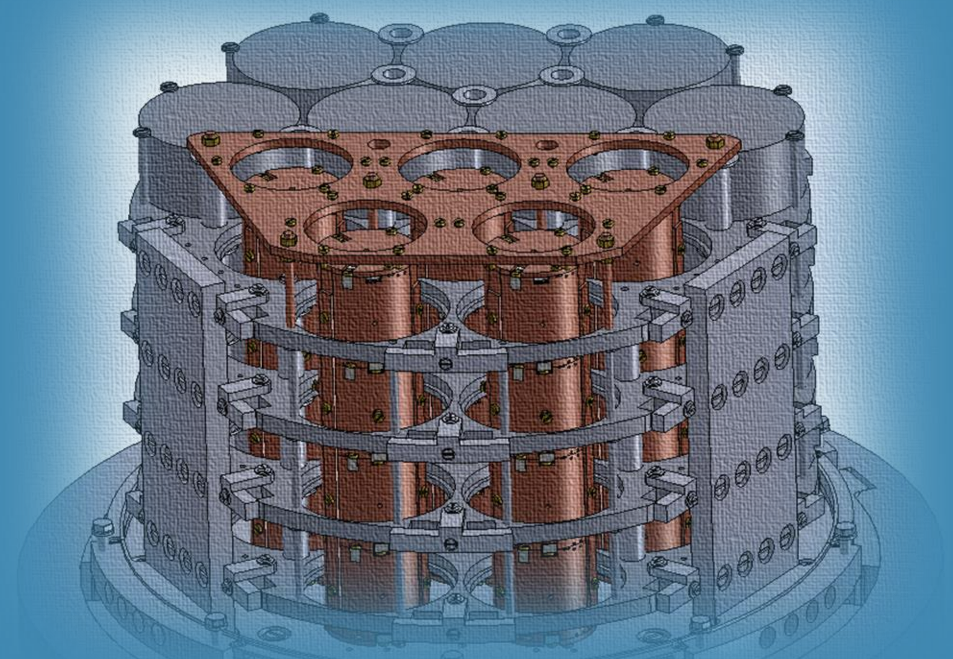
CUPID-Mo demonstrator: towards CUPID, a next generation $0\nu2\beta$ experiment



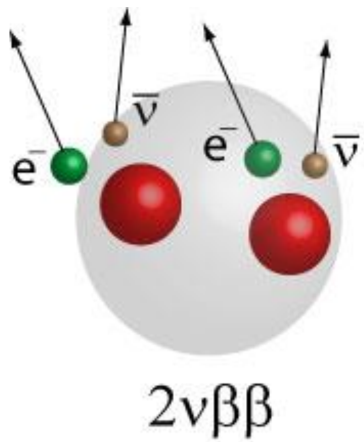
Anastasiia ZOLOTAROVA (IRFU/DPhP)

on behalf of the CUPID-Mo collaboration

Double Beta Decay

<u>Two neutrino 2β decay</u>

<u>Allowed by SM:</u>



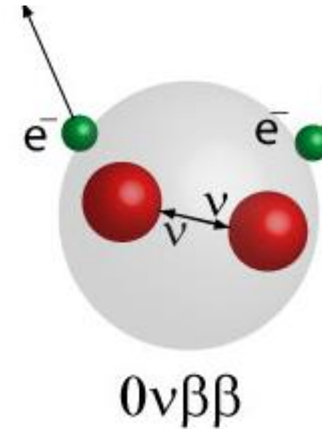
$$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\overline{\nu_e}$$

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

$T_{1/2}$ (2ν2β) ~ 10^{18}-10^{24} years

<u>Neutrinoless 2β decay</u>

<u>Beyond the SM:</u>



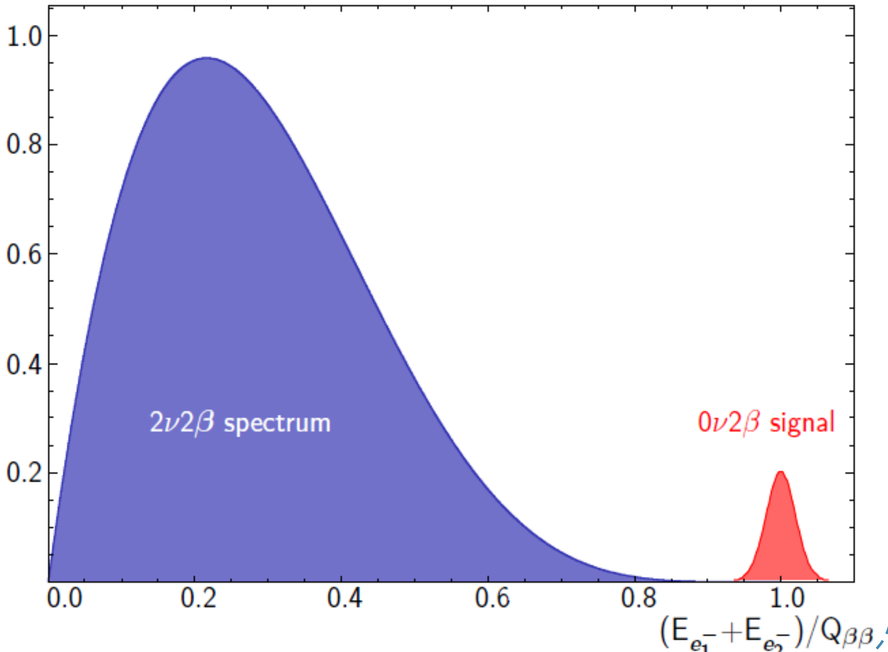
$$(A, Z) \rightarrow (A, Z+2) + 2e^{-}$$

If observed:

- Majorana nature of neutrino
- Lepton number violation: ΔL=2
- Absolute neutrino mass scale determination and information about the mass hierarchy
- **$T_{1/2}$ (0ν2β) > 10^{24} - 10^{26} years**

Experimental signature

Sum energy spectrum of 2β decay:



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

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: $T_{1/2}^{0\upsilon 2\beta} \propto a \cdot \epsilon \cdot M \cdot t$

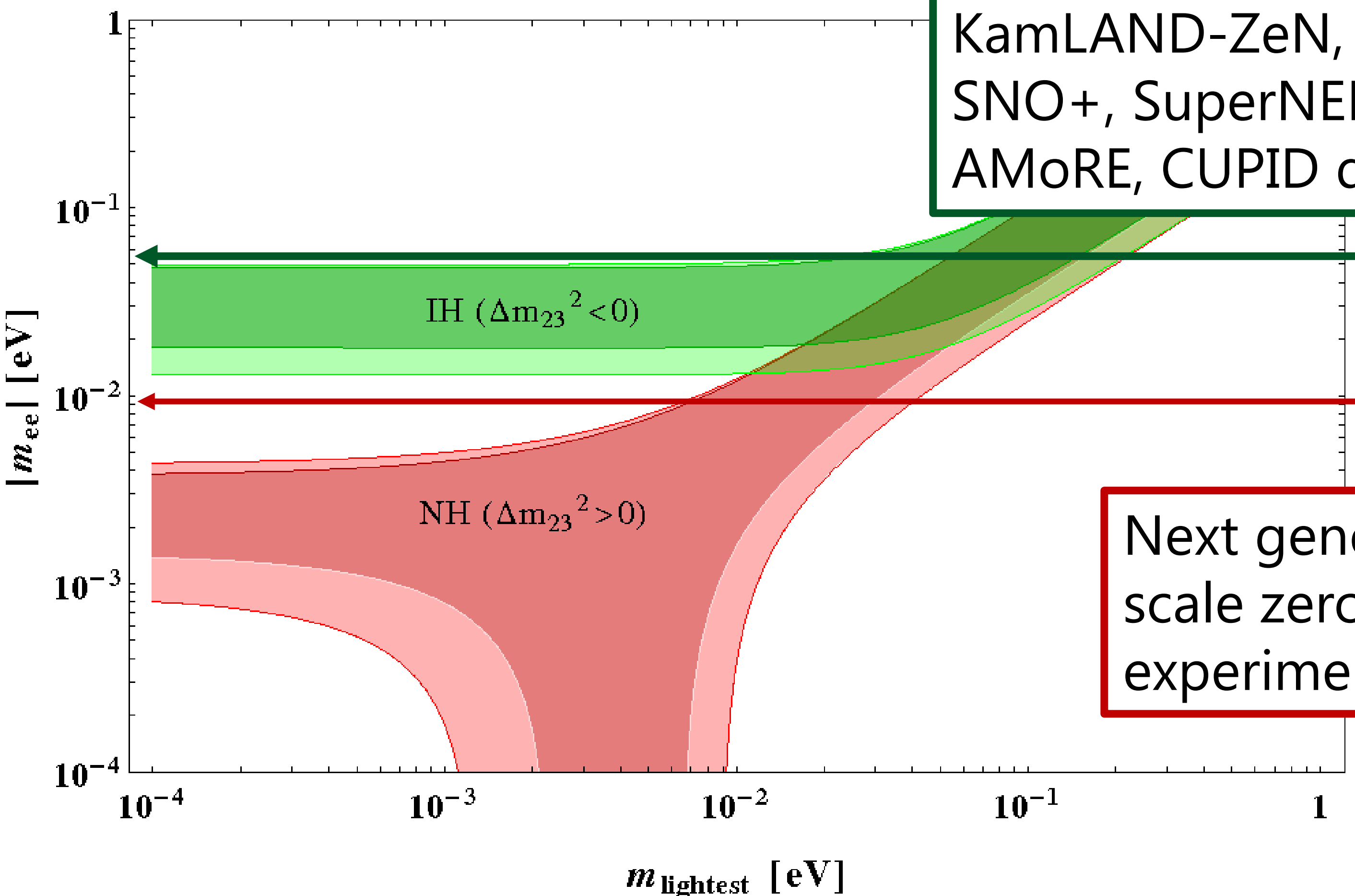
«Zero-background» ton-scale experiment
with high energy resolution (~ 0.2%):
b ≤10^{-4} c/(keV×kg×y)

