CUPID-Mo results
New limit on the 0νββ decay of ^{100}Mo

Dounia Helis on behalf of the CUPID-Mo collaboration

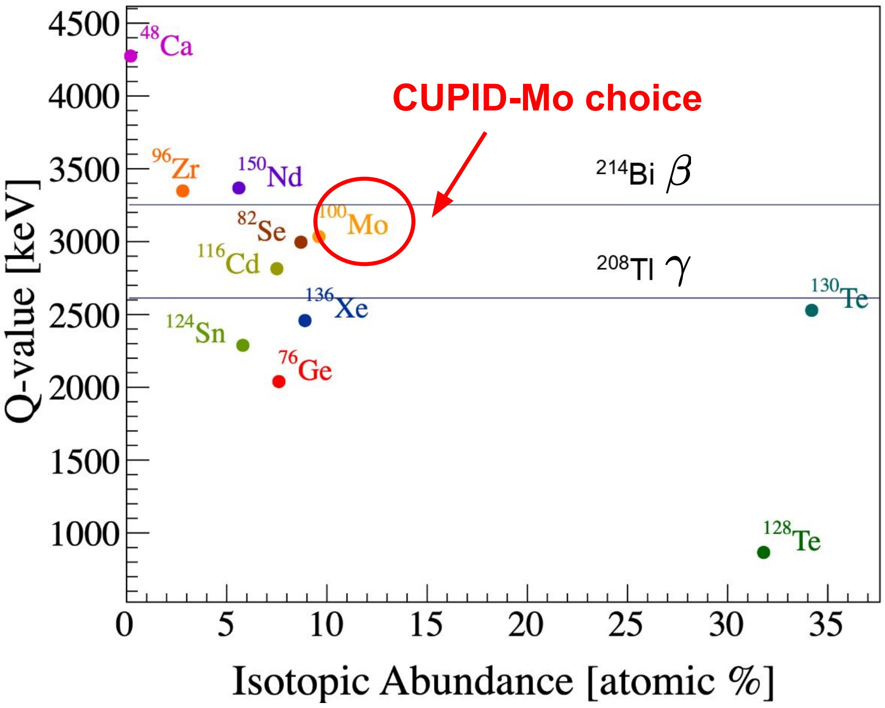
GDR Deep Underground Physics kick-off meeting

31/05/2021

Outline

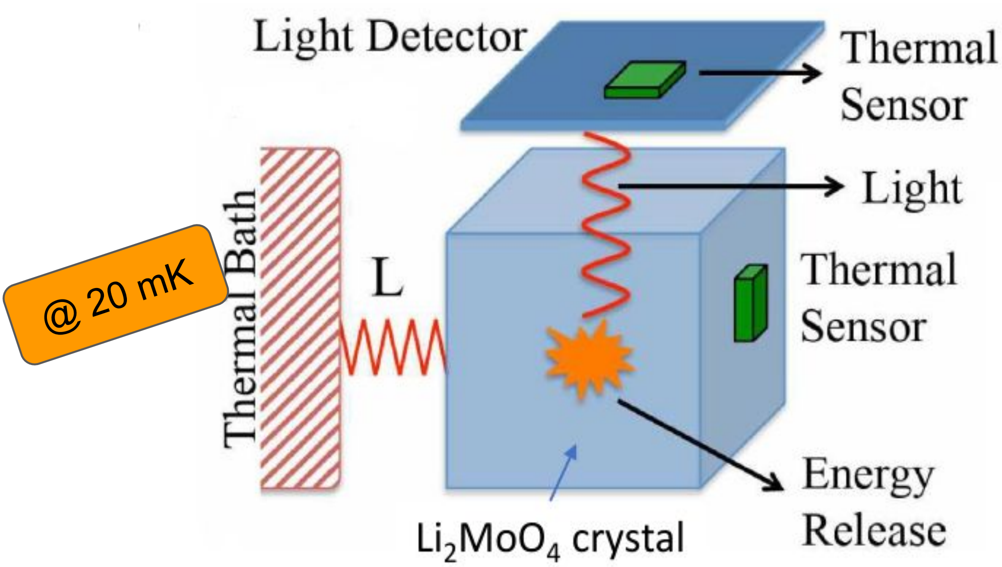
- $0\nu\beta\beta$ decay of ^{100}Mo in Li_2MoO_4 crystals
- Scintillating bolometers
- From LUMINEU to CUPID-Mo
- The CUPID-Mo detector array
- CUPID-Mo detector performances
- Analysis chain
- Search for $0\nu\beta\beta$ decay of ^{100}Mo

Why ^{100}Mo ?



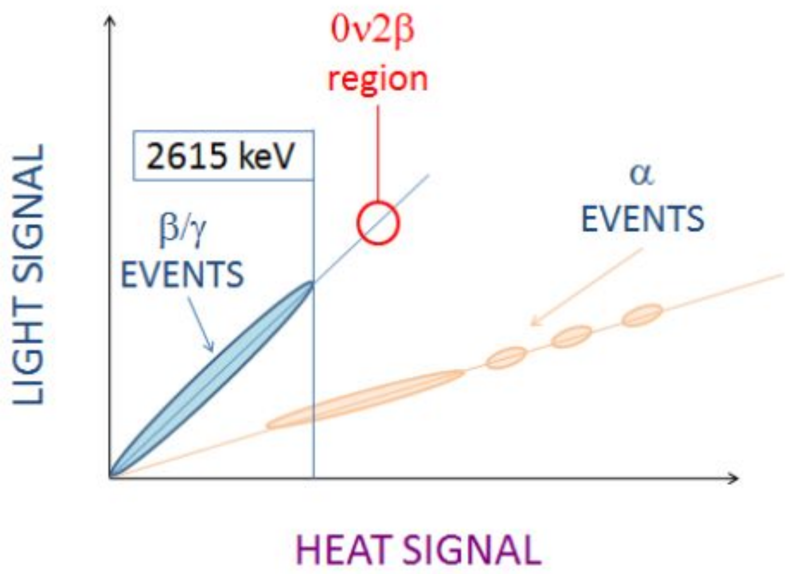
- $^{100}Mo \rightarrow ^{100}Ru + 2e^-$
- $Q_{\beta\beta}$ = 3034 keV
- I.A. = 9.7%
- Enrichable by gas centrifugation
- Can be embedded in scintillating crystals ⇨ **Li_2MoO_4 crystals**

Scintillating bolometers



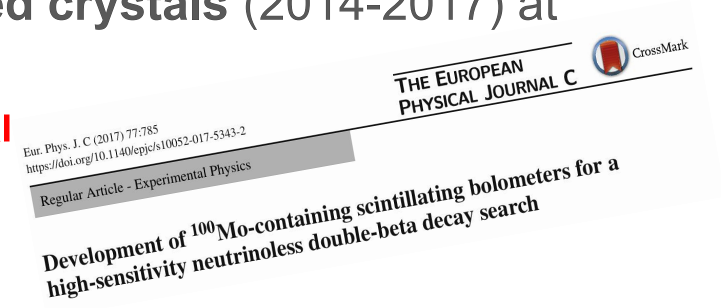
CUPID-Mo thermal sensor: **Neutron Transmutation Doped Ge (NTD-Ge)**

- Bolometer=high energy resolution
- Double readout ⇒ particle ID and full α/β(γ) separation
- Source=detector ⇒ high efficiency



From LUMINEU to CUPID-Mo

- The technology based on scintillating bolometers with **$Li_2{}^{100}MoO_4$** crystals was successfully developed by LUMINEU
- **Multiple** tests were done with **natural and enriched crystals** (2014-2017) at **LSM** and LNGS leading to important results:
  - High-purity crystals → **negligible loss of enriched material**
  - Reproducibility → excellent performance uniformity
  - Energy resolution → **4-6 keV FWHM in ROI**
  - α/β separation power → **> 99.9 %**
  - Internal radiopurity → **< 5 μBq/kg in ^{232}Th, ^{226}Ra; < 5 mBq/kg in ^{40}K**



Eur. Phys. J. C (2017) 77:785
https://doi.org/10.1140/epjc/s10052-017-5343-2

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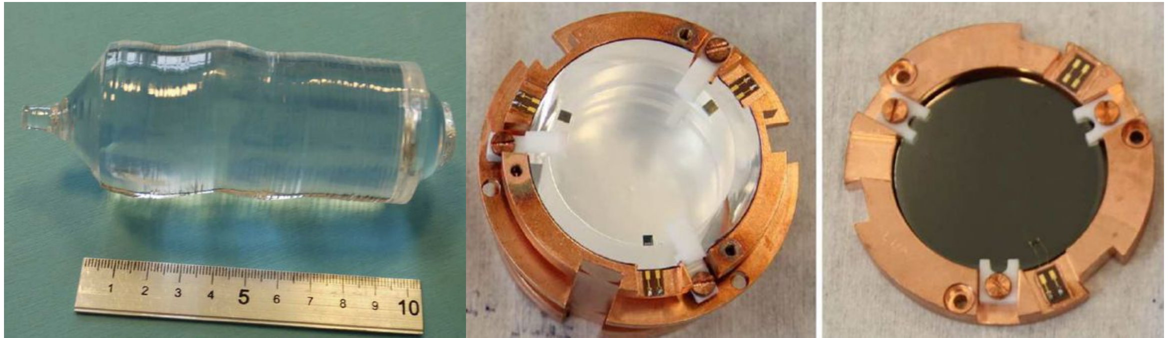
Regular Article - Experimental Physics

Development of ^{100}Mo-containing scintillating bolometers for a high-sensitivity neutrinoless double-beta decay search

Compatible with

$b \lesssim 10^{-4}$ [counts/(keV kg y)]

