LA PLATA

ORSAY MEDEX 11th PRAGUE

JYVÄSKYLÄ

May 29 – June 2, 2017

^{100}Mo-enriched Li_2MoO_4 scintillating bolometers for $0\nu2\beta$ decay search: from LUMINEU to CUPID-0/Mo projects

D.V. Poda on behalf of the LUMINEU Collaboration

CSNSM, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, 91405 Orsay, France
Institute for Nuclear Research, MSP 03680 Kyiv, Ukraine

LUMINEU in cooperation with Edelweiss LUCIFER

MEDEX'17 meeting, Prague, 01 June 2017

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

Luminescent Underground Molybdenum Investigation for NEUtrino mass and nature

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**)

R&D of the technology based on ^{100}Mo-containing scintillating bolometers for a next-generation $0\nu2\beta$ experiment

- **Development of $ZnMoO_4$ / Li_2MoO_4 based scintillating bolometers**
- **A 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)**

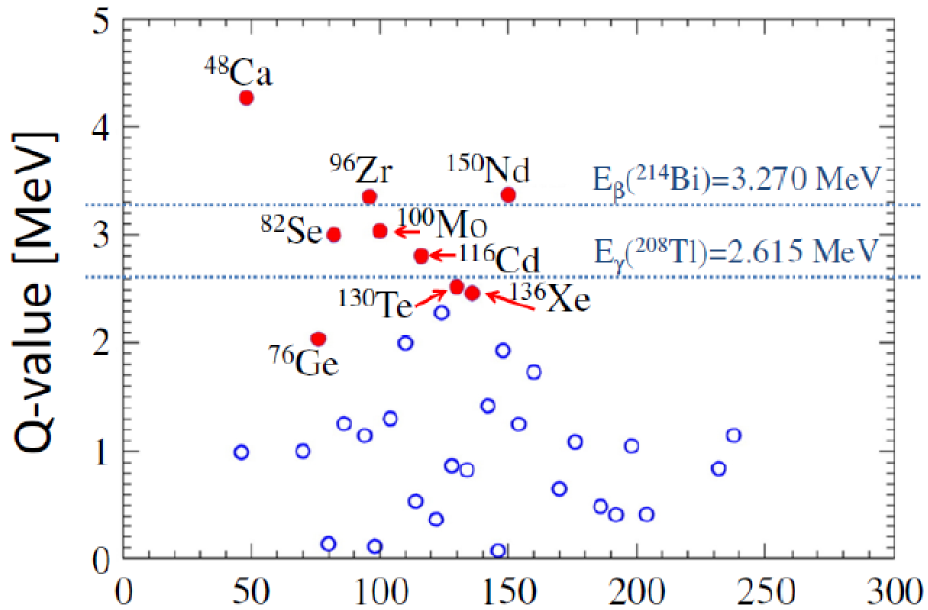
The choice of ^{100}Mo-containing scintillator

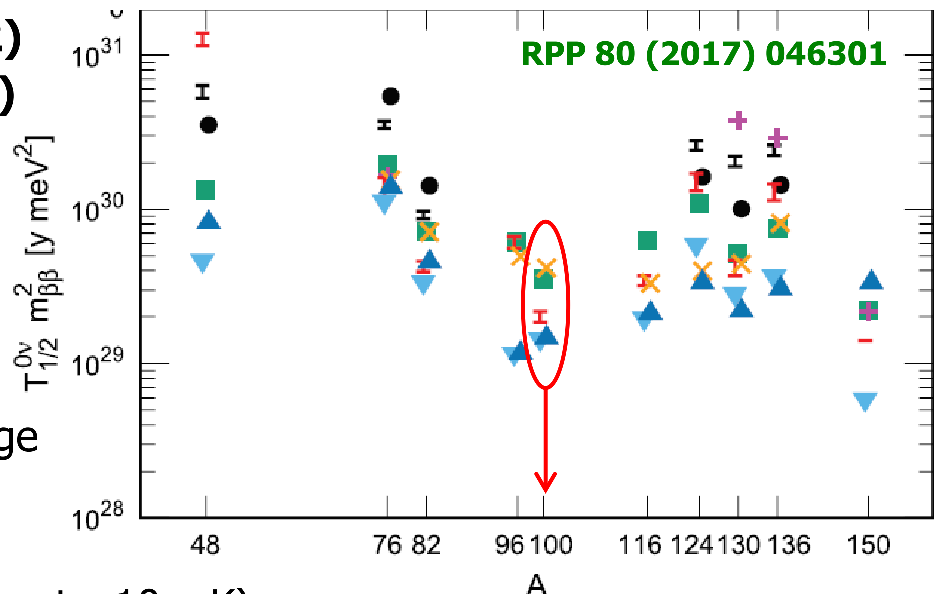
Advantages

- ✓ **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)





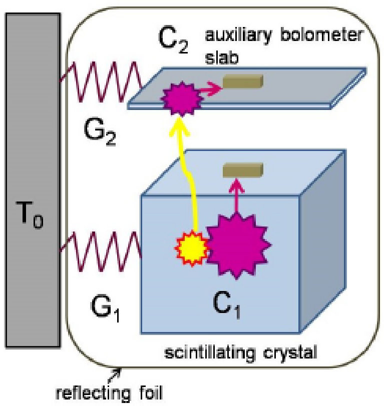
Warnings

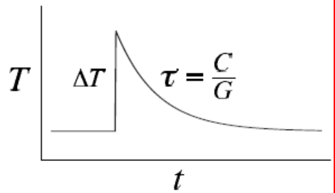
- ○ **Fastest 2ν2β process (7×10^{18} yr)**
  Pile-up issue for slow response detectors
- ○ **Weak γ line of ^{214}Bi close to ^{100}Mo $Q_{\beta\beta}$**
  3054 keV, 0.021% B.R.; 2818 keV Compton edge
- ○ **Weak hygroscopicity of Li_2MoO_4**
- ○ **^{40}K issue for Li_2MoO_4** (K is a homolog of Li)
- ○ **Low light yield of Li_2MoO_4** (~x0.5 of $ZnMoO_4$ at ~10 mK)

The choice of scintillating bolometer approach

Scintillating bolometers

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



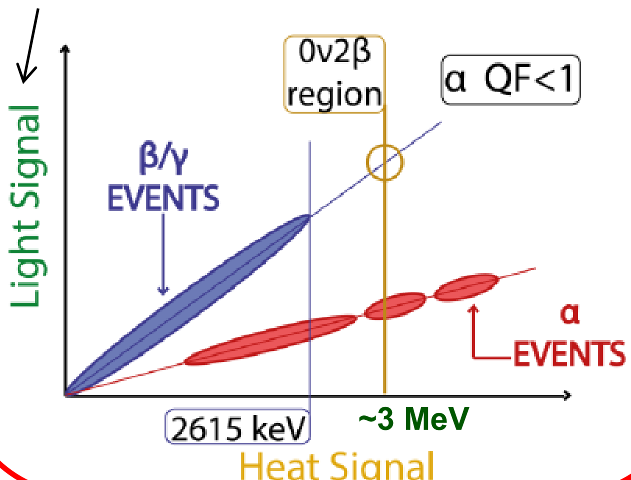


$$\Delta T = \frac{E}{C} \Rightarrow \Delta V$$

~0.1 mK/MeV

~0.1–0.5 mV/MeV

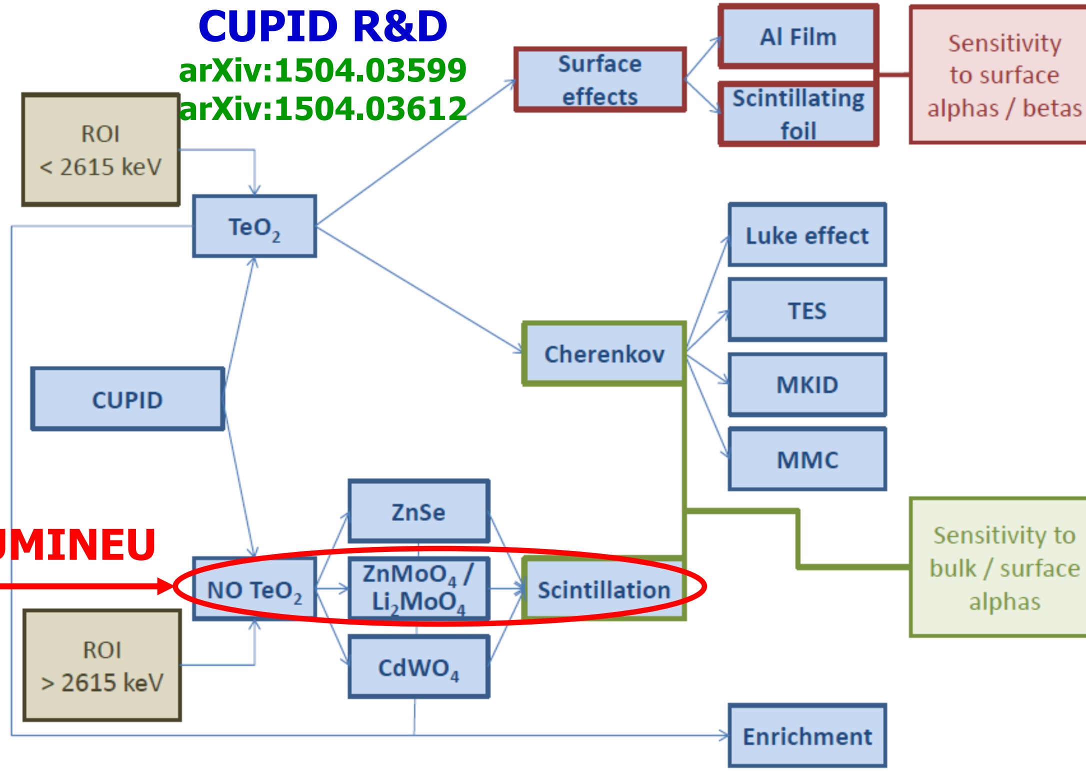
~1 keV/MeV



LUMINEU

CUPID R&D

arXiv:1504.03599
arXiv:1504.03612



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

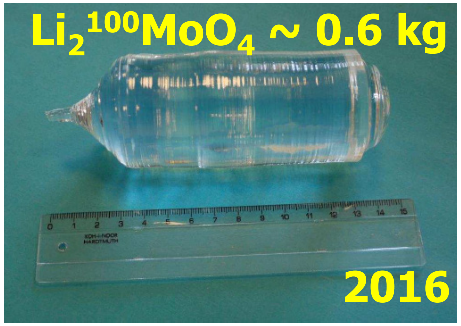
LUMINEU R&D of ^{100}Mo-enriched Li_2MoO_4 crystals

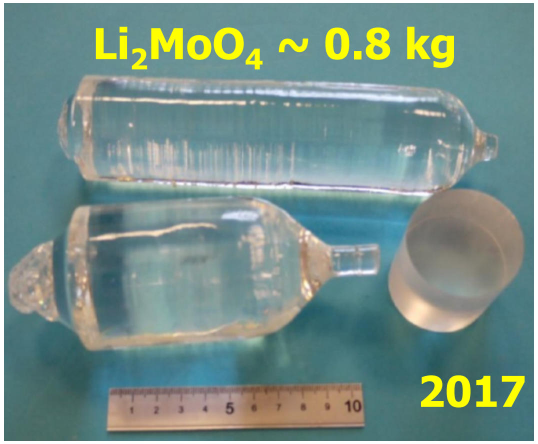
LUMINEU protocol of LMO production

- **^{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 (Submitted to EPJC)
Submitted to Cryst. Eng. Comm.

✓ **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%)





Ready for a batch production of $Li_2{}^{100}MoO_4$ crystals

Li_2MoO_4 crystals for low temperature tests

Full cycle of LMO growth in NIIC (Russia)

arXiv:1704.01758;
Submitted to Cryst. Eng. Comm.

