Double Beta Decay and scintillating bolometers

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Outline

- **Introduction to Double Beta Decay**
  - Experimental challenges
  - Factors driving isotope and technology choice

- **A promising technology: scintillating bolometers**
  - LUCIFER
  - LUMINEU
  - AMoRE

Decay modes for Double Beta Decay

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

Processe ② would imply new physics beyond the Standard Model

violation of total lepton number conservation

Why is neutrinoless Double Beta Decay important

- Majorana nature of neutrino (irrespectively of the mechanism)
- See-saw mechanism ⇒ naturalness of small neutrino masses
- Leptogenesis and matter-antimatter asymmetry in the Universe

The mass mechanism

How **0ν-DBD** is connected to **neutrino mixing matrix** and **masses** in case of process induced by light ν exchange (**mass mechanism**)

neutrinoless Double Beta Decay **rate**

Phase space

Nuclear matrix elements

Effective **Majorana mass**

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

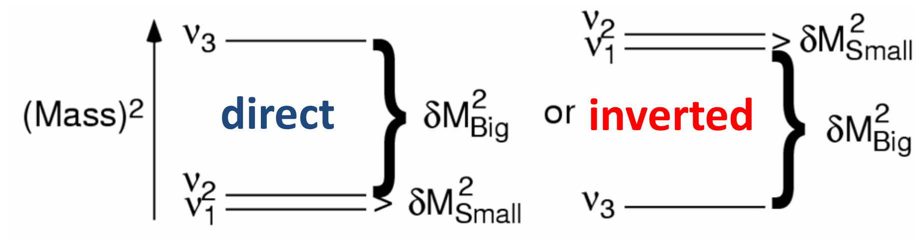
what the experimentalists try to measure

what the nuclear theorists try to calculate

parameter containing the physics: **Effective Majorana mass**

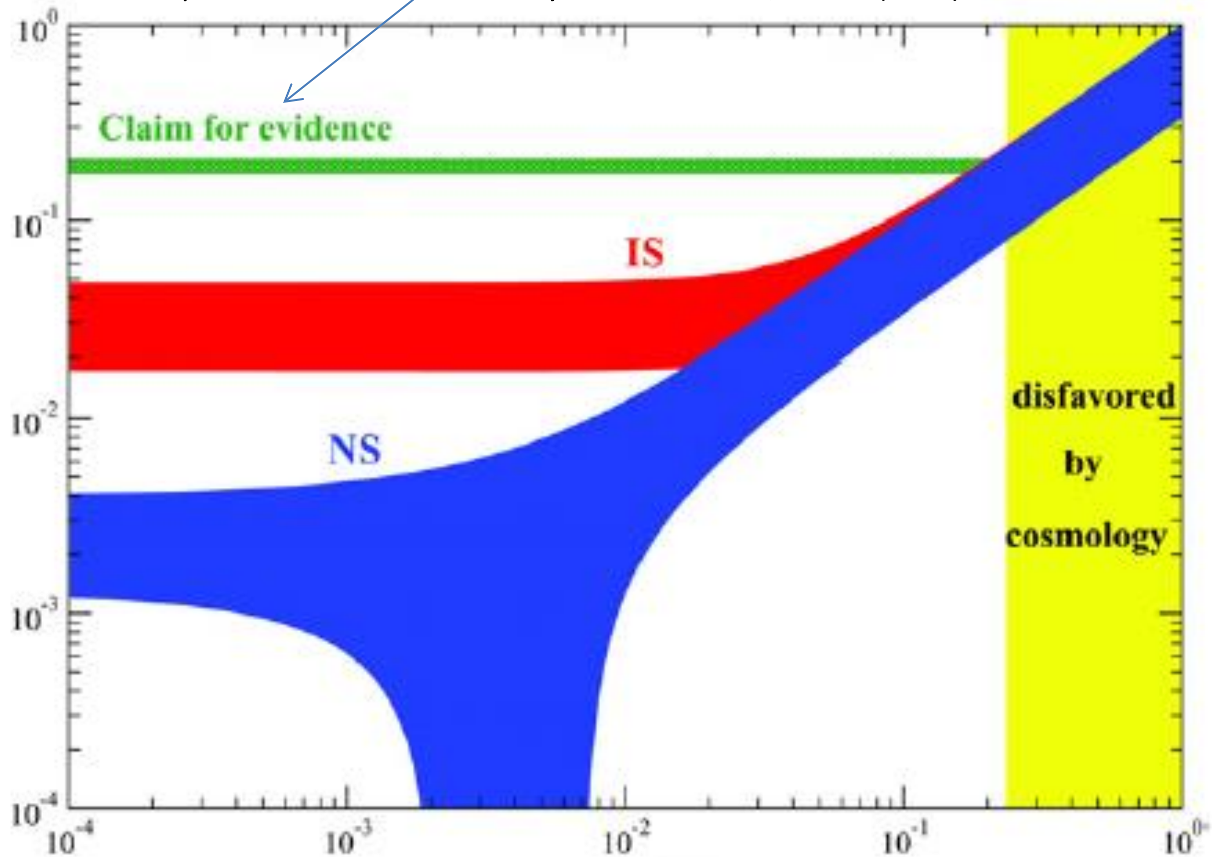
$$\langle \mathbf{M}_{\beta\beta}\rangle = \left|\, |U_{e1}|^2 M_1 + e^{i\alpha_1} |U_{e2}|^2 M_2 + e^{i\alpha_2} |U_{e3}|^2 M_3 \,\right|$$

Neutrino mass hierarchy



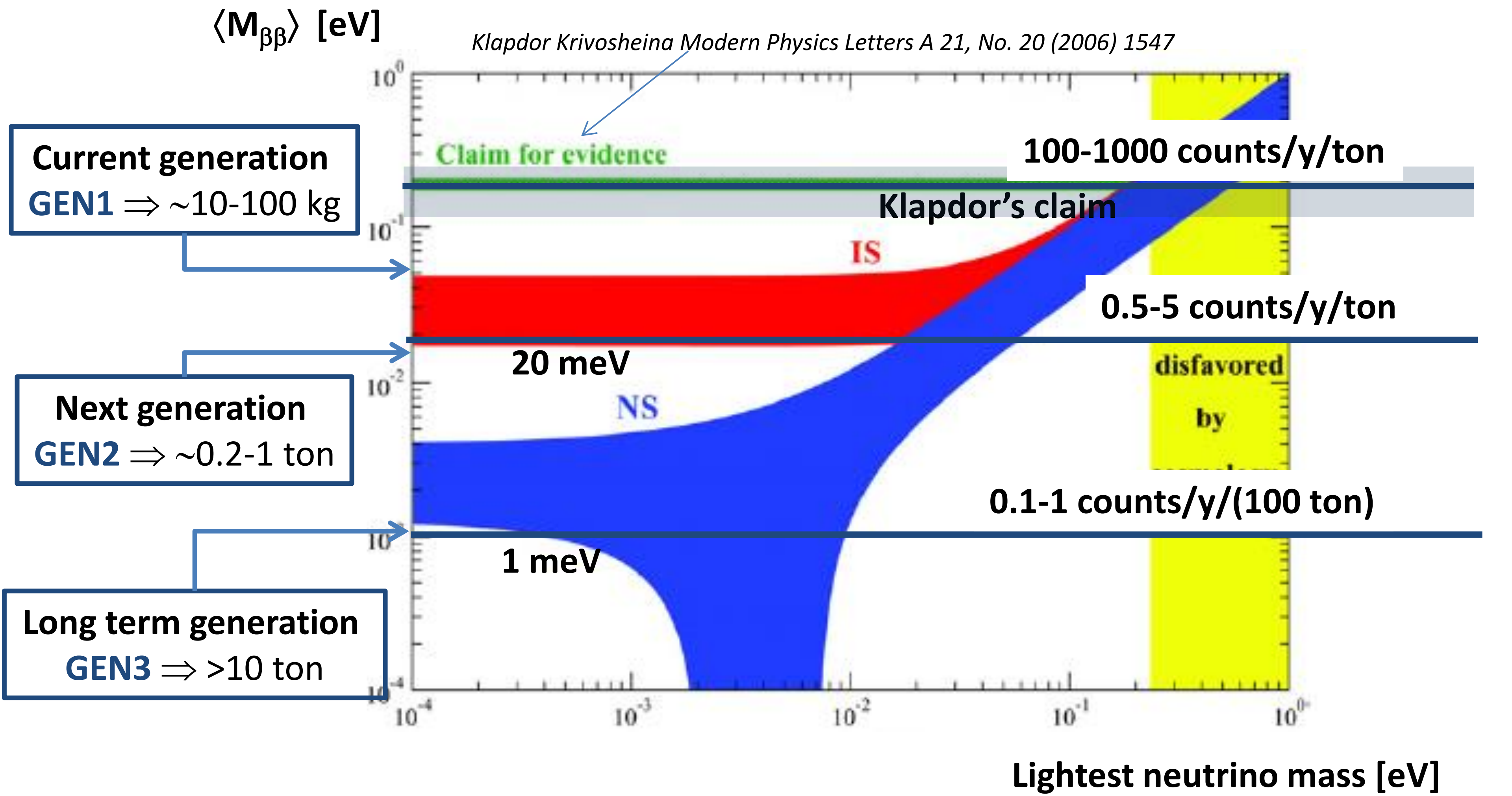
$\langle M_{\beta\beta} \rangle$ [eV]

Klapdor Krivosheina Modern Physics Letters A 21, No. 20 (2006) 1547



Lightest neutrino mass [eV]

Three challenges for 0ν-DBD search



Background demands

Approach the inverted hierarchy region [GEN1]

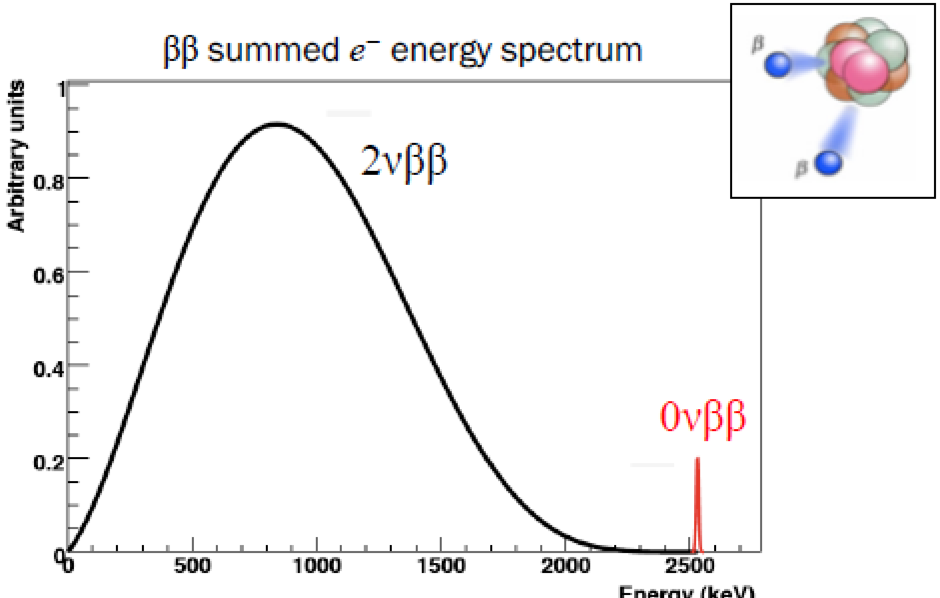
Sensitivity at the level of 1-10 counts / y ton

Cover the inverted hierarchy region [GEN2]

Sensitivity at the level of 0.1 -1 counts / y ton

Order of magnitude of the target bakground in the Region Of Interest: ≤ **1 counts / y ton**

Signal and background sources



^{100}**Mo ⇒ 7.1x10^{18} y**

^{136}**Xe ⇒ 2.2x10^{21} y**

- Natural radioactivity of materials
  (source itself, surrounding structures)
- Neutrons (in particular muon-induced)
- Cosmogenic induced activity (long living)
- 2ν Double Beta Decay

$$\frac{S}{B} = \frac{m_e}{7Q\delta^6}\frac{\Gamma_{0\nu}}{\Gamma_{2\nu}} = \frac{m_e}{7Q\delta^6}\frac{T^{2\nu}_{1/2}}{T^{0\nu}_{1/2}}$$

δ=ΔE/Q

Background index and energy resolution

Take **energy resolution** [keV] → ΔE

Take **background index** [counts/(keV kg y)] → b

Multiply them [counts/(kg y)] → $\Delta E x b$

Multiply by **detector mass, live time** → bkg counts → $\Delta E x b x M x T$

Calculate limit → $N_{lim} \sim (\Delta E x b x M x T)^{½}$

Limit: invert, multiply by number of atoms and live time → $T \; x \; N_{at} / N_{lim}$

Figure of Merit for the technology

Scalability of the technology
Isotopic abundance and enrichment

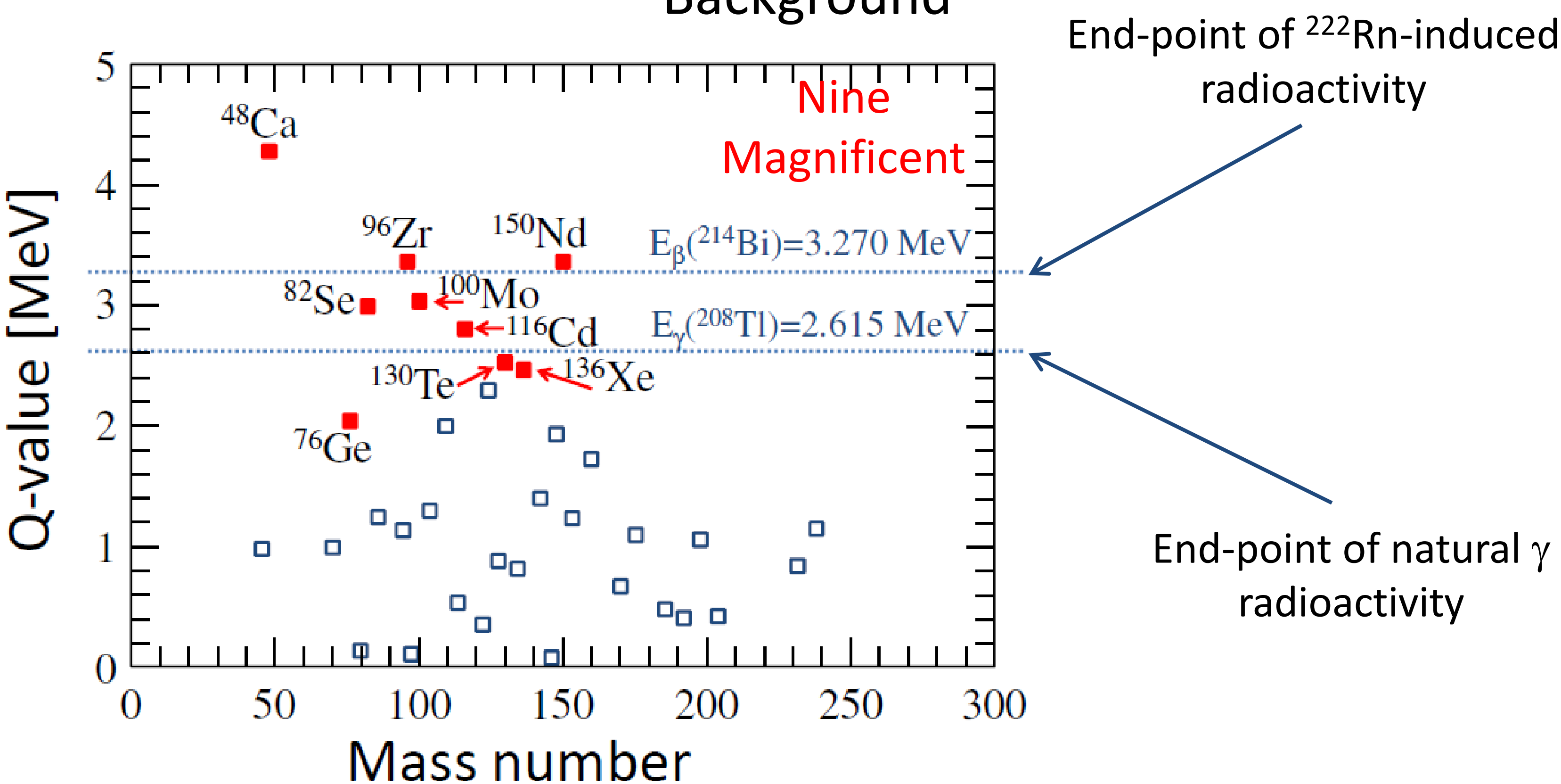
b ~ 10^{-1} in « classical » source=detector experiments
b ~ 10^{-2} - 10^{-3} in current source=detector and in classical external-source experiments
b ~ 10^{-4} in future experiments (minimum request to cover inverted hierarchy)

