



# BINGO: Bi-Isotope $0\nu 2\beta$ Next Generation Observatory An Overview

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HAWRAA KHALIFE \*

ON BEHALF THE BINGO COLLABORATION

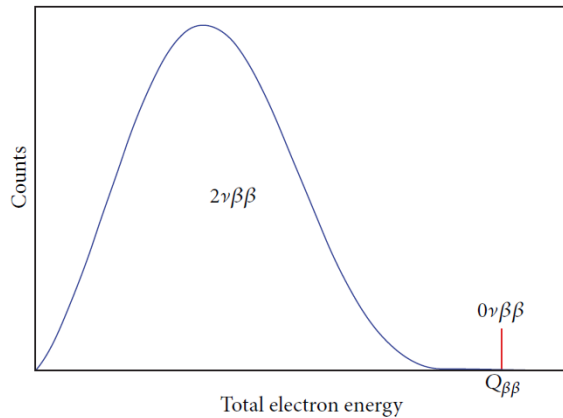
European Nuclear Physics Conference  
24-28 Oct 2022

# Neutrinoless double beta decay

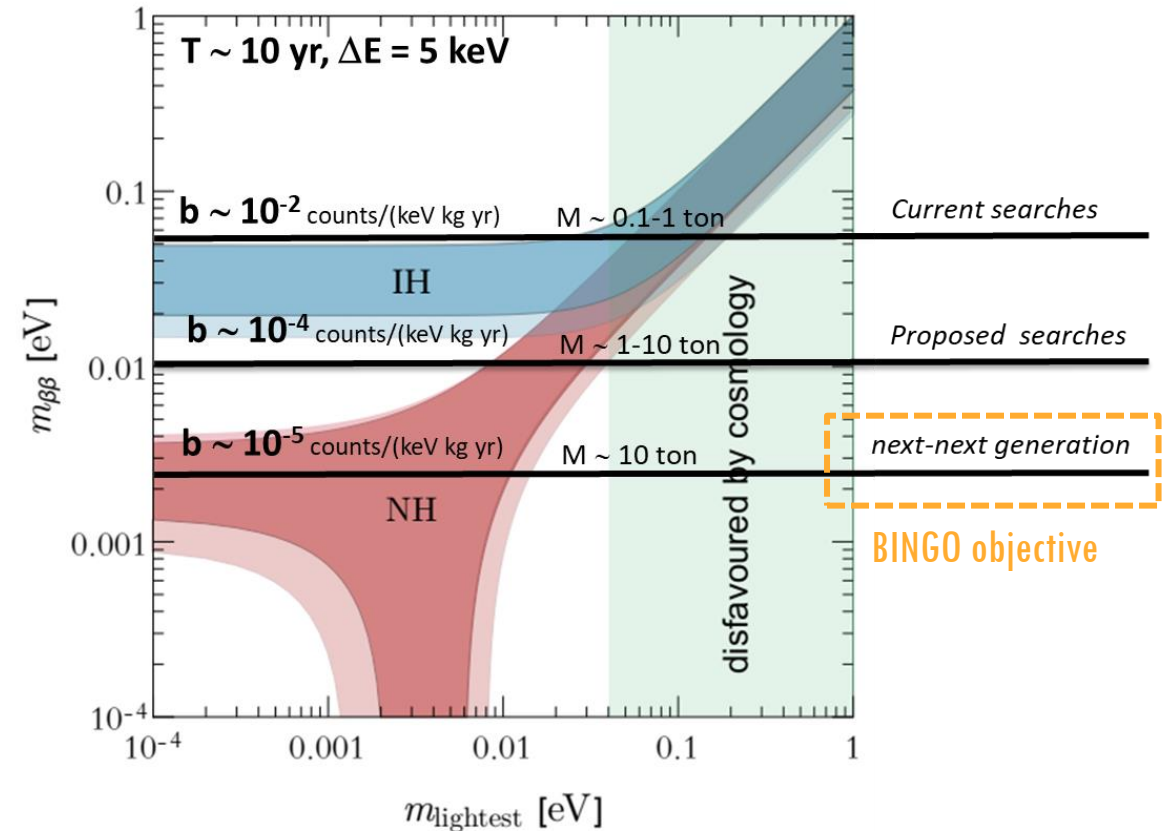
Neutrinoless double-beta decay:  $(A, Z) \rightarrow (A, Z+2) + 2e^-$

Its observation will:

- Ascertain the Majorana nature of neutrino ( $\nu = \bar{\nu}$ )
- Confirm lepton number violation
- Measure  $T_{1/2}^{0\nu}$  that will lead to  $m_{\beta\beta}$  measurement



- BINGO will set the grounds for a large scale bolometric experiment searching for neutrinoless double-beta decay ( $0\nu 2\beta$ ) using revolutionary technologies
- It aims to reduce dramatically the background in the region of interest, which is one of the most limiting factors for current and future  $0\nu 2\beta$  experiments



$$b = \frac{\text{number of background counts}}{M \times t \times \Delta E}$$

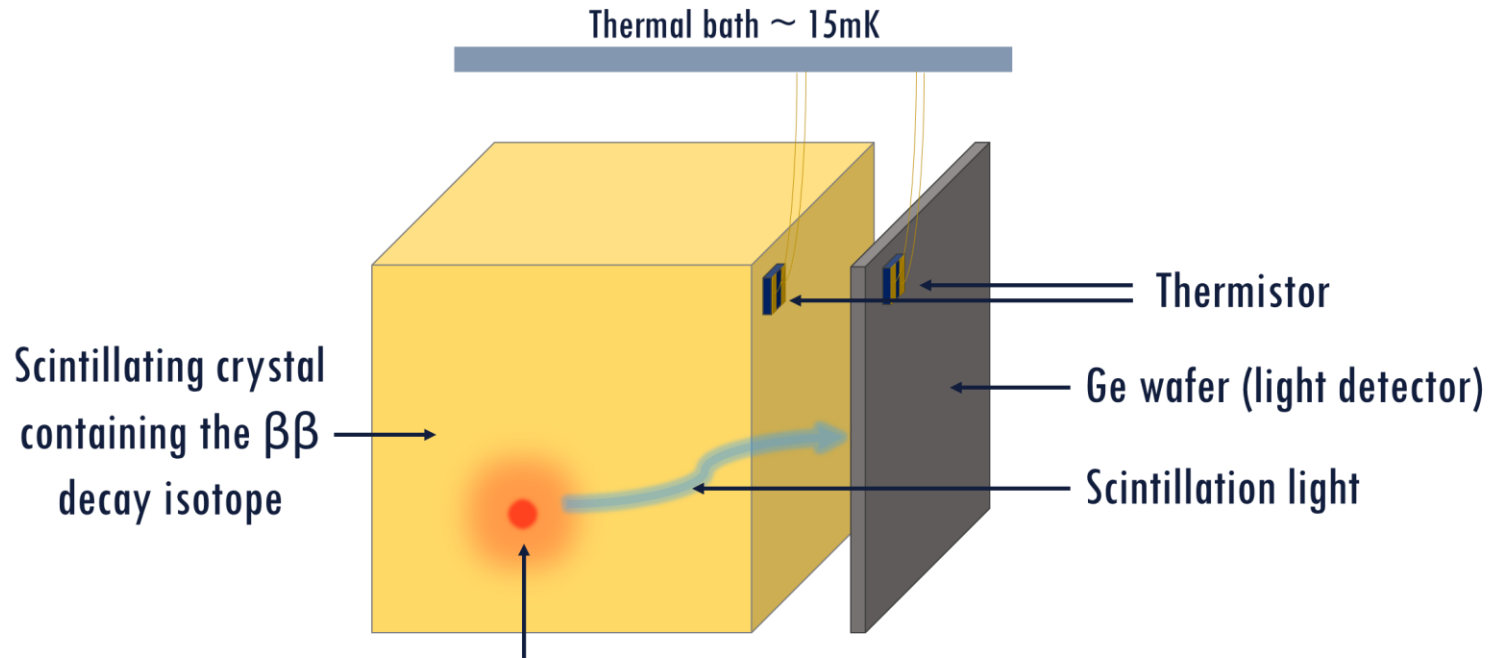
$M$ : detector mass

$t$ : time of measurement

$BI$ : background index

$\Delta E$ : energy resolution of the detector (FWHM)

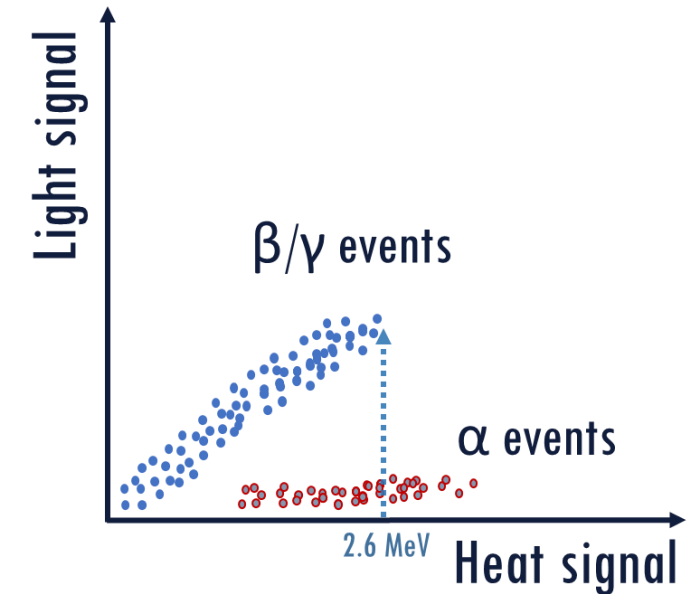
# Bolometric technique (Dual read-out)



Particle interaction leads to:

- Heat signal
- Light signal

The dual heat-light readout allows to reject the alpha contamination thanks to the lower light output of  $\alpha$ s



