CUPID: The next generation upgrade of CUORE to search for $0\nu\beta\beta$ decay

TeVPA 2024
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on behalf of the CUPID Collaboration
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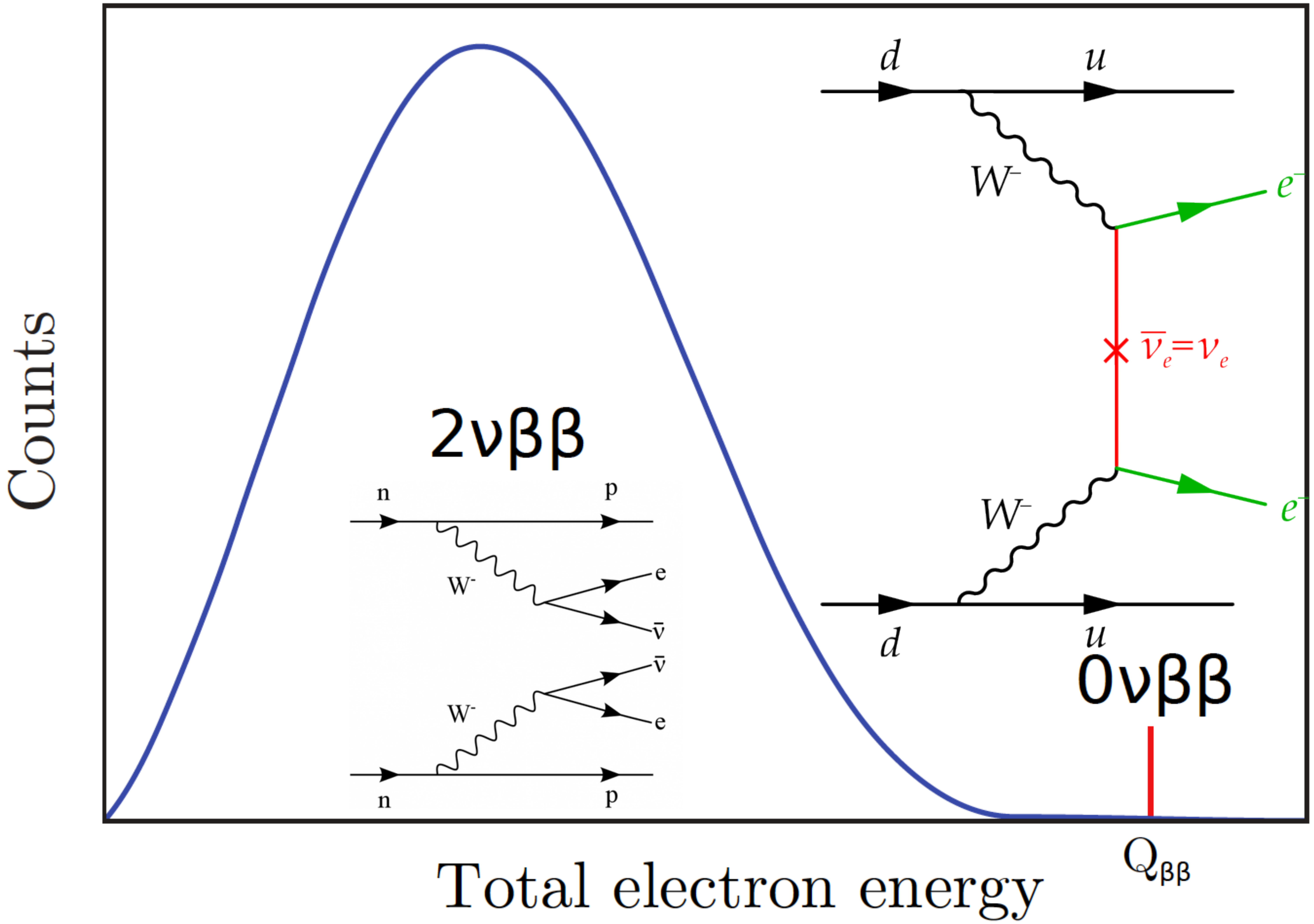
Neutrinoless Double Beta Decay

- 2νββ is a rare standard model process predicted in 1935 by Maria Goeppert-Mayer
- Broad energy distribution
- Observed half-life τ > 10^{19} years
- Even-even nuclei
- 35 known isotopes
- 0νββ is a hypothetical decay mode if the neutrino is a Majorana fermion
- ΔL=2 => lepton number violation!
- New physics!
- Leptogensis: matter/anti-matter asymmetry
- Constraints on ν mass hierarchy



Experimental Searches

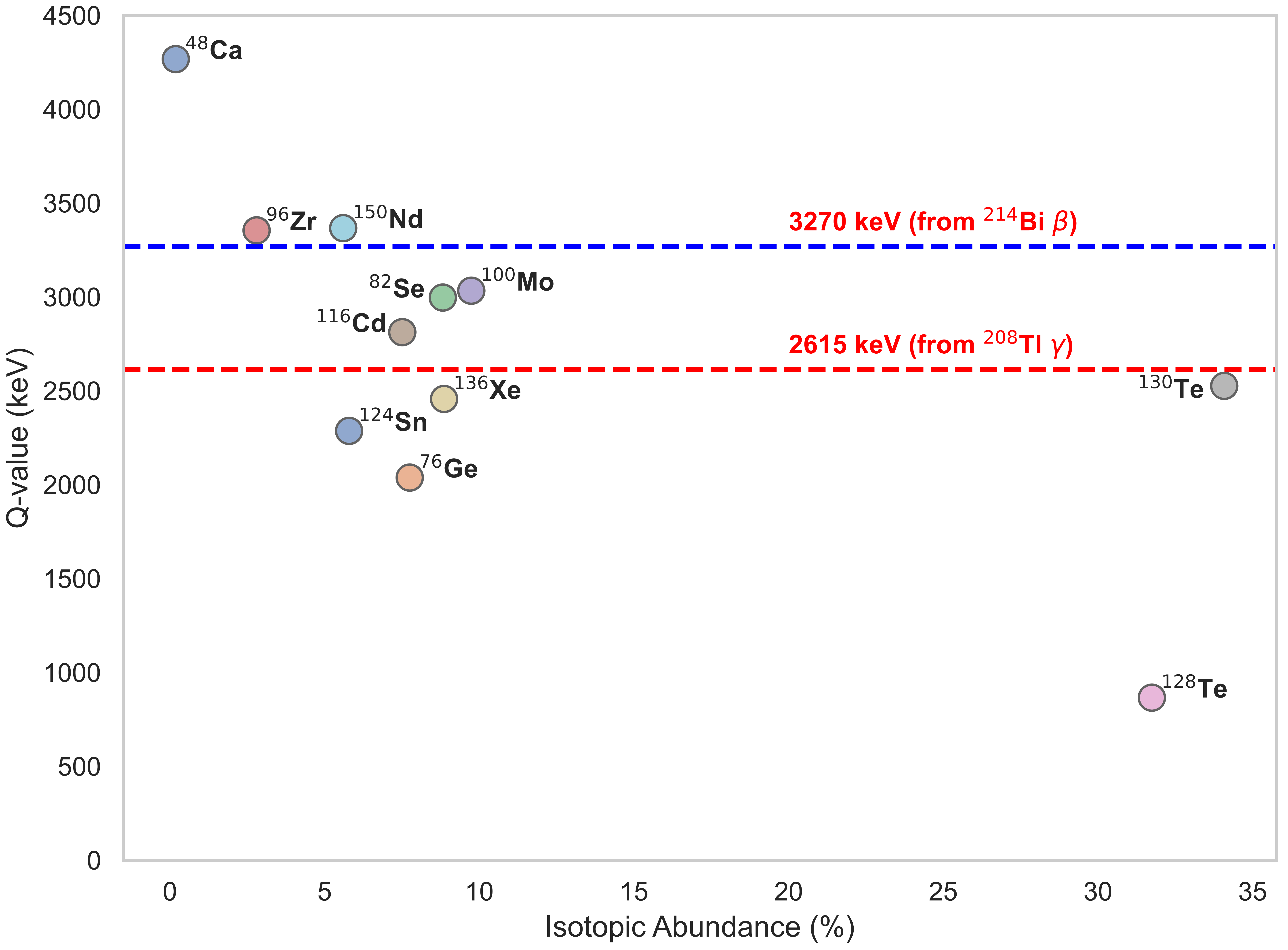
Background Limited

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

Background Free

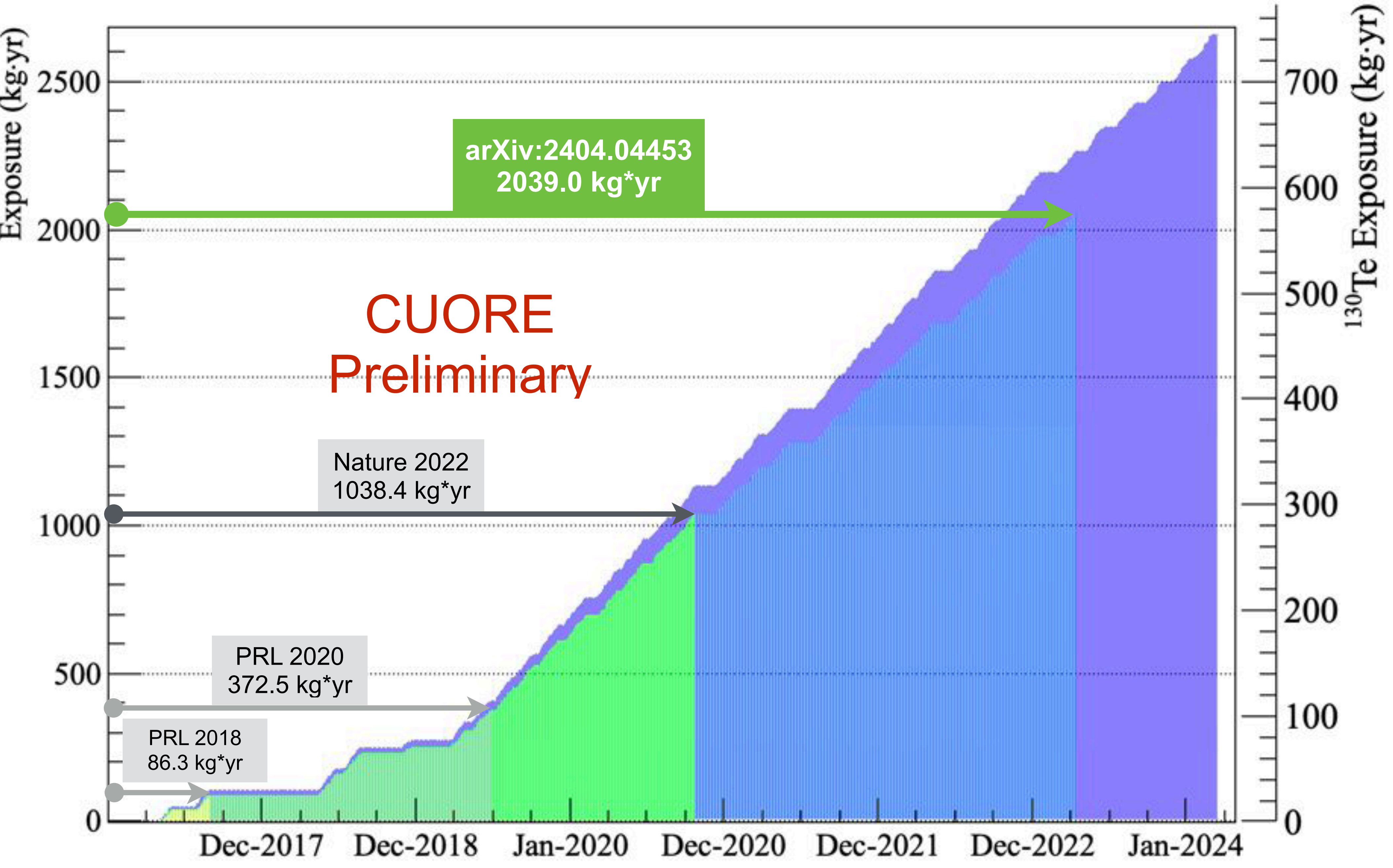
$$S \propto \frac{N_A a \eta \epsilon}{M_{mol}} MT$$

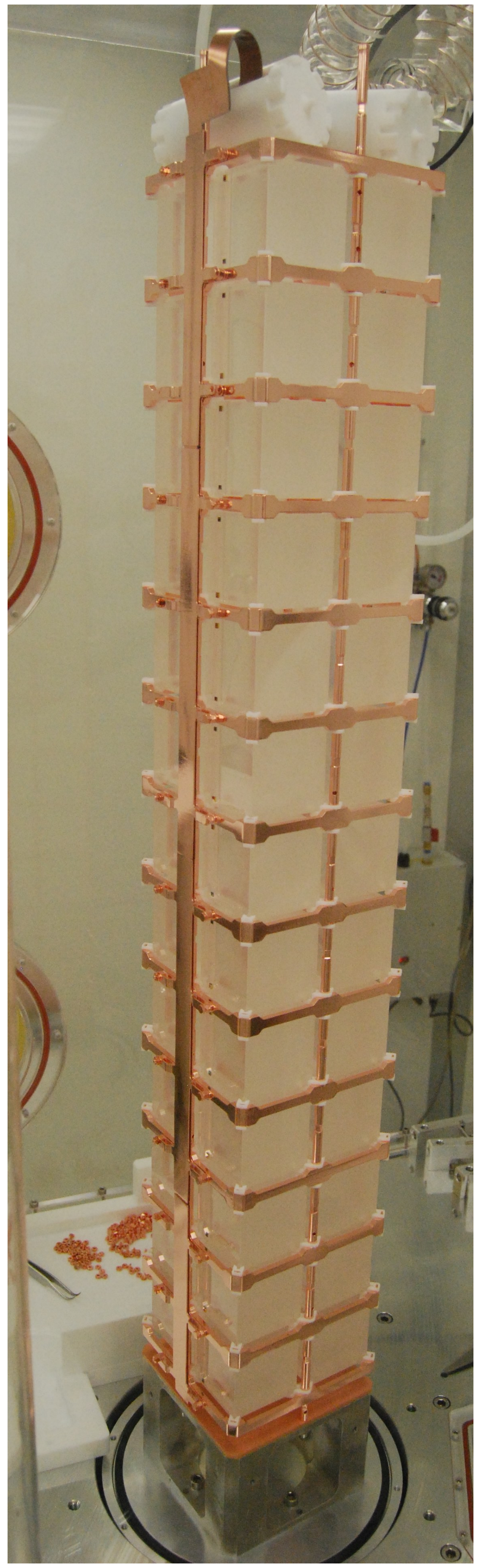
- Isotope choice important
- Background due to radioactive contaminants
- Energy resolution
- Exposure (MT)
- Detection efficiency



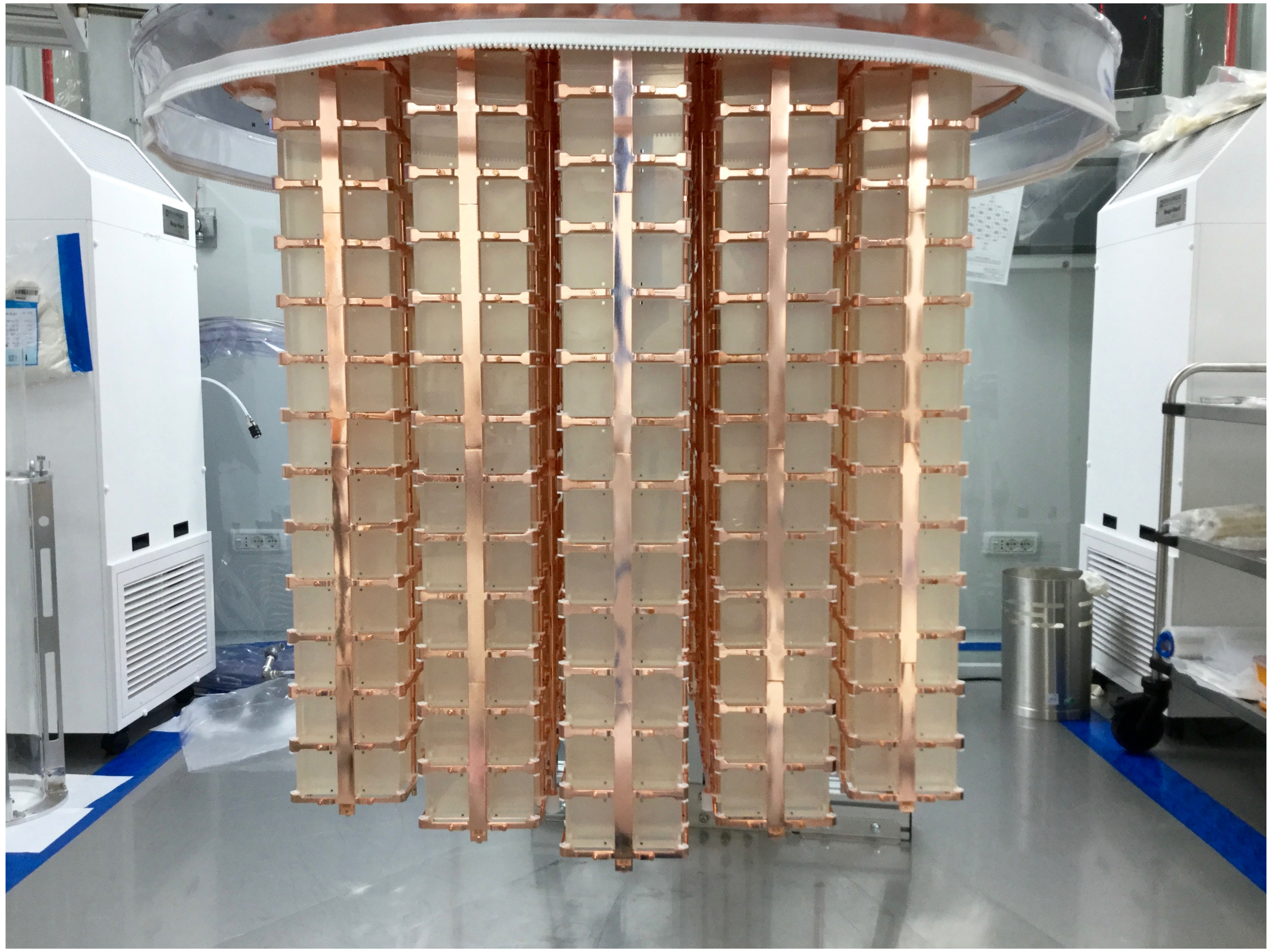
CUORE

- Array of 988 5x5x5 cm^3 $^{nat}TeO_2$ crystals (742 kg)
- ^{130}Te active isotope (206 kg)
- $Q_{\beta\beta}$ ~ 2527.52 keV
- Source = detector
- $0\nu\beta\beta$ containment ε ~ 88%
- 984 active channels!





CUORE Tower



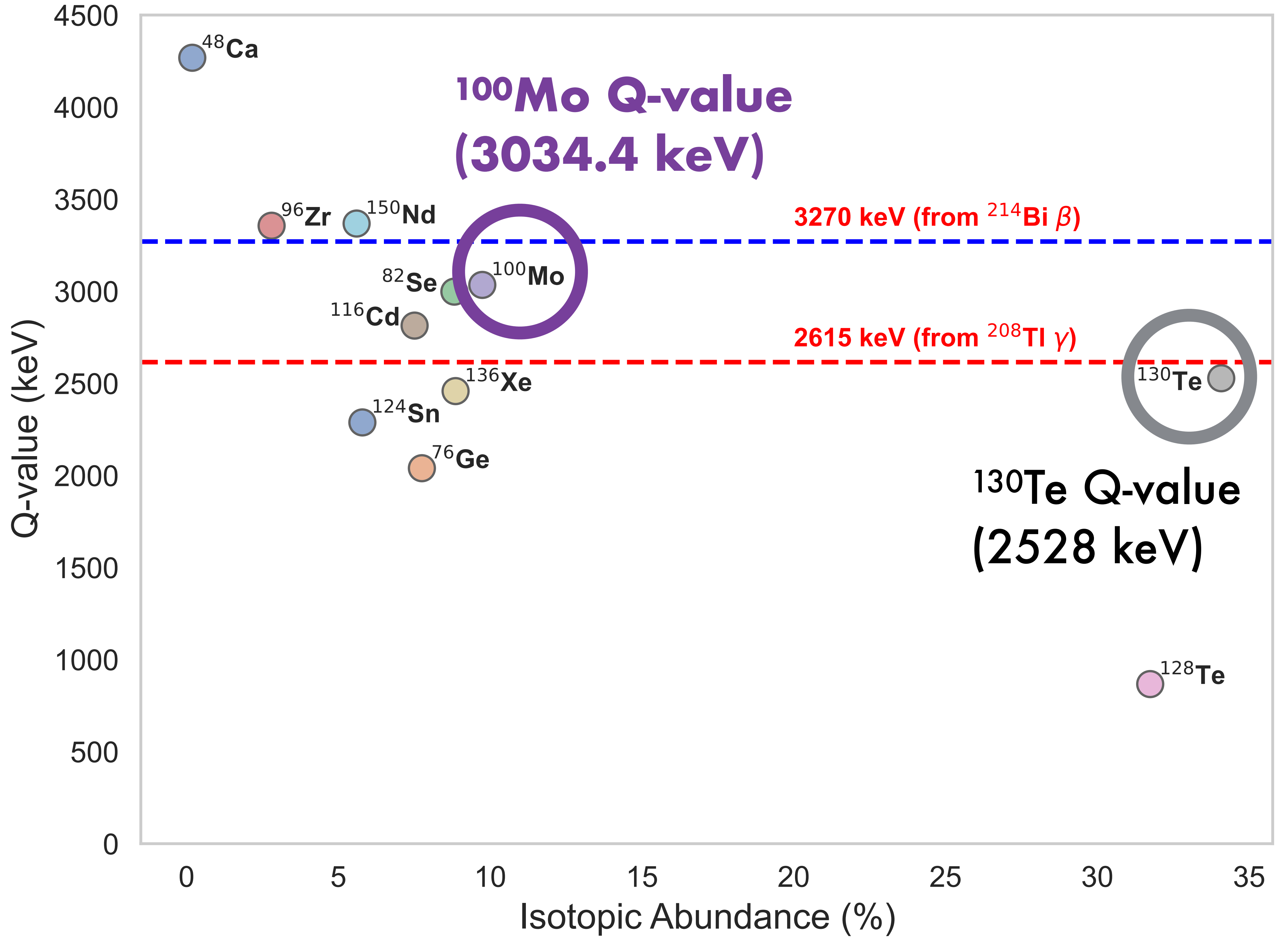
CUORE Detector Fully Assembled

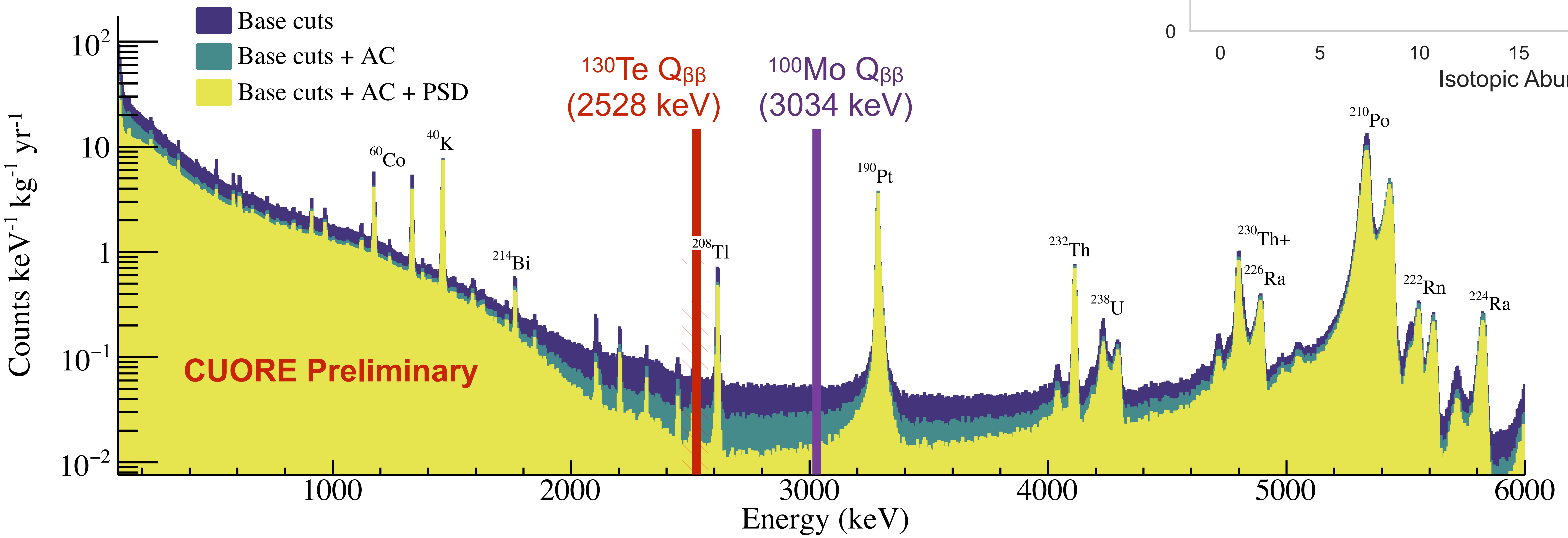
19 towers, 13 floors, 4 per floor

Median Exclusion Sensitivity: 4.4×10^{25} yr
(66.6% chance of more stringent limit)
$m_{\beta\beta} < [70 - 240]$ meV (depending on NME)
Average BI: $(1.42 \pm 0.02) \times 10^{-2}$ cts/keV/kg/yr