Factors guiding isotope selection

No super-isotope in terms of **nuclear matrix elements**

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

→ Background



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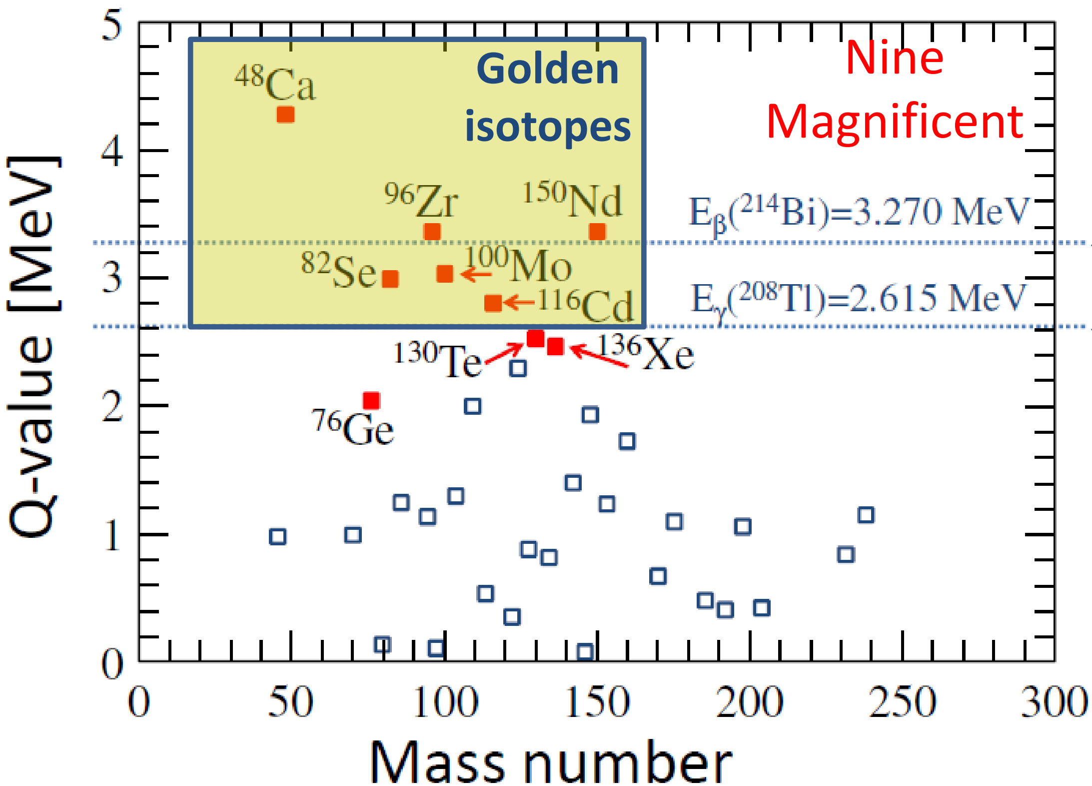
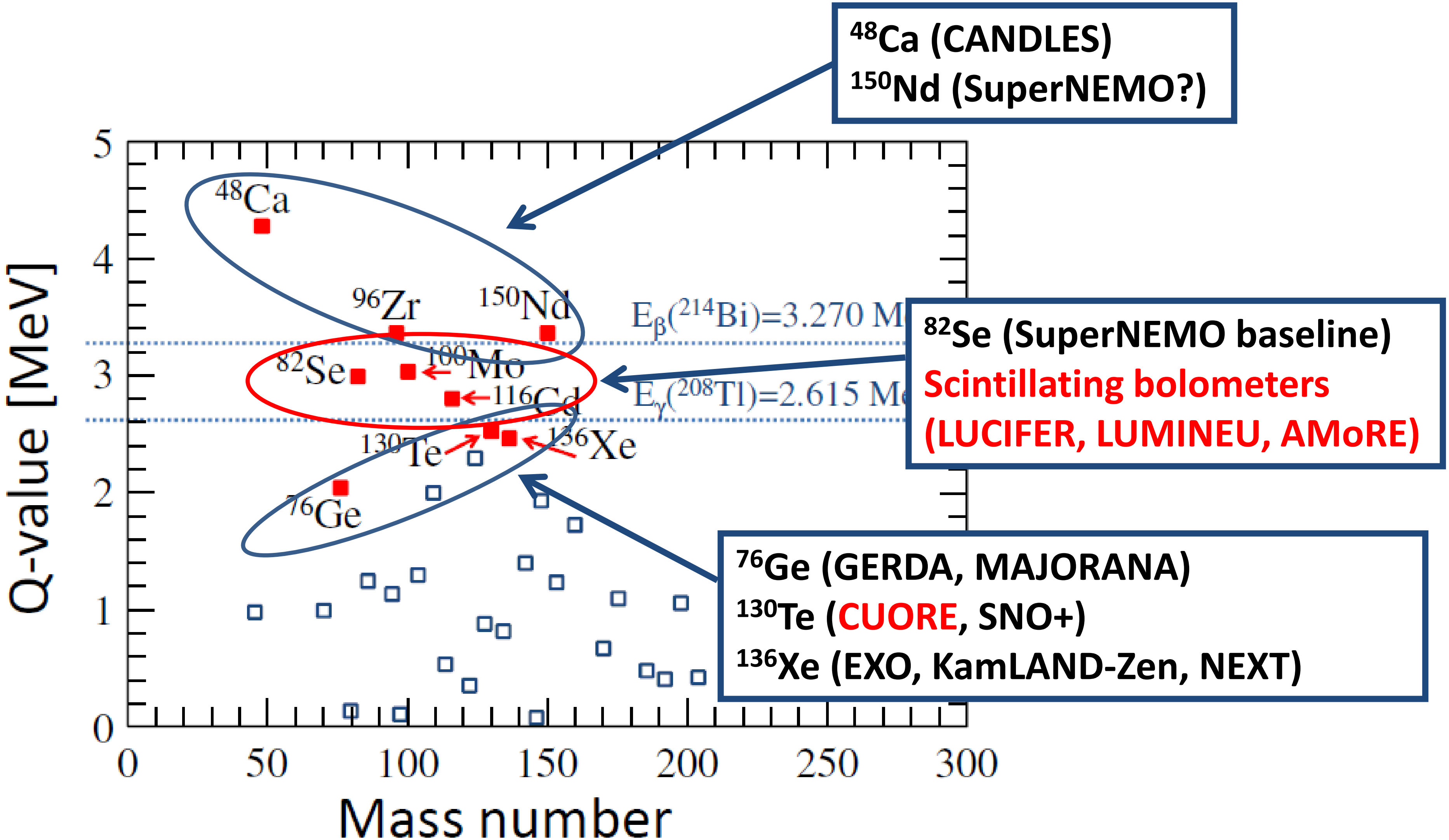


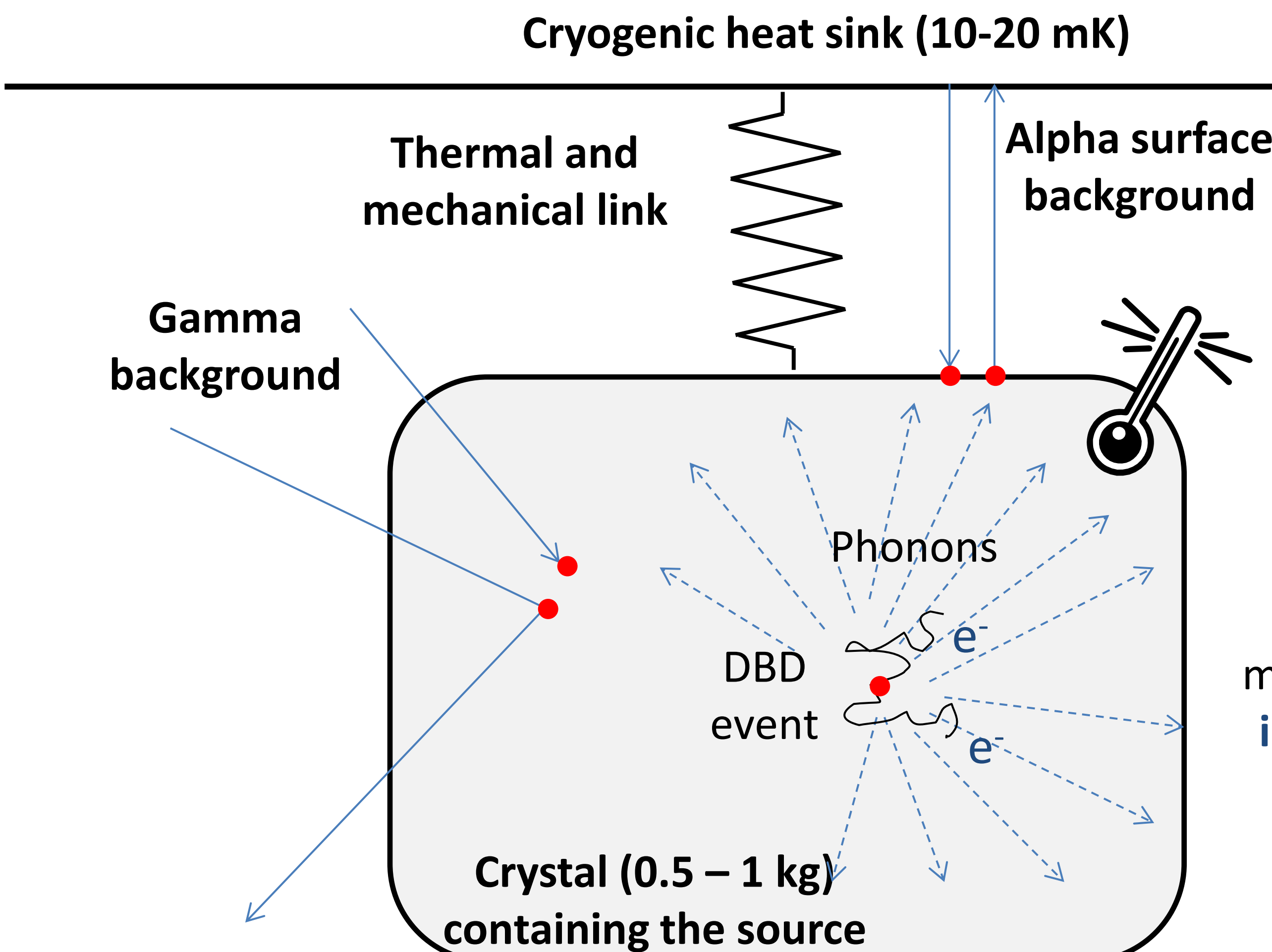
End-point of ^{222}Rn-induced radioactivity

End-point of natural γ radioactivity

Isotope, enrichment and technique



Basic structure of a bolometer



Thermometer
Phonon signal
- **NTD Ge thermistors**
- Transition Edge Sensor
- MMC magnetic sensor

The nuclear **energy** is measured as a **temperature increase** of a single crystal

$$\Delta T = E/C$$

Thanks to the thermistor $\Delta T \Rightarrow \Delta V$

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

CUORE

Technique/location: natural **988 TeO_2 bolometers** at 10-15 mK– LNGS (Italy)

A.I. (^{130}Te) = 34% (all the other isotopes have <10%) - evolution of **Cuoricino**

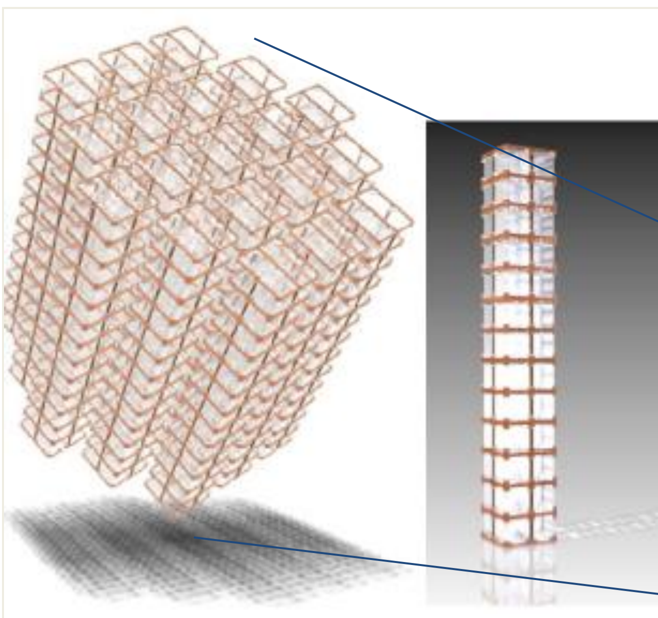
Source: TeO_2 – 741 kg with natural tellurium (**206 kg of ^{130}Te**) - **9.5×10^{26} nuclides of ^{130}Te**

Sensitivity (90% cl): **40 – 100 meV** (5 years) – approach/touch inverted hierarchy region **(GEN1)**

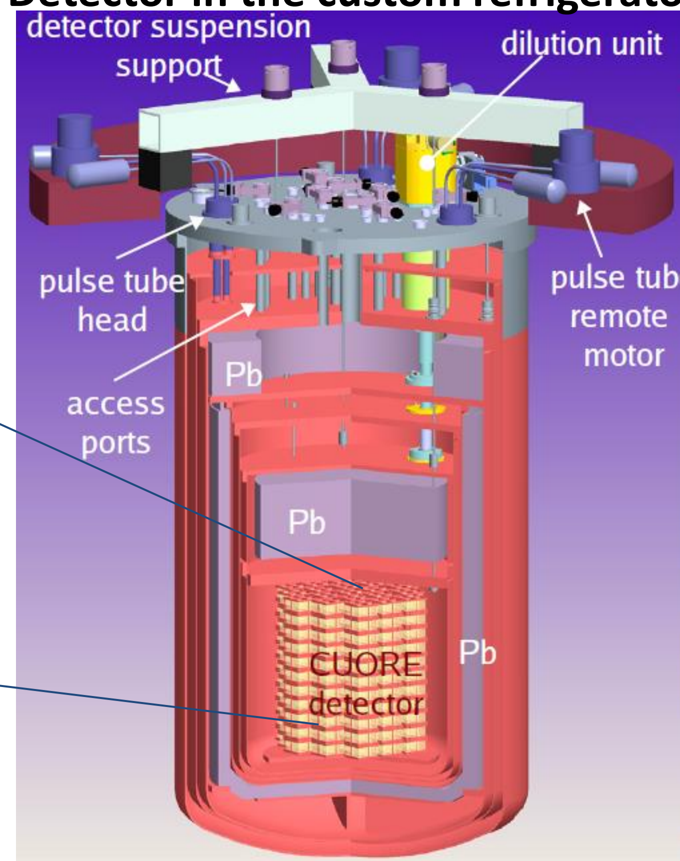
Timeline: first CUORE tower in 2013 (**CUORE-0**) – **taking data**

Data taking with full apparatus in 2015 – **18 towers over 19 completed** – **cryostat proceeds well**

