GdR Neutrino

CUPID-Mo: new results on ^{100}Mo $0\nu/2\nu$ 2β

Denys Poda

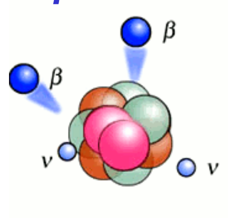
Université Paris-Saclay, CNRS/IN2P3, IJCLab (Orsay, France)

on behalf of the CUPID-Mo Collaboration

GDR Neutrino remote meeting, 23-24 November 2020

Double-beta decay: (A,Z)→(A,Z+2)+…

Two-neutrino mode: 2ν2β



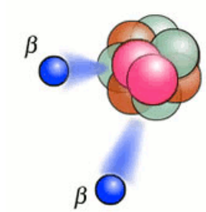
- **Allowed for 35 nuclides**
  1% nuclides from Table of Isotope
  Decay energy $Q_{\beta\beta}$ up to few MeV
- **Second order weak process**
  extremely long half-life, $T_{1/2} > 10^{17}$ yr [1935]
- **Test of theoretical description**

$$[T_{1/2}]^{-1} = G_{2\nu} \cdot |M_{2\nu}|^2$$

Observed for 11 nuclides

$T_{1/2}$~10^{18}–10^{24} yr

Neutrinoless mode: 0ν2β

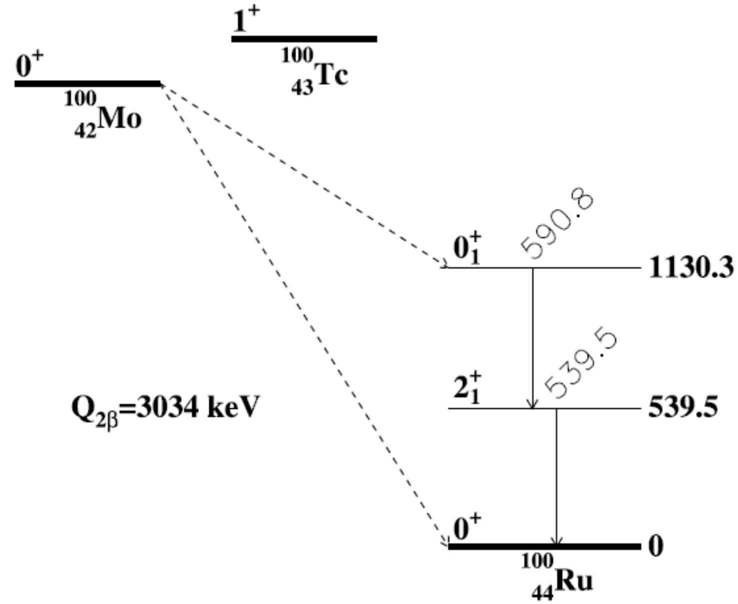


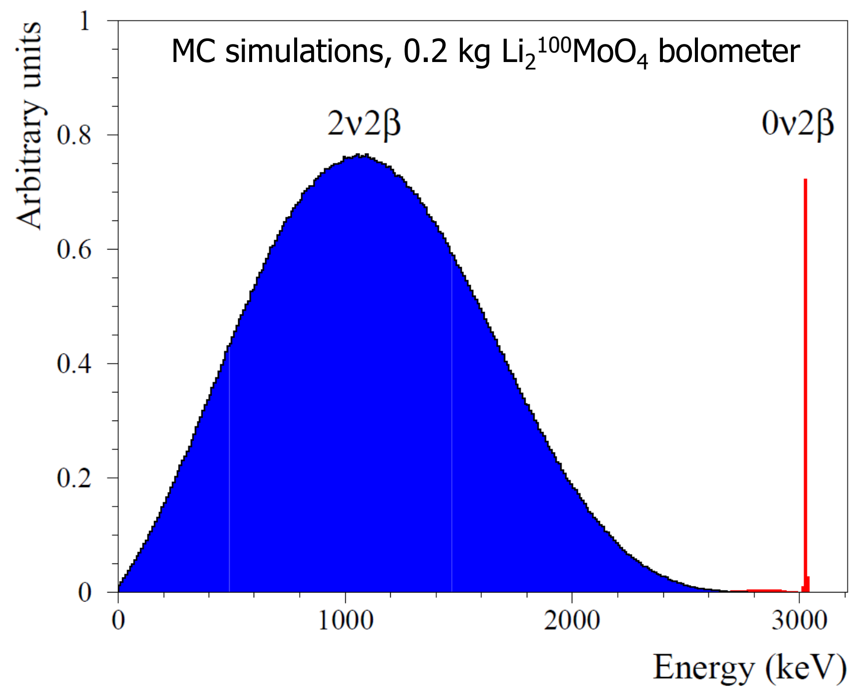
- **Beyond the Standard Model**
- **Lepton number violation**
- **Massive Majorana neutrino**
- **Neutrino mass scale**
  effective Majorana neutrino mass $\langle m_{\beta\beta}\rangle^2 = |\, \Sigma U_{ei}{}^2 \cdot m_i \,|^2$

$$[T_{1/2}]^{-1} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot \langle m_{\beta\beta}\rangle^2$$

Not yet observed

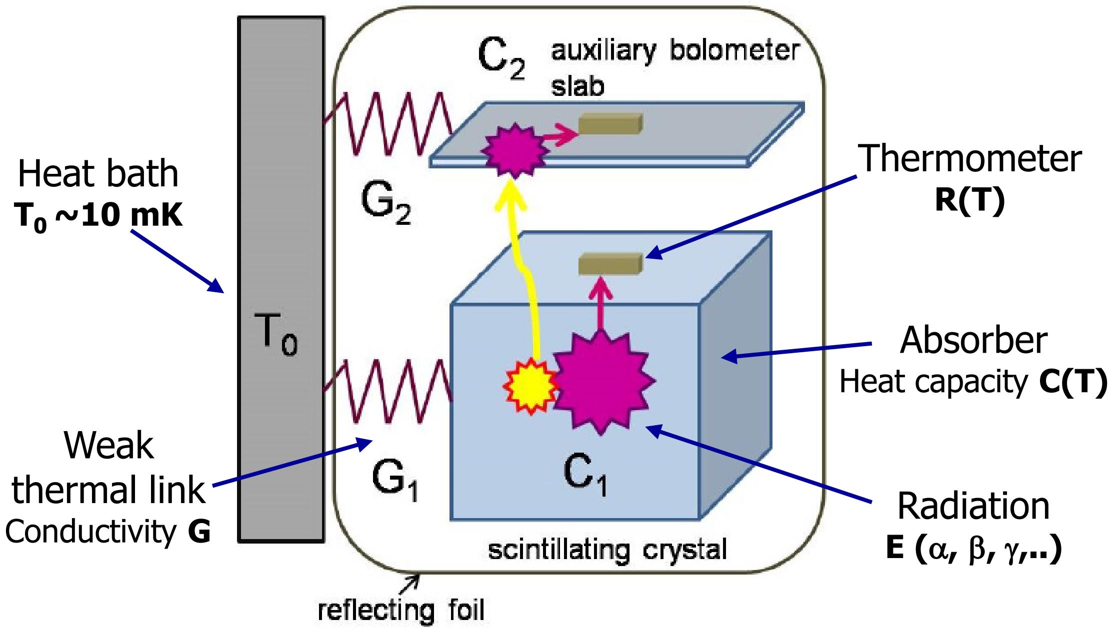
Best $T_{1/2} > 10^{24}$–10^{26} yr, $\langle m_{\beta\beta}\rangle < 0.06$–$0.6$ eV

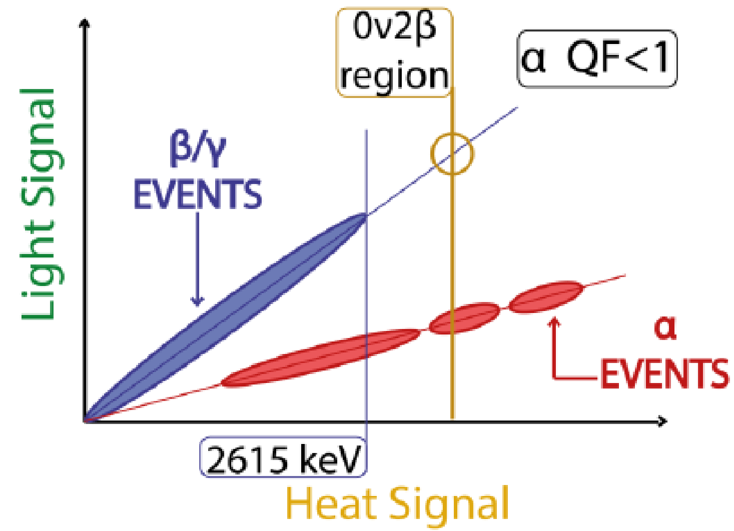




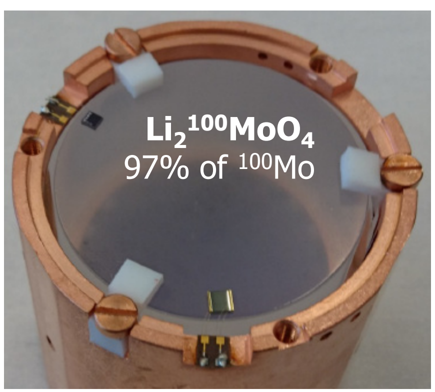
^{100}Mo $0\nu2\beta$ decay search

Scintillating bolometers for 0ν2β search





Technology of ^{100}Mo-enriched scintillating bolometers



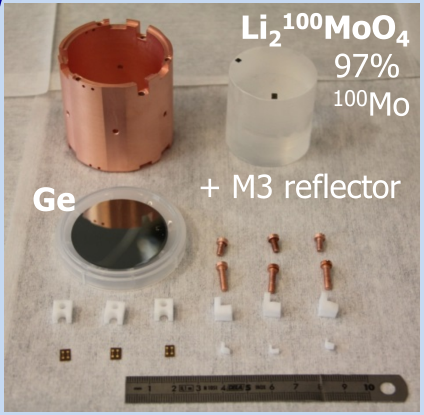
LUMINEU project (ANR funds) related developments

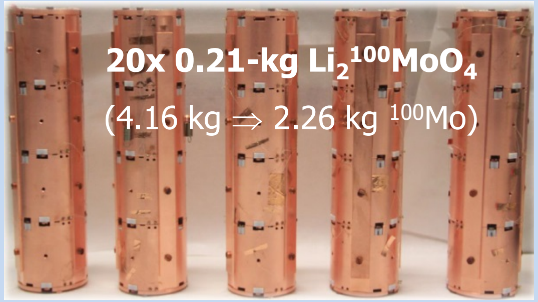
JINST 9, P06004 (2014); EPJC 77, 785 (2017);
JMSEB 7, 63 (2017); AIP Conf. Proc. 1894, 020017 (2017)

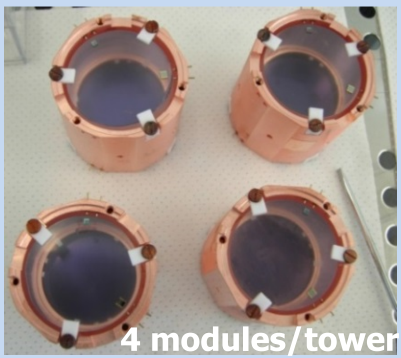
- ✓ **High crystal quality & radiopurity**
  ⇒ ^{100}Mo-enriched lithium molybdate ($Li_2{}^{100}MoO_4$)
- ✓ **High performance of $Li_2{}^{100}MoO_4$ bolometers**
  ⇒ High energy resolution
  ⇒ Low energy threshold
  ⇒ High detection efficiency (2β source = detector)
- ✓ **Efficient scintillation-based particle ID**
  ⇒ Active background rejection
- ✓ **Used in LUMINEU & CUPID-Mo 2β experiments**

