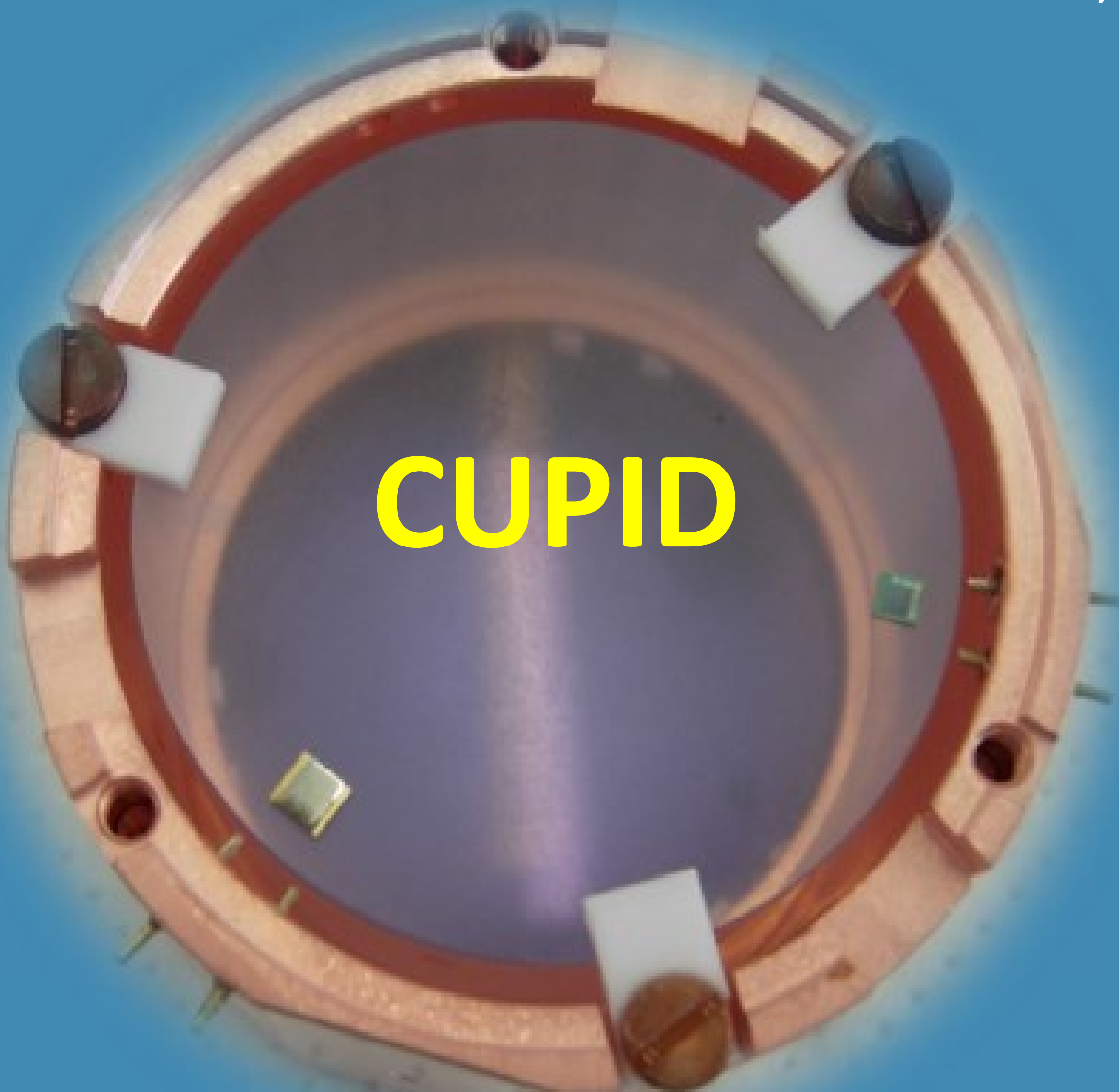
Journée Double Bêta
France

September 4th, 2018
APC, Paris



CUPID

Andrea Giuliani

(on behalf of the bolometric Double Beta Decay community in France)

Strategy

Objective

Build a **word-leading** next-generation experiment on $0\nu\beta\beta$ decay: **CUPID**

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How to reach this objective:

R&D on LMO technology +

CUORE infrastructure +

Demonstrators +

Enrichment/Crystallization =

CUPID

$Li_2{}^{100}MoO_4$ scintillating bolometers developed in **ANR LUMINEU** (2012-2017)

CUORE is taking data in LNGS: successful implementation of 1 ton bolometric mass

Test of the technology at the ~20 kg scale
CUPID-Mo is installed in LSM – two more setups in LNGS, LSC (**ERC CROSS** (2018-2022)

Russian companies
Encouraging results in France with crystals from **ANR CLYMENE** (2016-2020)

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PAST

CUORE is tak… LNGS: successful implementati… of 1 ton bolometric mass

Test of the technol… 20 kg scale **CUPID-Mo** … – two more setups in LN… **ERC CROSS** (2018-2022)

PRESENT

Russian companies
Encouraging … with crystals from **ANR** … 016-2020)

FUTURE

Outline

- Challenges in $0\nu2\beta$ decay and the CUPID way
- Scintillating bolometers and ^{100}Mo
- Results with $Li_2{}^{100}MoO_4$ crystals
- Demonstrators: CUPID-Mo and CROSS
- CUORE and its background model
- Mo-based CUPID

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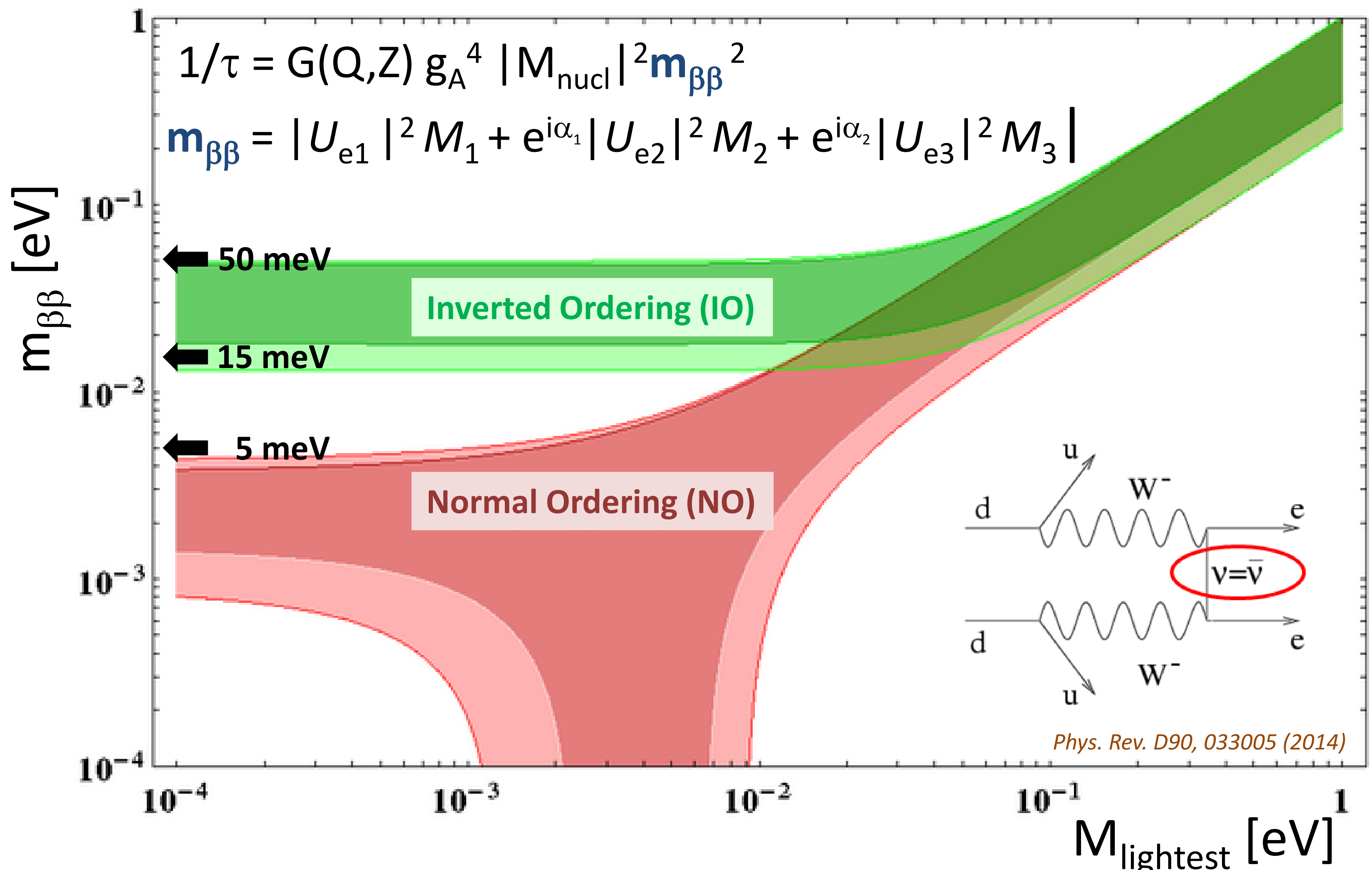
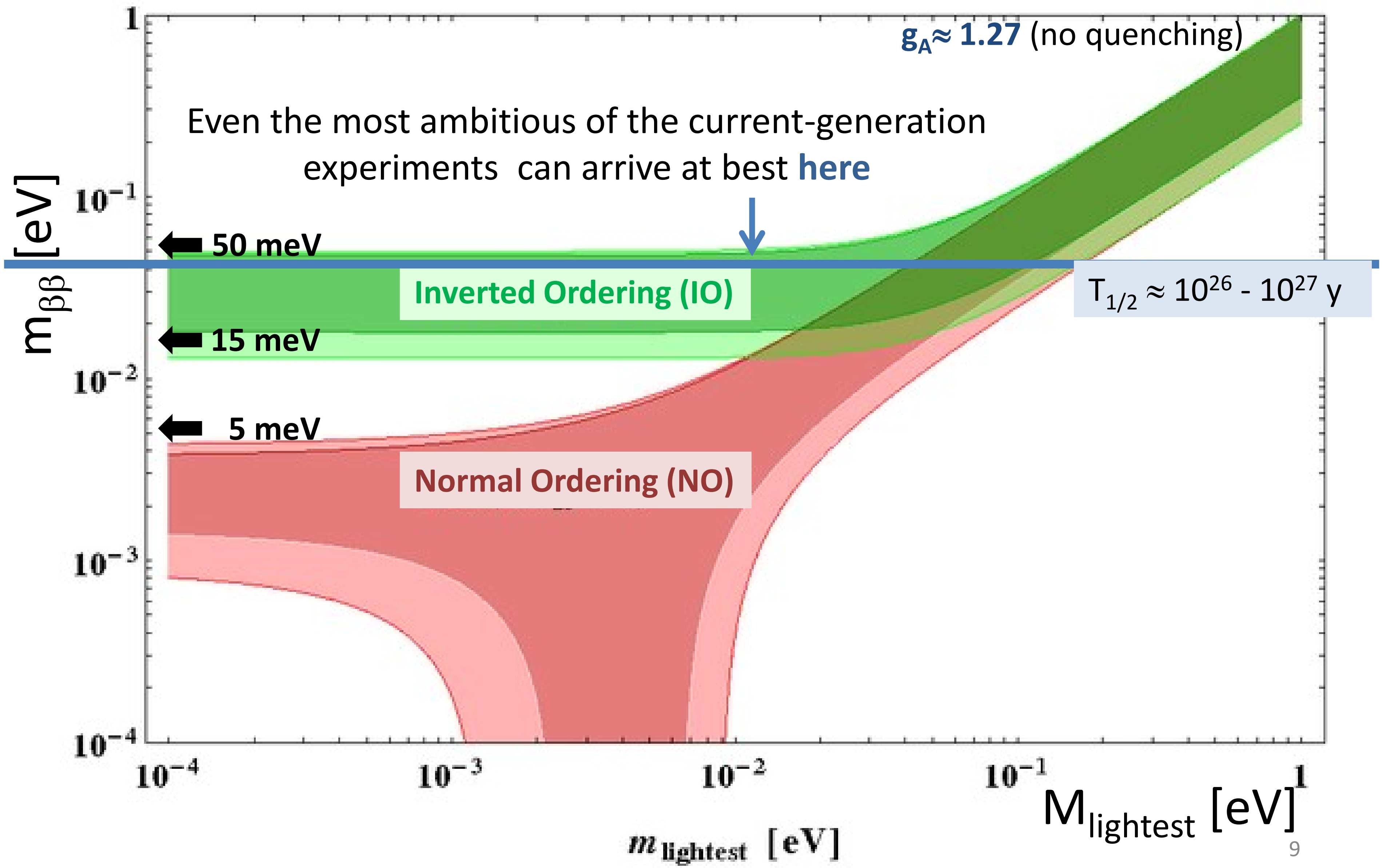
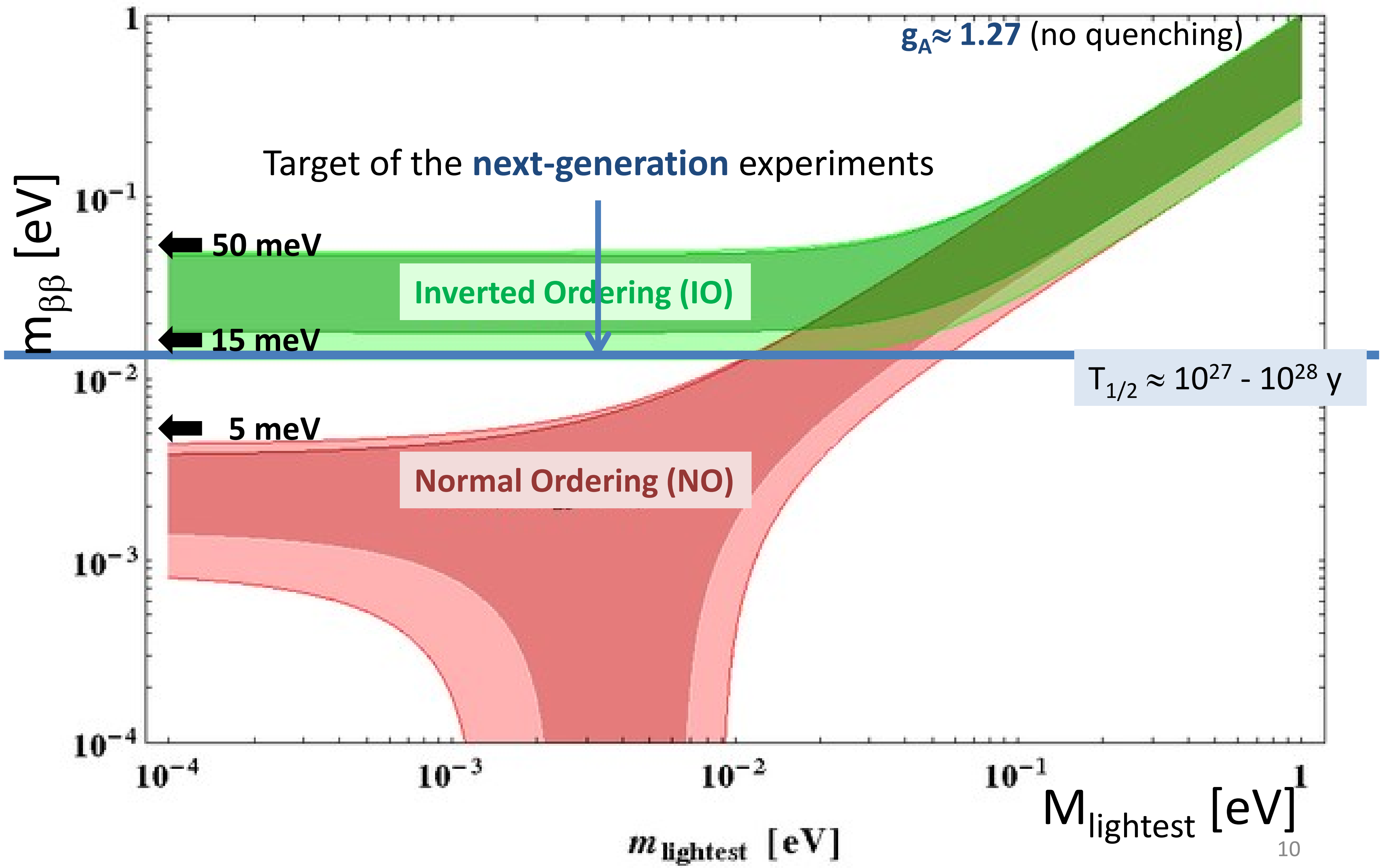
Standard mechanism: $m_{\beta\beta}$ vs. lightest ν mass



