BINGO: a new proposal for background reduction in $0\nu\beta\beta$ bolometric experiments

Hawraa Khalife for the BINGO collaboration

XX International Workshop on Neutrino Telescopes

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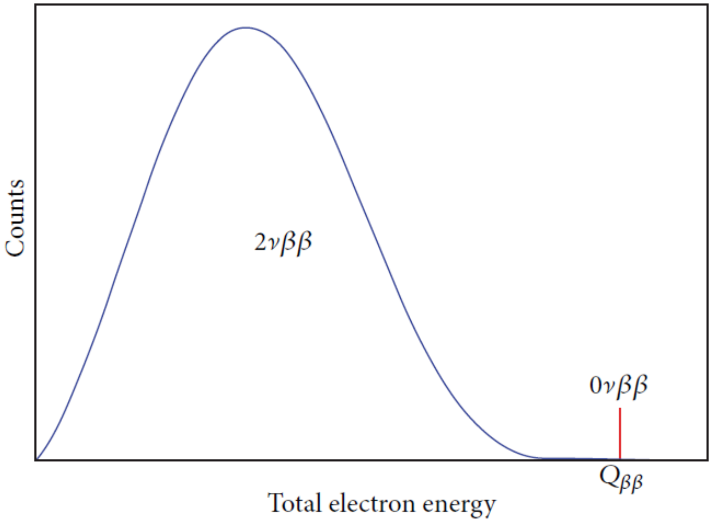
What are we searching for?

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

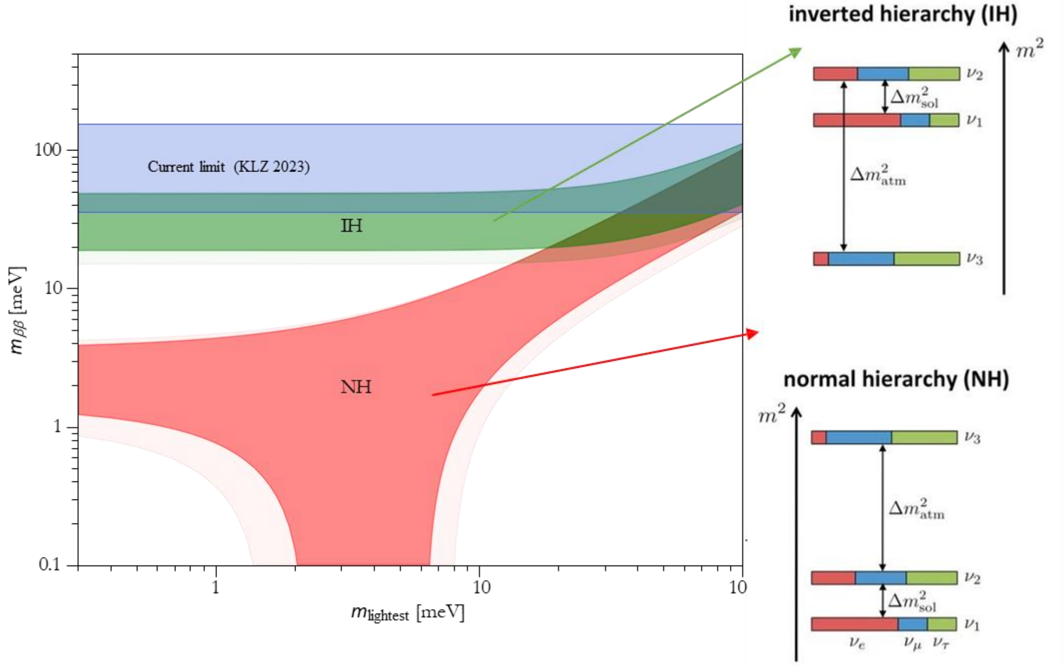
- Hypothetical nuclear transition
- Not allowed in SM
- Current half-lives limits 10^{24}-10^{26} yr

Matteo Agostini talk



Its observation will:

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



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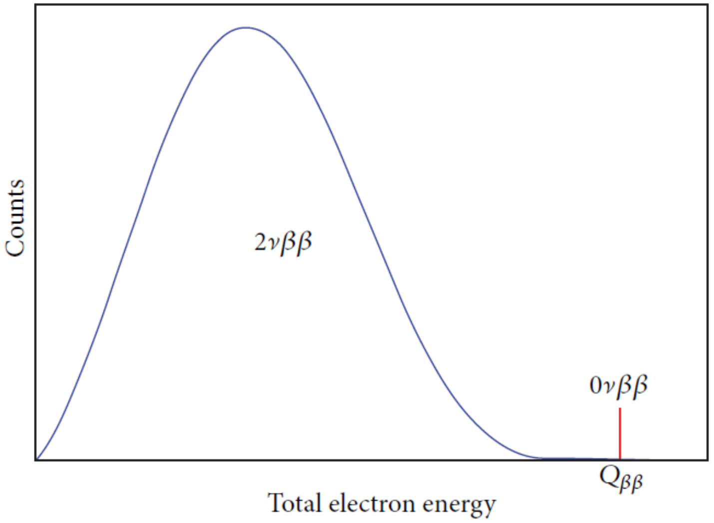

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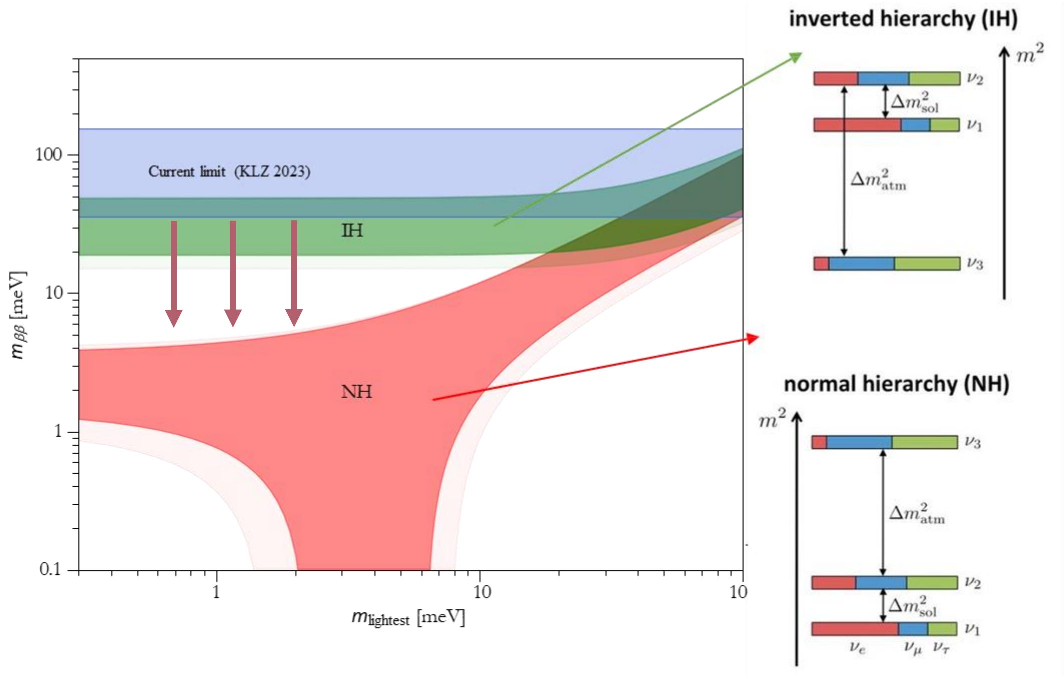
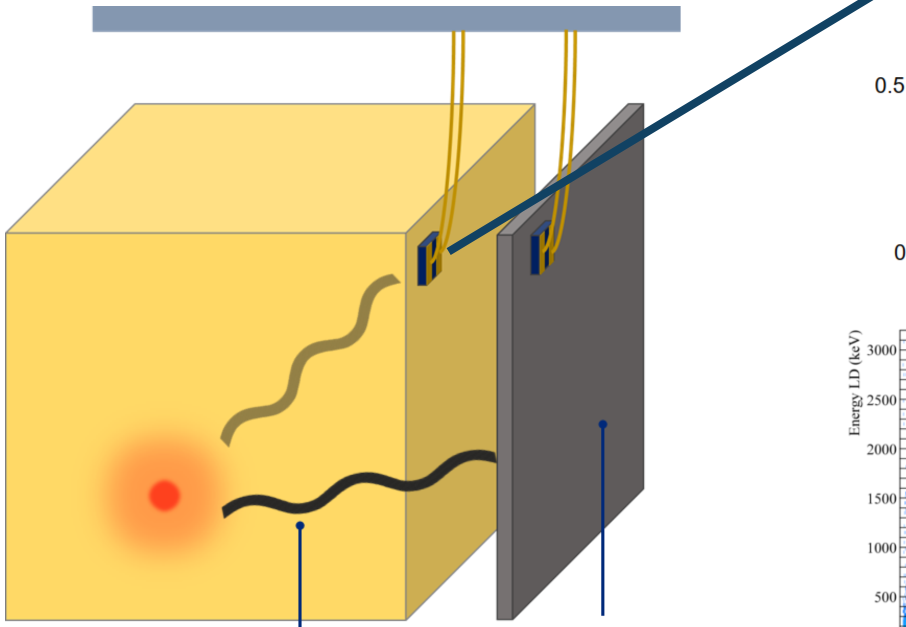


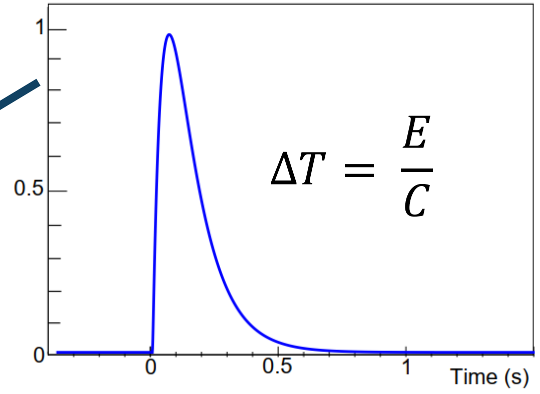
How to search for 0νββ decay?

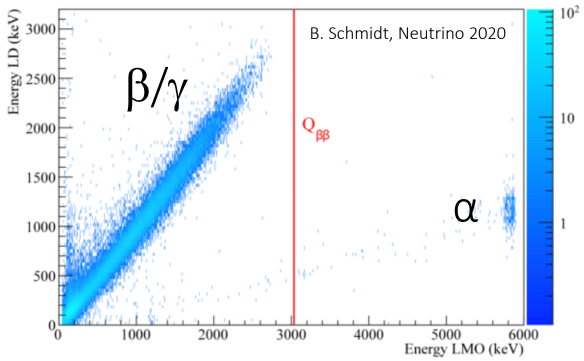
bolometer

Thermal bath ~ 10 -20 mK



Thermometer (NTD-Ge) signal





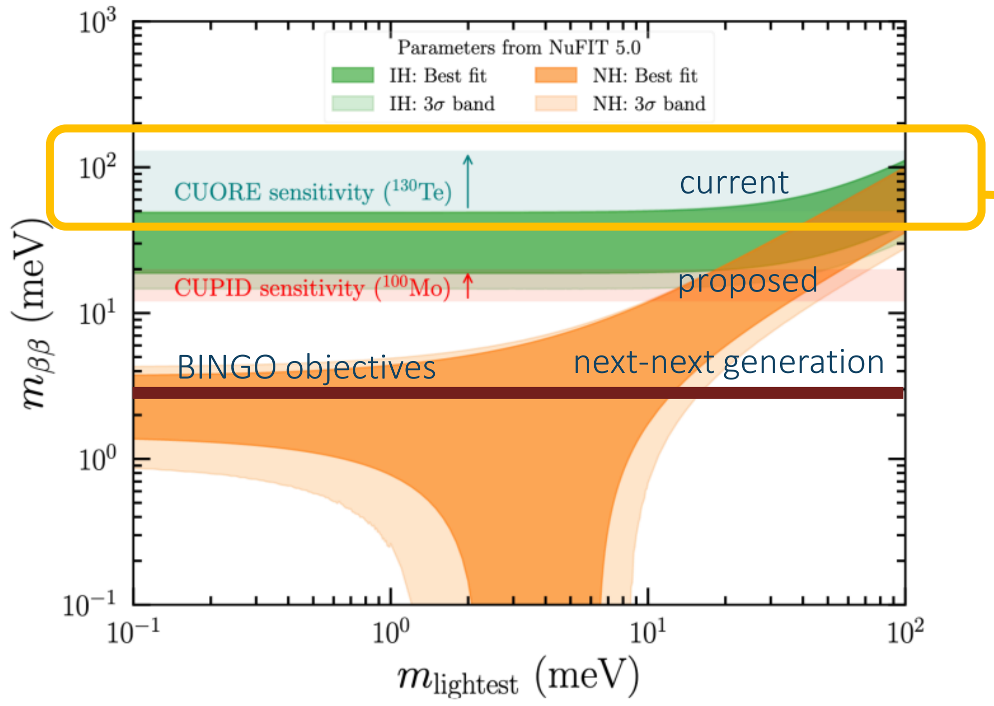
Bolometer features

- High energy resolution
- Full active volume (no dead layer)
- Flexible material choices

