Li-containing scintillating bolometers for low background physics

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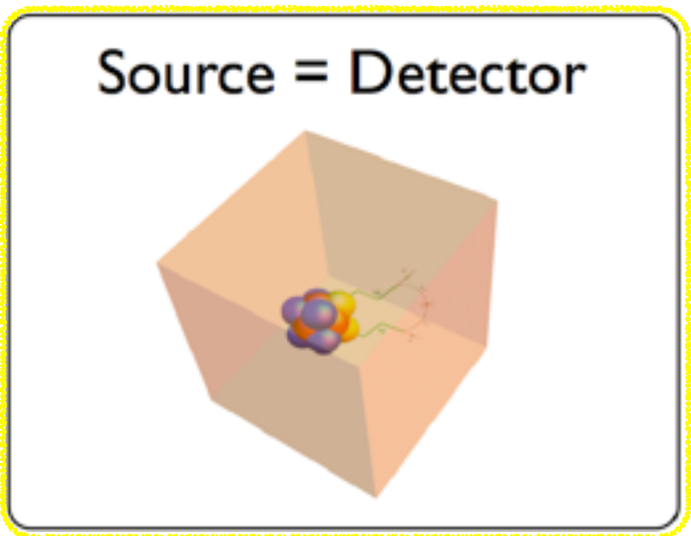
OUTLINE

- Rare event physics sensitivity
- The bolometric technique
    - pros and cons
- Scintillating bolometers
    - LMO & LEBO
- Conclusions

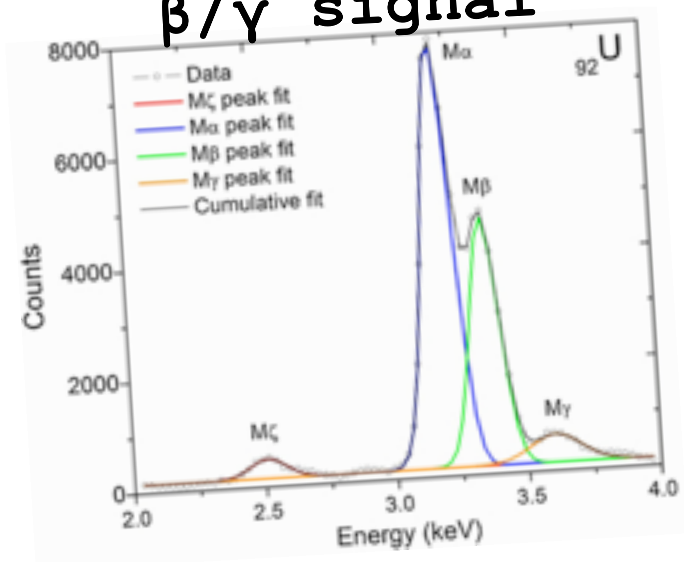
Detection principle

General idea:

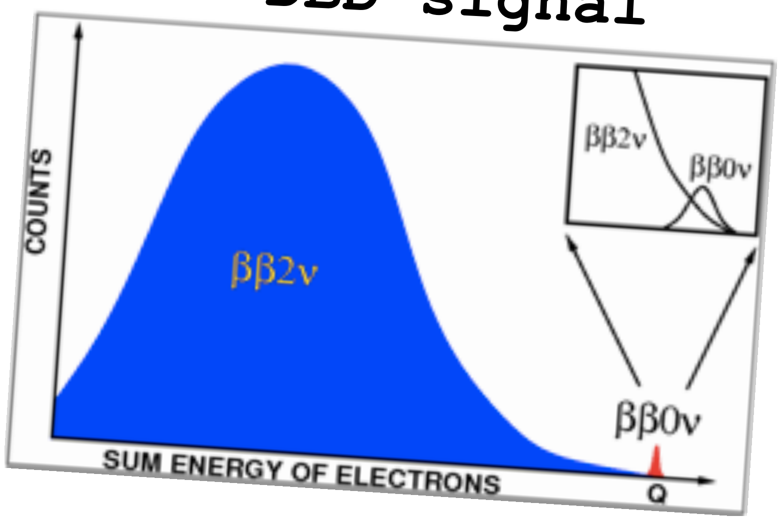
to measure the kinetic energy of the decay products/secondary particles/...
(keV-MeV energy scale)



β/γ signal



DBD signal

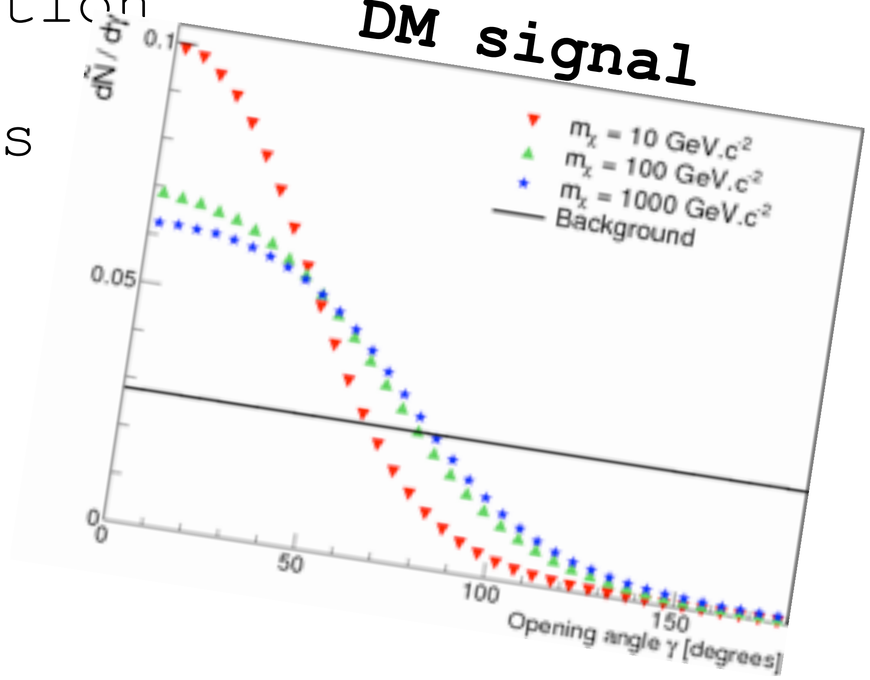


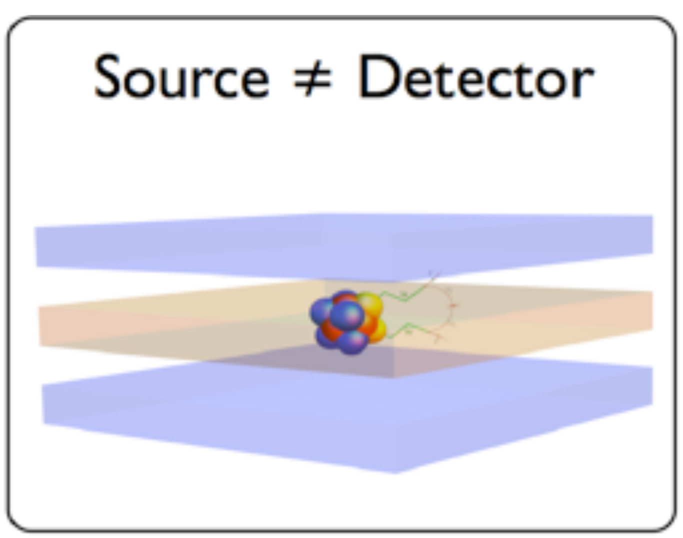
Calorimetry

Bolometers

* Excellent energy resolution
* High efficiency
* Wide choice of compounds

DM signal





Scint./Track

* Large mass source
* Particle identification

Sensitivity for DBD0v, rare decays, ...

S_{0v}: half-life corresponding to the minimum number of detectable signals above background at a given C.L.

high natural i.a. of nuclide candidates or enrichment

a.i.: isotopic abundance

Large mass array

M: detector mass

Stable over long time (~y)

t: measuring time

$$S_{0\nu} \propto a.i.\sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

B: background

- **Deep underground location**
- **Material selection (radio-pure)**
- **High granularity**

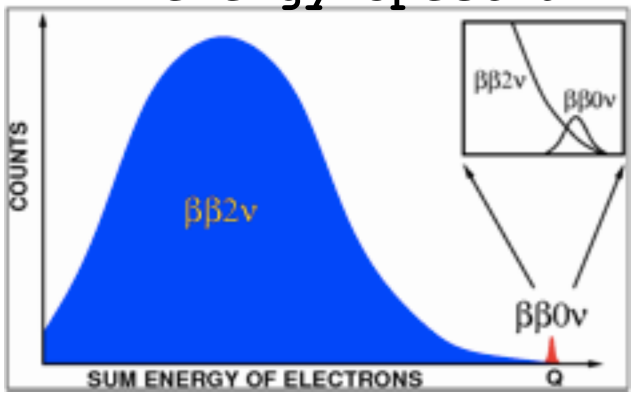
ΔE: energy resolution

Bolometric approach

DBD experiment

Q-value: 2995 keV
Material: ZnSe
Enriched a.i.: 95%
Source Mass: ~10 kg of Se-82
Projected Bkg: ~0.001 c/keV/kg/y
Resolution: ~ **10 keV** @ ROI
Sensitivity $T_{1/2}$: ~10^{26} **y** in **5 y**

DBD energy spectrum



The bolometric technique

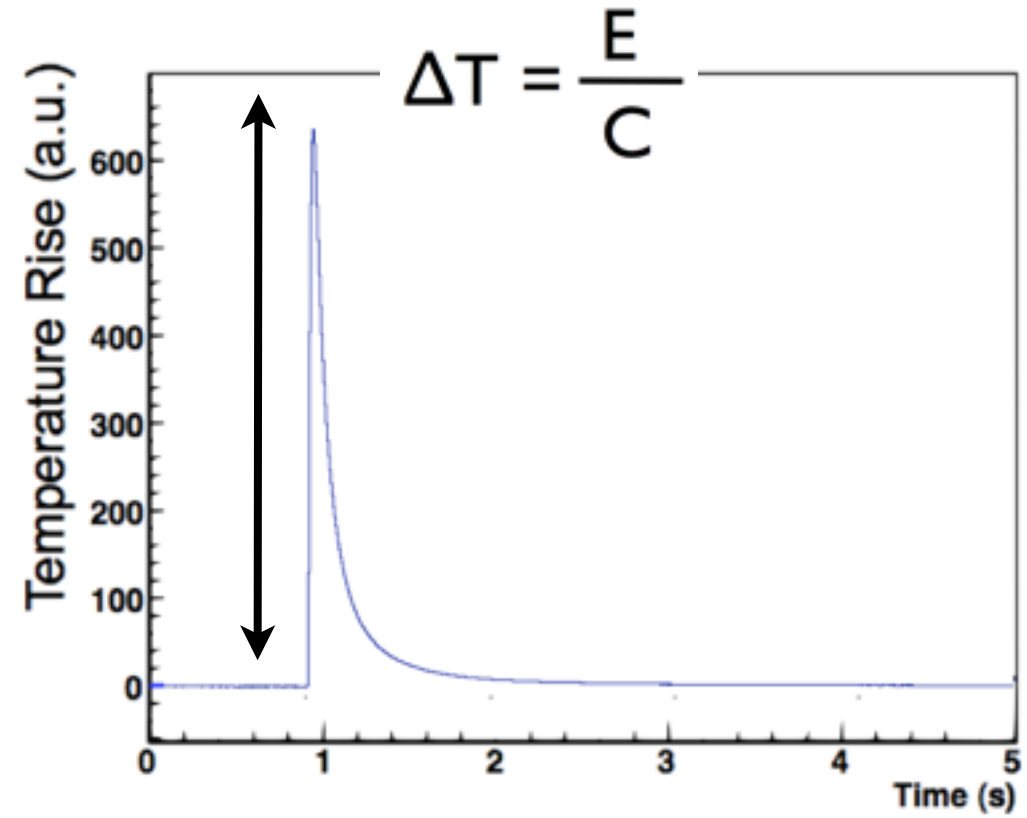
Almost all the deposited energy is converted into phonons which induce a measurable temperature rise

