



CUPID-Mo

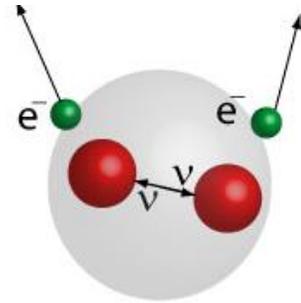
A. Zolotarova (CEA/IRFU/DPhP, France)

on behalf of the CUPID-Mo Collaboration



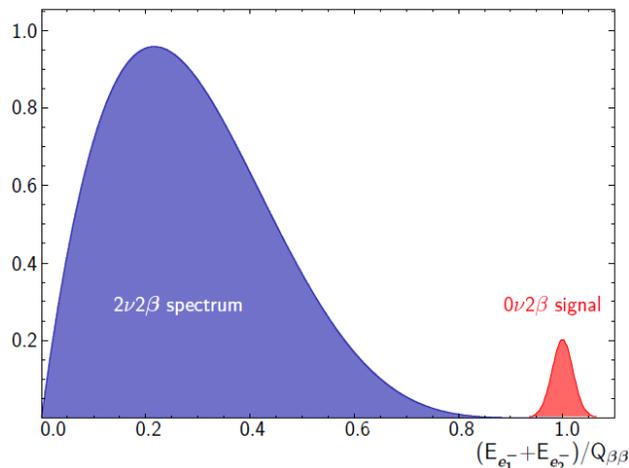
$0\nu 2\beta$ search with ^{100}Mo

- $^{100}_{42}\text{Mo} \rightarrow ^{100}_{44}\text{Ru} + 2e^{-}$
- $T_{1/2}^{0\nu 2\beta} > 1.1 \times 10^{24} \text{ yr}^*$



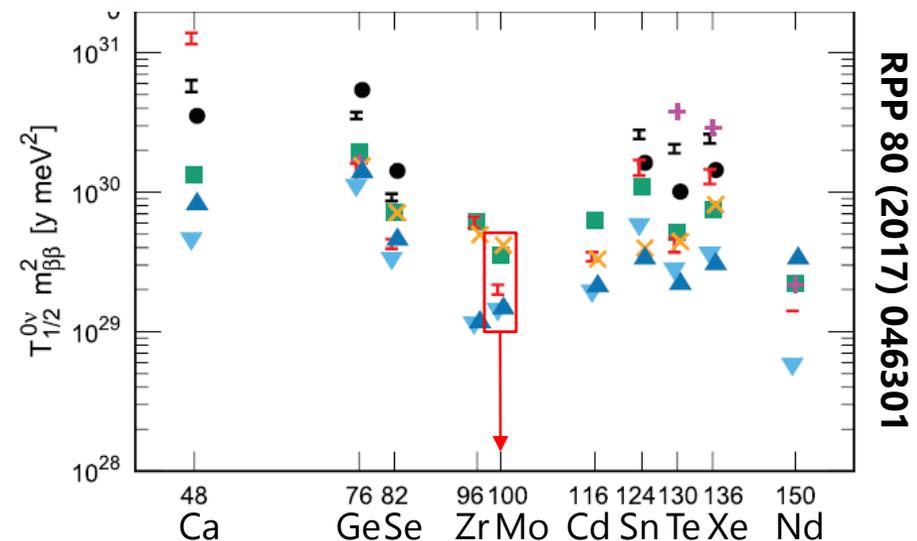
If observed:

- **Majorana nature of neutrino**
- **Lepton number violation: $\Delta L=2$**
- Determination of **absolute neutrino mass** scale and information about **neutrino mass hierarchy**



Isotope ^{100}Mo :

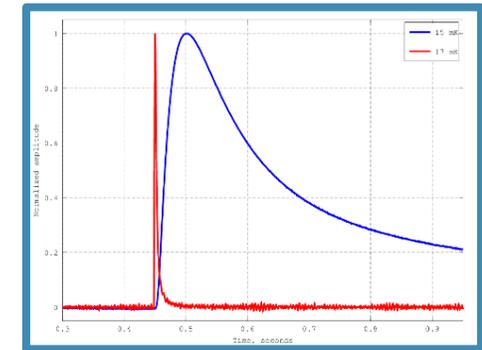
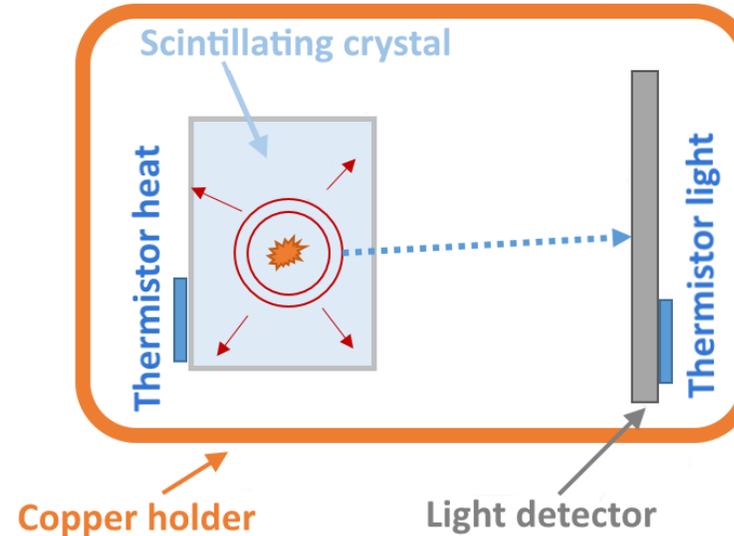
- **High transition energy:** $Q_{\beta\beta} = 3034 \text{ keV}$
- Natural abundance = 9.7%
- Possible **large-scale enrichment**
- **Favorable theoretical predictions**
- Can be embedded in high performance detectors (**scintillating bolometers**)



