DE LA RECHERCHE À L'INDUSTRIE

DOUBLE-BETA-DECAY RESEARCH LINE AT SPP

CSTS du SPP – 14 November 2014 | Claudia Nones

www.cea.fr

DOUBLE-BETA-DECAY SEARCH LINE AT SPP

- Development of a demonstrator experiment based on $ZnMoO_4$ scintillating bolometers ($M_{\beta\beta} \sim$ 100 meV)
- Participation to R&D in view of a next-generation experiment – ton scale ($M_{\beta\beta} \sim$ 15 meV)

OUTLINE

- Introduction to Double beta decay (DBD)
- Short status of DBD search
- Scintillating bolometers for a zero background DBD experiment
- LUMINEU – introduction and results on natural and enriched $ZnMoO_4$ detectors
- Follow-up to LUMINEU: LUCINEU
- Covering the inverted hierarchy region of the neutrino mass: CUORE-IHE
- Scintillating bolometers as a promising technology for CUORE-IHE

DOUBLE BETA DECAY IN A NUTSHELL

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$ → 2ν Double Beta Decay
allowed by the Standard Model
already observed – $\tau \sim 10^{18} - 10^{21}$ y

② $(A,Z) \rightarrow (A,Z+2) + 2e^-$ → Neutrinoless Double Beta Decay (0ν-DBD)
never observed
$\tau > 10^{25}$ y

Process ② would imply new physics beyond the Standard Model

violation of total lepton number conservation

Basic importance of DBD in particle phsycics

Standard Model as a low-energy limit of an unknown more general theory

Bottom-up approach: add effective operators to the SM Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

New physics high energy scale (Λ) — DBD ($\mathcal{L}_5$) — Proton decay ($\mathcal{L}_6$)

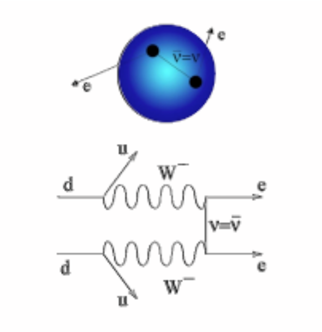
THE RATE IN THE MASS MECHANISM

Observation of $0\nu\beta\beta$ →

OPEN QUESTIONS

1) Which is the neutrino mass hierarchy
2) Which is the absolute neutrino mass scale
3) DIRAC or MAJORANA nature of neutrinos

To be more quantitative:



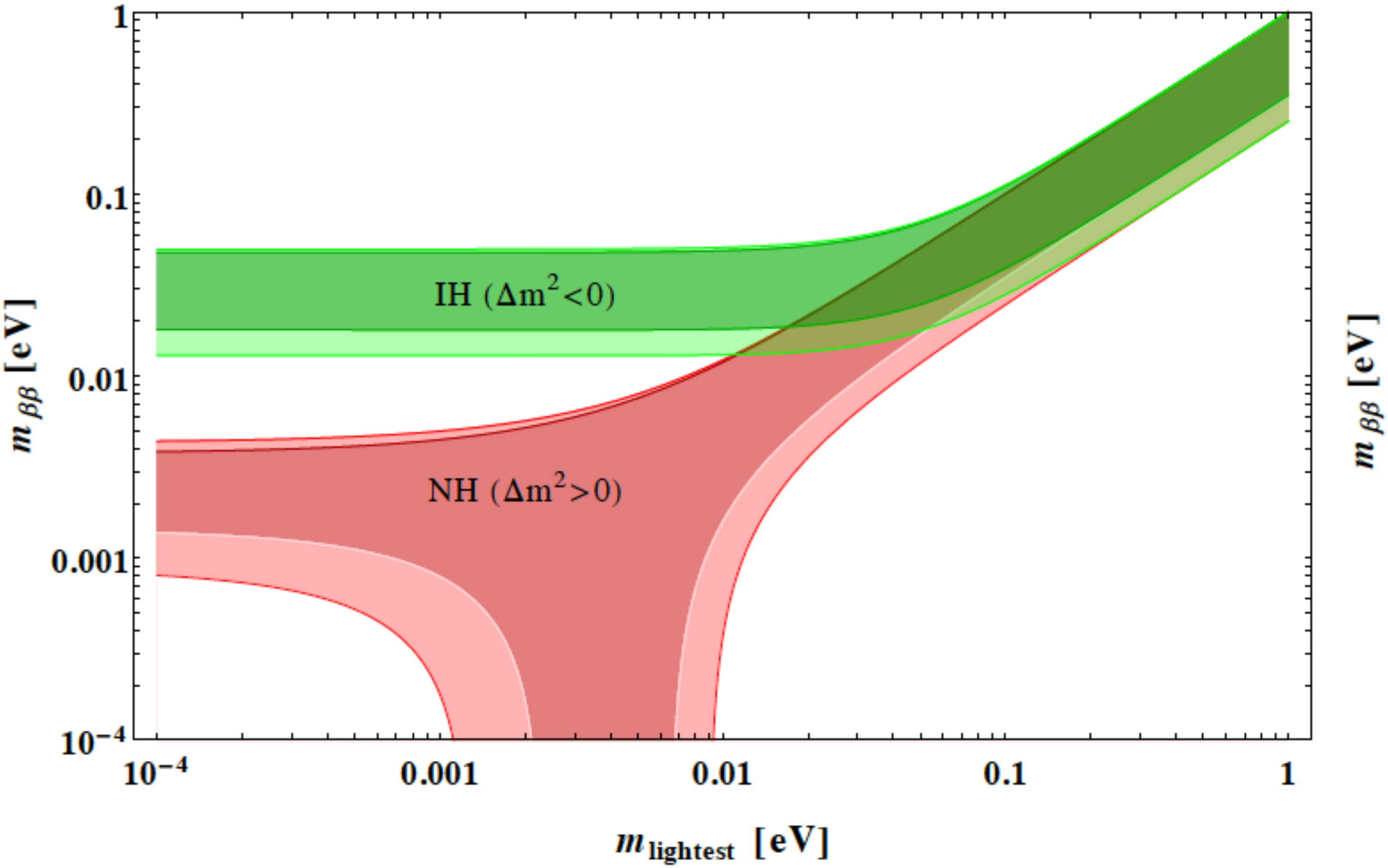
neutrinoless Double Beta Decay rate; Phase space; Nuclear matrix elements; Effective Majorana mass

$$\frac{1}{\tau} = G(Q,Z) \cdot |M|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

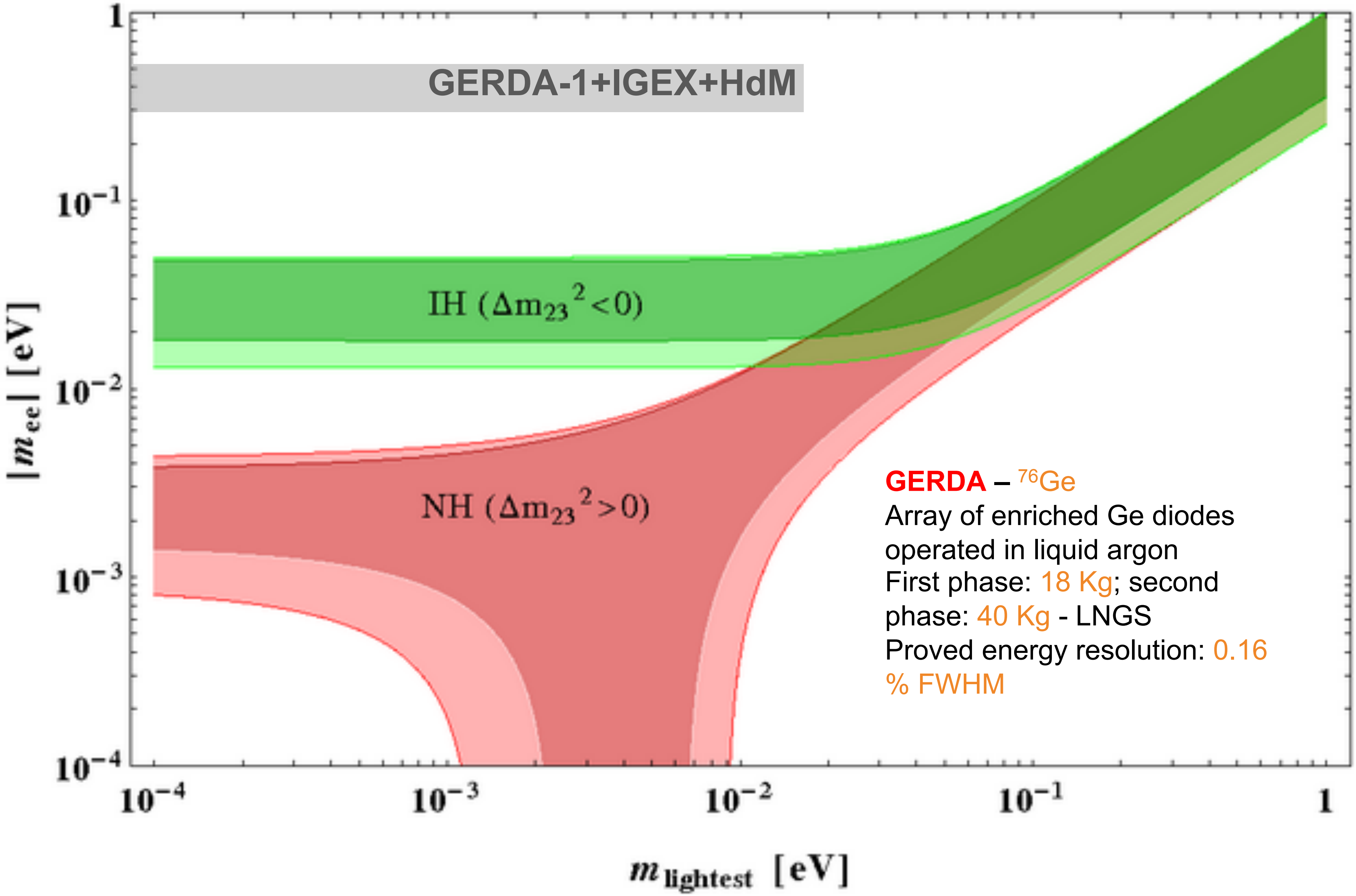
$$\langle m_{\beta\beta} \rangle = \left| |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \right|$$

