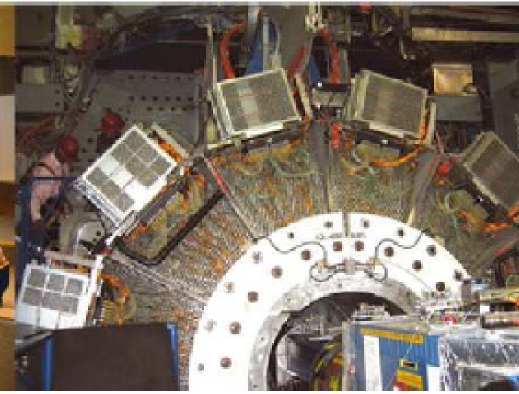
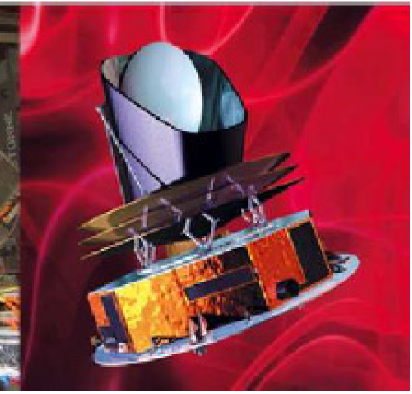
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

LAL, Orsay, France, 10 March 2015

Scintillating bolometers for double-beta decay search

D.V. Poda

CSNSM, CNRS-IN2P3, Univ. Paris-Sud, 91405 Orsay, France

INR, NASU, 03680 Kyiv, Ukraine

About myself

2004–2007: Postgraduate studies at Institute for Nuclear Research, Lepton Physics Department (INR, Kyiv, Ukraine)

Development of $CdWO_4$, $PbWO_4$, $ZnWO_4$ scintillation detectors for DBD search

2009: Candidate of Science Degree (comparable to PhD), INR (Kyiv, Ukraine)

Thesis: “Search for double beta decay of $^{64,70}Zn$ and $^{180,186}W$ isotopes”

2008–present: Researcher at INR (Kyiv, Ukraine)

Development of $CaMoO_4$ and $^{106}CdWO_4$, realization of several DBD experiments (observation of 2ν DBD transition of ^{100}Mo to excited state of ^{100}Ru)

2010–2012: Postdoc at LNGS, DAMA group (Assergi, Italy)

Development of $^{116}CdWO_4$, realization of several small-scale DBD experiments (observation of 2ν DBD of ^{116}Cd)

2013–present: Postdoc at CSNSM, Solid Physics group, Cryogenic detectors team (Orsay, France)

Development of $ZnMoO_4$, $Zn^{100}MoO_4$ and Li_2MoO_4 scintillating bolometers for DBD search

In total: 11 years research devoted to DBD studies and R&D of detectors based on crystal scintillators for rare event search experiments

Outline

Double Beta Decay

- Two neutrino and neutrinoless DBD
- Present experimental status
- Choice of DBD isotope and technology

Bolometric technology for DBD search

- CUORE and its predecessors with TeO_2

Scintillating bolometers for DBD search

- Čerenkov light from TeO_2
- R&D of $CdWO_4$-based detector
- LUCIFER project with ZnSe
- AMoRE project with $CaMoO_4$
- LUMINEU and LUCINEU programs ($ZnMoO_4$ / Li_2MoO_4)
- CUORE-IHE: beyond CUORE

Summary

Double Beta Decay (Two-neutrino)

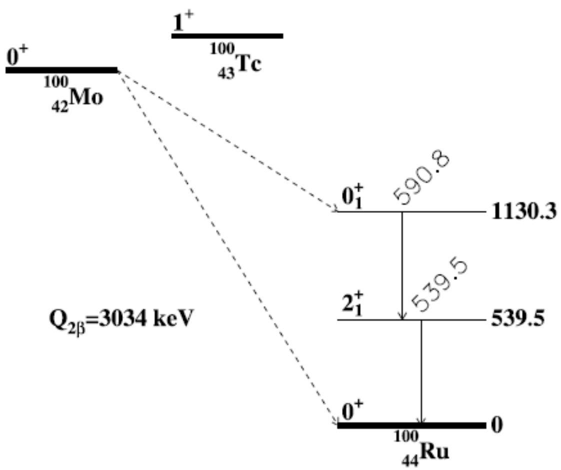
SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Double Beta-Disintegration

M. GOEPPERT-MAYER, *The Johns Hopkins University*

(Received May 20, 1935)

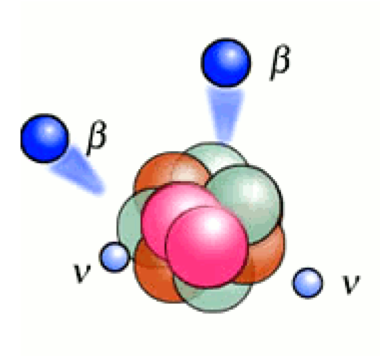
From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.



2νββ decay $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

- Allowed in the Standard Model
- Second order process in weak interactions (very rare decay rate)

$$\left[T_{1/2}^{2\nu}\right]^{-1} = G^{2\nu}(Q_{\beta\beta},Z)\cdot|M^{2\nu}(A,Z)|^2$$



Investigation of 2νββ decay

1950: First geochemical evidence (^{130}Te, $T_{1/2}$ = 1.4×10^{21} yr) [Phys. Rev. 78 (1950) 822]

1987: First observation in direct experiment (^{82}Se, $T_{1/2}$ = 1.1×10^{20} yr) [PRL 59 (1987) 1649]

Up to-date: Registered for 11 from 35 potentially ββ-active nuclides [ADNDT 80 (2002) 83]
Measured $T_{1/2}$ ~ 10^{18} –10^{21} yr (~ 10^{24} yr for ^{128}Te), see e.g. in [Nucl. Phys. A 935 (2015) 52]
Observed 2νββ transition to first 0^+ excited level (for ^{100}Mo and ^{150}Nd)

Double Beta Decay (Neutrinoless)

Teoria simmetrica dell'elettrone e del positrone

Particle = Antiparticle
e.g. for neutrino

NOTA DI ETTORE MAJORANA

"Il Nuovo Cimento", vol. 14, 1937, pp. 171-184.

SULLA SIMMETRIA TRA PARTICELLE E ANTIPARTICELLE

Majorana's theory test
with neutrinos

Nota di GIULIO RACAH

Il Nuovo Cimento July 1937, Volume 14, Issue 7, pp 322-328

DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

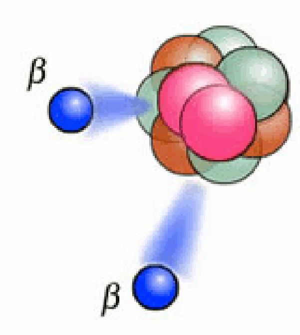
On Transition Probabilities in Double Beta-Disintegration

W. H. FURRY
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts
(Received October 16, 1939)

Test by using NLDBD

The phenomenon of double β-disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double β-disintegration involves the emission of four particles, two electrons (or positrons) and two antineutrinos (or neutrinos), and the probability of disintegration is extremely small. In the Majorana theory only two particles—the electrons or positrons—have to be emitted, and the transition probability is much larger.

Neutrinoless Double Beta Decay

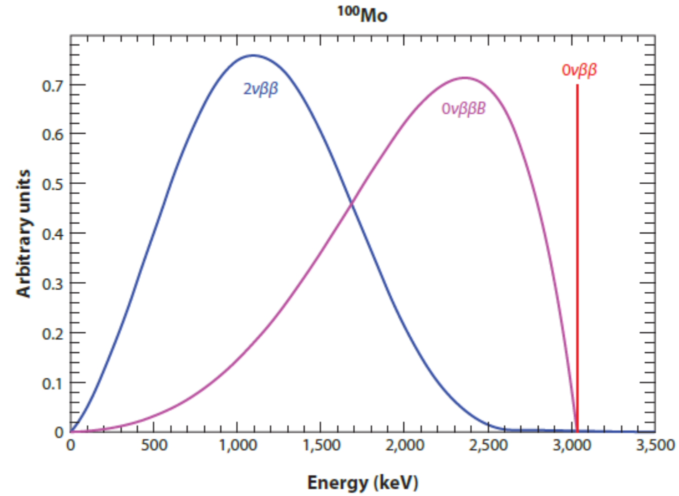


0νββ decay $(A,Z) \rightarrow (A,Z+2) + 2e^-$

- Forbidden in the Standard Model (total lepton number violation, ΔL = 2)

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(Q_{\beta\beta},Z) \cdot |M^{0\nu}(A,Z)|^2 \cdot \langle\mu\rangle^2$$

- $\left[T_{1/2}^{0\nu}\right]^{-1}$: Neutrinoless 0νββ rate
- $G^{0\nu}(Q_{\beta\beta},Z)$: Phase-space factor
- $M^{0\nu}(A,Z)$: Nuclear matrix element
- $\langle\mu\rangle$: L number-violating parameter



Schechter-Valle theorem (independent on mechanism) [PRD 25 (1982) 2951]:

- If a 0νββ occurs, there must be an effective Majorana mass term

Light Majorana neutrino exchange (standard mechanism) [1–6]

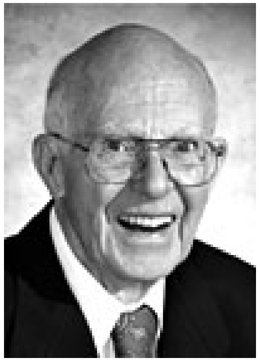
- Neutrinos have non-zero masses and Majorana origin

$$\langle\mu\rangle^2 = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

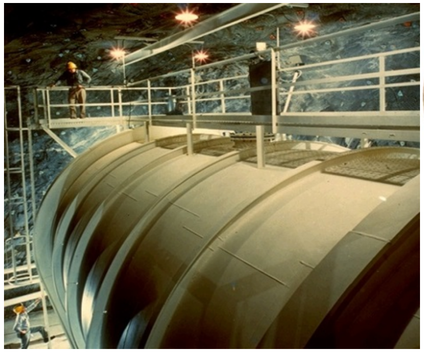
Effective Majorana neutrino mass $\langle m_{\beta\beta}\rangle^2 = \left|\sum_{i=1}^{3} m_i \cdot U_{ei}^2\right|^2$

See recent reviews and references therein:
[1] S.M. Bilenky, C. Giunti, Int. J. Mod. Phys. A 30 (2015) 1530001.
[2] O. Cremonesi and M. Pavan, AHEP 2014 (2014) 951432.
[3] J.D. Vergados at al., Rep. Prog. Phys. 75 (2012) 106301.
[4] J.J. Gomez-Cadenas et al., Riv. Nuovo Cim. 35 (2012) 29.
[5] A. Giuliani and A. Poves, AHEP 2012 (2012) 857016.
[6] W. Rodejohann, Int. J. Mod. Phys. E 20 (2011) 1833.

Neutrino oscillations

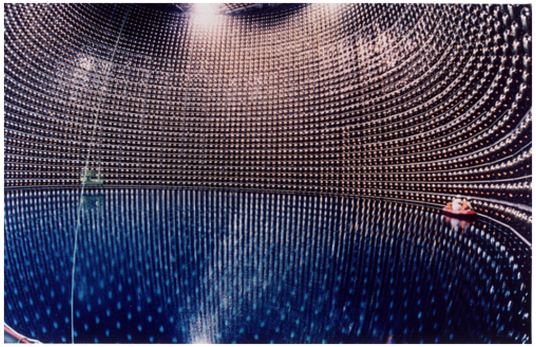


R. Davis Jr.



Homestake exp.

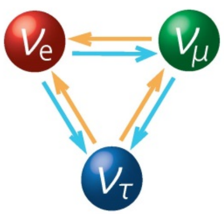
The Nobel Prize in Physics 2002



Super-Kamiokande exp.

M. Koshiba

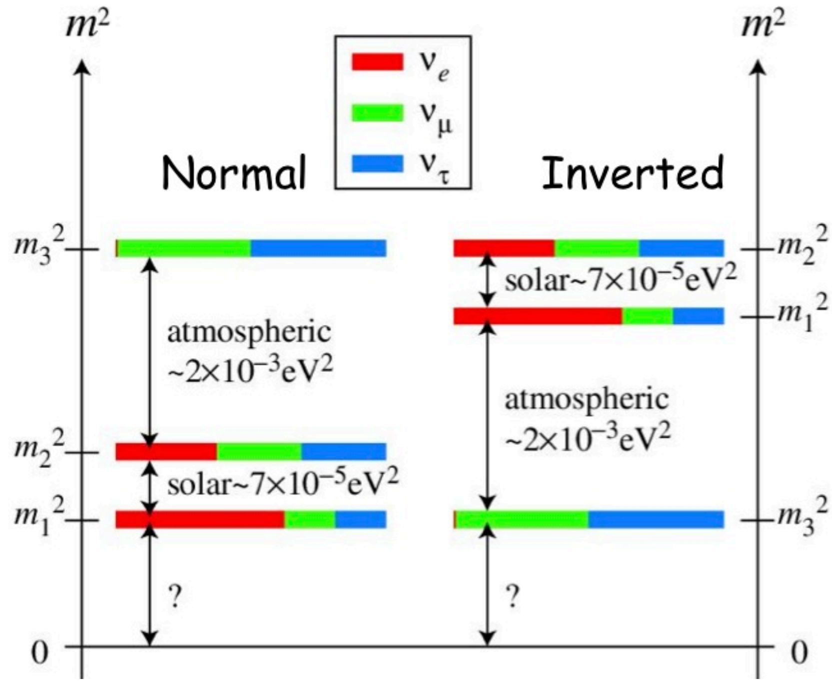
Discovery of neutrino oscillations



- **Lepton flavor number non-conservation**
- **Non-zero neutrino masses**
- **Neutrino flavor mixing**

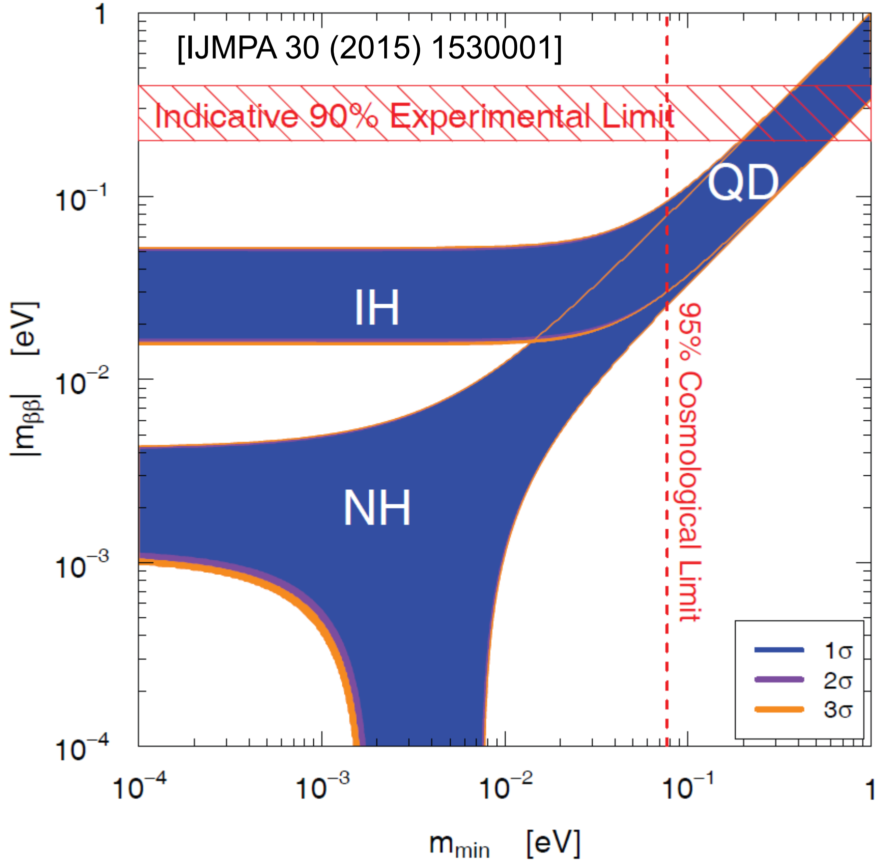
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

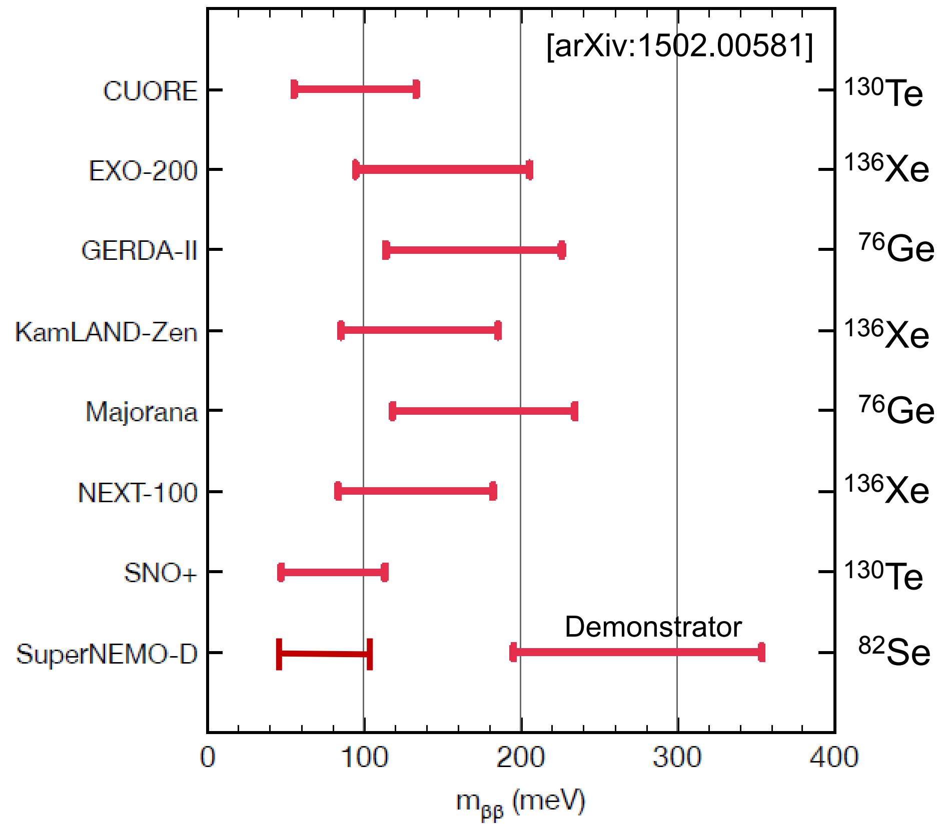
Pontecorvo-Maki-Nakagawa-Sakata matrix



See e.g. [Particle Data Group, Chin. Phys. C 38 (2014) 090001]

Status of 0νββ search



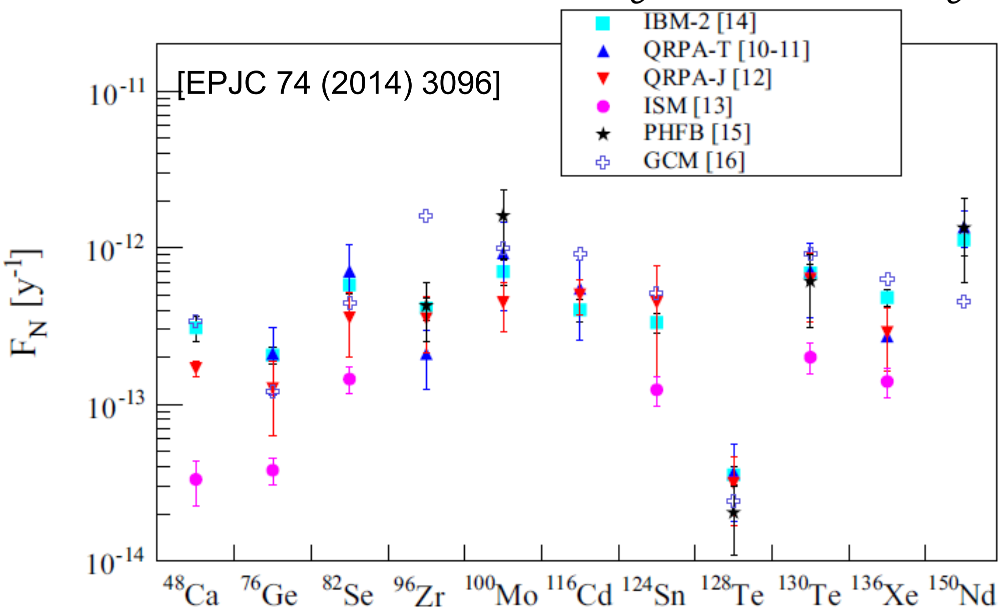


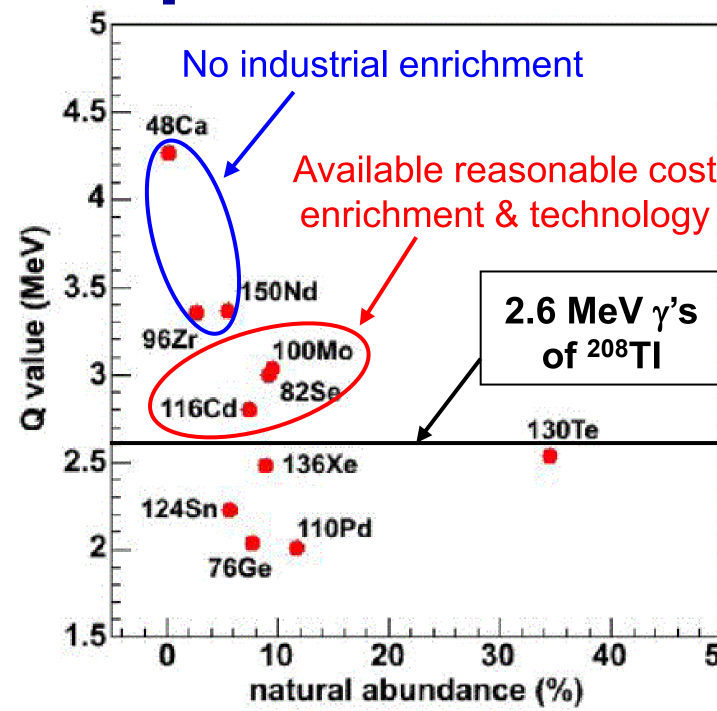
- **Best current sensitivity: $\langle m_{\beta\beta}\rangle$ ~ 0.15–0.9 eV, $T_{1/2}$ ~ 10^{24}–10^{25} yr**
  KamLAND-ZeN (^{136}Xe), GERDA-I (^{76}Ge), CUORICINO (^{130}Te), NEMO-3 (^{100}Mo)
- **Current generation experiments will start probe IH**
  $\langle m_{\beta\beta}\rangle$ ~ 0.05–0.2 eV, $T_{1/2}$ ~ 10^{26} yr
- **New / advanced technology is needed to cover IH**
  $\langle m_{\beta\beta}\rangle$ ~ 0.02–0.05 eV, $T_{1/2}$ ~ 10^{27} yr

See e.g. [AHEP 2014 (2014) 951432] and refs. therein

Choice of ββ isotope

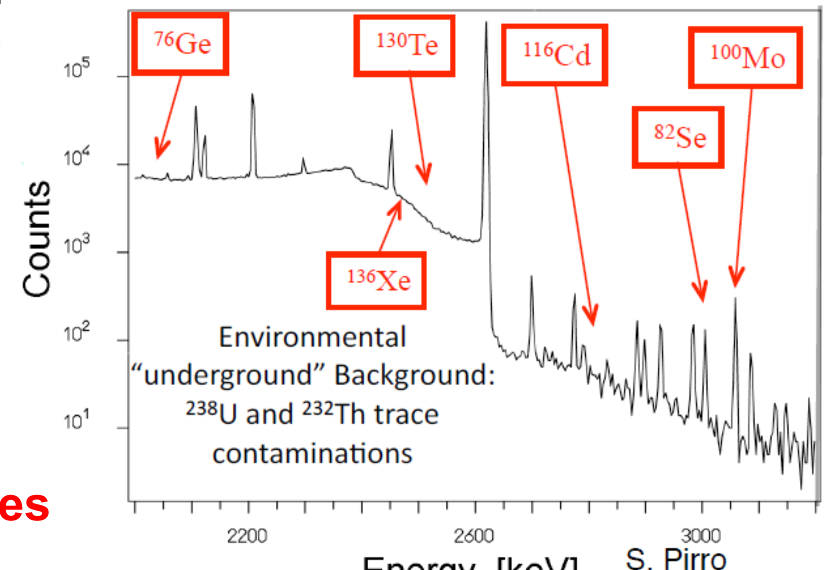
$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} = F_N^{0\nu} \cdot \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$





- **No super ββ isotope exists**
  (in term of nuclear factor F_N)
- **Higher $Q_{\beta\beta}$ is preferred**
  ($G^{0\nu} \propto Q^5$; natural γ's below 2.6 MeV)
- **Higher isotopic abundance**
  (existence of reasonable cost enrichment)
- **Compatibility to existing technology**

^{82}Se, ^{100}Mo, ^{116}Cd – "golden" ββ isotopes



Choice of experimental technology

Sensitivity to $0\nu\beta\beta$ decay

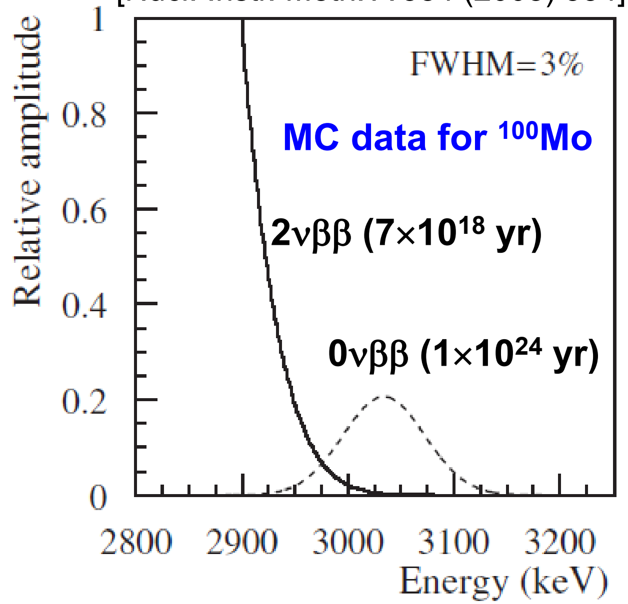
$$\lim T_{1/2}^{0\nu} \propto \begin{cases} \delta/W \cdot \varepsilon \cdot M \cdot t \\ \delta/W \cdot \varepsilon \cdot \sqrt{\dfrac{M \cdot t}{B \cdot \Delta E}} \end{cases}$$

zero / non-zero Background

- δ – isotopic abundance of ββ nuclide
- W – molecular weight of ββ source
- ε – detection efficiency
- M – mass of ββ source [kg]
- t – time of measurements [yr]
- ΔE – energy range of interest (ROI) [keV]
- B – background index in ROI [counts/kg/keV/yr]

[New J. Phys. 7(2005) 6]

[Nucl. Instr. Meth. A 584 (2008) 334]



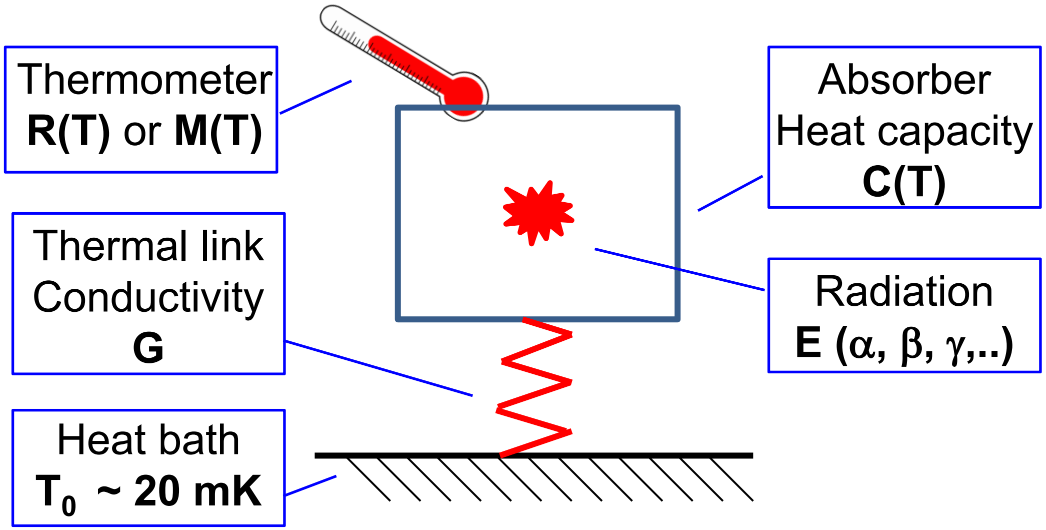
- **High isotopic abundance**
  enrichment of ββ source
- **High registration efficiency**
  "detector = ββ source"
- **Large detector mass**
  scalability of a technology
- **Long-term measurements**
  operational stability

- **Extremely low background in ROI**
  underground conditions
  massive passive / active shields
  high radiopurity of a detector
- **High detector performance**
  high energy resolution
  tracking / topology capability
  background rejection capability
  fast time response

No technology can satisfy all requirements

[see e.g. AHEP 2012 (2012) 857016]

Bolometric technique

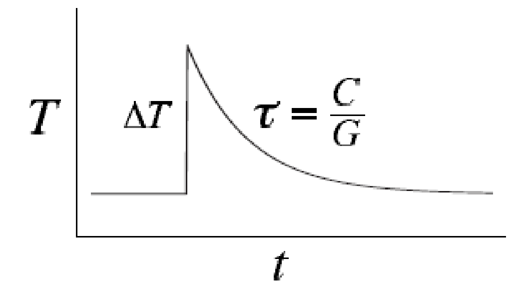


$$C(T) \propto \left(\frac{T}{\Theta_D}\right)^3$$

$$\Delta T = \frac{E}{C} \Rightarrow \Delta V$$

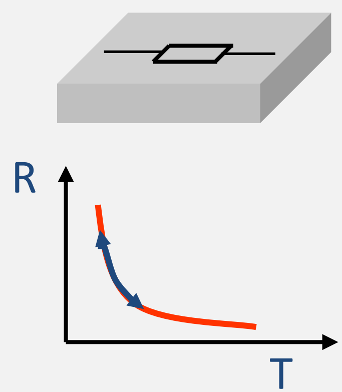
~0.1 mK/MeV

~0.1–0.5 mV/MeV

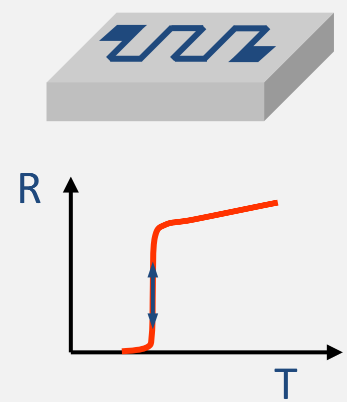


Temperature sensors

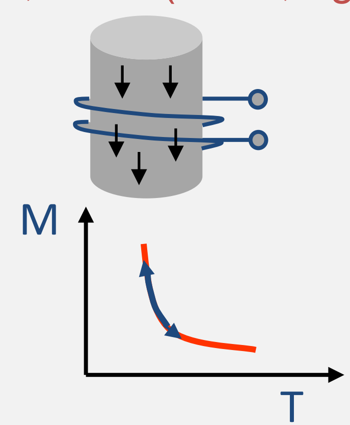
Highly doped semiconductors, NTD Ge



Superconducting transition, TES (IrAu, NbSi,..)



Magnetization of paramagnetic material, MMC (Au:Er, Ag:Er,..)



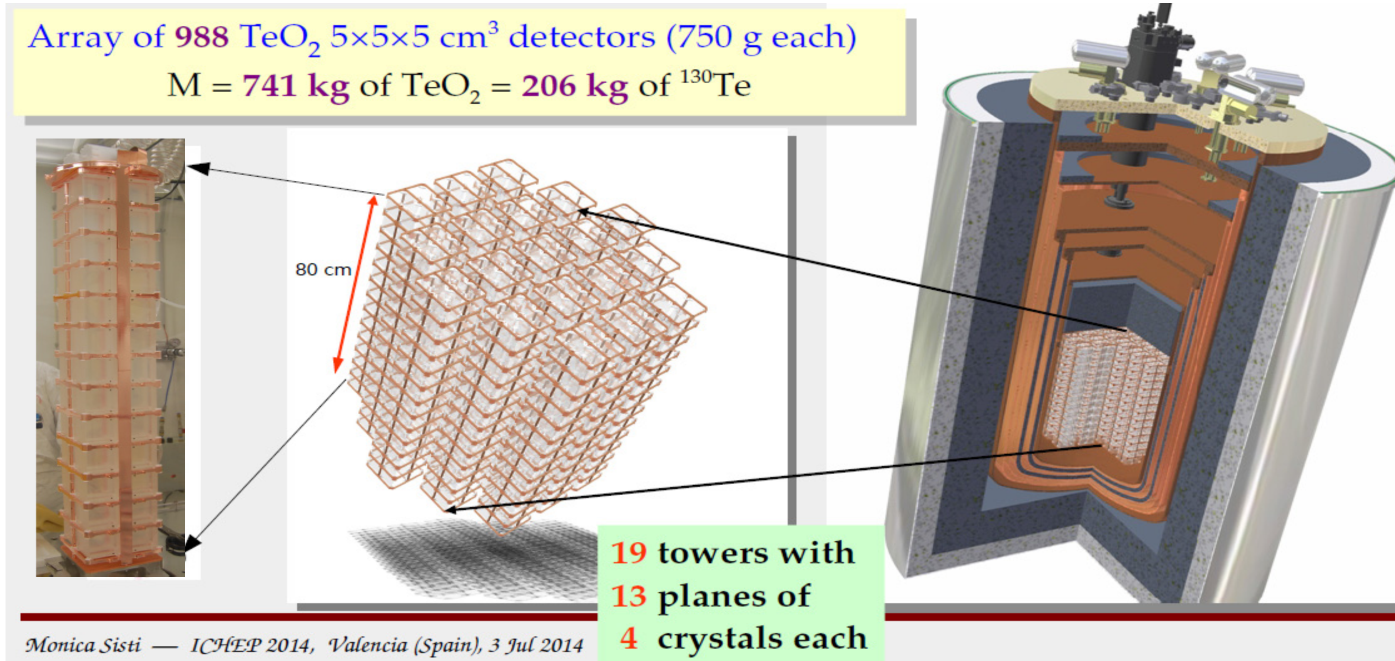
[A. Fleischmann, talk at LUMINEU meeting, Orsay, France, 7-8 Dec. 2014]

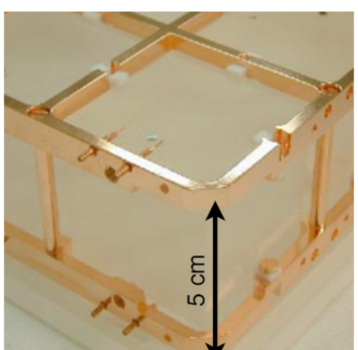
See also [Cryogenic Particle Detection, Topics Appl. Phys. 99 (2005) 501 pp.]

