Search for double-beta decay of ^{100}Mo with the scintillating bolometer approach

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on behalf of LUMINEU, EDELWEISS and CUPID-0/Mo Collaborations

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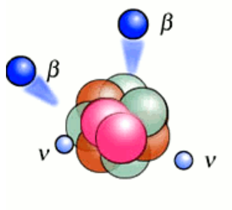
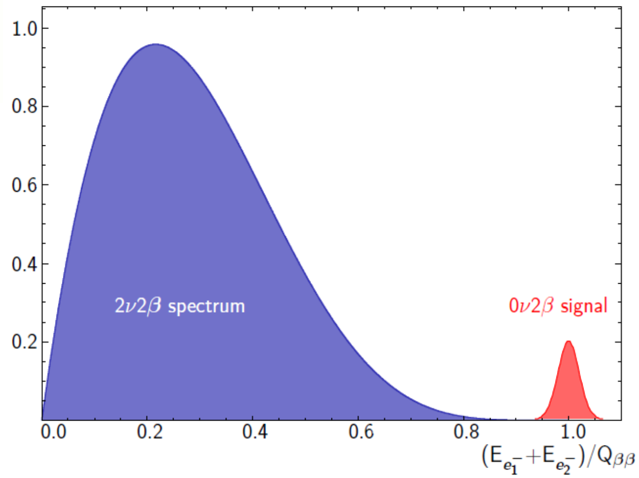
Double-beta decay: (A,Z)→(A,Z+2)+…

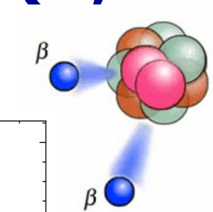
Two neutrino 2β decay



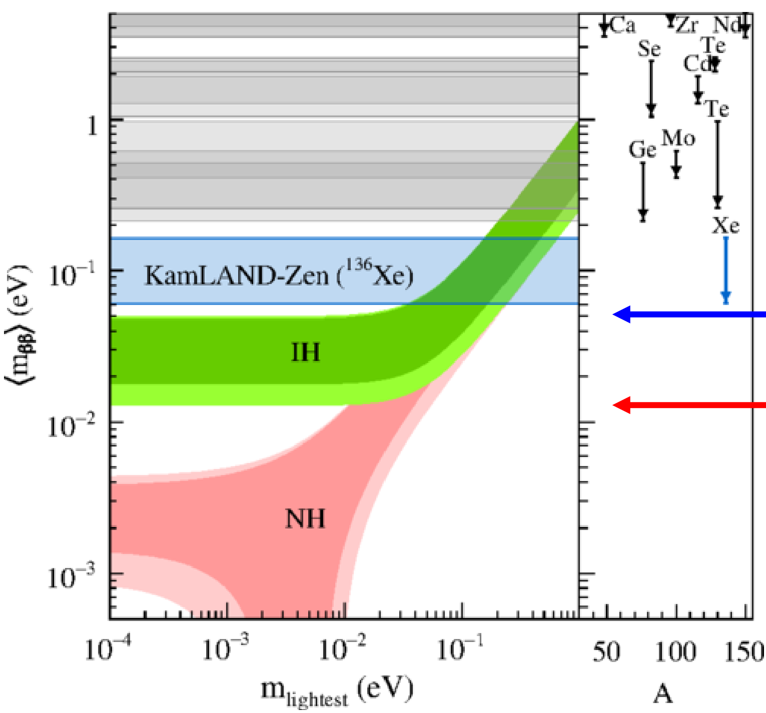
Allowed in the SM
- Rarest observed nuclear decay ($T_{1/2} \sim 10^{18}$–10^{24} yr)
- Information about nuclear matrix elements ⇒ test of theoretical description



Neutrinoless 2β decay



Beyond the SM
- Total lepton number violation
- Majorana nature of neutrino
- Non-zero neutrino mass
- Scale of neutrino masses (best limit $T_{1/2} \sim 10^{26}$ yr, $\langle m_{\beta\beta} \rangle \sim$ 0.06–0.16 eV)



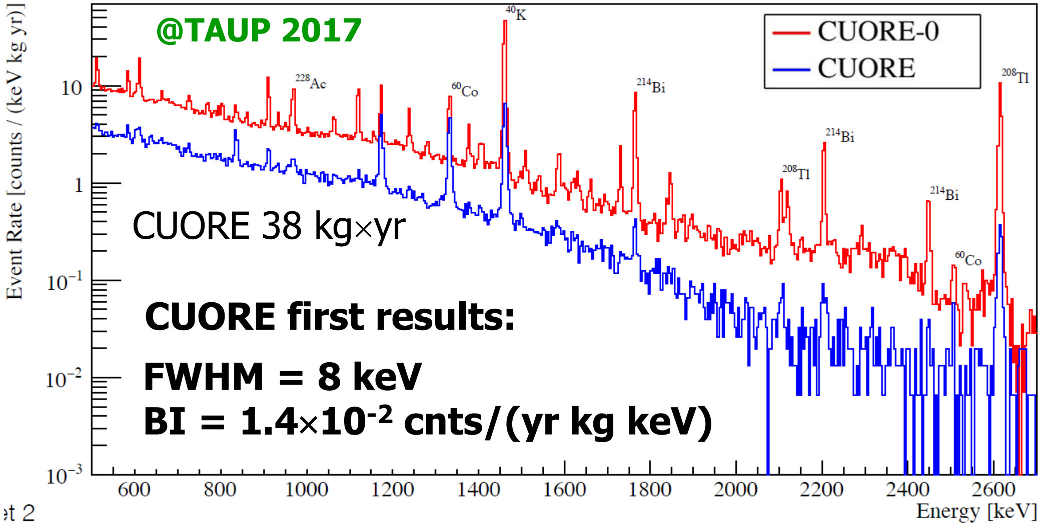
Near future: $T_{1/2} \sim 10^{26-27}$ yr
- ^{76}Ge (GERDA, Majorana)
- ^{82}Se (CUPID-0, SuperNEMO)
- ^{136}Xe (KamLAND-ZeN, EXO)
- ^{130}Te (CUORE, SNO+)
- Best BI = 10^{-3} -10^{-2} cnts/(yr kg keV)

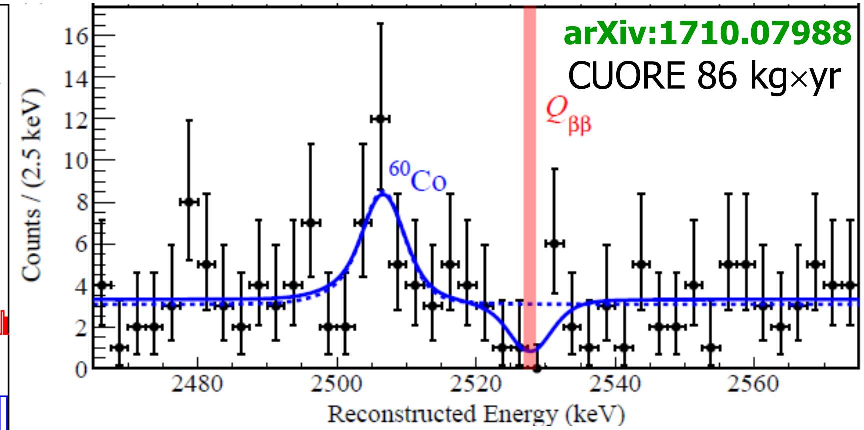
Far future: $T_{1/2} \sim 10^{27-28}$ yr
New / advanced technology
1t-scale bkg-free experiment(s):
BI < 10^{-4} cnts/(yr kg keV)

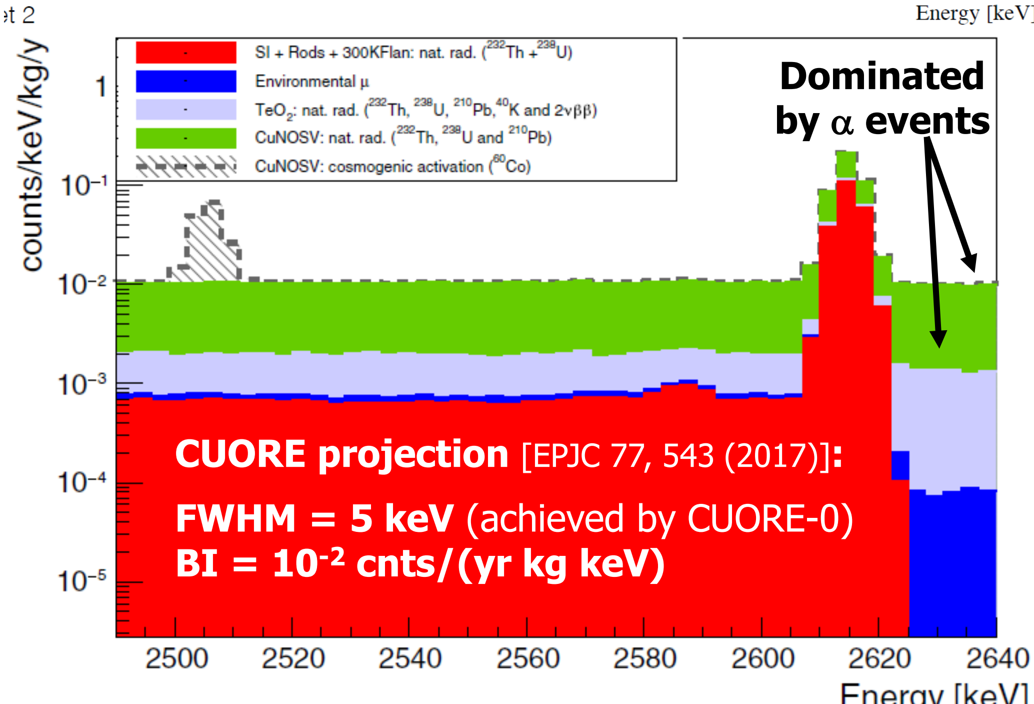
arXiv:1710.07988

CUPID
CUORE Upgrade with Particle IDentification
arXiv:1504.03599

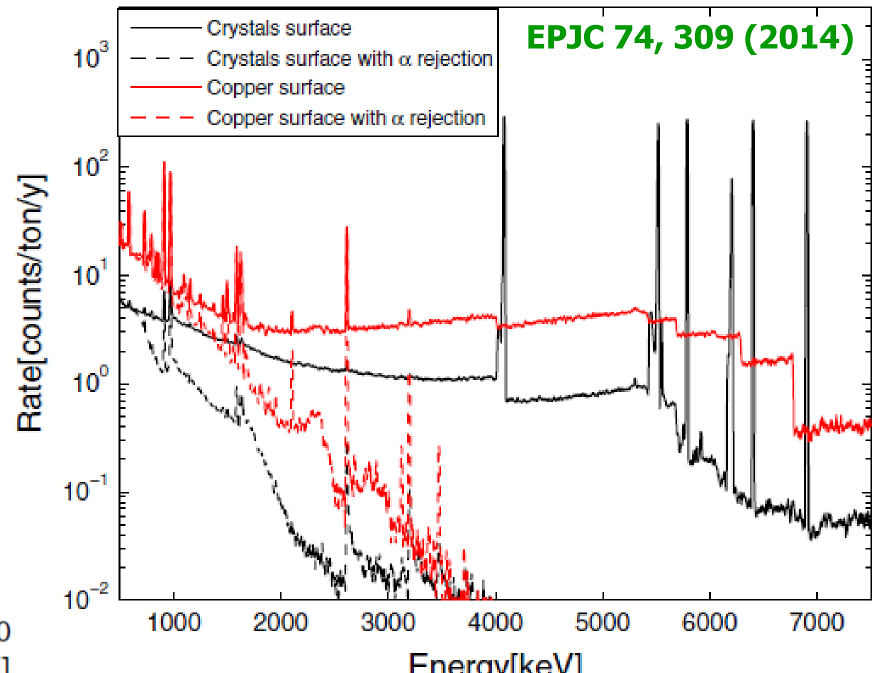
CUORE first results and background issue