Investigation of neutrino mass hierarchy

$$(T_{1/2}^{0\upsilon 2\beta})^{-1} \sim m_{\beta\beta}^2$$

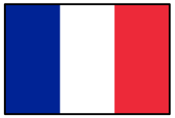
Effective Majorana Mass of the neutrino

Current and near future experiments: GERDA, Majorana, KamLAND-ZeN, EXO, CUORE, SNO+, SuperNEMO, NEXT, AMoRE, CUPID demonstrators



Next generation: ton-scale zero-background experiments

The CUPID-Mo collaboration



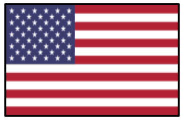
- Centre de Sciences Nucléaires et de Sciences de la Matière (CSNSM), Orsay, France
- CEA, Direction de la Recherche Fondamentale (CEA/DRF), Gif-sur-Yvette, France
- Institut de Physique Nucléaire de Lyon (IPNL), Lyon, France
- Laboratoire de l'Accélérateur Linéaire (LAL), Orsay, France

- Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

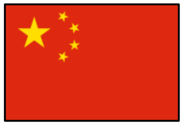
- Istituto Nazionale di Fisica Nucleare (Sezioni di Milano-Bicocca and Roma 1) (INFN), Frascati, Italy
- Laboratori Nazionali del Gran Sasso (LNGS), INFN, L'Aquila, Italy

- Kiev Institute of Nuclear Research (KINR), Kyiv, Ukraine

- Joint Institute of Nuclear Research (JINR), Dubna, Russia
- National Research Centre "Kurchatov Institute", Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
- Nikolaev Institute of Inorganic Chemistry (NIIC), Novosibirsk, Russia



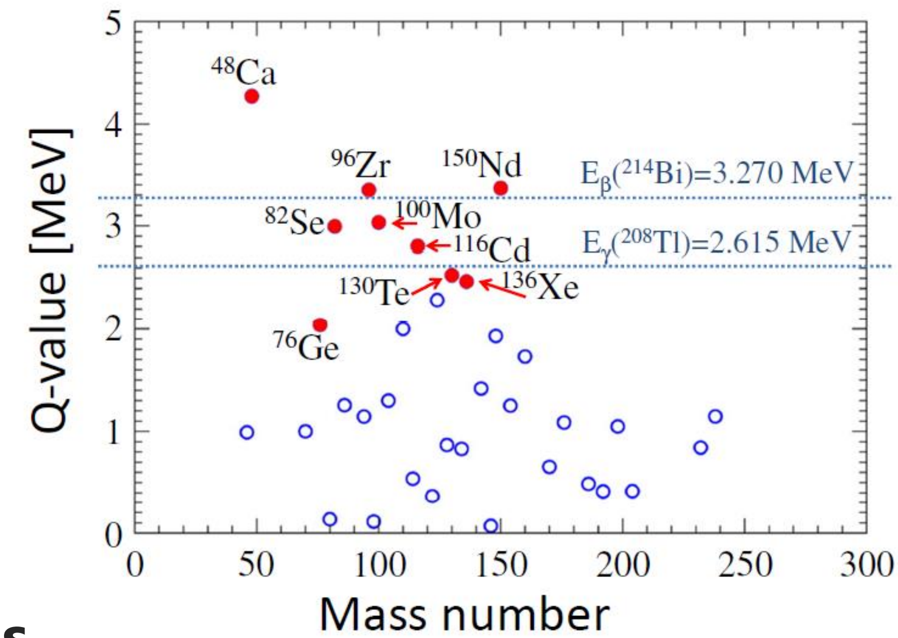
- Massachusetts Institute of Technology (MIT), Boston, US
- University of California, Berkeley (UCB/LBNL), Berkeley, US

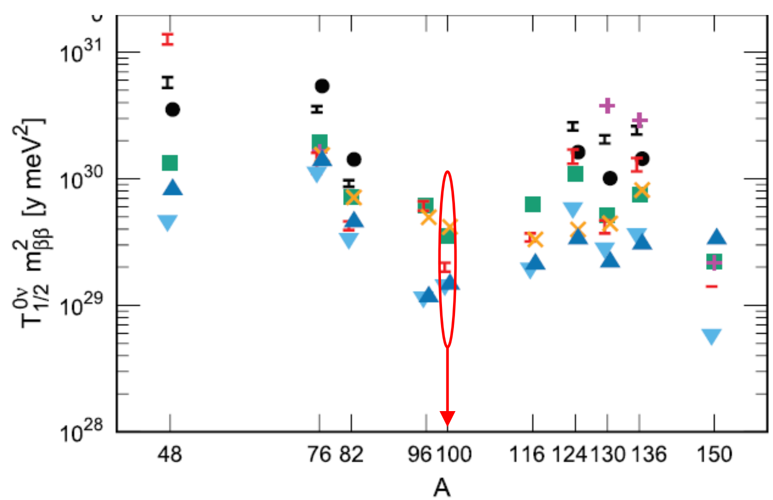


- Chinese CUPID Institutes (CUPID-China: Fudan, USTC), P.R. China

Isotope selection: why ^{100}Mo?

- High transition energy: **$Q_{\beta\beta}$ = 3034 keV**
- Natural abundance = 9.7%
- **Large-scale enrichment** is possible
- **Favorable theoretical predictions**
- High detection efficiency, energy resolution and powerful particle discrimination (**cryogenic scintillating bolometers**)

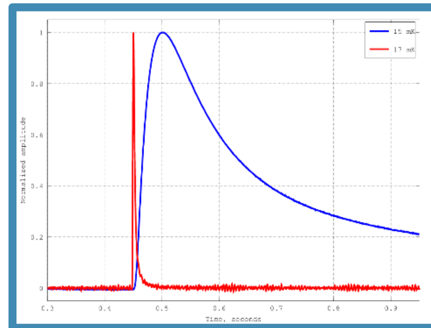




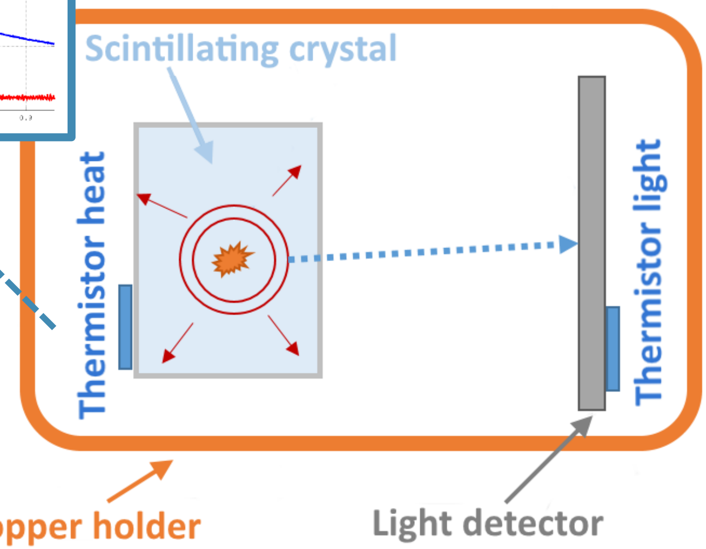
The most sensitive study of ^{100}Mo 0ν2β decay was performed by NEMO-3 using tracking-calorimetric approach

