BERKELEY LAB

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U.S. DEPARTMENT OF ENERGY

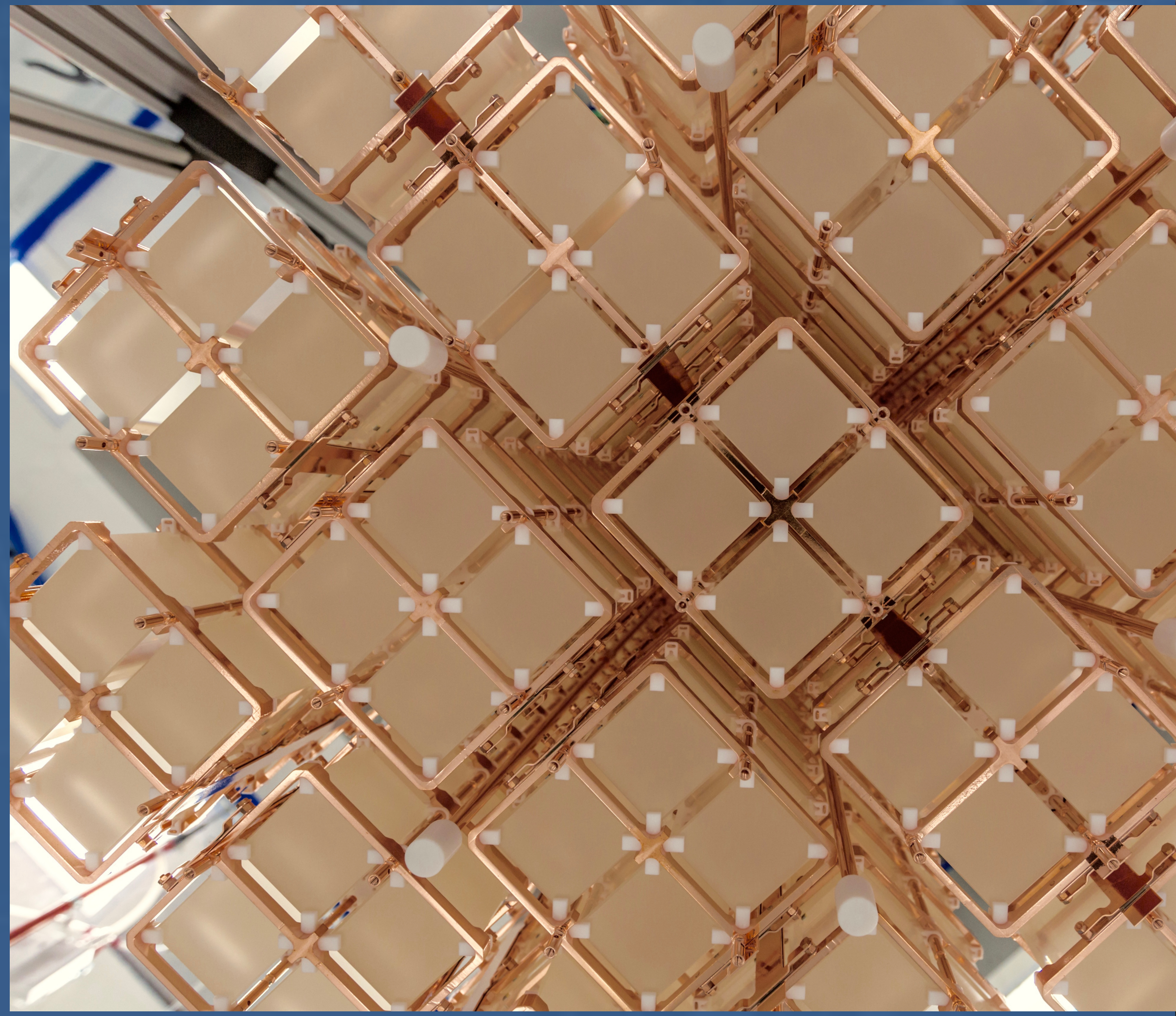
First 0νββ Decay Search Results from CUORE and Status of CUPID R&D

CIPANP 2018

B. Welliver

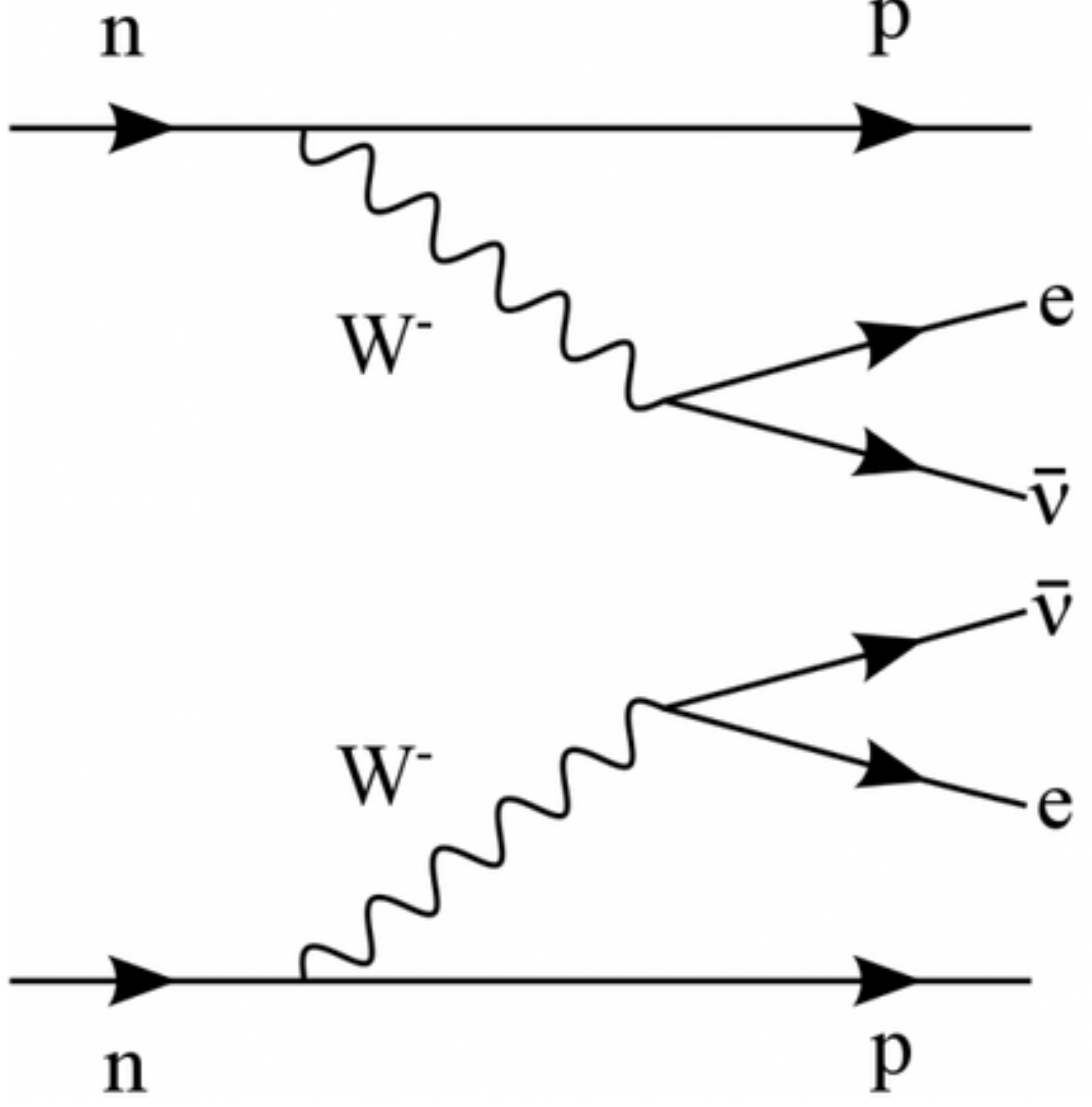
2018-05-29

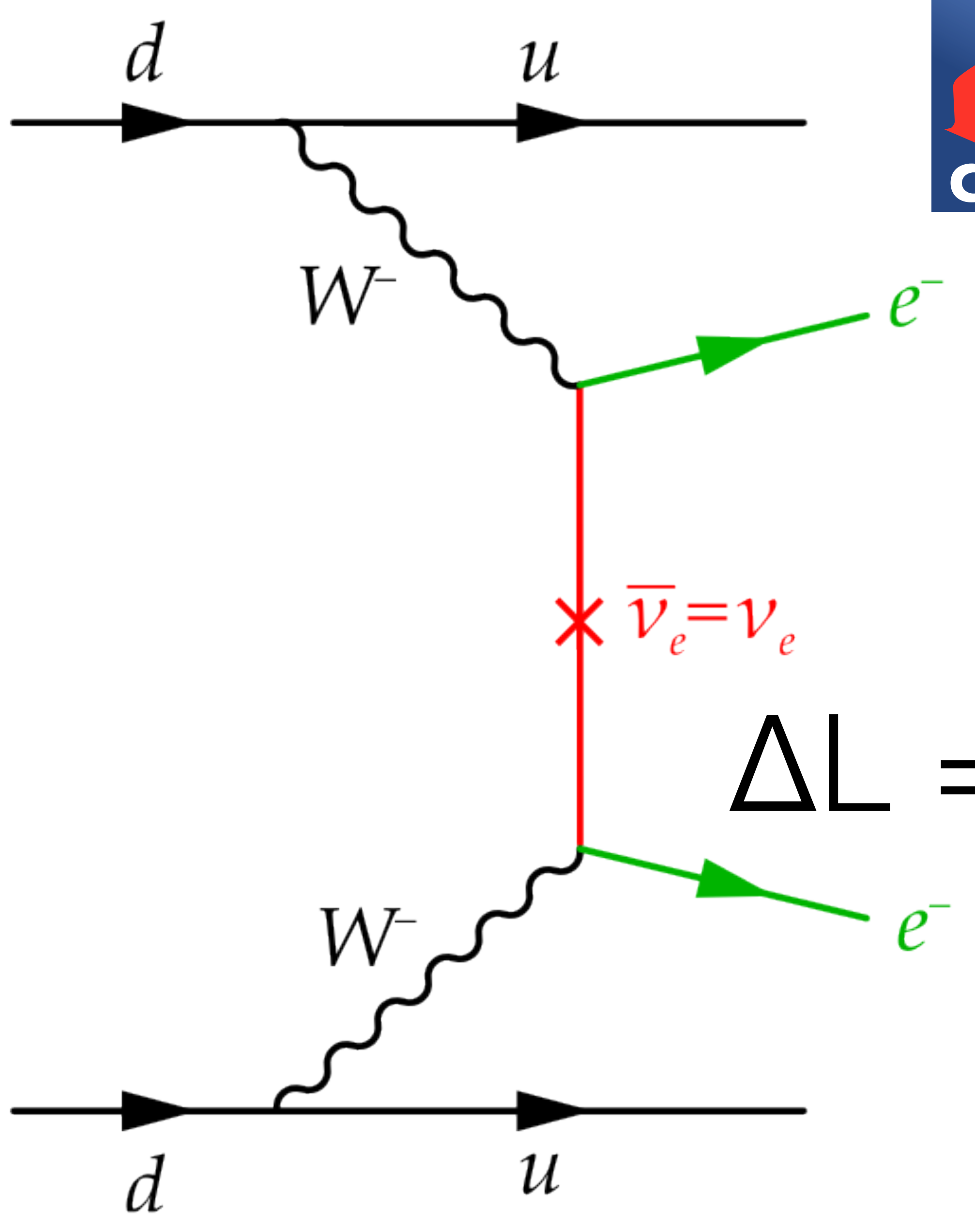
CUORE



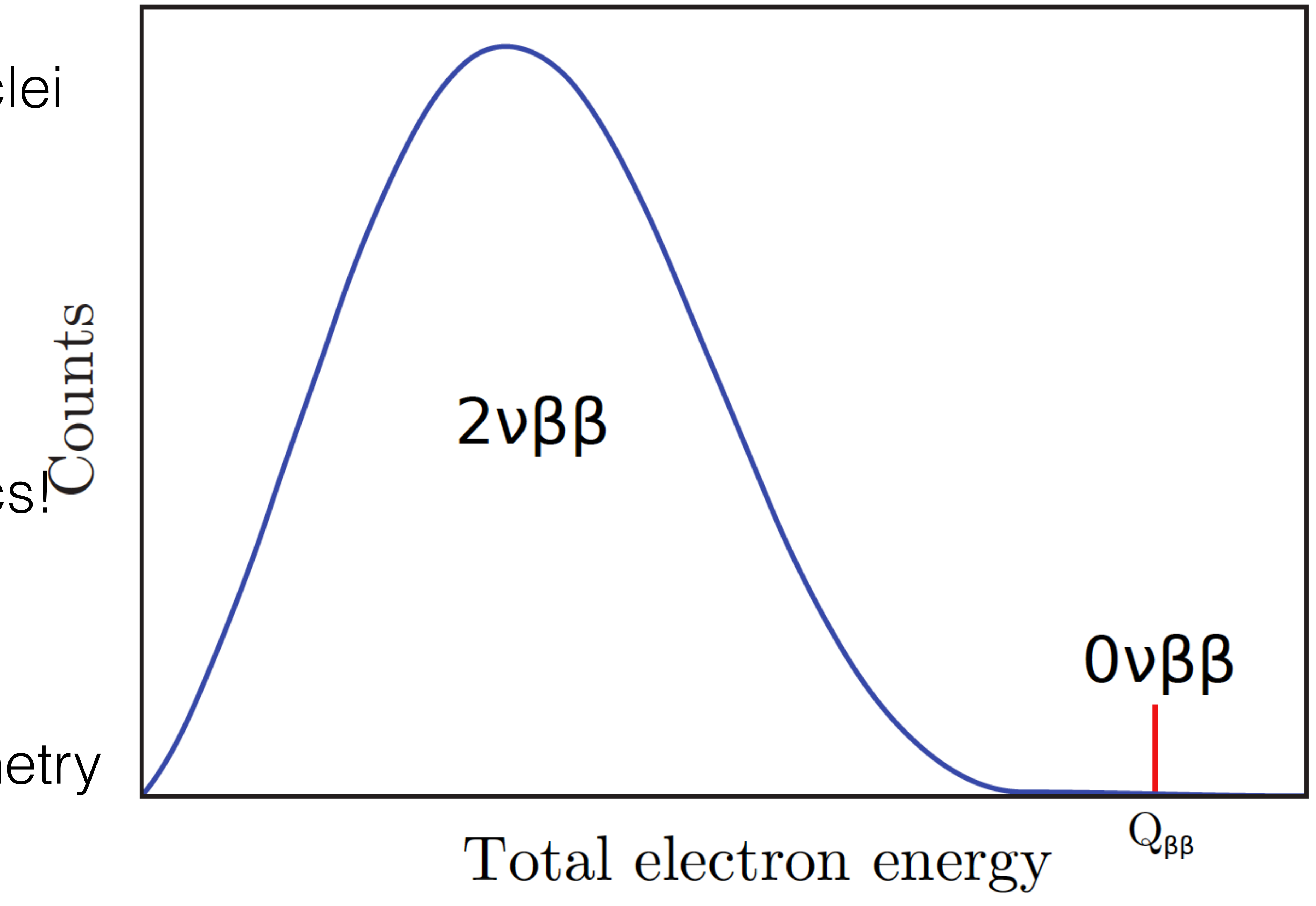
Double Beta Decay

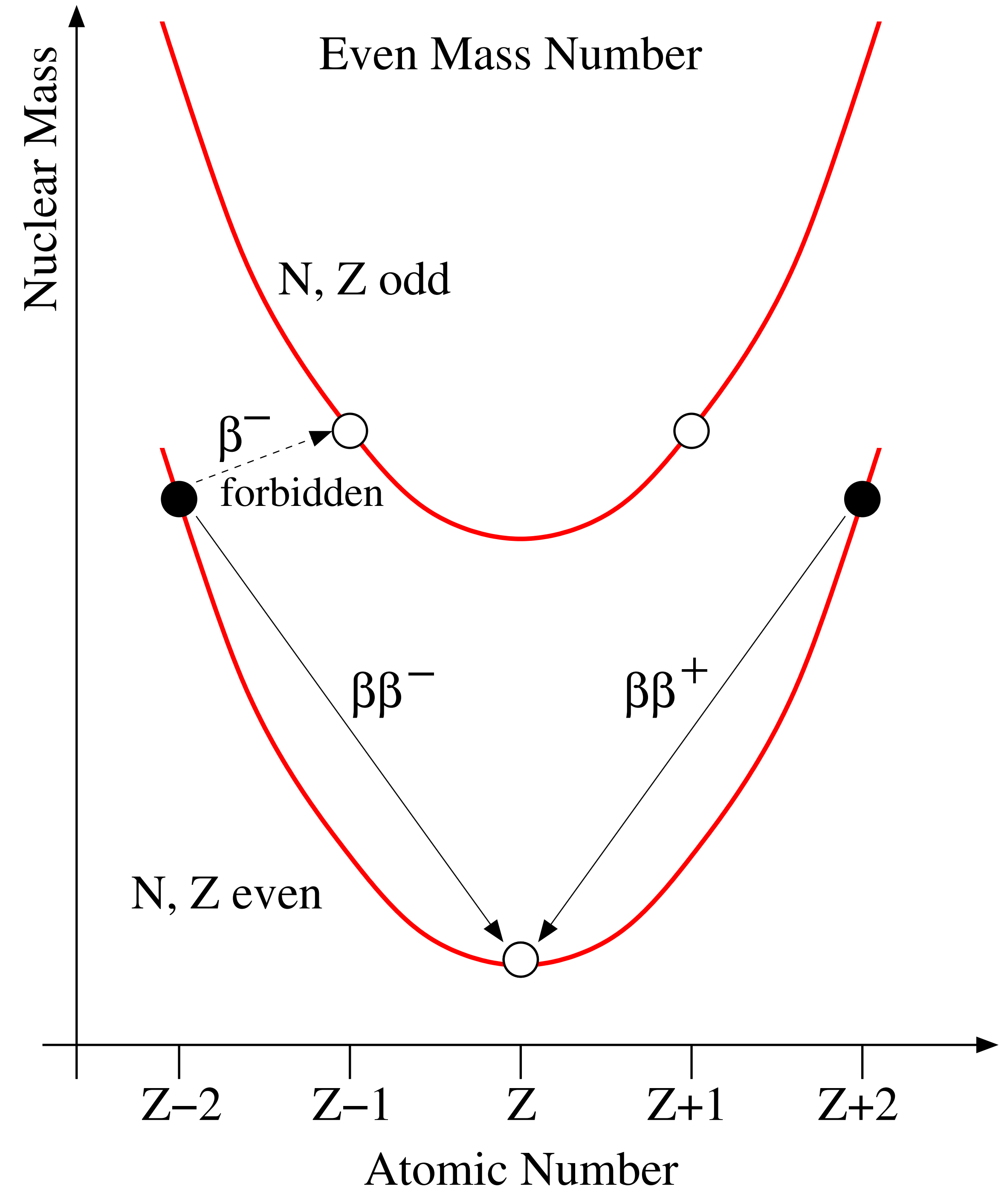
- 2νββ is rare but allowed standard model process
- Conversion of 2n —> 2p + 2e⁻ + 2$\bar{\nu}$ in nucleus
- Broad energy distribution
- Observed half-life $\tau > 10^{19}$ years
- 0νββ is a hypothetical, unobserved process
- Look at 2νββ isotopes with even-even nuclei
  - β-decay energetically forbidden
- Immediate implication of $\Delta L \neq 0$
  - Lepton number violation = new physics!
  - Can imply Majorana mass of ν
  - Possible connection to baryon asymmetry





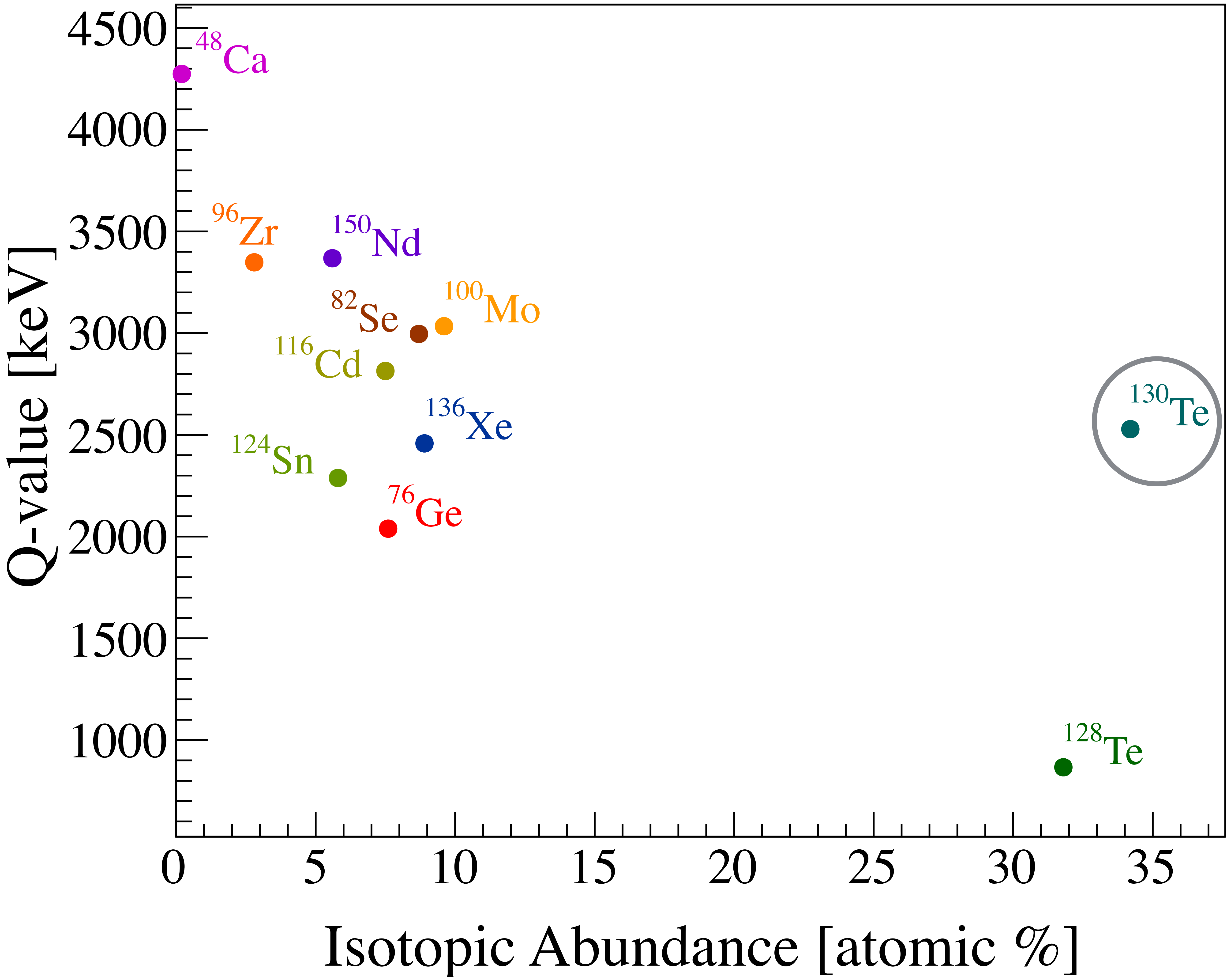
ΔL = 2





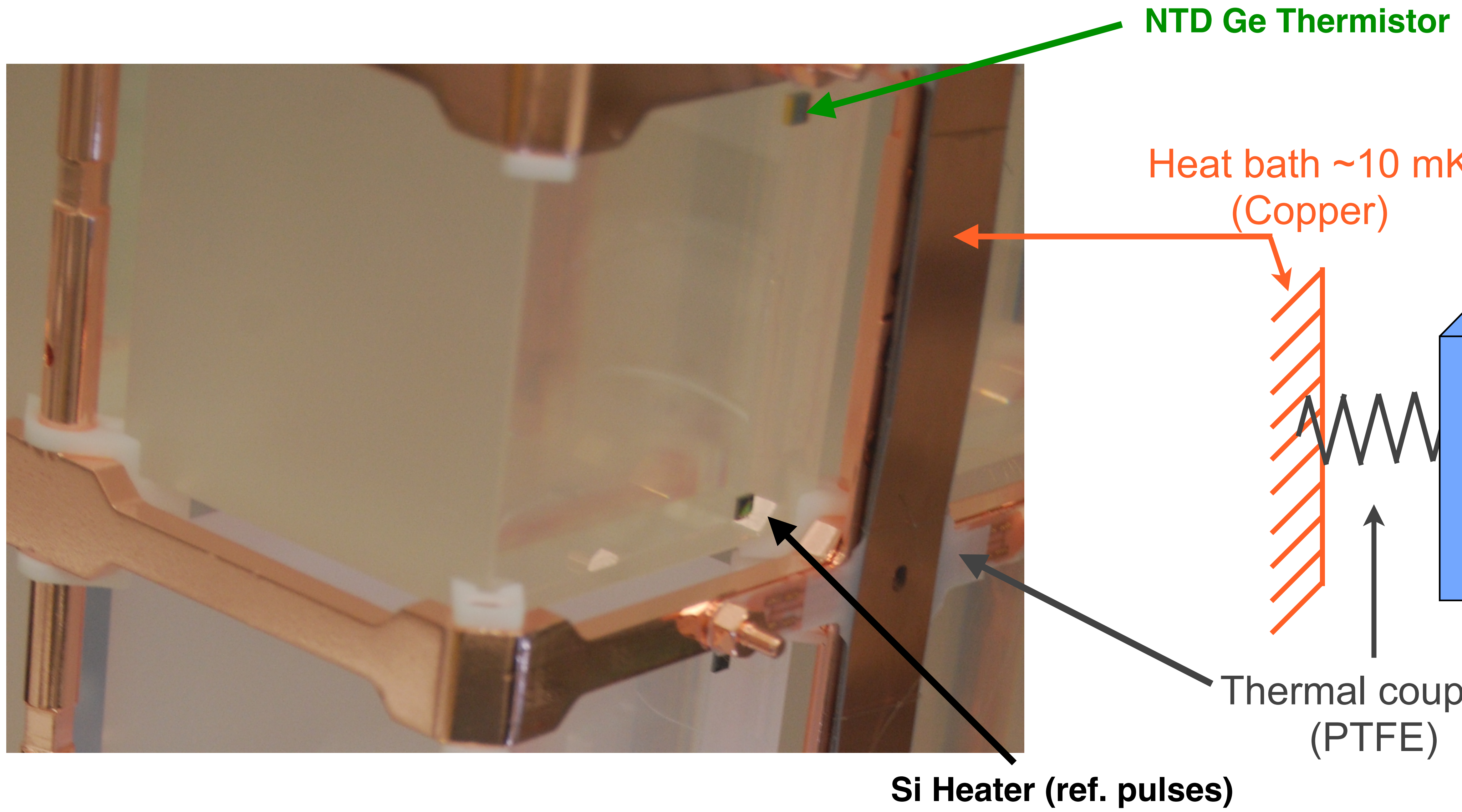
Isotope Choice

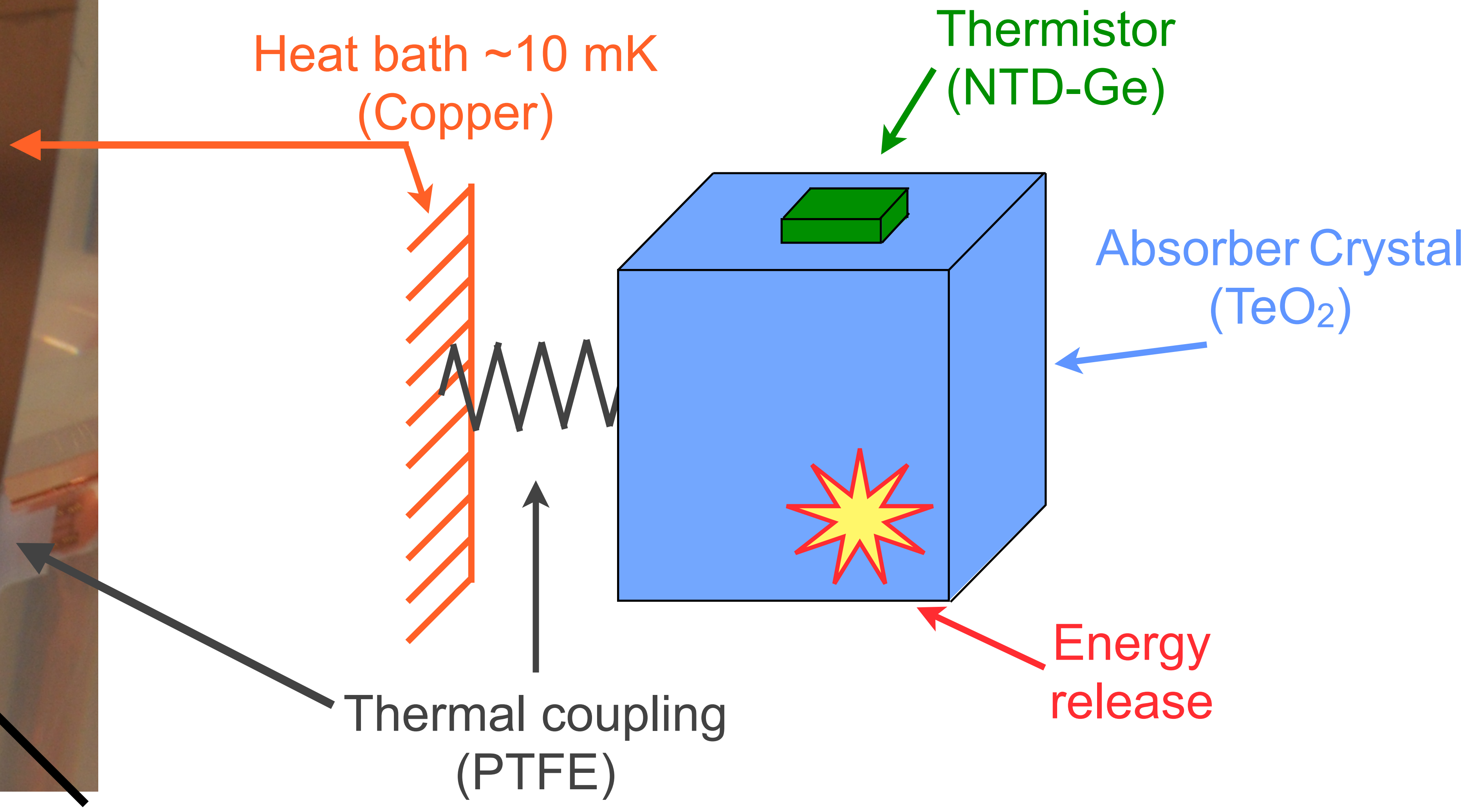
- Desired traits for 0νββ
  - High isotopic abundance (active mass)
  - High Q-value
- ^{130}Te occurs with high natural abundance (~34%) and has a relatively high Q-value (2527.518 keV)
- High Q-value puts expected signal above natural gamma background
- High natural abundance - can avoid enrichment
- Easy to grow crystal - source = detector