## Features

- high energy resolution
- full active volume (no dead layer)
- flexible material choice ( $\text{Li}_2\text{MoO}_4$ ,  $\text{TeO}_2$ )

# Bolometric compounds' strong and weak points



- Embeds  $^{100}\text{Mo}$  with a  $Q_{\beta\beta}$  at 3034 keV
- This crystal was validated by the CUPID-Mo demonstrator
  - Excellent energy resolution
  - High internal radio-purity
  - Easiness in crystallization
- Fast  $2\nu 2\beta$  decay  $\rightarrow$  background in the region of interest (ROI) due to  $2\nu 2\beta$  random coincidences



- Embeds  $^{130}\text{Te}$  with a  $Q_{\beta\beta}$  at 2527 keV
- This crystal was validated by the CUORE experiment
  - Excellent energy resolution
  - High internal radio-purity
  - Easiness in crystallization
- $Q_{\beta\beta}$  below the end line (at 2615 keV line of  $^{208}\text{Tl}$ ) of natural gamma radioactivity
- Very poor scintillator  $\rightarrow$  no alpha background rejection

Background problems, in addition to possible surface contamination from surrounding materials

# The 3 pillars for background reduction

## Assembly upgrade

### Less passive materials

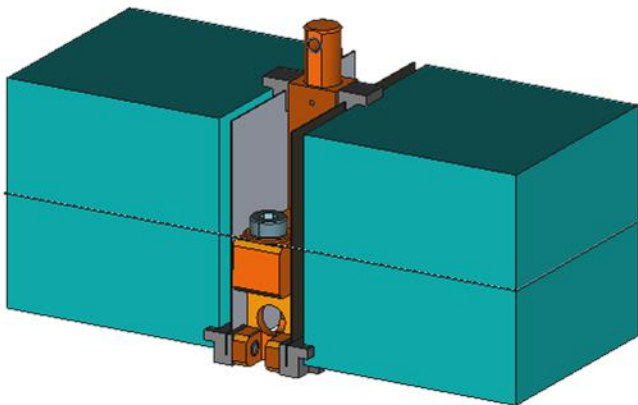
Reduce the Cu materials seen by the main absorber using a LD as an active shield



reduction of the total surface radioactivity contribution

### Compact assembly

Background reduction through anticoincidence cuts

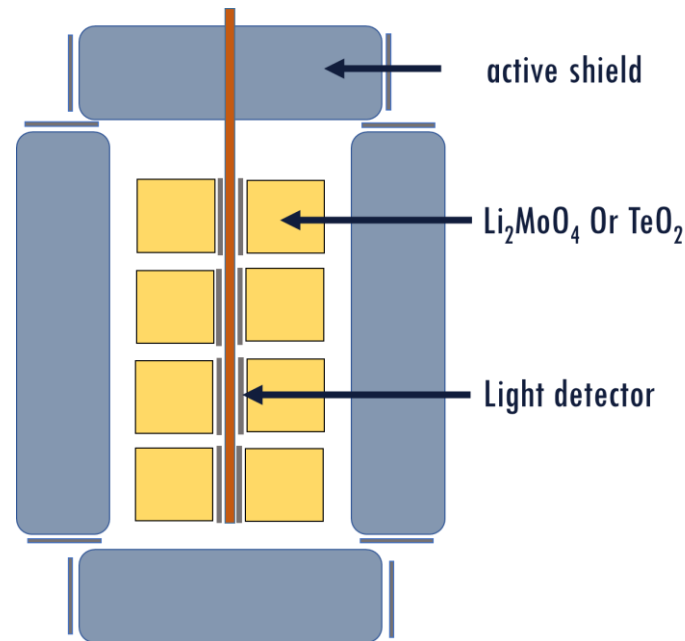


## Active veto

Use an active shield, based on  $\text{ZnWO}_4$  or BGO scintillators



Suppress the external gamma background and reject surface radioactivity from the crystals that face the active shield using anti-coincidence



## Neganov-Luke light detectors

Higher signal to noise ratio

1- lower energy threshold



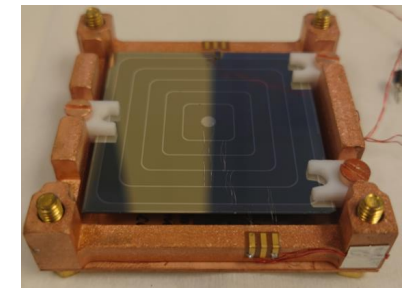
suppress external  $\gamma$  background using the active shield

2- reject the background induced by the random coincidences of  $2\nu 2\beta$  events in LMO

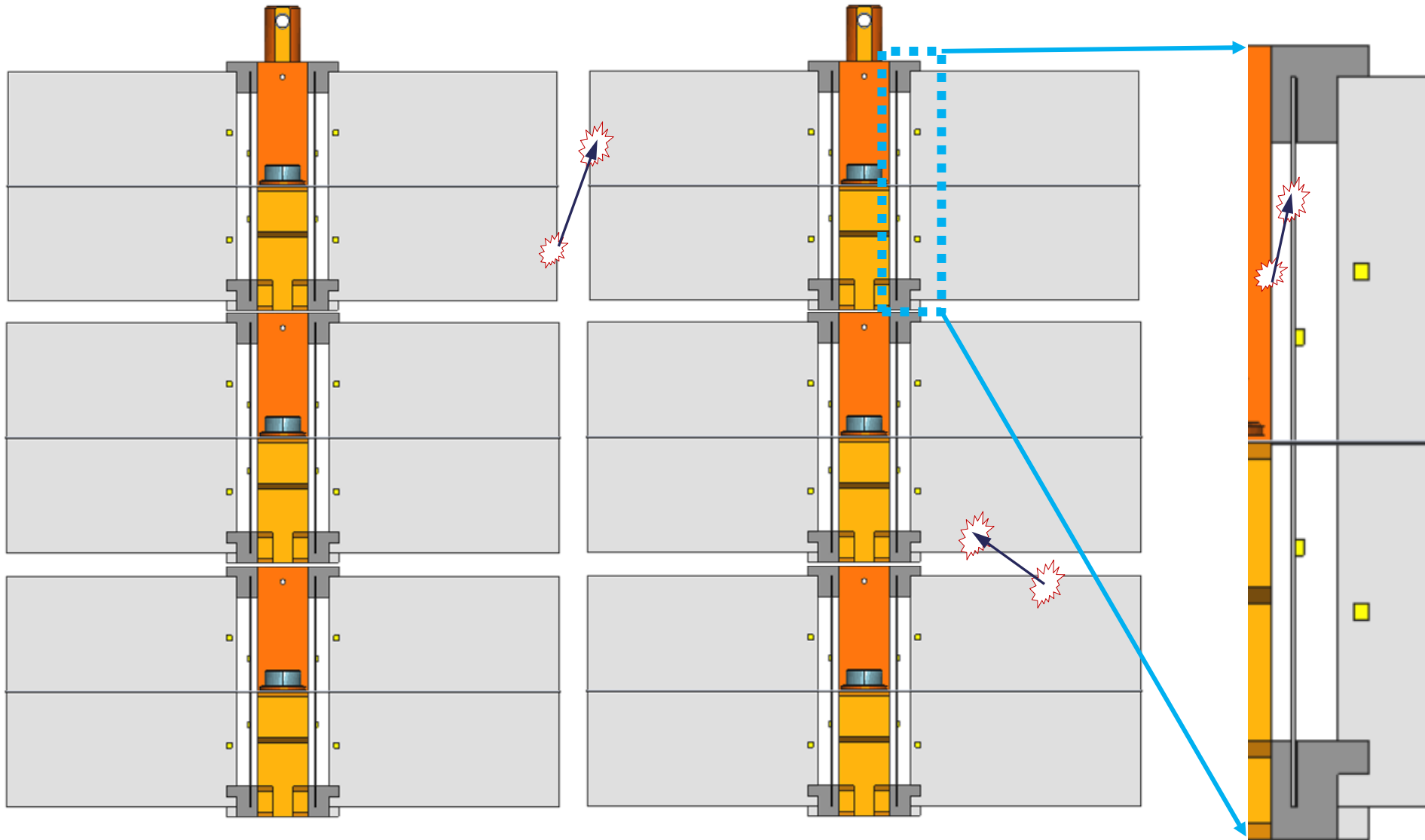
Amplification of the tiny Cherenkov signal ( $\text{TeO}_2$ )