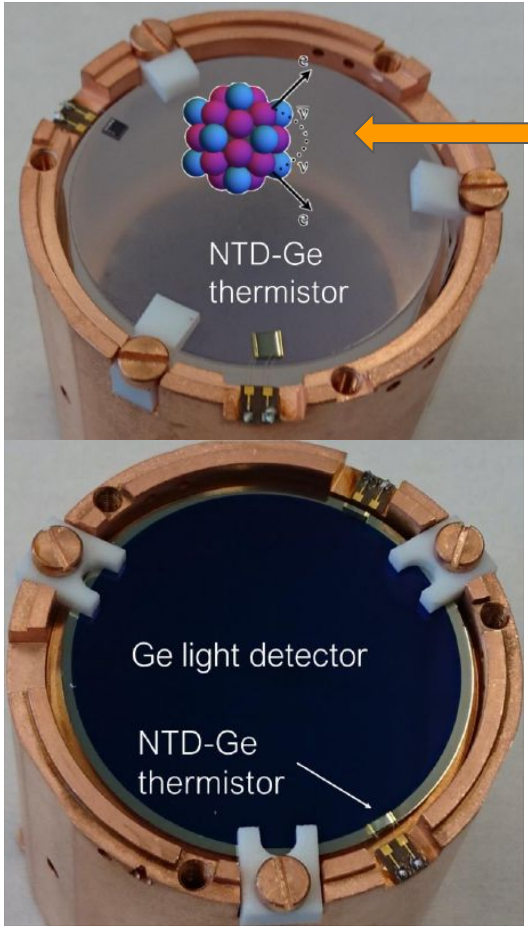
NIM A 729, 856 (2013)
JINST 9, P06004 (2014)
EPJC 74, 3133 (2014)
JINST 10, P05007 (2015)
AIP Conf. 1894, 020017 (2017)



The CUPID-Mo collaboration

CUPID-Mo detectors

Single module

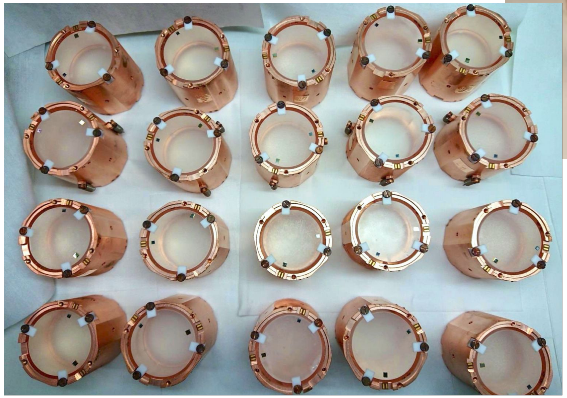


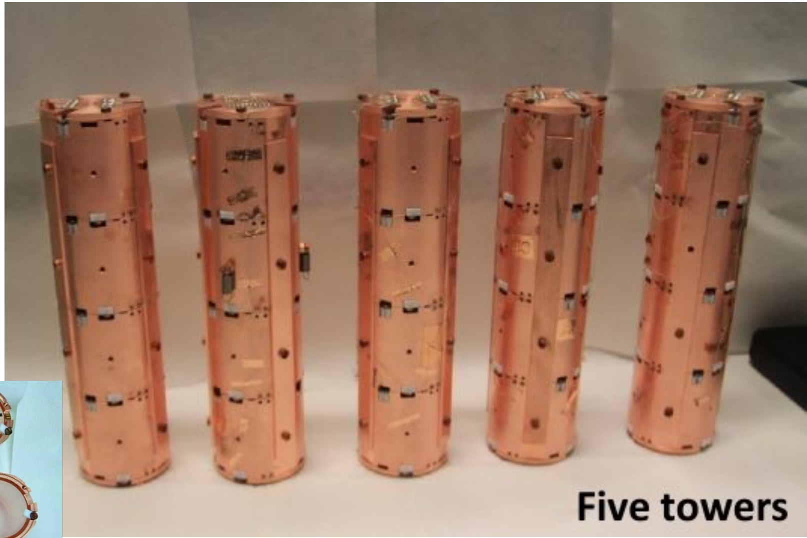
Copper = thermal bath

Teflon = weak thermal link

Source ^{100}Mo = Detector $Li_2{}^{100}MoO_4$
High efficiency

× 20



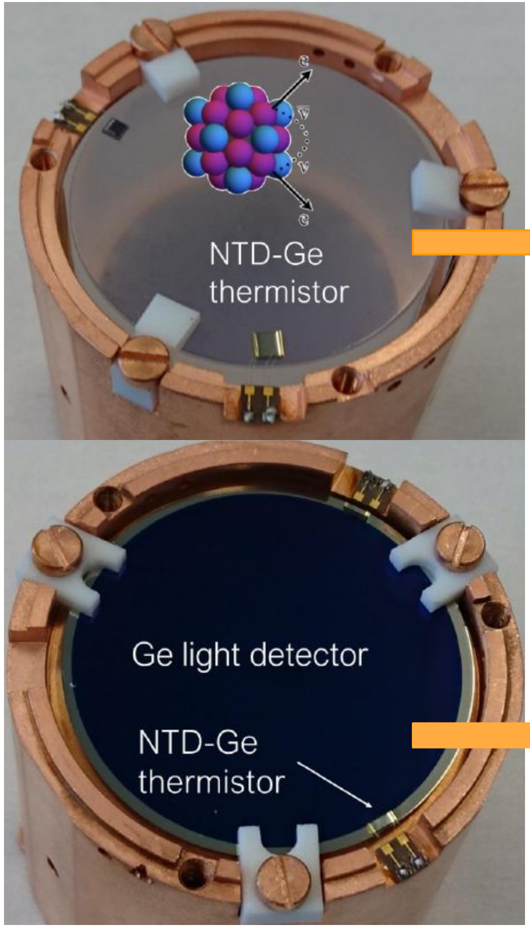


20 x $Li_2{}^{100}MoO_4$ (Φ44*45 mm, ~0.21 kg)

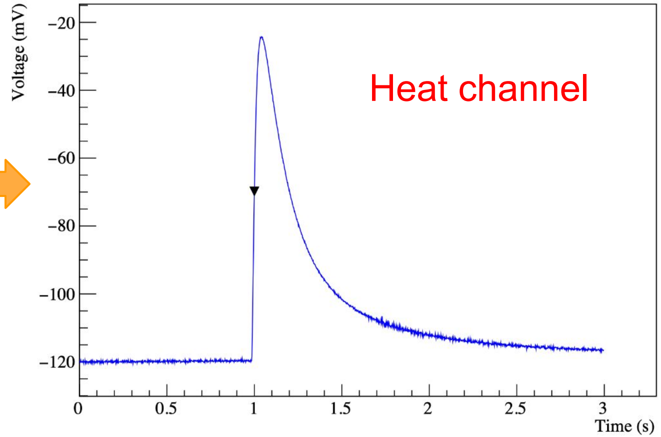
- **Enrichment 96.6 ±0.2 %**
- **4.158 kg $Li_2{}^{100}MoO_4$**
- **2.264 kg ^{100}Mo**