MC of bkg suppression by α rejection

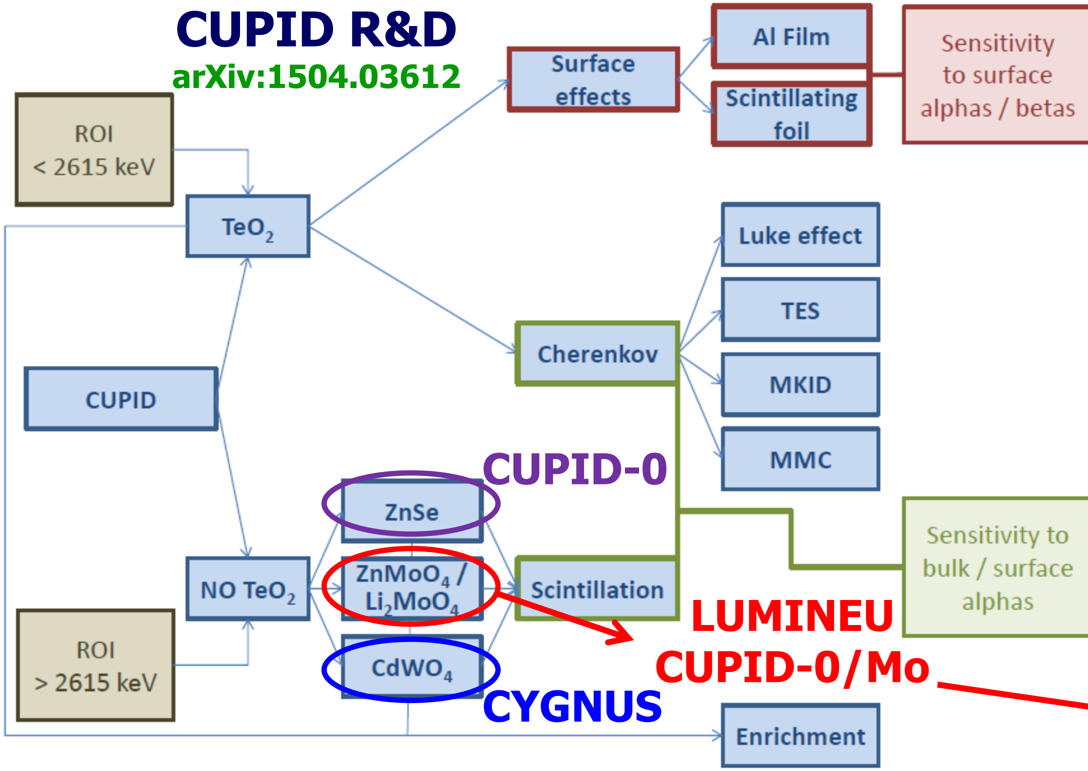


CUPID needs enriched bolometers + environmental/surface bkg suppression

Scintillating bolometer approach towards CUPID

CUPID R&D

arXiv:1504.03612

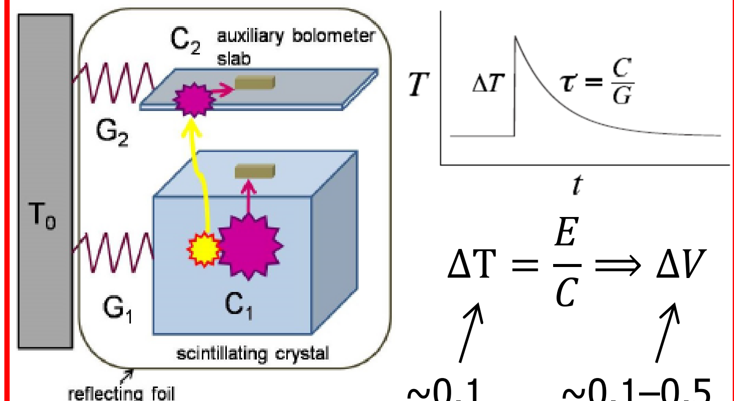


Demands in view of CUPID

Sensor technology	NTD (as in CUORE)
Enriched isotope	≥ 90%
Low material losses	few %
Radiopure crystal	^{228}Th, ^{226}Ra ≤ 10 μBq/kg
High performance	5 keV FWHM @ ROI
Rejection of α's	≥ 99.9%

Scintillating bolometers

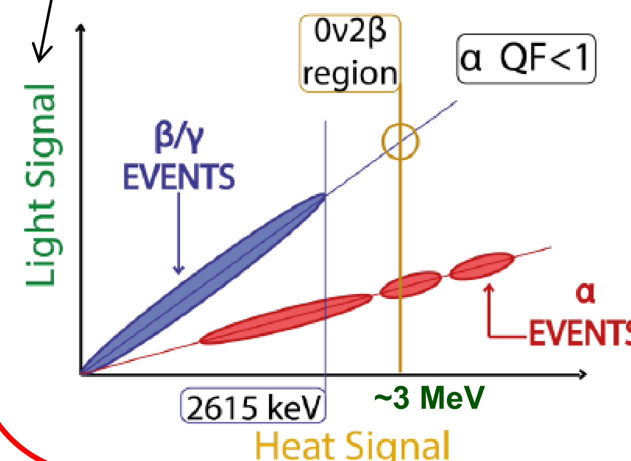
- ✓ **Active-source technique**
- ✓ **High energy resolution**
- ✓ **Particle identification**



$$\Delta T = \frac{E}{C} \Longrightarrow \Delta V$$

~0.1 mK/MeV   ~0.1–0.5 mV/MeV

~1 keV/MeV



LUMINEU and its follow up (CUPID-0/Mo)

Luminescent Underground Molybdenum Investigation for NEUtrino mass and nature

LUMINEU $\beta\beta$ 0ν

Agence Nationale de la Recherche ANR

2012-2016

http://lumineu.in2p3.fr

Initially involved institutions:
CSNSM and IAS Orsay, ICMCB Bordeaux, CEA Saclay (**France**);
INR Kyiv (**Ukraine**); NIIC Novosibirsk (**Russia**);
KIP Heidelberg (**Germany**); INFN Milano Bicocca (**Italy**)

Further involved participants:
EDELWEISS collaboration (**France, Germany, UK, Russia**);
ITEP Moscow (**Russia**); **INFN / LUCIFER** coll. LNGS/Rome (**Italy**)

New participants:
LAL Orsay (**France**); Fudan Shanghai, USTC Hefei (**China**);
MIT Massachusetts, UCLA California, UCB and LBNL Berkley (**USA**)

Technology of ^{100}Mo-enriched scintillating bolometers for a next-generation $0\nu2\beta$ experiment

- **Development of radiopure $ZnMoO_4$ / Li_2MoO_4 scintillating bolometers**
- **Pilot $0\nu2\beta$ experiment with up to ~1 kg of ^{100}Mo: LUMINEU project**
- **Extension to ~5 kg of ^{100}Mo: CUPID-0/Mo project to prove the technology in view of CUPID (CUORE follow-up)**

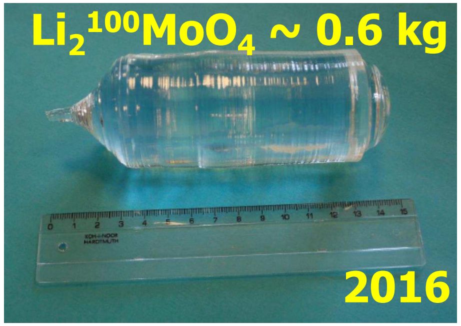
LUMINEU R&D on ^{100}Mo-enriched Li_2MoO_4 crystals

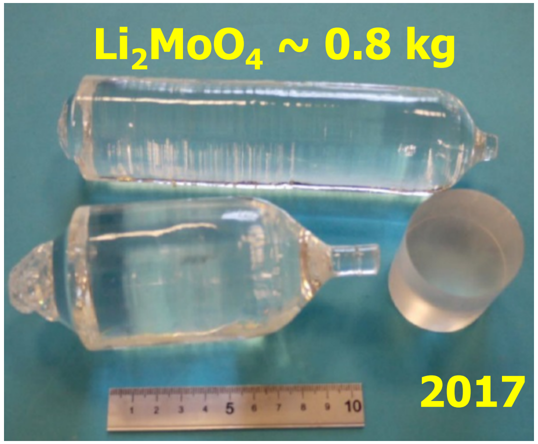
LUMINEU protocol of LMO production

- **^{100}Mo-enriched molybdenum**
  1 kg (^{100}Mo~99%; KINR) + 10 kg (^{100}Mo~97%; ITEP)
- **Deep purification of enriched material**
  sublimation in vacuum
  recrystallization from aqueous solutions
- **Advanced crystallization technology**
  low-thermal-gradient Czochralski crystal growth
  possible size: ∅6 cm; 14 cm length of cylindrical part
- **Dedicated R&D to control ^{40}K content in LMO**
  selection of ultra-pure Li_2CO_3 powder
  LMO growth by double crystallization
  R&D of Li_2CO_3 purification is in progress
- **Extraction of $^{100}MoO_3$ from residues**

arXiv:1704.01758 (To appear in EPJC)
J. Mat. Sci. Eng. 7 (2017) 63
AIP Conf. Proc. 1894 (2017) 020017

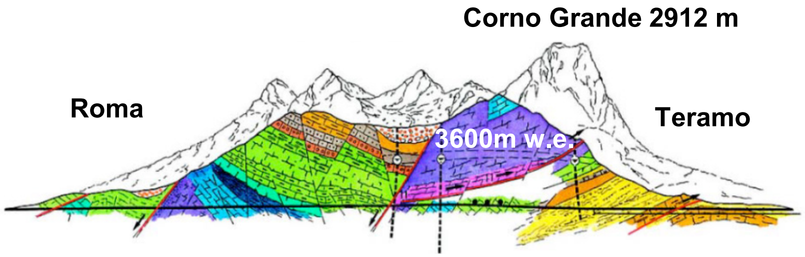
- ✓ **Developed large mass ^{100}Mo-enriched LMO**
  high optical quality and scintillation properties
  high crystal yield (~ 80-85%)
  low irrecoverable losses of ^{100}Mo (~3%)
- ✓ **Batch production of 20x 0.2-kg $Li_2{}^{100}MoO_4$ elements**



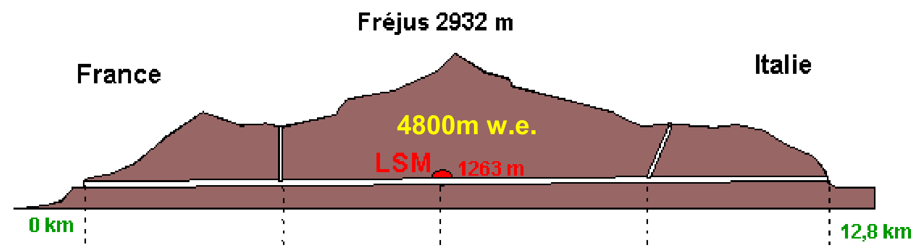


Used underground cryogenic facilities

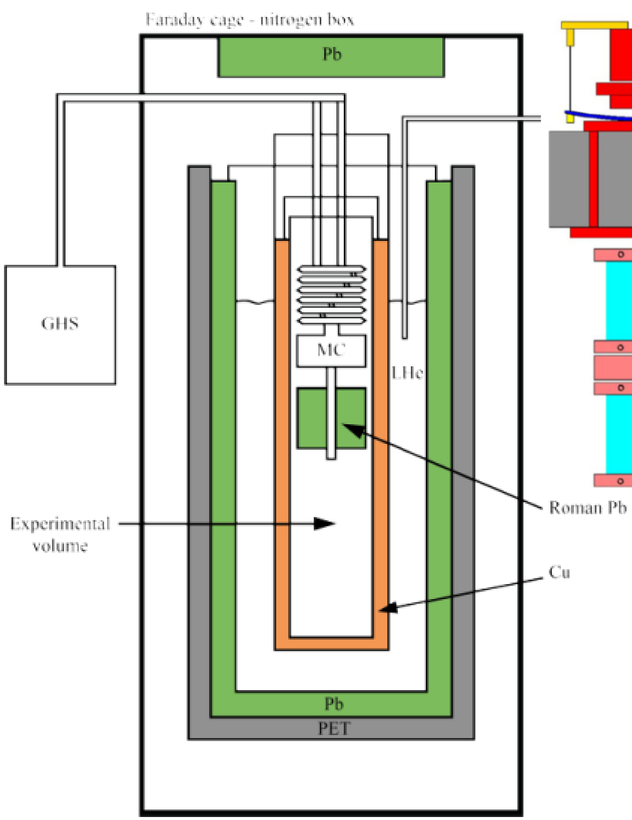
CUPID R&D @ LNGS (Italy)

