BINGO: Bi-Isotope $0\nu2\beta$ Next Generation Observatory
An Overview

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ON BEHALF THE BINGO COLLABORATION

GDR Deep Underground Physics plenary meeting
19-21 Oct 2022

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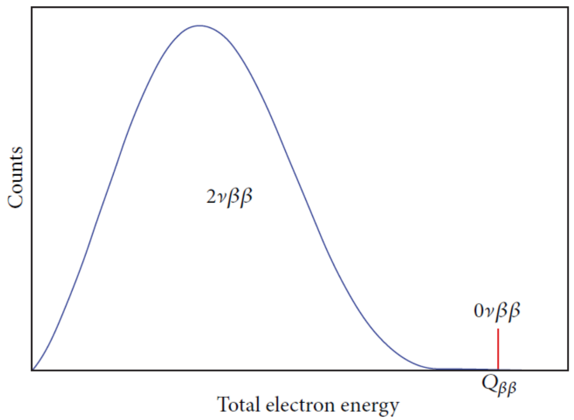
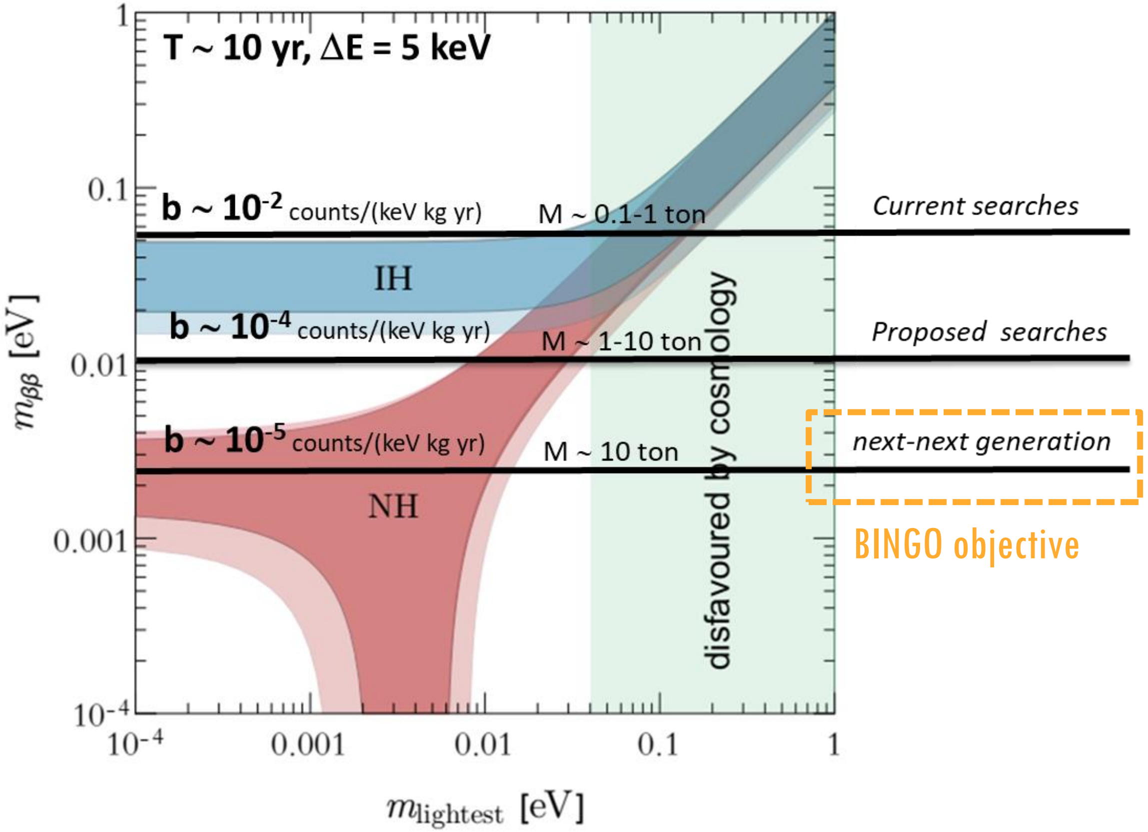
Neutrinoless double beta decay

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

Its observation will:

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



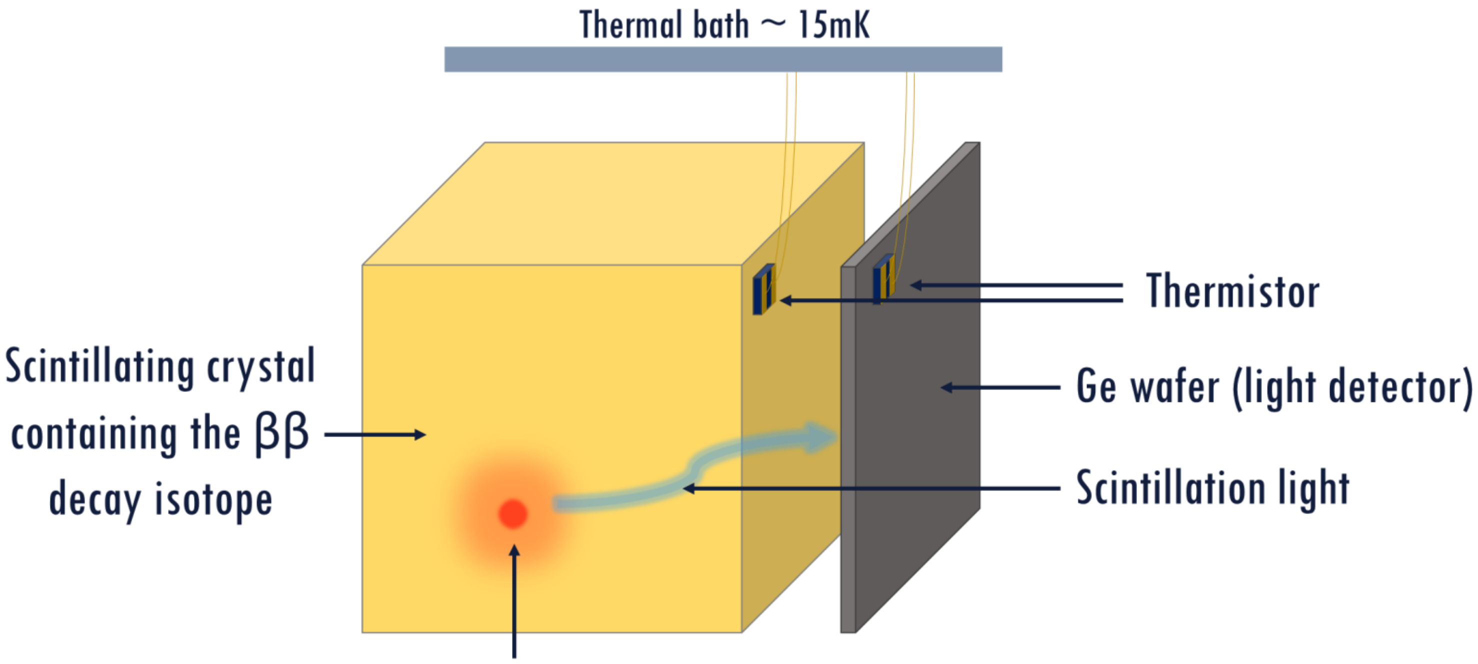


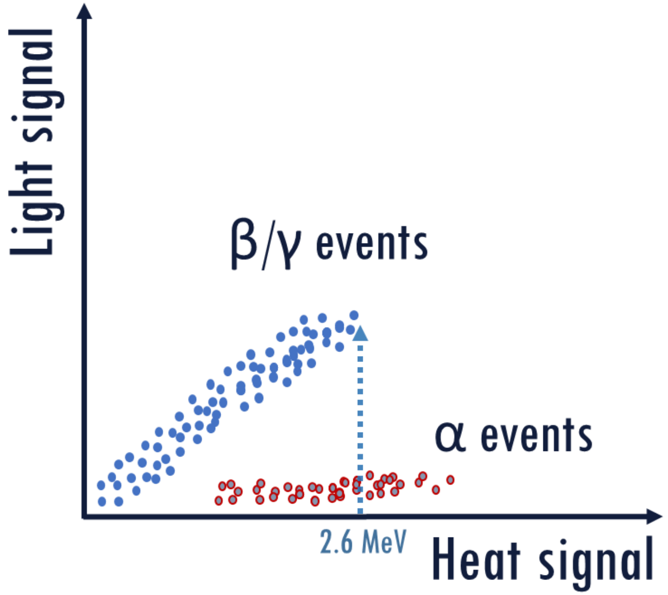
- BINGO will set the grounds for a large scale bolometric experiment searching for neutrinoless double-beta decay (0ν2β) using revolutionary technologies
- It aims to reduce dramatically the background in the region of interest, which is one of the most limiting factors for current and future 0ν2β experiments

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

M: detector mass
t: time of measurement
BI: background index
ΔE: 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 αs

Features

- high energy resolution
- full active volume (no dead layer)
- flexible material choice (Li_2MoO_4, TeO_2)

Bolometric compounds' strong and weak points

Li_2MoO_4

- Embeds ^{100}**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 $2\nu2\beta$ decay → background in the region of interest (ROI) due to $2\nu2\beta$ random coincidences

TeO_2

- Embeds ^{130}**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}Tl) of natural gamma radioactivity
- Very poor scintillator → 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