CUORE => CUPID

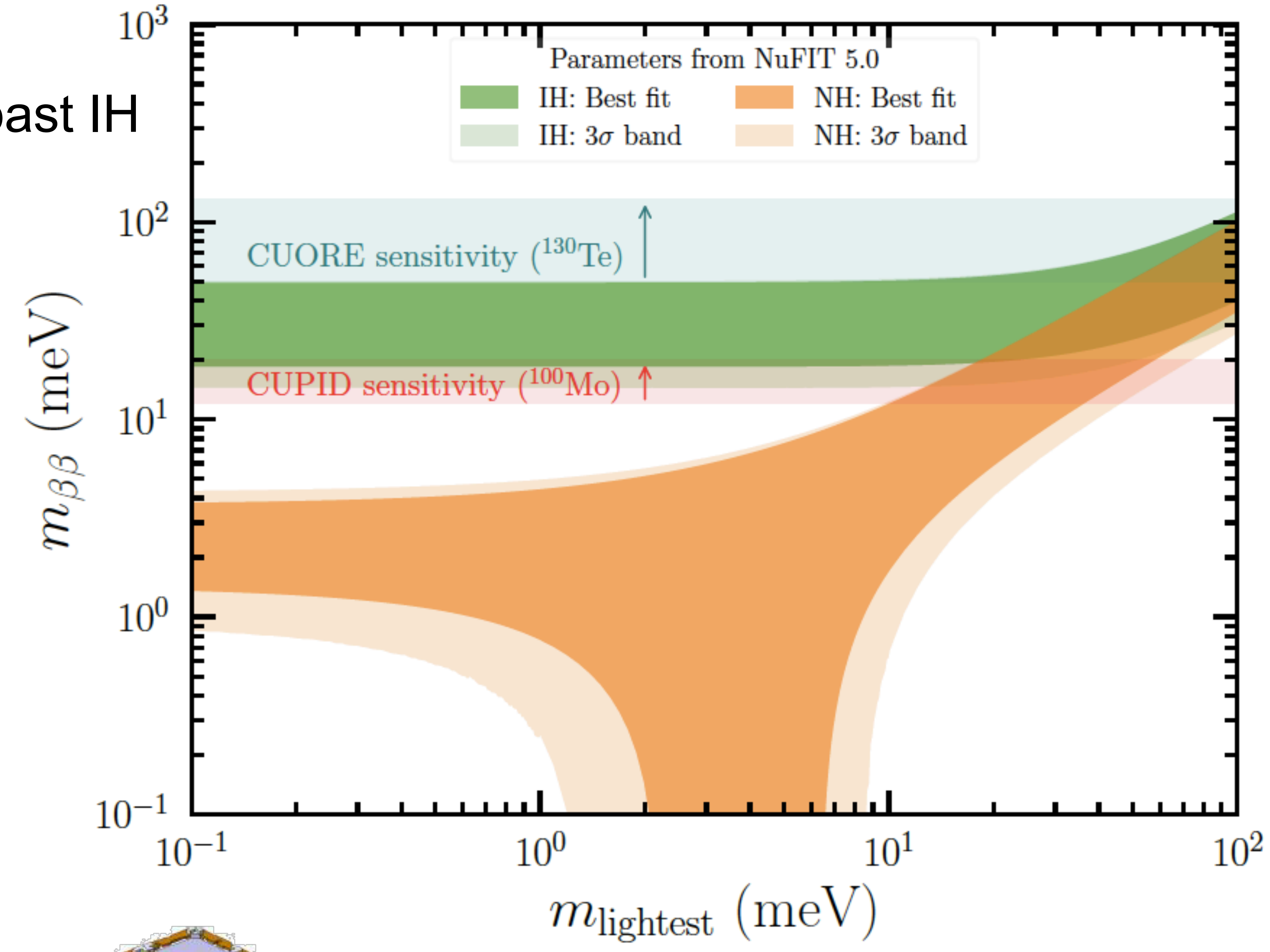
- CUORE uses ^{130}Te (Q-value 2527.515 keV)
- Results published so far
  Phys. Rev. Lett. 120, 132501
  Phys. Rev. Lett. 124, 122501
  Nature 604, 53–58 (2022) (1 Ton-yr)
  arXiv: 2404.04453 (2 ton-yr)
- **Degraded α's pose problem**
- **C**UORE **U**pgrade with **P**article **ID** (CUPID)
- Use scintillating calorimeters => $Li_2{}^{100}MoO_4$ (LMO)

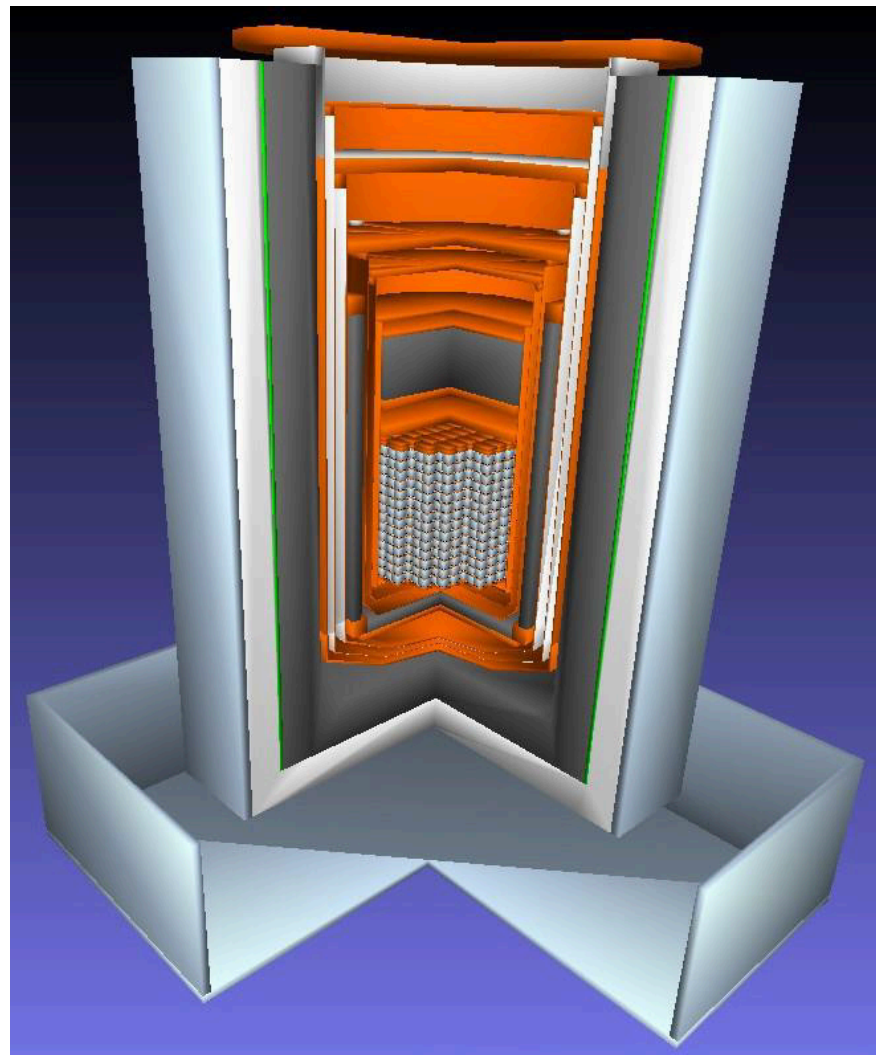




CUPID

Aim to explore past IH

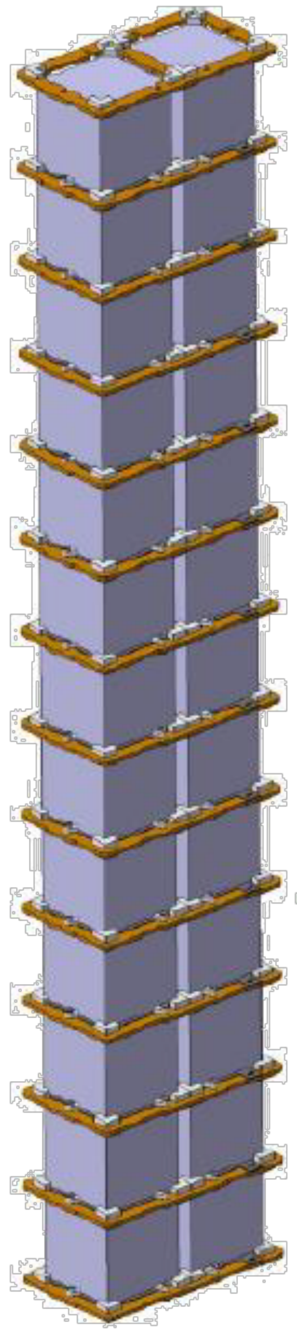


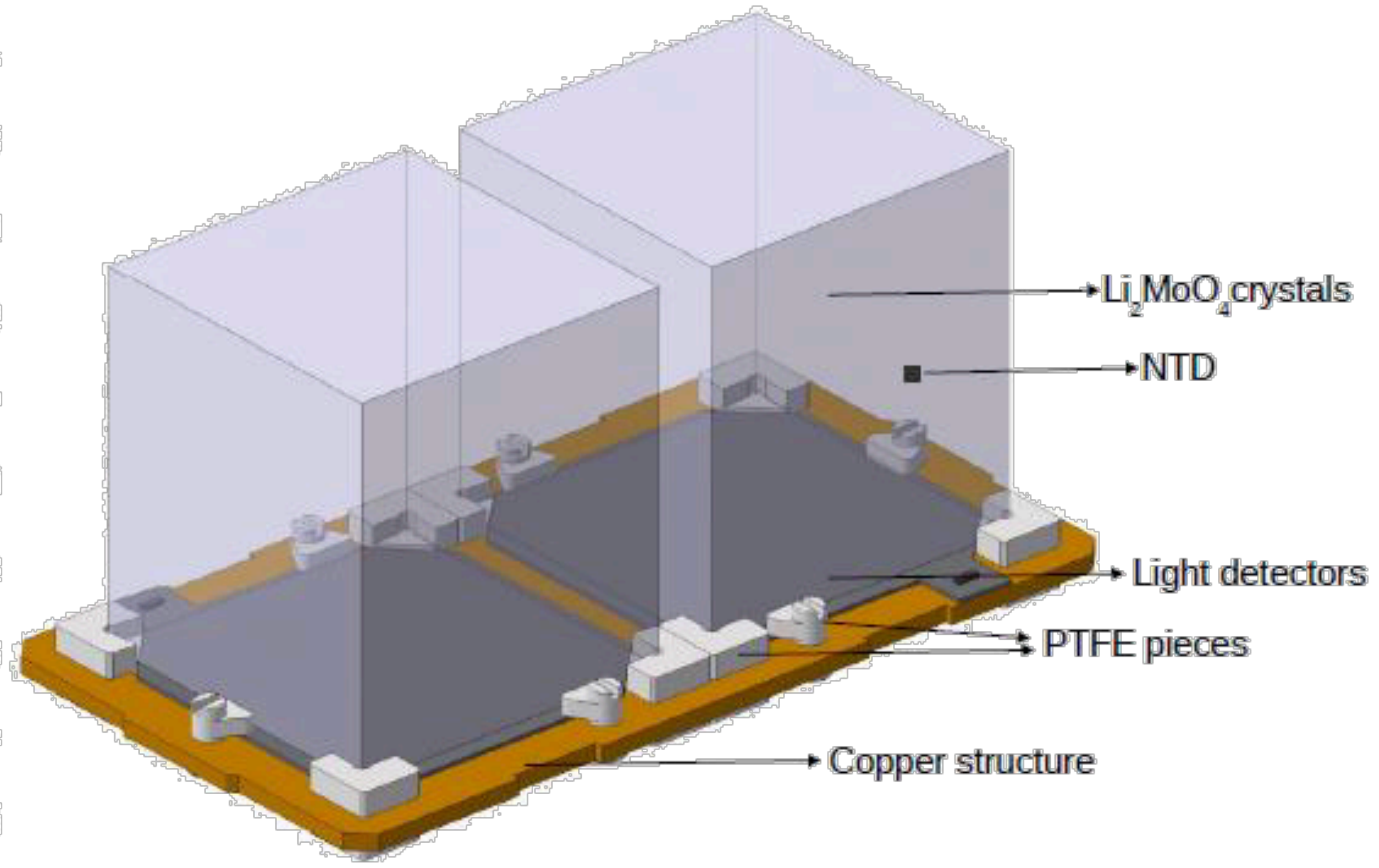


- CUPID: CUORE **Upgrade** with **Particle ID**
- ^{100}Mo enriched Li_2MoO_4 crystals
- Builds off successful demonstration of CUPID-Mo + experience of CUORE
- Scintillating calorimeters using NTD-Ge thermistors
- Meant to fully probe the inverted hierarchy region

CUPID Numbers

- ✦ 45x45x45 mm^3 cubic crystals ~ 280 g
- ✦ Each facing 2 Ge LD
- ✦ 1596 LMO crystals total (95% enrichment)
- ✦ 1710 Ge LDs
- ✦ δE $Q_{\beta\beta}$: ≤ 5 keV FWHM
- ✦ LD baseline resolution: 100 eV RMS
- ✦ LD timing resolution: < 170 μs
- ✦ Background Index: < 10^{-4} cts/keV/kg/yr
- ✦ Half-life exclusion sensitivity: 1.4×10^{27} yr