TeO_2-based bolometric ββ experiments

MIDBD-I	MIDBD-II	CUORICINO	CUORE-0	CUORE
1997	2001	2003–2008	2013–2015	2015–2020
6.8 kg TeO_2	**6.8 kg** TeO_2	**41 kg** TeO_2	**41 kg** TeO_2	**741 kg** TeO_2

Cryogenic
Underground
Observatory for
Rare
Events





Radiopurity control protocol to limit bulk and surface contaminations in crystals
[J. Cryst. Growth 312 (2010) 2999]

Dedicated runs @ LNGS
[Astropart. Phys. 35 (2012) 839]

Nuclide	Allowed	Measured
^{238}U	≤ 0.3 ppt	≤ 0.05 ppt
^{232}Th	≤ 0.3 ppt	≤ 0.2 ppt
^{210}Pb	≤ 10 μBq/kg	≤ 3.3 μBq/kg
^{210}Po	≤ 0.1 Bq/kg	≤ 0.05 Bq/kg

Background in CUORICINO and CUORE-0

CUORICINO

Bkg in ROI

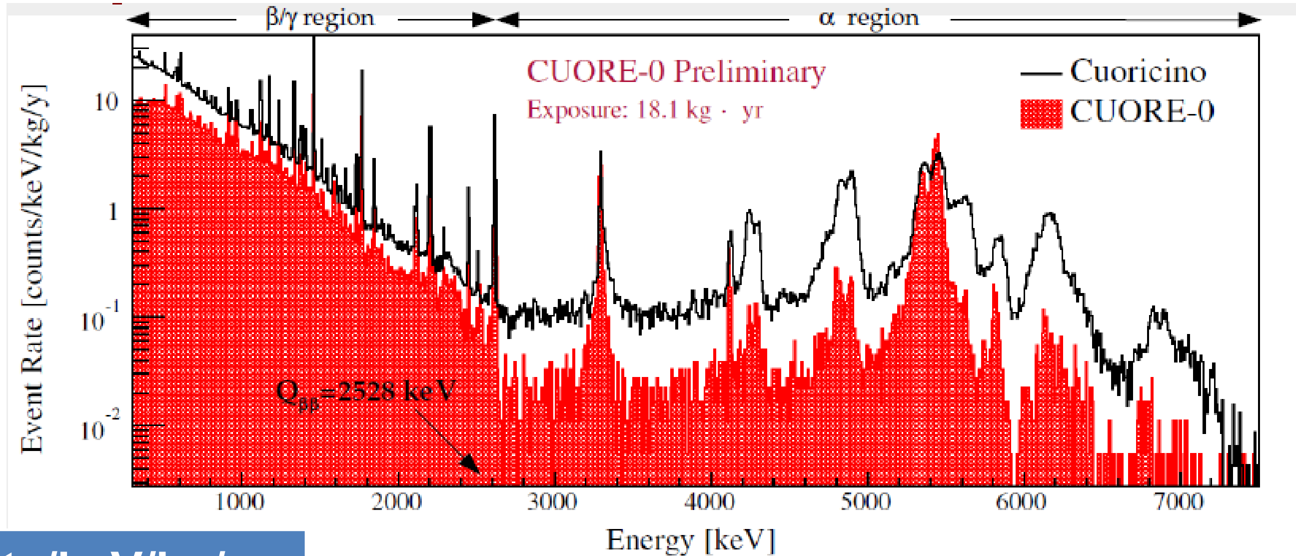
0.153(6) counts/keV/kg/yr

Contribution to ROI:

TeO_2 surface ~ 10±10 %

Cu surface ~ 50±20 %

Th in set-up ~ 30±10 %



	Bkg, counts/keV/kg/yr	
	ROI	2.7–3.9 MeV
CUORICINO	0.153(6)	0.110(1)
CUORE-0	0.063(6)	0.020(1)

In the same set-up [Eur. Phys. J. C 74 (2014) 2956]

CUORE goal

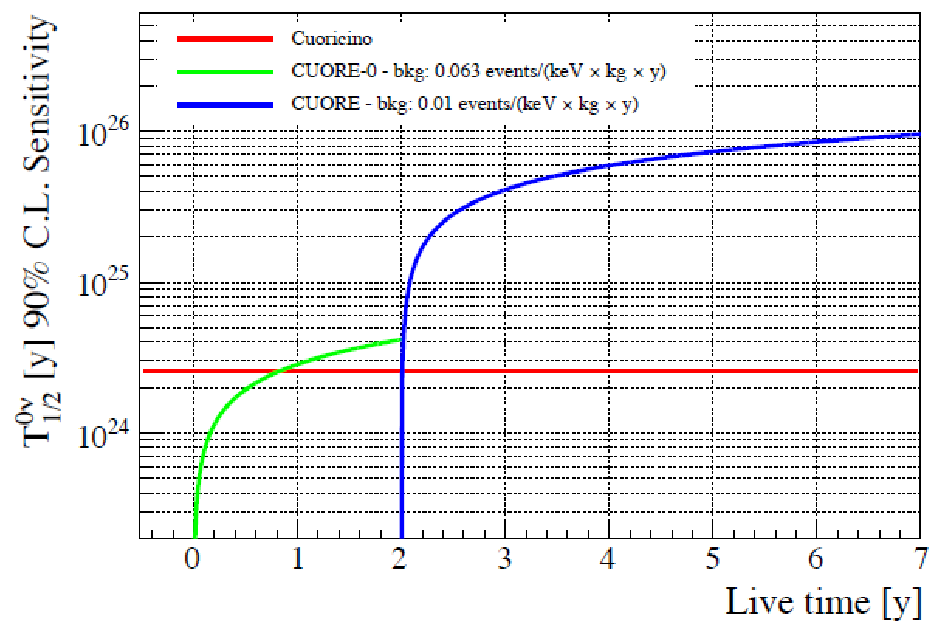
Bkg in ROI: 0.01 counts/keV/kg/yr

FWHM = 5 keV

Live time = 5 yr

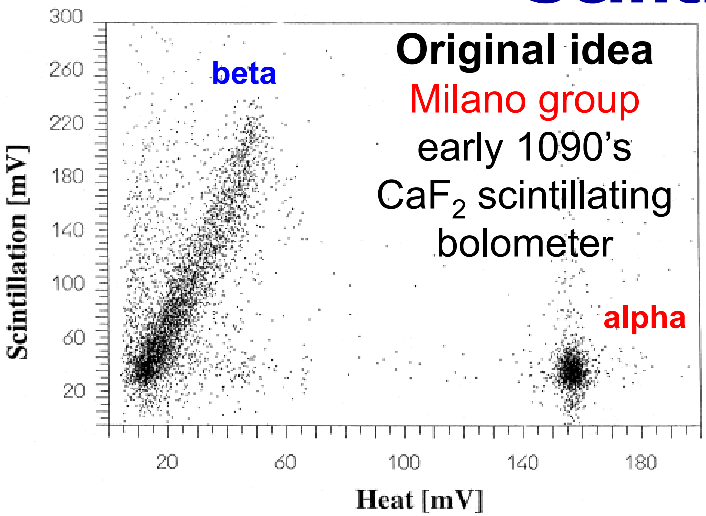
$T_{1/2}$ ~ 10^{26} yr, $\langle m_{\beta\beta} \rangle$ ~ 50–130 meV

[Nucl. Instr. Meth. A 518 (2004) 775]

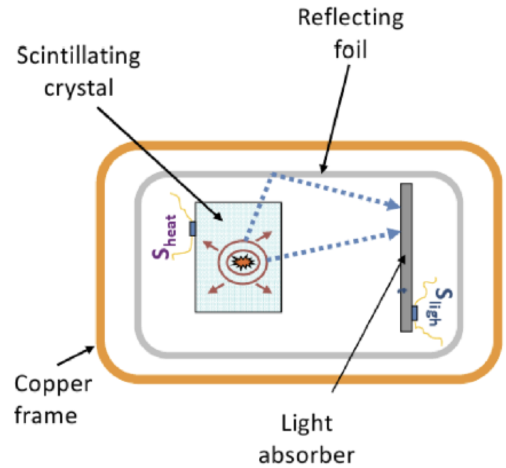


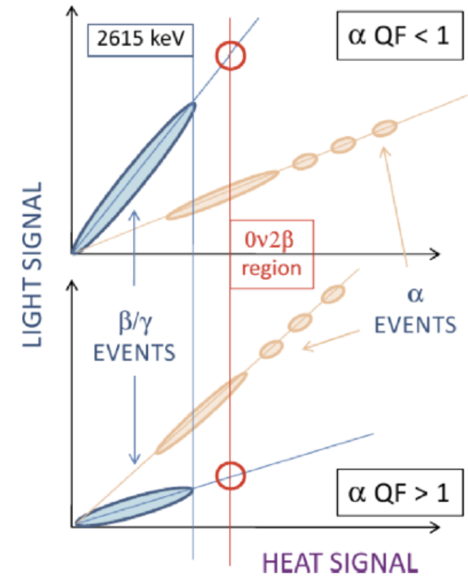
[M. Sisty, talk at ICHEP 2014, Valencia, Spain, 2-7.07.2014]

Scintillating bolometer



[Mater. Sci. Eng. R11 (1993) 1; PLB 420 (1998) 109]





ISSN 1063-7788, *Physics of Atomic Nuclei*, 2006, Vol. 69, No. 12, pp. 2109–2116. © Pleiades Publishing, Inc., 2006.

Proceedings of the 5th International Conference
on NONACCELERATOR NEW PHYSICS
Double-Beta Decay and Rare Processes

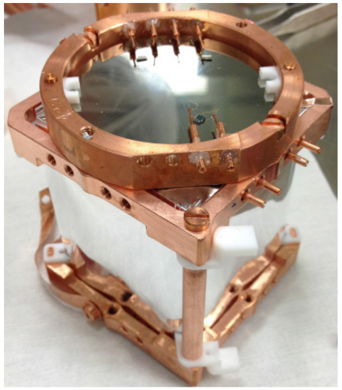
Scintillating Double-Beta-Decay Bolometers*

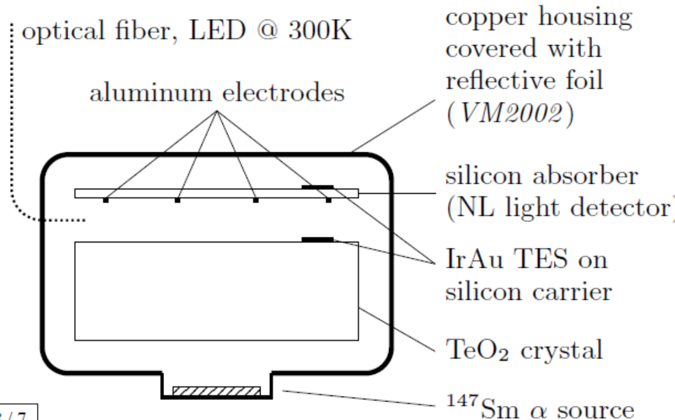
S. Pirro[1)**], J. W. Beeman[2)], S. Capelli[1)], M. Pavan[1)], E. Previtali[1)], and P. Gorla[3)]

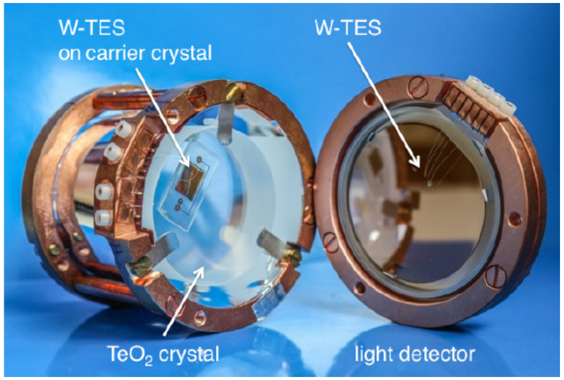
Received November 23, 2005

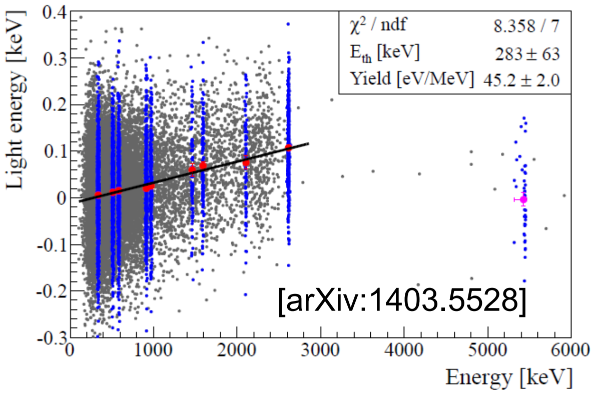
Abstract—We present the results obtained in the development of scintillating double-beta-decay bolometers. Several Mo and Cd based crystals were tested with the bolometric technique. The scintillation light was measured through a second independent bolometer. A 140-g $CdWO_4$ crystal was run in a 417-h live time measurement. Thanks to the scintillation light, the α background is easily discriminated, resulting in *zero* counts above the 2615-keV γ line of ^{208}Tl. These results, combined with an extreme easy light detector operation, represent the first tangible proof demonstrating the feasibility of this kind of technique.

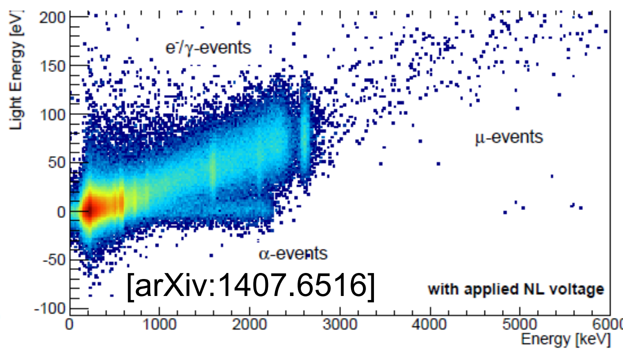
Čerenkov light emitted by TeO_2 bolometer

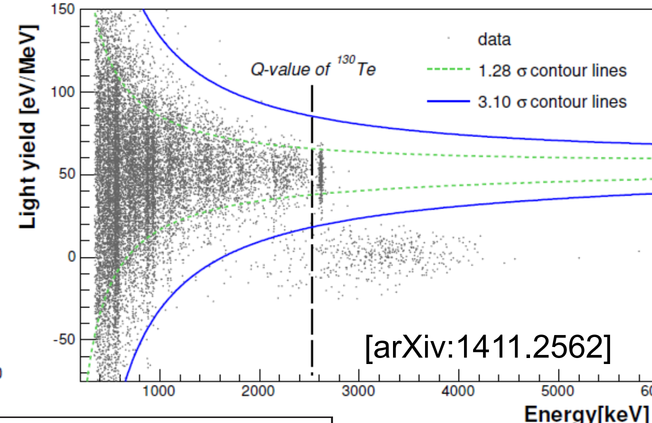


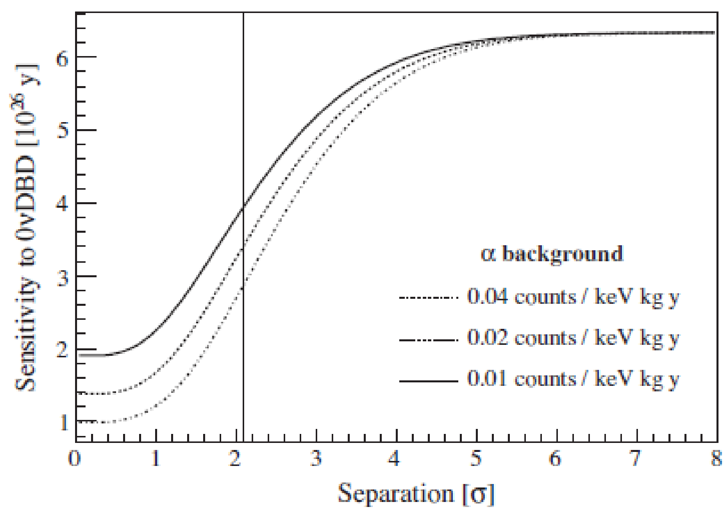








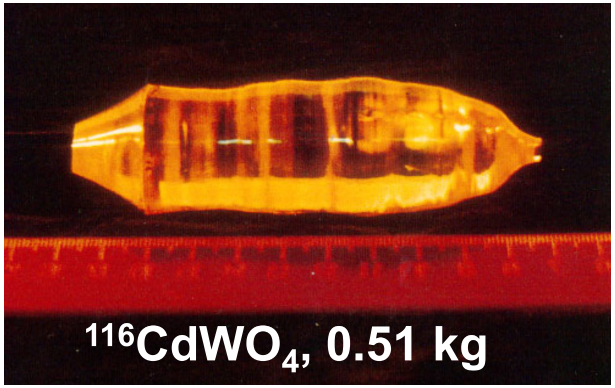




Discrimination of α's in the ROI allows to improve the CUORE sensitivity by a factor 3–4

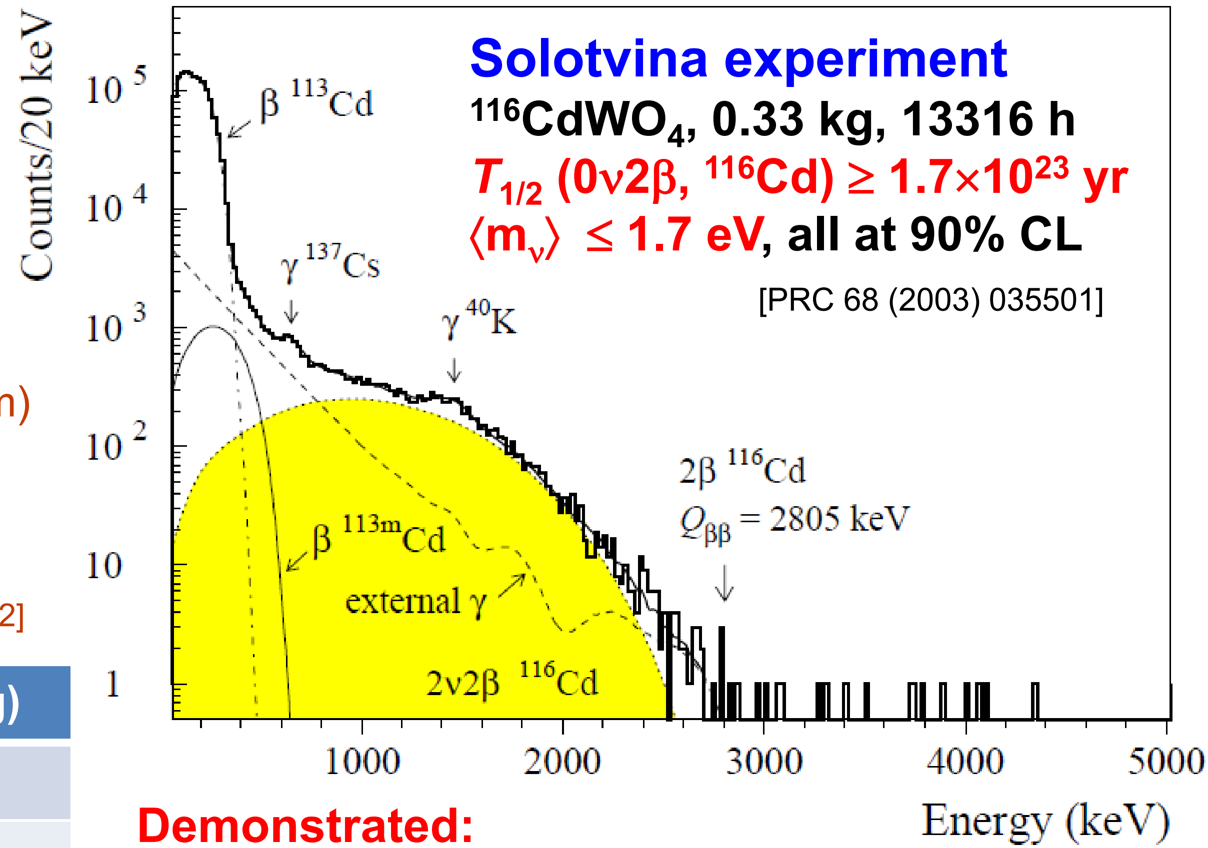
[Astropart. Phys. 35 (2012) 558]

Cadmium tungstate ($CdWO_4$) as a ββ detector



- $^{116}CdWO_4$ crystal (∅35×112 mm) enriched in ^{116}Cd to 83%
- Cz growth in ISMA (Kharkiv)
- ^{116}Cd purified twice by vacuum distillation [Phys. Lett. B 334 (1995) 72]

Nuclide	Activity (mBq/kg)
^{228}Th	0.039(2)
^{226}Ra	≤ 0.004
^{40}K	0.3(1)
^{113}Cd	91(5)
^{113m}Cd	1.1(1)
^{137}Cs	0.43(6)



Demonstrated:

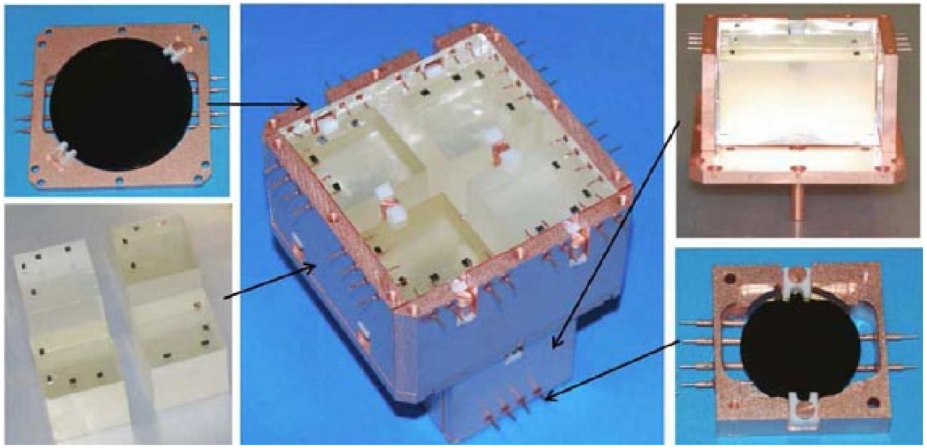
- Possibility to grow from enriched ^{116}Cd
- Excellent radiopurity
- Promising scintillator for 0ν2β search

Required:

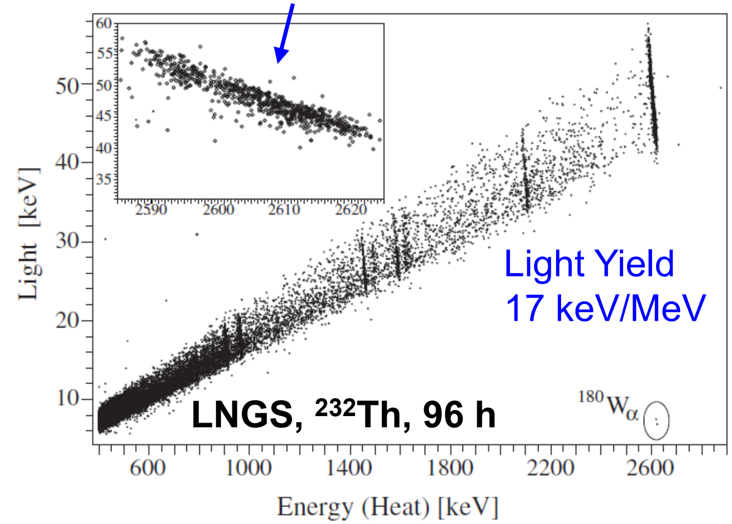
- Higher quality and larger size
- Higher enrichment to reduce long-live ^{113}Cd (i.a ~12%, $T_{1/2}$ ~ 8×10^{15} yr) and bkg $^{113}Cd(n,\gamma)$

$CdWO_4$ – excellent scintillating bolometer

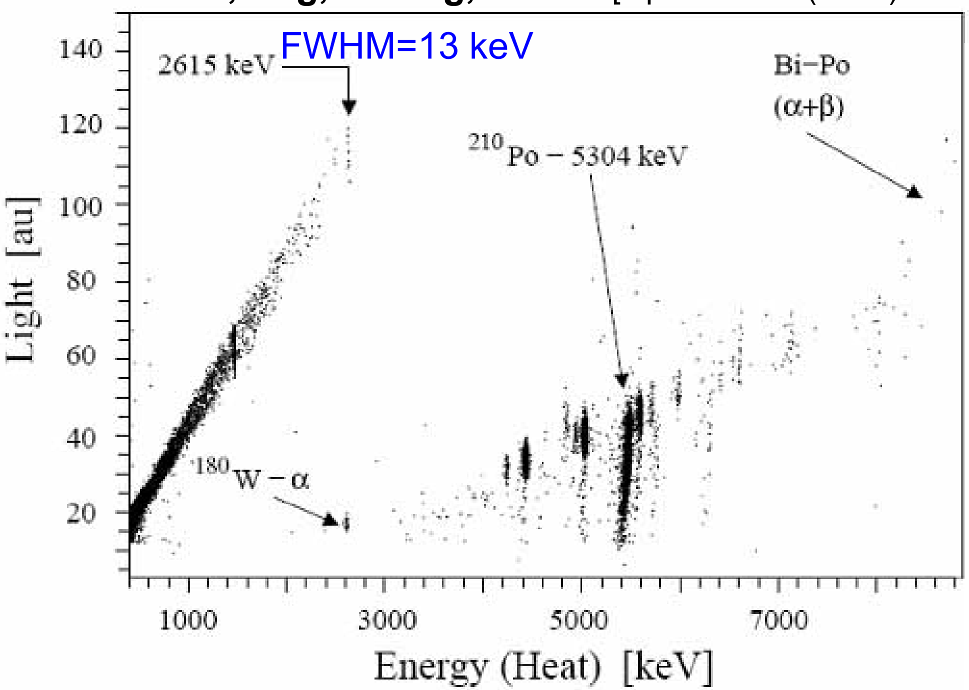
First $CdWO_4$ array (4x 3×3×3 cm & 3×3×6 cm)

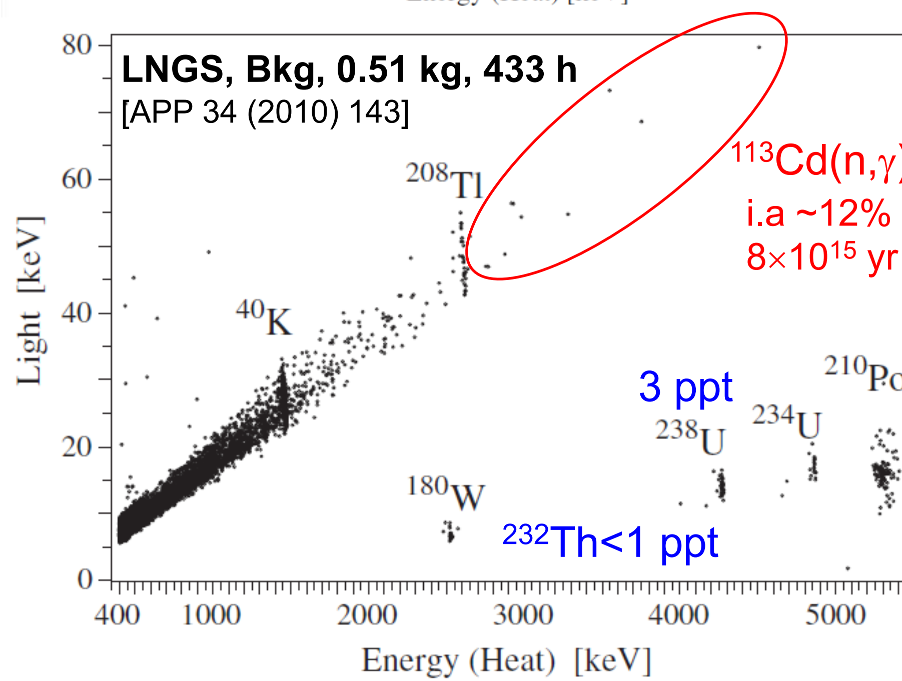


Anticorrelation: FWHM = 16→ 6 keV

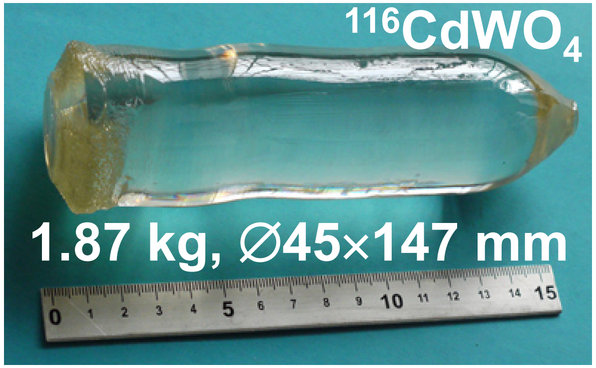


LNGS, Bkg, 0.43 kg, 1066 h [Opt. Mat. 31 (2009) 1382]





Development of large enriched $^{116}CdWO_4$ crystal



- Enriched cadmium (^{116}Cd – 82.2%, but ^{113}Cd ~ 2%)
- Deep purification of initial materials
- Low-thermal-gradient Czochralski (LTG Cz) method
- High crystal yield (87%)
- Low irrecoverable losses of ^{116}Cd (< 2.3%)
- Excellent optical and scintillation properties
- High radiopurity (except ^{113}Cd / ^{113m}Cd)
- DBD search in DAMA\R&D at LNGS (since 2011)

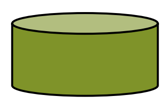
Nuclide	Activity (mBq/kg)	
	No.1	No.2
^{228}Th	0.031(3)*	0.054(2)*
^{238}U	0.5(2)	0.7(2)
^{226}Ra	≤ 0.005	≤ 0.005
^{210}Po	0.6(2)	0.8(2)
^{40}K	≤ 0.9	≤ 0.9
^{113}Cd	100(10)	100(10)
^{113m}Cd	460(20)	460(20)

* - Varies in time ⇒ $T_{1/2}$ (^{228}Th) ~ 1.9 yr

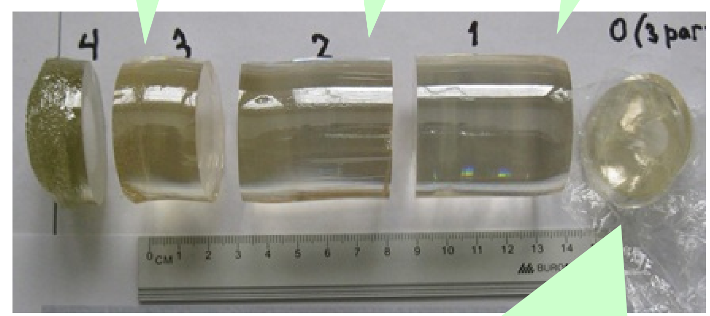
Radiopurity can be further improved by recrystallization

Activity of ^{228}Th (mBq/kg) in the crystal boule

10(2) | 0.09(1) | 0.04(1) | 0.02(1)



rest of the melt after the crystal growth



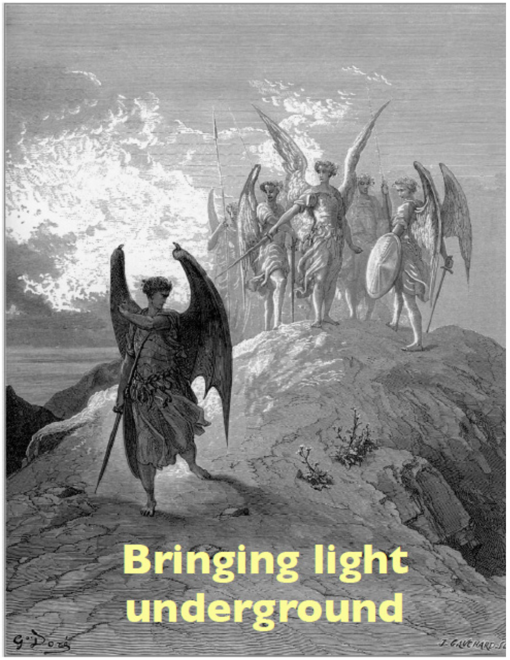
Bolometric test is expected

[JINST 6 (2011) P08011; Rad. Meas. 56 (2013) 66; EPJ WC 65 (2014) 01005]

LUCIFER project

Low-background Underground Cryogenics Installation For Elusive Rates

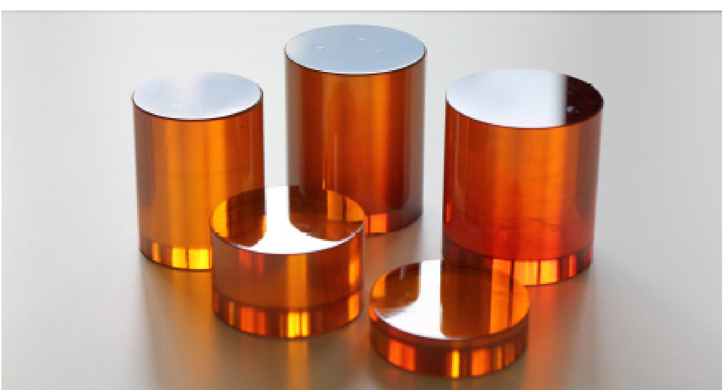
ERC-2009-AdG 247115



Principal Investigator:
F. Ferroni

Co- Investigator:
A.Giuliani

Coordinator: S.Pirro



Double Beta Decay pilot project based on scintillating bolometers

The experimental basis for **LUCIFER** is the R&D performed by **S. Piro** at LNGS in the framework **BoLux** (INFN) and **ILIAS-IDEA** (EC WP2-P2)

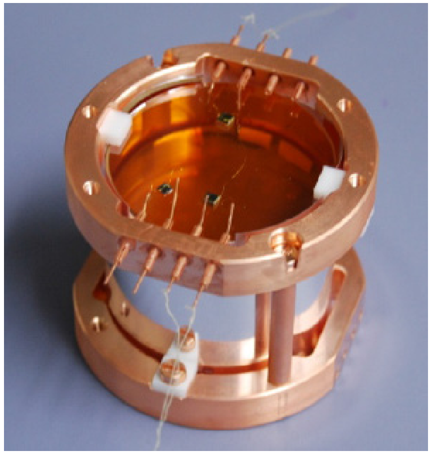
Crystal	Isotope ($Q_{\beta\beta}$, keV)	Useful material	$LY_{\gamma(\beta)}$, keV/MeV
$CdWO_4$	^{116}Cd (2814)	32%	~ 17
$ZnMoO_4$	^{100}Mo (3034)	44%	~ 1
ZnSe	^{82}Se (2996)	56%	~ 7

Primary solution: ZnSe

- ✓ Higher % of useful material
- ✓ Lower price of enrichment
- ✓ Quite high light yield (essential for PSD)
- ✓ ZnSe is well known compound (used as an IR optical material and scintillation detector)

But: High melting point, volatility of Zn and Se, low crystal yield, no commercial use of large size

LUCIFER: performance of large mass ZnSe bolometer

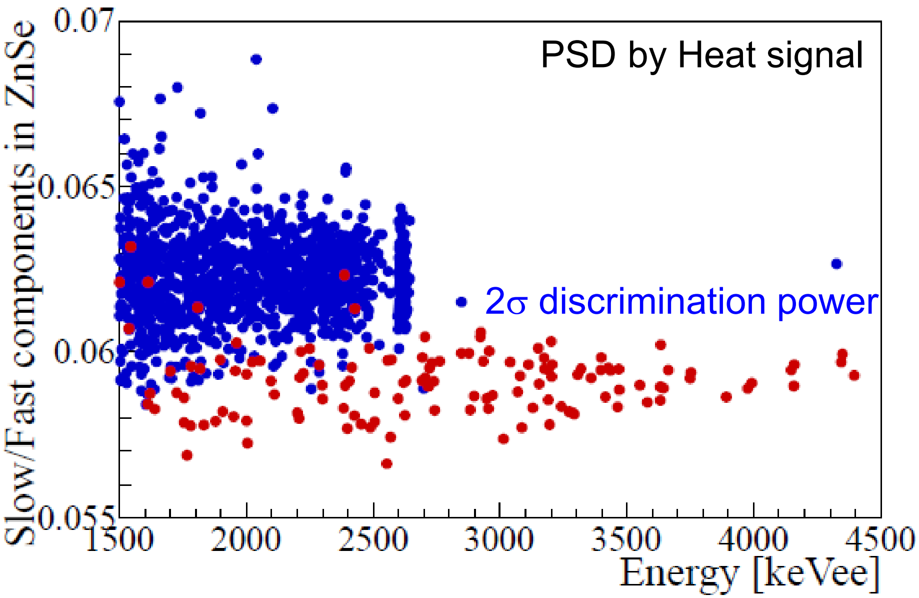


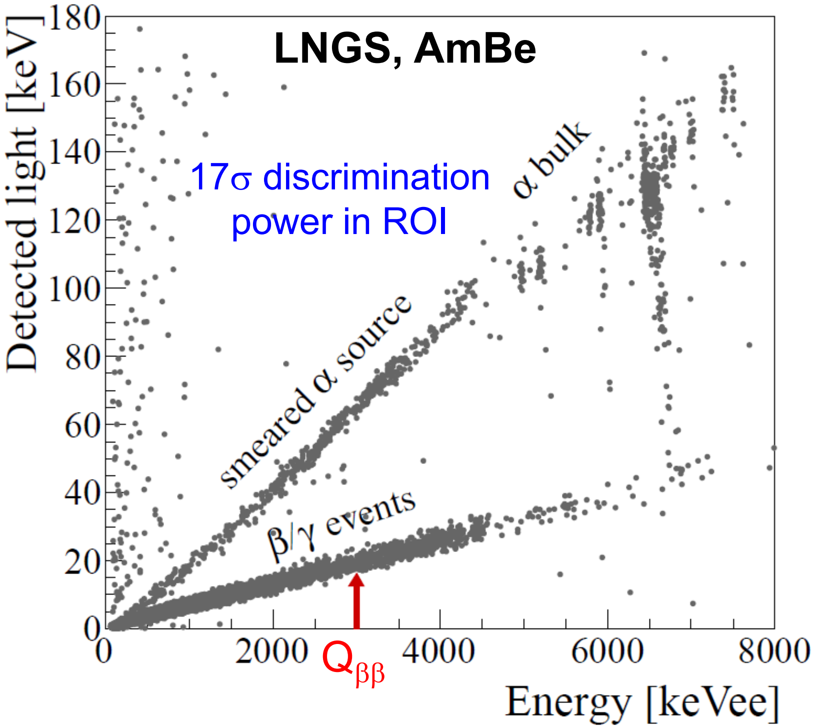
ZnSe, 431 g,
∅44 × 48 mm
SmiLab Svitlovodsk (Ukraine)

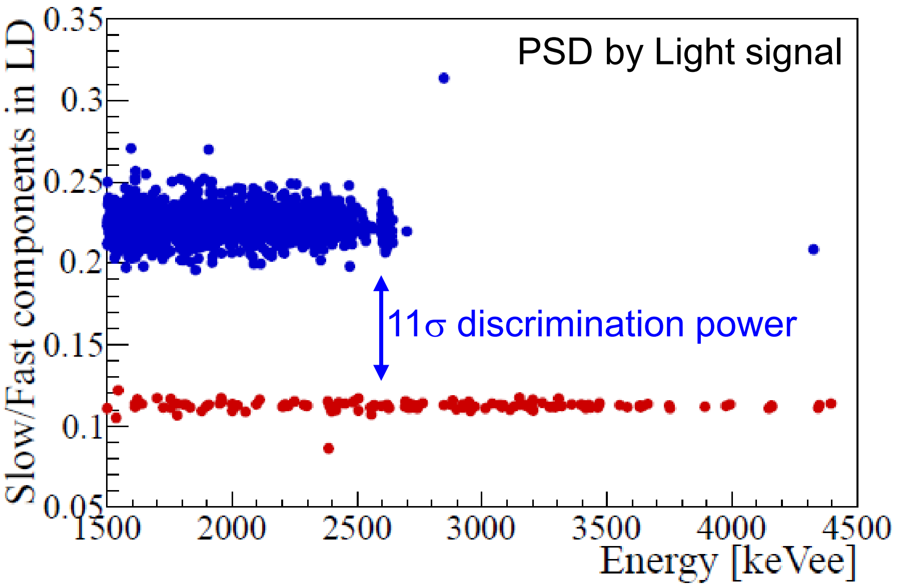
Ge light detector covered by SiO_2

NTD-based sensors

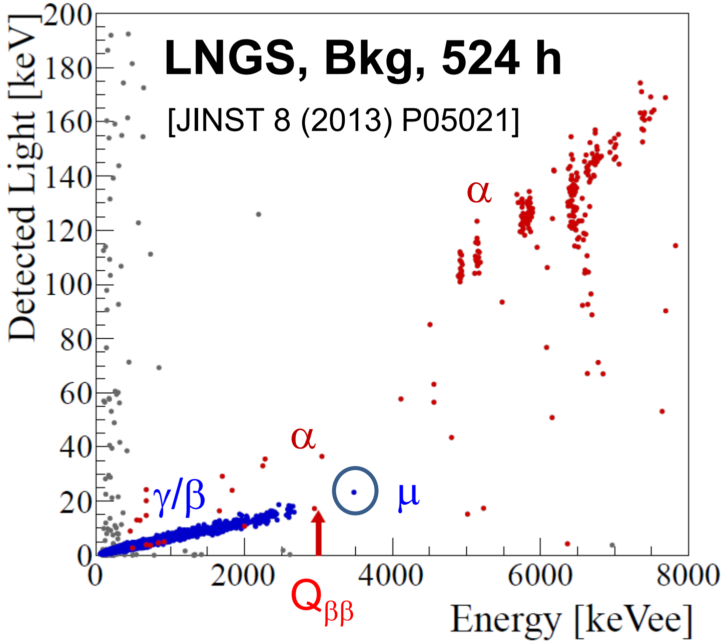
[JINST 8 (2013) P05021]