→ can be of the order of ~ 50 meV in case of inverted hierarchy

THE IMPORTANT PLOT

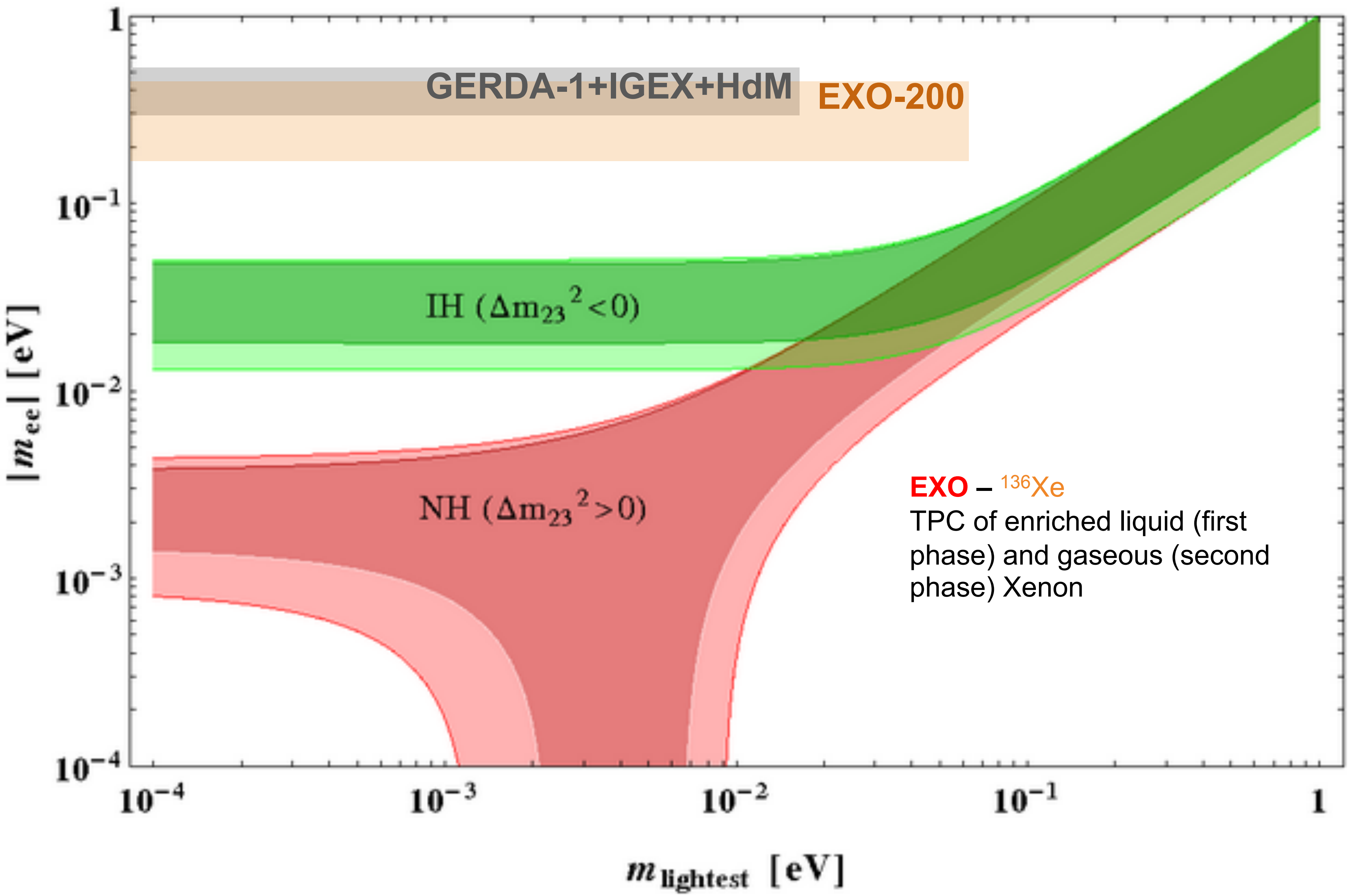


EXPERIMENTAL STATUS

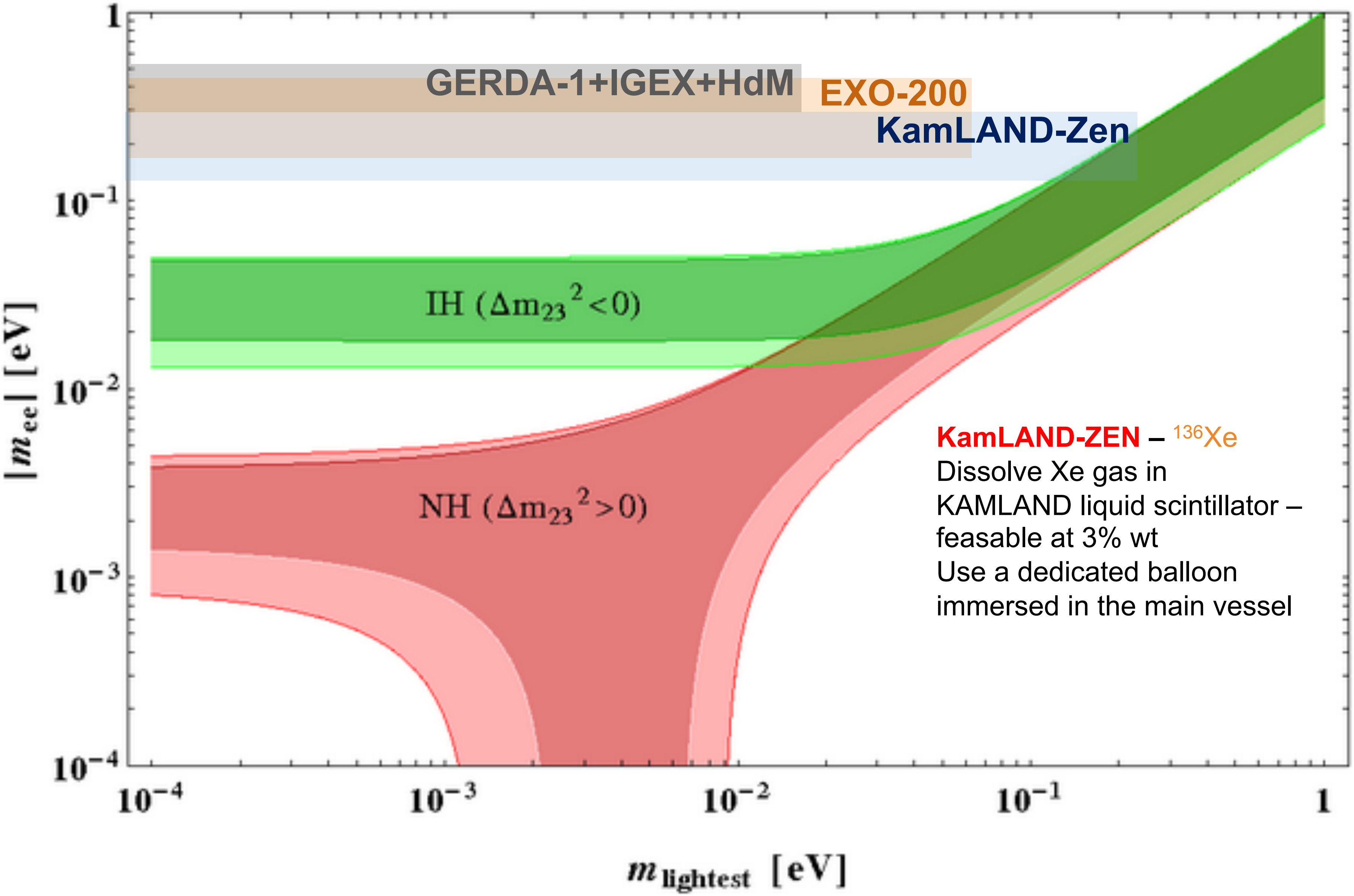


GERDA – ^{76}Ge
Array of enriched Ge diodes operated in liquid argon
First phase: 18 Kg; second phase: 40 Kg - LNGS
Proved energy resolution: 0.16 % FWHM

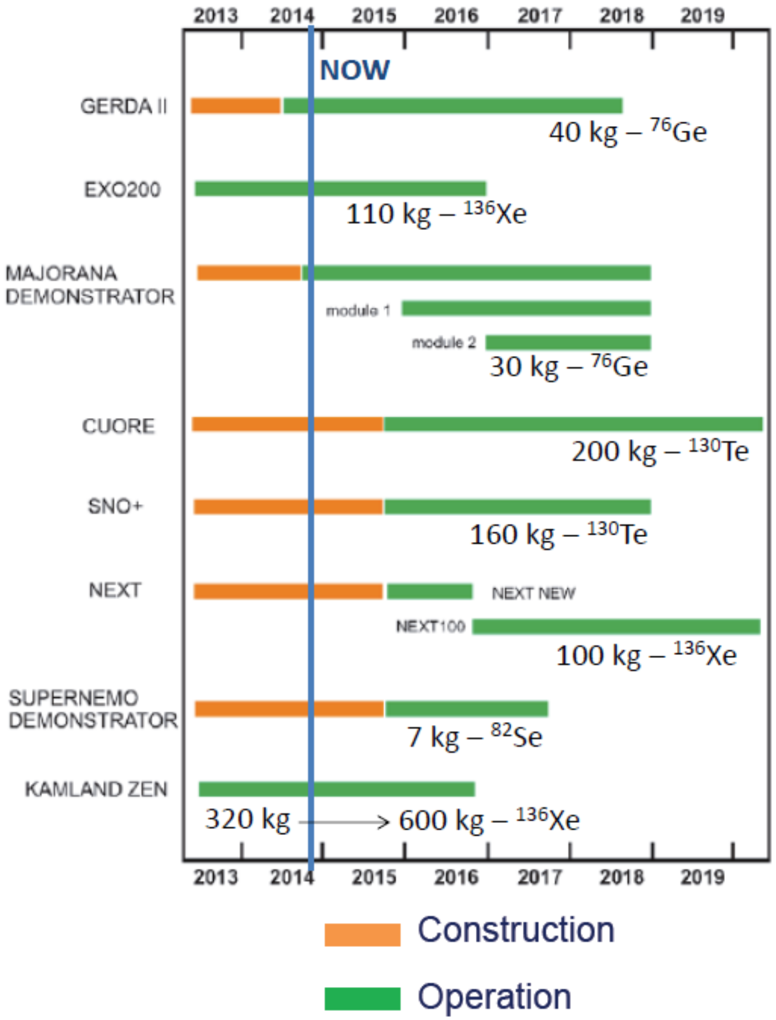
EXPERIMENTAL STATUS

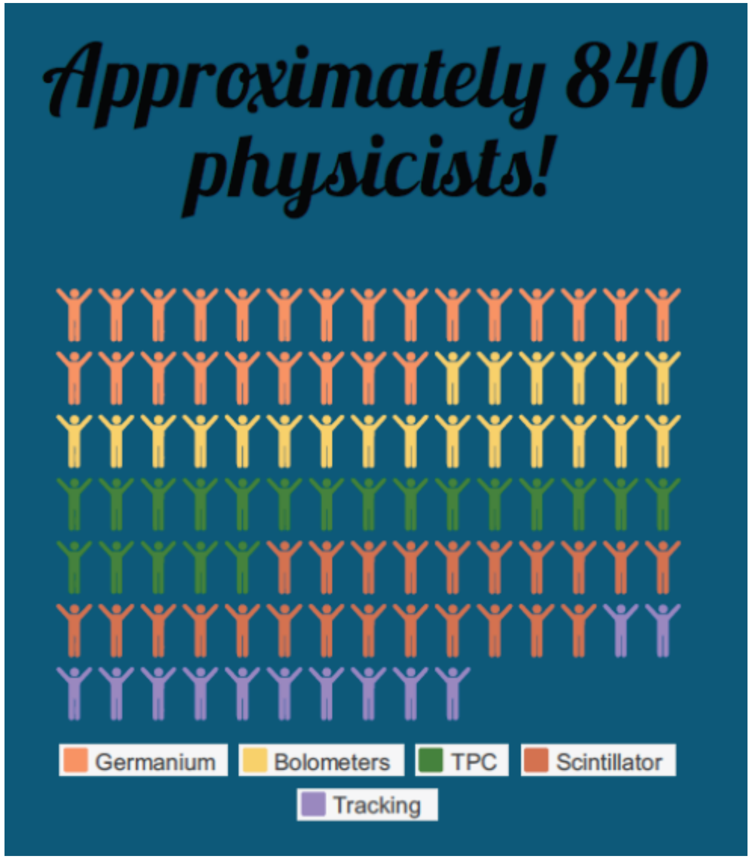


EXPERIMENTAL STATUS



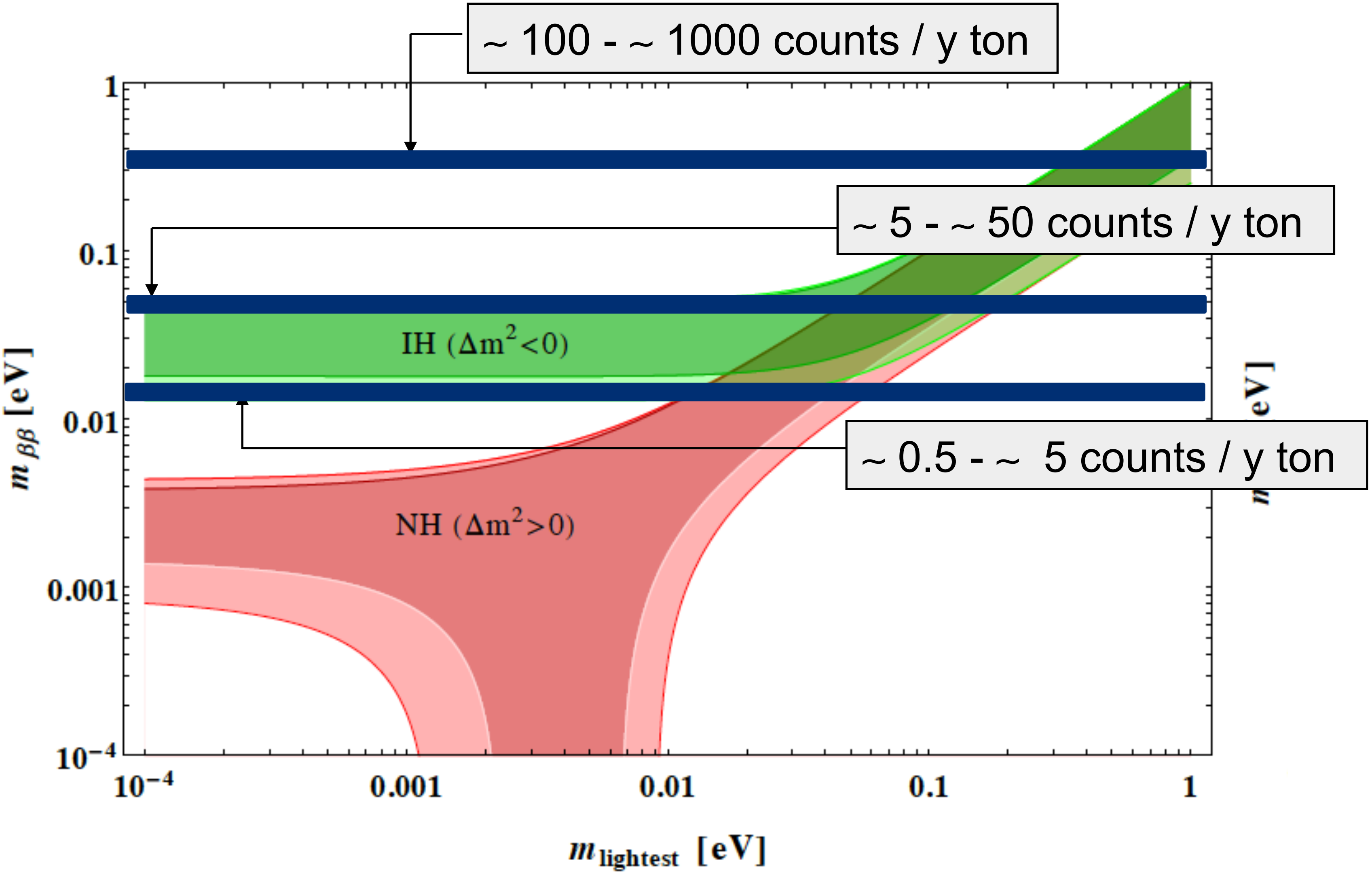
KamLAND-ZEN – ^{136}Xe
Dissolve Xe gas in KAMLAND liquid scintillator – feasable at 3% wt
Use a dedicated balloon immersed in the main vessel





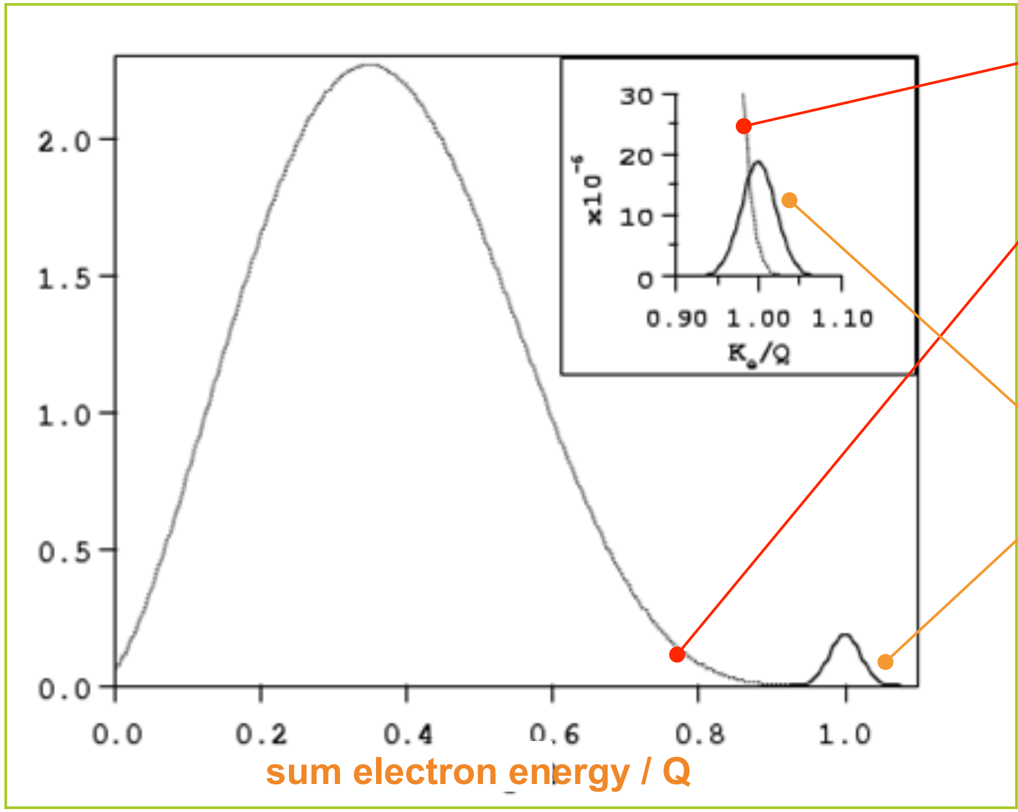
From NLDBD-NSAC document (April 2014)

HOW DIFFICULT IS IT?



