

CUPID: CUORE Upgrade with Particle Identification

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UGRP, Tokyo 2026



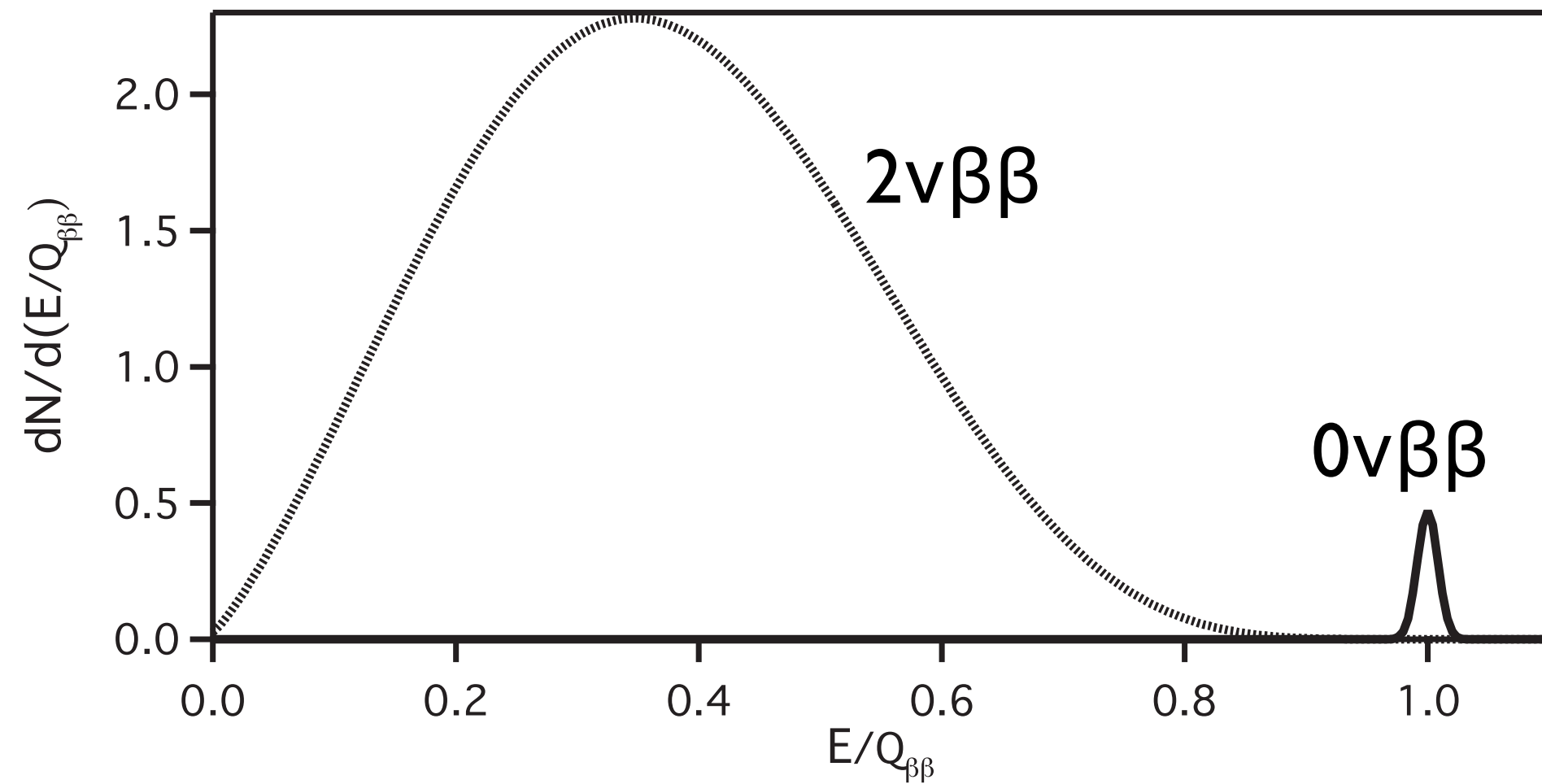
Outline



- Cryogenic calorimeters
- CUORE
- Cryogenic Infrastructure
- CUPID: CUORE Upgrade with Particle ID

Double-Beta Decay Signature

Summed-energy spectrum of final state electrons



Assumes BR $0\nu/2\nu = 1\%$ and detector energy resolution is 2%

a	isotopic abundance of source
ϵ	detection efficiency
M	detector mass
BI	background index near $Q_{\beta\beta}$
t	exposure time
ΔE	energy window (resolution)

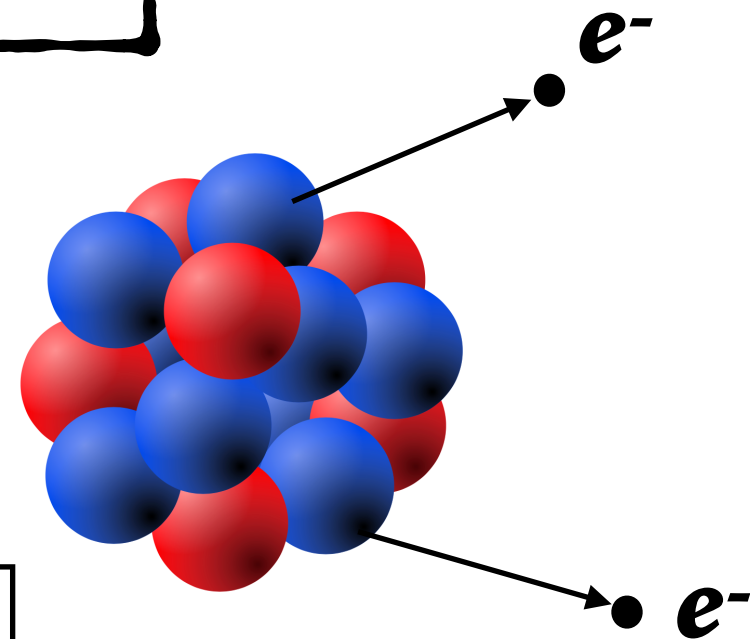
- Experiment searches for a peak at $Q_{\beta\beta}$
- Sensitivity S

In case of background:

$$S \propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{(BI) \cdot \Delta E}}$$

If background free:

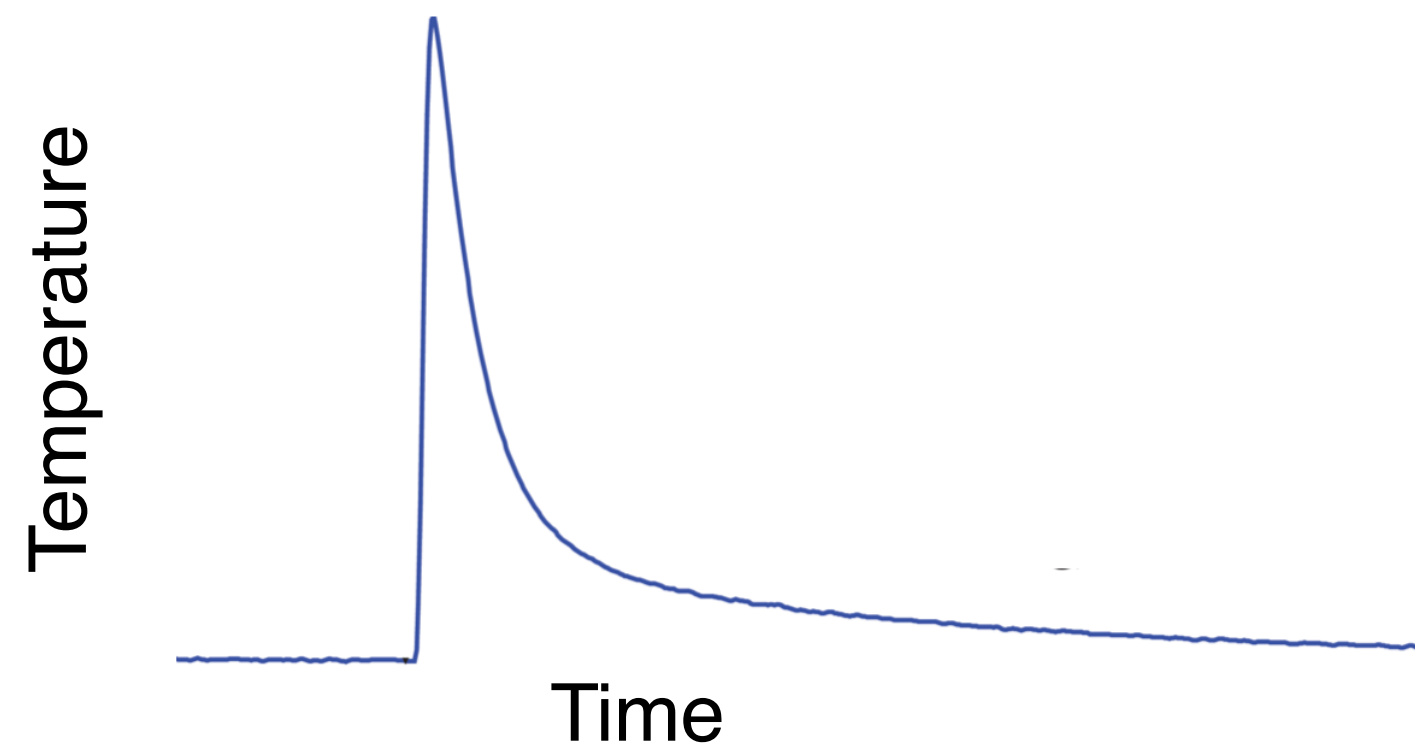
$$S \propto a \cdot \epsilon \cdot M \cdot t$$



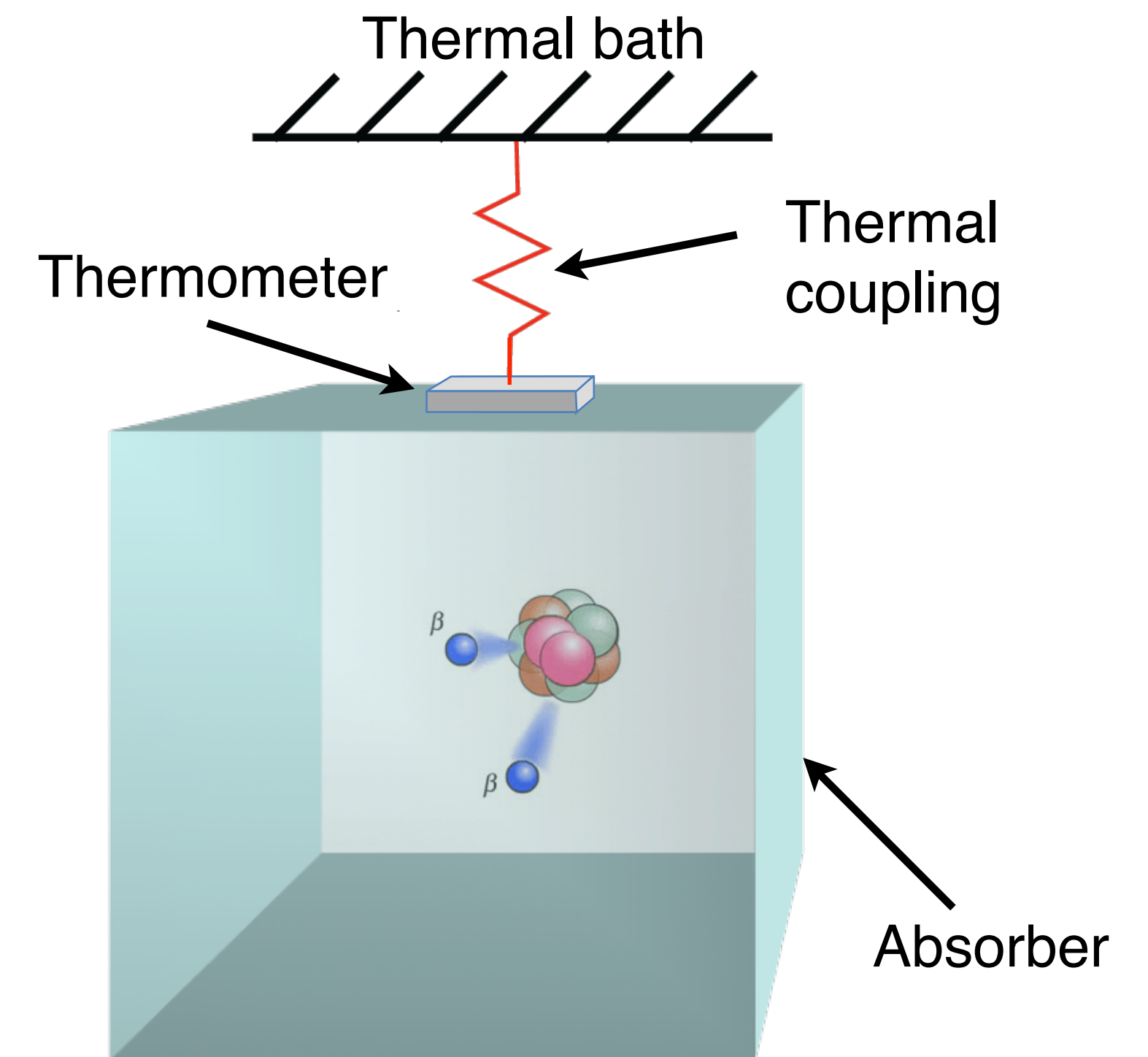
- Diverse techniques employed by the community, CUORE/CUPID/AMoRE use cryogenic calorimeters

Cryogenic Calorimeters

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

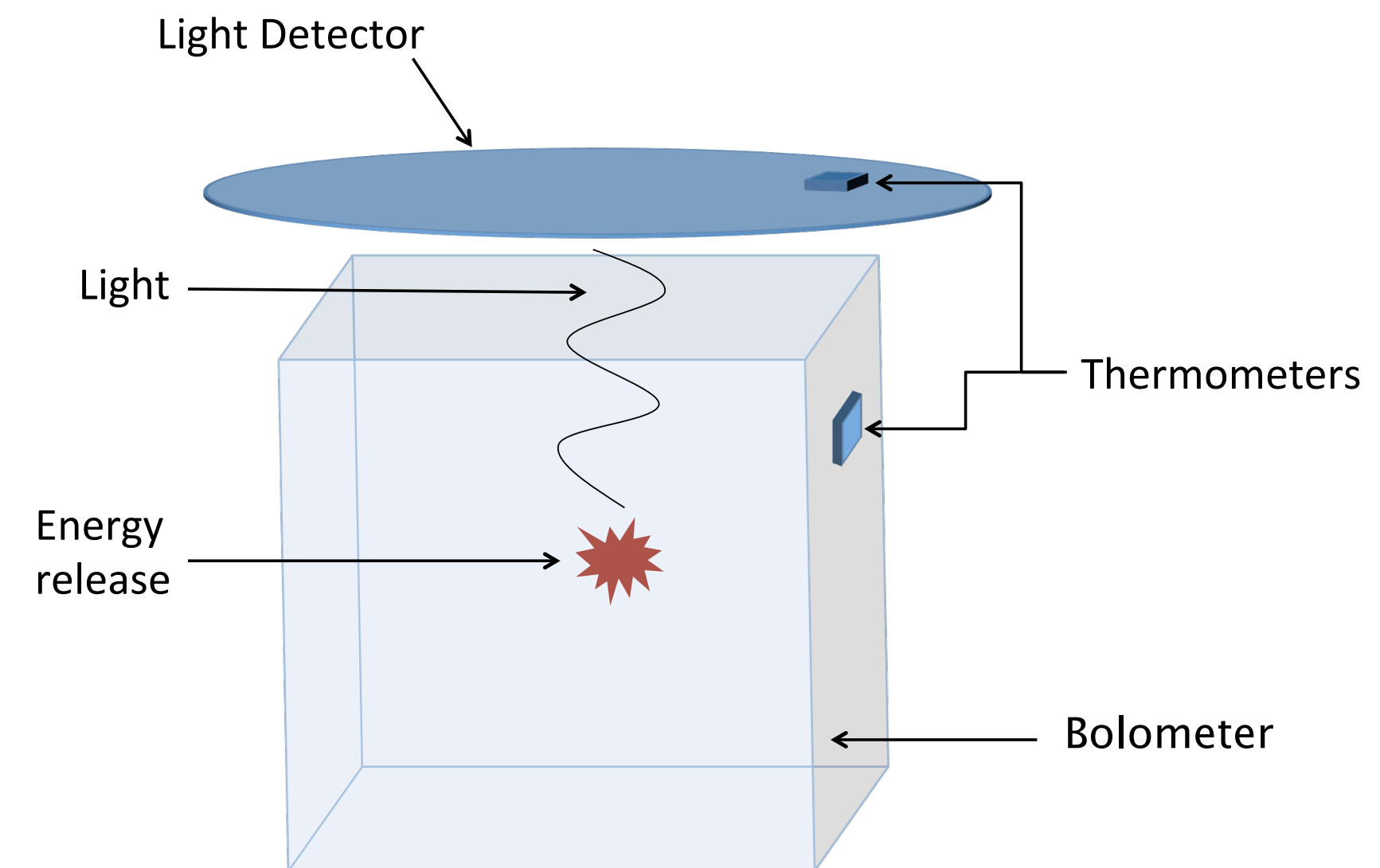
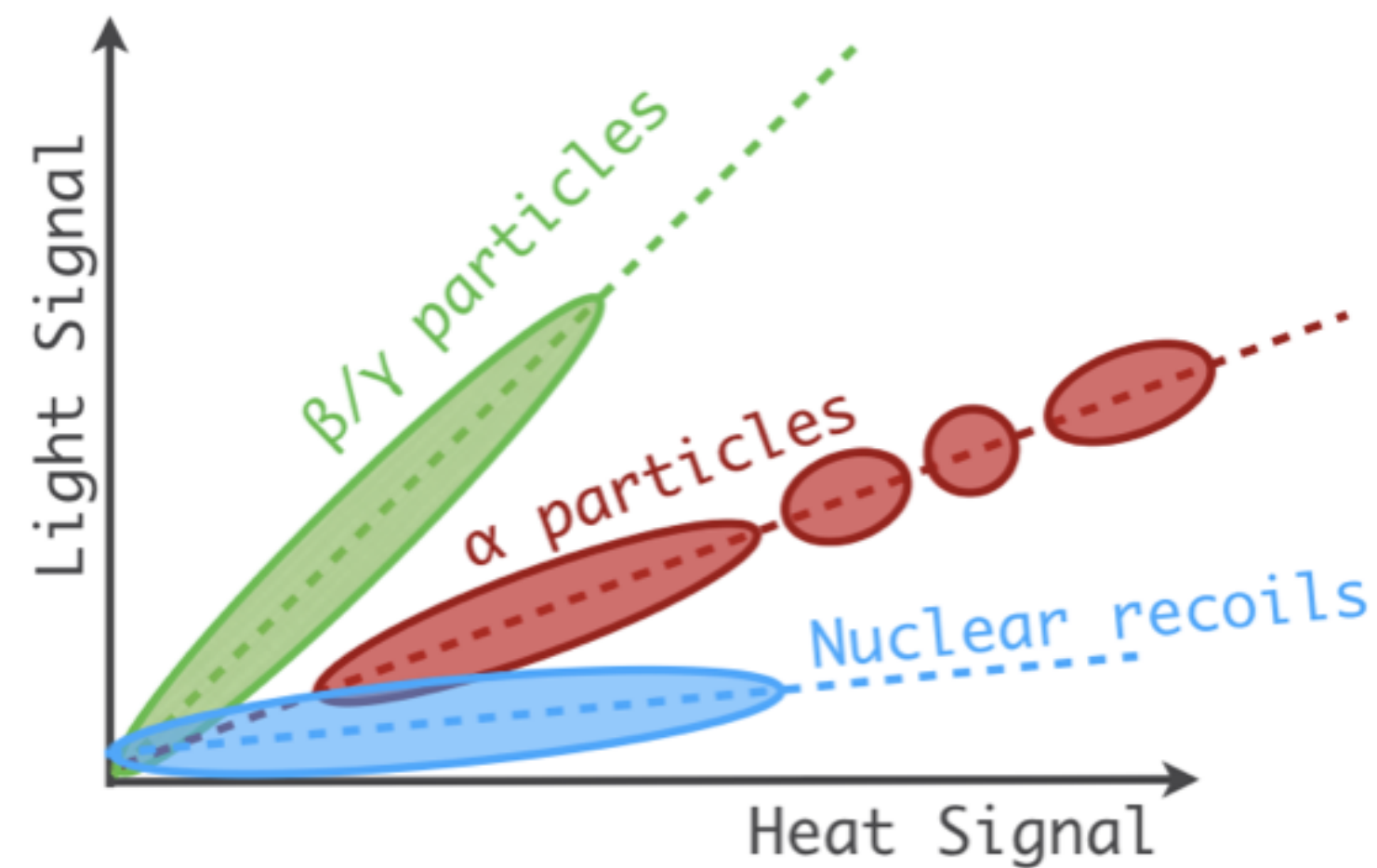


- For dielectric crystal absorbers, heat capacity $\sim T^3$
- Typically operated at $\sim 10\text{mK}$
- Relative energy resolution of 0.2~0.3% FWHM routinely achieved



Scintillating Cryogenic Calorimeters

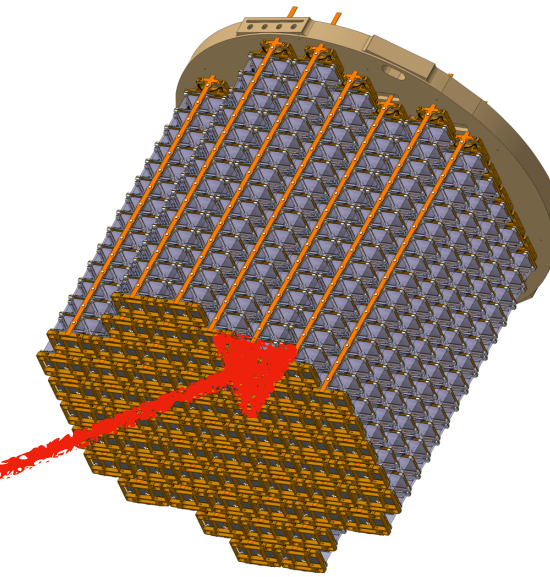
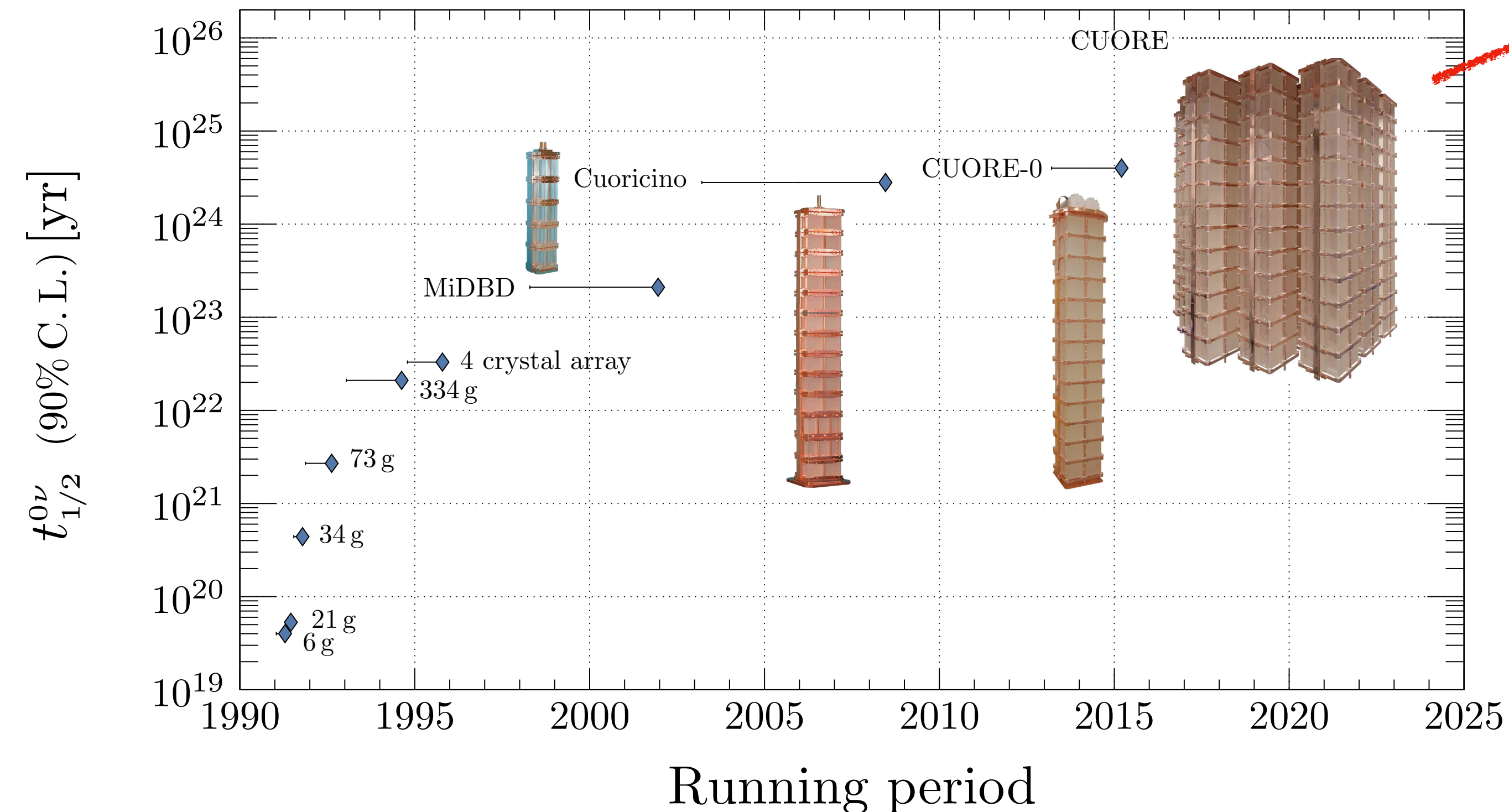
- If the absorber also scintillates measuring both the thermal and light signal can allow particle discrimination