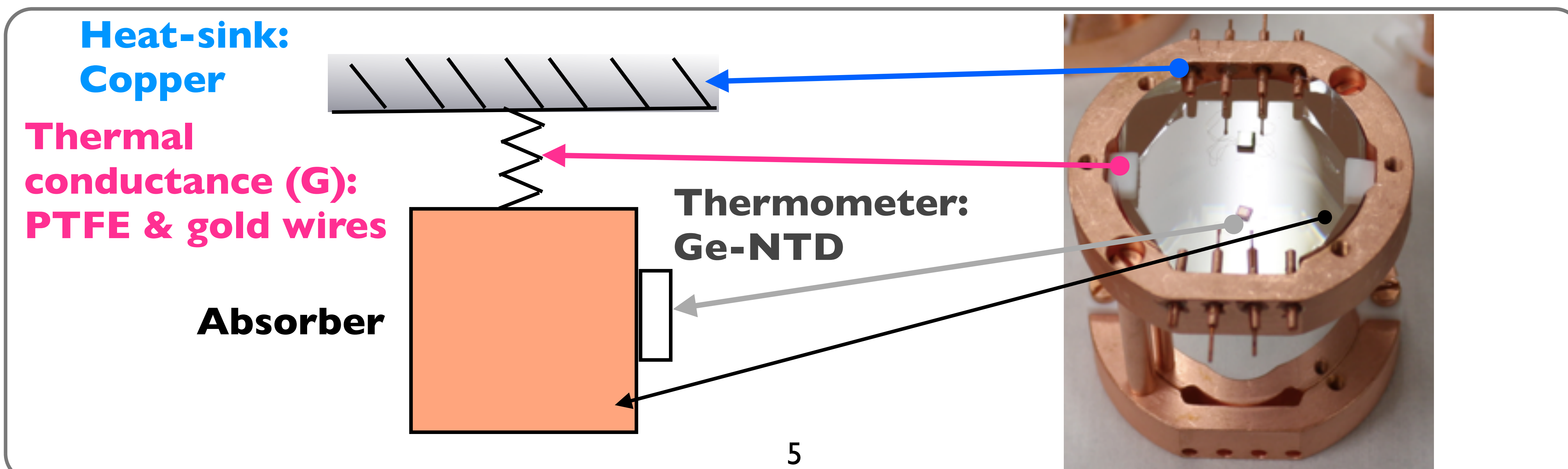
The heat capacity of the crystal must be very small
(-> **low Temperature ~10 mK**)

Absorber
- M ~ 0.45 kg
- C ~ 10^{-10} J/K
- $\Delta T/\Delta E$ ~ 500μK/MeV

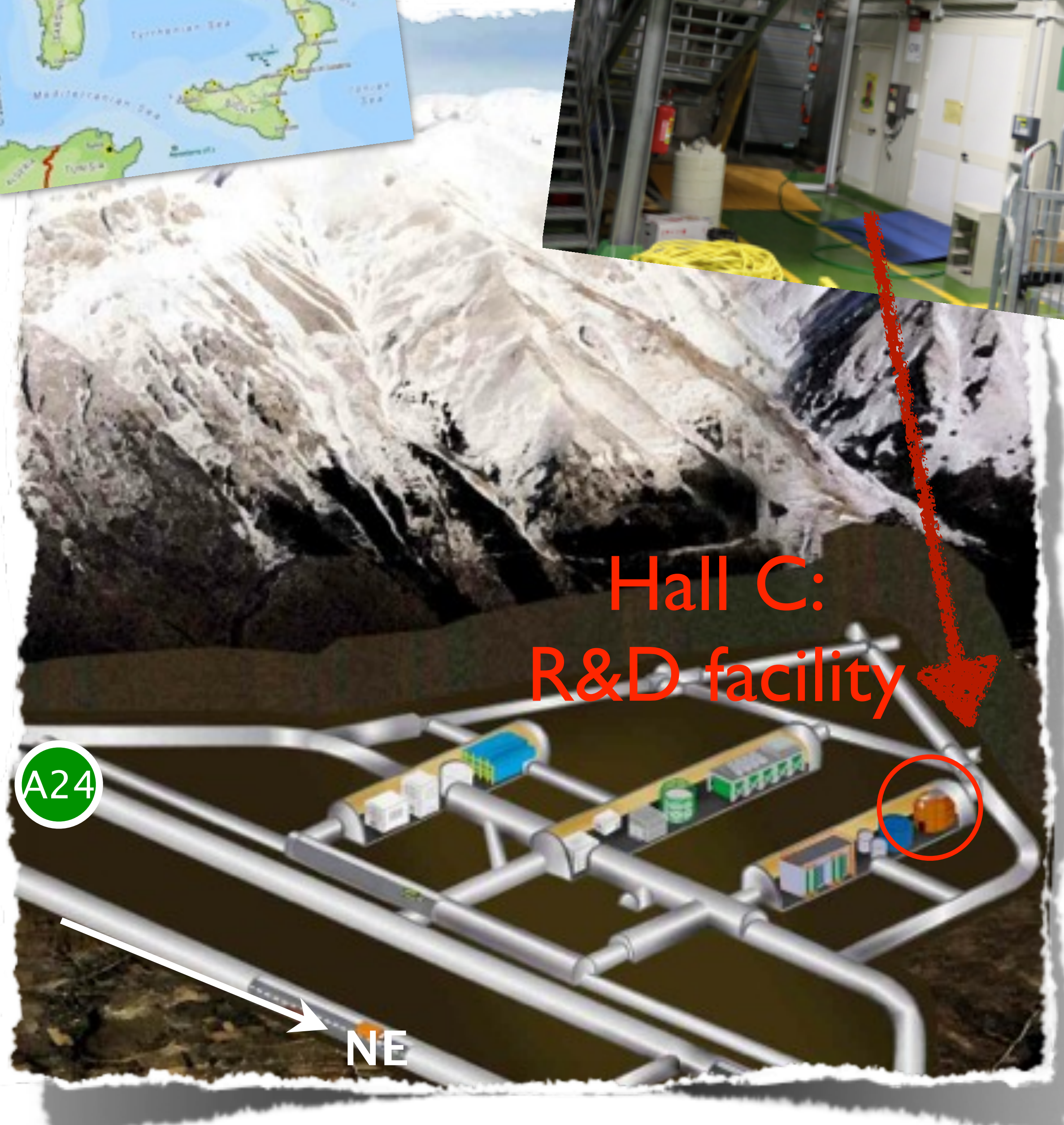
Sensor
- $R = R_0 \exp[(T_0/T)^{1/2}]$
- R ~ 100 MΩ
- $\Delta R/\Delta E$ ~ 3 MΩ/MeV

fully-active detector





The underground facility



Laboratori Nazionali del Gran Sasso INFN, Italy

<u>Experimental location</u>:

- Average depth ~ 3650 m w.e.
- Muon flux ~ 2.6×10^{-8} $\mu/s/cm^2$
- Neutrons < 10 MeV: $4*10^{-6}$ $n/s/cm^2$
- Gamma < 3 MeV: 0.73 $\gamma/s/cm^2$

Bkg sources in bolometric experiments

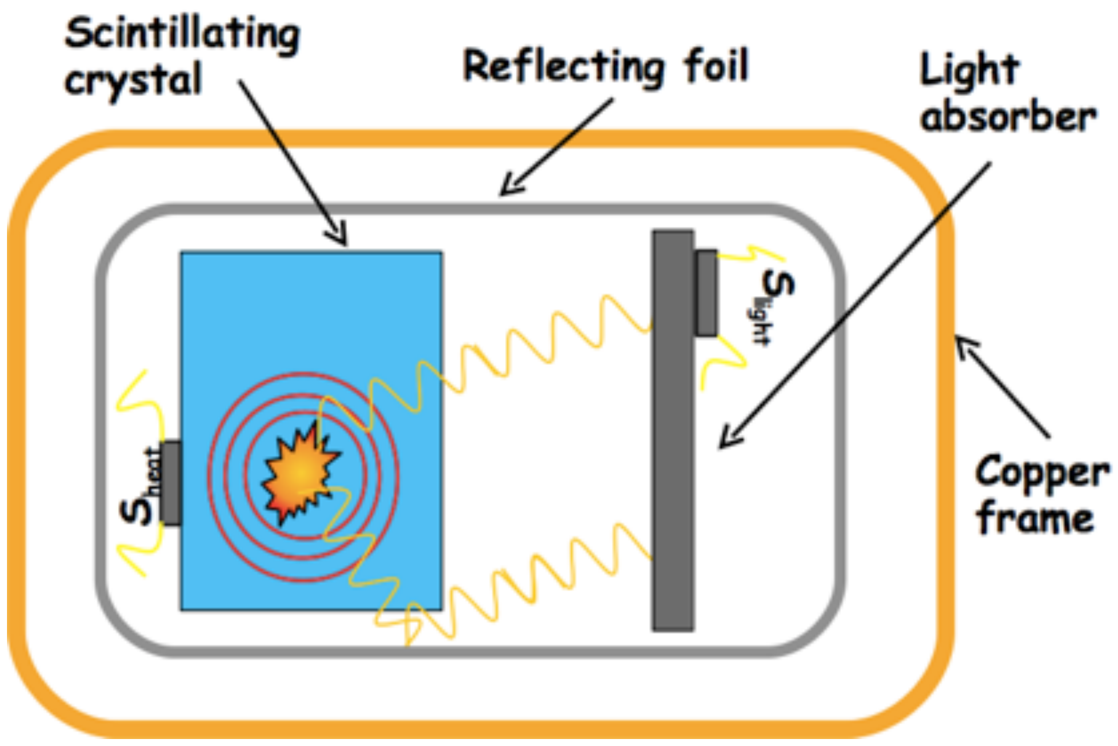
Since bolometers are **fully-active detectors** and are sensitive to all radiation types, various sources can limit the experimental sensitivity