THE EXPERIMENTAL SIGNATURES

The shape of the two electron sum energy spectrum enables to distinguish among the two different discussed decay modes



2ν double beta decay
continuum with maximum at ~1/3 Q

0ν double beta decay
peak enlarged only by the detector energy resolution

AN IDEAL EXPERIMENT

SENSITIVITY $S_{0\nu}$: lifetime corresponding to the minimum detectable number of events over background at a given confidence level

$$S_{0\nu} \propto \left(\frac{M t_{live}}{b \Delta E} \right)^{\frac{1}{2}}$$

$$\langle m \rangle \propto \left(\frac{b \Delta E}{M t_{live}} \right)^{\frac{1}{4}}$$

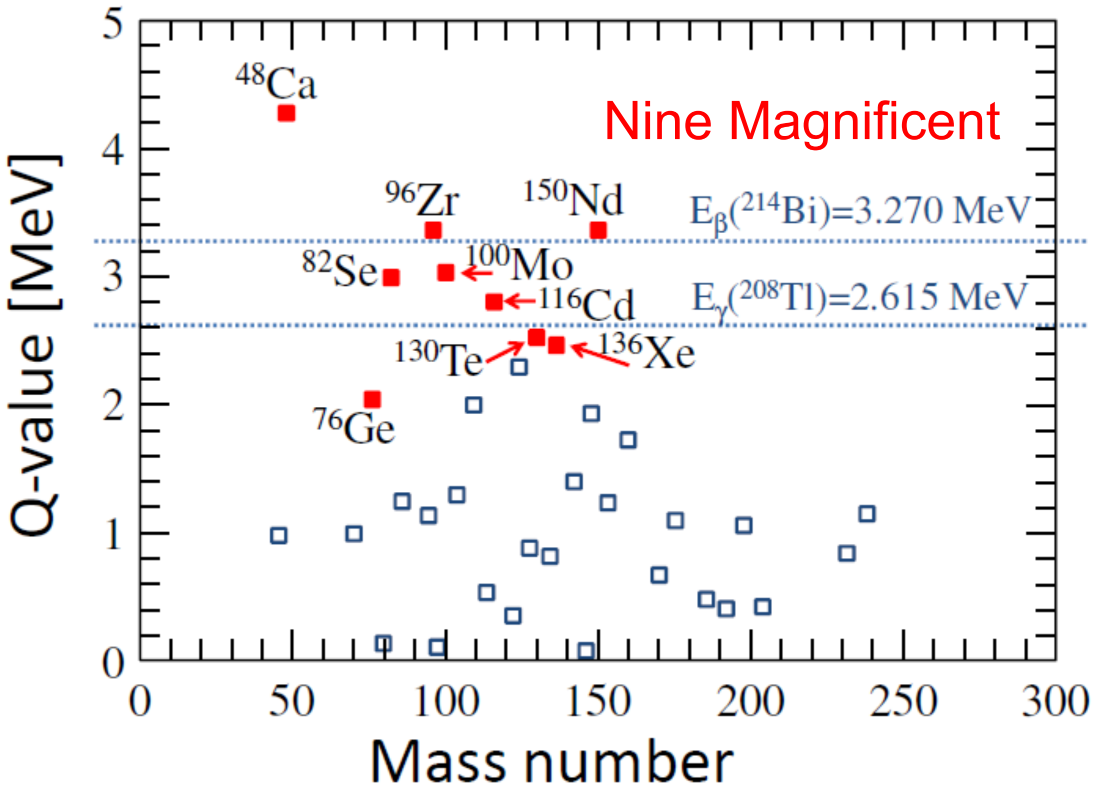
Desirable features

Large Mass (~ 1 ton)
Large Q value, fast $0\nu\beta\beta$
Good source radiopurity
Demonstrated technology
Ease of operation
Natural isotope
Small volume, source = detector
Good energy resolution
Slow $2\nu\beta\beta$ rate
Identify daughter in real time
Event reconstruction
Nuclear theory

FACTORS GUIDING ISOTOPE SELECTION

Q is the crucial factor → Phase space: $G(Q,Z) \propto Q^5$

→ Background



Other factors favour certain isotopes with respect to others:

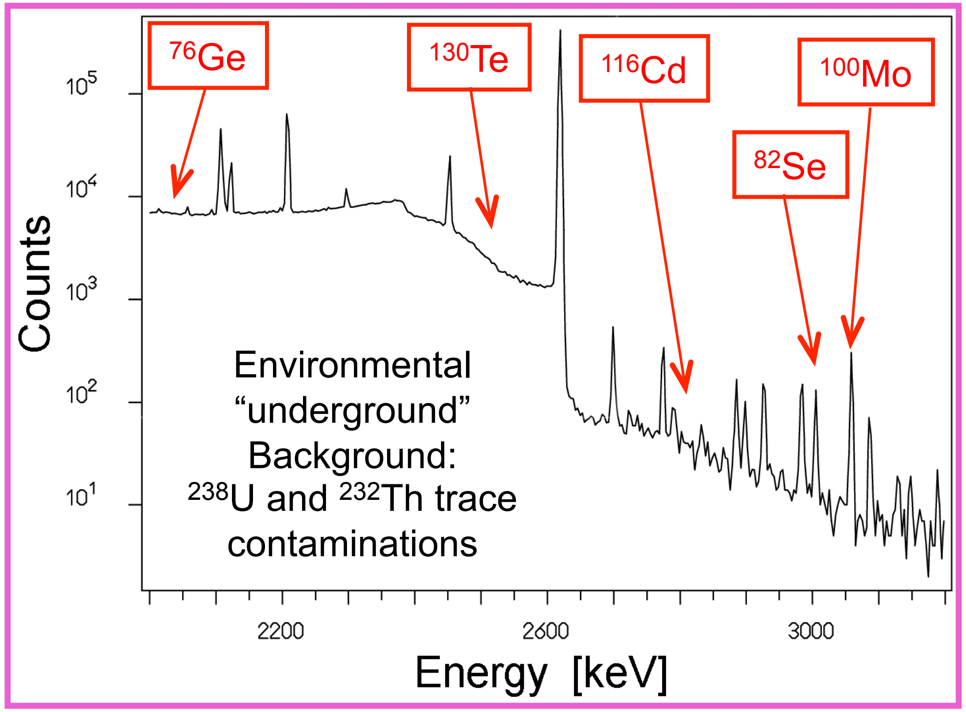
- Easy association to an **experimental technique**
- High **isotopic abundance** and/or easy **enrichment**
- Achievable **radiopurity**

THE IMPORTANCE OF A HIGH Q-VALUE

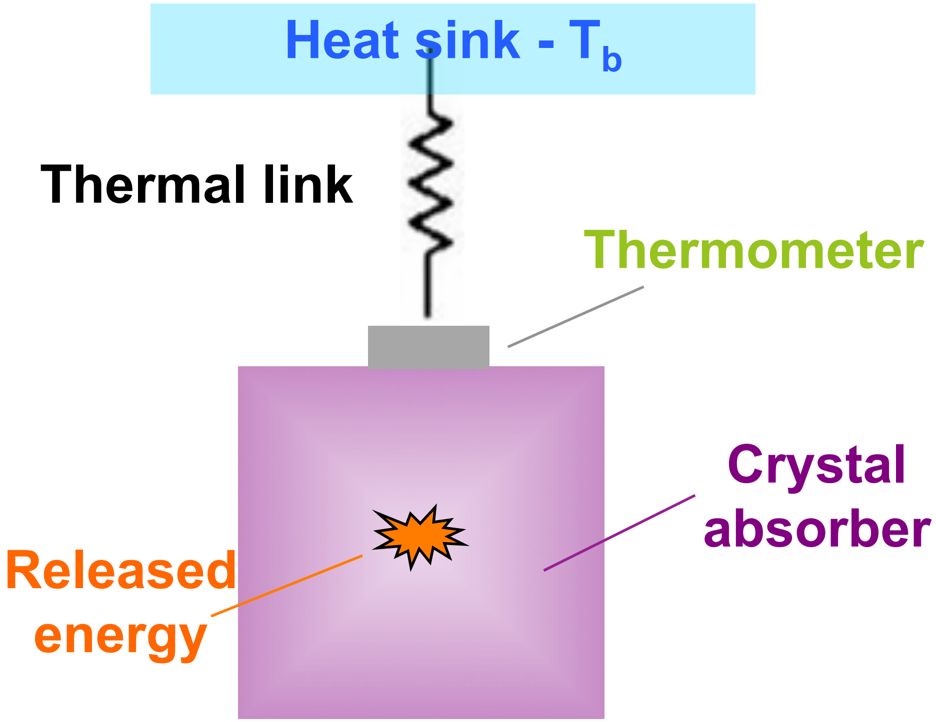
A **high Q-value** is important for two reasons:

- High phase space for the decay: $\propto$ **Q^5**
- If **Q > 2615 keV**, the signal is out of the bulk of the natural γ radioactivity

Position of the Q-values for some interesting candidates superimposed to a gamma spectrum taken underground without any form of passive shielding



THE BOLOMETRIC TECHNIQUE



Main features:

- high energy resolution
- wide versatility (few constrains on absorber material)
- the detector is fully sensitive (no dead layer)

This technique measures **all** the energy deposited by particle in form of increase of temperature in the absorber.

From a very simple thermal model:

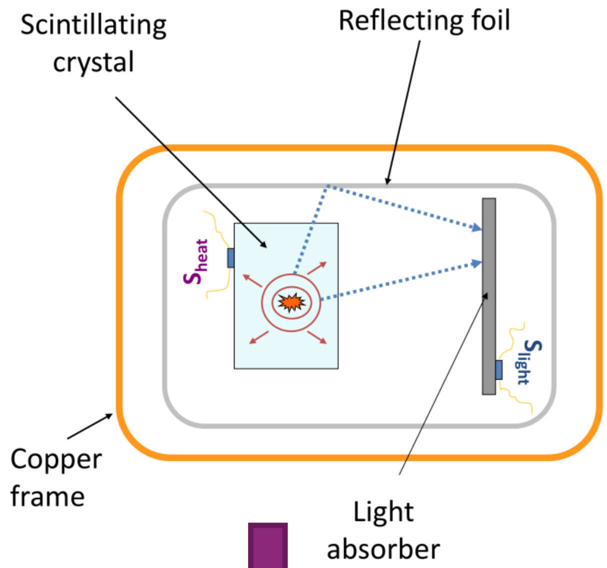
Signal: $\Delta T = E/C$

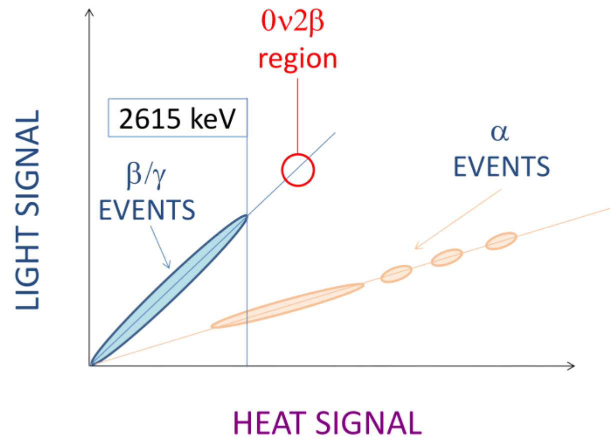
Time constant $= C/G$

→ to develop high pulses the detector has to work at **low temperatures** (10 – 50 mK).

