July 20th, 2017
Quy Nhon, Vietnam

A ^{100}Mo pilot experiment with scintillating bolometers and related CUPID activities

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DISAT, University of Insubria, Como, Italy

Outline

- CUPID: a next-generation $0\nu2\beta$ bolometric experiment
- The ^{100}Mo way: LUMINEU → CUPID-Mo
- Surface sensitivity: the CROSS project

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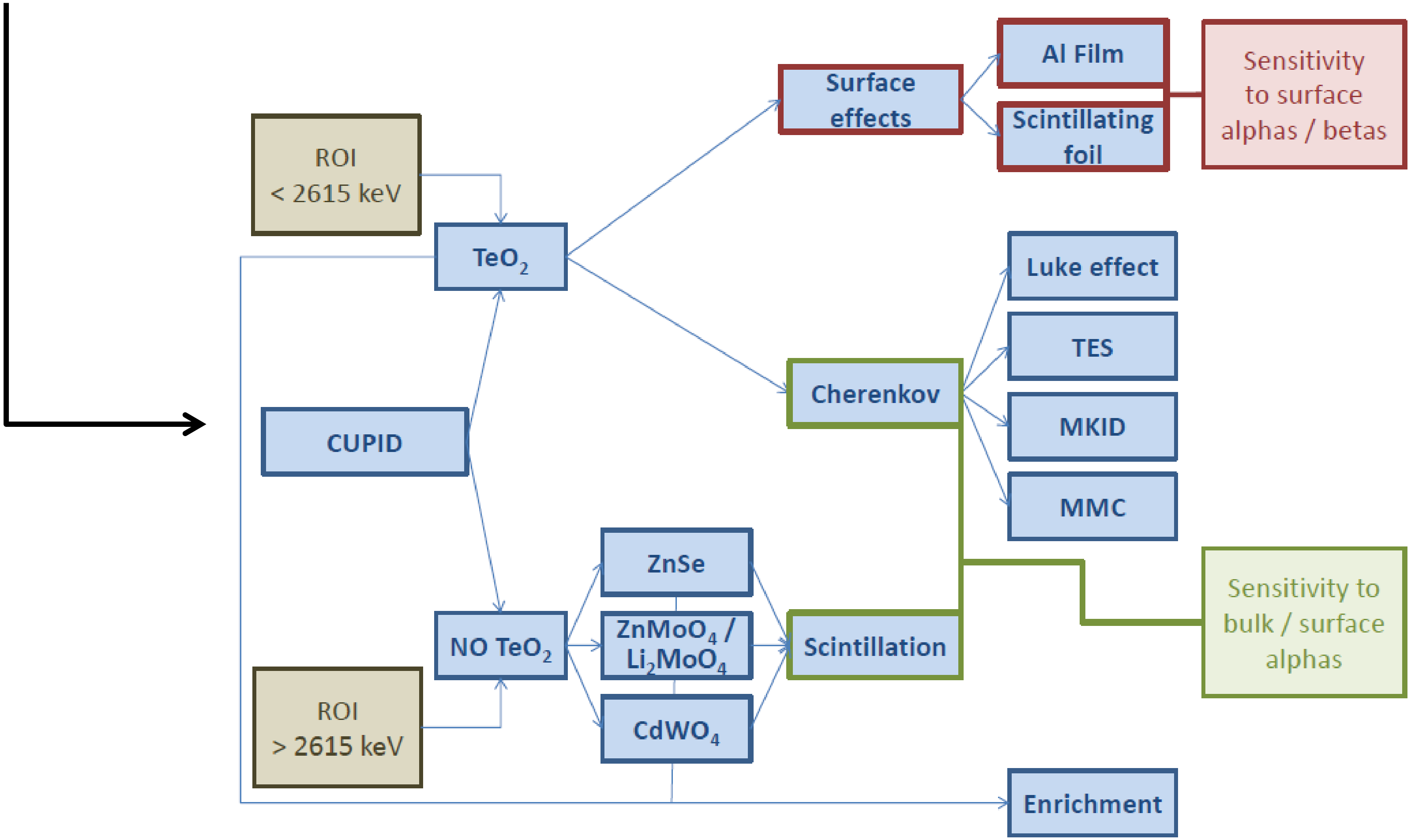
CUPID

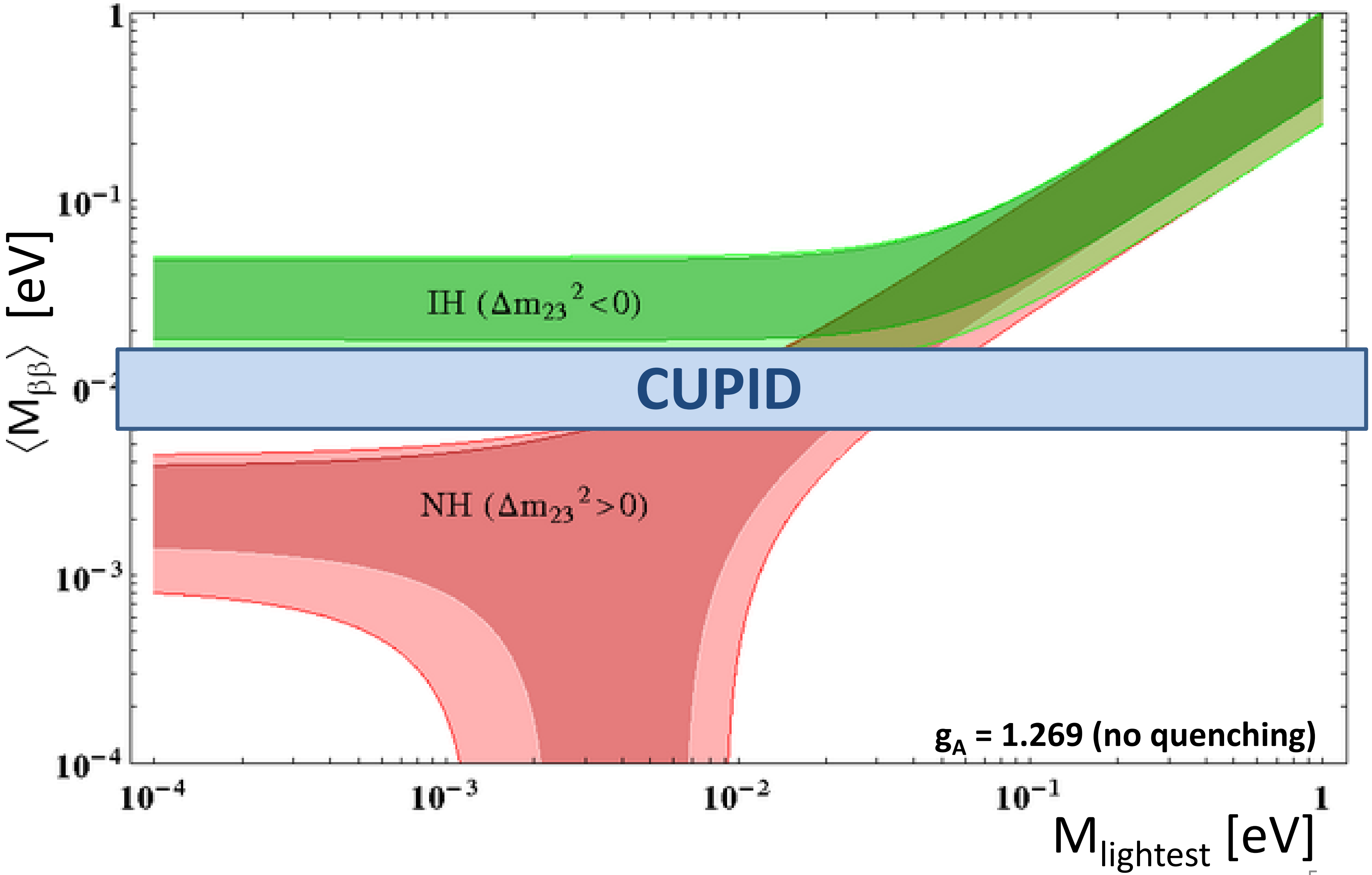
Follow-up to CUORE with background improved by a factor 100

About CUORE
see B. Fujikawa's talk

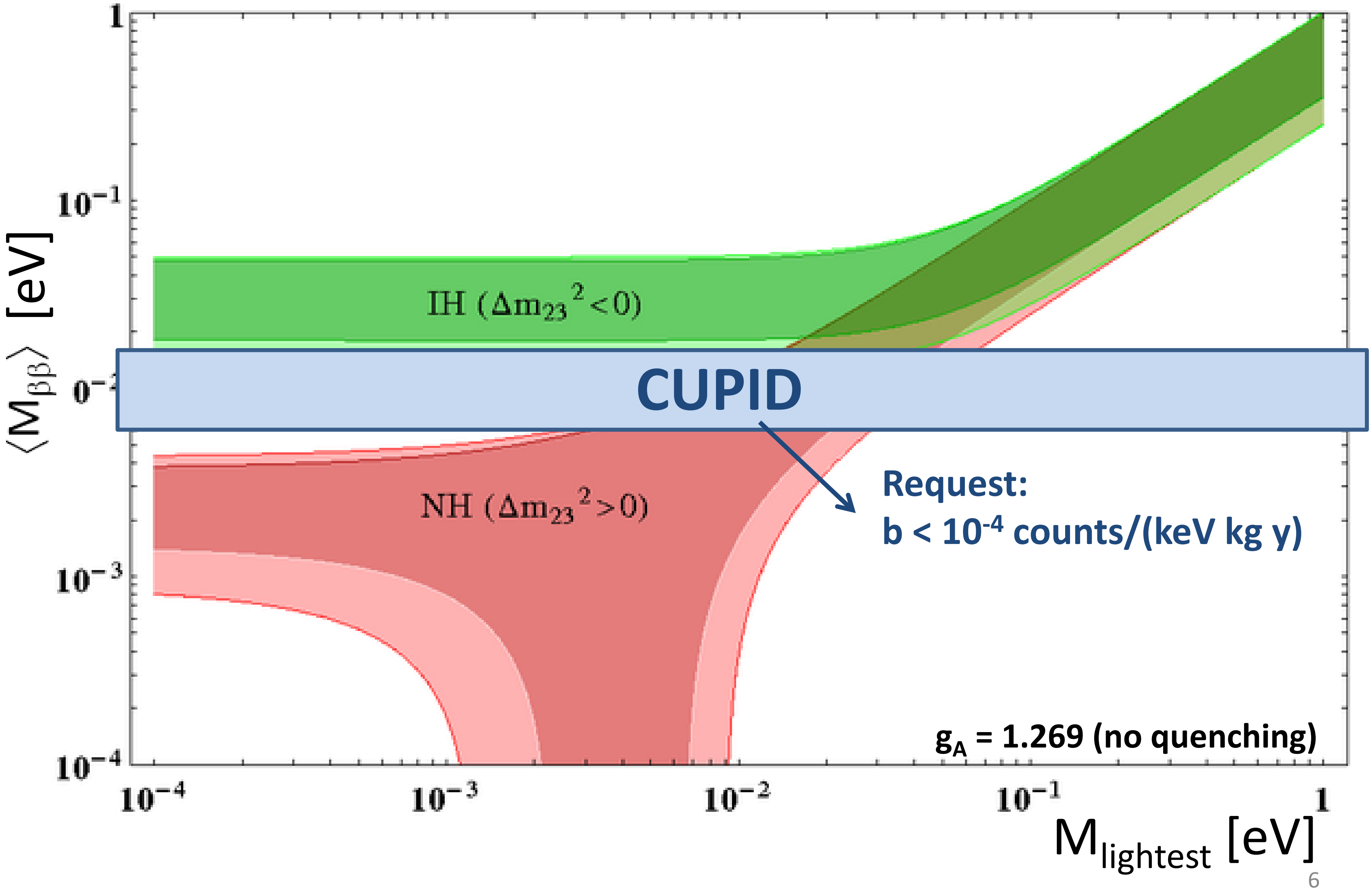
- Keep high energy resolution of CUORE (< 10 keV FWHM)
- Reduce / control background from materials and from muon /neutrons
- Optimize the enrichment-purification-crystallization chain
- **Improve detector technology to get rid of α / surface background**



CUPID goal


1
10^{-1}
10^{-3}
10^{-4}
$\langle M_{\beta\beta} \rangle$ [eV]
IH ($\Delta m_{23}{}^2 < 0$)
CUPID
NH ($\Delta m_{23}{}^2 > 0$)
g_A = 1.269 (no quenching)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$M_{lightest}$ [eV]

CUPID goal



CUPID

Request:
$b < 10^{-4}$ counts/(keV kg y)

$g_A = 1.269$ (no quenching)

CUPID

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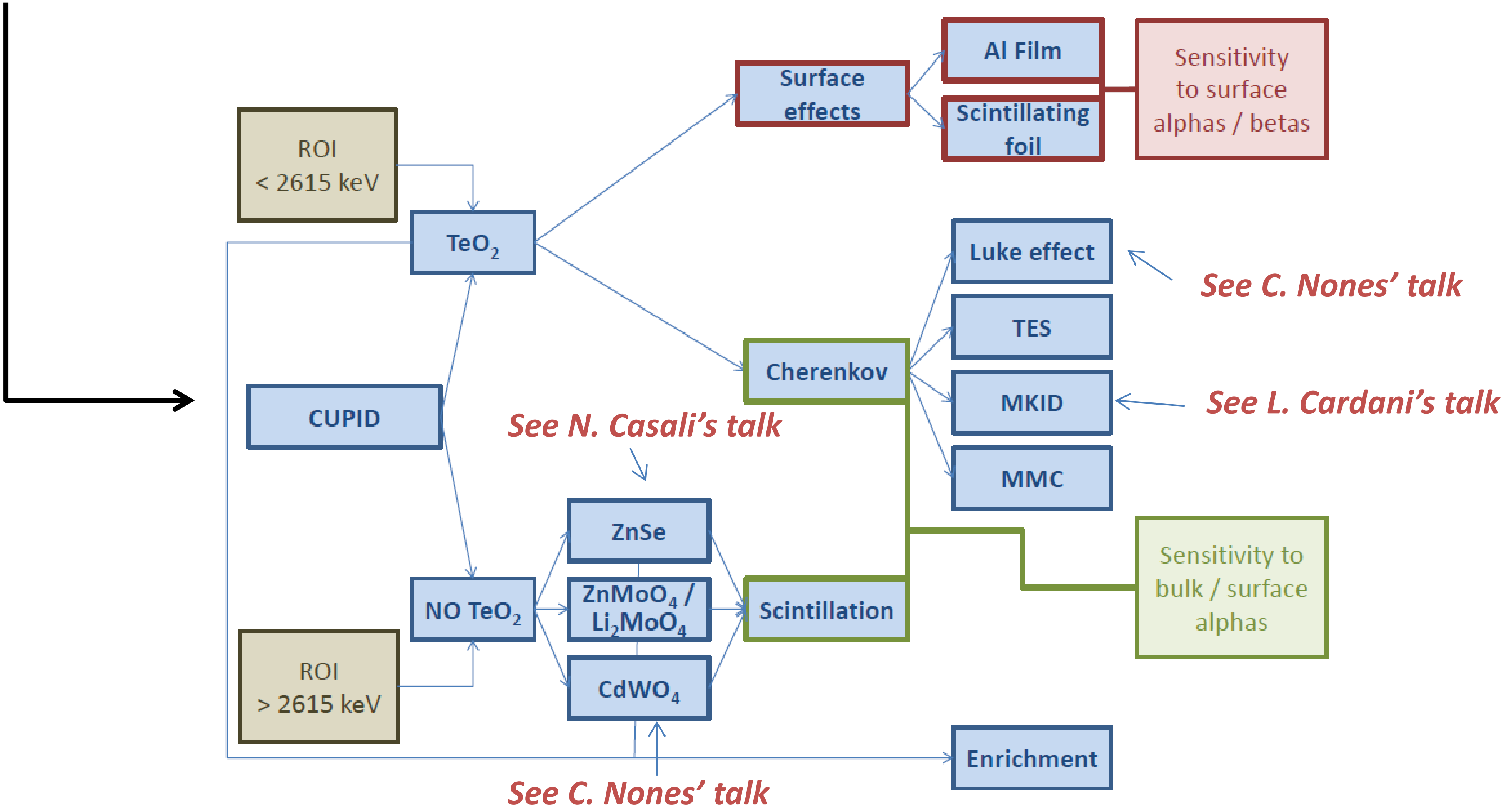

