Validation of LMO Crystals for the CUPID Experiment

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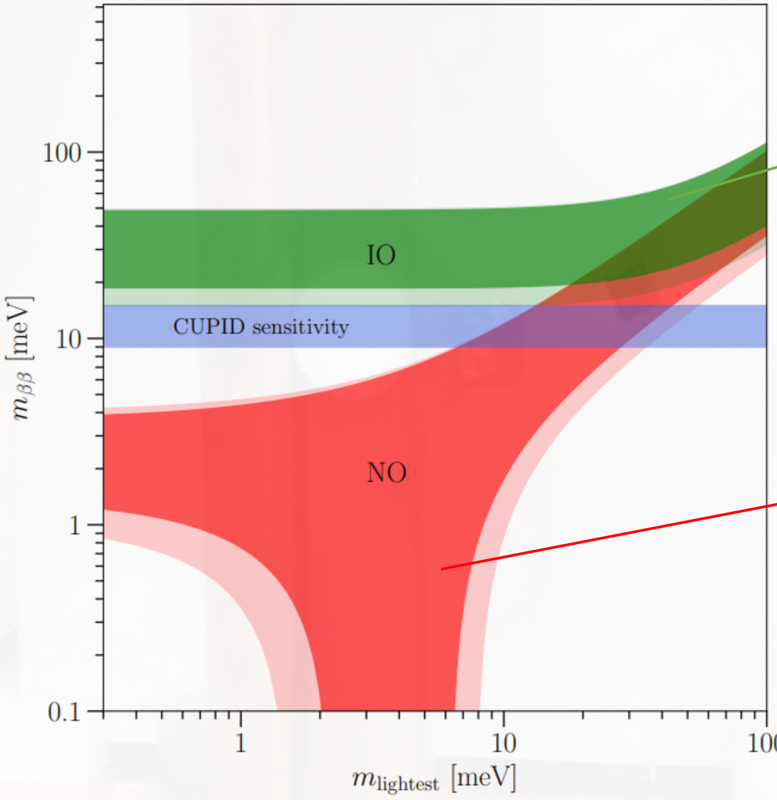
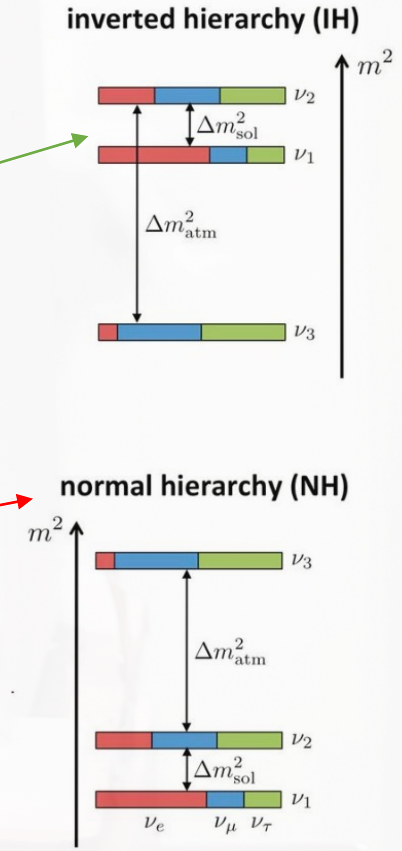
Xichang - China

Neutrinoless double-beta decay

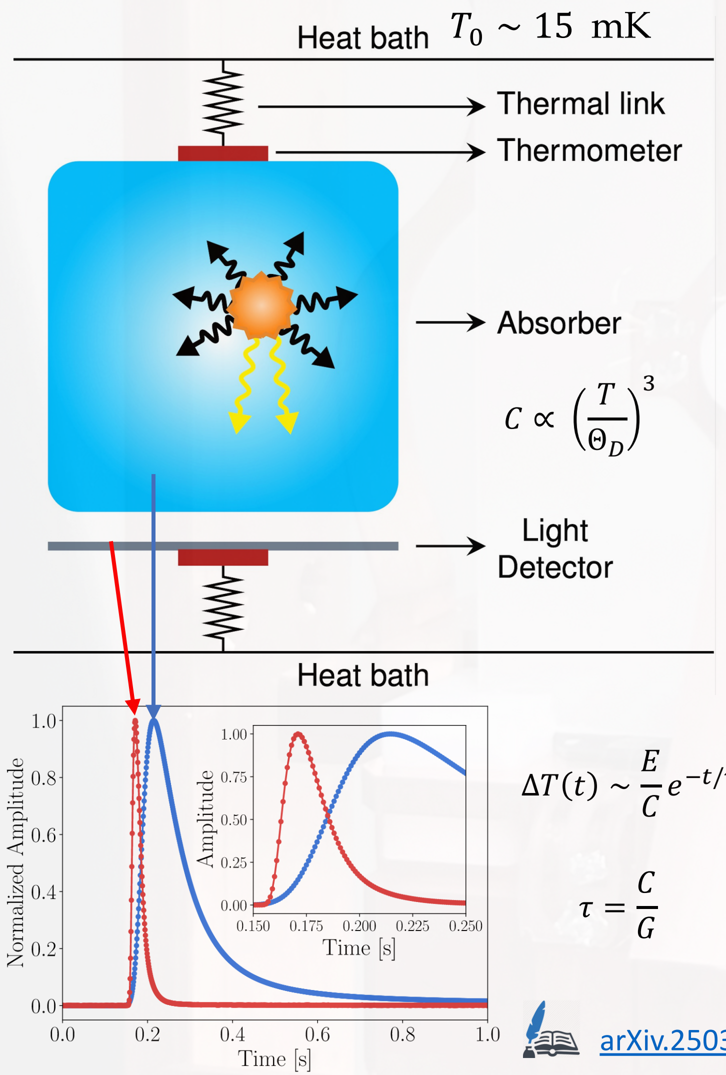
- $\mathbf{0\nu\beta\beta}$
  - $(A, Z) \rightarrow (A, Z \pm 2) + 2e^{\mp}$
  - not allowed in SM
  - not observed (yet): $T_{1/2}^{0\nu} > 10^{25} - 10^{26}$ yr
    $m_{\beta\beta} \leq 28 - 240$ meV
  - probe for New Physics:
    - would imply $\Delta L = 2 \rightarrow L$ is not a symmetry of nature
    - Majorana nature of ν ($\nu = \bar{\nu}$)
    - constraints ν mass scale and hierarchy
    - effective Majorana mass ($m_{\beta\beta}$)

$$m_{\beta\beta} = \left|\sum_{k=1,2,3} U_{ek}^2 m_k\right|$$





A powerful technique: scintillating cryogenic calorimeters



$\Delta T(t) \sim \frac{E}{C} e^{-t/\tau}$

$\tau = \frac{C}{G}$

Working principle:

Sensitive to phonon contribution
(~ 100% of energy release) $T_0 \sim 15$ mK

Energy deposition read via T variation
$\Delta T(t) \sim \frac{E}{C} e^{-t/\tau}$ with $\tau = \frac{C}{G}$

arXiv.2503.04481

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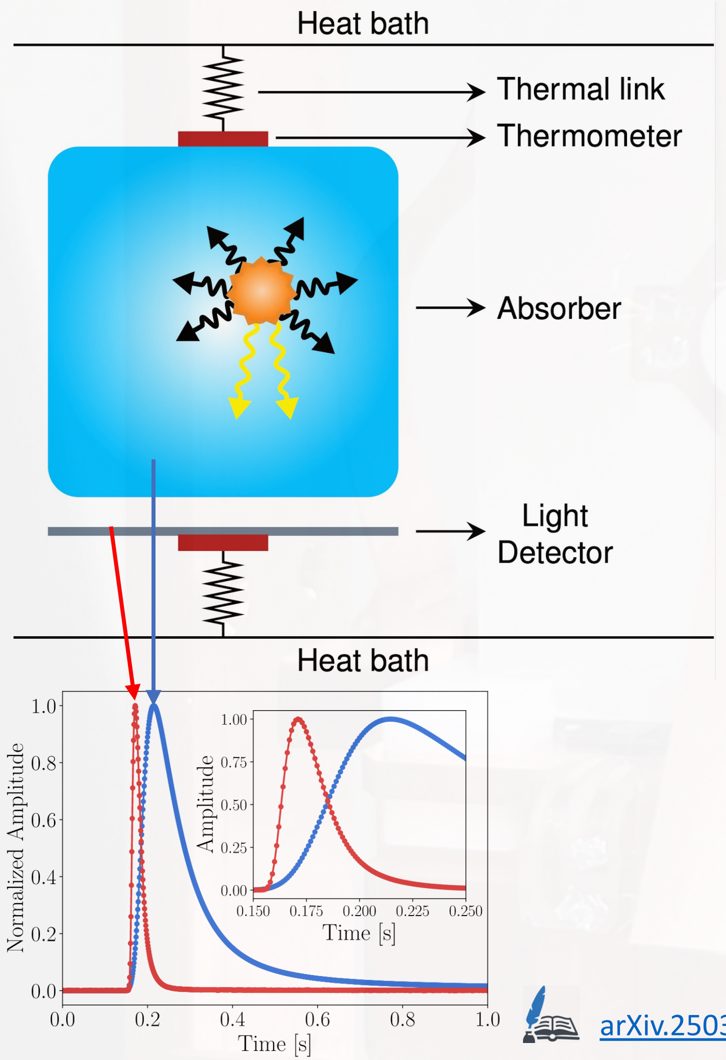