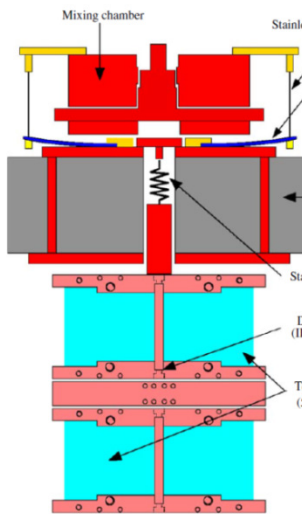


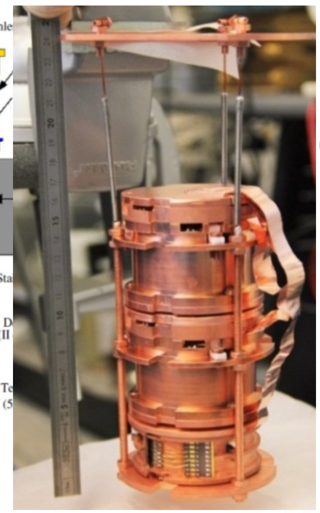
EDELWEISS @ LSM (France)

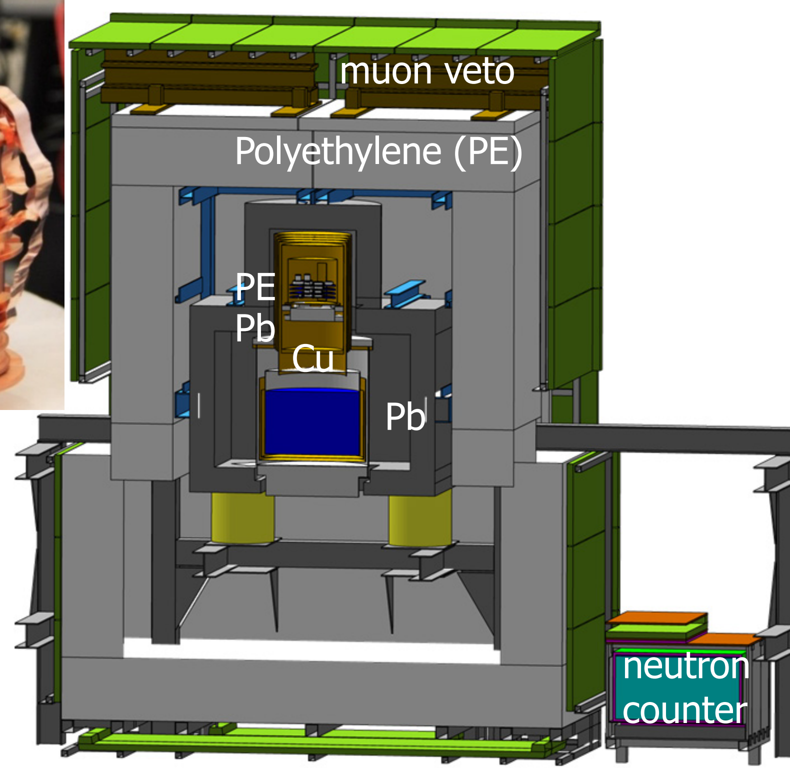


Suspended systems to reduce vibrations



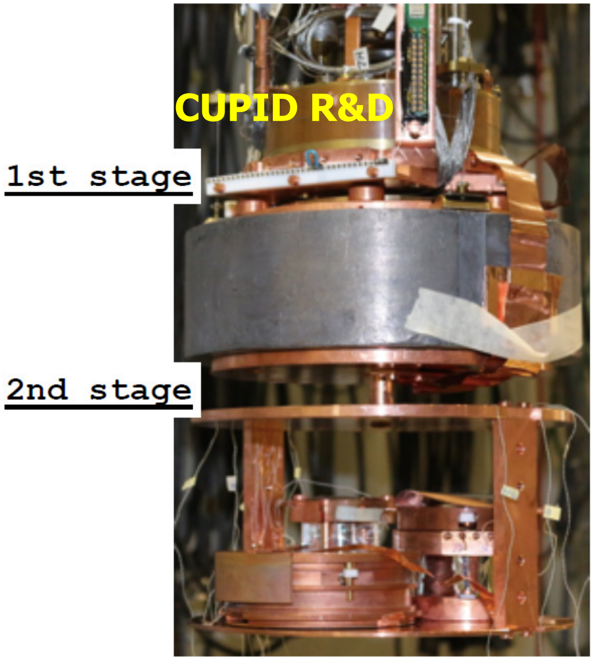


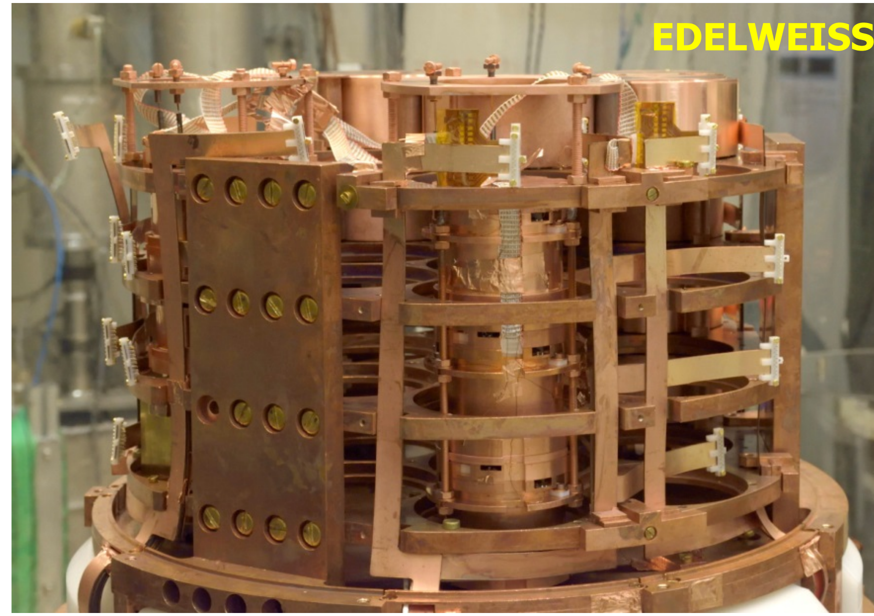


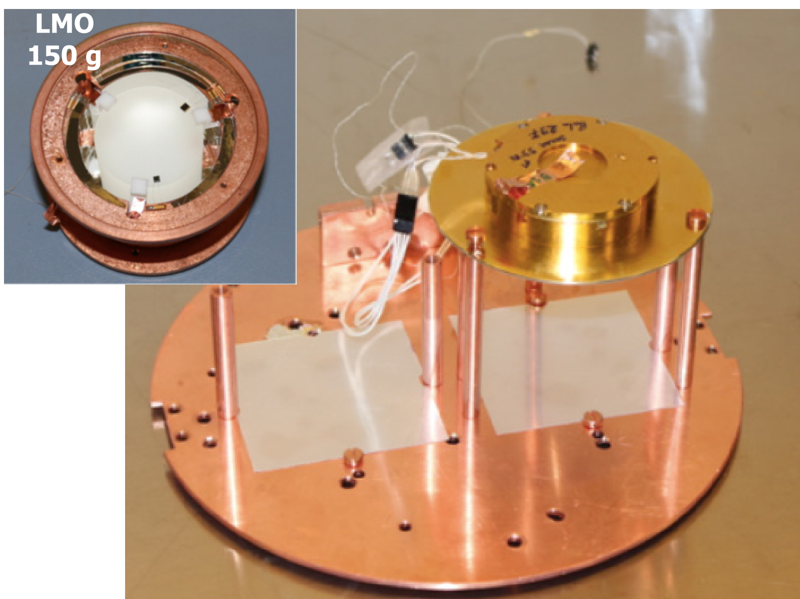


See e.g. in arXiv:1704.01758

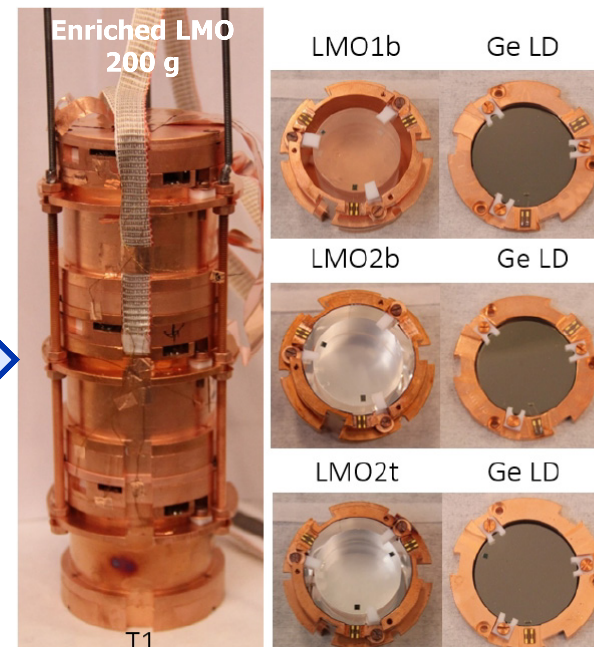
From single Li_2MoO_4 module to 4x $Li_2{}^{100}MoO_4$ array