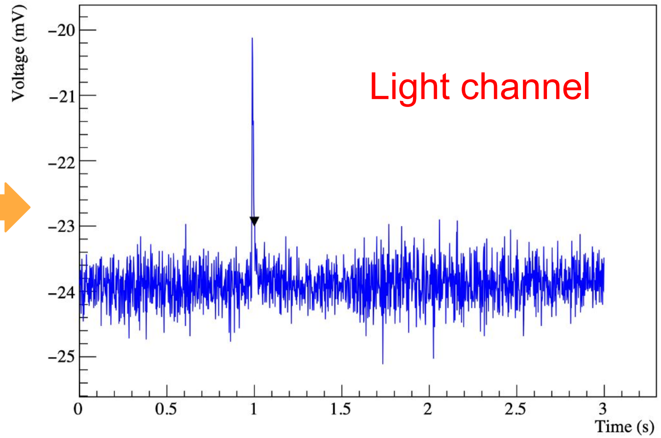
CUPID-Mo detector response

Copper = thermal bath

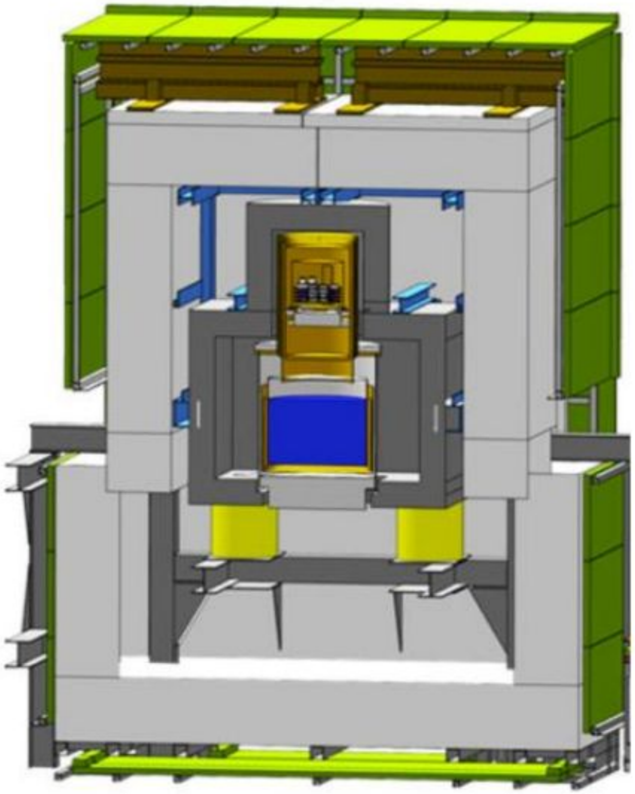


Teflon = weak thermal link

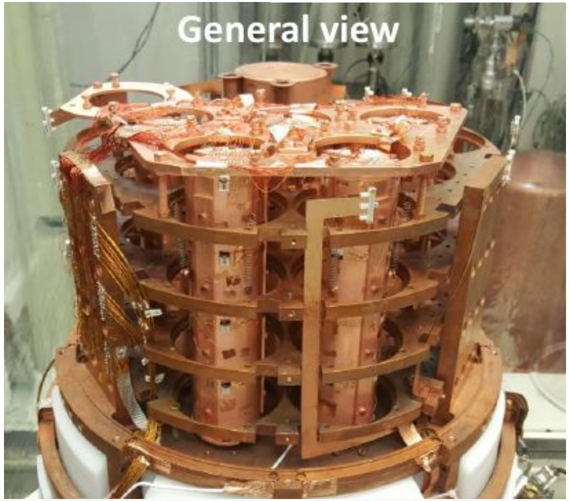


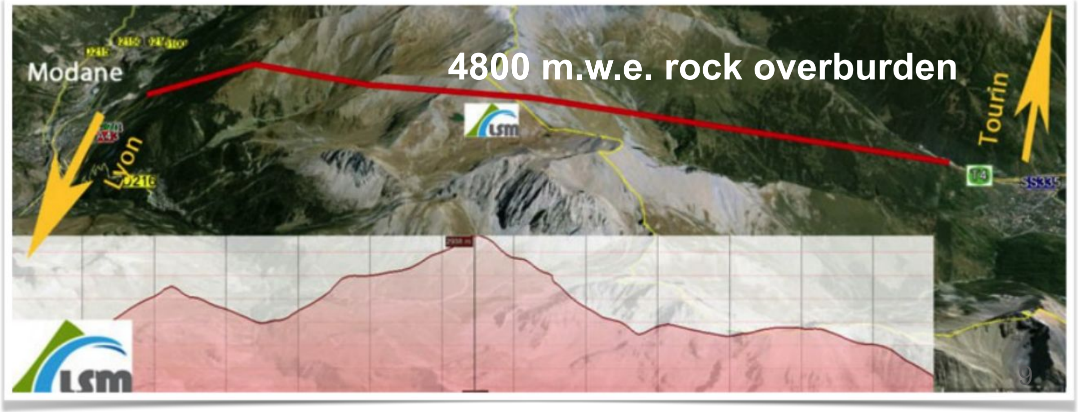


The CUPID-Mo experiment at Modane

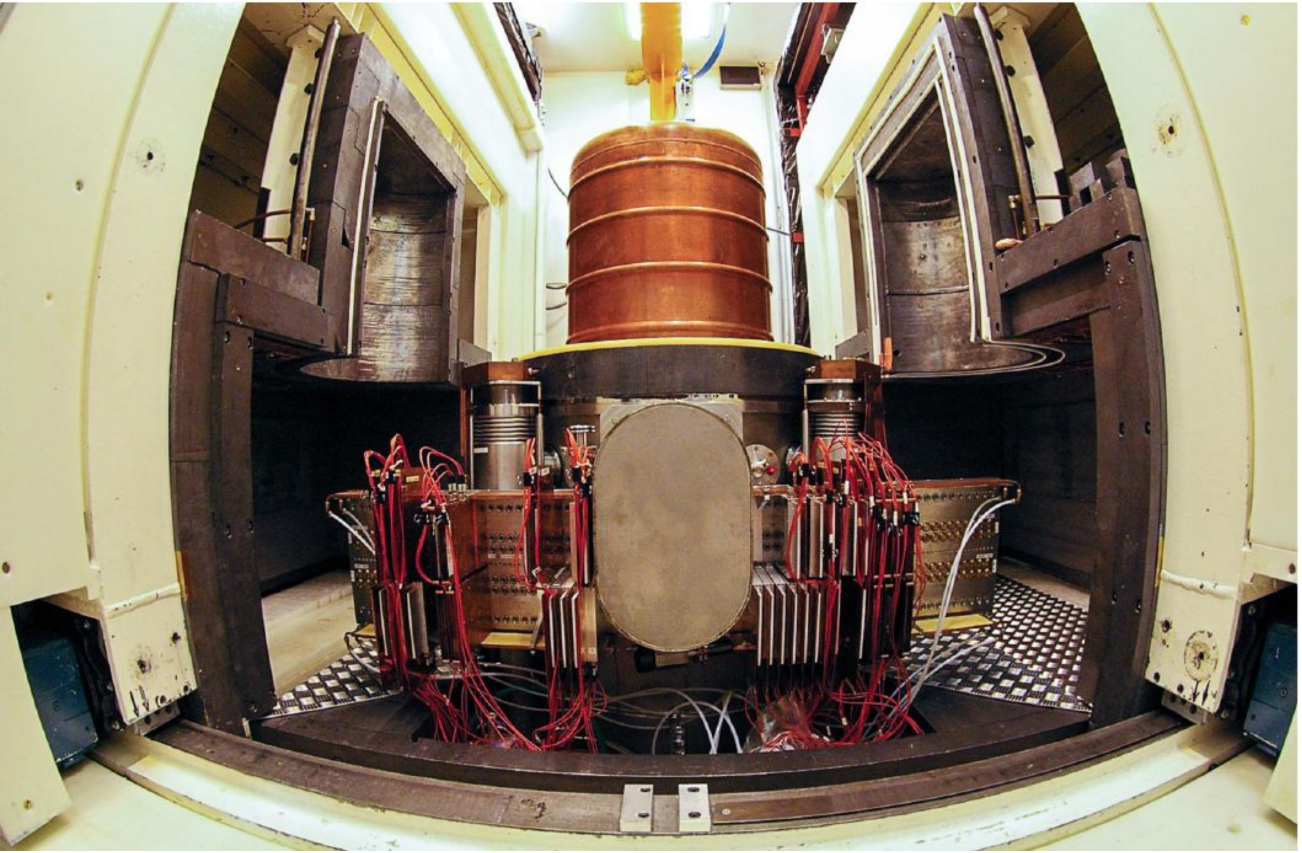


- Shared cryogenic EDELWEISS set-up
- The detectors were operated at 20-22 mK
- Physics data taking from March 2019 to July 2020





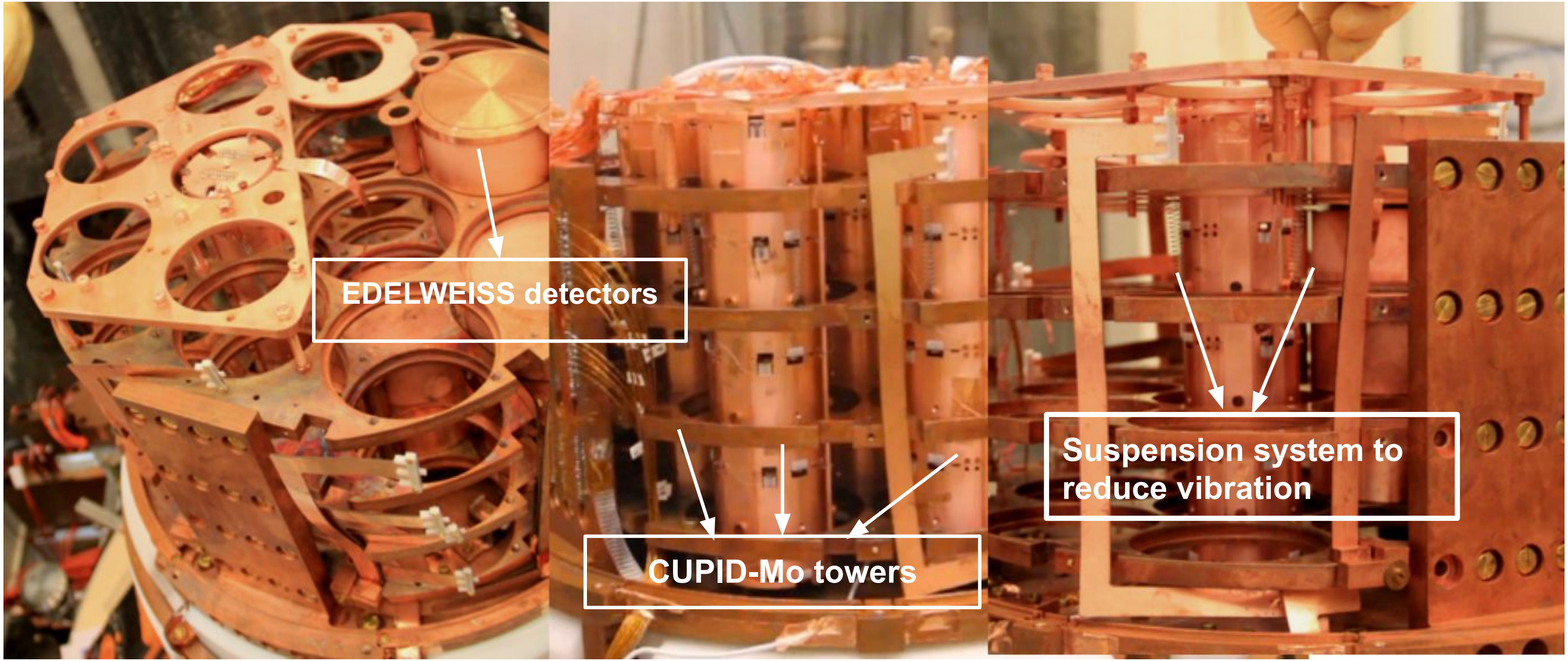
EDELWEISS/CUPID-Mo cryogenic facility



Active and passive shielding designed for the **EDELWEISS dark matter search**

- 100 m^2 plastic scintillator **muon-veto** system
- 50 cm **PE shielding**
- 20 cm **lead shield**
  innermost 2 cm is roman lead
- **Radon free air** circulation in between lead and Cu cryostat
- Inversed geometry **wet dilution refrigerator with GM cryocoolers** for 100K screen and He liquefier
- **10 days between LHe refill**
- **In-house front end electronics** (Grenoble, CEA-Saclay)

