CUPID-Mo inauguration
December 12th, 2019

Status of CROSS

Andrea Giuliani, for the CROSS team

Outline

- General presentation of the project
- Actions and measurements in LSC
- Progress in $Li_2{}^{100}MoO_4$ crystal procurement and tests
- Progress in $^{130}TeO_2$ crystal procurement
- Above-ground study of surface sensitivity
- Relationship with CUPID
- Where we are and what’s next

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CROSS ID card

CROSS is a bolometric experiment to search for 0ν-DBD

CROSS is at the same time **conservative** and **revolutionary**

Conservative aspects:

- ^{130}**Te** in **TeO$_2$** crystals
- ^{100}**Mo** in **Li$_2$MoO$_4$** crystals

→ Excellent detector performance
Excellent radiopurity
Well-established protocols

- **High-impedance** (1-100 MΩ) **temperature sensors** – R(T)
- **Room temperature electronics** based on low-noise JFETs

Revolutionary aspects:

Use **Pulse Shape Discrimination** to **reject background**

- **Superconductive Al film coating** for surface radioactivity
- **Fast temperature sensors** based on superconductive NbSi

⇒ No light detector, but **double phonon readout** (energy + time)

Rejection of β surface radioactivity

The background index predicted for CUPID is **10^{-4} counts/(keV kg y)**, after rejection of surface α radioactivity

In order to go substantially below this value (**CUPID-reach**, **CUPID-1-ton**), it is mandatory to get rid of other components of the surface radioactivity (especiall high energy β's)

^{238}U chain → **^{214}Bi** β Q-value: 3.270 MeV

$^{214}Bi \xrightarrow{\beta} {}^{214}Po \xrightarrow[164\ \mu s]{\alpha} {}^{210}Pb$

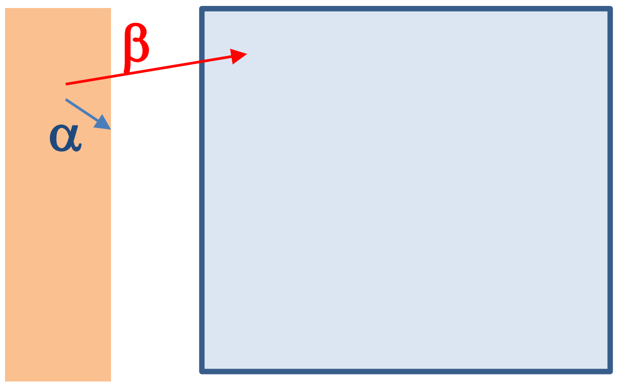
Harmless in the crystak bulk
Mixed α/β event

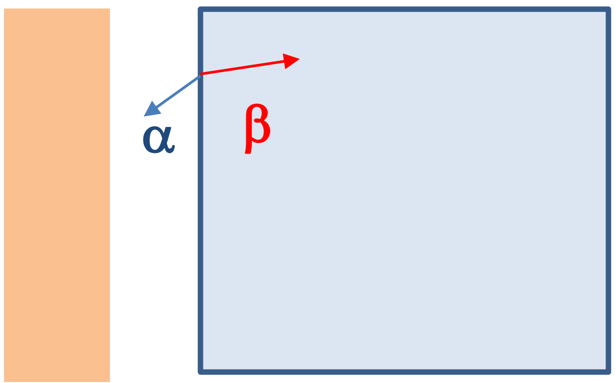
^{232}Th chain → **^{208}Tl** β Q-value: 5.001 MeV

$^{212}Bi \xrightarrow{\alpha} {}^{208}Tl \xrightarrow[3.053\ min]{\beta} {}^{208}Pb$

Under control in the crystal bulk
Delayed coincidence

These processes become challenging at the surface → it may happen that **α escape detection** and **β is (partially) absorbed**





CROSS rationale

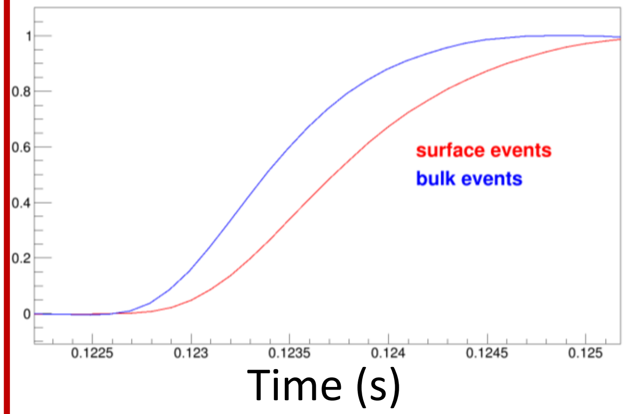
NbSi film:
Deposited directly on the crystal over a large surface, making them sensitive to the prompt **athermal** component of the phonon population produced by the impinging particle

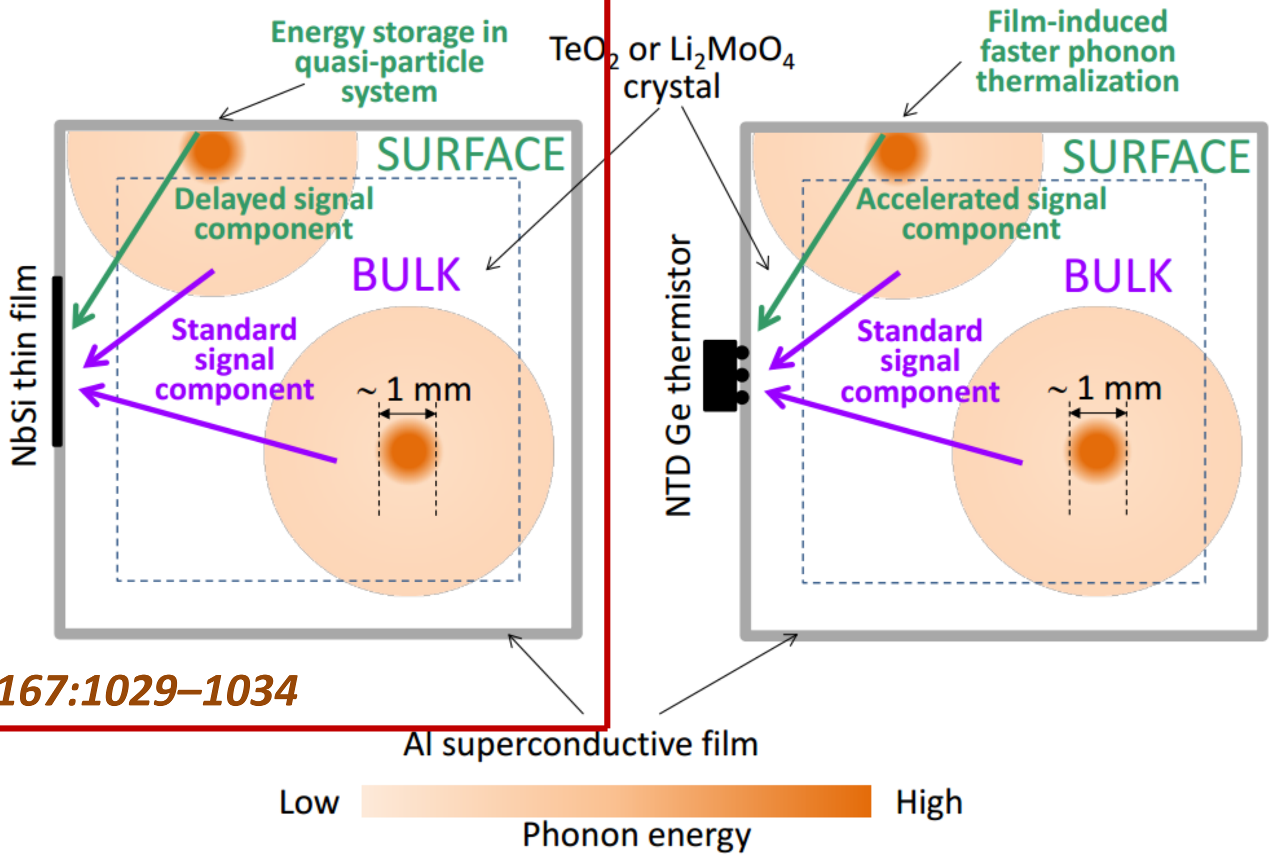
Athermal phonons are immediately produced after particle interaction in the crystal, and then they evolve toward **thermal phonons**

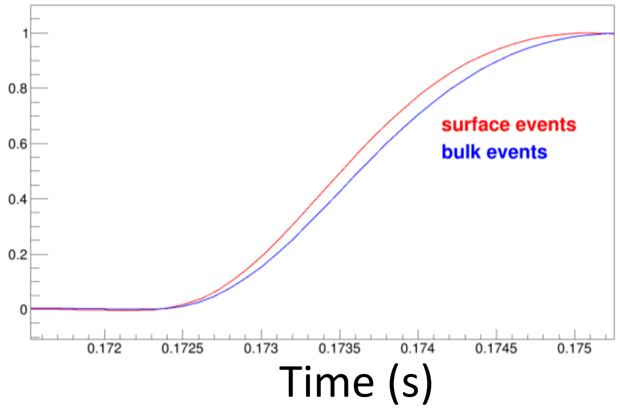
NTD (neutron-transmutation-doped) Ge thermistors:
NTDs are sensitive rather to the **thermal** component due to their intrinsic slowness and the glue interface.

