CUORE Results and the CUPID Project

T. O'Donnell
Center for Neutrino Physics
Virginia Polytechic Institute and State University

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Outline

- Introduction to cryogenic bolometers
- The CUORE experiment
  - Detector Design
  - Cryogenic infrastructure
  - CUORE Results
- The CUPID Project

CUORE/CUPID Poster Summary

(Link to poster page)

A. Campani, *The Bayesian software for the 0vββ CUORE analysis* (Poster #101 Session 1)

G. Fantini, *Latest results from the CUORE experiment on ββ decay of ^{130}Te to the first 0^+ excited state of ^{130}Xe* (Poster #295 Session 2)

V. Singh, Precise measurement of 2*vββ deca*y half-life of ^{100}Mo using enriched $Li_2{}^{100}MoO_4$ scintillating crystals (Poster #525 Session 2)

I. Colantoni, *A dual-readout cryogenic detector for double-beta decay: the CUPID-0 experiment* (Poster #111 Session 3)

V. Dompè, *Understanding the contributions to the CUORE background* (Poster #146 Session 3)

T. Dixon, *CUPID-Mo,first sensitivity estimates for 2vββ(0vββ) decay of ^{100}Mo to excited states (*Poster #382 Session 4)

B. Welliver, I*mplementation of an Optimal Trigger in CUPID-Mo to allow for low energy searches (*Poster #448 Session 4)

V. Singh, *Development of transition-edge sensor based large area photon detectors for CUPID* (Poster #97 Session 2)

P. Loaiza, *Background model of the CUPID-Mo 0vββ experiment (*Poster #418 Session 2)

R.Huang, *Characterization of 180 nm CMOS technology at 100 mK for rare event searches* (Poster #98 Session 3)

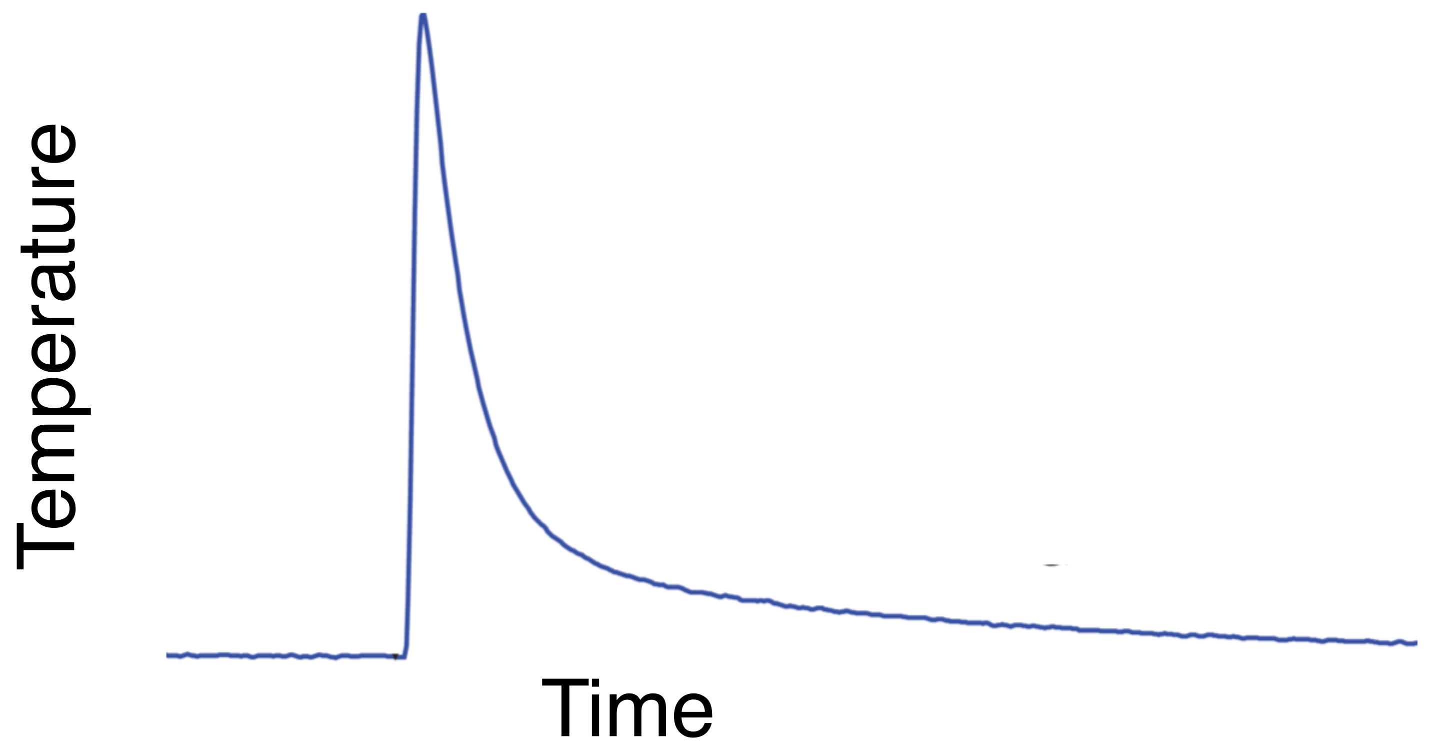
B. Schmidt, *New limit from the search for 0vββ of ^{100}Mo with the CUPID-Mo experiment* (Poster #419 Session 3)

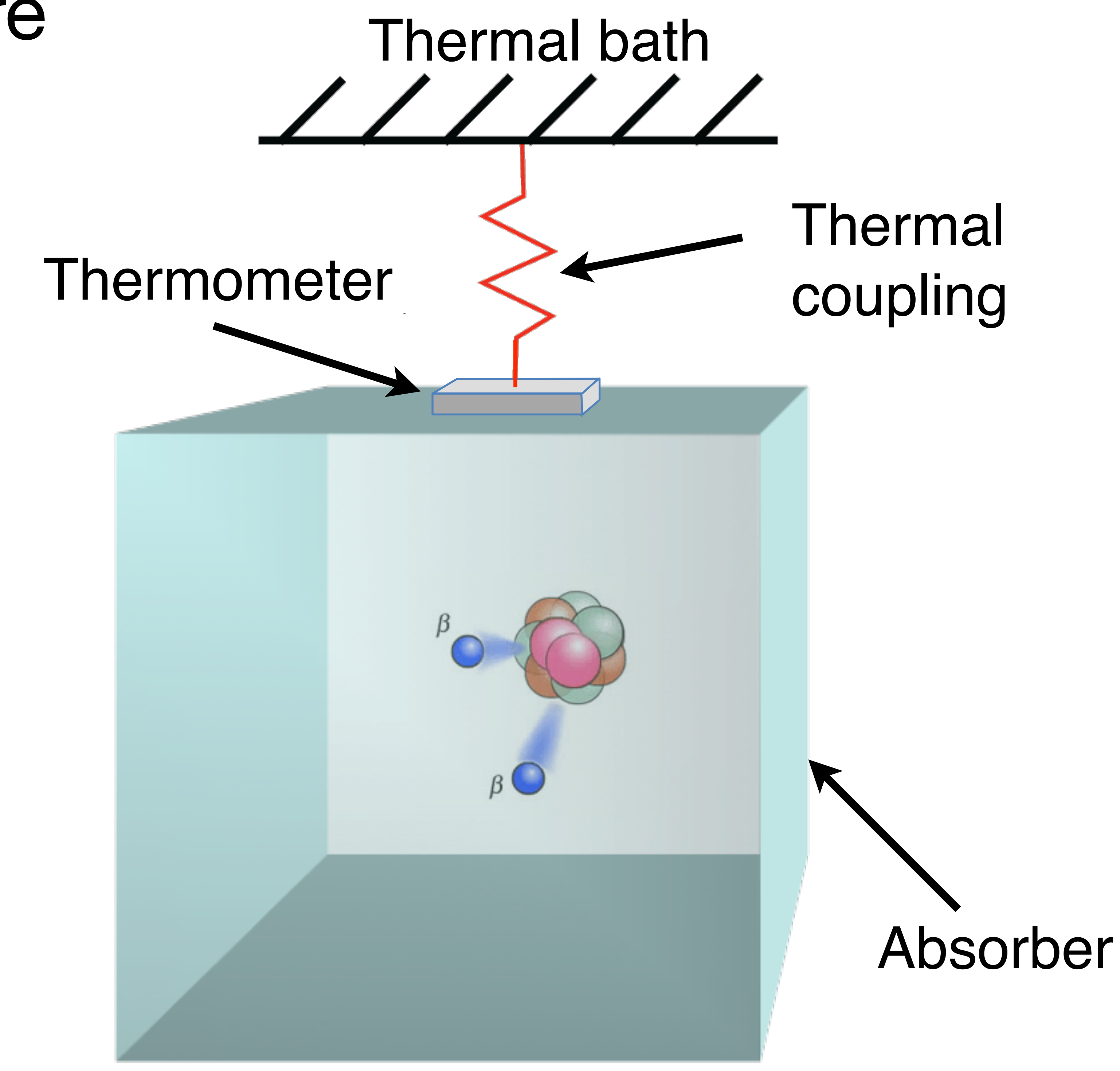
M. Zarysky, *Calibration of $Li_2{}^{100}MoO_4$ bolometers with ^{56}Co sources for searches of 0vββ decay of ^{100}Mo (*Poster #374 Session 4)

D. Poda, *The CUPID-Mo double beta decay bolometric experiment and performance* (Poster #404 Session 4)

Macro Bolometer Technique

- The absorbed energy causes an increase in absorber temperature
- Use temperature change to measure energy absorbed



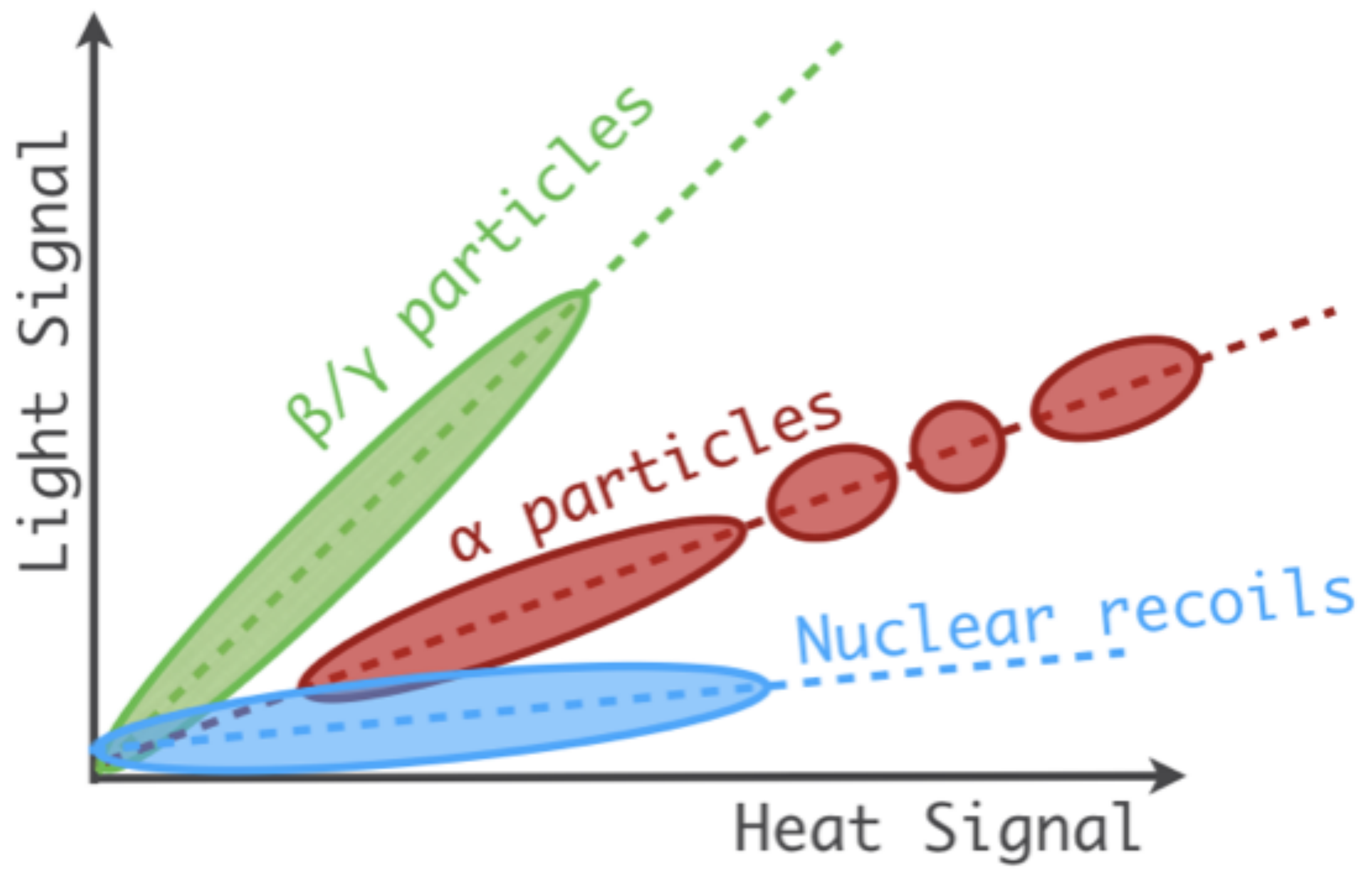


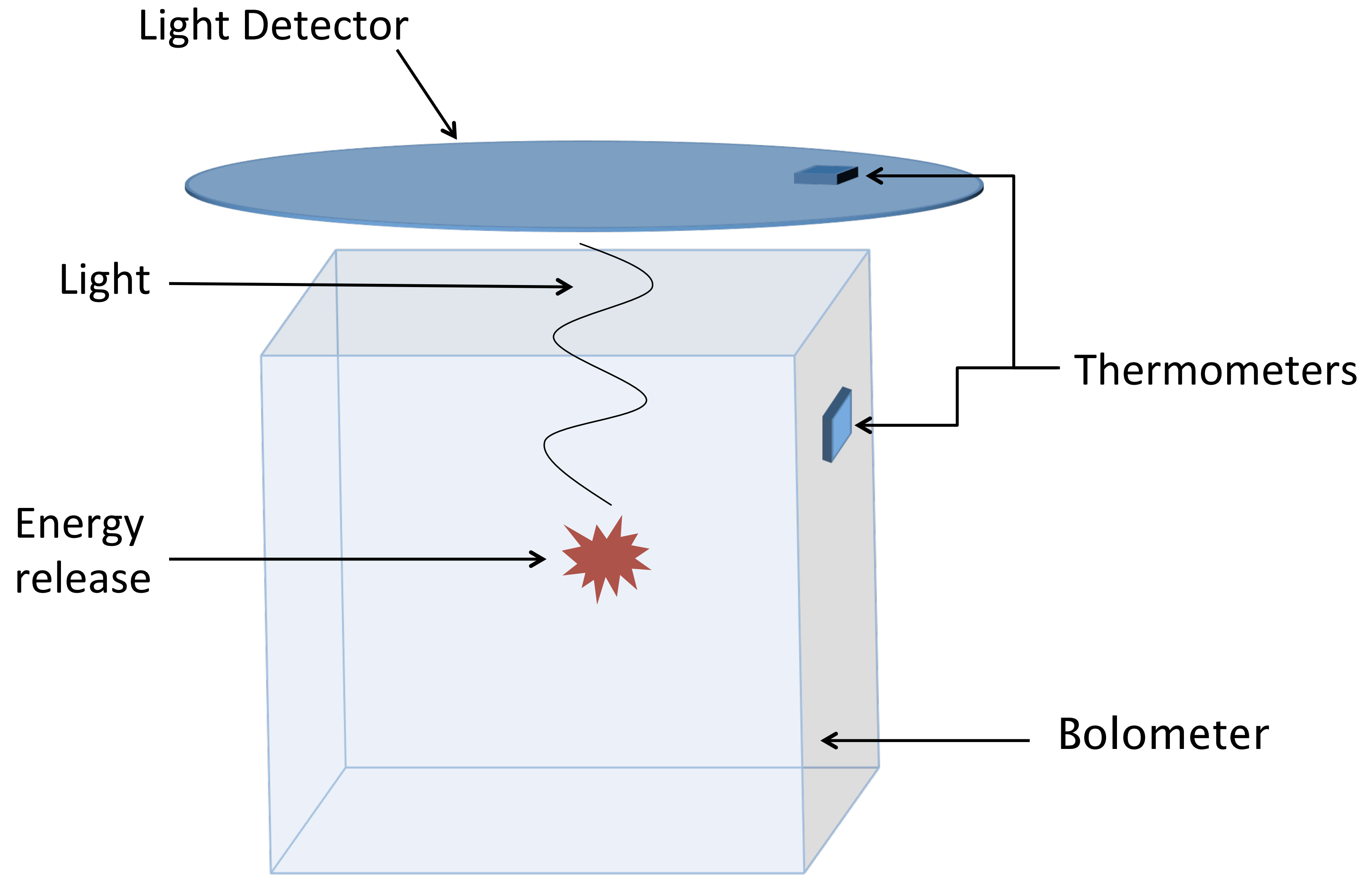
- For dielectric crystal absorbers, heat capacity $\sim T^3$
- Typically operated at ~10mK
- Relative energy resolution of 0.2~0.3% FWHM routinely achieved

CUORE uses this technique

Scintillating Macro Bolometer

- If the absorber also scintillates measuring both the thermal and light signal enables particle discrimination

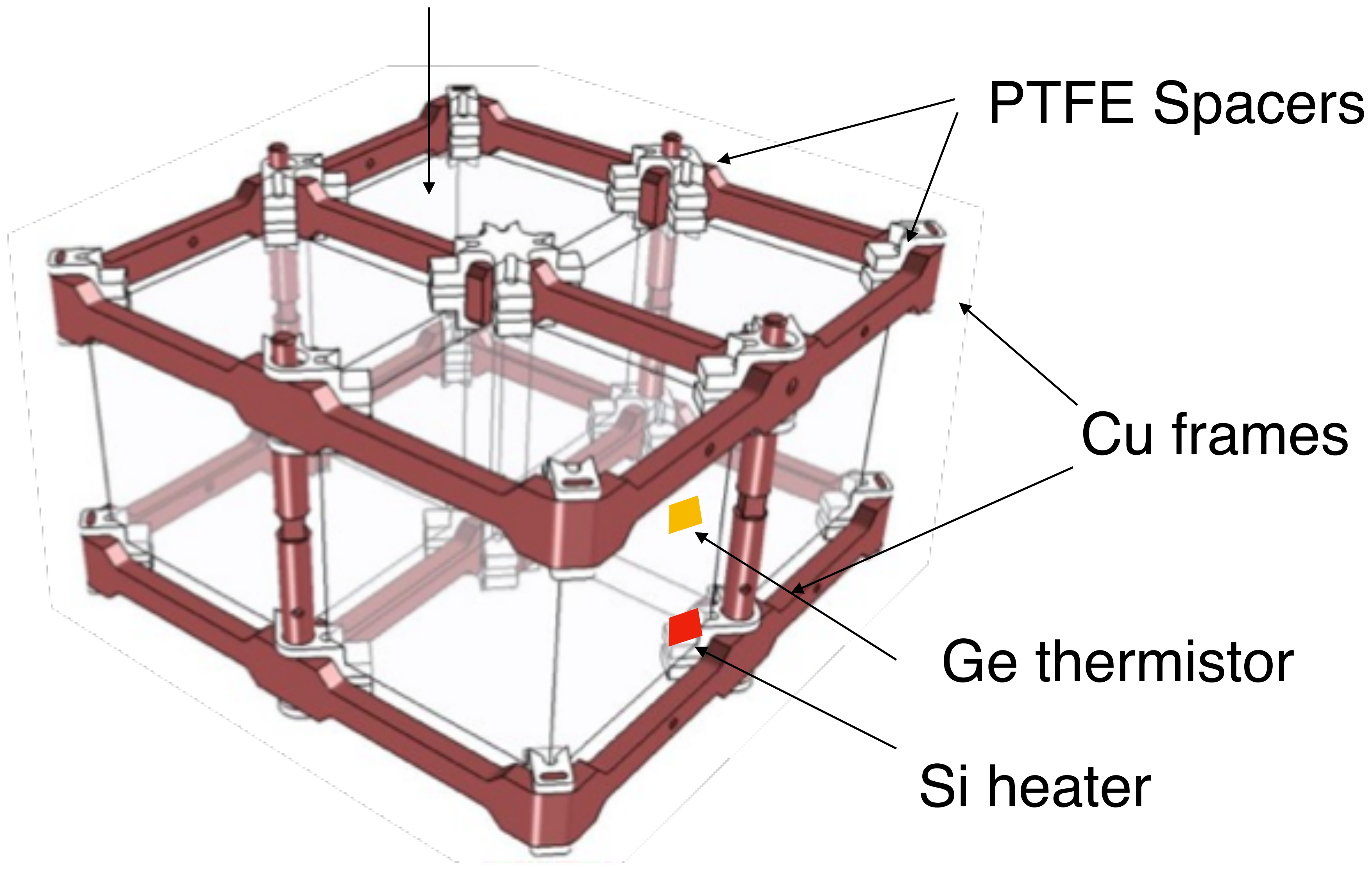




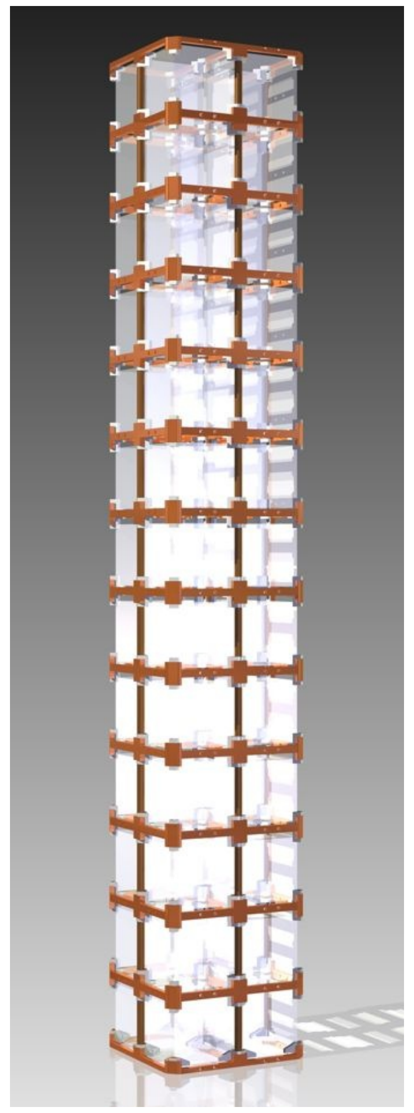
- Light detection at mK temperatures is achieved with secondary bolometer (such as Ge wafer)

CUPID will use this technique

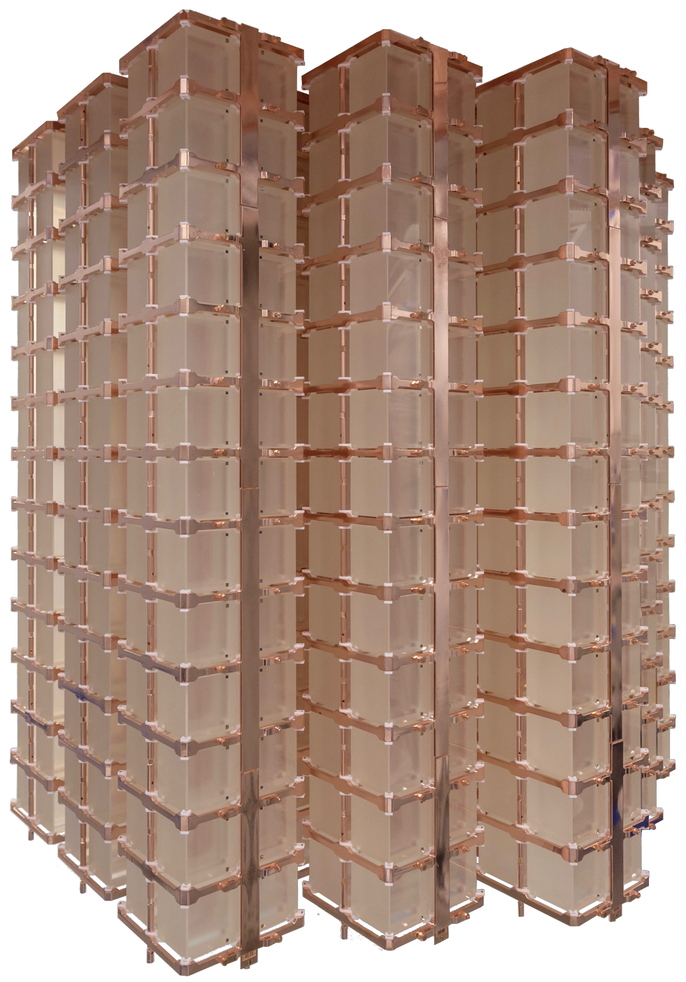
CUORE Cryogenic Underground Observatory for Rare Events