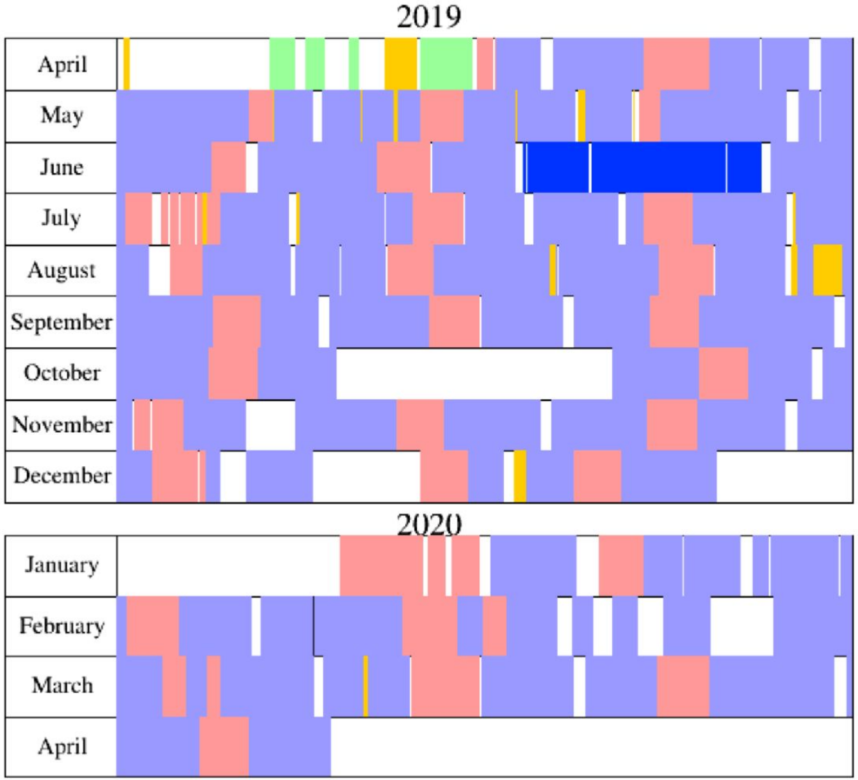
The CUPID-Mo experiment at Modane

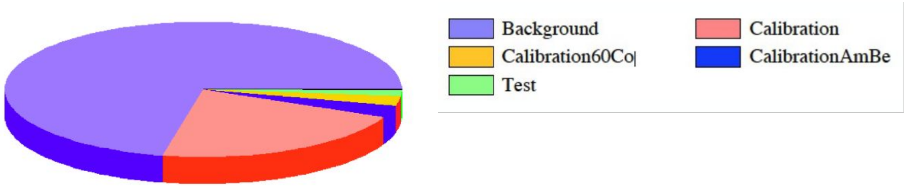


CUPID-Mo data taking

PHYSICAL REVIEW LETTERS **126,** 181802 (2021)

New Limit for Neutrinoless Double-Beta Decay of ^{100}Mo from the CUPID-Mo Experiment





March 2019 - April 2020 (380 days)

- **7 long datasets**, 1-2 month scale
- 3 short datasets (single calibration periods)

Not used in the Neutrino 2020 analysis - extra work needed on energy-scale uncertainty

- Rejection of periods of temperature instabilities

Selected data for Neutrino 2020

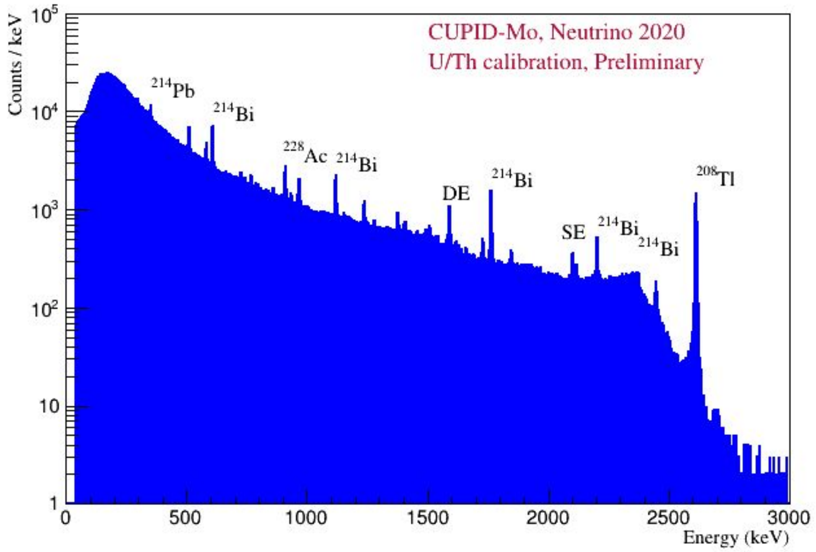
➔ 200 days of physics data (94%)

➔ 59 days of calibration data (88%)

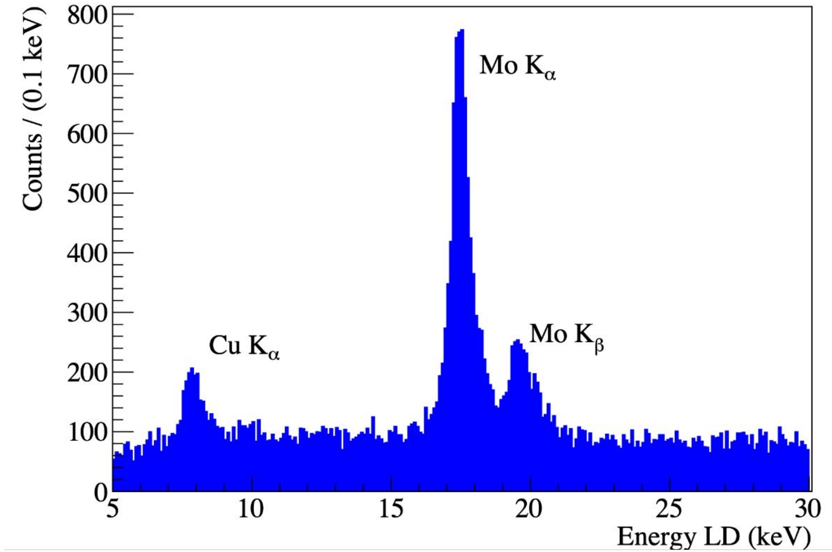
2.16 kg.yr of physics data

CUPID-Mo calibration

- LMO detectors have relatively low mass ~210 g and low density 3.07 g/cm^3
- Time dedicated to calibration ~ 23% of data taking
- U/Th source

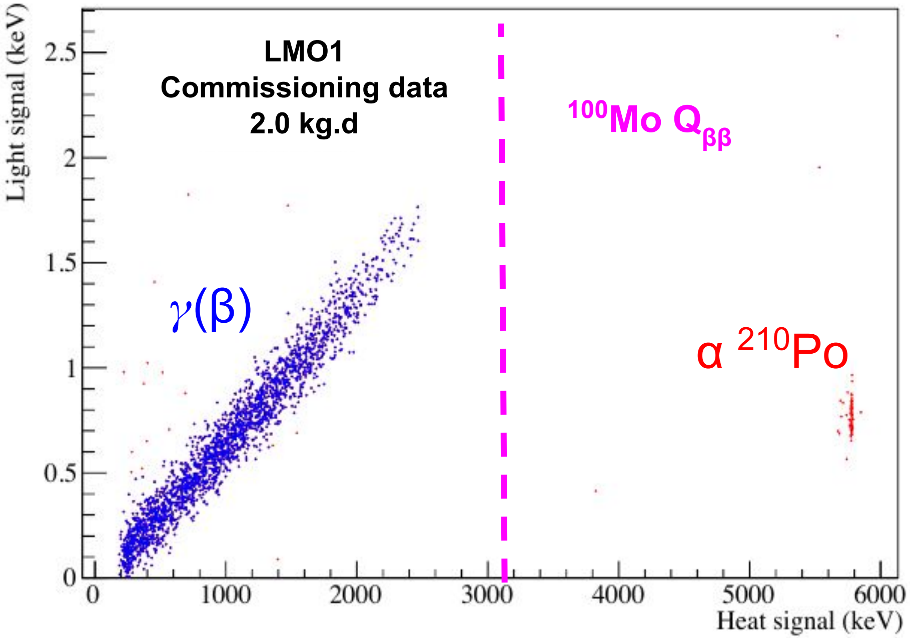


- Low energy calibration sources are potentially dangerous for the EDELWEISS dark matter search => Impossible to use low energy source for LD calibration
- Use the Mo X-ray escape peak from high intensity irradiation of the crystals (^{60}Co)



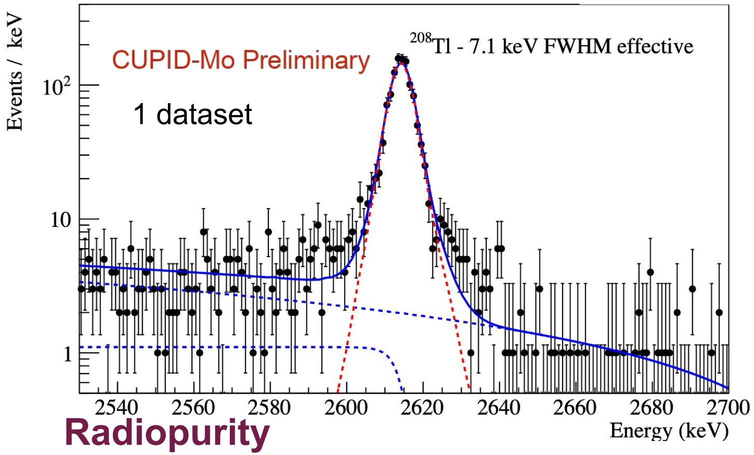
CUPID-Mo performances

Light yield



- Typical $\gamma(\beta)$ LY: 0.6-0.7 keV/MeV
- Quenching factor of α: 20%
- > 99.9 % of $\gamma(\beta)/\alpha$ separation

Energy resolution



Radiopurity

Chain	Nuclide	Activity [μBq/kg]
^{232}Th	^{232}Th	0.22(9)
	^{228}Th	0.38(9)
	^{224}Ra	0.34(9)
	^{212}Bi	0.22(7)
^{238}U	^{238}U	0.35(10)
	^{234}U+^{226}Ra	1.22(17)
	^{230}Th	0.48(12)
	^{222}Rn	0.47(10)
	^{218}Po	0.35(9)
	^{210}Po	95(6)
	^{190}Pt	0.19(8)

Crystals bulk α activity
19/20 Li_2MoO_4 2.17 kg.yr

Analysis chain and quality cuts

CUORE based data production chain at NERSC

Trigger efficiency

Total efficiency (exposure weighted avg.)

$$\epsilon = (90.6 \pm 0.4\,(\mathrm{stat.})\,^{+0.8}_{-0.2}\,(\mathrm{syst.}))\%$$

Base cuts

Single trigger
BaselineSlope

Multiplicity

Pulser rejection
M1 - single crystal

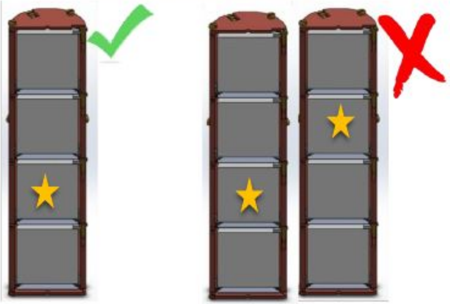
Pulse Shape analysis

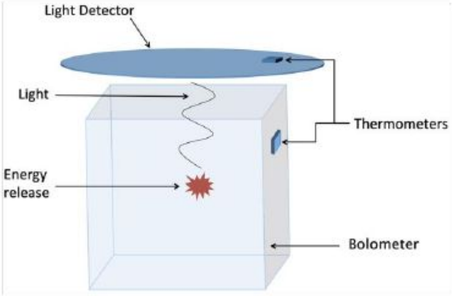
Principal component analysis (PCA)