CUPID – pilot experiments

Follow-up to CUORE with background improved by a factor 100

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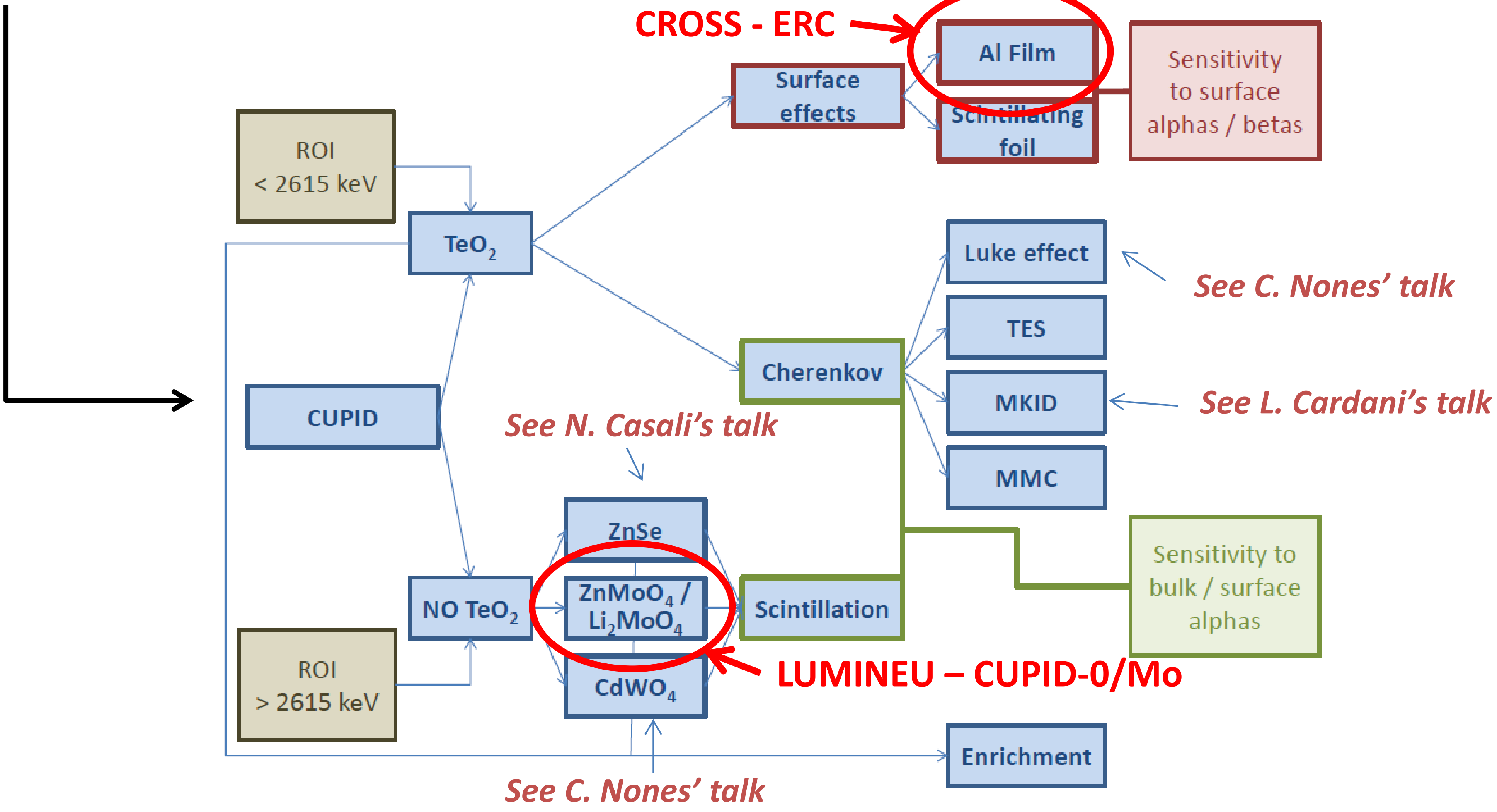

CROSS - ERC

Surface effects

Al Film

Scintillating foil

Sensitivity to surface alphas / betas

ROI < 2615 keV

TeO$_2$

Luke effect

TES

MKID

MMC

See C. Nones' talk

See L. Cardani's talk

Cherenkov

CUPID

See N. Casali's talk

ZnSe

ZnMoO$_4$ / Li$_2$MoO$_4$

CdWO$_4$

NO TeO$_2$

Scintillation

Sensitivity to bulk / surface alphas

LUMINEU – CUPID-0/Mo

ROI > 2615 keV

Enrichment

See C. Nones' talk

CUPID – pilot experiments

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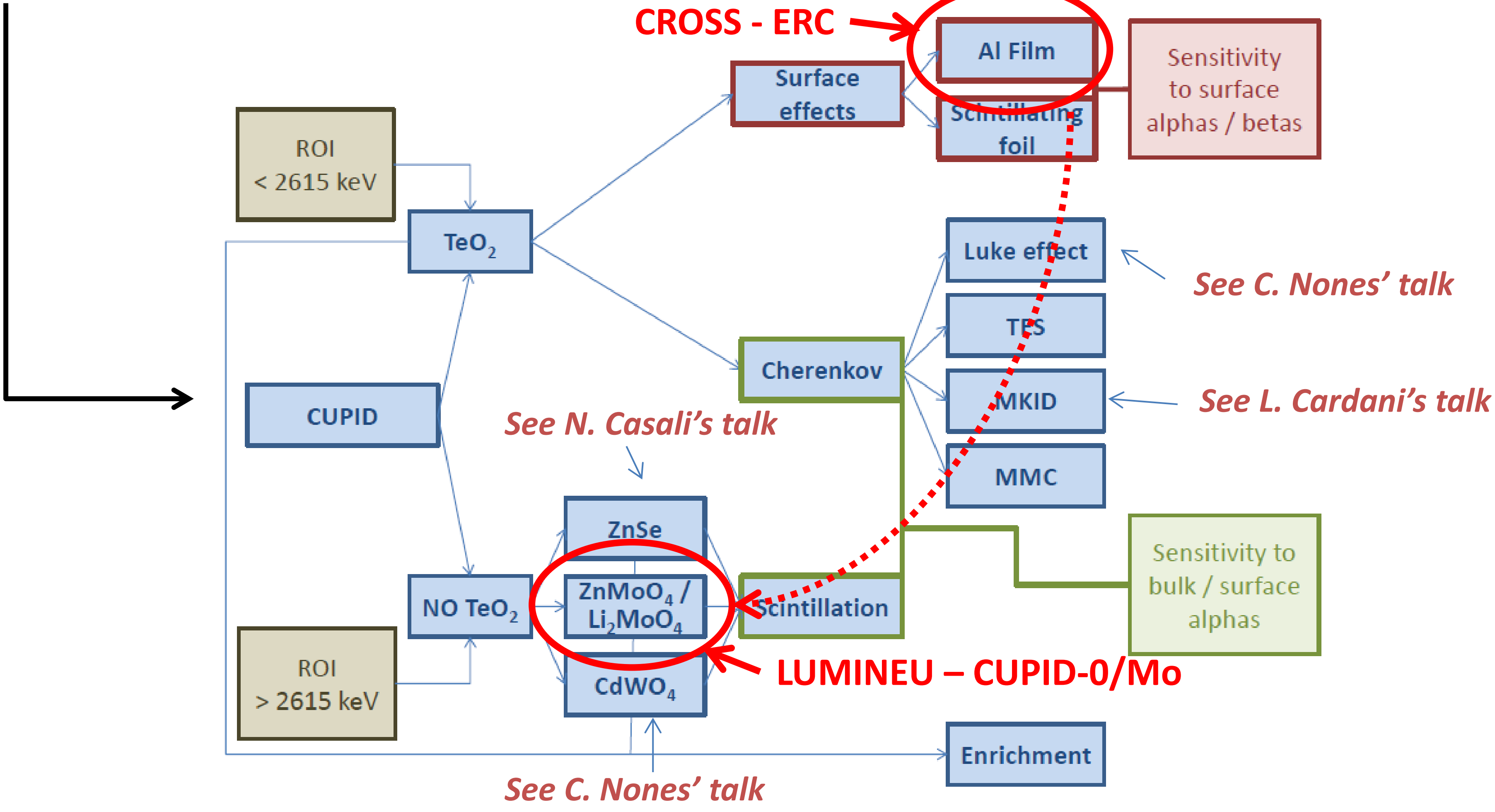
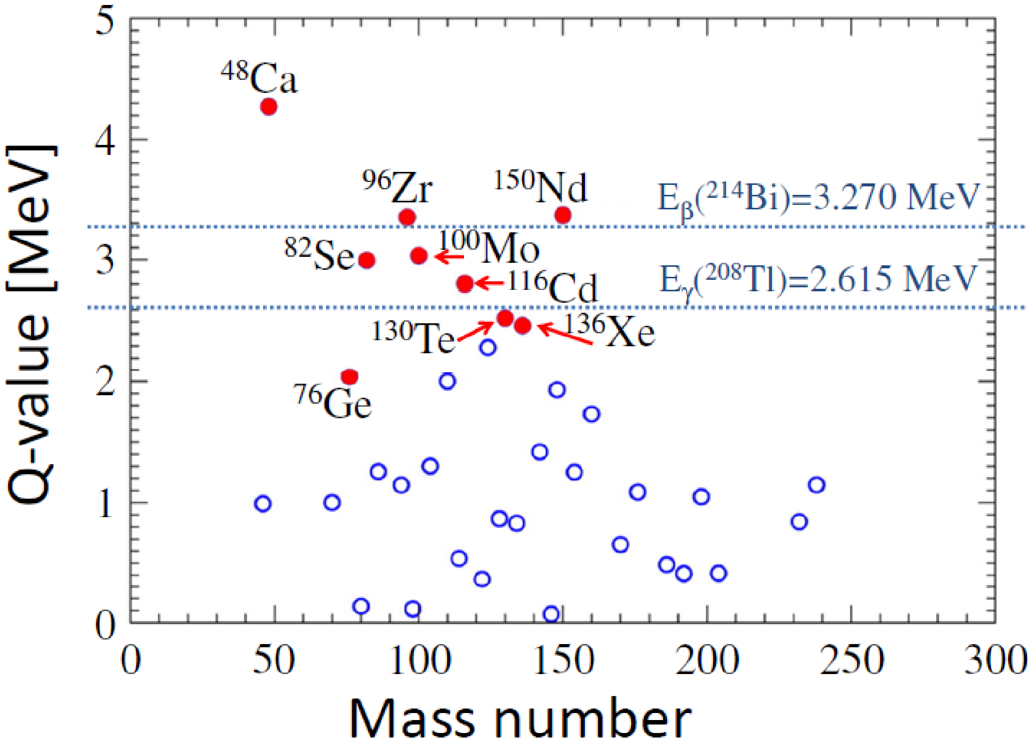


Outline

- CUPID: a next-generation $0\nu2\beta$ bolometric experiment
- The ^{100}Mo way: LUMINEU → CUPID-Mo
- Surface sensitivity: the CROSS project

Interest of ^{100}Mo as a 0ν2β emitter

- $^{100}\mathrm{Mo} \rightarrow {}^{100}\mathrm{Ru} + 2e^{-}$
- $Q_{\beta\beta}$ = **3034 keV**
- I.A.(100) = 9.7 %
- enrichable by gas centrifugation



Caveats (but not showstoppers)

- $T_{1/2}(2\nu) = 7.1 \times 10^{18}$ y – the fastest one in all 0ν2β candidates
- ^{214}Bi line at 3054 keV – B.R. 0.021 % - Compton edge 2818 keV

Viable Mo-based crystals

Crystals succesfully tested so far as scintillating bolometers:

$CdMoO_4$

$PbMoO_4$

$SrMoO_4$

$CaMoO_4$

$ZnMoO_4$

Li_2MoO_4

AMoRE ← *See C. Nones' talk*

Drawbacks:

- Necessity of ^{48}Ca depletion
- Radiopurity (difficult to purify Ca from U, Th, Ra)

LUMINEU

Initial choice (2012): $ZnMoO_4$

First tests on large Li_2MoO_4 crystals: spring 2014

Astropart. Phys. 72, 38 (2016)

Selection of Li_2MoO_4 for a pilot experiment (March 2016)

- Better bolometric performance
- Easy crystallization / excellent quality
- Outstanding radiopurity

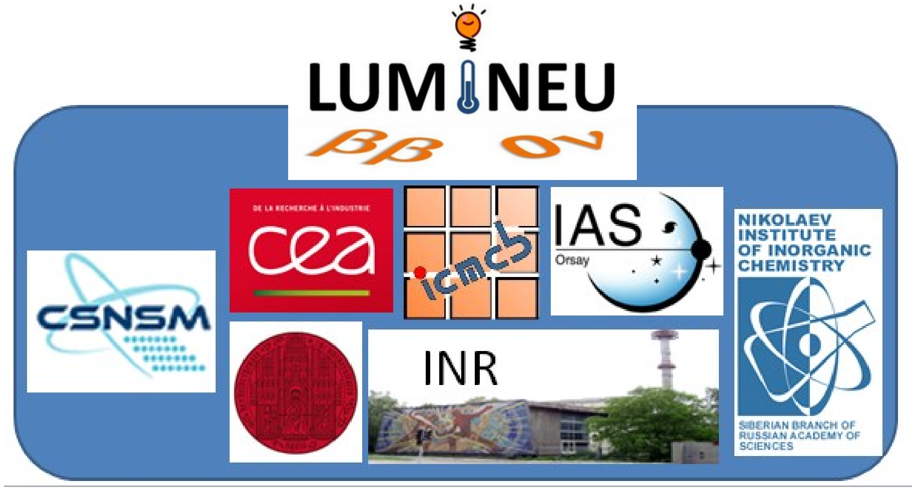
Caveats

- Hygroscopic material
- ^{40}K is natural contaminant
- Lower light yield (~0.8 keV/MeV)

Preparing a ^{100}Mo experiment

Funding / resources from

- **ANR (France) – main fund provider (LUMINEU: 2012-2017)**
- CEA-Saclay – substantial funds / PhD
- CSNSM direction – funds for crystals (« AP interne »)
- EDELWEISS – underground facility, electronics & DAQ
- IN2P3 – dedicated personnel (Post-Doc, technician)
- KINR Kiev – radiopure scintillator know-how, simulation, – enriched ^{100}Mo
- ITEP Moscow – enriched ^{100}Mo
- NIIC Novosibirsk - crystals
- INFN / LUCIFER (LNGS / Rome) – underground facility and manpower for R&D



Extension of the Mo collaboration: CUPID-Mo

New participants

LAL – Orsay, **France**

MIT
UCB and LBL
UCLA

USA

Fudan Shanghai
USTC Hefei

China

MoU in preparation

Li_2MoO_4: purification and crystallization

From 2013 to 2016, **a series of important milestones were achieved**:

- **Mo purification / crystallization protocol** (**NIIC, Novosibirsk**, Russia) (**Mo irrecoverable losses < 4%**)
- Selection of the **appropriate Li_2CO_3 powder** for compound formation
- Successful program to **control internal content of ^{40}K** (from ~60 mBq/kg to < 5 mBq/kg)

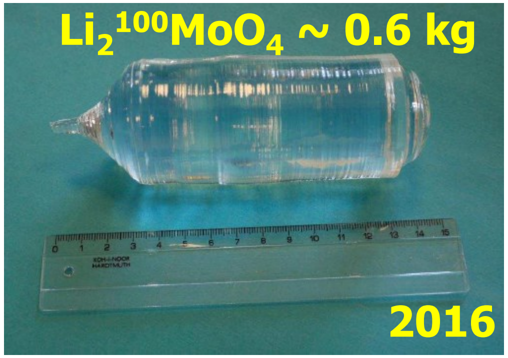
  → Random coincidences: $2\nu2\beta + {}^{40}K \ll 2\nu2\beta + 2\nu2\beta$

- Efficient use of existing **~10 kg of ^{100}Mo (A.I. 96-99%)** (~9 kg to ITEP-Moscow and ~1 kg to KINR-Kiev) (MoU among IN2P3 / INFN / ITEP – February 2015)

  → Natural isotopic abundance: **9.7%**

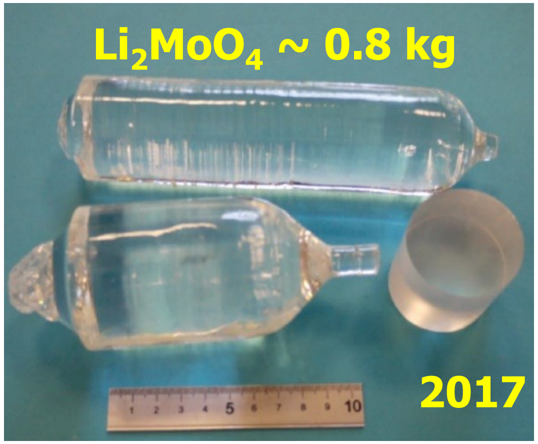
NIM A 729, 856 (2013)
JINST 9, P06004 (2014)
EPJC 74, 3133 (2014)
JINST 10, P05007 (2015)
http://arxiv.org/abs/1704.01758
(submitted to EPJC)

Li_2MoO_4 ~ 0.2-0.5 kg **2015**



$Li_2{}^{100}MoO_4$ ~ 0.6 kg

2016



Li_2MoO_4 ~ 0.8 kg

2017

$Li_2{}^{100}MoO_4$ scintillating bolometers: a mature technology

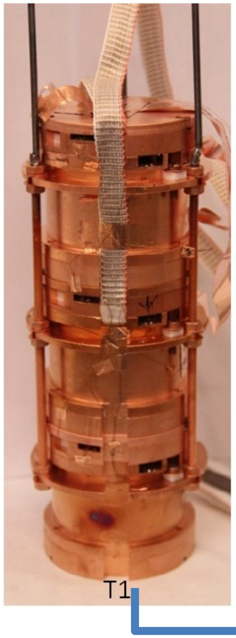
Multiple tests with **natural and enriched crystals** (2014-2017) in LSM and LNGS with outstanding results in terms of: *http://arxiv.org/abs/1704.01758*