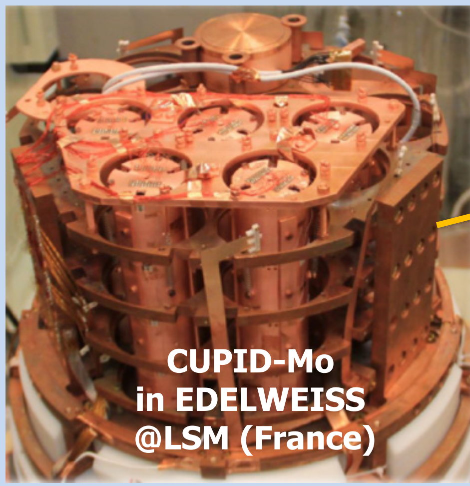
CUPID-Mo experiment

CUPID-Mo
20-scintillating-bolometer array

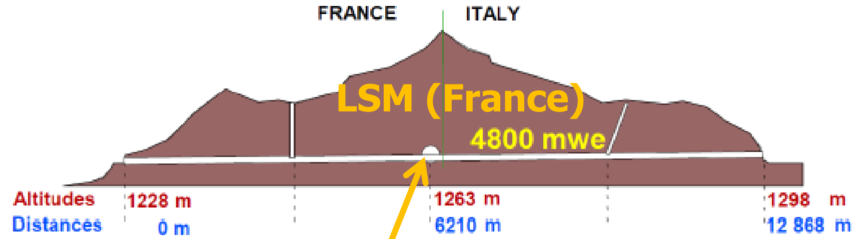


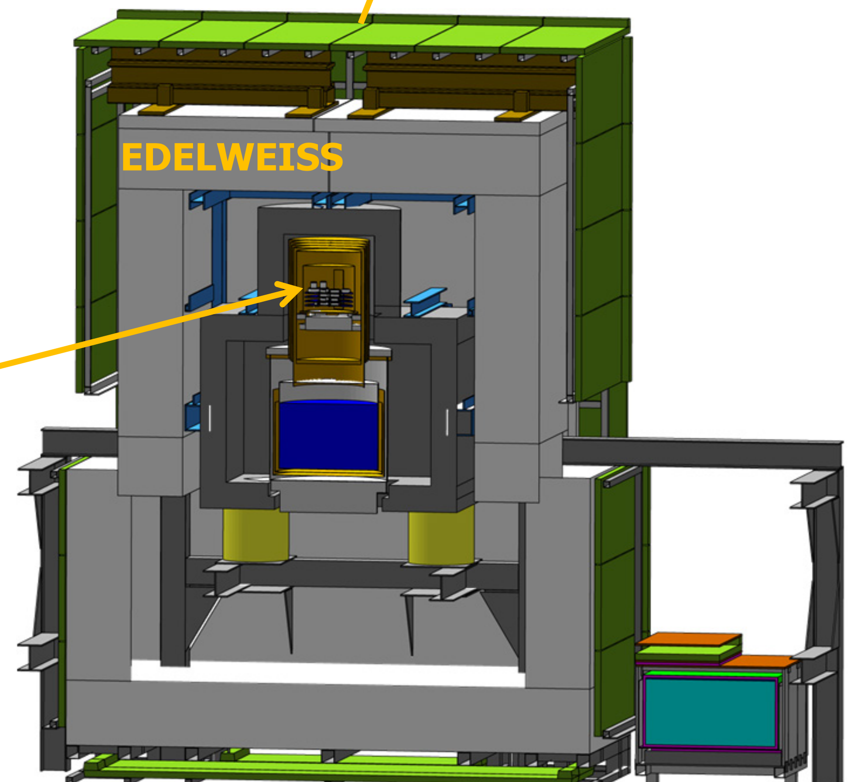






EPJC 80, 44 (2020)

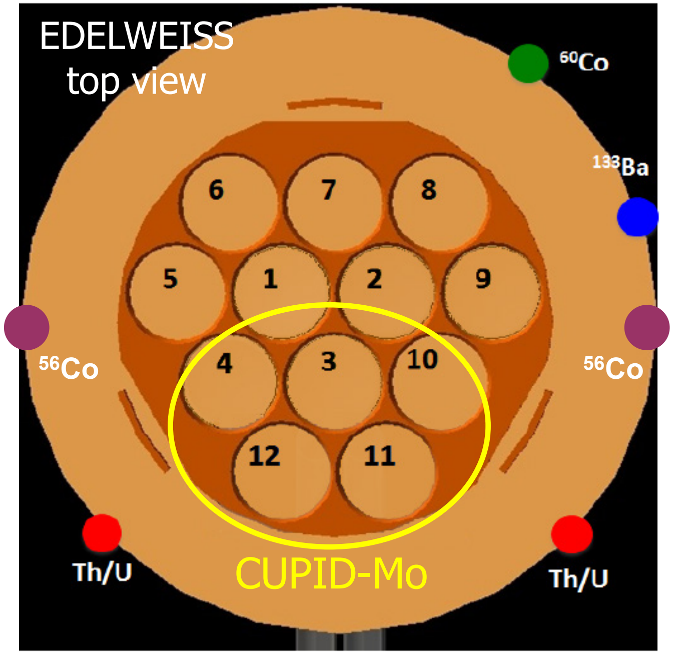




EDELWEISS cryogenic facility

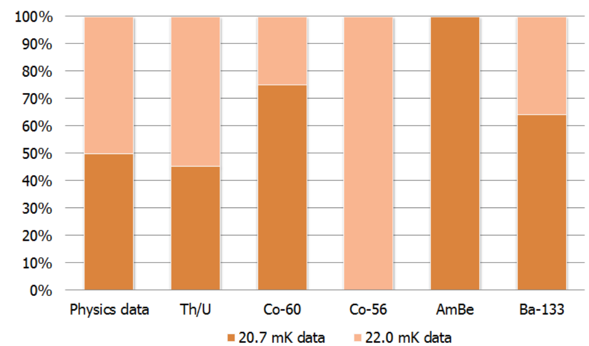
- **$^3He/^4He$ "wet" cryostat** in a **clean room** (ISO Class 4) with a **deradonized air** supply
- **Shield: external** (20 cm of Pb + 50 cm of PE) & **internal @1K** (14 cm of Pb + 10 cm of PE)
- **Muon veto** (98.5% covering)
- **Radon monitoring**
- **Low noise cold electronics**

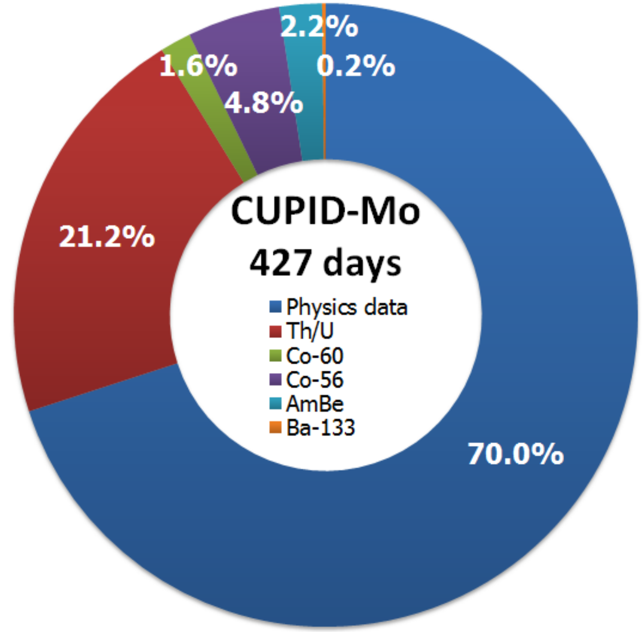
CUPID-Mo data



Data taking
(23/03/19 – 15/07/20; 481 d)

Duty cycle:	**89%**
Calibration:	**30%**
Physics data:	**70%**





- **Physics data taking**

  @ **20.7 mK** (Mar. 2019 – Oct. 2019)
  @ **22.0 mK** (Nov. 2019 – Jun. 2020)

- **Calibration**

  regular: Th/U (every ~10 days)
  special: AmBe, ^{56}Co, ^{133}Ba, ^{60}Co

- **Notable interruptions**

  LHe refills (every ~10 days)
  partial warm-ups (Mar., Oct., Dec. 2019)

- **Data release**

  0.12 kg×yr [EPJC 80, 44 (2020)]
  [@ GDR Neutrino, 25/06/2019]

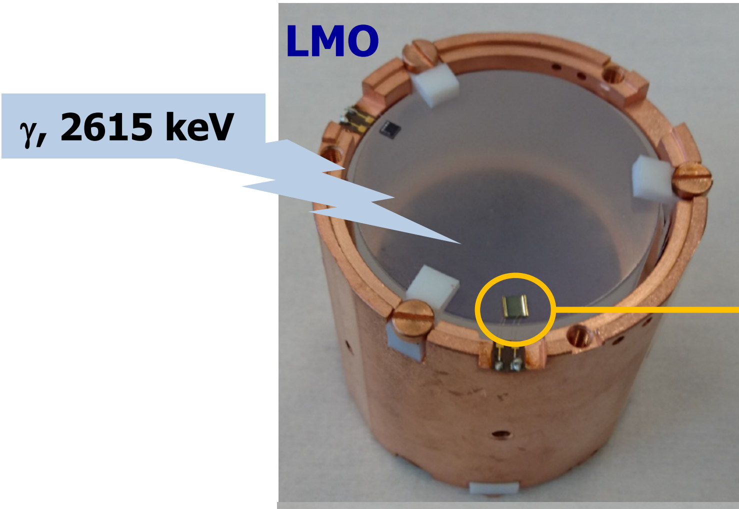
  0.51 kg×yr @ TAUP 2019
  [JPCS 1468, 012129 (2020)]

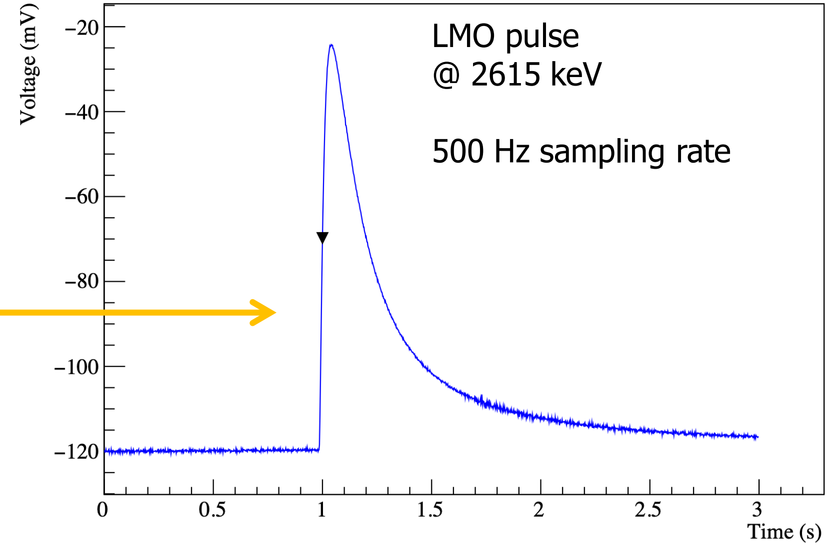
  ⇒ **Blinding:** Jun. **2019**
  ⇒ **Unblinding:** Jun. **2020**

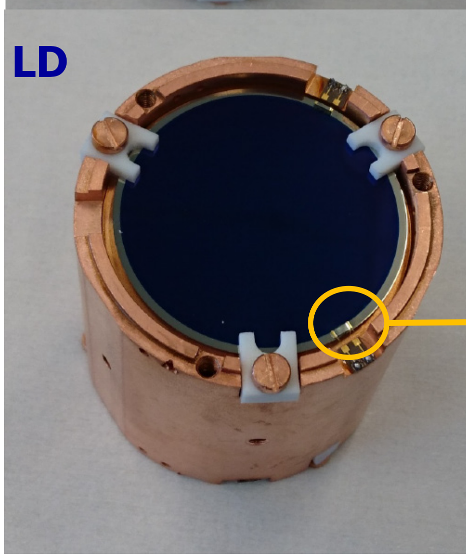
  2.17 kg×yr @ Neutrino 2020
  [Posters # 382, 404, 418, 419, 448]

