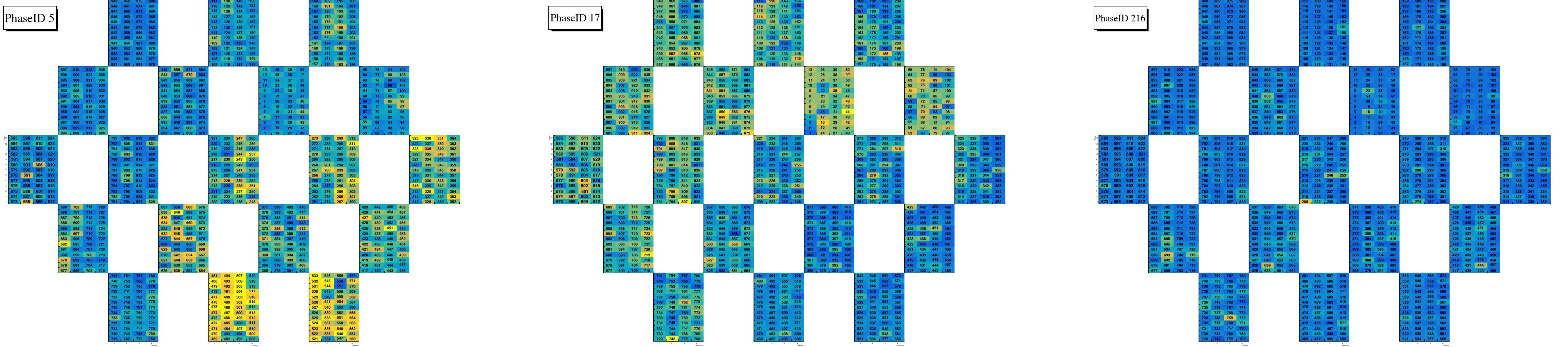
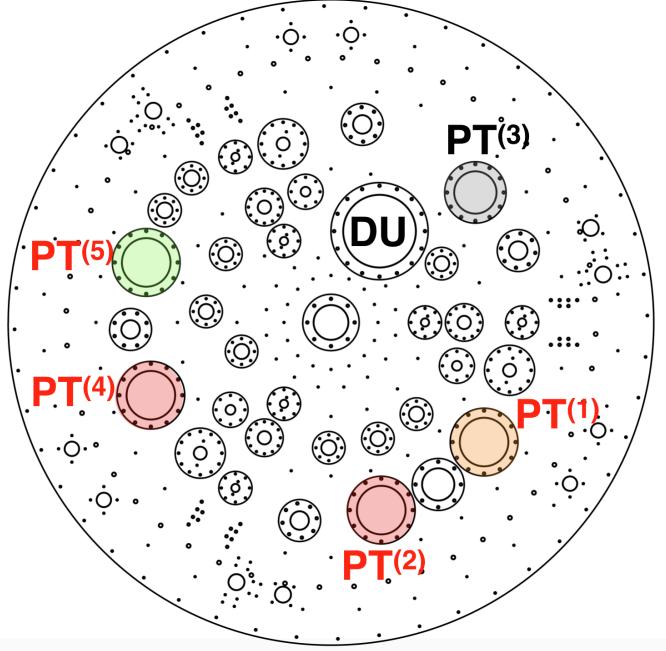
All Runs AP Weighted Normalized Total Noise Power Medians All Channel