suppress alphas



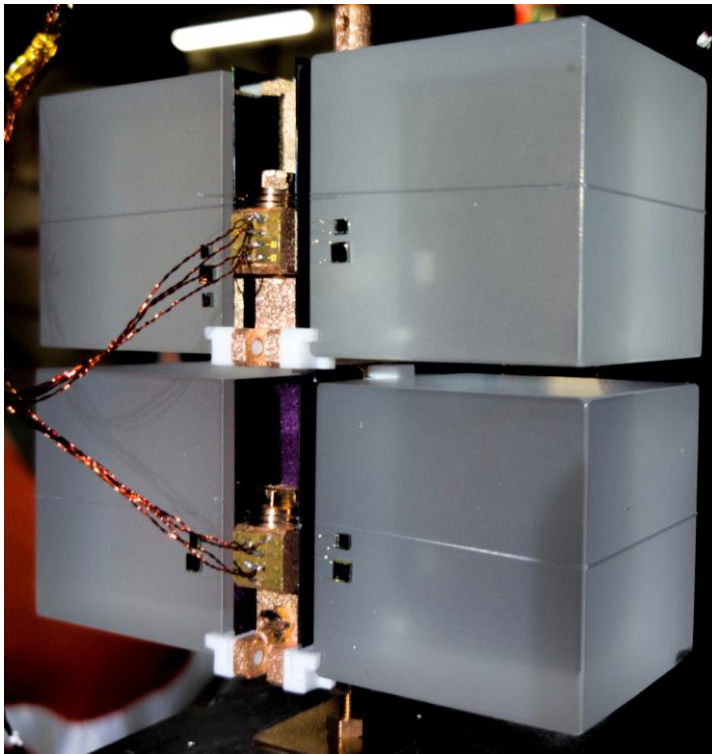
# Assembly upgrade



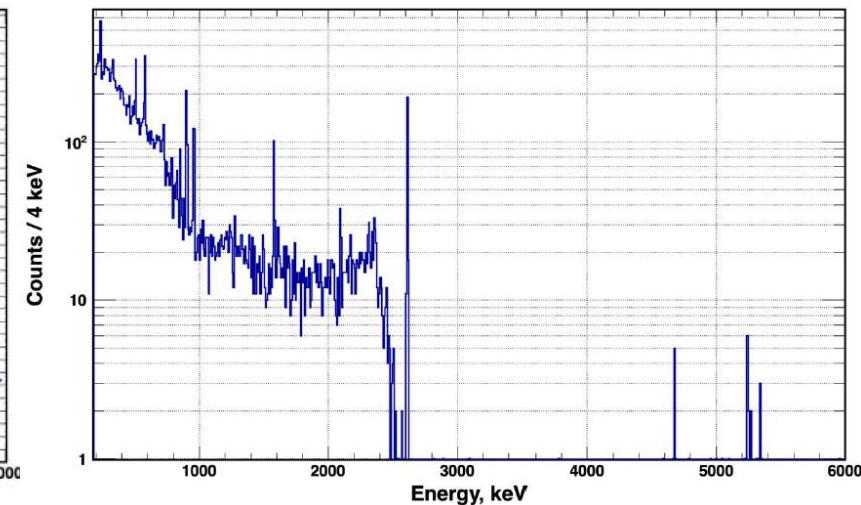
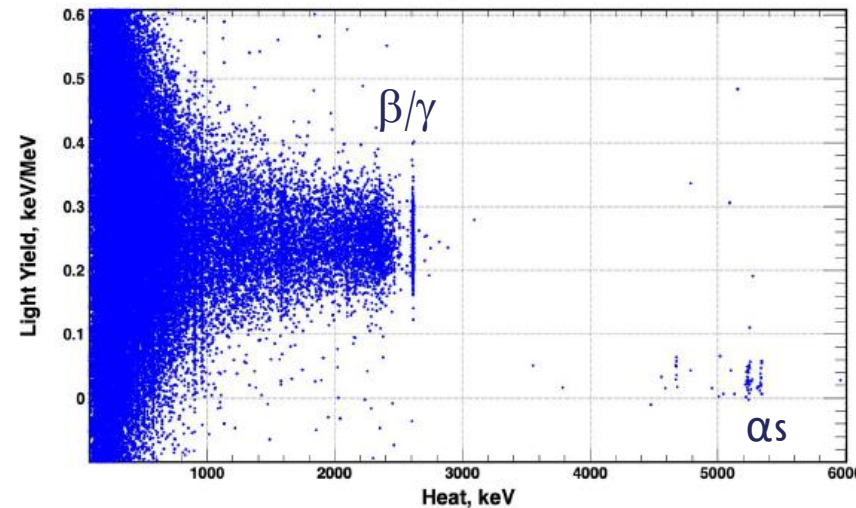
Surface contaminations can be rejected with coincidence thanks to the compact assembly and LD shielding

# New assembly test on $\text{Li}_2\text{MoO}_4$

- The assembly was tested in two cryostats: aboveground at IJCLab and Canfranc underground laboratory (LSC) in CROSS facility
- The tests validated and showed a good bolometric performance of the assembly



- The average baseline resolution FWHM is  $\sim 2.3$  keV for heat channels and 220 eV for light channels
- No impact of nylon wire on noise or thermal coupling
- Good discrimination between  $\alpha$  and  $\beta/\gamma$



# The 3 pillars for background reduction

## Assembly upgrade

### Less passive materials

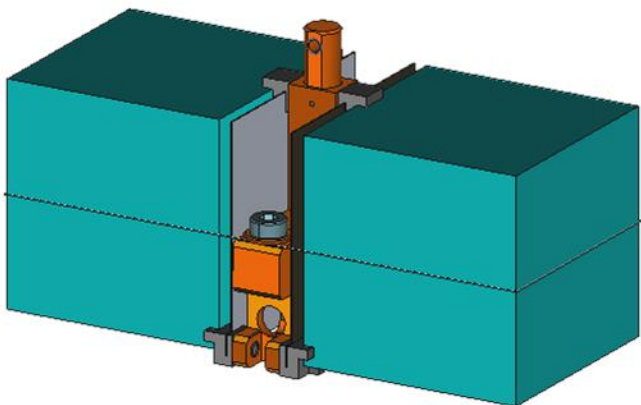
Reduce the Cu materials seen by the main absorber using a LD as an active shield



reduction of the total surface radioactivity contribution

### Compact assembly

Background reduction through anticoincidence cuts

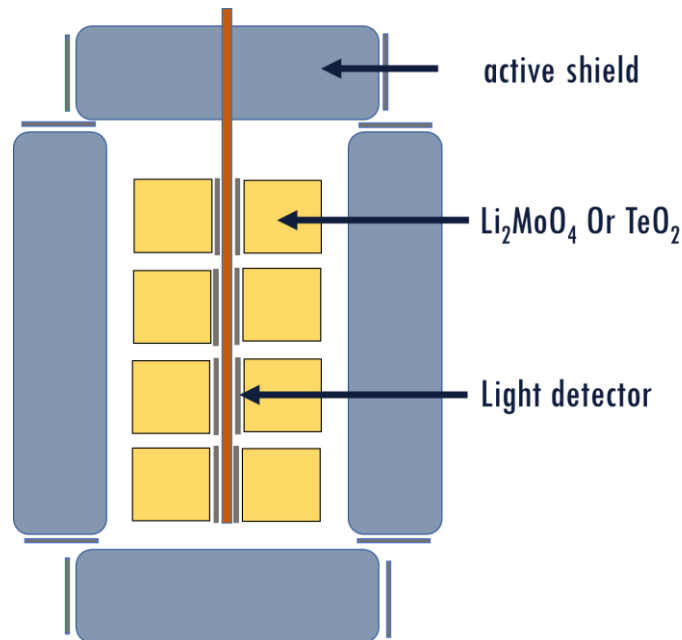


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## Neganov-Luke light detectors

Higher signal to noise ratio

1- lower energy threshold



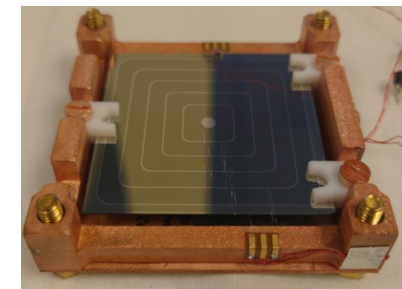
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2- reject the background induced by the random coincidences of  $2\nu 2\beta$  events in LMO

Amplification of the tiny Cherenkov signal ( $\text{TeO}_2$ )

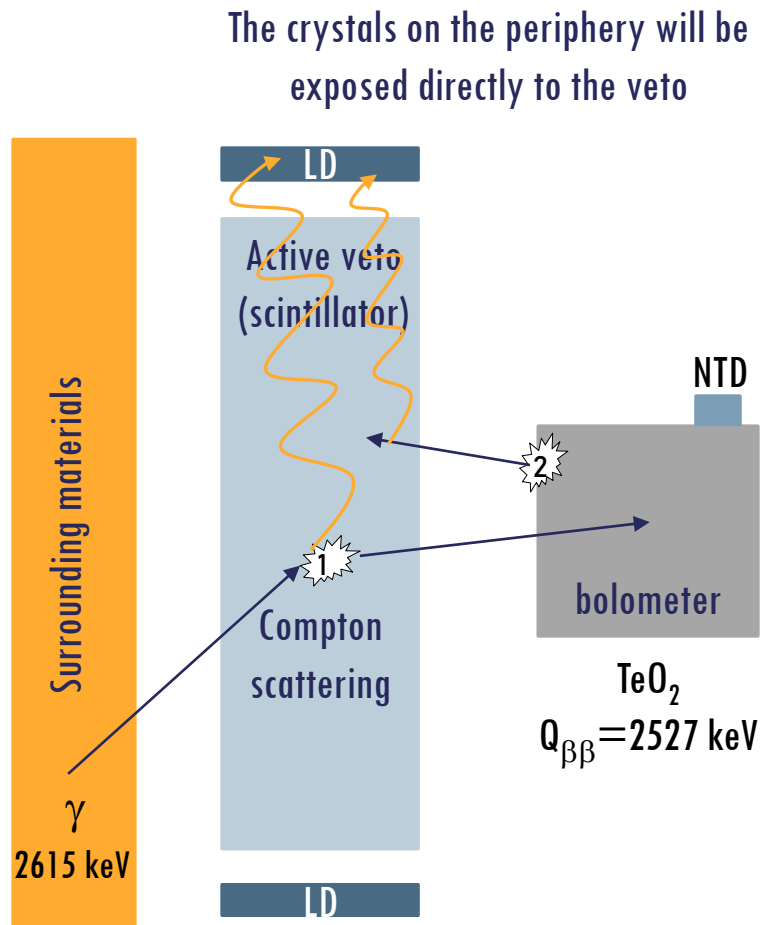


suppress alphas





# How does the veto work



1

- If the 2615 keV  $\gamma$  deposit a small amount of energy in the surrounding material ( $\sim 80$  keV) and the rest in TeO<sub>2</sub>  $\rightarrow$  background in ROI
- Thanks to the active veto and the LDs, these events can be rejected:
  - The energy deposition in the active veto will lead to scintillation light detected by the LD
  - Using anti-coincidence these events can be rejected from TeO<sub>2</sub>

2

- Some surface contamination on the crystal can be dangerous if part of the energy escapes. This can be also rejected with anti-coincidence with the veto

For this to work, we need a Neganov-Luke LD (higher signal to noise ratio) in order to achieve a low energy threshold ( $\sim 50$  keV in the scintillator corresponding to few keV in LD)