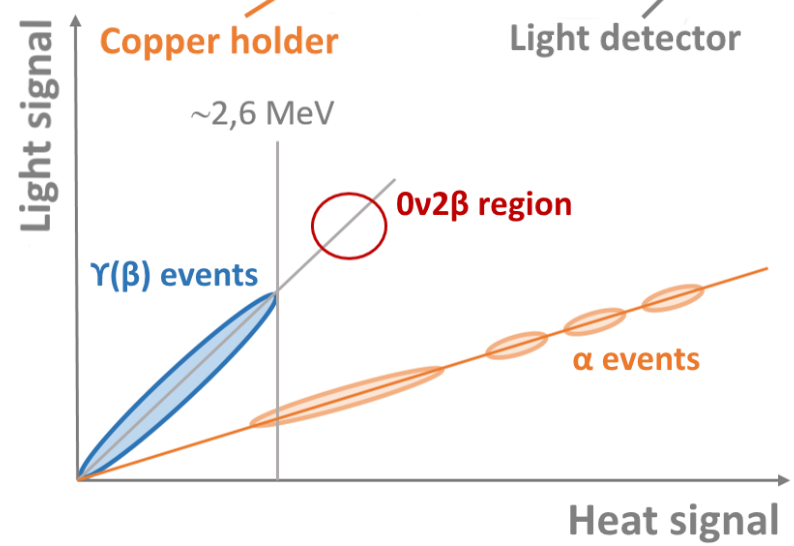
Scintillating bolometers

- **Source is embedded** in a crystal → High detection efficiency **(~100%)**
- **0.1-0.5 kg** typical crystal mass: possible to achieve large masses through arrays
- The deposited **energy** is measured as a **temperature increase** in a crystal, detectors operated at **~10 mK**
- High energy resolution: **5-10 keV (~0.2%)** in the ROI
- Scintillator →Particle discrimination using light: **>99.9 α background rejection**

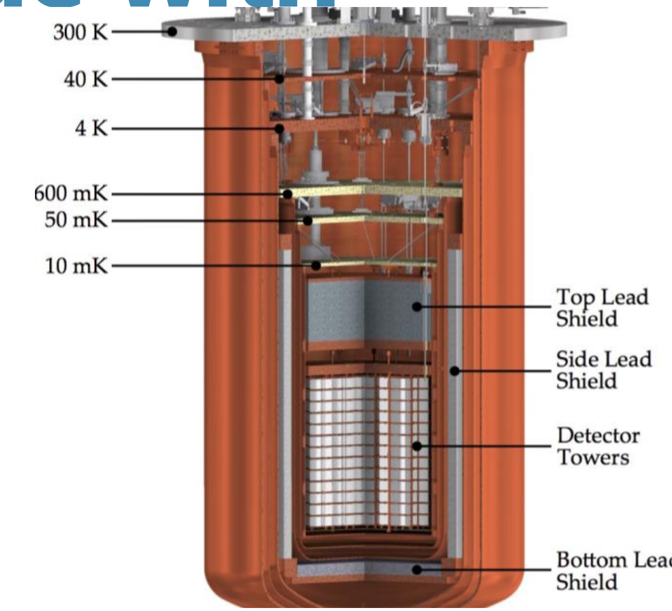


Typical signal**: 0.1 mK / MeV**, converted to **0.1-0.5 mV / MeV**



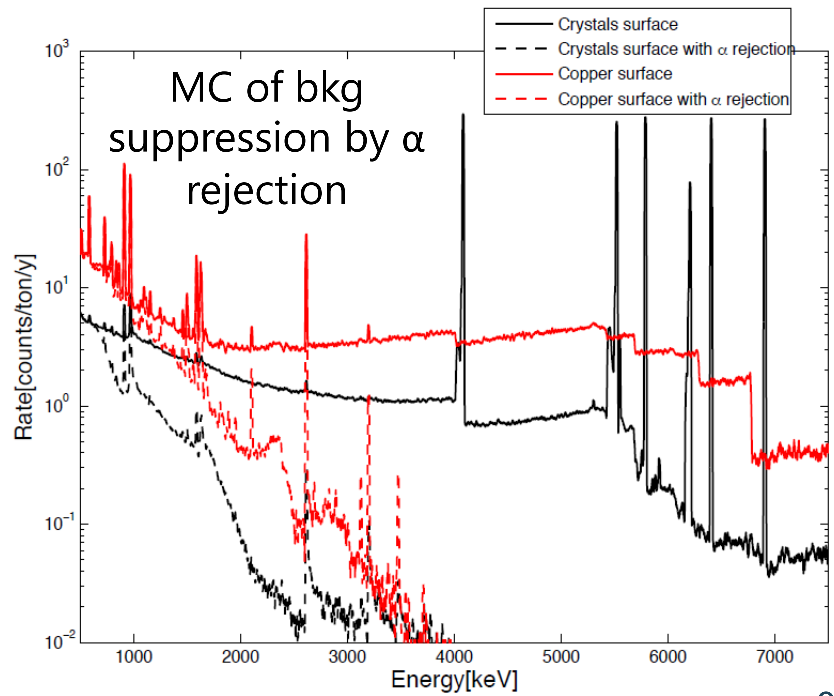


CUPID (CUORE Upgrade with Particle IDentification)



CUORE:

Cryogenic **U**nderground **O**bservatory for **R**are **E**vents: the first cryogenics **ton-scale double beta experiment (988×0.75 kg TeO_2 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

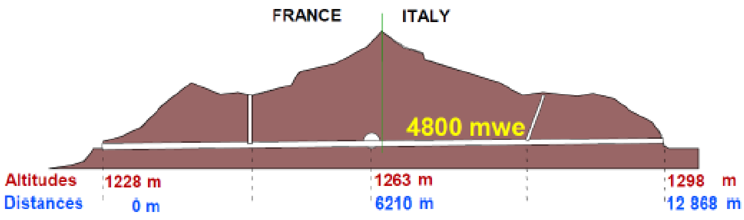
- **Protocol of $Li_2{}^{100}MoO_4$ production was developed:**
  - **Mo purification / crystallization protocols**
  - Successful program to **control ^{40}K content** (< 5 mBq/kg)
  - Efficient use of existing **10 kg of ^{100}Mo**

- **Batch of 20 $Li_2{}^{100}MoO_4$ 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

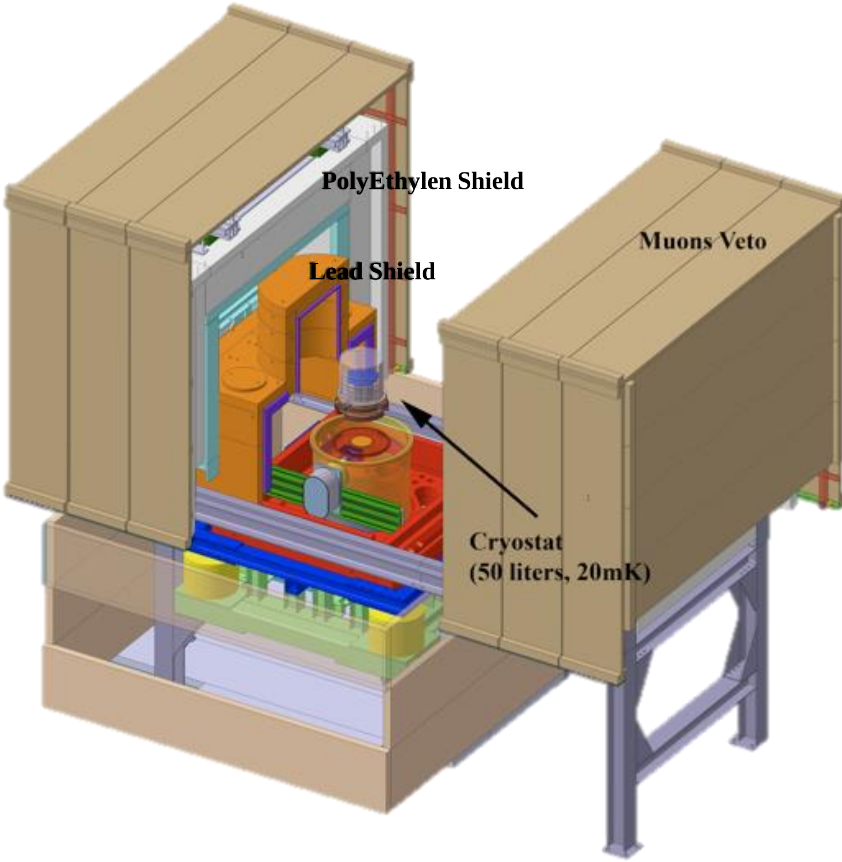
Laboratoire Souterrain de Modane (LSM):