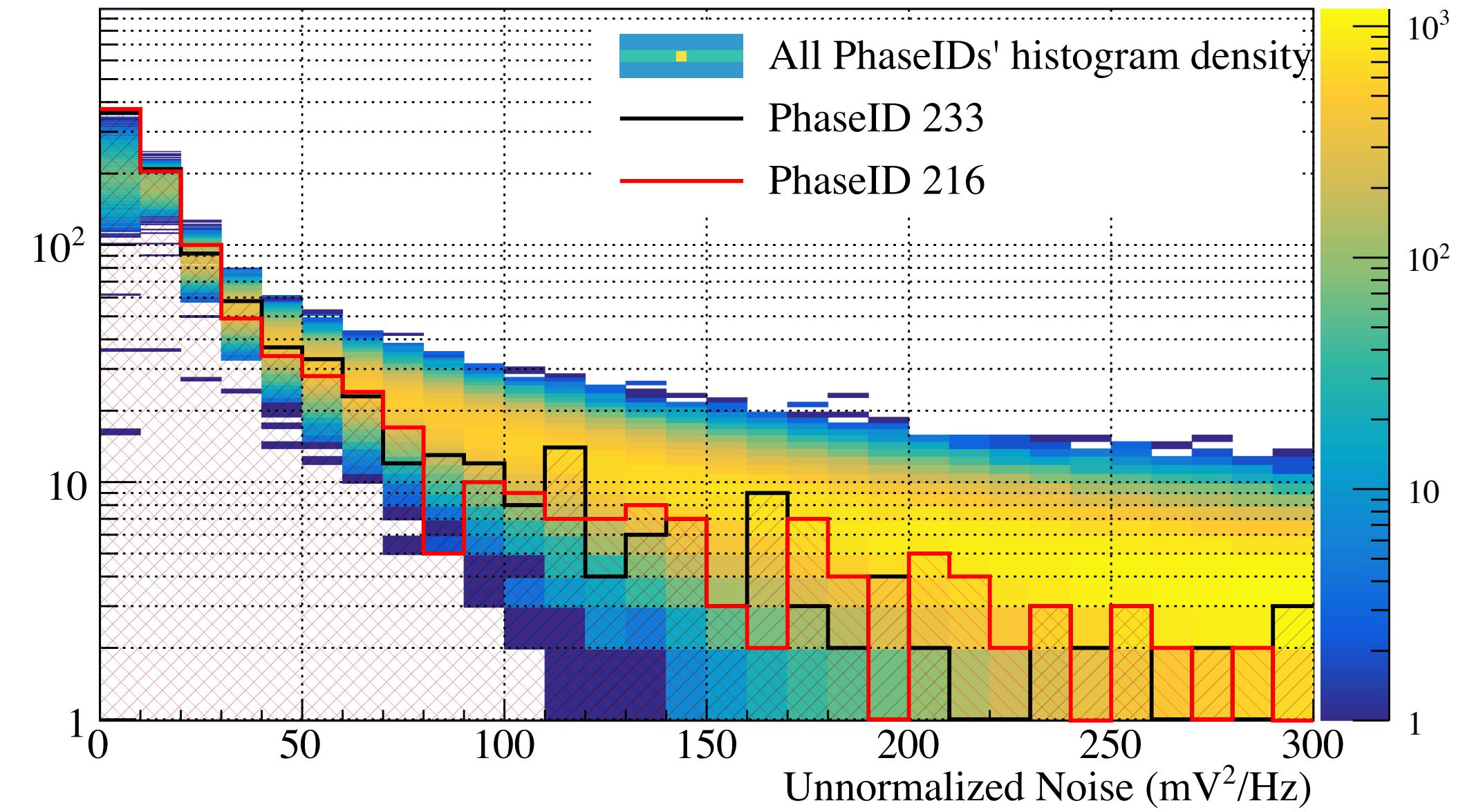
Pulse Tube Vibrations



Lock at minimum noise

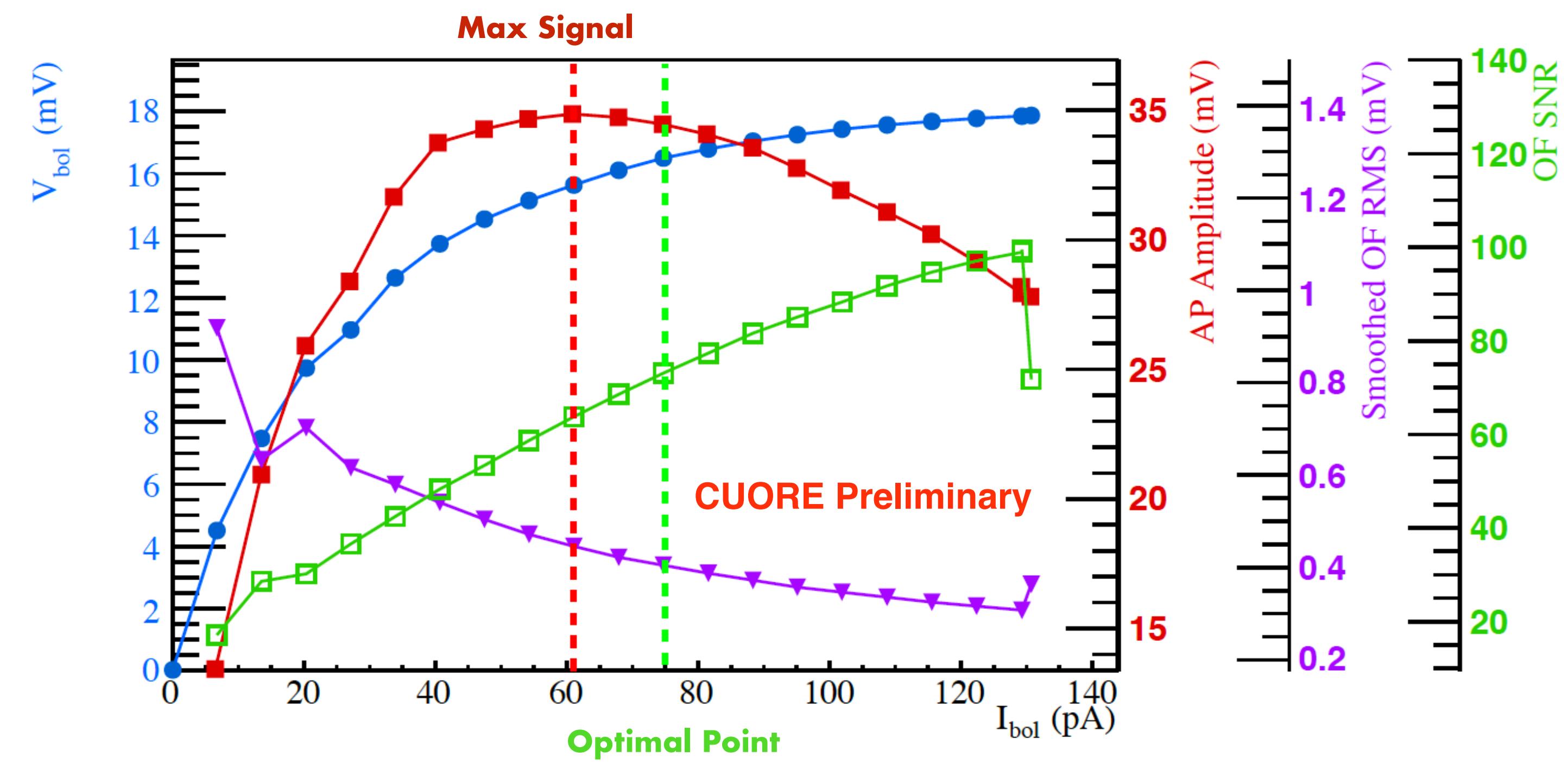


Different phase configurations excite different parts of detector



Optimize SNR

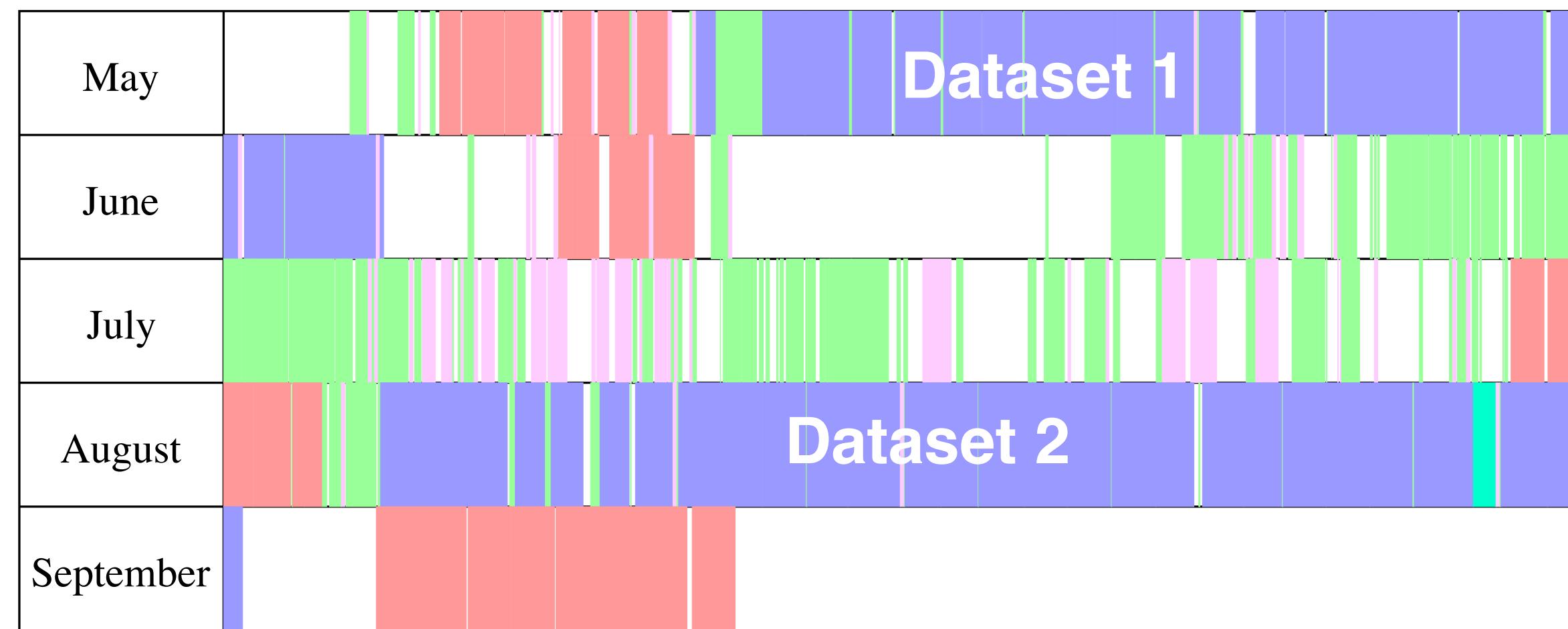
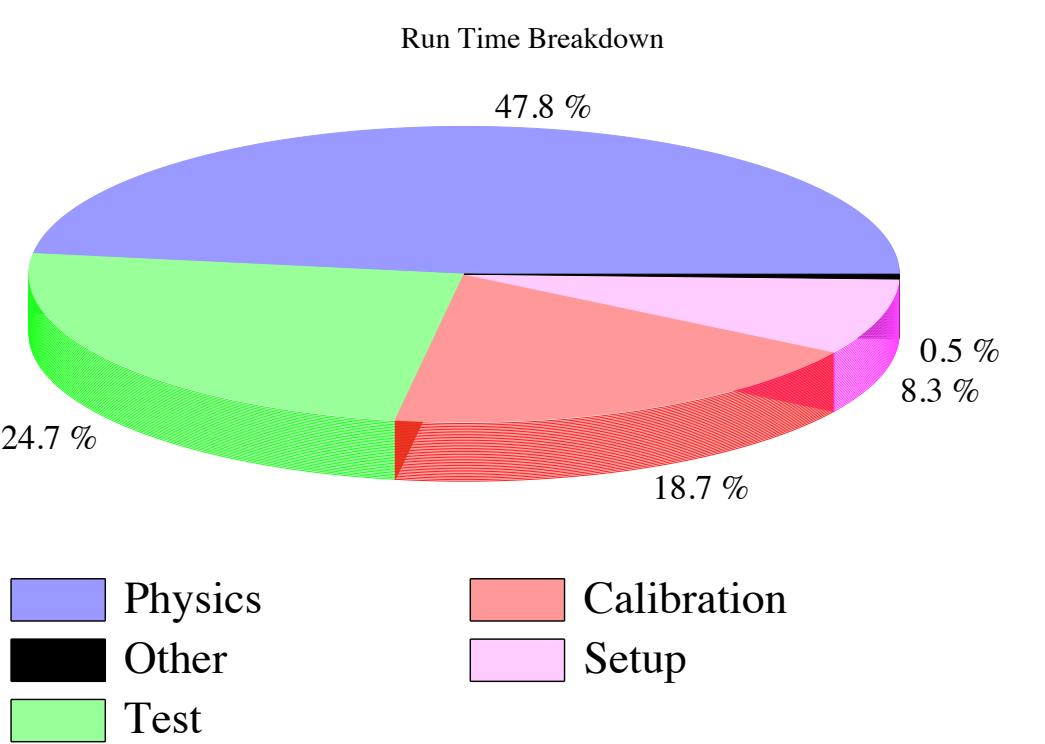
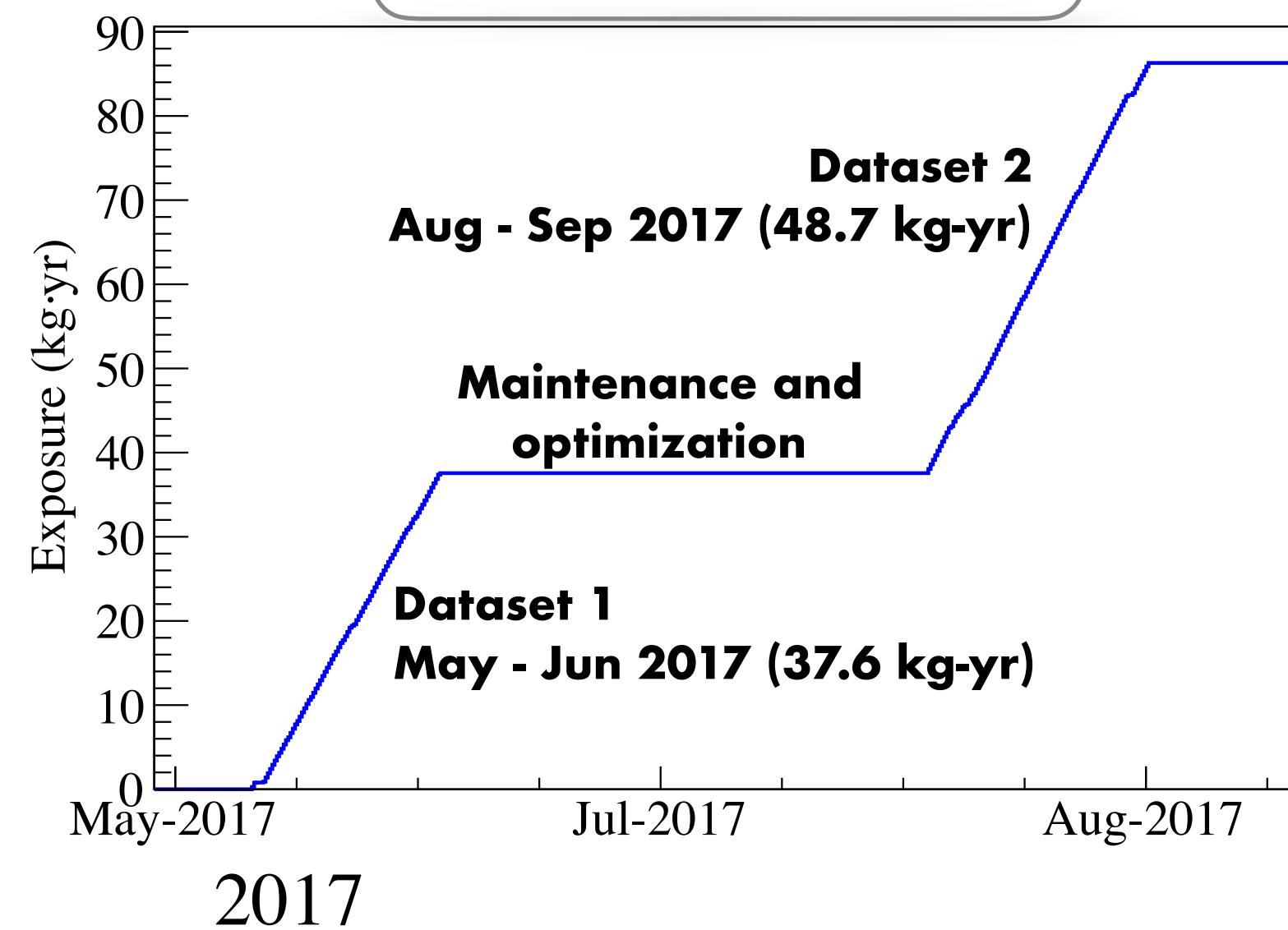
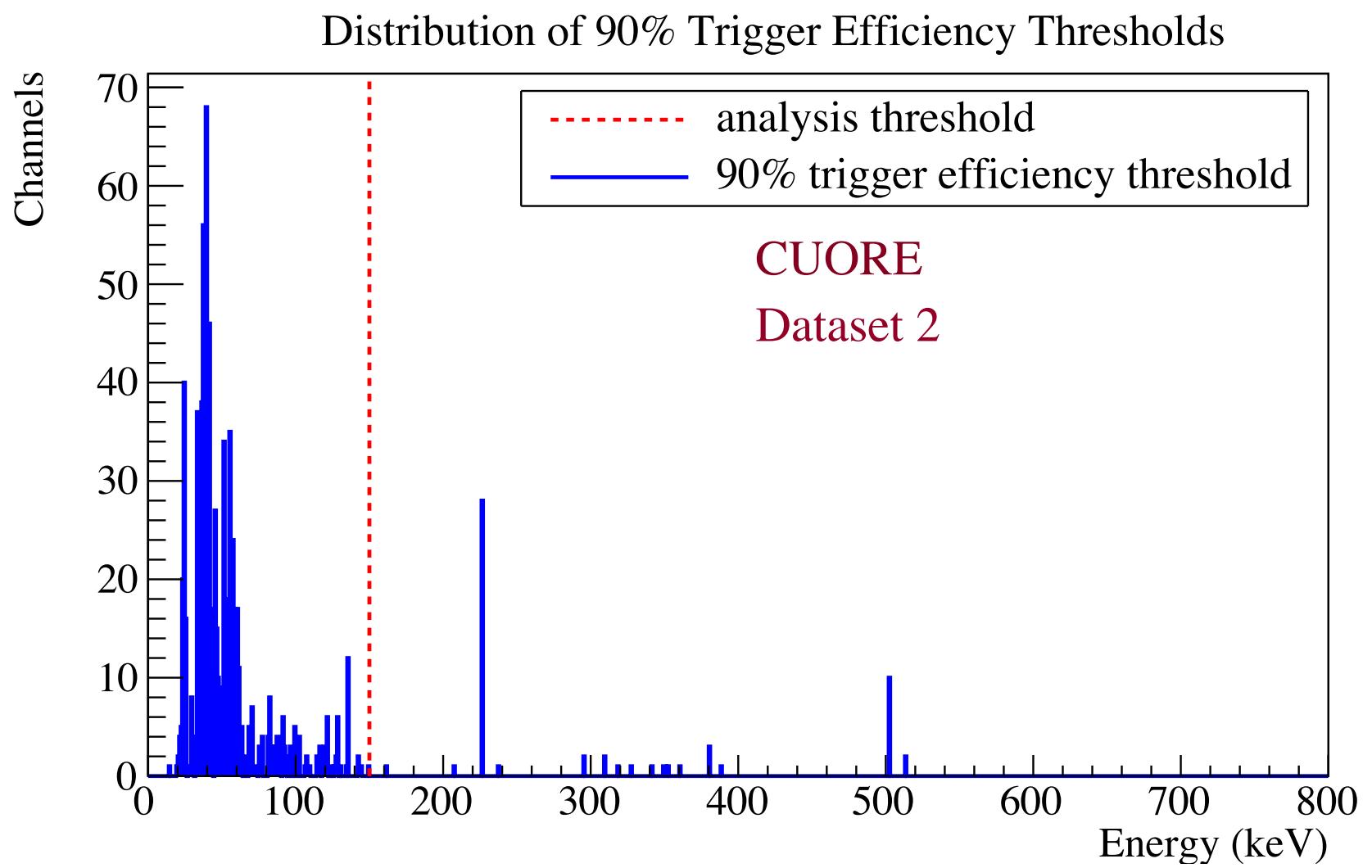
- After optimize Temp → Optimize bias current
- Obtain I-V curve ('load curve')
- Examine variation of NTD resistance, signal amplitude, and noise as function of applied voltage



- Selected point must yield linear detector response in the presence of small thermal fluctuations
- CUORE compromises by selecting an operating point that maximizes signal amplitude and minimal RMS

CUORE Data Year 1

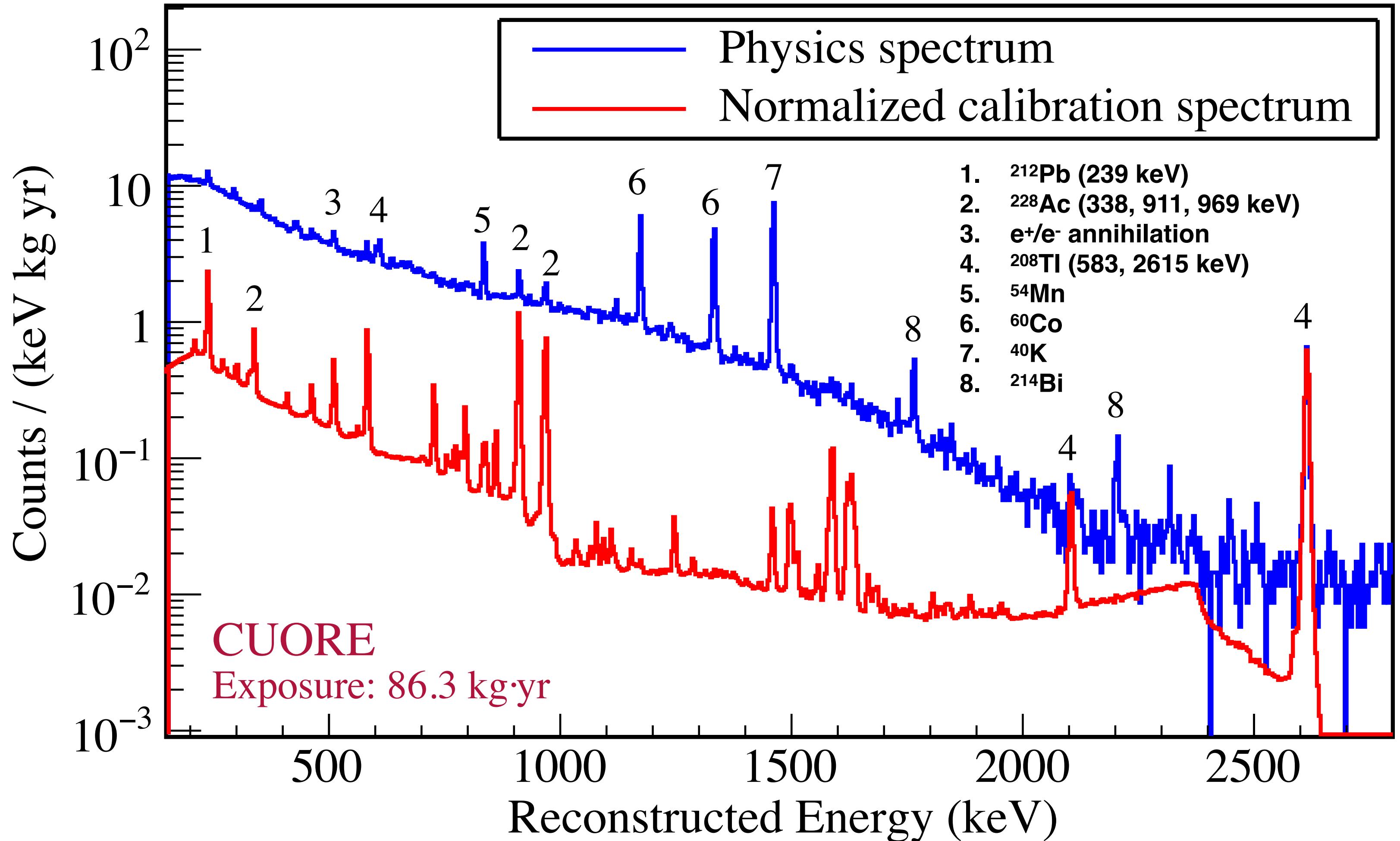
- Detector stability is excellent
- Trigger rate per bolometer
 - Physics: 6 mHz
 - Calibration: 50 mHz
- 984/988 bolometers functional
 - (99.6% of detector)
- Thresholds from 20 keV - few hundreds of keV
- Each dataset starts and ends with calibration
- More exposure than all of CUORE-0!