Light Yield

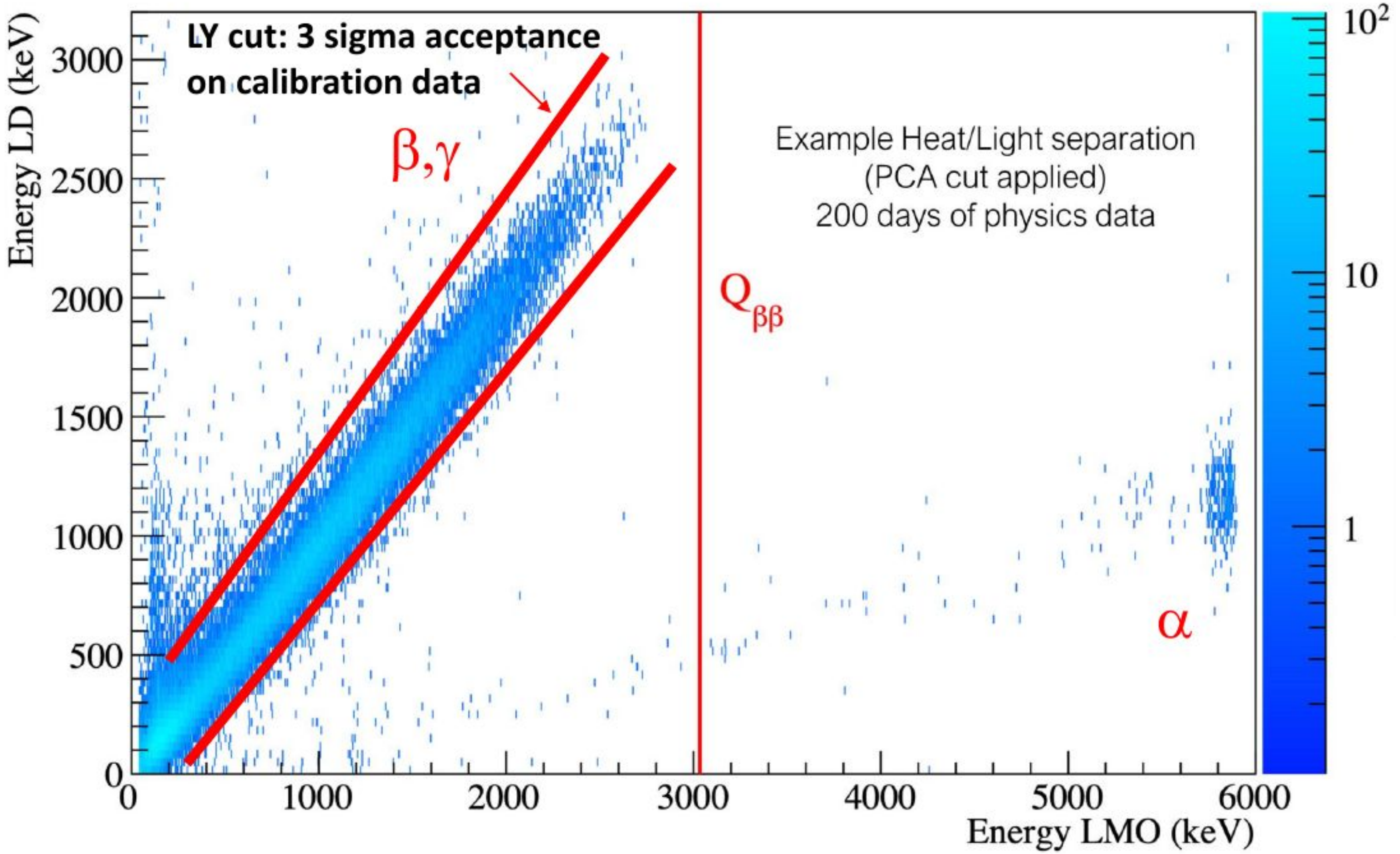
Sum of LD
Consistency of LD

Muon veto anti-coincidence

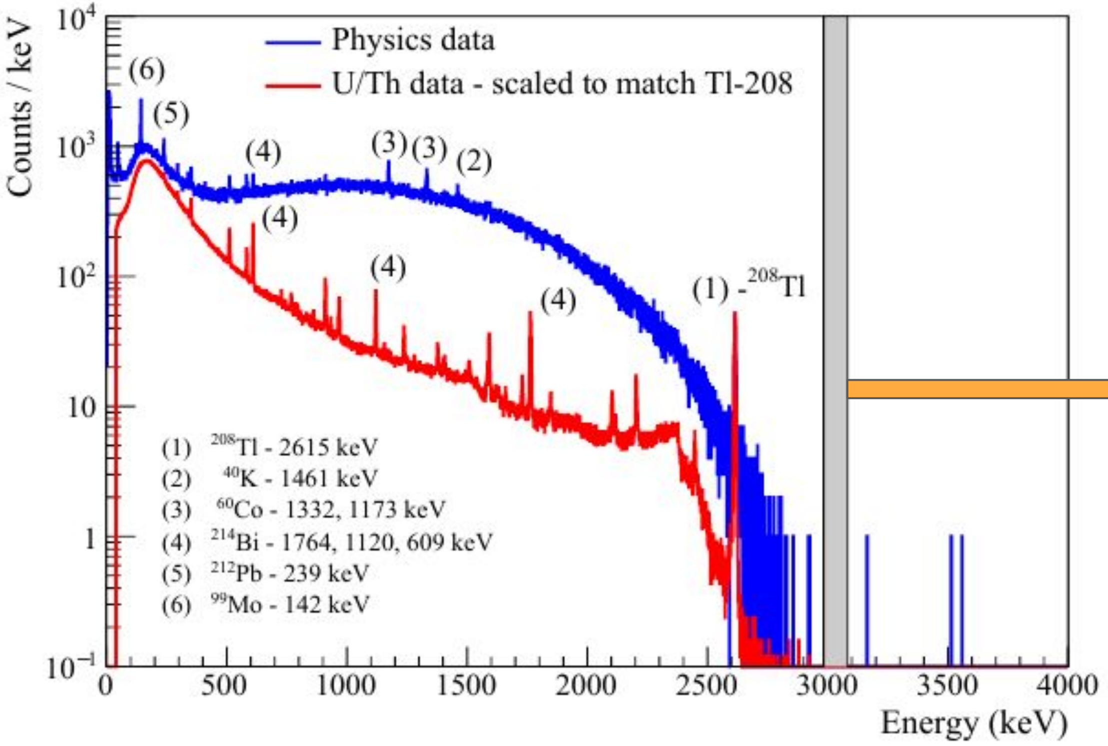




Light yield cut



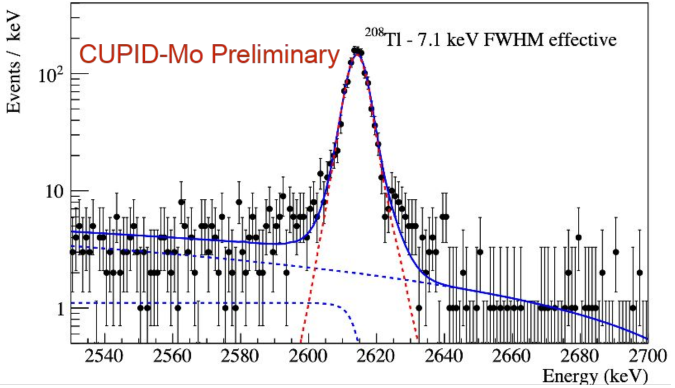
CUPID-Mo blinded data

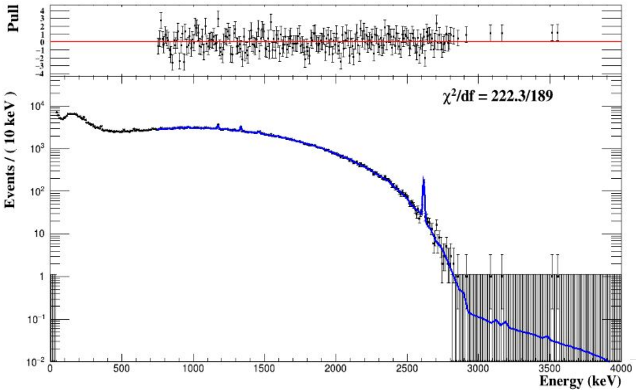


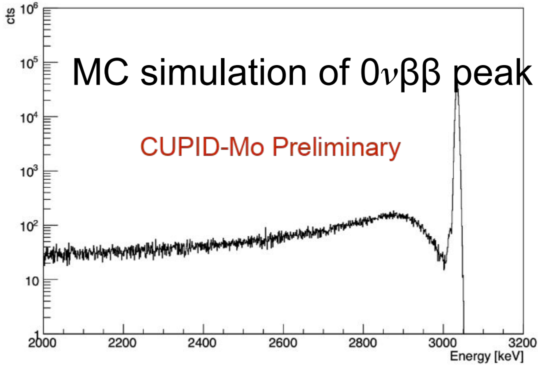
- 200 days of physics data
- 19/20 detectors
- ~7 keV FWHM @ 2615 keV (calibration)

Blinded region
=
100 keV centred around $Q_{\beta\beta}$

How did we define our ROI?