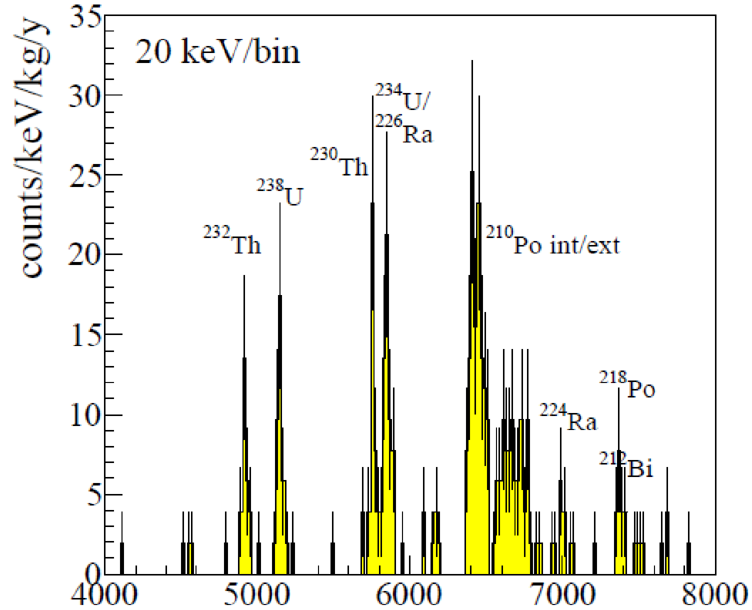




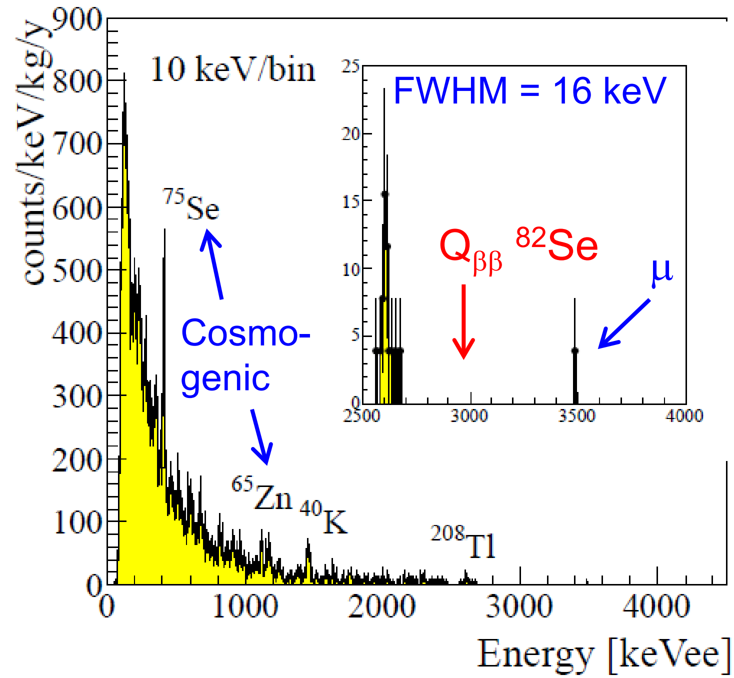


LUCIFER: performance of large mass ZnSe bolometer

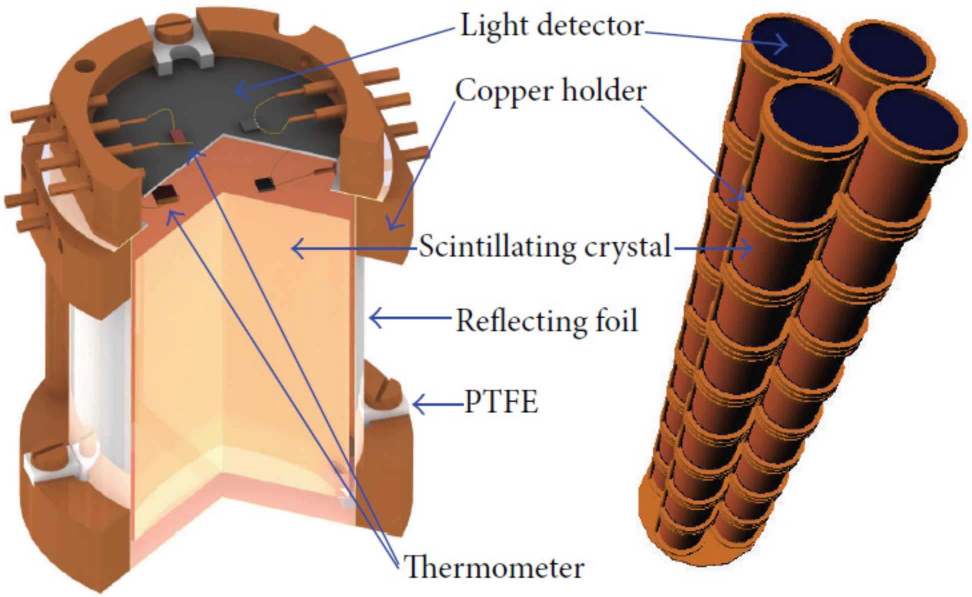




Nuclide		A, μBq/kg
^{232}Th	^{232}Th	17(5)
	^{228}Th	11(4)
^{238}U	^{238}U	25(6)
	^{234}U	18(3)
	^{230}Th	25(6)
	^{226}Ra	18(3)
	^{210}Po	91(11)

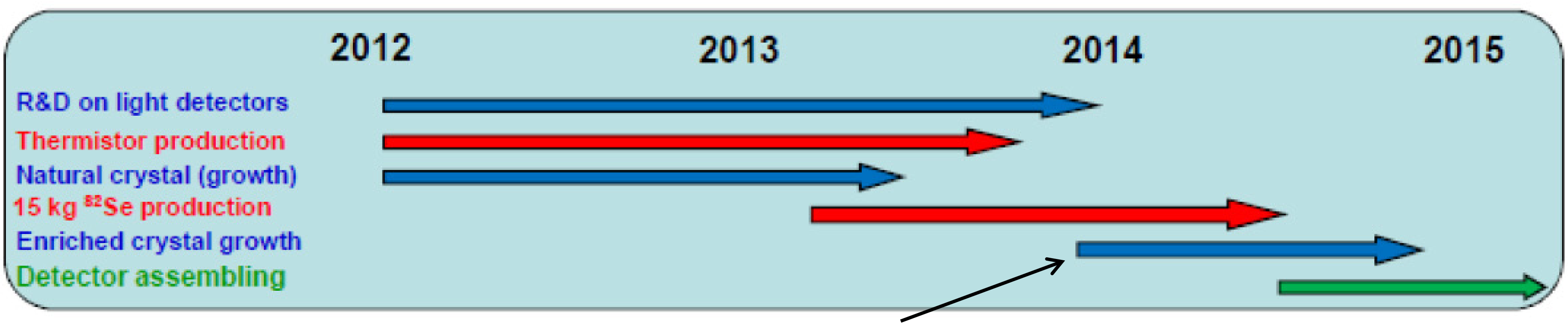


LUCIFER Schedule



LUCIFER goal

- **15 kg of 95% enriched ^{82}Se**
- **36 Zn^{82}Se crystals** (∅45×55 mm, ~ 461 g)
- **FWHM at ROI: 10÷15 keV**
- **Bkg in ROI: ~10^{-3} counts/keV/kg/yr**
- **Cuoricino cryostat @ LNGS**
- **5-yr sensitivity: $T_{1/2}$ ~ 6 × 10^{25} yr, ⟨$m_{\beta\beta}$⟩ ~ 0.065–0.19 eV**



Delay ~1 year due to crystallization issue

[J.W. Beeman et al., AHEP 2013 (2013) 237973]

$CaMoO_4$ as a detector of $0\nu\beta\beta$ of ^{100}Mo

2002: **Idea**, $CaMoO_4$ growth in Korea

2003: Russian group joined, R&D

2004: 1st talk at VIETNAM'2004, idea of $CaMoO_4$ cryogenic detector

2005–2007: 1st ISTC project for large CMO crystal growth in Russia

2006: Ukrainian group joined, CMO crystal growth in Ukraine

2007: start R&D of CMO cryogenic technique

2008: 2nd ISTC project for 1 kg enriched $^{40}Ca^{100}MoO_4$ crystal growth

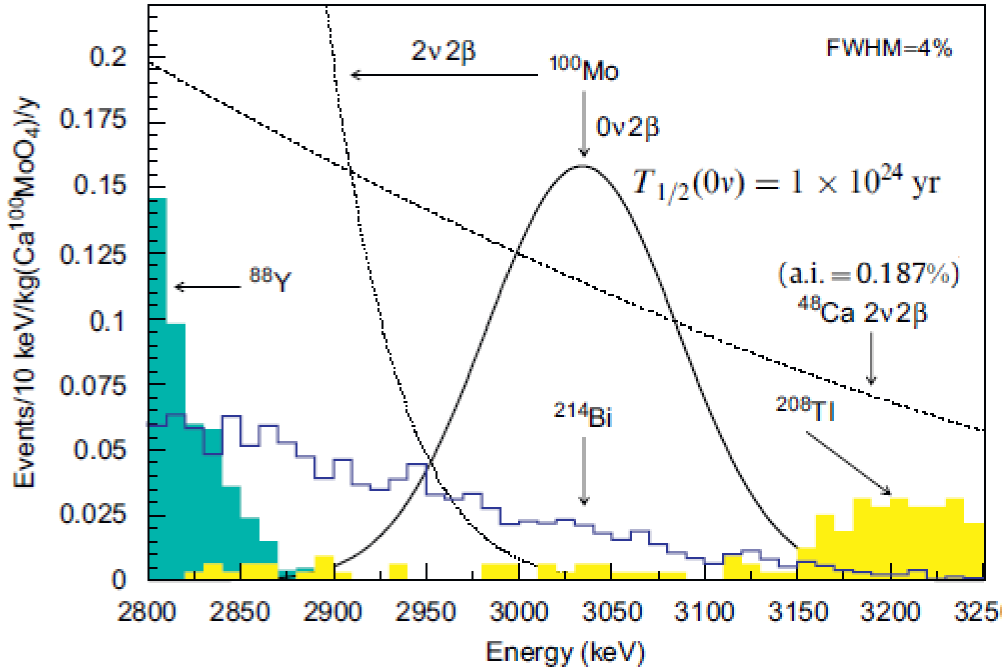
2009: **AMoRE collaboration formed** with 5 countries

2010–2011: studies $^{40}Ca^{100}MoO_4$ properties and radiopurity

2012: **$^{40}Ca^{100}MoO_4$ production line funded** by Russia

2013: **AMoRE project fully funded for 10 years** by Korea (IBS CUNPA)

[Nucl. Instr. Meth. A 584 (2008) 334]



Perspectives for a high sensitivity experiment to search for the $0\nu2\beta$ decay of ^{100}Mo are discussed. The energy resolution of 4–5% is enough to reach a sensitivity at the level of 10^{25} yr. The contamination of crystals by ^{226}Ra and ^{232}Th should not exceed the level of 0.1 mBq/kg. The two neutrino 2β decay of ^{48}Ca restricts the sensitivity of an experiment to search for the $0\nu2\beta$ decay of ^{100}Mo using $CaMoO_4$ crystal scintillators. A possible solution would be to produce $CaMoO_4$ scintillators from Calcium depleted in ^{48}Ca. A further improvement of sensitivity could be achieved by using $CaMoO_4$ crystals as scintillating bolometers.

AMoRE: Advanced Mo based Rare process Experiment

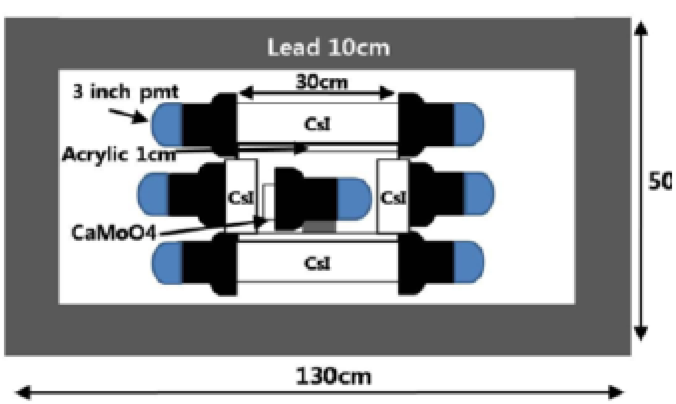
8 countries, 18 institutions, ~ 90 collaborators from 

~ 1.5 kg of $^{40}Ca^{100}MoO_4$ crystals (^{100}Mo – 96.1%, ^{40}Ca – 99.964%, ^{48}Ca < 0.001%)

produced by Czochralski method at the FOMOS-Materials plant (Moscow, Russia) [1–3]

Radiopurity tested at Yangyang underground laboratory (Korea)

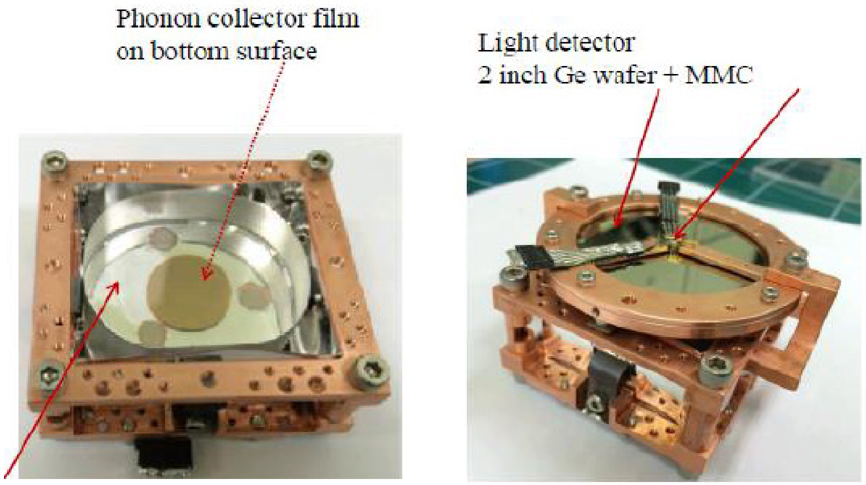
4π gamma veto system



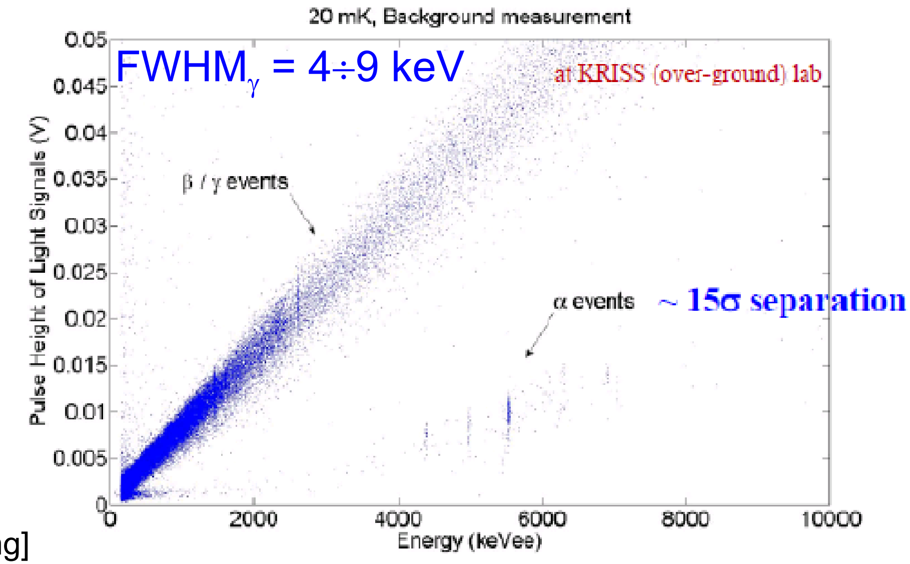
Nuclide	Activity (mBq/kg)				
	SB28	NSB29	S35	SS68	SS81
^{228}Th	0.07	0.032	0.64	0.027	
^{227}Ac	-	0.67	1.6	0.24	
^{226}Ra	0.08	0.23	4.5	0.062	1.6 *

[1] H. Bhang et al., J. Phys. Conf. Ser. 375 (2012) 042023.
[2] J.H. So et al., IEEE Trans. Nucl. Sci. 59 (2012) 2214.
[3] Jungho So, 9th AMoRE Coll. meeting, SNU, Korea, 12-13.02. 2015]

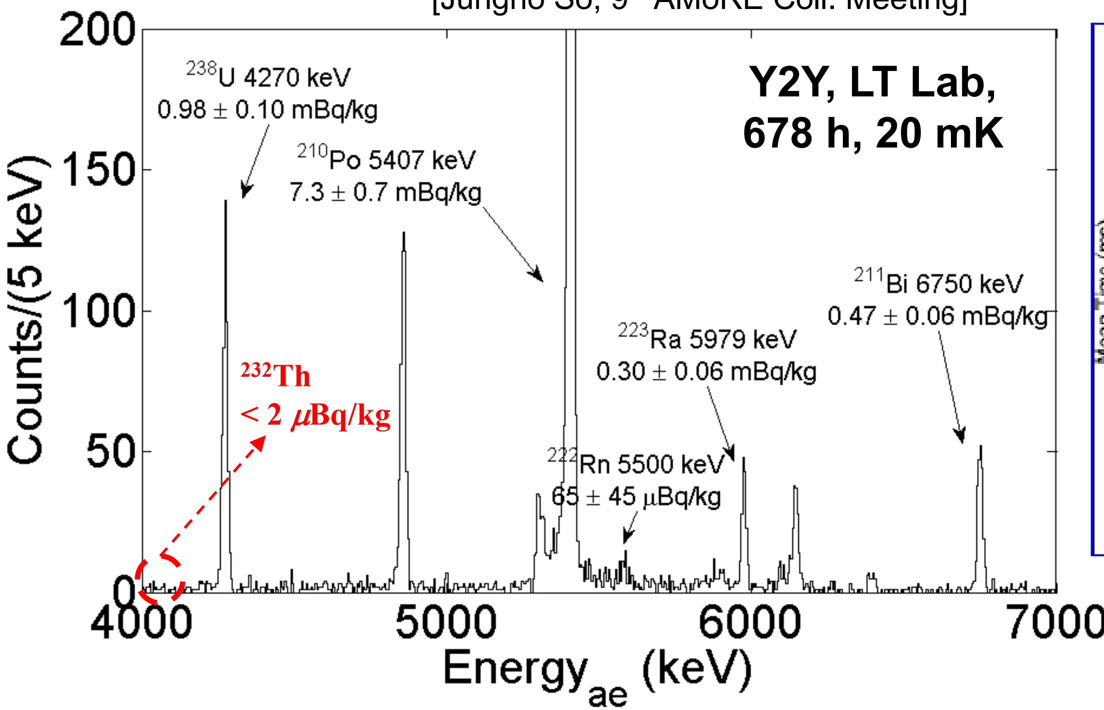
AMoRE: $^{40}Ca^{100}MoO_4$ scintillating bolometer

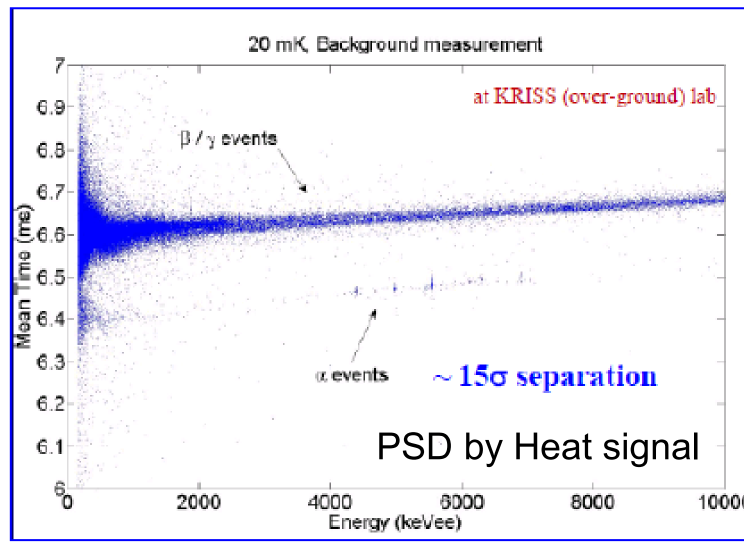


$^{40}Ca^{100}MoO_4$, 196 g



[Jungho So, 9th AMoRE Coll. Meeting]



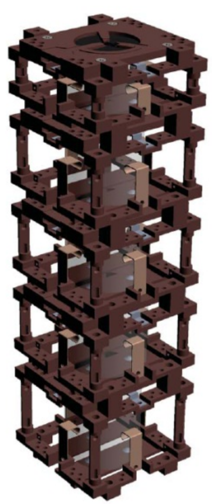


Rise time: ~0.5 ms (heat), ~0.2 ms (light)

[F.A. Danevich, 4th ISOTTA meeting]

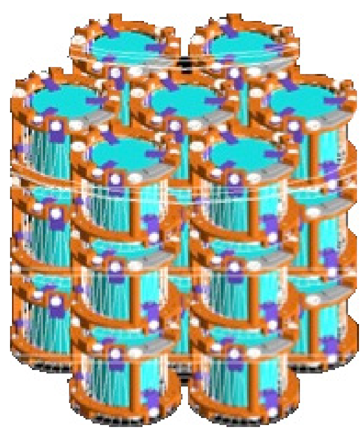
AMoRE Schedule

	Pilot	Phase I	Phase II
$^{40}Ca^{100}MoO_4$ crystals	1.5 kg	10 kg	200 kg
Bkg in ROI (c/keV/kg/yr)	0.01	0.002	0.0002
Sensitivity to $T_{1/2}$ (yr)	$>1.1\times10^{24}$	$\sim2\times10^{25}$	$\sim4\times10^{26}$
Sensitivity to $m_{\beta\beta}$ (eV)	0.3–0.9	0.08–0.22	0.016–0.047
Location	Yangyang	Yangyang	Duta Mt. (new)
Schedule	Mar. 2015	Sept. 2016	2019–2023



5 CMOs: ~ 1.5 kg

AMoRE Pilot (2015)

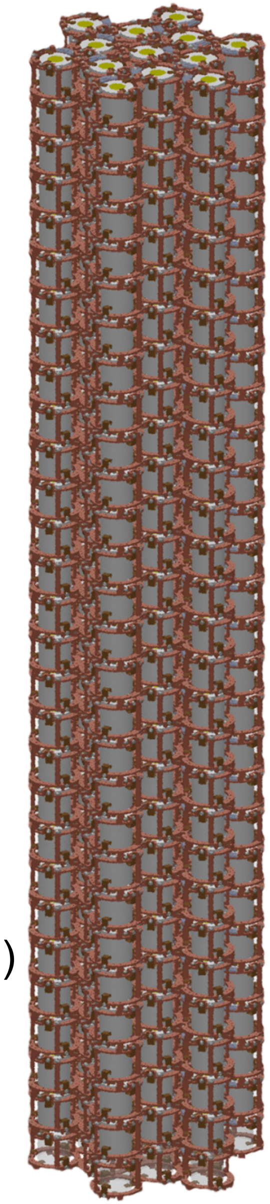


35 CMO (∅45×45 mm, 0.3 kg)
5 layers × 7 columns
$^{238}U/^{232}Th$ ~ 0.05 mBq/kg

AMoRE10 (2016)

390 CMO (∅5×6 cm, 0.5 kg)
30 layers × 13 columns
(2.4 m height),
$^{238}U/^{232}Th$ ~ 0.01 mBq/kg

AMoRE200 (2019)



Luminescent Underground Molybdenum Investigation for NEUtrino mass and nature

LUMINEU

ANR funds; Start: October, 2012 – duration 4 years

FRANCE
CSNSM Orsay (CNRS/IN2P3 + Paris Sud)
IAS Orsay (CNRS + Paris SuD)
ICMCB Bordeaux (CNRS + Bordeaux Univ.)
CEA Saclay

UKRAINE INR Kyiv
RUSSIA NIIC Novosibirsk
GERMANY KIP Heidelberg (Heidelberg Univ.)
ITALY INFN Milano Bicocca (Univ. Milano Bicocca)

Development of the technology based on scintillating bolometers for a next-generation $0\nu\beta\beta$ experiment

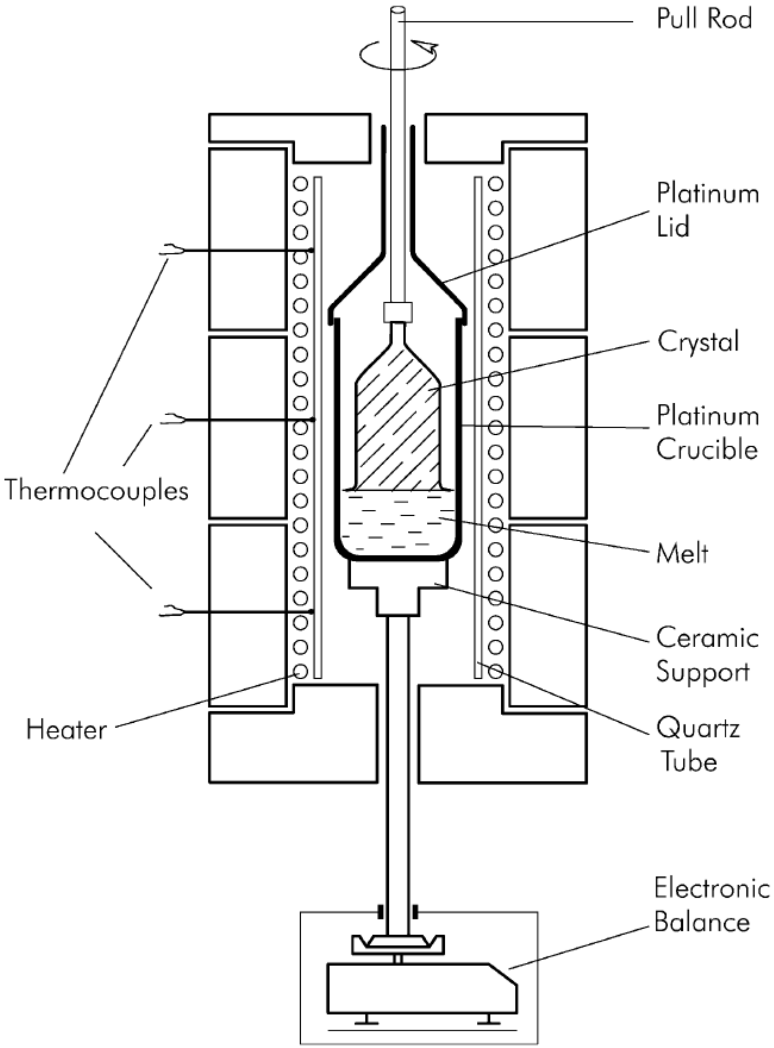
- **$ZnMoO_4$ crystal production** (R&D of Mo purification and ZMO growth conditions to produce large mass colorless samples from natural and enriched Mo; high radiopurity: ^{228}Th and ^{226}Ra ~ 0.01 mBq/kg, total α activity of U/Th ~ 1 mBq/kg)
- **Temperature sensors production and optimization** (NTD, TES, MMC)
- **Light detectors development** (based on HP Ge wafers)
- **A pilot $0\nu\beta\beta$ experiment** (~1 kg ^{100}Mo)

5-yr sensitivity at 90% CL [PLB 710(2012)318]
$ZnMoO_4$ nat. or enriched in ^{100}Mo to 97%
Bkg ≈ 4×10^{-4} cnts/keV/kg/yr in 6 keV window

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

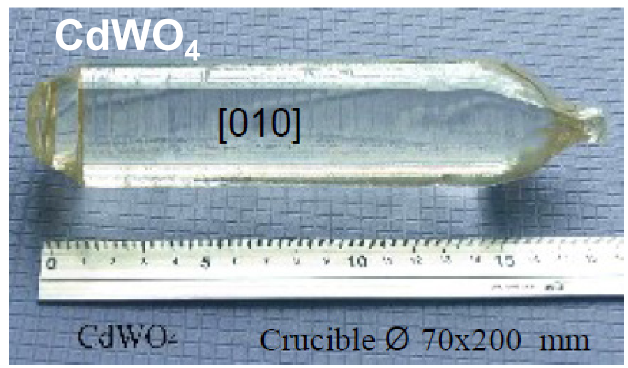
NEMO-3:
6.9 kg ^{100}Mo, 5 yr, 8% FWHM, 10^{-3} c/keV/kg/yr
$T_{1/2}(0\nu\beta\beta) > 1.1\times10^{24}$ yr, $\langle m_{\beta\beta}\rangle$ < 0.3–0.9 eV
[R. Arnold et al., PRD 89(2014)111101(R)]

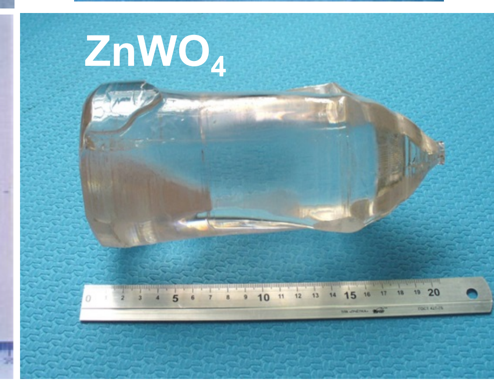
Advanced growth technique: LTG Czochralski



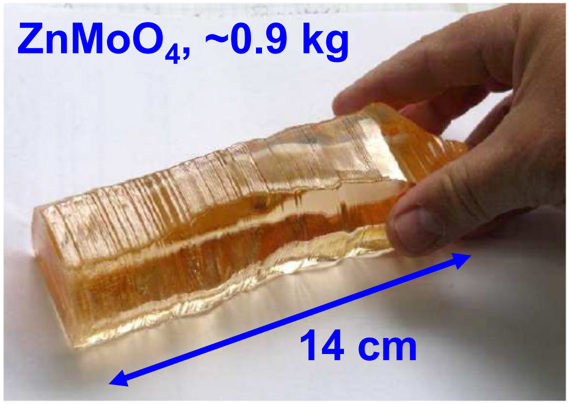
Low-Thermal-Gradient Czochralski
(NIIC, Novosibirsk, Russia)
[JCG 229 (2001) 305]

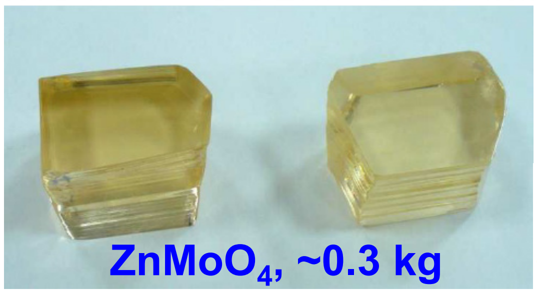
- **Low temperature gradients** (~ 1.0 K/cm)
- **Crystal inside a crucible during the process**
- **Weighing control at all the stages**
- **Pipe socket as a diffusion barrier** (evaporation and decomposition processes are suppressed ⇒ losses < 1% of charge)
- **Layered growth mechanism** (dominant) and the **faceted crystallization front**
- **Diameter of crystal up to 0.8∅ of crucible** (up to 90% crystal yield from initial compound)





Large volume precursor of LUMINEU program



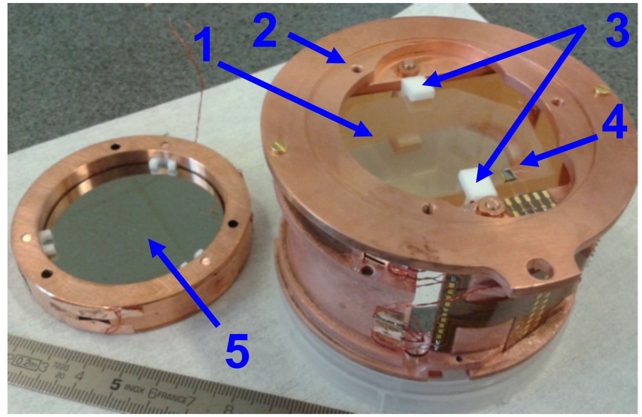


$ZnMoO_4$ development

- ZnO (99.995%) provided by Umicore (Belgium)
- MoO_3 (99.999%) purified at NIIC (Novosibirsk)
- Platinum crucible ∅8 cm
- LTG Cz crystal growth along the [001] axis

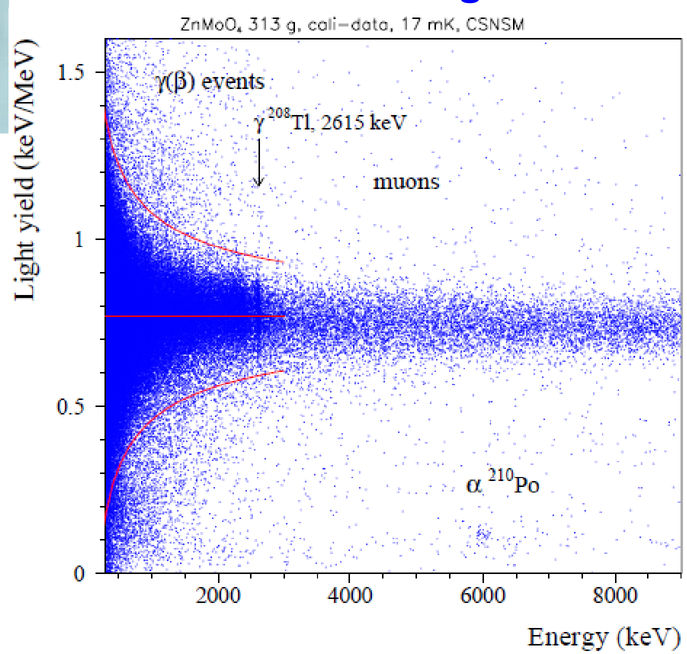
[Crystallogr. Rep. 59 (2014) 288]

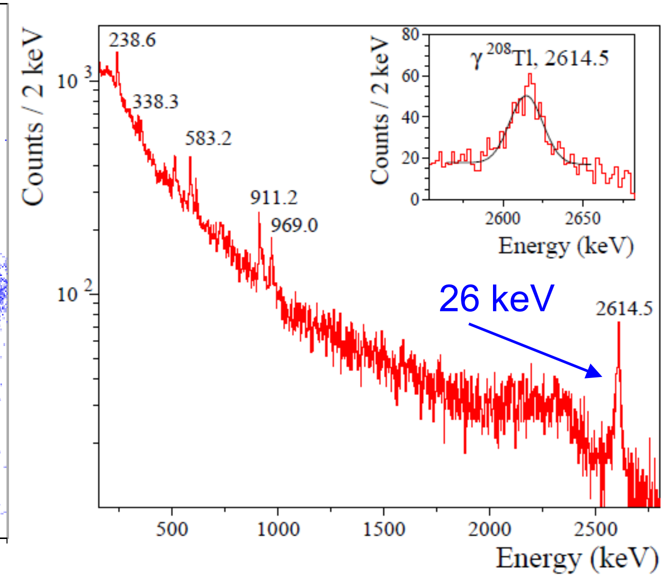
$ZnMoO_4$ scintillating bolometer



(1) 313 g $ZnMoO_4$ crystal grown in NIIC (Novosibirsk, Russia)
(2) Cu holder of the detector
(3) PTFE supporting elements
(4) Two NTD thermistors
(5) Two Ge light detectors

Aboveground test at 17 mK at CSNSM





Then, it was tested at Modane Underground Lab

LUMINEU: Purification of molybdenum

Two stage purification technique was developed at NIIC (Novosibirsk)

Sublimation in vacuum

with addition ~1% of $ZnMoO_4$

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

Efficient removing of U/Th is expected

Material	Concentration of impurities (ppm)			
	Si	K	Fe	W
Initial MoO_3	600	100–500	6	200–500
Sublimation	100–500	10–50	2–6	100–200
Double sublimation	**70**	**1–8**	**< 1**	**30–40**

Recrystallization from aqueous solutions

$MoO_3 + 2NH_4OH = (NH_4)_2MoO_4 + H_2O$ (using zinc molybdate as a collector)

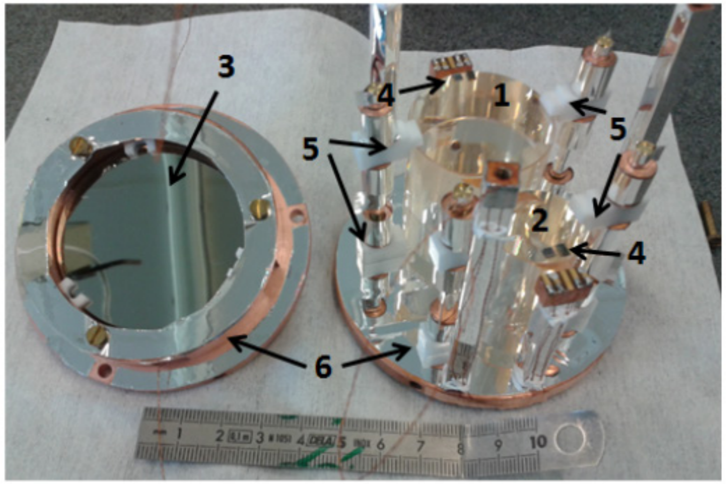
Material	Concentration of impurities (ppm)				
	Si	K	Ca	Fe	W
High purity MoO_3	60	50	60	8	200
Sublimation and recrystallization from aqueous solutions	30	10	12	5	130
Double sublimation and recrystallization from aqueous solutions	**-**	**< 10**	**< 10**	**< 5**	**< 50**

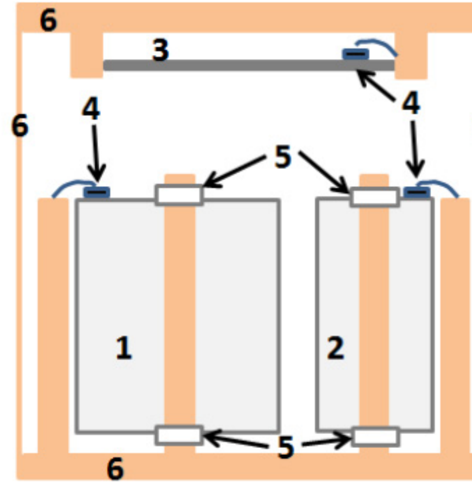
[L. Bergé et al., JINST 9 (2014) P06004]

First LUMINEU samples: test at CSNSM

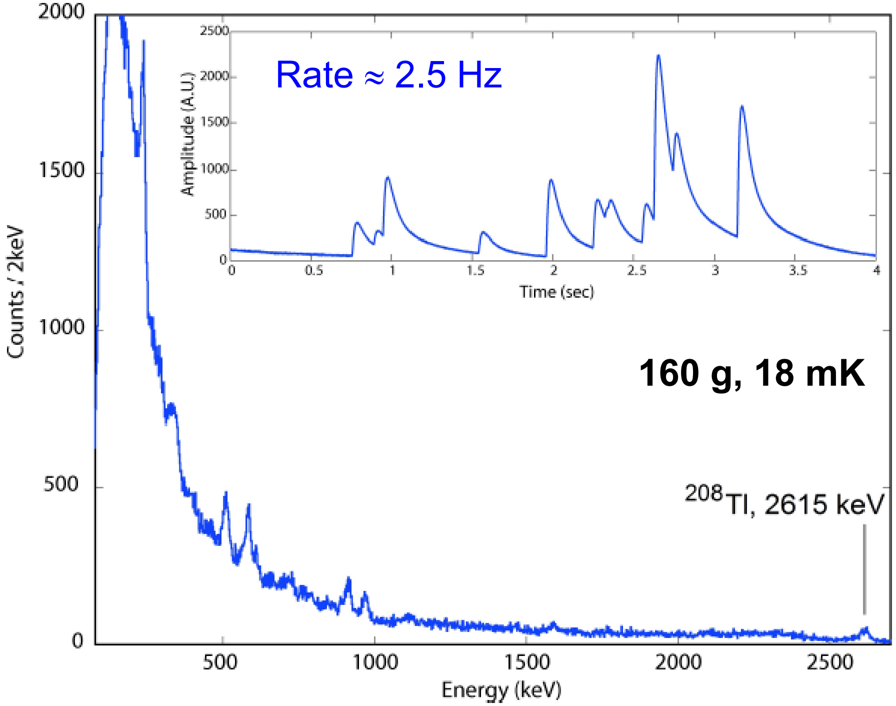
$ZnMoO_4$ development

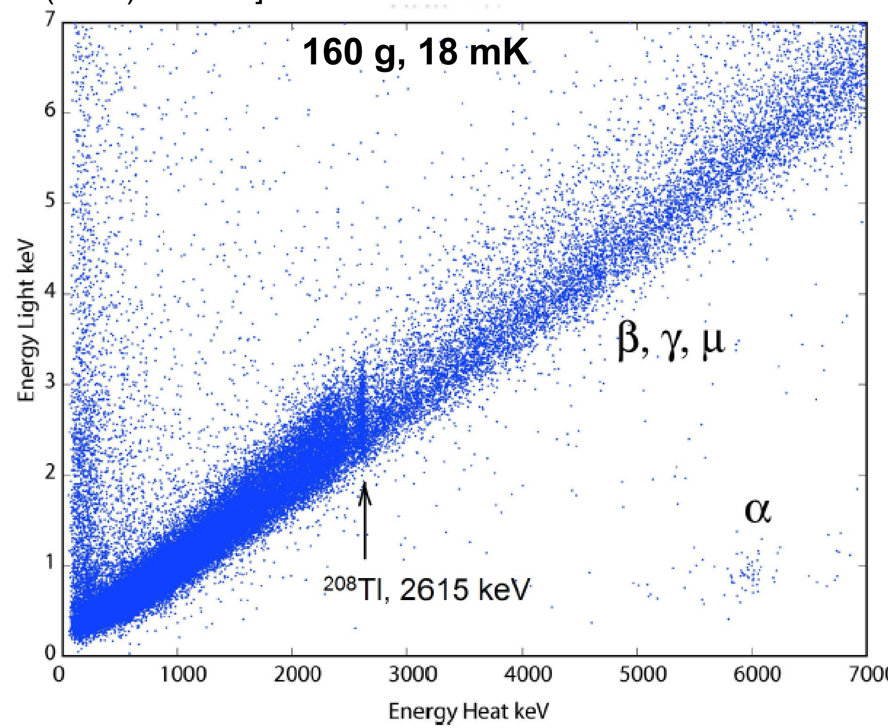
- MoO_3 purified by double recrystallization from aqueous solutions
- HP ZnO (Umicore)
- LTG Cz crystal growth
- Crystal yield ~ 80%
- Four $ZnMoO_4$ samples produced (55 g and 160 g)