Physics, Calibration, Test, Special Configuration runs

Observed Spectra

- 1811 channel-dataset pairs utilized
 - 92% of active channels
 - Energy spectrum from sum of all active channels used in $0\nu\beta\beta$ search

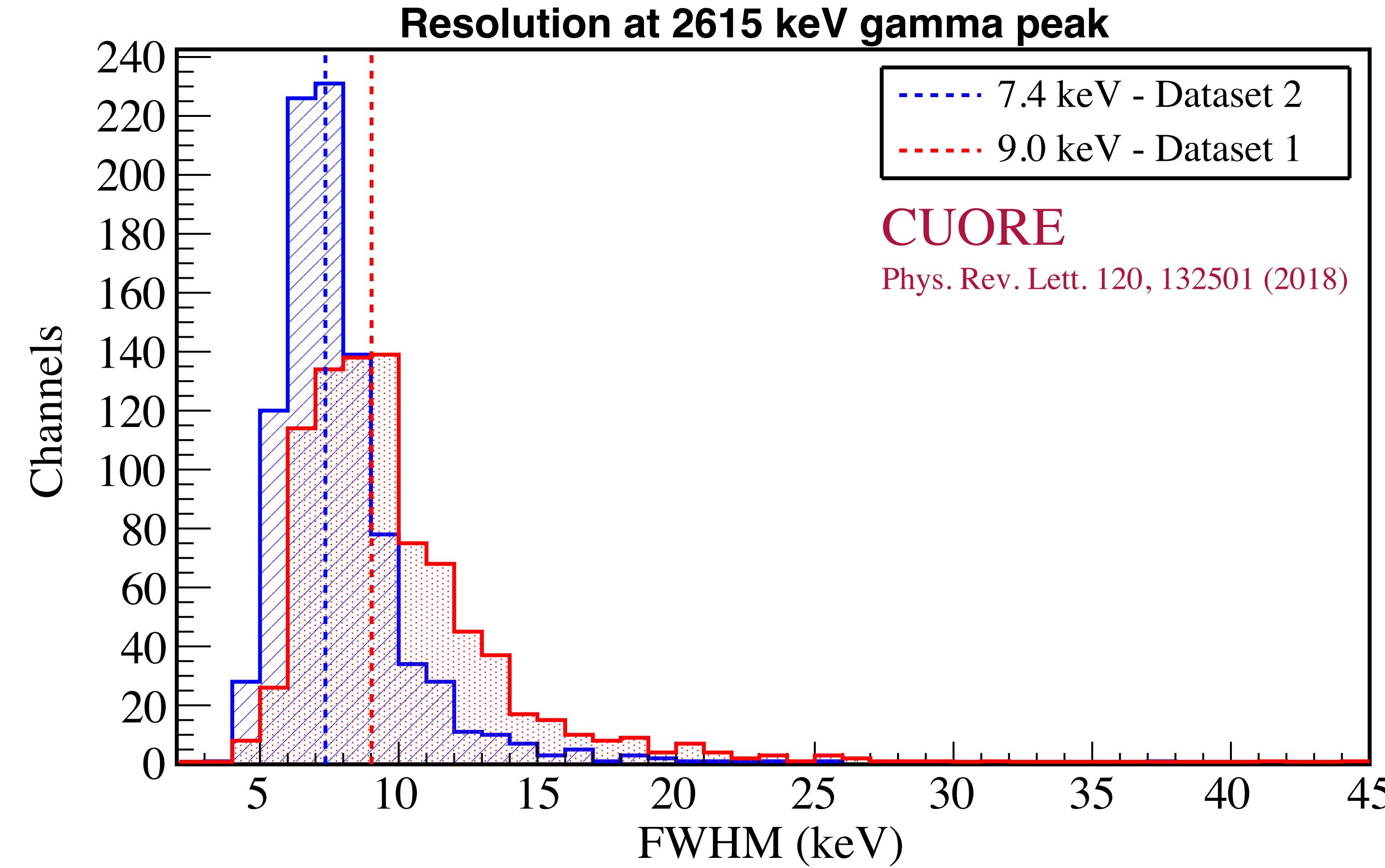


Physics: Consistent with expectations for background

Calibration: ^{232}Th source strings deployed into cold space near detector

Energy Resolution

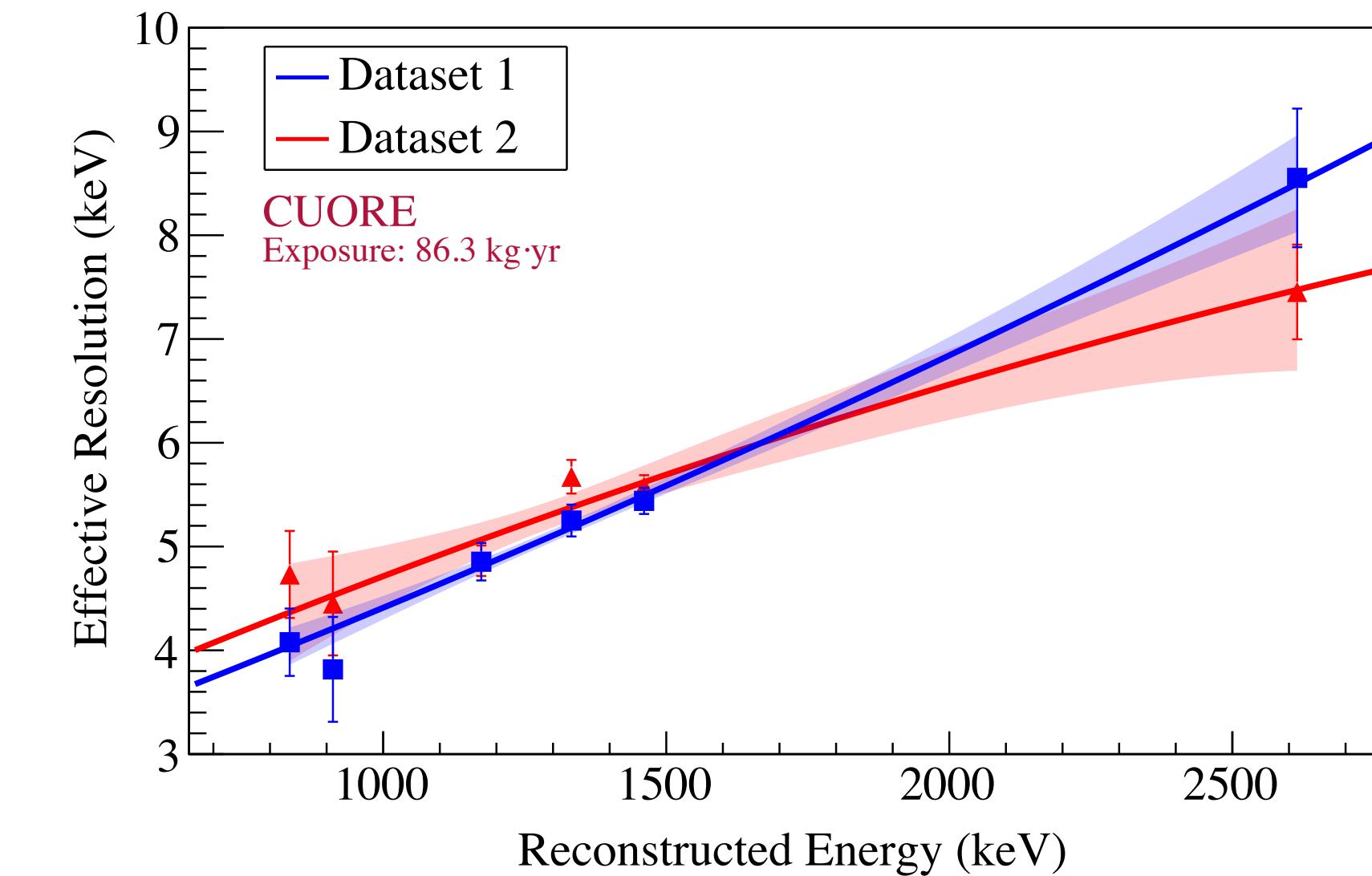
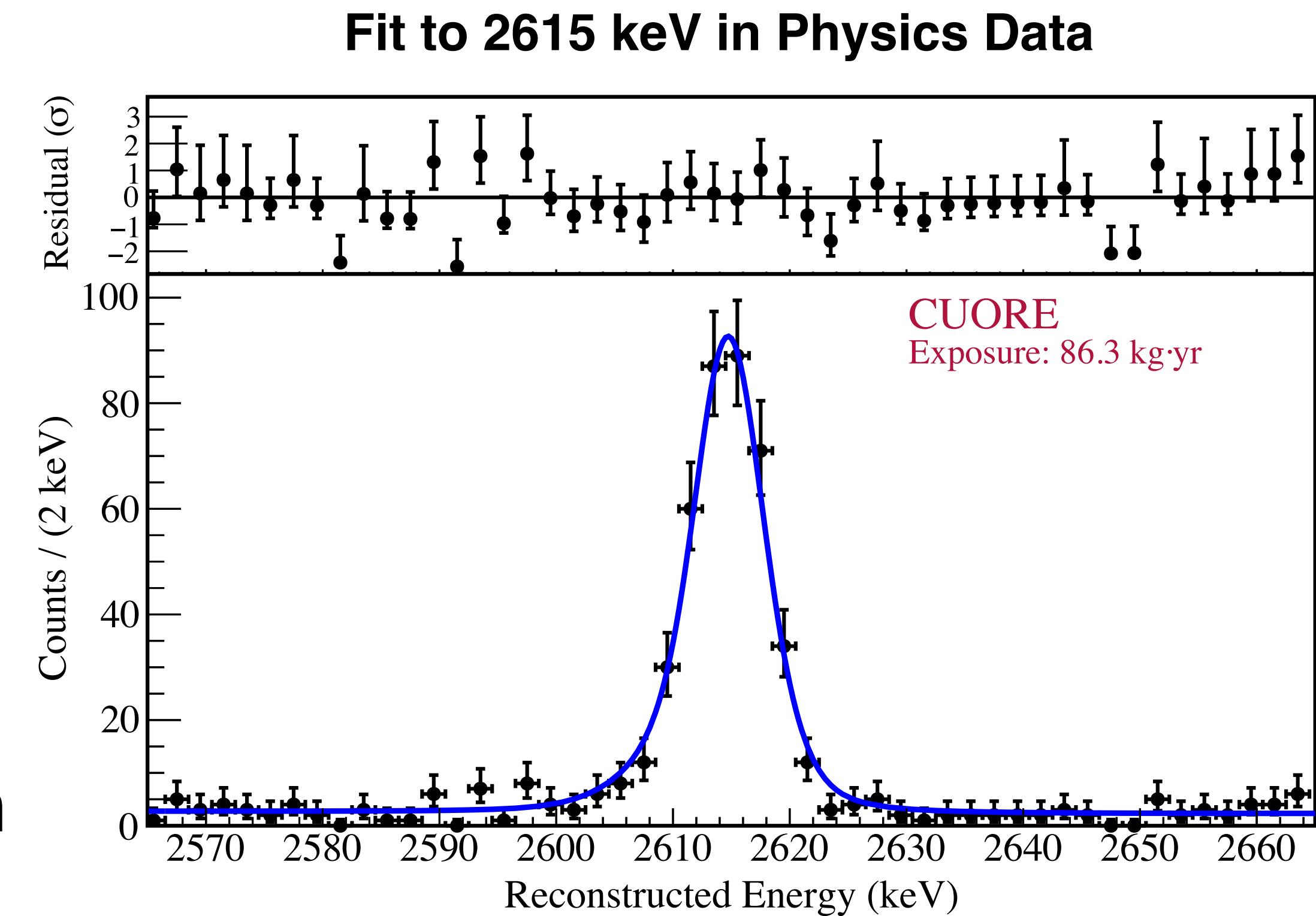
- Energy resolution key for separation of spectral features
- Exposure weighted average resolution of **8.0 keV FWHM**
- **Dataset 1 - 9.0 keV FWHM**
- **Dataset 2 - 7.4 keV FWHM**