CROSS detector with athermal phonon sensor*

CROSS detector with thermal phonon sensor



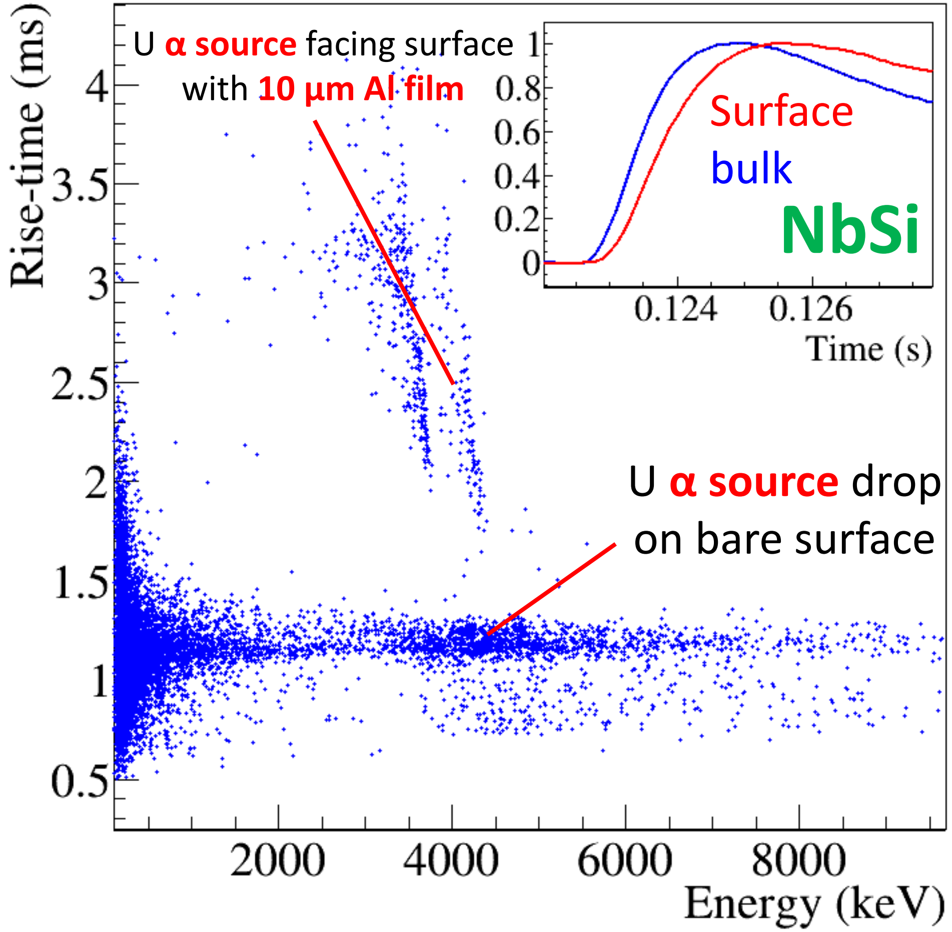


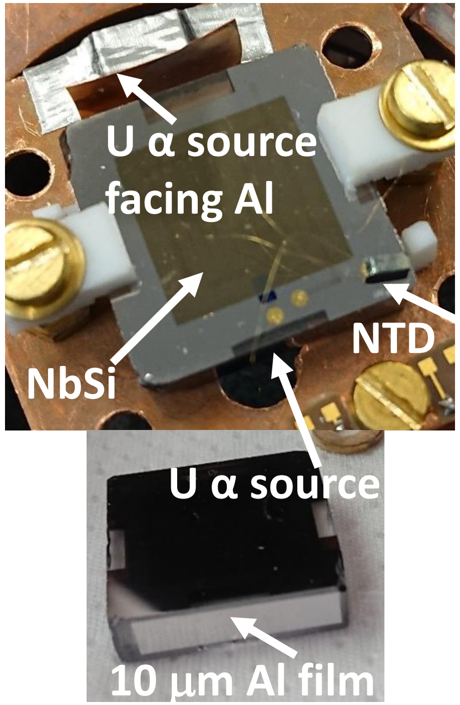


****J Low Temp Phys (2012) 167:1029–1034***

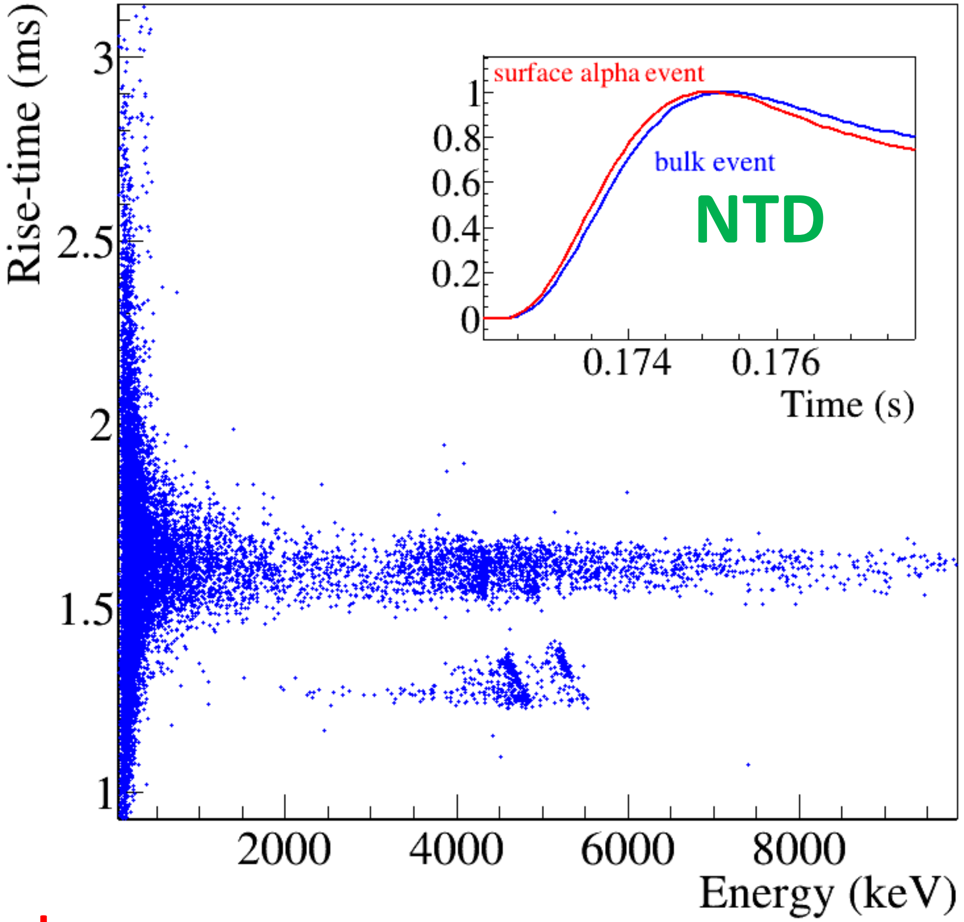
Original CROSS idea

Proof of principles





U α source
^{238}U = 4.2 MeV
^{234}U = 4.78 MeV



Surface events have a longer rise-time than bulk events

Opposite behavior of NbSi and NTD on the same crystal!

Surface events have a shorter rise-time than bulk events

http://arxiv.org/abs/1906.10233 Accepted by **JHEP**

Solid bases of the CROSS approach

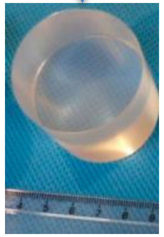
Isotopes

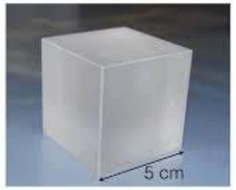
- ^{100}**Mo** — **Q = 3034 keV > 2615 keV** – Al: 9.7%
- ^{130}**Te** — Q = 2527 keV < 2615 keV – **Al: 34%**

Crystals

Li_2MoO_4

TeO_2





Excellent bolometric properties – **FWHM 5 keV**

High radiopurity

Extensively tested → CUPID-Mo, CUORE

Thermometers / Electronics →

Keep as far as possible CUORE solutions

- Room temperature JFET-based electronics
- Neutron Transmutation Doped (NTD) Ge thermistors

^{130}Te is more difficult but keep it for high isotopic abundance

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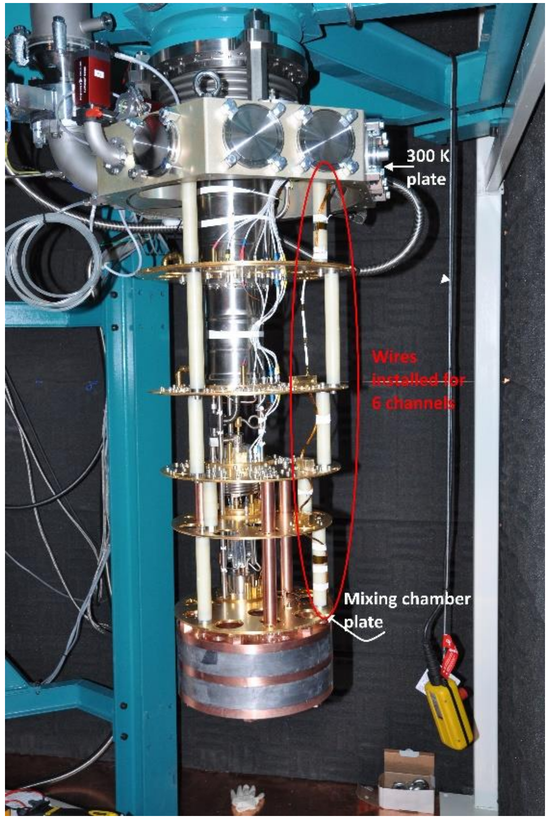
The CROSS cryostat

- **Tender**: October 2017 – December 2017
- **Order**: January 2018 – Company: CRYOCONCEPT
- **Delivery**: 14 months from order: **April 2019**

In a nutshell:

- It will be able to host up to **90 dual-readout bolometers** (after upgrade)
- Fabricated with l**ow background materials**
- **Remote-controlled** (cryogenics and detector operation)
- Cooling powers:
  320 uW@100 mK, 6 uW@20 mK, 250 nW@10 mK
- **Installation: week of April 8th, 2019**
  - Cryostat assembly and cooling down
  - Preliminary lead shielding: brick cleaning and assembly
- **Base temperature: ~10 mK reached**
- Working detectors from April to July 2019 **(98% duty cycle)**

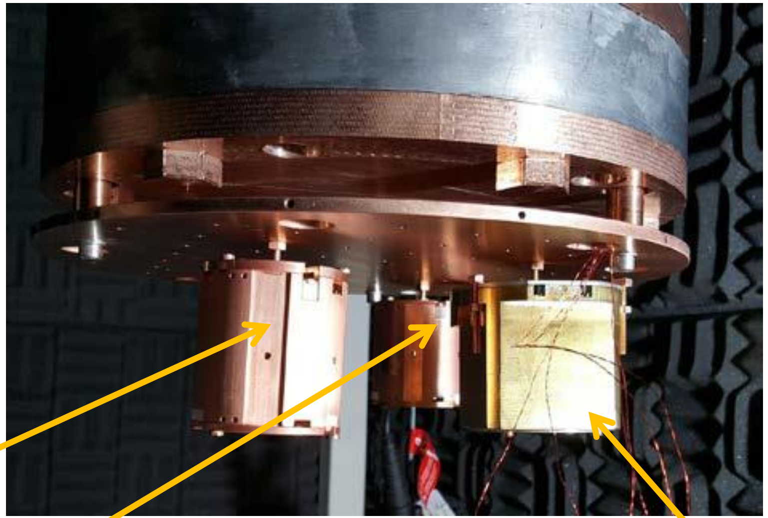


Installed detectors

Two scintillating and one pure bolometers have been assembled and are installed to test preliminarily the facility performance during the commissioning phase.

Detectors are operated **without suspensions** to test ultra-quiet technology of Cryoconcept

➡ **A suspension will be introduced next week**



Enriched ^{116}**$CdWO_4$** scintillating bolometer with a mass of 580 g

D. Poda talk, this inauguration (D. Helis)

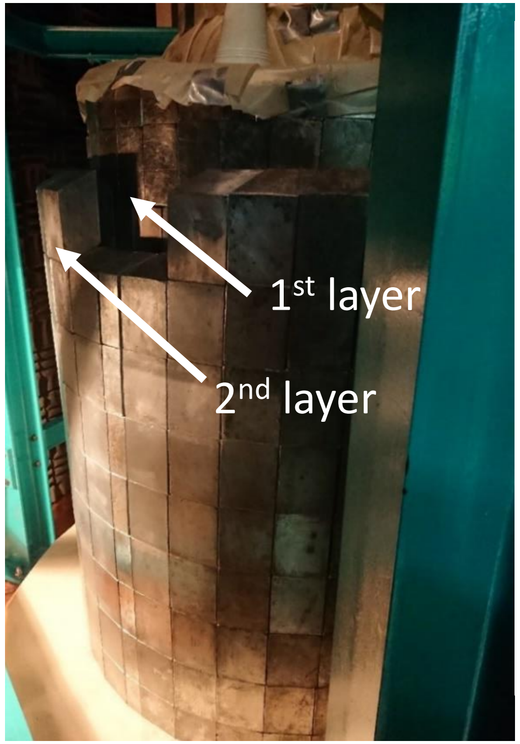
Natural **Li_2MoO_4** scintillating bolometers with a mass of 210 g (heat + light)
Same structure as CUPID-Mo (Modane)

Natural **TeO_2** pure bolometer with a mass of 780 g (only heat)

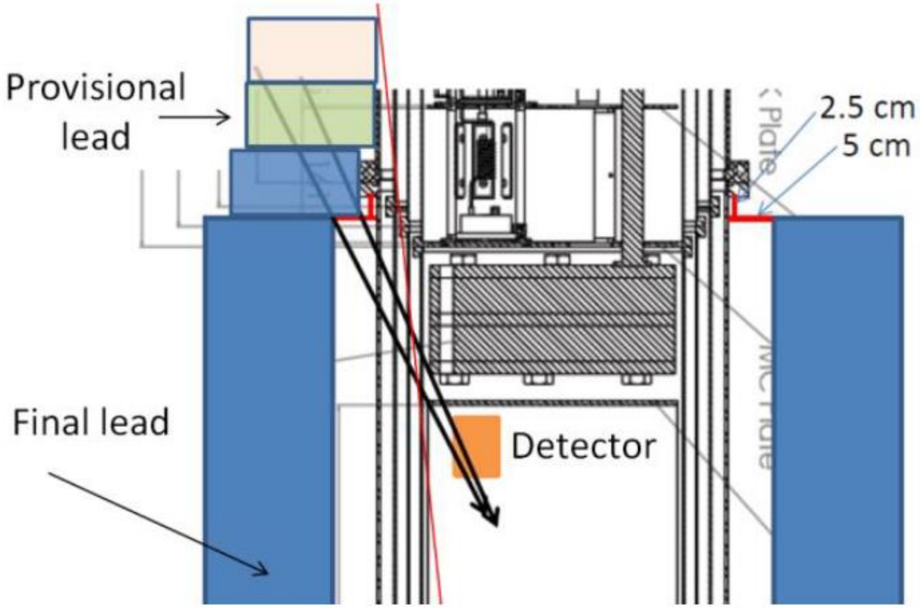
Shielding

Lead shielding was installed around the outer vacuum chamber (OVC) in two steps (15 cm thickness $\rightarrow$ 25 cm thickness), protecting the detectors from a high fraction of the external γ field

Additional internal lead elements will be installed before February 2020 to fully shield the experimental space



