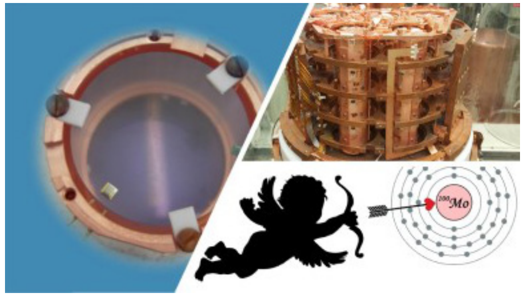


CUPID-Mo inauguration

Fourneaux, France

11-12 December 2019

History of lithium molybdate low-temperature detectors

Denys Poda

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

Outline

- **^{100}Mo as a ββ source**

- **History of Li_2MoO_4 cryogenic detectors**
  - First low-temperature tests of small Li_2MoO_4 crystals
  - Advanced Li_2MoO_4 scintillating bolometers: from LUMINEU to CUPID
  - Other CUPID oriented activities with Li_2MoO_4 crystals
  - CUPID competitor: AMoRE path to Li_2MoO_4 bolometers

- **Summary**

^{100}Mo as a ββ source

Periodic Table of the Elements

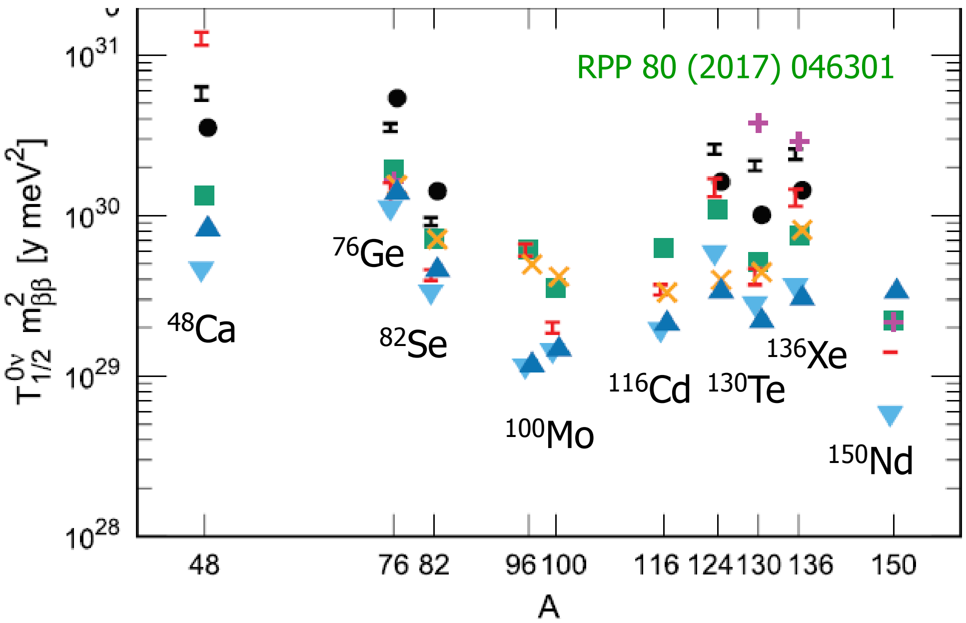
Double-beta decay

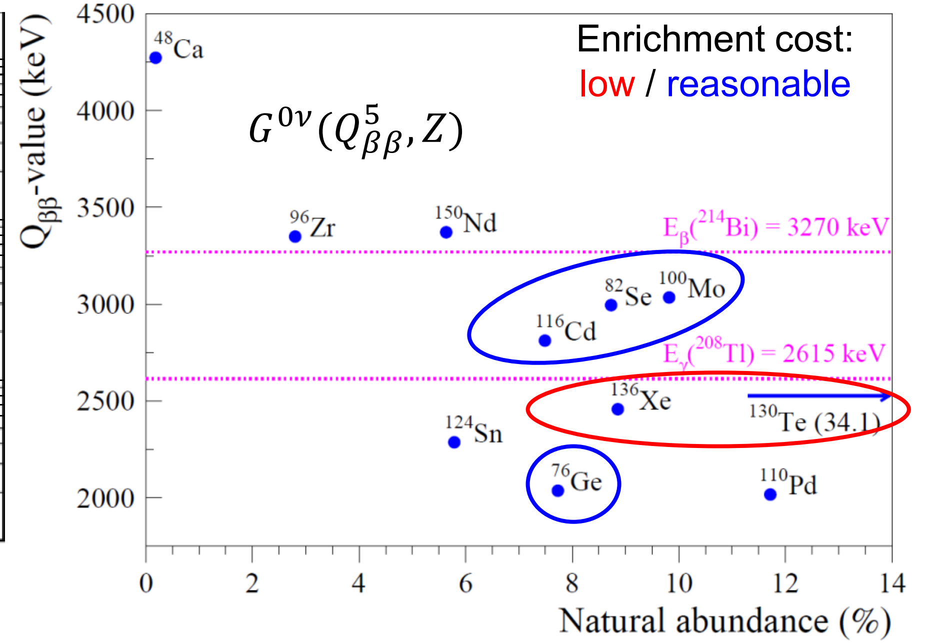
- **Energetically allowed for 69 nuclides**
  - 1/3 of the chemical elements: marked by
  - 2% of nuclides from Table of Isotope (~3500)
  - half of them, 35, can undergo via (A,Z)→(A,Z+2)

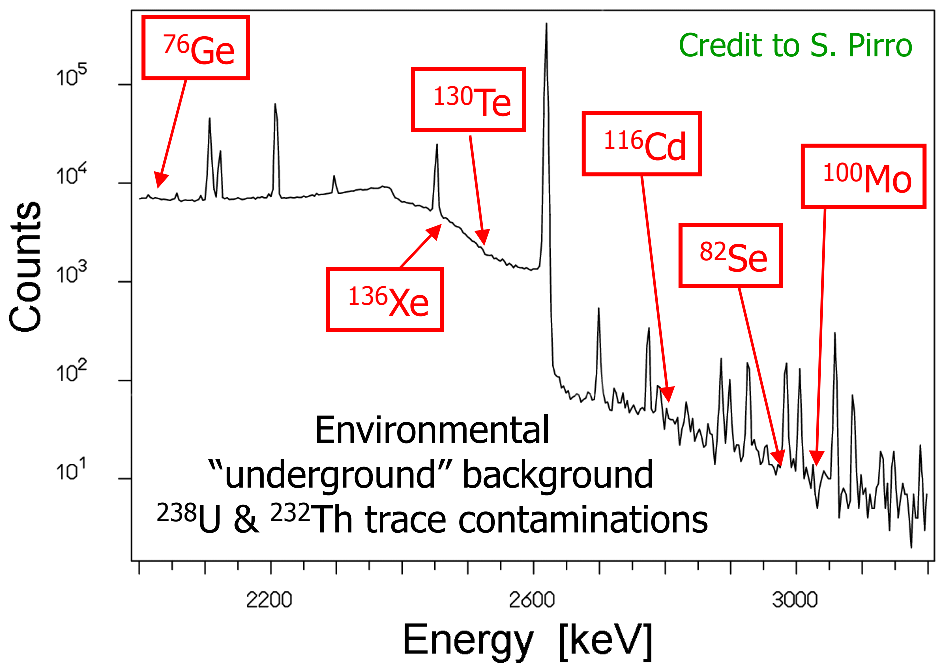
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H Hydrogen 1.01																	2 He Helium 4.00
3 Li Lithium 6.94	4 Be Beryllium 9.01											5 B Boron 10.81	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 19.00	10 Ne Neon 20.18
11 Na Sodium 22.99	12 Mg Magnesium 24.31											13 Al Aluminum 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.95
19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.88	23 V Vanadium 50.94	24 Cr Chromium 51.99	25 Mn Manganese 54.94	26 Fe Iron 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.38	31 Ga Gallium 69.72	32 Ge Germanium 72.63	33 As Arsenic 74.92	34 Se Selenium 78.97	35 Br Bromine 79.90	36 Kr Krypton 84.80
37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.95	43 Tc Technetium 98.91	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.6	53 I Iodine 126.90	54 Xe Xenon 131.29
55 Cs Cesium 132.91	56 Ba Barium 137.33	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.85	75 Re Rhenium 186.21	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.97	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.20	83 Bi Bismuth 208.98	84 Po Polonium [208.98]	85 At Astatine 209.98	86 Rn Radon 222.02
87 Fr Francium 223.02	88 Ra Radium 226.03	89-103 Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [278]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [280]	112 Cn Copernicium [285]	113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscovium [289]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]
		57 La Lanthanum 138.91	58 Ce Cerium 140.12	59 Pr Praseodymium 140.91	60 Nd Neodymium 144.24	61 Pm Promethium 144.91	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.93	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.93	70 Yb Ytterbium 173.06	71 Lu Lutetium 174.97	
		89 Ac Actinium 227.03	90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium 237.05	94 Pu Plutonium 244.06	95 Am Americium 243.06	96 Cm Curium 247.07	97 Bk Berkelium 247.07	98 Cf Californium 251.08	99 Es Einsteinium [254]	100 Fm Fermium 257.10	101 Md Mendelevium 258.10	102 No Nobelium 259.10	103 Lr Lawrencium [262]	

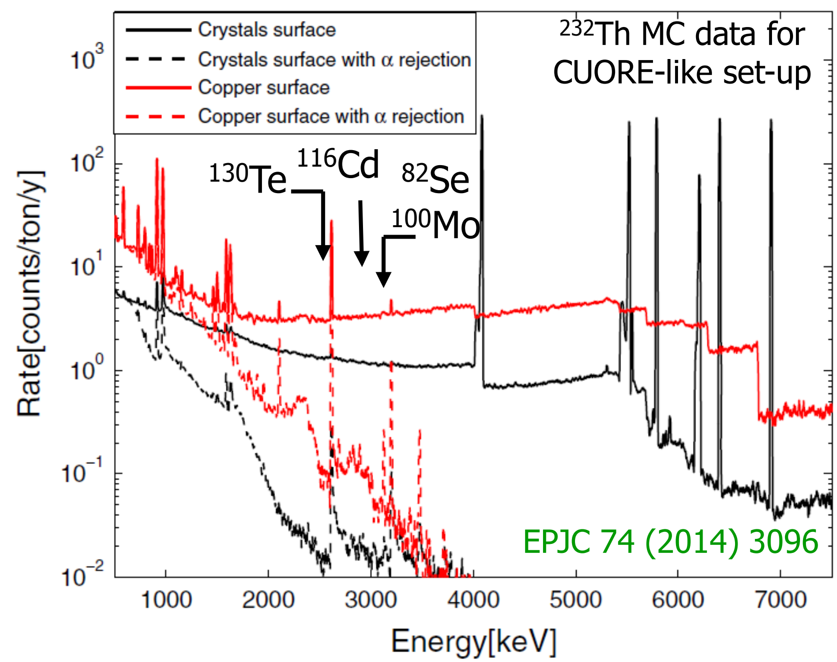
Alkali Metal | Alkaline Earth | Transition Metal | Basic Metal | Metalloid | Nonmetal | Halogen | Noble Gas | Lanthanide | Actinide

Most promising isotopes for 0ν2β decay search



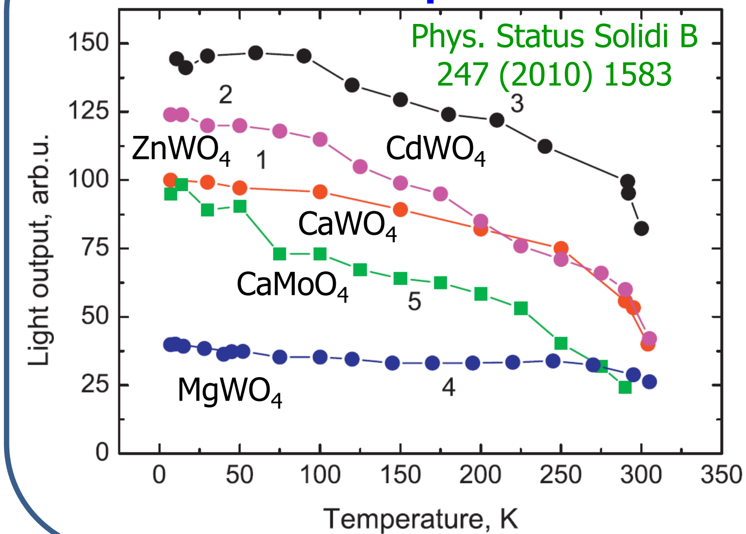






Scintillating bolometer approach

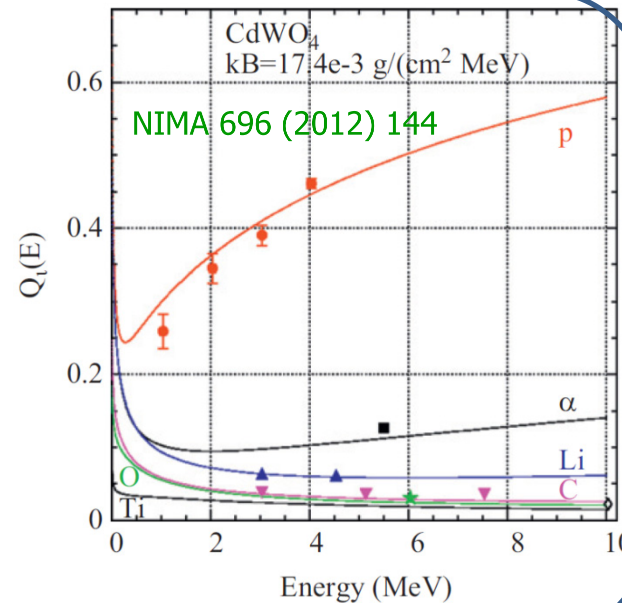
Some absorbers scintillate at low temperatures



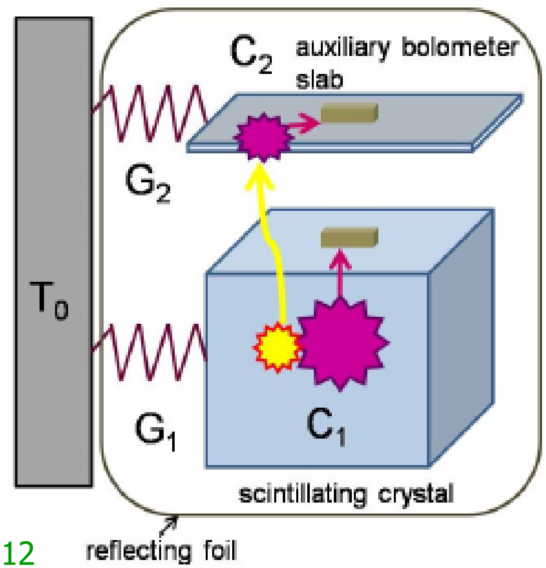
Light signal for ions is quenched

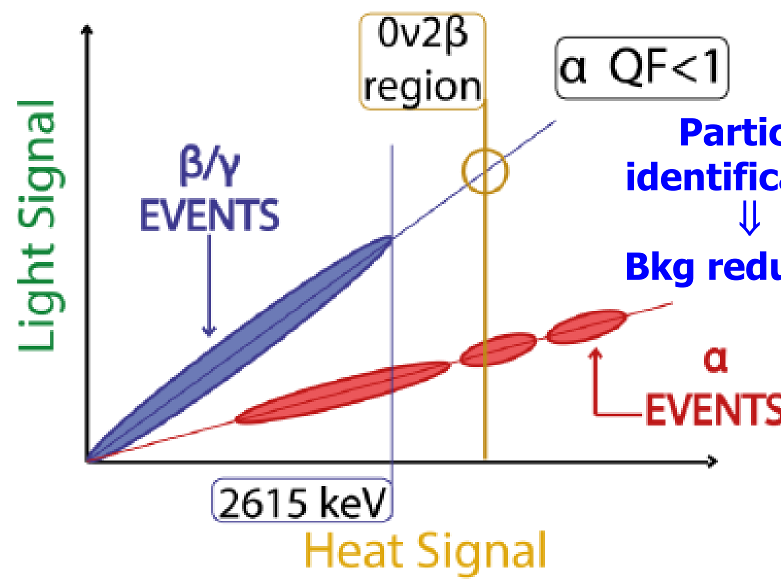
Amount of light produced in a scintillator by highly ionizing particles is lower than that for electrons of the same energy. (e.g., a light signal induced by α's inside a crystal scintillator is typically quenched to ~10-20%)

Astropart. Phys. 33 (2010) 40



Hybrid bolometer with light-heat dual read-out





Particle identification
⇓
Bkg reduction

See also review
IJMPA A 32 (2017) 1743012

Further details: S. Pirro, talk @ CUPID-Mo inauguration

ββ source = bolometric detector

ββ Isotope	δ (%)	$Q_{\beta\beta}$ (keV)	Materials
^{110}Pd	12	2018	None
^{76}Ge	7.7	2039	Ge (*no scintillation, but ionization*), BGO (*good scintillator*)
^{124}Sn	5.8	2287	Sn
^{136}Xe	8.9	2458	None
^{130}Te	34	2527	TeO_2 (*extremely poor scintillator*)
^{116}Cd	7.5	2813	$CdWO_4$, $CdMoO_4$ (*both are good scintillators*)
^{82}Se	8.7	2998	ZnSe, $LiInSe_2$ (*both are good scintillators*)
^{100}Mo	9.8	3034	$PbMoO_4$, $CaMoO_4$, $CdMoO_4$, $SrMoO_4$, $MgMoO_4$, Na_2MoO_4, $ZnMoO_4$, **Li_2MoO_4**, $Na_2Mo_4O_{13}$, $Li_2Mg_2(MoO_4)_3$ (*most are good scintillators*)
^{96}Zr	2.8	3356	ZrO_2 (*poor scintillator*)
^{150}Nd	5.6	3371	None (many attempts)
^{48}Ca	0.2	4268	CaF_2, $CaWO_4$, $CaMoO_4$ (*all are good scintillators*)

Isotopic abundances:
[Pure Appl. Chem. 88 (2016) 293]
$Q_{\beta\beta}$ values:
[Pure Appl. Chem. 88 (2016) 293]

Compilation is based on results of multiple bolometric tests performed by
S. Pirro et al. @LNGS (Italy),
A. Giuliani et al. @CSNSM & @LSM (France),
H.J. Kim et al. @CUP & @Y2Y (South Korea)
Scintillation of some materials was also studies by H. Kraus et al. @Oxford

Bolometers can be used for studies of almost all most promising ββ isotopes!

History of Li_2MoO_4 cryogenic detectors

Lithium molybdate (Li_2MoO_4)

Compound: inorganic, soluble in water, slightly hygroscopic, not hazardous material.