- Frejus tunnel
- 1.7 km rock overburden (~4.8 km w.e.)
- cosmic μ reduction= 10^{-8}(1/m^{2}h)
- Deradonized air flow (~30 mBq/m^3)



EDELWEISS set-up:

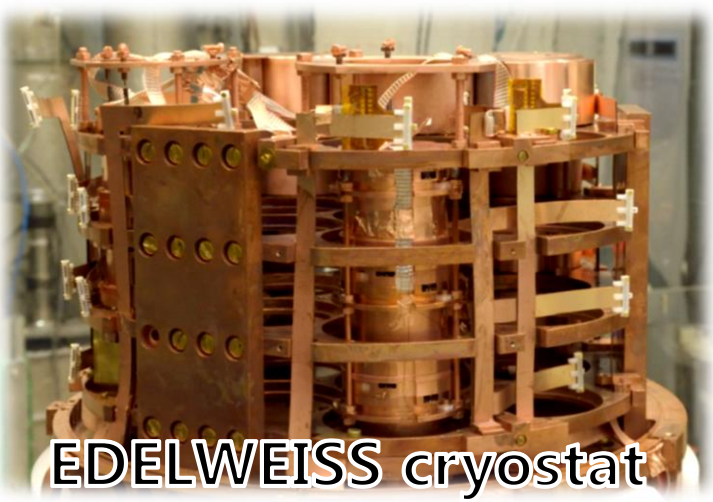
- Clean room
- Copper cryostat
- Low radioactivity lead (min. 20 cm)
- Polyethylene (min. 50 cm)
- Monitoring of μ / n / Ra
- Muon veto

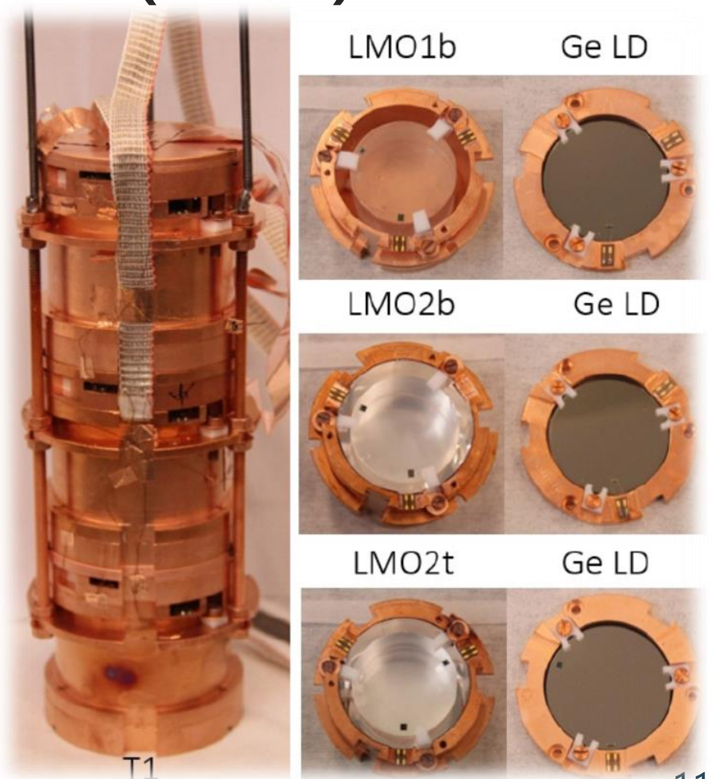


$Li_2{}^{100}MoO_4$ scintillating bolometers performance

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

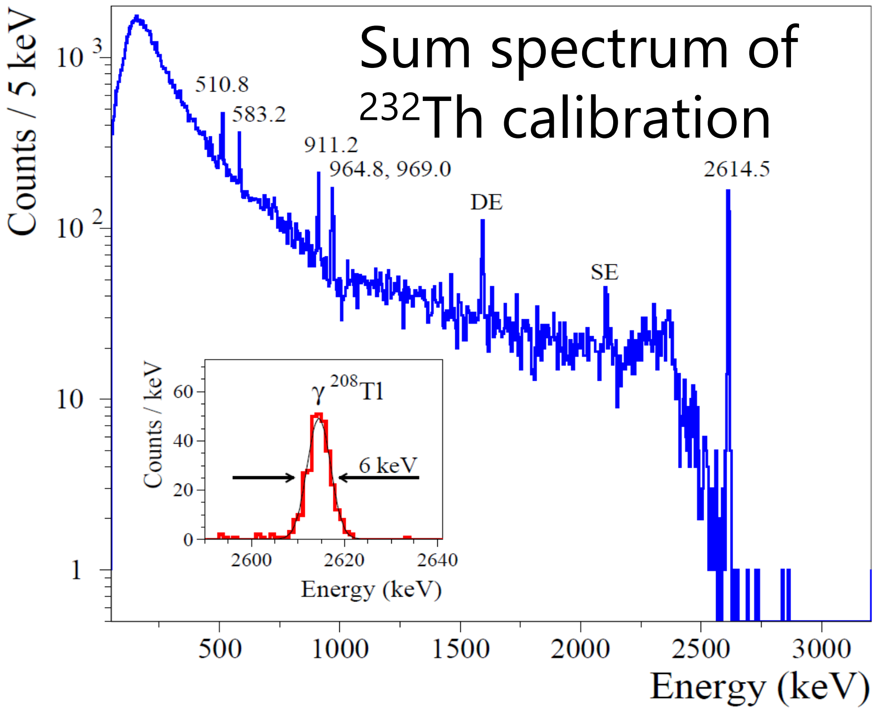
- uniform performance, good reproducibility
- high energy resolution: **4-6 keV FWHM** in ROI **(~0.2%)**
- rejection of α's at the level of **>9σ**
- high radiopurity: **^{232}Th, ^{238}U <6 μBq/kg; ^{40}K< 1.3 mBq/kg**

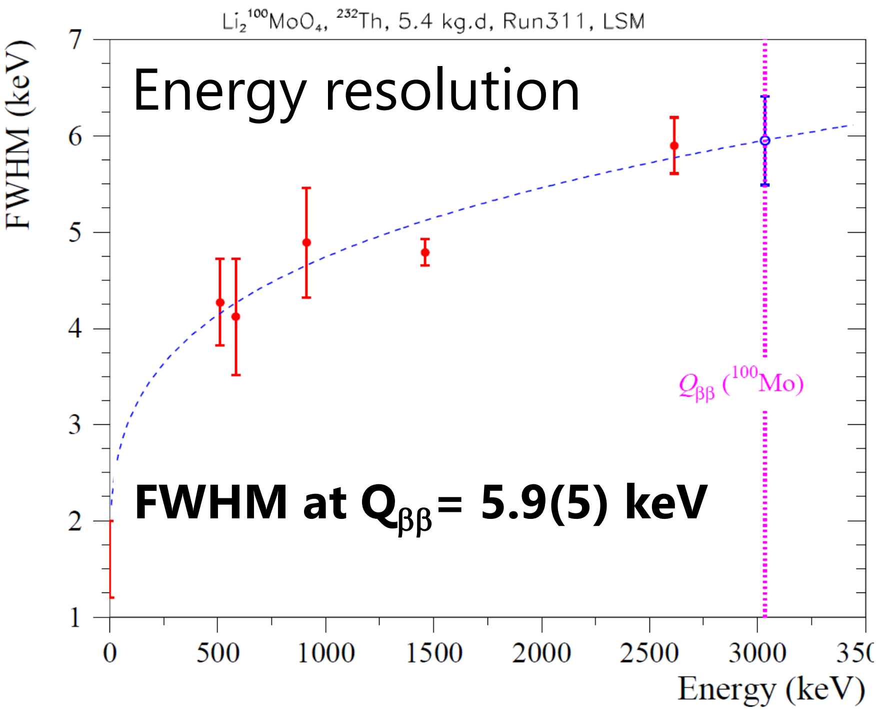




Energy resolution

Test on array of four enriched detectors, m =4×0.2 kg, LSM (EDELWEISS setup)