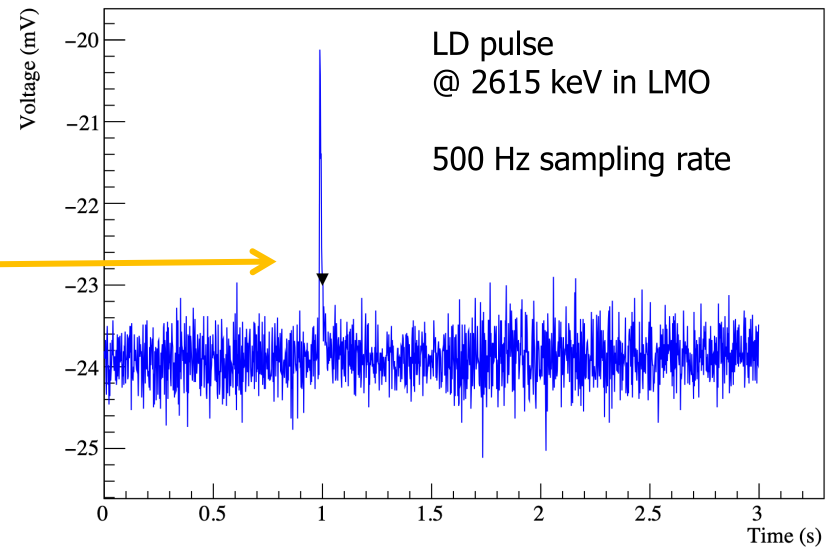
  Full data (~2.8 kg×yr) analysis is ongoing

Detector response





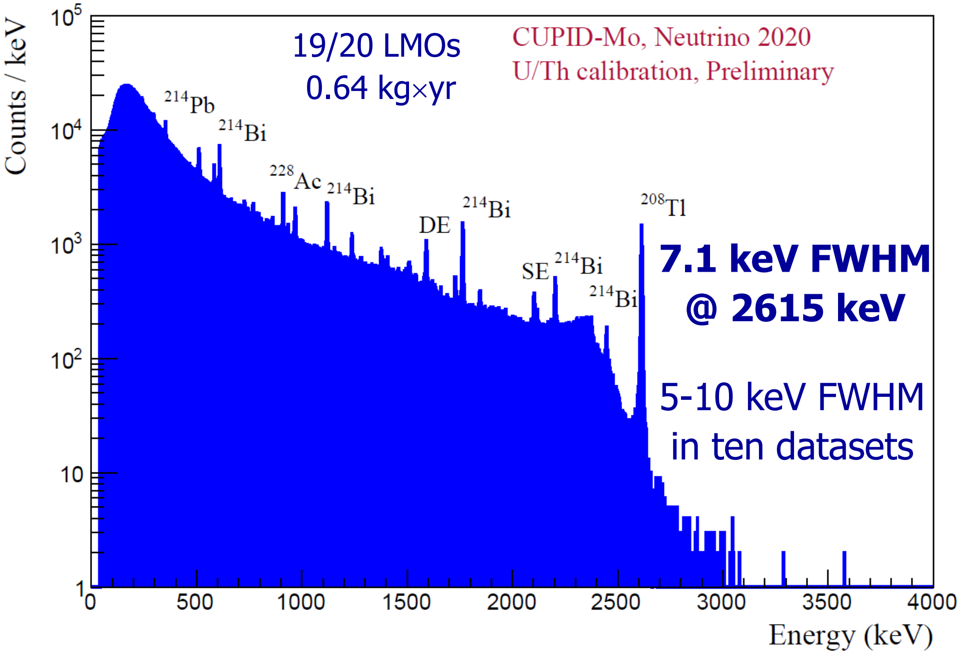


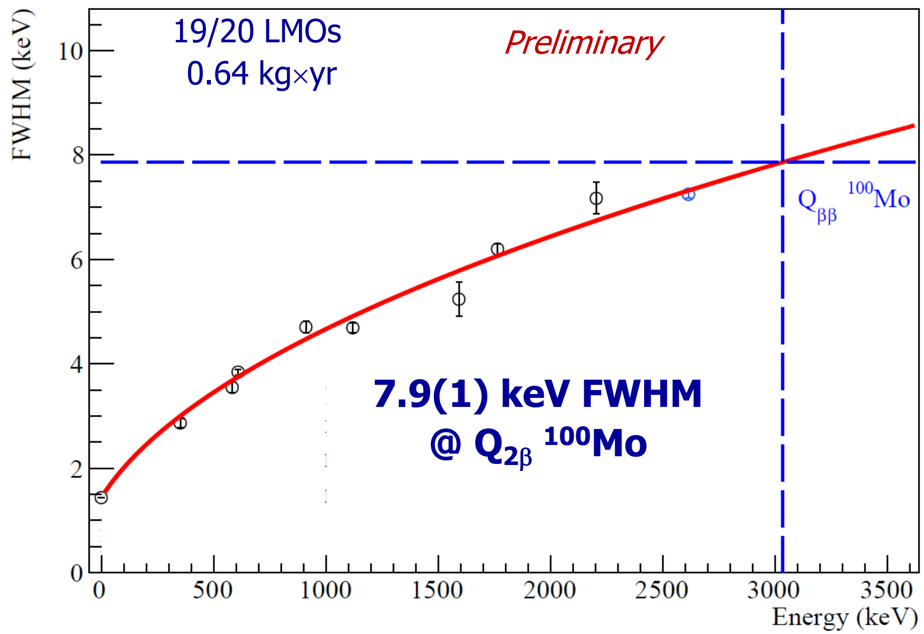


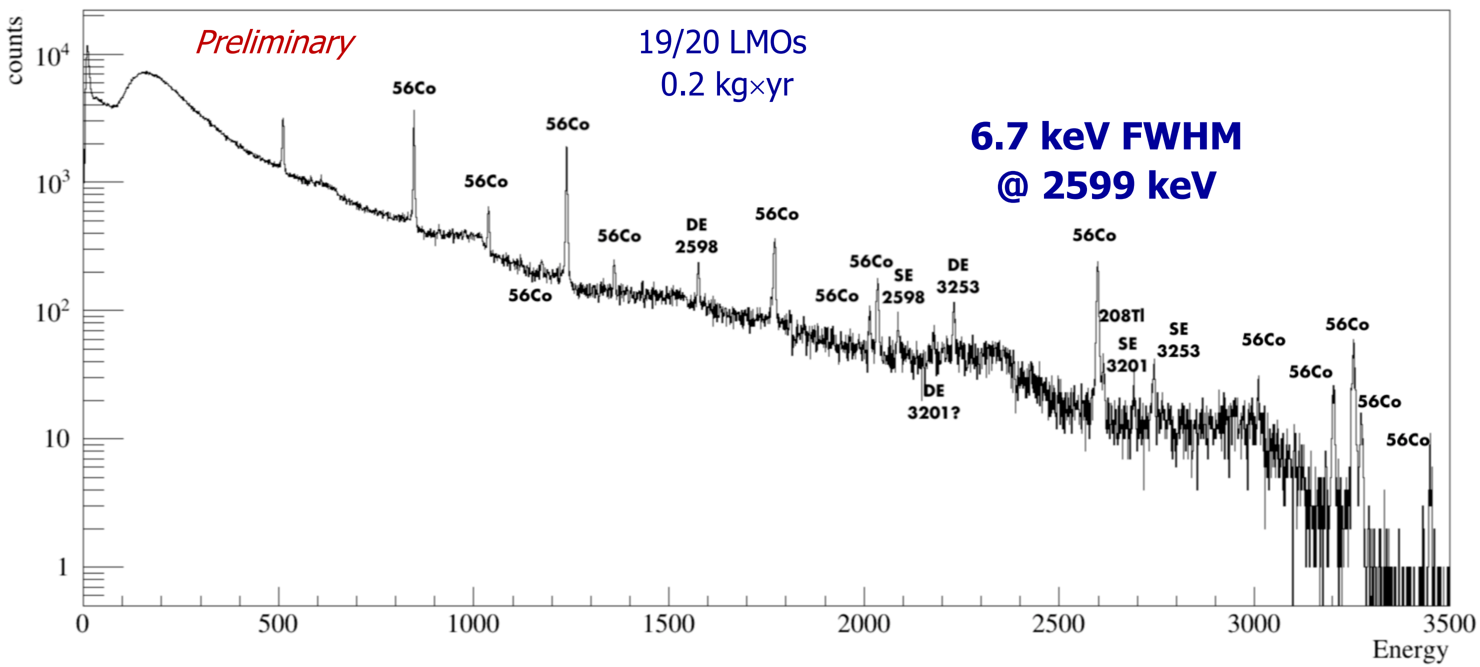
Detector		20/20 **LMOs**	19/20 **LDs**
Rise time	10%-90% of A_{max} [ms]	24	4
Decay time	90%-30% of A_{max} [ms]	300	9

EPJC 80, 44 (2020)