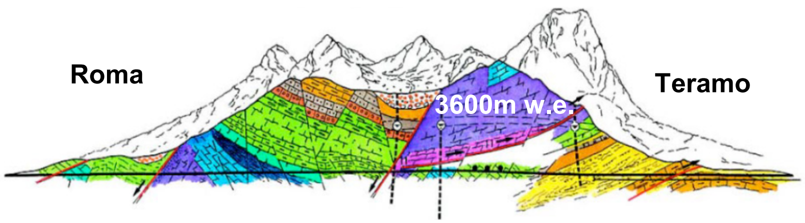
- **Deeply purified MoO_3 powder**
  Commercial MoO_3 with natural isotopic abundance
  ^{100}Mo-enriched Molybdenum (97%) used in NEMO-3
- **Commercial Li_2CO_3 powder**
  Novosibirsk Rare Metal Plant (Russia), by default
  Alfa Aesar (USA), for LMO-3 only
- **Solid state synthesis of Li_2MoO_4 compound**
- **LTG Cz growth from Pt crucible in air atmosphere**
- **Cutting, extraction of MoO_3 from residues**

Nuclide	Activity (mBq/kg)		
	NRMP	Alfa Aesar	Sigma-Aldrich
^{228}Ra	≤ 2.9	≤ 14	16(8)
^{228}Th	≤ 3.7	12(4)	13(4)
^{226}Ra	≤ 3.3	705(30)	53(6)
^{40}K	≤ 42	≤ 42	210(70)

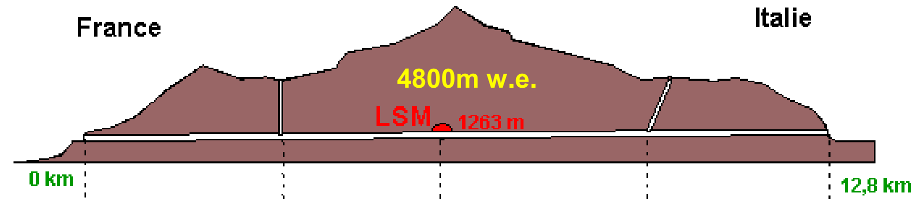
Scintillator	Mo purification		Boule crystallization	Produced elements		
	Subl.	Recryst.		ID	Size (mm)	Mass (g)
Li_2MoO_4	Single	Double	Single	LMO-1	∅40×40	151
	Single	Double	Double	LMO-2	∅50×40	241
	Single	Double	Single	LMO-3	∅50×40	242
$Li_2{}^{100}MoO_4$	Double	Double	Triple	enrLMO-1t enrLMO-1b	∅44×40 ∅44×44	186 204
	Double	Double	Double	enrLMO-2t enrLMO-2b	∅44×46 ∅44×44	213 207

Used underground cryogenic facilities

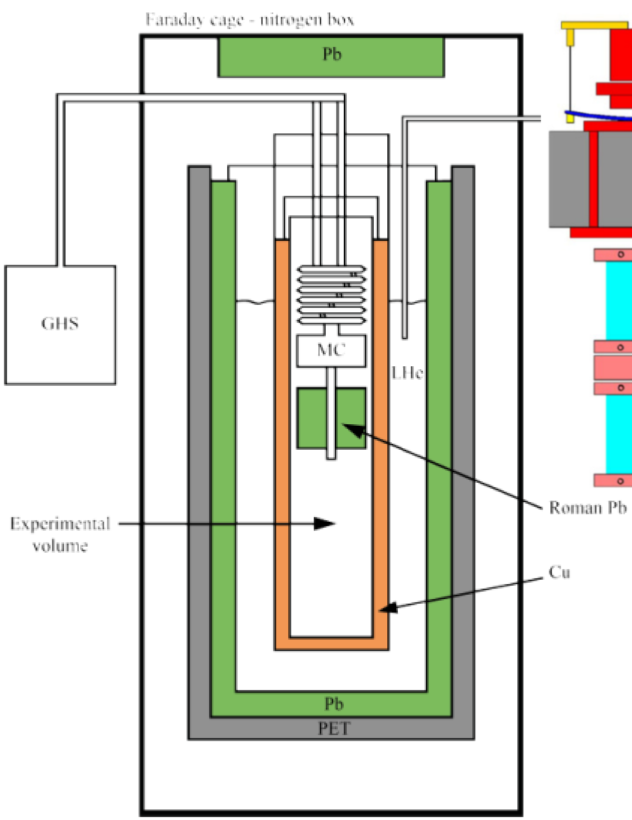
CUPID R&D @ LNGS (Italy)

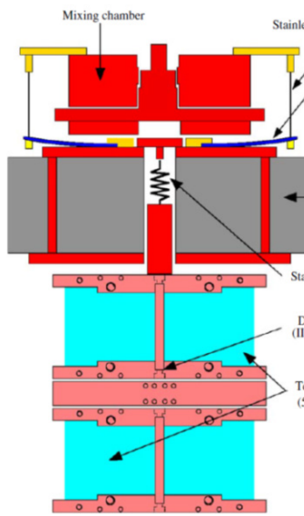


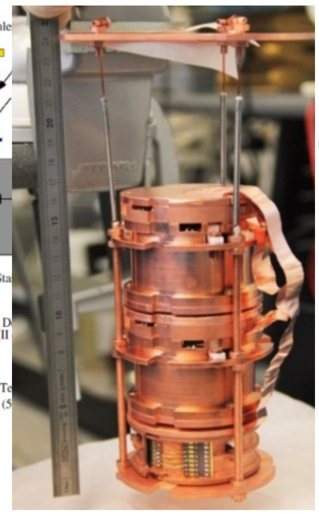
EDELWEISS @ LSM (France)