Production: solid-phase synthesis from a stoichiometric mixture of MoO_3 and Li_2CO_3 powders followed by a recrystallization from acqueous solutions / a crystal growth from a melt

Application:
industry and basic research

- ✓ **Corrosion inhibitor** (in LiBr absorption chiller) in some types of industrial air conditioning
- ✓ **Electrode material** in the fabrication of lithium-ion batteries

- ✓ **Cryogenic particle detector for rare event searches** (double beta decay, dark matter, solar axions) **and neutron spectroscopy**

First low-temperature tests of small Li_2MoO_4 crystals

(grown by the Czochralski method)

2009: First bolometric test of a gram-scale Li_2MoO_4

Crystals production at Russian Chemistry-Technological University of D.I. Mendeleev (Moscow, Russia)

- **Solid-state synthesis** from MoO_3 and Li_2CO_3 powders (both of 99.5% purity) with subsequent recrystallization from water solutions

- **Czochralski growth** (4 mm/h) of transparent Li_2MoO_4 crystals up to ∅25×35 mm (Progress: up to ∅50×60 mm from the 99.98% purity mixture [J. Cryst. Growth 401 (2014) 853])

Radiopurity measurements @LNGS

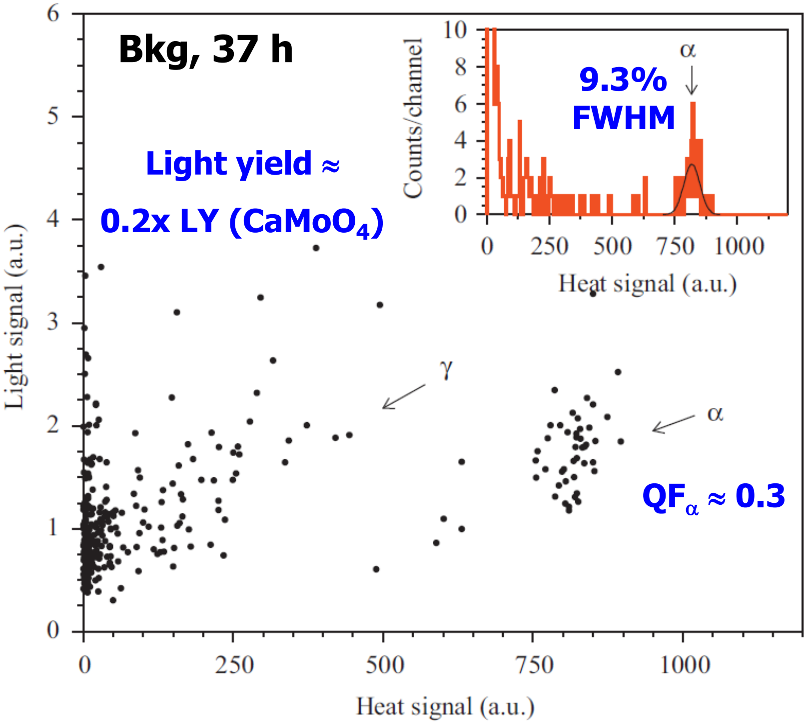
- **Li_2MoO_4 crystal (34 g, ∅22×33 mm)**
- **HPGe detector** at LNGS (Assergi, Italy)

Chain	Nuclide	Activity (mBq/kg)
^{232}Th	^{228}Ac	≤ 32
	^{208}Tl	≤ 12
^{238}U	^{214}Bi	≤ 21
	^{40}K	170(80)
	^{60}Co	≤ 8
	^{137}Cs	≤ 4

Nucl. Instrum. Meth. A 607 (2009) 573

Bolometric test @LNGS

- **Li_2MoO_4 crystal (1.3 g, ∅25×0.9 mm)**
- **CUORE R&D set-up** at LNGS (Assergi, Italy)

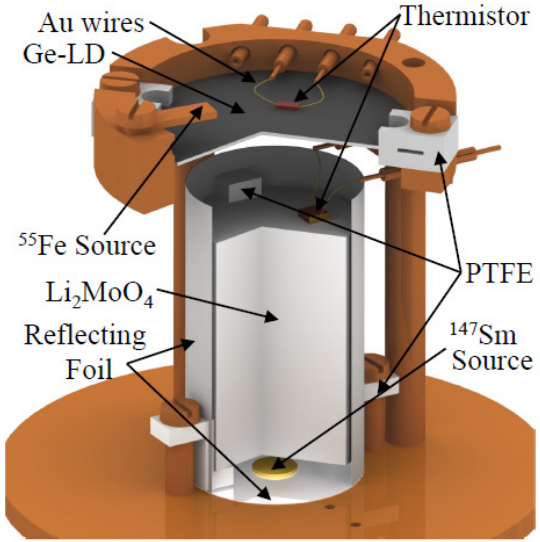


Nucl. Instrum. Meth. A 613 (2010) 54

2013: Further study of a larger Li_2MoO_4 (34 g)

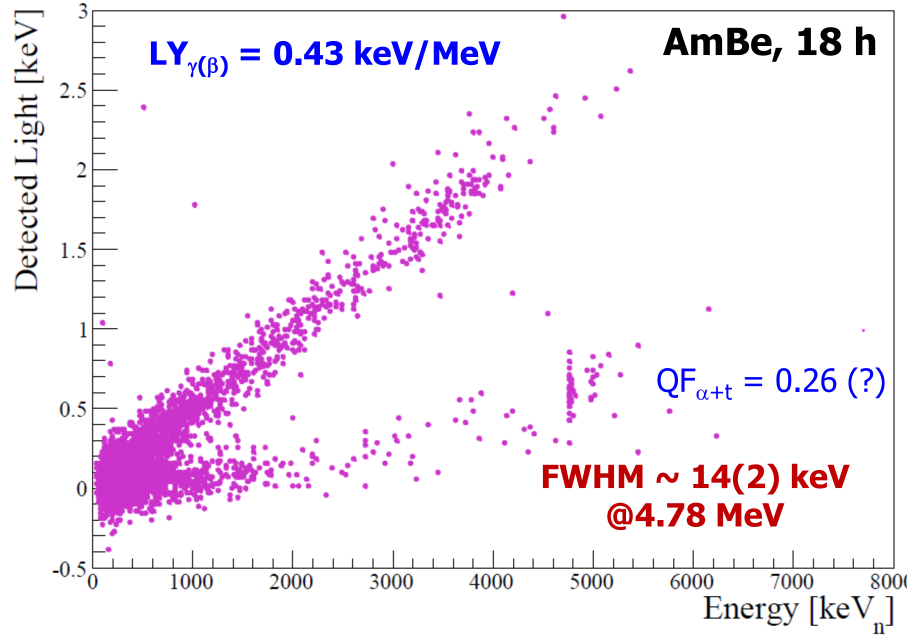
Bolometric test @LNGS

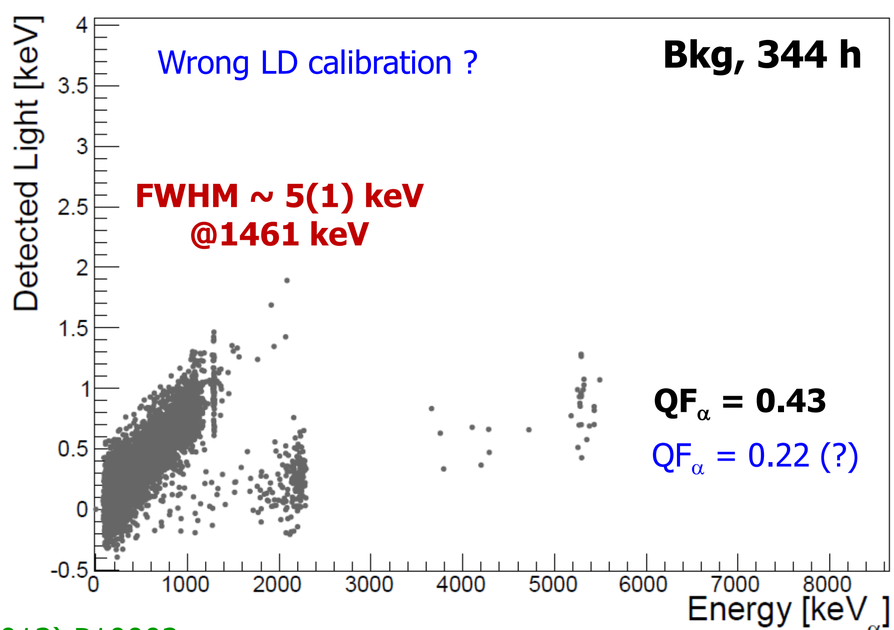
- **Li_2MoO_4 crystal (34 g, ∅22×33 mm)**
- **CUORE R&D set-up** at LNGS (Assergi, Italy)



Chain	Nuclide	Activity (mBq/kg)
^{232}Th	^{232}Th	≤ 0.094
^{238}U	^{238}U	≤ 21
	^{40}K	170(80) *

* - by HPGe

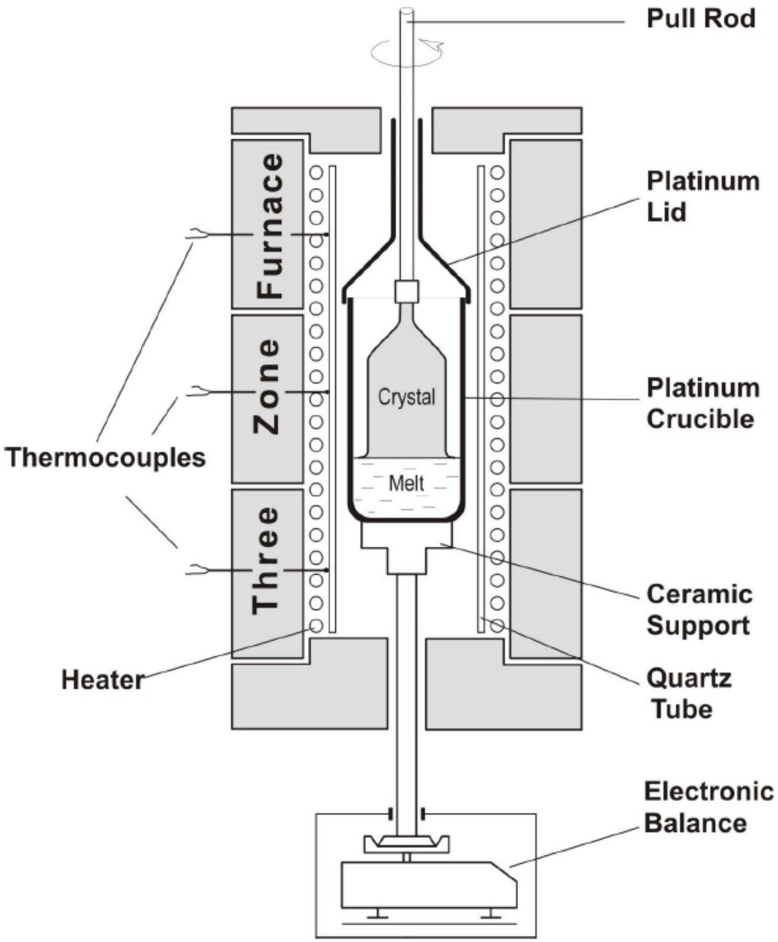




JINST 08 (2013) P10002

Advanced Li_2MoO_4 scintillating bolometers:
(based on crystals grown by the LTG Cz method)
from LUMINEU to CUPID

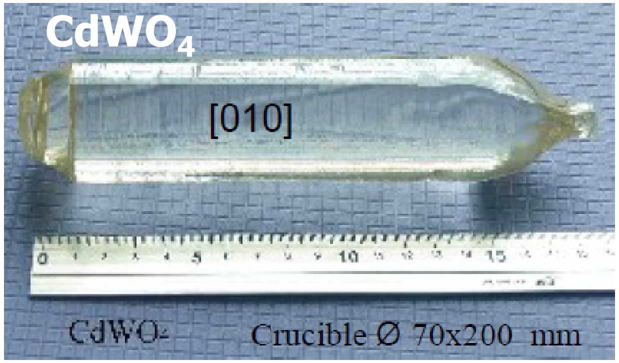
Low-temperature-gradient Czochralski technique

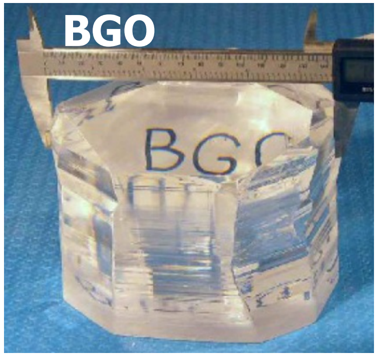


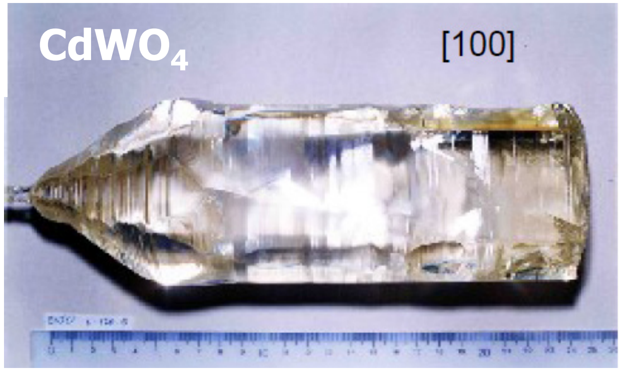
LTG Czochralski method
Nikolaev Institute of Inorganic Chemistry
(NIIC, Novosibirsk, Russia)
J. Cryst. Growth 229 (2001) 305

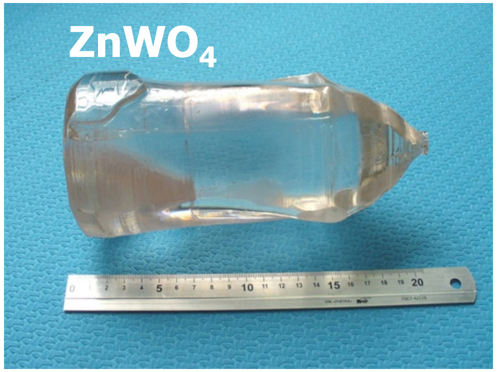
- **Low temperature gradients** (~ 1.0 K/cm)
- **Crystal inside a crucible during the process**
- **Weighing control at all the stages**
- **Closed crucible during the process**

  ⇒ losses < 1% of a charge
- **Crystal's yield is up to 90% of a charge**
- **Crystal's diameter is up to 0.8x ∅ of a crucible**







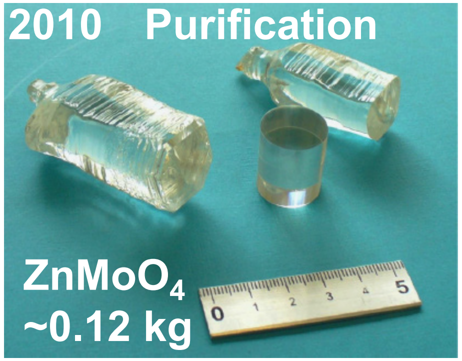


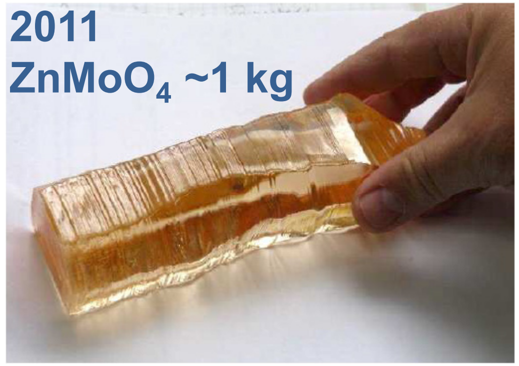
R&D of ZMO & LMO crystals

LUMINEU ISOTTA ISOTope Trace Analysis

Precursors grown by LTG Cz @ NIIC

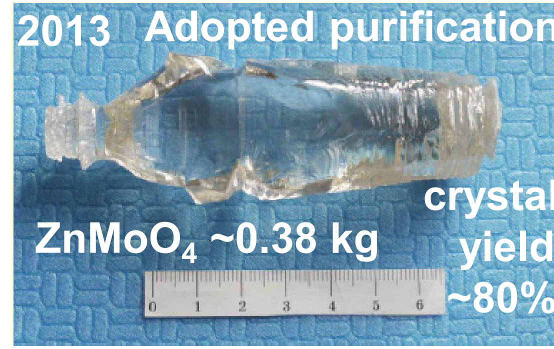
Funct. Mat. 17(2010)504; NIMA 729(2013)856; Crystallogr. Rep. 59(2014)288





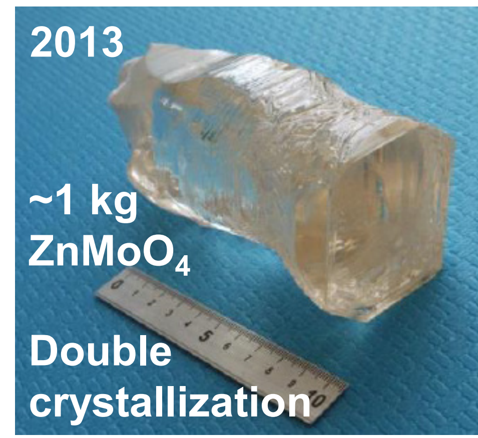
First LUMINEU crystals - ZMO

JINST 9(2014)P06004



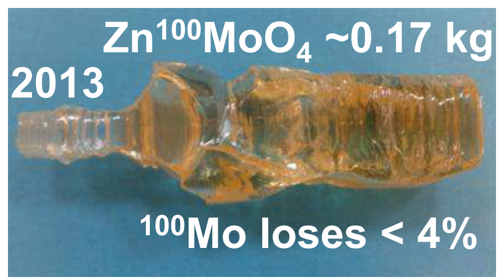
First large ZMO

JINST 10 (2015) P05007



First enriched ZMO

EPJC 74(2014)3133



W-doped ZMO

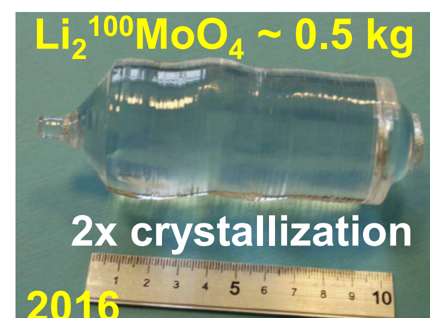
Opt. Mat. 49(2015)67

First large LMO

Astropart. Phys. 72(2016)38

First large enriched ZMO & LMO

AIP Conf. Proc. 1672(2015)040003; EPJC 77(2017)785



LUMINEU: $Zn^{100}MoO_4$ scintillating bolometers

Agence Nationale de la Recherche ANR

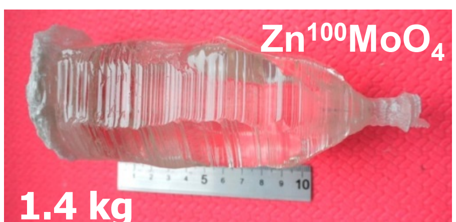
LUMINEU ββ 0ν

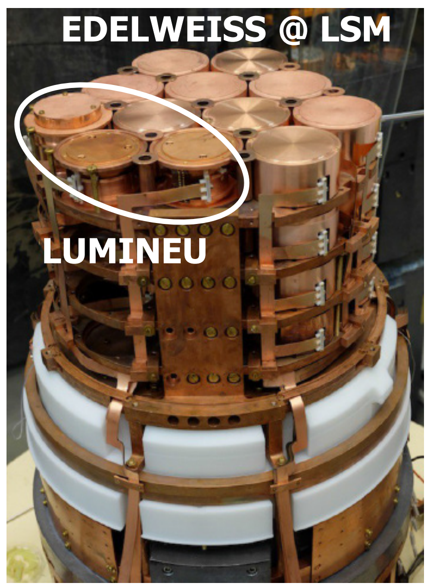
2012-2016

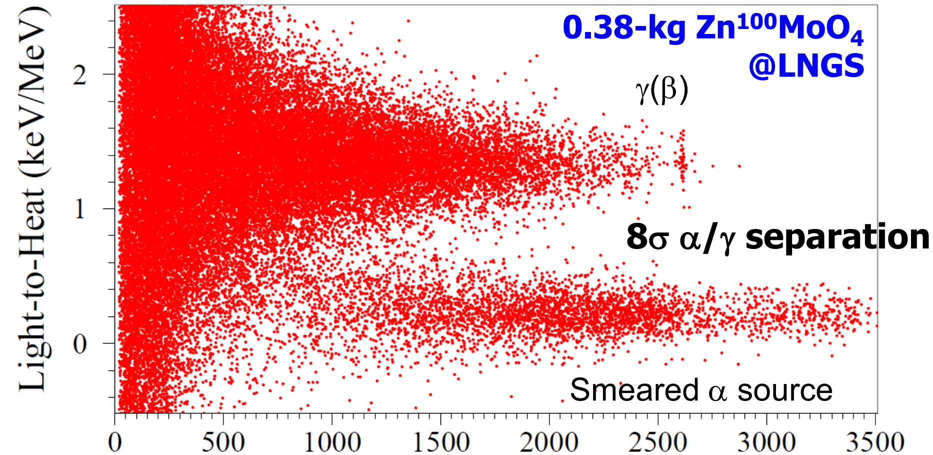
http://lumineu.in2p3.fr

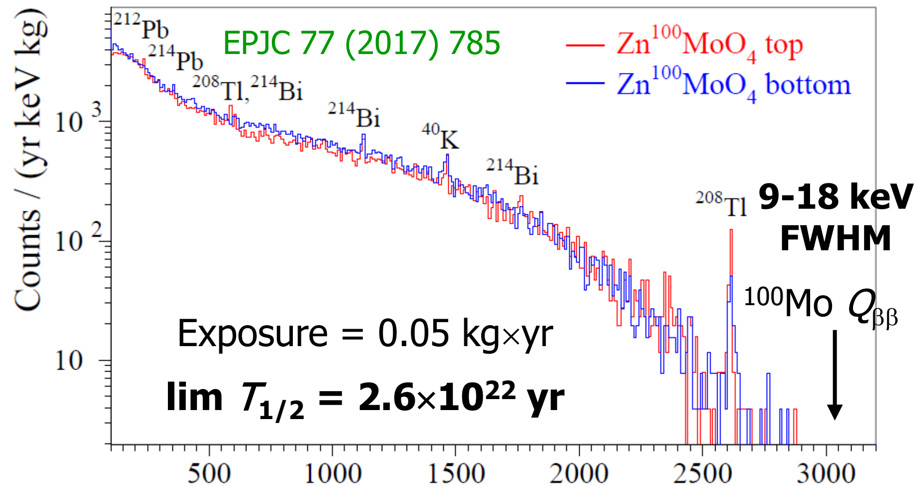
Key developments

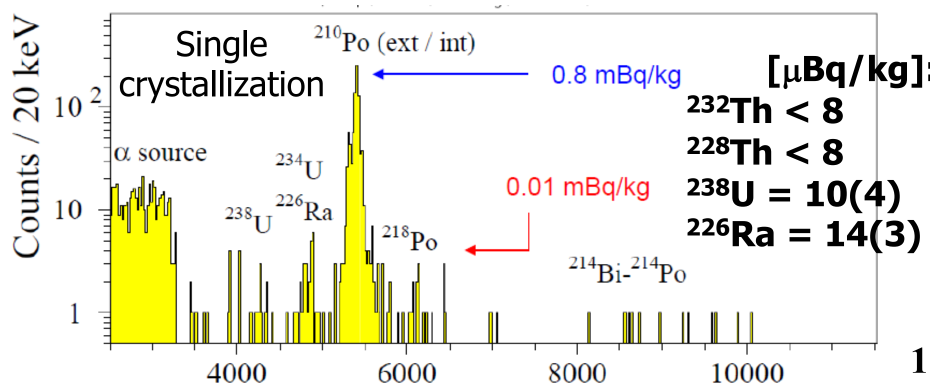
- ✓ **^{100}Mo purification** — JINST 9 (2014) P06004
- ✓ First $Zn^{100}MoO_4$ — EPJC 74 (2014) 3133
- ✓ Advanced $ZnMoO_4$ — JINST 10 (2015) P05007
- ✓ **MC of 48x $Zn^{100}MoO_4$** — AIPCP 1686 (2015) 020007
- ✓ NTD-Ge development — JLTP 184 (2016) 292
- ✓ **Advanced $Zn^{100}MoO_4$** — EPJC 77 (2017) 785
  - Large mass & high crystal yield (>80%)
  - Good optical quality & scintillating properties
  - Low irrecoverable losses of ^{100}Mo (~4%)
  - Good performance
  - High radiopurity