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Features:

- ✓ Excellent energy resolution (few keV FWHM @ 3 MeV)
- ✓ Scalability: array of detectors
- ✓ Large variety of absorbers
- ✓ Detector = Source approach

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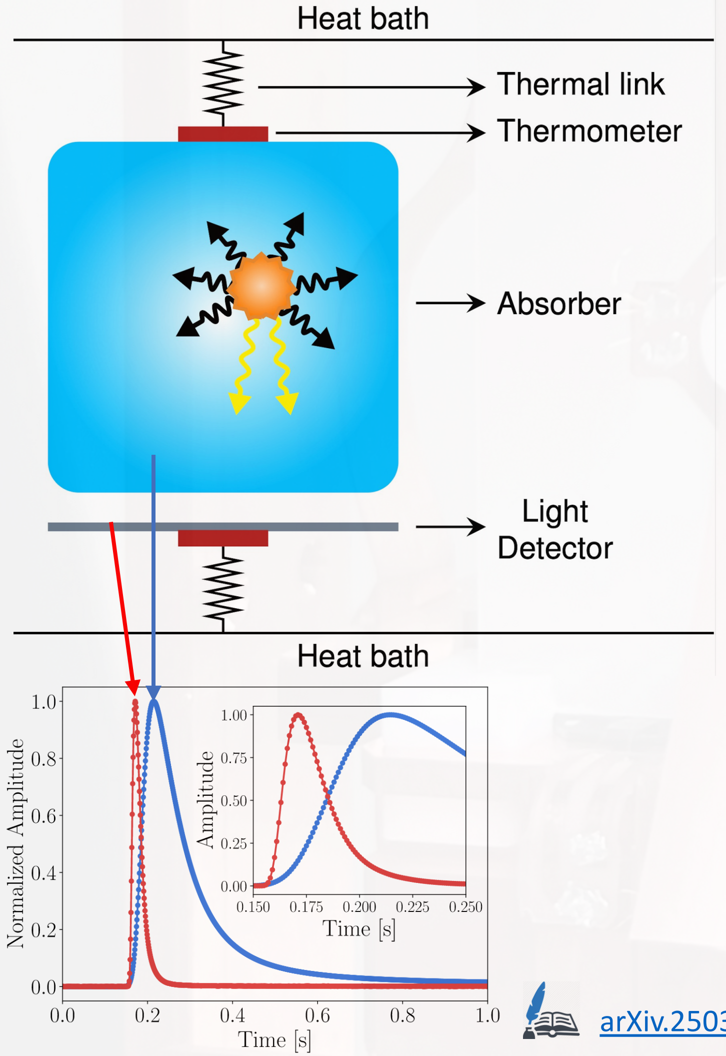

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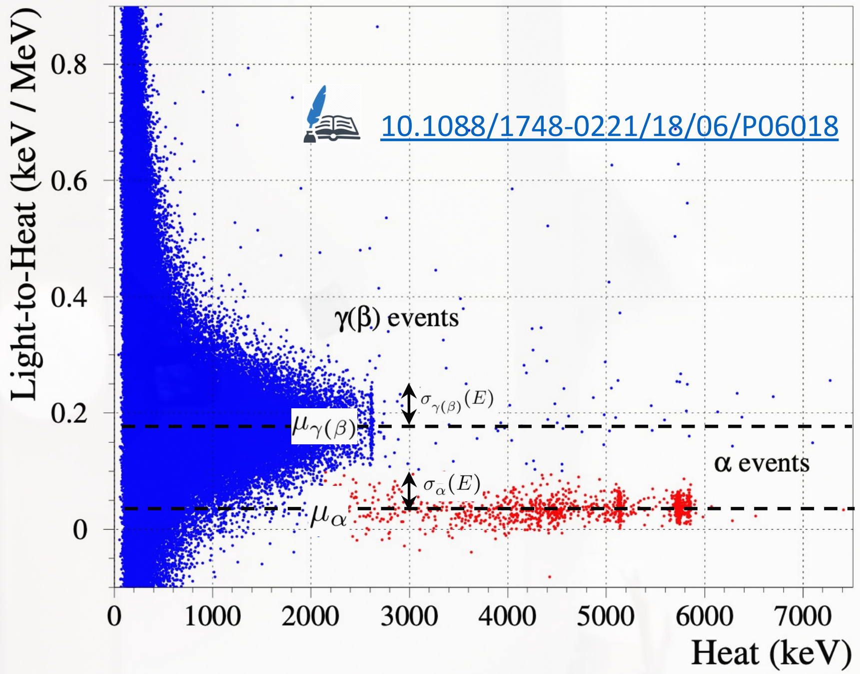
Features:

- ✓ Excellent energy resolution (few keV FWHM @ 3 MeV)
- ✓ Scalability: array of detectors
- ✓ Large variety of absorbers
- ✓ Detector = Source approach
- ✓ Efficient α background suppression by **Particle IDentification (PID)**



Dual channel (heat and light) readout allows for efficient suppression of α backgrounds.

Discrimination Power (DP):

$$\mathrm{DP}_{\alpha/\gamma(\beta)}(E) = \frac{|\mu_{\gamma(\beta)}(E) - \mu_{\alpha}(E)|}{\sqrt{\sigma^2_{\gamma(\beta)}(E) + \sigma^2_{\alpha}(E)}}$$

The CUPID Experiment

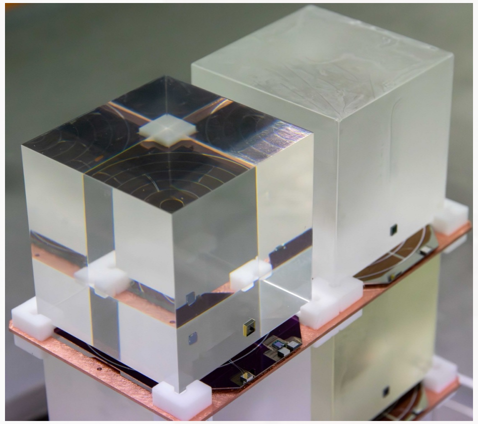
See Irene Nutini's talk for a presentation of **CUPID** and Pía Loaiza's talk for its sensitivity projections

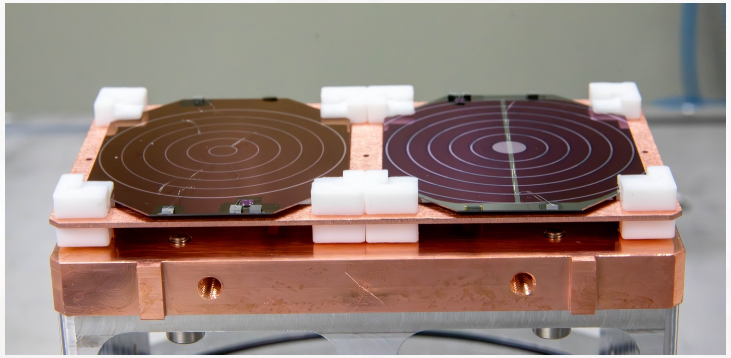
✓ **CUORE** cryostat + infrastructure

→ See Alice Campani's talk

Very large array:

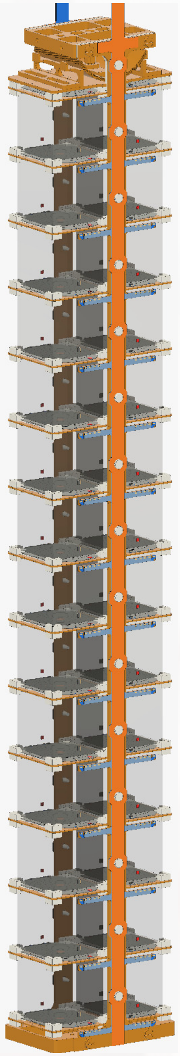
- 57 towers
  - 14 floors, 2 crystals per floor
- 1596 Li_2MoO_4 cryogenic calorimeters
- 1710 Ge light detectors
  - Neganov-Luke amplification
- 3306 Ge-NTD sensors





10.1140/epjc/s10052-025-14352-1

arXiv:2504.14369



The CUPID Li_2MoO_4 crystals

- **1596 Li_2MoO_4 crystals needed**
  - enriched in ^{100}Mo to ~ 95%
  - cubic 45×45×45 mm^3
  - ~285 g each
  - 450 kg $Li_2{}^{100}MoO_4$
  - 240 kg ^{100}Mo

- **Crystal quality requirements**
  - Ultra-high bulk radiopurity
    ^{232}Th < 5 μBq/kg, ^{238}U < 5 μBq/kg, ^{40}K < 1 mBq/kg
  - Ultra-high surface radiopurity
  - Excellent calorimetric performances (intrinsic gain, energy resolution)
  - Good β/γ Light Yield (LY)
  - Good crystal and optical quality
  - Ultra-high chemical purity

Enriched $Li_2{}^{100}MoO_4$ crystals procurement

- ✓ CUPID has established a supply chain for producing 1596 Li_2MoO_4 crystals grown with ~95% enriched ^{100}Mo
- ✓ **SICCAS** (Shanghai, China) has the capability to produce the enriched crystals
  SICCAS successfully produced the 988 **CUORE** TeO_2 crystals
- ✓ Isotope procurement done by SICCAS from IPC (CNNC, China)
- ✓ The first sample of isotope, measured by ICP-MS at LNGS, fully matches radiopurity requirements

