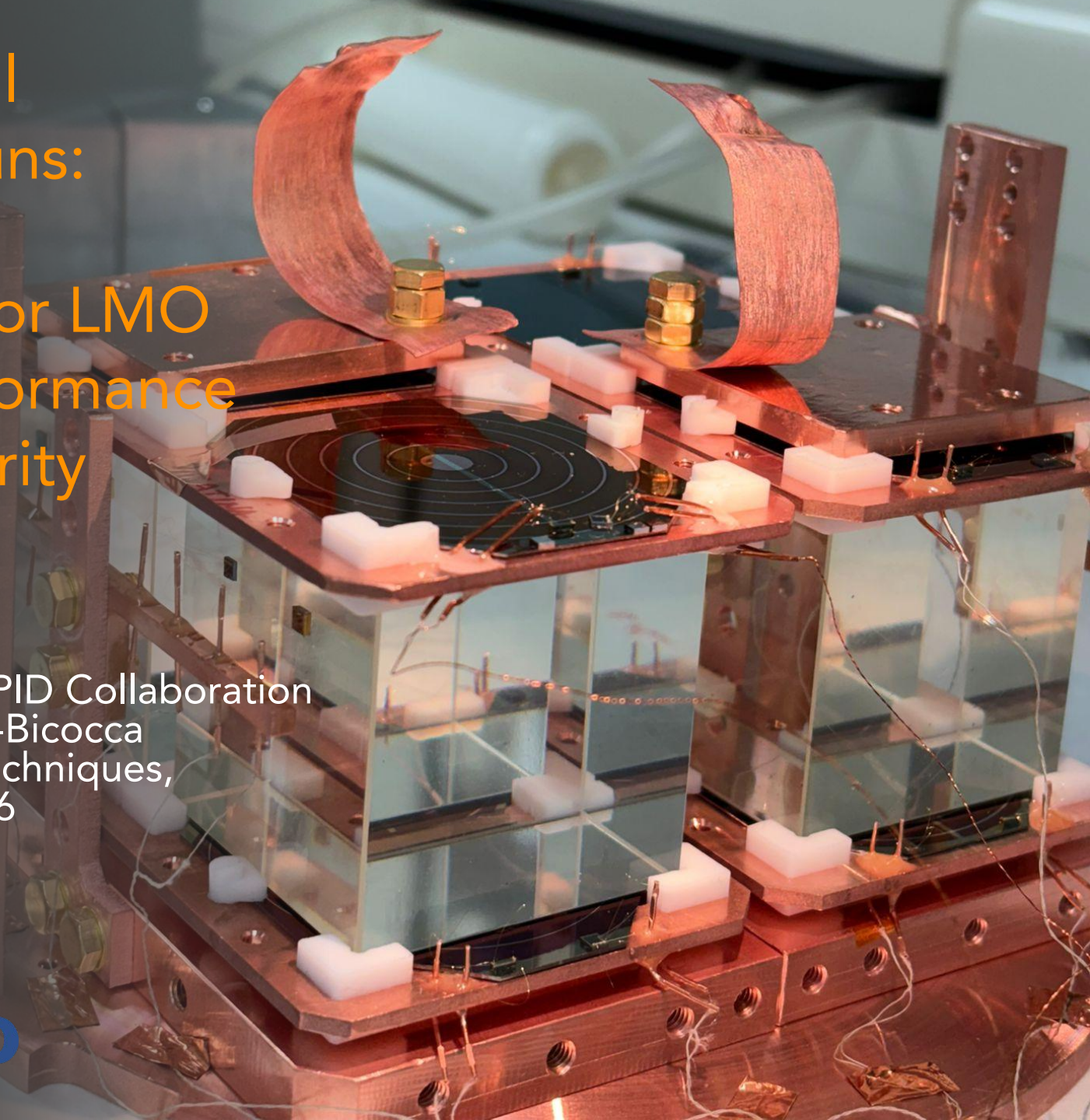


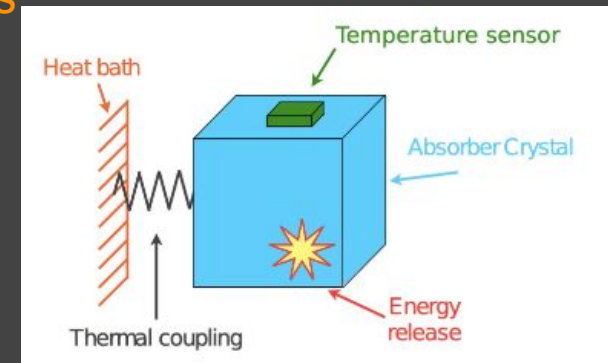
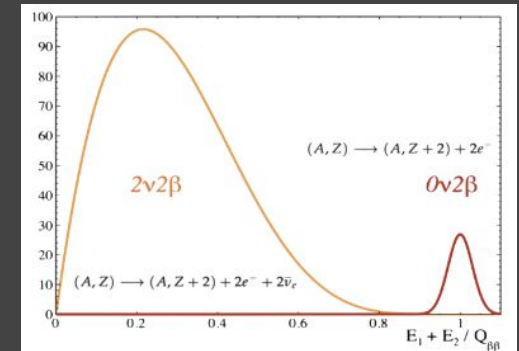
Cupid Crystal Validation Runs: a Systematic Framework for LMO Crystals Performance and Radiopurity Assessment

Tommaso Bradanini
on behalf of the CUPID Collaboration
Università di Milano-Bicocca
Low Radioactivity Techniques,
September 24th 2026



$0\nu\beta\beta$ Decay Search with Cryogenic Calorimeters

- Beyond SM process: lepton-number violation $\Delta L=2$
- Lepton-number violation could provide important input for scenarios explaining the matter–antimatter asymmetry
- Unlike SM allowed $2\nu\beta\beta$, no experimental evidence
[\[Arxiv/2202.01787\]](https://arxiv.org/abs/2202.01787)
- Signature is peak at $Q_{\beta\beta}$ $T_{1/2} > 10^{24} - 10^{26}$ yr
- Cryogenic calorimeters: absorber containing target isotope, decay energy deposit converted into phonons
- Operated at ≈ 10 mK, ΔT measured with sensor (Ge thermistor)
- Excellent energy resolution (FWHM $\approx 0.1\%$ at $Q_{\beta\beta}$) and scalable technology for ton-scale experiments
- Slow detectors, timescale ≈ 1 s



$0\nu\beta\beta$ Sensitivity and Background Reduction

Experimental sensitivity to $0\nu\beta\beta$ can be expressed as:

$$S_{0\nu} \propto \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$$

With Background in the $0\nu\beta\beta$ ROI

$$S_{0\nu} \propto M \cdot T$$

Zero Background case

ΔE = energy resolution at $Q_{\beta\beta}$

M = detector active mass

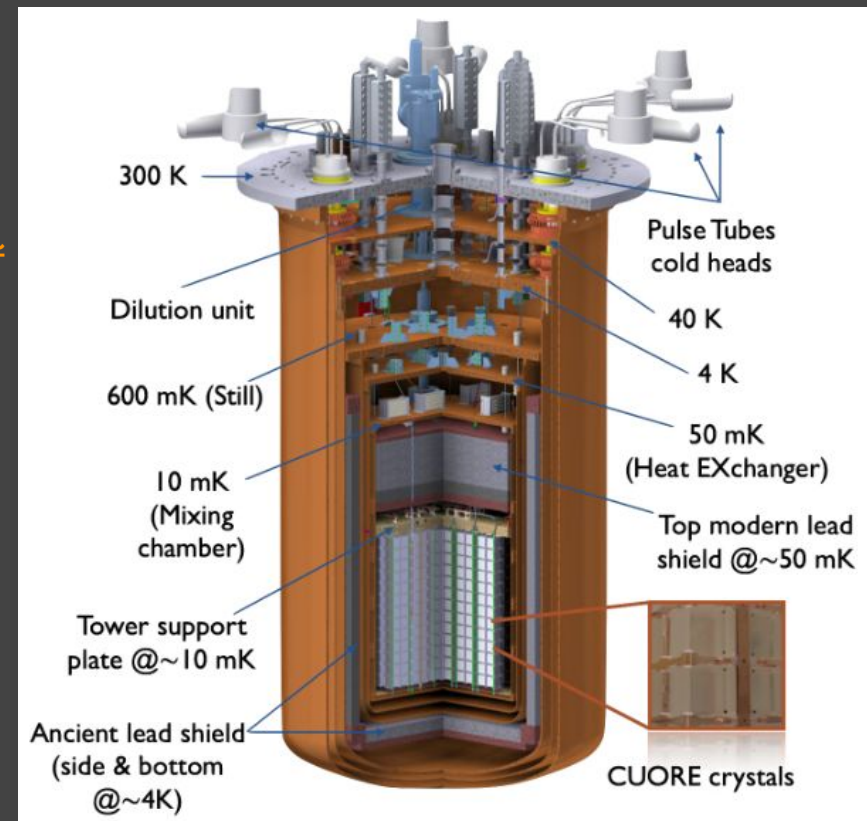
b = Background in the ROI of $Q_{\beta\beta}$

T = total live time

Minimization of background crucial to maximize the experiment sensitivity!

