# BINGO active veto

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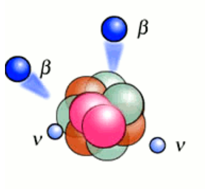
# double beta decay

## Two-neutrino mode: 2νββ

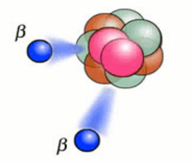
$$(\boldsymbol{A},\boldsymbol{Z}) \rightarrow (\boldsymbol{A},\boldsymbol{Z}+\mathbf{2}) + \mathbf{2}\boldsymbol{e}^{-} + \mathbf{2}\overline{\boldsymbol{\nu}}_{\boldsymbol{e}}$$



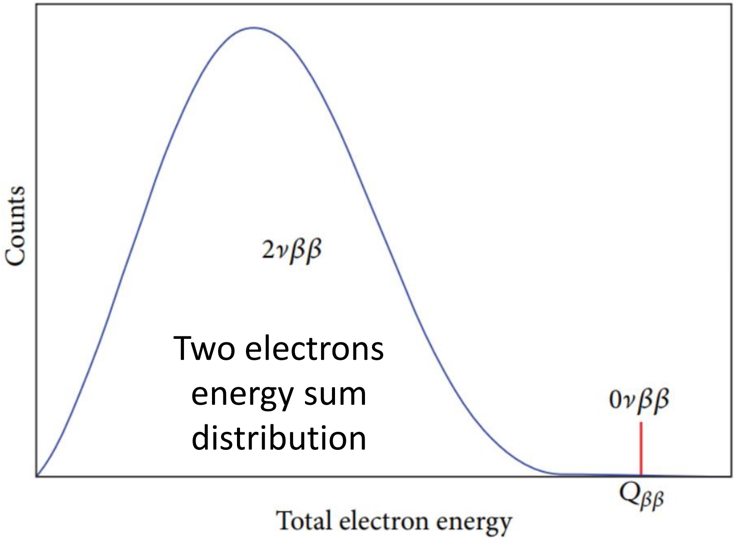
- It can occur for even-even nuclei
- Allowed in the SM
- It is energetically allowed for 35 nuclides and has been observed in 1/3 of them ($^{48}$Ca, $^{76}$Ge, $^{82}$Se, $^{96}$Zr, $^{100}$Mo, $^{116}$Cd, $^{128}$Te, $^{130}$Te, $^{136}$Xe, $^{150}$Nd, $^{238}$U)
- Extremely long half-life $T_{1/2} \sim 10^{18} - 10^{24}$ yr

## Neutrinoless mode: 0νββ

$$(\boldsymbol{A},\boldsymbol{Z}) \rightarrow (\boldsymbol{A},\boldsymbol{Z}+\mathbf{2}) + \mathbf{2}\boldsymbol{e}^{-}$$