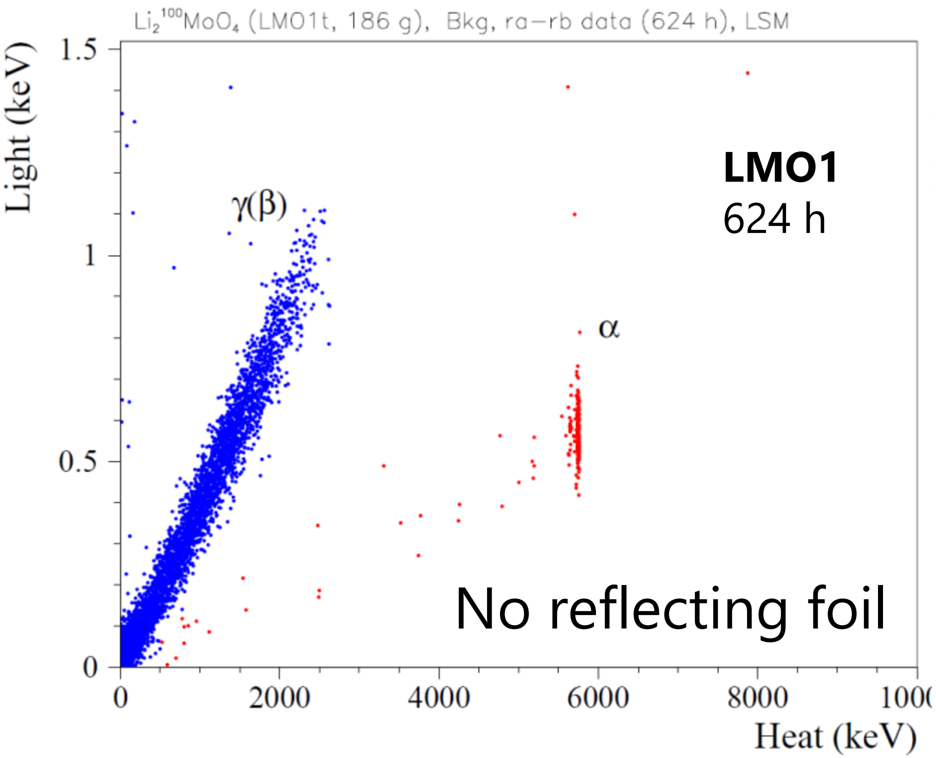


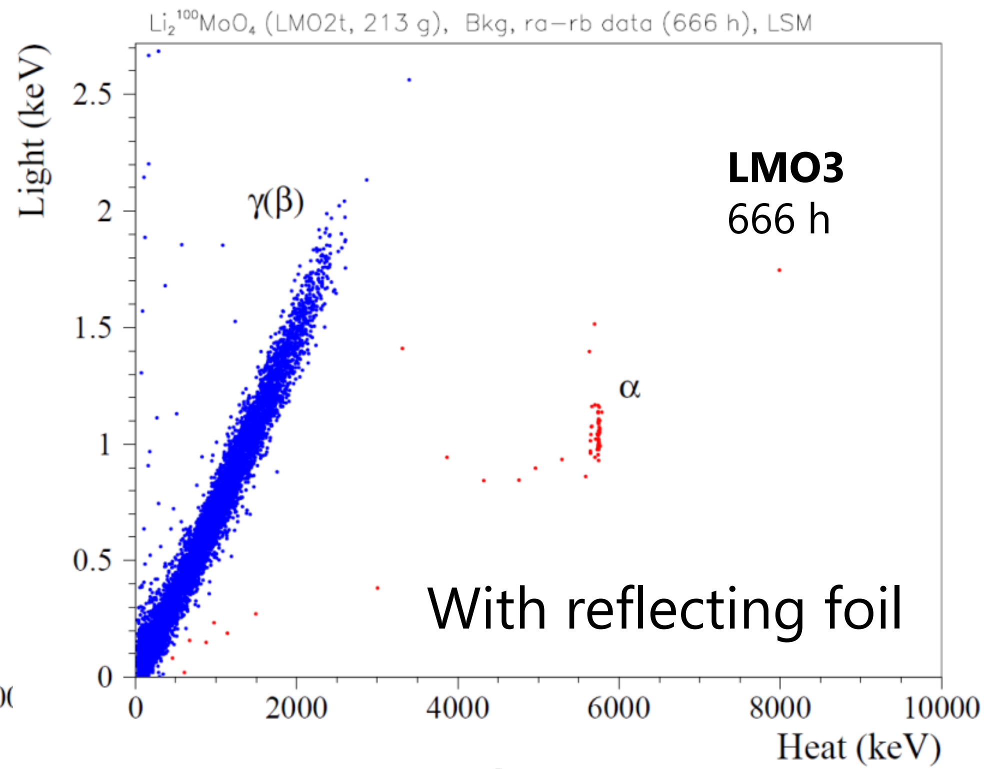


	$Li_2{}^{100}MoO_4$ crystal #			
	1	2	3	4
FWHM (keV) at 2615 keV	**5.8±0.6**	**5.7±0.6**	**5.5±0.5**	**5.7±0.6**

α rejection

>9σ α rejection with **>99 % β acceptance** (LY ~ 0.4-0.7 keV/MeV)

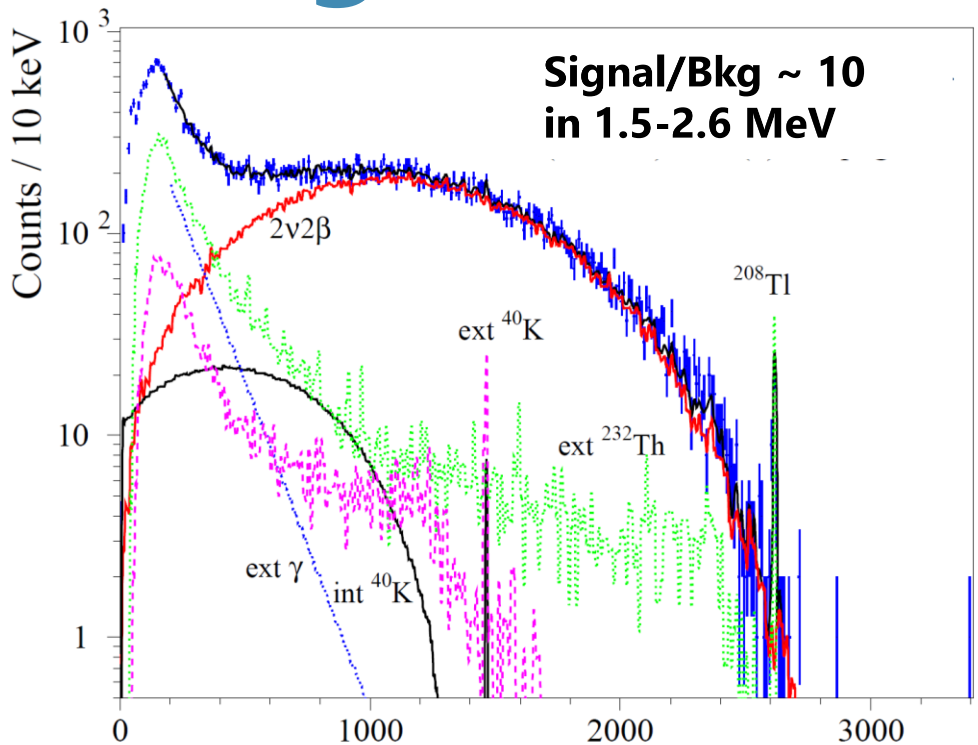




Internal activity is compatible with b ~ 10^{-4} c/(keV kg y)