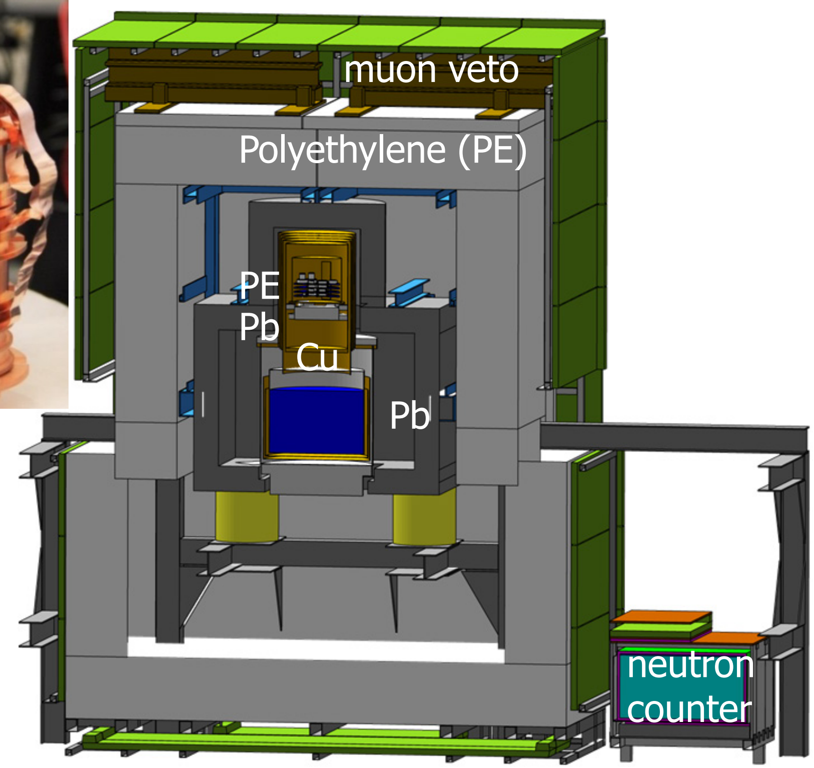


Suspended systems to reduce vibrations



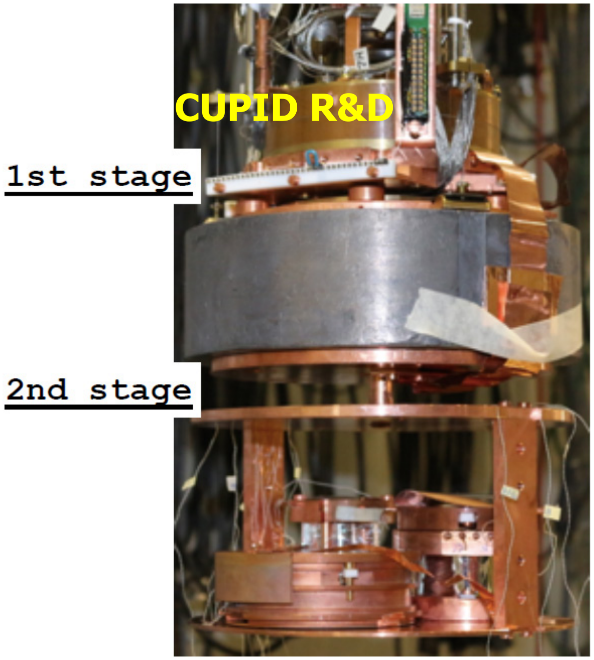


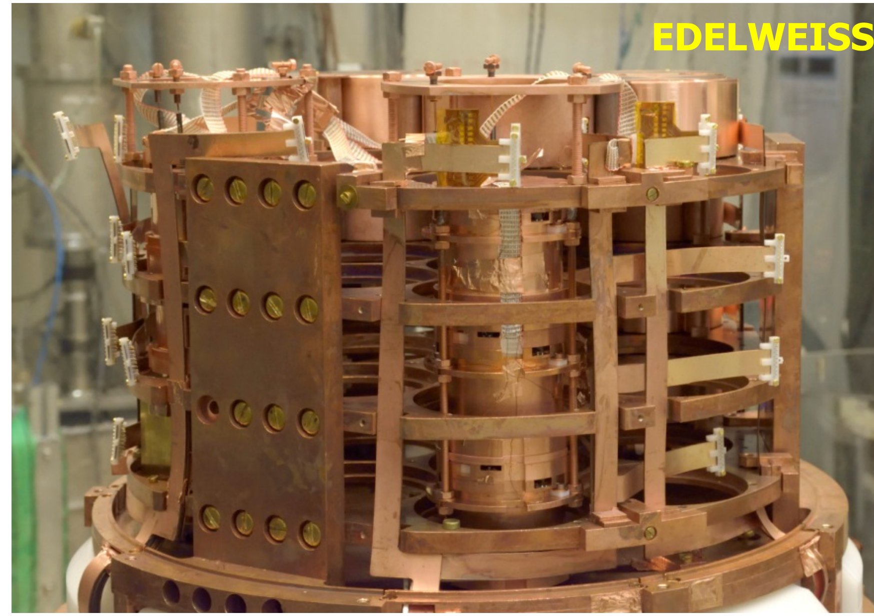


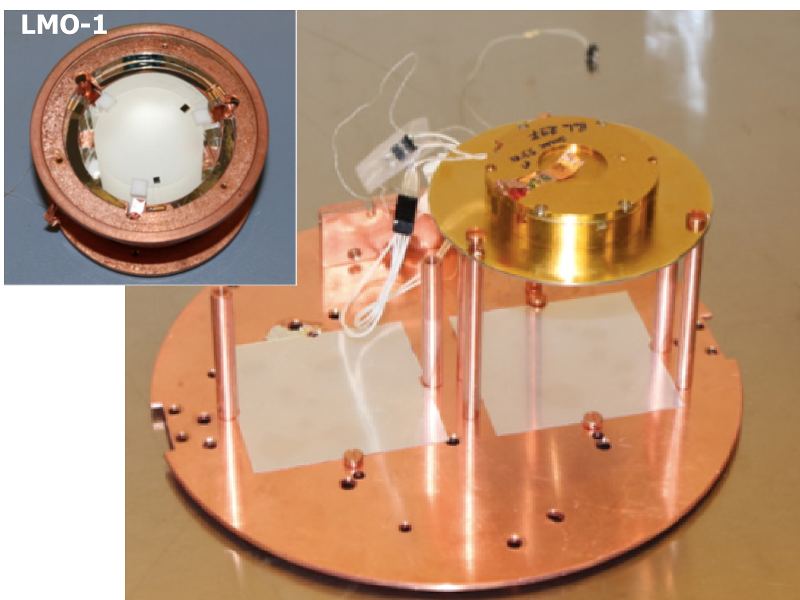


See e.g. in arXiv:1704.01758

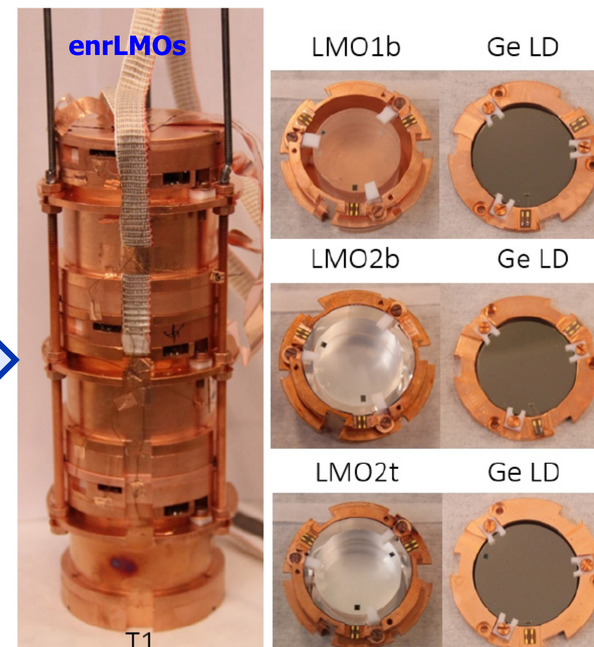
From single Li_2MoO_4 module to x4 $Li_2{}^{100}MoO_4$ array







~3 years of LUMINEU activity



Tests of Li_2MoO_4-based scintillating bolometers

Detector	Crystal ID	Crystal mass (g)	Light detector standard	Lab	Tempera-ture (mK)	Acquired data (h)
Li_2MoO_4	LMO-1	151	IAS	LNGS	11	328
	LMO-2 LMO-3	241 242	LUCIFER IAS	LNGS	11	201
$Li_2{}^{100}MoO_4$	enrLMO-1b	204	LUCIFER	LNGS	12	487
	enrLMO-1t	186	LUMINEU	LSM	19	2090
	enrLMO-1t enrLMO-1b enrLMO-2t enrLMO-2b	186 204 213 207	LUMINEU	LSM	17	2570

Ge light detector by	Diameter (mm)	Thickness (mm)	Antireflecting coating	NTD mass (mg)
IAS	25-40	0.03-0.04	No	~1
LUCIFER	45	0.30	No	9
LUMINEU	44	0.17	70 nm SiO	5-9

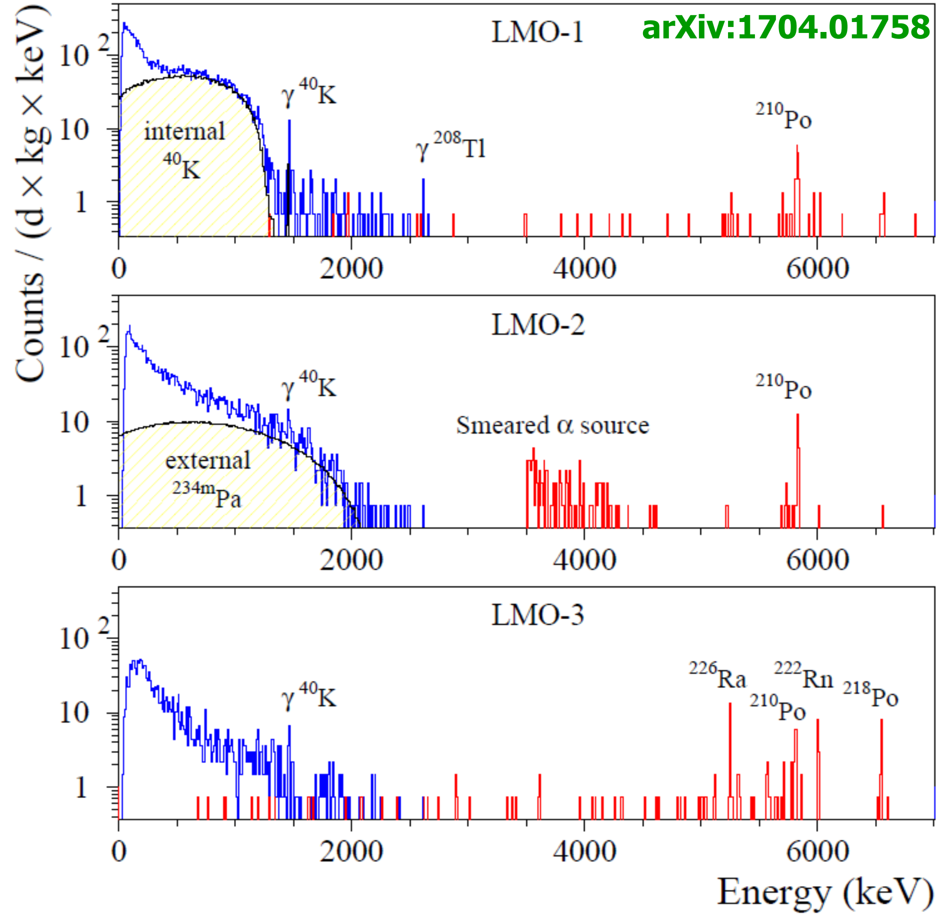
arXiv:1704.01758

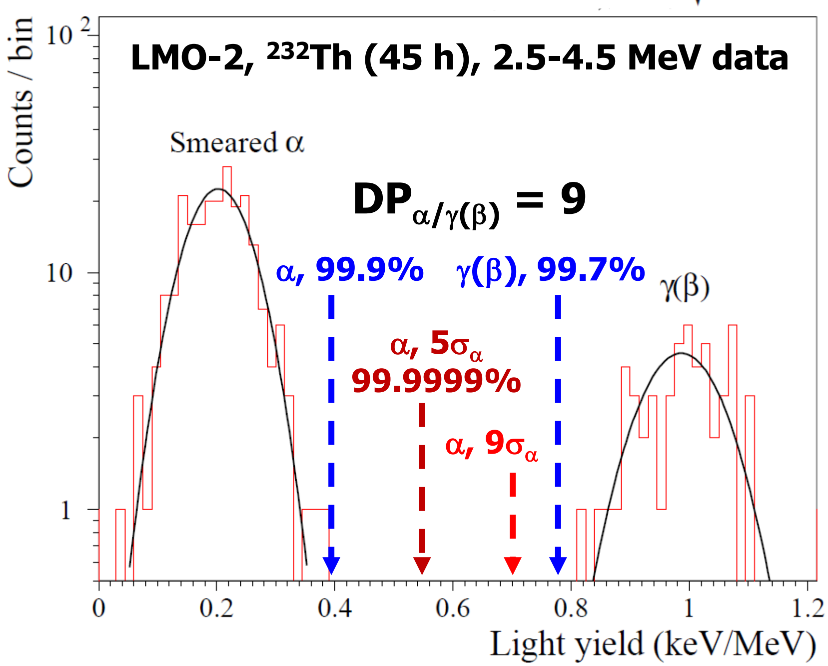
Performance & radiopurity of Li_2MoO_4 bolometers

	LMO-1 151 g	LMO-2 241 g	LMO-3 242 g
Signal [nv/keV]	166	11	23
FWHM [keV] @ 2615 keV	4 ± 1	6 ± 1	5 ± 1
$LY_{\gamma(\beta)}$ [keV/MeV]	0.7	1.0	0.12*
$DP_{\alpha/\gamma(\beta)}$, > 2.5 MeV	16	9	11

Discrimination Power between α and γ(β)

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





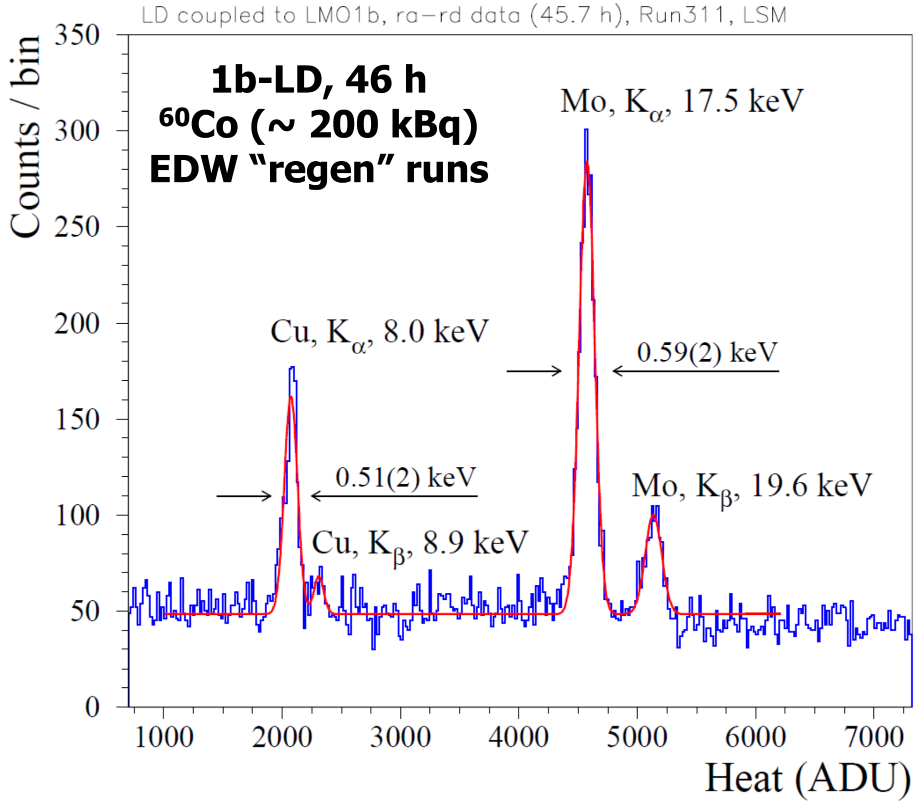
	Activity (mBq/kg)				
	Powder NRMP	LMO-1 Single cr.	LMO-2 Double cr.	Powder Alpha Aesar	LMO-3 Single cr.
^{228}Th	≤ 3.7	≤ 0.023	≤ 0.026	**12(4)**	**≤ 0.024**
^{226}Ra	≤ 3.3	≤ 0.051	≤ 0.044	**705(30)**	**0.13(2)**
^{40}K	≤ 42	**62(2)**	**≤ 12**	≤ 42	≤ 3.3

LUMINEU 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



Effect of LD performance on α/γ DP:

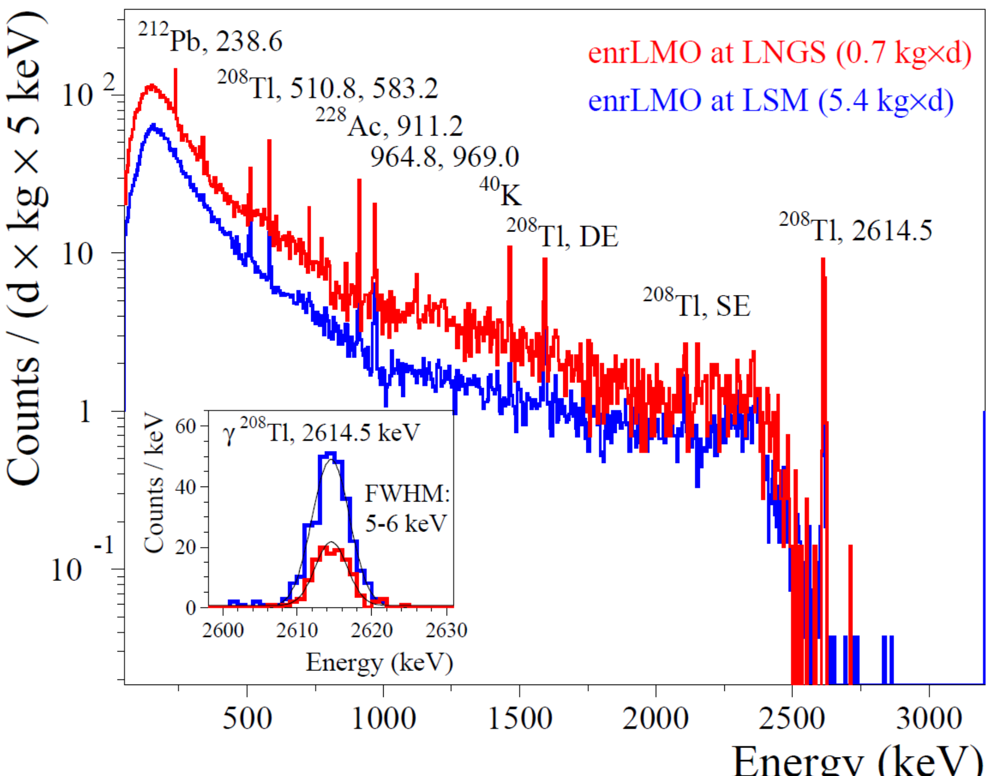
$FWHM_{Bsl}$ ~ 0.5 keV ⇒ expected DP ~ 8

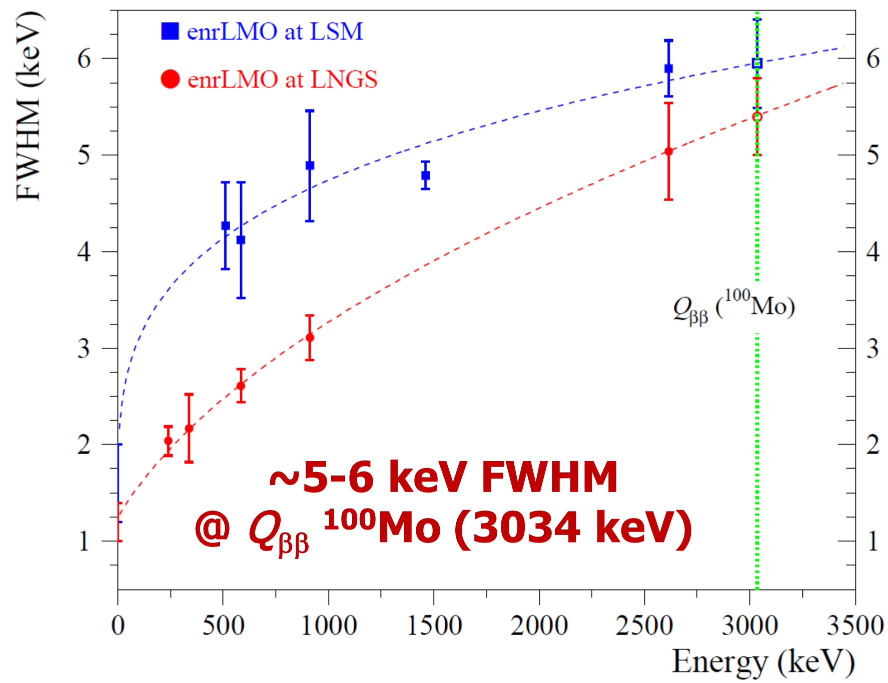
$FWHM_{Bsl}$ ~ 0.1 keV ⇒ expected DP ~ 14

Good reproducibility of "standard" high performance

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

enrLMO-#	1t		1b		2t	2b
	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] @ 2615 keV	**6.3±0.6**	**5.8±0.6**	**5.7±0.6**	**5.0±0.6**	**5.5±0.5**	**5.7±0.6**

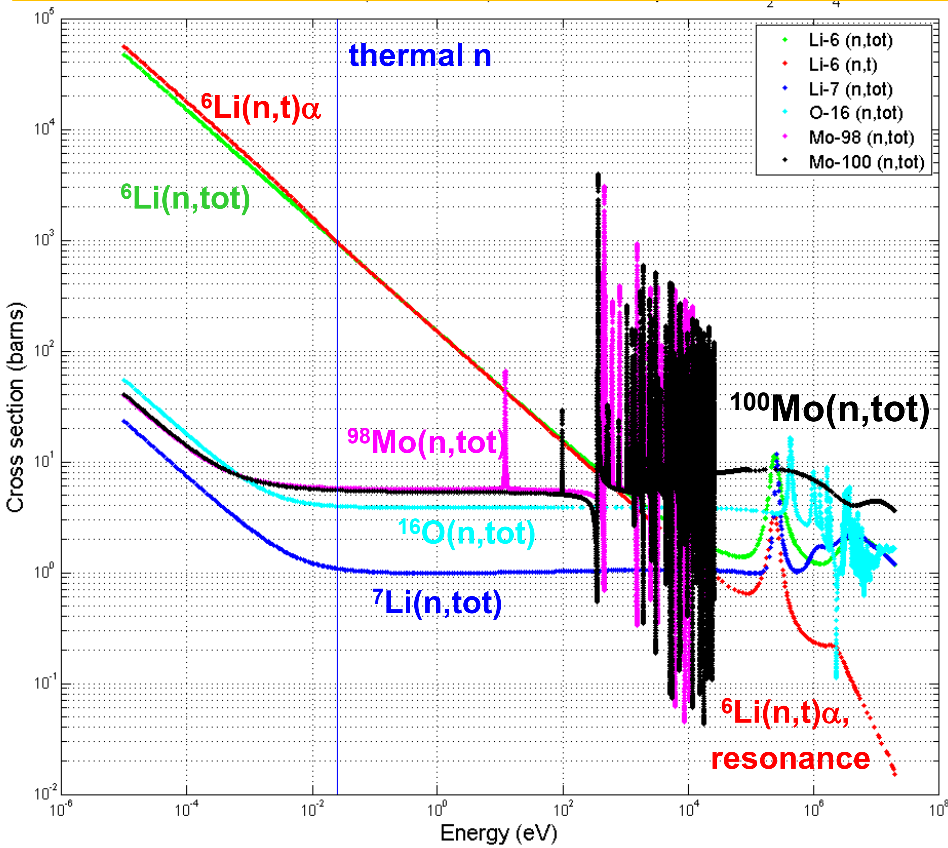




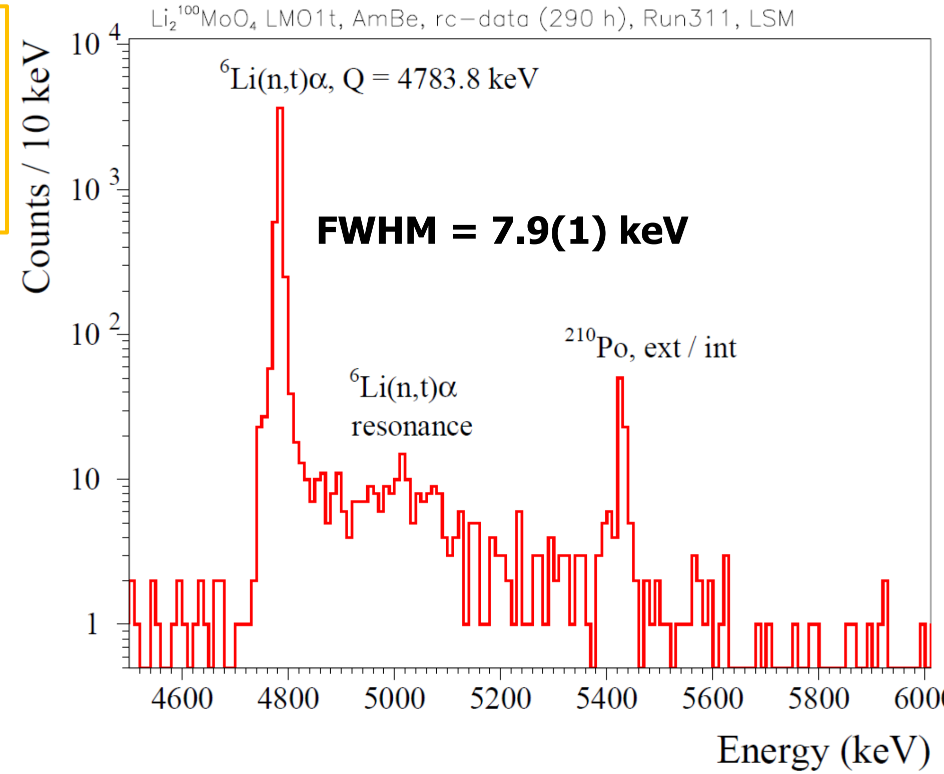
Excellent performance

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

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



enrLMO-1t, AmBe (290 h)



Advantages

- ✓ ~100% detection of thermal n
- ✓ clear α+t signature @ $Q+E_n$
- ✓ γ(β) background-free ROI
- ✓ world record resolution of thermal n capture on ^{6}Li (6-11 keV FWHM @ 4783 keV)