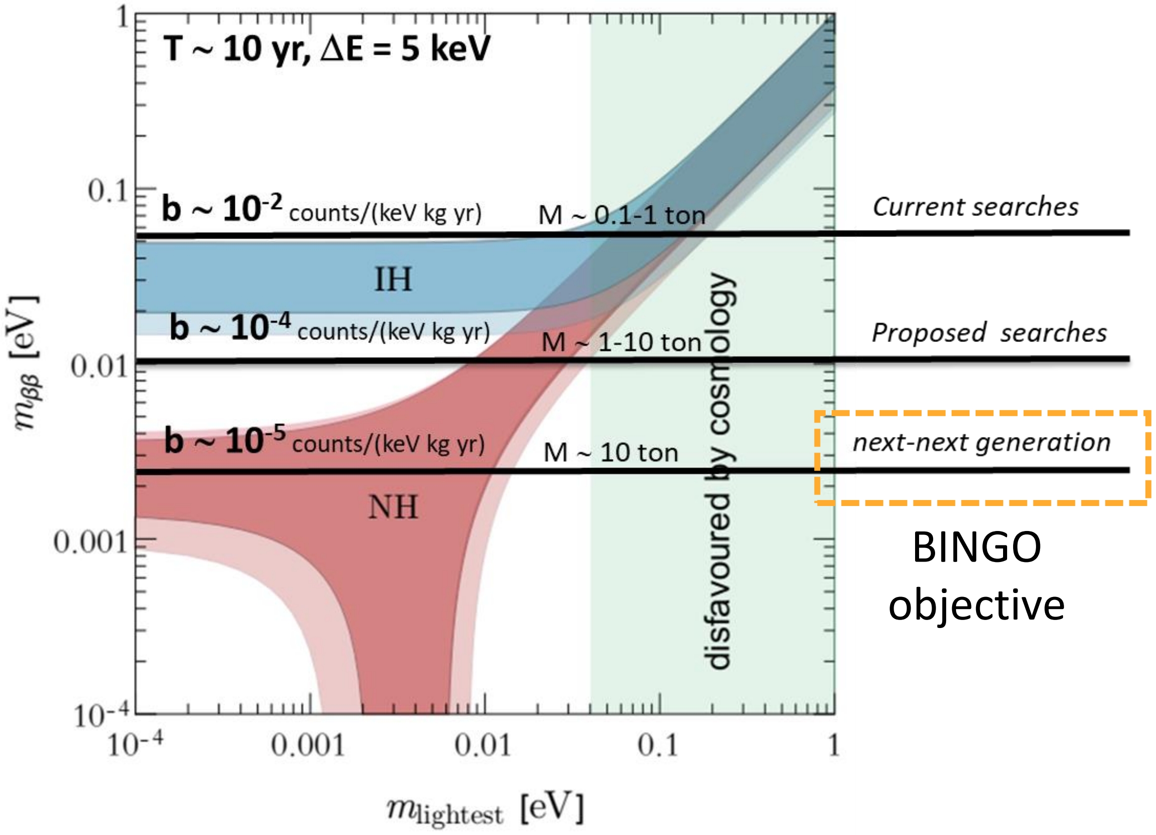


- Lepton number violation
- Neutrinos are massive Majorana particles ($\bar{\nu} = \nu$)
- Measure $T_{1/2}^{0\nu}$ that will lead to effective Majorana neutrino mass $\boldsymbol{m}_{\boldsymbol{\beta\beta}}$ measurement