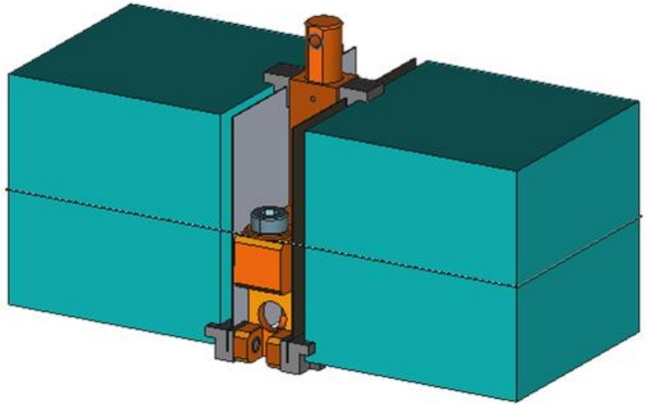
Reduce the Cu materials seen by the main absorber using a LD as an active shield

↓

reduction of the total surface radioactivity contribution

Compact assembly

Background reduction through anticoincidence cuts

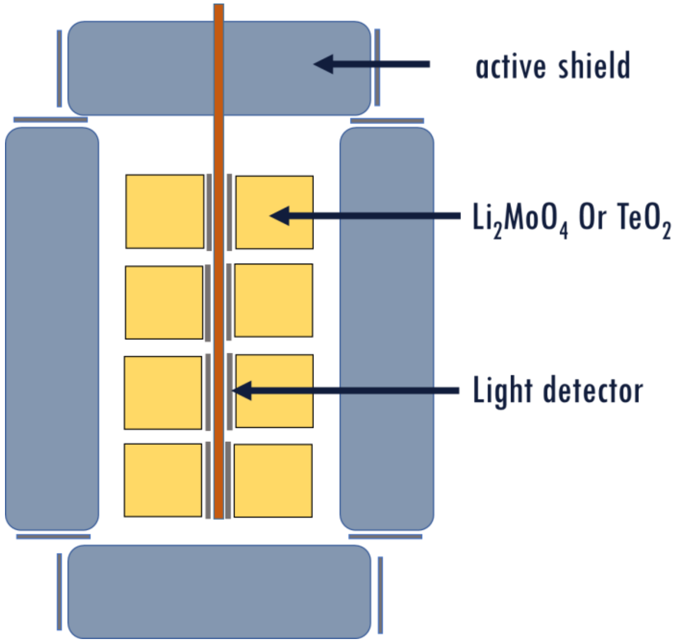


Active veto

Use an active shield, based on $ZnWO_4$ 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

↓

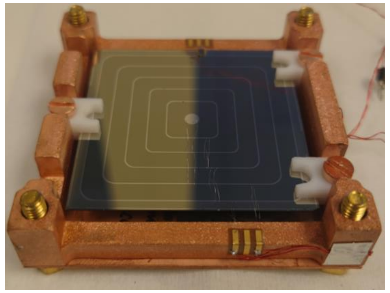
suppress external γ background using the active shield

2- reject the background induced by the random coincidences of $2\nu2\beta$ events in LMO

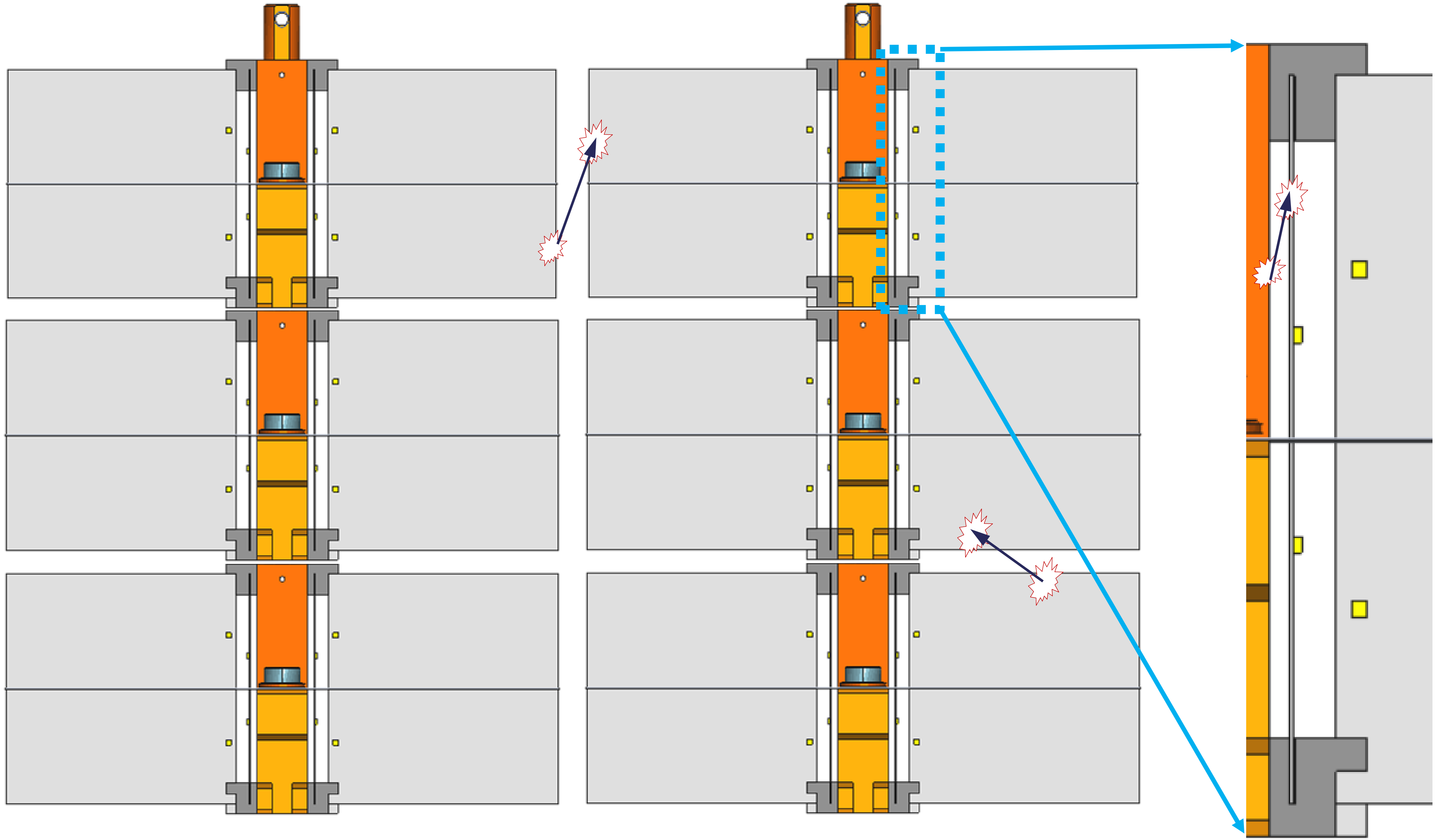
Amplification of the tiny Cherenkov signal (TeO_2)

↓

suppress alphas



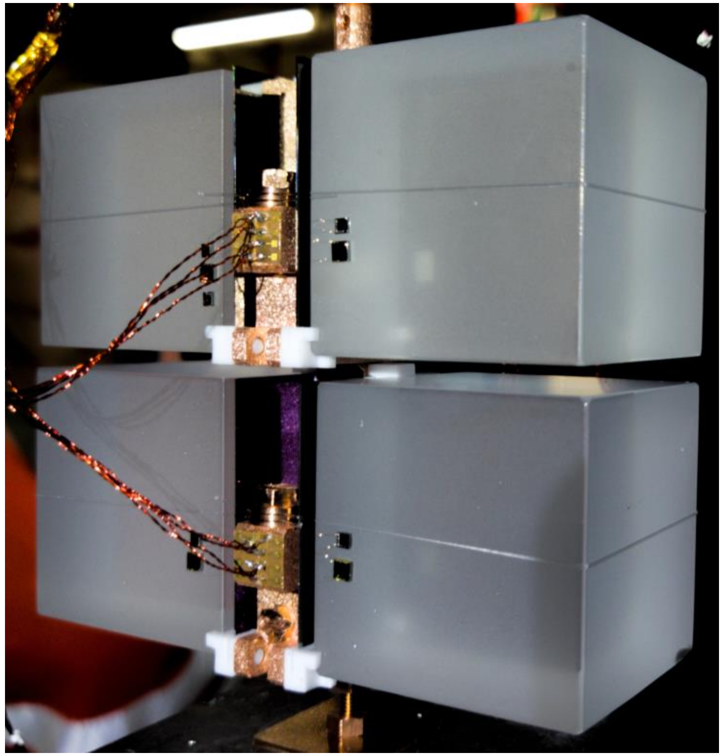
Assembly upgrade



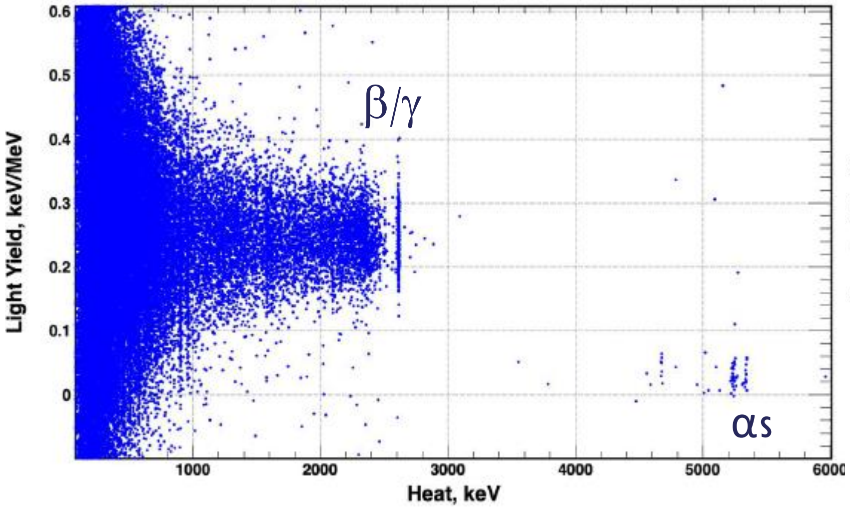
Surface contaminations can be rejected with coincidence thanks to the compact assembly and LD shielding

