

CUORE: A DECADE OF $0\nu\beta\beta$ SEARCH AND THE PATH TOWARDS CUPID

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On behalf of the CUORE and CUPID collaborations



Neutrino 2026 — UC Irvine — 21-26 June 2026

THE CUORE EXPERIMENT

CRYOGENIC UNDERGROUND OBSERVATORY FOR RARE EVENTS

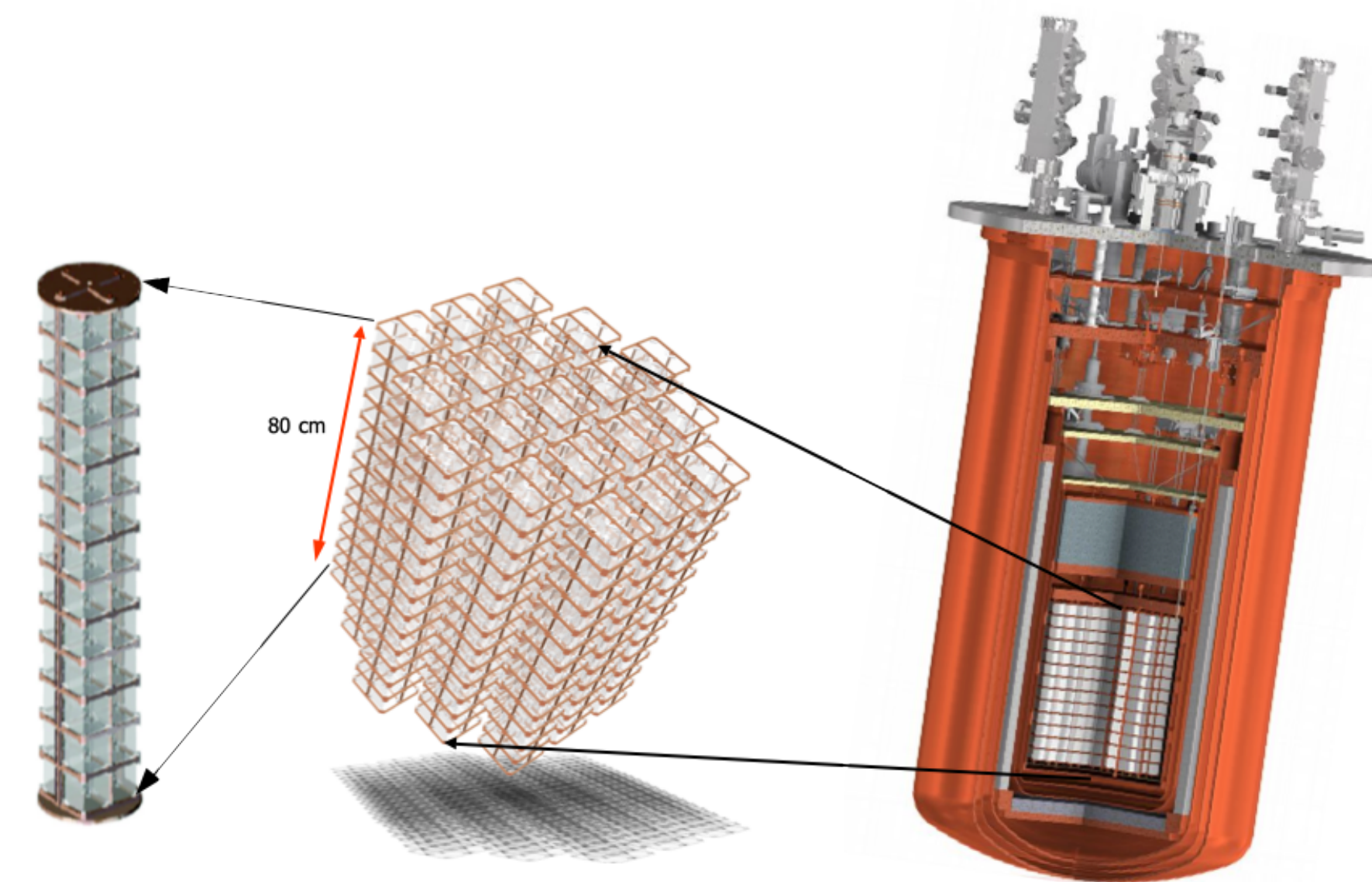
Primary goal: search for $0\nu\beta\beta$ decay of ^{130}Te

^{130}Te as $0\nu\beta\beta$ candidate:

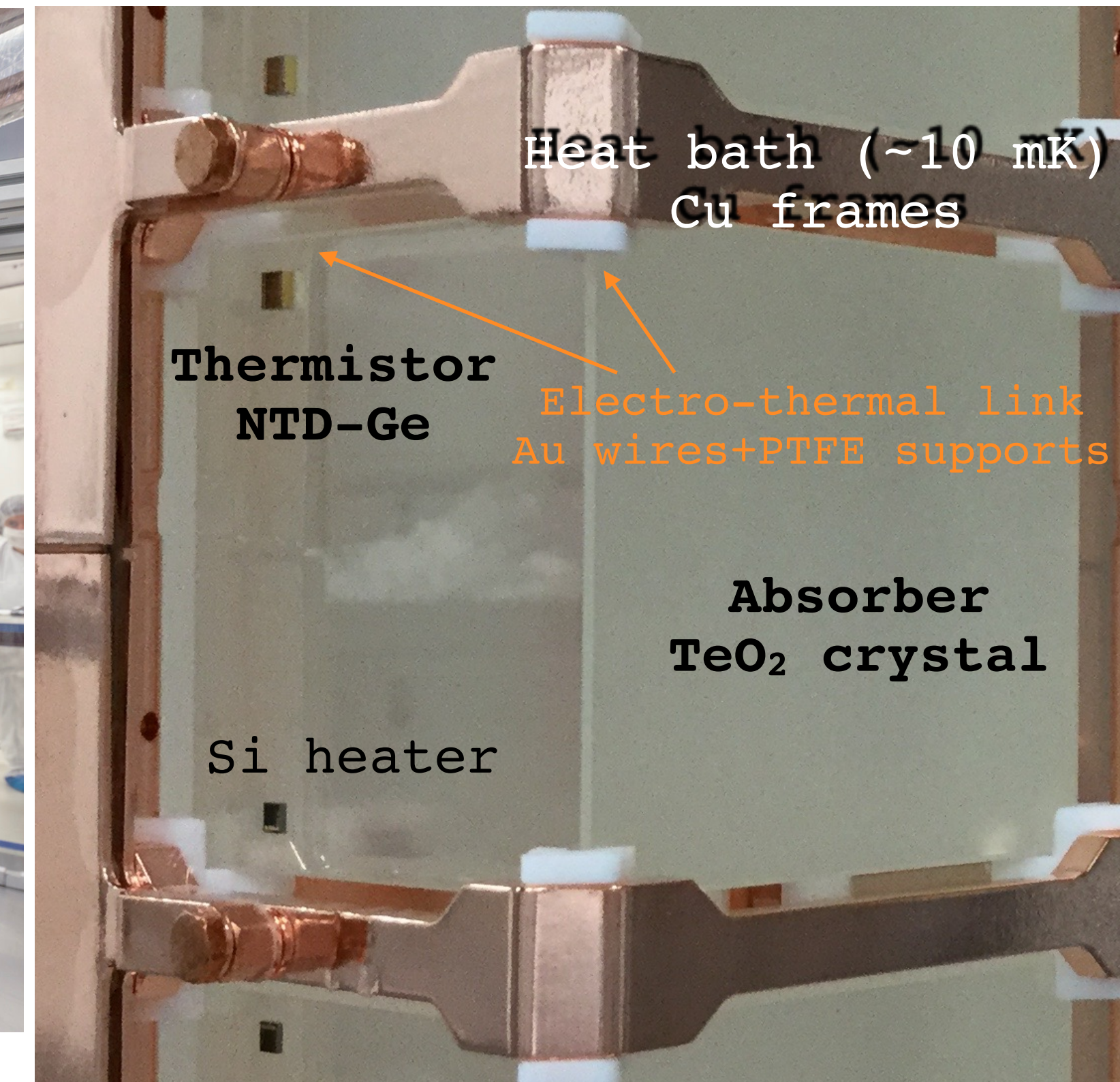
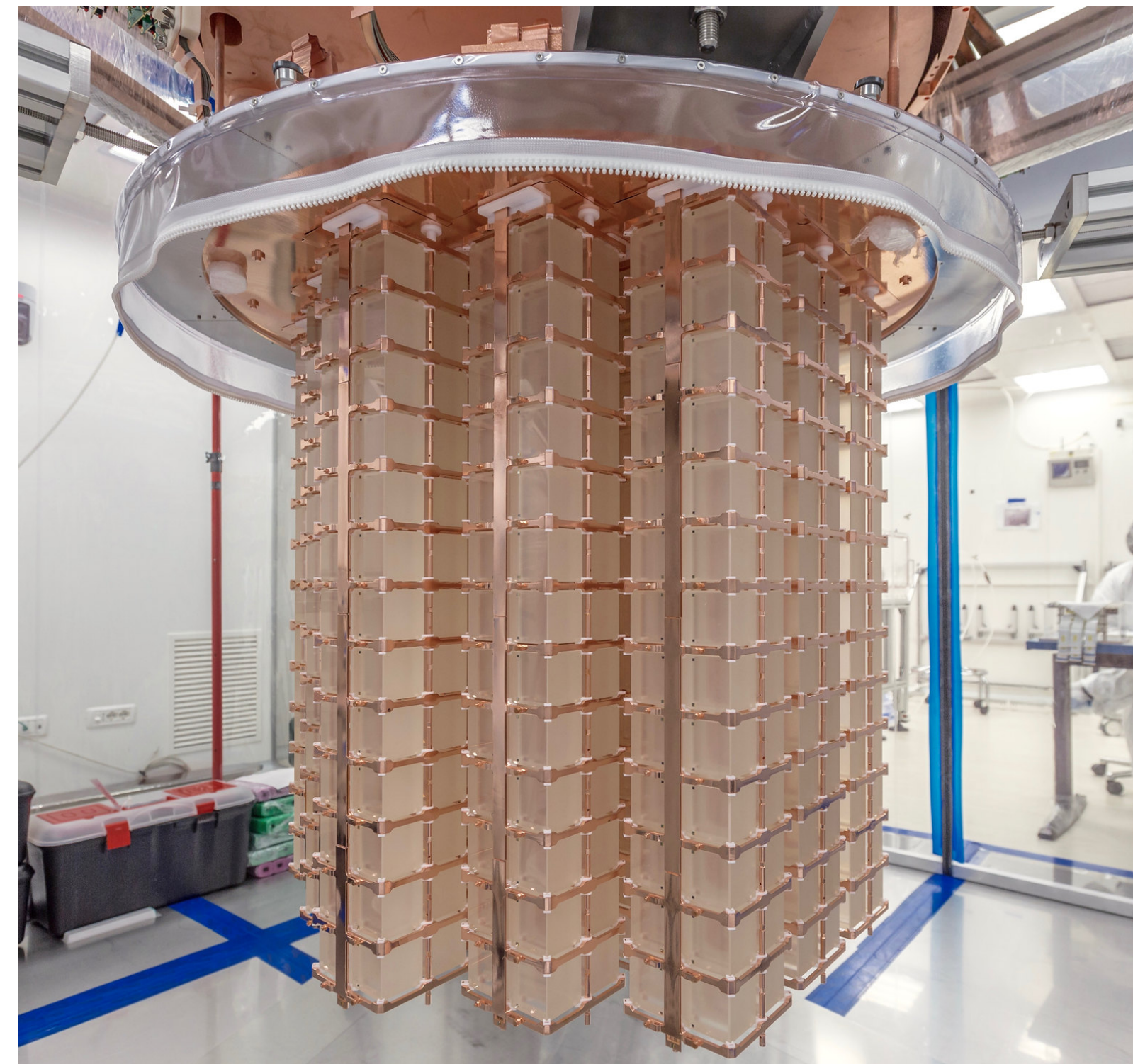
- High natural isotopic abundance: 34.2%
- Transition energy: $Q_{\beta\beta} = 2527.5 \text{ keV}$

The detector:

- Array of 988 TeO_2 $5\times 5\times 5 \text{ cm}^3$ detectors (750 g each)
- Total mass: $M = 742 \text{ kg}$ of TeO_2 (~206 kg of ^{130}Te)



19 towers with
13 floors of
4 detectors each

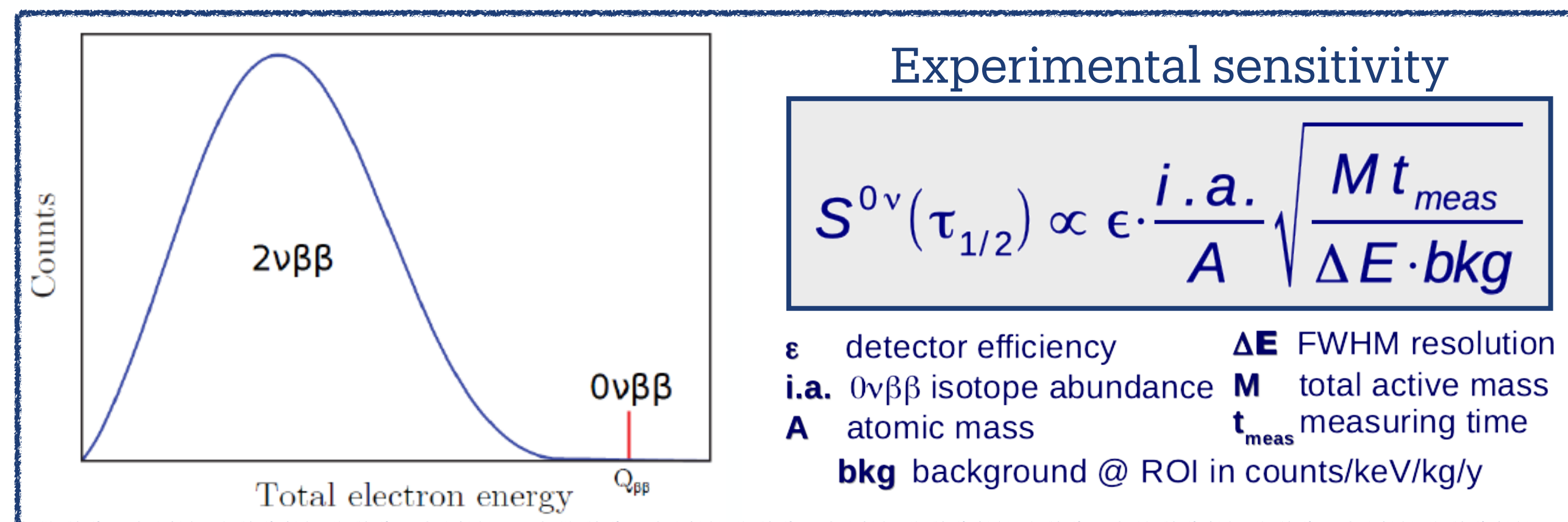
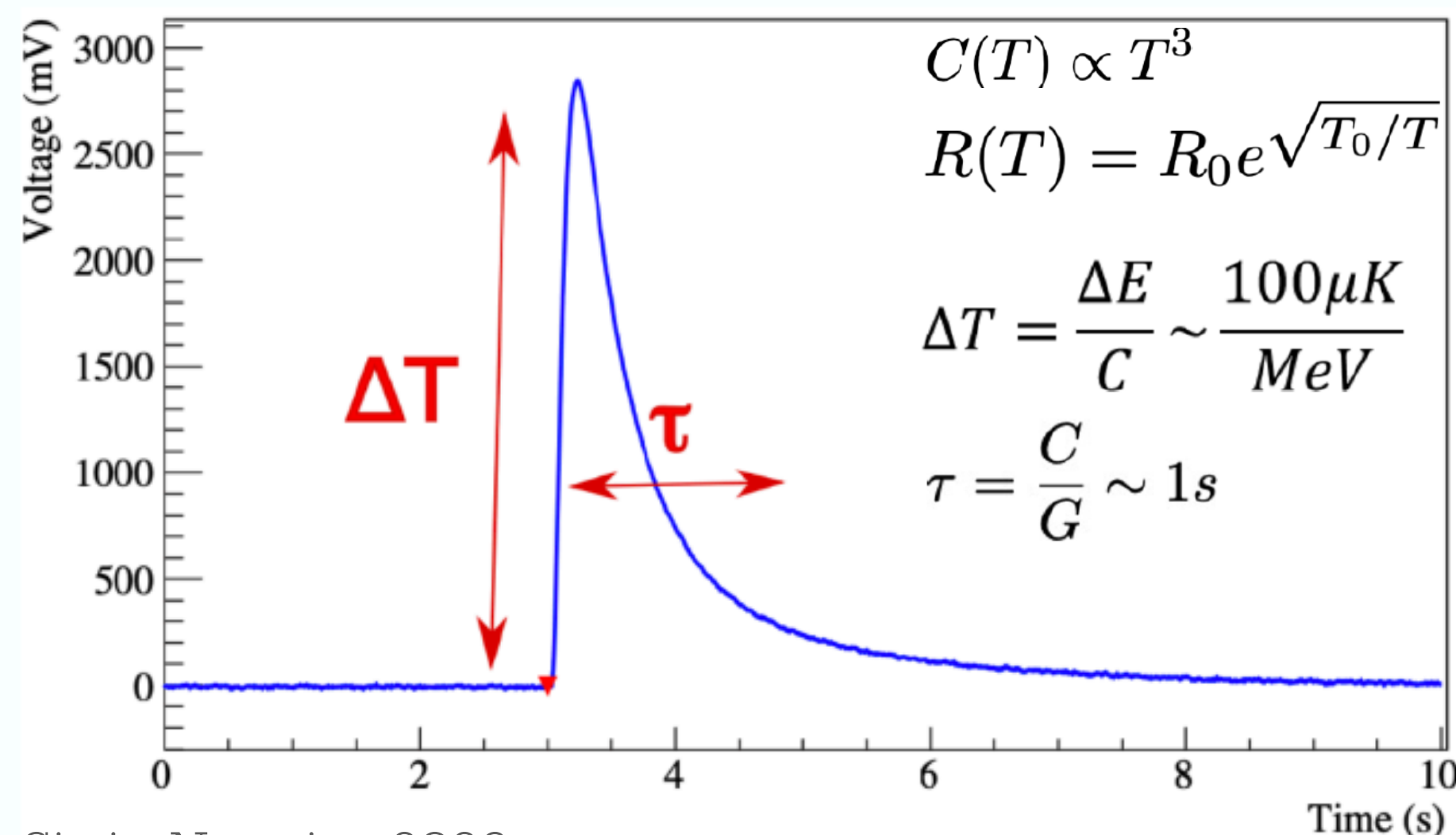
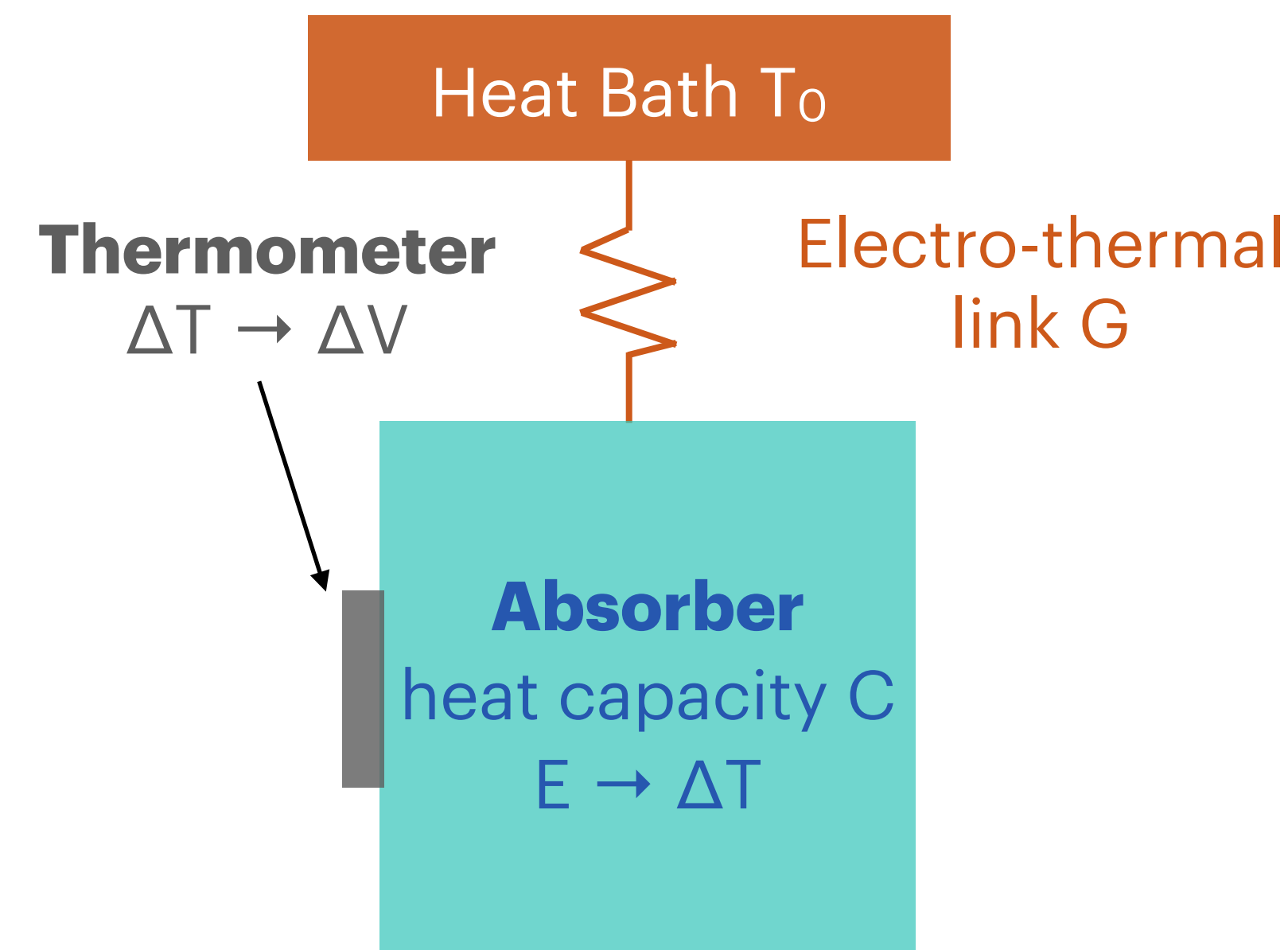


CRYOGENIC CALORIMETERS

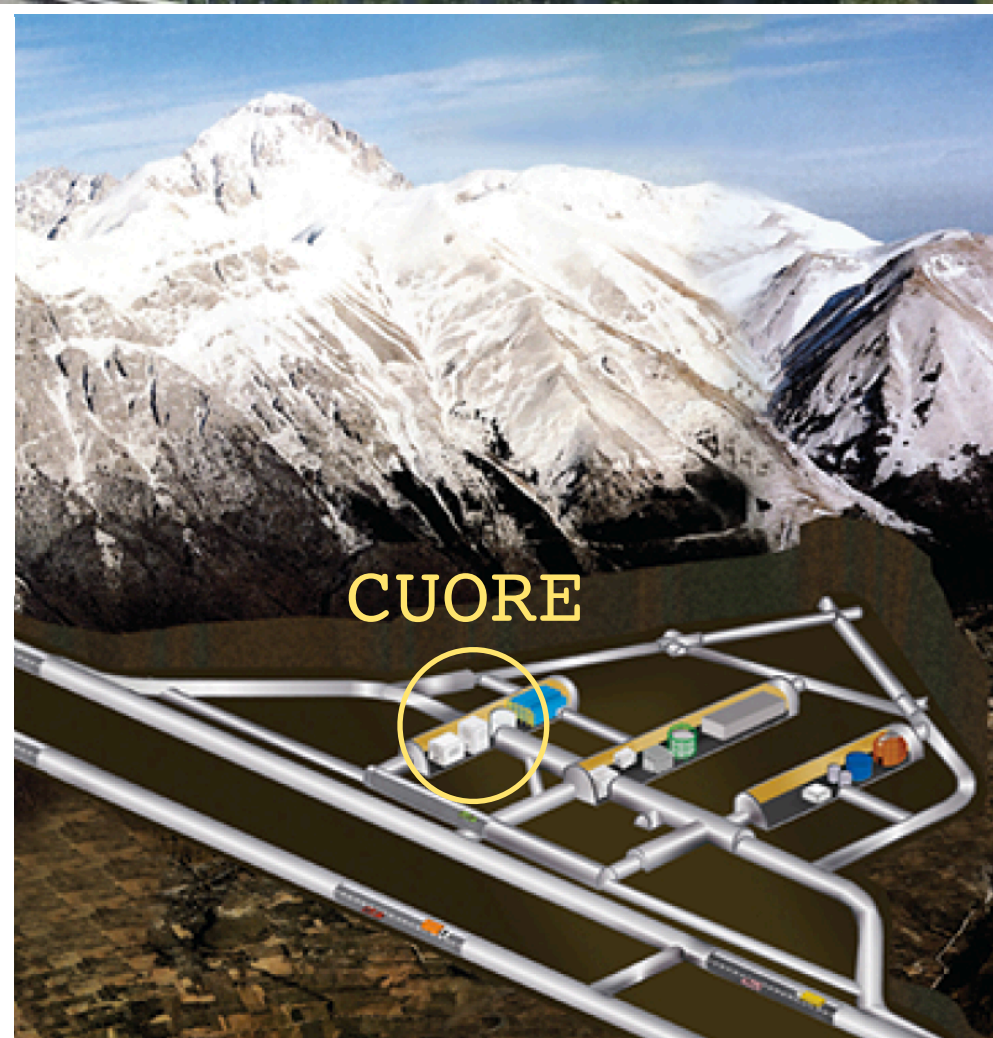
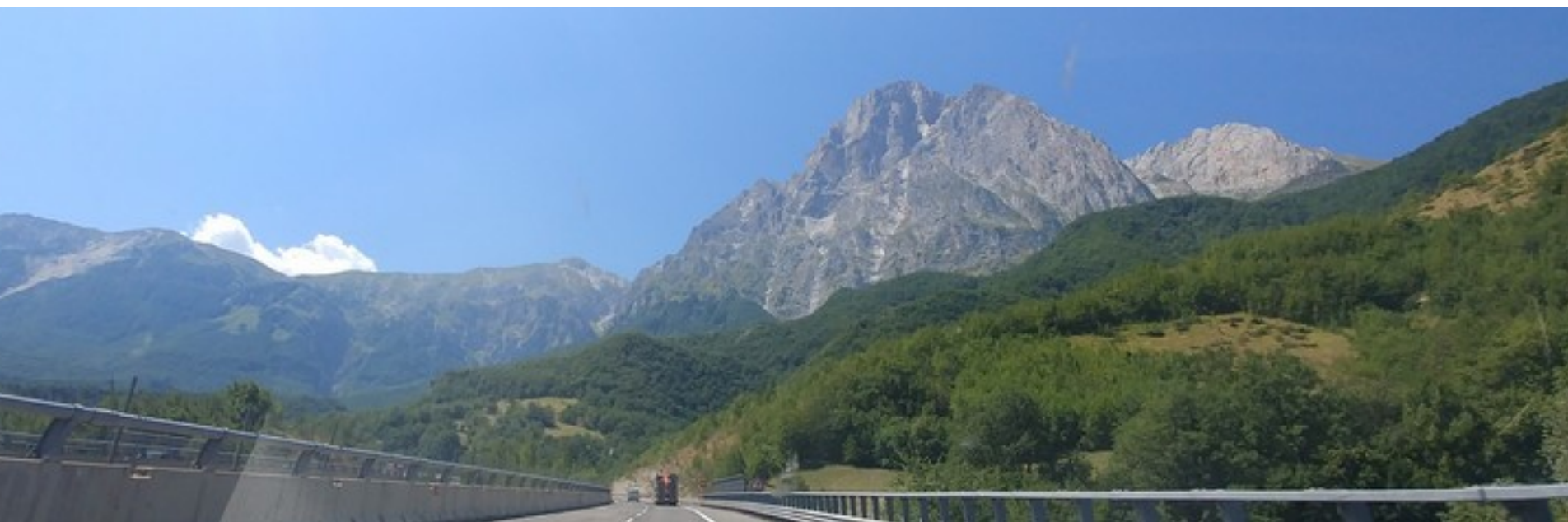
APPLIED TO $0\nu\beta\beta$ SEARCHES