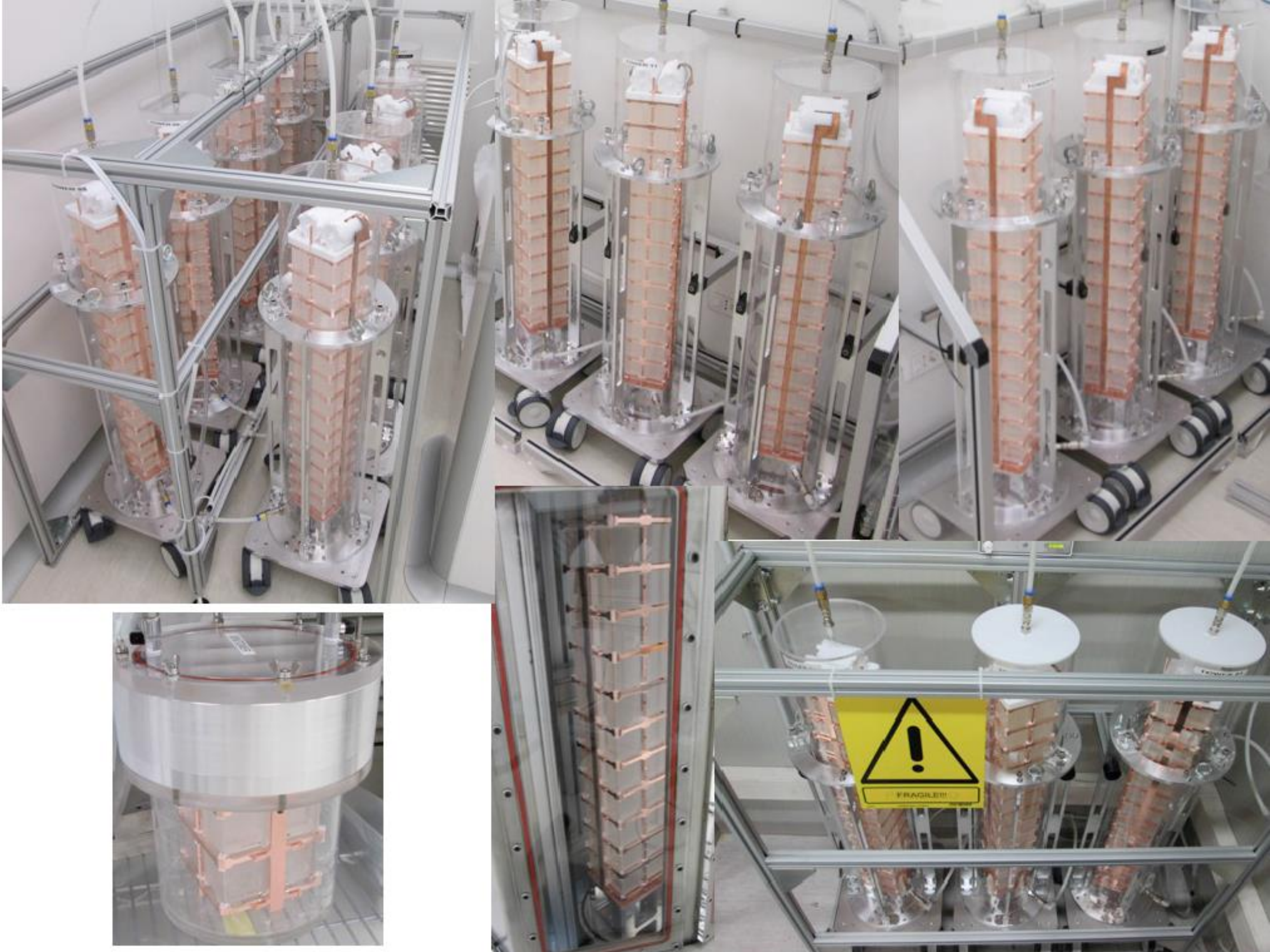
Structure of the detector



Detector in the custom refrigerator



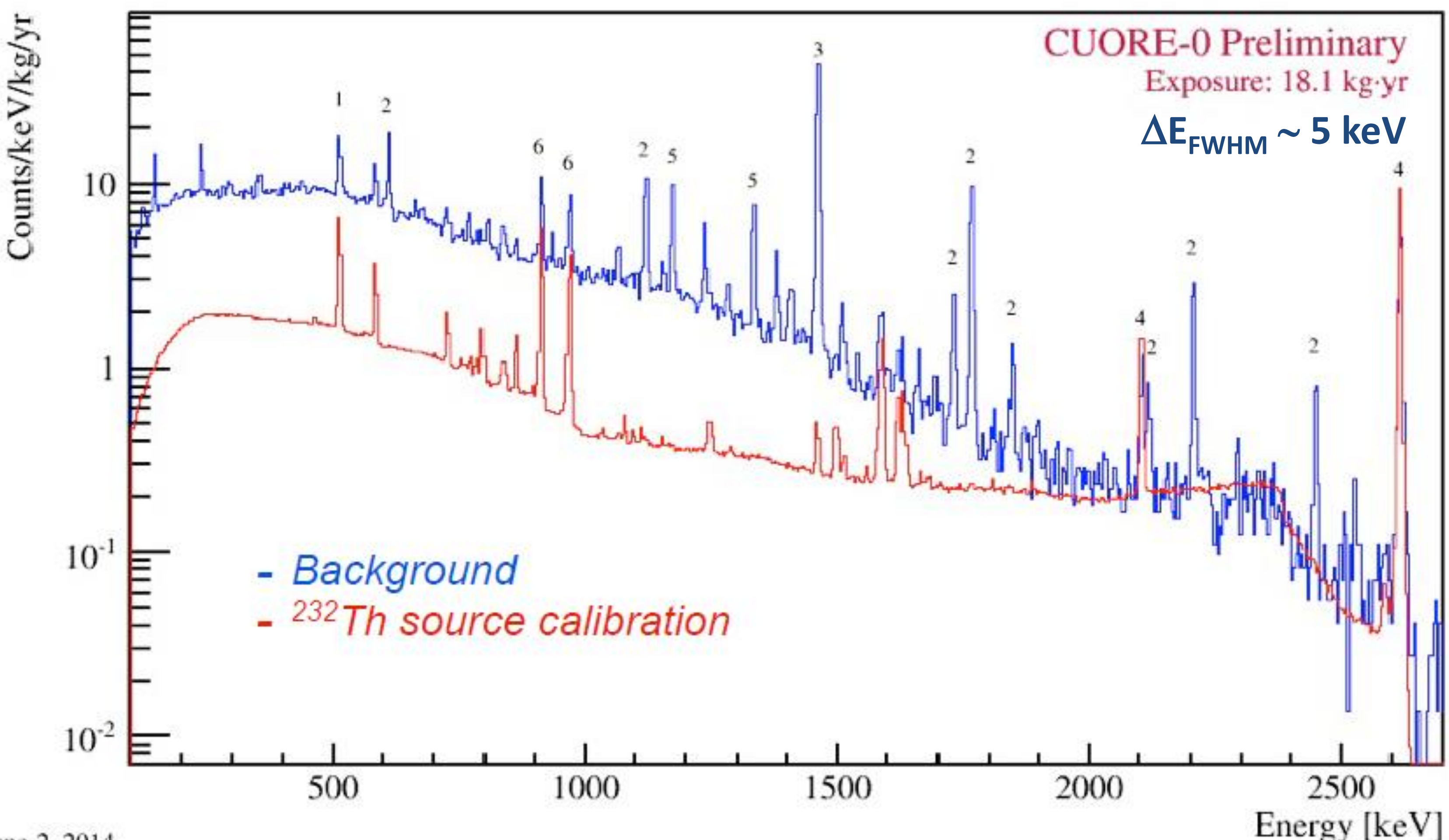
Expected background index: **b ~ 10^{-2}**


FRAGILE!!!

CUORE-0 - performance

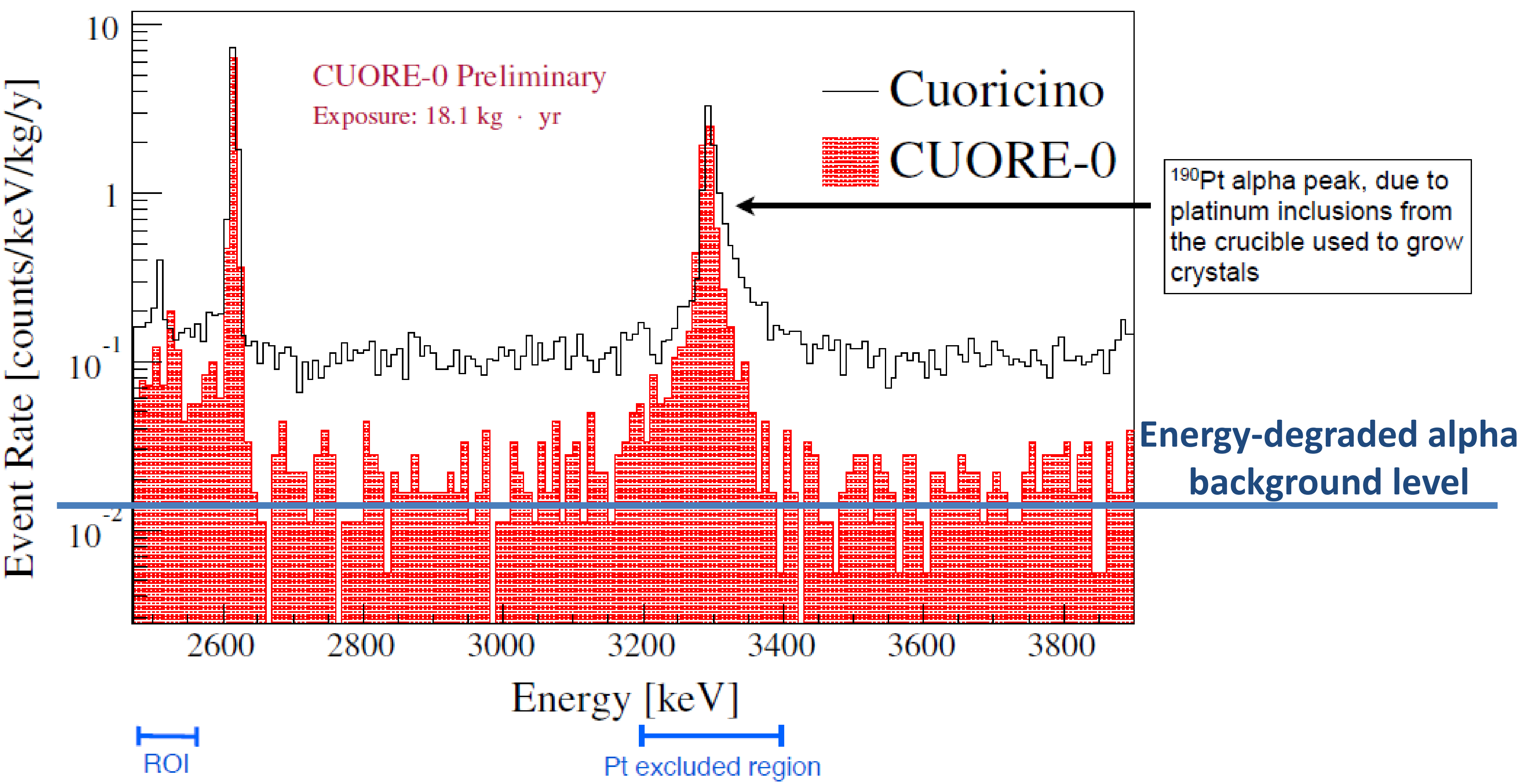
First CUORE tower now operating in the former Cuoricino cryostat

Excellent detector and background results



June 2, 2014

CUORE-0 - background



Scintillating bolometers and DBD

Bolometric technique (**CUORE**) + Simultaneous detection of heat and light

Choice one of golden isotopes
Q-value > 2615 keV
"zero" **gamma** background

Full alpha/beta separation
"zero" **alpha** background

= **zero background** at the ≈ **1 ton x year scale**

Achievable goals:

b ~ 10^{-4} counts/(keV kg y)
ΔE < 10 keV

Control internal contamination of the crystals

^{214}Bi(^{238}U – ^{226}Ra)
^{208}Tl (^{232}Th – ^{228}Th)

High Q-value β transitions

≤10 μBq/kg

List of interesting crystals

Isotope	I. A. [%]	Q-value [keV]	Materials successfully tested as bolometers in crystalline form
^{76}Ge	**7.8**	2039	Ge
^{136}Xe	**8.9**	2479	NONE
^{130}Te	**33.8**	2527	TeO_2
^{116}Cd	**7.5**	**2802**	$CdWO_4$, $CdMoO_4$
^{82}Se	**9.2**	**2995**	ZnSe
^{100}Mo	**9.6**	**3034**	$PbMoO_4$, $CaMoO_4$, $SrMoO_4$, $CdMoO_4$, $SrMoO_4$, $ZnMoO_4$,Li_2MoO_4, $MgMoO_4$
^{96}Zr	**2.8**	**3350**	ZrO_2
^{150}Nd	**5.6**	**3367**	NONE → many attempts
^{48}Ca	**0.187**	**4270**	CaF_2, $CaMoO_4$

⇩

Seven excellent candidates can be studied with high energy resolution and with the bolometric approach

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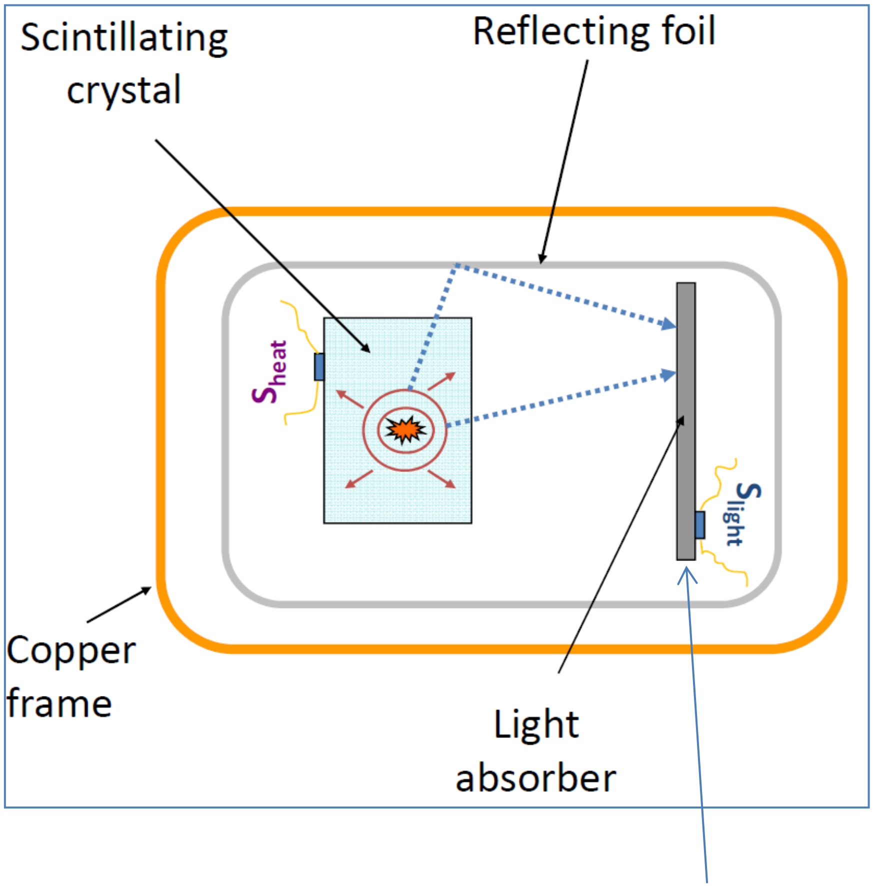
^{48}Ca	**0.187**	**4270**	**CaF_2, $CaMoO_4$**

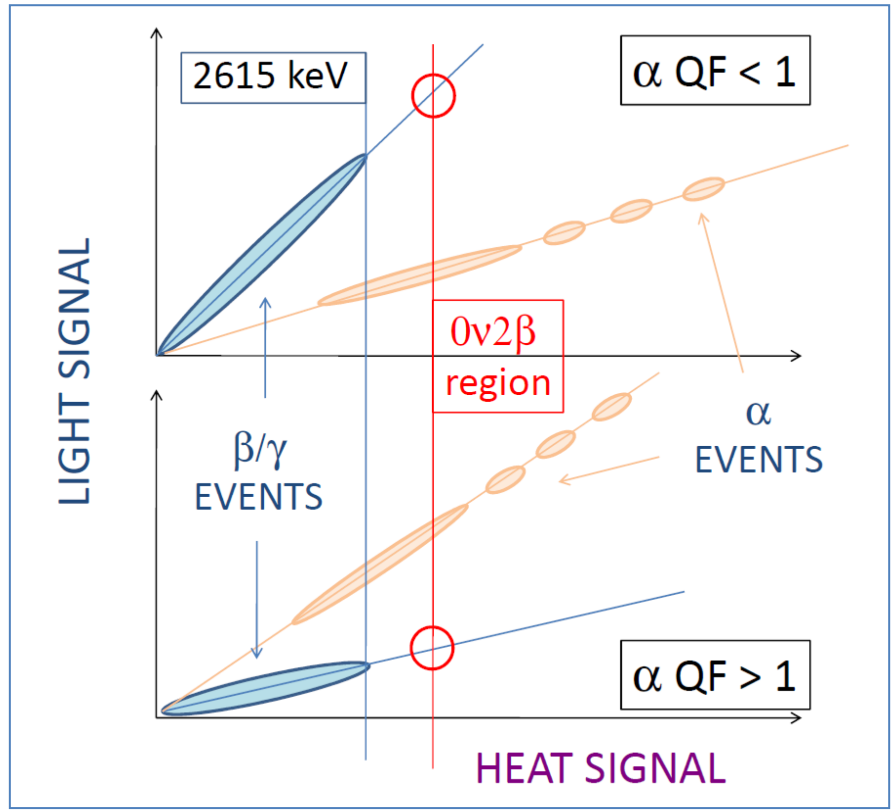
Compounds in boldface are **reasonable / good scintillators**

Ruled out by low isotopic abundance and difficult enrichement

Four golden candidates (^{116}Cd – ^{100}Mo – ^{82}Se – ^{48}Ca) can be studied as **scintillating bolometers**

Concept of a scintillating bolometer for double beta decay





Auxiliary bolometer for light detection

Experimental situation

Intense R&D activity in the framework of **three projects**:

LUCIFER → $ZnSe$, $ZnMoO_4$
(ERC advanced grant – INFN Italy, Orsay France)

LUMINEU → $ZnMoO_4$
(funded by ANR - France, Ukraine, Russia, Germany)

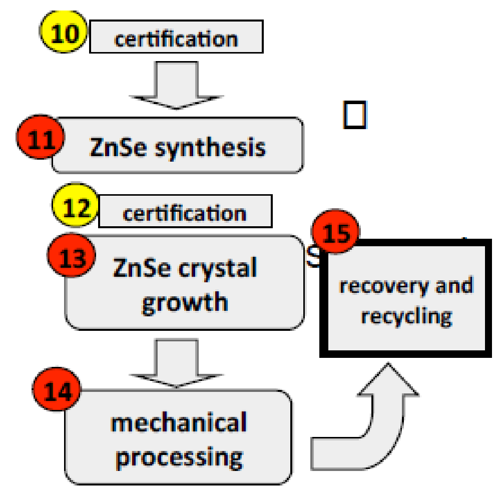
AMoRE → $CaMoO_4$
(Korea, Russia, Ukraine, China, Germany, Pakistan)