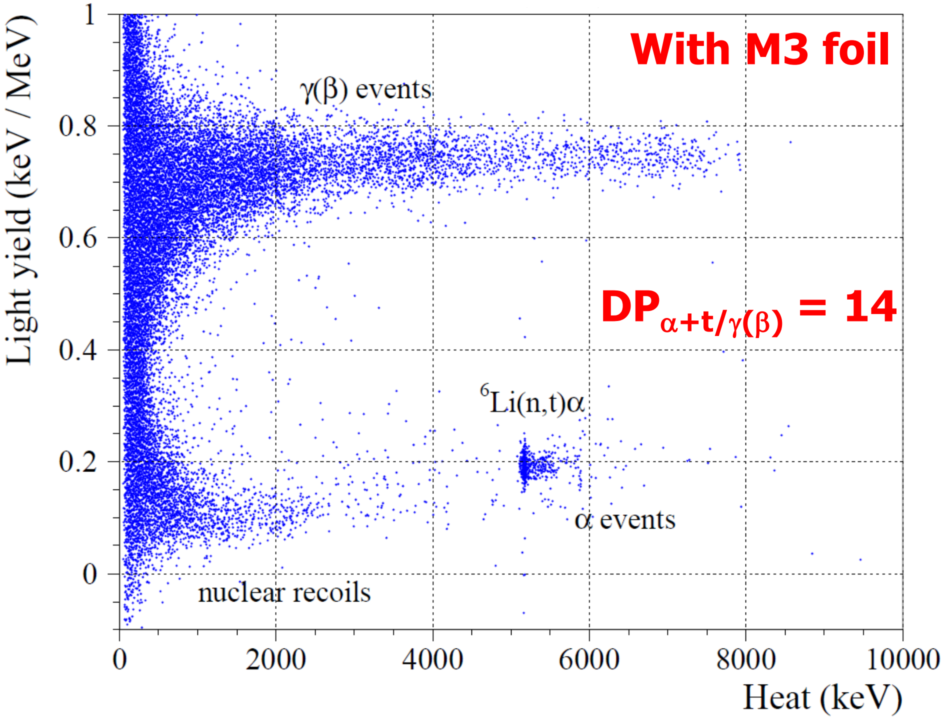
Prospects for in-situ neutron detection

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

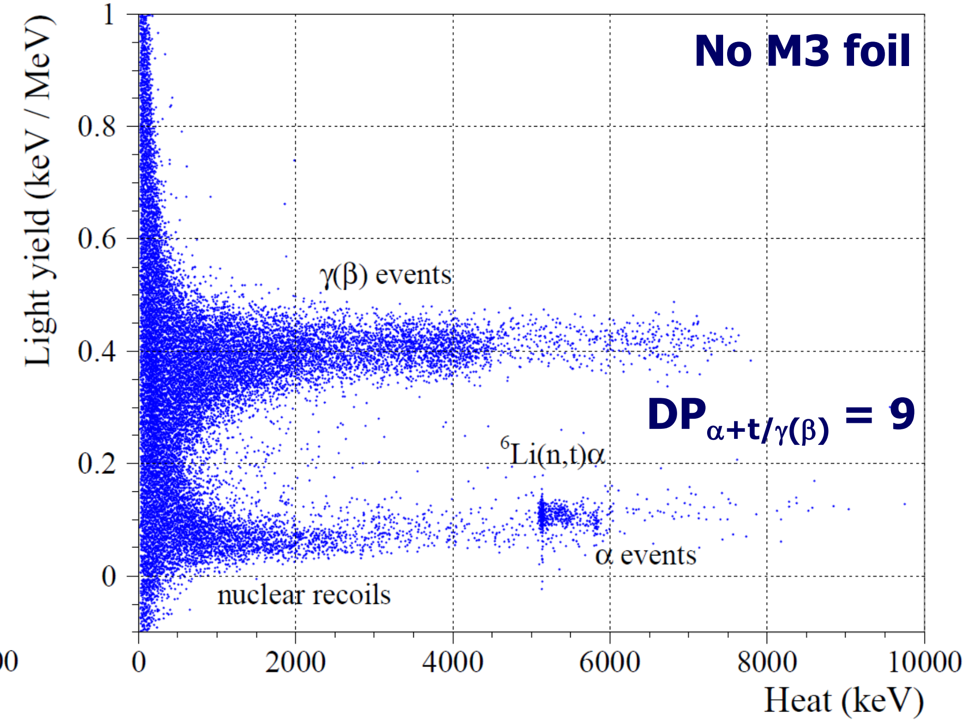
enrLMO-#	1t		1b		2t	2b
M3 reflecting foil	yes	no	yes	no	yes	yes
$LY_{\gamma(\beta)}$ [keV/MeV]	n.a.	**0.41**	**0.77**	**0.38**	**0.73**	**0.74**
$DP_{\alpha/\gamma(\beta)}$, > 2.5 MeV*	**18**	**9**	**12**	**9**	**14**	**14**

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

enrLMO-2t, AmBe (290 h)



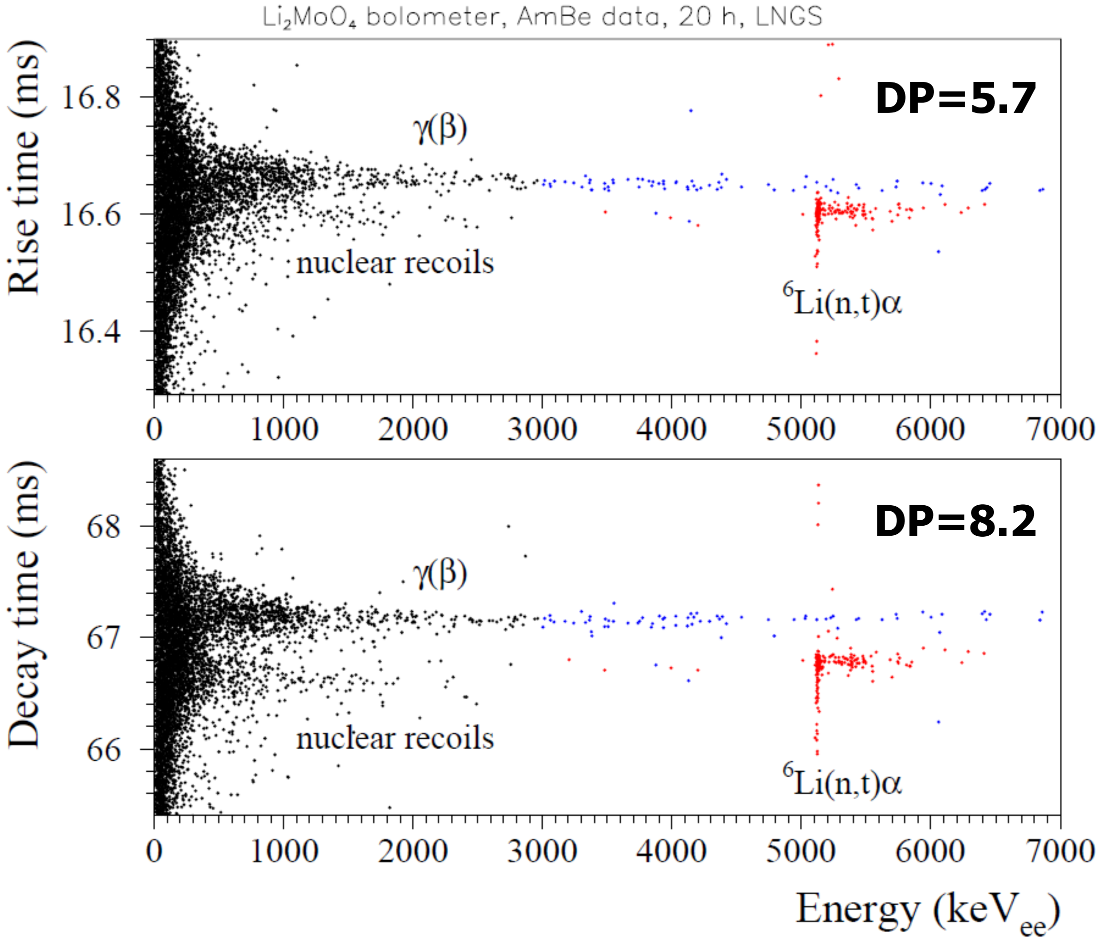
enrLMO-1t, AmBe (290 h)