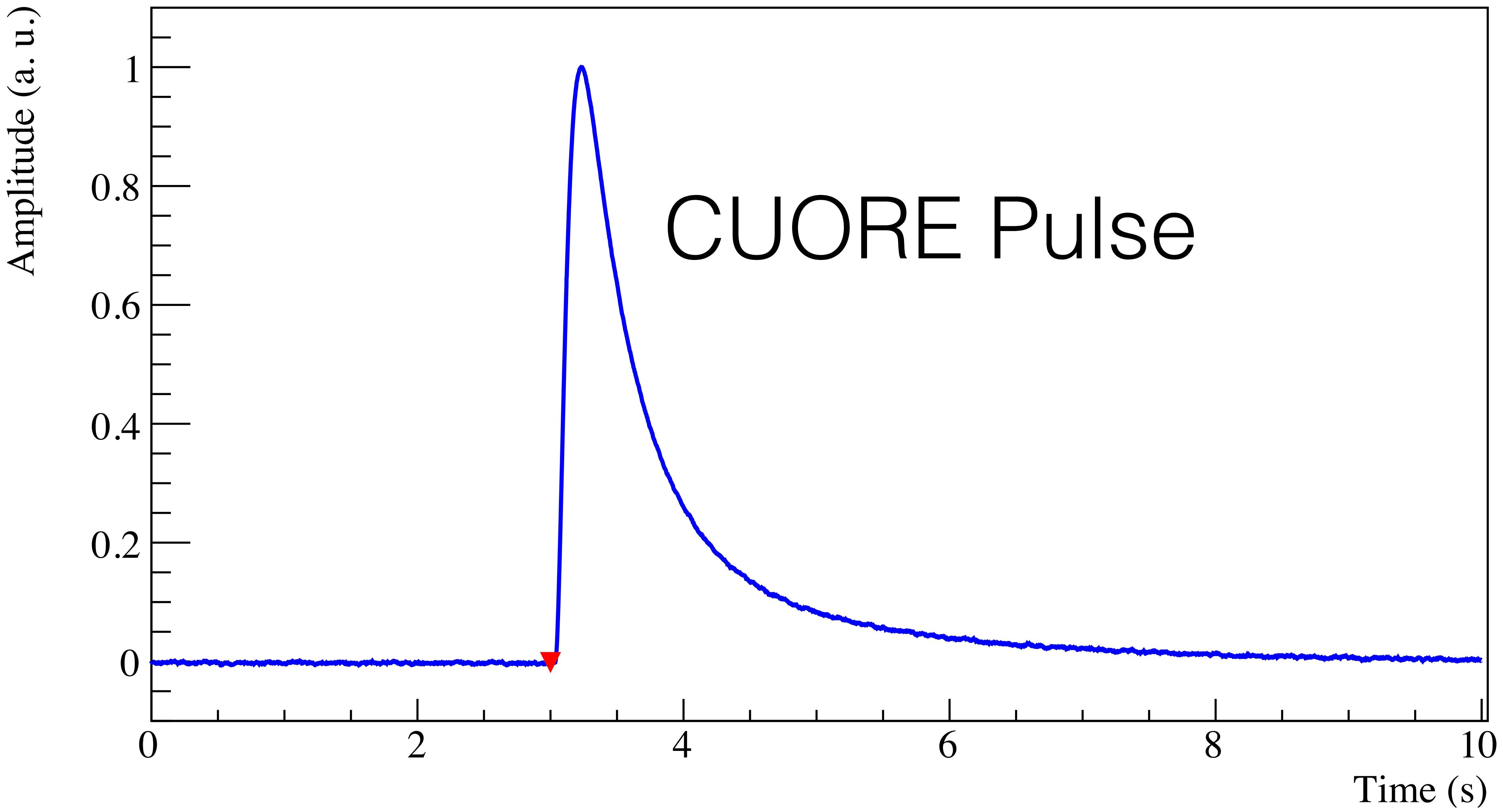


Bolometers

- Sensitive devices with good energy resolution
- Deposited energy changes temperature
    - $\Delta T = \frac{E_{ev}}{C_{crys}}$
- CUORE TeO_2 crystals
    - 5 cm x 5cm x 5cm
    - Neutron transmutation doped (NTD) Ge sensor
    - temperature sensitive
    - $R = R_0 e^{\sqrt{T_0/T}}$





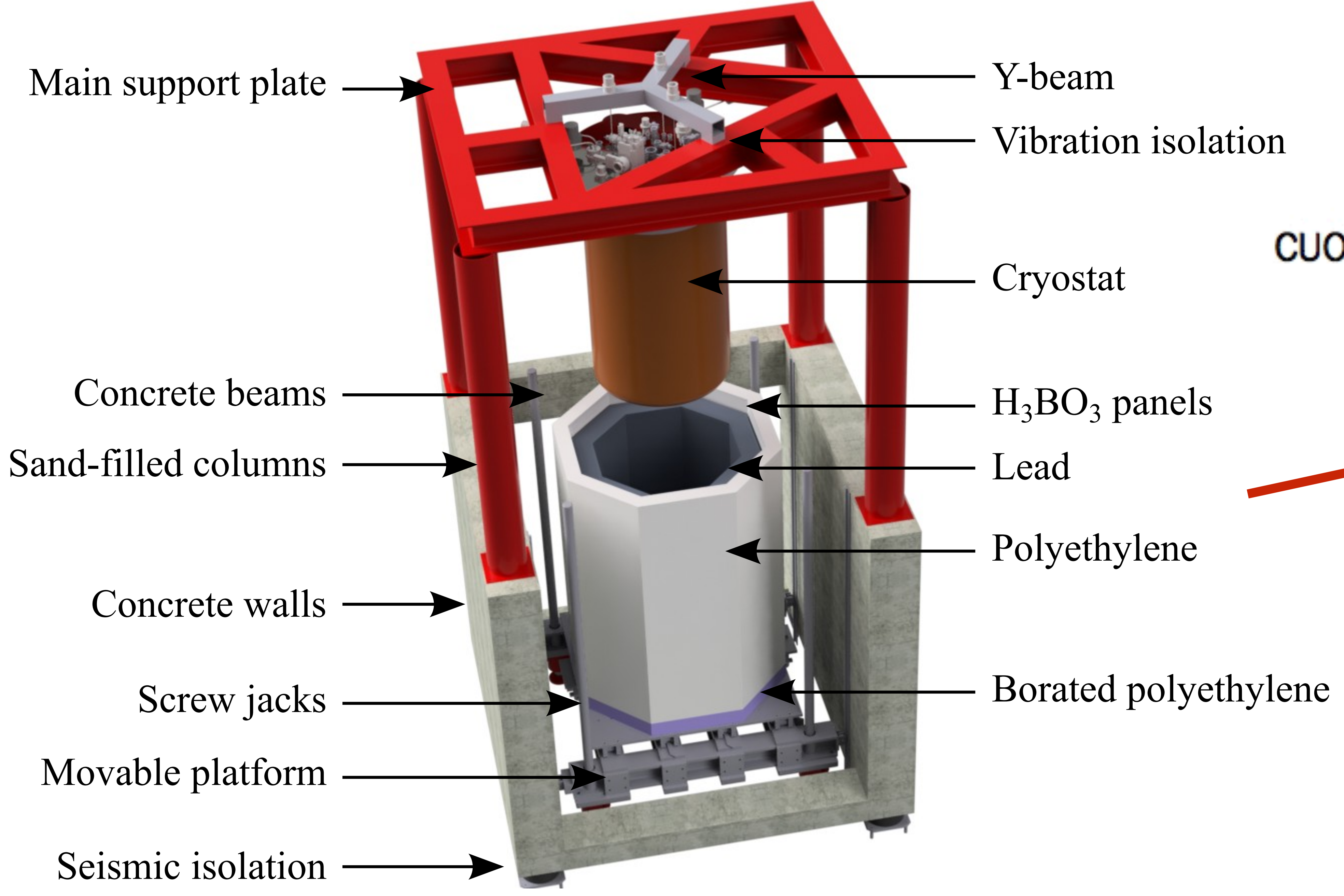


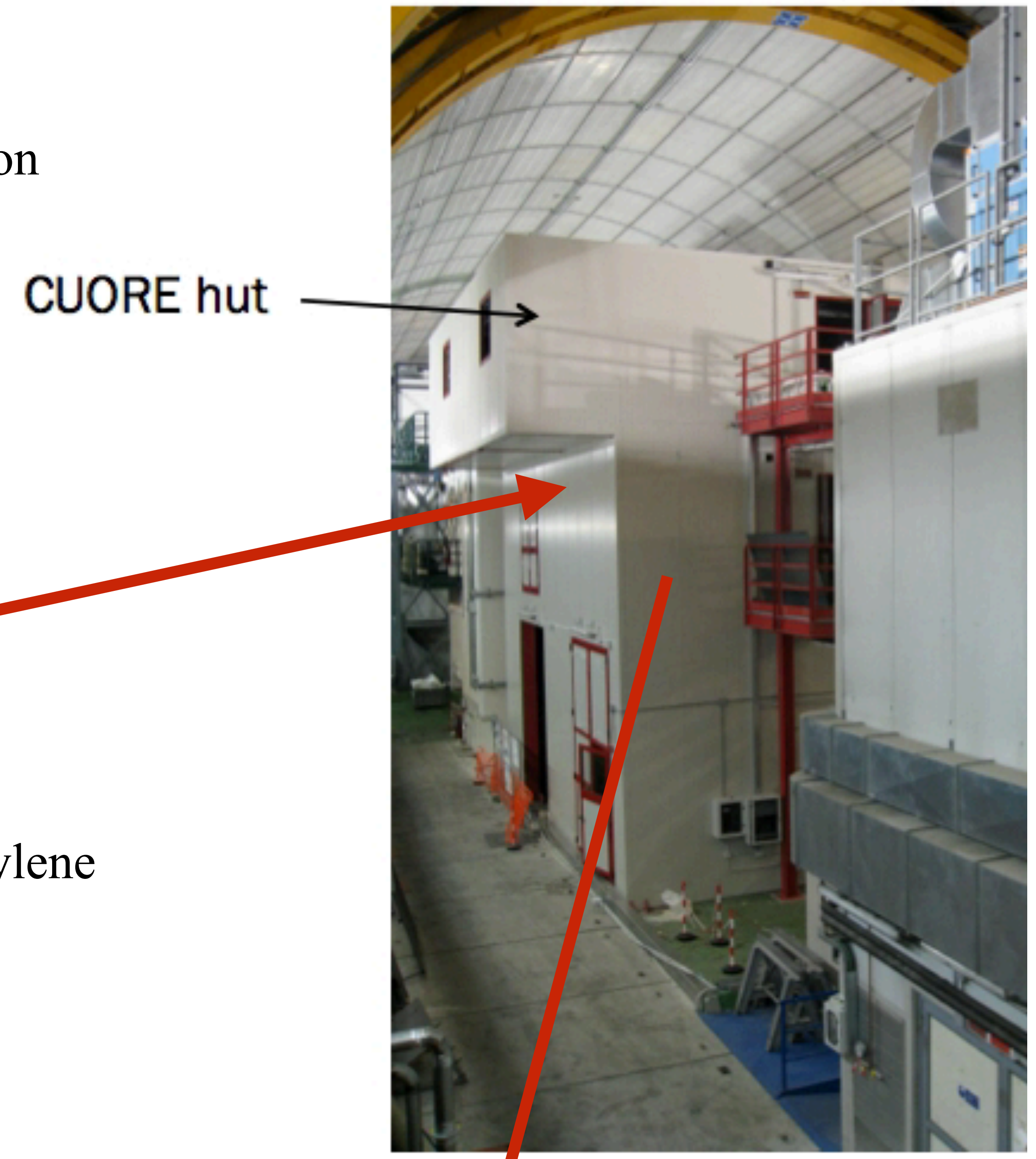
$\tau \sim C/G \sim 1s$

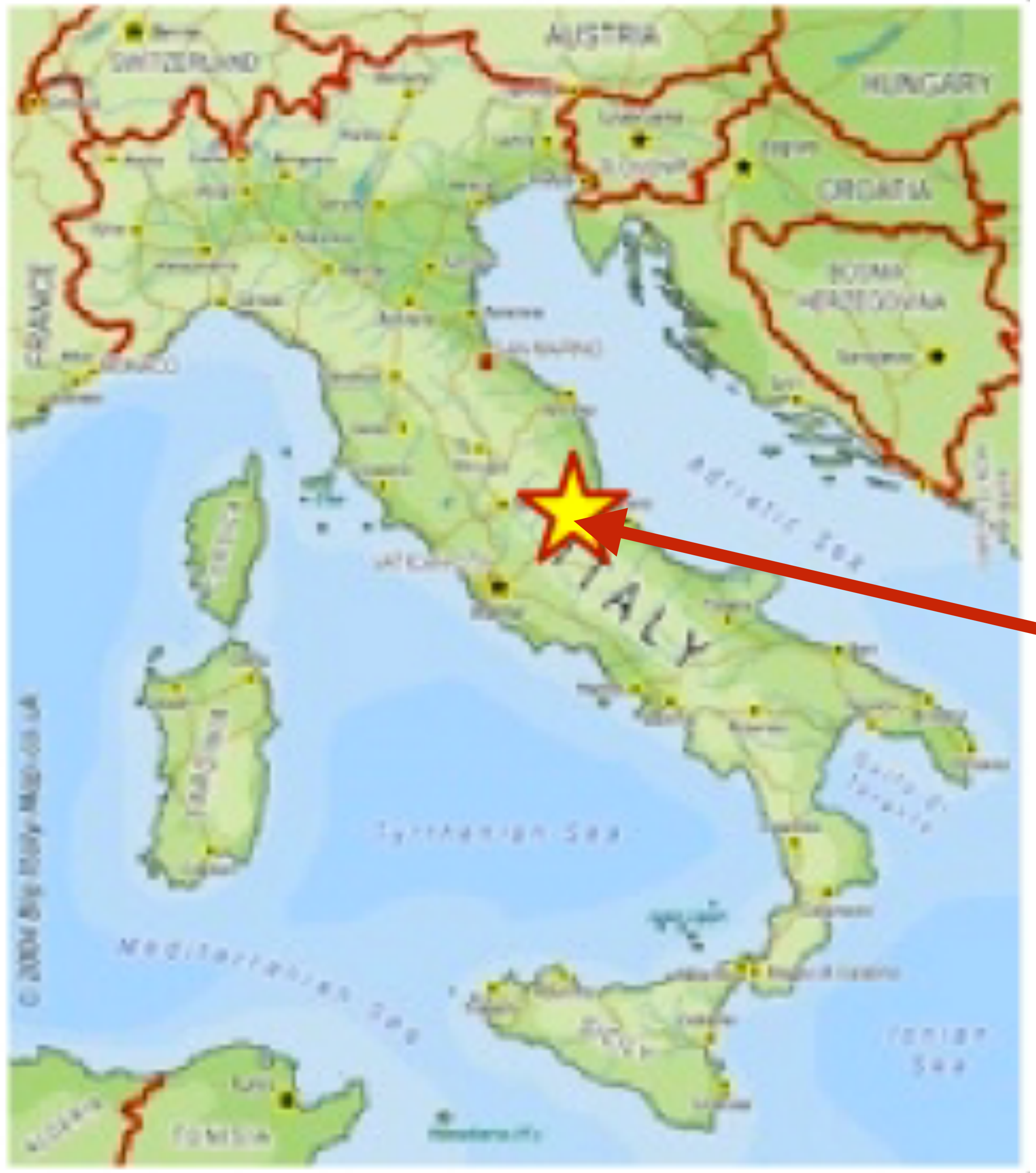
$C^{-1} \sim 100\mu\mathrm{K/MeV}$

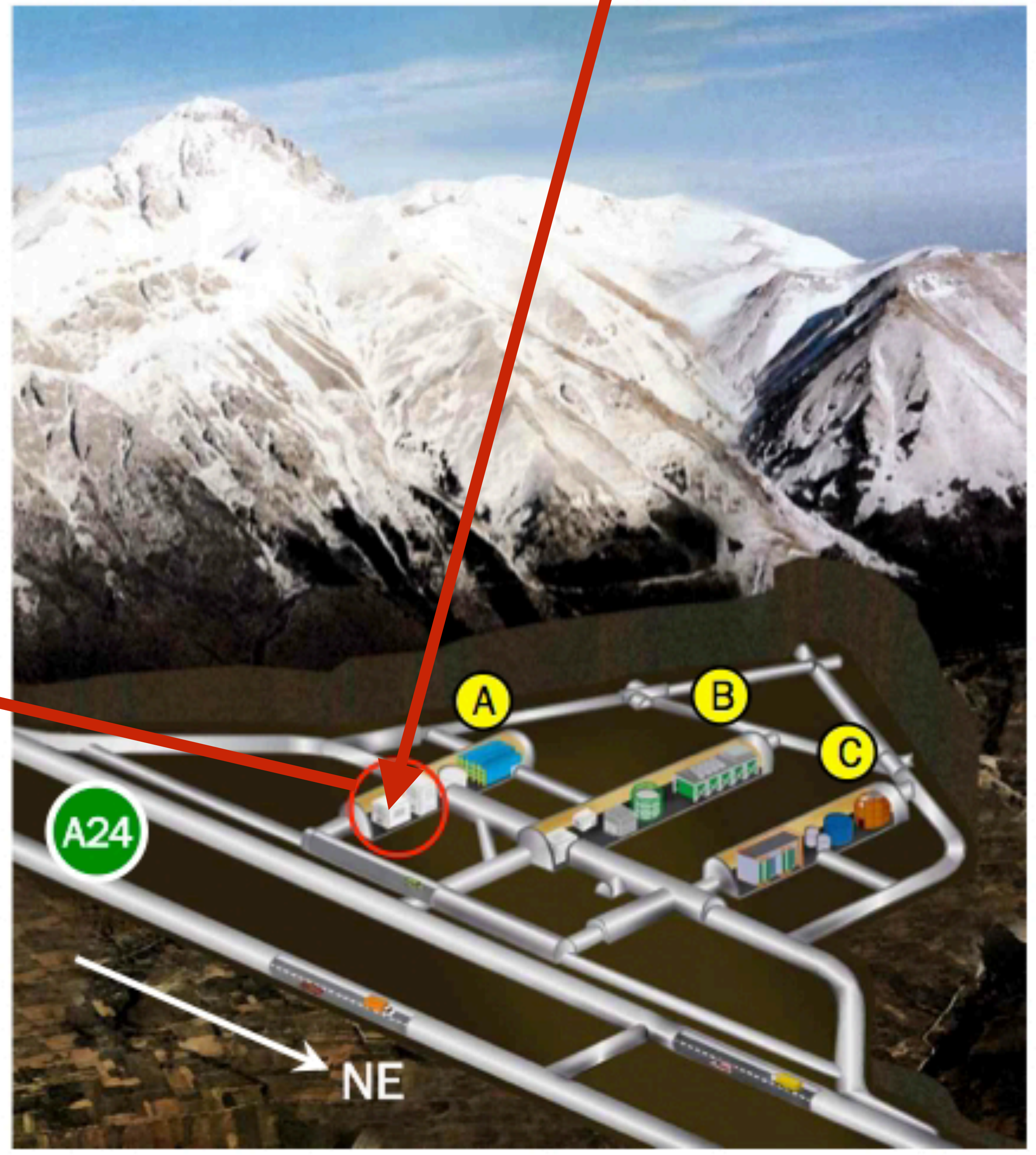
CUORE@LNGS

- **C**ryogenic
  Underground
  Observatory for
  Rare
  Events
- To detect rare events:
  - sensitive detector
  - very low background
- Located at LNGS
  - 3600 m.w.e overburden



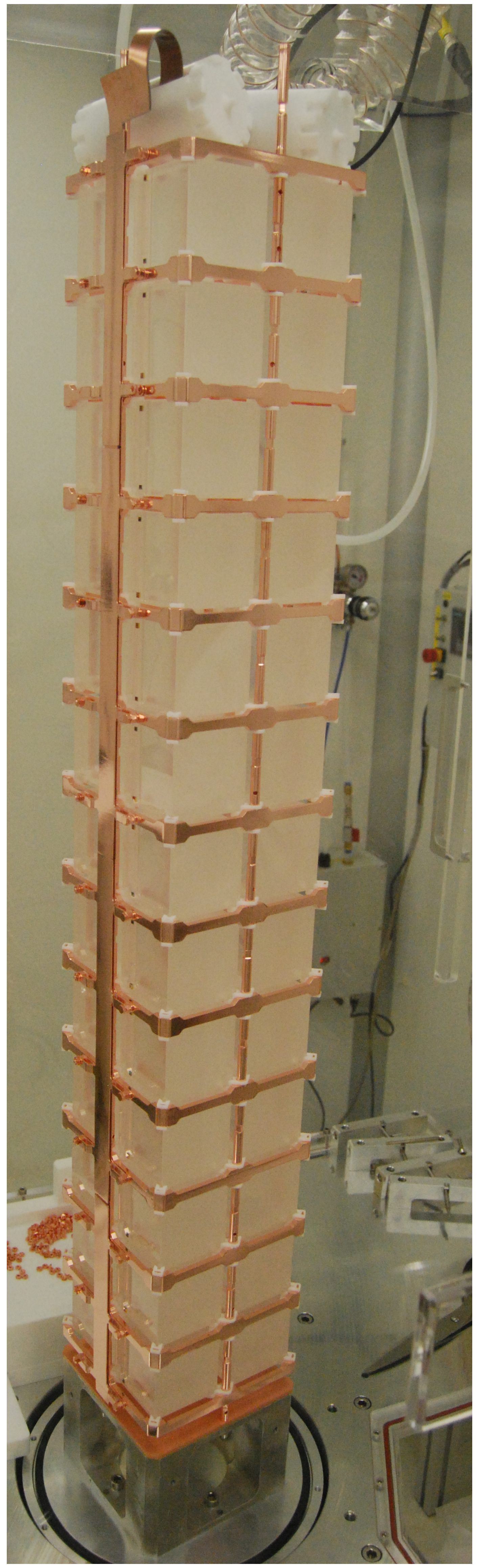


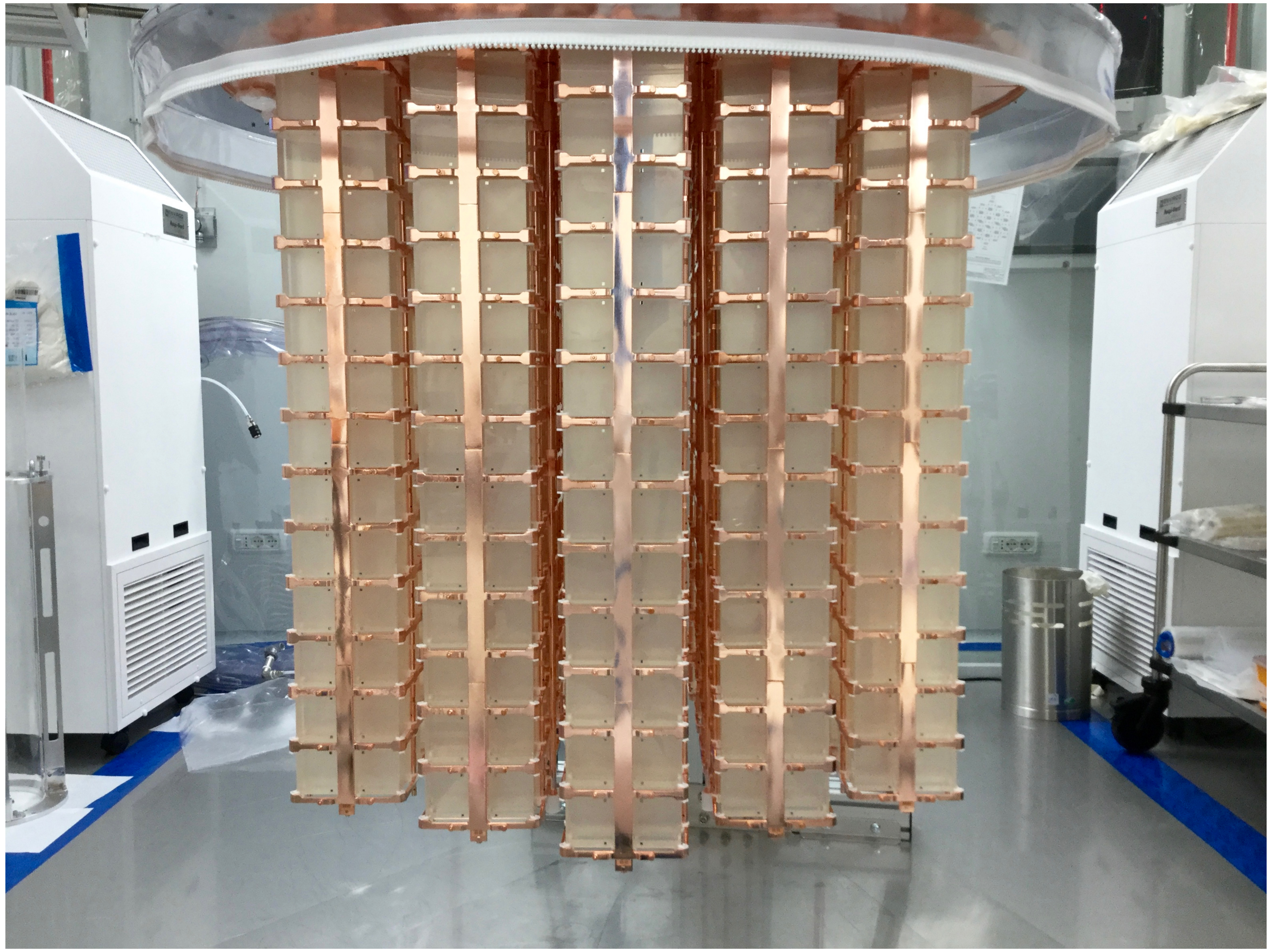




CUORE Detector

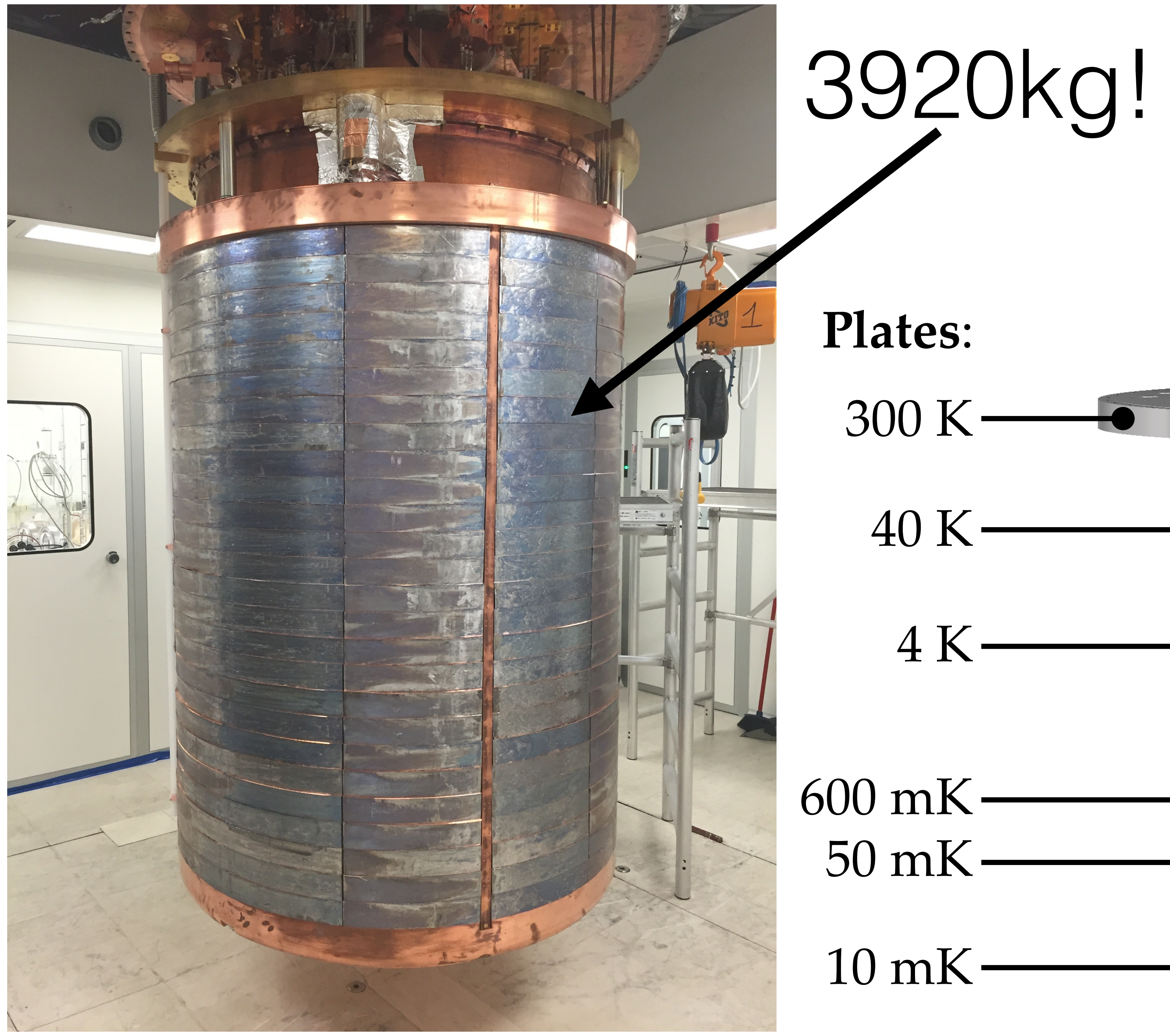
- Array of 988 5x5x5 cm^3 $^{nat}TeO_2$ crystals
  - ^{130}Te active isotope
  - $Q_{\beta\beta}$ = 2527.518 keV
  - Source = detector: ε ~ 88%
- 19 towers, 13 floors, 4 per floor
- m = 742 kg
  - $m_{isotope}$ = 206 kg
- 984 active channels!