The CUORE experiment

- Located in **Laboratori Nazionali del Gran Sasso (LNGS, Italy)** u.g. facility (≈ 3400 *m.w.e*)
- Designed for search of $0\nu\beta\beta$ in ^{130}Te ($Q_{\beta\beta} = 2528$ *keV*), 988 TeO_2 crystals
- End of physics program in 2026 after 8 years of continuous operation



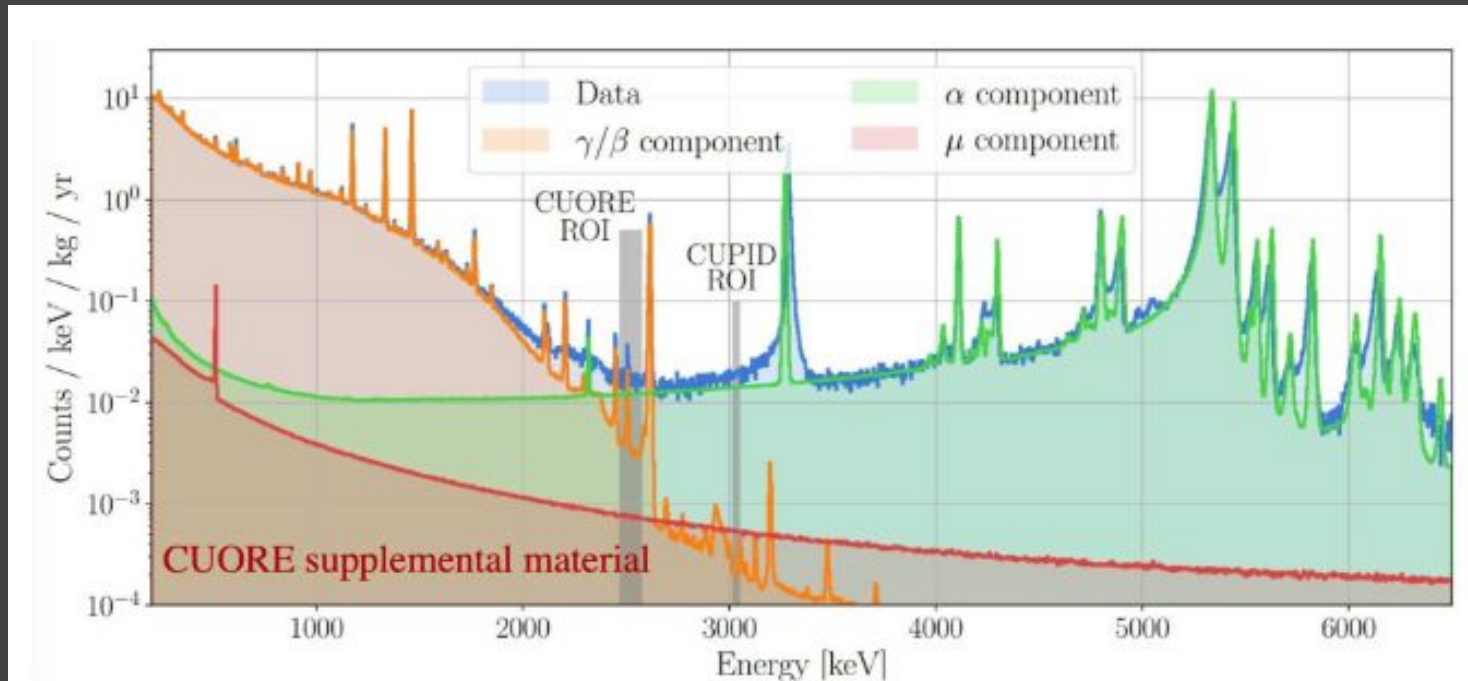
- **Stringent radiopurity requirements** for materials employed
- TeO_2 crystals: **dedicated radiopurity control protocol** for crystal production

Detailed presentation on CUORE and its results covered in Vladyslav Berest's talk on Tuesday: **Current Status and Latest Results from the CUORE Experiment**

CUORE Background and its Experience

CUORE background index in the ROI $\approx 1.42 \cdot 10^{-2}$ counts/(keV kg yr):

- Dominated by surface α particles (crystals and close components)
- Residual γ/β component: radioactive impurities in crystals and shields
- Cosmic ray flux: six orders of magnitude reduction in comparison to above ground



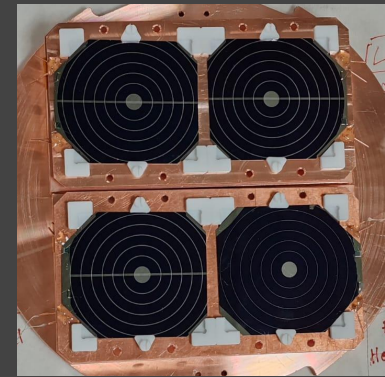
[PRD 110
052003
(2024)]

How to improve for a next-generation experiment?

CUPID: CUORE Upgrade with Particle IDentification

Same cryogenic infrastructure, but radical changes in the detector:

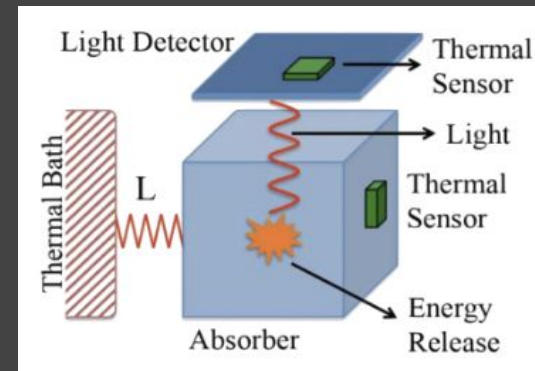
- Target isotope: ^{100}Mo ($Q_{\beta\beta} = 3034 \text{ keV}$), total 240 kg of ^{100}Mo
- 1596 $\text{Li}_2^{100}\text{MoO}_4$ (LMO) scintillating crystals, each coupled with two Ge bolometric light detectors (LD)
- Dual heat/light readout for α/β discrimination
- Active μ -veto and improved neutron shielding



Target Background index in the ROI:

$\sim 10^{-4} \text{ counts}/(\text{keV kg yr})$

Detailed BKG description covered in Ben Schmidt's talk on Tuesday: **Background and radio-purity control for the assembly of the CUPID neutrinoless double beta decay experiment**



LMO Crystal Background

LMO crystal background:

- $Q_{\beta\beta} > 3 \text{ MeV}$: above 2.615 MeV ^{208}Tl line, reduced γ/β Background in the ROI
- **$2\nu\beta\beta$ pile-up events**: random coincidences, mitigated using the faster timing response of the light detectors