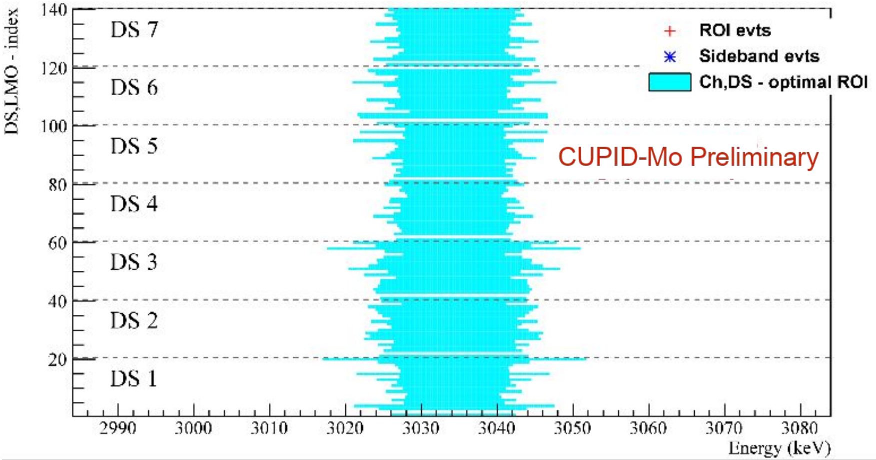




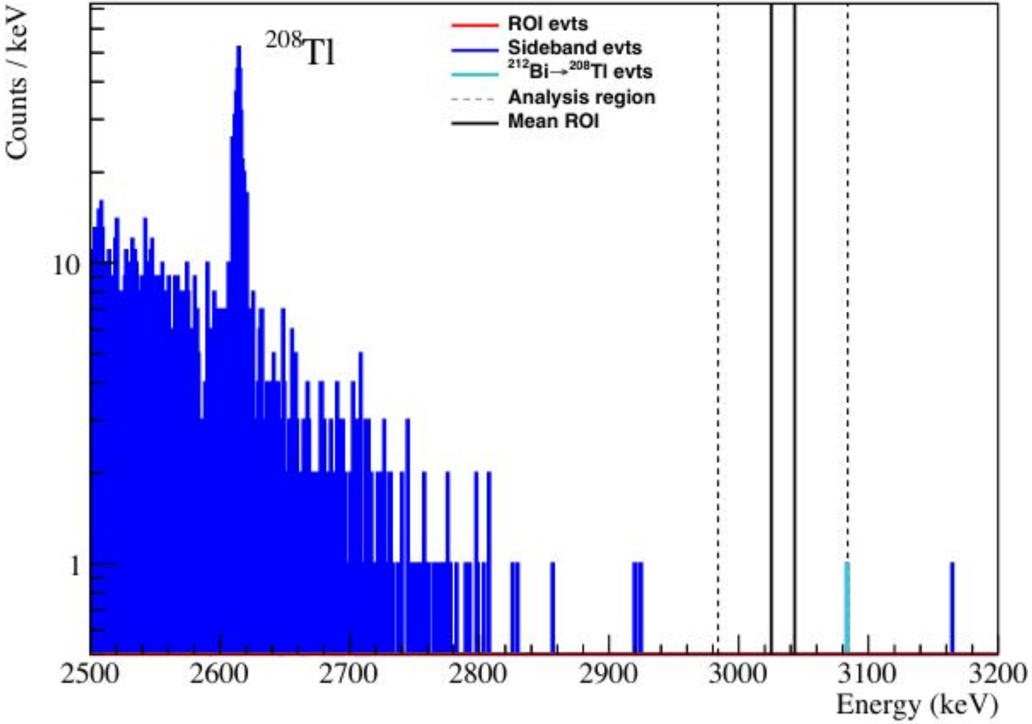


Detector resolution + **Background index** + **0νββ containment Bremsstrahlung escape**

= **ROI**



The new $0\nu\beta\beta$ decay CUPID-Mo limit



New world leading limit

$$T^{0\nu}_{1/2} > 1.5 \times 10^{24}\,\text{yr}\ (90\%\ \text{C.I.}).$$

Effective Majorana mass

$$m_{\beta\beta} < (0.31 - 0.54)\ eV$$

dependent on the Nuclear Matrix Element in the light Majorana neutrino exchange interpretation

Conclusions and outlook

- The CUPID-Mo demonstrator based on LUMINEU results took data successfully from March 2019 to July 2020 at LSM
- 19/20 scintillating bolometers showed excellent performances with a good energy resolution (~7 keV at 2615 keV), a PID capability (> 99.9 %) and high radiopurity
- CUPID-Mo set a new world leading limit on the $0\nu\beta\beta$ decay of ^{100}Mo
- The LUMINEU/CUPID-Mo technology is the baseline for the future ton-scale experiment **CUPID** at LNGS (stay tuned for A. Armatol talk)
- The analysis of the full data (2.8 kg.yr) is ongoing, and the background model is under construction
- A beyond $0\nu\beta\beta$ decay analysis is ongoing for spin-dependent dark matter searches

CUPID-Mo publications

New Limit for Neutrinoless Double-Beta Decay of ^{100}Mo from the CUPID-Mo Experiment

10.1103/PhysRevLett.126.181802

Pulse Shape Discrimination in CUPID-Mo using Principal Component Analysis

10.1088/1748-0221/16/03/P03032

Precise measurement of $2\nu\beta\beta$ decay ^{100}Mo with the CUPID-Mo detection technology

10.1140/epjc/s10052-020-8203-4

The CUPID-Mo experiment for neutrinoless double-beta decay: performance and prospects

10.1140/epjc/s10052-019-7578-6

Posters at Neutrino 2020

CUPID-Mo $0\nu\beta\beta$ analysis

https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-419.pdf

CUPID-Mo performance

https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-404.pdf

CUPID-Mo ^{56}Co calibration campaign

https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-374.pdf

CUPID-Mo background model

https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-418.pdf

CUPID-Mo low energy analysis prospects

https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-448.pdf

CUPID-Mo sensitivity for $0\nu\beta\beta/2\nu\beta\beta$ decay to excited states

https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-382.pdf

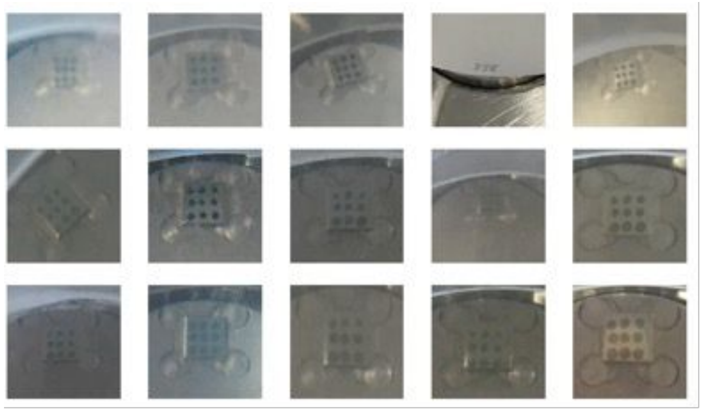
$2\nu\beta\beta$ analysis with CUPID-Mo technology