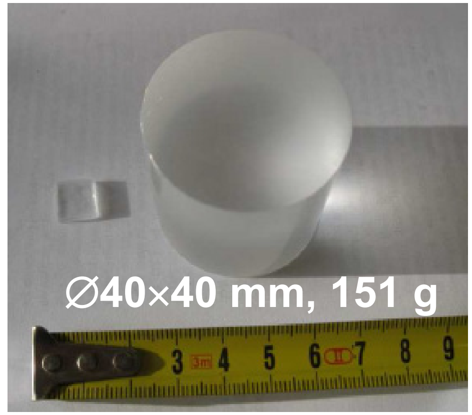


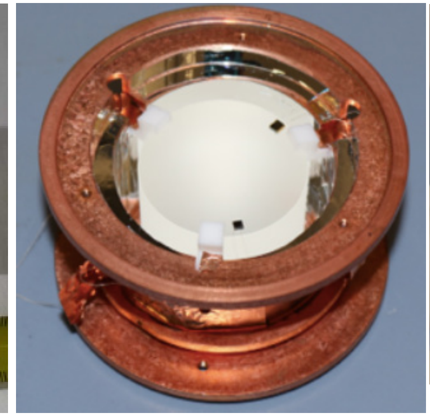


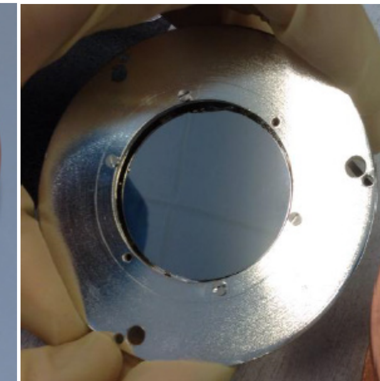
[μBq/kg]:
^{232}Th < 8
^{228}Th < 8
^{238}U = 10(4)
^{226}Ra = 14(3)

2014: Advanced Li_2MoO_4 scintillating bolometer

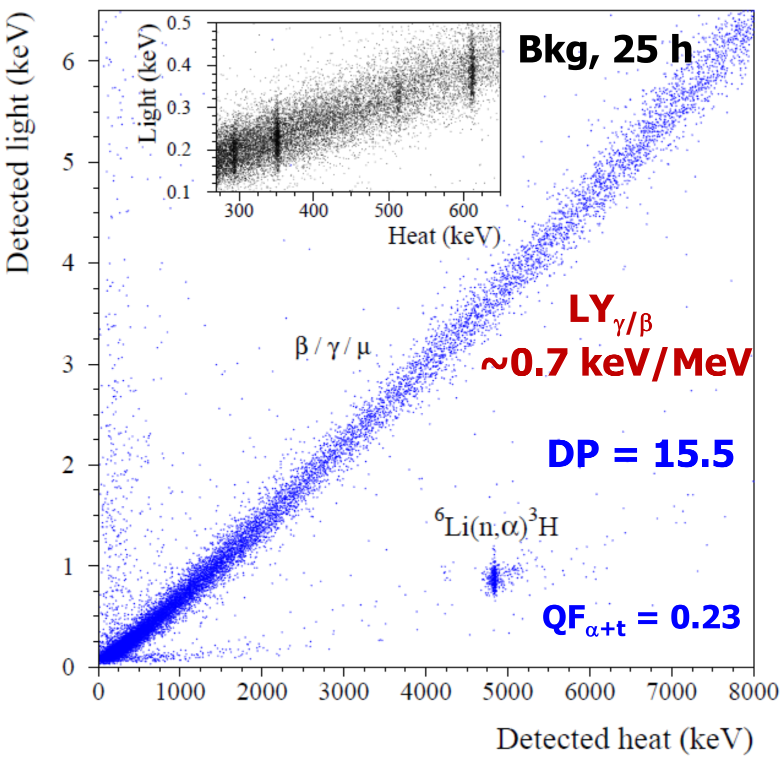
Crystal production @NIIC: highly purified MoO_3 + commercial Li_2CO_3 (4N purity grade) + LTG Cz growth

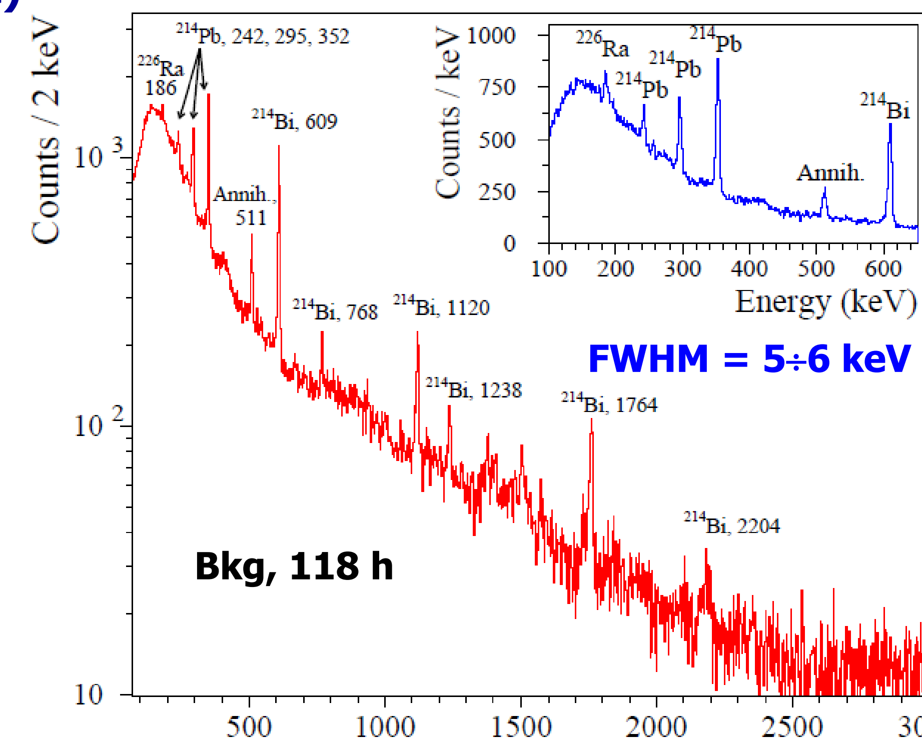






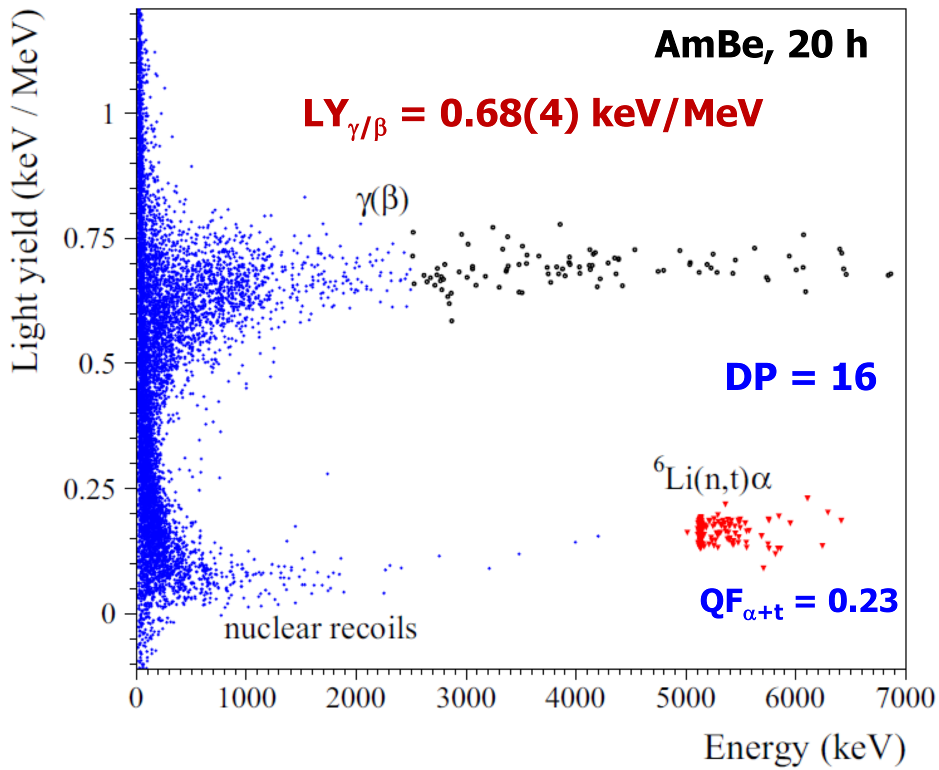
Bolometric test @CSNSM (Orsay, France)

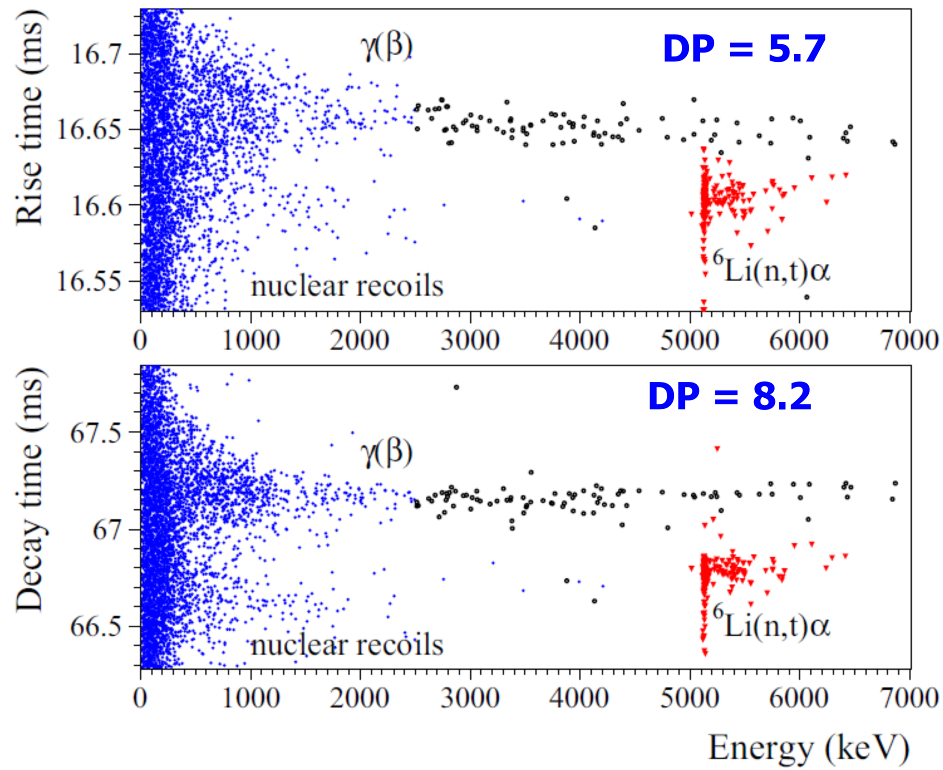


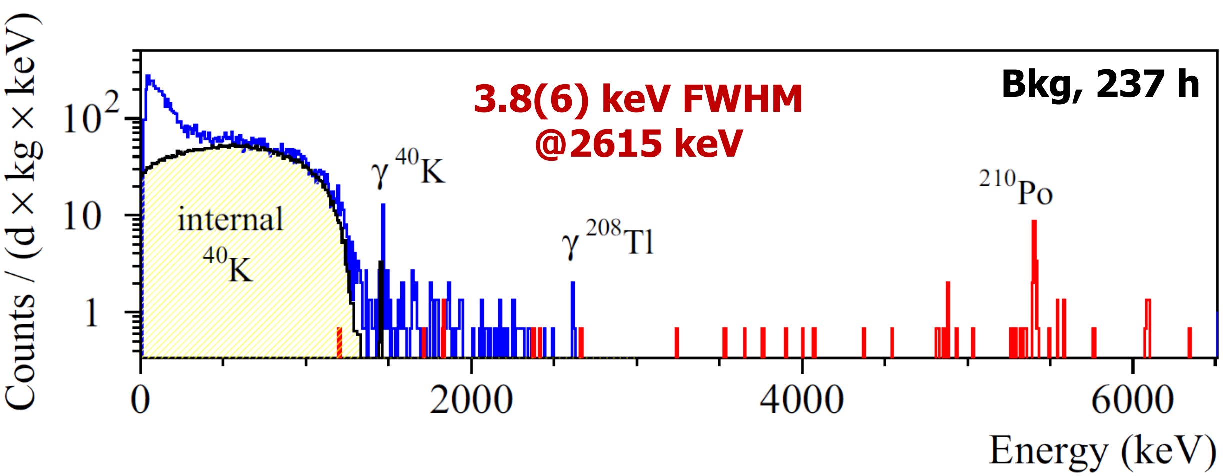


Astropart. Phys. 72 (2016) 38

2014: Advanced Li_2MoO_4 scint. bolometer test @LNGS







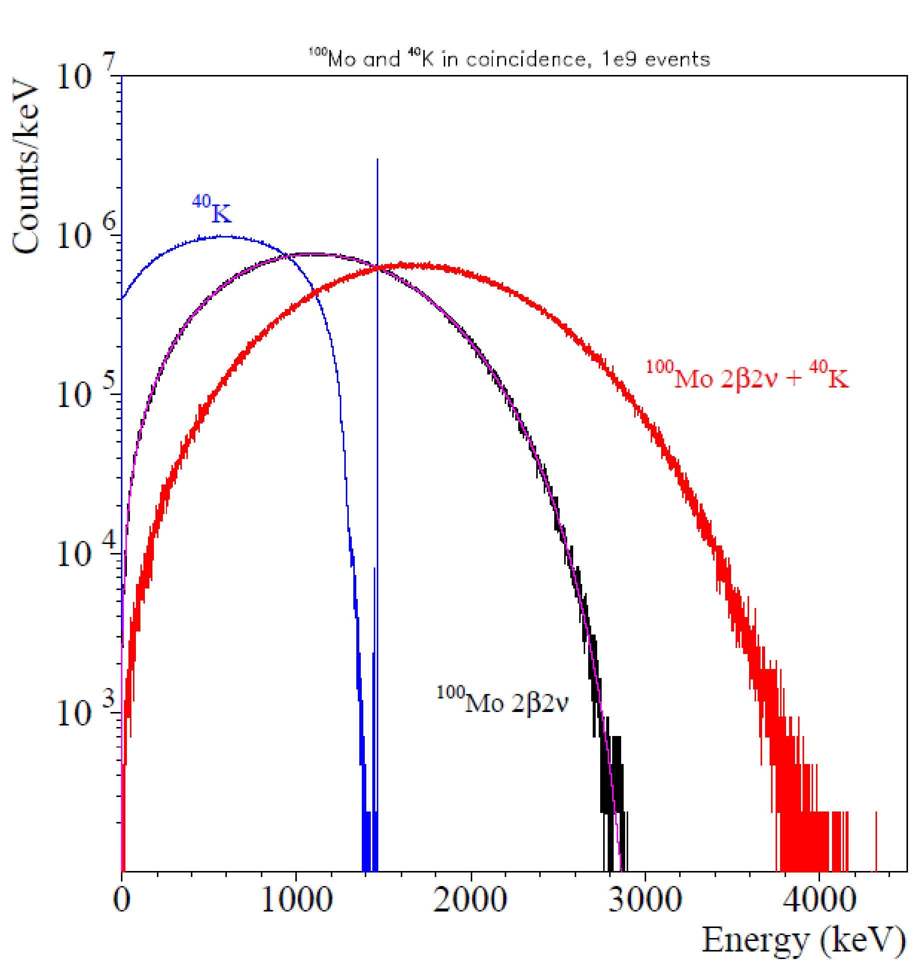
Chain	Nuclide	Activity (mBq/kg)
^{232}Th	^{232}Th	≤ 0.018
^{238}U	^{238}U	≤ 0.018
	^{226}Ra	≤ 0.044
	^{221}Po	0.14(3)
	^{40}K	62(2)

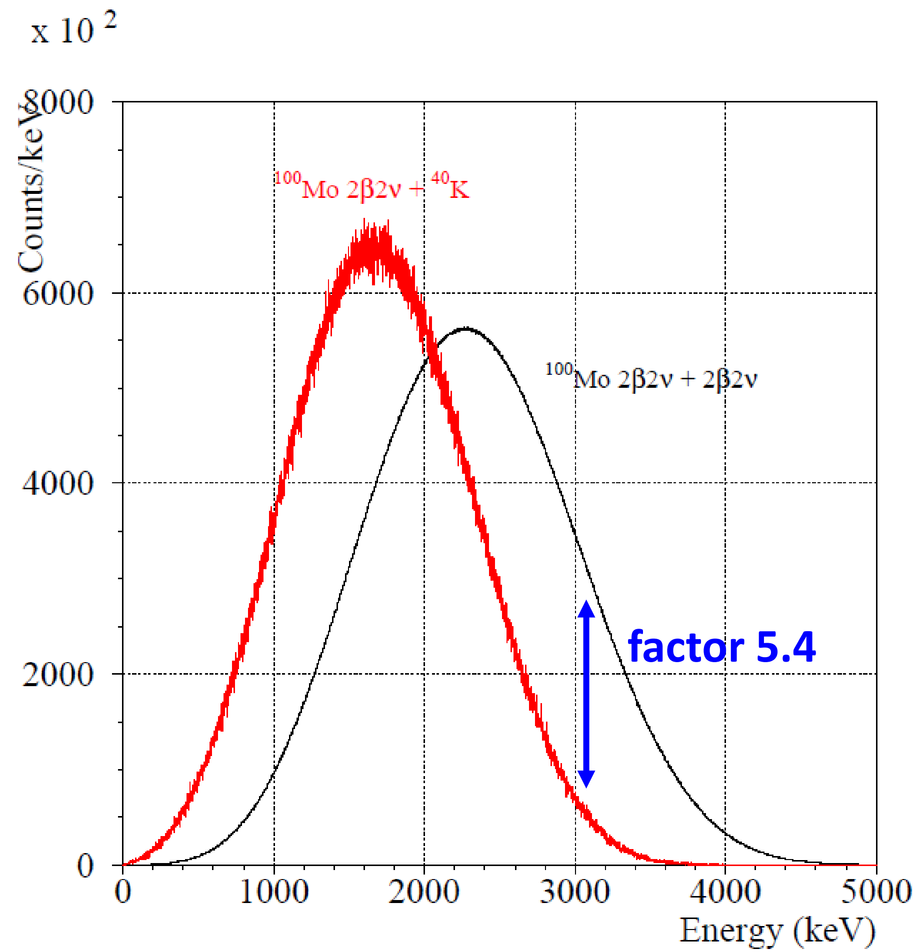
Eur. Phys. J. C 77 (2017) 785

Pile-up problem due to high activity of ^{40}K

Random coincidences generation:

- **Li_2MoO_4 crystal (∅50×40 mm)**
- **10^9 events of ^{40}K and $2\nu2\beta$ of ^{100}Mo**





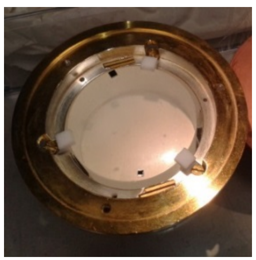
Bkg @ ROI: ^{40}K+$2\nu2\beta$ ~ $2\nu2\beta$ pile-ups ⇒ ^{40}K ~ 57 mBq/kg in $Li_2{}^{100}MoO_4$ ∅50×40 mm

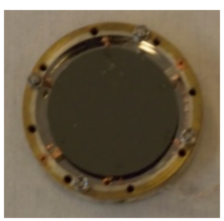
Credit to V.I. Tretyak

2015: R&D of radiopure Li_2MoO_4 crystals

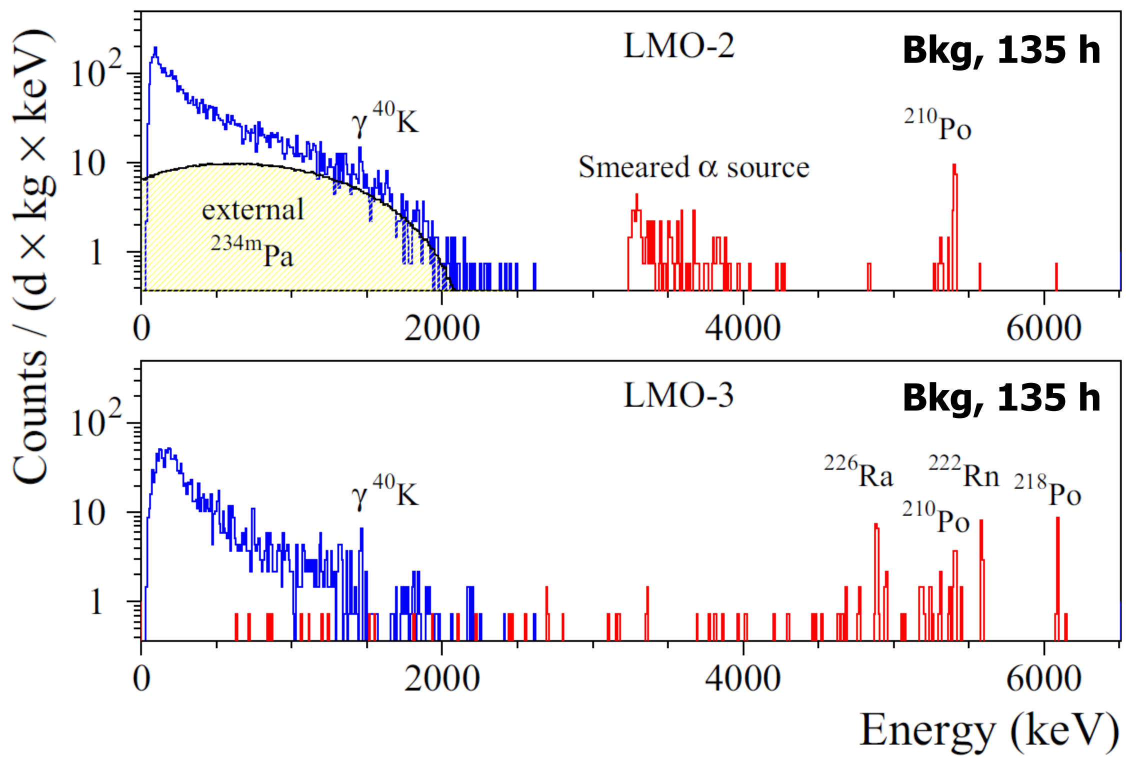
- **Optimization of the LMO growth @NIIC** J. Mat. Sci. Eng. 7 (2017) 63
- **Li_2CO_3 powder screening @LNGS** Eur. Phys. J. C 77 (2017) 785
- **Bolometric tests of large volume LMOs @LNGS**