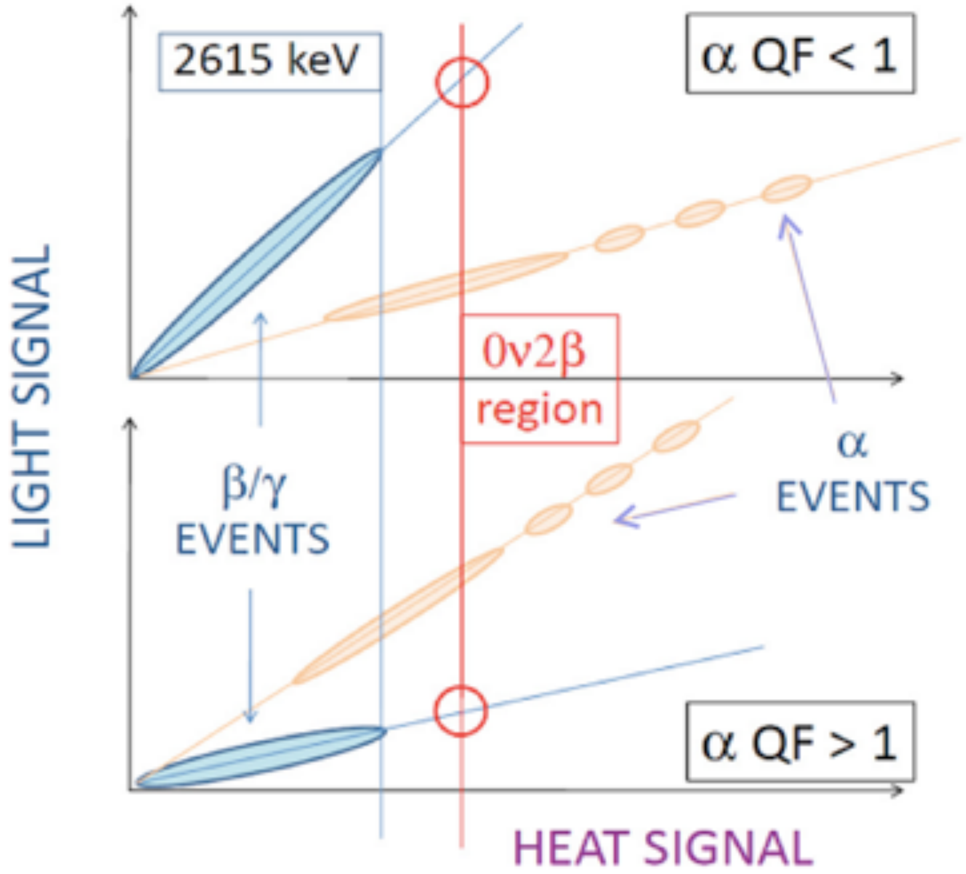
Neutrons =>	- neutron activation: (n,γ) reactions * appropriate shields are needed
Muons =>	- energy deposit in the ROI * underground installation & granularity & veto
β/γs =>	- natural radioactivity (^{238}U & ^{232}Th) * material selection
degraded αs =>	- αs coming out from detector surfaces * surface cleaning and particle discrimination

Scintillating bolometers

When a **bolometer is an efficient scintillator** at low temperature, a small but significant fraction of the deposited energy is converted into scintillation photons while the remaining dominant part is detected through the heat channel.

The simultaneous read-out of **light** and **thermal** signals allows to discriminate the α background thanks to the scintillation yield different from β particles.

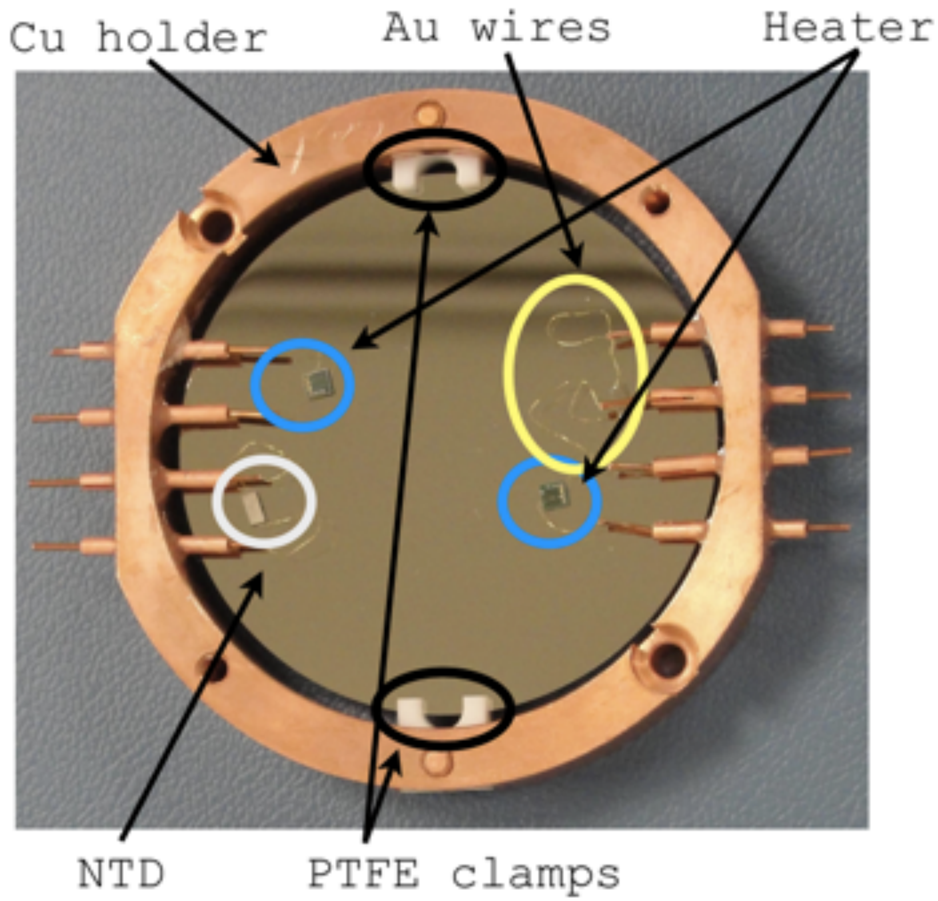




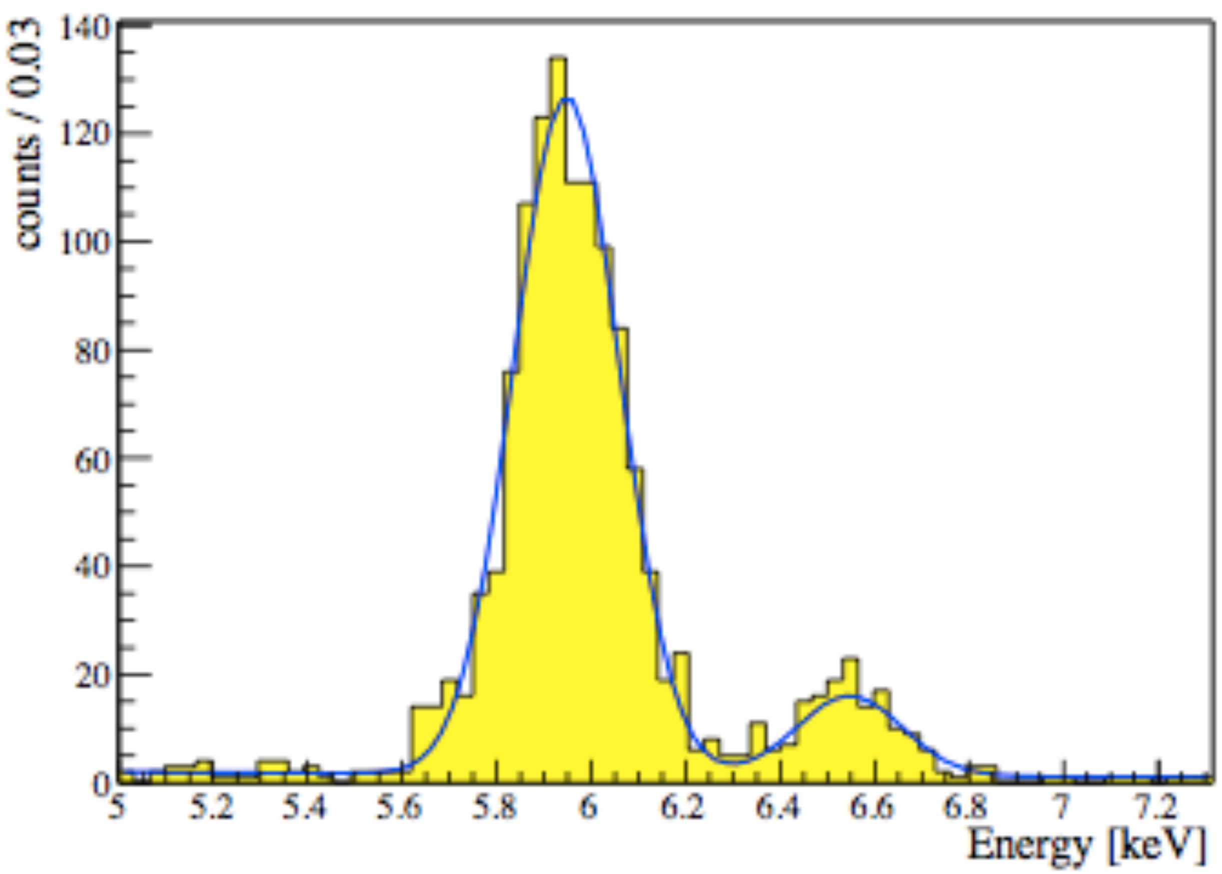
QF: is defined as the ratio of the signal amplitudes induced by an α and an β/γ of the same energy.