Proof of concept essentially demonstrated in all the three cases.
At LNGS, positive results obtained also for $CdWO_4$ and Li_2MoO_4

In two-year scale, a **10-kg-isotope experiment** is possible for the three cases.
$\Rightarrow$ GEN1 experiments approaching the inverted hierarchy mass region

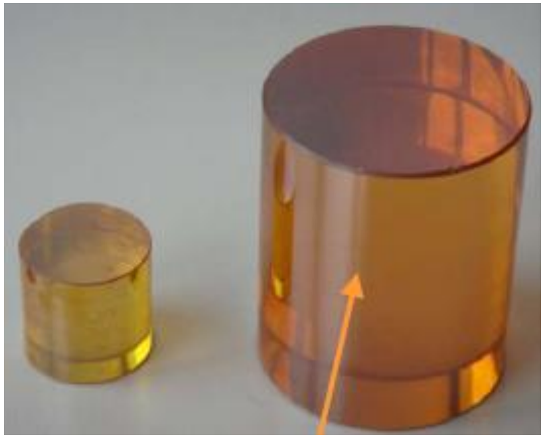
ZnSe – LUCIFER – crystal production

- Crystal dimension fixed: cylinder ∅=45mm, h=55mm, w=460.7g(nat Se),
- SmiLab Ltd(Ukraine): only supplier able to perform synthesis and crystal growth
- Crystals growth is difficult:
  - High melting point(1525°C) & total vapor pressure(~2Bar) deviation from stoichiometry
  - Very difficult control of local temperature defects



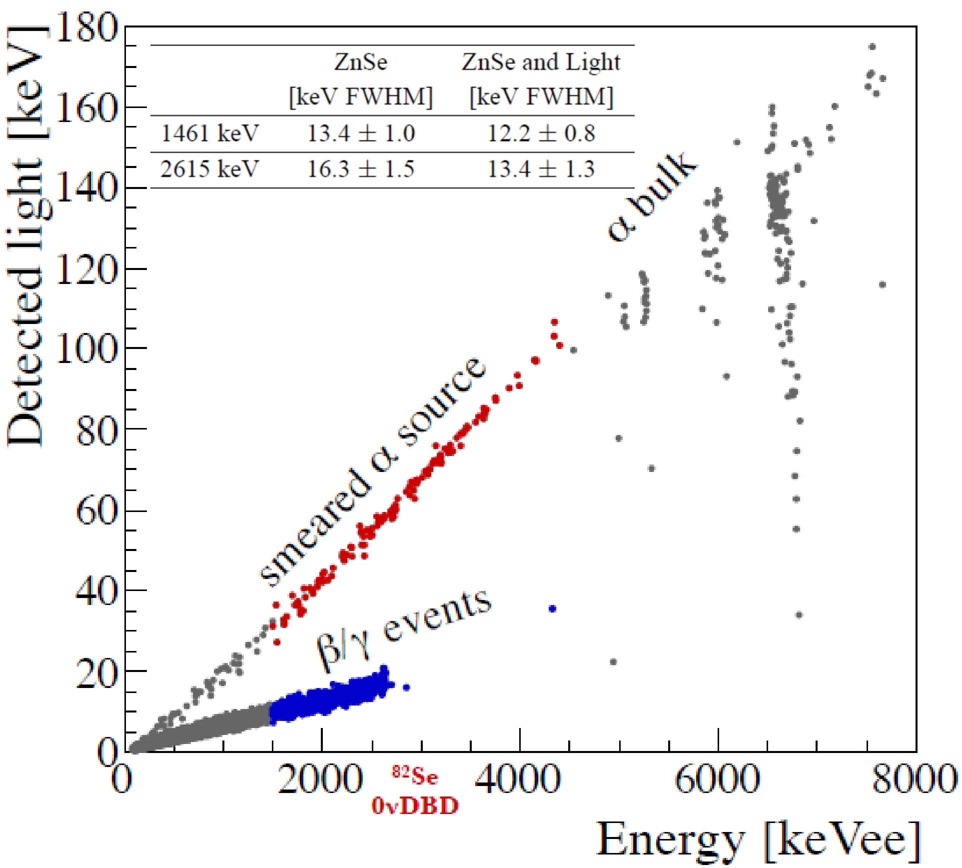
(or even 75%)

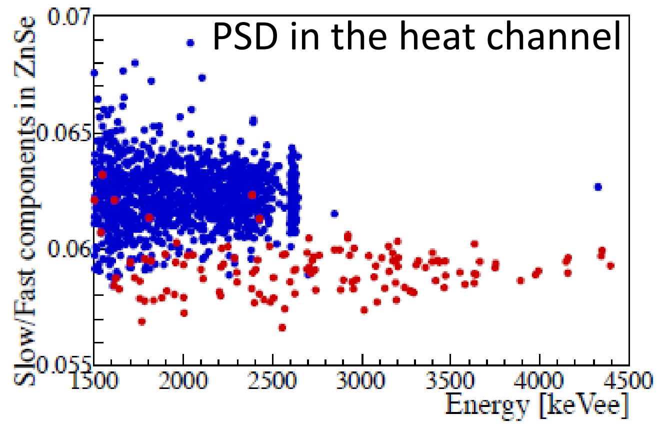
- Required efficiency of growth and processing > 65%
- Smilab not able to reach such efficiency: TPY ~22%
- Alternative supplier ISMA Kharkov is being tested.

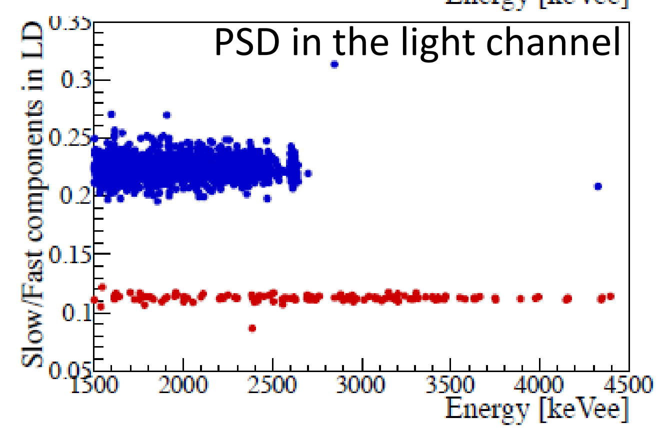


ZnSe – LUCIFER – single module performance

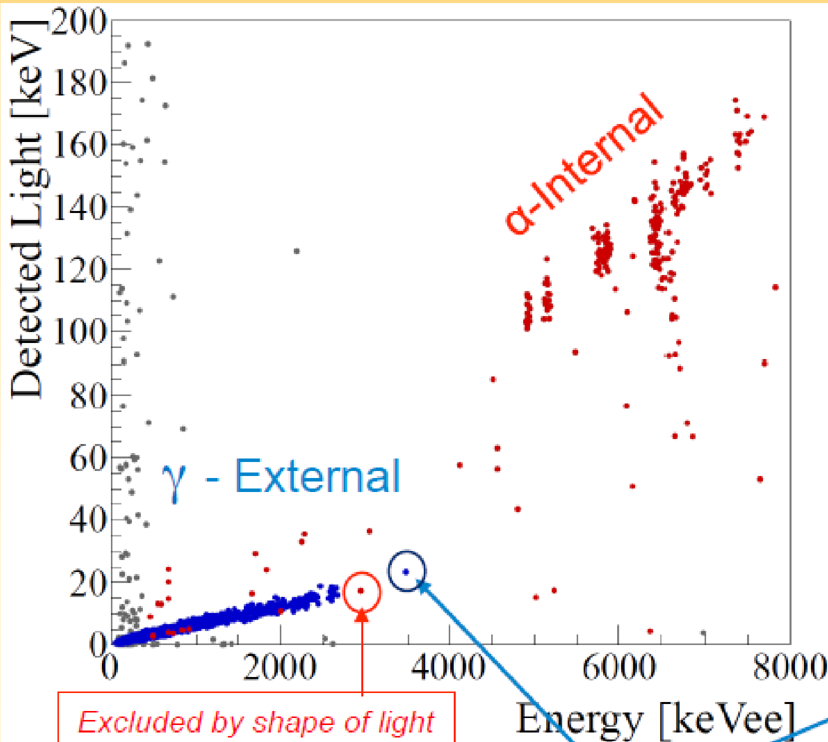
- 430 g ZnSe crystal **JINST 1305 (2013) P05021**
- LY ~6.5 keV/MeV for β/γ, QFα ~4, poor light collection□ pulse shape discrimination on light detector

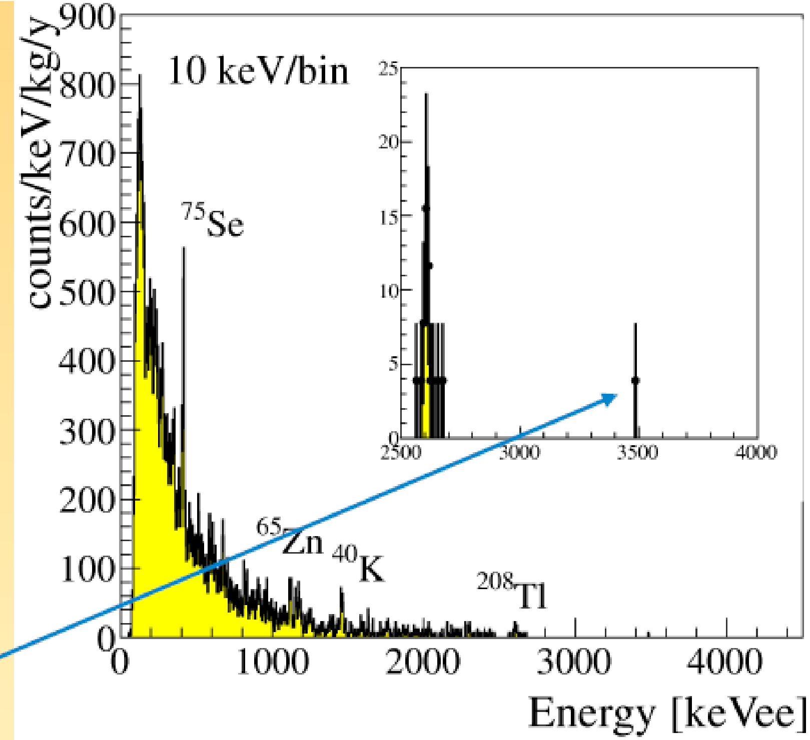






ZnSe – LUCIFER – Background





1 Event survives above 2615 keV. But it is tagged as induced by a cosmic μ, that generated a triple coincidence with other detectors present in the setup

Activity of the isotopes belonging to ^{232}Th and ^{238}U chains.

Chain	Nuclide	Activity [μBq/kg]
^{232}Th	^{232}Th	17.2 ± 4.6
	^{228}Th	11.1 ± 3.7
^{238}U	^{238}U	24.6 ± 5.5
	^{234}U	17.8 ± 3.3
	^{230}Th	24.6 ± 5.5
	^{226}Ra	17.8 ± 3.3
	^{210}Po	90.9 ± 10.6

This and following slides about LUCIFER are from S. Pirro

From Majorana to LHC: Workshop on the Origin of Neutrino Mass, Trieste 3 October 2013

ZnSe – LUCIFER – Experiment scheme

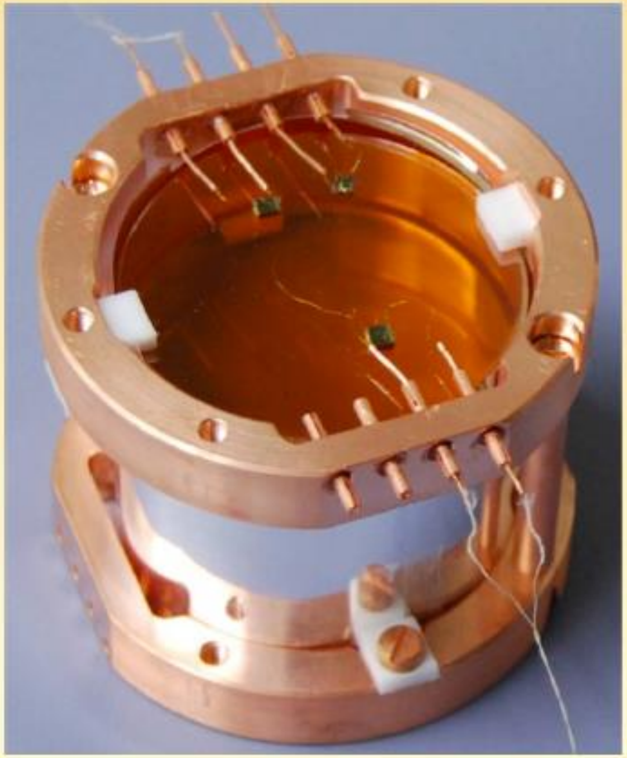
Lucifer will be composed by an array of 32÷36 enriched (95%) $Zn^{82}Se$ crystals.
The total ^{82}Se nuclei will be (6.7÷8.0) 10^{25}

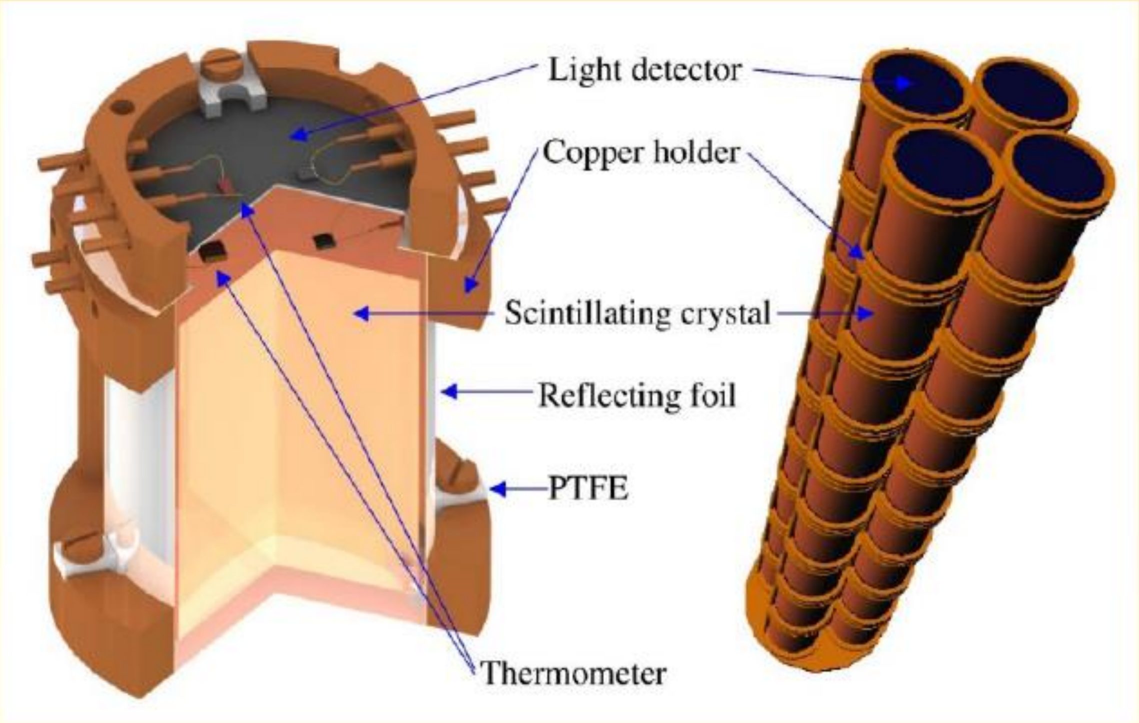
The mass of the single detector will be 460 g

The expected background in the ROI (2995 keV) is of the order of 1÷2 10^{-3} c/keV/kg/y