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

Cryogenic Calorimeters

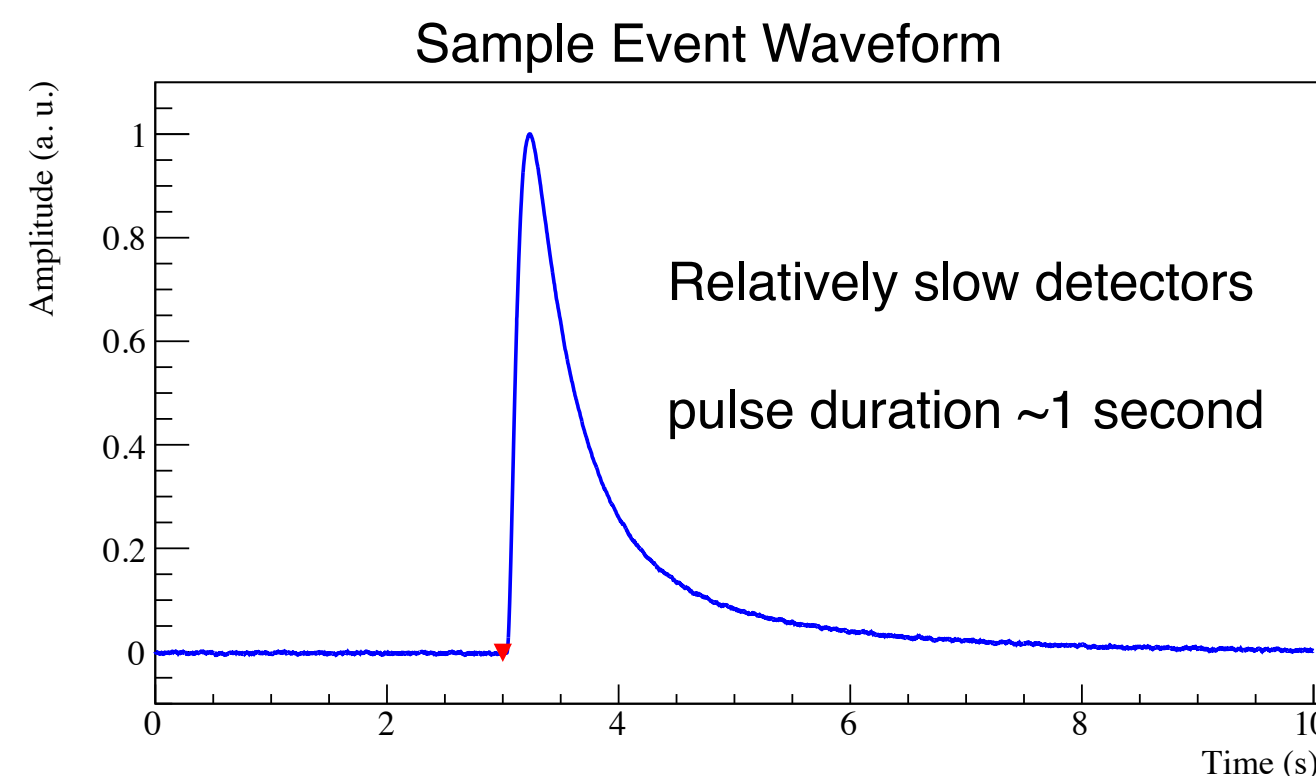
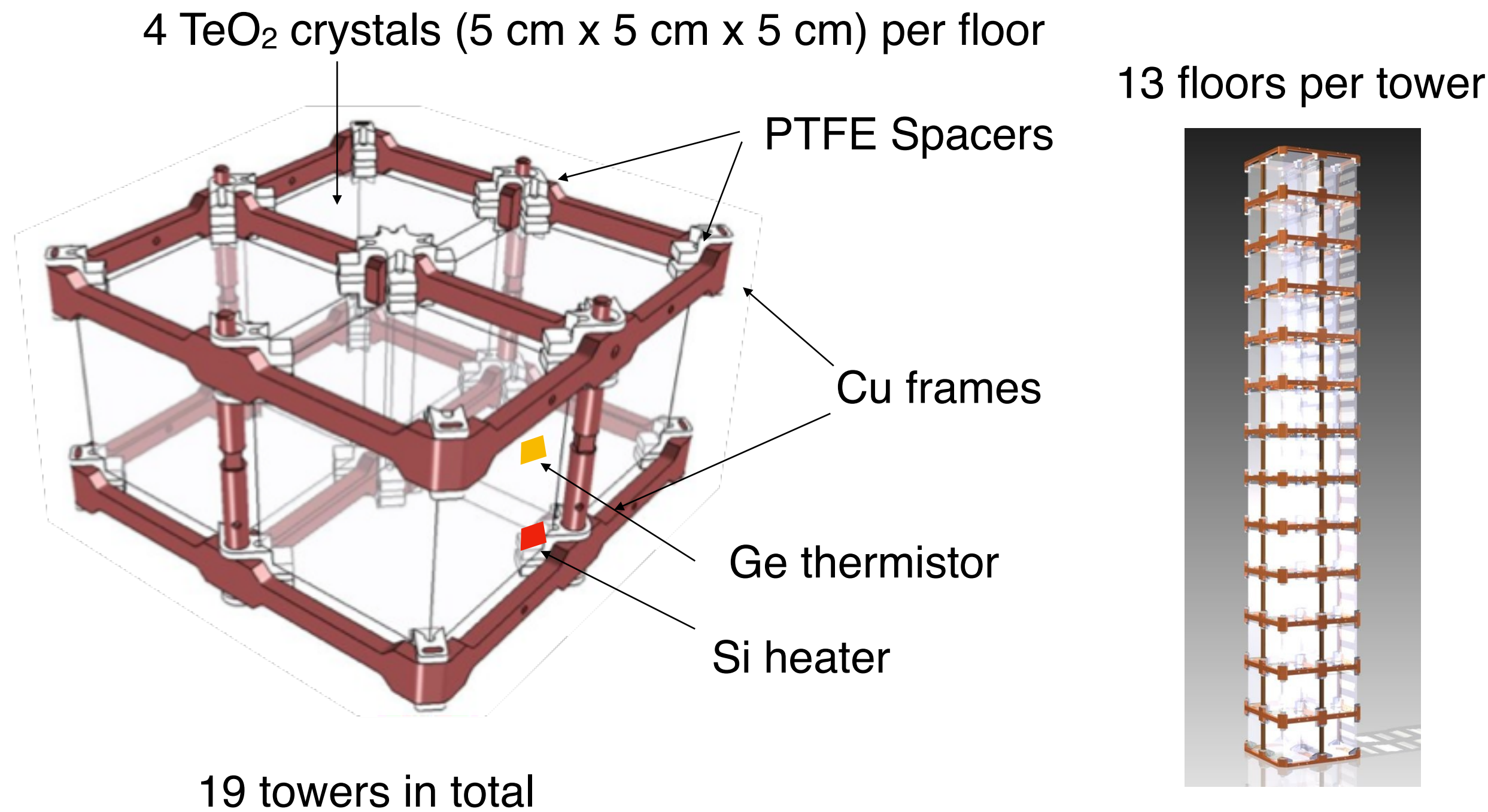
Adapted from *Rev Sci Instrum* **89**, 121502 (2018)



CUPID: 10^{27} yr

- Cryogenic calorimeters have a long history in double beta decay
- Pioneered by Fiorini and collaborators since the 1980s, (E. Fiorini and T.O. Niinikoski, Nucl. Instrum. Meth. A 224, 83 (1984))
- CUORE demonstrates that large, tonne-scale arrays can be operated stably at ~ 10 mK for long exposures

CUORE: cryogenic Underground Observatory for Rare Events

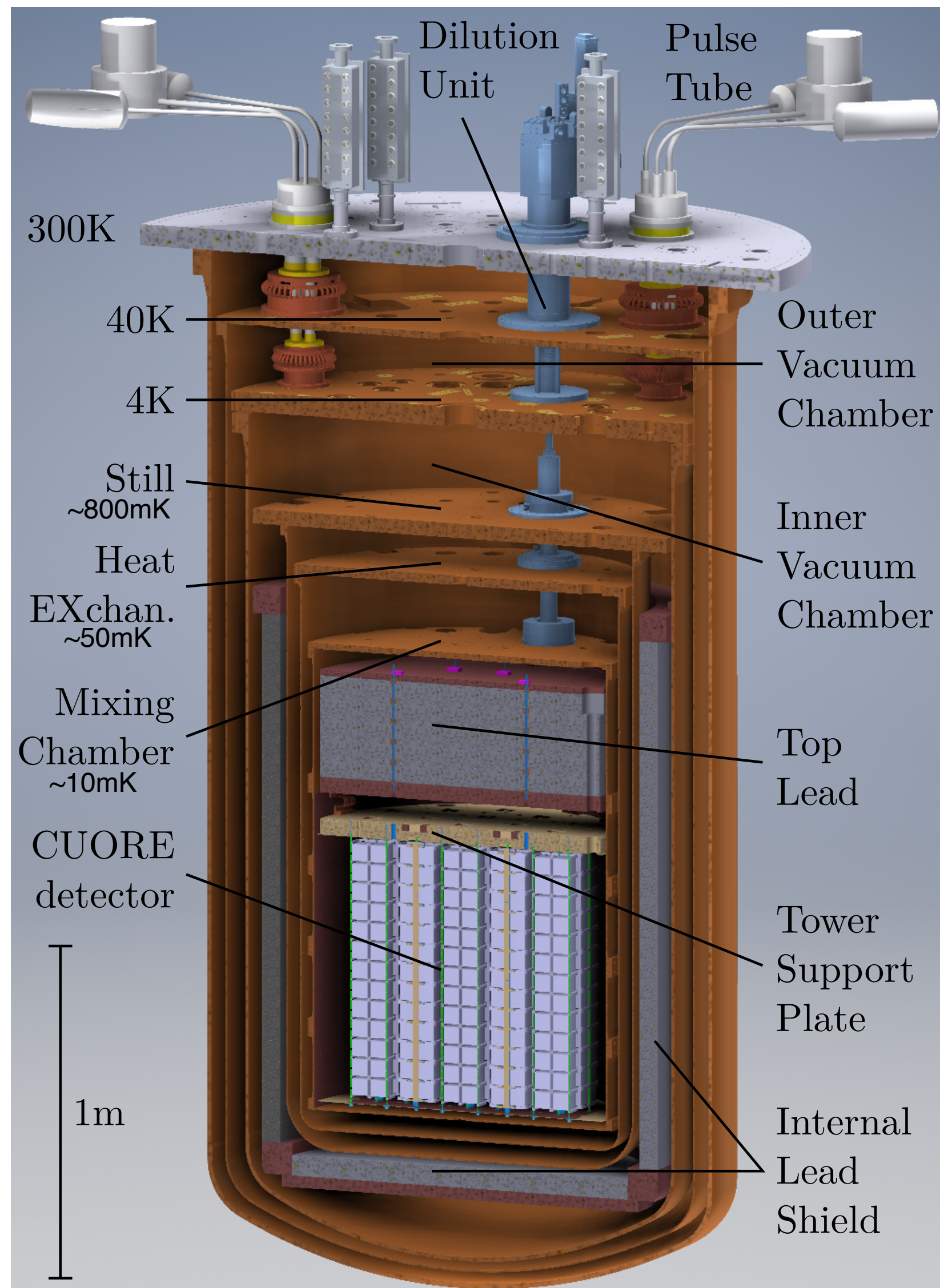


- Hosted at Gran Sasso Underground Lab
- Close-packed array of 988 ^{nat}TeO₂ bolometers (Total active mass: 742 kg)
- Operated at T~15 mK
- Primary physics goal: $0\nu\beta\beta$ decay of ¹³⁰Te
 - ▶ Isotopic abundance 34% => 206 kg
 - ▶ Q-value: 2527.5 keV
- Cooled in a custom-built dilution refrigerator cryostat
- CUPID keeps the concept: close-packed array, copper frames, PTFE spacers, NTD thermistors, Si heaters.

The CUORE Cryogenic facility

Cryogenics **102**, 9-21 (2019). [arxiv:1904.05745](https://arxiv.org/abs/1904.05745)

Cryogenics **93**, 56-65 (2018). [arxiv:1712.02753](https://arxiv.org/abs/1712.02753)



- A milli-Kelvin facility for tonne-scale detectors
- Precooled by 4 cryomech PT415 pulse tubes (+1 spare)
- Custom-built ^3He - ^4He dilution refrigerator
 - cooling power: $\sim 5 \mu\text{W}$ at 10 mK (“unloaded”)
 - $\sim 3 \mu\text{W}$ at 10 mK (with cryogenic lead shielding)
- Cryogenic vessels and internal shielding:
 - 12.7 tonnes < 4 K
 - 4.5 tonnes < 50 mK
 - 1500 kg @ ~ 10 mK (detectors + materials)
- Largest cold mass operated continuously for nearly a decade
- CUPID will reuse this facility, radiogenic backgrounds well characterized with CUORE data

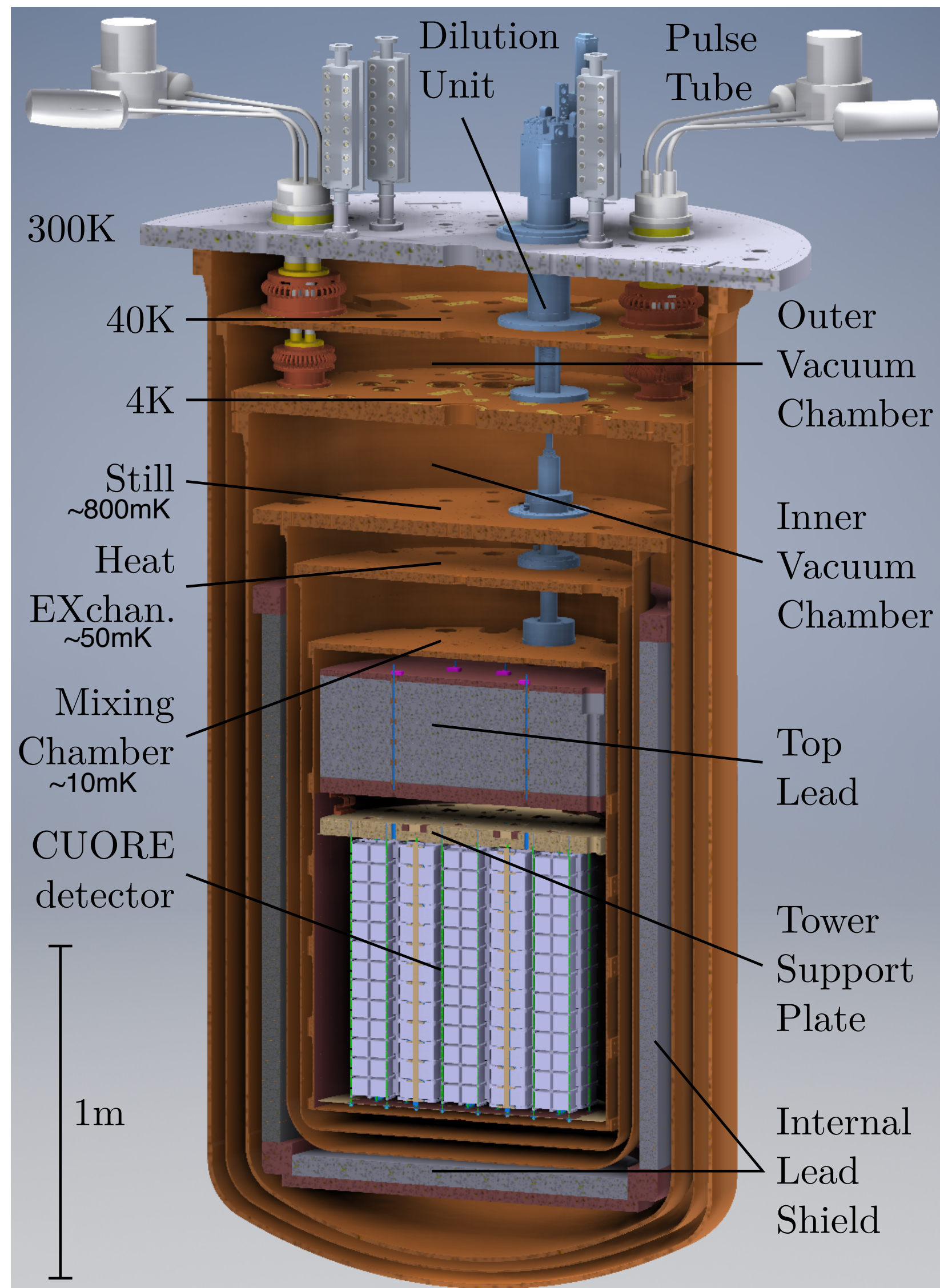
The CUORE Cryogenic facility



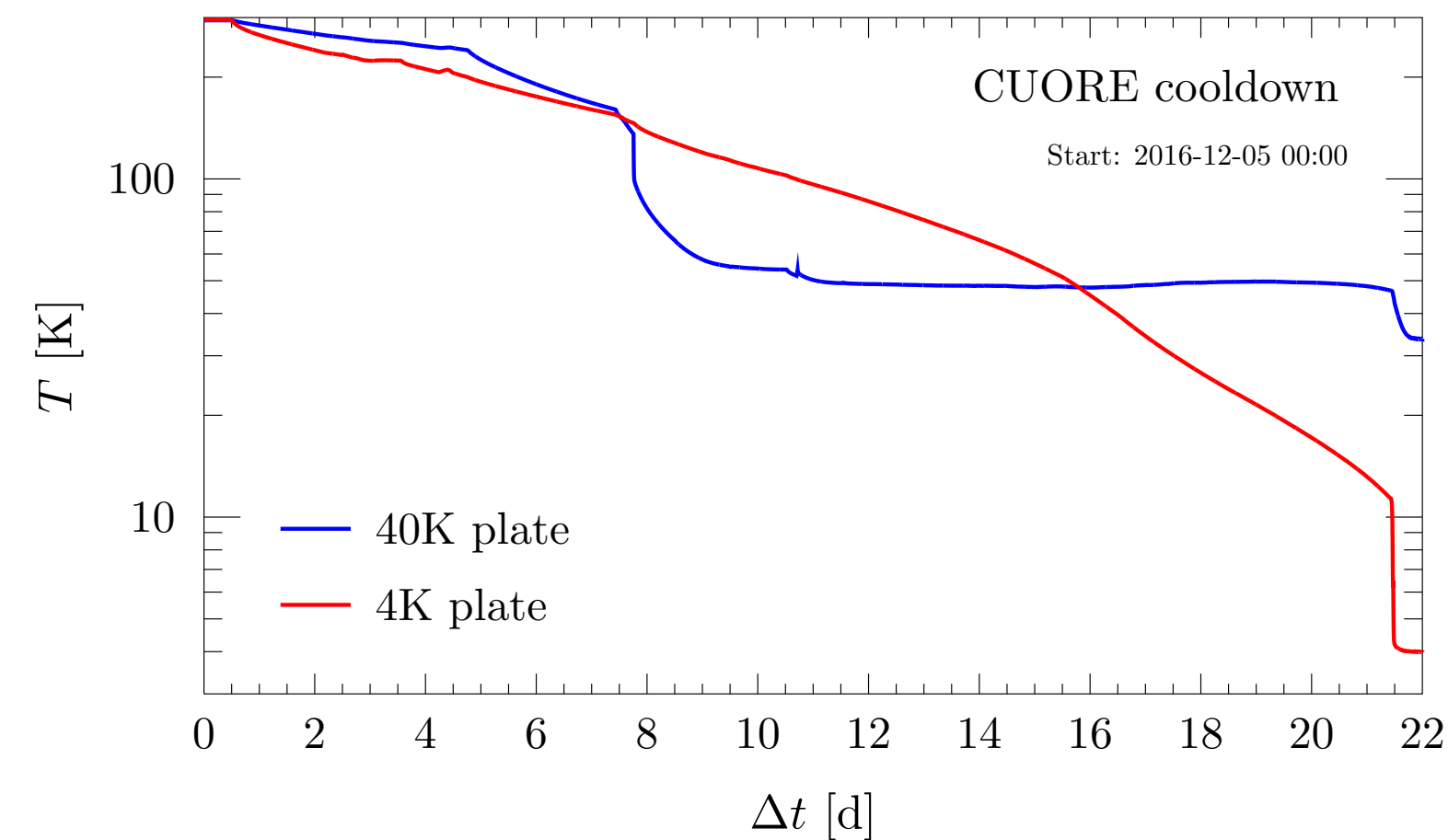
Cryogenics **102**, 9-21 (2019). [arxiv:1904.05745](https://arxiv.org/abs/1904.05745)

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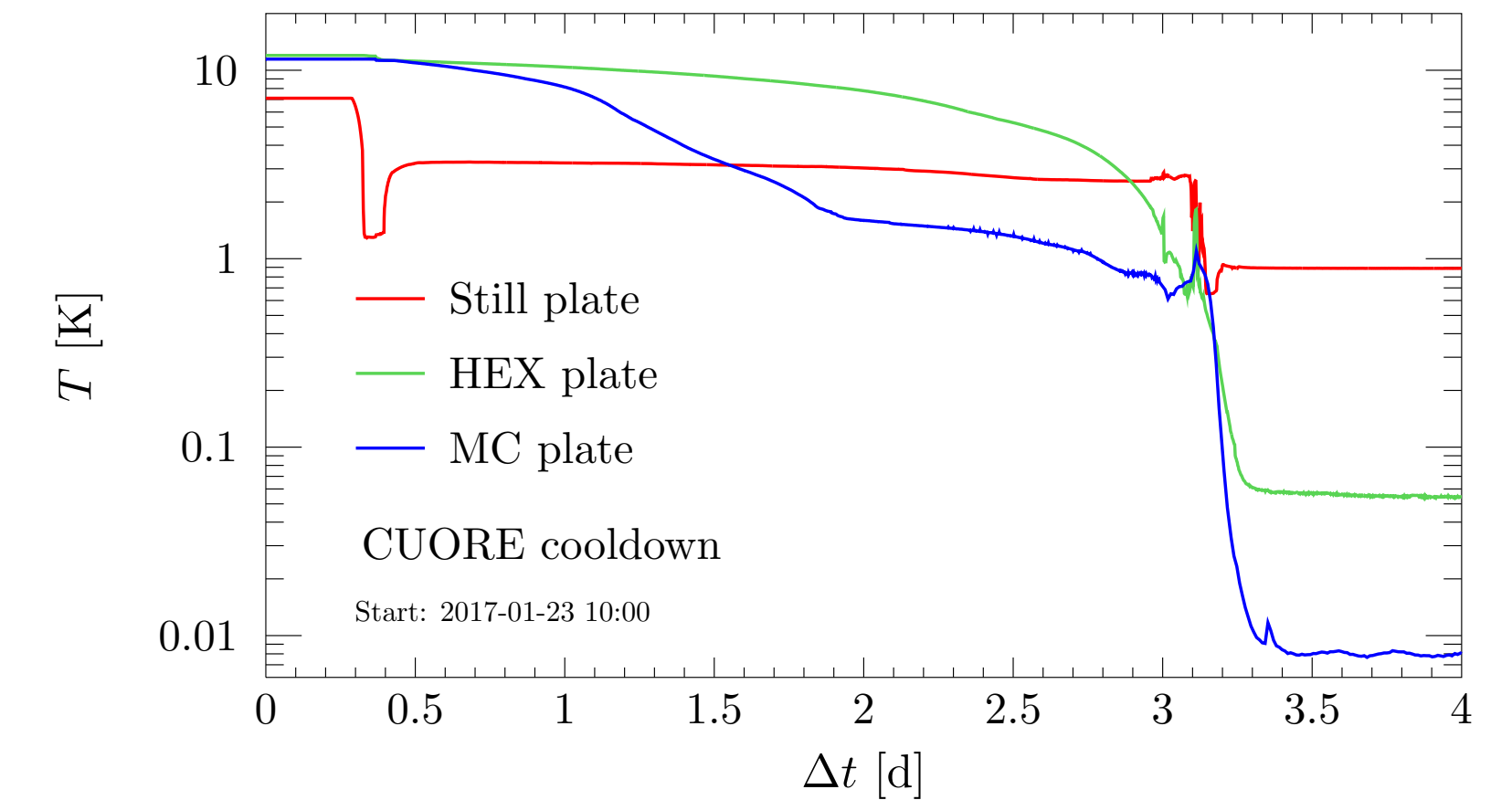
- Cooldown time ~ 1 month