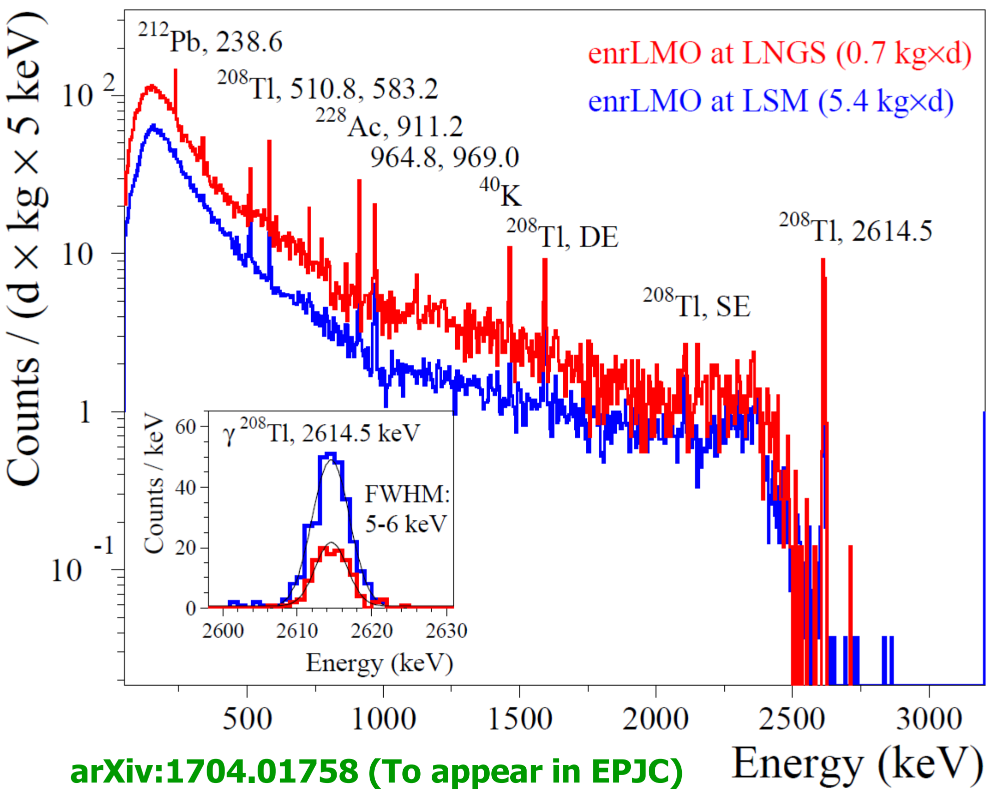


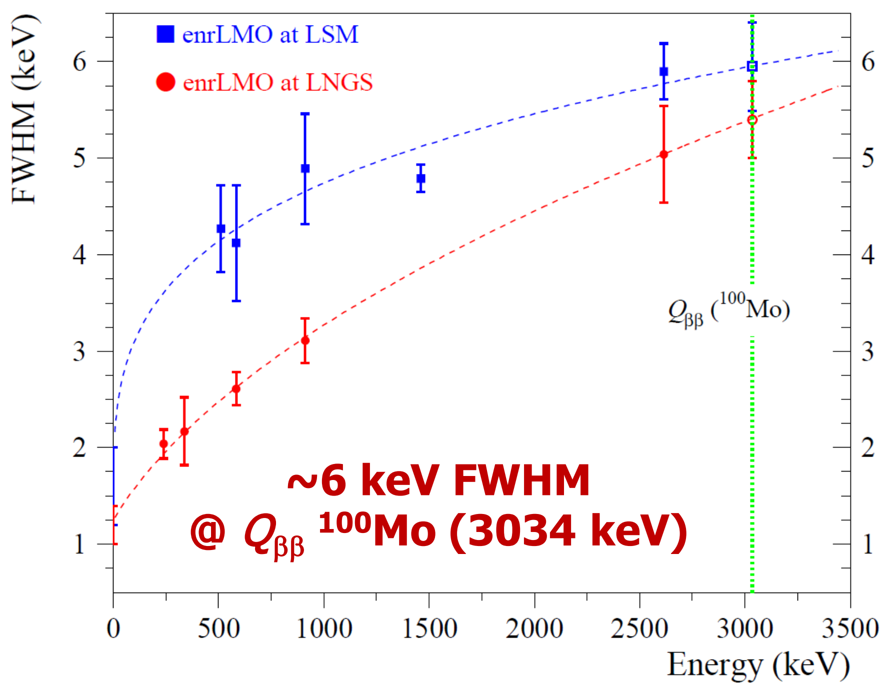
~3 years of LUMINEU activity



Performance of $Li_2{}^{100}MoO_4$ bolometers

enrLMO-#	1t		1b		2t	2b
Test @	LSM	LSM	LNGS	LSM	LSM	LSM
Temperature	20 mK	17 mK	17 mK	12 mK	17 mK	17 mK
Signal [nV/keV]	32	40	47	89	50	48
FWHM [keV] @ 0 keV	~1.2	~1.0	~1.2	~1.2	~2.4	~2.0
FWHM [keV] @ 2.6 MeV	**6.3±0.6**	**5.8±0.6**	**5.7±0.6**	**5.0±0.6**	**5.5±0.5**	**5.7±0.6**





Excellent performance

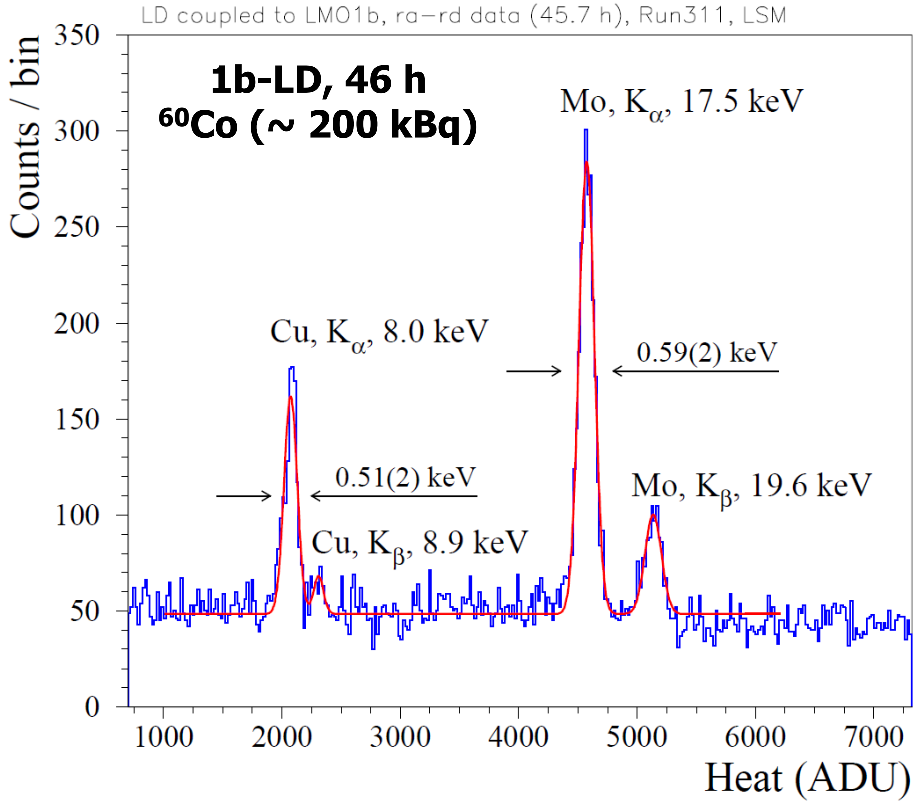
arXiv:1704.01758 (To appear in EPJC)
AIP Conf. Proc. 1894 (2017) 020017

Ge light detectors performance

Light detectors coupled to $Li_2{}^{100}MoO_4$ bolometers

Light detector	Condi-tions	Signal μV/keV	$FWHM_{Bsl}$ keV
1b-LD	optimal over bias	1.3 0.7	0.08 0.11
1t-LD	optimal over bias	2.4 1.2	- 0.07
2b-LD	optimal over bias	1.5 1.1	0.11 0.12
2t-LD	optimal over bias	1.1 0.85	0.09 0.11
LUMINEU	17 mK	**1.5**	**0.1**
CUPID-0	20 mK	**1.3**	**0.1**

Performance of CUPID-0 LDs: EPJC 76 (2016) 364



Good reproducibility of "standard" high performance

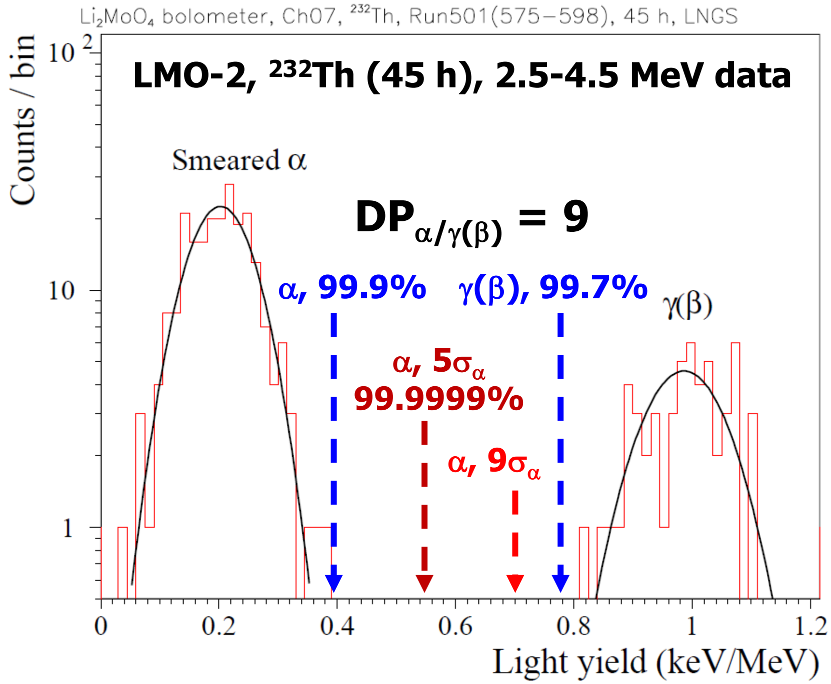
Light-assisted particle identification for $Li_2{}^{100}MoO_4$

enrLMO-#	1t		1b		2t	2b
Test @	LSM	LSM	LNGS	LSM	LSM	LSM
M3 reflecting foil	yes	no	yes	no	yes	yes
$LY_{\gamma(\beta)}$ [keV/MeV]	**n.a.**	**0.41**	**0.77**	**0.38**	**0.73**	**0.74**
$DP_{\alpha/\gamma(\beta)}$, > 2.5 MeV*	**18**	**9**	**12**	**9**	**14**	**14**

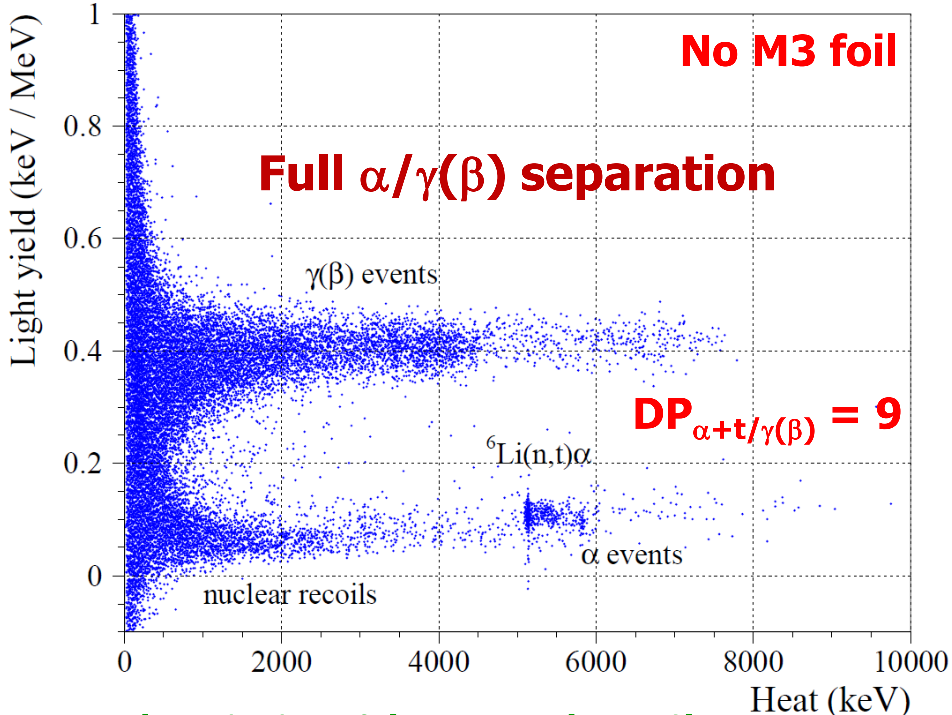
* - Data selection for DP: γ(β)'s in 2.5-2.7 MeV, α's ~ 5.4 MeV_{ae} ^{210}Po or ~ 4.8 MeV_{ae} $^{6}Li(n,t)\alpha$

Discrimination Power between α and γ(β)