Dataset 2 occurred after a period of detector optimization, including the first use of the active noise cancellation technique

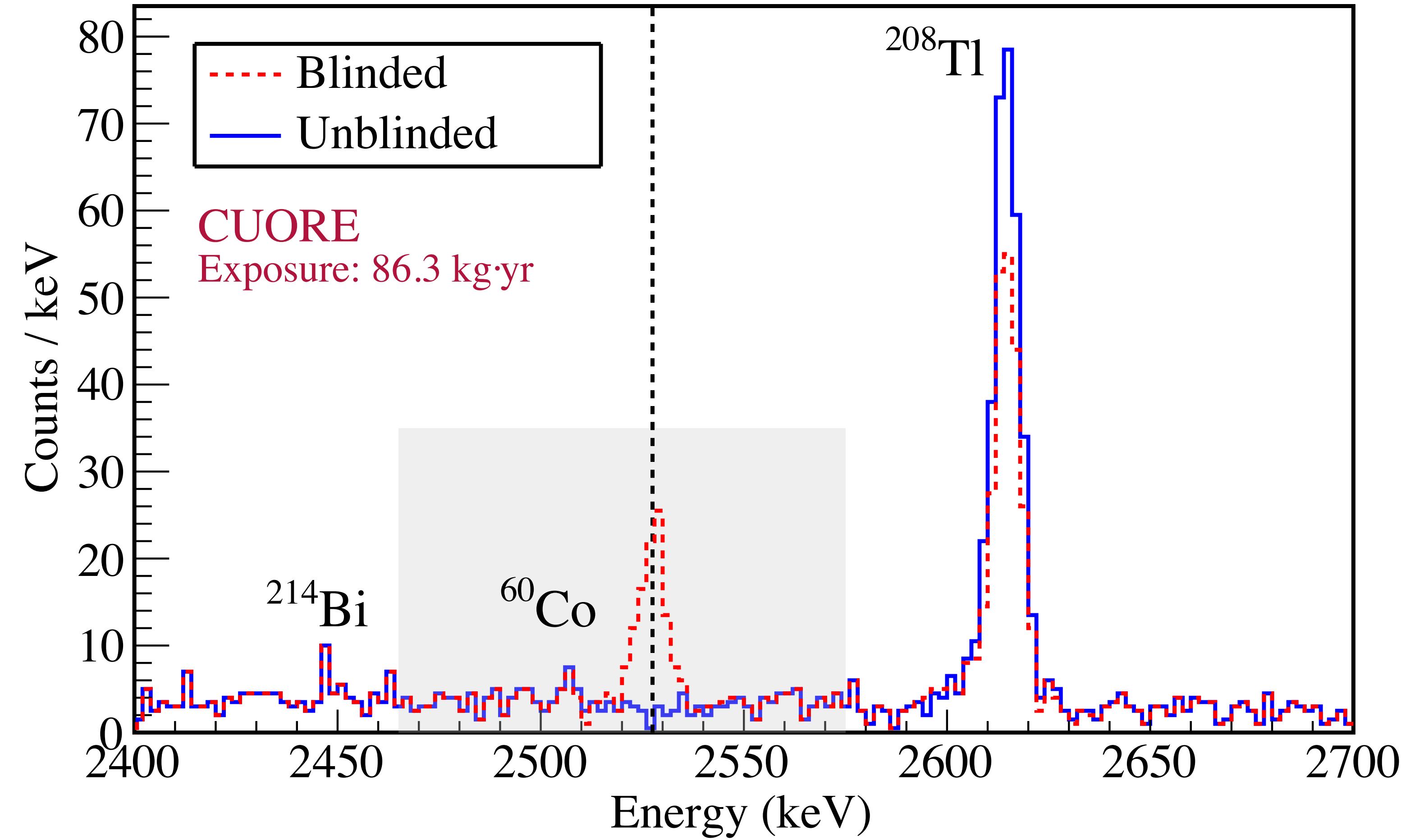
Energy Resolution

- Resolution in physics data at Q-value slightly better
- Exposure weighted average resolution at Q-value of 7.7 ± 0.5 keV FWHM
- **Dataset 1 - 8.3 ± 0.4 keV FWHM**
- **Dataset 2 - 7.4 ± 0.7 keV FWHM**



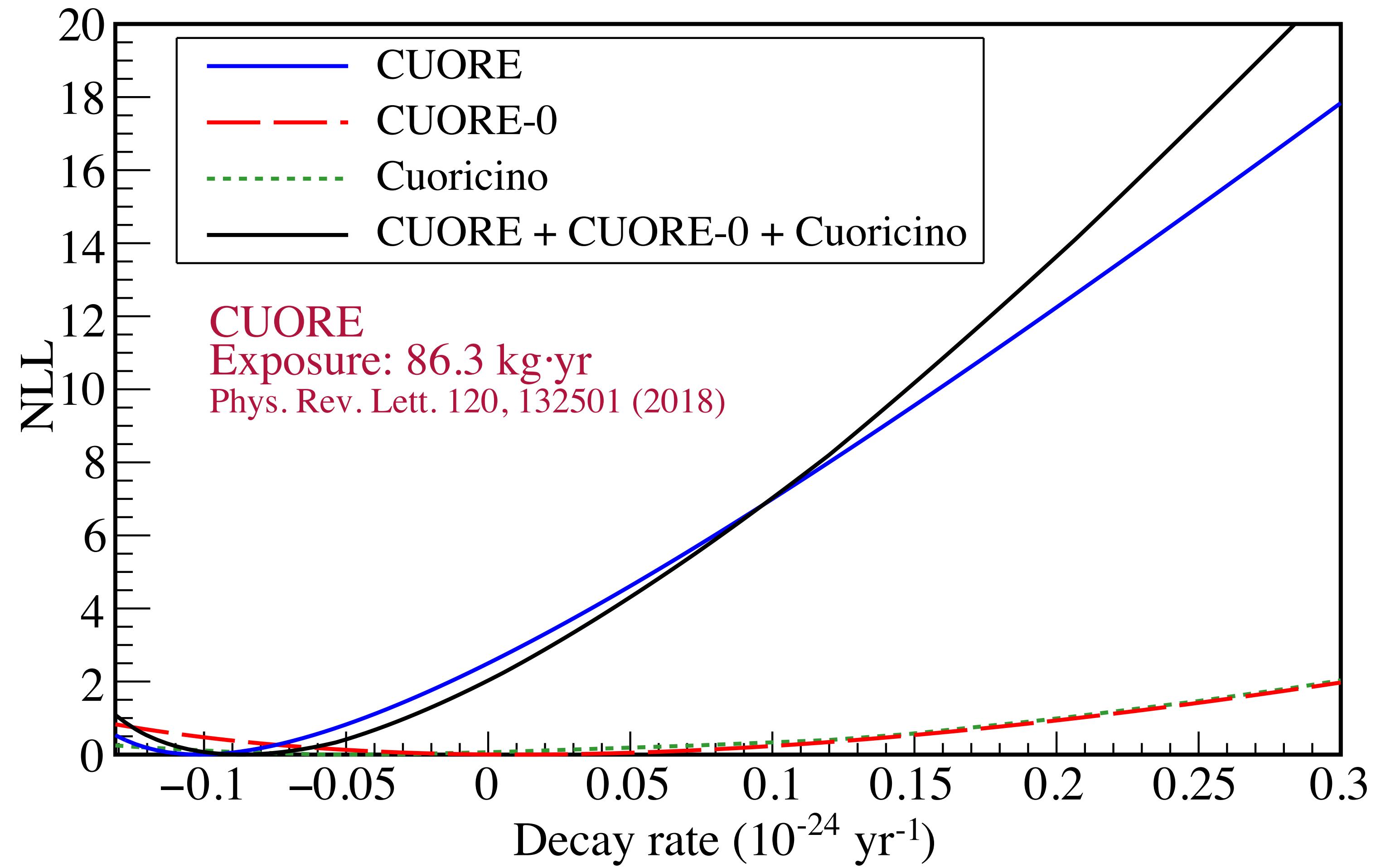
Blinding

- Performed via salting
 - Select some fraction of events from within 20 keV of the 2615 keV line
 - Likewise select some fraction of events near $Q_{\beta\beta}$
 - Swap these two populations
 - Produces artificial peak around the Q-value while hiding real $0\nu\beta\beta$ rate in physics data
 - After all analysis cuts and steps are defined and frozen, undo blinding



Half Life Limit

- Limit Computation
 - Profile likelihood integrated over the physical region ($\Gamma > 0$)



^{130}Te Half-life limits (90% C.L., including systematics)

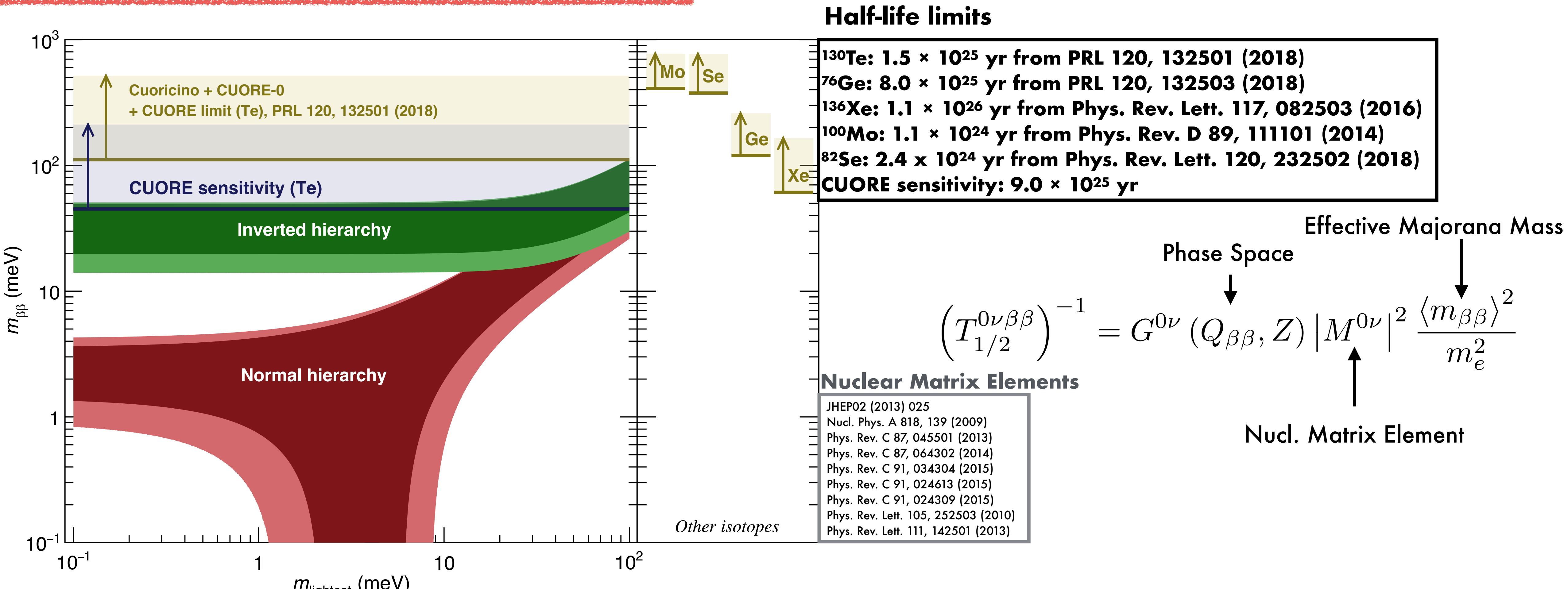
CUORE Half-life limit (90% C.L.): $T_{1/2}^{0\nu} > 1.3 \times 10^{25} \text{ y}$

Rolke: $T_{1/2}^{0\nu} > 2.1 \times 10^{25} \text{ y}$

CUORE + CUORE0 + Cuoricino Half-life limit (90% C.L.): $T_{1/2}^{0\nu} > 1.5 \times 10^{25} \text{ y}$