Cooldown 300K → 4K

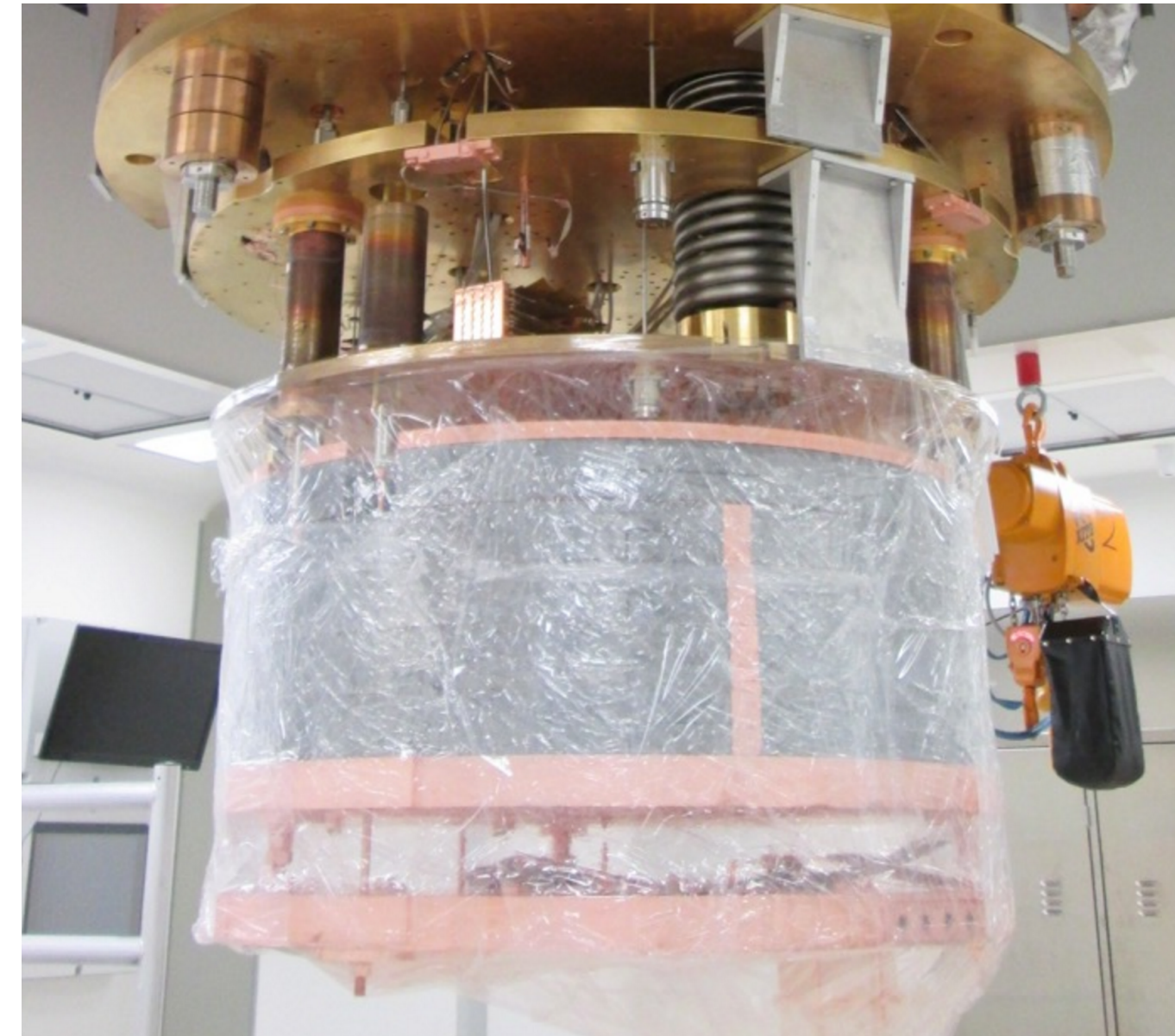


Cooldown 4K → 10mK

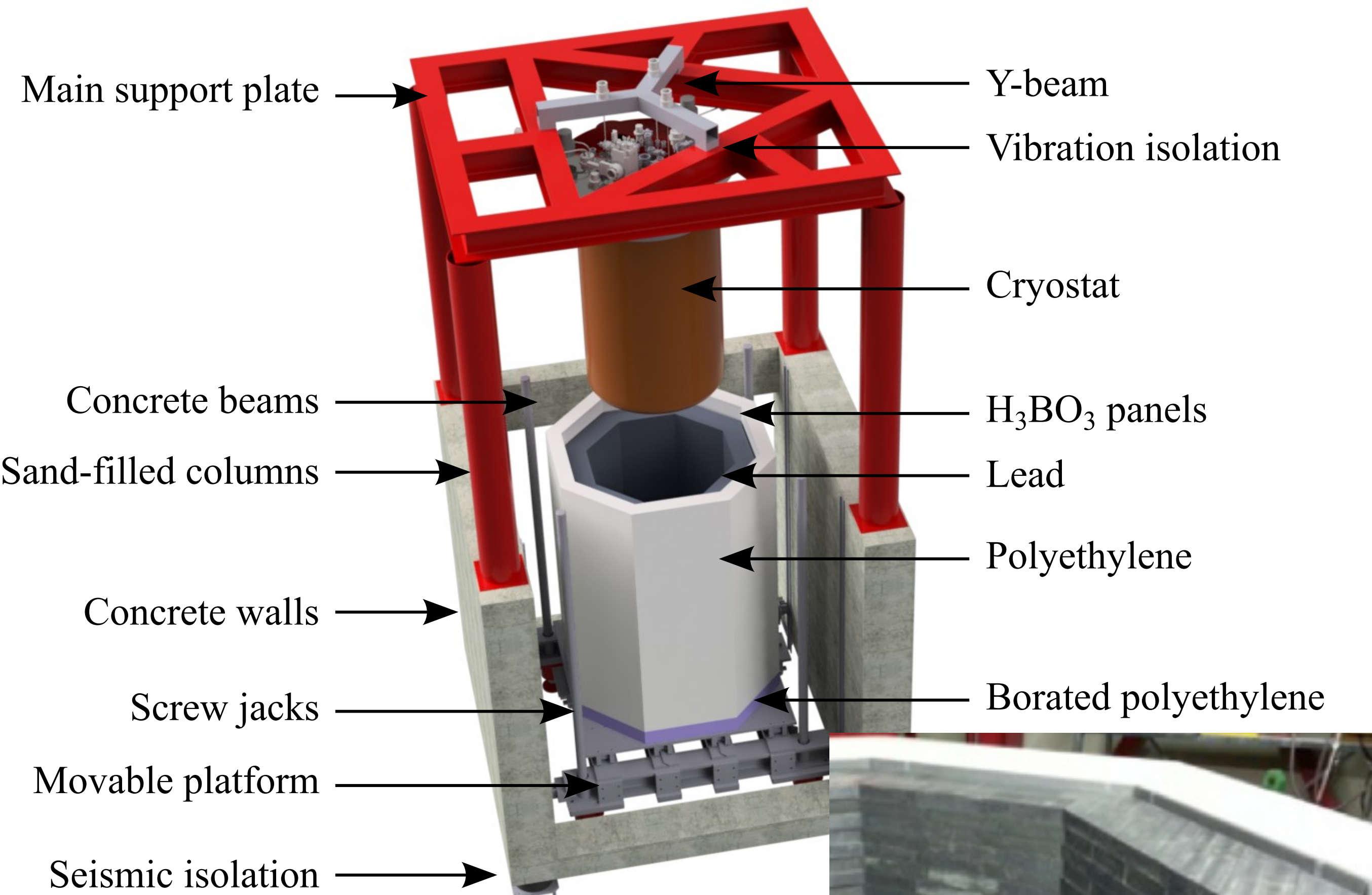


Cryogenic facility: Shielding

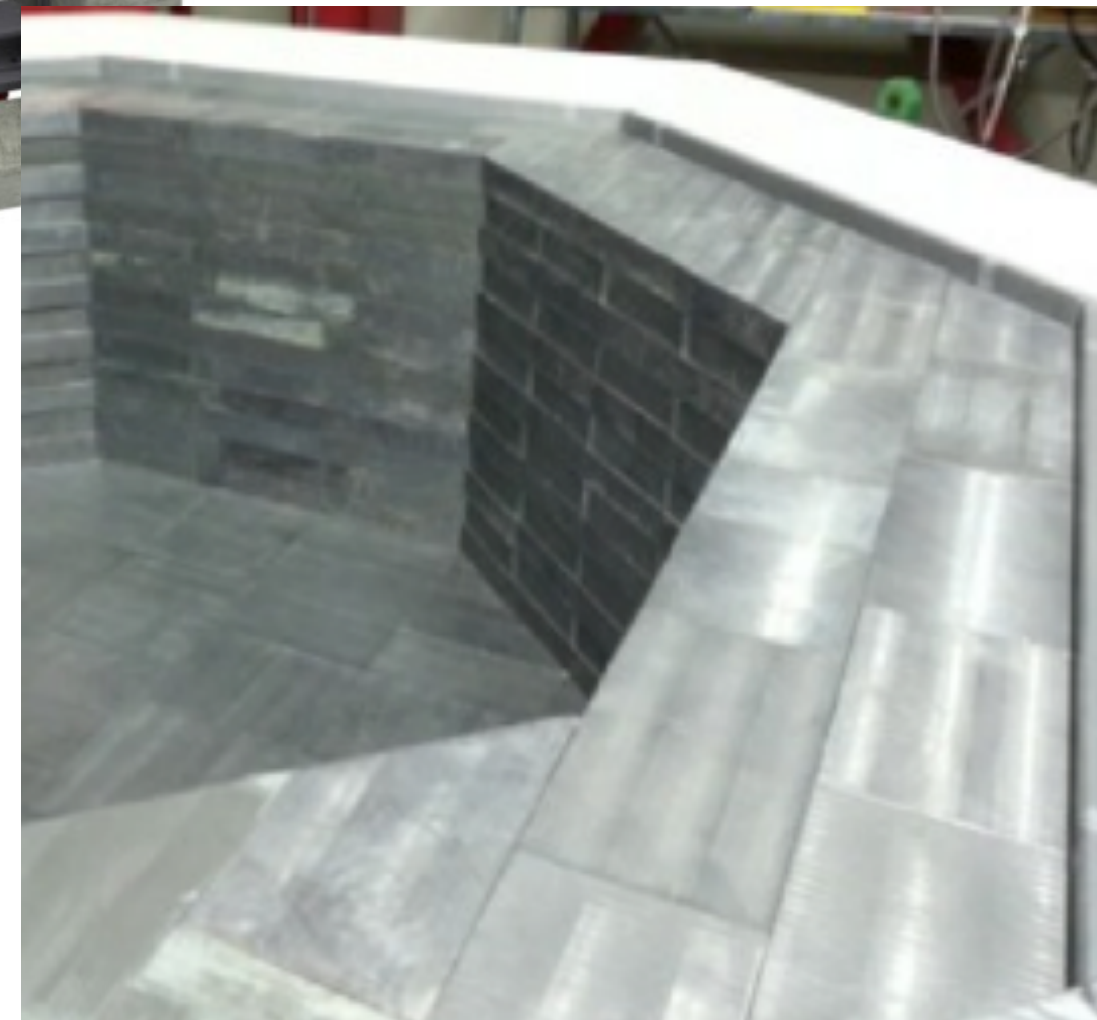
- Internal cryogenic lead
 - ➔ ~30 cm thick top lead (modern)
 - ➔ ~6 cm thick ancient Roman lead (lateral and bottom)



Cryogenic facility: External Shielding



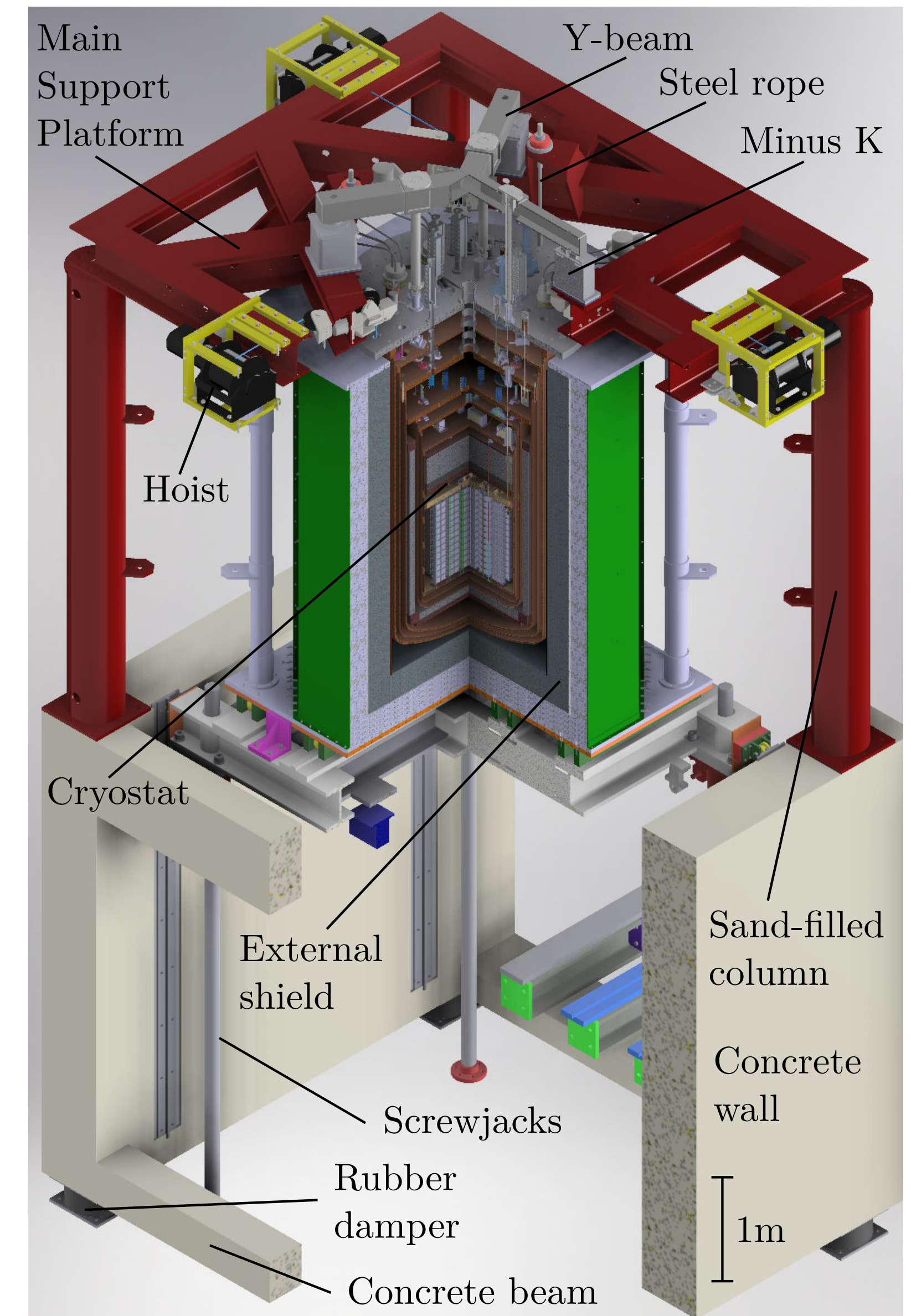
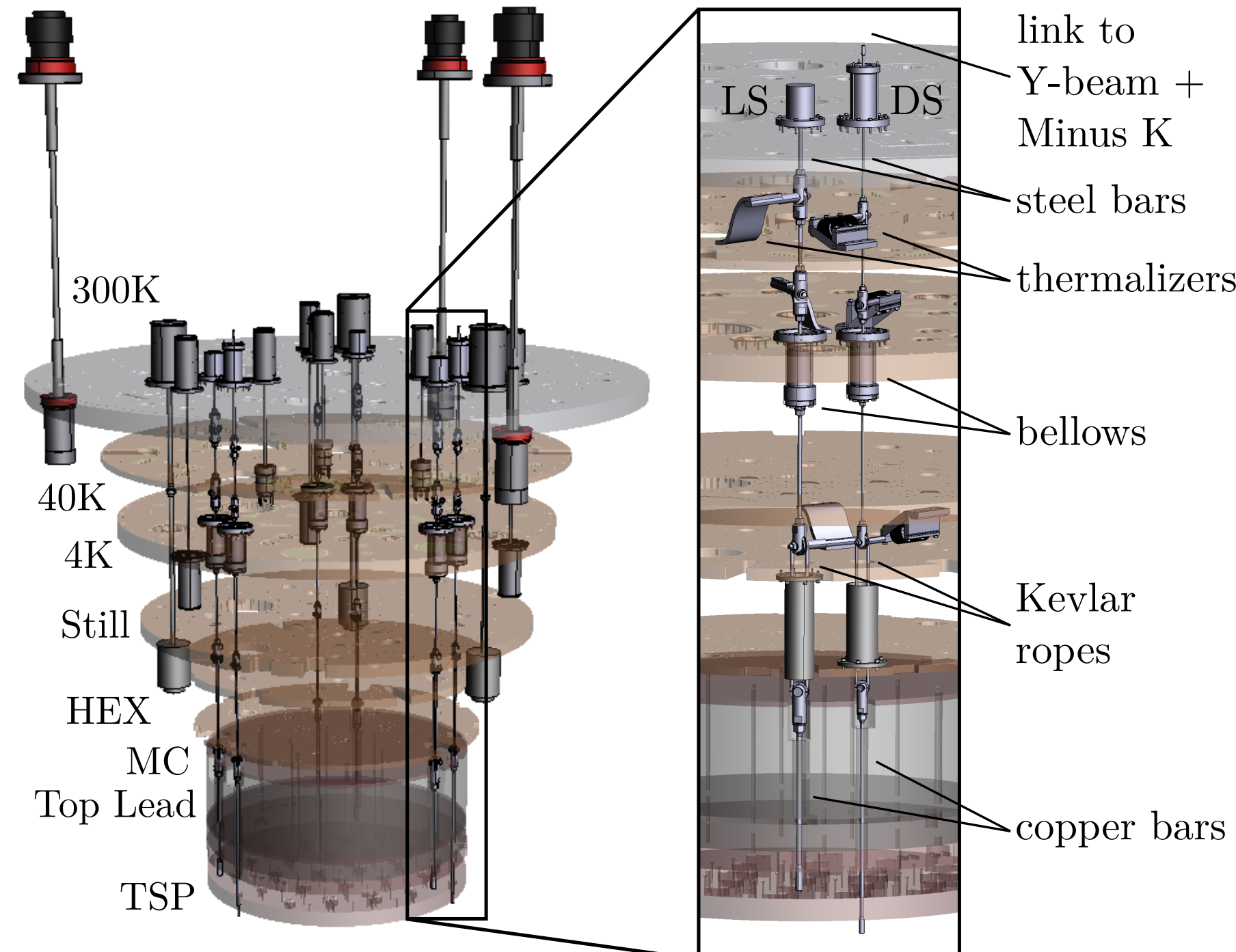
- External radiation shielding
 - ➡ 18-cm-thick polyethylene (lateral and bottom)
 - ➡ 2-cm-thick borated panels (lateral and bottom)
 - ➡ 25-cm-thick lead shield (lateral and bottom)
 - ➡ Shield can be lowered for cryostat access



Cryogenic facility: Vibration Mitigation

- Vibration mitigation:

- ➔ Detectors suspended from Y-beam mounted on Minus-K vibration isolation platforms on main support plate
- ➔ Flexible bellows feedthrough and flexible thermalizers reduce mechanical coupling



Cryogenic facility: Vibration Mitigation

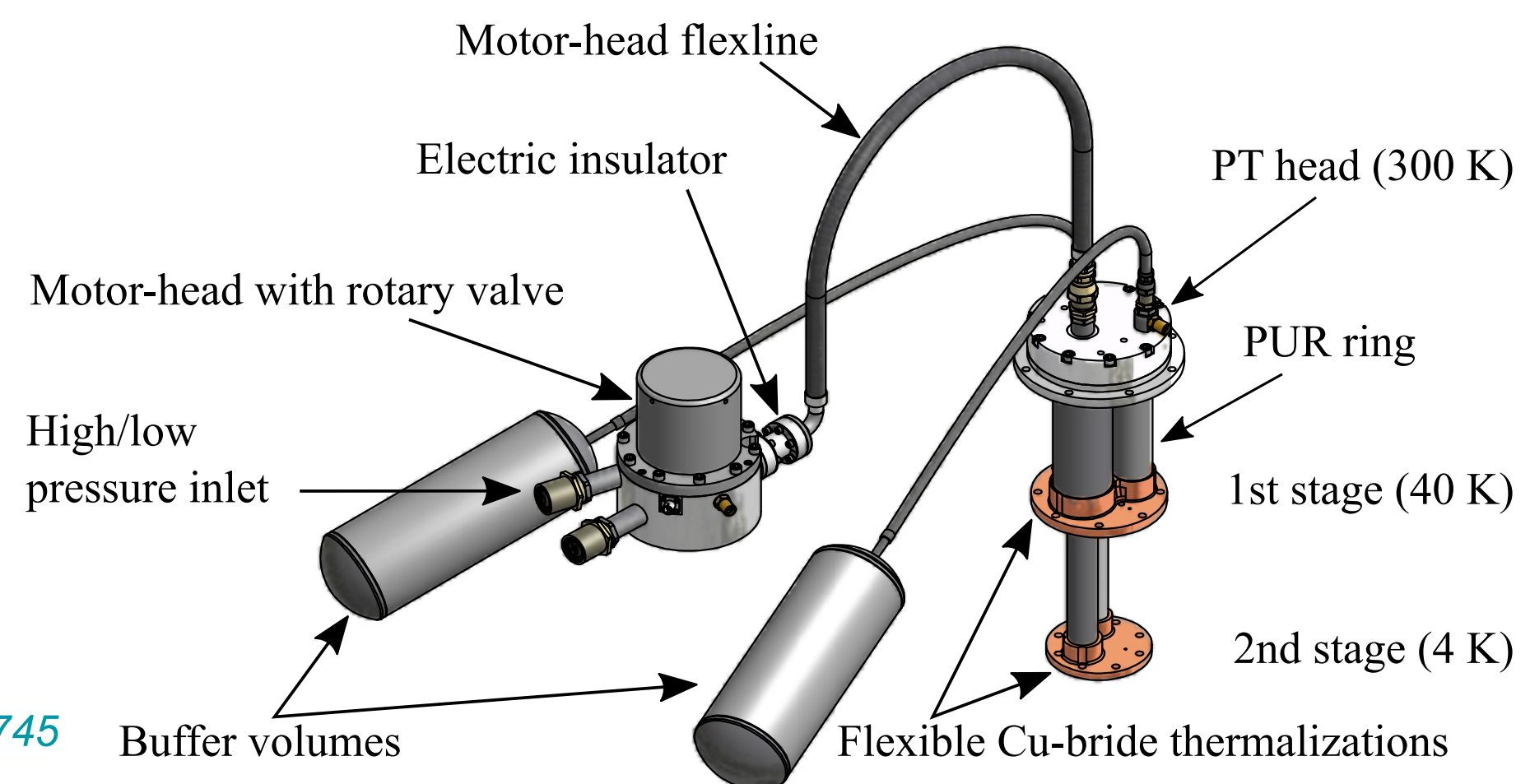
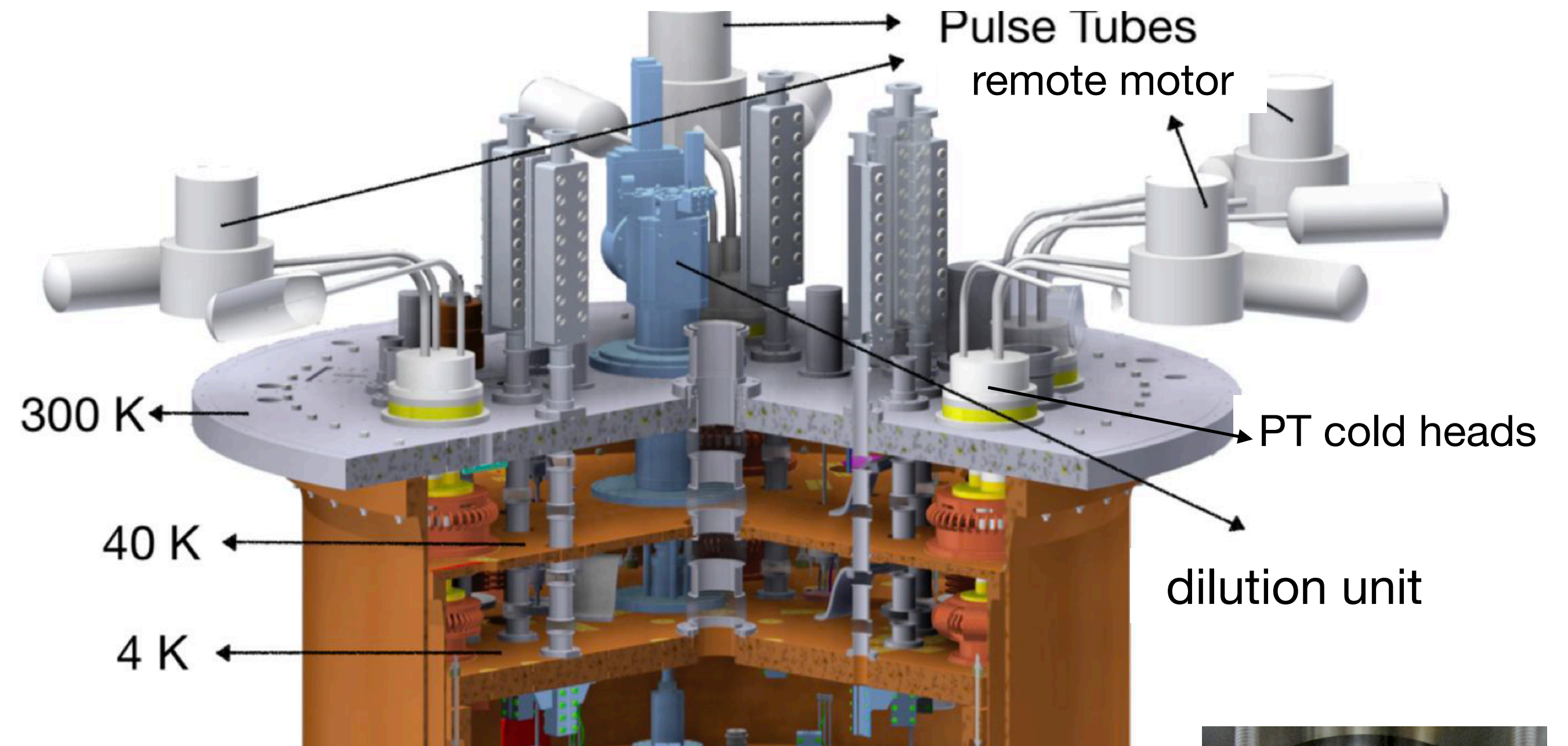
ation mitigation Pulse Tubes (PTs)

rotary valves removed from the PT
ads and hung on bungee cords;

urethane ring at the 300 K plate
urface; flexible copper braids to the 40 K
d 4 K plates

