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

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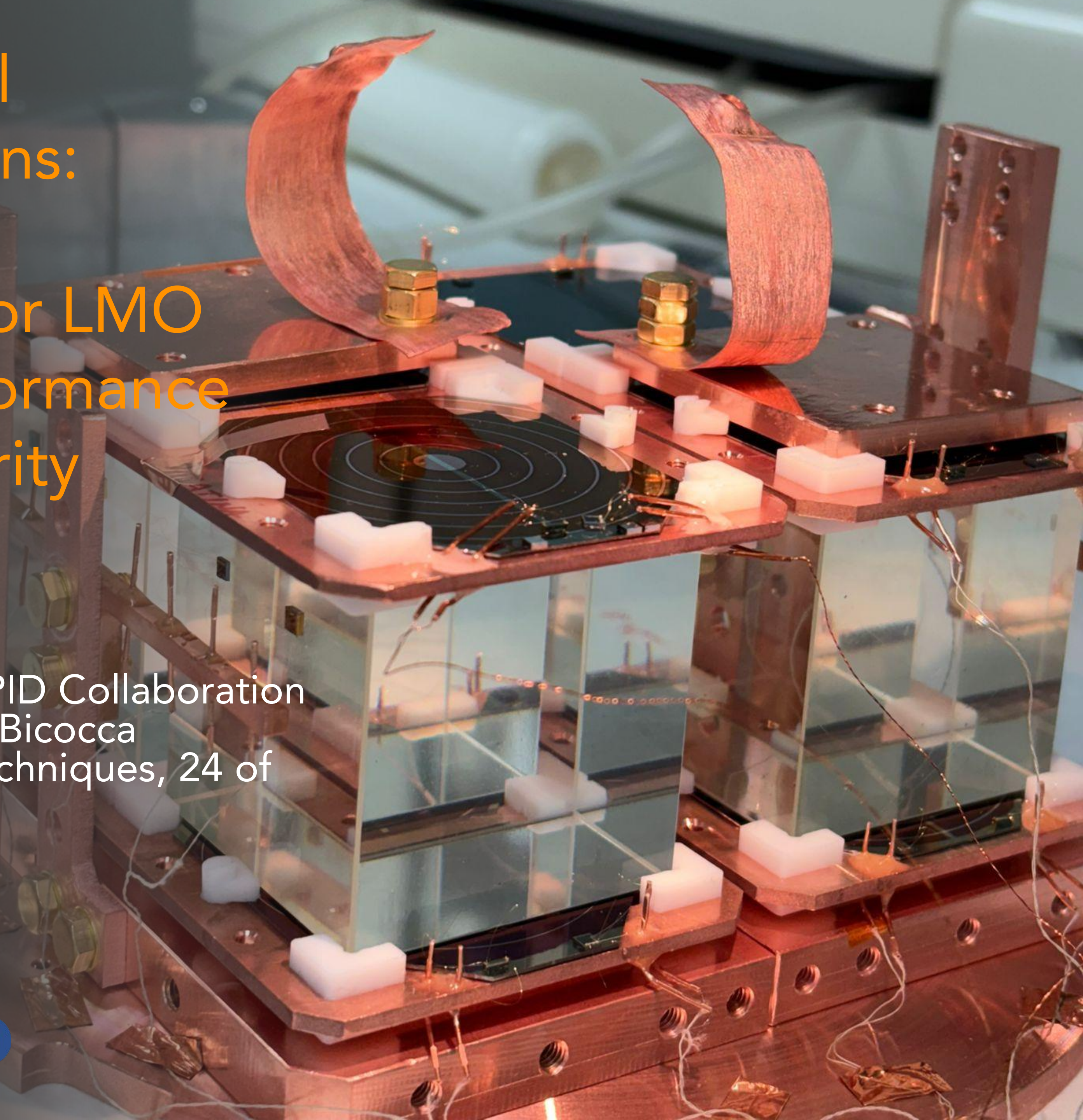
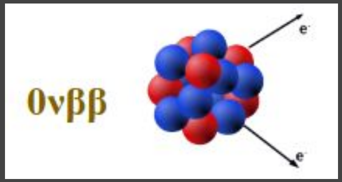
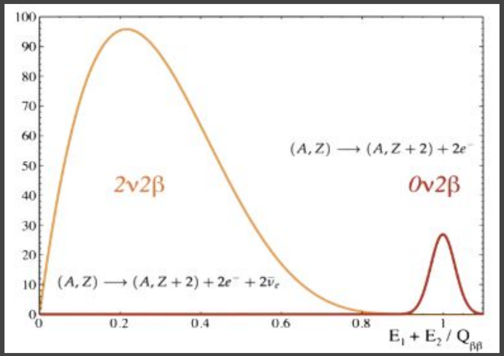
on behalf of the CUPID Collaboration
Università di Milano-Bicocca
Low Radioactivity Techniques, 24 of September 2026



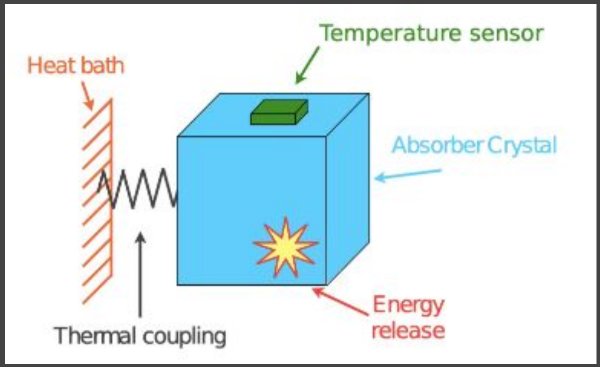
0νββ Decay Search with Cryogenic Calorimeters