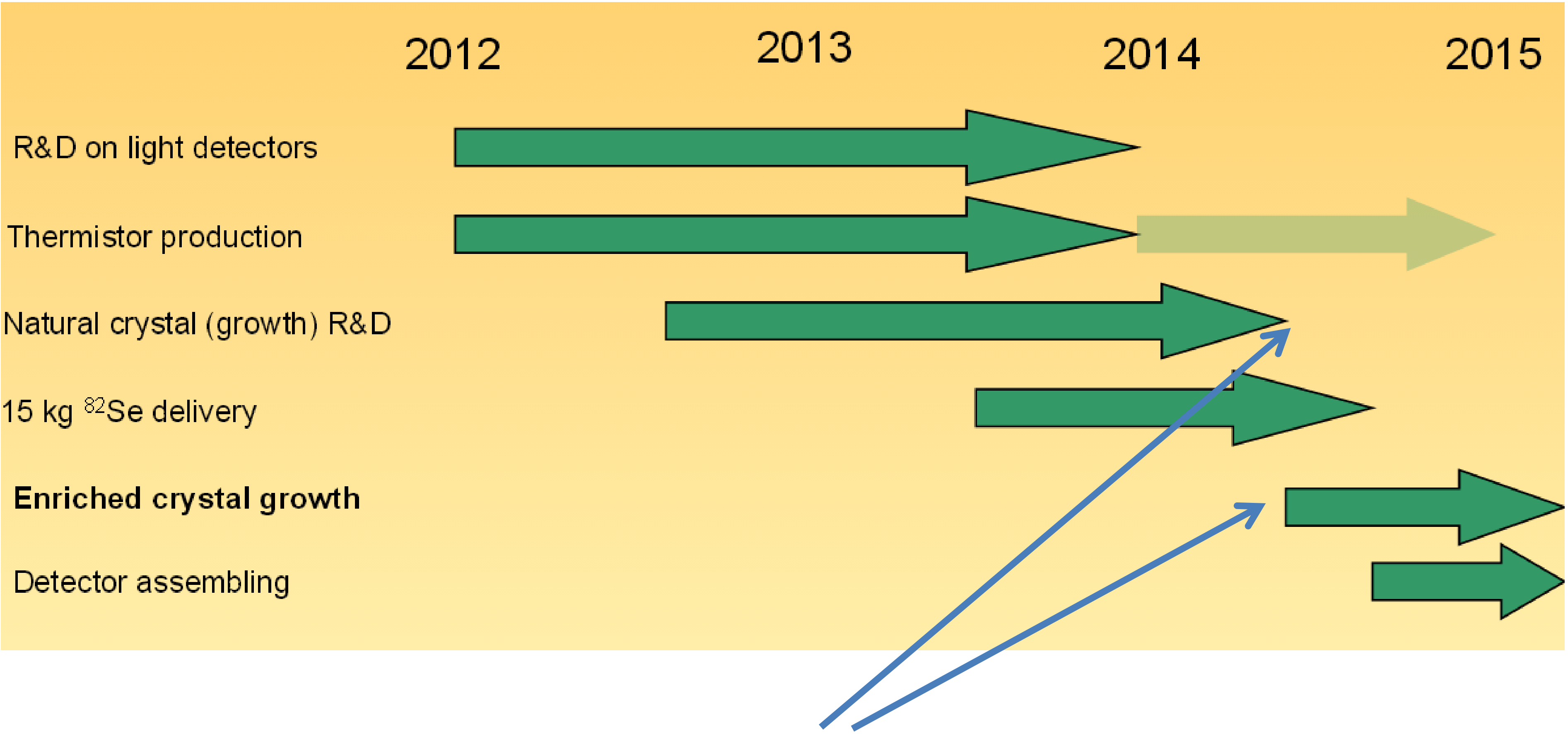
The energy resolution of the single detector is expected to be ~ 10÷15 keV FWHM

LNGS
CUORE-0 cryostat





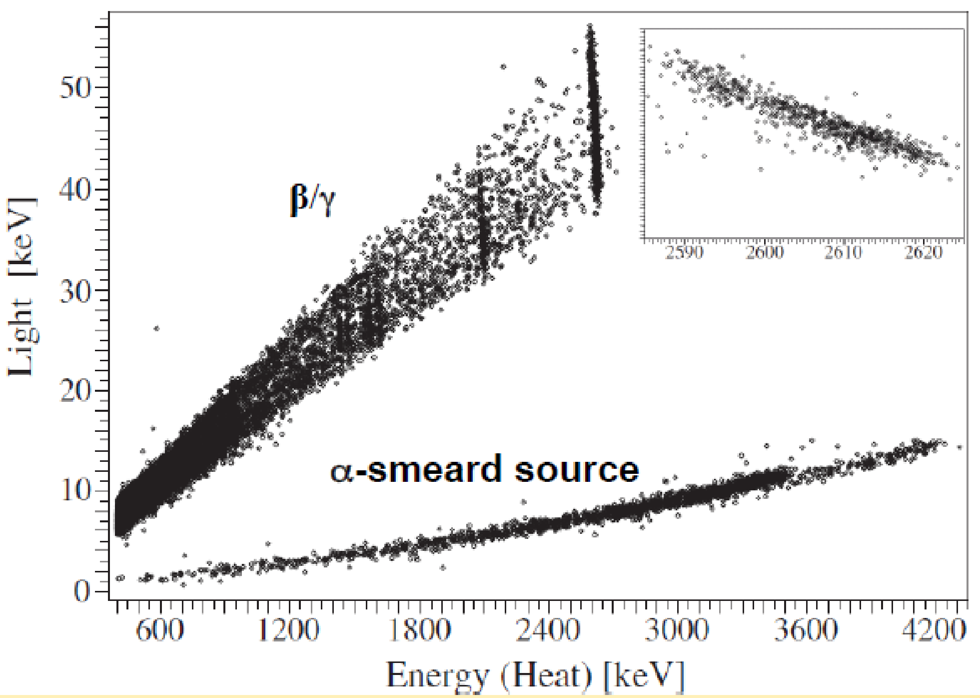
ZnSe – LUCIFER – Schedule

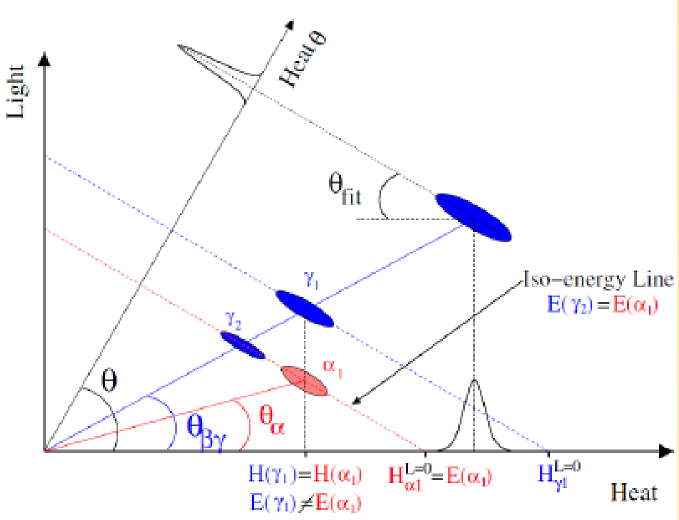


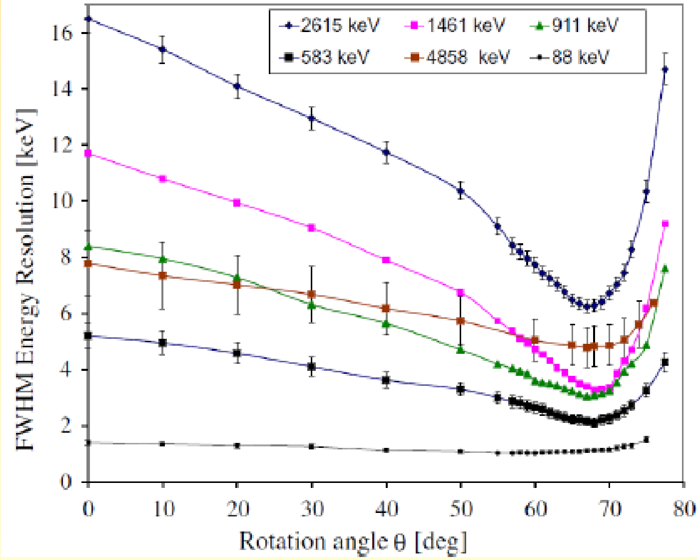
Delay of about 6 months due to the crystallization issue

Adv. High En. Phys. 2013 (2013) 237973

A result with $CdWO_4$ at LNGS







Scintillating bolometers show directly the energy partition that takes place in a calorimeter between different systems (lattice and scintillation groups)

C. Arnaboldi et al, Astrop. Phys 34 (2010) 143

$ZnMoO_4$ – LUMINEU
Purification of MoO_3 and crystallization

Both performed at the **Nikolaev Instute of Inorganic Chemistry, Novosibirsk, Russia**

JINST 09 (2014) P06004

Double purification step

(1) Sublimation of MoO_3 in vacuum

$$ZnMoO_4 + WO_3 = ZnWO_4 + MoO_3\uparrow$$

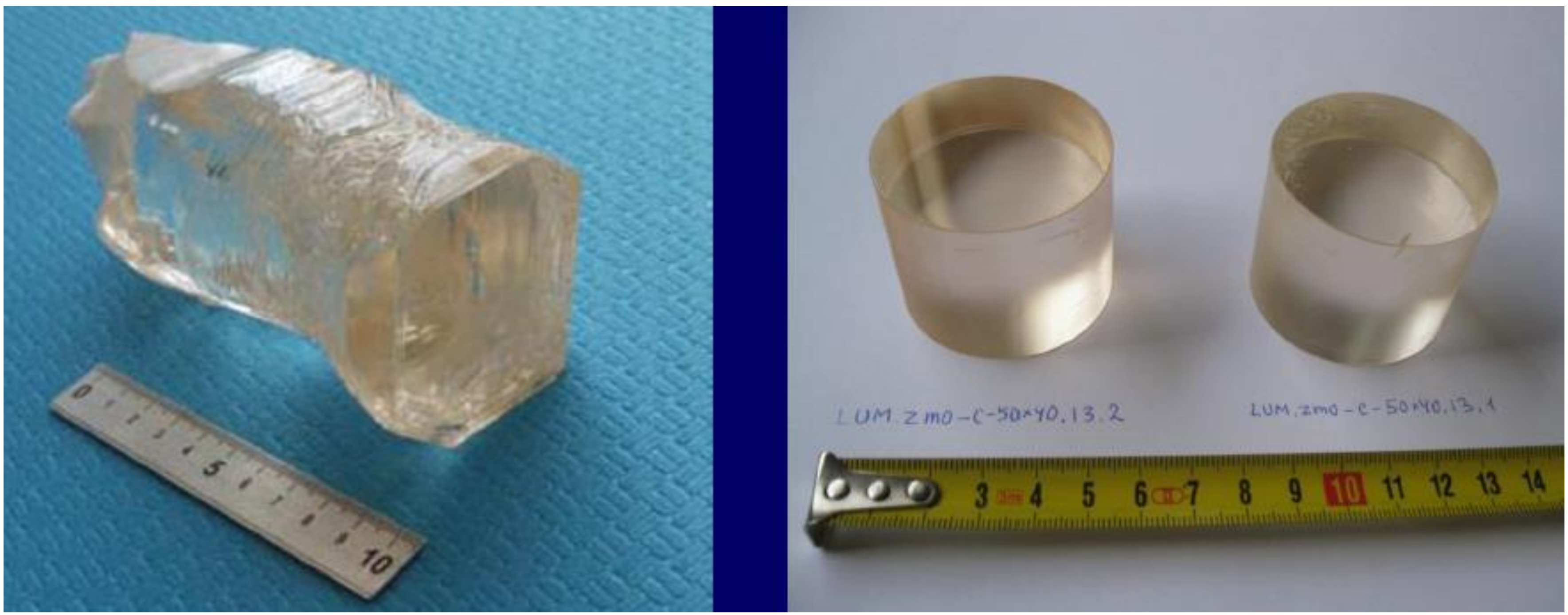
(2) Re-crystallization from aqueous solution of ammonium molybdate

$$MoO_3 + 2NH_4OH = (NH_4)_2MoO_4 + H_2O$$

$ZnMoO_4$ – LUMINEU
Purification of MoO_3 and crystallization

JINST 09 (2014) P06004

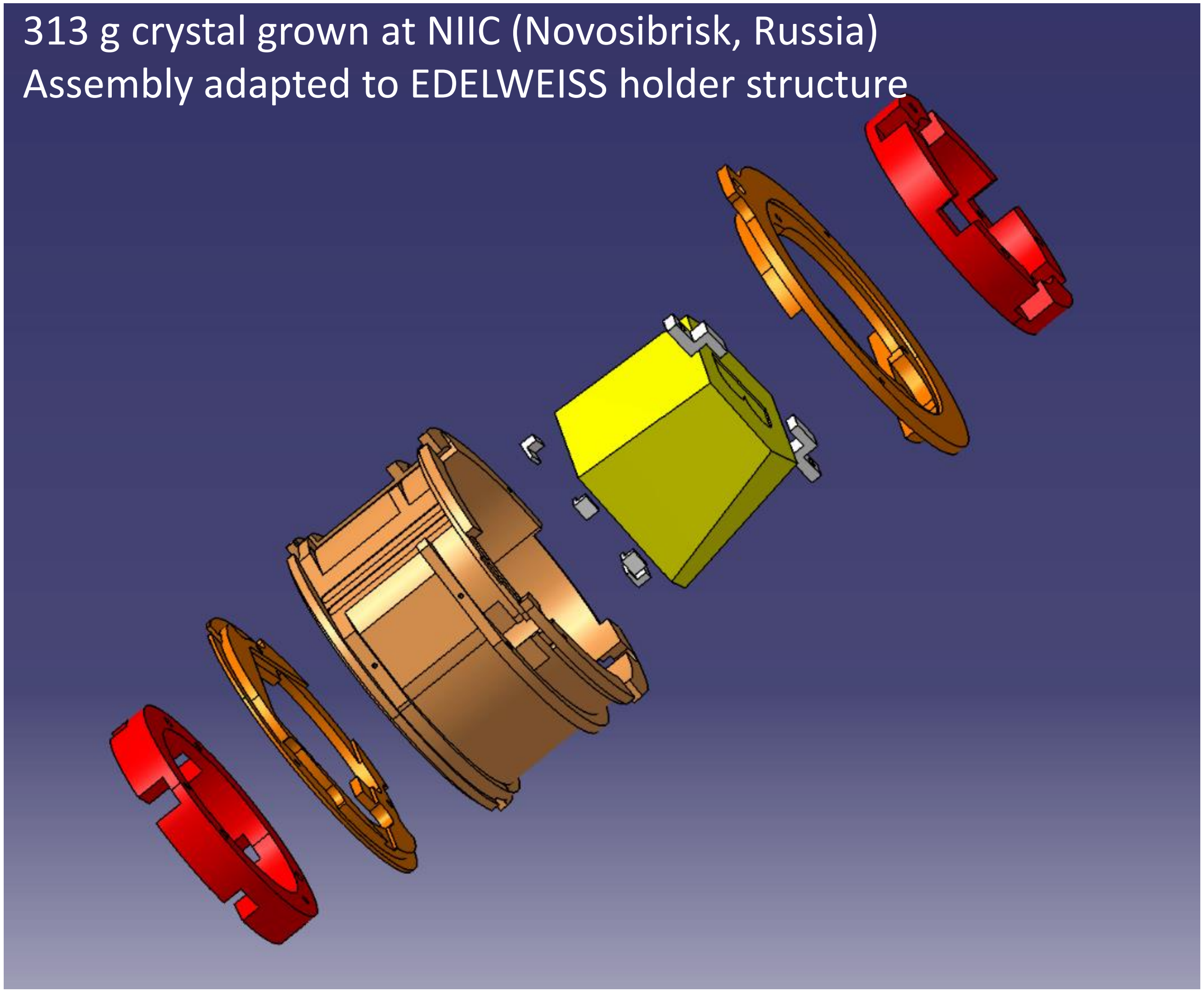
Crystallization by low-thermal gradient Czochralski technique