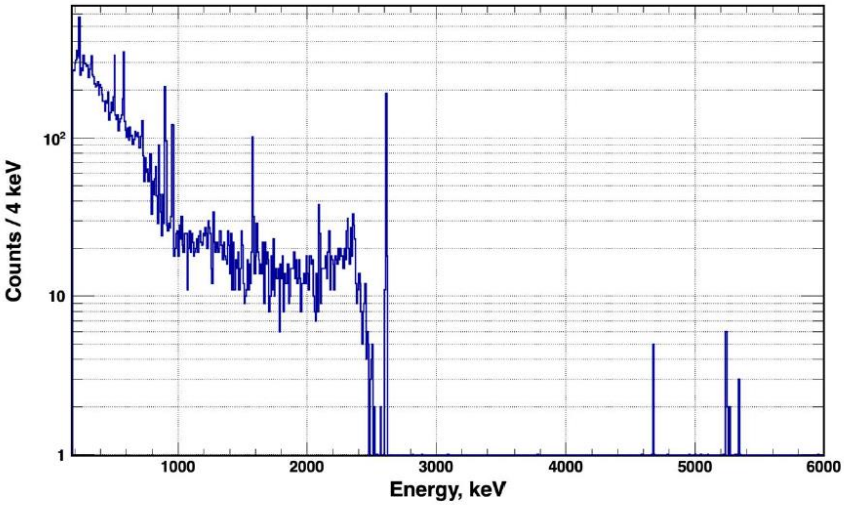
New assembly test on Li_2MoO_4

- 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 ~ 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 α and β/γ





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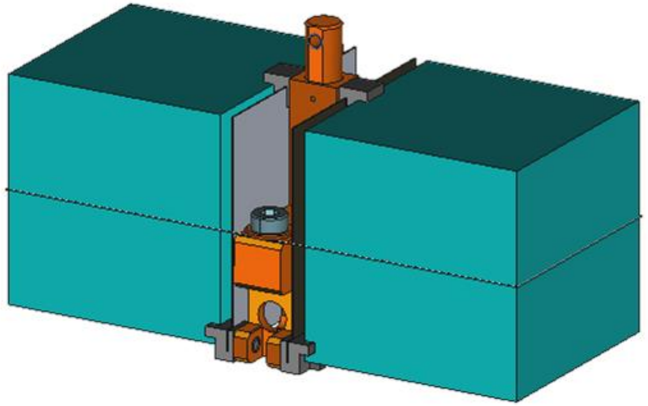

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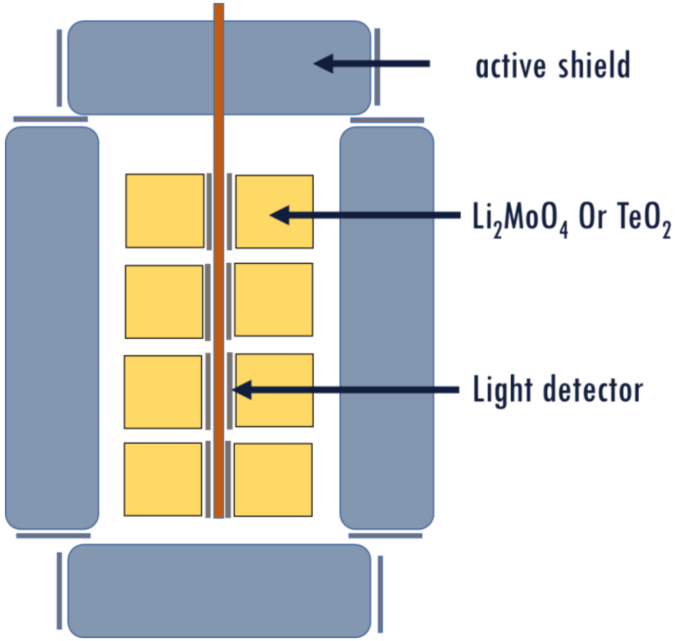

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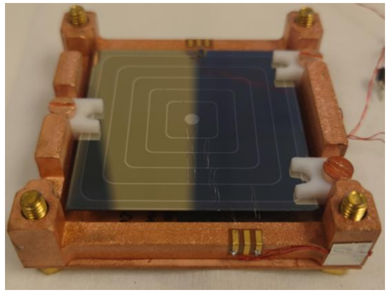
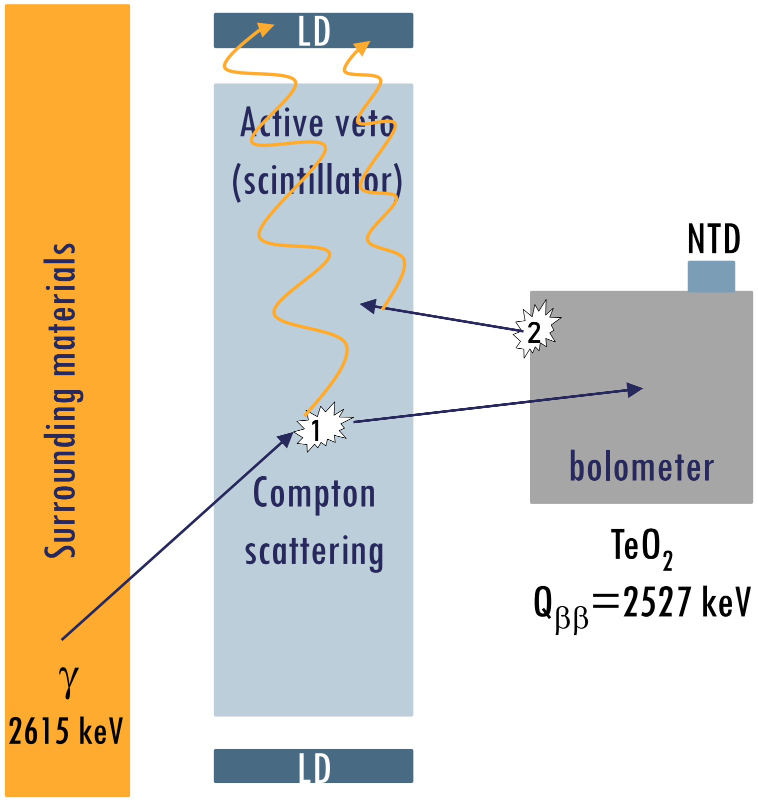


How does the veto work

The crystals on the periphery will be exposed directly to the veto



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- If the 2615 keV γ deposit a small amount of energy in the surrounding material (~80 keV) and the rest in TeO$_2$ ⟶ 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$_2$

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 (~50 keV in the scintillator corresponding to few keV in LD)

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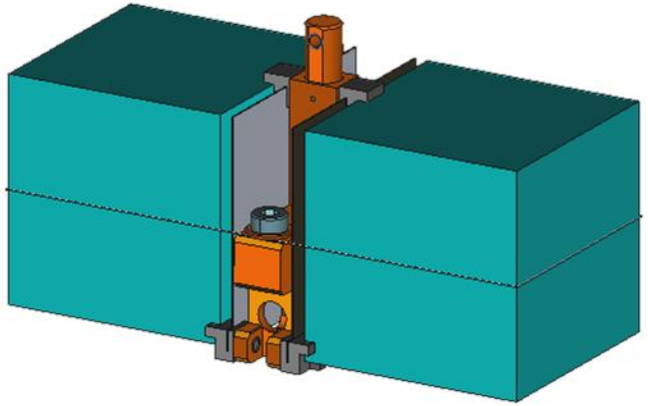

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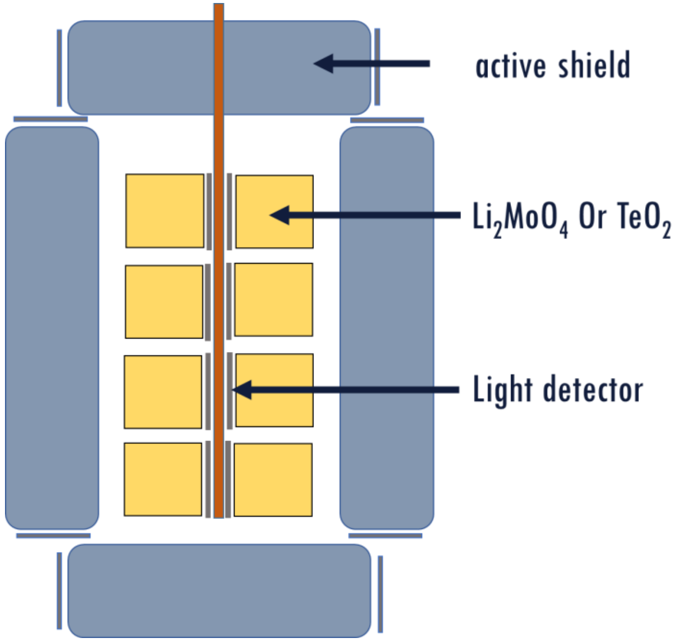

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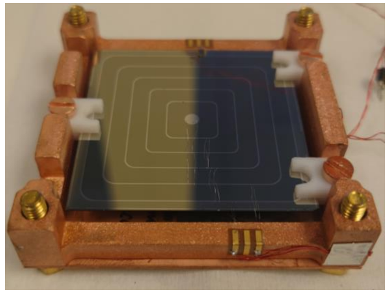