Properties of cryogenic detectors:

- ▶ Excellent energy resolution: $\sim 0.3\%$ FWHM
- ▶ Wide choice of absorber materials (low heat capacity C)
- ▶ True calorimeters: identical response to different particles
- ▶ Source \equiv Detector: high detection efficiency
- ▶ Challenging technology
- ▶ Slow time response

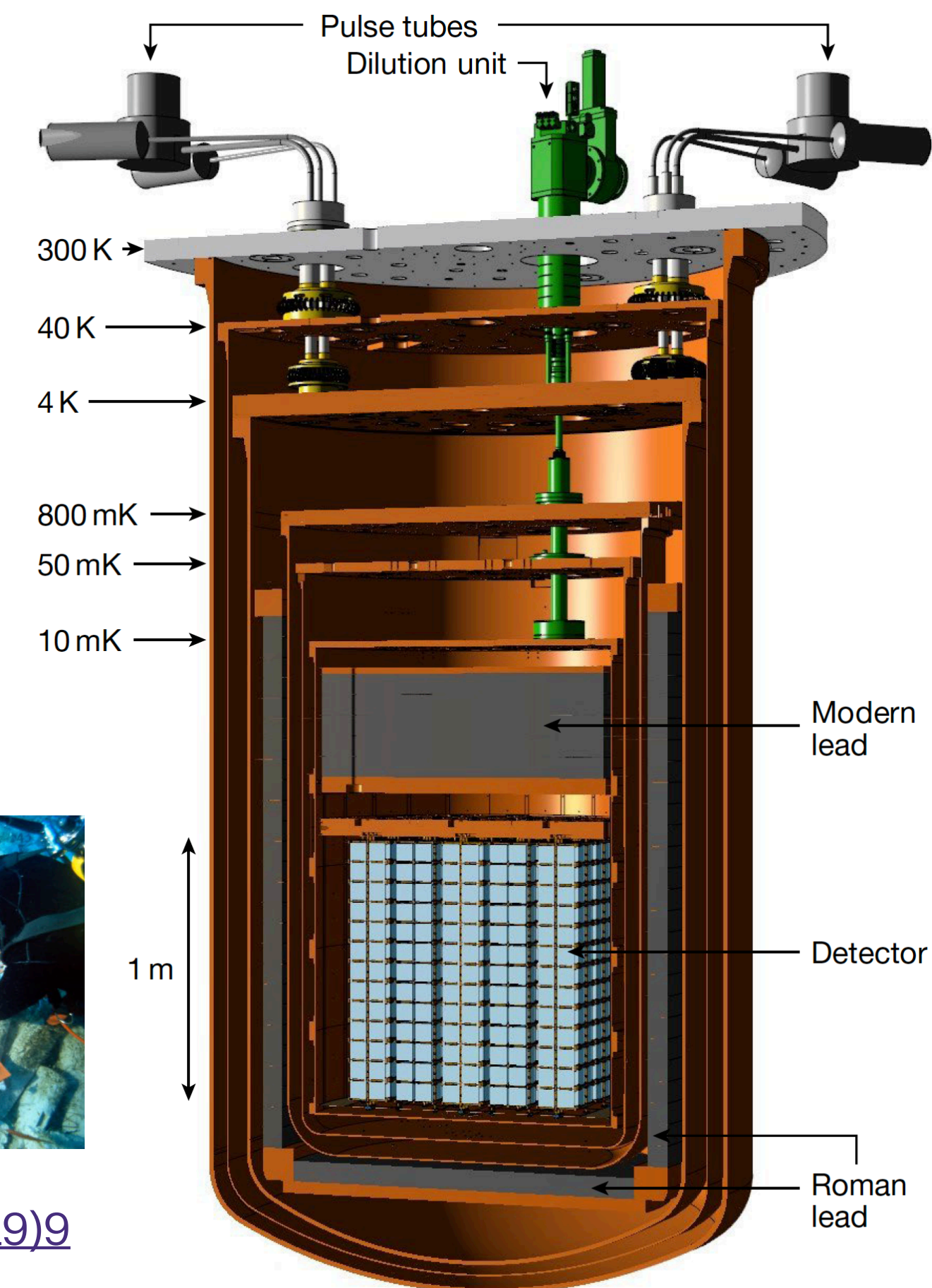


LOCATION AND INFRASTRUCTURE



CUORE cryogenic system

- Designed to cool a ~1 ton detector to ~10 mK.
- Internal lead and copper shielding to suppress radioactivity
- Careful selection of materials to achieve ultra-low background



[Cryogenics 102\(2019\)9](#)

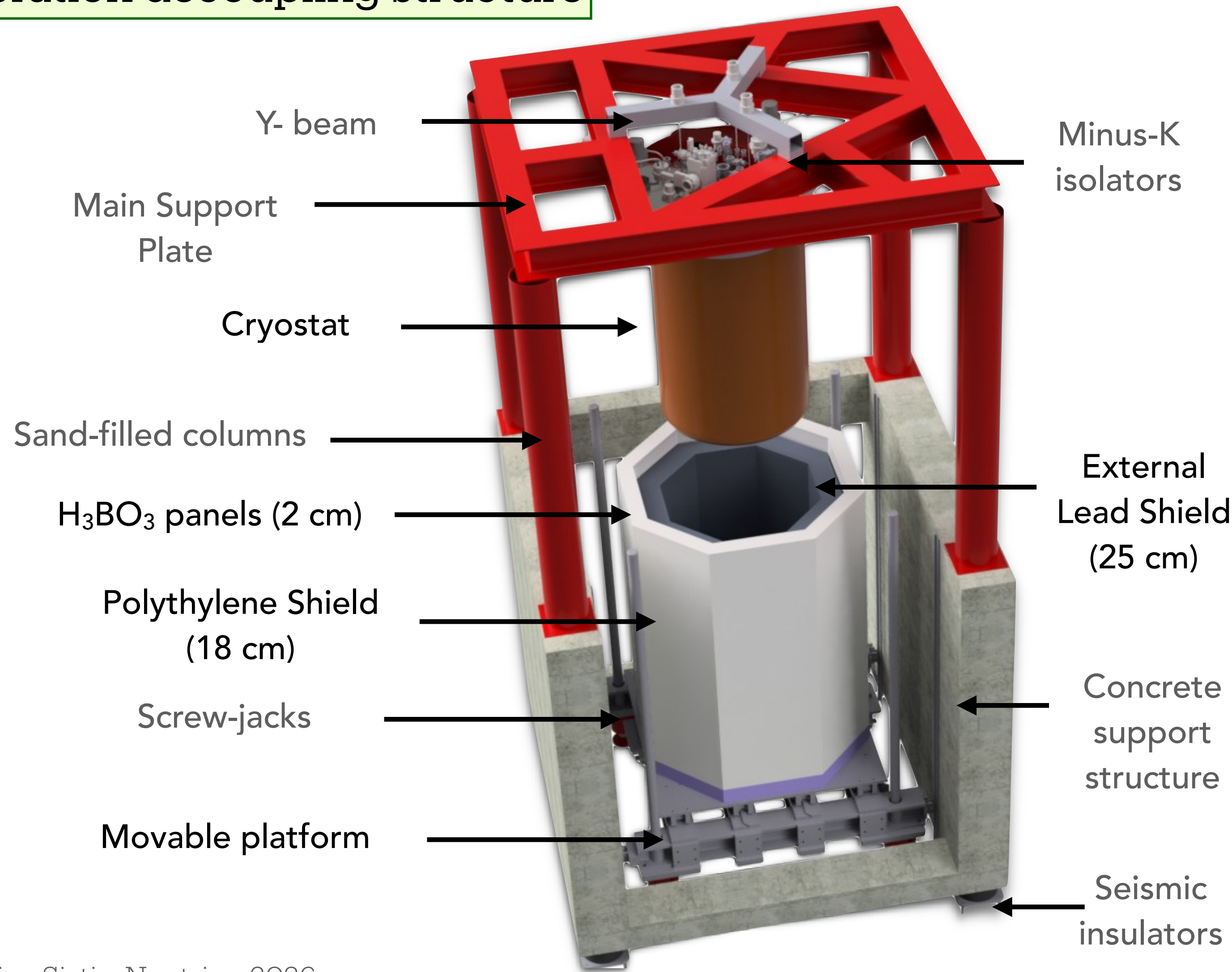
Average depth ~ 3600 m.w.e.
 μ flux: $3 \times 10^{-8} \mu/s/cm^2$
 n flux: $4 \times 10^{-6} n/s/cm^2 < 10 \text{ MeV}$
 γ flux: $\sim 0.73 \gamma/s/cm^2 < 3 \text{ MeV}$

TeO₂ crystals operated at 11-15 mK

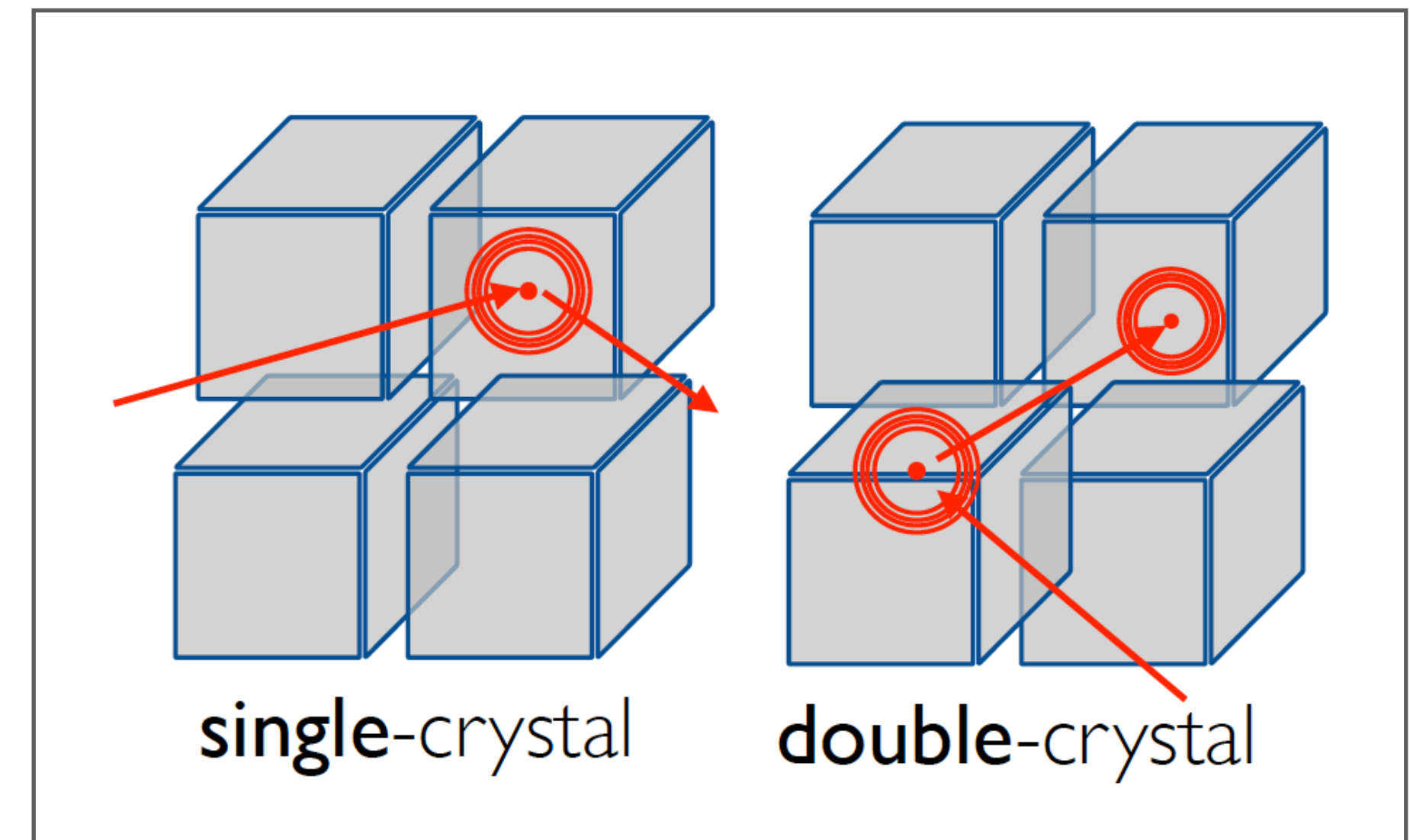
- Cryostat total mass: ~30 ton
- Mass cooled below 4K: ~15 ton
- Mass cooled below 50 mK: ~3 ton (Pb, Cu, TeO₂)

PASSIVE AND ACTIVE SHIELDING

External passive shielding and vibration decoupling structure



Anti-coincidence among detectors allows further background reduction during the off-line analysis



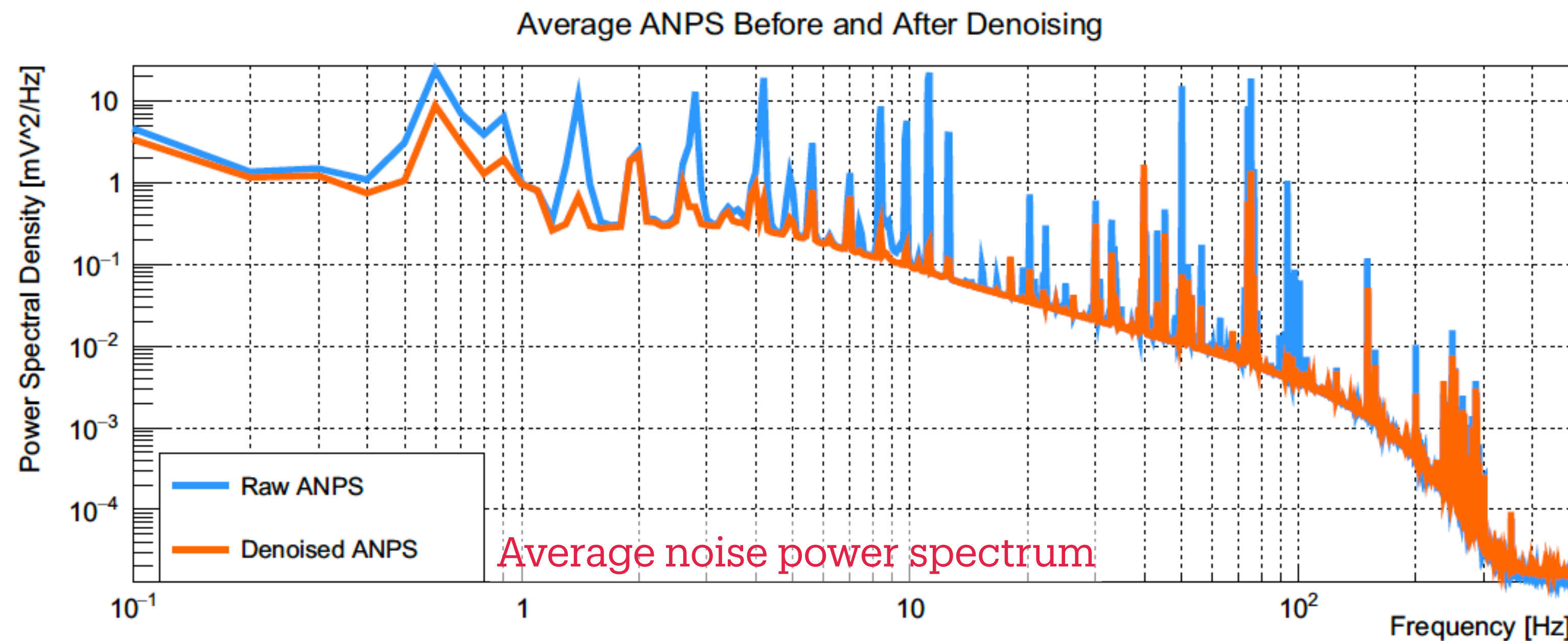
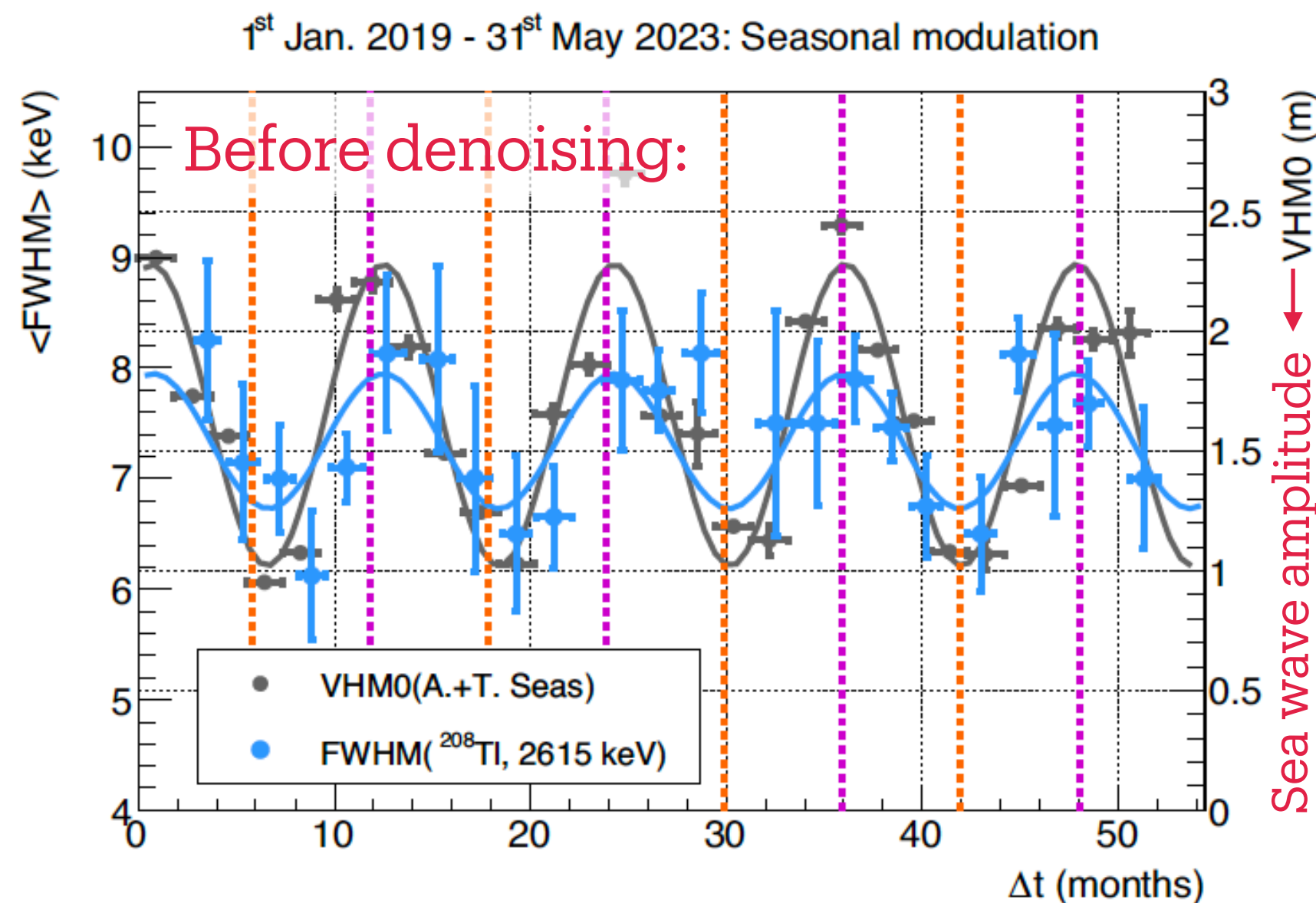
[Nature 604\(2022\)53](#)

VIBRATIONAL NOISE CONTROL

NOISE SOURCES: CRYOGENIC SYSTEM, ANTHROPOGENIC ACTIVITIES, ENVIRONMENT (MICROSEISMIC, EARTHQUAKES, AND SEA SWELL MOTION)

- ▶ Cryogenic detectors are **extremely sensitive** to vibrational noise.
- ▶ Pulse Tube cryocoolers (PT) are the **dominant source of noise** in the signal bandwidth (0–20 Hz) → we developed a system to tune the relative phases of the PTs, minimizing their induced noise.
- ▶ Software denoising using auxiliary sensors is performed to further suppress PT and **microseismic noise** in our detector measurements:

SARA SLO6 MK2 seismometers installed in the CUORE hut

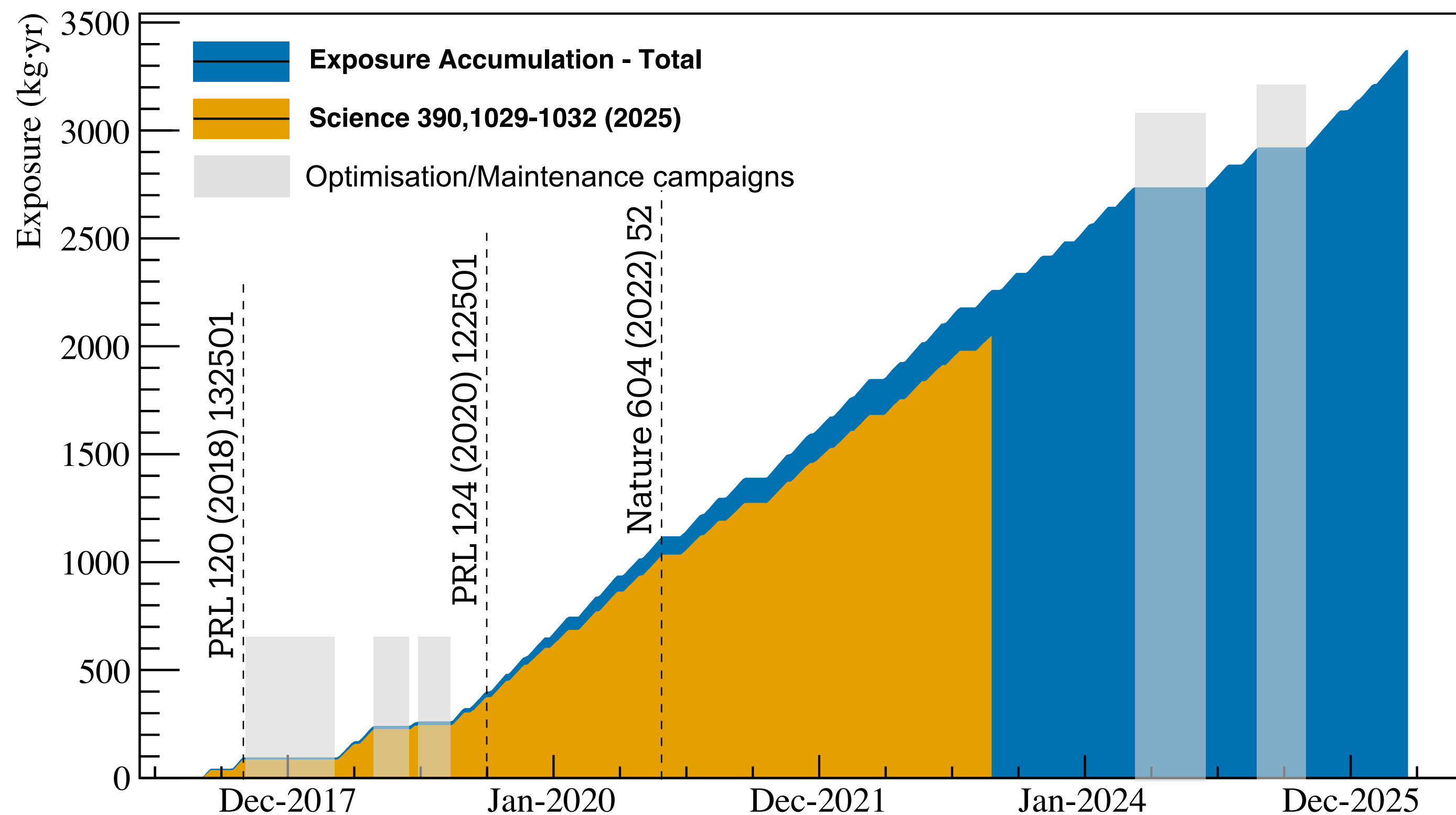
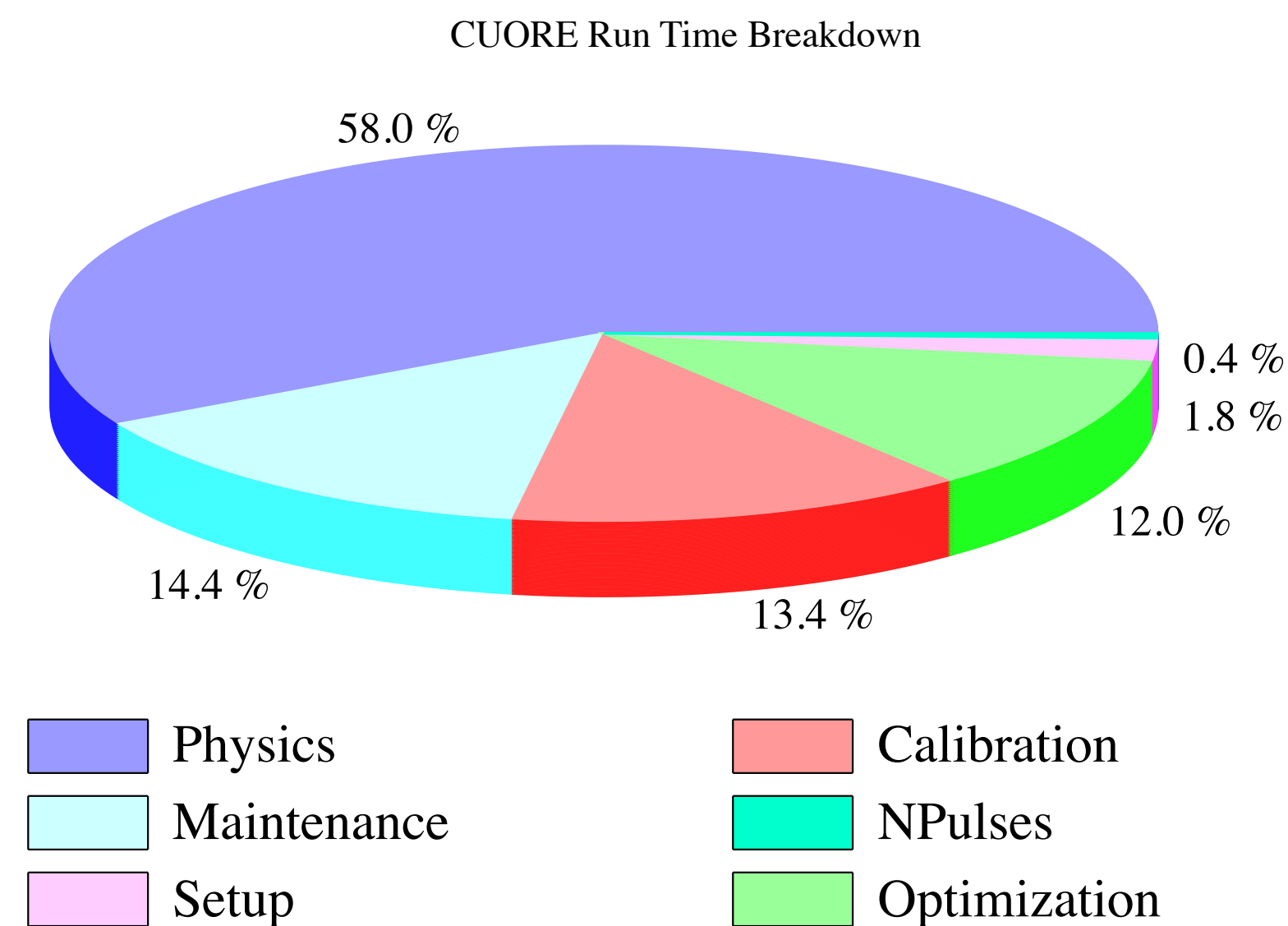


CUORE DATA ACCUMULATION

~ 10 YEARS OF CUORE DATA TAKING (2017-2026)

- ▶ **CUORE completed its $0\nu\beta\beta$ data-taking campaign on June 9, 2026** 🎉
- ▶ **Nearly a decade of stable cryogenic operation with > 99% active detectors**
- ▶ A benchmark for future large-scale cryogenic experiments
- ▶ Total accumulated data: **3.37 tonne-year of TeO_2** (before analysis cuts)

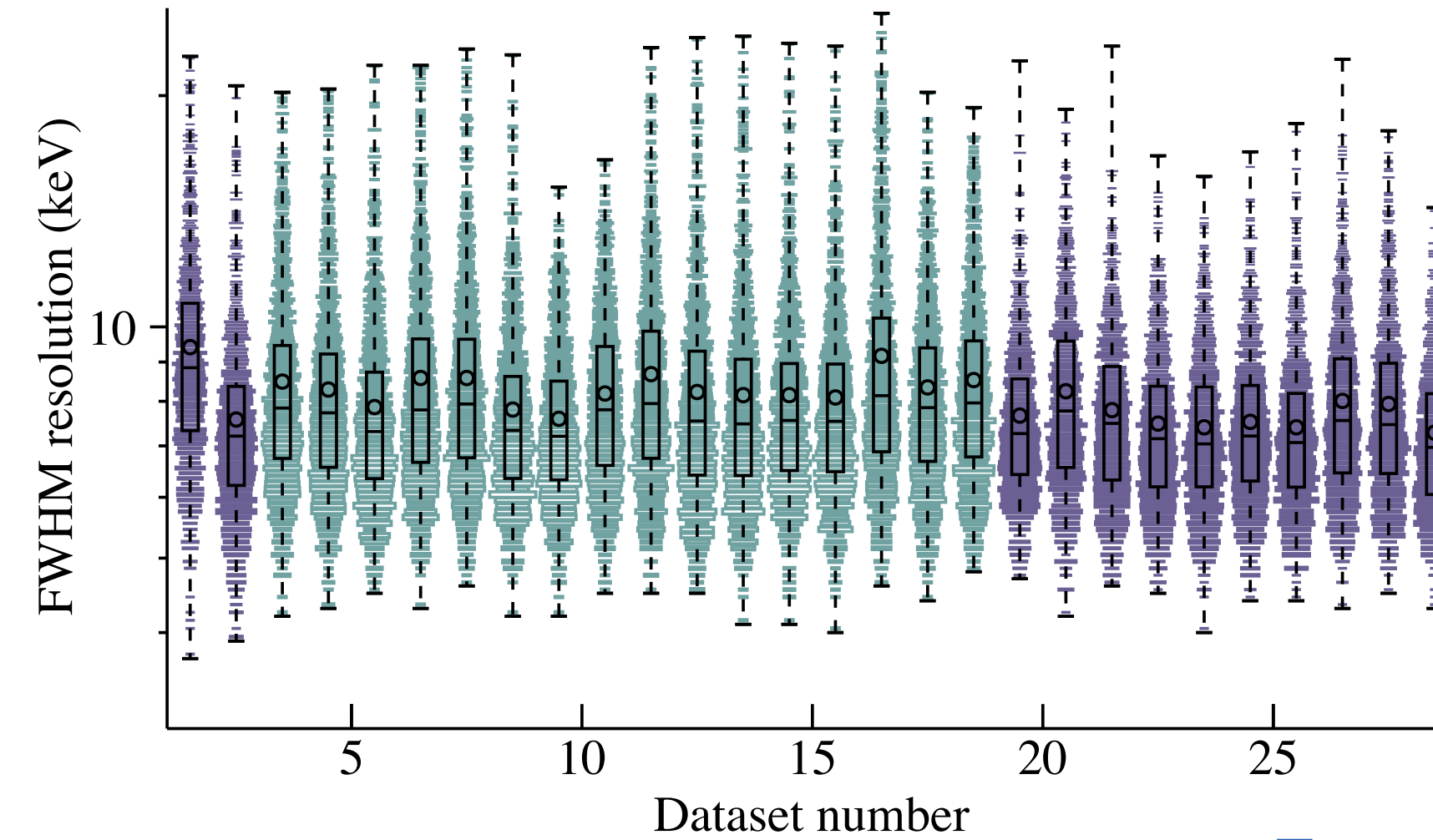
2019 – 2026 operation efficiency:



ANALYSED STATISTICS (SO FAR)

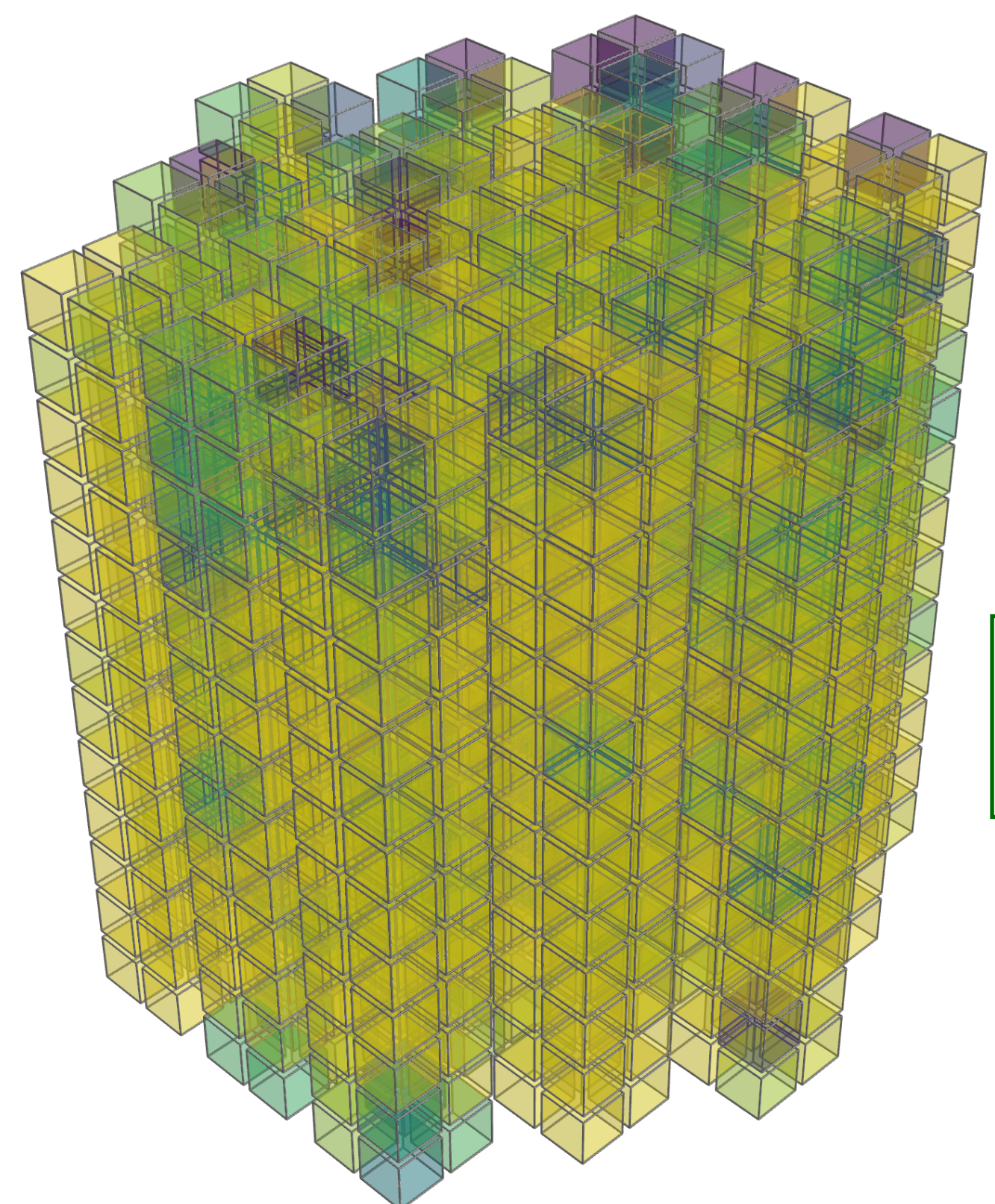
2 TONNE-YEAR CUORE EXPOSURE AND ENERGY RESPONSE AT $Q_{\beta\beta}$

Data analysis of the ~3rd tonne-year TeO_2 is ongoing → results in the fall!



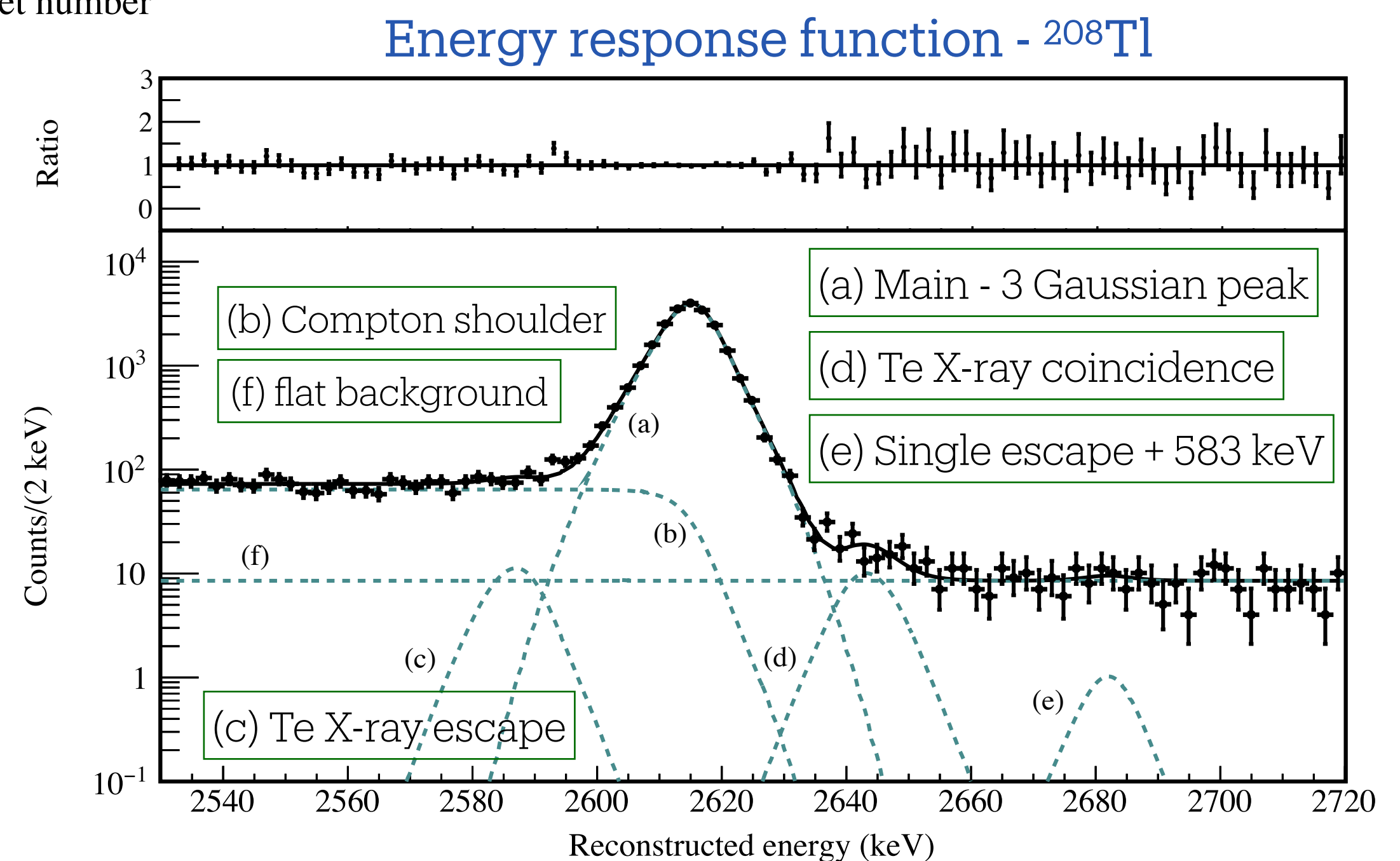
~0.3% FWHM in the ROI

FWHM (^{208}Tl) = (7.540 ± 0.024) keV
 FWHM ($Q_{\beta\beta}$) = (7.310 ± 0.024) keV
 $\Delta(Q_{\beta\beta}) = 0.40^{+0.21}_{-0.44}$ keV



2039.0 kg·y TeO_2
 567.0 kg·y ^{130}Te

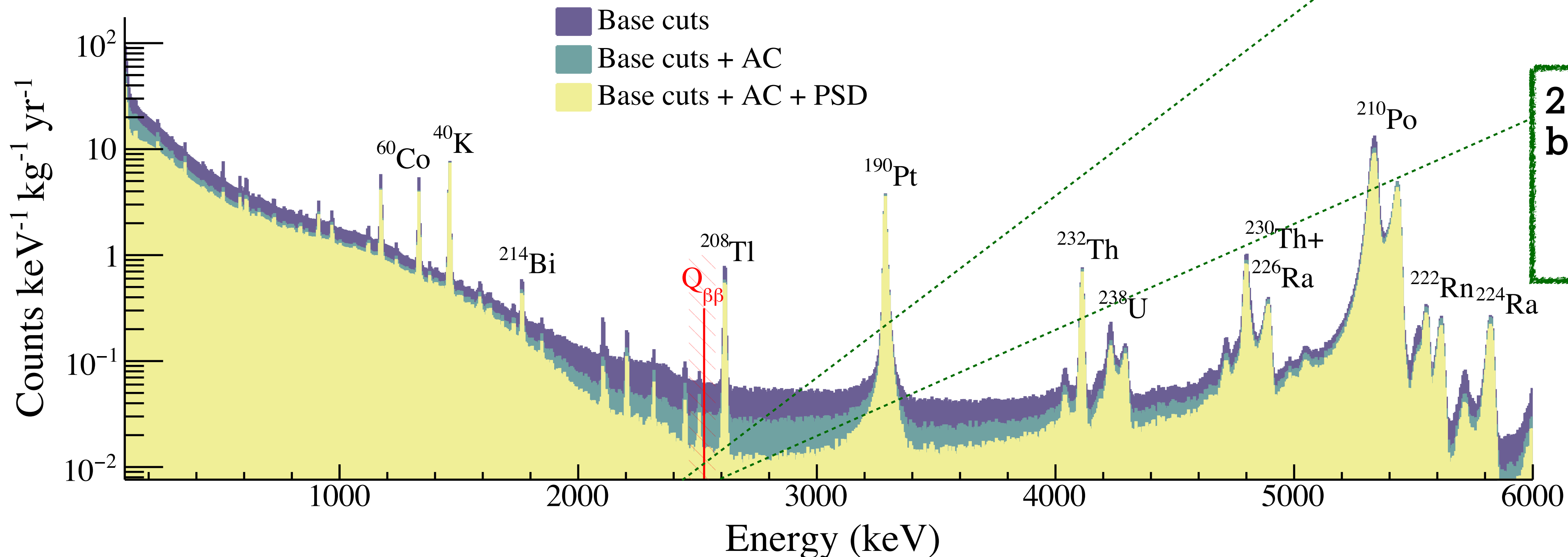
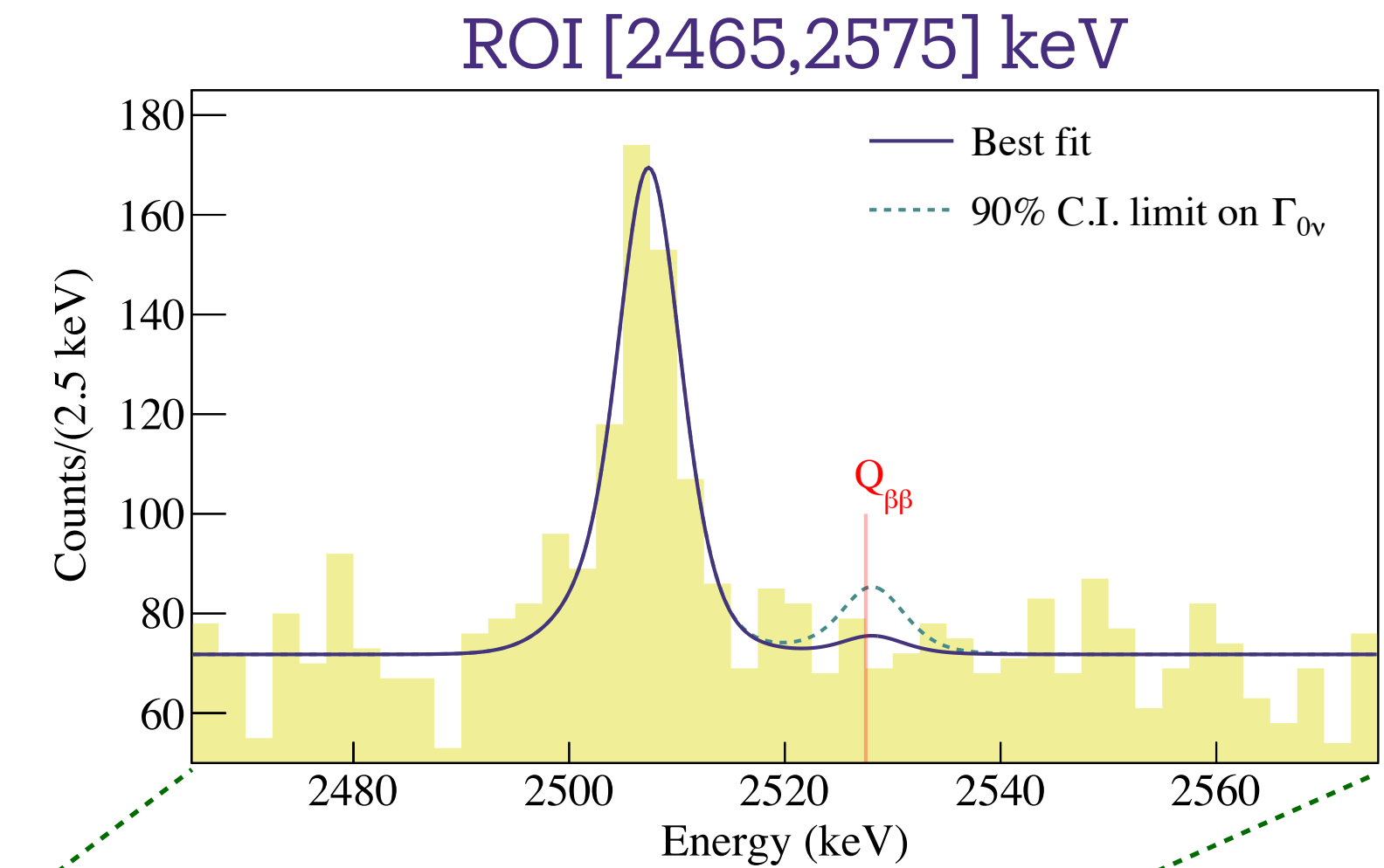
arxiv.org/2510.25720
[Science.390\(2025\)](https://doi.org/10.1126/science.390.2025)



CUORE 2 TONNE-YEAR SPECTRUM

AFTER ANALYSIS CUTS

- Several sequential analysis cuts (analysis threshold = 40 keV):
 - ◆ Base cuts: trigger, energy reconstruction, pile-up
 - ◆ Anti-coincidence (AC): only single-crystal events
 - ◆ Pulse shape discrimination (PSD): only signal-like events
- ➔ Total analysis cut efficiency: 93.4(18)%



**2 tonne-year average
bkg index in the ROI:**
 $(1.42^{+0.03}_{-0.02}) \times 10^{-2}$
counts/keV/kg/y

Science.390(2025)