Large cylindrical crystals with excellent optical properties

Ø = 5 cm – h = 4 cm – M = 340 g

$ZnMoO_4$ – LUMINEU
Preliminary test on a 313 g crystal



$ZnMoO_4$ – LUMINEU
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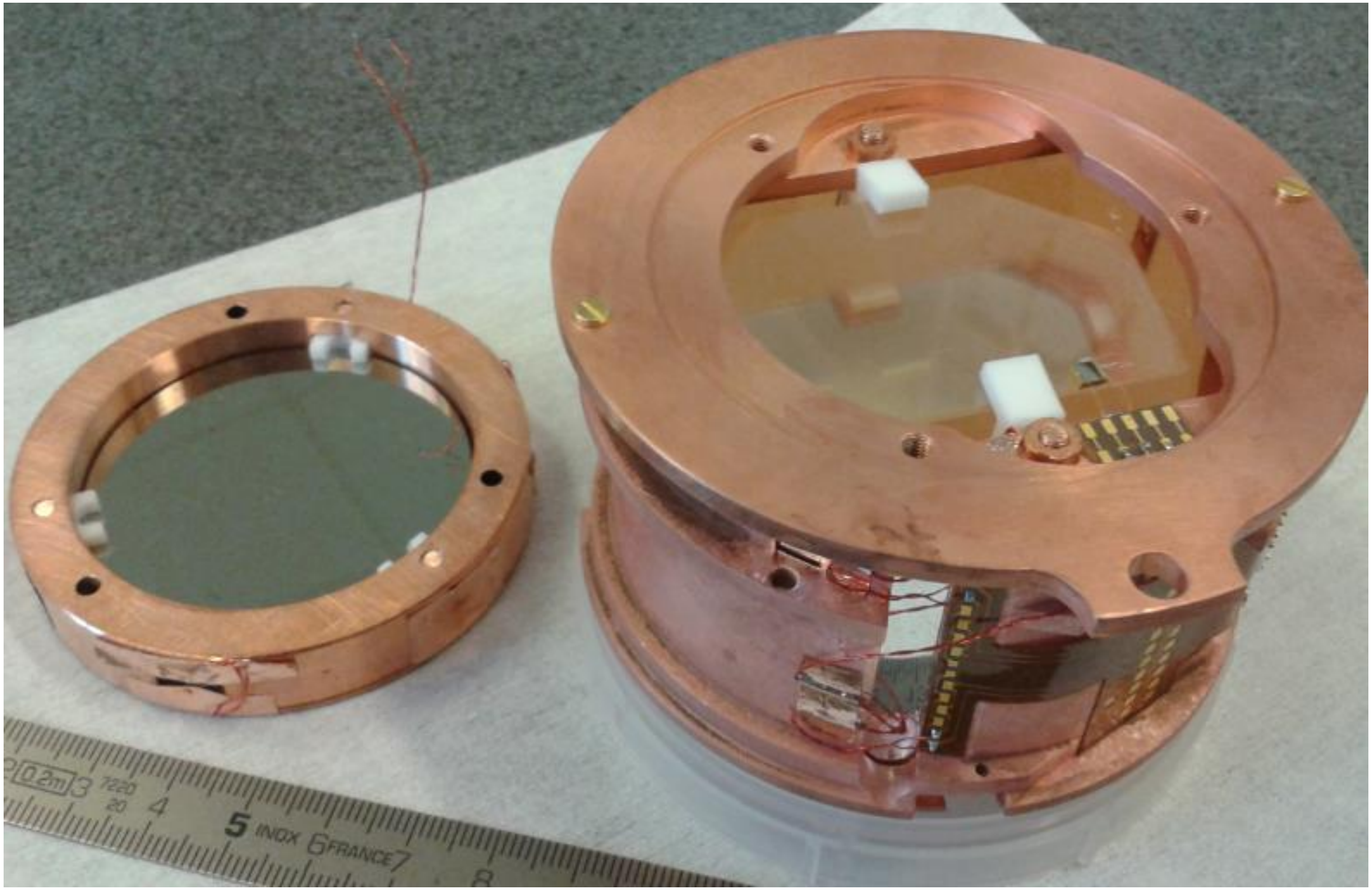
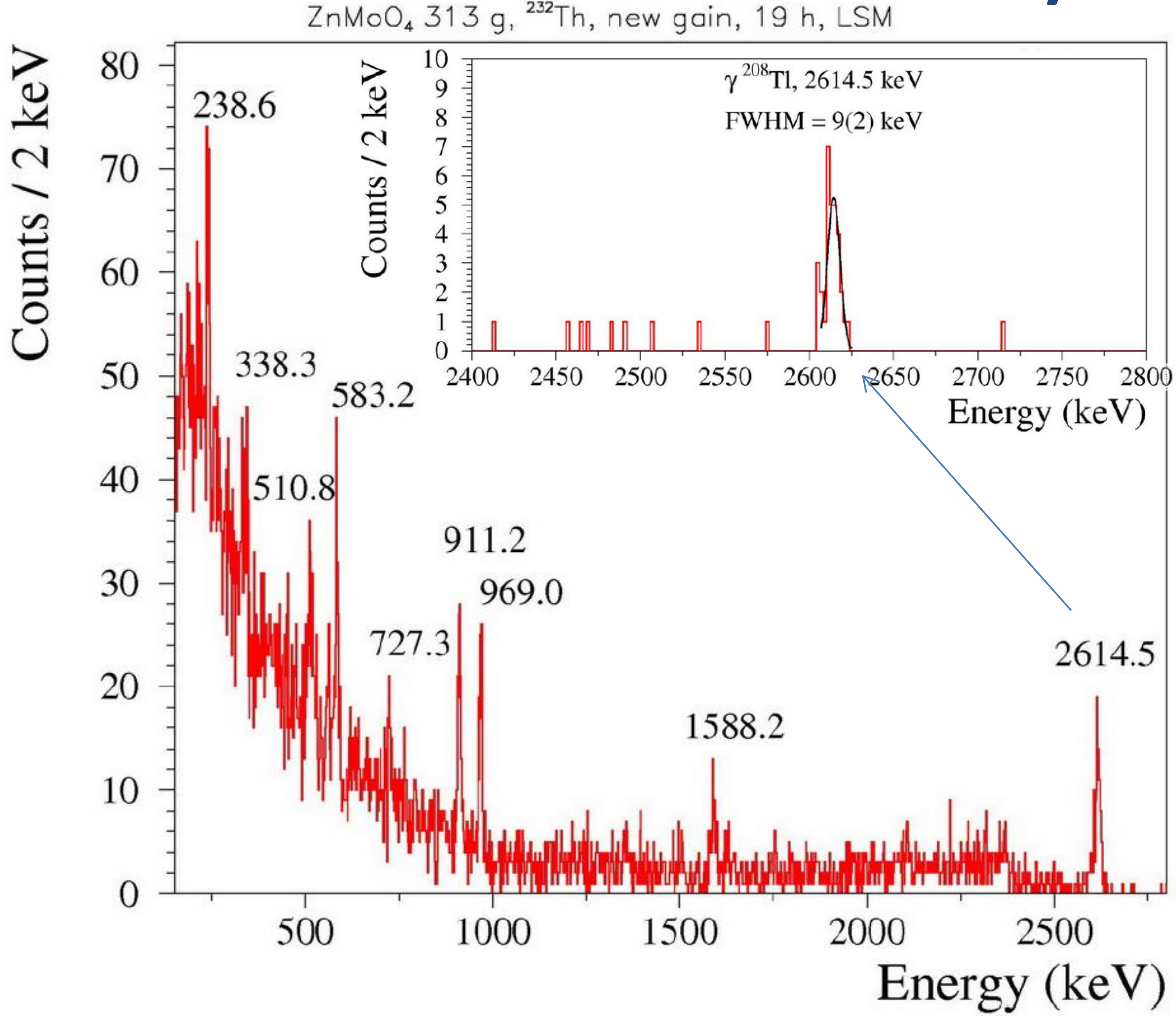
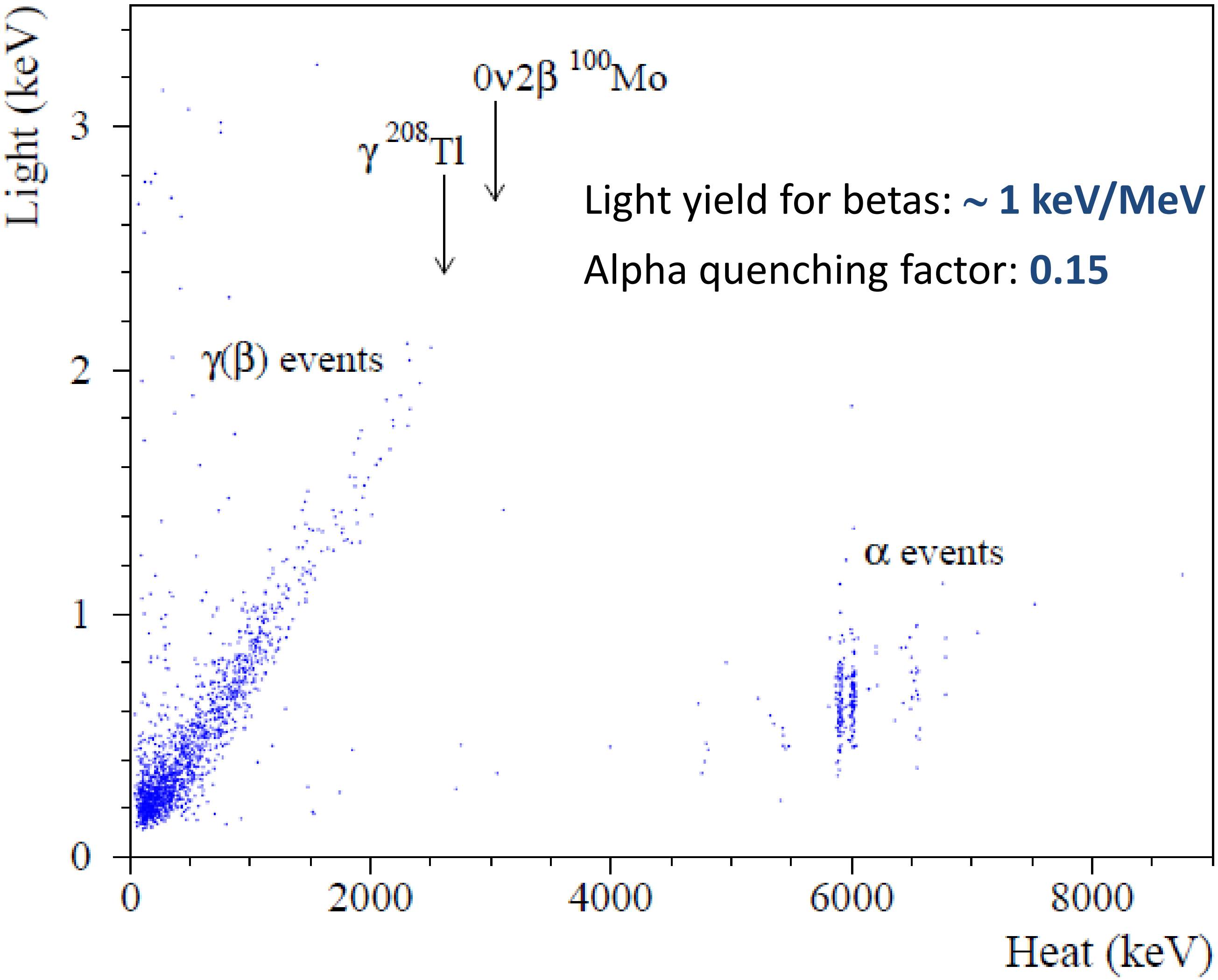


$ZnMoO_4$ – LUMINEU
^{232}Th calibration in the EDELWEISS cryostat (LSM)



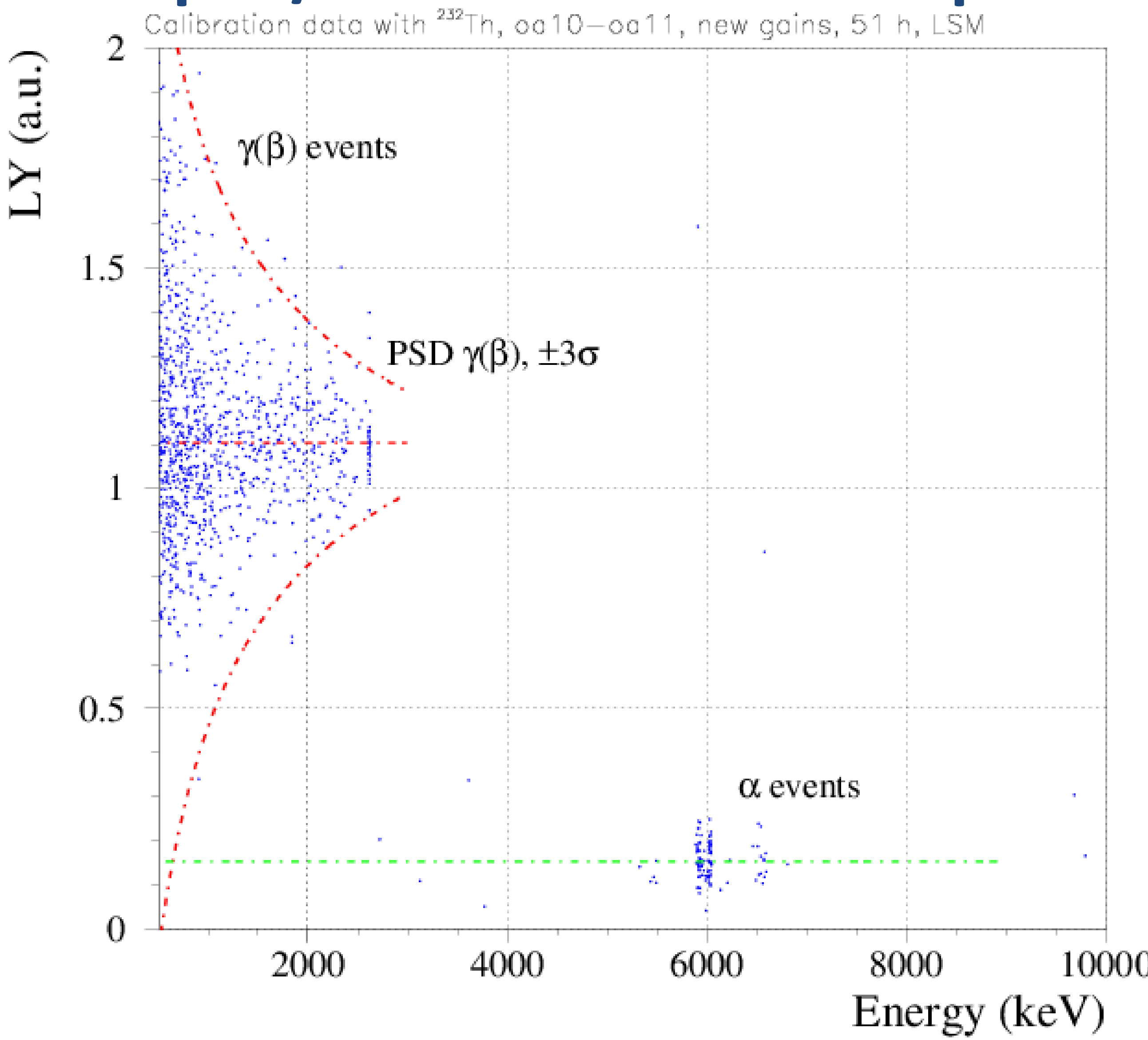
$ZnMoO_4$ – LUMINEU
Scatter plot light vs. heat



Light yield for betas: **~ 1 keV/MeV**

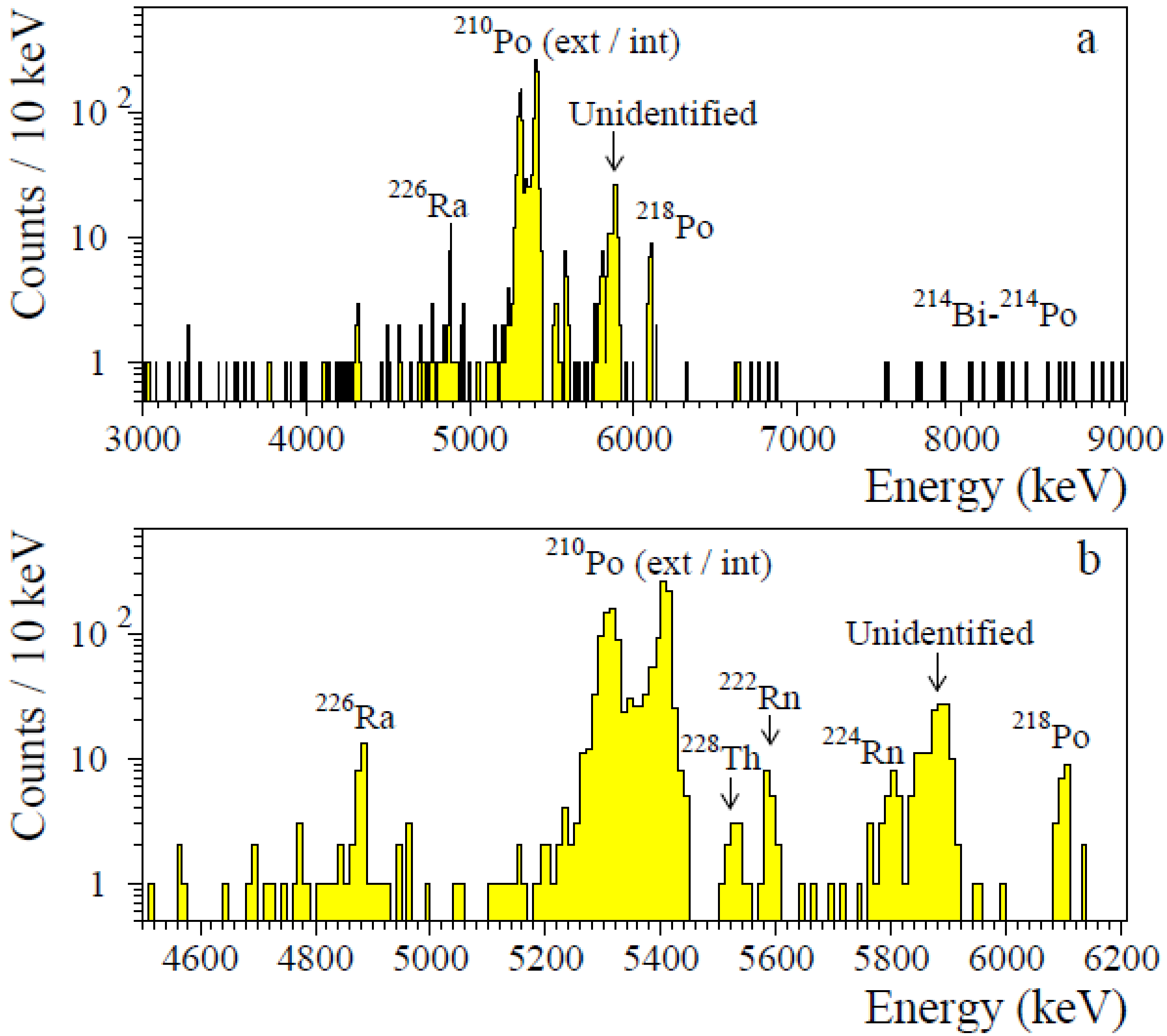
Alpha quenching factor: **0.15**

$ZnMoO_4$ – LUMINEU
Alpha/beta discrimination power



(gamma-calibrated scale)

