June 29th, 2018
Daejeon, Korea

NDM 2018
6th Symposium on Neutrinos and Dark Matter in Nuclear Physics 2018

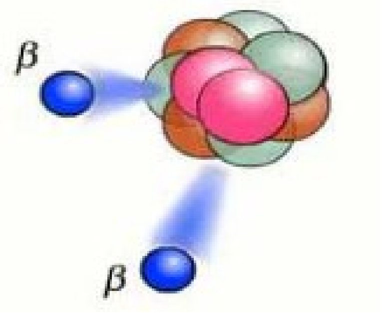
Study of the neutrinoless double beta decay of ^{100}Mo with the CUPID-Mo demonstrator

Andrea Giuliani

Outline

- Challenges in neutrinoless double beta decay
- Scintillating bolometers and ^{100}Mo
- Results with $Li_2{}^{100}MoO_4$ crystals
- CUPID-Mo
- Prospects

Neutrinoless double beta decay ($0\nu2\beta$): standard and non-standard mechanisms



$0\nu2\beta$ is a test for « creation of leptons »:

$2n \rightarrow 2p + 2e^-$ $\Rightarrow$ LNV

This test is implemented in the nuclear matter:

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

Energetically possible for **35 nuclei**

Only a few are experimentally relevant: **^{82}Se**, **^{76}Ge**, **^{100}Mo**, **^{130}Te, ^{136}Xe**

Enrichement is mandatory, **with the exception of ^{130}Te**

$0\nu2\beta$

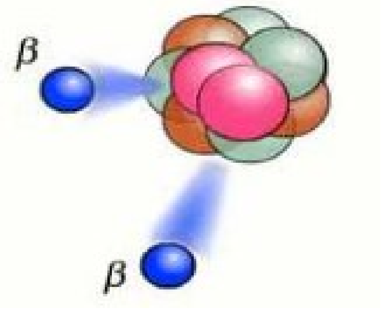
Standard mechanism: **neutrino physics**

$0\nu2\beta$ is mediated by **light massive Majorana neutrinos** (exactly those which oscillate)

Non-standard mechanism: **BSM, LNV**

Not necessarily neutrino physics

Neutrinoless double beta decay ($0\nu2\beta$): standard and non-standard mechanisms



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Neutrinoless double beta decay is the only experimentally viable process that can ascertain the Majorana nature of neutrinos:

- New form of matter (fermions ≡ antifermions)
- Naturally incorporated in Grand Unification Theories
- Explain smallness of neutrino masses (see-saw mechanism)
- Explain matter / antimatter asymmetry in the Universe (leptogenesis)

Neutrinoless double beta decay ($0\nu2\beta$): standard and non-standard mechanisms

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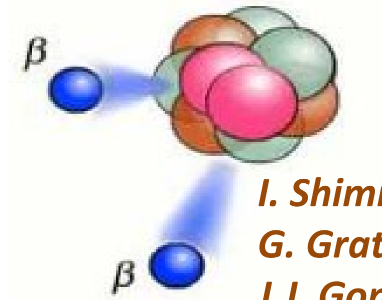

This test is implemented in the nuclear matter:

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

I. Shimizu
G. Gratta
J.J. Gomez-Cadenas
Ke Han

S. Schoenert
B. Zhu

S. Pirro
R. Saakyan

HongJoo Kim

Energetically possible for **35 nuclei**

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M. Chen
Ke Han

F. Simkovic
H. Ejiri
S. Stoica
R. Dvornicky
F. Cappuzello
J. Engel
J. Suhonen
S. Eliseev
J. Menendez

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- Naturally incorporated in G n Theories
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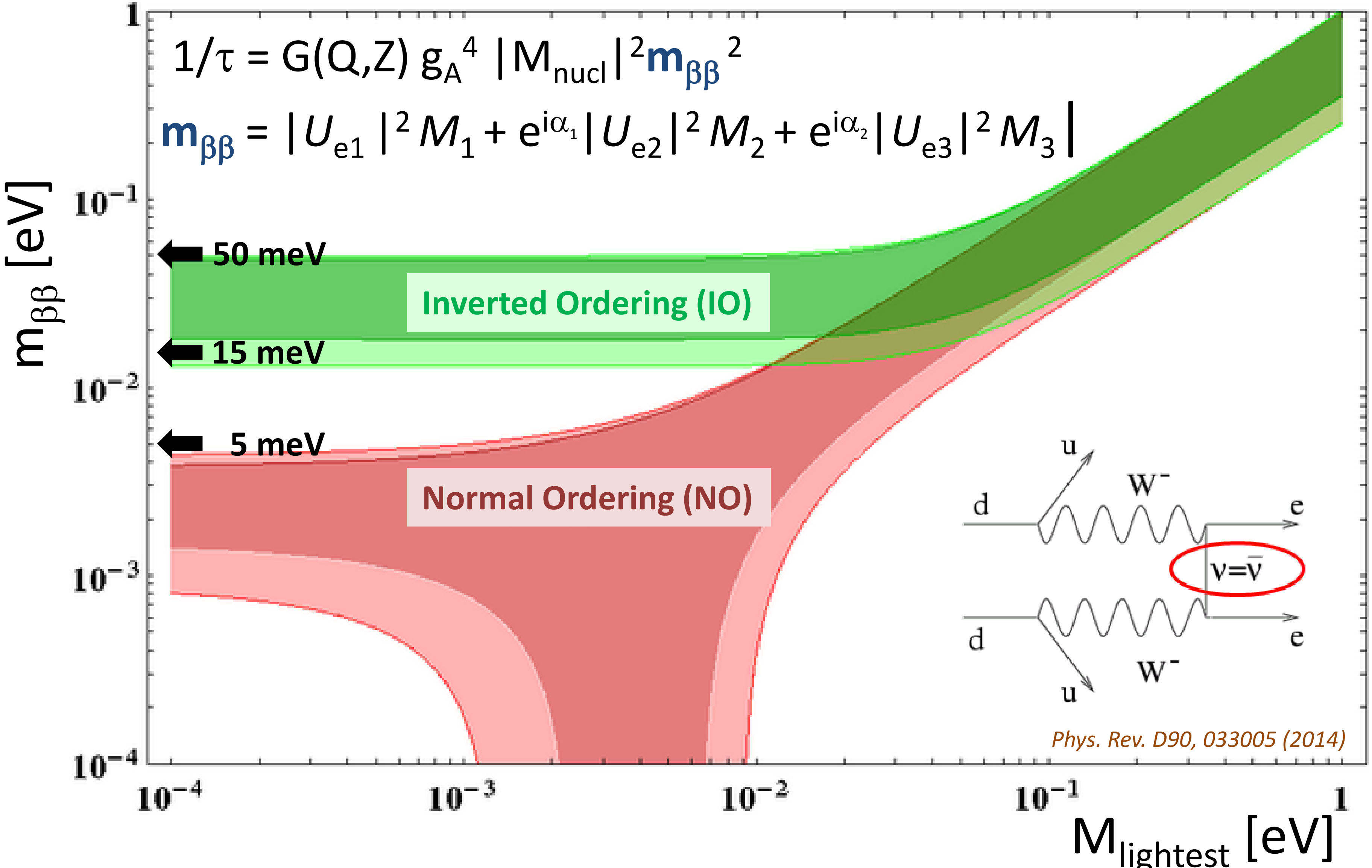
- Explain matter / antimatte the Universe (leptogenesis)

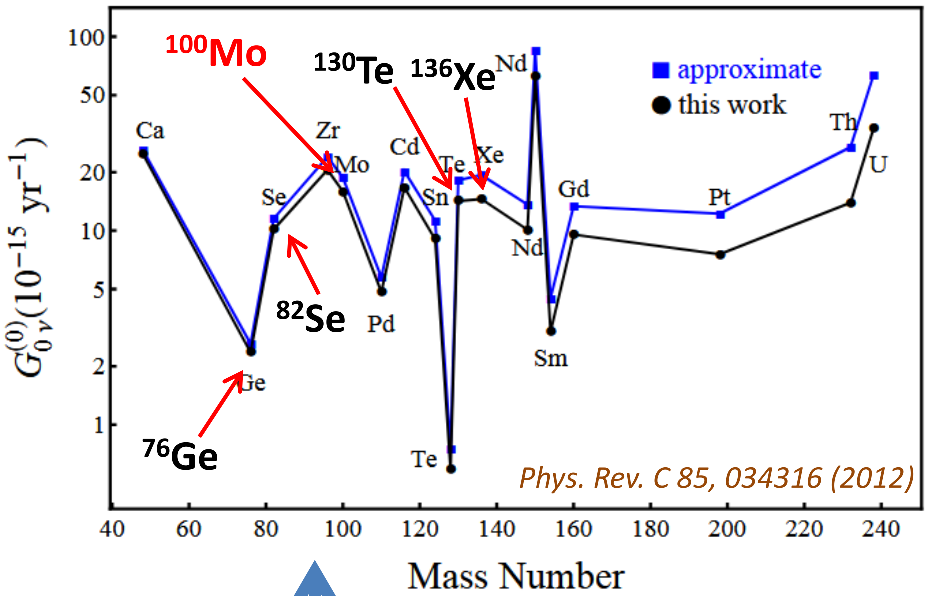
Standard mechanism: $m_{\beta\beta}$ vs. lightest ν mass



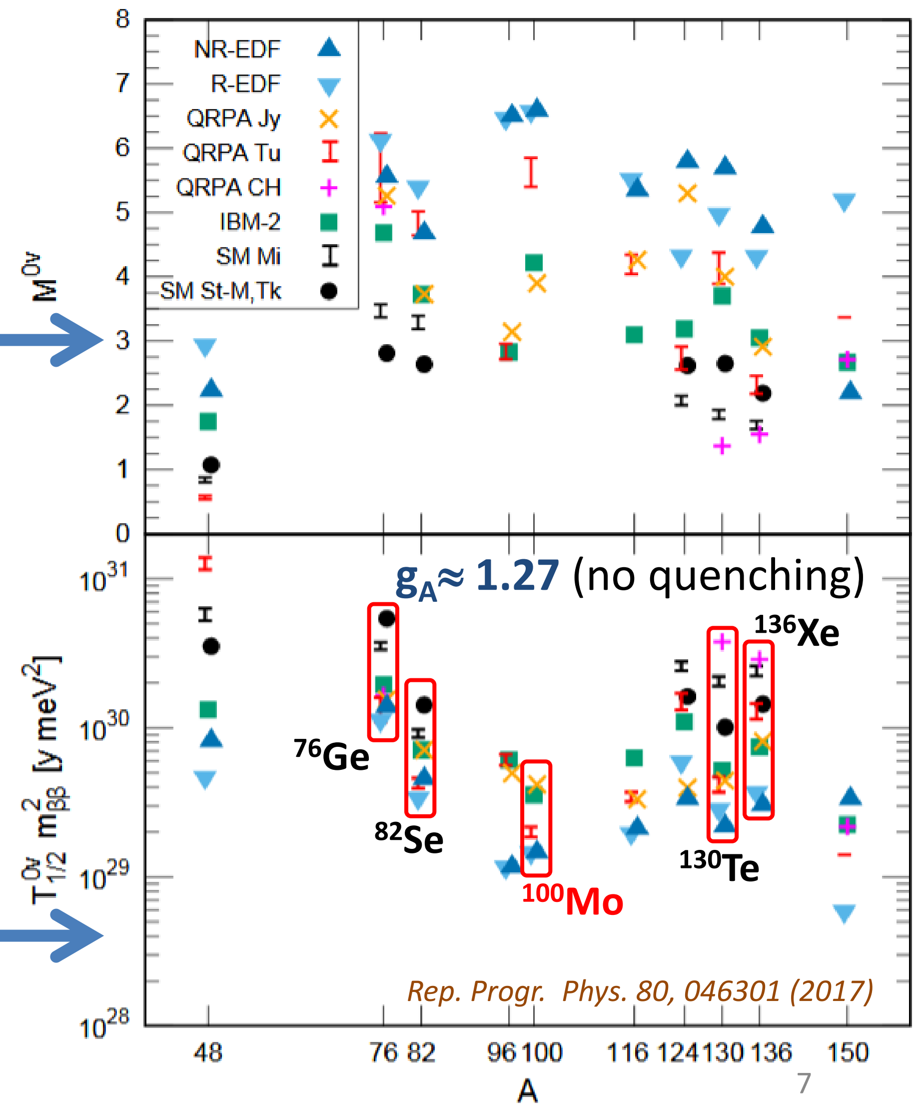
How difficult is it?

F. Simkovic *R. Dvornicky*
S. Stoica *J. Suhonen*
J. Engel *J. Menendez*

Phase space: exactly calculable



Nuclear matrix elements: several models



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

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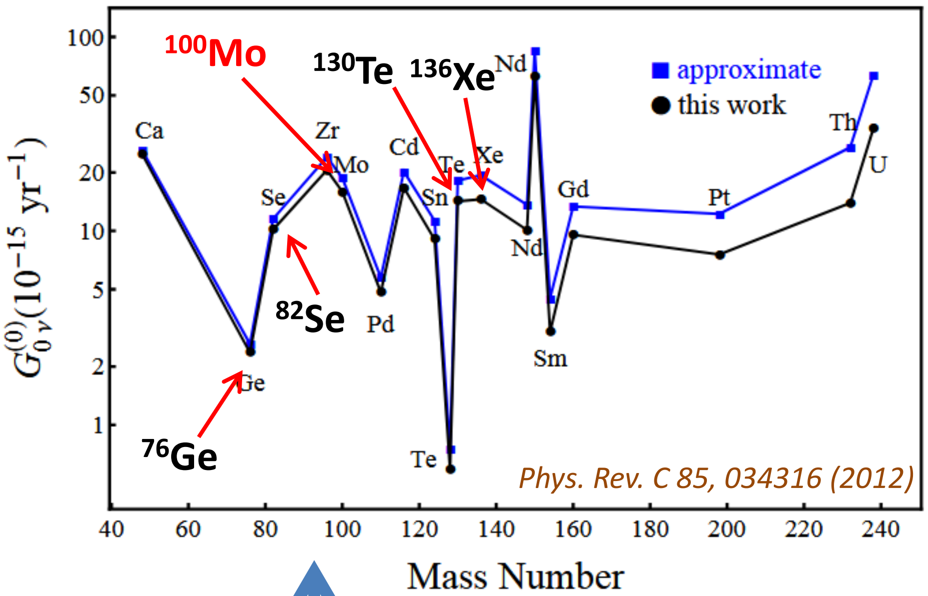

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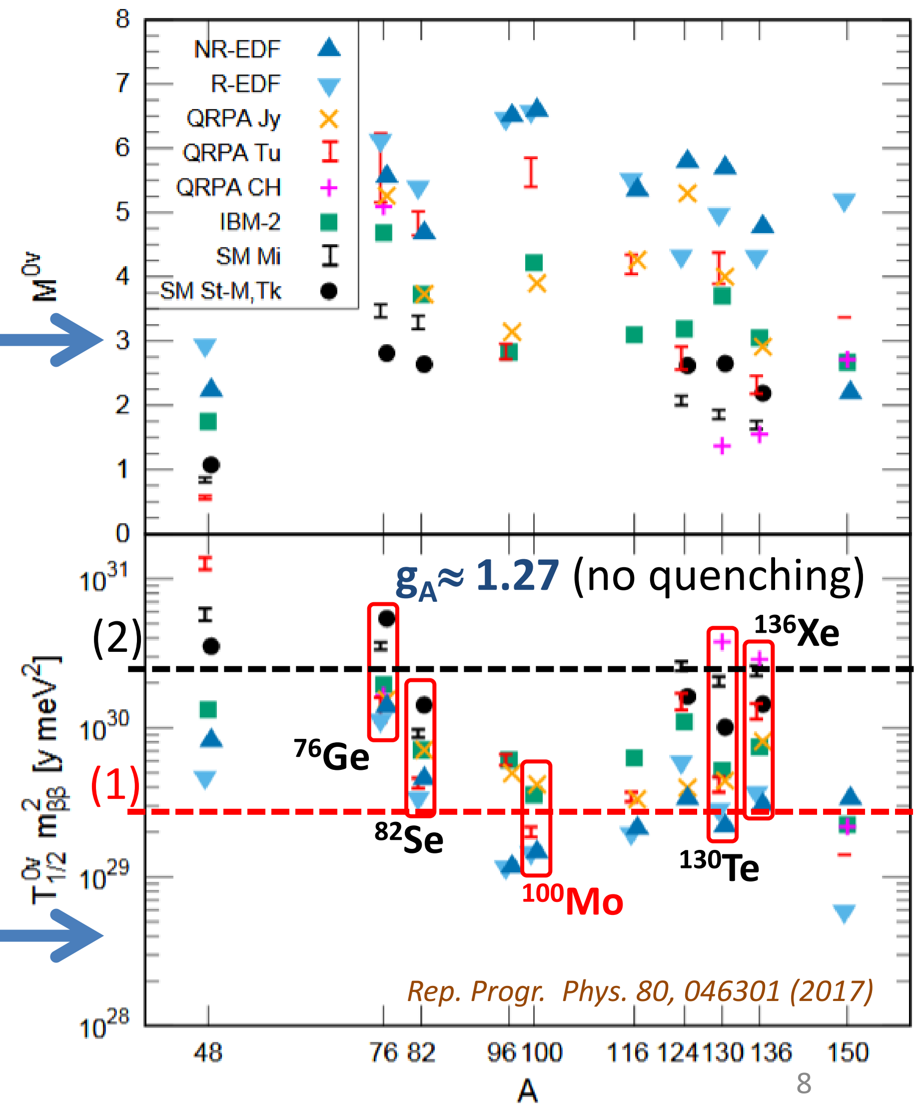
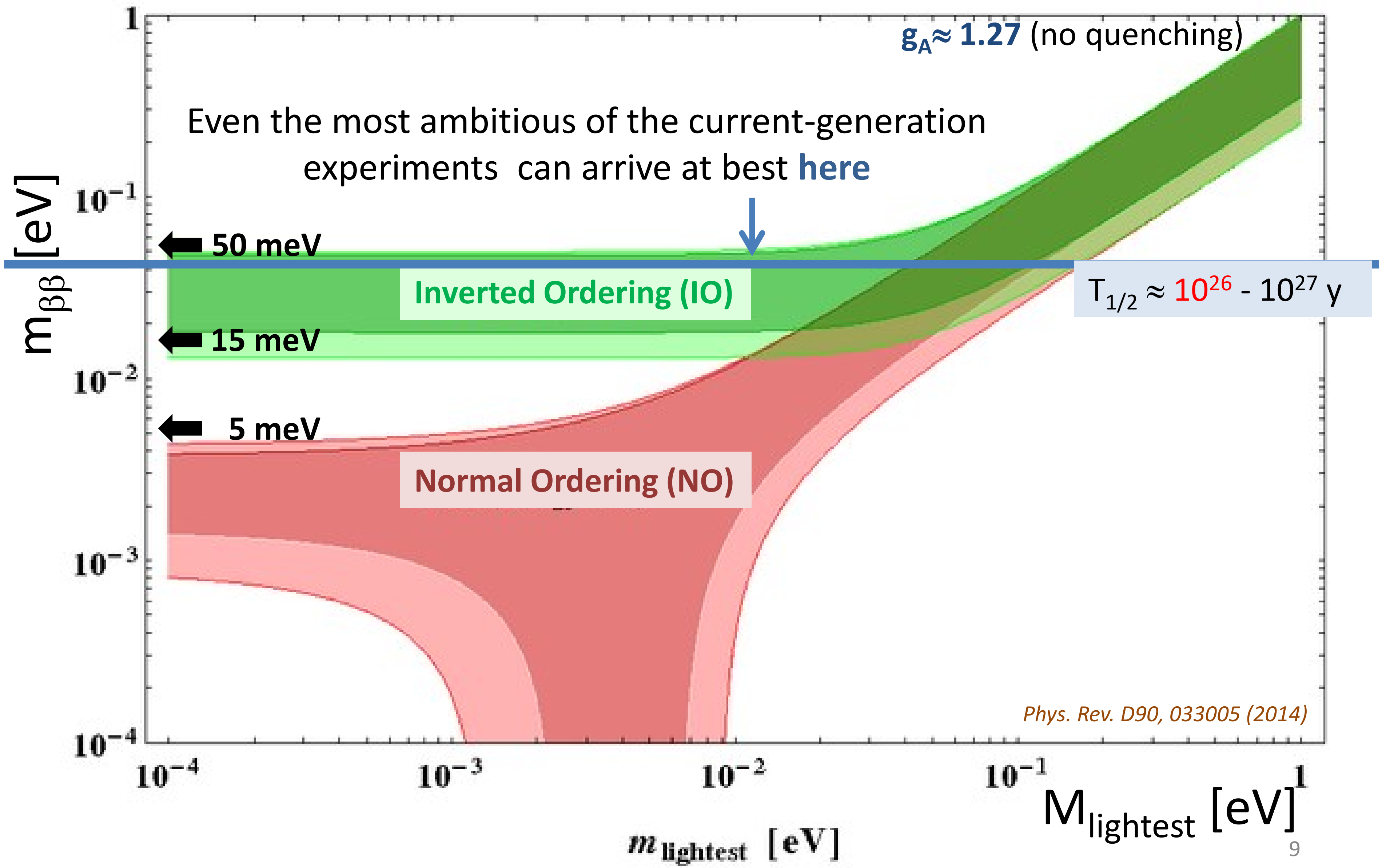
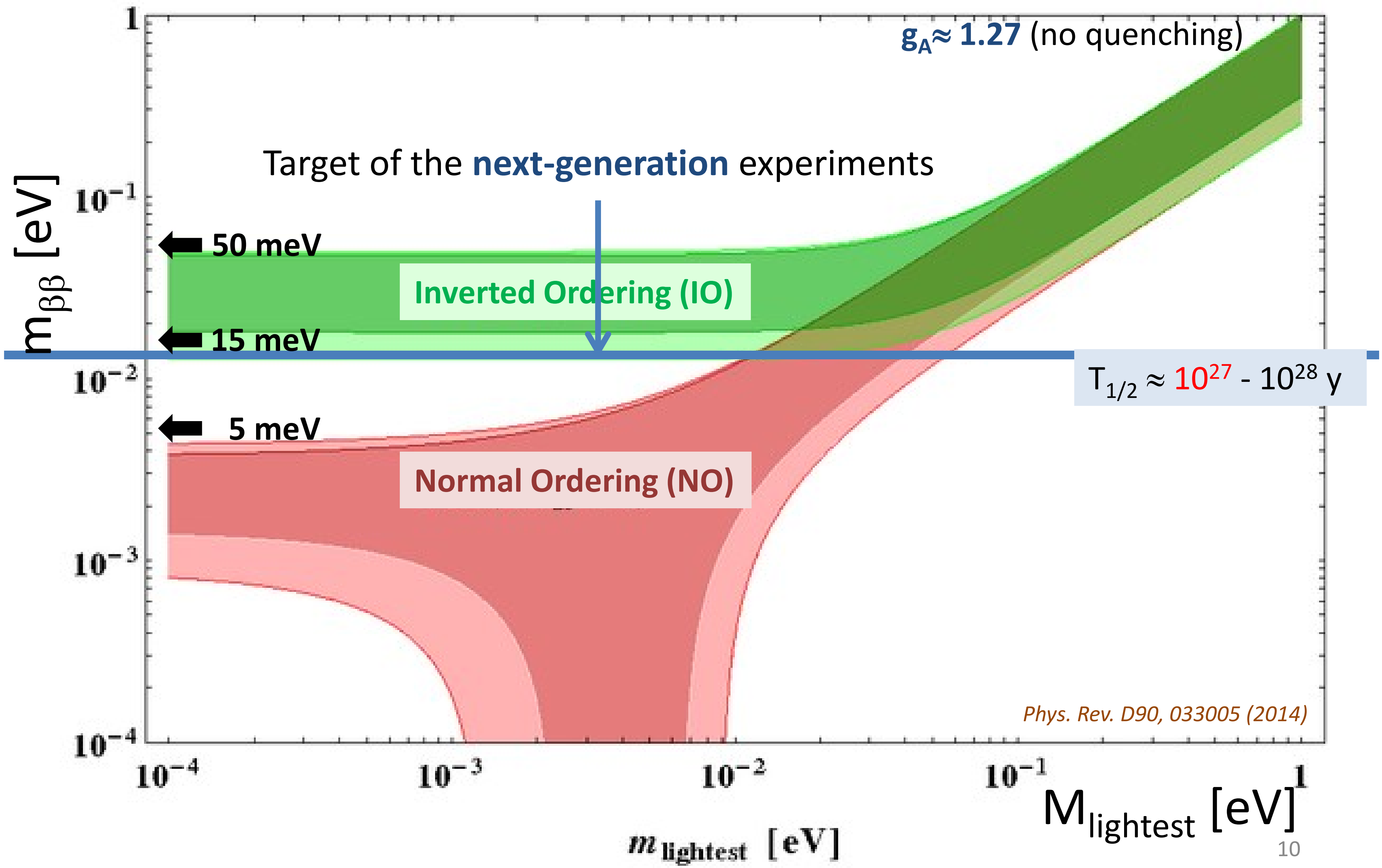