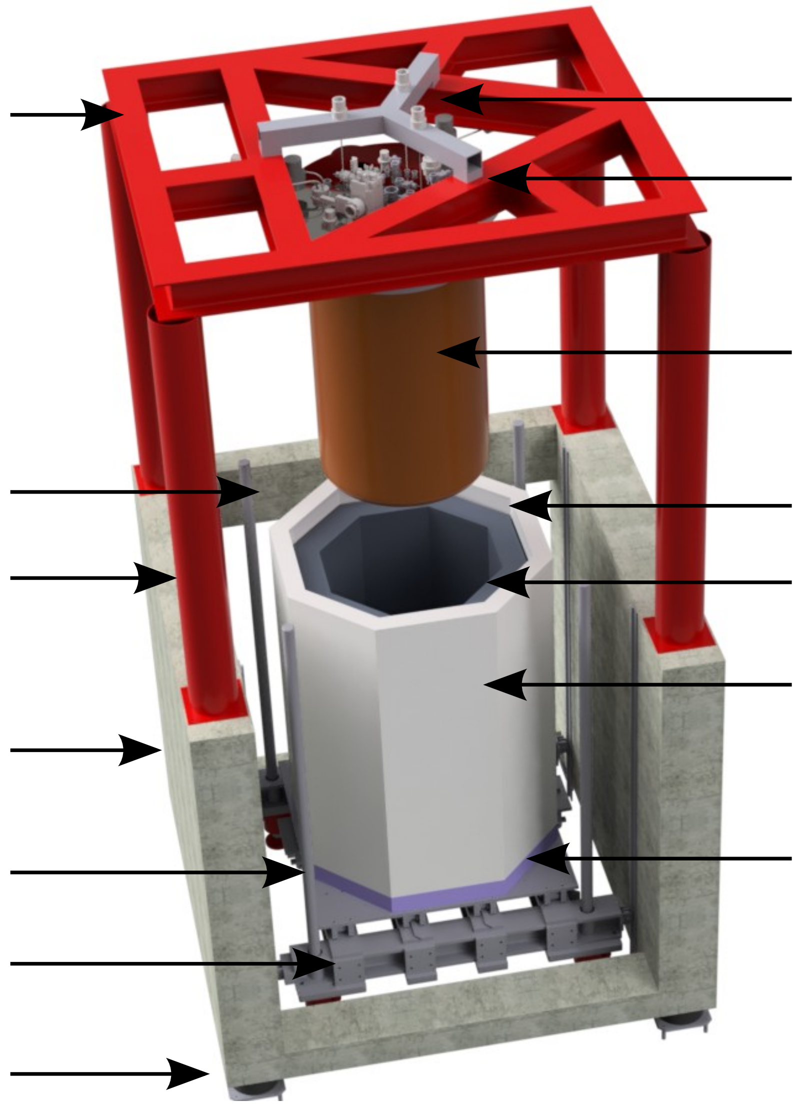


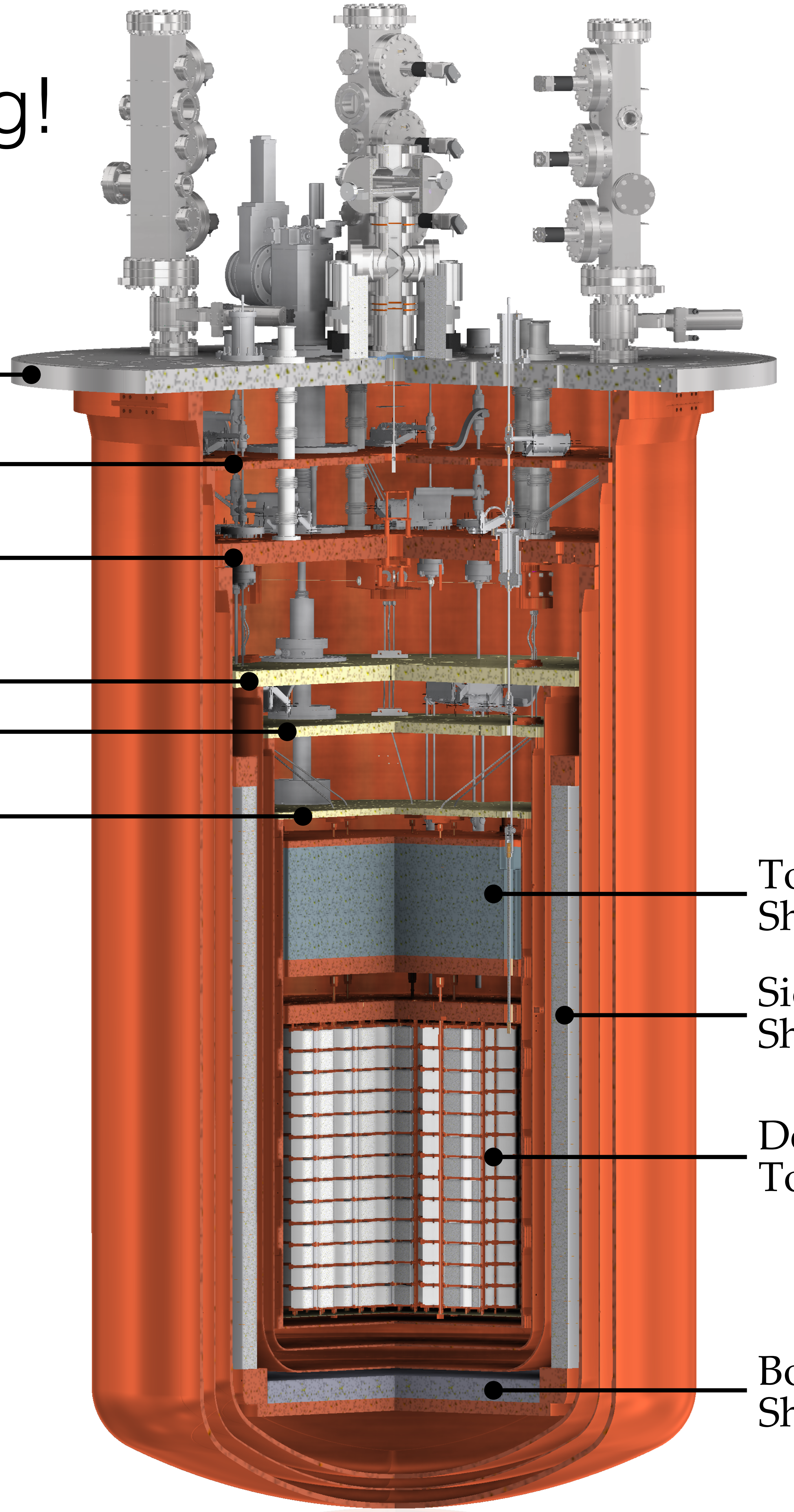


CUORE Cryostat

- Difficult task - cool 15 tons to 4K and 3 tons below 50 mK
- World leading cryostat in size and power
- Five 1.5 W Cryomech pulse tube coolers
- 2 mW (at 100mK) cooling power
    - DU from Leiden Cryogenics
- Radiopurity central to material selection
- Vibration isolation
- Cold Roman lead
- Lowest base temperature of ~ 6 mK!

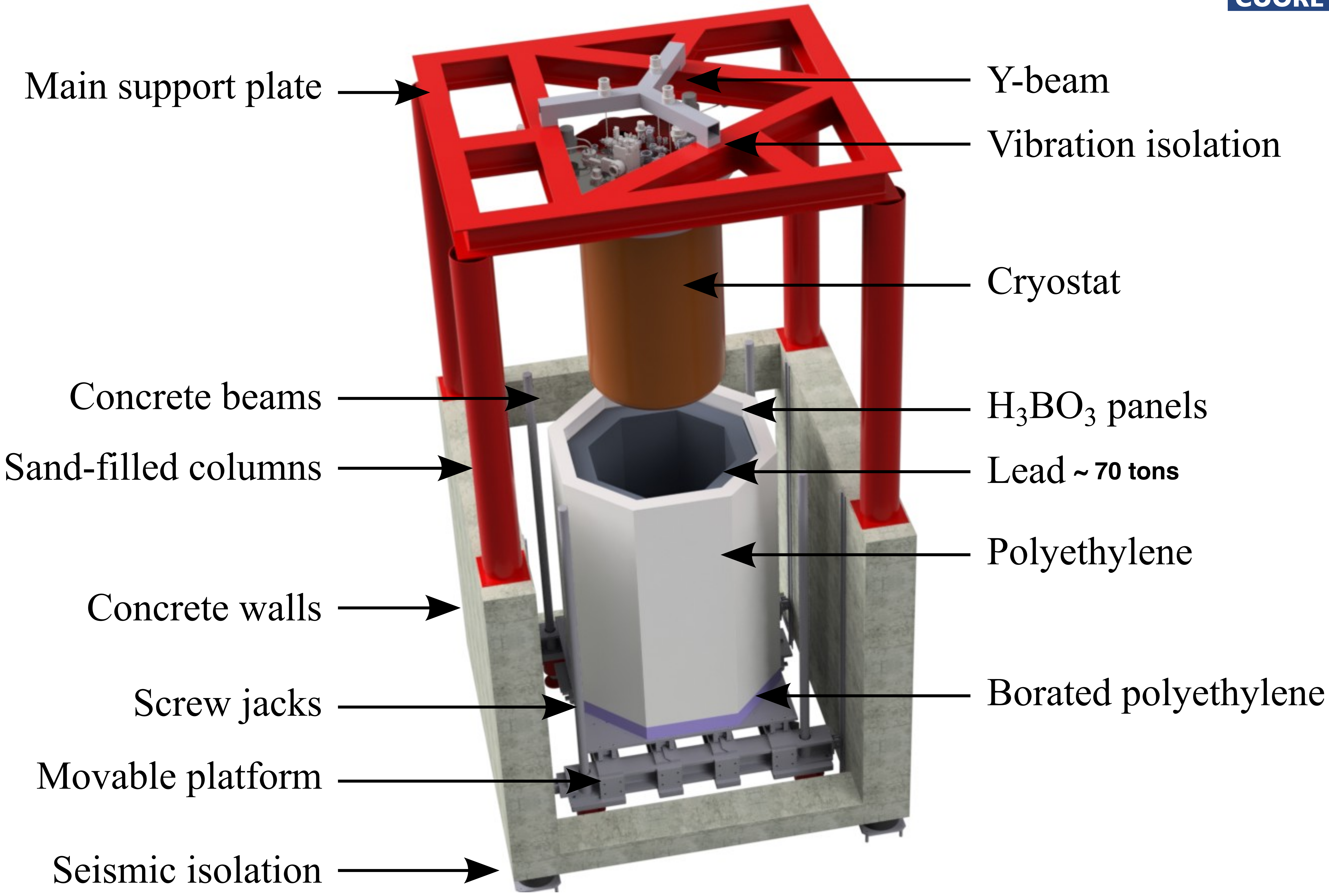






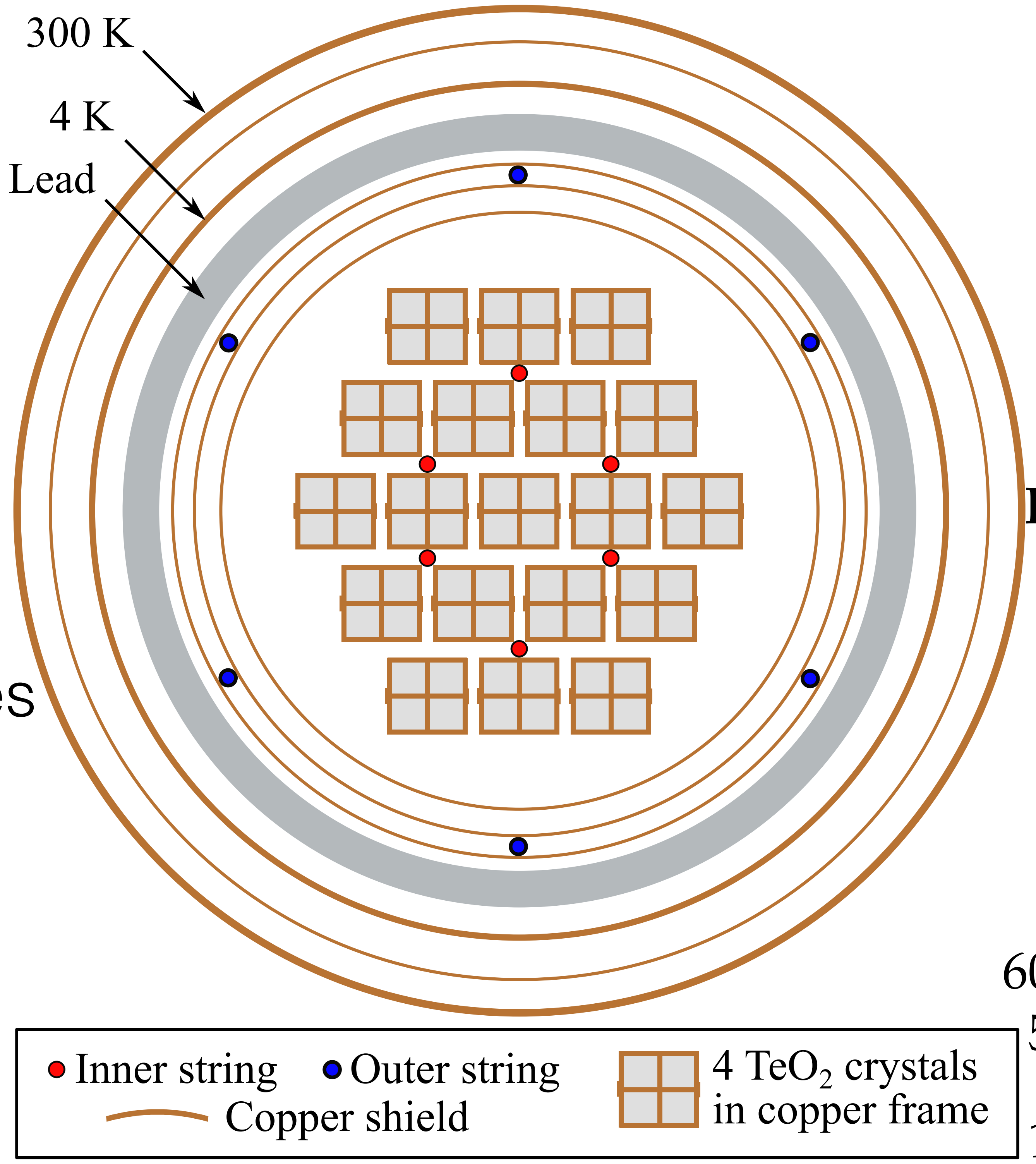
CUORE Suspension

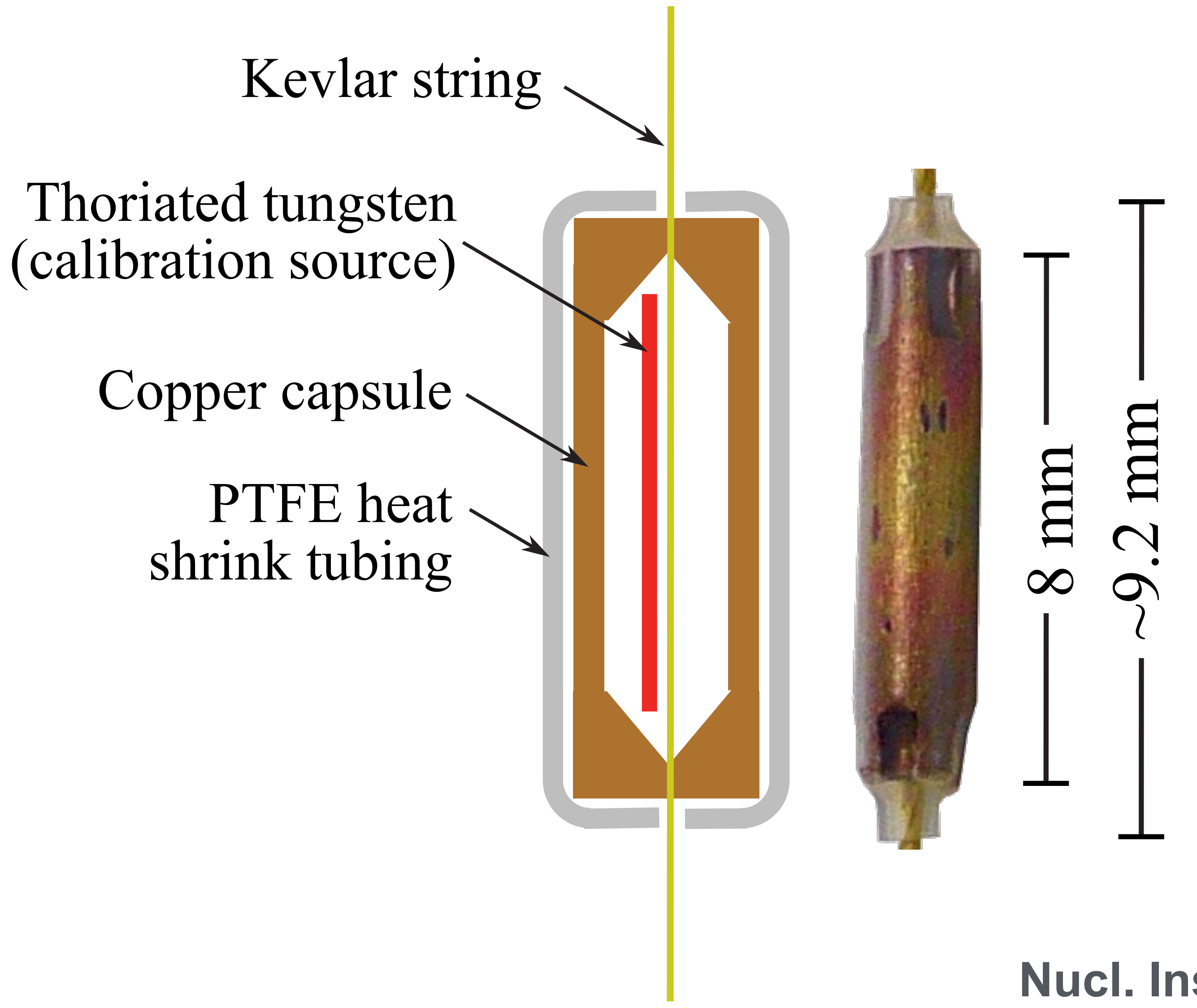
- Detector suspension is independent of cryostat suspension
- Y-beam attached to stainless steel ties, Kevlar rope, and copper bars
  - Dampens horizontal oscillation
- 3 minus-K springs connect Y-beam to main support plate (MSP)
  - 35 dB attenuation
- Seismic isolation via elastomers

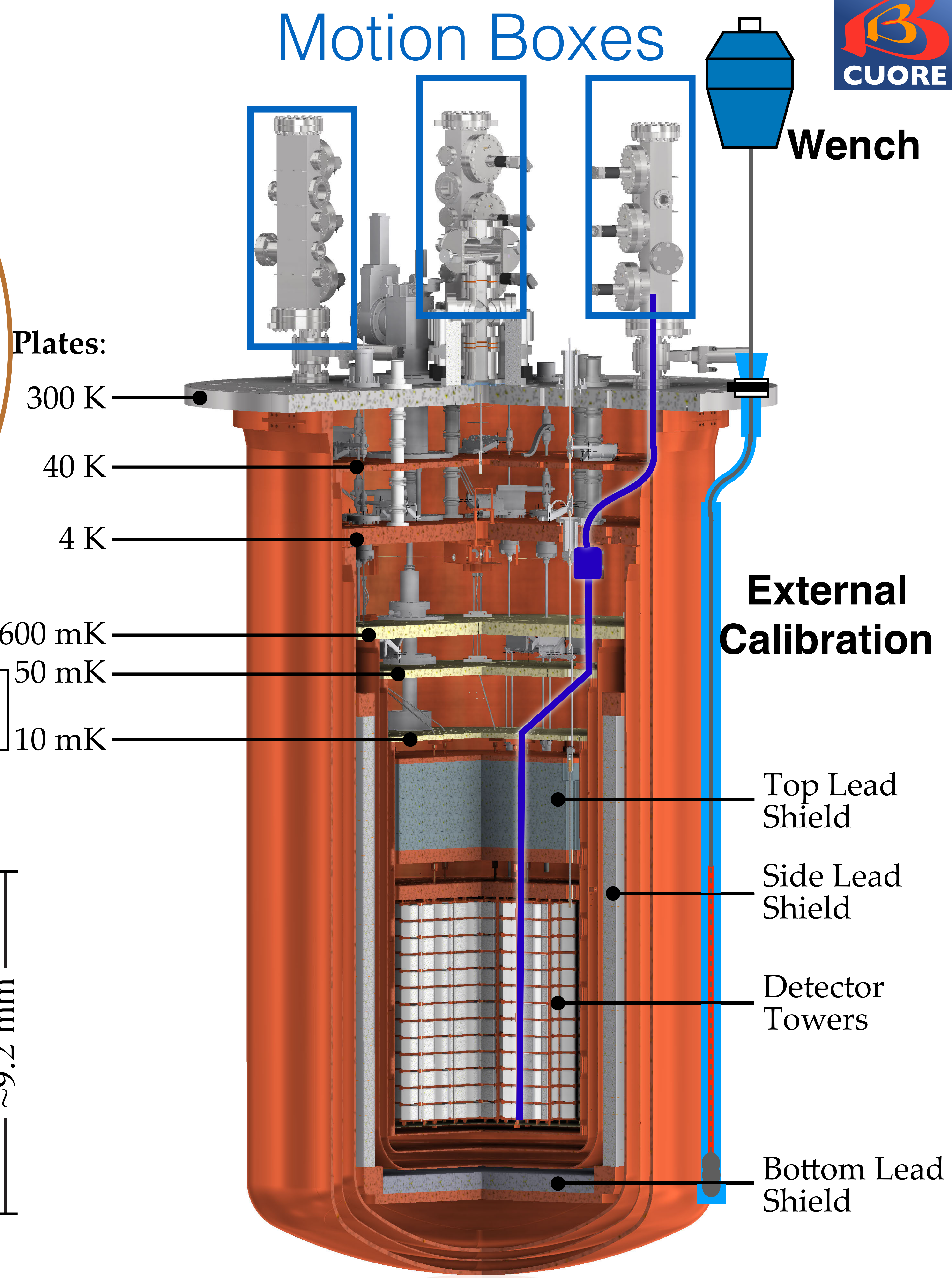


CUORE Calibration

- 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
- External Calibration
  - Sources drop down outside shielding
  - Provides auxiliary calibration method
- Constant-energy pulsers
  - Generate reference pulses
  - Measure detector stability
  - Correct for variations in detector gain



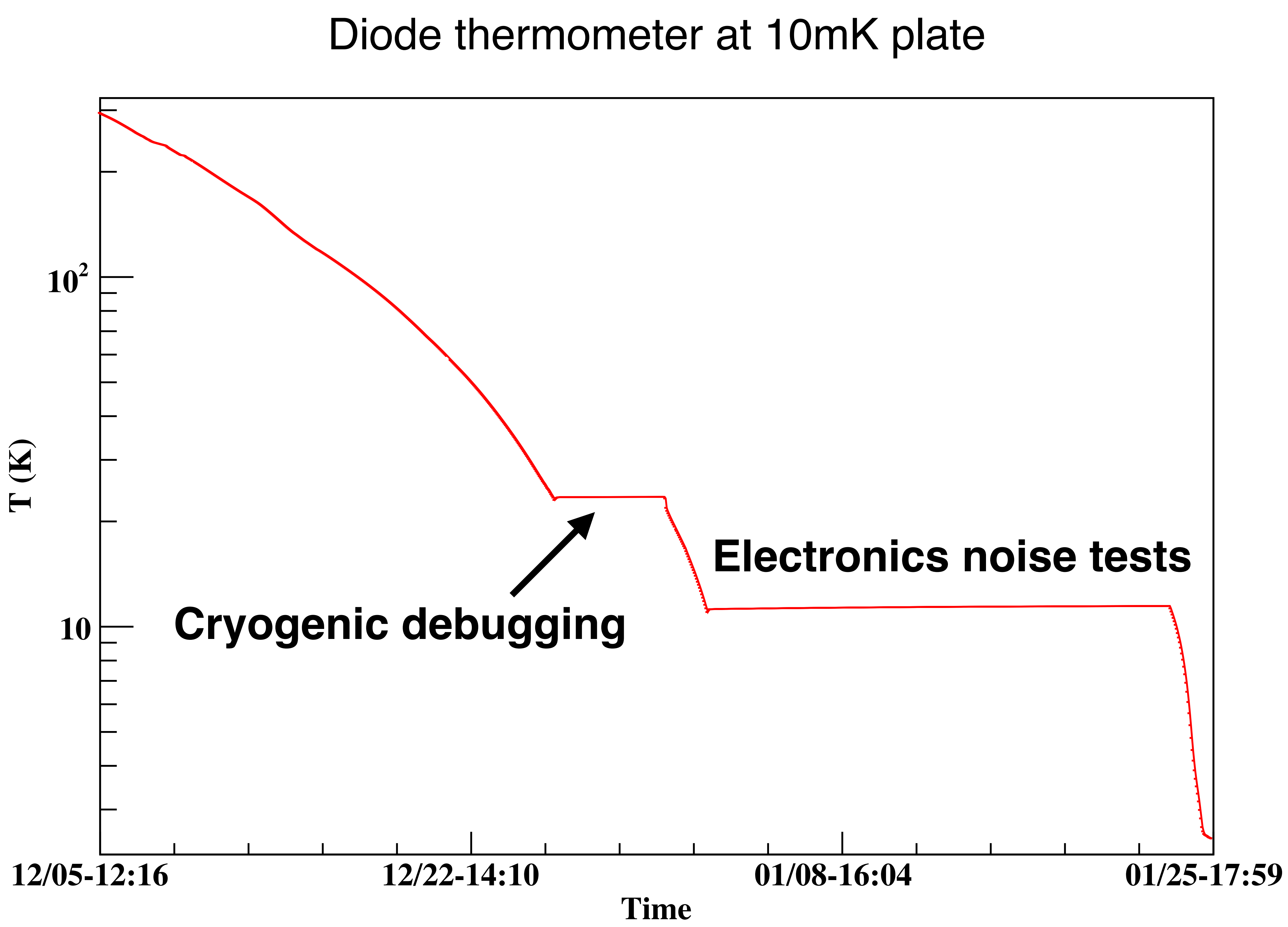


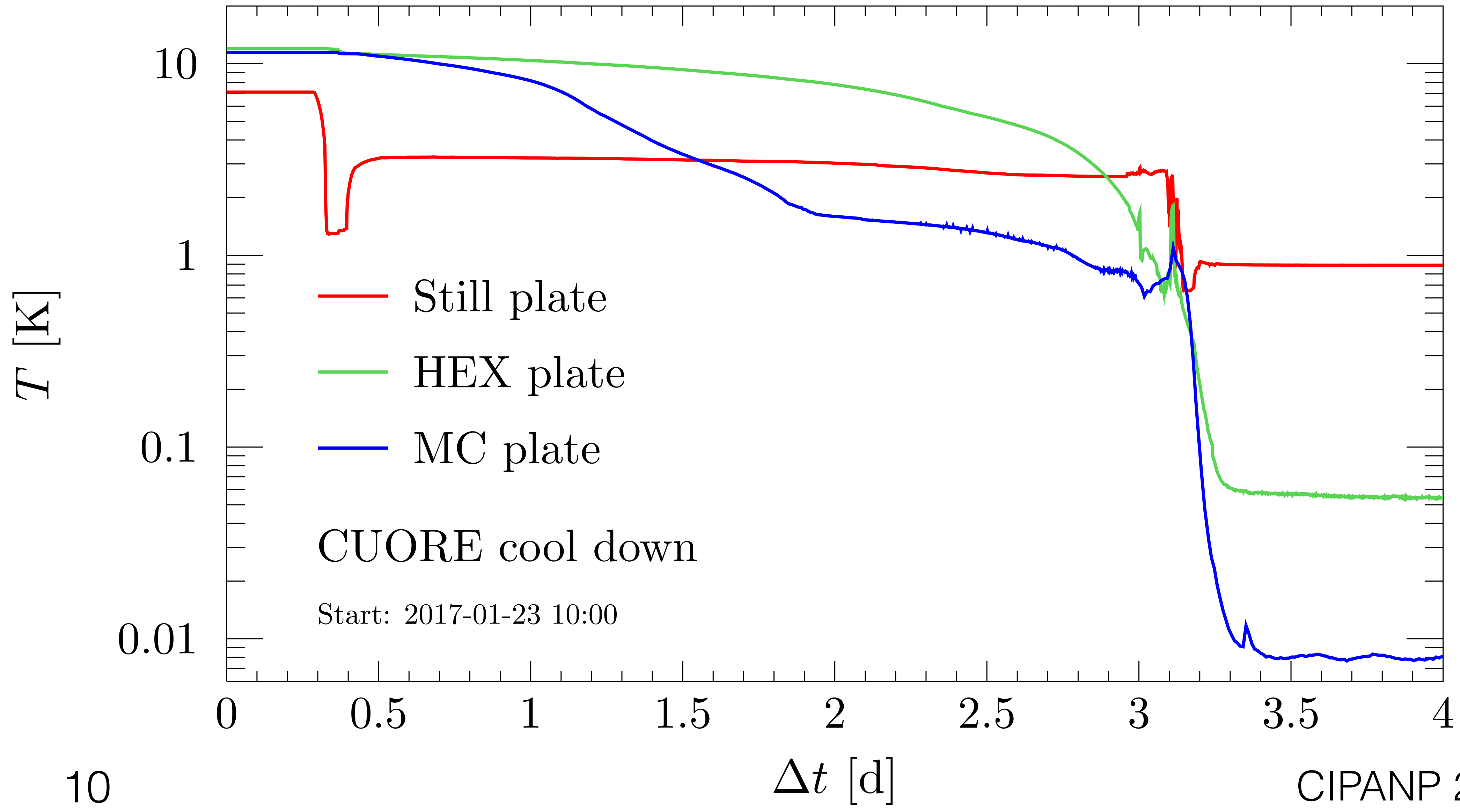


Nucl. Instr. Meth. A 844, 32–44 (2017)

CUORE Cooldown

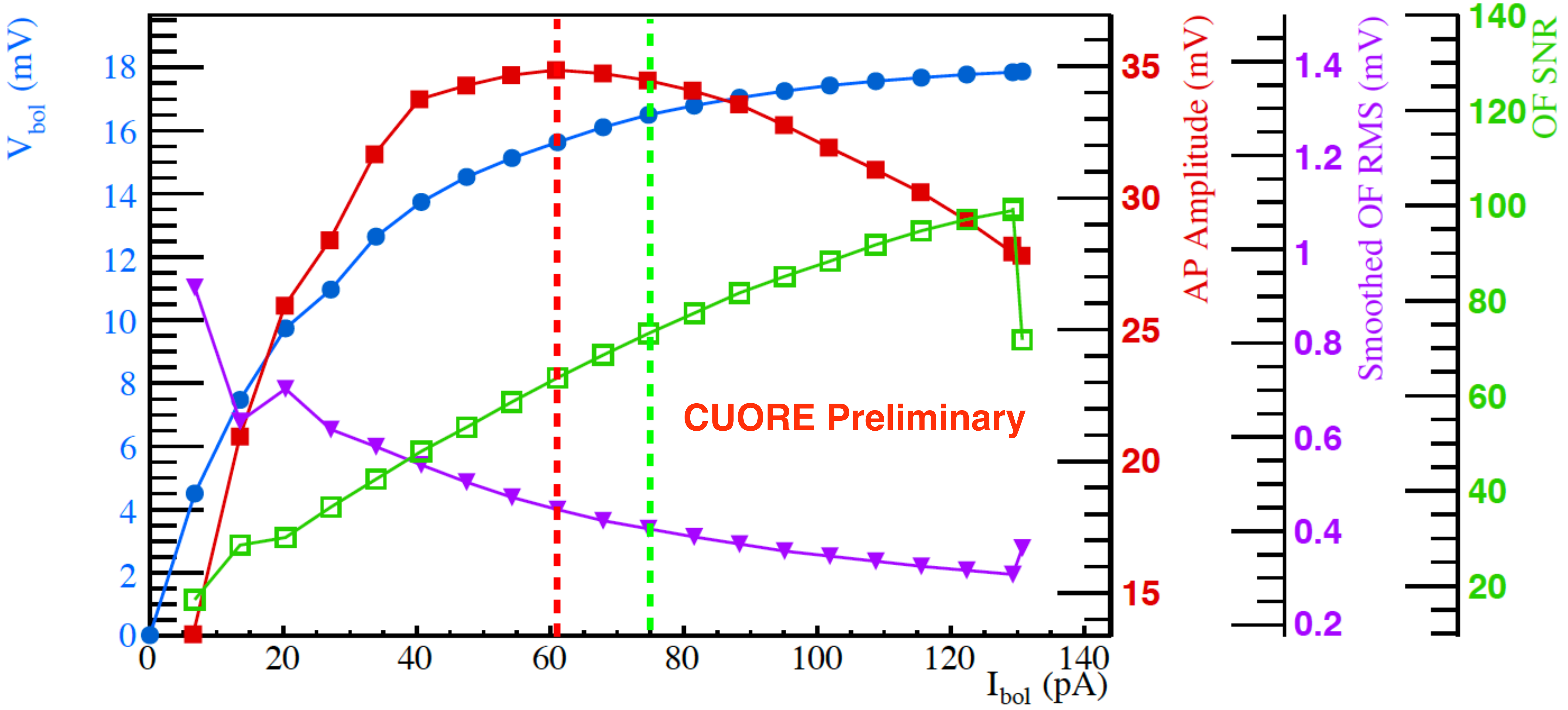
- Fast cooling system (^4He gas) allows quick cool down to ~40 K
- All 5 PT coolers activated to bring cryostat to ~4 K
- DU brings temp down to ~ 6.3 mK
  - Residual cooling power at 10 mK: 3 μW