Two electrons energy sum distribution

# Sensitivity to effective Majorana mass



BINGO objective

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

$b$: background index

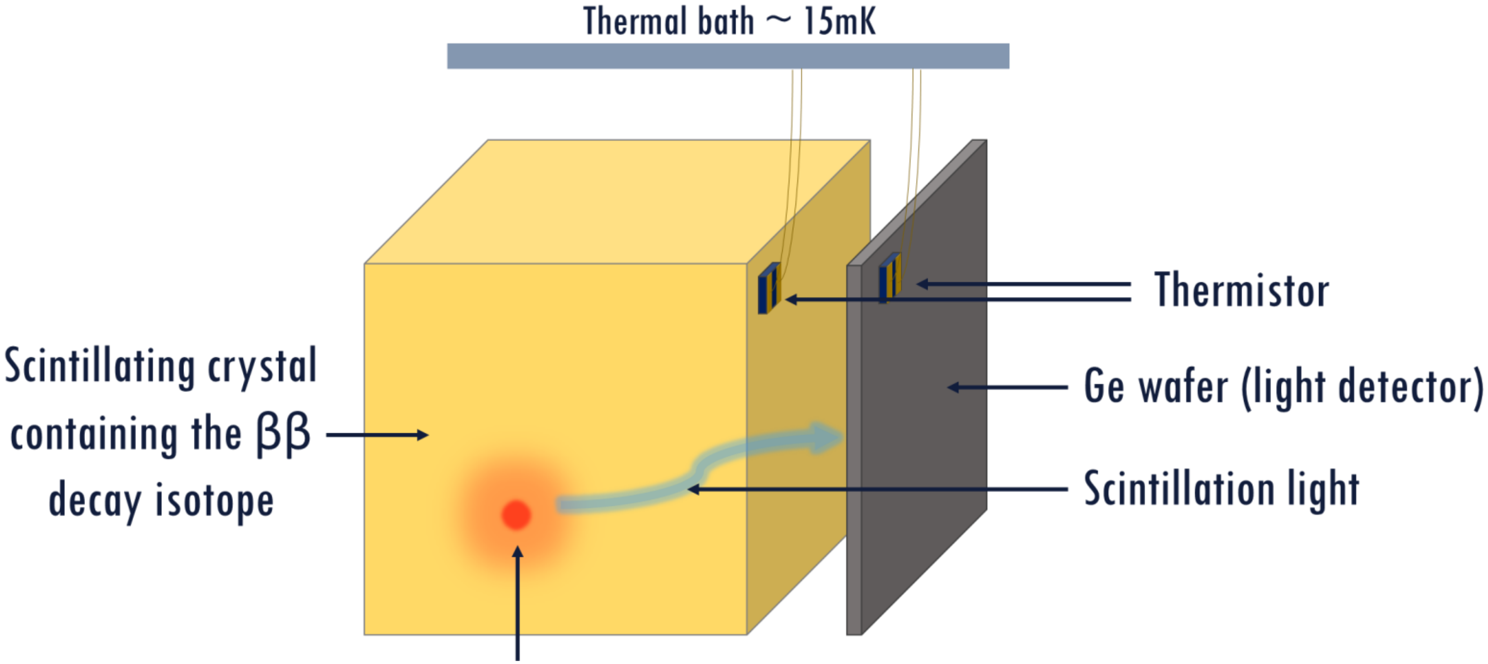
$M$: detector mass

$T$: time of measurement

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

BINGO aims to reduce the background in the region of interest, which is one of the most limiting factors for current and future 0ν2β bolometric experiments

# Bolometric technique (Dual read-out)



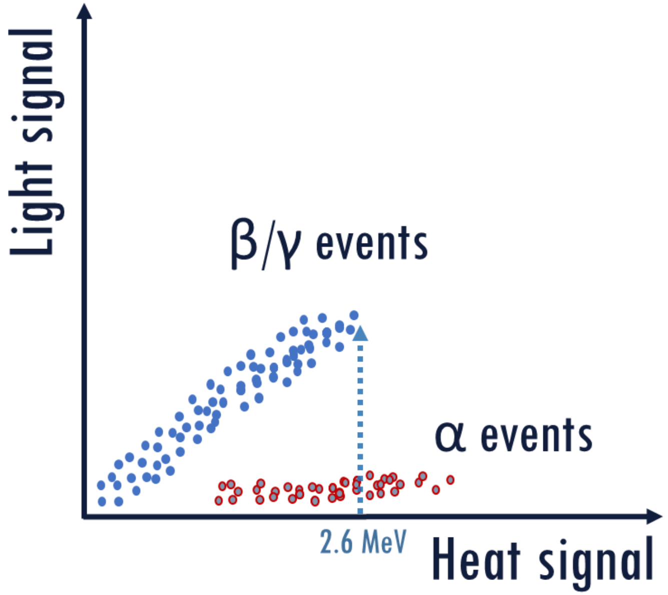
Thermal bath ~ 15mK

Thermistor

Ge wafer (light detector)

Scintillation light

Scintillating crystal containing the ββ decay isotope



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 (**BINGO will use $Li_2MoO_4$ ($^{100}Mo$) and $TeO_2$ ($^{130}Te$) with $Q_{\beta\beta}$ at 3034 keV and 2527 keV respectively**)

# Mitigating the background

## $\alpha$ surface contamination

- $Li_2MoO_4$ (scintillator): dual heat-light readout
- $TeO_2$ (bad scintillator): Cherenkov light detection using Neganov-Luke (NL) light detector (proposed by BINGO)

## $\beta$ Surface contamination

- New technology: surface sensitive detectors (proposed by CROSS)
- **Use an active shield (the crystal should be facing the veto)**

## $2\nu2\beta$ pile up

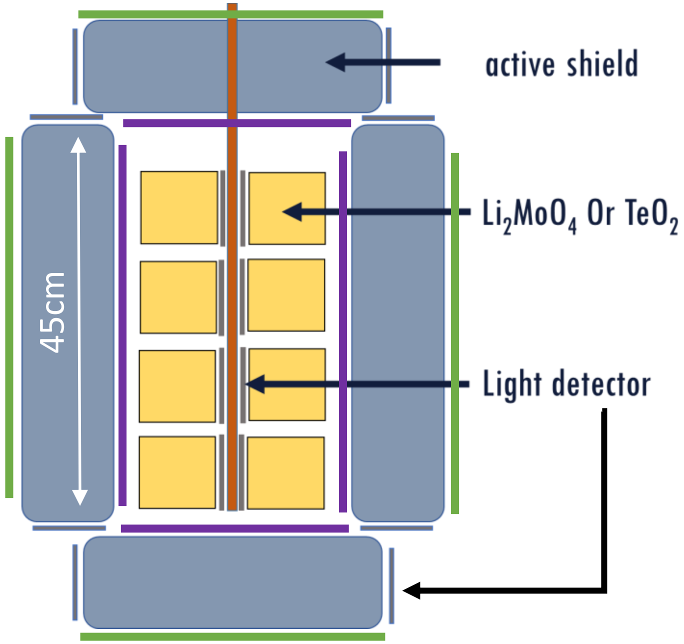
- $Li_2MoO_4$: increase light detector speed and signal to noise ratio (NL LDs)
- $TeO_2$: 100 times lower rate than $^{100}Mo$