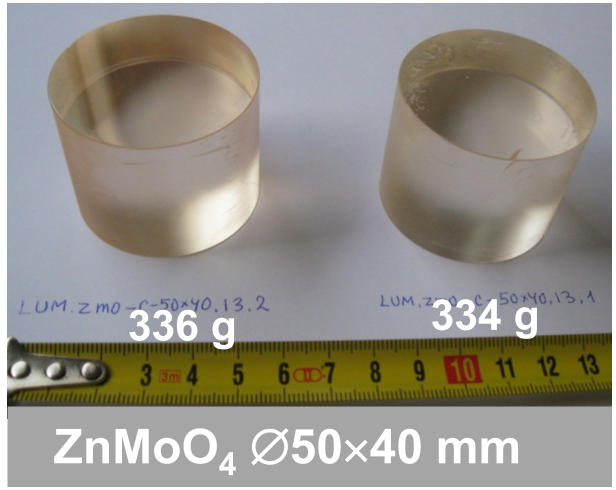


[L. Bergé et al., JINST 9 (2014) P06004]



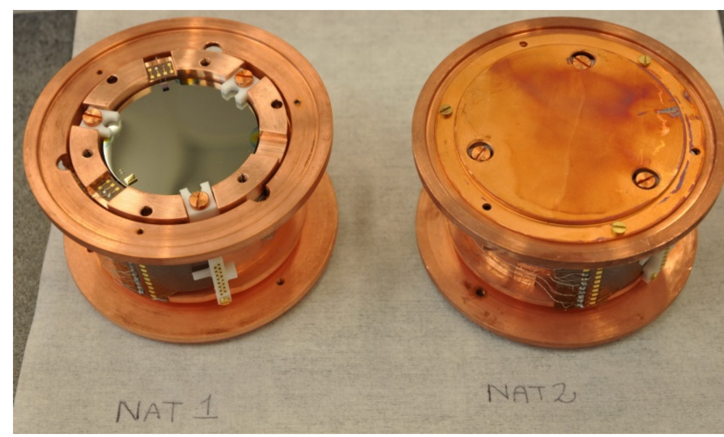


LUMINEU: first massive $ZnMoO_4$ bolometers



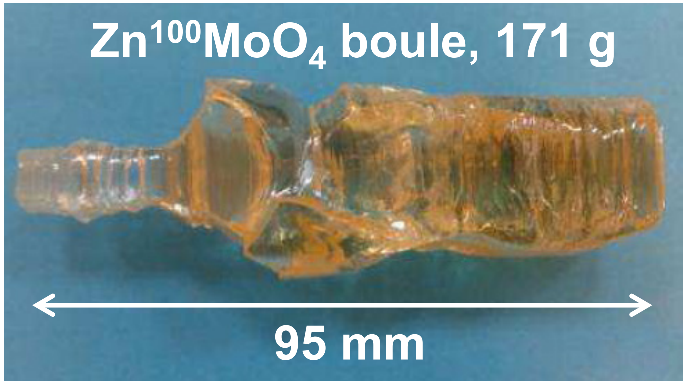
Technology of high quality large $ZnMoO_4$ crystal producing is developed

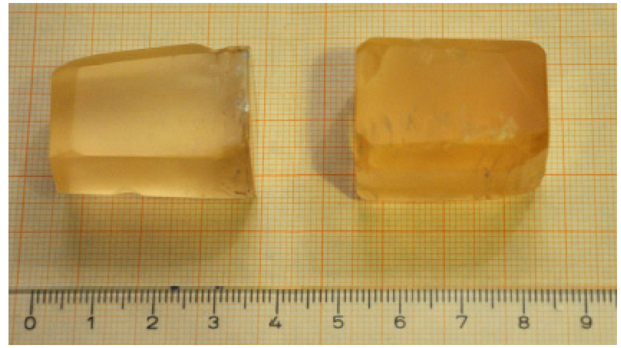
- Molybdenum was purified by using double recrystallization from aqueous solutions
- Advanced quality $ZnMoO_4$ boule was grown by directional solidification along [001] using LTG Cz (crystal yield ~ 80% of initial charge)
- $ZnMoO_4$ crystal boule was melted and then crystallized again (to test recrystallization)
- Produced $ZnMoO_4$ elements have the size expected for a pilot LUMINEU $0\nu\beta\beta$ experiment

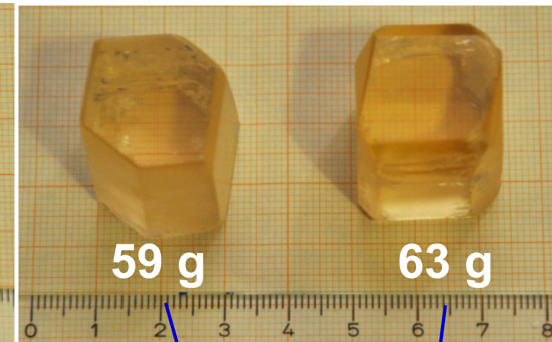


[E. Armengaud et al., submitted to JINST]

LUMINEU: First enriched $Zn^{100}MoO_4$ detectors

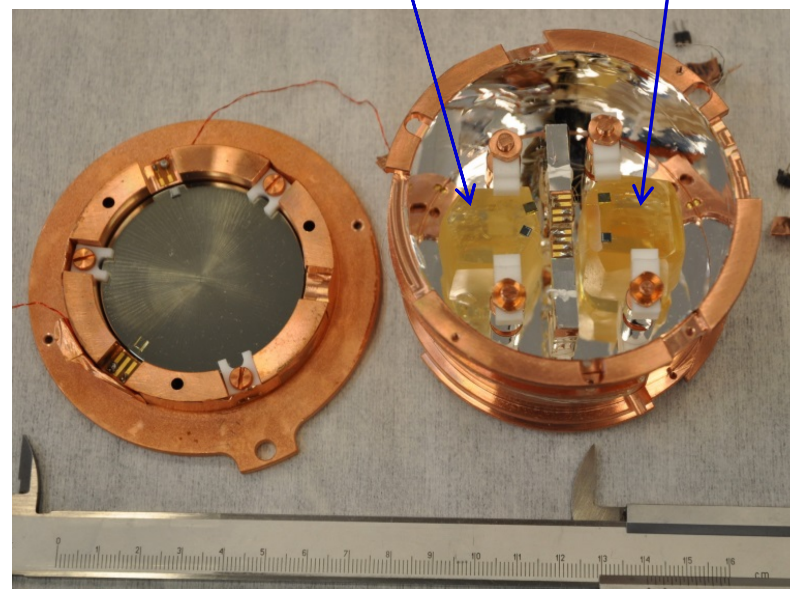






First $Zn^{100}MoO_4$ crystal is developed from enriched molybdenum

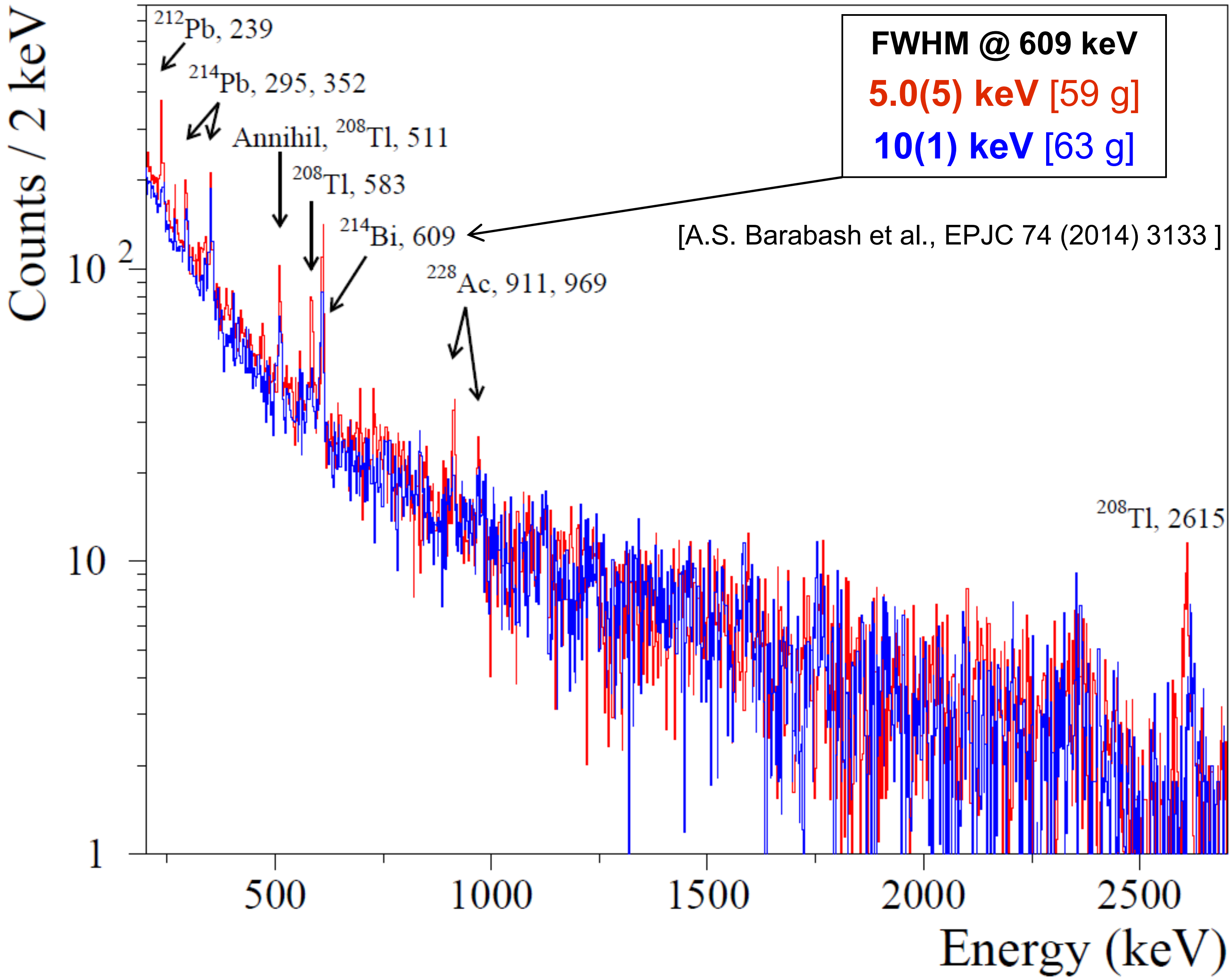
- $^{100}MoO_3$ (99.5% enrichment in ^{100}Mo) was purified by using sublimation in vacuum and recrystallization from aqueous solutions
- $Zn^{100}MoO_4$ boule was grown at NIIC by using low-thermal-gradient Czochralski process (crystal yield – 84% of initial compound)
- Total irrecoverable losses of ^{100}Mo ~ 4%



[A.S. Barabash et al., EPJC 74 (2014) 3133]

LUMINEU: Aboveground test of $Zn^{100}MoO_4$ array

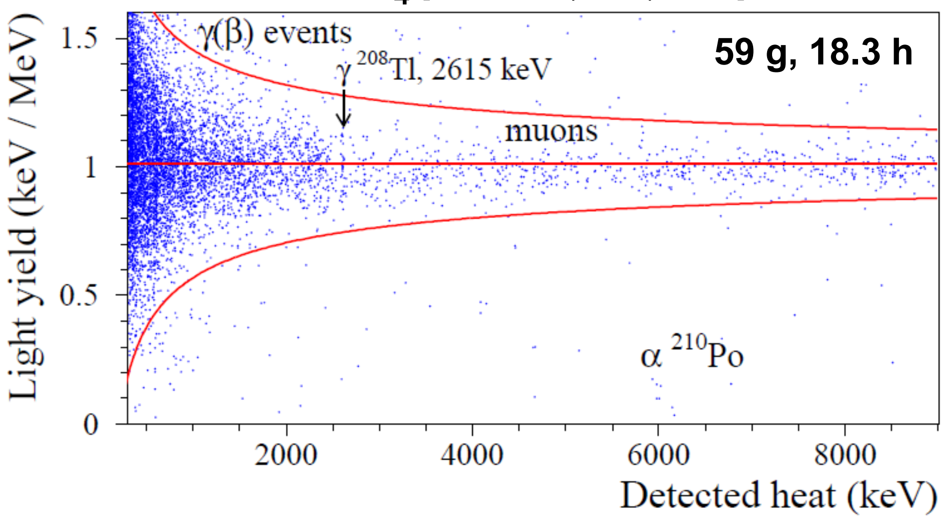
$Zn^{100}MoO_4$ show bolometric properties similar to $ZnMoO_4$ detectors

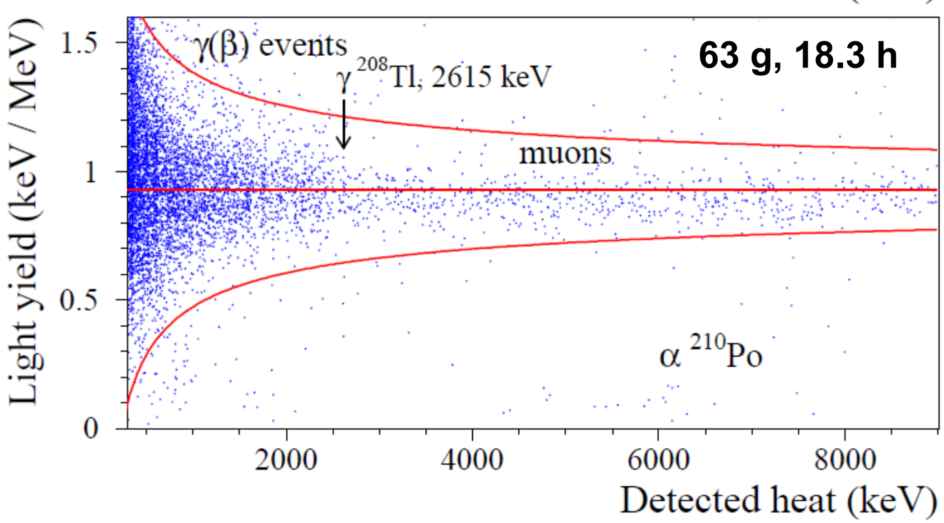


LUMINEU: Aboveground test of $Zn^{100}MoO_4$ array

$Zn^{100}MoO_4$ crystals demonstrate encouraging radiopurity

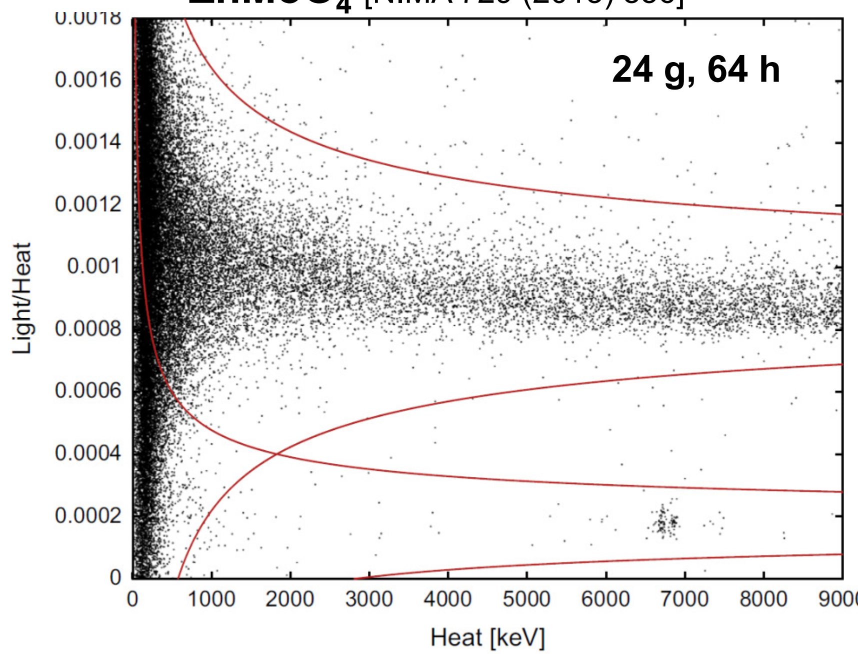
$Zn^{100}MoO_4$ [EPJC 74 (2014) 3133]





Activity of ^{210}Po ~ 1 mBq/kg
Total α activity ~ (3–5) mBq/kg

$ZnMoO_4$ [NIMA 729 (2013) 856]

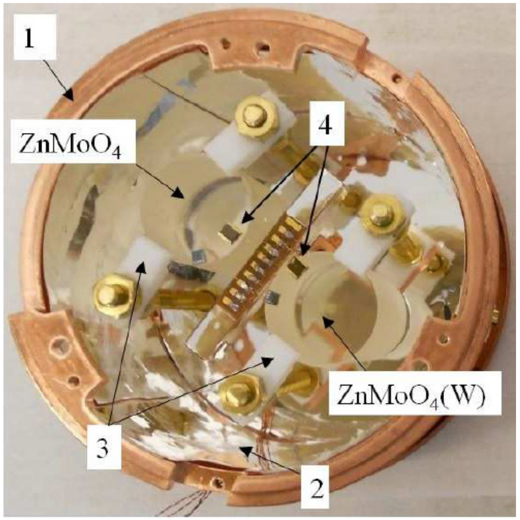


^{232}Th	^{232}Th	≤ 0.5
	^{228}Th	≤ 0.8
^{235}U	^{227}Ac	≤ 0.5
^{238}U	^{238}U	≤ 1.0
	^{234}U	≤ 0.8
	^{230}Th	≤ 0.8
	^{226}Ra	≤ 0.8
	^{210}Po	8(1) (mBq/kg)
Total α activity		22 (2)

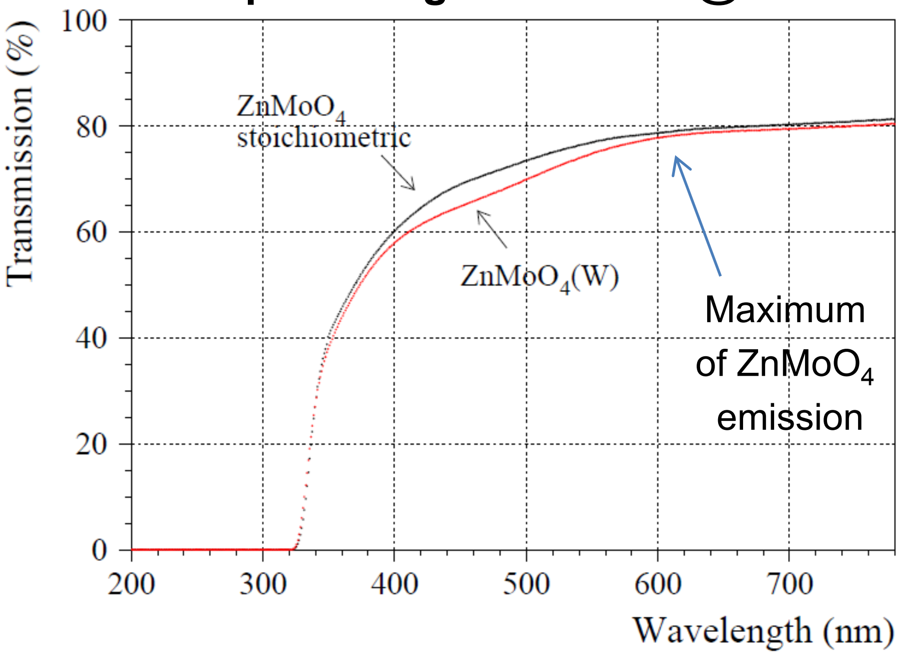
LUMINEU: Effect of W doping on $ZnMoO_4$ properties

W-doped $ZnMoO_4$ grown by LTG Cz

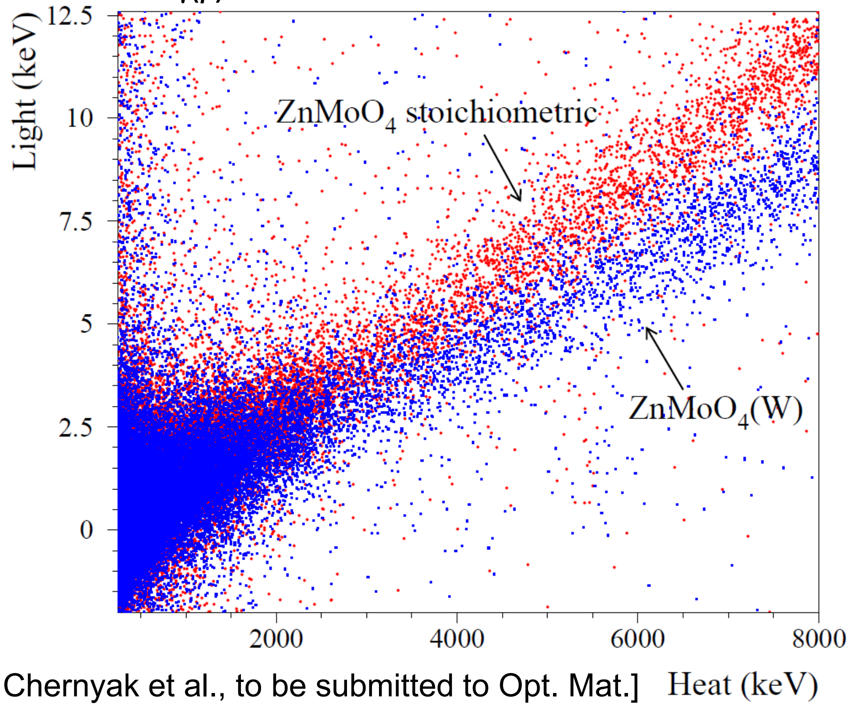
- **Admixture of (0.5–1) mol. % of WO_3 improves quality of $ZnMoO_4$ crystals** (leads to the melt stability and reduces the mechanical stresses)
- **Properties of W-doped $ZnMoO_4$ are similar to stoichiometric crystals** (high transmission, no deterioration of bolometric performance by dopant)



Absorption length = 55 cm^{-1} @ 600 nm



$LY_{\gamma(\beta)}$(W-doped) = 1.08(1) keV/MeV

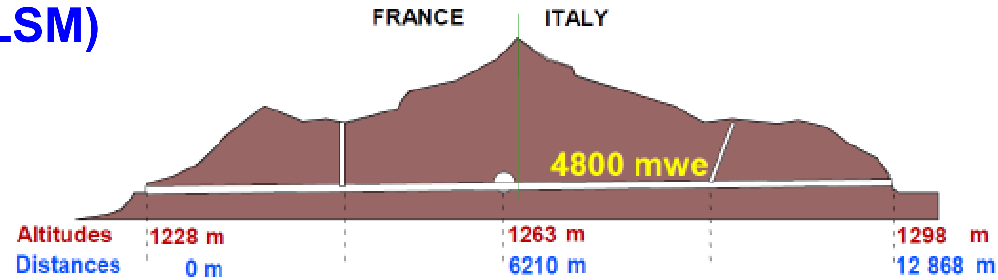


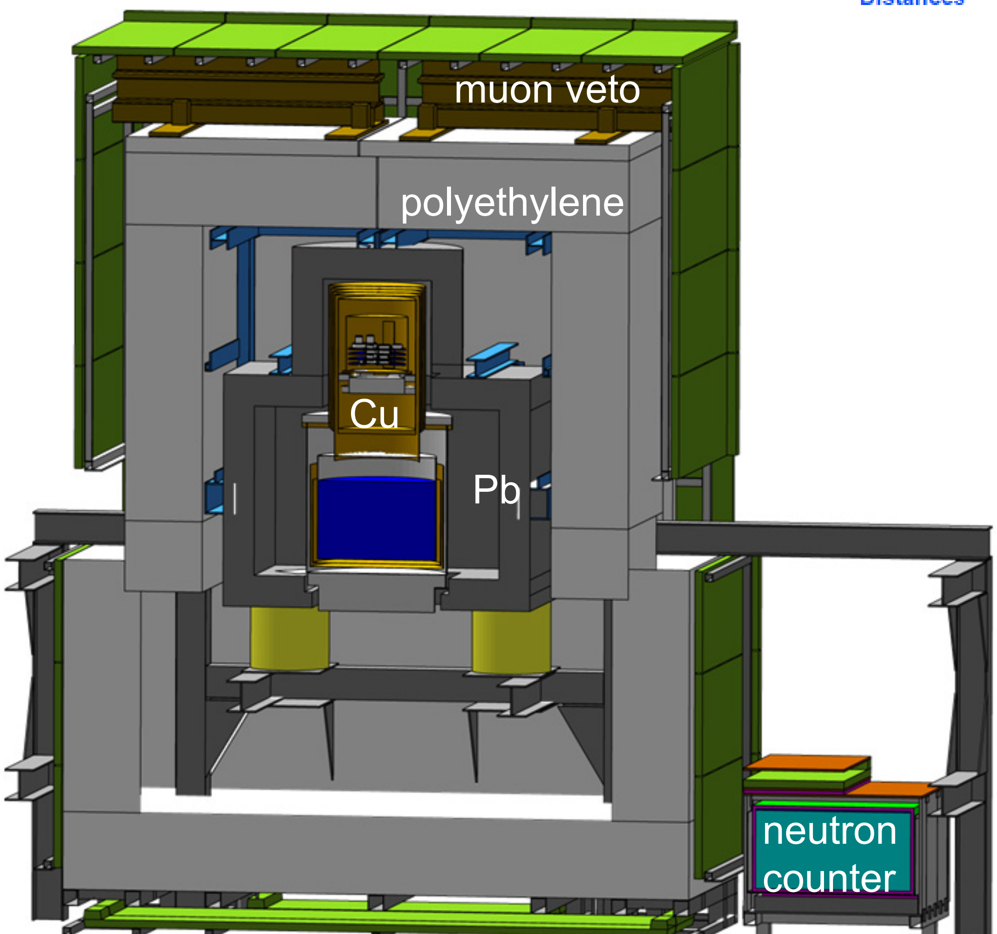
[D.M. Chernyak et al., to be submitted to Opt. Mat.]

LUMINEU: Underground tests at Modane

Laboratoire Souterrain de Modane (LSM)

1.7 km rock overburden (~4.8 km w.e.)
5 μ/day/m^2; 10^{-6} n/day/cm^2 (>1 MeV)
Deradonized air flow (~30 mBq/m^3)





EDELWEISS set-up

Installation at LSM
Clean room (ISO Class 4)

Copper cryostat
^{3}He/^{4}He table top dilution refrigerator
Large experimental volume (50 liters)

Passive shield
Low radioactivity lead (min. 20 cm)
Polyethylene (min. 50 cm)

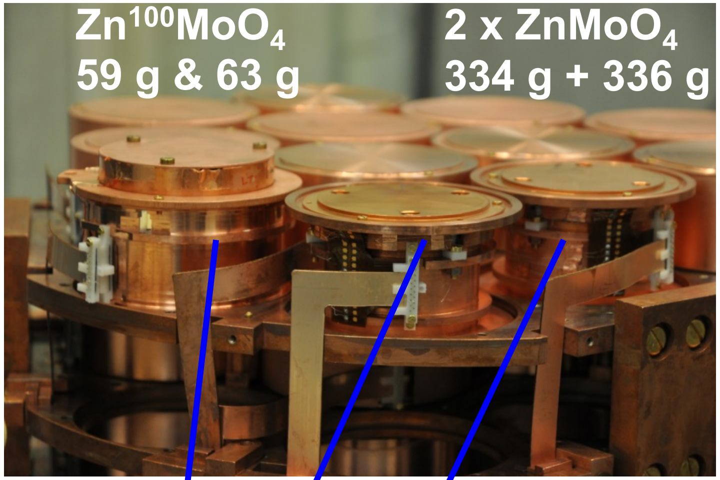
Detection μ / n / Ra
Muon veto (98.5% covering)
Neutron counter
Radon counter

[E. Armengaud et al., PLB 702 (2011) 329]

LUMINEU detectors in the EDELWEISS set-up

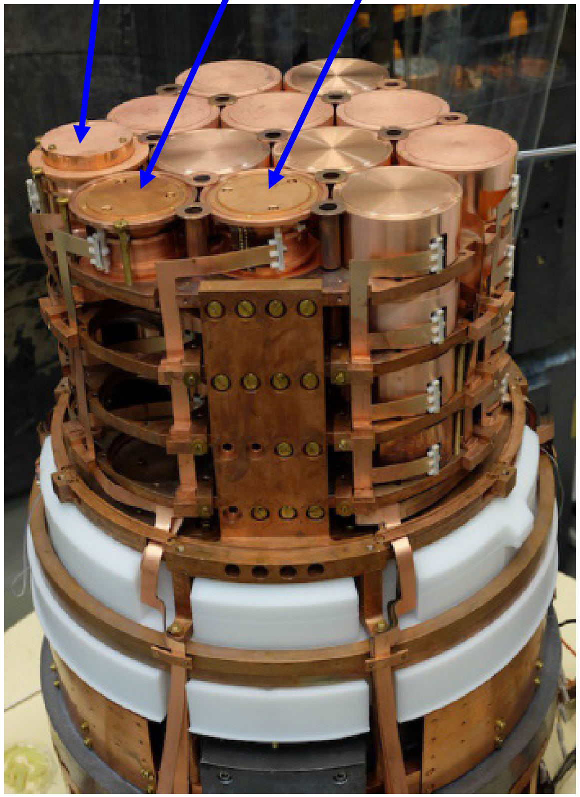
EDELWEISS-III commissioning run @ 19mK

- Improved cryogenic system
- Polyethylene at 1 K plate
- NOSV copper screens
- 15 germanium bolometers 800 g each
- Scintillating bolometer based on precursor $ZnMoO_4$ (313 g)
- Sept. 2013 – Feb. 2014



EDELWEISS-III physics run @ 18 mK

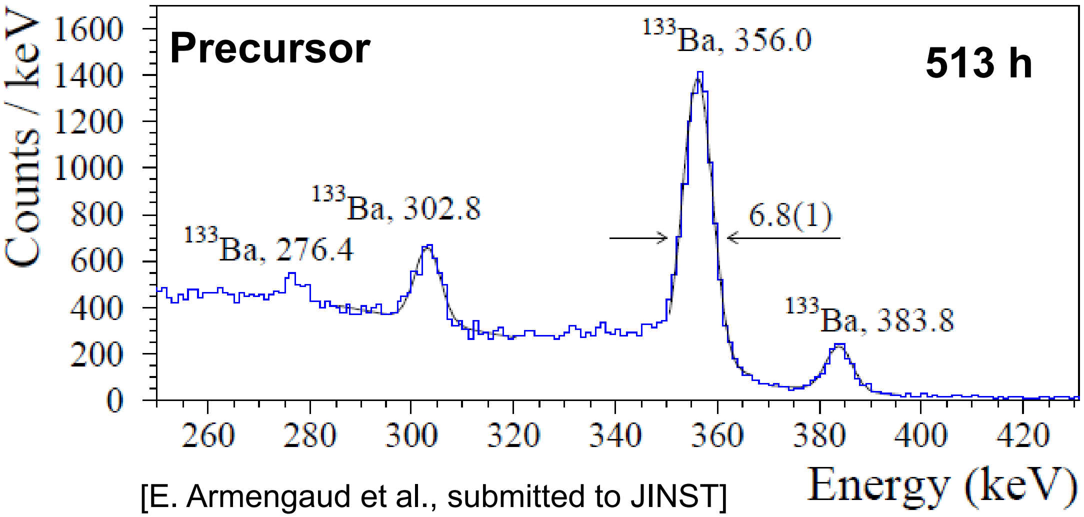
- Individual low bkg Kapton
- Implementation of device for thermal response control of LUMINEU detectors (since Feb. 2015)
- 36 germanium bolometers 800 g each
- $Zn^{100}MoO_4$ scintillating bolometers array
- 2 scintillating bolometers based on advanced $ZnMoO_4$ crystals
- June 2014 – present



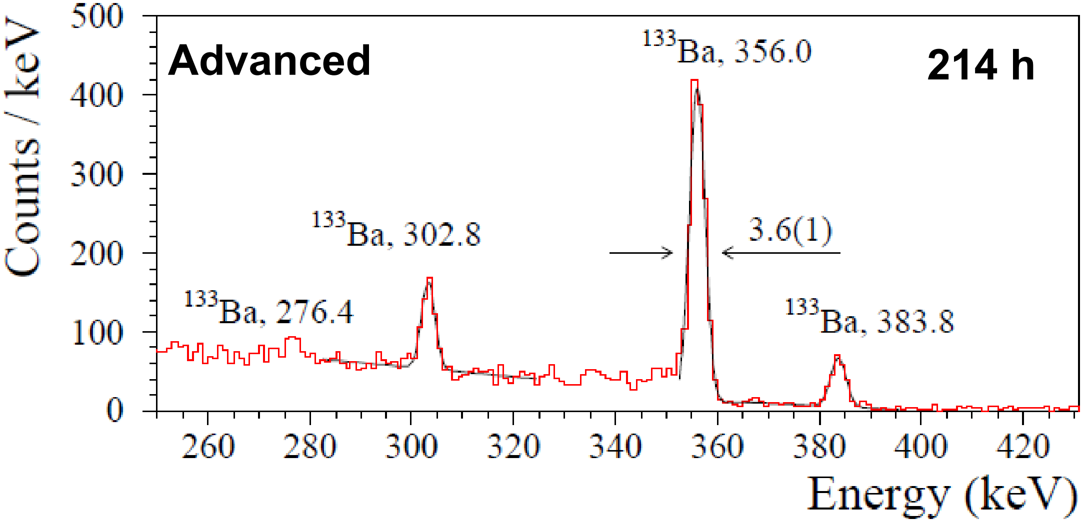
[E. Armengaud et al., submitted to JINST]

Precursor / Advanced $ZnMoO_4$: Calibration by ^{133}Ba

Excellent performance of $ZnMoO_4$ bolometers

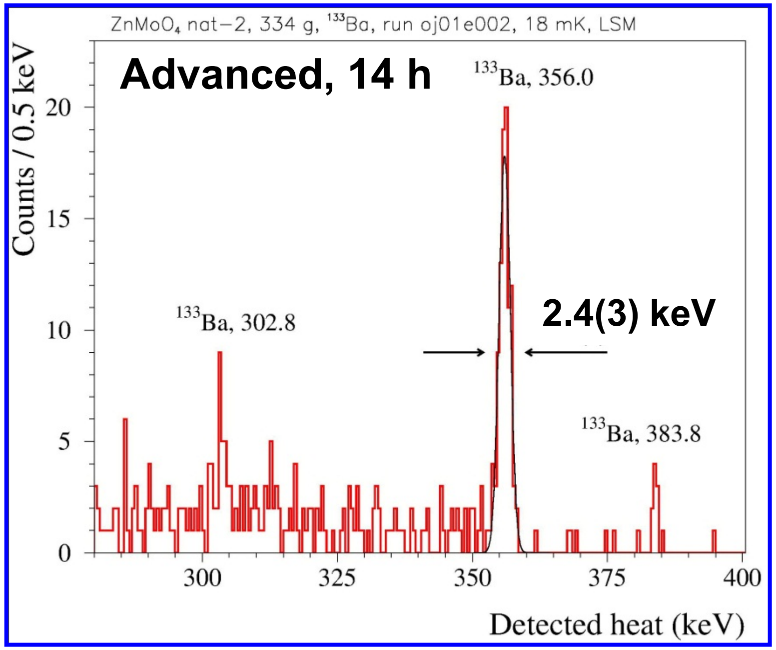


[E. Armengaud et al., submitted to JINST]



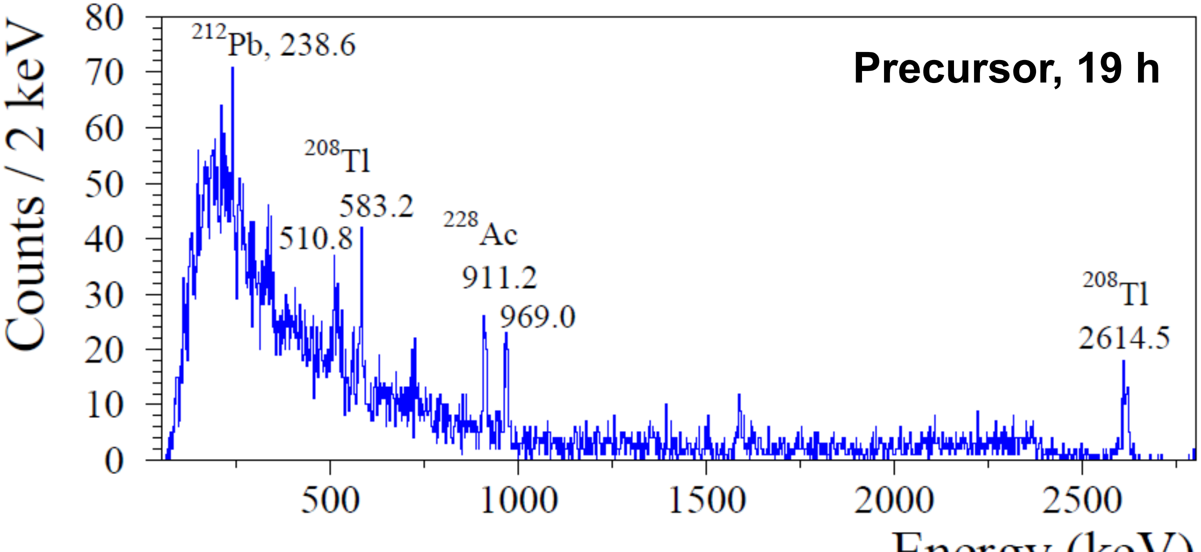
Performance in runs

- Precursor: FWHM = (6–13) keV
- Advanced: FWHM = (3–5) keV
- Baseline: FWHM ≈ 1.5 keV