Rolke: $T_{1/2}^{0\nu} > 2.2 \times 10^{25} \text{ y}$

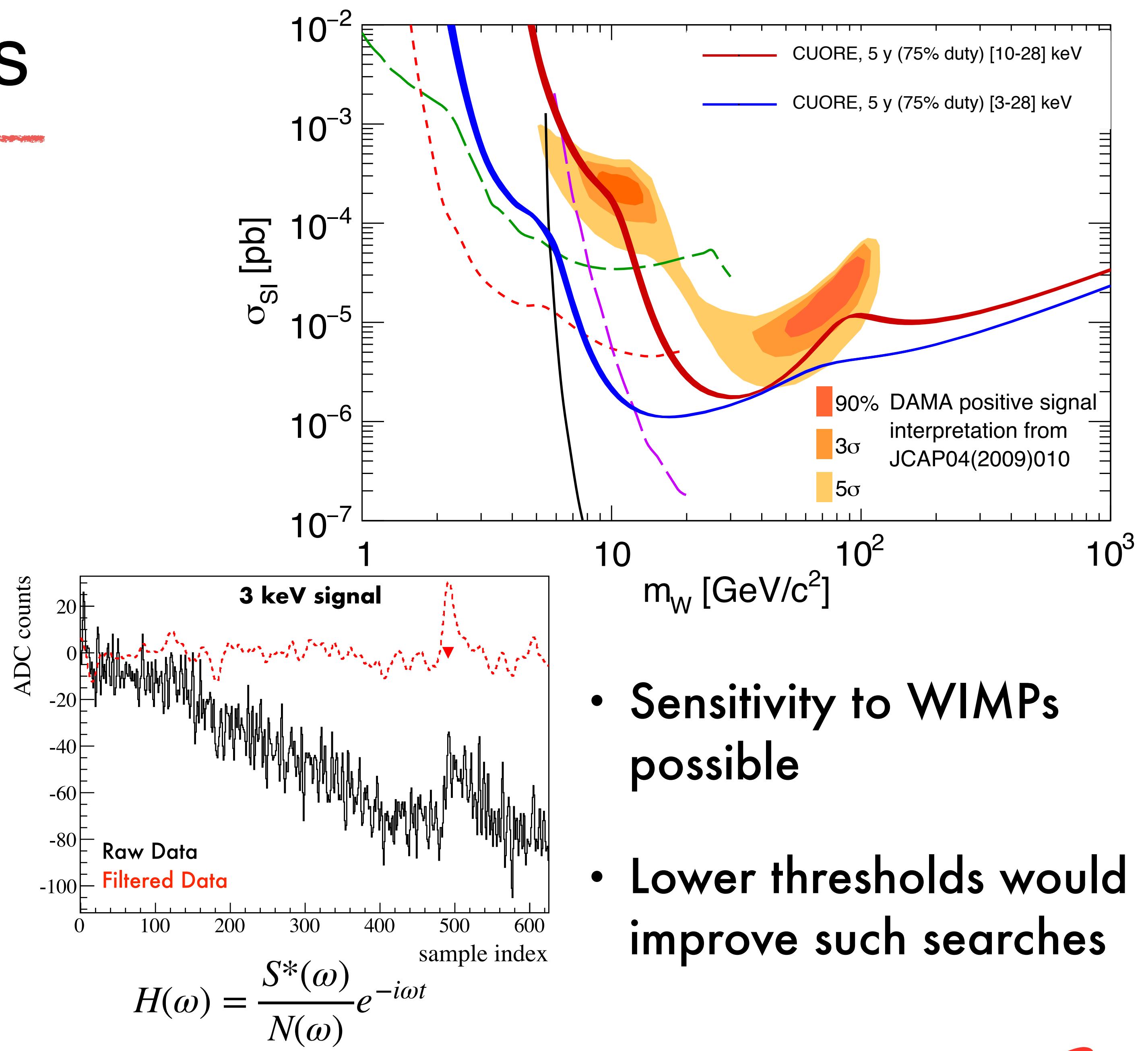
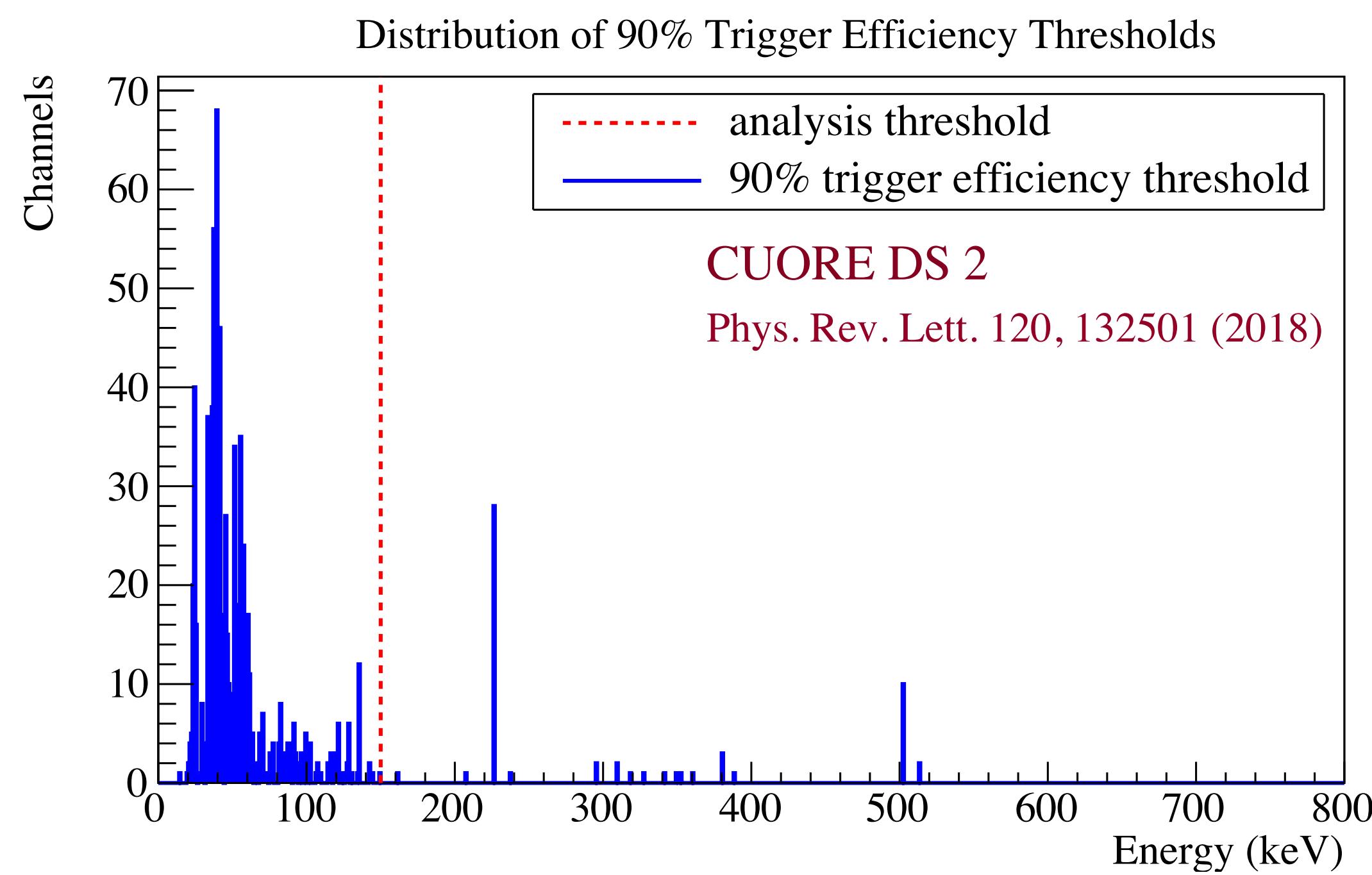
Combined $m_{\beta\beta}$ Limit



110 meV < $m_{\beta\beta}$ < 520 meV - NME dependent Phys. Rev. Lett. 120, 132501

Low Threshold Searches

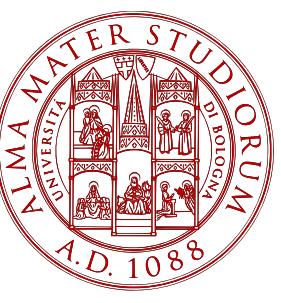
- Noise decorrelation in Optimal Filter to improve energy resolution
- Current detector thresholds range from 20 - 150 keV
- Efforts to lower these under investigation
 - Filtering to improve SNR
 - Trigger based off of Optimal Filter under development



- **Sensitivity to WIMPs possible**
- **Lower thresholds would improve such searches**

Conclusions

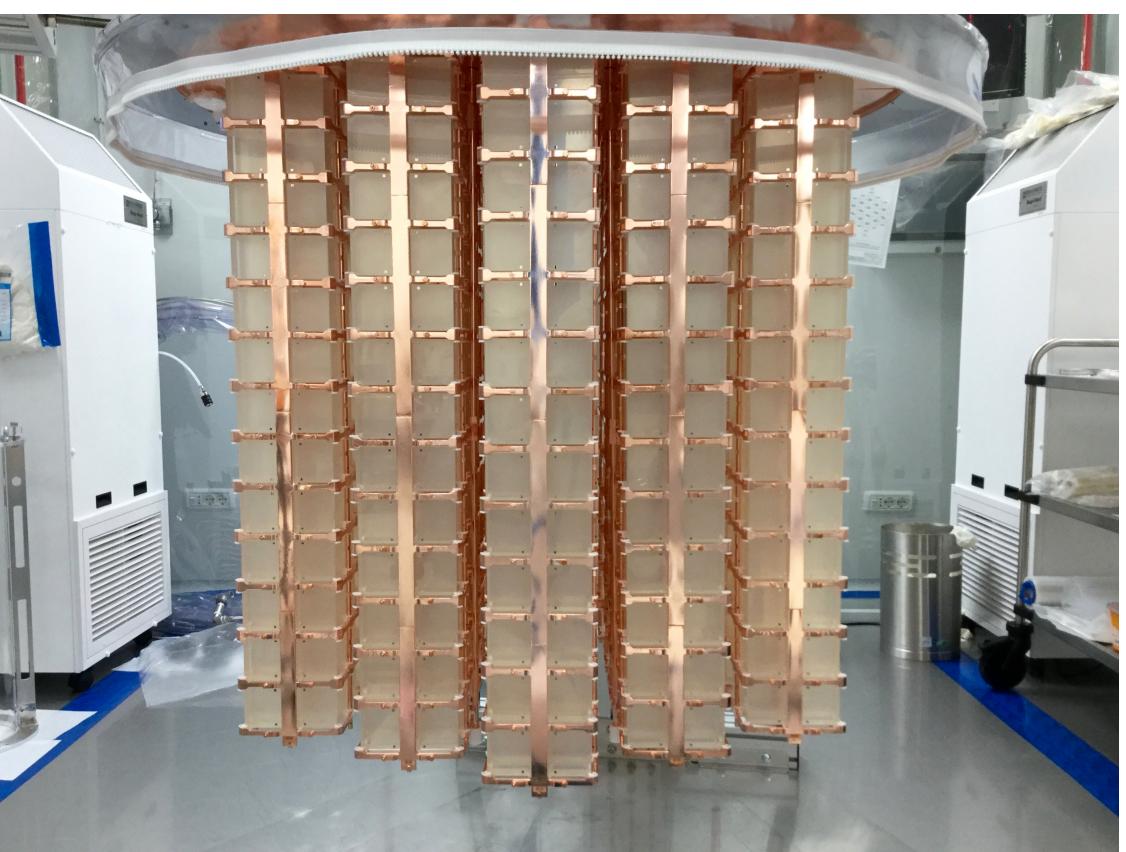
- Operation of world's largest ton-scale cryogenic bolometric array
 - Largest and most powerful cryogen free dilution refrigerator
- Detector resolution improved from 9 keV to 7.5 keV via optimization campaign
- Further detector optimization techniques under development such as optimal triggering, decorrelation
- $2\nu\beta\beta$ analysis with 2018 data nearing completion
- Other analyses (other isotope, dark matter) possible
- First result from CUORE
 - Strongest limit on ^{130}Te $0\nu\beta\beta$ decay to date after 2 months ($>1.5 \times 10^{25}$ yr)
- CUORE detector is robust and powerful tool for probing interesting physics
- Stay tuned for more results!