Phases: rotary valves driven by
pecially selected low-noise microstepping
tors, relative phases of the pulse tubes
ed to minimize detector noise

mpressors: ~15 m away, on elastomer
unts; He flex lines pass through a 1.5
ne quartz-sand box



Cryogenics **102**, 9-21 (2019). [arxiv:1904.05745](https://arxiv.org/abs/1904.05745)

Cryogenics **93**, 56-65 (2018). [arxiv:1712.02753](https://arxiv.org/abs/1712.02753)

CUORE: Active Vibration Mitigation

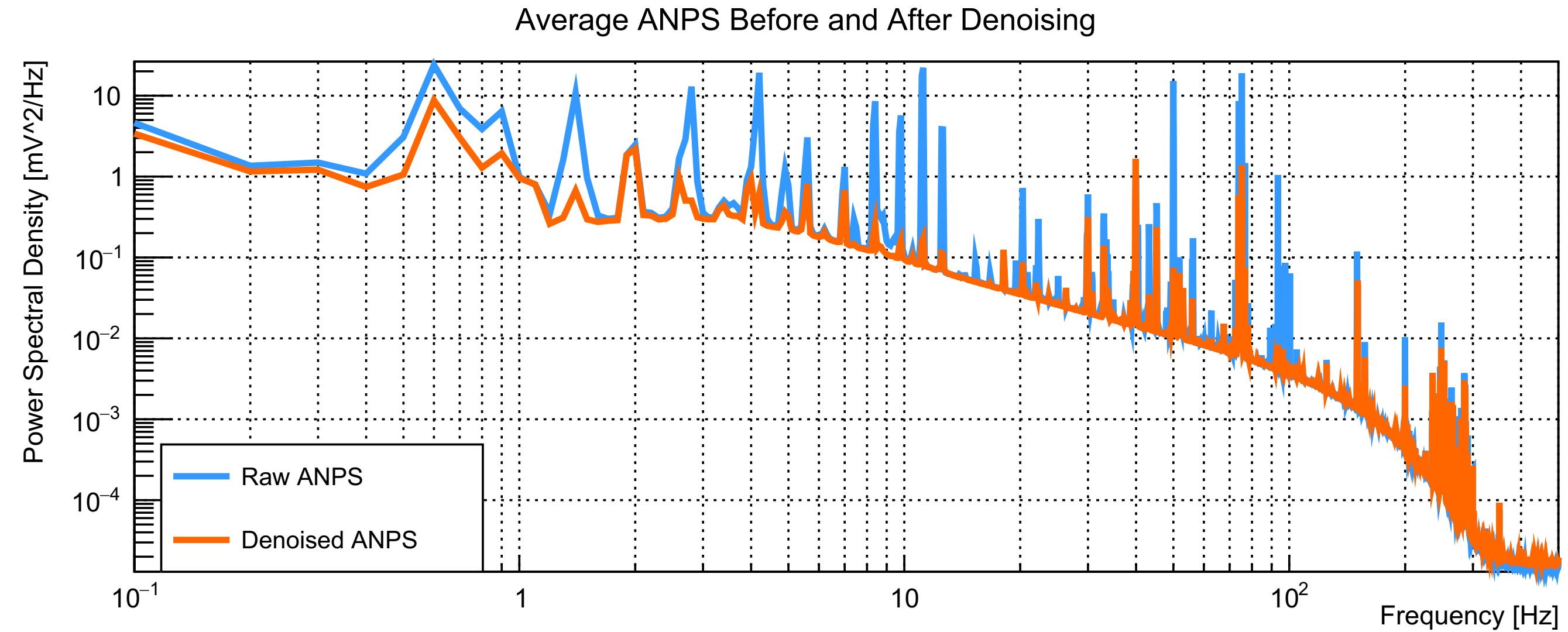


- Noise sources:

- ➔ pulse tubes (dominant, in the 0–20 Hz signal band),
- ➔ human activity
- ➔ seismic noise, earthquakes, sea swell

- Mitigation:

- ➔ Active control: PT phase tuning
- ➔ Monitoring: seismometers, accelerometers and microphones in the CUORE hut
- ➔ Software denoising with these sensors



EPJC 84, 243 (2024);
Commun. Phys. 9, 121 (2026);

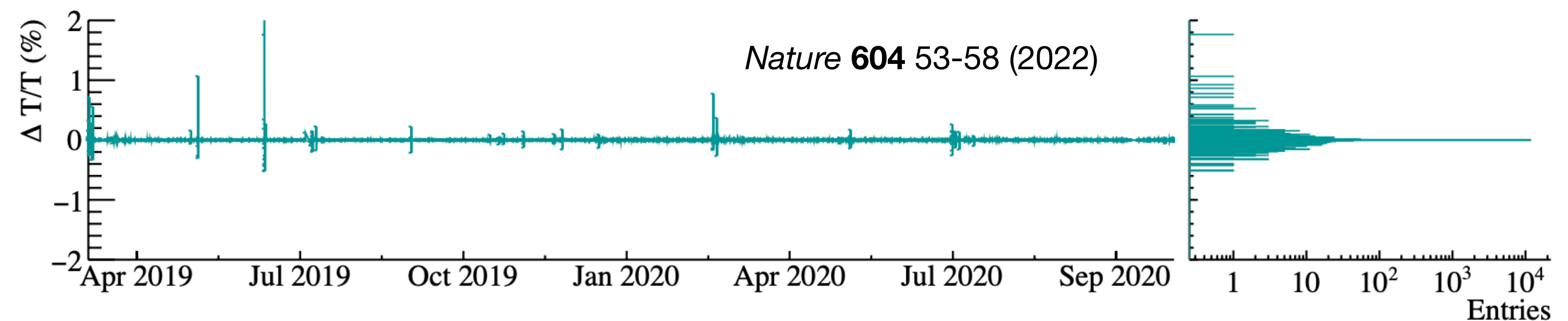
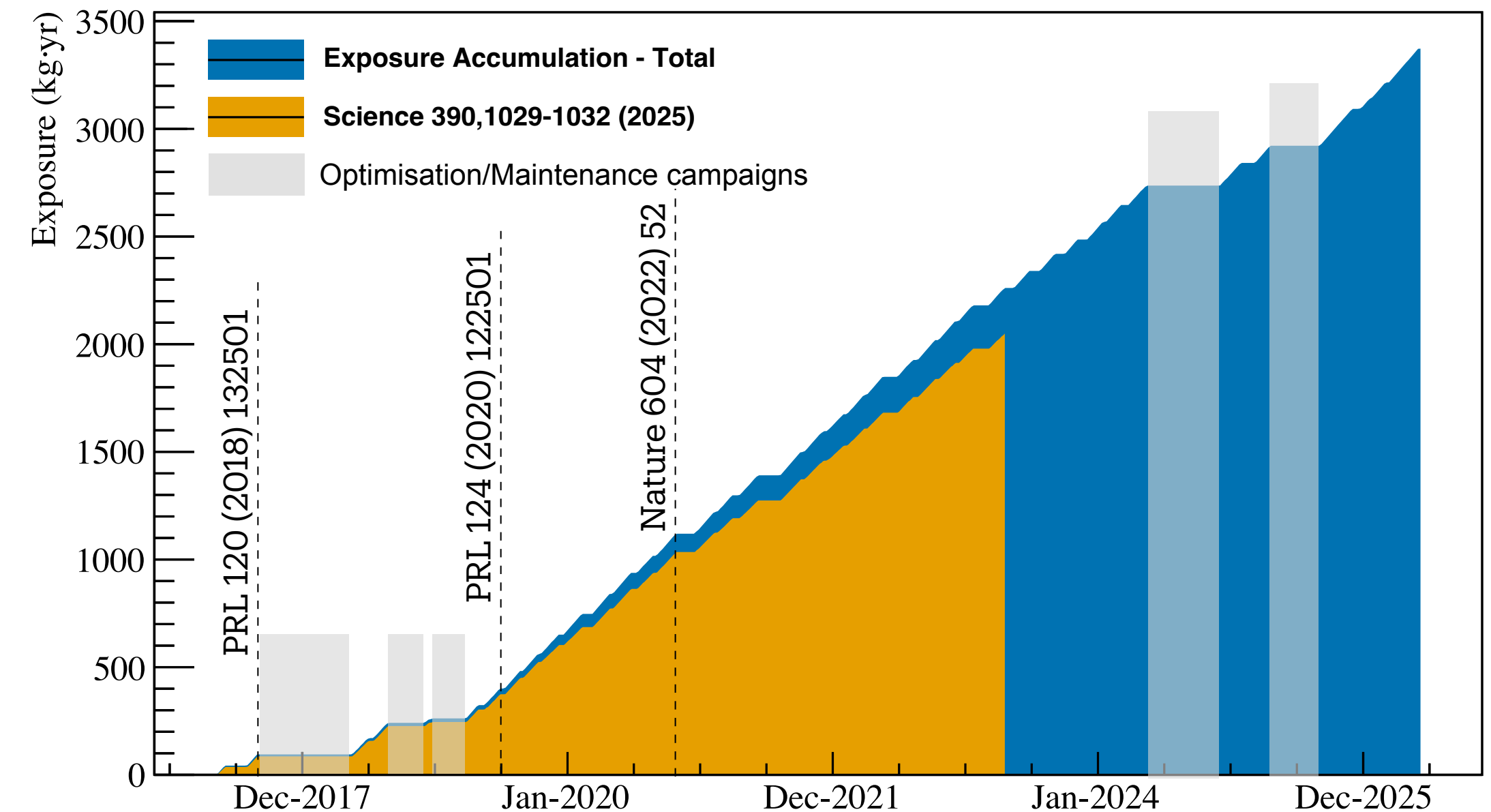
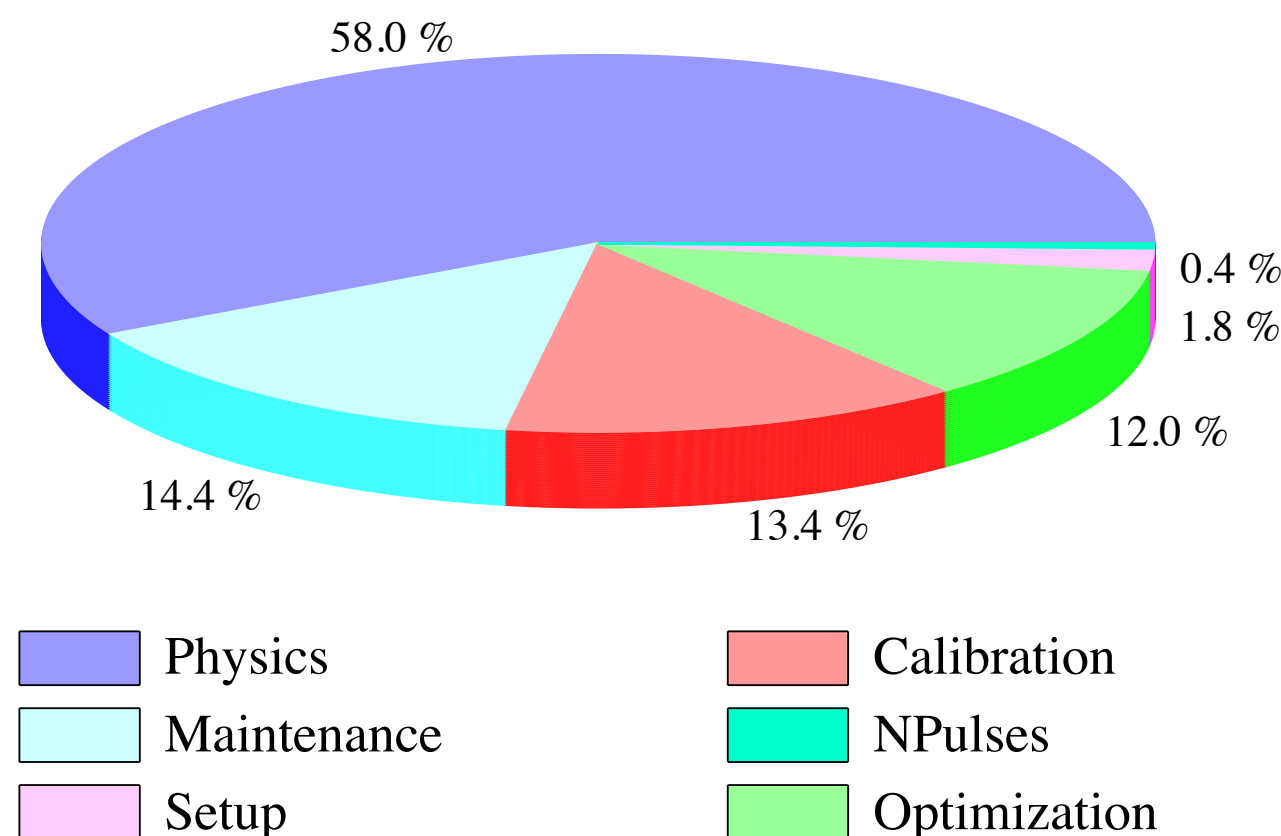
CUORE Status



- A decade of data taking: 2017- 2026
- 983/988 detectors operational (~99.5%)
- Main physics data-taking concluded in June 2026 with 3.37 tonne-year of TeO₂ (before analysis cuts)
- Technical runs ongoing (low gain runs, temperature scan etc)
- Analysis of full exposure ongoing

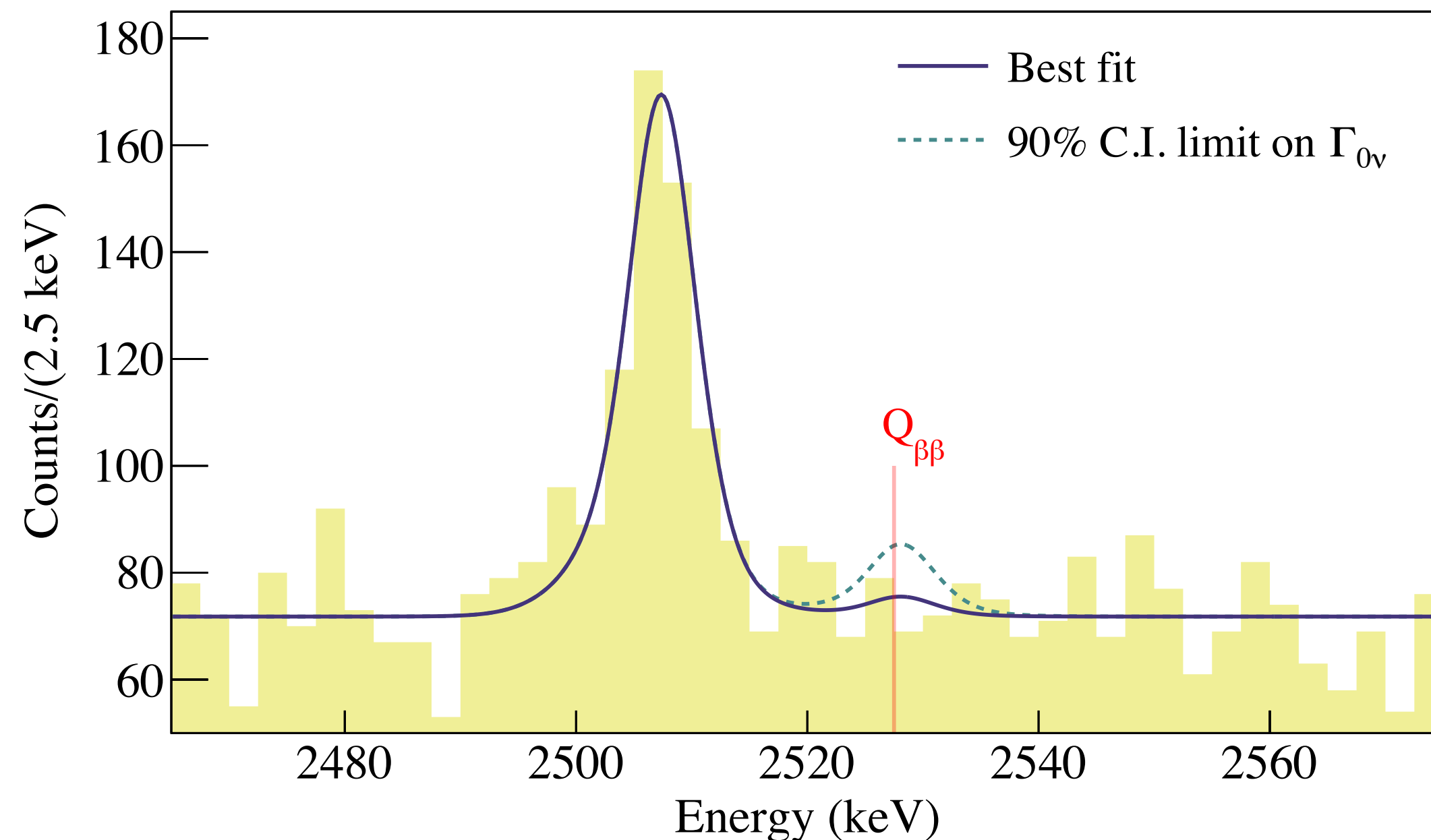
2019 — 2026 operation efficiency:

CUORE Run Time Breakdown



- Cryogenic temperature stable to <0.2% level

Current ^{130}Te $0\nu\beta\beta$ decay results



- No evidence for $0\nu\beta\beta$ decay

$$T_{1/2}^{0\nu} > 3.5 \times 10^{25} \text{ yr (90 \% C.I.)}$$

- Interpretation in context of light Majorana neutrino exchange

$$m_{\beta\beta} < 70 - 250 \text{ meV}$$

- Total exposure: 2039.0 kg-yr TeO_2 / 567.0 kg-yr ^{130}Te
- Bayesian Analysis
- Likelihood model: flat continuum (BI), posited peak for $0\nu\beta\beta$ (rate), peak for ^{60}Co (rate + position)
- Unbinned fit on physical range (rates non-negative), uniform prior on $\Gamma_{0\nu}$

Detector Performance Parameters

ROI Background Index

$$(1.42^{+0.03}_{-0.02}) \times 10^{-2} \text{ ccky}$$

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

$$(7.310 \pm 0.024) \text{ keV}$$

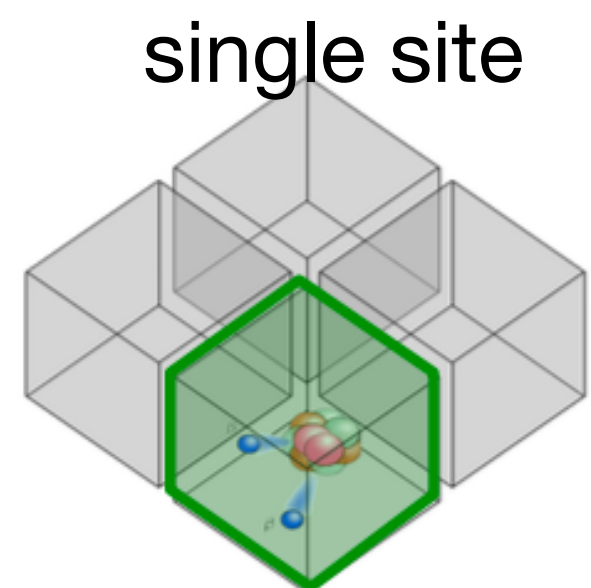
Science 390, 1029-1032 (2025)

CUORE Background model

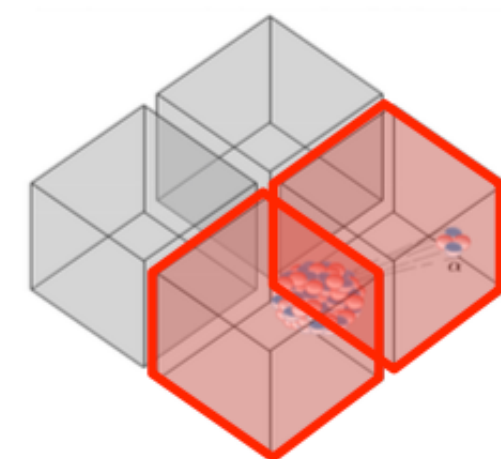


Phys. Rev. D 110, 052003 (2024)

- Reconstruct CUORE continuum background
- GEANT4 simulation with high-fidelity detector geometry
- 62 sources considered
- Post processing to account for detector response (energy response, timing, pileup etc) to produce expected detector spectra
- Exploit coincidences & detector self-shielding to constrain location and particle type of sources
- Bayesian fit to single-site, multi-site, summed multi-site spectra



single site

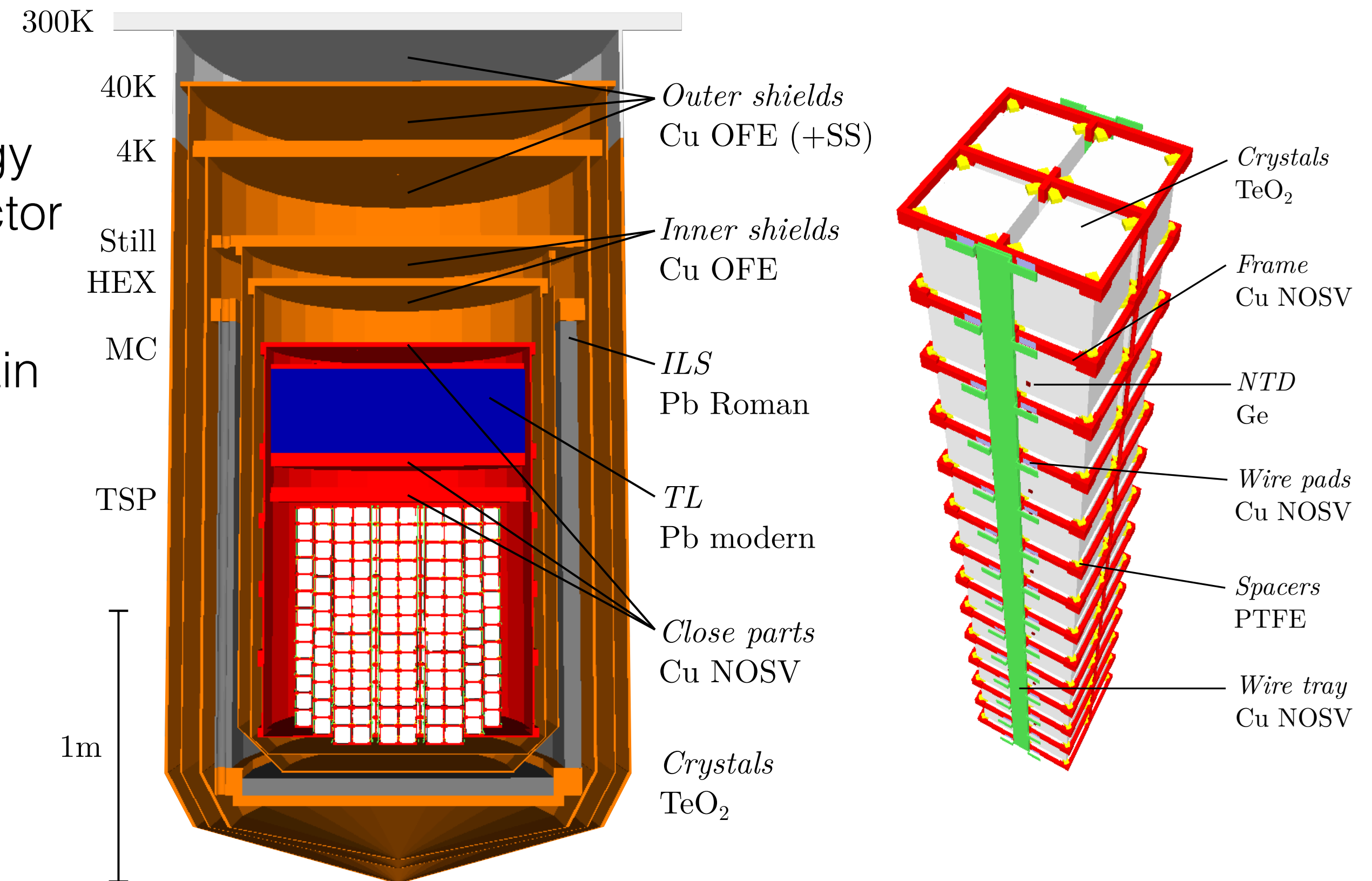


multi site

Surface β/α ,
multi-compton

Bulk β/α , single compton

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“Shields”: cryogenic thermal radiation shields + ionizing radiation shields