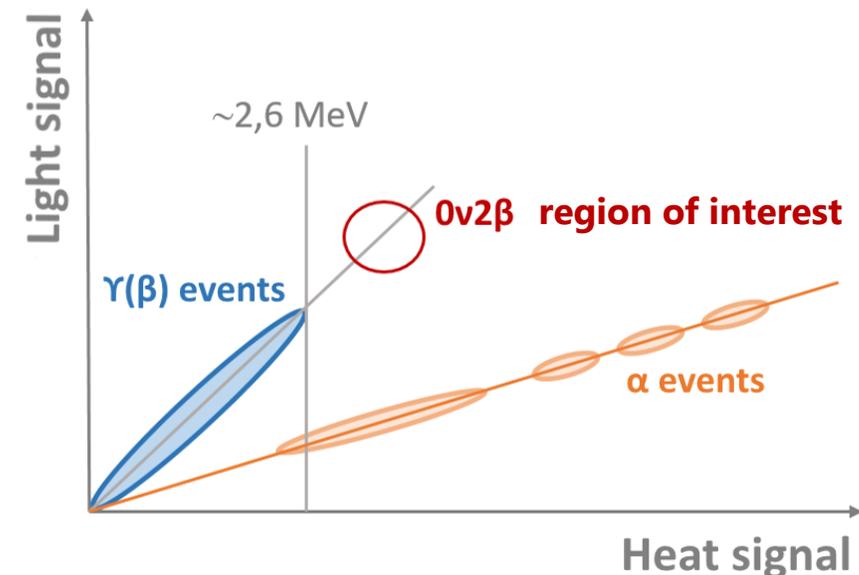
*The most sensitive study of ^{100}Mo $0\nu 2\beta$ decay was performed by NEMO-3: PRD 92, 072011 (2015)

Scintillating bolometers (Li_2MoO_4)

- **Source is embedded** in a crystal \rightarrow high detection efficiency (**>70%**)
- **0.1-0.5 kg** typical crystal mass, scalability to a large-mass array
- Detectors are operated at **~ 10 mK**, the deposited **energy** is measured as a **temperature increase** in a crystal
- **High energy resolution:**
 ~ 5 keV FWHM ($\sim 0.2\%$) at the $Q_{\beta\beta}$
- **Scintillator** \rightarrow Particle discrimination using light: **>99.9 α background rejection**



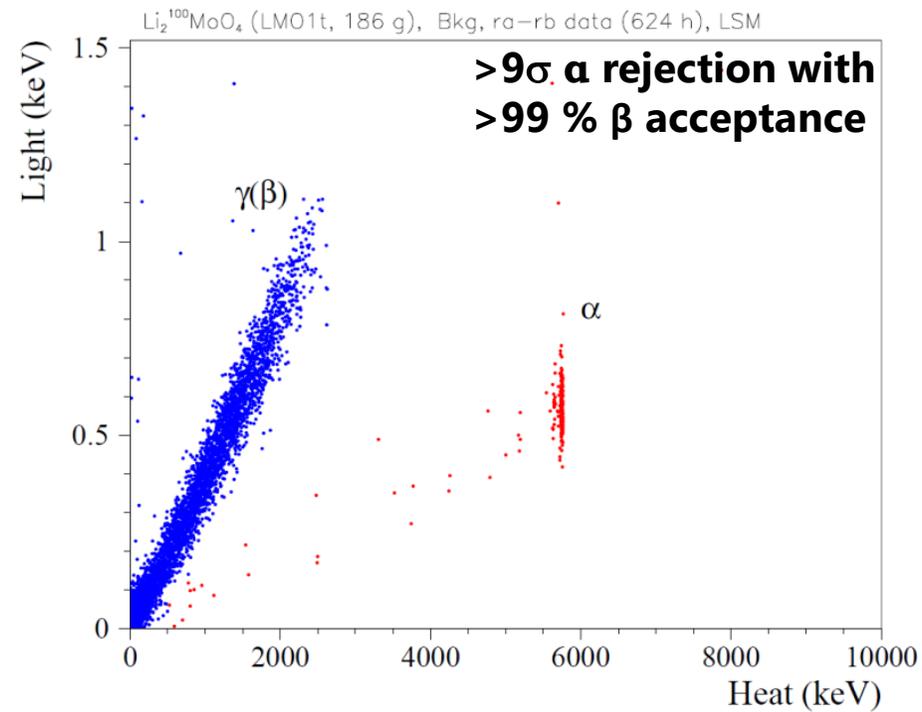
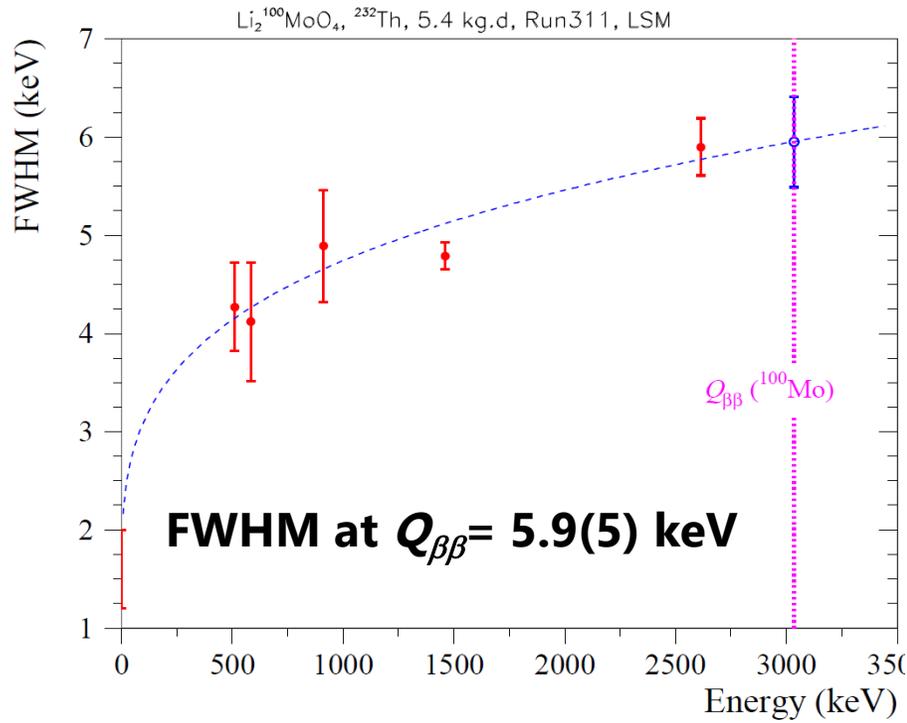
Typical signal: **0.1 mK / MeV**, converted to **0.1-0.5 mV / MeV**



R&D on $\text{Li}_2^{100}\text{MoO}_4$ scintillating bolometers

Multiple tests with natural and enriched crystals were performed in 2014-2017 (LUMINEU project) with excellent results:

- uniform performance \rightarrow good reproducibility
- rejection of α 's at the level of $>9\sigma$
- high energy resolution: **4-6 keV FWHM** at the $Q_{\beta\beta}$ (**$\sim 0.2\%$**)
- high radiopurity: ^{232}Th , $^{238}\text{U} < 6 \mu\text{Bq/kg}$; $^{40}\text{K} < 1.3 \text{ mBq/kg}$ \rightarrow negligible background in ROI