Shanghai Institute of Ceramics, Chinese Academy of Sciences

Current status:

- ➢ **Pre-production phase**
  funded by INFN (Italy) and CNRS (France)
- ➢ Validation of the pre-production crystals
- ➢ Constant interaction with SICCAS to finalize the definition of a radiopurity protocol

CUPID crystal validation program

<u>Pre-production phase</u> goals:

- Optimize production yield at SICCAS to minimize isotope loss during crystal growth and cutting
- Define a radiopurity protocol, with continuous monitoring of raw materials, auxiliaries, intermediate products, and final crystals
- Improve light yield and transmission (surface quality)
- Establish a validated CCVR protocol

How: *Both **natural** and **enriched** crystals produced during this phase.*

→ **Pre-CCVR** measurement campaign

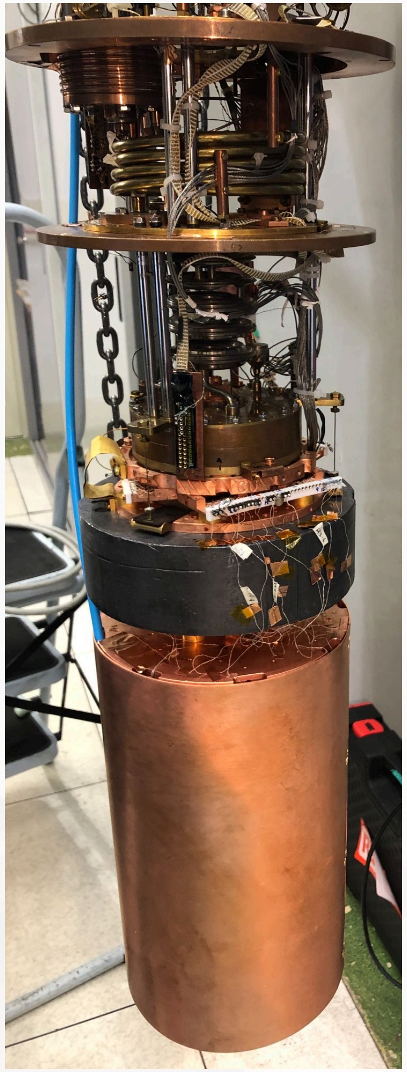
<u>Production phase</u> goal: continuous monitoring of the 1596 enriched crystals **during full scale production** to:

- Assess radiopurity
- Ensure calorimetric and scintillation properties stability

→ CUPID **C**rystal **V**alidation **R**uns **"CCVR"**

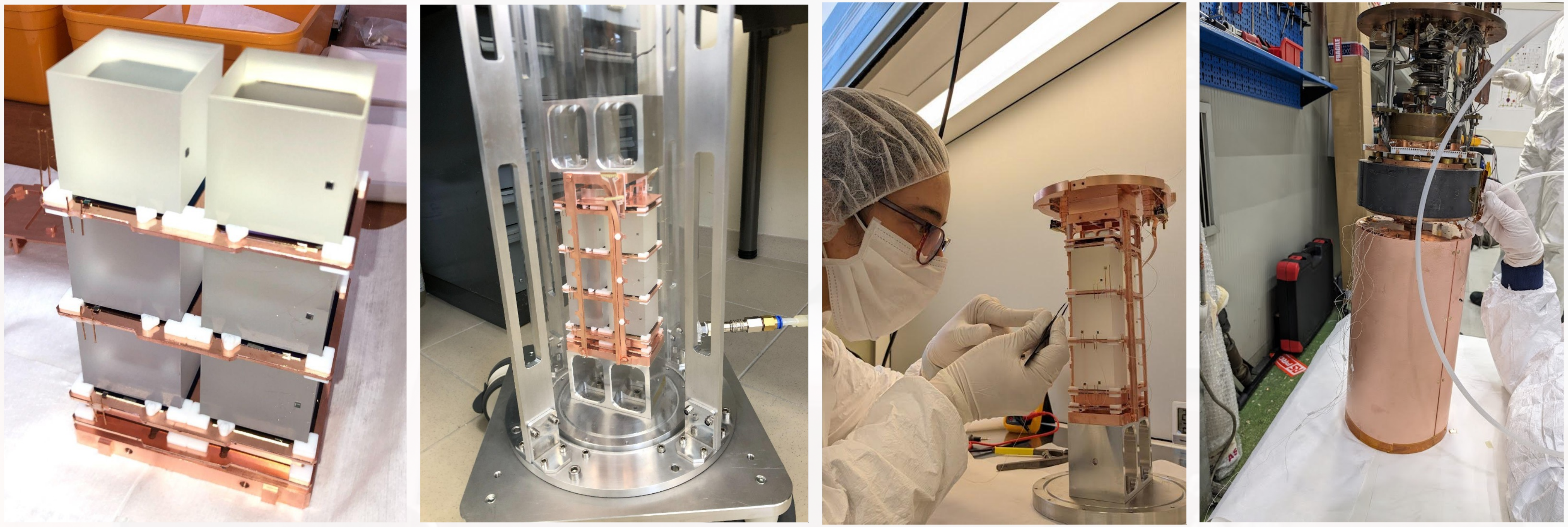
Defining a CCVR protocol

- **Facility**:
  - Low-background for radiopurity assessment
    → **LNGS underground laboratory, shielded cryostat**
  - Low-noise cryostat for calorimetric performance assessment and optimal operation of light detectors → **Same cryogenic facility used to validate CUORE crystals**
  - Clean room availability for detector assembly
- **Data-taking**:
  - Dedicated calibration runs at different Working Points (WP) to measure crystal properties:
    - Calorimetric performance (intrinsic gain and energy resolution)
    - Scintillation performance (light yield)
  - ~ 1 month background runs to assess radiopurity
- **Analysis strategy**:
  - Validated CUORE/CUPID processing software to ensure trustable and reproducible results
  - Coincidence studies to assess surface radiopurity



The pre-CCVR campaign

- SICCAS provided the first natural crystals at the end of 2023
- Pre-CCVR measurement on **natural** crystals began in early 2024
- Pre-CCVR measurements on the first batches of **enriched** crystals are currently **ongoing**



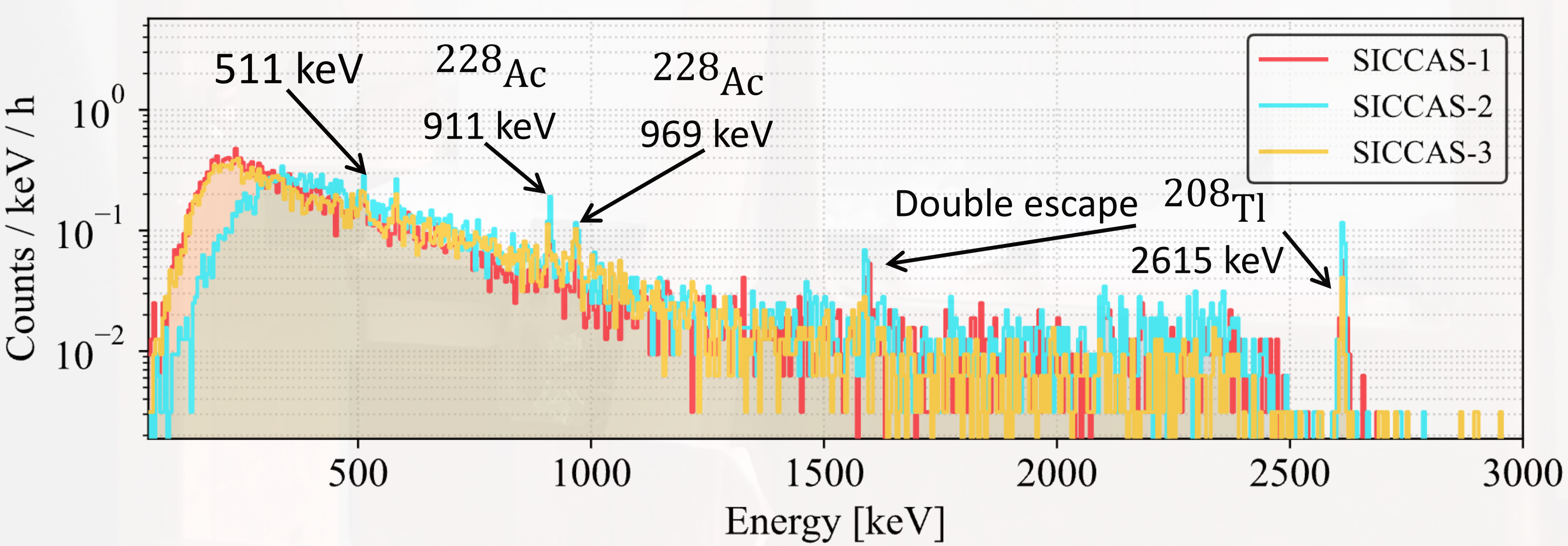
Gran Sasso National Laboratories (LNGS) - CUPID underground cryogenic facility