CUORE ^{130}Te $0\nu\beta\beta$ SEARCH RESULTS

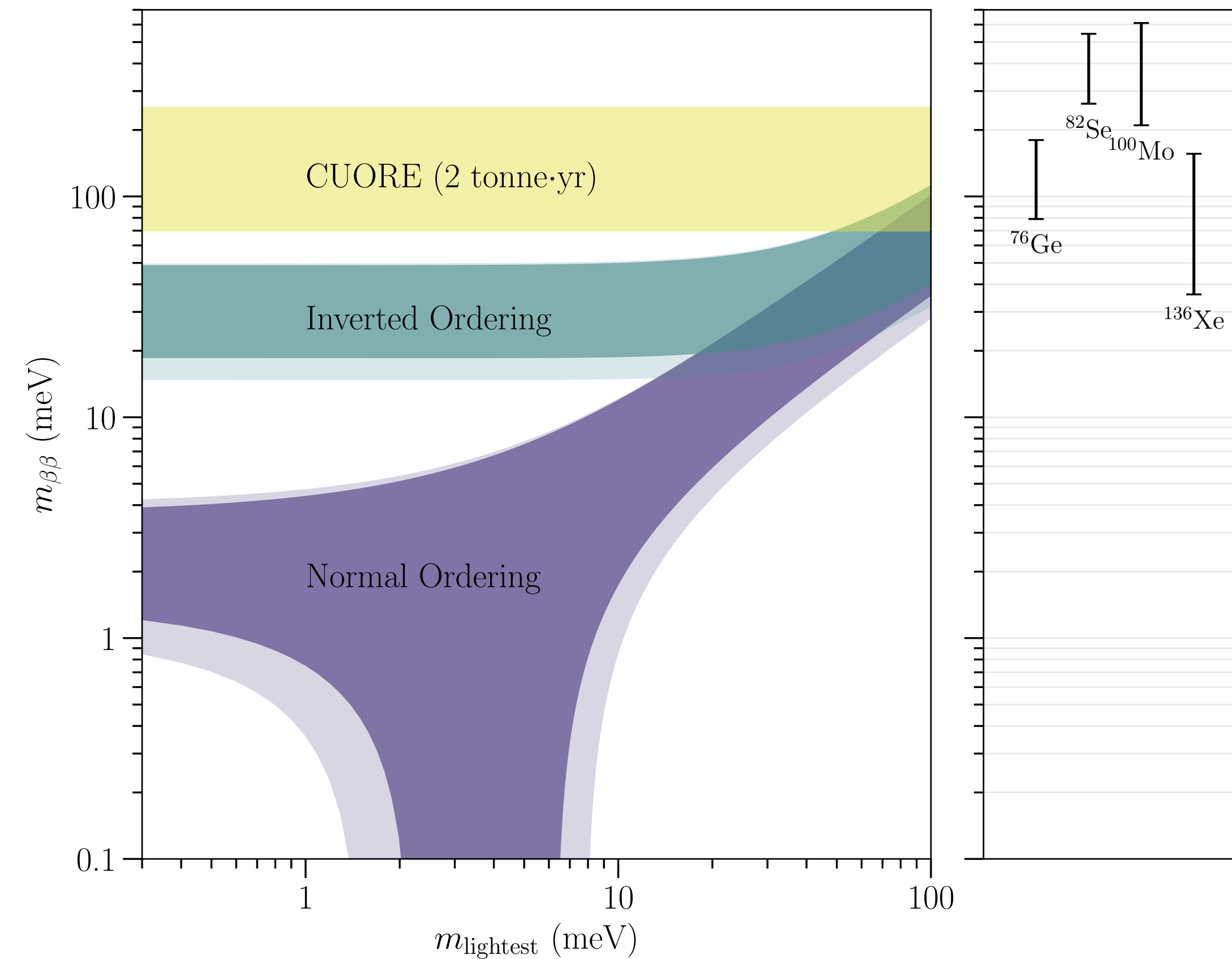
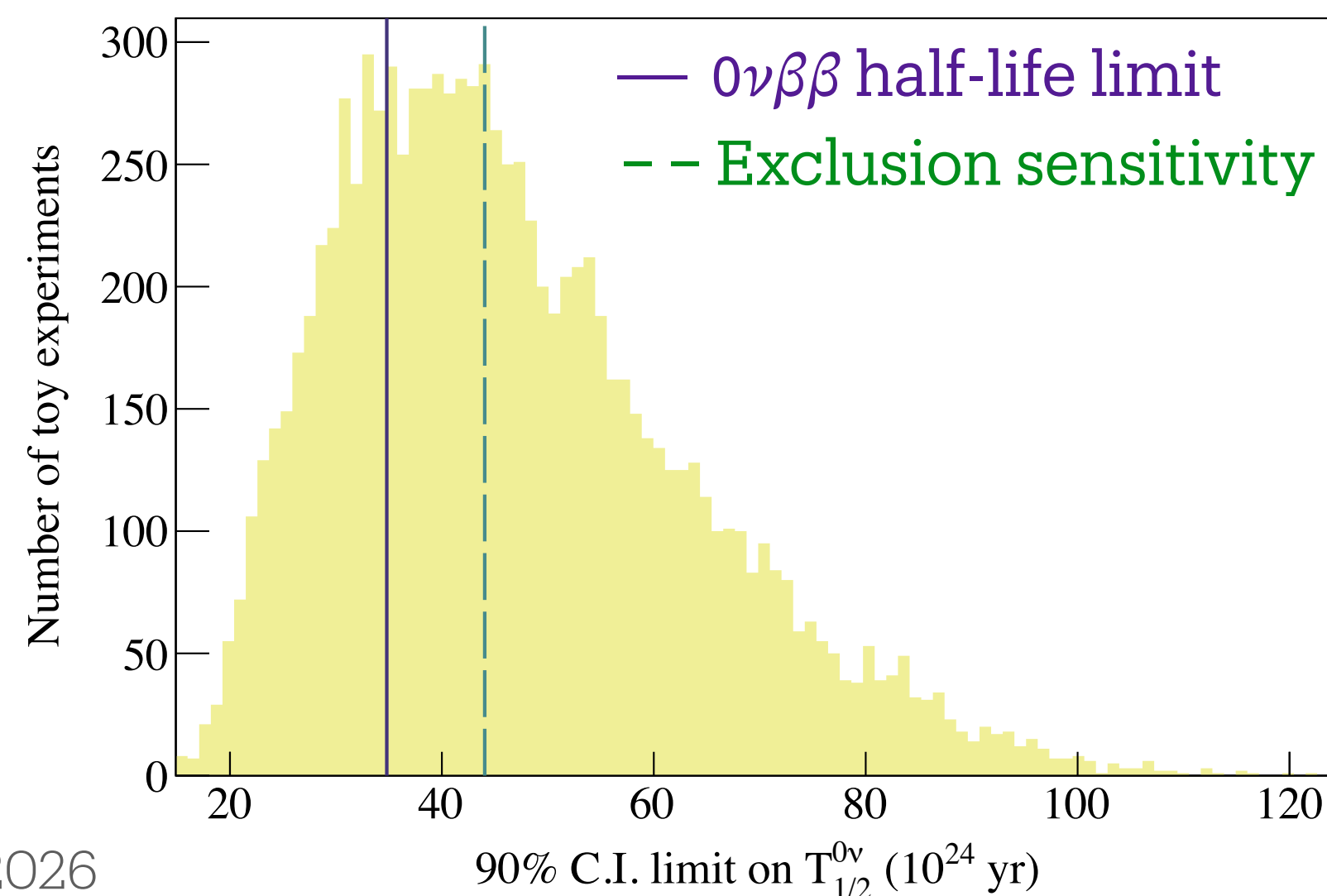
2 TONNE-YEAR EXPOSURE

[Science.390\(2025\)](#)

- ▶ Unbinned Bayesian fit with $\Gamma_{0\nu} > 0$
- ▶ Decay rate limit $\Gamma_{0\nu} < 2.0 \times 10^{-26}/\text{yr}$ (90% C.I.)
- ▶ **We find no evidence of ^{130}Te $0\nu\beta\beta$ decay:**

^{130}Te $0\nu\beta\beta$ half-life $T_{1/2} > 3.5 \times 10^{25}$ yr (90% C.I.)

- ▶ Median exclusion sensitivity from 10^4 toy MC experiments in background-only hypothesis: $T_{1/2} = 4.4 \times 10^{25}$ yr (90% C.I.)



Assuming the exchange of a light Majorana ν , the limit on the effective Majorana mass with 2 tonne-year of data of CUORE is:
 $m_{\beta\beta} < 70\text{--}250$ meV at 90% C.I.

CUORE ^{130}Te $2\nu\beta\beta$ RESULTS

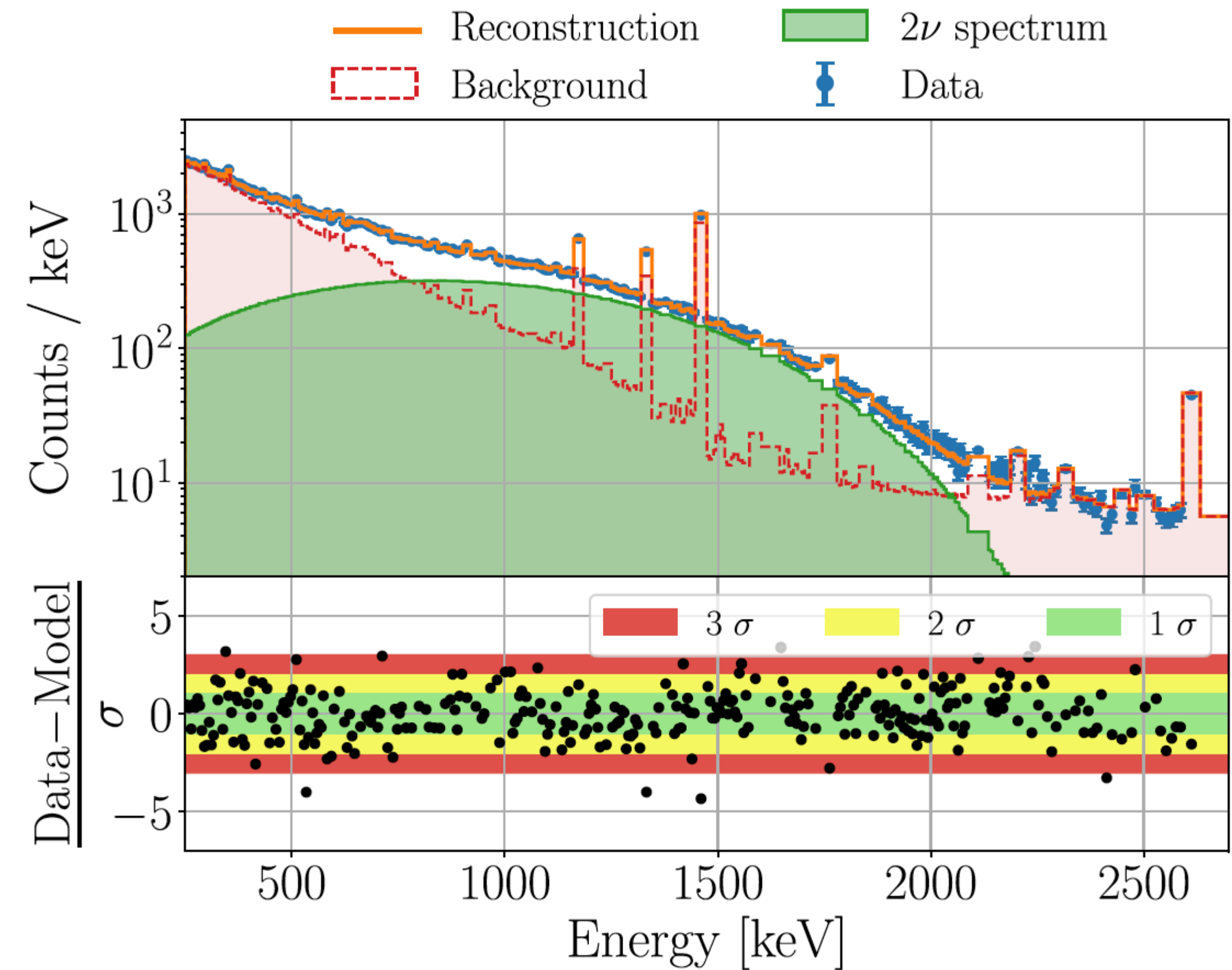
STANDARD MODEL ALLOWED DECAY

- A robust background model was developed using 1038.4 kg-year of TeO_2 exposure, validating the design background projections

- This model enabled the most precise measurement of the ^{130}Te $2\nu\beta\beta$ half-life:

$$T_{1/2}^{2\nu} = (9.32^{+0.05}_{-0.04} \text{stat } ^{+0.07}_{-0.07} \text{syst}) \times 10^{20} \text{ yr}$$

- The $2\nu\beta\beta$ decay spectral shape was also studied, confirming the preference for the Single State Dominance (SSD) model.



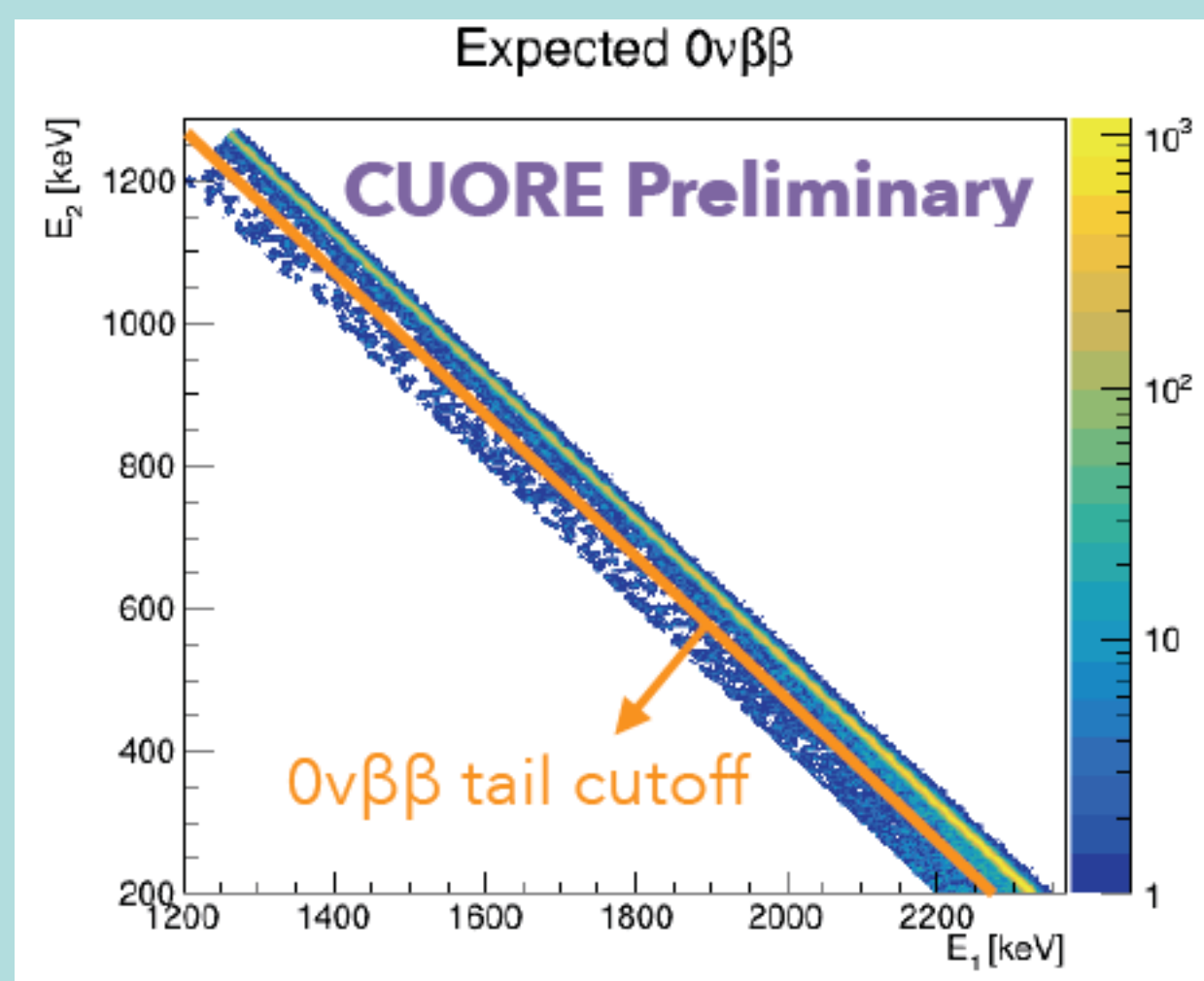
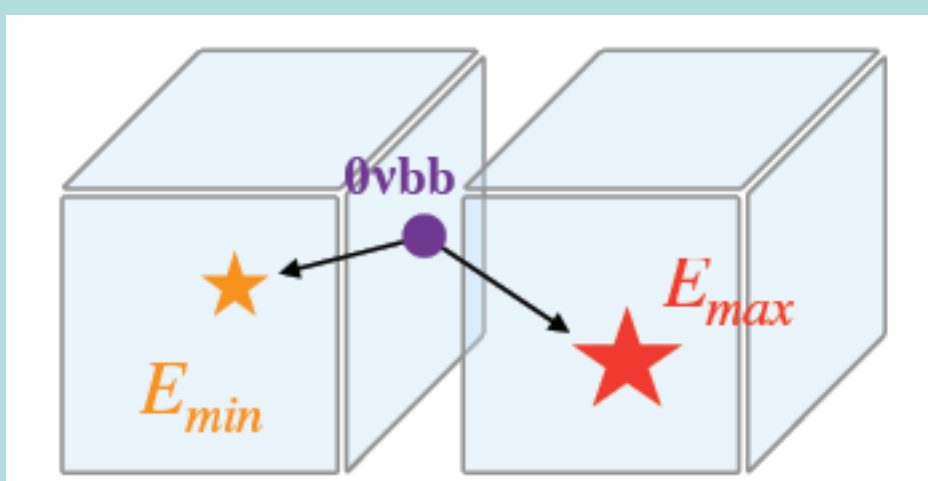
[PRL.135\(2025\)](#)

[PRD.110\(2024\)](#)

OTHER CUORE RESULTS

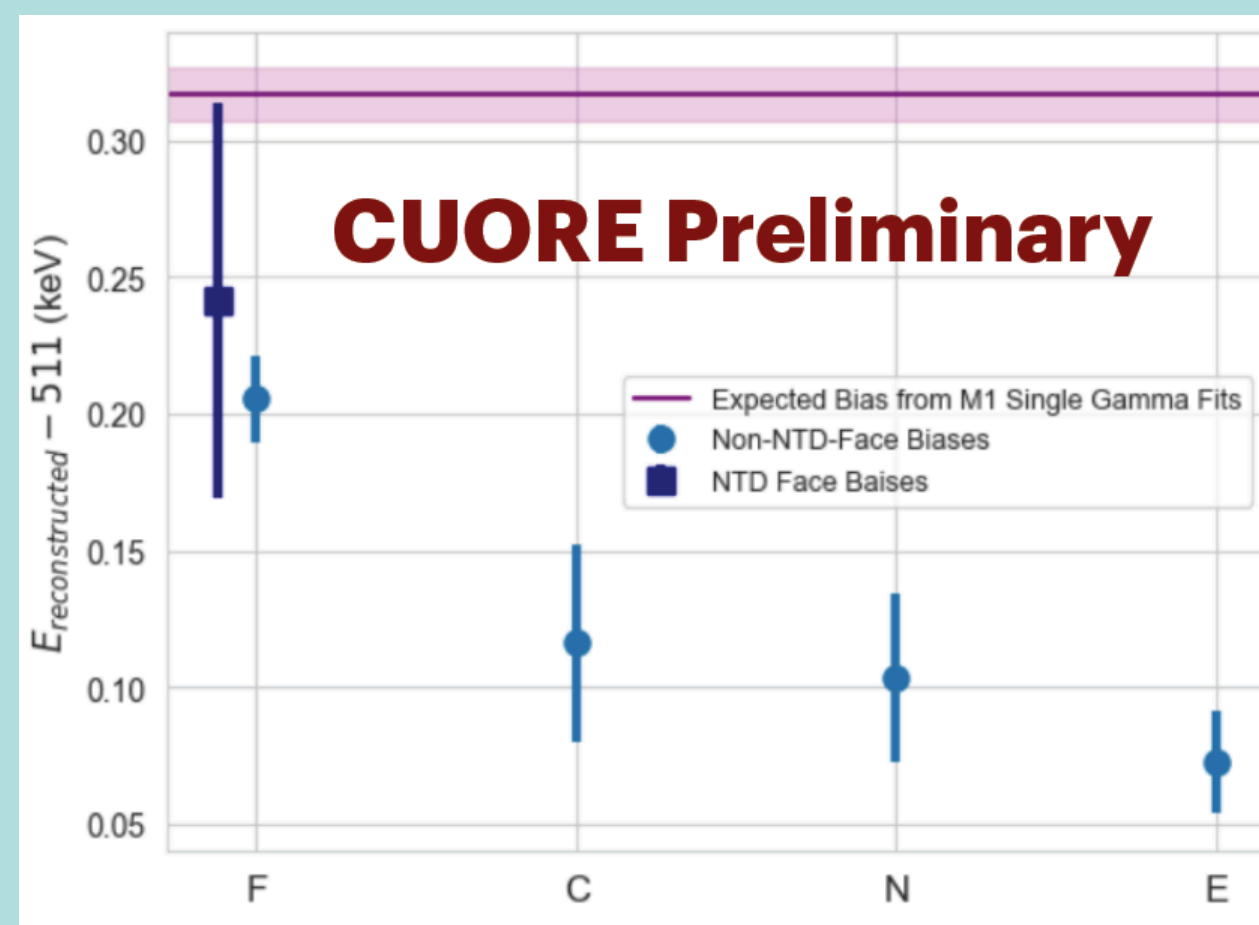
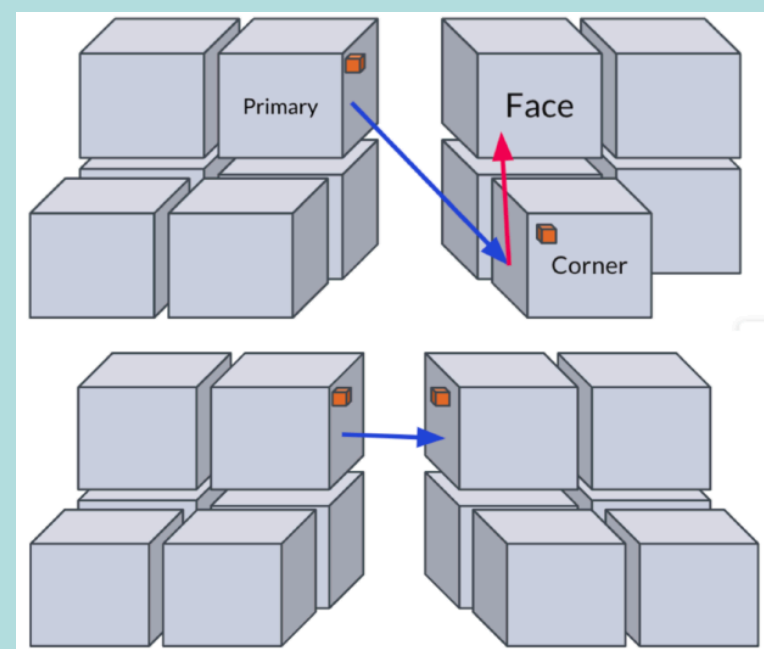
#303

Multiplicity-2 Analysis in CUORE and CUPID experiments



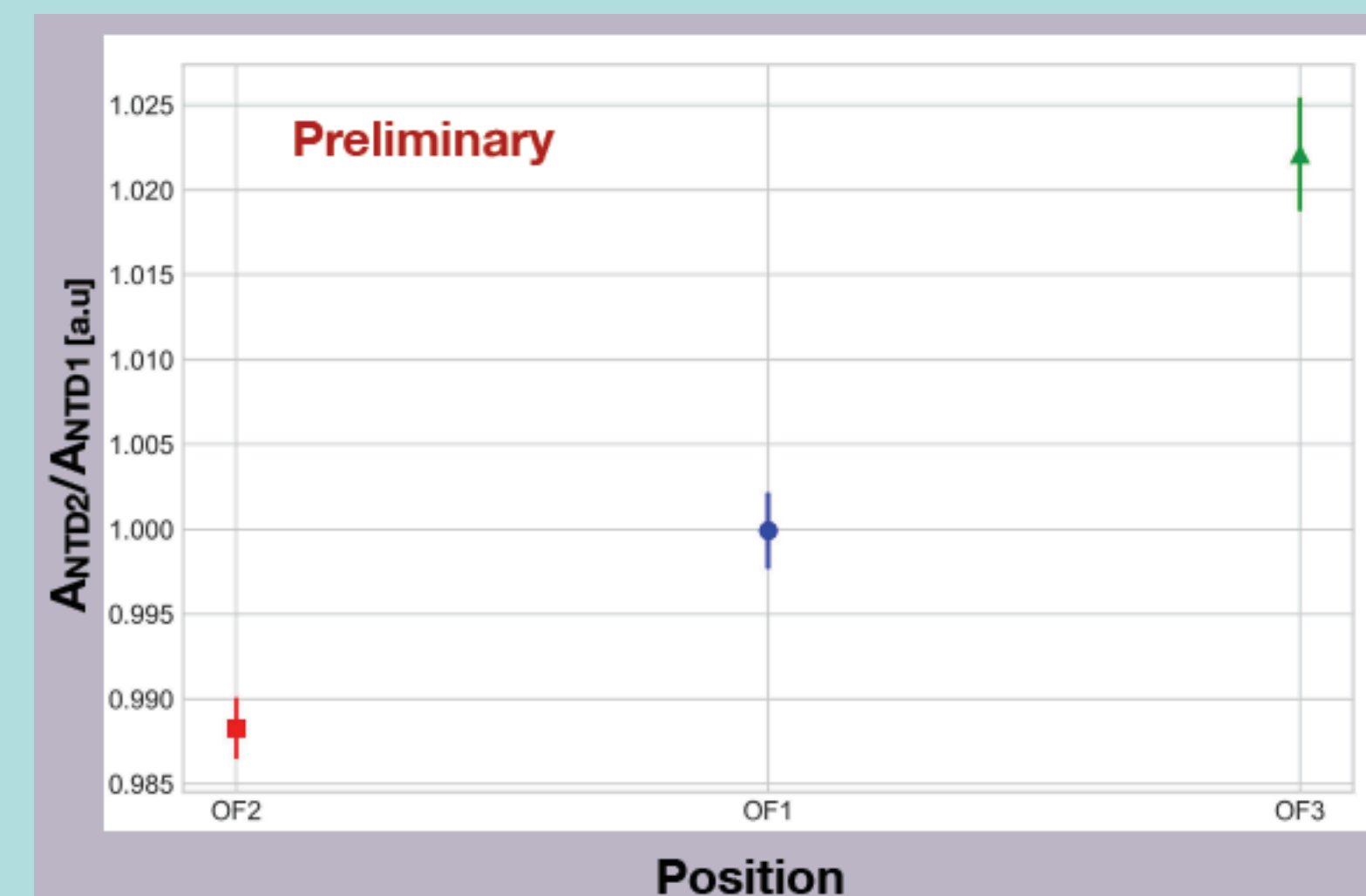
#101

Effects of event topology on energy reconstruction in the CUORE TeO_2 bolometers



#291

Initial Results from CERES: Cryogenic Experiment to Reconstruct Energy Systematics in TeO_2 bolometers with CUORE