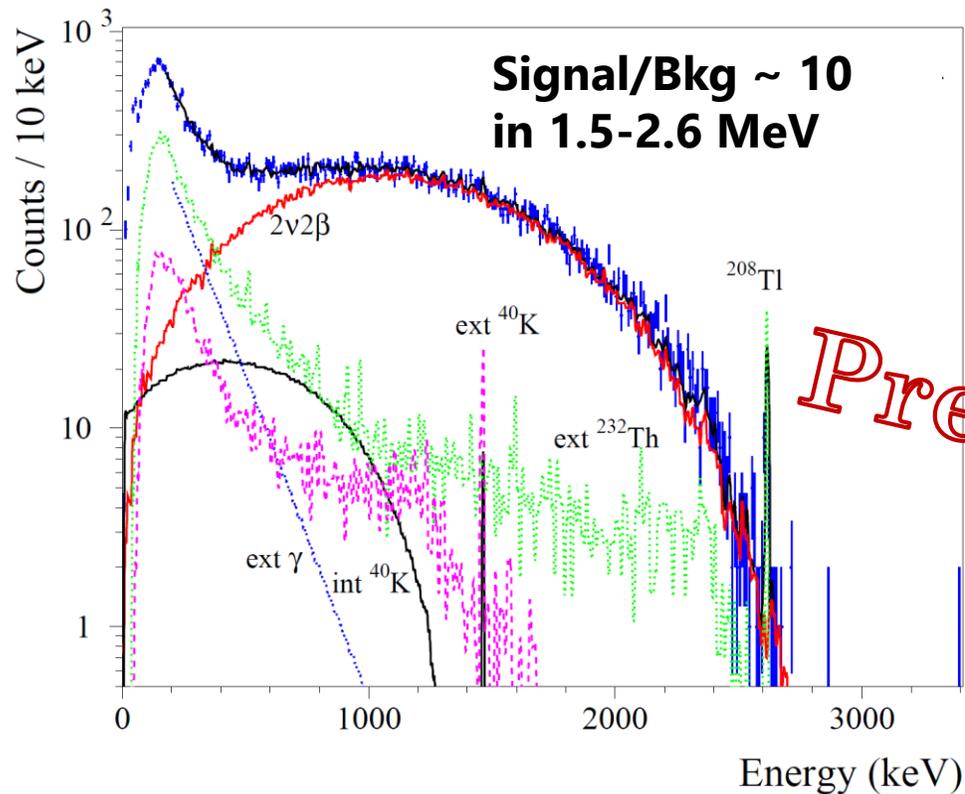


Investigation of 2β decay (LUMINEU)

The **most precise** ^{100}Mo $2\nu 2\beta$ half-life value, measured over a short exposure **29 kg×d**:

Fit: 160 – 2650 keV, effect: 24320 ± 229 decays

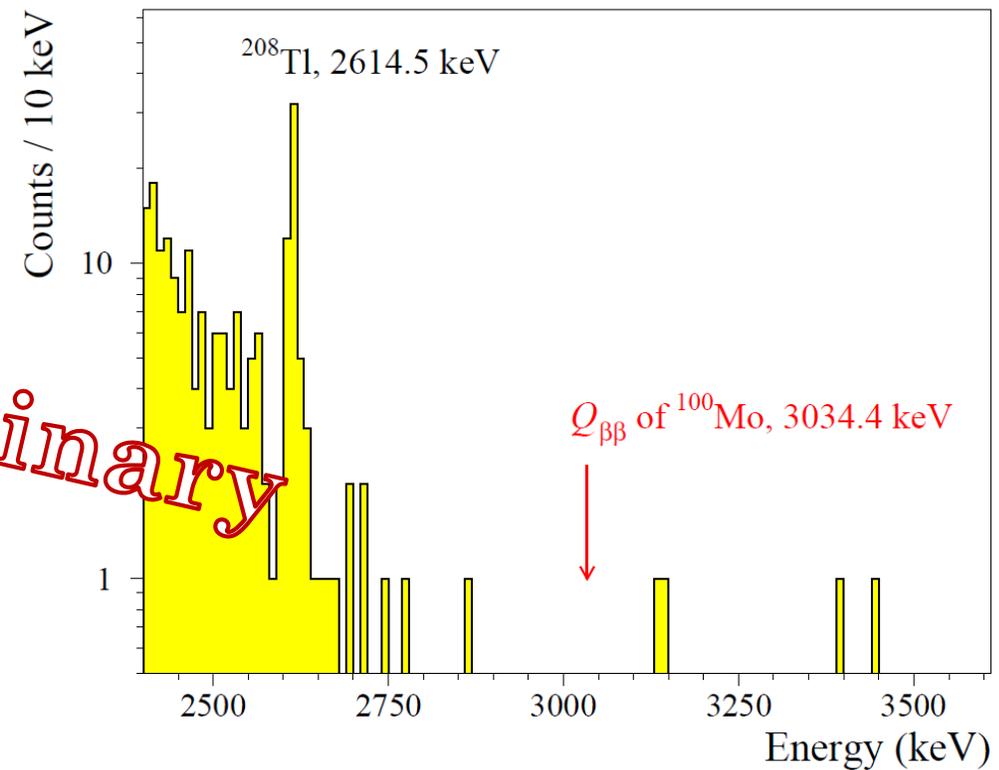
$$T_{1/2}^{2\nu 2\beta} = 6.92 \pm 0.06(\text{stat}) \pm 0.36(\text{syst}) \times 10^{18} \text{ yr}$$



Limit on the $0\nu 2\beta$ half-life (39 kg×d exposure)

Background = $0.06(3)$ counts/(keV×kg×yr)

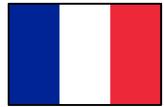
$$T_{1/2}^{0\nu 2\beta} > 0.7 \times 10^{23} \text{ yr at 90\% C.L.}$$



Preliminary

The LUMINEU follow-up: CUPID-Mo

CUPID-Mo Collaboration:



- CSNSM, Orsay, France
CEA/DRF, Gif-sur-Yvette, France
IPNL, Lyon, France
LAL, Orsay, France