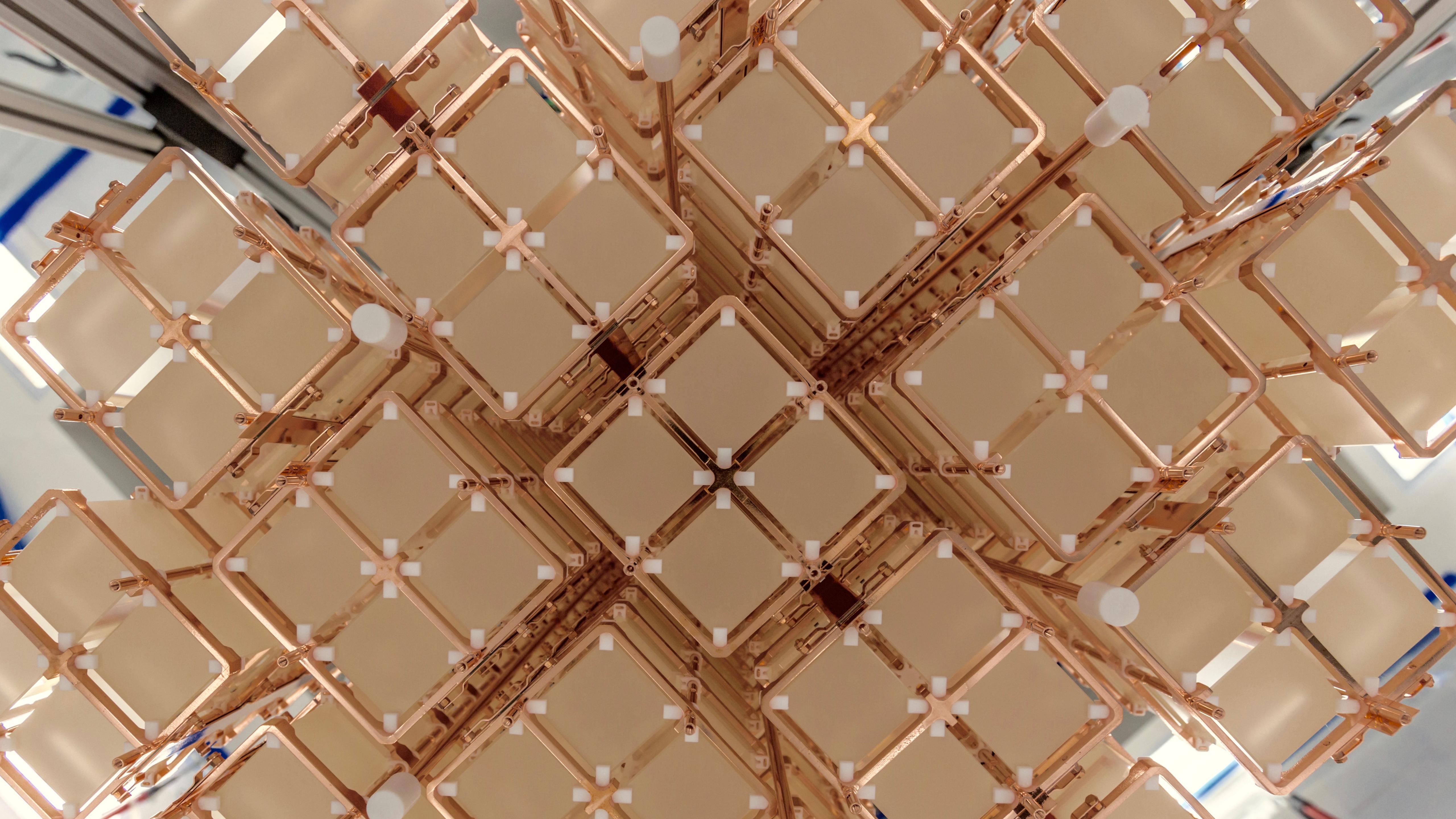


UCLA



CUORE

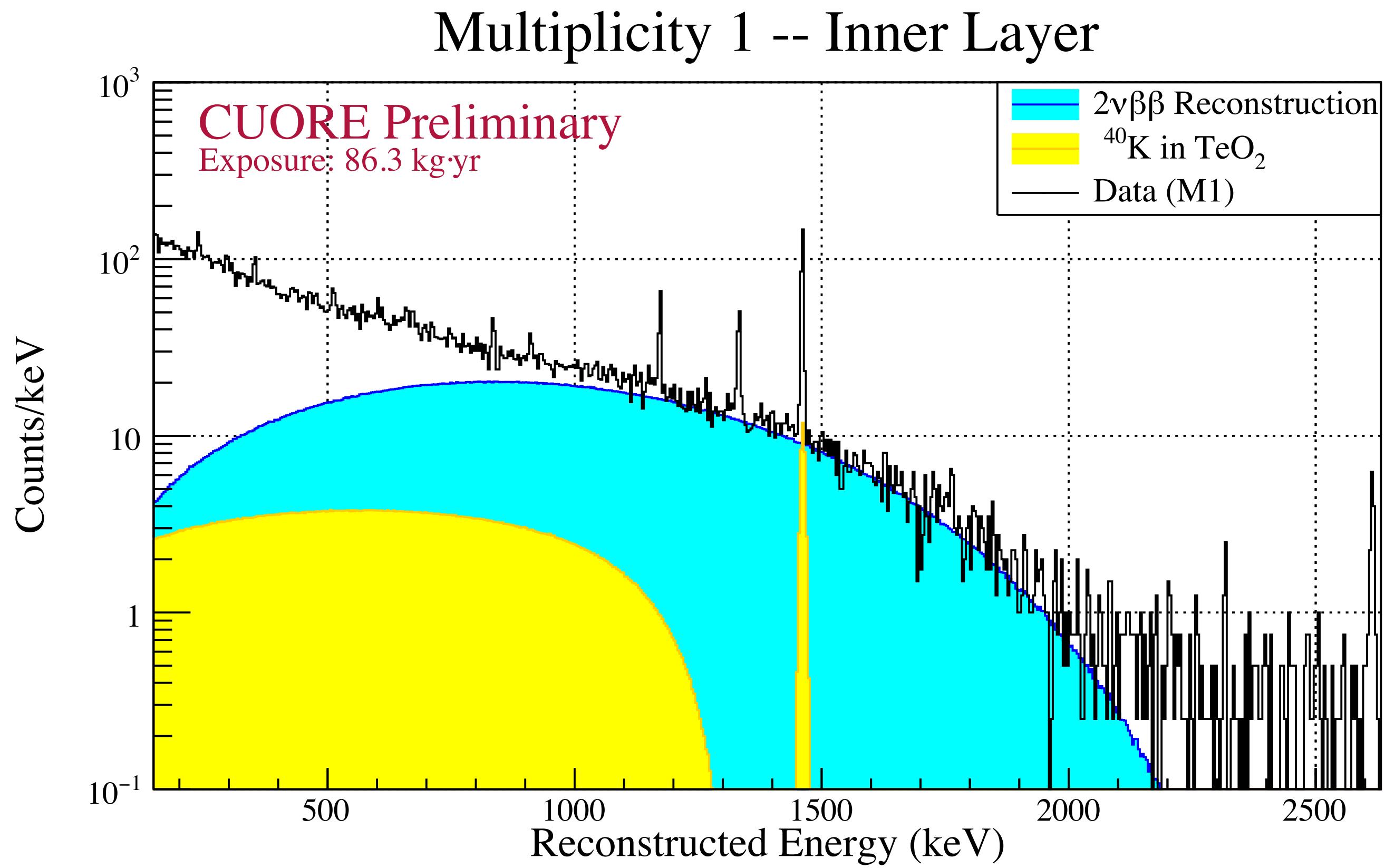




Backups

$2\nu\beta\beta$ Decay

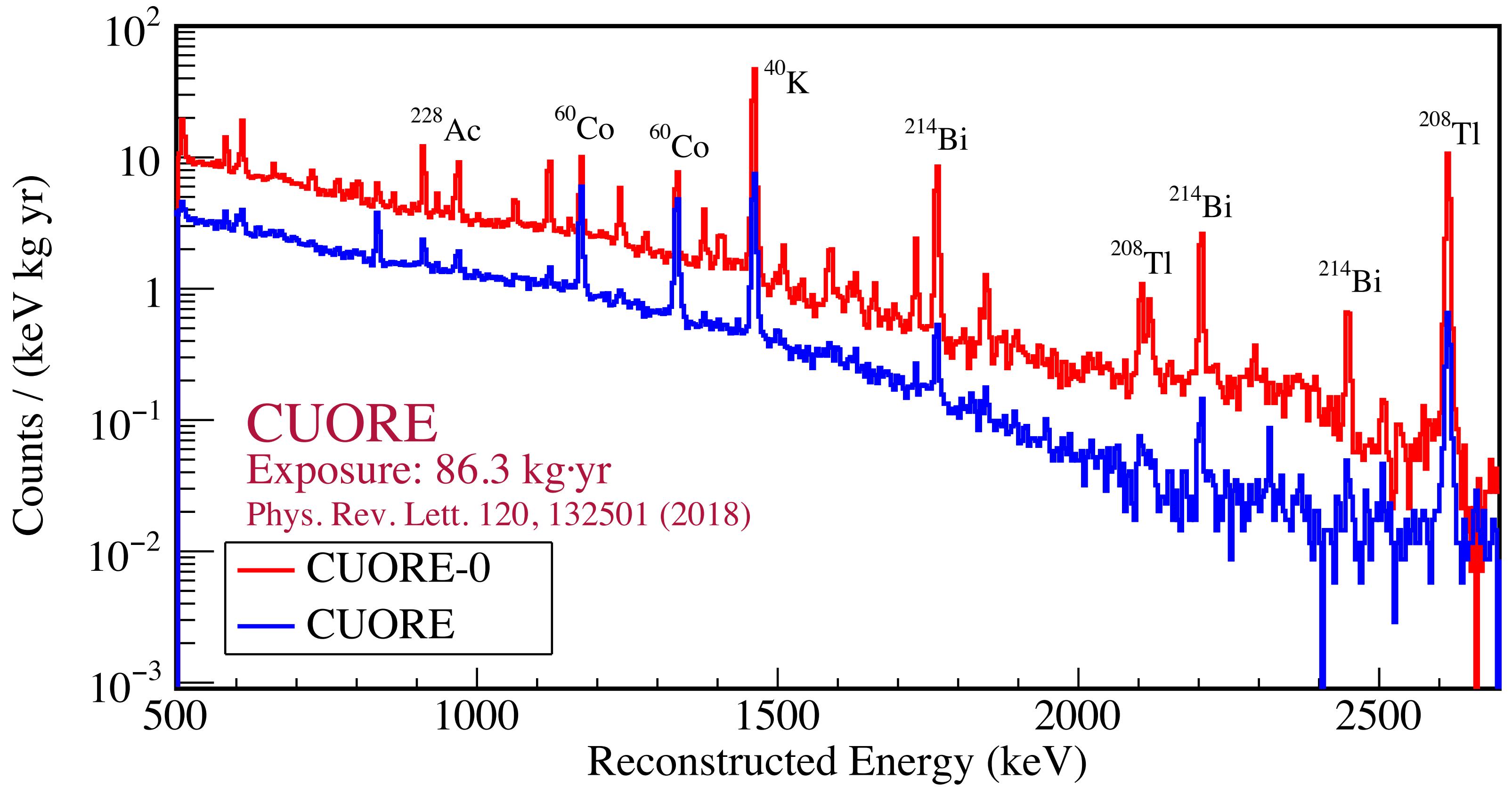
- Can place limit on this decay
- Background model constructed
- Use multiplicity of events to isolate signal from background
- Geometrical split into inner and outer layers
- Analysis with 2018 data wrapping up



CUORE: $T_{1/2} = [7.9 \pm 0.1(\text{stat}) \pm 0.2(\text{syst})] \cdot 10^{20} \text{ yr}$
CUORE-0: $T_{1/2} = [8.2 \pm 0.2(\text{stat}) \pm 0.6(\text{syst})] \cdot 10^{20} \text{ yr}$
NEMO: $T_{1/2} = [7.0 \pm 0.9(\text{stat}) \pm 1.1(\text{syst})] \cdot 10^{20} \text{ yr}$