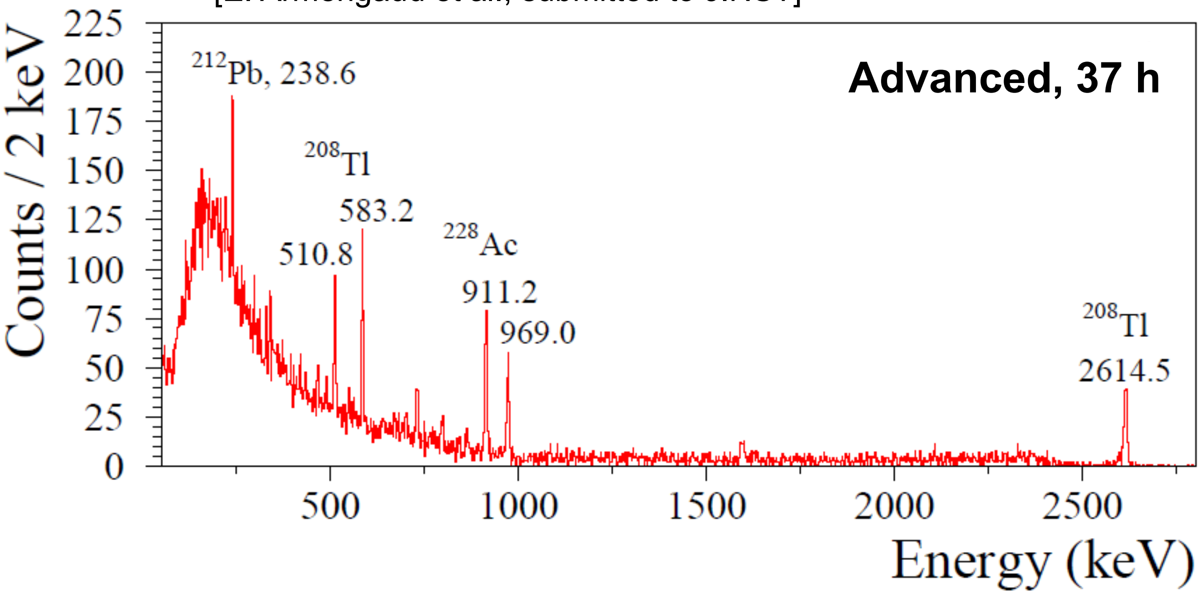


Precursor / Advanced $ZnMoO_4$: Calibration by ^{232}Th

Excellent performance of $ZnMoO_4$ bolometers



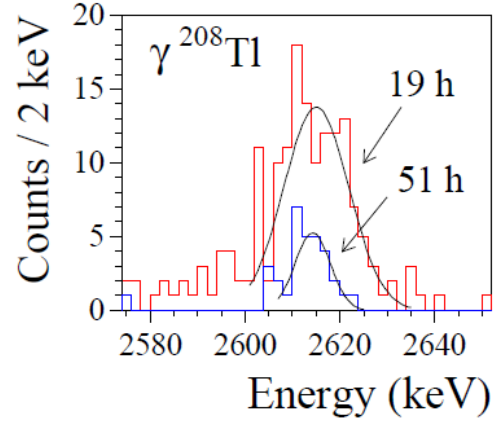
[E. Armengaud et al., submitted to JINST]



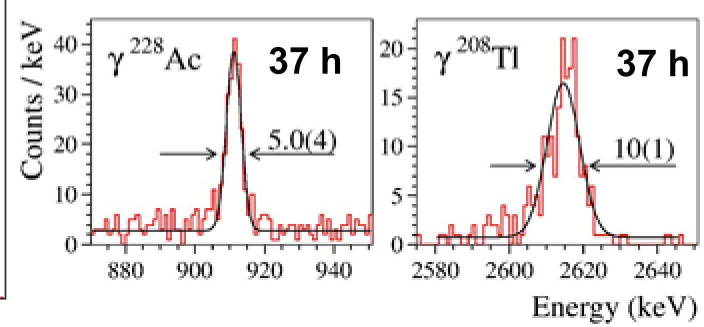
Strong / weak source

19 h: FWHM = 17(1) keV

51 h: FWHM = 9(2) keV

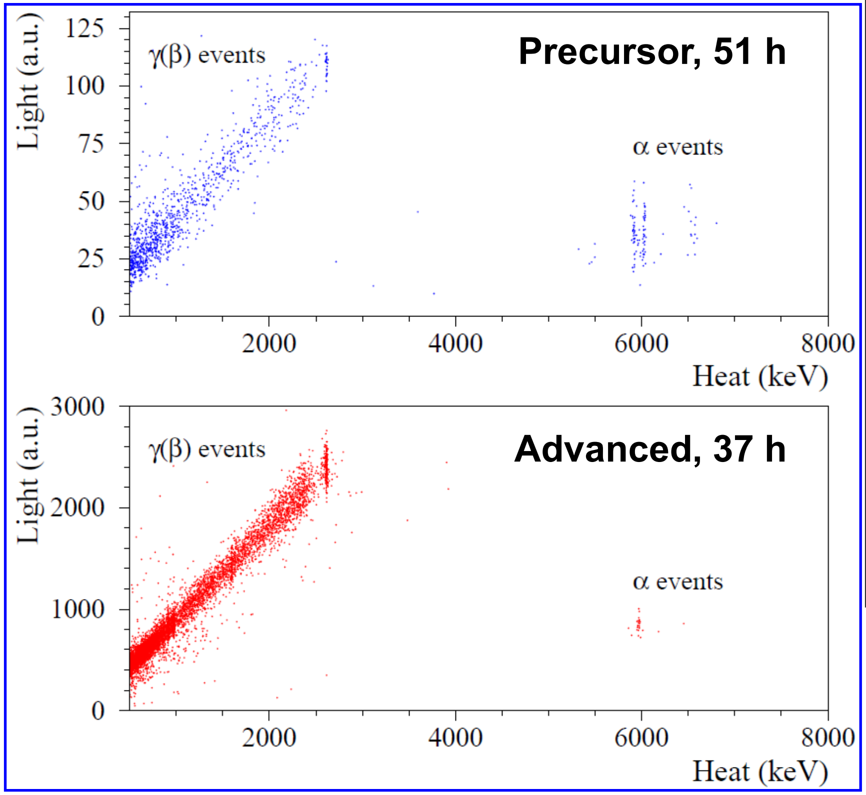


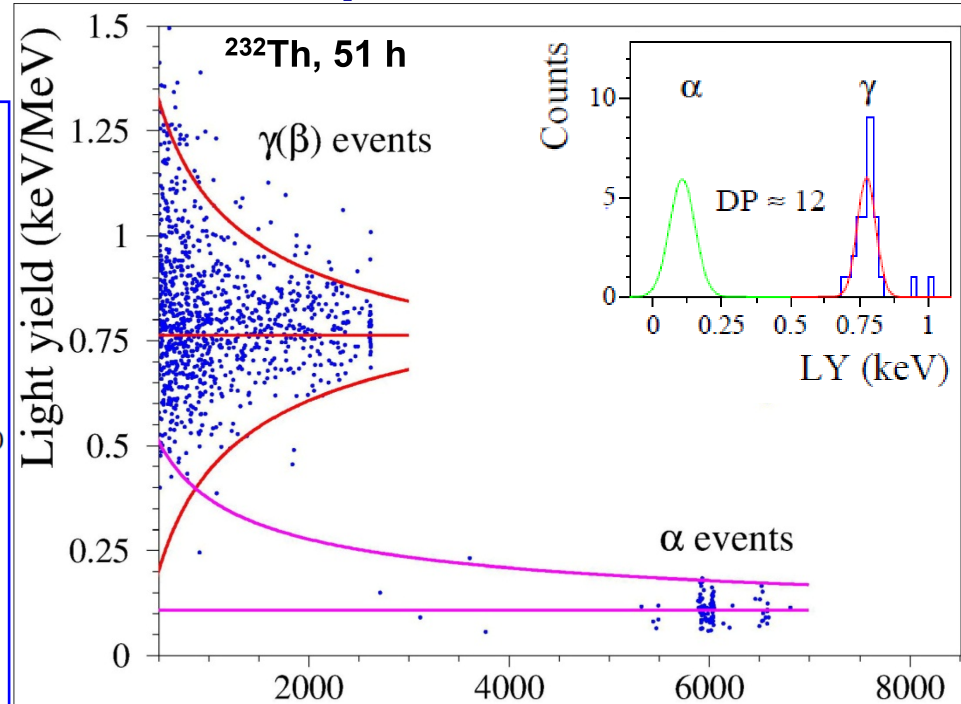
Strong source

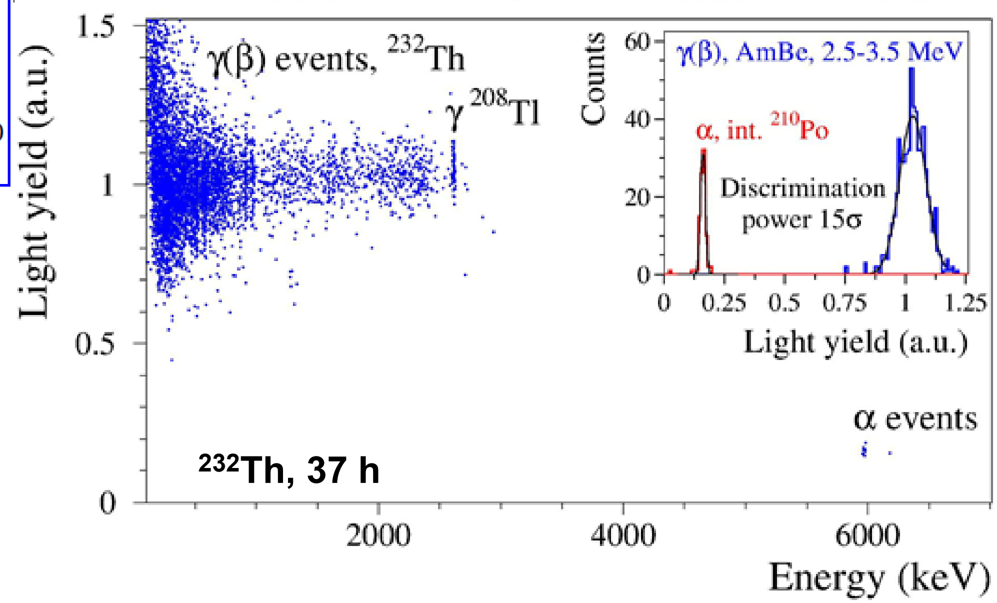


Precursor / Advanced $ZnMoO_4$: α/γ separation

Excellent α/γ separation







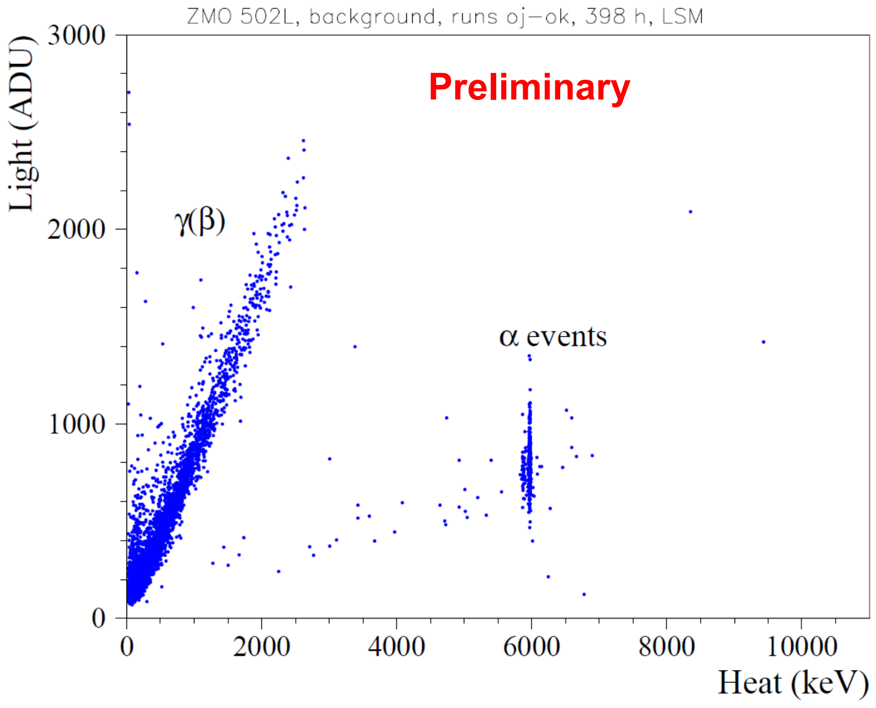
Discrimination power

$$DP(E) = \frac{\mu_{\gamma(\beta)}(E) - \mu_{\alpha}(E)}{\sqrt{\sigma^2_{\gamma(\beta)}(E) + \sigma^2_{\alpha}(E)}}$$

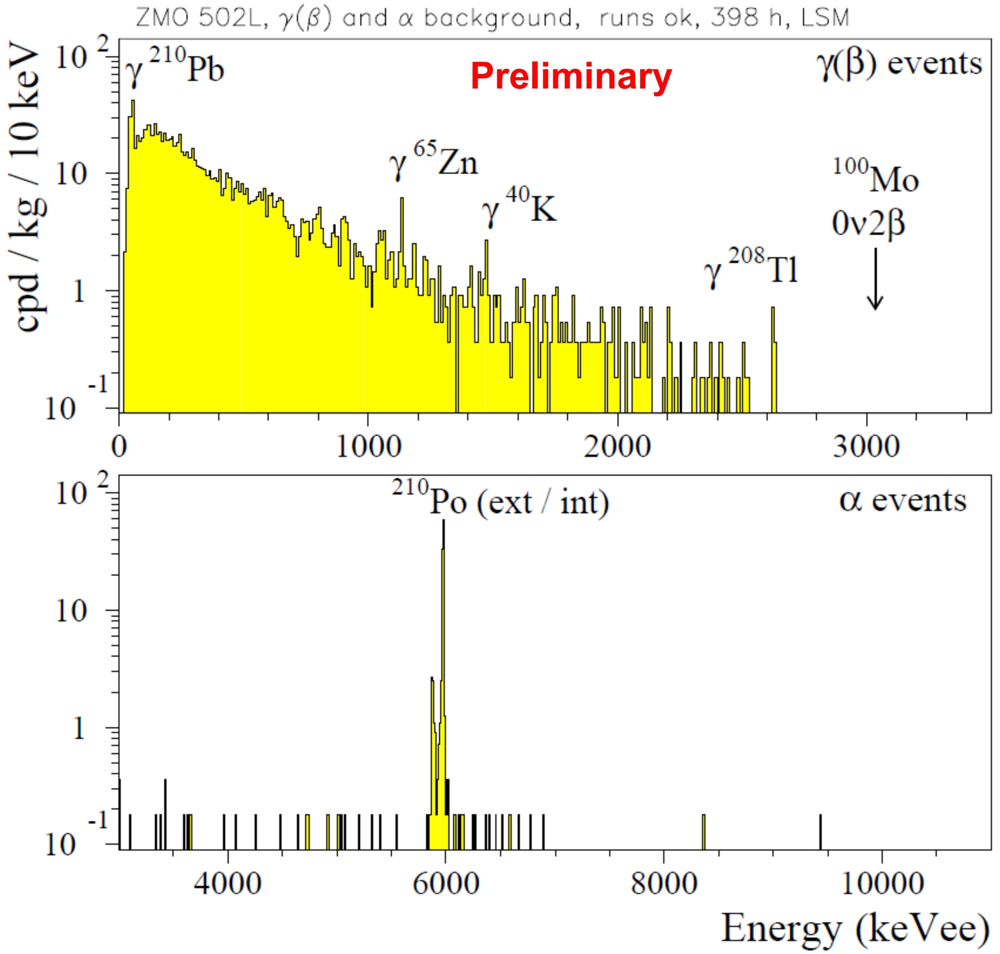
Background measurements with advanced $ZnMoO_4$

Perfect capability to get "zero" background in the ROI

$ZnMoO_4$, 334 g, Bkg, 398 h, LSM
Heat-vs-Light scatter-plot

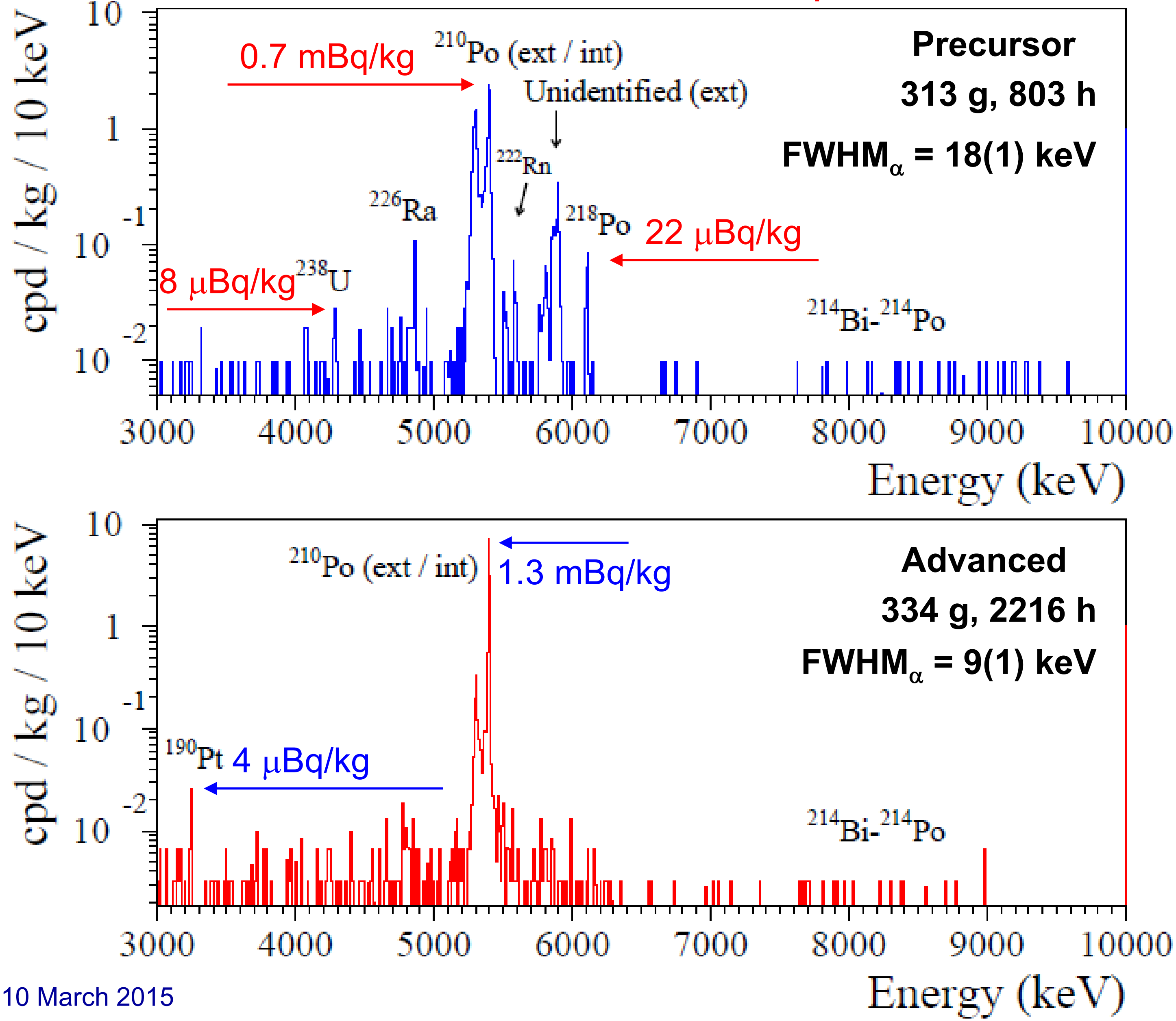


Selected γ(β) and α background



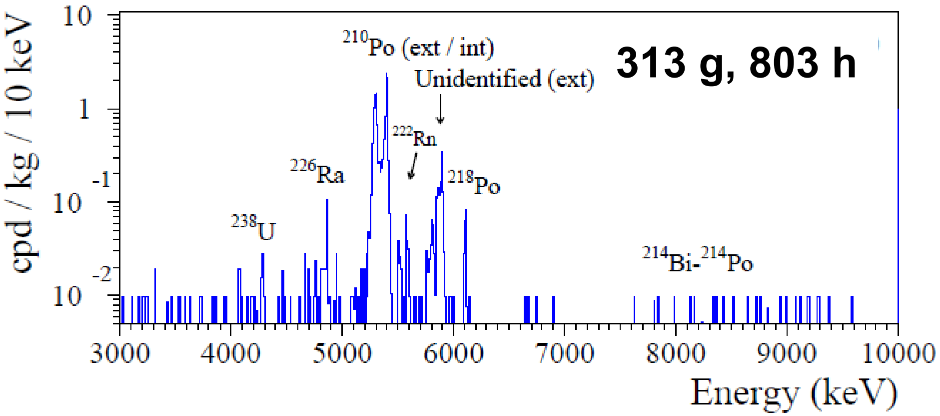
Precursor / Advanced $ZnMoO_4$: α Background

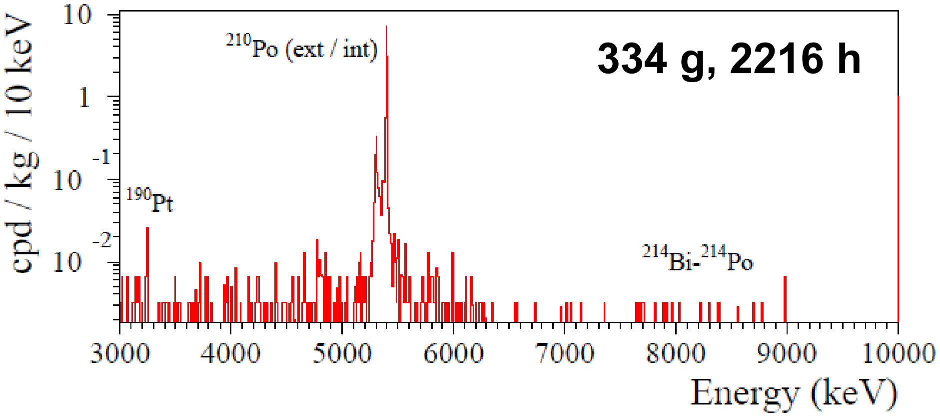
High radiopurity of $ZnMoO_4$ crystals



Precursor / Advanced $ZnMoO_4$: Radiopurity

Radiopurity of $ZnMoO_4$ crystal satisfies the LUMINEU requirements





$ZnMoO_4$ radiopurity is even higher than one discussed in [PLB 710(2012)318] for a next-generation $0\nu\beta\beta$ experiment (^{228}Th / ^{226}Ra ~ 0.01 mBq/kg)

	Activity, μBq/kg			
	LUMINEU crystals		Precursor crystals	
	LSM [1]	LSM [2]	LSM [1]	LNGS [3]
	334 g	336 g	313 g	329 g
	2216 h	291 h	803 h	524 h
^{232}Th	≤ 2	≤ 10	≤ 6	≤ 8
^{228}Th	≤ 5	≤ 24	12(4)	≤ 6
^{238}U	≤ 2	≤ 8	8(3)	≤ 6
^{234}U	≤ 3	≤ 22	≤ 8	≤ 11
^{230}Th	≤ 2	≤ 13	≤ 8	≤ 6
^{226}Ra	≤ 5	≤ 21	22(5)	27(6)
^{210}Po	1271(22)	939(52)	703(28)	700(30)
^{235}U	≤ 3	≤ 10	≤ 7	–
^{190}Pt	4(1)	≤ 5	≤ 7	–

[1] E. Armengaud et al., submitted to JINST.
[2] D.V. Poda et al., arXiv:1502.01161.
[3] J. Beeman et al., EPJC 72 (2012) 2142.

Advanced Li_2MoO_4 bolometer: development

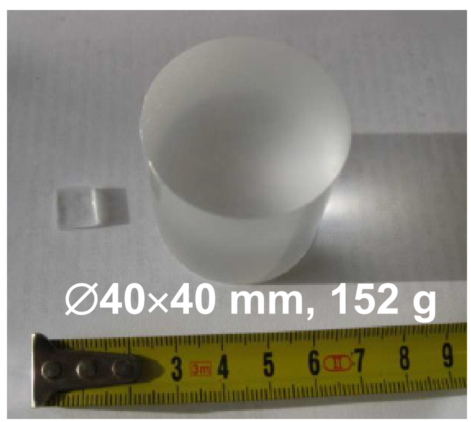
Li_2MoO_4 as a perspective $\beta\beta$ detector

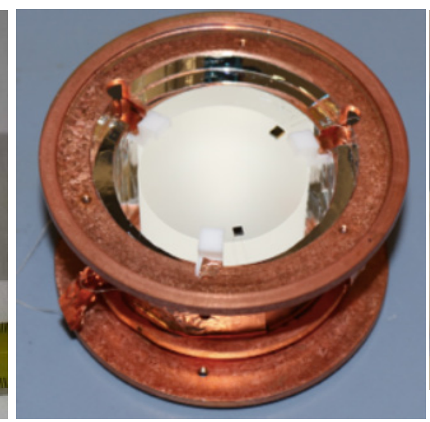
- ✓ High concentration of Mo (55% in mass!)
- ✓ Possible scintillating bolometer (but low LY)
- ✓ High (n,α) cross-section for ^{6}Li (i.a. 8%): no neutron induced events in $\gamma(\beta)$ band
- ✓ Comparatively easy crystal growth process (progress in growth 0.1–0.35 kg LMO by Cz)

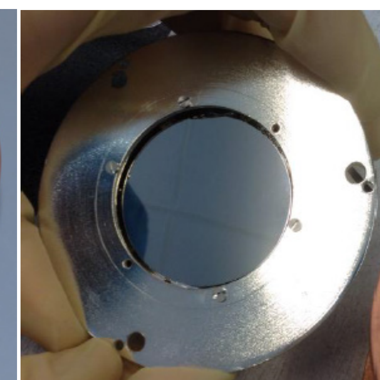
Property	Value
Density (g/cm^3)	3.02 – 3.07
Melting point (K)	974 ± 2
Hygroscopicity	Weak
Index of refraction	1.44
Radioactive contamination (mBq/kg)	
^{40}K	170(80)
^{232}Th	≤ 0.11
^{238}U	≤ 0.09

Successful growth (0.1–0.37) kg LMO by LTG Cz method from deeply purified Mo and commercial Li_2CO_3 (99.99% purity grade)

[T.B. Bekker et al., arXiv 1410.6933]

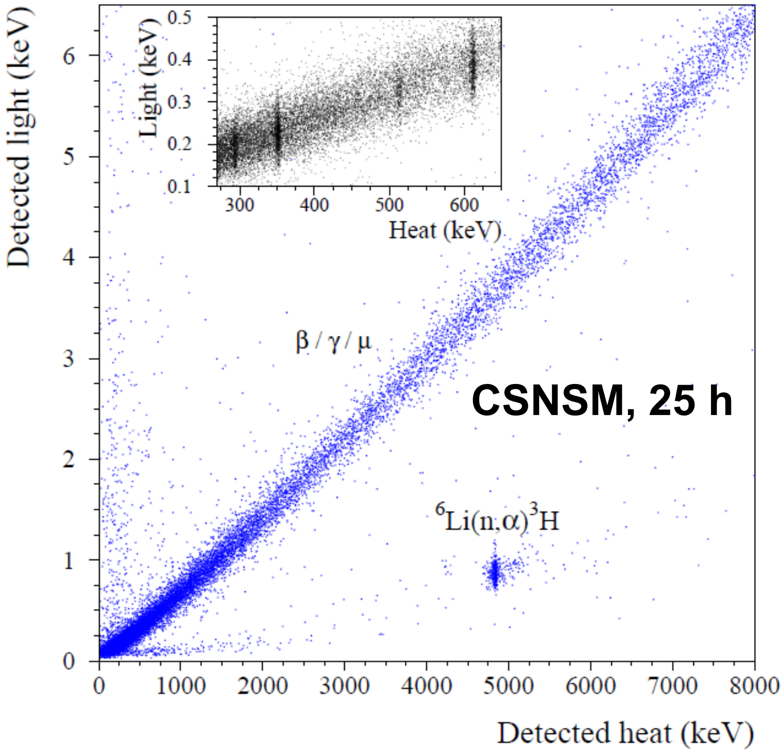


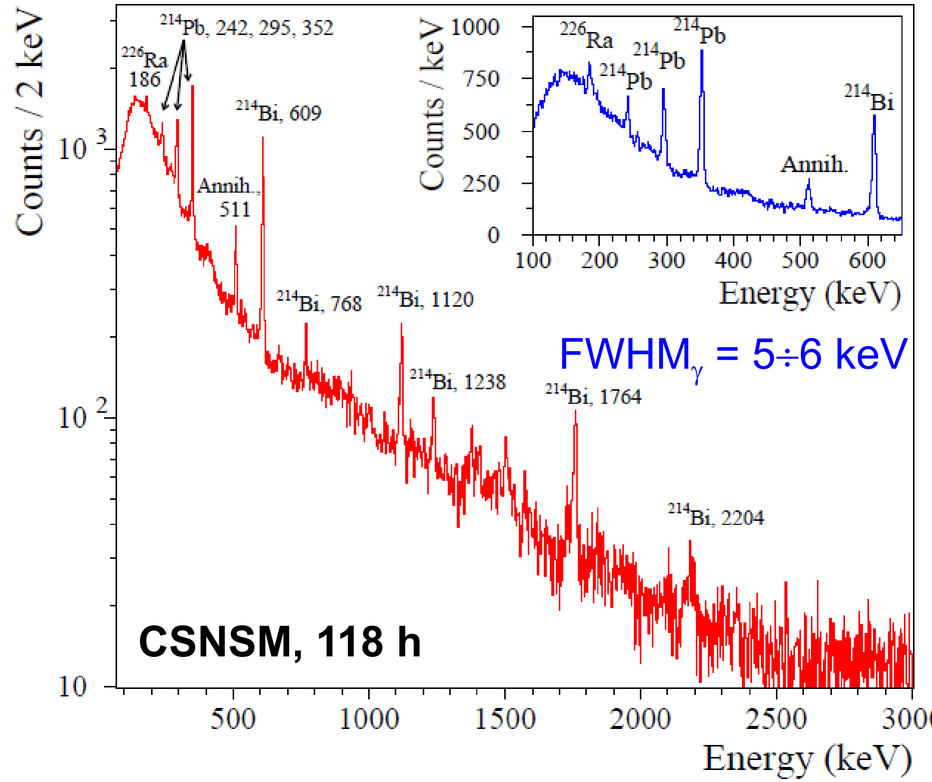


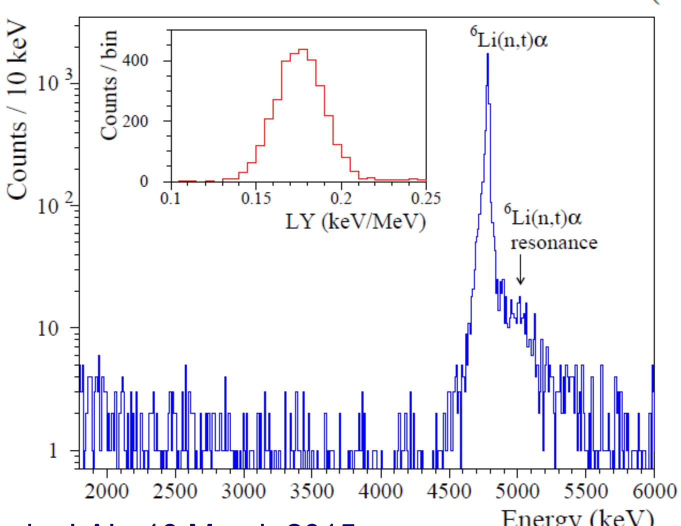


In ≈ 4.6 larger than previously tested sample !

Advanced Li_2MoO_4 bolometer: aboveground tests







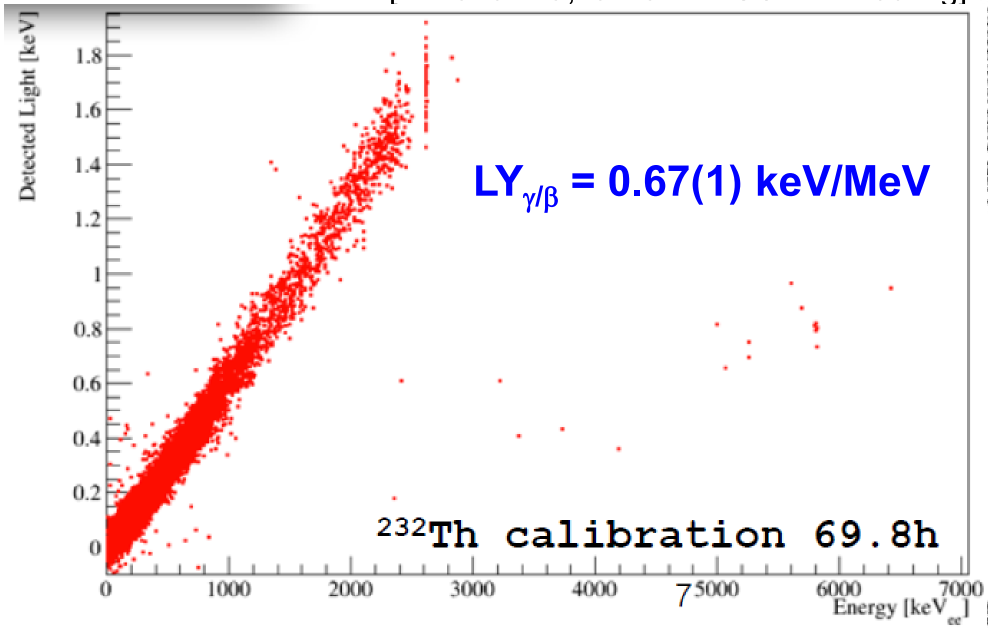
Li_2MoO_4 crystal	Light Yield (keV/MeV)		DP
	γ(β)	α+^{3}H	3.5-7 MeV
Precursor [1]	**0.43(1)**	**0.12(2)**	**~ 3**
Advanced [2]	**0.70(1)**	**0.17(1)**	**~ 16**

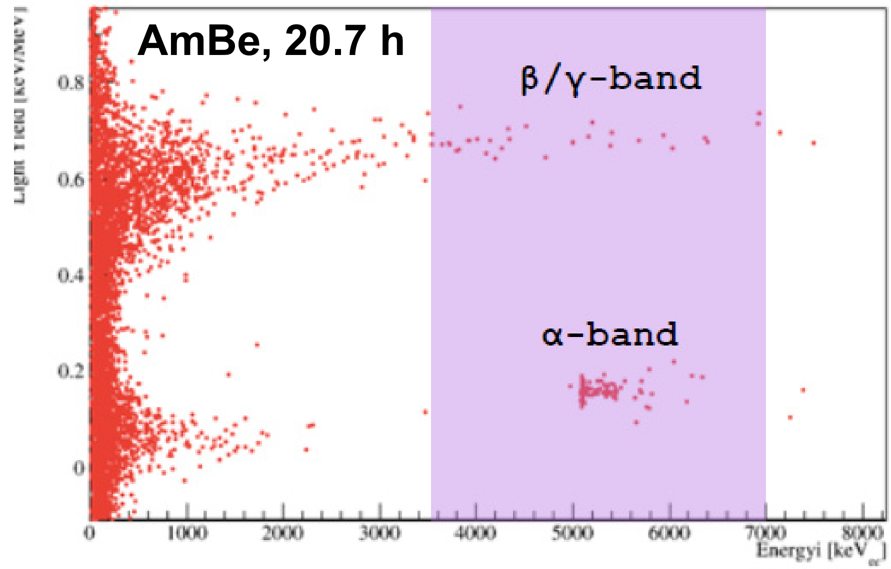
Improvement: LY ≈ in 1.5, DP ≈ in 5 !

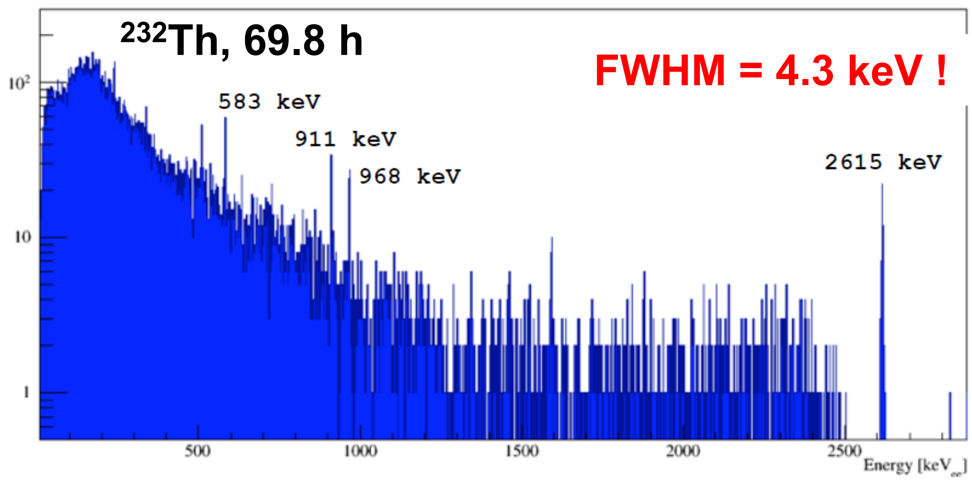
[1] T.B. Bekker et al., arXiv 1410.6933.
[2] L. Cardani et al., JINST 8 (2013) P10002.

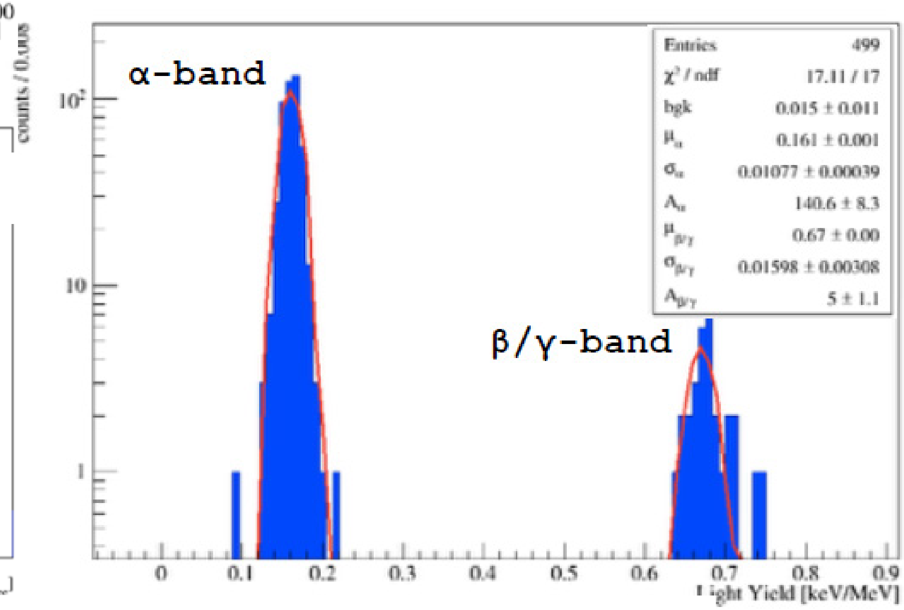
Advanced Li_2MoO_4 bolometer: test at LNGS

[L. Pattavina, talk at 4th ISOTTA meeting]





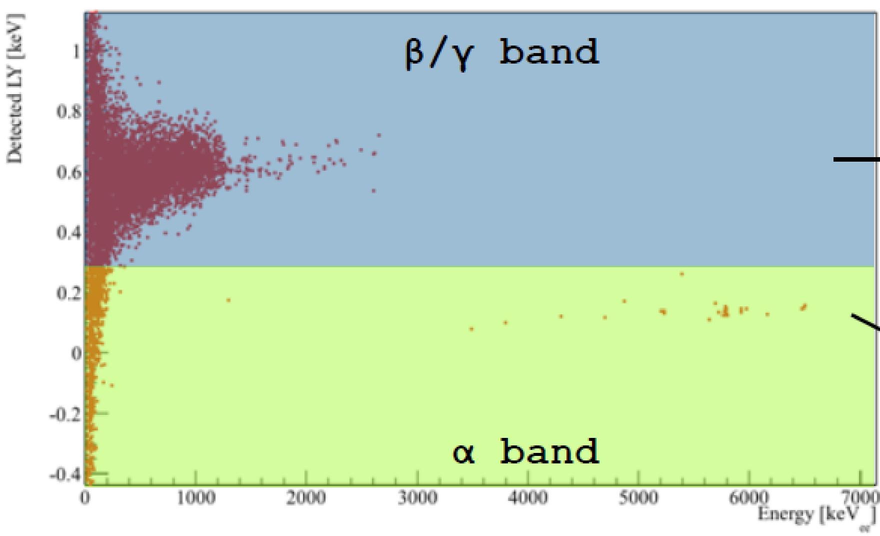




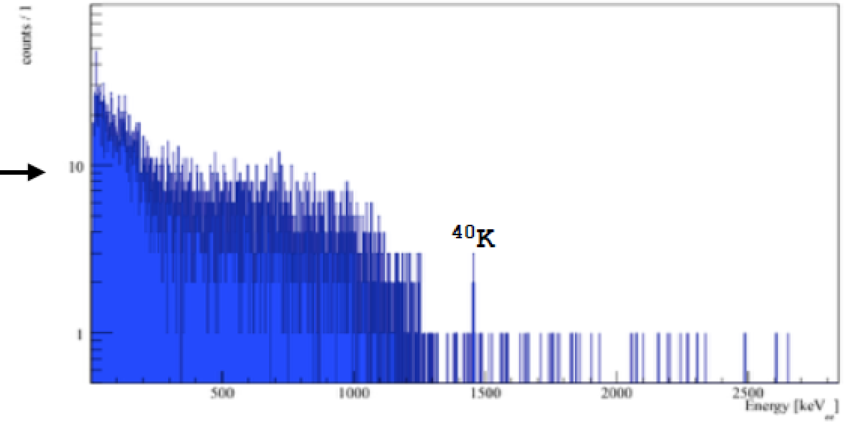
DP (3.5–7 MeV) = 30 !