Bolometric LD

- HP-Ge disk (3-5 cm diameter, 0.1-1 mm thick)
- SiO_2 coating for darkening the surface => reduce light reflections
- Calibration with ^{55}Fe X-rays @ 5.9 keV and 6.5 keV
    - Energy resolution: ~100 eV
    - Energy threshold: ~100 eV



Detector	$FWHM_{baseline}$ [keV]	$FWHM_{^{55}Fe}$ [keV]
	0.144±0.002	0.209±0.003

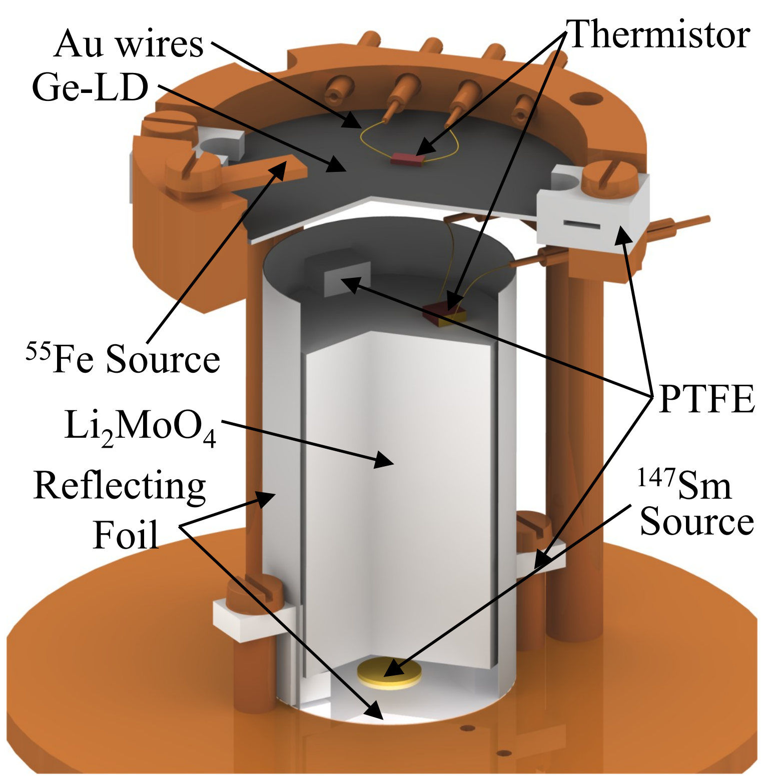


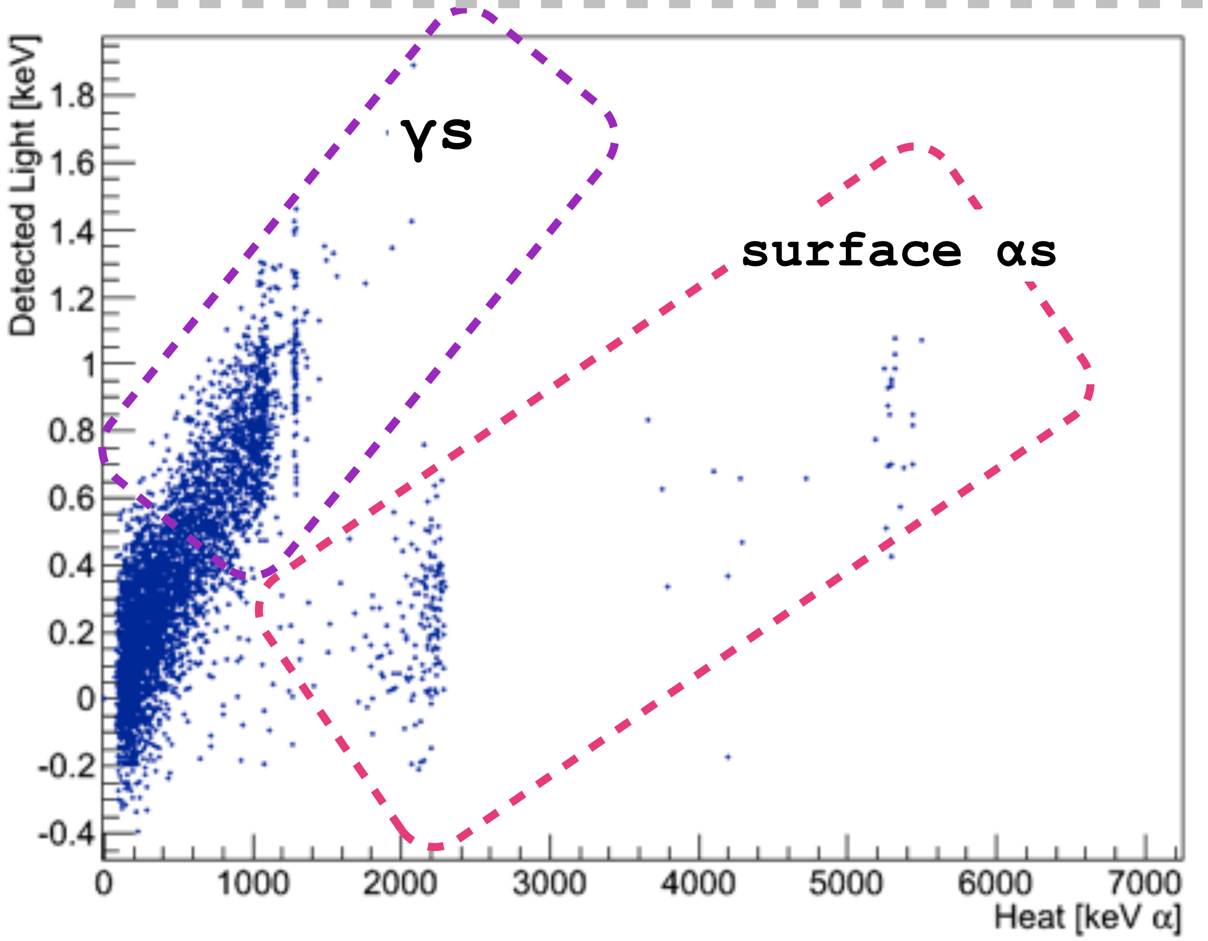
J.W.Beeman et al., *2013 JINST 8 P07021*

Li_2MoO_4

Interesting for:
- DBD-^{100}Mo
- n-detection
- solar axions

Crystal features:
- growth: Czochralski method
- materials: pure (99.5%) MoO_3 and Li_2CO_3
- weakly hygroscopic





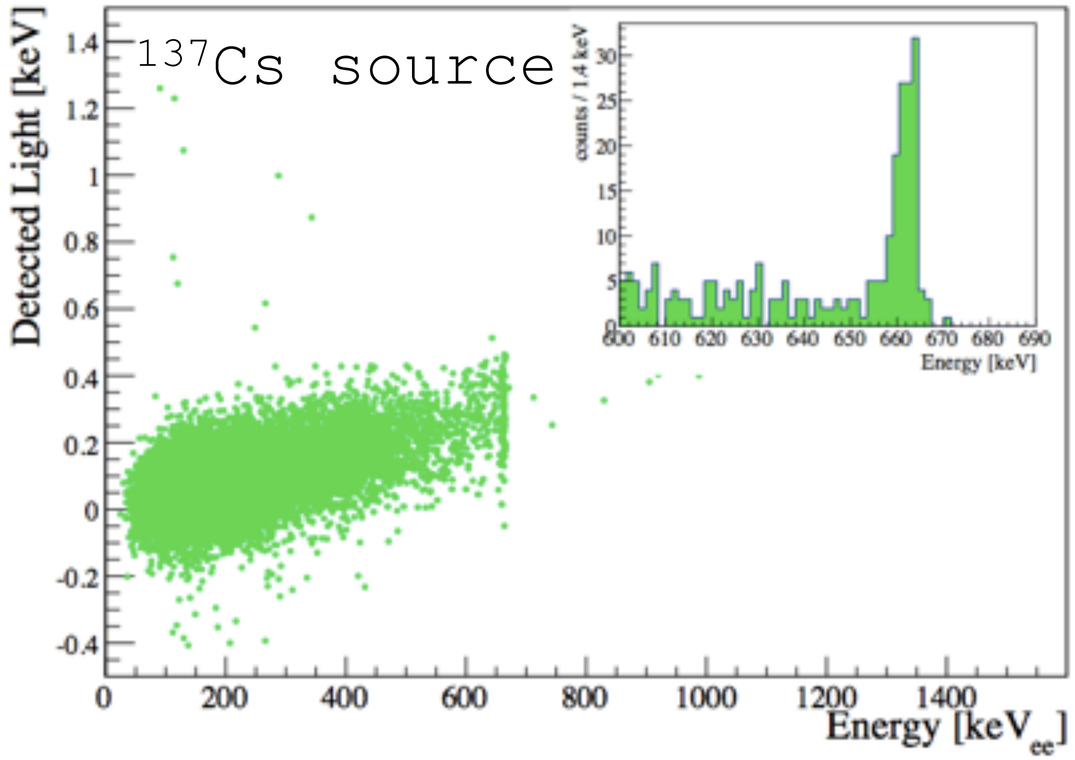
m=33 g
Calibrations α & n & γ
Background 344 h