$$1/\tau = G(Q,Z)\, g_A^{\,4}\ |M_{nucl}|^2\ m_{\beta\beta}^{\;2}$$

Current-generation experiments



Next-generation experiments



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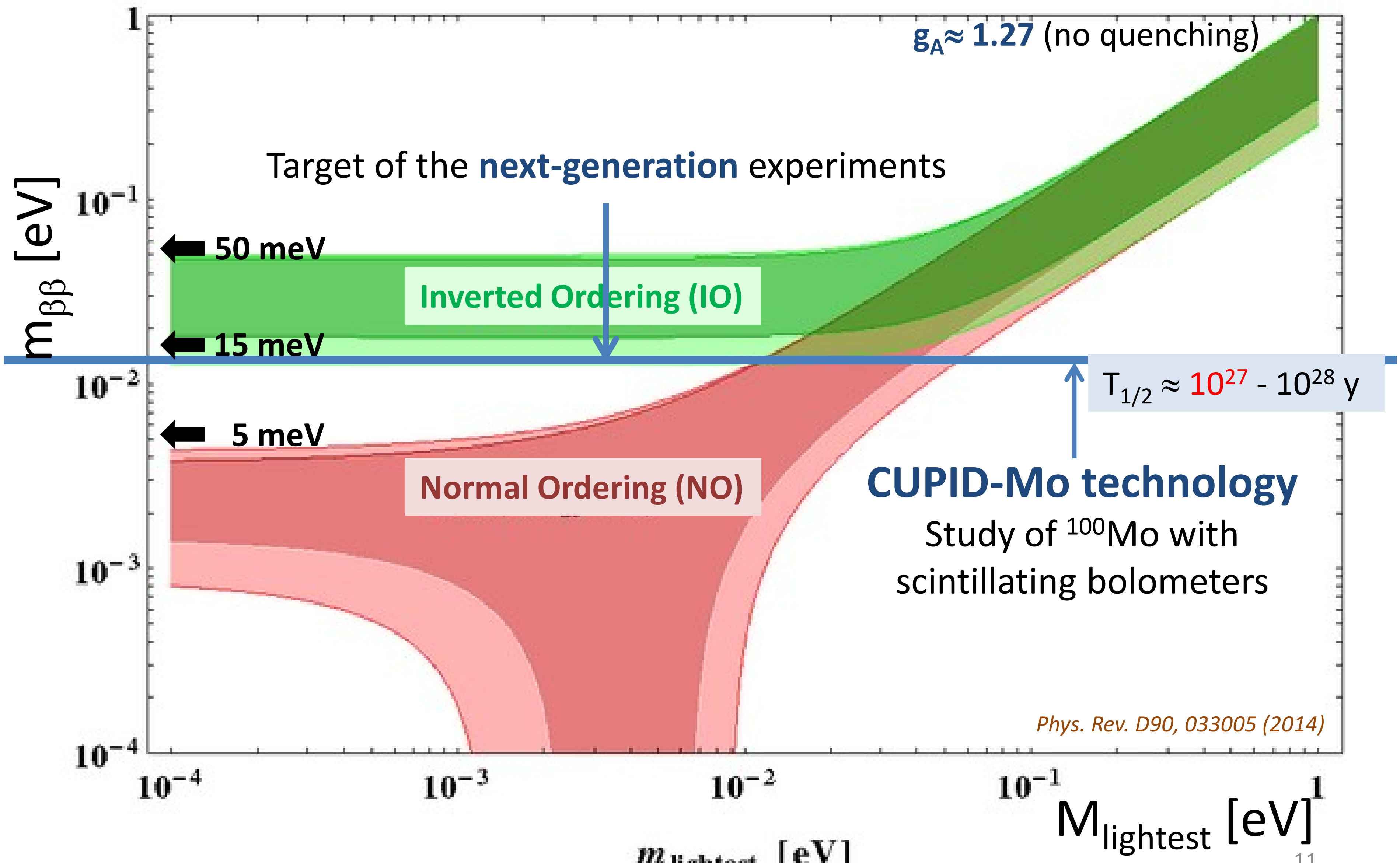
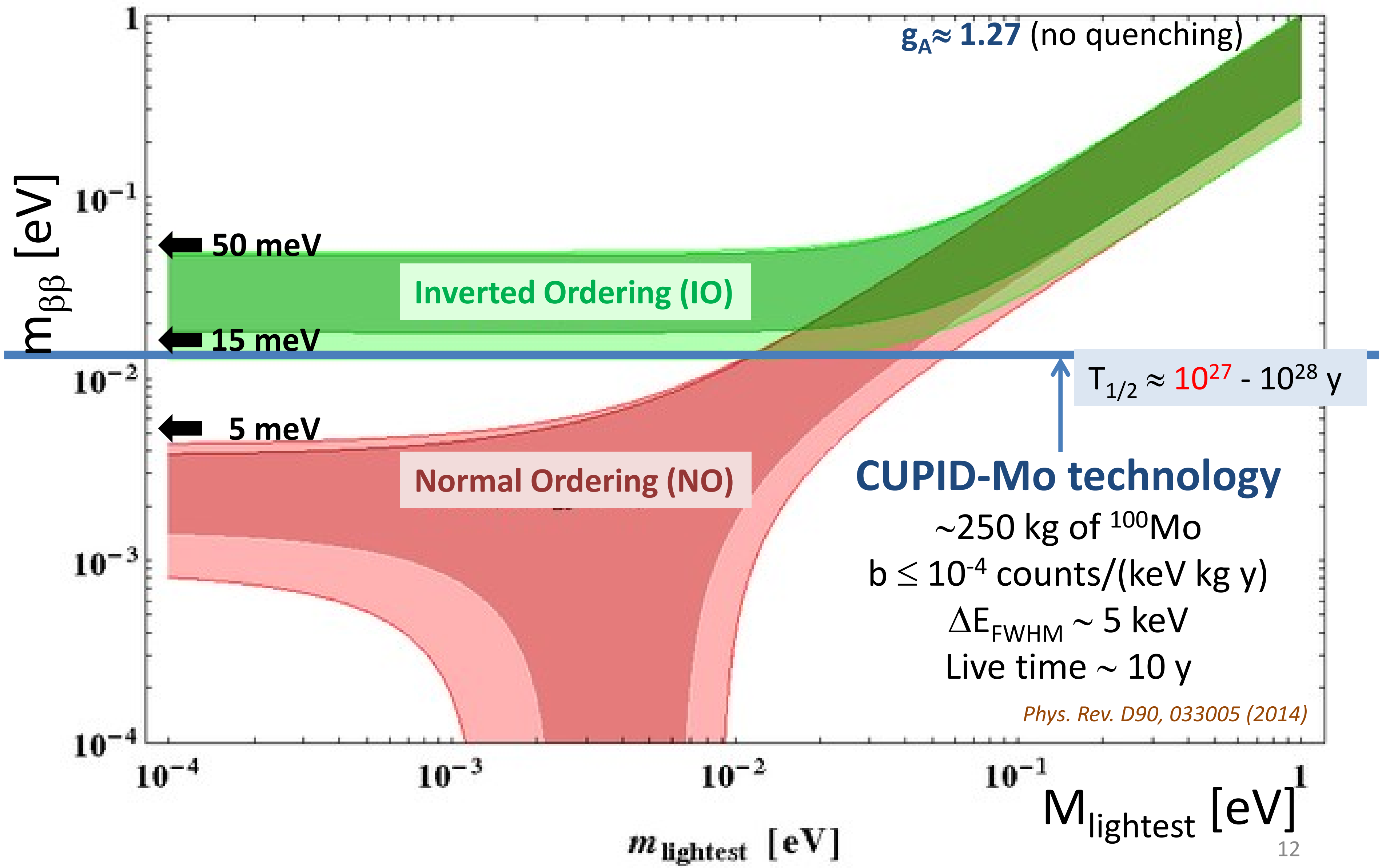
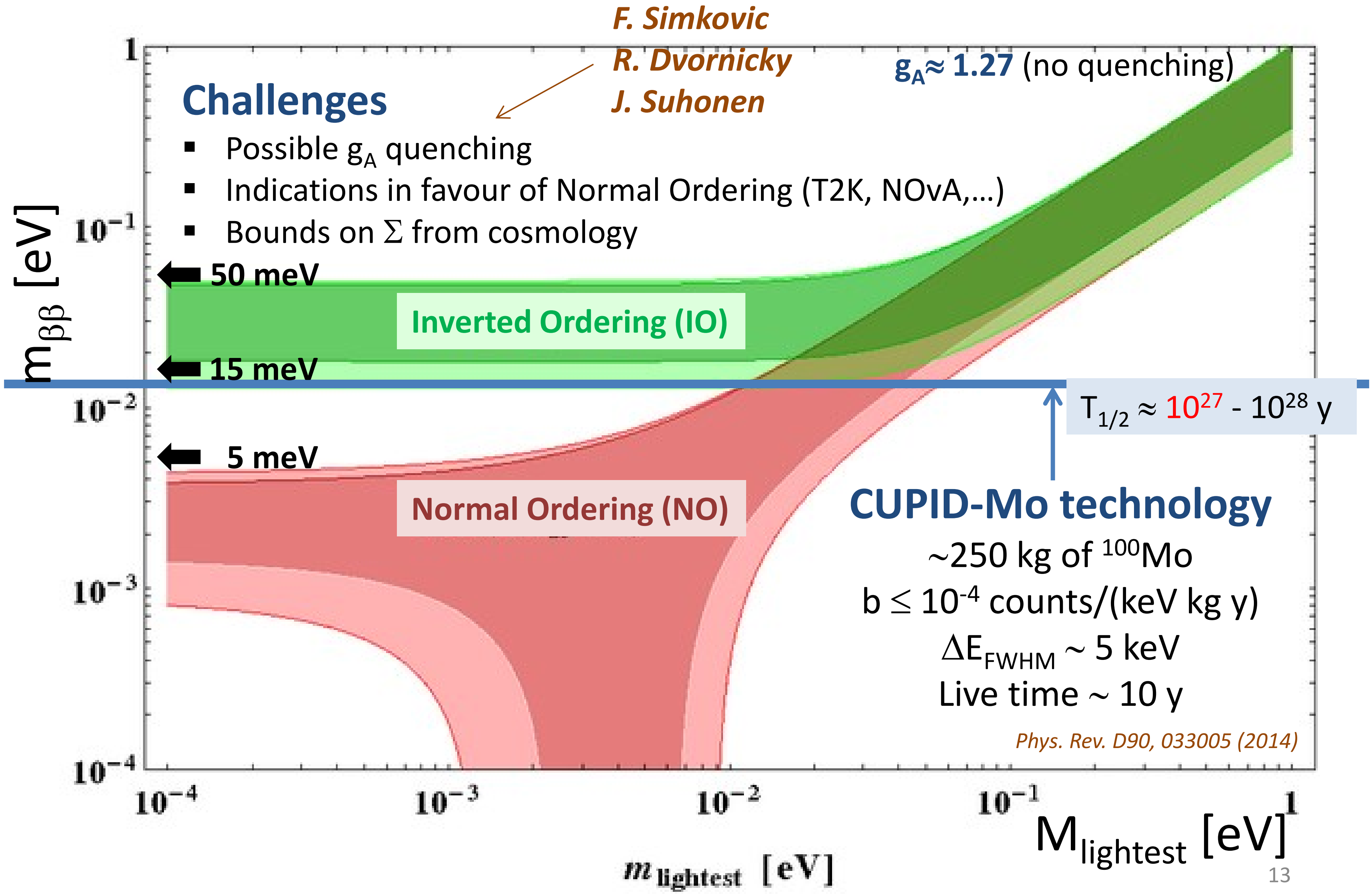


Next-generation experiments

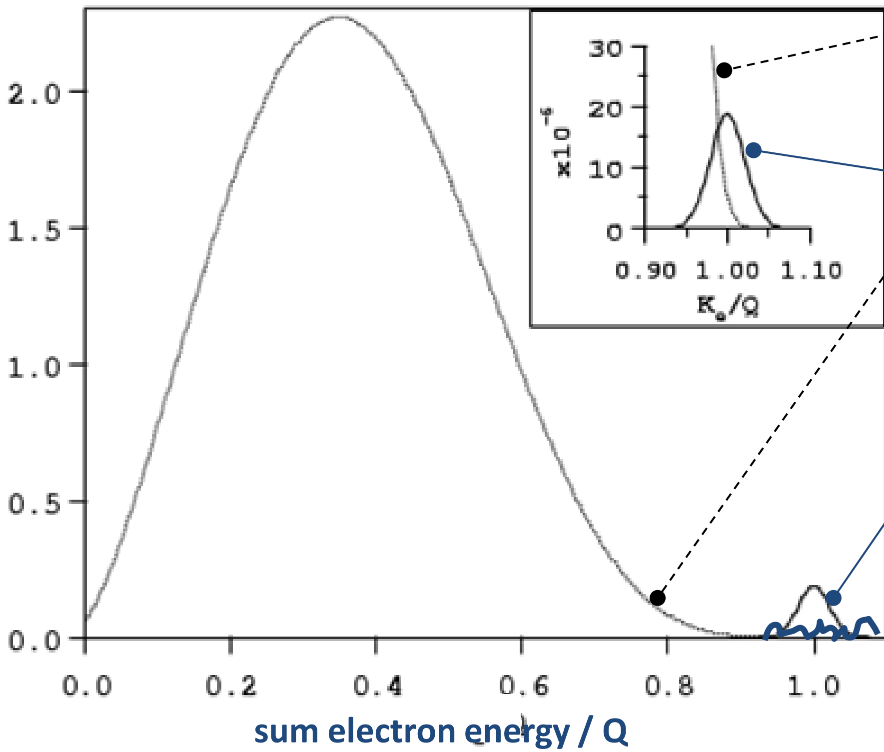


Next-generation experiments



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

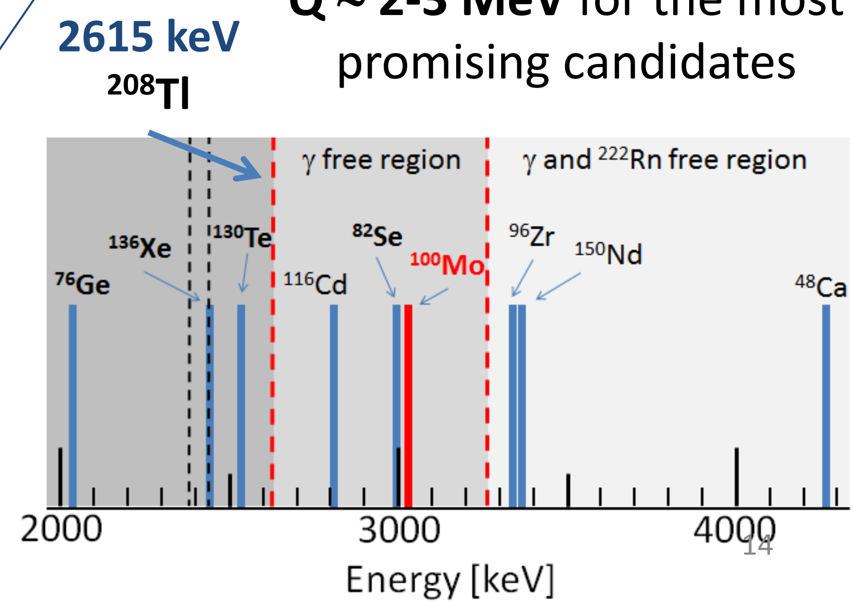


2ν DBD: (A,Z)→(A,Z+2)+2e+2$\overline{\nu}$
continuum with maximum at ~1/3 Q

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

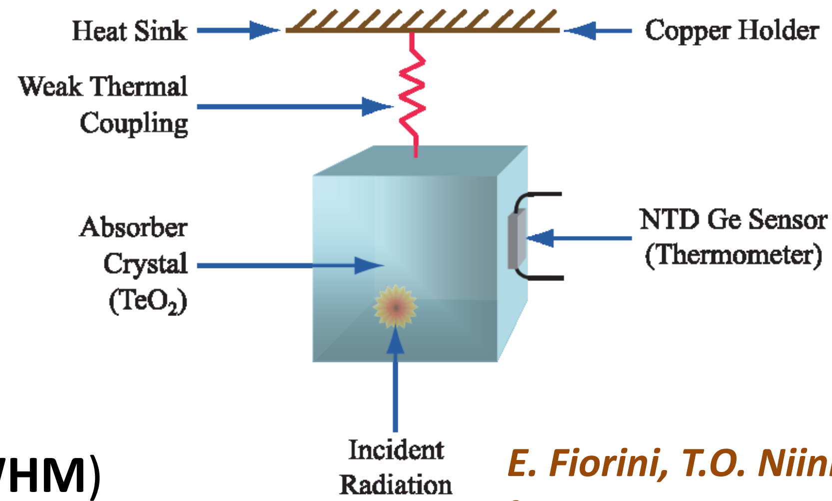
Q ~ 2-3 MeV for the most promising candidates

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



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**



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

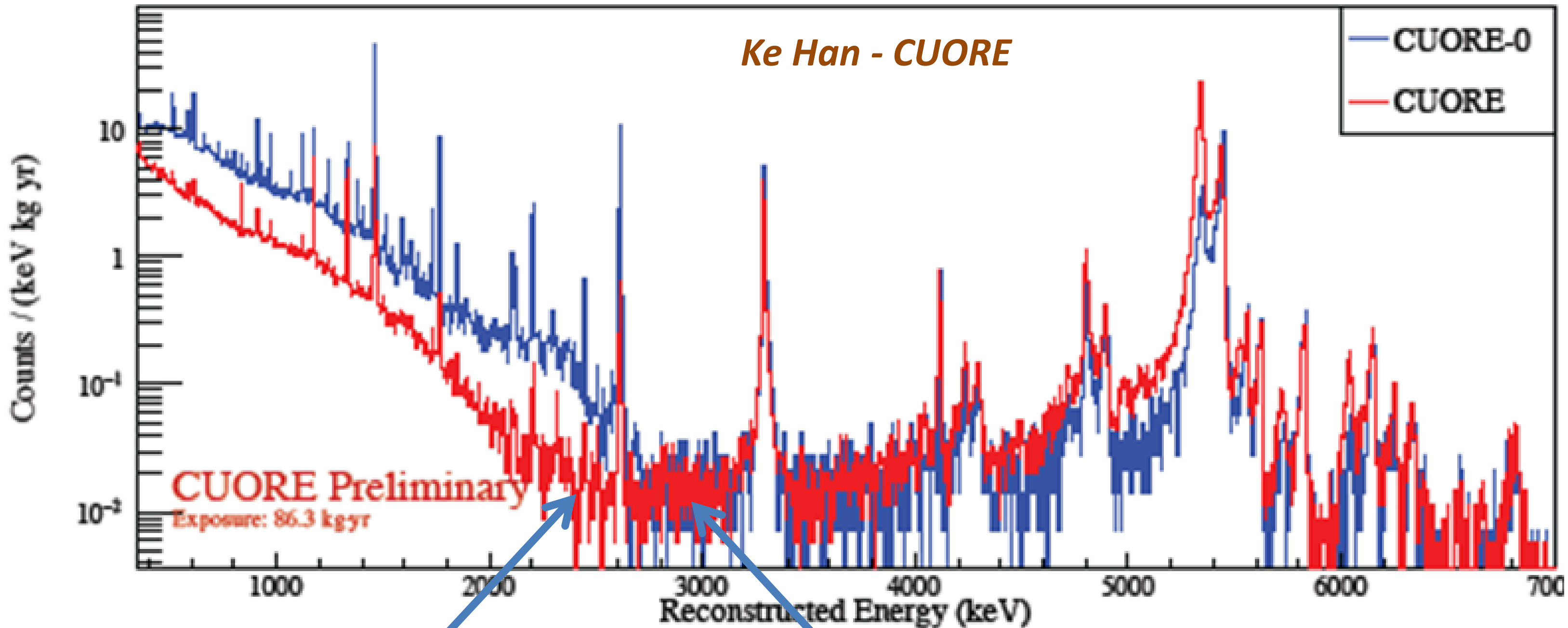
$$\Delta T = E/C$$

- 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**) *Ke Han - CUORE*
- **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** *S. Pirro – CUPID-0* *HongJoo Kim - AMoRE*

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

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

$b \sim 10^{-2}$ [counts/(keV kg y)]

CUORE is not background free

Improvement by a factor 10^2 is required

M. Vignati – CALDER

Current solution: scintillating / Cherenkov bolometers

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

Alpha / beta separation

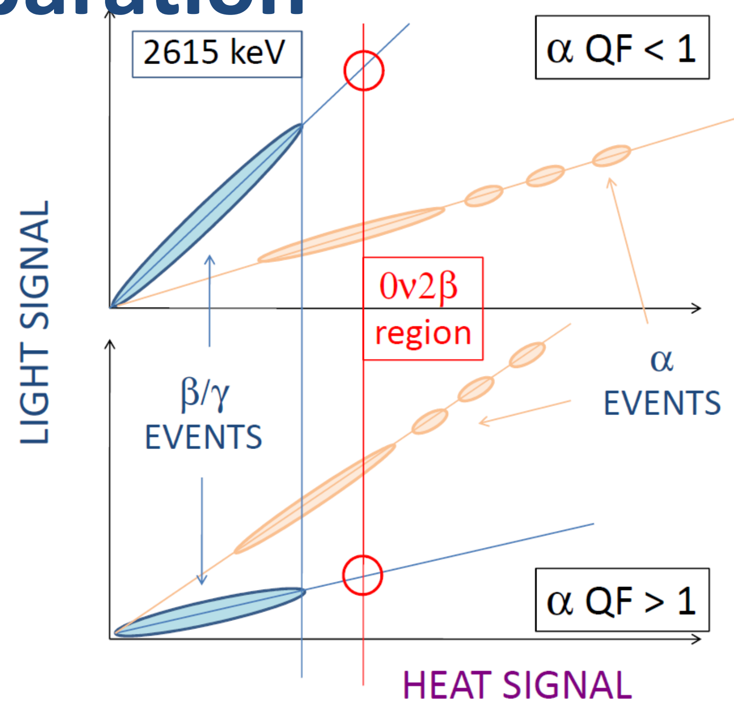
Alphas emit a different amount of light with respect to beta/gamma of the same energy (normally lower → **α QF < 1, but not in all cases – ZnSe is an exception**).

HongJoo Kim - AMoRE

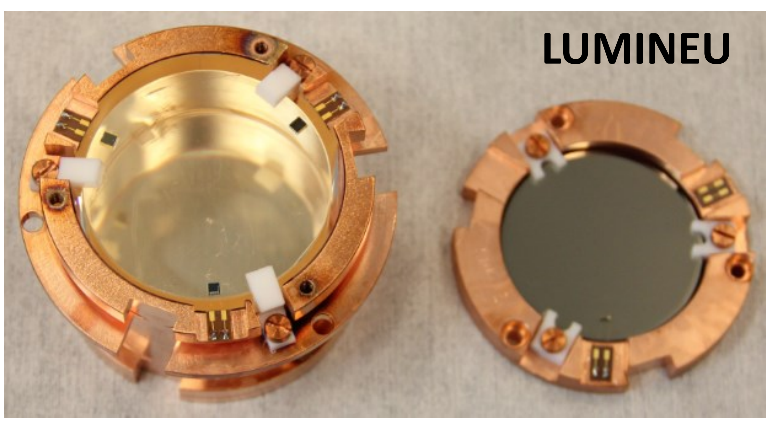
A **scatter plot light vs. heat** or a **plot light-yield vs. heat)** separates alphas from betas / gammas.