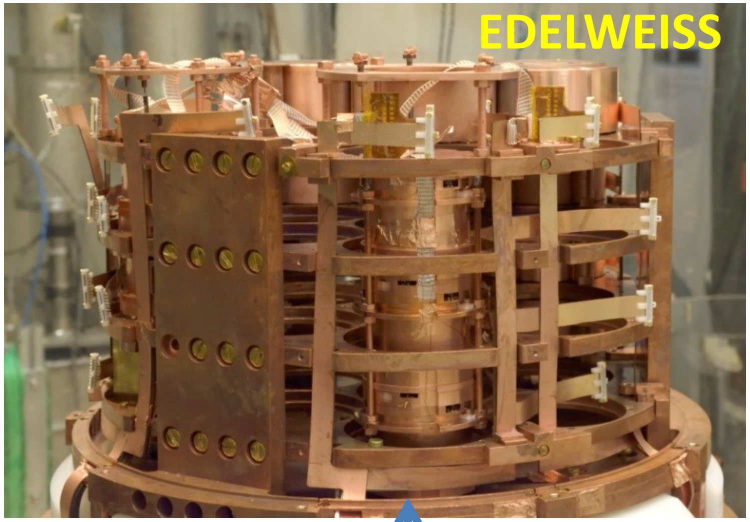
Reproducibility → excellent performance uniformity
Energy resolution → ~ **4-6 keV FWHM** in RoI
α/β separation power → **> 99.9 %**
Internal radiopurity → **< 5 – 10 μBq/kg in ^{232}Th, ^{238}U**; **< 5 mBq/kg in ^{40}K**

→ Compatible with **$b \leq 10^{-4}$ [counts/(keV kg y)]**

Temperature readout

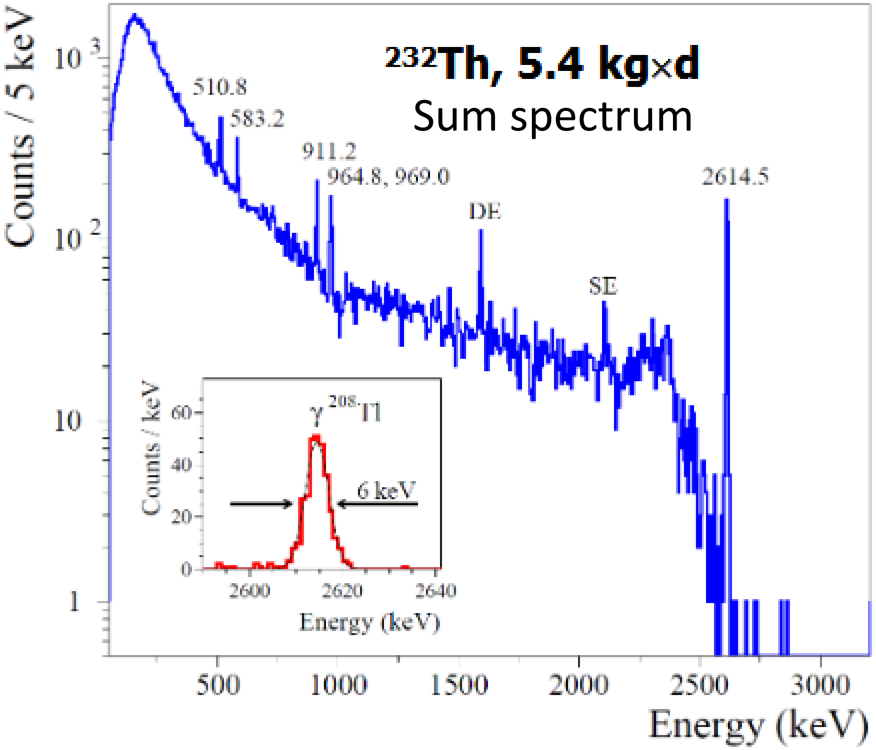
NTD Ge thermistors
+
Room temperature electronics (CUORE style)
or
Cooled JFET (EDELWEISS)

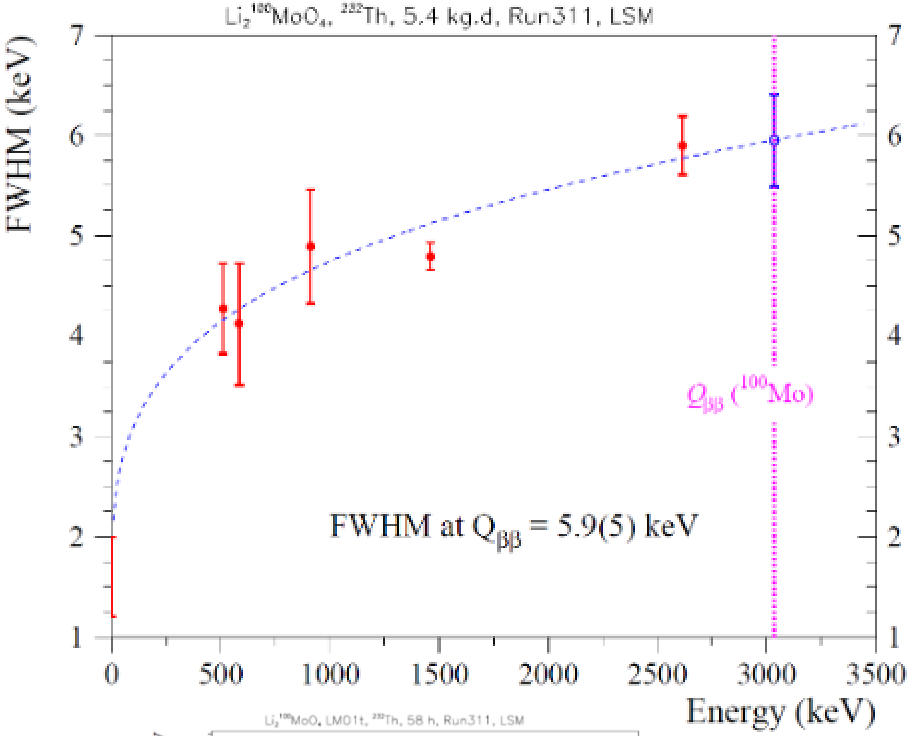




Energy resolution

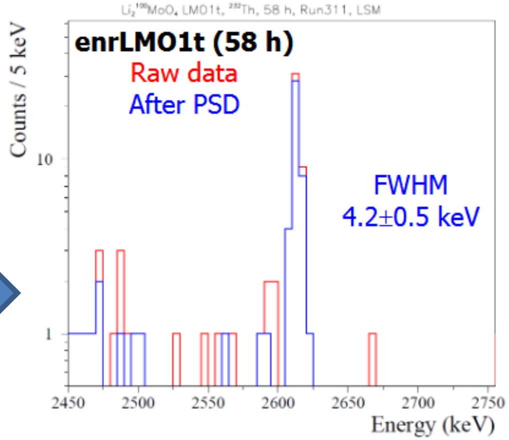
Array of **four** enriched detectors, **M ~ 210 g (**∅=44mm-h=45 mm), **LSM** (EDELWEISS setup)





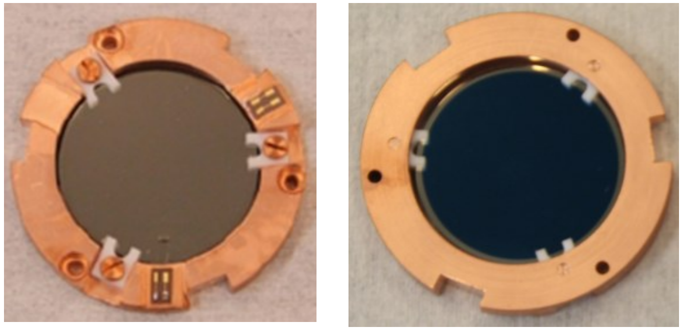
Non-optimal calibration condition:
high pile-up effect

For the detector farther from the source
(low pile-up effect)
better energy resolution (**~4keV FWHM**)

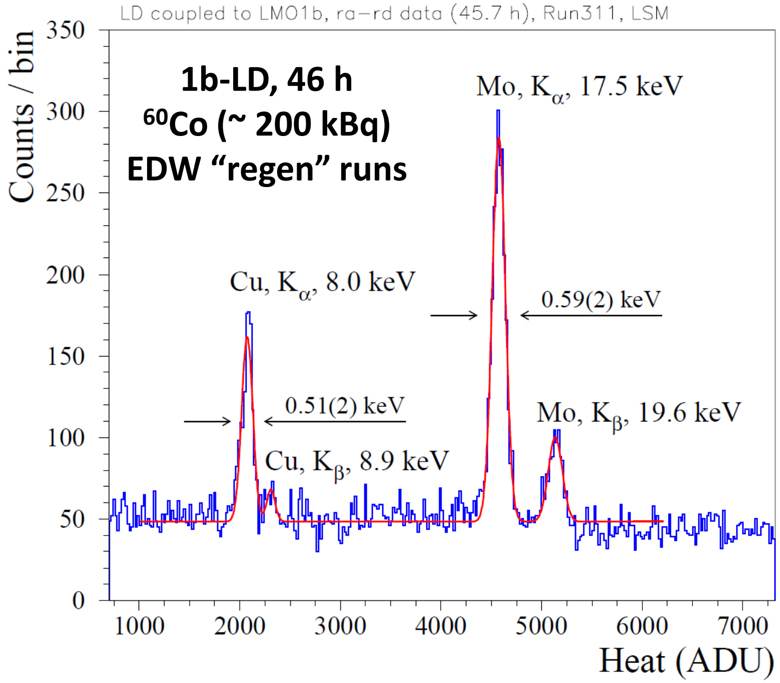


Light detector performance

Light detectors coupled to $Li_2{}^{100}MoO_4$ bolometers



- Electronic-grade pure Ge wafer (UMICORE)
- Diameter: 44 mm – Thickness: 0.17 mm
- Equipped with NTD Ge thermistor (~ 5 – 9 mg)
- Exposed side coated with SiO layer (70 nm) to increase light absorption



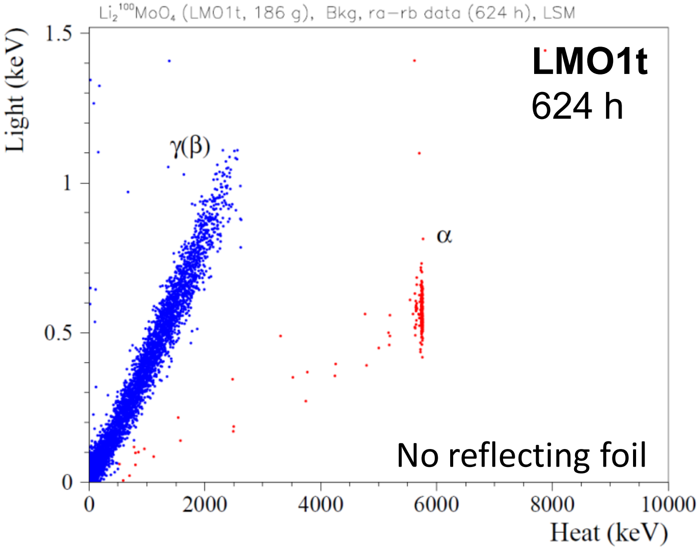
1b-LD, 46 h
^{60}Co (~ 200 kBq)
EDW “regen” runs

Light detector	Condi-tions	Signal μV/keV	$FWHM_{Bsl}$ keV
1b-LD	optimal over bias	1.3 0.7	0.08 0.11
1t-LD	optimal over bias	2.4 1.2	 0.07
2b-LD	optimal over bias	1.5 1.1	0.11 0.12
2t-LD	optimal over bias	1.1 0.85	0.09 0.11

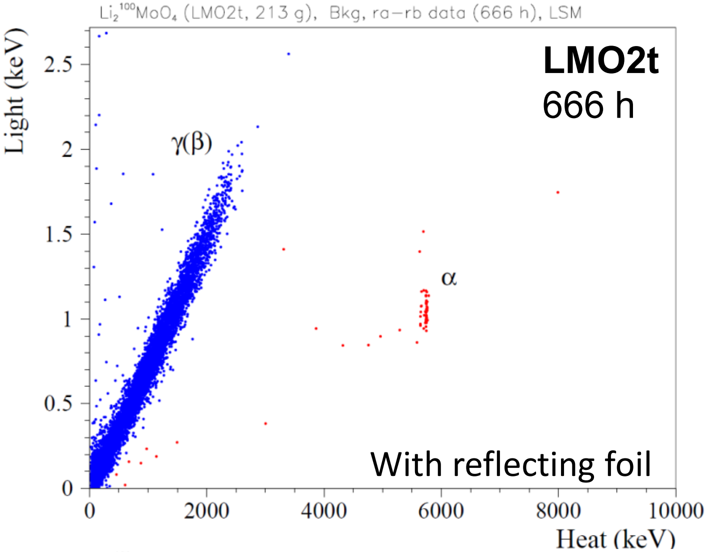
Satisfactory performance (**~100 eV FWHM** baseline) – Good reproducibility

α rejection

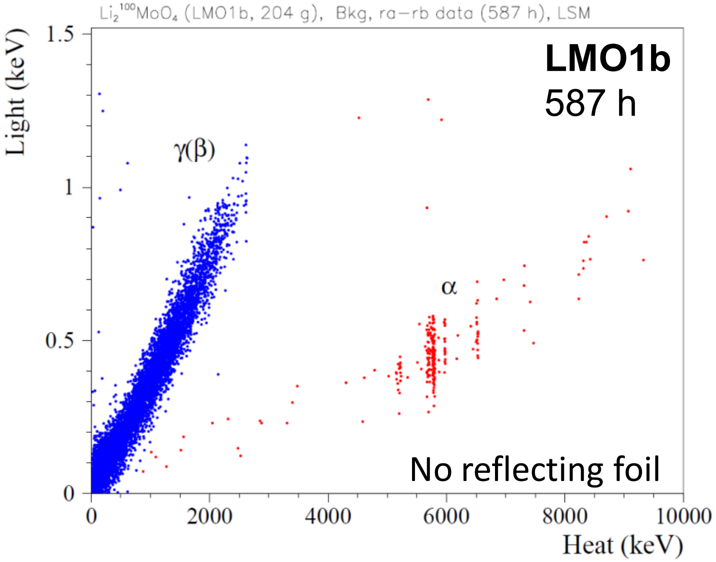
99.9% α rejection with **> 99 % β acceptance** (LY ~ 0.4-0.7 keV/MeV)



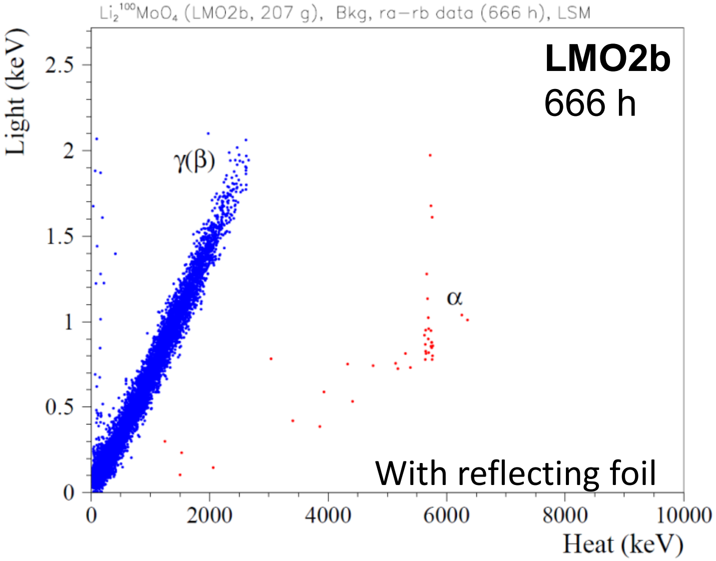
Li$_2$^{100}MoO$_4$ (LMO1t, 186 g), Bkg, ra−rb data (624 h), LSM