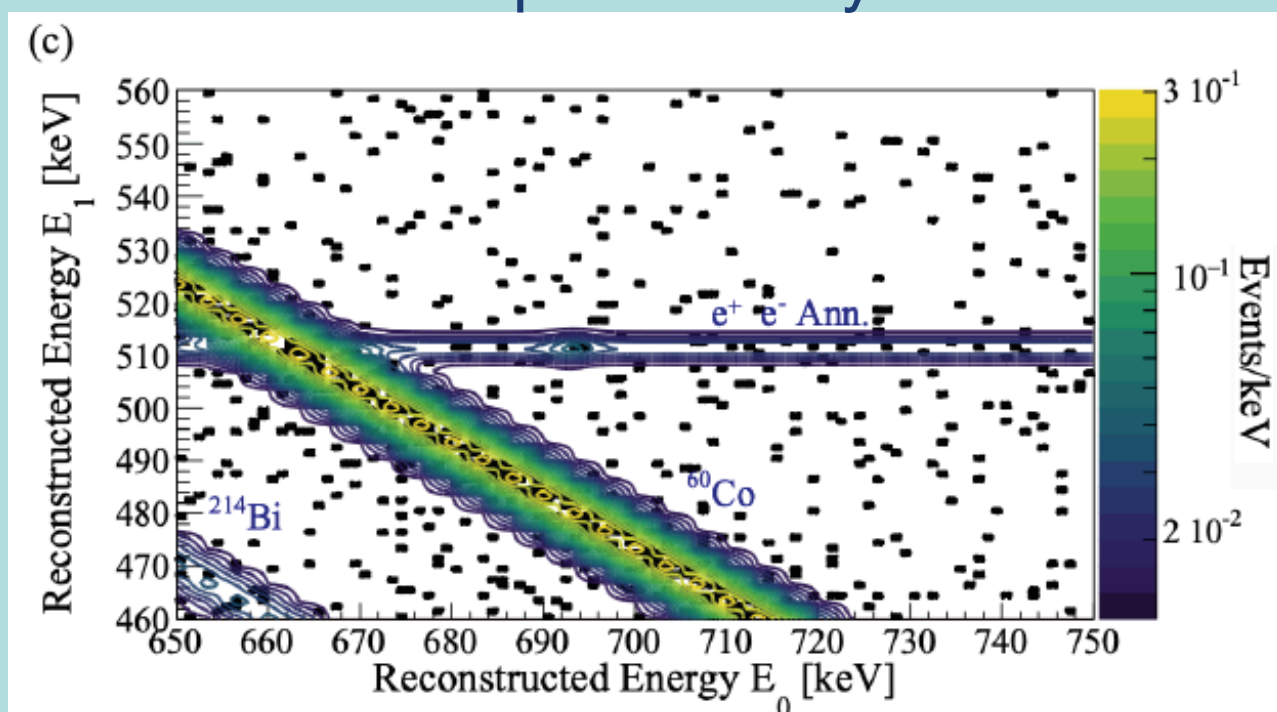


OTHER CUORE RESULTS

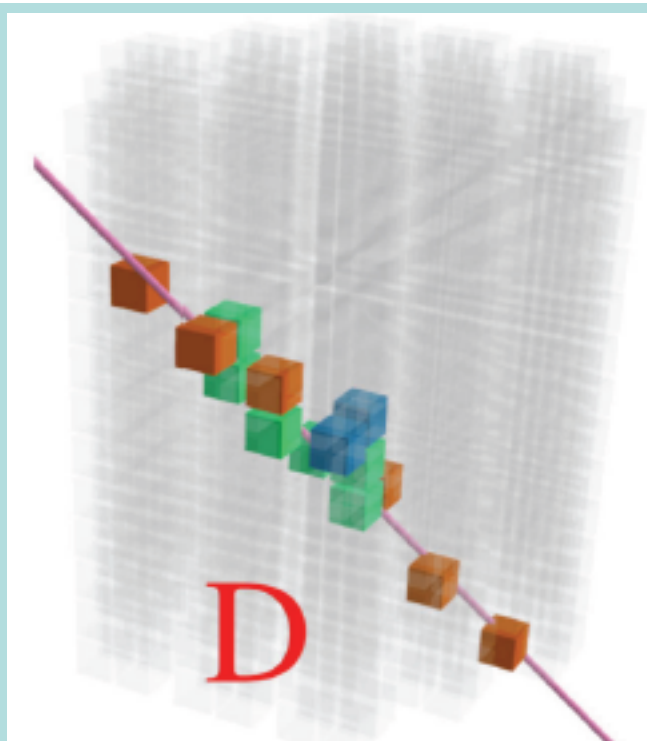
#326

End-to-End Data Analysis Methods for the CUORE Experiment

Search for neutrinoless positron-emitting electron capture decay of ^{120}Te



[PhysRevC.105.065504](https://arxiv.org/abs/1905.06550)

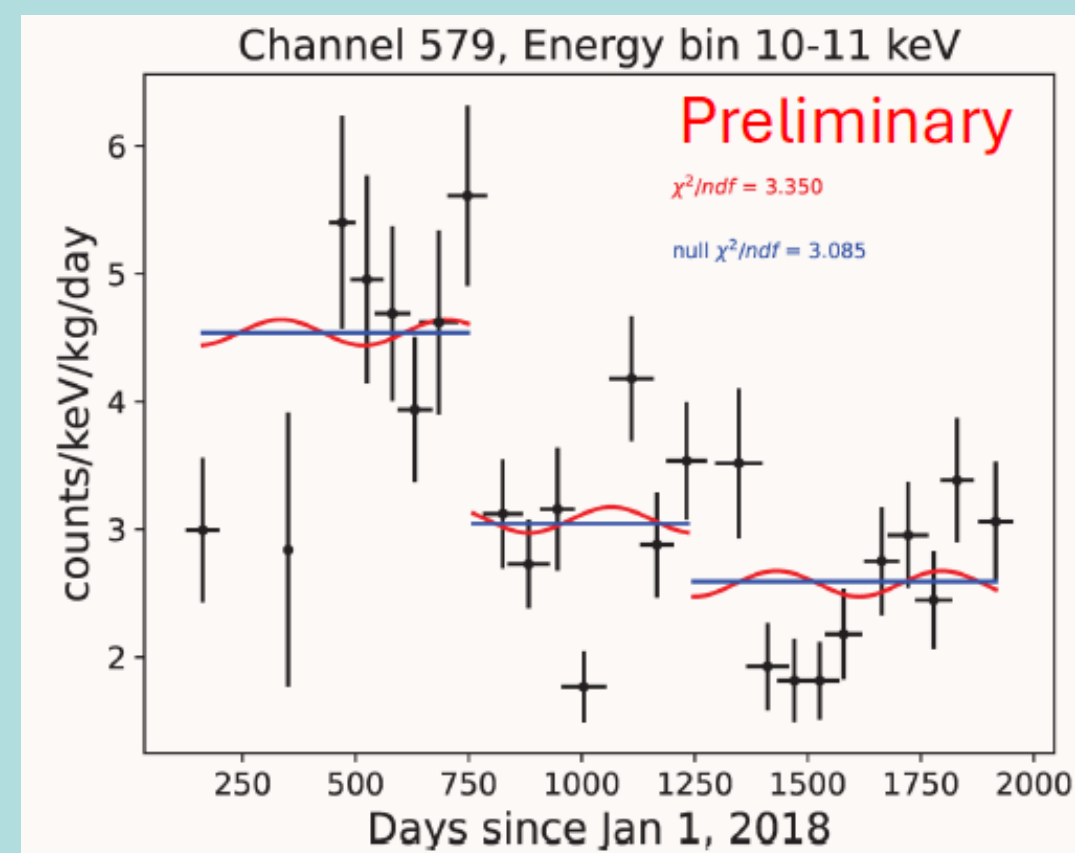


Search for relativistic fractionally charged particles (FCPs)

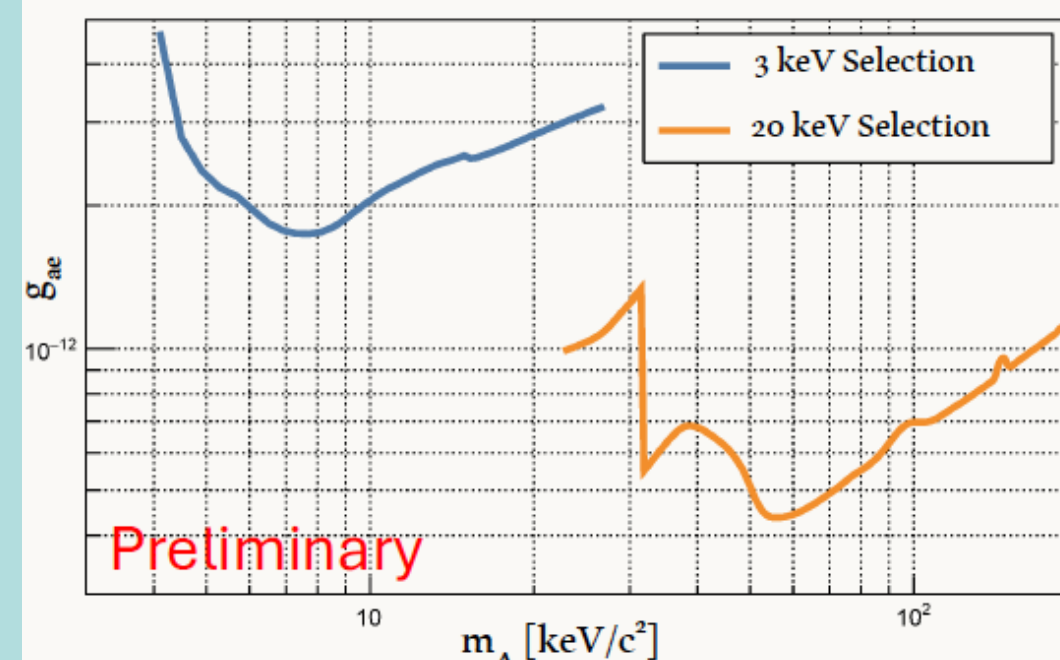
[PhysRevLett.133.241801](https://arxiv.org/abs/1905.06550)

#111

A search for WIMP Induced Annual Modulation using Low Energy Techniques with CUORE

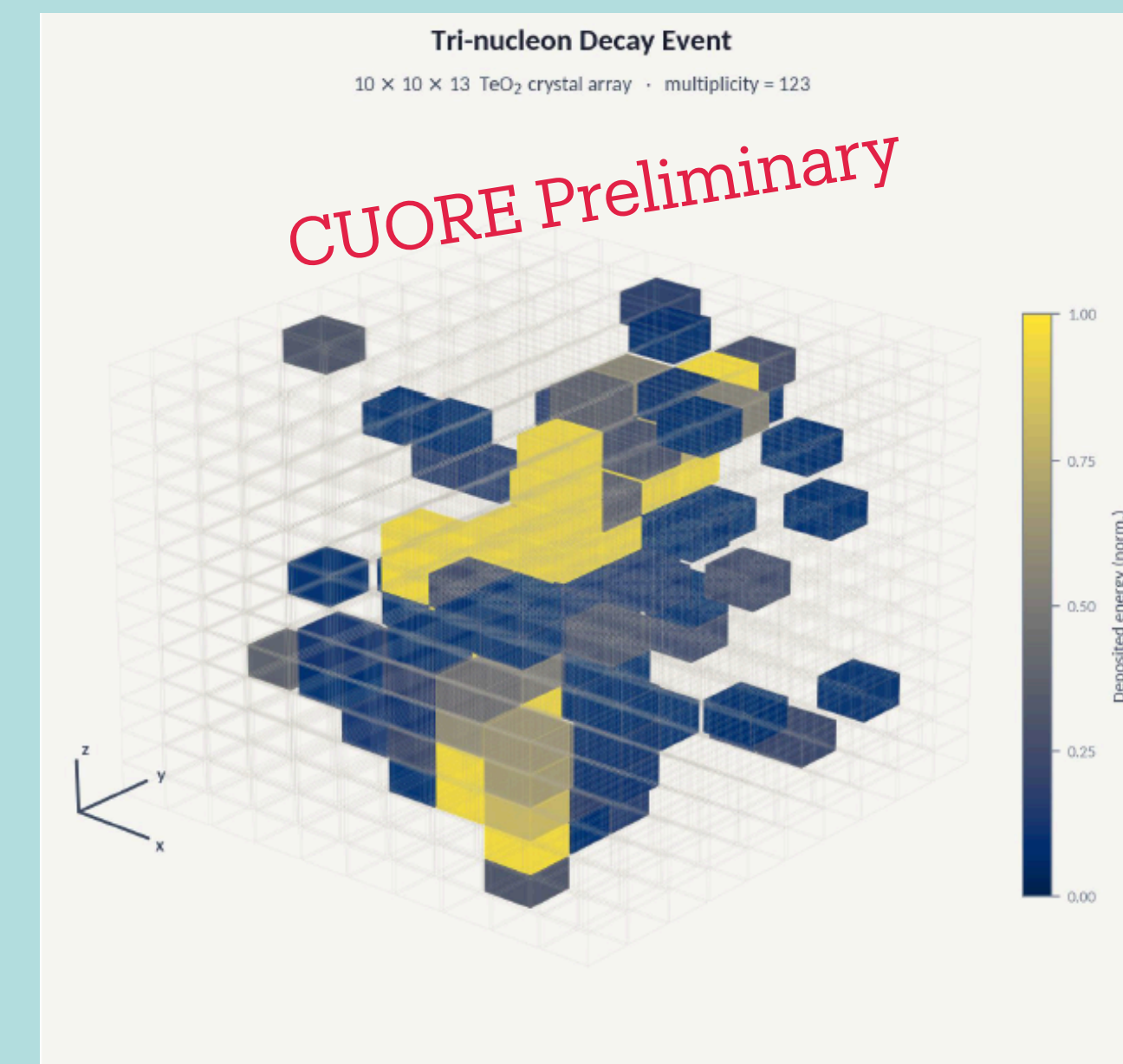
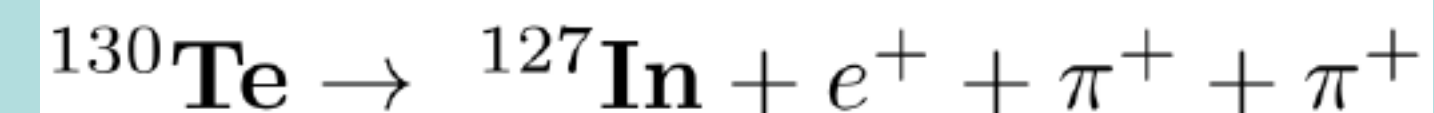


Galactic Axion Sensitivity



#294

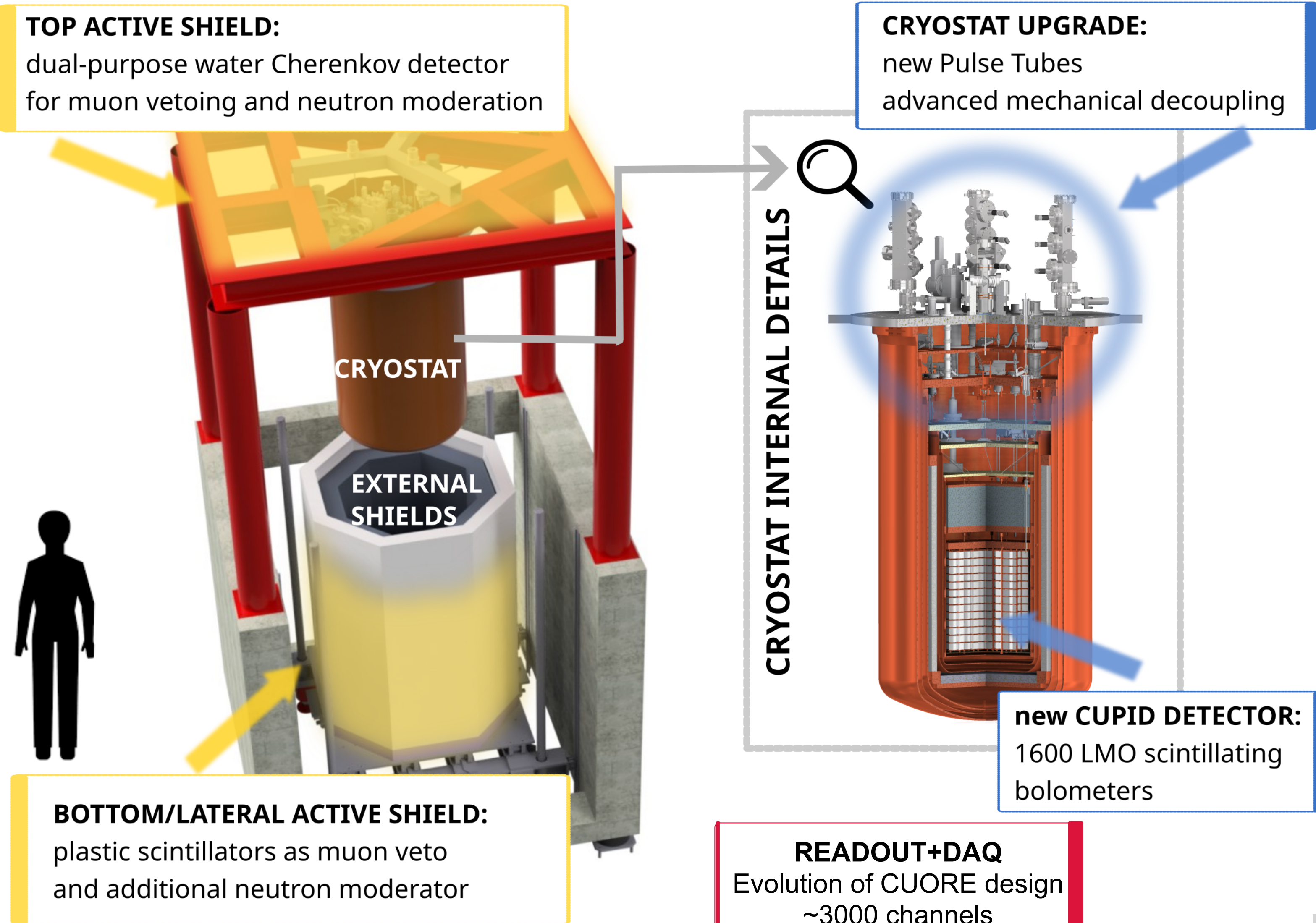
Search for Baryon Number Violation with CUORE



CUORE INFRASTRUCTURE UPGRADE

PREPARING FOR CUPID

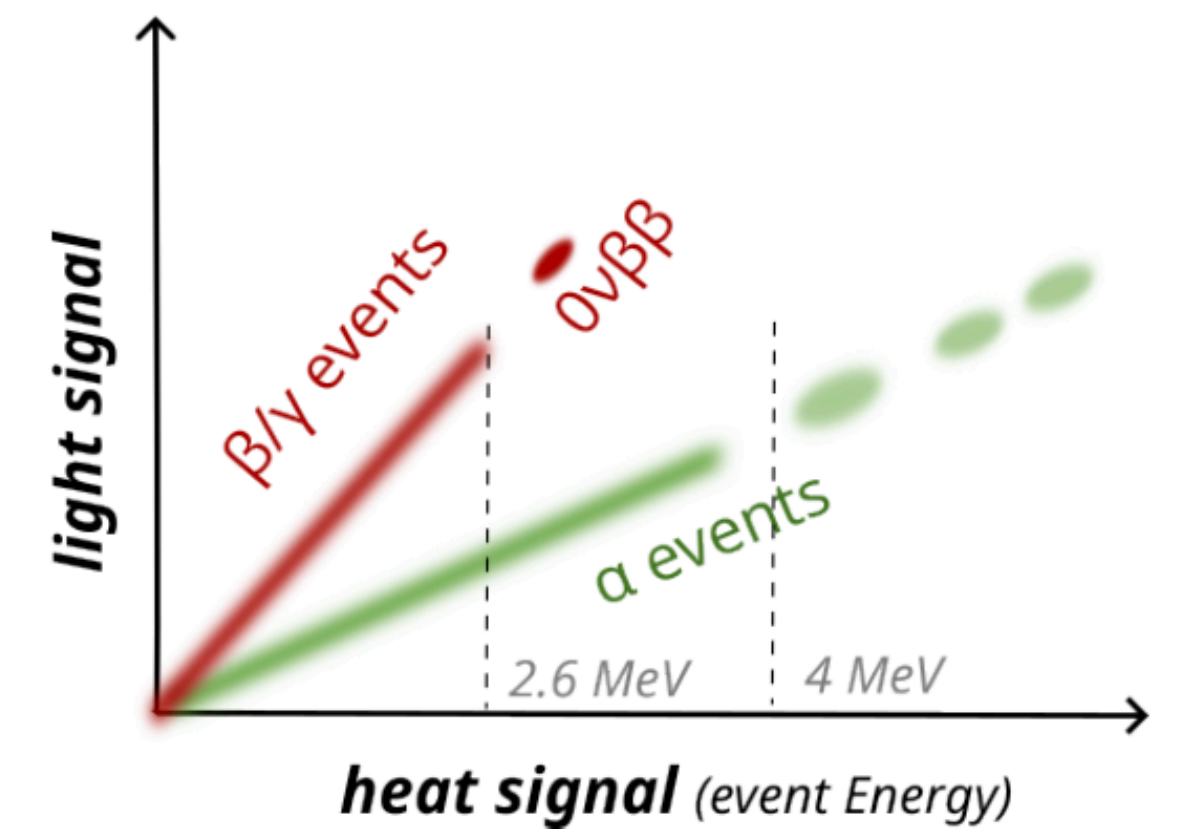
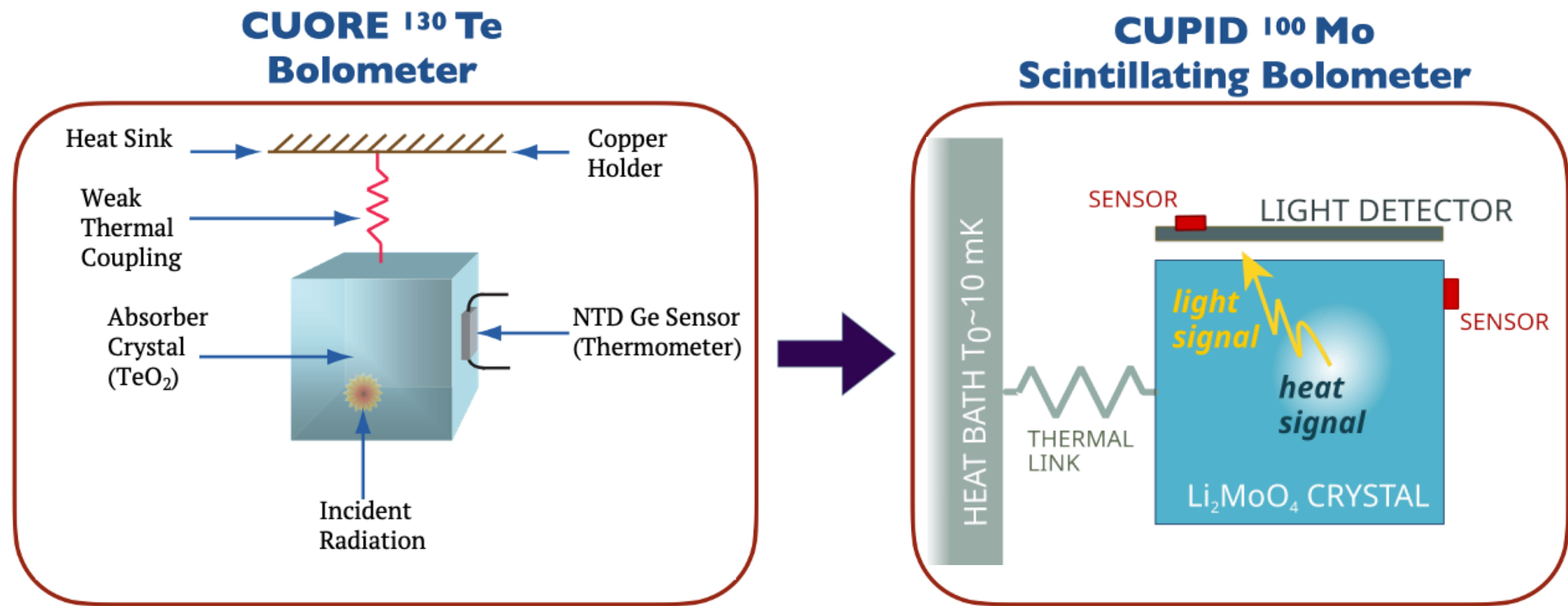
- CUORE is currently undergoing technical runs and will be warmed up in late fall.
- The CUORE detector array will remain in place; will be cooled down again to validate the performance improvements after the cryostat upgrade and the installation of bottom and lateral muon veto.
- Subsequently, the top active shield, the upgraded readout, and the CUPID detector array will be installed.