Activity μBq/kg	$Li_2{}^{100}MoO_4$ crystal #			
	1	2	3	4
^{228}Th	≤4	≤6	≤3	≤5
^{226}Ra	≤6	≤11	≤3	≤9

Investigation of 2ν2β in ^{100}Mo

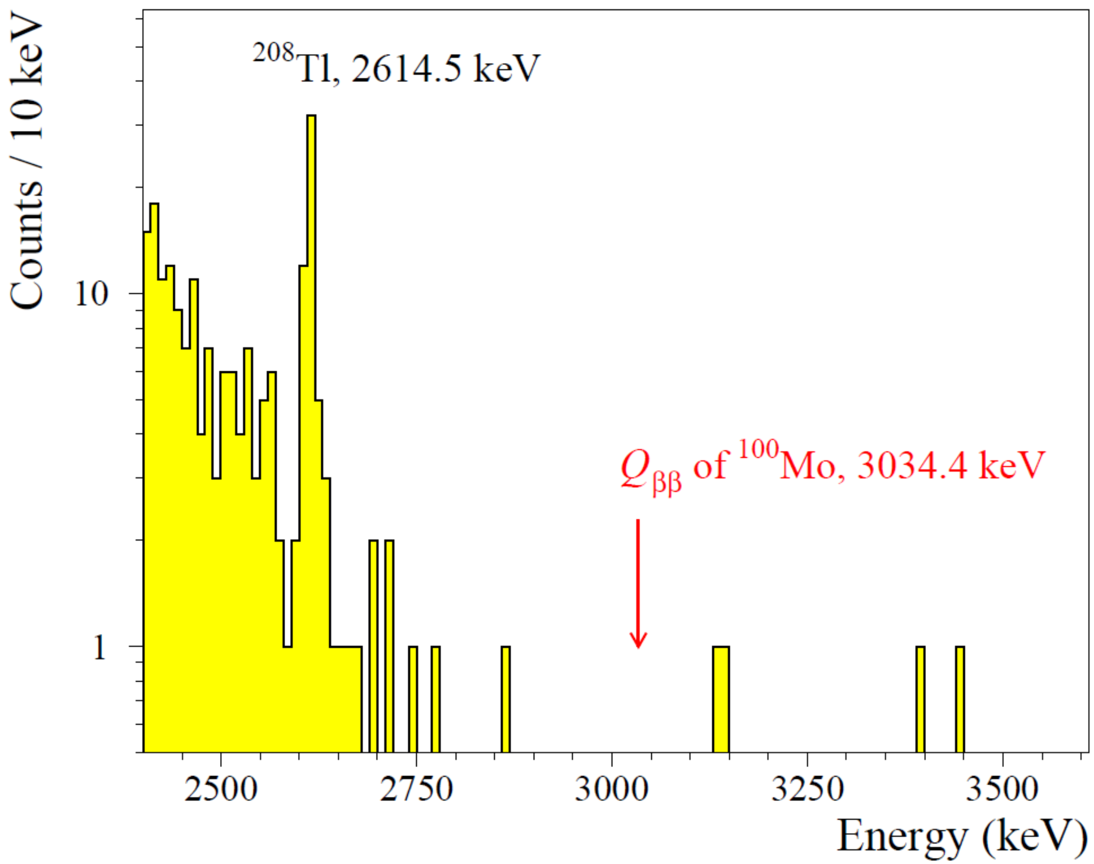


- Exposure = 29 kg×d
- Eff_{PSD} =97%
- Enrichment: 96.9% of ^{100}Mo
- Fit: 160 – 2650 keV
  Effect: 24320±229 decays

One of the **most precise** ^{100}Mo **2ν2β** half-life values

Experiment	$T_{1/2}^{2\nu2\beta}$ (10^{18} y)	Exposure of ^{100}Mo	Reference
LUMINEU	**6.92±0.06(stat)±0.36(syst)**	0.04 kg×y	AIP CP 1894, 020017 (2017)
LUMINEU	**6.90±0.15(stat)±0.37(syst)**	0.02 kg×y	EPJC 77, 785 (2017)
LUCIFER (ZMO)	**7.15±0.37(stat)±0.66(syst)**	0.08 kg×y	JPG 41 075204 (2014)
NEMO-3	**7.11±0.02(stat)±0.54(syst)**	7.37 kg×y	PRL 95,182302 (2005)

Search for 0ν2β in ^{100}Mo



- ROI = 10 keV window
- $\text{eff}_{0\nu2\beta}$ = 73 % ROI
- Eff_{PSD} =97%
- Exposure = 39 kg×d
- b=0.06(3) c/(keV kg y)
- limS=2.49 counts

Origin of the background:

- ^{208}Tl coincidences from close Th contamination
- Muon-induced events (muon veto data not yet used)

These issues will be solved in the next run

Experiment	lim $T_{1/2}^{0\nu2\beta}$ (y)	Exposure of ^{100}Mo	$\langle m_{\beta\beta}\rangle$ (eV)	Reference
LUMINEU	**0.7 × 10^{23}**	0.11 kg×y	**≤(1.4-2.4)**	AIP CP 1894, 020017 (2017)
NEMO-3	**1.1 × 10^{24}**	34.3 kg×y	**≤(0.3-0.6)**	PRD 92, 072011 (2015)

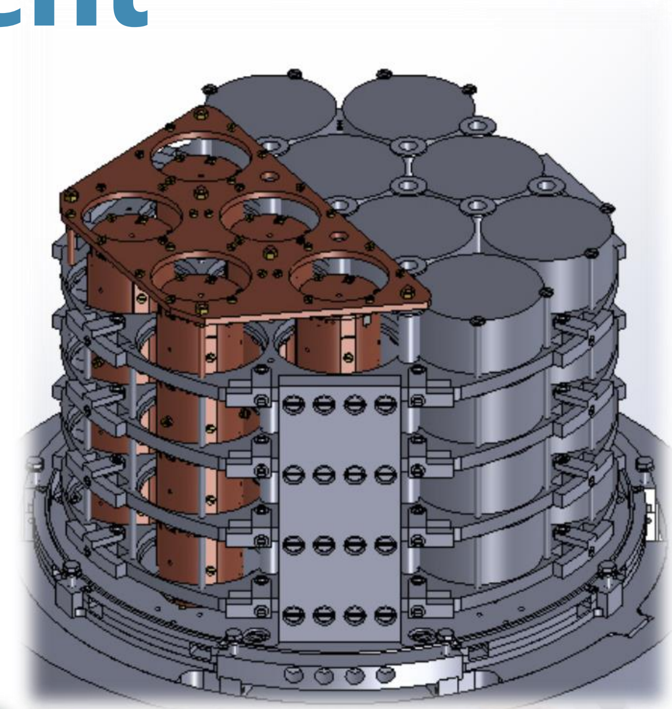
CUPID-Mo experiment

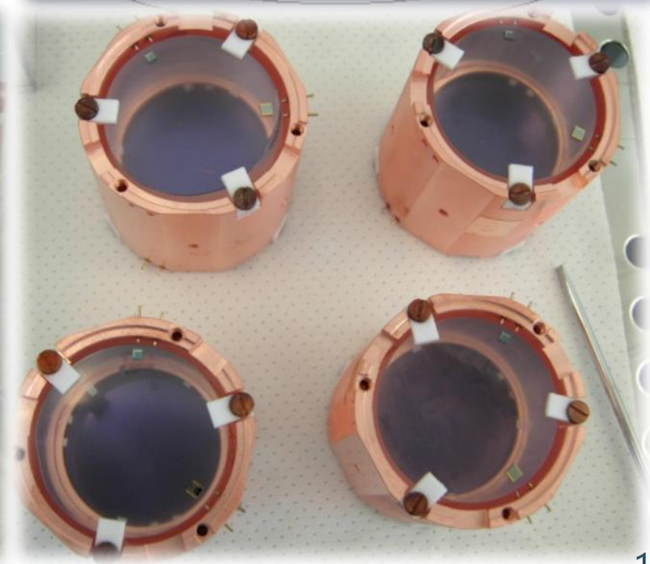
LUMINEU R&D successfully finished

CUPID-Mo $0\nu2\beta$ experiment with ≈ 5 kg of ^{100}Mo is in preparation

Phase I: 20 $\mathbf{Li_2{}^{100}MoO_4}$ (2.34 kg of ^{100}Mo) +20 Ge light detectors in the EDELWEISS set-up (LSM, France)