	Activity (mBq/kg)					
	Powder NRMP	**LMO-1** Single cr.	**LMO-2** Double cr.	**Powder** Alpha Aesar	**LMO-3** Single cr.	**Powder** Sigma-Aldrich
^{228}Th	≤ 3.7	≤ 0.023	≤ 0.026	**12(4)**	**≤ 0.024**	**13(4)**
^{226}Ra	≤ 3.3	≤ 0.051	≤ 0.044	**705(30)**	**0.13(2)**	**53(6)**
^{40}K	≤ 42	**62(2)**	**≤ 12**	≤ 42	≤ 3.3	**210(70)**



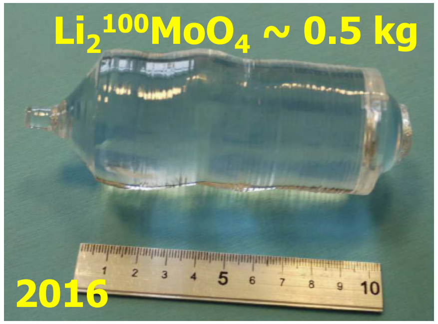


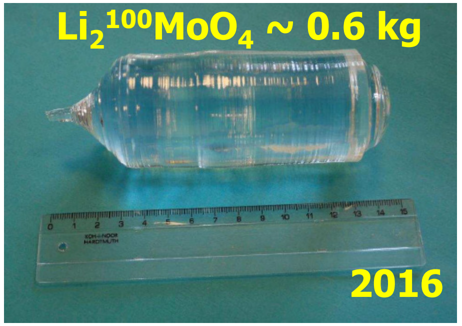
Li_2MoO_4 ∅50×40 mm	LMO-2 241 g	LMO-3 242 g
FWHM [keV] @ 2615 keV	**6 ± 1**	**5 ± 1**
$LY_{\gamma(\beta)}$ [keV/MeV]	**1.0**	0.12*
$DP_{\alpha/\gamma(\beta)}$	**9**	**11**

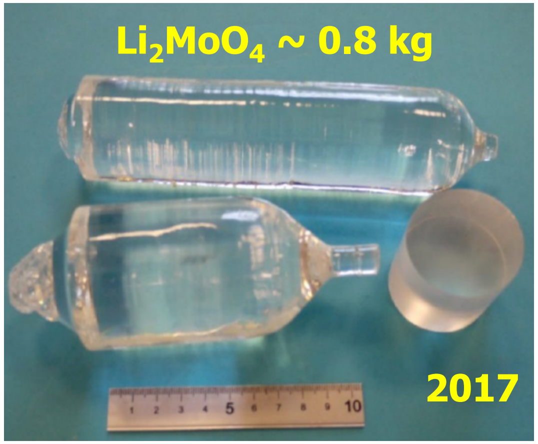


LUMINEU protocol of the $Li_2{}^{100}MoO_4$ production

- **Purification of ^{100}Mo-enriched MoO_3**
  sublimation in vacuum
  recrystallization from aqueous solutions
- **Control of ^{40}K content in $Li_2{}^{100}MoO_4$**
  ultra-pure Li_2CO_3 powder (+ R&D of Li_2CO_3 purification)
  LMO growth by double crystallization
- **Low-temperature-gradient Cz growth**
  possible size: ∅6 cm; 14 cm length
- **Cut of scintillation elements**
- **Extraction of $^{100}MoO_3$ from residues**







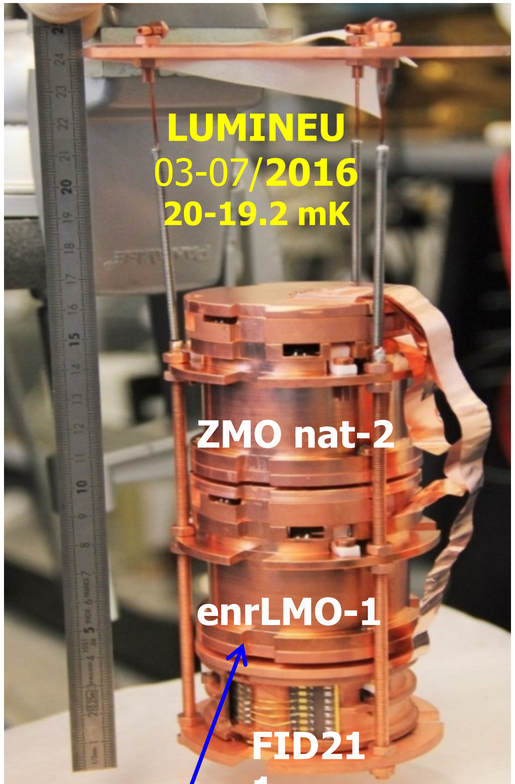
Eur. Phys. J. C 77 (2017) 785
J. Mat. Sci. Eng. 7 (2017) 63
AIP Conf. Proc. 1894 (2017) 020017

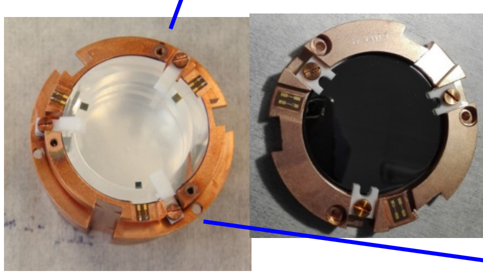
✓ **Batch production of large mass $Li_2{}^{100}MoO_4$ scintillation elements**
high optical quality crystal scintillators
high crystal yield (~80-85% of charge)
low irrecoverable losses of ^{100}Mo (~3%)

arXiv:1909.02994

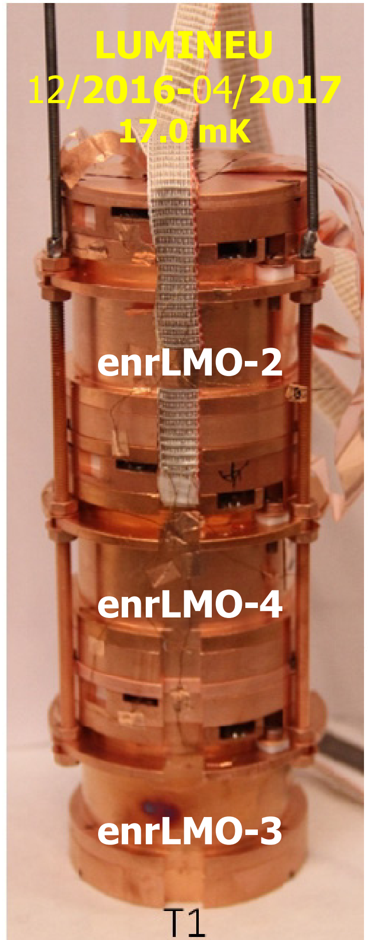
arXiv:1906.10233

2016-2017: Tests of $Li_2{}^{100}MoO_4$ scint. bolometers

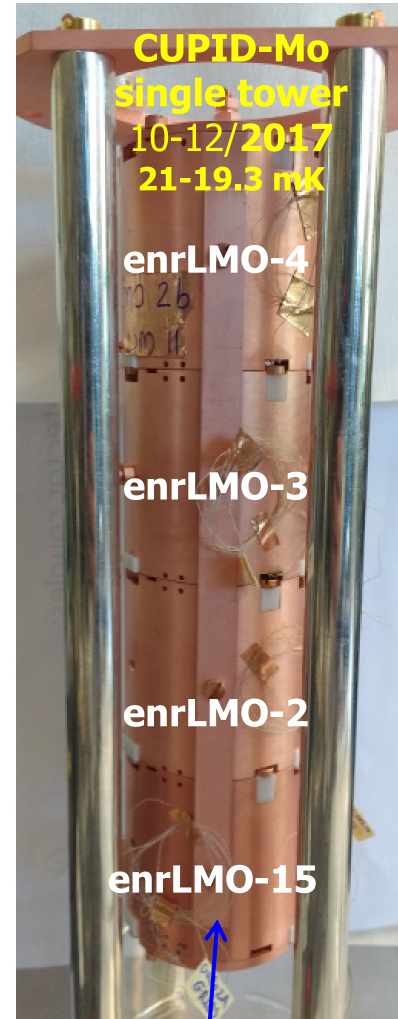




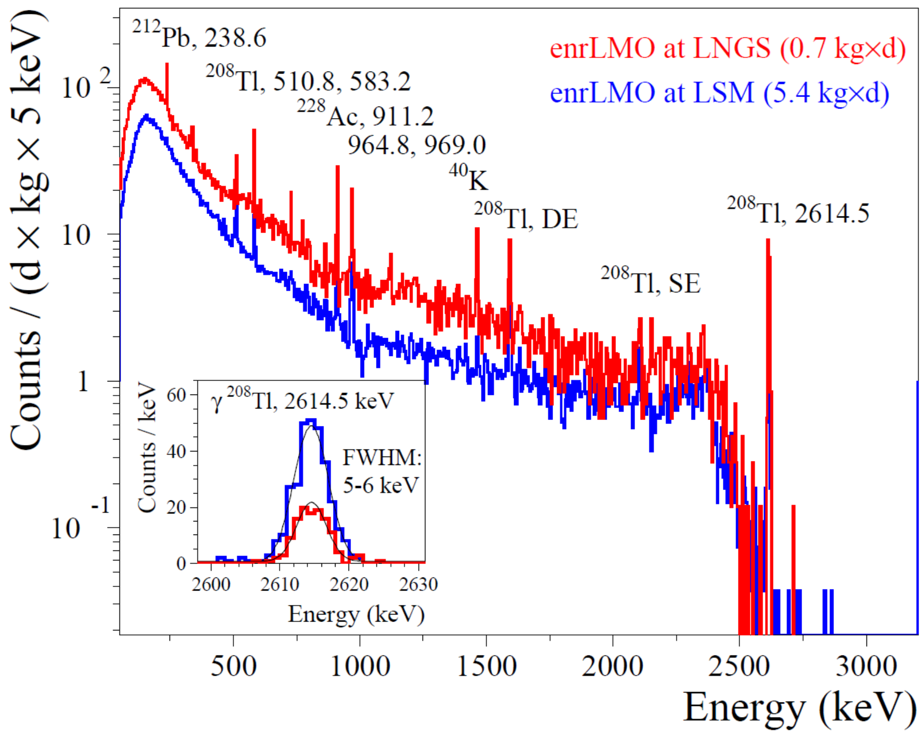
+ enrLMO-2
test @LNGS
05/2016
12 mK

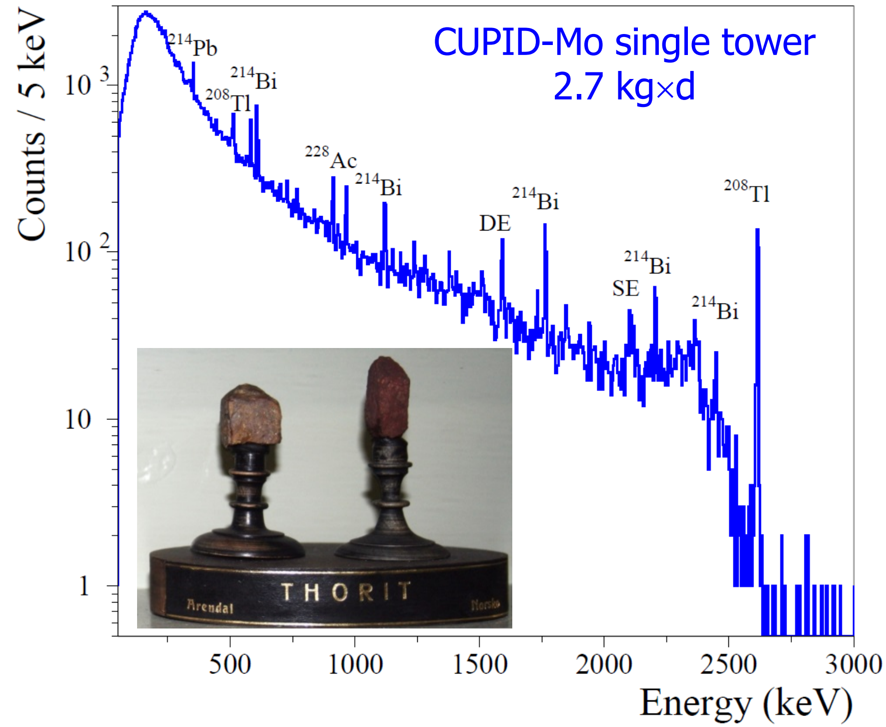


+ enrLMO-1
in tower T2

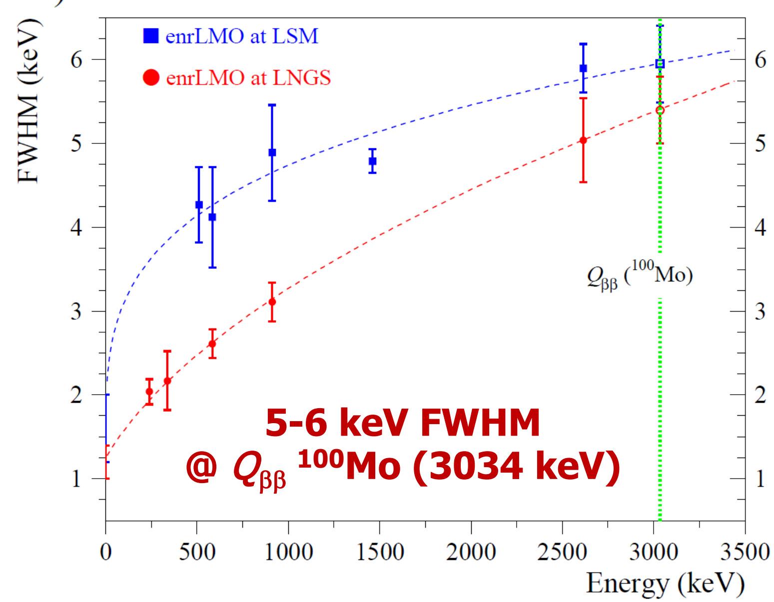


Energy resolution of $Li_2{}^{100}MoO_4$ bolometers





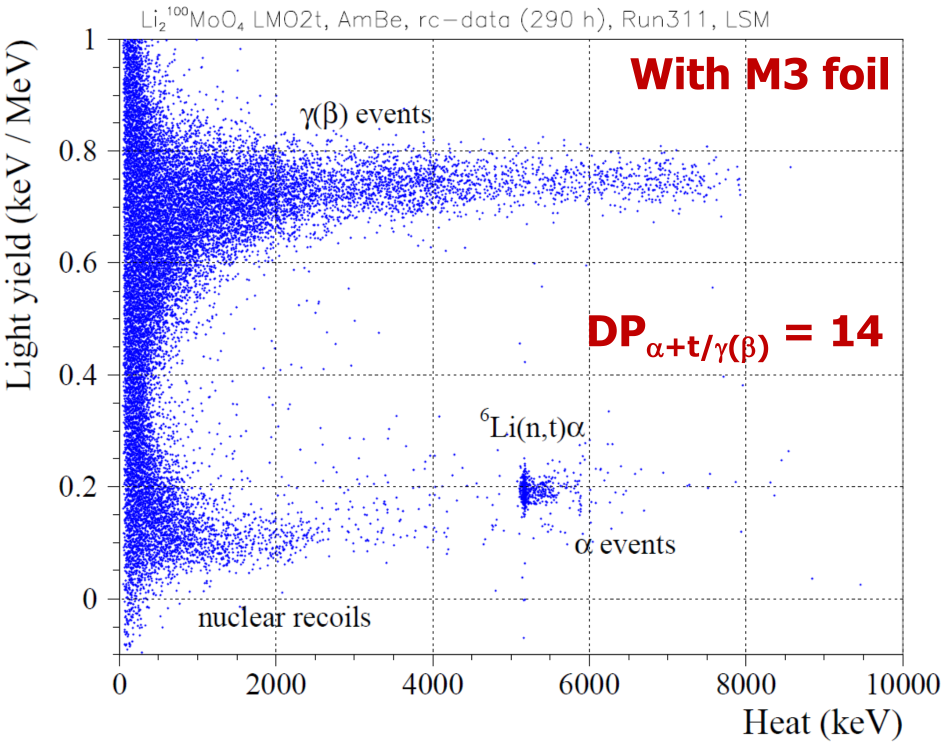
$Li_2{}^{100}MoO_4$ tests	FWHM (keV) @ 2615 keV
LUMINEU single module	5.0(5)-6.3(6)
LUMINEU 4-detector array	4.2(5)-6.4(6)
CUPID-Mo 4-detector tower	5.6(4)-7.1(8)



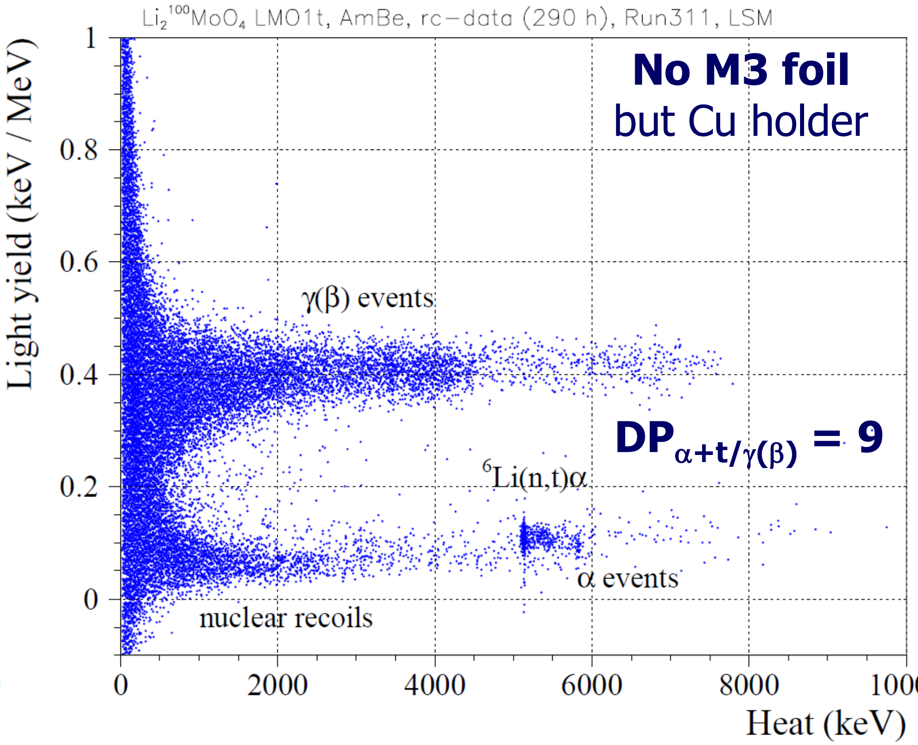
Eur. Phys. J. C 77 (2017) 785
AIP Conf. Proc. 1894 (2017) 020017

Particle ID with $Li_2{}^{100}MoO_4$ scintillating bolometers

enrLMO-3, AmBe (290 h)



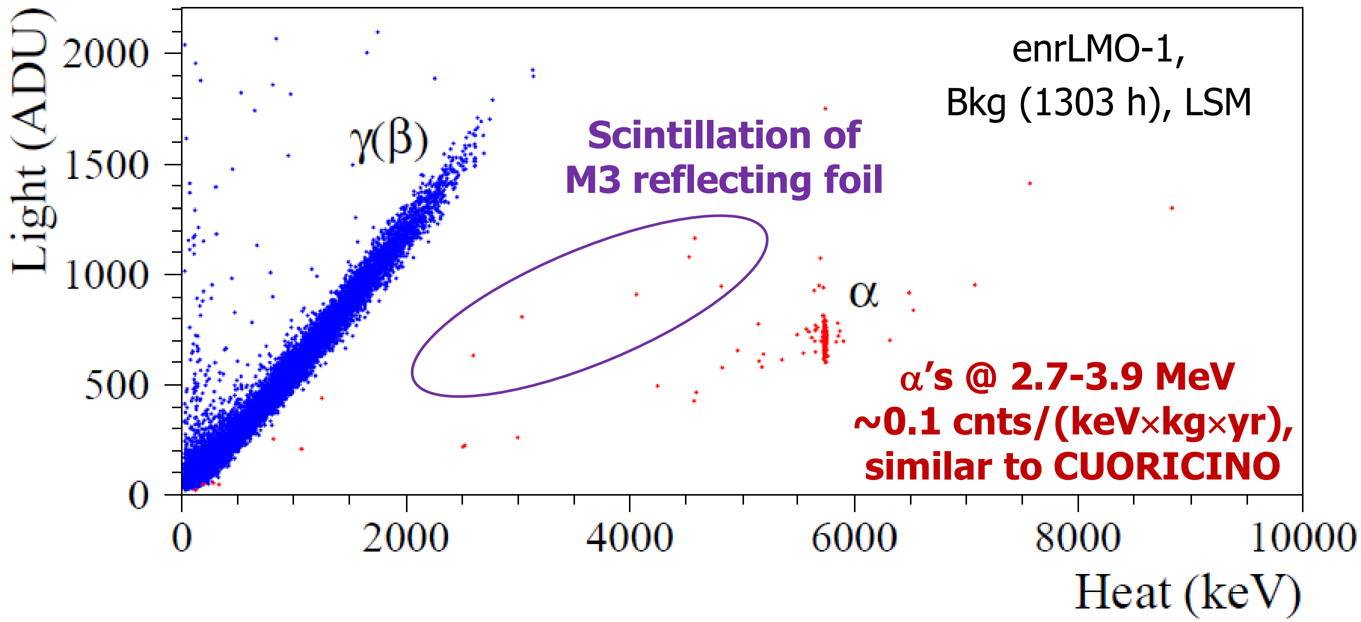
enrLMO-1, AmBe (290 h)

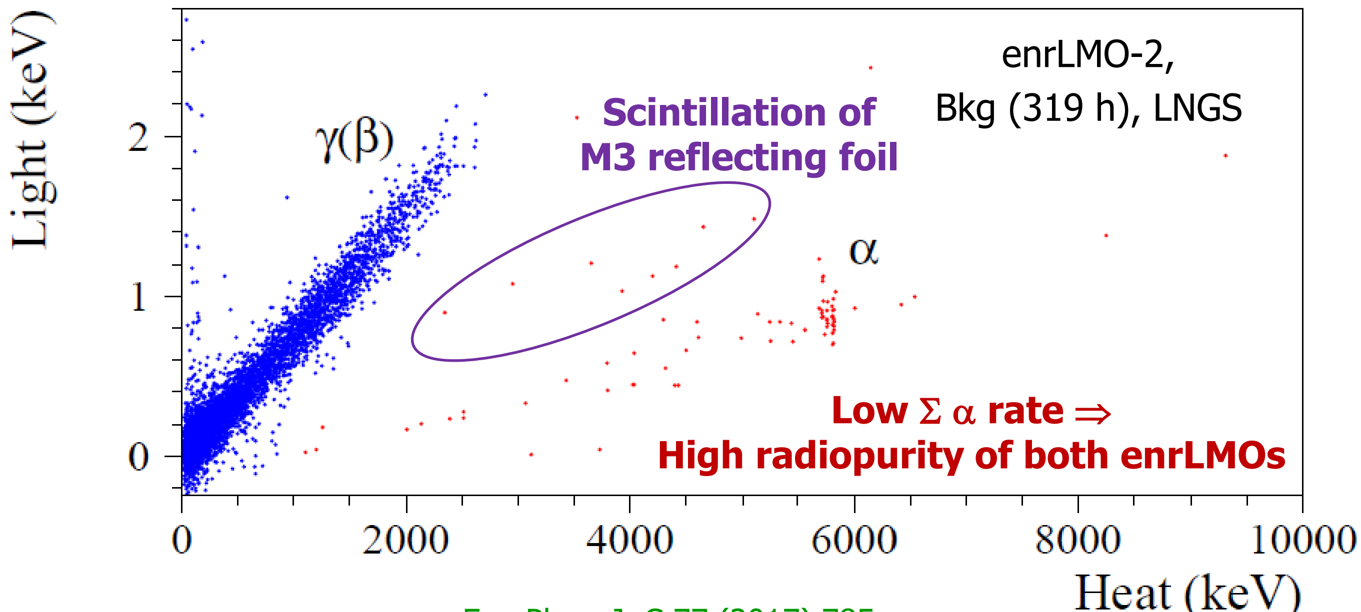


Light collection conditions	LD coating, M3 reflector	LD coating, no M3 reflector	no LD coating, no M3 reflector
LY (keV/MeV) @ γ(β)	0.73-0.77	0.38-0.41	~0.2
DP @ α+t/γ	14	9	n.a.