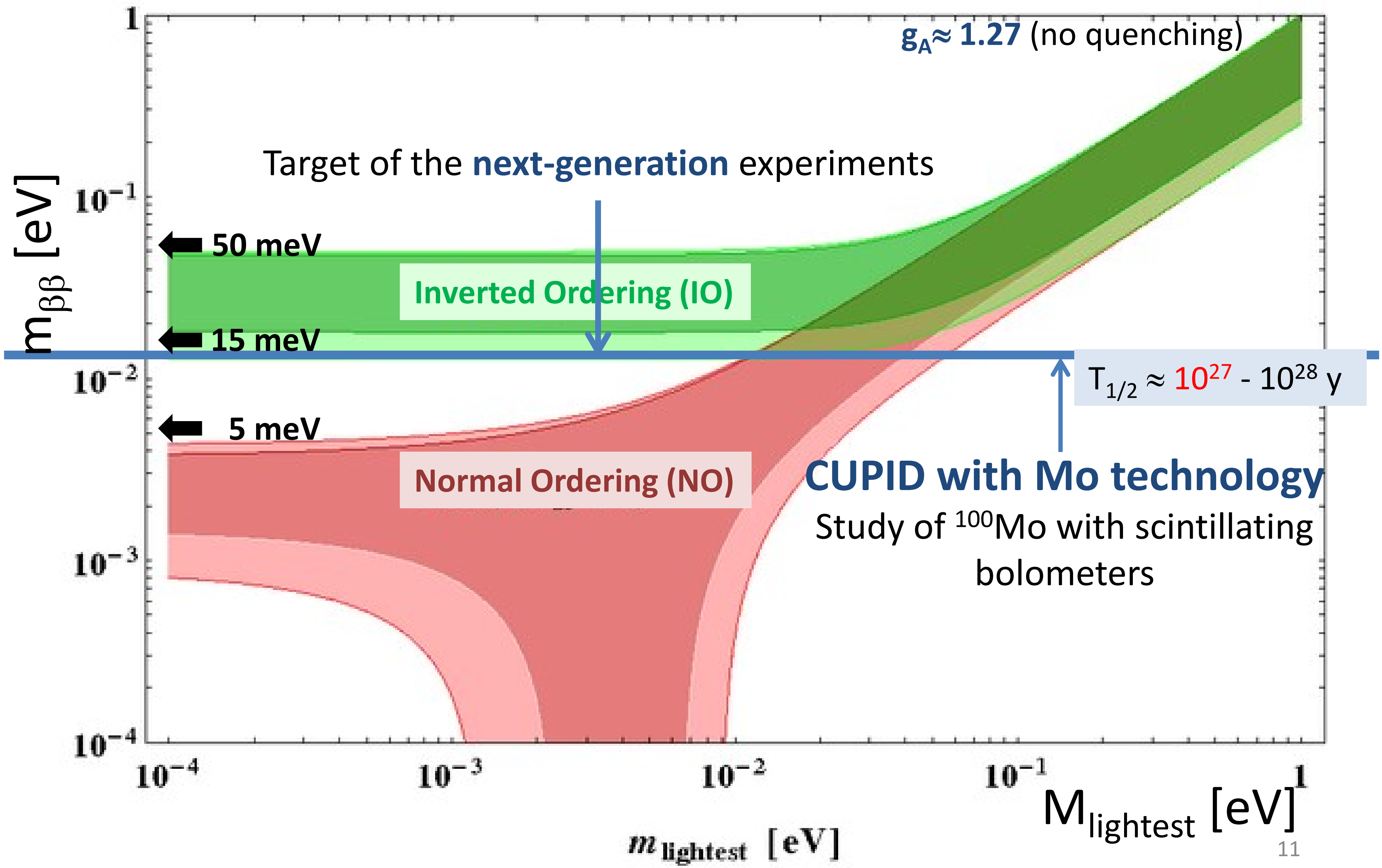
Current-generation experiments



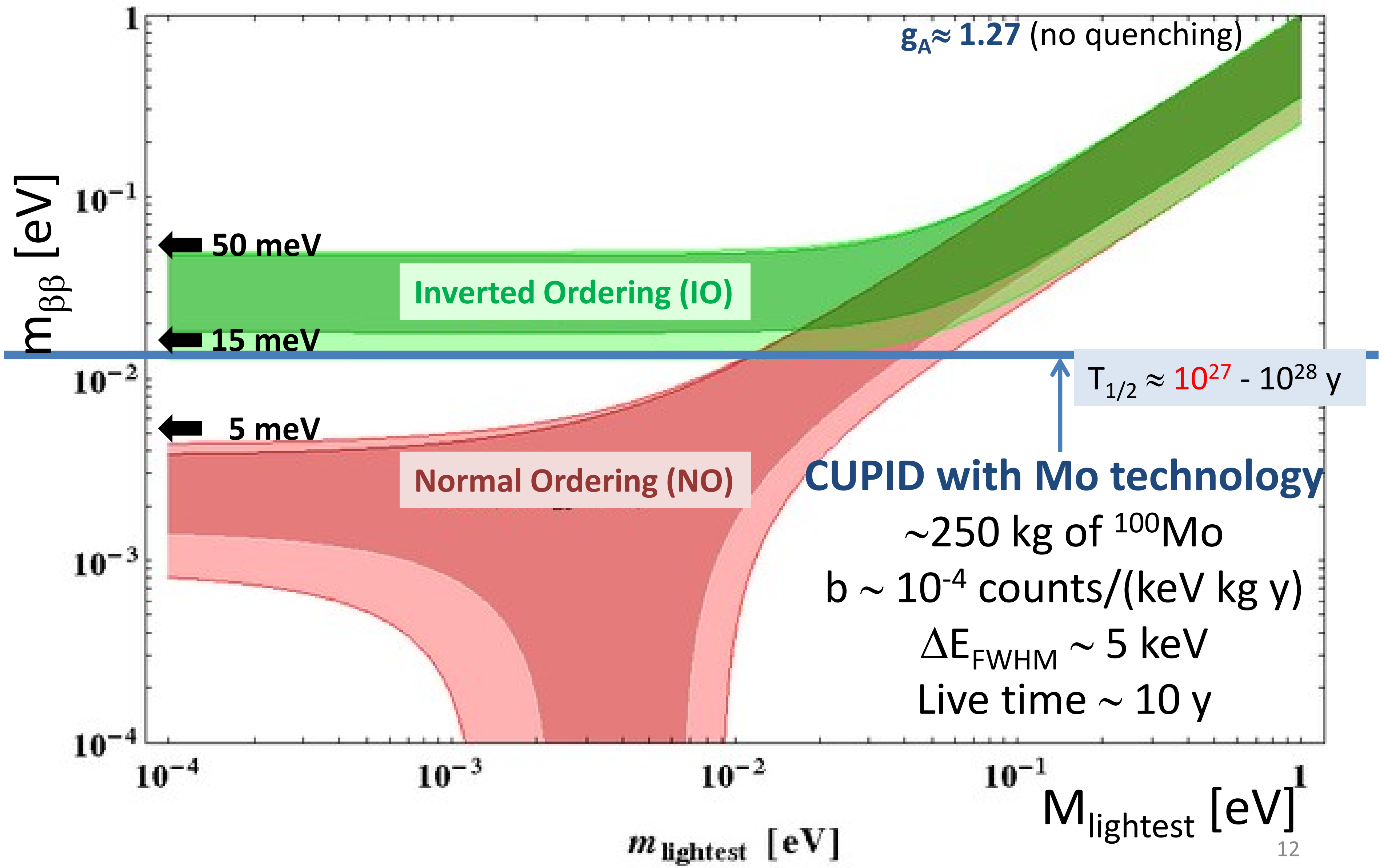
Next-generation experiments



Next-generation experiments

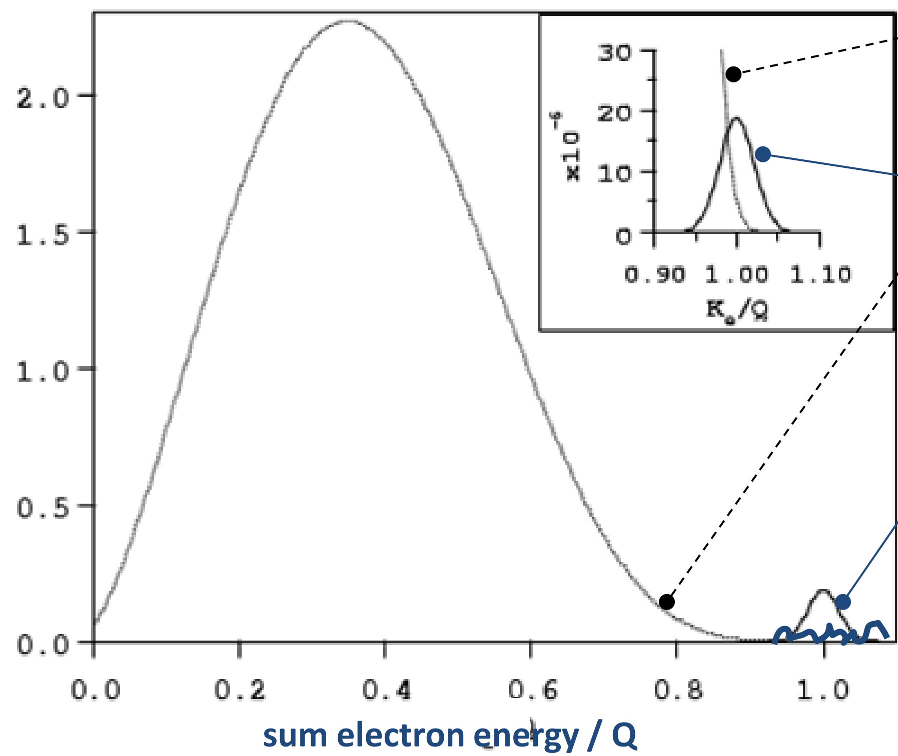


Next-generation experiments



What we are looking for

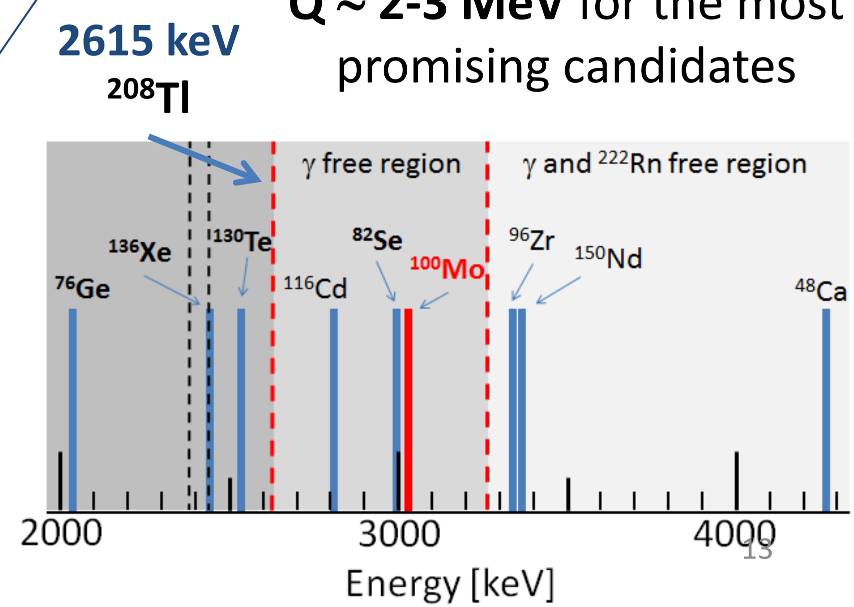
The shape of the two-electron sum-energy spectrum enables to distinguish between the **0ν** (new physics) and the **2ν** decay modes



2ν DBD: (A,Z)→(A,Z+2)+2e+2$\overline{\nu}$
continuum with maximum at ~1/3 Q

0ν DBD: (A,Z)→(A,Z+2)+2e
peak enlarged only by
the detector energy resolution

Q ~ 2-3 MeV for the most promising candidates



The signal is a **peak (at the Q-value)** over an almost **flat background**

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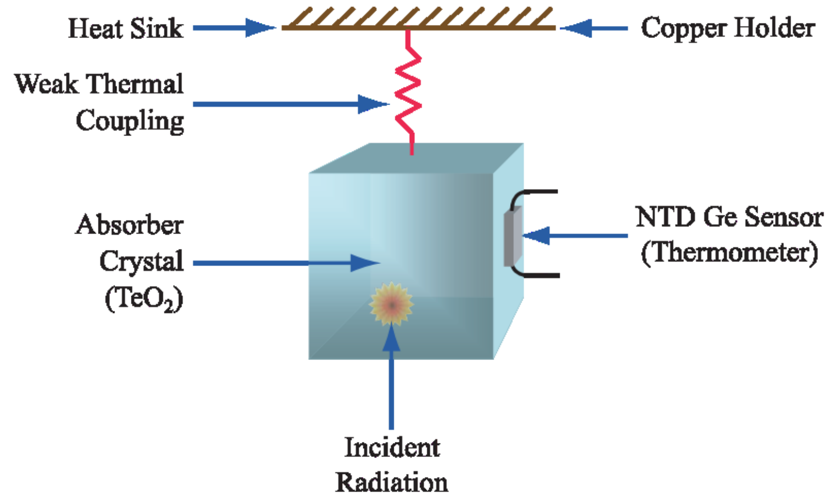
How we do it: bolometers

Bolometric approach: the source is embedded in a crystal, which is cooled down to 10-20 mK and works as a **perfect calorimeter**

$$\Delta T = E/C$$



- High energy resolution (~ **5 keV FWHM**)
- **~ 0.1 - 0.5 kg** source in each crystal → arrays
- High efficiency **(~ 70 – 90 %)**
- **Cuoricino – CUORE** experiments → crystals of **TeO_2** (isotope **^{130}Te**)
- **Large flexibility in the detector material choice:**

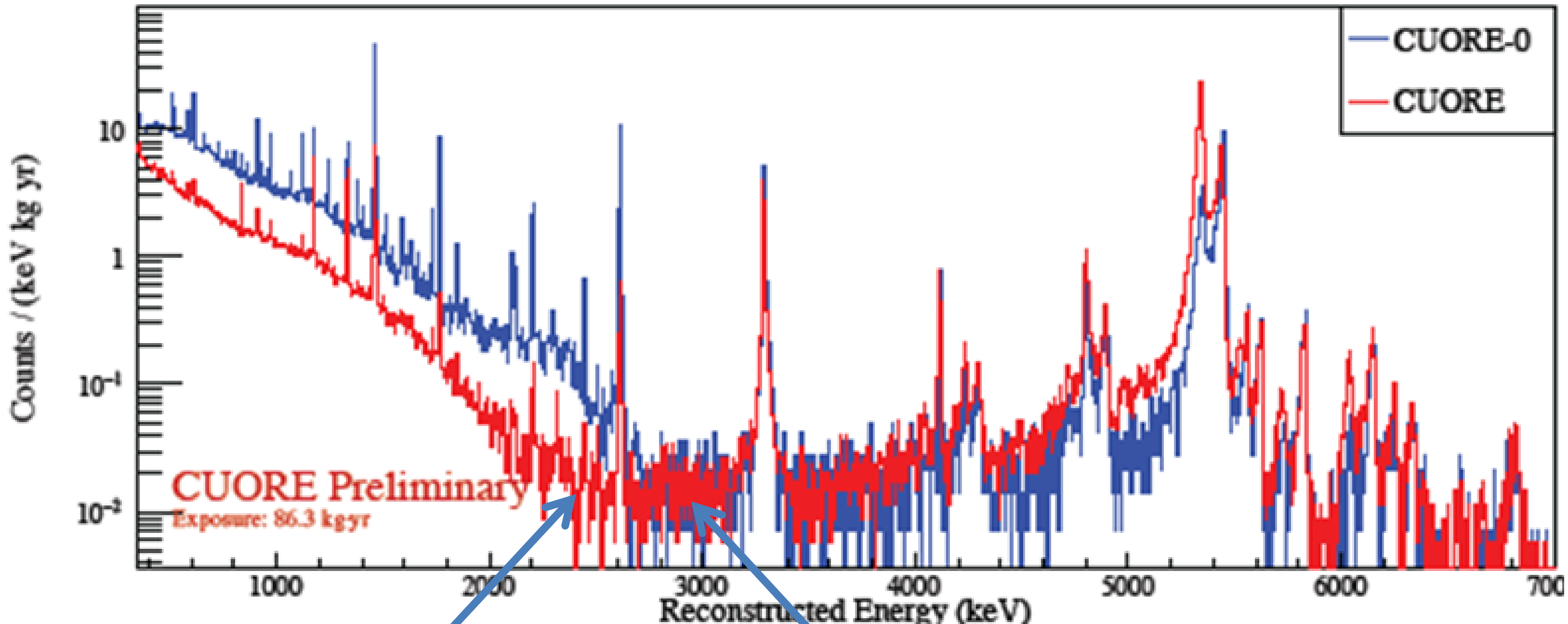
^{130}Te, and **three isotopes with Q > 2615 keV (^{82}Se, ^{100}Mo, ^{116}Cd) can be studied**

→ **Single multi-isotope experiment** → *AG et al., Eur. Phys. J. C 78 (2018) 272*

E. Fiorini, T.O. Niinikoski
Low-temperature calorimetry for rare decays
NIM 224 (1984) 83

CUORE-technology lessons about background

CUORE and its precursors are affected by **alpha particle background**



Irreducible background due to **alpha particles**, emitted at the **surfaces** and energy-degraded

b **~ 10^{-2} [counts/(keV kg y)]**

CUORE is not background free

Improvement by a factor 10^2 is required

Current solution: scintillating / Cherenkov bolometers

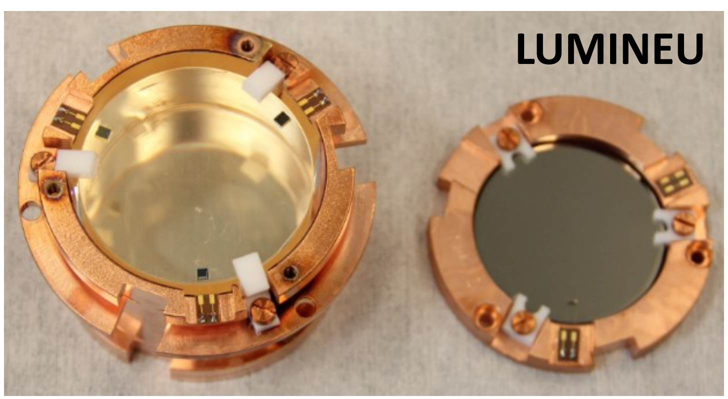
Alpha / beta separation

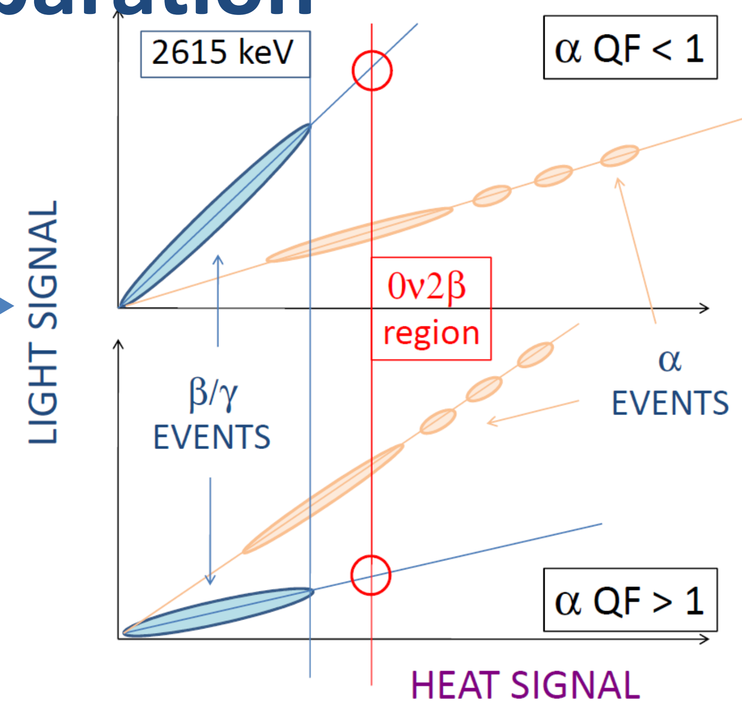
Alphas emit a different amount of light with respect to **beta/gamma** of the same energy (normally lower → **α QF < 1, but not in all cases – ZnSe is an exception**).