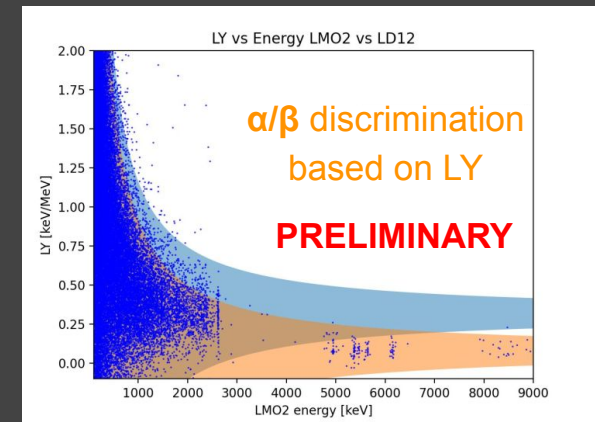
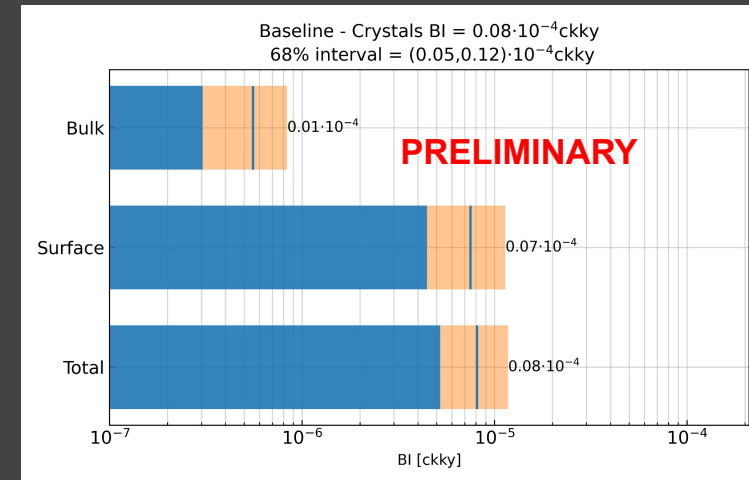
Minimization of radioactive contamination in LMOs essential to reach CUPID physics goal

LMO production by **SICCAS**, different provider than previous crystals

Ultra high radiopurity and bolometric performances to be assessed

Must possess **good optical qualities** and intrinsic **Light Yield (LY)** to guarantee good **α/β discrimination**

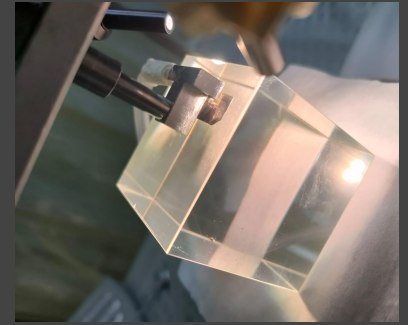
CUPID crystal contamination requirements		
	Bulk	Surface
^{226}Ra	$< 0.2 \mu\text{Bq/Kg}$	$2 \pm 0.5 \text{ nBq/cm}^2$
^{228}Th	$0.4 \pm 0.2 \mu\text{Bq/Kg}$	$< 2.5 \text{ nBq/cm}^2$



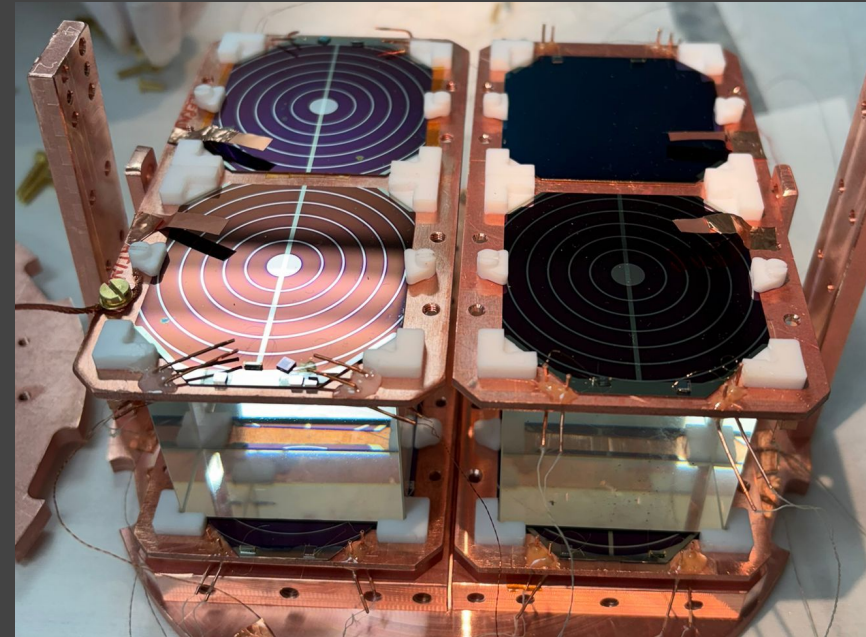
CUPID Crystal Validation Runs (CCVRs)

Dedicated **cryogenic tests** to verify **bolometric performance** and **radiopurity**

In addition: validation of **optical performances** of LMO



- Cryogenic runs performed with sandwiched **LMO + LD setup**
- Standardized geometry for performance comparison
- Main facility: **low background facility at LNGS Hall C**
- To be extended during whole mass production phase: **quality test of randomly chosen LMOs**



Main advantage:

simultaneous assessment of the key bolometric, optical and radiopurity properties

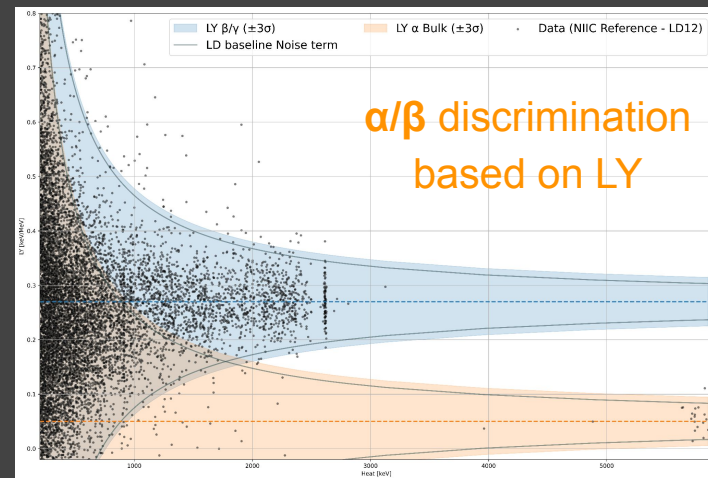
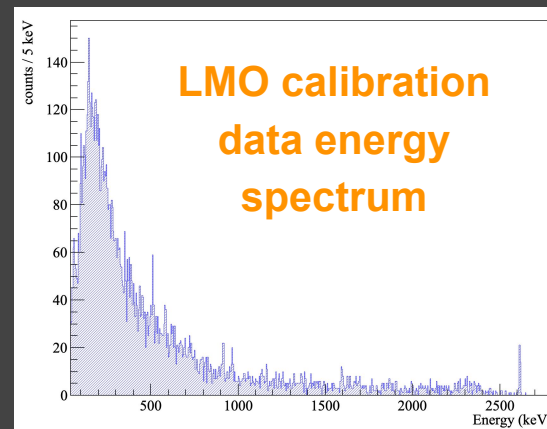
Bolometric and optical properties evaluation

Crystal properties of interest probed with CCVRs:

Energy resolution: FWHM at 2.615 MeV

Scintillation Light Yield: extracted as Light/Heat signal (keV/MeV)

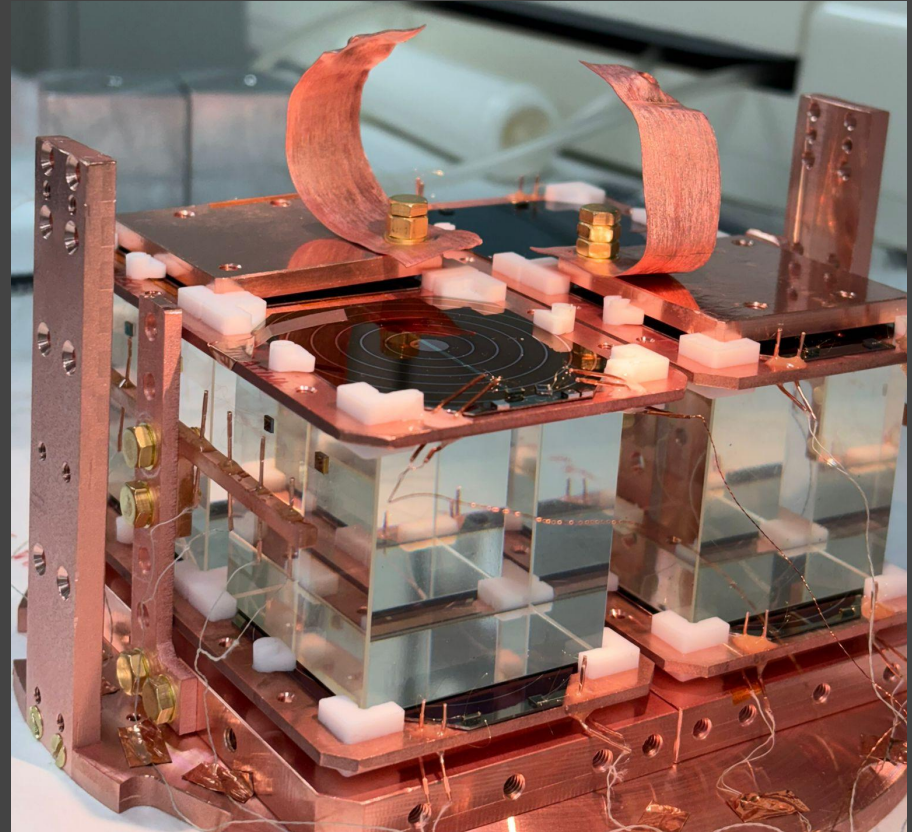
- T of operation ≈ 10 mK: optimization of working conditions for each detector
- LMO γ calibration with ^{232}Th sources for high statistics FWHM extraction even in low BKG environment
- LD X-ray calibration: estimation of absolute value of LY using γ and α peaks (nominal quenching factor: $\text{LY}_\alpha / \text{LY}_\beta \approx 20\%$)