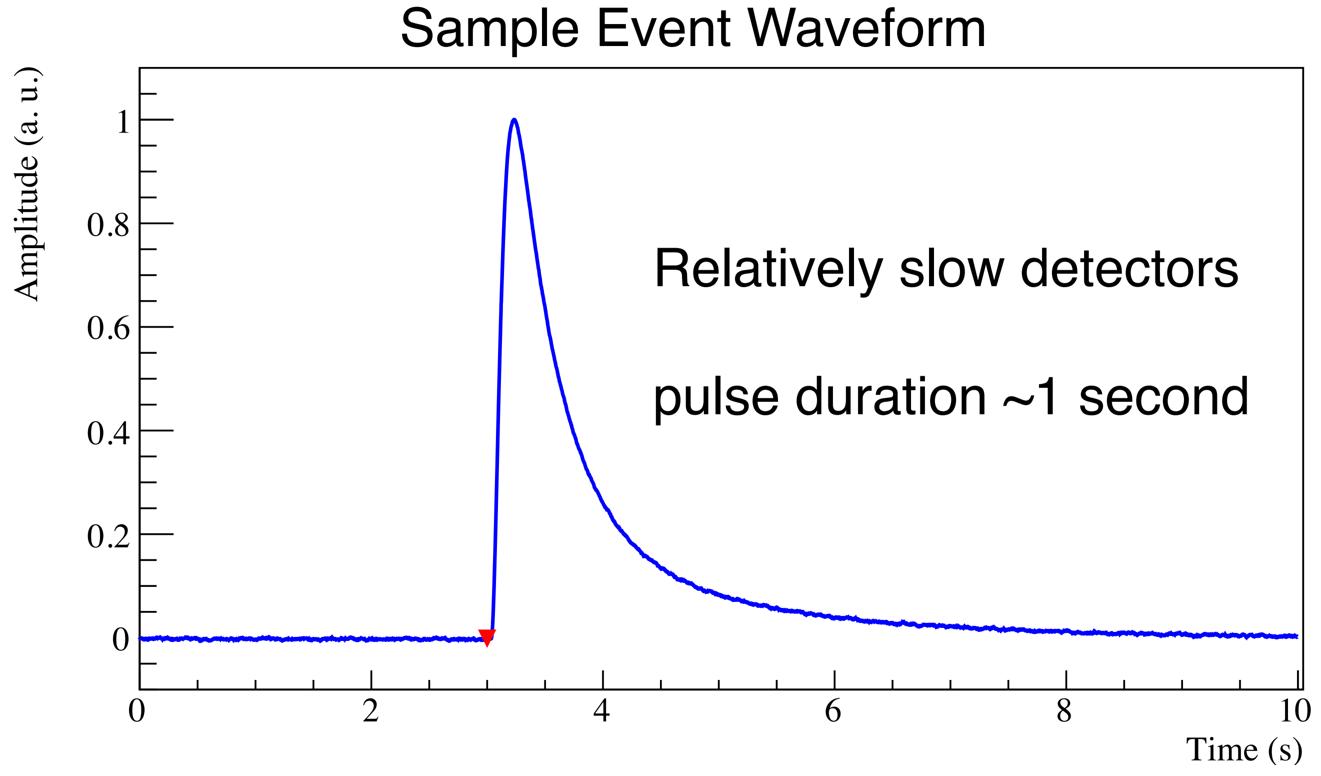


13 floors per tower



19 towers in total

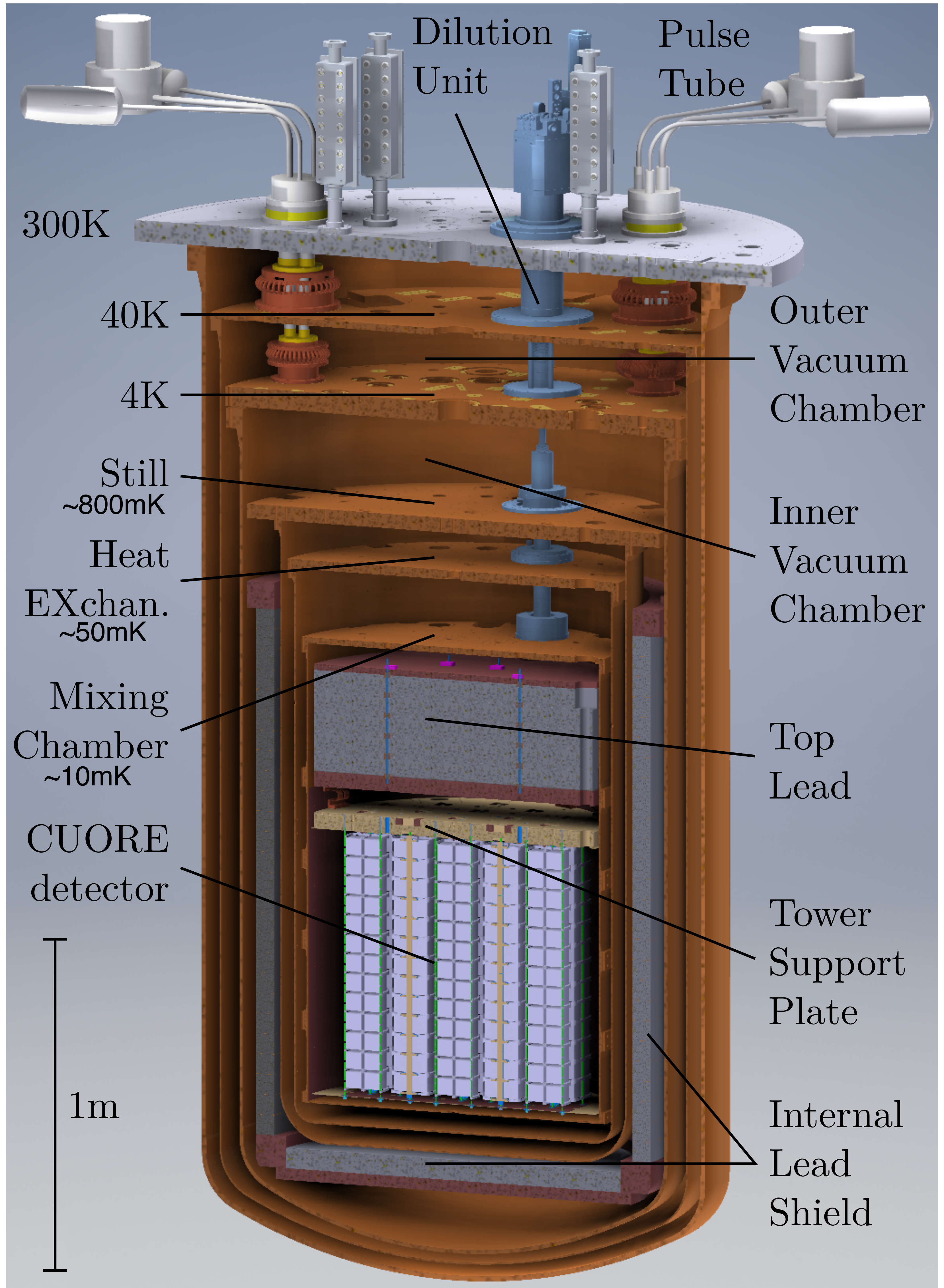




- Hosted at Gran Sasso Underground Lab
- Close-packed array of 988 $^{nat}TeO_2$ bolometers (Total active mass: 742 kg)
- Operated at T~11 mK
- Primary physics goal: 0νββ decay of ^{130}Te
  - Isotopic abundance 34% => 206 kg
  - Q-value: 2527.5 keV
- CUORE design goals:
  - Energy resolution: 5 keV FWHM near $Q_{\beta\beta}$
  - Background: 0.01 c/keV/kg/y near $Q_{\beta\beta}$
  - 0νββ sensitivity for 5 years of livetime:

$$T^{0\nu}_{1/2} = 9 \times 10^{25} yr$$

milli-Kelvin facility for tonne-scale detectors

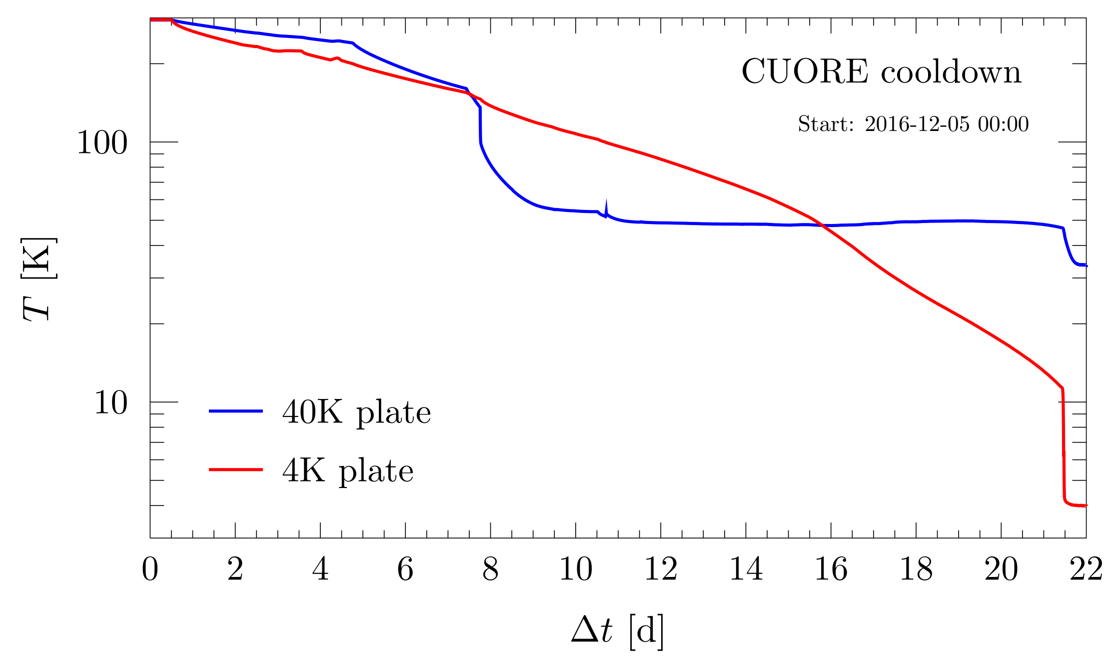


- Powerful ^{3}He-^{4}He dilution refrigerator cooling power: 5 μW at 10 mK
- Precooled by 4 pulse tubes
- Cryogenic vessels and shielding:
  - 13 tonnes < 4 K
  - 5 tonnes < 50 mK
  - 1500 kg @ 10 mK (detectors + materials)
- Experimental volume ~1 m^3 a.k.a "Coldest cubic meter in the known universe"
- Cooldown time ~ 1 month
- External Shielding:
  - 18 cm polyethylene + 2 cm borated material
  - 30 cm lead

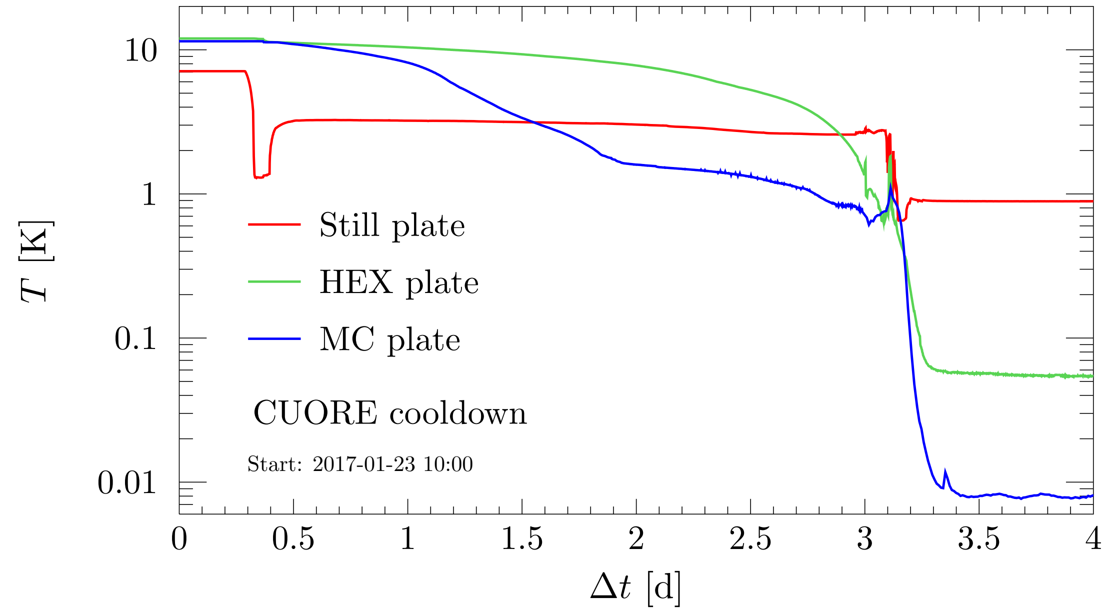
Cryogenics ***102****, 9-21 (2019). arxiv:1904.05745*

Cryogenics ***93****, 56-65 (2018). arxiv:1712.02753*

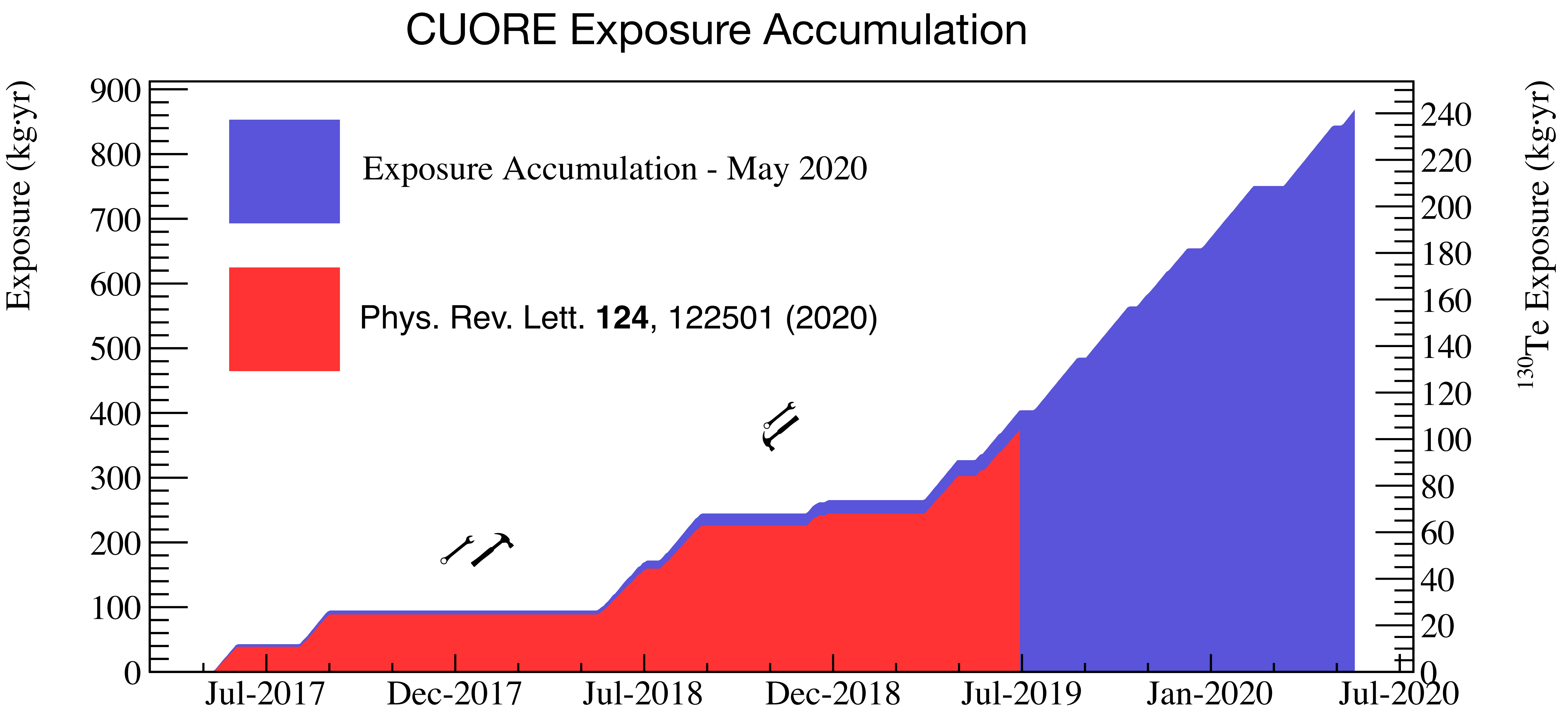
Cooldown 300K —> 4K

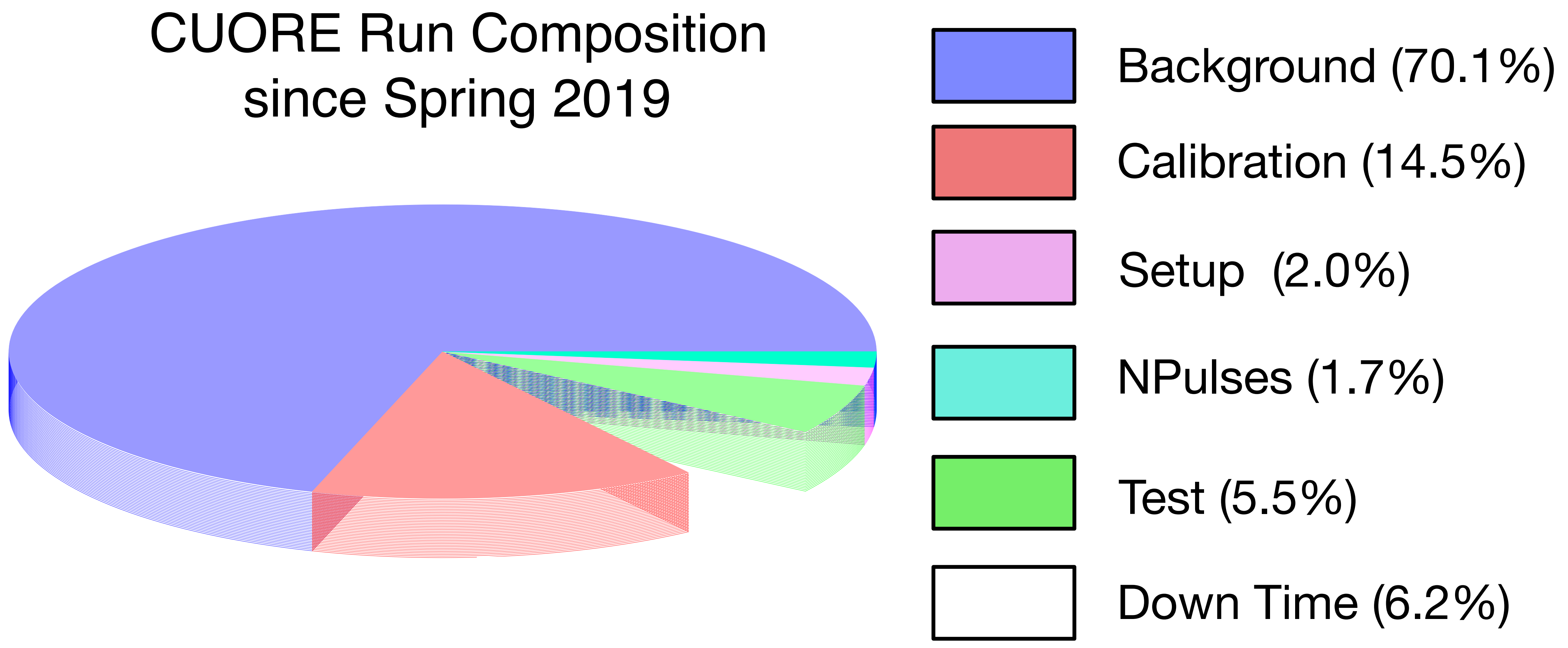


Cooldown 4K —> 10mK



CUORE Status/Data taking

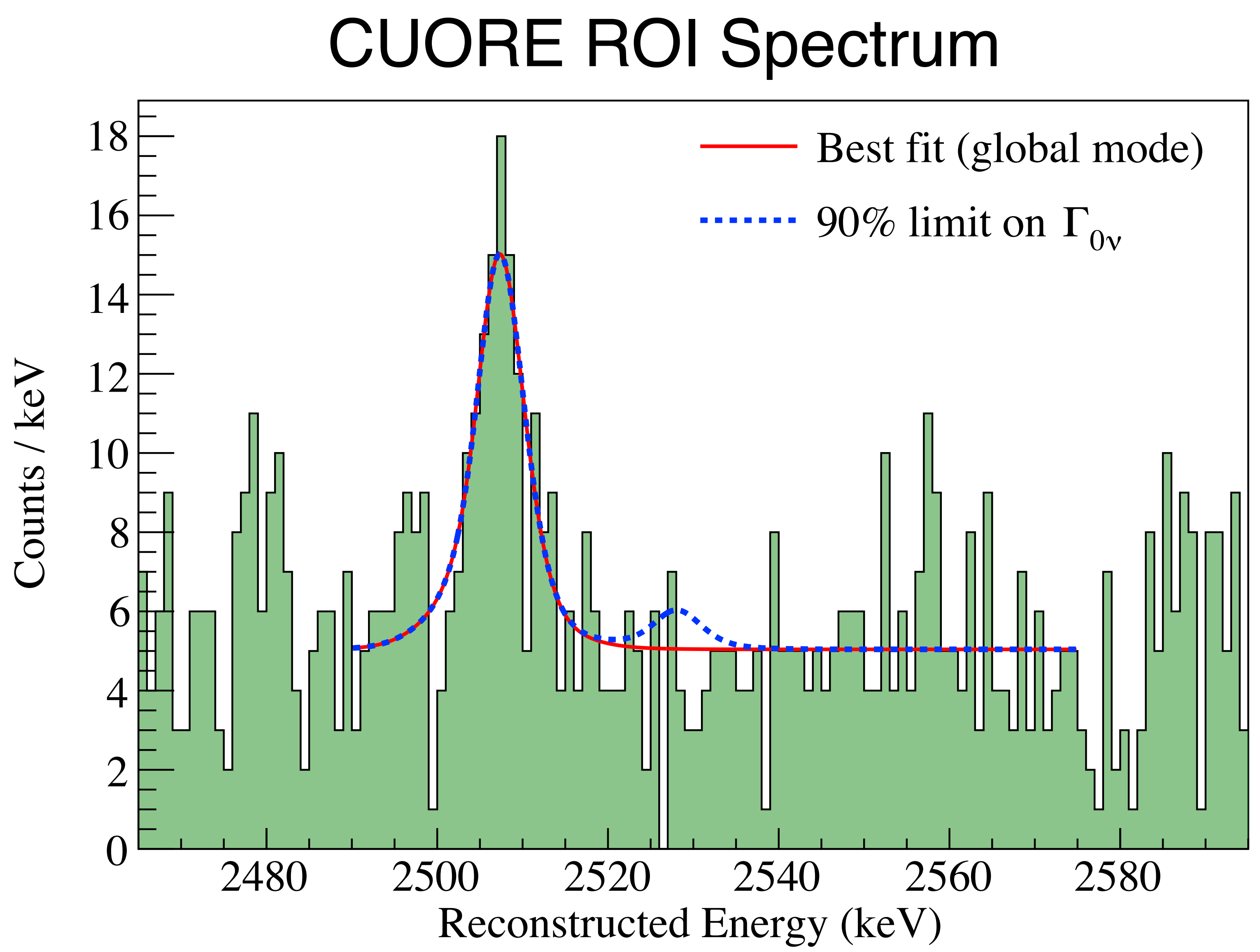


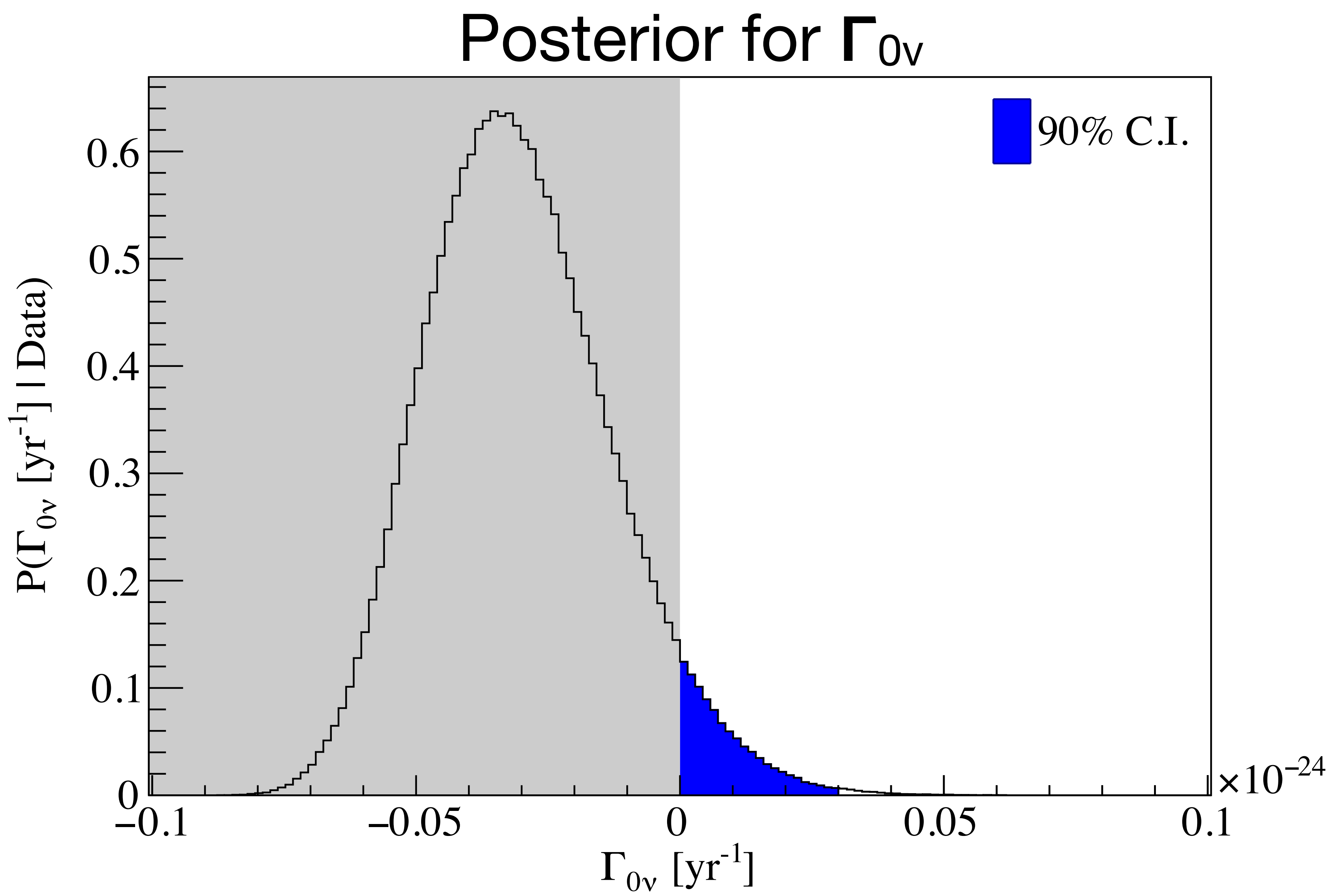


- Data taking started in Spring 2017
- After initial data taking phase, significant effort devoted to understanding the system and optimizing data taking conditions
- Since March 2019 data taking is continuing smoothly with > 90% uptime
- CUORE “data set”: ~1 month of background data taking with a few days of calibration at the start and end