Double read-out detector

light/heat





Candidate choice
Q-value > 2615 keV

“zero” **gamma background**

Full discrimination
alpha/beta

“zero” **alpha background**

= zero bkg **at the stage ≈ 1 tonne × an**

IS A ZERO BACKGROUND ACHIEVABLE?

b ~ 10^{-1} count/keV/kg/y in « classical » calorimetric experiments
b ~ 10^{-2} - 10^{-3} count/keV/kg/y in present calorimetric experiments and in « tracko-calo »
b ~ 10^{-4} count/keV/kg/y in future experiments

With this background index it is possible to get zero background at the ton x year scale in high energy resolution experiment [bolometers, Ge diodes]

In scintillating bolometers, dangerous bulk contaminants are high energy β decays:

^{214}Bi → Q -value = 3.270 MeV (progenitors: ^{238}U, ^{226}Ra, ^{228}Th)
^{208}Tl → Q -value = 4.999 MeV (progenitors: ^{232}Th, ^{228}Th)

With MC simulations one can show that:

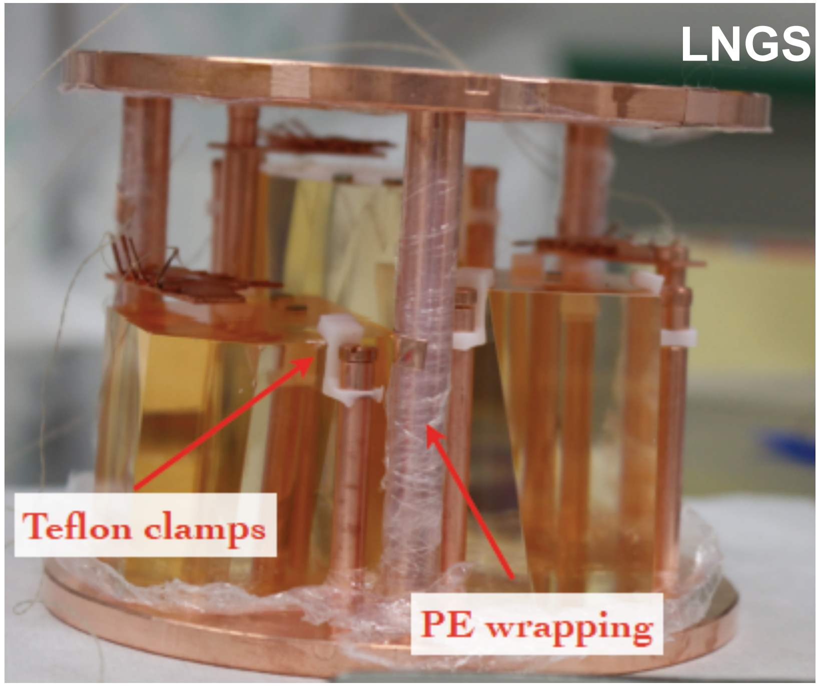
A(^{228}Th) ≤ 10 μBq/kg ⇒ b ~ 10^{-4} counts/keV/kg/y

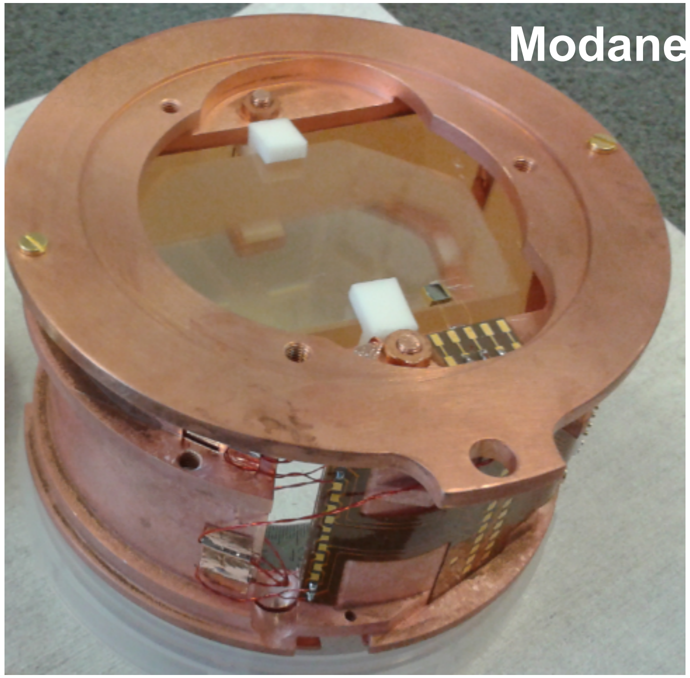
Target for the internal contamination

SPP ACTIVITY

- Participation to the ANR LUMINEU
- Strong collaboration with CSNSM for R&D on different topics (easy access to test facilities)
- New above-ground test facility at IRAMIS/SPEC (thanks to P2IO)
- Participation to the CUORE/CUORE-0 collaboration
- Collaboration with people in LNGS

Precursor ZMO crystals

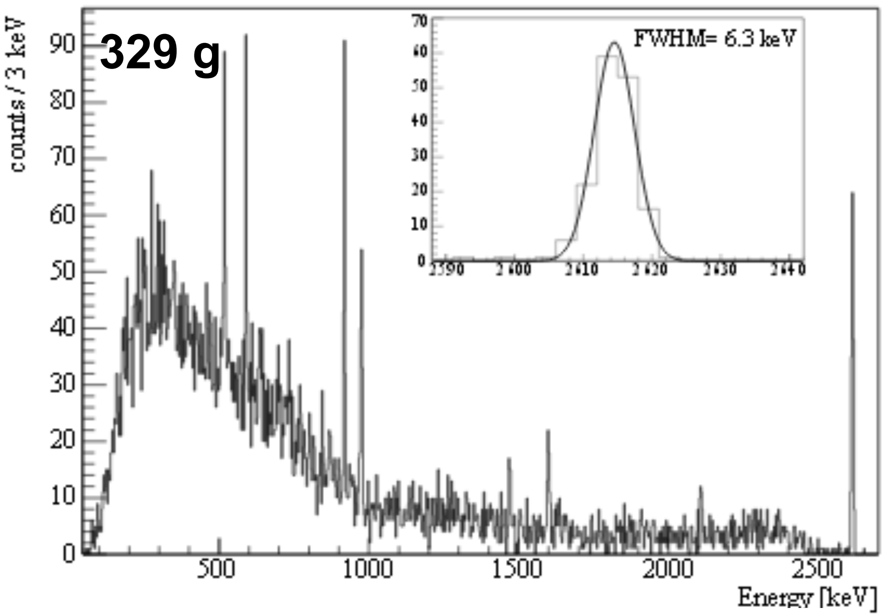




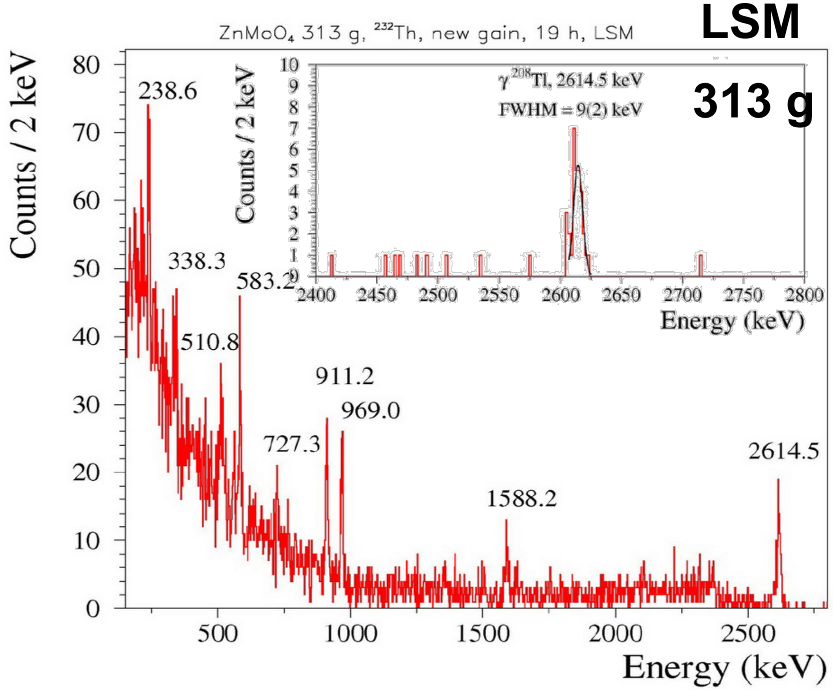
- Irregular shape
- More or less intense orange color (impurities)

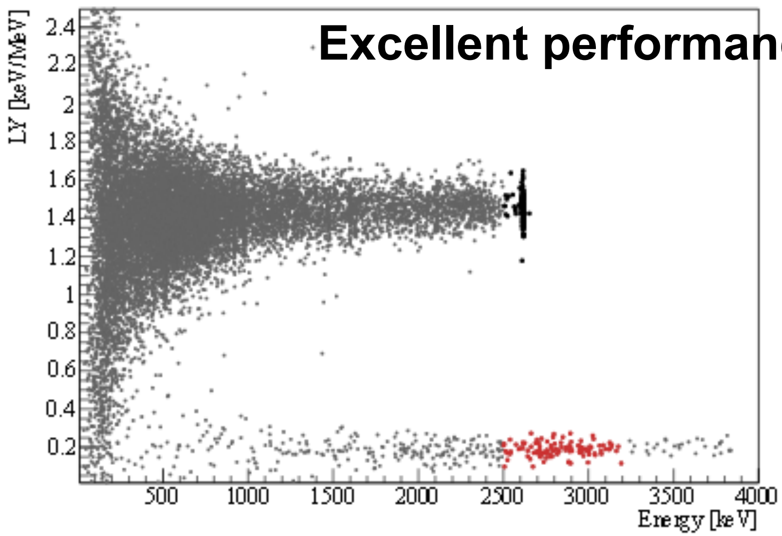
Precursor ZMO crystals - results

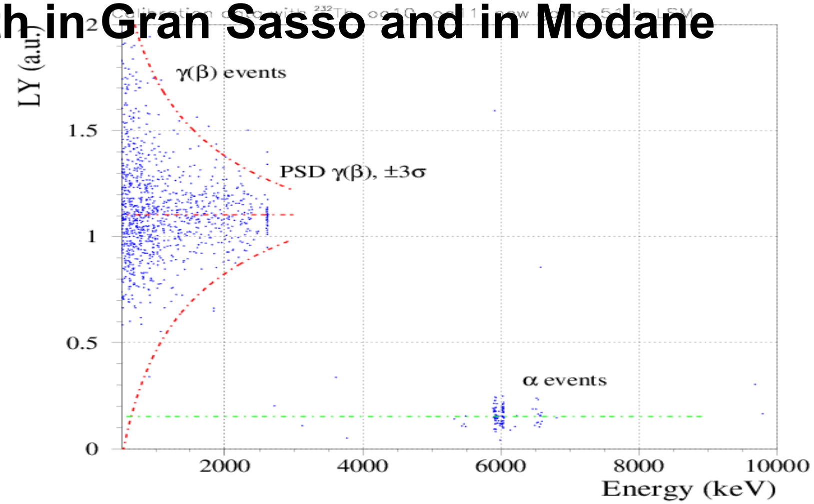
LNGS



LSM







Excellent performance both in Gran Sasso and in Modane

Precursor ZMO crystals - radiopurity

- Internal contamination (acitvities in μBq/kg)
  (determined by internal alphas)

Nuclide	313 g (Modane)	329 g (LNGS)	235 g (LNGS)	247 g (LNGS)
^{228}Th	10(3)	≤ 6	12(4)	11(4)
^{238}U	≤ 8	≤ 6	≤ 8	25(6)
^{226}Ra	26(5)	27(6)	6(3)	63(9)
^{210}Po	620(30)	700(30)	860(34)	860(33)

- Dangerous contaminant: ^{228}Th – must be less than 10 μBq/kg
- Very good as a first attempt, but improvement is necessary

ANR LUMINEU

Luminescent **U**nderground **M**olybdenum **I**nvestigation for **NEU**trino mass and nature

Expérience souterraine avec détecteurs luminescents de molybdate de zinc pour l'étude de la masse et la nature des neutrinos

Set the bases for a **next-generation neutrinoless double-beta** decay experiment

- $ZnMoO_4$ crystal production
- Temperature sensor production and optimization
- Light detector development (both NTD and MMC technology)
- Pilot experiment with enriched material

Funded by **ANR** in France (Agence National de la Recherche)
Collaboration : **CNRS-Orsay**, **CEA-Saclay**, **IAS-Orsay, ICMCB Bordeaux**, **KINR Kiev (Ukraine)**, **NIIC Novosibirsk (Russia), KIP Heidelberg (Germany)**.
In total, ~ 40 participants.
Start: October 1st, 2012 – duration: 4 years

LUMINEU procedure for crystal production

JINST

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REVISED: *April 1, 2014*
ACCEPTED: *April 14, 2014*
PUBLISHED: *June 4, 2014*

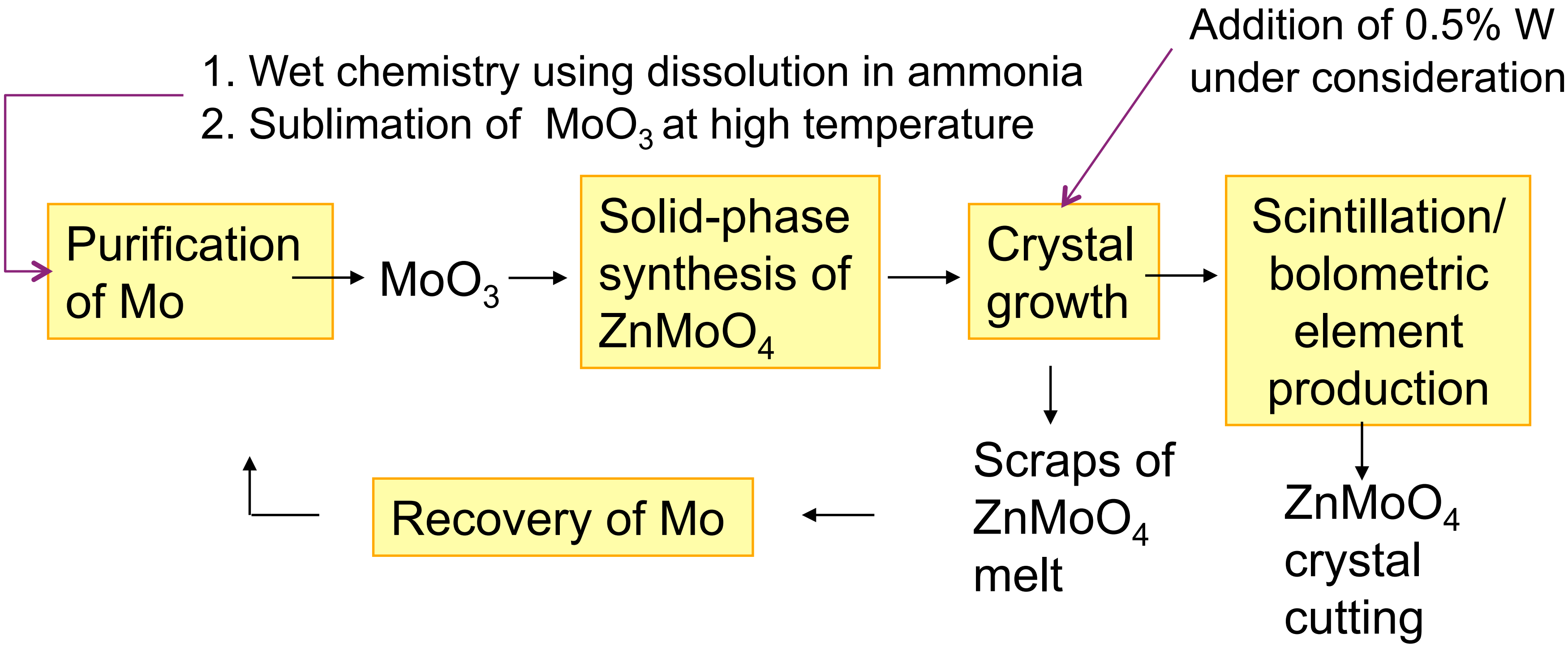
Purification of molybdenum, growth and characterization of medium volume $ZnMoO_4$ crystals for the LUMINEU program