- Beyond SM process: lepton number violation **ΔL=2**
- Possible important role in Matter-Antimatter asymmetry
- Unlike SM allowed 2νββ, no experimental evidence



- $T_{1/2}$ > *10^{24} - 10^{26} yr*, signature is peak at $Q_{\beta\beta}$
- 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 ≃ 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:

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

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

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

Zero Background case

η = Isotopic abundance of candidate isotope

ε = efficiency of detection

M = active mass of the detector

T = total live time

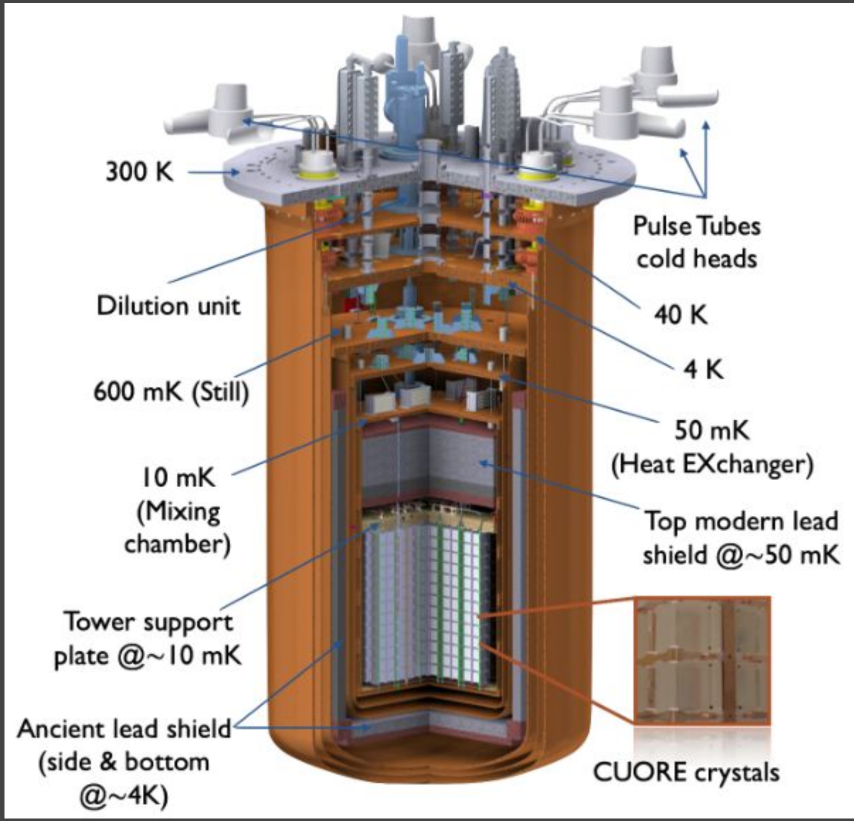
ΔE = energy resolution at $Q_{\beta\beta}$

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

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 0νββ in ^{130}Te ($Q_{\beta\beta}$ = 2528 *keV*), 988 TeO_2 crystals
- End of physics program in 2026 after 8 years of continuous operation