Good particle discrimination using **Light vs. Heat**

Cardani et al. *arXiv:1307.0134, in pubblication on JINST*

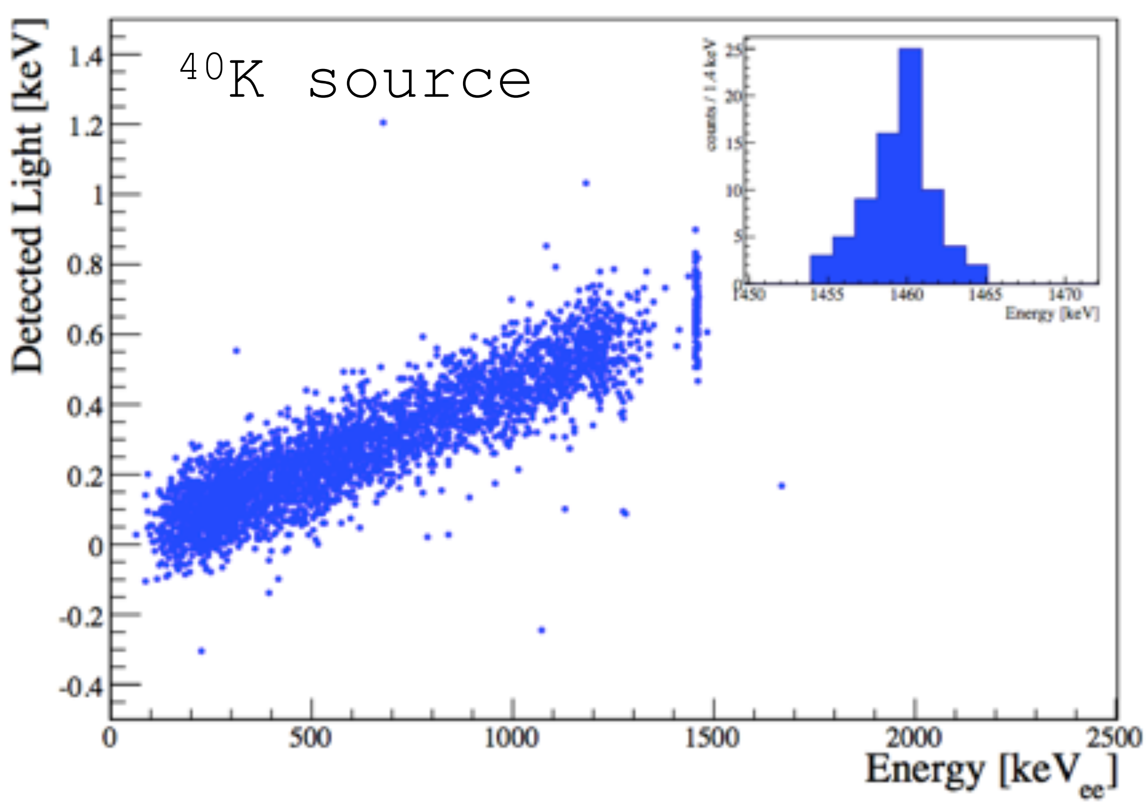
Li_2MoO_4 with γ-source

Small crystal
=> no calibration at 2615 keV



FWHM: 3.7±0.8 keV
@ 661 keV

$LY_{\beta/\gamma}$ = 0.433±0.012 keV/MeV

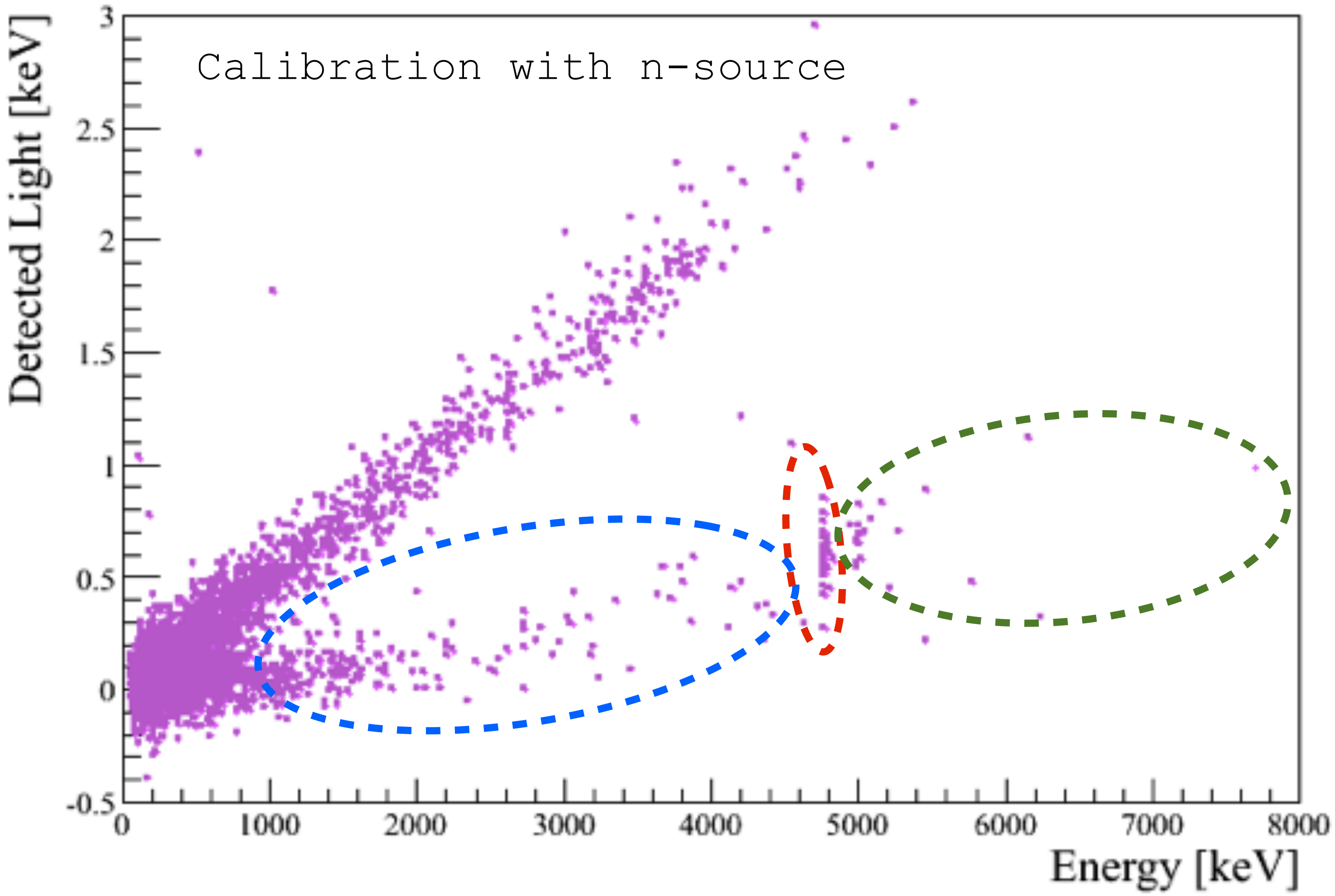


FWHM: 4.7±1.1 keV
@ 1460 keV

Li_2MoO_4 with AmBe-source

Easy (fast) neutron tagging:

$$^{6}\text{Li} + {}^{1}\text{n} \rightarrow {}^{3}\text{H} + {}^{4}\text{He} + 4.78\ \text{MeV}$$

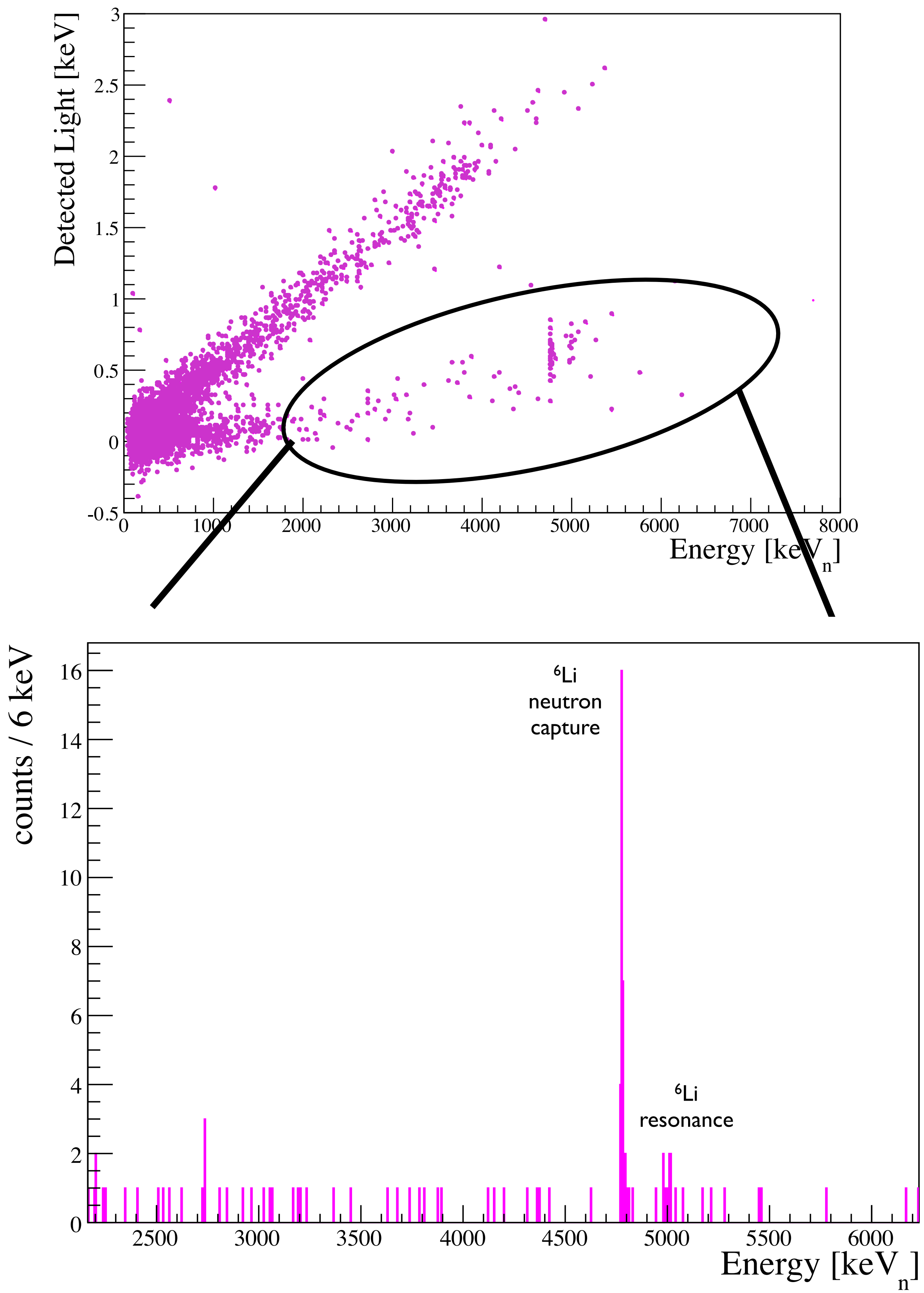


^{6}Li:
large absorption
n cross section
940 b @ 25 meV

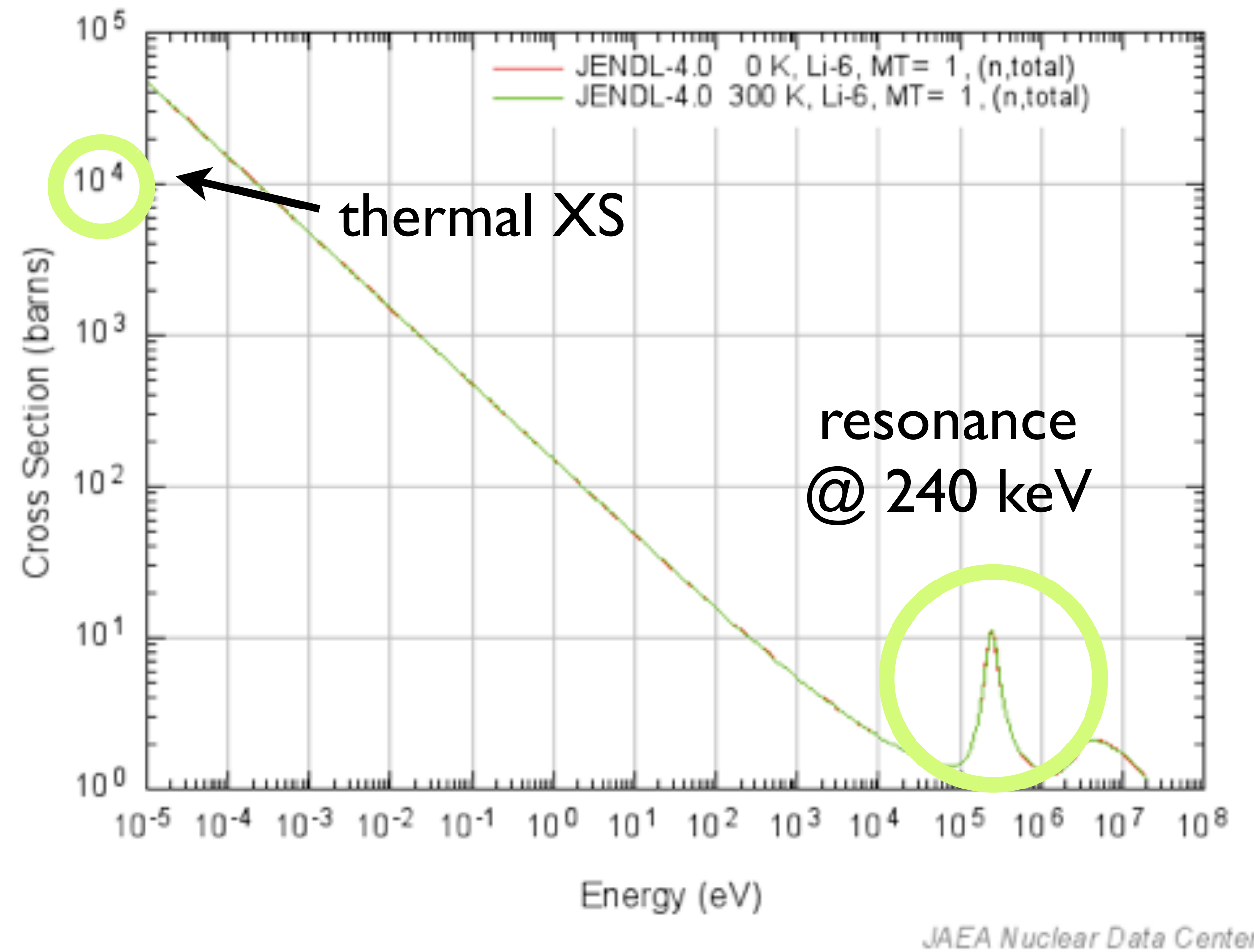
^{6}Li:
natural i.a.
7.6%

* elastic neutrons scattering on Li, Mo and O
* thermal neutron absorptions
* fast neutron absorptions