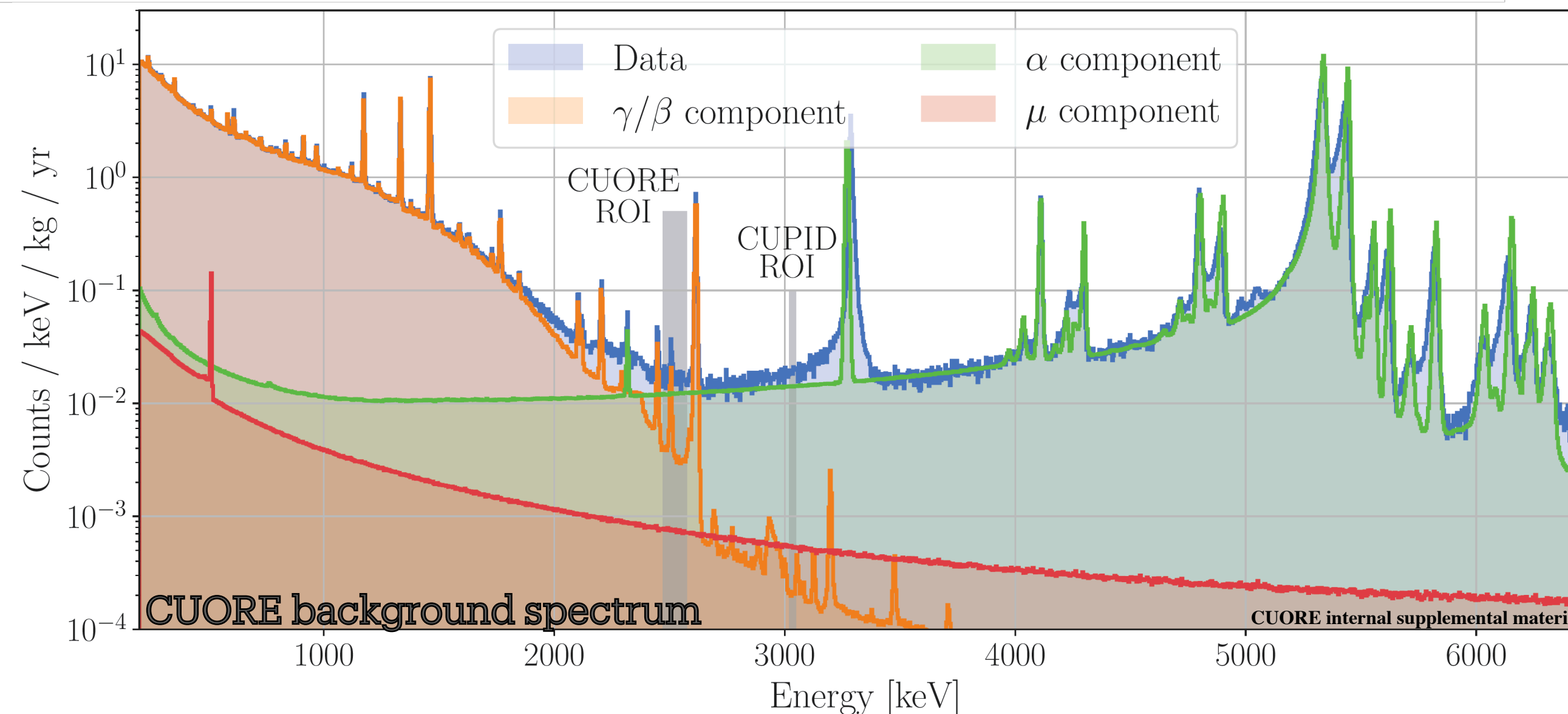
CUORE UPGRADE WITH PARTICLE IDENTIFICATION

SCINTILLATING CRYOGENIC CALORIMETERS FOR SIMULTANEOUS HEAT+LIGHT MEASUREMENT

Cryogenic detectors with PID:



^{100}Mo as $0\nu\beta\beta$ candidate isotope ($Q_{\beta\beta} = 3034.4$ keV) natural i.a. 9.7%



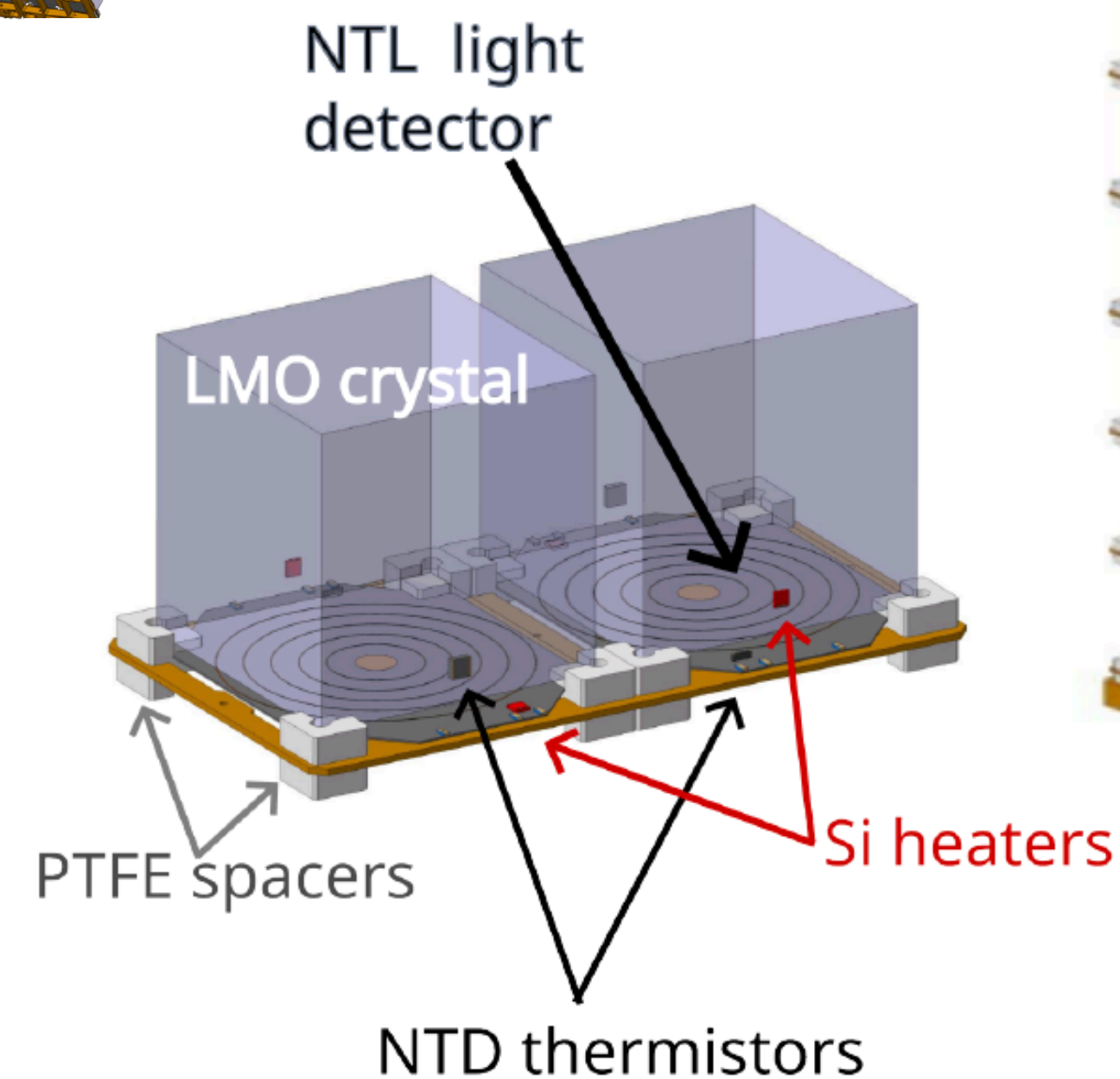
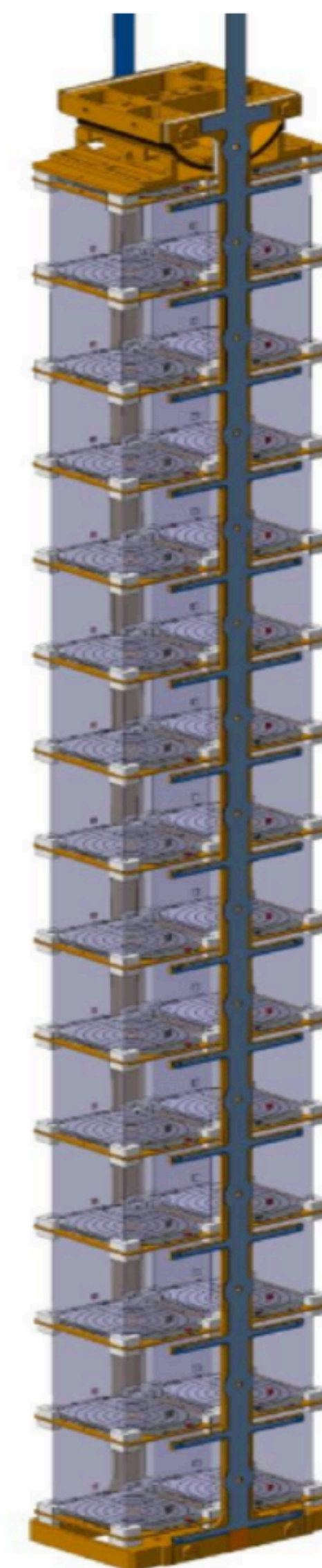
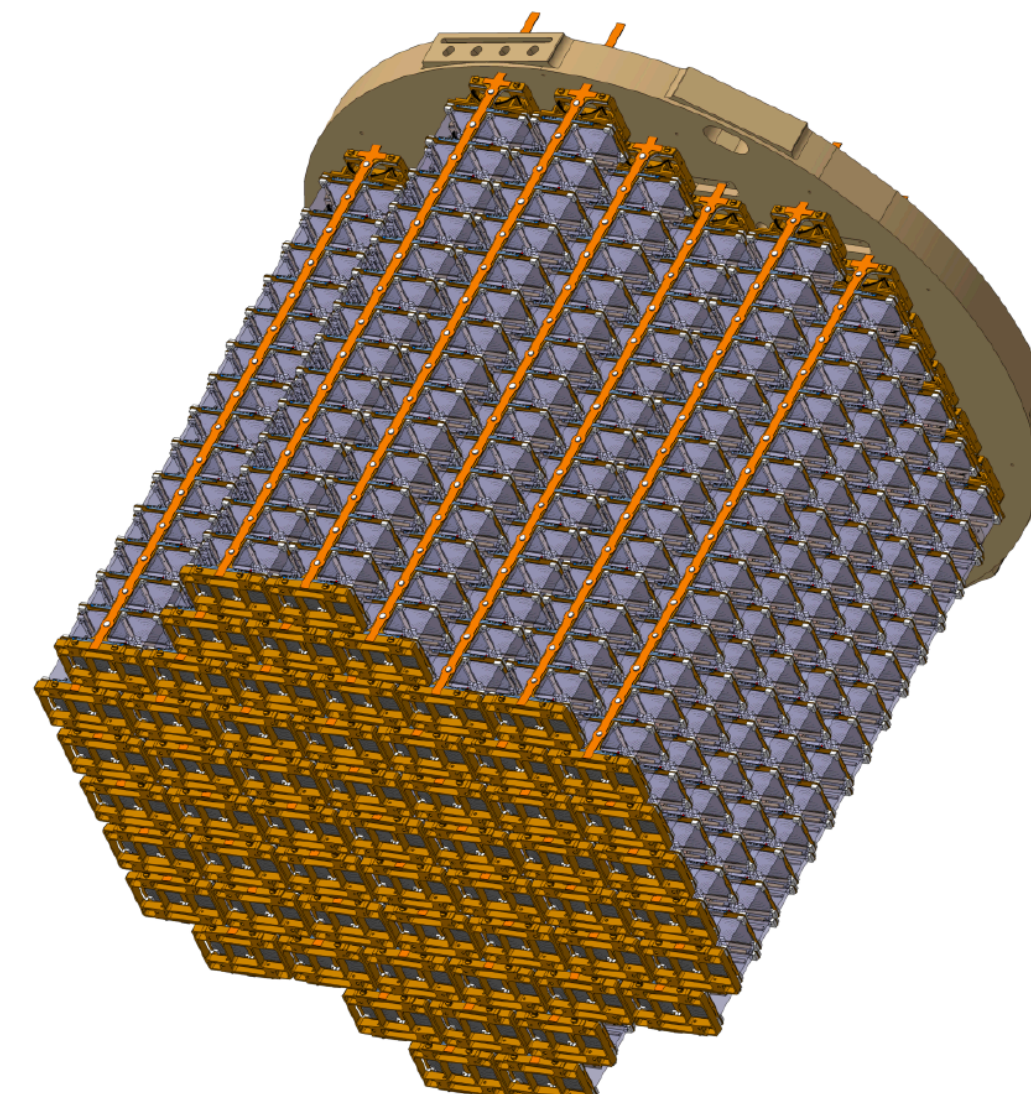
Li_2MoO_4 scintillating absorbers

CUORE data driven background model: PRD.110(2024)

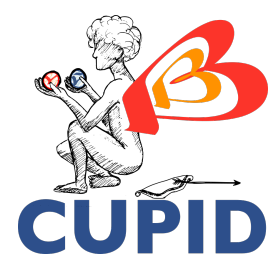
CUPID BASELINE DESIGN

IN THE CUORE INFRASTRUCTURE

- ▶ **45×45×45 mm³ Li₂¹⁰⁰MoO₄ crystals**
 - Single crystal mass: 280 g
- ▶ **1596 crystals in the array**
 - 450 kg of Li₂¹⁰⁰MoO₄ (LMO)
 - 95% enrichment in ¹⁰⁰Mo: 240 kg of ¹⁰⁰Mo
 - 57 towers of 14-floors, 28 crystals each
- ▶ **Ge light detectors (LD) with SiO anti-reflective coating**
 - Top and bottom LD for each crystal: 1710 LDs
 - Open geometry to maximise coincidence tagging
 - Signal amplification via the Neganov-Trofimov-Luke (NTL) effect



[EPJC.85\(2025\)737](#)



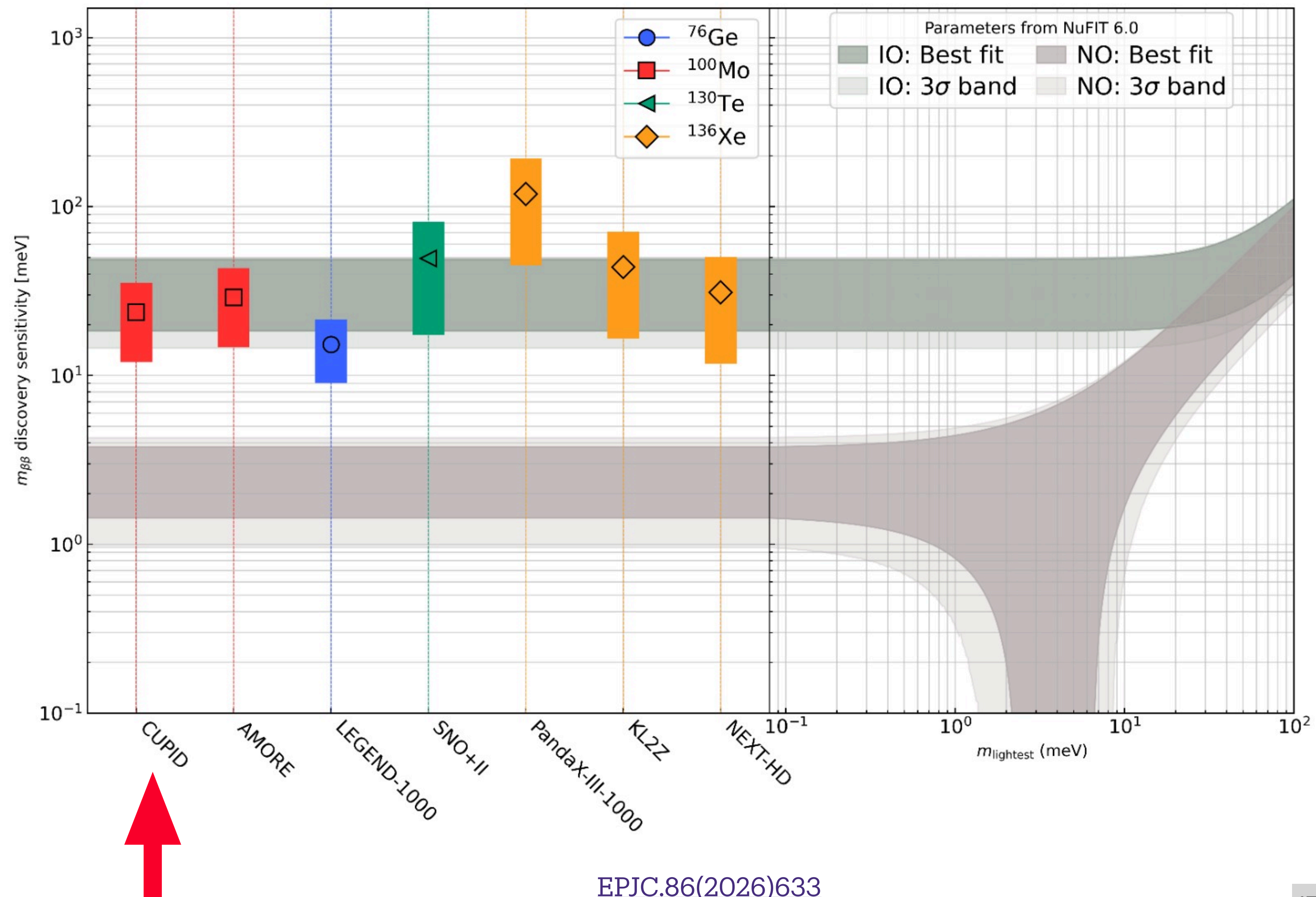
CUPID EXPECTED SENSITIVITY

A TON-SCALE EXPERIMENT FOR THE SEARCH OF $^{100}\text{Mo } 0\nu\beta\beta$

CUPID performance goals:

- ▶ Energy resolution:
5 keV FWHM
- ▶ $\beta/\gamma-\alpha$ discrimination:
99.7%
- ▶ Background:
 10^{-4} ckky (counts/keV/kg/yr)
- ▶ Live time: **10 yr**

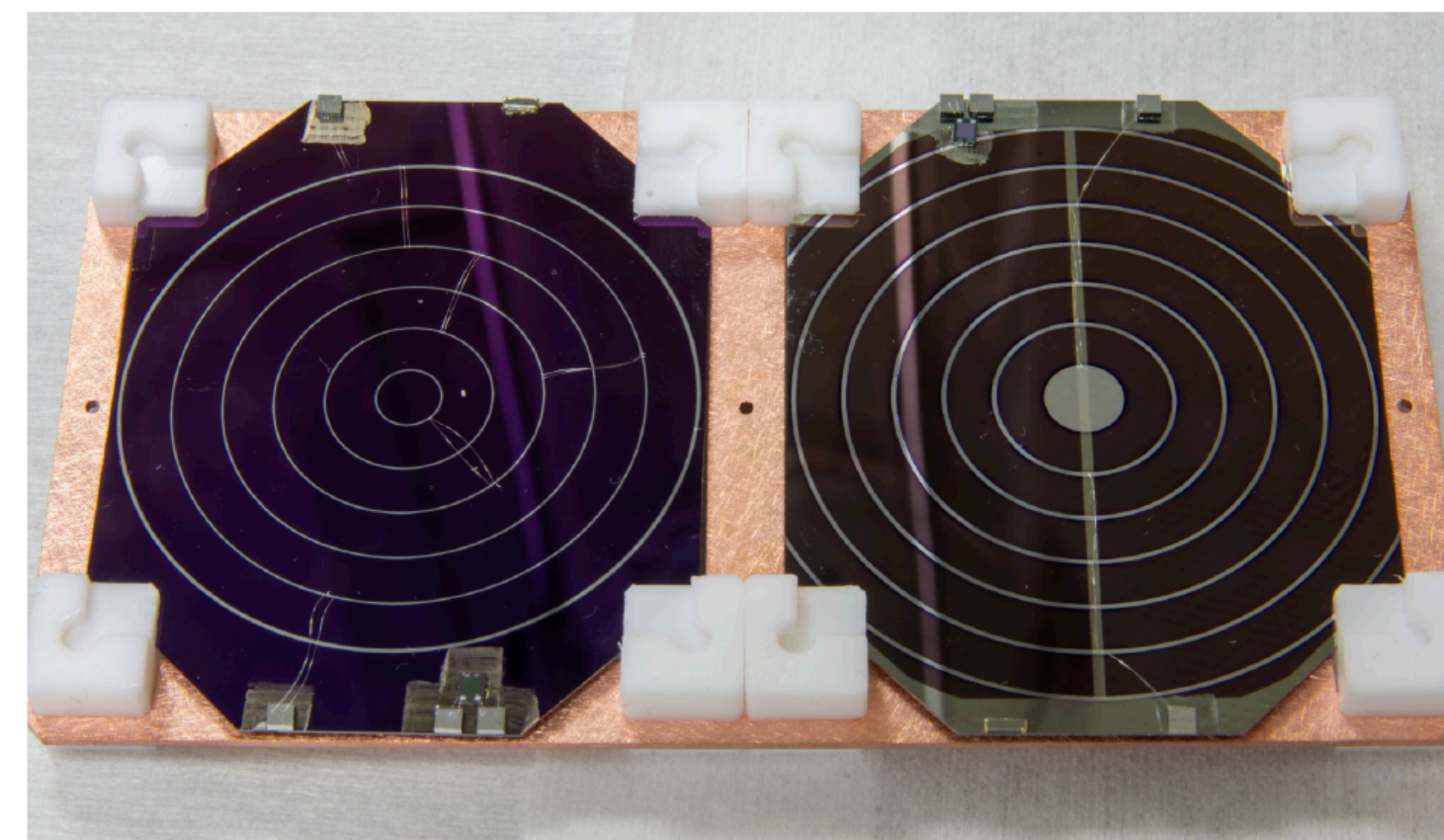
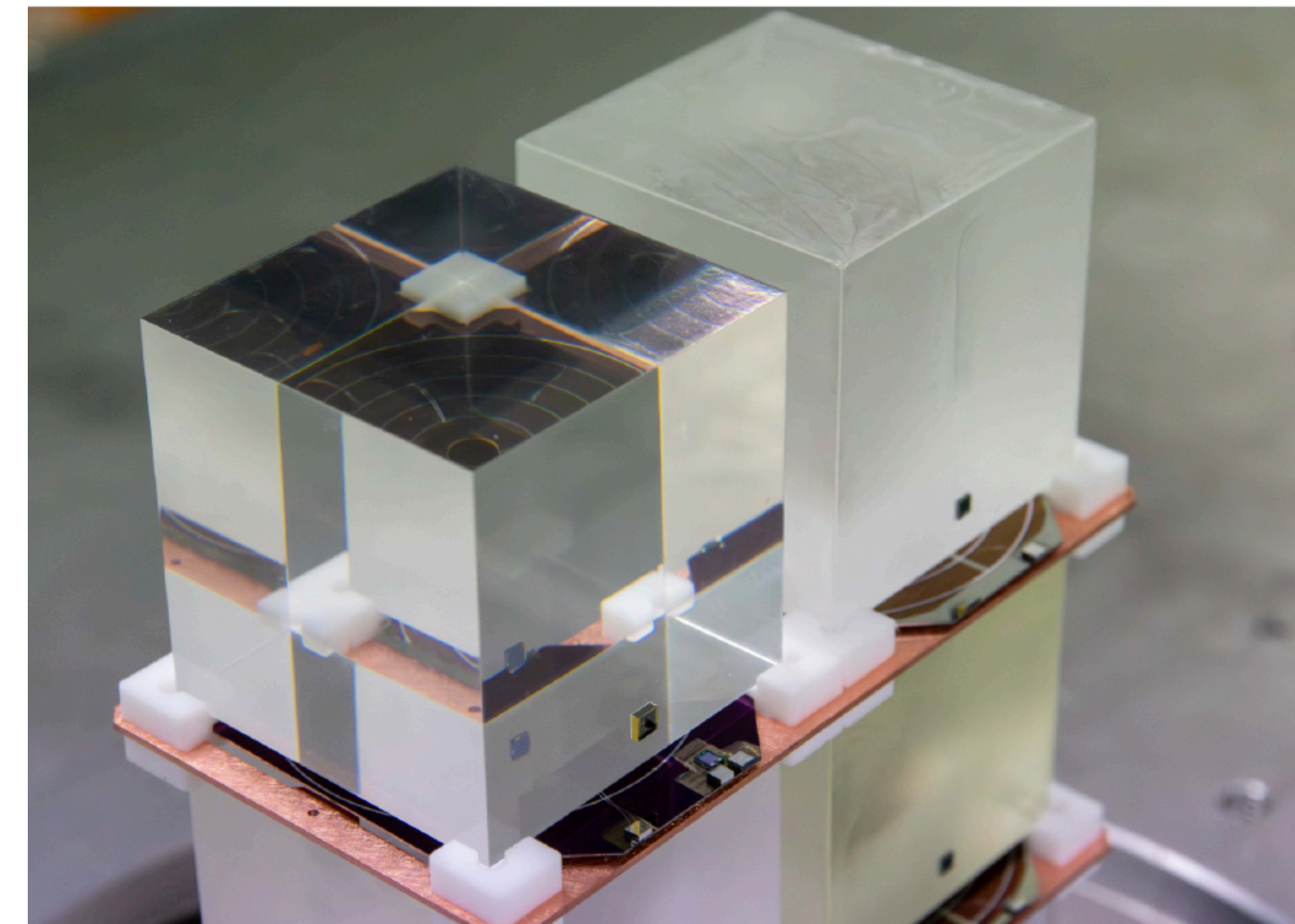
3σ discovery sensitivity:
 $^{100}\text{Mo } 0\nu\beta\beta T_{1/2}: 1 \times 10^{27}$ yr
 $m_{\beta\beta}: [12-35]$ meV