LMO calibration

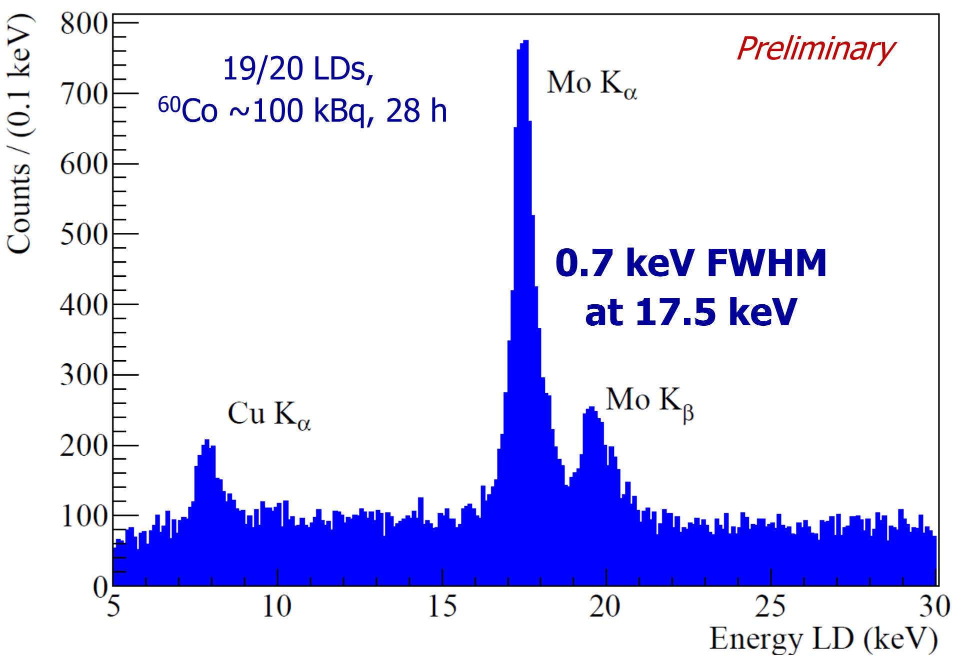


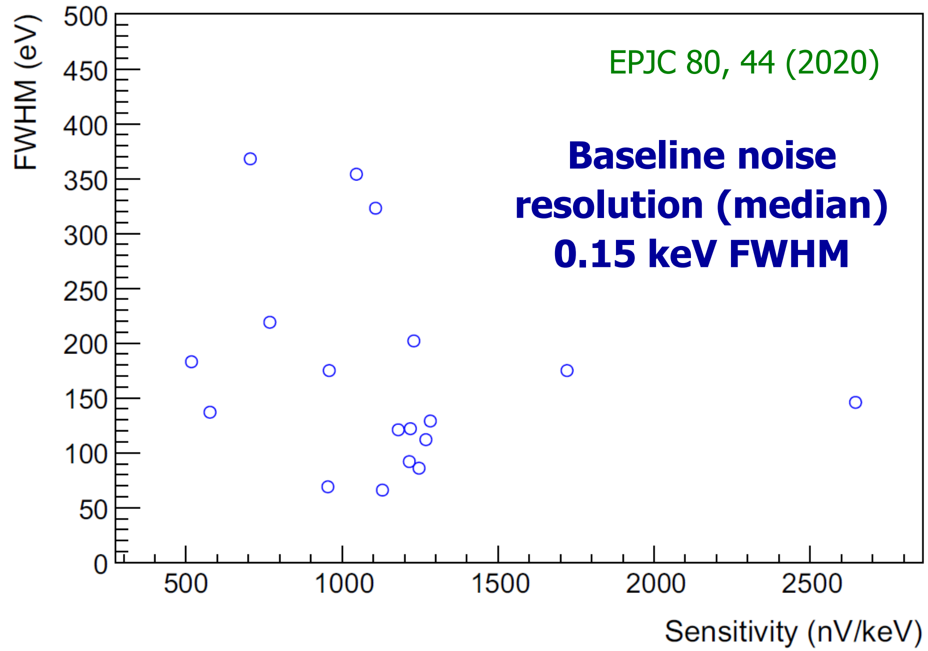




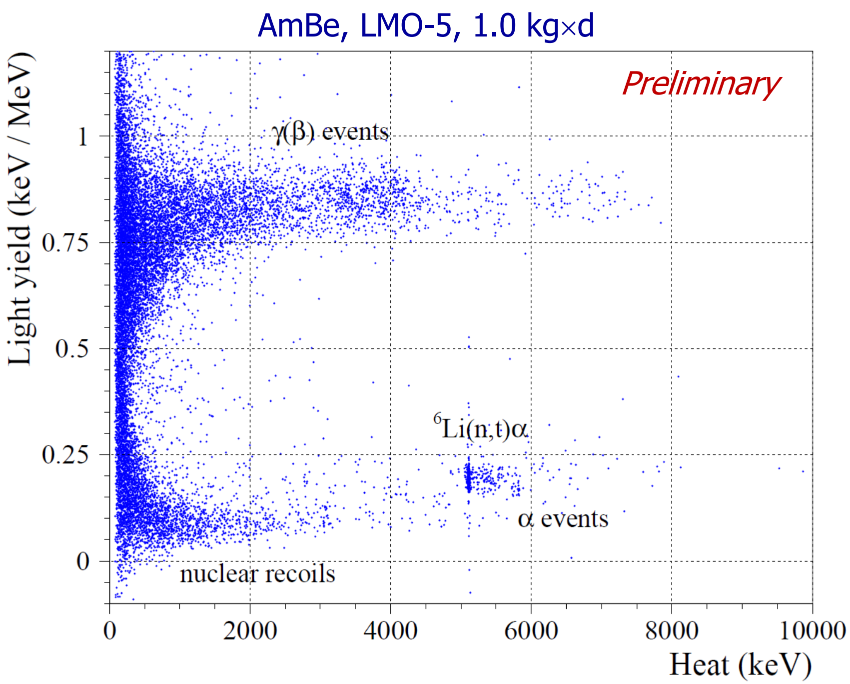
LD calibration

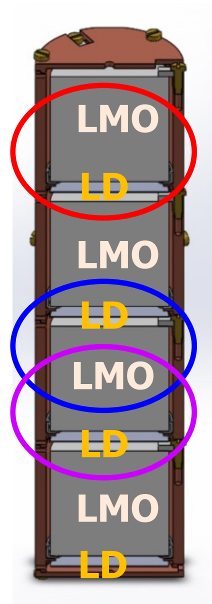
- LD calibration is not mandatory for scintillation-based particle identification, but it provides valuable information about LD performance and LMO scintillation
- Low energy calibration sources are potentially dangerous for the EDELWEISS dark matter search
- High intensity γ irradiation, used in the EDELWEISS to neutralize heat-ionization Ge bolometers, can be exploited to induce X-ray fluorescence to be detected by LDs

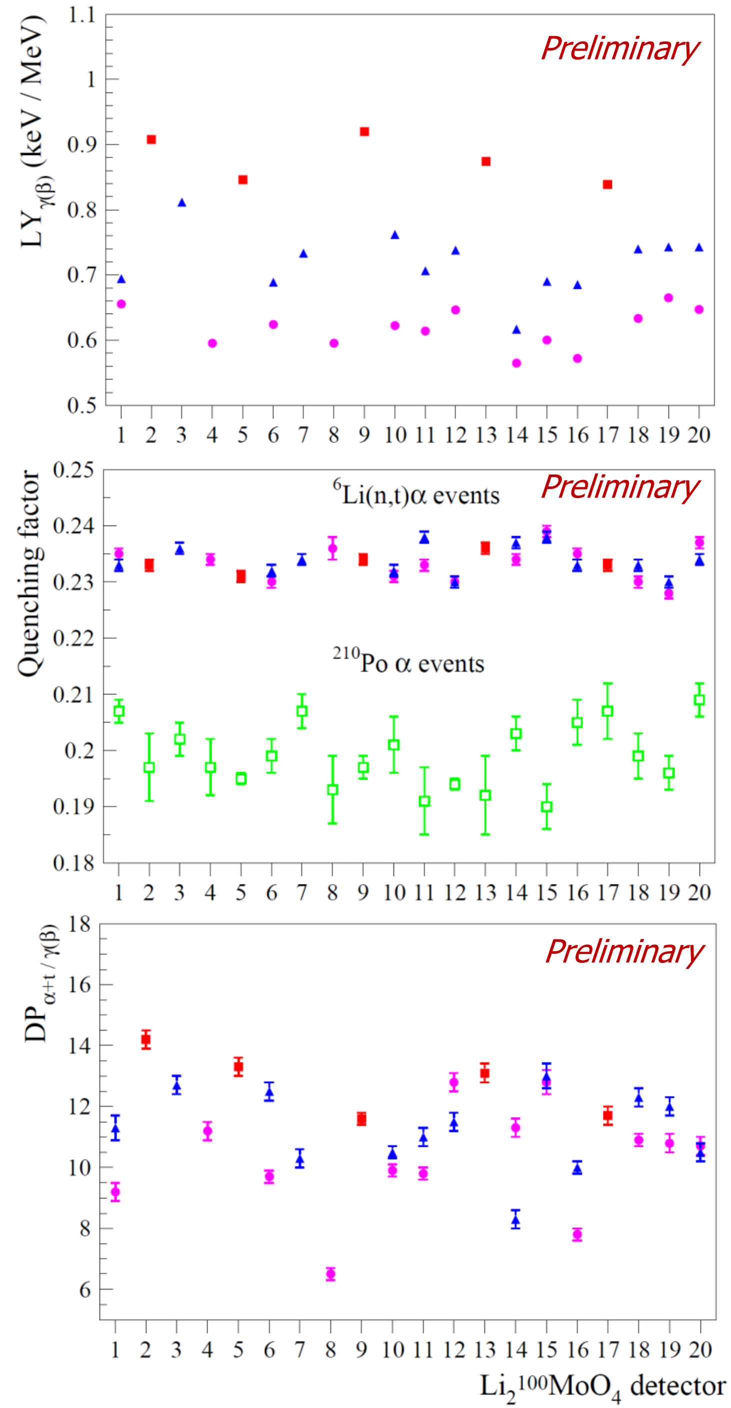




Particle identification







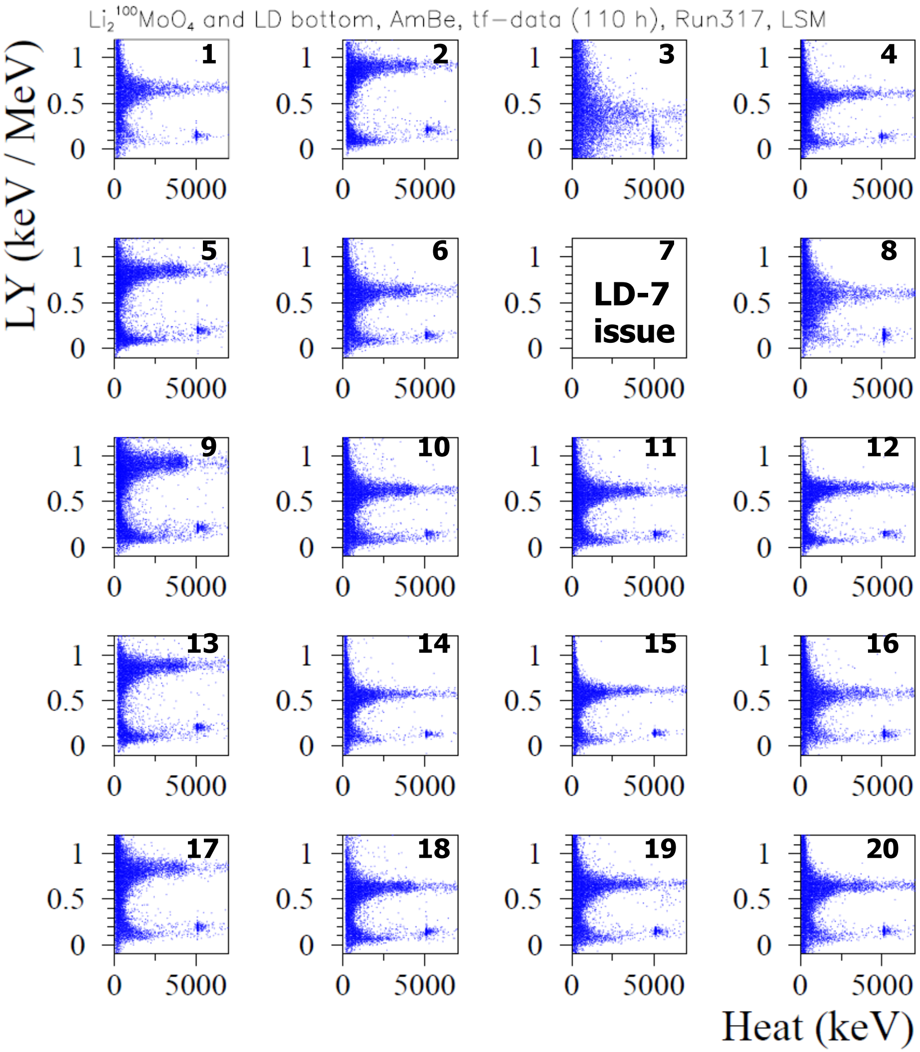
Light detector	Single	Top	Bottom
Light yield for γ(β)'s [keV/MeV]	0.87	0.73	0.62
Light yield quenching: α+t α	23% 20%		
Discrimination α+t vs. γ(β)	13σ	11σ	11σ

Similar light yield for γ(β)'s & quenching factor for α's are evaluated from the CUPID-Mo first dataset [EPJC 80, 44 (2020)]