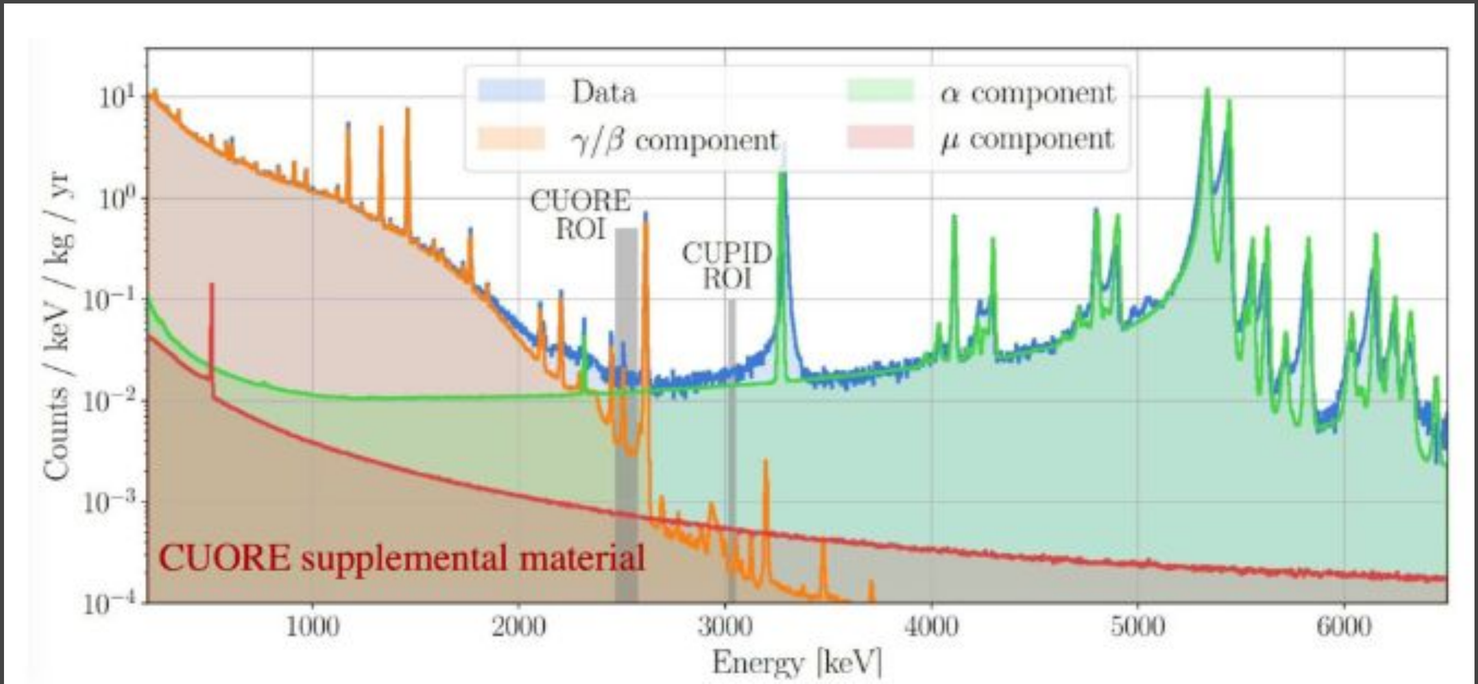


- Stringent radiopurity requirements for materials employed
- TeO_2 crystals: dedicated radiopurity control protocol for crystal production (SICCAS)
- CUORE Crystal Validation Runs: dedicated cryogenic test runs for TeO_2 crystals compliance of bolometric performances and radiopurity

CUORE Background and its Experience

CUORE background index in the ROI ≃ **1.42 · 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 order of magnitude reduction in comparison to above ground



How to improve for a next-generation experiment?

CUPID: CUORE Upgrade with Particle IDentification

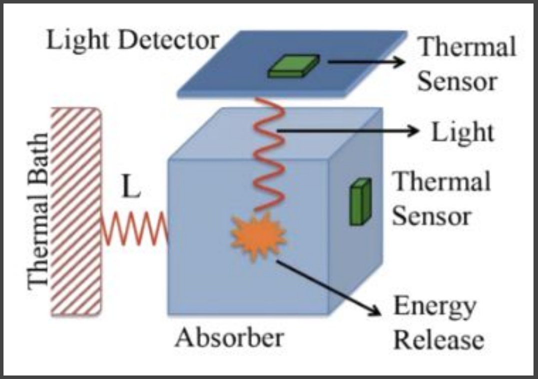
Same cryogenic infrastructure, but radical changes in the detector:

- Candidate isotope: ^{100}Mo ($Q_{\beta\beta}$ = 3034 *keV*), total 240 kg
- 1596 $Li_2{}^{100}MoO_4$ (LMO) scintillating crystals, each coupled with two Ge bolometric light detectors (LD)
- Dual heat/light readout employed for **α/β** discrimination
- Neganov-Trofimov-Luke (NTL) amplification on LDs: boost SNR
- Implementation of active μ-veto and improved neutron shielding

Target Background index in the ROI:

~ 10^{-4} counts/(keV kg yr)

with α and μ rejection

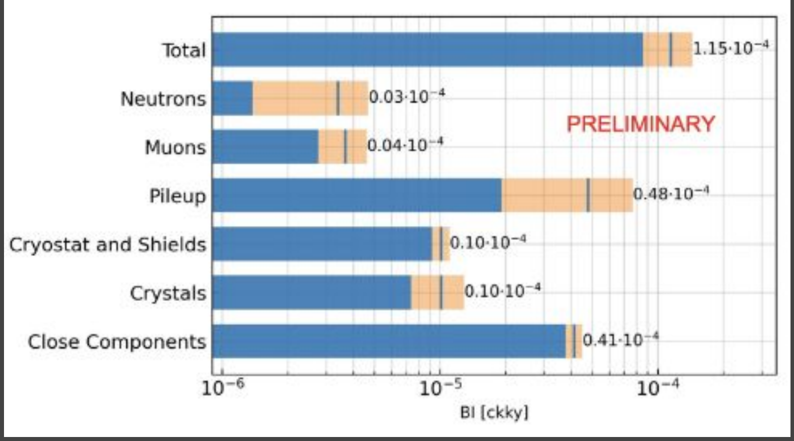


CUPID Projected Background

$Q_{\beta\beta}$ > 3 MeV: above most intense natural emissions, reduced γ/β Background in the ROI

Most prominent sources of BKG (simulations and CUORE + CUPID-Mo BKG models):

- **2νββ *pile-up* events**: random coincidences, suppressed with faster LDs readout
- **Muons and neutrons**: mitigated with enhanced neutron shielding and active μ-veto
- **Close components, cryostat and shielding**: high radiopurity materials required



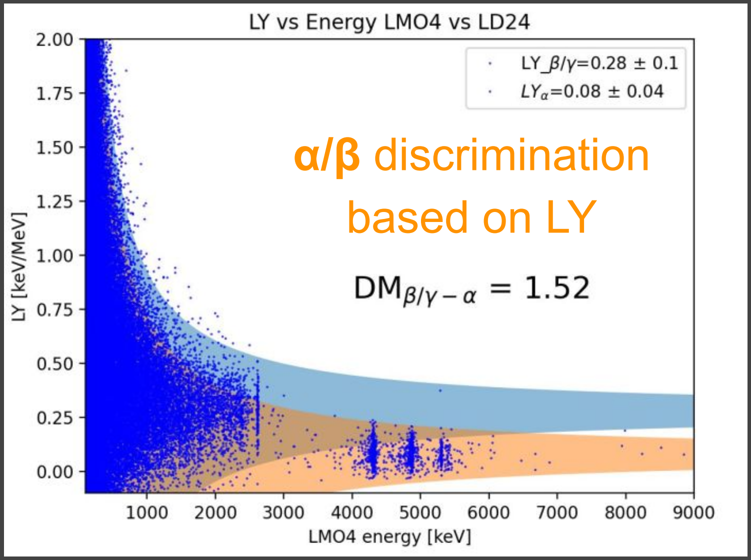
Lastly and crucially:

LMO crystals

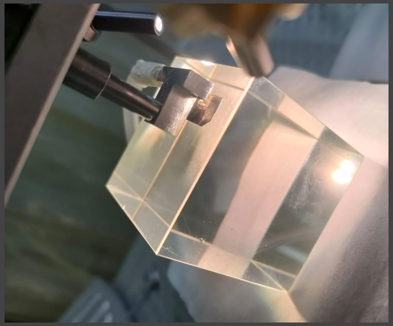
Moved to SICCAS, different producer than CUPID-Mo

Required high radiopurity and bolometric performances required

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



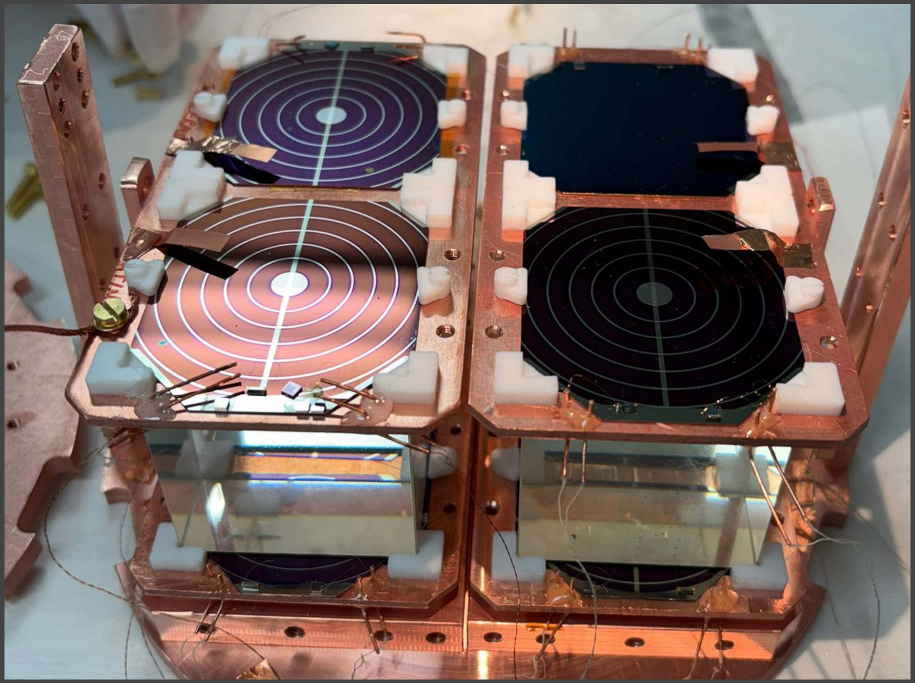
CUPID Crystal Validation Runs (CCVRs)



Learning from the experience of CUORE CCVRs

In addition: validation of optical performances of LMO

- Cryogenic runs performed with LMO + LD setup that replicates CUPID modules
- Standard facility: low background wet cryostat at LNGS Hall C
- Standardized geometry for performance comparison
- To be extended during whole mass production phase: quality test of randomly chosen LMOs



Main advantage:

Single measurement to fully characterize all the properties of interest!

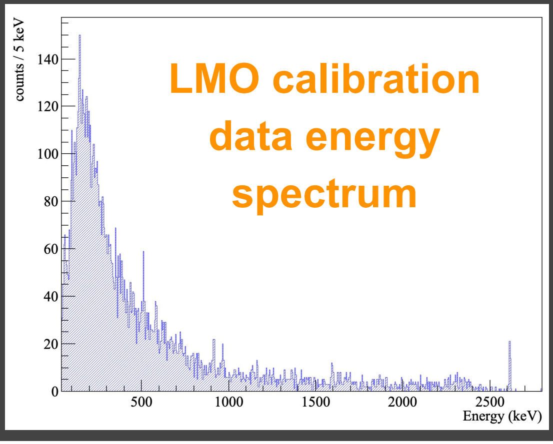
Bolometric and optical properties evaluation

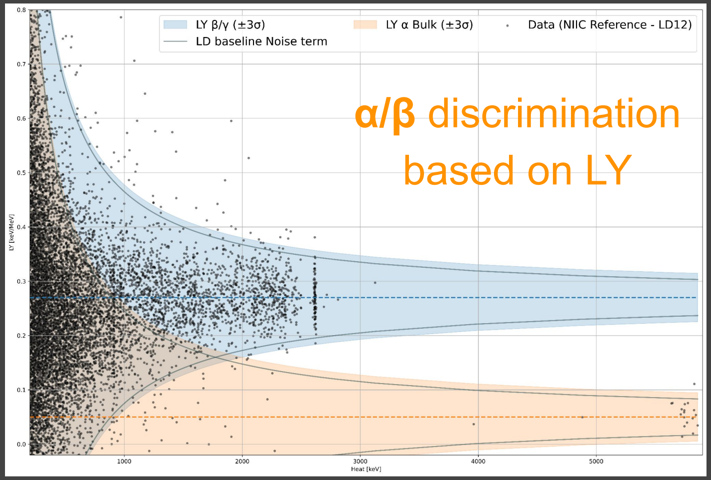
Crystal properties of interest probed with CCVRs:

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 ≃ 20%)