- Molybdenum was purified by using double recrystallization of ammonium molybdate in aqueous solutions

- Advanced $ZnMoO_4$ crystals were produced in NIIC by using low-thermal-gradient Czochralski method

  - **low-thermal-gradient Czochralski technique**
  - **platinum crucibles ø40 and ø80mm**
  - **temperature gradient below 1 K/cm**
  - **rotational speed in the range of 5–20 rotations per minute**
  - **crystallization rate of 0.8–1.2 mm/hour**

Very good collaboration with NIIC, Novosibirsk

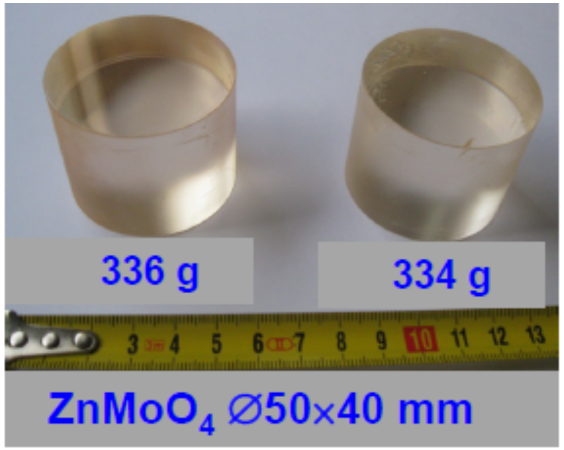


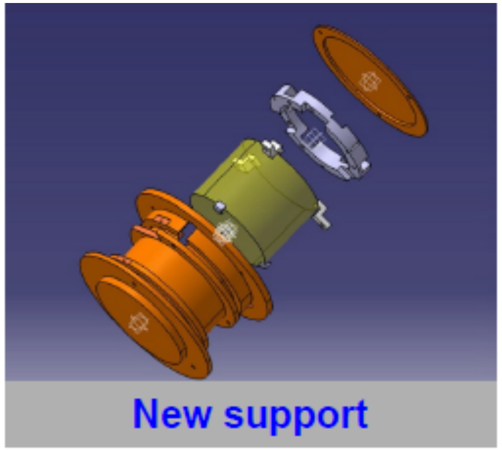
Two set-ups are ready with crucibles:

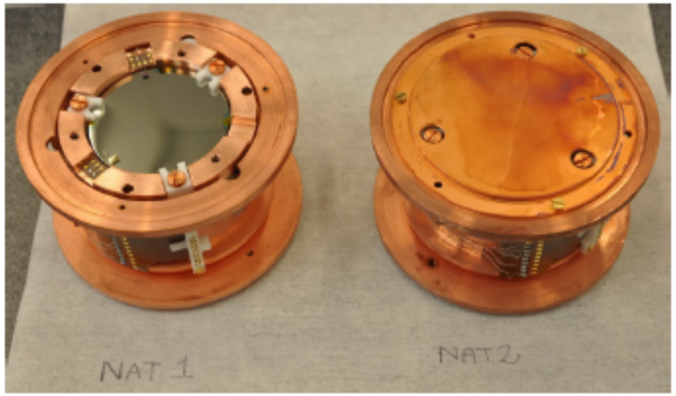
1) ∅40 mm → $ZnMoO_4$ ∅25 mm

2) ∅80 mm → $ZnMoO_4$ ∅60 mm

LUMINEU large natural crystals







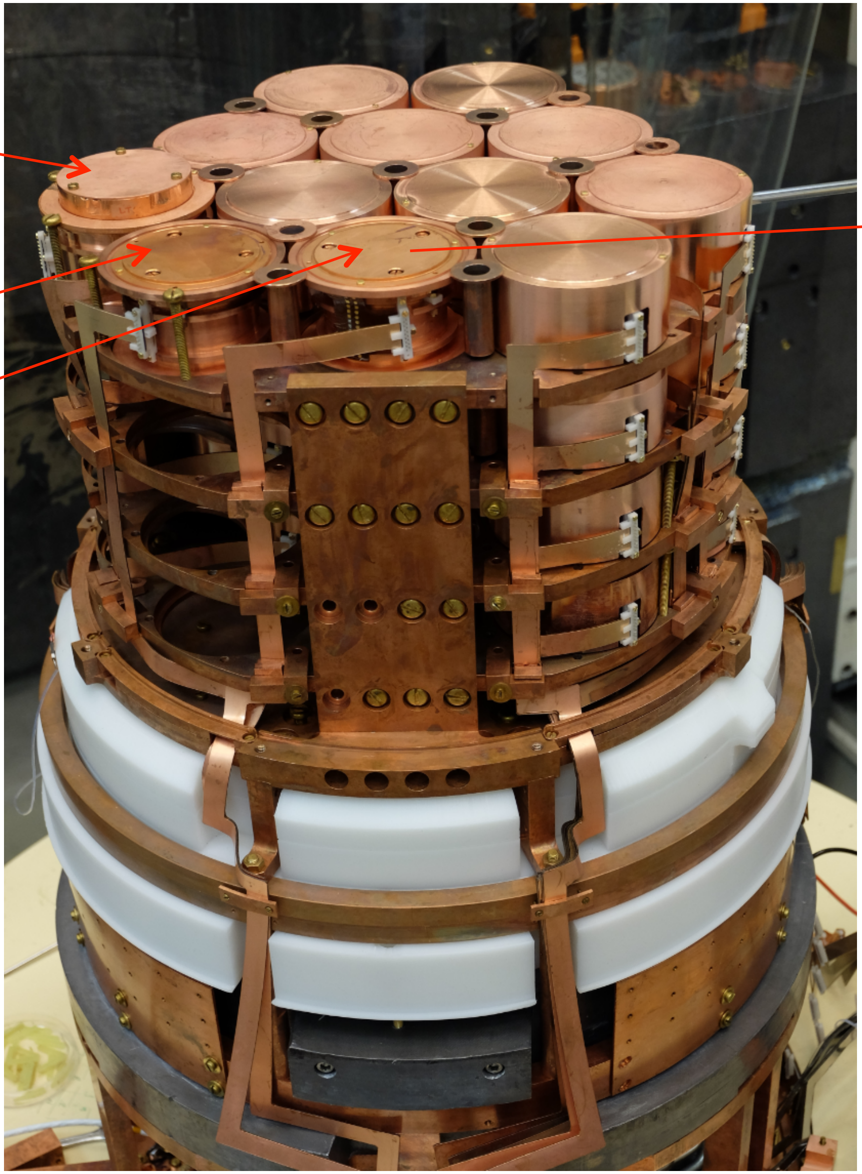
- Different successful tests above ground on medium scale crystals (100-200 g)
- Development of two large regular crystals
- Assembly of these crystals for test in Modane

LUMINEU crystals in the EDELWEISS cryostat

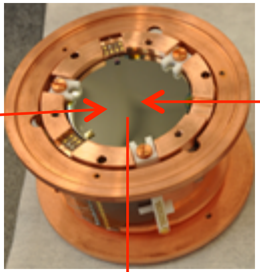
Enriched ZMO 1 & 2

Natural ZMO 1

Natural ZMO 2

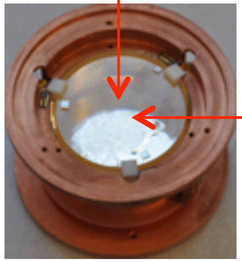


Removing the Cu cover….



Light detector

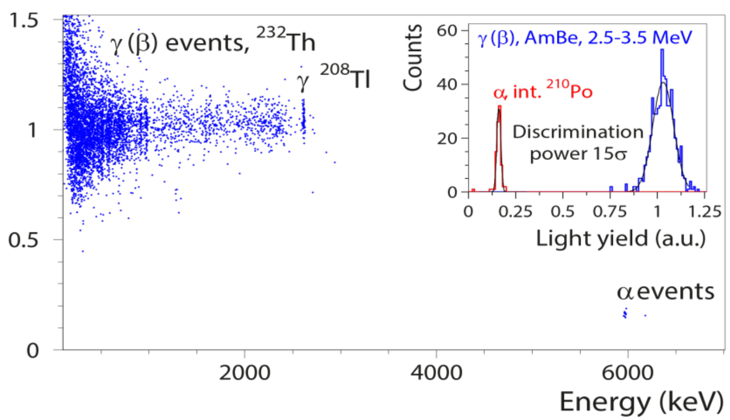
…removing the light detector

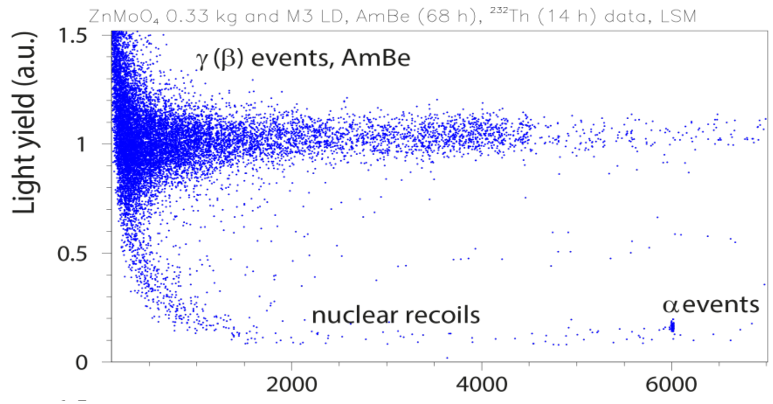


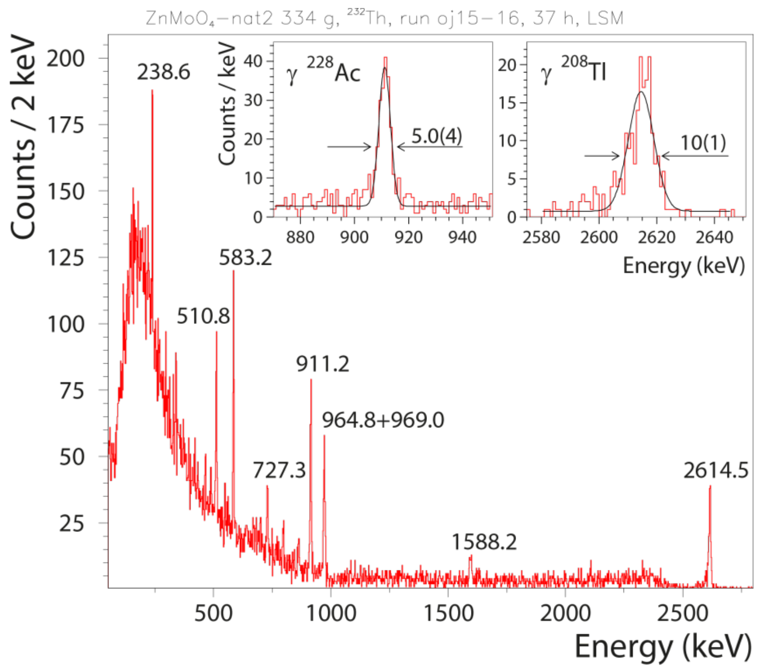
ZMO crystal

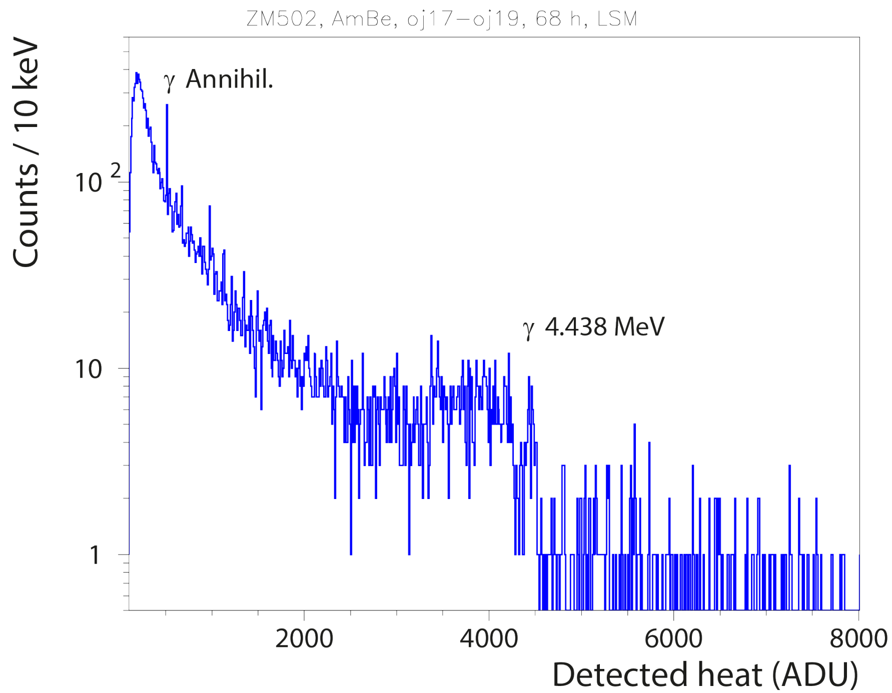
MoU already signed between the LUMINEU and EDELWEISS collaborations