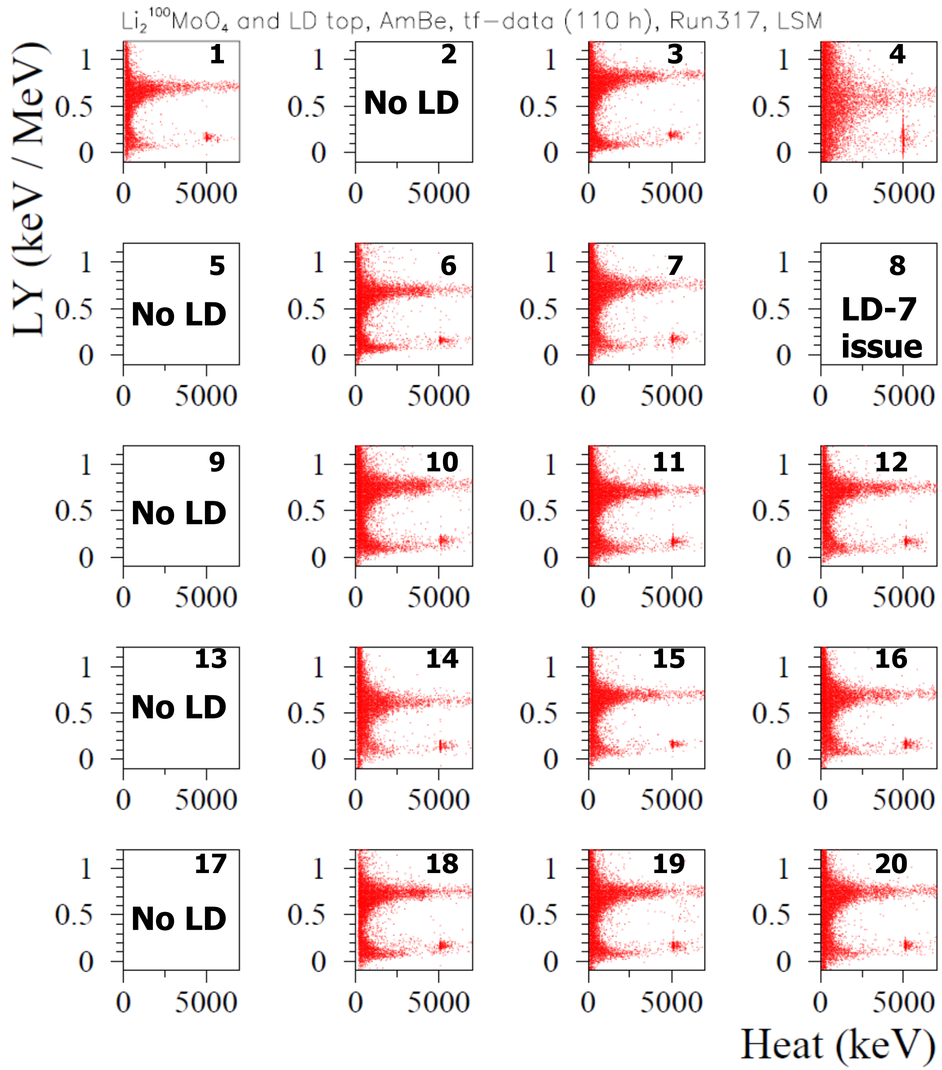
Particle identification

Preliminary

LMO + LD bottom



LMO + LD top



CUPID-Mo physics data for 0ν2β analysis

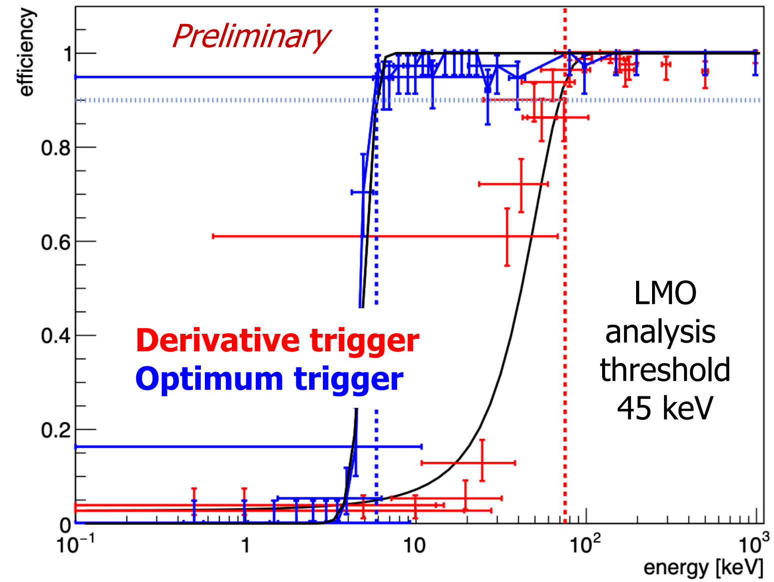
Physics data selection

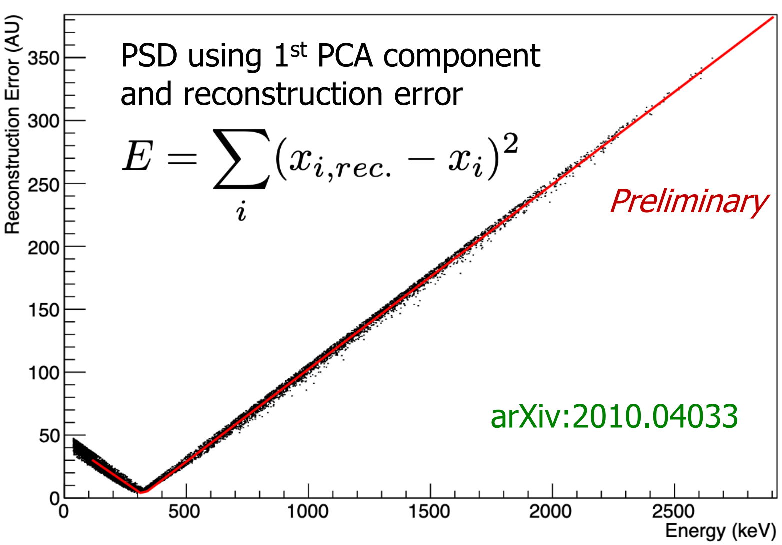
- ✓ **23 March 2019 – 09 April 2020**
  ⇒ 240 days (10 datasets)
- ✓ **At least two Th/U calibrations in a dataset**
  ⇒ 224 days (7 datasets)
- ✓ **No temperature instability / excessive noise**
  ⇒ 200 days

Events selection (blinded 0ν2β ROI)

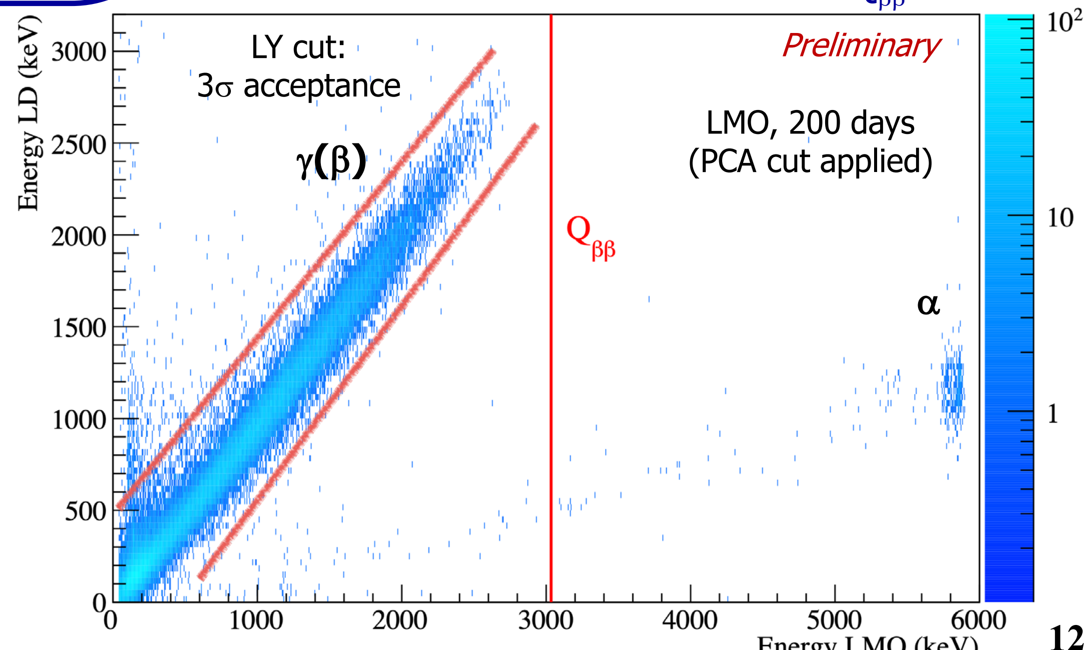
- ➢ **Base cuts** (single trigger, baseline slope)
- ➢ **Multiplicity cuts** (single crystal, muon veto)
- ➢ **Principal Component Analysis** (PCA)
- ➢ **Light yield cut**

$$\epsilon = (90.5 \pm 0.4\,(\mathrm{stat.})\,{}^{+0.8}_{-0.2}\,(\mathrm{syst.}))\%$$