Chosen bolometric compounds

- Li_2MoO_4 (CUPID-Mo) and TeO_2 (CUORE)
  - ^{100}Mo, $Q_{\beta\beta}$ = 3034 keV
  - ^{130}Te, $Q_{\beta\beta}$ = 2527 keV
- Excellent energy resolution
- High internal radio-purity
- Easiness in crystallization

Current sensitivity of bolometric experiments



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

b: background index

M: detector mass

T: time of measurement

ΔE: energy resolution of the detector (FWHM)

- TeO_2 crystals (^{130}Te with IA ~ 34%, the highest among all ββ isotopes)
- Good energy resolution 7.4 keV FWHM
- b= 1.5×10^{-2} counts/(keV kg yr)
  - ~ 90% degraded α particles from surface contamination
  - ~ 10% β/γ natural radioactivity ($Q_{\beta\beta}$ < 2.6 MeV, endline of natural γ radioactivity)
  - < 1% muons

CUORE talk – Alberto Ressa

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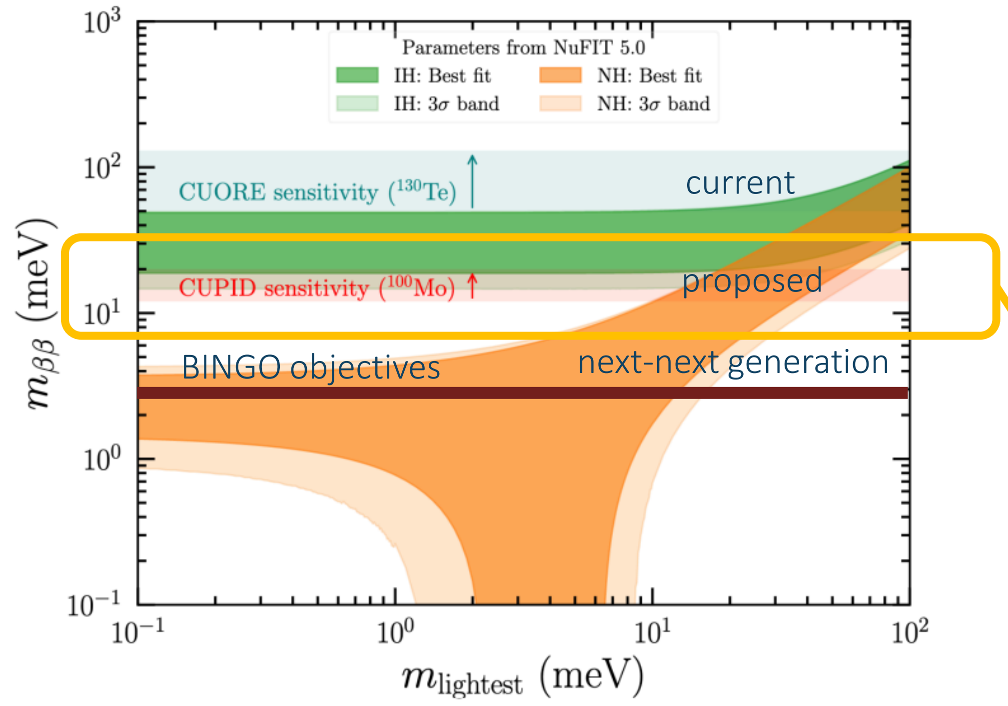

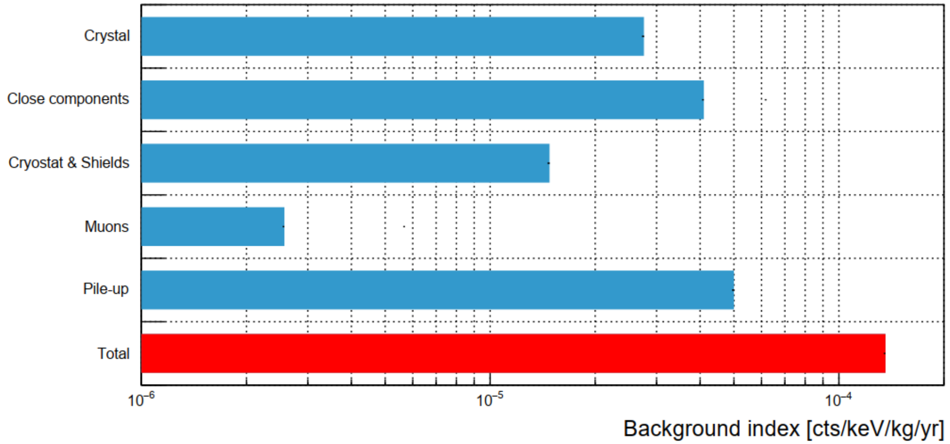

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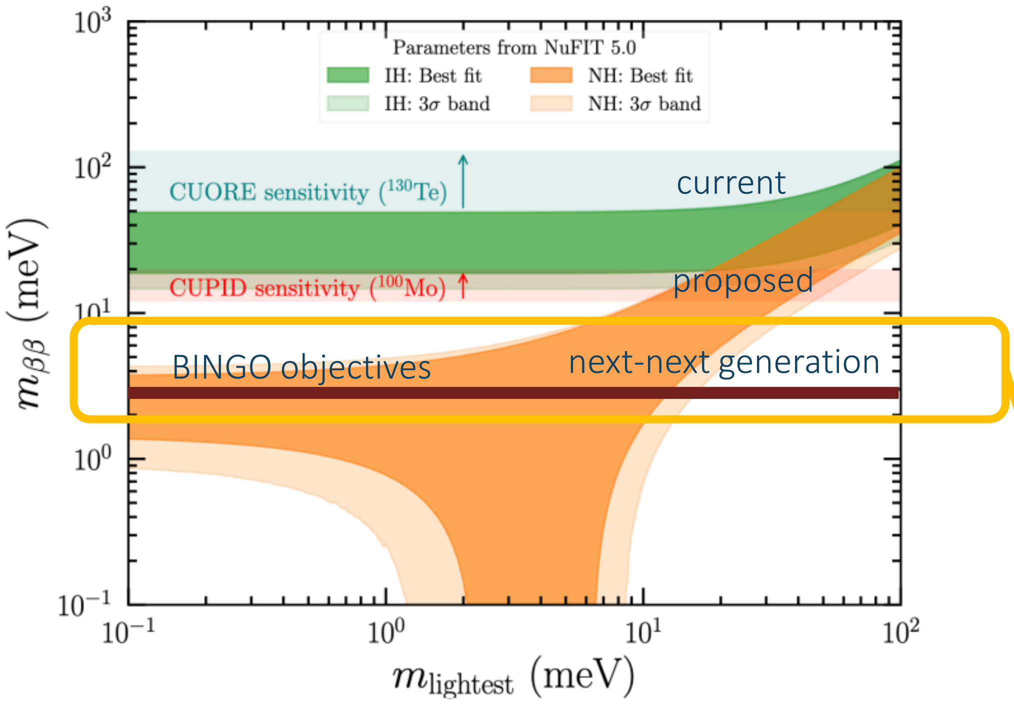
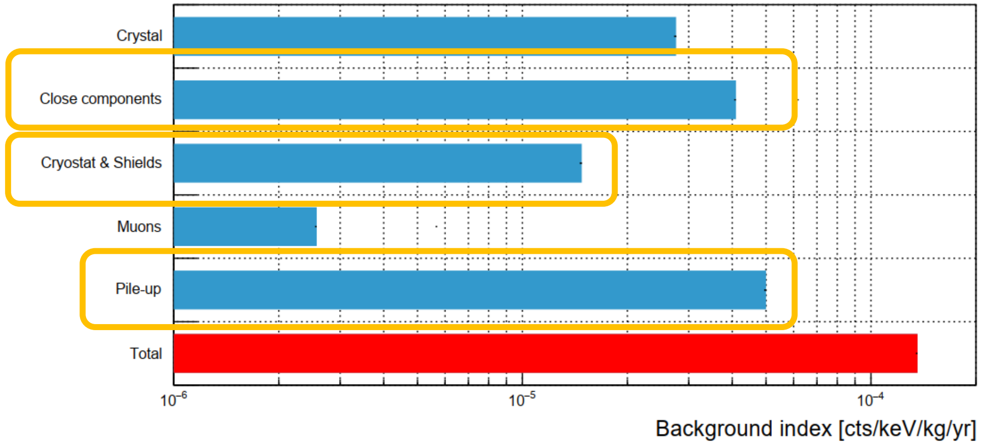
- $Li_2{}^{100}MoO_4$ scintillator coupled to Ge light detector
- CUPID-Mo/0 demonstrated > 99.9% α rejection
- CUPID-baseline goals: b ~ 10^{-4} counts/(keV kg yr)

CUPID talk – Fabio Bellini

Current sensitivity of bolometric experiments





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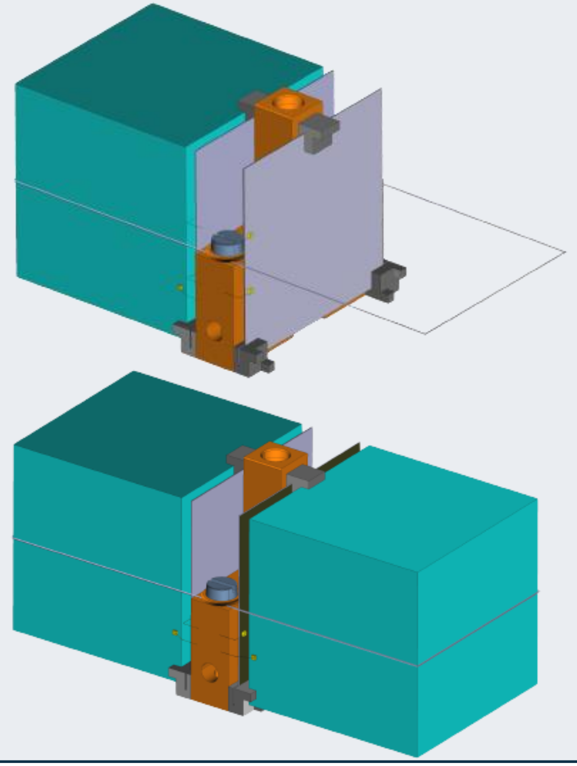
CUPID talk – Fabio Bellini

- Further background reduction with innovative technique
- Setting the ground for future bolometric experiments
- b ~ 10^{-5} counts/(keV kg yr)