## $\gamma$ radioactivity

- Detector holders: fine selection and reduction of materials (new assembly design proposed by BINGO)
- **Shields and external materials: use an active shield**

# The BINGO veto

- An active inner shield will be used to surround the $Li_2MoO_4$ and $TeO_2$ towers
  - Suppress the external gamma background and reject surface radioactivity from the crystals that face the active shield
  - The background reduction will be achieved through anti-coincidence between the veto and $Li_2MoO_4$/$TeO_2$
- The shield will be composed of BGO scintillator (initially $ZnWO_4$ was chosen):
- Each bar (in fact two bars on top of each other) will be read by two light detectors (with Neganov-Luke effect for signal amplification)
- A reflecting material will be added 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 , ...?)

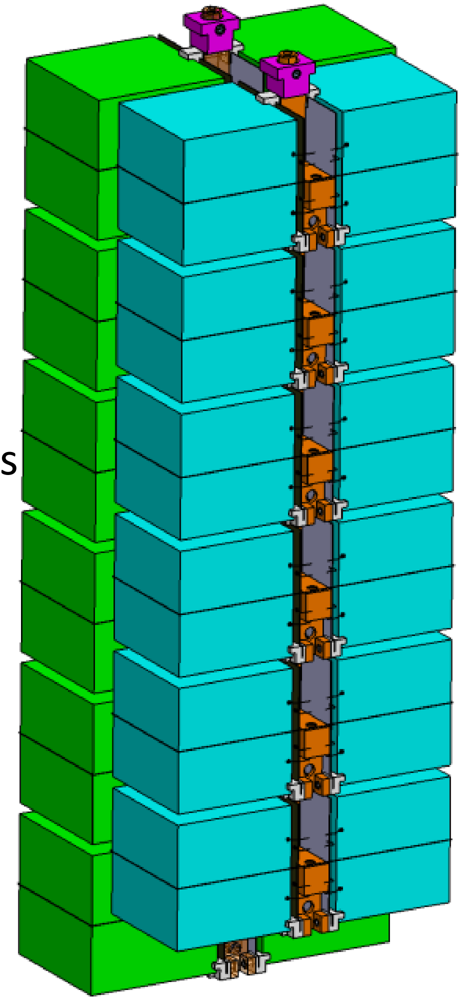