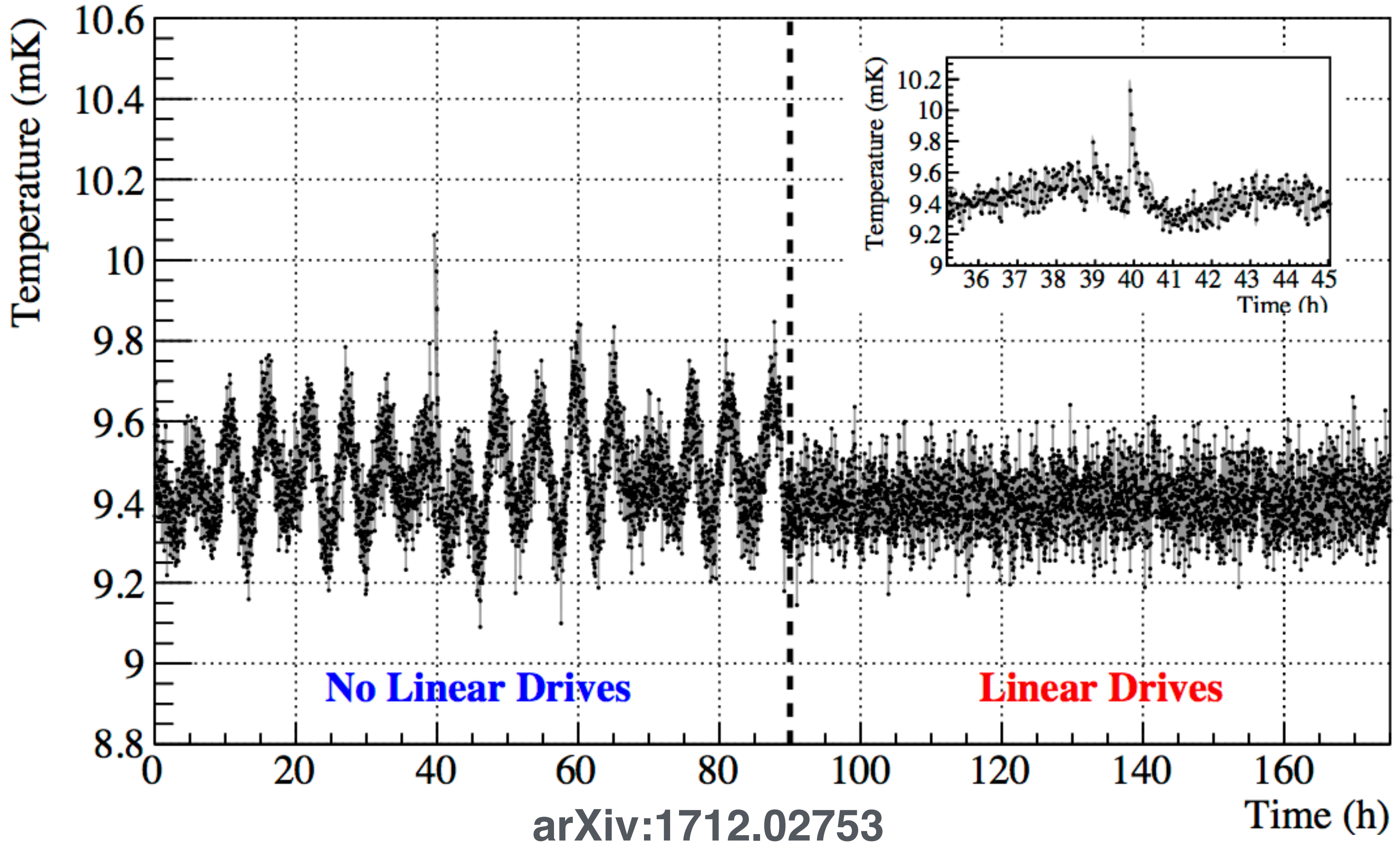




Detector Characterization/Optimization

- Temperature Scan
  - Attempt to locate temperature that optimized signal to noise ratio, resolution, and electronics performance
  - 15 mK operation
- Working point
  - Load curve scans to select optimal bias voltage
  - Maximize signal to noise ratio
  - Optimize pulse amplitude
- Noise optimization
  - Electronic noise attenuation
  - Vibration reduction
  - Pulse tubes use linear drives and optimize relative phases

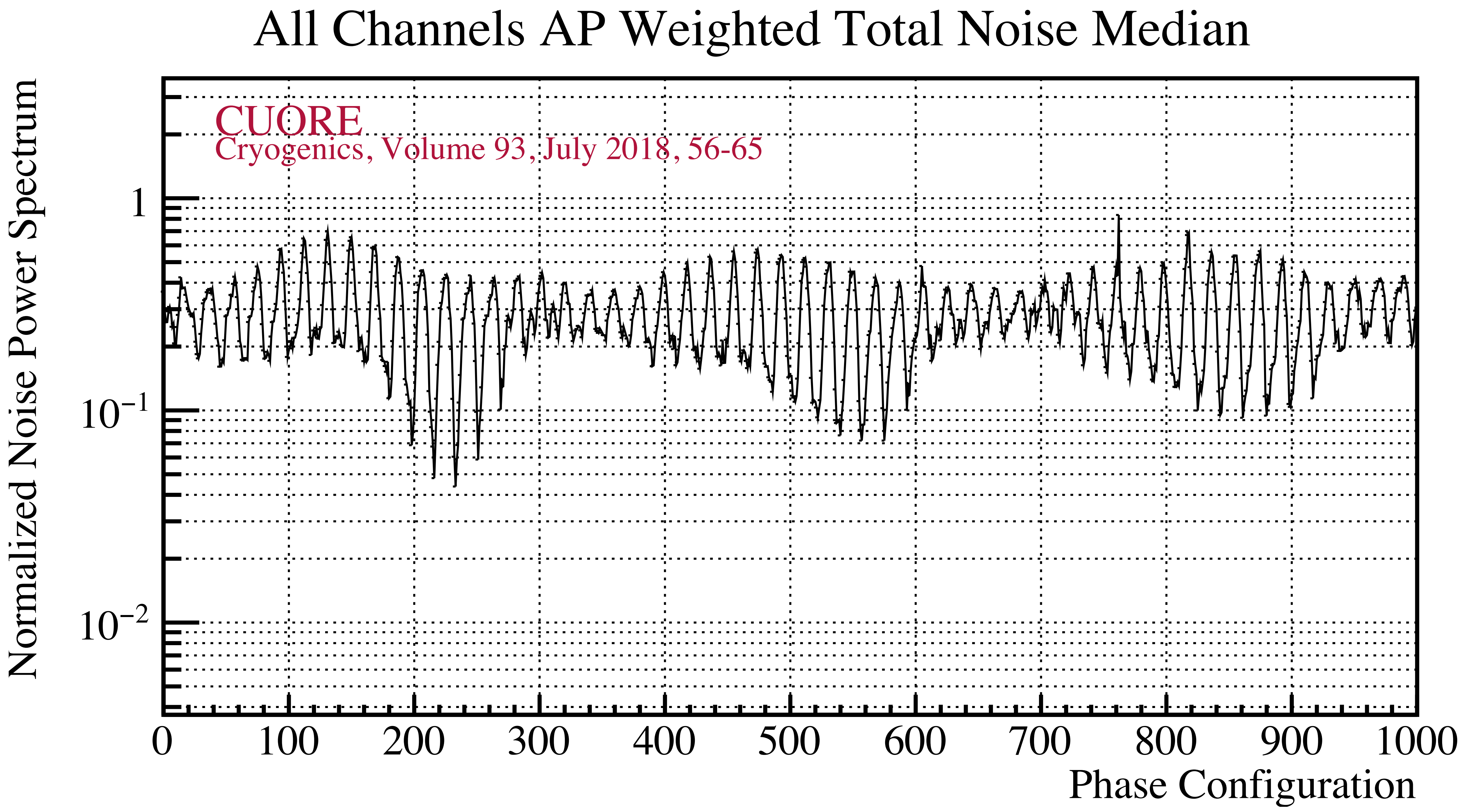


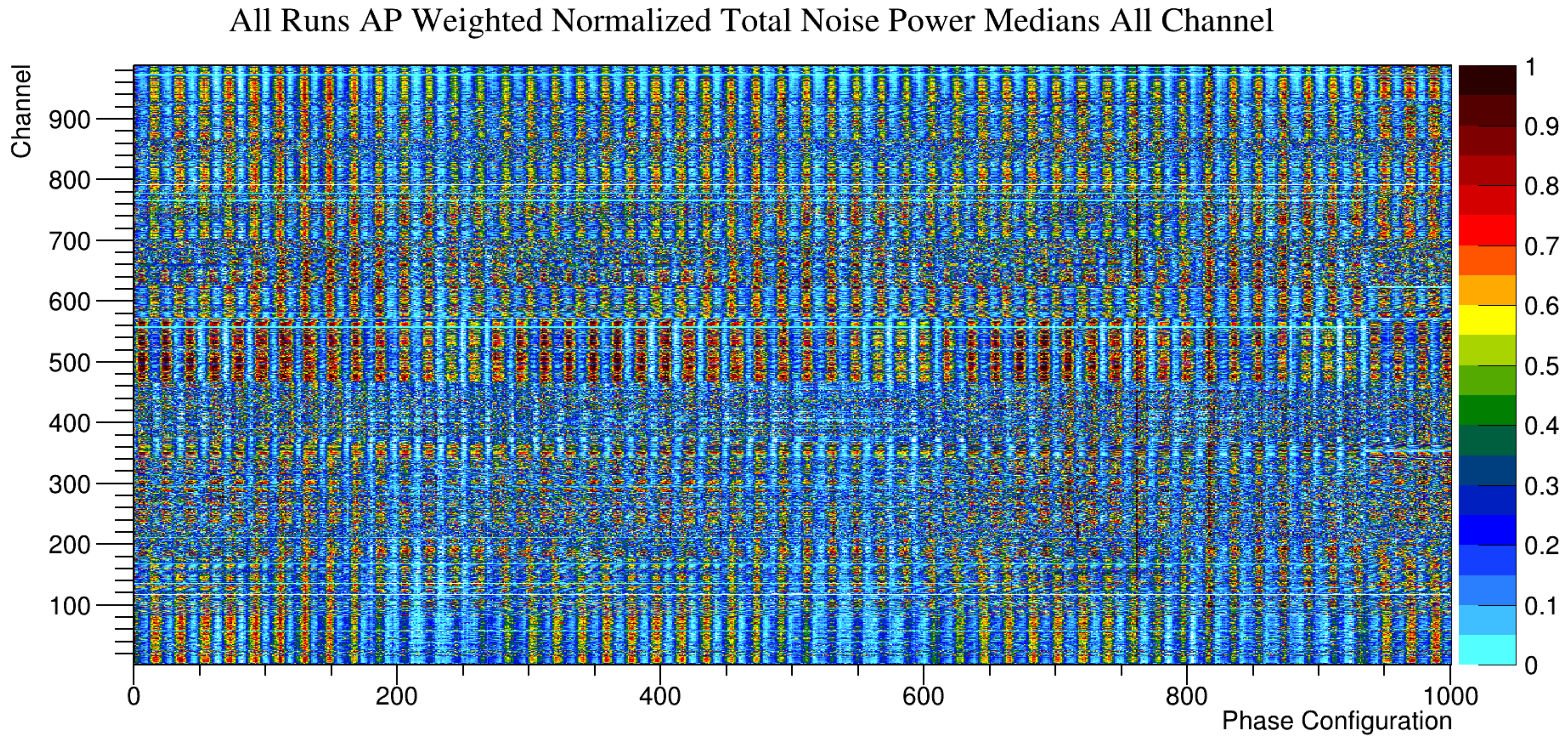


arXiv:1712.02753

Pulse Tube Optimization

- Five pulse tubes create significant vibration
- Operate with only 4 active pulse tubes
    - 1.4 Hz and harmonics
- Passive vibration dampening is implemented
    - Suspended rotary valves, soft bellows, Cu braids
- Active vibration dampening possible
    - Phases of PT rotary valves measured relative to one
    - Discretize space of all possible relative phases into distinct phase configurations and scan
    - Tune relative phase of vibrations to cause maximal destructive interference

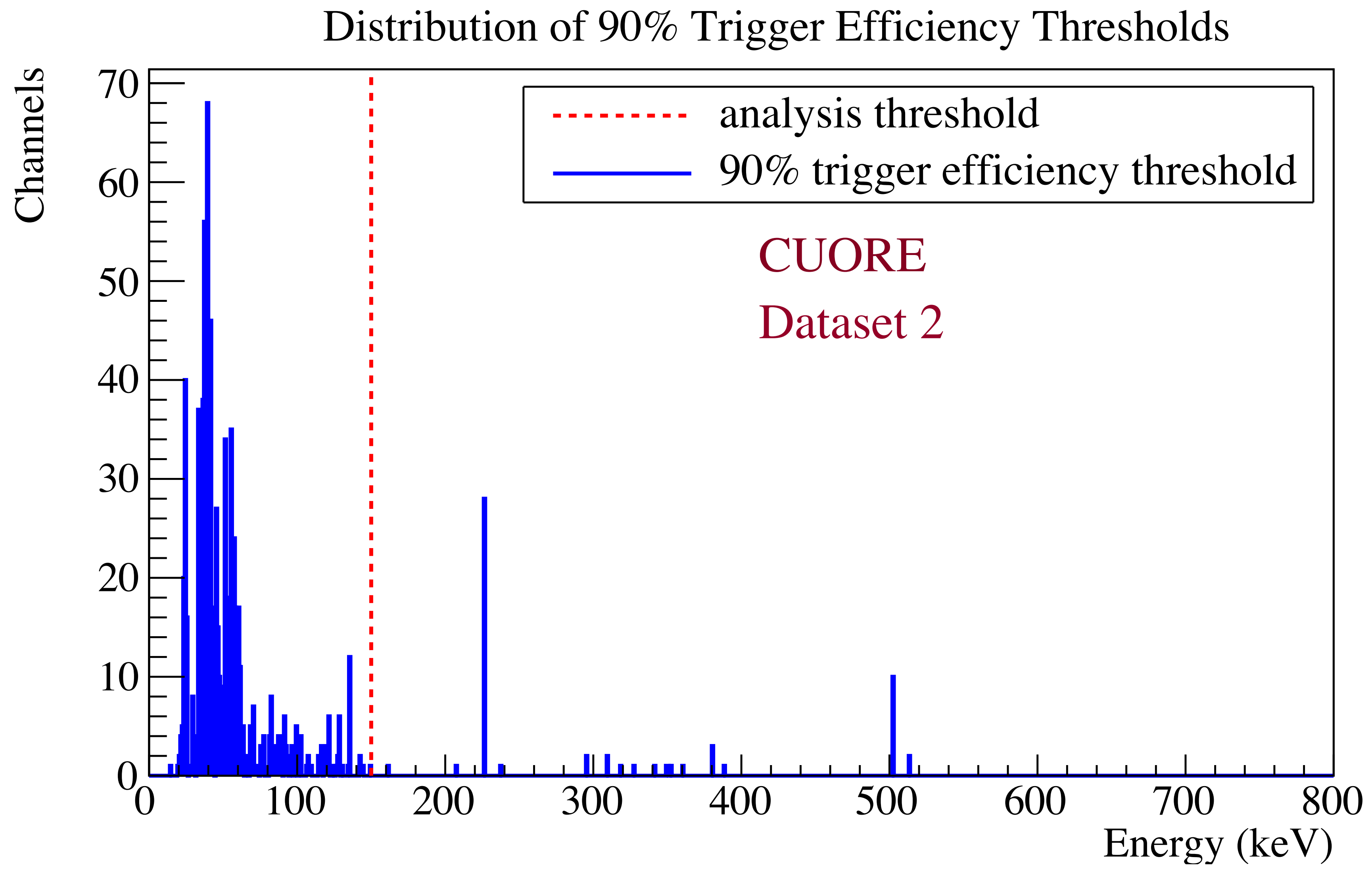


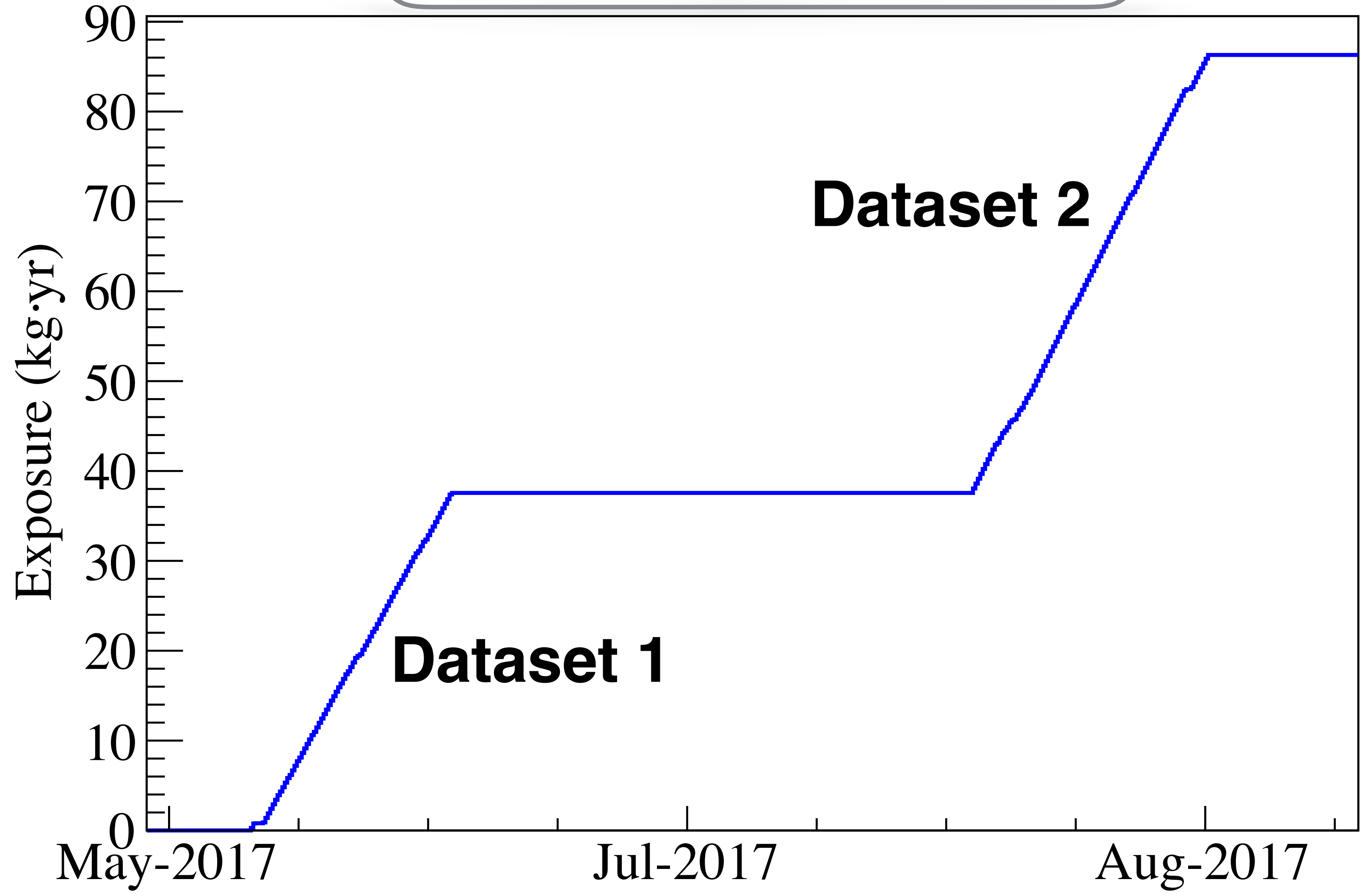


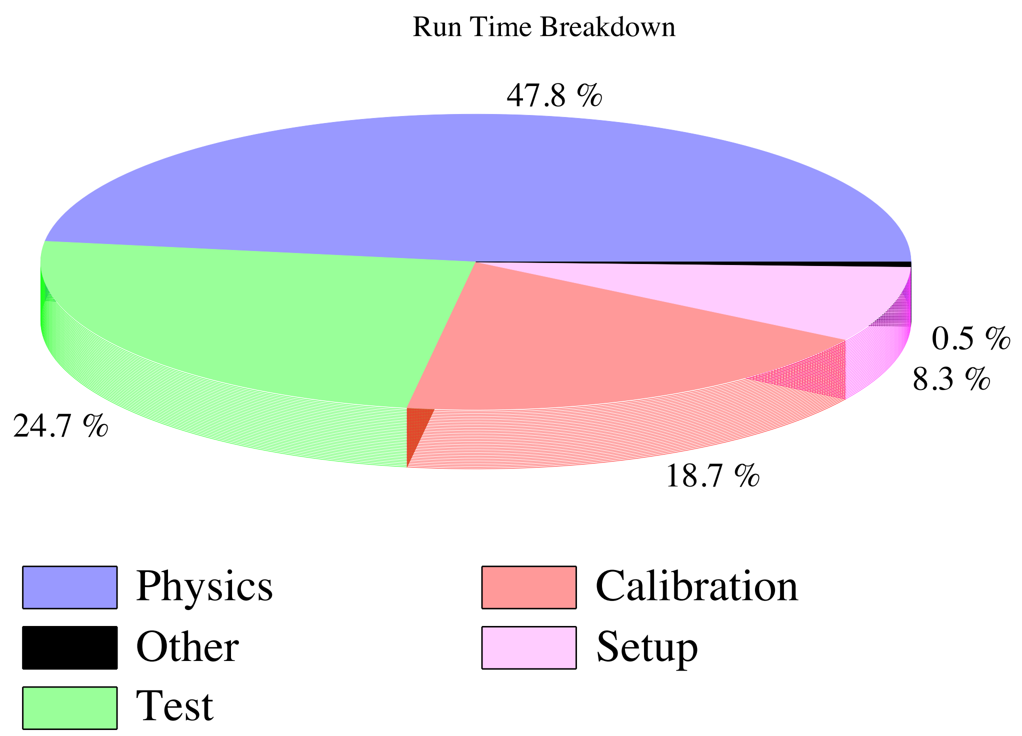
CUORE Data

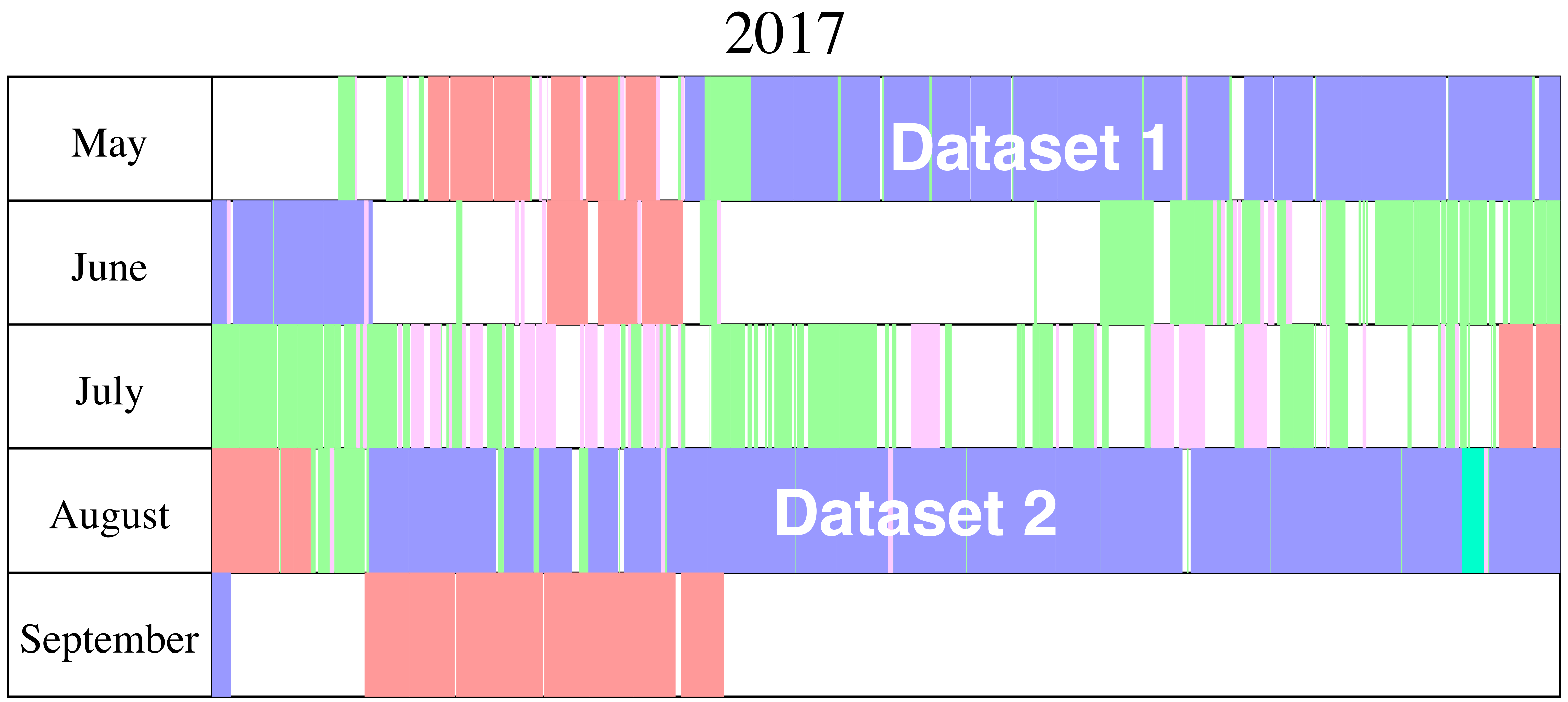
Exposure
86.3 kg-yr ^{nat}Te
24.0 kg-yr ^{130}Te

- 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
- Dataset 1
  - May - Jun 2017 (37.6 kg-yr)
- Dataset 2
  - Aug - Sep 2017 (48.7 kg-yr)
- More exposure than all of CUORE-0!





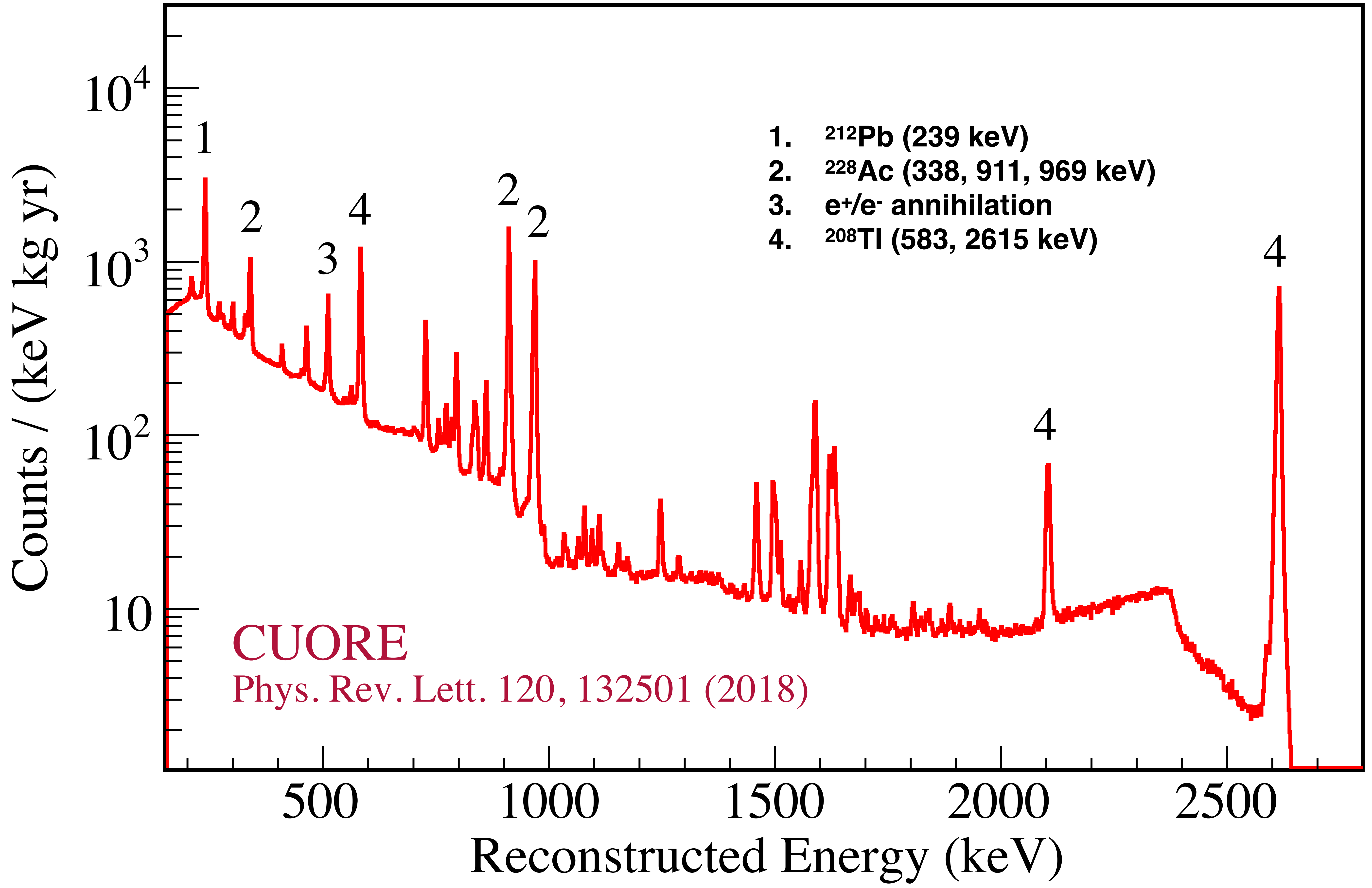




Physics, Calibration, Test, Special Configuration runs

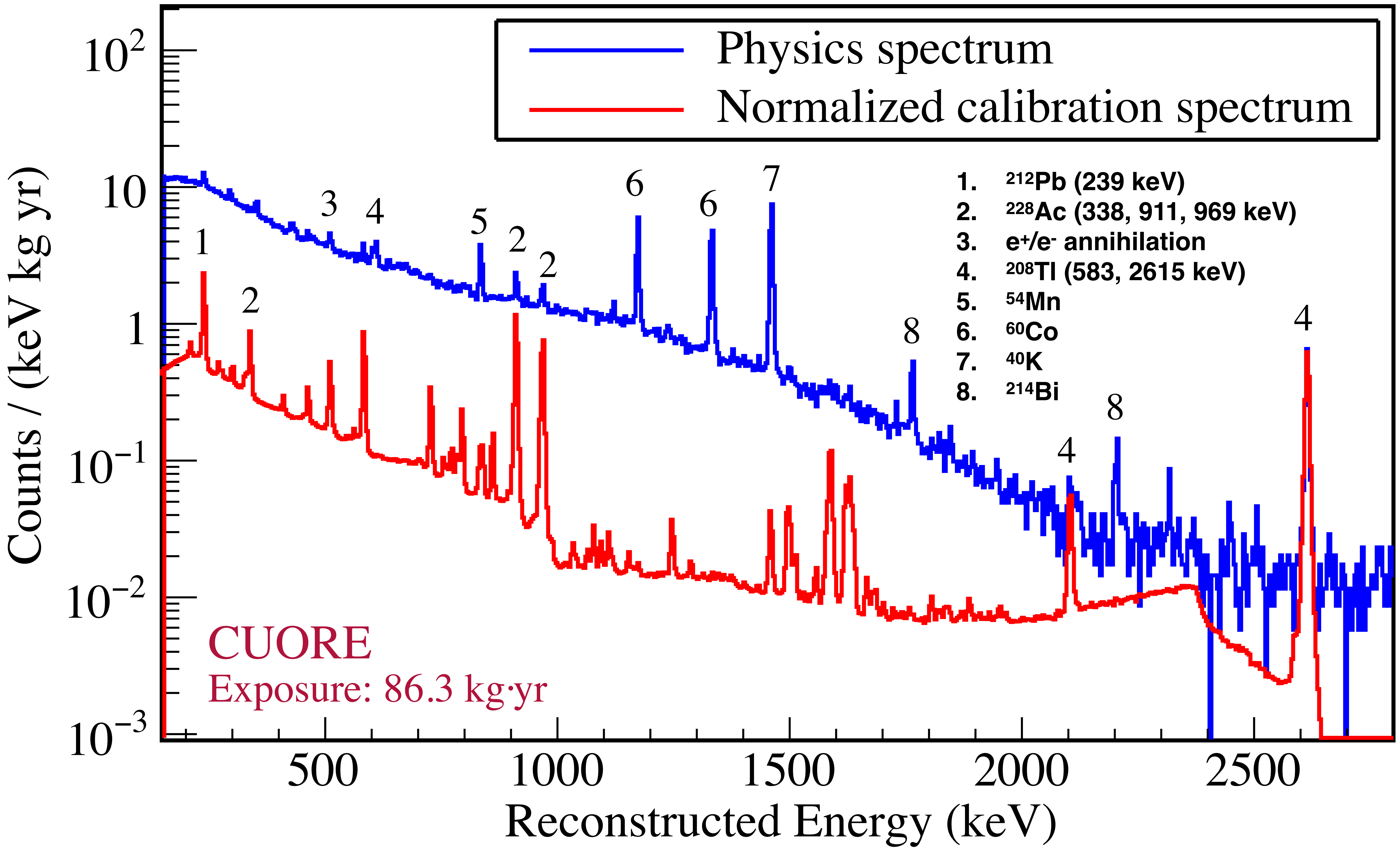
Calibration Spectra

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



Observed Spectra

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



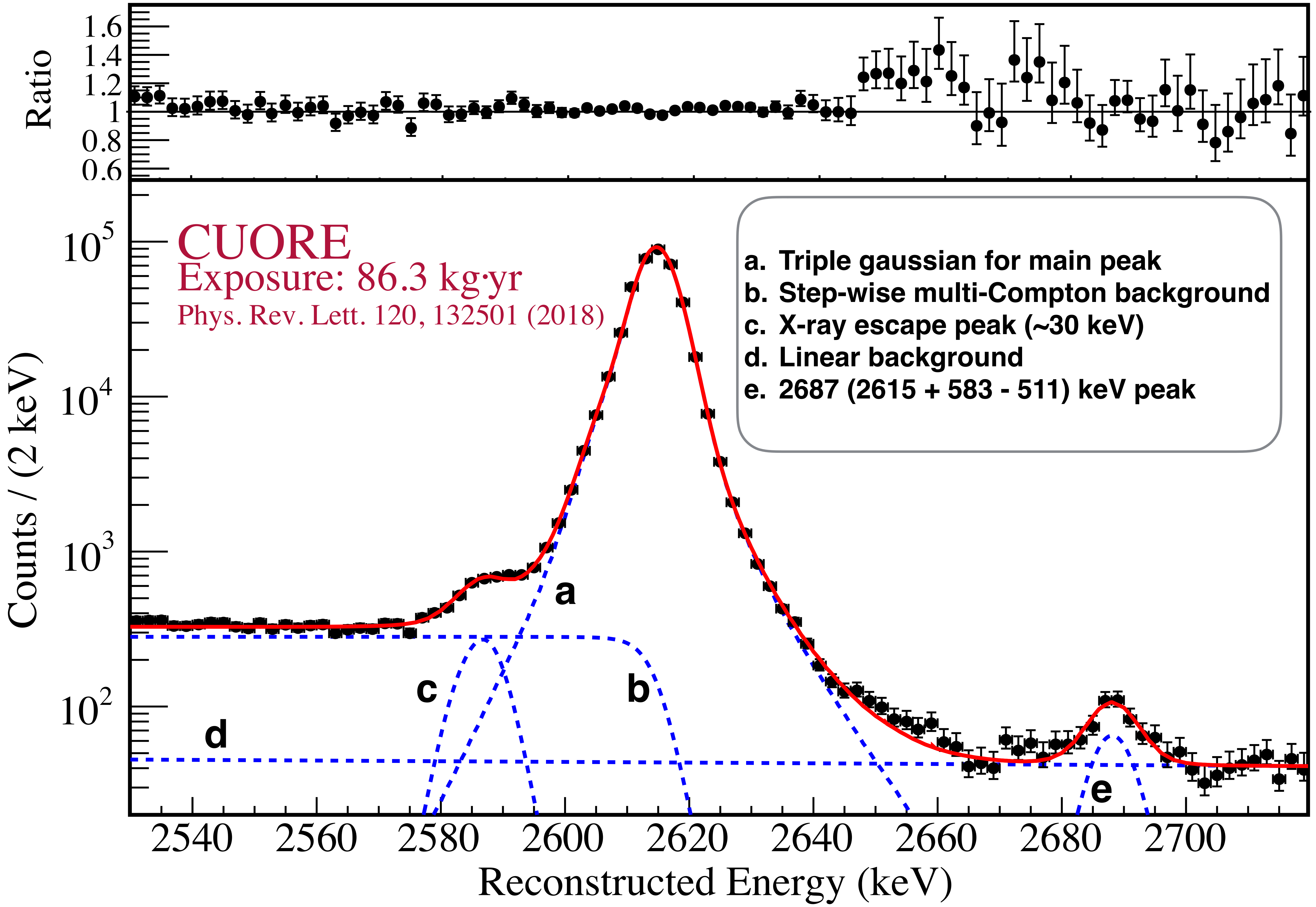
Physics: Consistent with expectations for background