- KIT, Karlsruhe, Germany



- INFN Bicocca and Roma, Italy
LNGS, INFN, L'Aquila, Italy



- KINR, Kyiv, Ukraine



- JINR, Dubna, Russia
ITEP, Moscow, Russia
NIIC, Novosibirsk, Russia



- MIT, Boston,
UCB/LBNL, Berkeley, US

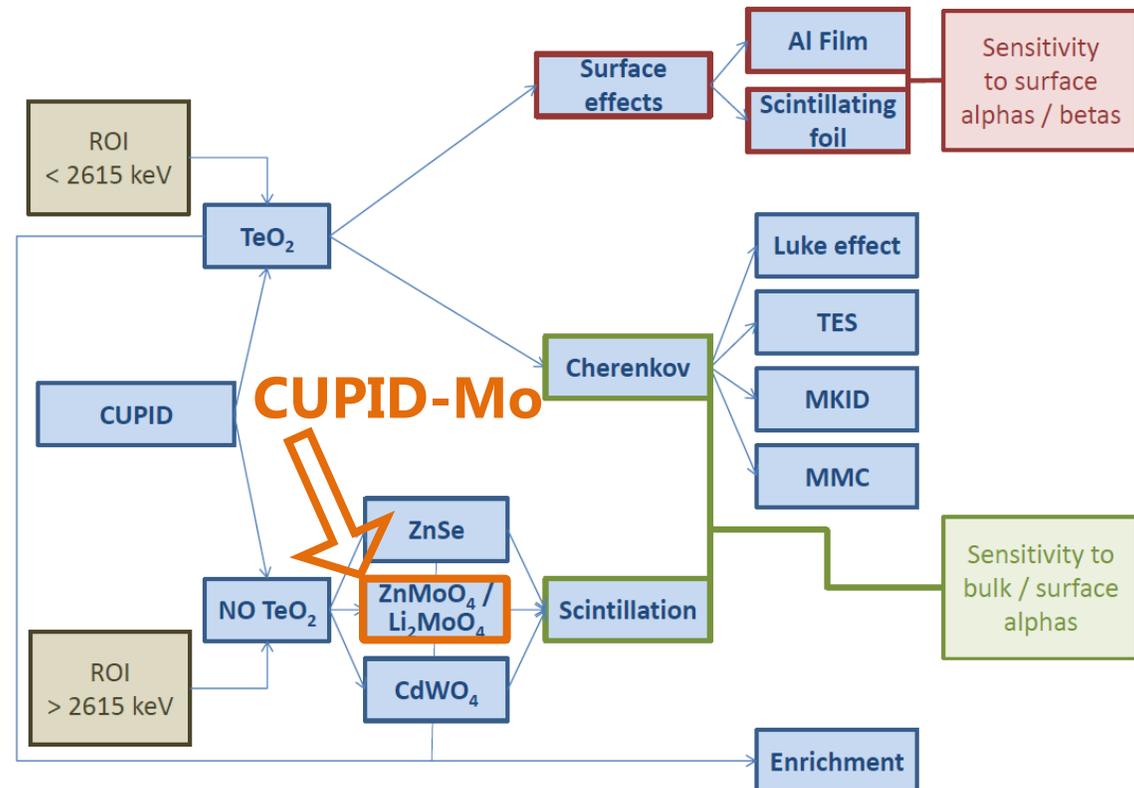


- CUPID-China: Fudan, USTC, P.R. China

R&Ds toward CUPID

(CUORE Upgrade with Particle IDentification)

- Follow-up of CUORE (tonne-scale cryogenic experiment) with background improved by a factor 100

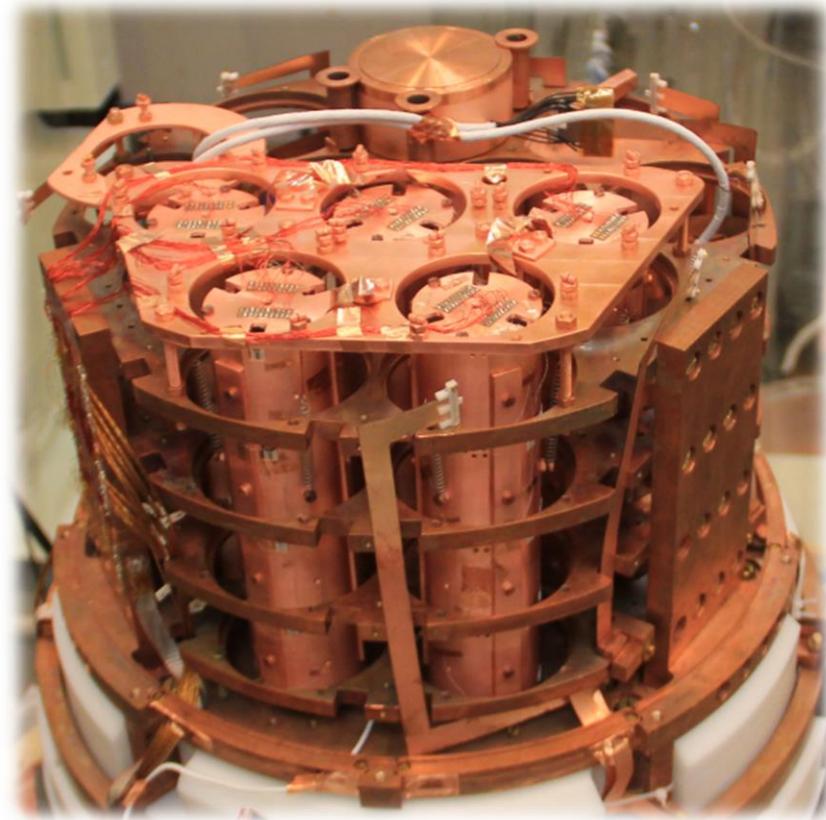
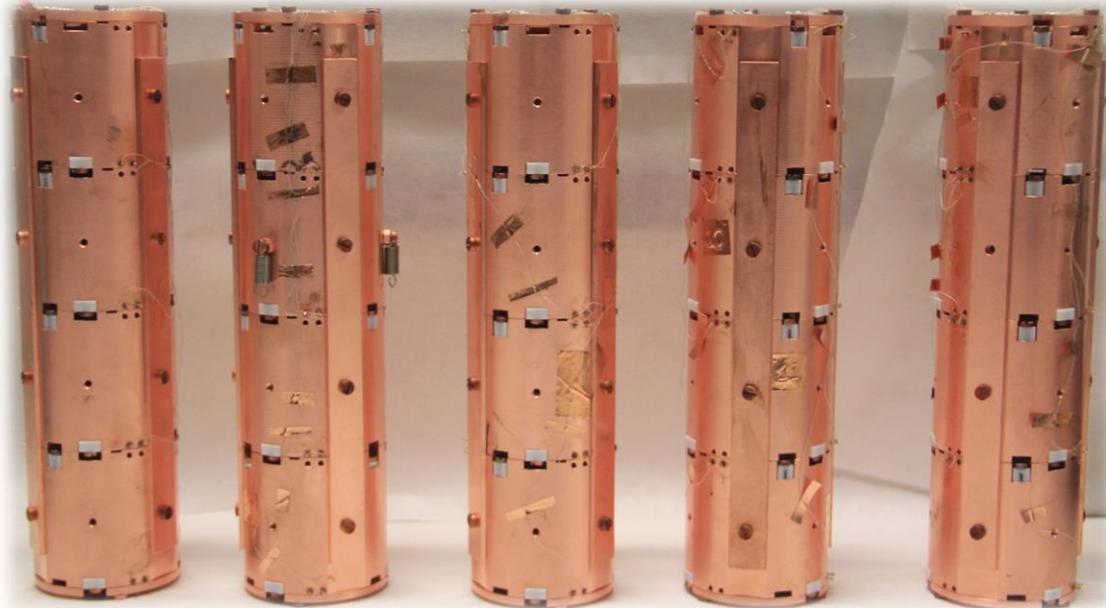
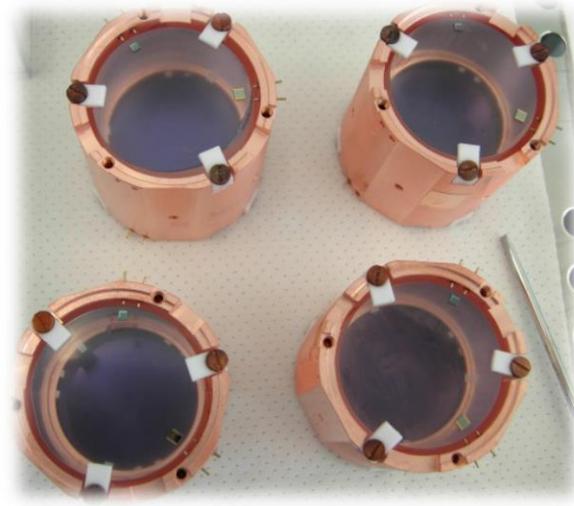