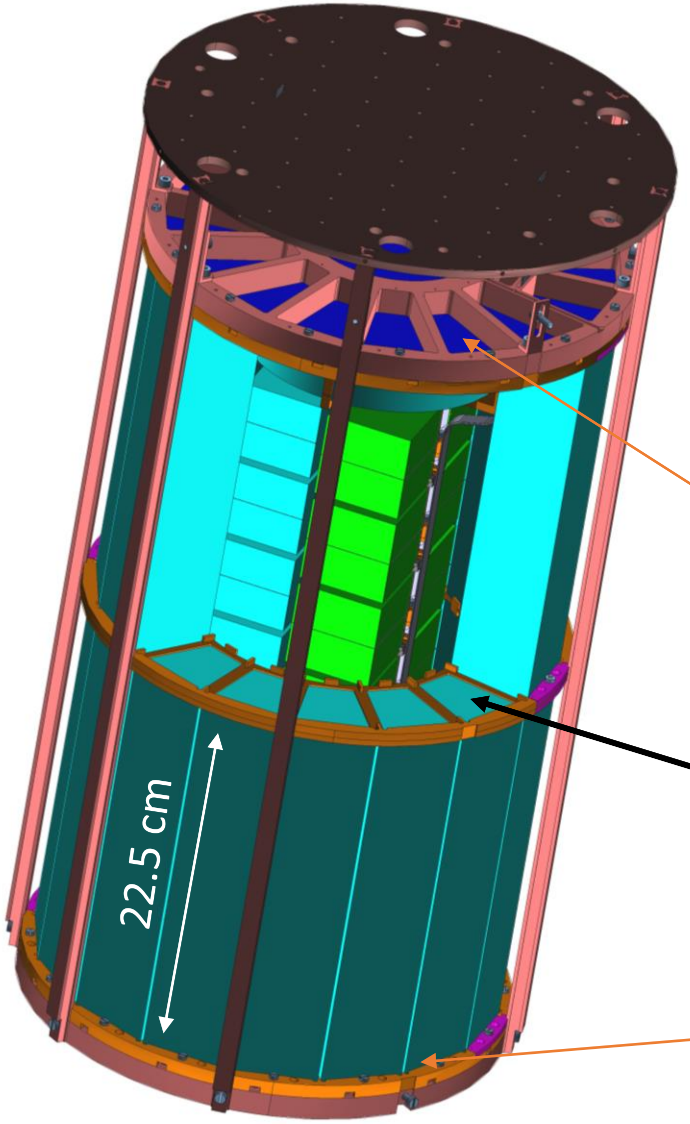
# BGO internal $^{207}$Bi contamination

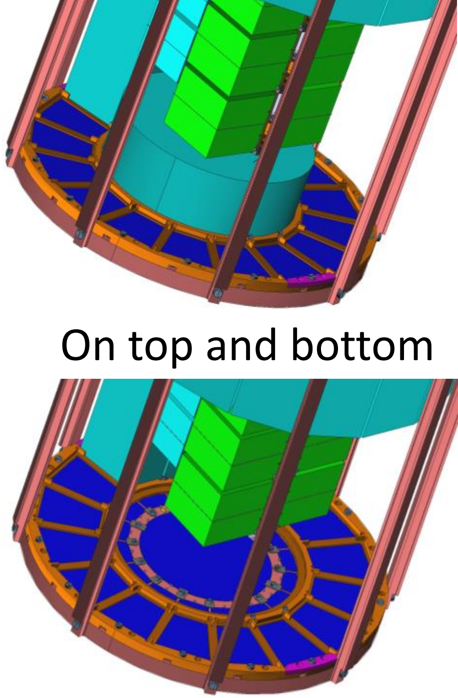
- BGO can show a significant internal $^{207}$Bi contamination up to 300mBq/kg
- A careful selection of the raw materials for growing BGO is ongoing from different providers worldwide. Different samples are being screened to select the ones with lower $^{207}$Bi contamination (some samples have shown good radiopurity)
- **MC simulation is ongoing to see the effect of $^{207}$Bi contamination on the experiment**

# The veto design

$Li_2MoO_4$ and $TeO_2$ towers







On top and bottom

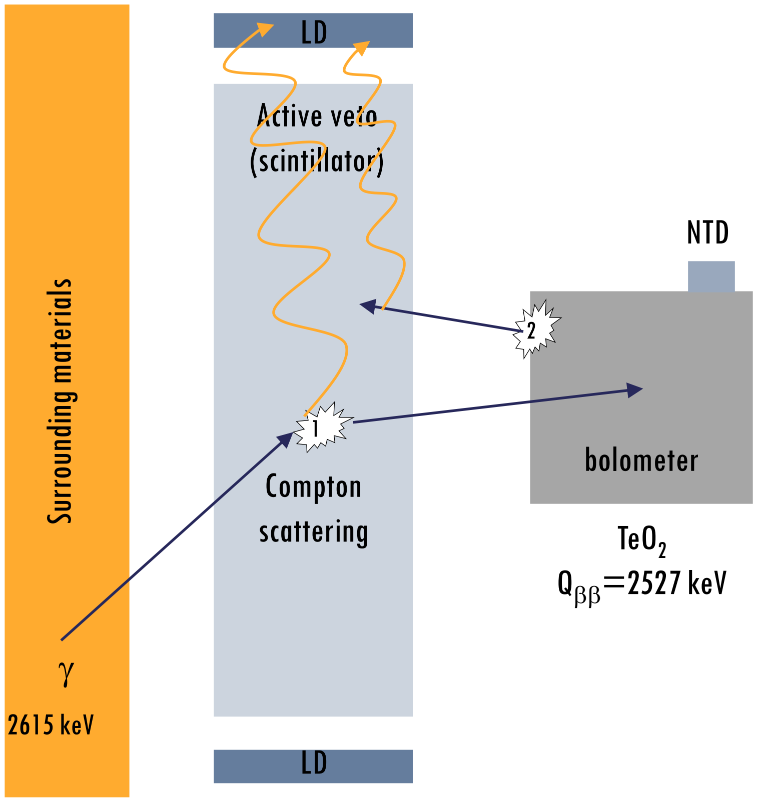
NL LDs

Possibility to add reflecting material in between the two BGO bars

NL LDs

# How does the veto work

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



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- 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