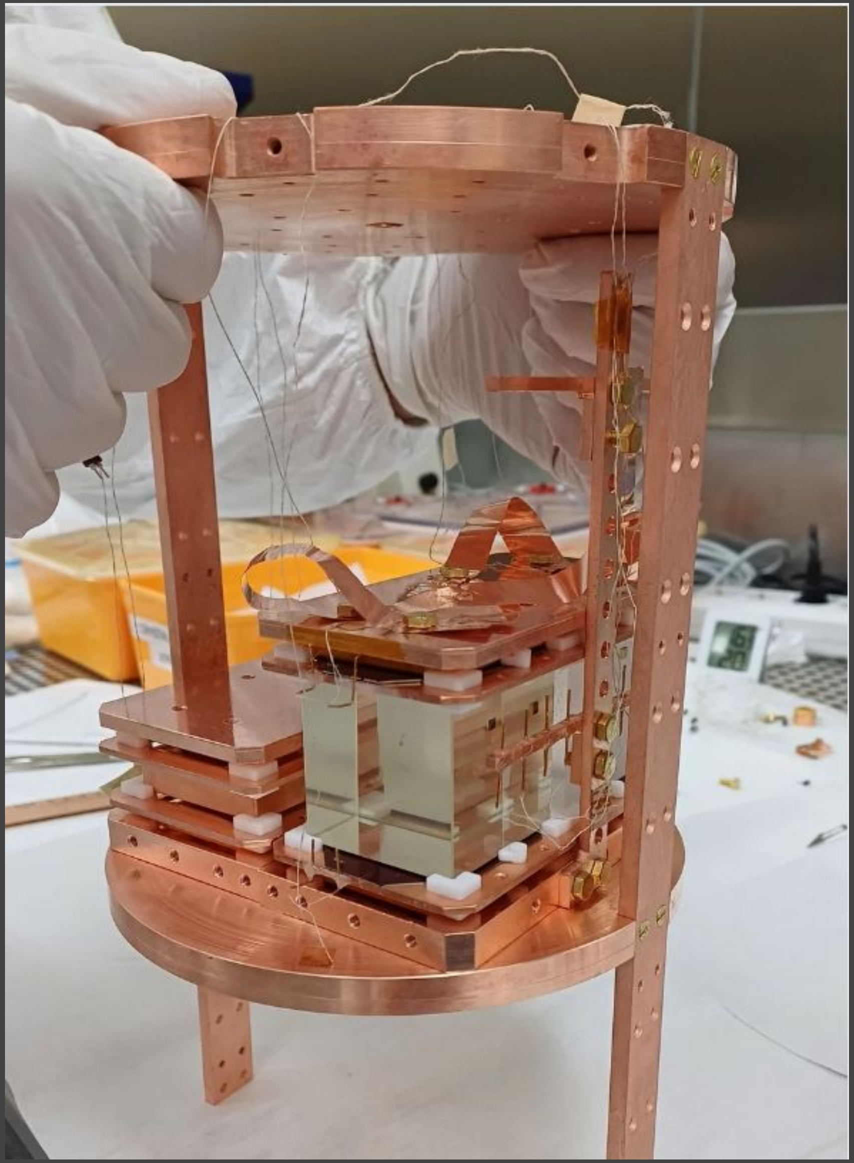




Radiopurity measurement and evaluation

Many advantages of cryogenic runs as radiopurity assessment technique:

- Sensibility to the entirety of natural U and Th chains, ^{40}K and anthropogenic
- Measurement time compatible with γ spectroscopy, independent of sample mass
- Capability to discern bulk and surface α contamination
- Very high detection efficiency



Radiopurity measurement and evaluation

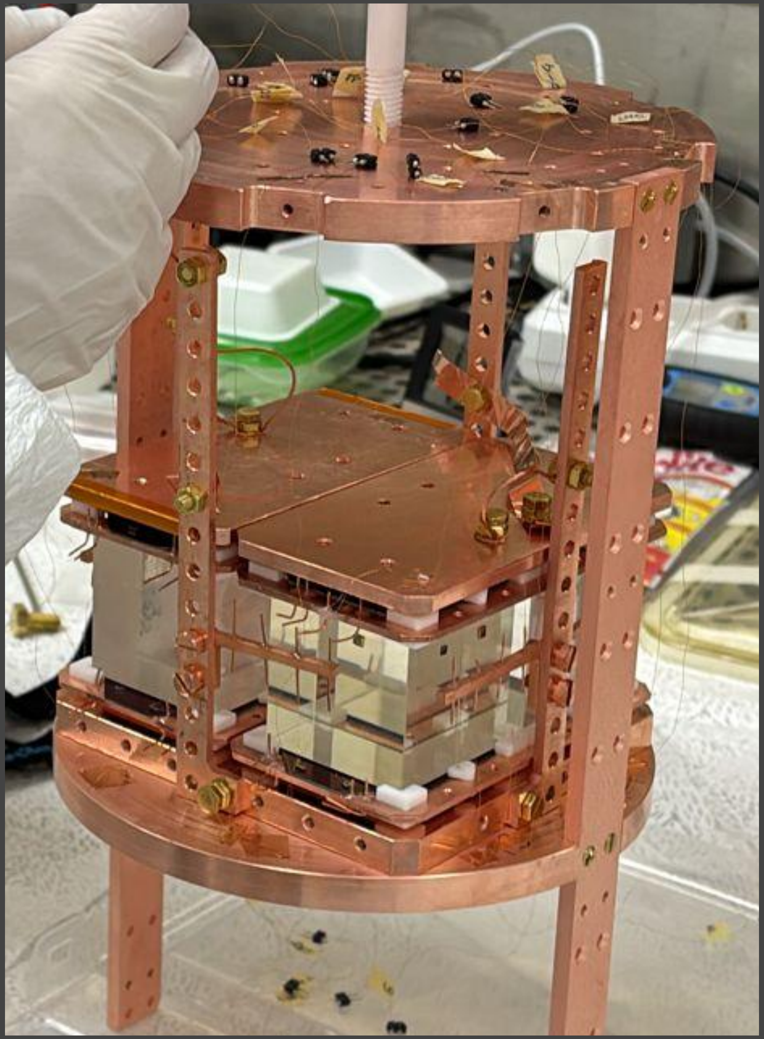
- Exact same procedure and setup for the final experiment: clear indication of expected background