CUPID-Mo experiment

Phase I: 20 0.2-kg $\text{Li}_2^{100}\text{MoO}_4$ scintillating bolometers in the EDELWEISS set-up (LSM, France)

The goals for 6 months run:

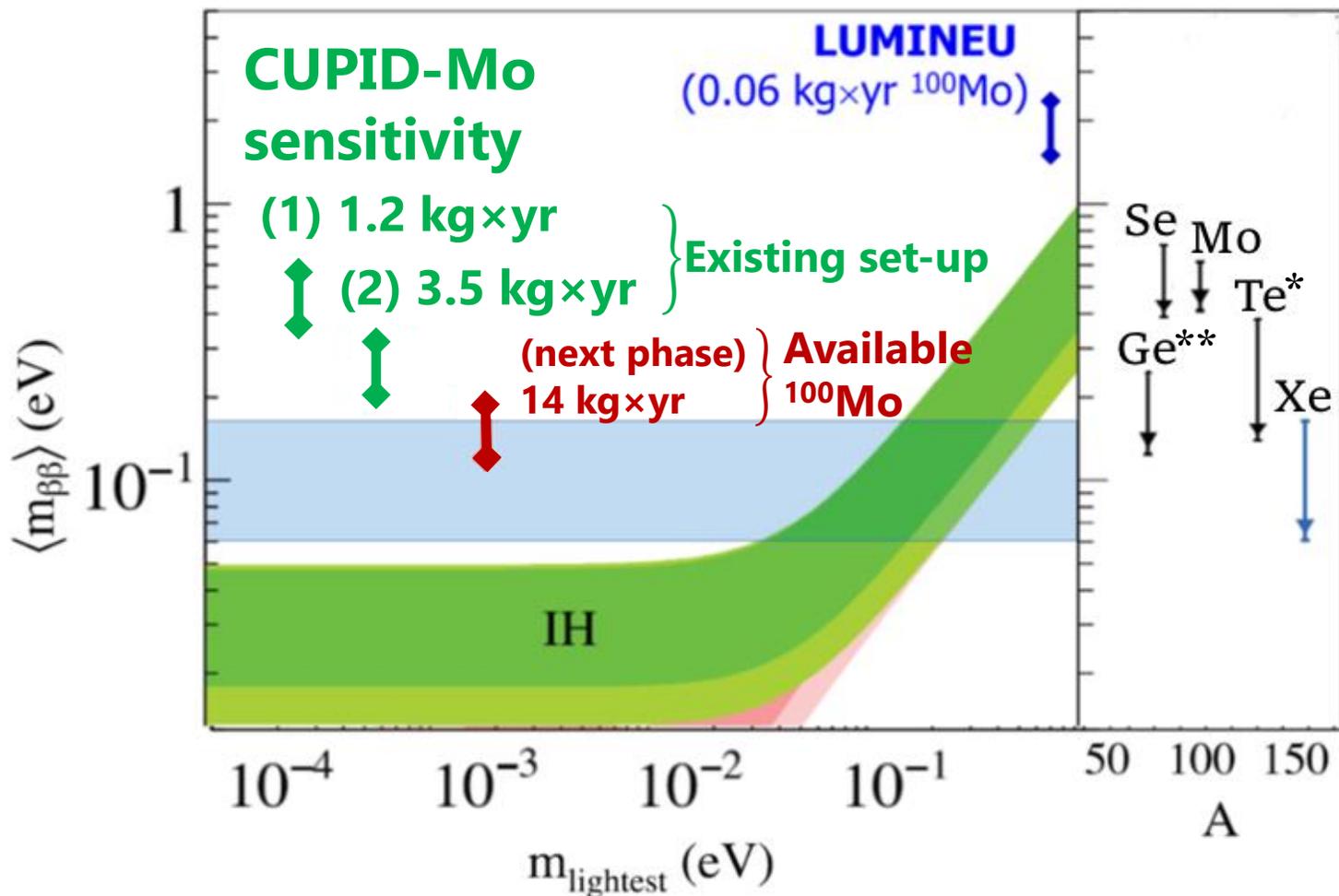
- Confirm the $\text{Li}_2^{100}\text{MoO}_4$ **technology on a larger scale**
- **Zero background in ROI**
- **improved limit** on $^{100}\text{Mo } 0\nu 2\beta$ half-life



CUPID-Mo sensitivity

Projected CUPID-Mo sensitivity (90% C.L.)