Li_2MoO_4 with AmBe-source



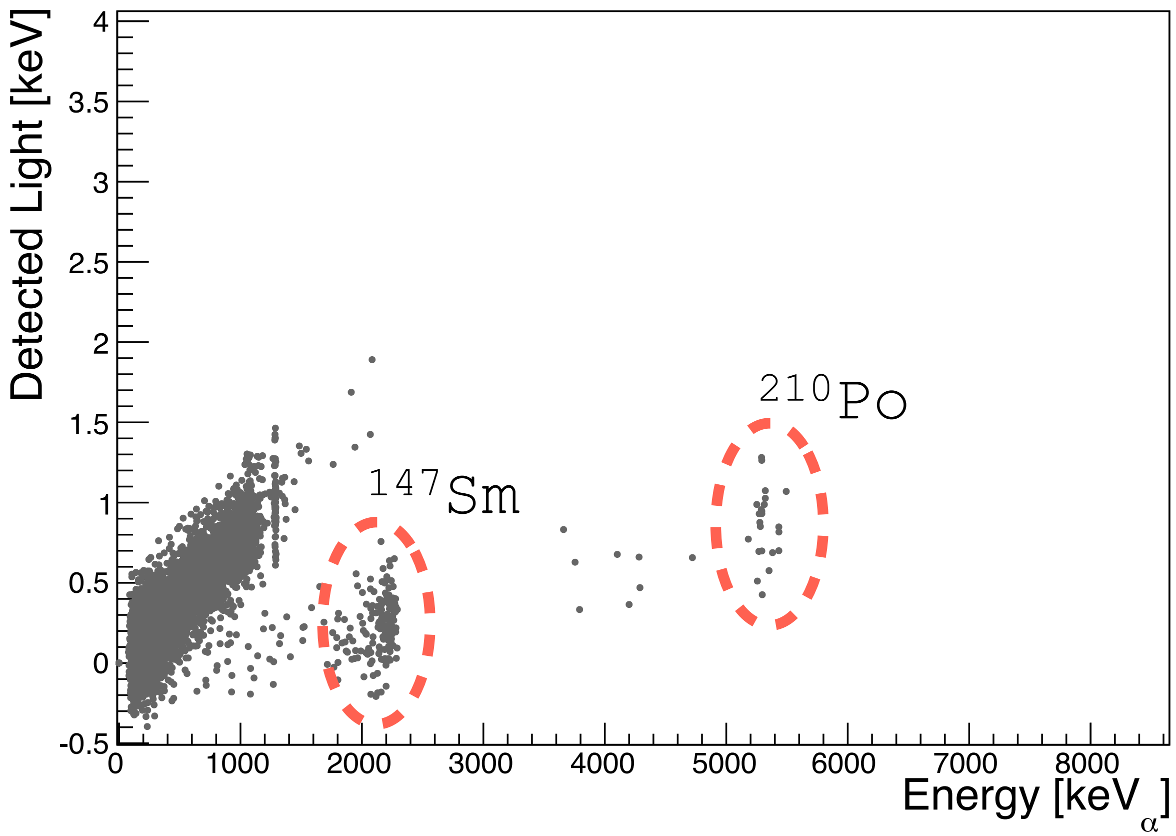
^{6}Li neutron absorption cross section



LY(^{3}H+^{4}He)= 0.122±0.022 keV/MeV

FWHM @ 4.78 MeV: 14±2 keV

Li_2MoO_4 with α-source



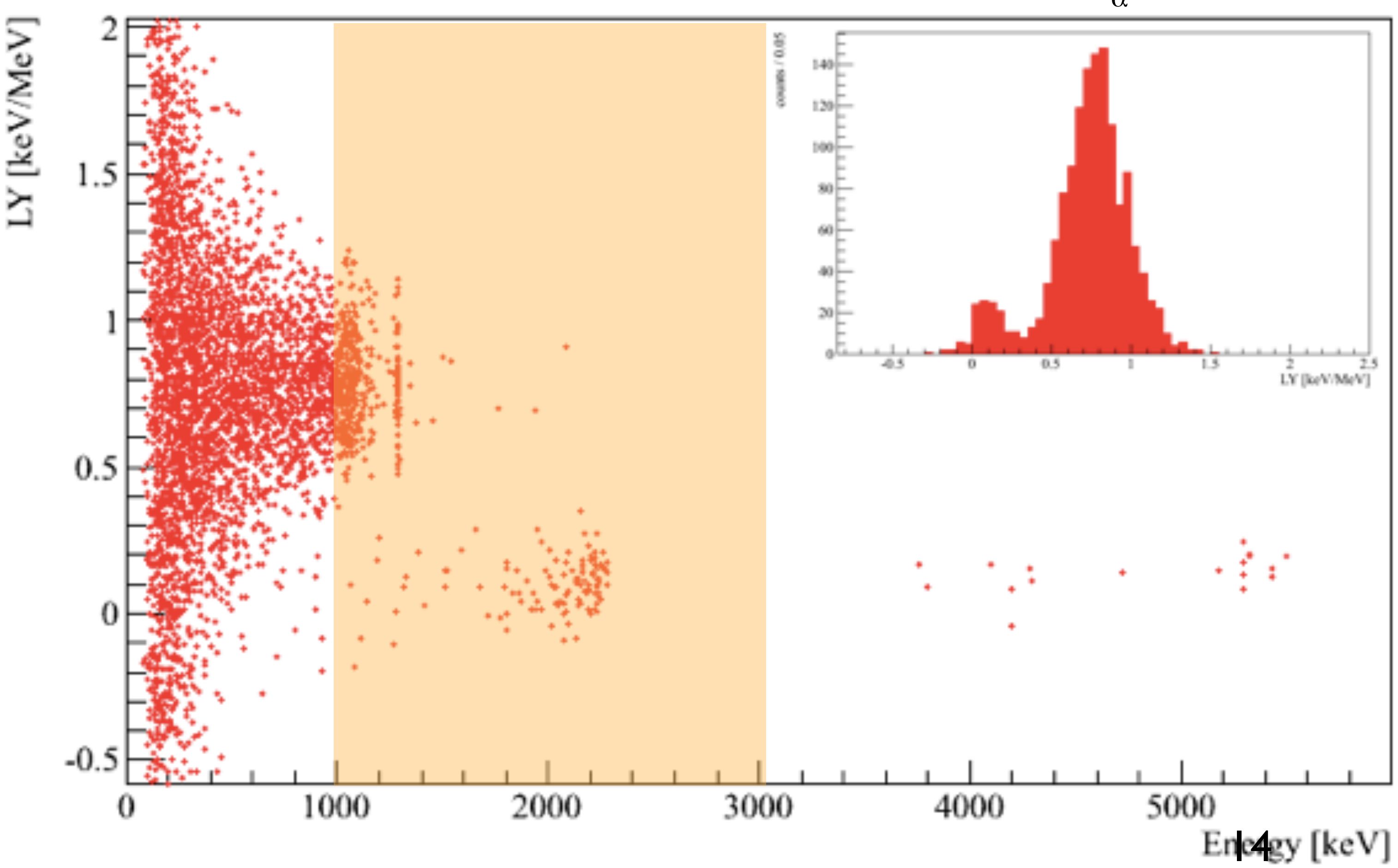
Assuming linearity of $LY_{\beta/\gamma}$:

$QF_\alpha(E) = LY_\alpha(E)/LY_{\beta/\gamma}(E)$

$QF_\alpha(^{147}Sm) = 0.29 \pm 0.01$

$QF_\alpha(^{210}Po) = 0.42 \pm 0.03$

QF_α is larger compared to other MO compounds like: ZnMoO4 and PbMoO4 (x2.5)



Discrimination Power:

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

DP(1 MeV-2.3 MeV) ~ 3

No evidence of particle discrimination with PSA
=> larger crystals are needed!
PSD works very well MO xtals

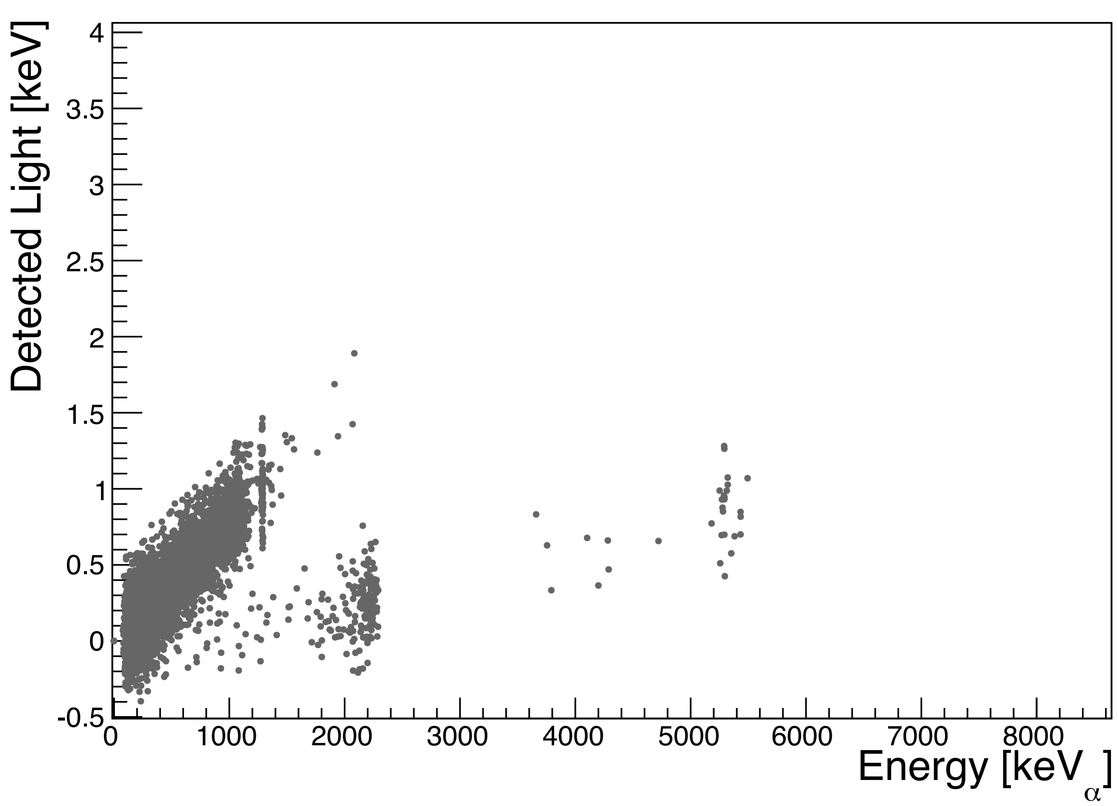
Li_2MoO_4 background

First measurement:
HP-Ge (1240 h)