https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-525.pdf

Backup slides

Detector assembly chain

Gluing

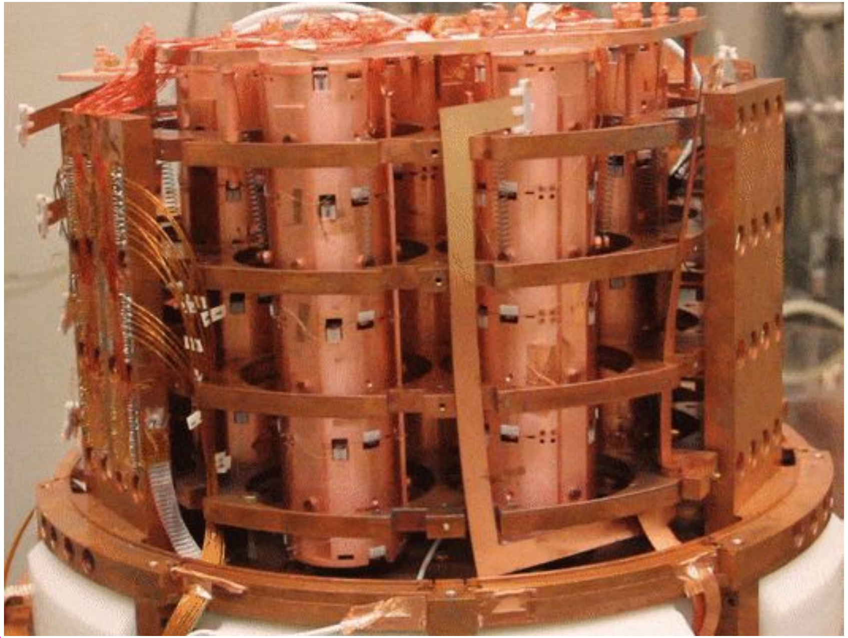


Bonding and assembly

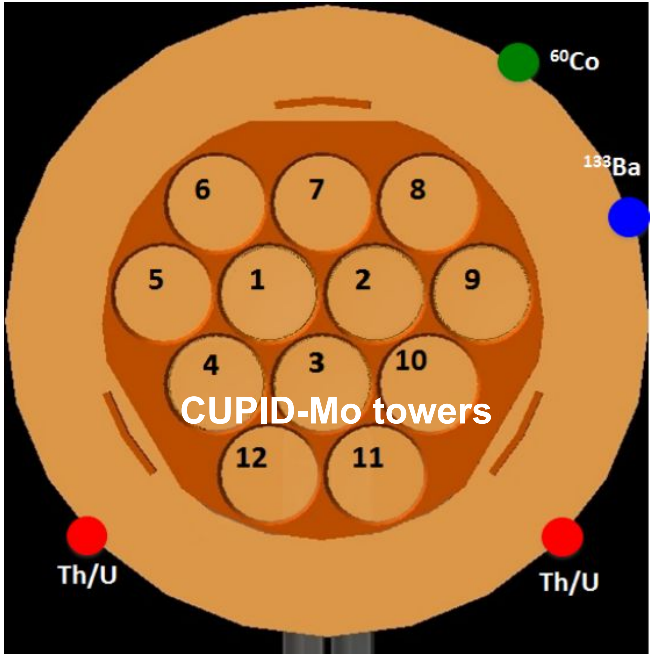
at IJCLab

CUPID-Mo at Modane

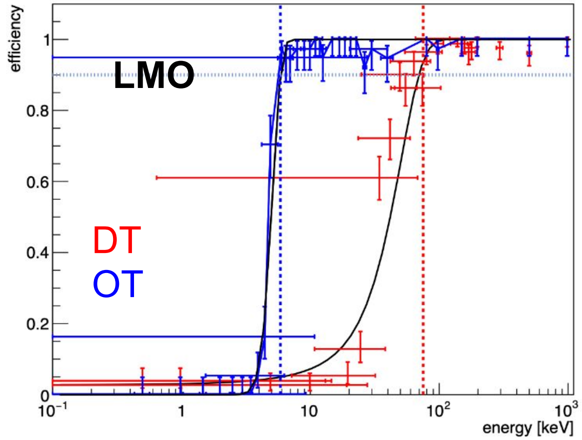
Suspension system



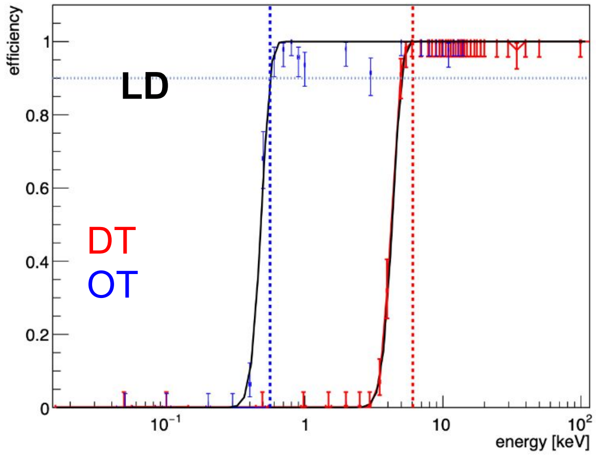
Calibration source position

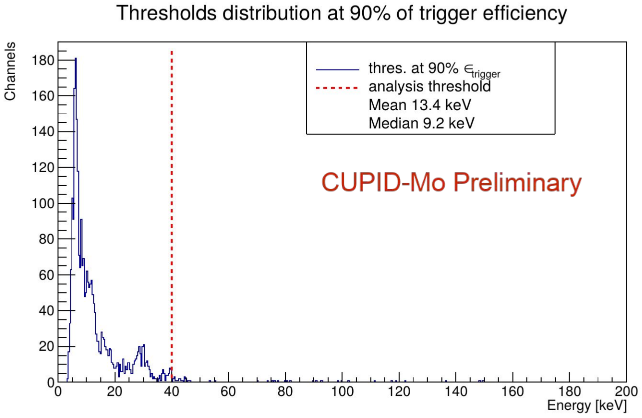


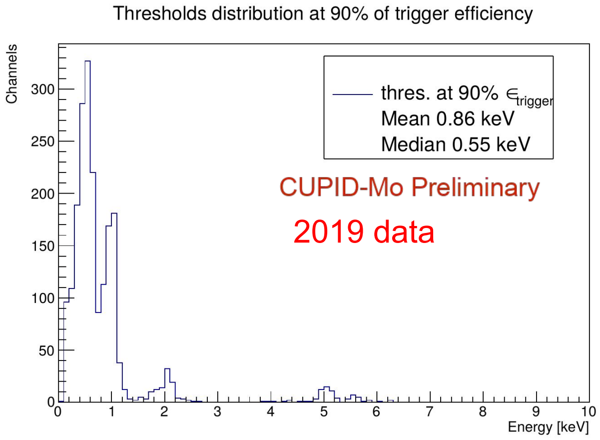
CUPID-Mo performances
Trigger efficiency



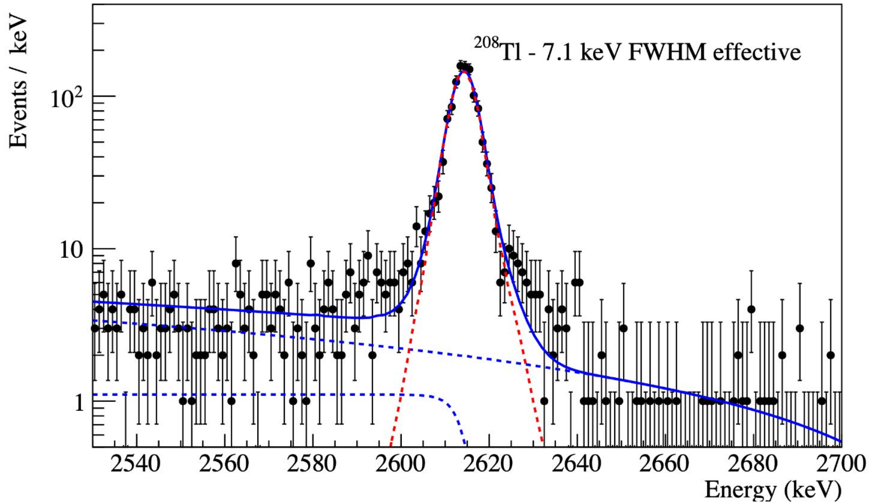
- Use of Optimum triggering allows better discrimination between single events and multi-crystal events
- Conservative threshold set to 10 sigma of the baseline rms
- Energy threshold evaluation at 90% of trigger efficiency:
  - inject synthetic events built on the avg. pulse into noise
  - typical LMO threshold ~ 9 keV
  - typical LD threshold ~ 0.5 keV
- Lower threshold can be obtained for low energy analysis such as dark matter searches

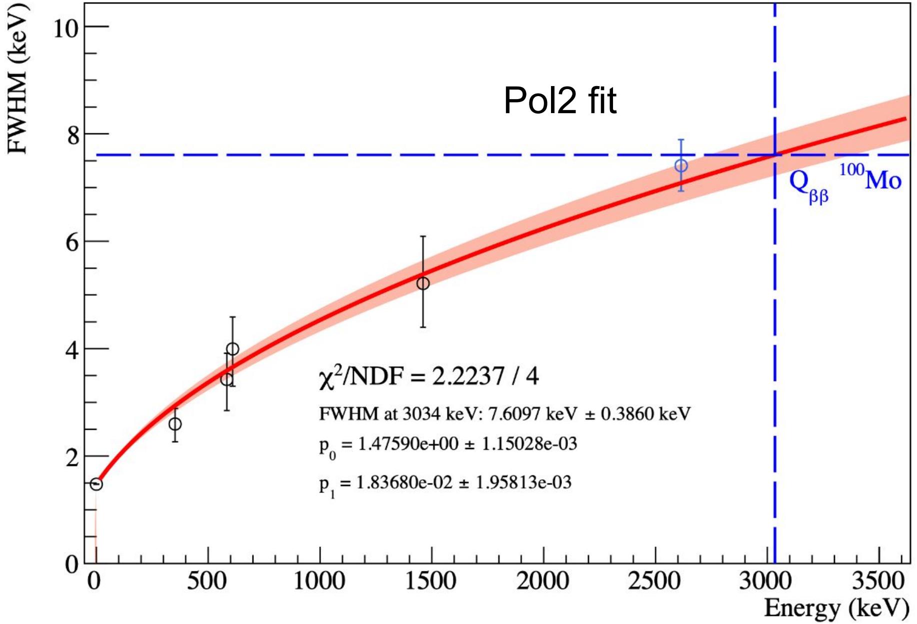






CUPID-Mo energy resolution





Simultaneous unbinned extended maximum likelihood (UEML) fit to extract the (Ch,DS) - based resolutions

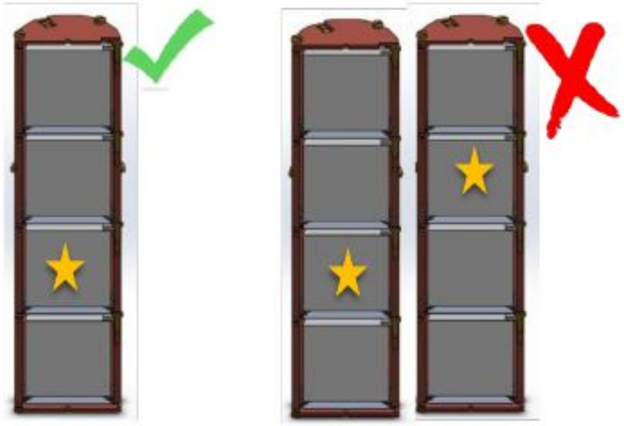
Fit model: smeared step function (multi-compton)+Gauss (photopeak)+Linear (multi-photon + 2νββ)

scaling factor from calibration data at 2615 keV applied to physics data at 3034 keV

CUPID-Mo cuts

Quality cuts

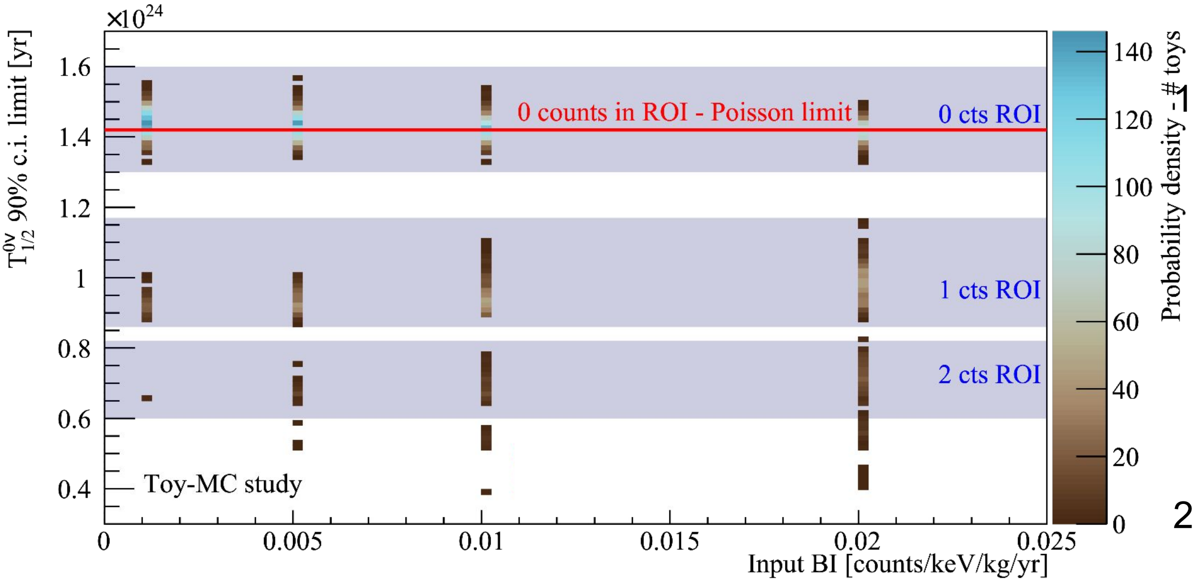
- No energy dependence
- Single trigger in 3 s pulse window
- flat pulse pre-trace (baseline slope)
- Single crystal events (M1)