How does Neganov-Luke LD work

Ge wafer provided with Al electrodes on its surface

↓

When applying voltage across these electrodes an electric field is establish

↓

The absorption of photons produces electron-hole pairs

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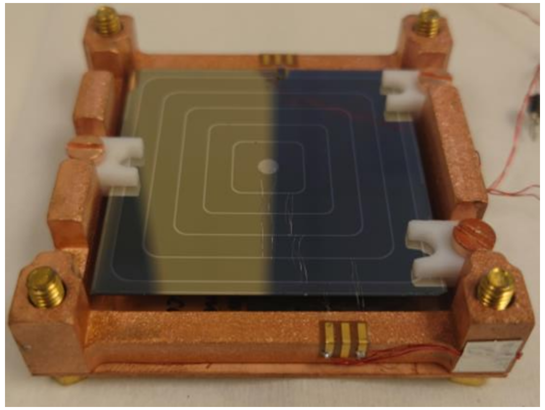
The electric field drifts the charges and it prevents their recombination

↓

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

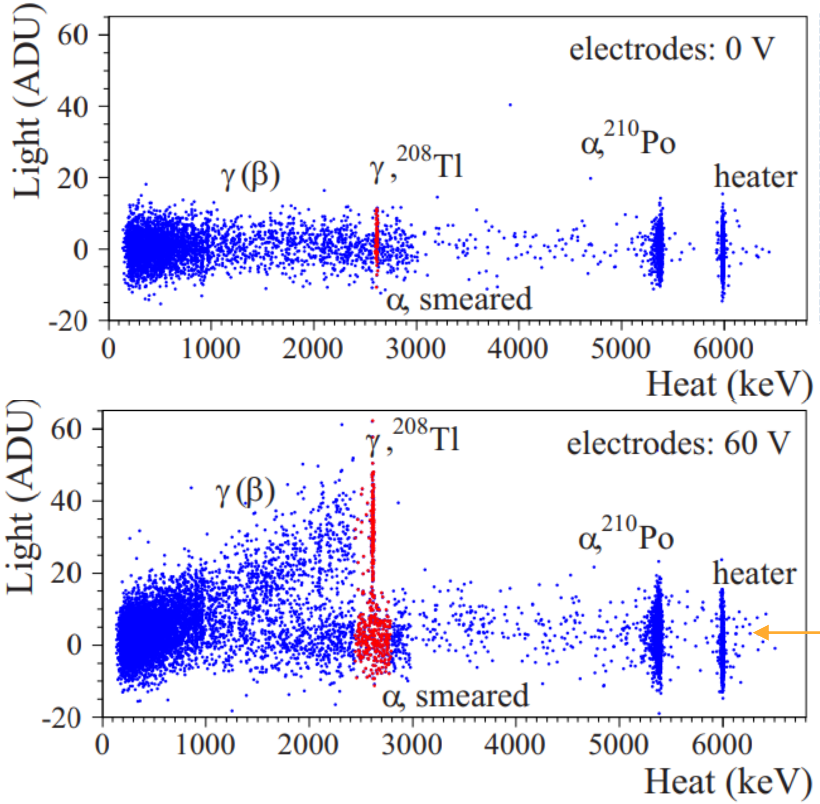
↓

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



The effect

CUORE-size TeO_2 bolometer (5×5×5 cm^3 as in BINGO) coupled to NL LD tested at LSM in 2017 proved the concept (PHYSICAL REVIEW C 97, 032501(R) (2018))



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

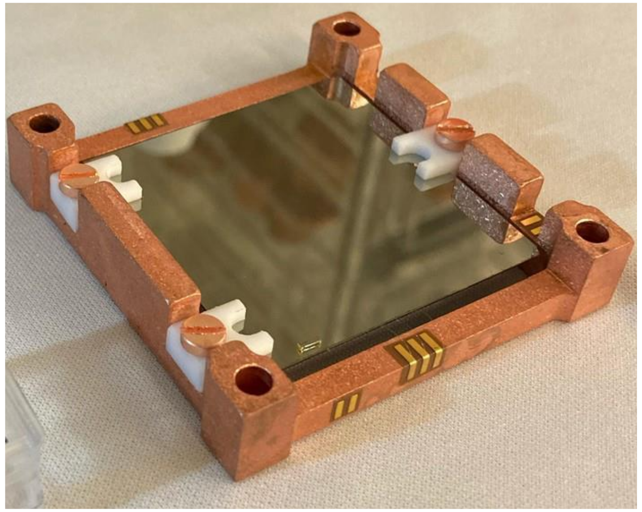
Alpha rejection is achieved

Amplification factor ~ 13

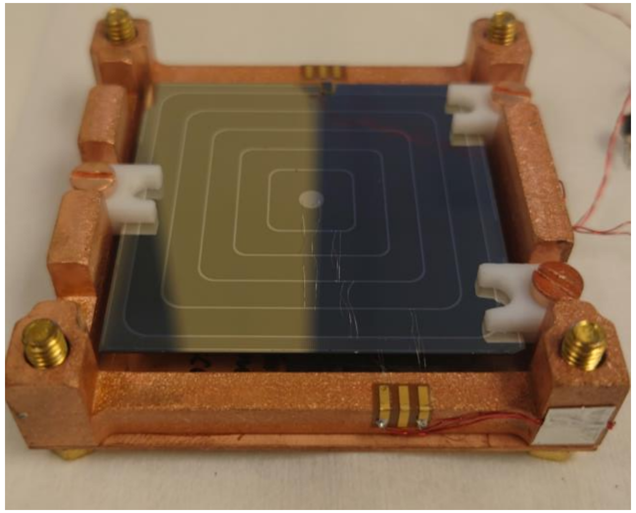
In addition, with NL LD we can get a lower energy threshold thanks to higher signal to noise ratio

Neganov-Luke light detector

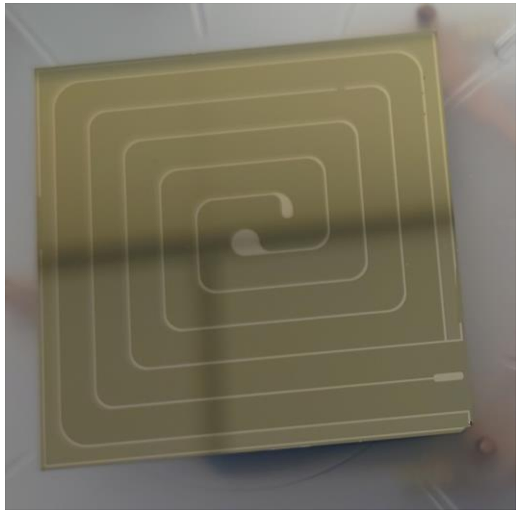
- Currently we are testing NL LD with different electrodes geometry in order to achieve a high amplification gain and good bolometric performances



Electrodes on 2 opposite edges



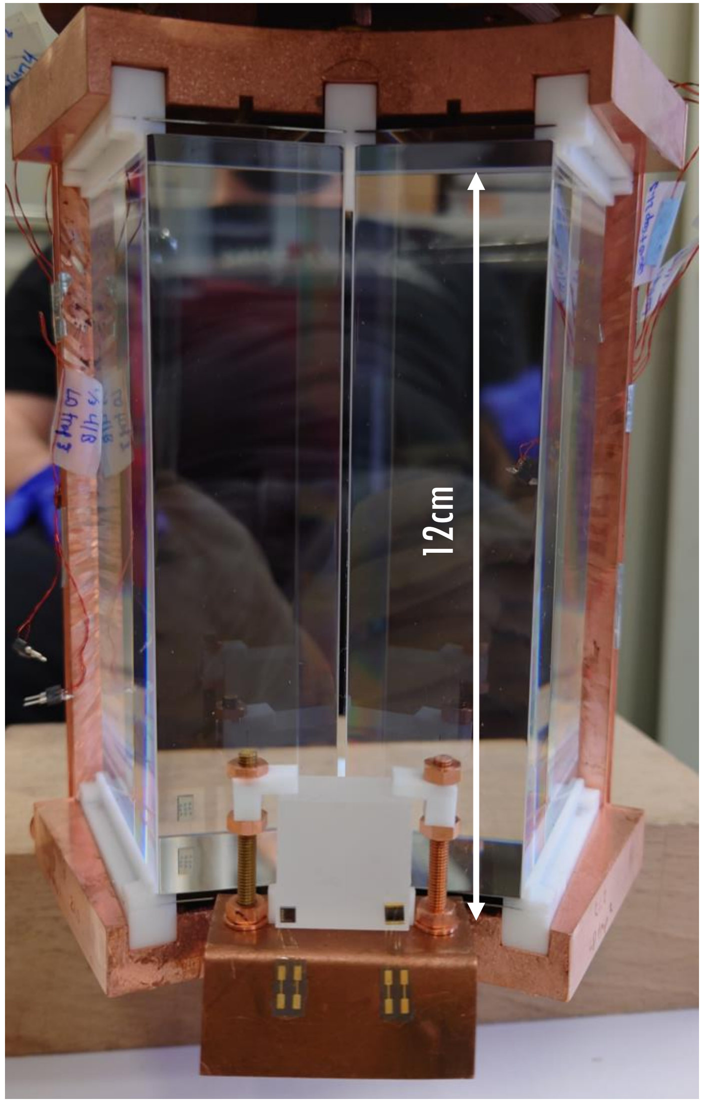
Concentric Electrodes



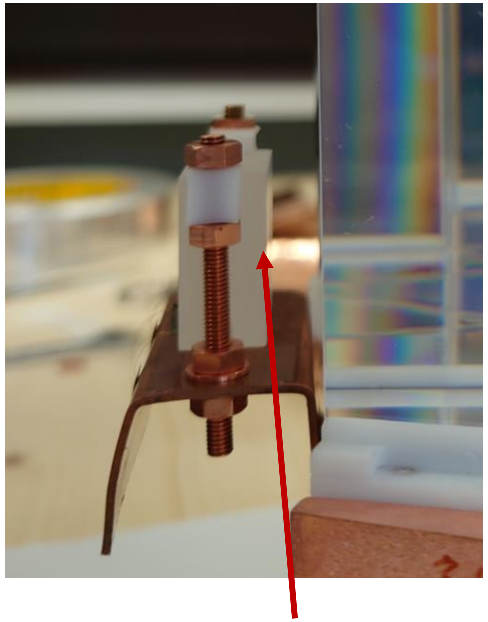
Double meander Electrodes

Active veto aboveground prototype test

- We have two choices for the veto: BGO or $ZnWO_4$
- Small crystals samples were tested to check the light yield and energy threshold
- BGO showed higher light yield, while $ZnWO_4$ showed better radiopurity
- BGO can be grown as long bars, while for the moment for $ZnWO_4$ it is not clear it can be done
- Further investigation is needed to choose the veto material