The 3 pillars for background reduction

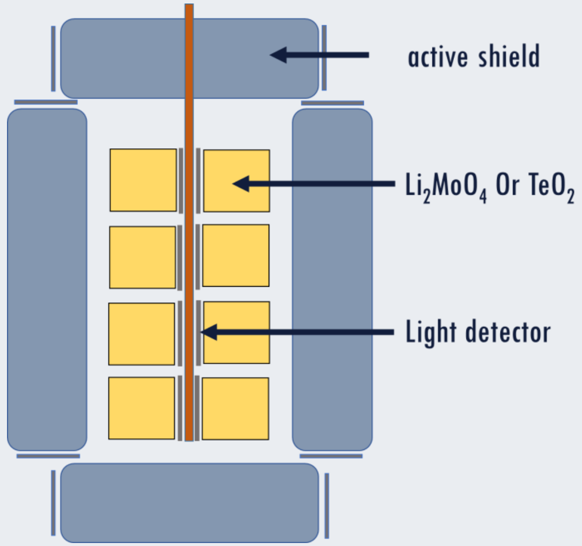
Assembly upgrade

- Less passive materials
- Compact assembly



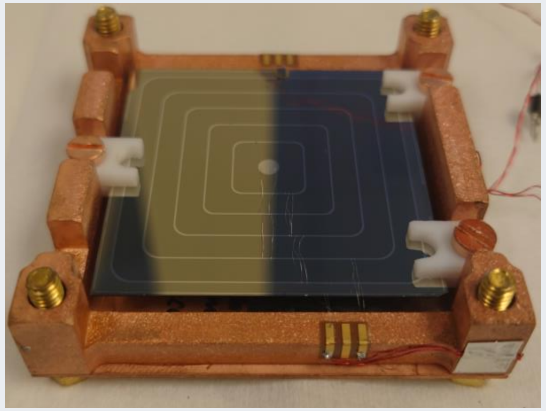
Active veto

Use an active shield, based on BGO scintillator

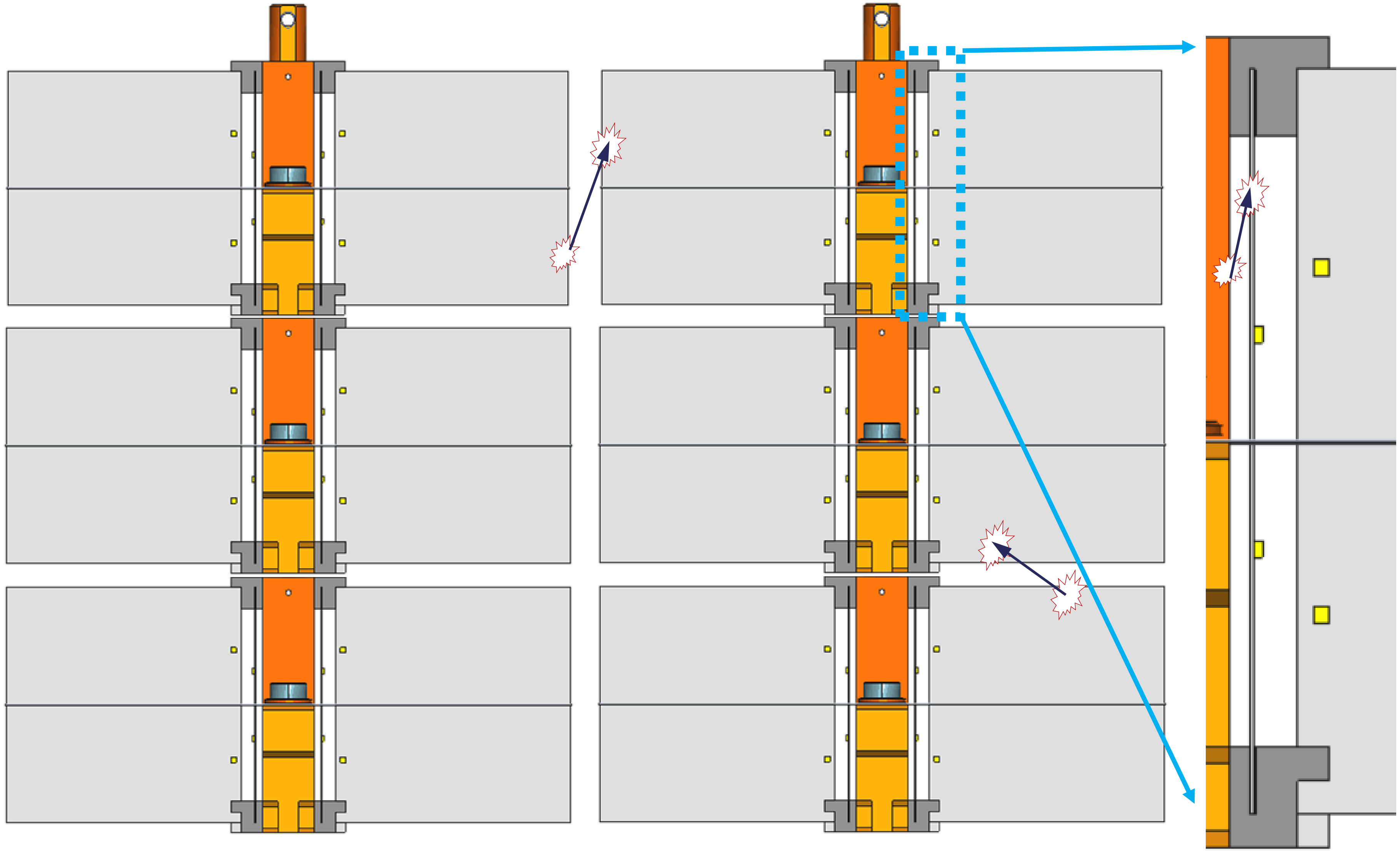


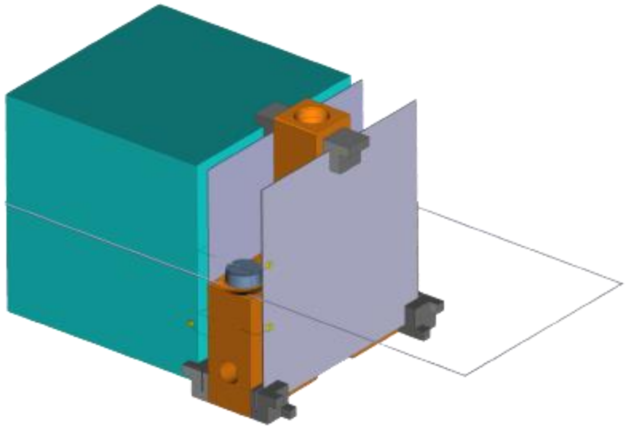
Neganov-Trofimov-Luke LD

- Amplification of light signals
- Higher signal-to-noise ratio → lower energy threshold



Assembly Upgrade

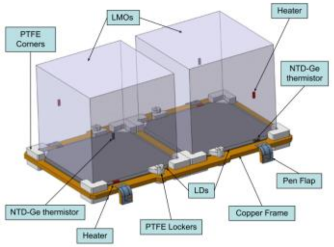


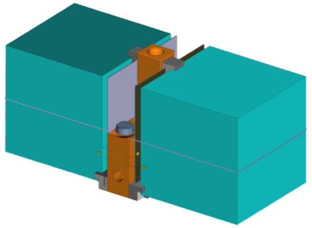


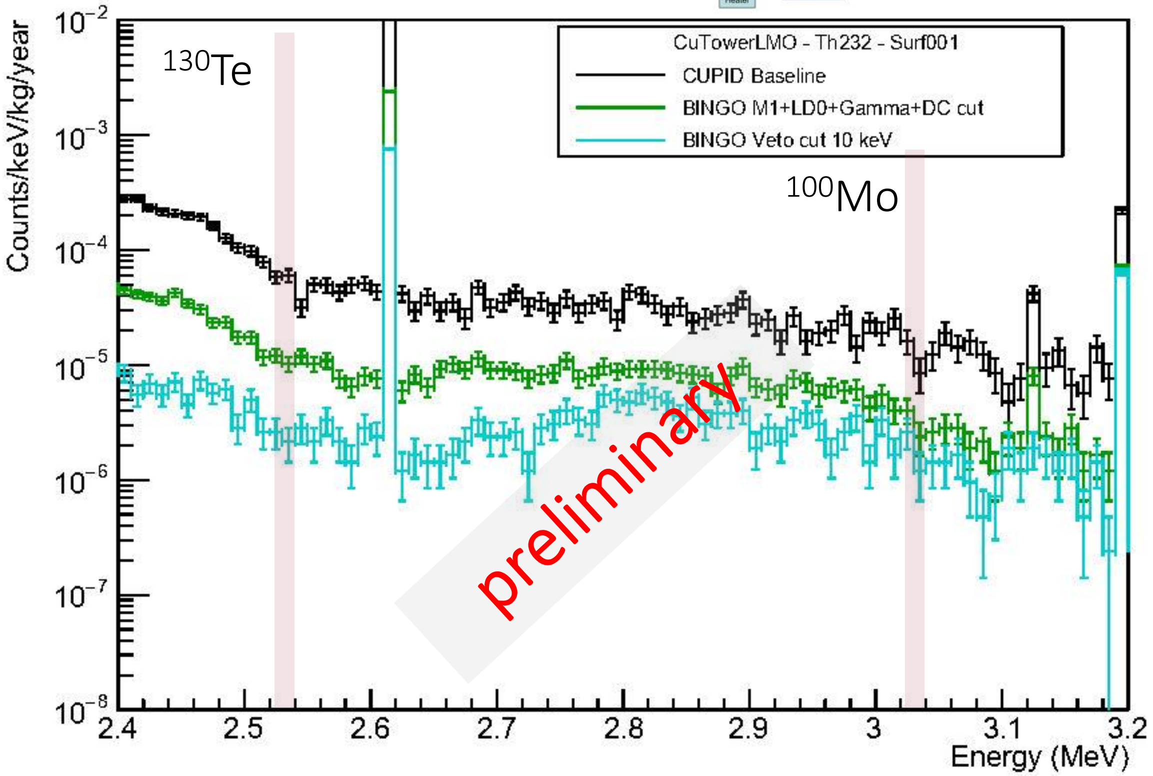
- Reduction of the total surface radioactivity contribution
- Surface contaminations can be rejected with coincidence thanks to the compact assembly and LD shielding

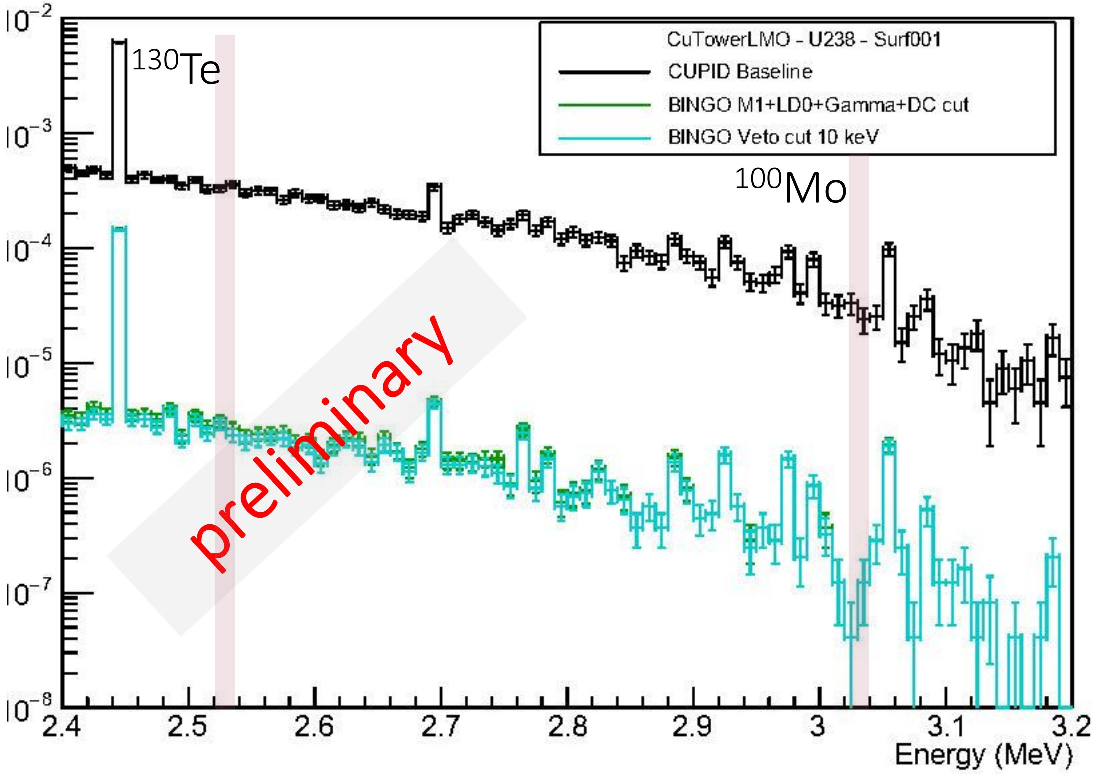
Geant4 simulations: surface contamination reduction