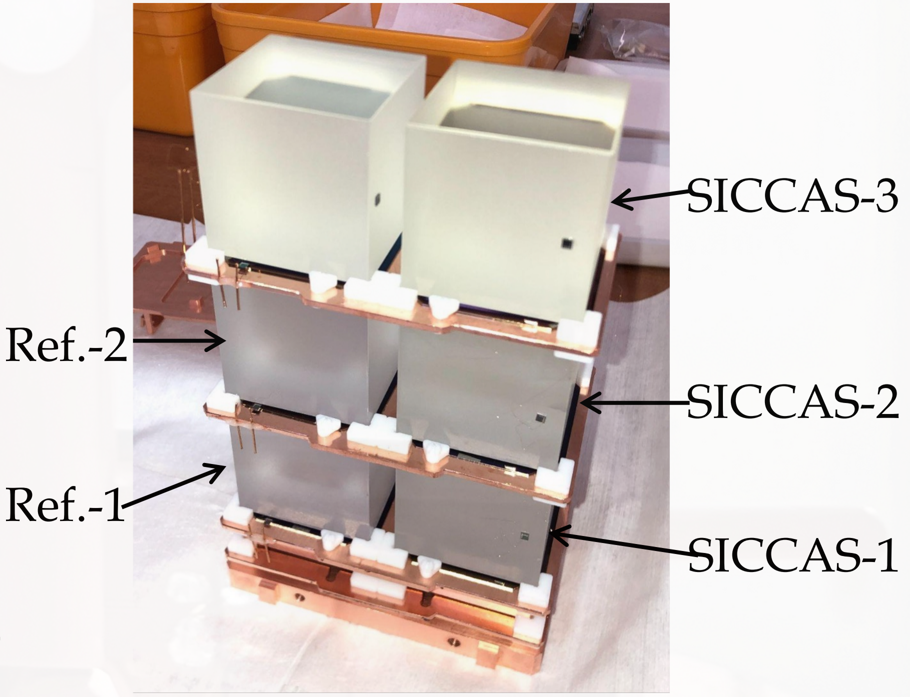
Calorimetric performance of the first batch of natural crystals

- Three natural pre-production crystals tested (SICCAS-1, SICCAS-2, SICCAS-3)
- No strict radiopurity requirements were applied to raw material selection or crystal growth for this first batch
- Results compared against two reference crystals (Ref.-1, Ref.-2) from the same producer as the CUPID-Mo demonstrator
- Ref. crystals were also measured separately before starting the pre-CCVR campaign
- Each crystal was coupled to two light detectors (LD Top and LD Bottom)

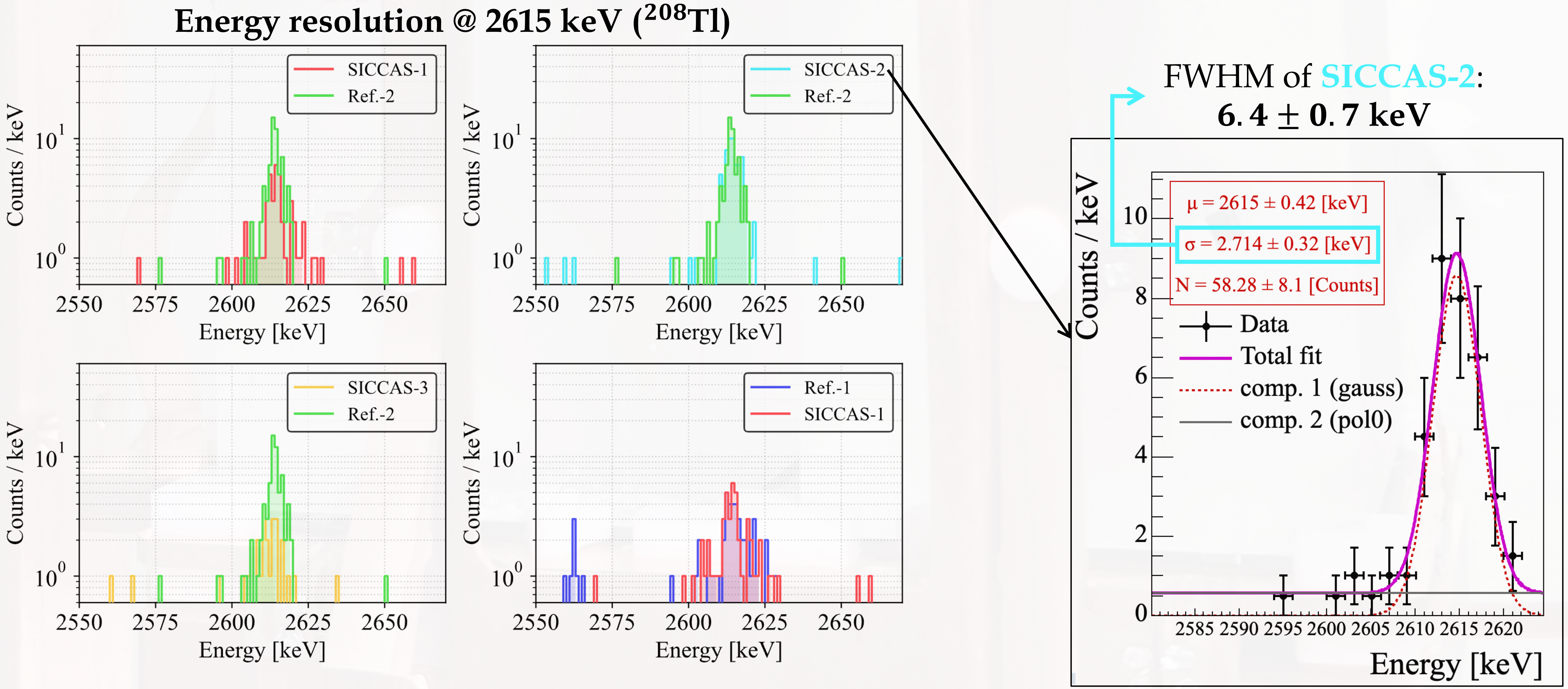
10.1140/epjc/s10052-022-10942-5

Calibration spectrum (~ 4 days with external ^{232}Th sources)





Calorimetric performance of natural crystals



Energy resolution of SICCAS crystals and Ref. crystals are comparable

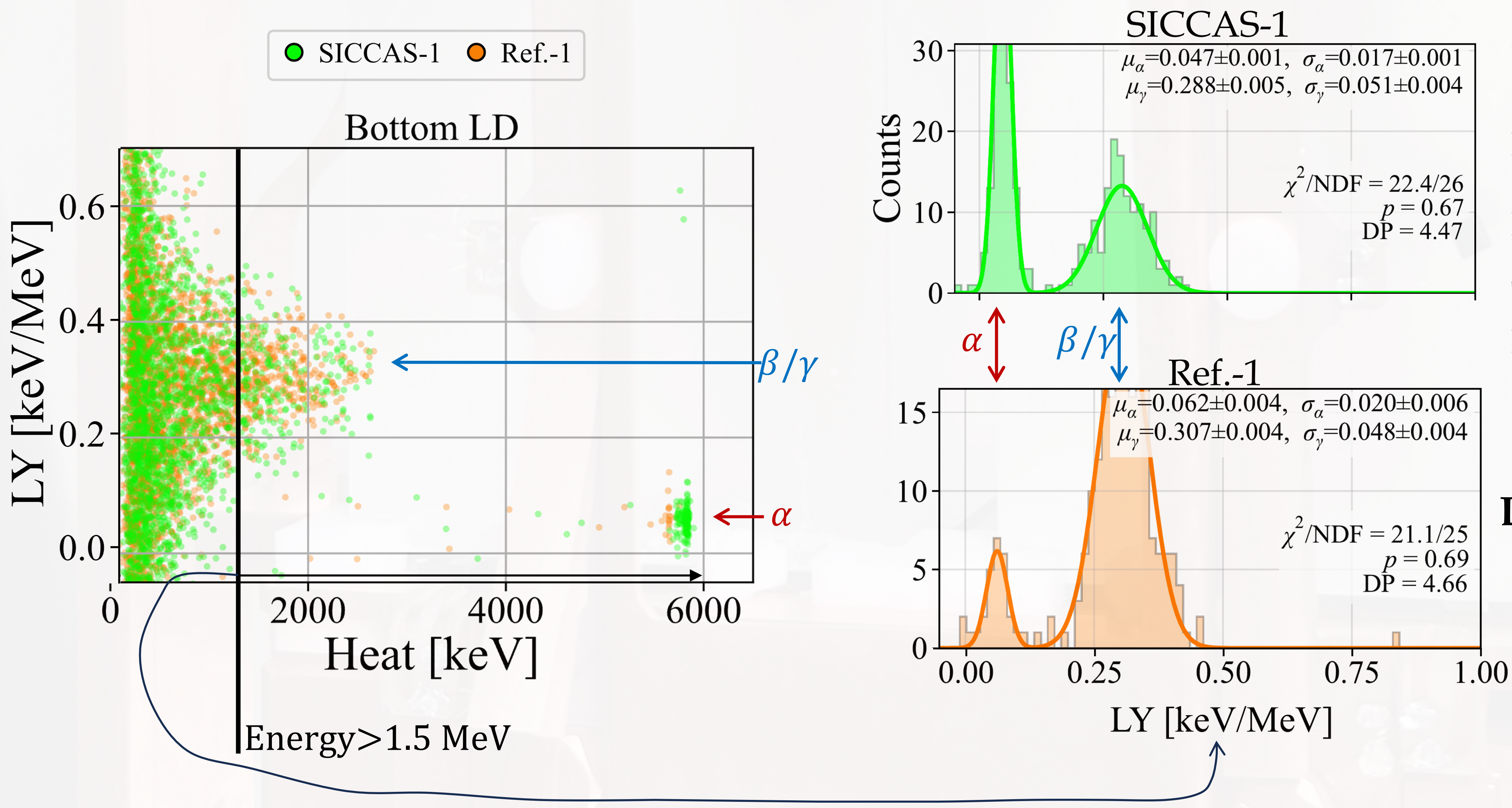
Calorimetric performance of natural crystals

Crystal	FWHM @ Baseline [keV]	FWHM @ 2615 keV [keV]	Intrinsic gain [nV / keV]
Ref.-1	6.6 ± 0.1	9.6 ± 2.6	~ 13
Ref.-2	3.0 ± 0.9	5.8 ± 0.9	~ 23
SICCAS-1	6.2 ± 0.1	6.9 ± 0.9	~ 12
SICCAS-2	5.2 ± 0.1	6.4 ± 0.7	~ 17
SICCAS-3	4.3 ± 0.3	6.3 ± 2.4	~ 25

SICCAS crystals show excellent calorimetric performance

- Large uncertainties are due to limited statistics
- Overall performance of SICCAS crystals is comparable to the reference ones
- Small differences across channels can be attributed to working point selection (WP not fine-tuned in these measurements)
- The first batch of pre-CCVR SICCAS natural crystals demonstrates very good calorimetric performance

Light Yield of natural crystals



Discrimination Power (DP) depends also on the performance of the LDs and is not solely a property of the crystal.