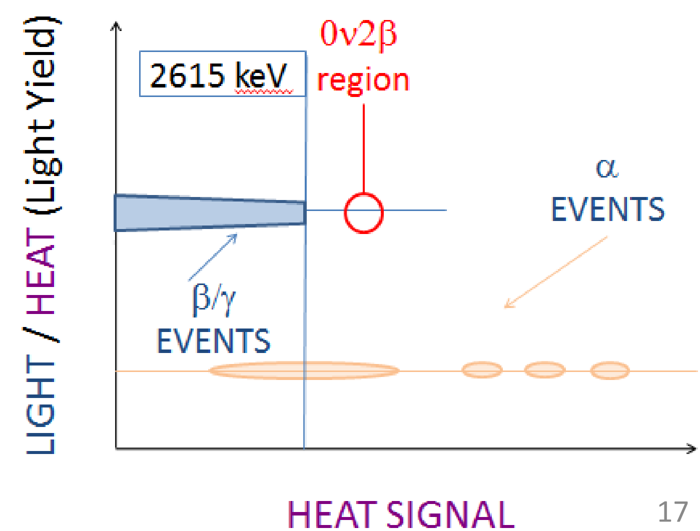
A **scatter plot light vs. heat** or a **plot light-yield vs. heat)** separates alphas from betas / gammas.

PSD can work as well

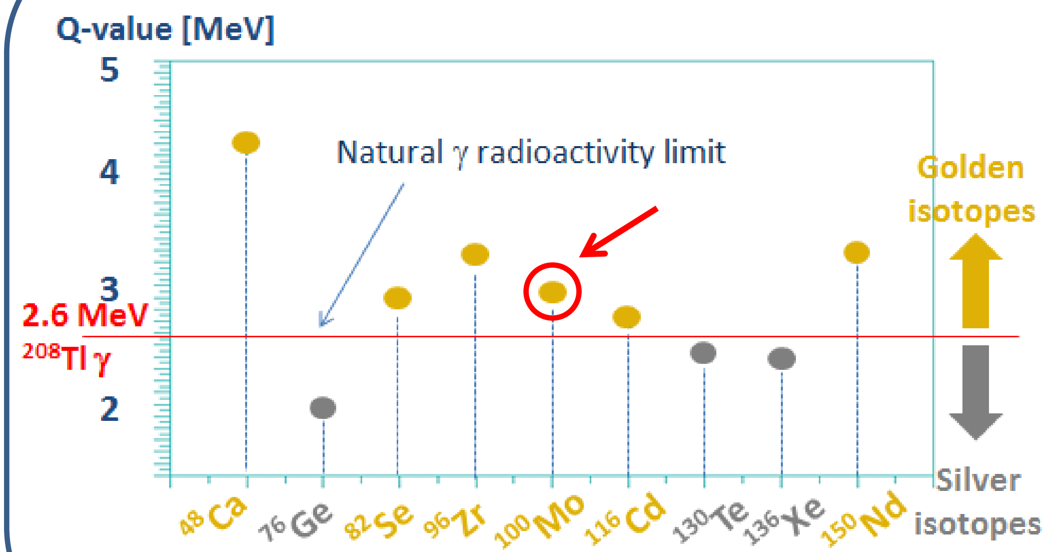
A bolometric light detector is needed, facing the main crystal







Some properties of ^{100}Mo



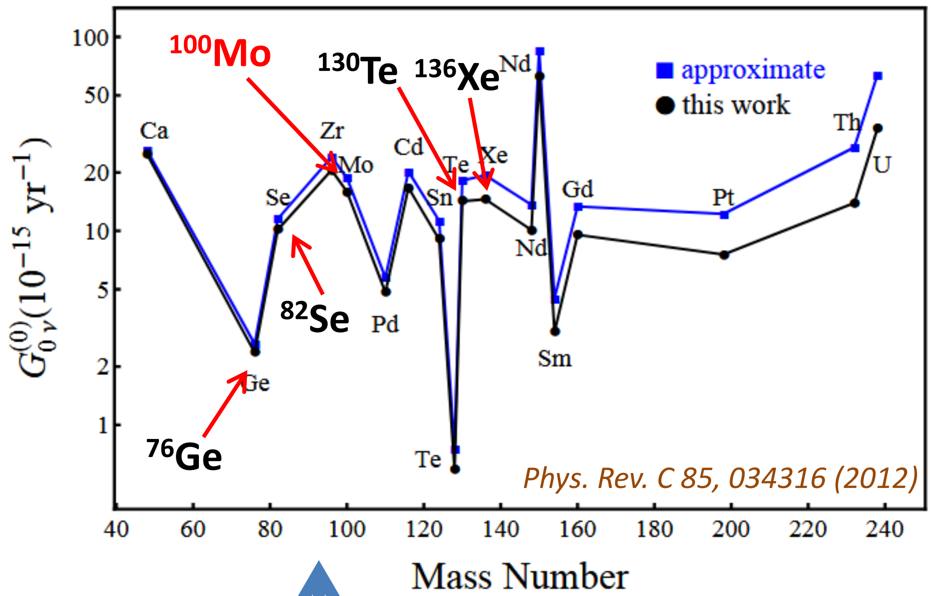
- $^{100}Mo \rightarrow {}^{100}Ru + 2e^-$
- $Q_{\beta\beta}$ = **3034 keV**
- I.A.(100) = 9.7 %
- enrichable by gas centrifugation

Caveats

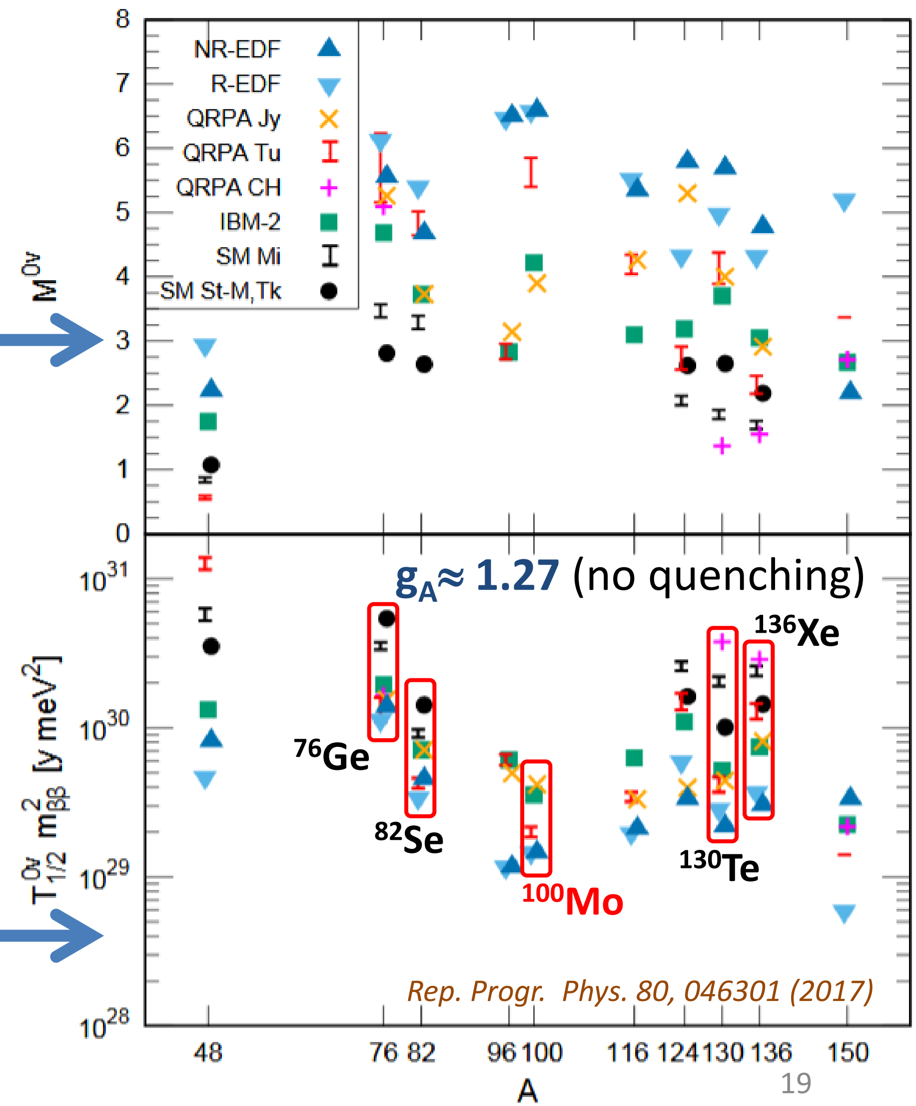
- $T_{1/2}(2\nu) = 6.9 \times 10^{18}$ y – the fastest one in all $0\nu2\beta$ candidates
- ^{214}Bi line at 3054 keV – B.R. 0.021 % - Compton edge 2818 keV

Mo vs other isotopes

Phase space: exactly calculable



Nuclear matrix elements: several models



$$1/\tau = G(Q,Z)\ g_A^{\ 4}\ |M_{nucl}|^2\ \mathbf{m_{\beta\beta}}^{\ 2}$$

Useful Mo-based crystals

Crystals succesfully tested so far as scintillating bolometers:

$CdMoO_4$
$PbMoO_4$
$SrMoO_4$
$CaMoO_4$
$ZnMoO_4$
Li_2MoO_4

AMoRE
Drawbacks:
- Necessity of ^{48}Ca depletion
- Radiopurity (difficult to purify Ca from U, Th, Ra)

LUMINEU
Initial choice (2012): $ZnMoO_4$
First tests on large Li_2MoO_4 crystals: spring 2014

Astropart. Phys. 72, 38 (2016)

LUMINEU: Selection of Li_2MoO_4 for a pilot experiment (March 2016)

- Better bolometric performance
- Easy crystallization / excellent quality
- Outstanding radiopurity

Caveats
- Hygroscopic material
- ^{40}K is natural contaminant
- Lower light yield (~0.8 keV/MeV)

Preparing a ^{100}Mo experiment: LUMINEU

Funding / resources from

- **ANR (France) – main fund provider (LUMINEU: 2012-2017)**
- CEA-Saclay – substantial funds / PhD
- CSNSM direction – funds for crystals (« AP interne »)
- EDELWEISS – underground facility, electronics & DAQ
- IN2P3 – dedicated personnel
- KINR Kiev – radiopure scintillator know-how, simulation, – enriched ^{100}Mo
- ITEP Moscow – enriched ^{100}Mo
- NIIC Novosibirsk - crystals
- INFN / LUCIFER – underground facility and manpower for R&D

Extension of the Mo collaboration: CUPID-Mo

New participants

IN2P3 laboratories

LAL joins CSNSM, IPNL, CEA/IRFU

http://cupid-mo.mit.edu

7 countries, 15 institutions, ~110 scientists

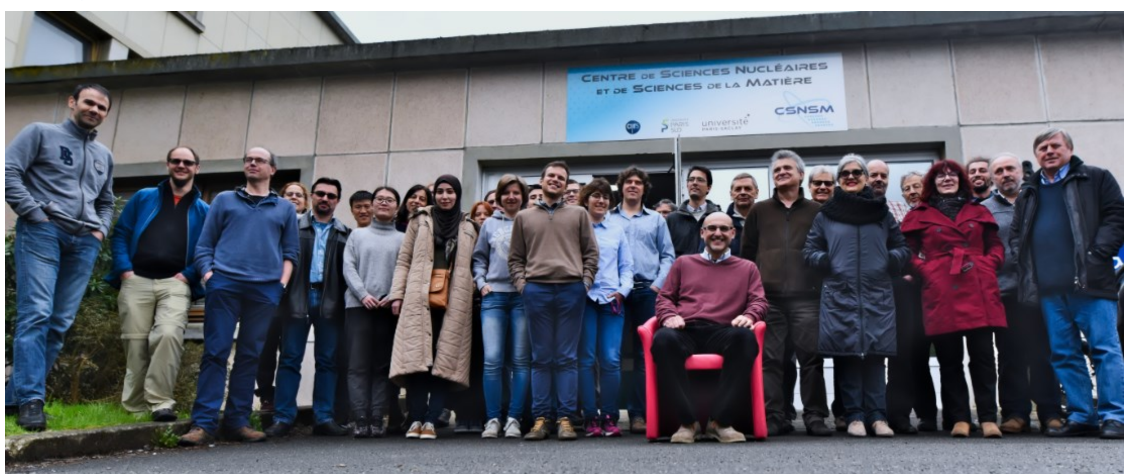
MIT
UCB/LNBL

USA

Fudan Shanghai
USTC Hefei

China

Strong interest in China
Large CUPID group.
Project for a "parallel CUPID"
at JinPing laboratory

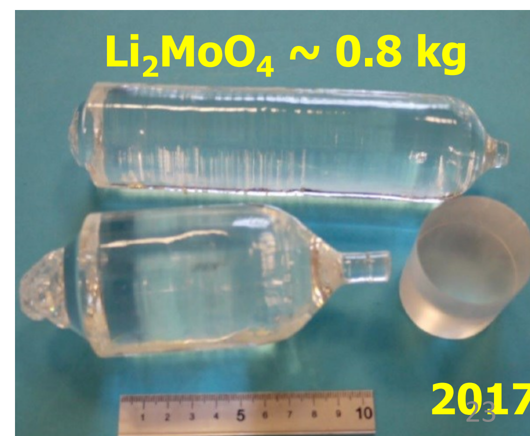


Li_2MoO_4: purification and crystallization

From 2013 to 2016, a series of important milestones were achieved:

- **Mo purification / crystallization protocol** (**NIIC, Novosibirsk**, Russia) (**Mo irrecoverable losses < 4%**)
- Selection of the **appropriate Li_2CO_3 powder** for compound formation
- Successful program to **control internal content of ^{40}K**
  (from ~60 mBq/kg to < 5 mBq/kg)
  Random coincidences: $2\nu2\beta$ + ^{40}K << $2\nu2\beta$ + $2\nu2\beta$
- Efficient use of existing **~10 kg of ^{100}Mo**
  (~9 kg to ITEP-Moscow and ~1 kg to KINR-Kiev)
  (MoU among IN2P3 / INFN / ITEP – February 2015)
  Natural isotopic abundance: **9.7%**

NIM A 729, 856 (2013)
JINST 9, P06004 (2014)
EPJC 74, 3133 (2014)
JINST 10, P05007 (2015)



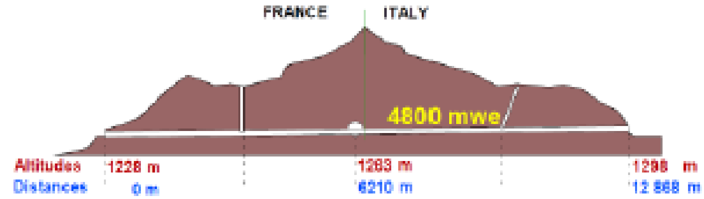
EDELWEISS-III cryogenic facility at LSM (France)

Laboratoire Souterrain de Modane

1.7 km rock overburden (~4.8 km w.e.)