Comparison between CUPID-baseline and BINGO assemblies in terms of surface contamination



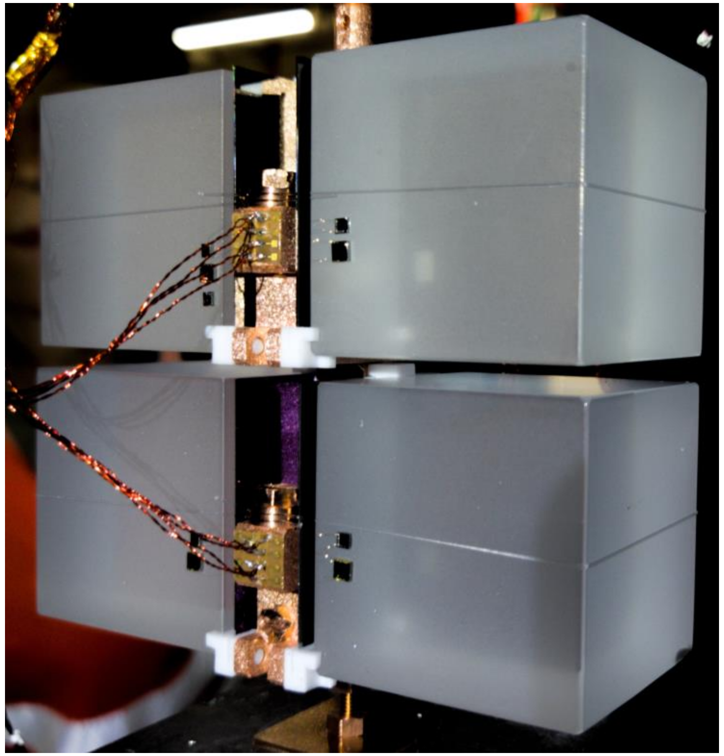




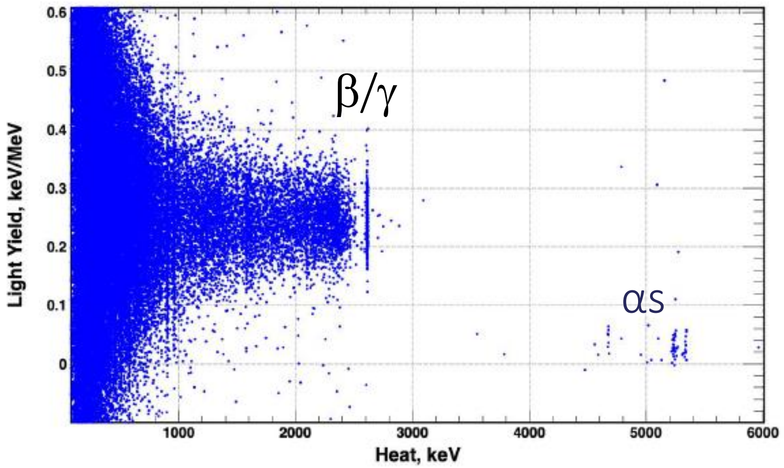


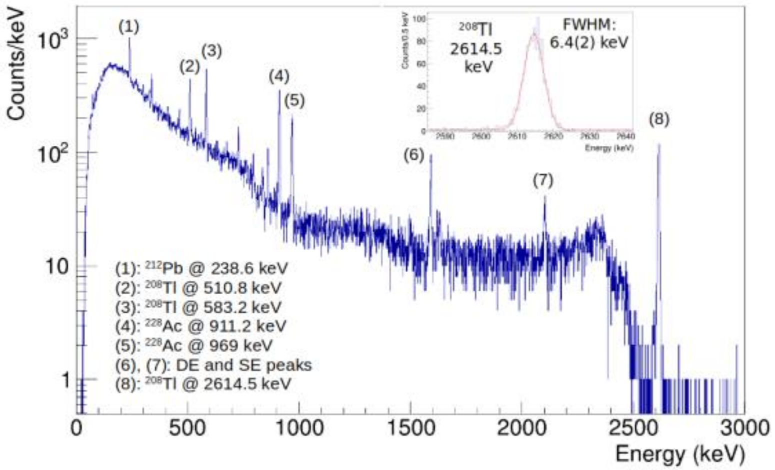
New assembly test on Li_2MoO_4

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



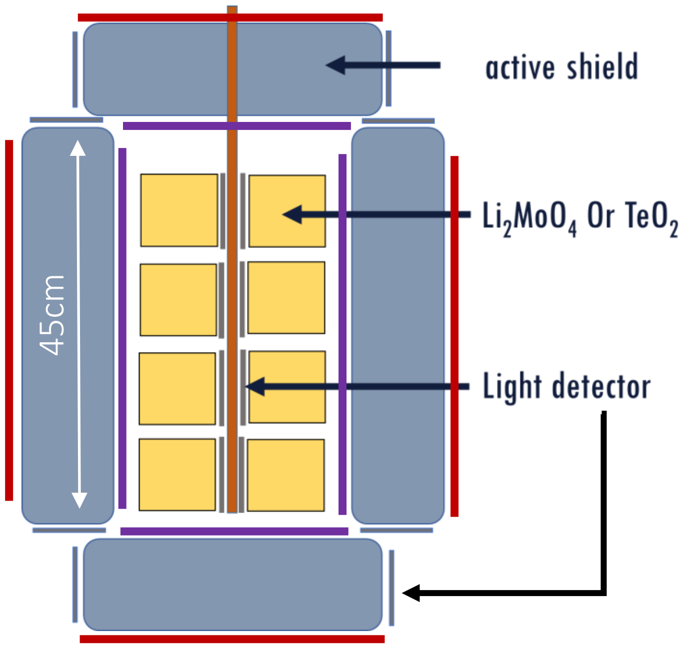
- The average resolution at 2.6 MeV FWHM is ~ 6.3 keV for heat channels and baseline resolution FWHM is 218 eV for light channels
- No impact of nylon wire on noise or thermal coupling
- Good discrimination between α and β/γ

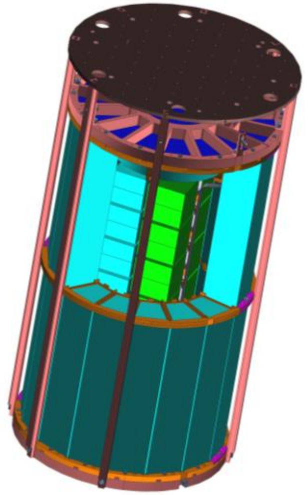




The BINGO active veto

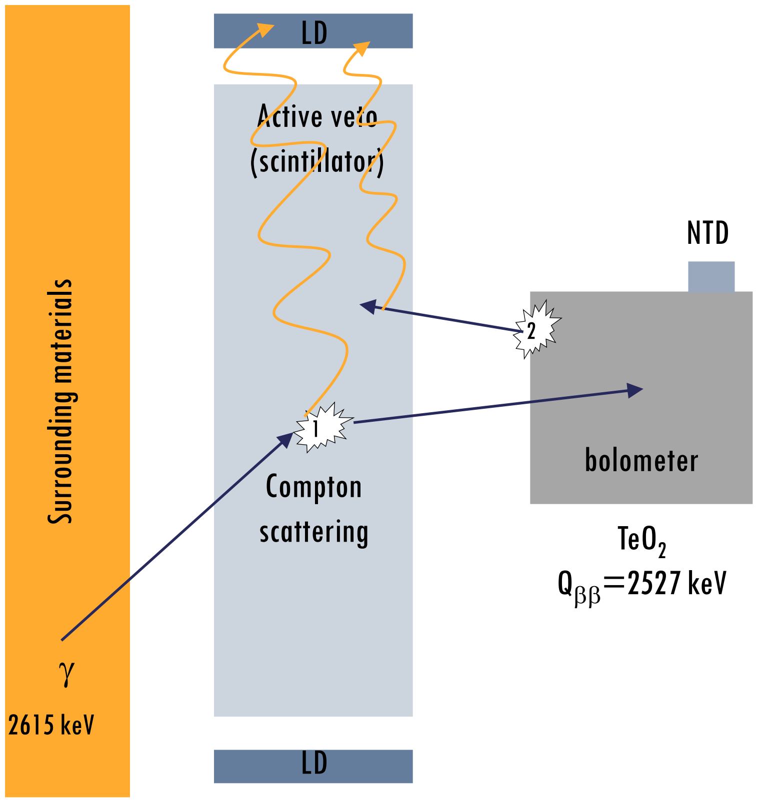
- An active inner shield will be used to surround the Li_2MoO_4 and TeO_2 towers
  - Suppress the external γ background and reject surface radioactivity from the crystals that face the active shield through anti-coincidence
- The shield will be composed of BGO scintillator
- Each bar (in fact two bars on top of each other) will be read by two light detectors (with NTL effect for signal amplification)
- A reflecting material on the lateral side of the veto to increase light collection in LDs
- On the internal side of veto, facing the crystals, a material will be added that should **not** be an α stopper and that should prevent scintillation light from BGO to reach Li_2MoO_4 and TeO_2 LDs (Al, Au , ...?)





Active veto role

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



1

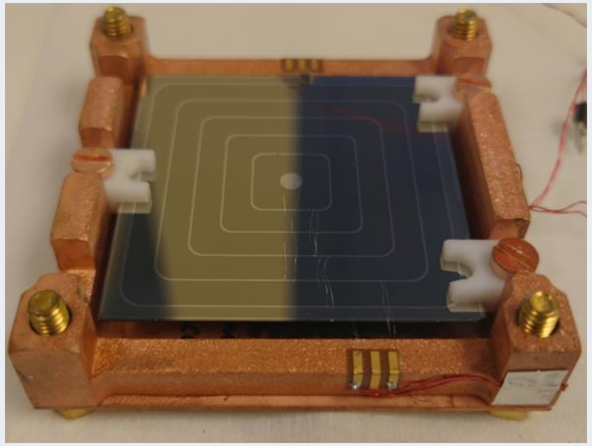
- If a 2615 keV γ deposits a small amount of energy in the surrounding material (~80 keV) and the rest in TeO_2 → background in ROI
- Thanks to the active veto and the LDs, these events can be rejected:
  - The energy deposition in the active veto will lead to scintillation light detected by the LD
  - Using anti-coincidence these events can be rejected from TeO_2