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



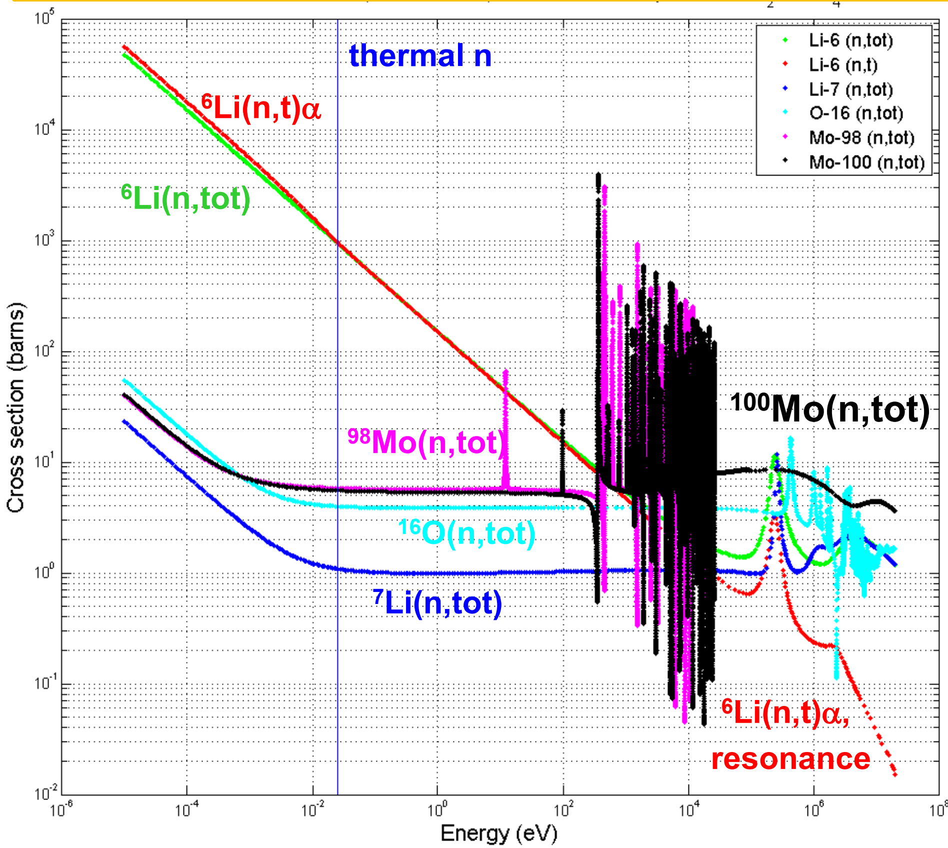
enrLMO-1t, AmBe (290 h)

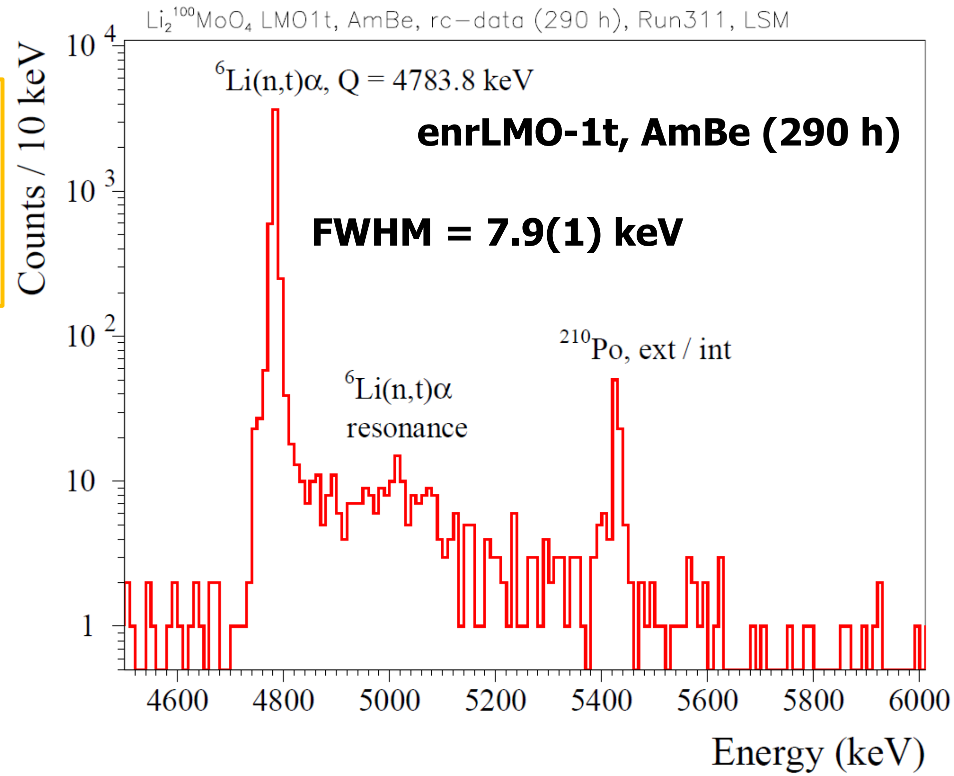


arXiv:1704.01758 (To appear in EPJC)
AIP Conf. Proc. 1894 (2017) 020017

Neutron spectroscopy with $Li_2{}^{100}MoO_4$ bolometers

$Li_2{}^{100}MoO_4$ ⇒ 7.6% of ^6Li
^6Li + n → t + α (Q = 4783 keV)
E(t+α) = 4783 keV (thermal n, ~25 meV)
E(t+α) = 5022 keV (resonance @ ~240 keV)



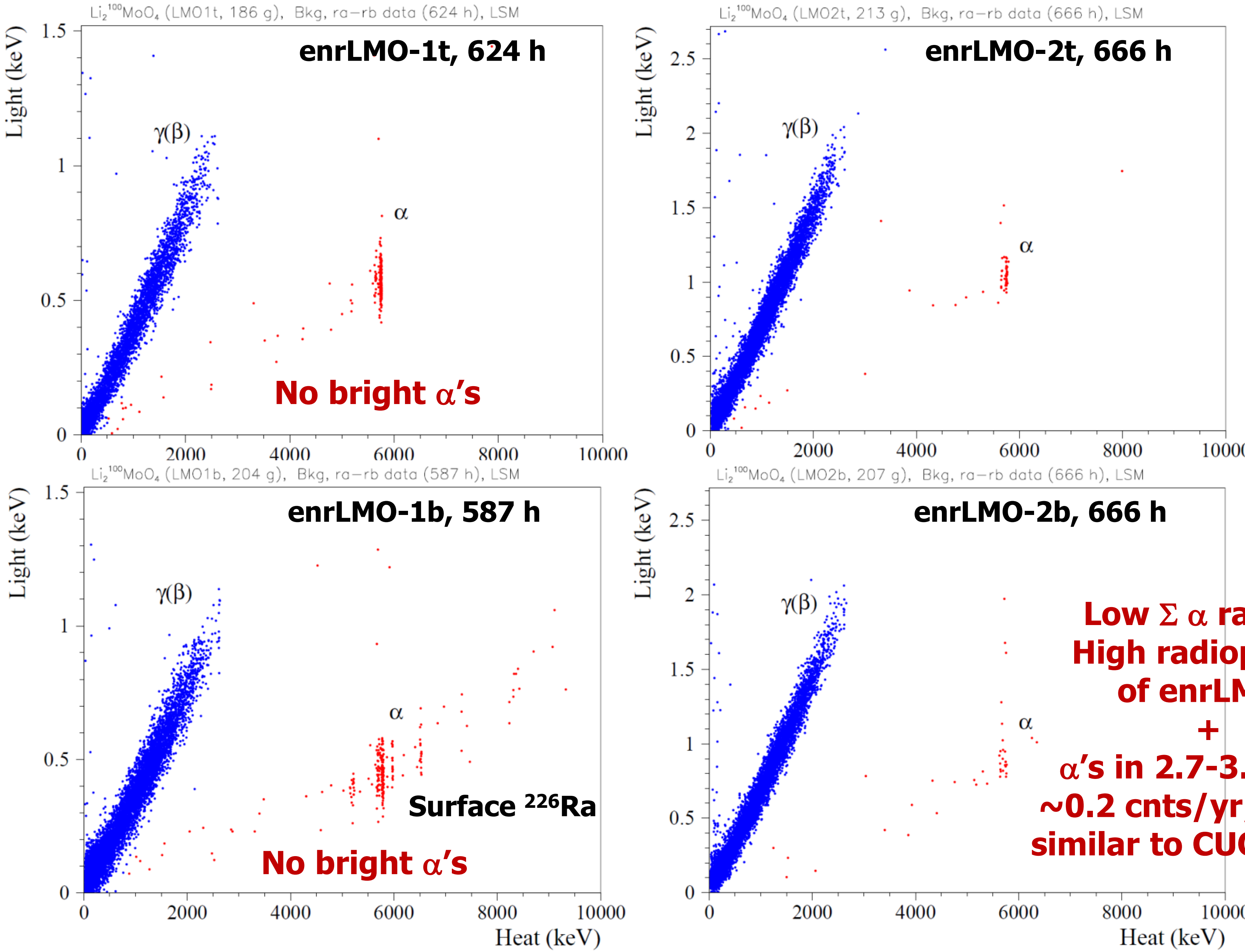


Advantages

- ✓ ~100% detection of thermal n
- ✓ clear α+t signature @ Q+E_n
- ✓ γ(β) background-free ROI
- ✓ world record resolution of thermal neutron capture on ^6Li (6-10 keV FWHM @4783 keV)

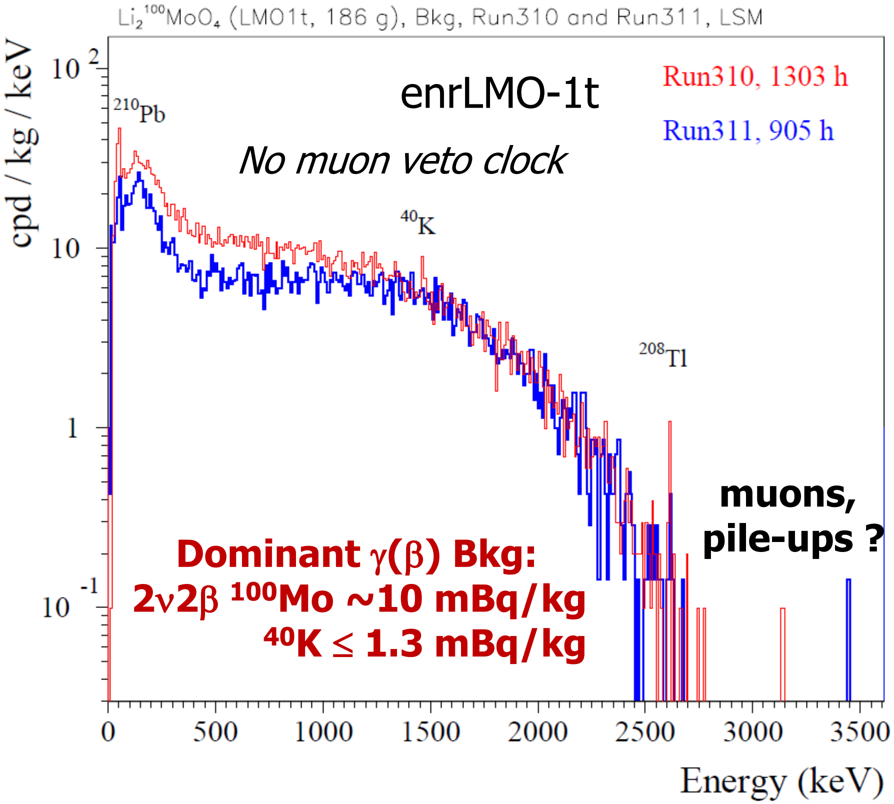
Prospects for in-situ neutron detection

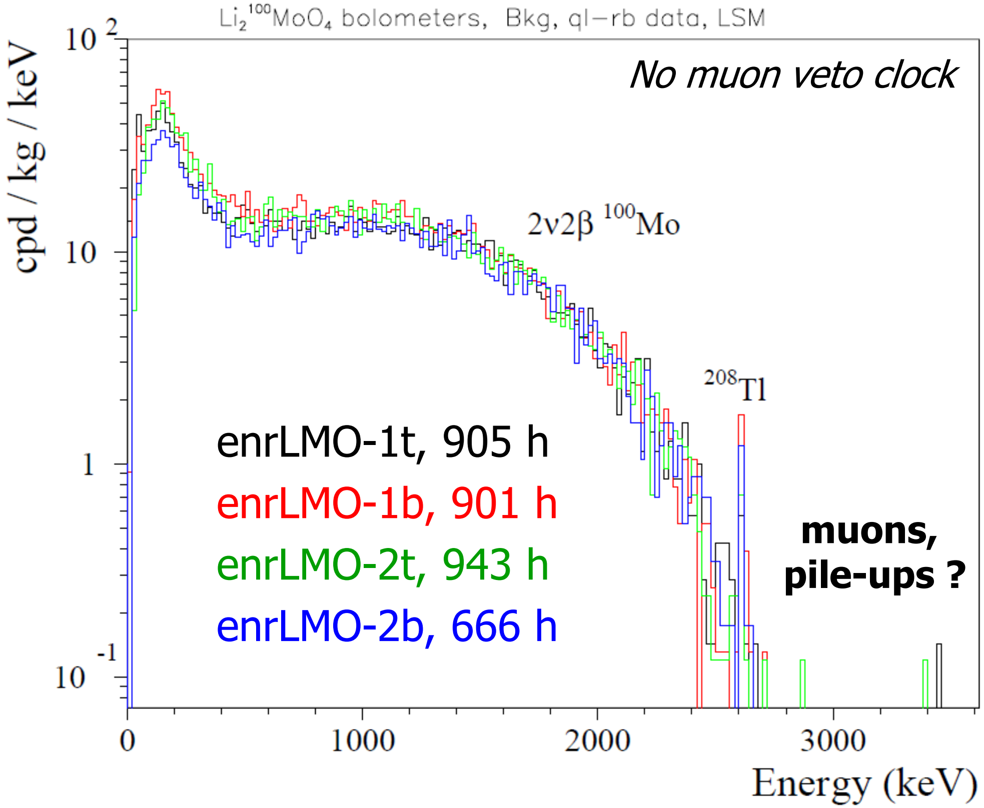
Background measurements with 4 $Li_2{}^{100}MoO_4$ array