Li$_2$^{100}MoO$_4$ (LMO2t, 213 g), Bkg, ra−rb data (666 h), LSM

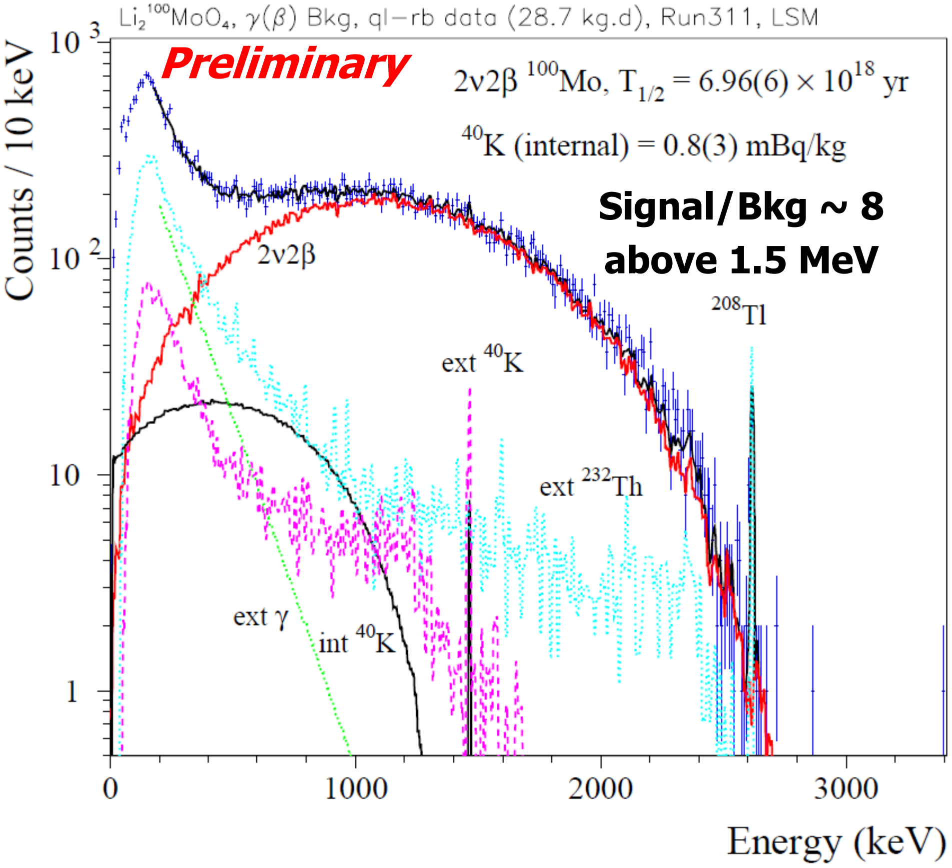


Li$_2$^{100}MoO$_4$ (LMO1b, 204 g), Bkg, ra−rb data (587 h), LSM



Li$_2$^{100}MoO$_4$ (LMO2b, 207 g), Bkg, ra−rb data (666 h), LSM

Investigation of ^{100}Mo 2ν2β decay



Investigation of ^{100}Mo 2ν2β:

- Exposure: 28 kg×d
- Enrichment: 96.9% of ^{100}Mo
- eff_{PSD}: 97%
- Fit: 160-2650 keV ⇒
  Effect = 24320±229 decays

⇓

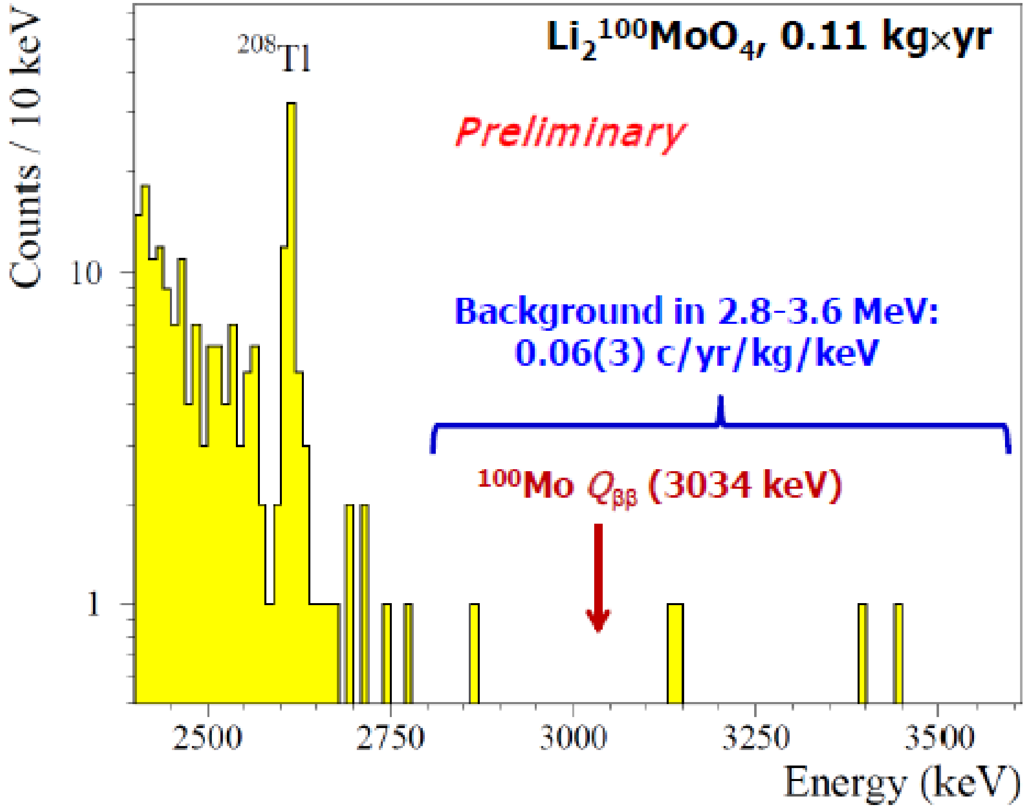
$T_{1/2} = [6.96 \pm 0.06] \times 10^{18}$ yr

One of the most precise ^{100}Mo half-life values

$T_{1/2}$ [10^{18} yr]	Exposure	Experiment	Ref.
7.11±0.02(stat)±0.54(syst)	7.37 kg×yr	NEMO-3	PRL 95 (2005) 182302
7.15±0.37(stat)±0.66(syst)	0.08 kg×yr	LUCIFER	JPG 41 (2014) 075204
6.90±0.15(stat)±0.42(syst)	0.03 kg×yr	LUMINEU	arXiv:1704.01758
6.96±0.06(stat)±0.35(syst)	0.08 kg×yr	LUMINEU	Presented here

Investigation of ^{100}Mo 0ν2β decay

We performed **0ν2β search** joining the two runs involving enriched crystals at LSM



Sensitivity to ^{100}Mo 0ν2β:

- $Q_{\beta\beta}(^{100}Mo)$ = 3034 keV
- ROI = 10 keV window @ $Q_{\beta\beta}$
- $eff_{0\nu2\beta}$ = 73% in ROI
- eff_{PSD} = 97%
- Enrichment = 96.9% of ^{100}Mo
- Exposure = 39 kg×d
- BI: 0.06 cnts/yr/kg/keV
  ⇒ Bkg: 0.064 counts
- 90% CL sensitivity (by F.-C.):
  lim*S*: 2.49 counts

⇓

lim $T_{1/2}$ = 0.7x10^{23} y @ 90% C.L.

lim<$m_{\beta\beta}$> = 1.2-2.1 eV

NEMO-3 (34.3 kg×yr):

$T_{1/2} \geq 1.1 \times 10^{24}$ yr @ 90% CL

PRD 92 (2015) 072011

Possible origin of the background:

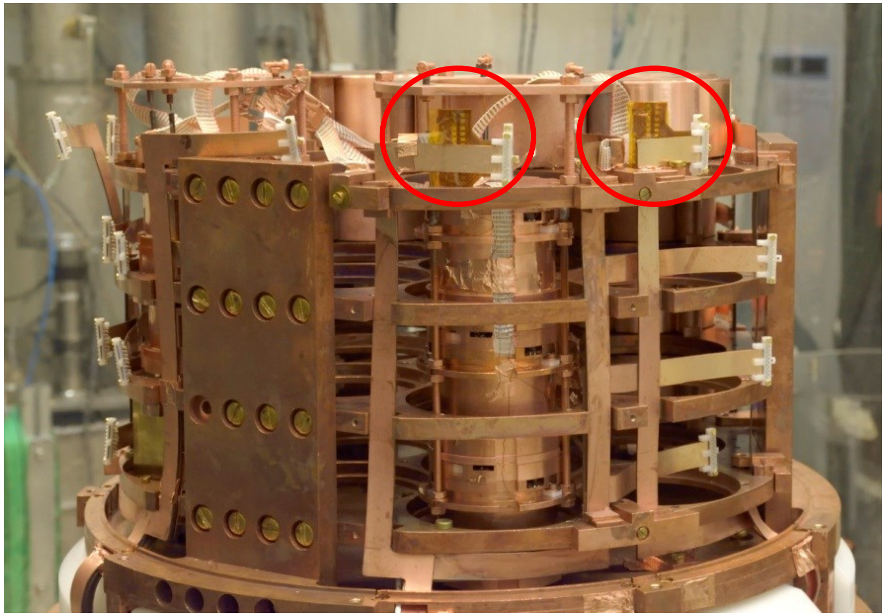
- 2615+583 keV from close Th contamination [^{208}Tl peak 40x wrt Cuoricino]
- Multiple high energy γ's induced by muons [no coincidence study in our analysis]

Measures to mitigate the background

Remove known Th sources in the vicinity of the detectors

- Connectors and cables belonging to the EDELWEISS setup

Substantial simplification of the cabling system



Activate coincidences among detectors and with the muon veto

- EDELWEISS data on γ's above 2.6 MeV show a substantial contribution to background coming from events in coincidence

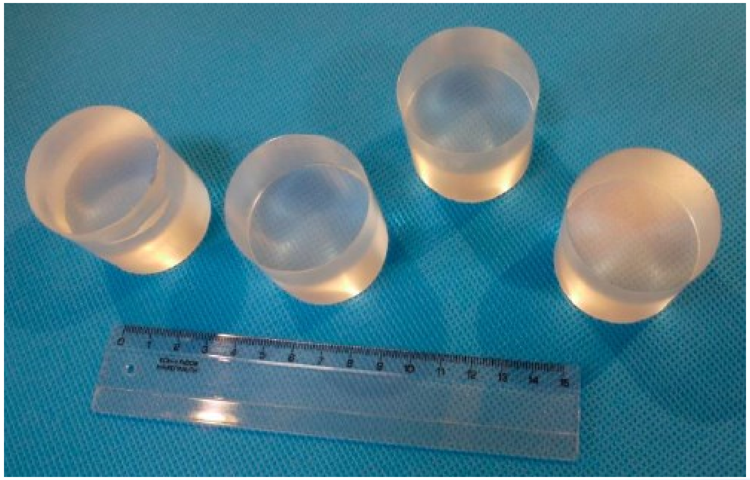
Goal: background reduction by one order of magnitude in the β band above 2.6 MeV → **$b \sim 10^{-3}$ counts/(keV kg y)**

Next pilot experiments

CUPID-Mo Phase I (20 crystals):

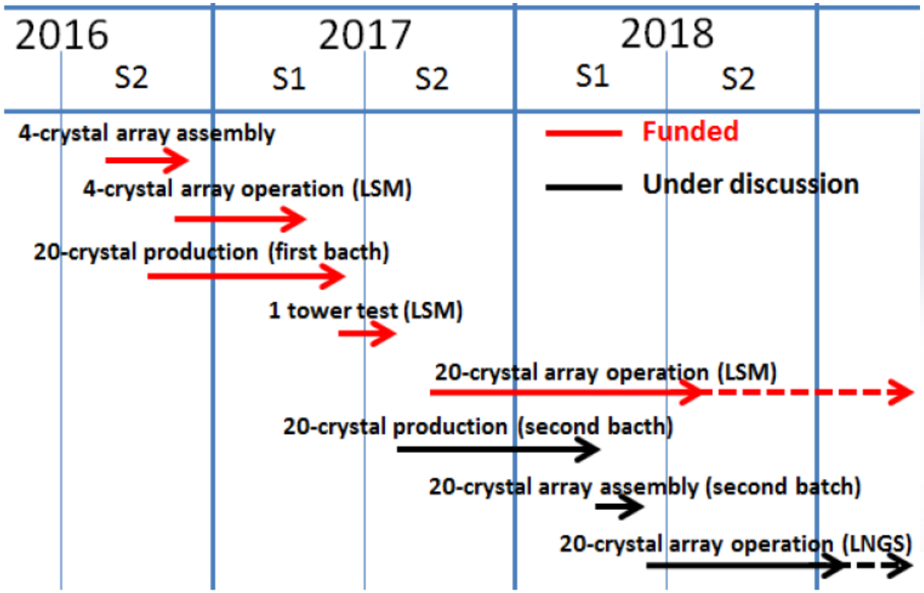
- **20 ^{100}Mo-enriched (97%) Li_2MoO_4 presently in France** (∅44×45 mm, 0.21 kg each; 4.18 kg total) ⇒ 2.34 kg of ^{100}Mo (1.37×10^{25} ^{100}Mo nuclei)
- **20 Ge light detectors** (∅44×0.175 mm)+SiO
- **EDELWEISS set-up** @ LSM (France)

START DATA TAKING: December 2017



CUPID-Mo Phase II (20+20 - or more - crystals):

- At least additional **20 $Li_2{}^{100}MoO_4$**
- **CUPID-0 set-up in hall A** @ LNGS (Italy) (under discussion)



2016 | 2017 | 2018

S2 | S1 | S2 | S1 | S2

4-crystal array assembly

4-crystal array operation (LSM)

20-crystal production (first bacth)

1 tower test (LSM)

20-crystal array operation (LSM)

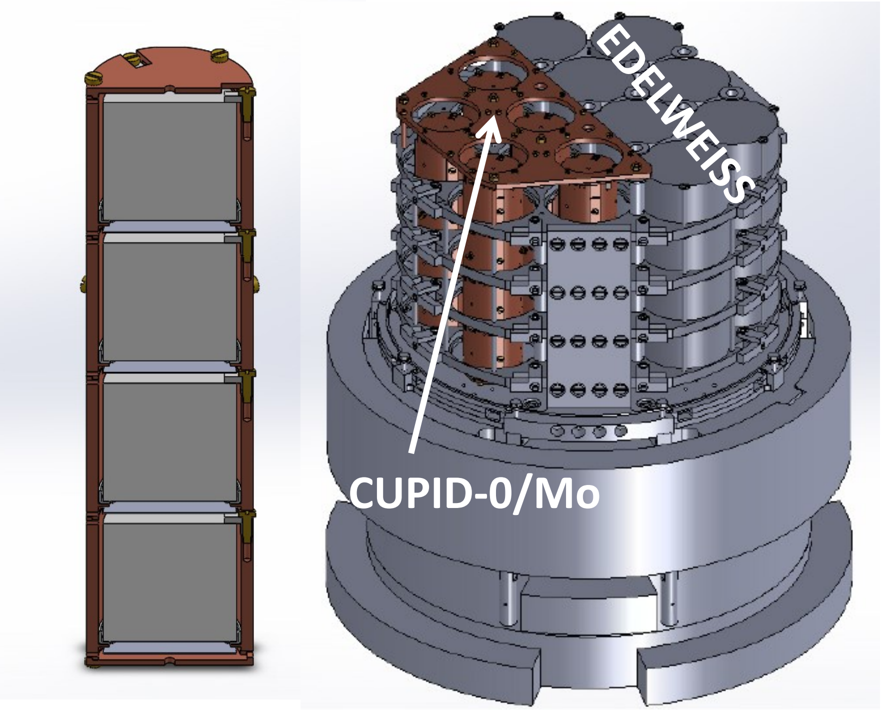
20-crystal production (second bacth)

20-crystal array assembly (second batch)

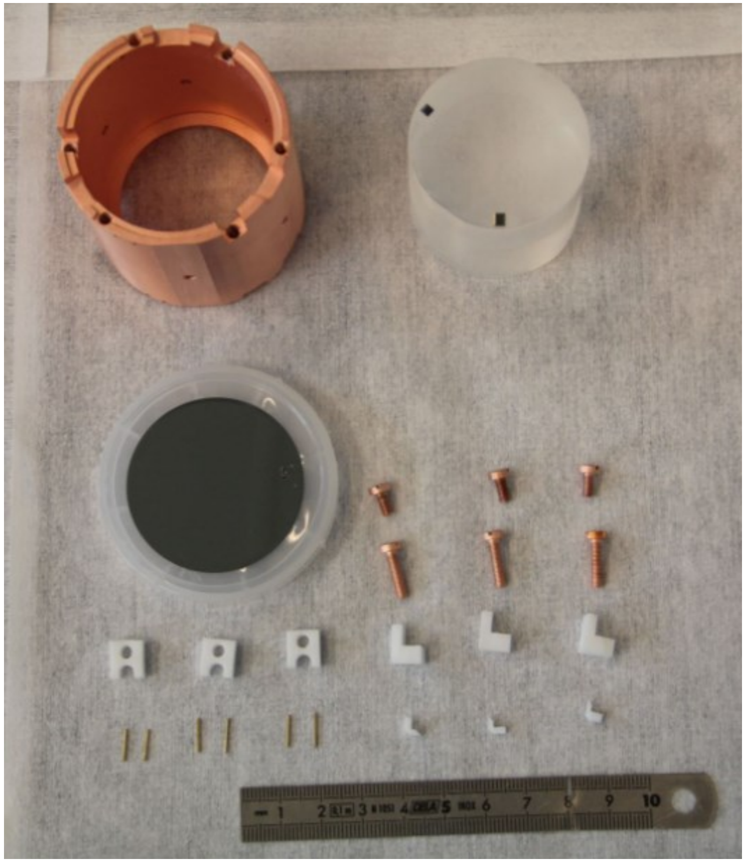
20-crystal array operation (LNGS)