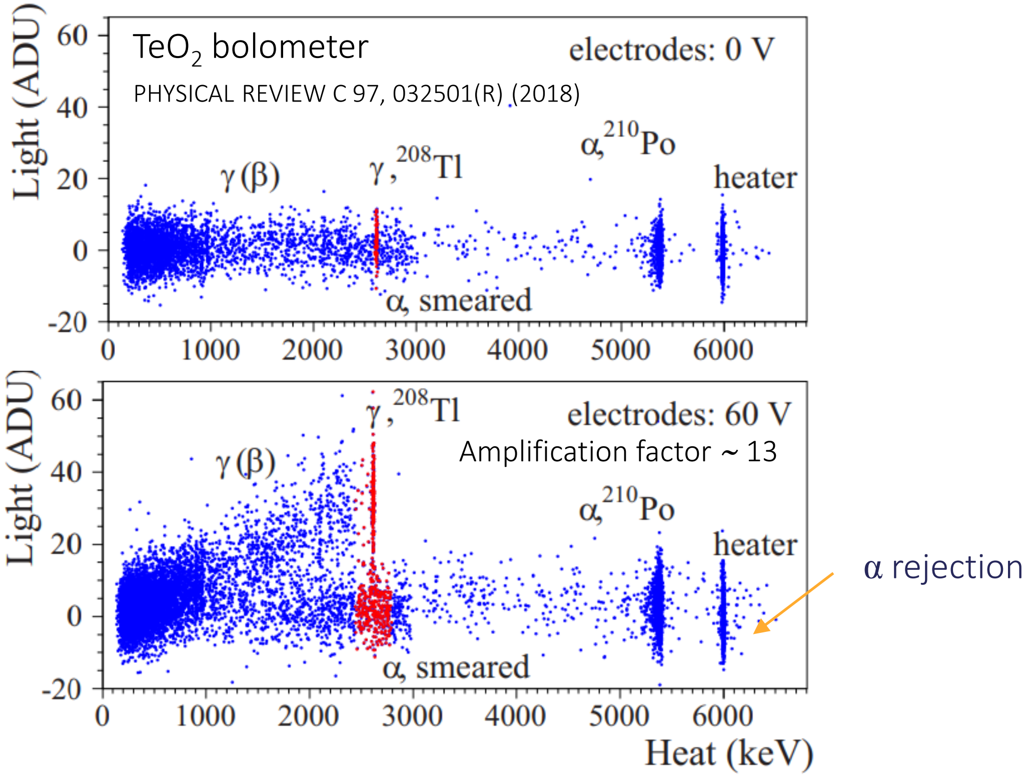
2

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

Neganov-Trofimov-Luke light detector

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
↓
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)





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

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

Neganov-Trofimov-Luke light detector role

NTL light detector is essential for the veto, Li_2MoO_4 and TeO_2:

Veto:

High signal to noise ratio in order to achieve a low enough energy threshold in LD

- 50 keV energy threshold in BGO is required
  - It corresponds to the dangerous small energy deposition of the 2615 keV line in BGO
- 50 keV in the BGO scintillator corresponds to a few keV in LD
  - Few keV in LD is achieved by taking into account the expected gain from NL effect (10-20)

Li_2MoO_4:

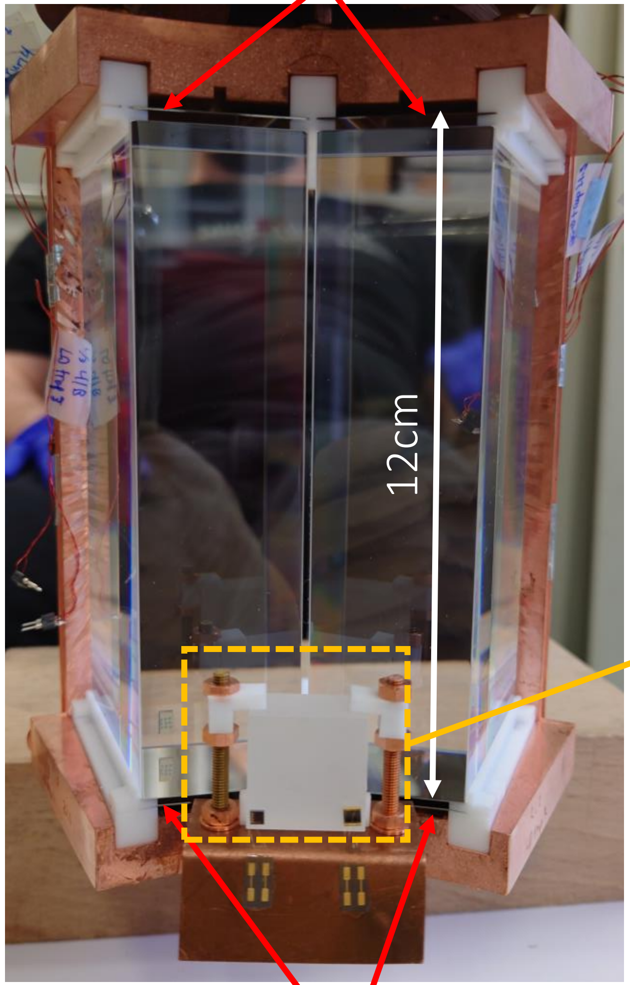
- Relatively fast decay rate of ^{100}Mo ($T_{1/2}^{2\nu} = 8.1 \times 10^{18}\ yr$) + the slow pulses in heat channel $\rightarrow$ Random coincidences of $2\nu\beta\beta$ decay in ROI
  - Rely on NTL light channel (which is faster) to reject pileups with PSD

TeO_2:

- Amplification of the tiny Cherenkov signal (TeO_2) $\rightarrow$ suppress alphas

Active veto first cryogenic prototype test

LDs



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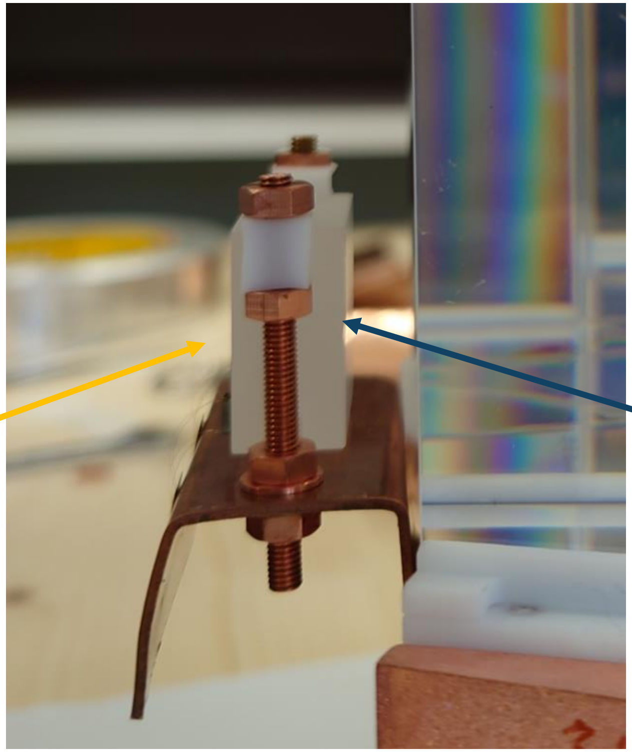
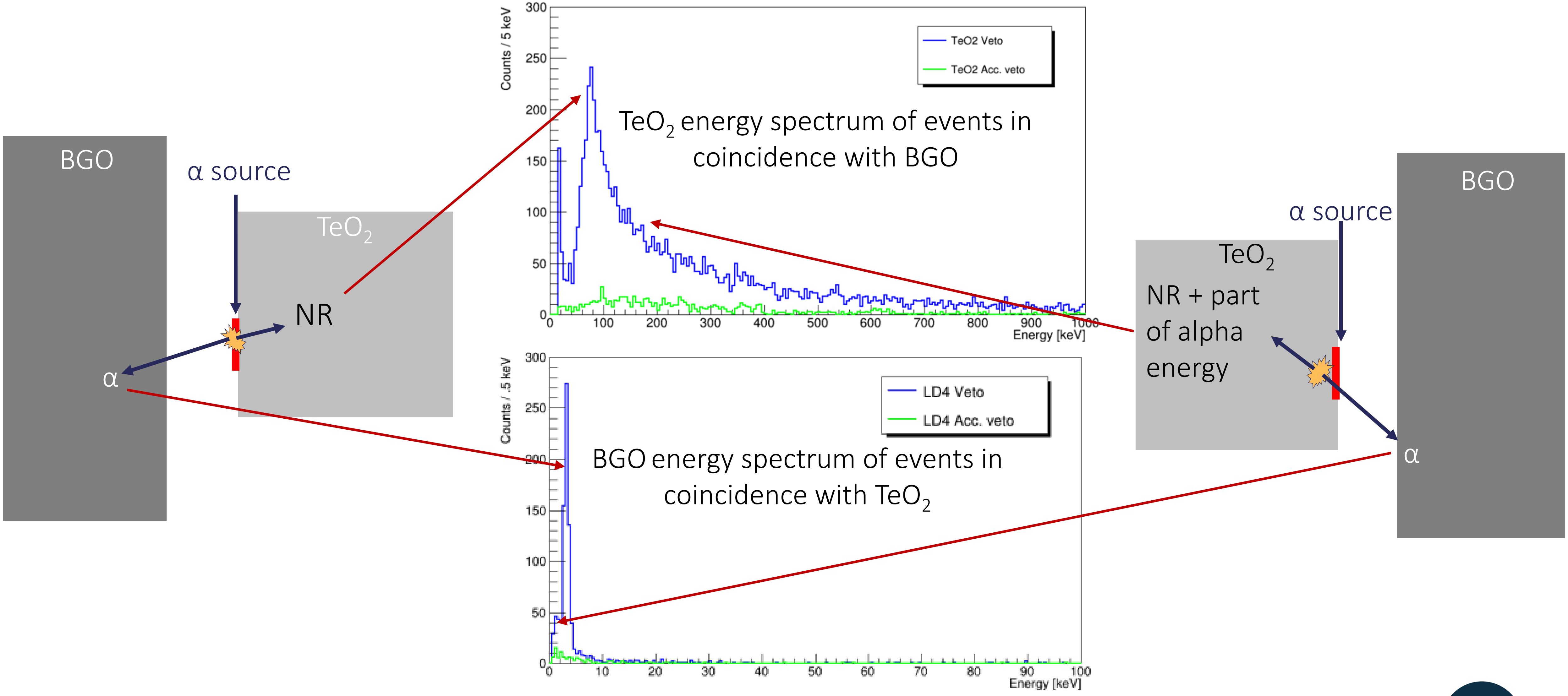


- 2 BGO crystals (~1.6kg each)
- 2 normal LDs facing each BGO
- TeO_2 crystal facing both BGOs
- The test was performed above-ground in a pulse-tube cryostat at IJCLab (Orsay)

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

Hunting the α source with coincidence



Mini-BINGO

- Mini-Bingo will be a technology demonstrator of the background reduction techniques described
- The demonstrator will be tested in Modane underground laboratory (France)
- The cryostat will be installed in spring 2024

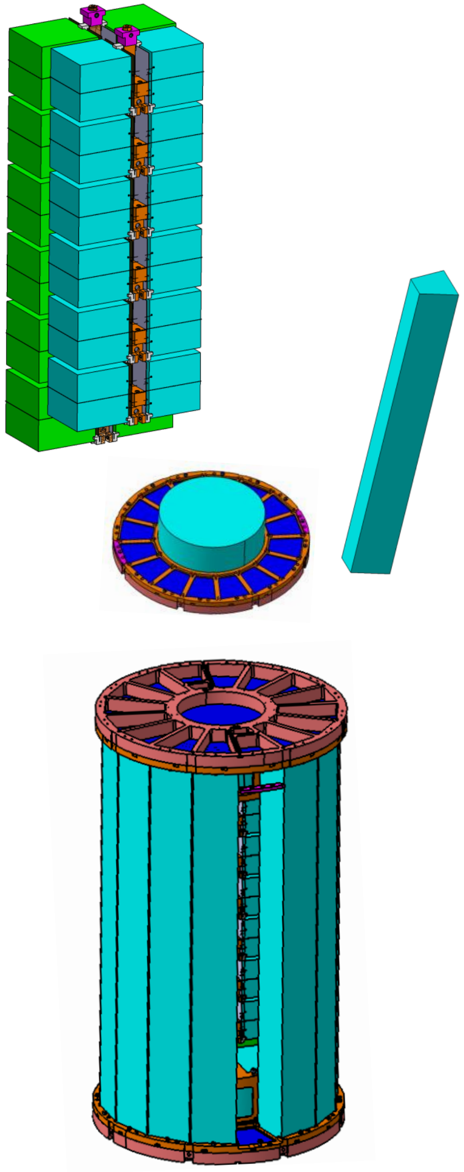
Double beta decay part

- 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

- 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)