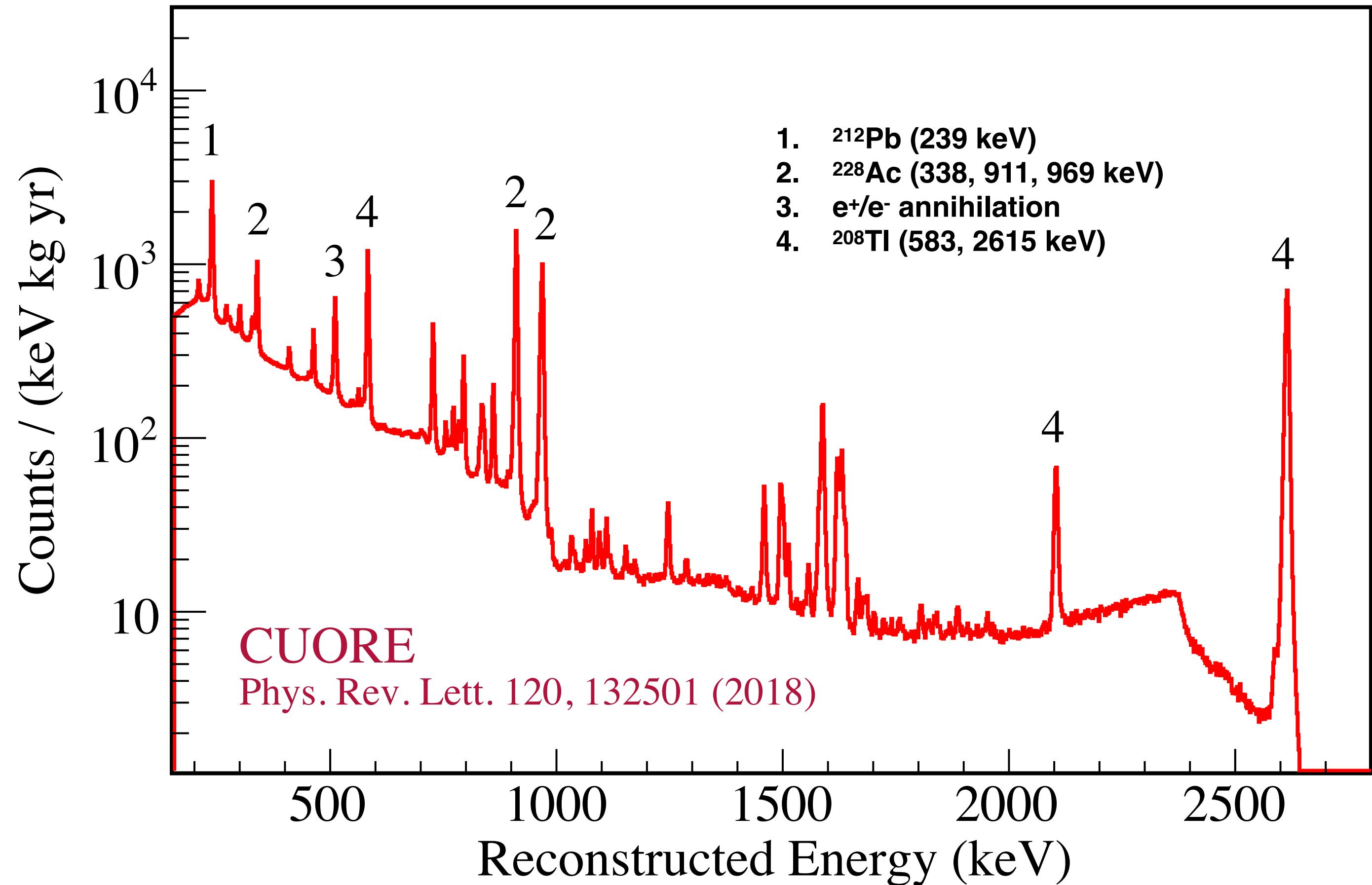
CUORE vs CUORE-0

- Significant reduction in gamma spectrum compared to CUORE-0



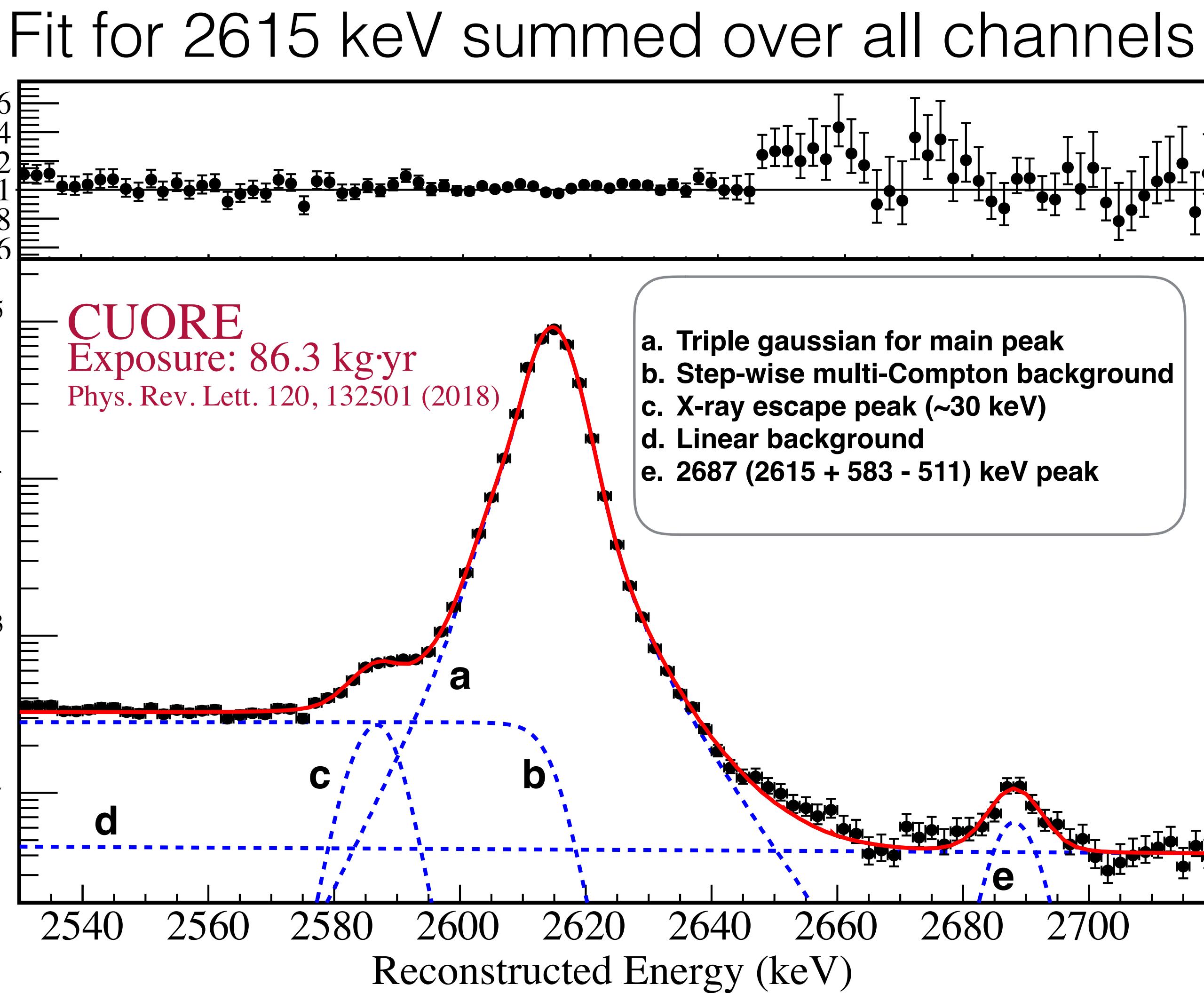
Calibration Spectra

- Multiple spectral peaks present
- Allows for setting channel dependent energy scale
- 2615 keV peak most prominent and closest to ^{130}Te Q-value



Line Shape

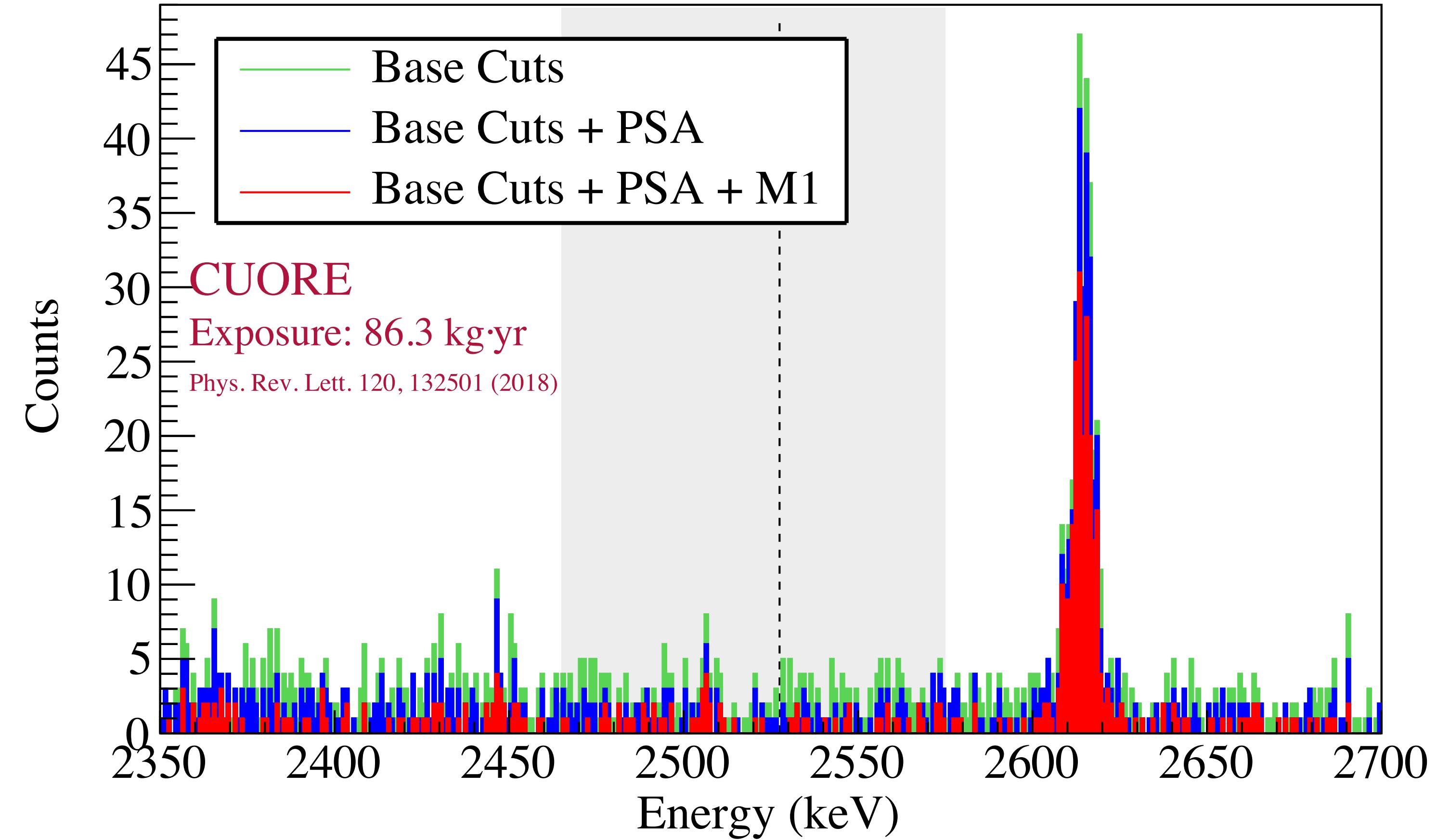
- Model the ^{208}TI 2615 keV line
 - Most prominent peak from ^{232}Th calibration
 - Present in background spectrum
 - Near the $0\nu\beta\beta$ Q-value for ^{130}Te
 - Complex shape
 - Fit performed tower-by-tower



- Combination of channel-dataset and global parameters
- Photopeak is unique to each channel-dataset pair
- Yields pdf for each channel-dataset pair

Cuts

- Base cuts are simple data quality cuts, removal of bad periods of detector performance, and pile-up rejection
- PSA - pulse shape cuts use a 6D Mahalanobis distance distribution based on 6 pulse shape parameters
- M1 refers to multiplicity-1, imposing a constraint that no events are seen in other detector channels within 10 ms



CUORE ROI Fit

- Once analysis finalized fit for decay rate in the ROI performed
- ROI: 2465 - 2575 keV
- Simultaneous unbinned extended maximum likelihood fit
 - Dataset dependent flat background
 - ^{60}Co sum peak
 - $Q_{\beta\beta}$ peak - fixed position, floating rate
- Peaks are channel dependent - derived from line shape determined from calibration data