# The 3 pillars for background reduction

## Assembly upgrade

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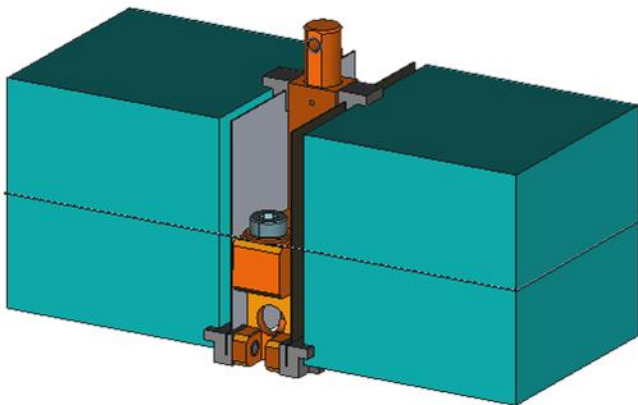
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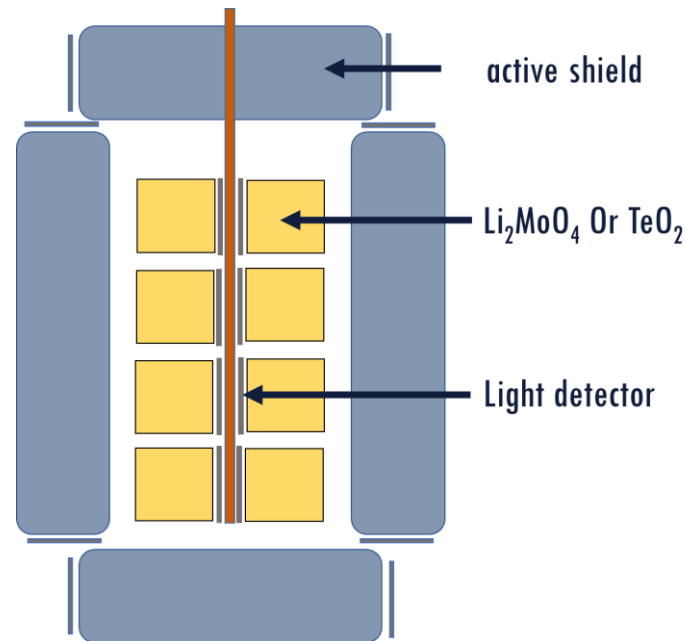


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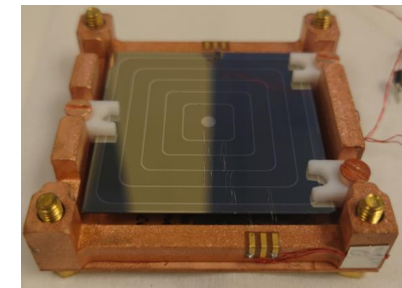
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Amplification of the tiny Cherenkov signal ( $\text{TeO}_2$ )



suppress alphas



# How does Neganov-Luke LD work

Ge wafer provided with Al electrodes on its surface



When applying voltage across these electrodes an electric field is established



The absorption of photons produces electron-hole pairs



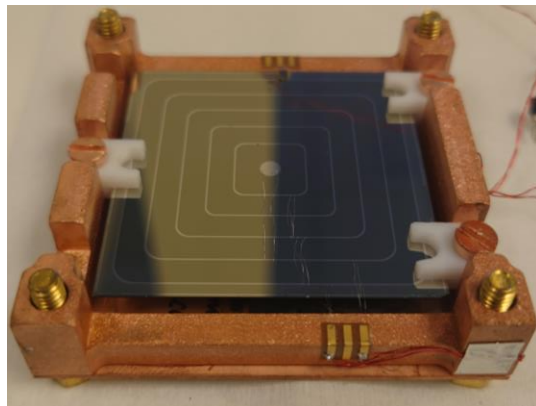
The electric field drifts the charges and it prevents their recombination



Carriers collide with the lattice during the drift, increasing the temperature

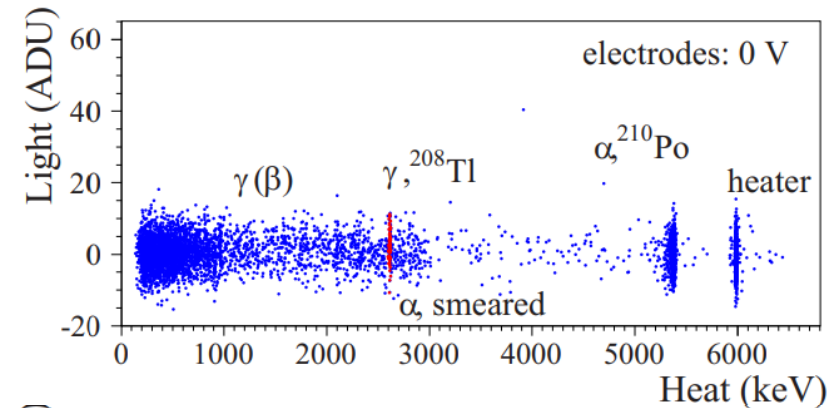


This means signal amplification that is read by a thermistor (NTD)

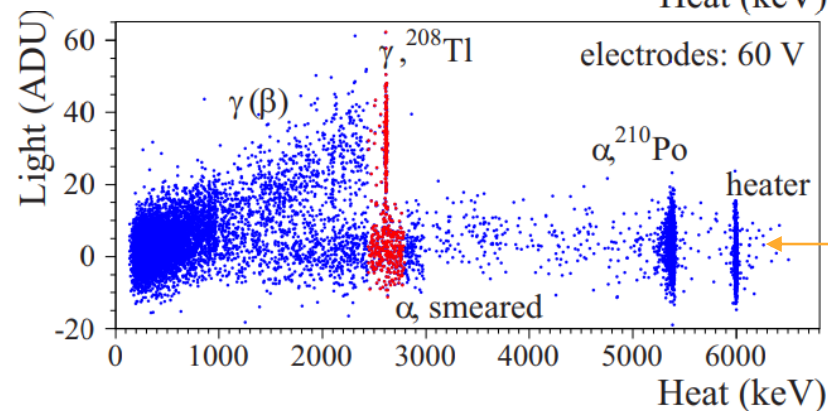


## The effect

CUORE-size  $\text{TeO}_2$  bolometer ( $5 \times 5 \times 5 \text{ cm}^3$  as in BINGO) coupled to NL LD tested at LSM in 2017 proved the concept (PHYSICAL REVIEW C 97, 032501(R) (2018))



$\text{TeO}_2$  is a poor scintillator, and we rely on detecting Cherenkov light. The energy threshold of electrons and alphas to produce Cherenkov light is respectively: 50 keV and 400 MeV



Alpha rejection is achieved

Amplification factor  $\sim 13$

In addition, with NL LD we can get a lower energy threshold thanks to higher signal to noise ratio

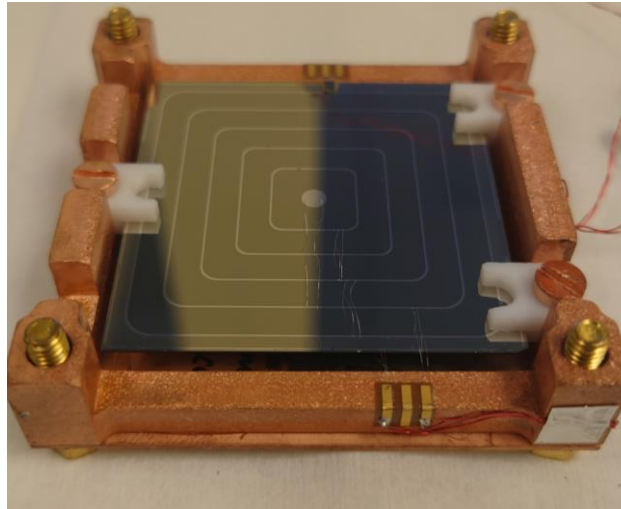
# Neganov-Luke light detector

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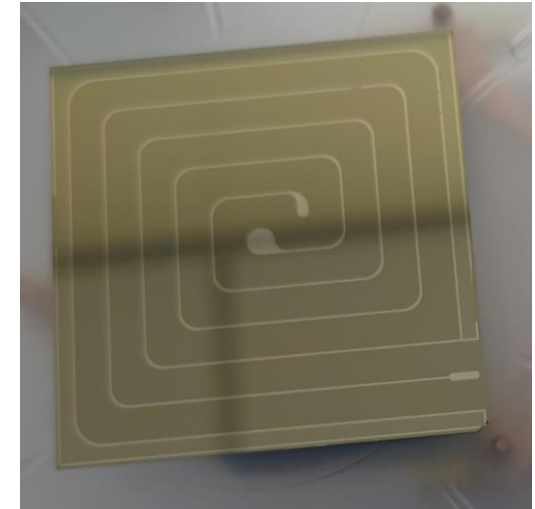
- Currently we are testing NL LD with different electrodes geometry in order to achieve a high amplification gain and good bolometric performances