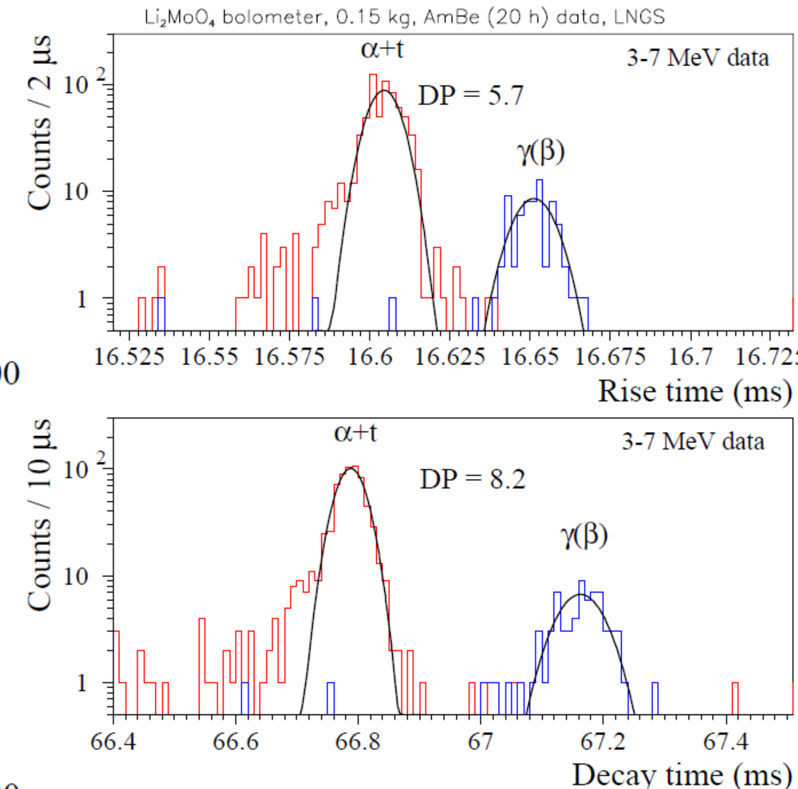


Full $\alpha/\gamma(\beta)$ separation

Particle identification by heat channel

LMO-1, AmBe (20 h), 2 kSPS sampling rate

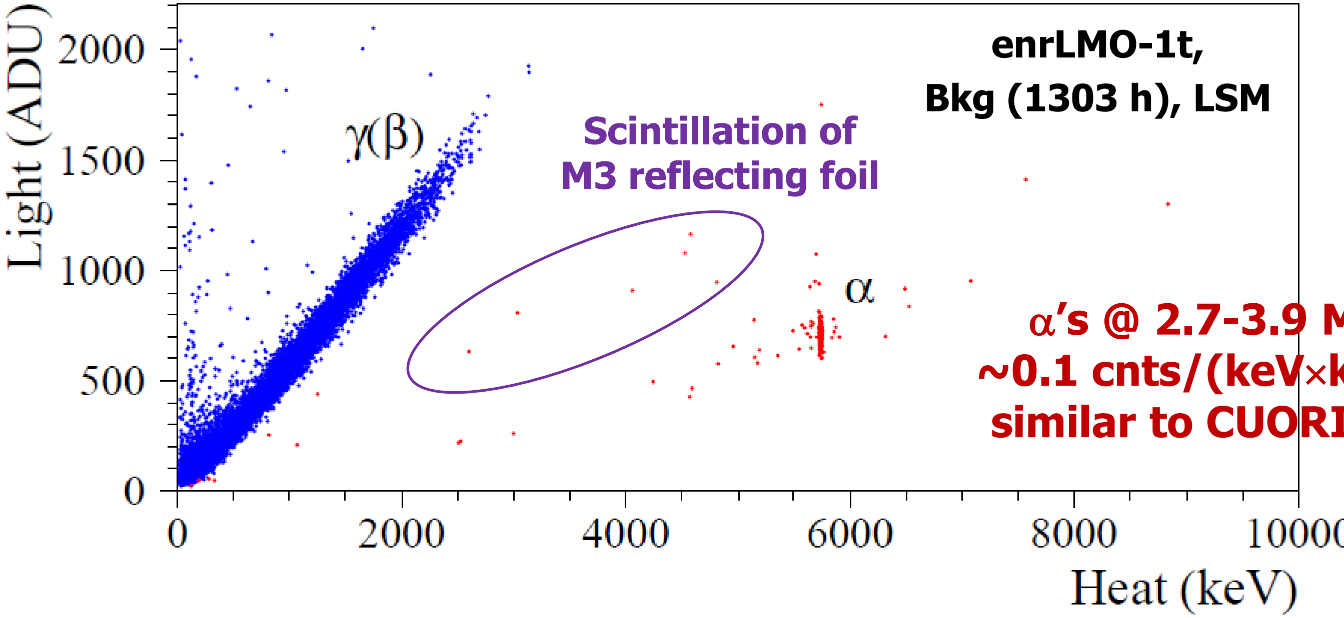




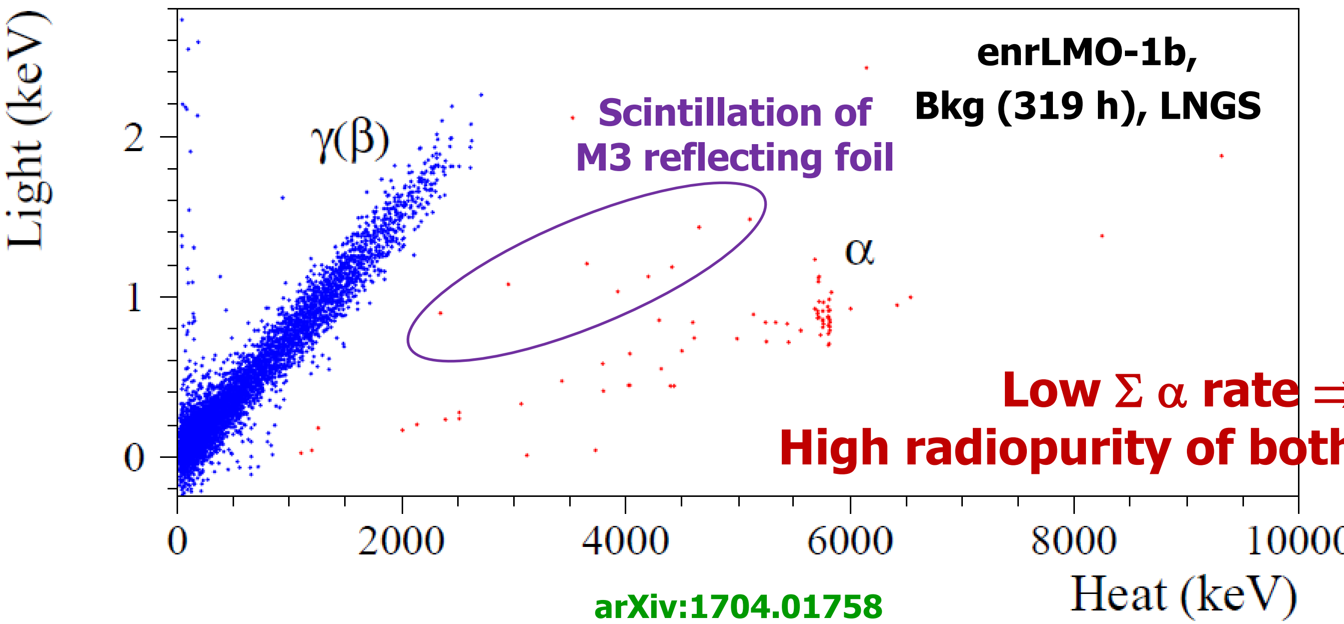
arXiv:1704.01758

Ability to particle identification by only heat signals

First background measurements with $Li_2{}^{100}MoO_4$



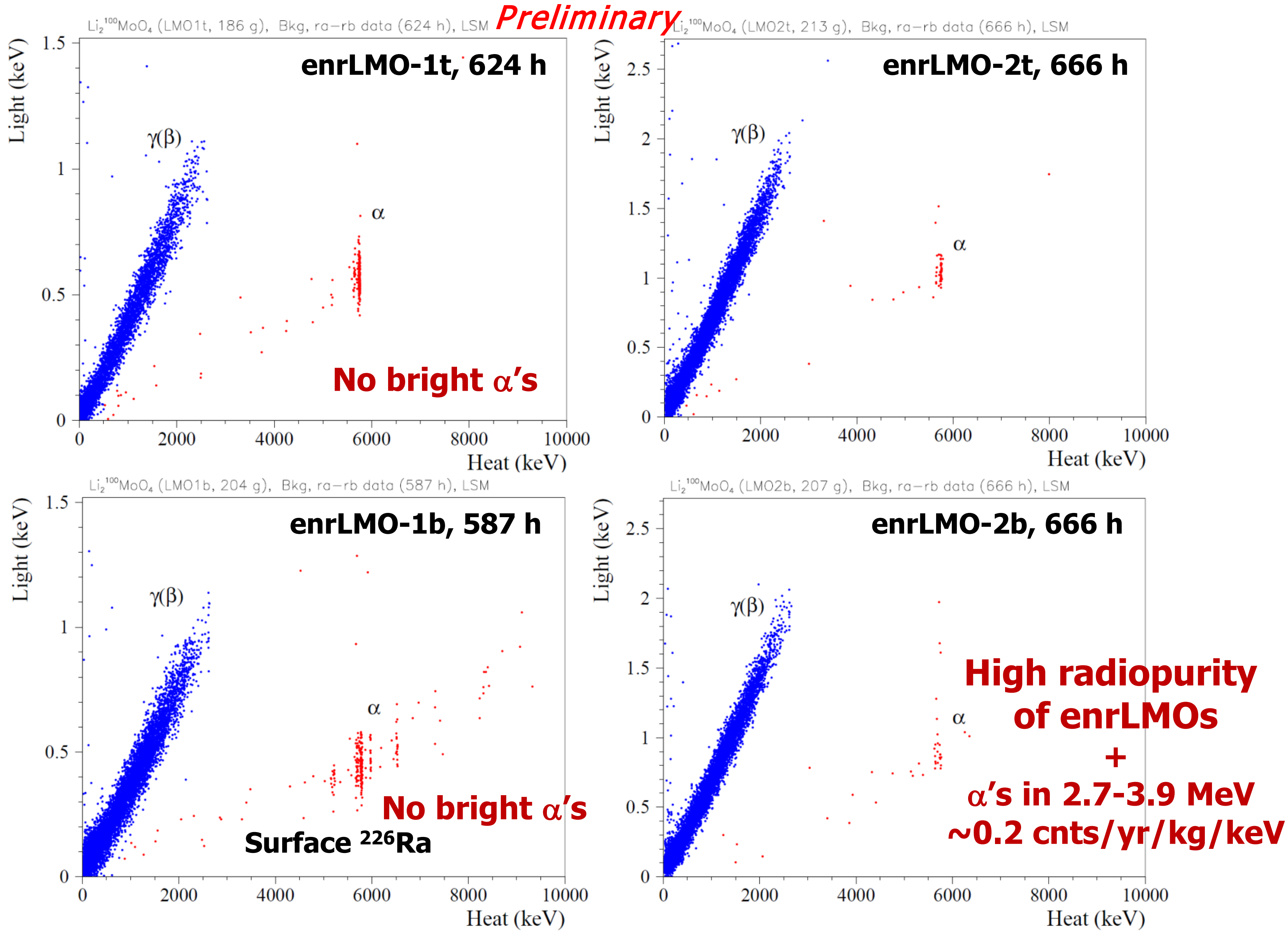
α's @ 2.7-3.9 MeV ~0.1 cnts/(keV×kg×yr), similar to CUORICINO



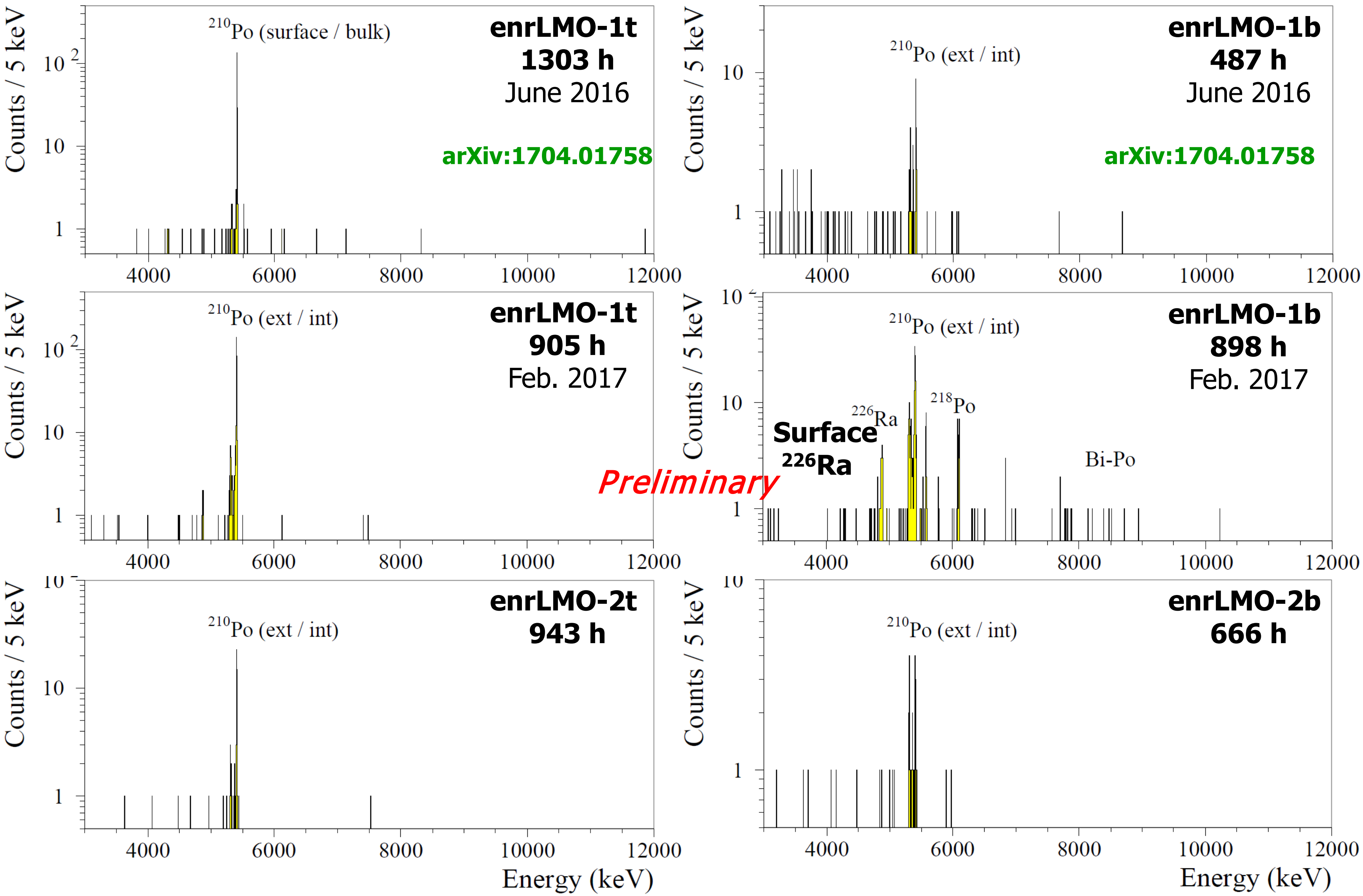
Low Σ α rate ⇒ High radiopurity of both enrLMOs

arXiv:1704.01758

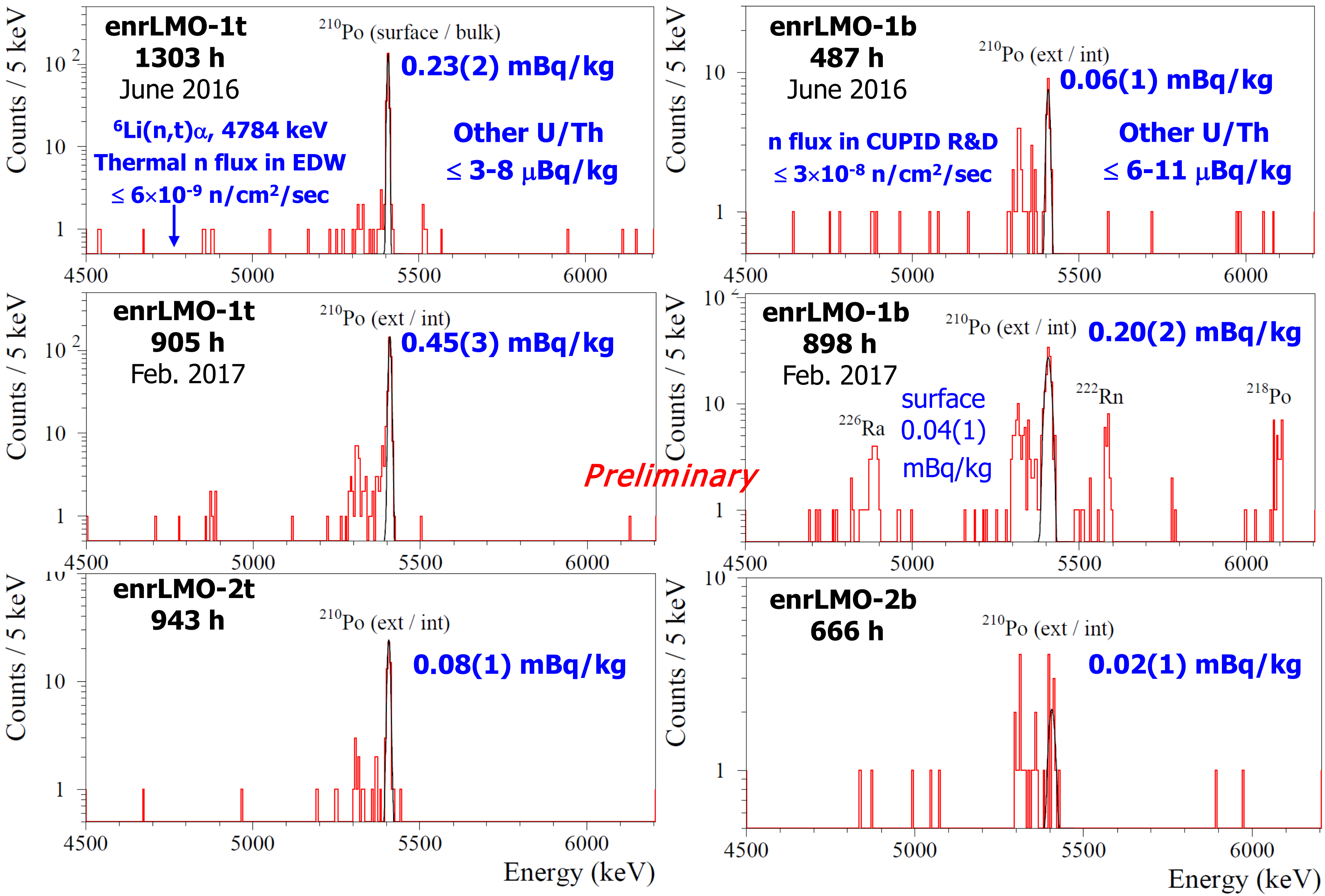
Background measurements with 4 $Li_2{}^{100}MoO_4$ array