LUMINEU large natural crystals: performance



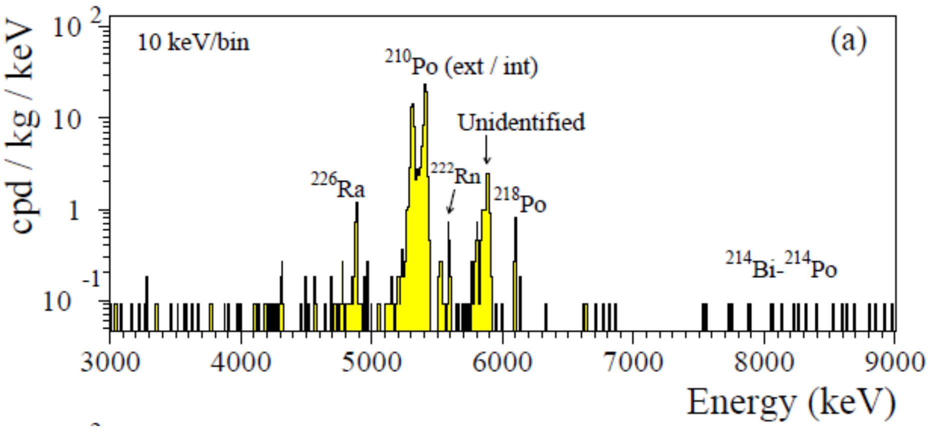




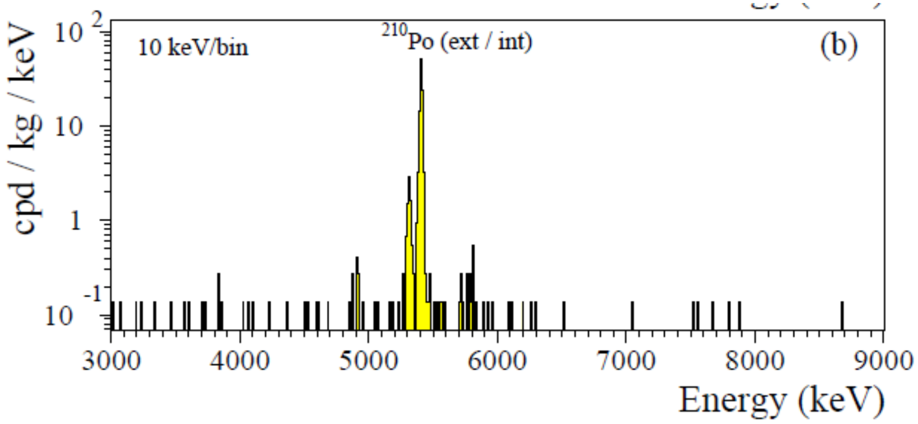


LUMINEU large natural crystals: radiopurity

Precoursor $ZnMoO_4$ 313 g



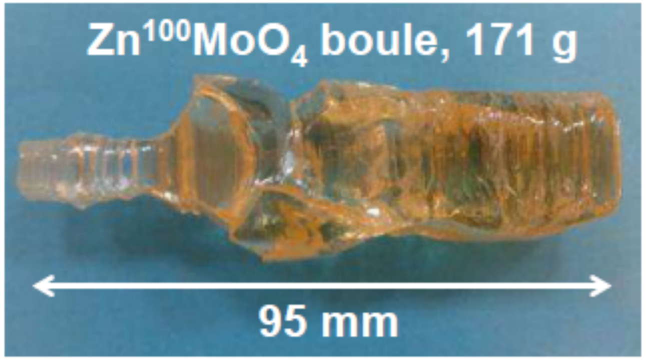
$ZnMoO_4$ 334 g

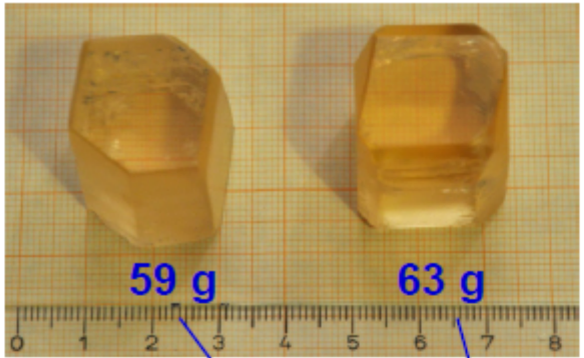


^{228}Th and ^{226}Ra contamination have been strongly reduced and are below the detection limit up to now

Nuclide	Activity (mBq/kg)			
	$ZnMoO_4$			
	336 g	334 g	313 g	329 g [11]
	291 h	527 h	851 h	524 h
^{228}Th	≤ 0.024	≤ 0.007	0.010(3)	≤ 0.006
^{238}U	≤ 0.008	≤ 0.002	≤ 0.008	≤ 0.006
^{226}Ra	≤ 0.021	≤ 0.009	0.26(5)	0.27(6)
^{210}Po	0.94(5)	1.02(7)	0.62(3)	0.70(3)

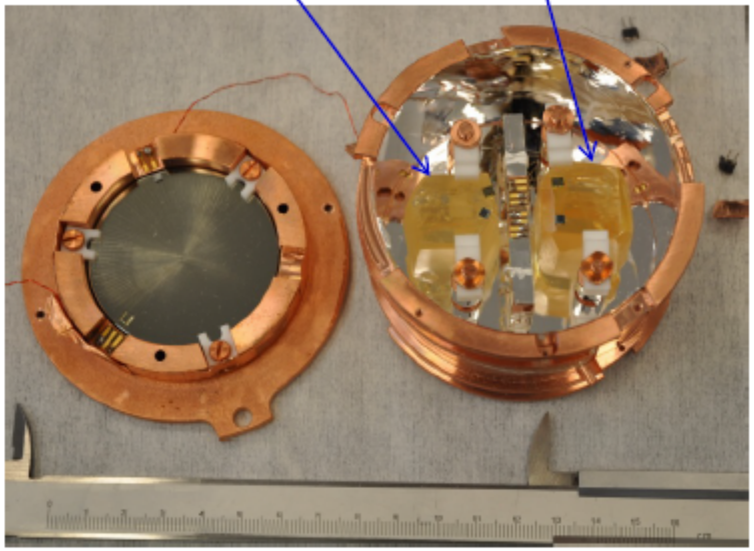
LUMINEU enriched crystals





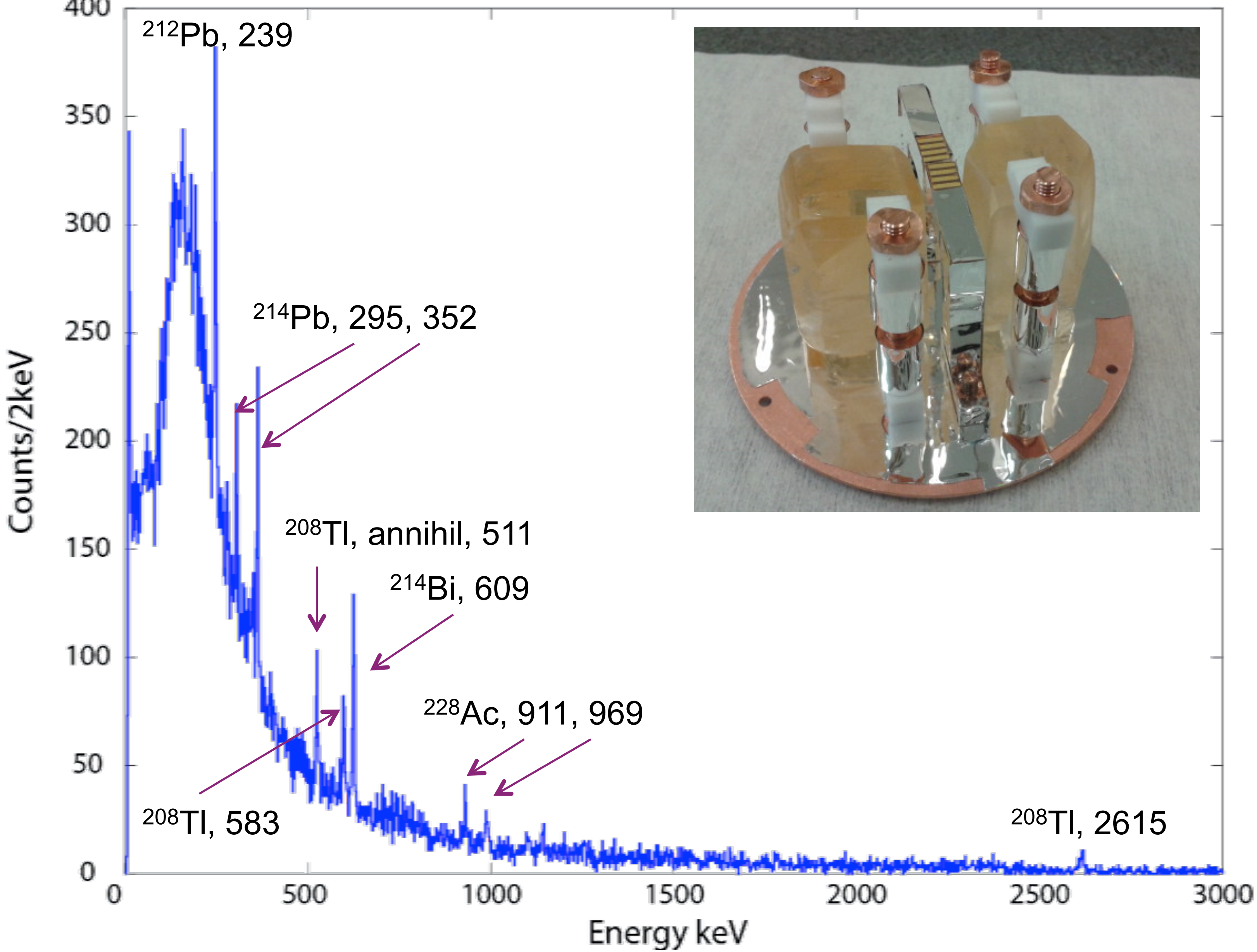
First $Zn^{100}MoO_4$ crystal is developed from enriched molybdenum

- $^{100}MoO_3$ (99.5% enrichment in ^{100}Mo) was purified by using sublimation in vacuum and recrystallization from solutions
- $Zn^{100}MoO_4$ boule was grown at NIIC by using low-thermal-gradient Czochralski process (84% of initial charge)
- Total irrecoverable losses of ^{100}Mo is ~4%
- Two samples (D24×30 mm) were produced
- $Zn^{100}MoO_4$ scintillating bolometers array was successfully tested

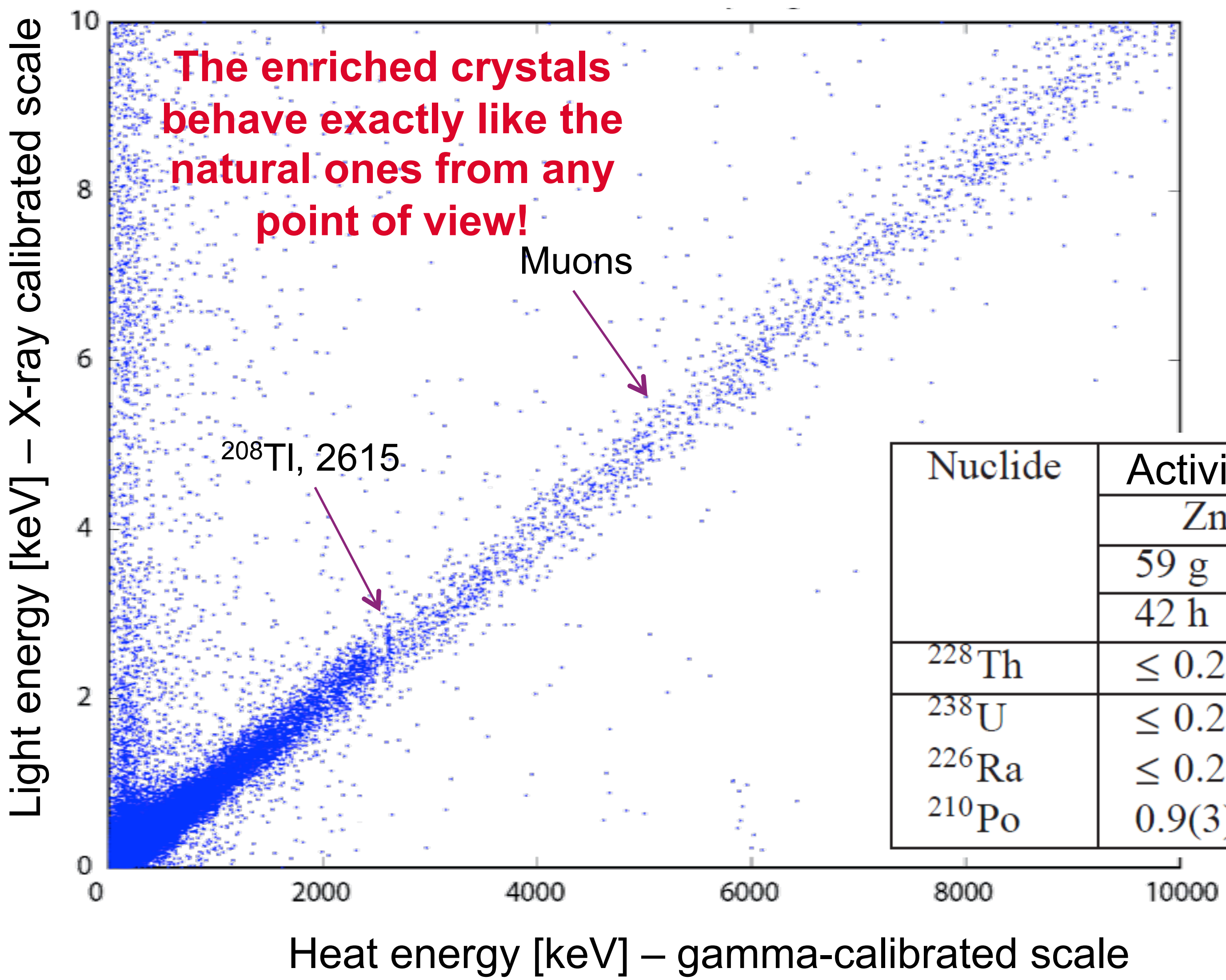


A.S. Barabash et al., arXiv:1405.6937.
Eur. Phys. J. C 74 (2014) 3133.