Stable conditions allowed continued data taking with minimal onsite activity during recent lockdowns

CUORE: 0νββ Search





- No evidence for 0νββ decay

$$T^{0\nu}_{1/2} > 3.2 \times 10^{25}\ \mathrm{yr}\ (90\%\ \mathrm{C.I.})$$

- Interpretation in context of light Majorana neutrino exchange

$$m_{\beta\beta} < 75 - 350\,\mathrm{meV}$$

Phys. Rev. Lett. 124, 122501 (2020)

- Total exposure TeO_2: $372.5\ \mathrm{kg \cdot yr}$
- Bayesian Analysis (BAT)
- Likelihood model: flat continuum (BI), posited peak for 0νββ (rate), peak for ^{60}Co (rate + position)
- Unbinned fit on physical range (rates non-negative), uniform prior on $\Gamma_{0\nu}$
- Systematics: repeat fits with nuisance parameters, allow negative rates (<0.4% impact on limit)

See **A. Campani**, Poster #101 Session 1

Detector Performance Parameters

Background Index

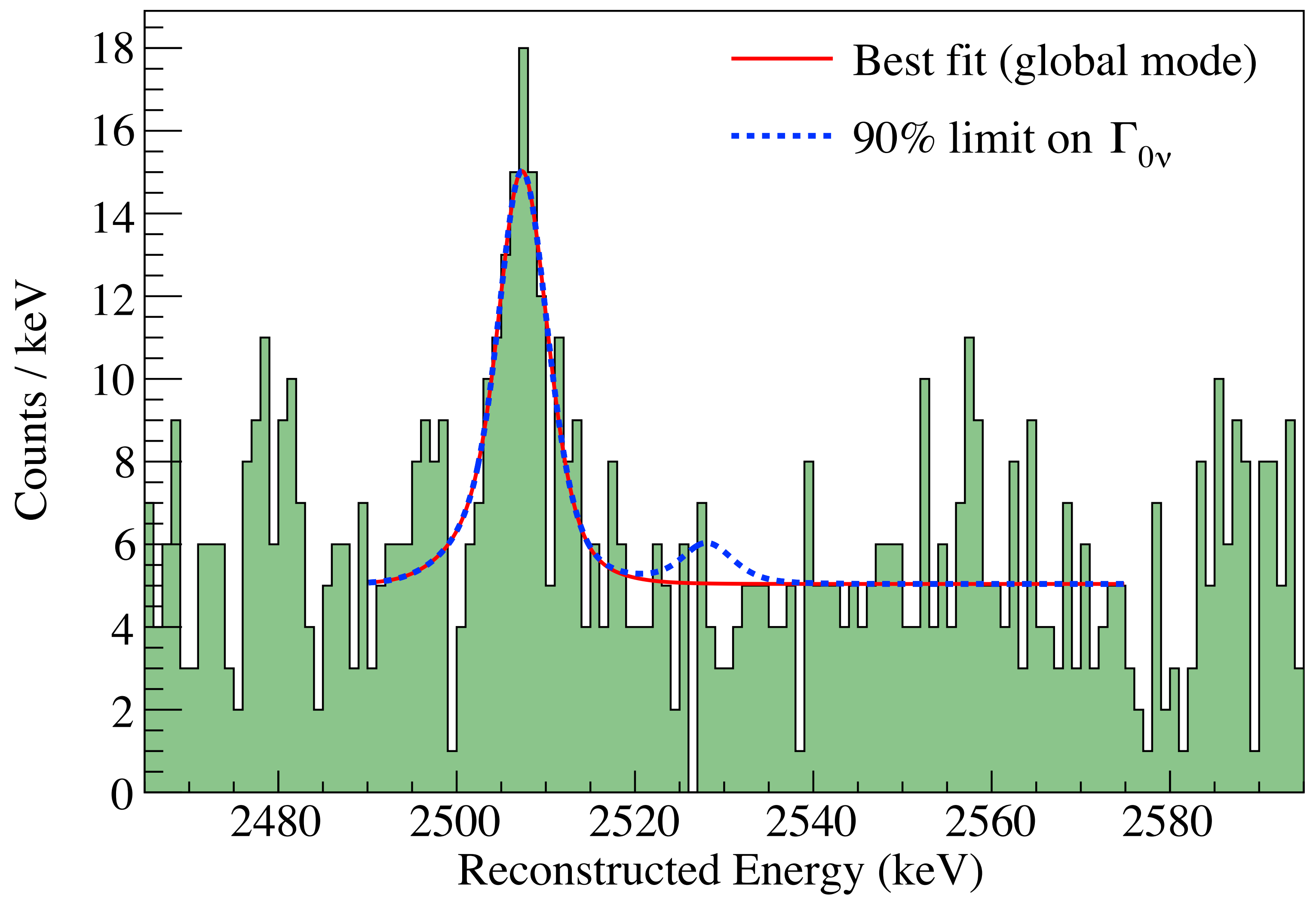
$$(1.38 \pm 0.07) \times 10^{-2} \mathrm{cnts/(keV \cdot kg \cdot yr)}$$

Characteristic FWHM ΔE at $Q_{\beta\beta}$

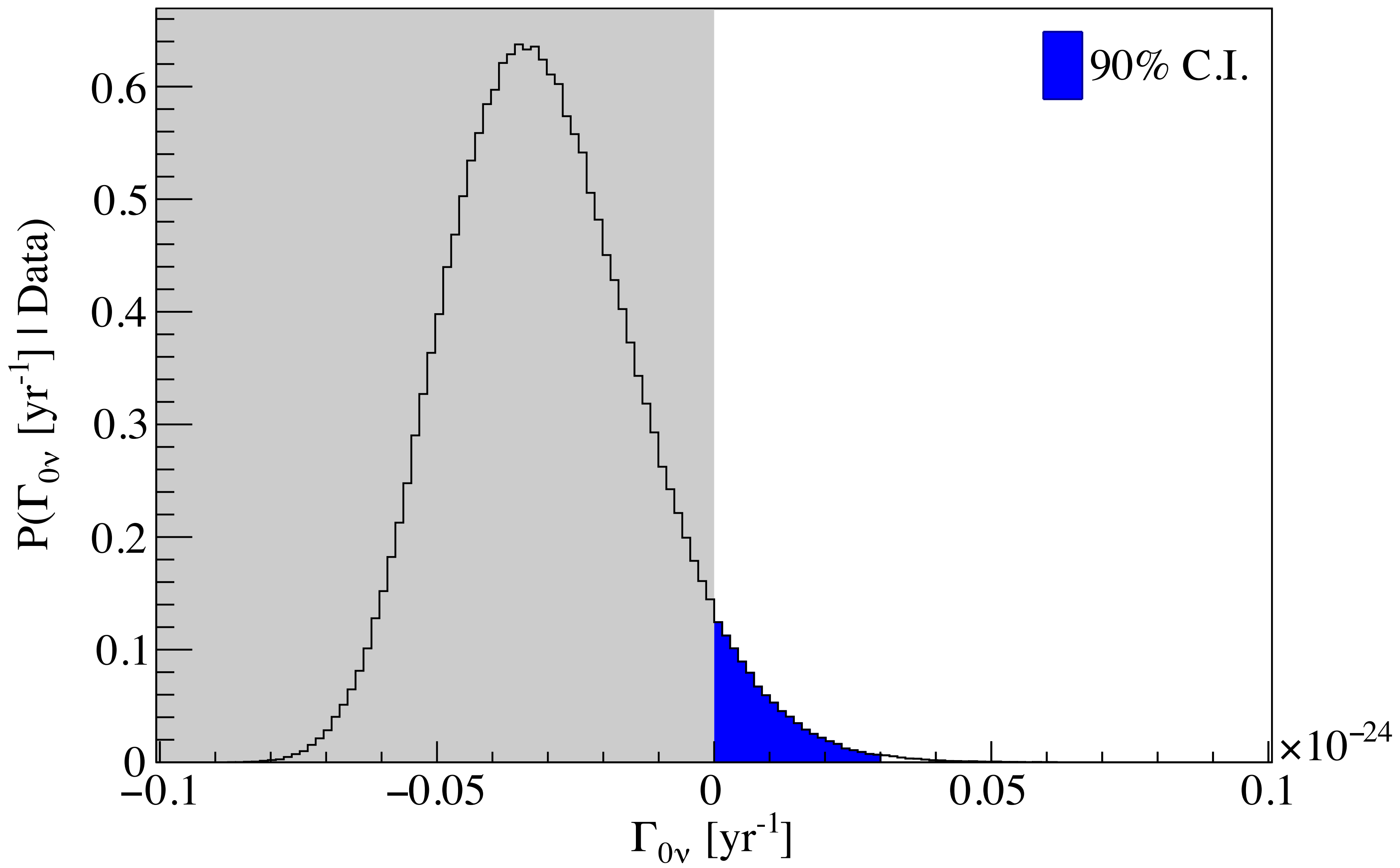
$$7.0 \pm 0.3\ \mathrm{keV}$$

CUORE: 0νββ Search

CUORE ROI Spectrum



Posterior for $\Gamma_{0\nu}$



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See **A. Campani**, Poster #101 Session 1

Detector Performance Parameters

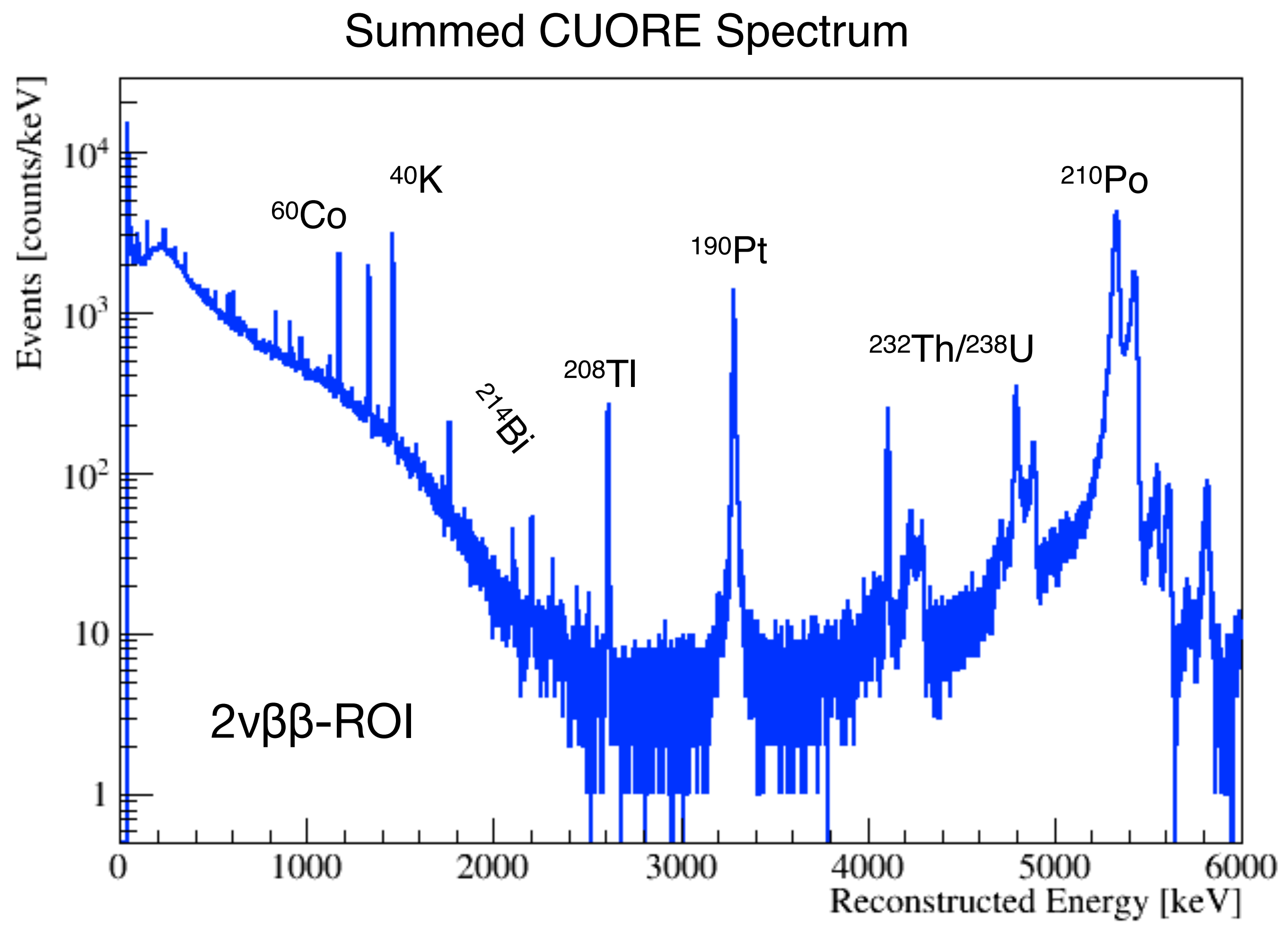
Data taking continues smoothly — next unblinding

$1\ \mathrm{tonne}\cdot\mathrm{yr}$

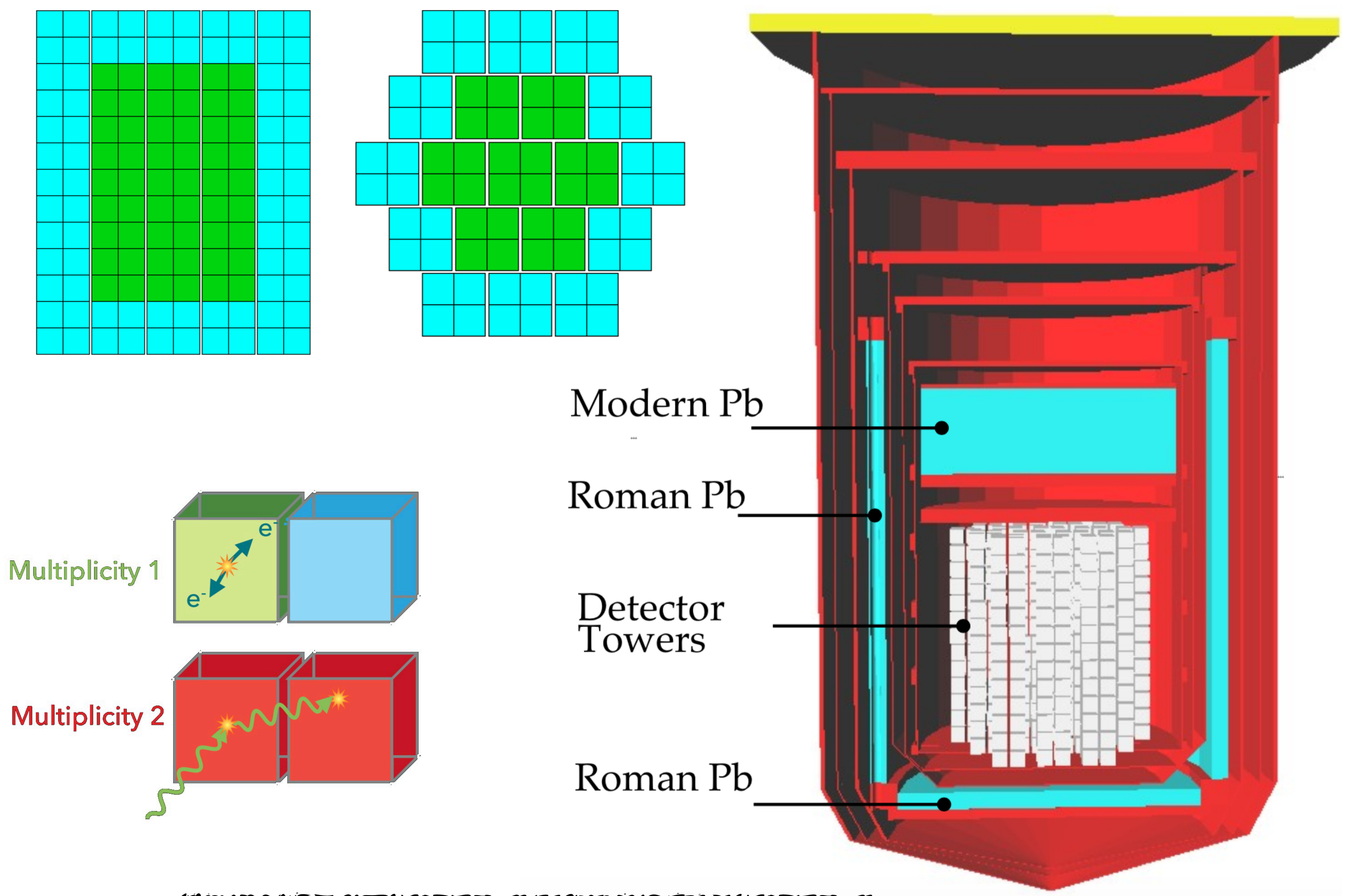
Stay tuned !

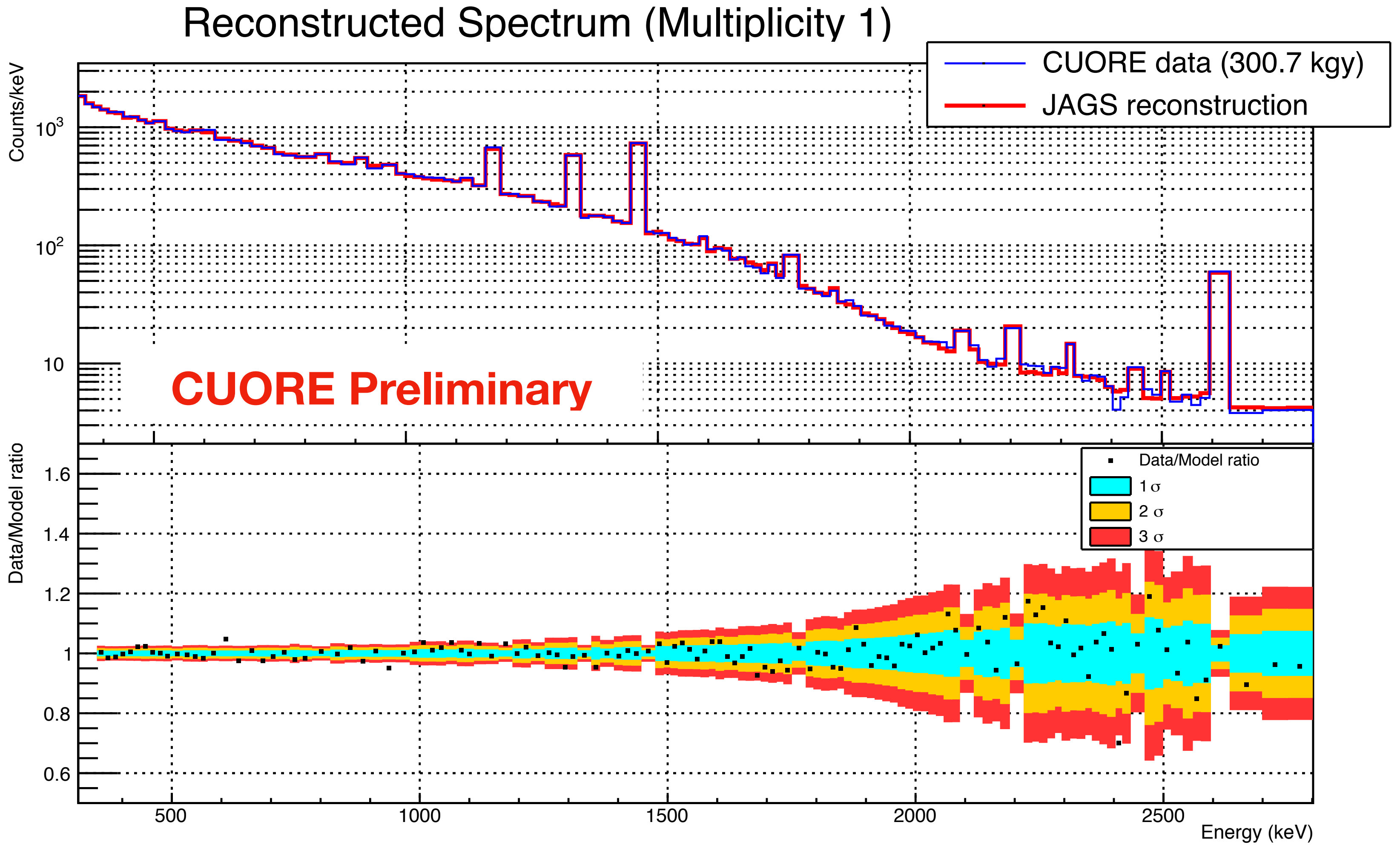
7.0 ± 0.3 keV

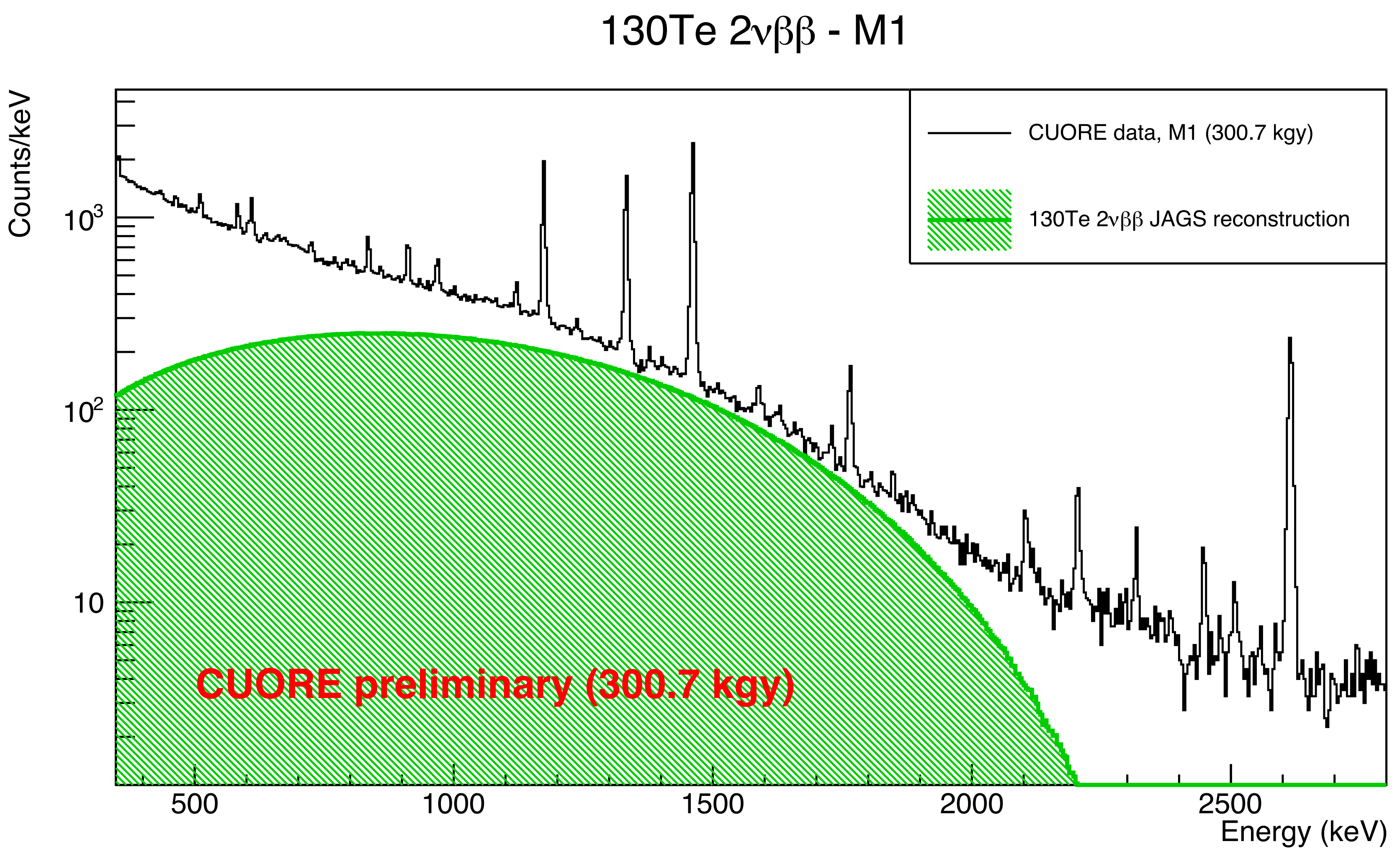
CUORE: 2νββ decay measurement



- Reconstruct CUORE continuum background
- GEANT4 simulation + measured detector response function to produce expected spectra
- 62 sources considered, Bayesian fit with flat priors (except for muons)
- Exploit coincidences & detector self-shielding to constrain location of sources