Start of the data taking: February 2018





Sensitivity of CUPID-Mo

The goal for 6 months run:

- Confirm the reproducibility of the $Li_2{}^{100}MoO_4$ technology on the larger scale
- 0-background in ROI
- Physics case: limits on $0\nu2\beta$ half-life:

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

- **b = 1×10^{-3} counts/(keV kg y)**
- **10 keV** energy window
- **70%** efficiency

Configuration	Exposure (kg×y ^{100}Mo)	lim $T_{1/2}^{0\nu2\beta}$ (y)	lim $\langle m_{\beta\beta}\rangle$ (meV)
20×0.5 crystal×y	**1.2**	**1.3 × 10^{24}**	**330 – 560**
20×1.5 crystal×y	**3.5**	**4.0 × 10^{24}**	**190 – 320**
40×3.0 crystal×y	**14**	**1.5 × 10^{25}**	**100 – 170**

Possible configurations of a Mo-based final CUPID experiment

Fill all the CUORE cryostat volume with enriched LMO crystals

Single element	Number of elements	Isotope mass (kg)	Number of ^{100}Mo nuclei
∅50×50 mm – 300 g	1260	213	1.2×10^{27}
∅60×40 mm – 350 g	1092		
45×45×55 mm – 340 g	1110		

If pulse-shape discrimination works for α/surface background rejection, a configuration **without light detectors** can be envisaged. If light detectors are kept, the available volume for the source will be reduced by ~10%.

Background (c/(keV kg y))	Number of BKG counts (8 keV, 10 y)	Count limit (90% c.l.)	Half life limit (90% c.l.)	$\langle m_{\beta\beta}\rangle$ (meV)
1×10^{-4}	3	4.4	1.4×10^{27}	7.3 – 21
2×10^{-5}	0.6	2.9	2.2×10^{27}	5.9 – 17

CROSS: new advancement opportunity

ERC advanced grant CROSS (start 1/1/2018)

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

CROSS is a pilot bolometric experiment to search for 0n-DBD

- **Core of the project** (high risk / high gain)
  Surface background rejection through **pulse shape discrimination**
  - **Surface sensitivity** through **superconductive Al film coating**
  - **Fast NbSi high-impedance TES** to replace / complement NTDs

  Technologies mastered by CSNSM

  → **get rid of light detectors**

- Complete crystallization of available **^{100}Mo (10 kg)** in Li_2MoO_4 elements
- Purchase / crystallize **^{130}Te (up to 15 kg)** in TeO_2 elements
- Run demonstrator in a dedicated cryostat (LSC – Spain)

Main CUPID R&D in France

CLYMENE
Li_2MoO_4 crystals in France
SSS 65, 41 (2017)

CUPID-Mo → Scintillating bolometers

- Favored isotope: ^{100}**Mo**
  EPJC, 77, 785 (2017)
- Keep technology ready for ^{116}**Cd**

CYGNUS
Paris Sud chair
EPJC 76, 487(2016)

CUPID-Te → High-performance light detectors

- Luke effect

PLB 767, 321 (2017), arXiv:1710.07988

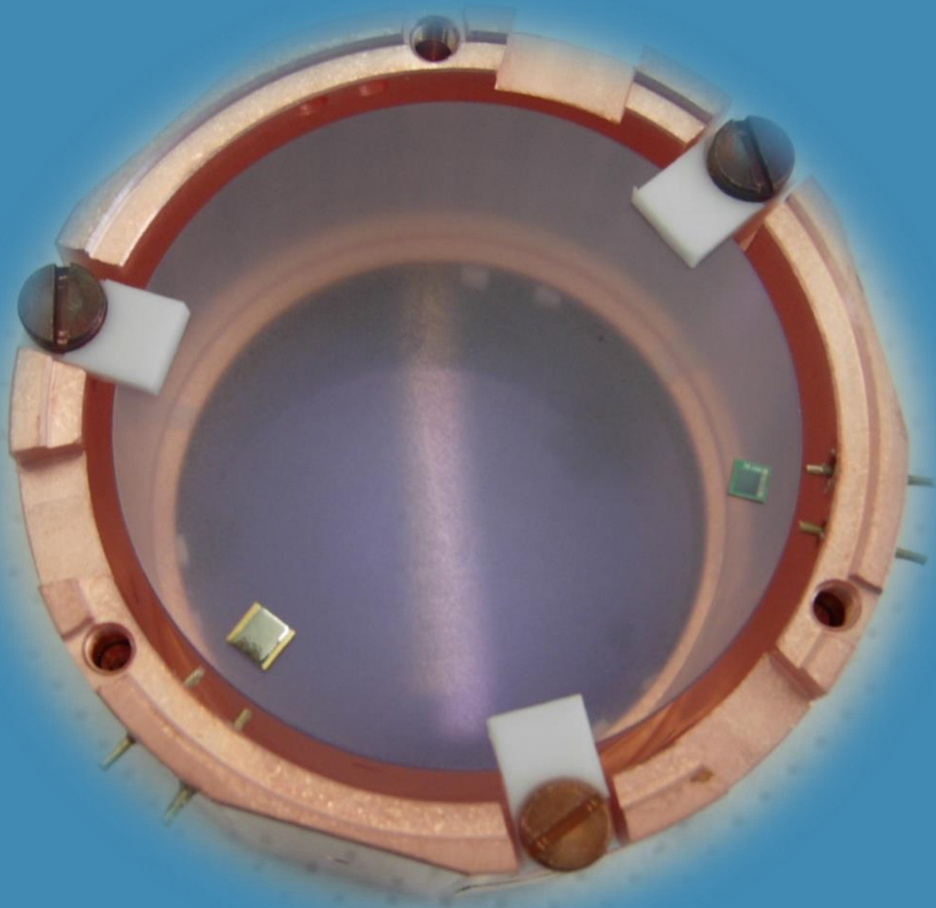
CUPID-CROSS → Surface sensitivity
(both in **TeO_2** and **Li_2MoO_4**)

Conclusions

- **LUMINEU R&D** successfully developed **mature technology** of **$Li_2{}^{100}MoO_4$** scintillating bolometers with high performance: **a few keV energy resolution, full α/β separation, radiopurity of less than few μBq/kg U/Th.**
- **One of the most precise** half-life measurement for the **$2\nu2\beta$ decay** of ^{100}Mo was performed with four crystals and reasonably **high sensitivity** to the **$0\nu2\beta$ decay** have been achieved even with considerably low statistics: **0.1 kg×y.**
- **CUPID-Mo:** measurement with 20 crystals will start in February 2018 → demonstration of the applicability of **$Li_2{}^{100}MoO_4$** technology for **CUPID, a ton-scale $0\nu2\beta$ experiment.**
- **Several CUPID R&D activities** are ongoing **in France.**

References

- D.V. Poda et al., **"^{100}Mo-enriched Li_2MoO_4 scintillating bolometers for 0ν2β decay search: from LUMINEU to CUPID-0/Mo projects"** AIP Conf. Proc. 1894 (2017) 02017
- E. Armengaurd 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!