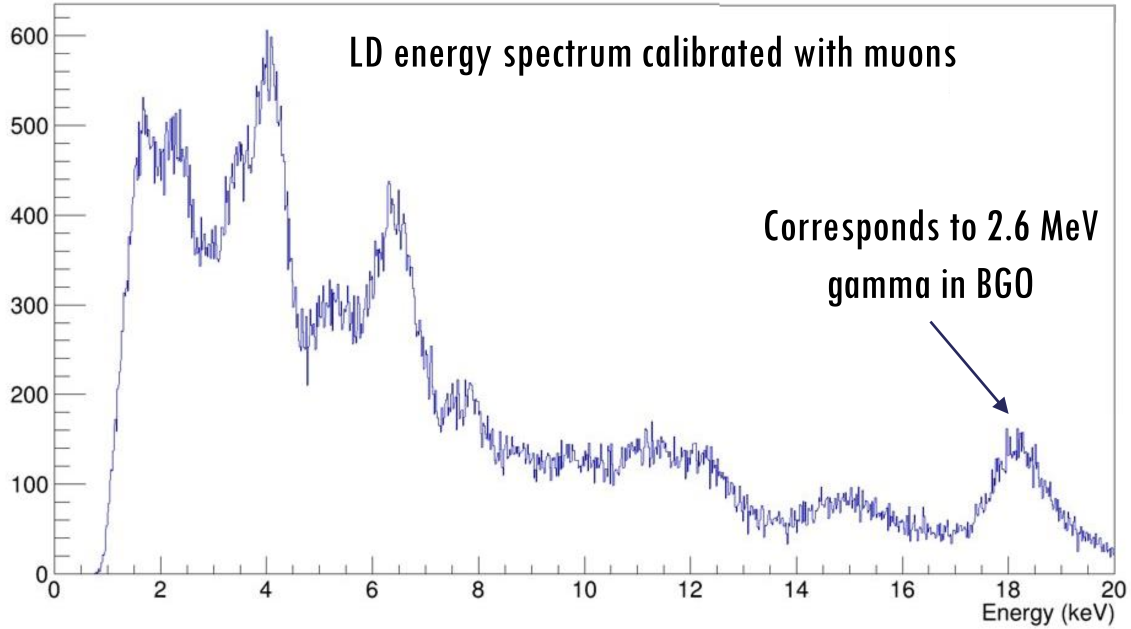
- 2 BGO crystals (~1.6kg each)
- 2 LDs facing each BGO
- TeO_2 crystal facing both BGOs



Uranium α source deposited on TeO_2 to imitate surface contamination (at 4.2 and 4.8 MeV)

Energy threshold and efficiency study

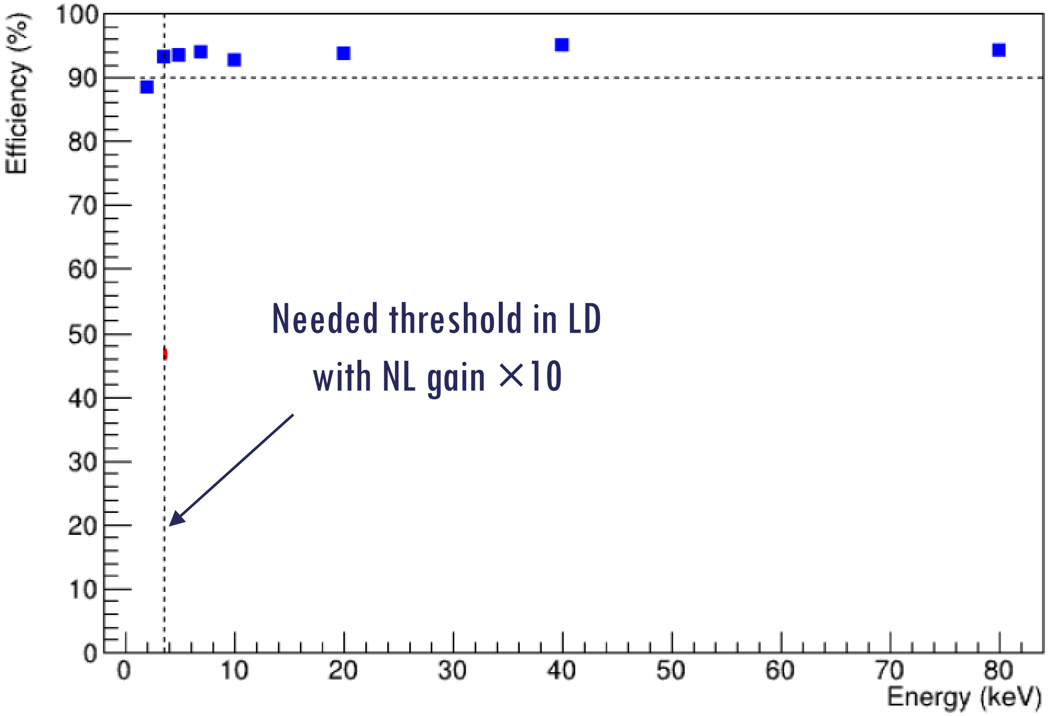
- 1000 fake pulses at different energies were injected into the data to estimated the efficiency after data processing
- The required energy threshold for the veto scintillator should be around 50 keV, which corresponds to around 3-4 keV in LD when taking into account the light yield (LY) which is around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