- Extreme care to sample and detector preparation to minimize background

- Radiopure material (copper, teflon…) and accurate cleaning procedures

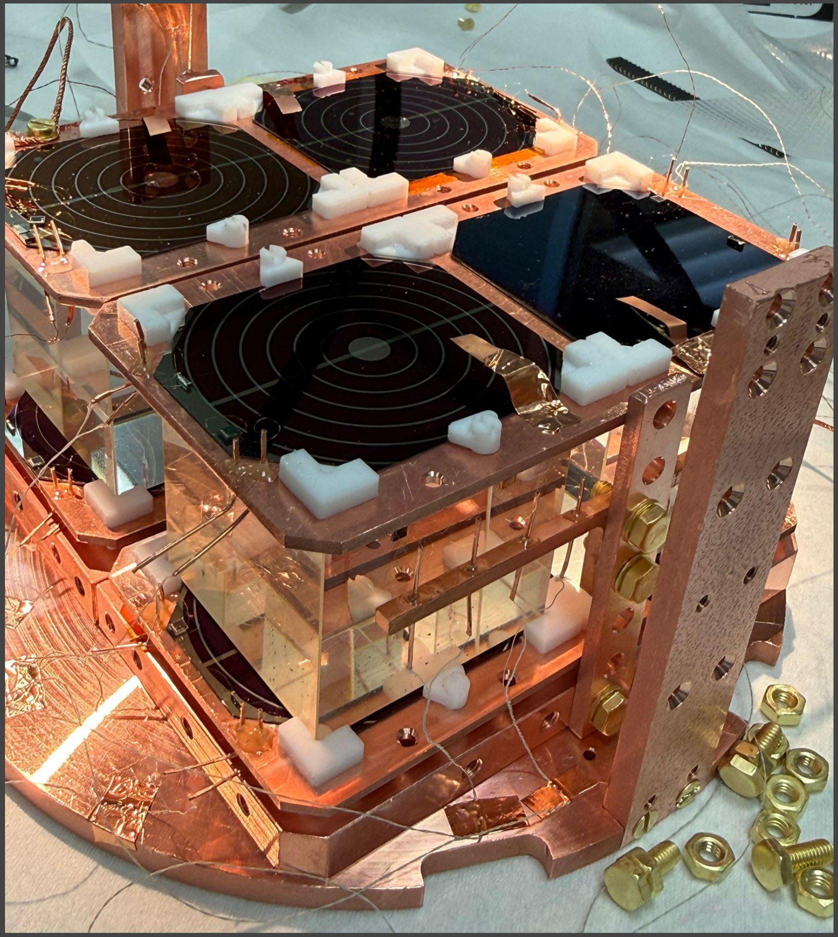
Coupled with screening of precursors and processing materials:

full assessment of radioactive contamination sources during LMOs growth and production



Current state CCVRs

- 2025: begin testing of $Li_2{}^{100}MoO_4$ crystals



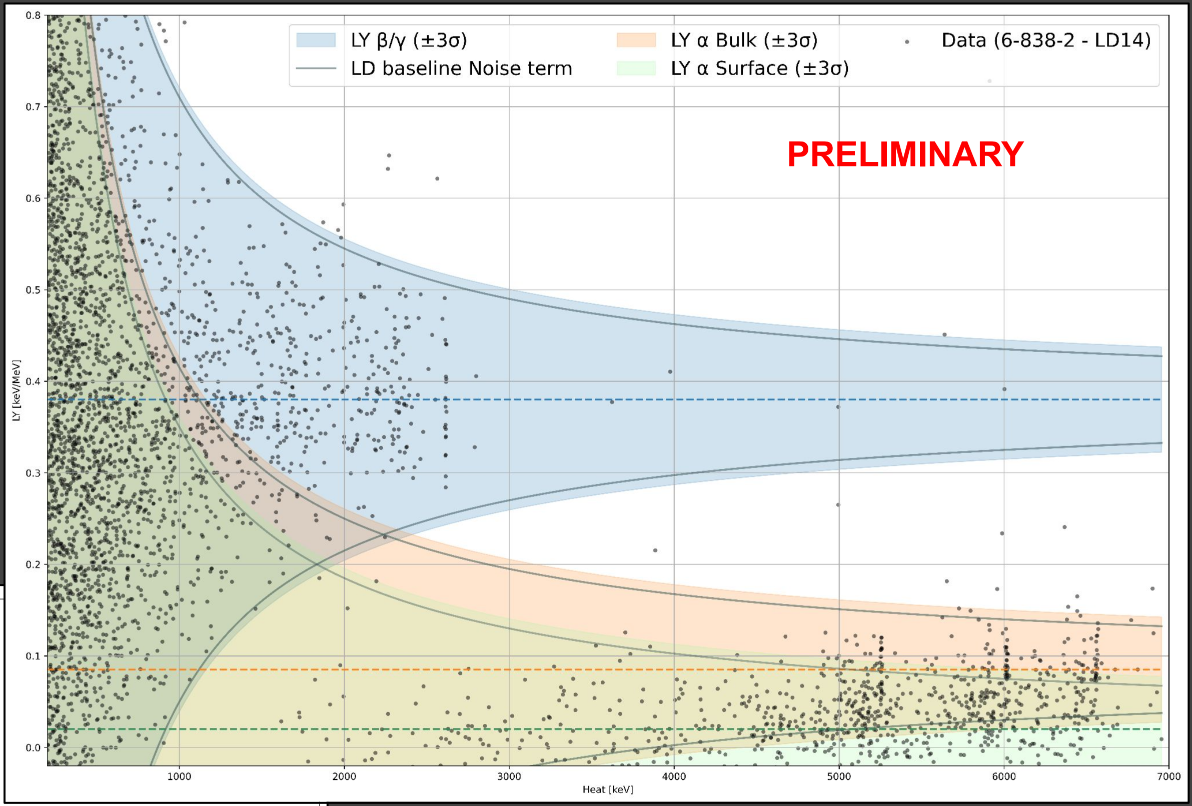
- Refurbishment of Hall C cryostat and detector assembly infrastructure. Support of other infrastructure during maintenance work