5 μ/day/m^2; 10^{-6} n/day/cm^2 (>1 MeV)

Deradonized air flow (~30 mBq/m^3)



EDELWEISS set-up

Clean room (ISO Class 4)

^{3}He/^{4}He inverted wet cryostat

Passive shield

Modern lead (18 cm)

Roman lead (2 cm; 14 cm at 1 K plate)

Polyethylene (external ~ 50+5 cm and 10 cm at 1 K plate)

Background monitors

Muon veto (98.5% covering)

Neutron counter

Radon counter

Electronics, DAQ (Samba)

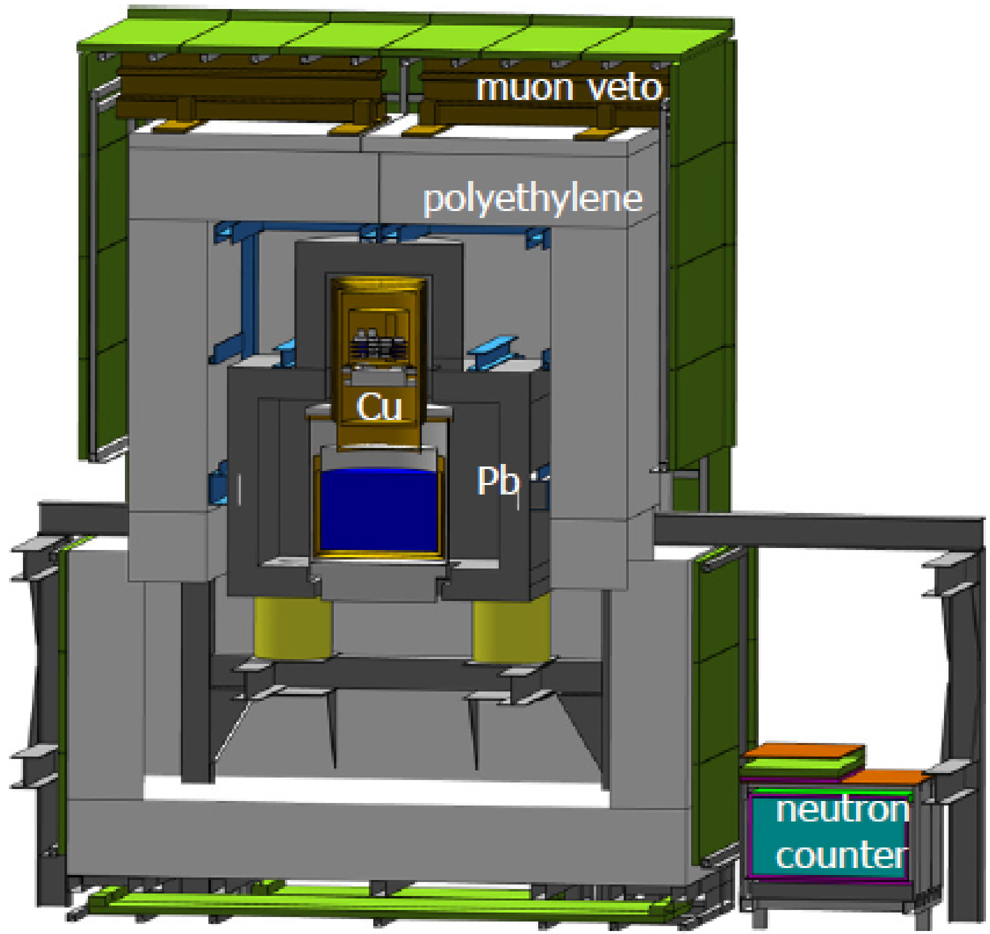
Low noise cold electronics

AC bias, modulation (100 kHz)

$\rightarrow$ demodulation (up to 1 kHz)

16-bit or 14-bit ADC

Trigger and/or Stream data



PLB 702 (2011) 329; JINST 12 (2017) P08010; EPJC 77 (2017) 785

D. Poda

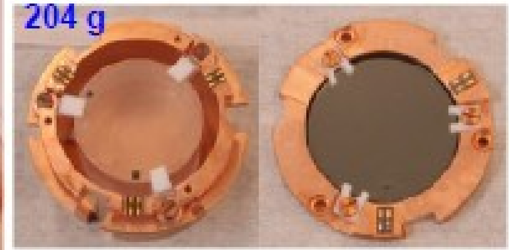
Tests of $Li_2{}^{100}MoO_4$ scintillating bolometers

+ enrLMO-2
was tested at LNGS
05/2016, 12 mK

T1

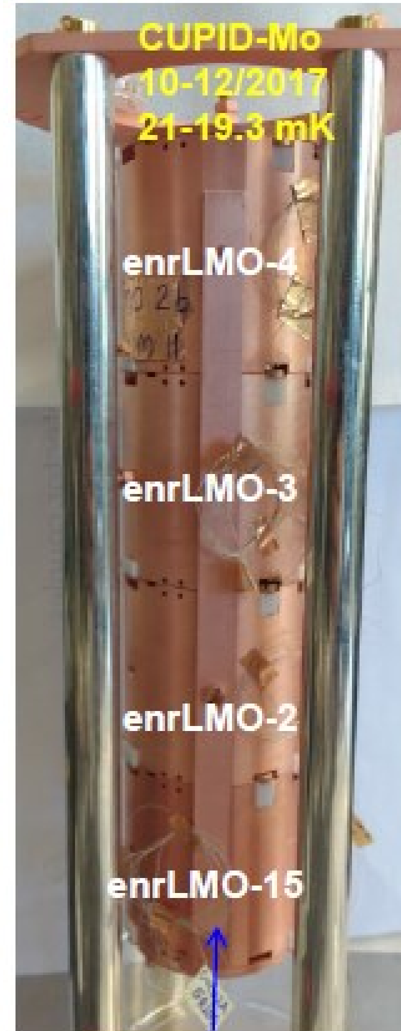
+ a tower T2
with enrLMO-1

LMO1b Ge LD



LMO2b Ge LD

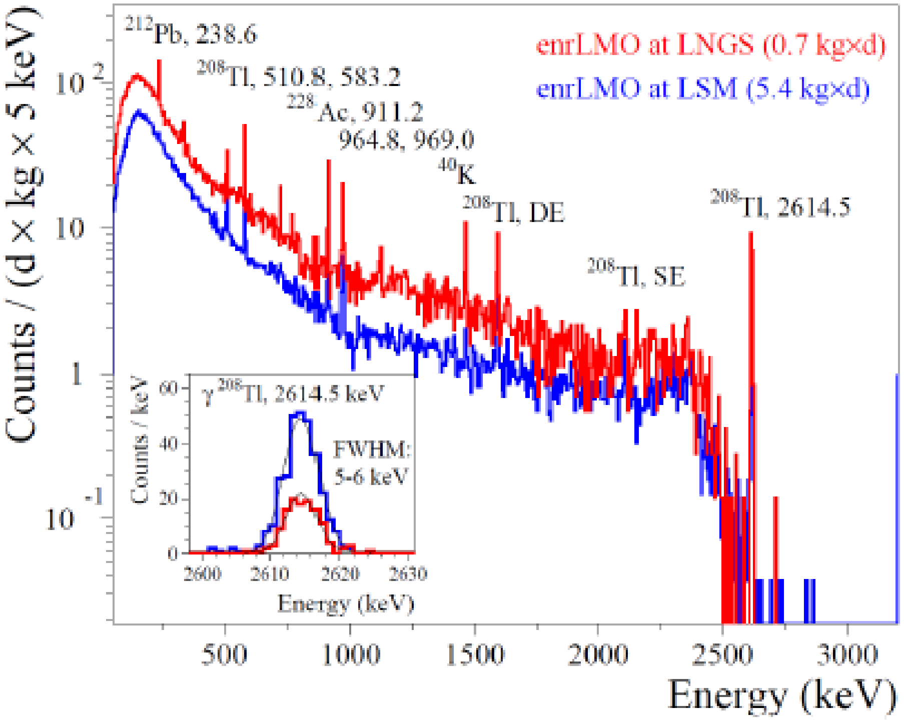
LMO2t Ge LD

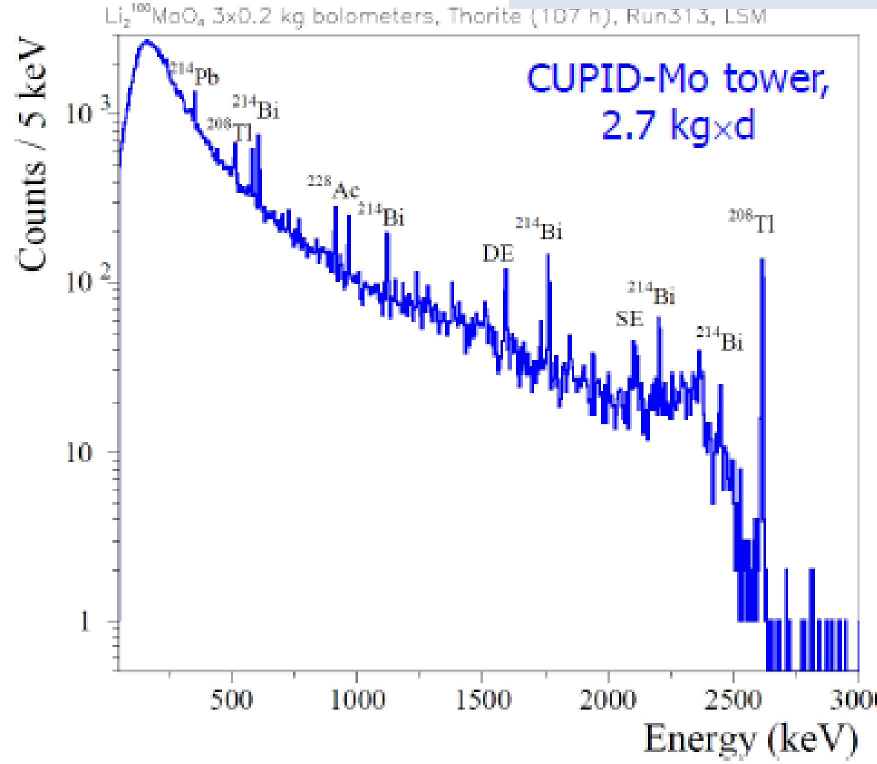


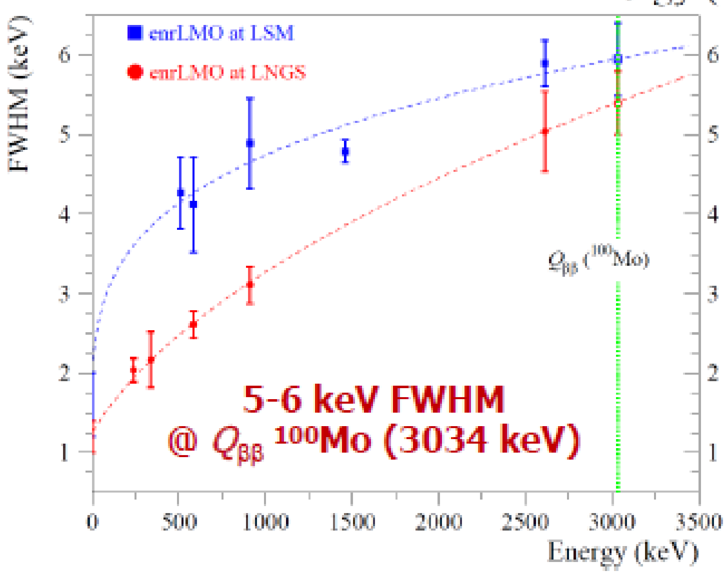
D. Poda

^{232}Th calibration

Heat channel





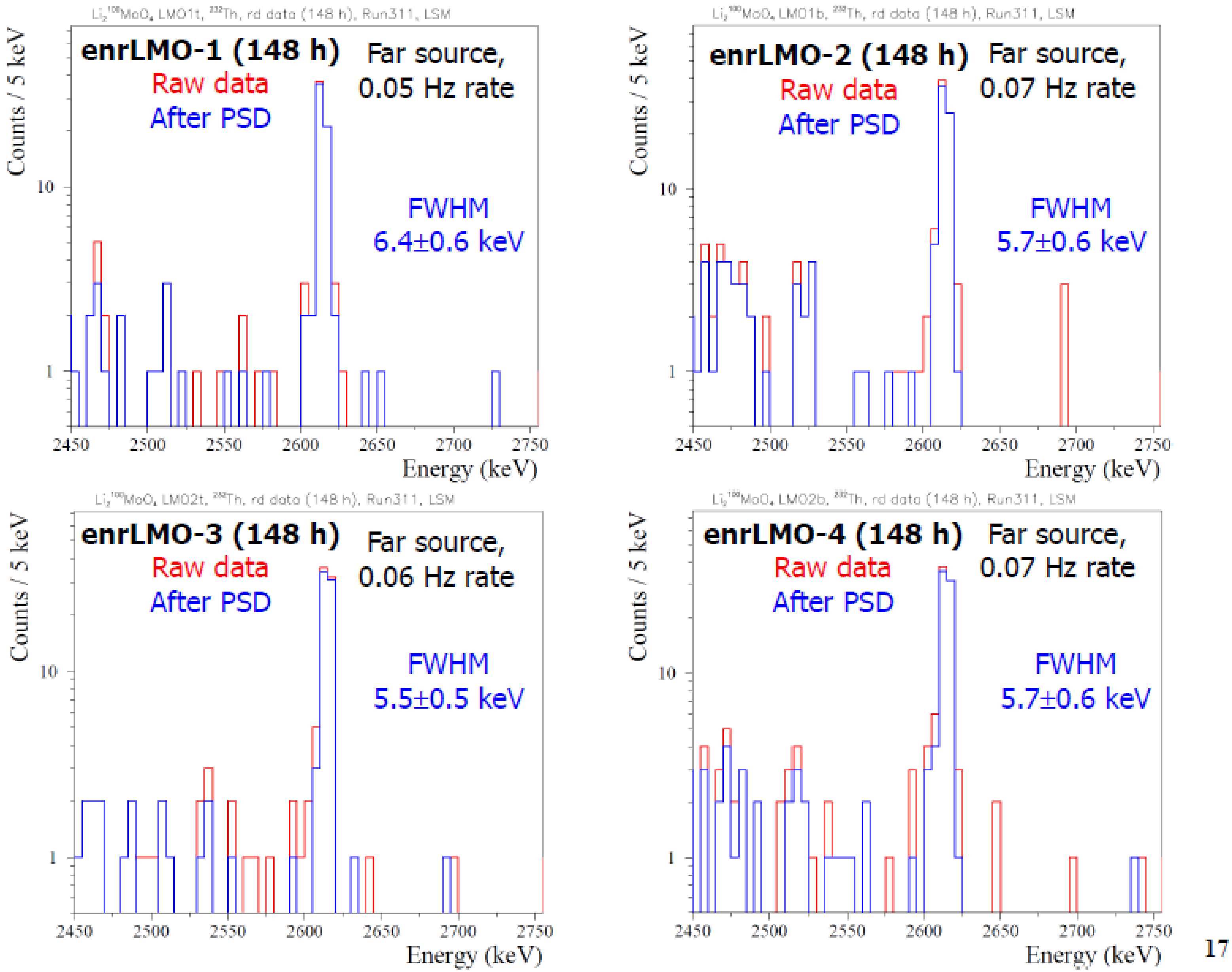


Mixed Th/U source is useful to estimate uncertainty of ^{100}Mo RoI determination

Calibration points	2615 keV peak @
Up to 2615 (^{208}Tl)	2614.8
Up to 2204 (^{214}Bi)	2616.1