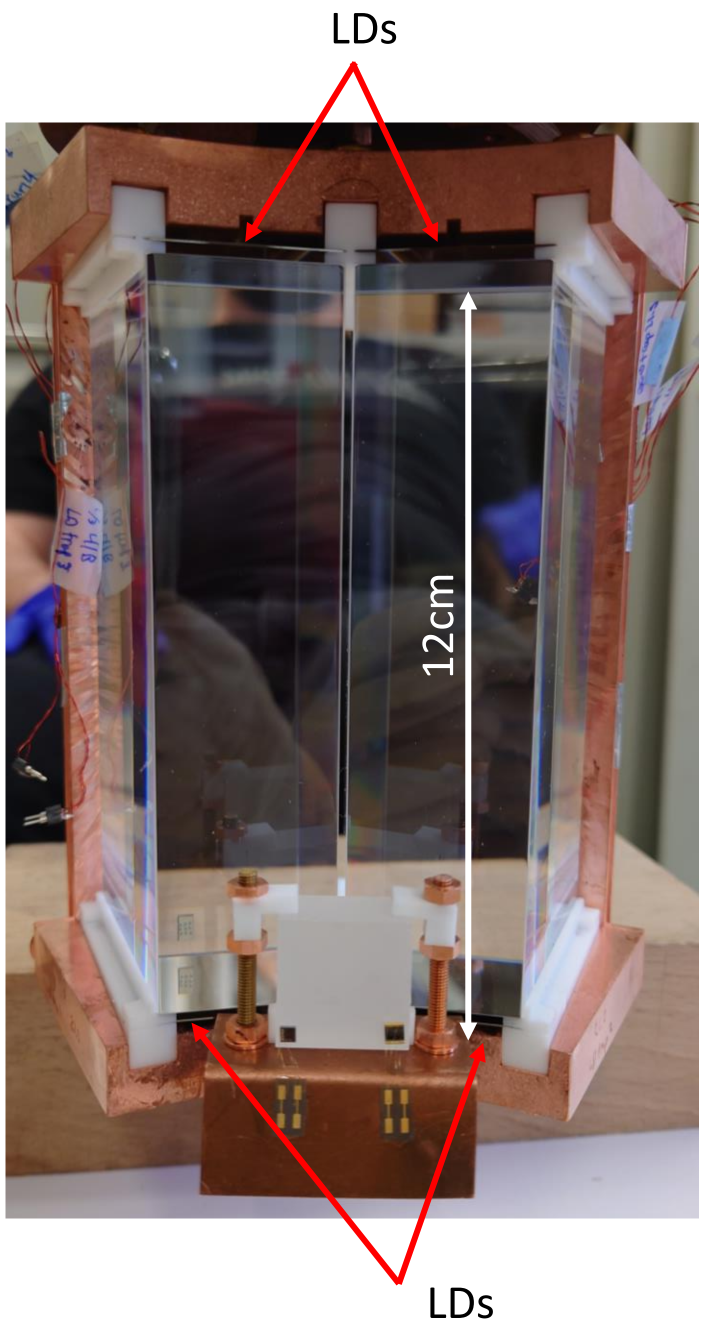
- Some surface contamination on the crystal can be dangerous if part of the energy escapes. This can also be rejected by anti-coincidence with the veto

# Requirements

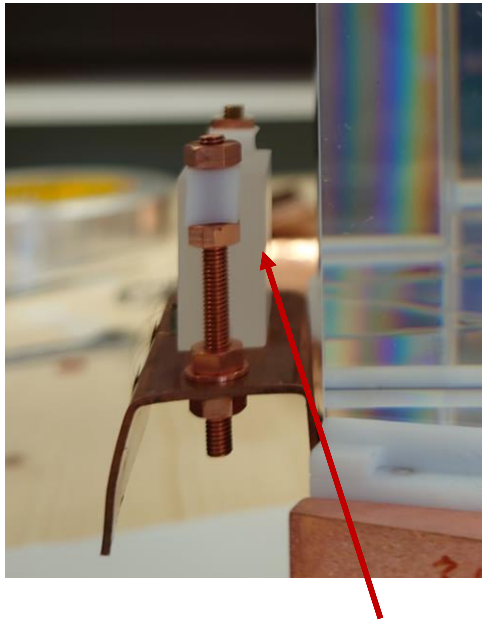
For this to work, a Neganov-Luke LD is needed:

- Higher 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)