Aboveground test (CSNSM) of enriched crystals
Energy spectrum



Aboveground test (CSNSM) of enriched crystals
Scatter plot



Preliminary

Nuclide	Activity [mBq/kg]	
	$Zn^{100}MoO_4$	
	59 g	63 g
	42 h	42 h
^{228}Th	≤ 0.25	≤ 0.21
^{238}U	≤ 0.26	≤ 0.21
^{226}Ra	≤ 0.26	≤ 0.31
^{210}Po	0.9(3)	1.1(3)

LUMINEU STATUS

DONE

Large regular ZMO crystals
Produced in Novosibirsk and tested in Modane
OK

Test on enriched ZMO crystals
Produced in Novosibirsk and tested in CSNSM
OK
Test in Modane: microphonics noise problem

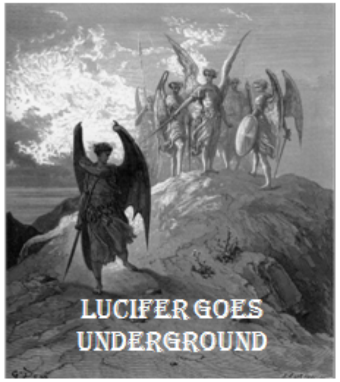
« Standard » NTD-based light detectors
They work satisfactorily at CSNSM and LNGS, microphonic problems in Modane

TO DO

Within the end of the year: **1 kg enriched crystals in four large size ZMO crystals** – to be tested in first half 2015 (completion of the LUMINEU program)
~1 % W doping under consideration
5 y sensitivity: 150-450 meV

POST-LUMINEU: THE LUCINEU PROPOSAL

LUCIFER
Low-background **U**nderground **C**ryogenics **I**nstallation **F**or **E**lusive **R**ates



&

LUMINEU
Luminescent **U**nderground **M**olybdenum **I**nvestigation for **NEU**trino mass and nature

LUMINEU

LUCINEU

LUCINEU STRUCTURE AND CALENDAR

- **10 kg enriched material belonging to ITEP are available (NEMO-3)**
MoU IN2P3-INFN-ITEP

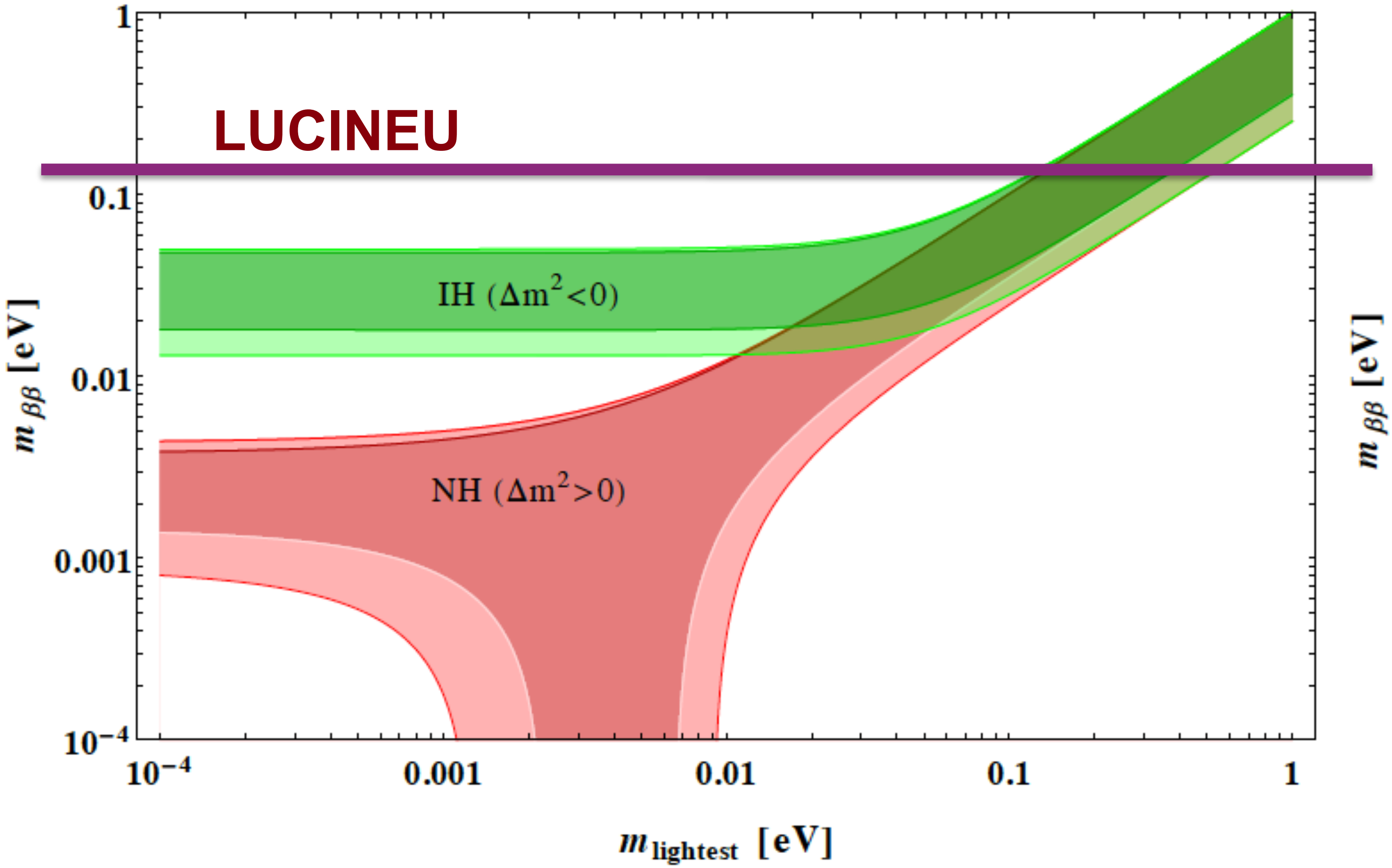
- If OK with the large enriched crystals, massive production of
40 enriched ZMO crystals (400 g each) containing ~ **7 kg enriched material**

- **Experiment** in LNGS or Modane in 2016

- 5 y sensitivity: 50-150 meV
The same as the best experiments under commissioning, e.g. CUORE

Option	Number of ≈ 400 g crystals	Total isotope mass [kg]	Half-life sensitivity [10^{25} y]	$M_{\beta\beta}$ sensitivity [meV]
(1) – LUMINEU	4	0.676	0.53	167 – 476
(2) – LUCINEU	40	6.76	4.95	55 – 156
(3)	2000	338	92.5	13 – 36

LUCINEU SENSITIVITY



LUCINEU TIME-SCHEDULE

Possible time-schedule

- Crystal production (40x400g $Zn^{100}MoO_4$) - second part of 2015
- Production of detector holders and light detectors - second part of 2015
- Detector assembly – first part of 2016
- Development and realization of electronics and DAQ system - mid-2015 to mid 2016
- the LUCINEU array will be cooled down in LNGS or LSM according to the cryostat availability – mid-2016
- LUCINEU data taking - by the end of 2016

REQUESTS ON HUMAN RESOURCES AT SPP

Now: $0\nu\beta\beta$ decay activity at SPP ⟶ **only one person (CN)**.

Future: a group of **2-4 people** working on this subject (**2 permanents and 2 post doc/students**).

Main items to cover with SPP staff:

Data Analysis: the present human resources are insufficient for a multi-channel setup as LUCINEU. In addition, in the present $ZnMoO_4$ prototypes there are clear indications that α/β rejection can be performed using the heat channel only, exploiting a slight pulse-shape difference in the two types of events → sophisticated analysis tools are required which at the moment are beyond the reach of the collaboration.

Simulations: lack of expertise in Monte Carlo simulations. It will be really important to implement a tool with Geant4 to make simulations for background in order to evaluate future sensitivities and to develop an adequate background model during LUCINEU operation. In addition, simulations on the thermal model for bolometers will be useful for a better comprehension and optimizations of the detectors.

The presence of **PhD students** and **post-docs** would help the start-up of the activity.
An application for a post-doc position has been submitted to P2IO as well as an application for a PhD fellowship to CEA.

REQUESTS ON HUMAN RESOURCES AT IRFU

Implication of technical services
the level of their participation will be partially related to the location of the LUCINEU experiment (LSM or LNGS) and to the possibility to use the EDELWEISS cryostat as an underground facility for R&D.

Possible contributions:

- a **technician** for the development of the **front-end electronics**, (voltage sensitive amplifiers for high-impedance sensors, low noise at low frequencies (DC -- 100 Hz), working at room temperature and DC coupled (80 channels) – SEDI

- a **technician or engineer** to design, develop and validate the **DAQ system** – SEDI

- a **technician or engineer** to design possible improvements of the **shielding system** of the cryostat (Pb & polyethylene) in view of the different energy range at which the DBD events are searched for with respect to dark matter.

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REQUESTS ON HUMAN RESOURCES AT IRFU

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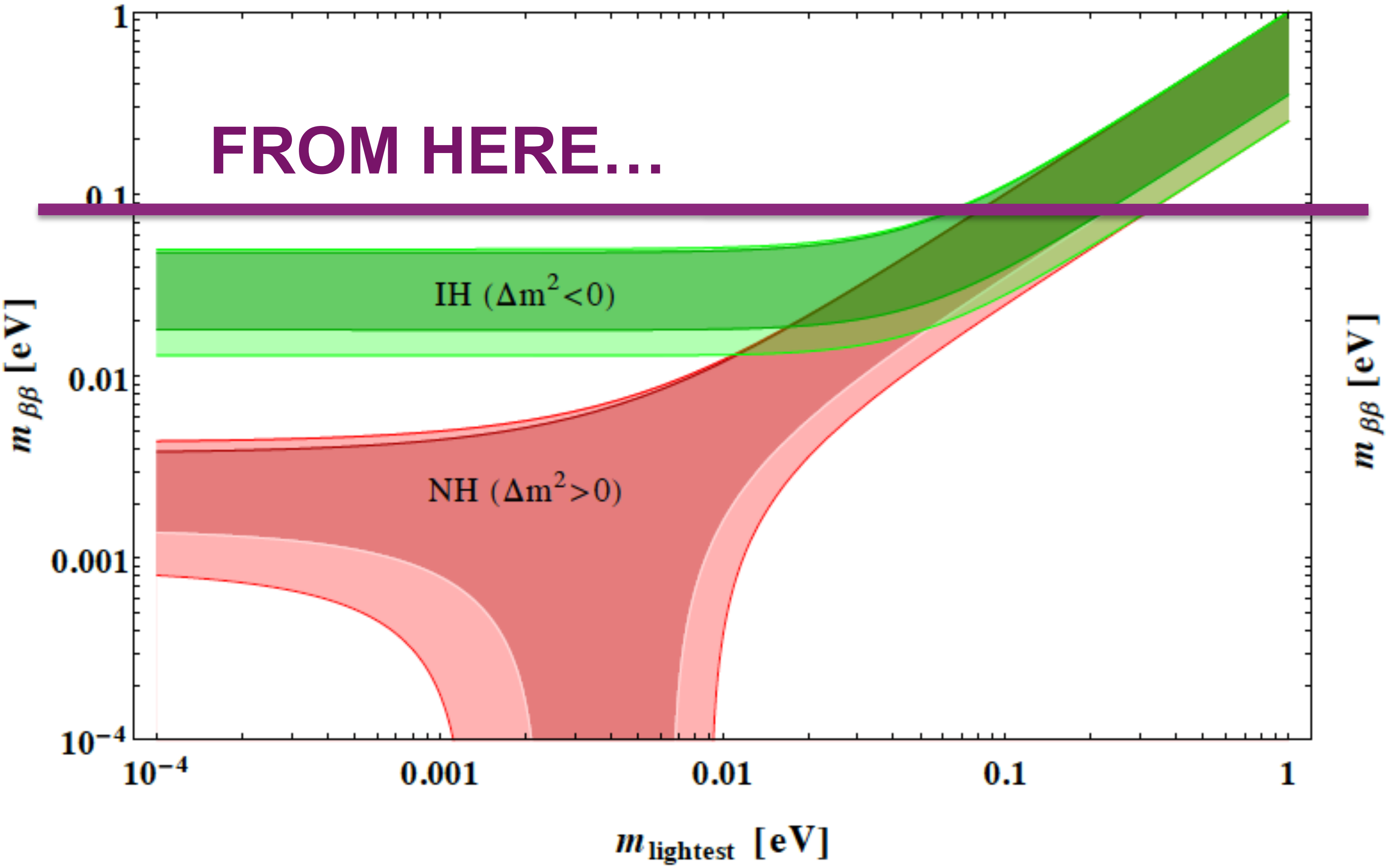
- a **technician** or **engineer** to design **mechanical pieces for bolometer holders**, with particular attention to light detectors, possibly provided with anti-vibration systems – SIS

- a **technician** or **engineer** for the **slow control** of the cryostat and all the other systems – SIS

- a **technician** expert in **cryogenics** and **vacuum technology** for any upgrade of the dilution refrigerators in the underground laboratories and their maintenance – SACM