Eur. Phys. J. C 77 (2017) 785
AIP Conf. Proc. 1894 (2017) 020017

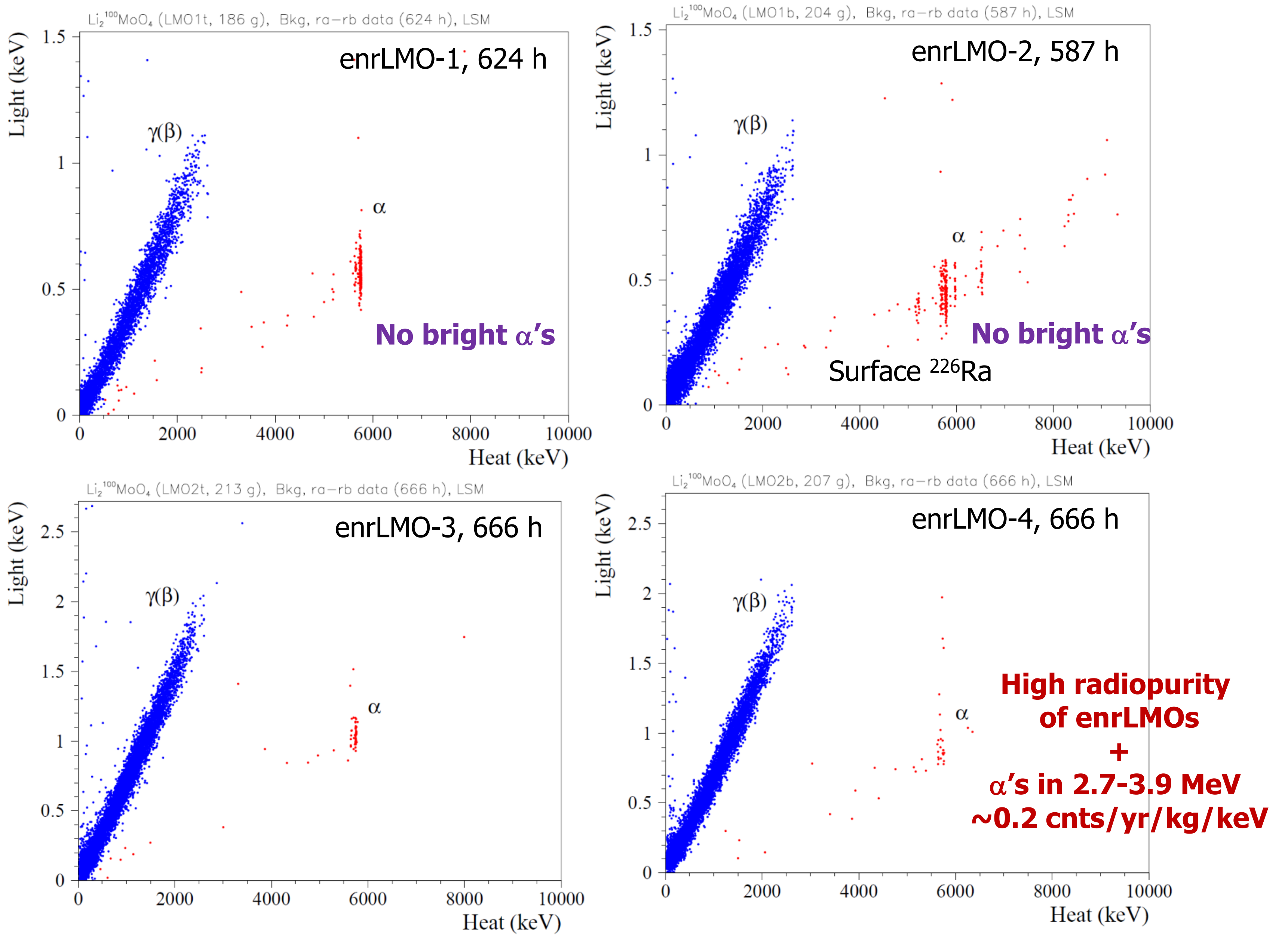
First background measurements with $Li_2{}^{100}MoO_4$



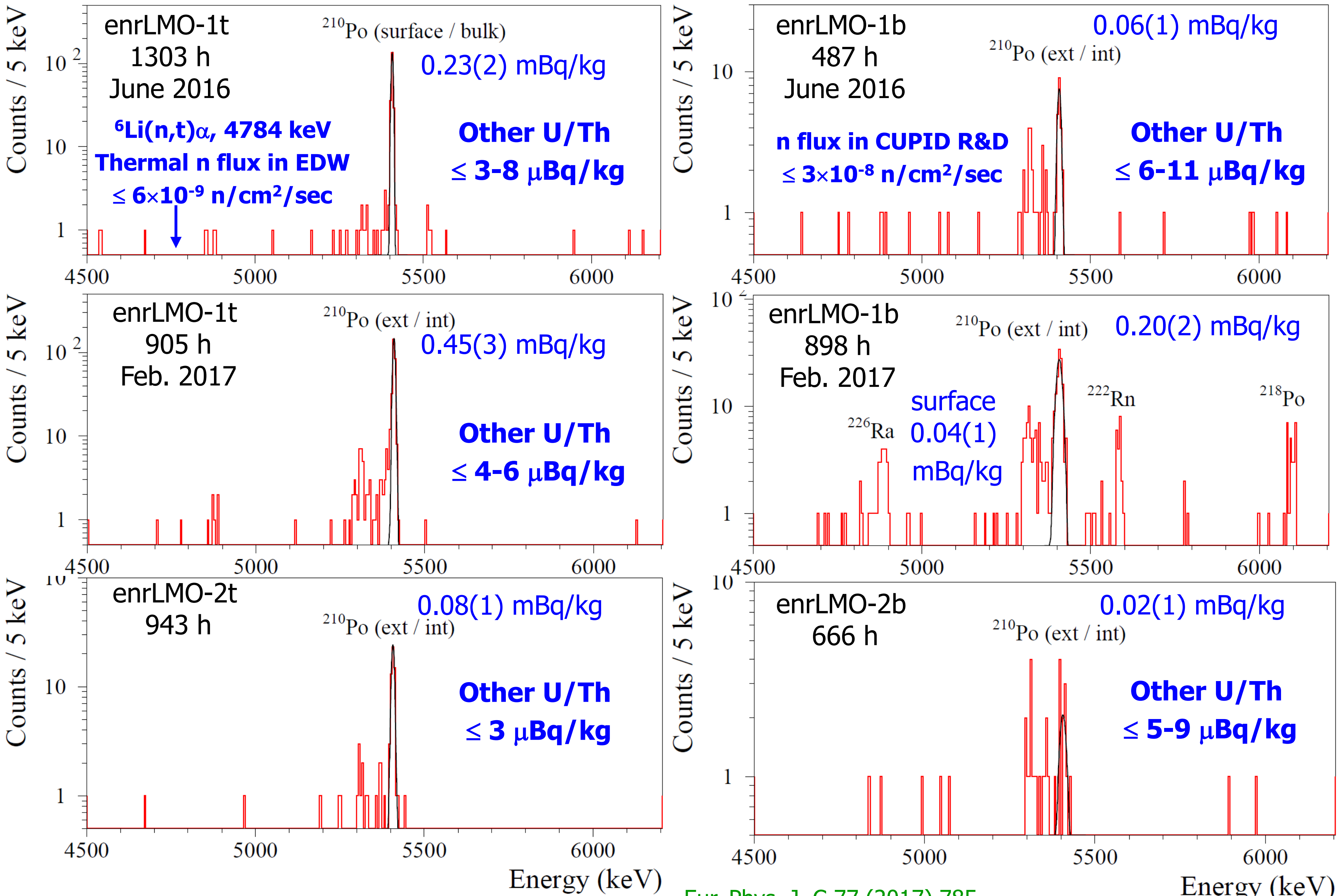


Eur. Phys. J. C 77 (2017) 785

First measurements with 4-detectors $Li_2{}^{100}MoO_4$ array

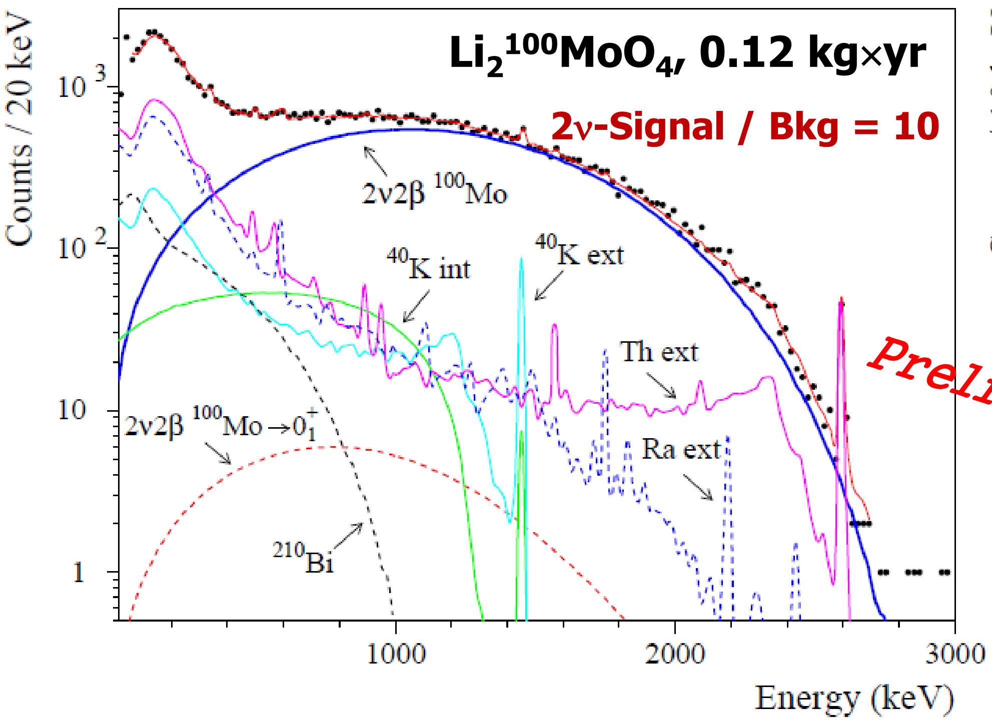


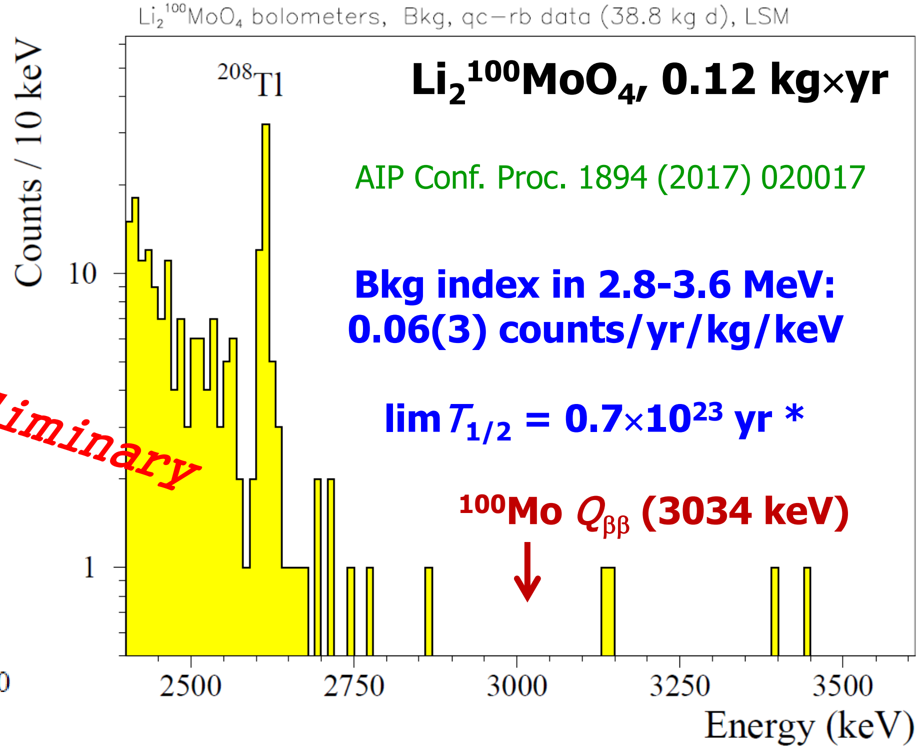
Radiopurity of $Li_2{}^{100}MoO_4$ detectors



Eur. Phys. J. C 77 (2017) 785
AIP Conf. Proc. 1894 (2017) 020017

LUMINEU search for 2β decay of ^{100}Mo with Li_2MoO_4





- **Stat. error = 0.8%** (~36000 2ν2β decays)
- **Syst. error ~ few %** (preliminary)

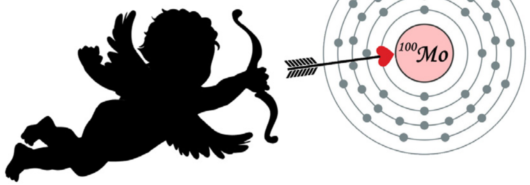
*** NEMO-3 (34.3 kg×yr ^{100}Mo):**
$T_{1/2} \geq 1.1\times10^{24}$ yr PRD 92, 072011 (2015)

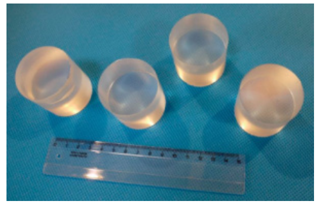
2ν2β $T_{1/2}$ [10^{18} yr]	^{100}Mo exposure	Experiment	Ref.
7.11 ± 0.02(stat) ± 0.54(syst)	7.37 kg×yr	NEMO-3	PRL 95, 182302 (2005)
6.90 ± 0.15(stat) ± 0.37(syst)	0.02 kg×yr	LUMINEU	EPJC 77, 785 (2017)
6.81 ± 0.01(stat) ± 0.46(syst)	34.7 kg×yr	NEMO-3	L. Simard @Neutrino 2018
6.90 ± 0.06(stat)	0.06 kg×yr	LUMINEU	D. Poda @Neutrino 2018

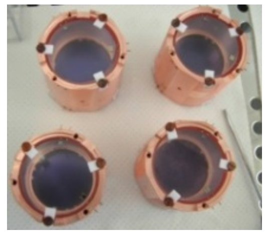
Follow ^{100}Mo 2ν2β updates: F.A. Danevich, talk @ CUPID-Mo inauguration

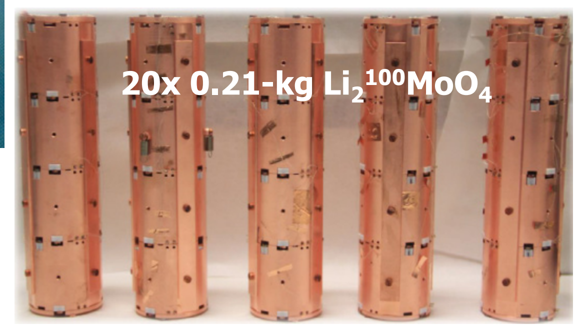
2018-present: CUPID-Mo experiment

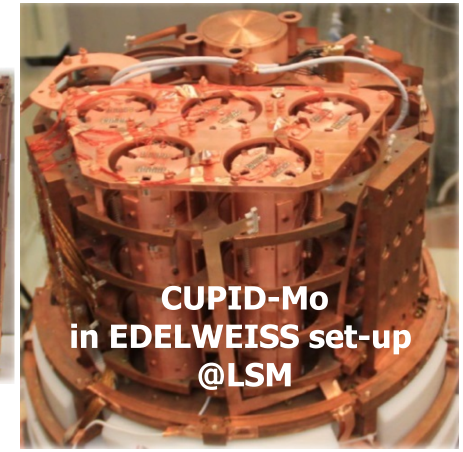
http://cupid-mo.mit.edu



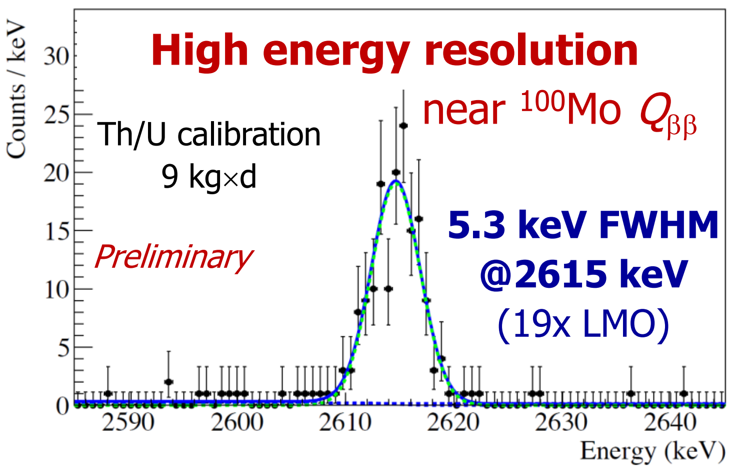


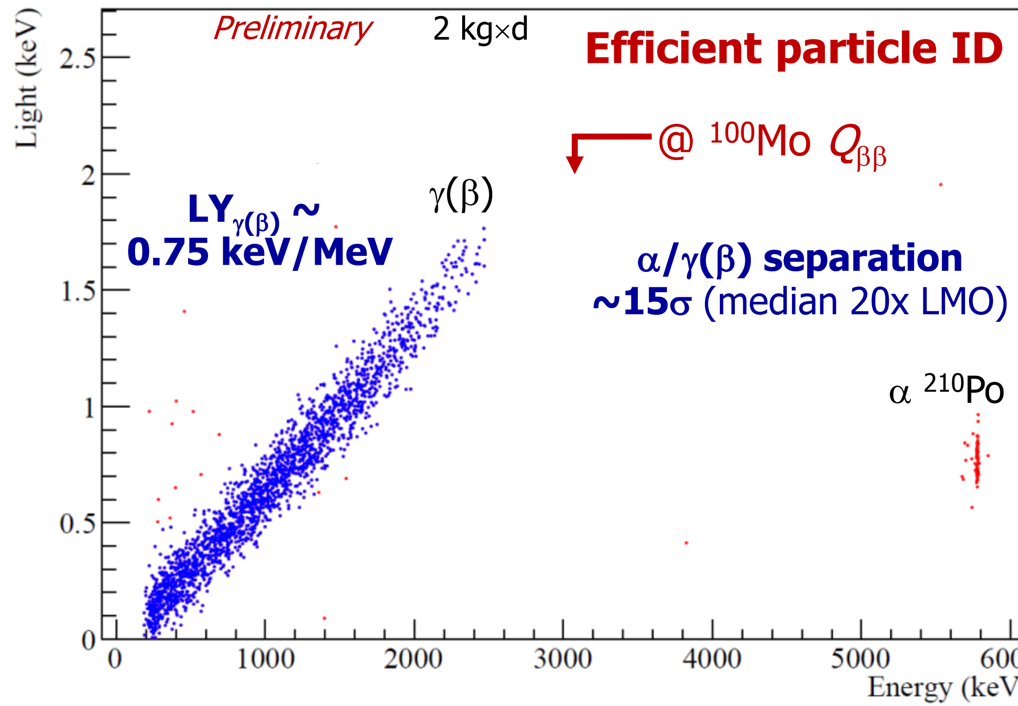






AIP Conf. Proc. 1894 (2017) 020017
A. Zolotarova @Moriond 2018
D.V. Poda @Neutrino 2018
arXiv:1909.02994
arXiv:1911.10426