Radiopurity measurement and evaluation

Many advantages of cryogenic runs as radiopurity assessment technique:

- **Sensitivity** to contaminants from the entirety of natural U/Th decay chains, as well as ^{40}K and selected anthropogenic radionuclides
- Competitive sensitivity with respect to γ spectroscopy thanks to the "source=detector" approach
- Very **high detection efficiency**
- Capability to **discern bulk and surface α contamination**

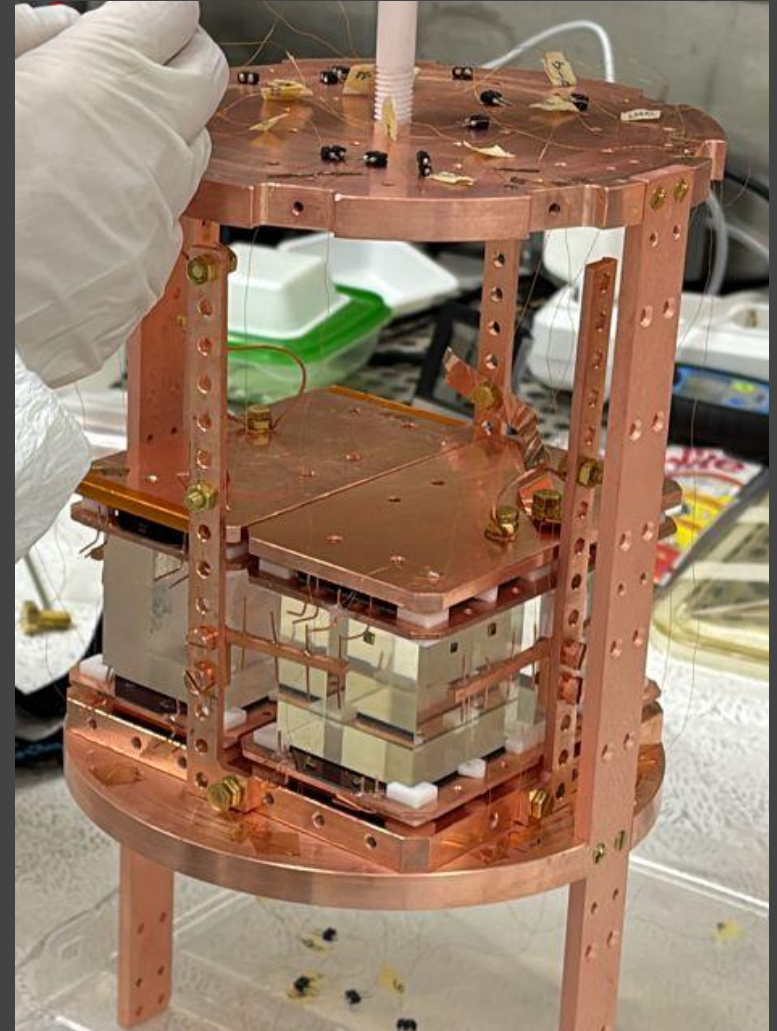


Radiopurity measurement and evaluation

- Cryogenic runs allow for a direct assessment of **crystal-related backgrounds under representative operating conditions**
- Extreme care to sample and detector preparation to minimize unrelated background

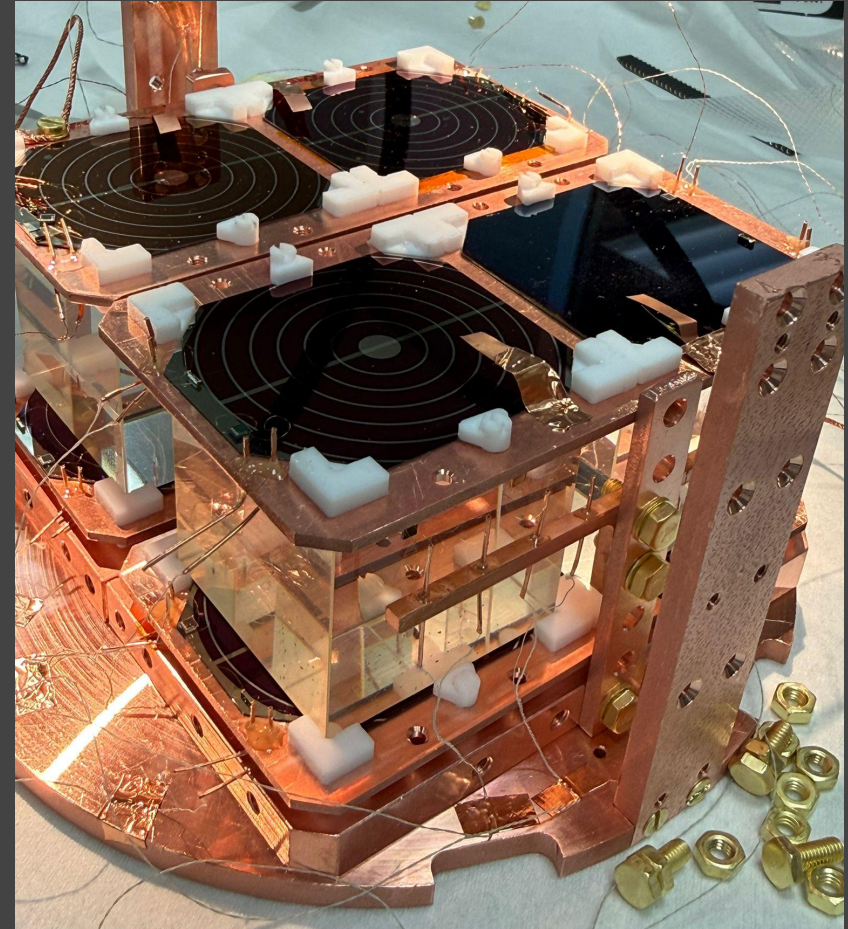
Coupled with screening of precursors and processing materials:

full assessment of radioactive contamination sources during LMOs growth and production