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

Line Shape

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

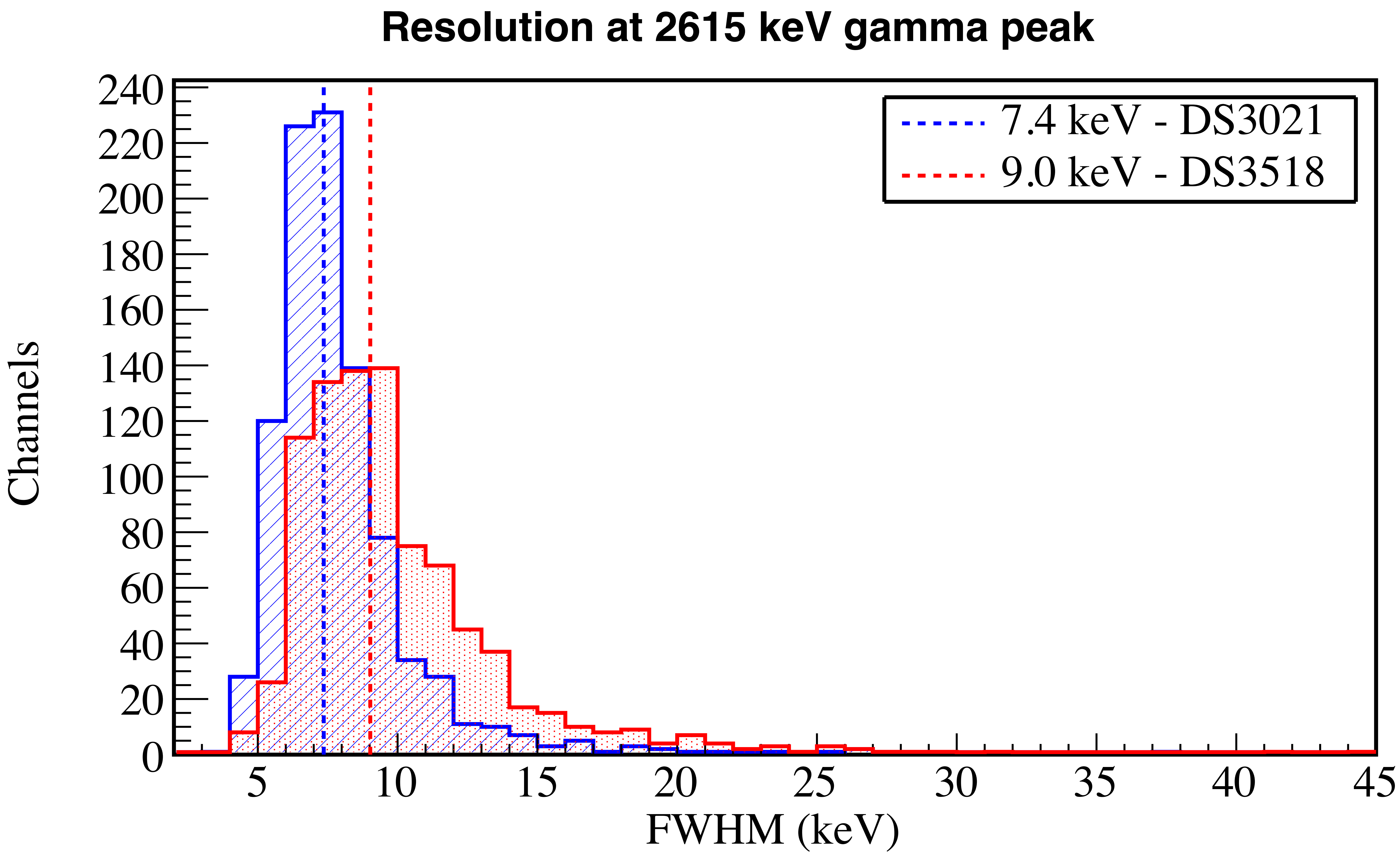
Fit for 2615 keV summed over all channels



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

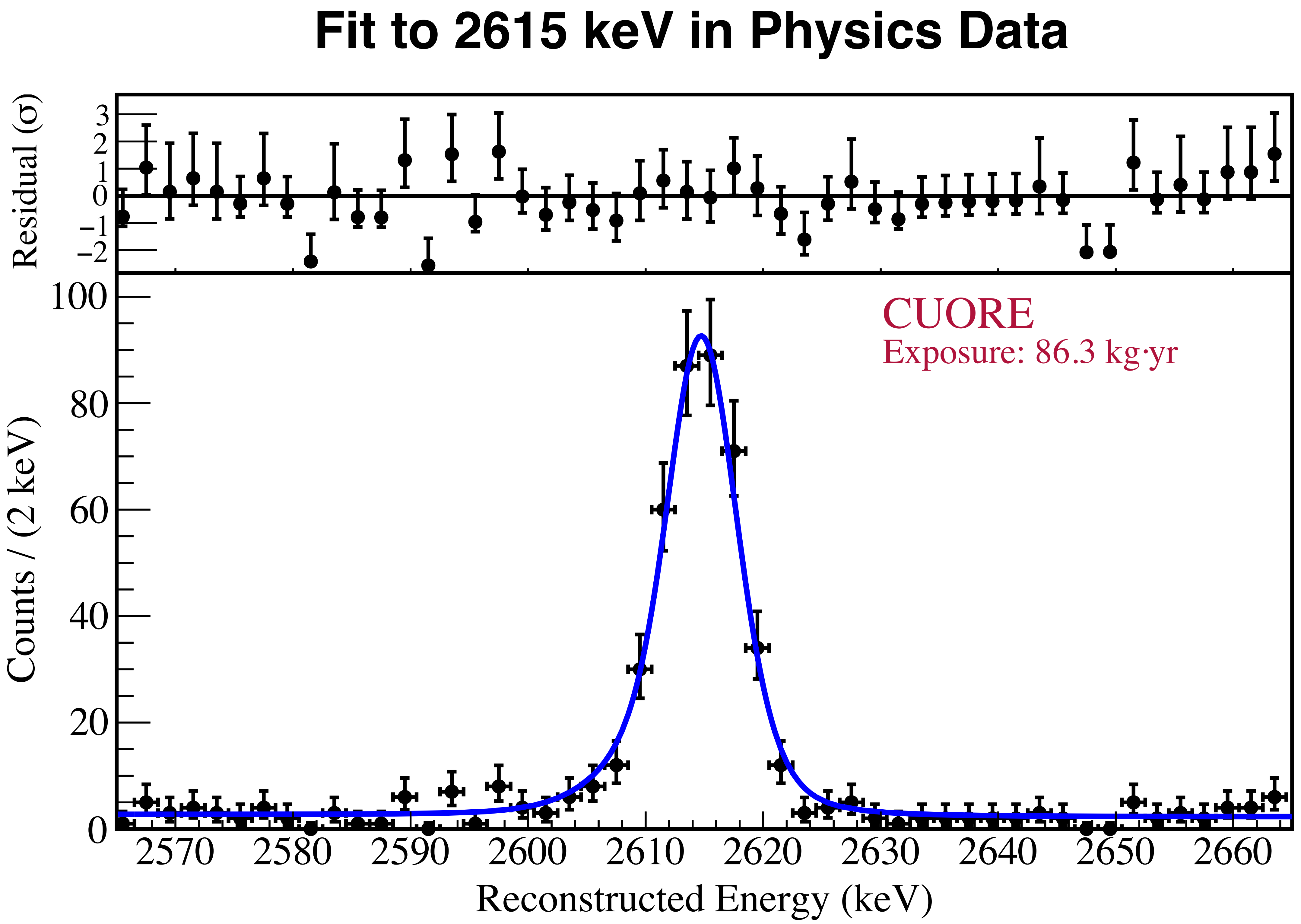
Energy Resolution

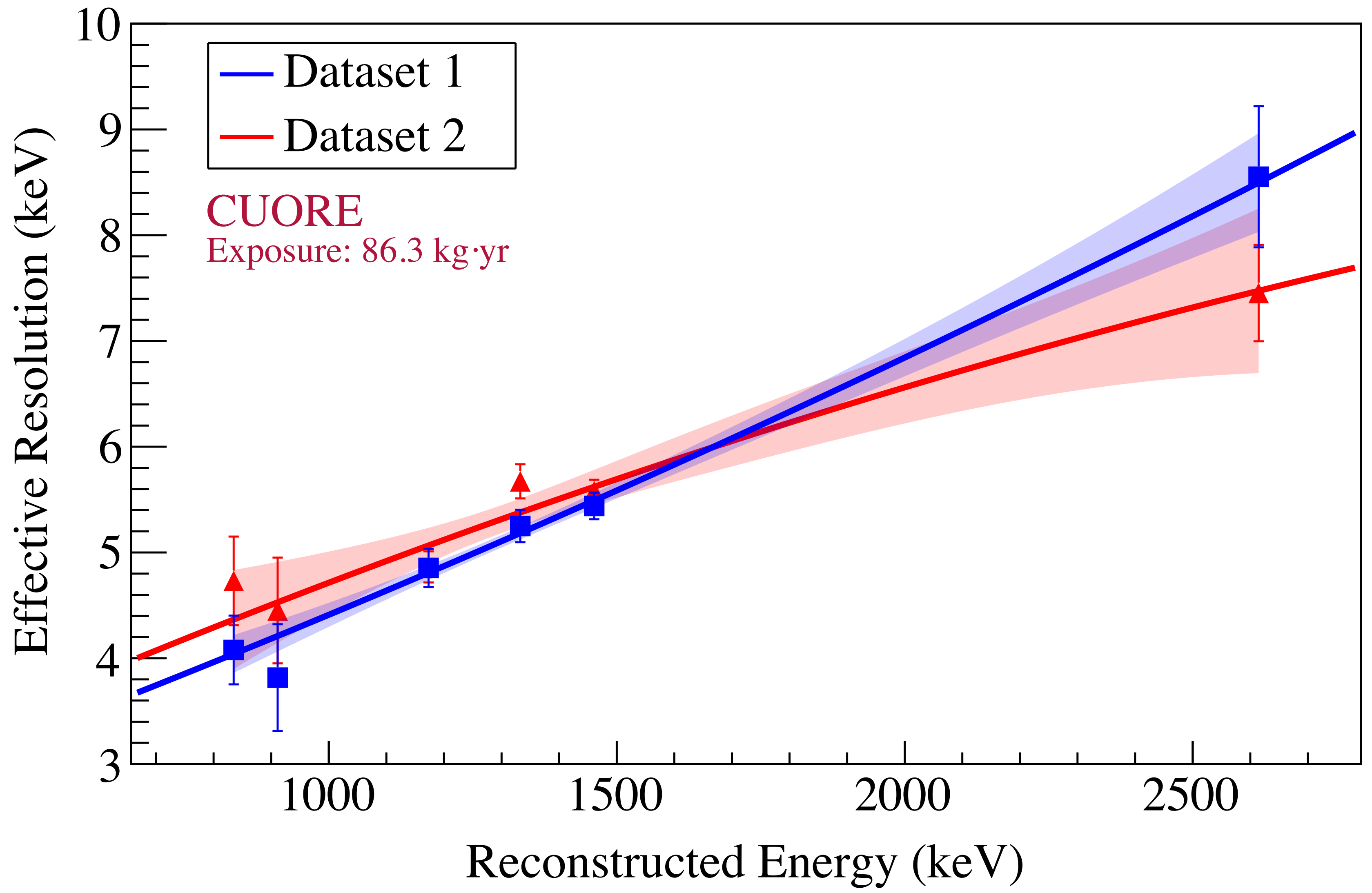
- Energy resolution key for separation of spectral features
- Exposure weighted average resolution of **8.0 keV FWHM**
- **Dataset 1 - 9.0 keV FWHM**
- **Dataset 2 - 7.4 keV FWHM**



Energy Resolution

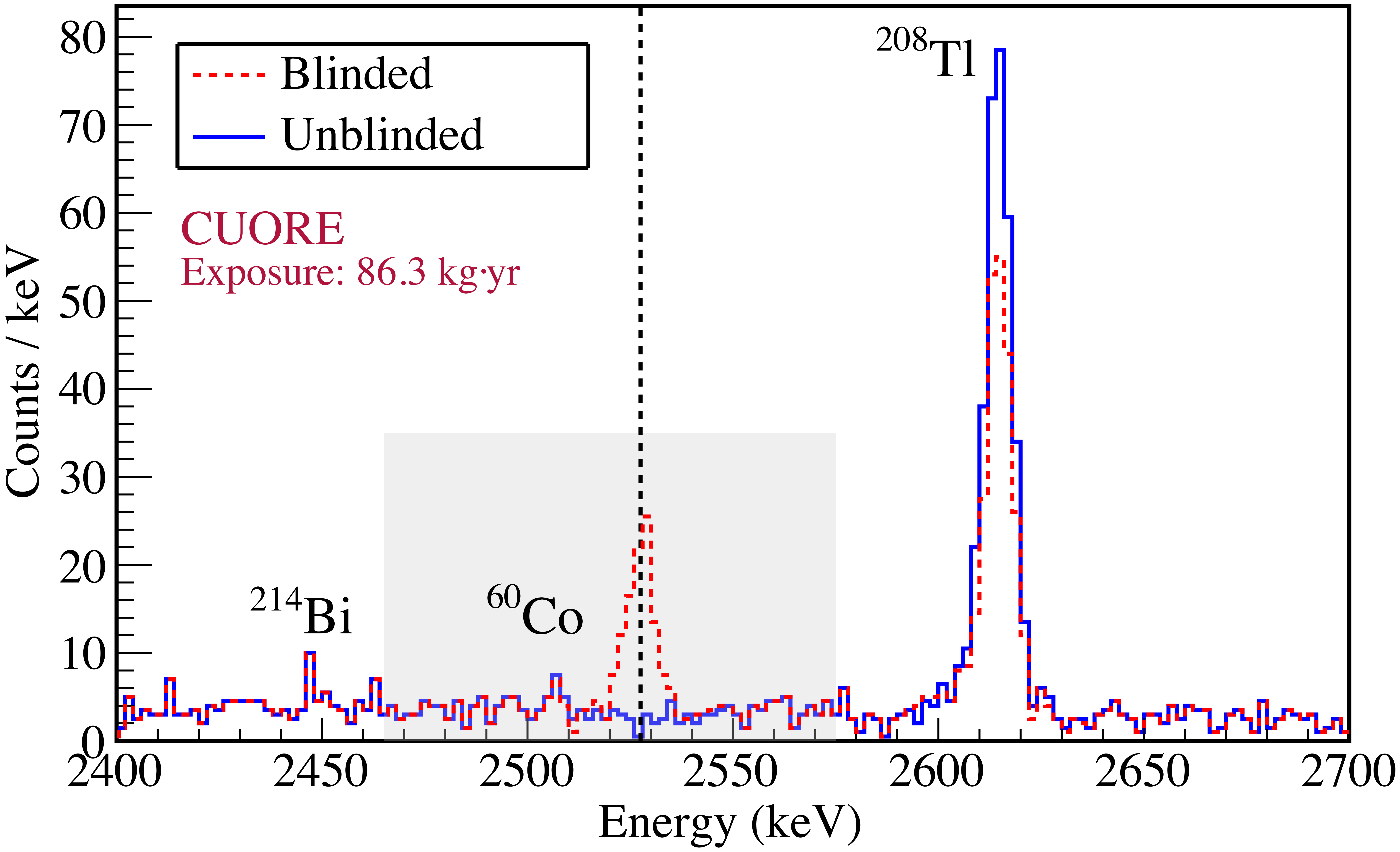
- Resolution in physics data at Q-value slightly better
- Exposure weighted average resolution at Q-value of **7.7 ± 0.5 keV FWHM**
- **Dataset 1 - 8.3 ± 0.4 keV FWHM**
- **Dataset 2 - 7.4 ± 0.7 keV FWHM**





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 0νββ rate in physics data
- After all analysis cuts and steps are defined and frozen, undo blinding



CUORE ROI Fit

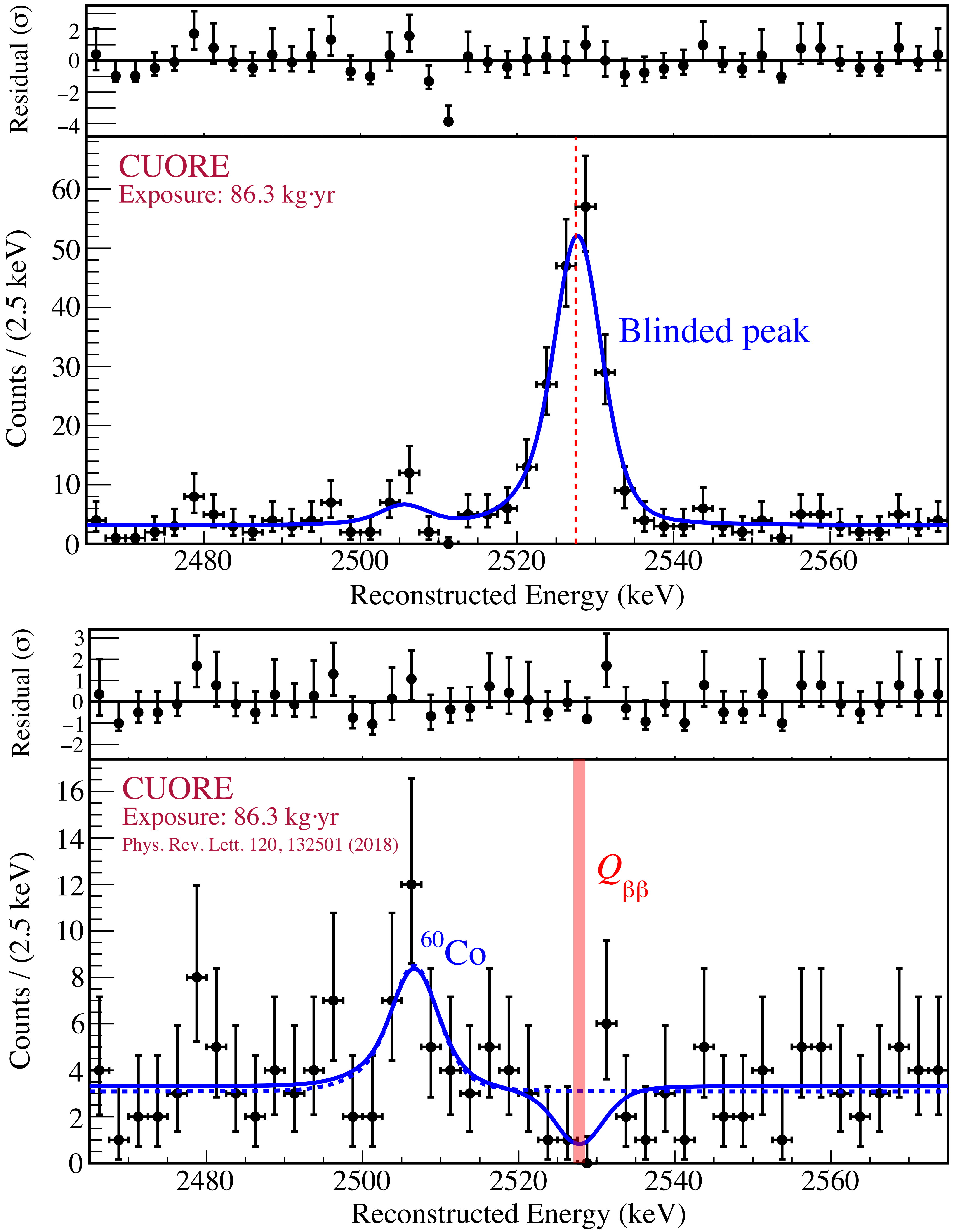
- Once analysis finalized fit for decay rate in the ROI performed
- ROI: 2465 - 2575 keV
- Simultaneous unbinned extended maximum likelihood fit
  - Dataset dependent flat background
  - ^{60}Co sum peak
  - $Q_{\beta\beta}$ peak - fixed position, floating rate
- Peaks are channel dependent - derived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

Background Index

Dataset 1	$BI = \left(1.49^{+0.18}_{-0.17}\right) \times 10^{-2} \dfrac{cnt}{keV \cdot kg \cdot yr}$
Dataset 2	$BI = \left(1.35^{+0.20}_{-0.18}\right) \times 10^{-2} \dfrac{cnt}{keV \cdot kg \cdot yr}$

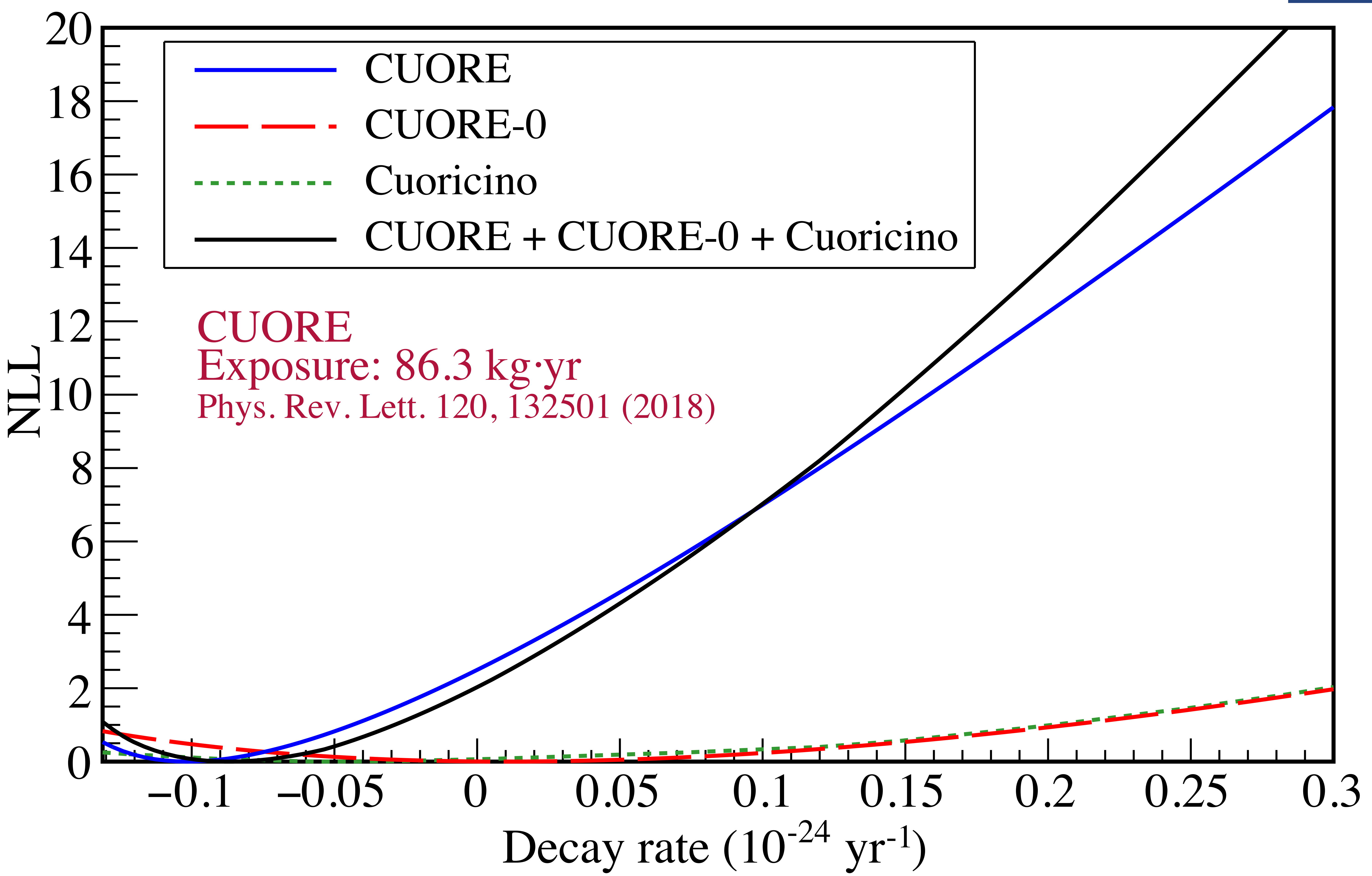
Best Fit Signal Decay Rate

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



Half Life Limit

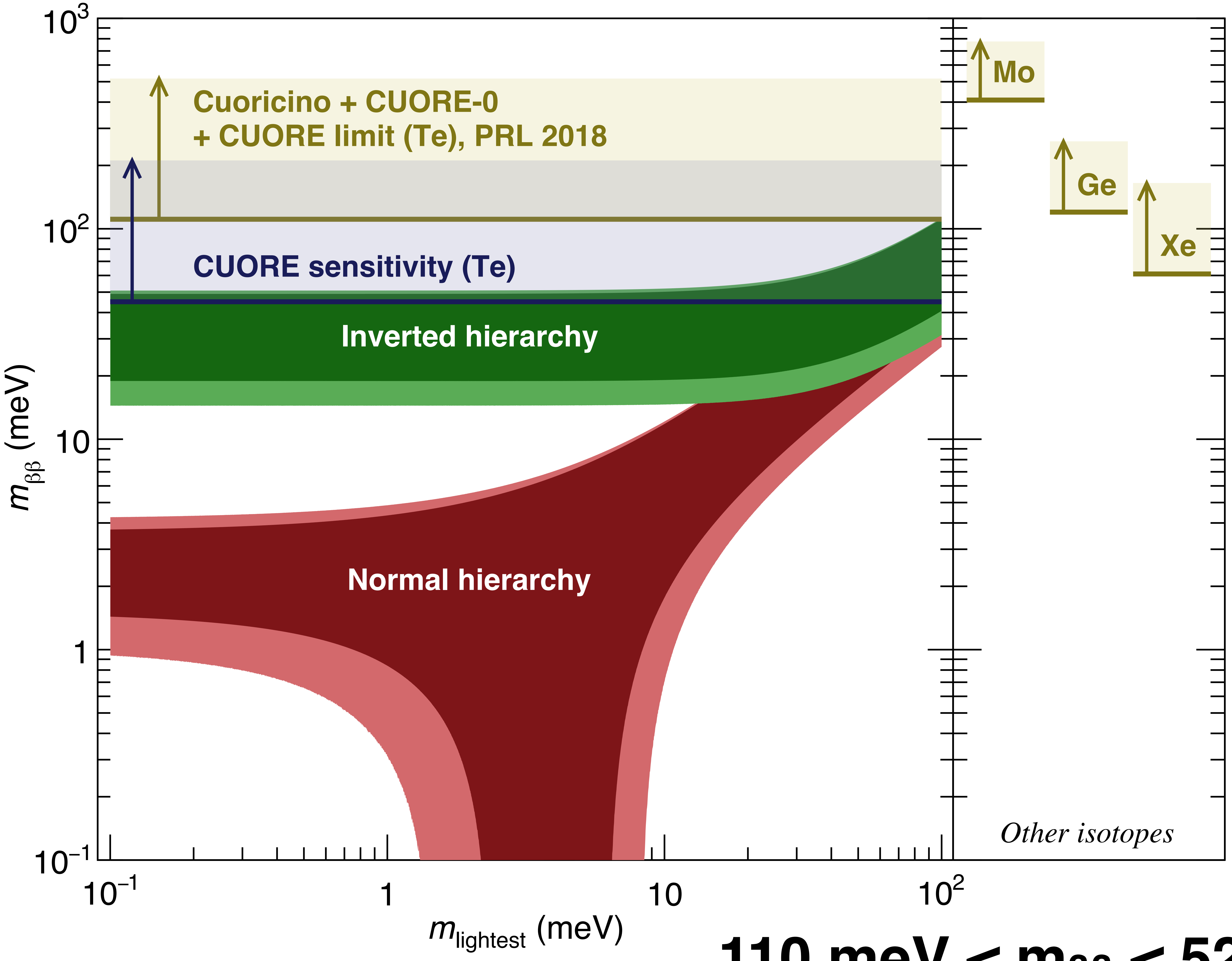
- Limit Computation
  - Profile likelihood integrated over the physical region ($\Gamma > 0$)



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

CUORE Half-life limit (90% C.L):	$T^{0\nu}_{1/2} > 1.3 \times 10^{25} y$	**Rolke:**	$T^{0\nu}_{1/2} > 2.1 \times 10^{25} y$
CUORE + CUORE0 + Cuoricino Half-life limit (90% C.L):	$T^{0\nu}_{1/2} > 1.5 \times 10^{25} y$	**Rolke:**	$T^{0\nu}_{1/2} > 2.2 \times 10^{25} y$

Combined $m_{\beta\beta}$ Limit



Half-life limits

^{130}Te: 1.5 × 1025 yr from this analysis PRL 120, 132501 (2018)
^{76}Ge: 8.0 × 1025 yr from PRL 120, 132503 (2018)
^{136}Xe: 1.1 × 1026 yr from Phys. Rev. Lett. 117, 082503 (2016)
^{100}Mo: 1.1 × 1024 yr from Phys. Rev. D 89, 111101 (2014)
CUORE sensitivity: 9.0 × 10^{25} yr