Electrodes on 2 opposite edges



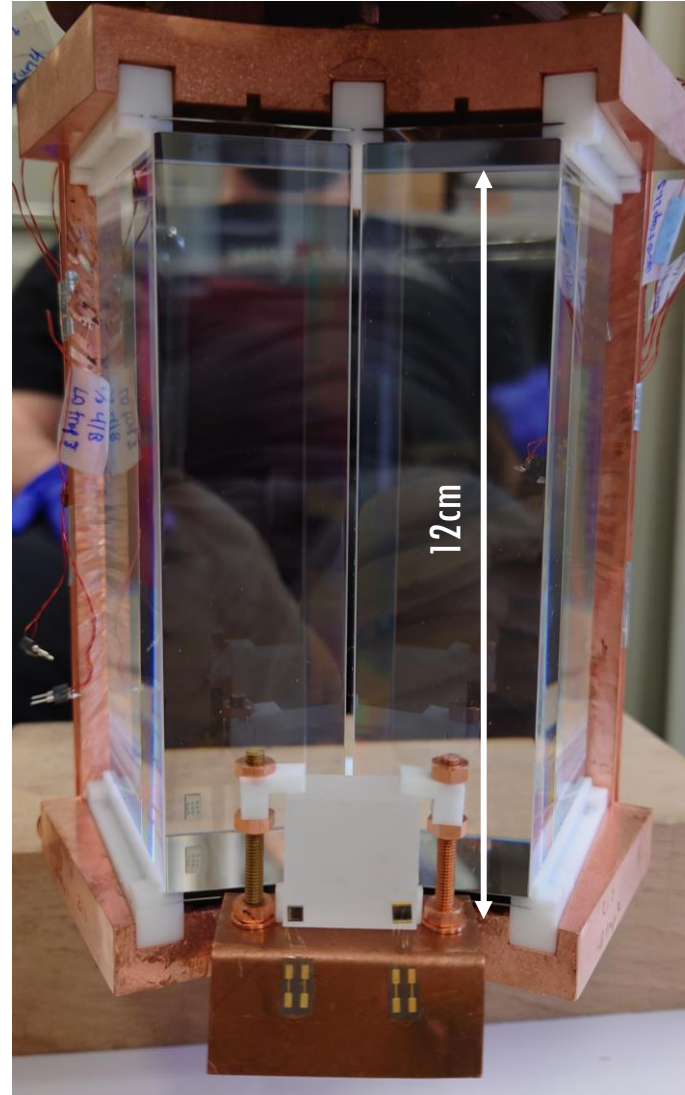
Concentric Electrodes



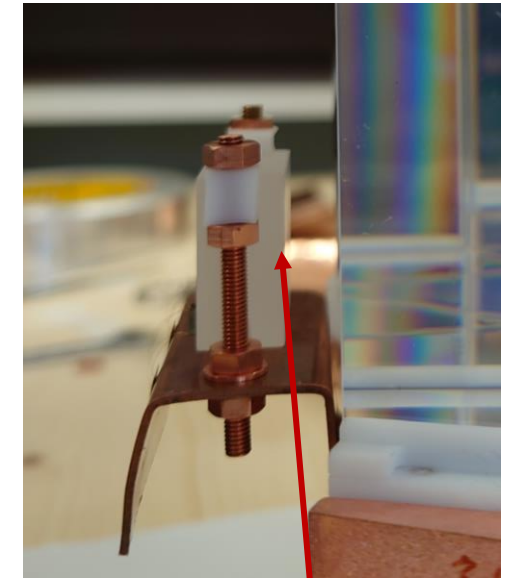
Double meander Electrodes

# Active veto aboveground prototype test

- We have two choices for the veto: BGO or  $\text{ZnWO}_4$
- Small crystals samples were tested to check the light yield and energy threshold
- BGO showed higher light yield, while  $\text{ZnWO}_4$  showed better radiopurity
- BGO can be grown as long bars, while for the moment for  $\text{ZnWO}_4$  it is not clear it can be done
- Further investigation is needed to choose the veto material



- 2 BGO crystals ( $\sim 1.6\text{kg}$  each)
- 2 LDs facing each BGO
- $\text{TeO}_2$  crystal facing both BGOs

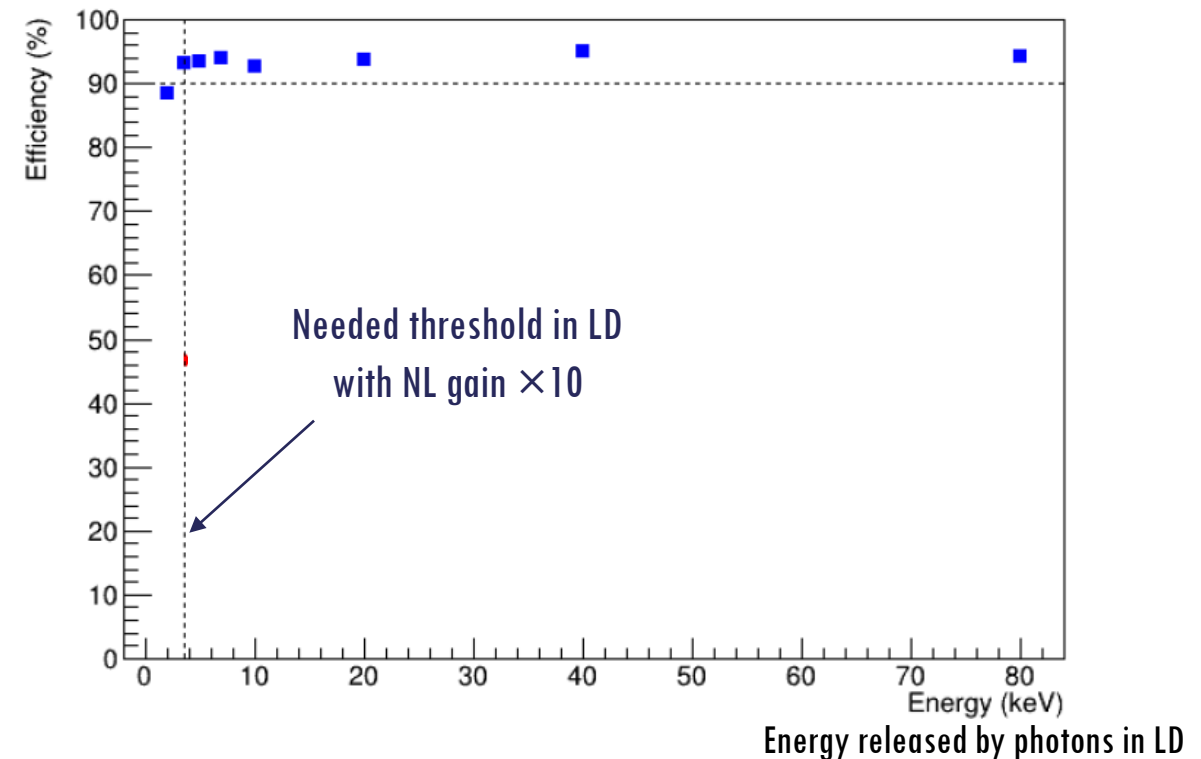
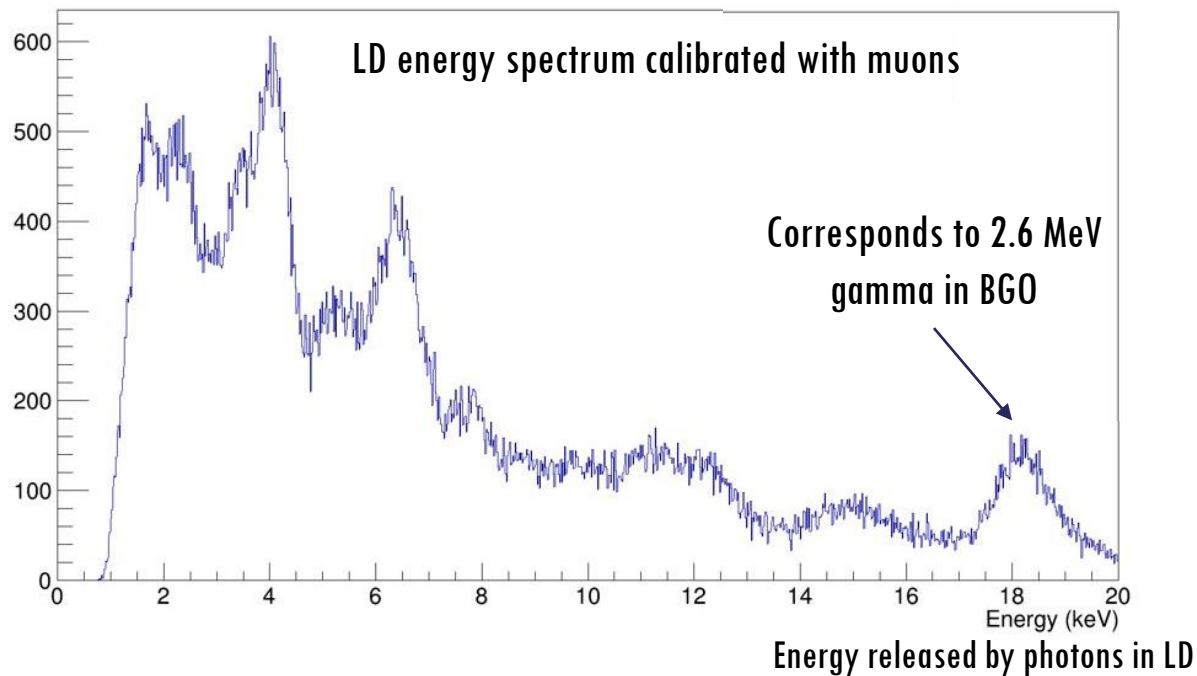


Uranium  $\alpha$  source deposited on  $\text{TeO}_2$  to imitate surface contamination (at 4.2 and 4.8 MeV)