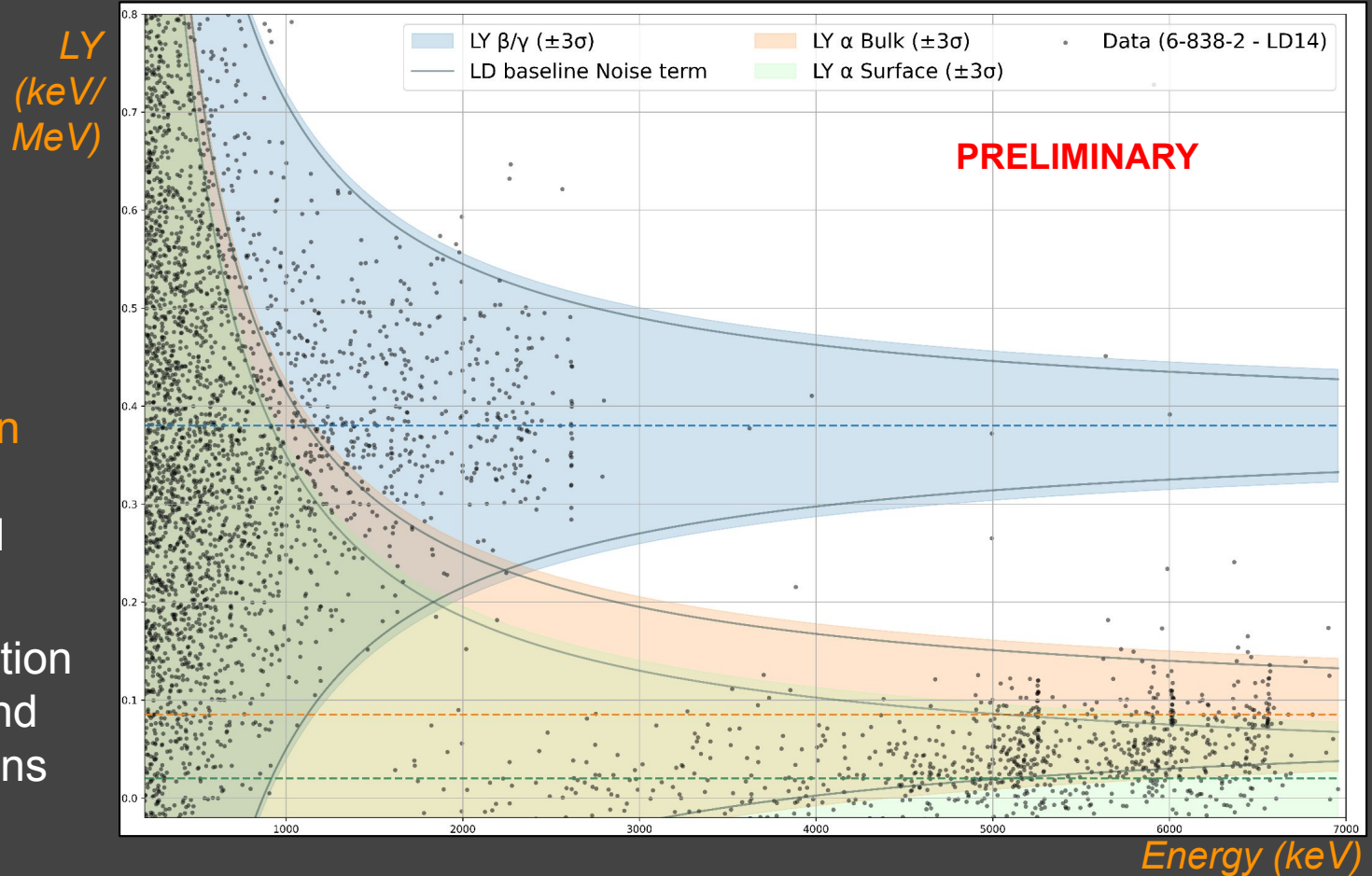
Current status of the CCVRs

- Testing of SICCAS enriched $\text{Li}_2^{100}\text{MoO}_4$ crystals began in 2025
- Multiple enriched LMOs by SICCAS tested in three runs. Focus on LMO performances, not at final radiopurity stage
- Fast feedback to SICCAS on material contamination and crystal quality. Direct indications on radiopurity improvements for growth and processing

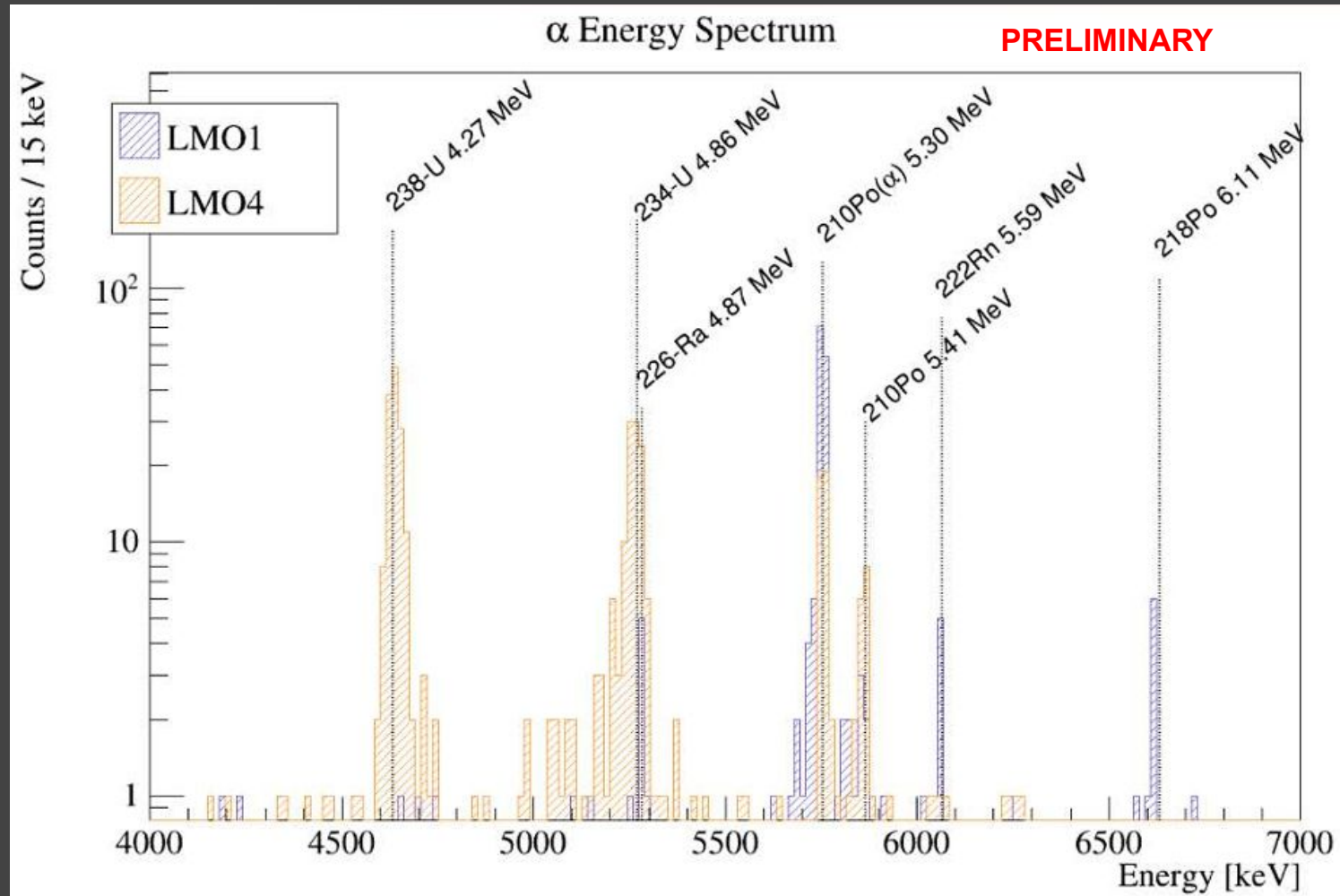


Current status of the CCVRs

- Evidence pointing to polishing powders as source of surface contamination with first crystal tested
- Good separation between α and β/γ populations with LY cut