$b = 1 \times 10^{-3}$ counts/(keV×kg×yr), 10 keV ROI, 70% efficiency



Configuration [crystal×yr]	Exposure [kg×yr]	lim $T_{1/2}^{0\nu 2\beta}$ [yr]
(1) 20×0.5	1.2	1.3×10^{24}
(2) 20×1.5	3.5	4.0×10^{24}
(next phase) 40×3.0	14	1.5×10^{25}

2β	Experiment	Exposure [kg×yr]
^{82}Se	CUPID-0	2
^{100}Mo	NEMO-3	34
^{76}Ge	GERDA-II	23
^{130}Te	CUORE	24
^{136}Xe	KamLAND-Zen	504

arXiv:1802.07791

PRD 92 (2015) 072011

arXiv:1710.07776

arXiv:1710.07988

PRL 117 (2016) 082503

References:

D.V. Poda et al., **" ^{100}Mo -enriched Li_2MoO_4 scintillating bolometers for $0\nu 2\beta$ decay search: from LUMINEU to CUPID-0/Mo projects"**

AIP Conf. Proc. 1894 (2017) 02017

E. Armengaud et al., **"Development of ^{100}Mo -containing scintillating bolometers for a high-sensitivity neutrinoless double-beta decay search"**

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

V. Grigorieva et al., **" Li_2MoO_4 Crystals Grown by Low-Thermal-Gradient Czochralski Technique"**

J. Mat. Sci. Eng. 7 (2017) 63

T.B. Bekker et al., **"Aboveground test of an advanced Li_2MoO_4 scintillating bolometer to search for neutrinoless double beta decay of ^{100}Mo "**

Astropart. Phys. 72 (2016) 03

L. Berge et al., **"Purification of molybdenum, growth and characterization of medium volume ZnMoO_4 crystals for the LUMINEU program"**

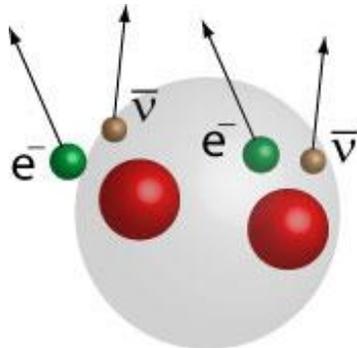
JINST 9 (2014) P06004

Thank you for the attention!

Double beta decay

Two neutrino 2β decay

Allowed by SM:



$2\nu\beta\beta$

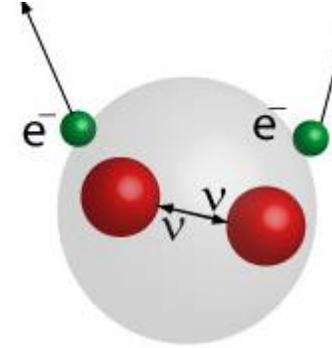


- The rarest observed nuclear decay
- Information about nuclear matrix elements \rightarrow test the theoretical description

$$T_{1/2} (2\nu 2\beta) \sim 10^{18} - 10^{24} \text{ years}$$

Neutrinoless 2β decay

Beyond the SM:



$0\nu\beta\beta$

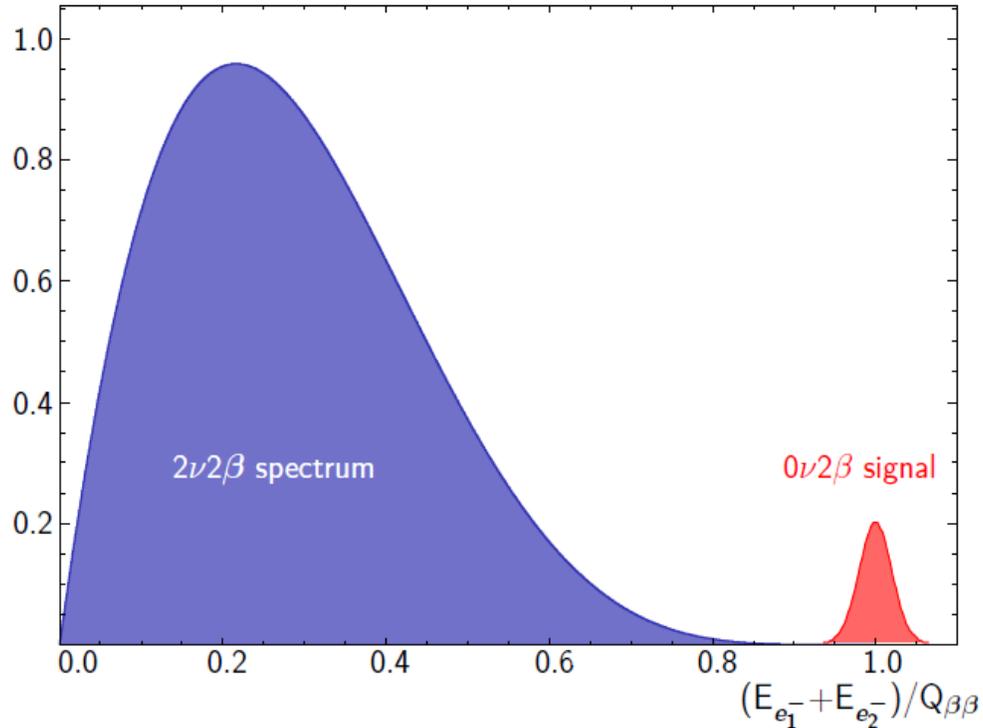


If observed:

- Majorana nature of neutrino
- Lepton number violation: $\Delta L=2$
- Absolute neutrino mass scale determination and information about the mass hierarchy
- $T_{1/2} (0\nu 2\beta) > 10^{24} - 10^{26} \text{ years}$

Experimental signature

- Sum energy spectrum of 2β decay:



$$T_{1/2}^{0\nu 2\beta} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

a – isotopic abundance

ϵ – detection efficiency

M – source mass

t – exposure time

b – background index at ROI

δE – energy resolution at ROI

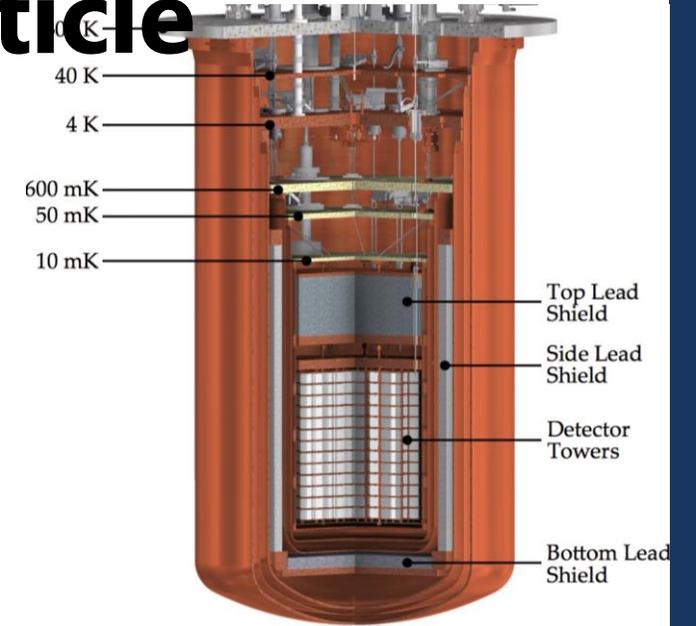
In case of zero-bkg: $T_{1/2}^{0\nu 2\beta} \propto a \cdot \epsilon \cdot M \cdot t$