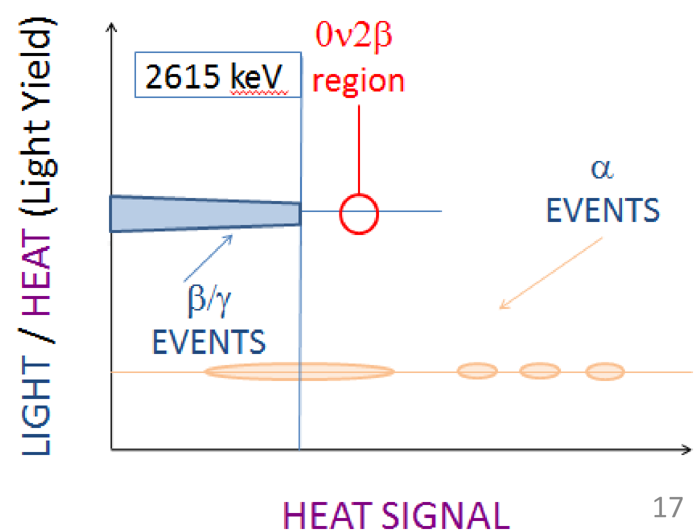
S. Pirro – CUPID-0

PSD can work as well

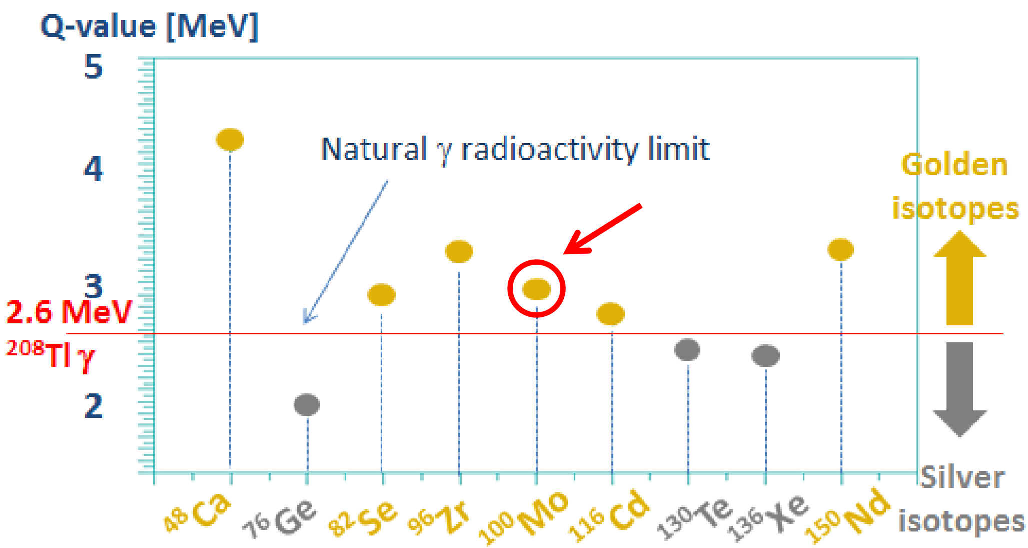


A bolometric light detector is needed, facing the main crystal





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

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 ← *HongJoo Kim*

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

LAL – Orsay France

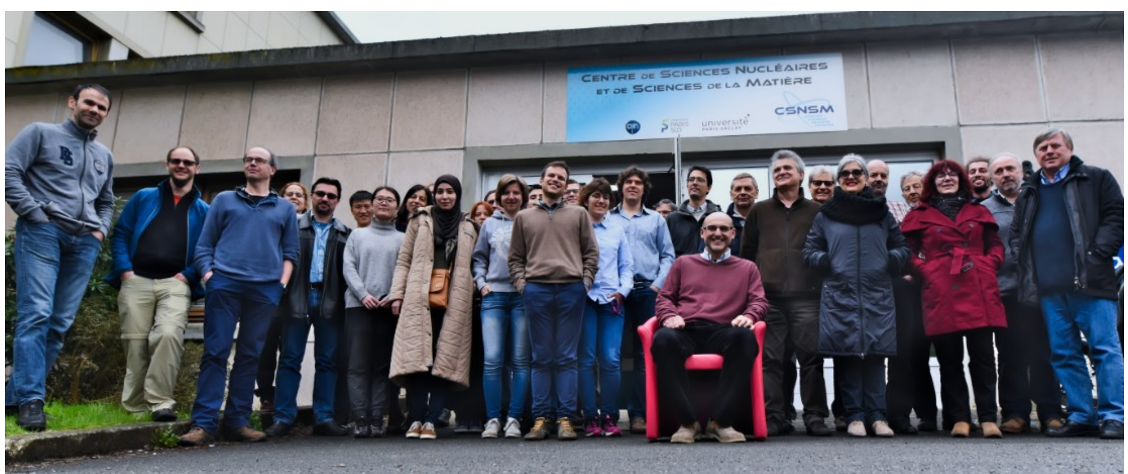
MIT
UCB/LNBL USA

Fudan Shanghai
USTC Hefei China

http://cupid-mo.mit.edu

7 countries, 15 institutions, ~110 scientists

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

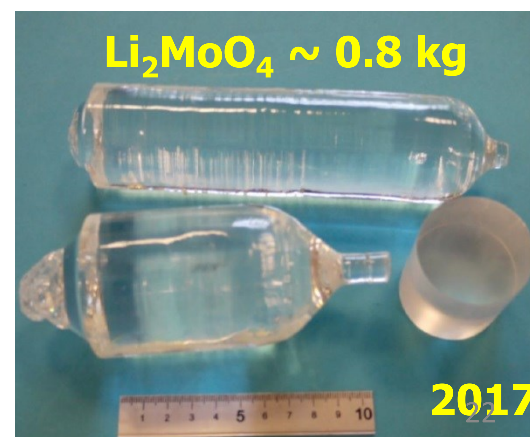


Li_2MoO_4: purification and crystallization

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: $2\nu2\beta + {}^{40}K \ll 2\nu2\beta + 2\nu2\beta$
- 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)



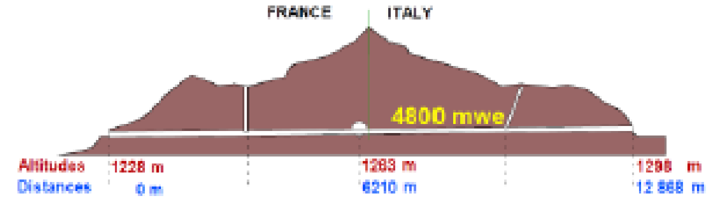
EDELWEISS-III cryogenic facility at LSM (France)

Laboratoire Souterrain de Modane

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

5 μ/day/m²; 10^{-6} n/day/cm² (>1 MeV)

Deradonized air flow (~30 mBq/m³)



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)

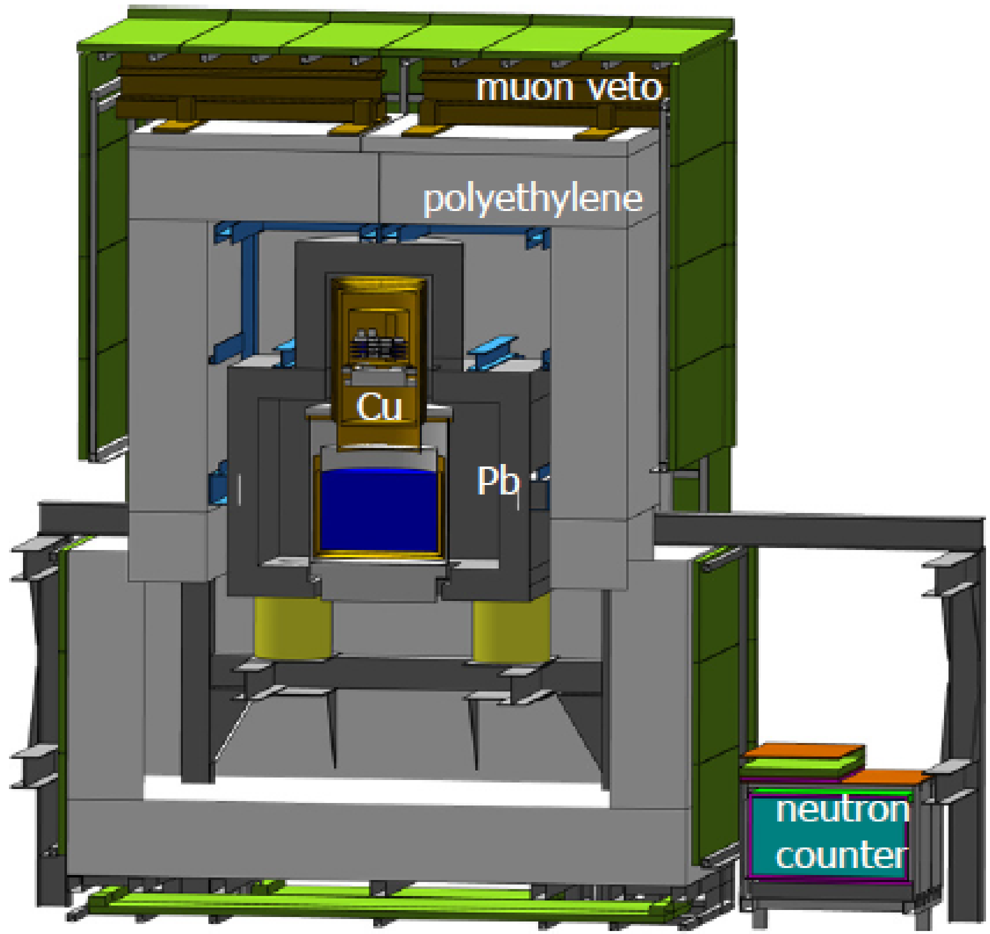
Low noise cold electronics

AC bias, modulation (100 kHz)

→ 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

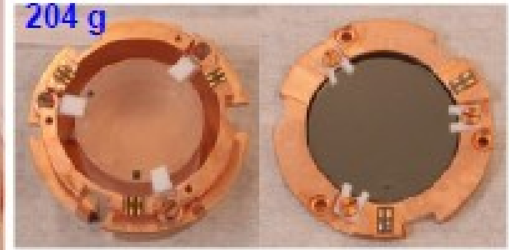
D. Poda

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

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

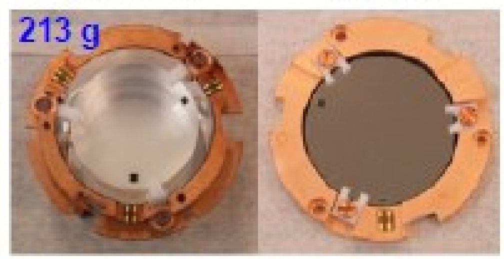
T1

LMO1b Ge LD

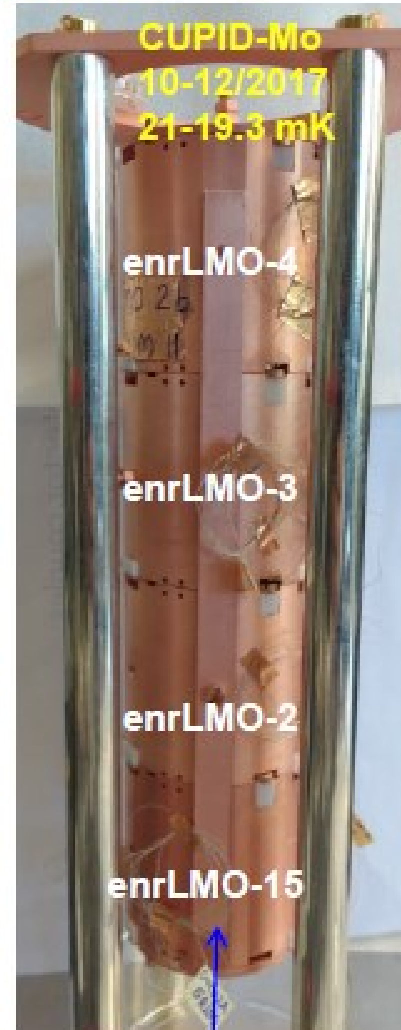


LMO2b Ge LD

LMO2t Ge LD



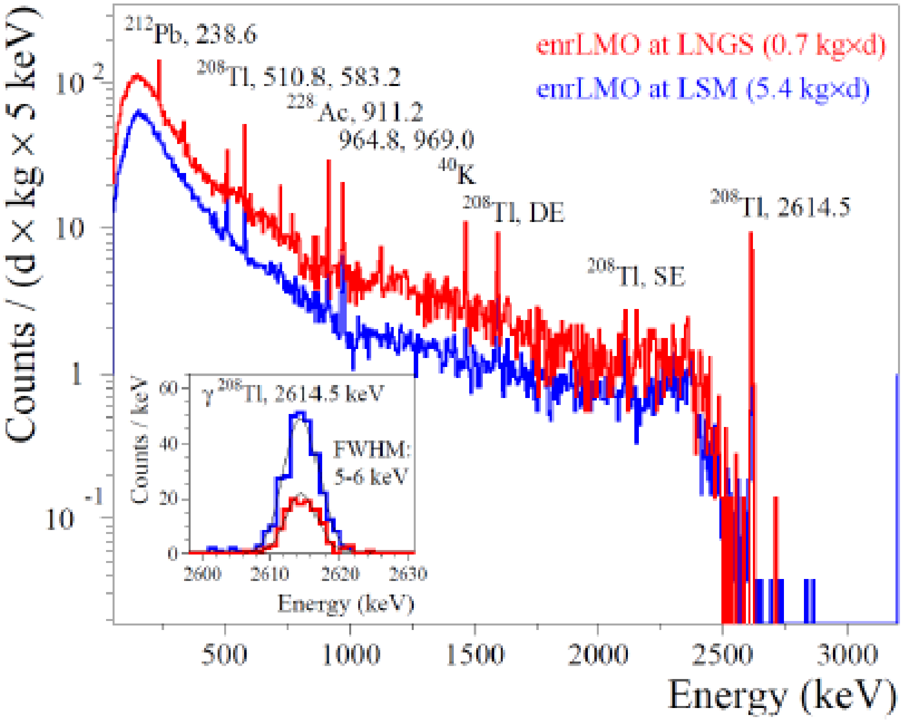
+ a tower T2
with enrLMO-1

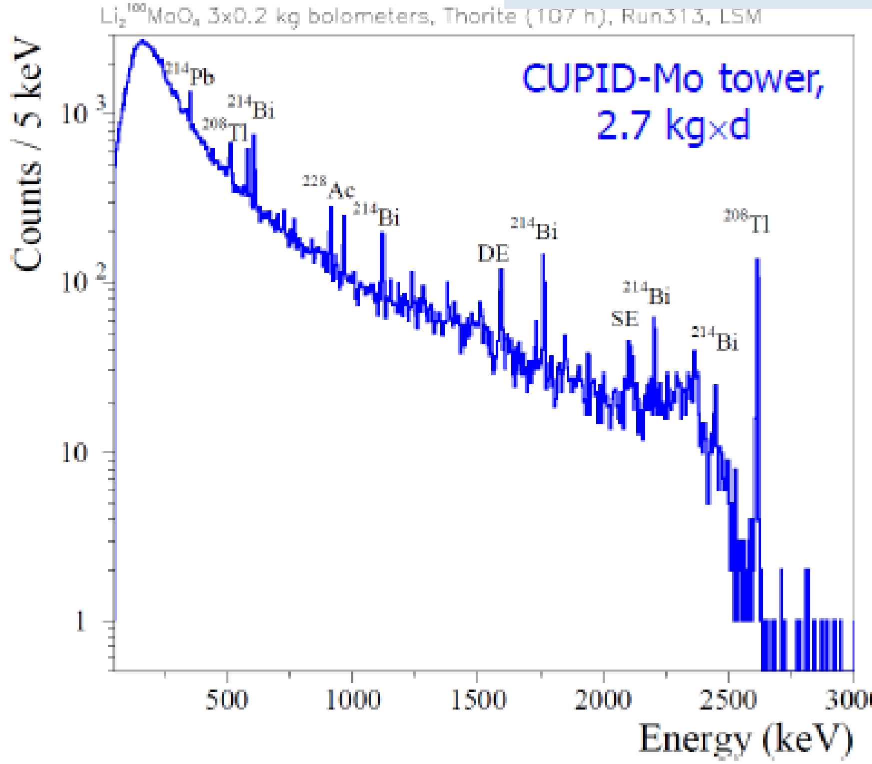


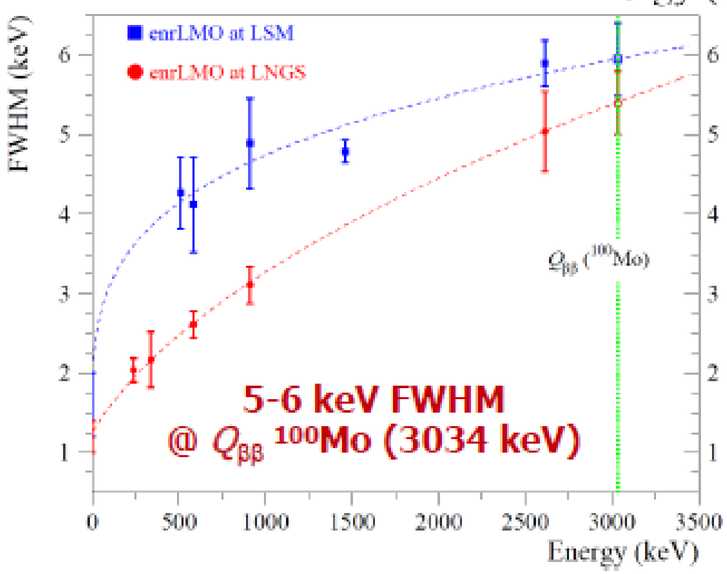
D. Poda

^{232}Th calibration

Heat channel





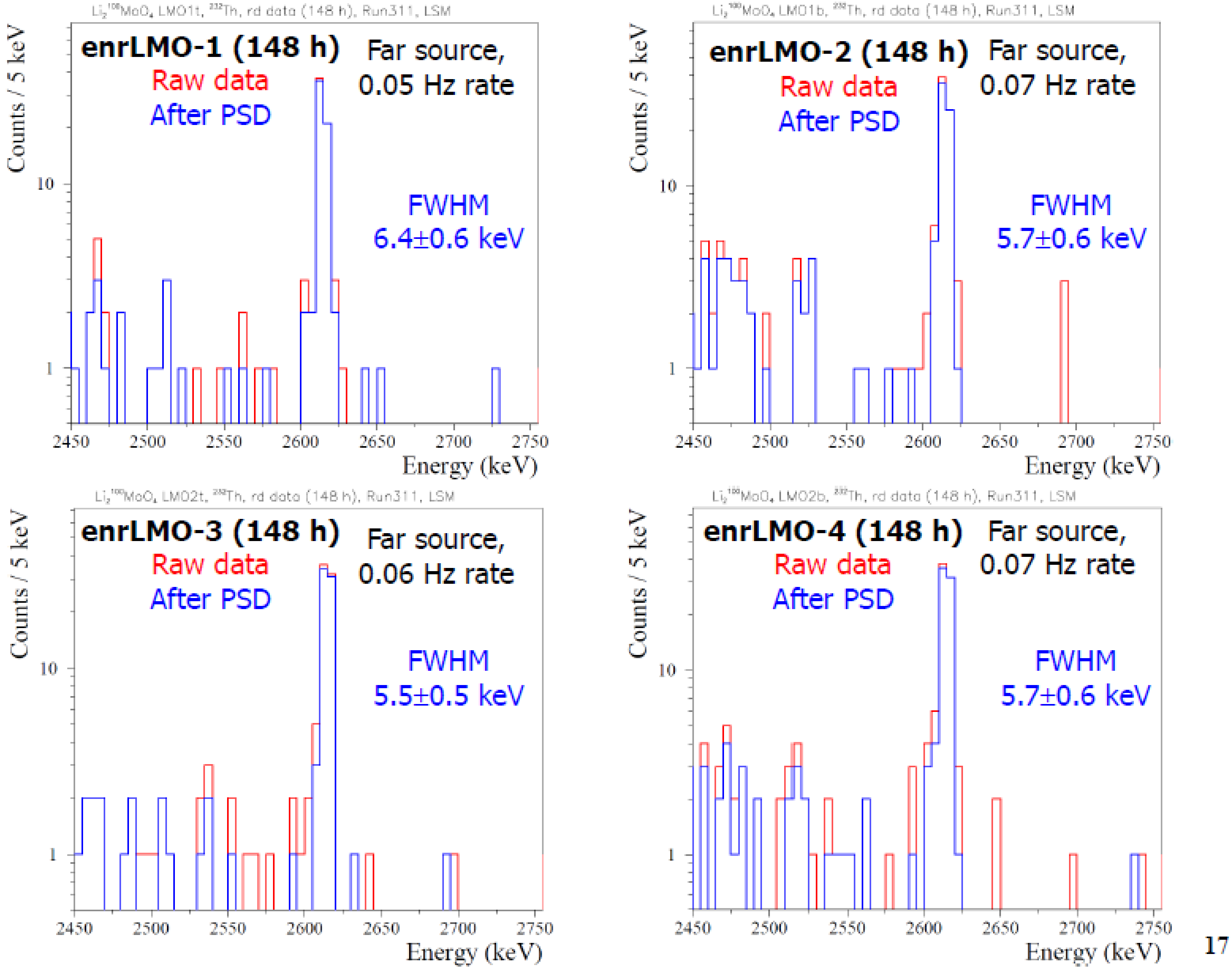


Mixed Th/U source is useful to estimate uncertainty of ^{100}Mo RoI determination