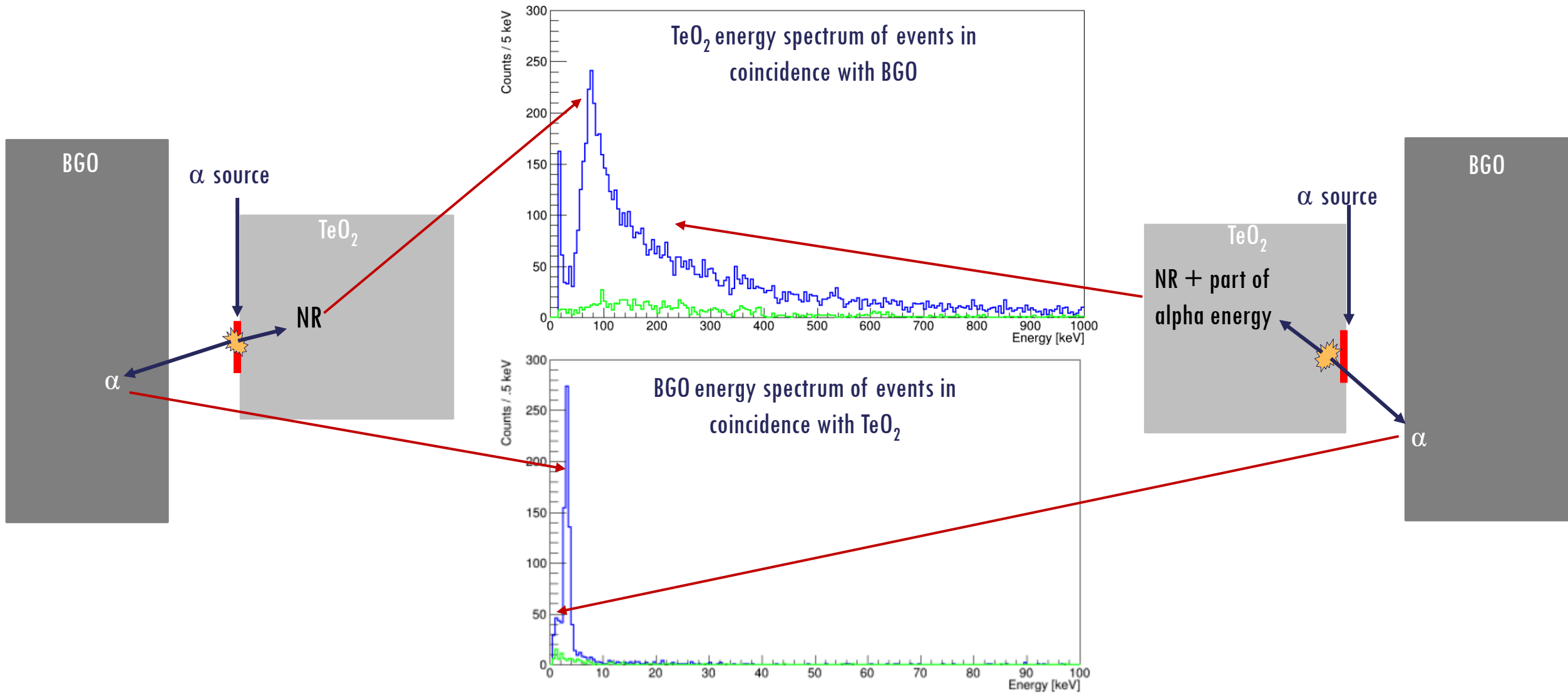


# Energy threshold and efficiency study

- 1000 fake pulses at different energies were injected into the data to estimate the efficiency after data processing
- The required energy threshold for the veto scintillator should be around 50 keV, which corresponds to around 3-4 keV in LD when taking into account the light yield (LY) which is around 7 keV/MeV in the current configuration and NL gain.



# Hunting the $\alpha$ source with coincidence



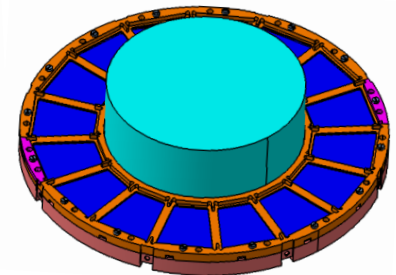
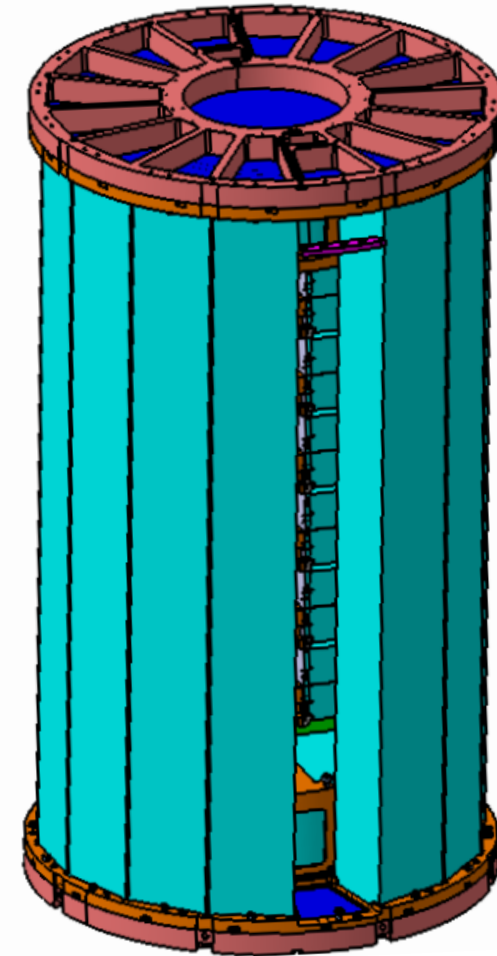
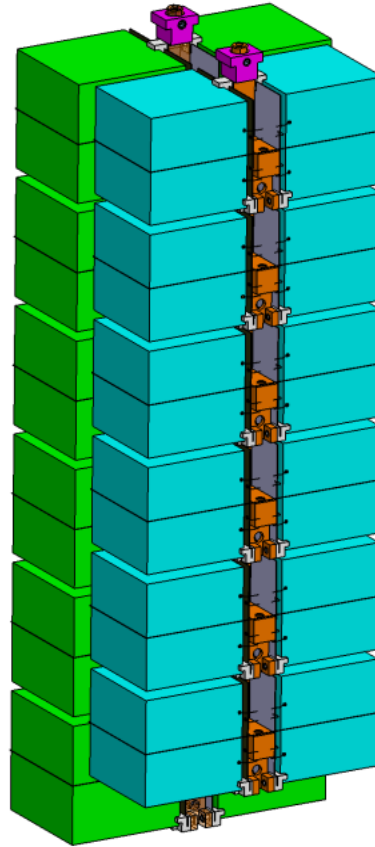
# The mini-BINGO ingredients

## Double beta decay part

- 12 cubic  $\text{Li}_2\text{MoO}_4$  scintillating crystals ( $45 \times 45 \times 45$  mm), each is coupled to a light detector ( $45 \times 45$  mm)
- 12 cubic  $\text{TeO}_2$  crystals ( $50 \times 50 \times 50$  mm), each is coupled to a light detector ( $50 \times 50$  mm)

## Cryogenic veto part surrounding the physics volume

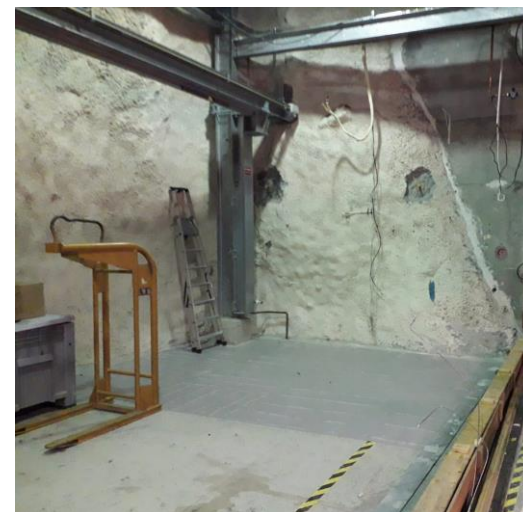
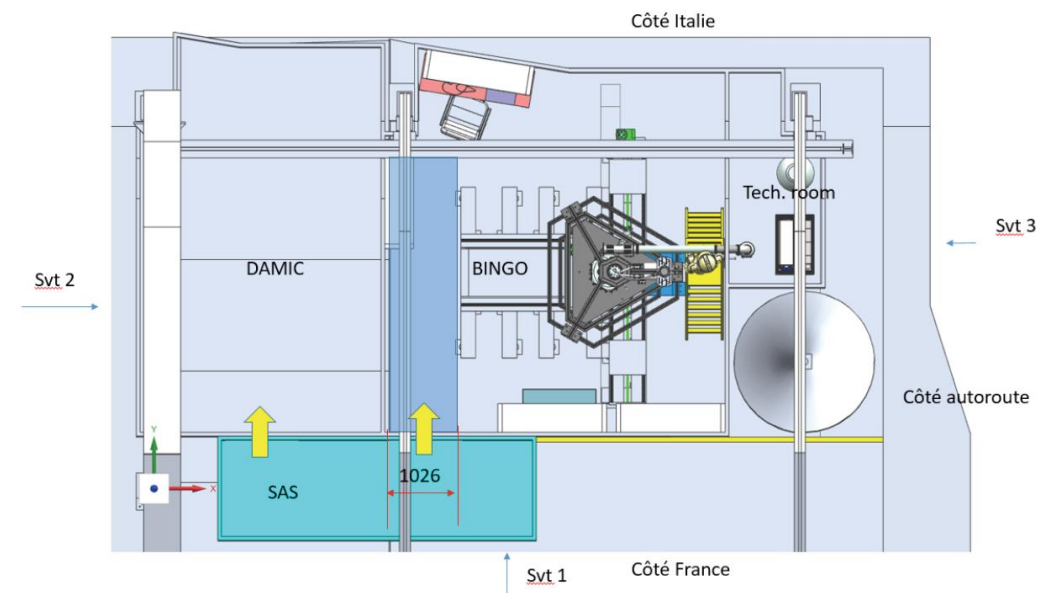
- 16 trapezoidal cross-section + 2 disc scintillators ( $\text{BGO}$  or  $\text{ZnWO}_4$ ) each coupled to LDs