Low Σ α rate ⇒
High radiopurity
of enrLMOs
+
α's in 2.7-3.9 MeV
~0.2 cnts/yr/kg/keV
similar to CUORICINO

$\gamma(\beta)$ Background of $Li_2{}^{100}MoO_4$ detectors

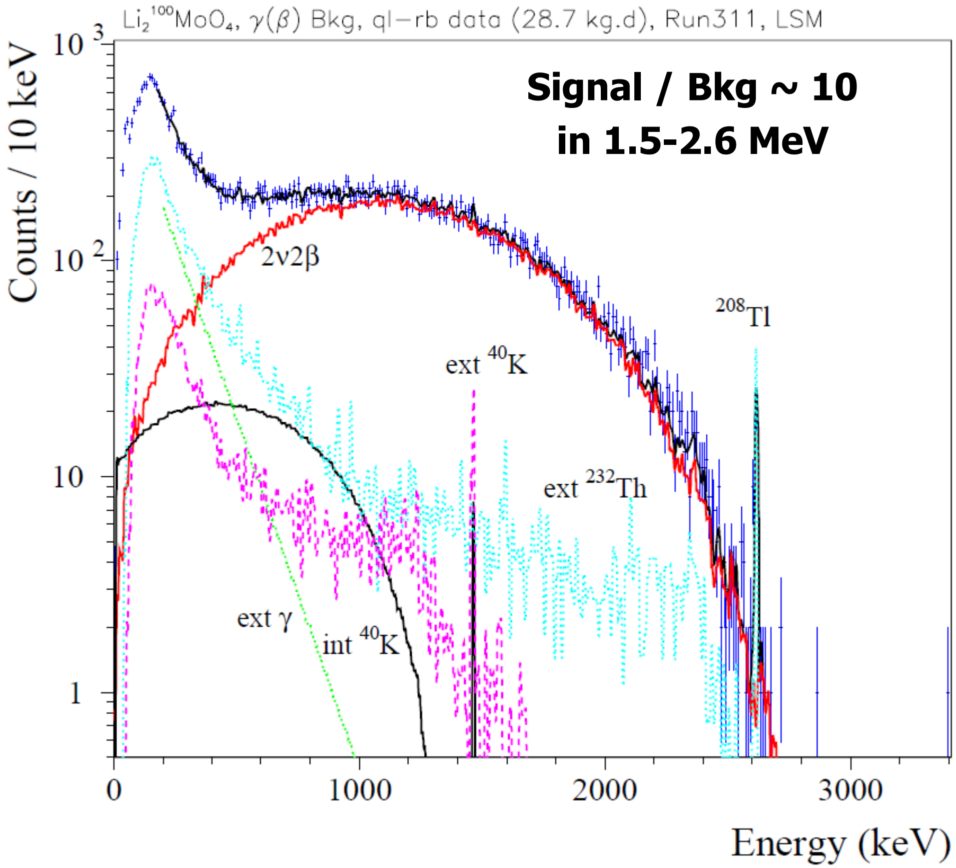




enrLMO-#	1t		1b	2t	2b	Average
Rate [cnts/day/kg] of 2615 keV γ's	1.5(4)	0.7(3)	2.1(5)	1.3(5)	1.0(3)	**1.1(2)**

^{208}Tl rate inside the EDELWEISS set-up is ~x40 of CUORICINO background

LUMINEU investigation of 2ν2β decay of ^{100}Mo



Measurement of ^{100}Mo 2ν2β decay:

- Exposure = 29 kg×d
- Enrichment = 96.9% of ^{100}Mo
- eff_{PSD} = 96.4%
- Fit in 160-2650 keV ⇒
  Effect = 24320 ± 229 decays

$T_{1/2}$ = [6.92±0.06(stat)] × 10^{18} yr

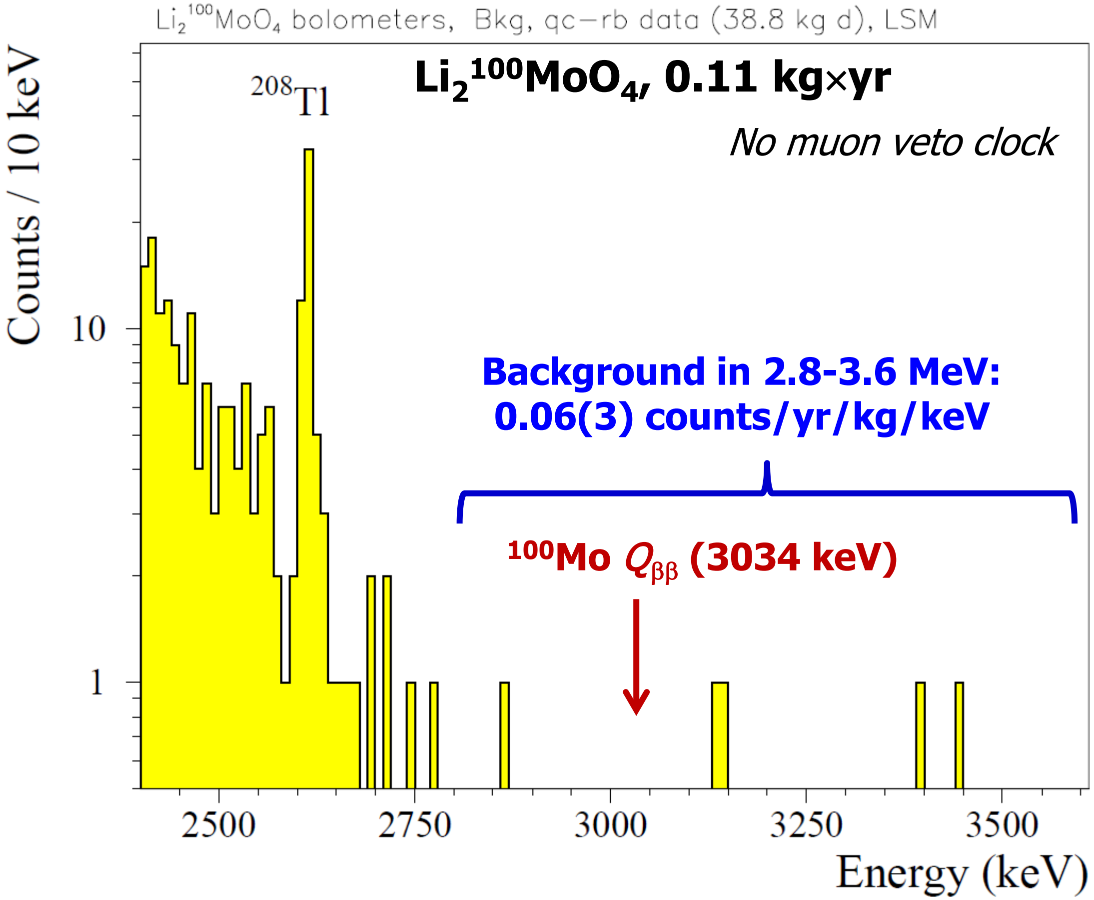
Systematic error = 6.5%

- Crystals' mass 0.025 %
- ^{100}Mo enrichment 0.2 %
- PSD cut efficiency 0.4 %
- Trigger efficiency 0.5 %
- Monte Carlo 5 %
- Fit 1.1 %

$T_{1/2}$ [10^{18} yr]	^{100}Mo exposure	Experiment	Ref.
7.11±0.02(stat)±0.54(syst)	7.37 kg×yr	NEMO-3	PRL 95, 182302 (2005)
7.15±0.37(stat)±0.66(syst)	0.01 kg×yr	LUCIFER	JPG 41, 075204 (2014)
6.90±0.15(stat)±0.37(syst)	0.02 kg×yr	LUMINEU	EPJC, arXiv:1704.01758
6.92±0.06(stat)±0.36(syst)	0.04 kg×yr	LUMINEU	AIP CP 1894, 020017 (2017)

The most precise ^{100}Mo half-life value

LUMINEU sensitivity to $0\nu2\beta$ decay of ^{100}Mo



Sensitivity to ^{100}Mo $0\nu2\beta$ decay:

- $Q_{\beta\beta}(^{100}Mo)$ = 3034 keV
- ROI = 10 keV window @ $Q_{\beta\beta}$
- $eff_{0\nu2\beta}$ = 73% in ROI
- eff_{PSD} = 97%
- Enrichment = 96.9% of ^{100}Mo
- Exposure = 39 kg×d
- BI = 0.06 cnts/yr/kg/keV ⇒ Bkg = 0.064 counts in ROI
- Signal = 0 ⇒ lim*S* = 2.38 counts at 90% CL

$T_{1/2} > 0.7 \times 10^{23}$ yr @ 90% CL

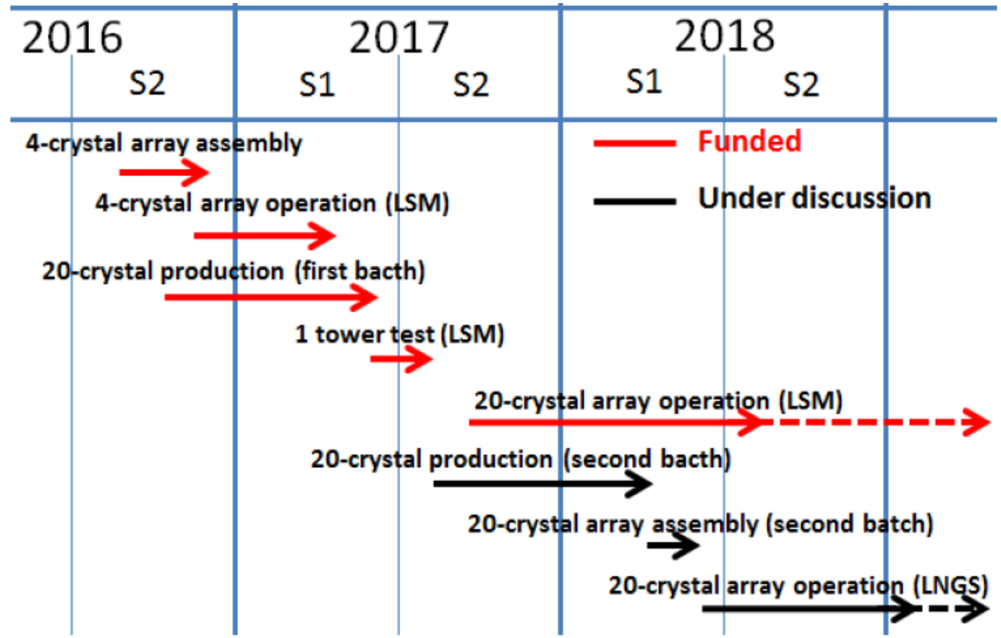
$T_{1/2}$ [10^{23} yr]	$<m_{\beta\beta}>$ [eV]	^{100}Mo exposure	Experiment	Ref.
≥ **11**	≤ **(0.3-0.6)**	34.3 kg×yr	NEMO-3	PRD 92, 072011 (2015)
≥ **0.7**	≤ **(1.4-2.4)**	0.06 kg×yr	LUMINEU	AIP CP 1894, 020017 (2017)