See **V. Dompè**
Poster #146 Session 3

CUORE Preliminary

$$T^{2\nu}_{1/2} = [7.71^{+0.08}_{-0.06}(\text{stat.})\,^{+0.17}_{-0.15}(\text{syst.})] \times 10^{20}\ \text{yr}$$

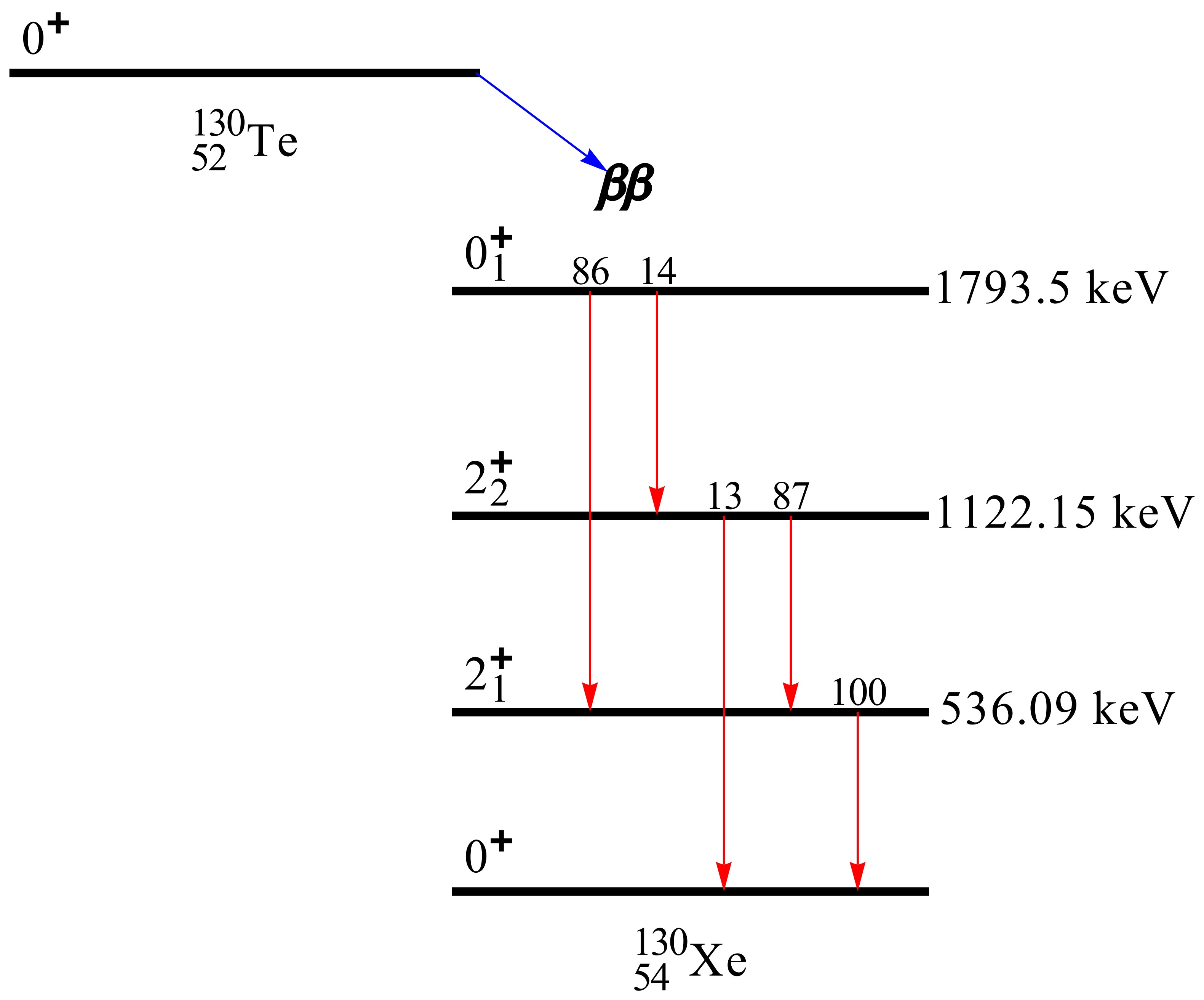
Systematic Uncertainties

- Data selection:
  - geometric splitting, time splitting, fit range
- Choice of 2νββ spectrum (single state vs. higher state dominance*)
- Unconstrained fallout products (^{90}Sr)

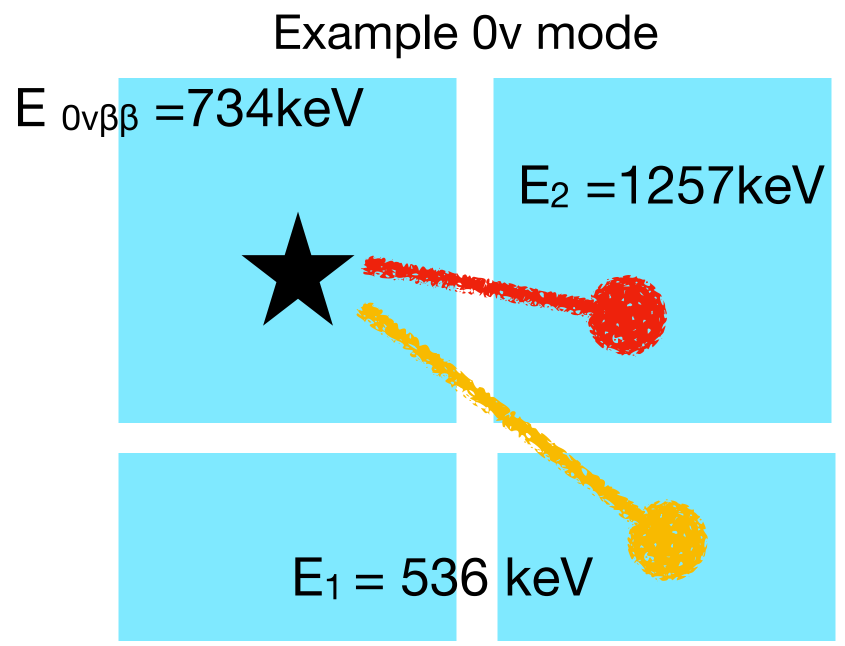
* Phys. Rev. C. 85, 034316 (2012)

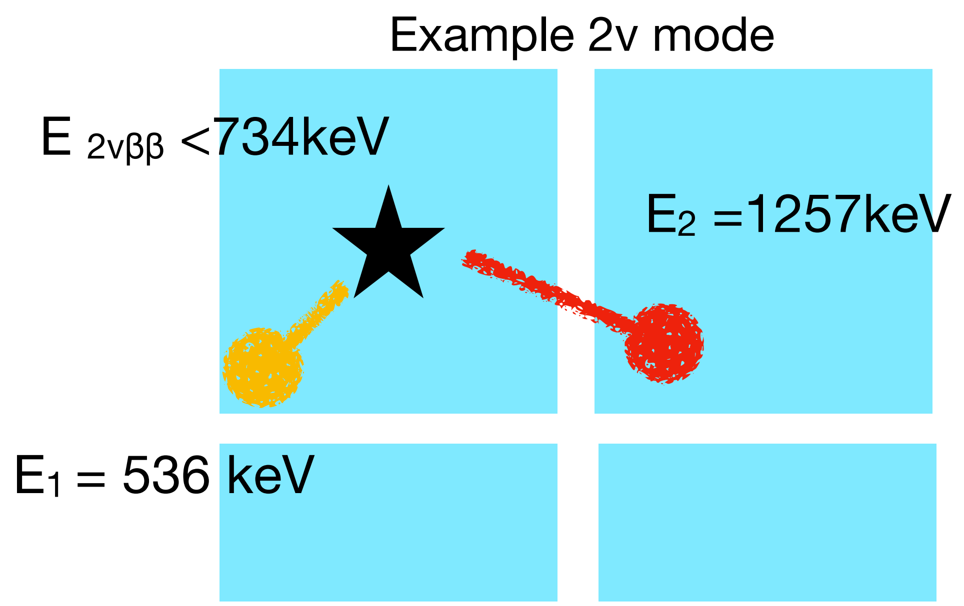
CUORE:Search for ββ decay to excited states

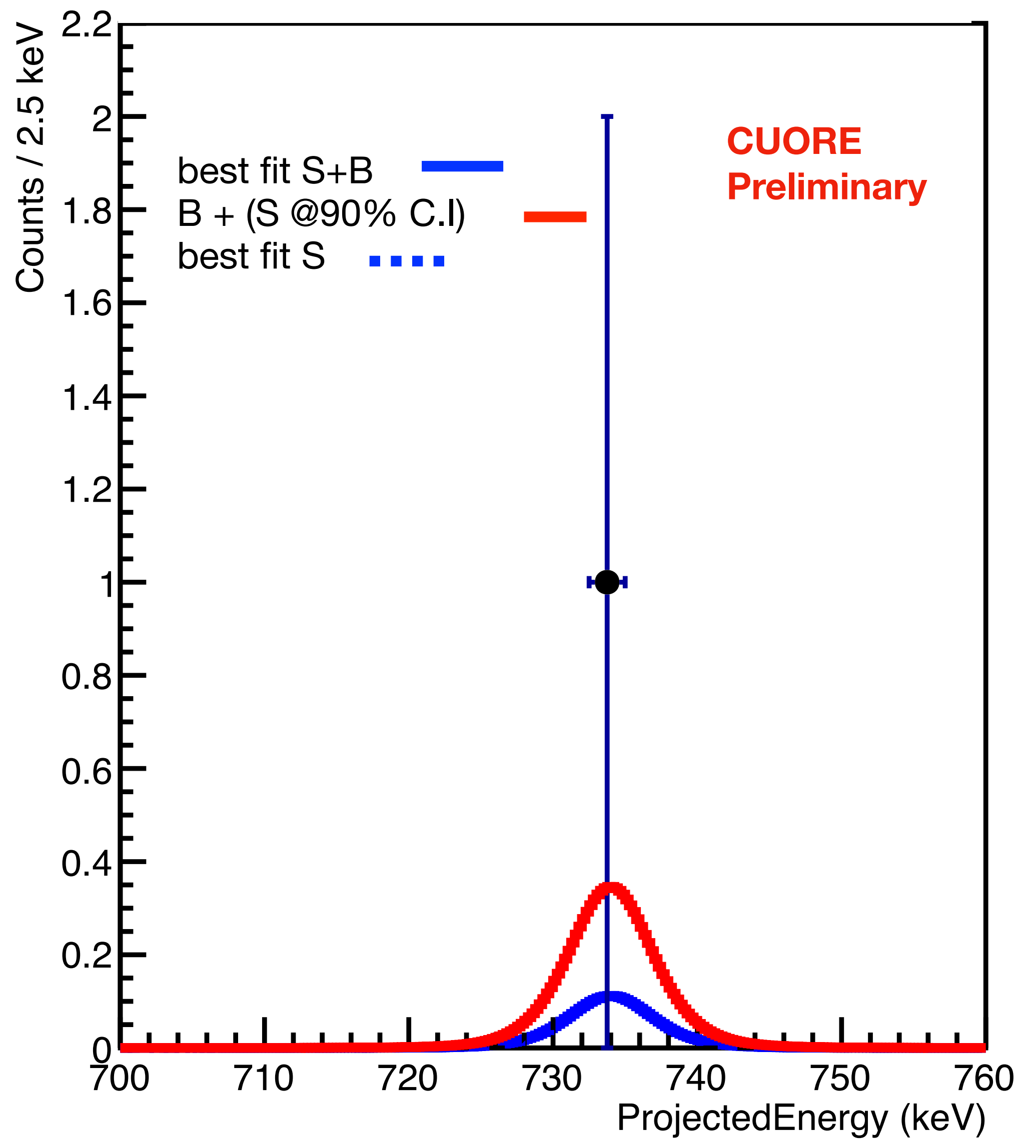
- ^{130}Te may also ββ decay to excited states of ^{130}Xe (this decay has never been observed)
- Cascade of de-excitation γs in coincidence with βs produces multi-site signatures

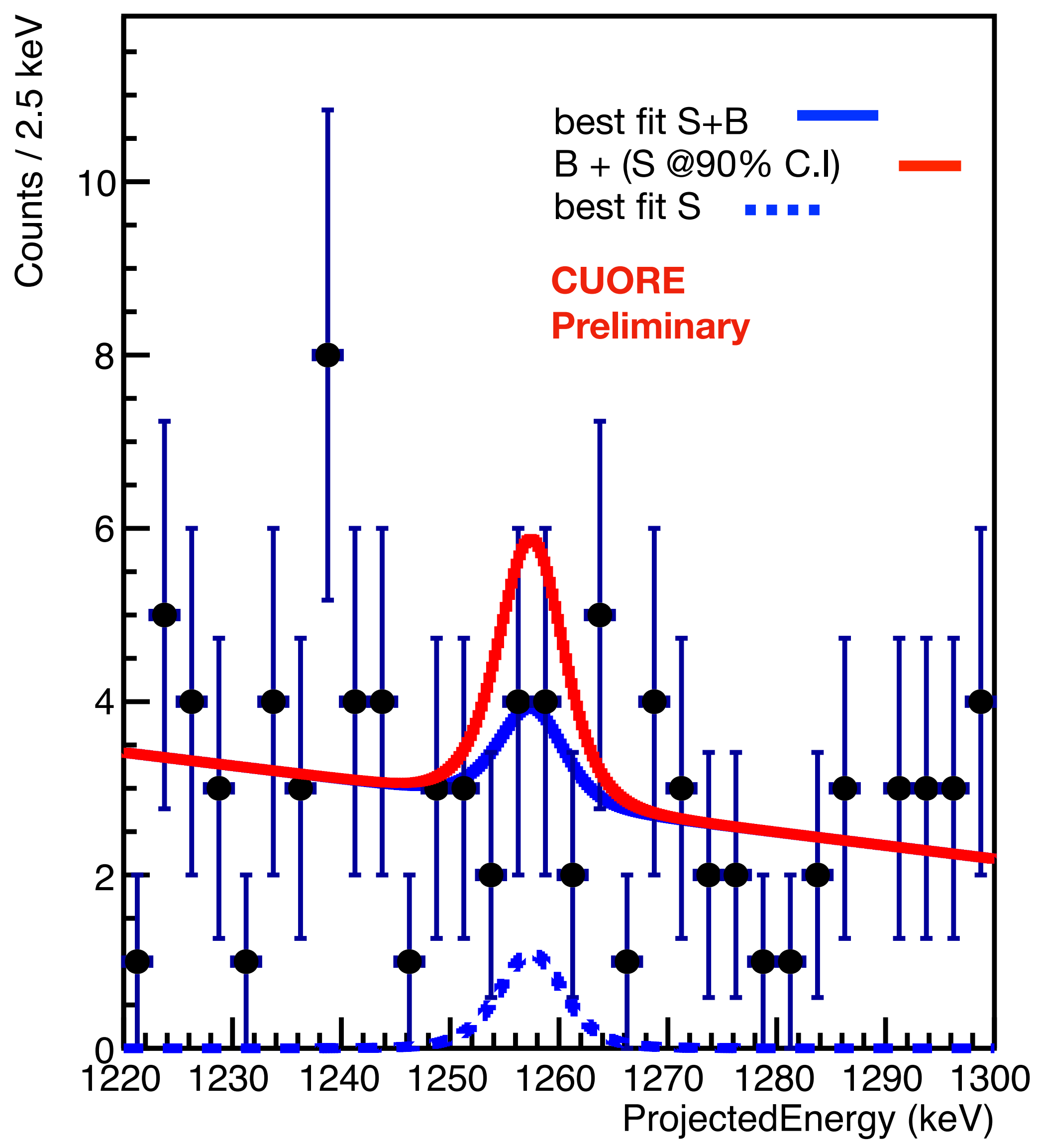


See **G. Fantini**, Poster #295 Session 2









CUORE Preliminary

$$T^{0\nu}_{1/2} > 5.4 \times 10^{24}\,\text{yr (90\%C.I.)}$$

CUORE Preliminary

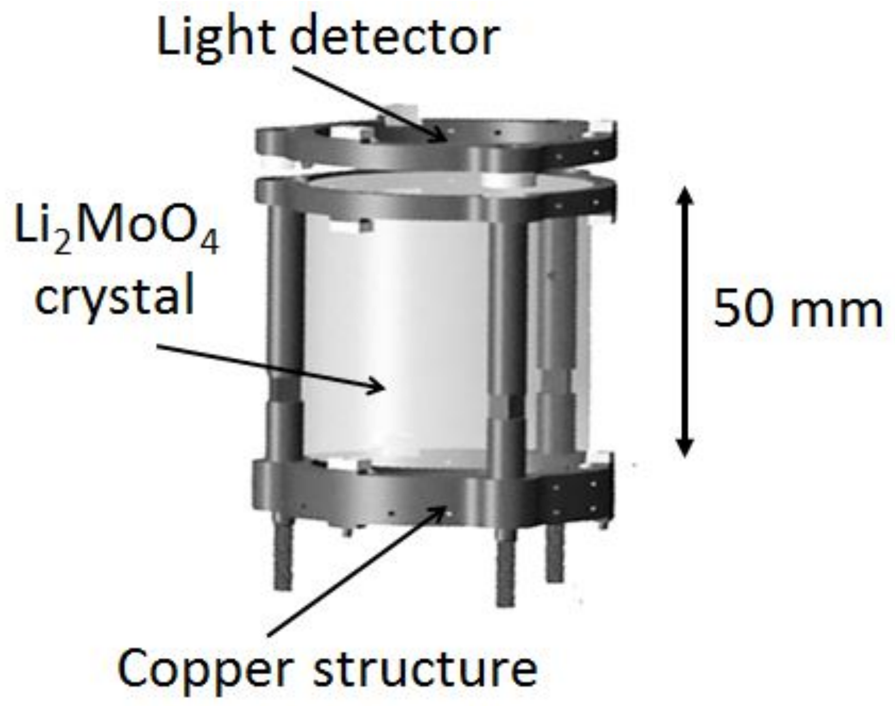
$$T^{2\nu}_{1/2} > 1.1 \times 10^{24}\,\text{yr (90\%C.I.)}$$

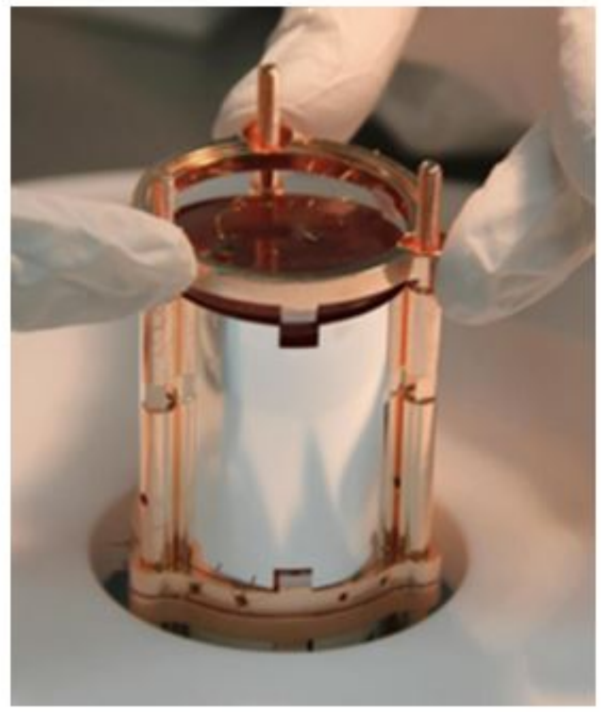
CUPID: CUORE Upgrade with Particle ID

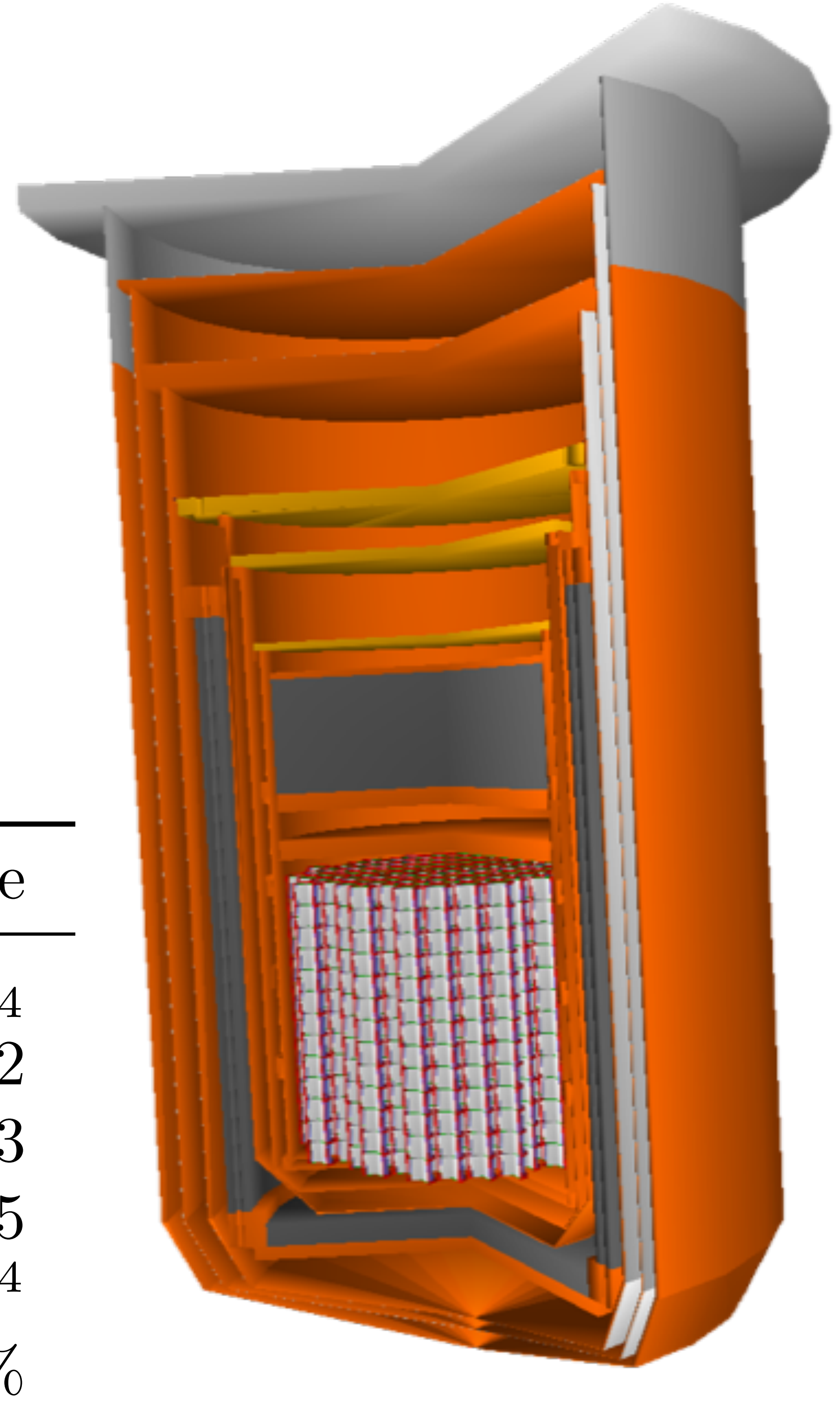
- Array of 1500 $Li_2{}^{100}MoO_4$ **scintillating** bolometers
- Enriched to >95% in ^{100}Mo (250kg of ^{100}Mo)
- ^{100}Mo Q-value: 3034 keV β/γ background significantly reduced
- Exploit Particle ID using scintillation bolometer technique
  - Technique robustly demonstrated by CUPID-0 and CUPID-Mo
- Reuse CUORE cryogenic infrastructure at LNGS
- Add external muon veto

CUPID baseline goals are within the reach of existing detector technology and infrastructure