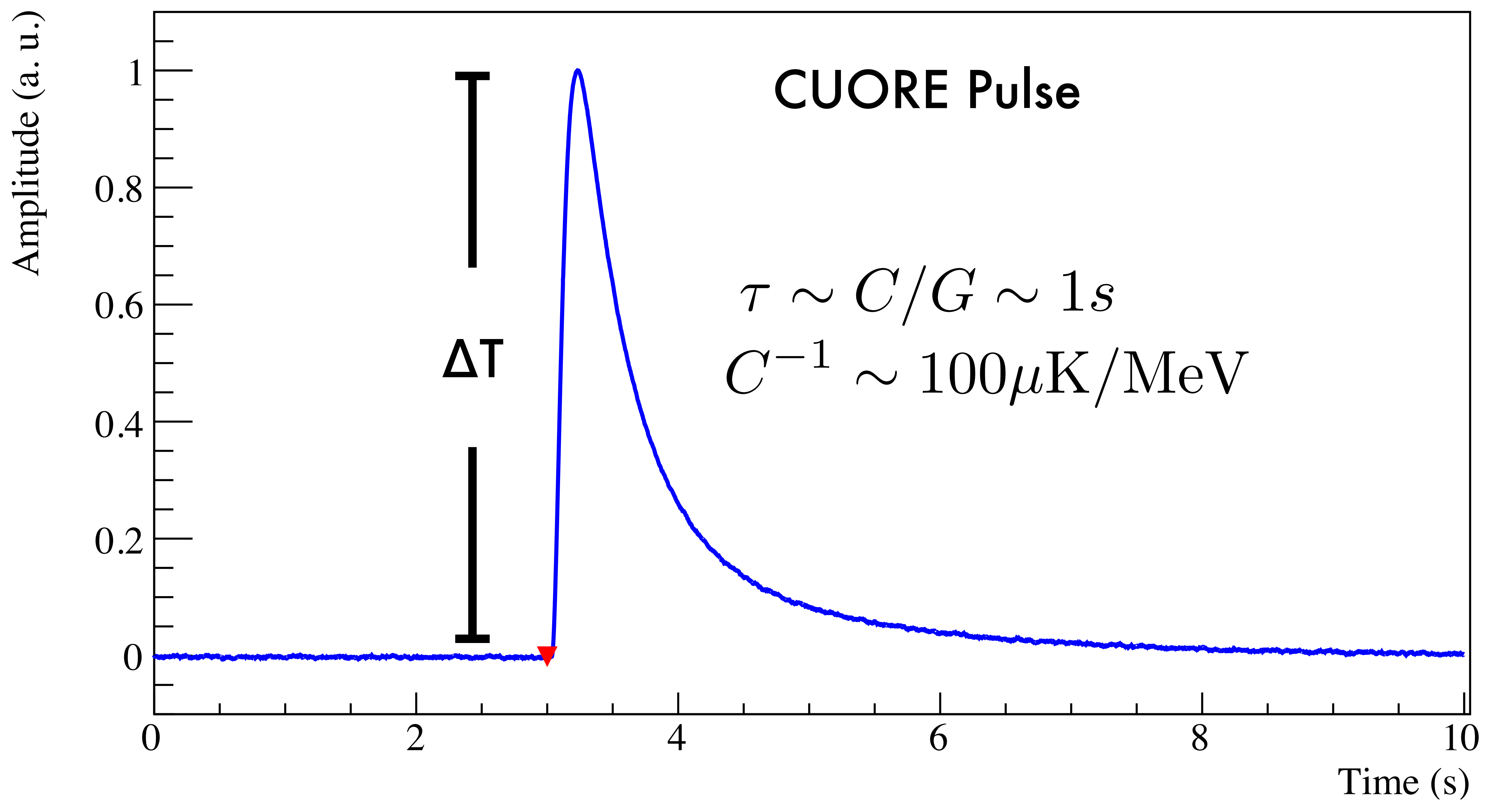


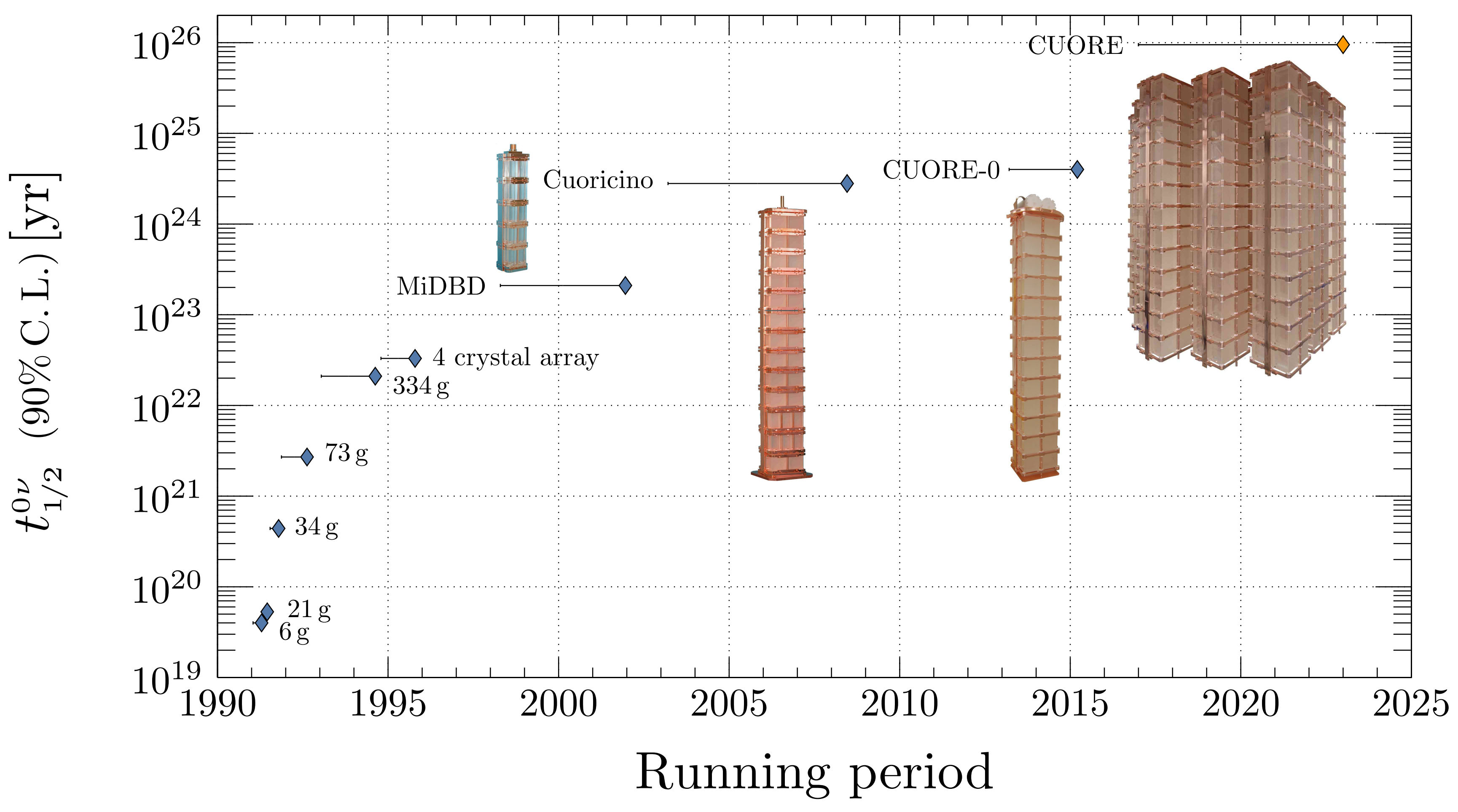


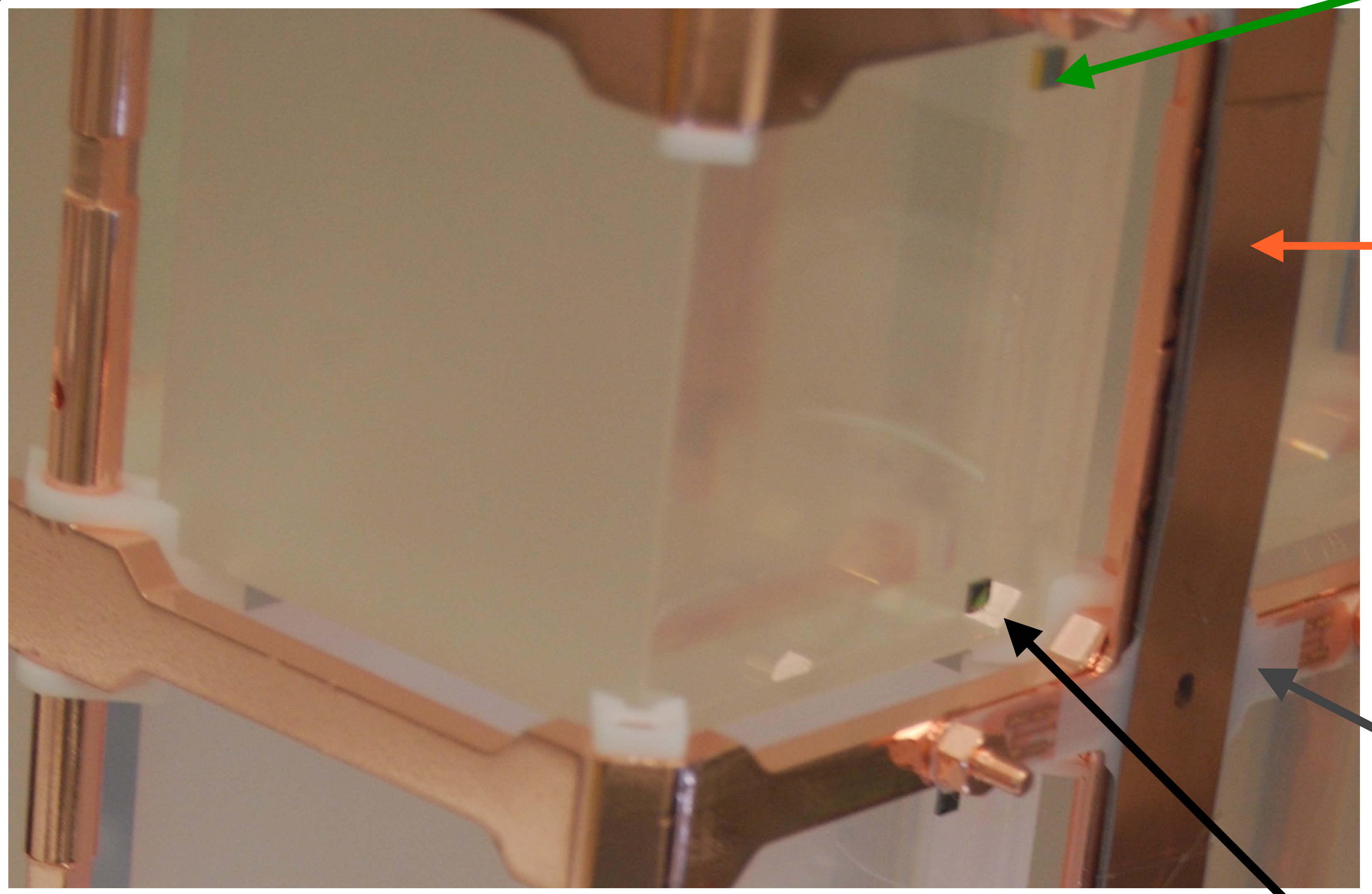
CUPID pre-CDR: arXiv:1907.09376

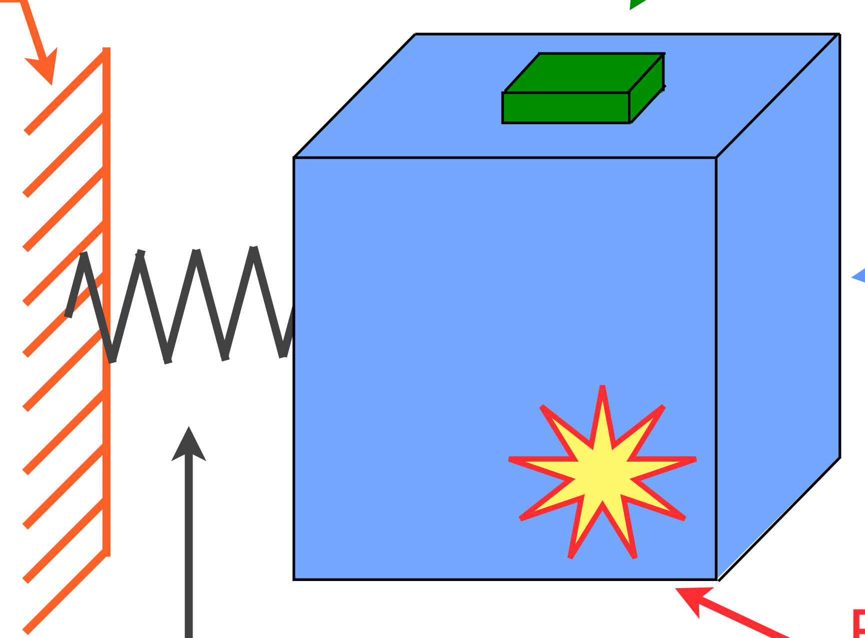
Calorimetric Sensors

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



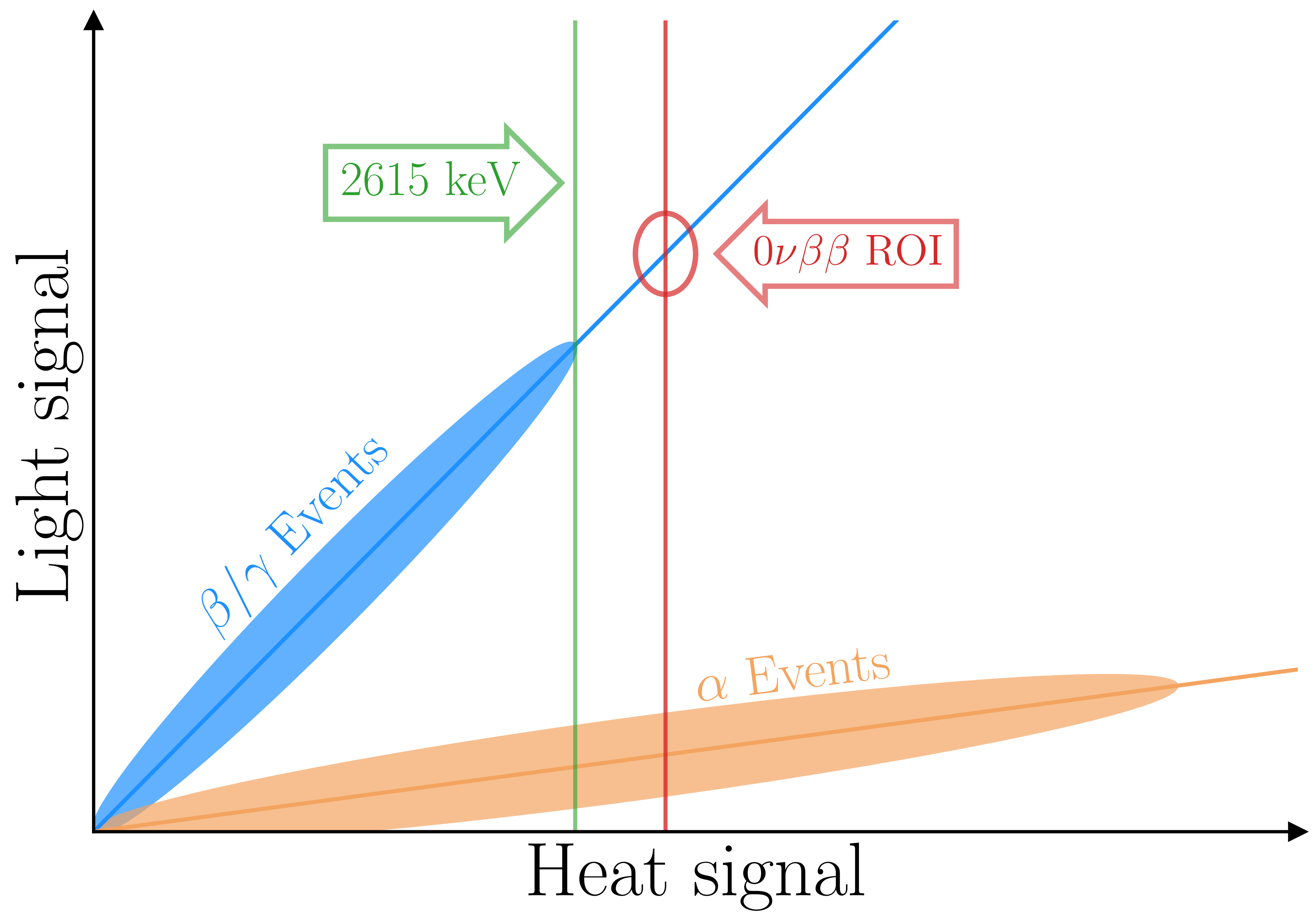


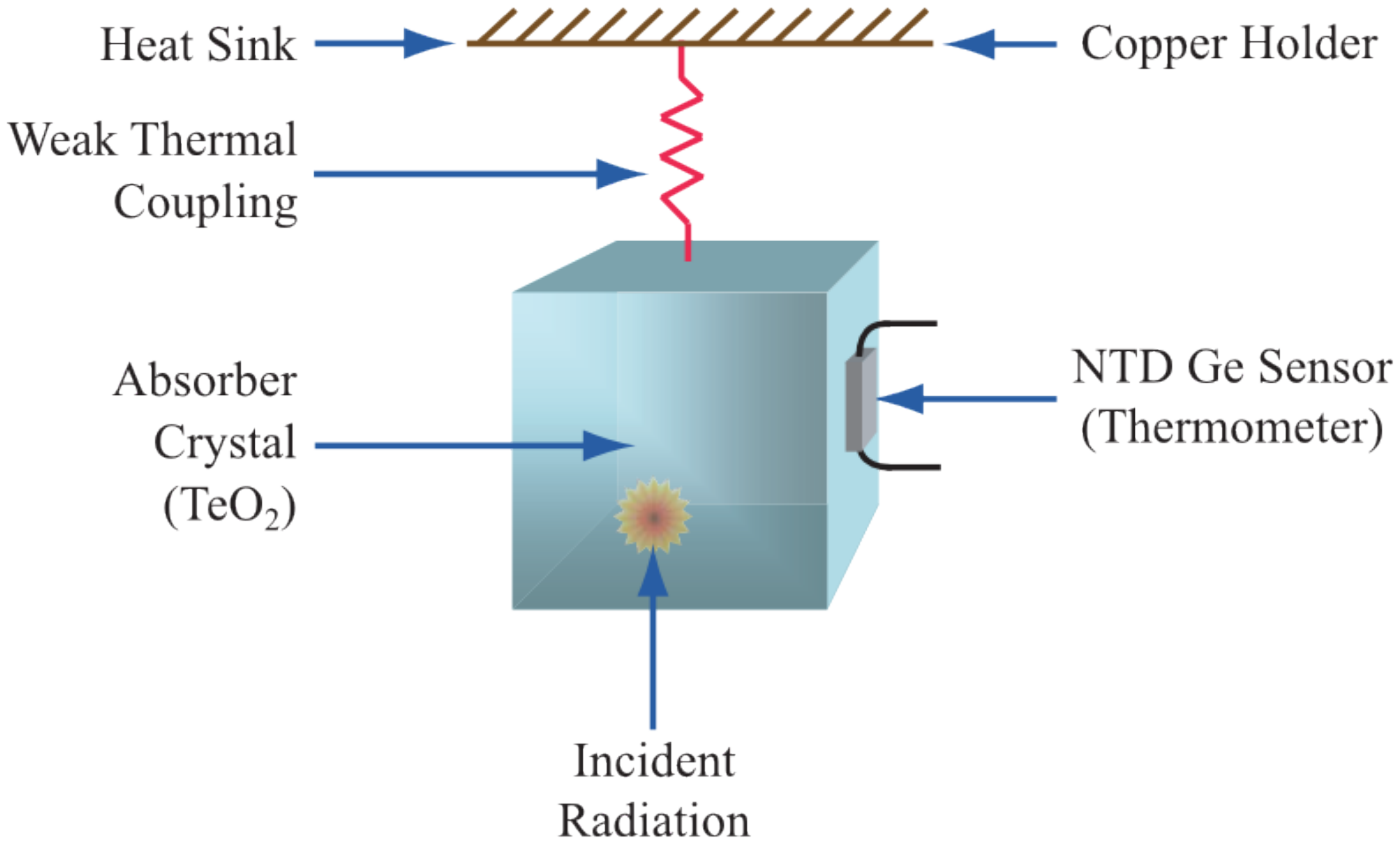




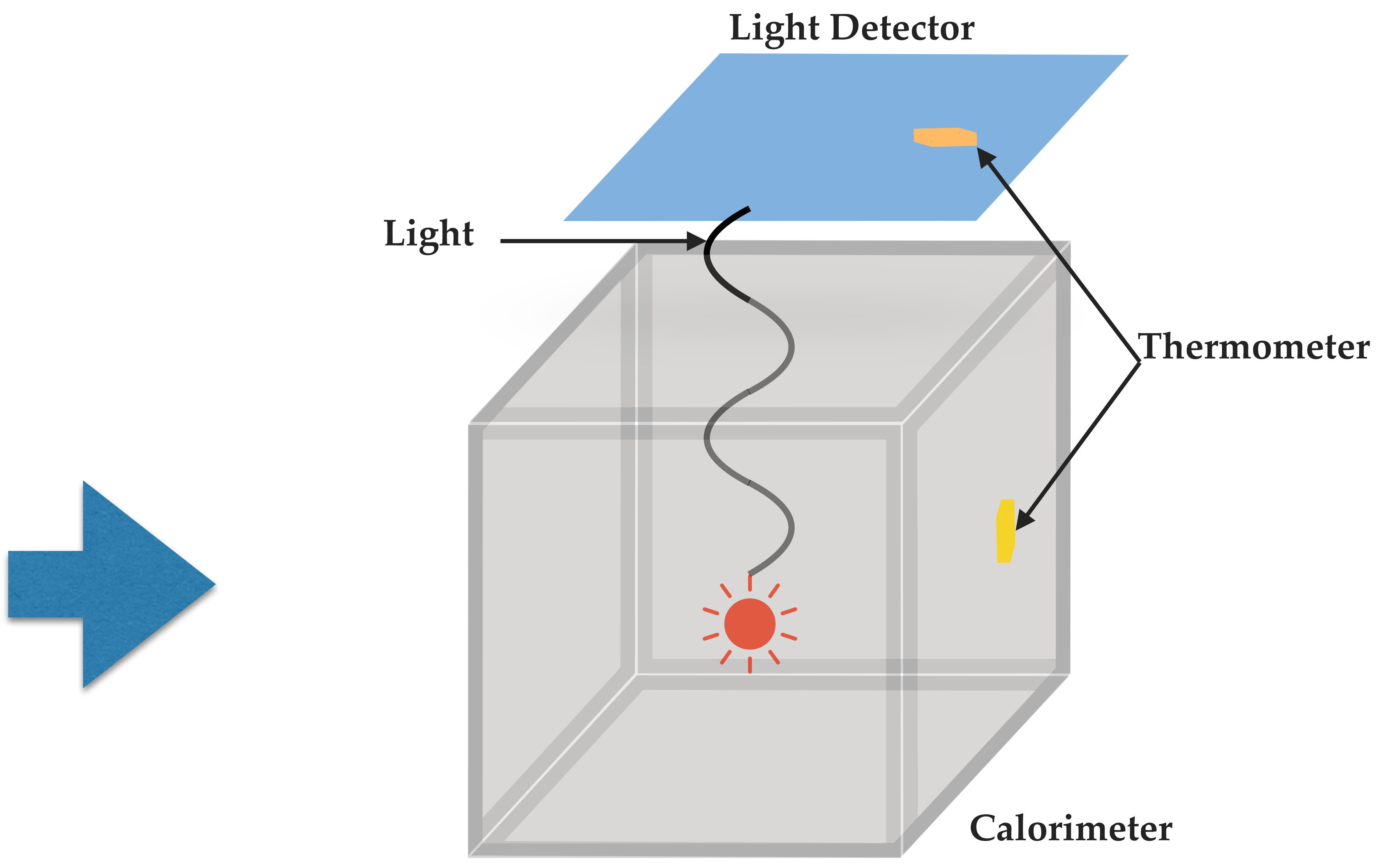
Scintillating Calorimeters

- Higher Q-value puts us in a lower background region
- LMO emits scintillation light - dual readout
- To mitigate degraded α's collect both heat and light
- 5x lower light yield from α events compared to β/γ





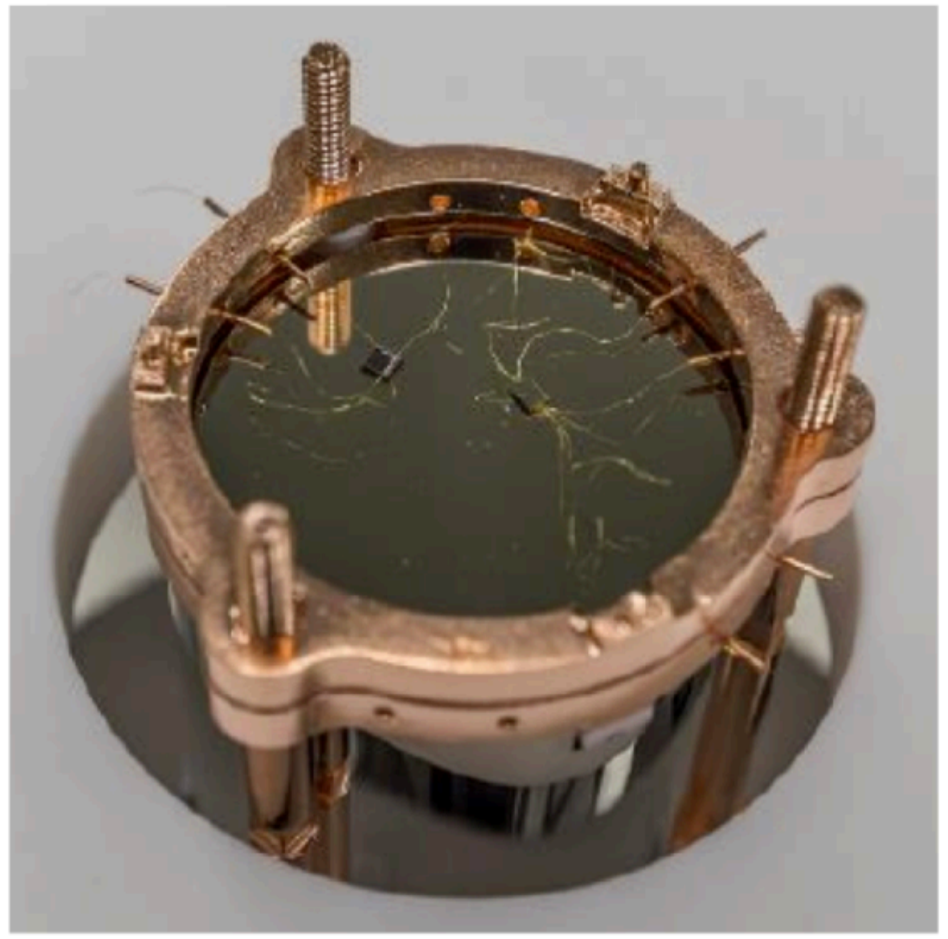
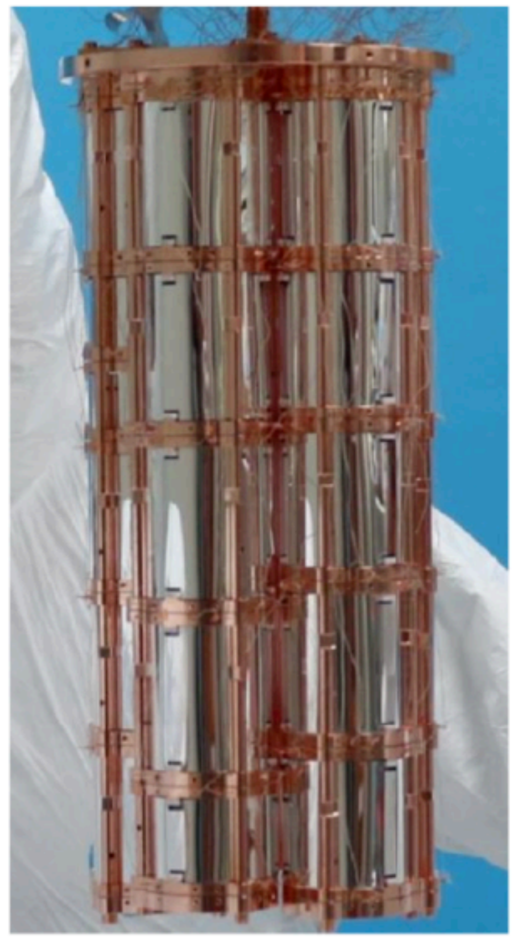
CUORE style detector



CUPID style detector

Demonstrators

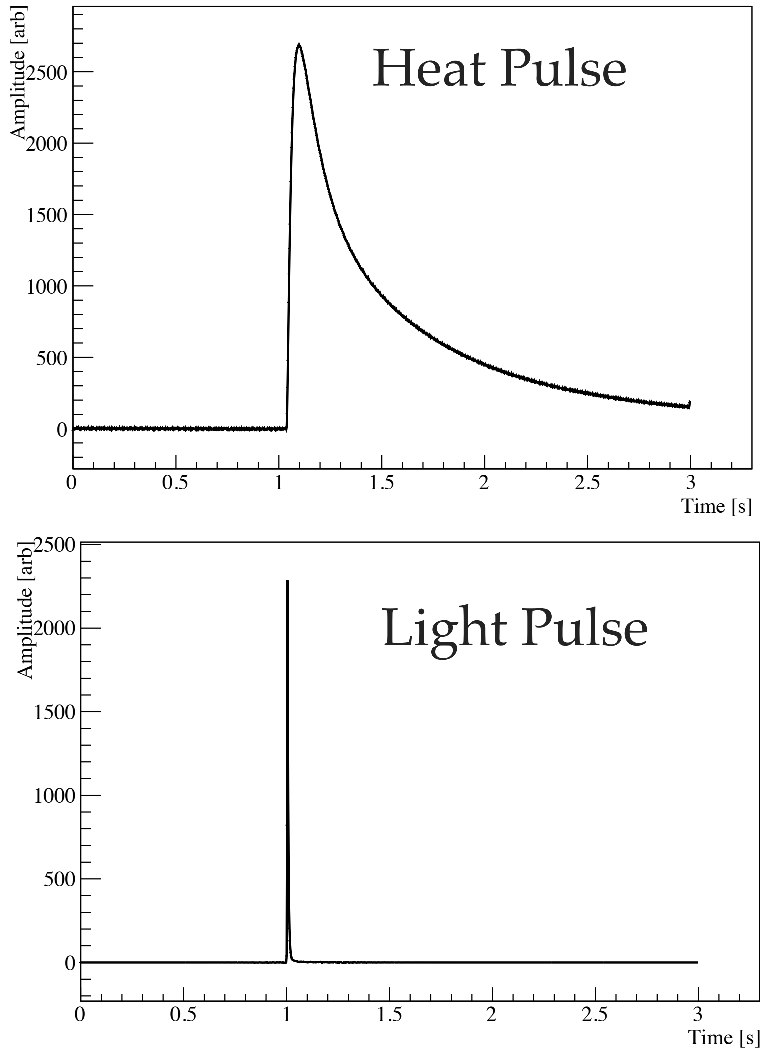
CUPID-0

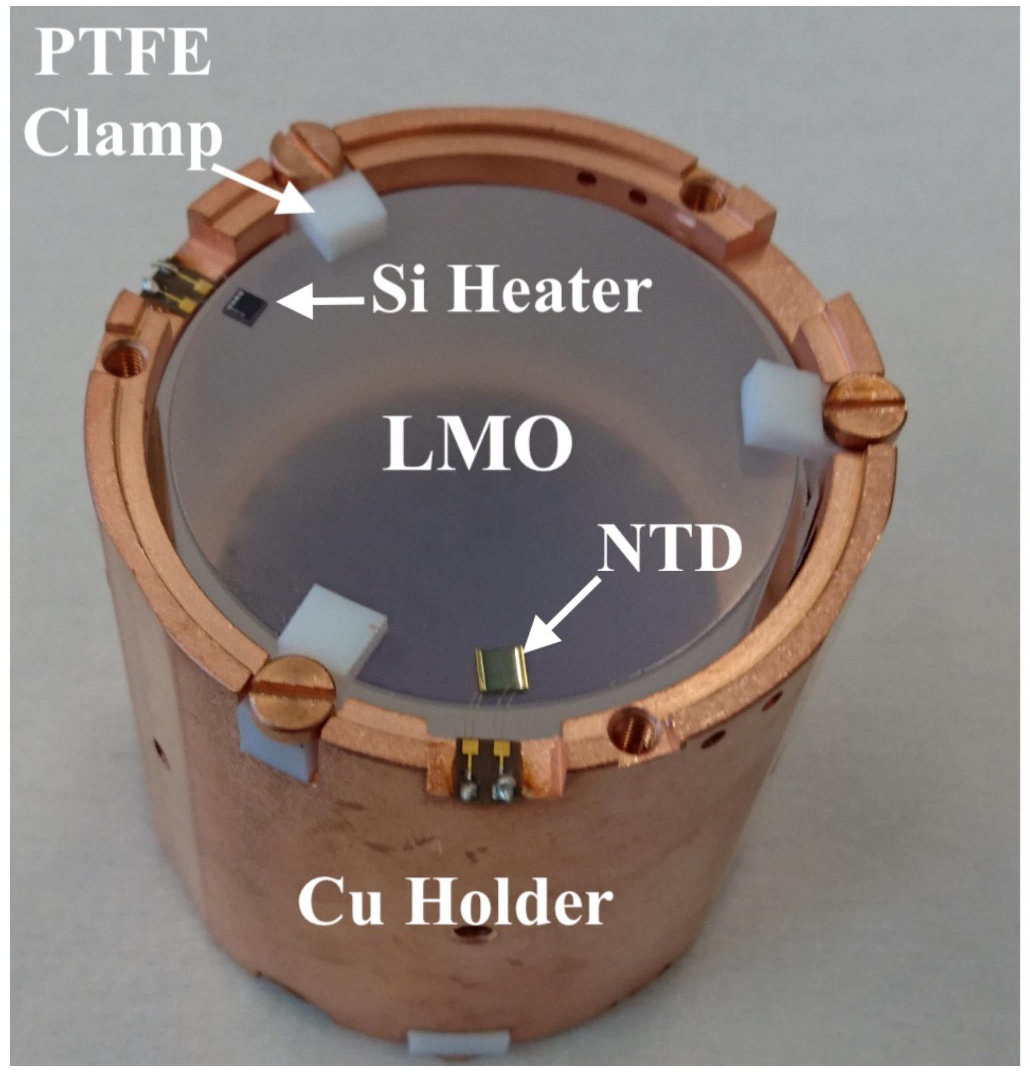



- CUPID-0 utilized $Zn^{82}Se$ crystals with 95% enrichment
- Operated at LNGS (Italy)
- $Q_{\beta\beta}$: 2998 keV
- α-rejection > 99.9%
- Background index: 3.5×10^{-3} counts/keV/kg/yr
- Energy resolution at $Q_{\beta\beta}$: 21.8 keV

O. Azzolini et al. PRL 129, 111801

CUPID-Mo



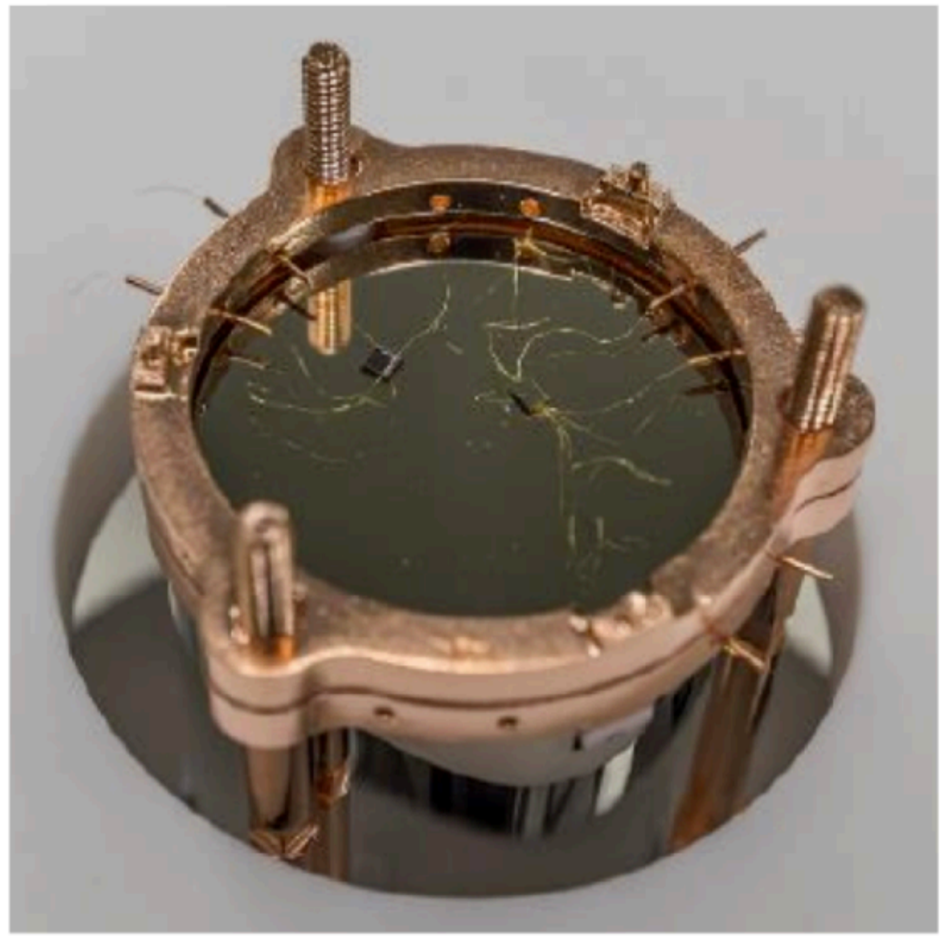


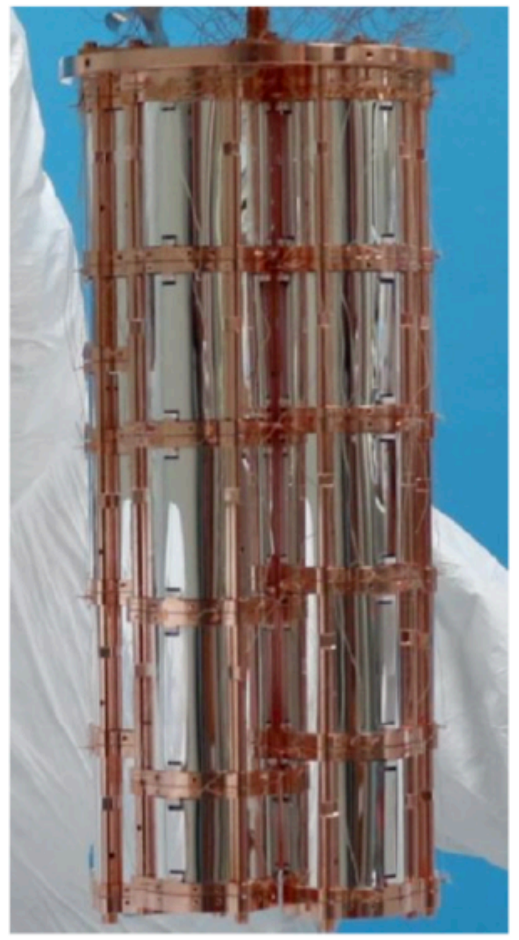
- CUPID-Mo utilized LMO crystals with 95% enrichment
- Operated at LSM (France)
- $Q_{\beta\beta}$: 3034 keV
- α-rejection > 99.9%
- Background index: 2.7×10^{-3} counts/keV/kg/yr
- Energy resolution at $Q_{\beta\beta}$: 7.4 keV