D. Poda

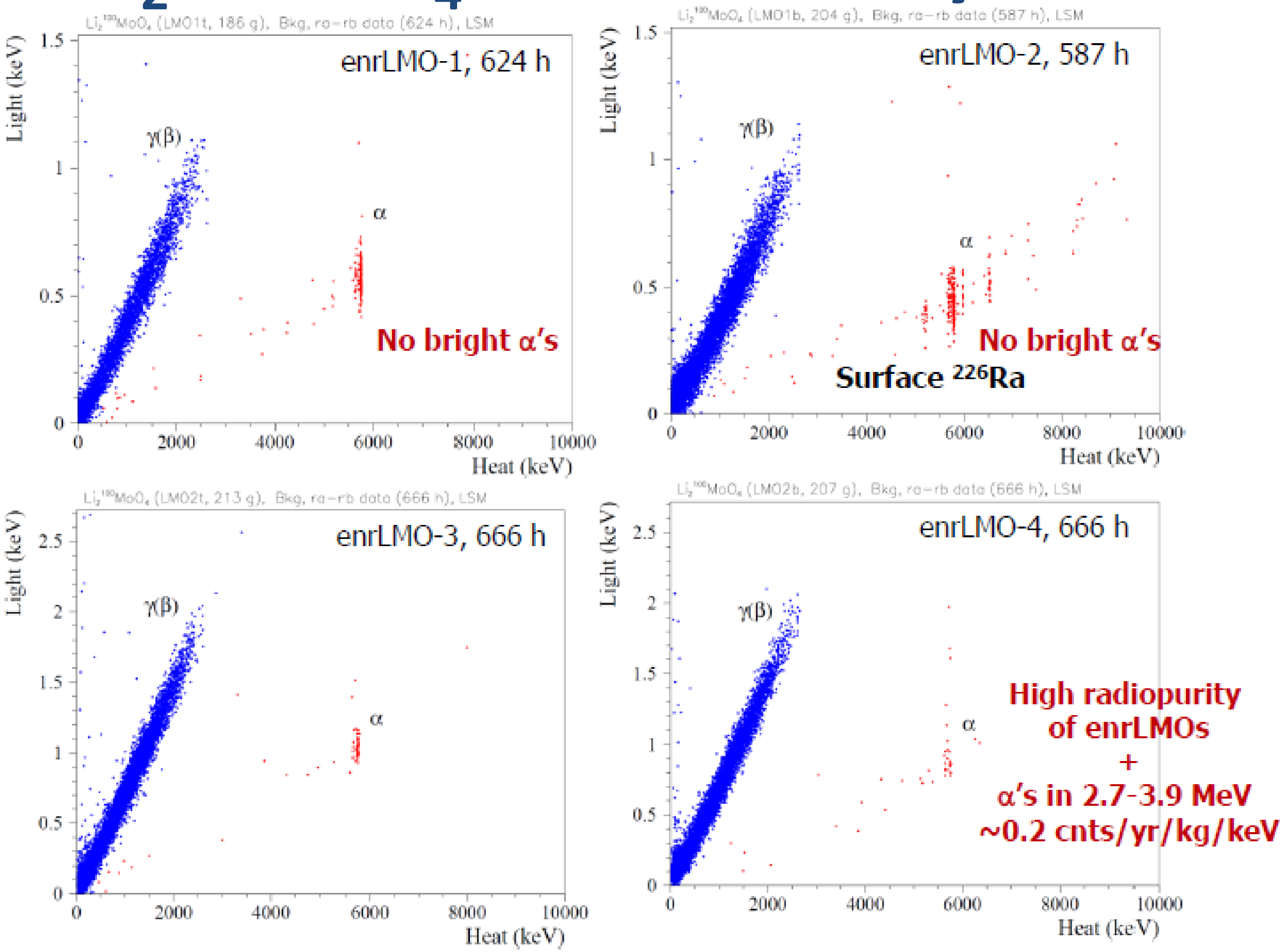
Heat channel



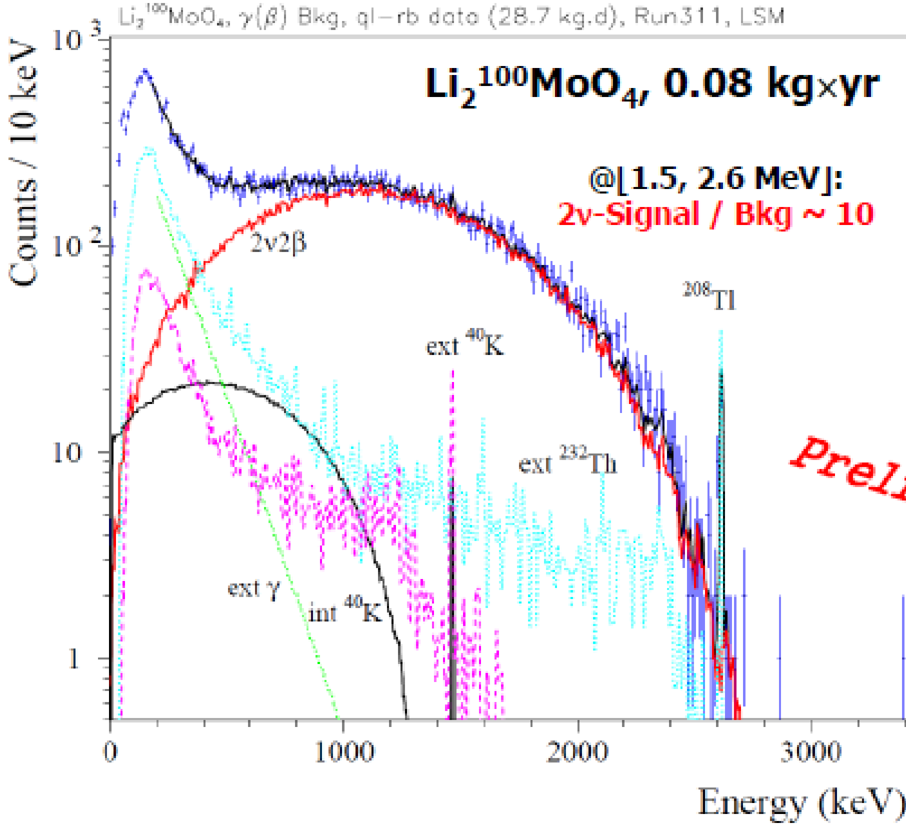
D. Poda

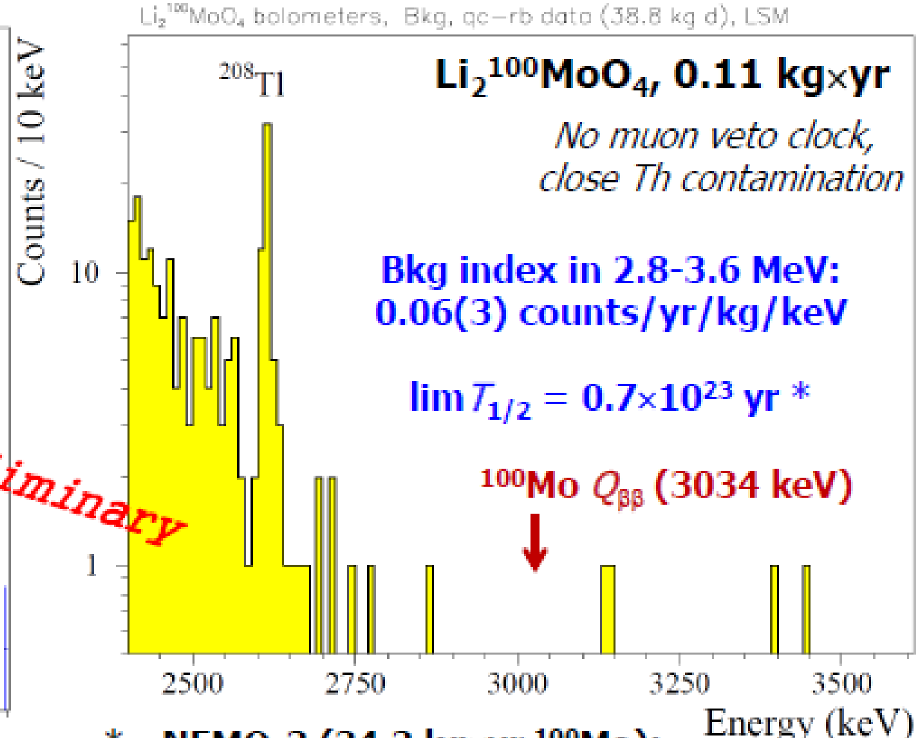
4 $Li_2{}^{100}MoO_4$ detector array

Heat + Light



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





* - **NEMO-3 (34.3 kg×yr ^{100}Mo):**
$T_{1/2}$ **≥ 1.1×10^{24} yr**, PRD 92, 072011 (2015)

$T_{1/2}$ [10^{18} yr]	^{100}Mo exposure	Experiment	Ref.
7.11±0.02(stat)±0.54(syst)	7.37 kg×yr	NEMO-3	PRL 95, 182302 (2005)
7.15±0.37(stat)±0.66(syst)	0.01 kg×yr	LUCIFER*	JPG 41, 075204 (2014)
6.90±0.15(stat)±0.37(syst)	0.02 kg×yr	LUMINEU	EPJC 77, 785 (2017)

Data with higher statistics are available
CUPID-Mo paper in preparation

D. Poda

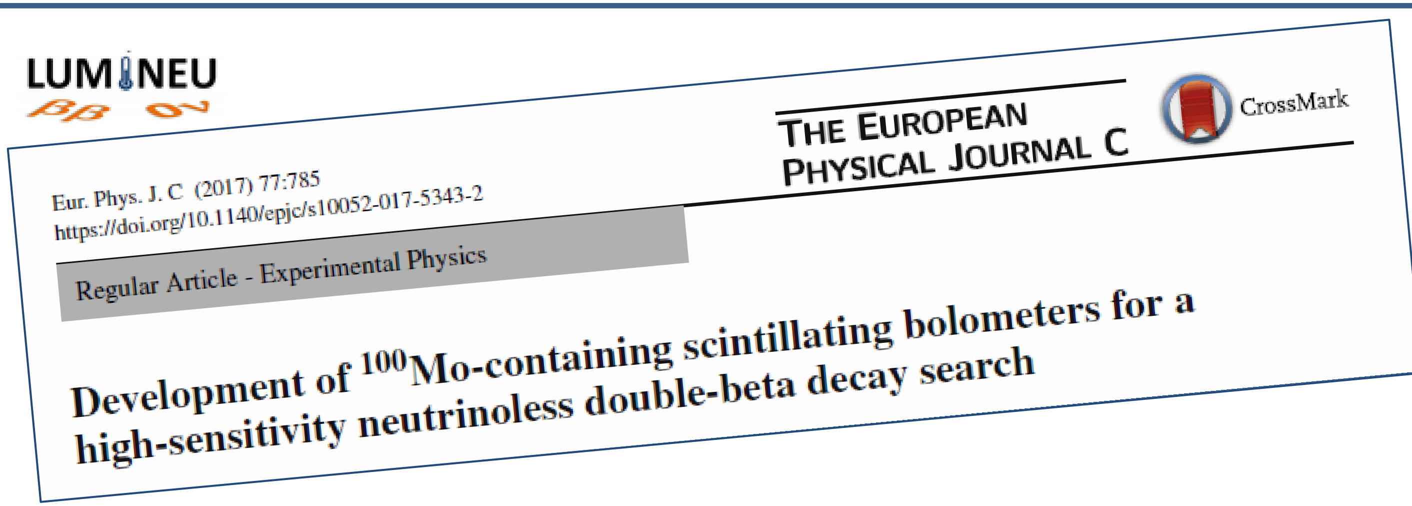
$Li_2{}^{100}MoO_4$ scintillating bolometers: a mature technology

LUMINEU has succesfully developed the $Li_2{}^{100}MoO_4$ technology

Multiple tests with **natural and enriched crystals** (2014-2017) in LSM and LNGS with outstanding results in terms of:

Reproducibility	→	excellent performance uniformity
Energy resolution	→	**~ 4-6 keV FWHM** in RoI
α/β separation power	→	**> 99.9 %**
Internal radiopurity	→	**< 5 μBq/kg in ^{232}Th, ^{238}U**; **< 5 mBq/kg in ^{40}K**

→ Compatible with **$b \leq 10^{-4}$ [counts/(keV kg y)]**



THE EUROPEAN PHYSICAL JOURNAL C

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Eur. Phys. J. C (2017) 77:785
https://doi.org/10.1140/epjc/s10052-017-5343-2

Regular Article - Experimental Physics

Development of ^{100}Mo-containing scintillating bolometers for a high-sensitivity neutrinoless double-beta decay search

Outline

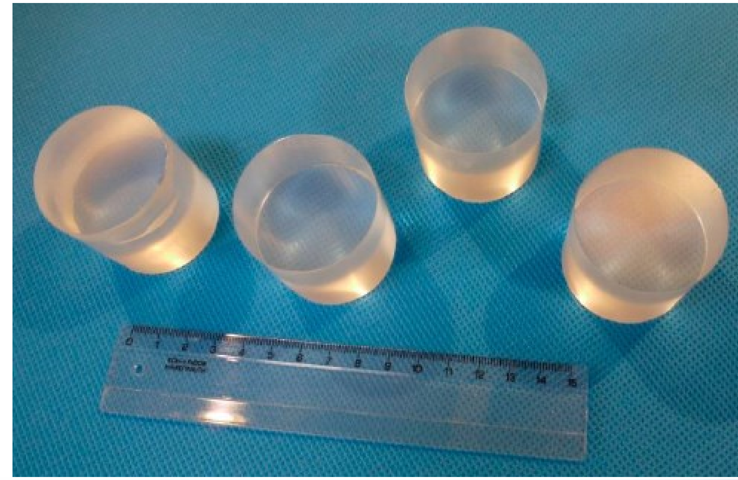
- Challenges in $0\nu2\beta$ decay and the CUPID way
- Scintillating bolometers and ^{100}Mo
- Results with $Li_2{}^{100}MoO_4$ crystals
- **Demonstrators: CUPID-Mo and CROSS**
- CUORE and its background model
- Mo-based CUPID

The CUPID-Mo demonstrators

CUPID-Mo Phase I (20 crystals)

- **20 ^{100}Mo-enriched (97%) Li_2MoO_4**
  (∅44×45 mm, 0.21 kg each; 4.18 kg total)
  ⇒ ~**2.5 kg of ^{100}Mo**
- **20 Ge light detectors** (∅44×0.175 mm)+SiO
- **EDELWEISS set-up** @ **LSM (France)**

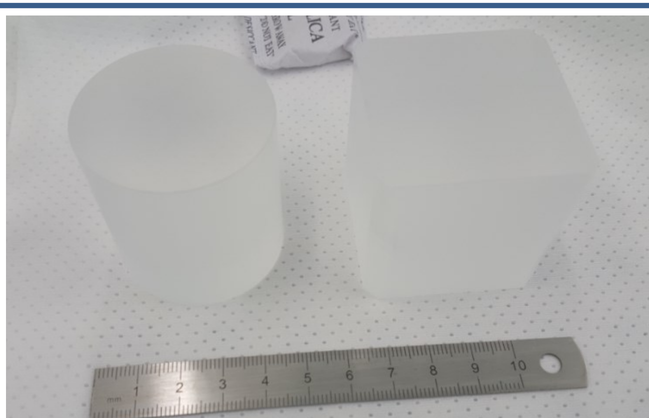
COMMISSIONING May - June 2018

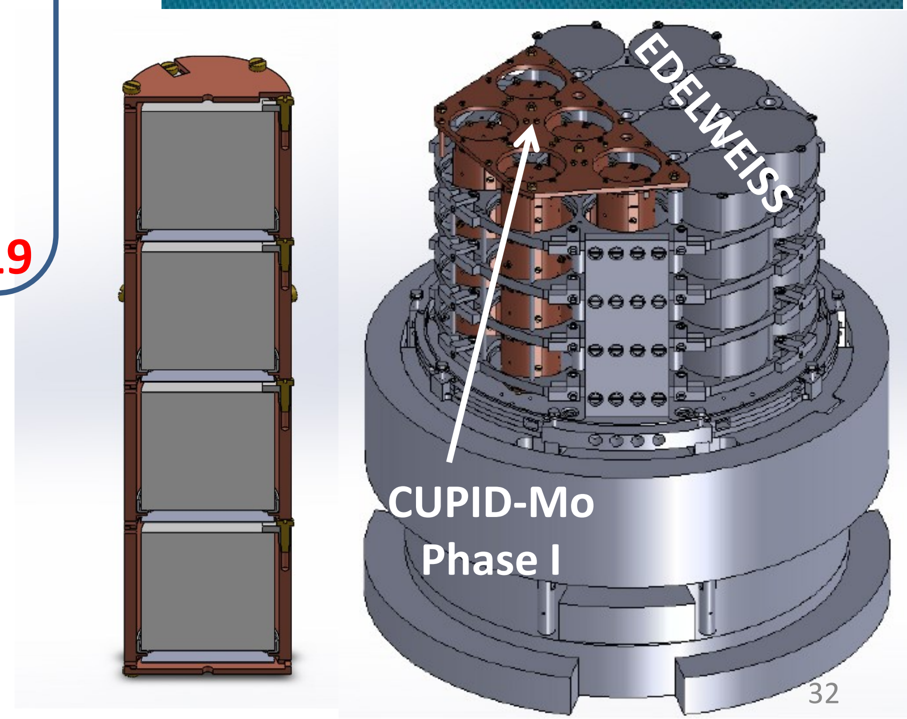


CUPID-Mo Phase II (20+26 crystals)

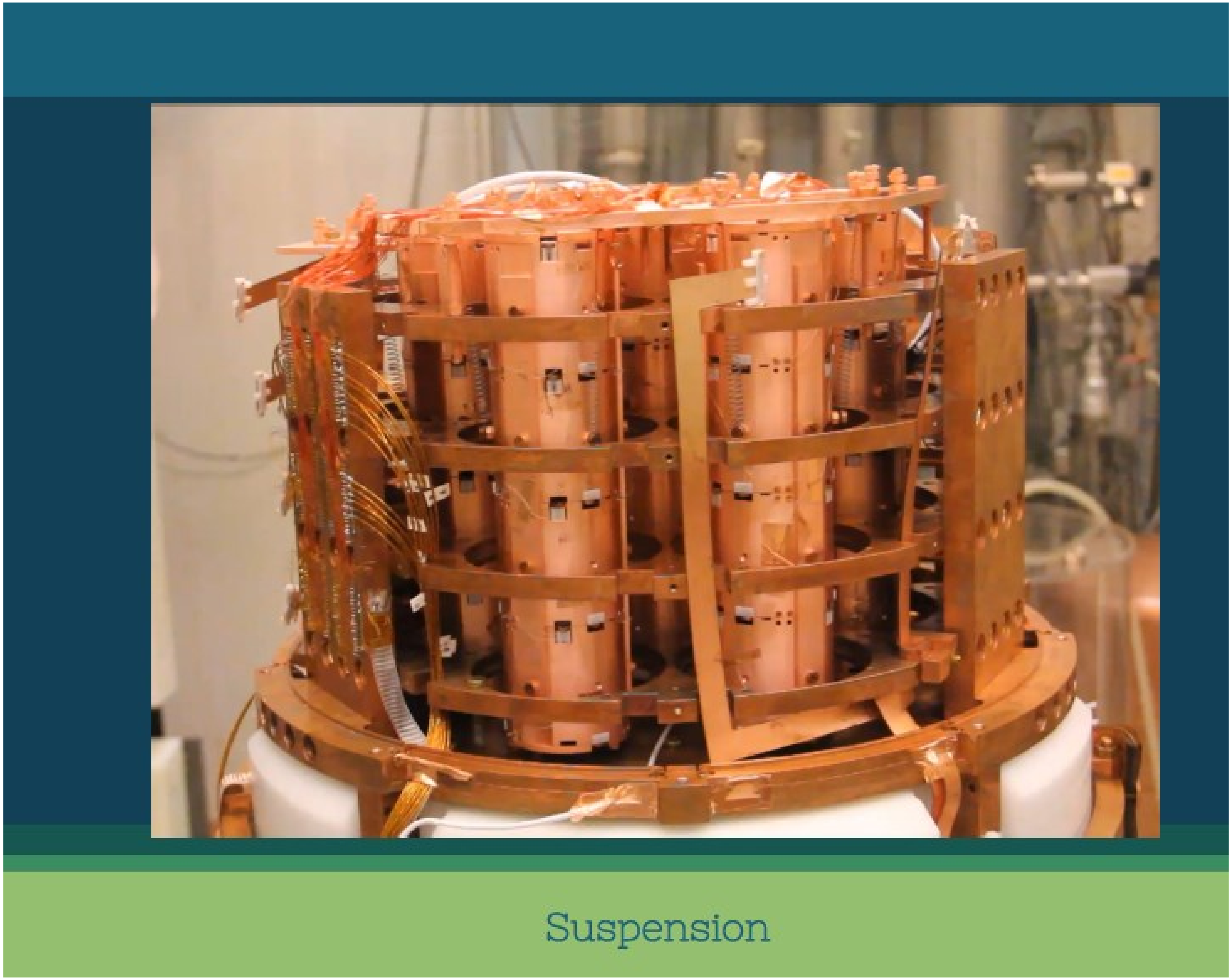
- Additional **26 cubic $Li_2{}^{100}MoO_4$**
  (45x45x45 mm, 0.28 g each)
  ⇒ **~4 kg of ^{100}Mo**
- **CUPID-0 set-up** @ **LNGS (Italy)**