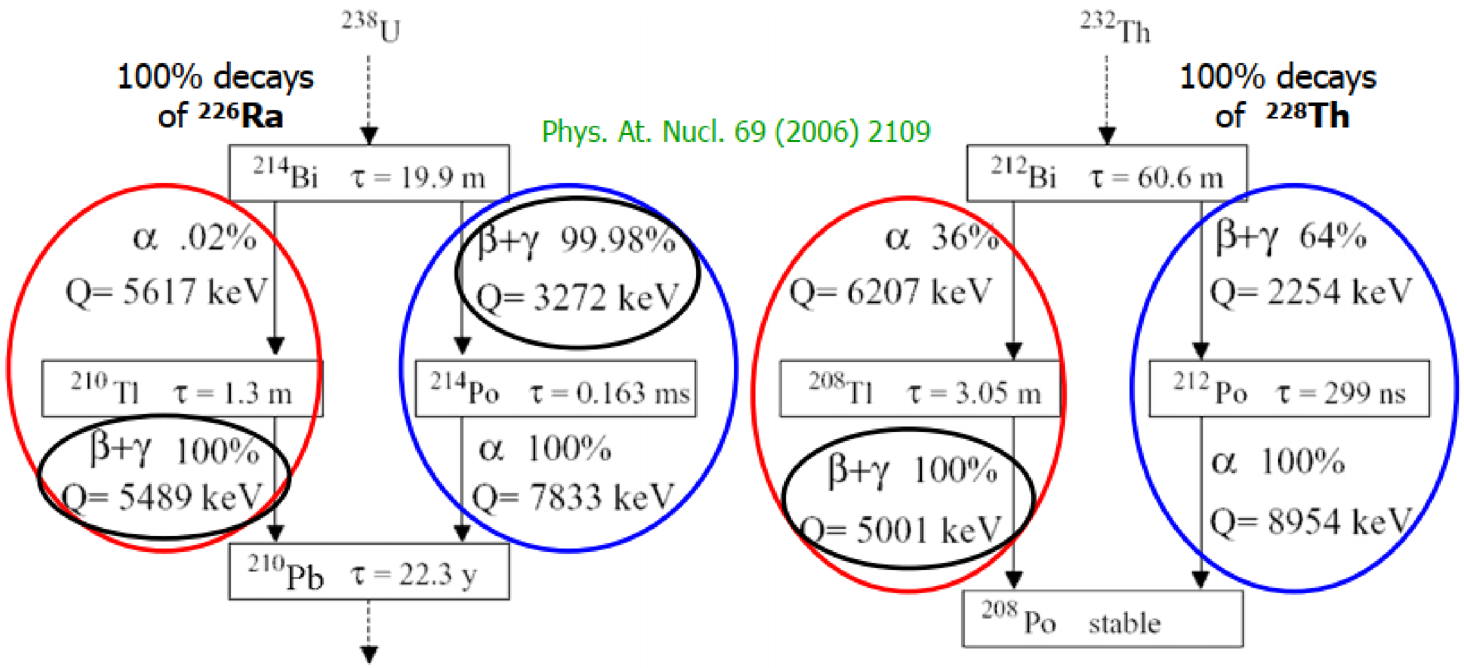


Conclusions

- BINGO is a promising project towards the meV scale of the effective Majorana mass
- BINGO proposed technologies are a possible candidate for CUPID-1T
- BINGO introduces innovative technology for background rejection that allows to reach $b{\sim}10^{-5}$ counts/(keV kg yr)
- Simulations show us that BINGO assembly design leads to at least one order of magnitude less background index from close components compared to present CUPID structure
- The nylon wire assembly is almost validated
- More R&D is needed to develop the suitable Neganov-Luke LD that fulfills BINGO goals
- Some simulations and further cryogenic measurements are ongoing on the active veto

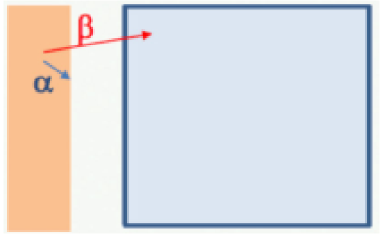
Backups

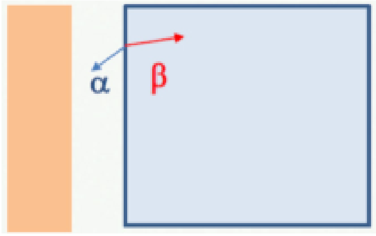
Sources of background

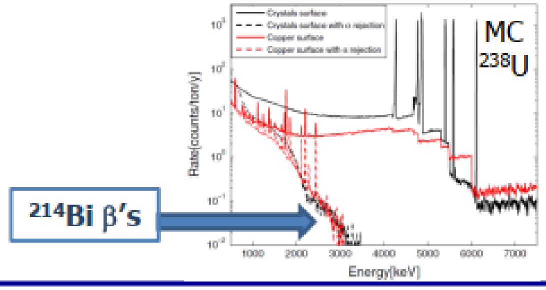


For DBD bolometers with particle ID:

- **BiPo events** (mixed $\beta+\alpha$ 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**

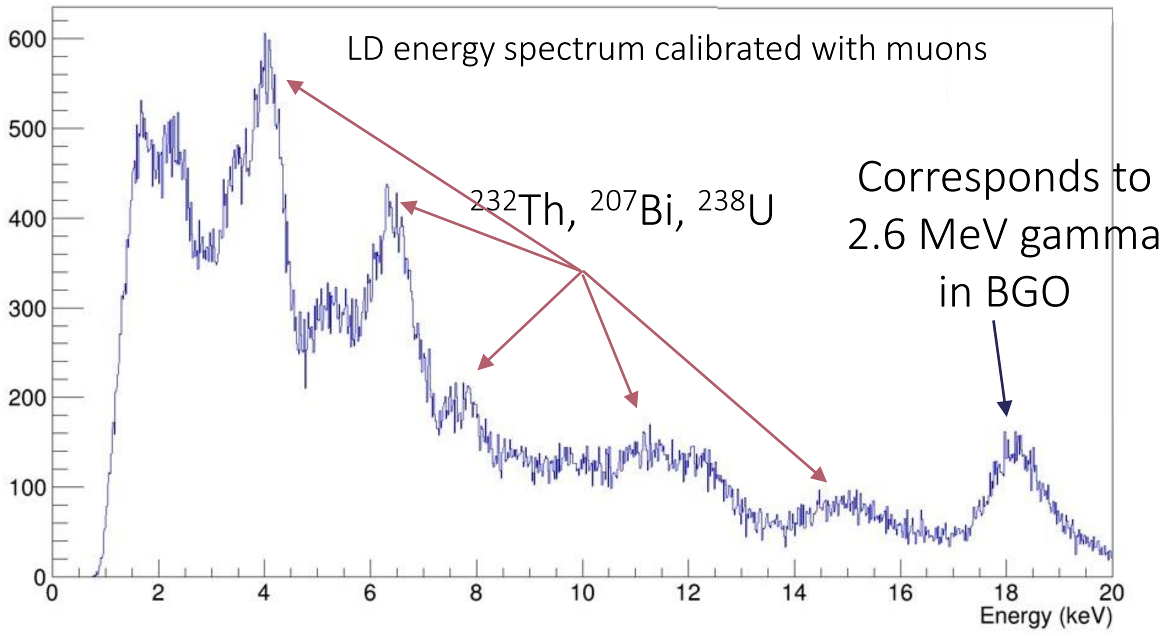


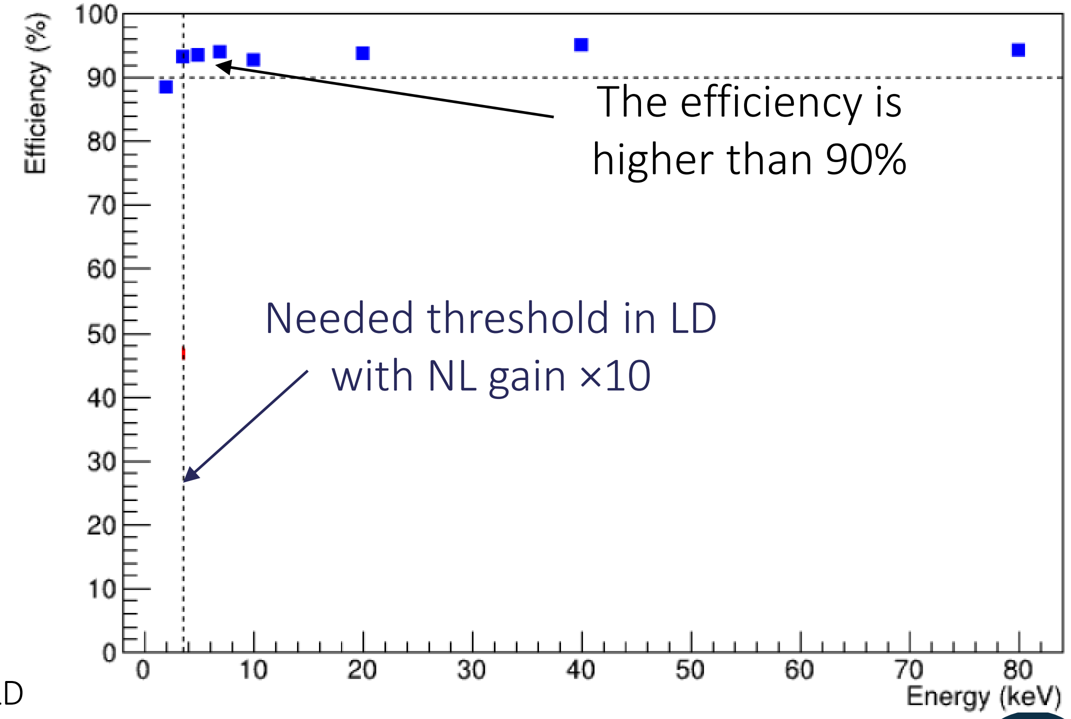




Efficiency study at the expected threshold

- 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 0.3-0.4 keV in LD when taking into account the light yield (LY) which is about 7 keV/MeV
  - With a NL gain of 10, the energy threshold would become 3-4 keV.