In the meantime, provisional lead bricks to limit γ flux from above



Shielding

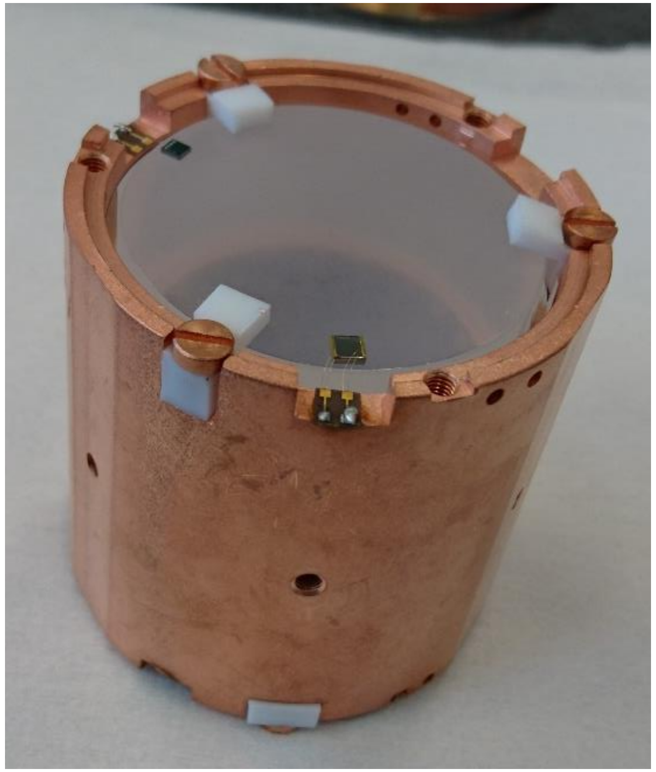
Lead shielding wa… s → 25 cm thickness), protecting the de…

Additional intern… ental space

…ux from above

Shielding and Li_2MoO_4 detector

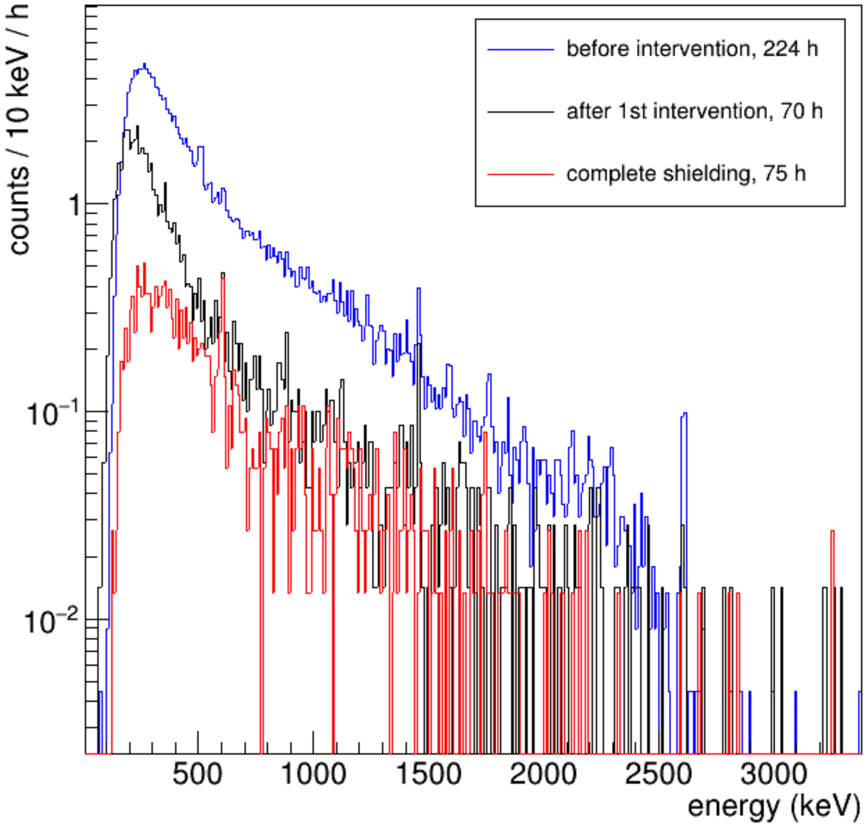
Natural Li_2MoO_4 scintillating bolometer (mass of 210 g) used to test shielding progress



	Sensitivity (nV/keV)	$FWHM_{bsl}$ (keV)
Before inter	**54**	**7.2**
After 1st inter	**50**	**6.8**
After 2nd inter	**78**	**7**

∅44×45 mm

FWHM @ ^{208}Tl 2615 keV ~ 7 keV



1st configuration: 1 layer of external lead shield around OVC (**15 cm thickness**)
2nd configuration: adding (1st intervention) **lead bricks on the top** to reduce detector exposition
3rd configuration: adding (2nd intervention) the 2nd layer of lead around the OVC (**25 cm thickness**)

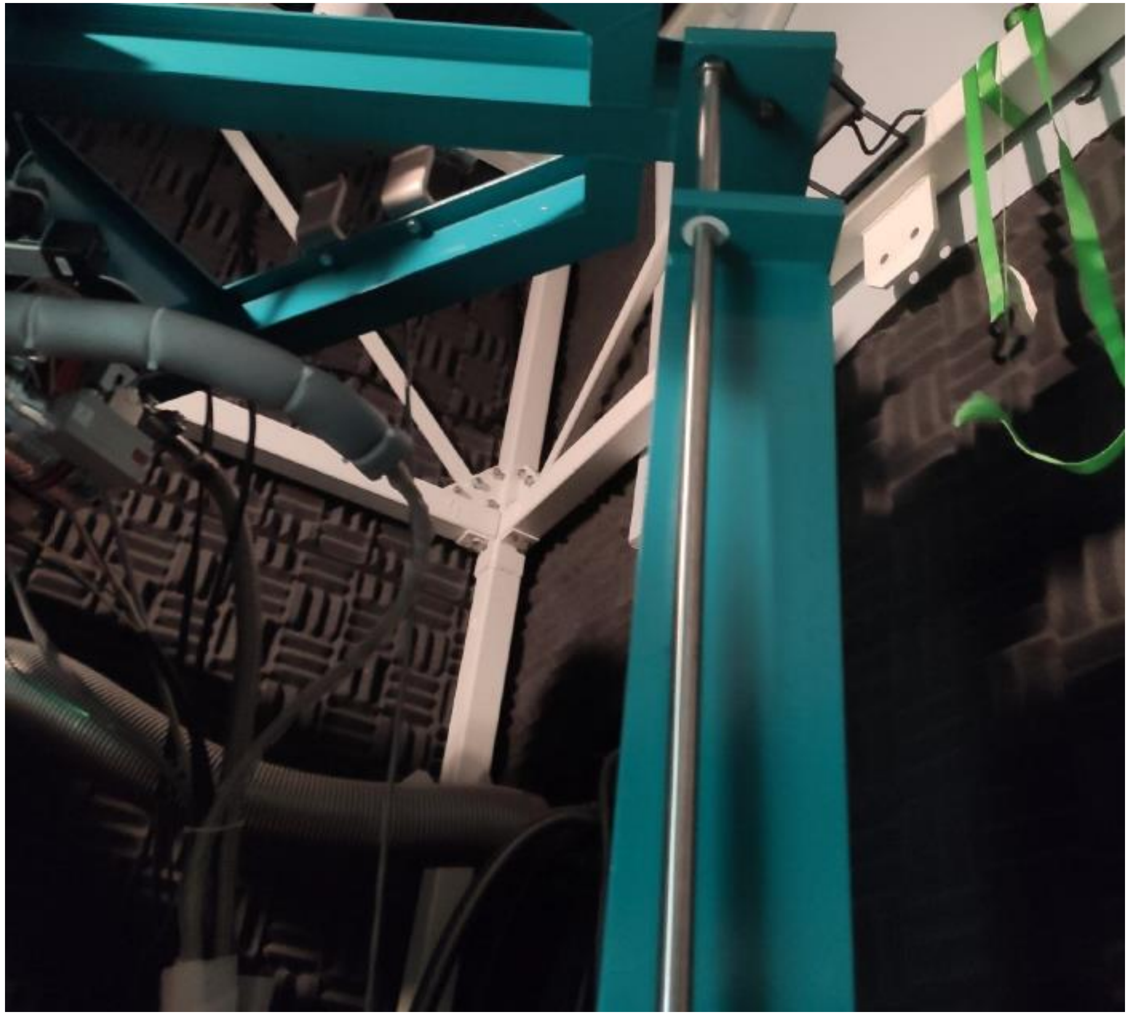
Shielding and Li_2MoO_4 detector

Counting rate		Before intervention		After 1st intervention		After 2nd intervention	
		counts/h	counts	counts/h	counts	counts/h	counts
Energy interval (keV)	[120,500]	105.9(7)	23722	45.3(8)	3171	10.4(3)	780
	[500,1000]	40.1(4)	8982	8.8(3)	616	5.0(2)	376
	[1000,1500]	13.8(2)	3091	3.3(2)	231	1.9(1)	143
	[1500,2000]	4.5(1)	1008	1.2(1)	86	0.65(9)	49
	[2000,2500]	1.9(1)	425	0.54(8)	38	0.16	12
	[2500,3000]	0.31(3)	69	0.11	8	0.05	4
	2615 keV	0.22(3)	49	0.04	3	0.01	1

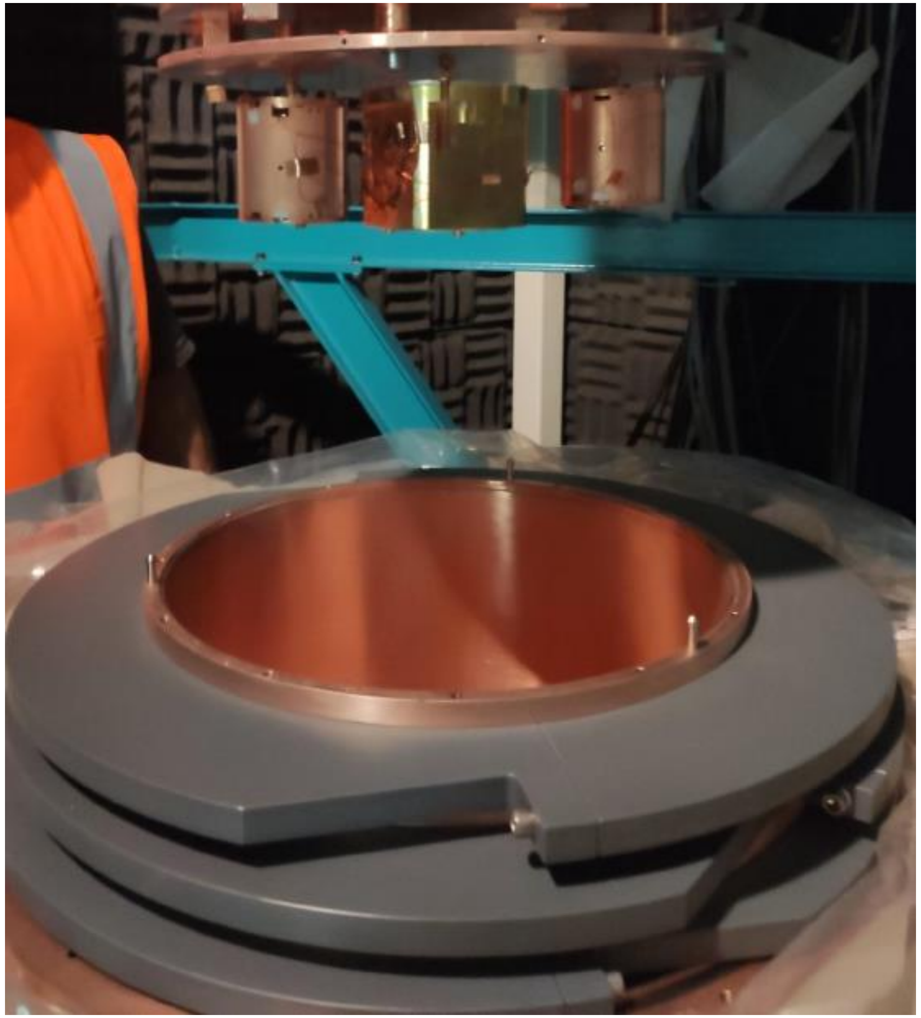
Background level has not been estimated since the experimental volume is **not yet fully shielded** from the external gamma's

Recent improvements

Alignment



Shield accommodation during opening



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Production of 33 Li_2MoO_4 crystals

CROSS will have a ^{100}Mo section based on Li_2MoO_4 crystals

The procedure to grow radiopure Li_2MoO_4 crystals starting from enriched molybdenum and with a few % of irrecoverable losses was set up during the LUMINEU project *Eur. Phys. J. C 77 (2017) 785*

3 different shapes:

CUBES

In total **33** 45×45×45 mm crystals:

- 30 enriched
- 2 depleted
- 1 natural

SMALL CYLINDERS

In total **20** ∅44×45 mm crystals, enriched

- Now in CUPID-Mo (Modane), available since April 2020

LARGE CYLINDERS

In total **4** ∅50×50 mm crystals, enriched

- At the Paris custom blocked by the strike

Cubic shape: more effective occupation of the experimental volume

Possible final choice for CUPID (decision in February 2020)