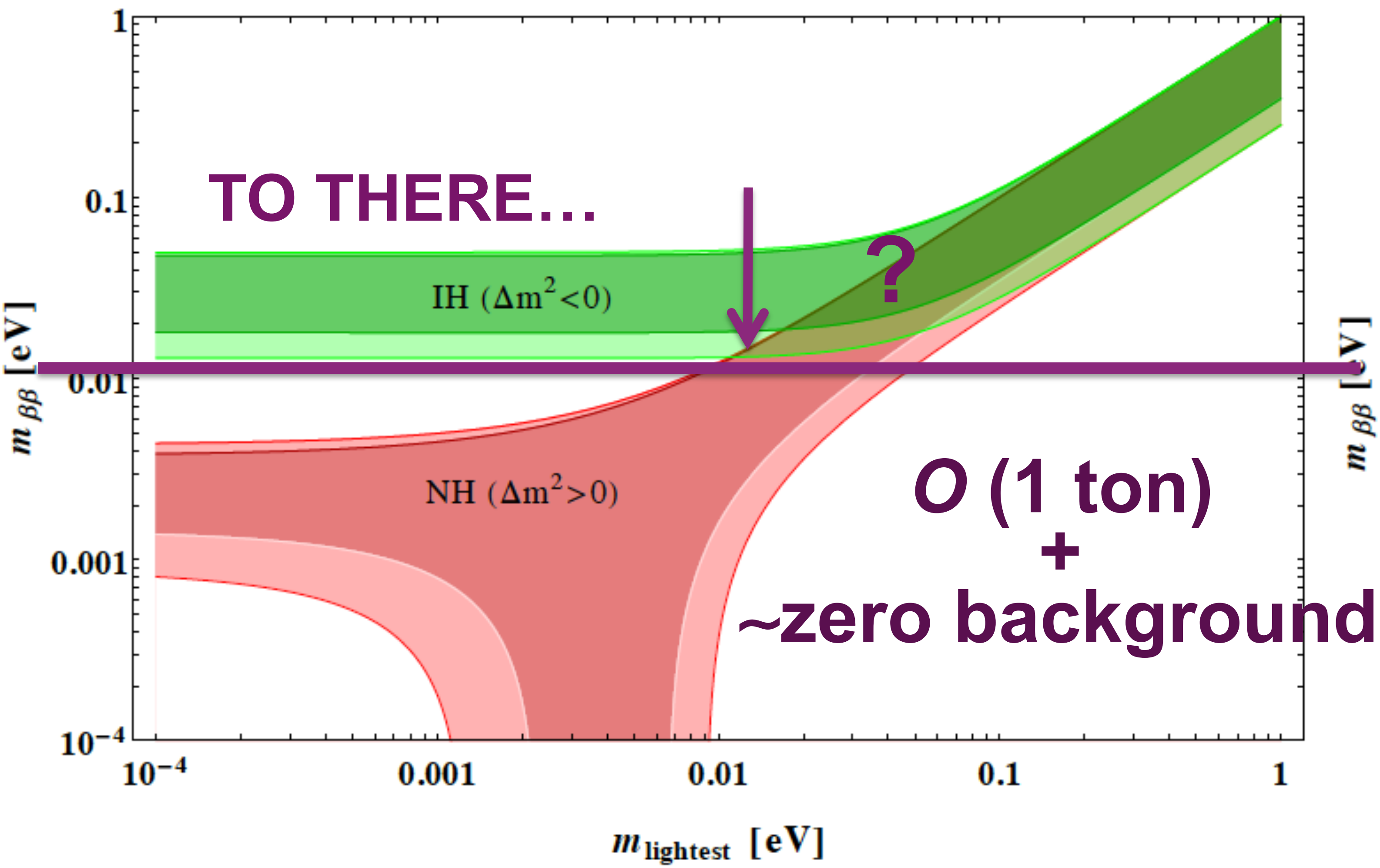
- No needs are foreseen for detector assembly since this task will be performed by CN in collaboration with the cryogenic detector group of CSNSM

WHAT'S NEXT



FROM HERE…
IH ($\Delta m^2<0$)
NH ($\Delta m^2>0$)
$m_{\beta\beta}$ [eV]
$m_{\beta\beta}$ [eV]
$m_{lightest}$ [eV]
1
0.1
0.01
0.001
10^{-4}
10^{-4}
0.001
0.01
0.1
1

WHAT'S NEXT



TO THERE…
?
IH (Δm²<0)
NH (Δm²>0)
O (1 ton)
+
~zero background
1
0.1
0.01
0.001
10⁻⁴
10⁻⁴
0.001
0.01
0.1
1
m_ββ [eV]
m_lightest [eV]

POSSIBLE ROUTES FOR 1-TON EXPERIMENT

❶ Xe way

^{214}Bi line not resolved from 0ν2β signal

- EXO-200 → nEXO (5 ton liquid ^{136}Xe TPC)
- KamLAND-Zen → KamLAND2-Zen (1 ton ^{136}Xe, higher energy resolution, pressurized Xe)

Low energy resolution (250 keV FWHM)
^{110m}Ag background

- NEXT-100 → MAGIX (1 ton high pressure TPC) ← Wait for NEXT-100

❷ Ge way

GERDA+MAJORANA → 1 ton ^{76}Ge

Extreme background demand (10^{-4} counts/keV/kg/y at 2 MeV)
Low Q-value
Enrichment

❸ Bolometer way

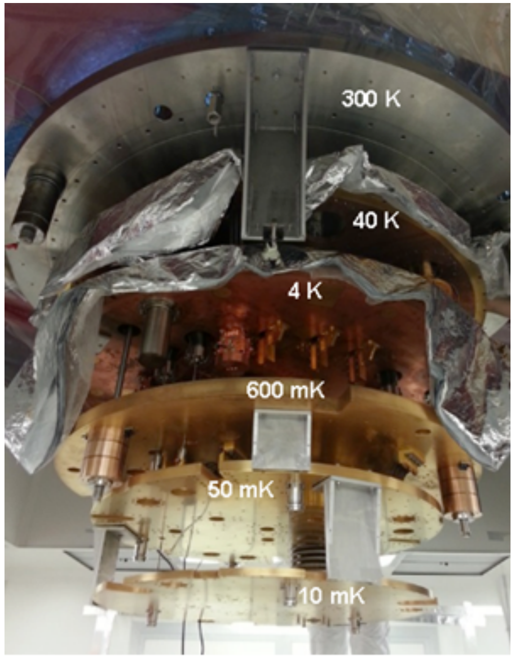
Cryogenics
Crystallization
Enrichment

CUORE → (LUCIFER, LUMINEU, AMoRE) → "CUORE-IHE" (1 ton ^{130}Te or ^{100}Mo or ^{82}Se), AMoRE

Cost → n*100M$, where n is "not large"

NEWS ON THE BOLOMETRIC FRONT

- **CUORE**
  - all 19 towers completed
  - first cryostat test successful (470 kg at 5.9 mK)
  - CUORE-0 shows that background goal of CUORE (b=10^{-2} counts/keV/kg/y) is achievable



Start to plan the follow-up to CUORE

- **CUORE-IHE** group of interest: well beyond CUORE
  34 Institutions: US, Italy, France, Russia, Germany, Ukraine, China, Spain
- Formation of the new collaboration – down-selection of the technology in 2-3 years

THE CUORE-IHE PROCESS

CUORE-IHE

the Cryogenic Underground Observatory for Rare Events as Inverted Hierarchy Explorer

The CUORE-IHE Interest Group

September 8, 2014

1 Introduction

The purpose of this document, drafted by the CUORE-IHE Steering Committee[1], is to define a possible follow-up to the present CUORE [1] experiment, expected to run for about 5 years after the start of data taking, foreseen in 2015. It is natural that the next experiment will be based on the experience, expertise, and lessons learned in CUORE; thus we refer to this future project in the following as CUORE-IHE, [2] alluding to its projected ability to fully explore the inverted hierarchy (IH) region of the neutrino mass pattern [2]. We will first discuss the scientific objective of CUORE-IHE; we will then describe a set of current R&D activities – performed in a more or less close connection to the present CUORE program – which aim to develop technologies capable of achieving the desired science goal; we will finally indicate a time schedule for CUORE-IHE definition, anticipating that the general goal is to select the CUORE-IHE technology by the end of 2016, so that a Conceptual Design Report (CDR) could be produced at that time.

The motivation for a such an analysis is that the CUORE program is in an advanced state with very positive indications in all the activity areas. CUORE-0, the first CUORE tower, shows excellent performance in terms of background and detector resolution [3]; all CUORE towers have been fully built; the CUORE cryostat is under commissioning [1]. We think therefore that the time has come to plan a future use, beyond CUORE, of the existing CUORE facilities with improved detectors aiming at an even higher sensitivity to neutrinoless double beta decay ($0\nu\beta\beta$). In fact, an upgrade of the present technology or a development of a new one requires sufficient head start in order to be ready in time by the end of the present CUORE program.

2 CUORE

CUORE will be one of the most sensitive $0\nu\beta\beta$ experiments of this decade. Using a bolometric array of 988 750 g crystals of natural TeO_2, it will begin to explore the neutrino mass values in the inverted mass hierarchy. CUORE is an established project within the INFN, DOE, and NSF.

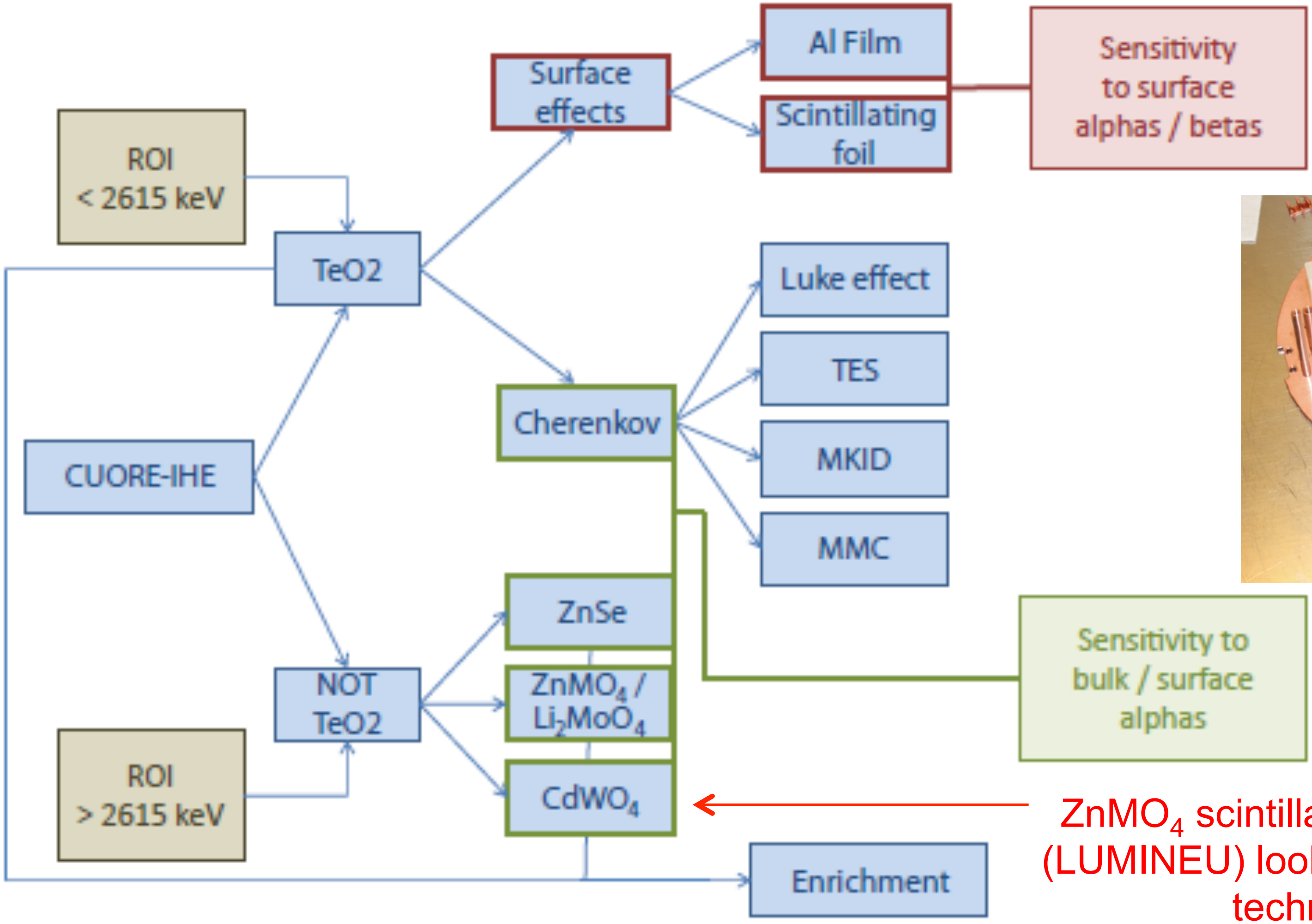
CUORE is in the final phase of construction at the Laboratori Nazionali del Gran Sasso (LNGS) in Assergi, Italy, and is expected to start operations in 2015. The construction of all 19 detector towers is now complete. The cryogenic system has been completely assembled and the commissioning is steadily progressing.

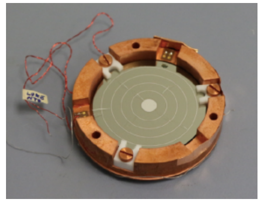
[1] CUORE-IHE steering committee: F.T. Avignone, F. Bellini, C. Bucci, O. Cremonesi, F. Ferroni, A. Giuliani, P. Gorla, K.M. Heeger, Yu.G. Kolomensky, M. Pallavicini, M. Pavan, S. Pirro, M. Vignati

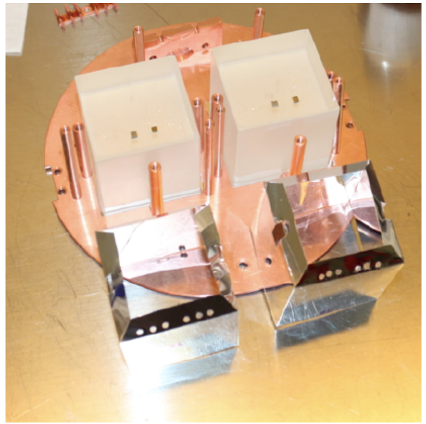
[2] This name is provisional.

- Review of the R&D
- ⇓ Form the interest group
- ⇓ Follow and guide the selection of the final CUORE-IHE technology
- ⇓ Form the new collaboration on the basis of the interest group
- ⇓ Proposal (~2017)

R&D FOR 1-TON BOLOMETRIC EXPERIMENT







$ZnMO_4$ scintillating bolometers (LUMINEU) look a nearly mature technology

BUDGET (1)

Item	Budget [k€]
^{100}Mo (MoU between INFN/ITEP/IN2P3)	0
Purification and crystallization	150
Light detectors	20
Electronics	80
DAQ system	20
Detector holders (material and fabrication)	50
Slow control	20
Cryostat upgrade	50
Total	390
Contingency ($\sim$ 20 %)	80
Grand Total	470

As far as missions are concerned – and limited to IRFU – we estimate about 10 person-weeks at LNGS or LSM for detector assembly and 20 more for measurement maintenance over two years. Their cost depends strongly on the experiment location (Italy, LNGS or France, LSM). In the latter case we estimate 25 k€ in total, to be doubled for the LNGS option.

BUDGET (2)

Beyond LUCINEU:

- **2015: possibility to perform shifts for CUORE-0 data-taking (3 k€)**
- **Aboveground R&D tests in the CUORE-IHE framework in collaboration with CSNSM and IRAMIS/SPEC (10 k€)**
- **2016: participation to CUORE data taking – contribution to be discussed + common funds (3 k€/year/person – 2016/2021)**
- **Missions to be defined**

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