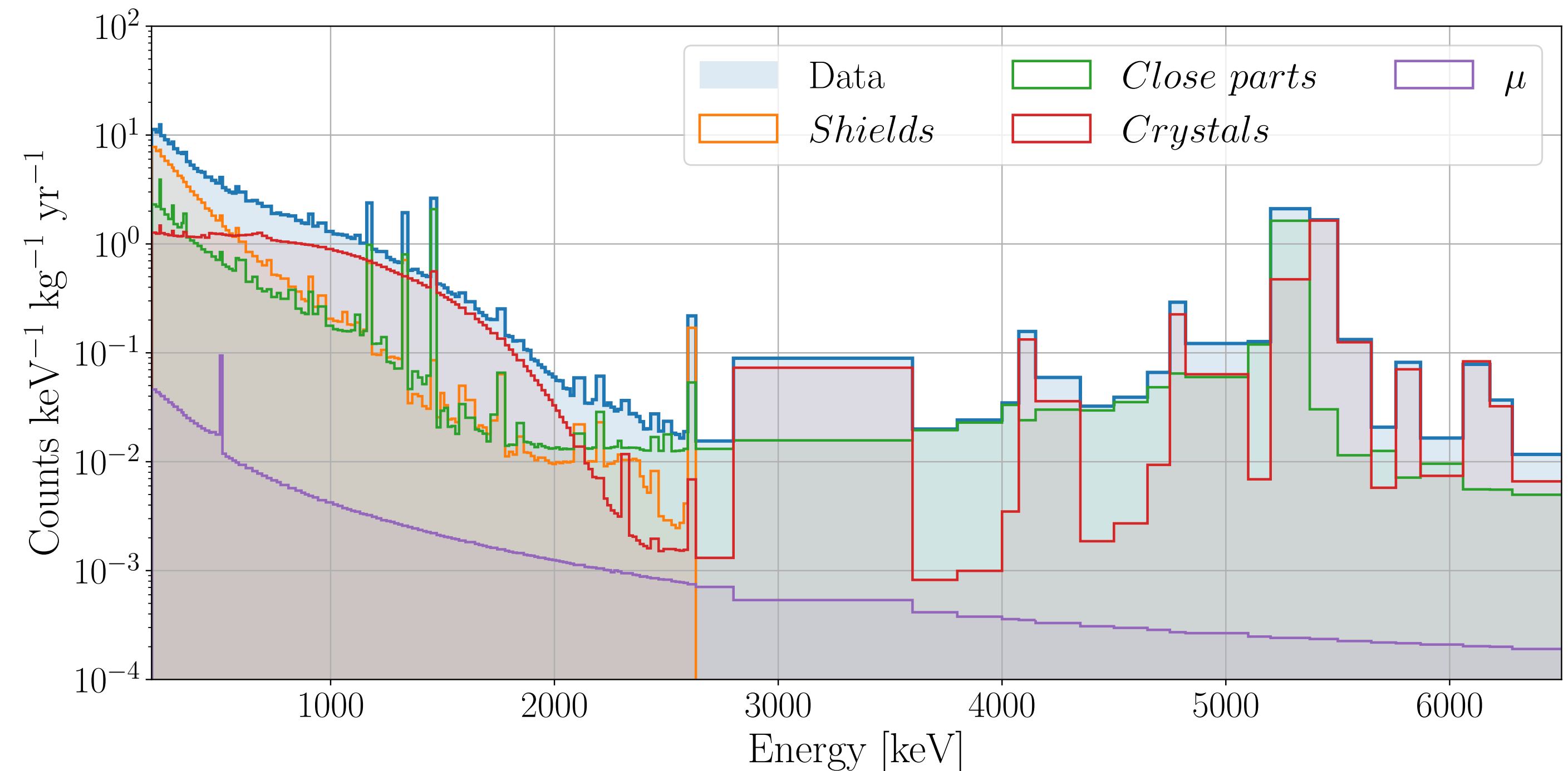
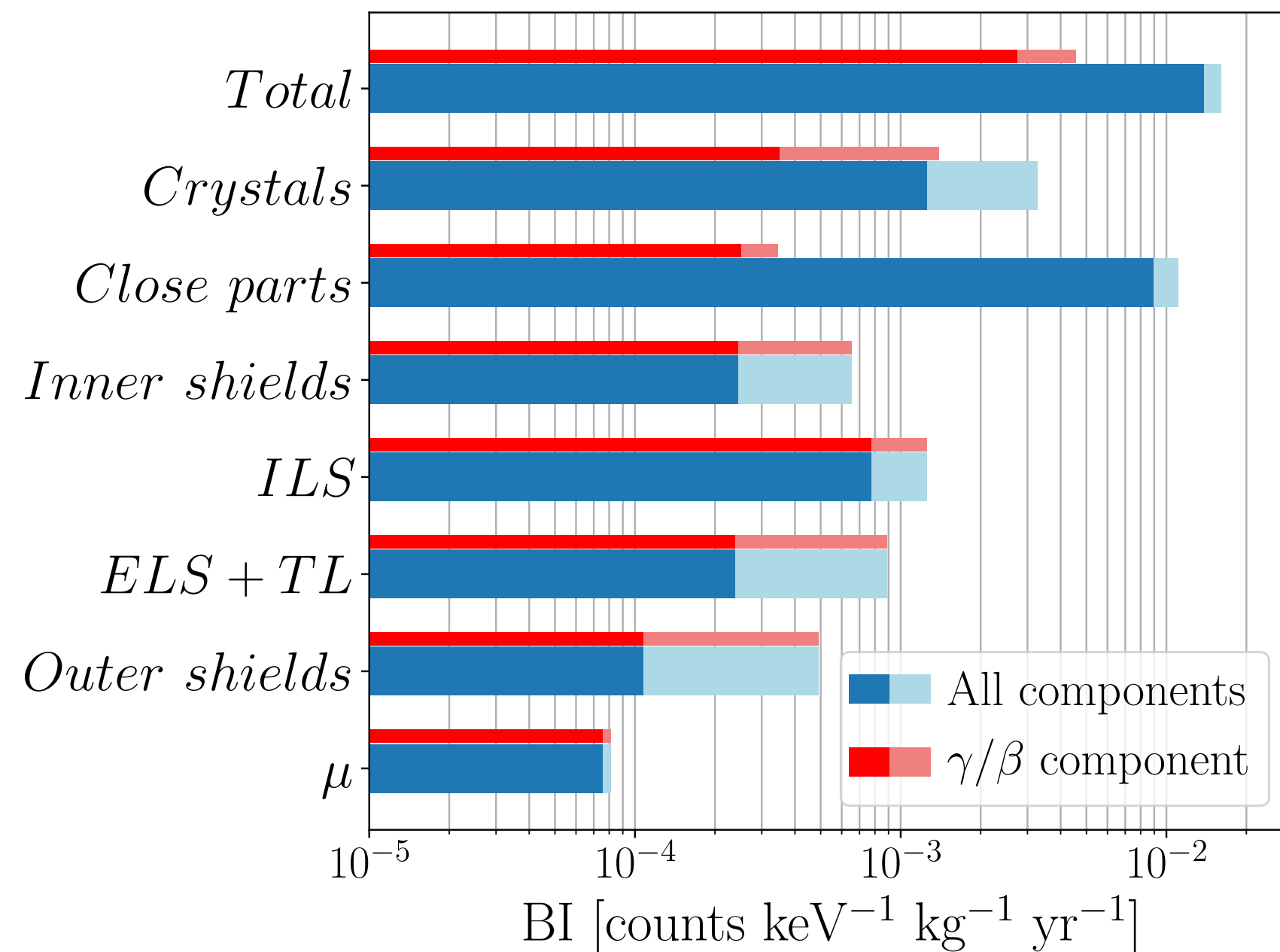
“Close parts”: Cu frames, PTFE spacers, wire trays

CUORE Background model



[Phys. Rev. D 110, 052003 \(2024\)](#)

- Allows sources/locations of background to be characterized, particularly those coming from cryogenic infrastructure vs crystals and holders



- Background from “Close parts” (copper tower frames, PTFE holders etc) is dominated by degraded alphas

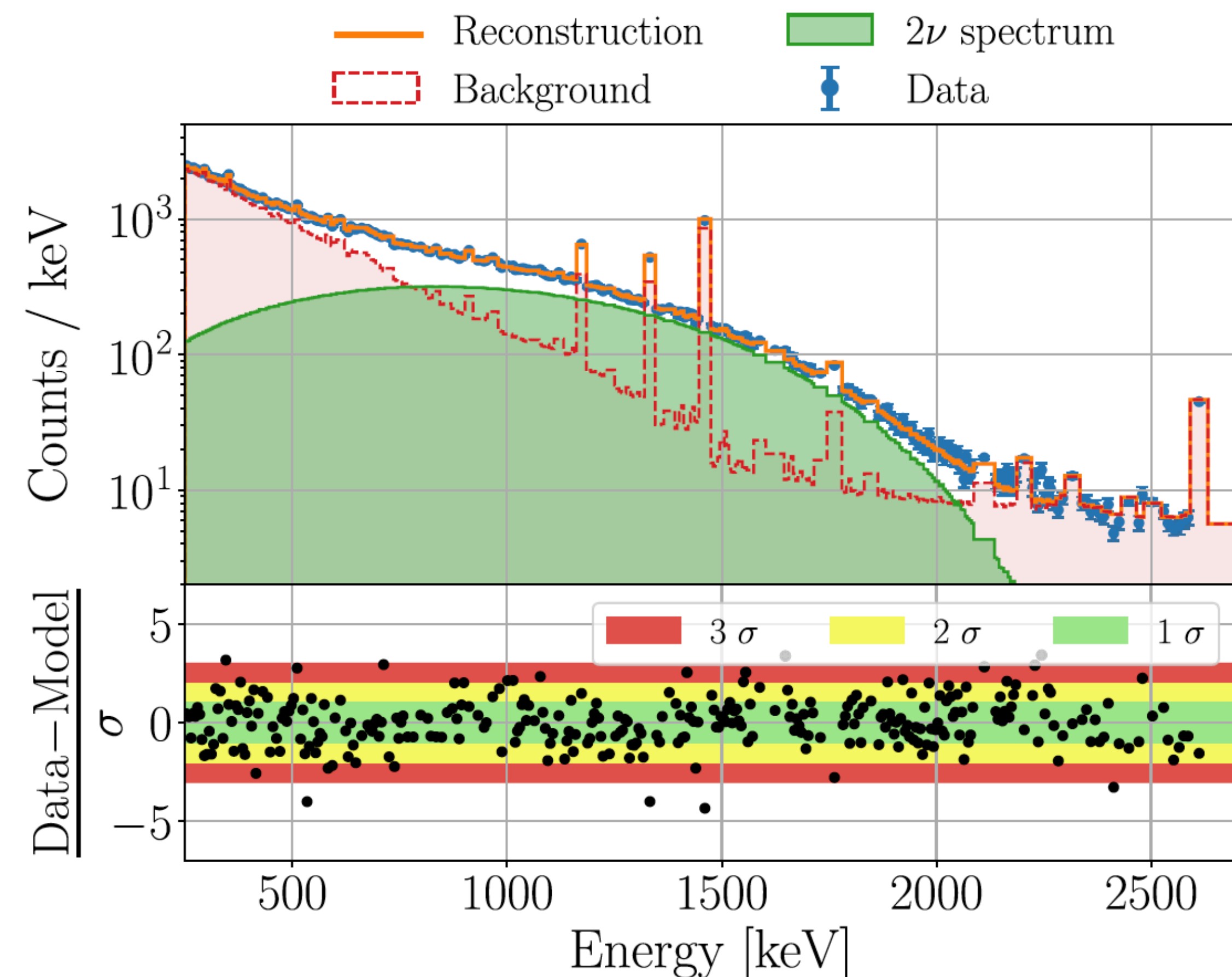
Current ^{130}Te $2\nu\beta\beta$ decay results

- An outcome of the background model is a measurement of the ^{130}Te $2\nu\beta\beta$ decay half-life and investigation of spectral shape

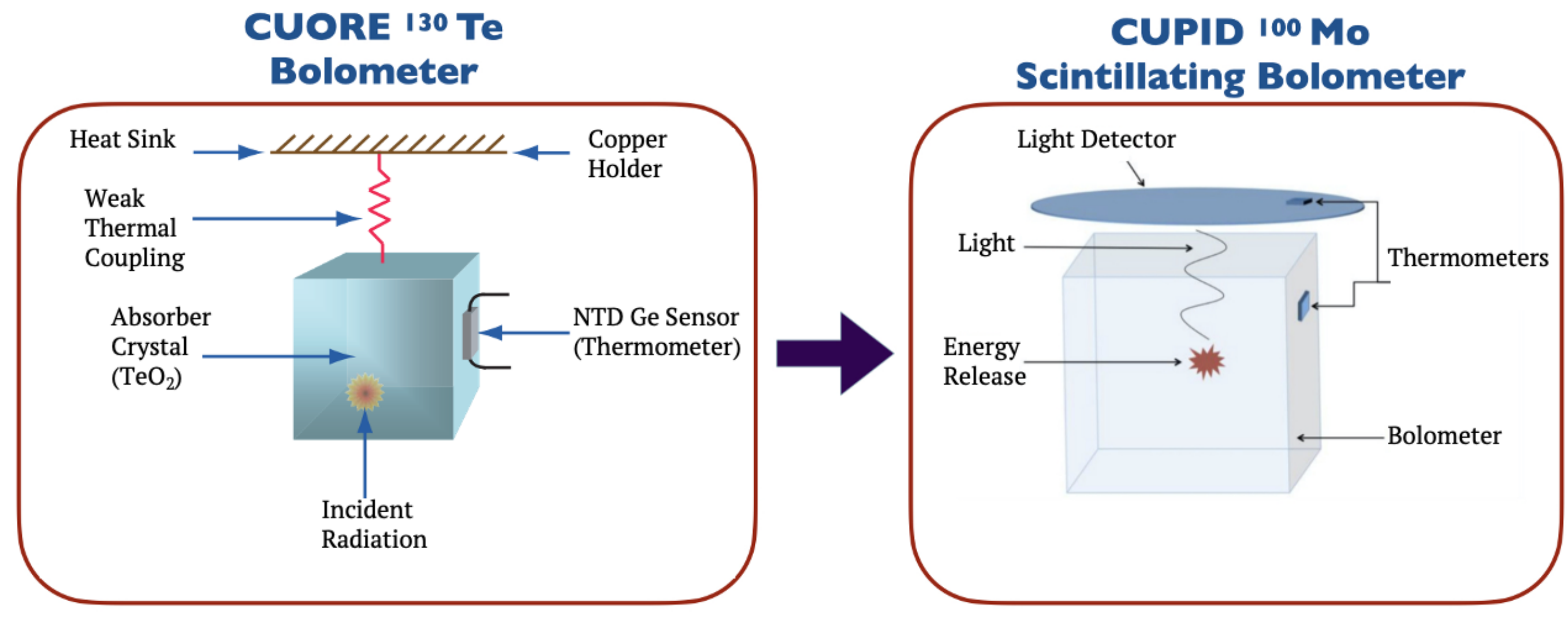
$$T_{1/2}^{2\nu} = \left(9.32_{-0.04}^{+0.05} \text{ stat } {}_{-0.07}^{+0.07} \text{ syst}\right) \times 10^{20} \text{yr}$$

- Most precise measurement of the ^{130}Te $2\nu\beta\beta$ decay half-life
- Data prefer the single state dominance (SSD) spectral shape
- Results from 1038kg-yr TeO_2 exposure (1 tonne-yr data set)

Phys. Rev. Lett. 135, 082501 (2025)



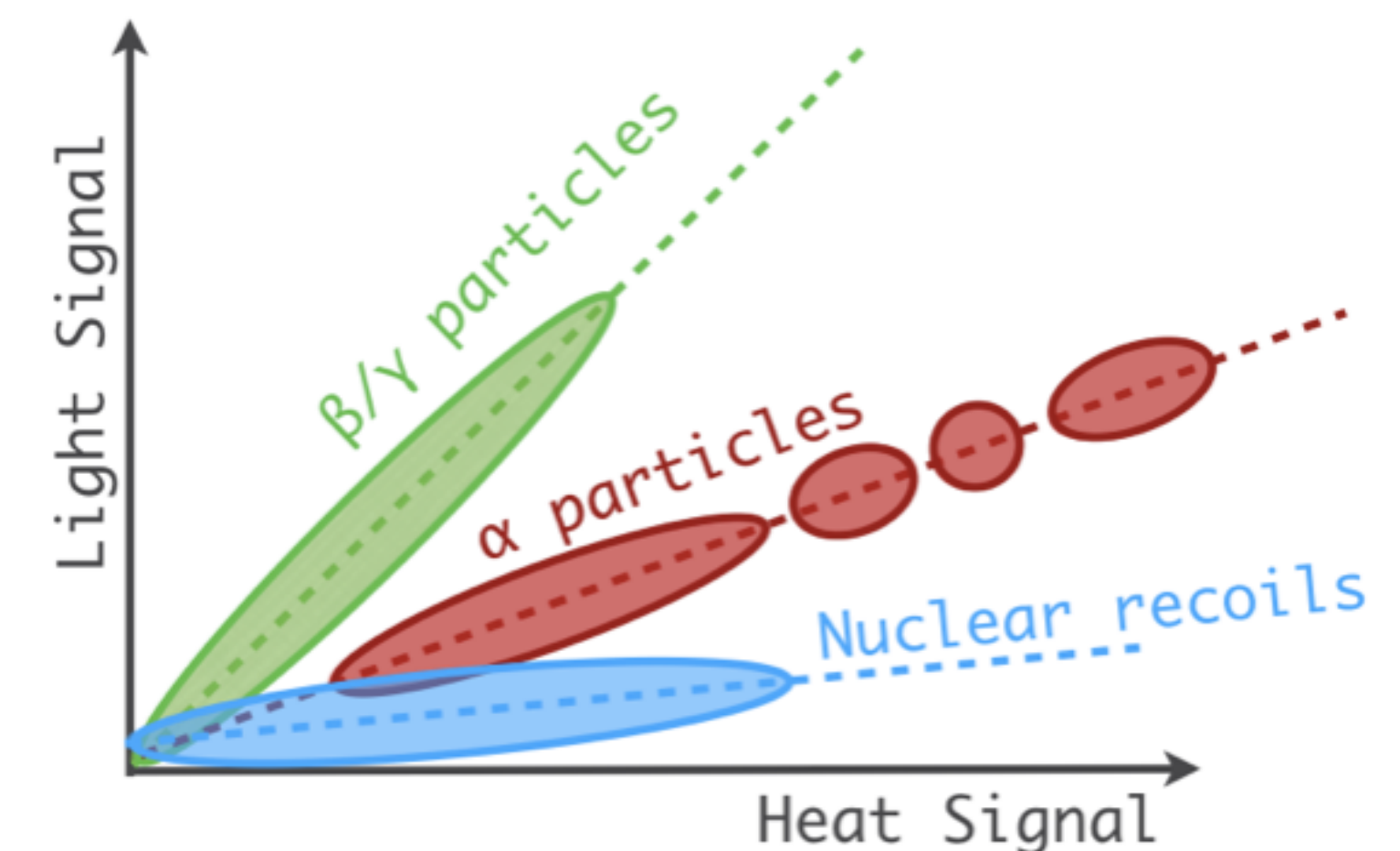
CUPID: CUORE Upgrade with Particle ID



- TeO_2 array will be replaced with scintillating $\text{Li}_2^{100}\text{MoO}_4$ array equipped cryogenic light detectors
- CUPID will reuse the CUORE cryogenic infrastructure
- Backgrounds from this infrastructure are characterized

- $Q_{\beta\beta} = 2527 \text{ keV} < 2615 \text{ keV}$ peak
- Measure only heat
- No particle ID

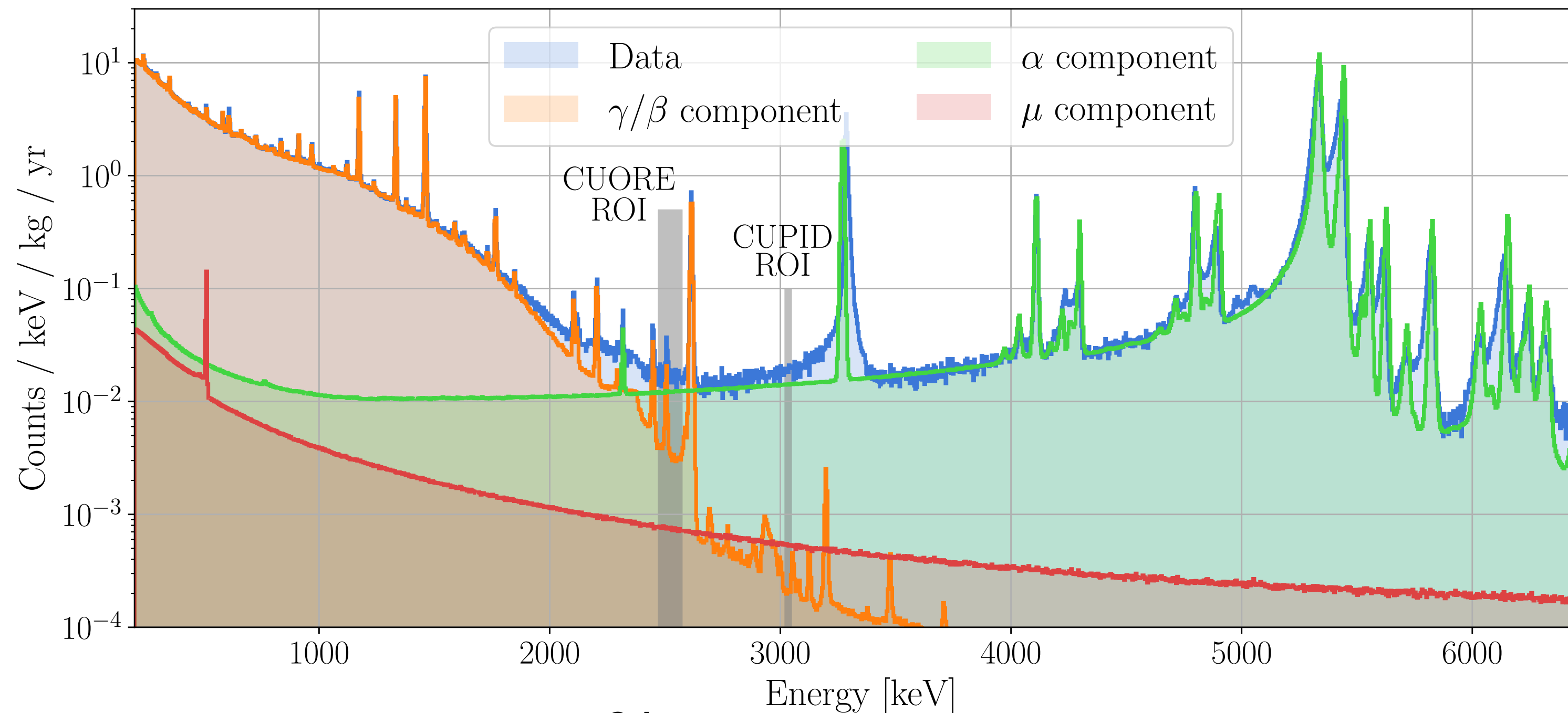
- $Q_{\beta\beta} = 3034 \text{ keV}$: Most β/γ backgrounds reduced
- Measure both heat + light
- Particle ID to actively discriminate α particles