~7 kg of ^{100}Mo

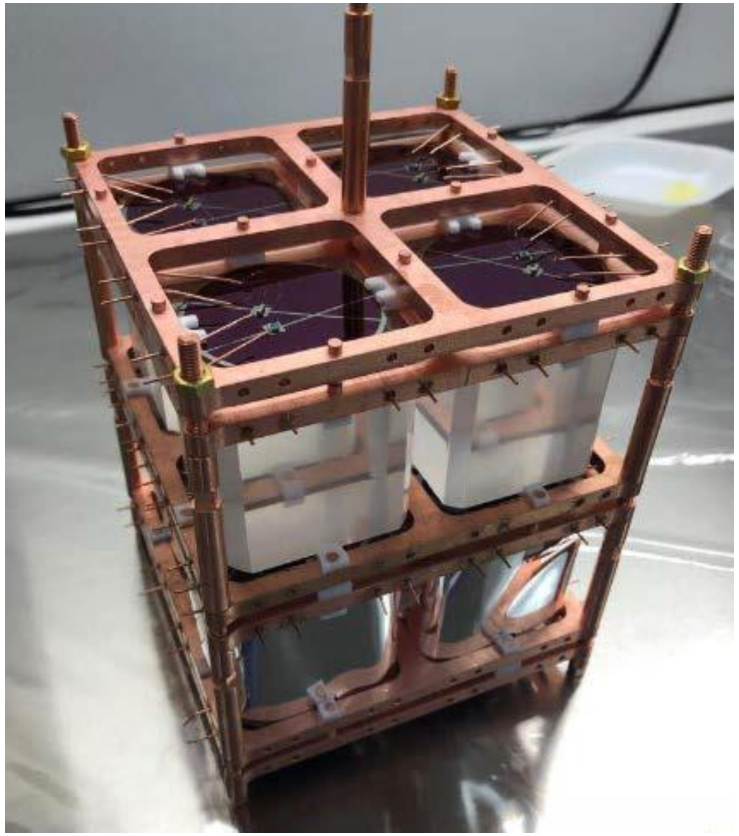
from Mo enriched in ^{100}Mo at ~96%

(from A. Barabash - ITEP, Moscow)

Already purified by NEMO-3 experiment

Test of 8 Li_2MoO_4 crystals at LNGS

- 8 Li_2MoO_4 (LMO) *cubic* crystals, each with 2 Ge LD (SiO coated)
  - new assembly designed & realized @ CEA and LAL
  - LMOs from CROSS ERC
    - top floor: *bare* LMOs
    - bottom floor: *reflecting foil* on side
  - sources ∀ detector: LMO: smeared αs / LD: ^{55}Fe
- Goals
  - check E_{res} of cubic LMOs (*vs.* cylinders)
  - measure Light Yield w/ *vs.* w/o reflecting foil
  - study of crystal time response

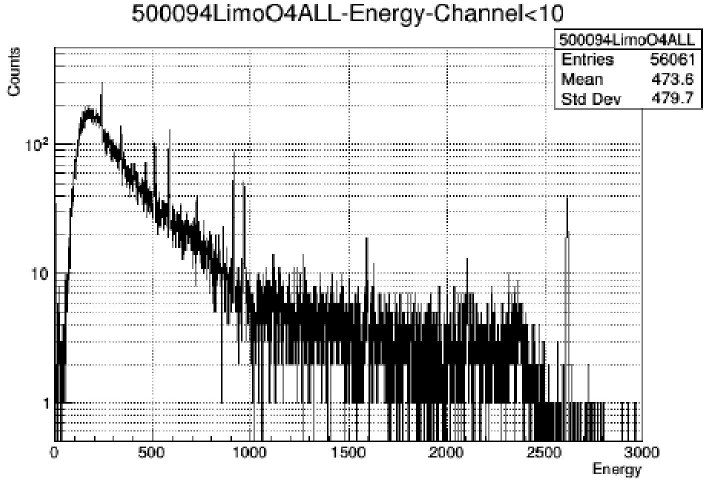


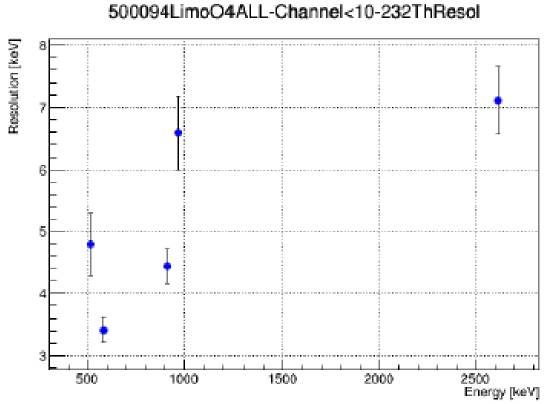
CROSS/CUPID collaboration

Test of 8 Li_2MoO_4 crystals at LNGS

- calibration is overall good: peaks sum consistently
  - peak residuals < ±0.3keV in whole E range
- noise resolution: (0.8-1.8)keV FWHM
- resolution @ 2615keV: **~7keV FWHM**
  - cylinders (CUPID-Mo): 5.3keV FWHM (best)

obs. software & hardware (→ noise) not optimized



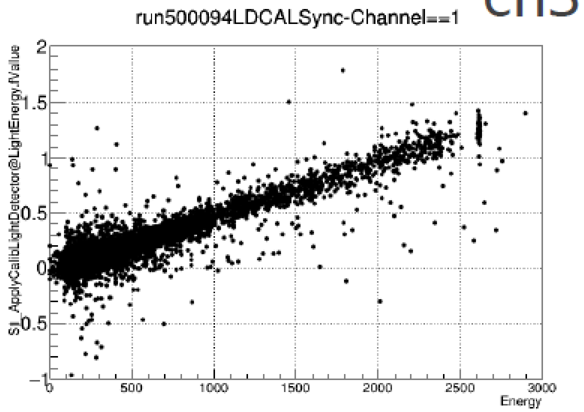


Test of 8 Li_2MoO_4 crystals at LNGS

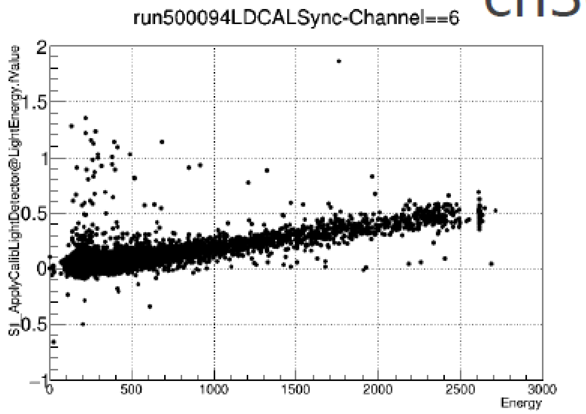
- Results with reflecting foil: **(0.5-0.6)keV/MeV**
  - cylinders: (0.64-0.74)keV/MeV (CUPID-Mo)
  - however, poor efficiency for light collection
    - LD disk over cubic crystal
    - LD far from the crystal
- Results with bare crystals: **(0.1-0.2)keV/MeV**

This detector configuration is the baseline in terms of holder structure for future cubic-crystal tests and demonstrators in Canfranc

ch31



ch36



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Development of $^{130}TeO_2$ crystals

- Premise: The **Te programme in CROSS is downsized** due to the choice of CUPID to develop an experiment based on Li_2MoO_4
- However, we intend to **keep a TeO_2 section in CROSS**, because of major advantages of this technology: ^{130}Te isotopic abundance (34%), excellent bolometric properties and radiopurity of TeO_2 $\rightarrow$ **ideal for next-to-next generation experiments**
- Size target: **60x60x60 mm** crystals (vs. **50x50x50 mm** as in CUORE)
- Unlike Mo, no reliable procedure for enrichment-purification-crystallization (with % level losses) was demonstrated so far $\rightarrow$ CROSS objective
- Collaboration with ***F. Avignone***'s group (SC, USA) who owns **8 kg of enriched Te**
  - Furnace for zone-refining purification in SC
  - American company able to grow large crystals by Chochralski method
- Minimum target: four **60x60x60 mm cubic crystals to be tested in LSC**

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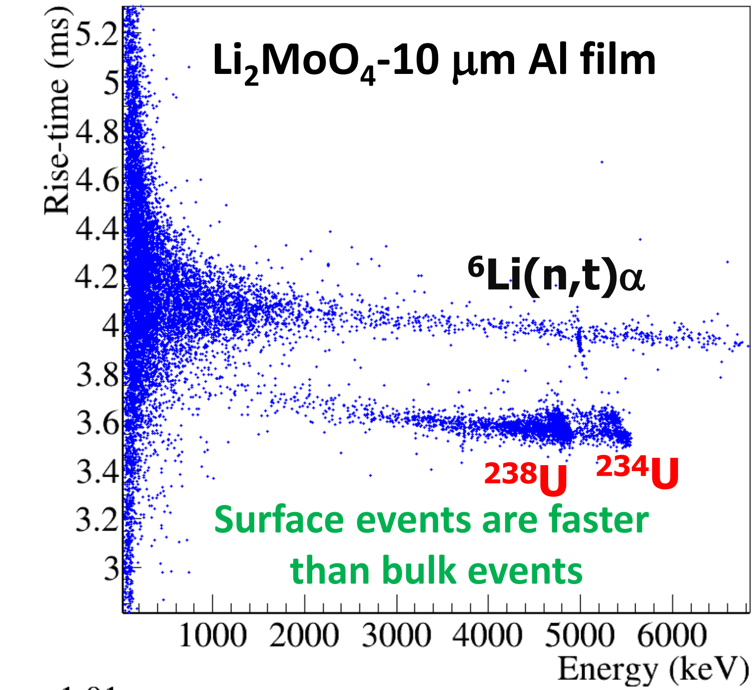
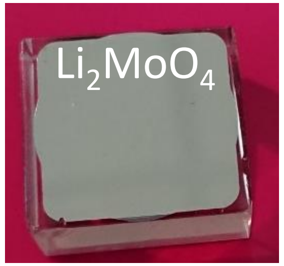
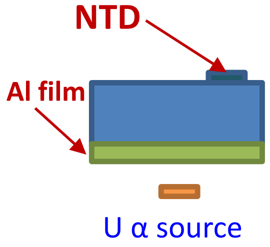
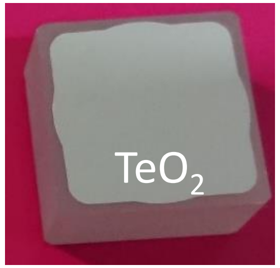
Few-µm Al films

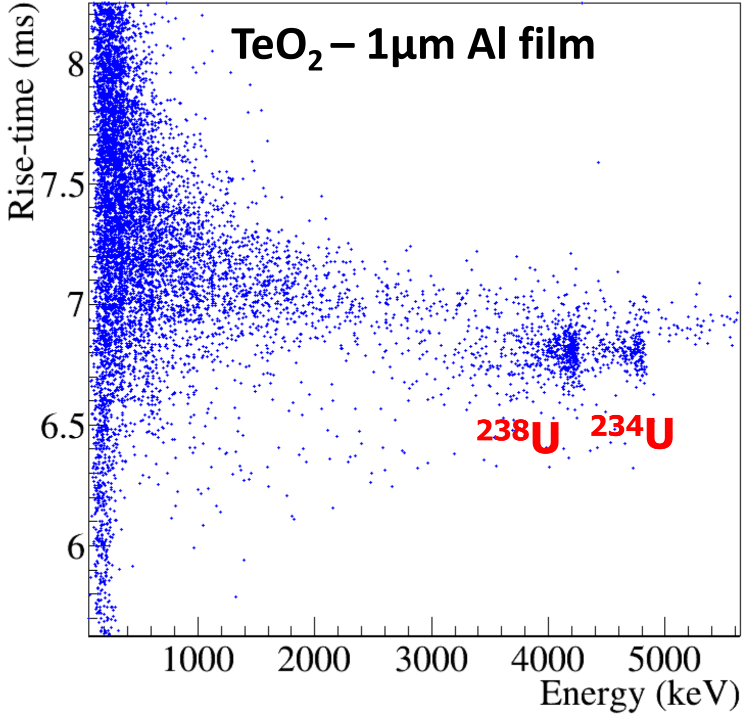


CROSS R&D run	Li_2MoO_4 2×2×1 cm³, 12 g	TeO_2 2×2×1 cm³, 25 g
#2	10µm	1µm



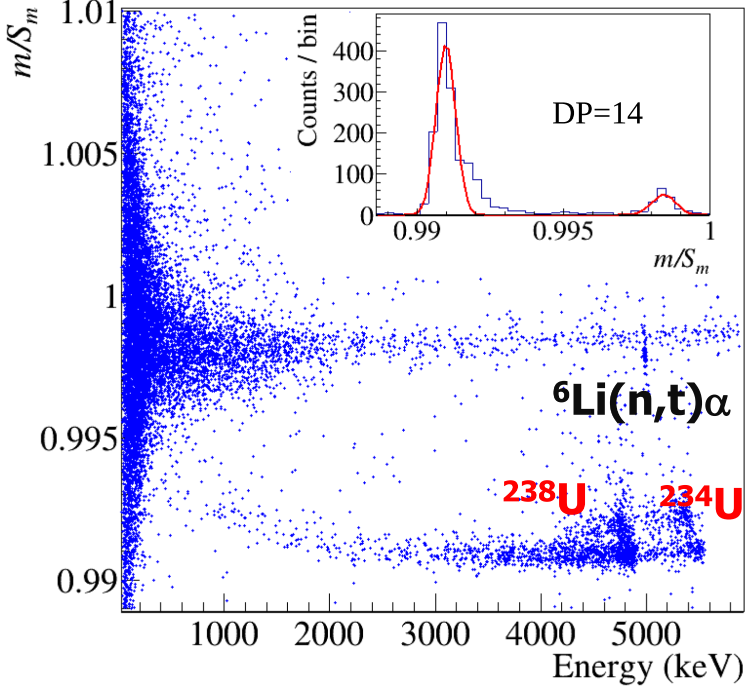






Discrimination power:

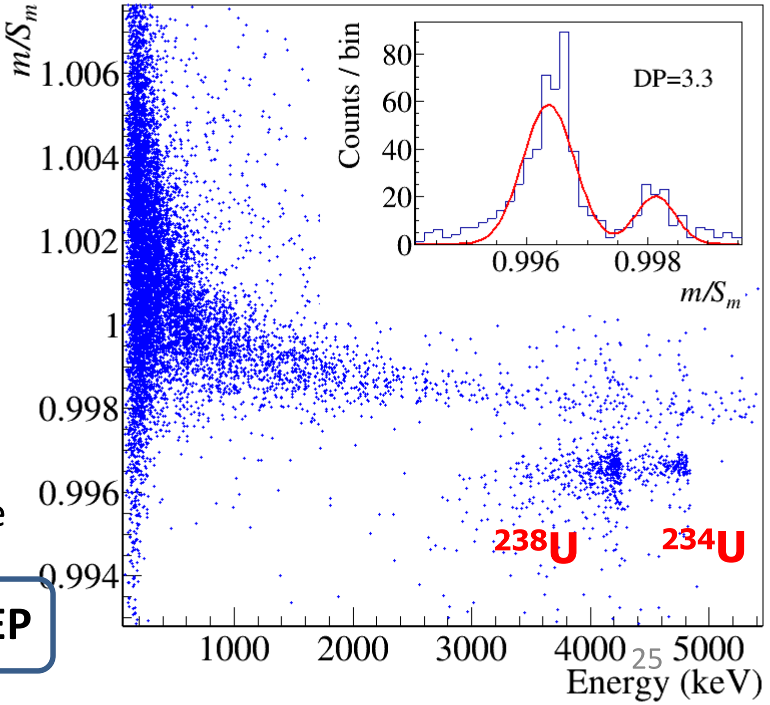
$$DP=\frac{|\mu_{\beta/\gamma}-\mu_{\alpha}|}{\sqrt{\sigma^2_{\beta/\gamma}+\sigma^2_{\alpha}}}$$



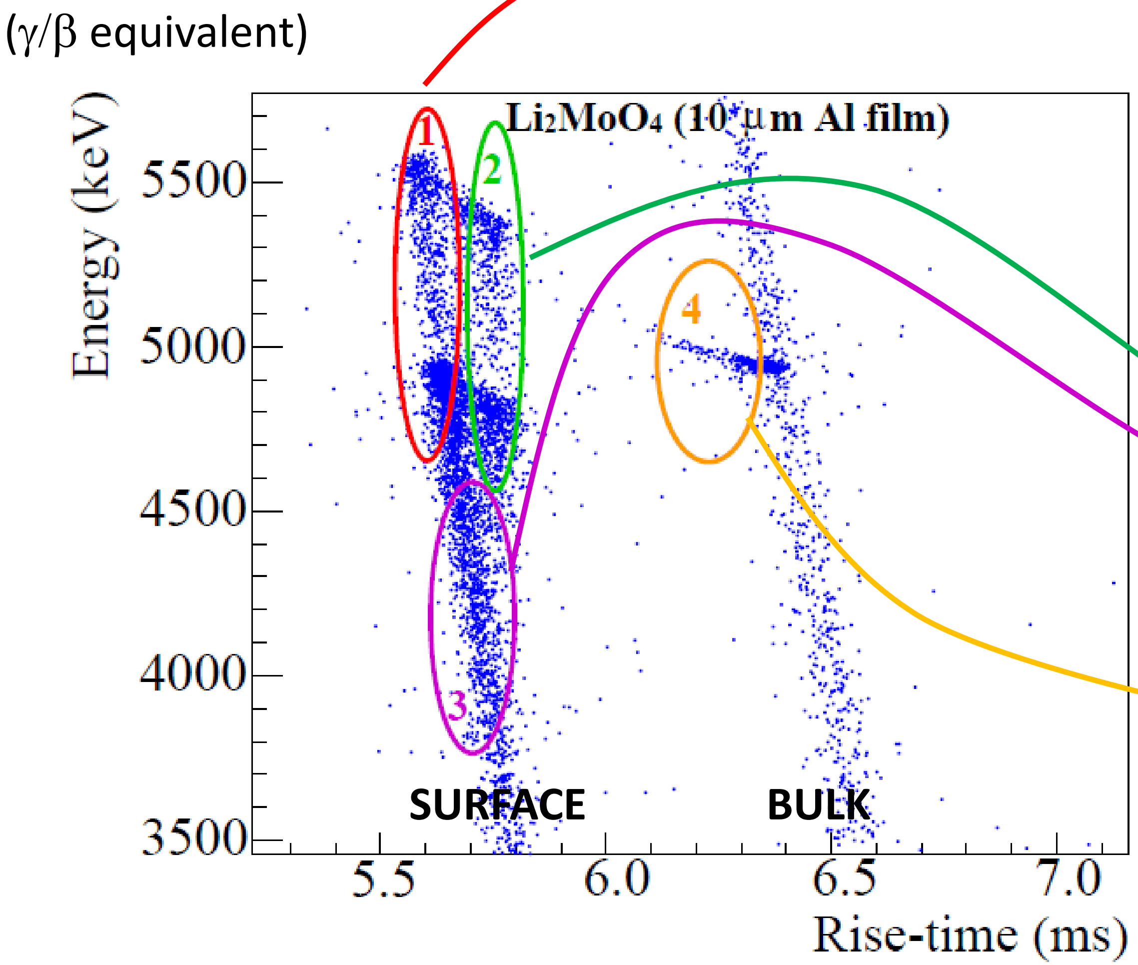
m/S_m

- Plot raw pulse vs. average pulse (at equal time)
- Perform linear fit
- Take the slope and divide by amplitude of raw pulse

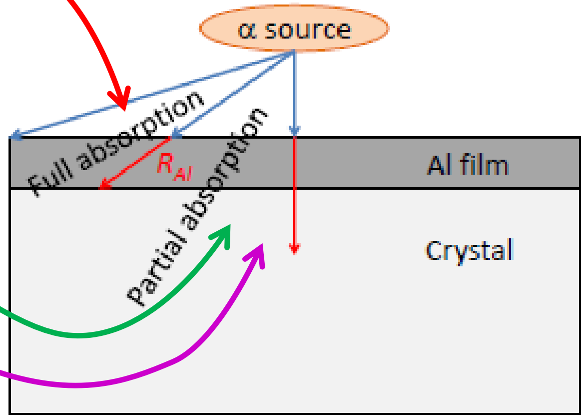
http://arxiv.org/abs/1906.10233 Accepted by **JHEP**