«Zero-background» ton-scale experiment with high energy resolution ($\sim 0.2\%$):

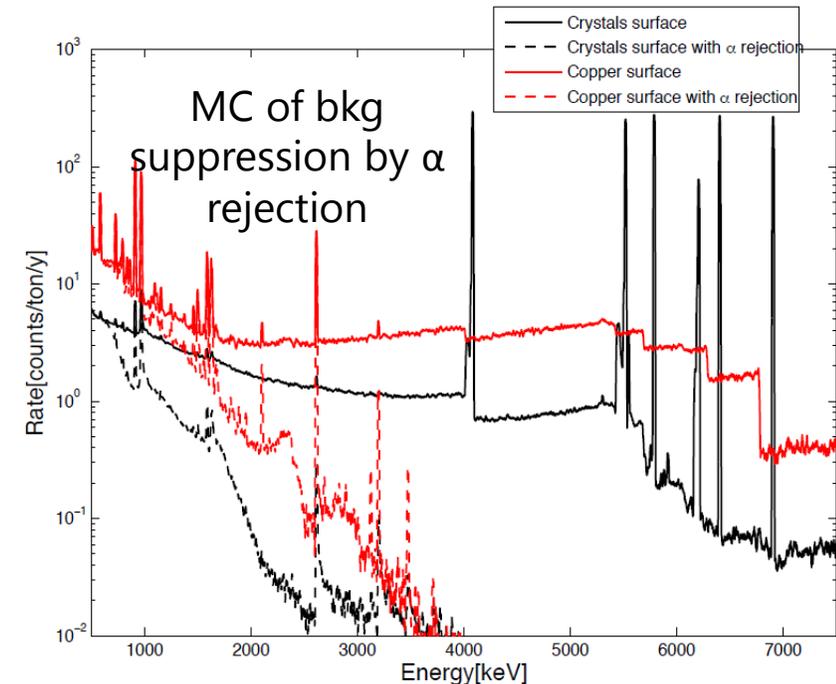
$$b \leq 10^{-4} \text{ c}/(\text{keV} \times \text{kg} \times \text{y})$$

CUPID (CUORE Upgrade with Particle IDentification)

- **CUORE:**
- **Cryogenic Underground Observatory for Rare Events:** the first cryogenics **ton-scale double beta experiment (988×0.75 kg TeO₂ bolometers)** currently in data-taking phase.

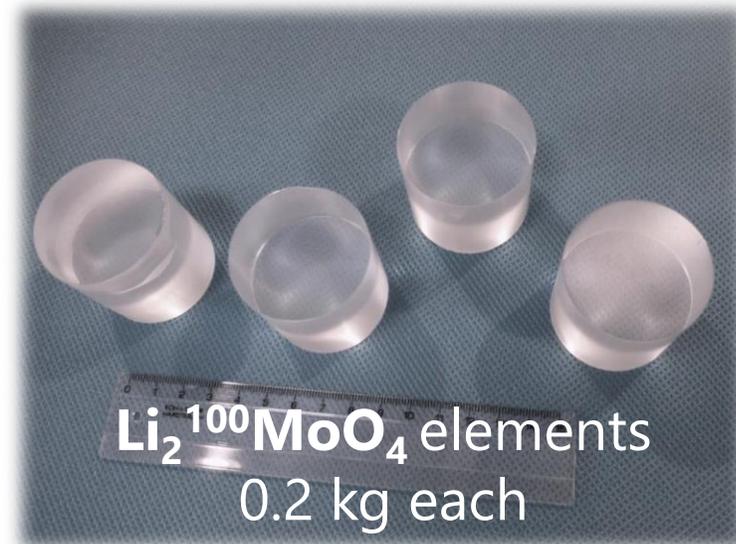


CUPID:
Follow-up using CUORE
facility with background
improved by a factor 100



5 years of LUMINEU R&D

- **Protocol of $\text{Li}_2^{100}\text{MoO}_4$ production was developed:**
 - **Mo purification / crystallization protocols**
 - Successful program to **control ^{40}K content** (< 5 mBq/kg)
 - Efficient use of existing **10 kg of ^{100}Mo**
- **Batch of 20 $\text{Li}_2^{100}\text{MoO}_4$ crystals of 0.2 kg each was produced:**
 - high optical quality
 - high crystal yield (**~ 80-85%**)
 - low irrecoverable losses of ^{100}Mo (**~3%**)