LD energy spectrum calibrated with muons

Corresponds to 2.6 MeV gamma in BGO

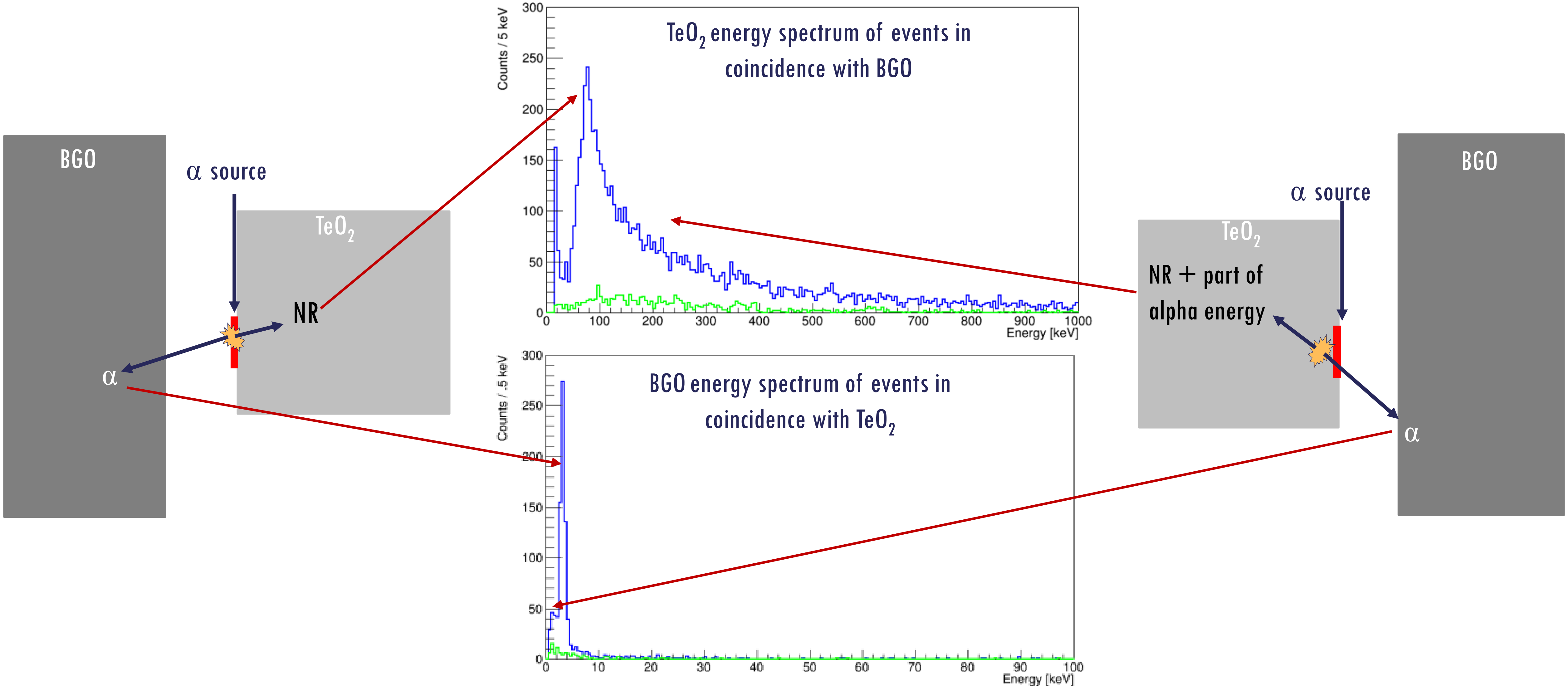
Energy released by photons in LD



Needed threshold in LD with NL gain ×10

Energy released by photons in LD

Hunting the α source with coincidence


TeO$_2$ energy spectrum of events in coincidence with BGO

BGO energy spectrum of events in coincidence with TeO$_2$

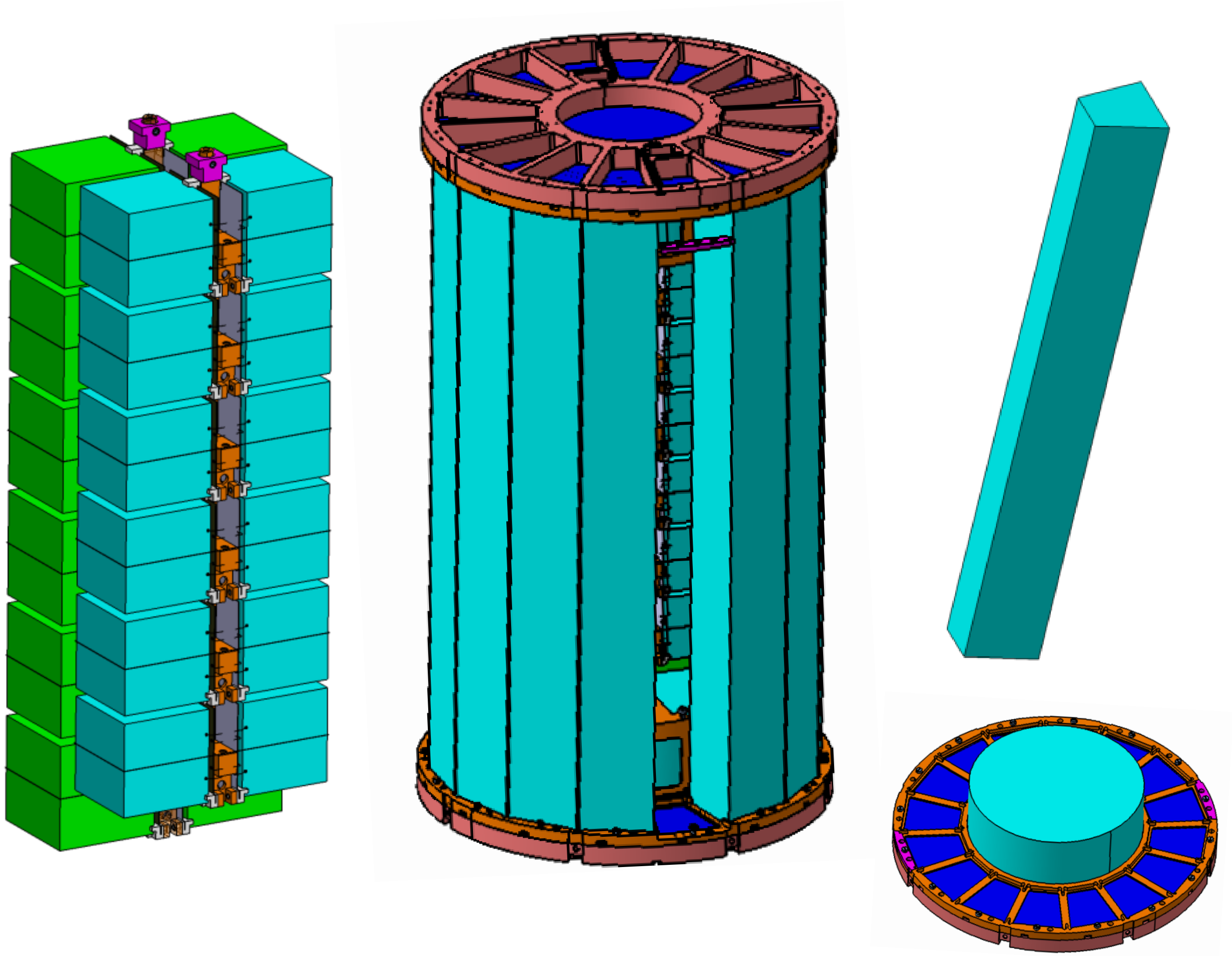
The mini-BINGO ingredients

Double beta decay part

- 12 cubic Li_2MoO_4 scintillating crystals (45×45×45 mm), each is coupled to a light detector (45×45 mm)
- 12 cubic TeO_2 crystals (50×50×50 mm), each is coupled to a light detector (50×50 mm)

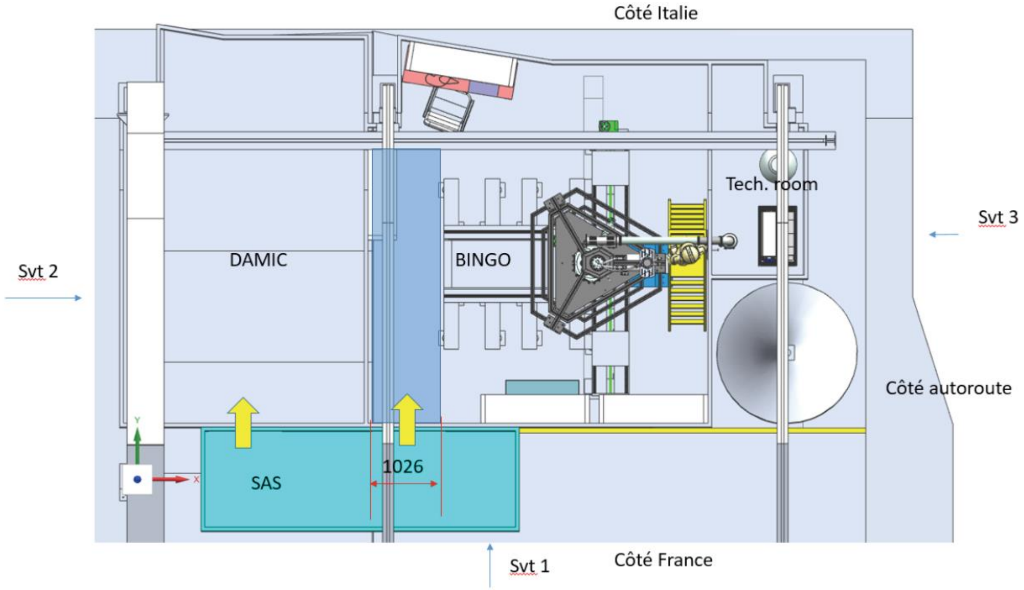
Cryogenic veto part surrounding the physics volume

- 16 trapezoidal cross-section + 2 disc scintillators (BGO or $ZnWO_4$) 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 TeO_2 towers can be tested in the cryostat and work on the background
- The goal is to reach background level below 10^{-3} c/(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] MeV interval, comprising both ROIs, a background level down to 10^{-4} c/(keV kg y) is in principle testable