Risetime vs. Amplitude: classes of events



Range of α particles in Al
4.2 MeV → 16.8 μm
4.7 MeV → 20.0 μm

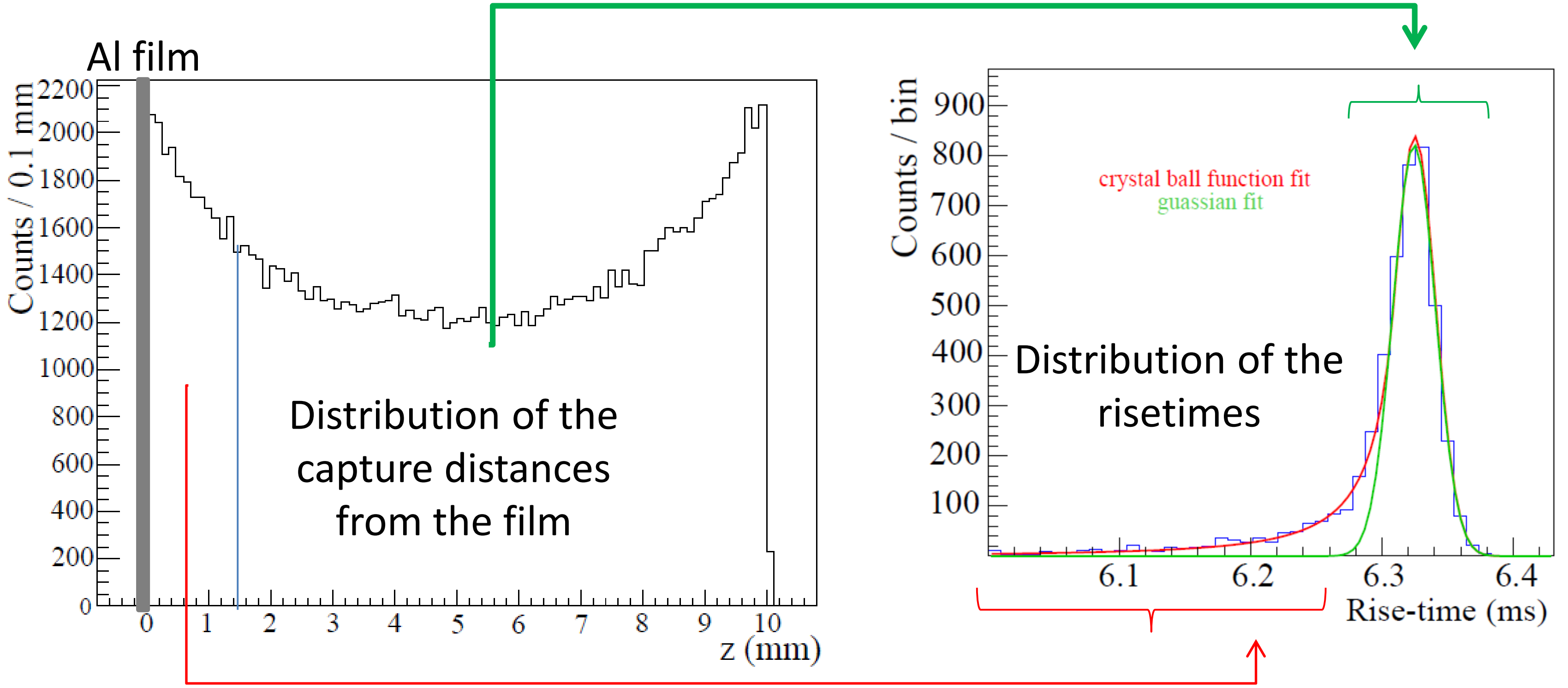


Neutron capture events
^{6}Li(n,t)a - ~ 4.8 MeV

Depth-dependence of surface sensitivity

Neutron capture: ideal tool

Bulk events: in the gaussian peak of the risetime distribution

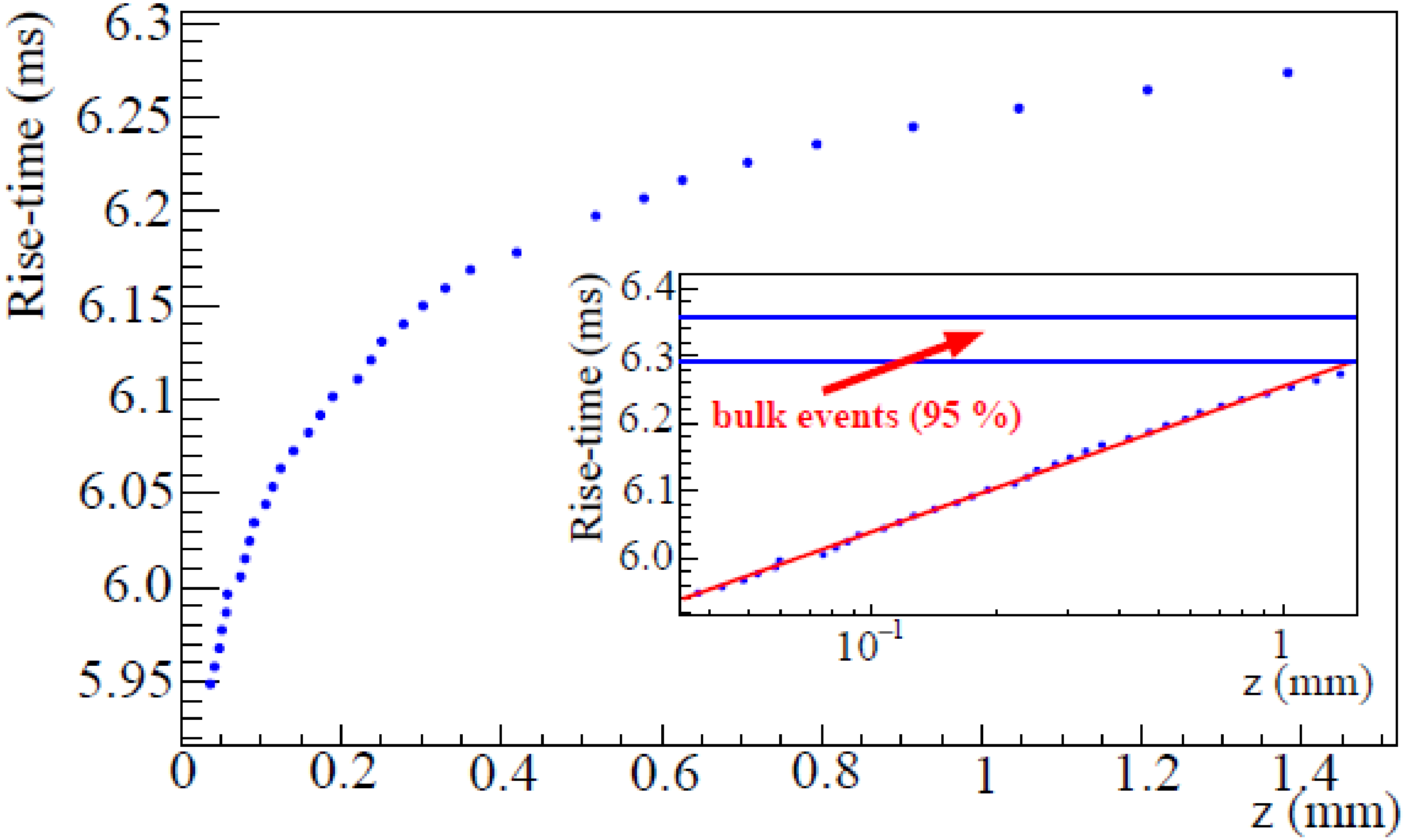


Surface events: in the risetime distribution tail

Depth dependance of surface sensitivity

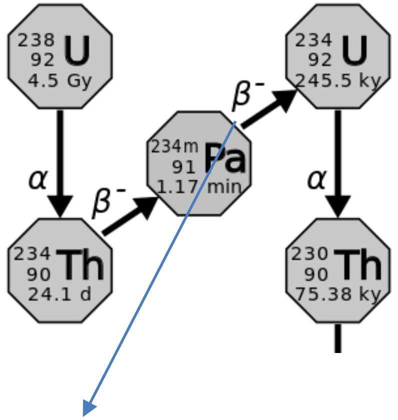
Neutron capture events
$^{6}Li(n,t)\alpha$ - ~ 4.8 MeV

Point-like energy deposition
on 1 mm scale



Pulse shape (rise time) dependence on the distance of the energy deposition spot from the coated surface down to ~1.5 mm

Unfortunately, **no sensitivity to β events**



Q = 2195 keV

How to improve?

→ Change coating material

http://arxiv.org/abs/1906.10233

PREPARED FOR SUBMISSION TO JHEP

Accepted on November 12th, 2019

The $0\nu2\beta$-decay CROSS experiment: preliminary results and prospects

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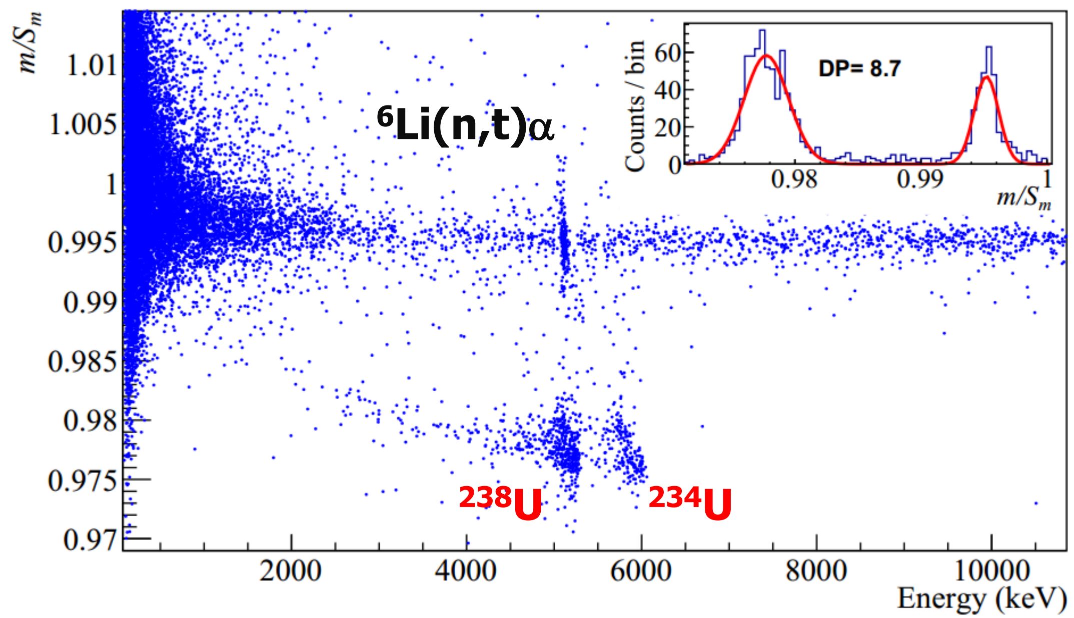
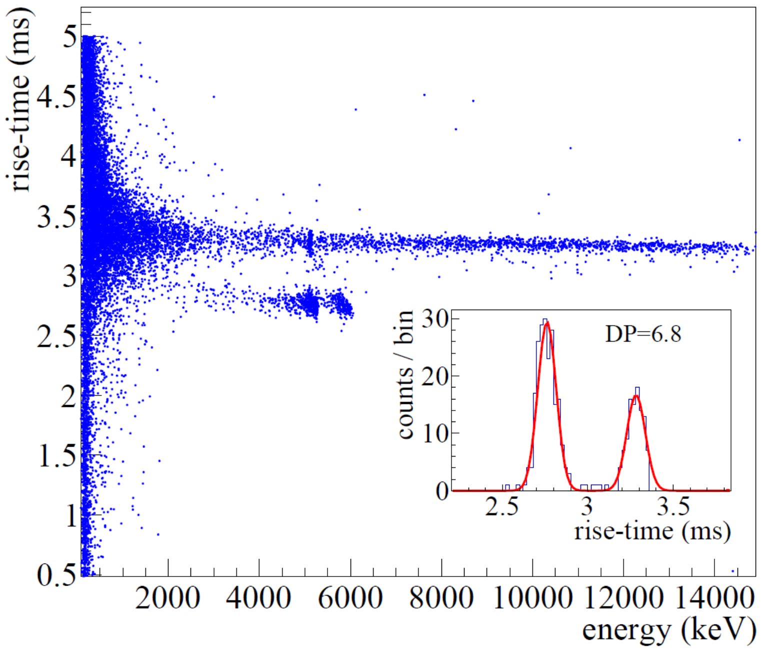
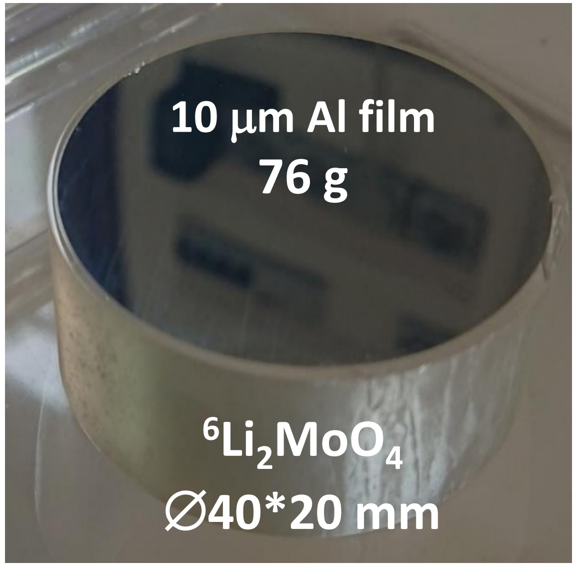
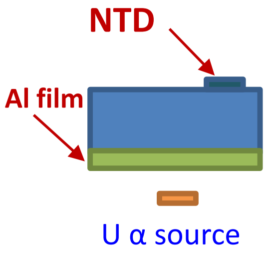
ABSTRACT: Neutrinoless double-beta decay is a key process in particle physics. Its experimental investigation is the only viable method that can establish the Majorana nature of neutrinos, providing at the same time a sensitive inclusive test of lepton number violation. CROSS (Cryogenic Rare-event Observatory with Surface Sensitivity) aims at developing and testing a new bolometric technology to be applied to future large-scale experiments searching for neutrinoless double-beta decay of the promising nuclei ^{100}Mo and ^{130}Te. The limiting factor in large-scale bolometric searches for this rare process is the background induced by surface radioactive contamination, as shown by the results of the CUORE experiment. The basic concept of CROSS consists of rejecting this challenging background component by pulse-shape discrimination, assisted by a proper coating of the faces of the crystal containing the isotope of interest and serving as energy absorber of the bolometric detector. In this paper, we demonstrate that ultra-pure superconductive Al films deposited on the crystal surfaces act successfully as pulse-shape modifiers, both with fast and slow phonon sensors. Rejection factors higher than 99.9% of α surface radioactivity have been demonstrated in a series of prototypes based on crystals of Li_2MoO_4 and TeO_2. We have also shown that point-like energy depositions can be identified up to a distance of ~ 1 mm from the coated surface. The present program envisions an intermediate experiment to be installed underground in the Canfranc laboratory (Spain) in a CROSS-dedicated facility. This experiment, comprising $\sim 3\times10^{25}$ nuclei of ^{100}Mo, will be a general test of the CROSS technology as well as a worldwide competitive search for neutrinoless double-beta decay, with sensitivity to the effective Majorana mass down to 70 meV in the most favorable conditions.

Test on a large crystal









Next step: fully-coated large crystals

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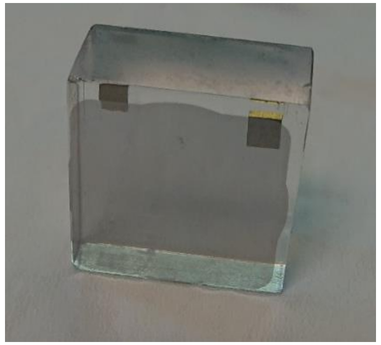
Mechanics for evaporation under development

Li_2MoO_4 with Palladium film

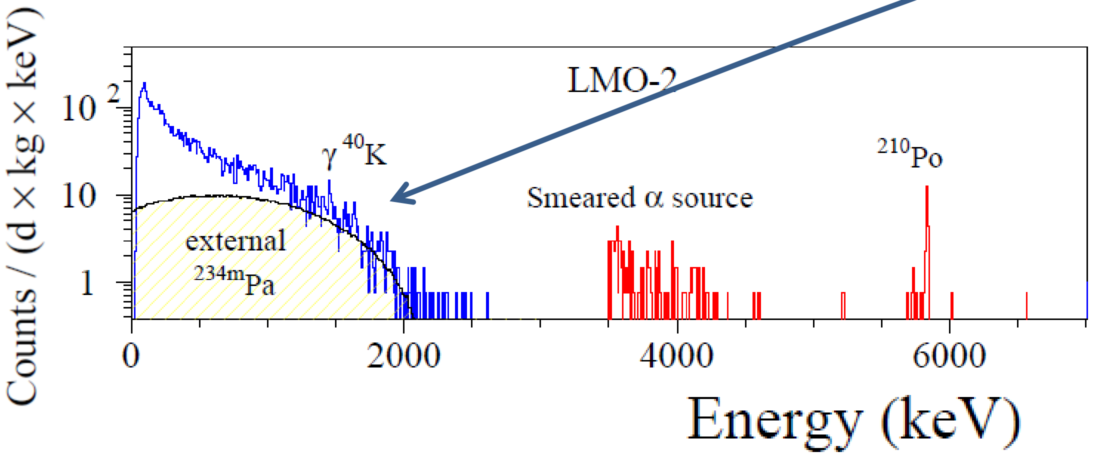
To have a better discrimination (when using NTDs), we rely to have a film that thermalizes faster the athermal phonons