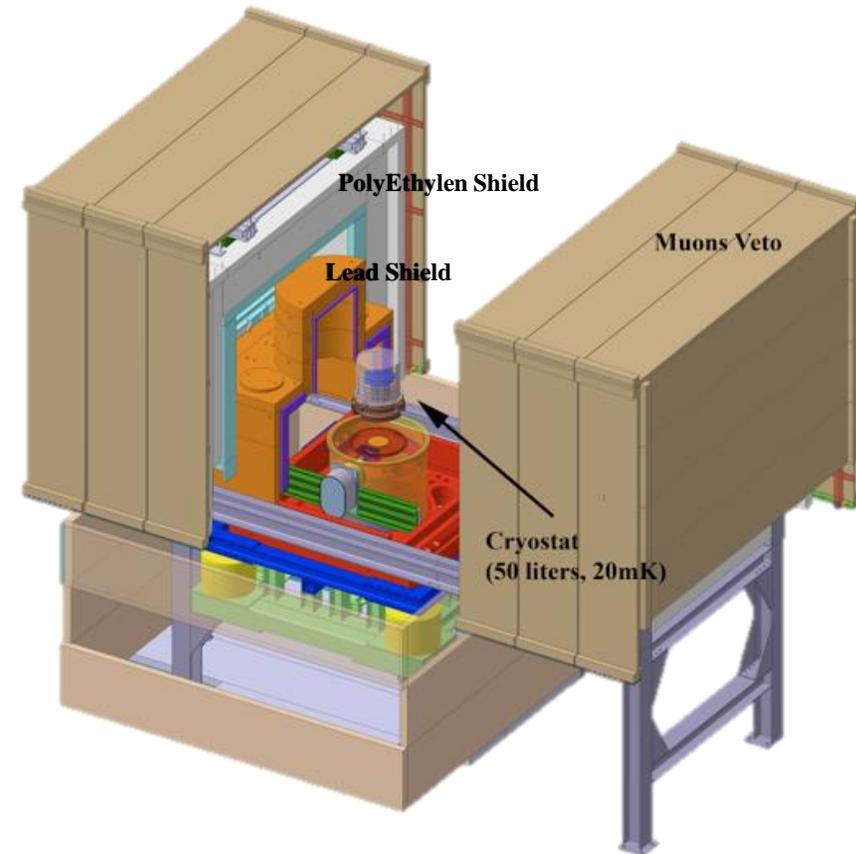
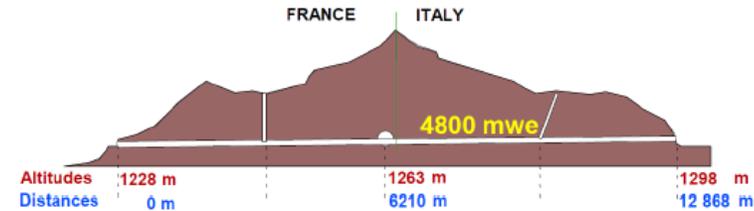
LSM underground laboratory

- **Laboratoire Souterrain de Modane (LSM):**

- Frejus tunnel
- 1.7 km rock overburden (~4.8 km w.e.)
- cosmic μ reduction = 5 muon/m²/day
- Deradonized air flow (~30 mBq/m³)

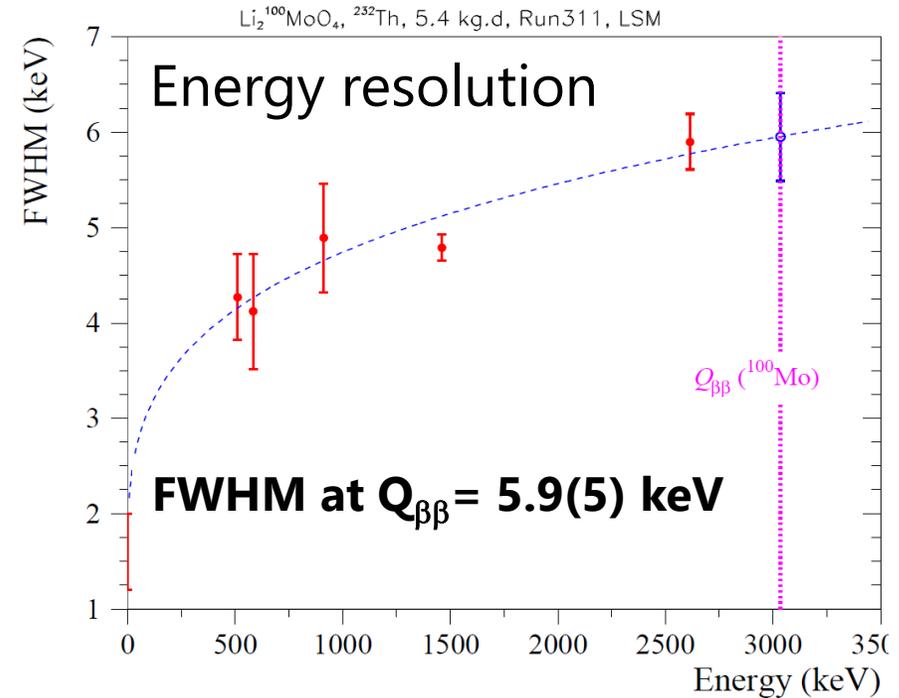
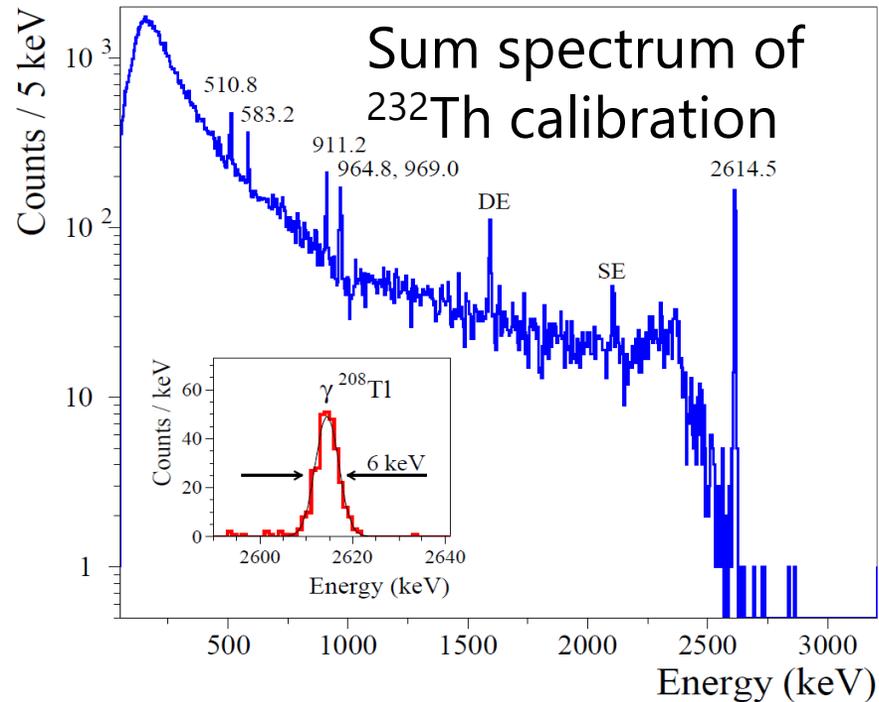
- **EDELWEISS set-up:**

- Clean room
- Copper cryostat
- Low radioactivity lead (min. 20 cm)
- Polyethylene (min. 50 cm)
- Monitoring of μ / n / Ra
- Muon veto



Energy resolution

- Test on array of four enriched detectors, $m = 4 \times 0.2$ kg, LSM (EDELWEISS setup)



	$\text{Li}_2^{100}\text{MoO}_4$ crystal #			
	1	2	3	4
FWHM (keV) at 2615 keV	5.8 ± 0.6	5.7 ± 0.6	5.5 ± 0.5	5.7 ± 0.6