CUPID: CUORE Upgrade with Particle ID



From CUORE background model

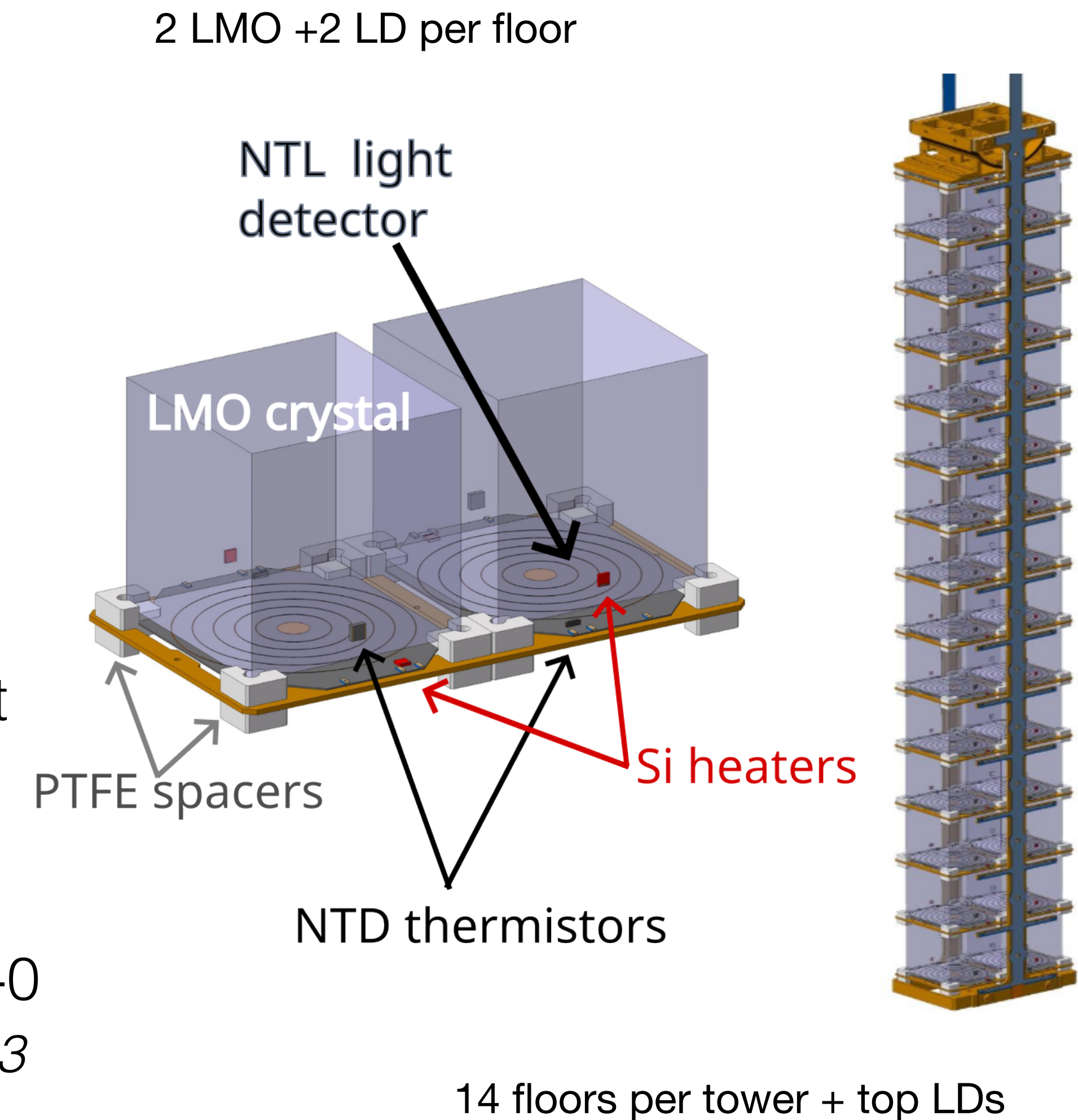


- Higher Q value (3034 keV) reduces β/γ background in CUPID ROI (10x w.r.t CUORE ROI)
- >99.9 % efficiency of α tagging with > 90% β/γ acceptance
- Add muon tagger, increase neutron shield thickness by 10cm and coverage to $\sim 4\pi$
- Optimize design, production, assembly, to minimize background from close parts and active detector elements

CUPID Baseline Design



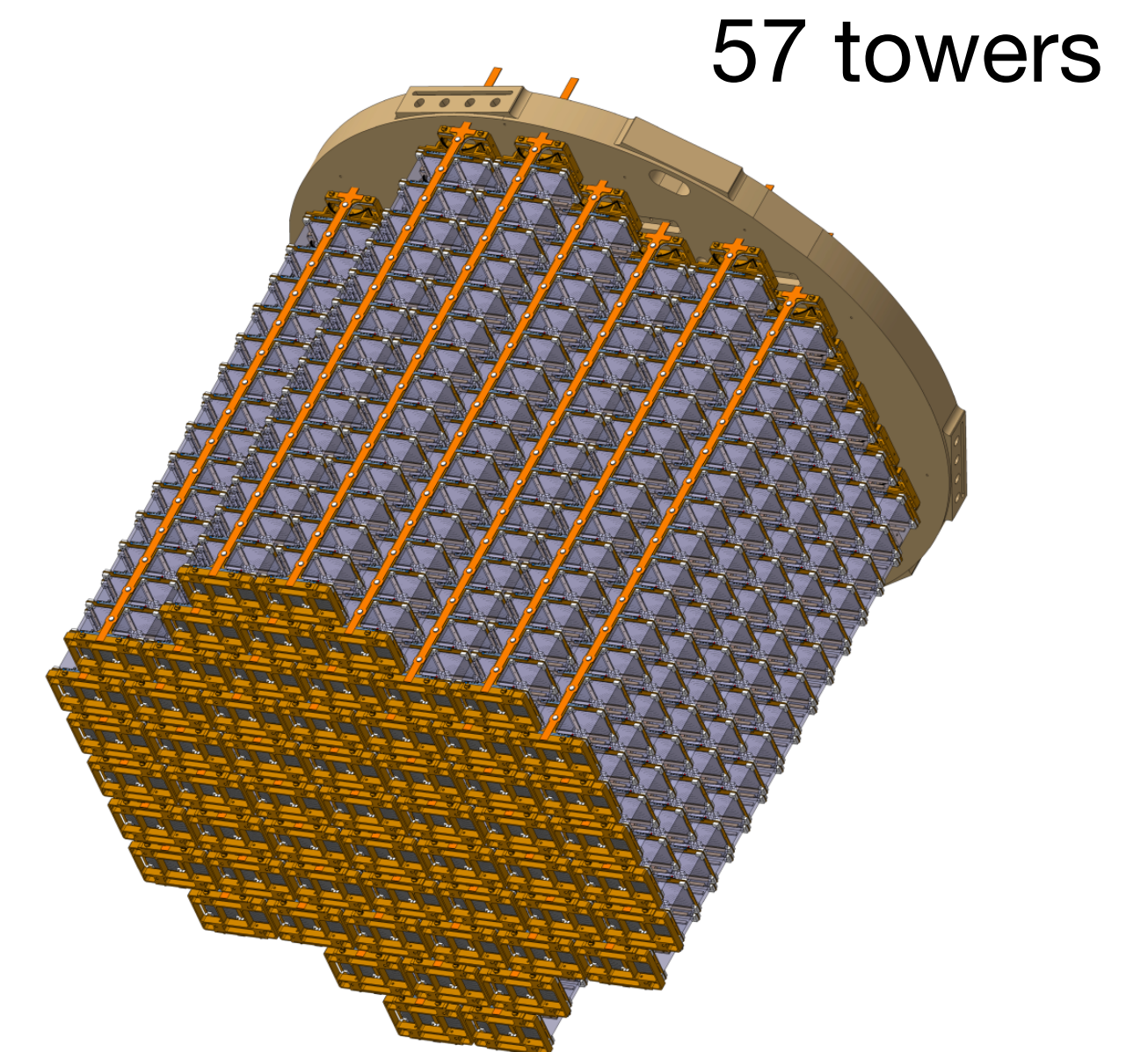
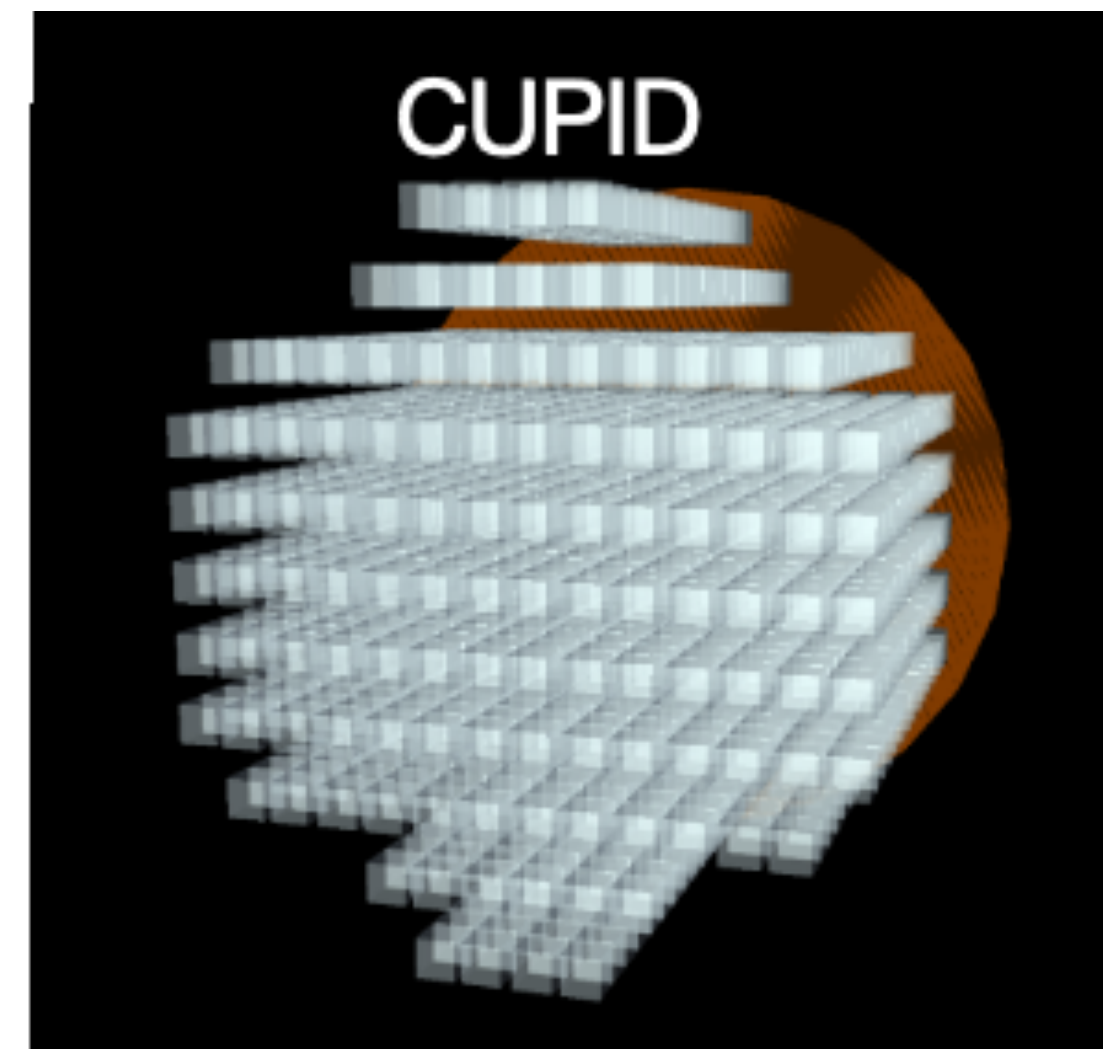
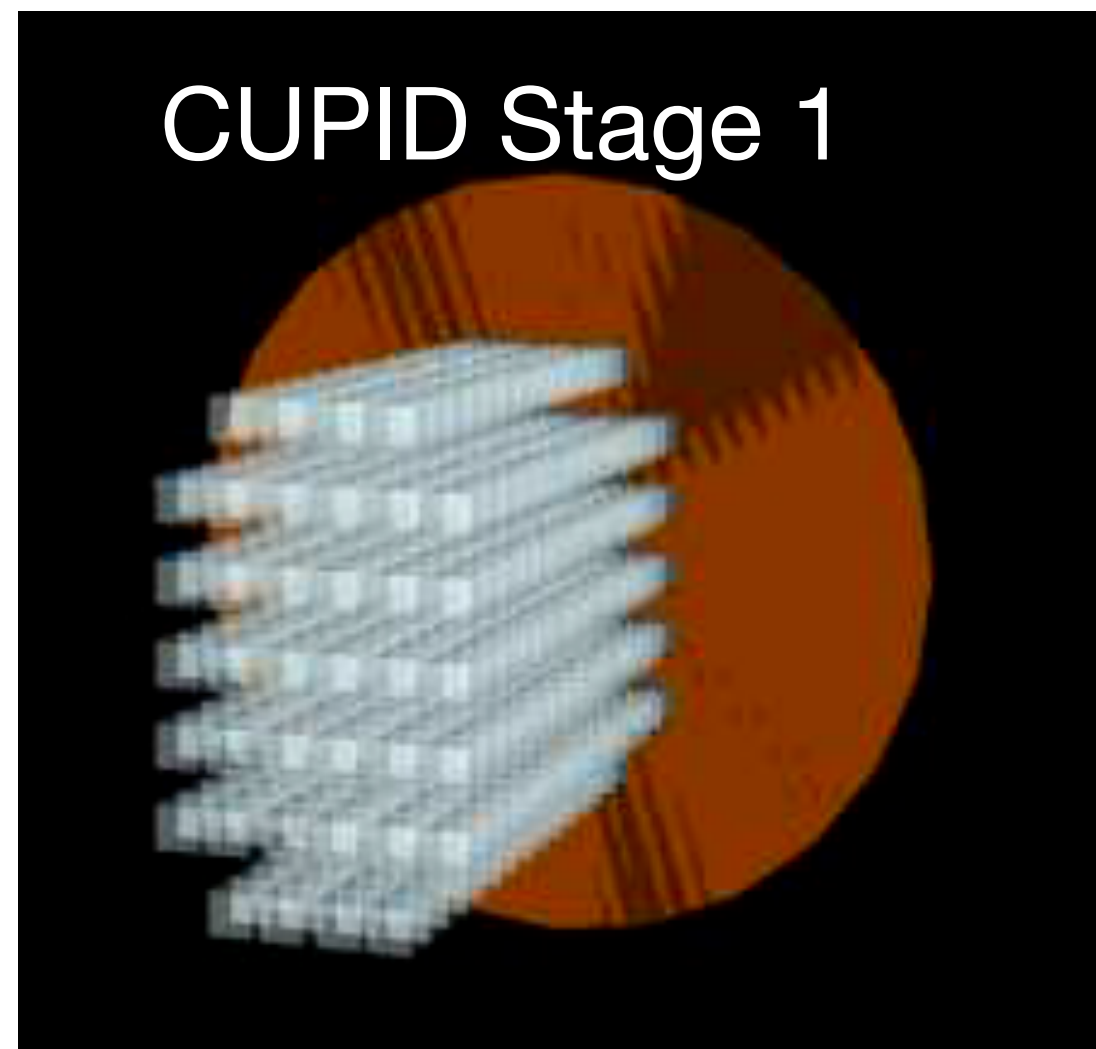
- Array of 1596 $\text{Li}_2^{100}\text{MoO}_4$ (LMO) scintillating crystals
 - ➔ Single crystal dimensions: $45 \times 45 \times 45 \text{ mm}^3$, mass: 280g
 - ➔ Enriched to 95% in ^{100}Mo (from 9.7% natural)
 - ➔ 450kg of LMO $\rightarrow$ 240 kg of ^{100}Mo
- Light readout with Ge wafer secondary calorimeter
 - ➔ Upper and lower light detectors for each LMO (1710 in total)
 - ➔ Signal amplification with Neganov-Trofimov-Luke (NTL) effect
- Open design to allow for coincidence tagging
- Based on experience with CUORE, and demonstrators CUPID-0 (^{82}Se) *PRL* 129, 111801 (2022) and CUPID-Mo(^{100}Mo) *EPJC* 82, 1033 (2022)



CUPID Staged Deployment



- Plan for a staged deployment in CUORE cryostat
 - CUPID Stage 1: 1/3 of full scale, 80 kg 100Mo
 - CUPID (full detector): 240 kg 100Mo

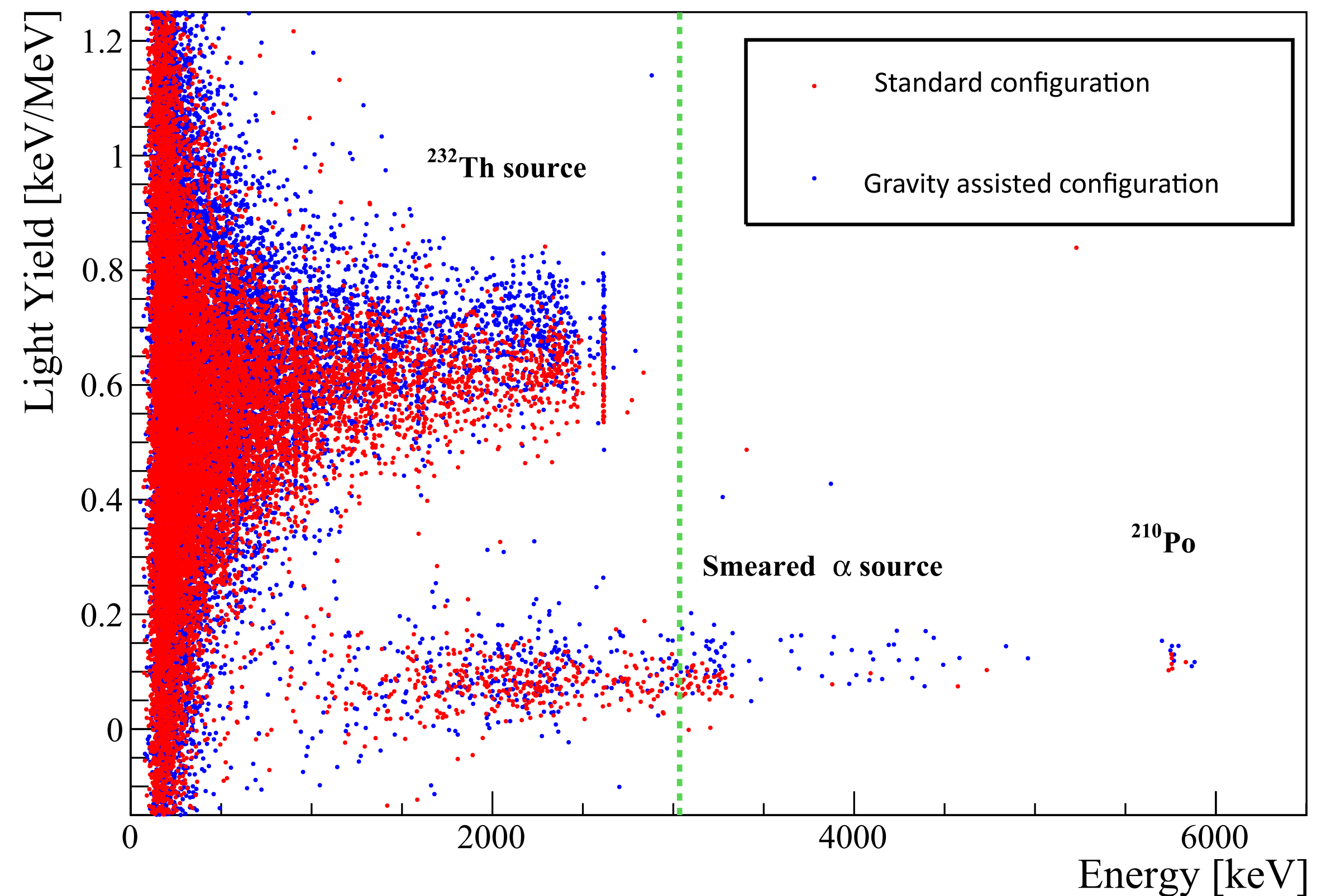
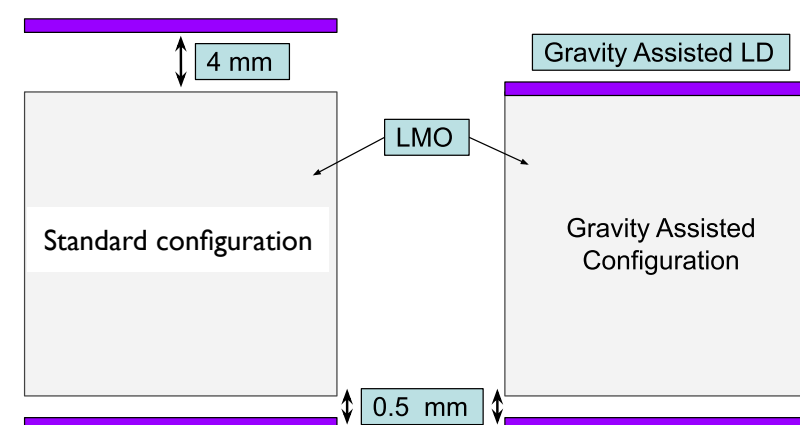
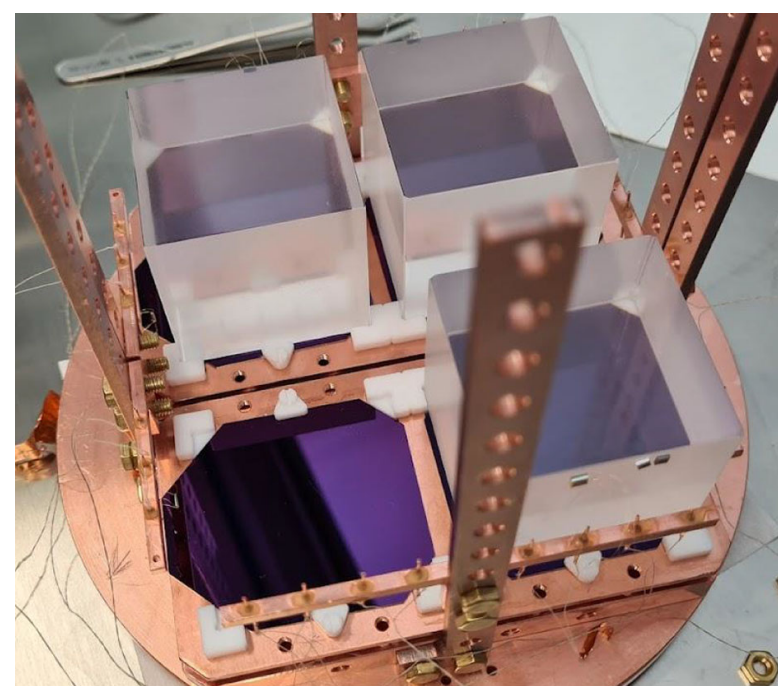