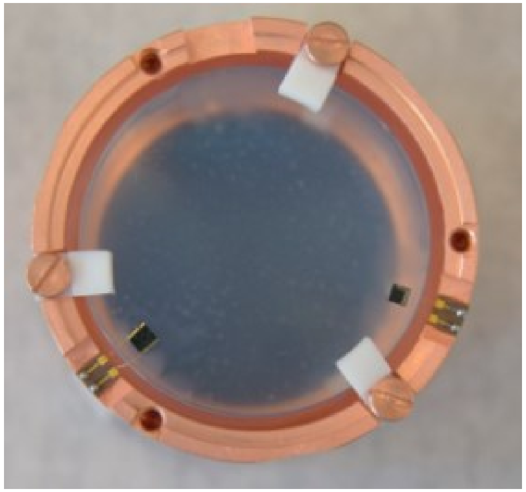
Funded

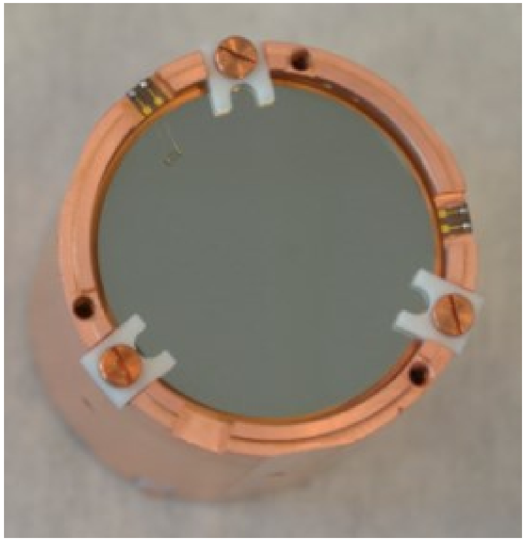
Under discussion



Tower structure in CUPID-Mo







Sensitivity of CUPID-Mo

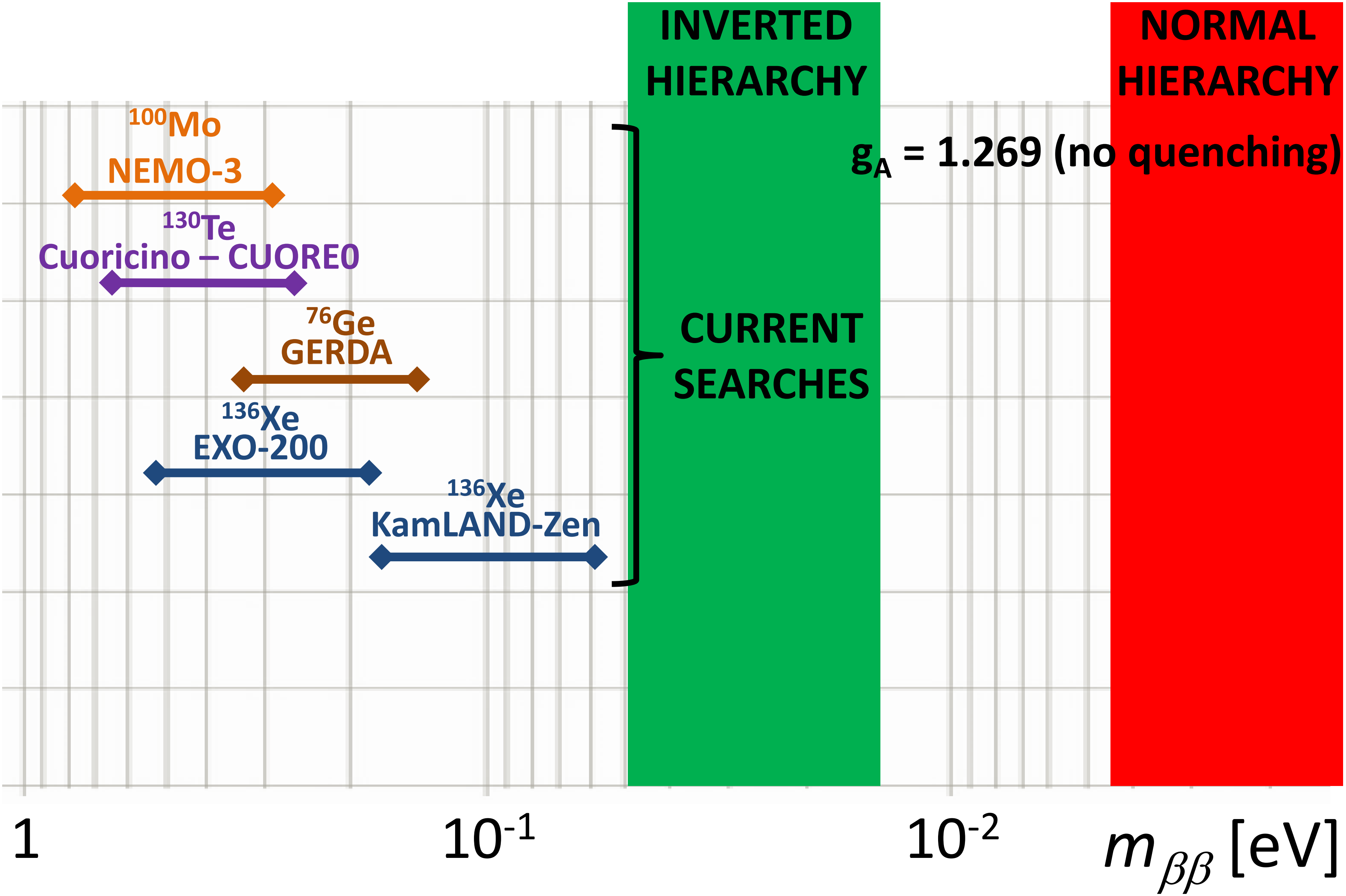
The primary aim of CUPID-0/Mo is to demonstrate **the maturity of the $Li_2{}^{100}MoO4$ technology** in terms of crystal purity, bolometric performance, active methods for background rejection and reproducibility of all the relevant parameters. However, **the physics reach of CUPID-Mo is quite interesting**.

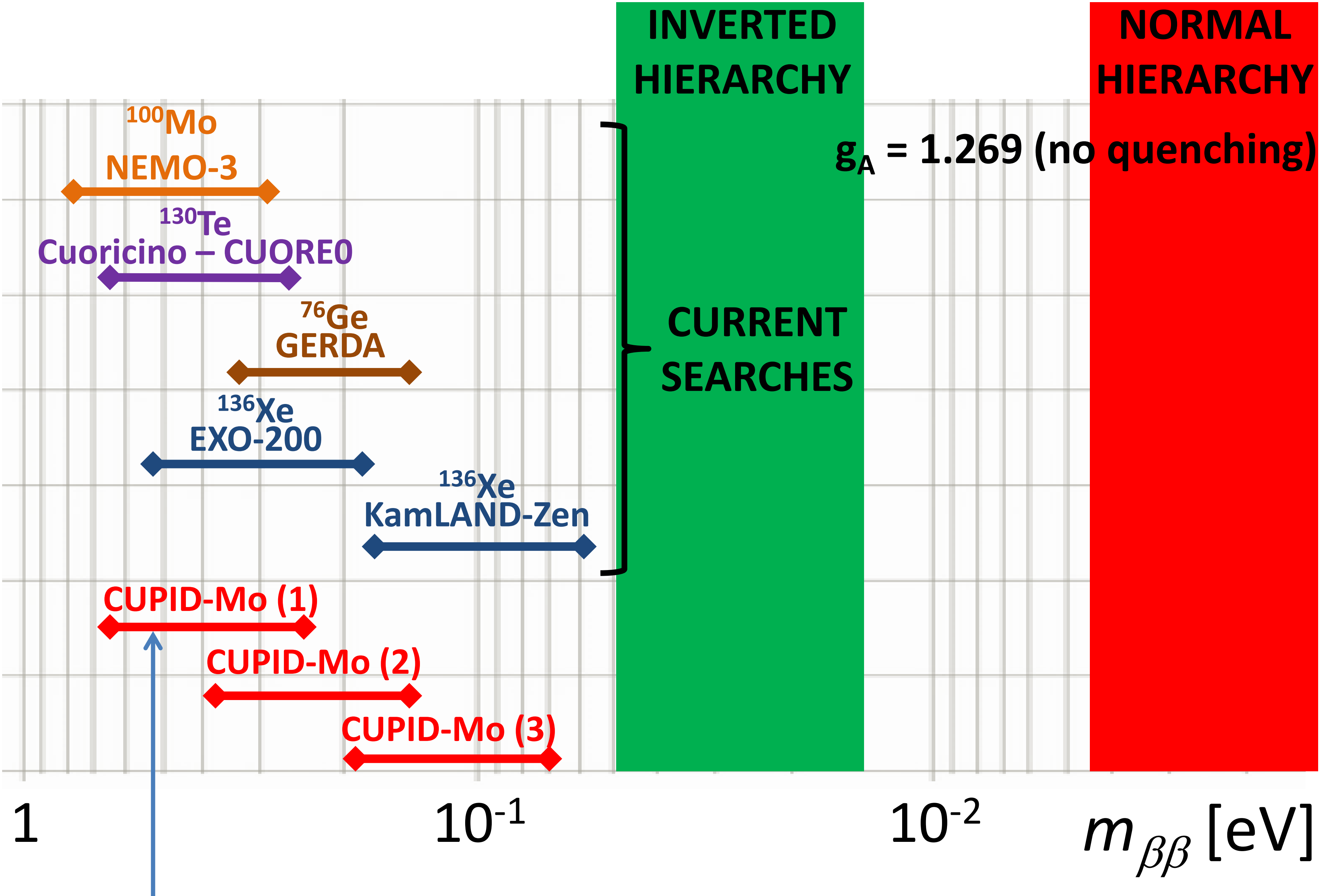
In calculating the sensitivity (90% C.L.), we will assume:

- **$b = 1 \times 10^{-3}$ counts/(keV kg y)**
- **8 keV** energy window
- **78%** efficiency

Configuration	Half life limit [90% c.l.]	$M_{\beta\beta}$ [meV]
(1) 20 crystal [20×0.5 cr.×y]	1.4×10^{24}	240 – 670
(2) 20 crystal [20×1.5 cr.×y]	4.2×10^{24}	140 – 390
(3) 40 crystal [40×3 cr.×y]	1.7×10^{25}	70 – 200

First two options sensitivities substantially unchanged by
$b = 1 \times 10^{-2}$ counts/(keV kg y)

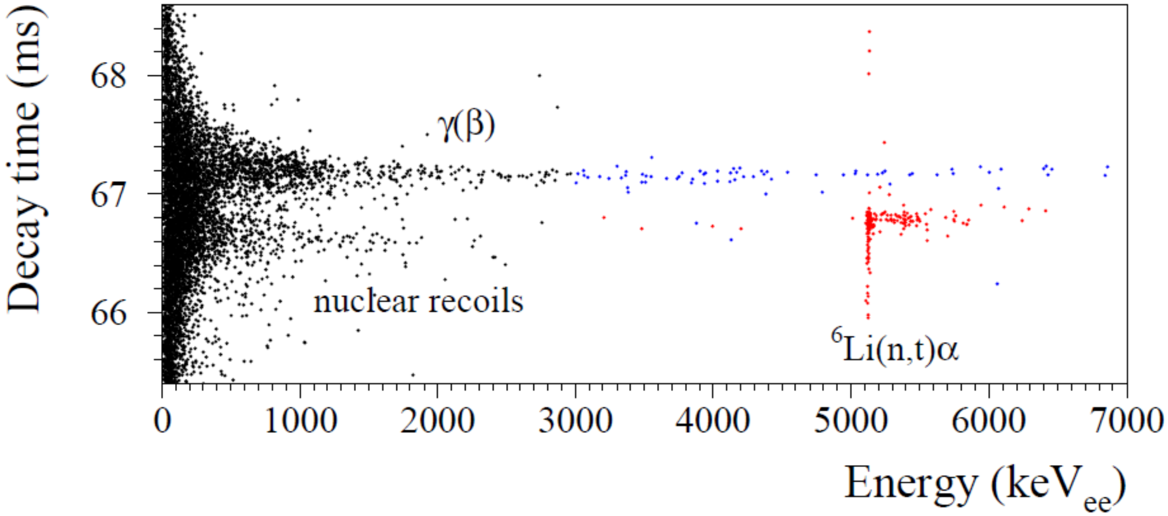

INVERTED HIERARCHY
NORMAL HIERARCHY
g_A = 1.269 (no quenching)
^{100}Mo
NEMO-3
^{130}Te
Cuoricino – CUORE0
^{76}Ge
GERDA
^{136}Xe
EXO-200
^{136}Xe
KamLAND-Zen
CURRENT SEARCHES
1
10^{-1}
10^{-2}
$m_{\beta\beta}$ [eV]

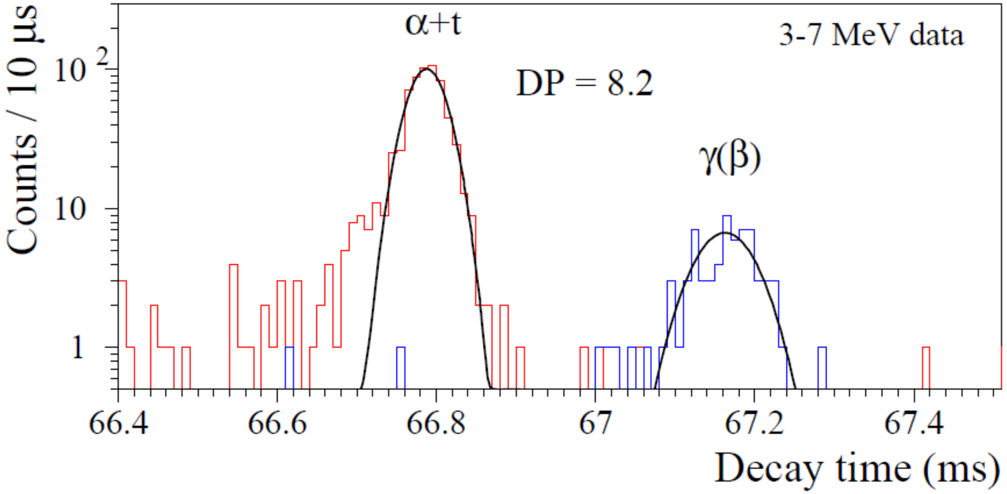


This can be achieved in **2018 in only 6 months !**

α/β separation without light detectors

We performed a specific study on a natural 150 g Li_2MoO_4 detector operated in LNGS.
A calibration with an AmBe source provided enough statistics in the β and α-like bands





Possible configurations in CUPID

Single element	Number of elements	Isotope mass [kg]	Number of ^{100}Mo nuclei
∅50×50 mm – 300 g	1260	213	1.2×10^{27}
∅60×40 mm – 350 g	1092		
45×45×55 mm – 340 g	1110		

If PSD works for α particle rejection (as preliminary results seem to demonstrate), a very simple configuration **without light detectors** can be envisaged.

If light detectors are kept, the available volume for the source will be reduced by ~10%.

Background [counts/(keV kg y)]	Number of BKG counts [8 keV, 10 y]	Count limit [90% c.l.]	Half life limit [90% c.l.]	$M_{\beta\beta}$ [meV]
1×10^{-4}	3	4.4	1.4×10^{27}	7.3 – 21
2×10^{-5}	0.6	2.9	2.2×10^{27}	5.9 – 17

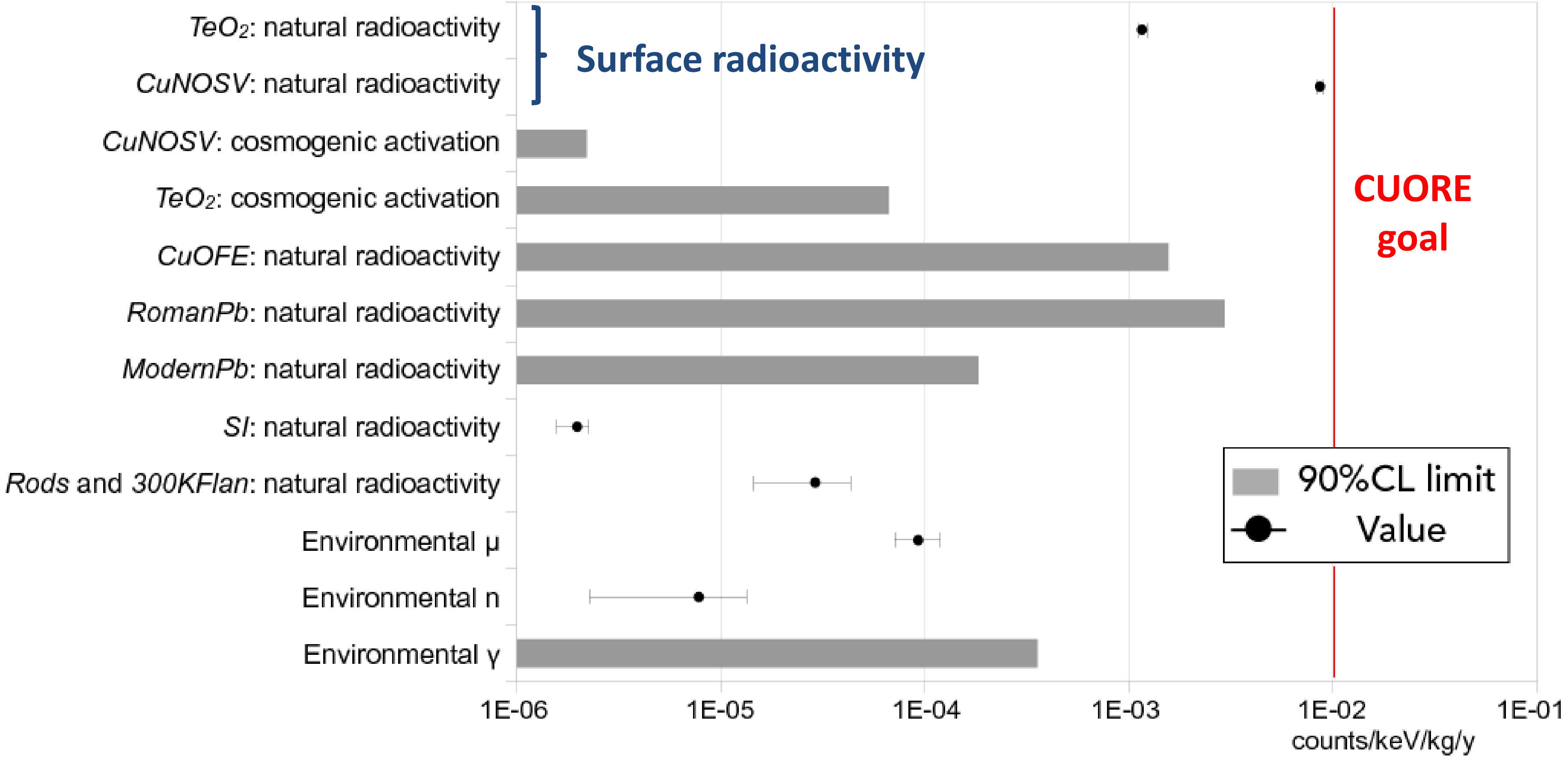
Outline

- CUPID: a next-generation $0\nu2\beta$ bolometric experiment
- The ^{100}Mo way: LUMINEU → CUPID-Mo
- Surface sensitivity: the CROSS project