Advanced Li_2MoO_4 bolometer: test at LNGS

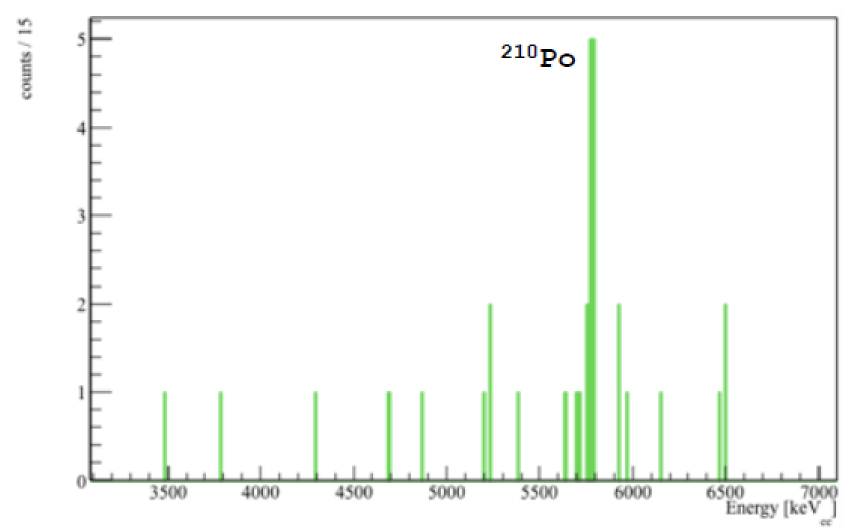
live time 237.5 h [L. Pattavina, talk at 4th ISOTTA meeting]



β/γ event selection



α event selection



Nuclide	Activity (mBq/kg)	
	Precursor 33 g [1,2]	**Advanced** 152 g
^{232}Th	≤ 0.094	≤ 0.019
^{238}U	≤ 0.107	≤ 0.019
^{226}Ra	≤ 0.107	≤ 0.008
^{210}Po	0.73(16)	0.09(3)
^{40}K	170(80)	~ 60

[1] O.P. Barinova et al., NIMA 607 (2009) 573.
[2] L. Cardani et al., JINST 8 (2013) P10002.

High radiopurity of Li_2MoO_4 even for not optimized crystal

LUMINEU schedule and extension

- 1 or 2 $Zn^{100}MoO_4$ crystal(s) ∅5×4 cm (March 2015)
- 1 or 2 Li_2MoO_4 crystal(s) ∅5×4 cm (March 2015)
- 1 or 2 $Li_2{}^{100}MoO_4$ crystal(s) ∅5×4 cm (May 2015)
- Tests of bolometric performance and radiopurity
- Choice between $ZnMoO_4$ and Li_2MoO_4

LUCINEU (joint efforts of LUCIFER and LUMINEU groups)

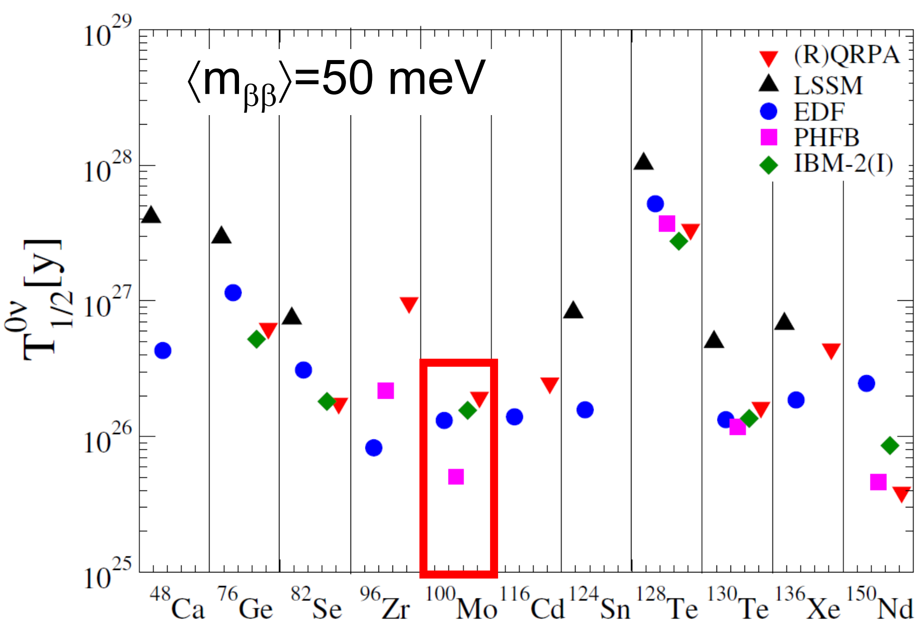
- ~10 kg of ^{100}Mo previously used in NEMO-3 (MoU IN2P3-ITEP-INFN)
- Systematic ^{100}Mo purification, crystal growth in NIIC
- 2016: batch of 20 + 20 Mo-containing crystals
- Experiments at LSM (France) and LNGS (Italy) underground labs

LUCINEU project

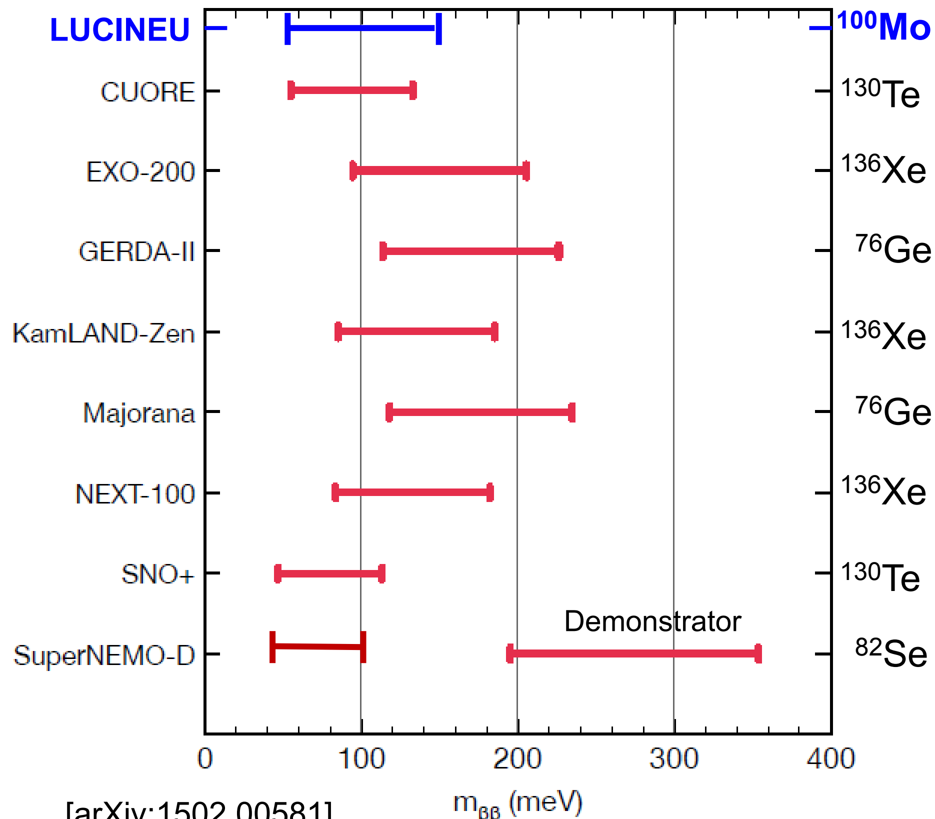
LUCINEU goal

- **~10 kg of ^{100}Mo (97%)**
- **40 $Zn^{100}MoO_4$ or $Li_2{}^{100}MoO_4$** (∅50×40 mm)
- **FWHM at ROI: 5÷9 keV**
- **Bkg in ROI:** **~4×10^{-3} counts/keV/kg/yr**
- **5-yr sensitivity:**
  $T_{1/2}$ ~ 5 × 10^{25} yr [Phys. Lett. B 710 (2012) 318]
  ⟨$m_{\beta\beta}$⟩ ~ 0.05–0.15 eV

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



[Rep. Prog. Phys. 75 (2012) 106301]

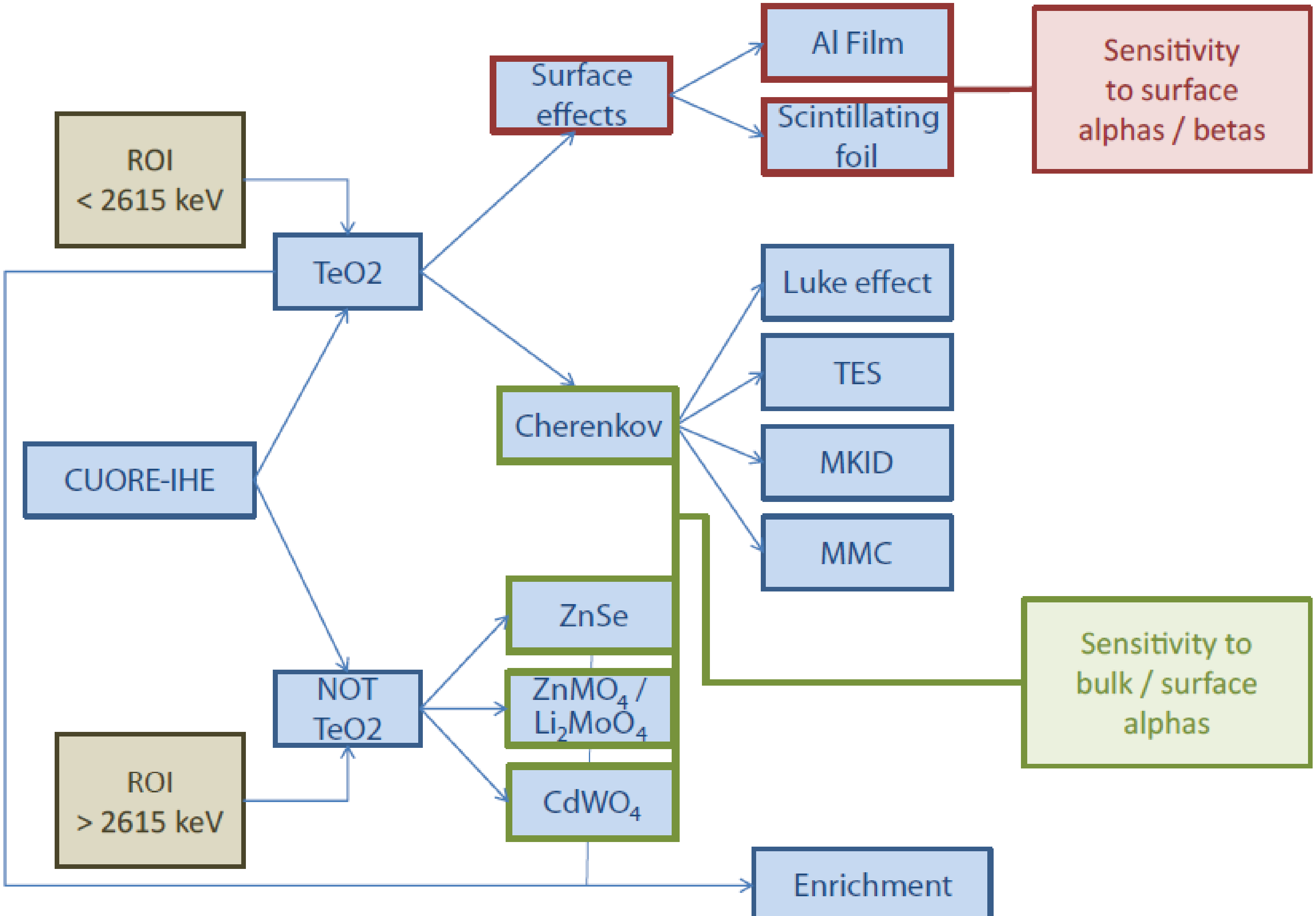


[arXiv:1502.00581]

Beyond CUORE: CUORE-IHE

The Cryogenic Underground Observatory for Rare Events – Inverted Hierarchy Explorer

http://fsnutown.phy.ornl.gov/fsnufiles/positionpapers/PositionPaper_CUORE-IHE.pdf



Summary

NLDBD is one of the hottest subjects in Astroparticle physics

- **Lepton number non-conservation** (leptogenesis ⇒ matter-antimatter asymmetry)
- **Neutrino properties** (Majorana nature of neutrino, the origin and absolute scale of neutrino masses, hierarchy of mass eigenstates, CP-violating phases)
- **Other effects beyond the Standard Model** (right-handed currents admixture in weak interactions, existence of Majoron,..)

Search for NLDBD is a challenging task due to extremely rare rate

- **Continuous enormous efforts to increase sensitivity** (fighting with background, increasing of source's mass towards to the ton-scale, improving of detector's performance, using costly enriched materials, long-term experiments)

Scintillating bolometer is an advanced technology for a high sensitivity NLDBD experiment capable to explore the inverted hierarchy

- **Prospects of "zero"-background NLDBD experiment** (isotopes with $Q_{\beta\beta}$ above 2.6 MeV, high energy resolution FWHM=0.1÷0.5%, excellent α/γ discrimination, high radiopurity e.g. ^{228}Th and ^{226}Ra < 5 μBq/kg in $ZnMoO_4$)
- **Several ~10 kg demonstrators are developing simultaneously with different isotopes to validate the technology** (LUCIFER, AMoRE, LUMINEU ⇒ LUCINEU)
- **AMoRE is funded to 200-kg scale** (the projected sensitivity is in the IH region)
- **CUORE-IHE is a possible 1-ton scale experiment with this technology** (with the aim to cover the IH neutrino mass pattern)

Backup slides

Next-generation $ZnMoO_4$-based 0νββ experiment

[Phys. Lett. B 710 (2012) 318]

Monte Carlo basis

Detectors:

- **2000 $Zn^{100}MoO_4$ crystals** (~0.4 kg each; ^{100}Mo ~ 97%)
- **PTFE clamps** (6x for ZMO)
- **Cylindrical Cu holders**
- **Ge-based light detectors** (∅60×0.5 mm)

Performance:

- **FWHM = 6 keV @ 3 MeV**
- **Threshold > 20 keV**
- **Rejection of α's ~ 99.9%**
- **Anticoincidence cut**
- **5-yr data taking**

Software:

- **COSMO** (3 months activation aboveground and 1 yr cooling underground)
- **DECAY0** (event generator)
- **GEANT4 package**

Source of background	Activity [μBq/kg]	BKG [counts/(keV kg y)]
^{208}Tl in ZMO	10	3.2×10^{-3}
^{214}Bi in ZMO	10	3×10^{-8}
^{228}Th in Cu	20	1.6×10^{-5}
^{226}Ra in Cu	70	1.3×10^{-7}
^{228}Th in PTFE	100	2×10^{-7}
^{226}Ra in PTFE	60	$< 10^{-9}$
^{56}Co in ZMO	0.06	1.8×10^{-5}
^{56}Co in Cu	0.02	8×10^{-6}
^{88}Y in ZMO	0.3	7×10^{-7}
Total		3.2×10^{-3}

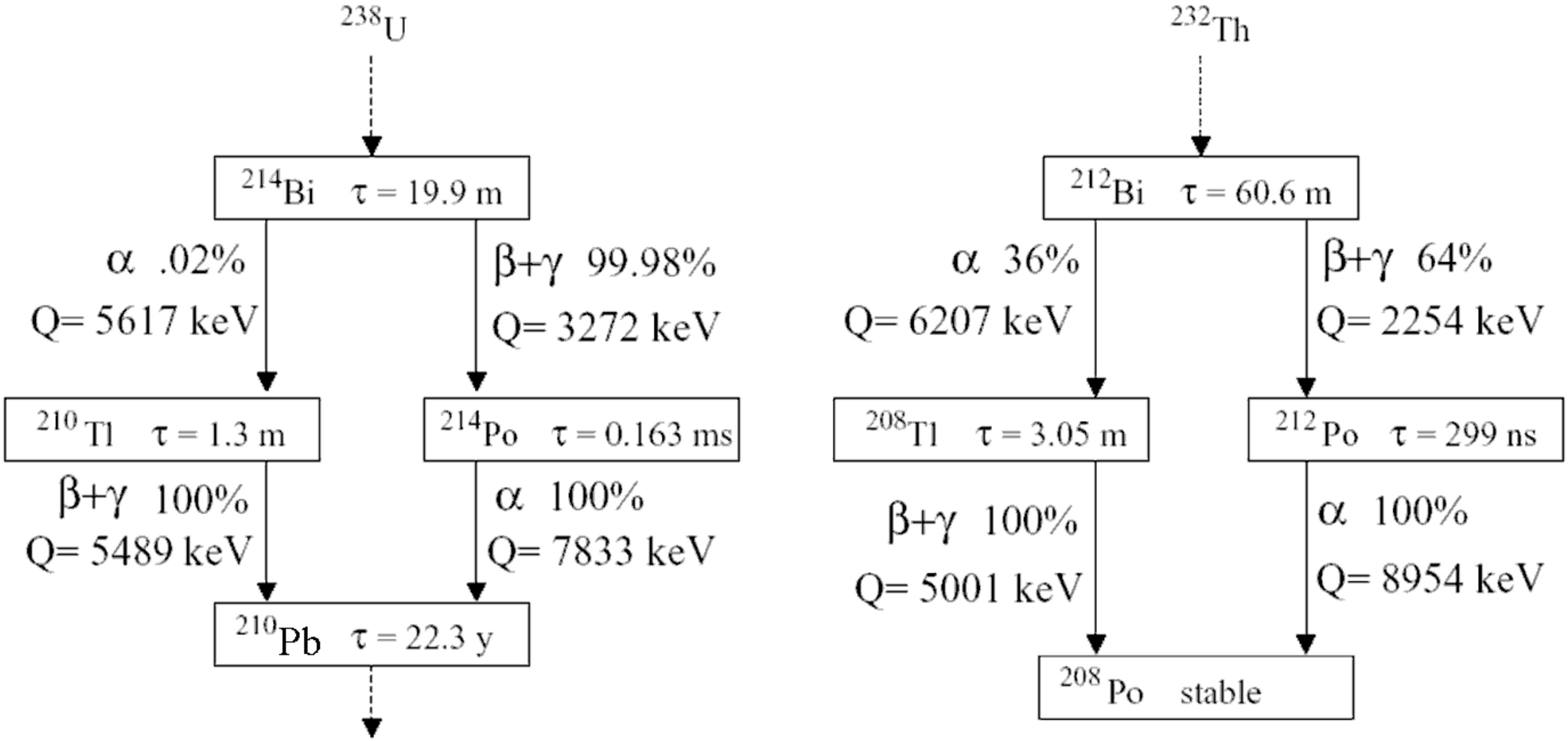
Bkg contribution to ROI (counts/keV/kg/yr)

- **"^{208}Tl in ZMO" ~10^{-4}** (reduced by vetoing 5×$T_{1/2}$ of ^{208}Tl, 15 m, after tagging of α ^{212}Bi; dead time ~ 1%)
- **Neutron's < 10^{-4}**
- **Muon's ~ 10^{-4}** (+ can be reduced by muon veto)
- **Pile-ups of 2νββ of ^{100}Mo ~ 3×10^{-4}** (+ possible reduction by PSD)

Total Background in ROI: ~ 4×10^{-4} counts/keV/kg/yr

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

Scintillating bolometer: ^{214,212}Bi-induced Bkg



- **BiPo's totally rejected** (pile-uped (β+α)-events)
- **Contribution from ^{210,208}Tl can be suppressed** (identification of α's of ^{214,212}Bi and 10 half-lives vetoing: e.g. 30 m for ^{208}Tl gives suppression 2^{10}=1024 times and negligible dead time, < 1%, if activity of ^{228}Th ~ 0.01 mBq/kg)

Specific background of bolometric DBD experiment

Eur. Phys. J. C (2012) 72:1989
DOI 10.1140/epjc/s10052-012-1989-y

THE EUROPEAN PHYSICAL JOURNAL C

Letter

Random coincidence of $2\nu2\beta$ decay events as a background source in bolometric $0\nu2\beta$ decay experiments

D.M. Chernyak[1,2], F.A. Danevich[1], A. Giuliani[2,a], E. Olivieri[2], M. Tenconi[2], V.I. Tretyak[1]

[1]Institute for Nuclear Research, MSP, 03680 Kyiv, Ukraine
[2]Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, 91405 Orsay, France

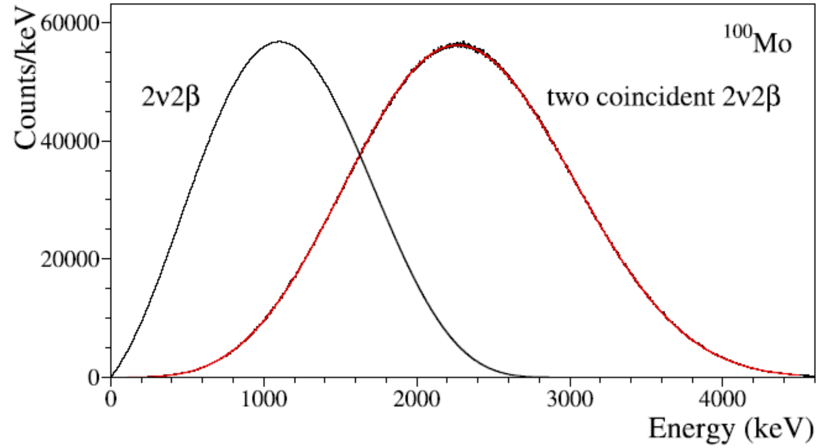


Table 2 Counting rate of two randomly coincident $2\nu2\beta$ events in cryogenic $Zn^{82}Se$, $^{40}Ca^{100}MoO_4$, $Zn^{100}MoO_4$, $^{116}CdWO_4$, and TeO_2 detectors of 100 cm^3 volume. Enrichment of ^{82}Se, ^{100}Mo, and ^{116}Cd is assumed to be 100 %, while for Te the natural isotopic abundance (34.08 %) is taken. C is the mass concentration of the isotope of interest, ρ is the density of the material (g/cm^3), N is the number of 2β candidate nuclei in one detector, and B_{rc} is the counting rate at $Q_{2\beta}$ (counts/(keV·kg·yr)) under the assumption of 1 ms time resolution of the detector

Isotope	$T_{1/2}^{2\nu2\beta}$ (yr) [27]	Detector (ρ)	C	N	B_{rc}
^{82}Se	9.2×10^{19}	$Zn^{82}Se$ (5.65)	55.6 %	2.31×10^{24}	5.9×10^{-6}
^{100}Mo	7.1×10^{18}	$^{40}Ca^{100}MoO_4$ (4.35)	49.0 %	1.28×10^{24}	3.8×10^{-4}
		$Zn^{100}MoO_4$ (4.3)	43.6 %	1.13×10^{24}	2.9×10^{-4}
^{116}Cd	2.8×10^{19}	$^{116}CdWO_4$ (8.0)	31.9 %	1.32×10^{24}	1.4×10^{-5}
^{130}Te	6.8×10^{20}	TeO_2 (5.9)	27.2 %	0.76×10^{24}	1.1×10^{-8}

Rejection of pile-ups by $ZnMoO_4$ bolometer

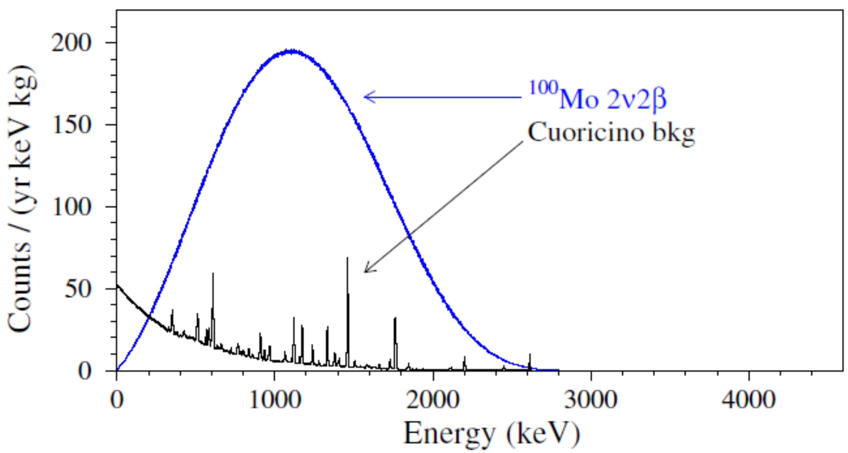
Eur. Phys. J. C (2014) 74:2913
DOI 10.1140/epjc/s10052-014-2913-4

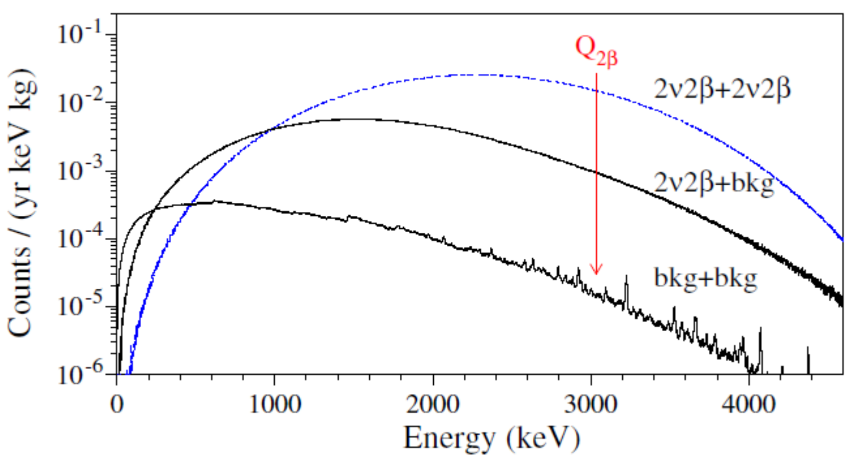
THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

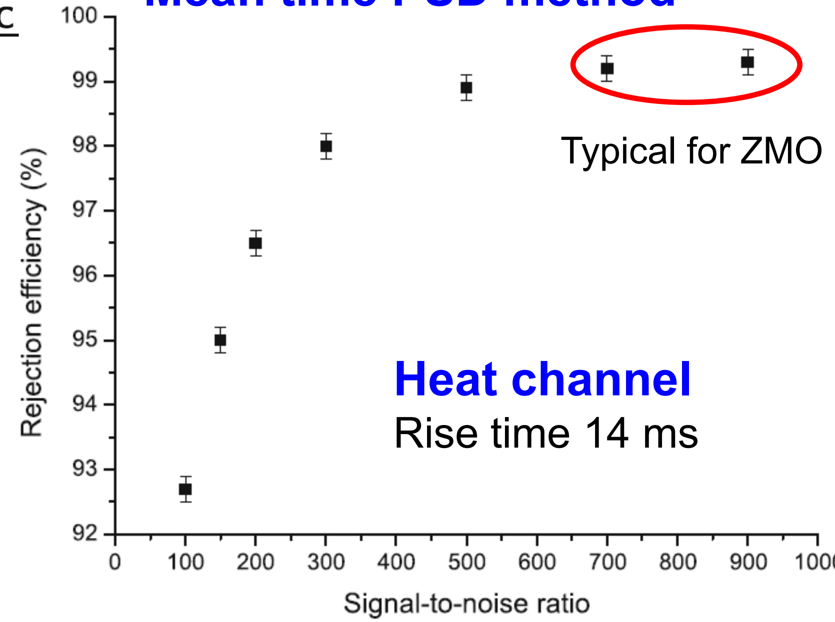
Rejection of randomly coinciding events in $ZnMoO_4$ scintillating bolometers

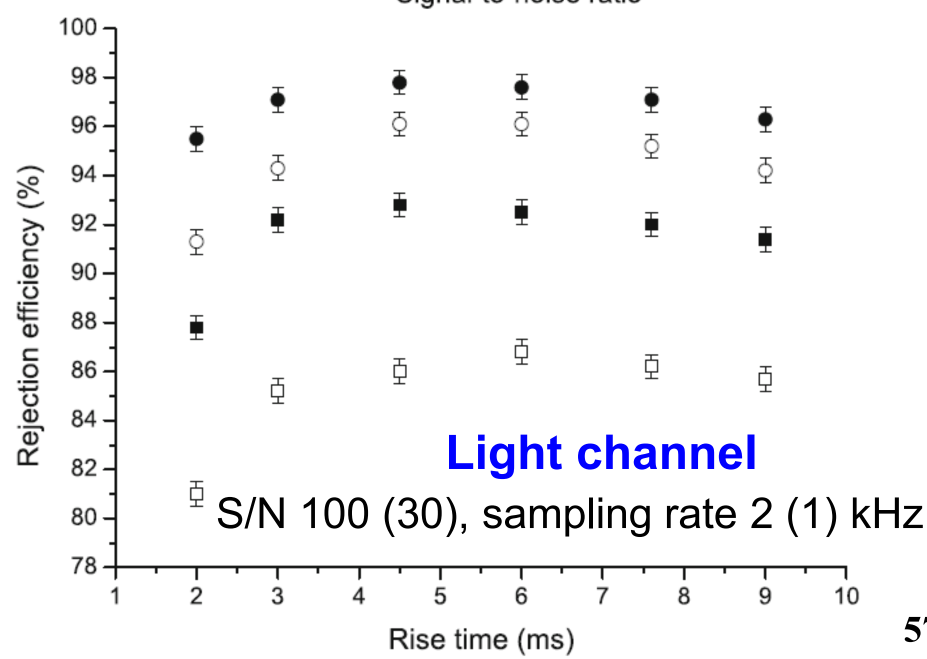
D. M. Chernyak[1,2], F. A. Danevich[1], A. Giuliani[2,3,a], M. Mancuso[2,3], C. Nones[4], E. Olivieri[2], M. Tenconi[2], V. I. Tretyak[1]



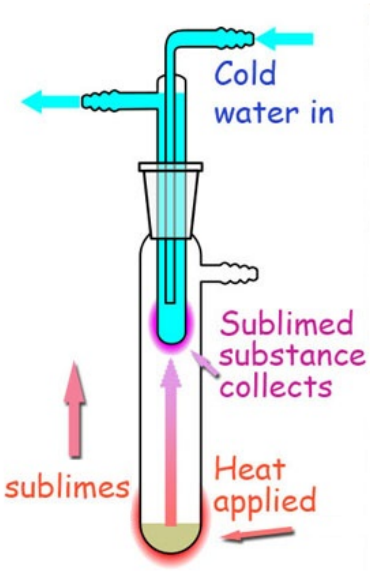


Mean time PSD method





Sublimation purification



Purification by sublimation

- Sublimation of molybdenum oxide is widely used in the industry of molybdenum
- Nevertheless the concentration of impurities, particularly of W (up to 0.5wt% even in the high purity grade materials) still exceeds the $ZnMoO_4$ crystal growth requirements
- We have developed a technique of molybdenum purification by sublimation of MoO_3 in vacuum (with addition of zinc molybdate $ZnMoO_4 + WO_3 \rightarrow ZnWO_4 + MoO_3\uparrow$)
- The technique is expected to be efficient to remove Th and U

[L. Bergé et al., JINST 9 (2014) P06004]

Sublimation at NIIC (Novosibirsk, Russia)

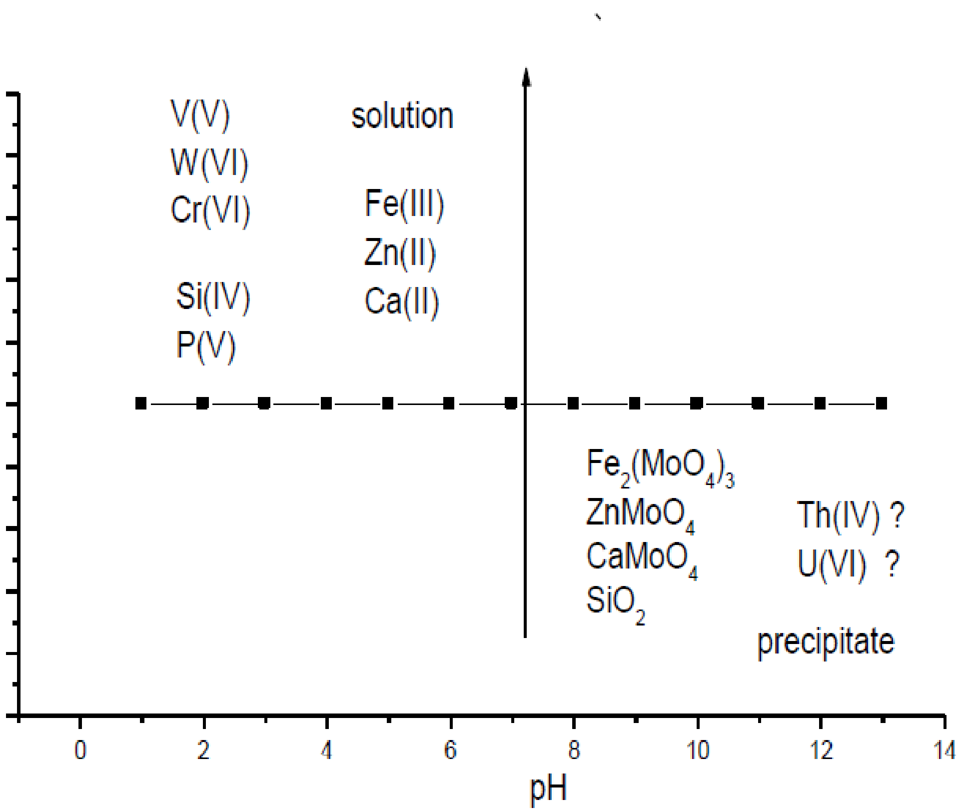
- The temperature up to 700°C
- Vacuum pump
- Initial material MoO_3 (impurities 10-100 ppm)
- Single entry sublimation reduces the content of W, Fe, Cr more than one order magnitude
- Productivity the laboratory setup 1–2 kg/week

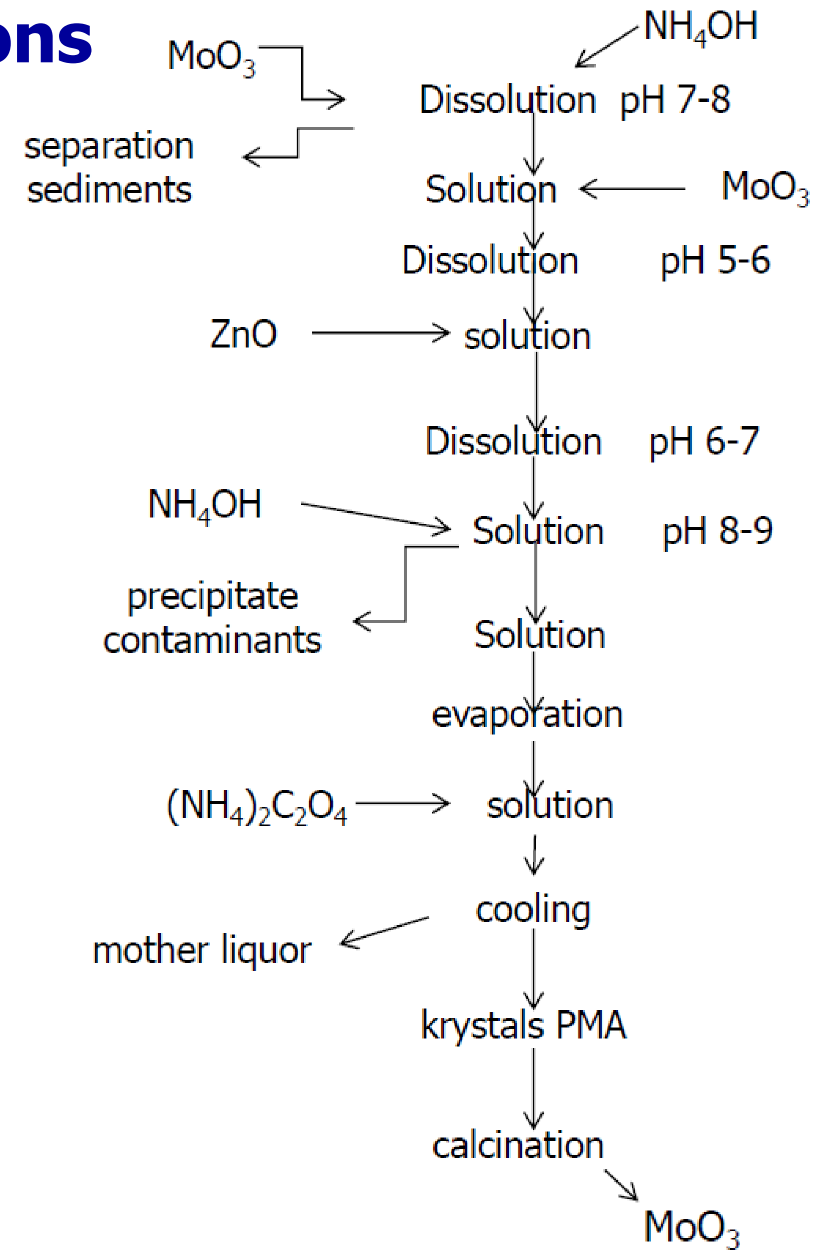
[V.N. Slegel, talk at RPSCINT 2013]

Recrystallization from solutions

Molybdenum in aqueous solutions

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





[V.N. Slegel, talk at RPSCINT 2013]

Development of $Zn^{100}MoO_4$ crystal boule

[A.S. Barabash et al., EPJC 74 (2014) 195]

- **Purification of $^{100}MoO_3$ in two stages**
  sublimation in vacuum:
  recrystallization from aqueous solutions:
- **$^{100}MoO_3$** (132 g, ^{100}Mo is 99.5%)
- **ZnO** (72 g, 99.995% purity, UMICORE)
- **$Zn^{100}MoO_4$ powder (204 g) was obtained by solid-phase synthesis**
- **$Zn^{100}MoO_4$ boule (171 g) was grown in Pt crucible ∅40×100 mm by using low-thermal-gradient Czochralski technique**
  20 rot/min (beginning) → 4 rot/min (end)
  temperature gradient ≤ 1 °C/cm
- **The yield of crystal boule is 84%**
- **Irrecoverable loses of ^{100}Mo at all stages is 4%** (compatible with results of $^{106,116}CdWO_4$ crystals developing [1,2])

[1] P. Belli et al., NIMA 615 (2010) 301.
[2] A.S. Barabash et al., JINST 06 (2011) P08011.