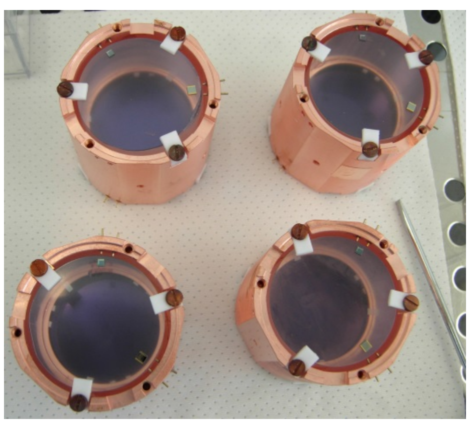
High potential of scintillating bolometers approach

LUMINEU follow-up: CUPID-0/Mo

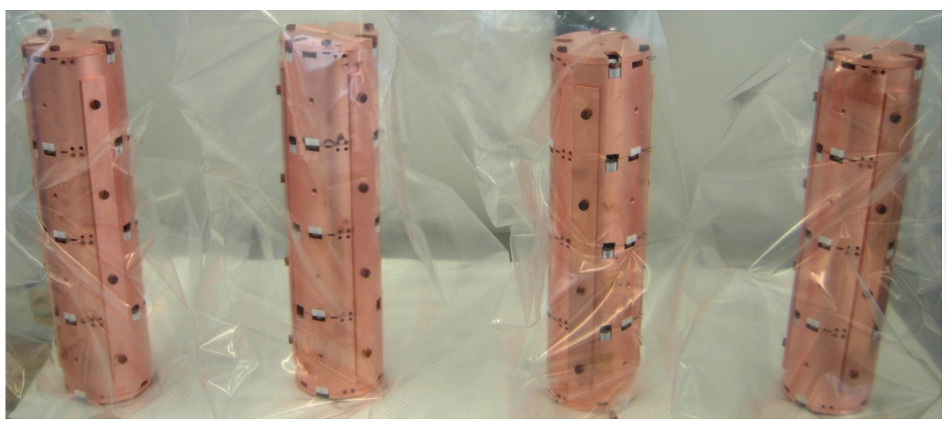
- **CUPID-0/Mo Phase I:**
  - **20 $Li_2{}^{100}MoO_4$** (4.18 kg total mass) $\Rightarrow$ 2.34 kg of ^{100}Mo (1.37×10^{25} of ^{100}Mo)
  - **20 Ge light detectors**
  - **EDELWEISS set-up** @ LSM (France)

- **CUPID-0/Mo Phase II:**
  - Additional **20 $Li_2{}^{100}MoO_4$**
  - **CUPID-0 set-up** @ LNGS (Italy) **or CROSS set-up** @ Canfranc (Spain)

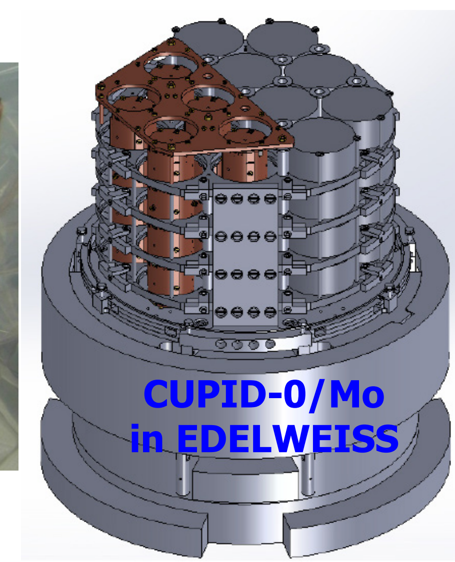




4 detector modules



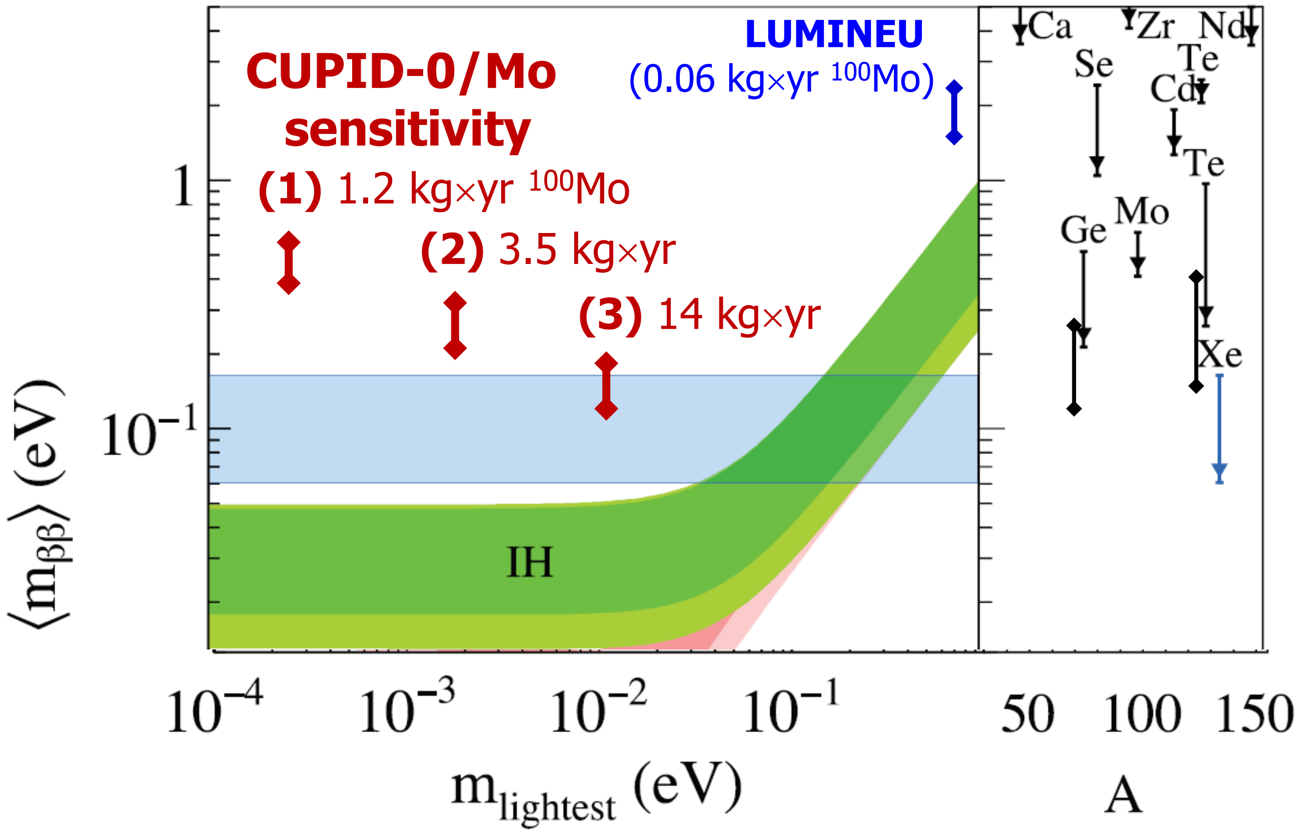
4 assembled towers (+ 1 is in EDELWEISS)



CUPID-0/Mo sensitivity

- **ROI = 10 keV window**
- **Efficiency = 69%**
  $\varepsilon_{0\nu2\beta}$ = 73%, ε_{PSD} = 95%
- **BI = 10^{-3} cnts/yr/kg/keV**
  Options (1) and (2) are substantially unchanged by **BI = 10^{-2} cnts/yr/kg/keV** (lower $T_{1/2}$ by 6%, 16%, 37%)

CUPID-0/Mo configuration	$T_{1/2}$ sensitivity [yr] 90% CL	$<m_{\beta\beta}>$ [eV]
(1) **20×0.5 cr.×yr**	**1.3 × 10^{24}**	**0.33-0.56**
(2) **20×1.5 cr.×yr**	**4.0 × 10^{24}**	**0.19-0.32**
(3) **40×3.0 cr.×yr**	**1.5 × 10^{25}**	**0.10-0.17**



ββ Nuclide	Exposure [kg×yr]
^{130}Te	32
^{100}Mo	34
^{76}Ge	41
^{136}Xe	504

^{130}Te: arXiv:1710.07988
^{100}Mo: PRD 92 (2015) 072011
^{76}Ge: arXiv:1710.07776
^{136}Xe: PRL 117 (2016) 082503
NME: RPP 80 (2017) 046301

Summary

- **Prospects of $Li_2{}^{100}MoO_4$ scintillating bolometers for high-sensitivity $0\nu2\beta$ searches have been unambiguously proved by results of LUMINEU project**

  - ✓ Developed mass production technology of high quality radiopure $Li_2{}^{100}MoO_4$
  - ✓ Established technology of high performance $Li_2{}^{100}MoO_4$ bolometers array
  - ✓ Achieved reasonably high sensitivity to ^{100}Mo $0\nu2\beta$ decay of over a short exposure
  - ✓ Performed the most precise measurement of ^{100}Mo $2\nu2\beta$ decay half-life

- **LUMINEU is extended to CUPID-0/Mo 2β experiment as a demonstrator of the $Li_2{}^{100}MoO_4$ scintillating bolometer technology for CUPID project**

  - $\beta\beta$ Source: ~5 kg of ^{100}Mo embedded in 40 $Li_2{}^{100}MoO_4$ crystals 0.2-kg each
  - Start: early 2018 (20 crystals), middle of 2018 (20+20 crystals)
  - Ambitious result in 3 yr: one of the highest sensitivity to effective Majorana neutrino mass
  - Main goal: demonstration of the LUMINEU technology viability for CUPID (CUORE follow-up)

The choice of ^{100}Mo-containing scintillator

Advantages

✓ **High $Q_{\beta\beta}$-value of ^{100}Mo (3034 keV)**
$T_{1/2}(0\nu2\beta) \sim Q^5$; dominant γ bkg < 2615 keV

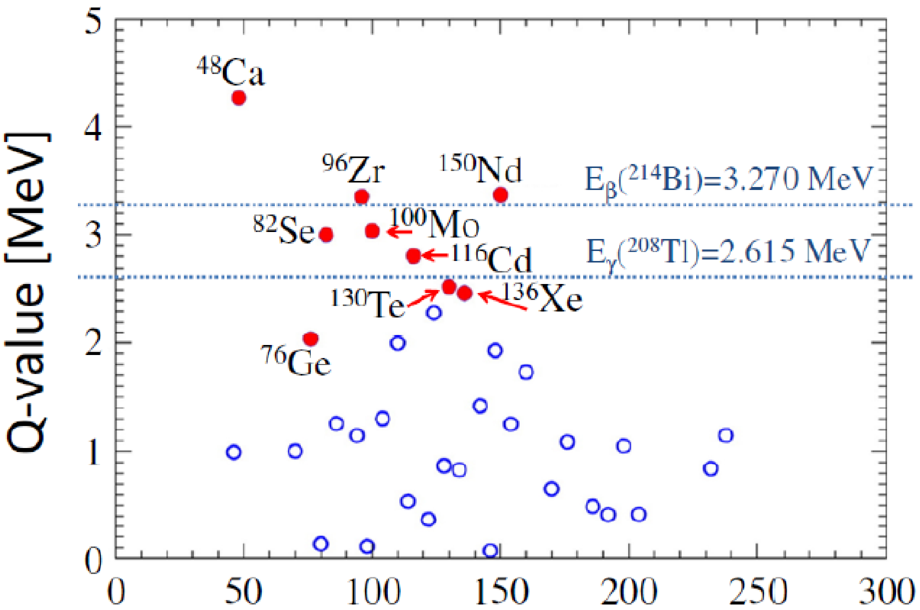
✓ **~10% of ^{100}Mo in natural Mo**

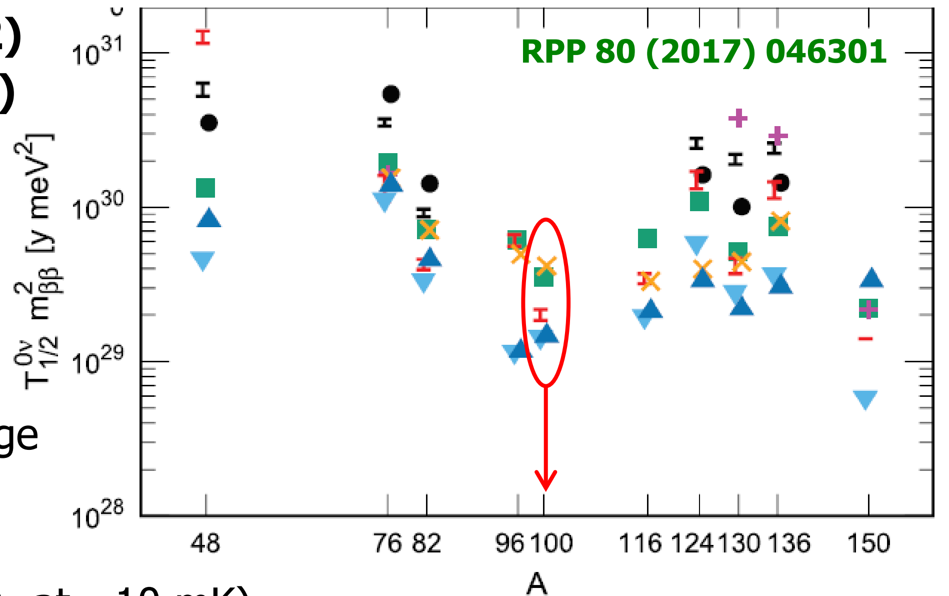
✓ **Industrial ^{100}Mo enrichment (> 95%)**
Reasonable cost ~80 $/g