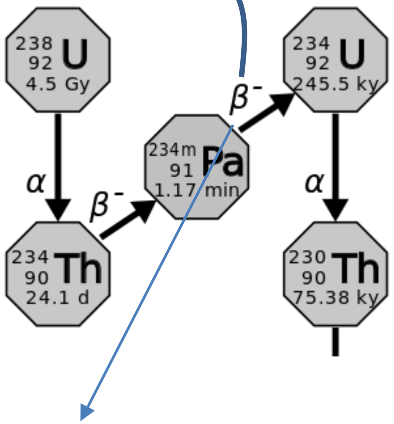
In principle, **a normal metal should be a better thermalizer for athermal phonons than a superconductor**

A test was performed on Li_2MoO_4 with 10 nm Pd film coating on one side facing a Uranium alpha source



20×20×10 mm^3 Li_2MoO_4 + light detector
10 nm thin Pd film
(nm thickness to reduce specific heat capacity of Pd)





Q = 2195 keV

Li_2MoO_4 with Palladium film

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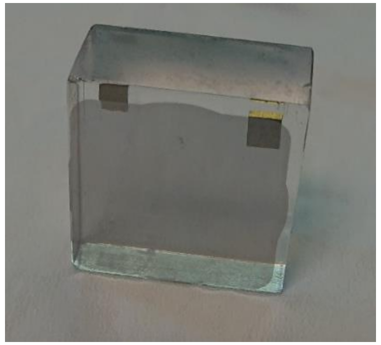

20×20×10 mm^3 Li_2MoO_4 + light detector
10 nm thin Pd film
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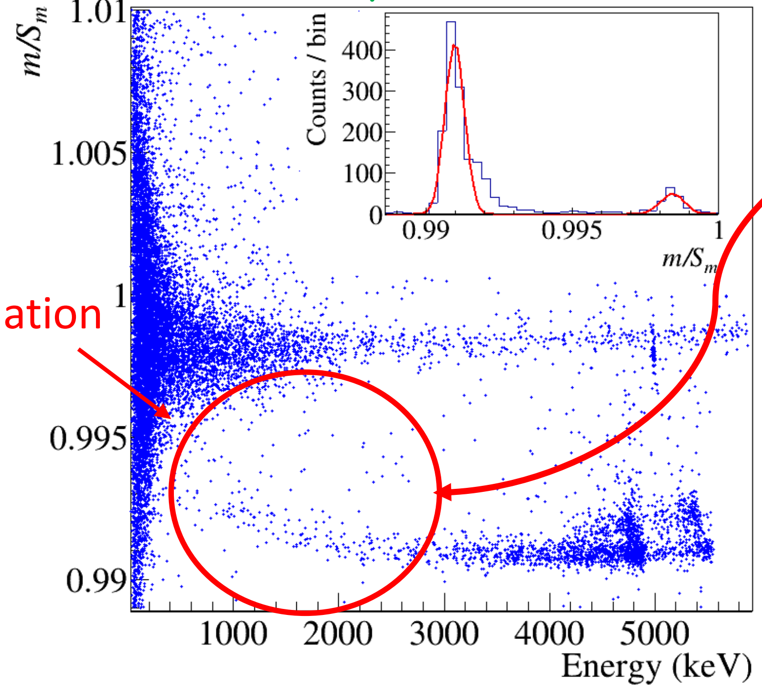
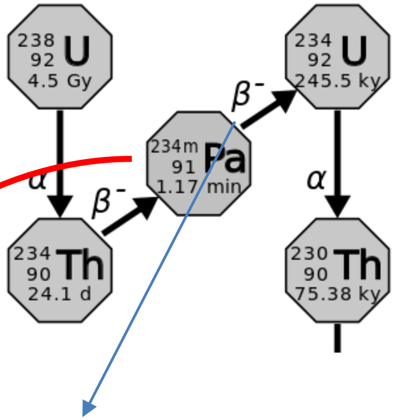
10 μm Al film

No population





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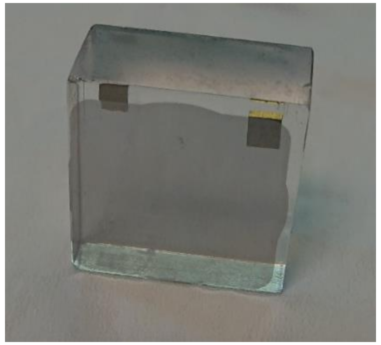

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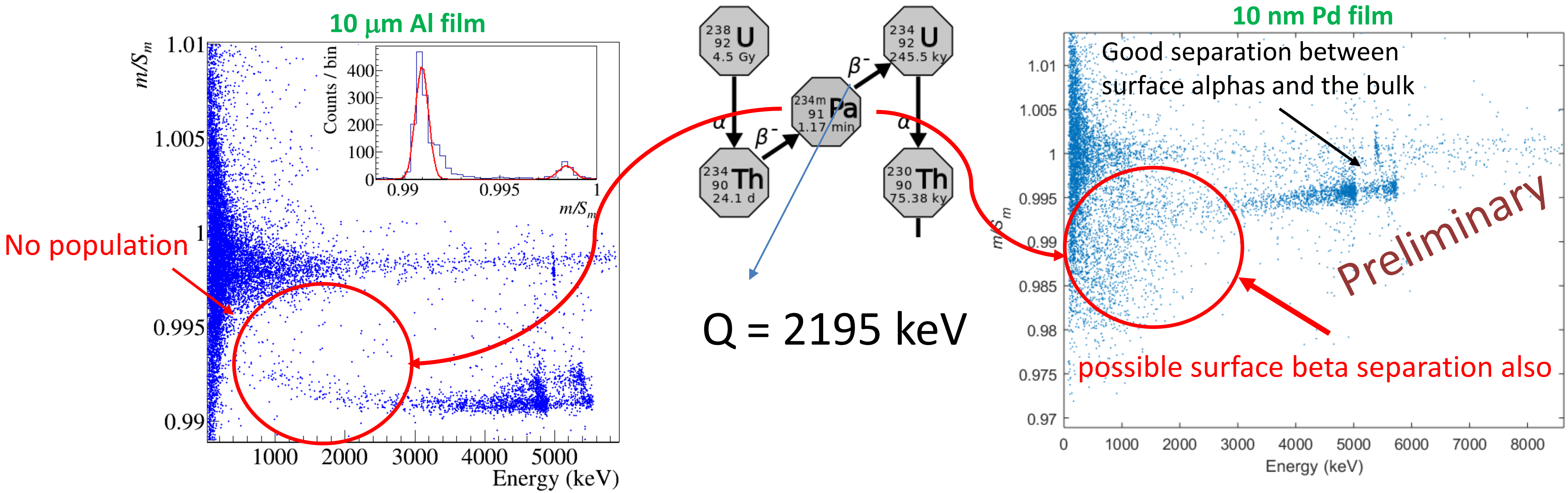
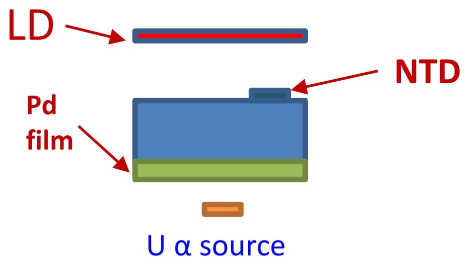
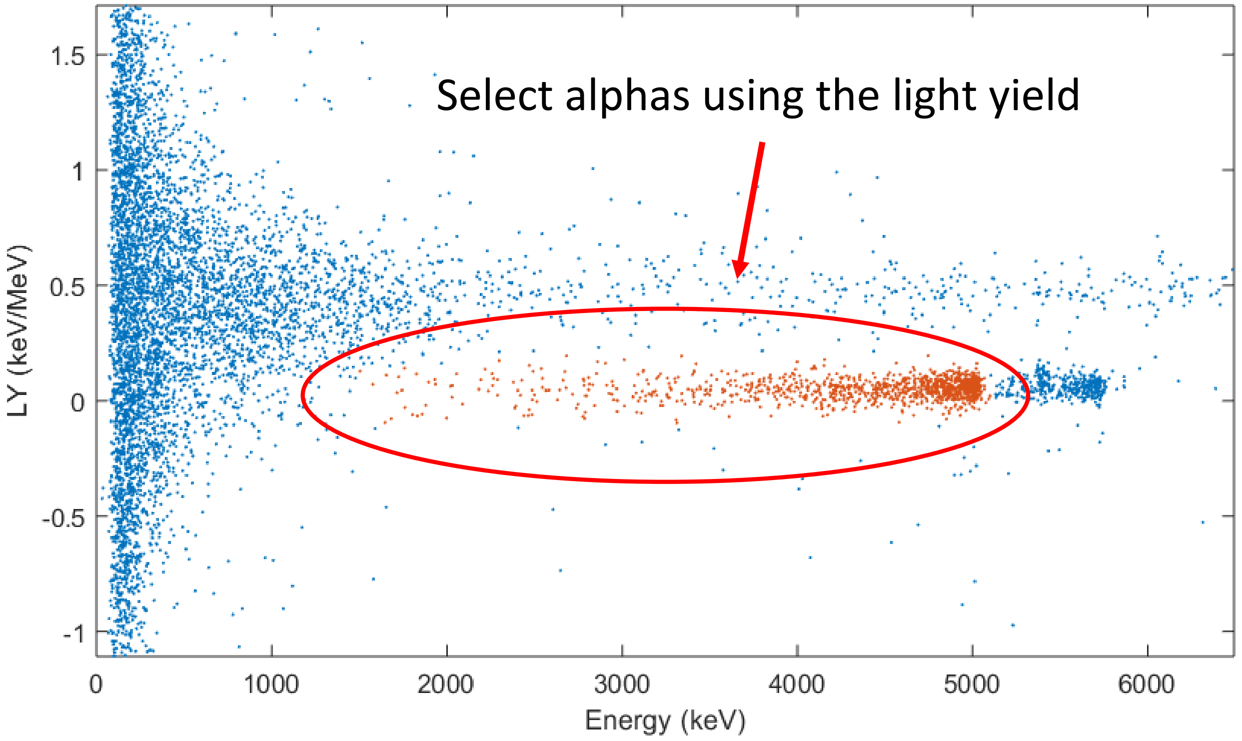


Li_2MoO_4 with Palladium film



Scintillating bolometer: isolation of α component



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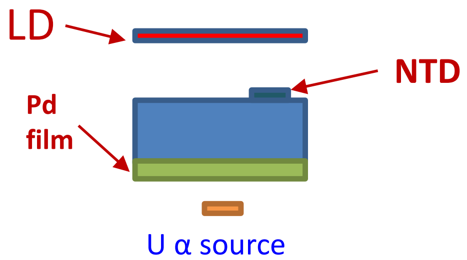