The LY is the key parameter of the crystals and directly influences DP

LY of SICCAS crystals and Ref. crystals are comparable

Light Yield of natural crystals

Crystal	LY LD Top [keV/MeV]	LY LD Bottom [keV/MeV]
Ref.-1	0.28 ± 0.05	0.31 ± 0.05
Ref.-2	x	x
SICCAS-1	0.29 ± 0.05	0.30 ± 0.07
SICCAS-2	0.28 ± 0.05	0.30 ± 0.06
SICCAS-3	0.24 ± 0.06	0.29 ± 0.04

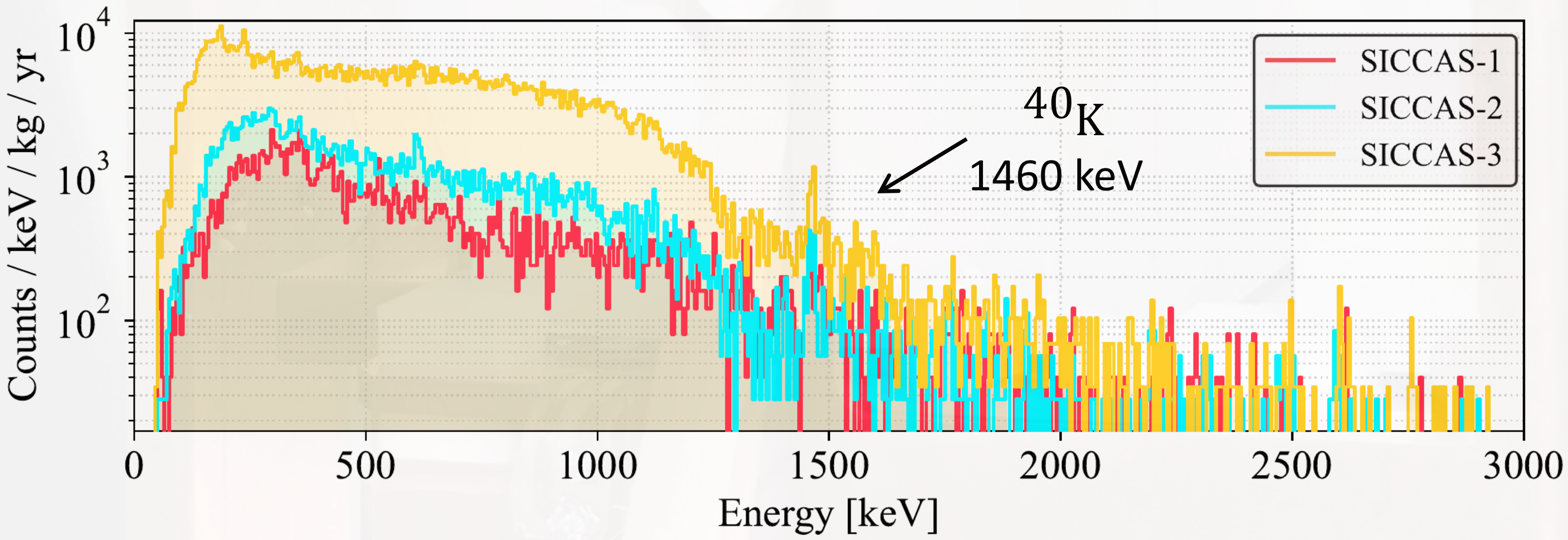
SICCAS crystals have good LY and can be used for PID

- LY values are not corrected for geometric light collection efficiency
- Overall scintillation performance of SICCAS crystals is comparable to the reference ones
- Some malfunctioning light detectors prevented the LY measurement of Ref.-2
- LY of SICCAS crystals is consistent with Ref.-1 as well as previous measurements on other Ref. crystals
- LY of SICCAS crystals is also consistent with values reported in the literature for similar detector geometries (e.g., arXiv.2503.04481)

Radiopurity of natural crystals

- **This growth did not employ raw materials selected for ultra-high radiopurity**
- Goals of the background measurement:
  - Provide initial feedback to SICCAS
  - Define a data analysis strategy for future background studies on enriched pre-production crystals

Background (~ 10 days, without PID, corrected for cut efficiencies)



Results from data + MC simulations:

- SICCAS-2 and SICCAS-1: bulk ^{40}K contamination $\leq 5\ m$Bq/kg (conservative estimate)
- SICCAS-3: bulk ^{40}K contamination $\leq 15\ m$Bq/kg (conservative estimate)

Raw materials meeting strict radiopurity requirements will be used for the growth of enriched crystals

Final enriched crystals will meet radiopurity requirements thanks to the inputs from the pre-CCVR program

Conclusions

CUPID is establishing a **crystal validation program** that is essential to guarantee ultra-high radiopurity, excellent calorimetric performance, and stable scintillation properties throughout **large-scale production**:

- First tests on natural pre-production SICCAS crystals show:
  - ✓ Excellent calorimetric performance, comparable to reference crystals
  - ✓ Light yield values consistent with both reference crystals and literature
- Pre-CCVR background measurements on enriched crystals are guiding the finalization of a radiopurity protocol with SICCAS

Next steps:

- Pre-CCVR measurements on the **first batches of enriched pre-production crystals** are currently **ongoing** and first data show excellent calorimetric and scintillation performance
- CUPID is finalizing a validated CCVR program

Thanks for your attention!

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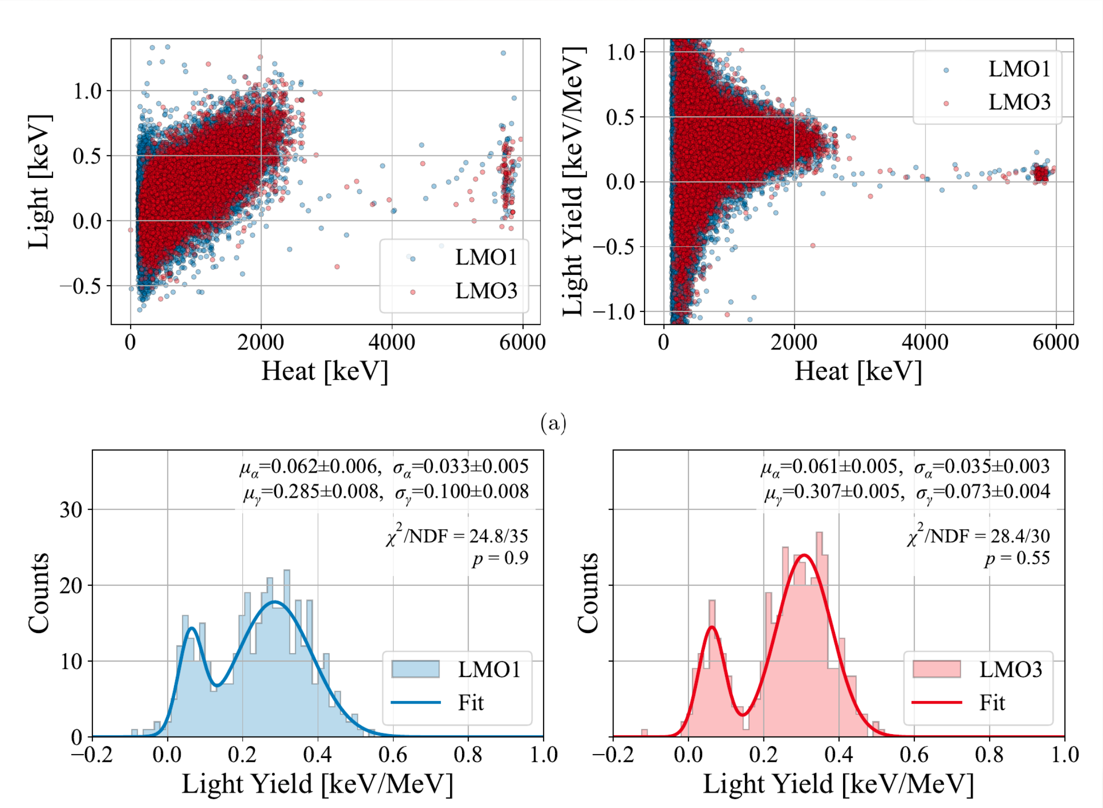
Other materials