Pulse Shape analysis PCA

- The LD-based cuts are independent from the event topology in the LMO crystals
- Principal component analysis
  - trained on 1-2 MeV of physics data
  - the 1^{st} component contains the shape of a *good pulse* similar to the avg. pulse
- Define the reconstruction error as pulse shape variable

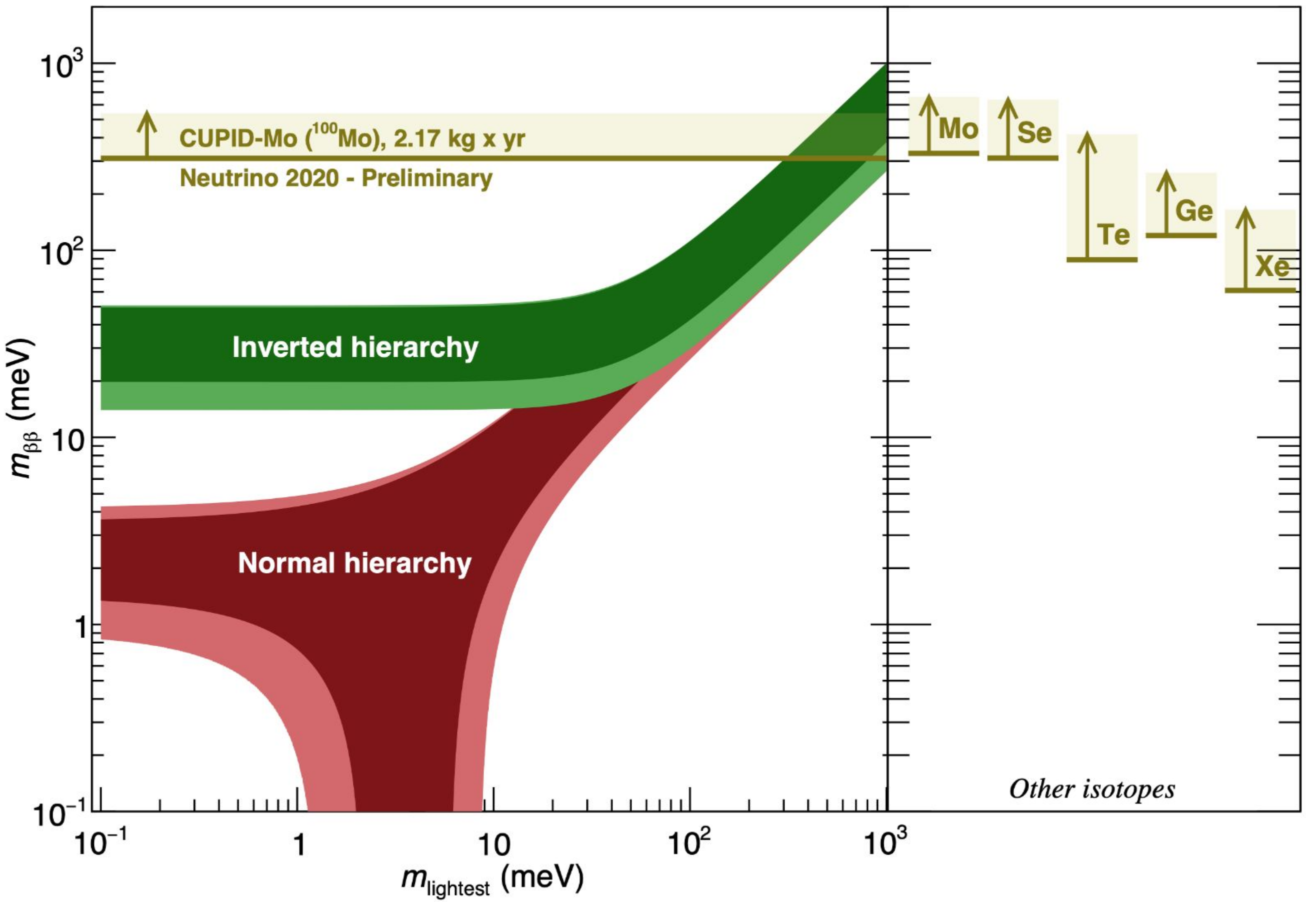
CUPID-Mo limit setting



Toy analysis was performed

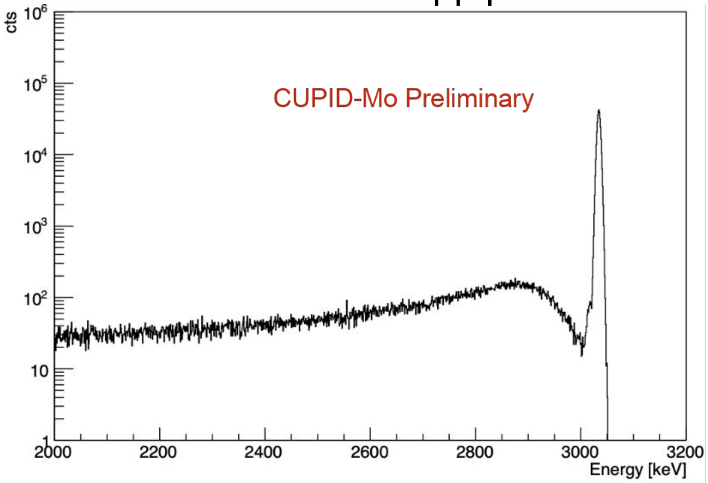
1. **Bayesian counting analysis**:
   - central bin/ROI: 75% signal and bkg
   - side band: 1% signal and bkg
   - bkg fit: exponential + linear
   - use Gaussian priors on exponential from fit in [2615-2980] keV
2. **Poisson counting analysis** as a cross-check

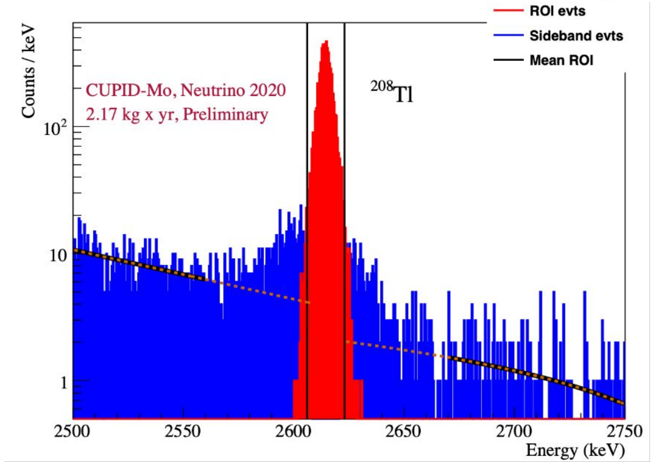
CUPID-Mo limit setting



CUPID-Mo systematics

MC simulation of $0\nu\beta\beta$ peak

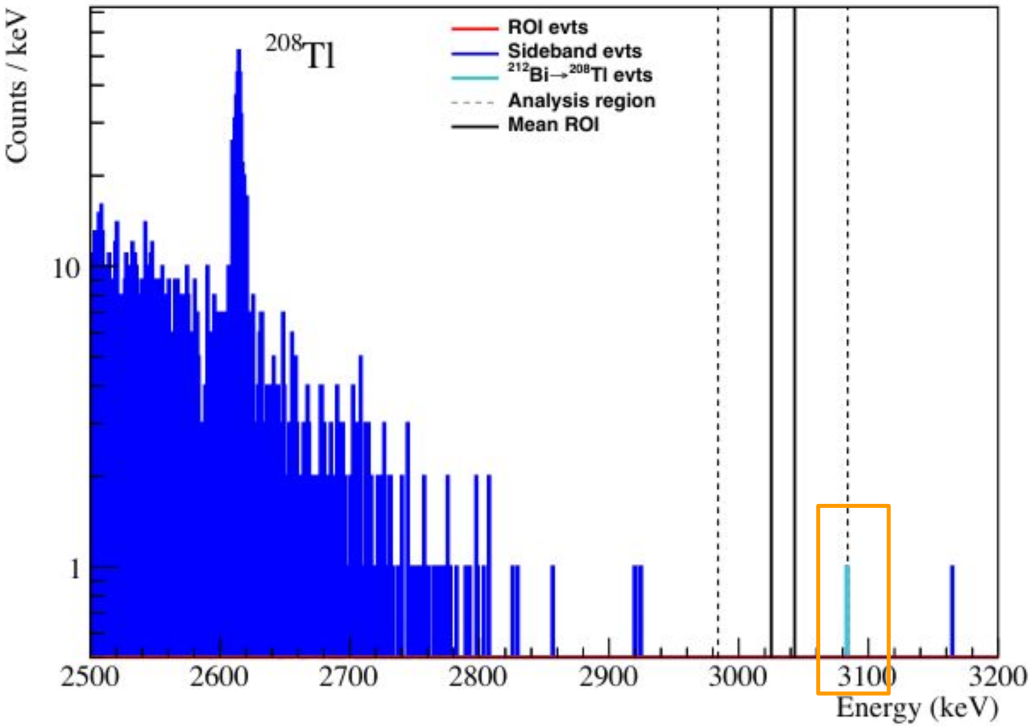




- ❖ Isotopic enrichment 0.966 ± 0.002 (gaussian prior)
- ❖ $0\nu\beta\beta$ containment MC (gaussian prior)
  - ➢ Geant4 modeling and density uncertainty (1.5%)
- ❖ $0\nu\beta\beta$ containment detector response (flat prior)
  - ➢ potential non-gaussianity of the $0\nu\beta\beta$ peak (5%)
- ❖ Analysis efficiency (gaussian prior)
  - ➢ all cuts stat. and PCA extrapolation (gaussian prior)

$$\epsilon = (90.6 \pm 0.4\,(\text{stat.})\,^{+0.8}_{-0.2}\,(\text{syst.}))\%$$

The new 0νββ decay CUPID-Mo limit



was rejected by delayed coincidence cut to reject pairs of ^{212}Bi-^{208}Tl

CUPID-Mo background index

- Perform unbinned extended maximum likelihood fit on Bkg data excluding [3010, 3060] keV
- Phenomenological Bg model:

Exponential + Flat component