No further R&D is needed







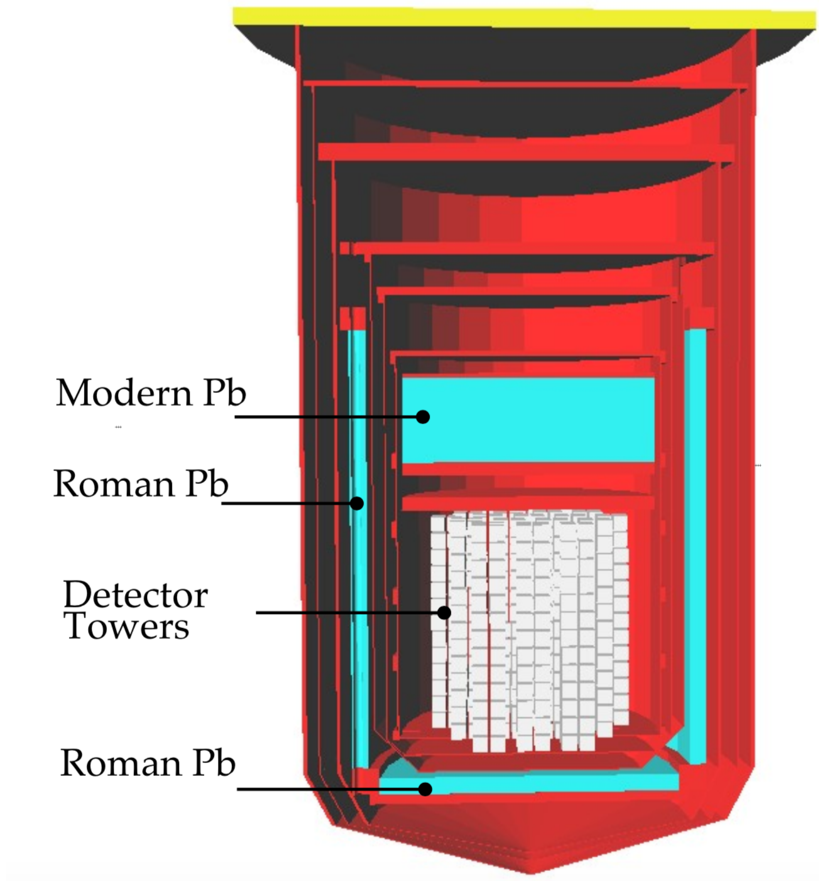
CUPID preCDR
https://arxiv.org/abs/1907.09376

Parameter	CUPID Baseline
Crystal	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472
^{100}Mo mass (kg)	253
Energy resolution FWHM (keV)	5
Background index (counts/(keV·kg·yr))	10^{-4}
Containment efficiency	79%
Selection efficiency	90%
Livetime (years)	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV

From CUORE to CUPID

- Data driven background model shows existing technology and infrastructure compatible with CUPID baseline goals —> no further R&D is needed

CUORE background model



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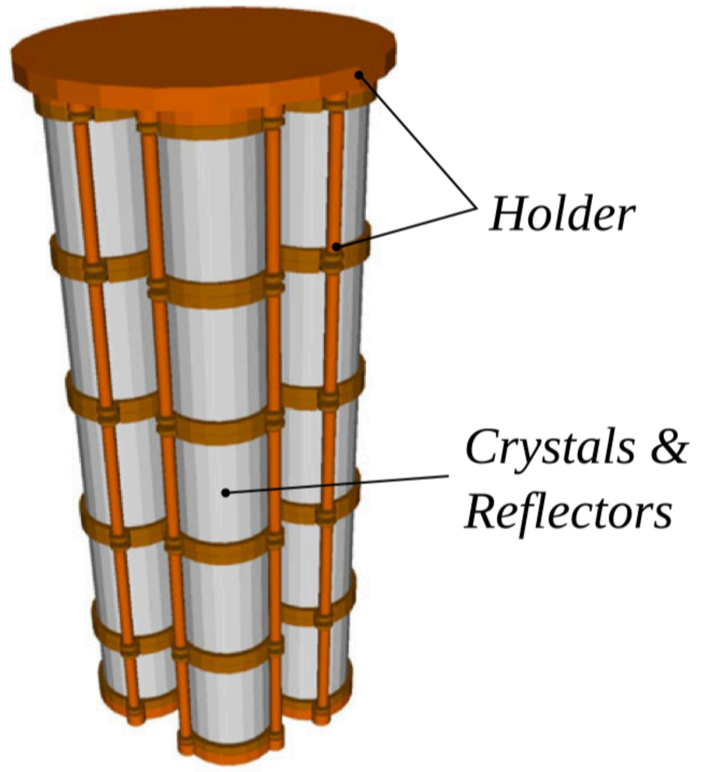
CUPID-0 background model



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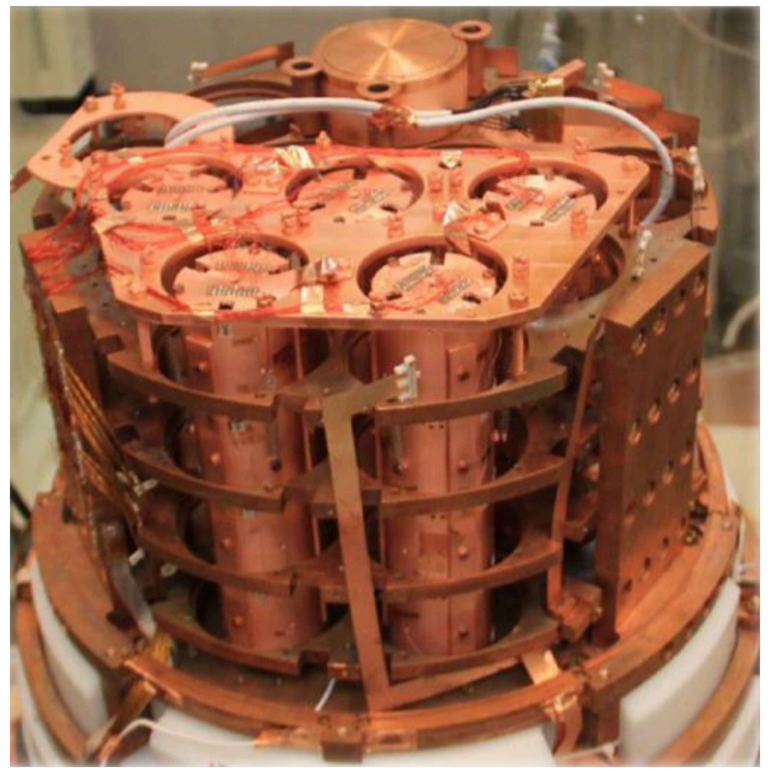
CUPID-Mo Li_2MoO_4 performance



Characterize β/γ background from cryogenic system and detector holders in the 3034 keV ROI

Model is fit to CUORE data

Alpha-rejection capable array
Confirms the β/γ background from detector holders in the 3034 keV ROI

Model is fit to CUPID-0 data

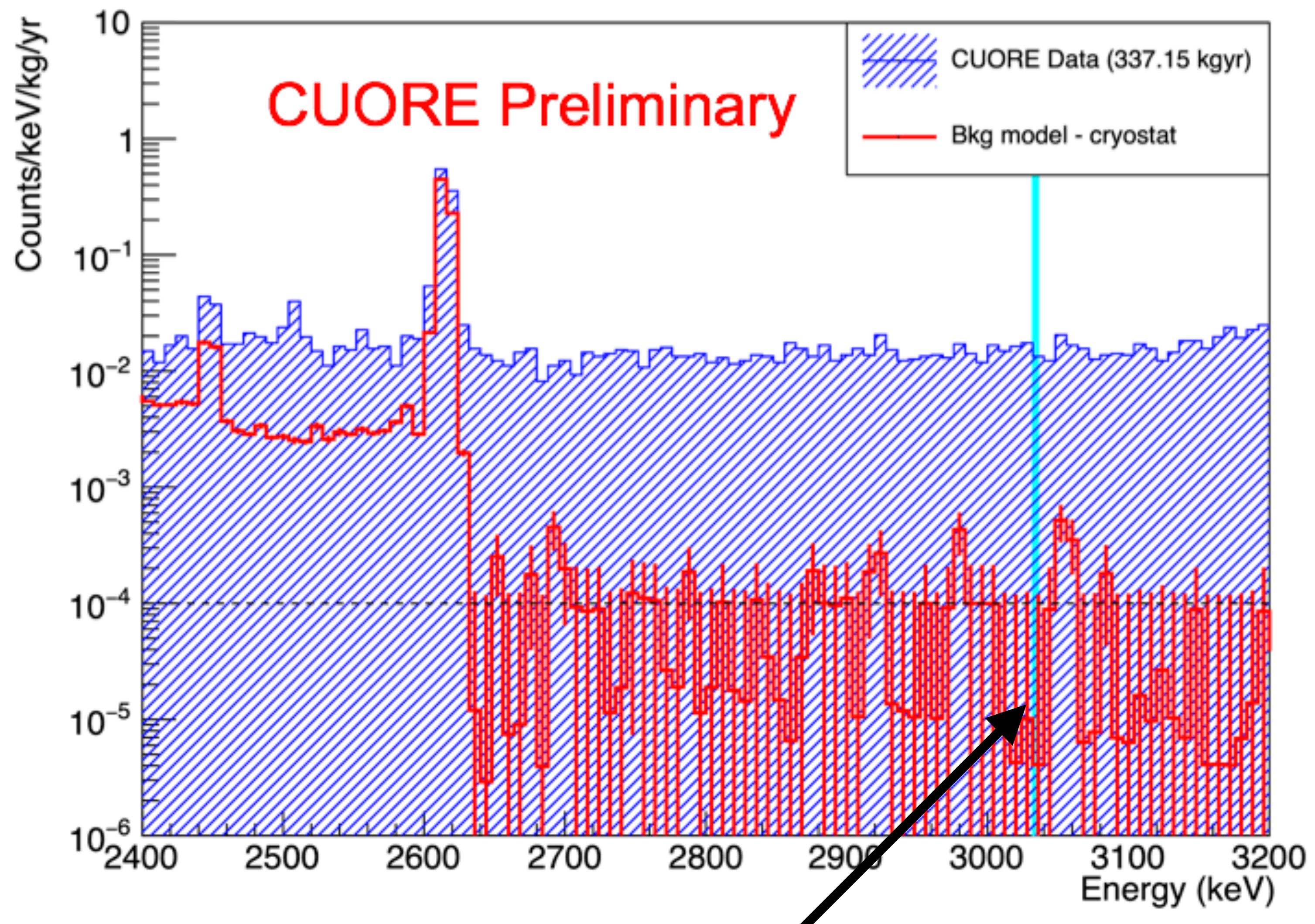
Array of large of highly enriched $Li_2\,^{100}MoO_4$

Data confirms:
- α tagging performance
- Radiopurity of crystals
- Energy resolution

From CUORE to CUPID: CUORE

- β/γ background in TeO_2 in the ^{100}Mo region of interest (3034 keV)

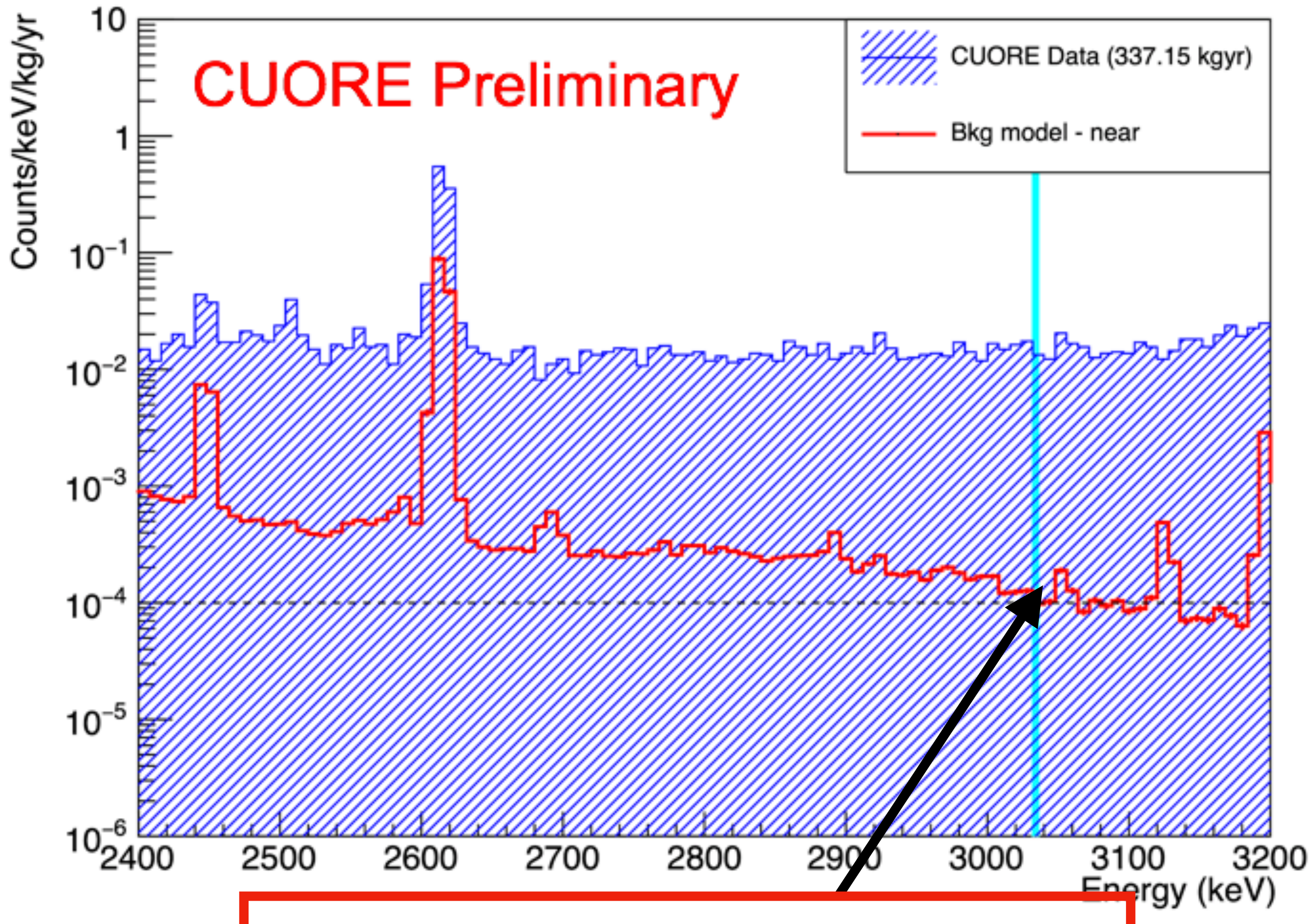
Background from Cryostat



β/γ component

$$< 1 \times 10^{-4} \frac{\text{cnts}}{(\text{keV} \cdot \text{kg} \cdot \text{yr})}$$

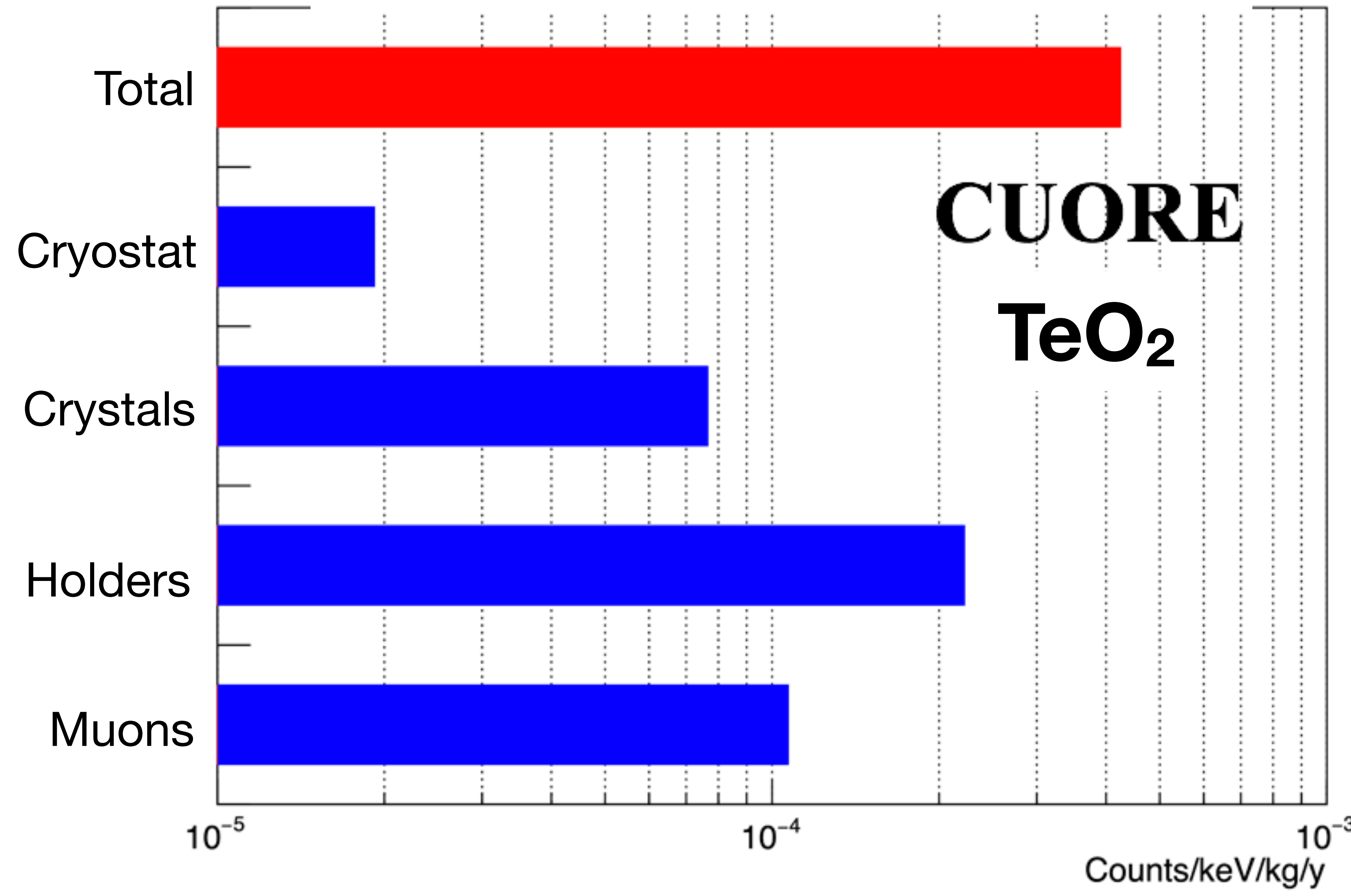
Background from holders



β/γ component

$$\sim 2 \times 10^{-4} \frac{\text{cnts}}{(\text{keV} \cdot \text{kg} \cdot \text{yr})}$$

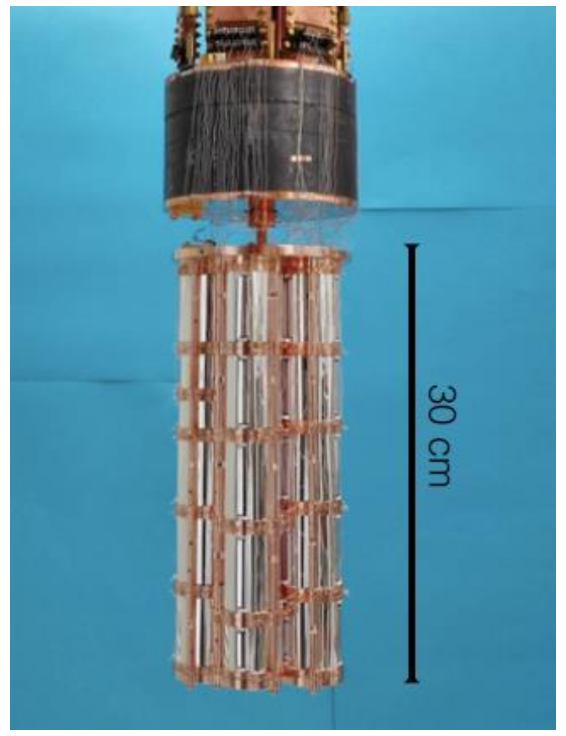
CUORE β/γ Background Summary
in 3034 keV ROI



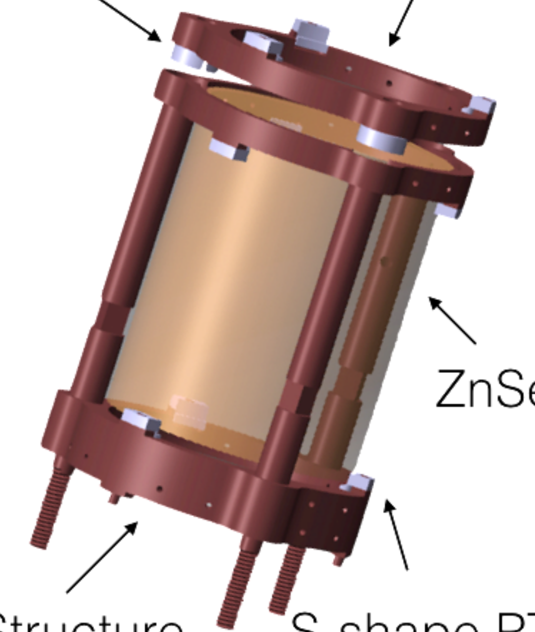
- γ interaction probability in Li_2MoO_4 is ~3x smaller than in TeO_2 in this ROI
- Muon veto will be added for CUPID

From CUORE to CUPID: CUPID-0

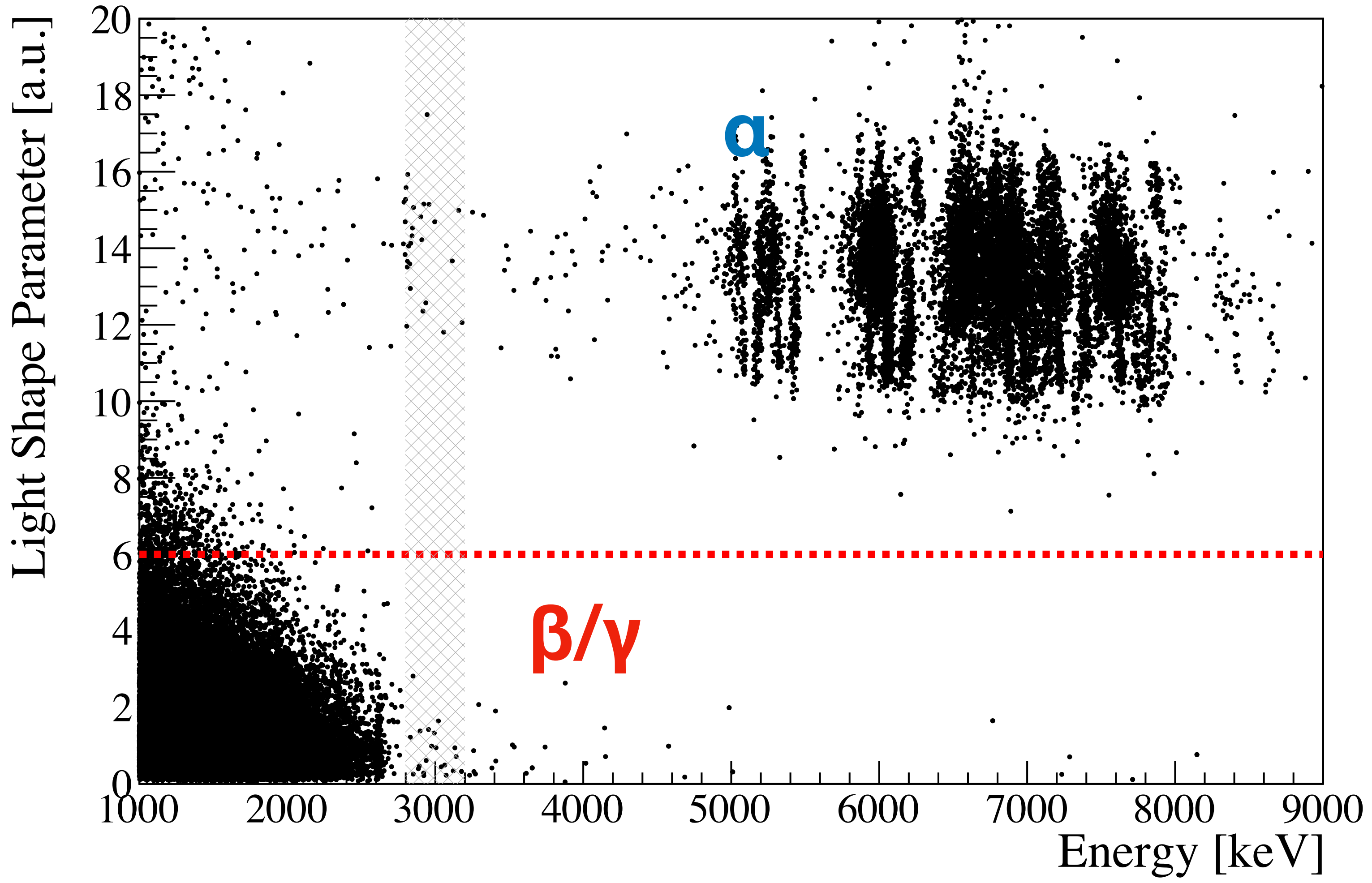
See **I. Colantoni**
Poster #111 Session 3