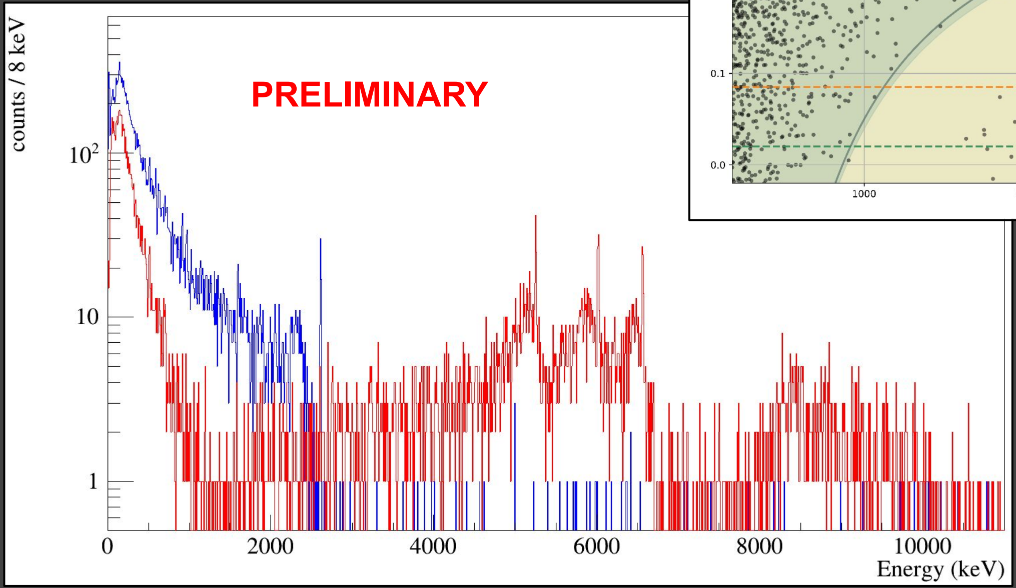
- To date 8 enriched LMO crystal tested Not at final radiopurity stage, focus on LMO performances

- Fast feedback to SICCAS on material contamination and crystal quality. Direct indications on radiopurity improvements for growth and processing

Current state of CCVRs

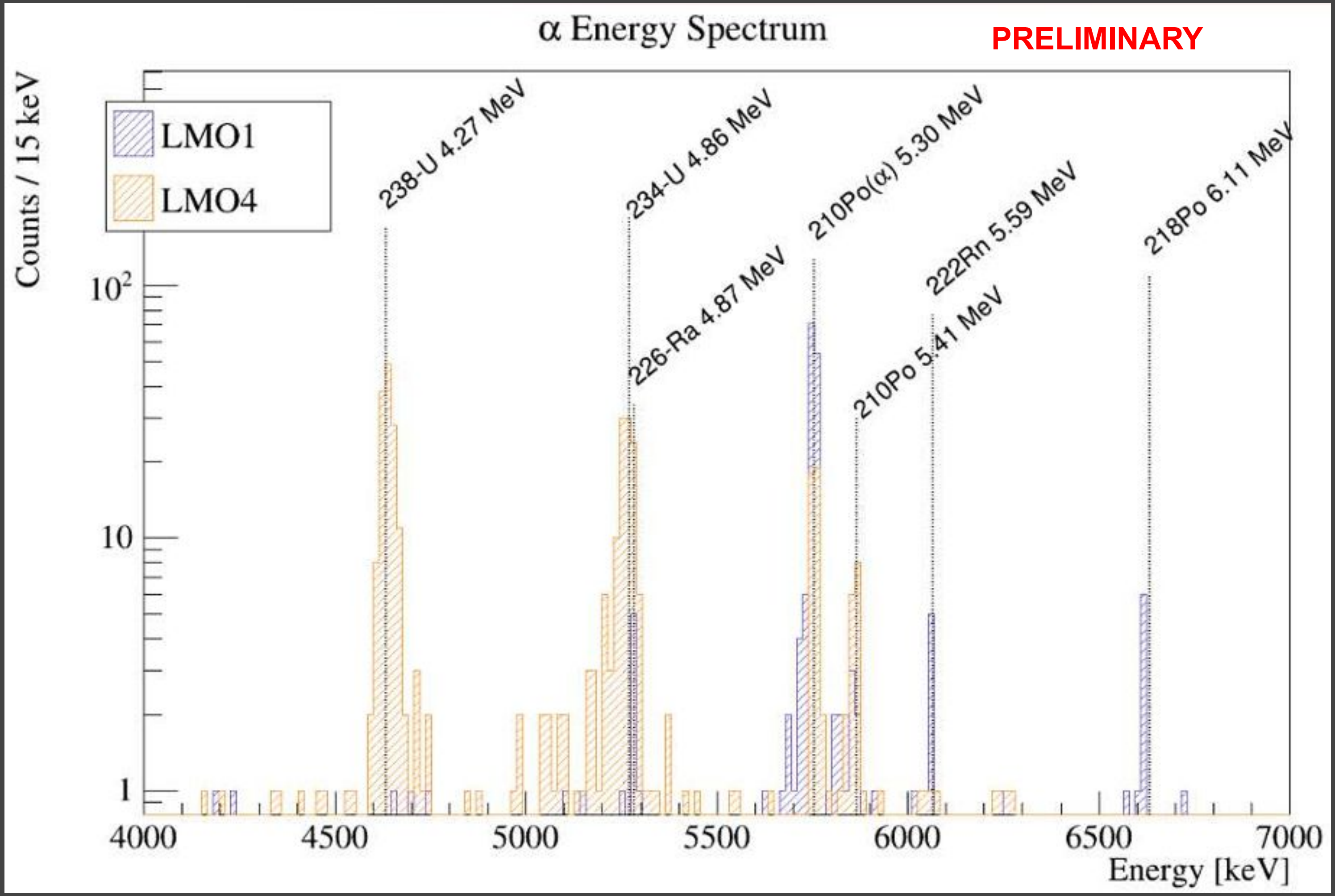
- Identification of polishing powders as source of surface contamination with first crystal tested