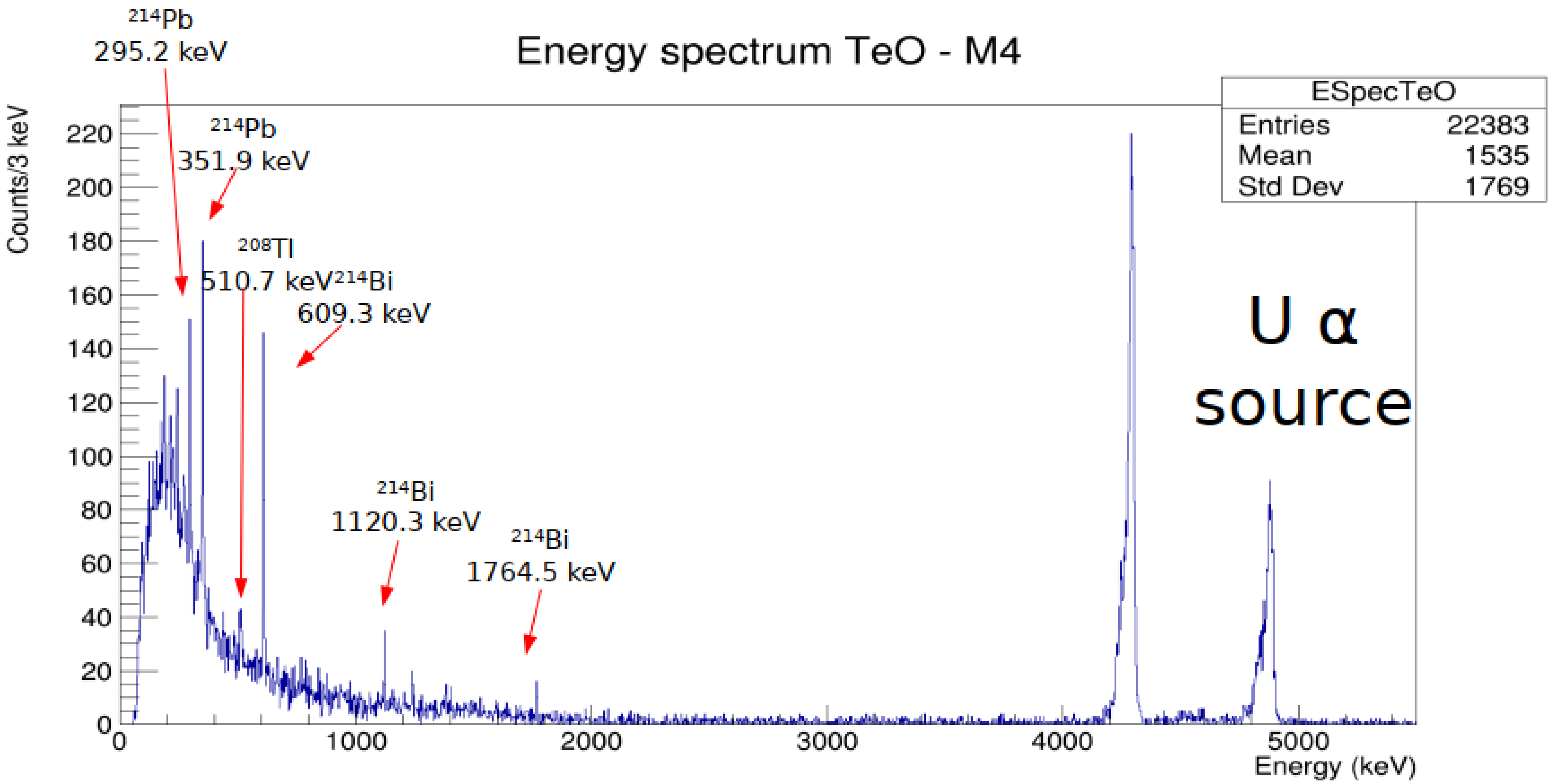
^{207}Bi contamination

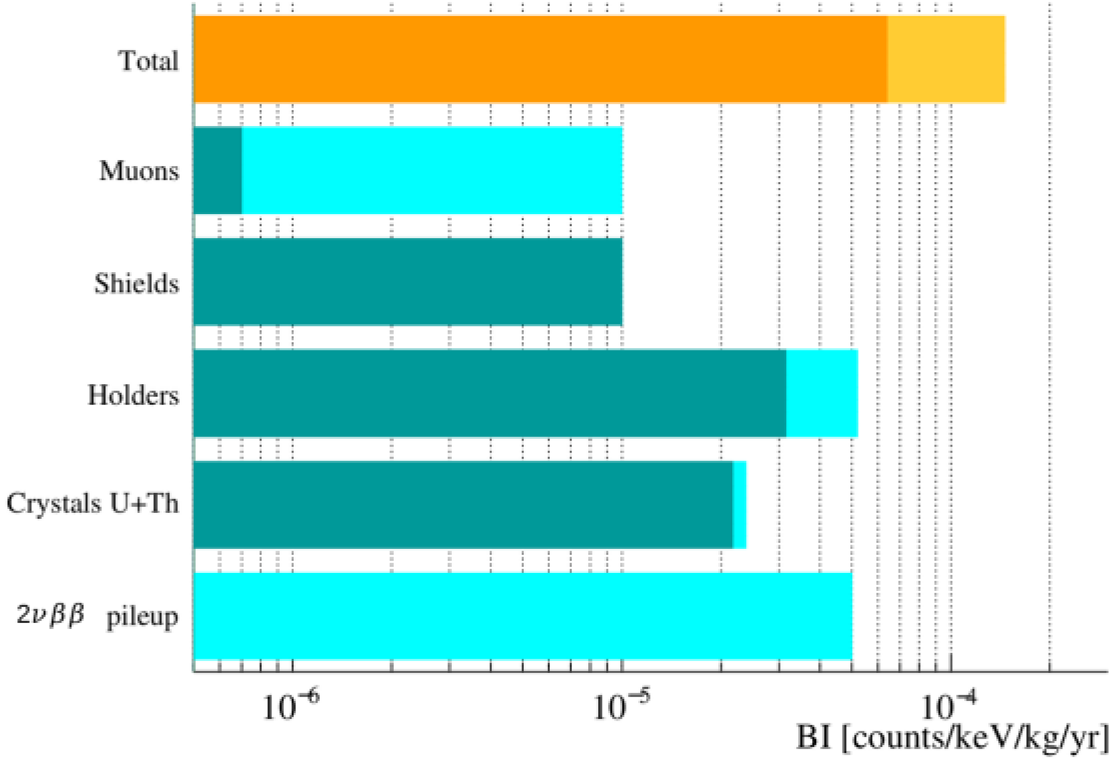
- With 328 mBq/kg, $M_{VETO} = 115$ kg and assuming a 5 ms coincidence time window, dead time is $\sim$17%
- Desirable to reach < 100 mBq/kg $\rightarrow$ deadtime is $\sim$6%

Supplier6	Type	Purity [%]	Mass [g]	Activity [mBq/kg]	Activity [mBq/kg BGO]	803 keV
SICCAS (CN)	BGO		301	173 ± 16	173 ± 16	N
(RU)	BGO		301	68 ± 11	68 ± 11	N
Alfa Aesar (DE)*	Bi_2O_3	99.999	212	< 21 (95% CL)	< 16 (95% CL)	N
Santech (CN)	Bi_2O_3	99.990	206	23 ± 6	17 ± 5	Y
Zhuzhou (CN)	Bi	99.999	460	37 ± 5	25 ± 3	N

**@ LSM for screening*

TeO_2 energy spectrum




Total
Muons
Shields
Holders
Crystals U+Th
$2\nu\beta\beta$ pileup
10^{-6}
10^{-5}
10^{-4}
BI [counts/keV/kg/yr]

Bolometric compounds choices

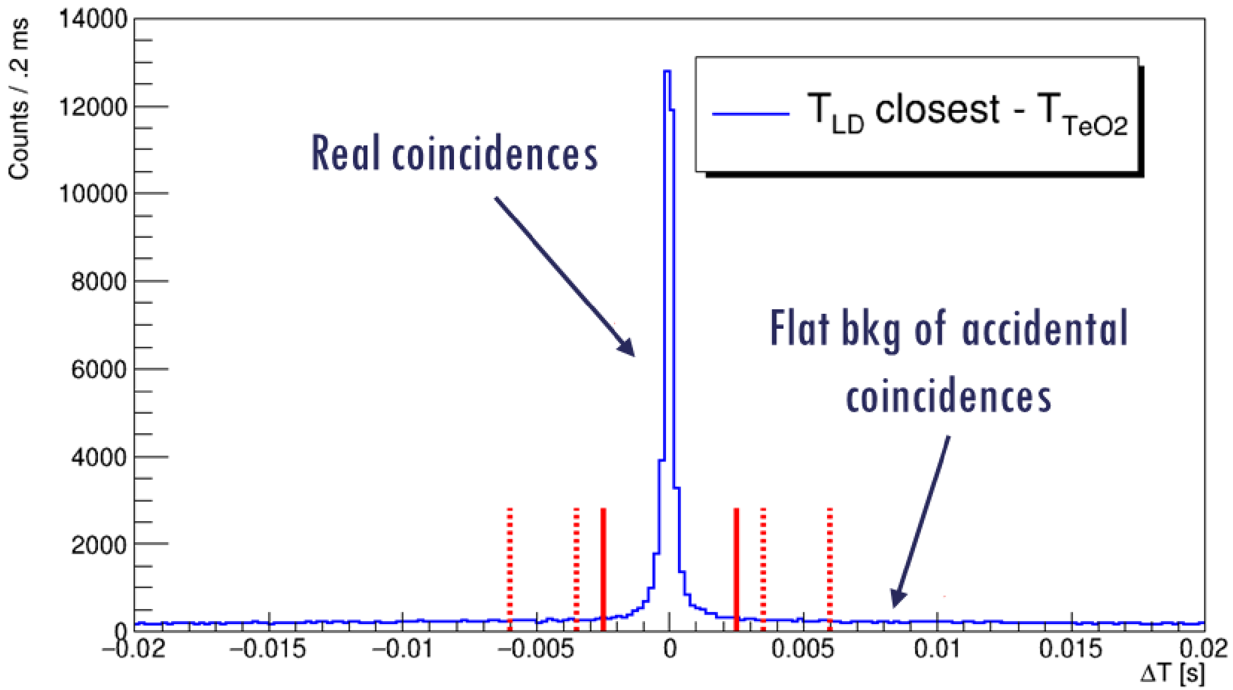
Li_2MoO_4

- 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
- High rate of $2\nu2\beta$ → 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

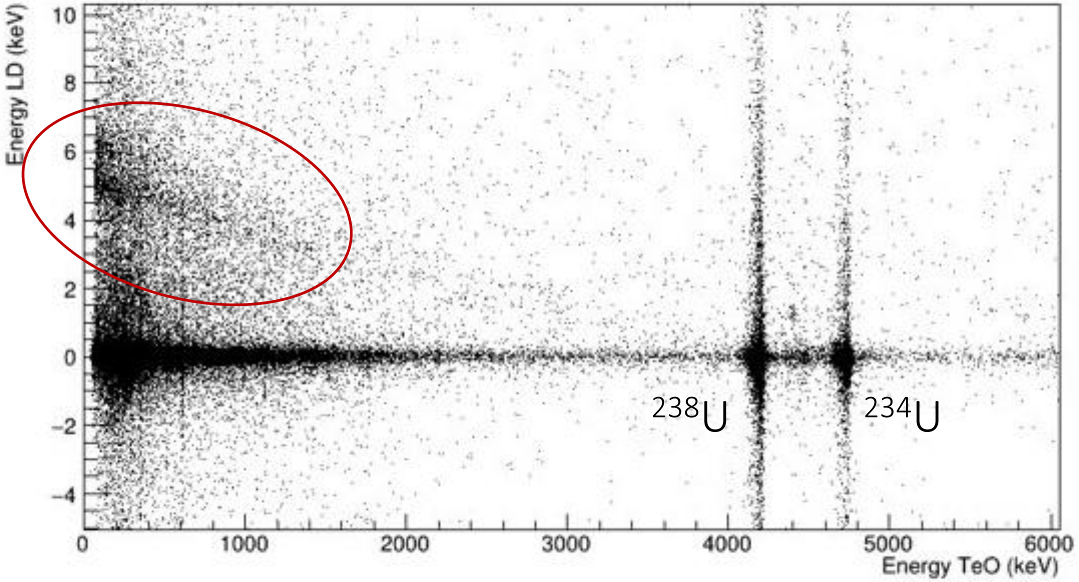
Hunting the α source with coincidence



- 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

Hunting the α source with coincidence

Coincidences between TeO_2 and LD (meaning BGO)



- The marked events are alphas (with shared energy in TeO_2) in LD
- At 0 keV in TeO_2 we have a full alpha absorption in BGO (LD)
- At higher energies in TeO_2 the alpha energy is shared between TeO_2 and the LD
- The extrapolation of this population to higher energies in the TeO_2 leads to full alpha absorption in TeO_2