Current role of surface radioactivity

CUORE background model

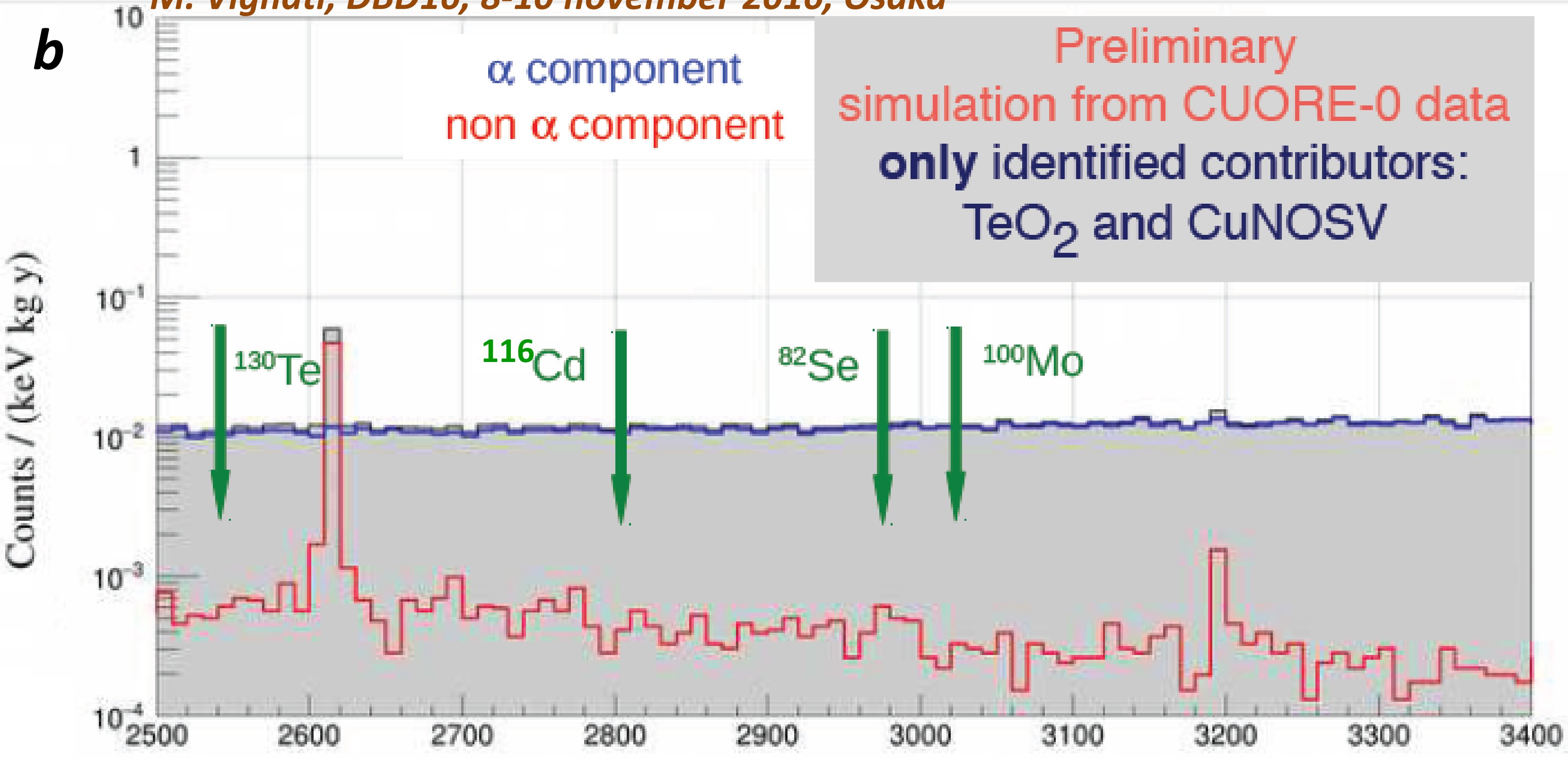
arXiv:1704.08970 [physics.ins-det]



b

Eliminating surface α's is enough?

M. Vignati, DBD16, 8-10 november 2016, Osaka

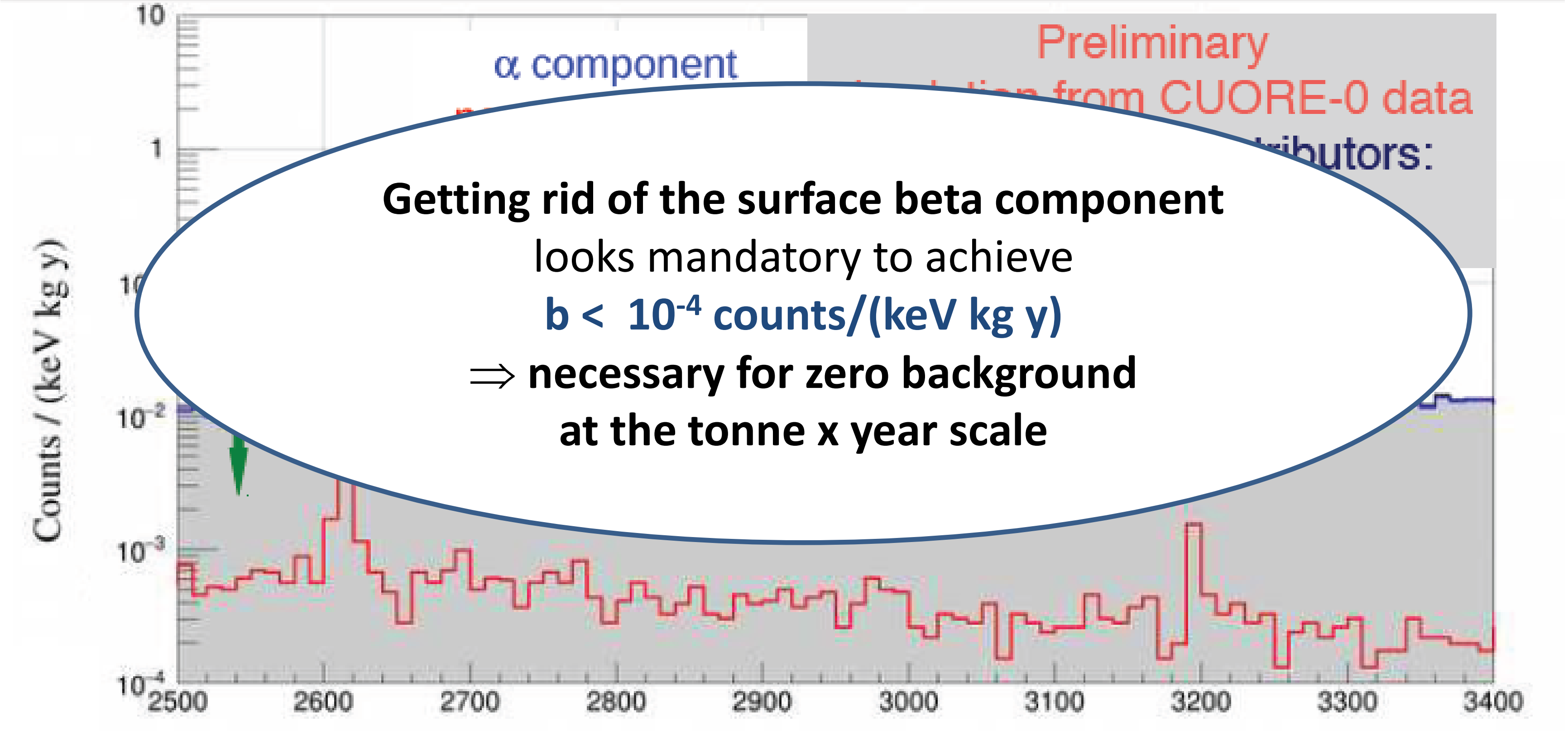


The residual background after alpha rejection comes mainly from **high Q-value beta emitters from surface contamination**

^{226}Ra – generates **^{214}Bi** – 3.27 MeV endpoint

^{228}Th – generates **^{208}Tl** – 5.00 MeV endpoint

Eliminating surface α's is enough?



Getting rid of the surface beta component
looks mandatory to achieve
$b < 10^{-4}$ counts/(keV kg y)
⇒ **necessary for zero background**
at the tonne x year scale

The residual background after alpha rejection comes mainly from **high Q-value beta emitters from surface contamination**

^{226}Ra – generates **^{214}Bi** – 3.27 MeV endpoint

^{228}Th – generates **^{208}Tl** – 5.00 MeV endpoint

CROSS: new advancement opportunity

ERC advanced grant CROSS

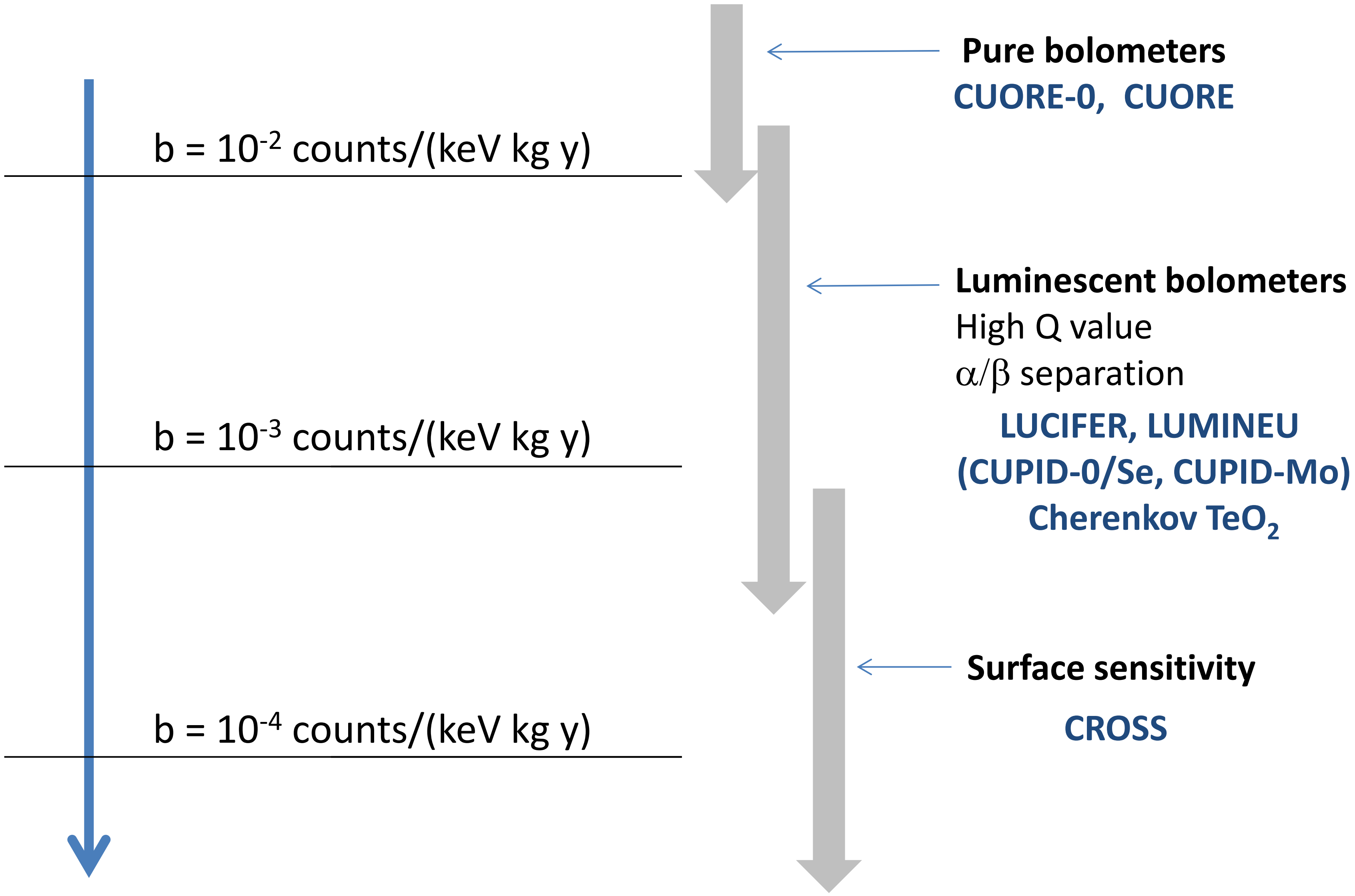
Cryogenic **R**are-event **O**bservatory with **S**urface **S**ensitivity

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

- **Core of the project** (high risk / high gain)
  Background rejection through **pulse shape discrimination**
  - **Surface sensitivity** through **superconductive Al film coating**
  - **Fast NbSi high-impedance TES** to replace / complement NTDs

  → **get rid of light detectors**
- Complete crystallization of available **^{100}Mo (10 kg)** in Li_2MoO_4 elements
- Purchase / crystallize **^{130}Te (up to 17 kg)** in TeO_2 elements
- Run demonstrator in a dedicated cryostat (LSC – Spain)

The evolution of the bolometric technique



Pure bolometers

CUORE-0, CUORE

b = 10^{-2} counts/(keV kg y)

Luminescent bolometers

High Q value

α/β separation

LUCIFER, LUMINEU

(CUPID-0/Se, CUPID-Mo)

Cherenkov TeO_2

b = 10^{-3} counts/(keV kg y)

Surface sensitivity

CROSS

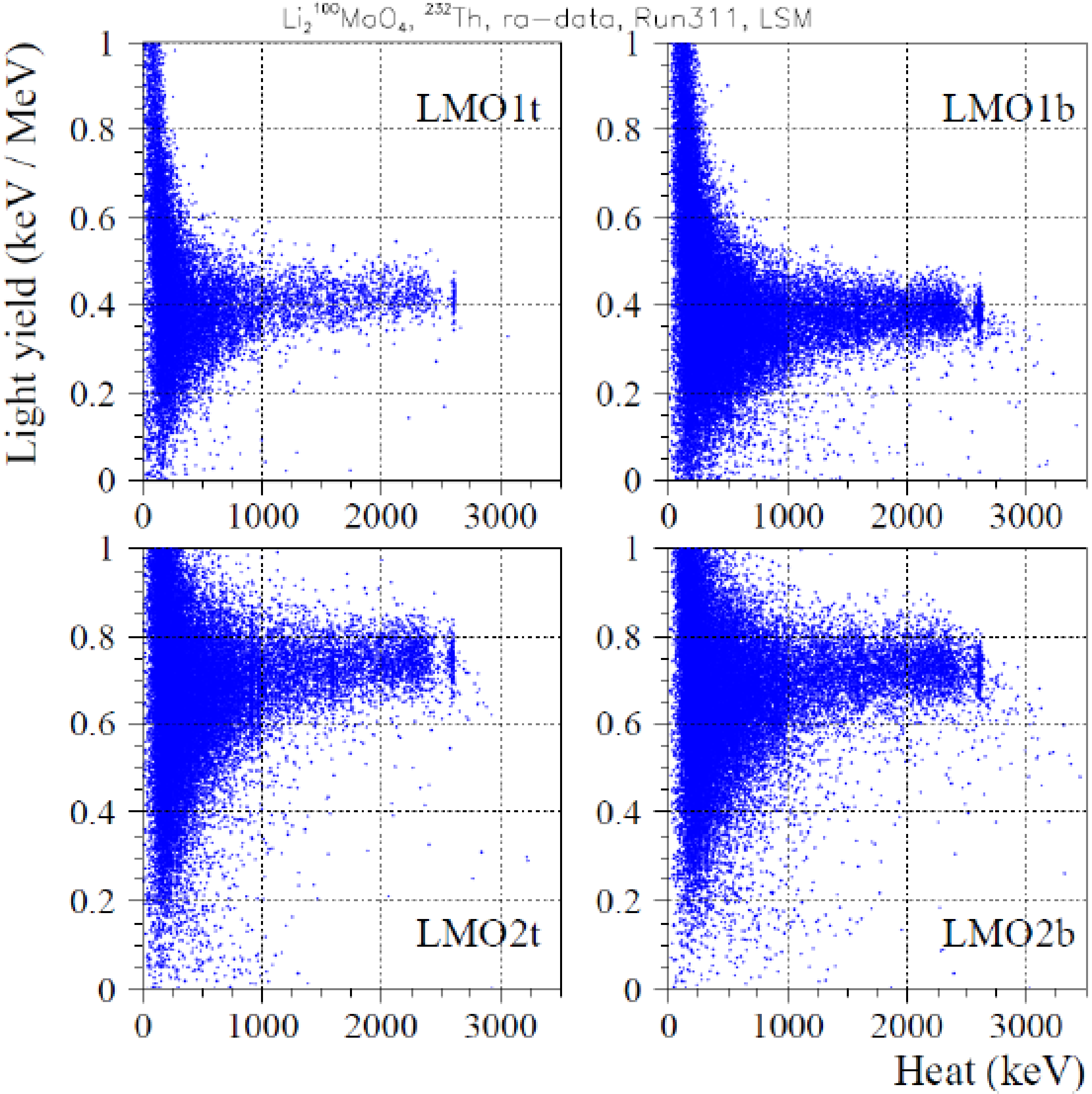
b = 10^{-4} counts/(keV kg y)