Chain	Nuclide	Activity (mBq/kg)
^{232}Th	^{228}Ac	≤ 32
	^{212}Pb	≤ 24
	^{208}Tl	≤ 12
^{238}U	^{214}Pb	≤ 20
	^{214}Bi	≤ 21
	^{40}K	$= 170(80)$
	^{60}Co	≤ 8
	^{137}Cs	≤ 4

O.P. Barinova et al., *NIM* A **607** (2009) 573

Scintillating bolometer:
344 h bkg



the crystal is hygroscopic: contaminated in ^{210}Pb (^{210}Po)

New limits:

Chain	Nuclide	Activity [μBq/kg]
^{232}Th	^{232}Th	< 94
^{238}U	^{238}U	< 107
	^{210}Pb	729 ± 160

Cardani et al. *arXiv:1307.0134, submitted to JINST*

Solar axions search

Detection of ^{7}Li solar axions by means of resonant absorption on analogue targets in the labs.

In the Sun : *pp* → ... → ^{7}Be + e^- → ^{7}Li* → ^{7}Li + axion

in the lab : ^{7}Li + axion → ^{7}Li* → ^{7}Li + γ

We look for a γ emission at about 478 keV

Doppler effects ~0.5 keV
nuclear recoil ~10^{-2} keV
...

Total number of absorptions:

^{7}Li nuclei **Time** **Constant** **Axion mass**

$$N_{abs} = N_{^7Li} \times T \times C^{te} \times \left(\frac{m_a}{1\,eV}\right)^4$$

M. Krcmar et al., *Phys. Rev.* D **64** (2001) 115016

A.V. Derbin et al., *JETP* Lett. **81** (2005) 365

If we reverse the equation (considering BR and detection ε(~5%)):

small crystal

$$m_a < 39\,keV \;\; @ \;\; 90\,C.L.$$

on a 33 g crystal & 344 h bkg measurement

Current best limit:

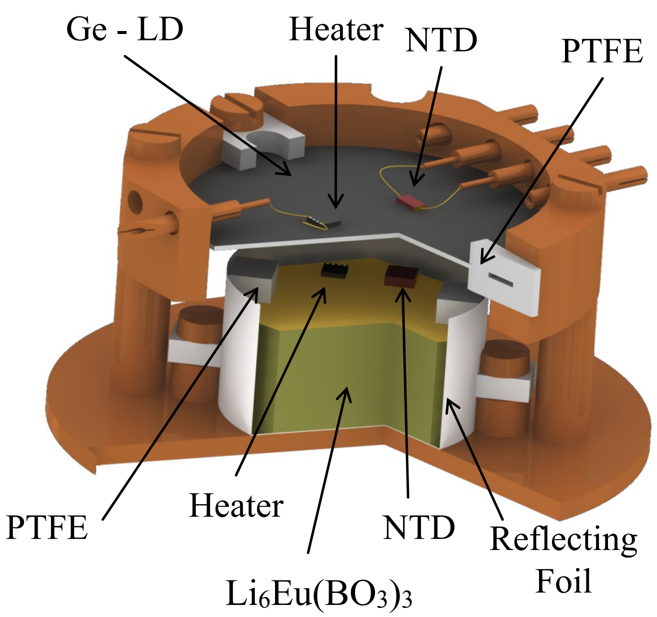
$$m_a < 8.6\,keV \;\; @ \;\; 90\,C.L.$$

P. Belli et al., *Phys. Lett.* B **711** (2012) 41-45

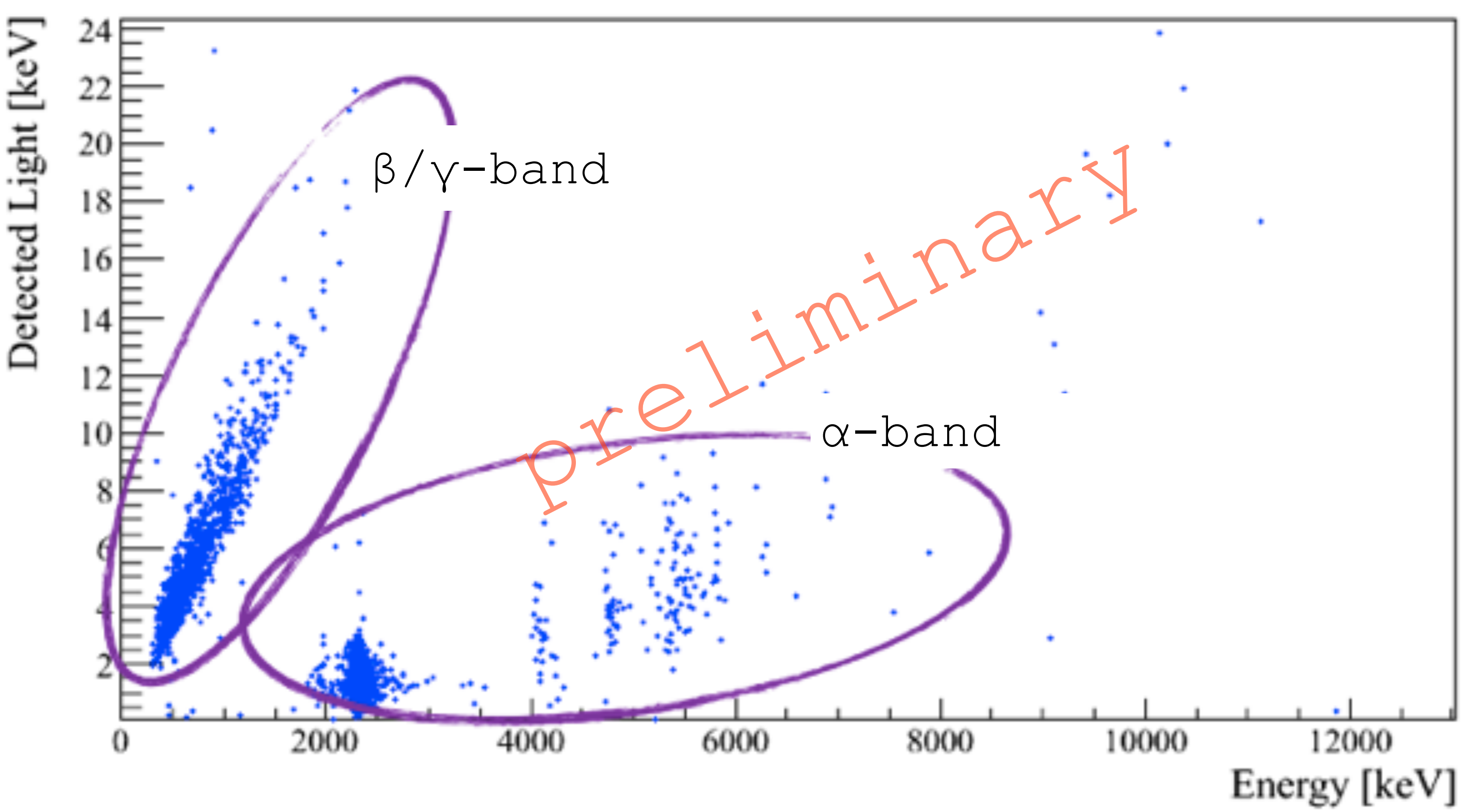
$Li_6Eu(BO_3)_3$

Interesting for:
- Eu-151 α decay
- n-detection
- solar axions

Crystal features:
- growth: Czochralski method in air atmosphere
- materials: high purity (99.99%) Li_2CO_3, Eu_2O_3 and B_2O_3



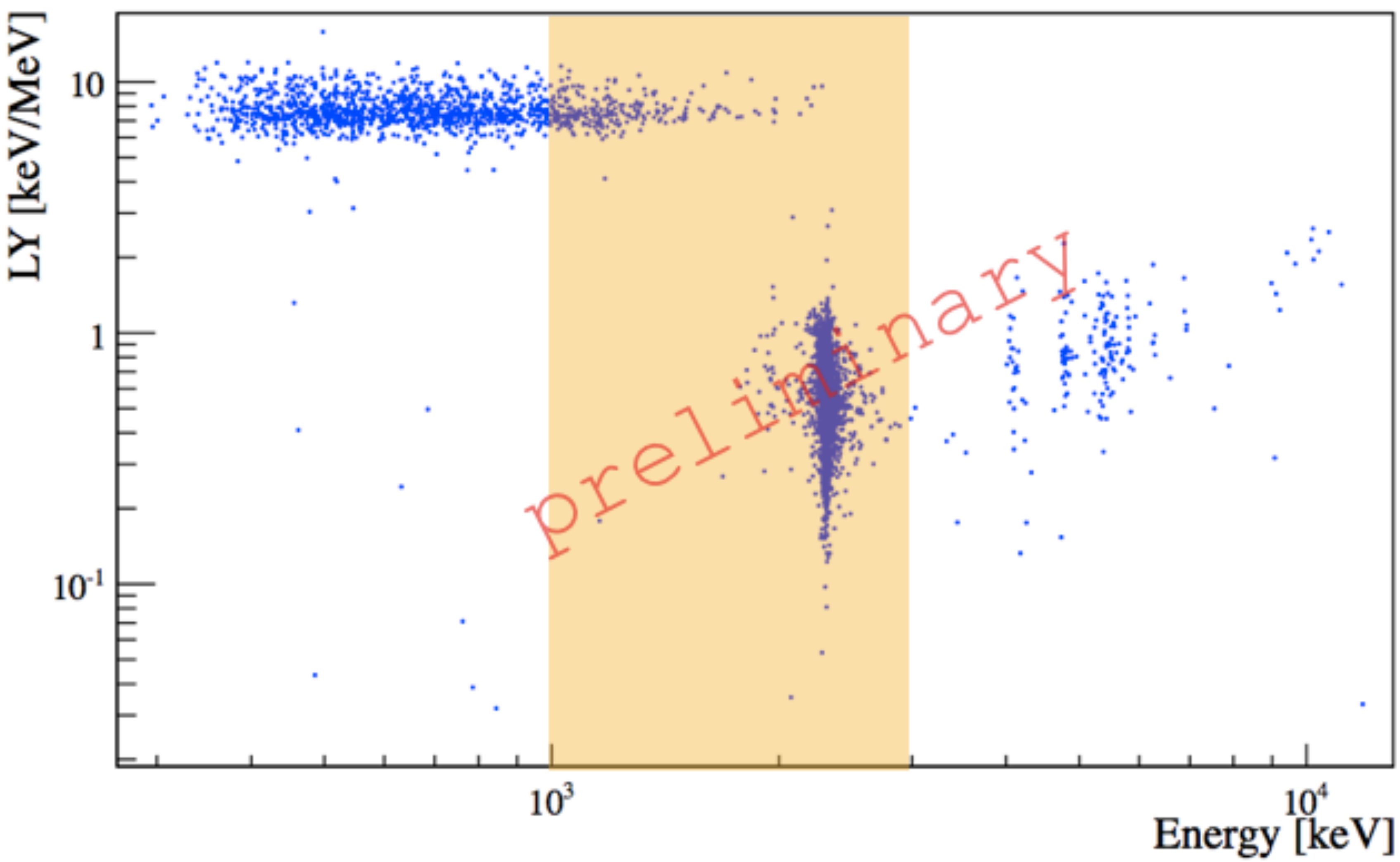
- m=6.15 g
- Calibrations γ
- Background