Effective Majorana Mass

Phase Space

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu}\left(Q_{\beta\beta}, Z\right)\left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

Nucl. Matrix Element

Nuclear Matrix Elements

JHEP02 (2013) 025
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 87, 064302 (2014)
Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 91, 024613 (2015)
Phys. Rev. C 91, 024309 (2015)
Phys. Rev. Lett. 105, 252503 (2010)
Phys. Rev. Lett. 111, 142501 (2013)

110 meV < $m_{\beta\beta}$ < 520 meV - NME dependent

Beyond CUORE

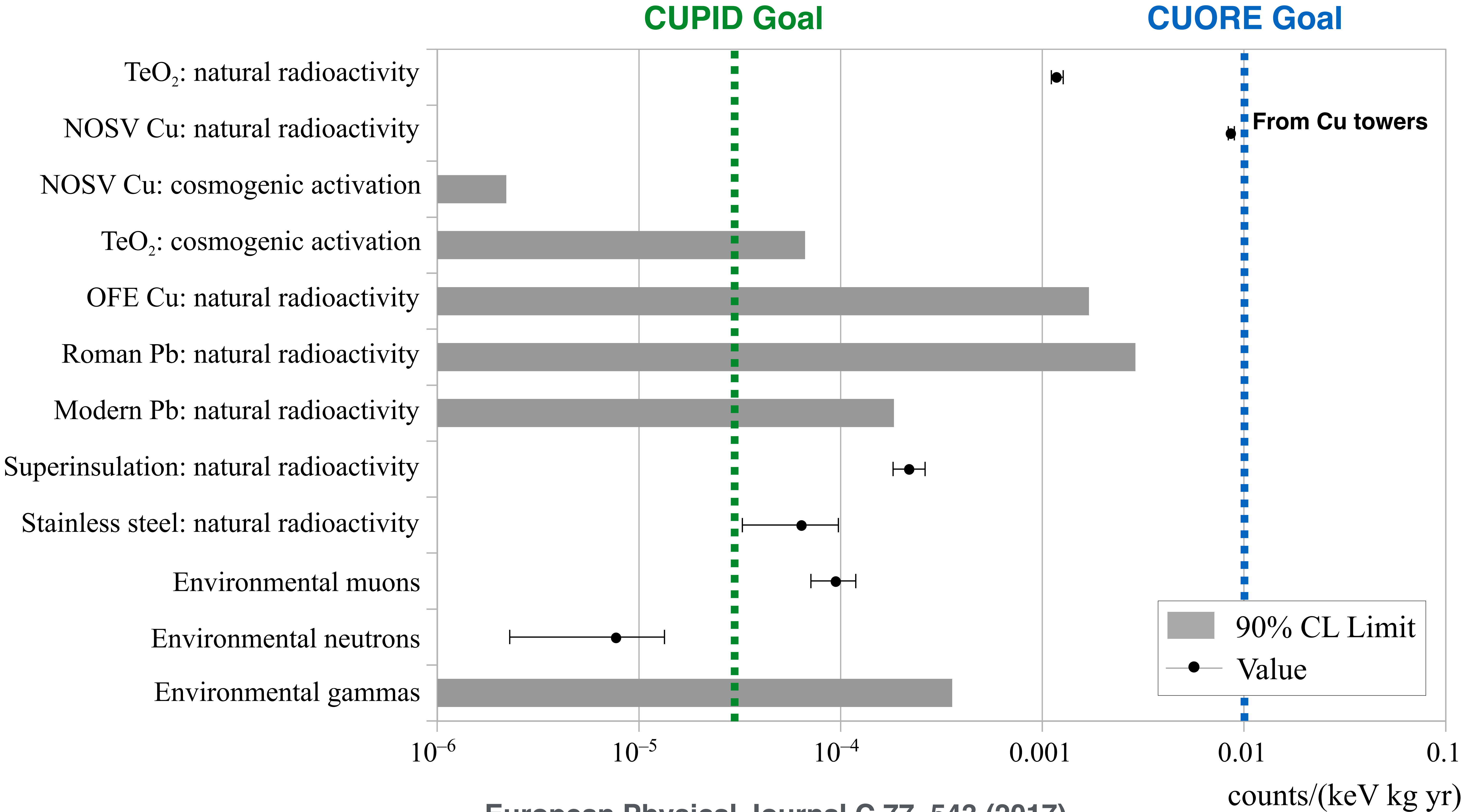
Background Limited

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

Background Free

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

- CUORE background goals met
- Degraded alpha's pose problem
  - Bolometric technique provides only 1 channel for energy - no particle ID
- **C**UORE **U**pgrade with **P**article **ID** (CUPID) aims to dramatically improve background discrimination
  - Particle ID via light detection



European Physical Journal C 77, 543 (2017)

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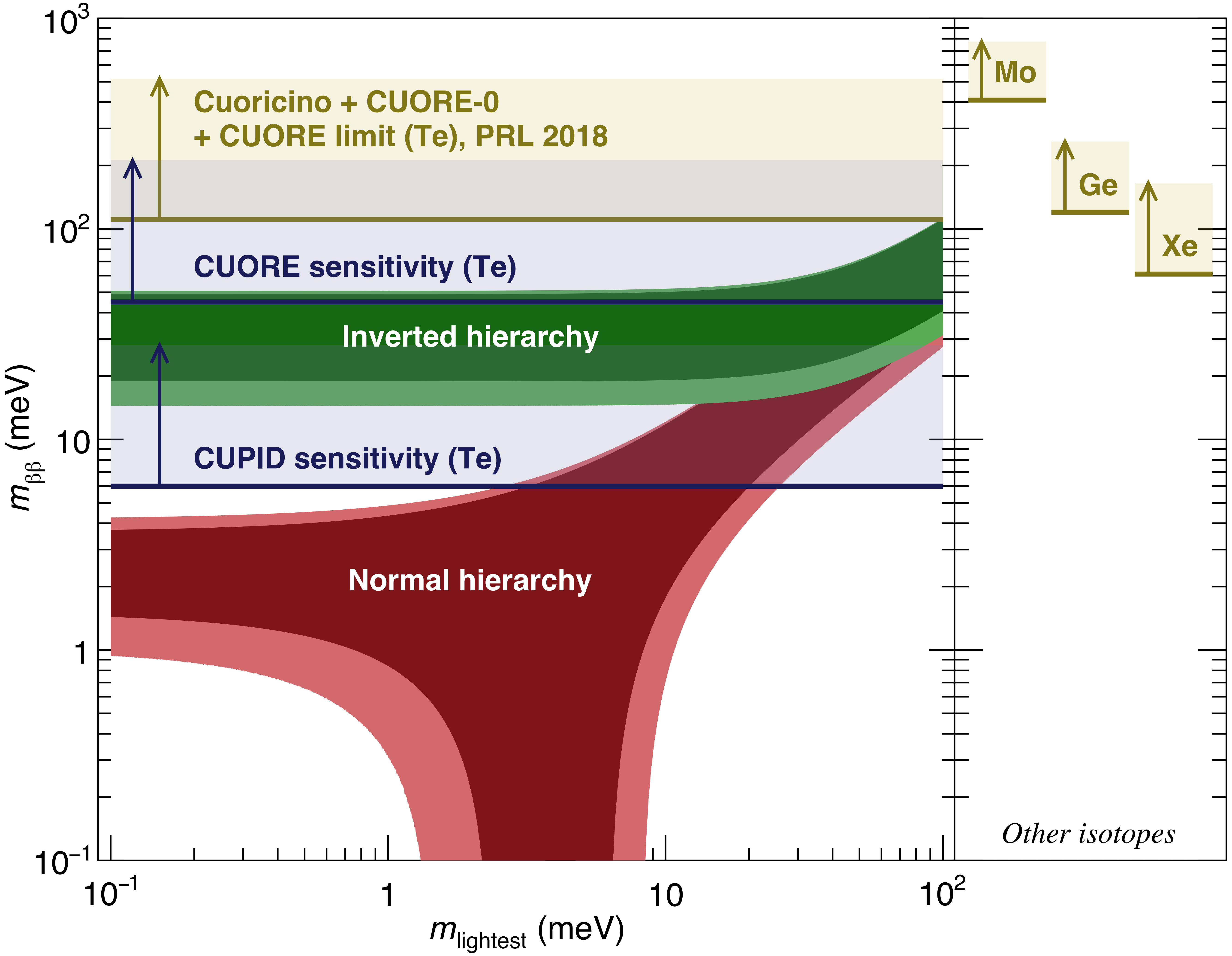
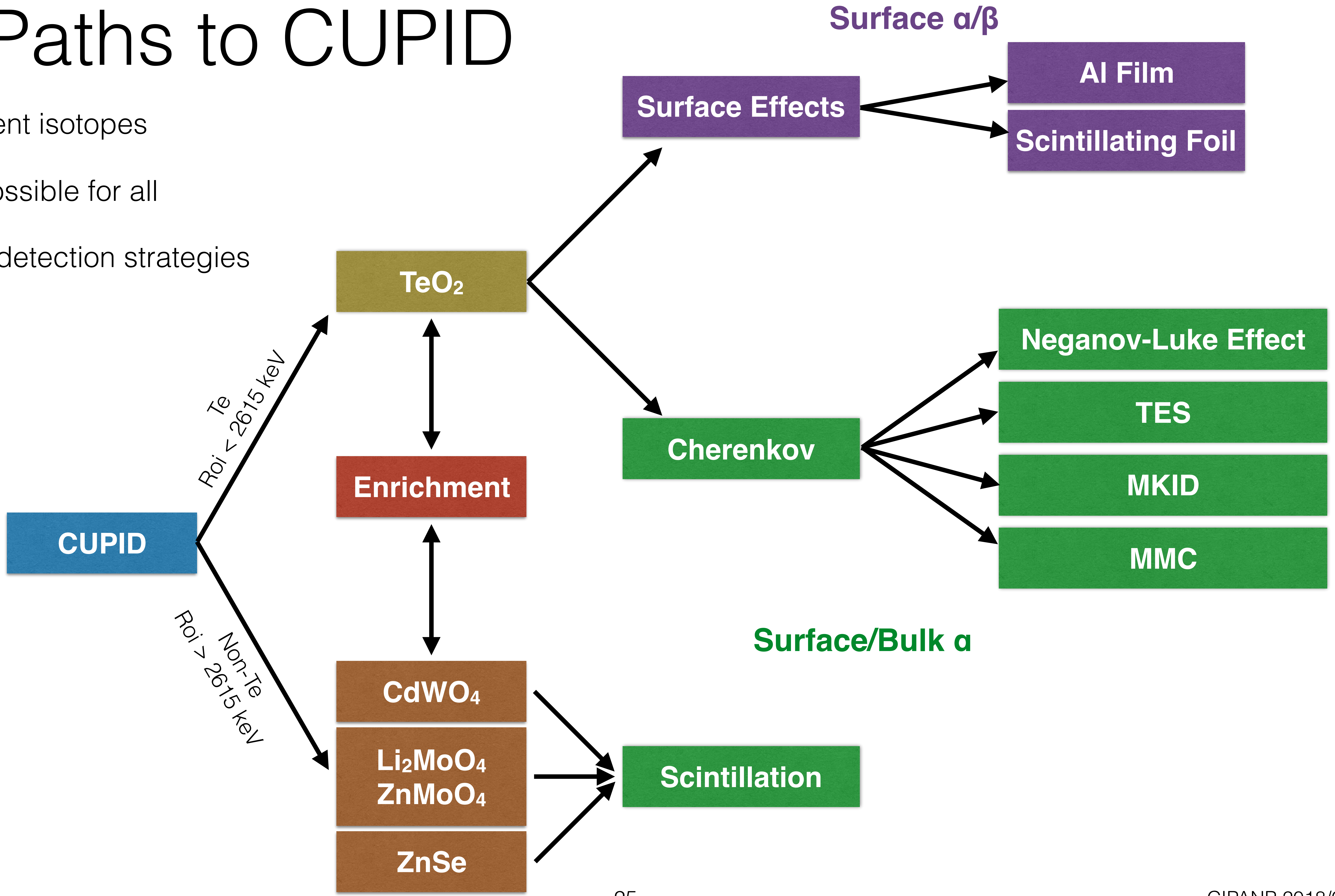


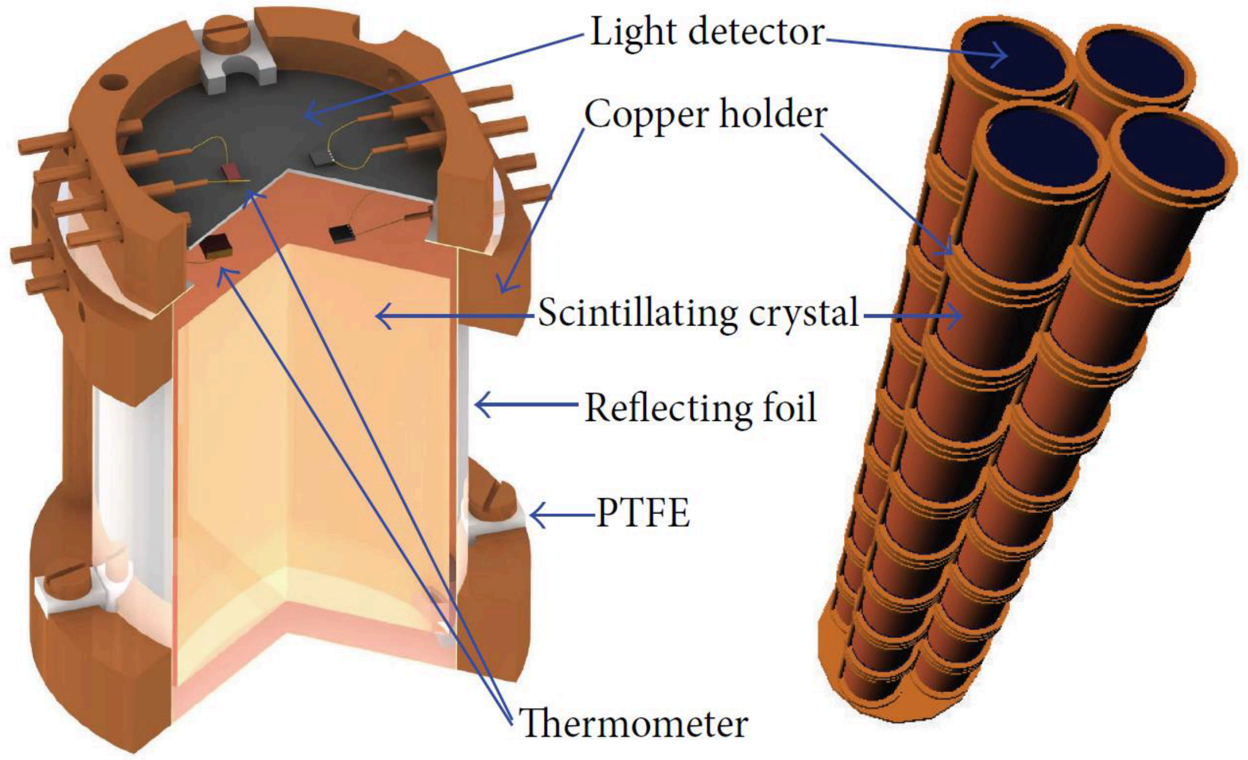
Many Paths to CUPID

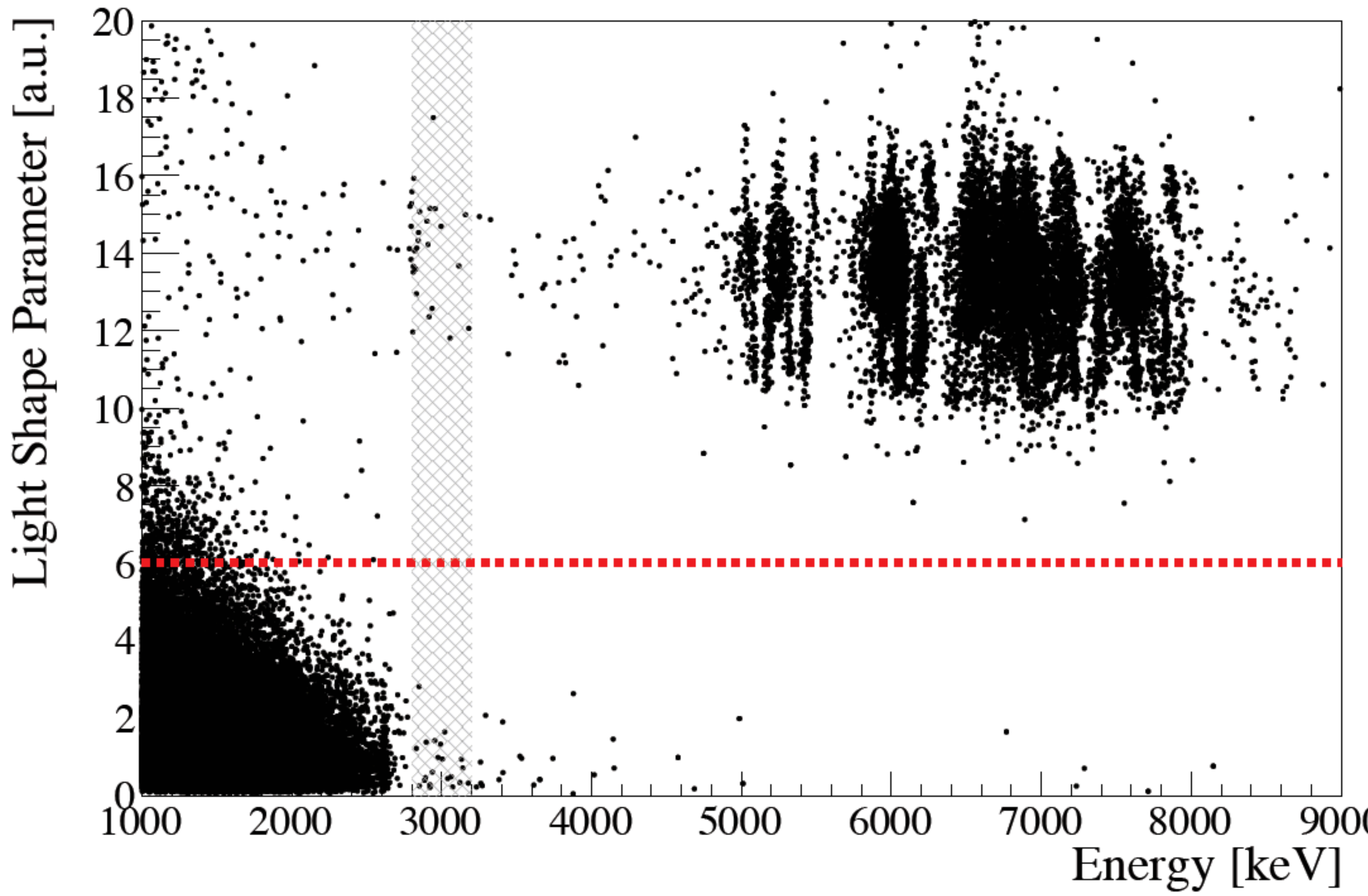
- Multiple different isotopes
- Enrichment possible for all
- Different light detection strategies under R&D



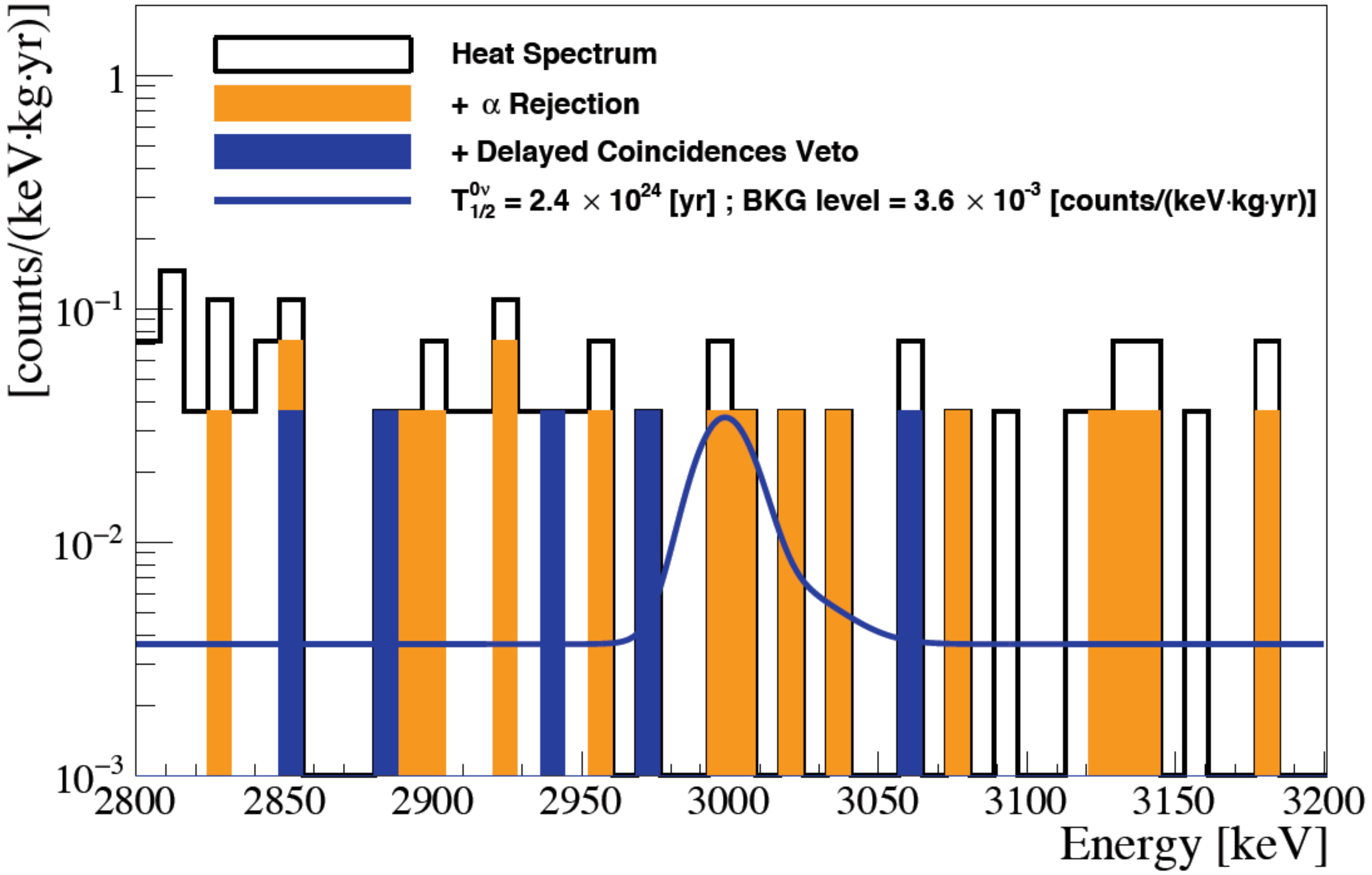
CUPID-0/Se

- $Zn^{82}Se$
- 96% enriched ^{82}Se
    - 5.17 kg of active isotope
    - Q-value - 2.997 MeV
- Ge wafer with SiO antireflective coating
- VIKUITI 3m reflective foil on detector housing
- NTD Ge thermistors
- 10^{-6} discrimination of α's
- Energy resolution - 23.0 ± 0.6 keV
- 3.6 x 10^{-3} cnt/kg/yr/keV background



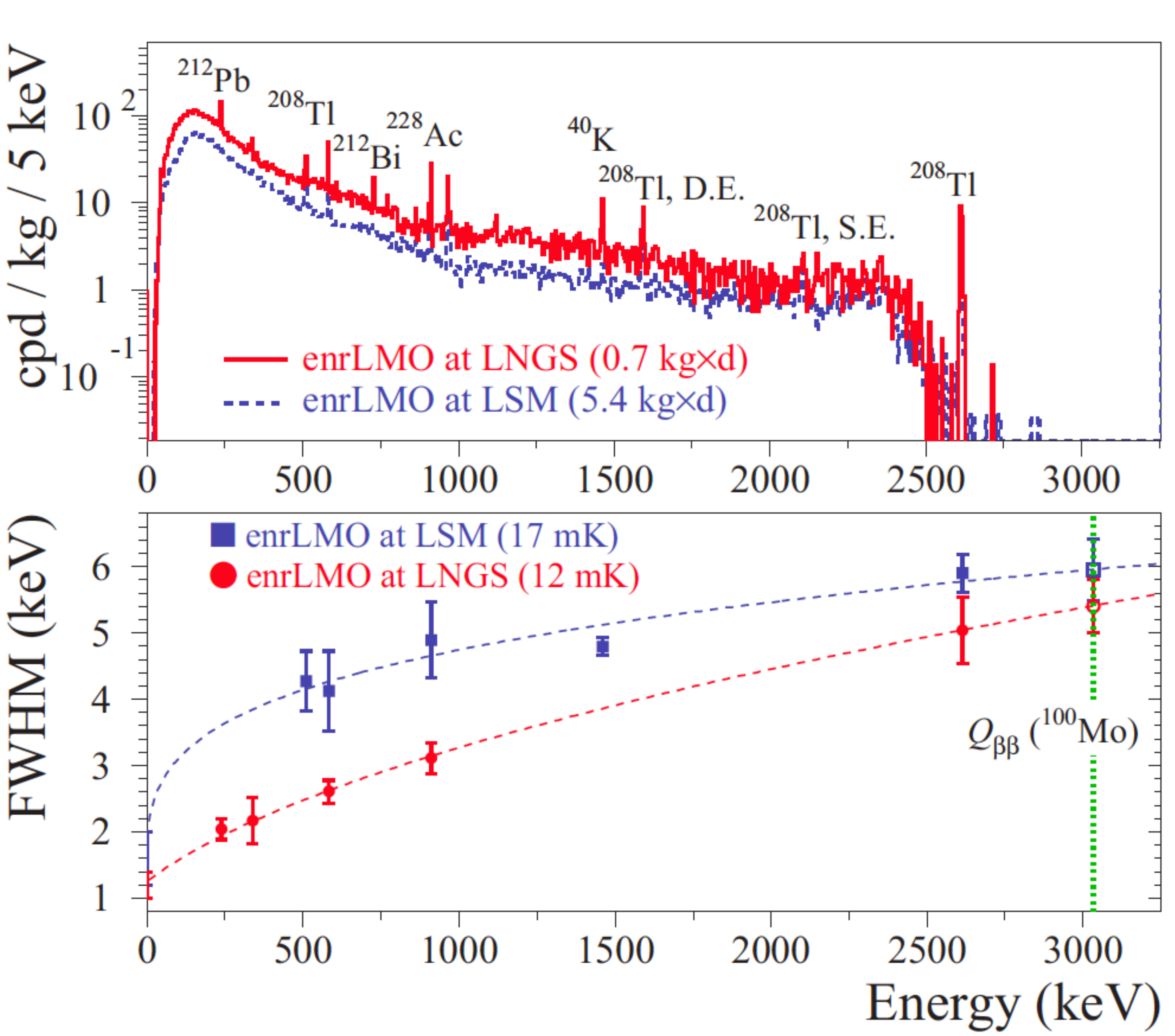


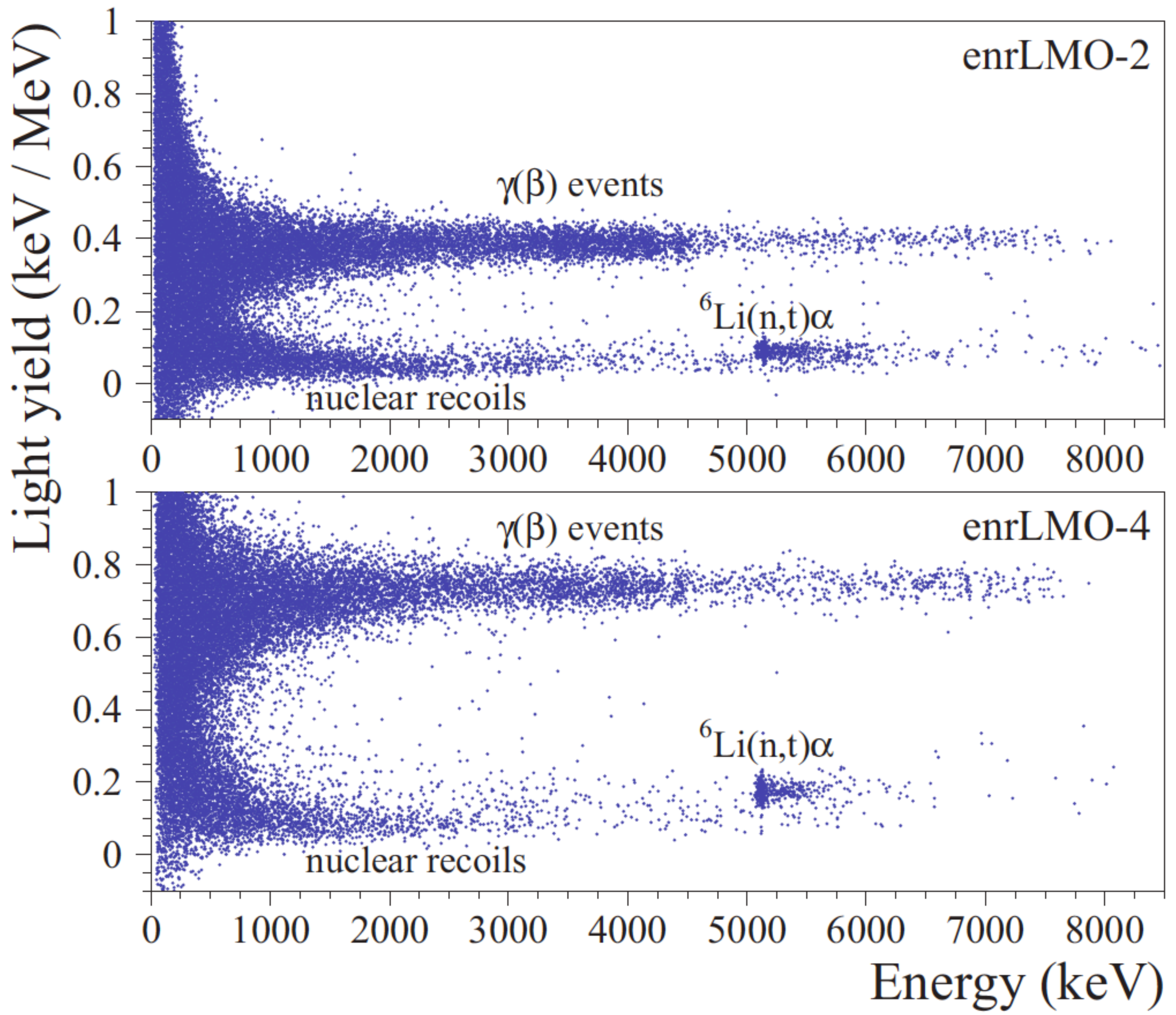
https://arxiv.org/pdf/1802.07791.pdf



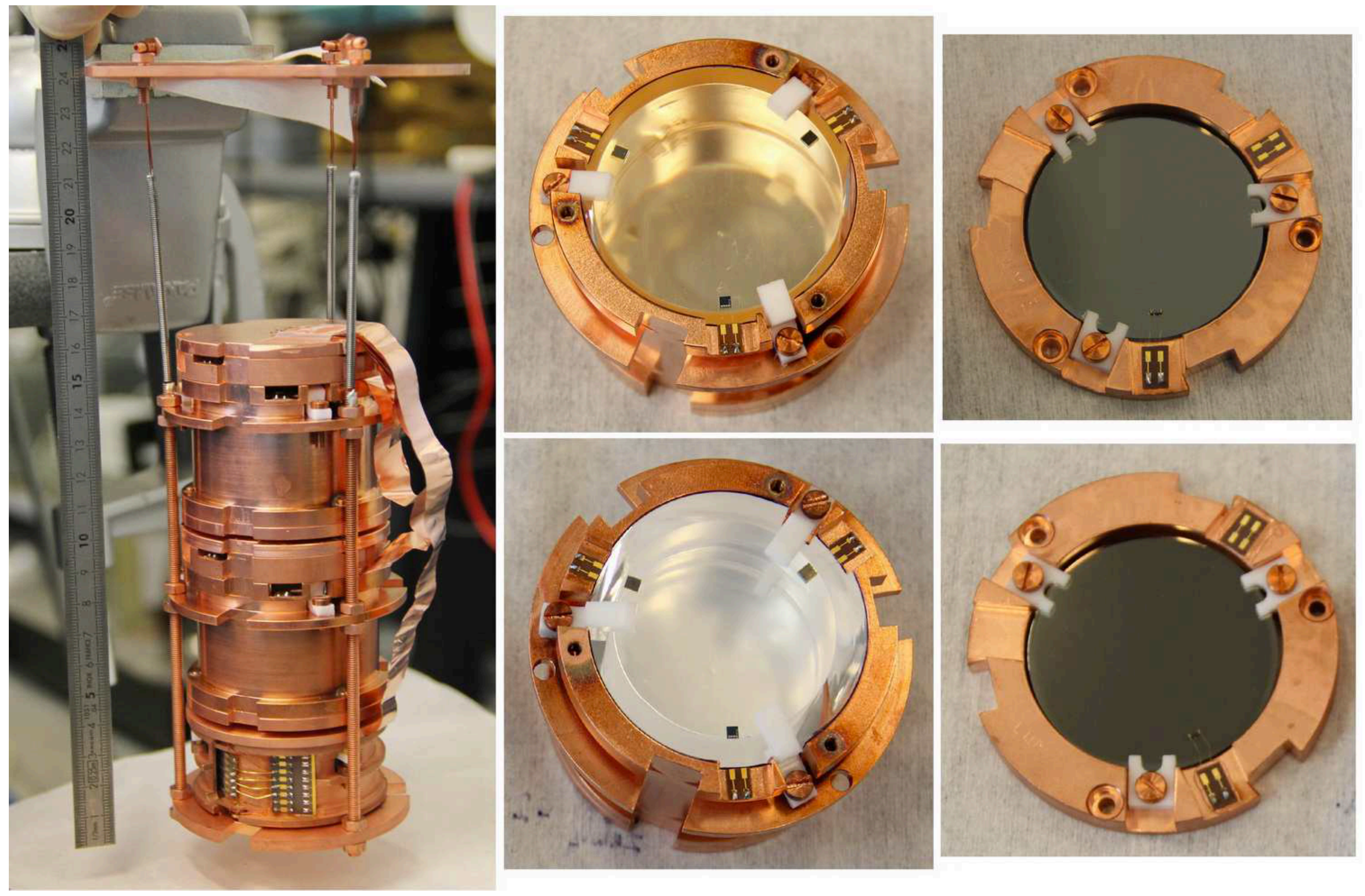
CUPID-Mo

AIP Conference Proceedings 1894, 020017 (2017)