# Prototype test



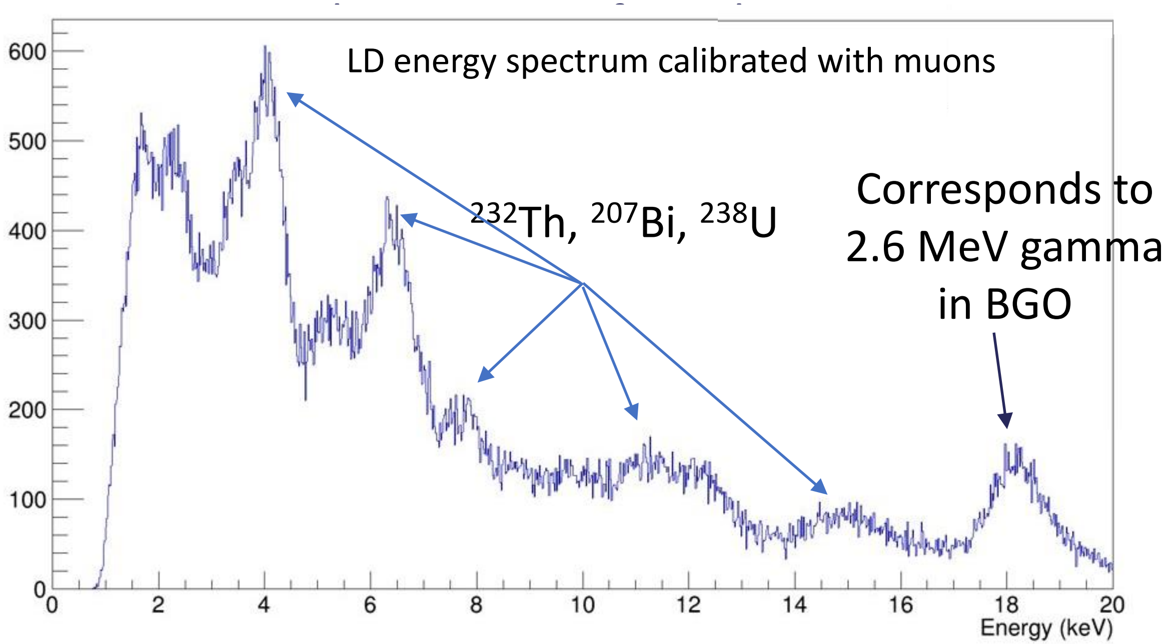
- 2  BGO crystals (~1.6kg each)
- 2 normal LDs facing each BGO
- $TeO_2$ crystal facing both BGOs
- Reflecting foil on the back
- The test was performed above-ground in a pulse-tube cryostat at IJCLab (Orsay)



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

# Efficiency study at the expected threshold

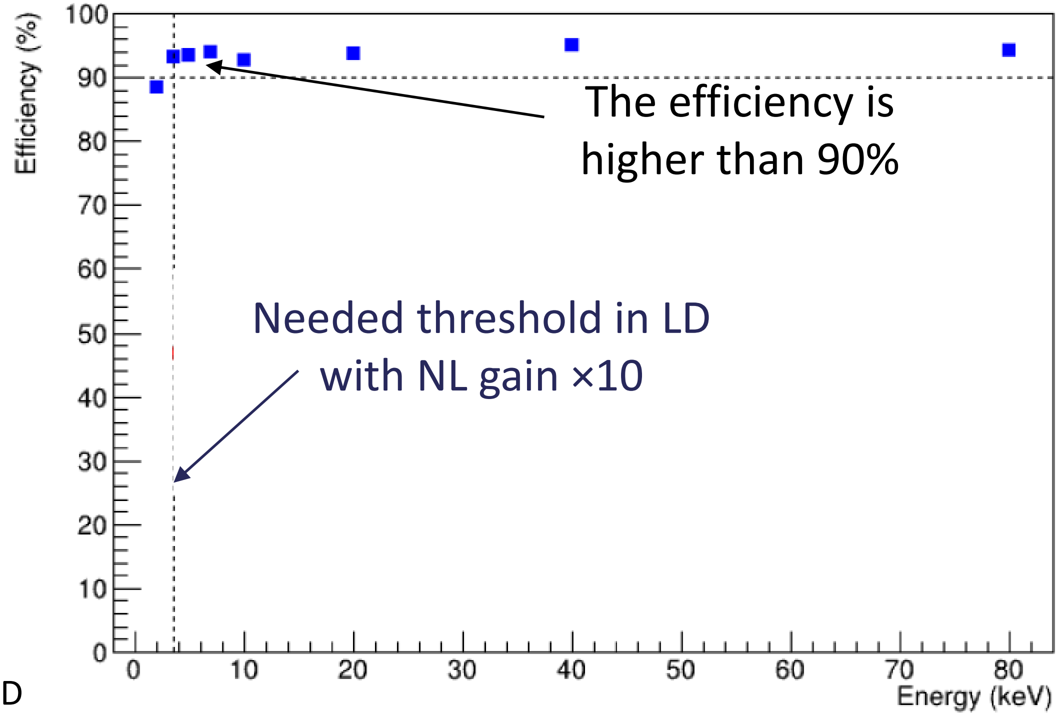
- 1000 fake pulses at different energies were injected into the data to estimated the efficiency after data processing
- The required energy threshold for the veto scintillator should be around 50 keV, which corresponds to around 0.3-0.4 keV in LD when taking into account the light yield (LY) which is about 7 keV/MeV