Backups

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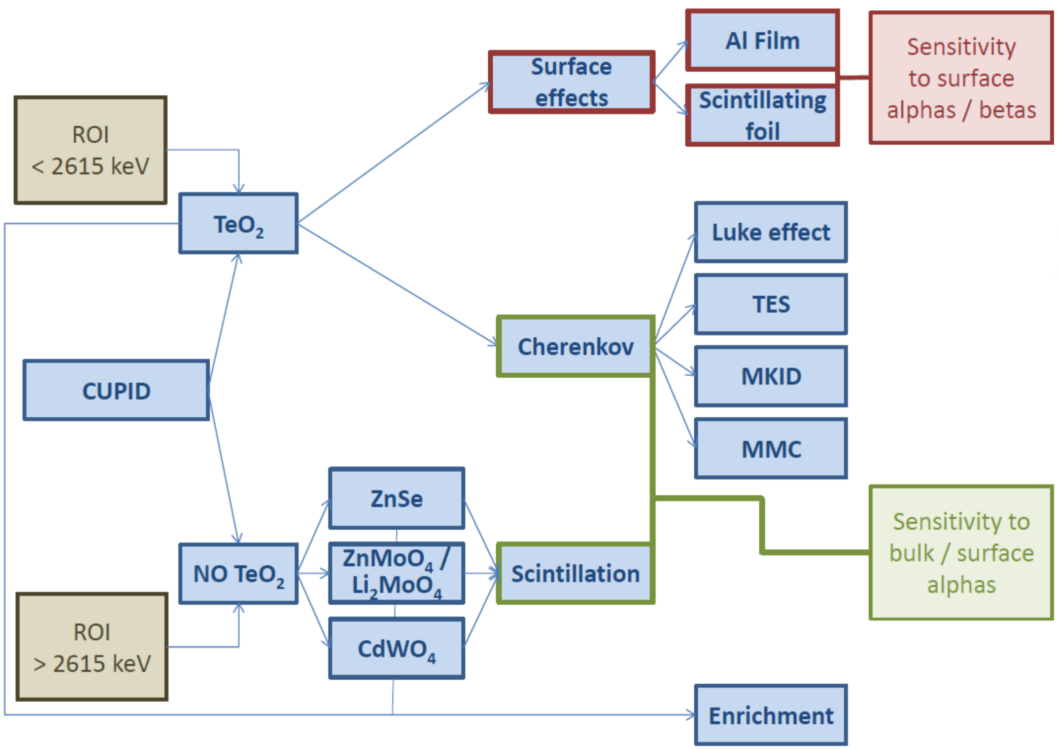
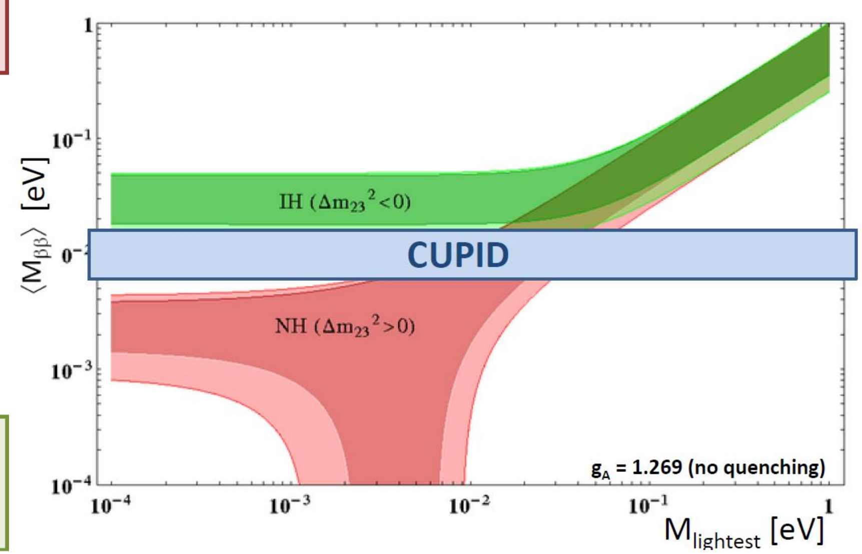
CUPID development

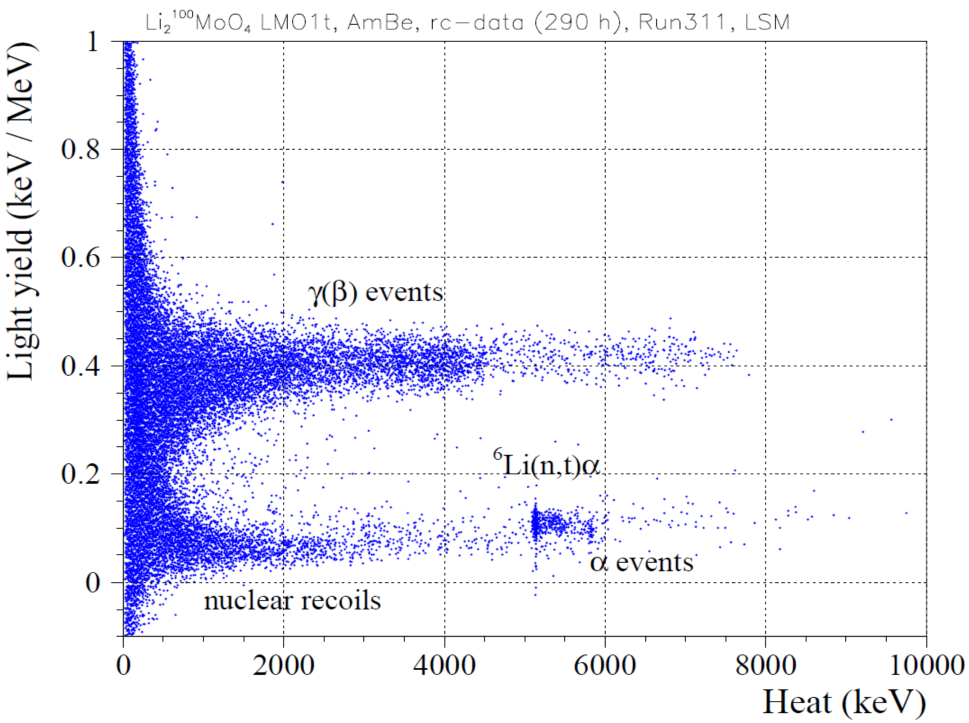
- Enriched materials
- Reduce/control background from materials and from muon /neutrons
- Improve detector technology to get rid of α/surface background

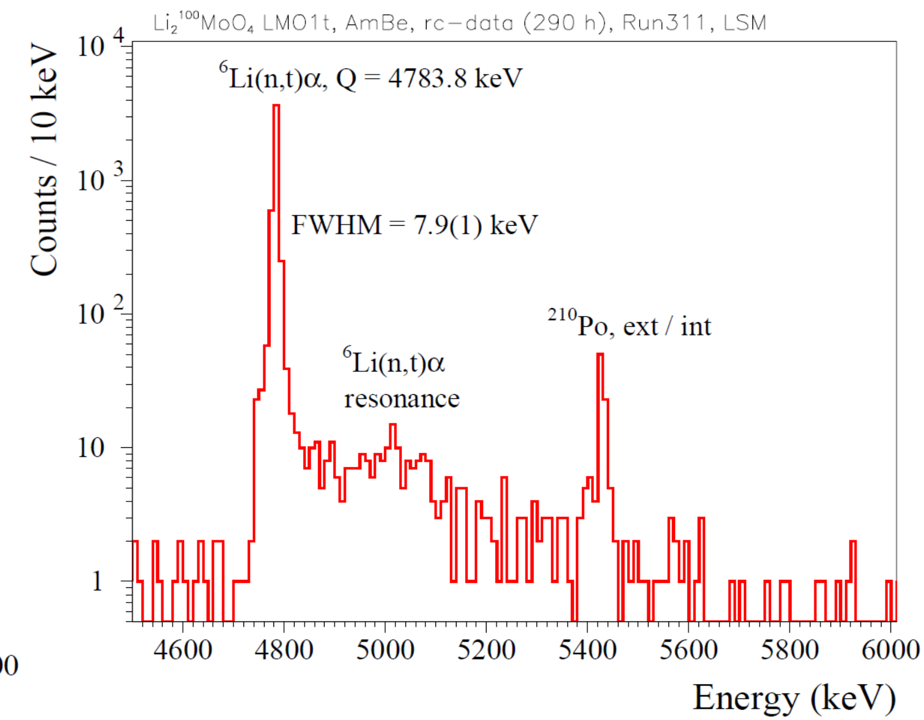




Neutron calibration

Discrimination power: 9-14 σ





$Li_2{}^{100}MoO_4$ contains **7.6% of ^{6}Li** which allows to detect neutrons capture on Li: **world record resolution** of thermal n capture on ^{6}Li **(FWHM = 6-11 keV at 4783 keV)**

Enrichment and crystallization: cost and time lines

Enrichment

Present knowledge about cost and production rate (AMoRE collaboration):
Cost: 80 € /g
Production rate: ~40 kg/y – Krasnoyarsk (Russia) - http://www.ecp.ru/eng/
Total cost: 17 M€
Total time: 5.6 y

Crystal growth

Estimation from NIIC-Novosibirsk
Preparation of ~ 10 set-ups (1 year, 250 k€ in advance)
Growth of ~ 1300 elements: 2 years
Cost: 3 k€/crystal
Total cost: 4.15 M€
Total time: 3 y

→ **Diversify crystal production plants**
(CLYMENE, CUPID-China…)