PLANNED START DATA TAKING: mid 2019





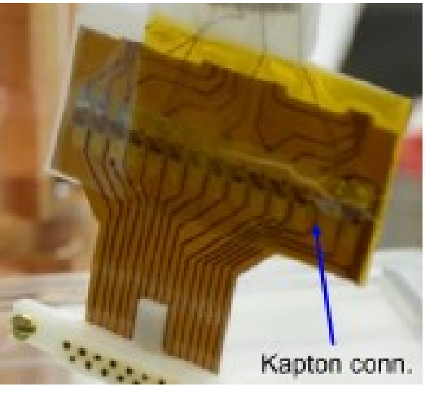
The CUPID-Mo Modane array (Phase I)



Background consideration for CUPID-Mo Modane (Phase I)

Background index in the CUPID-Mo **prototypes** → **b = 0.06(3) c/(keV kg y)**

This value is compatible with the presence of ^{232}**Th-contaminated connectors** close to the detectors



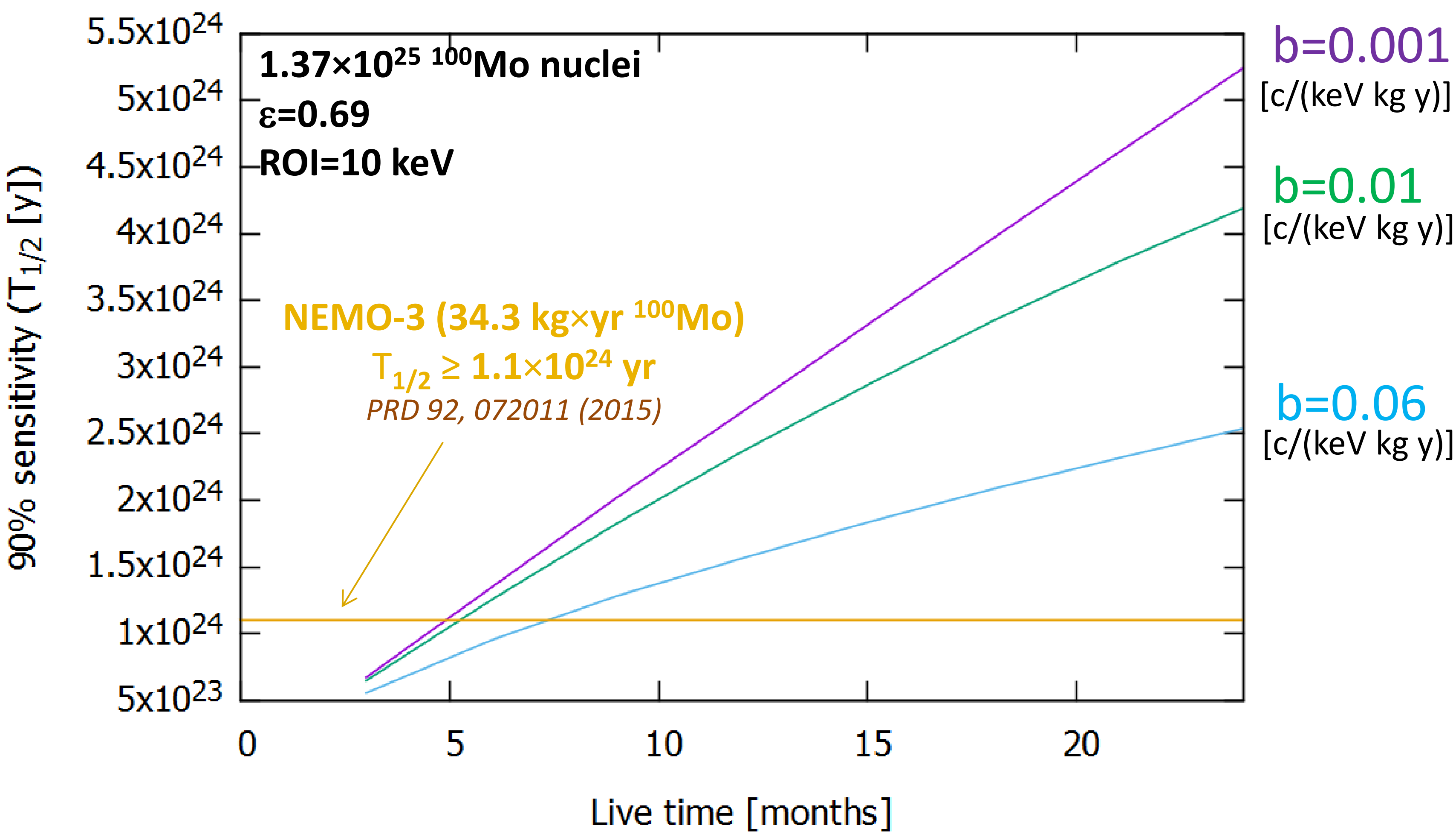
Simultaneous absorption of **2615 keV** γ and coincident **583 keV** γ (^{208}Tl)

The contaminated connectors were substantially reduced for the CUPID-Mo run (improvement by ÷10 is expected)

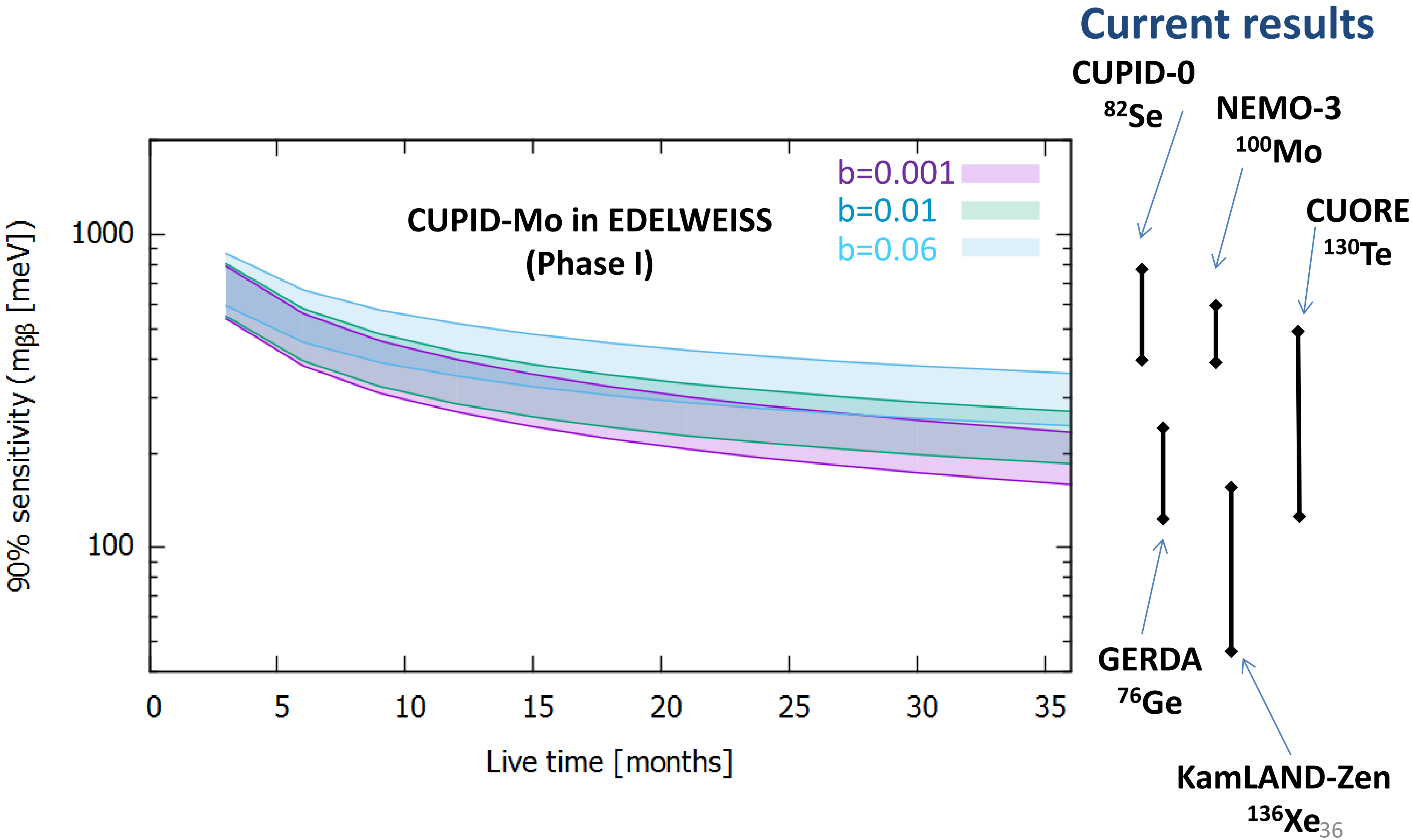
Full estimation of the background is in progress

Reasonable expectation: **b ~ 10^{-2} – 10^{-3} c/(keV kg ys)**

CUPID-Mo Modane (Phase I)
Evolution of the half-life sensitivity



CUPID-Mo Modane (Phase I)
Evolution of the Majorana mass sensitivity



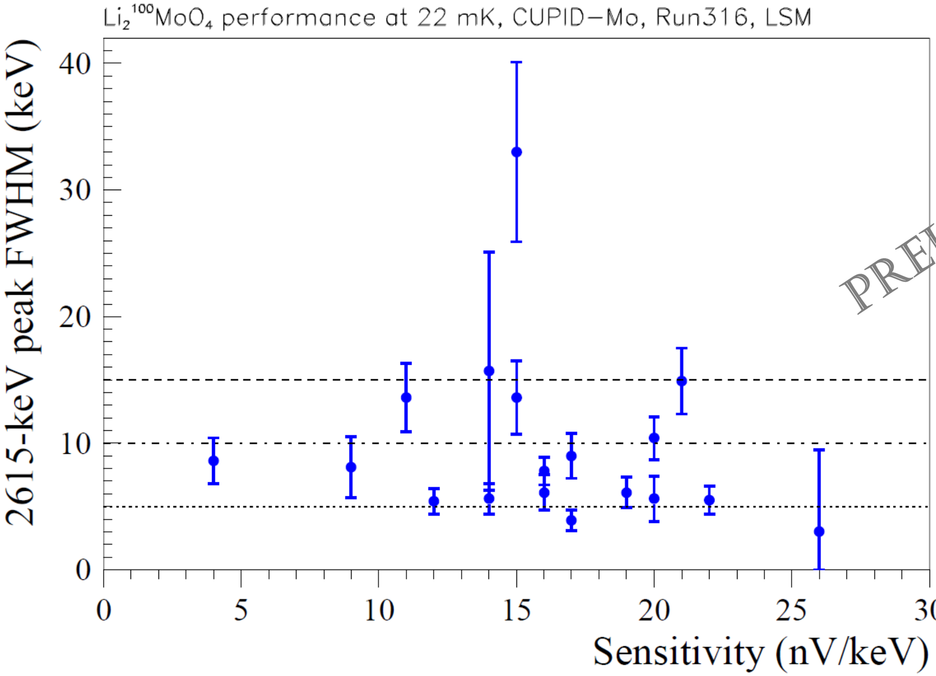
CUPID-Mo Modane (Phase I) Preliminary results at 22 mK

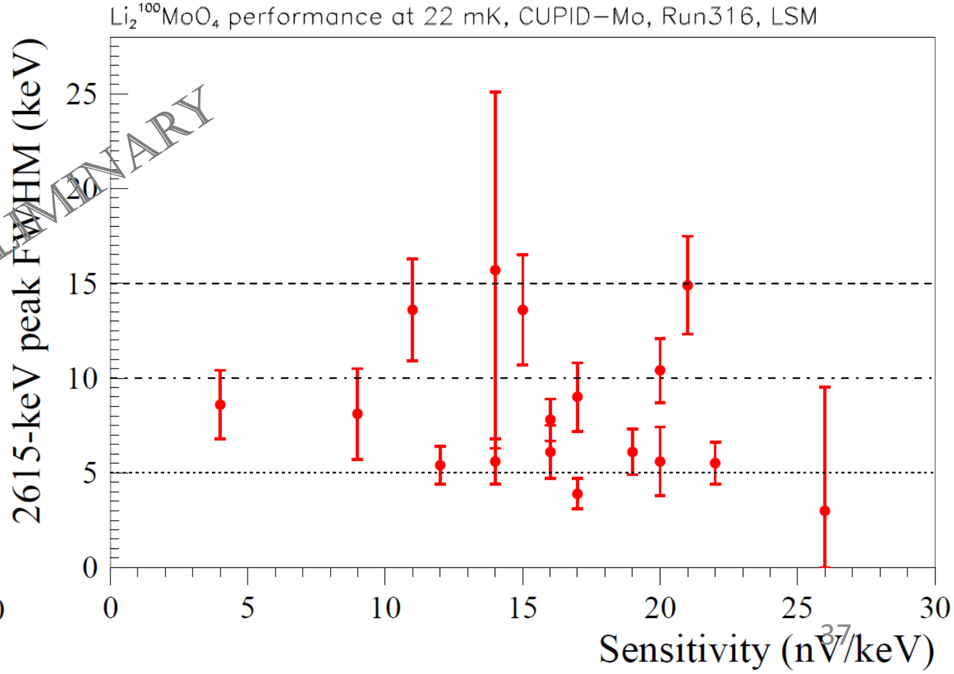
Long delay of the run start due to cryogenics (Nov 2017 → Apr 2018)

Preliminary data acquired at **22 mK**

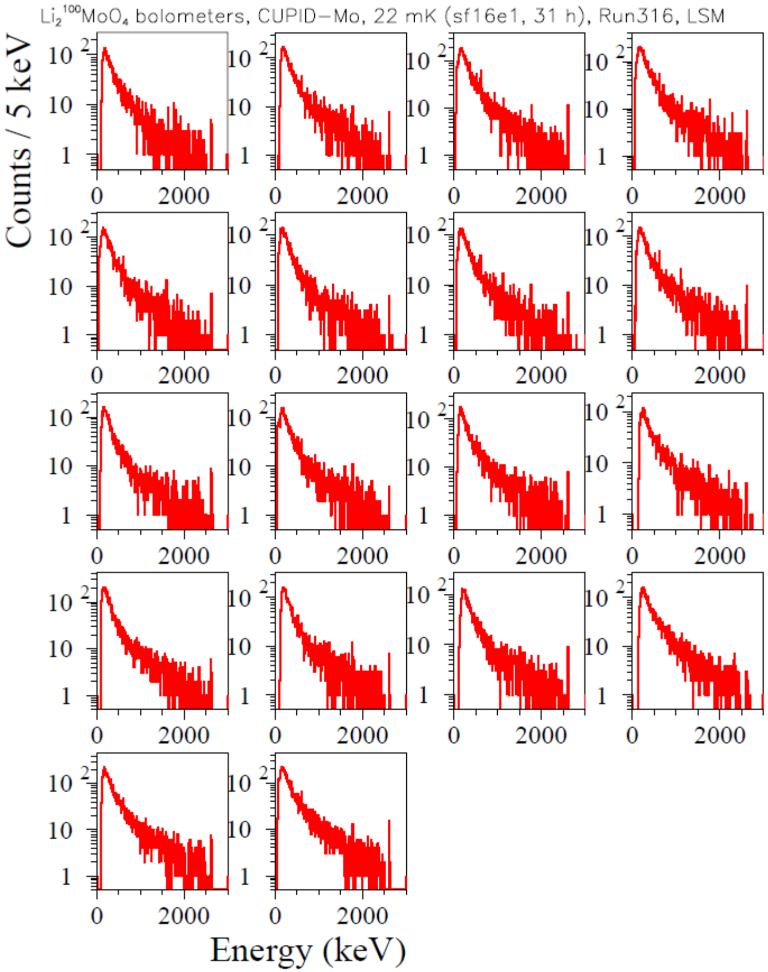
- Large microphonic noise, related in part to persisting cryogenic problems
- 2 heat channels are lost