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

D. Poda

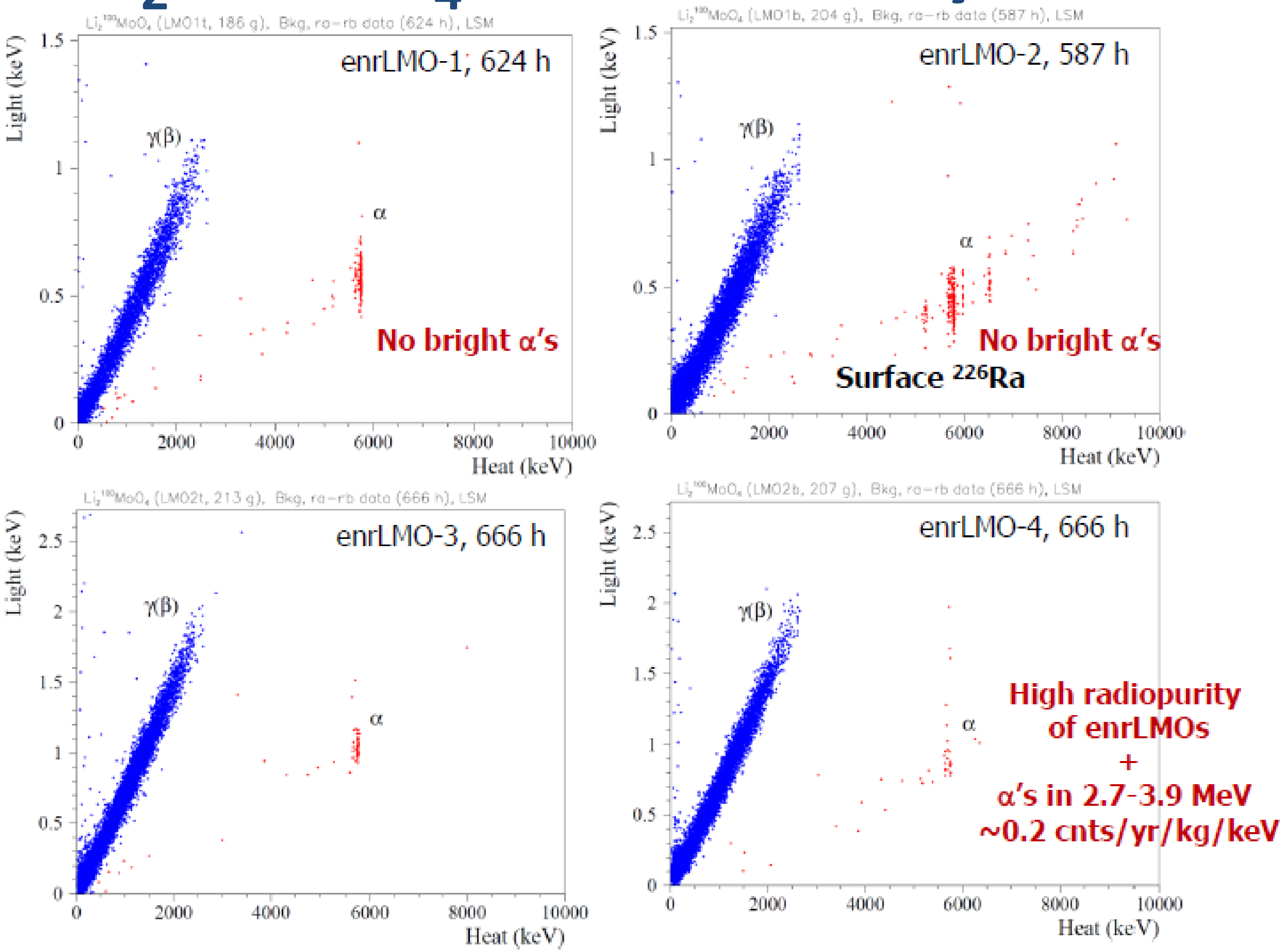
Heat channel



D. Poda

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

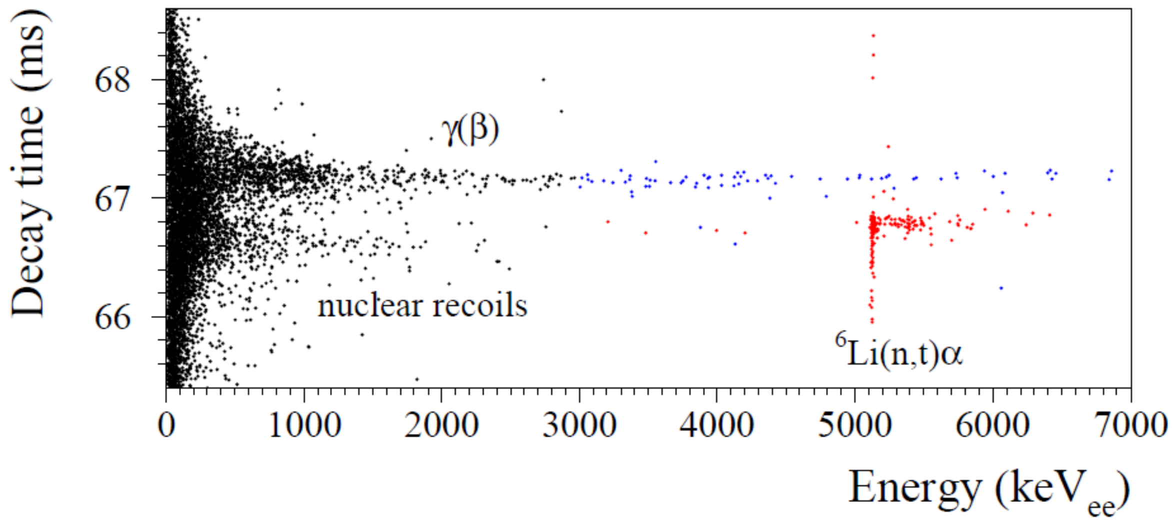
Heat + Light

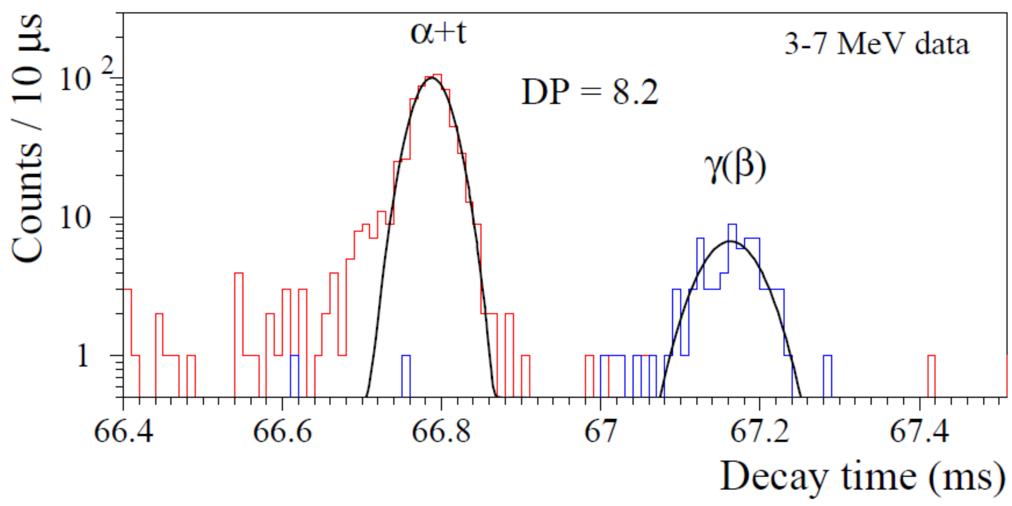


D. Poda

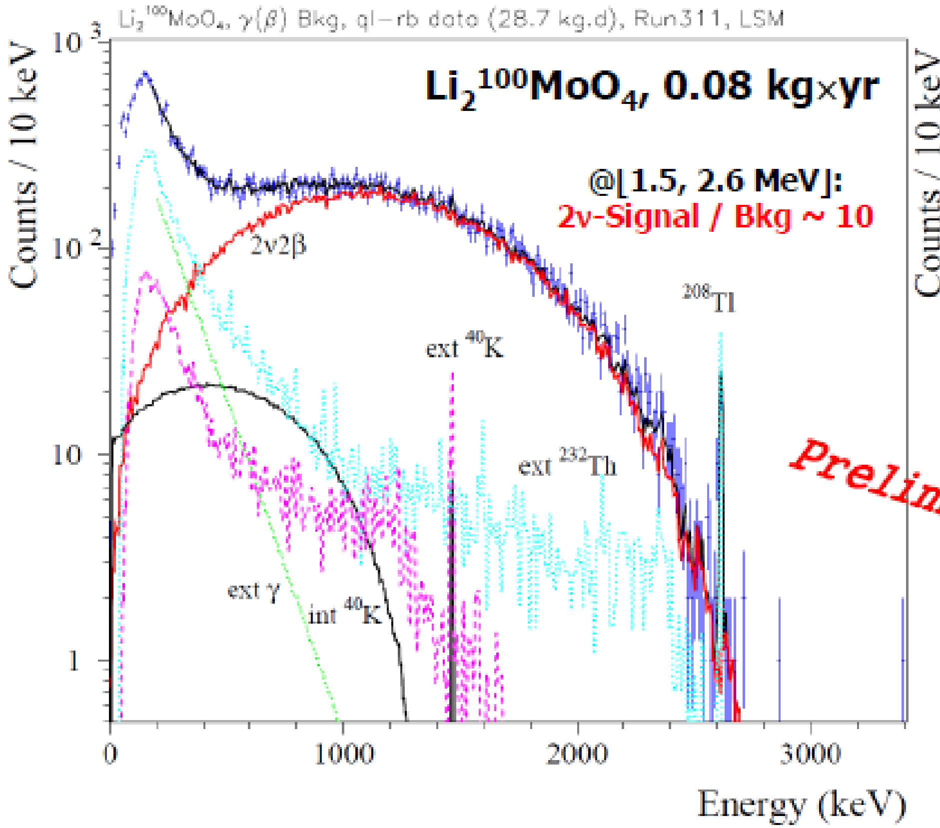
α/β separation without light detectors

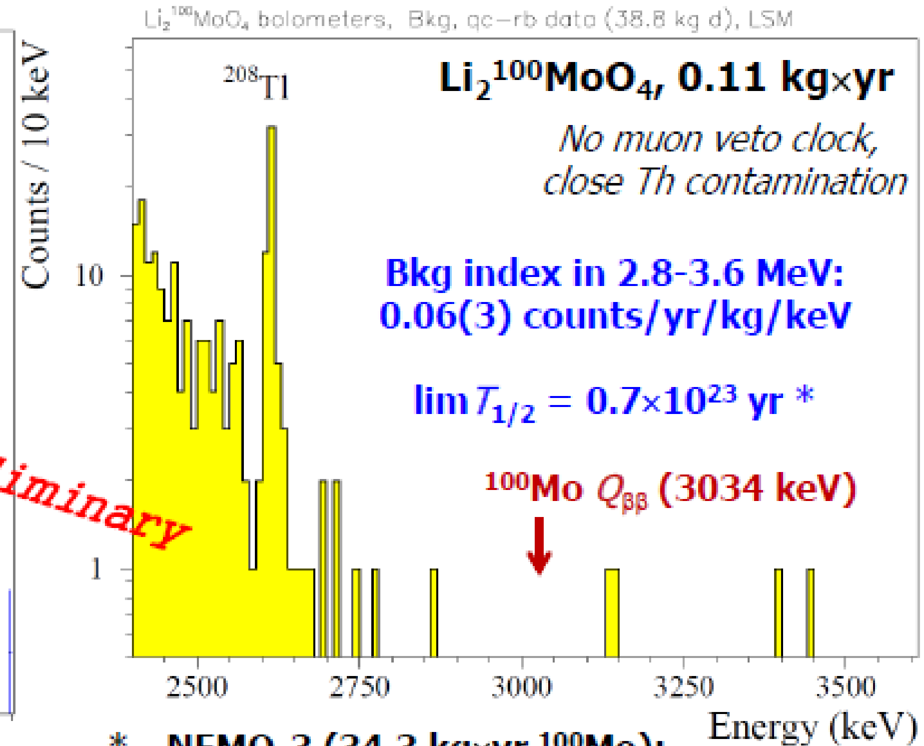
We performed a specific study on a natural 150 g detector operated in LNGS.
A calibration with an AmBe source provided enough statistics in the β and α-like bands





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





* - NEMO-3 (34.3 kg×yr ^{100}Mo):
$T_{1/2} \geq 1.1\times10^{24}$ 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*** **≤ 10^{-4} [counts/(keV kg y)]**

LUMINEU ββ 0ν

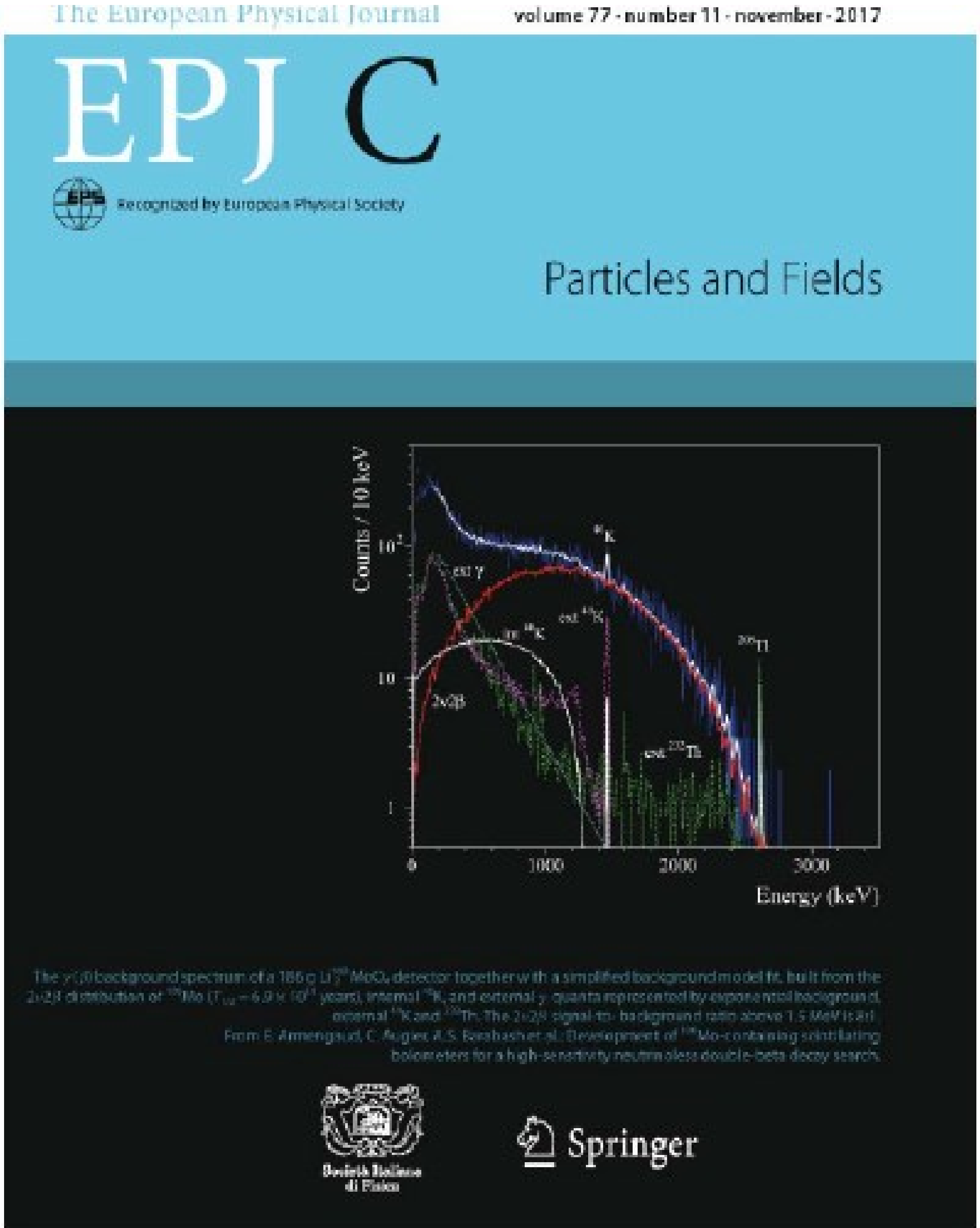
THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

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

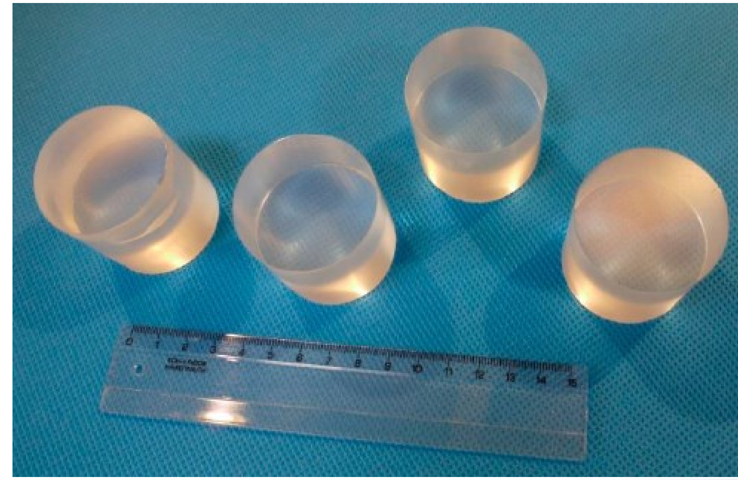

The European Physical Journal
volume 77 - number 11 - november - 2017
EPJ C
Recognized by European Physical Society
Particles and Fields
Counts / 10 keV
Energy (keV)
0
1000
2000
3000
10
1
Springer
Società Italiana di Fisica

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)

START DATA TAKING: in the next weeks

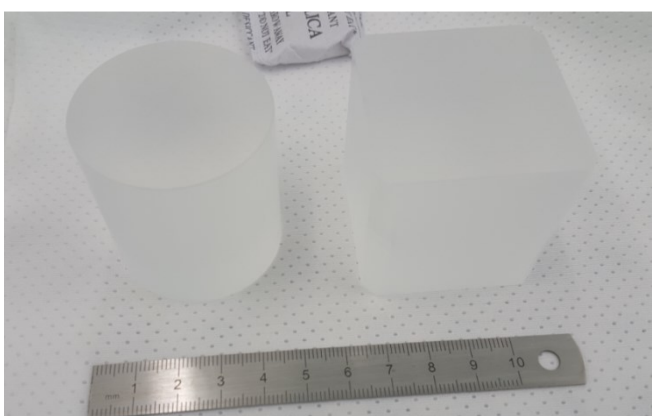


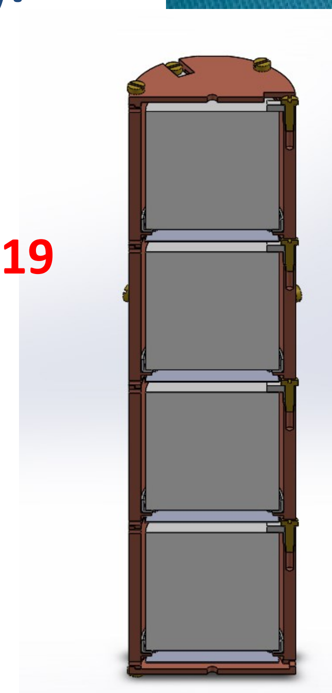
CUPID-Mo Phase II (20+26 crystals):

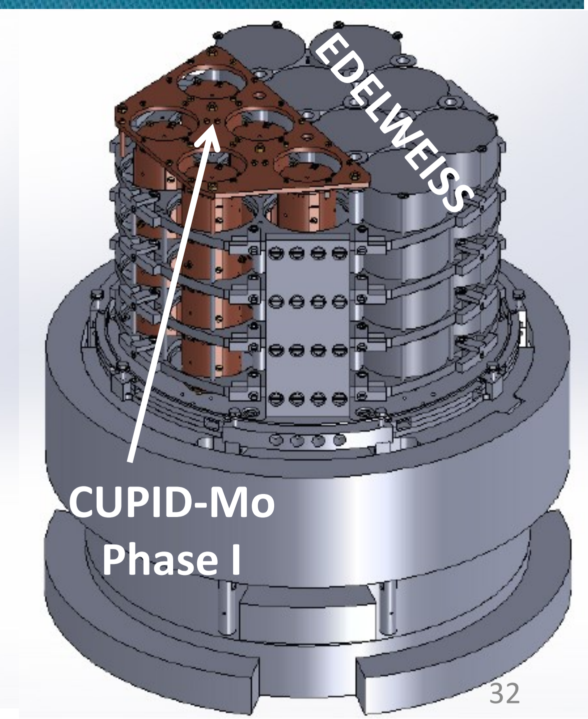
- Additional **26 cubic $Li_2{}^{100}MoO_4$**
  (45x45x45 mm, 0.28 g each)
  ⇒ **~5 kg of ^{100}Mo**
- **CUPID-0 set-up** @ LNGS (Italy)

S. Pirro

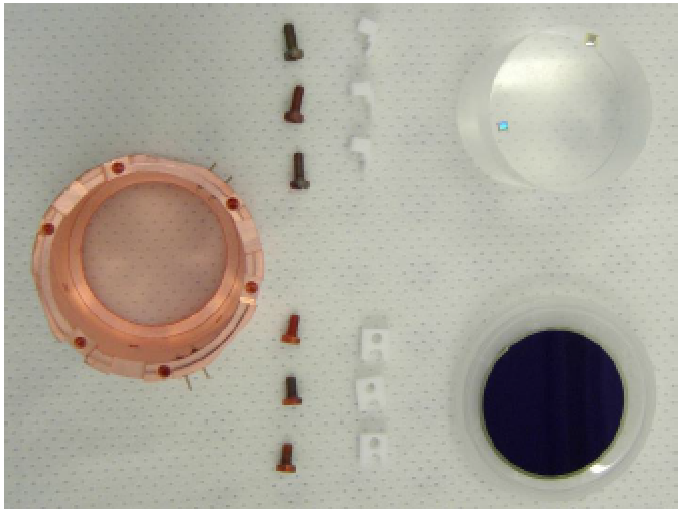
PLANNED START DATA TAKING: June 2019







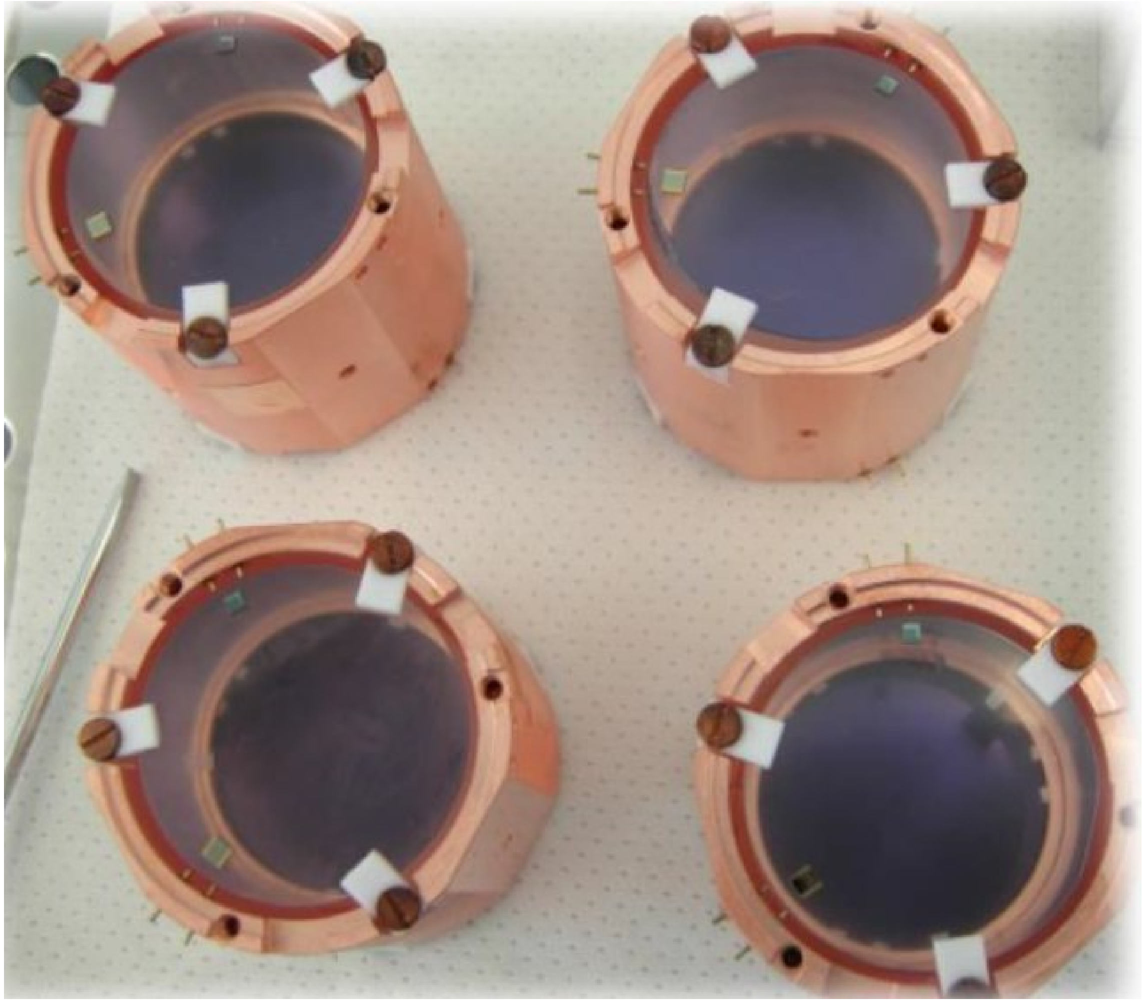
Structure

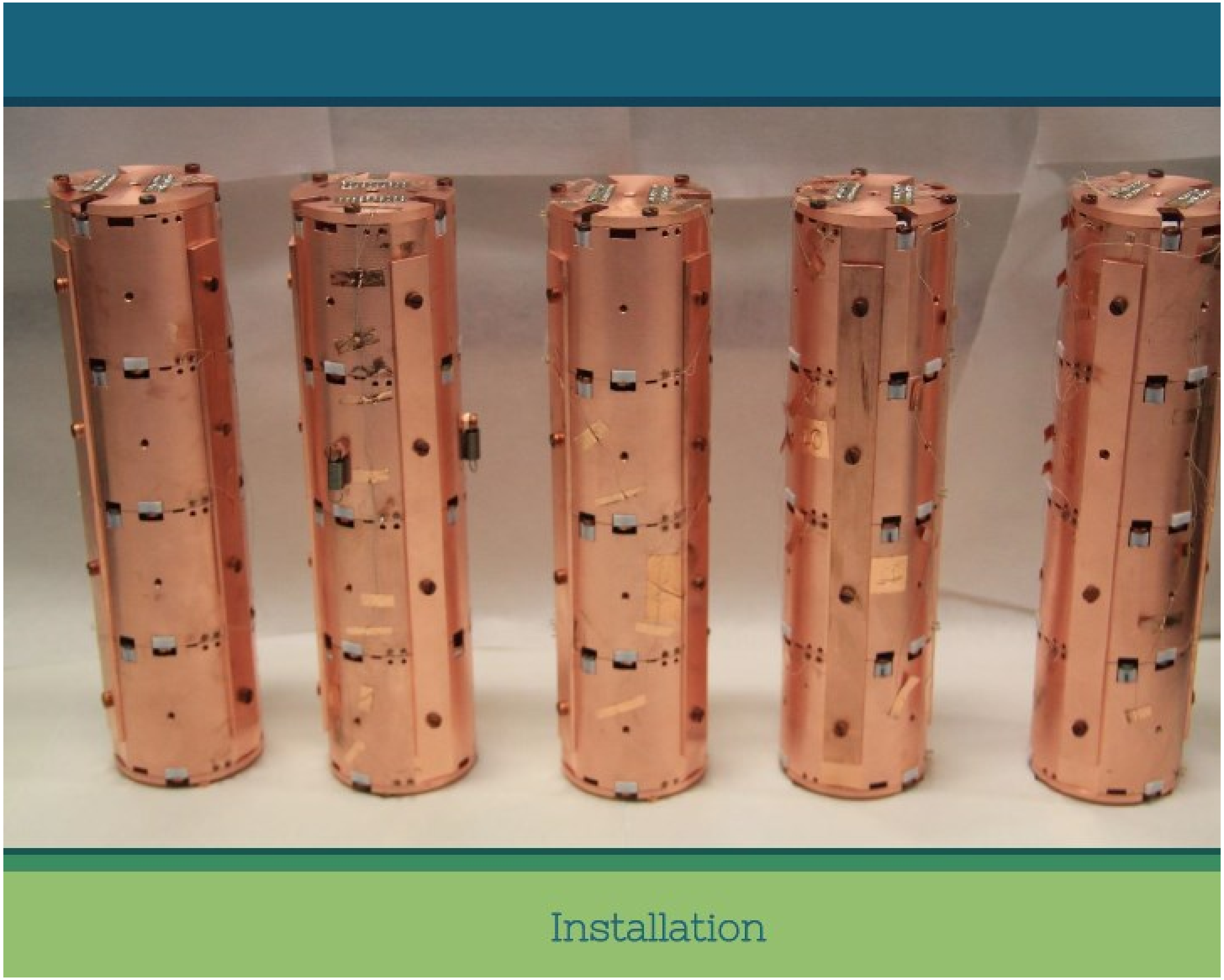


- Crystal: $Li_2{}^{100}MoO_4$ ∅ 43.8 × 45 mm
- Light detector: Ge wafer (UMICORE) ∅ 44.5 mm × 170 um with SiO coating on both sides
- Copper holders: radiopure NOSV copper
- Spacers (thermal and mechanical link): PTFE
- Electrical connections: copper gold-plated tubes