# Mini-BINGO plan in Modane

- Mini-Bingo will be a technology demonstrator of the background reduction techniques described
- The demonstrator will be tested in Modane underground laboratory
- The cryostat will installed in spring 2023
- There will be an adopted clean room for assembly preparation
- The schedule is to start mini-bingo mid-end 2024
- In the meantime, the LMO and  $\text{TeO}_2$  towers can be tested in the cryostat and work on the background
- The goal is to reach background level below  $10^{-3} \text{ c}/(\text{keV kg y})$ , improving the one achieved by similar scale demonstrators (CUPID-0, CUPID-Mo)
- Assuming to get zero background in a  $[2.5-3.5] \text{ MeV}$  interval, comprising both ROIs, a background level down to  $10^{-4} \text{ c}/(\text{keV kg y})$  is in principle testable



# Conclusion and perspectives

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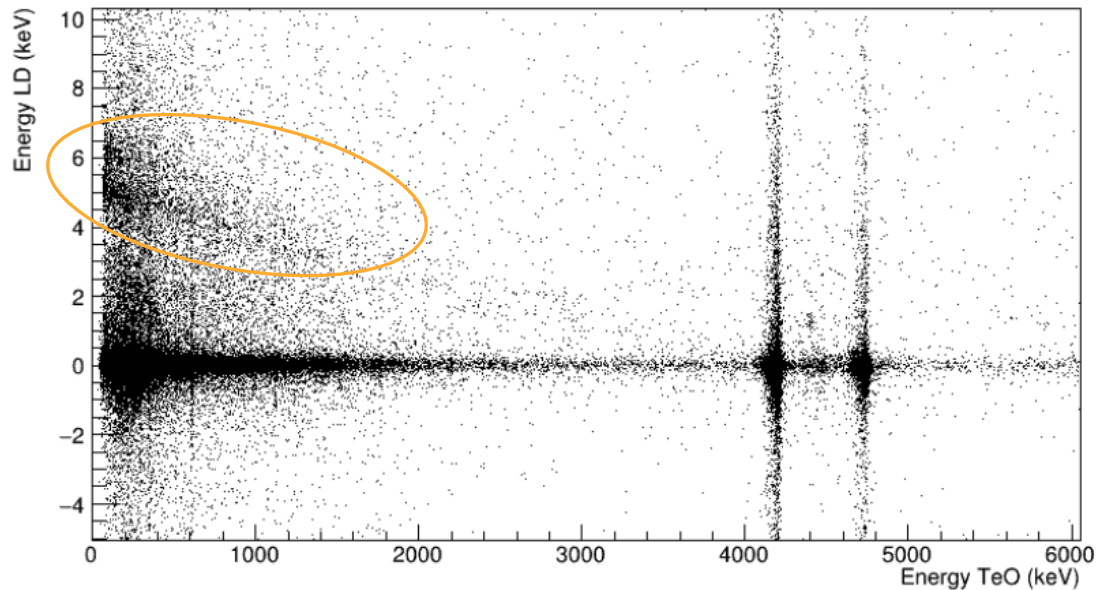
- BINGO is a promising project towards the meV scale of the effective Majorana mass
- BINGO proposed technologies are a possible candidate for CUPID-1T
- New technology that allows to reach  $b \sim 10^{-5}$  counts/(keV kg yr)
- The nylon wire assembly is almost validated
- More R&D is needed to develop the suitable Neganov-Luke LD that fulfills BINGO goals
- Some simulation and cryogenic measurements will be done to fix the scintillator to be used as a veto

# Backups

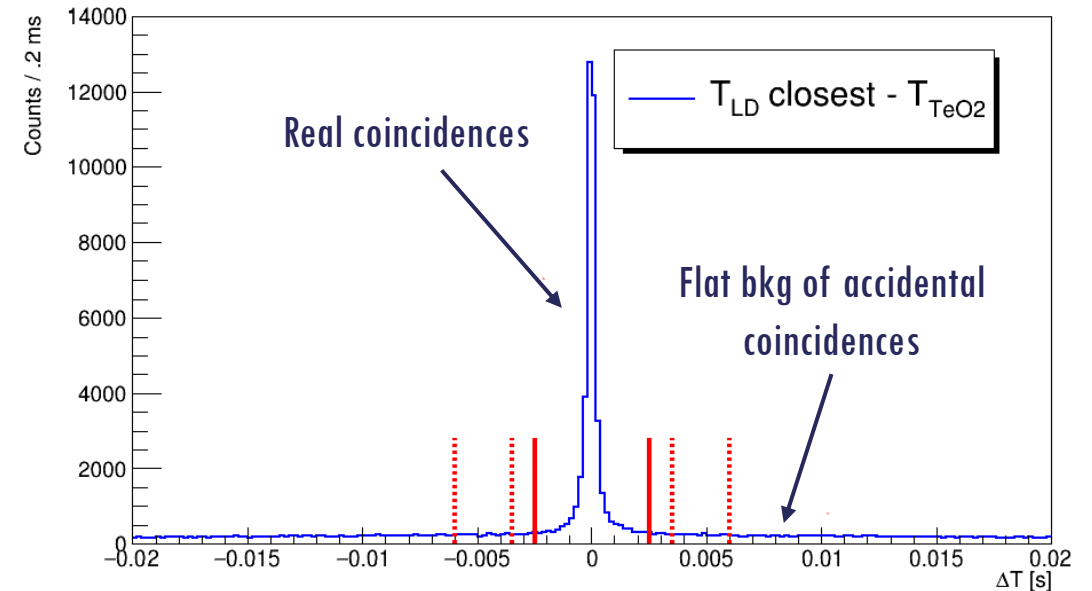
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# Hunting the $\alpha$ source with coincidence

Coincidences between  $\text{TeO}_2$  and one LD

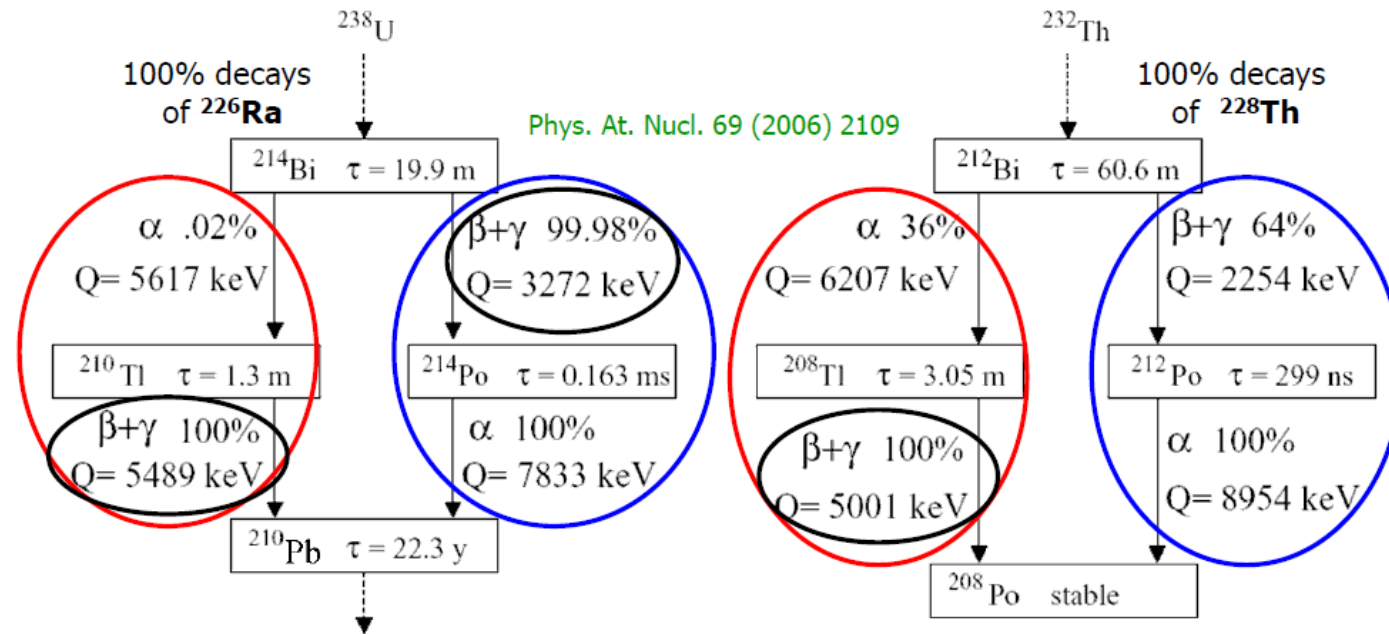


- The marked events are alphas (with shared energy in  $\text{TeO}_2$ ) in light detector



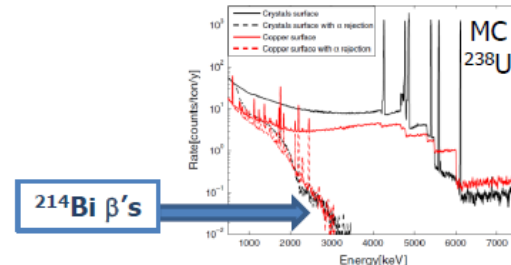
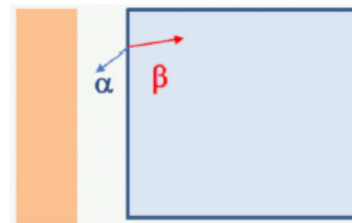
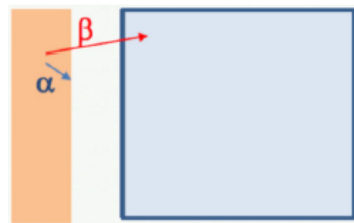
- Events in  $\text{TeO}_2$  are rejected if an event is found in a time window of 5ms in the light detectors.
- Accidental coincidences distribution is determined with the regions in red dashed lines since it should be the same under the peak

# Most harmful U/Th nuclides for $0\nu\text{DBD}$ search



## For DBD bolometers with particle ID:

- **BiPo events** (mixed  $\beta + \alpha$  decays with a total  $E > \sim 8\text{ MeV}$ ) **negligible contribute to ROI**
- **Delayed events of  $^{210,208}\text{Tl}$   $\beta$ 's can be rejected by an off-line gate after  $^{214,212}\text{Bi}$   $\alpha$ 's**
- **$\beta$ 's of  $^{212,214}\text{Bi}$  subchains ( $Q_\beta > Q_{\beta\beta}$ ) detected without  $\alpha$ 's contribute significantly to ROI**