Table 1 Contamination of $^{100}MoO_3$ measured by inductively coupled plasma mass-spectrometry (ICP-MS) and atomic absorption spectroscopy (AAS) methods.

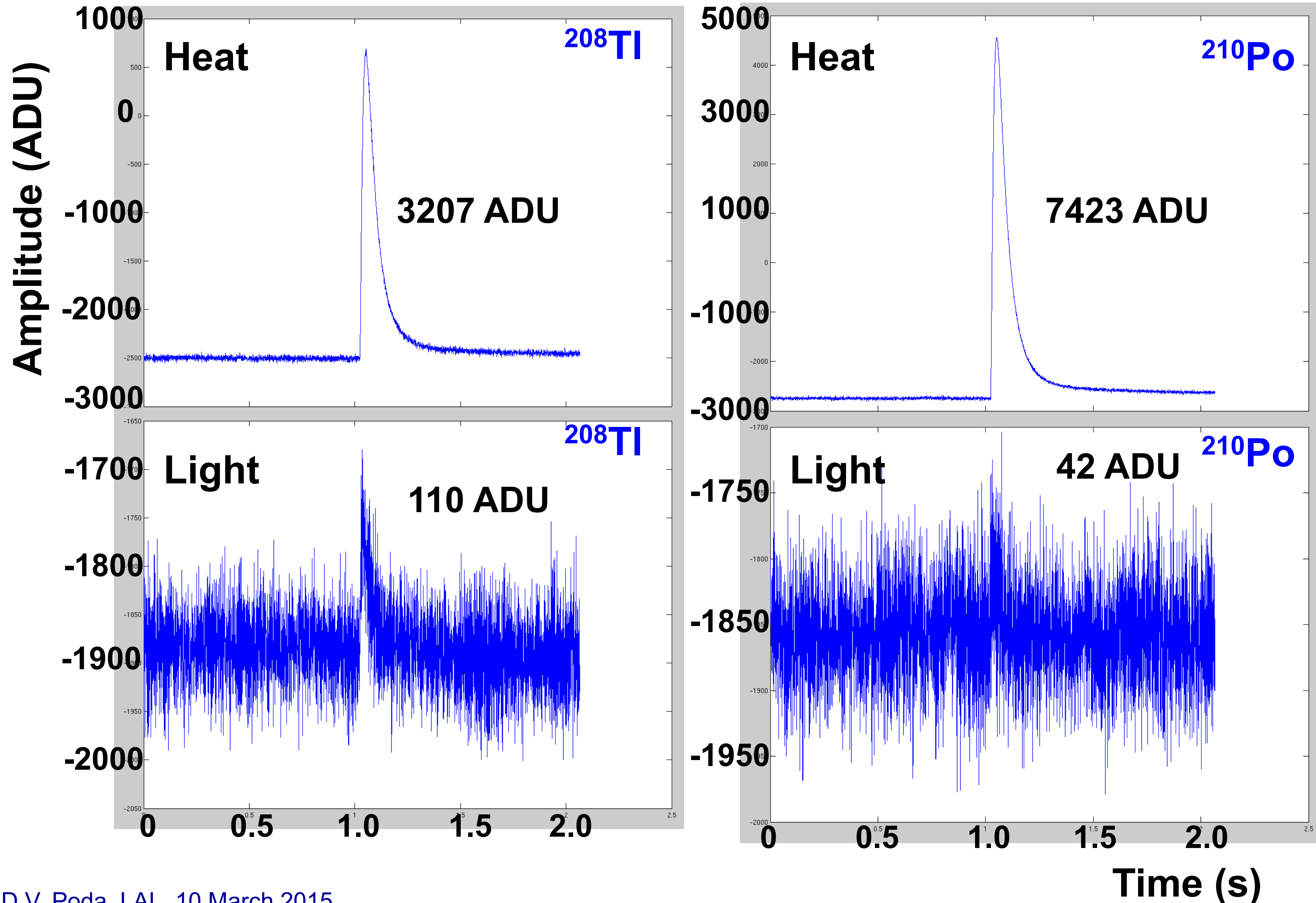
Element	Concentration of element in $^{100}MoO_3$ (ppm)	
	ICP-MS	AAS
Na	–	< 60
Mg	< 0.5	< 4
Al	2.4	–
Si	–	< 500
K	< 15	< 10
Ca	–	< 10
V	0.05	–
Cr	0.2	< 5
Mn	0.1	–
Fe	8	< 5
Ni	0.01	–
Cu	0.1	–
Zn	0.1	< 4
Ag	0.3	–
W	1700	550
Pb	0.008	–
Th	< 0.0005	–
U	0.001	–

Table 2 Irrecoverable losses of enriched molybdenum in all the stages of $Zn^{100}MoO_4$ crystal scintillator production.

Stage	Loss
Sublimation of $^{100}MoO_3$	1.4%
Recrystallization from aqueous solutions	2%
Crystal growth	0.6%
Total	4%

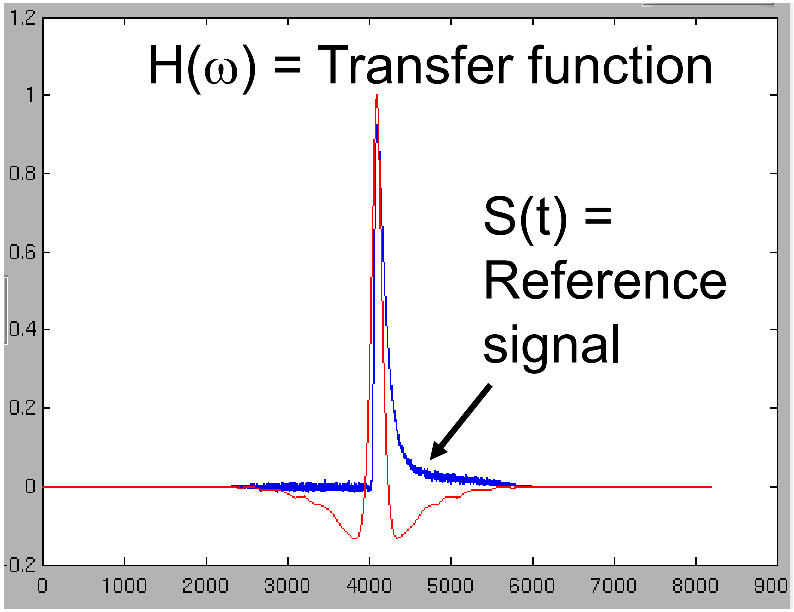
Raw data: Heat and Light signals

313 g $ZnMoO_4$ bolometer at LSM



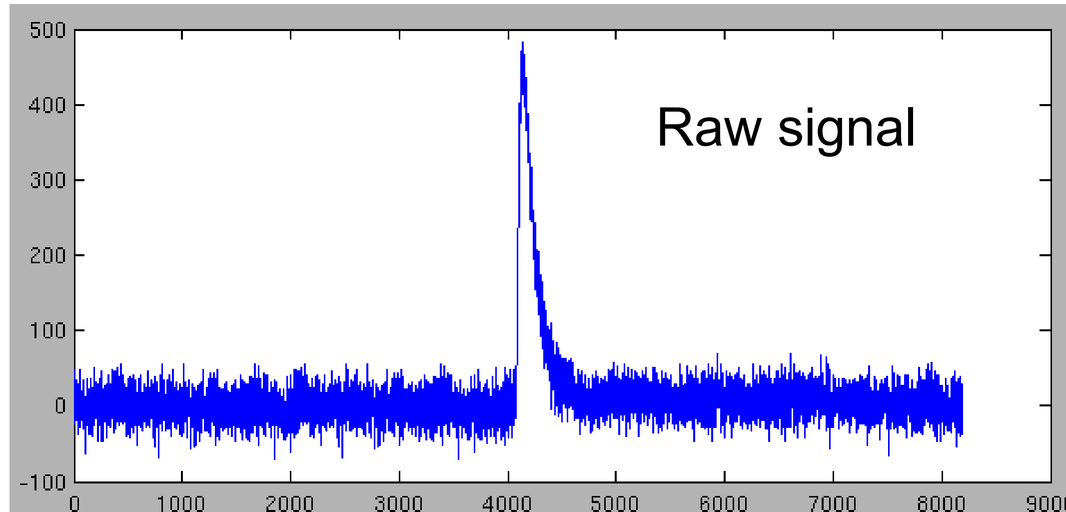
Data treatment by Optimum Filter technique

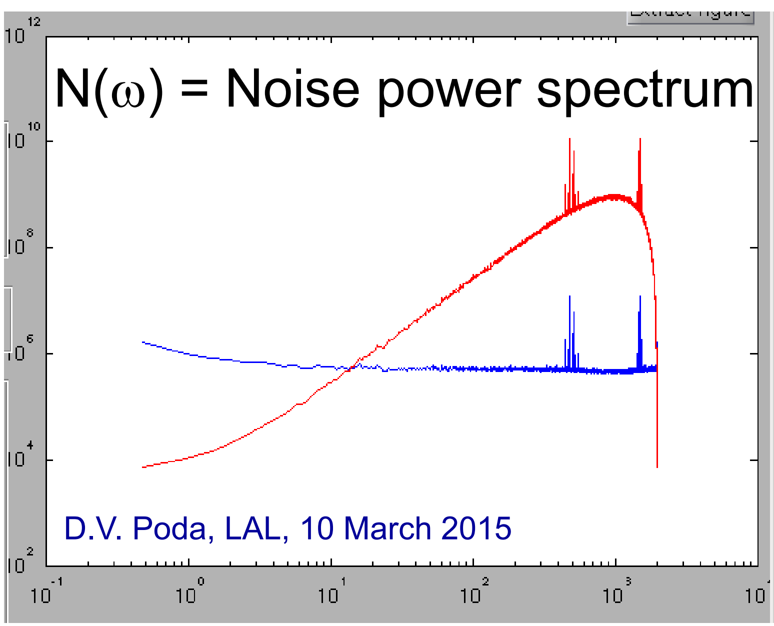
$$H(\omega) = k \times S^*(\omega) / N(\omega) \times \exp\{i\,\omega\, t_{max}\}$$

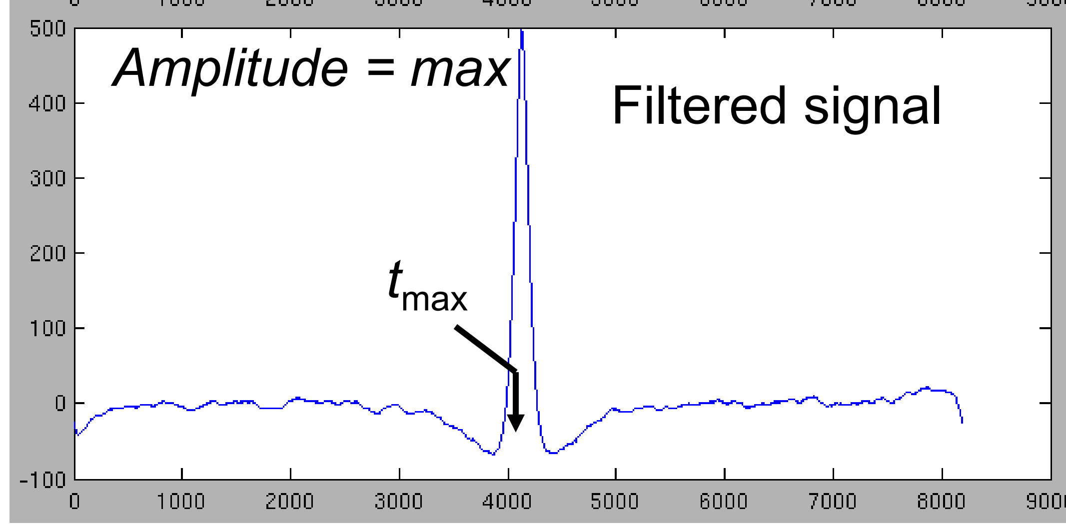


S(ω) – Fourier transform of S(t)

k – normalization constant

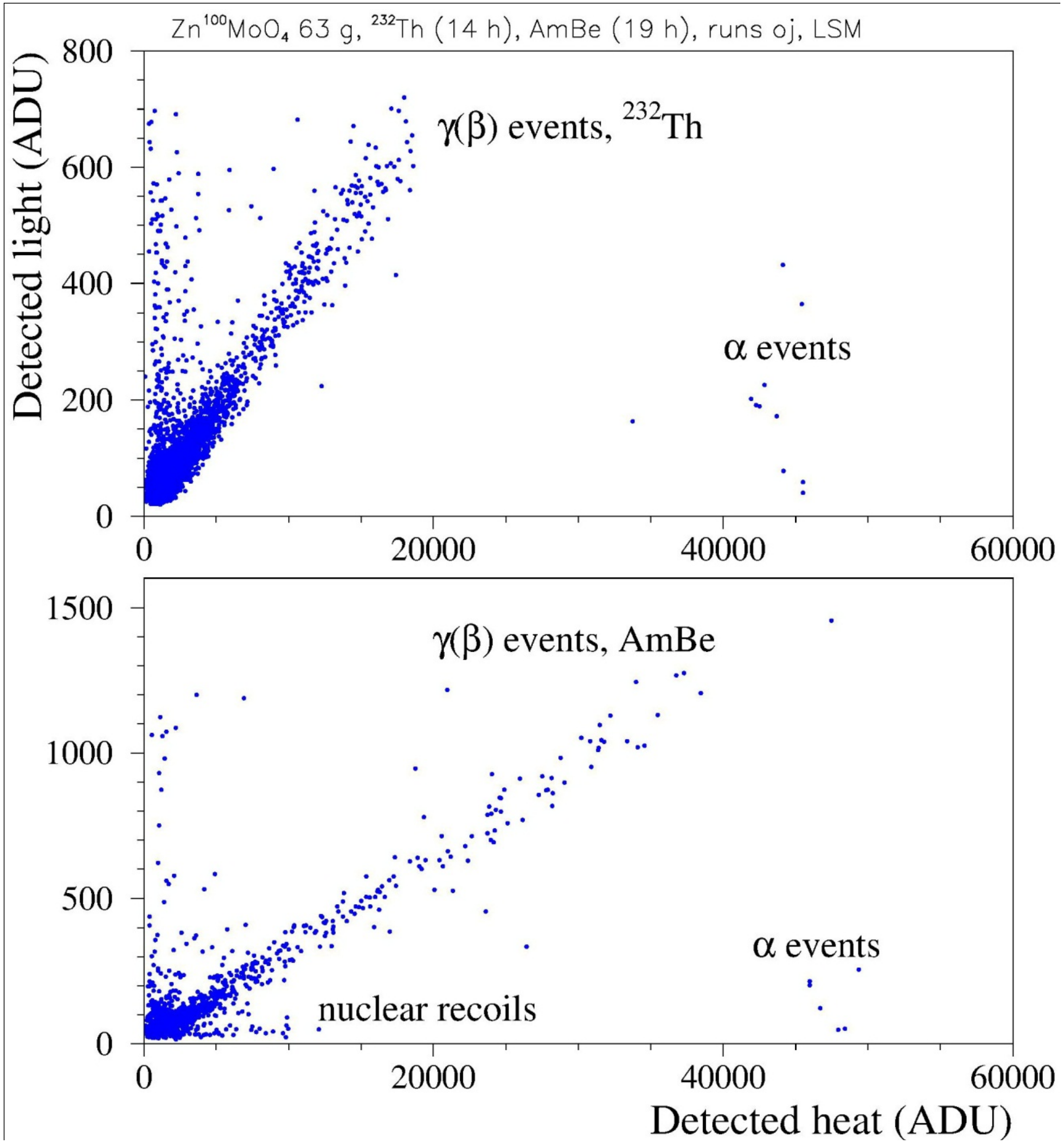




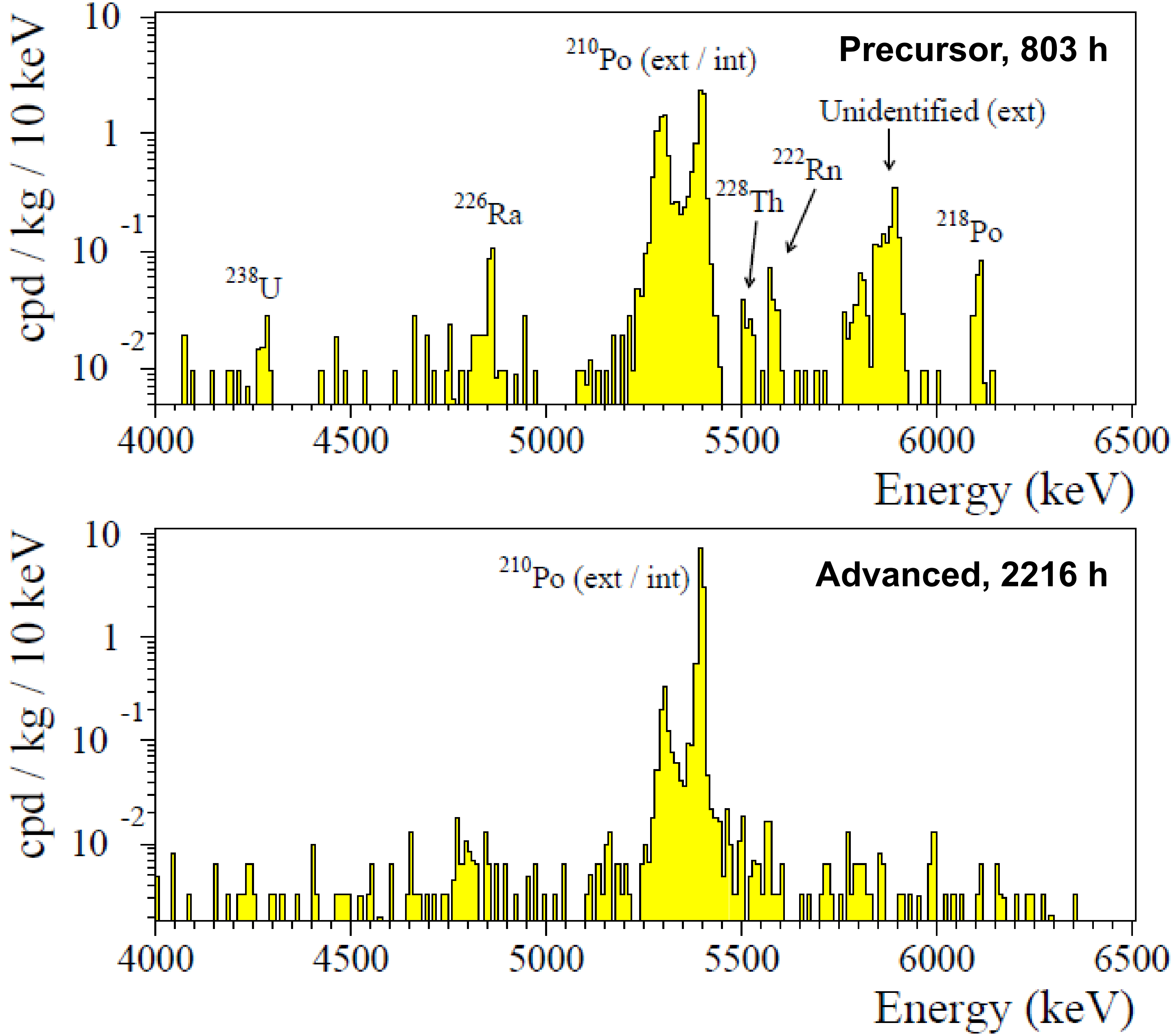


[1] E. Gatti, P.F. Manfredi, Riv. Nuovo Cim. 9(1986)1.

$Zn^{100}MoO_4$: Calibration by ^{232}Th and AmBe

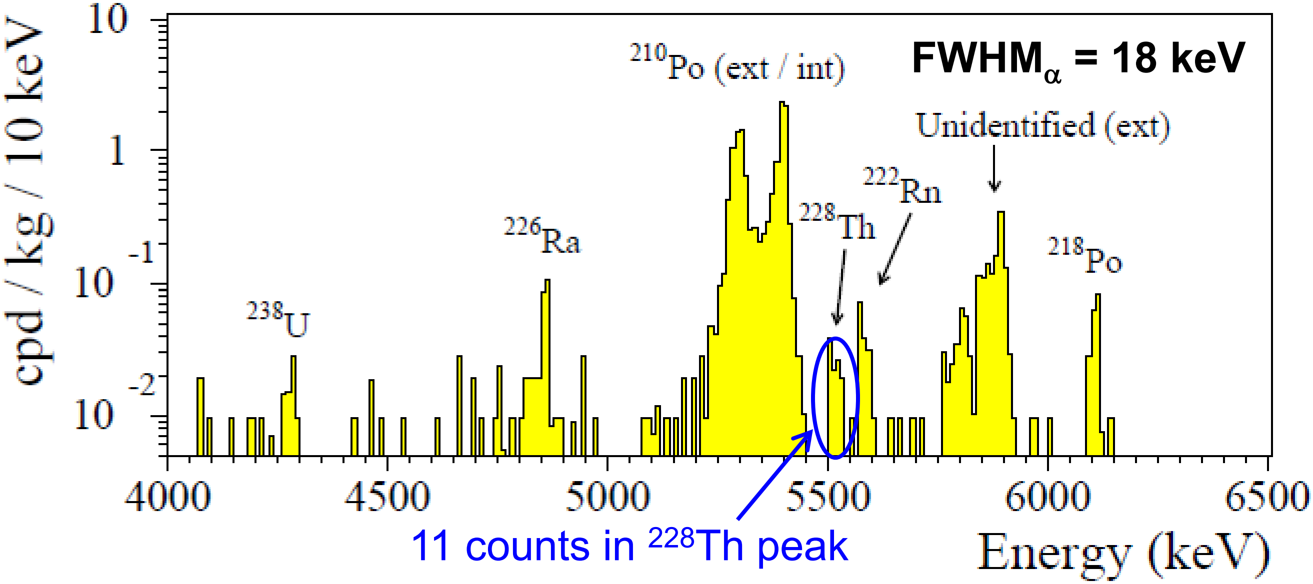


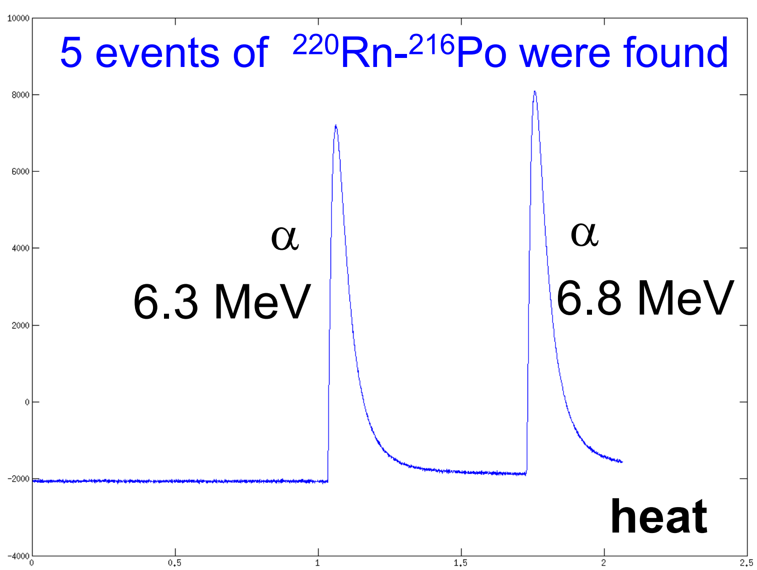
Precursor / Advanced $ZnMoO_4$: α Background

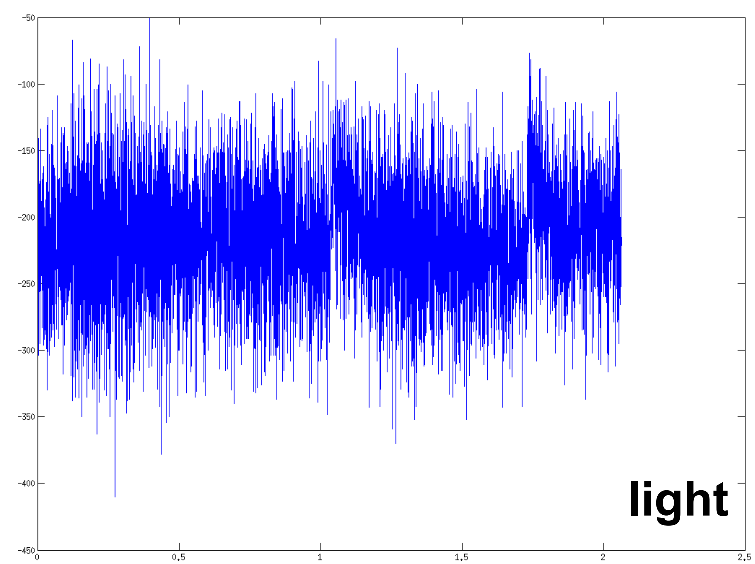


Precursor $ZnMoO_4$: internal ^{228}Th

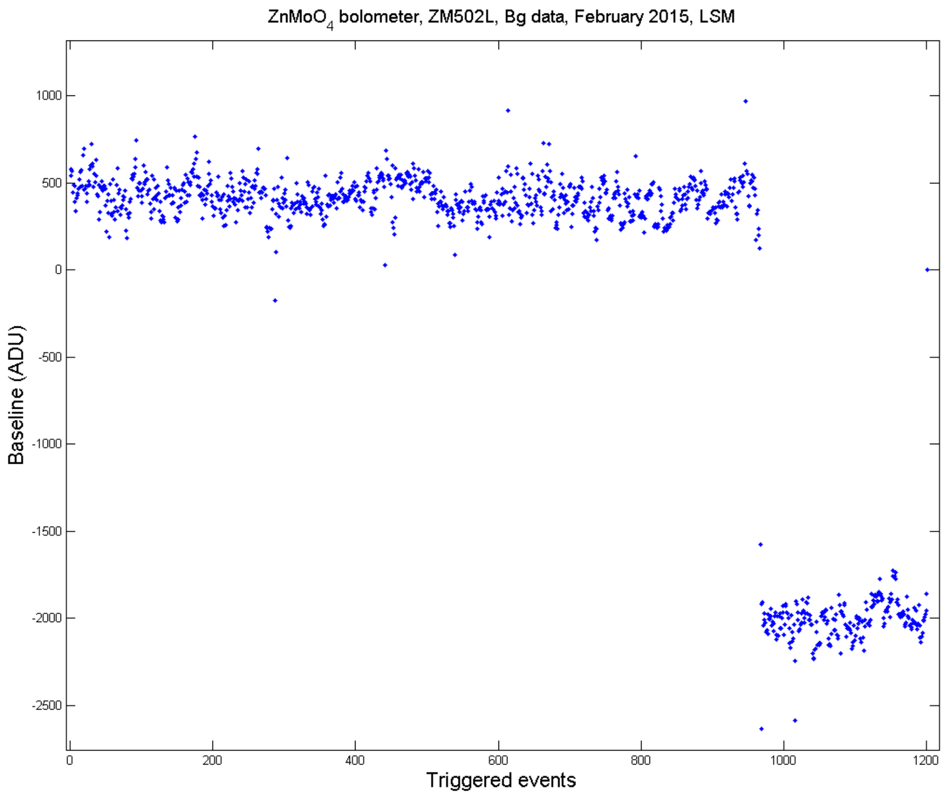
$ZnMoO_4$ 313 g, α spectrum, 803 h, LSM

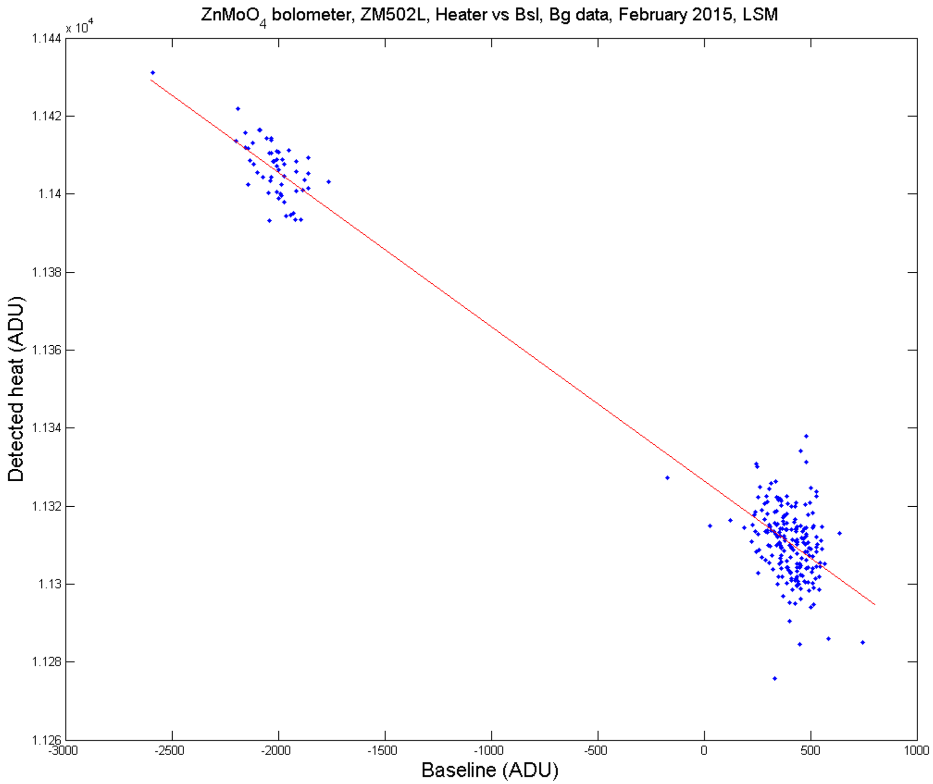




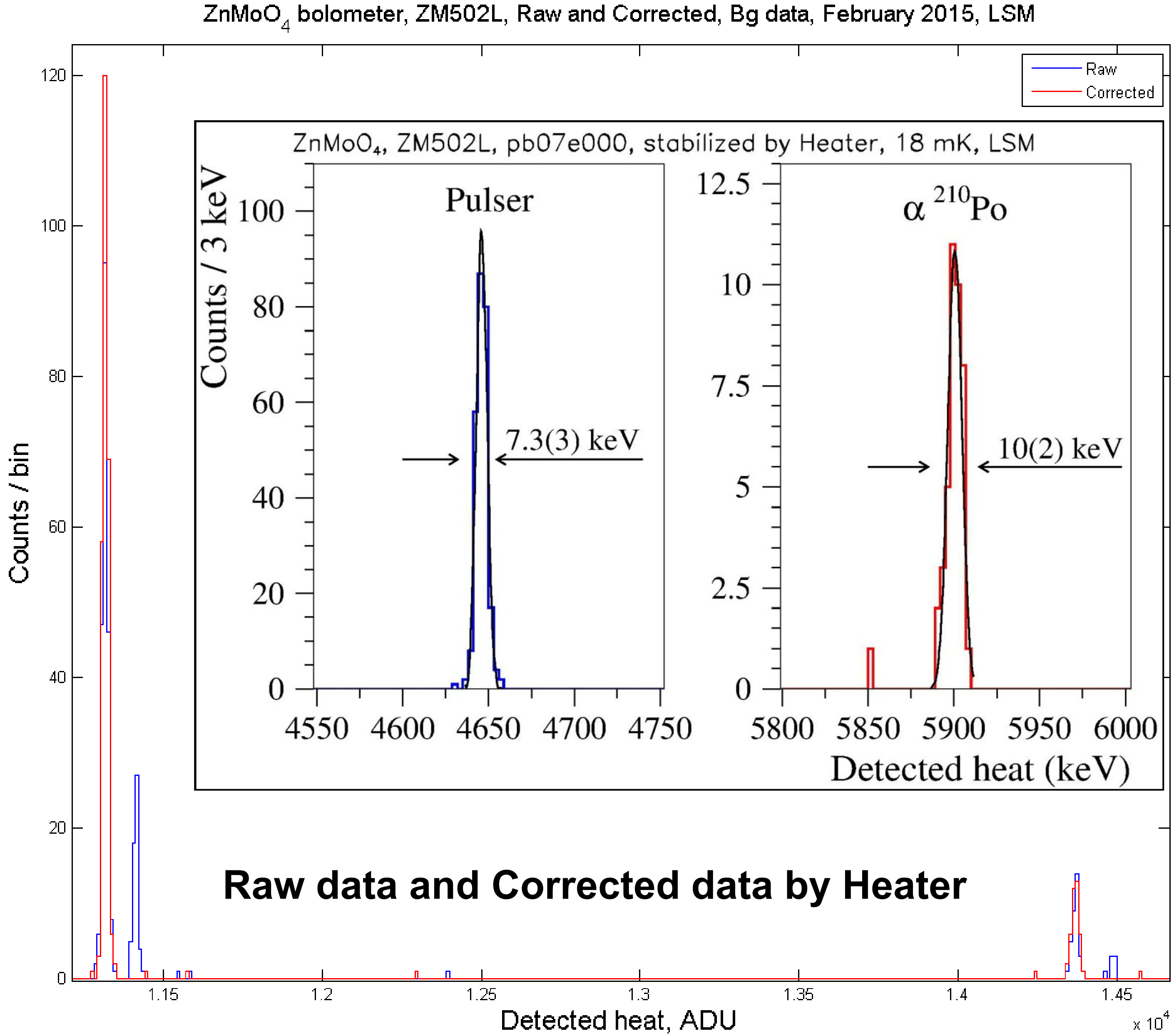


Advanced $ZnMoO_4$: pulser's performance



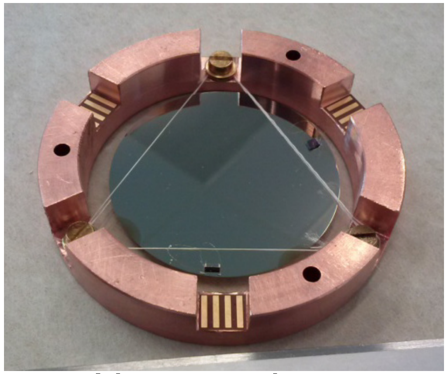


Advanced $ZnMoO_4$: pulser's performance

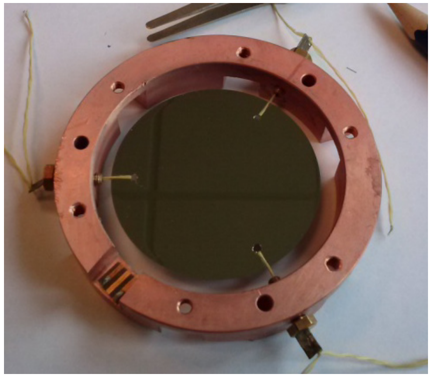


LUMINEU: development of light detectors

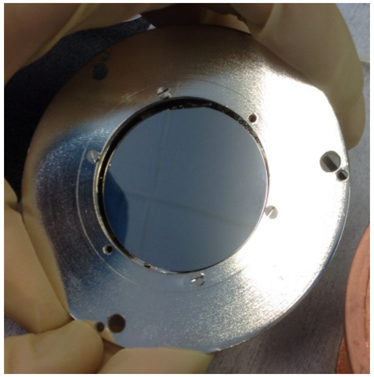
Optimisation of the way to held the detector + Optimisation of the NTD thermal coupling



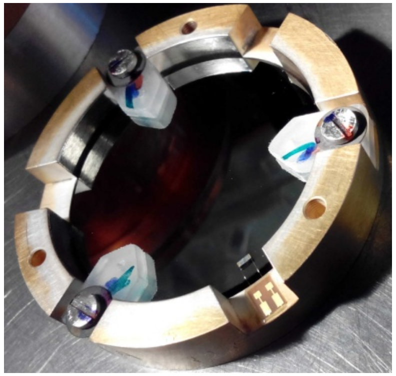
Nomex wires



Kevlar wires



12 thin ∅6 μm wires

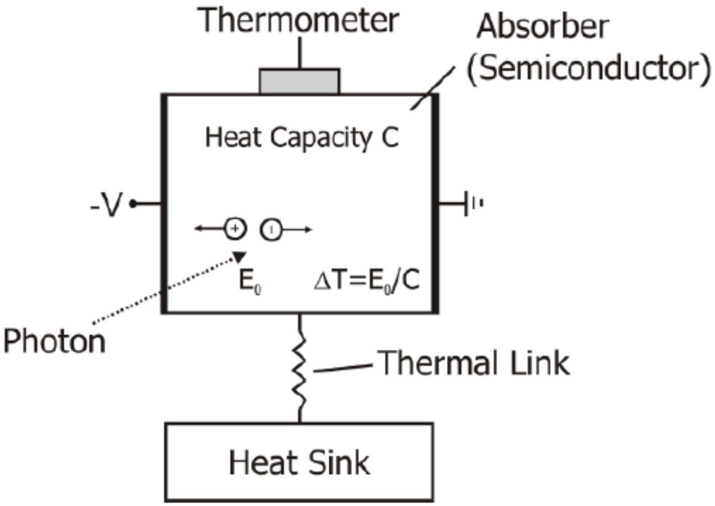


Sapphire sphere ∅1.5 mm

Performance of optical bolometers tested at CSNSM

	Optical bolometer	Size (mm)	Sensitivity (μV/keV)	FWHM noise (keV)
Developed within the LUCIFER project	LT8	∅50 × 0.250	0.3	0.56
	LT9	∅50 × 0.250	0.4	0.28
Developed @ CSNSM (coated by SiO)	M1	∅44 × 0.250	1.0	0.40
	M3	∅44 × 0.250	2.5	0.65
	M4	∅44 × 0.250	0.9	0.27
Developed @ IAS (new sapphire pat held)	IAS	∅40 × 0.043	6.6	0.07
Developed @ CSNSM	Luke	∅44 × 0.250	0.7 17.5	0.50 (0 V) 0.02 (53 V)

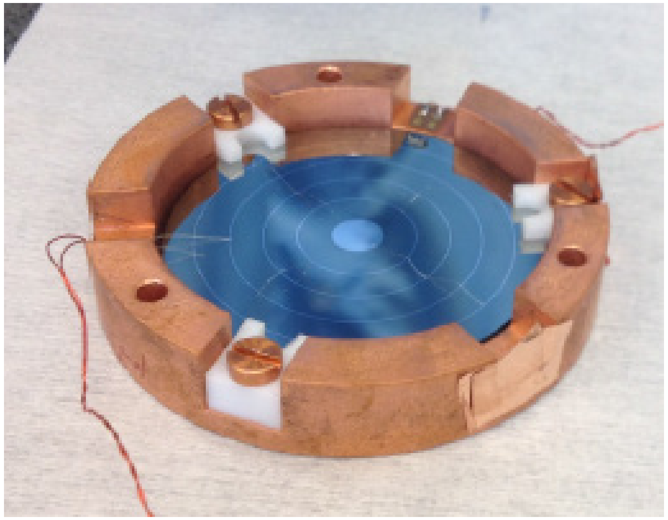
LUMINEU: Neganov-Luke effect assisted LD