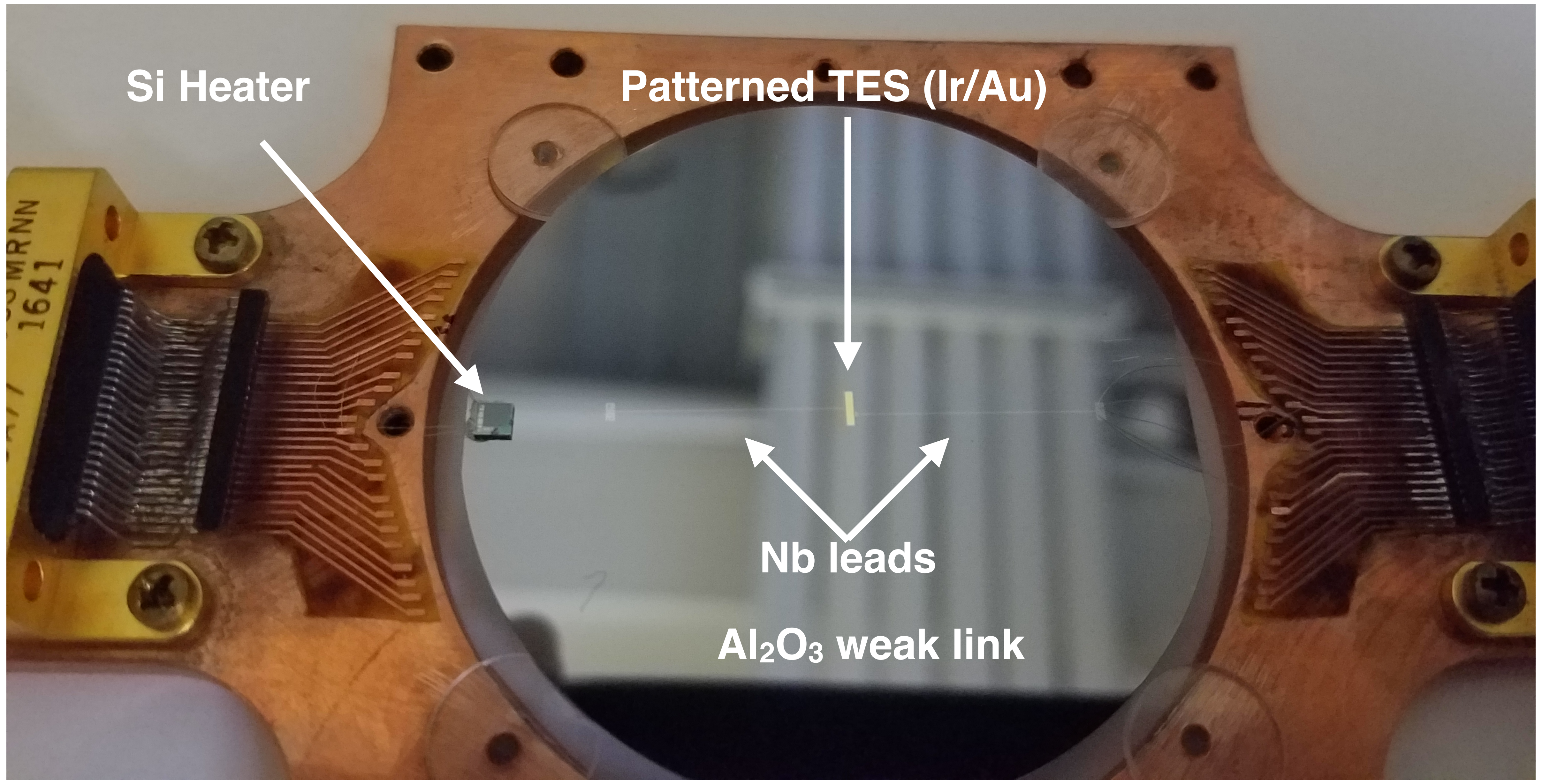
- $Li_2{}^{100}MoO_4$ crystals
  - Q-value - 3.035 MeV
- 20 detectors installed in EDELWEISS cryostat
- NTD Ge thermistors
- Energy resolution ~ 6 keV FWHM
- 9σ level for alpha/beta separation

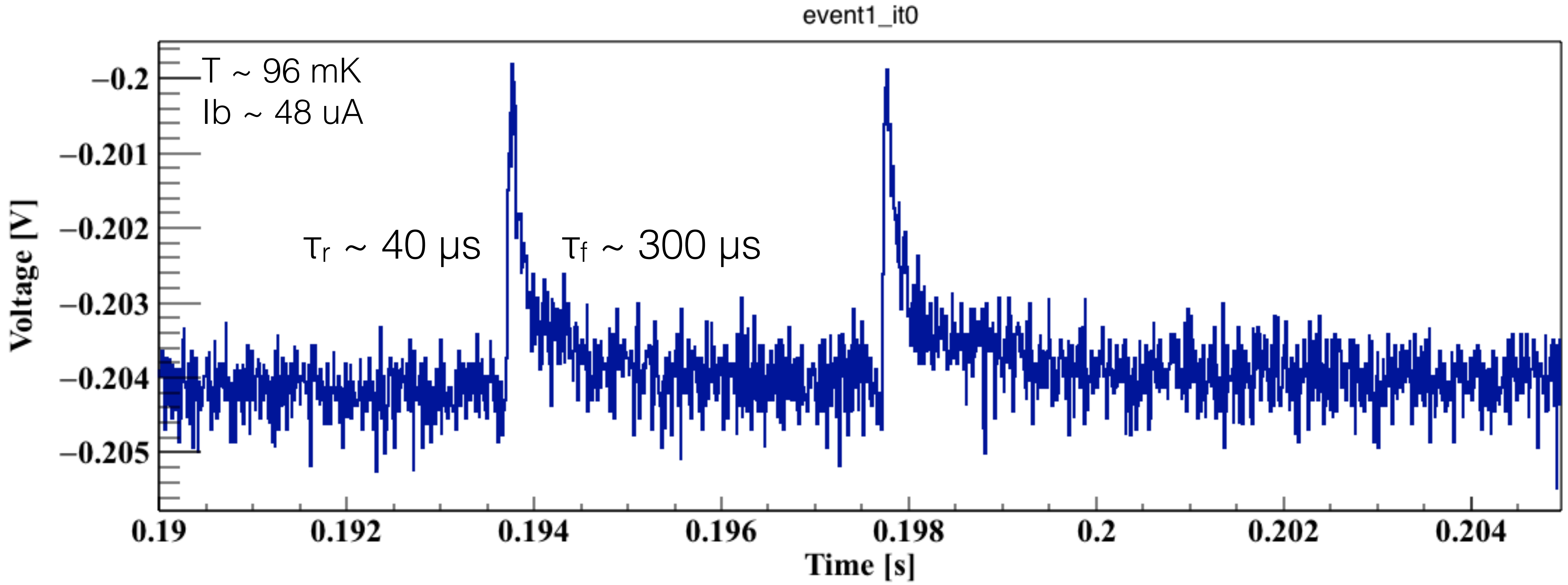


Eur. Phys. J. C 77 (2017) 785

Transition Edge Sensor Light Detector

- Si light detector with patterned TES
    - Ir/Pt and Ir/Au
- Magnicon XXF SQUID for readout
- Fiber optic cable mounted in cryostat
    - Delivery of light pulses via blue LED
- Timing resolution $\sigma_t \sim 5\ \mu s$





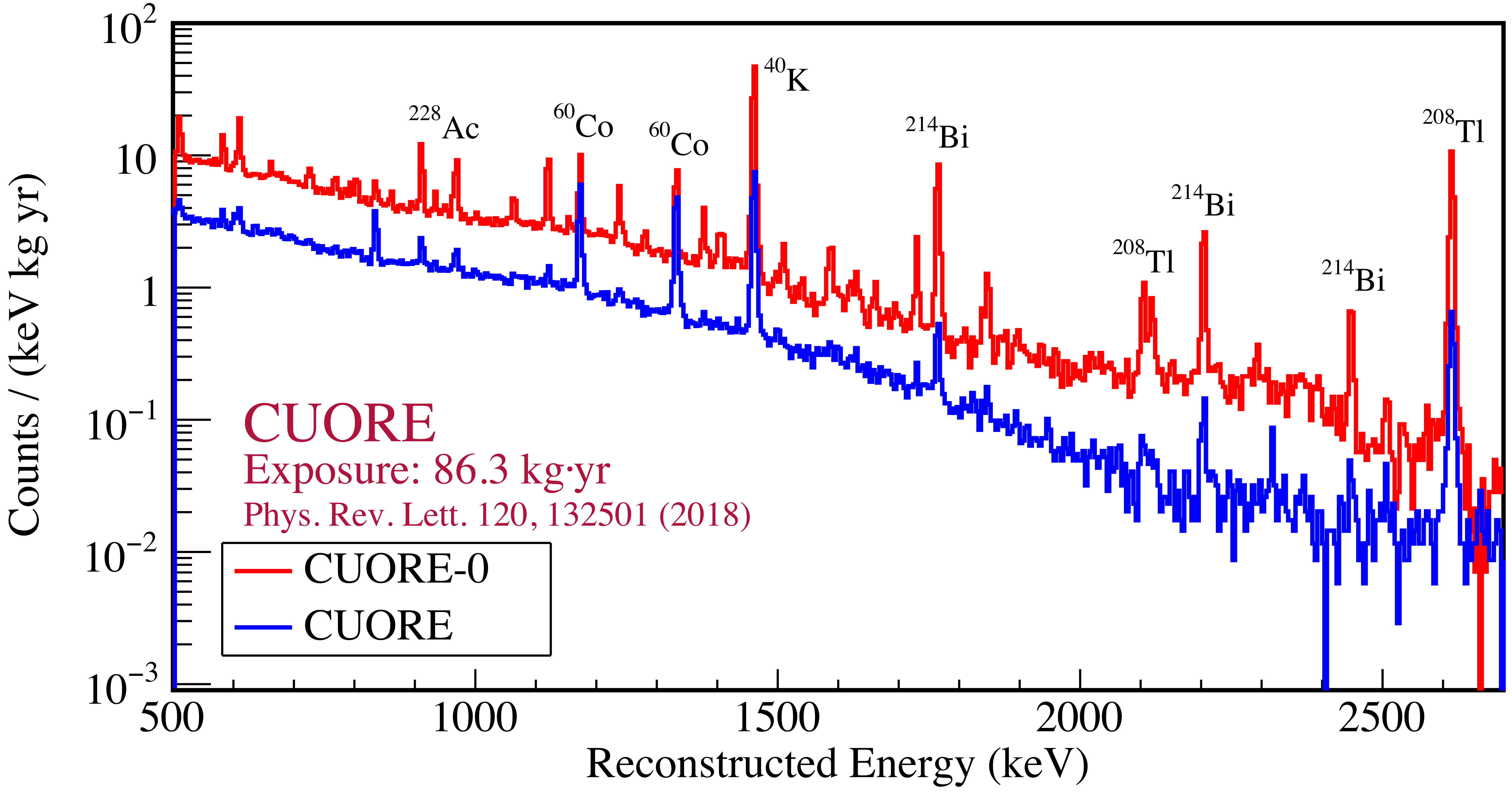
Conclusions

- First result from CUORE
    - Strongest limit on ^{130}Te 0νββ decay to date after 2 months (>1.5 x 10^{25} yr)
- Operation of world's largest ton-scale bolometric array
    - Largest and most powerful cryogen free dilution refrigerator
- Cryogenic maintenance and detector optimization campaign ending with resumption of data taking
    - Operating at 11 mK now
- Still plan for 5 years of live time
    - 9 x 10^{25} yr sensitivity, 5 keV FWHM
- Other analyses (other isotope, 2νββ, dark matter, …)
- Tune into Neutrino 2018 for exciting new results
- Many paths forward for next generation CUPID
    - Expect formation of CUPID collaboration in near future

Backups

CUORE vs CUORE-0

- Significant reduction in gamma spectrum compared to CUORE-0



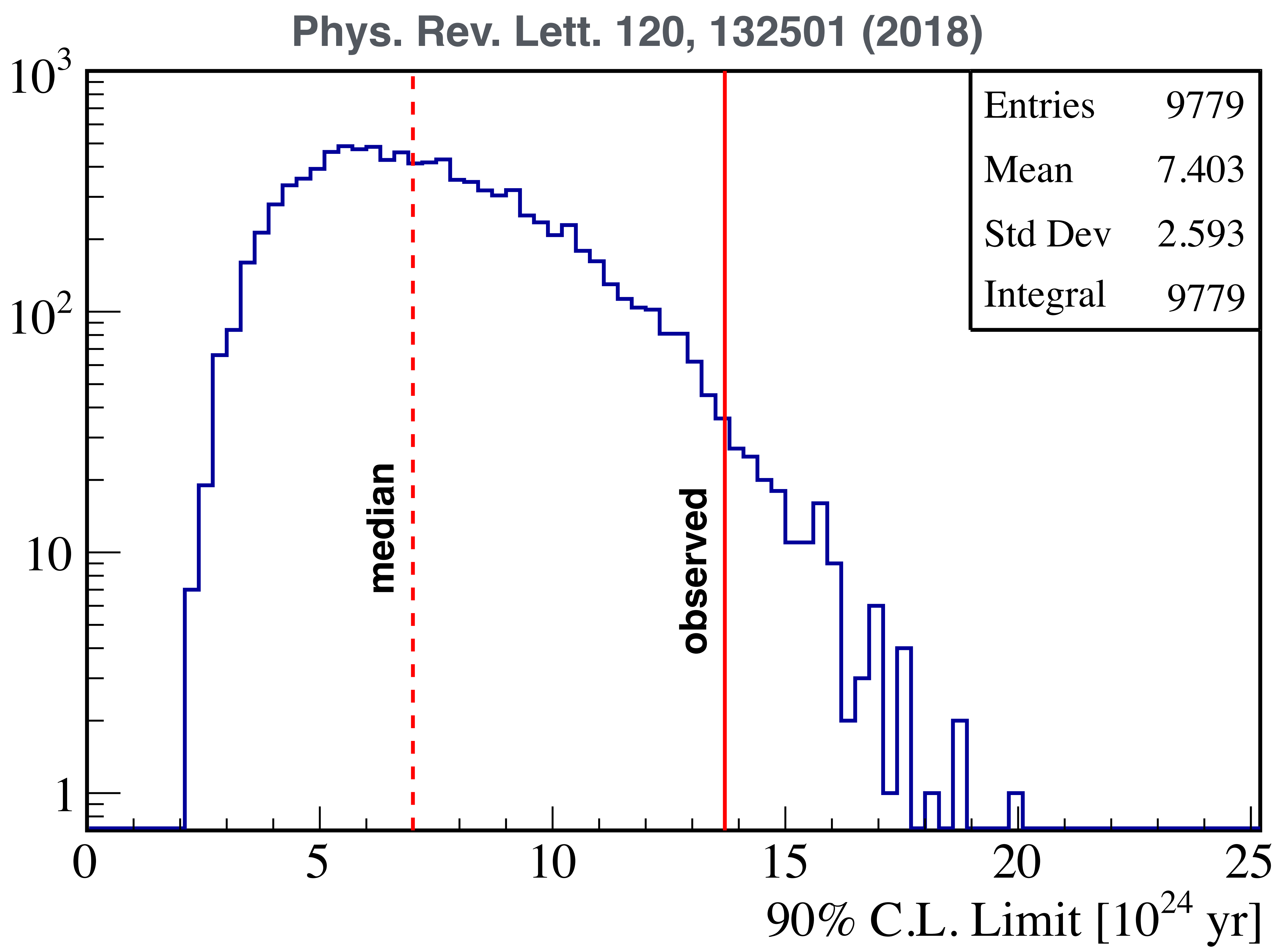
Line Shape Fit

- Complex fitting routine
- Channel-Dataset Parameters
  - Q-value of photopeak
  - shape parameter
    - Same for all gaussians
  - Total signal rate in main peak
    - Exposure from database
  - 2 sub-peak energy ratios
    - positions of the left and right shoulders
  - 2 sub-peak ratios
    - number of events in shoulders relative to main peak

- Global Parameters
  - Compton ratio
    - Number of events in Compton shoulder relative to main peak
  - Background ratio
    - Number of events in linear background relative to main peak
  - Linear Background coefficient
  - X-Ray ratio
    - Number of events in the 30 keV X-ray escape peak relative to main peak
  - 2687 keV Peak Ratio
    - Ratio of number of events in (2615 + 538 - 511) keV
  - 2687 keV Peak Energy Ratio
    - Position of (2615 + 538 - 511) keV peak relative to Q-value

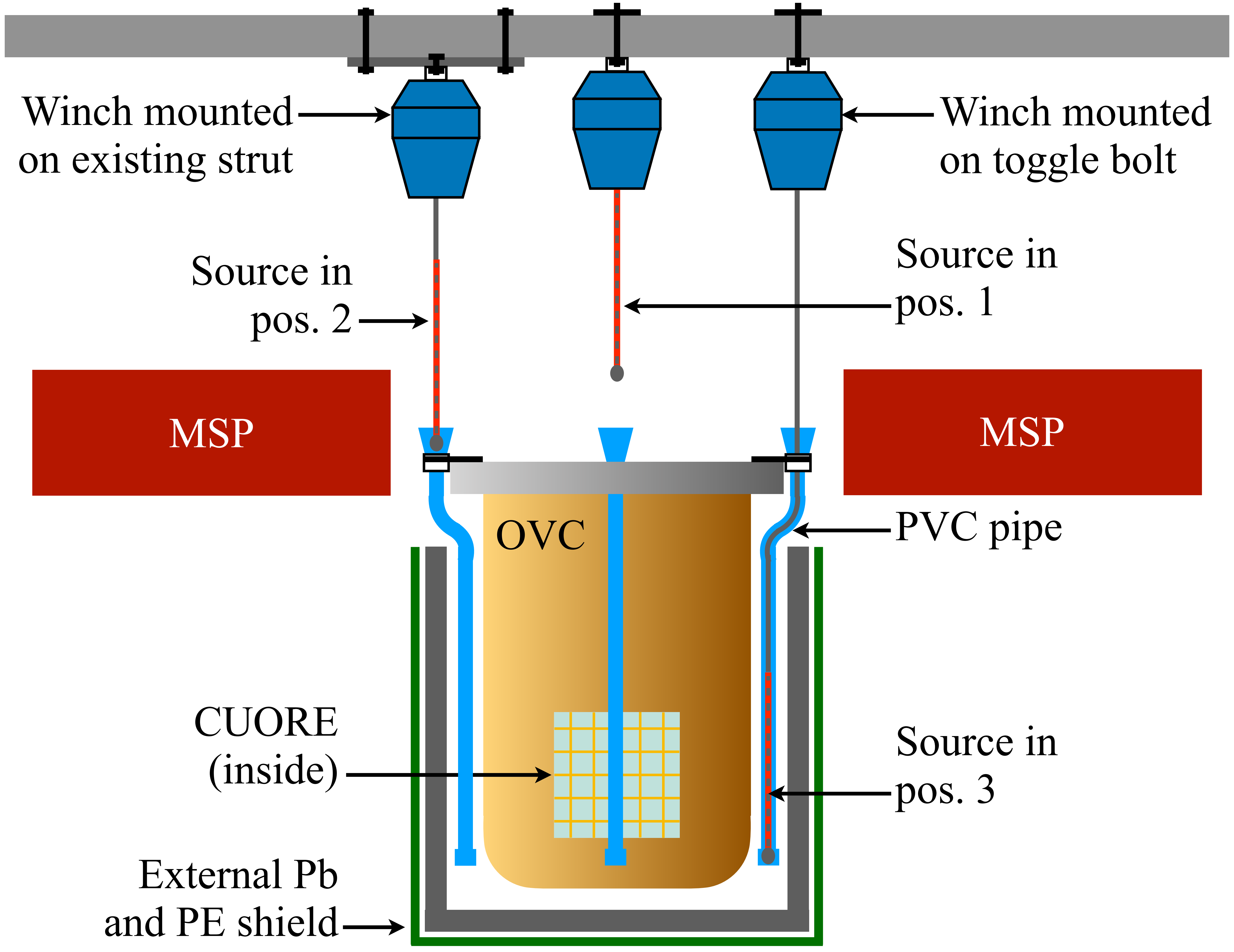
Downward Fluctuation

- Median sensitivity -> 7.0 x 10^{24} y
  - 2% probability of larger negative fluctuation than seen



External DCS

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



Detector Performance

Active channels	984 (99.6%)
Dead channels	4
Channel-dataset pairs used in analysis	1811 (92% of live channels) (876 in ds3518 + 935 in ds3021)
TeO_2 exposure	86.3 kg yr (37.6 kg yr in ds3518 + 48.7 kg yr in ds3021)
Te-130 exposure	24.0 kg yr
FWHM at 2615 keV in calibration data, ds3518	9.0 keV
FWHM at 2615 keV in calibration data, ds3021	7.4 keV
FWHM at 2615 keV in calibration data, exposure-weighted	8.0 keV
Trigger thresholds	
Analysis threshold	150 keV
Energy bias at Q-value	(0 ± 0.5) keV
Resolution scaling at 2615, ds3518	(95 ± 7)%
Resolution scaling at 2615, ds3021	(101 ± 6)%
FWHM in physics data at Q-value, ds3518	(8.3 ± 0.4) keV
FWHM in physics data at Q-value, ds3021	(7.4 ± 0.7) keV
FWHM in physics data at Q-value, exposure-weighted	(7.7 ± 0.5) keV

0νββ Analysis

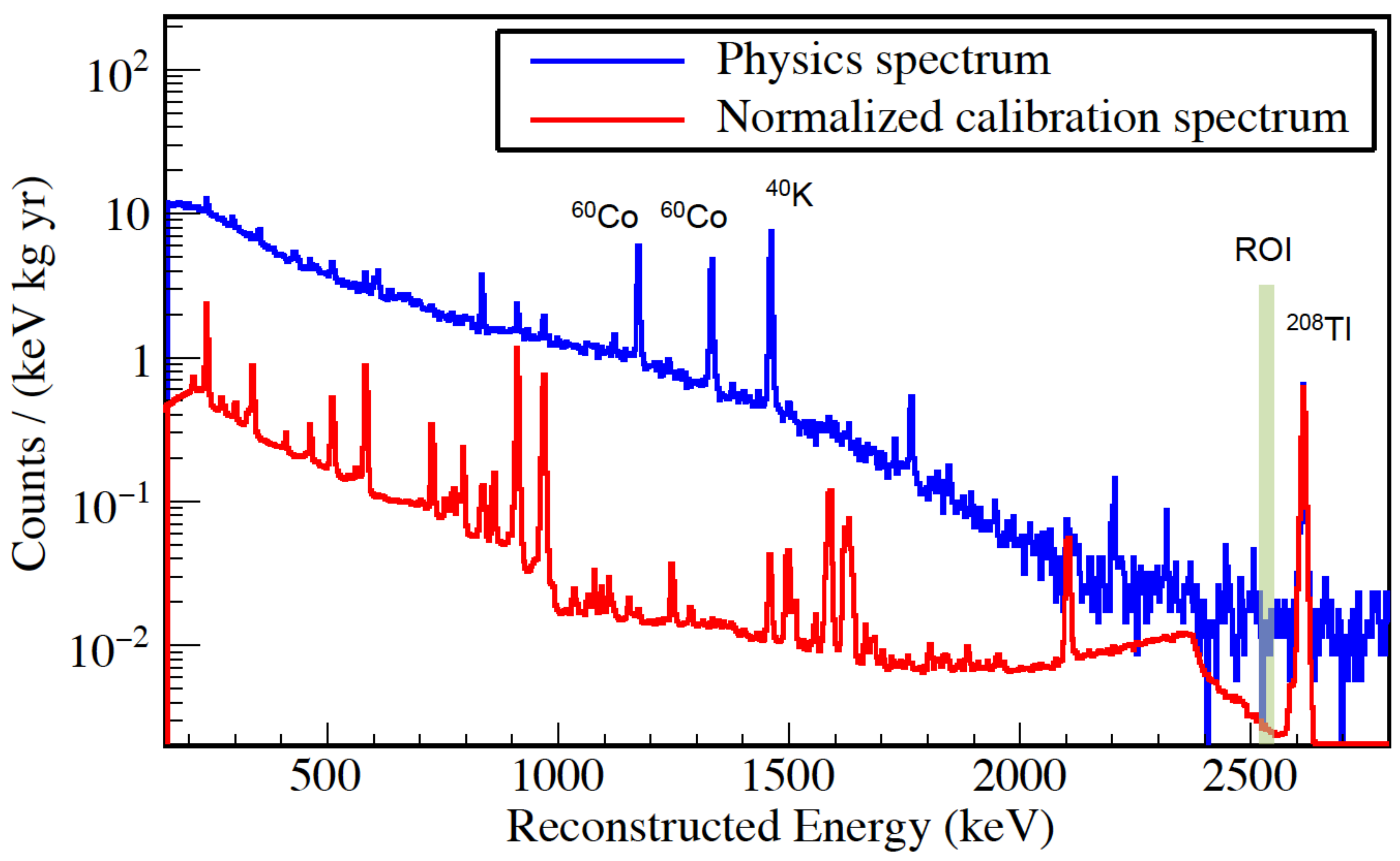
Region of interest	2465 to 2575 keV
Overall 0vBB signal efficiency, ds3518	(75.69 ± 3.02)%
Overall 0vBB signal efficiency, ds3021	(83.01 ± 2.56)%
Overall 0vBB signal efficiency, effective	(±)%
Resolution scaling at Q-value, ds3518	(91.5 ± 4.6)%
Resolution scaling at Q-value, ds3021	(100.0 ± 9.3)%
Events in the region of interest	155
Best fit for ^{60}Co mean	(2506.4 ± 1.2) keV
Best fit for ^{60}Co rate	(0.24 ± 0.09) c/(kg yr)
ROI background index, ds3518	$(1.49_{-0.17}^{+0.18}) \times 10^{-2}$ ckky
ROI background index, ds3021	$(1.35_{-0.18}^{+0.20}) \times 10^{-2}$ ckky
ROI background index, exposure weighted	$(1.4 \pm 0.2) \times 10^{-2}$ ckky
Median expected sensitivity	7.0×10^{24} yr (Bayesian)
	7.6×10^{24} yr (Rolke)
Best fit decay rate	$(-1.0_{-0.3}^{+0.4}$ (stat.) $\pm$ 0.1 (syst.)) $\times 10^{-25}$ / yr
Bayesian half-life limit (90% CL, including systematics)	1.3×10^{25} yr
Bayesian decay rate limit (90% CL, including systematics)	0.051×10^{-24} / yr
Bayesian half-life limit (90% CL, combination with Q0 + Qino)	1.5×10^{25} yr
Corresponding limit on $m_{\beta\beta}$	$m_{\beta\beta}$ < 110–520 meV
Rolke half-life limit (90% CL, including systematics)	2.1×10^{25} yr
Rolke decay rate limit (90% CL, including systematics)	0.033×10^{-24} / yr
Rolke half-life limit (90% CL, combination with Q0 + Qino)	2.2×10^{25} yr

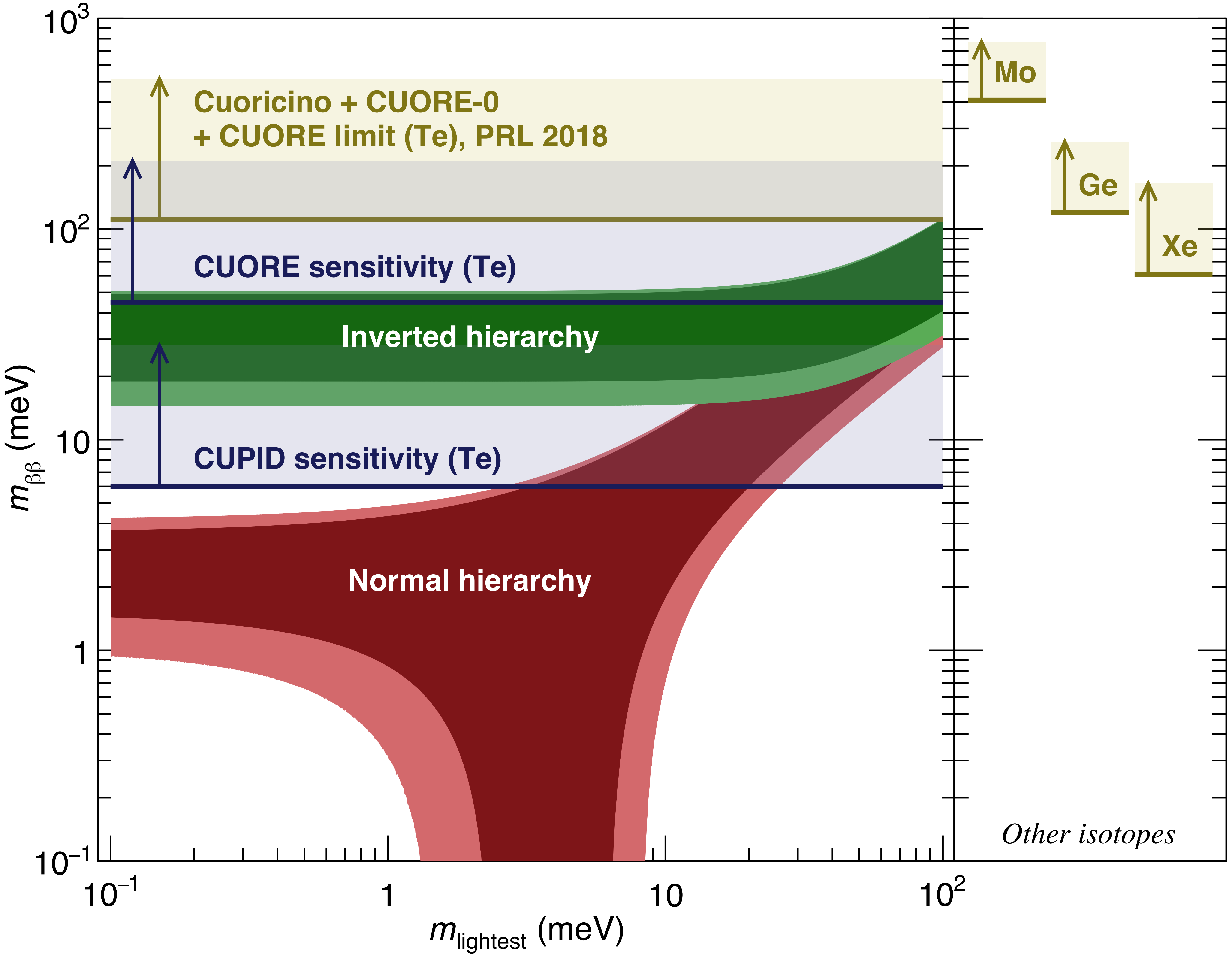
Cuts

	ds3518	ds3021
0vBB containment	(88.345 ± 0.085)%	(88.345 ± 0.085)%
Pulser detection	(99.7663± 0.0034)%	(99.7349 ± 0.0035)%
Pulser energy	(99.1677 ± 0.0064)%	(99.218 ± 0.006)%
Base cuts on pulser	(95.6288 ± 0.0088)%	(96.6907 ± 0.0084)%
Multiplicity	(99.4 ± 0.5)%	(100.0 ± 0.4)%
PSA	(91.1± 3.6)%	(98.2 ± 3.0)%
All cuts except containment	(85.67 ± 3.42)%	(93.96 ± 2.89)%