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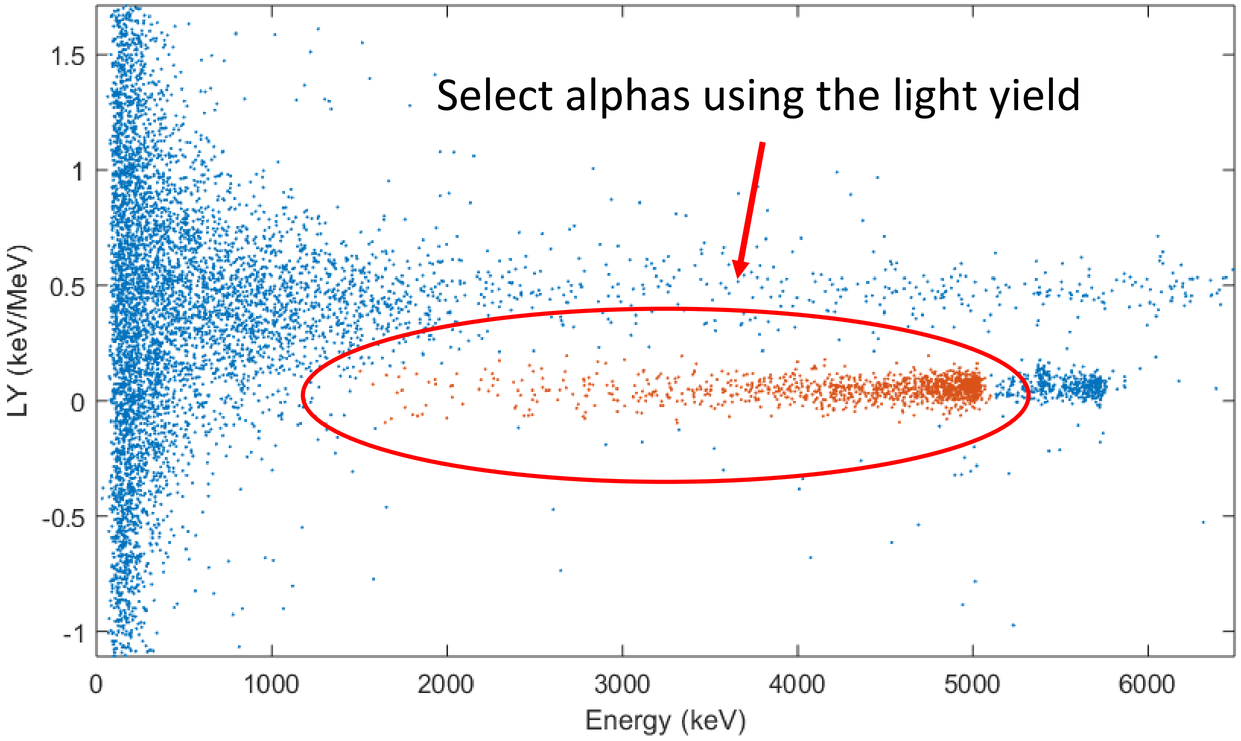
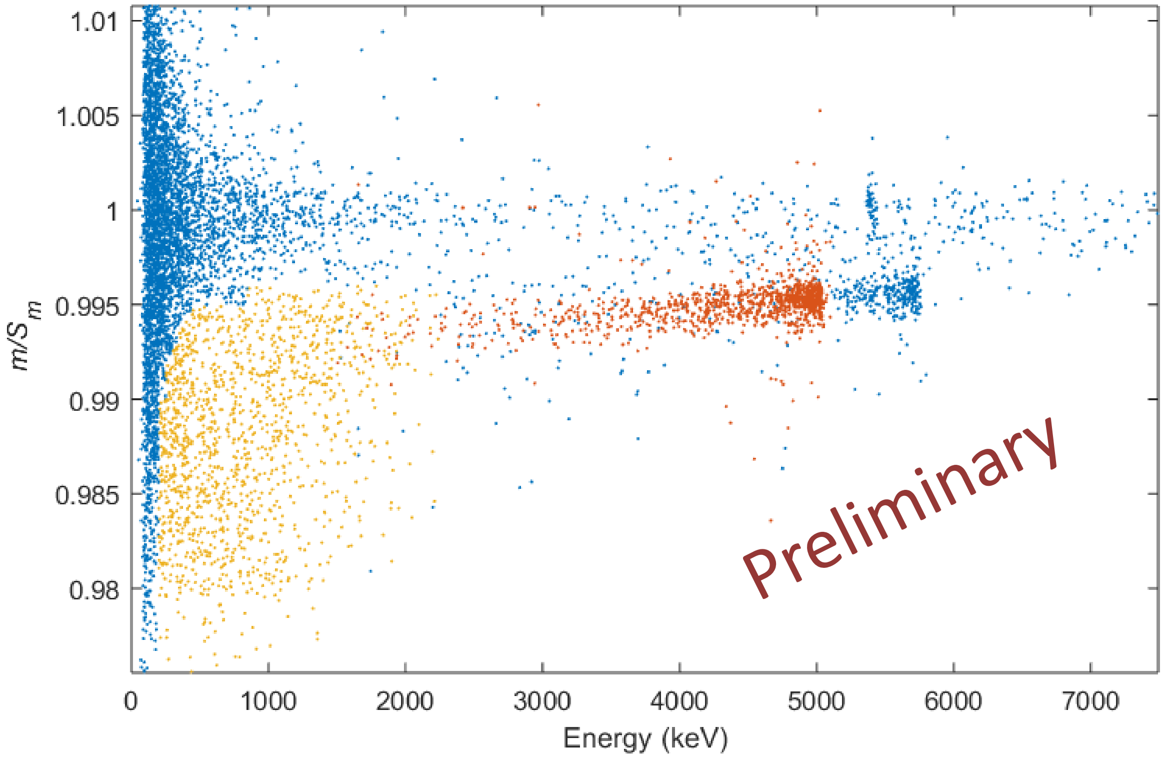


CROSS bolometer: isolation of surface α/β component



Outline

- General presentation of the project
- Actions and measurements in LSC
- Progress in $Li_2{}^{100}MoO_4$ crystal procurement and tests
- Progress in $^{130}TeO_2$ crystal procurement
- Above-ground study of surface sensitivity
- Relationship with CUPID
- Where we are and what's next

Collaboration items with CUPID

- Preliminary tests of **cubic crystals** (possible new baseline for CUPID, main component in CROSS)

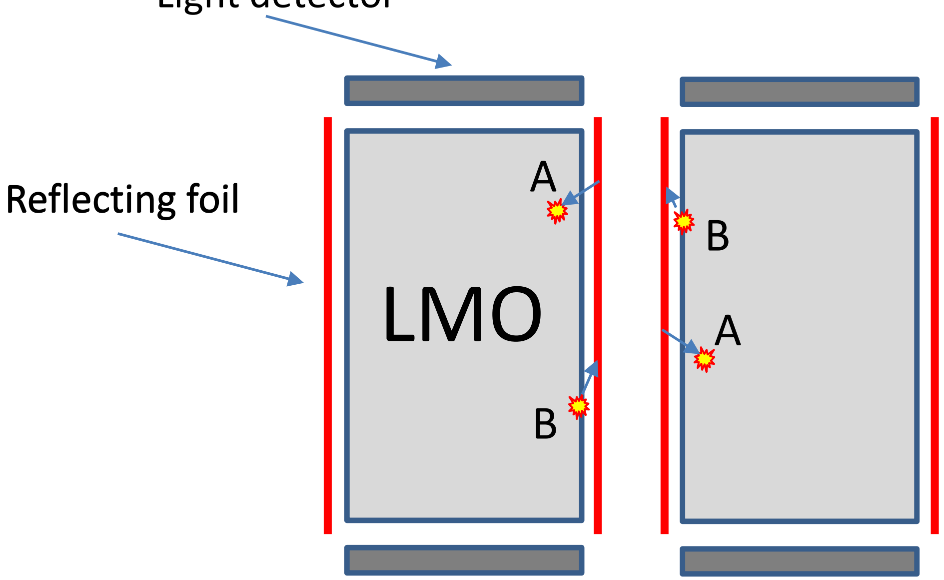
- Hosting **CUPID demonstrators in Canfranc** (study of light collection, optimization of light detectors, study of crystal radiopurity from recently purchased enriched material)

- Partial implementation of **CROSS coating method in CUPID**

- Frabrication and test of **room-temperature electronics and DAQ custom cards** with important innovations

Advantages of replacing reflective foil with Al coating

CUPID baseline



CUORE + CUPID-0 + CUPID-Mo

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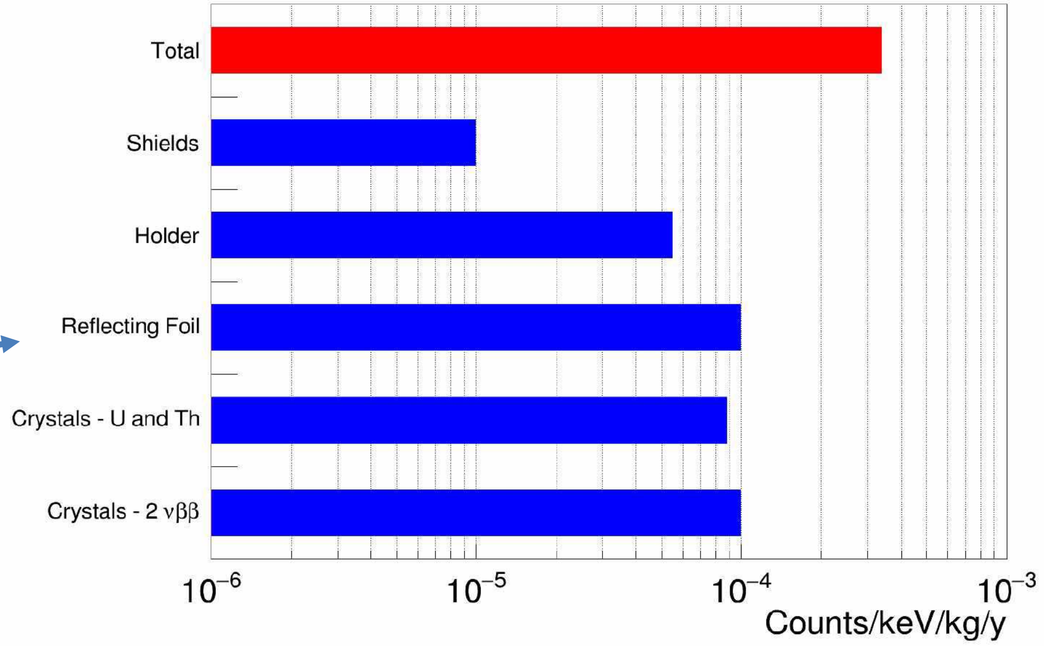
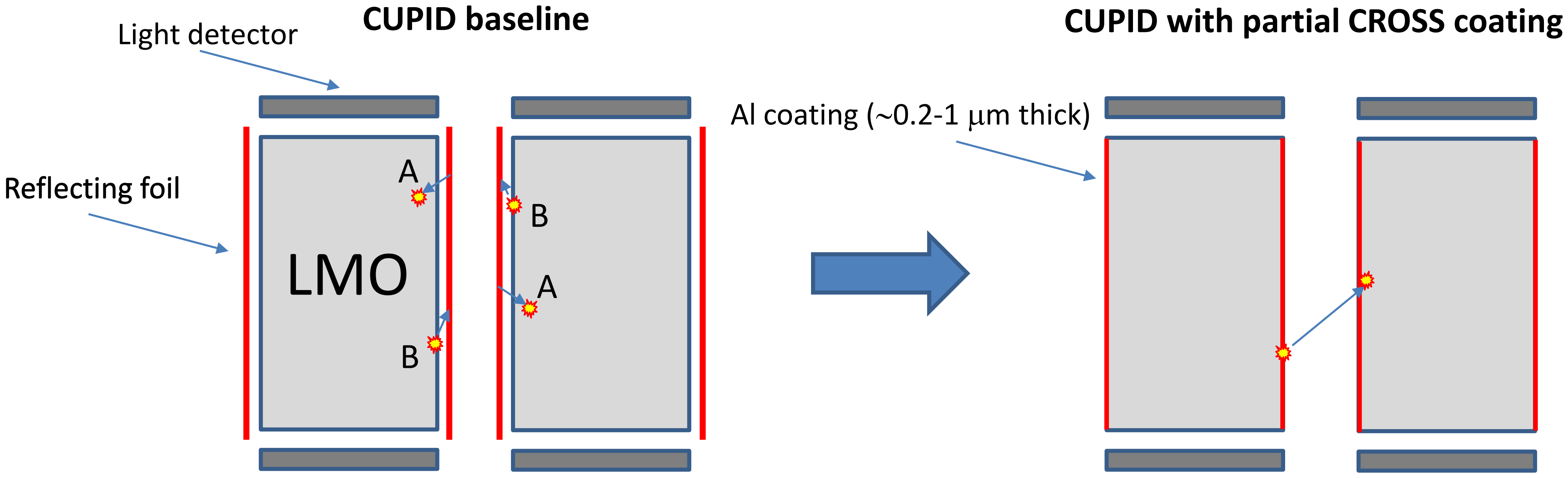
CUPID background model



A ⟶ Radioactivity of reflective foil

B ⟶ Prevented coincidences in crystal surface events

Advantages of replacing reflective foil with Al coating



~~A~~ → Radioactivity of reflective foil

~~B~~ → Prevented coincidences in crystal surface events

A → Replace reflective foil with >50-times-thinner ultra-pure Al film

B → Full surface sensitivity allows for anticoincidence cuts

BONUS → specific surface sensitivity

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Next run: November 2019 – February 2020

Two towers

Tower 1:

- CWO-enr: the same measured in previous run
- CWO-nat: for gA measurements

Tower 2:

French crystal producer alternative to NIIC

- LMO natural cylinder 0.1-0.2 um Al film lateral side, new LD +source
- CLYMENE 1 crystal +Neganov-Luke LD
- LMO cube enriched +2LD: one on the crystal directly (1 light detector broken)
- LMO cube depleted +1LD

- ➢ **Facility optimization: “intermediated” electronics, DAQ, suspensions**
- ➢ **Information for CROSS and CUPID**

Next-to-next run: from March 2020

- 8 or 12 cubic-LMO-crystal array + CWO tower(both enriched crystals)
- Test of light detectors and lateral coating for light collection
- Test at Canfranc of a small scale demonstrator prefiguring the final one
- First significant test of the background (lead shield completed)