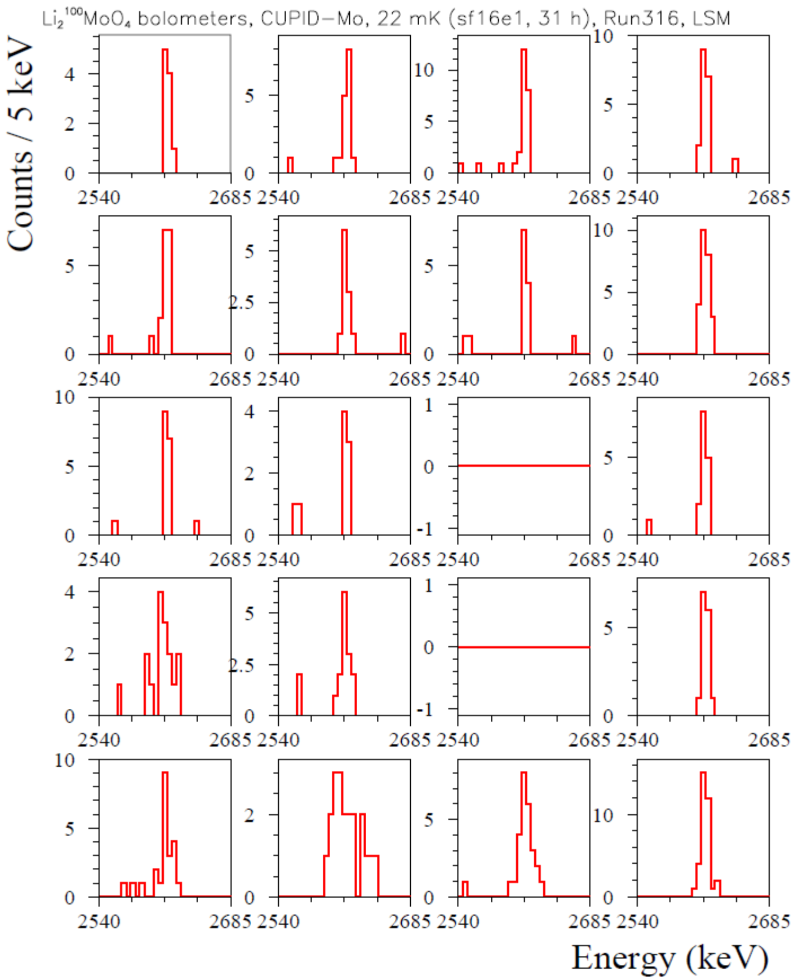
Calibration with thorite source – Th + U



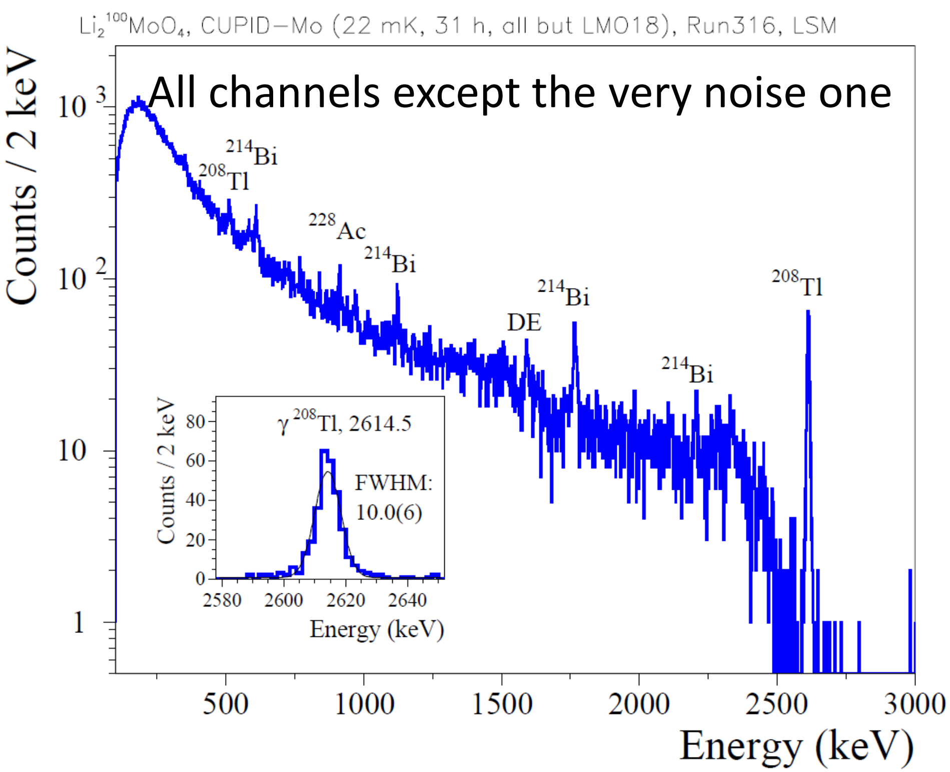


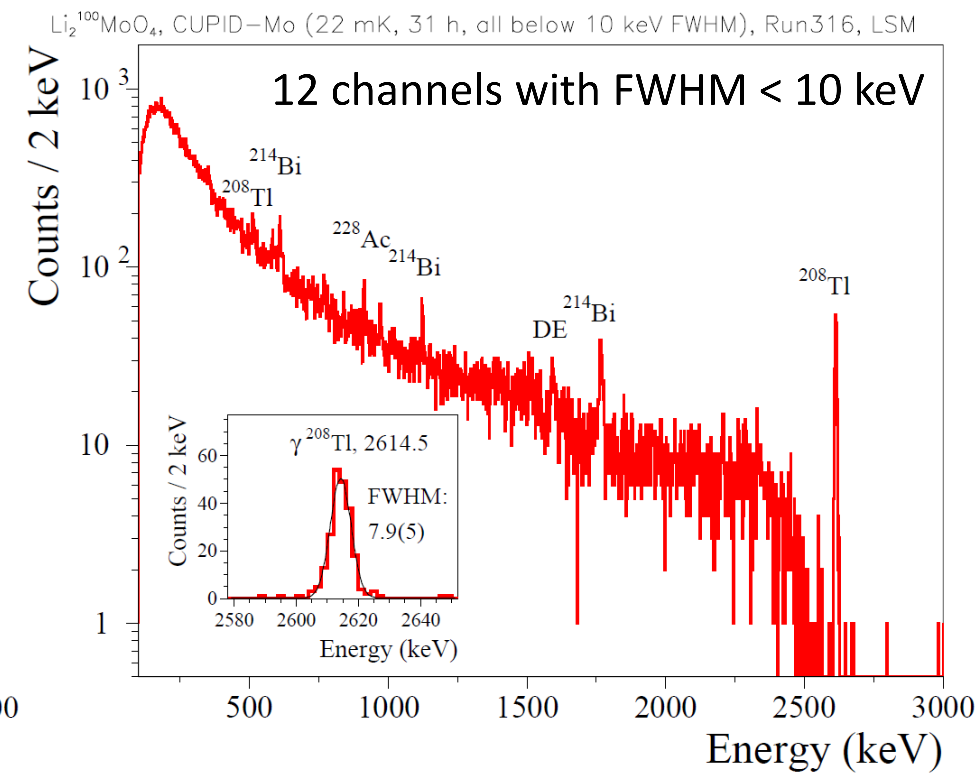
CUPID-Mo Modane (Phase I)
Preliminary results at 22 mK





CUPID-Mo Modane (Phase I) Preliminary results at 22 mK





- **Cryostat failure** forced us to stop the run at Agust 7th, 2018
- Maintenance of the cryostat is now ongoing
- Run resume is foreseen for this fall

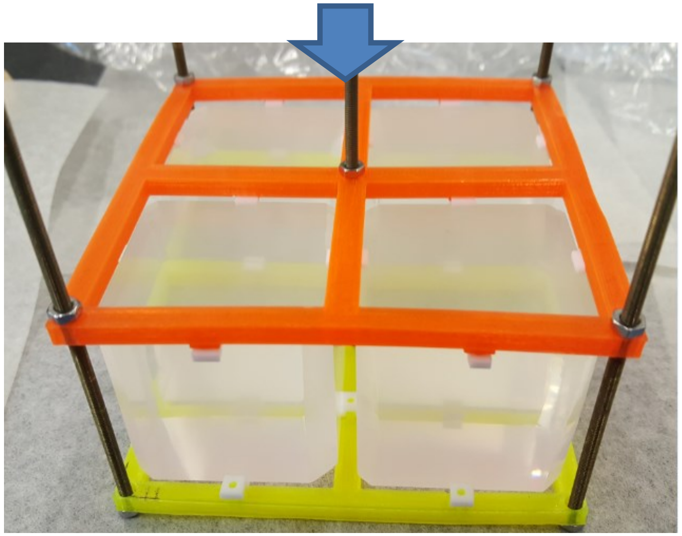
CUPID-Mo LNGS (Phase II)

Single CUORE-like tower with 4 elements in each floor

- 7 floors × 4 crystals/floor = 28 enriched crystals in total
- 26 enriched and 2 natural crystals
- Total mass: 28 × 280 g → **4.1 kg of ^{100}Mo**

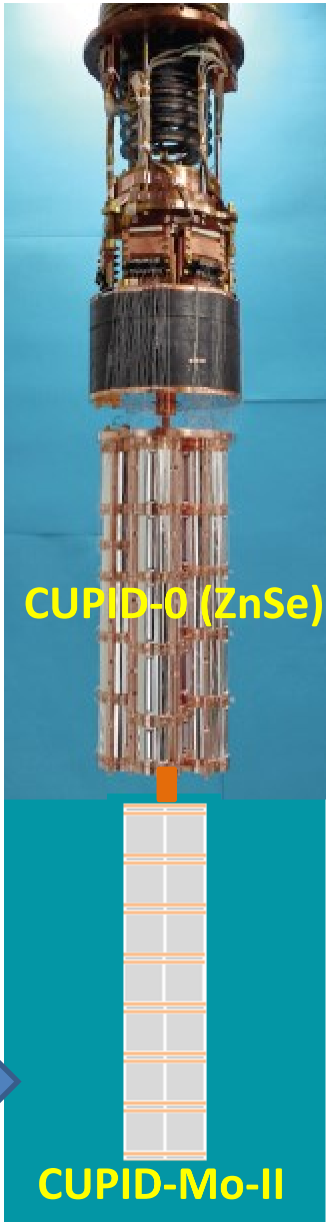
14 crystals already delivered
12 expected in November 2018

Mechanics tests are ongoing



Installation in LNGS is foreseen at mid-2019, below the CUPID-0 experiment

First bi-isotope search with bolometers



Beyond light detectors: CROSS

ERC advanced grant CROSS (2018-2022)

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

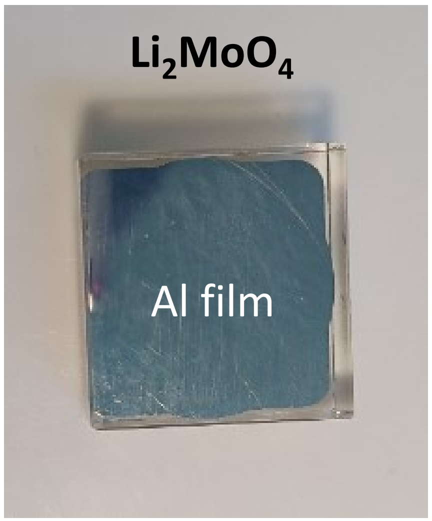
CROSS develops an innovative bolometric technology to search for 0ν-DBD

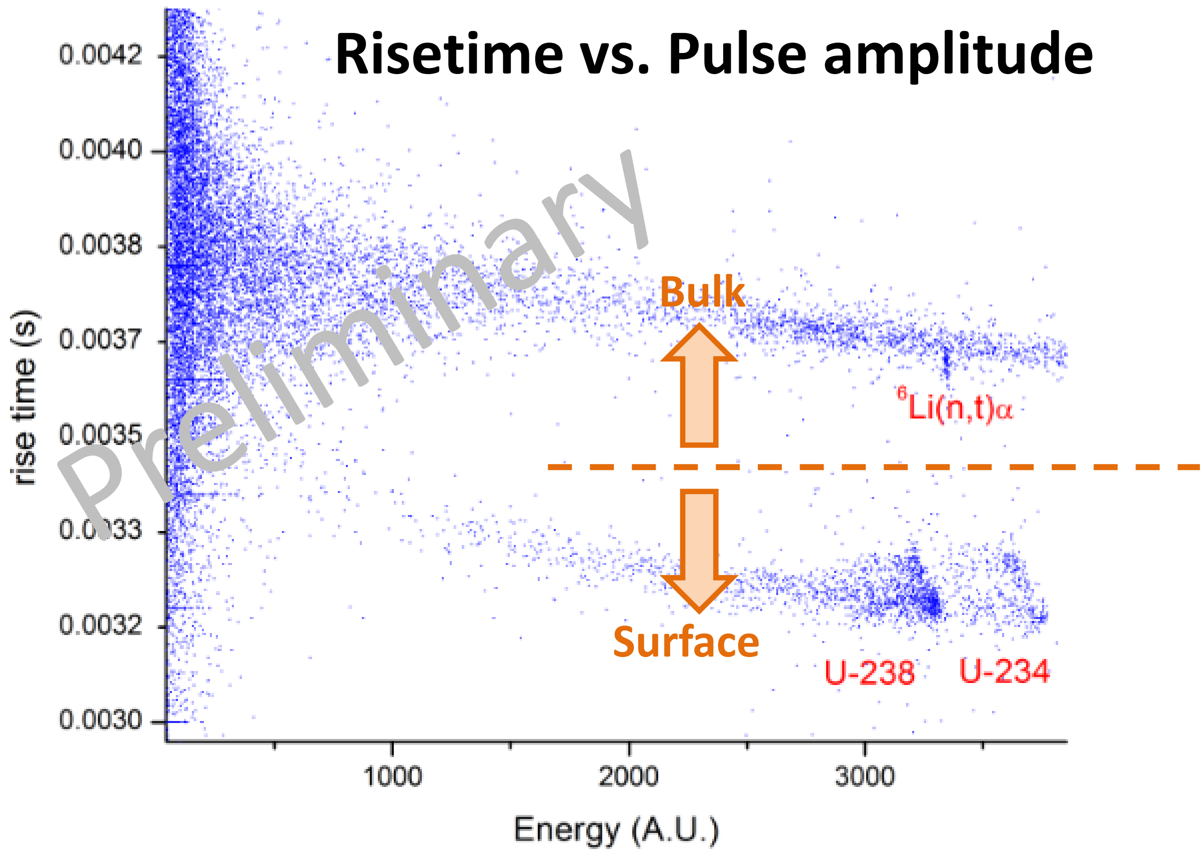
- **Core of the project** (high risk / high gain)
  Background rejection through **pulse shape discrimination**
  - **Surface sensitivity** through **superconductive Al film coating**
  - **Fast NbSi high-impedance TES** to replace / complement NTDs if necessary

  → **get rid of light detectors**
- Complete crystallization of available ^{100}**Mo (10 kg)** in Li_2MoO_4 elements → **CUPID-Mo demonstrator in LNGS (Phase II)**
- Purchase / crystallize ^{130}**Te (up to 10 kg)** in TeO_2 elements
- Run demonstrator in a dedicated cryostat **(LSC – Spain)**

Encouraging preliminary results

Above-ground tests (CSNSM) with **20x20x10 mm Li_2MoO_4** and **TeO_2 crystals**





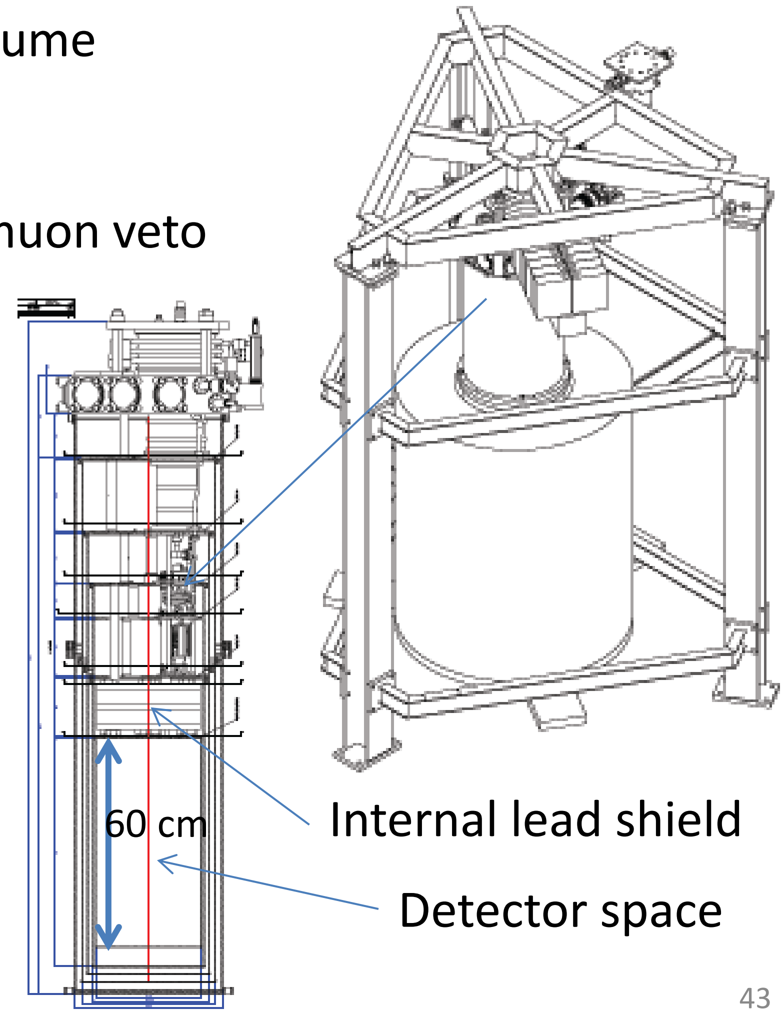
Alphas impacting on the film side are clearly discriminated

CROSS demonstrator in LSC

Dilution refrigerator on construction (French company CRYOCONCEPT)

- 10 mk base temperature
- Cylinder ∅30cm × h60cm experimental volume
- Antivibration system
- 180 electronics channels
- Passive shielding (lead, polyethilene) and muon veto

Commissiong: April 2019



Outline

- Challenges in $0\nu2\beta$ decay and the CUPID way
- Scintillating bolometers and ^{100}Mo
- Results with $Li_2{}^{100}MoO_4$ crystals
- Demonstrators: CUPID-Mo and CROSS
- **CUORE and its background model**
- Mo-based CUPID

CUORE

CUORE is an array of **TeO_2 bolometers** searching for $0\nu2\beta$ decay of the **isotope ^{130}Te** and taking data in LNGS (Italy)

The largest bolometric experiment ever

- 988 crystals 5x5x5 cm, closely packed
- Arranged in 19 towers of 13 floors each
- 742 kg (206 kg of ^{130}Te)
- Background according to expectations: **$1.4 \pm 0.2 \times 10^{-2}$ c/(keV·kg·yr)**
- Energy resolution close to expectations: **~7.7 keV FHWM** → margins for improvement

One of the most sensitive $0\nu2\beta$ experiments of the current generation

- Current limit (^{130}Te $T_{1/2}^{0\nu2\beta}$) : **> 1.5×10^{25} y**

  $m_{\beta\beta}$ < 110 – 520 meV (90% C.L.)