Towards CUPID

Phys. Rev. Lett. 120, 132501

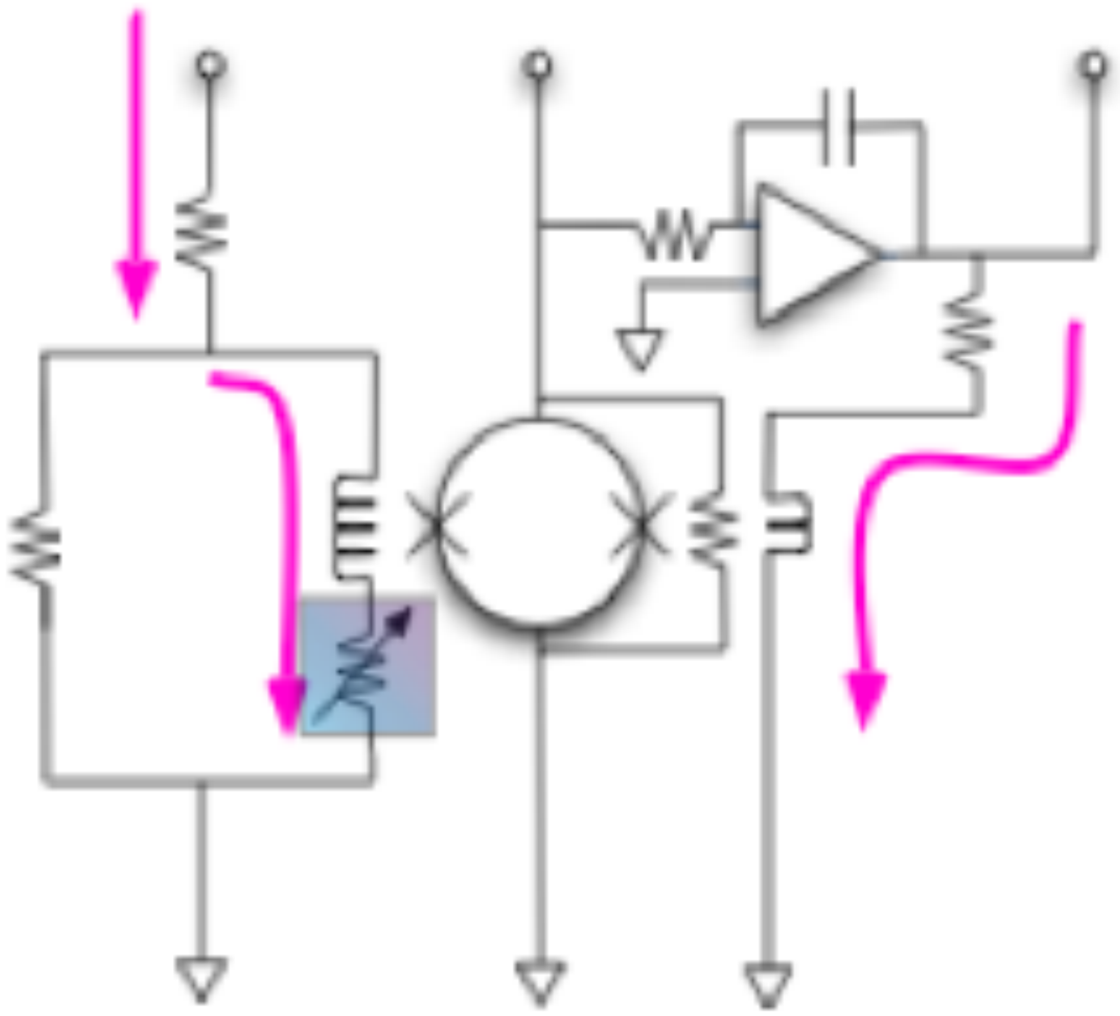


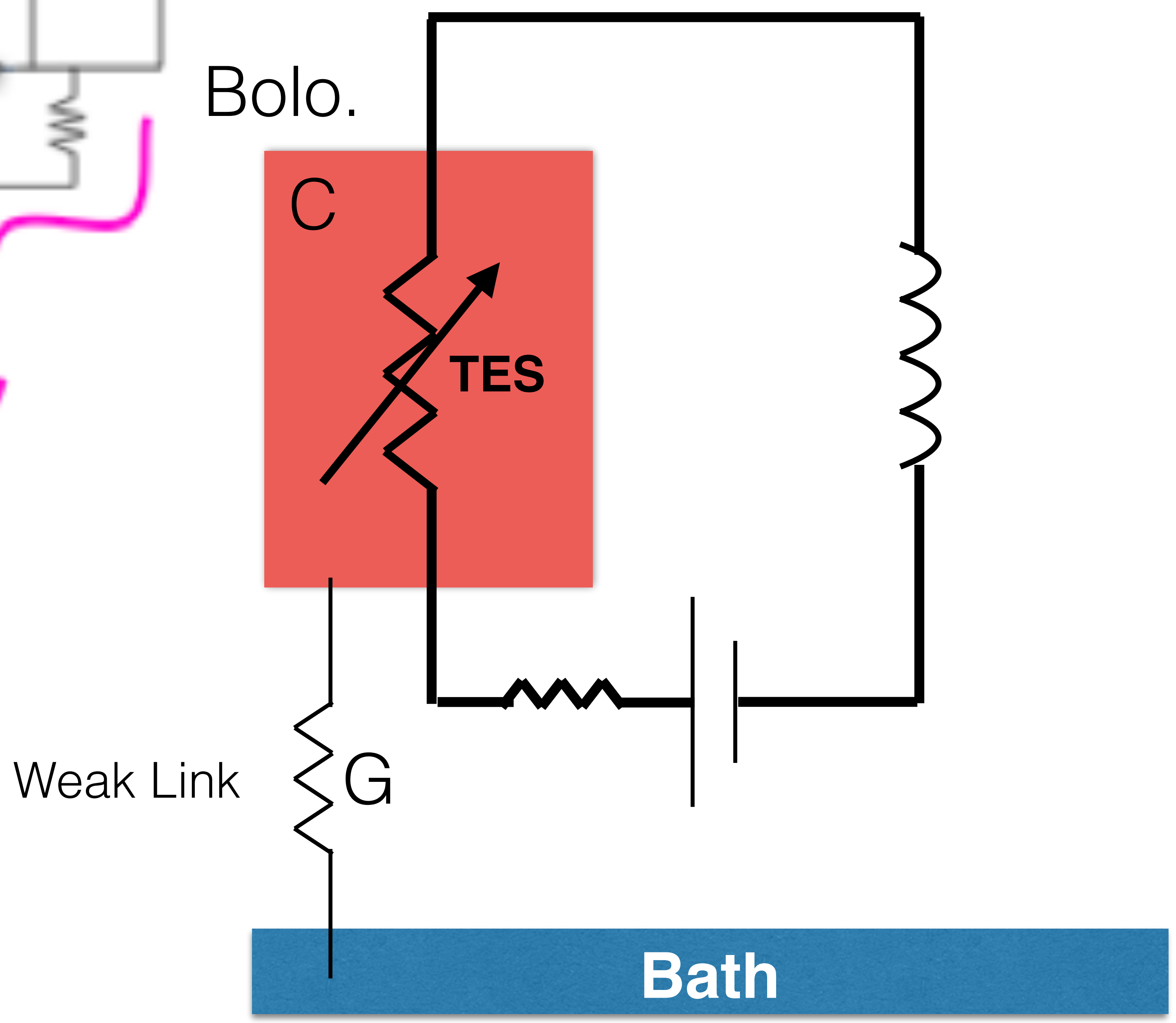


- Existing experiments do not yet rule out IH
- Next generation will try to probe IH region
- Degraded α's are a problem

TES Benefits

$$\alpha = \frac{T}{R}\frac{\partial R}{\partial T} \qquad \beta = \frac{I}{R}\frac{\partial R}{\partial I} \qquad L_0 = \frac{\alpha}{n}\left(1 - \left(\frac{T_b}{T_0}\right)^n\right)$$





- Self-biasing (ETF)
- Fast response

$$\tau = \frac{C}{G} \xrightarrow{\text{ETF}} \tau_{eff} = \frac{C}{G\,(1 + L_0)}$$

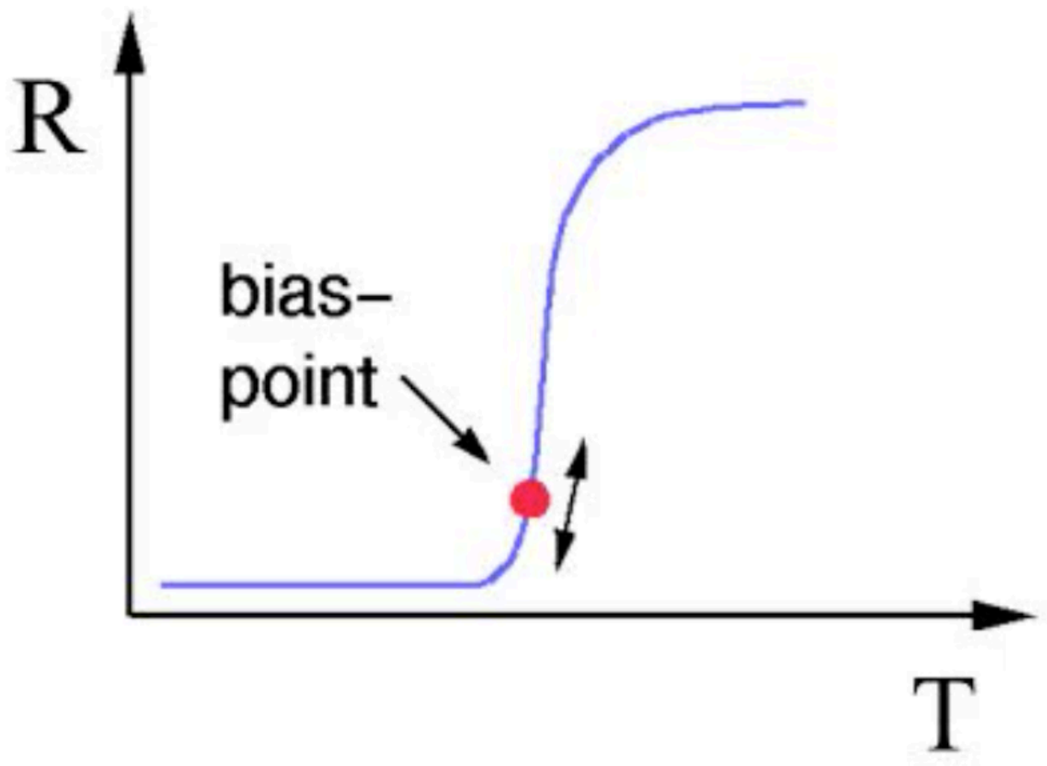
- Linear response

$$\delta R = \alpha \frac{R}{T}\delta T + \beta \frac{R}{I}\delta I$$

- Good energy resolution

$$\Delta E_{FWHM} \approx \sqrt{\frac{4k_B T^2 C_{tot}}{\alpha}\sqrt{\frac{n\,(1 + 2\beta)}{2}}}$$

- Low intrinsic noise

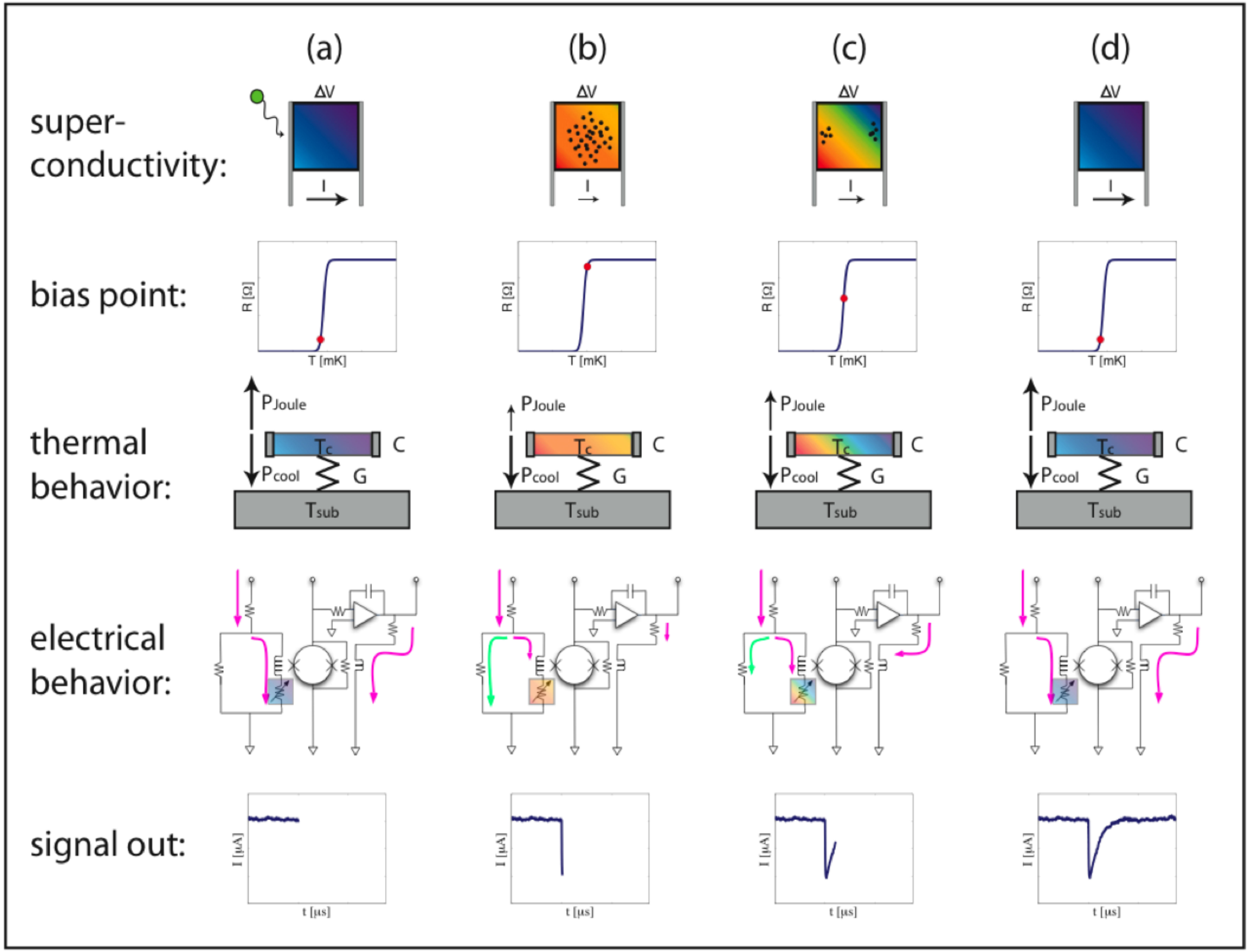


$$C_{tot} \approx C_{bolo}(T^3) + C_{TES}(T) + C_{impur}$$

K. D. Irwin and G. C. Hilton, Topics Appl. Phys. 99, 63-149 (2005)

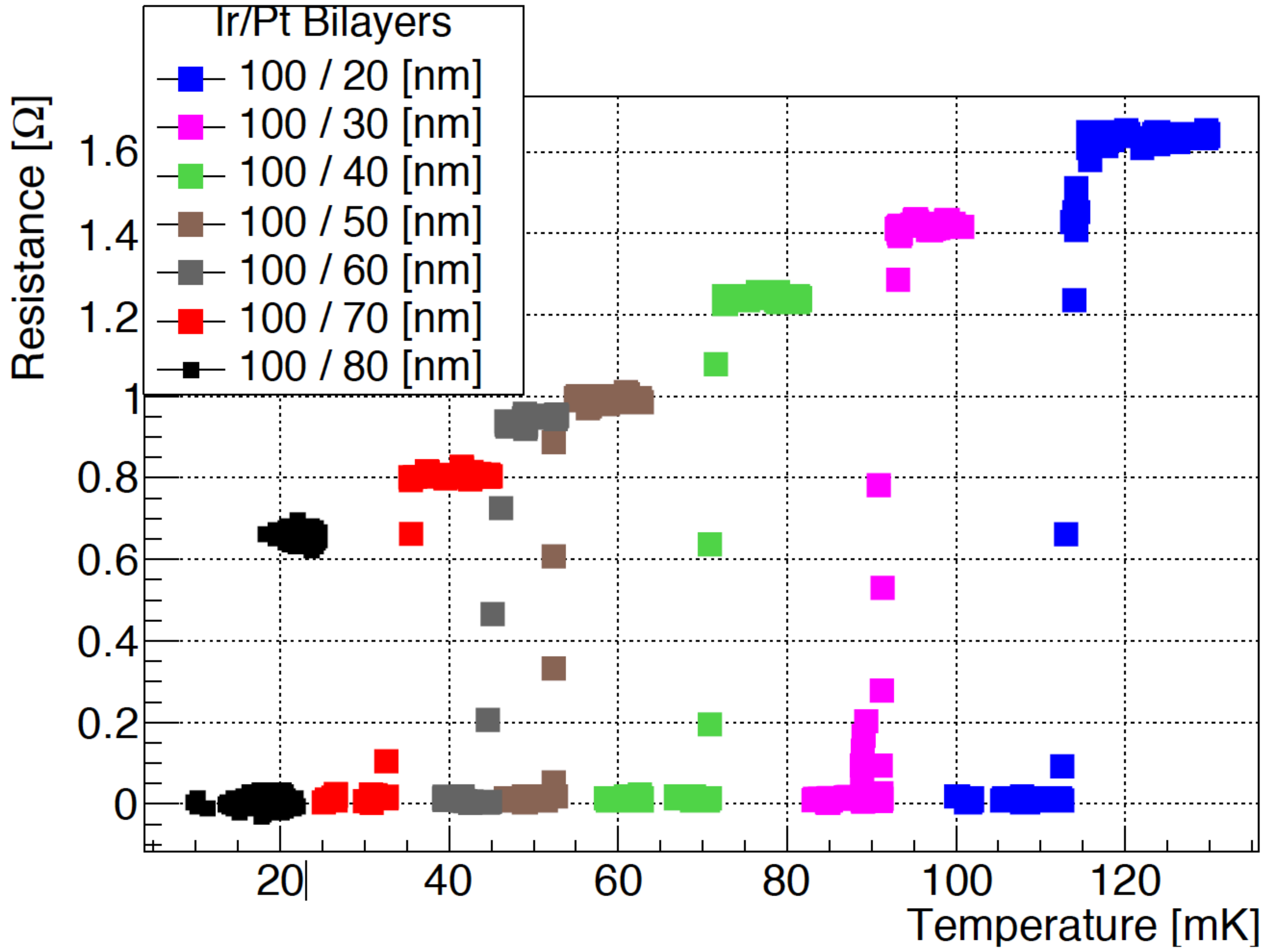
Transition Edge Sensor (TES)

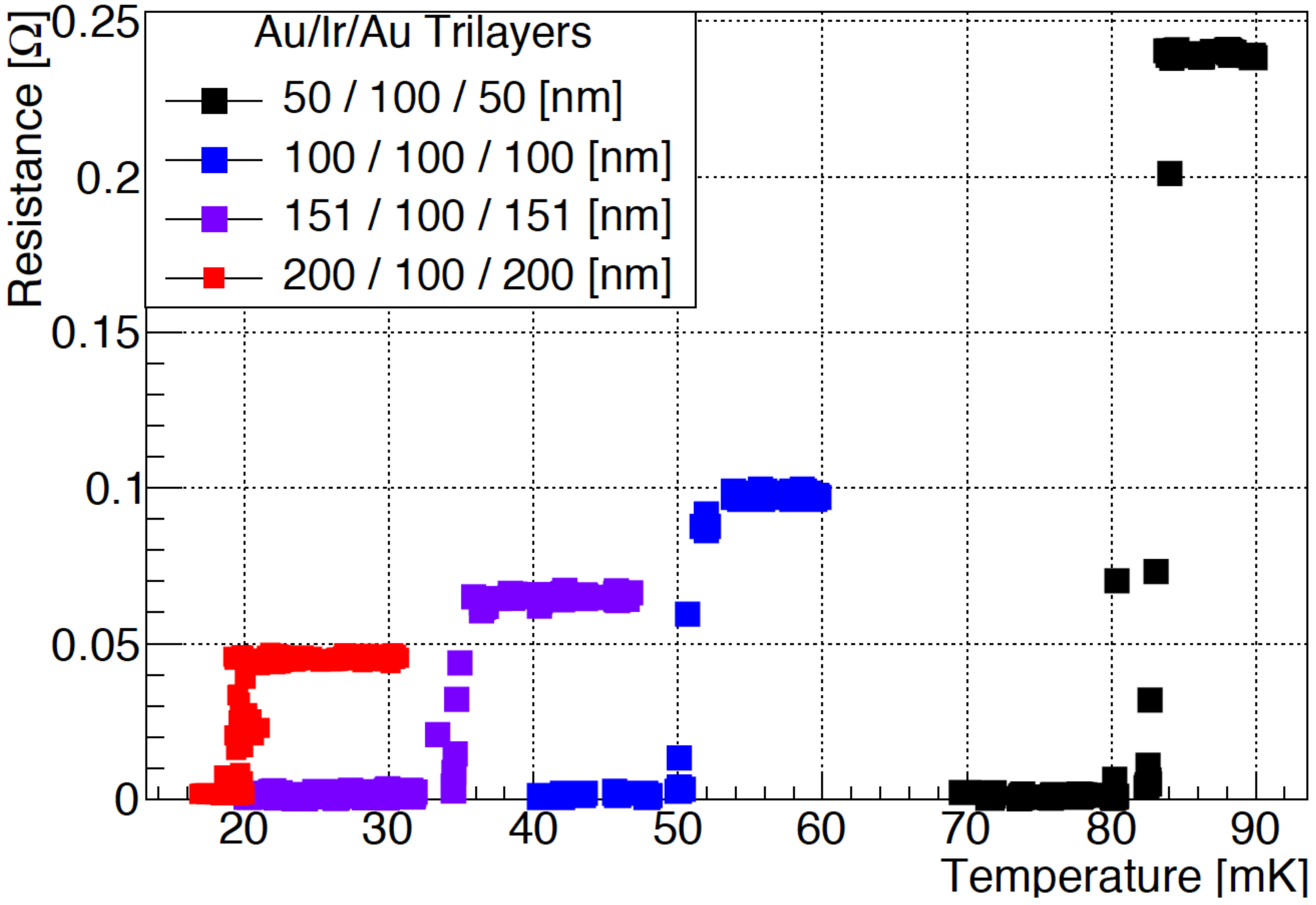
- Superconducting device (resistor)
- Voltage biased
- Electrothermal feedback (negative)
- SQUID readout and amplification



TES

- Ir/Pt bilayer Tc controlled by thickness of Pt layer
- Demonstrated Tc from 20mK to 110 mK
- Ir/Pt has larger normal resistance
- 4-wire measurement at multiple T
  - 3.16 μA excitation current



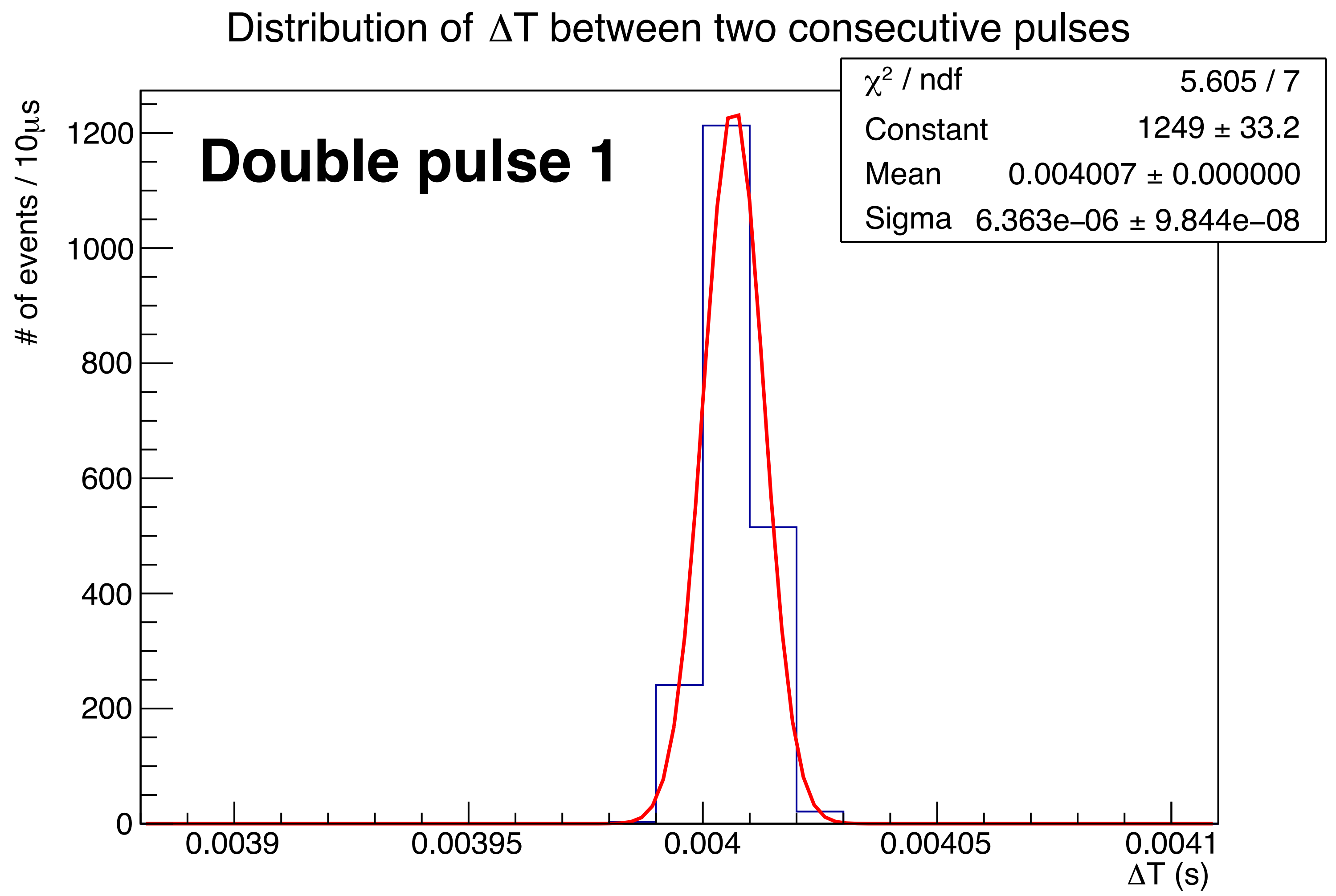


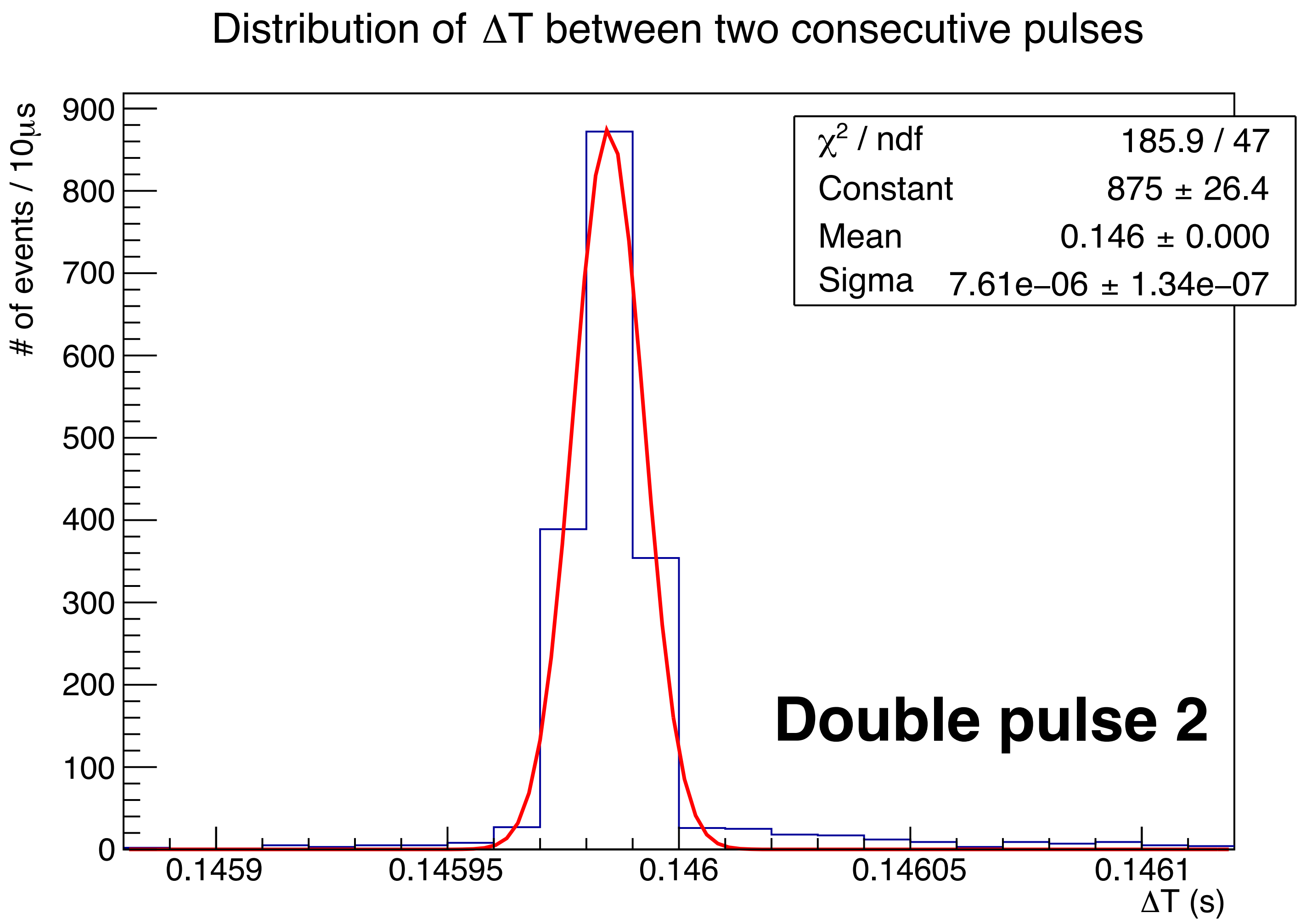
$$R = R_N \frac{e^{AT+B}}{1+e^{AT+B}} + R_{para}$$

$$T_c = -\frac{B}{A}$$

arXiv:1711.03648

Light Detector





- Pulse parameters:
  - 4 ms between each pulse
  - 145 ms between pairs
- Timing resolution $\sigma_t \sim 5\ \mu s$