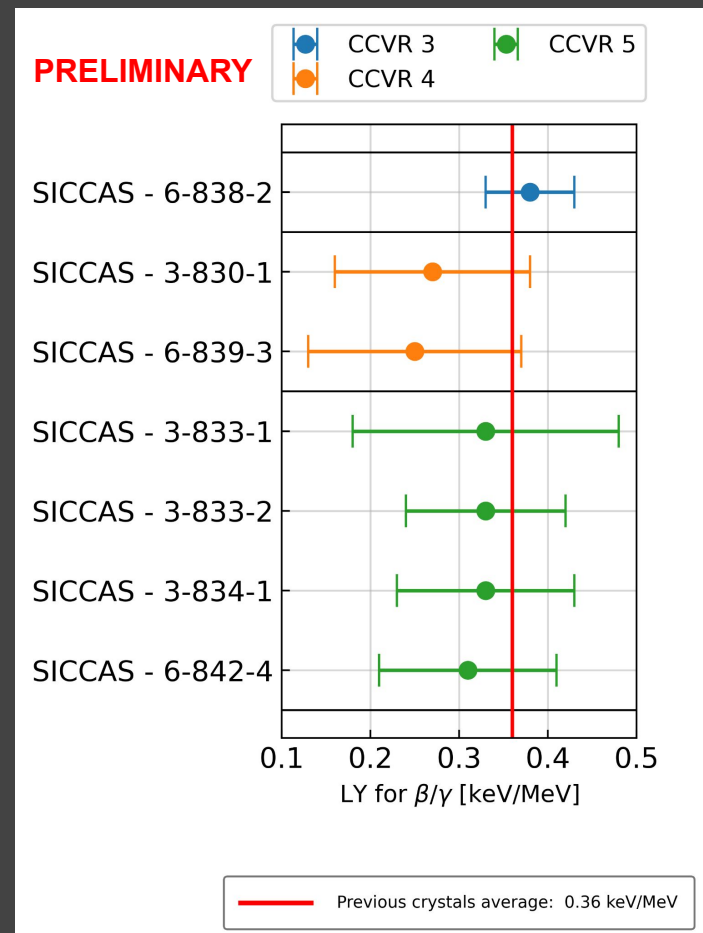
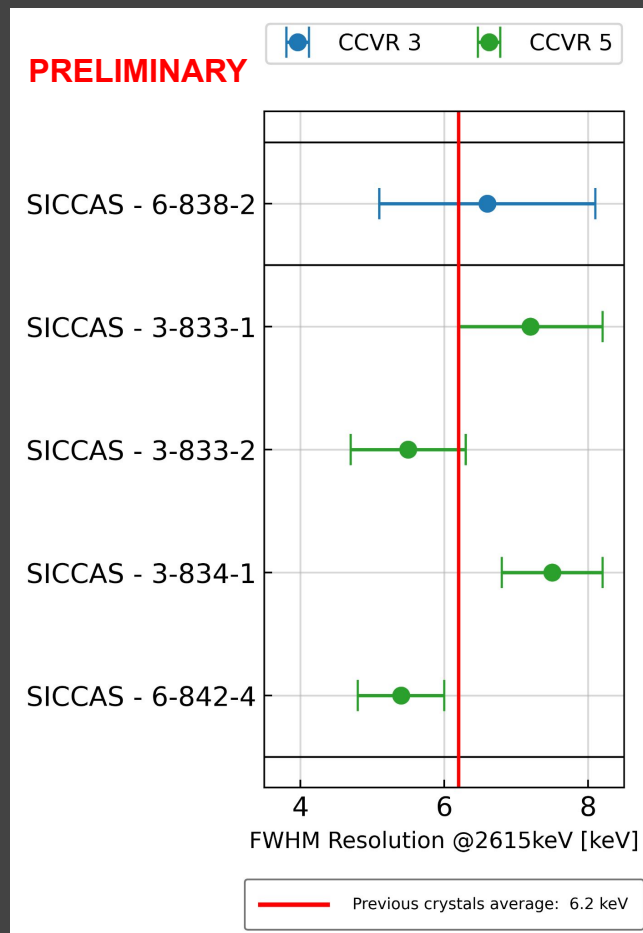


Current status of the CCVRs



- Study of LMO growth from **powder recycled** from unsuccessful growths (LMO4). Identification of clean recovery procedure **crucial for mass-scale production**

Current status of the CCVRs



- **SICCAS LMOs** preliminary performance is compatible with the range observed in larger scale test [[Arxiv/2503.0448](https://arxiv.org/abs/2503.0448)] for **crystals produced by NIIC**
- Currently studying macroscopic effects on LY measurement and noise mitigation with CCVR detector and infrastructure

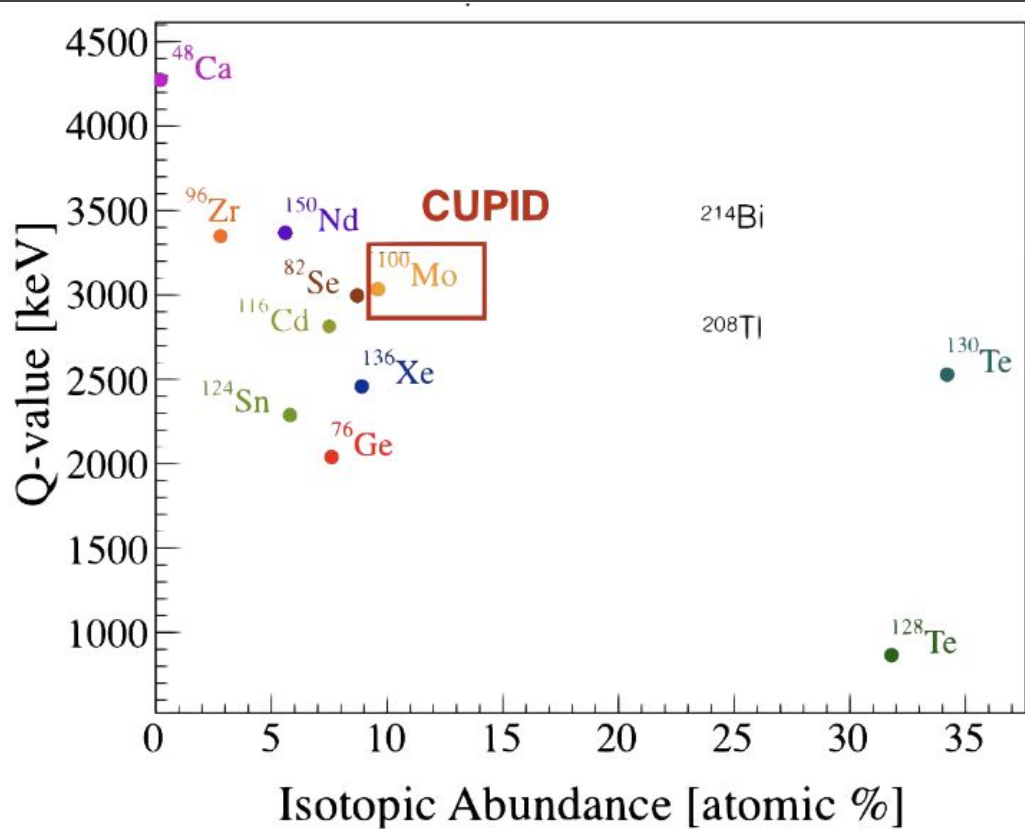
Summary

- CUPID physical reach dependent on LMO performances and radiopurity
- CCVRs: comprehensive technique to assess the key properties of interest
- Currently in crystal production optimization phase: feedback to SICCAS
- Crystal performances in line with previously tested LMOs
- Moving towards radiopurity optimization phase and mass production

Thank you

Backup slides and more informations

$0\nu\beta\beta$ candidates and CUPID



$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} \sim g_A^4 \cdot G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Effective Majorana mass:

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1,2,3} U_{e,i}^2 m_i \right|$$

CUPID Physics Reach

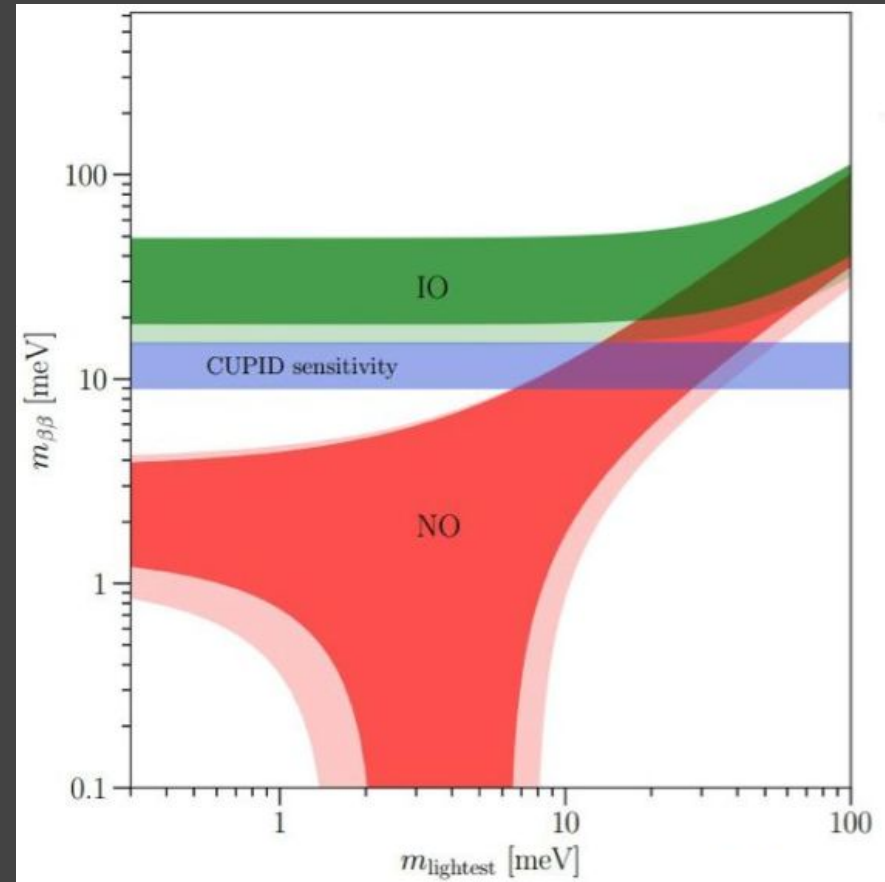
With BI = 10^{-4} counts/(keV kg yr) and 10 data taking/live time:

Bayesian exclusion (90% C.I.) sensitivity

$$T_{\frac{1}{2}} > 1.6^{+0.6}_{-0.5} \times 10^{27} \text{ yr}$$
$$m_{\beta\beta} < 9.6 - 16.3 \text{ meV}$$

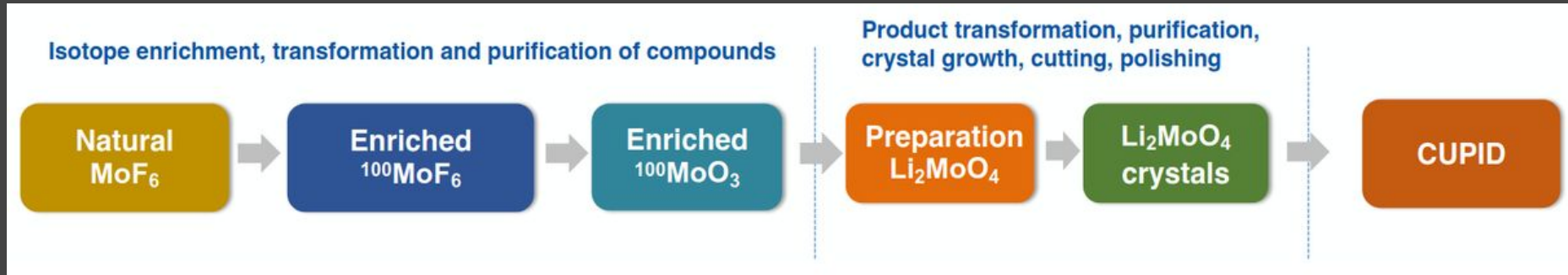
Frequentist discovery sensitivity (3σ):

$$T_{\frac{1}{2}} > 1.0 \times 10^{27} \text{ yr}$$
$$m_{\beta\beta} < 12.2 - 20.6 \text{ meV}$$



Sensitivity reaching the inverted-ordering region!

LMO production process at SICCAS



- ¹⁰⁰Mo enrichment > 95%
- $\text{Li}_2\text{CO}_3 + {}^{\text{enr}}\text{MoO}_3 \rightarrow \text{Li}_2{}^{\text{enr}}\text{MoO}_4 \text{ (LMO)} + \text{CO}_2$
- LMO powder synthesis, growth and machining performed at SICCAS
- Selection of radiopure materials for each production step: assessment with γ spectroscopy measurements and Neutron Activation Analysis

Hall C cryostat

- Located in Hall C LNGS
- Dilution wet cryostat
- Closed cycle liquefier
- Lead shielding
- Radon box
- Repair of the $^3\text{He}/^4\text{He}$ mixture circulation circuit in 2026



CCVRs: past runs for SICCAS LMOs

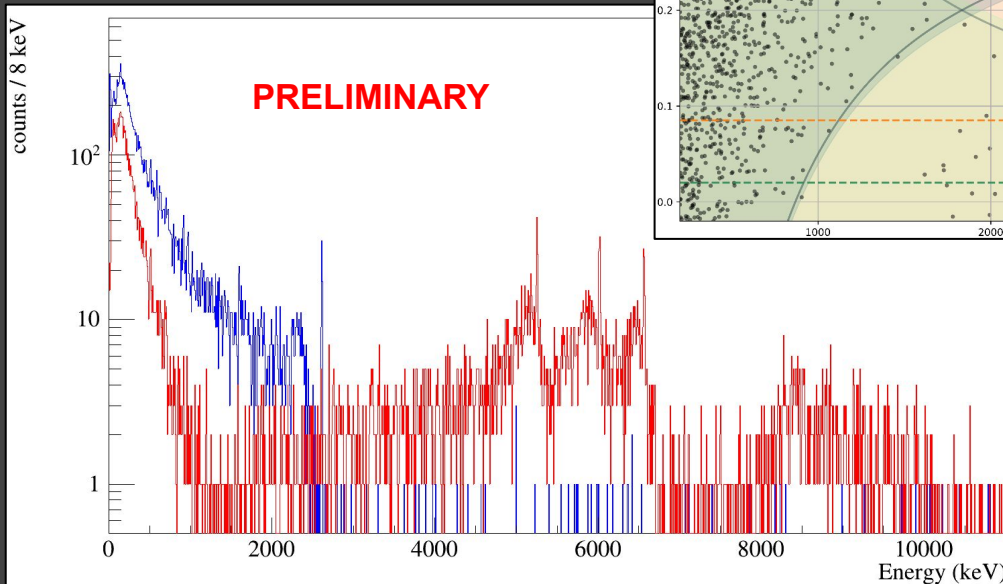
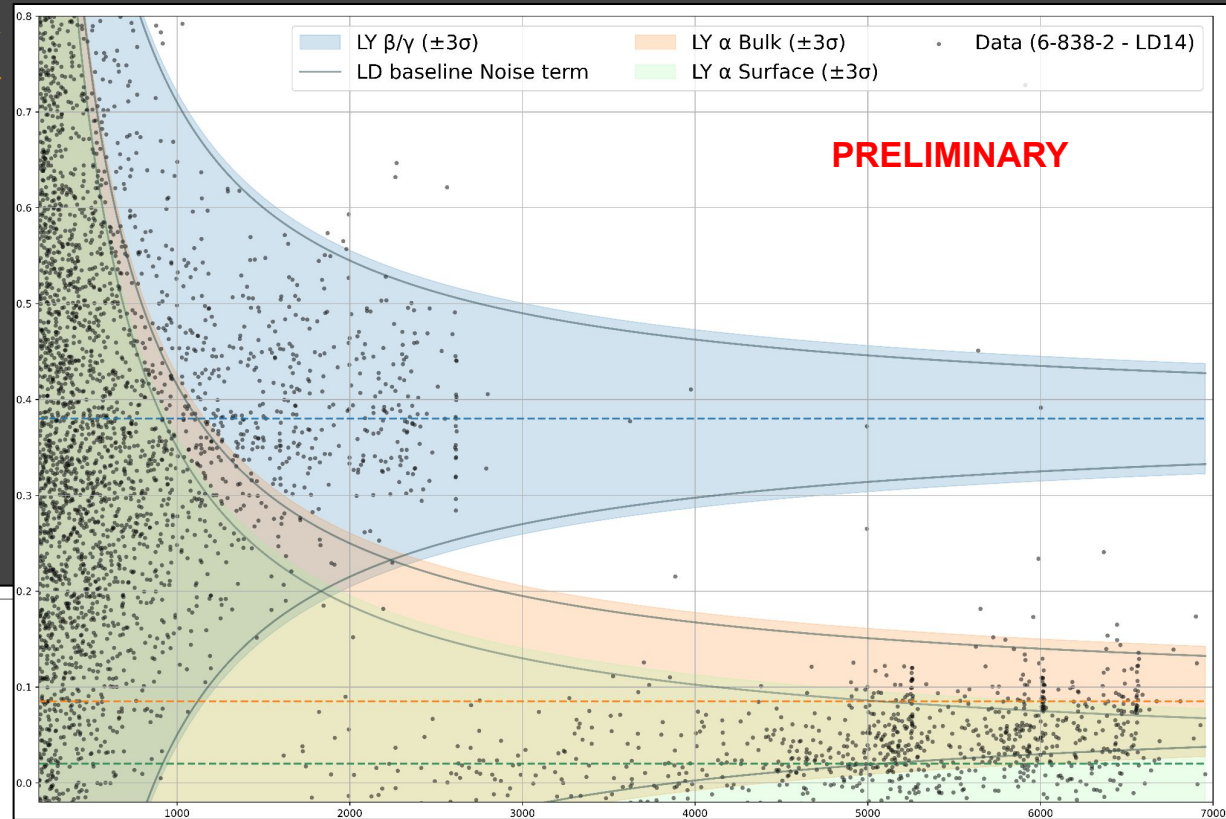