D.V. Poda @LTD-18 (2019)

High crystals' radiopurity

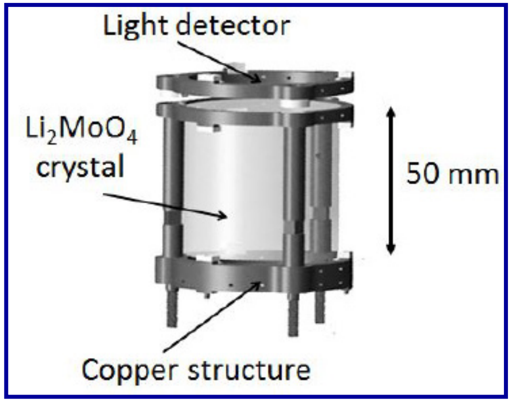
Chain	Nuclide	Activity [μBq/kg]
^{238}U	^{210}Po	~ 10^2
	^{226}Ra	< 3
^{232}Th	^{232}Th	< 1

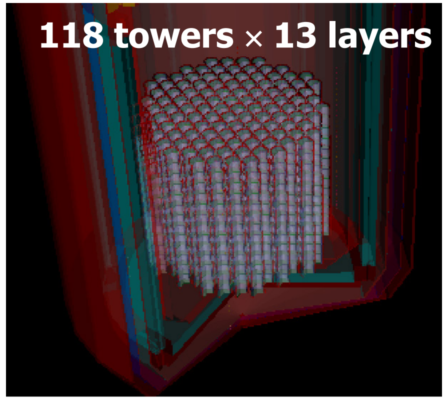
Details / updates: C. Nones, talk @ CUPID-Mo inauguration

CUPID: CUORE Upgrade with Particle IDentification

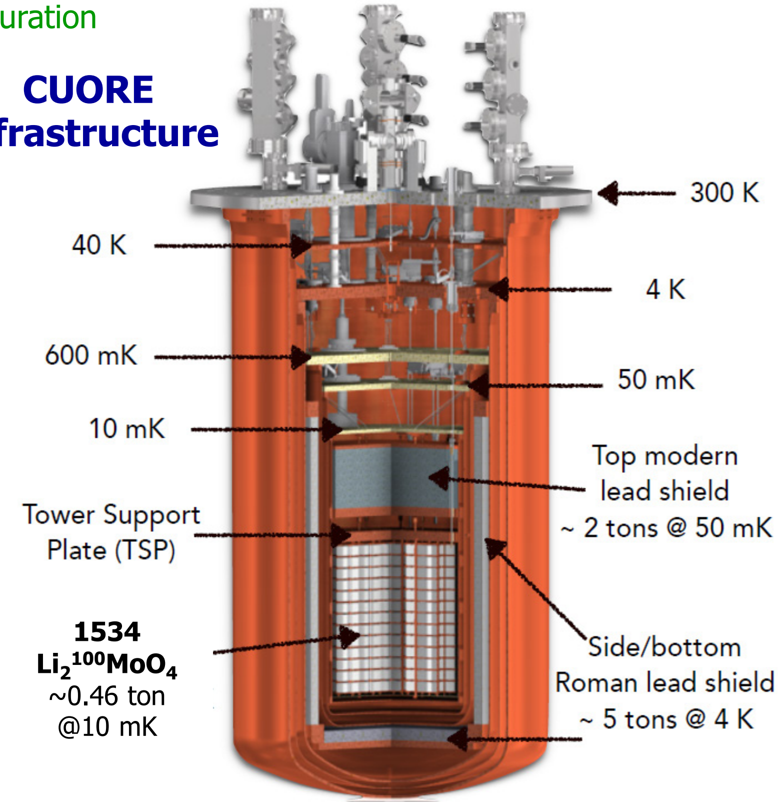
arXiv:1504.03599, arXiv:1907.09376 & M. Pavan, talk @ CUPID-Mo inauguration

^{100}Mo-enriched Li_2MoO_4 scintillating bolometers

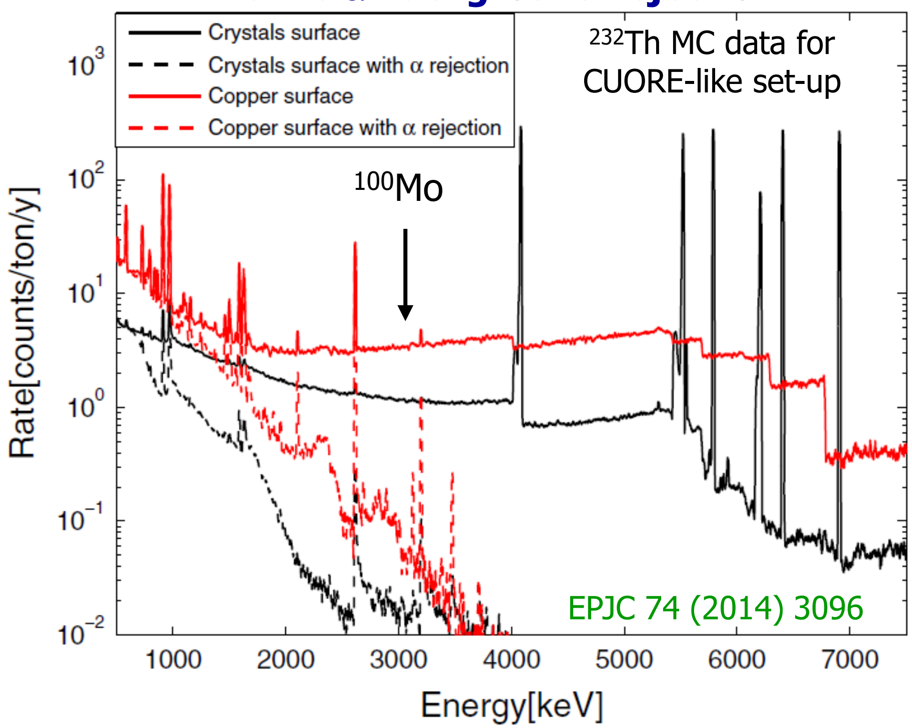


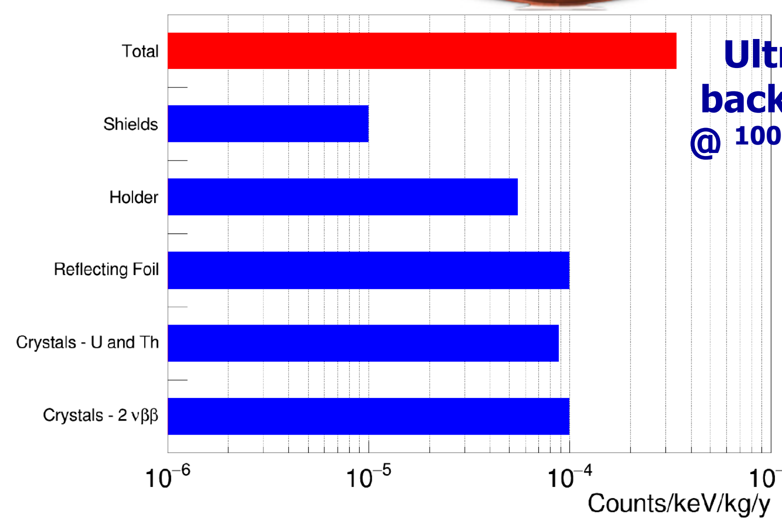


CUORE infrastructure



Active α background rejection



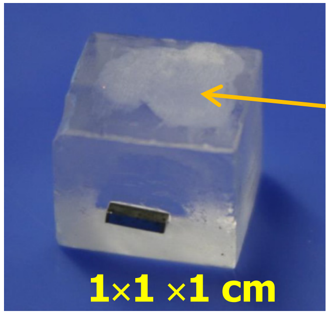


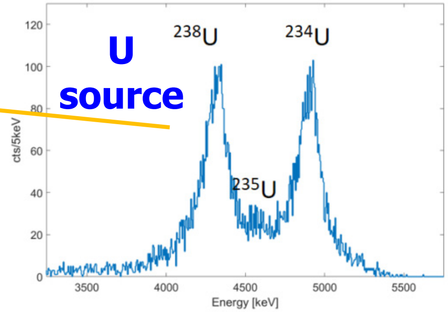
Ultra-low background @ ^{100}Mo ROI

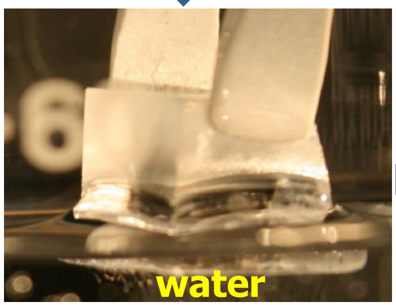
Other CUPID oriented activities with Li_2MoO_4 crystals

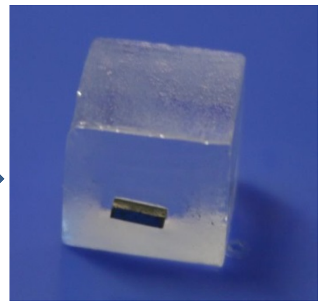
(grown by Cz, LTG Cz, and Bridgman methods)

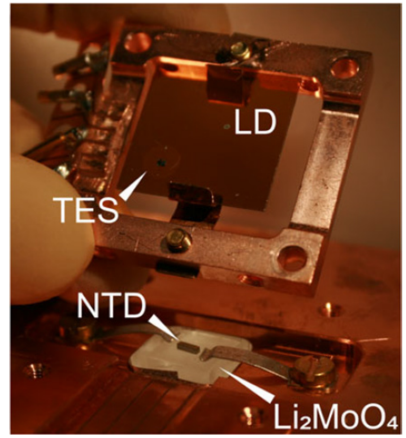
CRESST+LUMINEU: LMO water etching & DM search

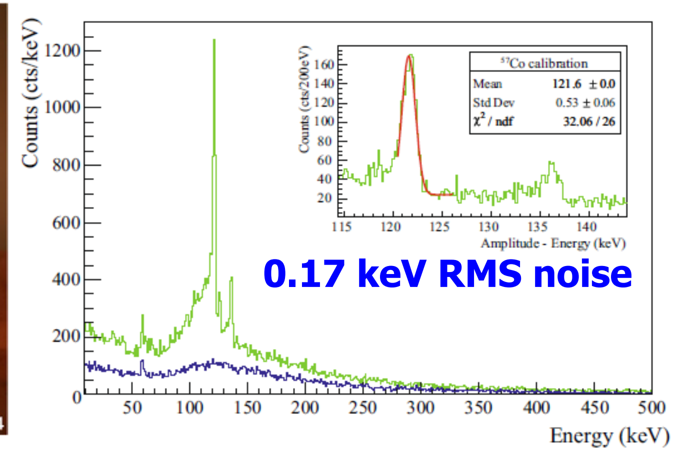


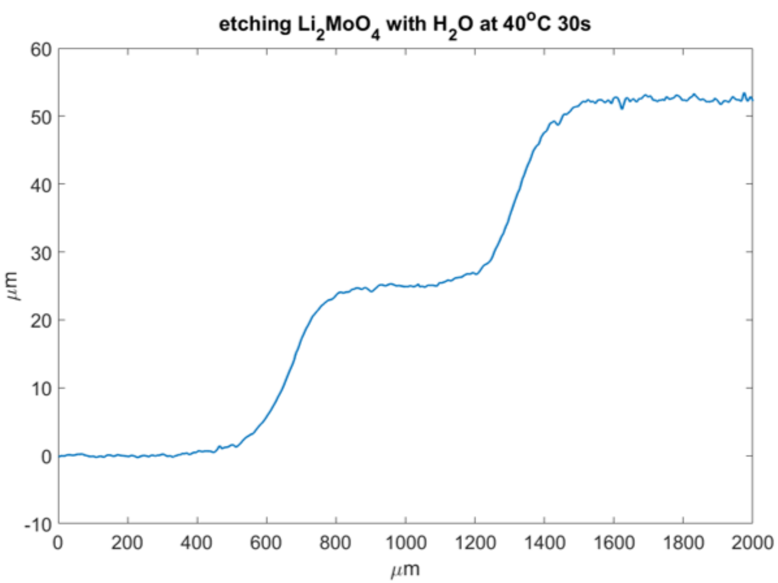


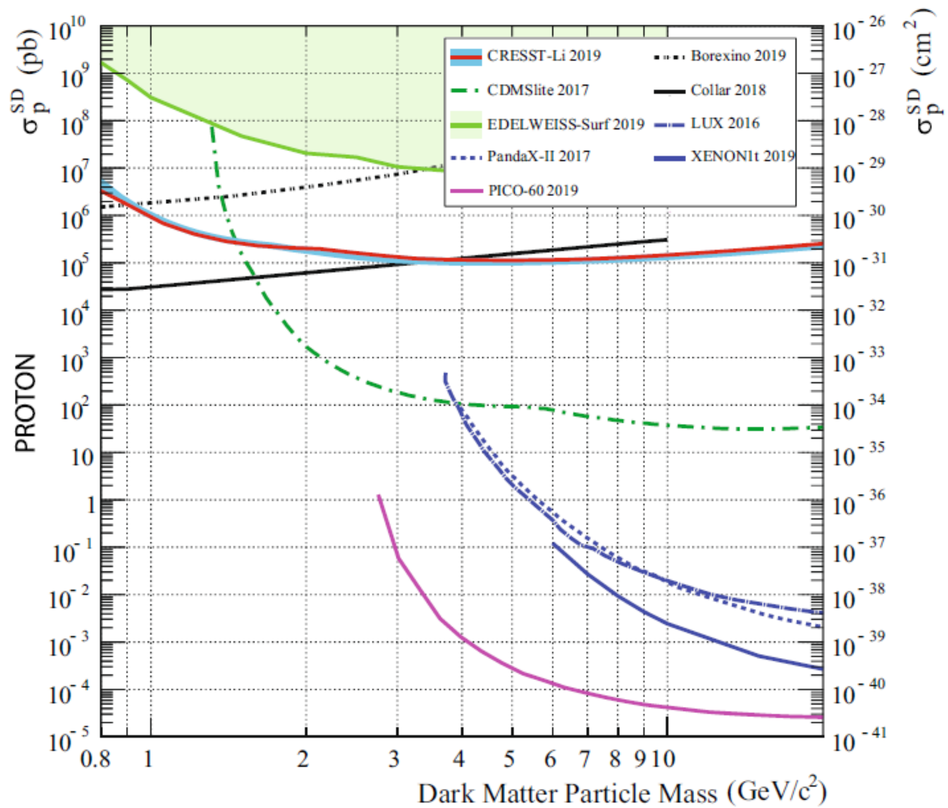












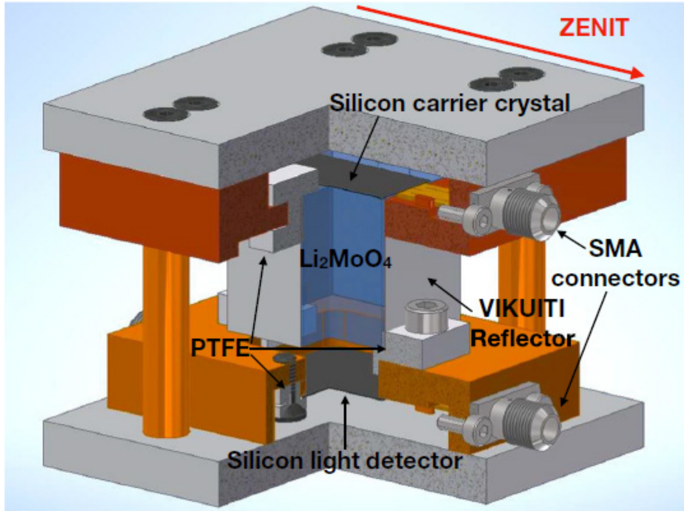
E. Bertoldo @ Ringberg Workshop 2018

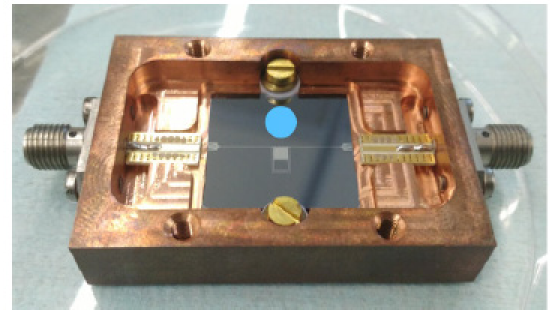
Eur. Phys. J. C 79 (2019) 630

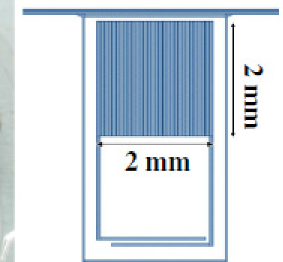
2019: KID-instrumented $Li_2{}^{100}MoO_4$ scint. bolometer

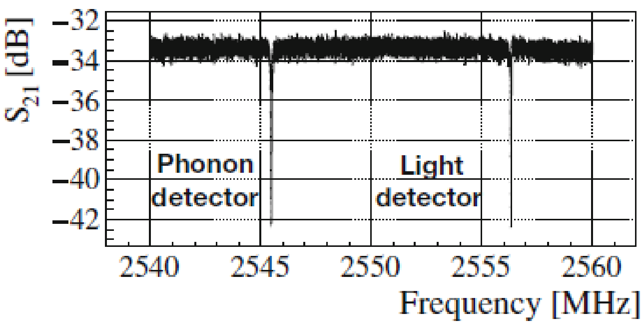
2015-2019

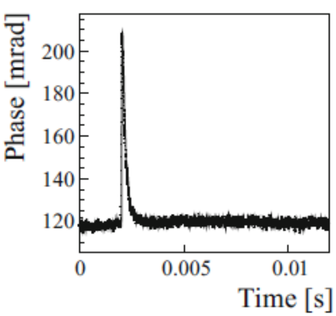
- Li_2MoO_4 (2×2×2 cm, 24 g) by LUMINEU
- Si wafer (2×2 cm² area)
- Al Kinetic Inductance Detectors (KIDs)

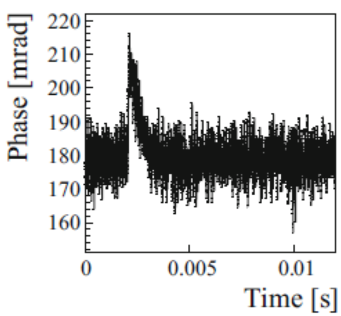


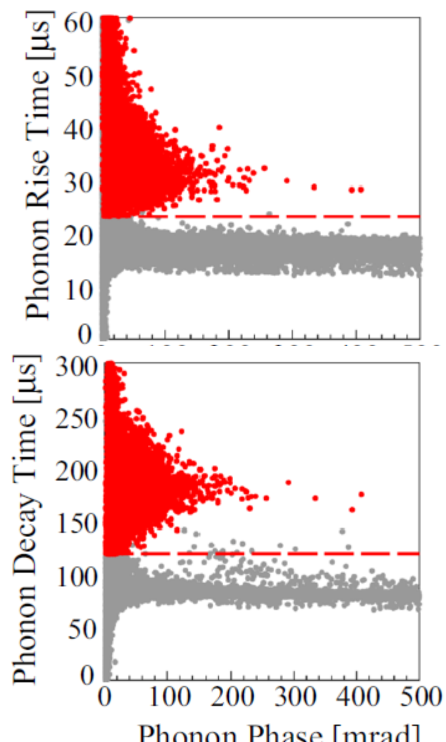


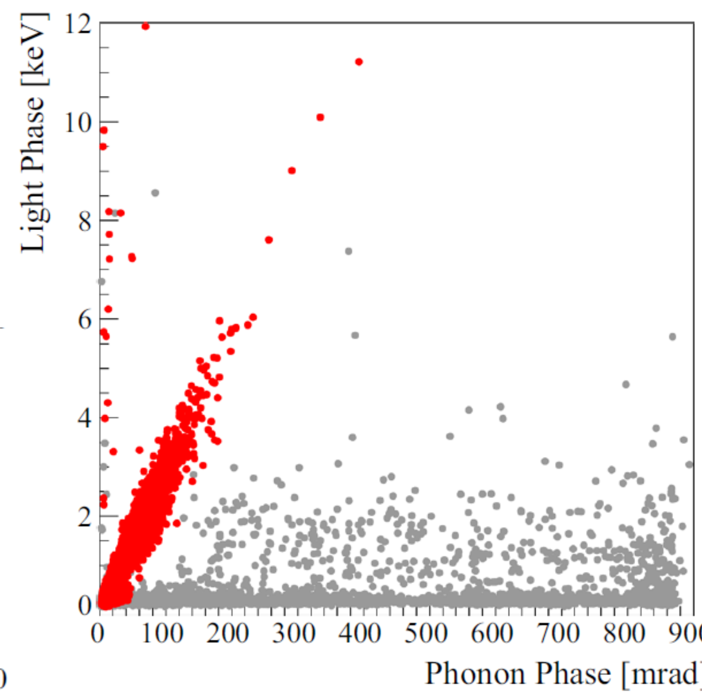












Eur. Phys. J. C 79 (2019) 724

CROSS: surface coated bolometers with particle ID

2018-2022

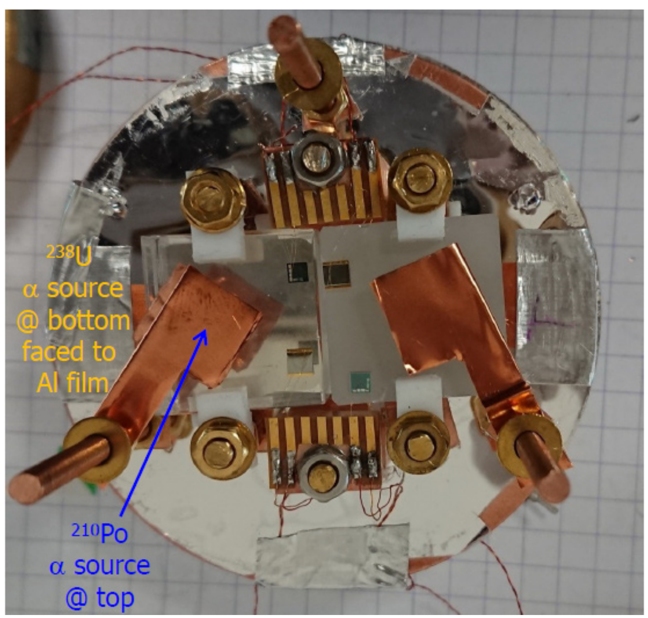
Cryogenic **R**are-event **O**bservatory with **S**urface **S**ensitivity