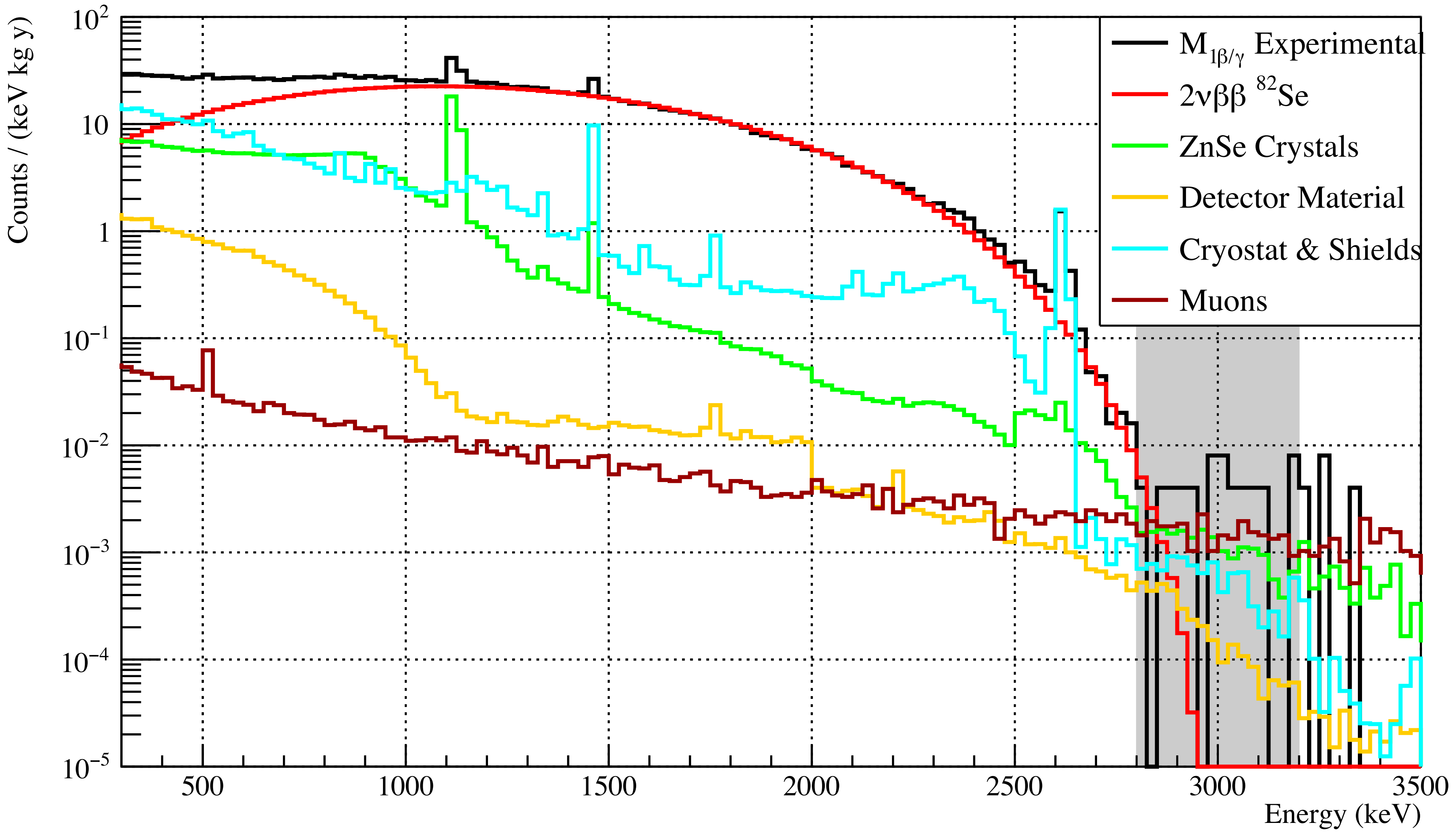
- 26 ZnSe scintillating bolometers (24 95% enriched in ^{82}Se + 2 natural)
- Ge wafers cryogenic light detectors
- ^{82}Se 0νββ decay Q-Value: 2998 keV
- Hosted in the same CUORE-0 dilution refrigerator (Hall A)



Complete alpha rejection for Energy > 2 MeV



Eur. Phys. J. C 78, 734 (2018).



CUPID-0 Background Model

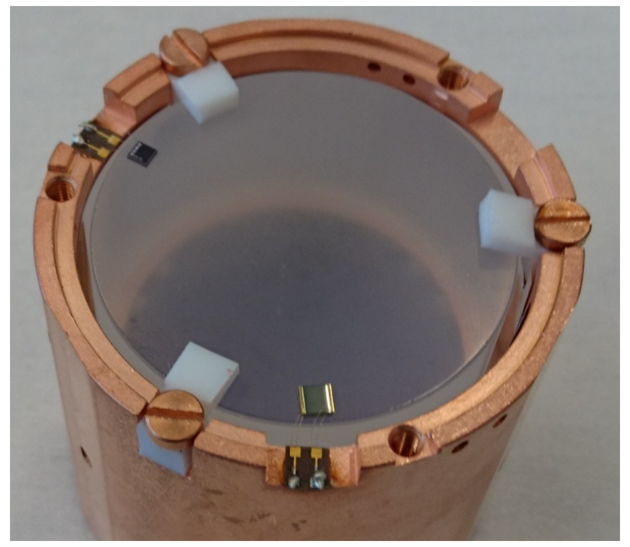
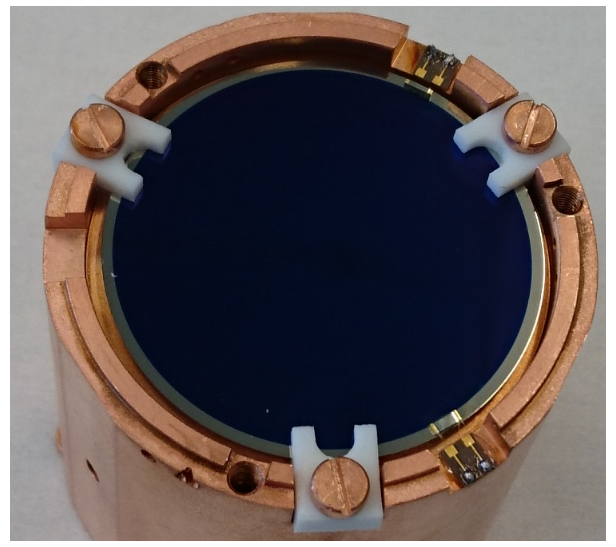
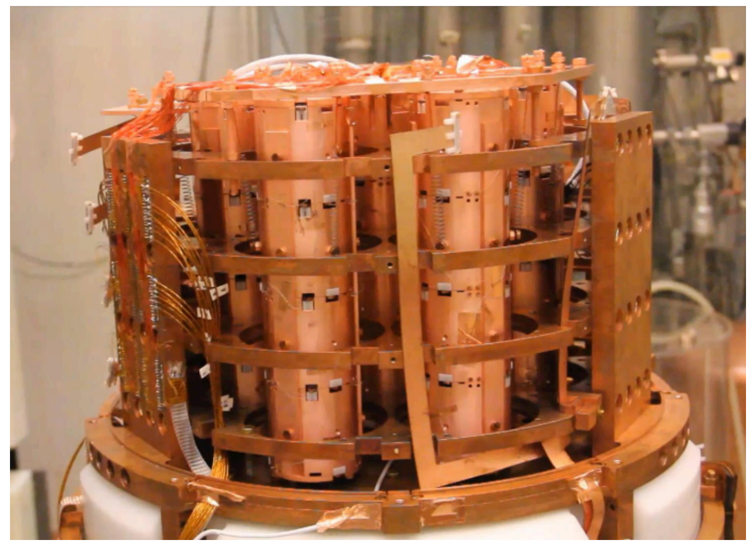
Source ROI = 2.8 - 3.2 MeV	ROI Background Index $[10^{-4}$ counts/(keV·kg·y)]
2νββ ^{82}Se	6.0 ± 0.3
ZnSe Crystals	$11.7 \pm 0.6 ^{+1.6}_{-0.8}$
Detector Material	$2.1 \pm 0.3 ^{+2.2}_{-1.0}$
Cryostat & Shields	$5.9 \pm 1.3 ^{+7.2}_{-2.9}$
Muons	$15.3 \pm 1.3 \pm 2.5$
Total	$41 \pm 2 ^{+9}_{-4}$

Eur. Phys. J. C 79, 583 (2019)

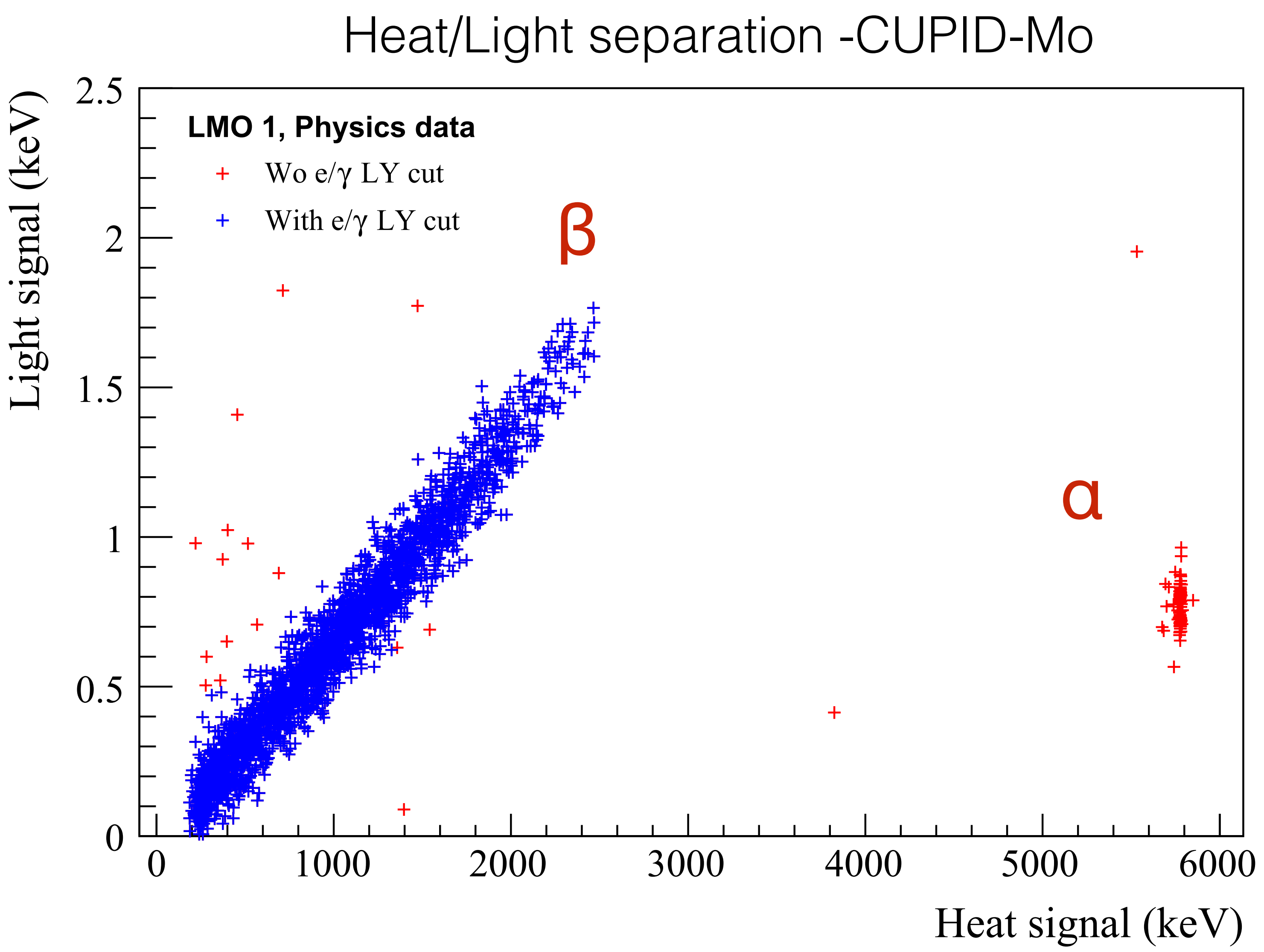
- Li_2MoO_4 radiopurity is 10x better than ZnSe
- CUPID detector holder will adopt reduced mass design
- CUORE/CUPID cryostat is cleaner than CUPID-0 cryostat
- Muon tagging with external veto

From CUORE to CUPID: CUPID-Mo

- Array of 20 $Li_2{}^{100}MoO_4$ detectors ~210 g each
- Enriched to 97% in ^{100}Mo (2.26 kg ^{100}Mo)
- Hosted in Modane underground lab 4800 m.w.e. overburden in EDELWEISS cryogenic system (20 mK)
- Ge wafer light detectors

- Physics data taking March 2019 - June 2020
- All $Li_2{}^{100}MoO_4$ bolometers and 19 light detectors operational
- Energy resolution @ $Q_{\beta\beta}$ (3034 keV): ~8 keV FWHM (operating temp = 20 mK)
- Good uniformity and stable performance (suitable for larger arrays in CUPID)

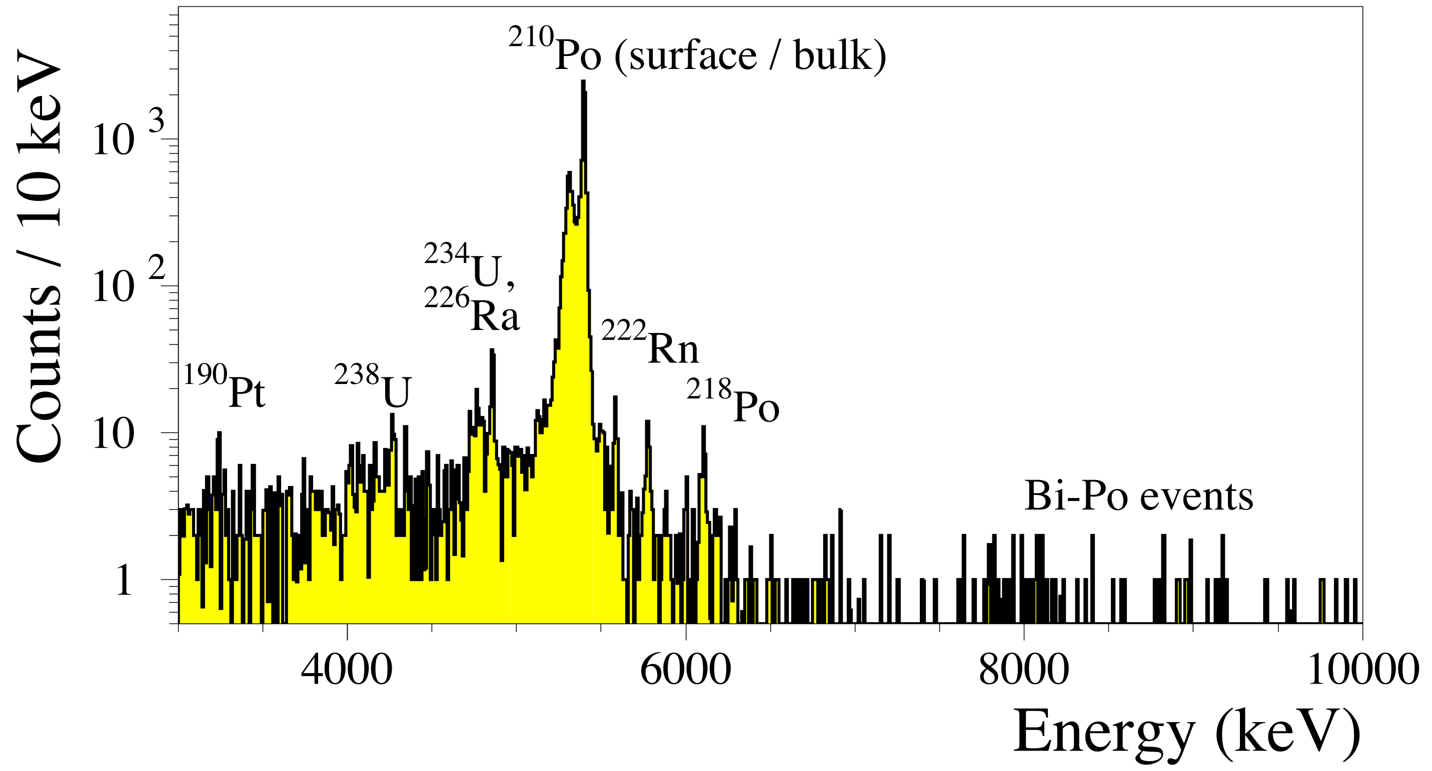


Alpha Rejection

- Light yield for β/γ events is 5x greater than for α particles
  - **> 99.9% α separation**
  - **> 99.9 % β/γ acceptance**

Meets the requirement for CUPID

See **D. Poda**
Poster #404 Session 4



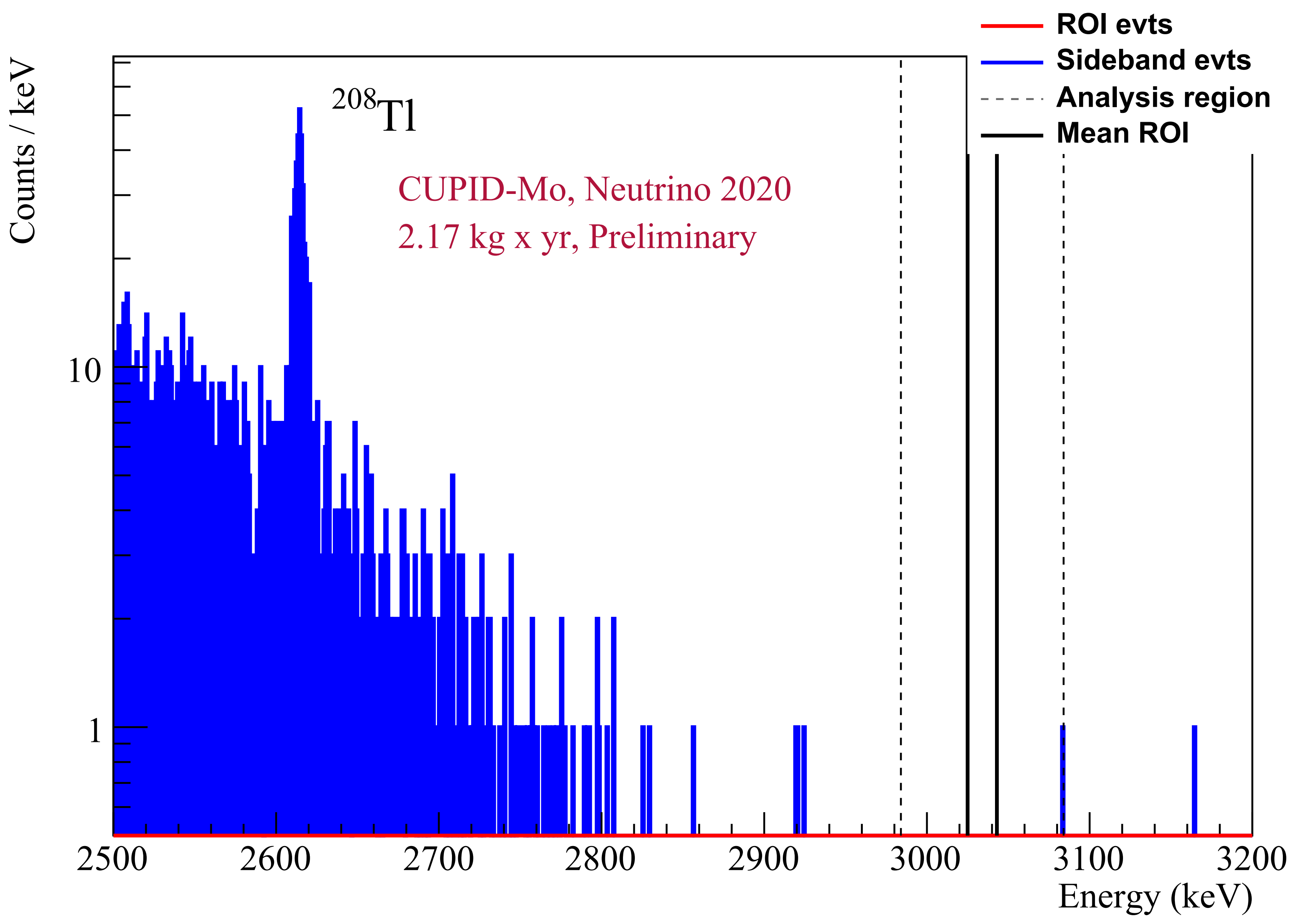
Excellent Radiopurity

^{210}Po: 100µBq/kg

^{238}U/^{232}Th: (0.3 - 1)µBq/kg

Meets the requirement for CUPID

CUPID-Mo: Results



- CUPID-Mo has a vibrant physics program
- New world-leading limit on $0\nu\beta\beta$ decay of ^{100}Mo

CUPID-Mo Preliminary

$$T^{0\nu}_{1/2} > 1.4 \times 10^{24} \text{ yr } (90\% \text{ c.i})$$ (stat. + syst.)

$$m_{\beta\beta} < 310 - 540 \text{ meV}$$

See **B. Schmidt**
Poster #419 Session 3

- Background index is very low despite conditions not optimized for $0\nu\beta\beta$

CUPID-Mo Preliminary

$$\text{BI} : (4 \pm 2) \times 10^{-3} \text{cnts/keV} \cdot \text{kg} \cdot \text{yr}$$

See **P. Loaiza**
Poster #418 Session 2

- High precision measurement of $2\nu\beta\beta$ decay of ^{100}Mo using CUPID-Mo technology

$$\text{T}^{2\nu}_{1/2} = [7.12^{+0.18}_{-0.14}(\text{stat.}) \pm 0.10(\text{syst.})] \times 10^{18}\text{yr}$$