$ZnMoO_4$ – LUMINEU
Background spectrum (alpha region)



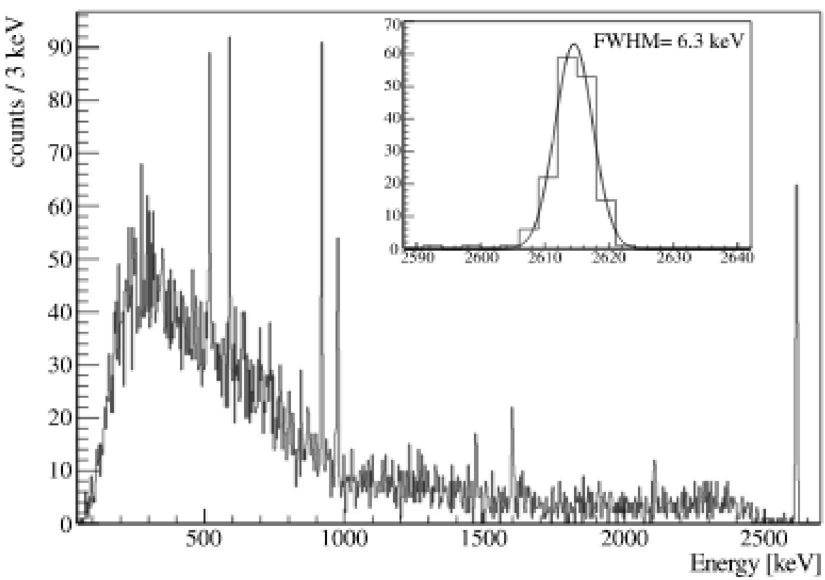
$ZnMoO_4$ – LUMINEU
Internal contamination

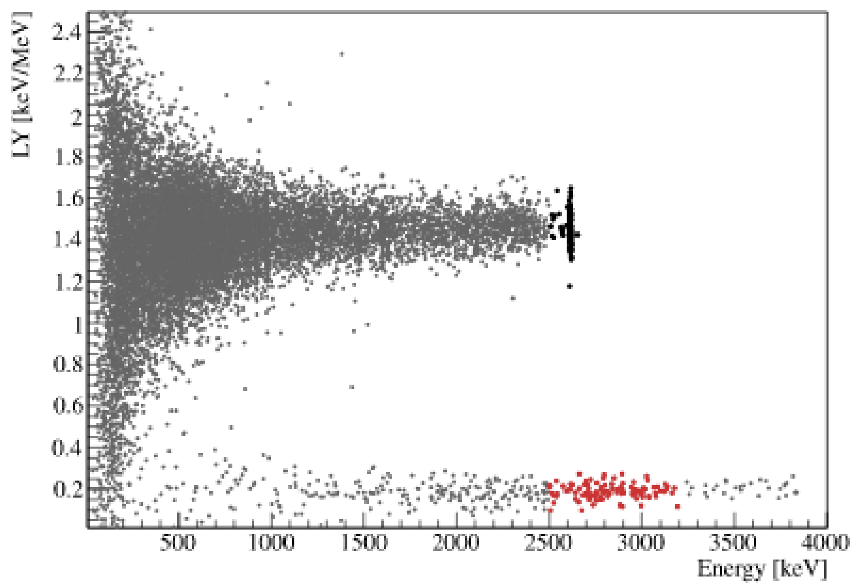
Nuclide	Activity (μBq/kg)					
	set-1		set-2		Full data	Ref. [11]
	Cali	Bg	Cali	Bg	Cali+Bg	Bg
	303 h	164 h	243 h	141 h	851 h	524 h
^{232}Th	≤ 6	≤ 11	≤ 8	≤ 15	≤ 5	≤ 8
^{228}Th	15(7)	≤ 22	≤ 21	≤ 37	10(3)	≤ 6
^{238}U	≤ 6	≤ 11	≤ 8	≤ 46	≤ 8	≤ 6
^{234}U	≤ 20	≤ 36	≤ 14	≤ 31	≤ 14	≤ 11
^{230}Th	≤ 12	≤ 11	≤ 26	≤ 27	≤ 9	≤ 6
^{226}Ra	32(10)	22(11)	26(10)	25(13)	26(5)	27(6)
^{210}Po	597(42)	752(64)	614(47)	510(57)	621(25)	700(30)
^{235}U	≤ 12	≤ 13	≤ 8	≤ 27	≤ 7	–
^{231}Pa	≤ 16	≤ 13	≤ 26	≤ 15	≤ 8	–
^{227}Th	≤ 16	≤ 24	≤ 8	≤ 15	≤ 3	–
^{223}Ra	≤ 16	21(11)	≤ 8	≤ 15	≤ 3	–
^{147}Sm	≤ 12	≤ 15	≤ 15	≤ 15	≤ 5	–
^{190}Pt	≤ 6	≤ 15	≤ 15	≤ 15	≤ 3	–
Unidentified (on surface)	120(19)	114(25)	102(19)	82(23)	98(10)	–

$ZnMoO_4$ – LUCIFER
Tests at LNGS

Similarly excellent results have been obtained in the framework of **LUCIFER at LNGS** with a twin crystal coming from the same boule

Eur. Phys. J. C 72 (2012) 2142



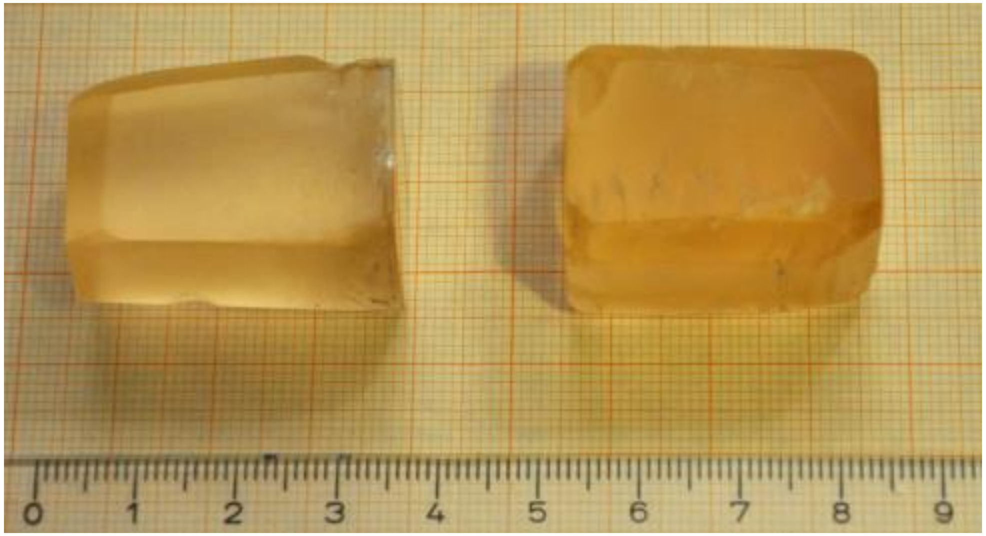


With three detectors with a total mass of **811 g**, the **two neutrino double beta decay** of **^{100}Mo** half life was measured with a **$T_{1/2}$ = 7.15 ± 0.37 (stat.) ± 0.66 (syst.) ·10^{18} y** (1. 3 kg day of exposure for ^{100}Mo)

NEMO3 results: **7.17 ± 0.01 (stat) ± 0.54 (syst) ·10^{18} y** (with 6.9 kg of ^{100}Mo)

$ZnMoO_4$ – LUMINEU
Enriched crystals

First $Zn^{100}MoO4$ boule was grown from deeply purified ^{100}Mo
Two samples with masses **64 g** and **61 g** were produced

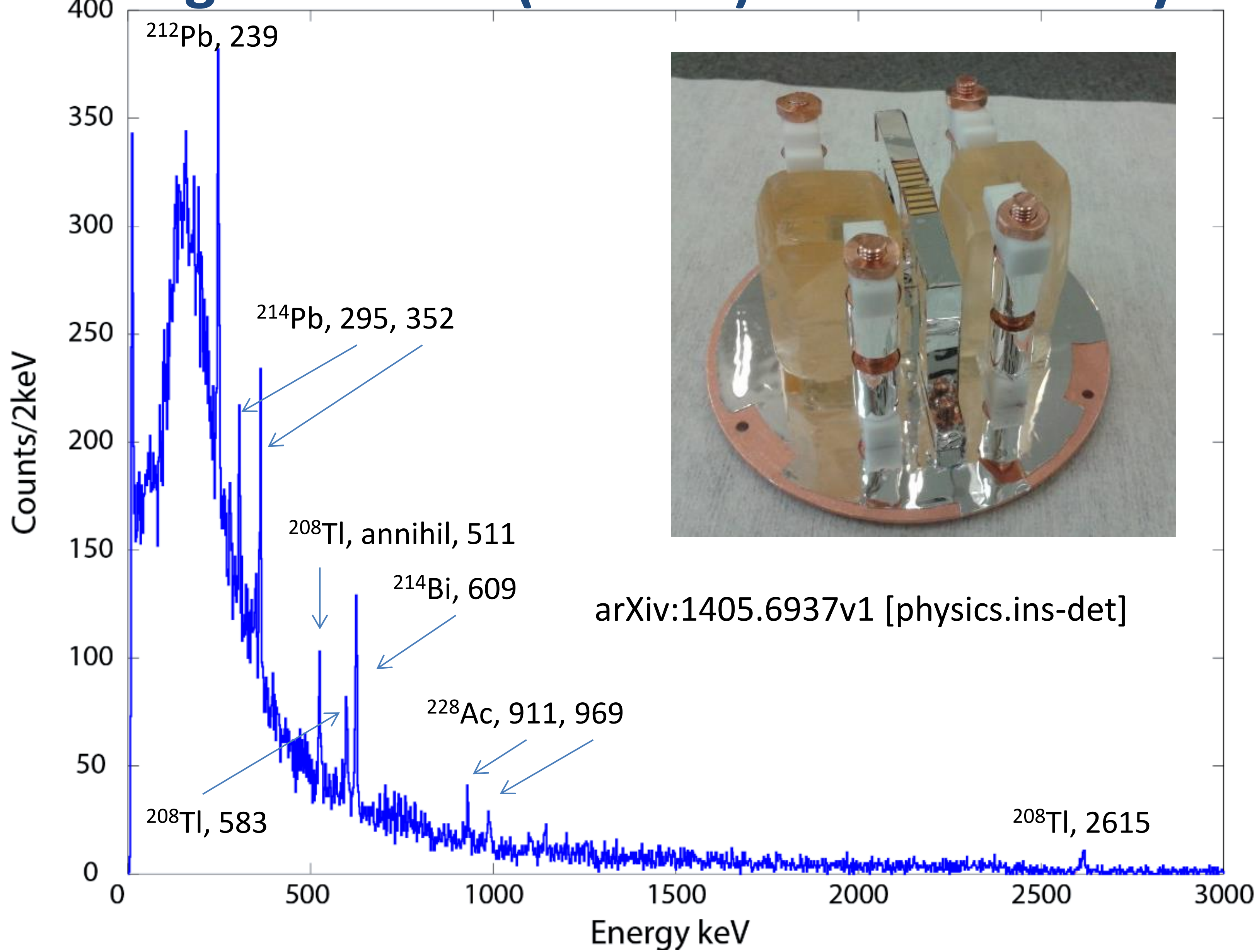


The reason why crystals are small is that in the first attempt we decided to use a small amount of enriched material in a small crucible

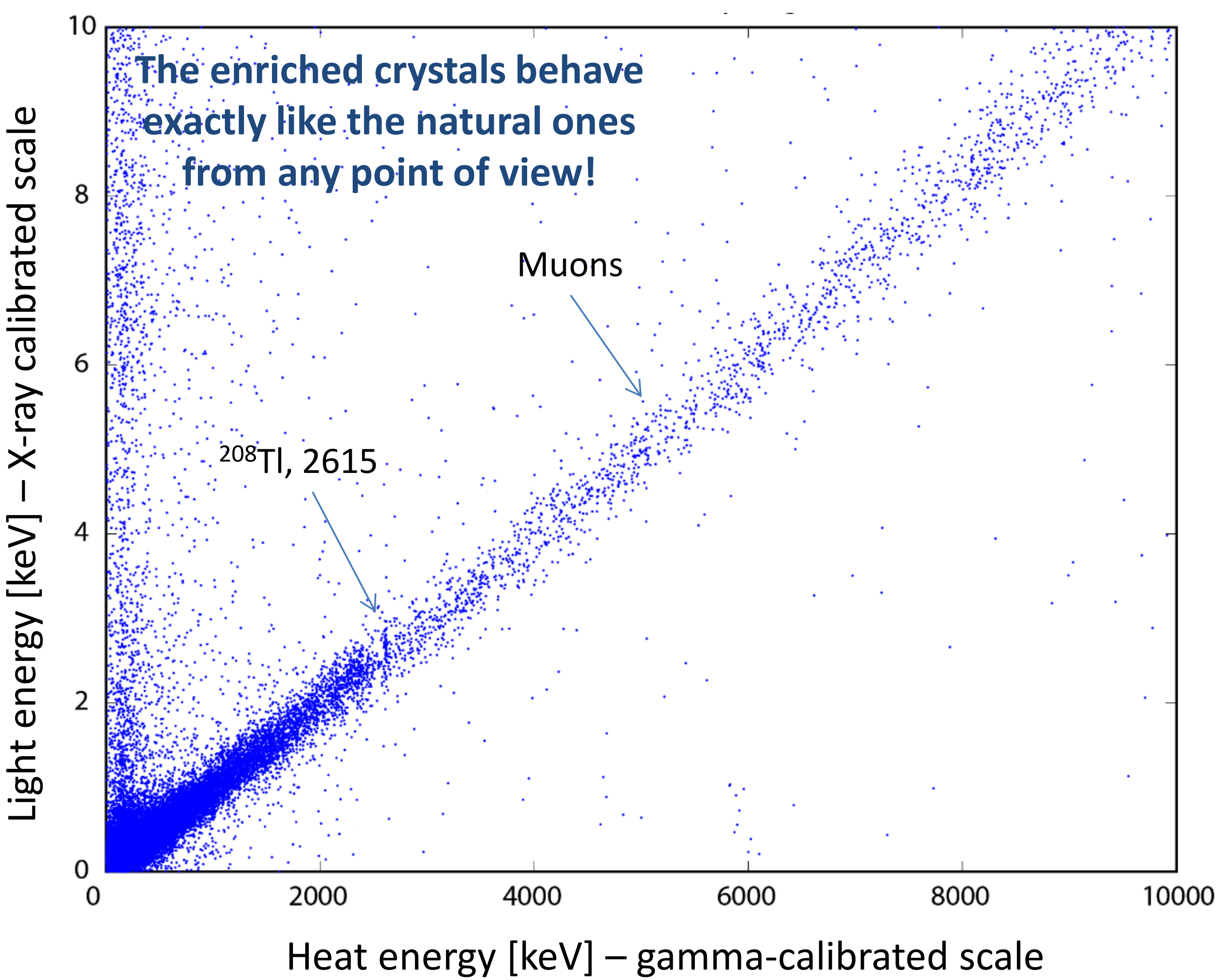
Irrecoverable losses of the purification/crystallization processes: **< 4 %**

Production of large mass enriched crystals is in progress

$ZnMoO_4$ – LUMINEU
Aboveground test (CSNSM) of enriched crystals



$ZnMoO_4$ – LUMINEU
Aboveground test (CSNSM) of enriched crystals

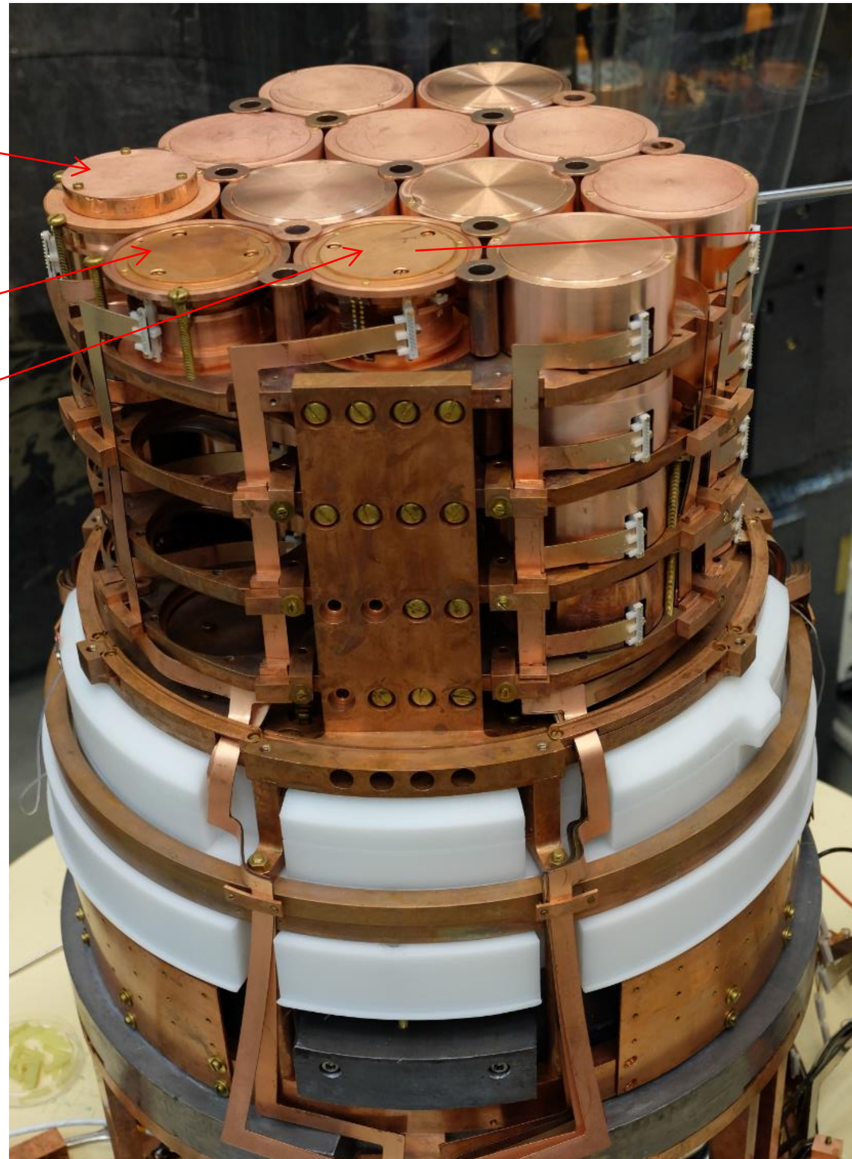


$ZnMoO_4$ – LUMINEU - Enriched and natural crystals in the EDELWEISS cryostat

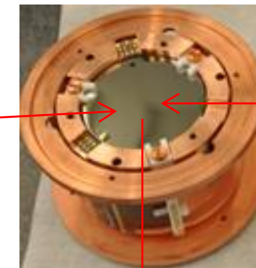
Enriched ZMO 1 & 2

Natural ZMO 1

Natural ZMO 2

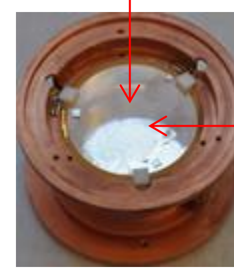


Removing the Cu cover….