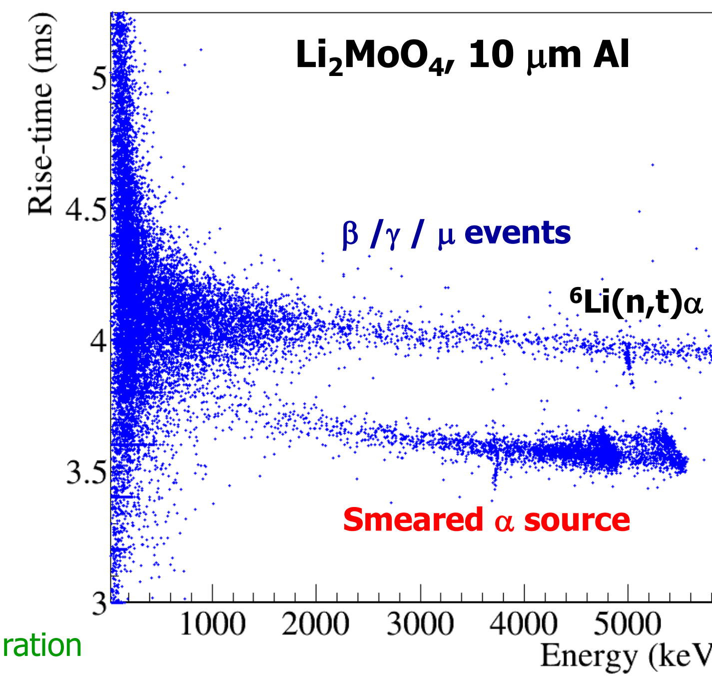
Core of the project (high risk / high gain):

- Background rejection through **pulse shape discrimination**
  - **Surface sensitivity** through **superconductive Al film coating**
  - **Fast NbSi high-impedance TES** to replace / complement NTDs

- Complete crystallization of available **^{100}Mo (10 kg)** in Li_2MoO_4 elements
- Purchase / crystallize **^{130}Te (up to 10 kg)** in TeO_2 elements
- Run **demonstrator** in a dedicated cryostat (LSC, Spain)

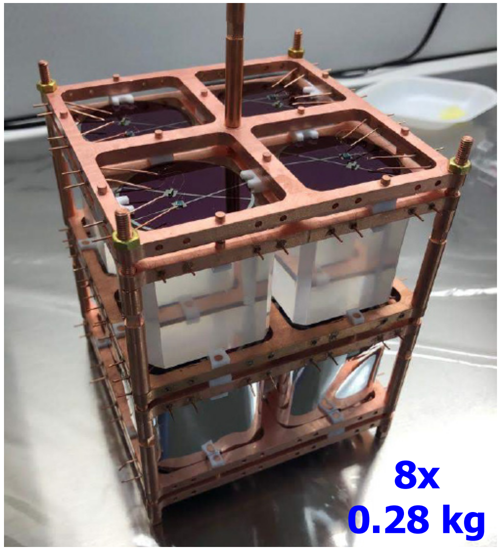
Tests of first prototypes of CROSS R&D @ CSNSM (Orsay France)





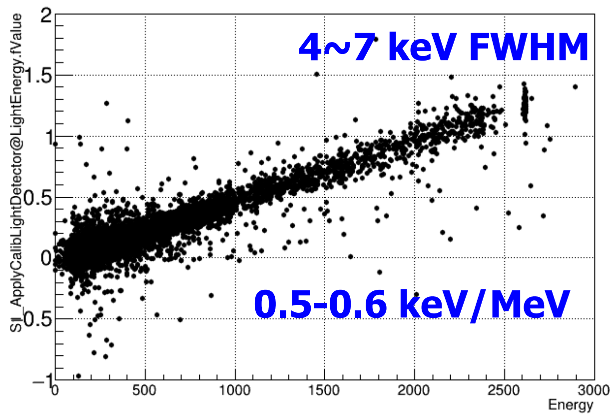
arXiv:1906.10233, arXiv:1907.11411 & A. Giuliani, talk @CUPID-Mo inauguration

CROSS: other Li_2MoO_4 tests in view of CUPID

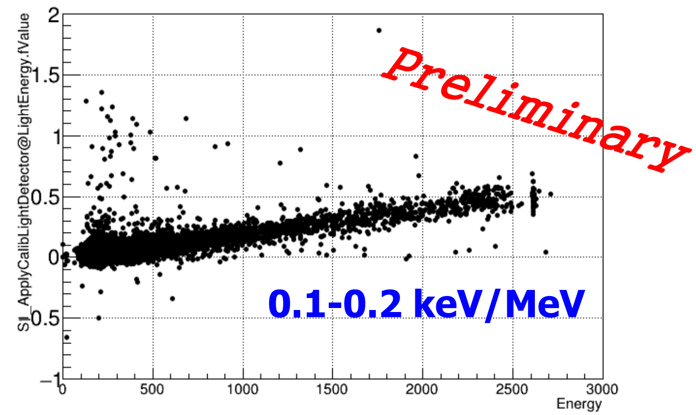


First bolometric test of cubic $Li_2{}^{100}MoO_4$ @ LNGS

w/ reflector



w/o reflector

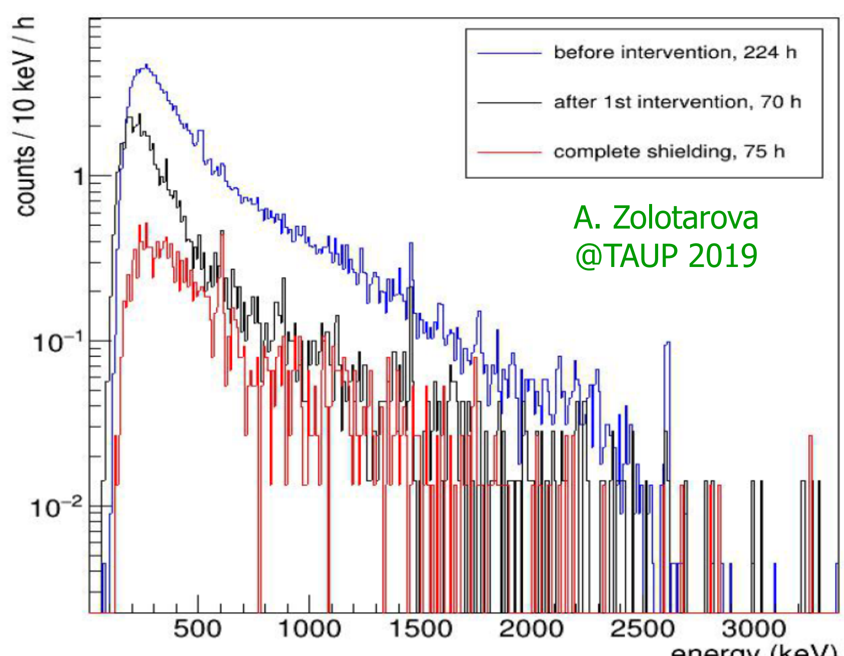


Note: not optimal noise conditions and light collection

S. Dell'Oro @ CUPID meeting (Rome, 18/10/2019)

First test of Li_2MoO_4 (purified Li) @ LSC

- **Li_2MoO_4 crystal (0.21 kg, ∅44×45 mm) developed from purified Li_2CO_3 powder**
- **CUPID-Mo like detector design**



CLYMENE: R&D of Li_2MoO_4 crystals for CUPID

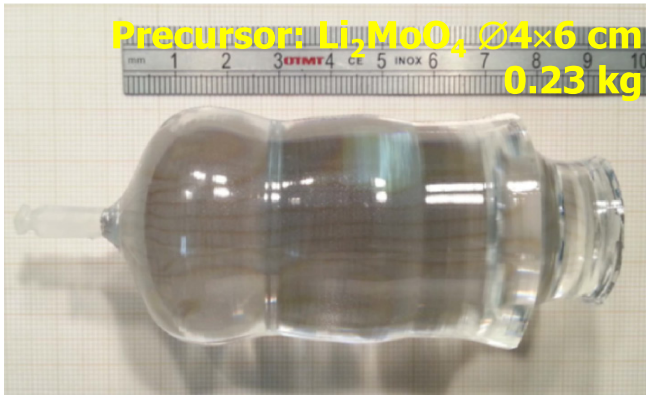
2012-2016

- **ICMCB (Bordeaux, France)**
  - **Czochralski method**
  - Commercial compounds
  - Li/Mo purification to 0.1/0.5 ppm K

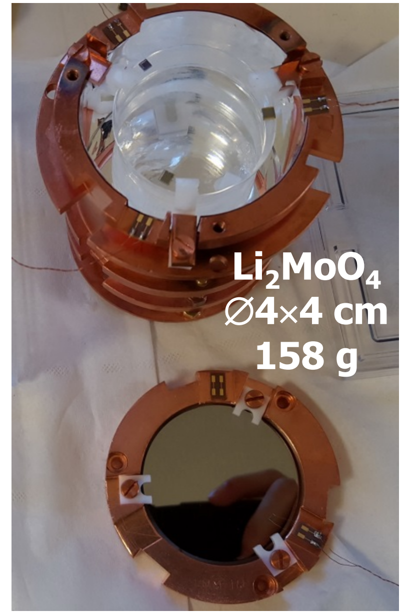
CLYMENE

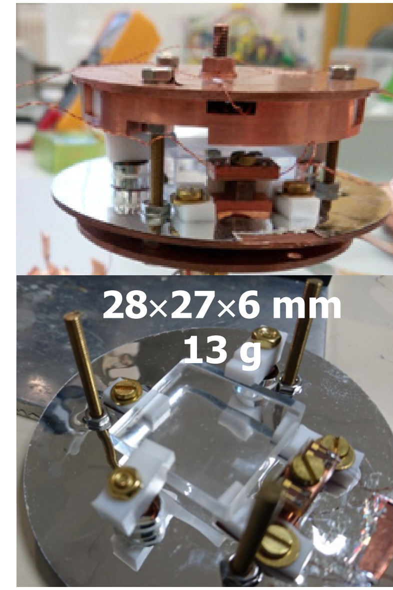
http://clymene.in2p3.fr

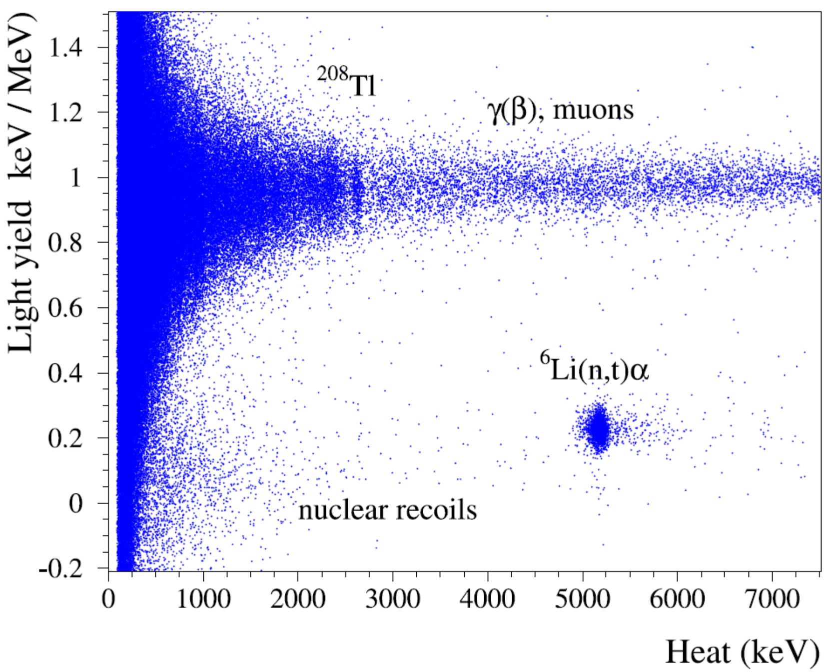
Agence Nationale de la Recherche ANR

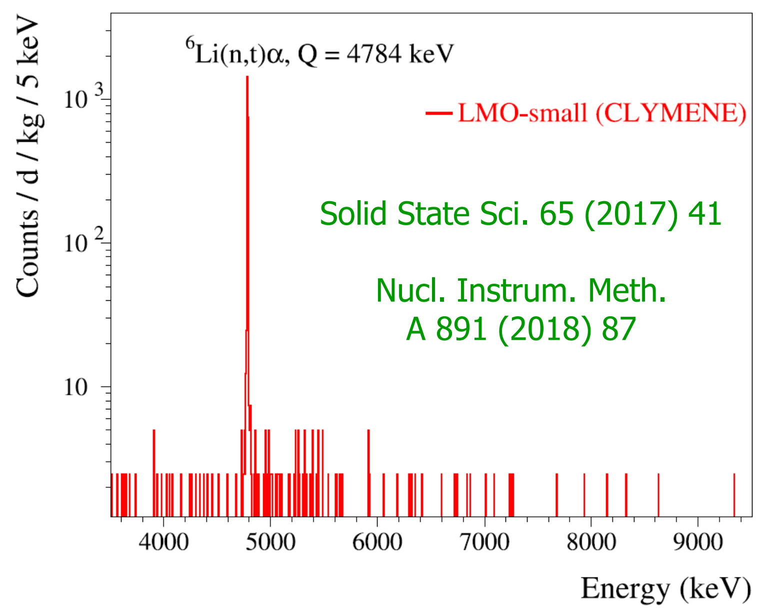


Bolometric tests @CSNSM [in 2016]









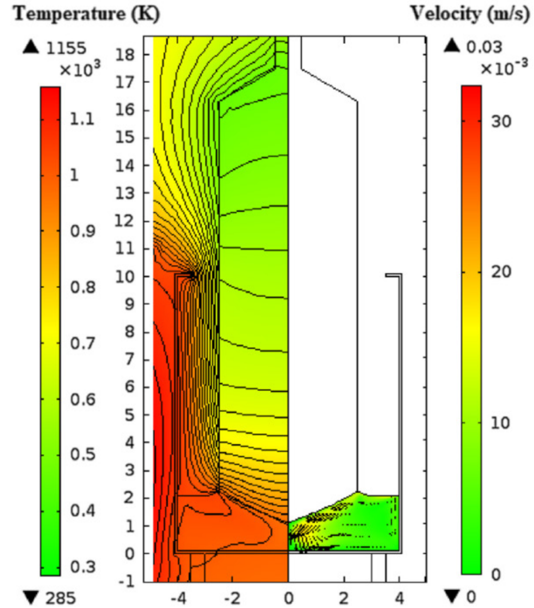
Solid State Sci. 65 (2017) 41

Nucl. Instrum. Meth. A 891 (2018) 87

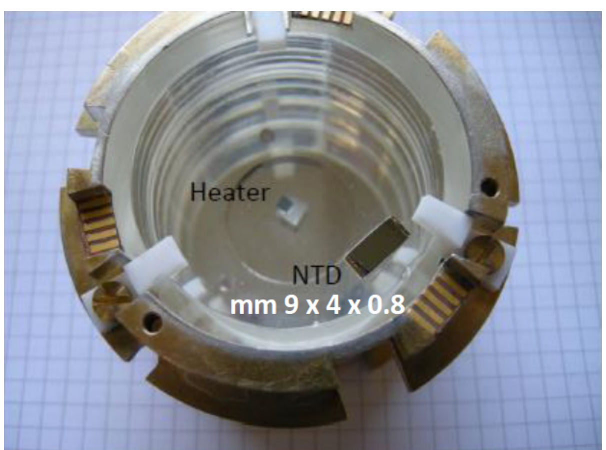
CLYMENE: R&D of Li_2MoO_4 crystals for CUPID

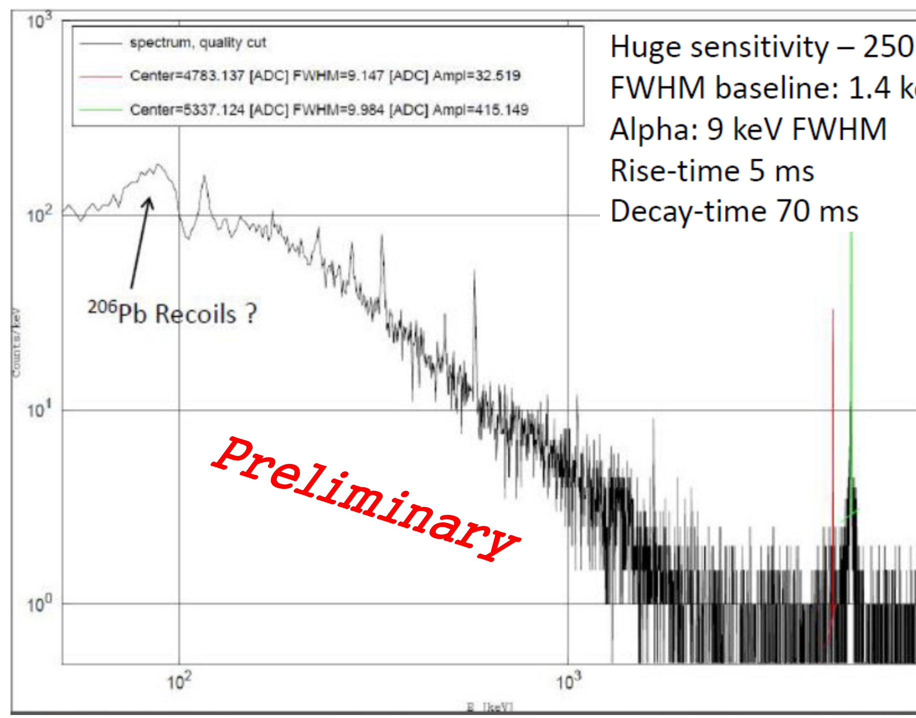
- **Ordinary Cz method**
- Purified commercial compounds
- **Numerically optimized furnace**
  ⇒ Improved Cz growth of LMO's

J. Cryst. Growth 492 (2018) 6
J. Cryst. Growth 531 (2019) 125385



Bolometric test @CSNSM [in 2019]





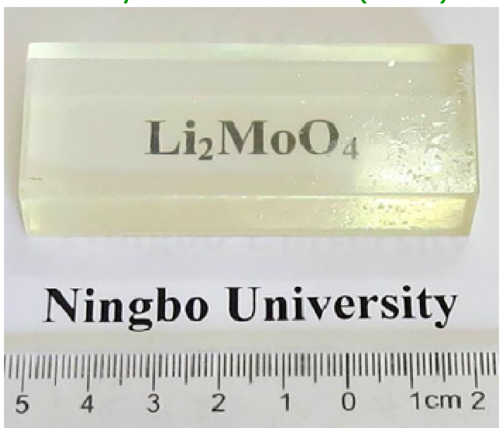
Huge sensitivity – 250 nV/keV
FWHM baseline: 1.4 keV
Alpha: 9 keV FWHM
Rise-time 5 ms
Decay-time 70 ms

A. Giuliani @ CUPID meeting (Rome, 18/10/2019)

Tests of Li_2MoO_4 crystals produced in China

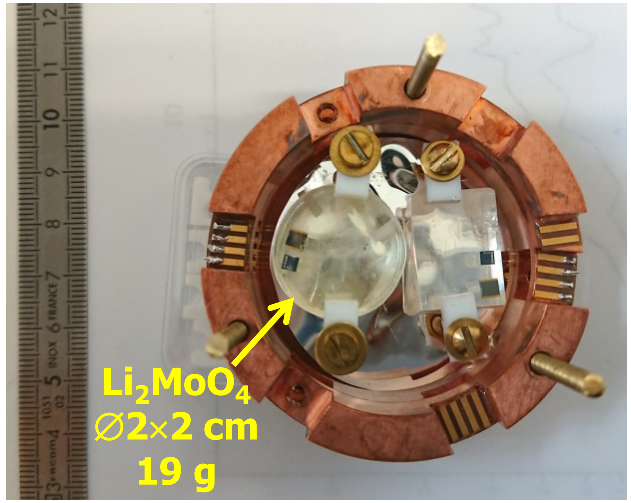
- **Ningbo University**
  - **Bridgman method**
  - Commercial compounds