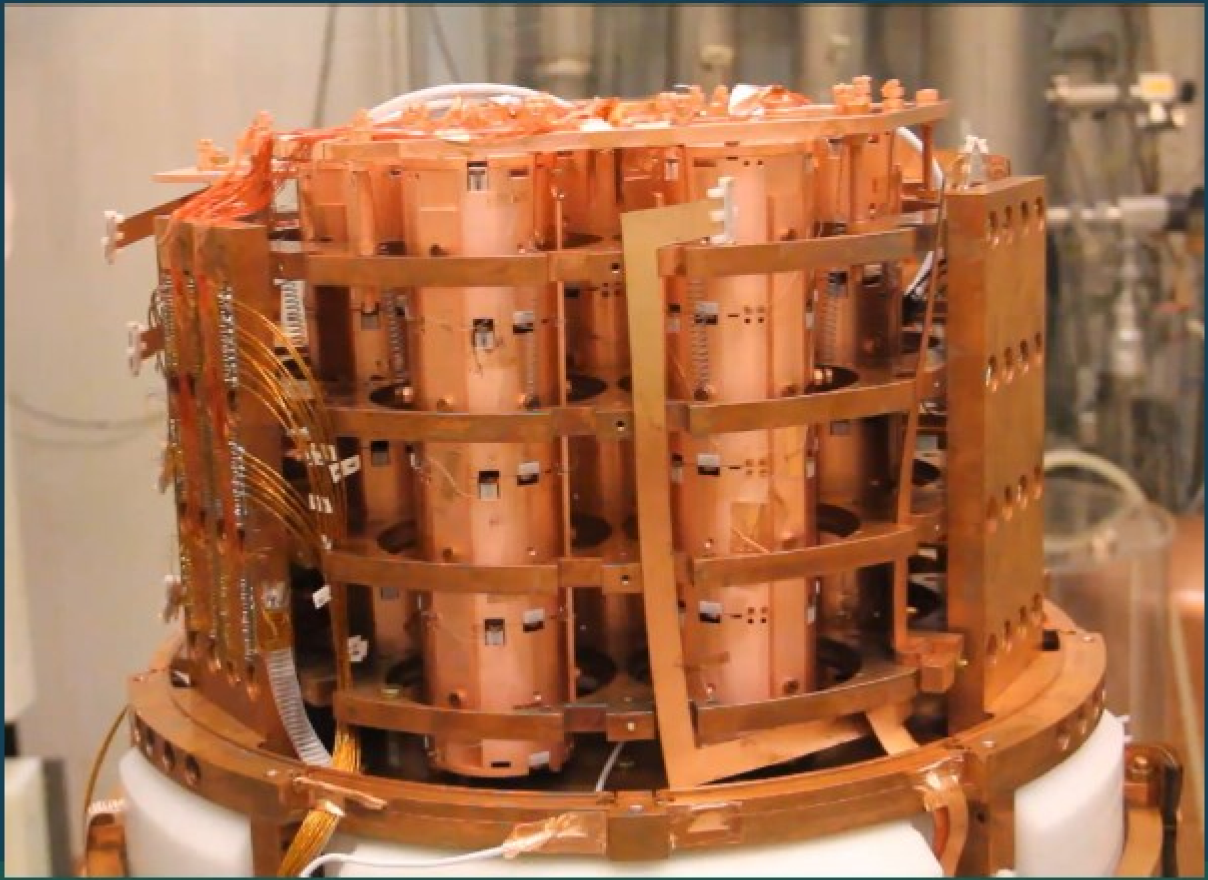
A. Zolotarova

Four modules





A. Zolotarova



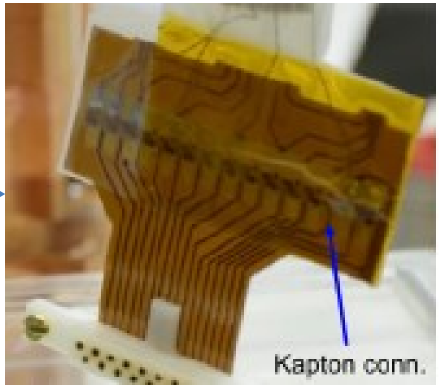
Suspension

A. Zolotarova

Background consideration

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

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



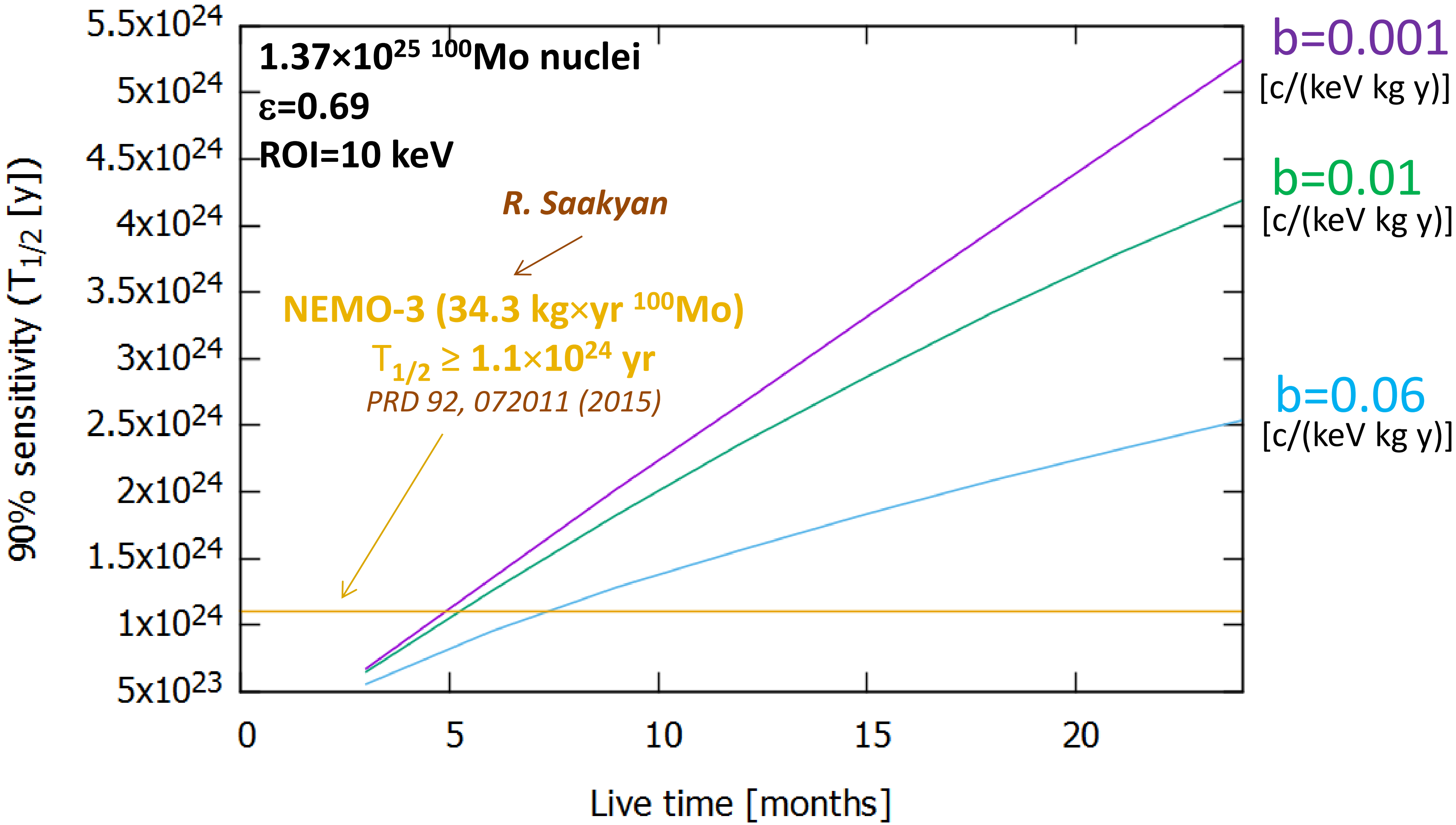
Simultaneous absorption of **2615 keV** γ and coincident **583 keV** γ (^{208}Tl)

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

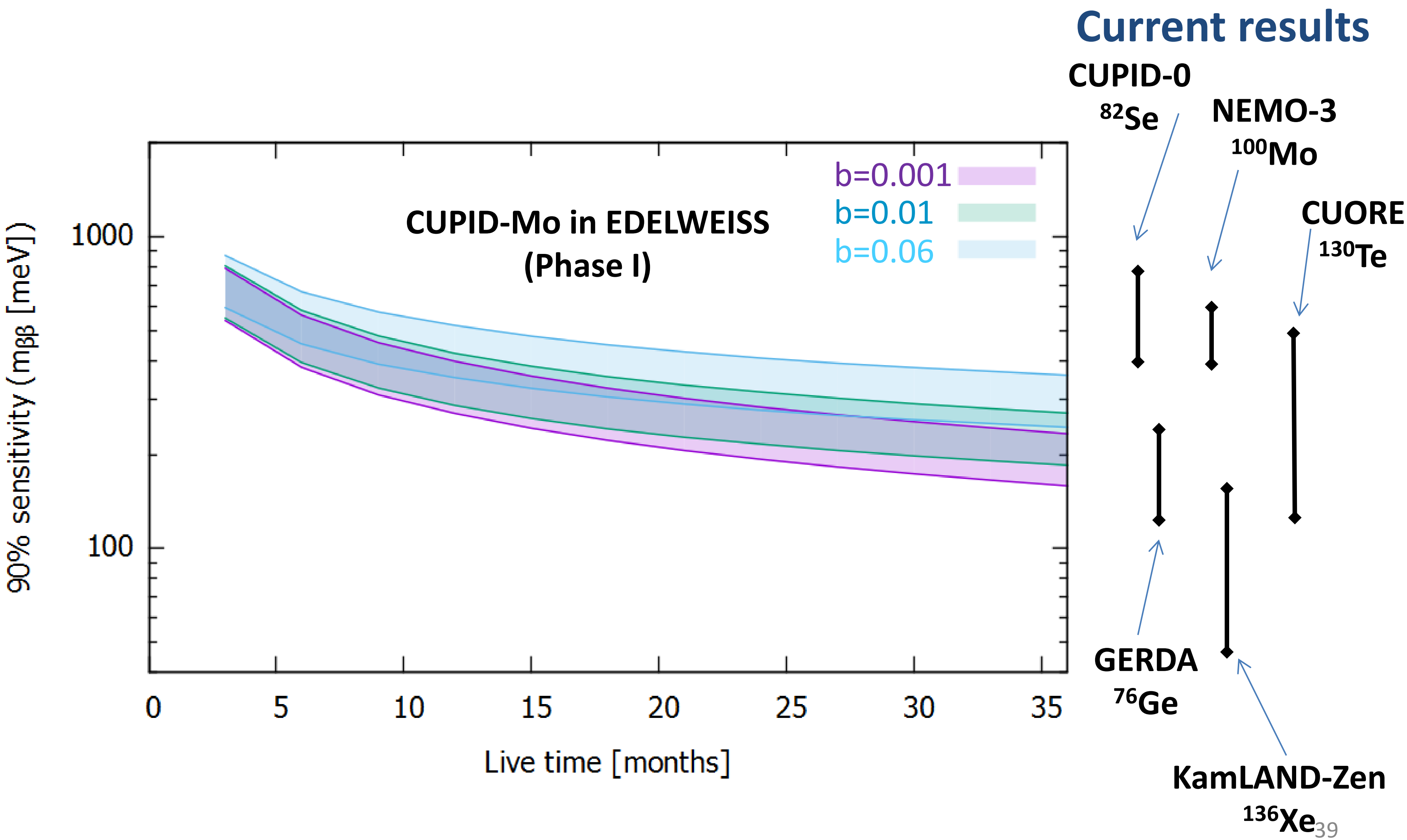
Full estimation of the background is in progress

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

CUPID-Mo Modane
Evolution of the half-life sensitivity



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



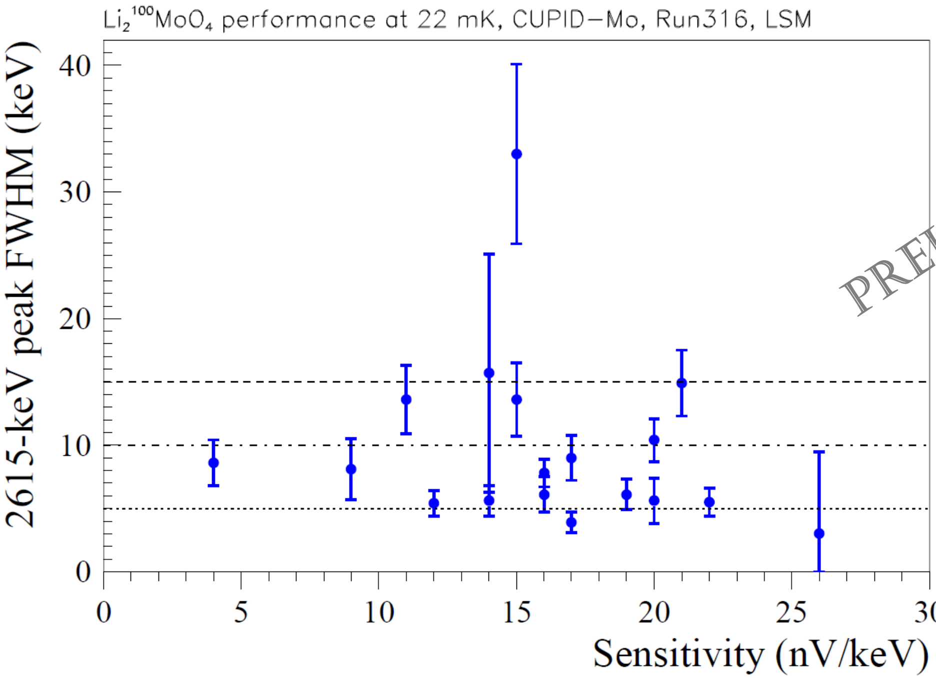
CUPID-Mo Modane (Phase I) Preliminary results at 22 mK

PLOTS RECEIVED YESTERDAY !

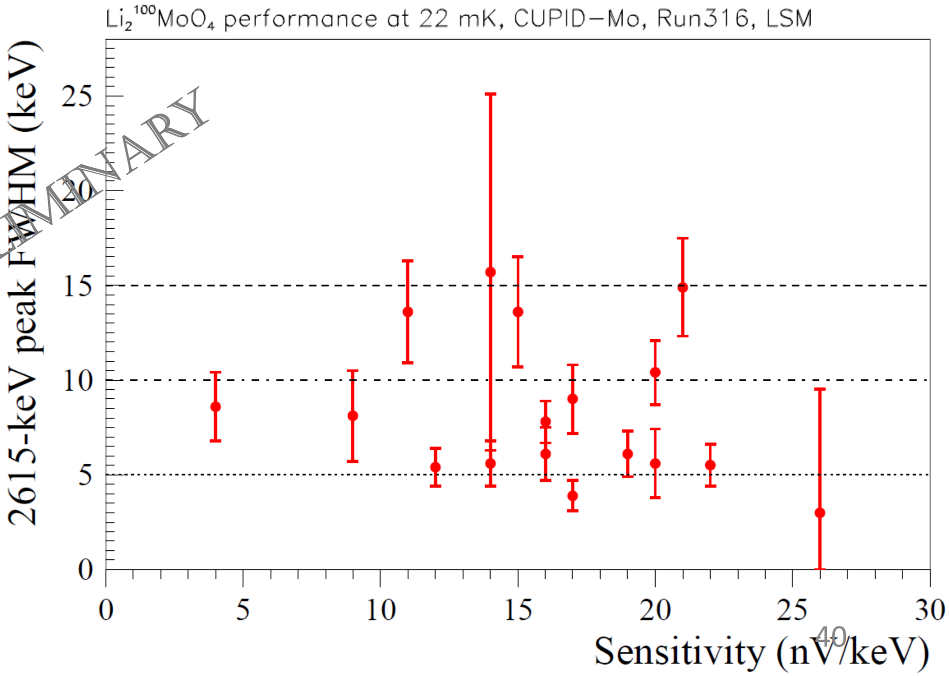
Preliminary data acquired at **22 mK**

- This is not the final configuration – temperature is still decreasing (now ~20 mK)
- Large microphonic noise, work to improve is in progress
- 2 heat channels are lost

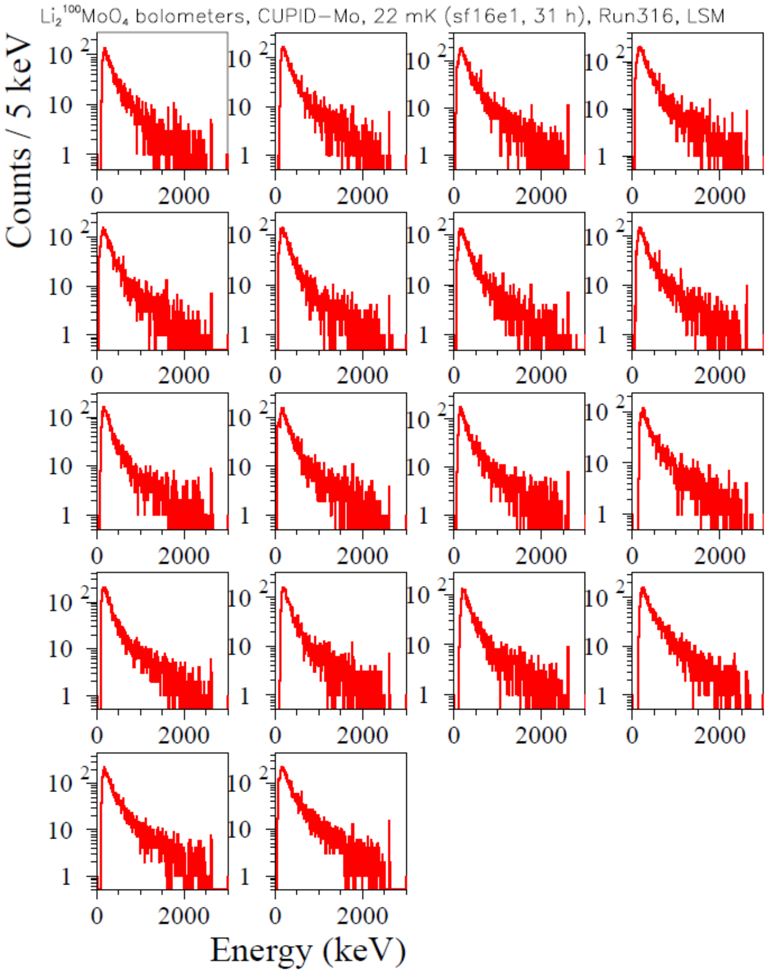
Calibration with thorite source – Th + U

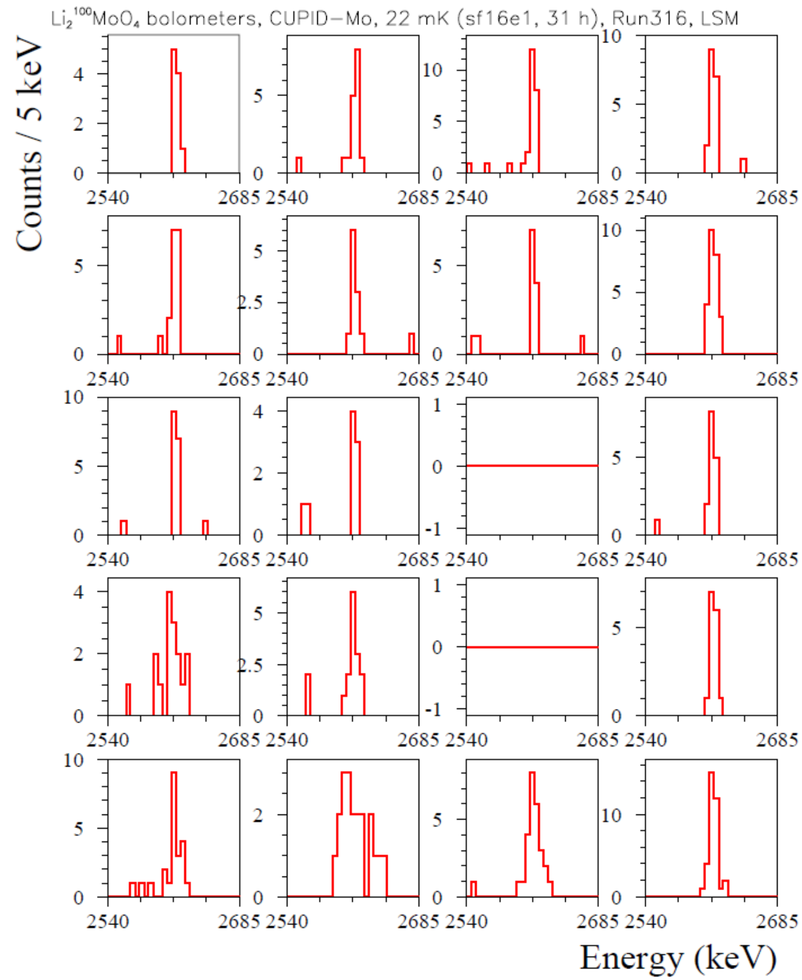


PRELIMINARY

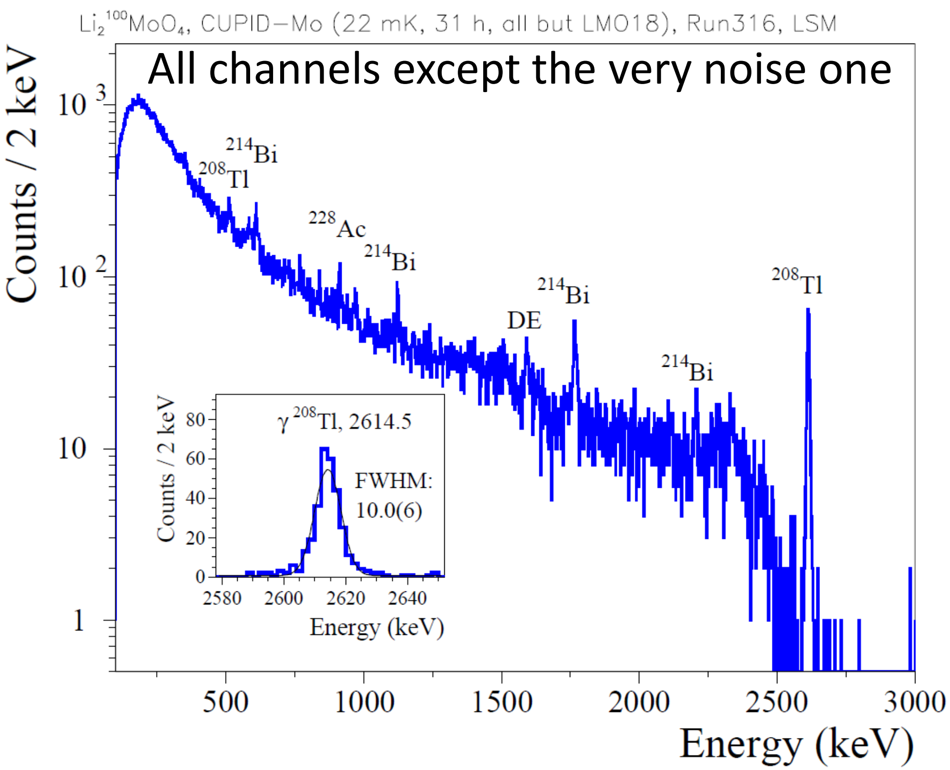


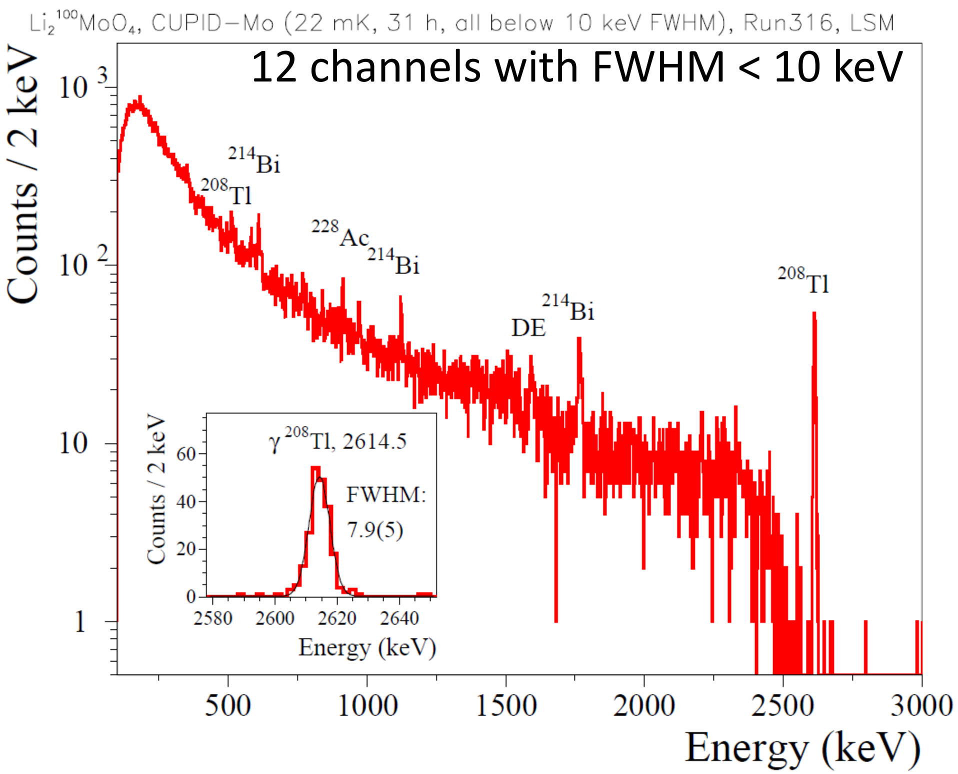
CUPID-Mo Modane(Phase I) Preliminary results at 22 mK