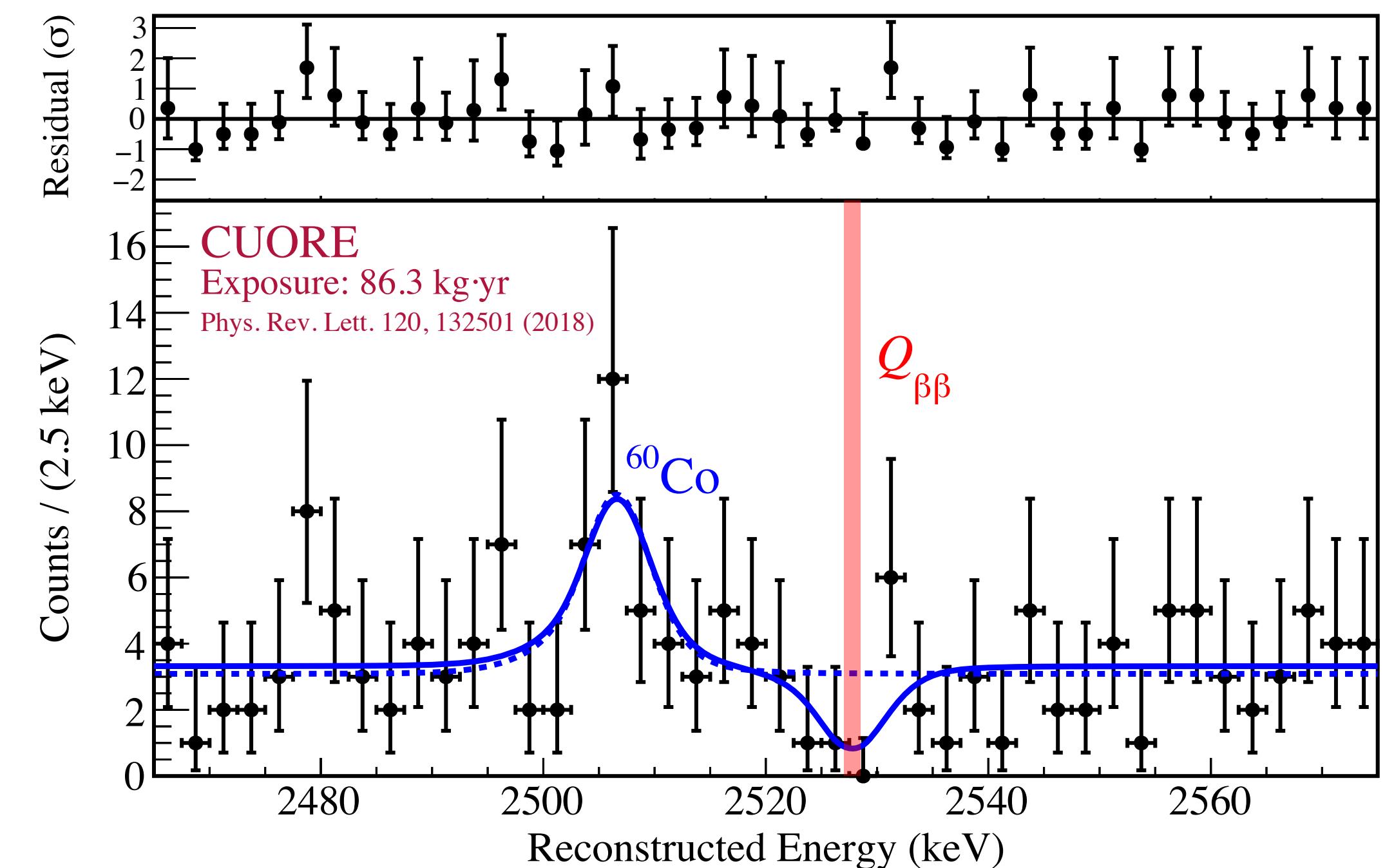
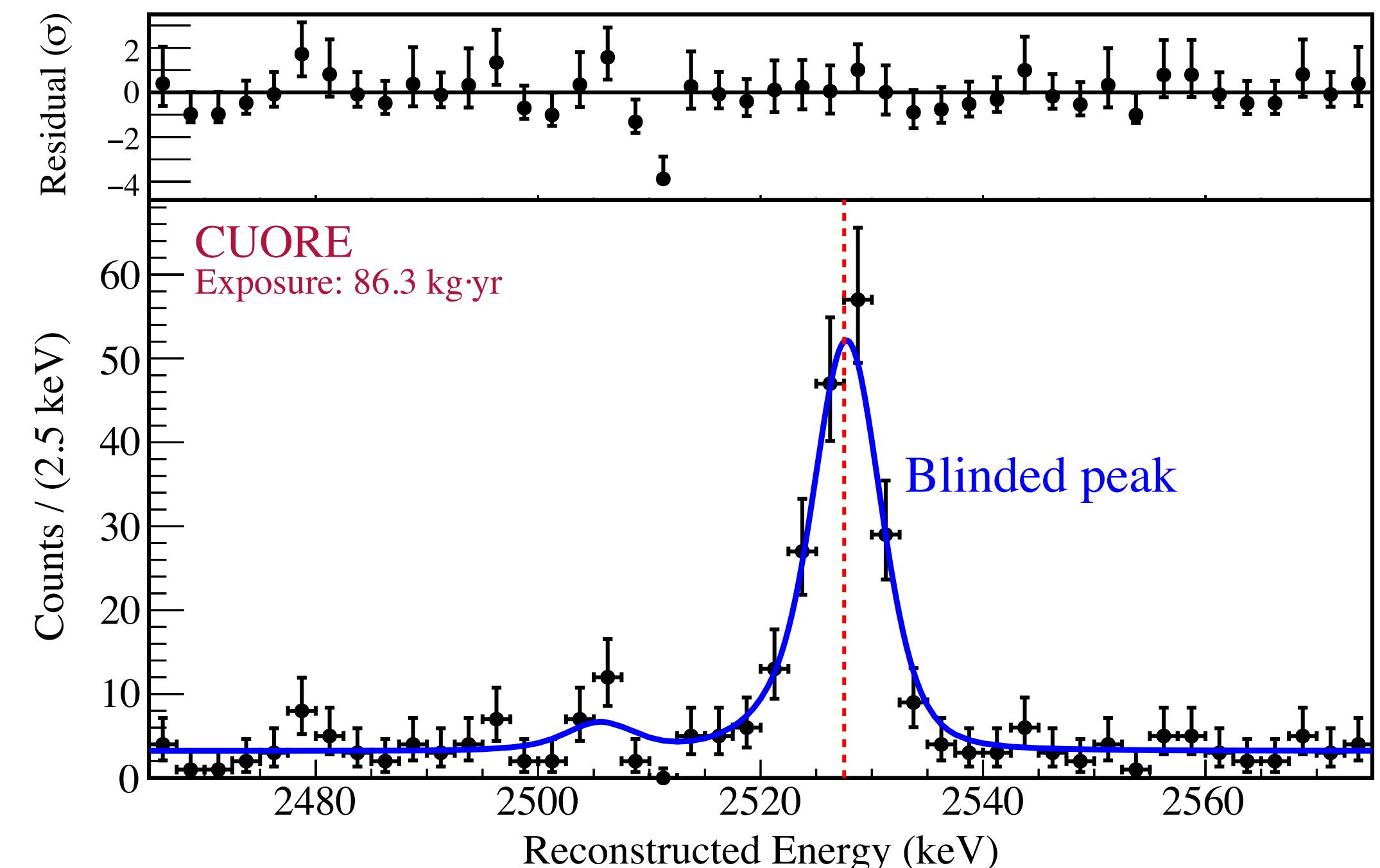
Background Index

Dataset 1 $BI = (1.49^{+0.18}_{-0.17}) \times 10^{-2} \frac{\text{cnt}}{\text{keV} \cdot \text{kg} \cdot \text{yr}}$

Dataset 2 $BI = (1.35^{+0.20}_{-0.18}) \times 10^{-2} \frac{\text{cnt}}{\text{keV} \cdot \text{kg} \cdot \text{yr}}$

Best Fit Signal Decay Rate

$$\Gamma_{0\nu}^{\text{fit}} = (-1.0^{+0.4}_{-0.3} \text{ (stat.)} \pm 0.1 \text{ (sys.)}) \times 10^{-25} \text{ yr}^{-1}$$



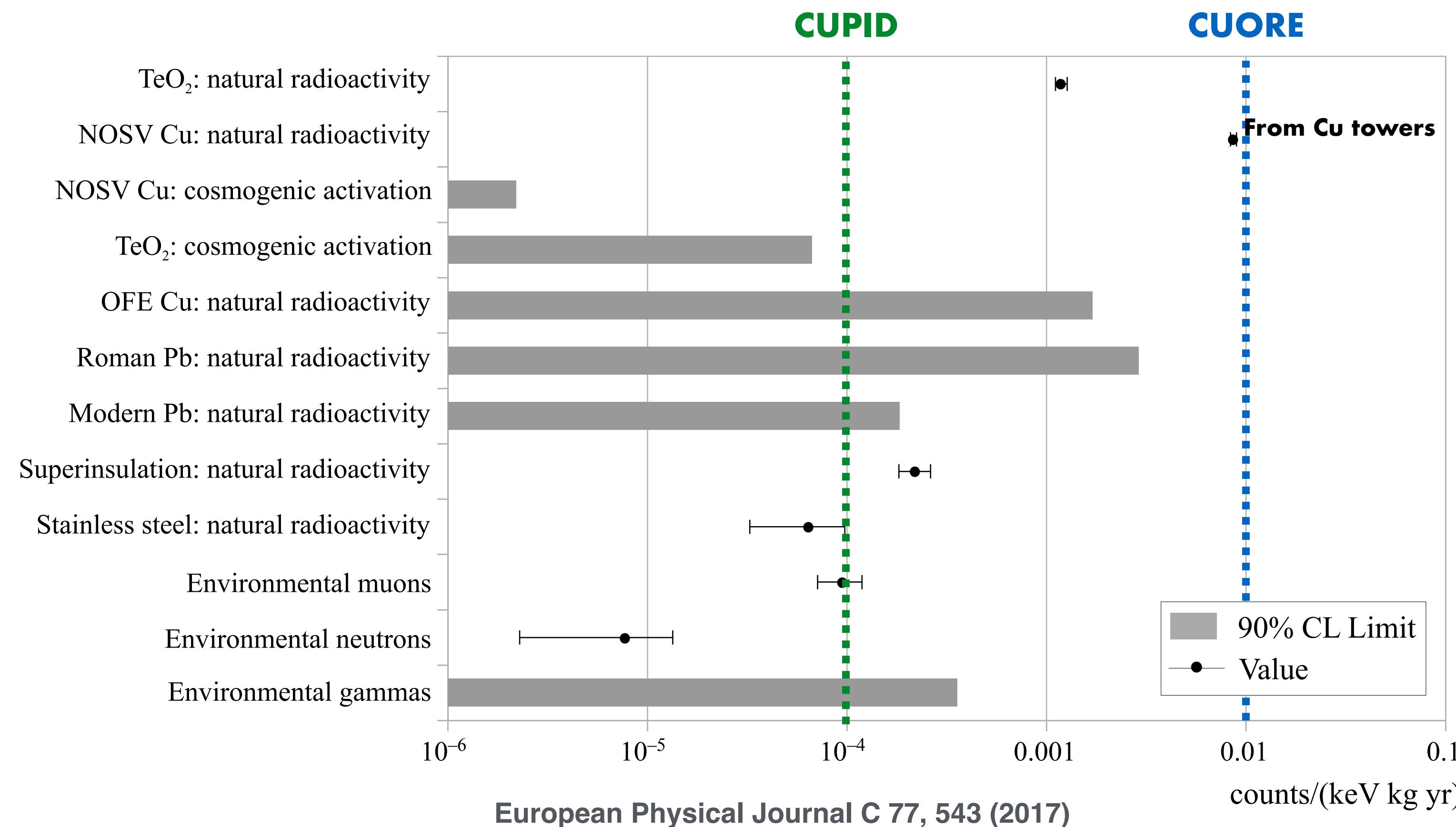
Beyond CUORE

- CUORE background goals met
- Degraded α 's pose problem
 - Bolometric technique provides only 1 channel for energy - no particle ID
- CUORE Upgrade with Particle ID (CUPID)
- Aims to dramatically improve background discrimination
 - Particle ID via light detection

Background Limited Background Free

$$S \propto \frac{N_A a \eta \epsilon}{M_{mol}} \sqrt{\frac{MT}{b \Delta E}}$$

$$S \propto \frac{N_A a \eta \epsilon}{M_{mol}} MT$$



European Physical Journal C 77, 543 (2017)

Note: For ^{100}Mo β and γ bkg. decreases x20

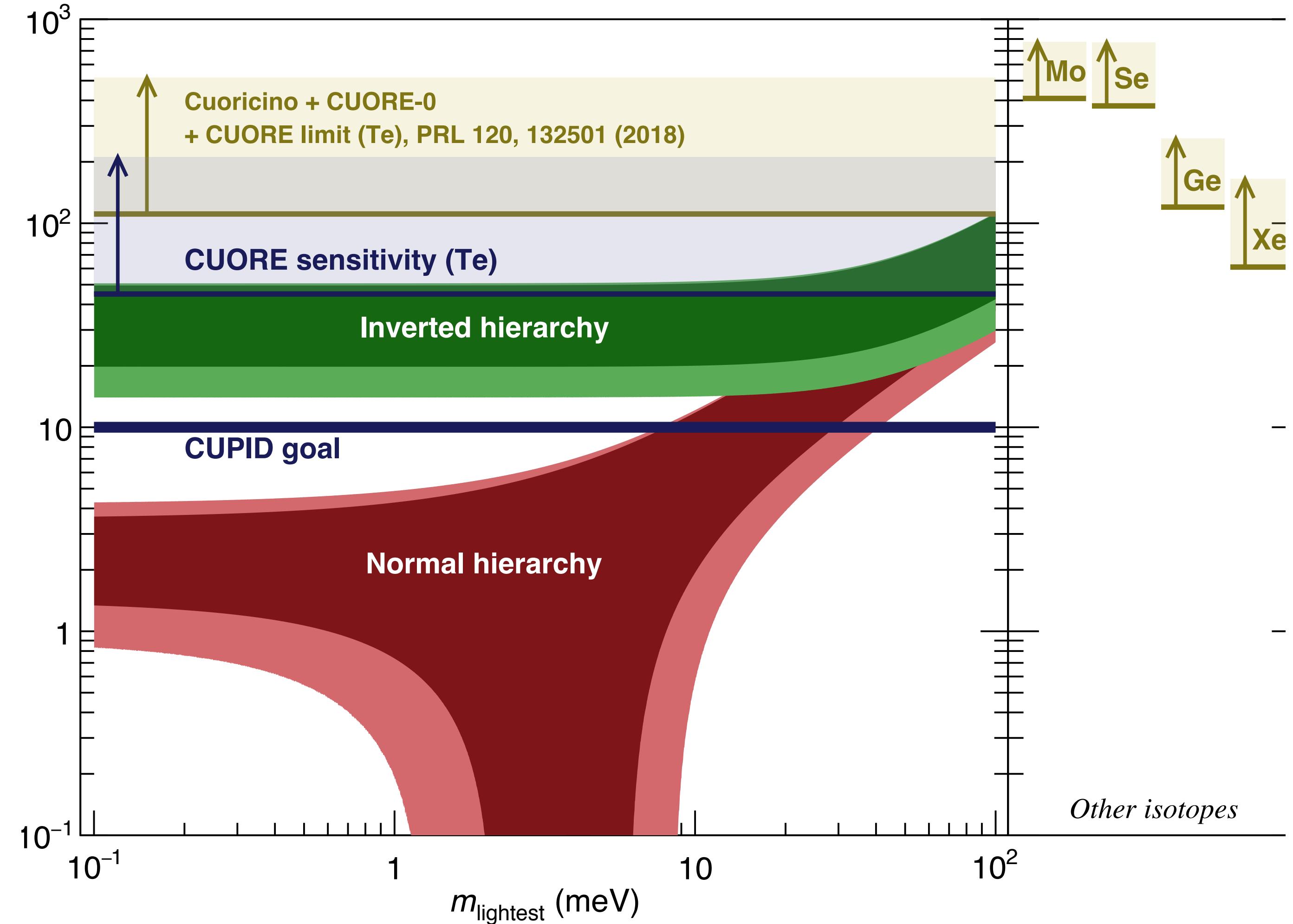
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Paths to CUPID

- Multiple different isotopes
- Enrichment possible for all
- Different light detection strategies under R&D