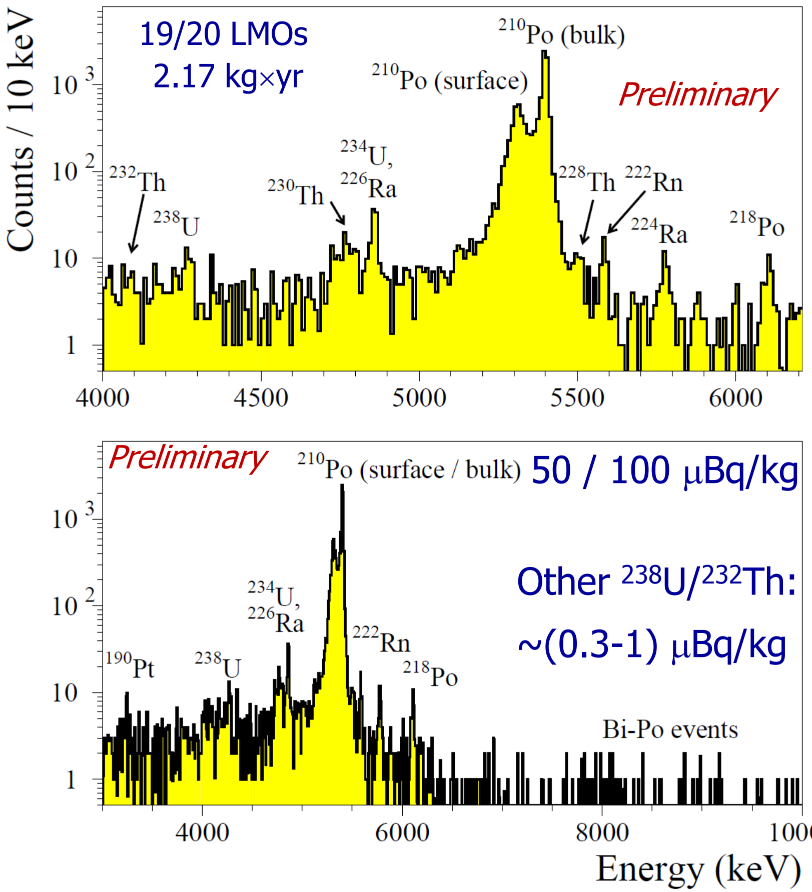




Blinded data: 100 keV centered at $Q_{\beta\beta}$

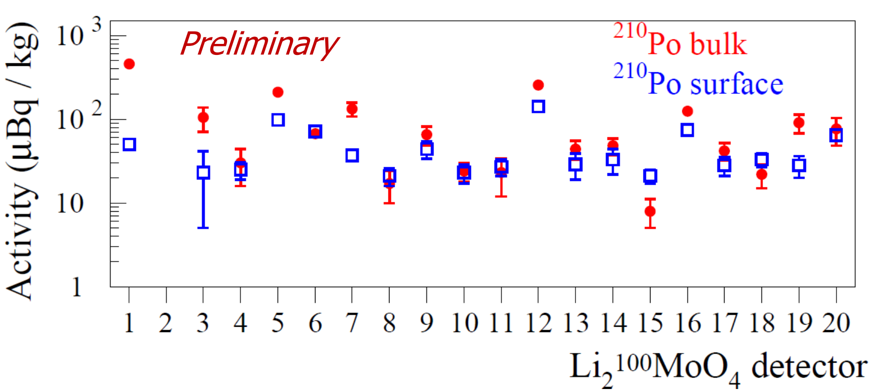


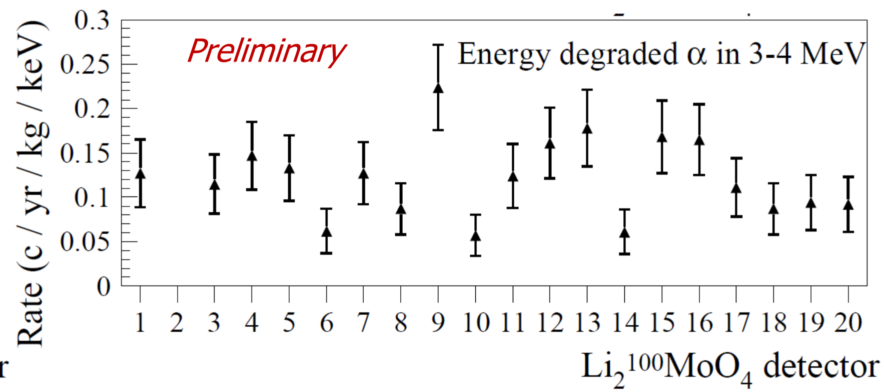
Combined spectrum of α events



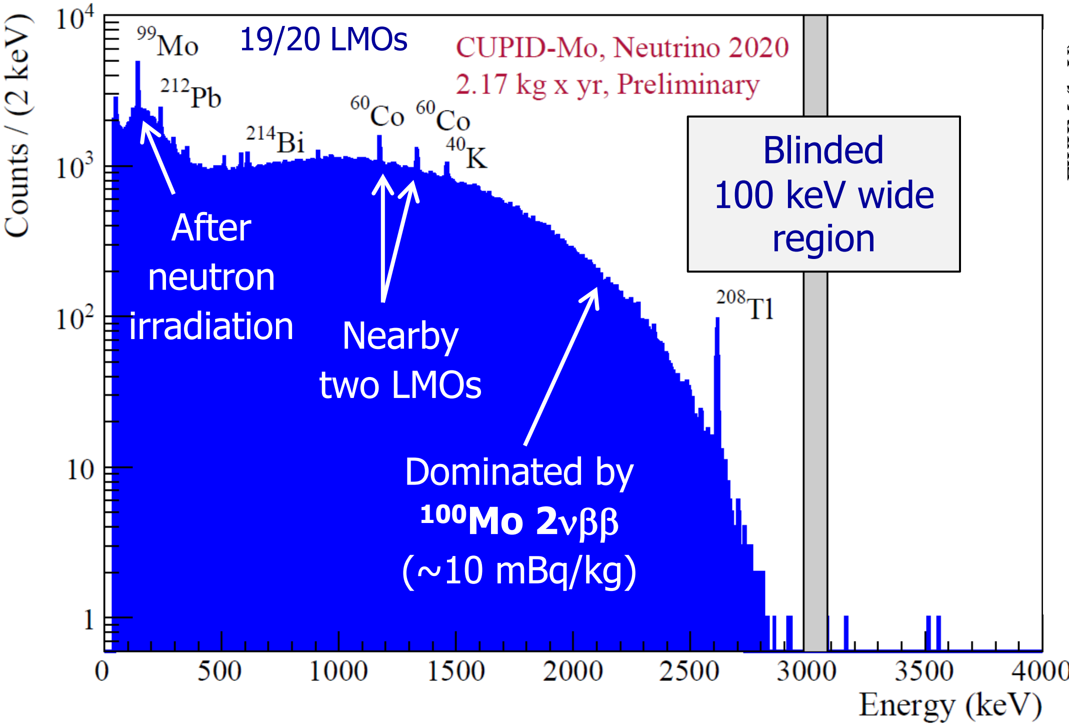
Chain	Nuclide	Activity in LMO [μBq/kg]
^{232}Th	^{232}Th	0.22(9)
	^{228}Th	0.38(9)
	^{224}Ra	0.34(9)
	^{212}Bi	0.22(7)
^{238}U	^{238}U	0.35(10)
	^{234}U+^{226}Ra	1.22(17)
	^{230}Th	0.48(12)
	^{222}Rn	0.47(10)
	^{218}Po	0.35(9)
	^{210}Po	95(6)
	^{190}Pt	0.19(8)

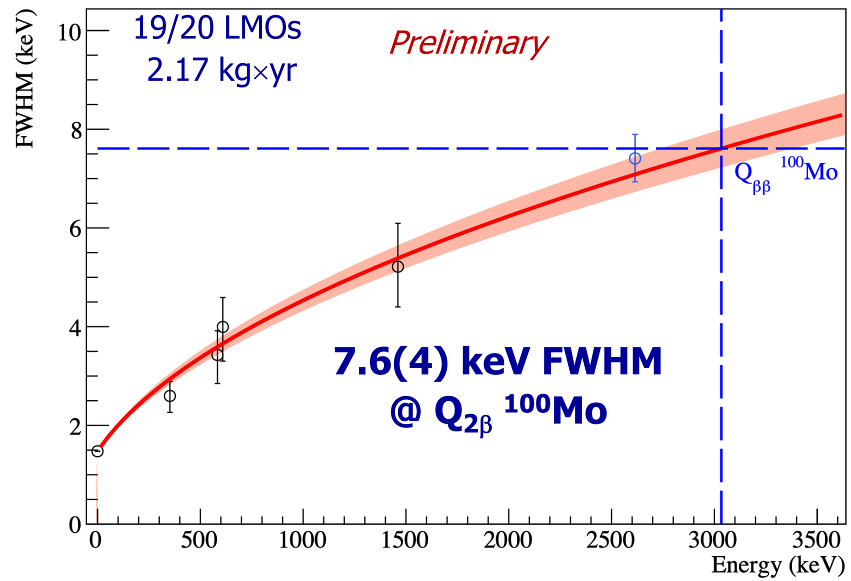
Preliminary

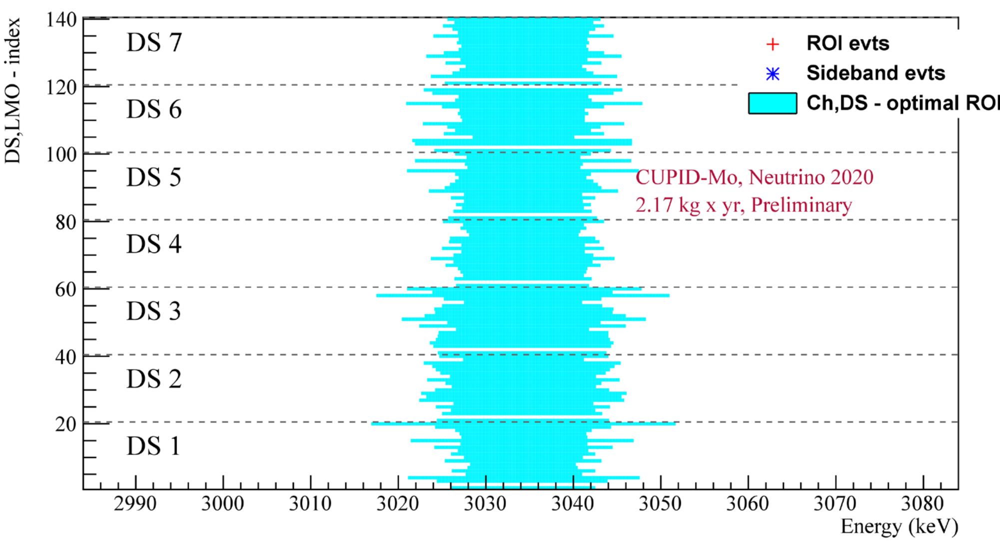




Combined spectrum of γ(β) events







ROI optimization prior unblinding

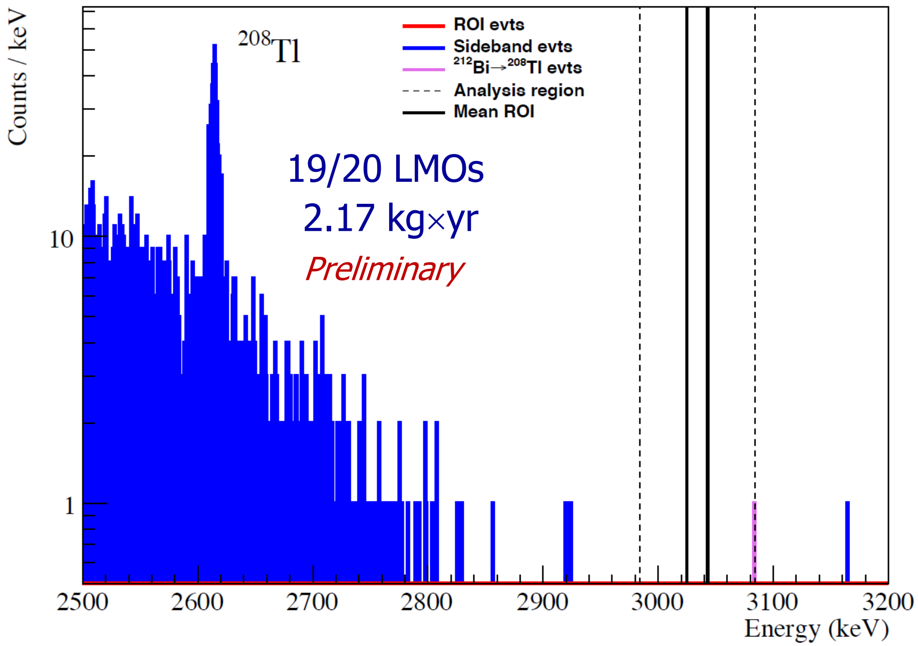
- **Detector & dataset based resolutions** 7.7(7) keV FWHM at ^{100}Mo $Q_{2\beta}$ (3034 keV)
- **Background estimate around ROI** 5×10^{-3} counts/yr/kg/keV (ckky)
- **Expected full exposure** 2.8 kg×yr
- **Maximization of the $T_{1/2}$ sensitivity**

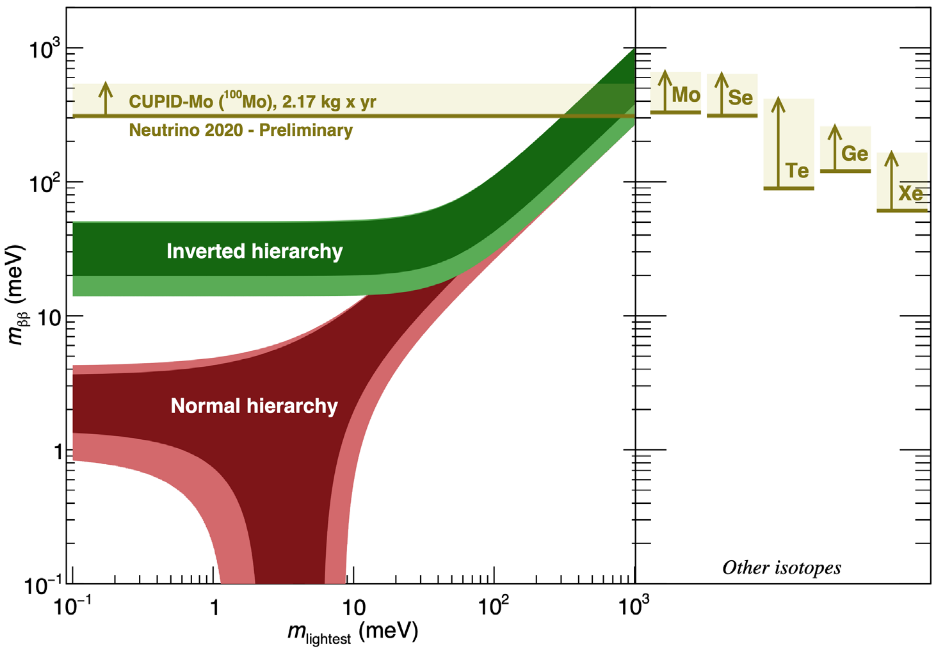
⇓

Mean ROI is 18 keV wide ($Q_{2\beta}\pm 2.7\sigma$)

⇒ Mean 0ν2β containment is 75.7%

CUPID-Mo search for ^{100}Mo $0\nu2\beta$ decay





^{100}Mo $0\nu2\beta$ search

- **Unblinding of 100 keV wide region**
  $\Rightarrow$ no event in the ROI
  $\Rightarrow$ a single event at the sideband
- **Use of Bayesian Analysis Toolkit** (BAT)
  $\Rightarrow$ an upper limit is 2.4 counts @ 90% C.I.
  $\Rightarrow$ posterior Bkg is $3^{+7}_{-3}\times10^{-3}$ ckky
- **Refined analysis adding the ^{212}Bi-^{208}Tl cut**
  (using ^{212}Bi α's to veto $10\times T_{1/2}$ of ^{208}Tl [183 s])
  $\Rightarrow$ 0.02% reduced live-time
  $\Rightarrow$ rejected sideband event (^{212}Bi-^{208}Tl Δt = 113 s)
  $\Rightarrow$ posterior Bkg = 0 (<1.1×10^{-2} ckky @ 90% C.I.)
  $\Rightarrow$ 1.3% stronger ^{100}Mo $0\nu2\beta$ half-life limit

$\Downarrow$

$T_{1/2} \geq$ **1.5×10^{24} yr** @ 90% C.I.