  Phys. Rev. Lett. 120, 132501 (2018)

- 5 y projected $T_{1/2}$ sensitivity: **~9×10^{25} y**

  $m_{\beta\beta}$ < 60 – 165 meV

CUORE is not background free

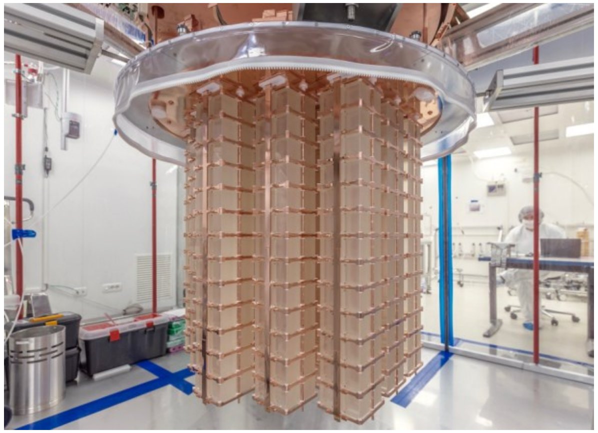
→ **~50 counts/y in the ROI**, dominated by **surface alpha background**

CUORE → CUPID

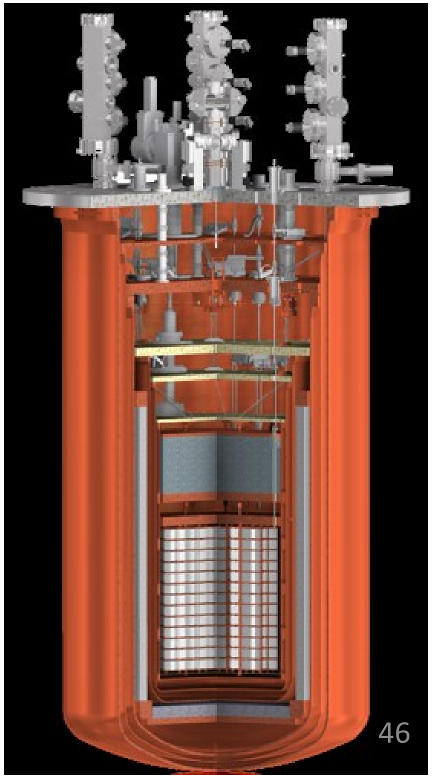
Three important messages from CUORE

1. A tonne-scale bolometric detector is technically feasable
2. Analysis of ~1000 individual bolometers is handable
3. An infrastructure to host a bolometric next-generation $0\nu\beta\beta$ experiment is already available

It is time to work on CUPID, the natural evolution of CUORE



CUPID (CUORE Upgrade with Particle ID) is a proposed $0\nu2\beta$ bolometric experiment exploiting the **CUORE infrastructure** and with a **background 100 times lower at the ROI**



Prospects for CUPID

Results of the ongoing **R&D and demonstrators** + **CUORE background model**

1. $Li_2{}^{100}MoO_4$ scintillating bolometers → promising **baseline option** for CUPID

2. $^{130}TeO_2$ Cherenkov bolometers → mature viable alternative

Phys. Rev. C 97 (2018) 032501(R)

→ Fast and high-sensitivity light detectors are a common R&D

- Detection of Cherenkov light in TeO_2
- Rejection of $2\nu2\beta$ random coincidences in $Li_2{}^{100}MoO_4$ *EPJ C 77 , 3 (2017)*

The purpose of CUPID is to fully explore the IO region

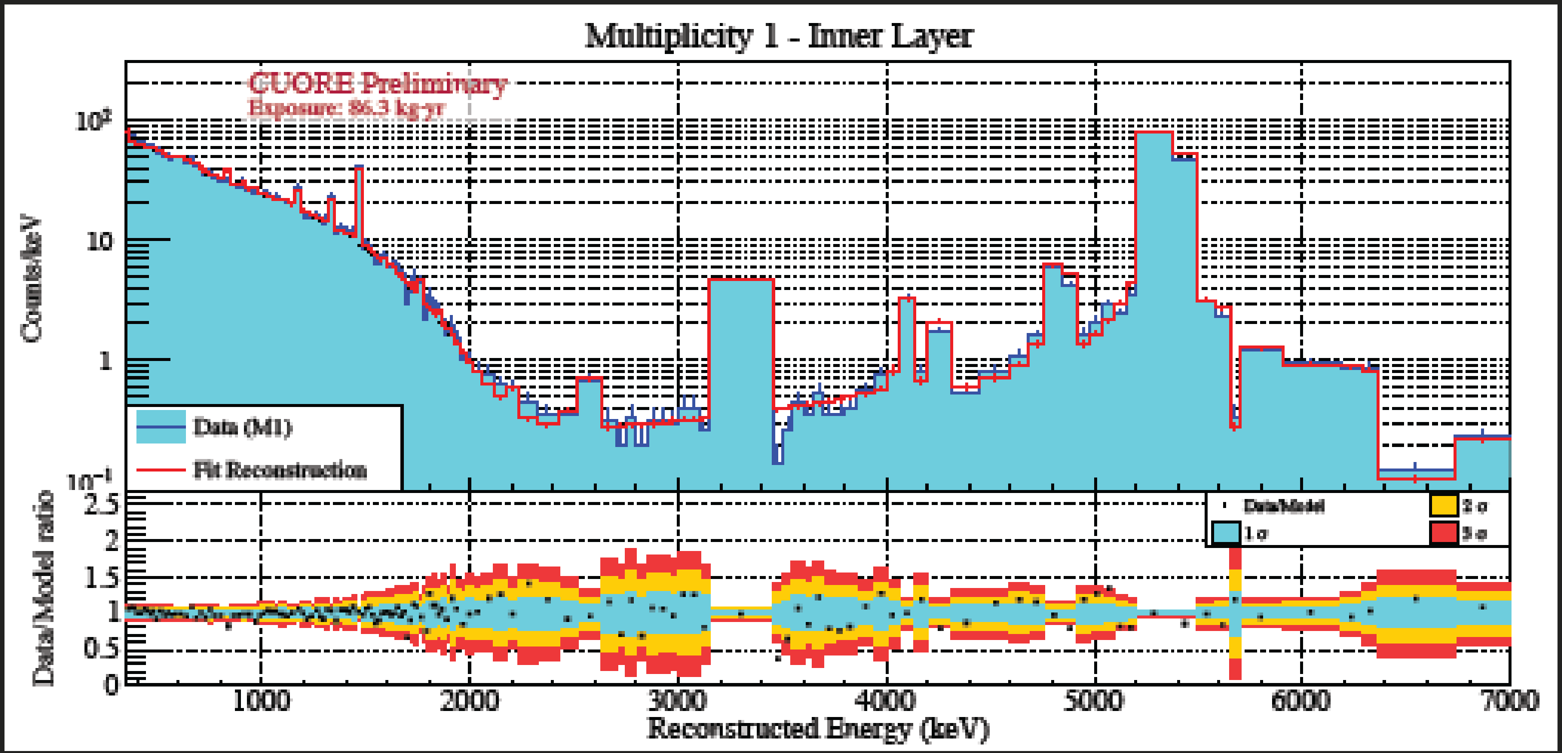
Mission: **half-life sensitivity higher than 10^{27} y** *arXiv:1504.03599*

With background < 0.1 counts/(ton y) in the ROI, ^{100}Mo sensitivity is **2.1×10^{27} y**

$m_{\beta\beta} < 6 – 17$ meV

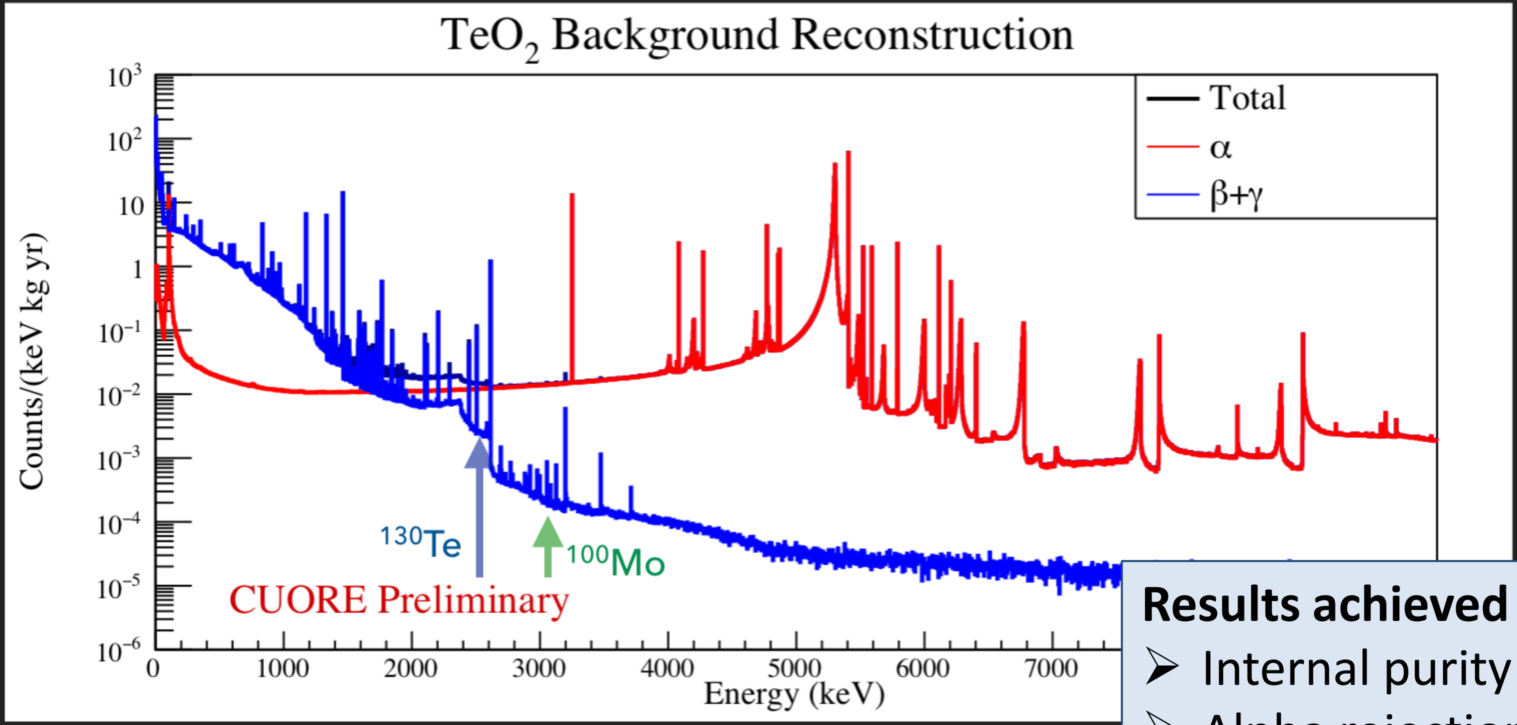
- **CUPID collaboration will be formed in the near future**
- **CUPID kick-off meeting is being planned in November 2018**

Fitting the CUORE Background



➡Able to reconstruct the major features of the observed spectrum in CUORE

Background Model Contamination Levels (Very Preliminary!)



Results achieved in LMO R&D

- Internal purity
- Alpha rejection factor

TeO_2 γ background at 2527 keV	~2.6×10^{-3} cnts/(keV·kg·yr)
Li_2MoO_4 γ background at 3034 keV	~1×10^{-4} cnts/(keV·kg·yr)

(Based on assumptions)

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Possible configurations in CUPID

Single element	Number of elements	Isotope mass [kg]	Number of ^{100}Mo nuclei
50×50×50 mm – 380 g	1150	~250	~1.4×10^{27}
45×45×45 mm – 280 g	1600		

Same size as in CUORE

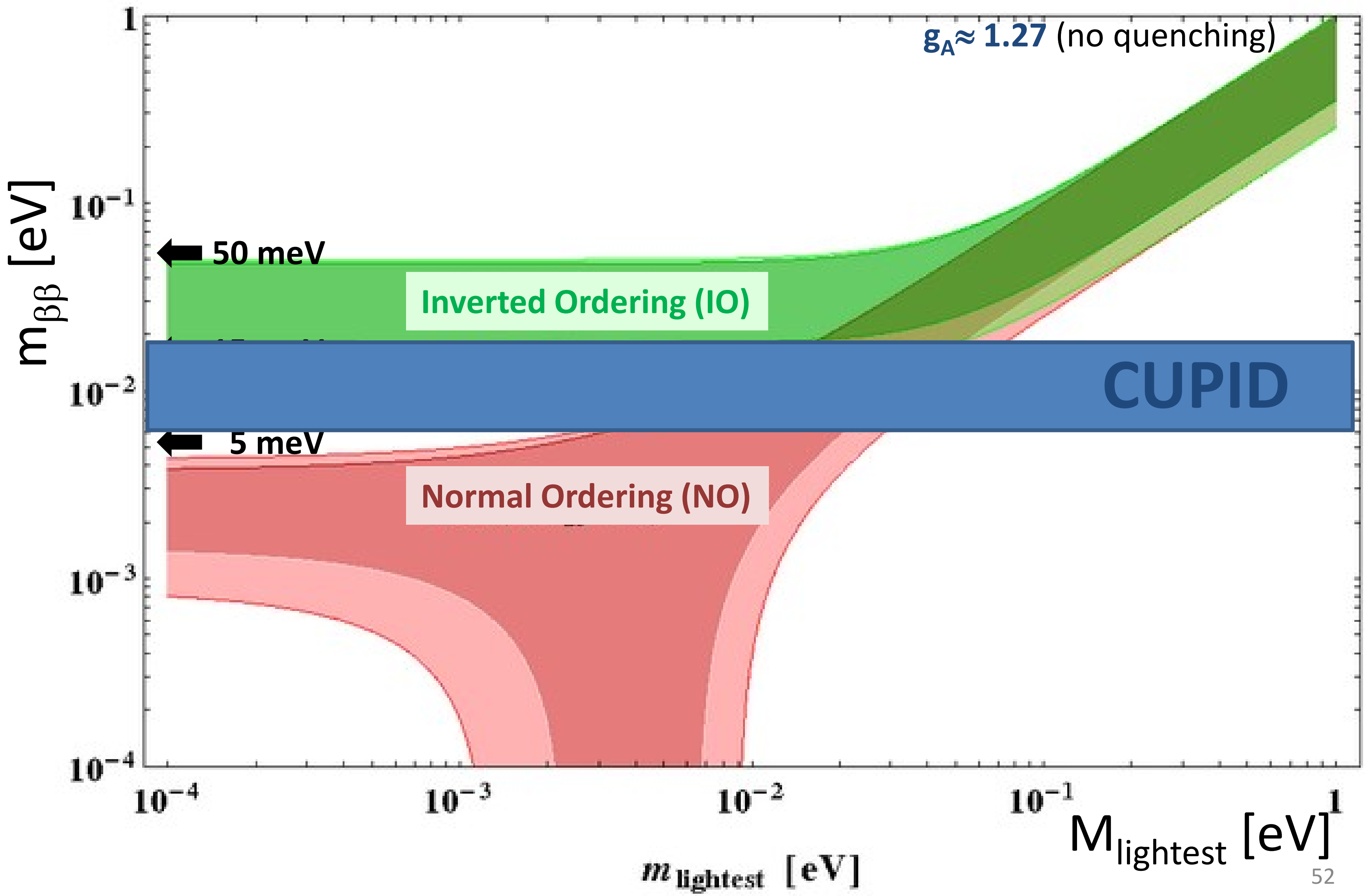
Already achieved size in the R&D

Preliminary

Background [counts/(keV kg y)]	Number of BKG counts [5 keV, 10 y]	Count limit Feldman Cousins [90% c.l.]	Half life limit [y] [90% c.l.]	$M_{\beta\beta}$ [meV]
1×10^{-4}	2.2	4.1	1.8×10^{27}	**6.6 – 19**

Next generation experiment → **cover completely the inverted ordering region**

CUPID reach



$g_A \approx$ 1.27 (no quenching)
50 meV
Inverted Ordering (IO)
CUPID
5 meV
Normal Ordering (NO)
$m_{\beta\beta}$ [eV]
$M_{lightest}$ [eV]
$m_{lightest}$ [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1

Final considerations

Advantages of CUPID in LMO version (baseline):

- The **infrastructure** already **exists** (CUORE cryostat)
- The **R&D** on the single modules of the detectors is **completed**

The objetives are achieved in terms of
- Internal radiopurity
- Alpha rejection factor
- Energy resolution

Possible simplifcation with the CROSS approach

- **CUORE background model** indicates **b ~ 10^{-4} counts/(keV kg y)**
- **Crystalization** and **enrichement** at large scale are **possible**

Uniquely favorable position when compared to other next-generation searches