C. Augier et al., EPJC 82, 1033 (2022)
C. Augier et al., EPJC 83, 675 (20223)

Demonstrators

CUPID-0





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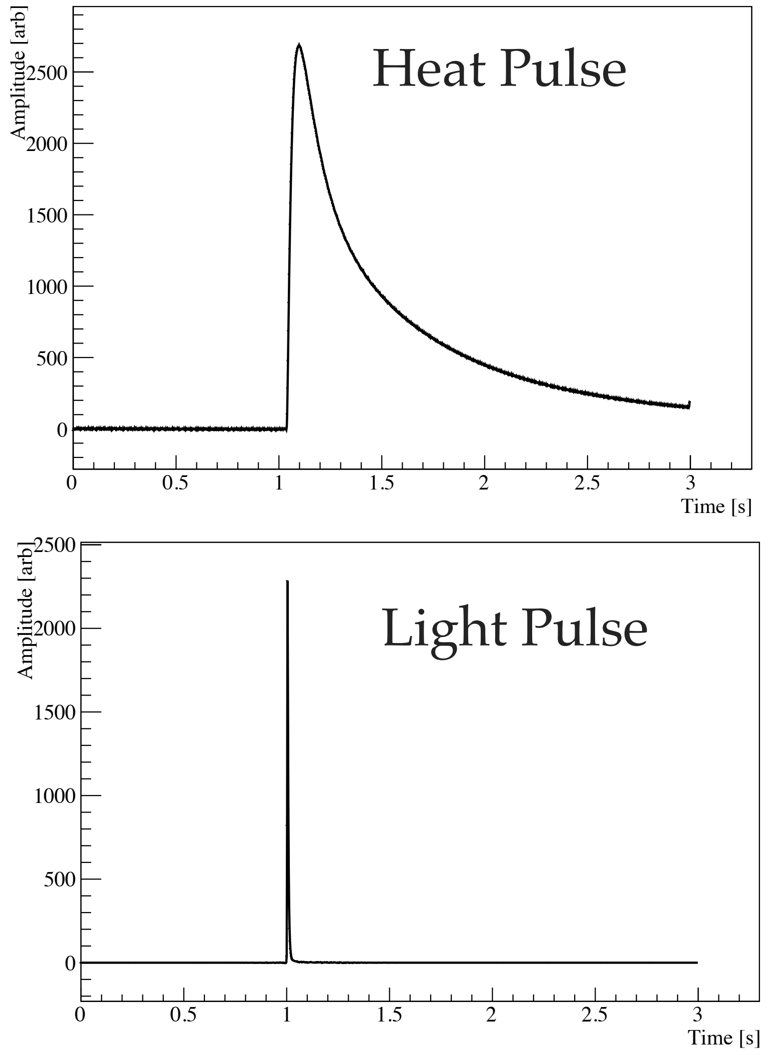
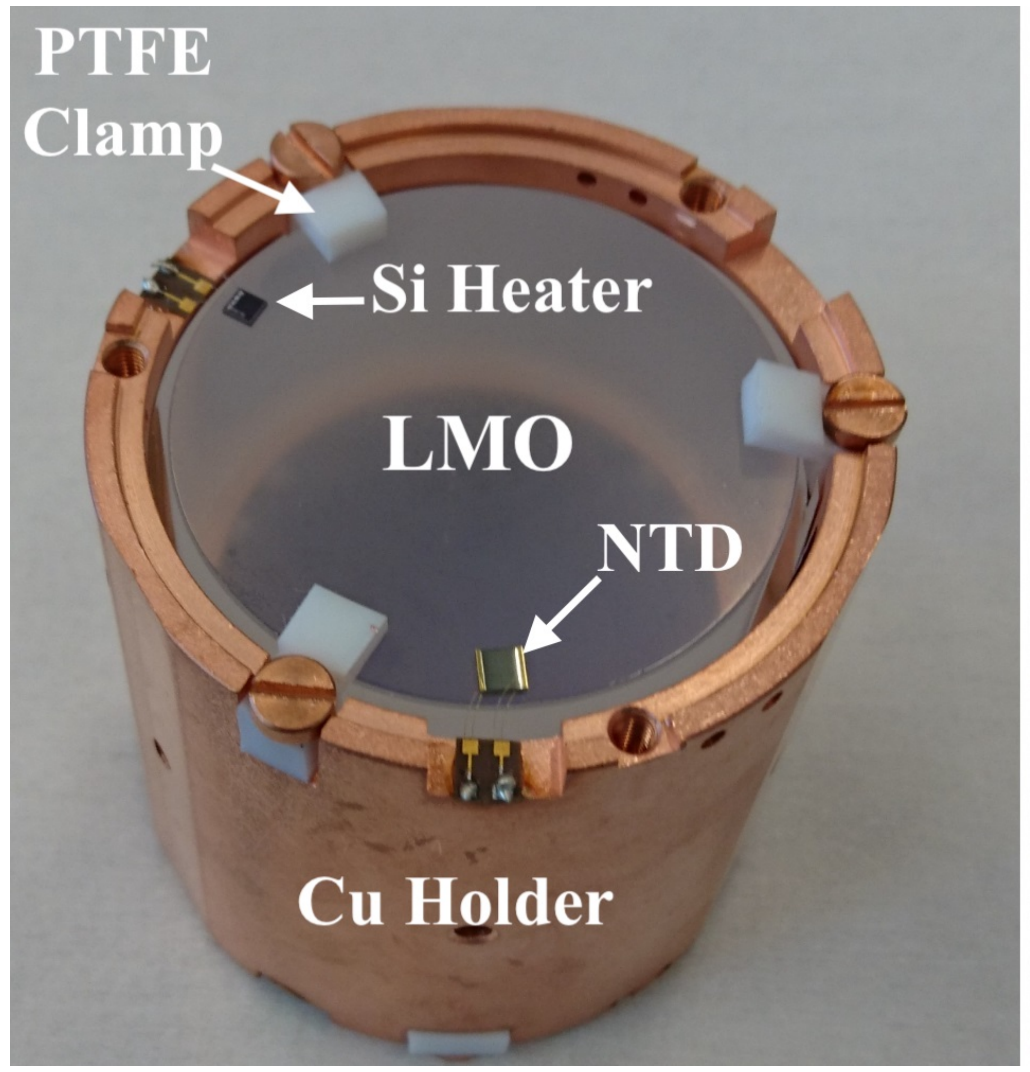
CUPID-Mo





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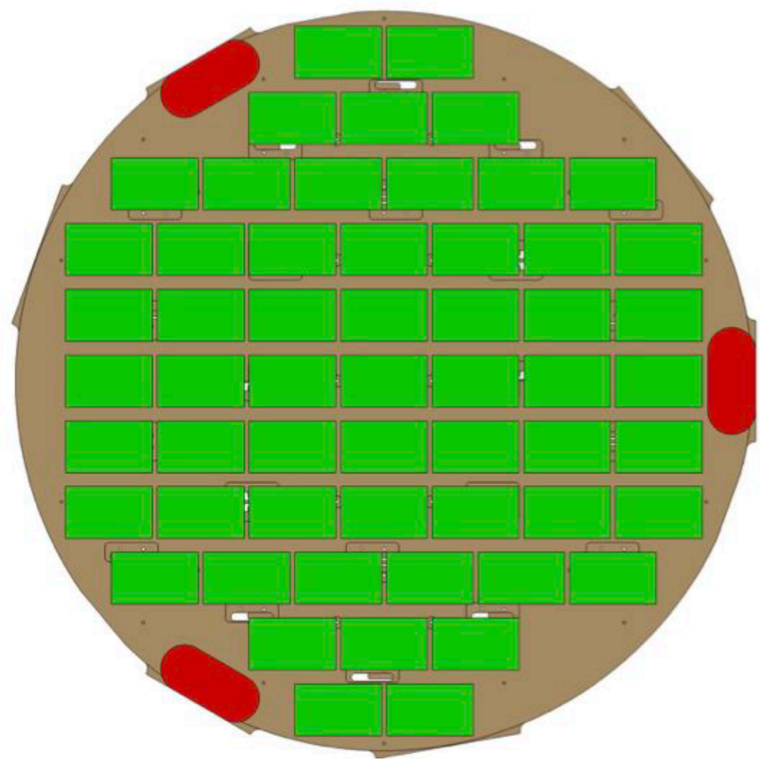
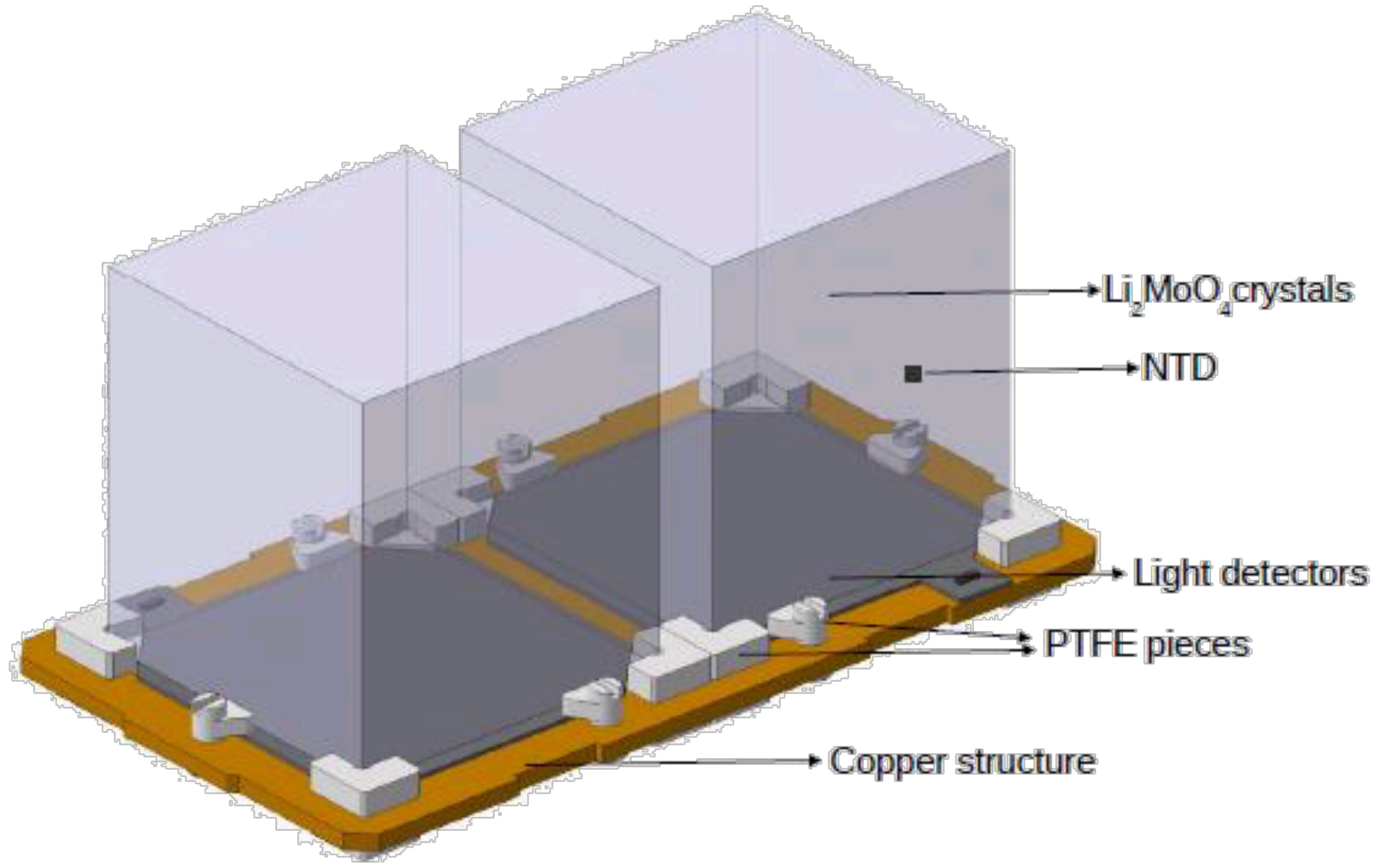
- **Background index: 2.7×10^{-3} counts/keV/kg/yr**
- **Energy resolution at $Q_{\beta\beta}$: 7.4 keV**

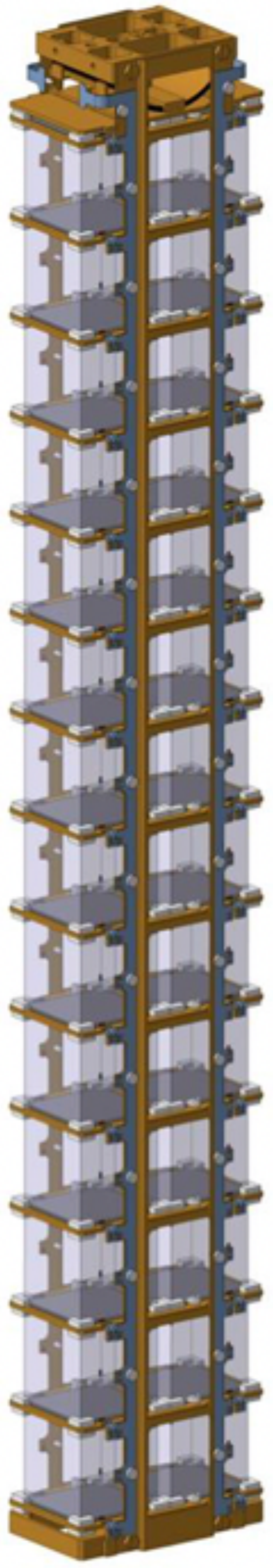
C. Augier et al., EPJC 82, 1033 (2022)
C. Augier et al., EPJC 83, 675 (20223)

CUPID Detector

- CUPID detector will be installed in CUORE cryostat
- 57 towers containing 14 floors
- High purity Cu structure with PTFE supports
- 1596 $Li_2{}^{100}MoO_4$ scintillating crystals - enrichment > 95%
- 45 mm cubic crystals (280g ea.)
- Total mass: 450 kg
- Readout via NTD thermistors
- 1710 light detectors - 2 per LMO
- Square Ge wafers readout via NTD thermistors
- Anti-reflective SiO coating





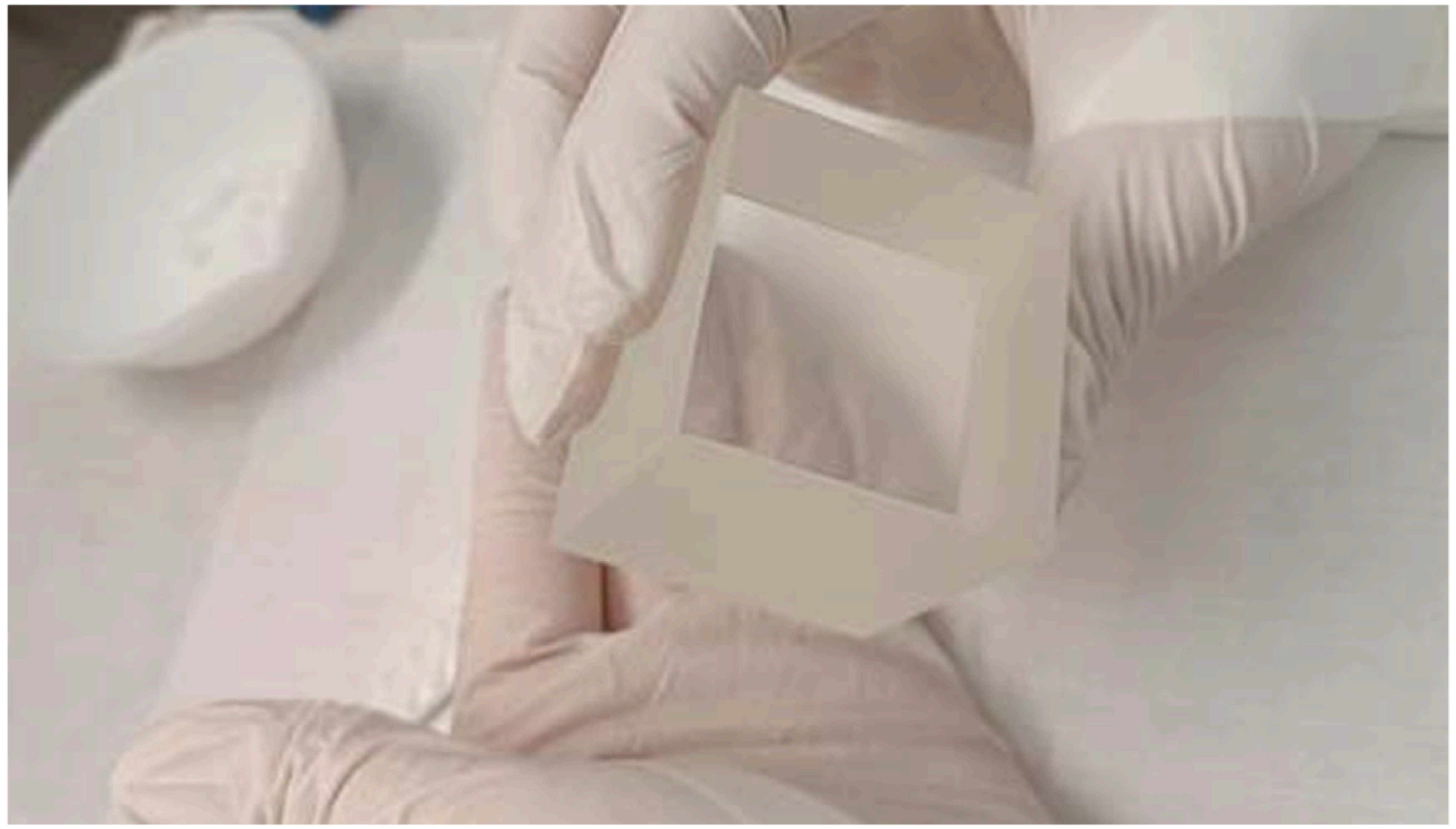


- α rejection demonstrated > 99.9%
- Energy resolution @ $Q_{\beta\beta}$ 7.4 keV FWHM (target: < 5 keV FWHM)
- LD baseline resolution < 100 eV RMS
- Light yield: 0.3 keV/MeV

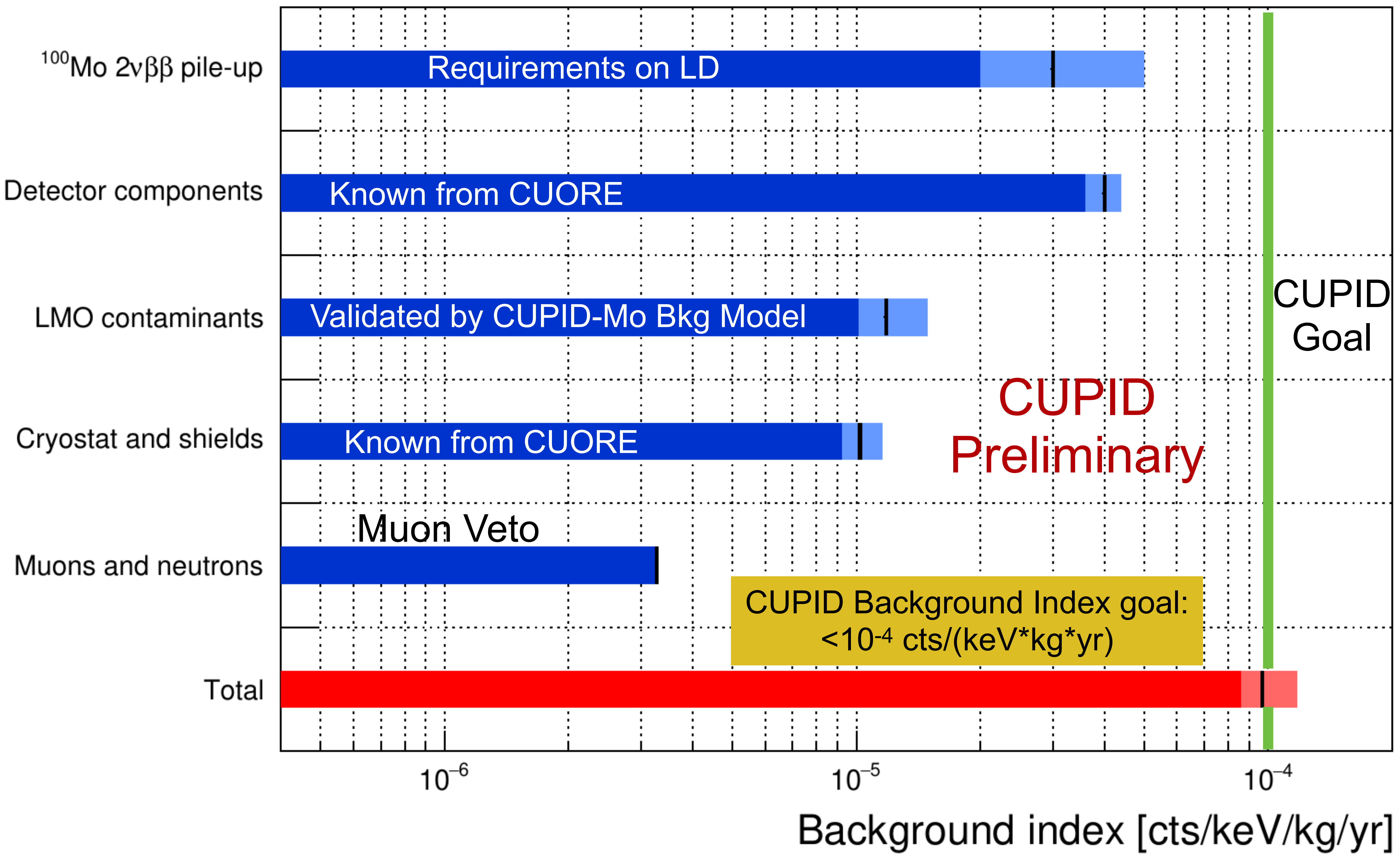
CUPID Crystals

- CUPID has established a supply chain for producing 1596 LMO crystals with 95% enrichment
- SICCAS (Shanghai, China):
  - Capability to produce the enriched crystals, isotope procured from Chinese manufacturer
  - Produced all the CUORE crystals with radiopurity requirements that are similarly strict
  - First sample produced and measured at LNGS via ICP-MS matched requirements
- Pre-production is ongoing, funded by INFN (Italy) and CNRS (France) with specific goals:
  - Reduce isotope loss during growth and cut
  - Optimization for radiopurity
  - Optimize surface quality (light yield and transmission)
- Tests at LNGS to validate performance, radiopurity, and quantify contamination