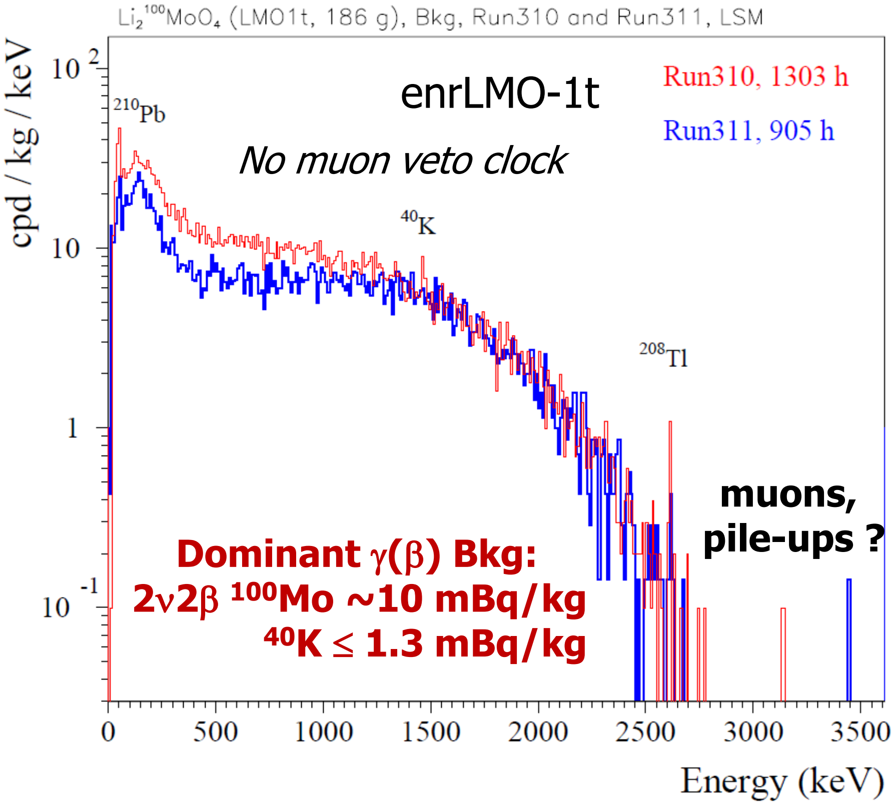
α Background of $Li_2{}^{100}MoO_4$ detectors

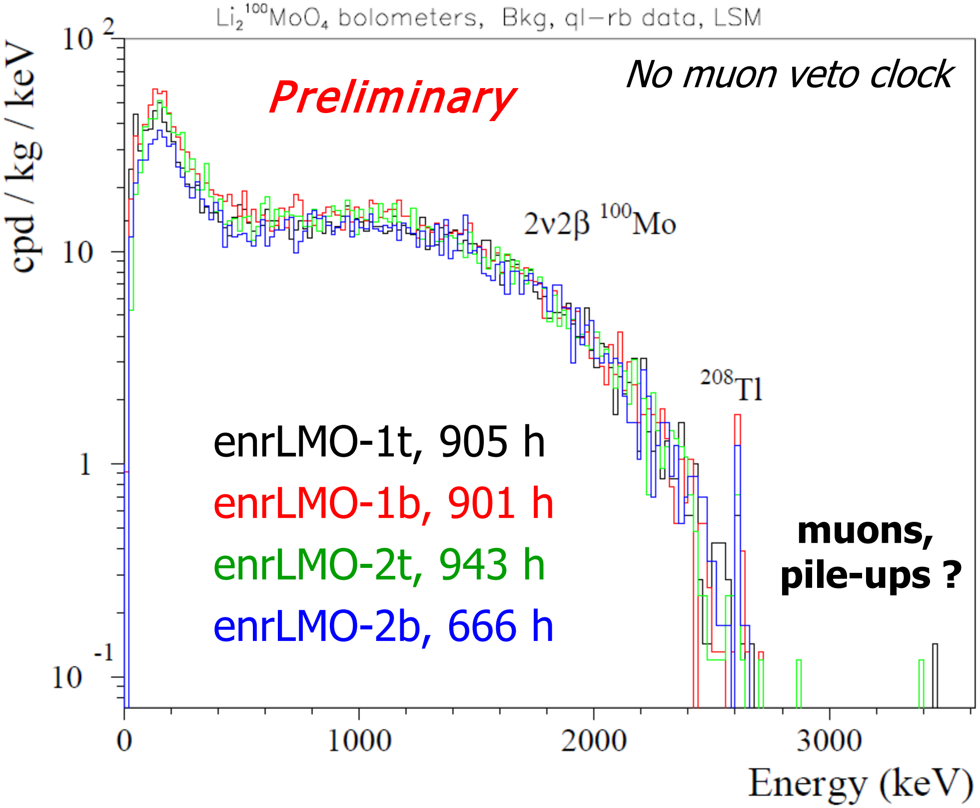


α Background of $Li_2{}^{100}MoO_4$ detectors



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

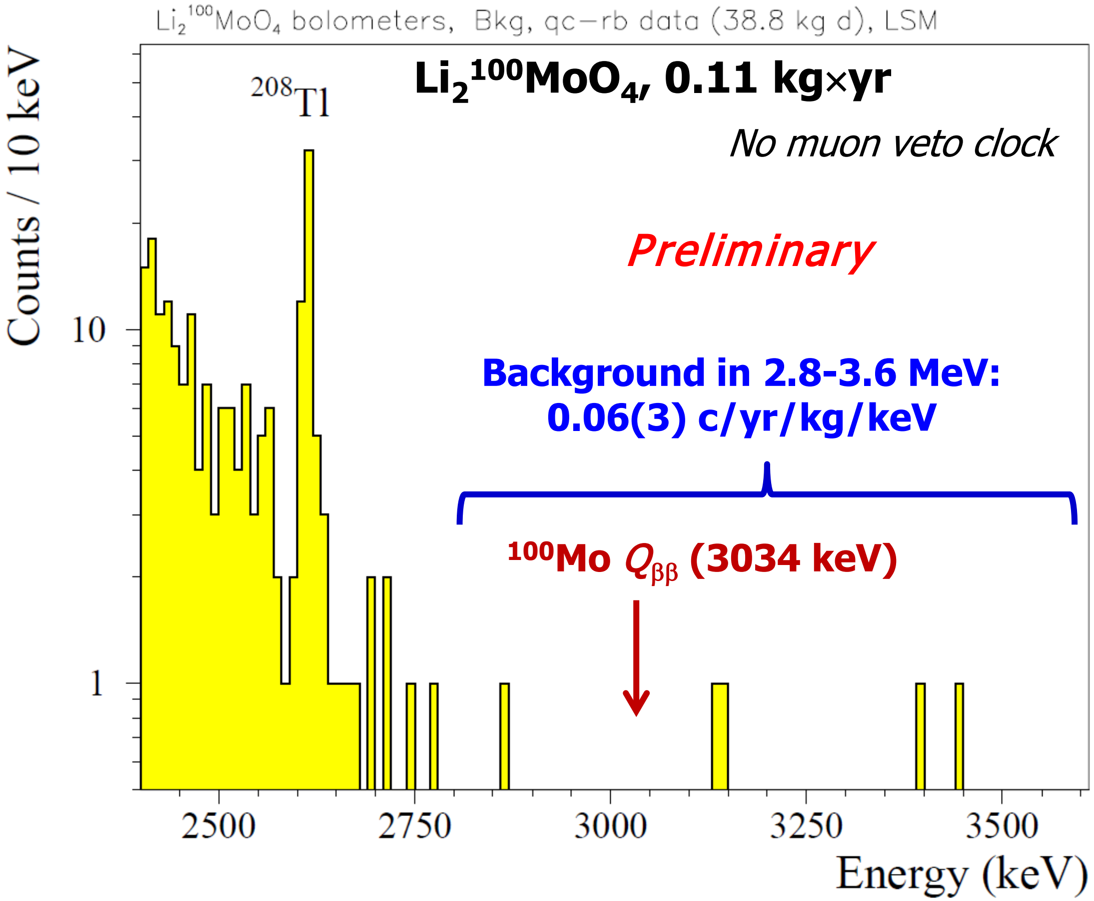




enrLMO-#	1t		1b	2t	2b	Average
Rate [cnts/day/kg] of 2615 keV γ's	1.5(4)	0.7(3)	2.1(5)	1.3(5)	1.0(3)	**1.1(2)**

Position dependent $\gamma(\beta)$ rate inside the EDELWEISS set-up
^{208}Tl rate is ~x40 of CUORICINO background
Work is in progress to reduce the external ^{232}Th background

Sensitivity to 0ν2β decay of ^{100}Mo



Sensitivity to ^{100}Mo 0ν2β 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