Light detector

…removing the light detector



ZMO crystal

LUMINEU and follow-up
Phased approach and sensitivity

Assuming background at **4 x 10^{-4} counts / (keV kg y)**, **T=5 y**, **ΔE = 6 keV**
(taking into account 2ν pile-up **EPJC, 72 (2012)1-6**)

PLB, 710 (2012) 318-323

	Option	Number of ≈ 400 g crystals	Total isotope mass [kg]	Half-life sensitivity [10^{25} y]	$m_{\beta\beta}$ sensitivity [meV]
	(1)	4	0.676	0.53	167 – 476
GEN1	(2)	40	6.76	4.95	55 – 156
	(3)	2000 (nat.)	33.1	15.3	31 – 89
GEN2	(4)	2000	338	92.5	13 – 36

This background figure is compatible with the internal contamination already measured in the $ZnMoO_4$ large mass single modules in the framework of LUMINEU and LUCIFER, especially for the isotope ^{228}Th

LUMINEU and follow-up
Phased approach and sensitivity

Assuming background at **4 x 10^{-4} counts / (keV kg y)**, **T=5 y**, **ΔE = 6 keV**
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PLB, 710 (2012) 318-323

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LUMINEU (in present EDELWEISS)	(1)	4	0.676	0.53	167 – 476
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GEN2	(4)	2000	338	92.5	13 – 36

Available to LUMINEU

LUMINEU and follow-up
Phased approach and sensitivity

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Available (MoU IN2P3 – ITEP – INFN)
Possible use of the EDELWEISS cryostat after EDELWEISS-III
2 year scale

Sensitivity at the level of the DBD experiments running or in construction (EXO-200, KamLAND-Zen, GERDA phase 2, CUORE, NEXT)

LUMINEU and follow-up
Phased approach and sensitivity

Assuming background at **4×10^{-4} counts / (keV kg y)**, **T=5 y**, **ΔE = 6 keV**
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- Molybdenum can be enriched by centrifugation at reasonable prices (50 – 100 $/g) and reasonable throughput
- 350 kg of enriched Mo fits the budget / timescale of a next generation double beta decay experiment
- Novosibirsk set-up $\Rightarrow$ 8 crystals/month is possible with only one furnace

$CaMoO_4$ – AMoRE Crystallization

In this case, not only **enrichment in ^{100}Mo** is highly desirable, but also **depleted Ca**, with negligible amount of ^{48}Ca, is necessary (background from two neutrino double beta decay of ^{48}Ca, which has Q ~ 4.3 MeV).

$^{40}Ca^{100}MoO_4$ crystals from Russia

40

- SB28

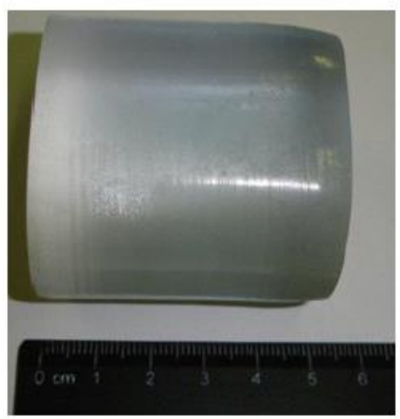
weight 196 g

- SB29

weight 390 g

- S35

weight ~300 g



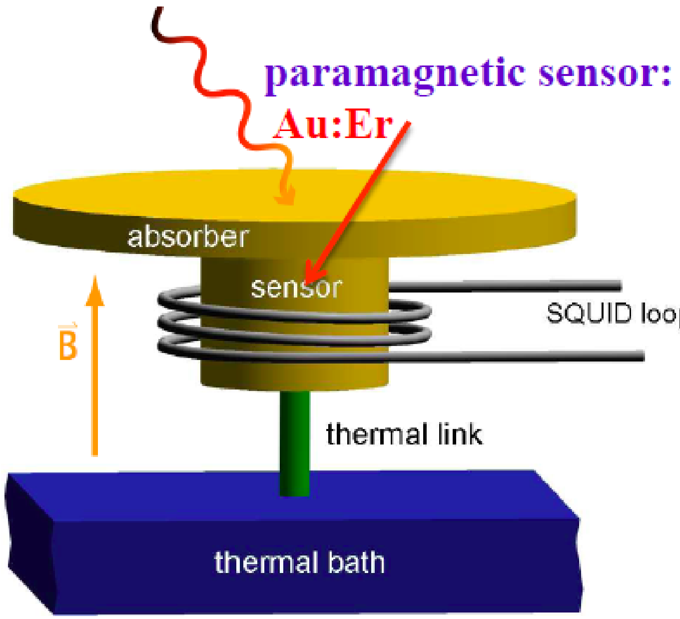
$CaMoO_4$ – AMoRE
Detector technology

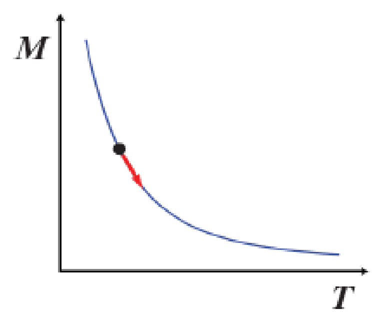
Principle of operation

1. Energy absorption in CMO crystal.
2. Phonon & Photon generation.
3. Temperature increase (gold film).
4. Magnetization of MMC decrease.
5. SQUID pickup the change.

Advantage of MMC

- **Fast signal. (critical for lower 2νβ β random coincidence.)**
- **Fairly easy to attach to absorber.**



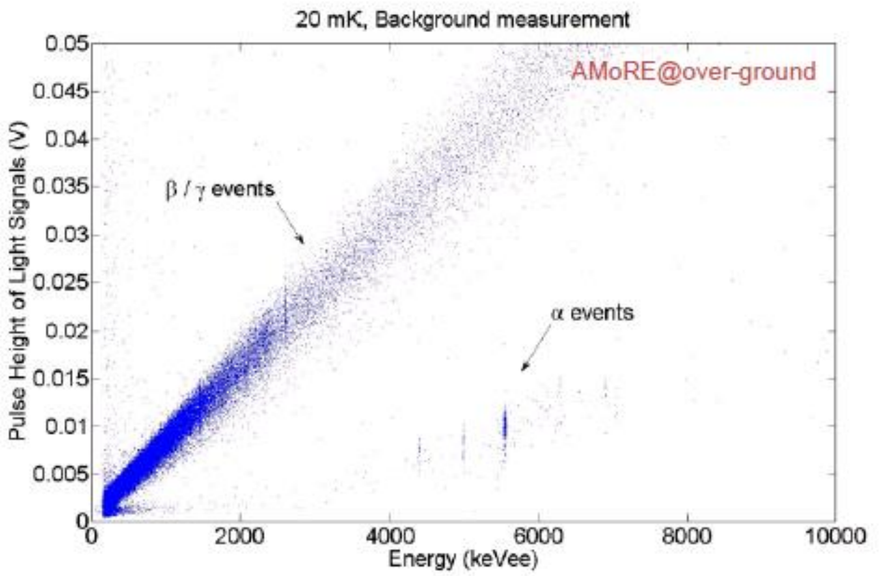


In principle, much better S/N ratio than in LUCIFER/LUMINEU
Read-out more complicated due to SQUIDs

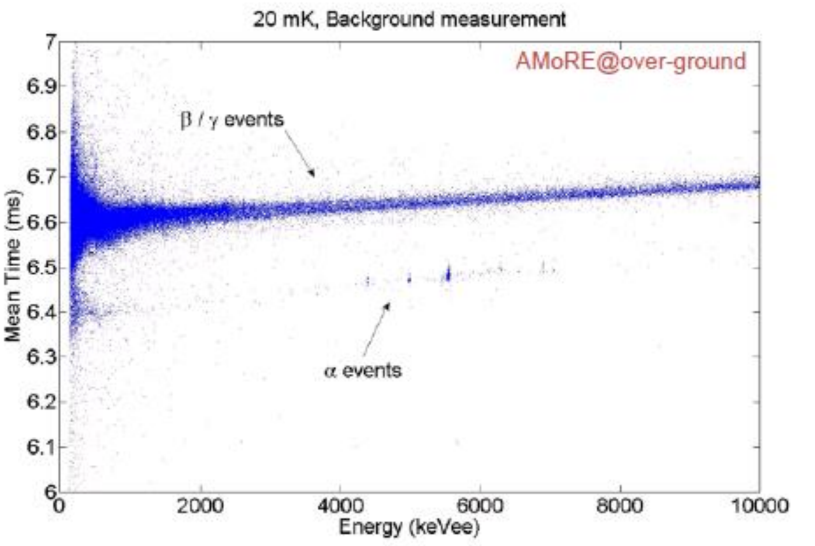
$CaMoO_4$ – AMoRE
Single-module aboveground results

M=196 g

Phonon vs Light



PSD with phonon only



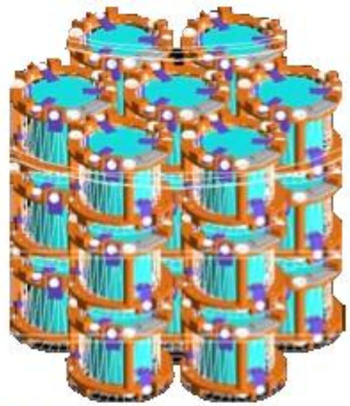
Excellent technical results

Very high light yield ~30,000 ph/MeV (the best among all molybdates)

The crystals show a non-negligible internal contamination

$CaMoO_4$ – AMoRE
Underground installation is in progress

$CaMoO_4$ – AMoRE
Phased approach and schedule



CMO: ~ 300g
5 layers-7 columns

<AMoRE10, 2015~6>

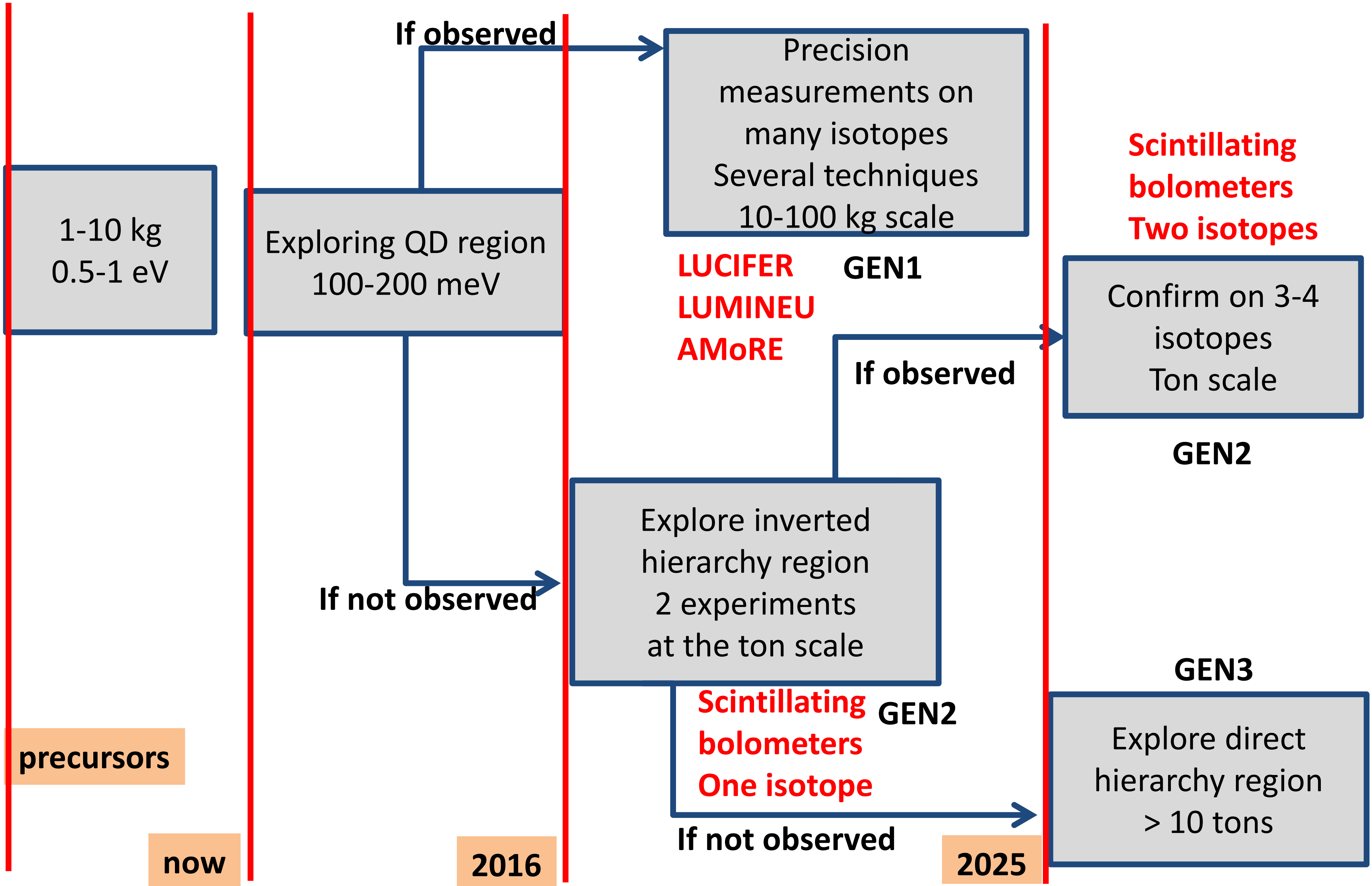
GEN1

Each Cell : D=70 mm, H=80 mm.
CMO (D=50mm, H=60mm, 506g)
30 layers(2.4 m height)-13 columns
or 20 layers(1.6 m height)-19 columns

<AMoRE200, 2018~9>

GEN2

Looking into the crystall ball



Adapted from Wilkerson, NuMass 2013

Conclusions

- **LUCIFER** – difficulties larger than expected in producing ZnSe crystals with the desired features in a reproducible way, complicated by geopolitical issues – now most of the technical problems have been solved - enriched crystal production starting from fall 2014 – about 36 crystals containing 10 kg of ^{82}Se (irrecoverable loss 35%) in Gran Sasso

- **LUMINEU** – excellent radiopurity and performance of the $ZnMoO_4$ crystals (natural and enriched) – irrecoverable loss negligible – pilot experiment with 1 kg of enriched Mo in Modane within 2015 – demonstrator with 10 kg of enriched Mo in Modane or Gran Sasso in 2016 $\Rightarrow$ MoU INFN – IN2P3 – ITEP

- **AMoRE**: excellent $^{40}Ca^{100}MoO_4$ detector performance – aggressive schedule foreseeing a 10 kg experiment at a 2 year scale and 200 kg at a 5 year scale

The scintillating bolometer technology has excellent prospects to reach zero background at the ton x year scale with high energy resolution and efficiency in more than one isotope