PID Demonstration in Scintillating Bolometers

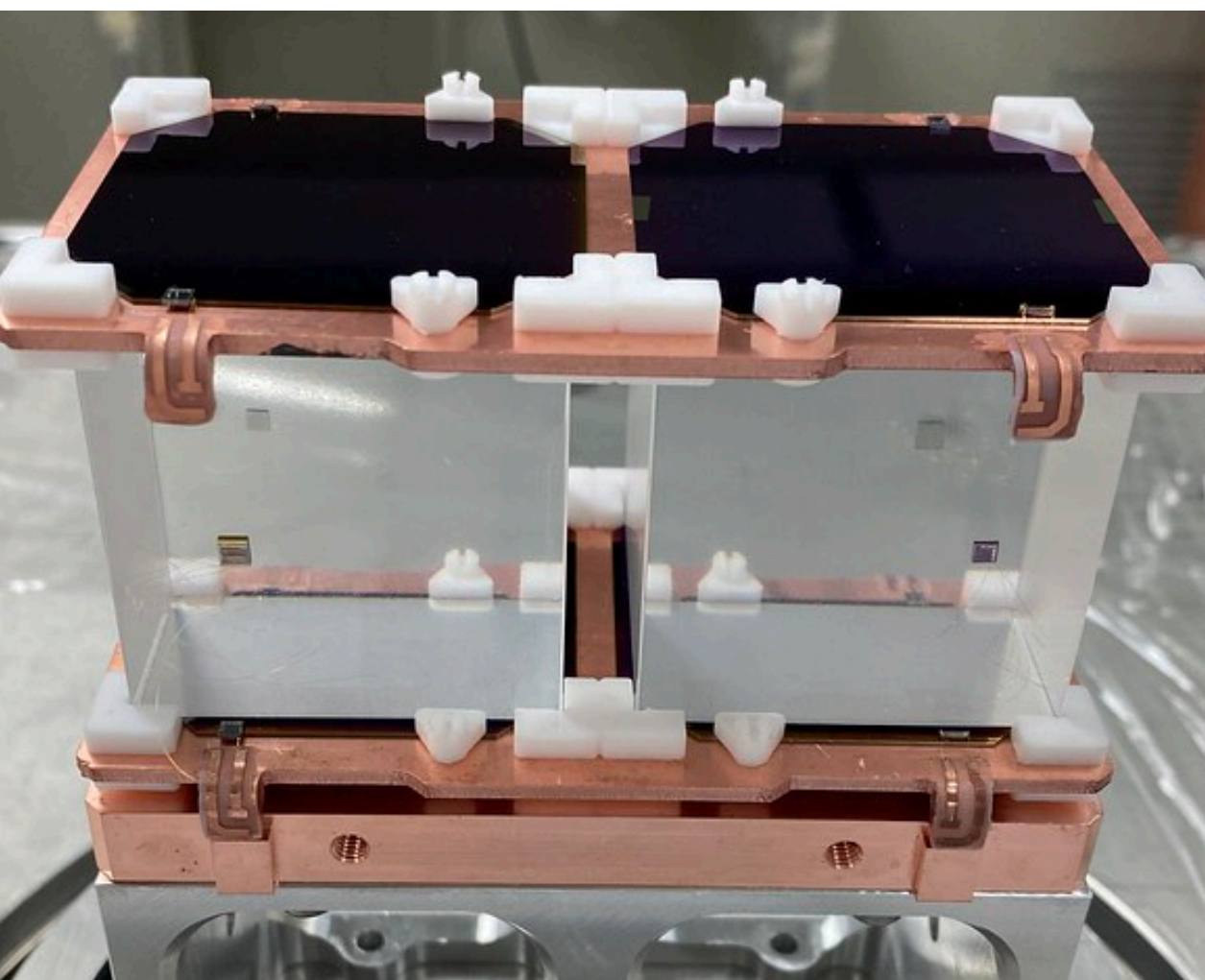
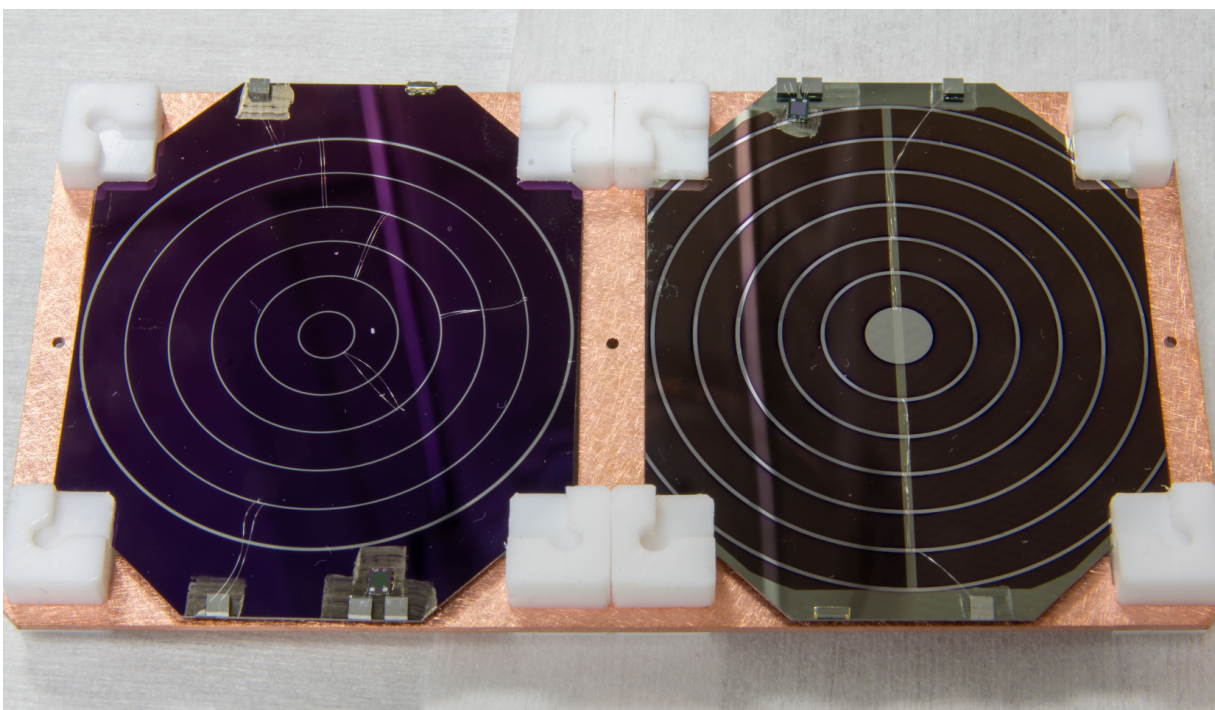


- Test array with CUPID-like geometry, natural LMO crystals operated at LNGS
- Tested with smeared alpha source to produce high-statistics degraded alpha events
- > 99.9% alpha rejection

Eur. Phys. J. C **82**, 810 (2022)

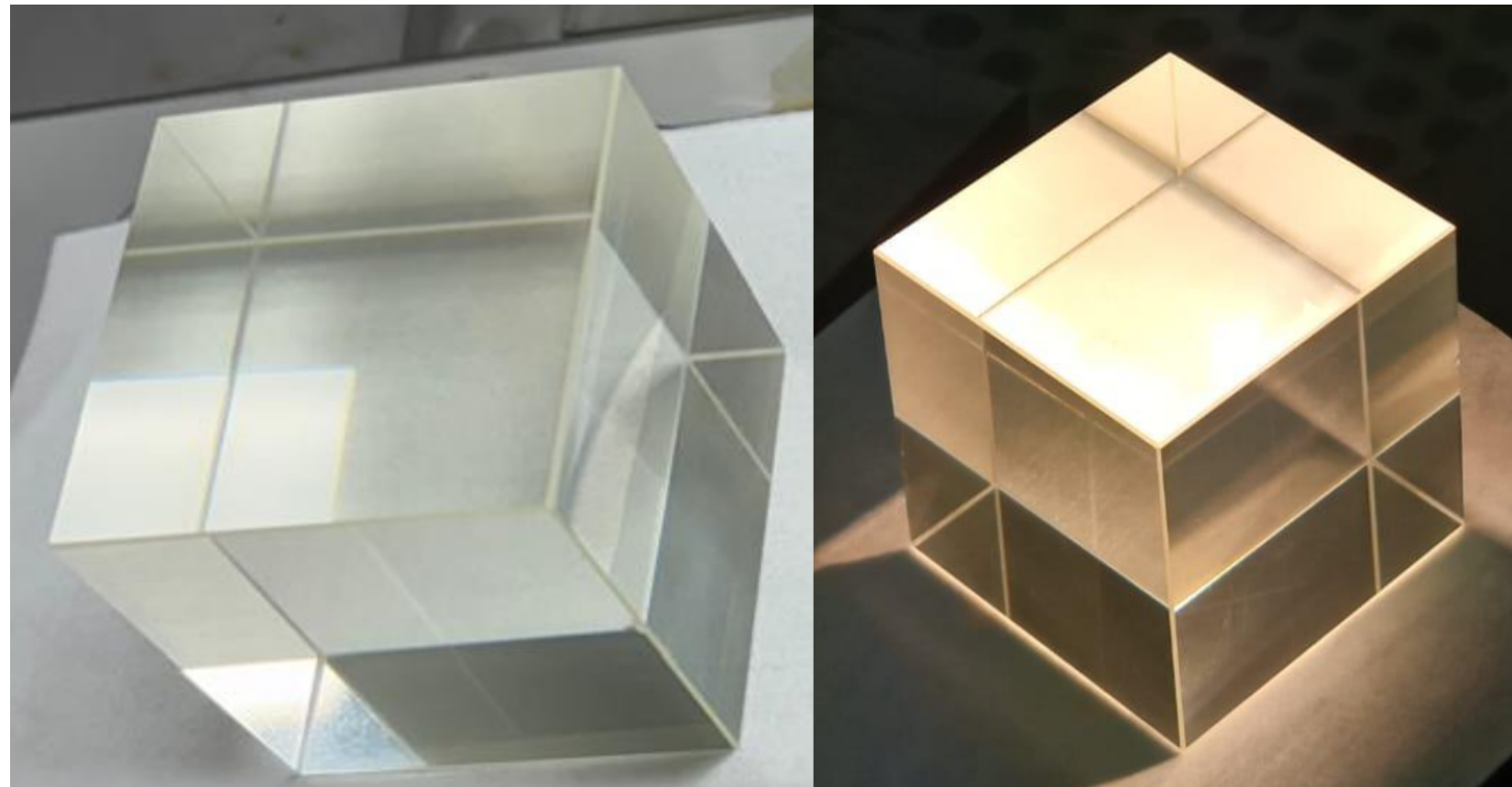


CUPID Prototype Towers at LNGS

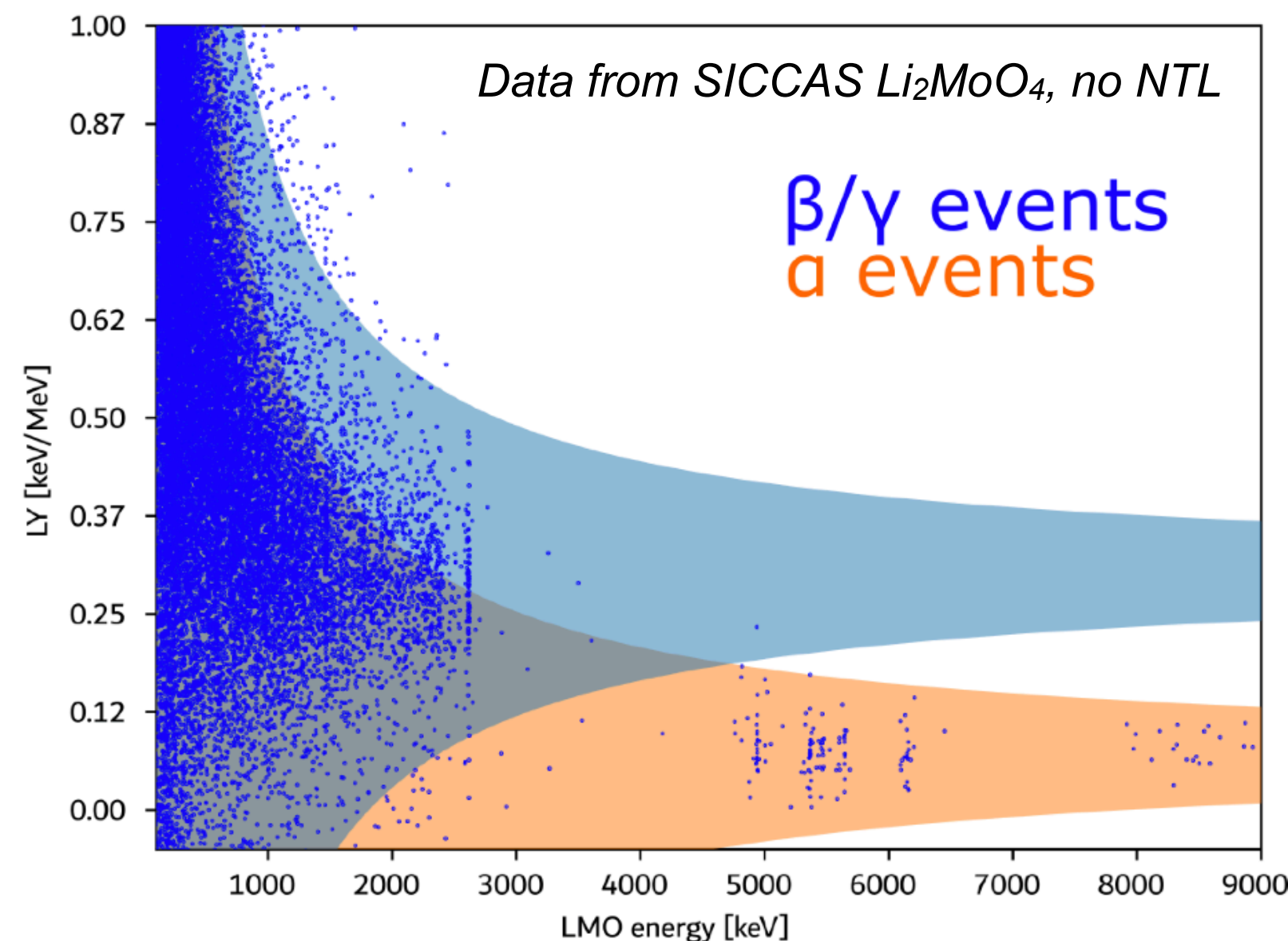


- “Gravity assisted” tower design, reduces inert materials around the crystals compared to CUORE
- Simpler shape for easier clean-machining and cleaning
- First prototype tower cryogenic test
 - ➔ (28 LMO crystals, 30 LDs; no NTL amplification)
 - ➔ Good temperature stability
 - ➔ Average FWHM resolution of LMO at 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 β/γ — α discrimination power

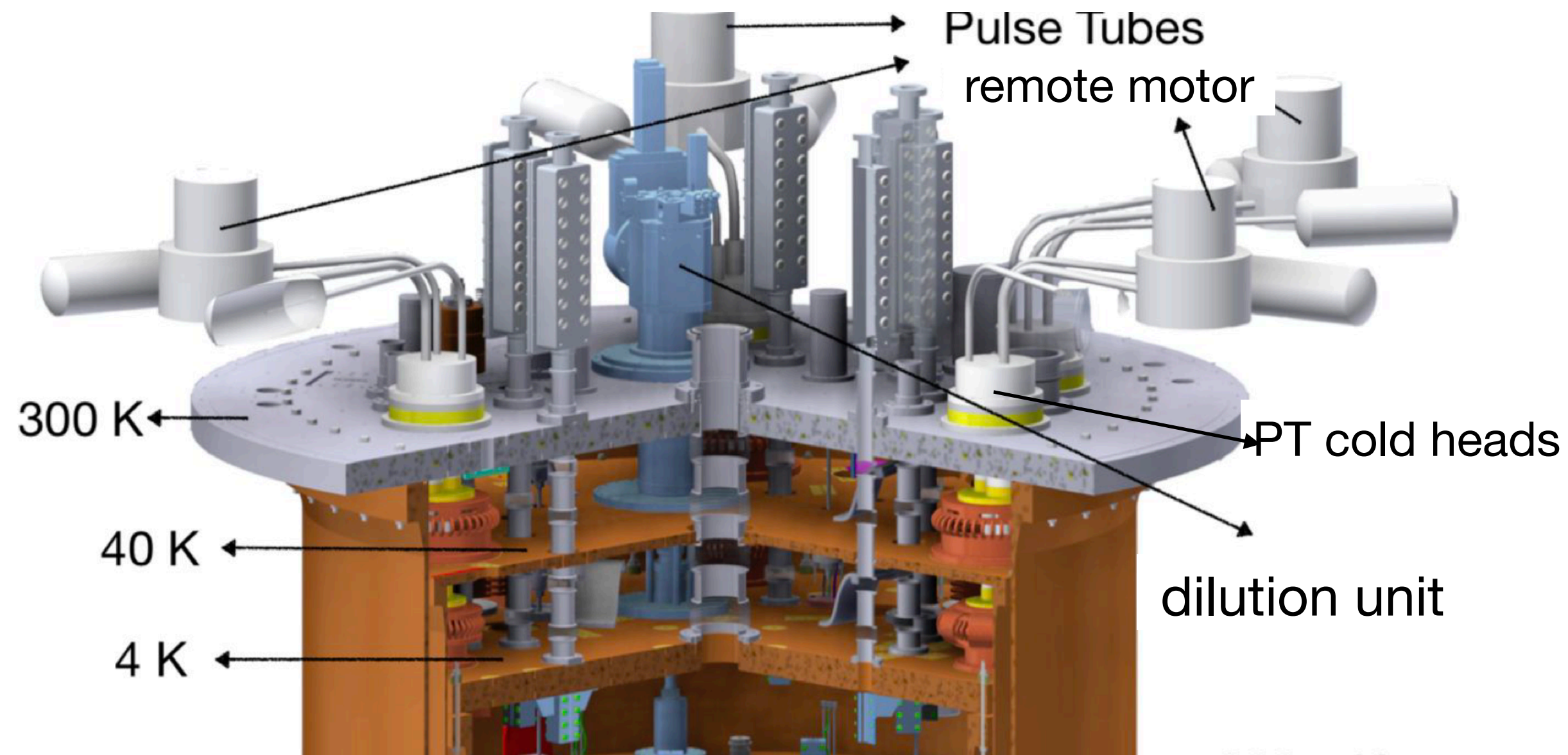
CUPID Enriched Crystal Production



- Test production of 15 enriched LMO crystals for CUPID is currently underway.
- 4.4 kg of enriched molybdenum ($> 95\%$) MoO_3 powder has been produced by IPCE (China)
- Enriched LMO crystals have been grown by SICCAS (China) same producer as 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
- Once in production mode, crystal batches will be tested in bolometer Crystal Validation Runs to monitor radio purity and detector performance



CUPID Infrastructure Upgrades



Cryogenics 154 (2026) 104276

Cryogenics 45 (2005) 9, 626-636

Cryogenics **102**, 9-21 (2019). [arxiv:1904.05745](https://arxiv.org/abs/1904.05745)

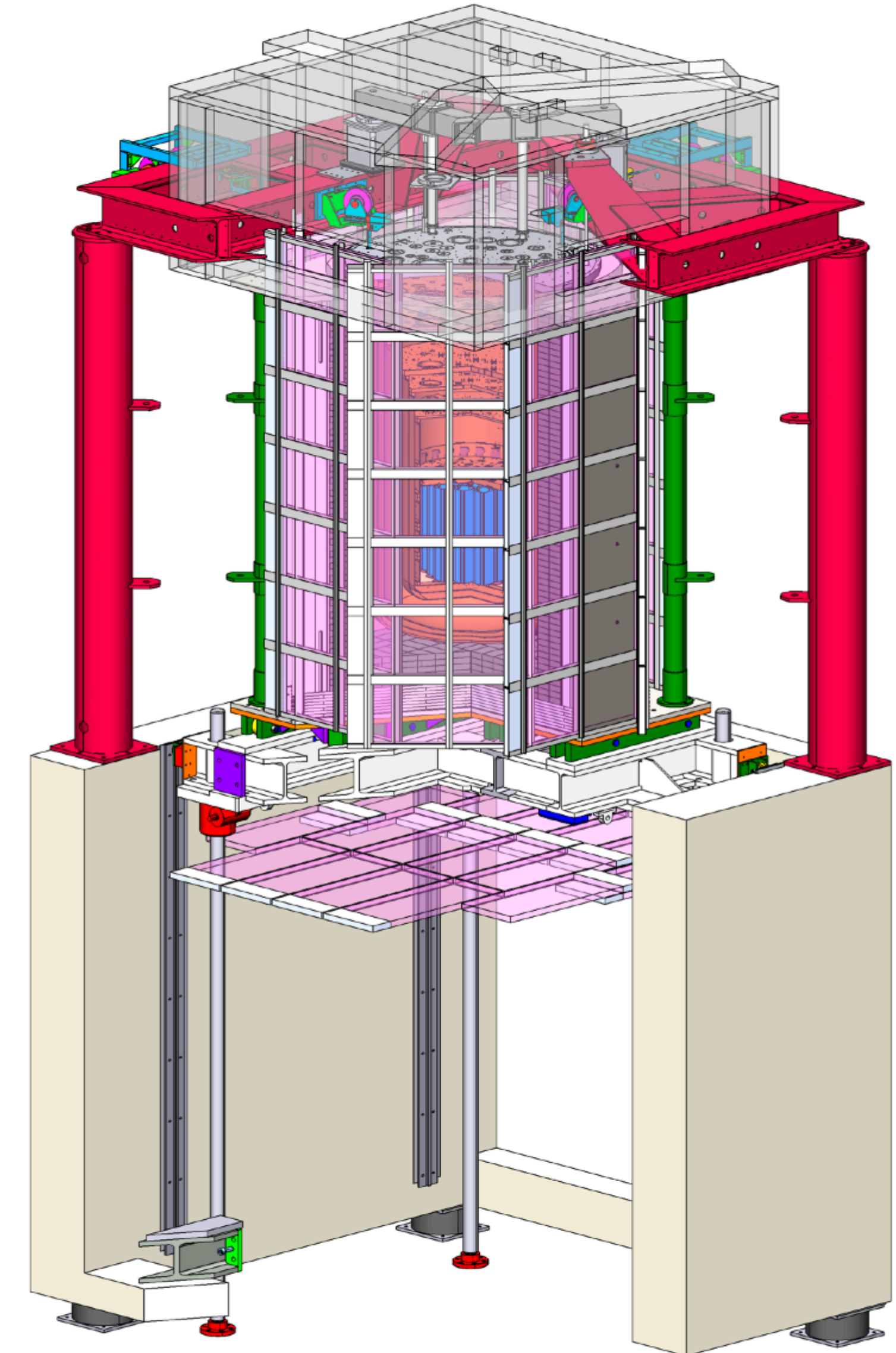
Cryogenics **93**, 56-65 (2018). [arxiv:1712.02753](https://arxiv.org/abs/1712.02753)

- Upgrade the pulse tubes from Cryomech 415-RM to Cryomech 425-RM
 - ➔ Higher cooling power at 4K
 - ➔ Allow to run with 3 PTs +1 spare instead of 4 +1 spare
 - ➔ Easier optimization of remote motor phases
- Add heat switches to reduce heat load from idle PT
- Replace copper braids coupling PT 40K and 4K heads to cryostat with 6N purity Al braids
 - ➔ Higher thermal conductivity in that temperature range
 - ➔ More flexible than Cu braids, reduces mechanical coupling
- ➔ Upgrades are planned for 2027 and data taking with the CUORE array in 2028 to characterize performance

CUPID Infrastructure Upgrades



- Add 10 cm of lateral and bottom polyethylene neutron shielding
- Add bottom and lateral scintillation panels for muon tagging
- Add 20 cm thick water Cherenkov neutron shielding around the top

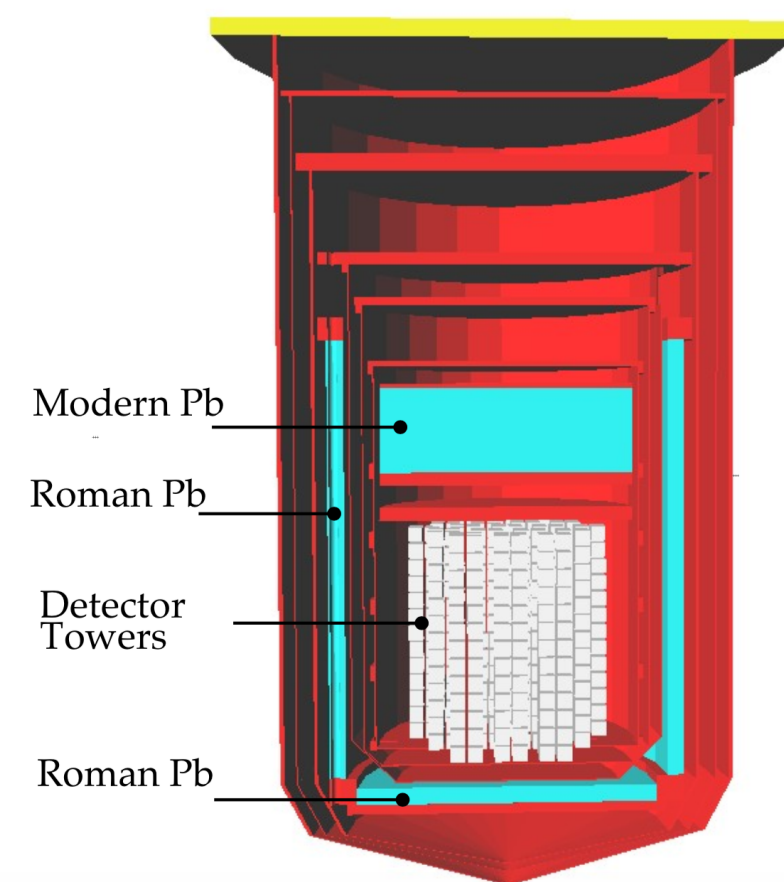


CUPID Background Budget/Projections



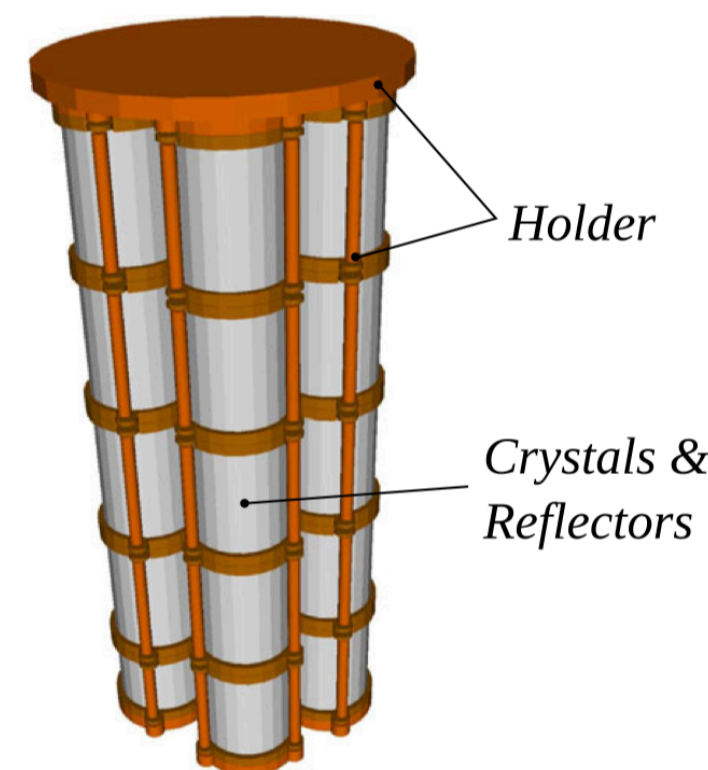
- CUPID background goal is 1×10^{-4} counts/keV/kg/yr
- Projections based on simulations with full detector geometry, data-tested cryostat background model, data-driven assumptions about detector purity, PID performance