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





CUORE → CUPID

Ke Han - CUORE

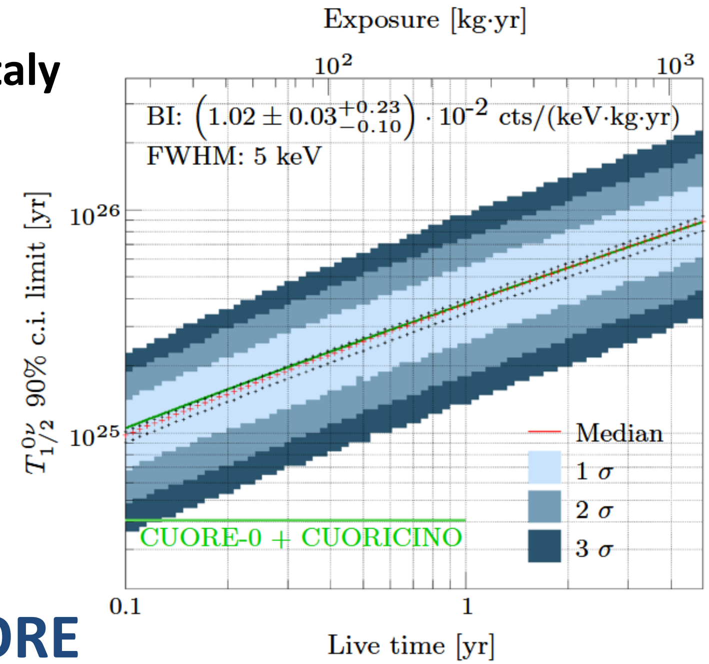
CUORE is collecting data succesfully

LNGS – Italy

➢ 5 y projected half-life sensitivity: **~10^{26} y**

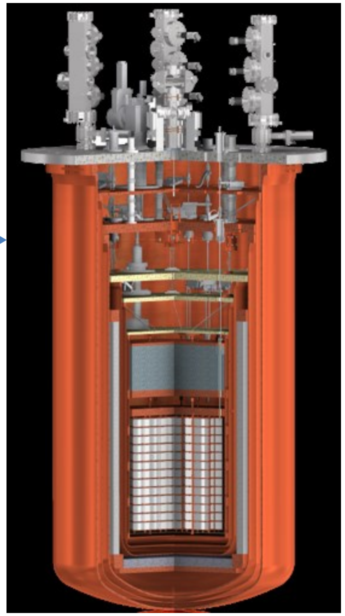
$m_{\beta\beta}$ < 50 – 190 meV

- Background according to expectations: **1.4±0.2×10^{-2} c/(keV·kg·yr)**
- Energy resolution close to expectations: **~7.7 keV FHWM** → margins for improvement



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**



CUPID is the natural evolution of CUORE

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 *M. Vignati – CALDER*
- 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 fall 2018**

Beyond light detectors: CROSS

ERC advanced grant CROSS

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

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

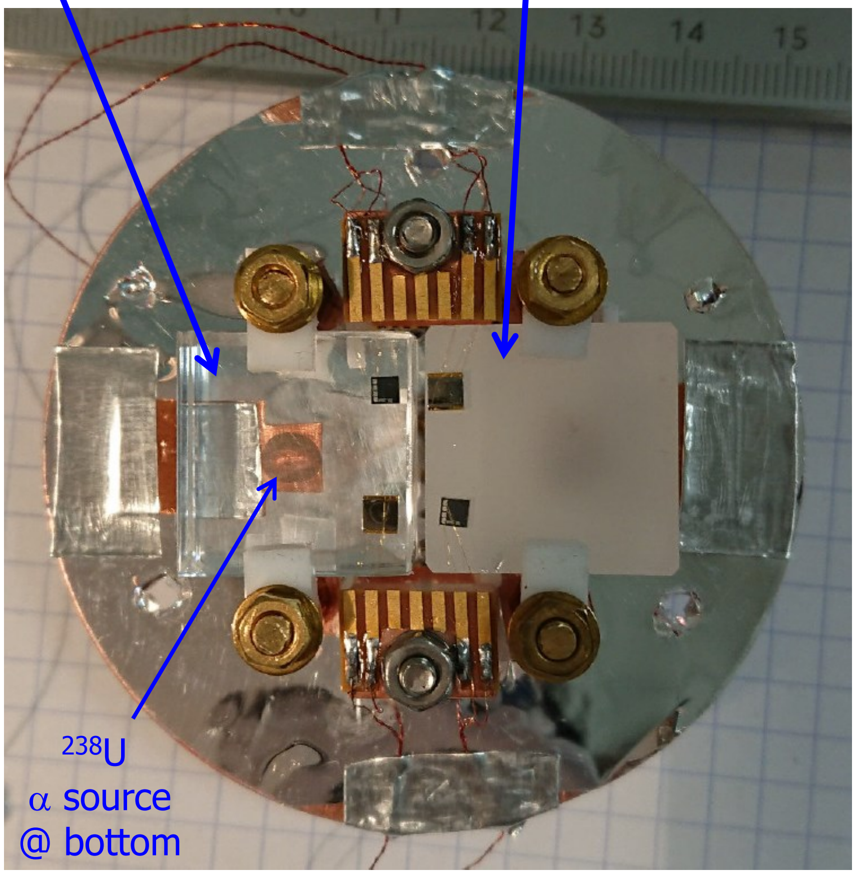
- **Core of the project** (high risk / high gain)
  Background rejection through **pulse shape discrimination**
  - **Surface sensitivity** through **superconductive Al film coating**
  - **Fast NbSi high-impedance TES** to replace / complement NTDs if necessary

  → **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)**

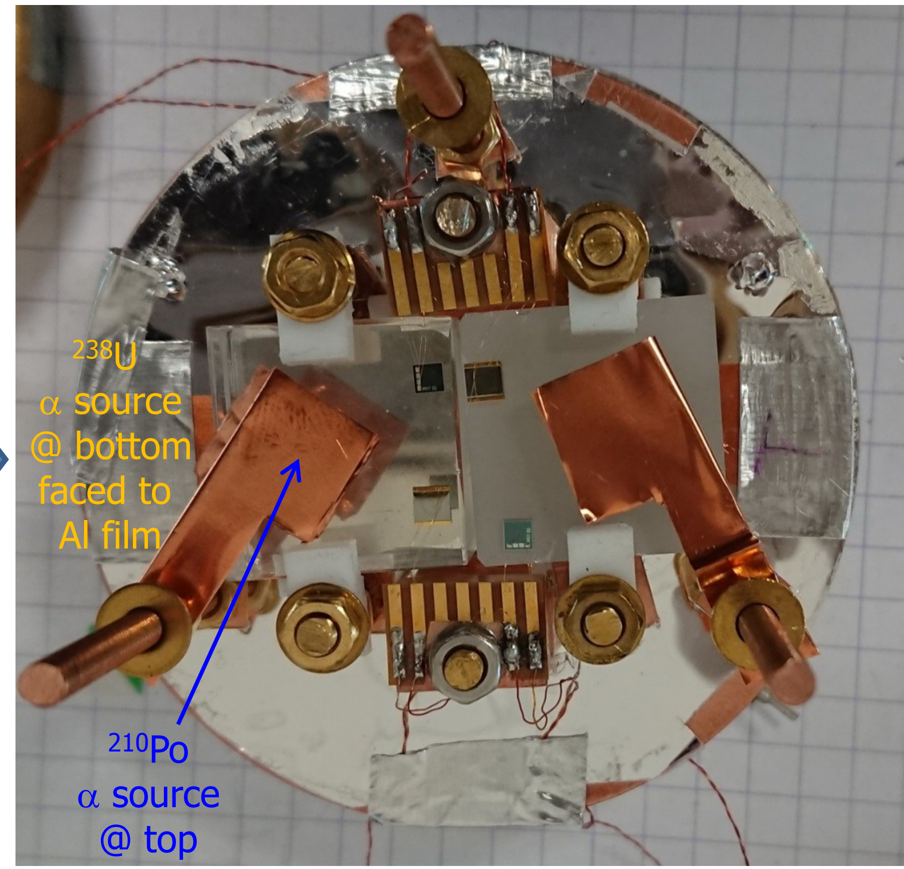
CROSS R&D at CSNSM

Above-ground runs at CSNSM

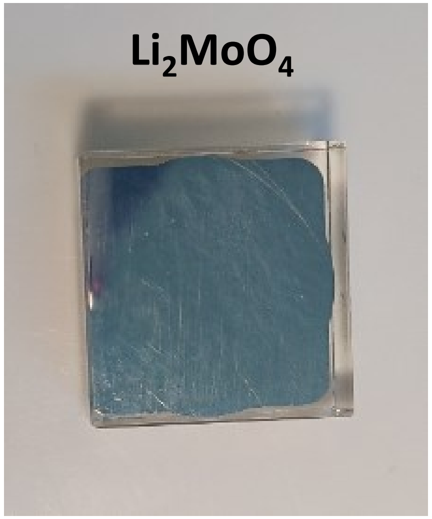
CROSS #1



CROSS #2



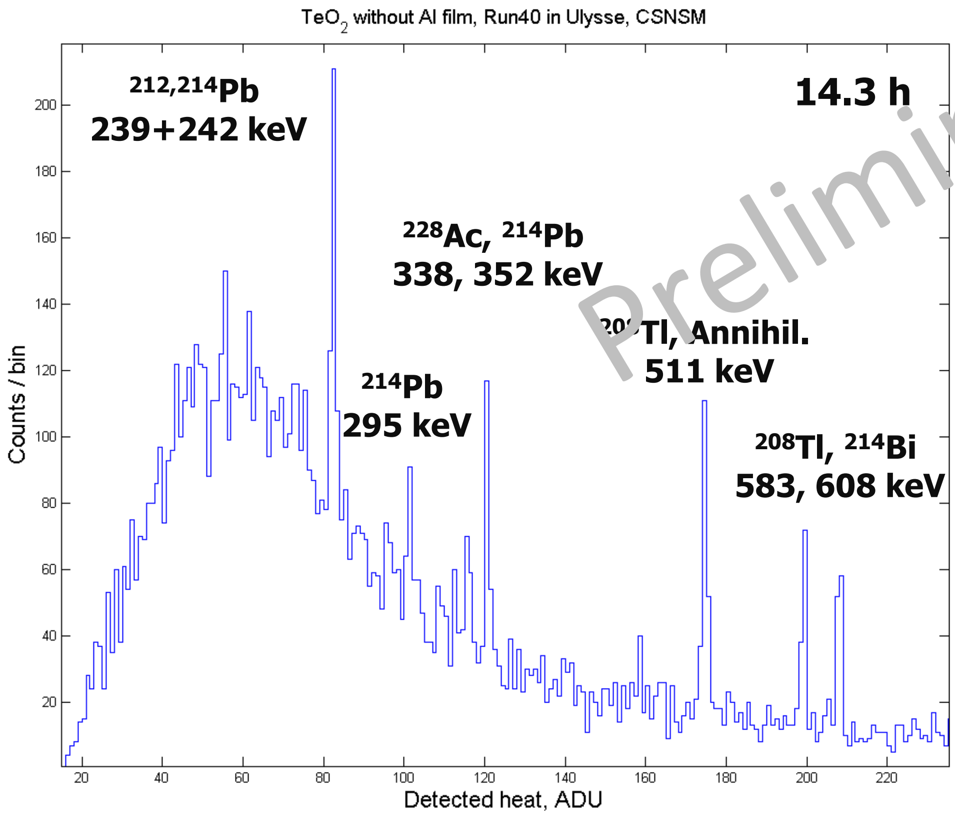
Preparation of the Al film test



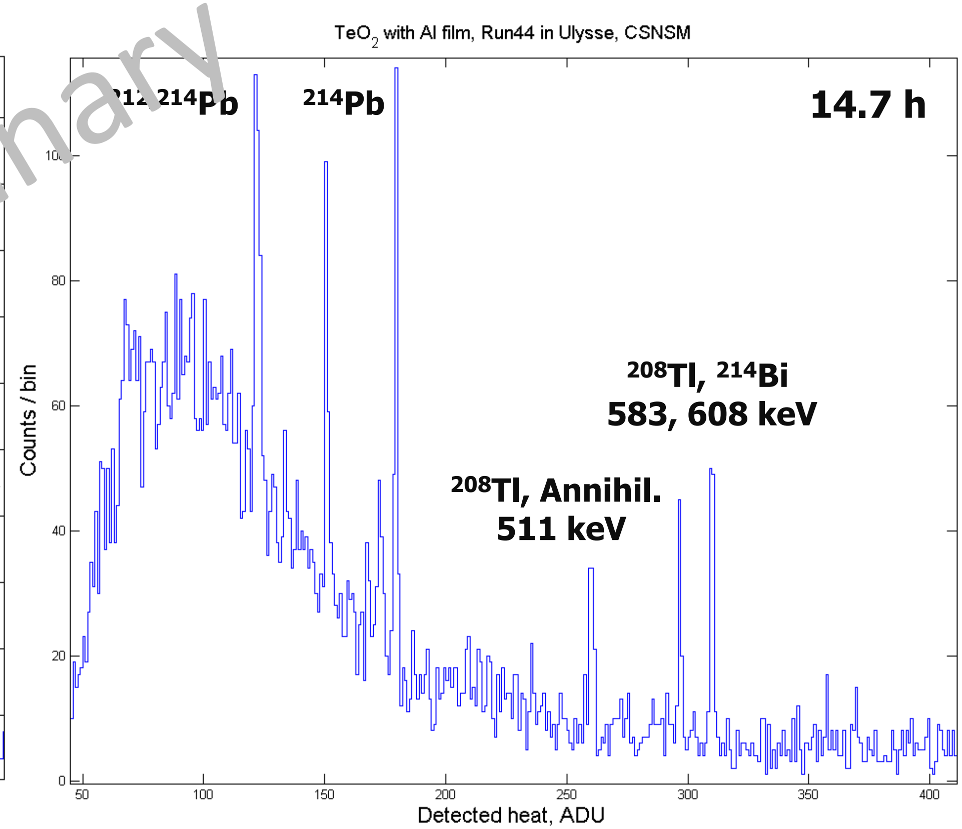
- **2x2x1 cm crystals**
- **Al coating** by evaporation on a **2x2 cm face** for both crystals (thickness: 10μm) – (**1/4 of crystal surface is covered**)

TeO_2 behaviour with Al coating

No Al film



With Al film

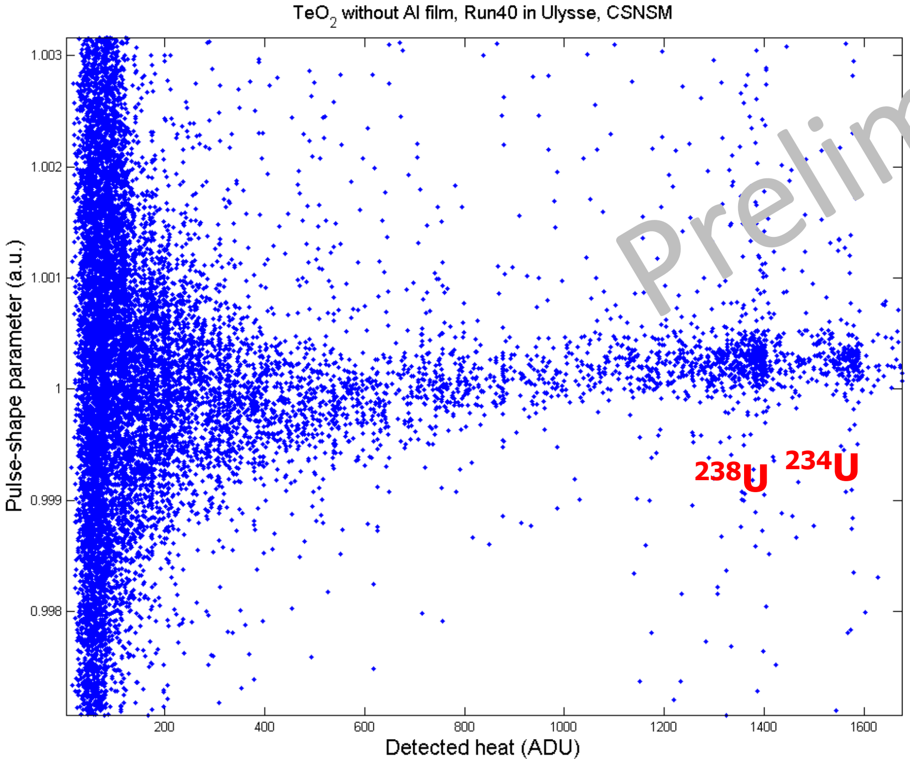


The **10 µm-thick aluminum film** affects **neither the sensitivity nor the energy resolution** of the TeO_2 bolometer.

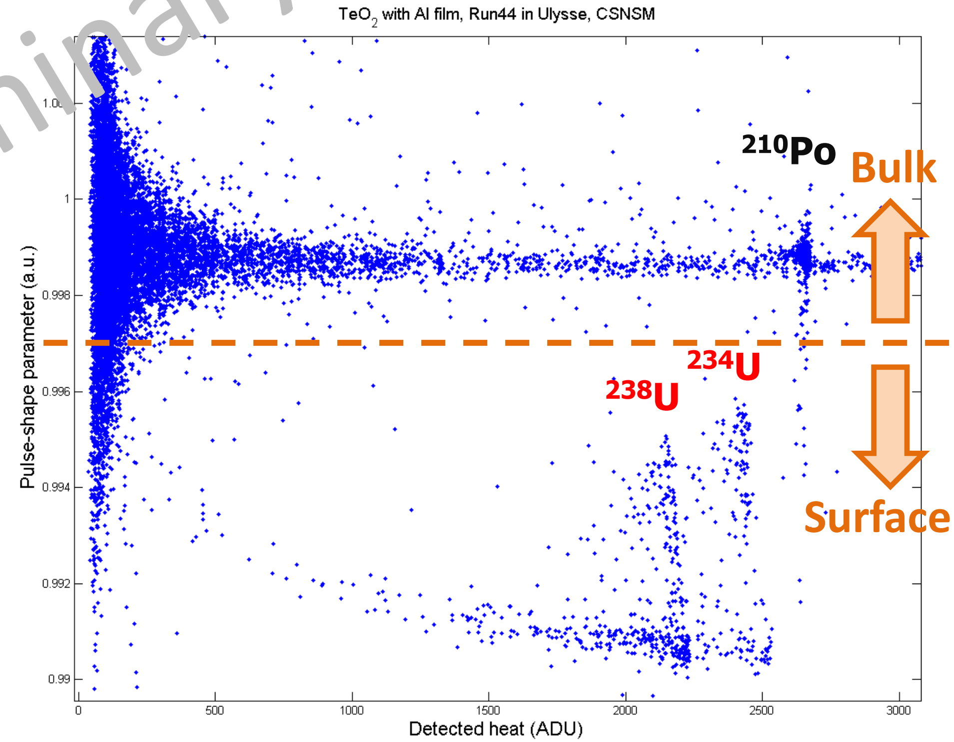
TeO: Pulse shape discrimination

Pulse shape parameter vs. Pulse amplitude

No Al film



With Al film



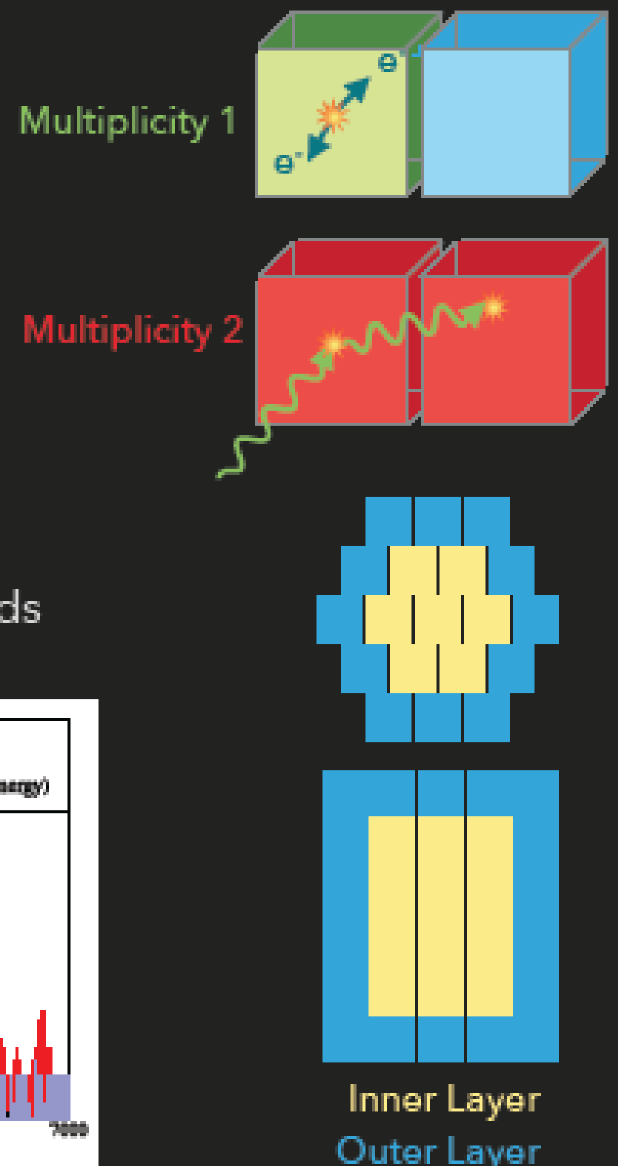
Alphas impacting on the film side are clearly discriminated

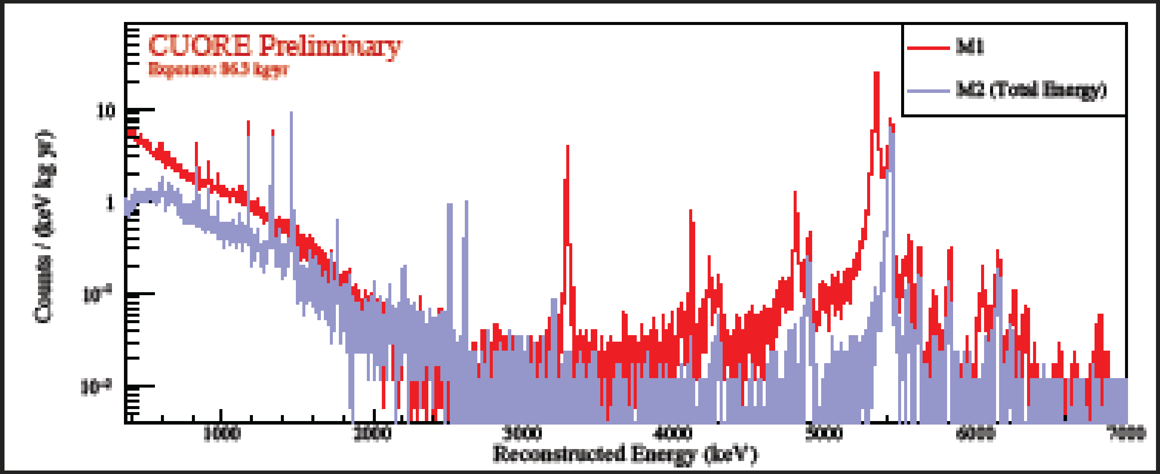
Conclusions

- Study of neutrinoless double beta decay is one of the most urgent topics in particle physics and cosmology
- The bolometric approach is a viable technique, confirmed at large scale by the CUORE results
- A promising technology based on enriched $Li_2{}^{100}MoO_4$ scintillating bolometers was developed and is now applied to the CUPID-Mo demonstrators
- Innovative approaches for surface background are under study
- CUPID (CUORE follow up) implemented with Li_2MoO_4 scintillating bolometers is one of the most promising next-generation searches