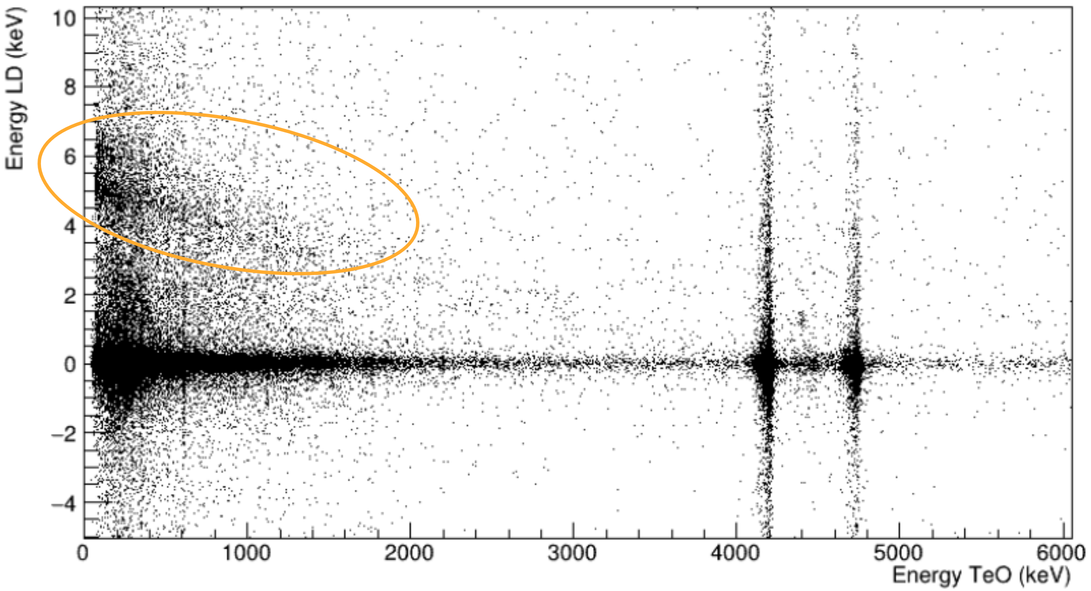
Conclusion and perspectives

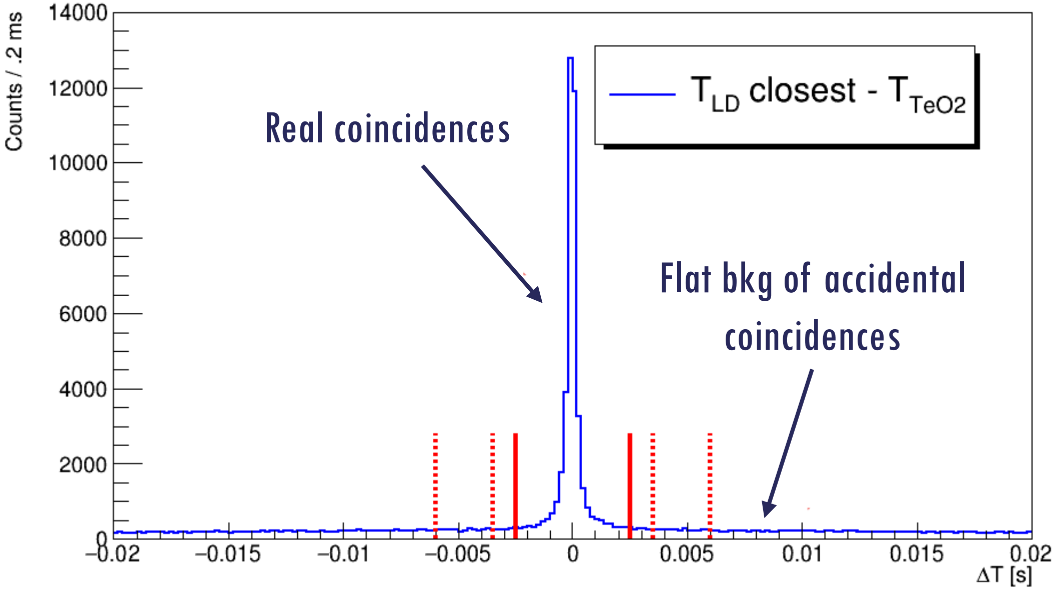
- BINGO is a promising project towards the meV scale of the effective Majorana mass
- BINGO proposed technologies are a possible candidate for CUPID-1T
- New technology that allows to reach b$\sim 10^{-5}$ counts/(keV kg yr)
- The nylon wire assembly is almost validated
- More R&D is needed to develop 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

Hunting the α source with coincidence

Coincidences between TeO_2 and one LD

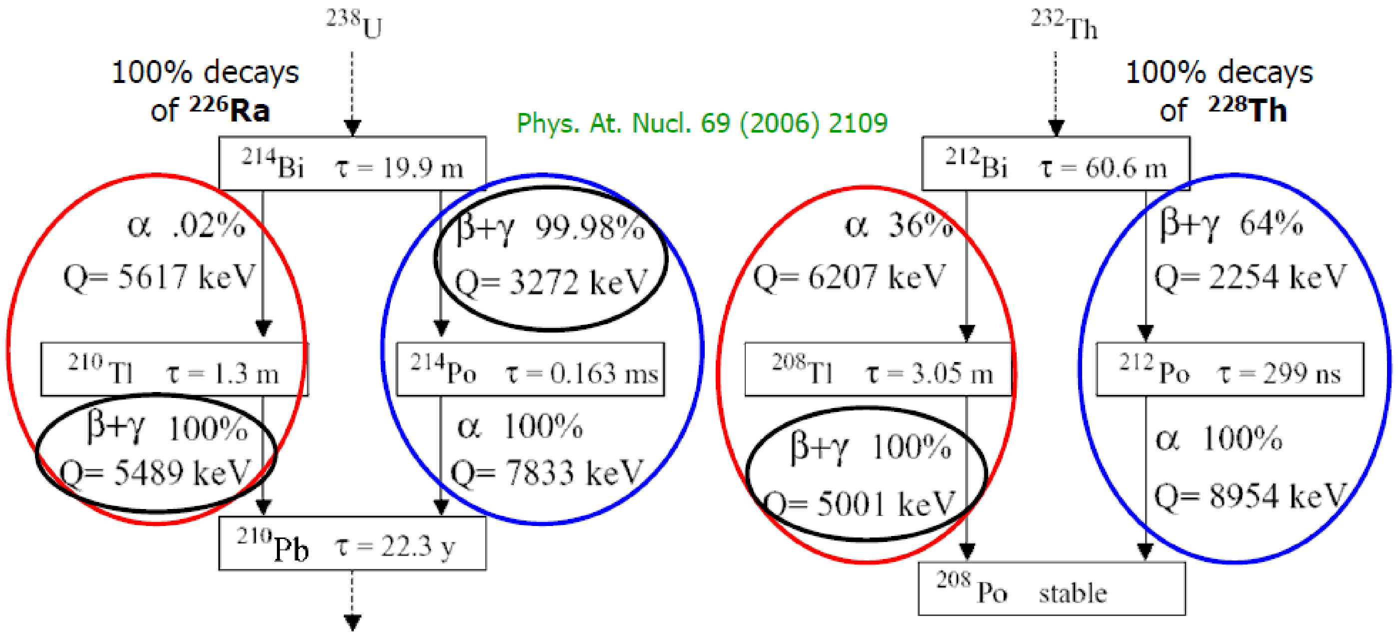




- The marked events are alphas (with shared energy in TeO_2) in light detector

- Events in 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 0νDBD search



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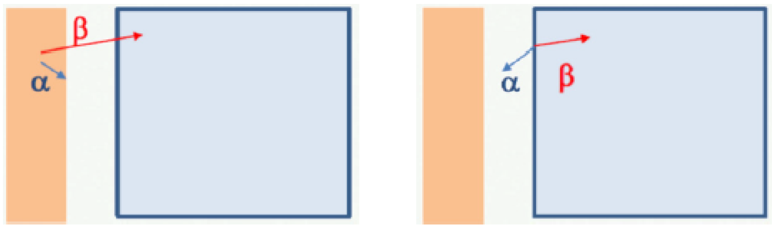
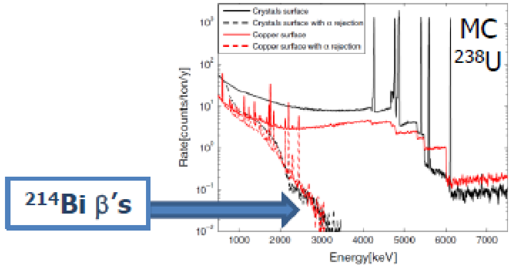
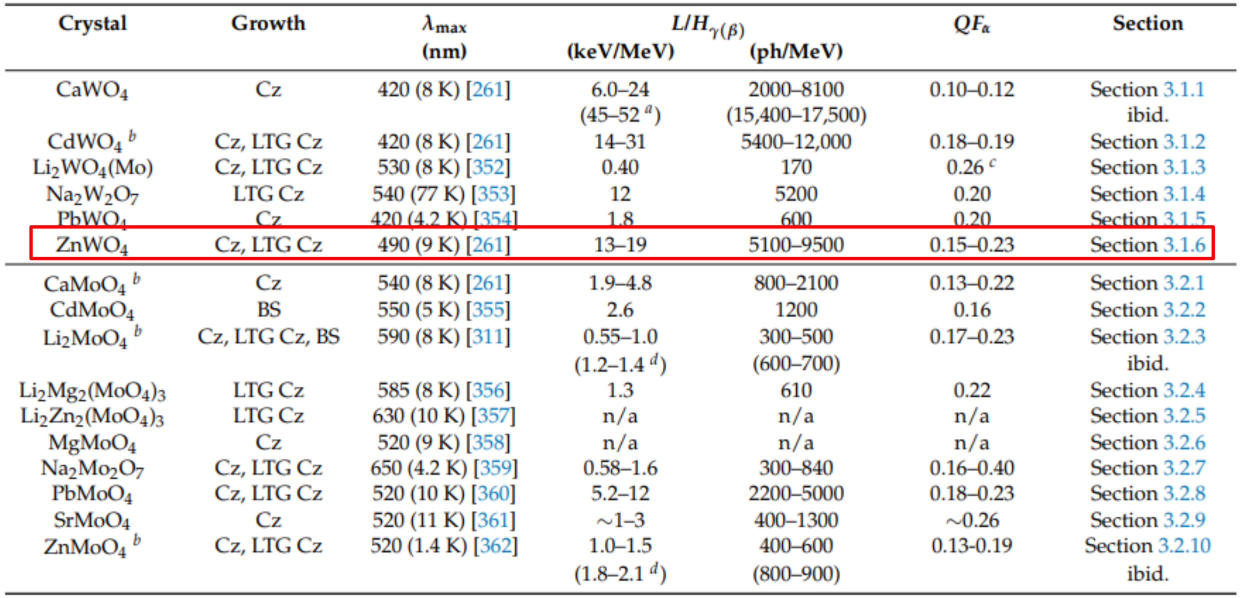
For DBD bolometers with particle ID:

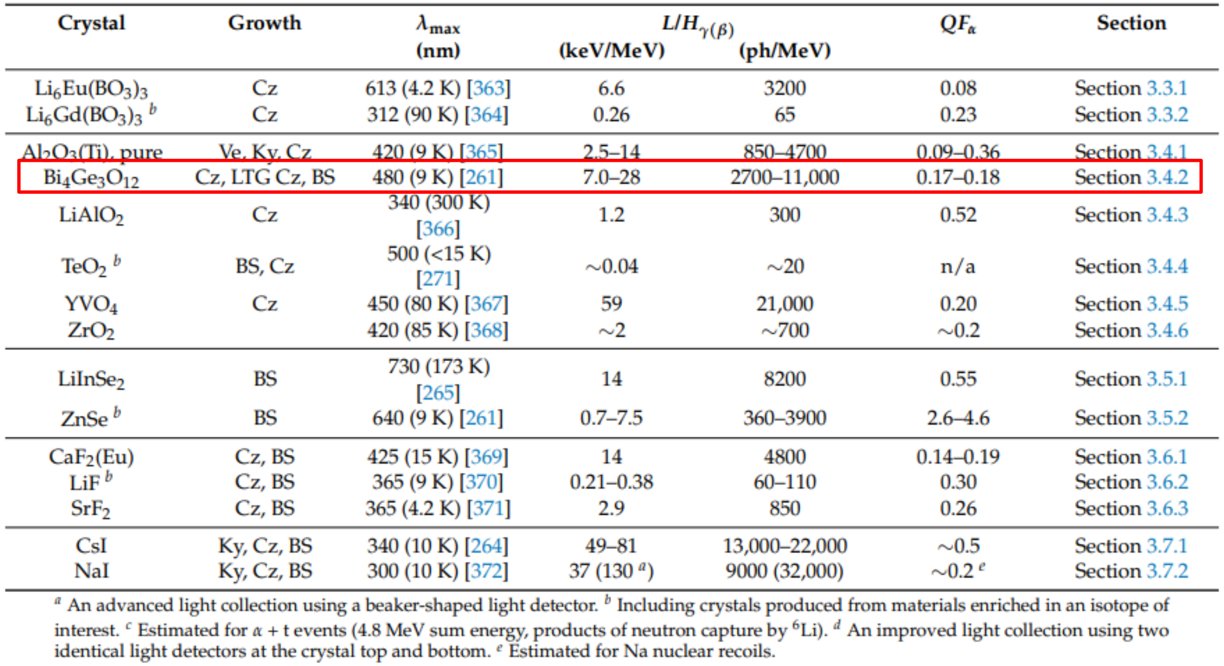
- **BiPo events** (mixed β+α decays with a total E > ~8 MeV) **negligible contribute to ROI**
- **Delayed events of ^{210,208}Tl β's can be rejected by an off-line gate after ^{214,212}Bi α's**
- **β's of ^{212,214}Bi subchains ($Q_{\beta} > Q_{\beta\beta}$) detected without α's contribute significantly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







Crystal	Growth	λ_{max}	$L/H_{\gamma(\beta)}$		QF_α	Section
		(nm)	(keV/MeV)	(ph/MeV)		
CaWO$_4$	Cz	420 (8 K) [261]	6.0–24	2000–8100	0.10–0.12	Section 3.1.1
			(45–52 [a])	(15,400–17,500)		ibid.
CdWO$_4$ [b]	Cz, LTG Cz	420 (8 K) [261]	14–31	5400–12,000	0.18–0.19	Section 3.1.2
Li$_2$WO$_4$(Mo)	Cz, LTG Cz	530 (8 K) [352]	0.40	170	0.26 [c]	Section 3.1.3
Na$_2$W$_2$O$_7$	LTG Cz	540 (77 K) [353]	12	5200	0.20	Section 3.1.4
PbWO$_4$	Cz	420 (4.2 K) [354]	1.8	600	0.20	Section 3.1.5
ZnWO$_4$	Cz, LTG Cz	490 (9 K) [261]	13–19	5100–9500	0.15–0.23	Section 3.1.6
CaMoO$_4$ [b]	Cz	540 (8 K) [261]	1.9–4.8	800–2100	0.13–0.22	Section 3.2.1
CdMoO$_4$	BS	550 (5 K) [355]	2.6	1200	0.16	Section 3.2.2
Li$_2$MoO$_4$ [b]	Cz, LTG Cz, BS	590 (8 K) [311]	0.55–1.0	300–500	0.17–0.23	Section 3.2.3
			(1.2–1.4 [d])	(600–700)		ibid.
Li$_2$Mg$_2$(MoO$_4$)$_3$	LTG Cz	585 (8 K) [356]	1.3	610	0.22	Section 3.2.4
Li$_2$Zn$_2$(MoO$_4$)$_3$	LTG Cz	630 (10 K) [357]	n/a	n/a	n/a	Section 3.2.5
MgMoO$_4$	Cz	520 (9 K) [358]	n/a	n/a	n/a	Section 3.2.6
Na$_2$Mo$_2$O$_7$	Cz, LTG Cz	650 (4.2 K) [359]	0.58–1.6	300–840	0.16–0.40	Section 3.2.7
PbMoO$_4$	Cz, LTG Cz	520 (10 K) [360]	5.2–12	2200–5000	0.18–0.23	Section 3.2.8
SrMoO$_4$	Cz	520 (11 K) [361]	~1–3	400–1300	~0.26	Section 3.2.9
ZnMoO$_4$ [b]	Cz, LTG Cz	520 (1.4 K) [362]	1.0–1.5	400–600	0.13-0.19	Section 3.2.10
			(1.8–2.1 [d])	(800–900)		ibid.



Crystal	Growth	λ_{max}	$L/H_{\gamma(\beta)}$		QF_α	Section
		(nm)	(keV/MeV)	(ph/MeV)		
Li$_6$Eu(BO$_3$)$_3$	Cz	613 (4.2 K) [363]	6.6	3200	0.08	Section 3.3.1
Li$_6$Gd(BO$_3$)$_3$ [b]	Cz	312 (90 K) [364]	0.26	65	0.23	Section 3.3.2
Al$_2$O$_3$(Ti), pure	Ve, Ky, Cz	420 (9 K) [365]	2.5–14	850–4700	0.09–0.36	Section 3.4.1
Bi$_4$Ge$_3$O$_{12}$	Cz, LTG Cz, BS	480 (9 K) [261]	7.0–28	2700–11,000	0.17–0.18	Section 3.4.2
LiAlO$_2$	Cz	340 (300 K) [366]	1.2	300	0.52	Section 3.4.3
TeO$_2$ [b]	BS, Cz	500 (<15 K) [271]	~0.04	~20	n/a	Section 3.4.4
YVO$_4$	Cz	450 (80 K) [367]	59	21,000	0.20	Section 3.4.5
ZrO$_2$		420 (85 K) [368]	~2	~700	~0.2	Section 3.4.6
LiInSe$_2$	BS	730 (173 K) [265]	14	8200	0.55	Section 3.5.1
ZnSe [b]	BS	640 (9 K) [261]	0.7–7.5	360–3900	2.6–4.6	Section 3.5.2
CaF$_2$(Eu)	Cz, BS	425 (15 K) [369]	14	4800	0.14–0.19	Section 3.6.1
LiF [b]	Cz, BS	365 (9 K) [370]	0.21–0.38	60–110	0.30	Section 3.6.2
SrF$_2$	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 [a])	9000 (32,000)	~0.2 [e]	Section 3.7.2

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

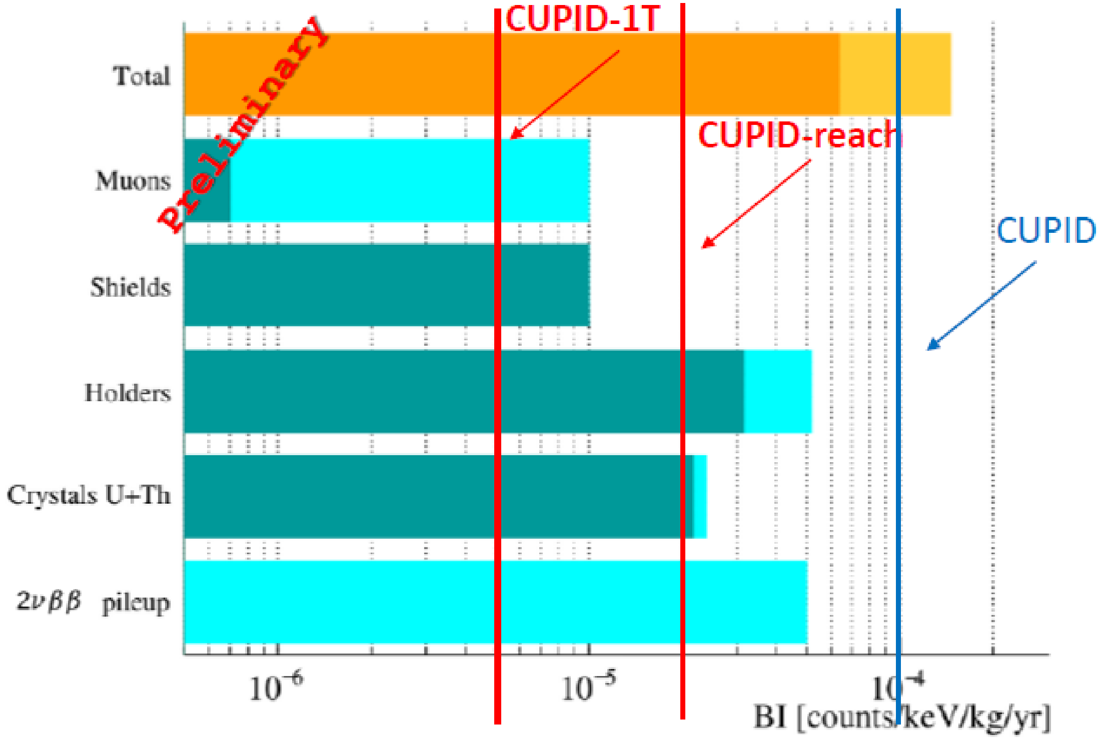
Poda, D. Scintillation in Low-Temperature Particle Detectors. Physics 2021, 3, 473–535

Background for ^{100}Mo: status

CUPID

CUPID background model

Data driven: based on CUORE, CUPID-0, CUPID-Mo



ROI: **3034 keV** – ^{100}**Mo**

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