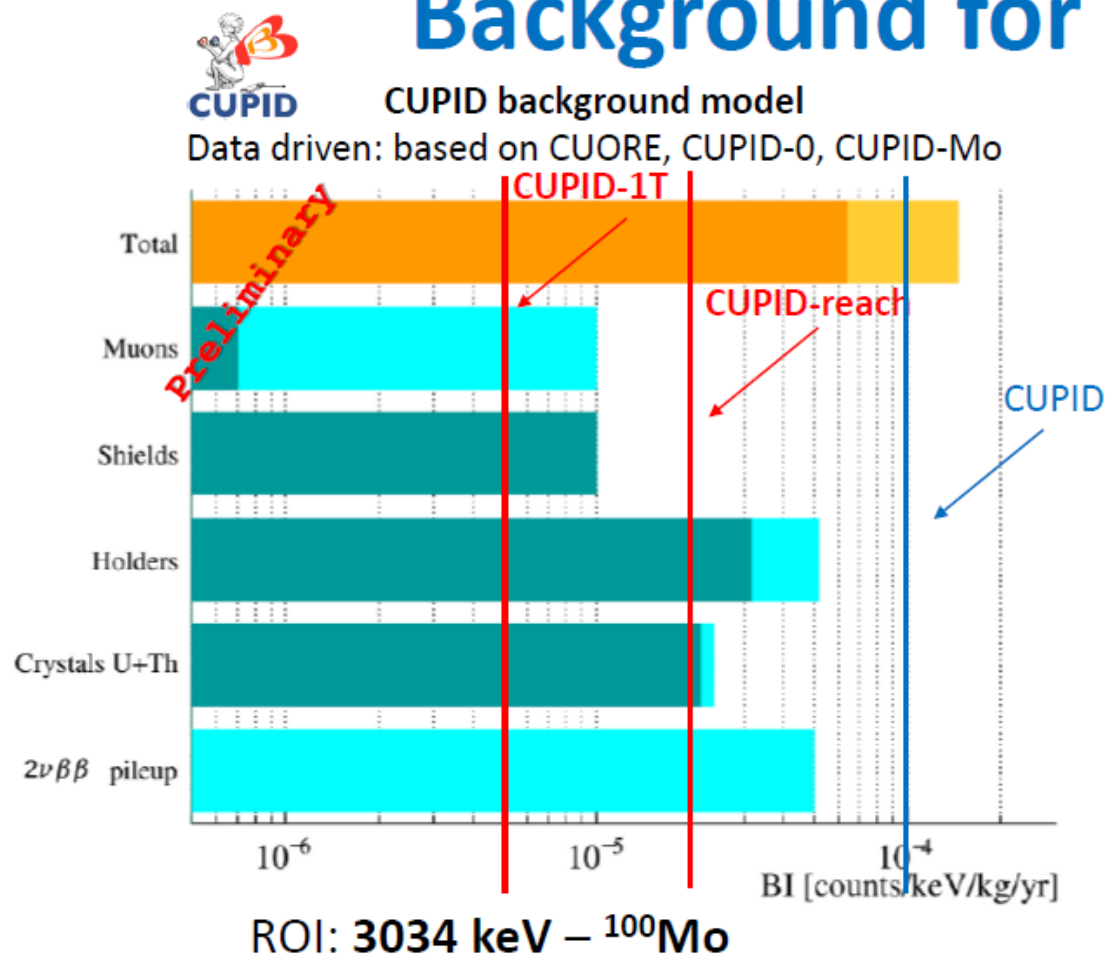


Crystal	Growth	$\lambda_{\max}$ (nm)	$L/H_{\gamma(\beta)}$ (keV/MeV) (ph/MeV)		$QF_{\alpha}$	Section
CaWO <sub>4</sub>	Cz	420 (8 K) [261]	6.0–24 (45–52 <sup>a</sup> )	2000–8100 (15,400–17,500)	0.10–0.12	Section 3.1.1 ibid.
CdWO <sub>4</sub> <sup>b</sup>	Cz, LTG Cz	420 (8 K) [261]	14–31	5400–12,000	0.18–0.19	Section 3.1.2
Li <sub>2</sub> WO <sub>4</sub> (Mo)	Cz, LTG Cz	530 (8 K) [352]	0.40	170	0.26 <sup>c</sup>	Section 3.1.3
Na <sub>2</sub> W <sub>2</sub> O <sub>7</sub>	LTG Cz	540 (77 K) [353]	12	5200	0.20	Section 3.1.4
PbWO <sub>4</sub>	Cz	420 (4.2 K) [354]	1.8	600	0.20	Section 3.1.5
ZnWO <sub>4</sub>	Cz, LTG Cz	490 (9 K) [261]	13–19	5100–9500	0.15–0.23	Section 3.1.6
CaMoO <sub>4</sub> <sup>b</sup>	Cz	540 (8 K) [261]	1.9–4.8	800–2100	0.13–0.22	Section 3.2.1
CdMoO <sub>4</sub>	BS	550 (5 K) [355]	2.6	1200	0.16	Section 3.2.2
Li <sub>2</sub> MoO <sub>4</sub> <sup>b</sup>	Cz, LTG Cz, BS	590 (8 K) [311]	0.55–1.0 (1.2–1.4 <sup>d</sup> )	300–500 (600–700)	0.17–0.23	Section 3.2.3 ibid.
Li <sub>2</sub> Mg <sub>2</sub> (MoO <sub>4</sub> ) <sub>3</sub>	LTG Cz	585 (8 K) [356]	1.3	610	0.22	Section 3.2.4
Li <sub>2</sub> Zn <sub>2</sub> (MoO <sub>4</sub> ) <sub>3</sub>	LTG Cz	630 (10 K) [357]	n/a	n/a	n/a	Section 3.2.5
MgMoO <sub>4</sub>	Cz	520 (9 K) [358]	n/a	n/a	n/a	Section 3.2.6
Na <sub>2</sub> Mo <sub>2</sub> O <sub>7</sub>	Cz, LTG Cz	650 (4.2 K) [359]	0.58–1.6	300–840	0.16–0.40	Section 3.2.7
PbMoO <sub>4</sub>	Cz, LTG Cz	520 (10 K) [360]	5.2–12	2200–5000	0.18–0.23	Section 3.2.8
SrMoO <sub>4</sub>	Cz	520 (11 K) [361]	~1–3	400–1300	~0.26	Section 3.2.9
ZnMoO <sub>4</sub> <sup>b</sup>	Cz, LTG Cz	520 (1.4 K) [362]	1.0–1.5 (1.8–2.1 <sup>d</sup> )	400–600 (800–900)	0.13–0.19	Section 3.2.10 ibid.

Crystal	Growth	$\lambda_{\max}$ (nm)	$L/H_{\gamma(\beta)}$ (keV/MeV) (ph/MeV)		$QF_{\alpha}$	Section
Li <sub>6</sub> Eu(BO <sub>3</sub> ) <sub>3</sub>	Cz	613 (4.2 K) [363]	6.6	3200	0.08	Section 3.3.1
Li <sub>6</sub> Gd(BO <sub>3</sub> ) <sub>3</sub> <sup>b</sup>	Cz	312 (90 K) [364]	0.26	65	0.23	Section 3.3.2
Al <sub>2</sub> O <sub>3</sub> (Ti), pure	Ve, Ky, Cz	420 (9 K) [365]	2.5–14	850–4700	0.09–0.36	Section 3.4.1
Bi <sub>4</sub> Ge <sub>3</sub> O <sub>12</sub>	Cz, LTG Cz, BS	480 (9 K) [261]	7.0–28	2700–11,000	0.17–0.18	Section 3.4.2
LiAlO <sub>2</sub>	Cz	340 (300 K) [366]	1.2	300	0.52	Section 3.4.3
TeO <sub>2</sub> <sup>b</sup>	BS, Cz	500 (<15 K) [271]	~0.04	~20	n/a	Section 3.4.4
YVO <sub>4</sub>	Cz	450 (80 K) [367]	59	21,000	0.20	Section 3.4.5
ZrO <sub>2</sub>		420 (85 K) [368]	~2	~700	~0.2	Section 3.4.6
LiInSe <sub>2</sub>	BS	730 (173 K) [265]	14	8200	0.55	Section 3.5.1
ZnSe <sup>b</sup>	BS	640 (9 K) [261]	0.7–7.5	360–3900	2.6–4.6	Section 3.5.2
CaF <sub>2</sub> (Eu)	Cz, BS	425 (15 K) [369]	14	4800	0.14–0.19	Section 3.6.1
LiF <sup>b</sup>	Cz, BS	365 (9 K) [370]	0.21–0.38	60–110	0.30	Section 3.6.2
SrF <sub>2</sub>	Cz, BS	365 (4.2 K) [371]	2.9	850	0.26	Section 3.6.3
CsI	Ky, Cz, BS	340 (10 K) [264]	49–81	13,000–22,000	~0.5	Section 3.7.1
NaI	Ky, Cz, BS	300 (10 K) [372]	37 (130 <sup>a</sup> )	9000 (32,000)	~0.2 <sup>e</sup>	Section 3.7.2

<sup>a</sup> An advanced light collection using a beaker-shaped light detector. <sup>b</sup> Including crystals produced from materials enriched in an isotope of interest. <sup>c</sup> Estimated for  $\alpha + t$  events (4.8 MeV sum energy, products of neutron capture by <sup>6</sup>Li). <sup>d</sup> An improved light collection using two identical light detectors at the crystal top and bottom. <sup>e</sup> Estimated for Na nuclear recoils.

# Background for $^{100}\text{Mo}$ : status



Full  $\alpha$  rejection down to BI <  $10^{-5}$  counts/keV/kg/y is assumed