Building the CUORE Background Model

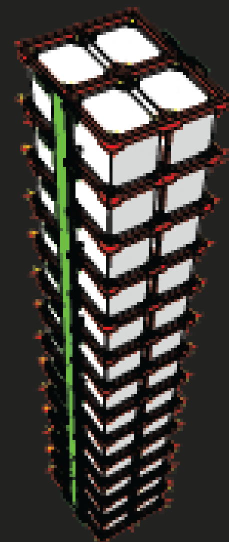
- 86.3 kg·yr of TeO_2 from summer 2017
- Split data into inner and outer layers
- Split data into Multiplicity 1 (M1), Multiplicity 2 (M2), and Multiplicity 2 Sum (Σ2) spectra
  - Higher multiplicity spectra sensitive to backgrounds

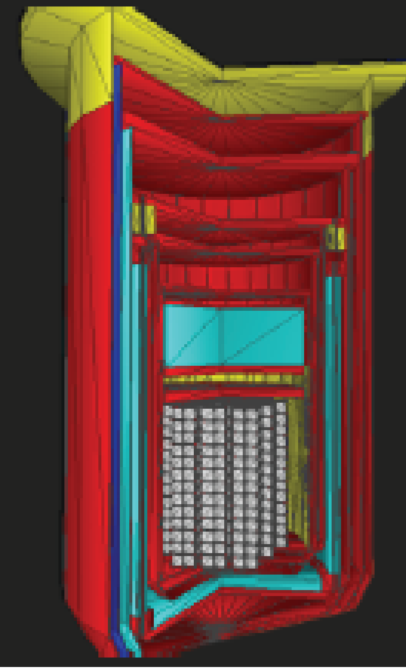




Fitting the CUORE Background Model

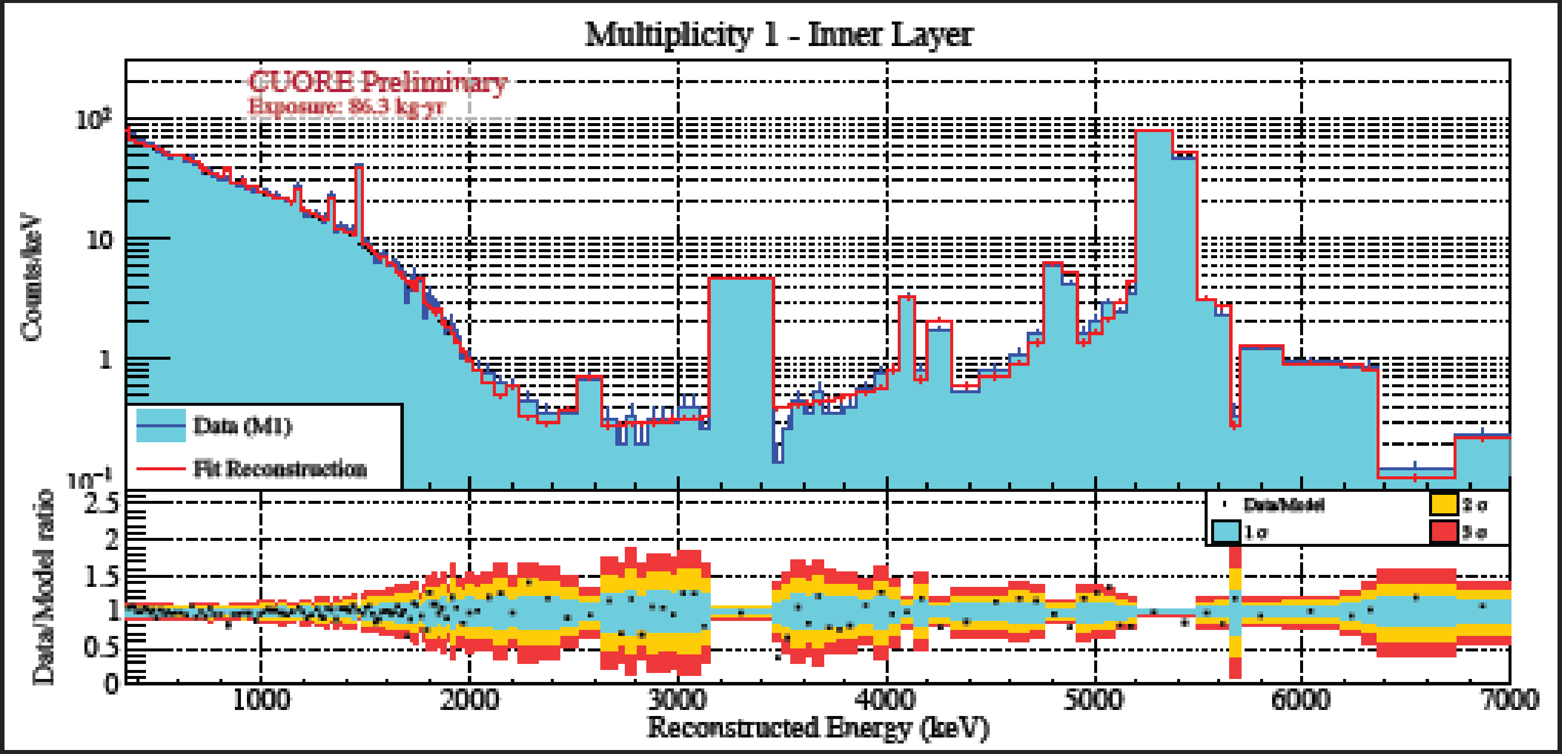
- Simulate the contaminations coming from different cryostat components using a detailed Geant4 MC simulation
- ~60 independent parameters representing various contaminations that could contribute to the CUORE background model
- Perform a large Bayesian fit to the data using a MCMC Gibbs sampler
- Flat priors on all parameters except muons which come from a cosmogenic analysis





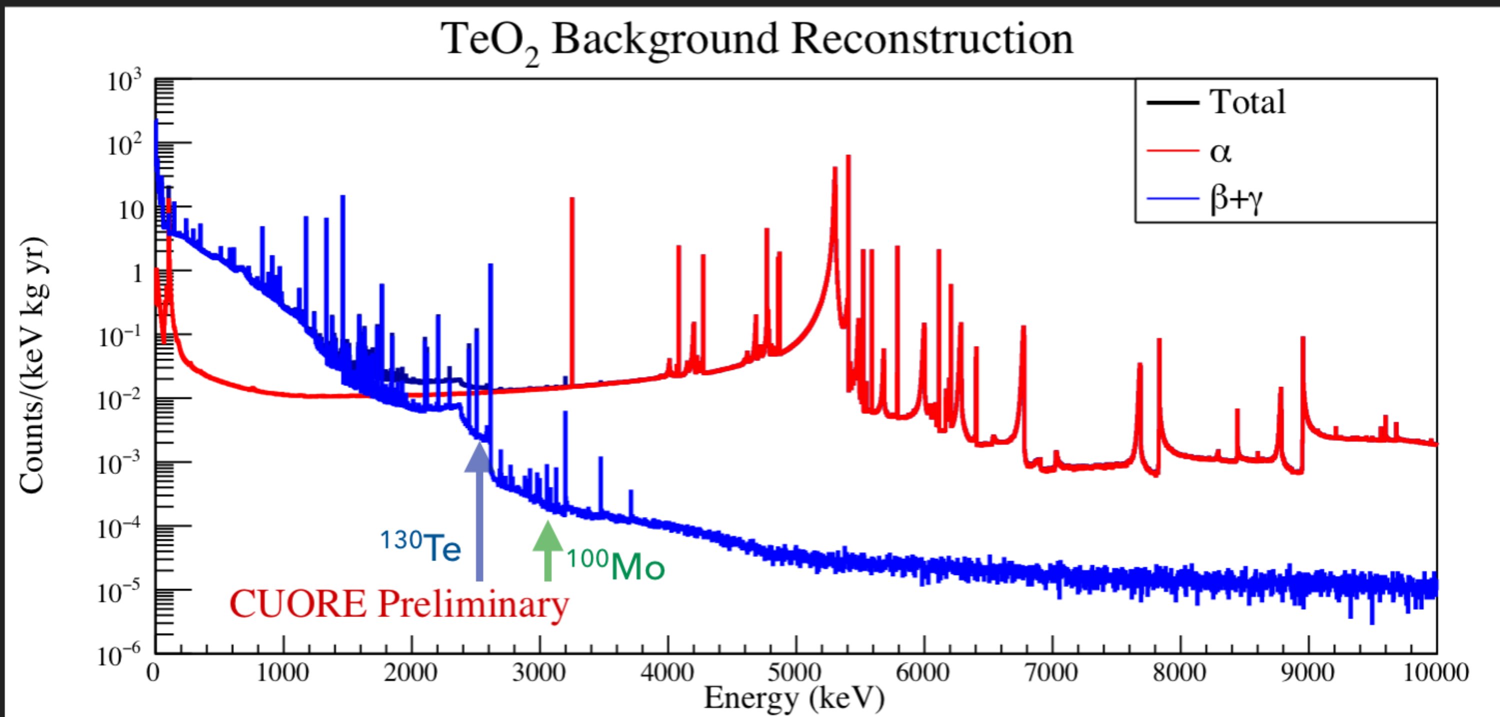
Volume	Type	Components
TeO_2	Bulk	$2\nu\beta\beta$, ^{210}Pb, ^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{230}Th, ^{226}Ra-^{210}Pb, ^{40}K, ^{60}Co, ^{125}Sb, ^{190}Pt
TeO_2	Surface (0.01 μm)	^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{226}Ra-^{210}Pb, ^{190}Pt
TeO_2	Surface (1 μm)	^{210}Pb
TeO_2	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Bulk	^{232}Th, ^{238}U, ^{40}K, ^{60}Co, ^{54}Mn
CuNOSV	Surface (0.01 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (1 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
Roman lead	Bulk	^{232}Th, ^{238}U, ^{108m}Ag
Top lead	Bulk	^{232}Th, ^{238}U, ^{210}Bi
Ext. lead	Bulk	^{210}Bi
CuOFE	Bulk	^{232}Th, ^{238}U, ^{60}Co
External	-	Cosmic muons

Fitting the CUORE Background



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

Background Model Contamination Levels (Very Preliminary!)



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)

$2\nu\beta\beta$ decay random coincidences

Contribution to the background index in the ROI: $\varnothing$50 mm × 50 mm (300 g)

BKG(rc) [counts/(keV kg y)] = 3×10^{-4} [T_R / 1 ms] [M / 300 g]

Our approach (partial simulation + PSD)

EPJ C 72, 1989 (2012)
EPJ C 74 , 2913 (2014)
EPJ C 77 , 3 (2017)

- Take a large value for T_R (typically $T_R \sim 3 \times$ rise time)
- Use real-shape pulses
- Use real noise baselines
- Generate pulses with correct 2ν pulse amplitude distribution
- Calculated rejection efficiency by PSD of pulse-pair separated by less than T_R
- Multiply the above formula by rejection efficiency

In a real case (heat channel):
T_R = 45 ms
Rejection efficiency by PSD = 99.3 % (using the so-called **mean-time method**)
(95% acceptance)

BKG(rc) [counts/(keV kg y)] $\sim 1 \times 10^{-4}$

It can be improved:

- Full simulation
- Advanced pulse shape parameters (after optimum filtering)
- **Using the light channel with high signal-to-noise ratio light detectors → Neganov-Luke**

2νββ decay random coincidences

Contribution to the background index in the ROI: ∅50 mm × 5... (300 g)

BKG(rc) [counts/(keV kg y)] = 3 × 10^{-4} [T... g]

Our approach (partial simulation + PSD)

- Take a large value for T_R (typica...
- Use real-shape pulses
- Use real noise ba...
- Generate ...
- Ca... ...an T_R

...9 (2012)

(2014)

...7)

I...

T_R

Reje... ...the so-called **mean-time method**)

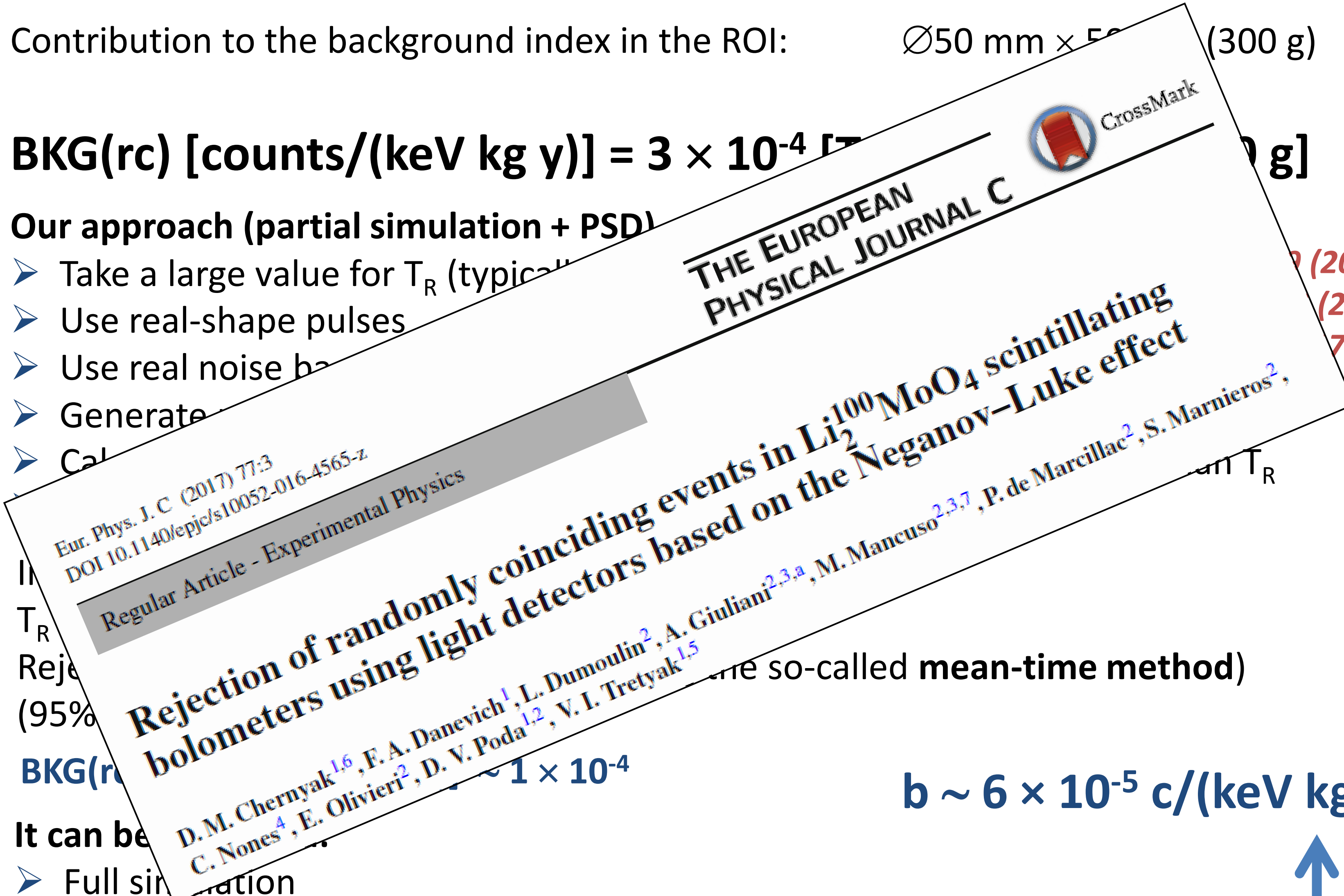
(95%...

BKG(r... ~ 1 × 10^{-4}

b ~ 6 × 10^{-5} c/(keV kg y)

It can be ...d:

- Full si...ation
- Advanced pulse shape parameters (after optimum filtering)
- **Using the light channel with high signal-to-noise ratio light detectors** → **Neganov-Luke**



Eur. Phys. J. C (2017) 77:3
DOI 10.1140/epjc/s10052-016-4565-z

Regular Article - Experimental Physics

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Rejection of randomly coinciding events in $Li_2{}^{100}MoO_4$ scintillating bolometers using light detectors based on the Neganov–Luke effect

D. M. Chernyak[1,6], F. A. Danevich[1], L. Dumoulin[2], A. Giuliani[2,3,a], M. Mancuso[2,3,7], P. de Marcillac[2], S. Marnieros[2], C. Nones[4], E. Olivieri[2], D. V. Poda[1,2], V. I. Tretyak[1,5]

Neutrons

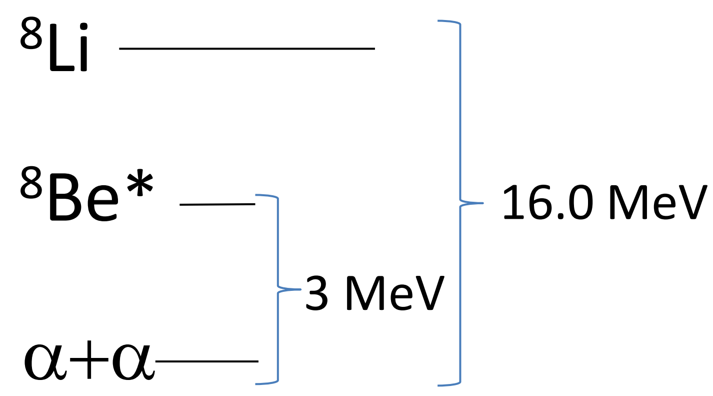
^{6}Li(n,t)α σ = 940 barn (thermal neutrons) Q = 4.78 MeV

Harmless
No associated β radiation
Huge internal energy deposition

^{7}Li(n,γ)^{8}Li σ = 45.4 mbarn (thermal neutrons)

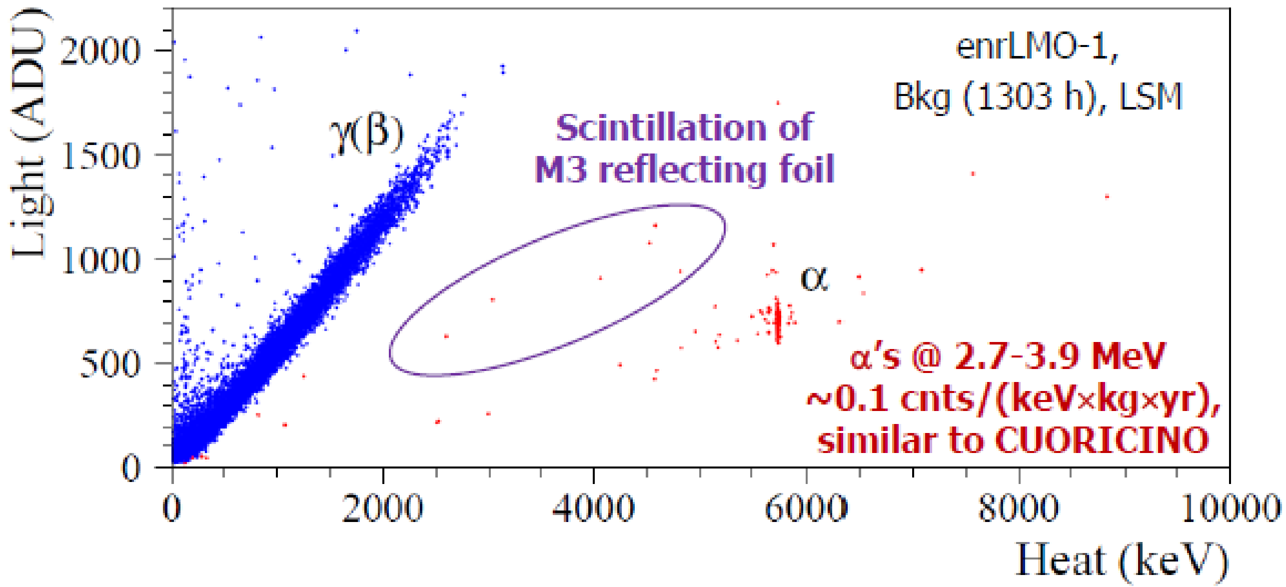
→ $^8Be^* + e^- + \nu$

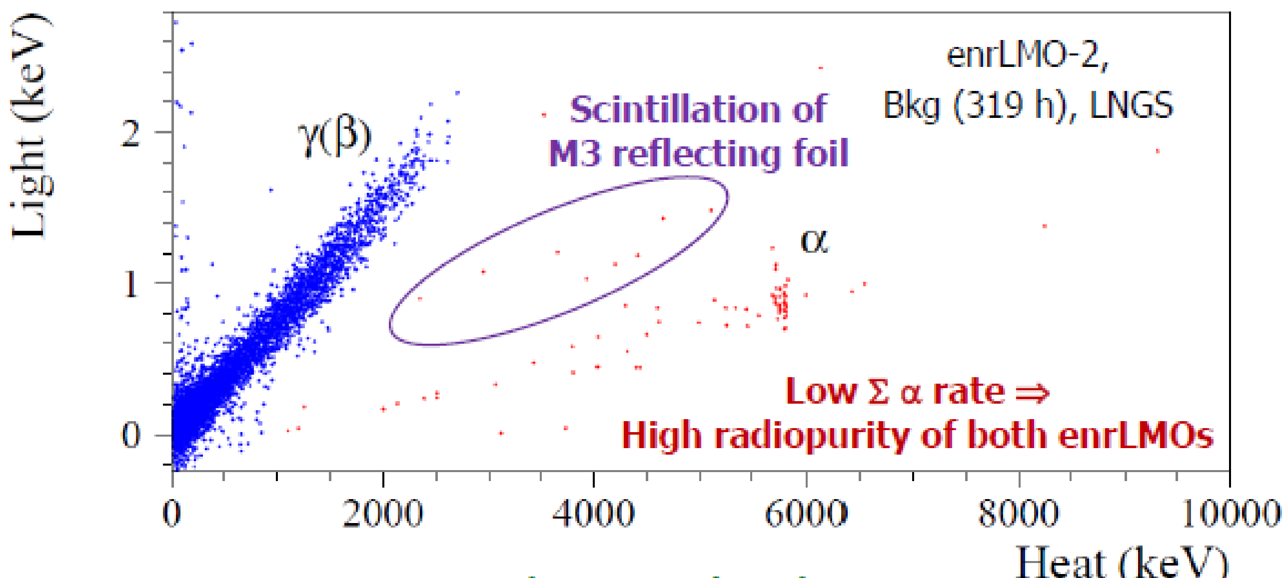
Prompt ($\Gamma \sim$ 1.5 MeV) → $\alpha+\alpha$