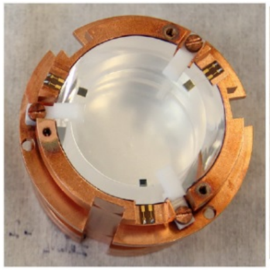
$\langle m_{\beta\beta}\rangle \leq$ **0.3–0.5 eV**

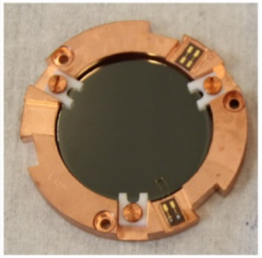
Preliminary

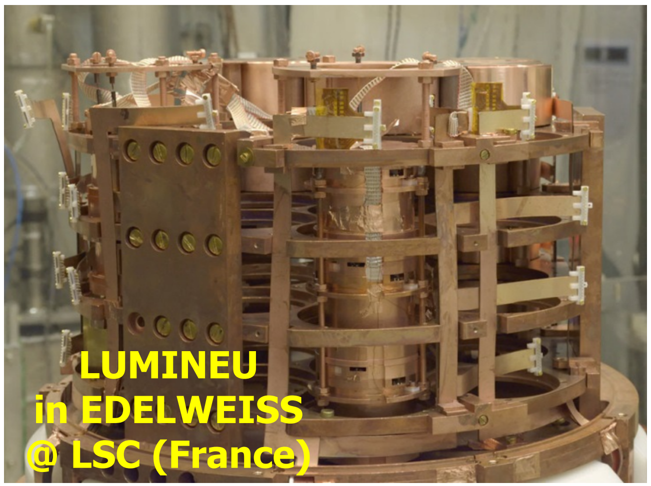
lim $T_{1/2}$ [yr]	^{100}Mo kg×yr	Experi-ment	Ref.
1.1×10^{24}	34.3	NEMO-3	PRD 92, 072011 (2015)
1.5×10^{24}	1.19	CUPID-Mo	Submitted to PRL (2020)

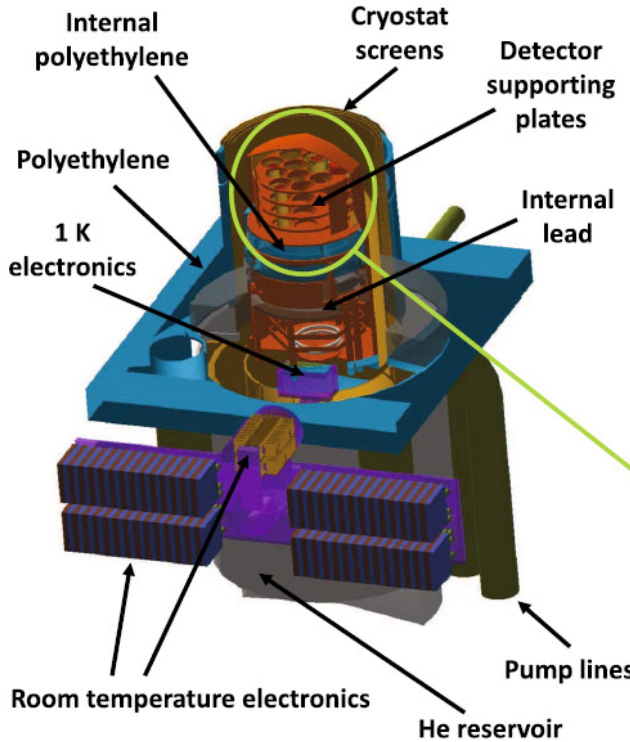
^{100}Mo 2ν2β decay investigation

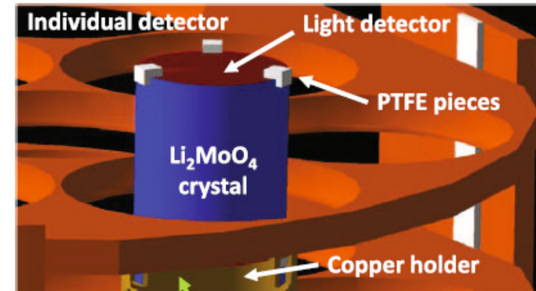
CUPID-Mo predecessor: LUMINEU experiment

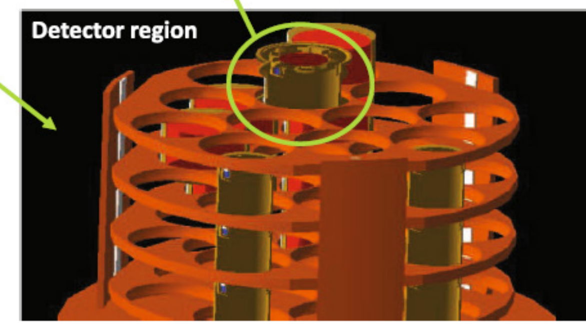












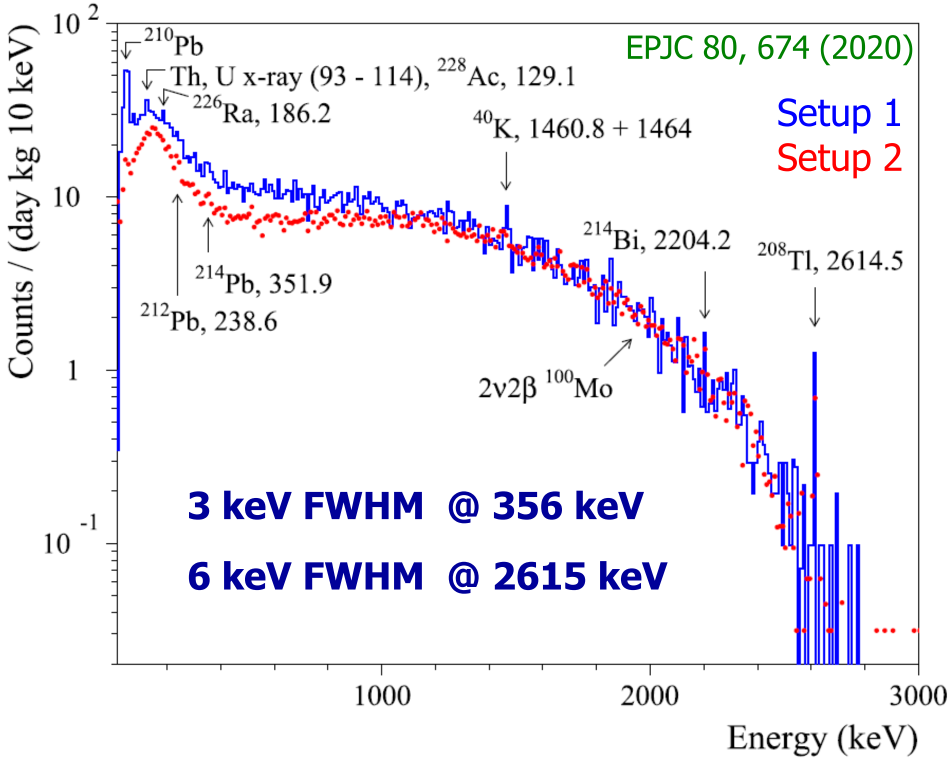
EPJC 77, 785 (2017); AIP Conf. Proc. 1894, 020017 (2017)

EPJC 80, 674 (2020)

$Li_2{}^{100}MoO_4$ mass [g]	^{100}Mo enrichment [%]	Setup 1 [h]	Setup 2 [h]
186	96.93(7)	1331	1001
204	96.93(7)		998
213	96.89(12)		1038
207	96.89(12)		757

Total $Li_2{}^{100}MoO_4$ exposure = 0.12 kg×yr (0.06 kg×yr of ^{100}Mo)

Experimental data and background components



Chain	Nuclide	Activity [μBq/kg] in the LMO bulk
^{232}Th	^{232}Th	≤ 3
	^{228}Th	≤ 3
^{235}U	^{235}U	≤ 5
	^{231}Pa	≤ 3
	^{227}Ac	≤ 5
^{238}U	^{238}U	≤ 5
	^{226}Ra	≤ 3
	^{210}Po	200(10)
	^{190}Pt	≤ 3
	^{100}Mo	**~10,000**

External sources
- ❑ ^{40}K
- ❑ ^{137}Cs
- ❑ ^{228}Ac
- ❑ ^{212}Pb, ^{212}Bi, ^{208}Tl
- ❑ ^{214}Pb, ^{214}Bi

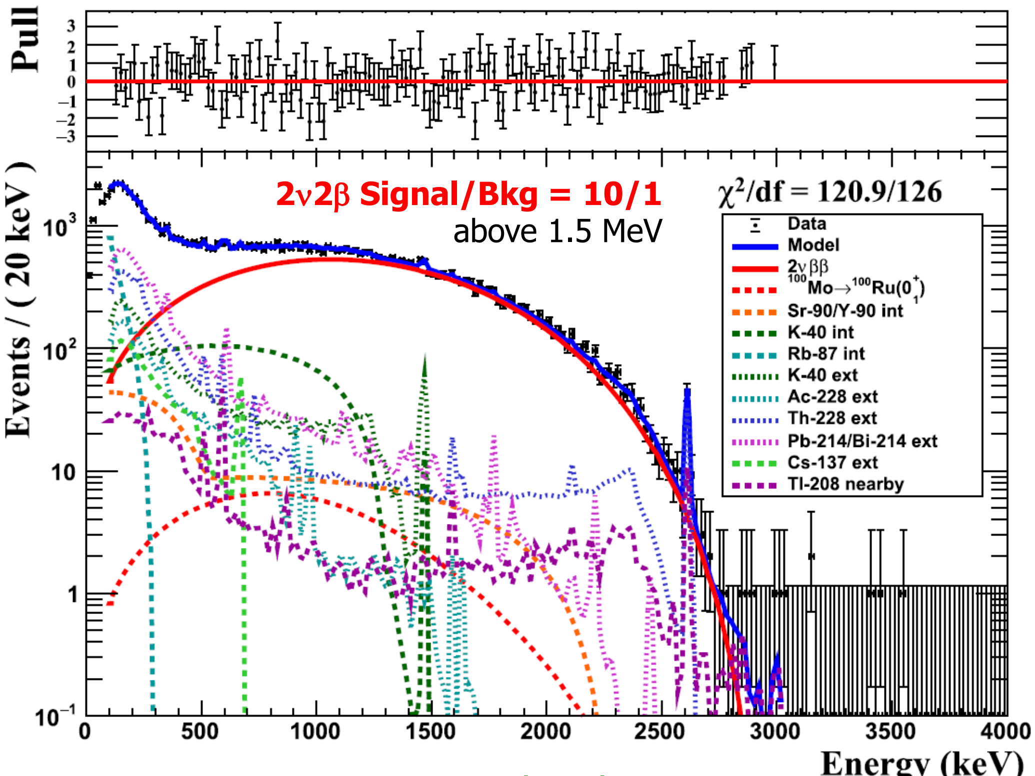
Nearby sources
- ❑ ^{210}Pb, ^{210}Bi
- ❑ ^{208}Tl

Monte Carlo model is tuned
to reproduce γ peaks intensities

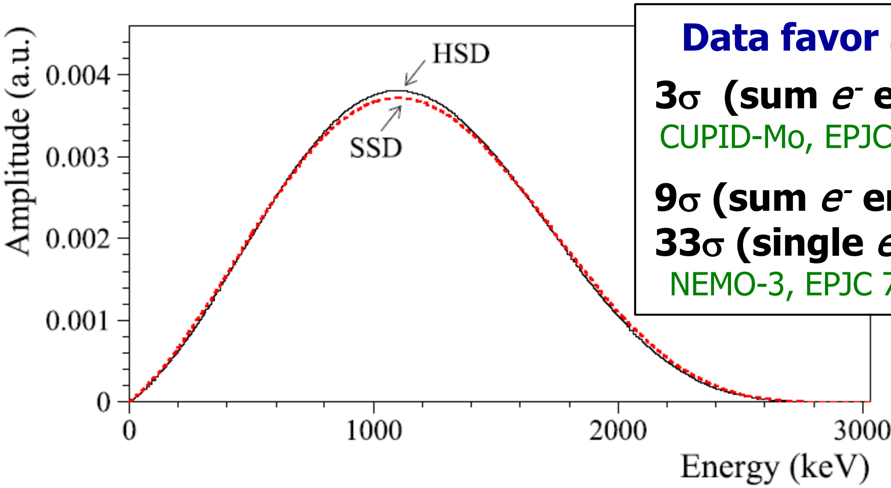
Internal sources
- ❑ ^{40}K
- ❑ ^{87}Rb
- ❑ ^{90}Sr, ^{90}Y
- ❑ ^{210}Pb, ^{210}Bi
- ❑ ^{100}Mo 2ν2β (g.s.→g.s.), to be investigated here
- ❑ ^{100}Mo 2ν2β (g.s.→0_1^+), $T_{1/2}$ = $(7.5\pm1.1)\times10^{20}$ yr

According to the crystals radiopurity,
and chemical affinity of Li with K & Rb

Measurement of the ^{100}Mo $2\nu2\beta$ decay half-life



EPJC 80, 674 (2020)



Data favor SSD ($\sqrt{\Delta\chi^2}$)