⇓

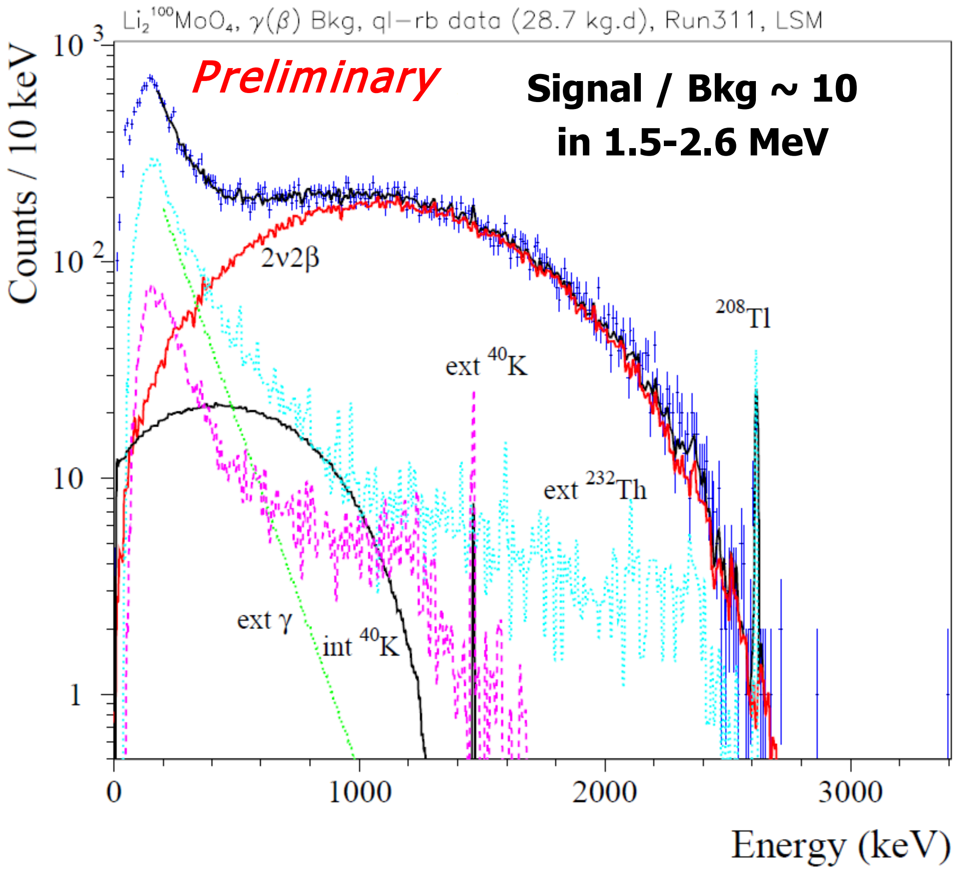
$T_{1/2}$ =≥ 0.7×10^{23} yr @ 90% CL

<$m_{\beta\beta}$> ≤ 1.4-2.4 eV

NEMO-3 (34.3 kg×yr):
$T_{1/2}$ ≥ 1.1 × 10^{24} yr @ 90% CL
PRD 92 (2015) 072011

High potential of scintillating bolometers approach

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 %

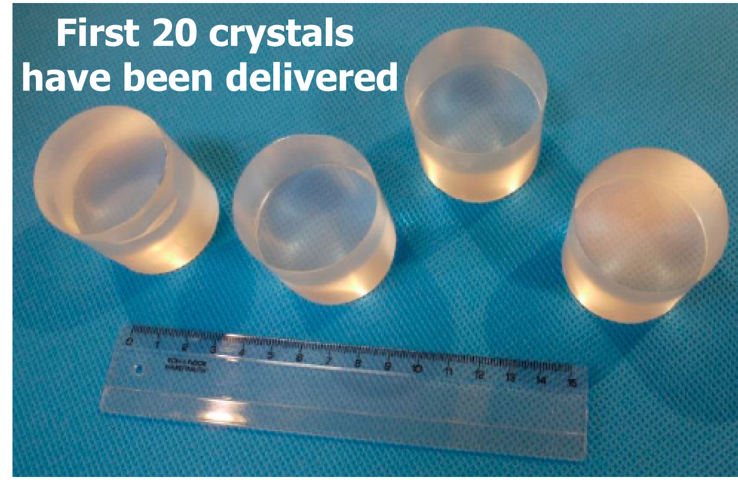
One of the most precise ^{100}Mo half-life value

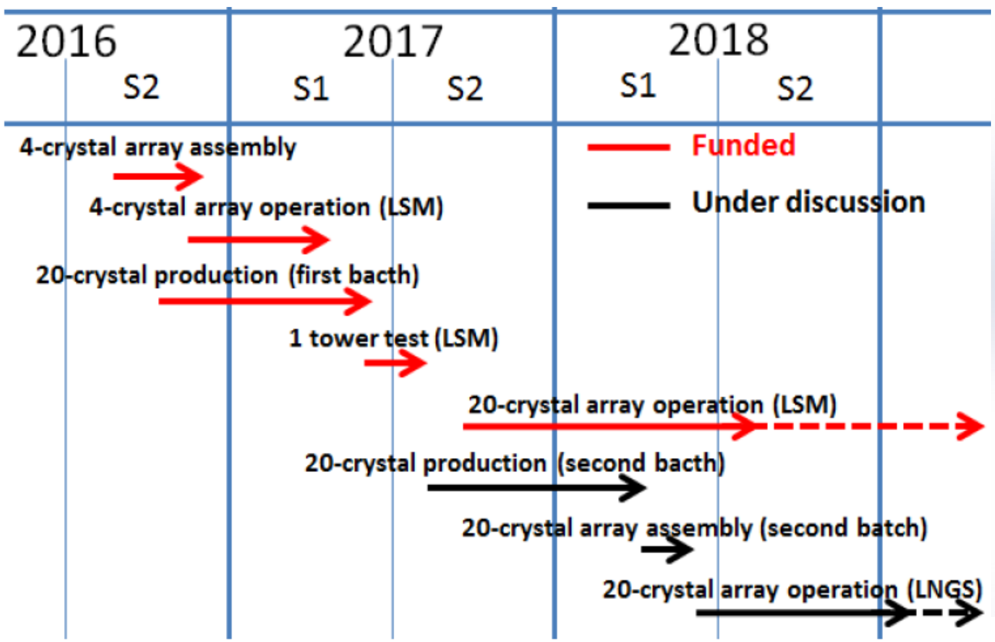
$T_{1/2}$ [10^{18} yr]	Exposure	Experiment	Ref.
7.11±0.02(stat)±0.54(syst)	7.37 kg×yr	NEMO-3	PRL 95, 182302 (2005)
7.15±0.37(stat)±0.66(syst)	0.08 kg×yr	LUCIFER	JPG 41, 075204 (2014)
6.90±0.15(stat)±0.42(syst)	0.03 kg×yr	LUMINEU	arXiv:1704.01758
6.92±0.06(stat)±0.36(syst)	0.08 kg×yr	LUMINEU	MEDEX'17

LUMINEU follow-up: CUPID-0/Mo

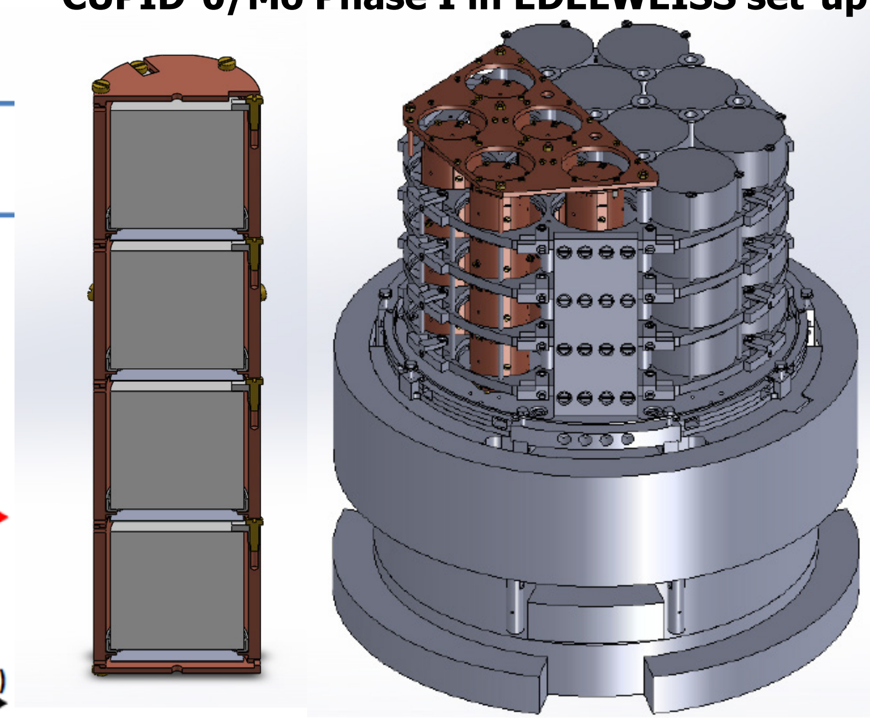
- **CUPID-0/Mo Phase I (20 crystals):**
  - **20 ^{100}Mo-enriched (97%) Li_2MoO_4**
    (∅44×45 mm, 0.21 kg each; 4.18 kg total)
    ⇒ 2.34 kg of ^{100}Mo (1.37×10^{25} ^{100}Mo nuclei)
  - **20 Ge light detectors** (∅44×0.175 mm)+SiO
  - **EDELWEISS set-up** @ LSM (France)

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





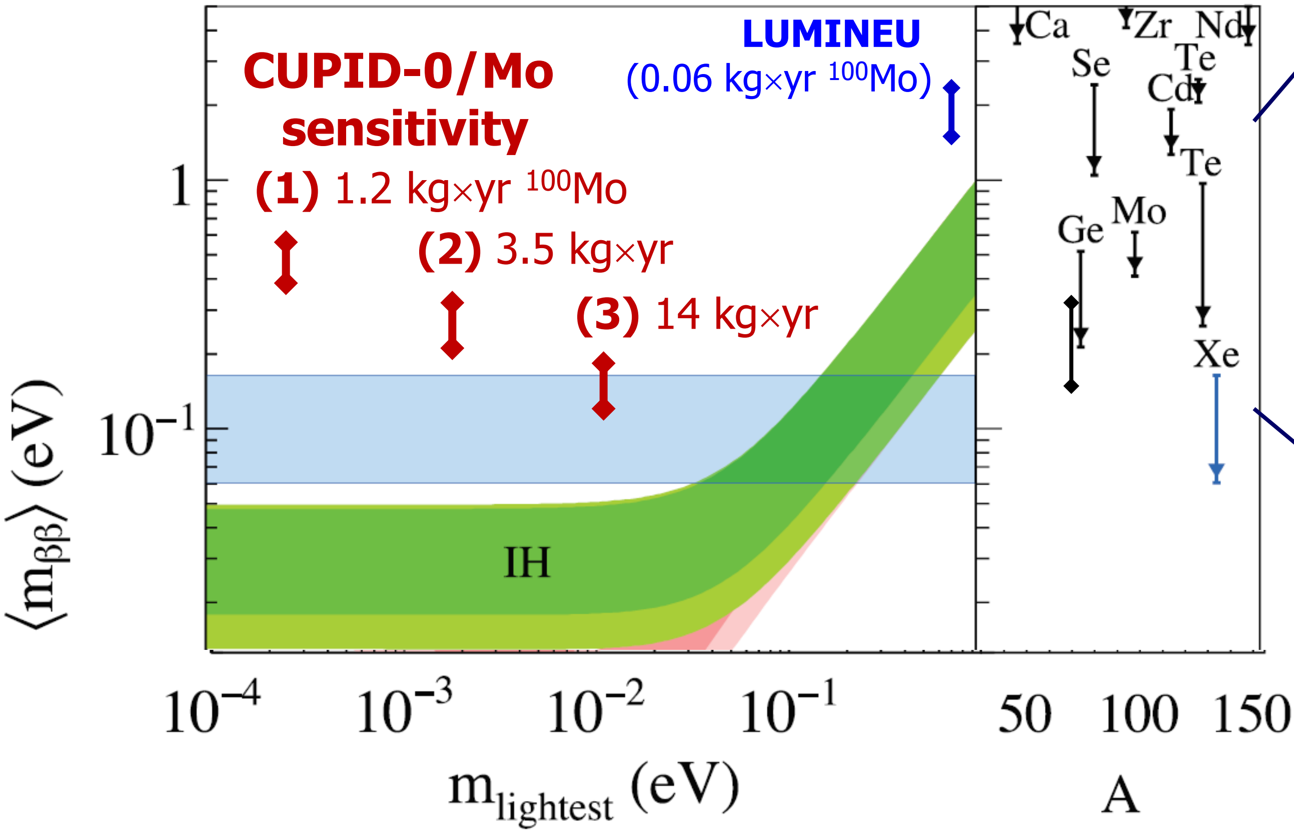
CUPID-0/Mo Phase I in EDELWEISS set-up



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	29.5
^{100}Mo	34.3
^{76}Ge	34.4
^{136}Xe	504

PRL 115 (2015) 102502
PRD 92 (2015) 072011
Nature 544 (2017) 5
PRL 117 (2016) 082503
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 one of the most precise measurements of the $2\nu2\beta$ decay half-life of ^{100}Mo

- **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 by: end of 2017 (20 crystals) and mid. 2018 (20+20 crystals)
  - Ambitious results in 3 yr: the best accurate ^{100}Mo $2\nu2\beta$ half-life value and one of the highest sensitivity to effective Majorana neutrino mass
  - Main goal: demonstration of the LUMINEU technology viability for CUPID, next generation 1t-scale bolometric $0\nu2\beta$ project (CUORE follow up)