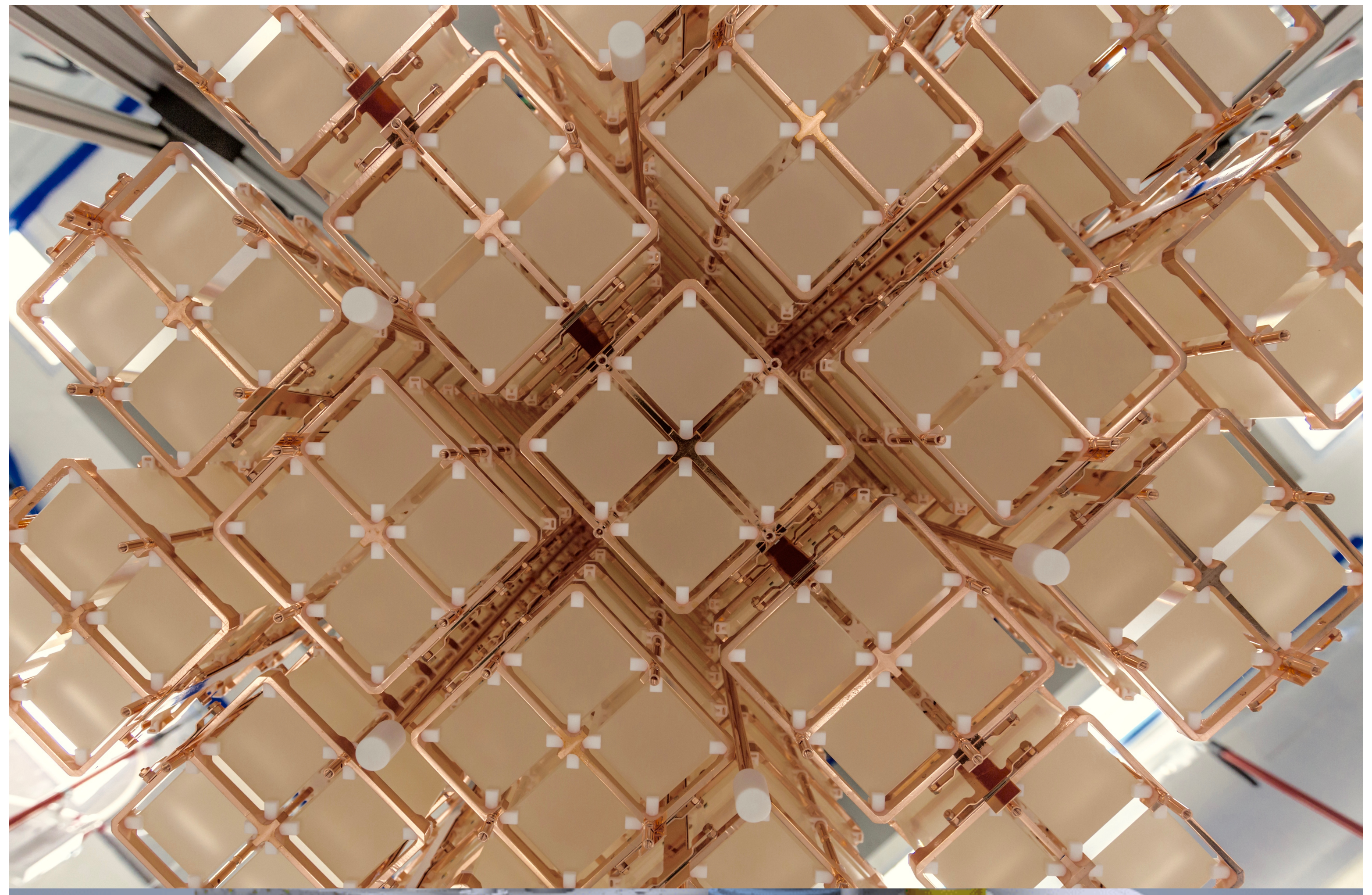
arXiv: 1912.07272

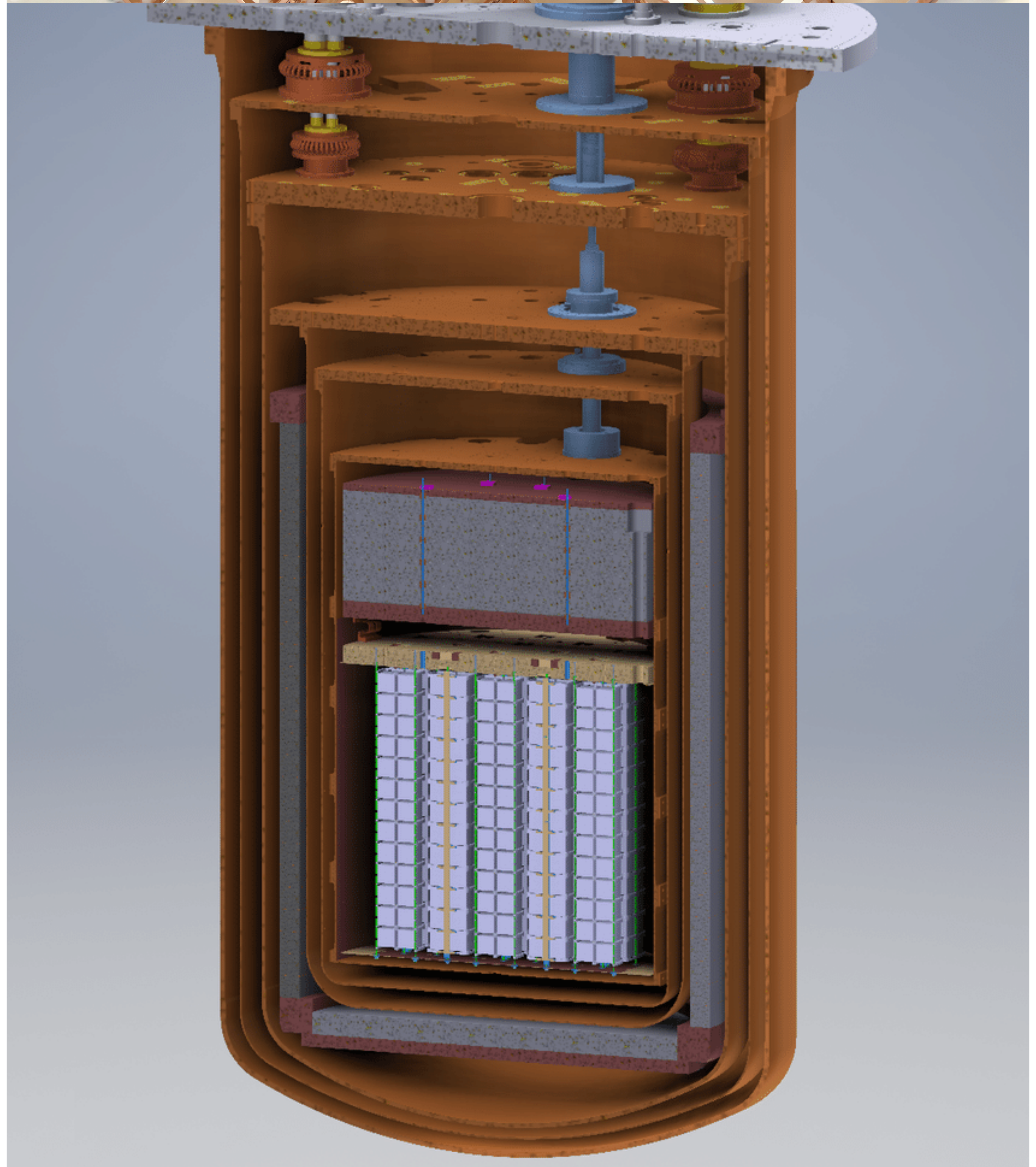
See **V. Singh**
Poster #525 Session 2

See also
T. Dixon
Poster #382 Session 4
B. Welliver
Poster #448 Session 4
M. Zarysky
Poster #374 Session 4

Summary

- The era of tonne-scale cryogenic bolometers has started
- The CUORE physics program is ongoing and will continue in parallel with preparations for CUPID
- CUPID baseline sensitivity: $T^{0\nu}_{1/2} : 10^{27} yr$ $\quad m_{\beta\beta} : 10 - 20\ meV$
- CUPID can achieve this with existing detector technology and infrastructure
  - ☑ CUPID-0 and CUPID-Mo robustly demonstrate the alpha rejection technique
  - ☑ Residual β/γ background in ^{100}Mo ROI meets the requirements
  - ☑ Radio-purity and bolometric performance of large, highly enriched $Li_2{}^{100}MoO_4$ crystals demonstrated in CUPID-Mo
- The future is *bright* for next-generation cryogenic bolometers





Acknowledgements

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CUORE Collaboration

CSNSM

Universitas Studii Paduani MCCXXII

Yale

INFN

Berkeley Lab

Cal Poly San Luis Obispo

Alma Mater Studiorum Università di Bologna A.D. 1088

Università degli Studi di Cassino e del Lazio Meridionale – Sol per noctem – 1979

UCLA

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University of South Carolina

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Sapienza Università di Roma

Università degli Studi di Milano Bicocca

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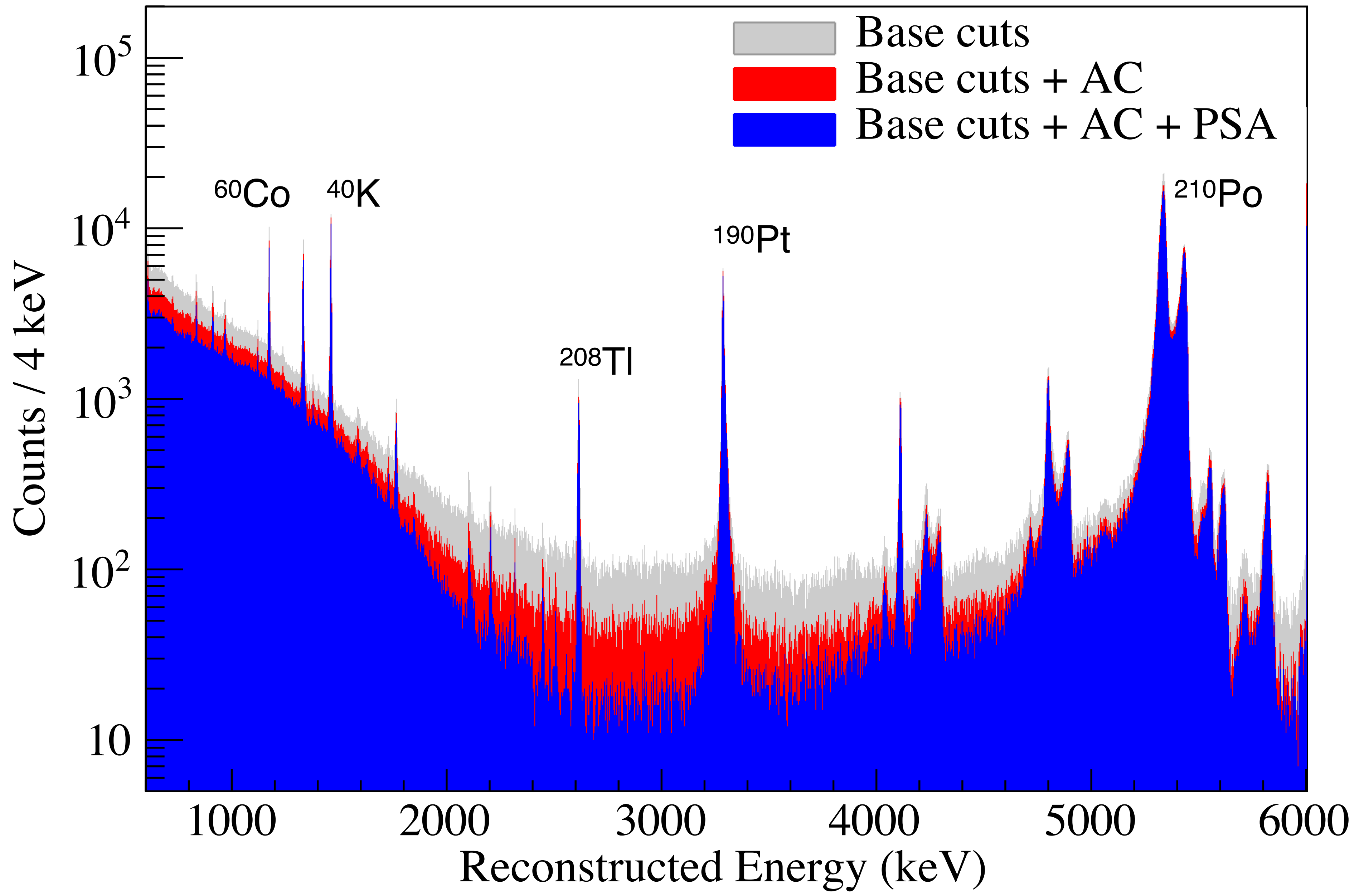
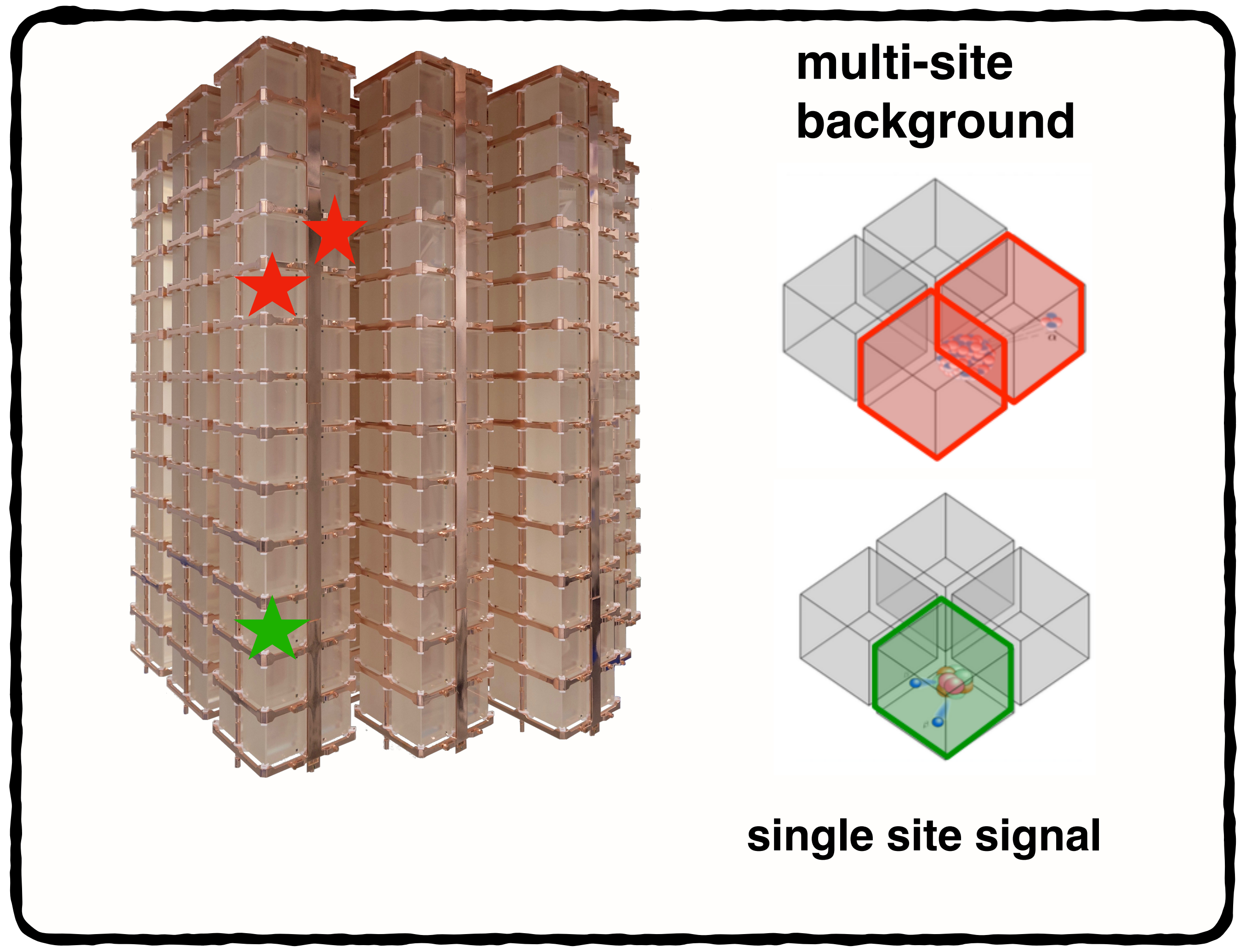
CUORE

CUORE Event Selection

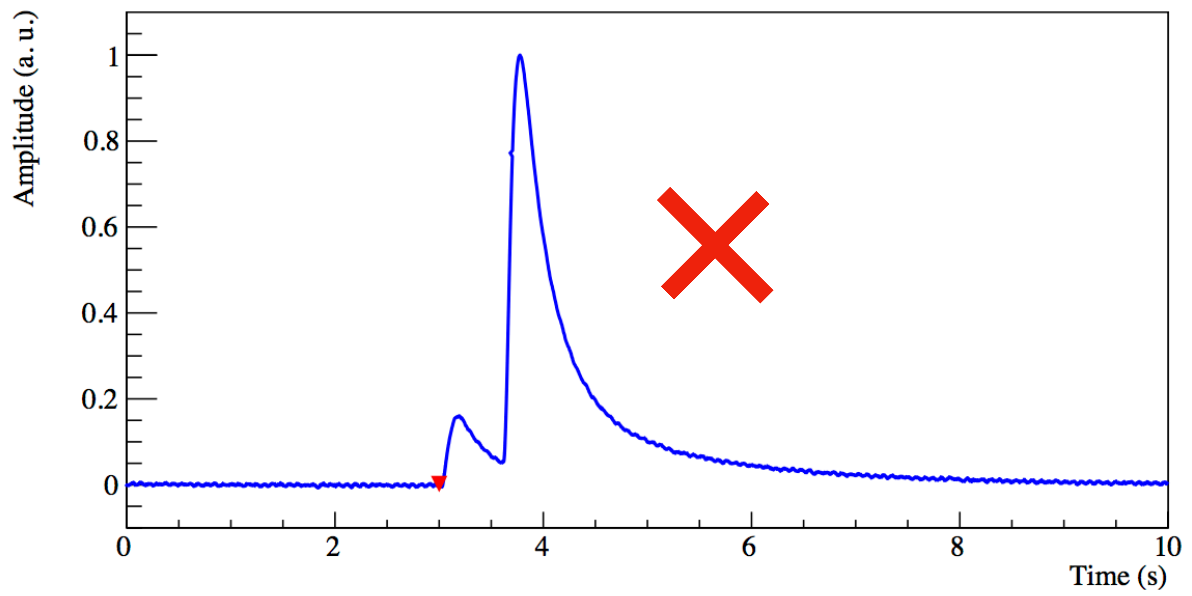


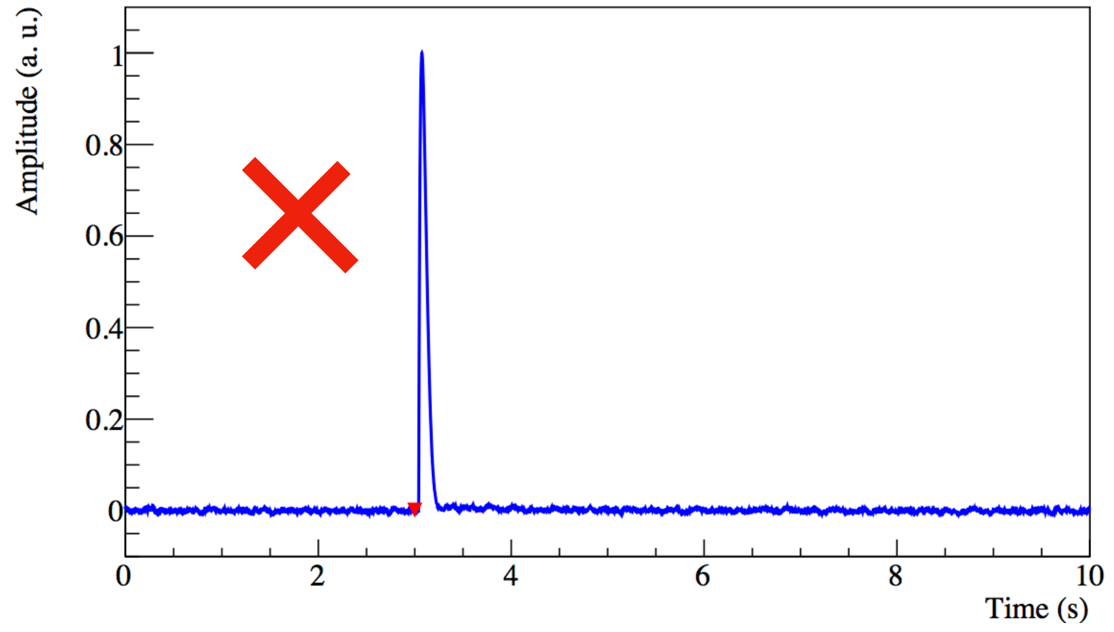
- Base Cuts: basic data cleaning, remove noisy periods, reconstruction etc

- Anti-coincidence Cut



- Pulse shape analysis (PSA)

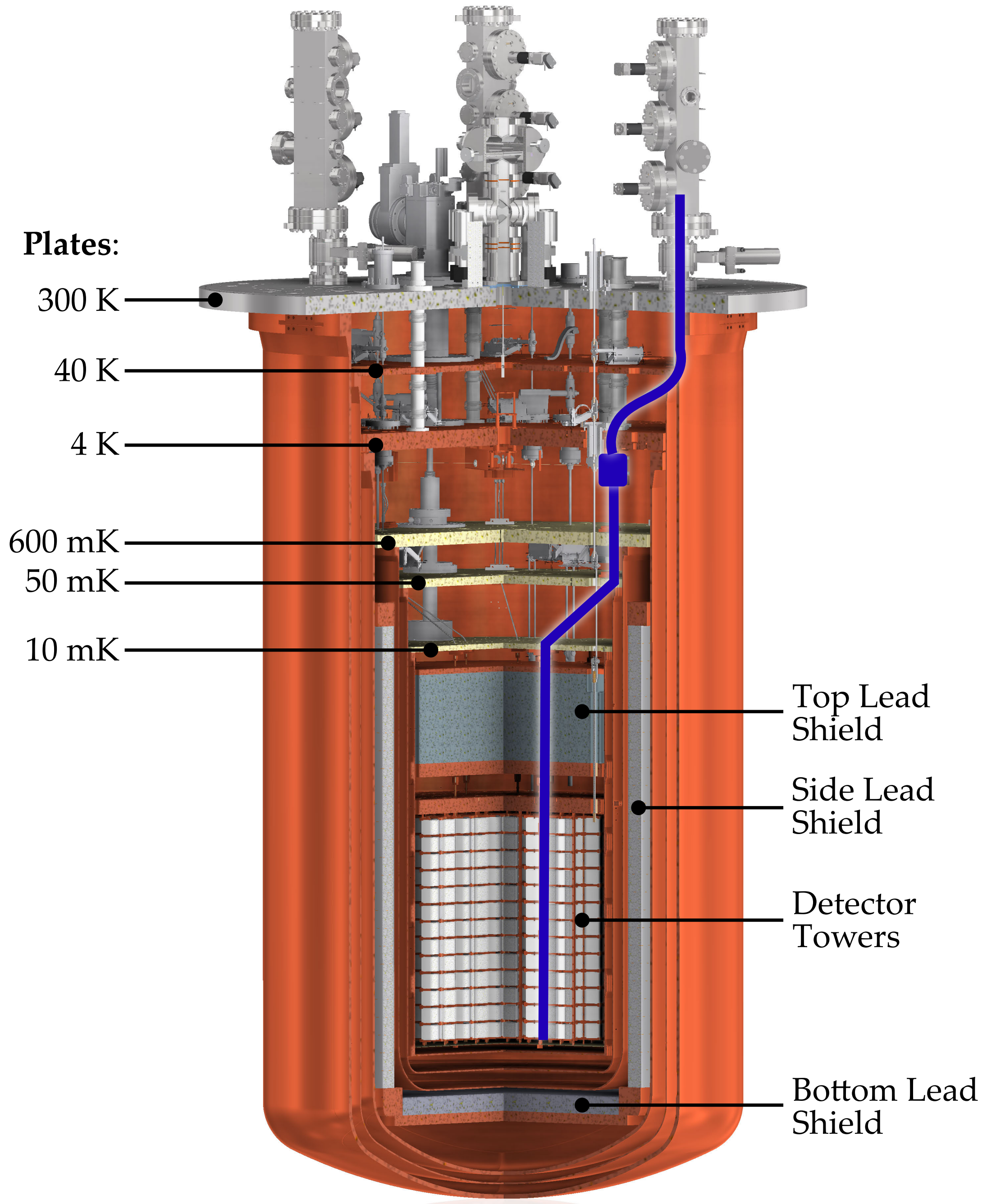




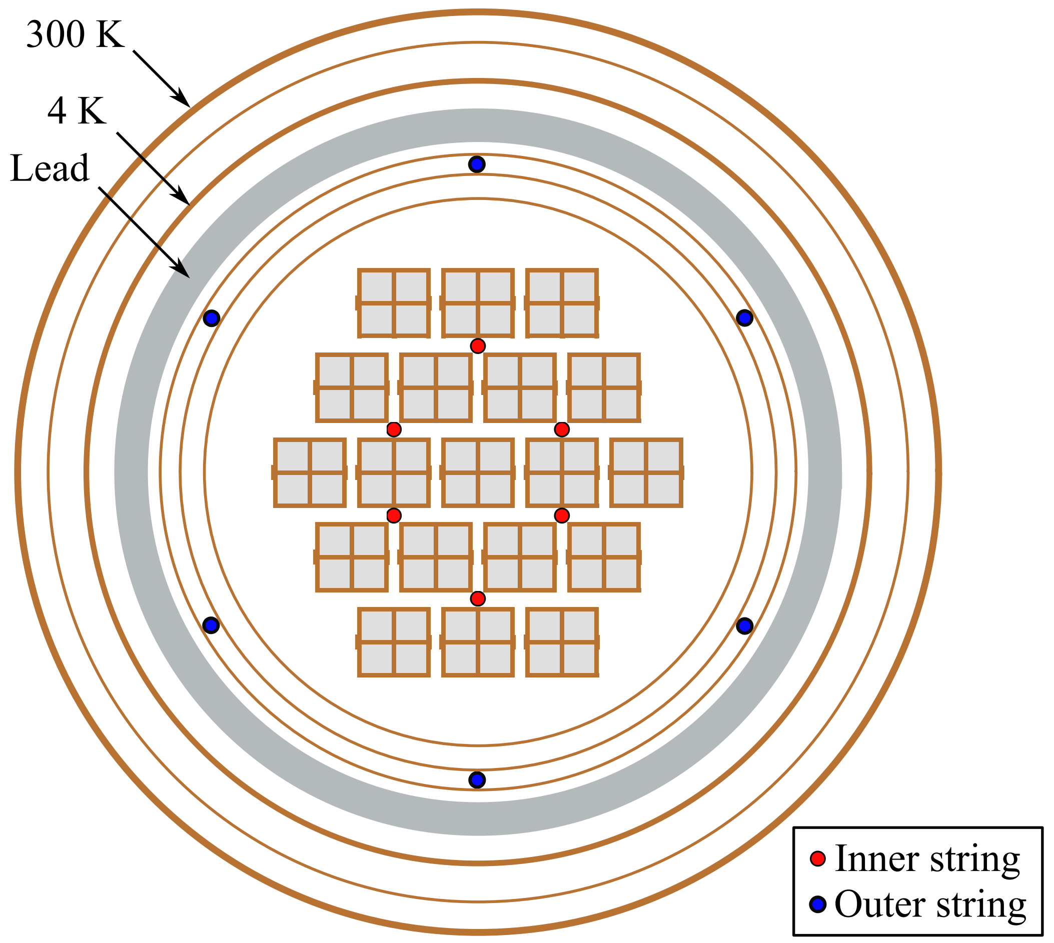
Selection Efficiencies

Reconstruction Efficiency	(95.802 ± 0.003) %
Anti-coincidence	(98.7 ± 0.1) %
Pulse shape analysis	(92.6 ± 0.1) %
All w/o containment	**(87.5 ± 0.2) %**
0νββ containment	(88.35 ± 0.09) %
Total	**(77.3 ± 0.2) %**