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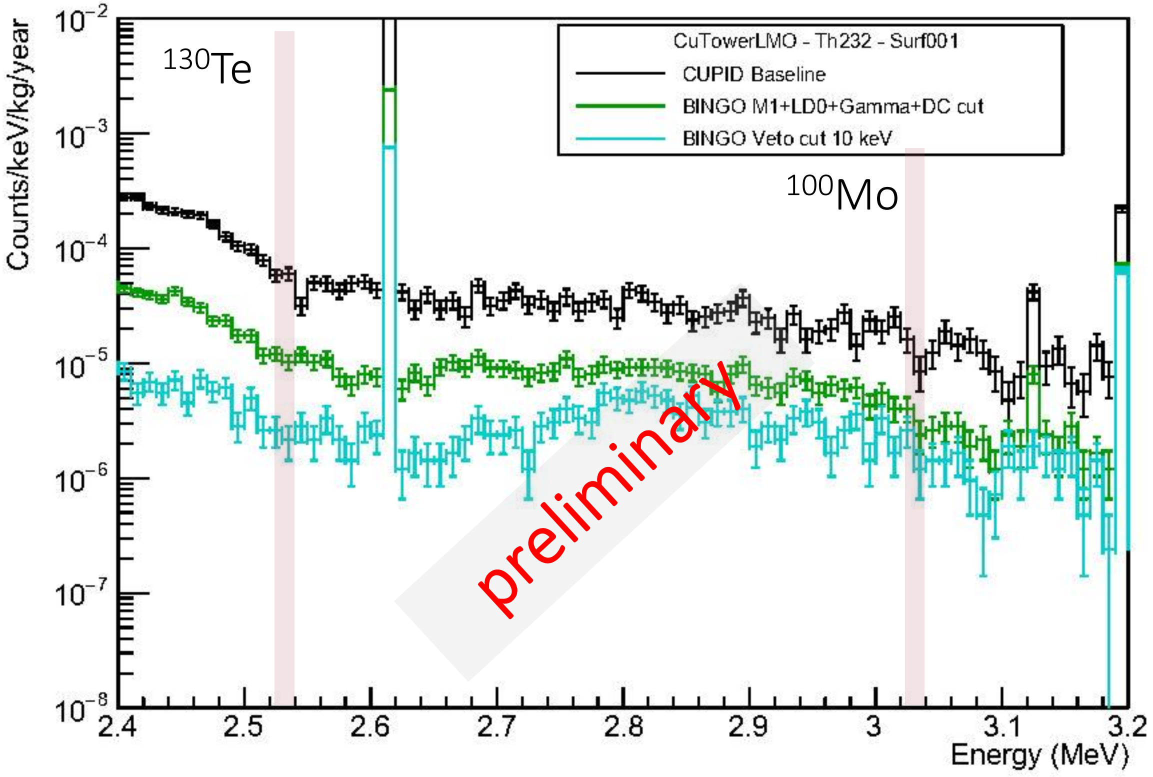
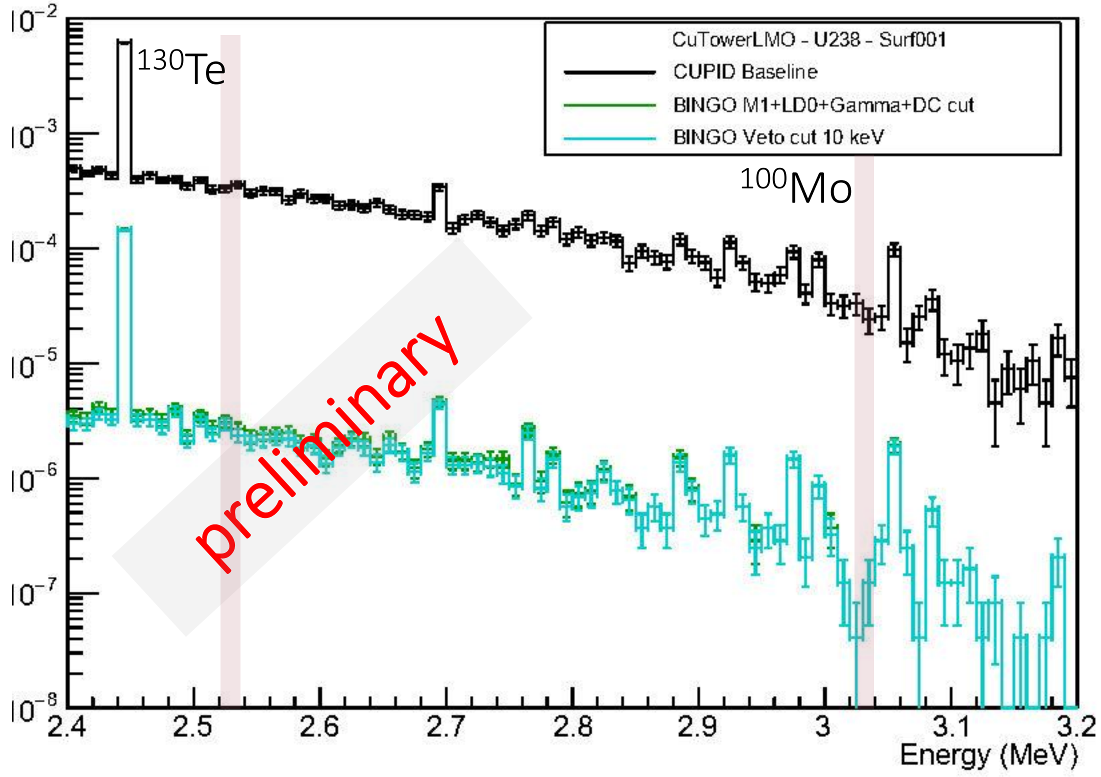
Crystal	Growth	λ_{max} (nm)	$L/H_{\gamma(\beta)}$ (keV/MeV)	(ph/MeV)	QF_α	Section
$CaWO_4$	Cz	420 (8 K) [261]	6.0–24	2000–8100	0.10–0.12	Section 3.1.1
			(45–52 [a])	(15,400–17,500)		ibid.
$CdWO_4$ [b]	Cz, LTG Cz	420 (8 K) [261]	14–31	5400–12,000	0.18–0.19	Section 3.1.2
$Li_2WO_4(Mo)$	Cz, LTG Cz	530 (8 K) [352]	0.40	170	0.26 [c]	Section 3.1.3
$Na_2W_2O_7$	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_2MoO_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.
$Li_2Mg_2(MoO_4)_3$	LTG Cz	585 (8 K) [356]	1.3	610	0.22	Section 3.2.4
$Li_2Zn_2(MoO_4)_3$	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
$Na_2Mo_2O_7$	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.
$Li_6Eu(BO_3)_3$	Cz	613 (4.2 K) [363]	6.6	3200	0.08	Section 3.3.1
$Li_6Gd(BO_3)_3$ [b]	Cz	312 (90 K) [364]	0.26	65	0.23	Section 3.3.2
$Al_2O_3(Ti)$, pure	Ve, Ky, Cz	420 (9 K) [365]	2.5–14	850–4700	0.09–0.36	Section 3.4.1
$Bi_4Ge_3O_{12}$	Cz, LTG Cz, BS	480 (9 K) [261]	7.0–28	2700–11,000	0.17–0.18	Section 3.4.2

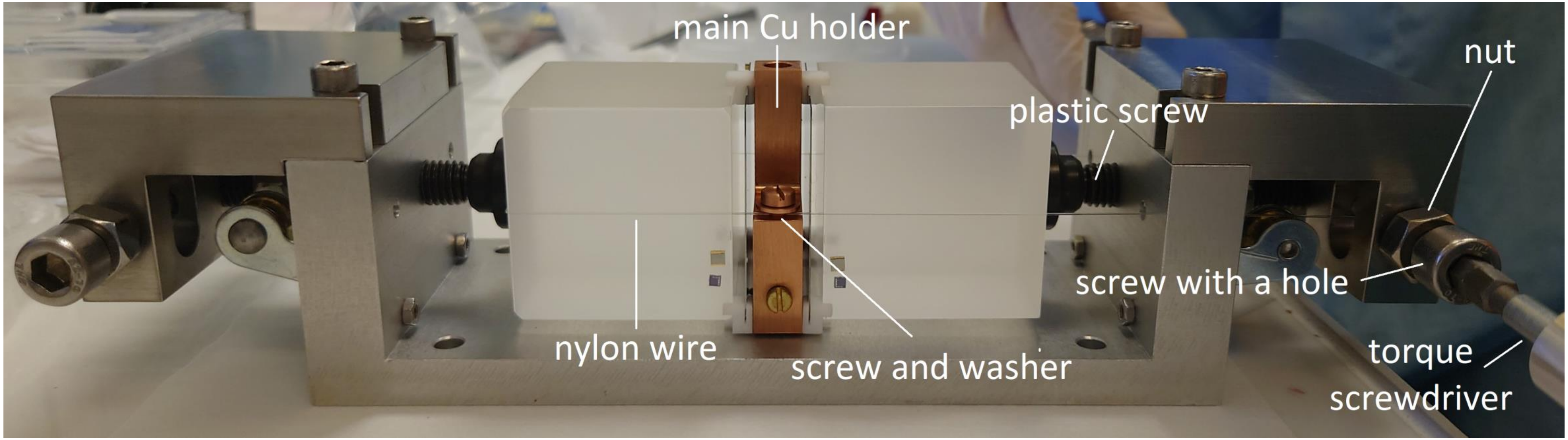
Geant4 simulations: surface contamination reduction

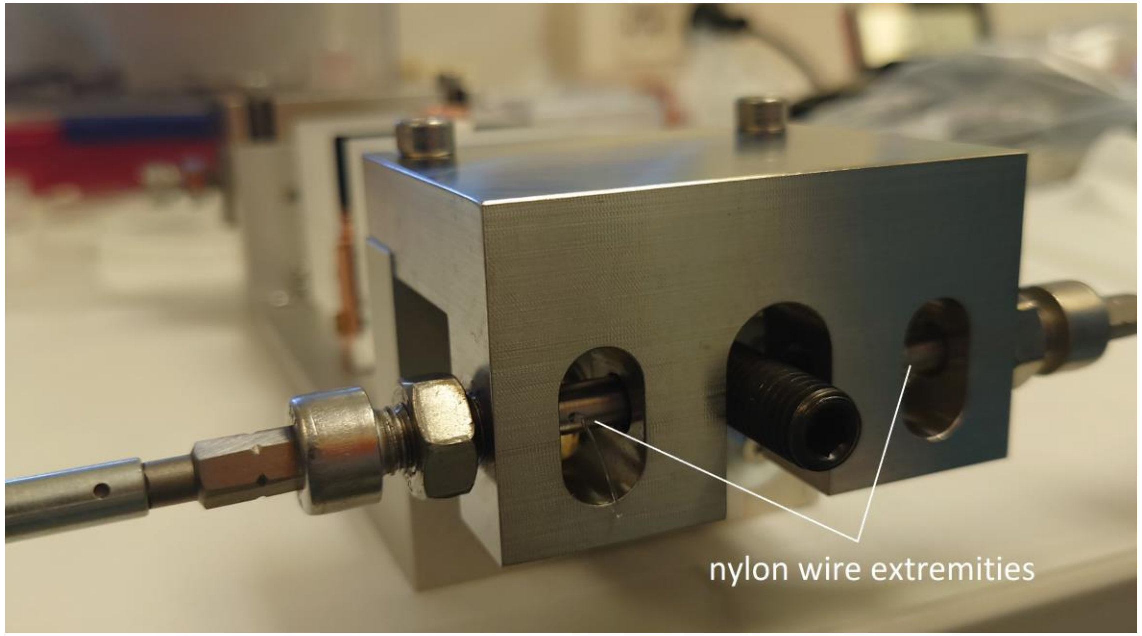
Comparison between CUPID-baseline and BINGO assemblies in terms of surface contamination

For ^{100}Mo ROI:
U-Chain dominated by ^{214}Bi beta contribution (Q_b = 3.27 MeV, avg. 1.5 MeV in gamma's) —> very efficient reduction > x100 to 1.4 E-7 ckky
Th-chain contribution, dominated by ^{208}Tl beta-decay (Q_b = 5 MeV, avg. 3.4 MeV in gamma's) reduced by ~ x5 to x10 to 2.0 E-6 ckky






main Cu holder
nut
plastic screw
screw with a hole
nylon wire
screw and washer
torque
screwdriver


nylon wire extremities