Since 1928 SICCAS



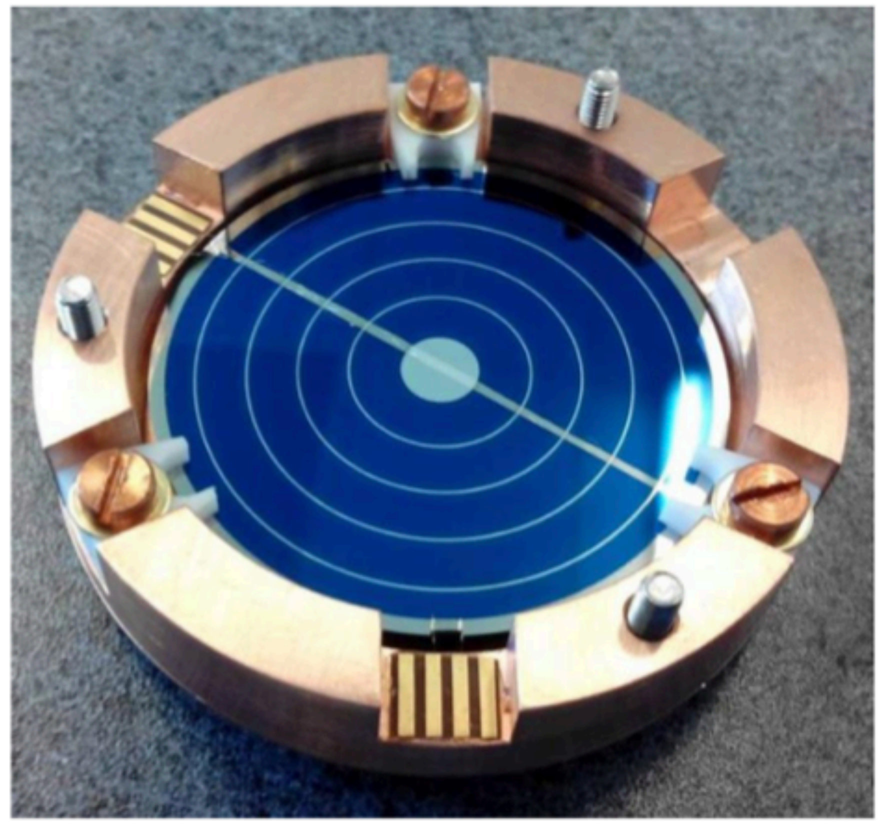
CUPID Background

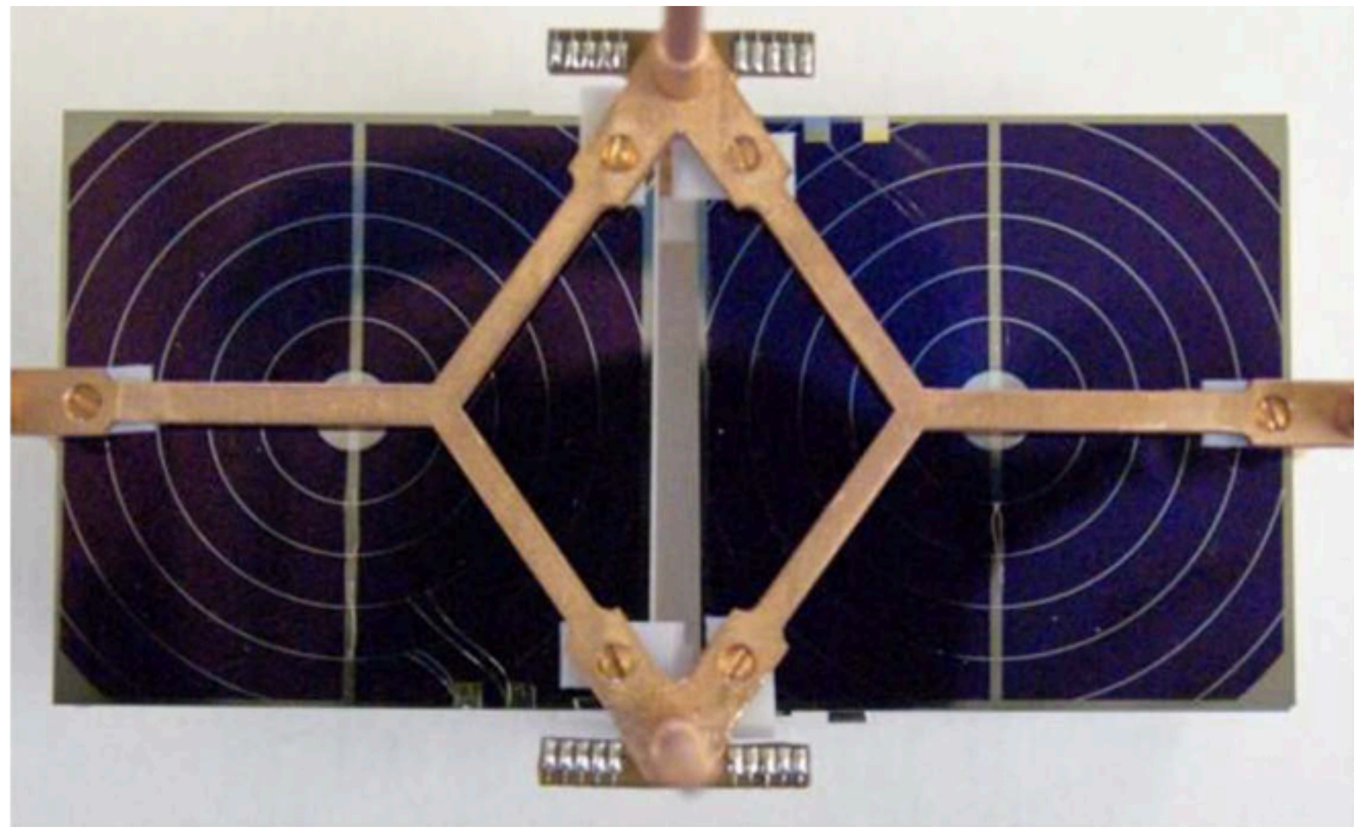


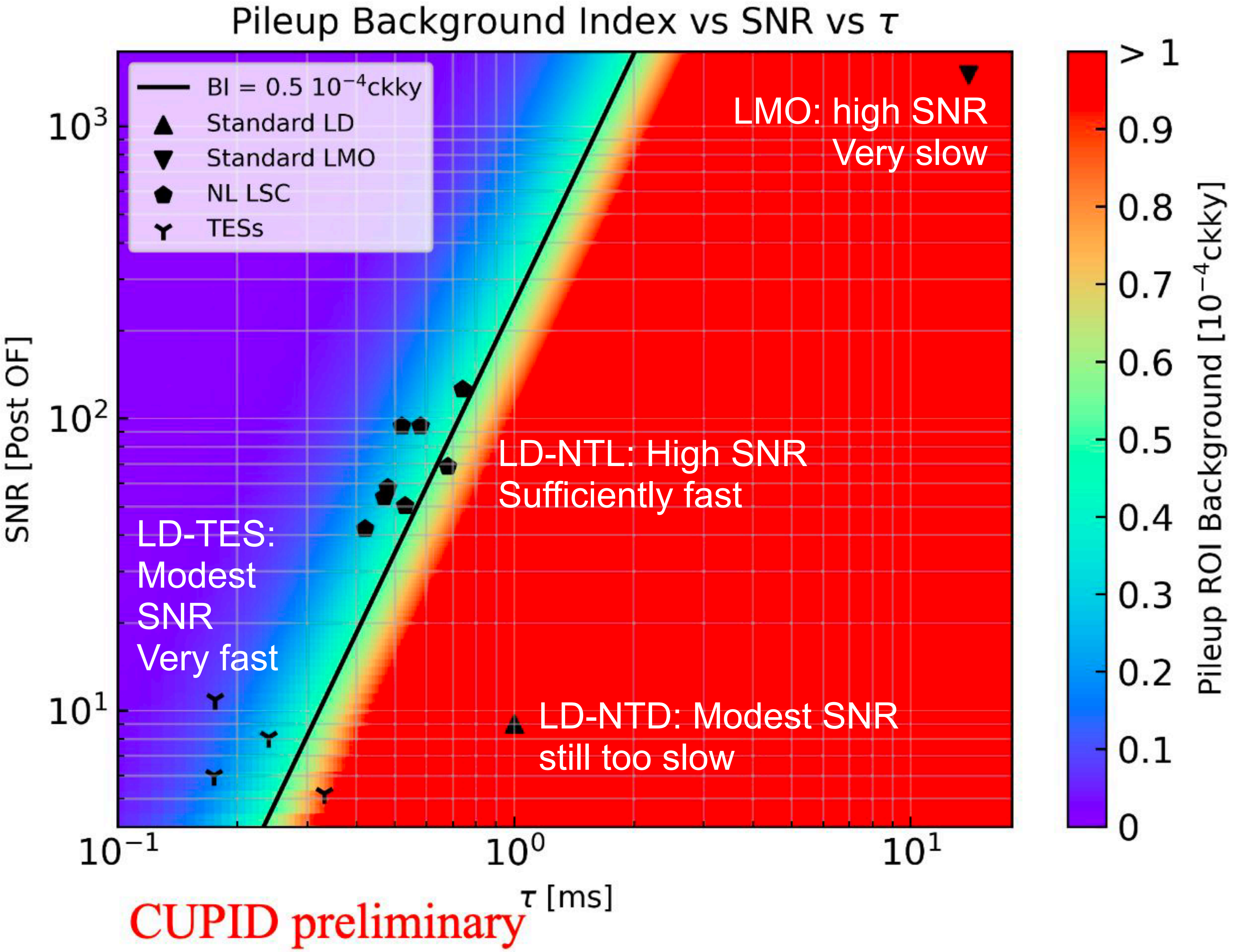
- Utilizing information from CUORE, CUPID-Mo, and CUPID-0
- Detector Components: dominated by surface contaminants
- Crystal: bulk exceptionally radiopure, surface contaminants
- α backgrounds rejected by light to heat ratio (>99.9%)
- β/γ contamination can be handled a few ways:
  - Strict radiopurity protocols as in CUORE
  - Delayed coincidence cuts that can reject U/Th chains
- Muons: muon veto system with 99% geometric efficiency
- Pile-up: dominated from 2νββ decays => improvements to LDs

2νββ Pileup

- 2νββ decay is (relatively) fast in ^{100}Mo (~7.1 x 10^{18} yr half-life)
- LMO calorimeters are also relatively slow
- Result: 2νββ decay events can pile-up within a crystal and wind up reconstructing in the 0νββ decay ROI
- Leverage LDs to mitigate => require fast sensors with good time resolution or increased SNR
- Neganov-Trofimov-Luke (NTL) effect can boost SNR for NTD based LDs
- Complimentary R&D for faster TES based sensors also underway

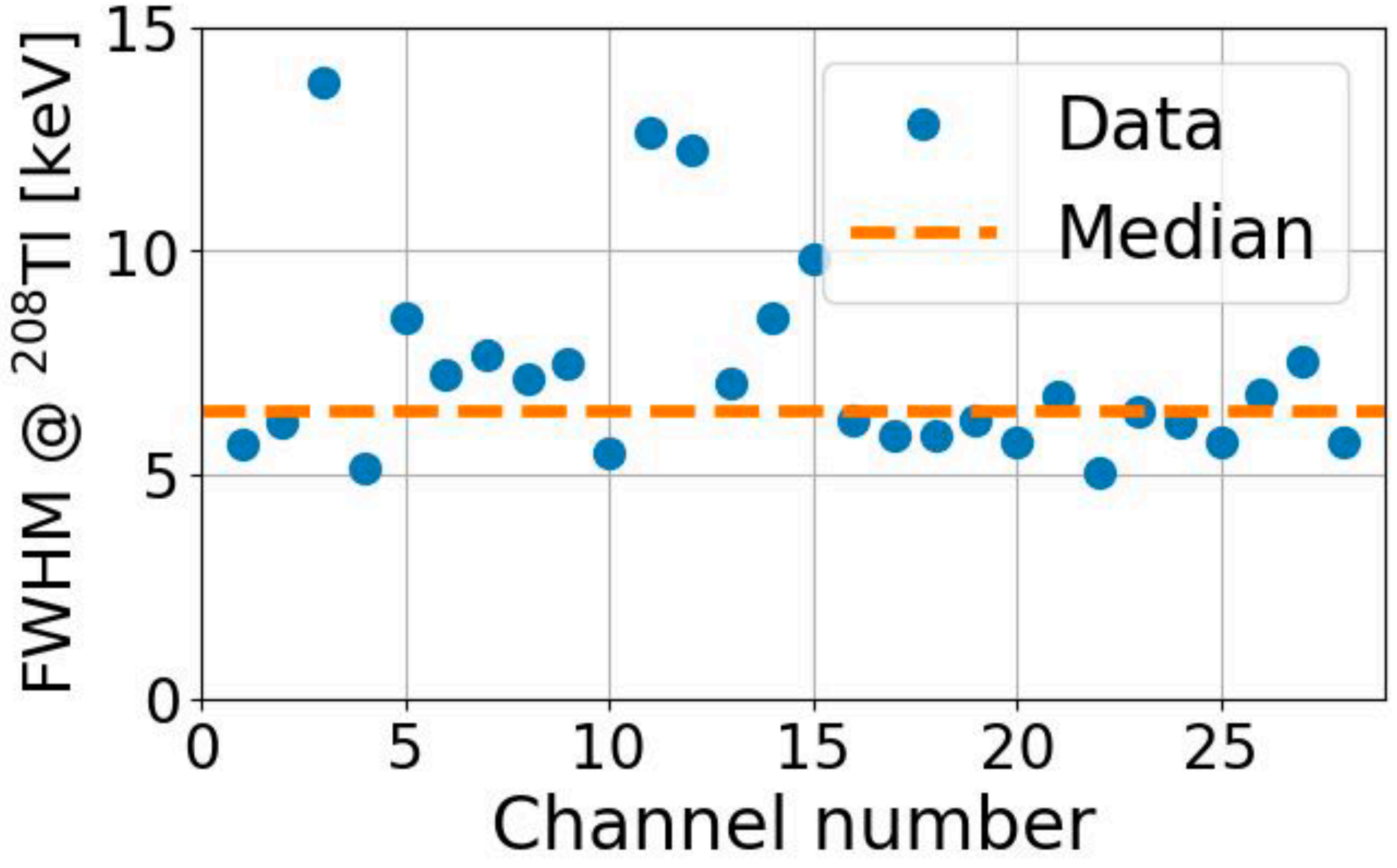




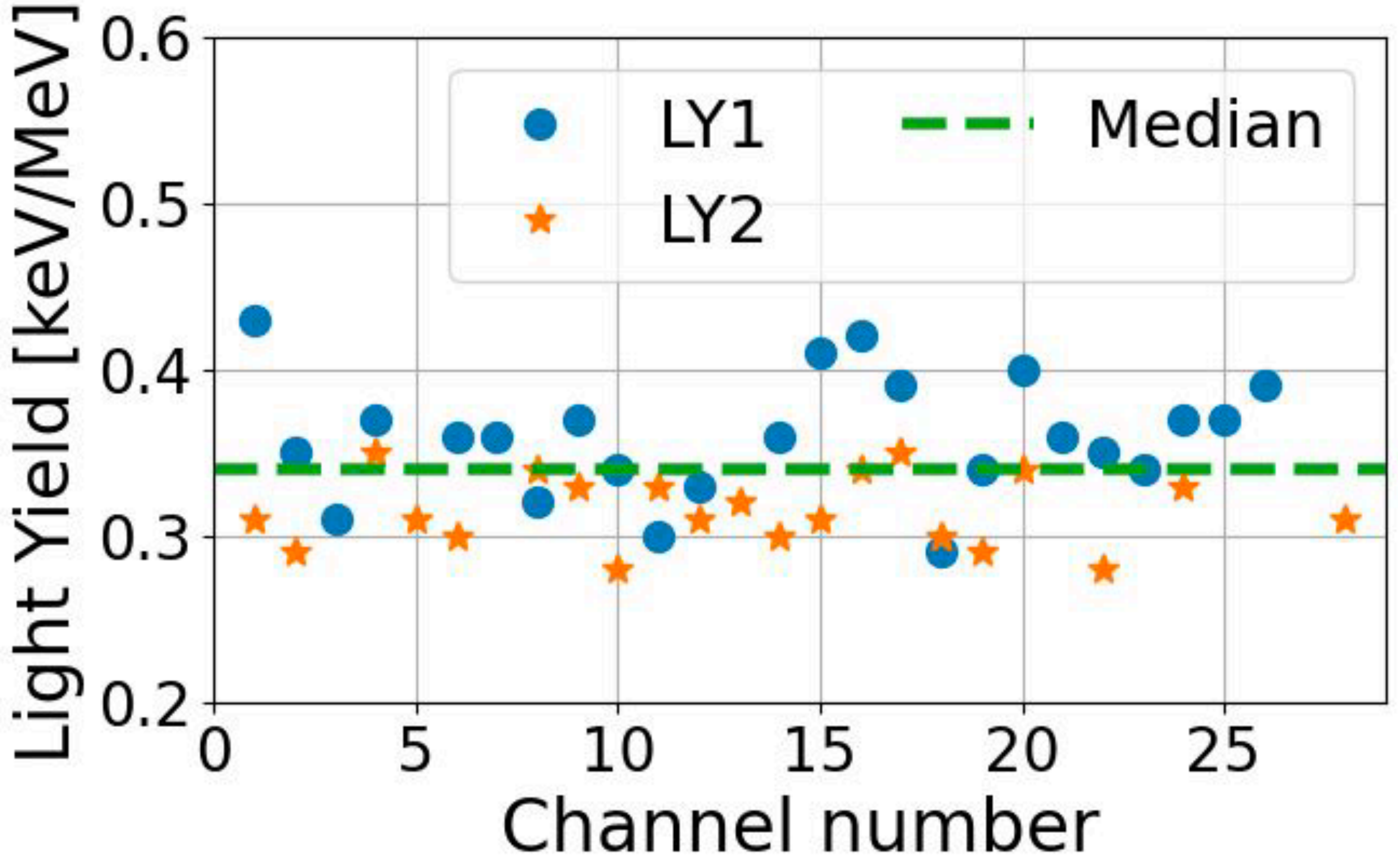


CUPID R&D Tests

- Various R&D tests runs underway
- Test runs for tower optimization
  - Validate assembly procedure, thermalization, structure
  - Validate performance of LMO and LDs
  - Vibrational studies
- 1 tower (14 floors, 28 LMO, 30LDs) — 2 runs
- Upcoming tests to test more of the full end-to-end CUPID technology are planned



Median LMO $FWHM_{baseline}$ = 3.1 keV
Median LMO $FWHM_{2615keV}$ = 6.2 keV

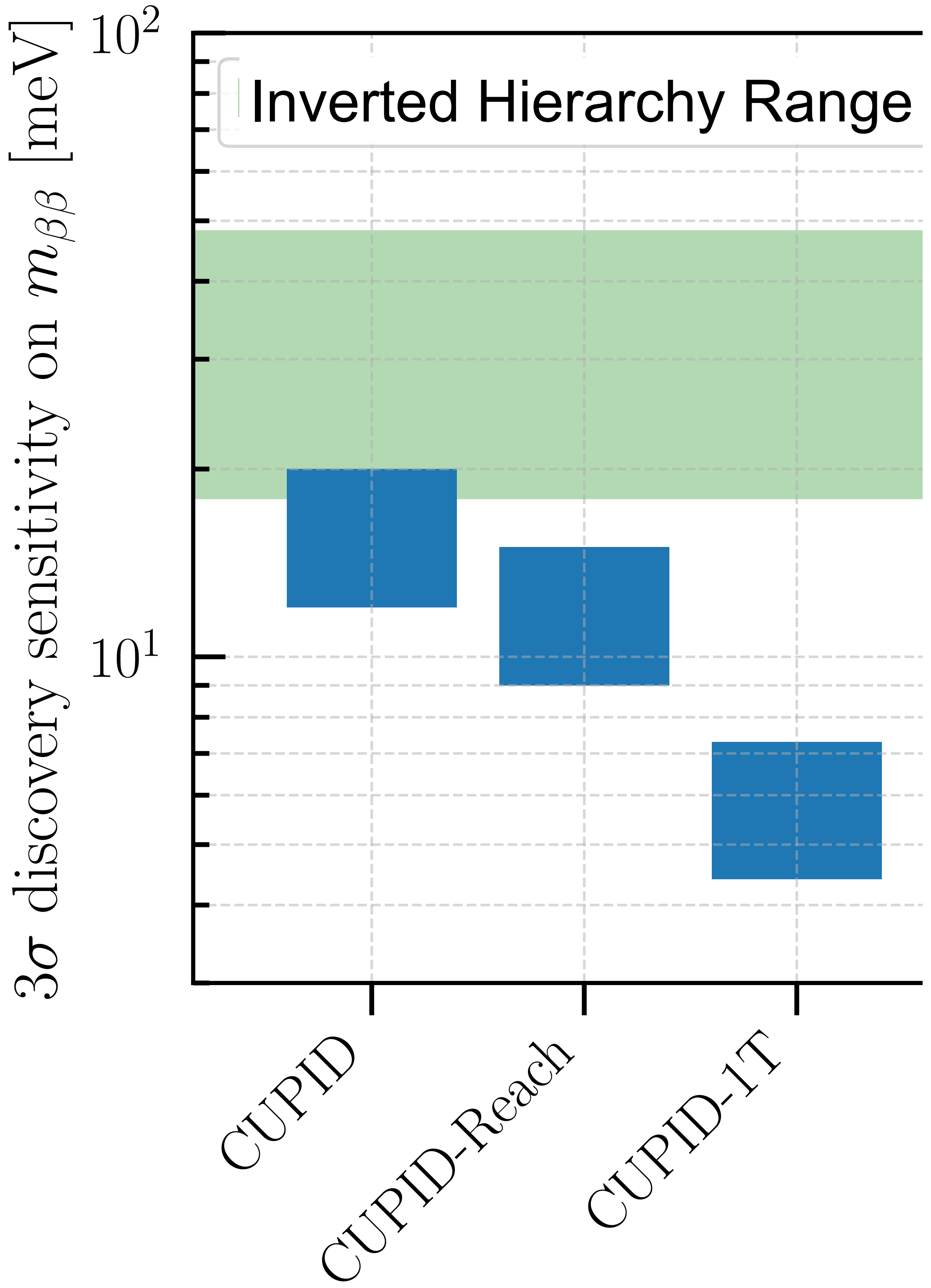


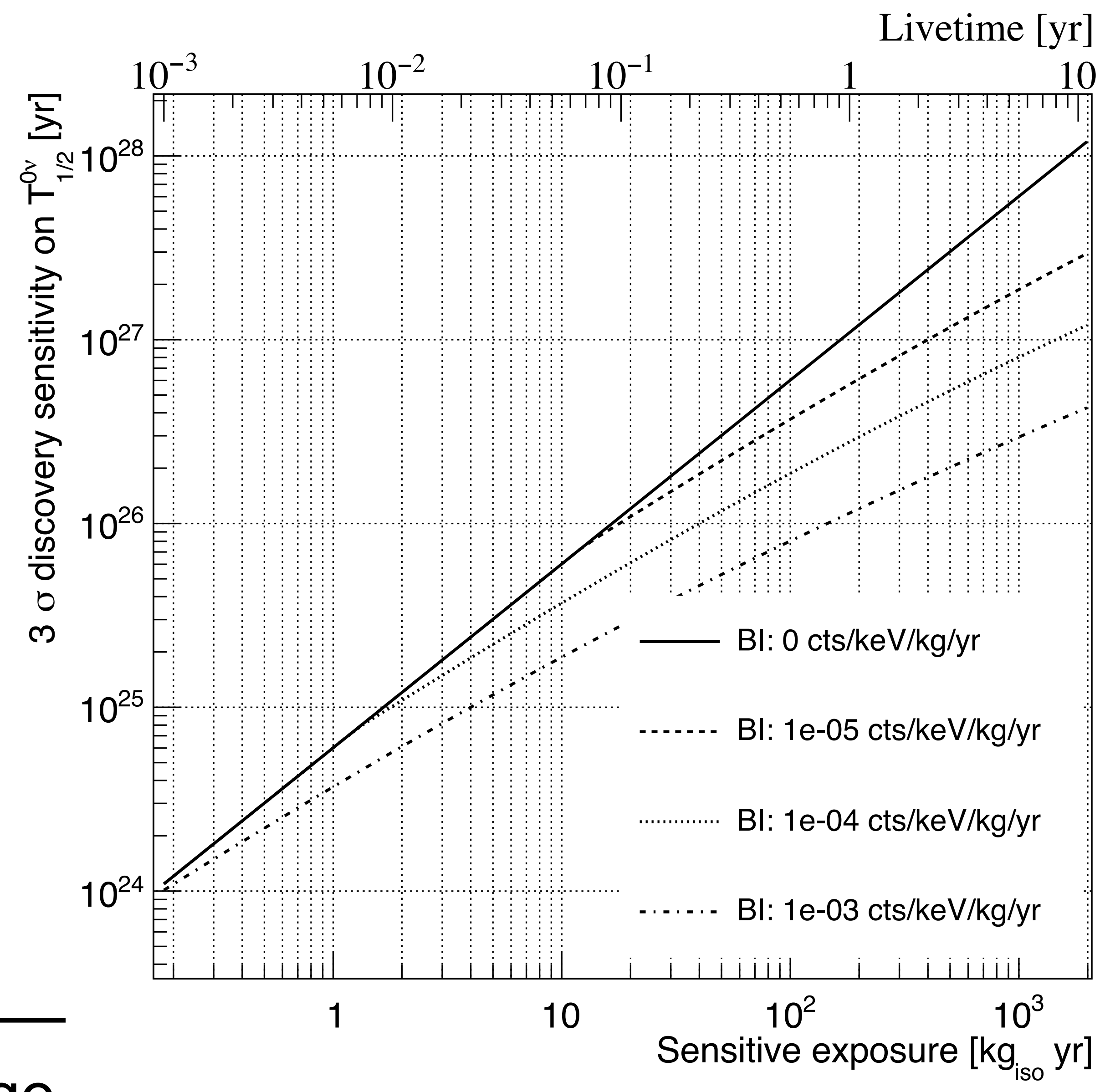
$$DP = \frac{|LY_{\beta,\gamma} - LY_{\alpha}|}{\sqrt{\sigma^2_{\beta,\gamma} - \sigma^2_{\alpha}}}$$

Median LY: 0.34 keV/MeV
Median Discrimination Power (DP): 3.21

CUPID & Beyond

- CUPID goal is BI of $1x10^{-4}$ cts/keV/kg/yr
- CUPID: Baseline, technically ready (we can do this today!)
- CUPID-reach: same cryostat but push as hard as possible to mitigate backgrounds by x10 compared to baseline
- CUPID-1T: A possible expansion of CUPID to utilize 1000kg of ^{100}Mo
  - 4x mass scale up
  - Background abatement x20 ($5x10^{-6}$ counts/keV/kg/yr)
  - 5x improvement in half-life sensitivity
  - Requires new technologies for LDs beyond NTL





Exclusion Sensitivity:

1.4×10^{27} yr : $m_{\beta\beta} < [10 - 17]$ meV

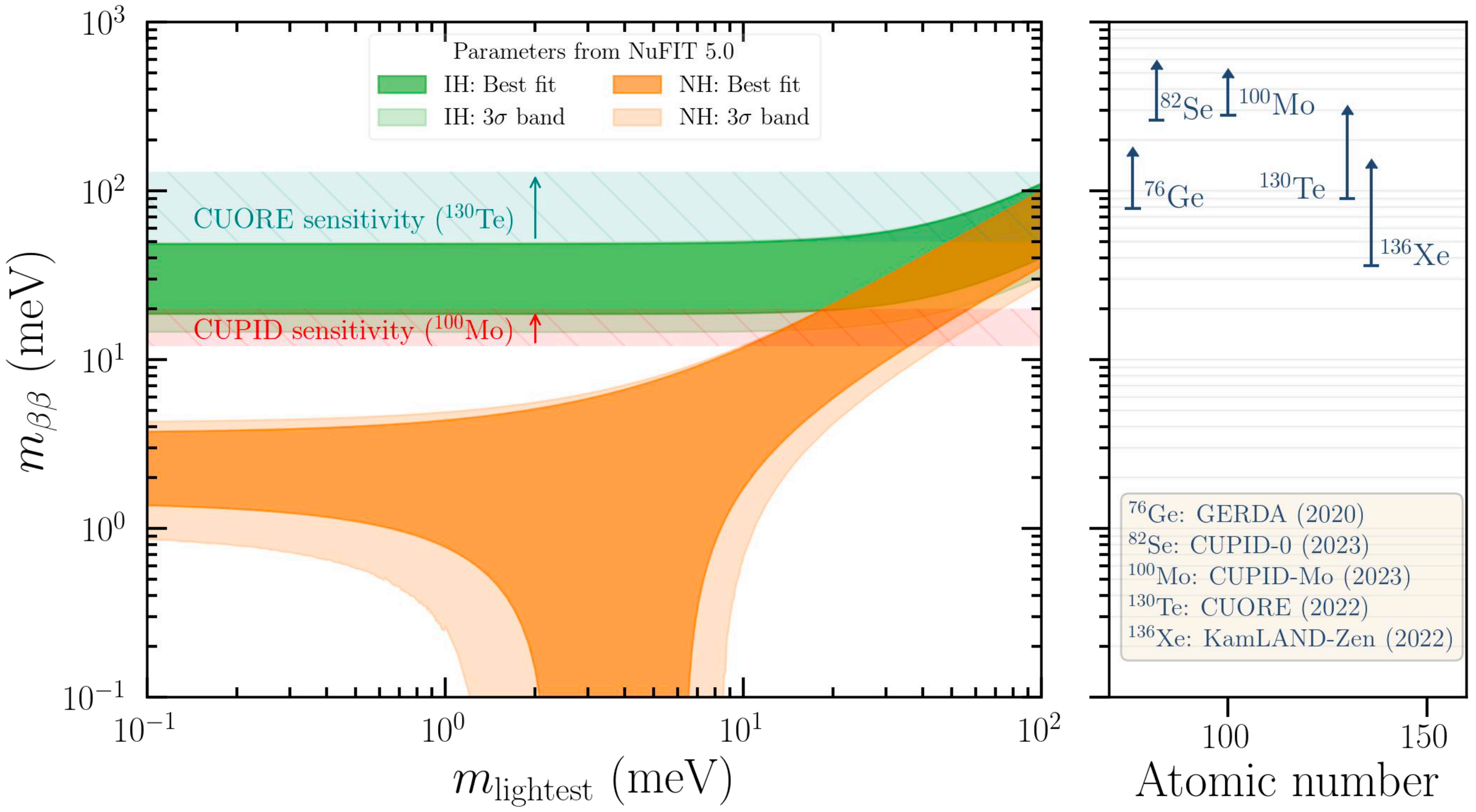
3σ discovery sensitivity:

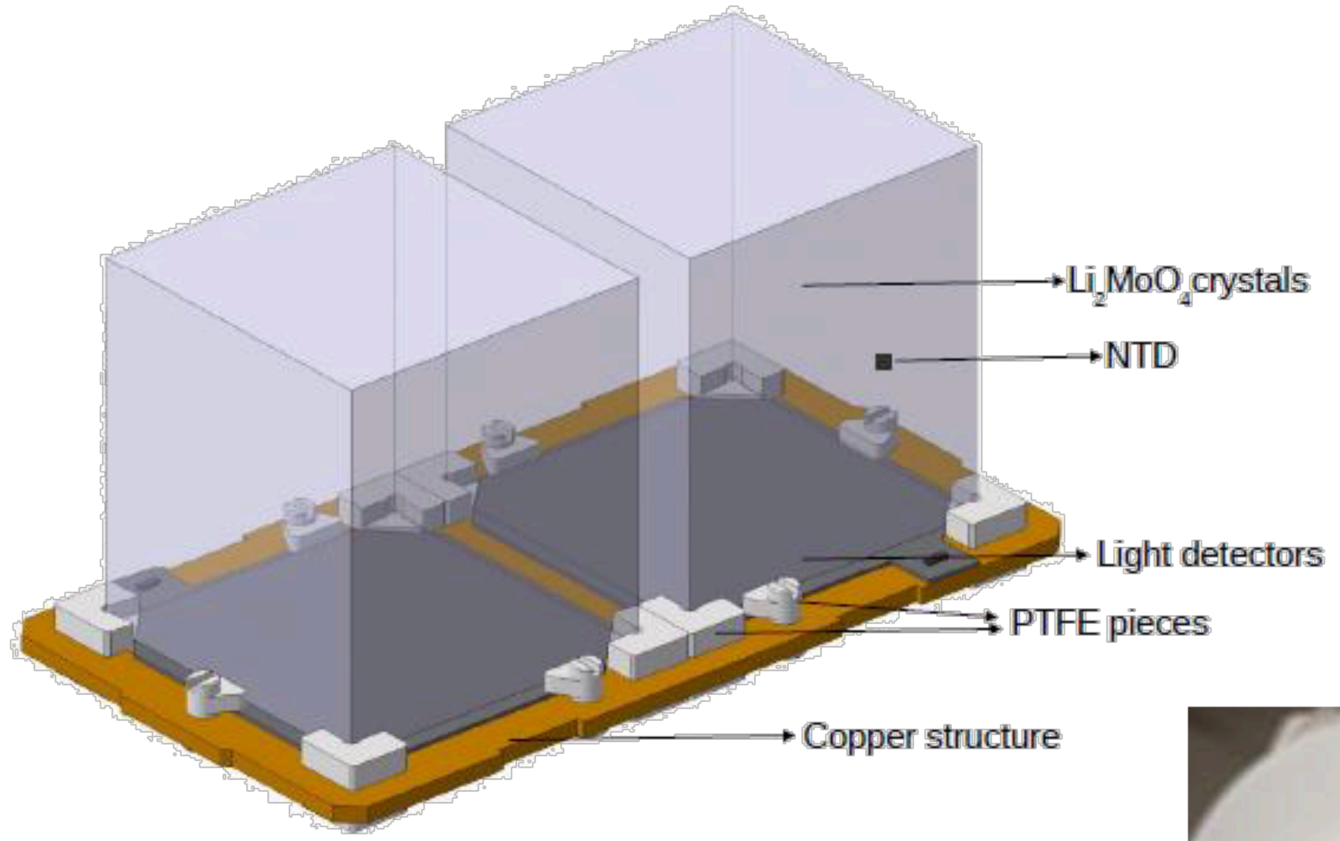
1×10^{27} yr : $m_{\beta\beta} < [12 - 20]$ meV

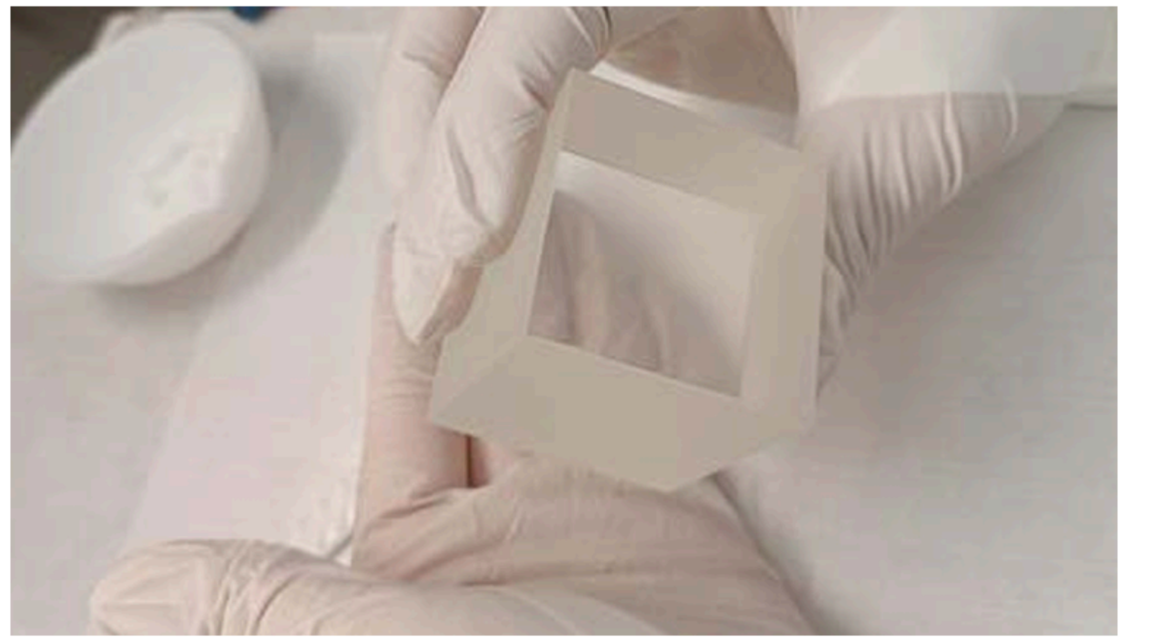
CUPID pre-CDR: arXiv:1907.09376

Summary

- CUPID is a well motivated upgrade to the successful CUORE experiment
- Explore the inverted hierarchy region
- Scintillating LMO crystals to reject α backgrounds via particle identification
- Baseline aims to reach a BI < 10^{-4} counts/keV/kg/yr
- Aim to take data by end of decade







Summary

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This research used resources of the National Energy ResearchScientific Computing Center (NERSC). This work makes use of both the DIANA data analysis and APOLLO data acquisition software packages, which were developed by the CUORICINO, CUORE, LUCIFER and CUPID-0 Collaborations.

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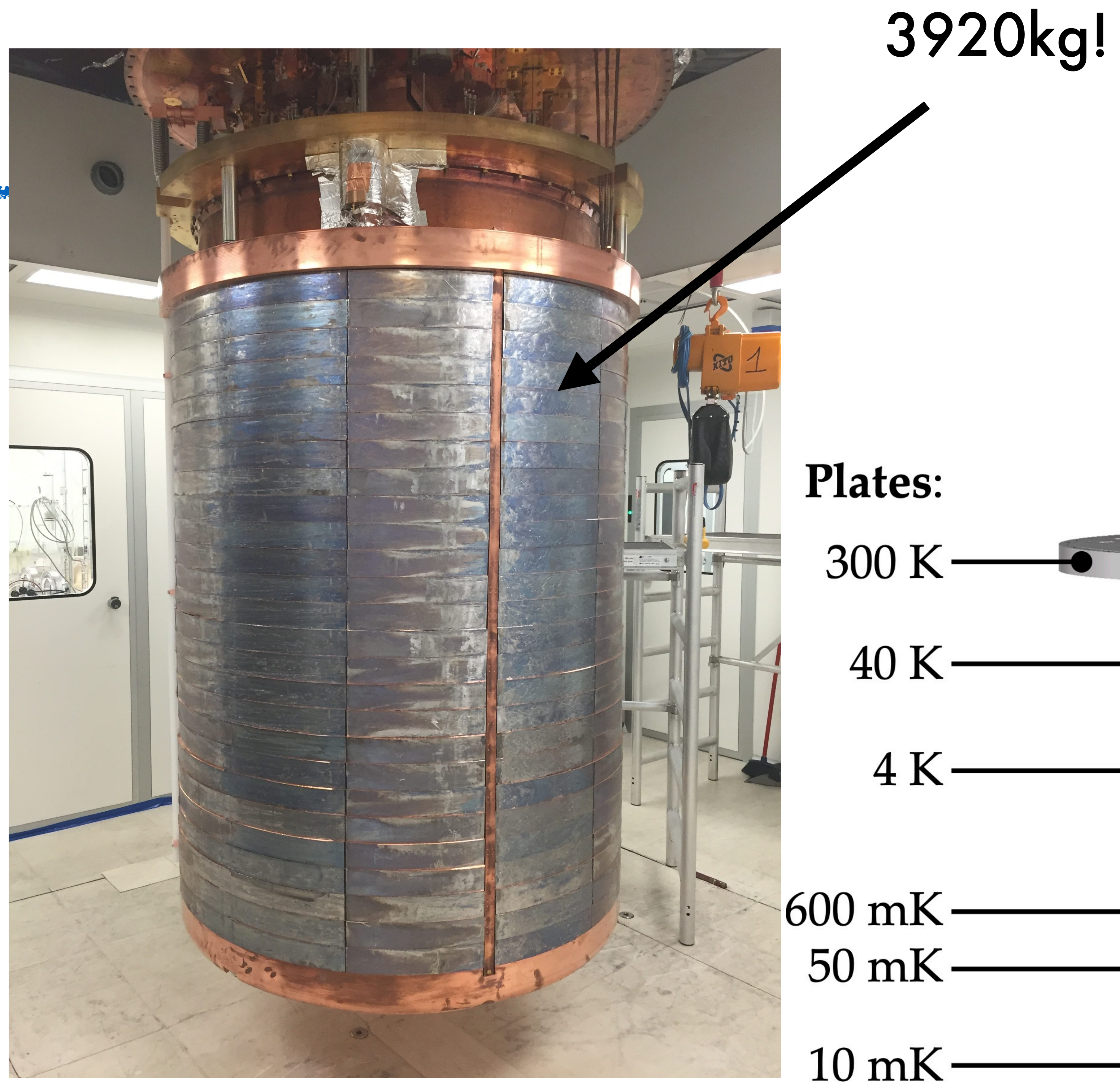
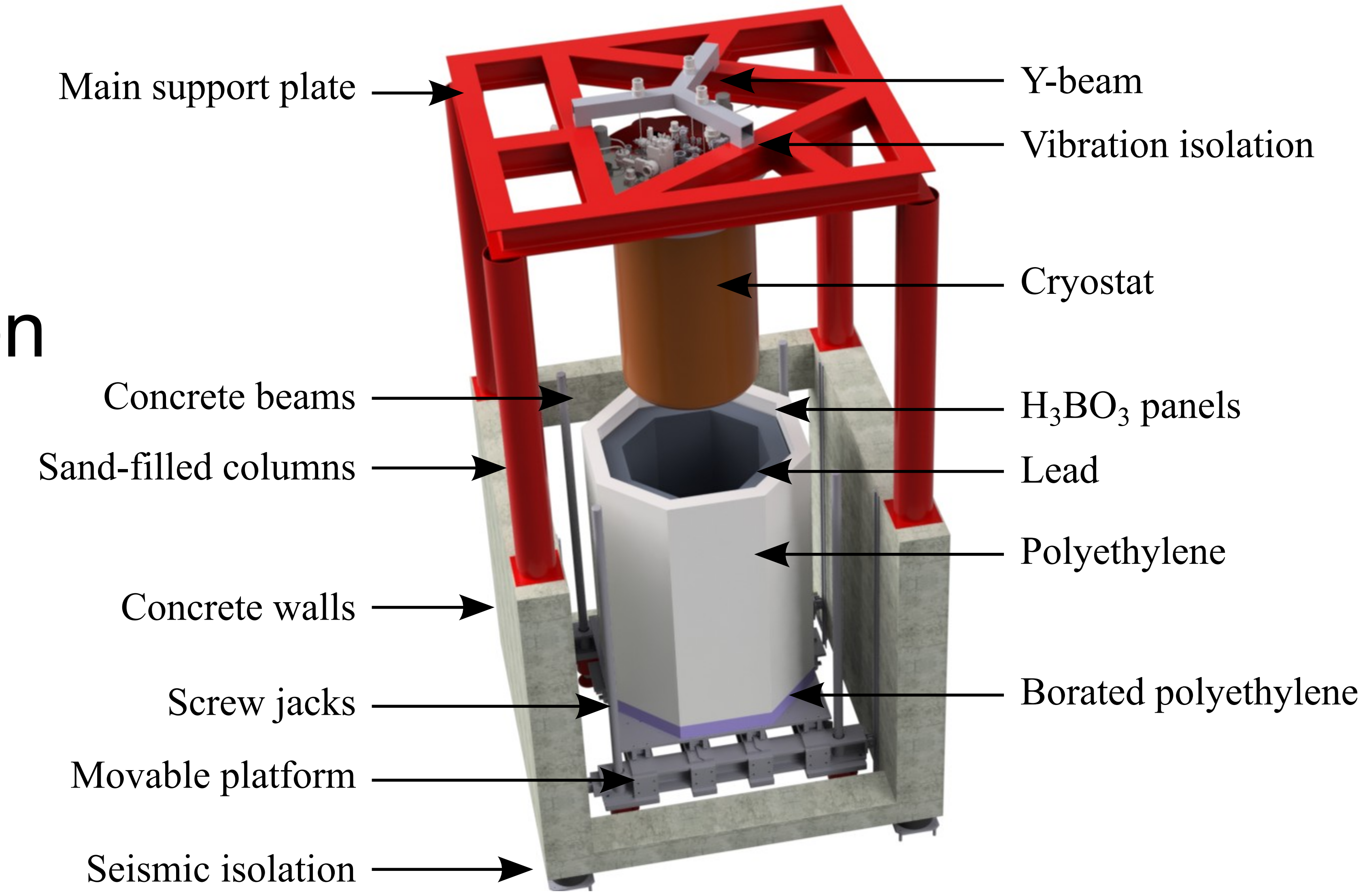
- CUPID-0 Collaboration, Final Result on the Neutrinoless Double Beta Decay of 82Se with CUPID-0 – arXiv:2206.05130
- CUPID-Mo Collaboration, Development of 100Mo-containing scintillating bolometers for a high-sensitivity neutrinoless double-beta decay search Eur. Phys. J. C 77, 785 (2017) – arXiv:1704.01758
- CUPID-Mo Collaboration, New Limit for Neutrinoless Double-Beta Decay of 100Mo from the CUPID-Mo Experiment Phys.Rev.Lett. 126, 181802 (2021) – arXiv:2011.13243

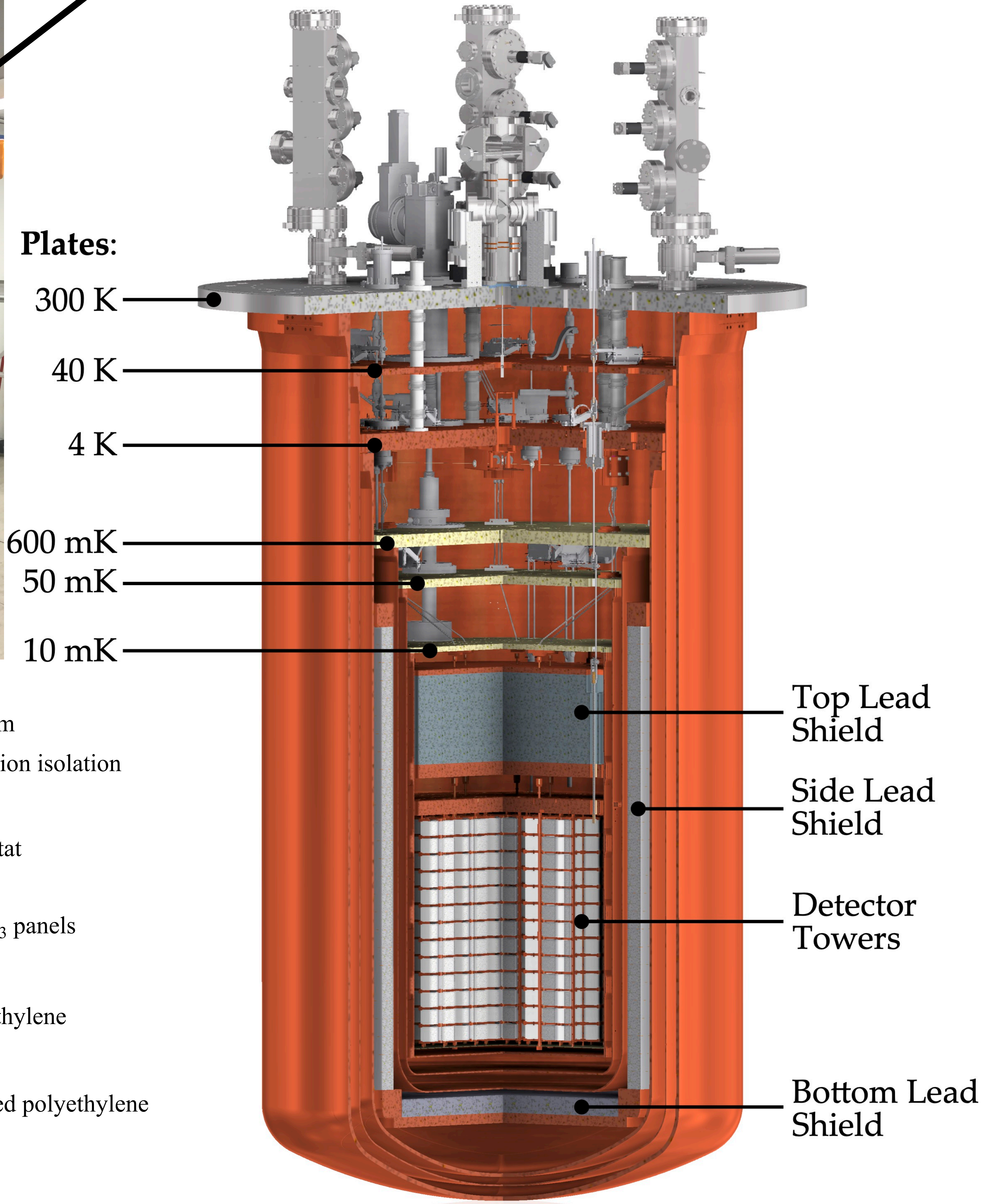
Thanks

CUORE Cryostat

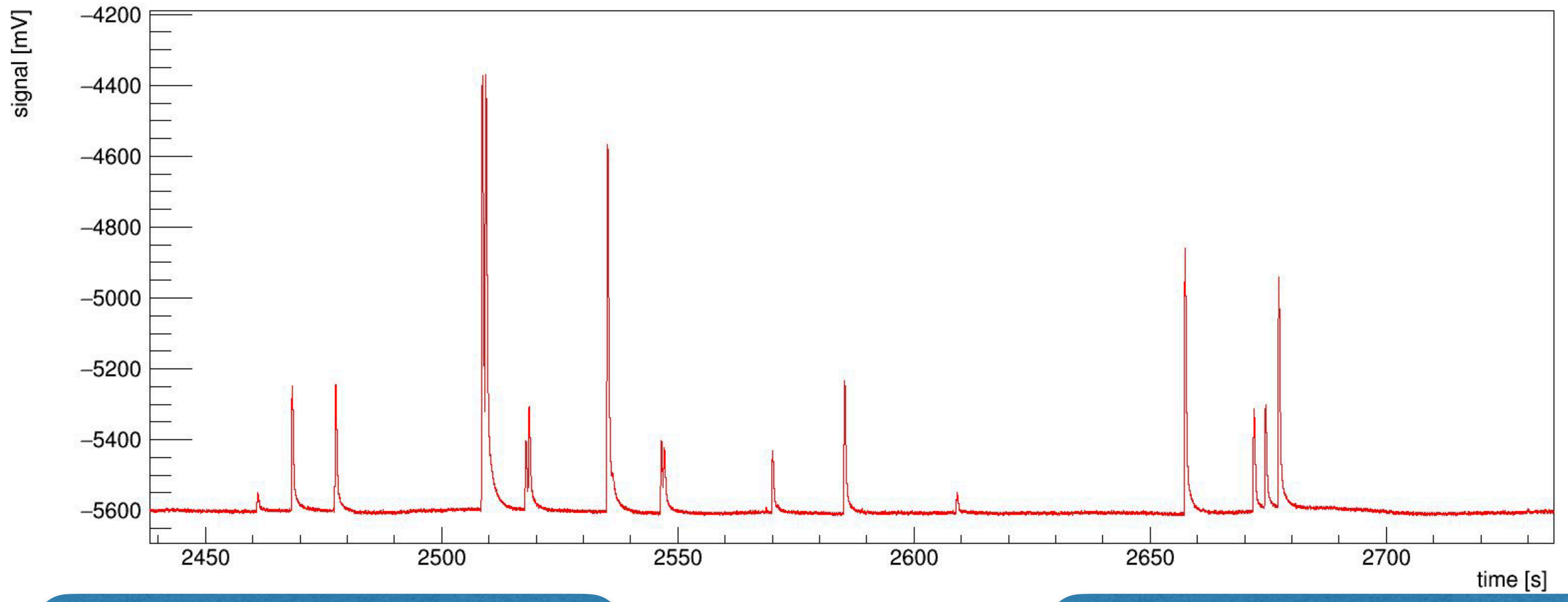
- Difficult task - cool 15 tons at or below 4K and 3 tons to below 50 mK
- World leading cryostat in size and power
- Five 1.2 W (@ 4.2 K) Cryomech pulse tube coolers
- DU from Leiden Cryogenics
  - 100 mK: 2 mW cooling power
  - 10 mK: 4 μW cooling power
- Radio-purity central to material selection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







CUORE Data Production



Denoising

Trigger & Optimal Trigger

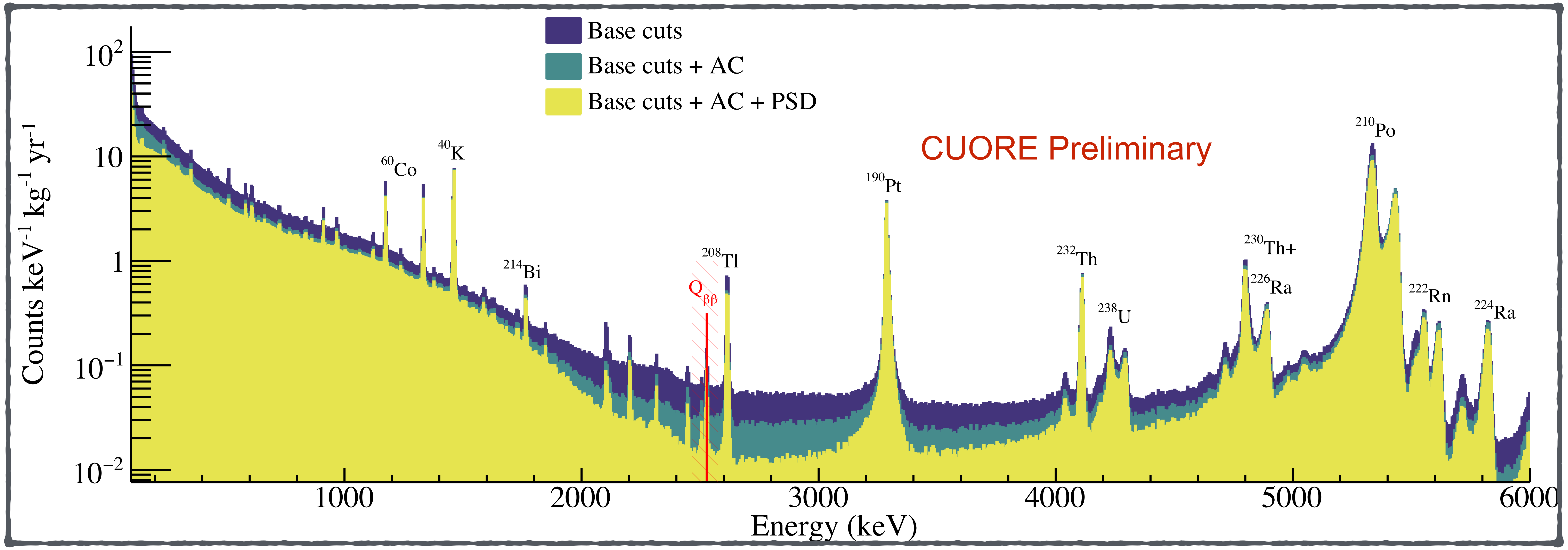
Raw Pulse Processing & Average Noise & Average Pulse