3σ (sum e^- energy)
CUPID-Mo, EPJC 80, 674 (2020)

9σ (sum e^- energy)
33σ (single e^- energy)
NEMO-3, EPJC 79, 440 (2019)

Analysis of ^{100}Mo $2\nu2\beta$ decay

- **Fit in 1500-3000 keV** (23.5% of $2\nu2\beta$)
  $\Rightarrow$ Signal = 8370^{+162}_{-214}(stat.) events
  $\Rightarrow$ Signal/Background = 10:1
- **Exposure** $3.798(9)\times10^{23}$ ^{100}Mo nuclei × yr
- **Selection efficiency** 96.5(6)%

$\Downarrow$

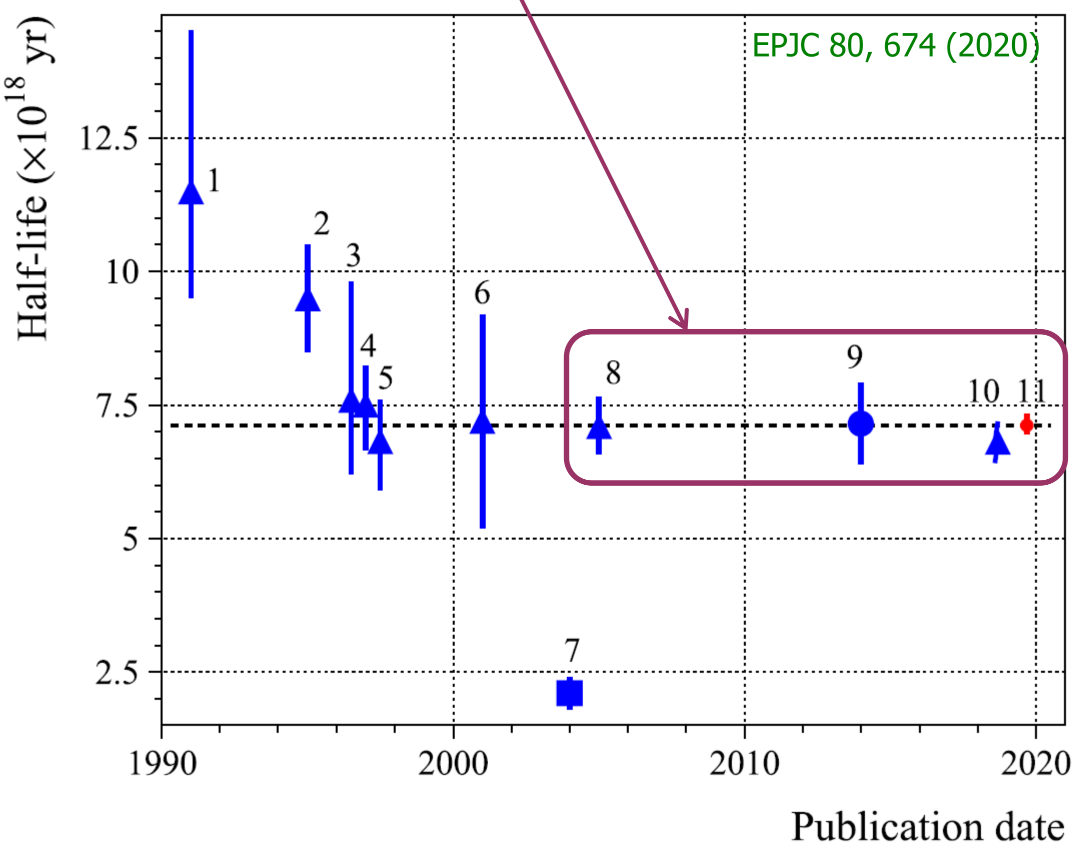
$T_{1/2} = [7.12\ ^{+0.18}_{-0.14}(\text{stat.})]\times10^{18}$ yr

EPJC 80, 674 (2020)

Systematic error	[%]
Energy spectrum binning	0.8
Localization of sources	0.8
Selection efficiency	0.6
$2\nu2\beta$ shape (SSD vs. HSD)	0.4
Monte Carlo statistics	0.4
Background composition	0.2
^{100}Mo exposure	0.2
Energy scale	0.2
^{100}Mo $2\nu2\beta \to$ ^{100}Ru (0_1^+)	0.1
Total	**1.4**

^{100}Mo $2\nu2\beta$ decay half-life

Most precise ^{100}Mo $2\nu2\beta$ half-life value [10^{18} yr]	Uncertainty [%]	Exposure [^{100}Mo kg×yr]	Experiment	Ref.
7.11 ±0.02(stat.) ±0.54(syst.)	± 7.6	7.37	NEMO-3	PRL 95, 182302 (2005)
7.15 ±0.37(stat.) ±0.66(syst.)	± 10.6	0.01	LUCIFER R&D	JPG 41, 075204 (2014)
6.81 ±0.01(stat.) $^{+0.38}_{-0.40}$(syst.)	+5.6 / -5.9	34.3	NEMO-3	EPJC 79, 440 (2019)
7.12 $^{+0.18}_{-0.14}$(stat.) ±0.10(syst.)	+2.9 / -2.4	0.06	LUMINEU / CUPID-Mo	EPJC 80, 674 (2020)



$2\nu2\beta$	Half-live uncertainty [%]
^{82}Se	+2.2 / -1.6
^{100}Mo	+2.9 / -2.4
^{130}Te	± 2.8
^{136}Xe	± 2.8
^{76}Ge	± 4.9
^{116}Cd	± 5.3
^{150}Nd	± 7.1
^{96}Zr	± 8.9
^{40}Ca, ^{128}Te, ^{238}U	≈ 10-30

Bolometric experiments

Prospects of 2ν2β study in CUPID-Mo

^{100}Mo 2ν2β → ^{100}Ru (g.s.)

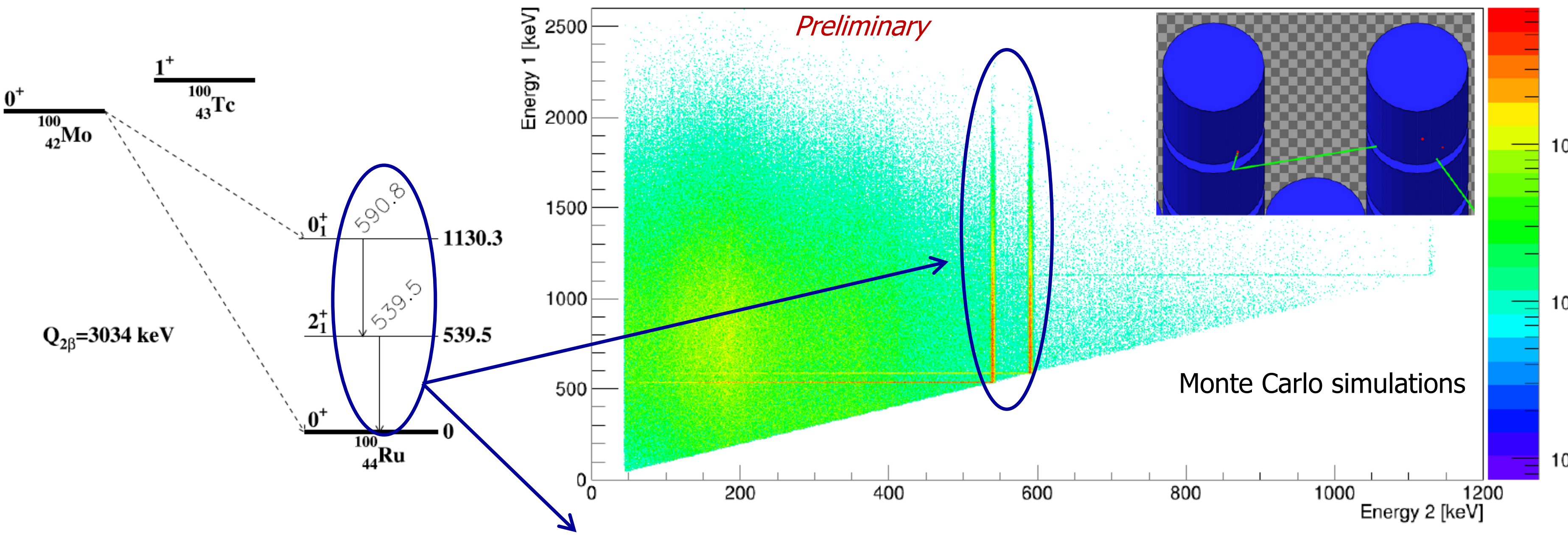
- ✓ About 20x LUMINEU exposure
- ✓ Improved background rejection (M2 & muon veto cuts)
- ✓ Advanced background model (based on M1 & M2 data)

⇒ Reduced stat. and syst. errors
⇒ Improved sensitivity to "SSD vs. HSD"

^{100}Mo 2ν2β → ^{100}Ru (0_1^+)

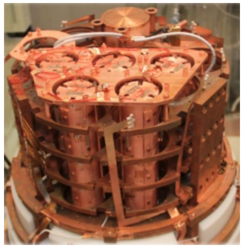
- ✓ Segmented detector
- ✓ Detection of coincidences (de-excitation γ's) with a high energy resolution
- ✓ Reasonably large exposure in low background environment

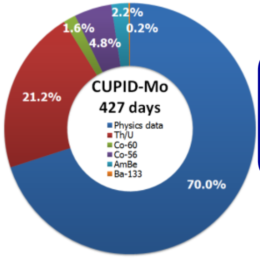
⇒ Detection with the statistical significance >5σ



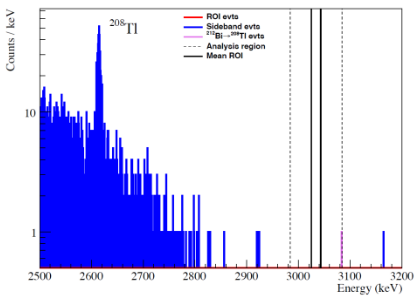
^{100}Mo 2ν2β	E1 [keV]	E2 [keV]	Eff. [%]	BI [ckky]	ΔE [keV]	S/√(S+B)
g.s.→0_1^+	535–2494	540	0.7	10	3.6	4.6
g.s.→0_1^+	586–2443	591	0.5	10	3.7	3.5

Summary





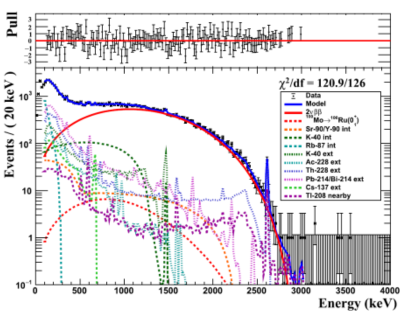
➢ **CUPID-Mo acquired 427 days of data** in the EDELWEISS set-up (with 89% duty cycle) at Modane underground laboratory in France



➢ **We set the most stringent limit on the ^{100}Mo 0ν2β half-life**

$T_{1/2}$ (0ν2β) > 1.5 × 10^{24} yr @ 90% C.I.

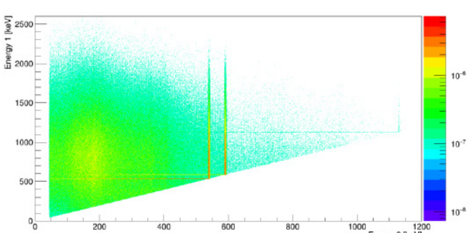
It corresponds to the 4th world wide stringent limit on **the effective Majorana ν mass** $<m_\nu> \leq$ 0.3–0.5 eV @ 90% C.I.



➢ **We measured the most precise ^{100}Mo 2ν2β half-life**

$T_{1/2}$ (2ν2β) = [7.11 $^{+0.18}_{-0.14}$(stat.) ±0.10(syst.)] × 10^{18} yr

It is the 2nd world wide precise $T_{1/2}$ among all 2β isotopes



➢ **^{100}Mo 2ν2β transition to the 0_1 level of ^{100}Ru will be detected**

Stay tuned !

CUPID-Mo Collaboration

http://cupid-mo.mit.edu

7 countries, 15 institutions, ~110 collaborators

CUPID-Mo unblinding meeting, via Zoom, 9 June 2020

CUPID-Mo kick-off meeting, CSNSM, Orsay, France, 29-30 March 2018