CUPID DETECTOR PROGRESS

DETECTOR TOWER DESIGN AND LIGHT DETECTOR TECHNOLOGY

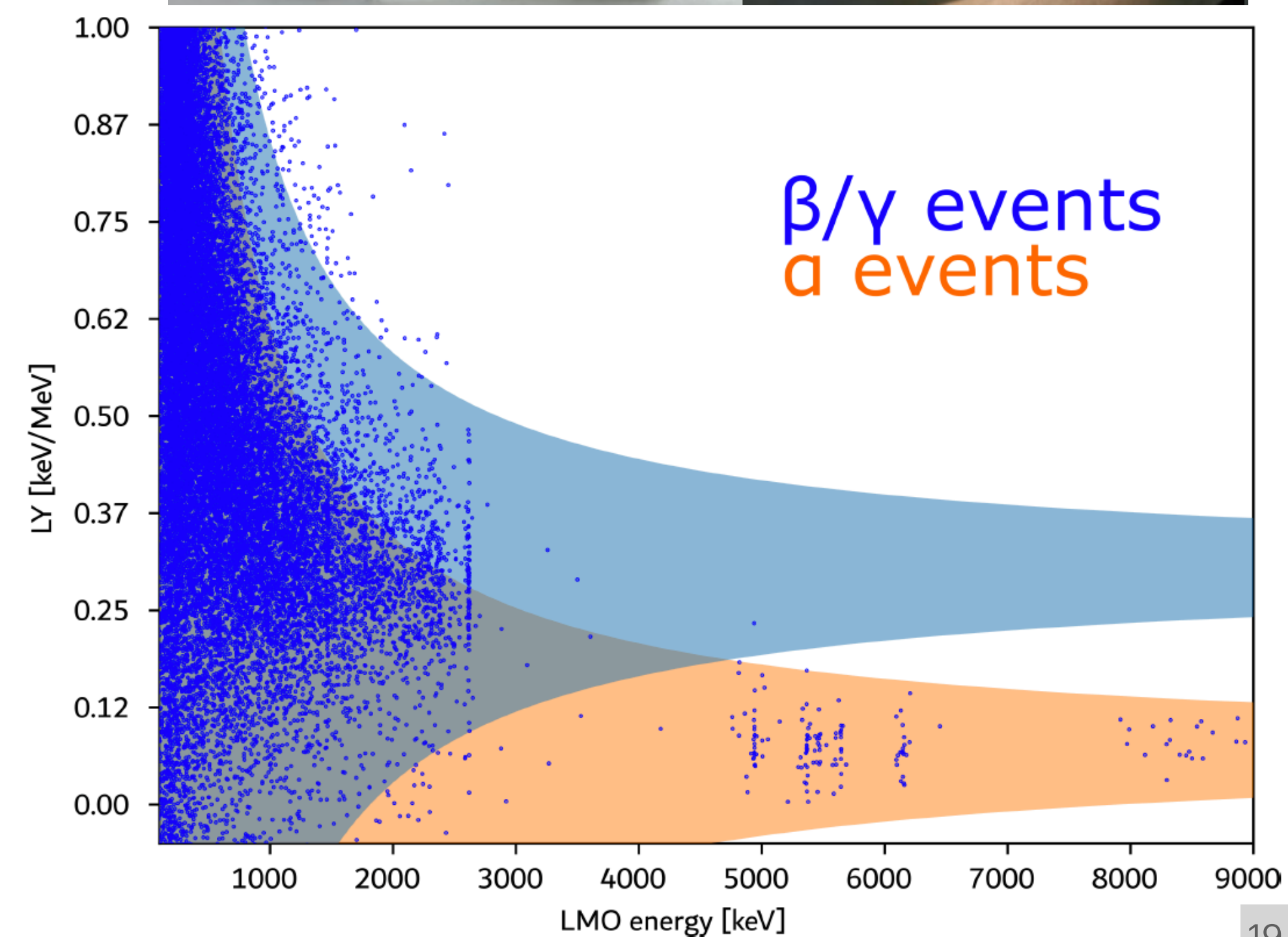
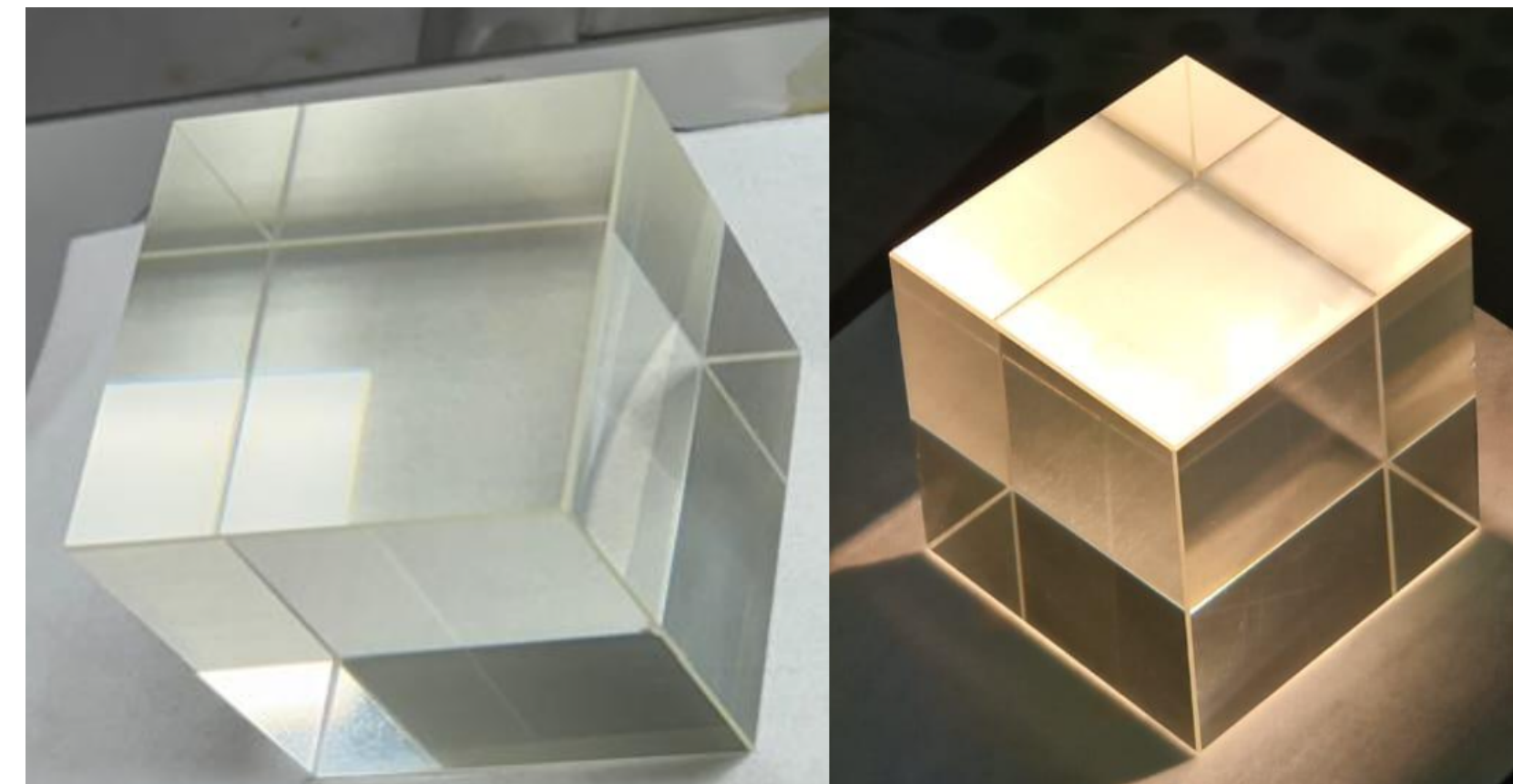
- ▶ Novel tower design with strong reduction of materials surrounding the crystals with respect to CUORE.
- ▶ First prototype tower cryogenic test (28 LMO crystals, 30 LDs; no NTL amplification):
 - ✓ Good temperature stability
 - ✓ Average FWHM resolution of LMO at ^{208}Tl (@2615 keV): (6.6 ± 2.2) keV
 - ✓ Median light yield of LMO: 0.36 keV/MeV
- ▶ Second prototype tower (28 LMO crystals, 30 LDs; improved LD mounting; with NTL amplification) — cryogenic test is ongoing.
Preliminary results indicate:
 - ✓ A factor ~ 3.5 improvement in the $\beta/\gamma-\alpha$ discrimination power

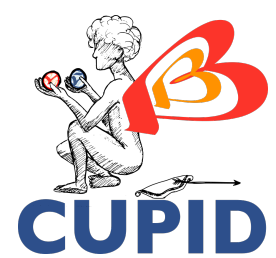


CUPID DETECTOR PROGRESS

ENRICHED CRYSTAL PRODUCTION AND TESTS

- ▶ A preliminary production of ~ 15 enriched LMO crystals for CUPID is currently underway.
- ▶ 4.4 kg of enriched molybdenum (> 95%) has been produced by IPCE (China) in the form of MoO_3 powder.
- ▶ Enriched LMO crystals have been grown by SICCAS (China), the same institute that produced the CUORE crystals. Preliminary measurements (without NTL amplification) show encouraging results:
 - Energy resolution close to CUPID target (5–8 keV)
 - Light Yield (LY) at the level required by CUPID
 - Bulk radiopurity not yet optimal due to the recent limited availability of high-purity Li_2CO_3
 - IPCE is developing a new conversion process from $^{100}\text{MoF}_6$ directly to LMO powder to address this issue

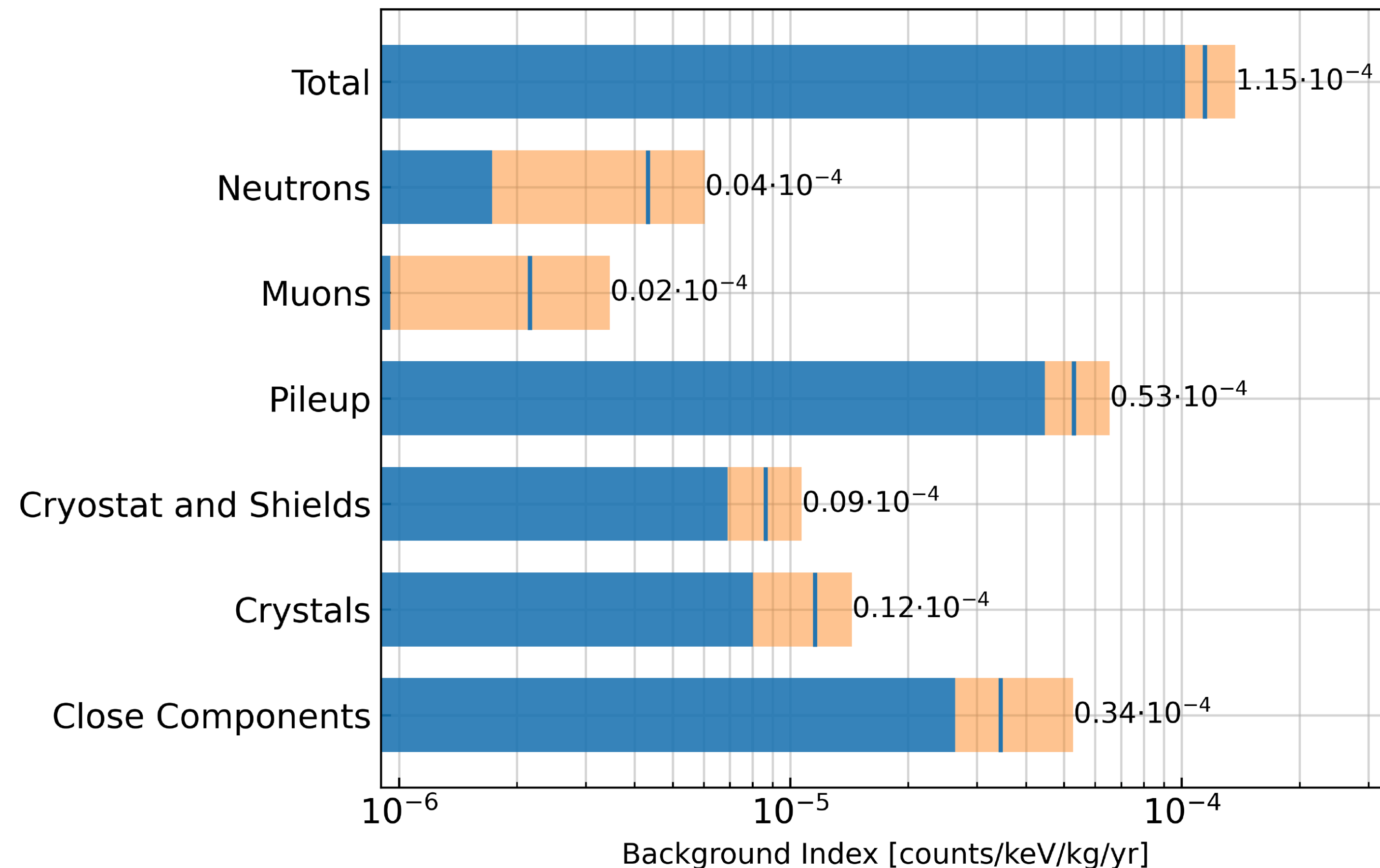




CUPID BACKGROUND PROJECTION

ALL BACKGROUND PREDICTIONS ARE DATA-DRIVEN

Uncertainties (orange band) include systematic ones

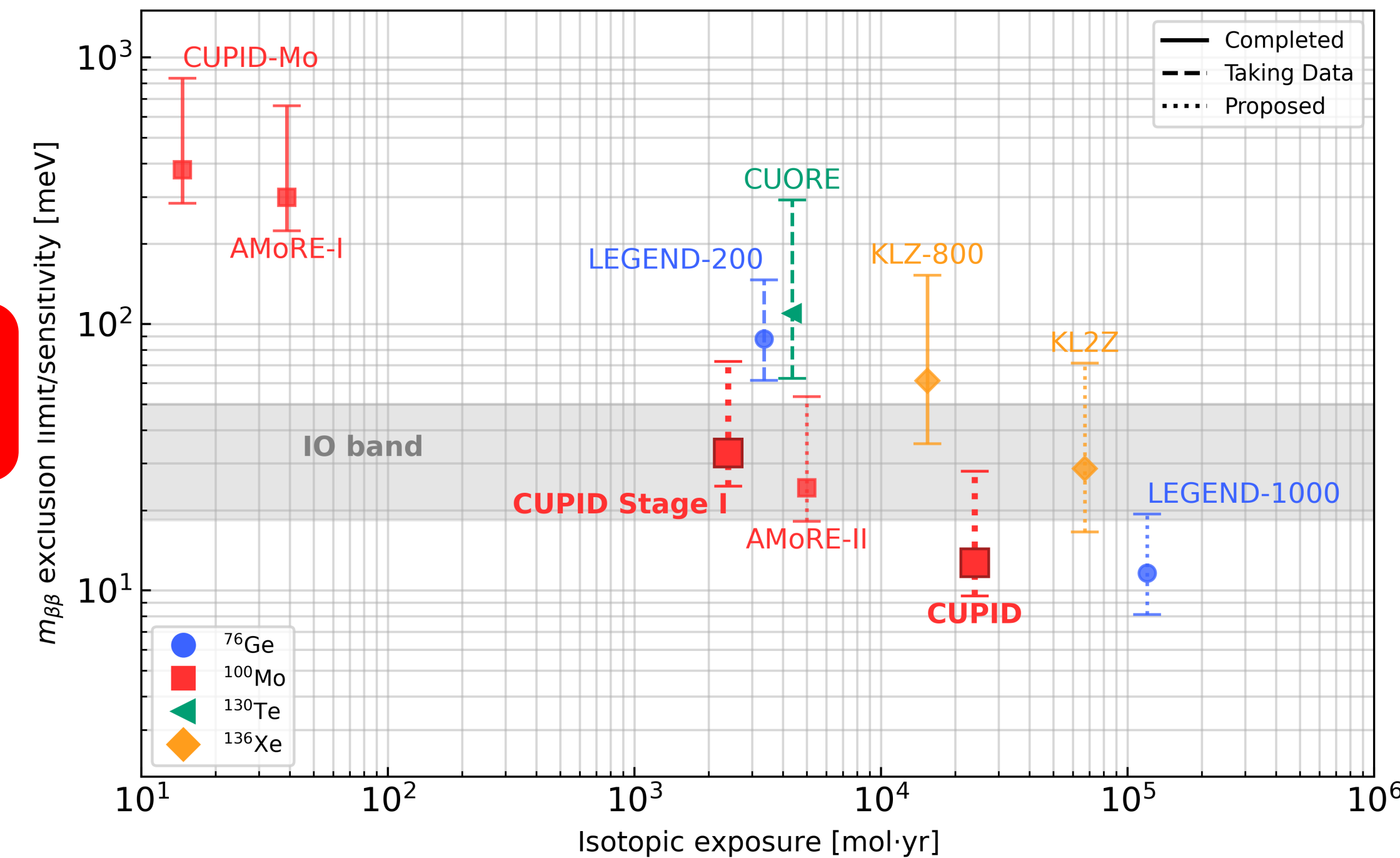
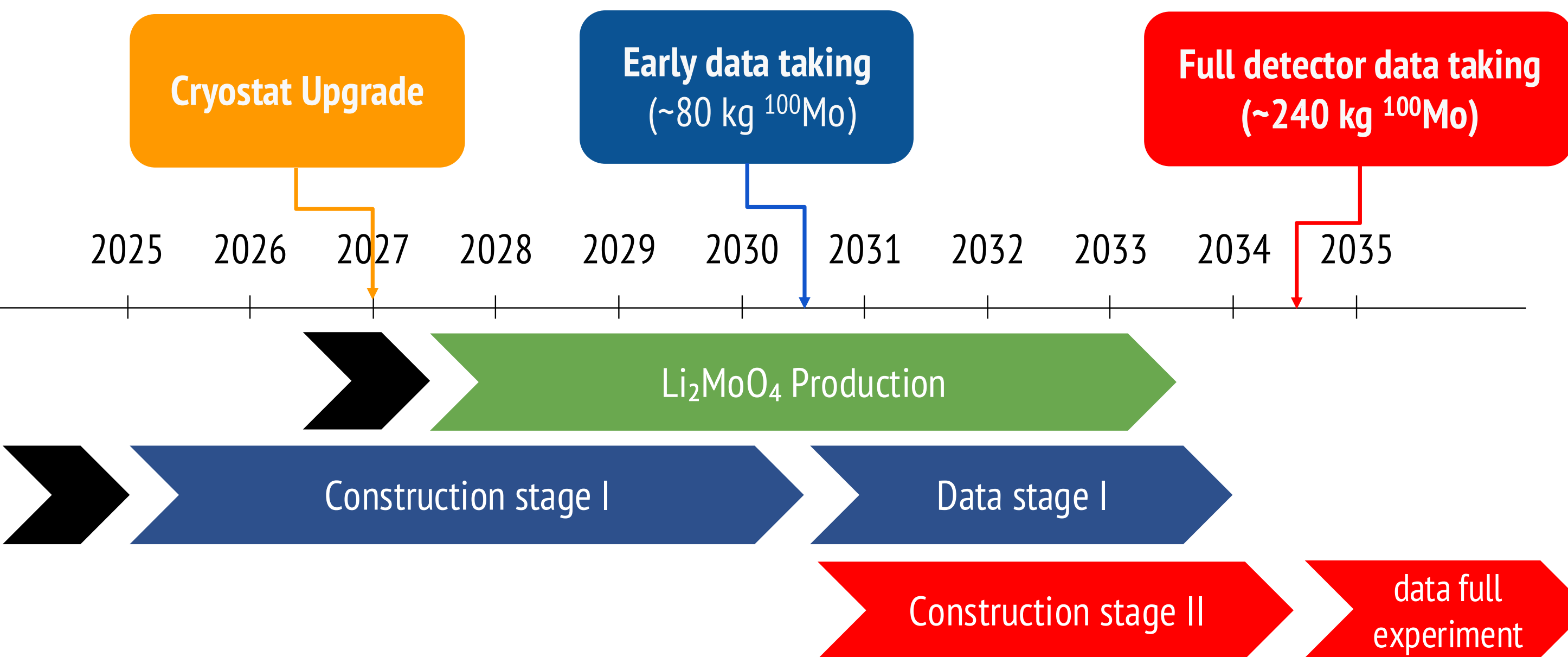


- ▶ CUPID's physics goals require a background index of 1×10^{-4} ckky in the ^{100}Mo ROI.
- ▶ The background budget is derived from MC simulations benchmarked against experimental data from CUORE, CUPID-0 and CUPID-Mo.
- ▶ Current projections indicate that the target background level is within reach, thanks to the high radiopurity of the materials.
- ▶ A factor 2 optimisation of the *Close Components* contribution is expected, thanks to the improved tower design and optimised cleaning and assembly procedures.

CUPID TIMELINE

STAGED DEPLOYMENT AND EARLY PHYSICS DATA

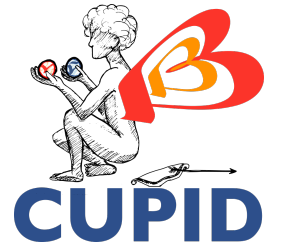
- ▶ **CUPID-Stage I:** installation of 1/3 of the final CUPID array (~532 enriched LMO crystals) in the refurbished CUORE cryostat, enabling an in-situ assessment of the overall performance.
- ▶ **CUPID-Stage II:** full CUPID detector deployment



CONCLUSIONS

- ▶ CUORE is the largest and longest operating double beta decay experiment.
- ▶ CUORE is the first experiment to demonstrate the stable operation of a tonne-scale millikelvin cryogenic calorimeter over nearly a decade.
- ▶ CUORE has successfully completed its $0\nu\beta\beta$ data-taking campaign: the data analysis is still ongoing with new results expected soon.
- ▶ After the infrastructure upgrade, CUORE is expected to improve the measurement efficiency at low energies, enabling precise data-quality control across the full energy range.
- ▶ Over the coming months, the planned facility upgrades will pave the way for CUPID, which will exploit the same infrastructure and technology. The CUORE detector will be used to validate the upgraded experimental performance.
- ▶ CUPID activities are progressing rapidly: crystal enrichment, crystal growth and characterization, light-detector development, and tower-design optimization are all advancing steadily.
- ▶ Stay tuned!

HAVE A LOOK AT OUR POSTERS!



101	Aaron	Chizhik	Effects of event topology on energy reconstruction in the CUORE TeO ₂ bolometers
111	Rebecca	Kowalski	A search for WIMP Induced Annual Modulation using Low Energy Techniques with CUORE
224	Tristan	Hurst	Latest results from the CUORE experiment
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339	Vladyslav	Berest	Frequency multiplexed TES-based light detectors for CUPID and beyond
458	Aaron	Torres	Neutron Transmutation Doping of Germanium for CUPID Thermistors

THANK YOU FOR YOUR ATTENTION!!!

<https://cuoreexperiment.org/>



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Technology



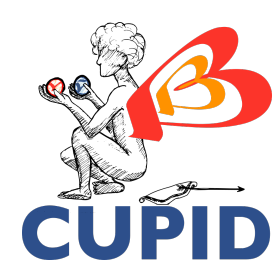
UCLA



University of
Pittsburgh



BACK-UP SLIDES



CUPID COLLABORATION



Leverages previous collaborative experience:

- ✦ CUORE
- ✦ CUPID-0
- ✦ Cupid-Mo

<https://cupidexperiment.org/>

CUORE ^{130}Te $0\nu\beta\beta$ SEARCH RESULTS

2 TONNE-YEAR EXPOSURE

Nuclear matrix elements used for the calculation of $m_{\beta\beta}$ range

- ^{130}Te $0\nu\beta\beta$ half-life:
 $T_{1/2} > 3.5 \times 10^{25}$ yr (90% C.I.)
- Effective Majorana mass:
 $m_{\beta\beta} < 70\text{--}250$ meV at 90% C.I.

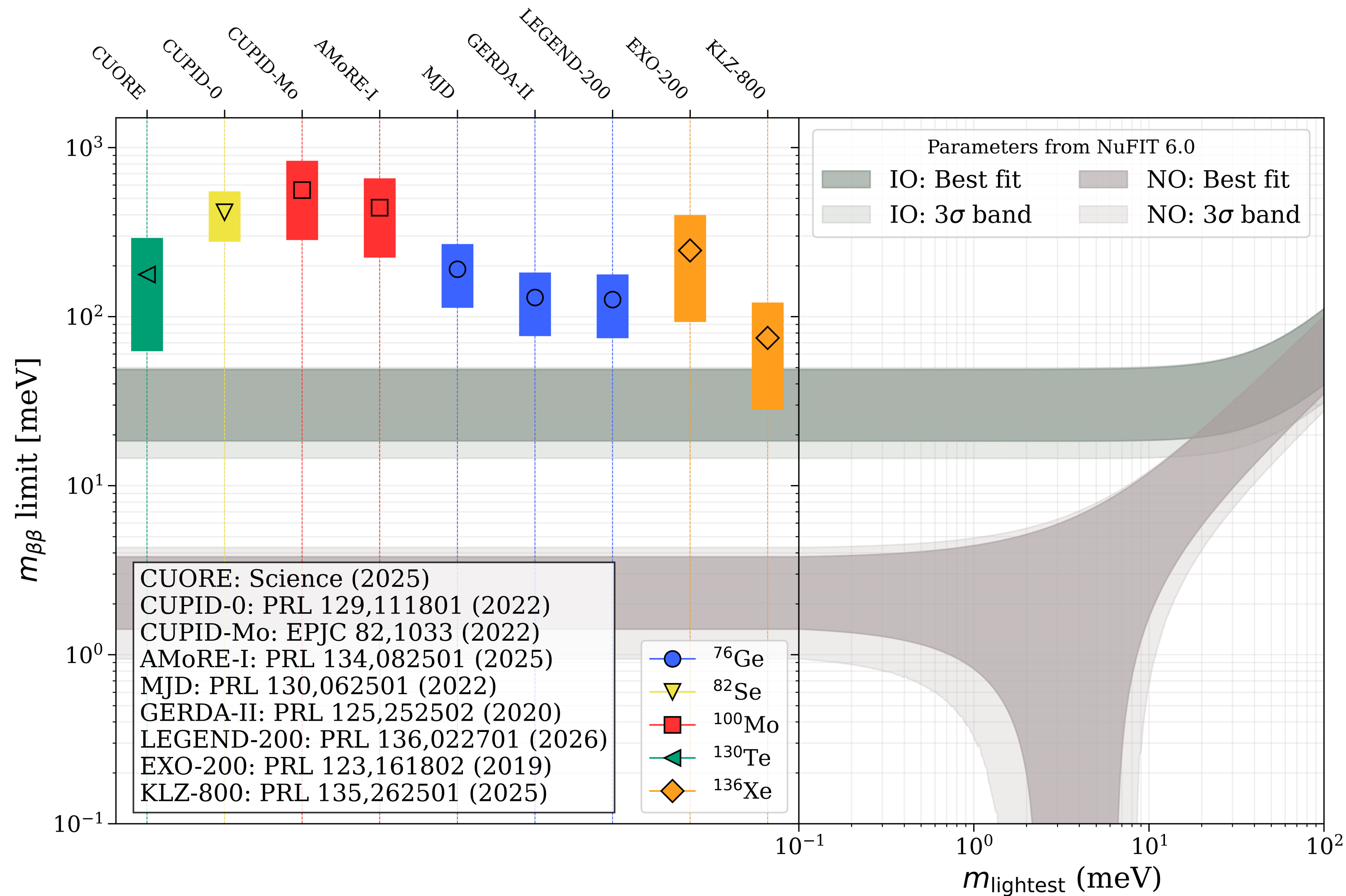
- ▶ Frequentist result:
 $T_{1/2} > 3.4 \times 10^{25}$ yr (90% C.I.)