Optimal Filter Amplitude & Thermal Gain Correction

Calibration U/Th Source

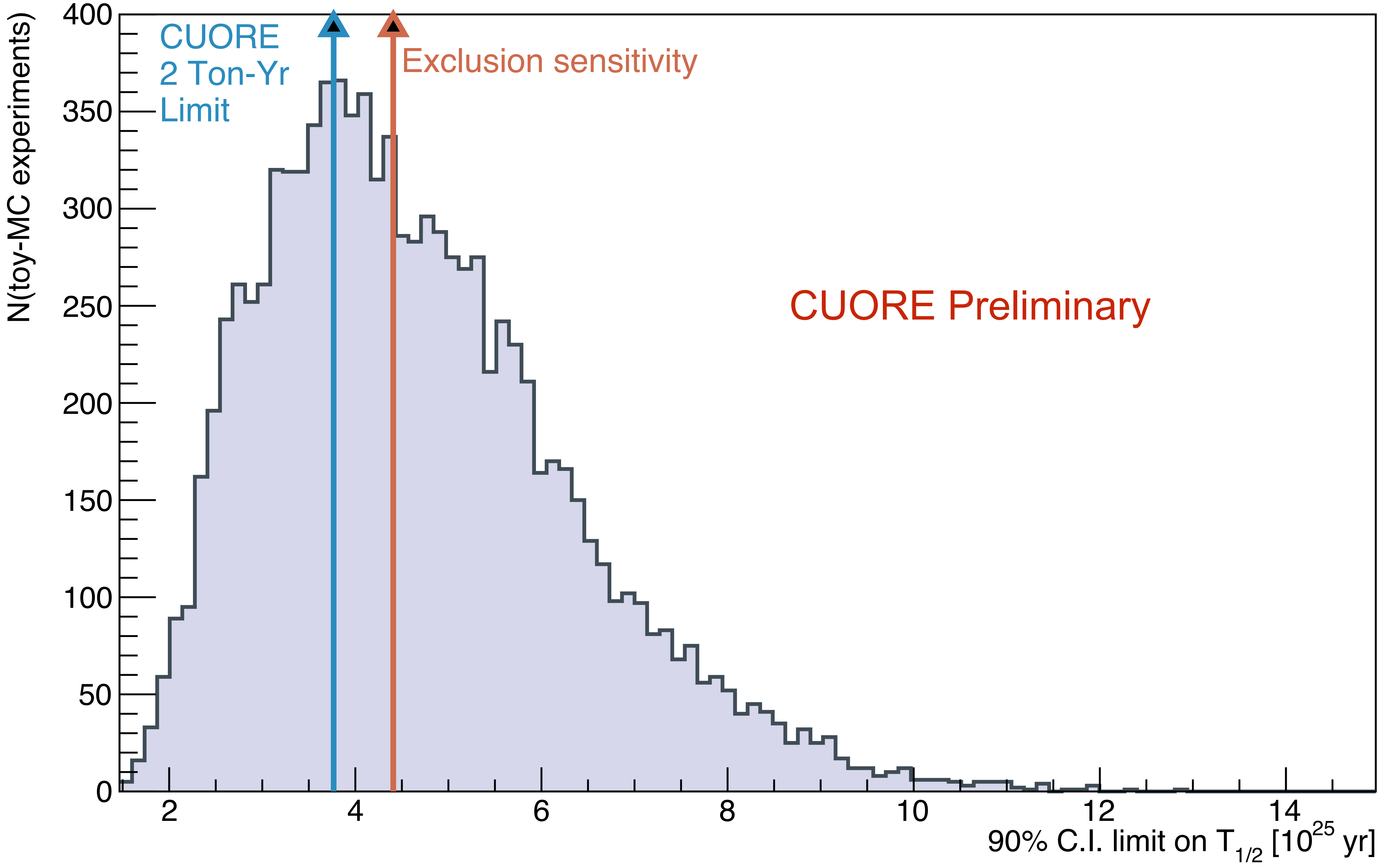
Coincidence Tagging
Allow selection of events based on number of crystals with energy deposition

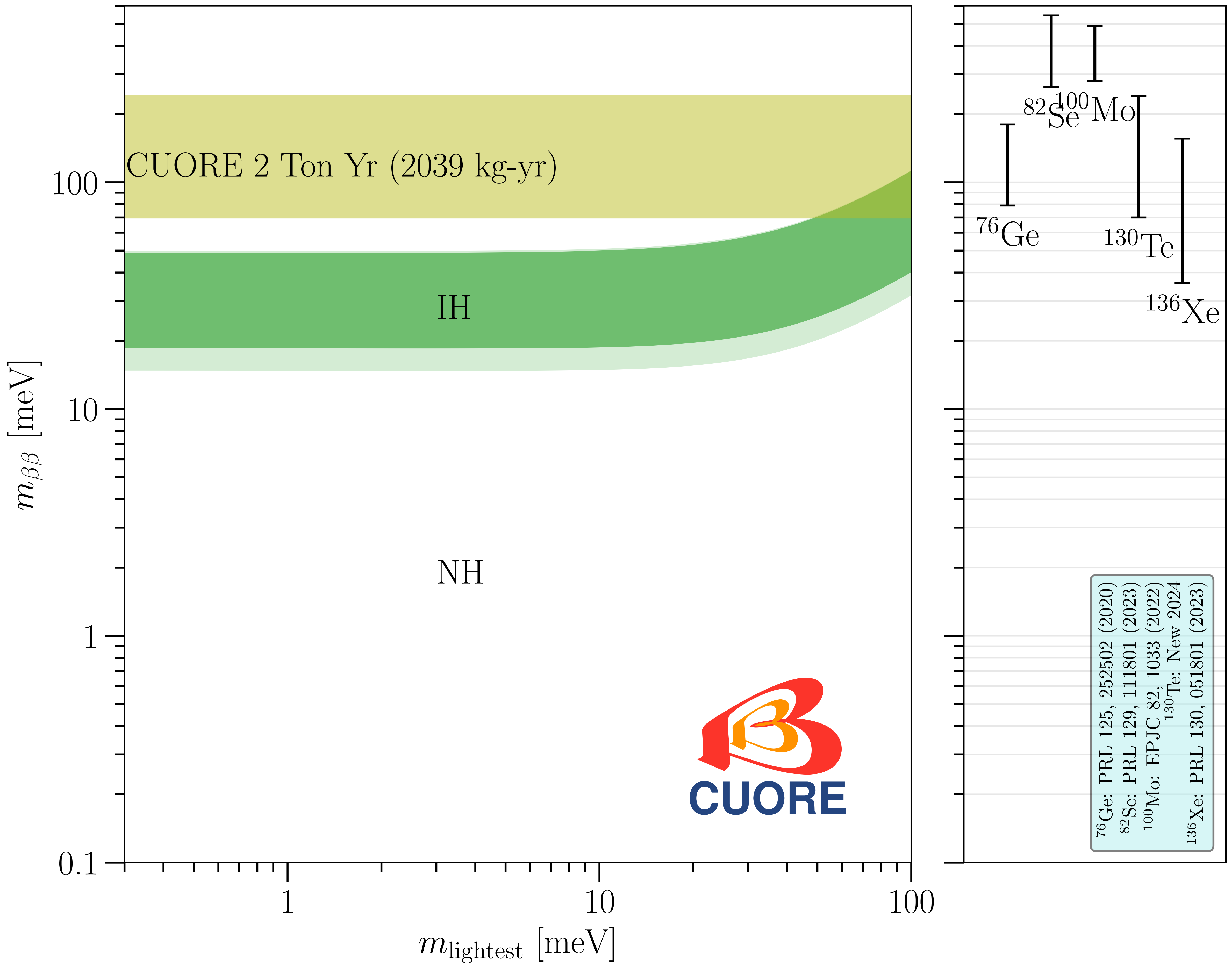
Pulse Shape Analysis (PCA)



CUORE: Systematics

- Extract background index by running fit with bkg-only hypothesis
- Use 10^4 Toy Monte Carlo simulations to extract exclusion sensitivity

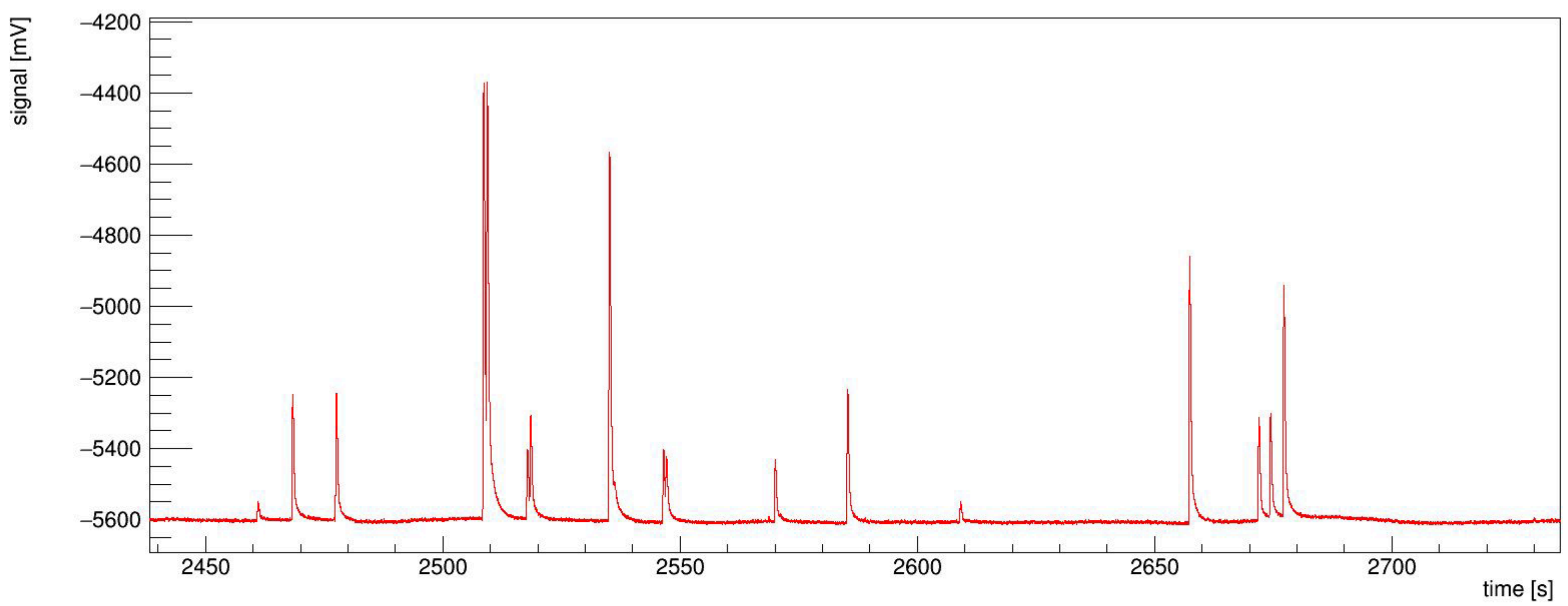


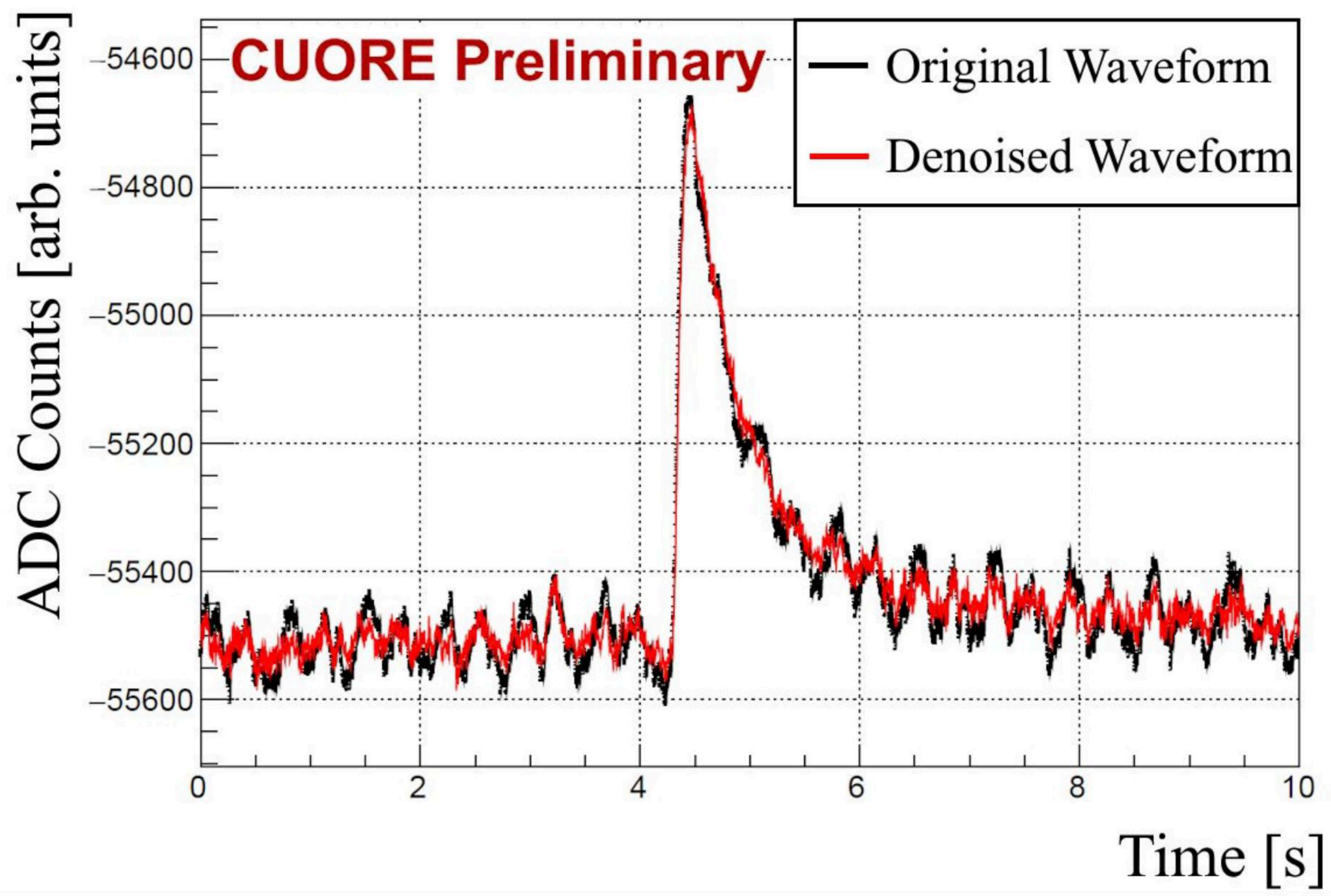


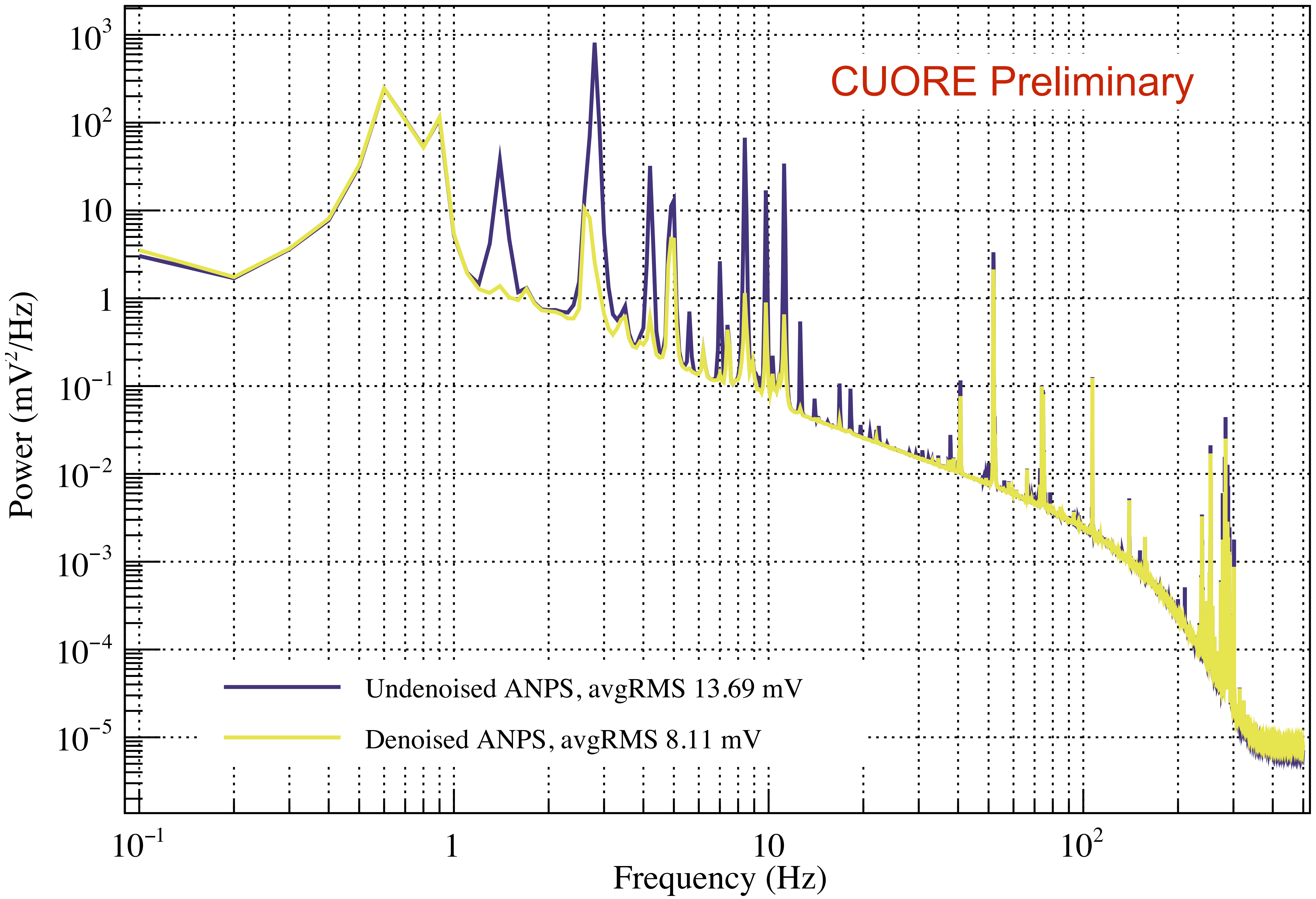
Median Exclusion Sensitivity: 4.4×10^{25} yr
(66.6% chance of more stringent limit)
$m_{\beta\beta} < [70 - 240]$ meV (depending on NME)
Average BI: $(1.42 \pm 0.02) \times 10^{-2}$ cts/keV/kg/yr

CUORE: Denoising

- New this analysis   Eur. Phys. J. C 84, 243 (2024)
- Various auxiliary environmental sensors around cryostat - microphones, accelerometers, seismometers
- Build up predicted noise contribution by correlating noise between auxiliary devices and correlating with calorimeter noise
- Produces less noisy data





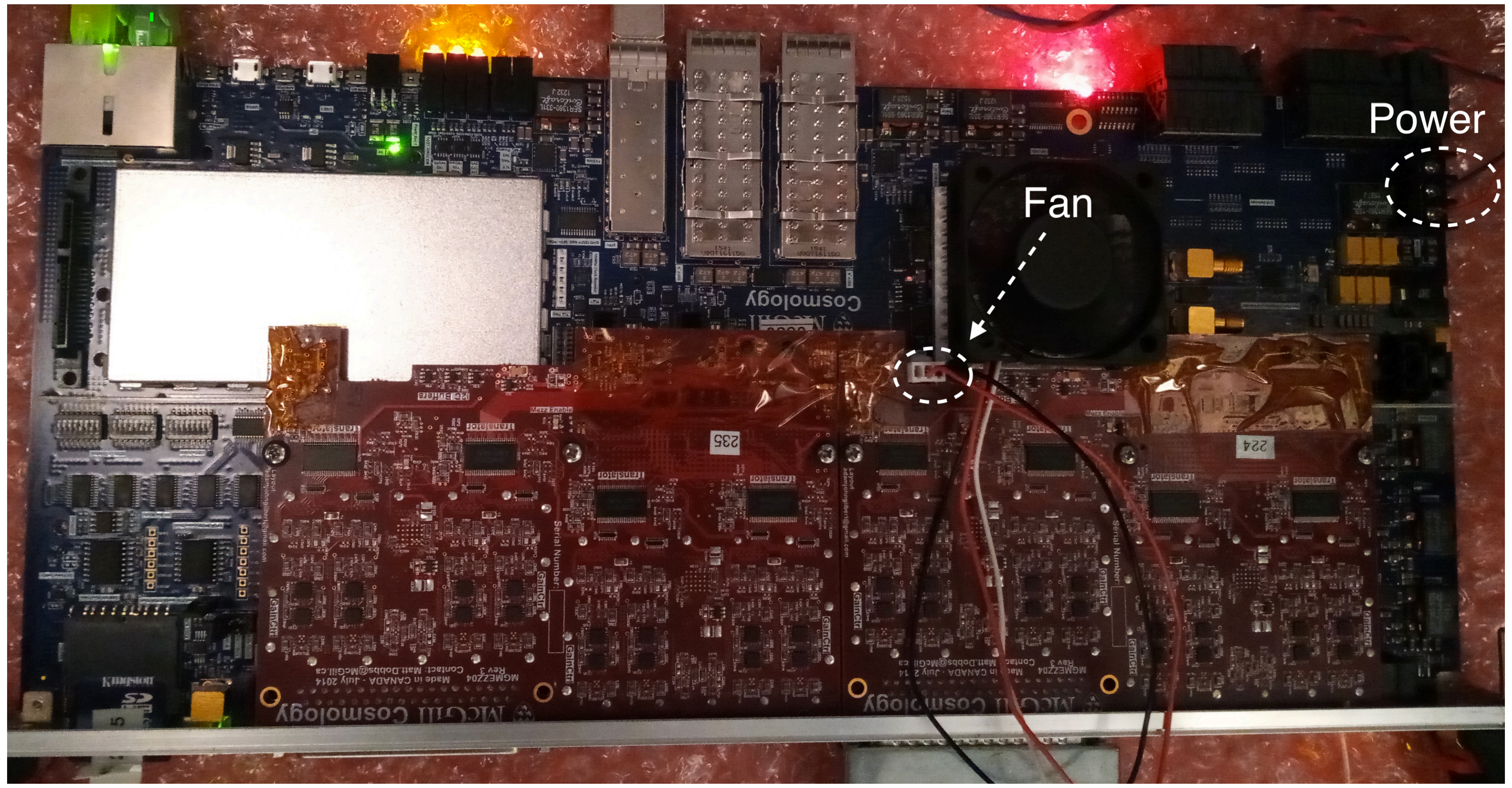


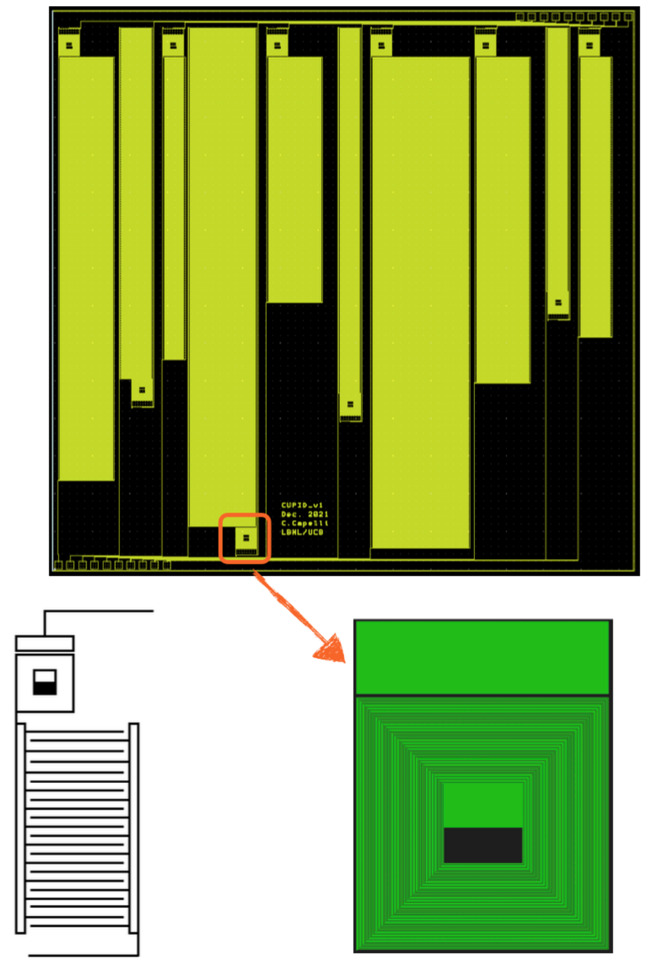
TES fMUX

- Working with Aritoki Suzuki CMB group at LBL & McGill
- 10 resonators with L ~4 μH and variable C
- Lithographic spiral inductors with interdigitated capacitors on Si substrate
- Cross talk expected < 0.4%, resonance Q-factor ~ 50
- Superconducting Al-PCB and superconducting flex cable