✓ **Variety of Mo-containing scintillators**
Active-source technique (~100% efficiency)
Some Mo based materials successfully tested as scintillating bolometer

⇓

$ZnMoO_4$ – initial choice by LUMINEU (2012)
Li_2MoO_4 – parallel R&D by LUMINEU (2014)





Warnings

○ **Fastest 2ν2β process (7×10^{18} yr)**
Pile-up issue for slow response detectors

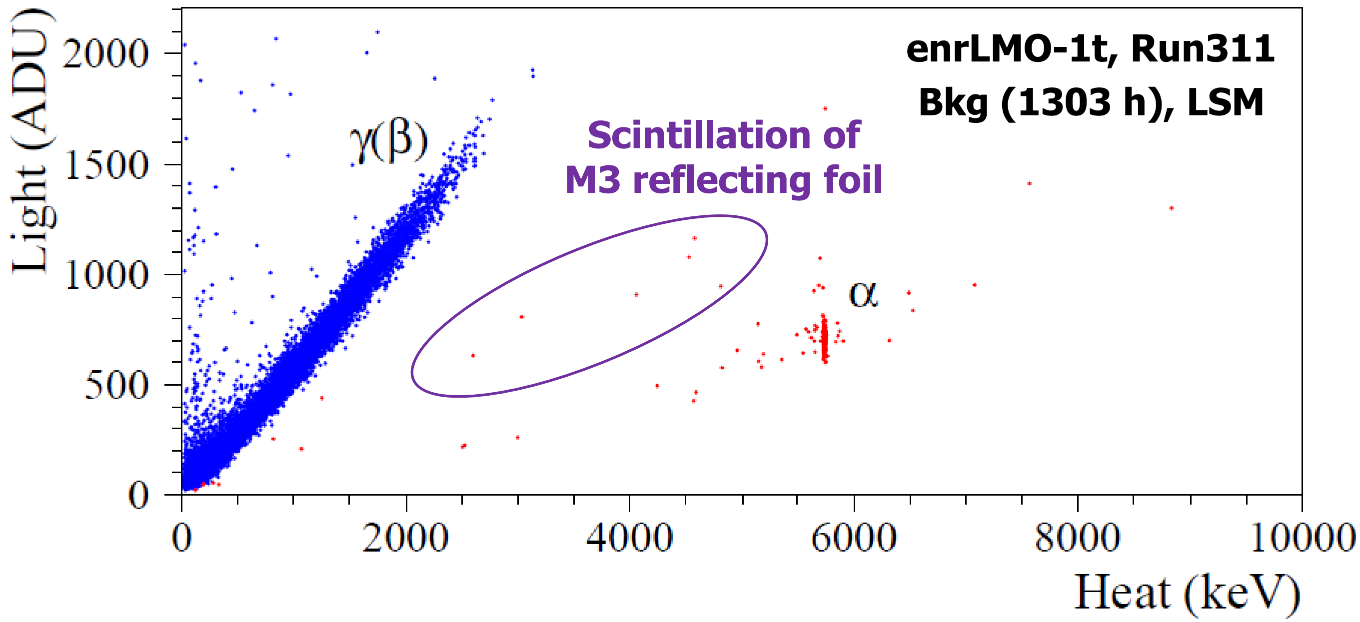
○ **Weak γ line of ^{214}Bi close to ^{100}Mo $Q_{\beta\beta}$**
3054 keV, 0.021% B.R.; 2818 keV Compton edge

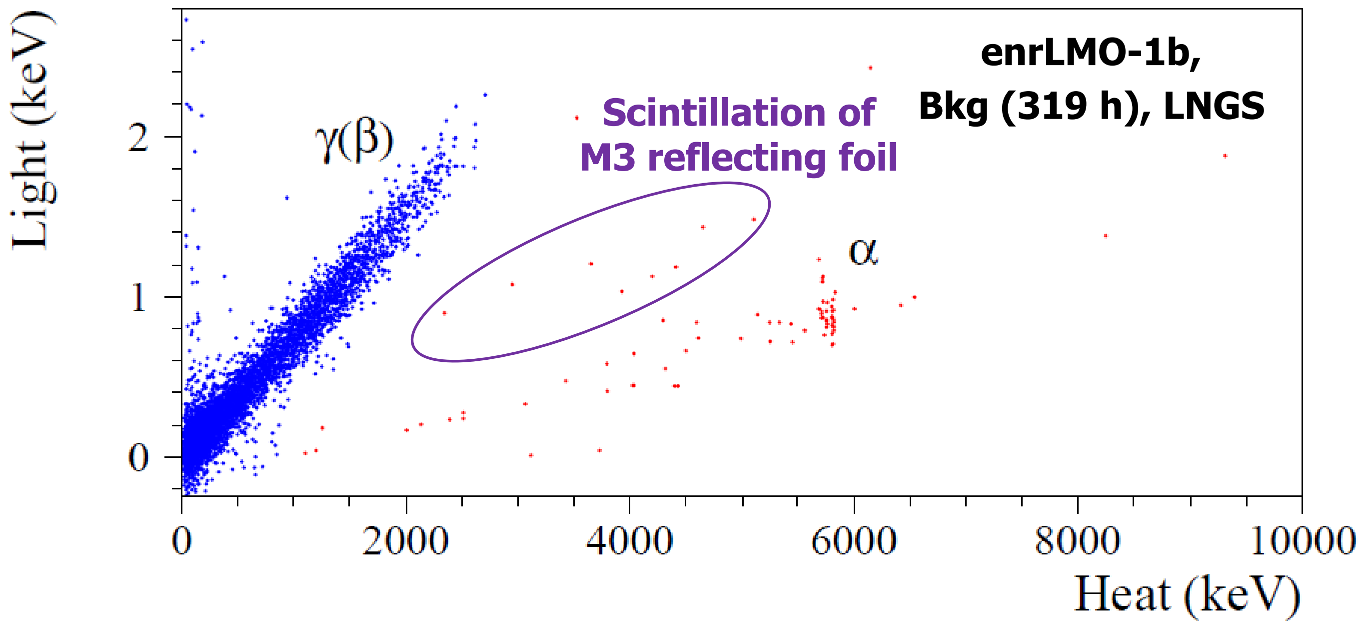
○ **Weak hygroscopicity of Li_2MoO_4**

○ **^{40}K issue for Li_2MoO_4** (K is a homolog of Li)

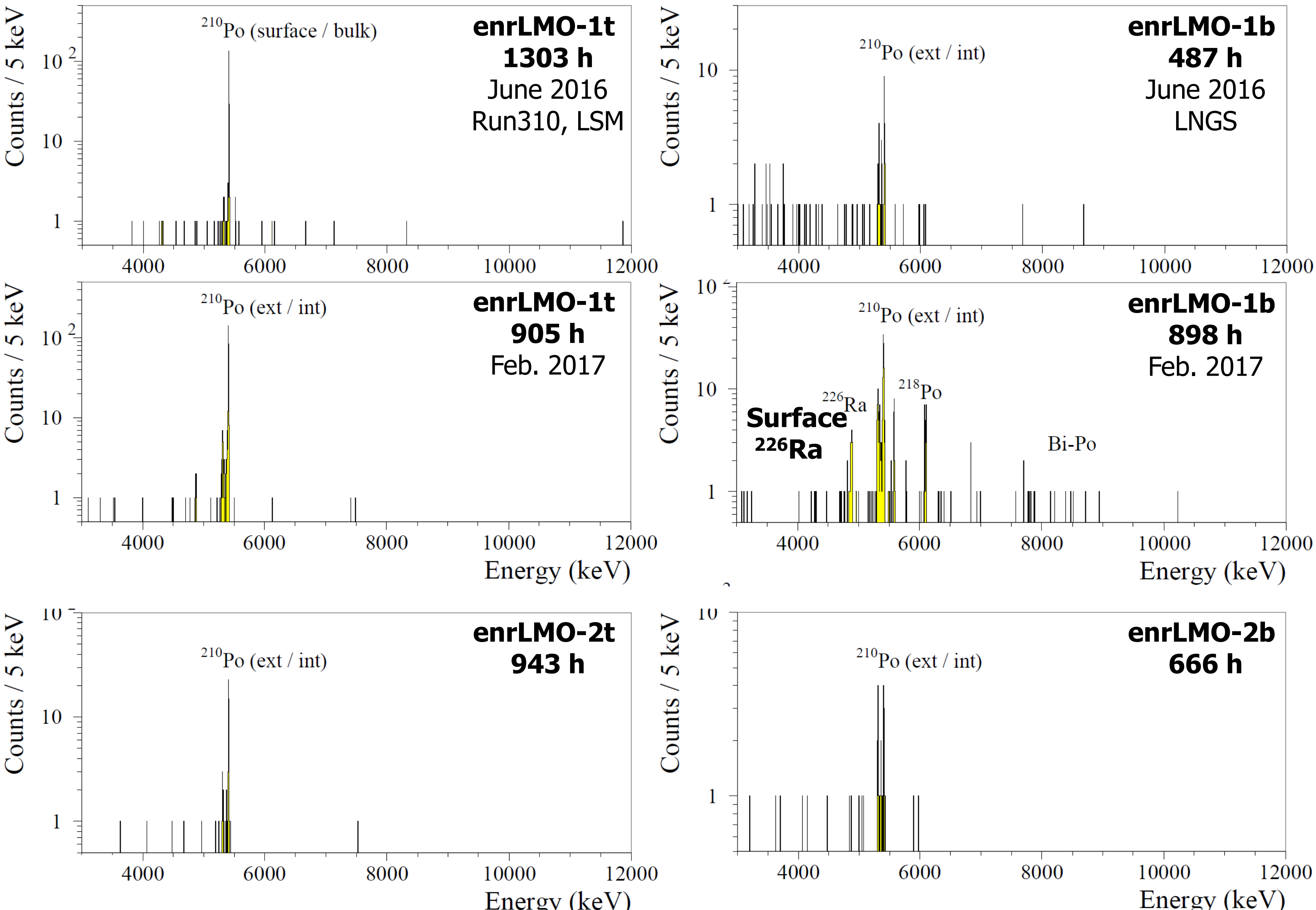
○ **Low light yield of Li_2MoO_4** (~x0.5 of $ZnMoO_4$ at ~10 mK)

"Bright α" issue in early tests with $Li_2{}^{100}MoO_4$





α Background of $Li_2{}^{100}MoO_4$ detectors



α Background of $Li_2{}^{100}MoO_4$ detectors