Light Yield of natural crystals

Crystal	LY LD Top [keV/MeV]	LY LD Bottom [keV/MeV]
Ref.-1	x	0.31 ± 0.05
Ref.-2	x	x
SICCAS-1	0.29 ± 0.05	0.30 ± 0.07
SICCAS-2	0.28 ± 0.05	0.30 ± 0.06
SICCAS-3	0.24 ± 0.06	0.29 ± 0.04

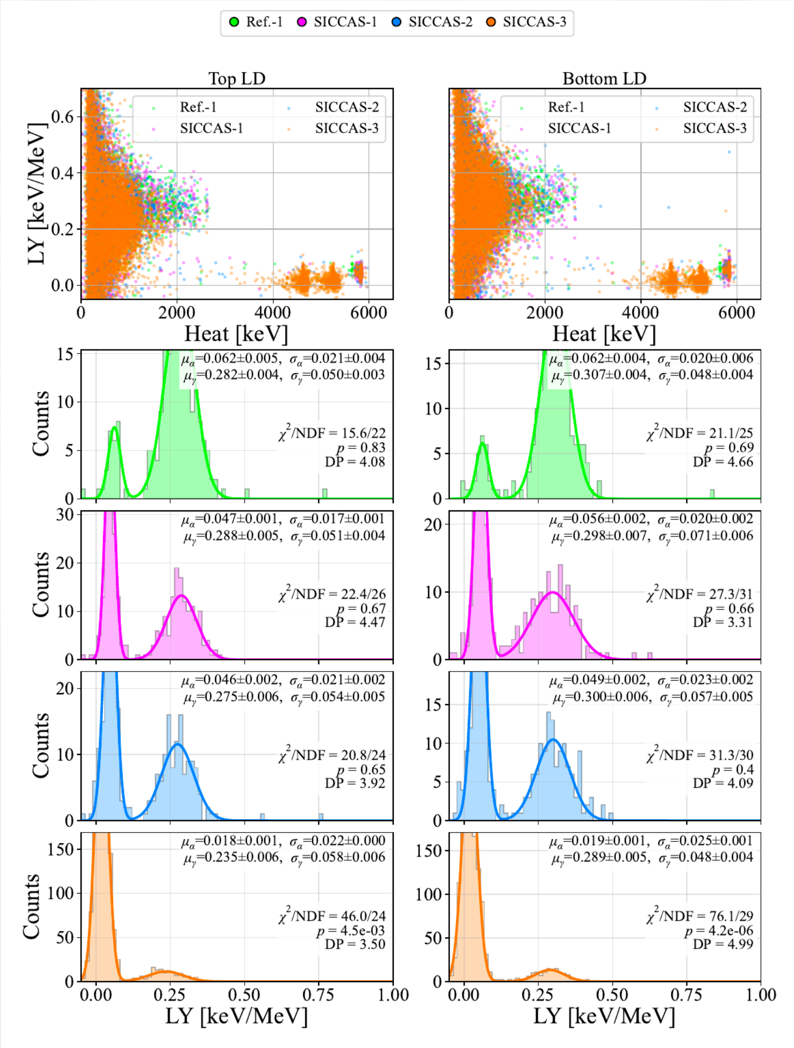
Ref. crystals measured separately* before pre-CCVR on SICCAS crystals



Crystal	LY LD Top [keV/MeV]	LY LD Bottom [keV/MeV]
Ref.-1	0.28 ± 0.10	x
Ref.-3	x	0.30 ± 0.07
Ref.-2	x	x