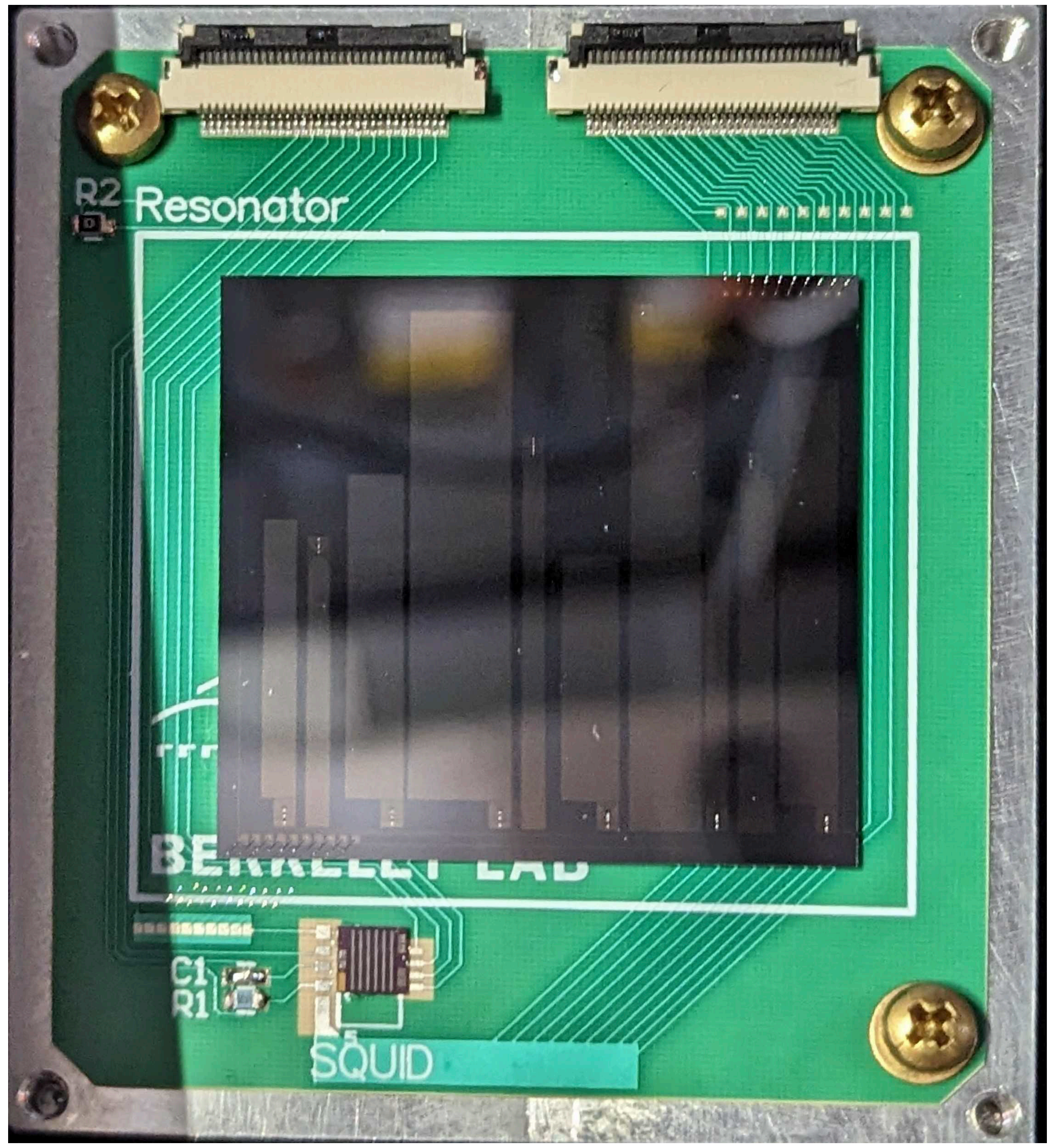
IceBoard that controls fMUX

A. N. Bender, et al. 1407.3161
T. De Haan, G Smecher, M. Dobbs 1210.4967

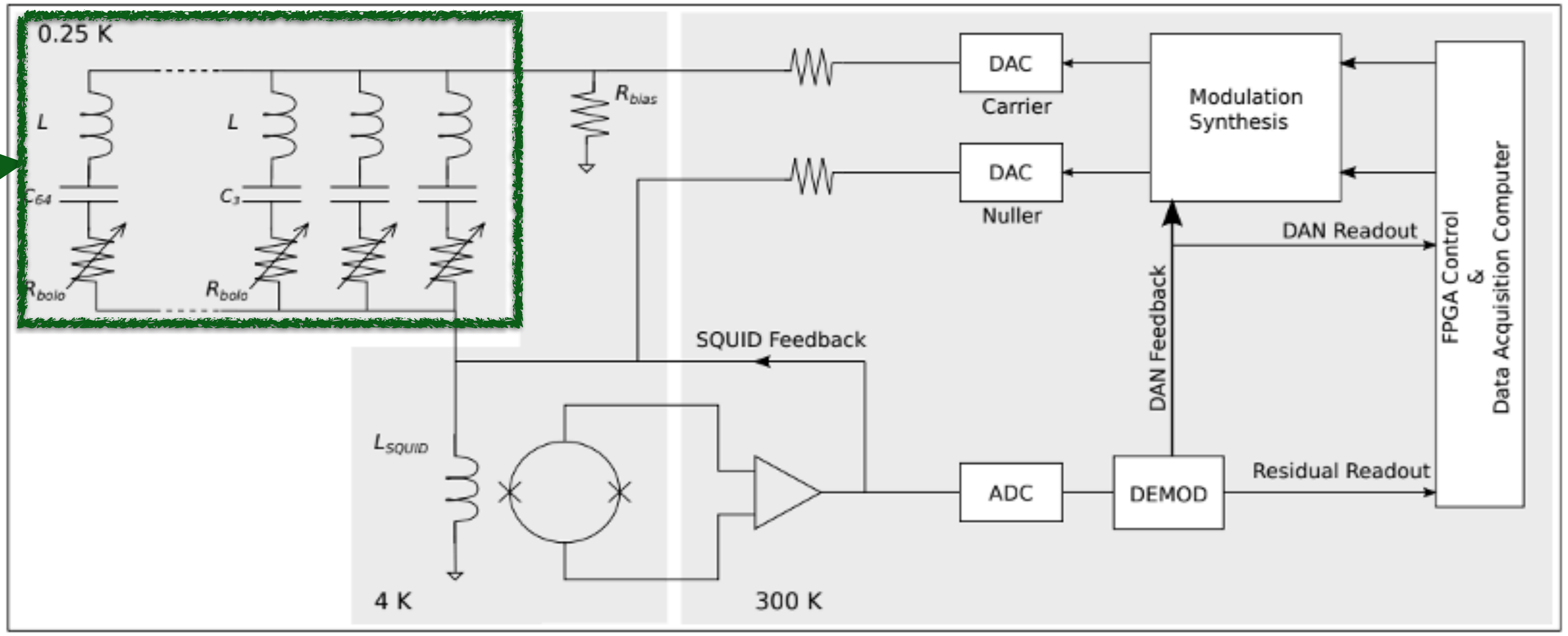




Adapted from CMB experiment:
J Low Temp Phys **184**, 486–491 (2016)



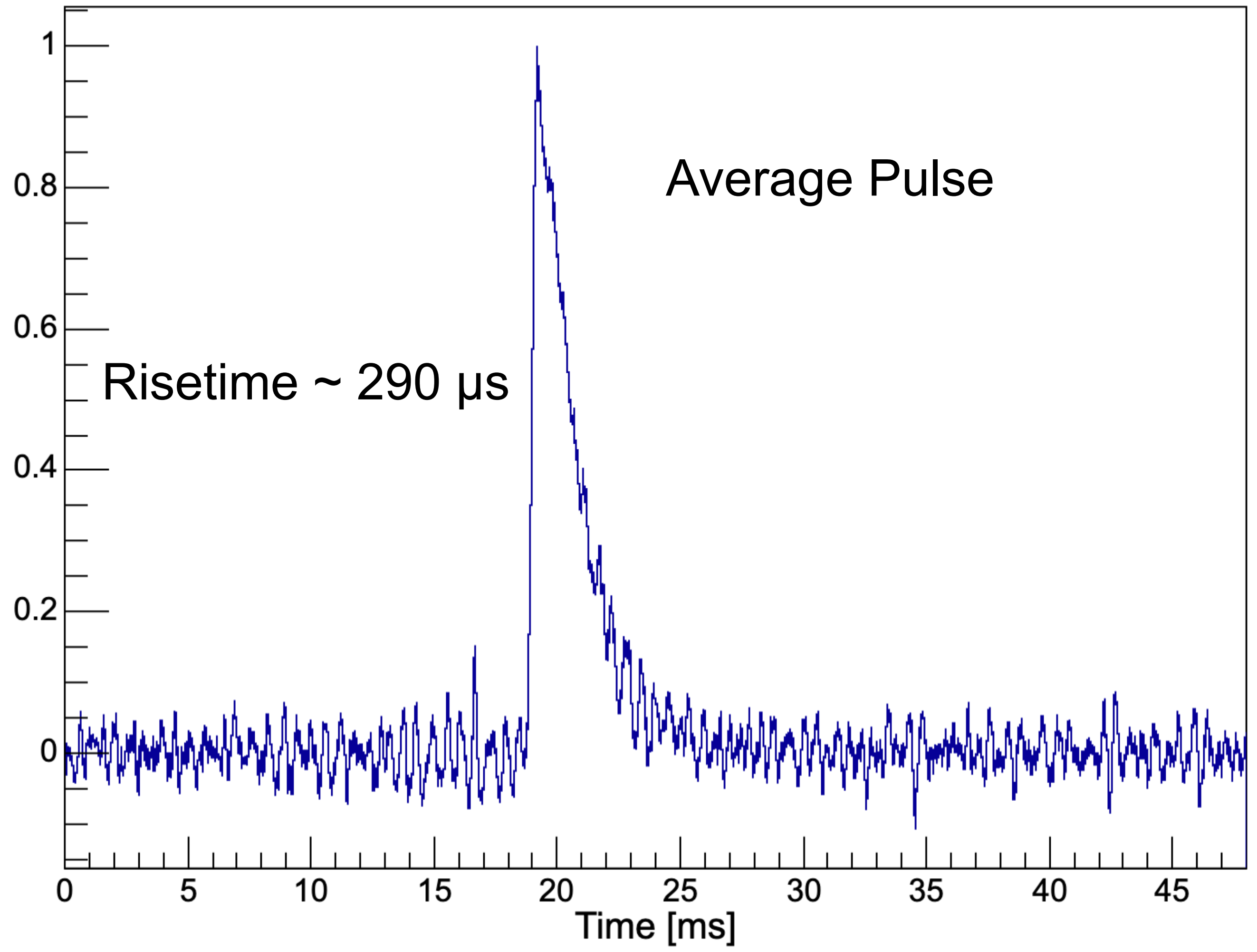
Prototype fMUX resonator
SA13 SQUID (NIST)

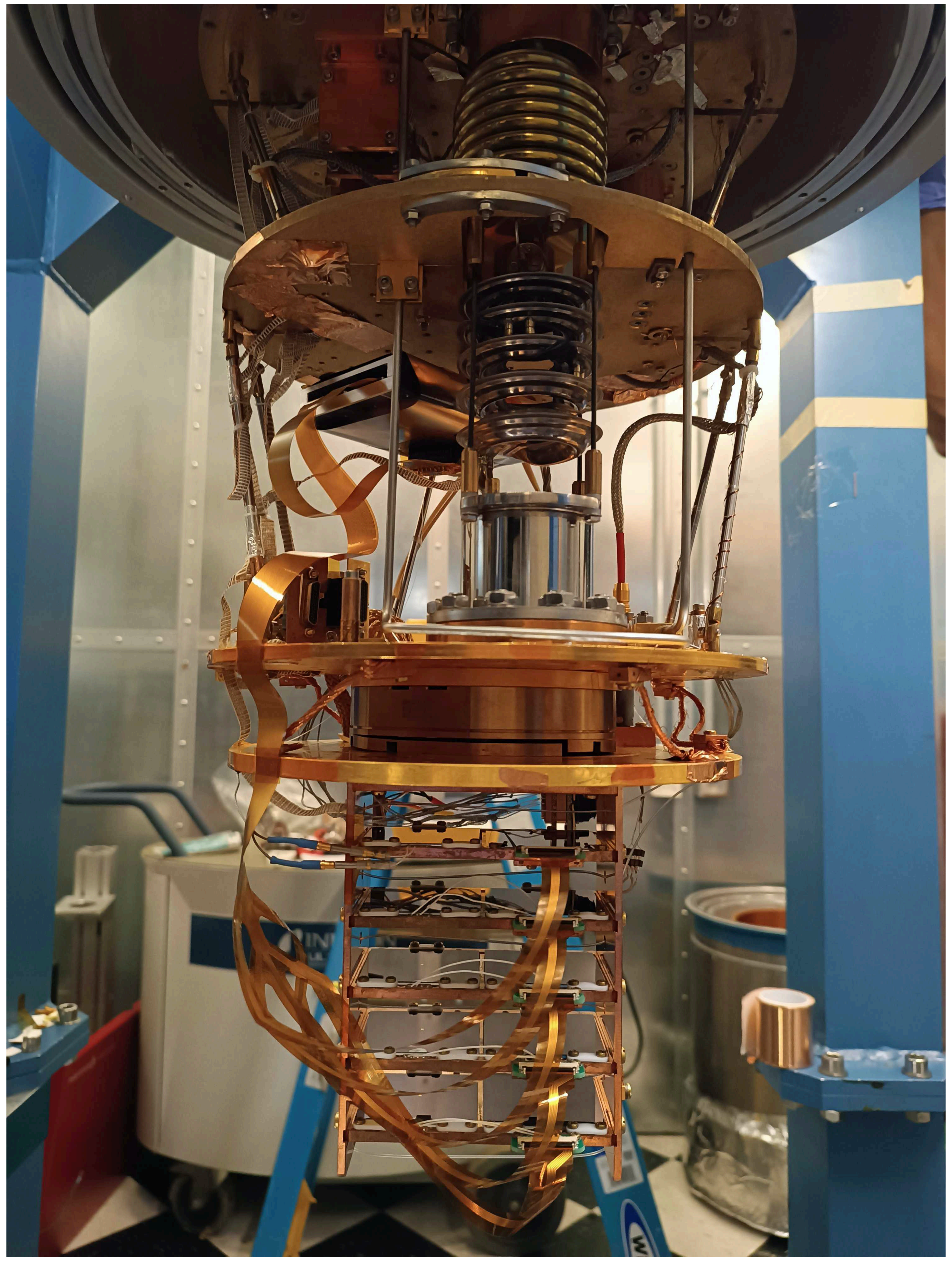


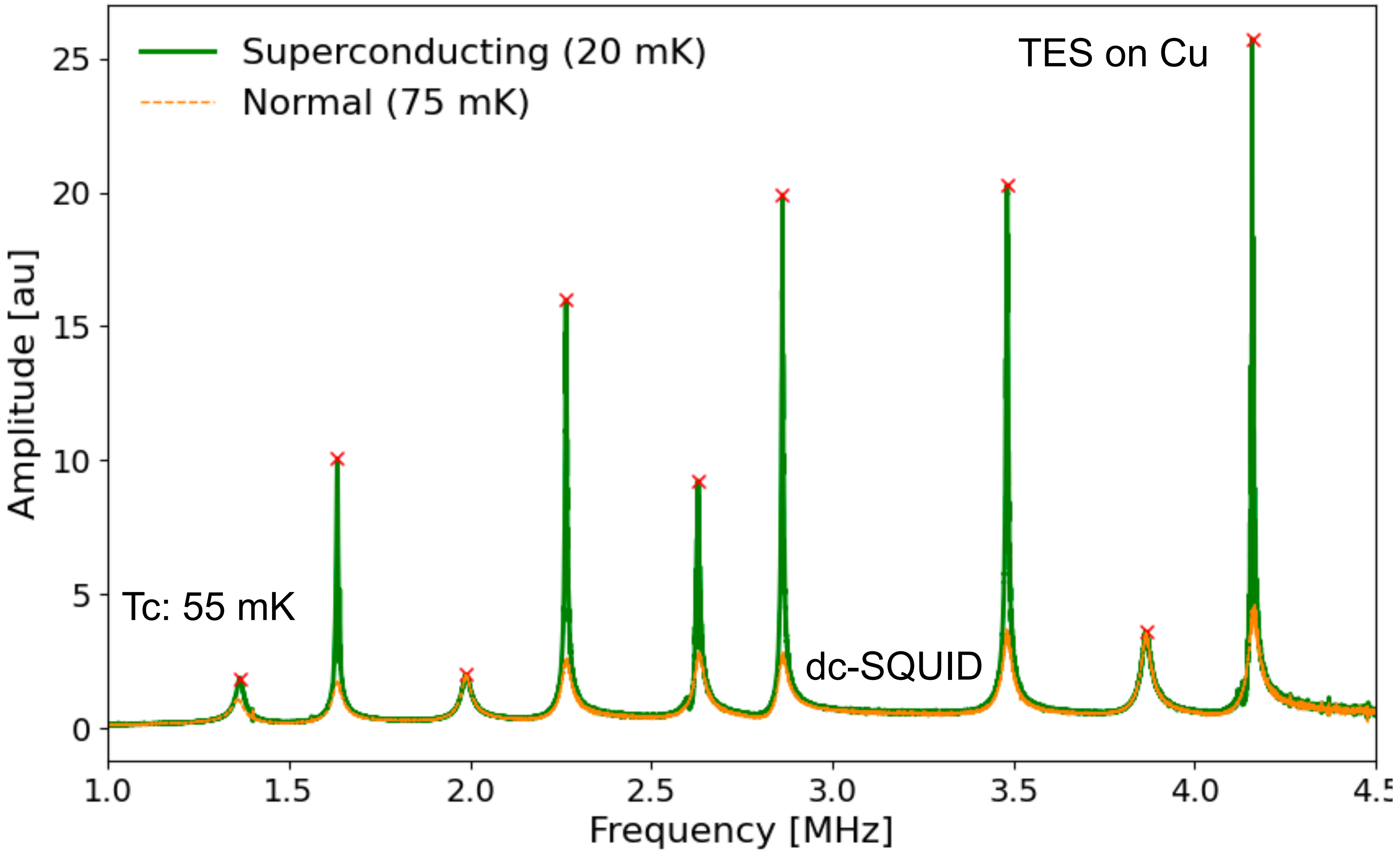
Proceedings of SPIE 9914 99141D-1

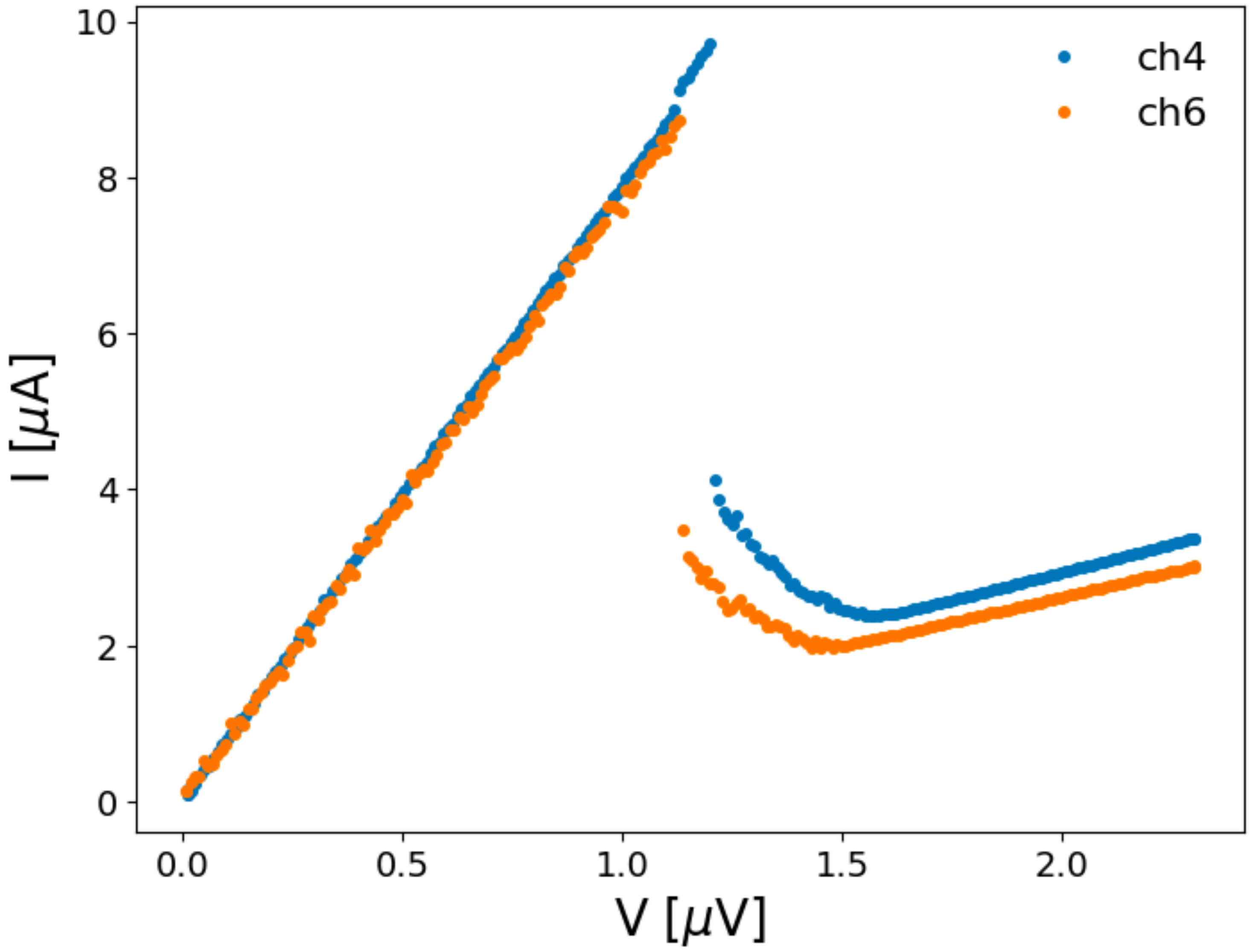
TES fMUX

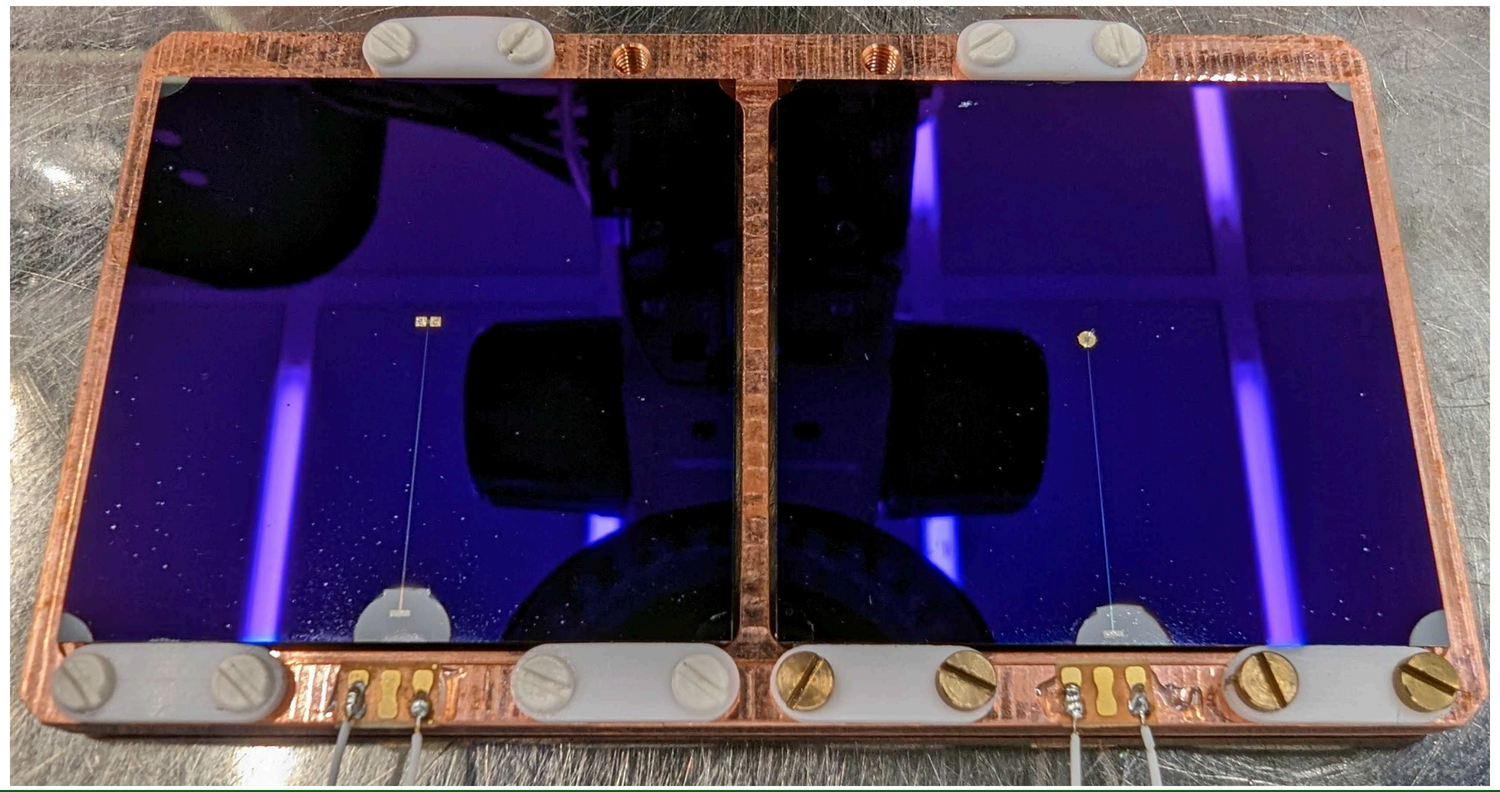
- PCB with resonator at 700 mK in magnetic shield (MetGlass)
- New square geometry to match CUPID + new semi-circular Au fins
- Detector frame that can hold 10 LDs
- Successful operation of multiple TES











MUX Upgrades

- Existing shunt impedance is inductive
  - Good for CMB but not needed here
- 5 nH: 30 mΩ at 1 MHz, 157 mΩ at 5 MHz —> switch to 20 mΩ resistive shunt
- R&D on connection between flex cable and LD mount
  - Al flex cable
  - nano-D connectors