- CCVR3: first measurement of enriched SICCAS LMO + NIIC reference in Hall C cryostat
- Hall C cryostat failure: fixed during summer + electronics upgrade
- CCVR4: 3 enriched SICCAS LMO + NIIC reference, performed at Ulysses cryostat at IJCLAB (Orsay, France)
- CCVR5: 4 enriched SICCAS LMOs, performed at IETI cryostat at LNGS

CCVR3

- Confirmation of good bolometric and scintillating properties: compatible with older LMO provider

LY
(keV/
MeV)



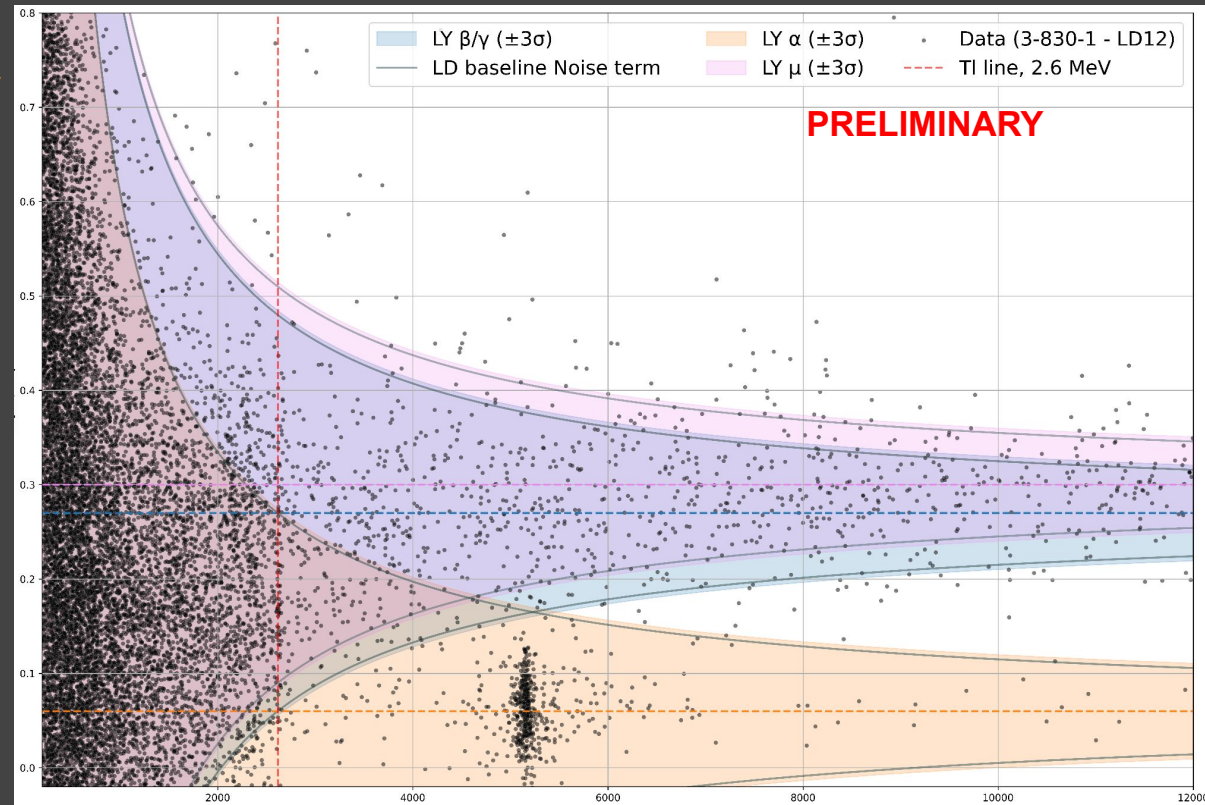
Energy (keV)

- Significant contamination due to use of non-optimized polishing powders

CCVR4

- Performed at above ground pulse tube ULYSSES cryostat
- High cosmic-ray rate resulting in substantial pile-up and degradation of the energy resolution
- Scintillation in line with other SICCAS LMO, worse discrimination due to noisy LDs
- Ongoing analysis

*LY
(keV/
MeV)*

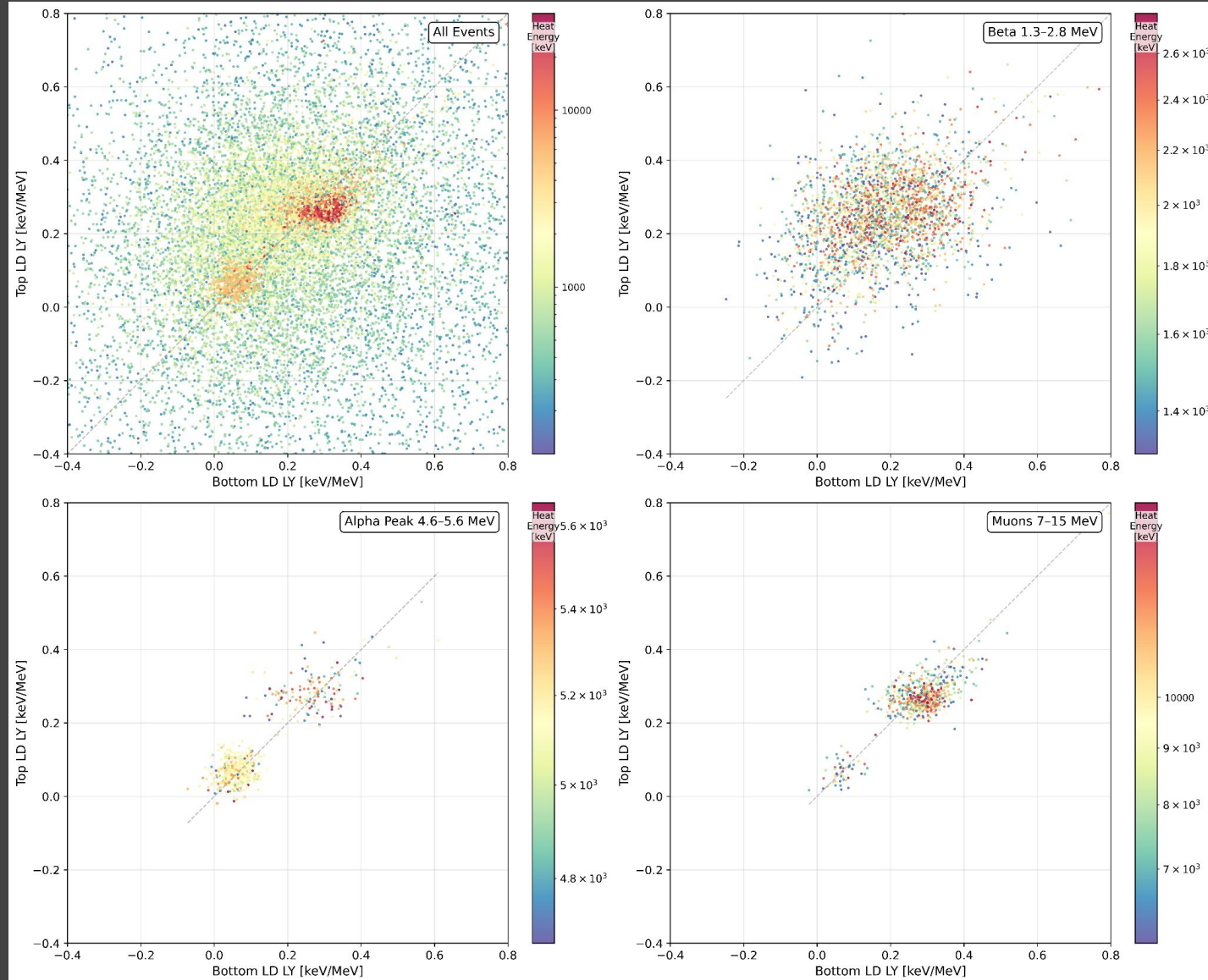


Energy (keV)

CCVR4

PRELIMINARY

- Scintillation in line with other SICCAS LMO, worse discrimination due to noisy LDs
- On-going analysis



CCVR5

- Performed at underground pulse tube IETI cryostat at LNGS
- One crystal grown from recycled material
- Excellent bolometric performance
- PID performance limited by LD noise
- Study of LD reflectivity on going

LY
(keV/
MeV)