Harmless
Very low cross section
Mixed events with α component

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



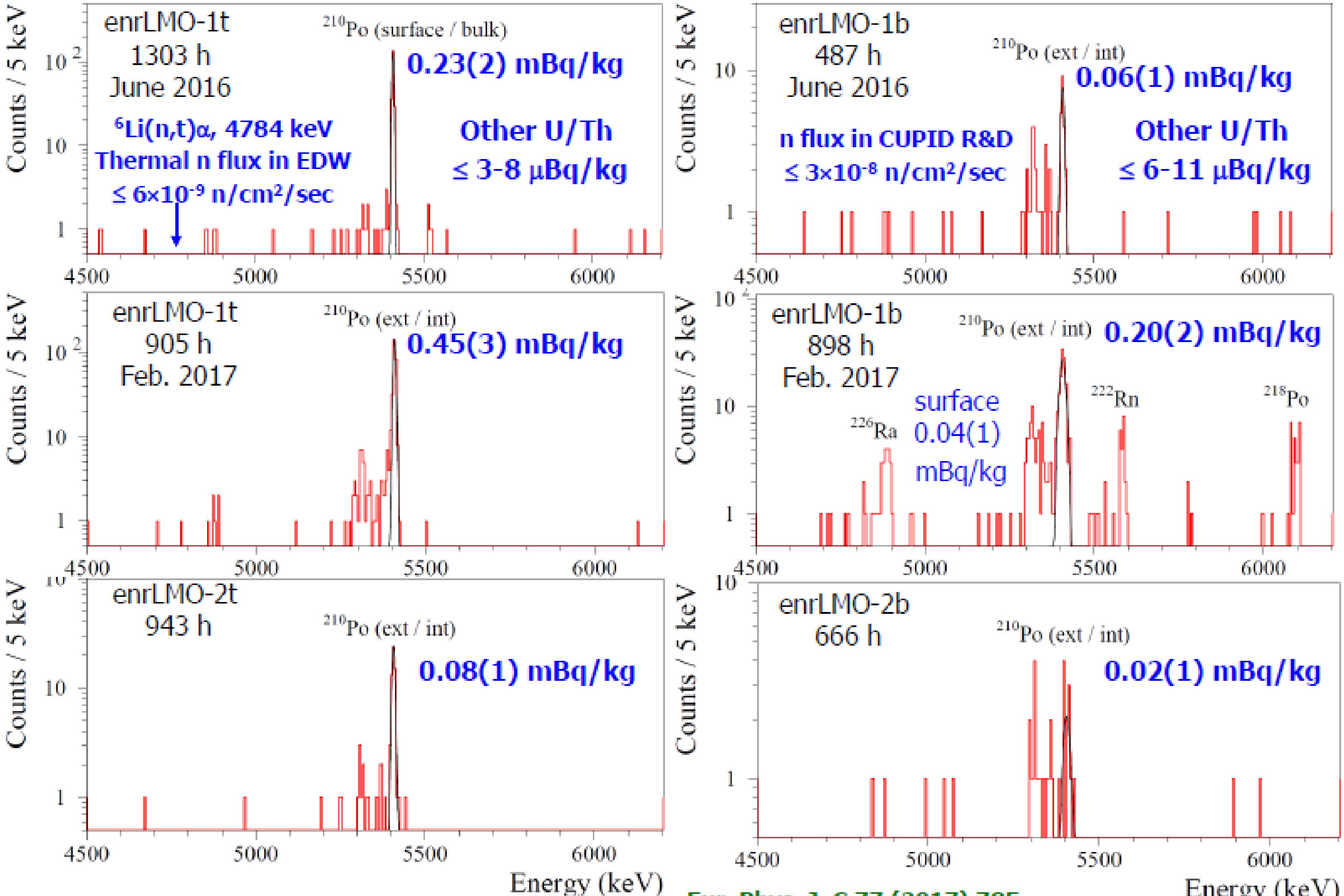


Eur. Phys. J. C 77 (2017) 785

24

D. Poda

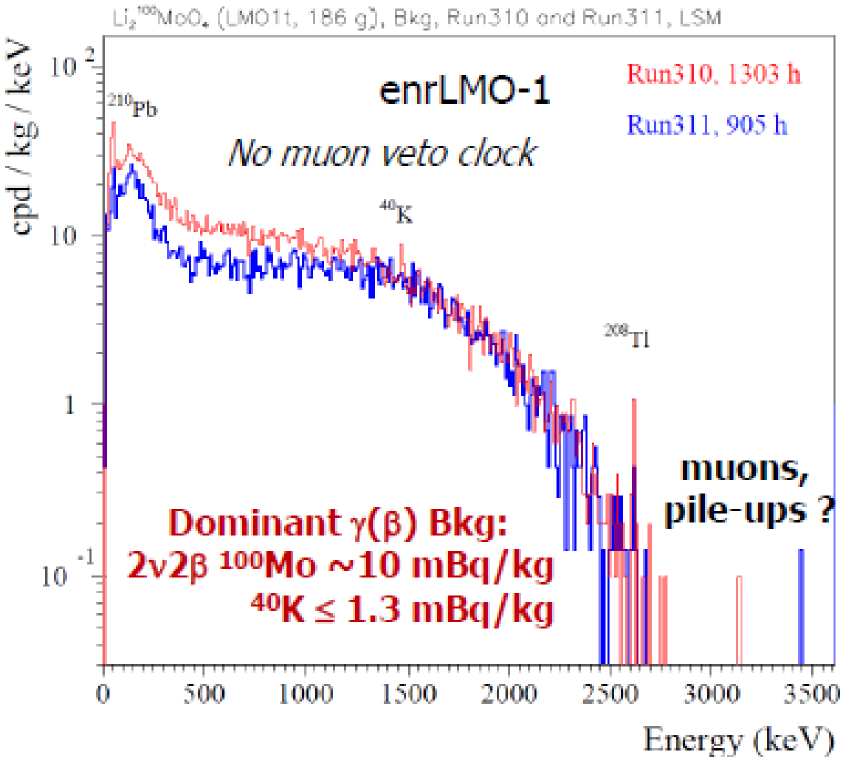
α Background of $Li_2{}^{100}MoO_4$ detectors

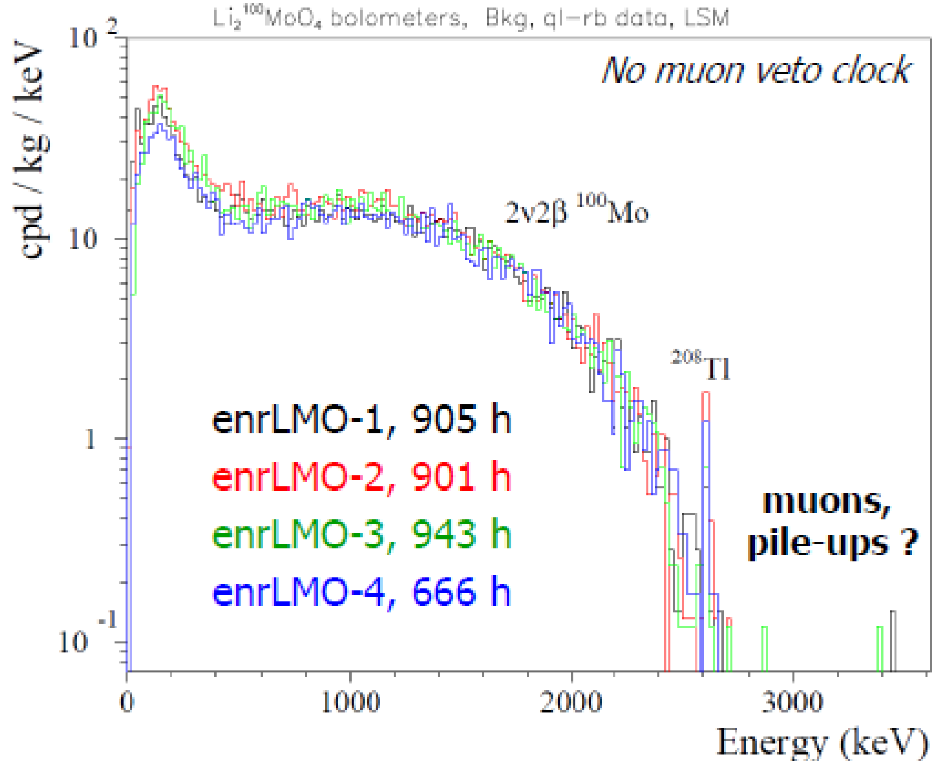


Eur. Phys. J. C 77 (2017) 785
AIP Conf. Proc. 1894 (2017) 020017

D. Poda

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





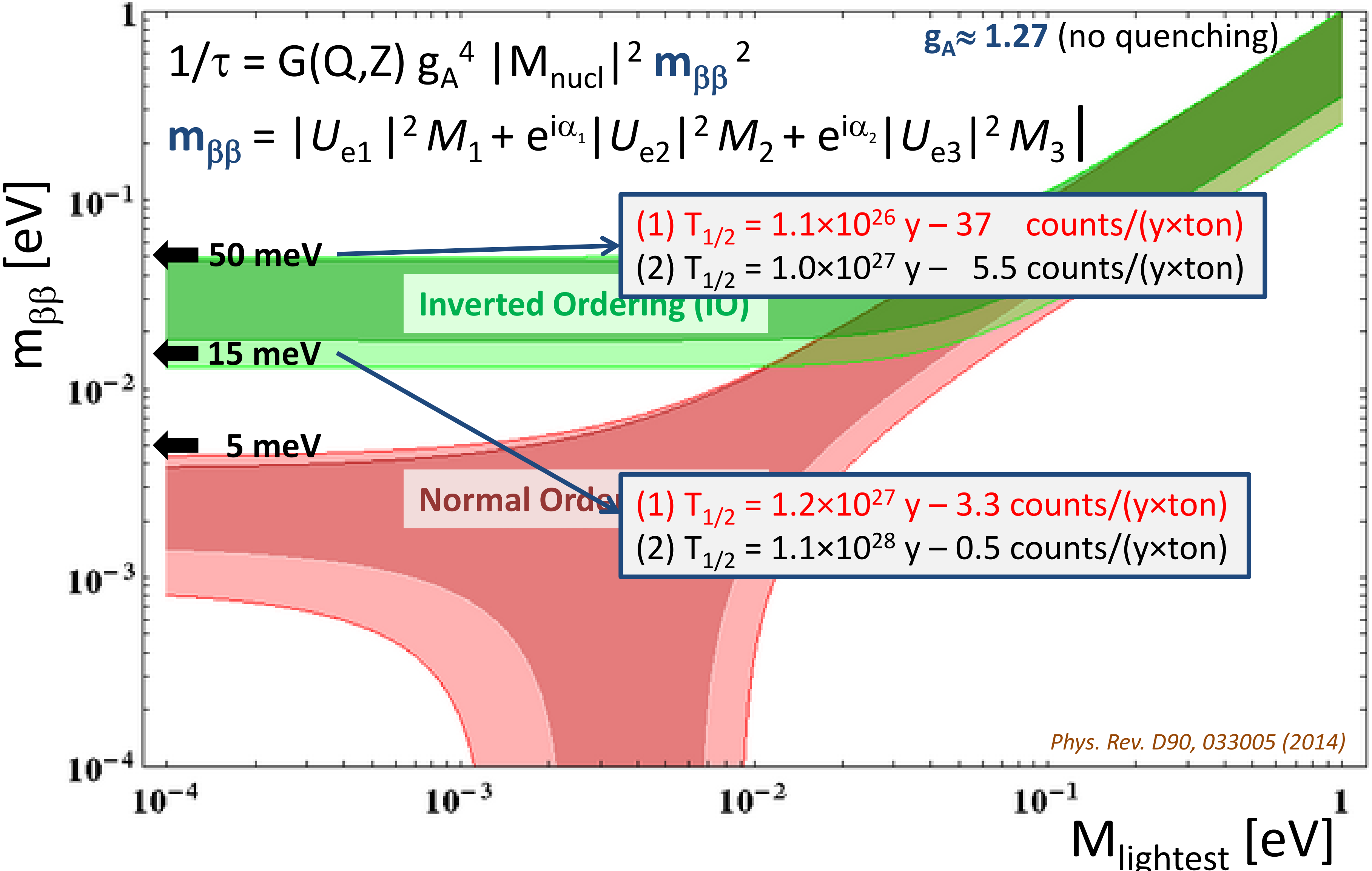
Rate [cnts/day/kg] of 2615 keV γ's	LUMINEU	CUPID-0
Spread	0.7(3) - 2.1(5)	0.03 - 0.33
Average	**1.1(2)**	**0.14**

L. Cardani, private communication

External ^{232}Th background is expected to be reduced thanks to a new wiring

D. Poda

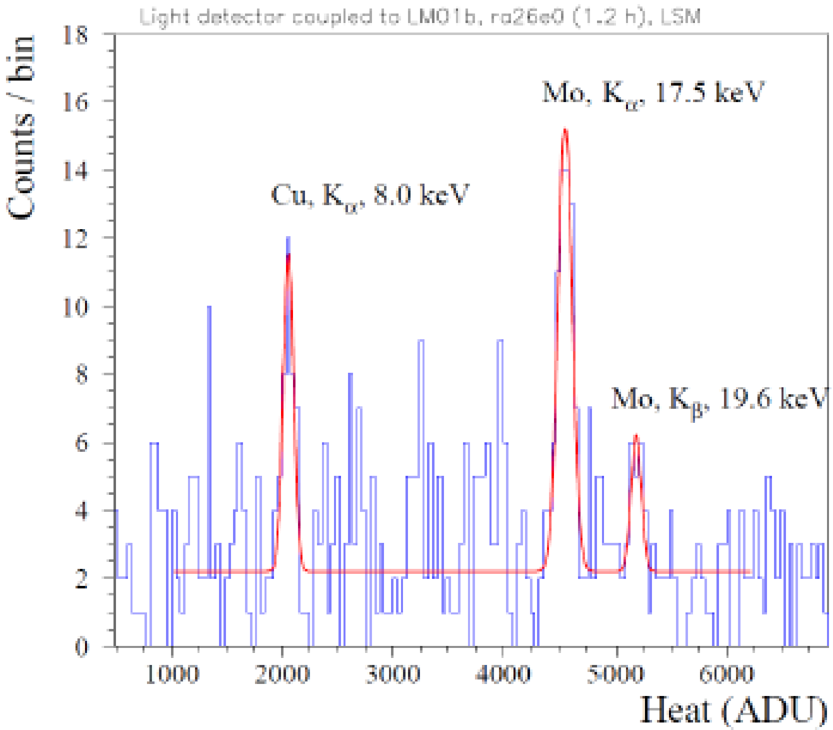
How difficult is it?



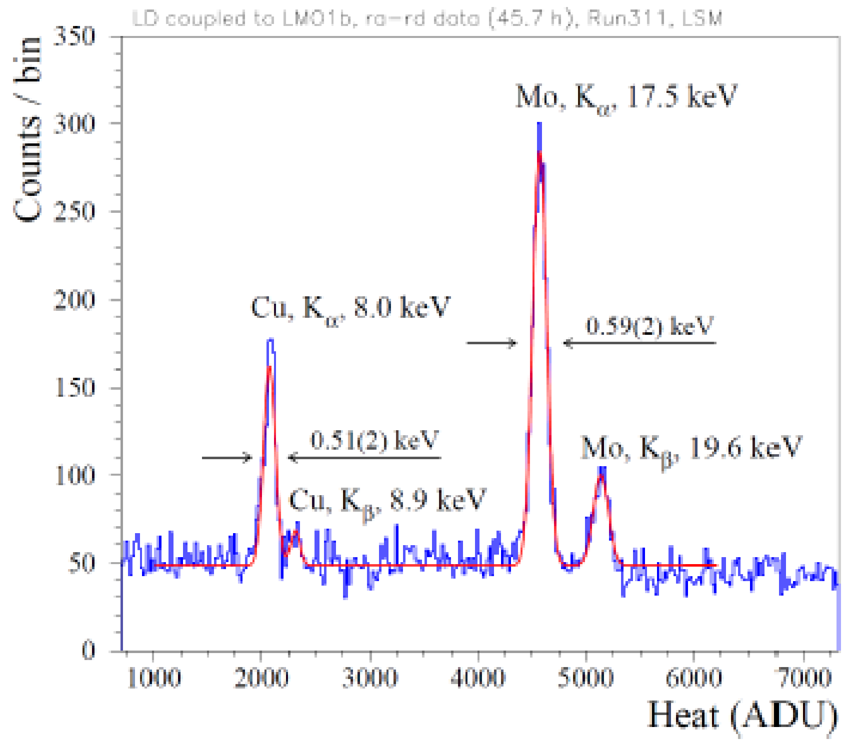
Light detectors calibration by external γ source

A high activity ^{60}Co source (~100 kBq) is used by EDELWEISS to regenerate Ge bolometers…

^{60}Co "regen" run, 1.2 h



^{60}Co "regen" runs, 45.7 h



A simple & fast way to calibrate LDs by γ source excited X-ray fluorescence

LUMINEU light detectors performance

More colder temperature conditions require stronger NTD polarization
to overcome operation instability of high resistivity NTDs (5 mg) with AC electronics

Light detector	T_{bolo} (mK)	I_{bolo} (nA)	R_{bolo} (MΩ)	Signal (μV/keV)	$FWHM_{baseline}$ (keV)
M3	17.0	6.8	0.55	0.86	0.11
Lum10	19.3 17.0	2.3 6.8	1.52 0.39	2.13 1.06	0.07 0.12
Lum11	19.3 17.0	2.3 7.3	1.32 0.51	1.78 1.15	0.07 0.07
Lum12	19.3 17.0	2.3 6.8	1.09 0.31	1.50 0.73	0.14 0.11
LUMINEU LD	19.3 17.0	2.3 6.9	1.3 0.4	**1.8** **0.9**	**0.08** **0.10**
CUPID-0 LD EPJC 76(2016)364	20.0	n.a.	0.8	**1.3**	**0.10**

Good reproducibility of high performance of NTD-instrumented LDs

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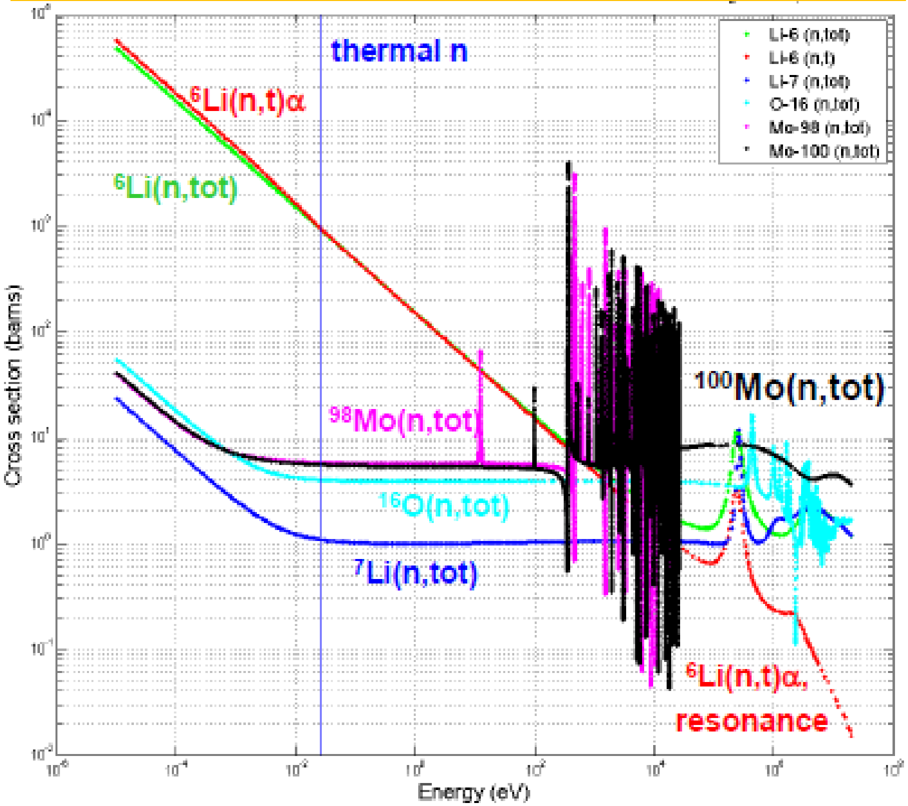
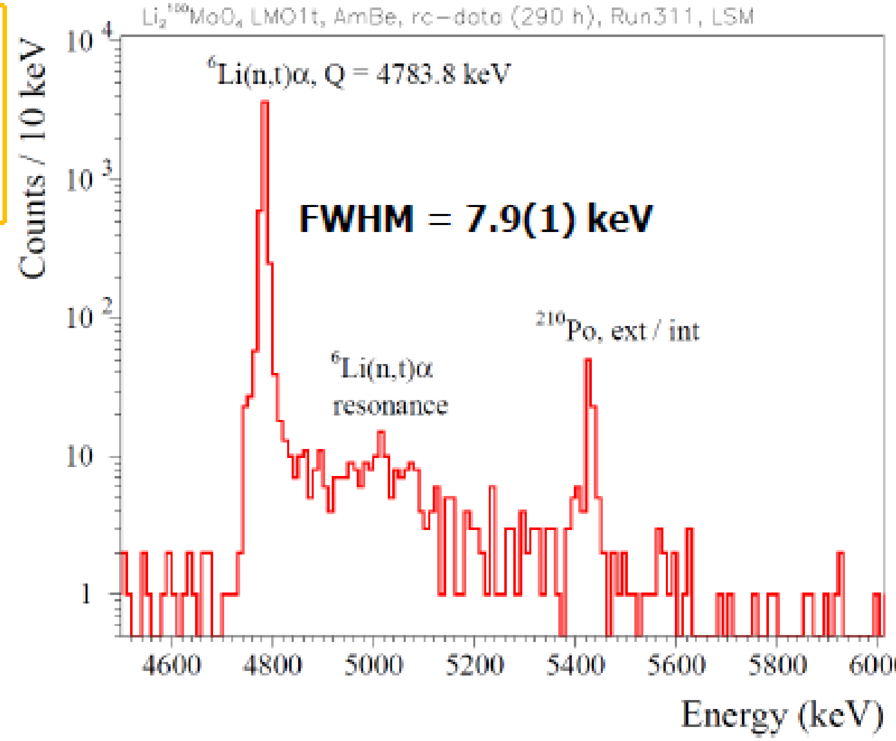
Neutron spectroscopy with $Li_2{}^{100}MoO_4$ bolometers

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



enrLMO-1, AmBe (290 h)



Advantages

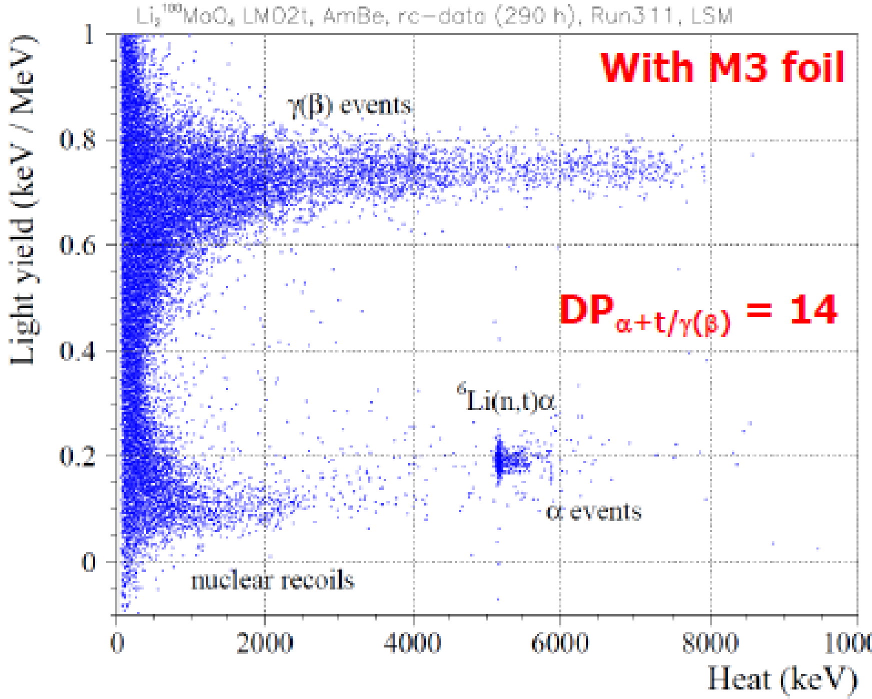
- ✓ ~100% detection of thermal n
- ✓ clear α+t signature @ $Q+E_n$
- ✓ γ(β) background-free ROI
- ✓ world record resolution of thermal n capture on ^{6}Li (6-11 keV FWHM @ 4783 keV)

Prospects for in-situ neutron detection

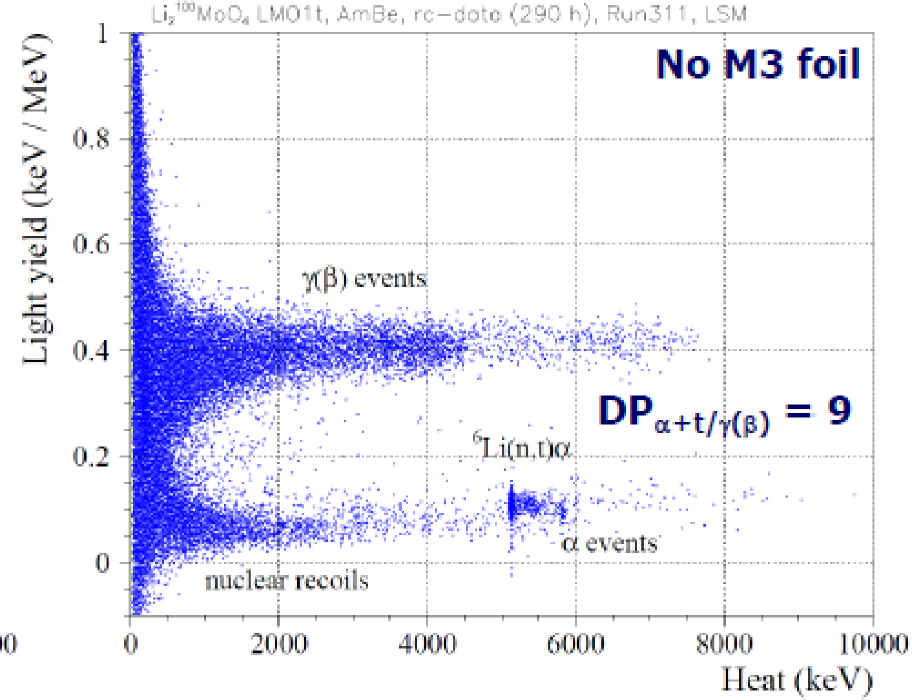
Light yield and α/γ separation

Heat + Light

enrLMO-3, AmBe (290 h)



enrLMO-1, AmBe (290 h)



Efficient α/γ(β) separation even for detectors operated without a reflecting foil

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

D. Poda

CROSS #3 – Al film in LMO crystal – 10 μm thick