*slightly different geometry

Light Yield pre-CCVR

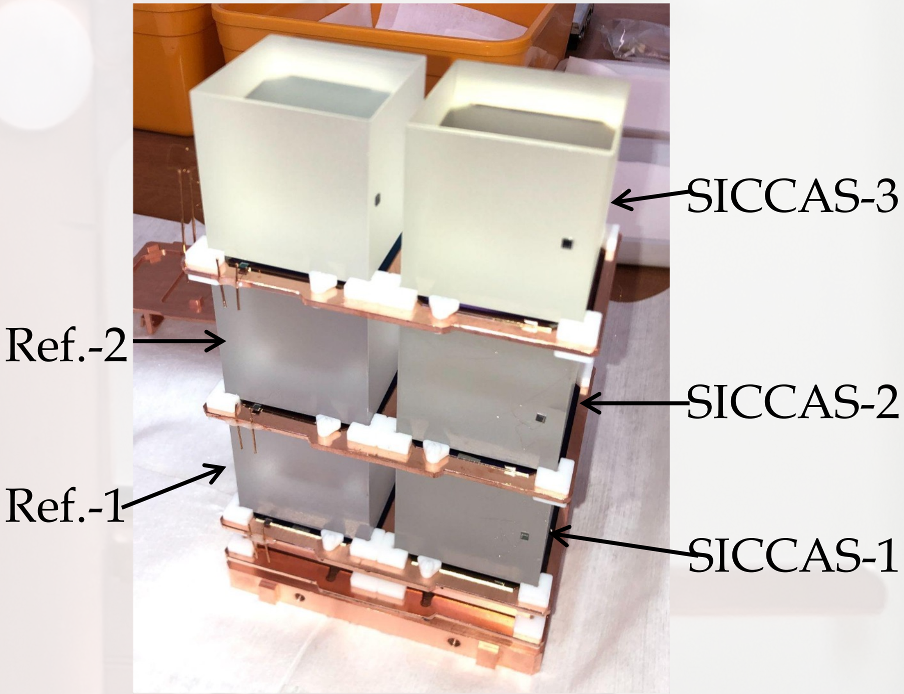


Ref.-1

SICCAS-1

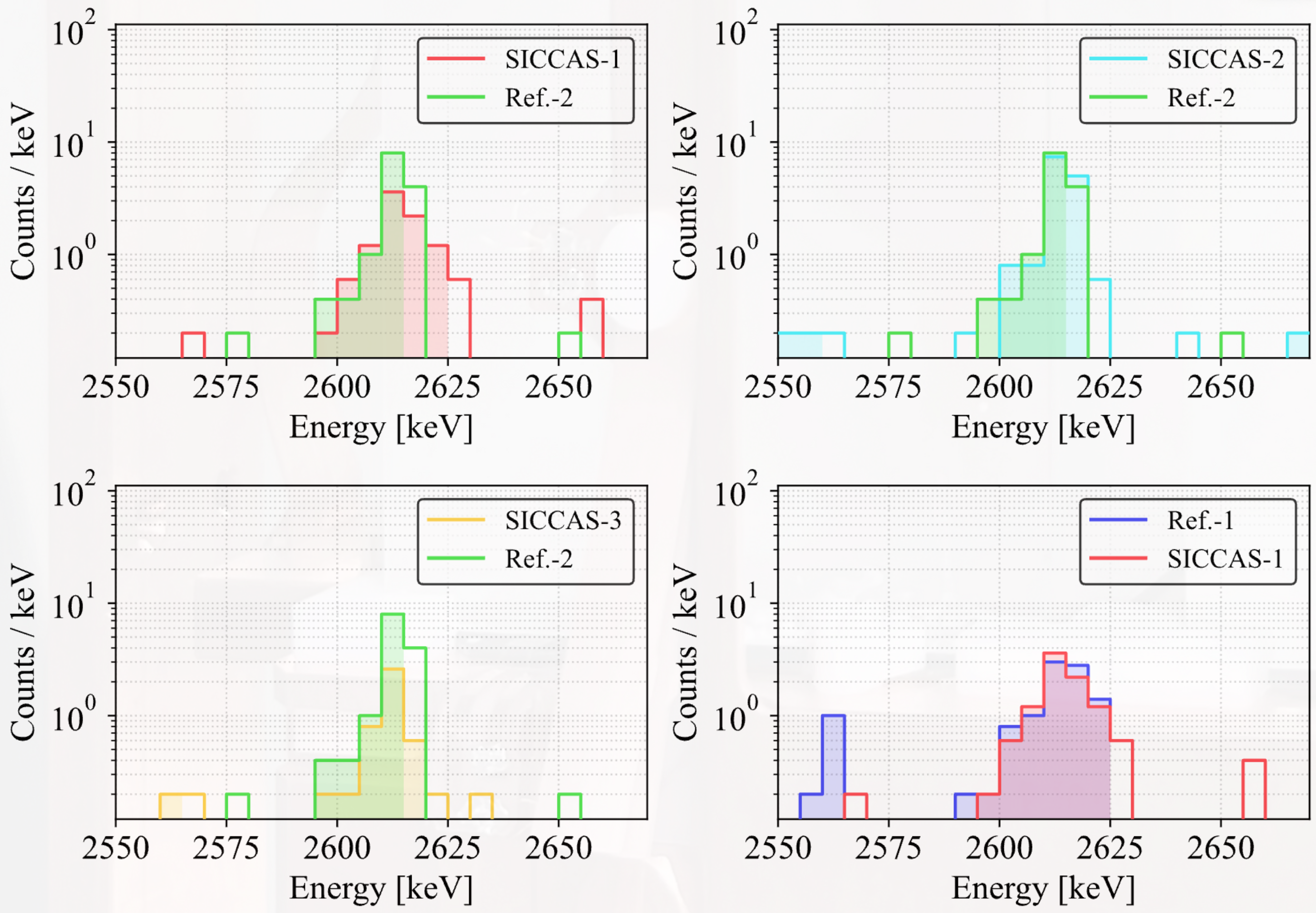
SICCAS-2

SICCAS-3

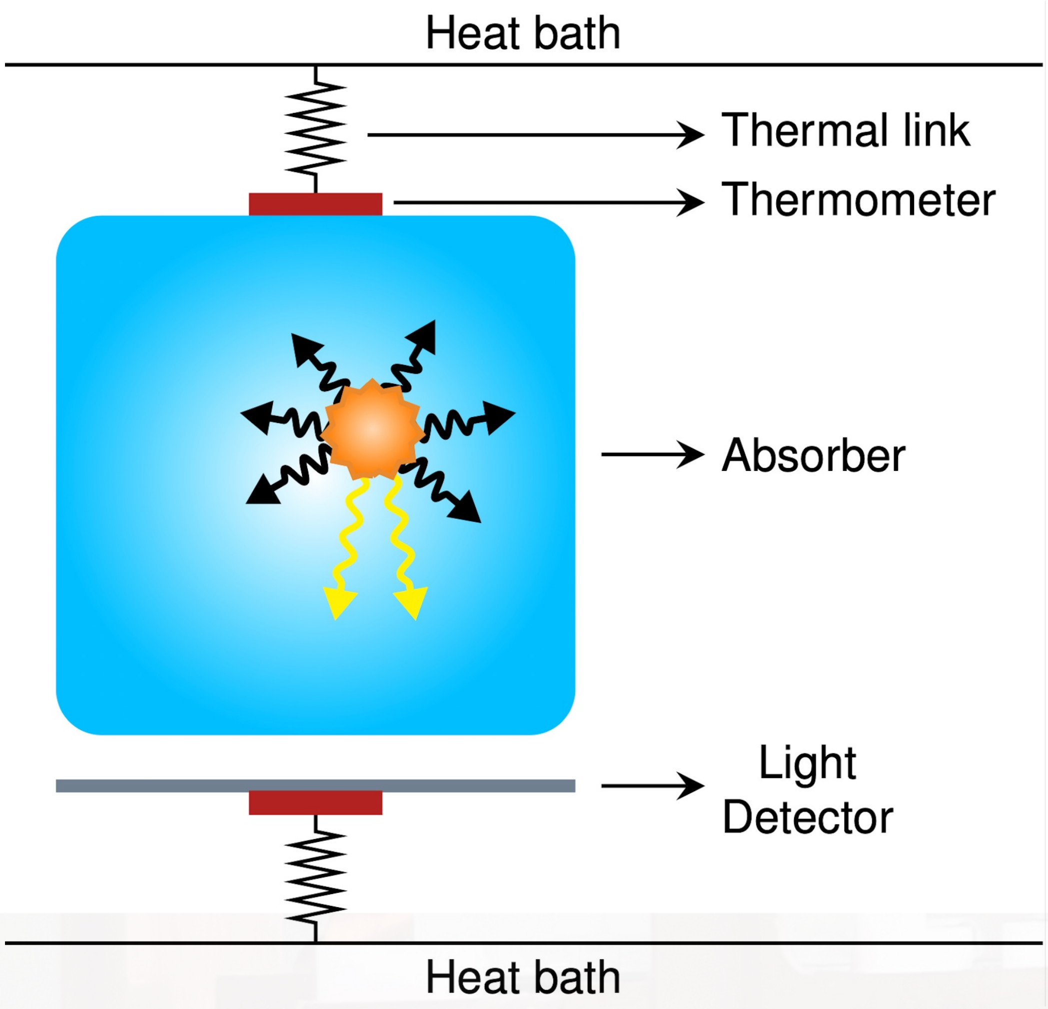


Calorimetric performance of natural crystals (different binning)

Energy resolution @ 2615 keV (^{208}Tl)

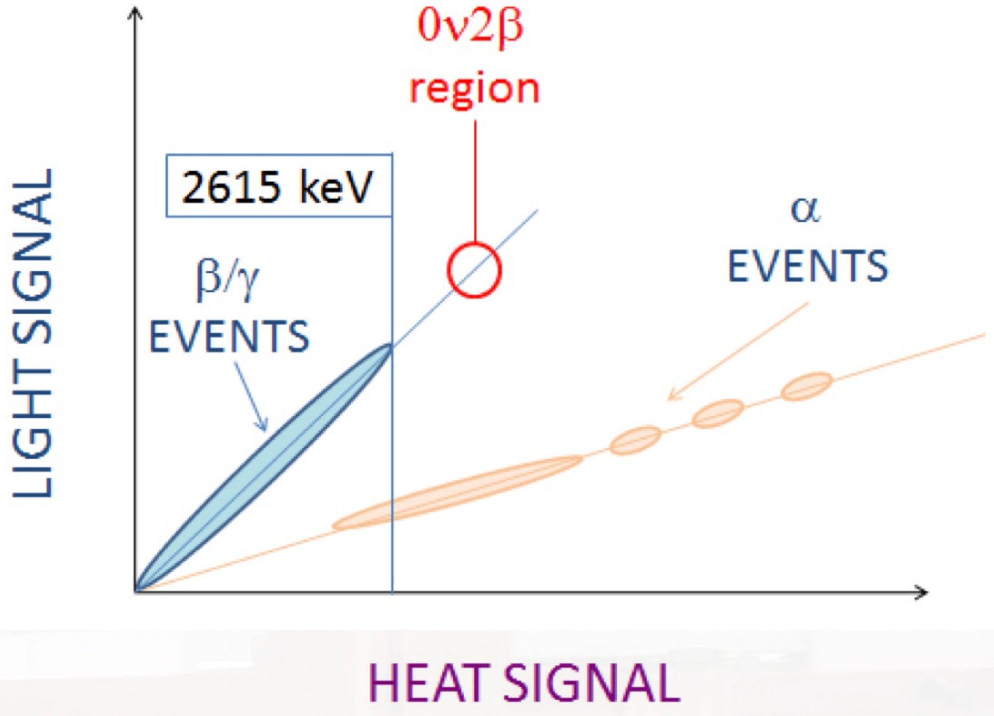


The **CUPID** experiment (**C**UORE **U**pgrade with **P**article **ID**entification)

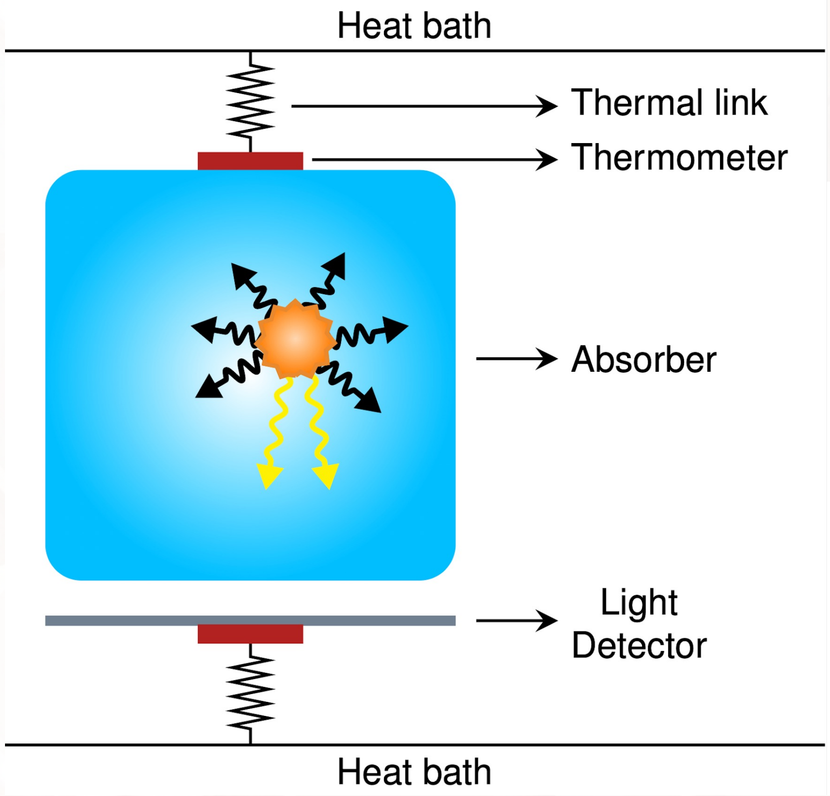


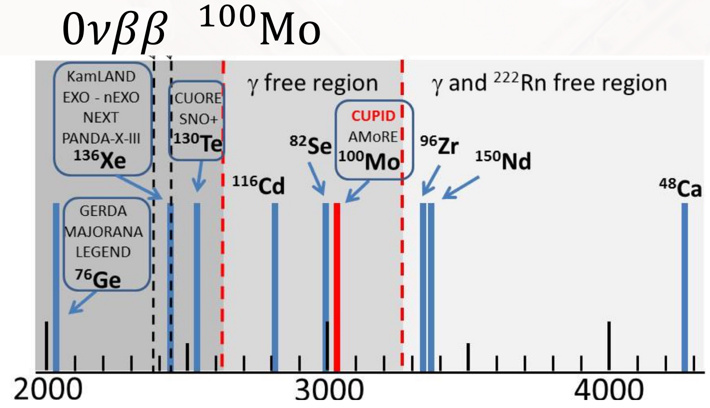
Scintillating cryogenic calorimeters:

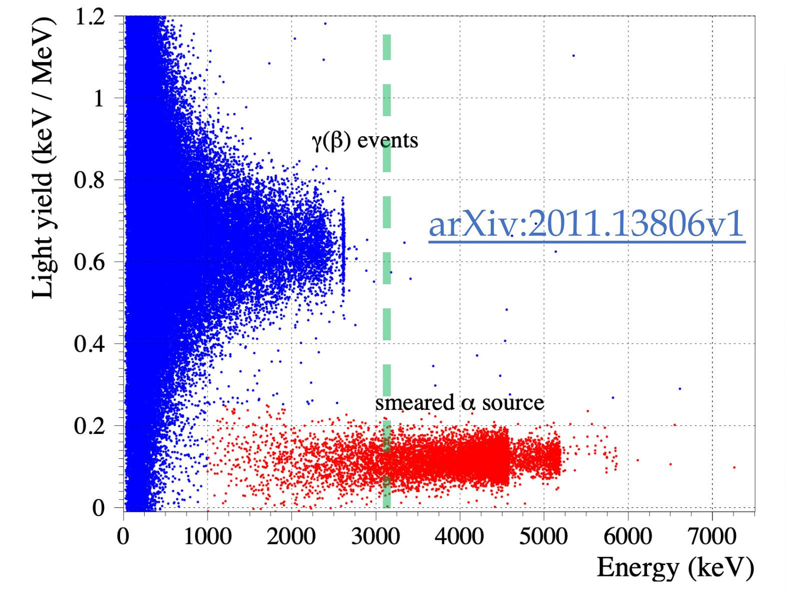
- active event-by-event particle identification strategy
- α - β/γ discrimination



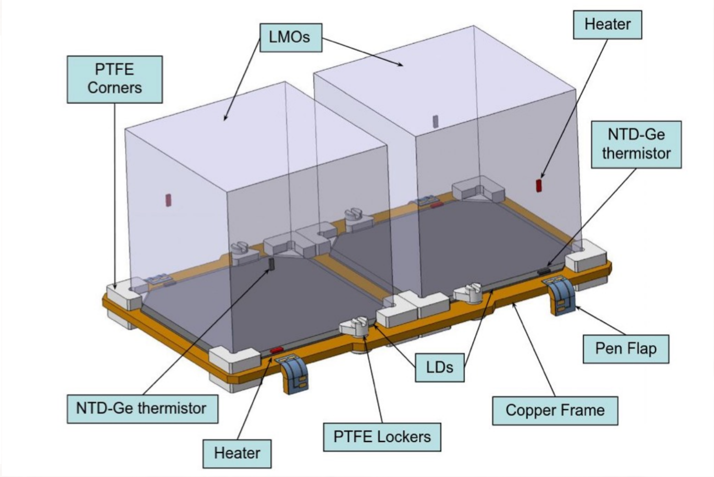
CUPID





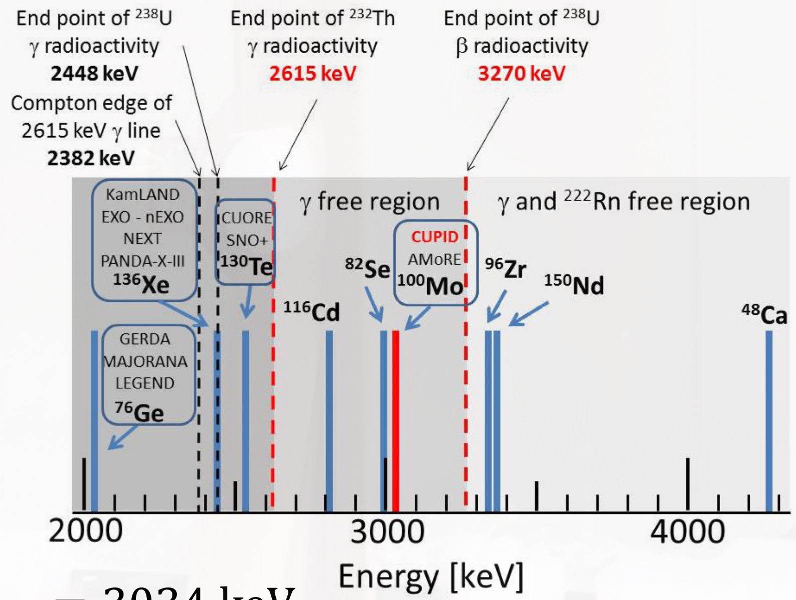


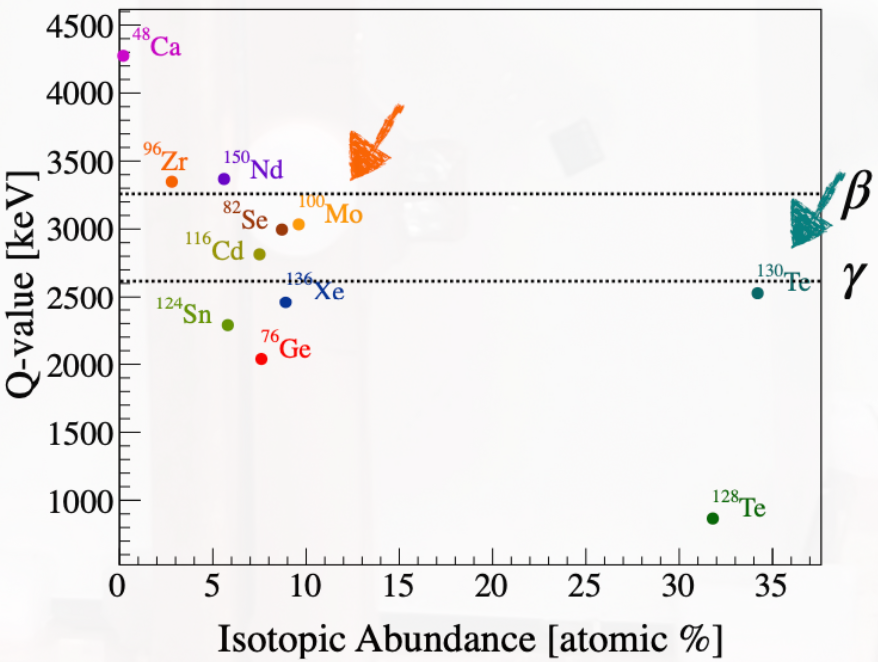
arXiv:2011.13806v1



CUPID: crystal and isotope selection

Choice criterion: **Balance** between **performance** (background, energy resolution, detector performance) and **feasibility** (cost, isotope enrichment, crystal growth).





$0\nu\beta\beta$ of ^{100}Mo $Q_{\beta\beta} = 3034$ keV

- Q-value above most of natural radioactivity
- good quality scintillating crystal for good $\alpha - \beta/\gamma$ discrimination → $Li_2{}^{100}MoO_4$
- existing enrichment technology

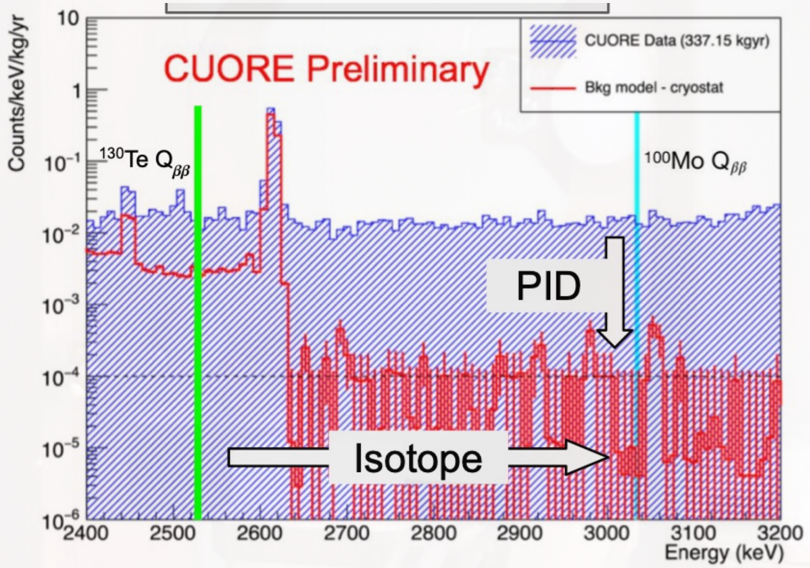
Towards a next-generation experiment

Main limitation to the CUORE sensitivity is background:

- ***Degraded*** $\boldsymbol{\alpha}$ **particles** (which lose energy before interacting with the crystal)
  - **dominant** component (~90% contribution to the *background index*)
  - from radioactive decays on the surface of nearby materials
  - from decays in the surface of crystals

- $\boldsymbol{\gamma}$ **backgrounds**
  - From radioactive chains $^{232}Th/^{238}U$ contaminants in the crystals and surrounding materials

CUPID background reduction



from CUORE to CUPID:

×100 background reduction in the ROI

achieved with **PID + isotope selection**

average CUORE background index in the ROI (preliminary)

CUPID projected background index: $\leq 10^{-4}$ cts/(keV · kg · yr)

Next-next generation experiment: CUPID-1T

CUPID-1T:

- 4× scale up – larger or multiple cryostat
- 1000 kg of ^{100}Mo

Parameter	CUPID baseline	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	450	450	1871
^{100}Mo mass (kg)	240	240	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	78%	78%	78%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.4×10^{27} y	2.2×10^{27} y	9.1×10^{27} y
Half-life discovery sensitivity (3σ)	1×10^{27} y	2×10^{27} y	8×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV	8.4–14 meV	4.1–6.8 MeV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	9–15 meV	4.4–7.3 meV