CUORE background model



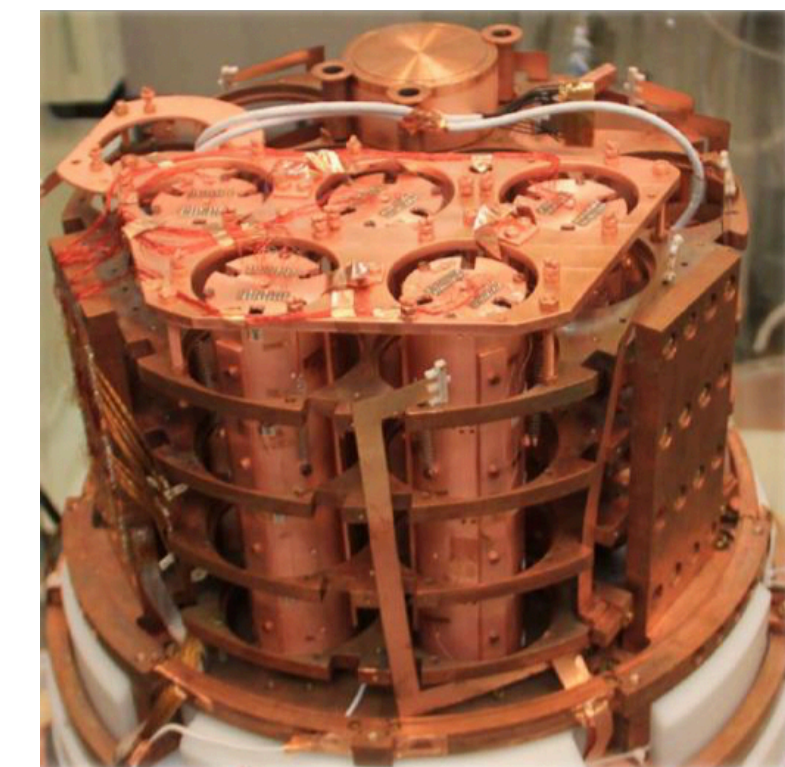
Characterize β/γ background from cryogenic system and detector holders in the 3034 keV ROI

CUPID-0 background model



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

CUPID-Mo Li_2MoO_4 performance



Array of large of highly enriched $\text{Li}_2^{100}\text{MoO}_4$

Data confirms:

- α tagging performance
- Radiopurity of crystals
- Energy resolution

Eur. Phys. J. C 83, 675 (2023), Eur. Phys. J. C 80, 44 (2020)
Eur. Phys. J. C 82, 1033 (2022), Phys. Rev. D 110, 052003 (2024)
Eur. Phys. J. C 79, 583 (2019), Phys. Rev. Lett. 129, 111801 (2022)

CUPID Background Budget/Projections



Assumes muon tagger + additional n shielding

Pileup of two $2\nu\beta\beta$ decays in ROI, assumes timing resolution of NTL light detectors (*JINST* **21** P01035, [arXiv:2606.17948](https://arxiv.org/abs/2606.17948))

Assumes radioactivity measured with CUORE

Assumes LMO radiopurity, PID, from CUPID-Mo

Assumes parts radiopurity measured in CUORE/CUPID-0/CUPID-Mo PID performance measured in CUPID-0/CUPID-Mo

Cryostat and Shields

Crystals

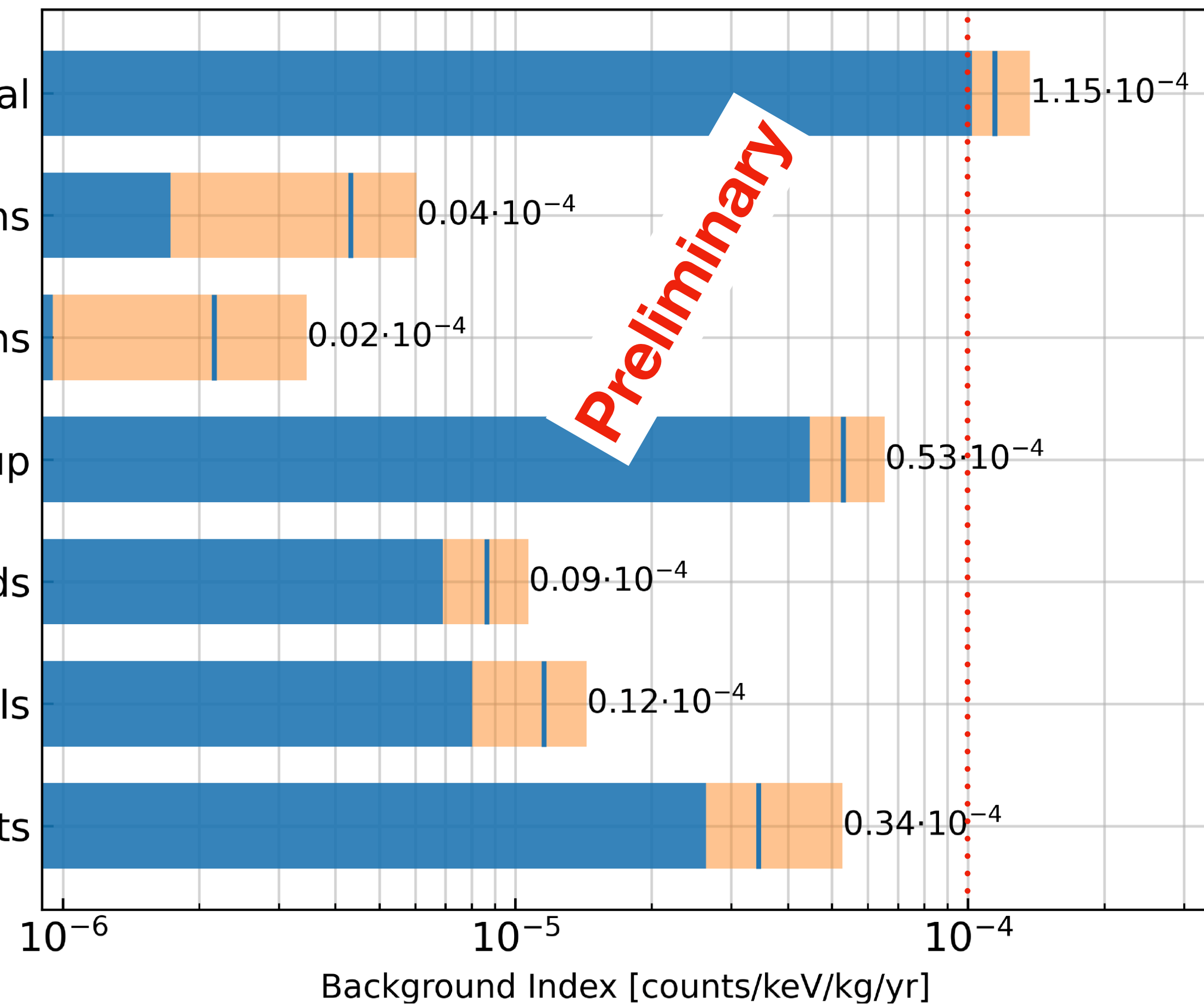
Close Components

Neutrons

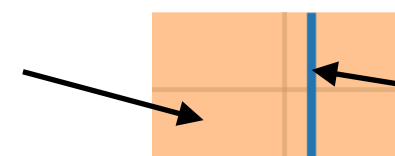
Muons

Pileup

Total



1 σ uncertainty band

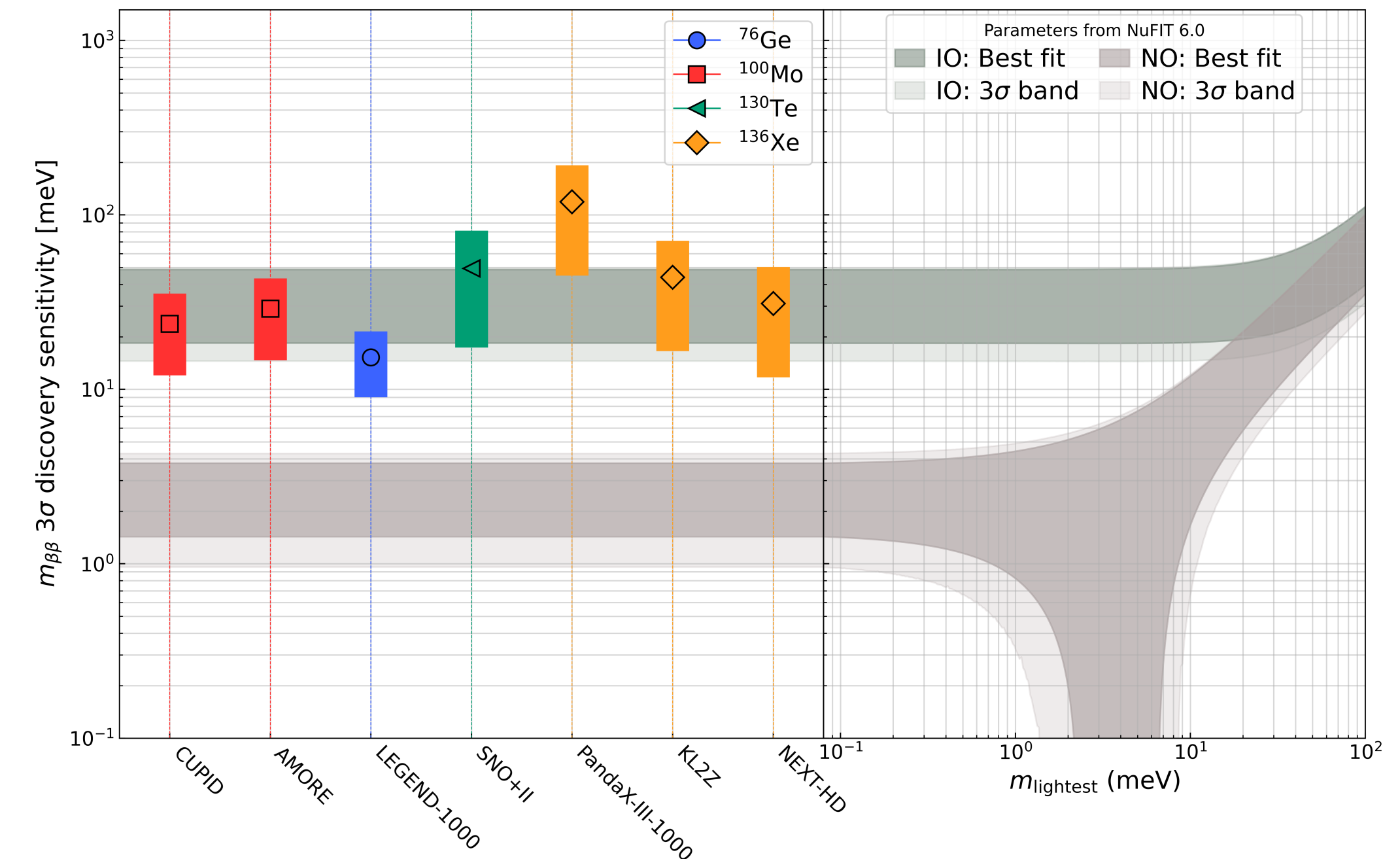


best estimate

CUPID Expected Sensitivity

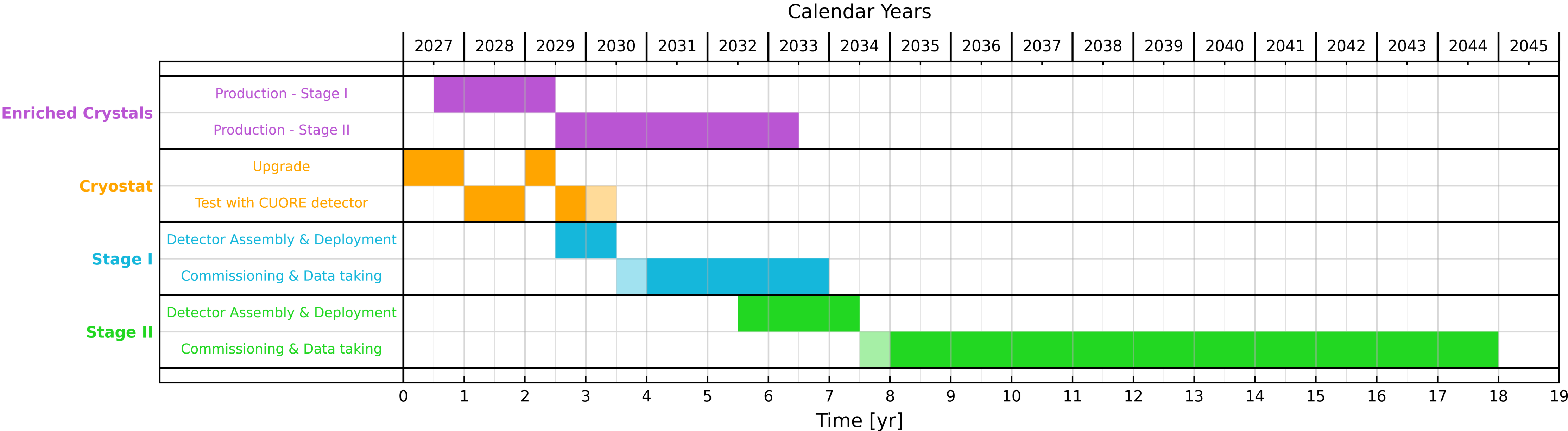
- Assumptions and sensitivity goal

^{100}Mo mass	240 kg
$Q_{\beta\beta}$	3034.4 keV
LMO detector mass	450 kg
Energy resolution FWHM in the ROI	5 keV
Background index	$1 \cdot 10^{-4}$ counts/(keV·kg·yr)
Signal efficiency (Containment×Selection)	77.7% × 86.3%
Livetime	10 yr
$T_{1/2}^{0\nu}$ discovery sensitivity (3σ)	$1 \cdot 10^{27}$ yr

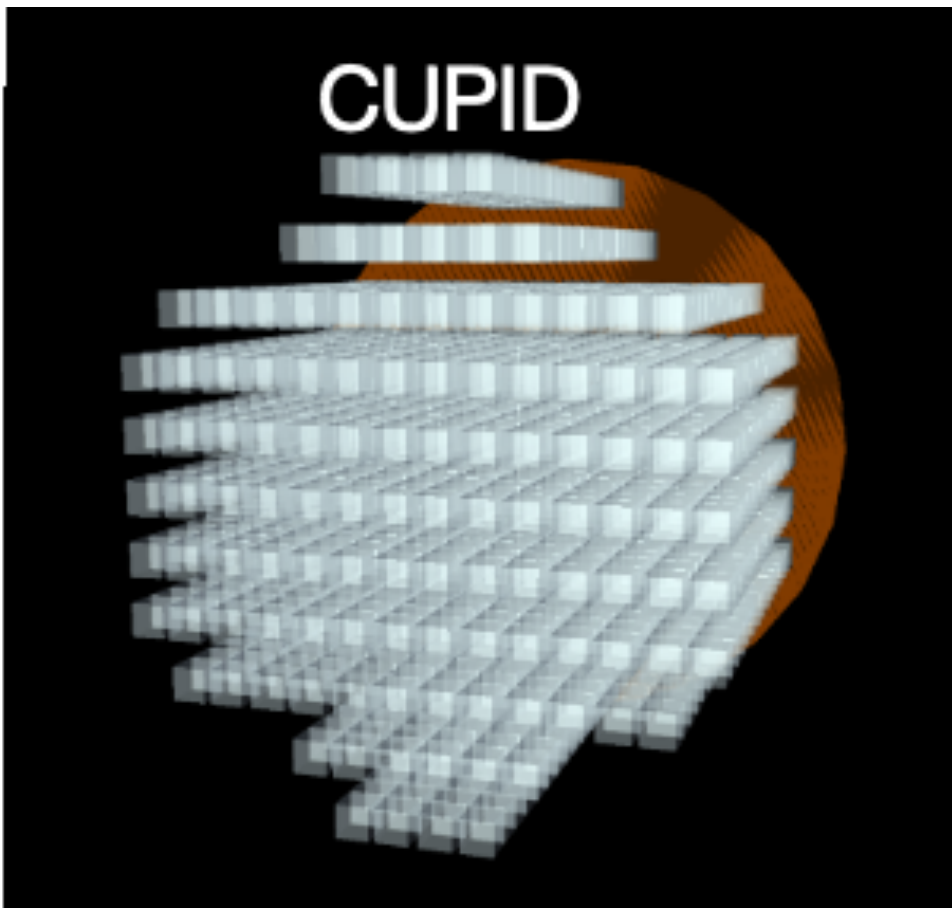
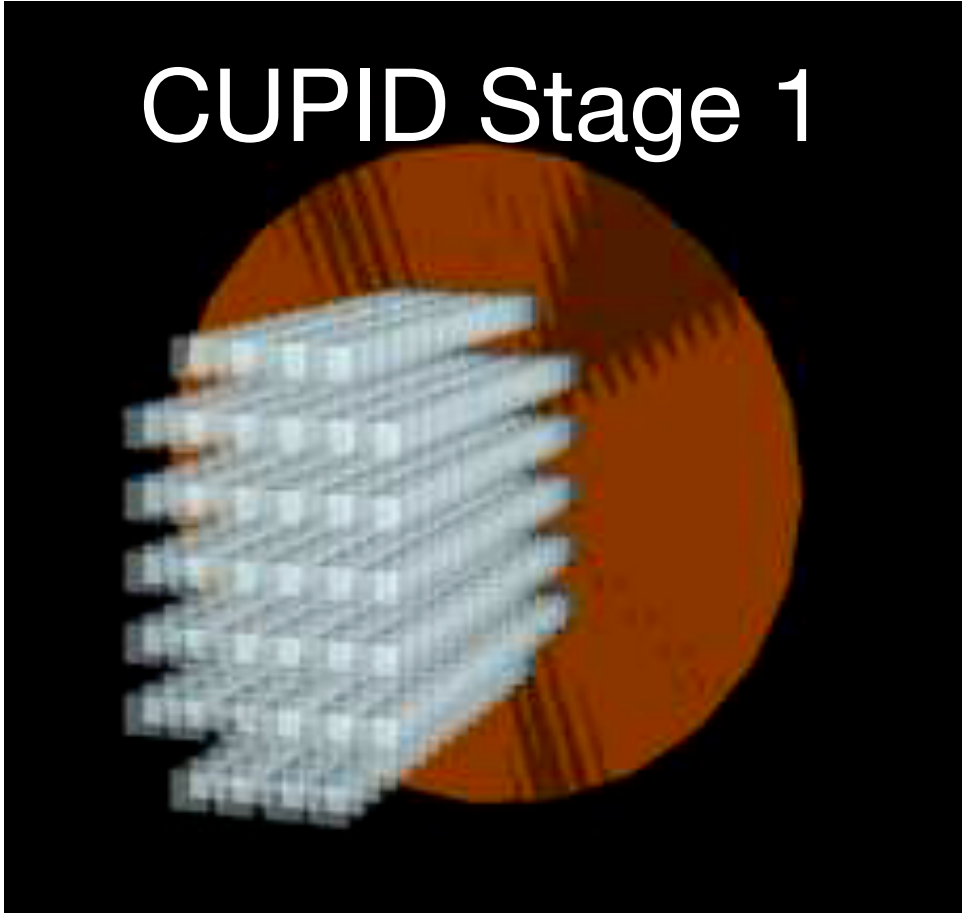


- 3σ discovery sensitivity on $m_{\beta\beta}$: 12 - 35 meV

CUPID Timeline



	CUPID-Stage I	CUPID-Full Detector
BI [10^{-4} counts/(keV·kg·yr)]	1.3	1
Li ₂ MoO ₄ mass	150 kg	450 kg
Live Time	3 yr	10 yr
Resolution	5 keV	5 keV
Containment efficiency	77.7%	77.7%
Signal selection efficiency	86.3%	86.3%
3σ discovery sensitivity ($T_{1/2}^{0\nu}$)	$0.2 \cdot 10^{27}$ yr	$1 \cdot 10^{27}$ yr
3σ discovery sensitivity ($m_{\beta\beta}$)	(27–79) meV	(12–35) meV



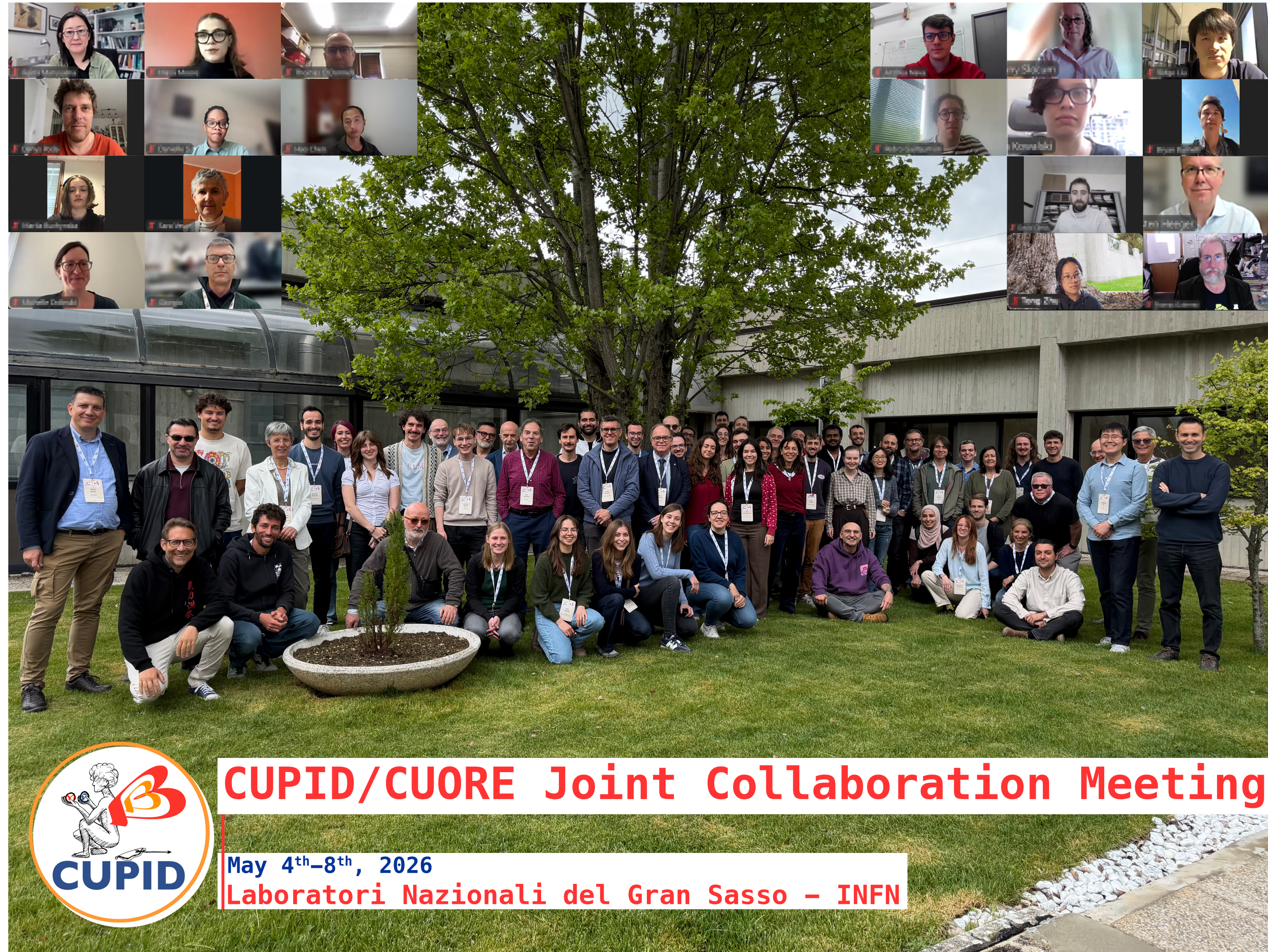


Summary



- CUORE demonstrates the era of tonne-scale cryogenic detectors for double beta decay has started
- CUORE has completed its main physics data taking program and analysis of the 3 tonne-yr dataset is ongoing
- CUPID will exploit the unique cryogenic infrastructure developed for CUORE
- Preparations for CUPID are underway
 - ➔ CUPID Stage 1: aims for 3σ discovery sensitivity on $m_{\beta\beta}$: 27 - 79 meV by 2034
 - ➔ CUPID: aims for 3σ discovery sensitivity on $m_{\beta\beta}$: 12 - 35 meV by 2045
- The planned generation of experiments offer complementary approaches and will probe well into the inverted hierarchy parameter space. This is “uncharted territory” a discovery may be waiting for us !

Acknowledgements



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