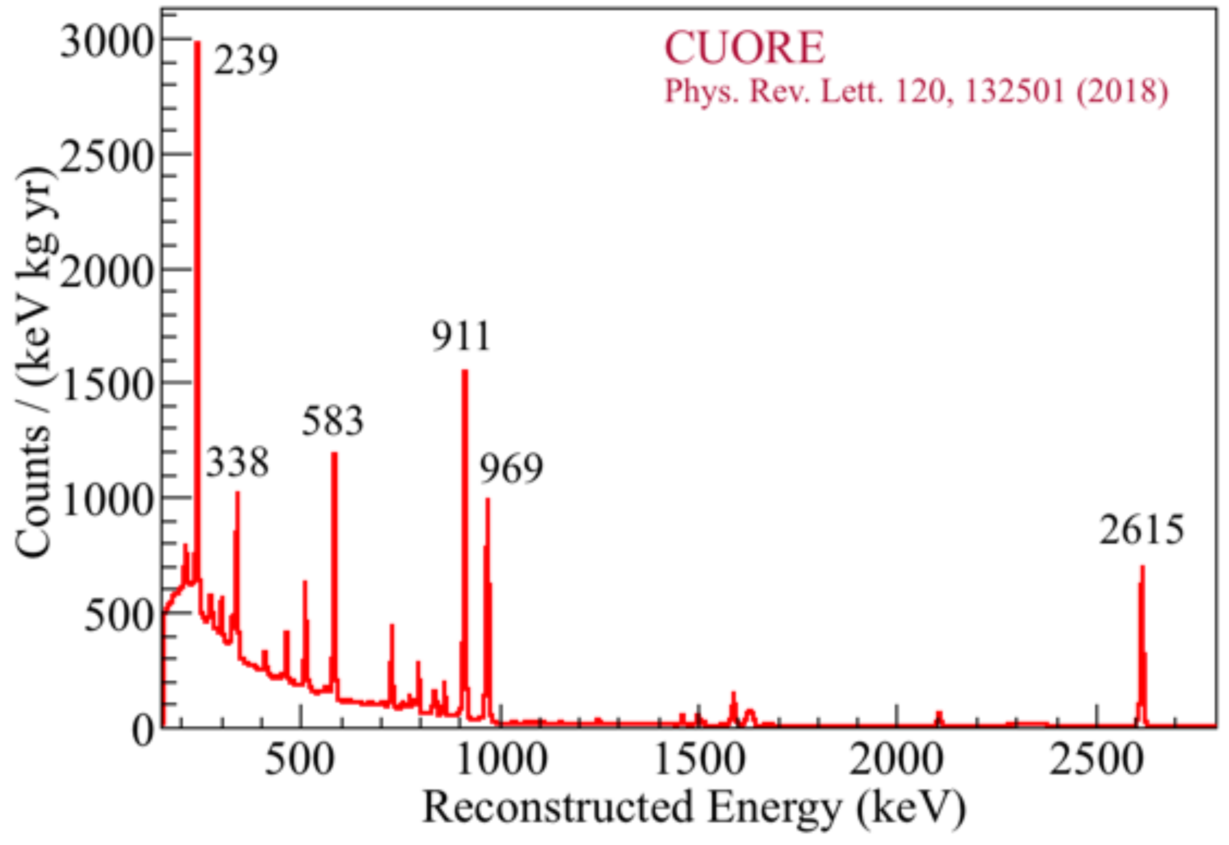
Detector calibration systems



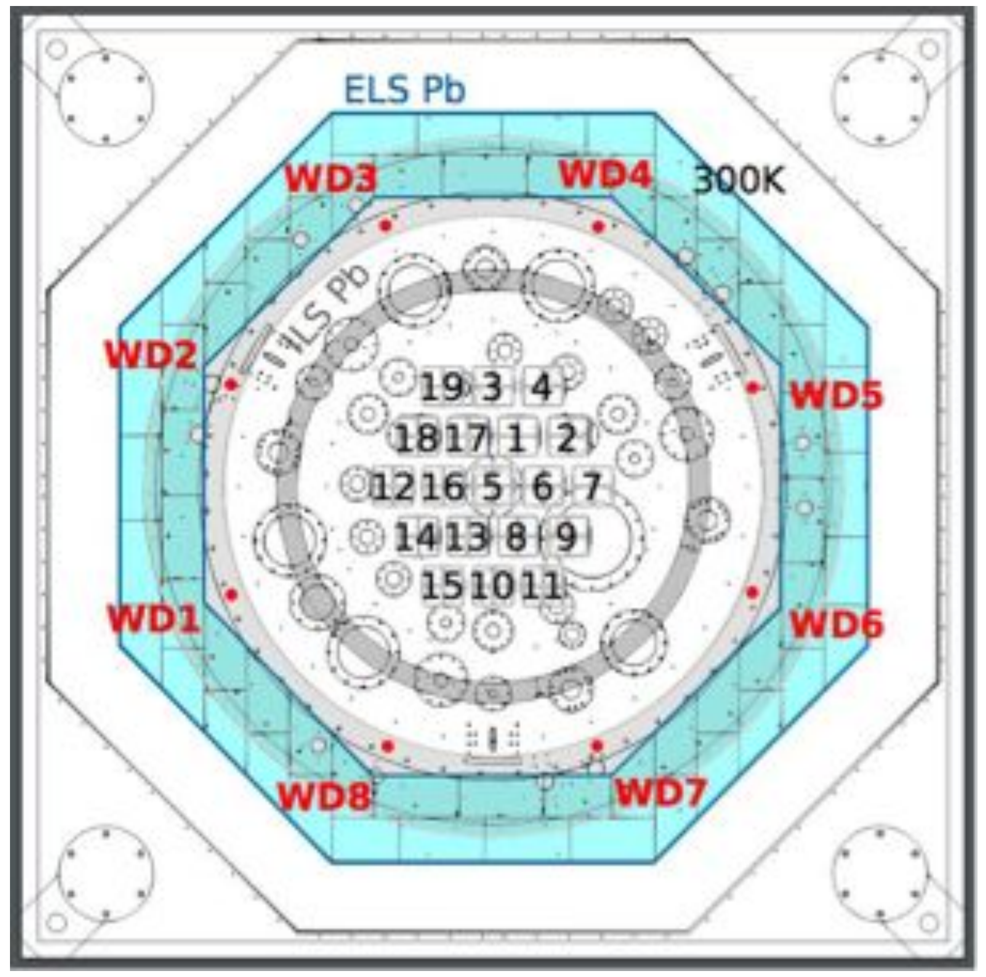
Internal system



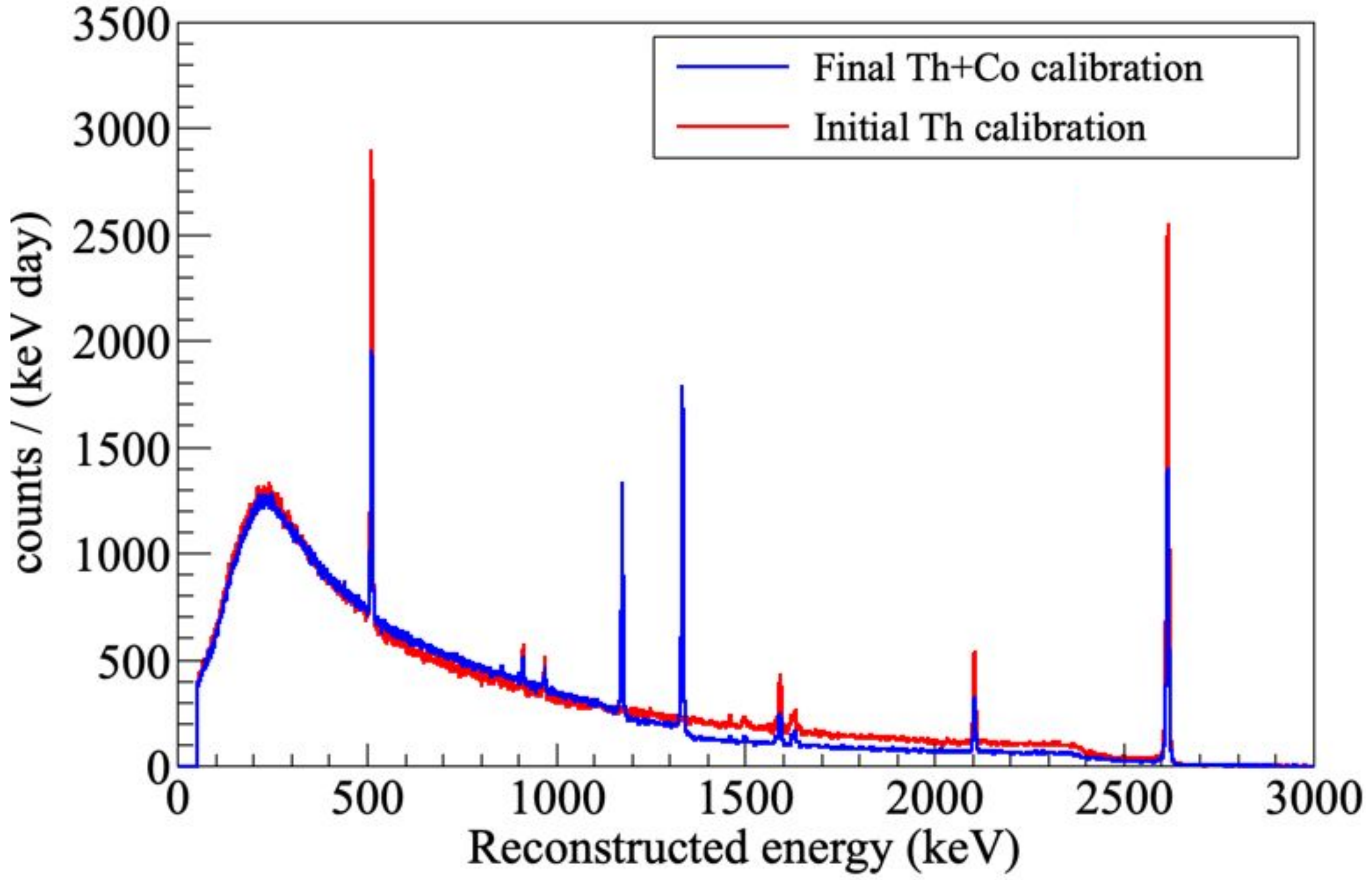
Th-232 strings deployed internally



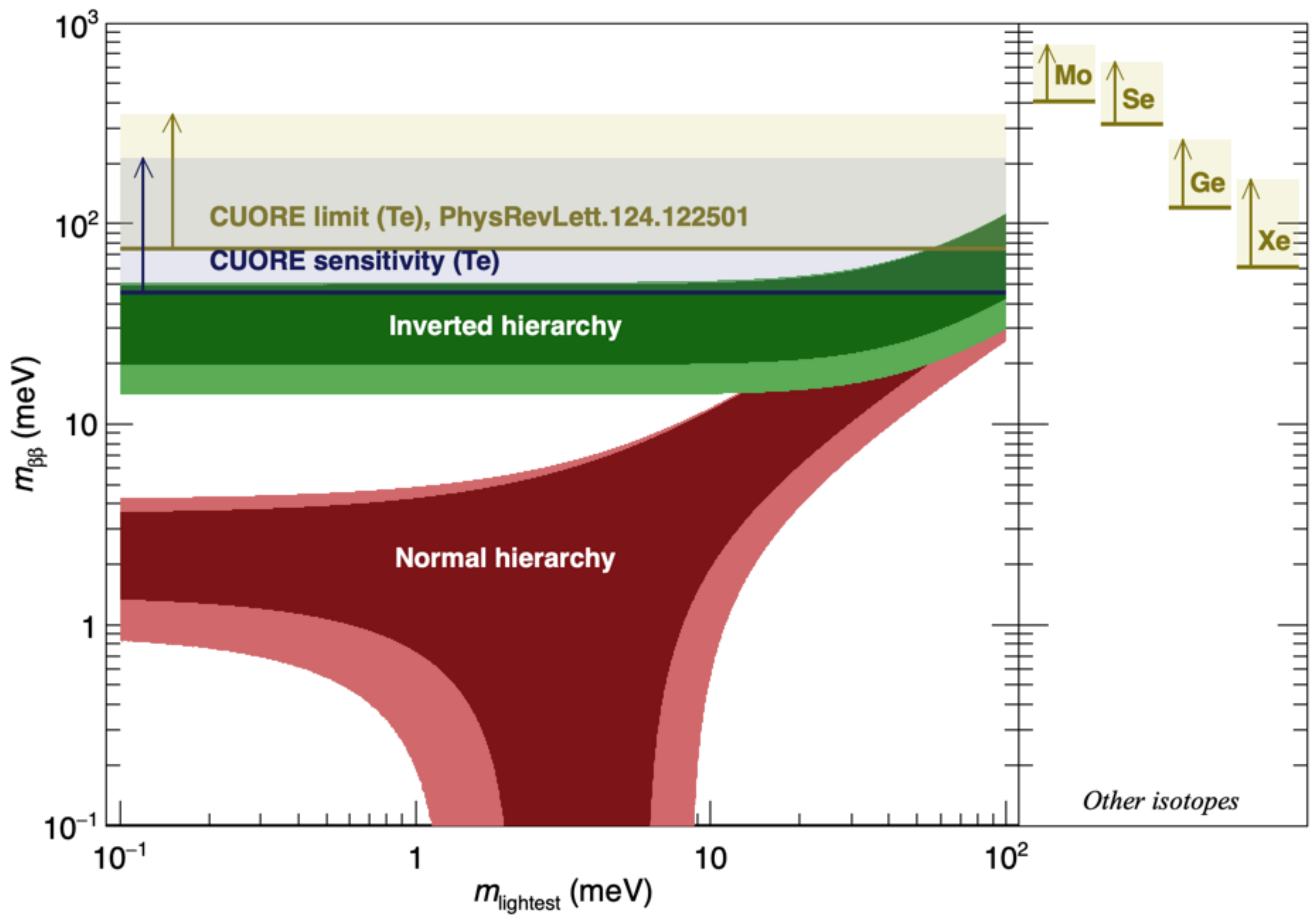
External system



Th-232/60-Co strings deployed externally



CUORE Interpretation NME Models



$$m_{\beta\beta} < 75 - 350\,\mathrm{meV}$$

NMEs Used

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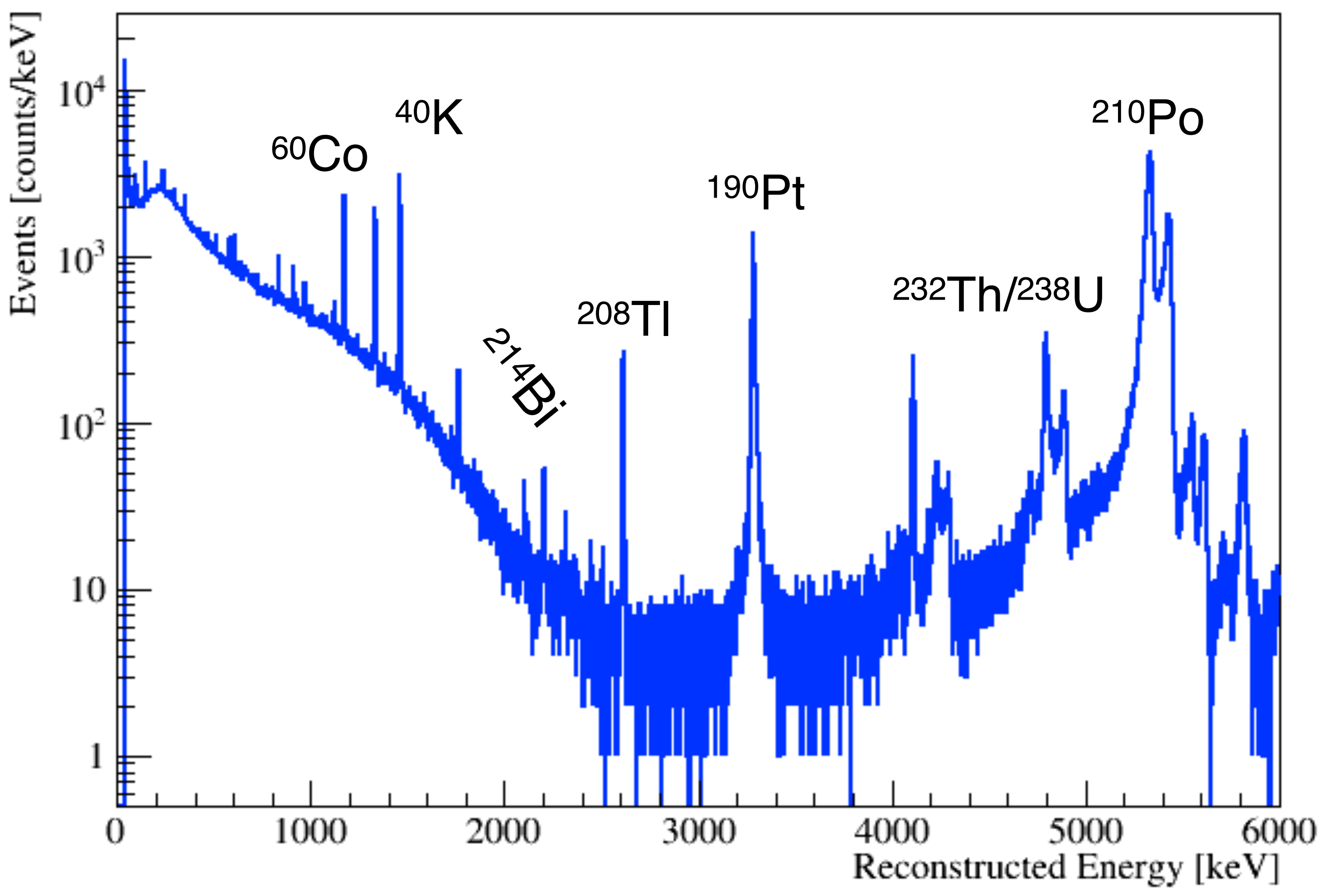
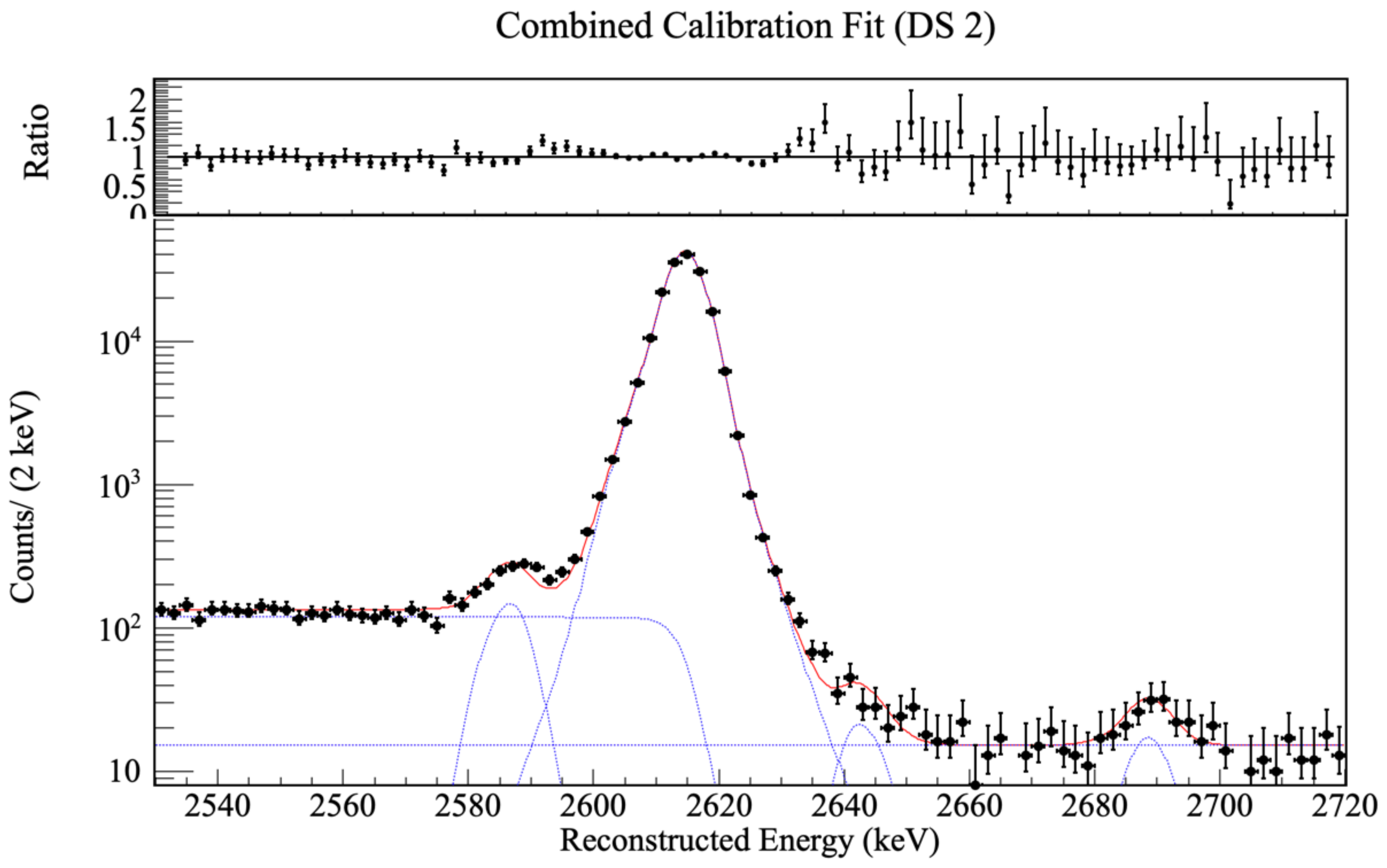
CUORE Detector Performance

Physics Spectrum (375.2 kg yr exposure)

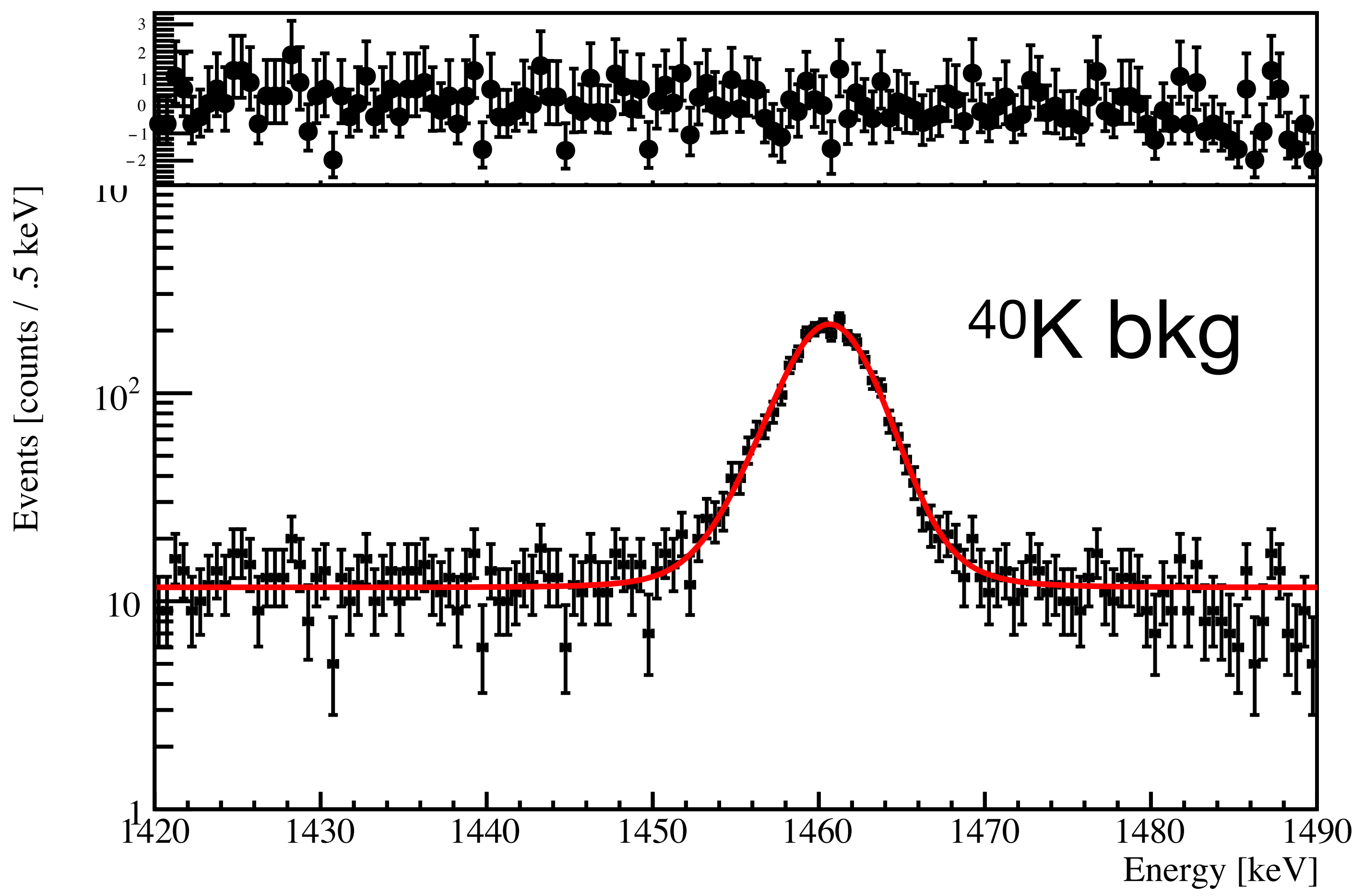


β/γ-dominated α-dominated

- Detector response function determined for 2615 keV line in calibration data



- Fit to prominent lines in the background data to determine energy bias and resolution vs. energy



- Effective energy resolution at $Q_{\beta\beta}$: 7.0 +/- 0.3 keV (exposure weighted harmonic mean)
- Energy scale bias: <0.7 keV