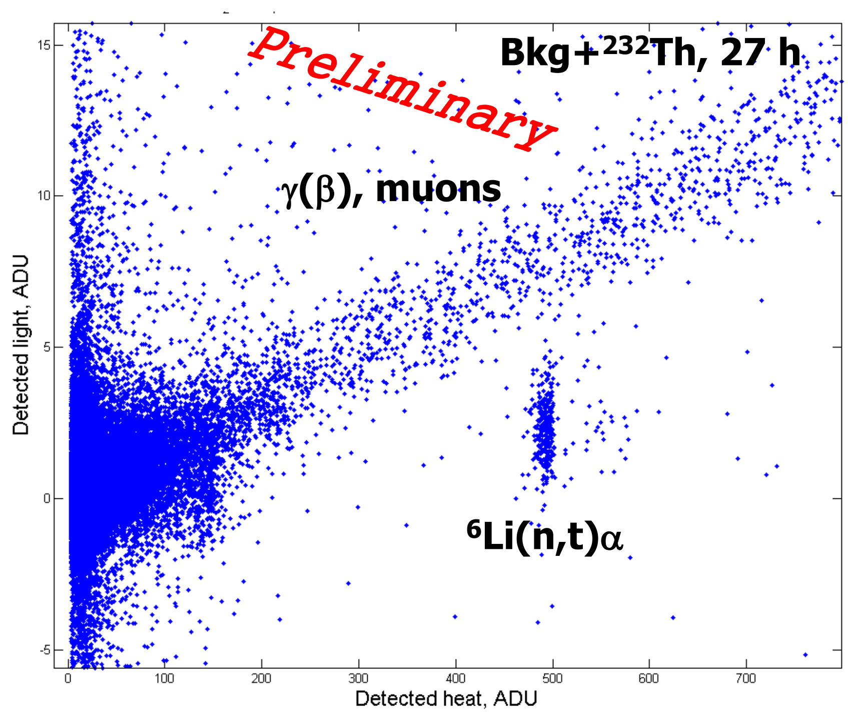
  Mat. Lett. 215 (2018) 225
  J. Cryst. Growth 500 (2018) 80



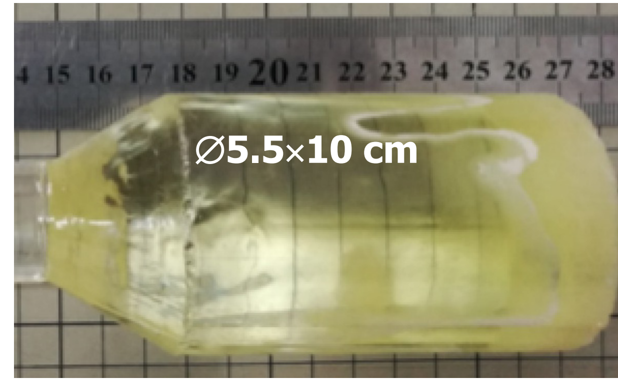
Nucl. Instrum. Meth. A 940 (2019) 320

Bolometric test @CSNSM [in 2018]





- **SICCAS Corporation**
  - **Bridgman method**
  - Commercial compounds

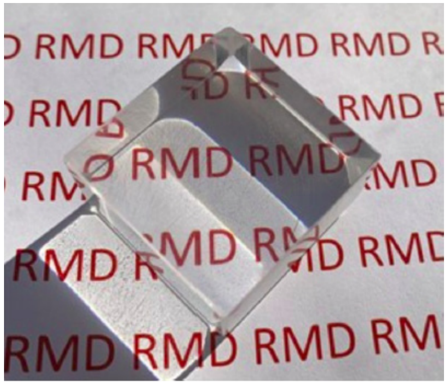


A bolometric test of a large sample (4.5×4.5×4.5 cm) is foreseen soon

Tests of Li_2MoO_4 crystals produced in the U.S.

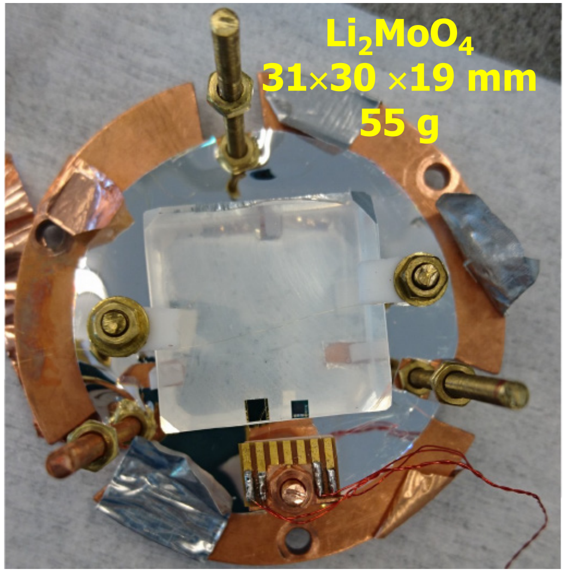
- **Radiation Monitoring Devices**
  - **Czochralski method**
  - Commercial compounds
  - Li_2MoO_4 samples up to ~∅5 cm

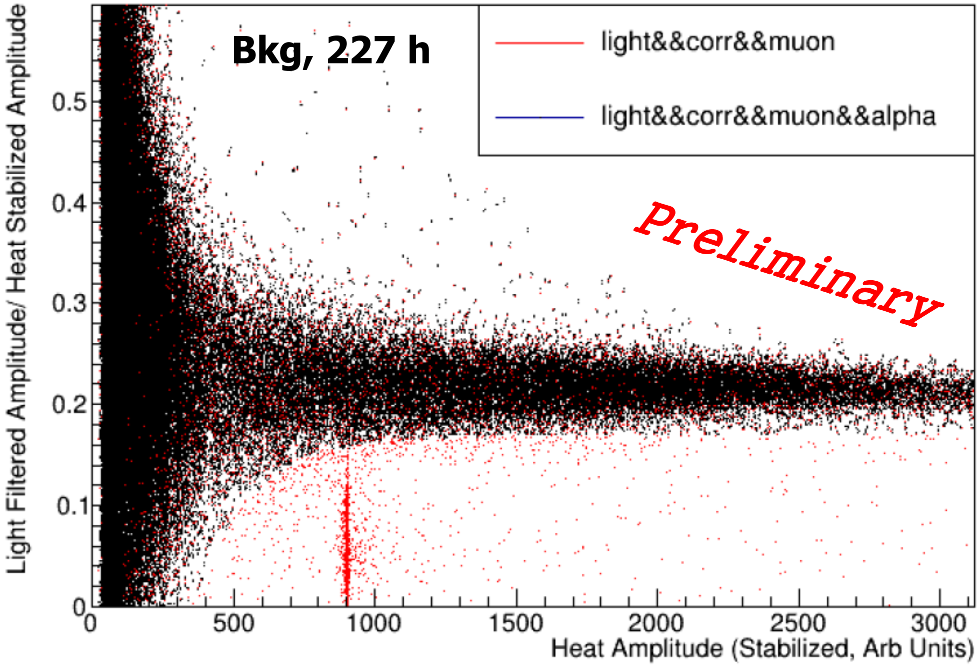
SBIR · STTR America's Seed Fund



J. Tower @ICCGE-2019

Bolometric tests @CSNSM [in 2019]





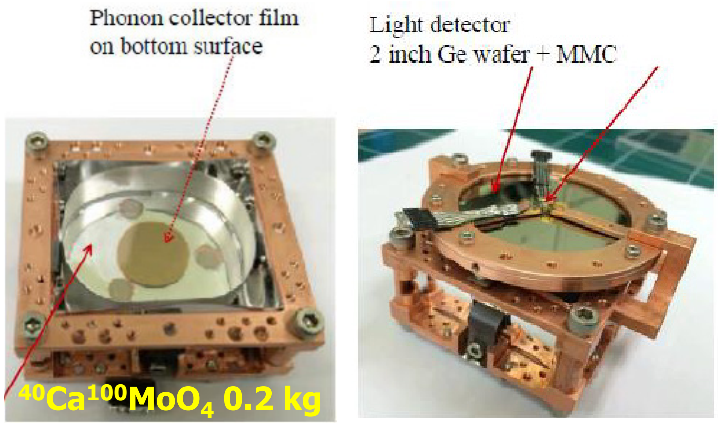
CUPID competitor: AMoRE path to Li_2MoO_4 bolometers

AMoRE: ^{100}Mo 0ν2β search w/ $CaMoO_4$ & alternatives

2013-2022 Project fully funded by Korea (IBS CUNPA); after ~10-yr R&D http://amore.ibs.re.kr

Baseline: MMC-instrumented $^{40}Ca^{100}MoO_4$ (^{40}Ca = 99.964%, ^{48}Ca < 0.001%, ^{100}Mo = 96%)

2015-2019 ^{100}Mo delivery



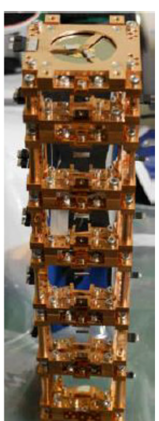
	AMoRE-Pilot	AMoRE-I	AMoRE-II
Crystals	$^{40}Ca^{100}MoO_4$	$^{40}Ca^{100}MoO_4$ +LMO,..	$X^{100}MoO_4$ X=Ca,Li,Zn,Na…
Crystals mass	1.5-1.9 kg	~6 kg	~200 kg
Bkg @ROI goal (c/keV/kg/yr)	0.01	0.001	0.0001
lim $T_{1/2}$ (yr)	$\sim 10^{24}$	$\sim 10^{25}$	$\sim 5\times 10^{26}$
lim $\langle m_{\beta\beta} \rangle$ (eV)	0.38–0.64	0.12–0.20	0.017–0.029
Location	Yangyang	Yangyang	Yemilab (new)
Schedule	2016-2018	2019~	2021~

Main issues of $CaMoO_4$ detectors

- **2ν2β ^{48}Ca** ($Q_{\beta\beta}$ = 4.3 MeV, i.a. 0.2%)
  ⇒ **requires Ca depleted in ^{48}Ca**
- **U/Th traces** (even after 2x crystallization)

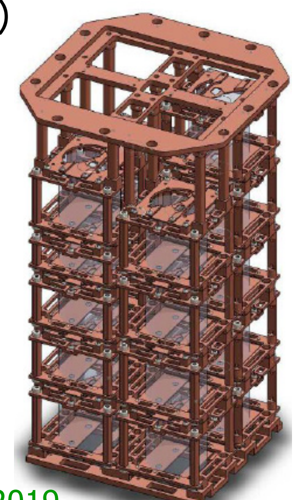
AMoRE-Pilot
5x-6x CMO

Best [μBq/kg]
^{228}Th = 50(15)
^{226}Ra = 40(12)



AMoRE-I
13x CMO
5x LMO

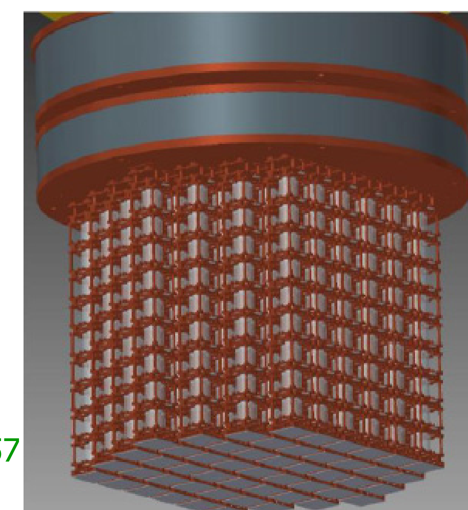
Best [μBq/kg]
^{228}Th = 10(3)
^{226}Ra = 10(3)



Kyungmin Seo @TAUP 2019

AMoRE-II

Technical Design Report
arXiv:1512.05957



AMoRE: R&D of Li_2MoO_4 crystal

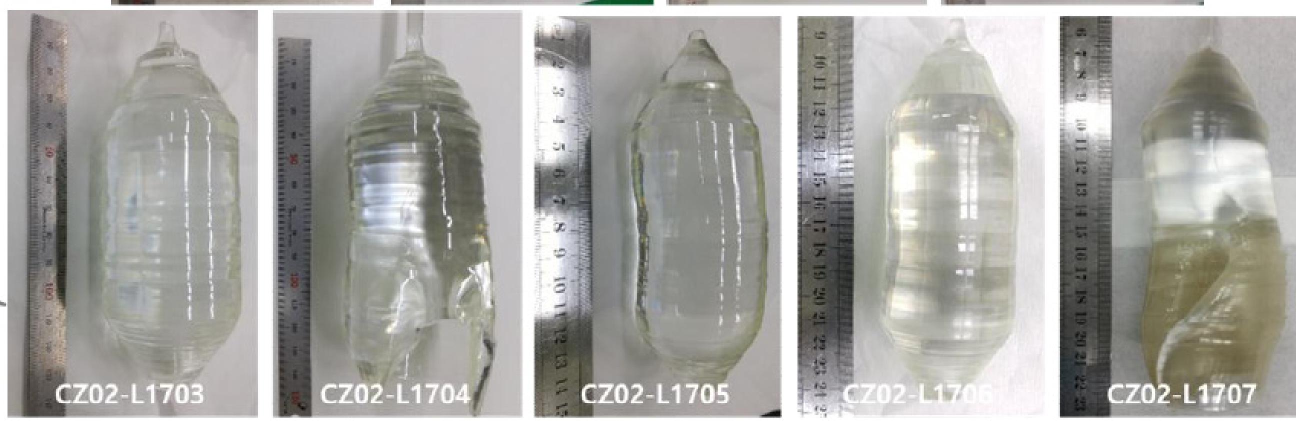
Center for Underground Physics

Grown Li_2MoO_4 crystals using the Czochralski method

Li_2CO_3 : 99.998 %
+
MoO_3 : 99.95 %

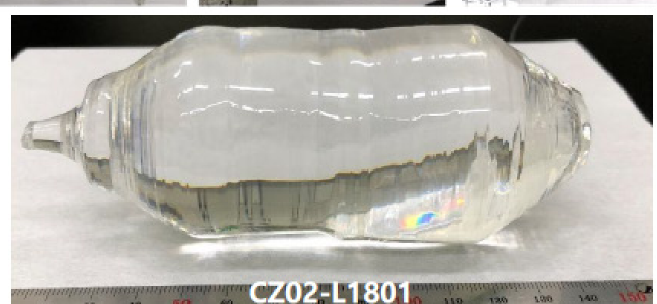
Quite yellowish
Because of
impurities

Li_2CO_3 : 99.998 %
+
MoO_3 Sublimed
(purified)



Less yellowish
Less impurities

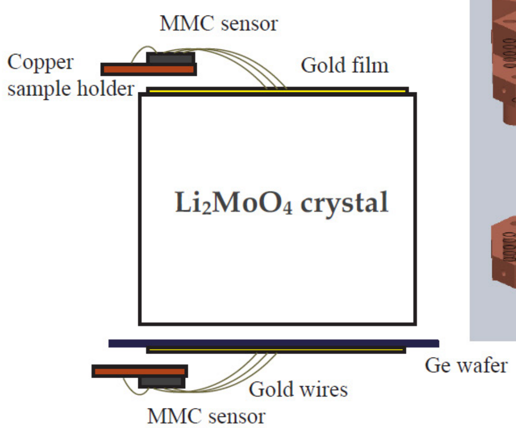
4 Grown LMO
crystals
CZ02-1704 ~ 1707

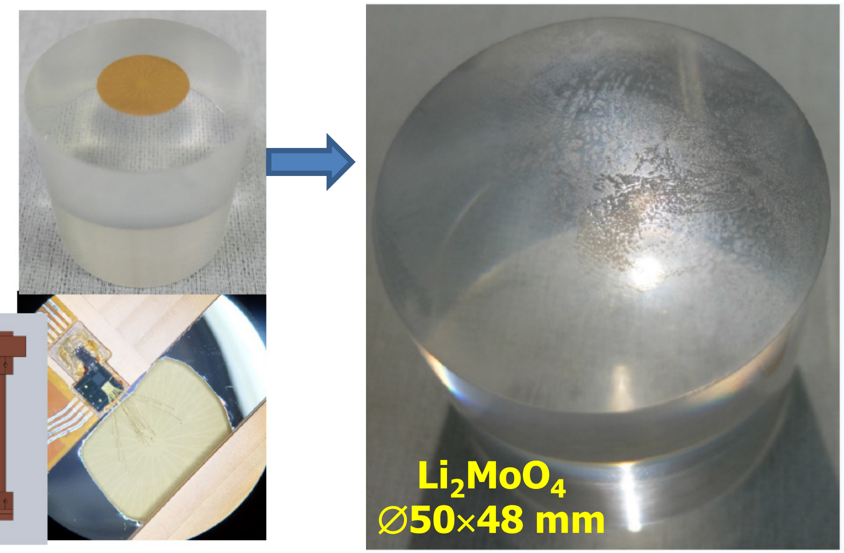


Double crystallization
Clear
Least impurities

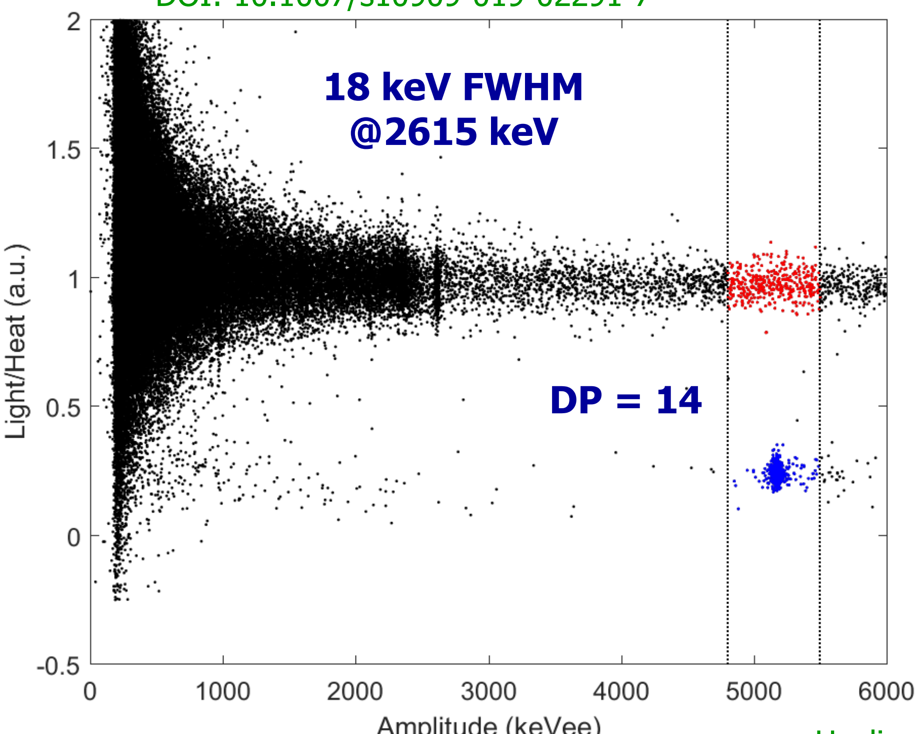
+ LMO supplied by NIIC (Russia),
LTG Cz using LUMINEU protocol

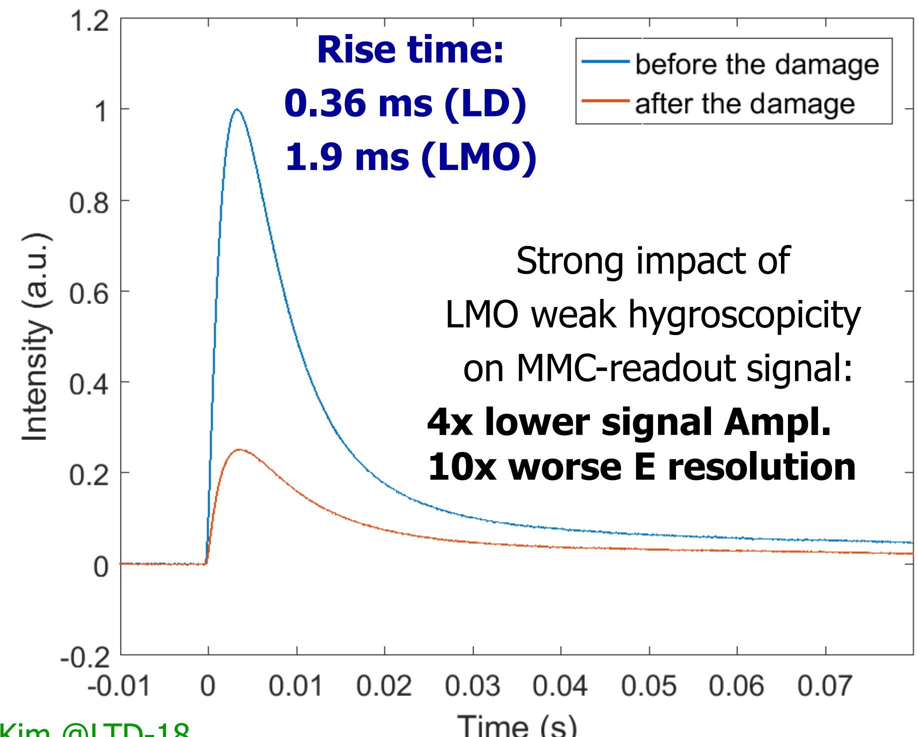
AMoRE: tests of MMC-instrumented Li_2MoO_4





DOI: 10.1016/j.nima.2019.04.061
DOI: 10.1007/s10909-019-02291-7





Summary

Summary

- ^{100}Mo is among the most promising isotopes for $0\nu2\beta$ decay search

- Over the last decade, natural and ^{100}Mo-enriched Li_2MoO_4 crystals have been extensively developed and tested as scintillating bolometers

- Li_2MoO_4 is the best Mo-containing material ever developed for cryogenic $0\nu2\beta$ experiments

- $Li_2{}^{100}MoO_4$ scintillating bolometers have been already used in LUMINEU, are operational in CUPID-Mo, will be used in AMoRE-I and CROSS, selected for CUPID & under consideration for AMoRE-II $0\nu2\beta$ experiments

Stay tuned !