CUPID

BACK UP

Light yield

Light-yield plots with ^{232}Th calibration



Without reflecting foil

With reflecting foil

Significant LY reduction without reflecting foil

However, α/β separation is sufficient even without reflecting foil

$2\nu\beta\beta$ decay random coincidences

Contribution to the background index in the ROI: ∅50 mm × 50 mm (300 g)

BKG(rc) [counts/(keV kg y)] = 3×10^{-4} [T_R / 1 ms] [M / 300 g]

Our approach (partial simulation + PSD)

- Take a large value for T_R (typically $T_R \sim 3 \times$ rise time)
- Use real-shape pulses
- Use real noise baselines
- Generate pulses with correct 2ν pulse amplitude distribution
- Calculated rejection efficiency by PSD of pulse-pair separated by less than T_R
- Multiply the above formula by rejection efficiency

EPJ C 72, 1989 (2012)
EPJ C 74 , 2913 (2014)
arXiv:1606.02287v1

In a real case (heat channel):
T_R = 45 ms
Rejection efficiency by PSD = 99.3 % (using the so-called **mean-time method**)
(95% acceptance)

BKG(rc) [counts/(keV kg y)] $\sim 1 \times 10^{-4}$

It can be improved:

- Full simulation
- Advanced pulse shape parameters (after optimum filtering)

Neutrons

^{6}Li(n,t)α σ = 940 barn (thermal neutrons) Q = 4.78 MeV

Harmless

No associated β radiation

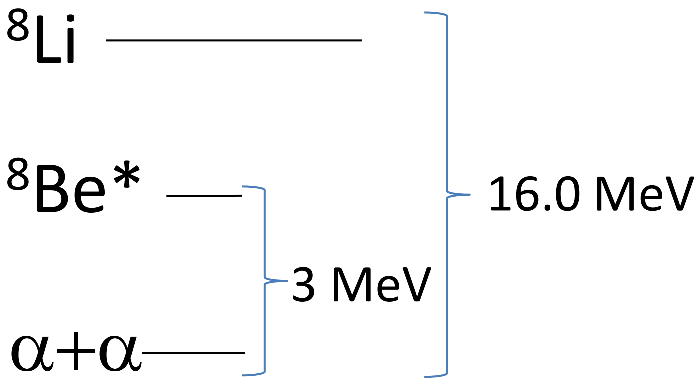
Huge internal energy deposition

^{7}Li(n,γ)^{8}Li σ = 45.4 mbarn (thermal neutrons)

$$^{7}\mathrm{Li}(n,\gamma)^{8}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be}^{*} + e^{-} + \nu$$

Prompt (Γ ~ 1.5 MeV)

$$^{8}\mathrm{Be}^{*} \rightarrow \alpha+\alpha$$

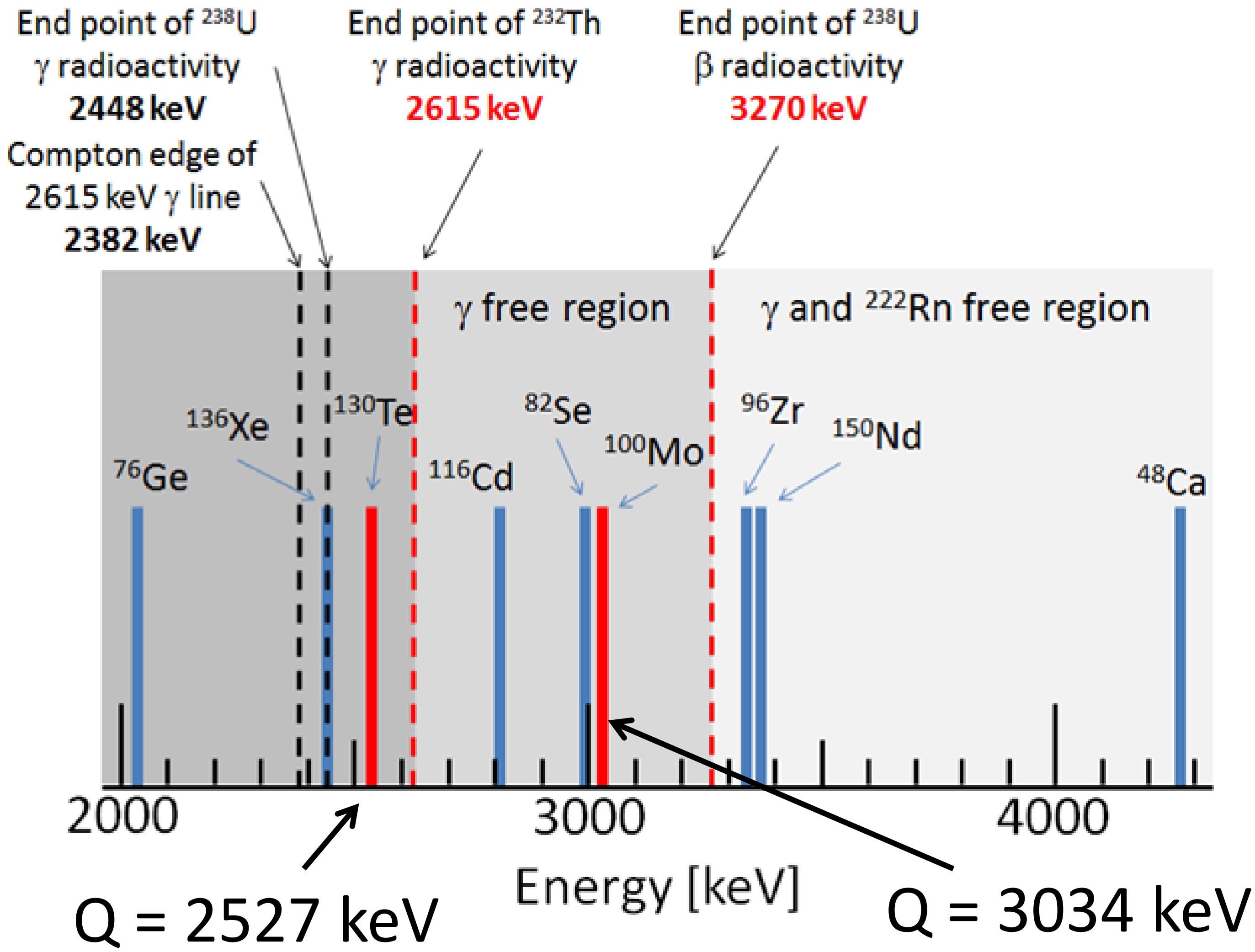


Harmless

Very low cross section

Mixed events with α component

Choice of CROSS material (^{100}Mo – ^{130}Te)



Q = 2527 keV

Q = 3034 keV

Choice of CROSS material (^{130}Te)

- Crystallization / purification chain for TeO_2 extensively studied in CUORE and precursors in natural crystals (SICCAS, Shanghai, China)
- Excellent results in terms of performance and radiopurity

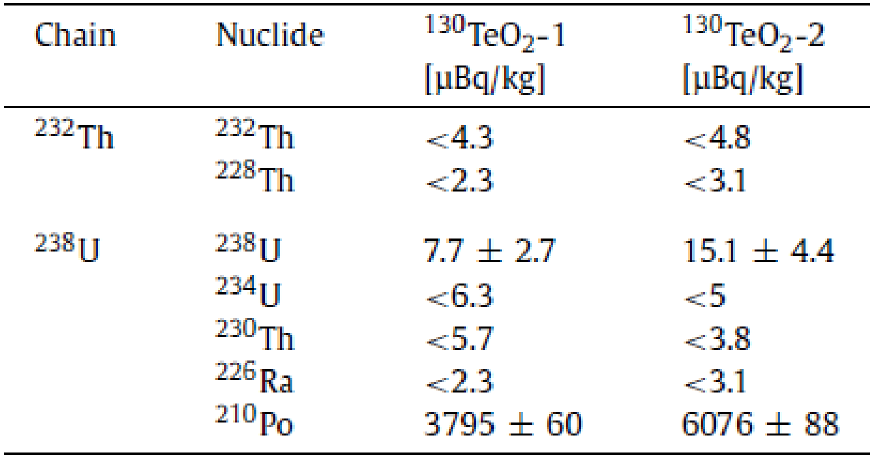
  ⇒ Internal contamination in ^{226}Ra and ^{228}Th are less than 1 μBq/kg

- Recently, the study was extended to enriched crystals (USC et al., SICCAS)
  - **Irrecoverable losses ~ 28 %** (less good than ^{100}Mo but lower isotope price)
  - Detector performance of natural crystals si confirmed

^{130}**Te**: **15-20 $/g**

vs

^{100}**Mo**: **90 $/g**



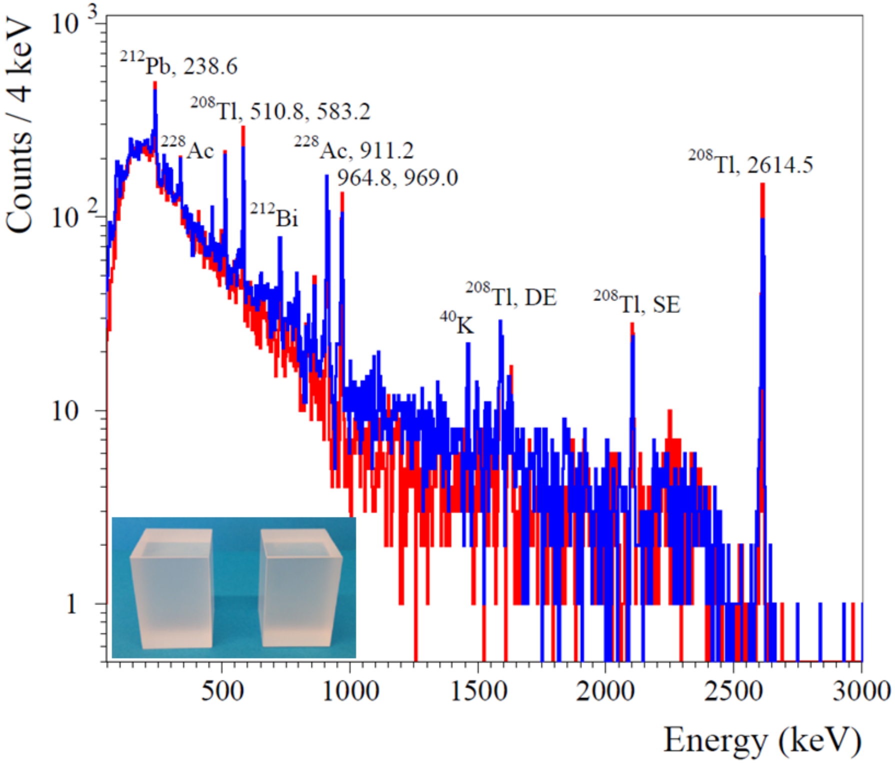
Chain	Nuclide	$^{130}TeO_2$-1 [μBq/kg]	$^{130}TeO_2$-2 [μBq/kg]
^{232}Th	^{232}Th	<4.3	<4.8
	^{228}Th	<2.3	<3.1
^{238}U	^{238}U	7.7 ± 2.7	15.1 ± 4.4
	^{234}U	<6.3	<5
	^{230}Th	<5.7	<3.8
	^{226}Ra	<2.3	<3.1
	^{210}Po	3795 ± 60	6076 ± 88

PLB 767, 321 (2017)

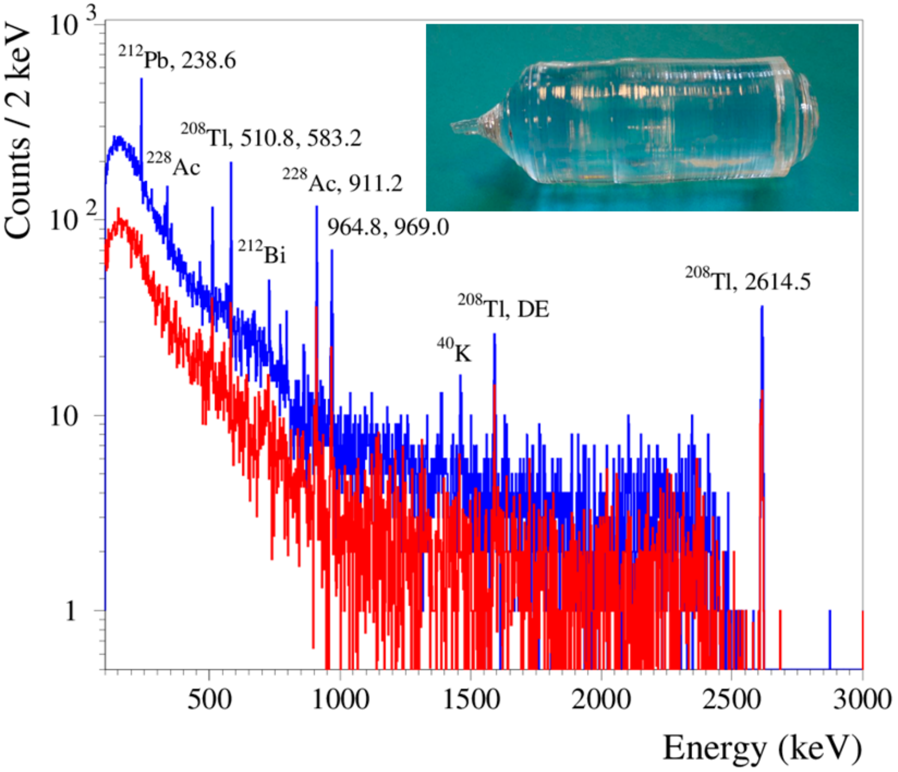
Radiopurity is less good than in natural crystals but compatible with **$b < 10^{-4}$ counts/(keV kg y)**

Detector performance

Two enriched TeO_2 modules (LNGS)
M = 430 g
$\Delta E_{FWHM} \sim$ 5 keV at 2.6 MeV



Two enriched Li_2MoO_4 modules (LNGS+LSM)
M = 210 g
$\Delta E_{FWHM} \sim$ 5 keV at 2.6 MeV