[Science.390\(2025\)](#)

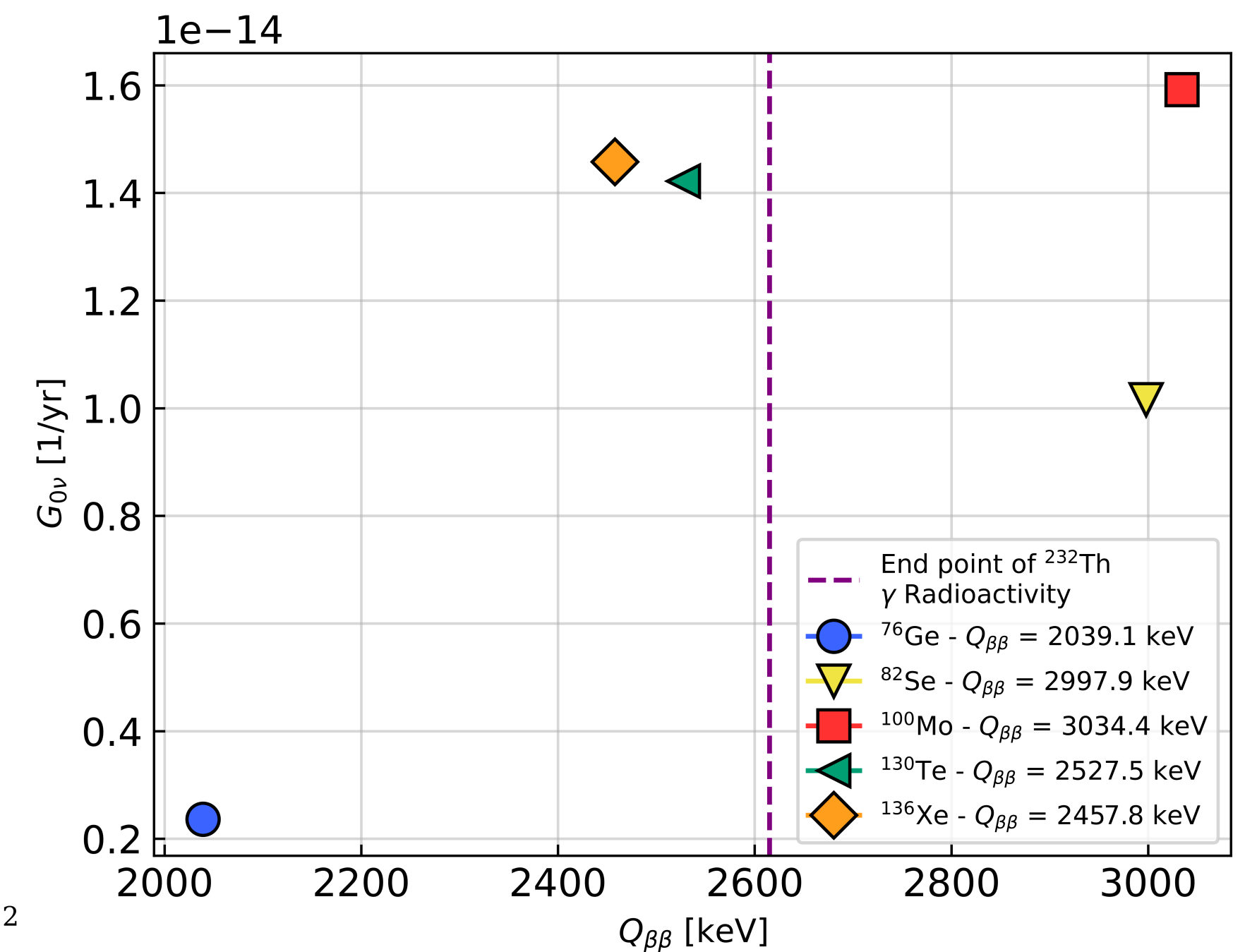
Model	$M_{0\nu}$	Reference	Link	Authors
QRPA-Jy (pnQRPA)	4.00	PRC 91, 024613 (2015)	http://journals.aps.org/prc/abstract/10.1103/PhysRevC.91.024613	Suhonen, Hyvärinen
NREDF	6.405	PRL 111, 142501 (2013)	http://dx.doi.org/10.1103/PhysRevLett.111.142501	Vaquero, Rodriguez
ISM	1.79	PRC C 93, 024308 (2016)	http://dx.doi.org/10.1103/PhysRevC.93.024308	Horoi, Neacsu
ISM	2.76	J. Phys. G 45, 014003 (2018)	https://doi.org/10.1088/1361-6471/aa9bd4	Menéndez
QRPA	3.939	PRC 98, 064325 (2018)	https://doi.org/10.1103/PhysRevC.98.064325	Šimkovic, Smetana, Vogel
QRPA deformed	2.9	PRC 97, 045503 (2018)	https://doi.org/10.1103/PhysRevC.97.045503	Fang, Faessler, Šimkovic
ISM	3.16	PRC 101, 044315 (2020)	https://doi.org/10.1103/PhysRevC.101.044315	Coraggio, Gargano, Itaco, Mancino, Nowacki
IBM-2	4.154	PRD 102, 095016 (2020)	https://doi.org/10.1103/PhysRevD.102.095016	Deppisch, Graf, Iachello, Kotila
CDFT	4.89	PRC 95, 024305 (2017)	https://doi.org/10.1103/PhysRevC.95.024305	Song, Yao, Ring, Meng

STATE OF THE ART OF $0\nu\beta\beta$ EXPERIMENTS

PRESENT AND PAST EXPERIMENTS



Comparison between phase space factor $G_{0\nu}$ and transition energy $Q_{\beta\beta}$ for the most important $0\nu\beta\beta$ isotopes



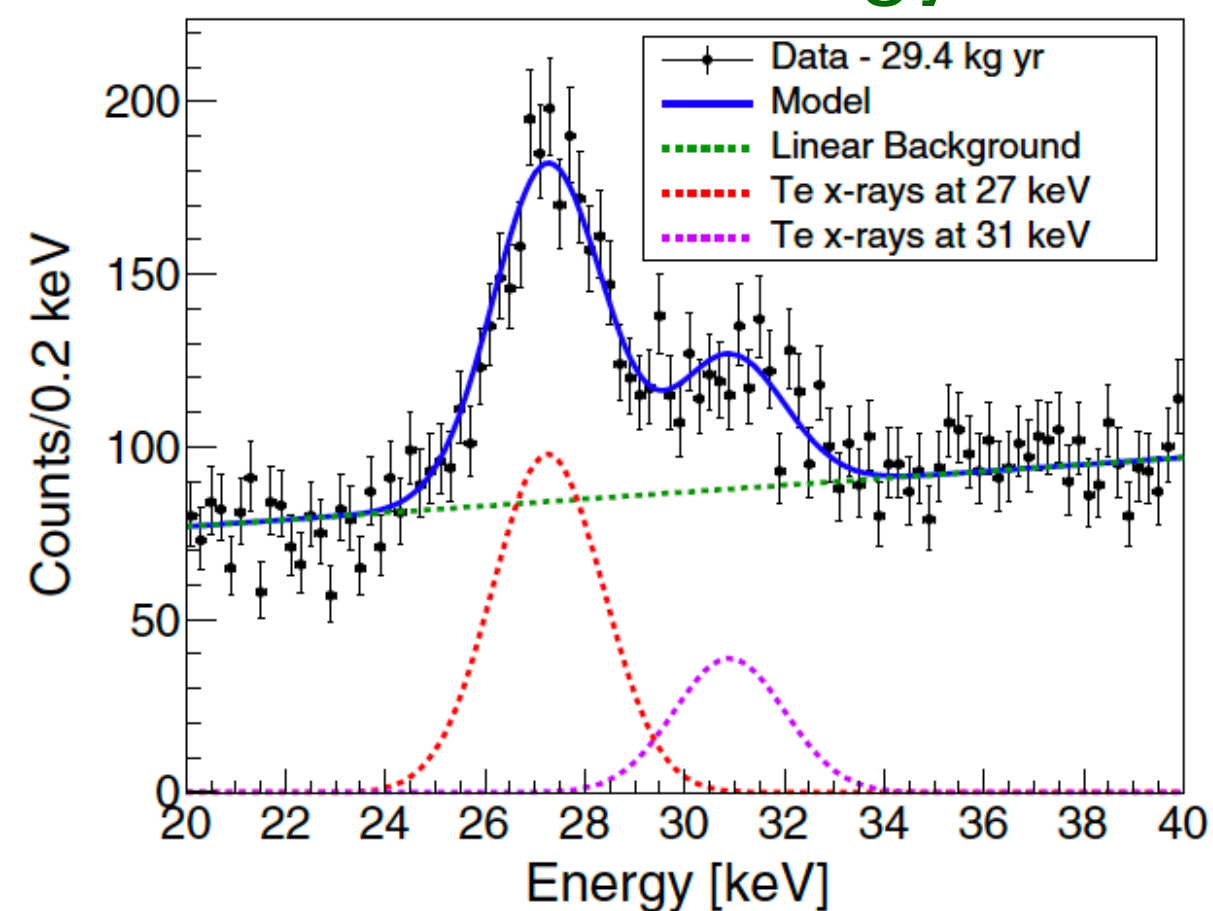
LOW ENERGY ANALYSIS IN CUORE

FOR DARK MATTER AND SOLAR AXIONS STUDIES

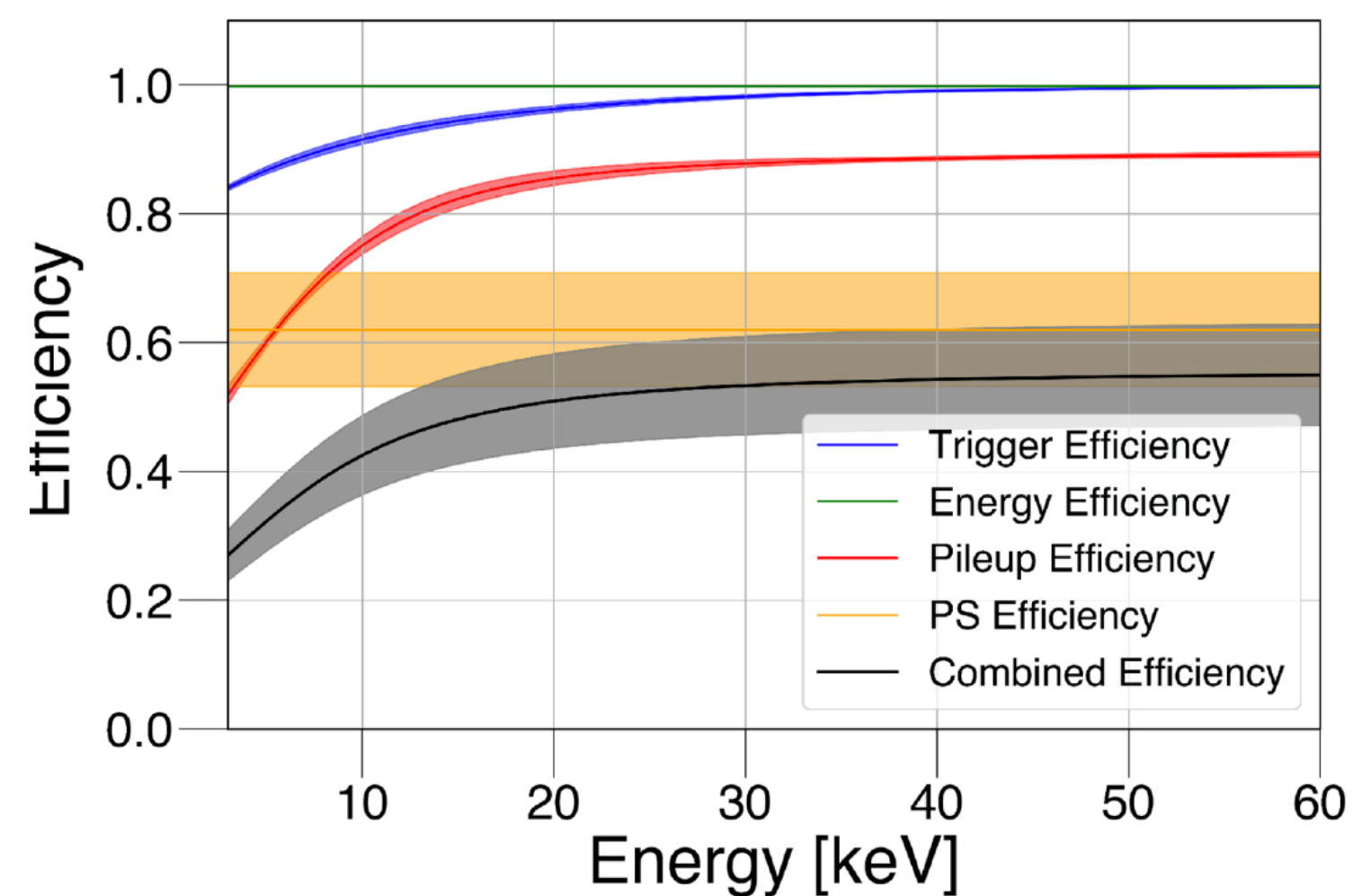
We can leverage CUORE's low background and high exposure with its sensitivity to a wide range of energies to perform searches for exotic physics in the keV region (chosen thresholds: 3 and 10 keV)

Parameter	3 keV	10 keV
Number of datasets	12	25
TeO ₂ exposure [kg yr]	11.0	691
Selected detectors	1.2%	35%
Baseline FWHM [keV]	1.18 ± 0.02	2.54 ± 0.14
Background level [d.r.u.]	16 ± 2	2.06 ± 0.05
Total efficiency	0.26 ± 0.04	0.50 ± 0.02

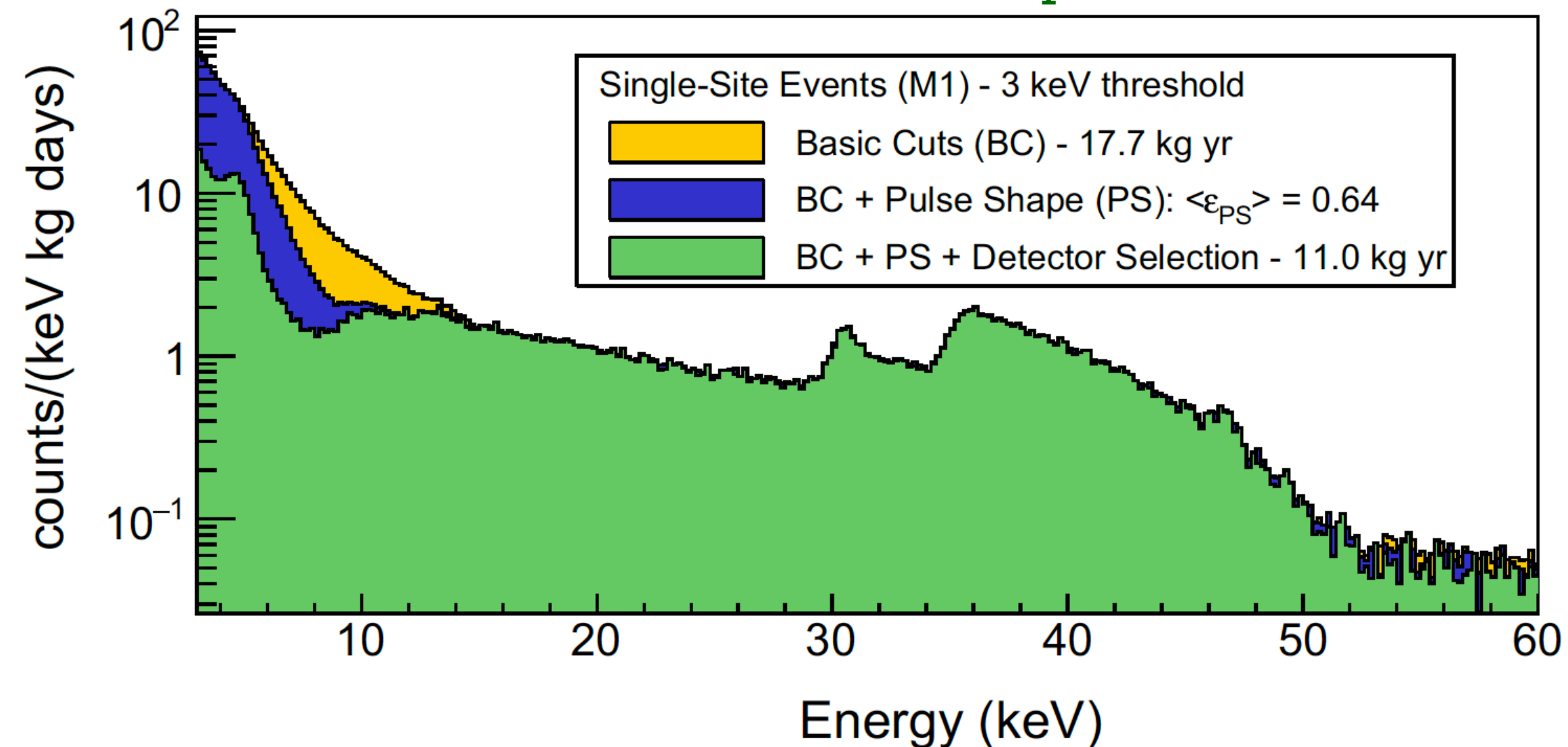
Te X-rays for calibration at low energy



3 keV threshold

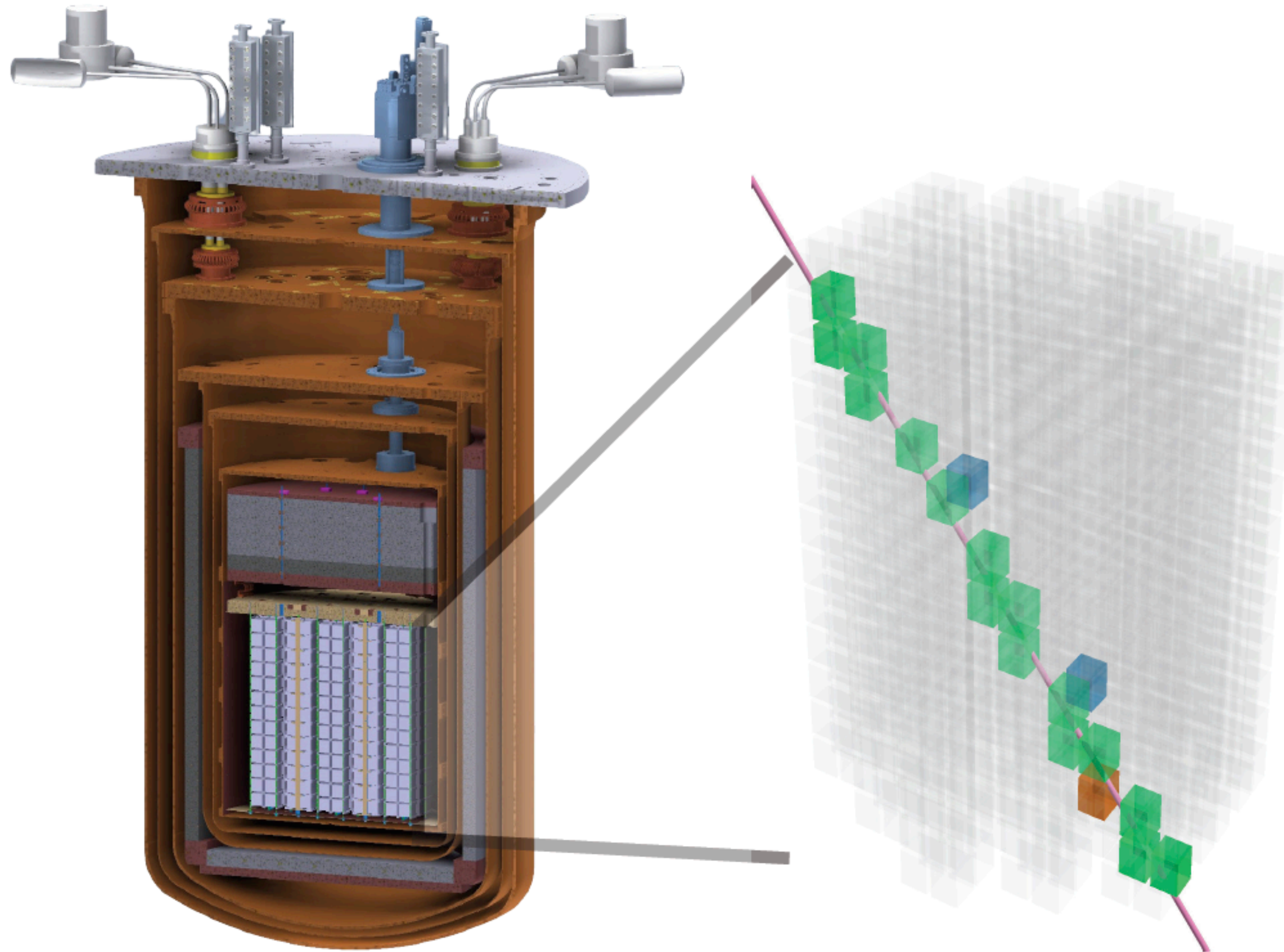


Final 3 keV threshold spectrum

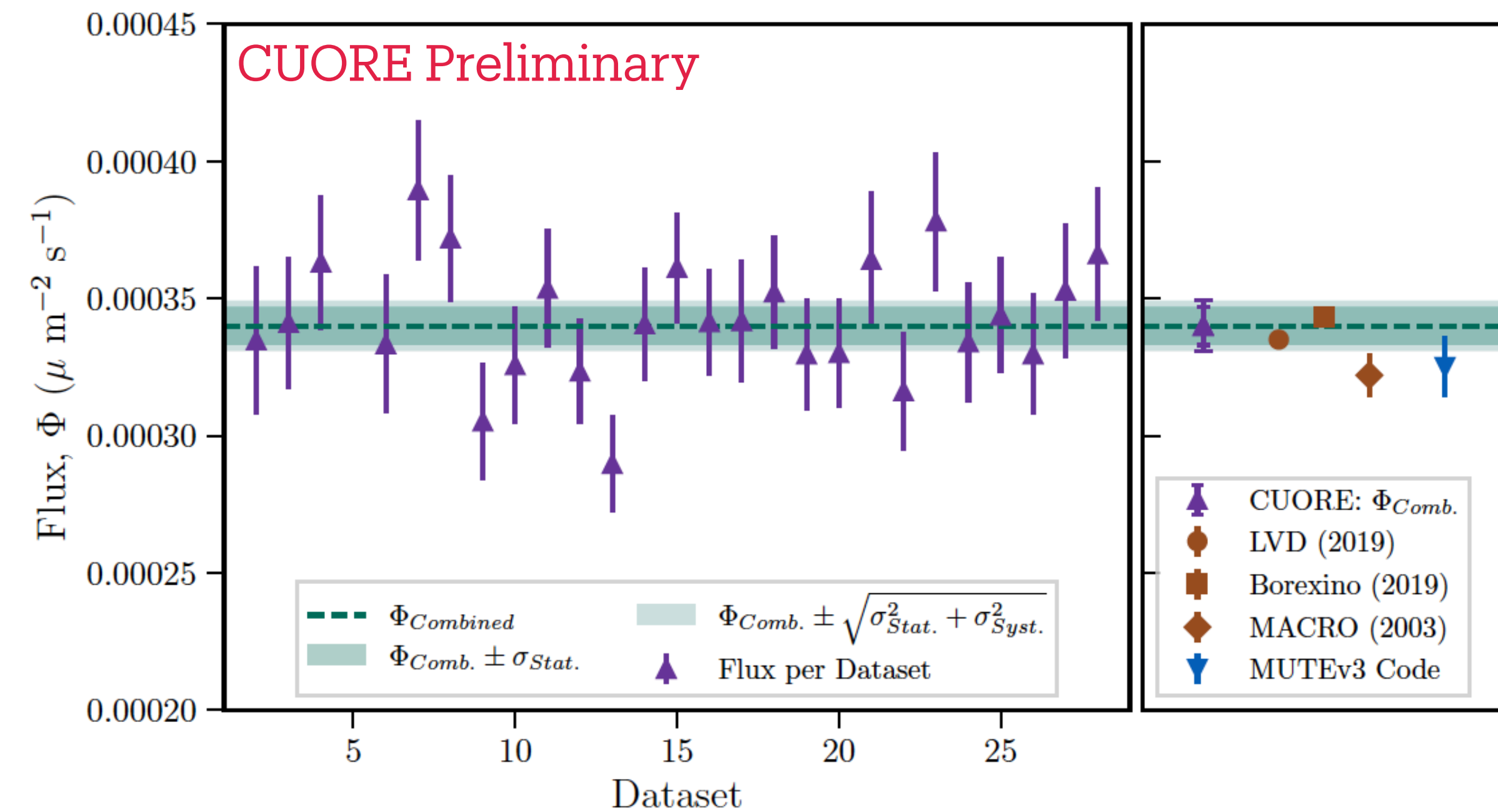


MUON STUDIES

ON THE 2 TONNE-YEAR DATA SET

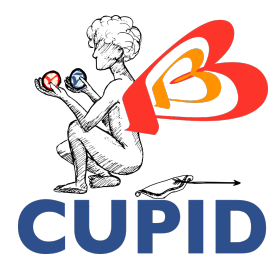


Measured muon flux @ CUORE/CUPID location:
 $\Phi = [3.40 \pm 0.07 \text{ (stat.)} \pm 0.06 \text{ (syst.)}] \times 10^{-4} \text{ s}^{-1} \text{ m}^{-2}$



An observed muon candidate through CUORE detector

[arXiv.org/2509.05528](https://arxiv.org/2509.05528)



CUPID OFFICIAL TIMELINE

STAGED DEPLOYMENT AND EARLY PHYSICS DATA