First bolometric test with 5x5x5 mm^3 crystal in: *2012 J. Phys.: Conf. Ser. 375 012025*

Excellent particle discrimination using **Light vs. Heat**

$Li_6Eu(BO_3)_3$ Light Yield



Assuming linearity of $LY_{\beta/\gamma}$:

$LY_{\beta/\gamma}$ = 7.38±0.02 keV/MeV

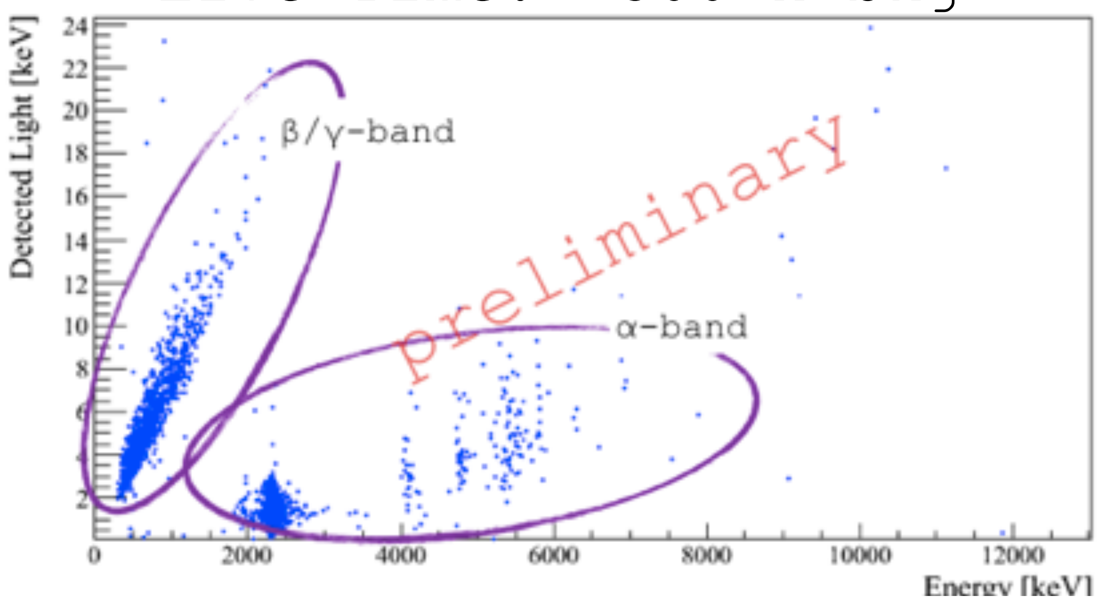
$QF_{\alpha}(E) = LY_{\alpha}(E)/LY_{\beta/\gamma}(E)$

$QF_{\alpha}(^{147}Sm) = 0.54 \pm 0.01$

$QF_{\alpha}(^{210}Po) = 0.84 \pm 0.05$

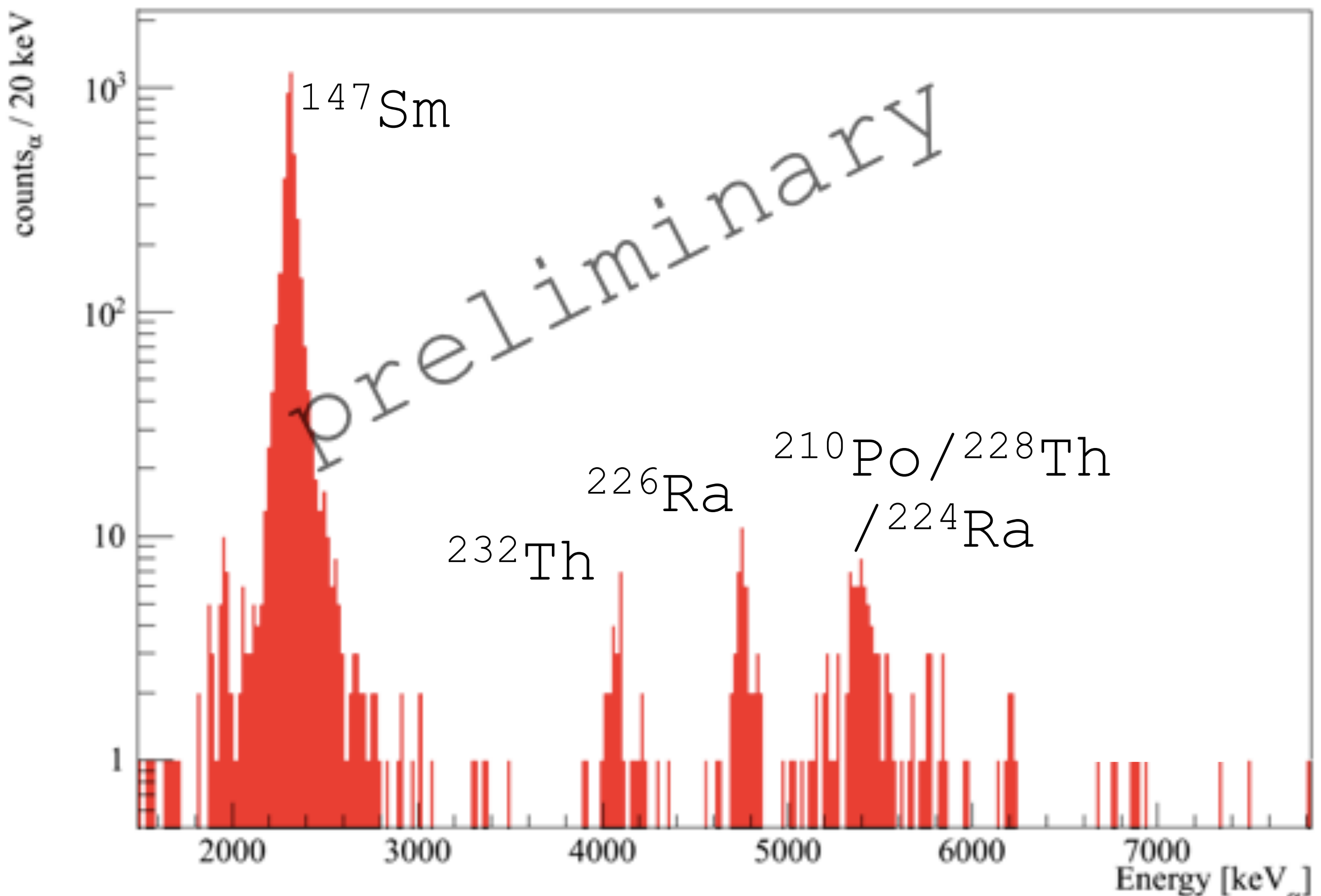
$Li_6Eu(BO_3)_3$ background

Live Time: >300 h bkg



Internal contaminations:

Chain	Nuclide	Activity
^{232}Th	^{232}Th	3.5 mBq/kg
^{238}U	^{238}U	<0.3 mBq/kg
	^{226}Ra	2.9 mBq/kg
	^{210}Po	6.2 mBq/kg
	^{147}Sm	4.5 mBq/kg



First evaluation of intrinsic radiopurity level in 2.7 g LEBO crystal:
NIM A 572 (2007) 734-738

Radioactive contaminations in $Li_6Eu(BO_3)_3$ crystal

Chain	Nuclide	Activity (Bq/kg)
^{232}Th	^{228}Ac	<0.20
	^{212}Pb	<0.25
	^{208}Tl	<0.13
^{238}U	^{214}Pb	<0.17
	^{214}Bi	<0.07
	^{40}K	<1.5
	^{60}Co	<0.026
	^{137}Cs	<0.081
	^{207}Bi	<0.009
	^{152}Eu	= 0.949(48)
	^{154}Eu	= 0.212(35)

Limits are given at 90% C.L.

^{151}Eu in $Li_6Eu(BO_3)_3$

About 40% of the crystal mass is made of Eu:
-> given ^{151}Eu isotopic abundance
-> about 1.5 g of the crystal is made of ^{151}Eu

α-decay of ^{151}Eu never observed, just an indication in:
Nucl. Phys. A 789 (2007) 15-29

Abstract
The indication for the α decay of ^{151}Eu ($Q\alpha$ = 1.964 MeV) with the half-life $T_{1/2}{}^{\alpha} = 5_{-3}^{+11} \times 10^{18}$ yr has been observed for the first time with the help of a low background $CaF_2(Eu)$ crystal scintillator (mass of 370 g) in measurement at the Gran Sasso National Laboratories of the INFN during 7426 h. In a conservative approach the lower limit on the half-life of ^{151}Eu has been established as $T^{\alpha} \geq 1.7 \times 10^{18}$ yr at 68% C.L.

The discovery of this decay is not far away...
... $Li_6Eu(BO_3)_3$ scintillating bolometer seems to be the perfect tool

large mass of Eu

particle discrimination

high detection efficiency

good energy resolution

Conclusions

- Li-scintillating bolometers are a suitable tool for low background physics from DBD to solar axions

- the double read-out brings an abrupt reduction of the background in the ROI

Li_2MoO_4

$QF_\alpha(^{147}Sm) = 0.29 \pm 0.01$

$QF_\alpha(^{210}Po) = 0.42 \pm 0.03$

* high radiopurity level
* good energy resolution

$Li_6Eu(BO_3)_3$

$QF_\alpha(^{147}Sm) = 0.54 \pm 0.01$

$QF_\alpha(^{210}Po) = 0.84 \pm 0.05$

* low radiopurity level
* poor energy resolution

... bright future is ahead
but still some work is needed ...