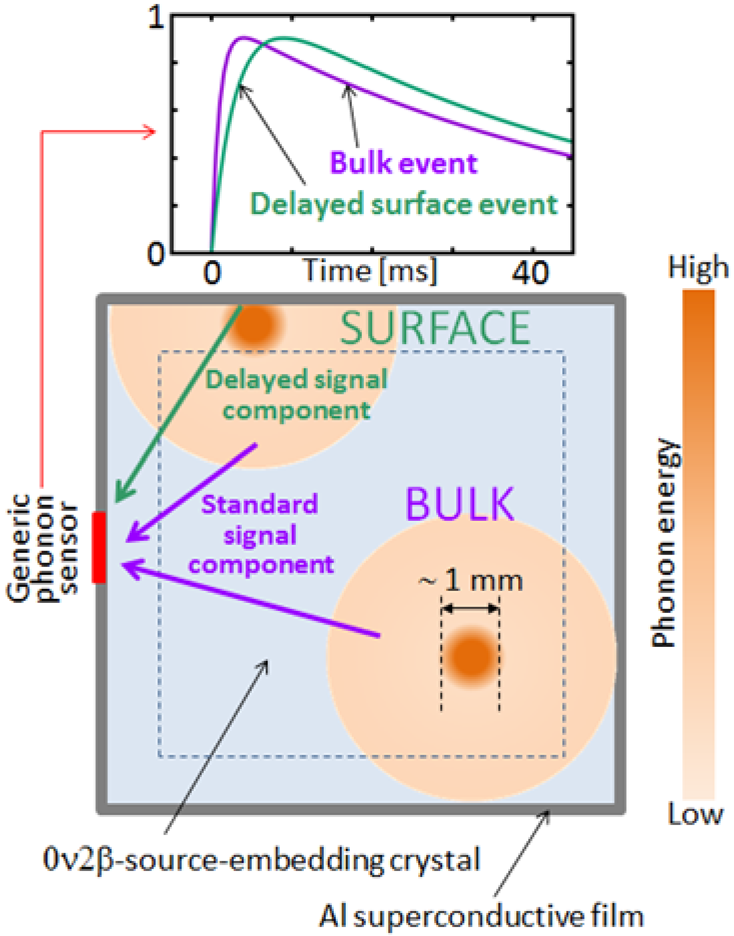


Th calibration

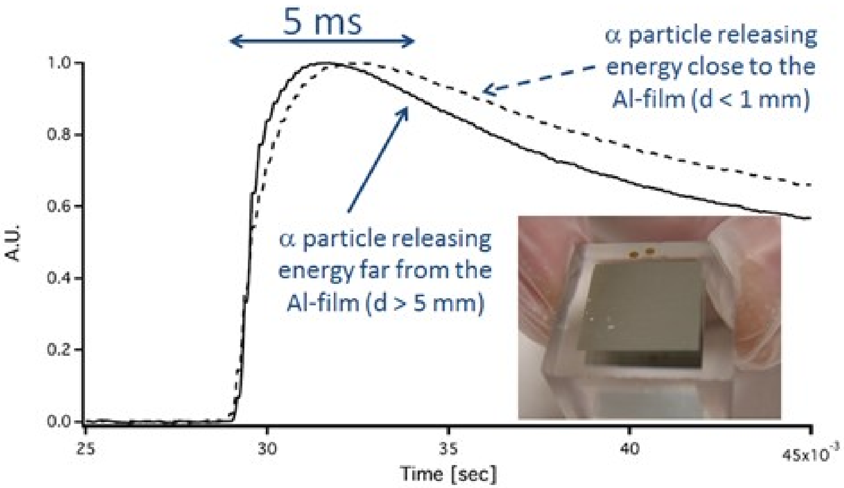
Al films as pulse shape modifiers

Coating of all crystal surfaces with **SC Al films**

Discriminate surface events by **pulse shape (PSD)**

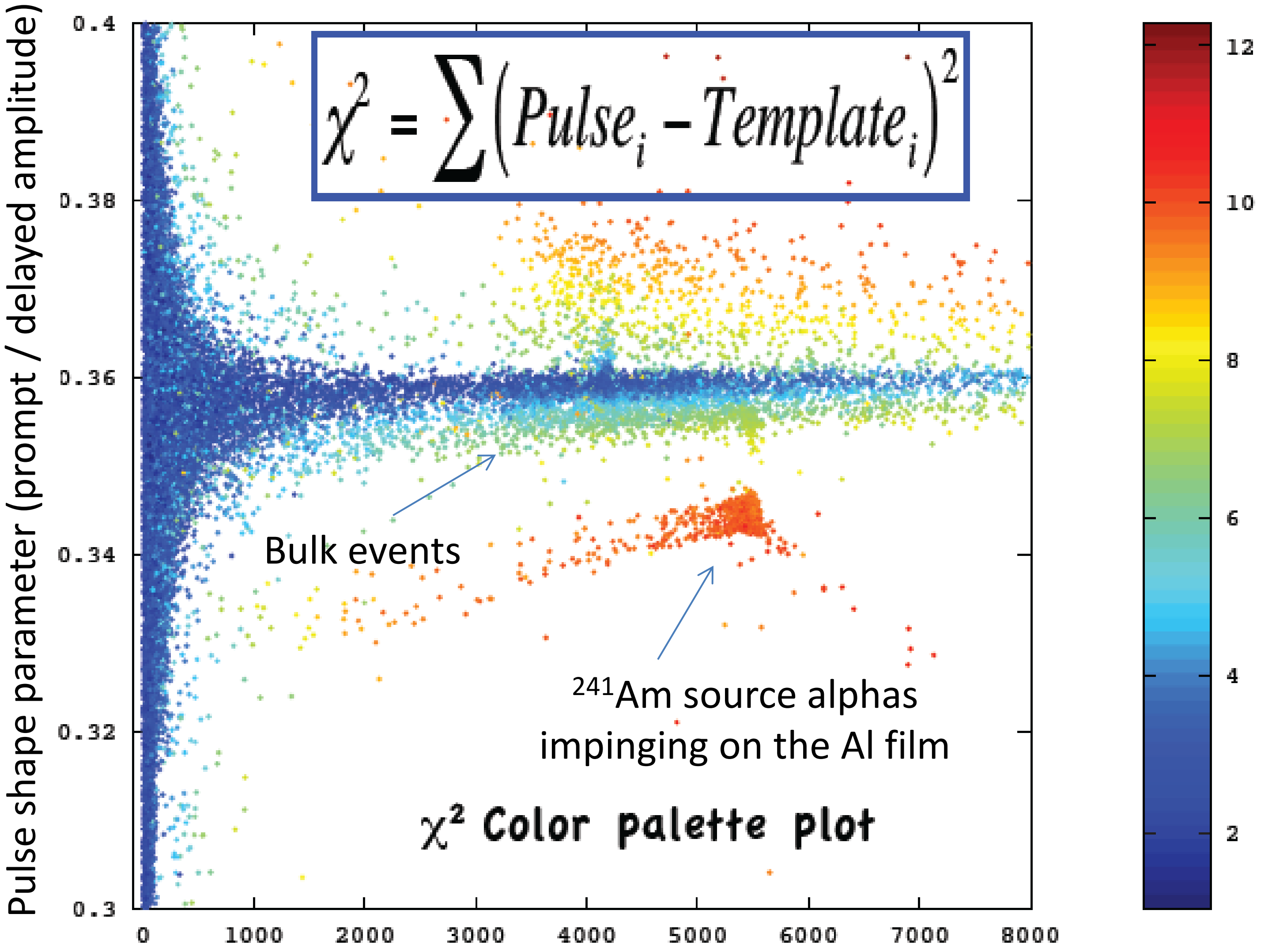


Proof of concepts achieved in 2010 in CSNSM



J. Low Temp. Phys. 167 (2012) 1029

Al films as pulse shape modifiers



$$\chi^2 = \sum \left(Pulse_i - Template_i \right)^2$$

Bulk events

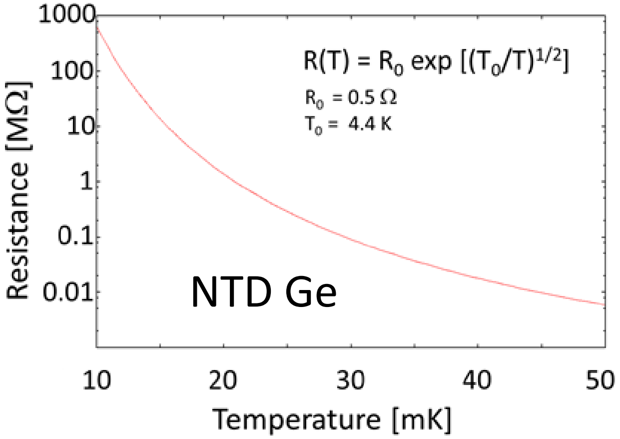
^{241}Am source alphas impinging on the Al film

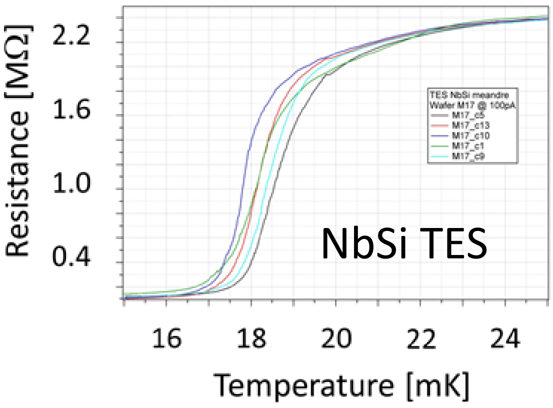
χ^2 Color palette plot

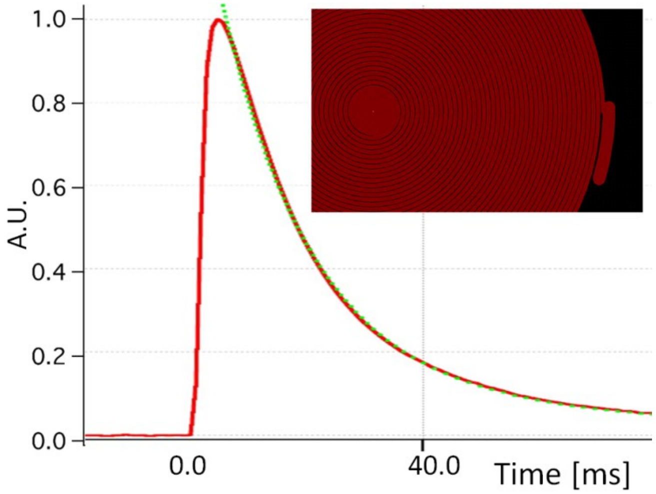
Fast NbSi sensors

Replace standard NTD Ge with **high impedance transition edge NbSi sensor**

Higher sensitivity (x 10) – **Faster response** ⇒ it may be necessary for PSD







Proof of concept achieved with a NbSi meander on a 32 g Ge absorber

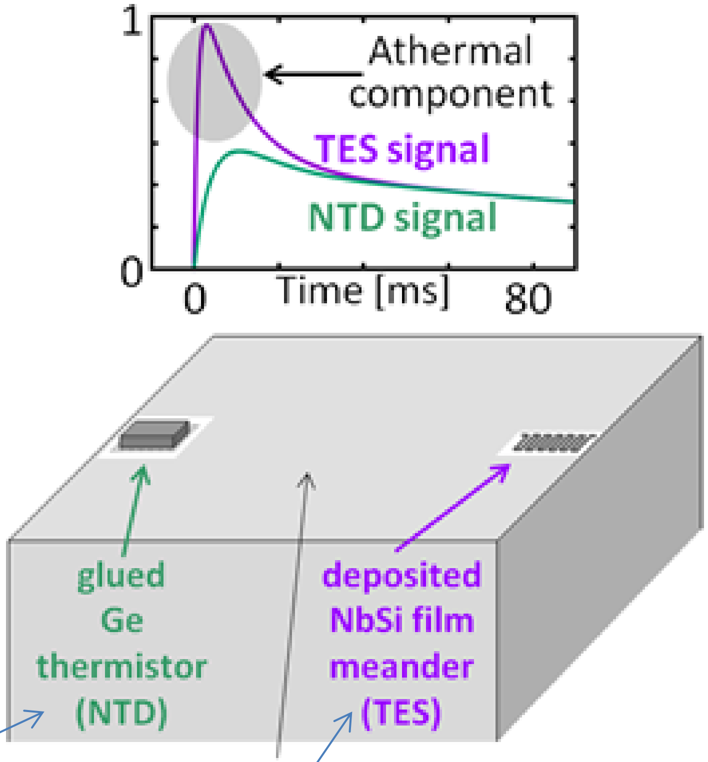
Rise time: 2.5 ms vs. 20 ms for NTDs

The meander has 6 mm diameter, a spiral shape, a line width of 45 μm and a pitch of 60 μm. The length/width aspect ratio is 9700.

Double readout

If the NbSi signal contains an important component of **athermal phonons**, signal-amplitude position dependence is possible with consequent **loss of energy resolution**

CROSS foresees in its baseline solution to keep NTD Ge readout (slow response, thermal signal)



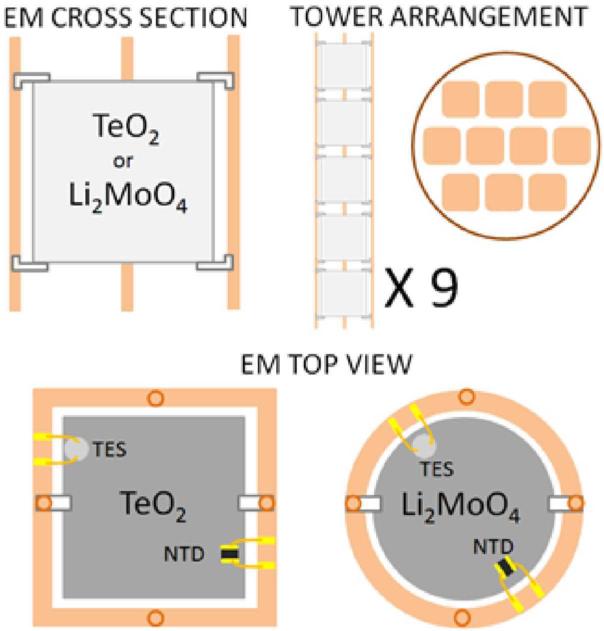
Energy readout

Time readout

CROSS demonstrator (CROSS-DEM)

- Complete crystallization of available ^{100}Mo (10 kg)
- Purchase / crystallize ^{130}Te (up to 17 kg)
- Fabricate demonstrator with 90 crystals in dedicated refrigerator

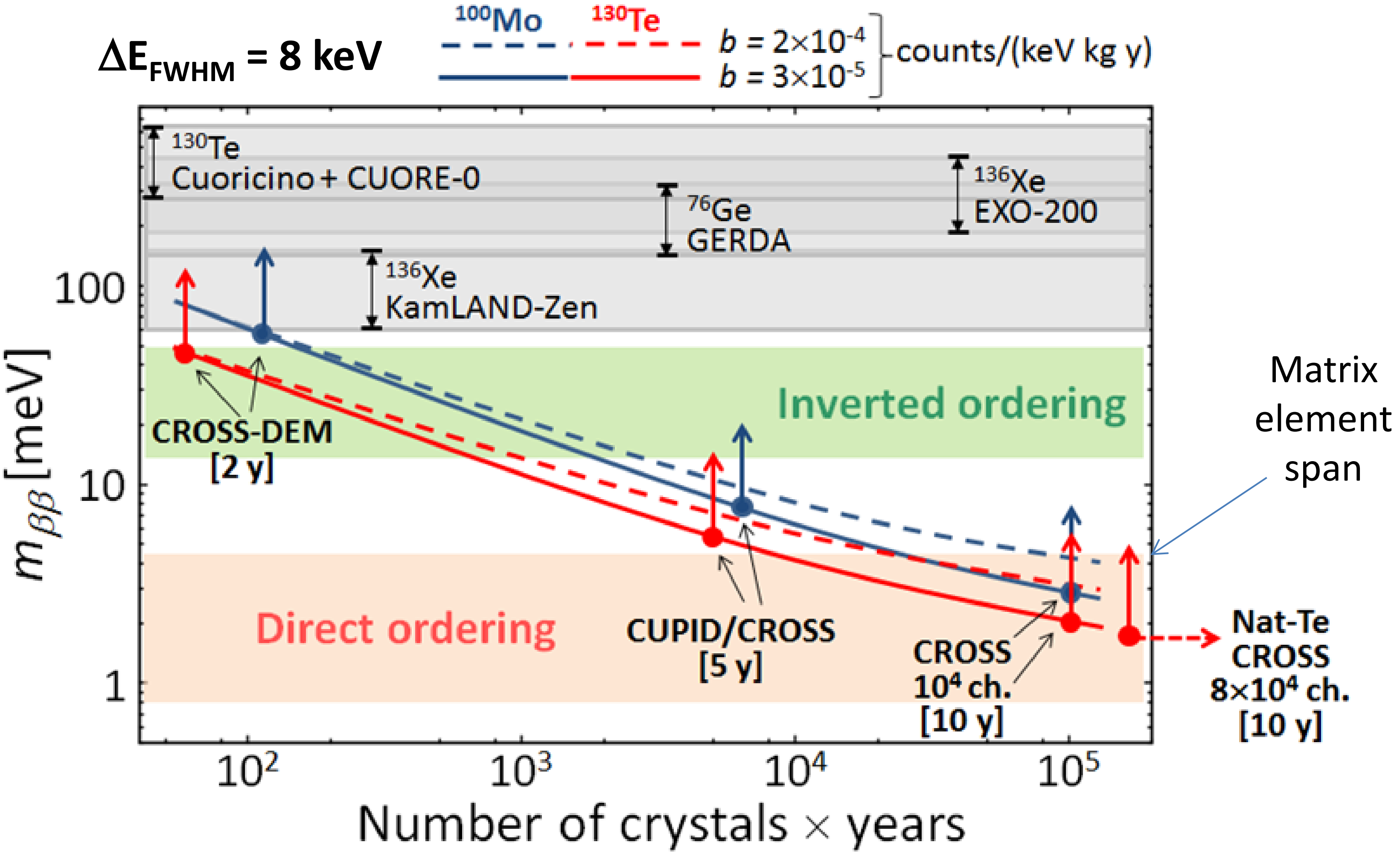
Section of CROSS-DEM	Number of crystals	Total detector mass [kg]	Isotopic abundance	Total isotope mass [kg]	Number of candidate nuclides
CROSS-DEM-Te	30	22.8	93% (^{130}Te)	17.0	7.9×10^{25} (^{130}Te)
CROSS-DEM-Mo	60	16.2	99% (^{100}Mo)	9.14	5.4×10^{25} (^{100}Mo)



Low radioactivity refrigerator, based on a pulse tube, with experimental space ∅30 x 60 cm – muon veto

To be installed in LSC
(former ROSEBUD hut)

CROSS sensitivity



CUPID/CROSS Te ⇒ 543 kg of ^{130}Te

CUPID/CROSS Mo ⇒ 212 kg of ^{100}Mo