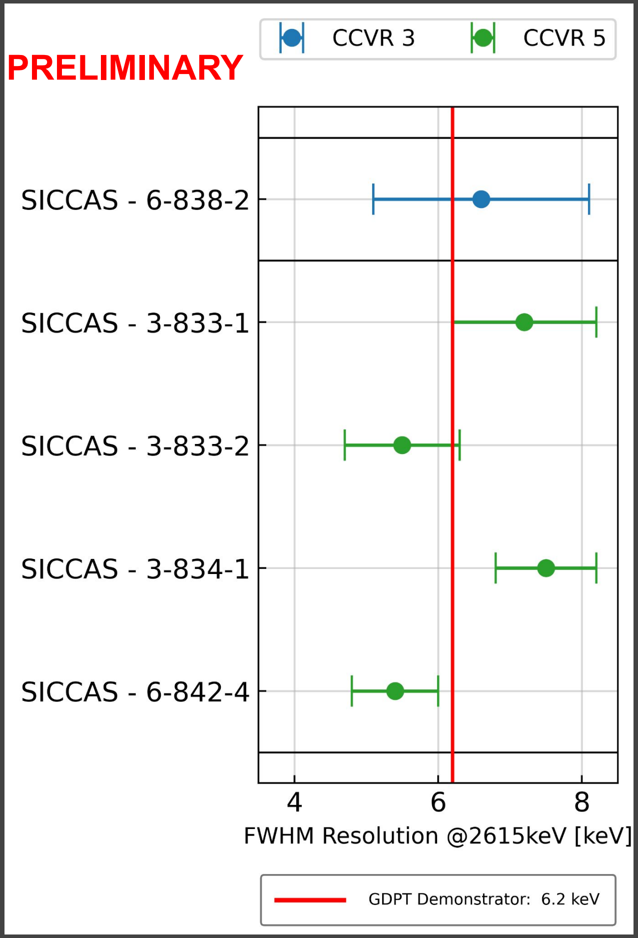
- Good separation of α and β component of the spectrum with LY cut

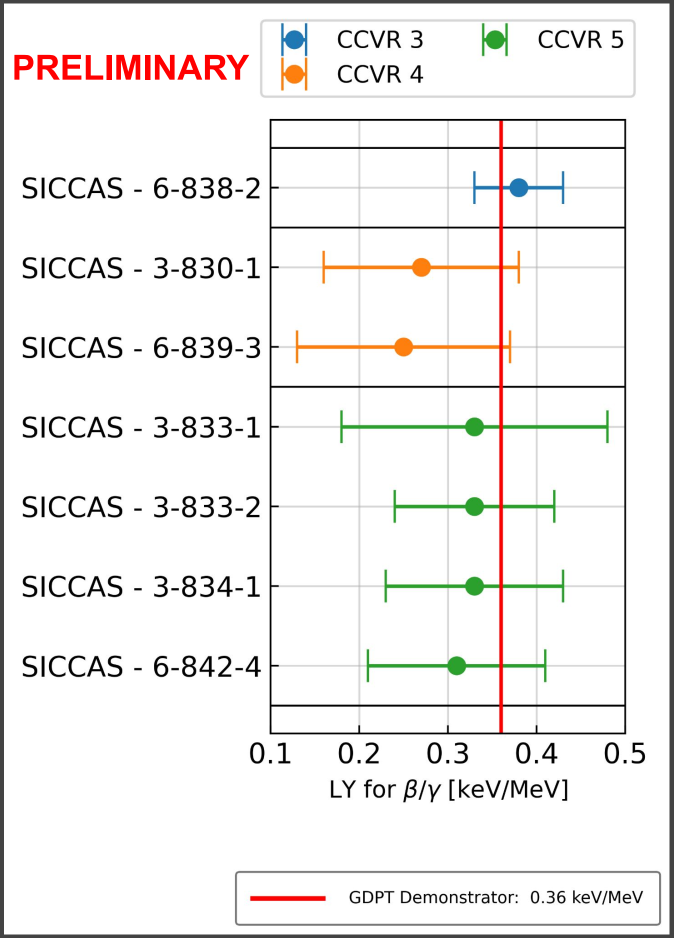
Current state of CCVRs



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

Current state of CCVRs





- Results of tested LMOs indicate good performances of the crystals in line with GDPT (CUPID-like tower demonstrator) with LMOs from NIIC producer
- Currently studying macroscopic effects on LY and noise mitigation with CCVR detector and infrastructure

Summary

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

Thank you on behalf of CUPID collaboration and CCVR team

Backup slides and more informations