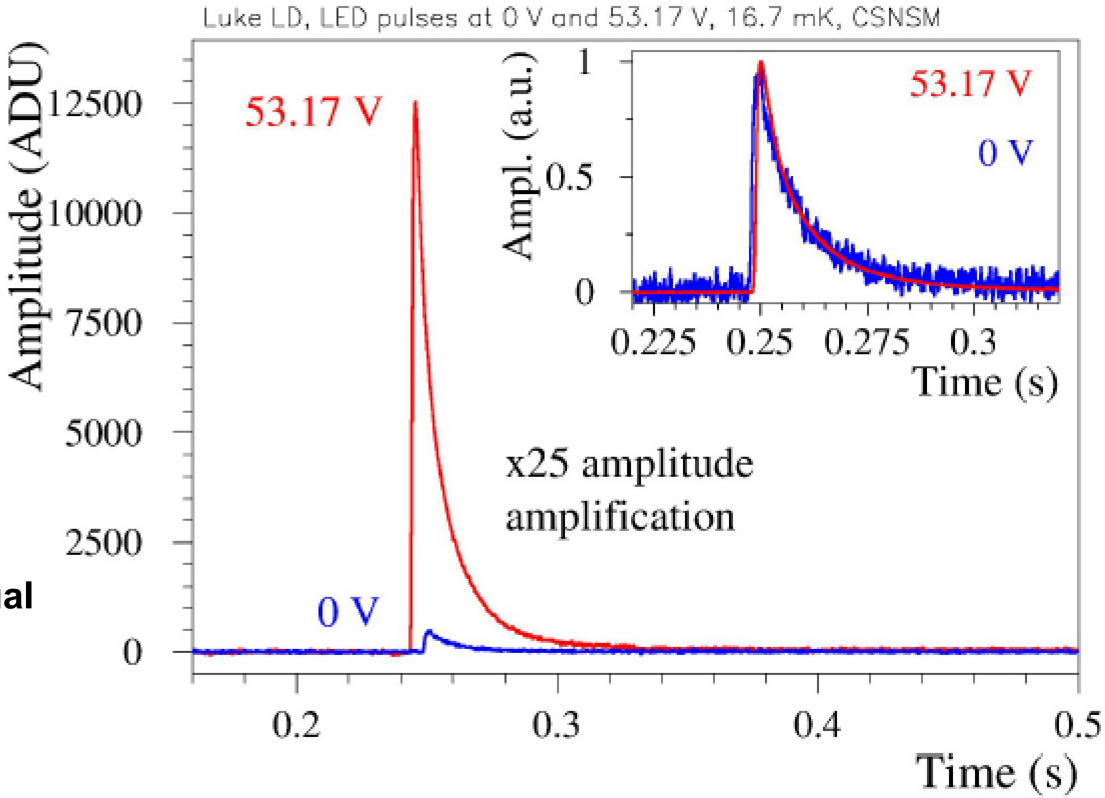


Photons
→ creates e-h pairs
→ e-h pairs are drifted by electric field

→ Phonon emission while e-h pairs drift

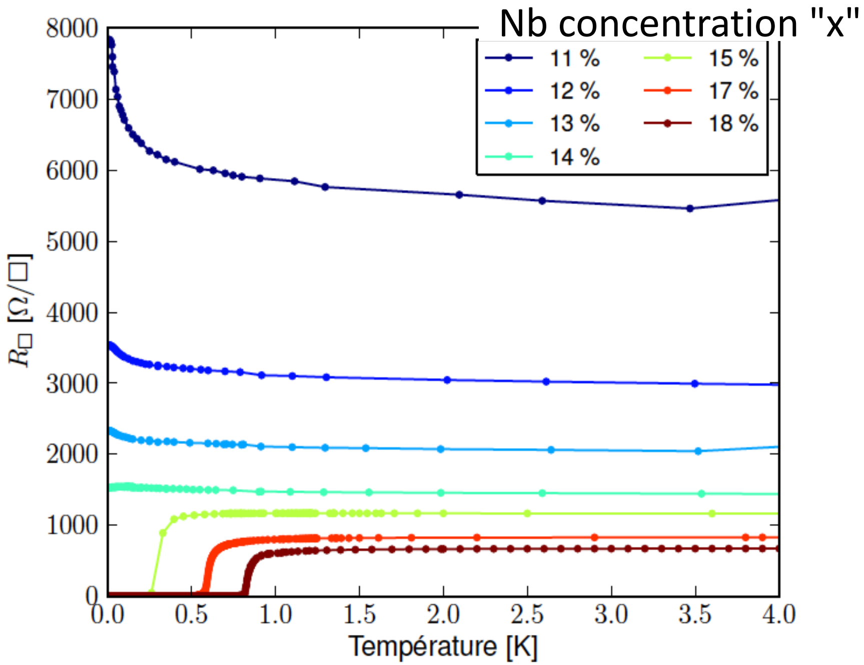
→ Amplification $E_{heat} = E(1+\frac{qV}{\varepsilon})$

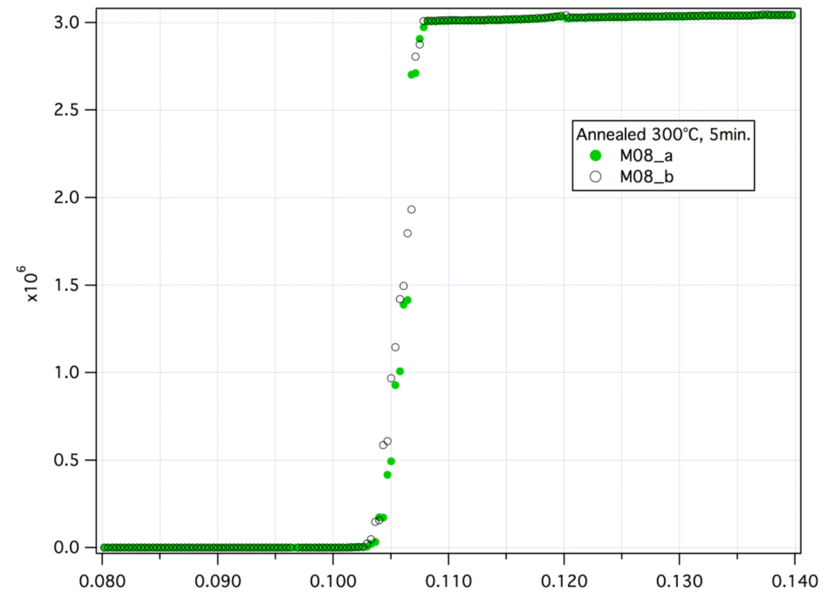


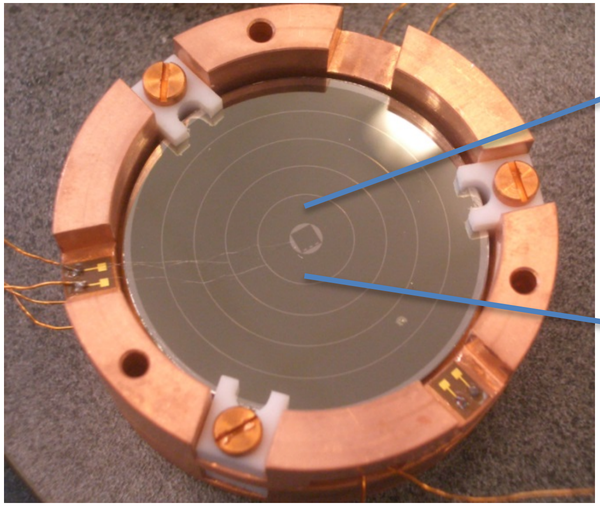


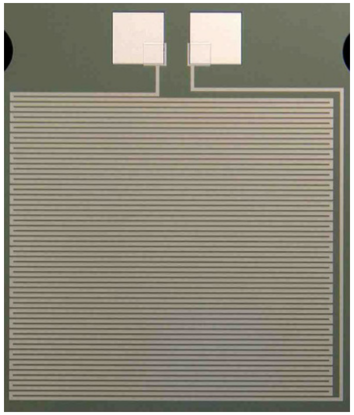
- HP Ge LD (∅50×0.2 mm) with annual Al electrodes
- NTD Ge (3×1.5×0.6 mm)
- Hamamatsu LED

High impedance Nb_xSi_{1-x} TES for LUMINEU









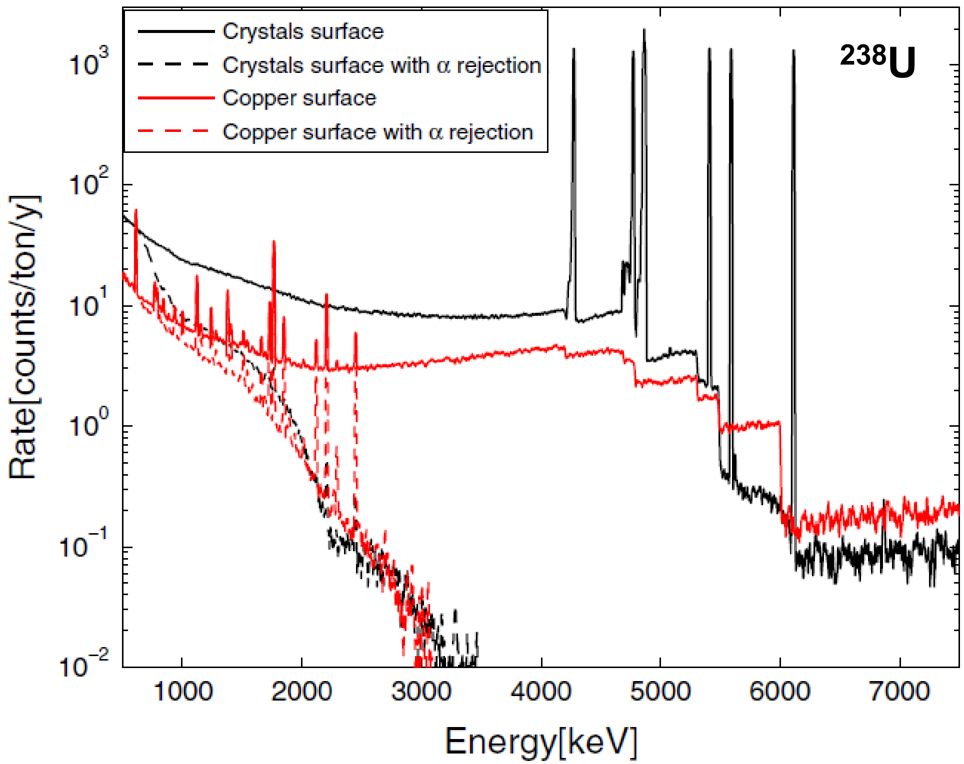
[S. Marnieros, 3rd LUMINEU meeting]

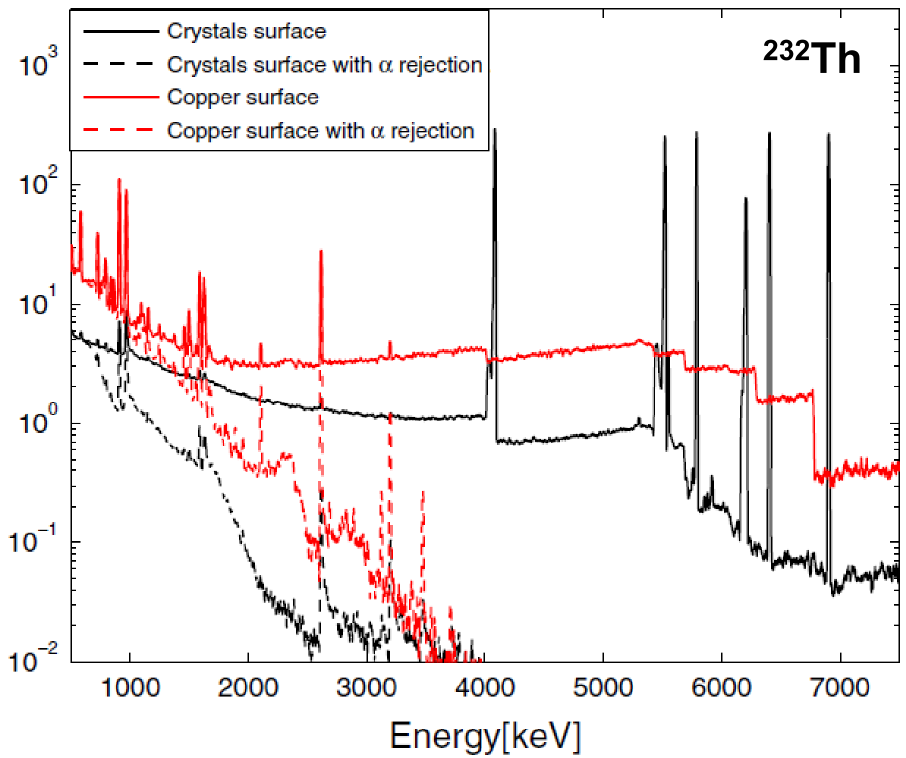
Background in ROI: Effect of α rejection

Element	Contamination [Bq/cm^2]	Te [cnts/ton/y]	Se/Cd/Mo [cnts/ton/y]
^{238}U on crystal surface	$<9 \times 10^{-9}$	<2	<1
^{232}Th on crystal surface	$<2 \times 10^{-9}$	$<1 \times 10^{-1}$	$<2 \times 10^{-1}$
^{210}Pb on crystal surface	$<2 \times 10^{-8}$	$<8 \times 10^{-3}$	$<9 \times 10^{-3}$
^{238}U on copper surface	$<3 \times 10^{-8}$	<1	$<3 \times 10^{-1}$
^{232}Th on copper surface	$<4 \times 10^{-8}$	<1	<2
^{210}Pb on copper surface	$<2 \times 10^{-7}$	$<3 \times 10^{-2}$	$<4 \times 10^{-2}$

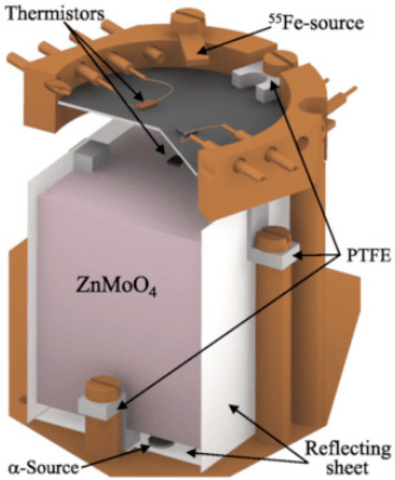
[D.R. Artusta at al., EPJC 74 (2014) 3096]

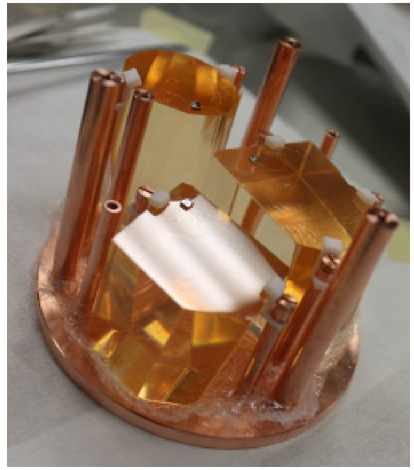
- 5 keV ROI
- 99.9% α rejection and anticoincidence cuts





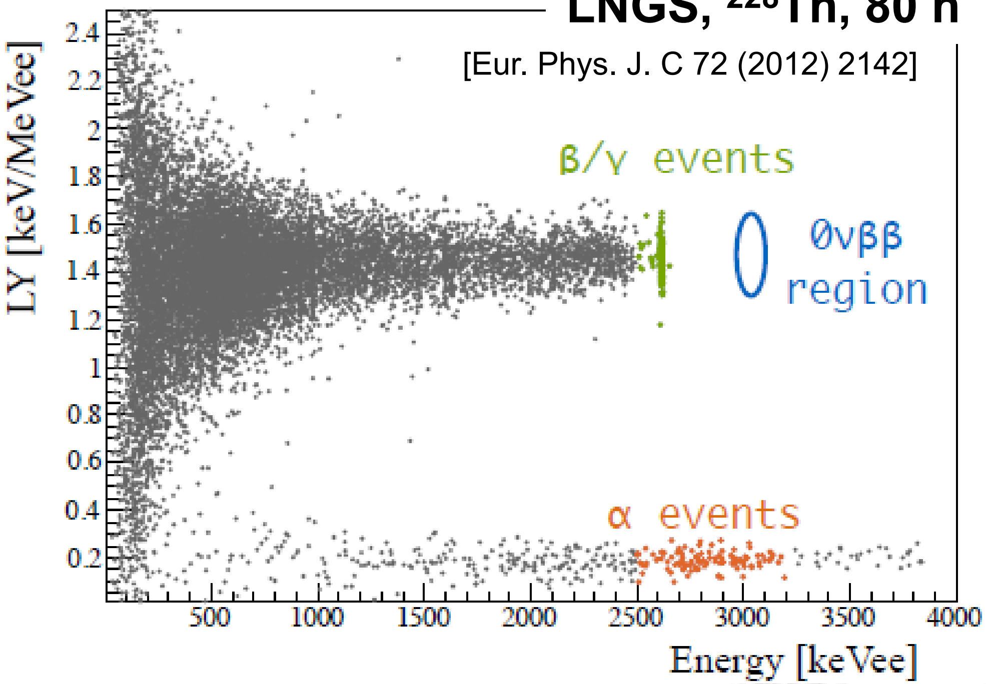
LUCIFER: $ZnMoO_4$-based bolometers



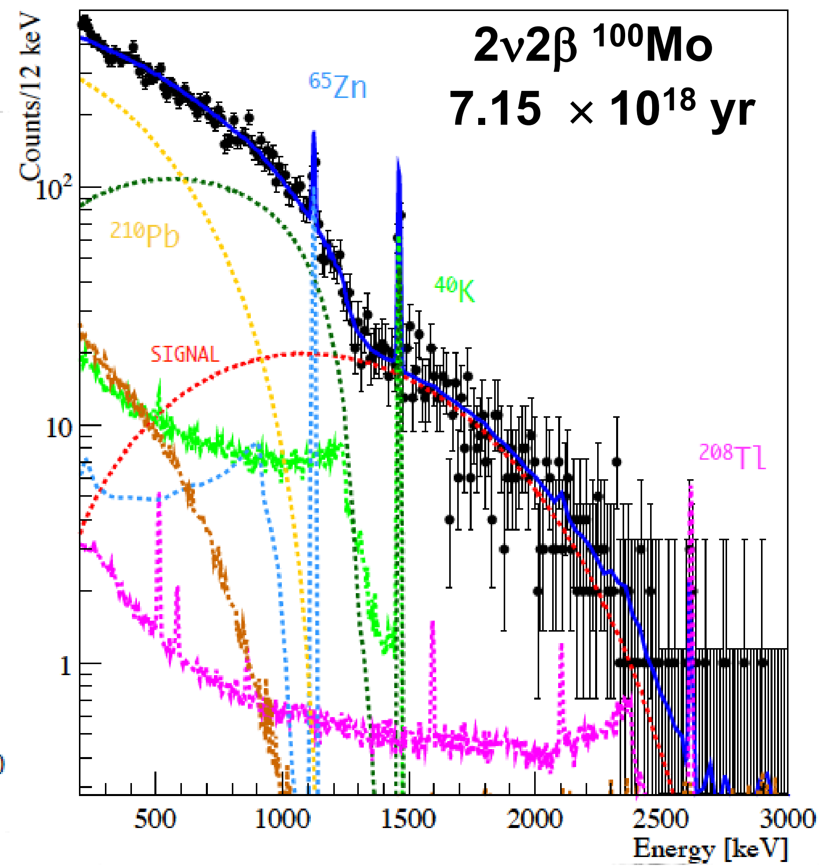


$ZnMoO_4$ (247, 235 и 329 г) grown in NIIC (Novosibirsk, Russia)

LNGS, ^{228}Th, 80 h

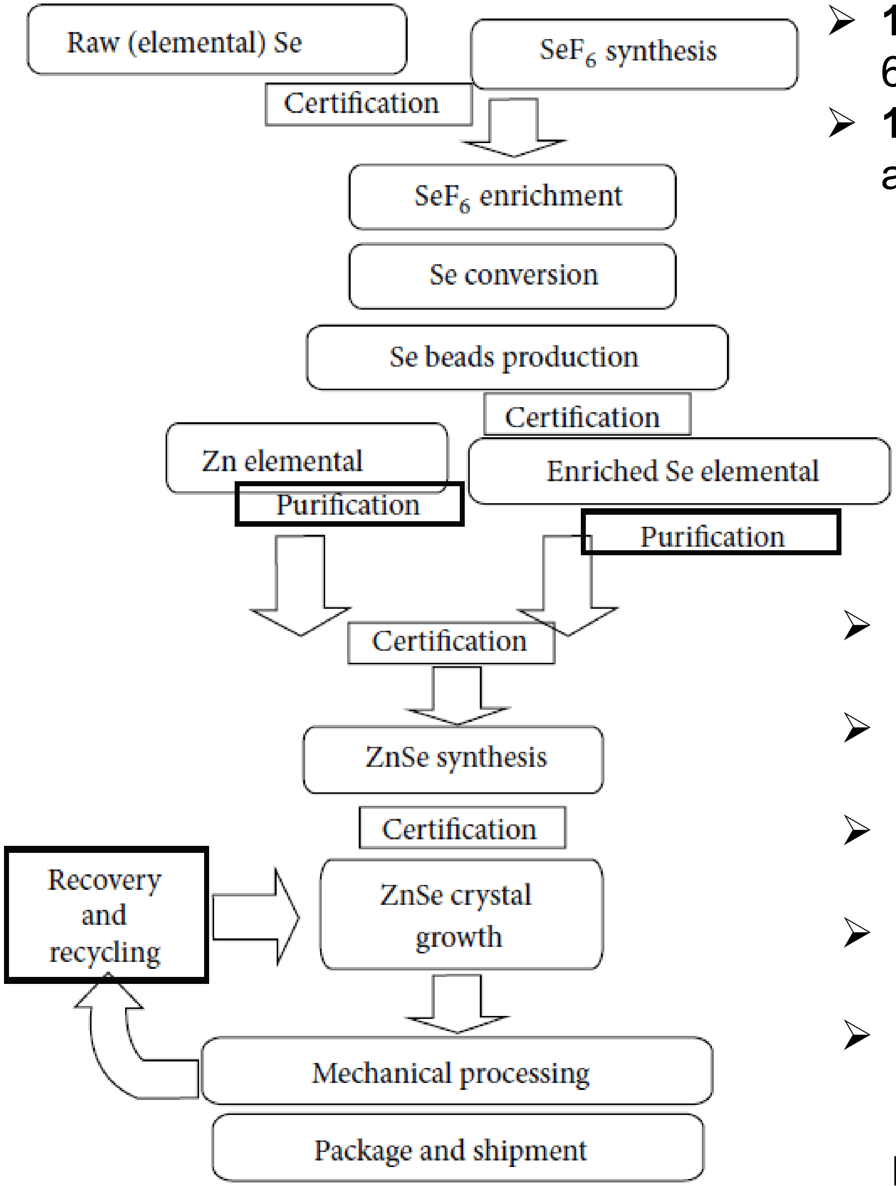


LNGS, Bg, 900 h [J. Phys. G 41(2014) 075204]



ZnSe crystal production

[J.W. Beeman et al., AHEP 2013 (2013) 237973]



Deeply purified materials

- **15 kg of ^{82}Se (95.5%) by URENCO (Netherland)**
  6 kg of ^{82}Se grains are stored @ LNGS
- **15 kg of HP Zn grains by NSC KIPT (Ukraine)**
  all amount is stored @ LNGS

	Activity, mBq/kg			
	^{228}Th	^{226}Ra	^{75}Se	^{65}Zn
^{82}Se	< 0.27	< 0.3	0.19(6)	-
HP Zn	< 0.04	< 0.07	-	5.2(6)

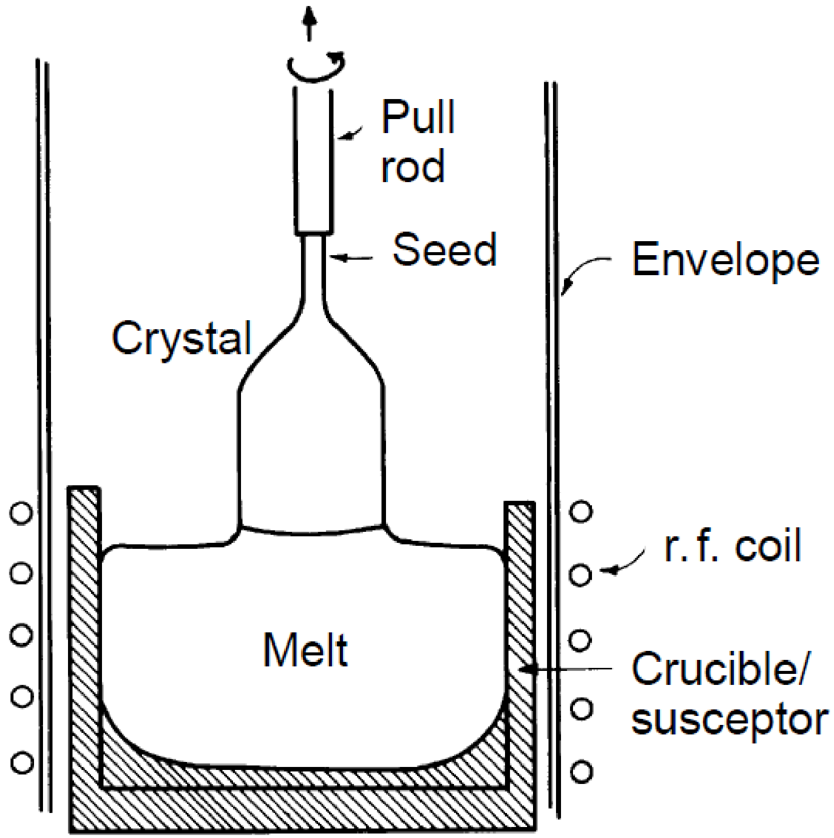
Zn^{82}Se crystal production

- **Crystal production in ISC (Kharkiv, Ukraine)**
  (by Bridgman growth technique)
- **R&D for natural ZnSe crystal production**
  (should be finished in Jan. 2015)
- **First enriched Zn^{82}Se crystal growth**
  (planned to be in Feb. 2015)
- **A few days for 1 kg Zn^{82}Se synthesis**
  (3 synthesis/day + annealing in H_2 within 2 days)
- **Almost one year for whole amount of Zn^{82}Se**
  (1 furnace × 3 crystals/month ⇒ 36 crystals/yr)

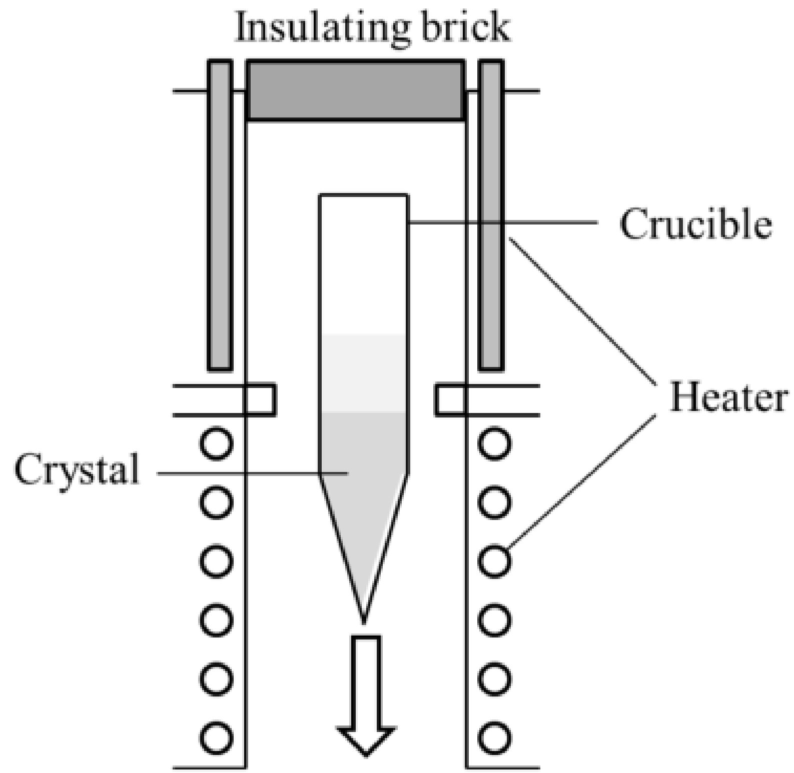
[F. Orio, talk at 4th ISOTTA meeting, Orsay, France, 1-2.12.2014]

Czochralski and Bridgman growth techniques

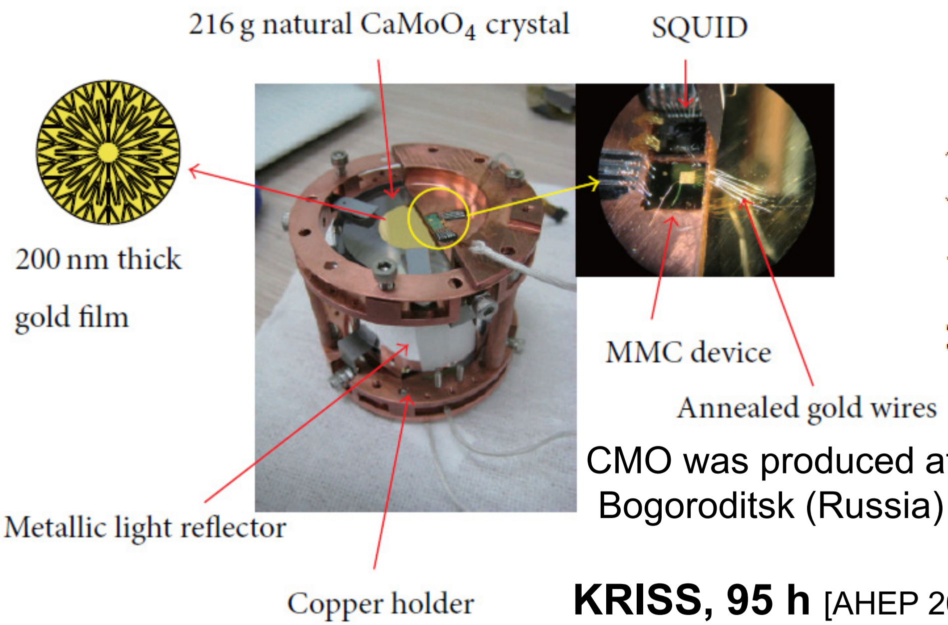
Czochralski process



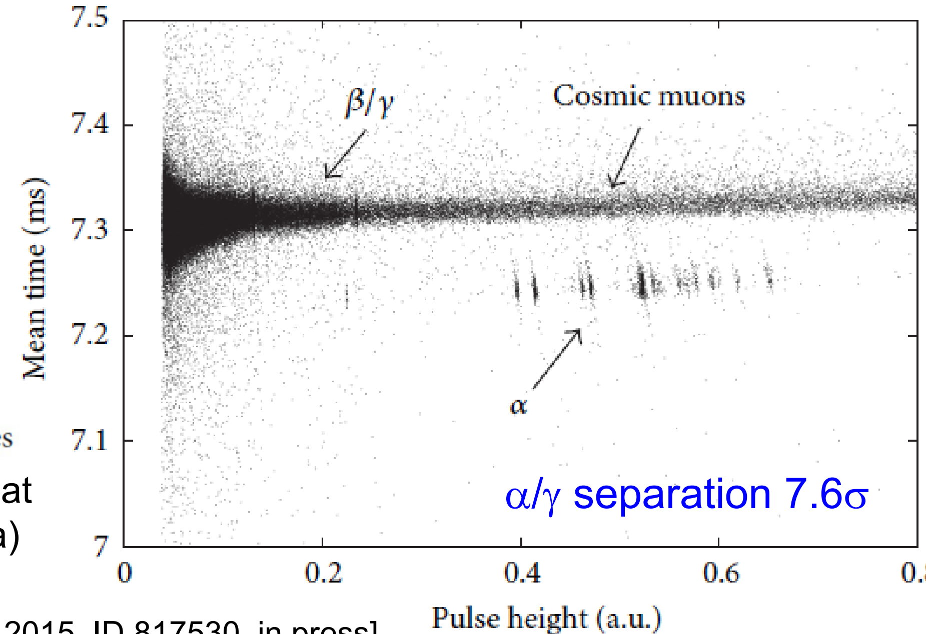
Bridgman-Stockbarger process



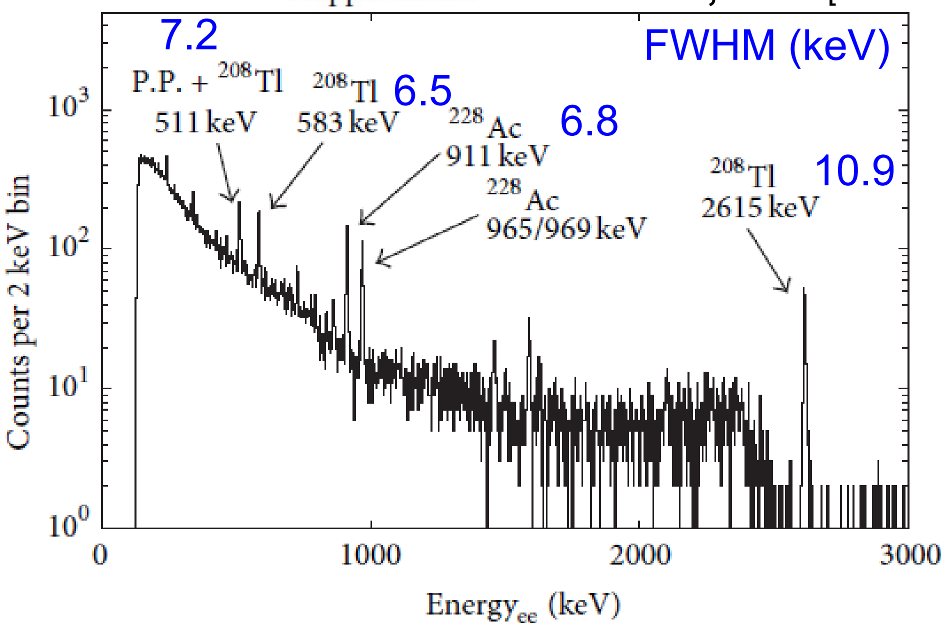
AMoRE: $CaMoO_4$-based prototype

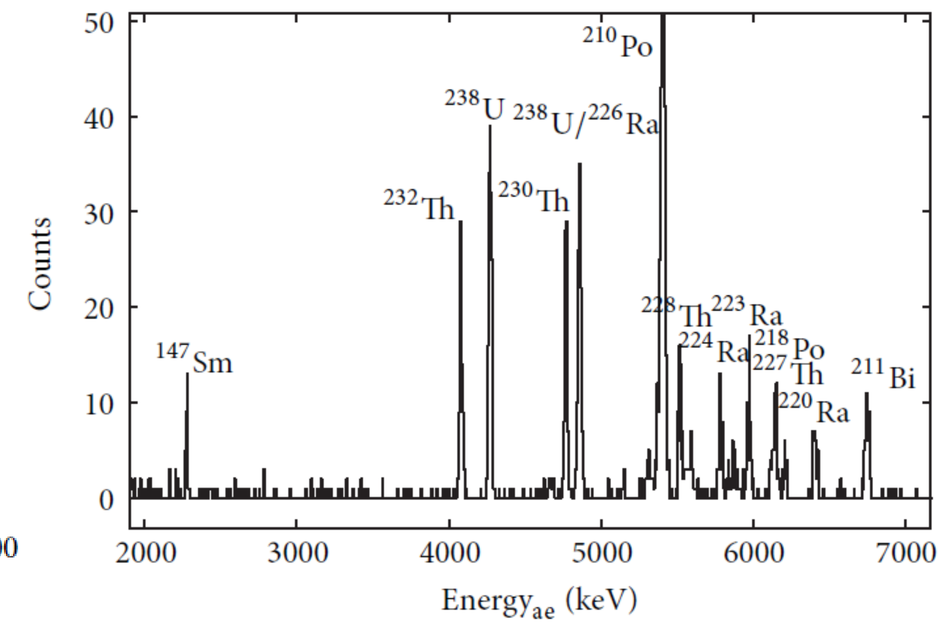


CMO was produced at Bogoroditsk (Russia)



KRISS, 95 h [AHEP 2015, ID 817530, in press]





AMoRE: Geant4 Monte Carlo simulations

Background source	Activity [μBq/kg]	Bg [10^{-4} cnt/keV/kg/yr]	Bg reduced by PSD [10^{-4} cnt/keV/kg/yr]
Tl-208, internal	10 (^{232}Th)	0.36	0.36
Tl-208, in Cu	16 (^{232}Th)	0.22	0.22
BiPo-214, internal	10	0.11 [1)]	≤ 0.01
BiPo-214, in Cu	60	1.8 [1) 2)]	≤ 0.18
BiPo-212, internal	10 (^{232}Th)	0.08 [1)]	≤ 0.01
BiPo-212, in Cu	16 (^{232}Th)	0.36 [1) 2)]	≤ 0.04
Y-88, internal	20	0.19	0.19
Random 2ν2β	8.7×10^{3} [3)]	3.1 [3)]	1.2
Total		**6.2**	**≤ 2.2**

1) Can be reduced x0.1 by alpha/beta PSD

2) Can be reduced by Teflon coating of Cu (to remove surface α)

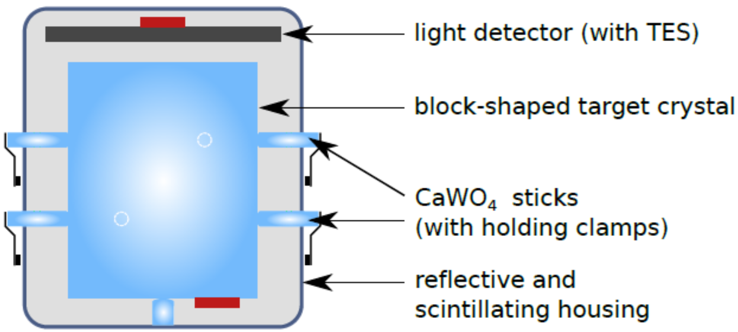
3) Can be reduced by pulse-shape discrimination

Muon background @Y2L : ~1.4e^{-4} cnt/keV/kg/yr

[F.A. Danevich, 4th ISOTTA meeting]

CRESST-II: Radiopurity of $CaWO_4$ scint. bolometer

[R. Strauss at al., arXiv 1410.4188]



Nuclide		A, μBq/kg
^{232}Th	^{232}Th	9(2)
	^{228}Th	15(4)
^{238}U	^{238}U	$1.01(2)\times10^3$
	^{234}U	$1.08(3)\times10^3$
	^{230}Th	56(5)
	^{226}Ra	43(10)
	^{210}Po	18(4)
^{235}U	^{235}U	40(4)
	^{231}Pa	23(4)
	^{227}Th	105(20)
	^{223}Ra	104(7)