LD energy spectrum calibrated with muons

$^{232}$Th, $^{207}$Bi, $^{238}$U

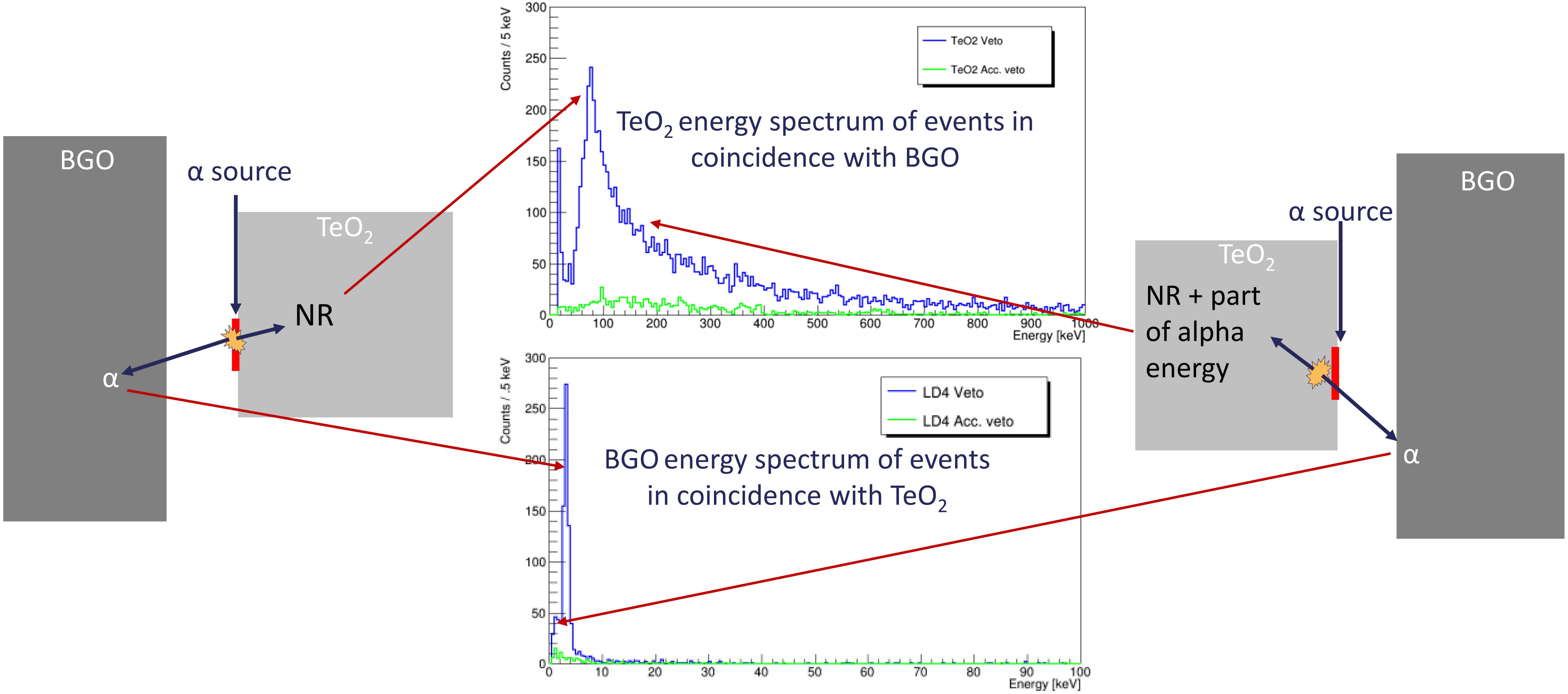
Corresponds to 2.6 MeV gamma in BGO

Energy released by photons in LD


The efficiency is higher than 90%

Needed threshold in LD with NL gain ×10

# Hunting the α source with coincidence

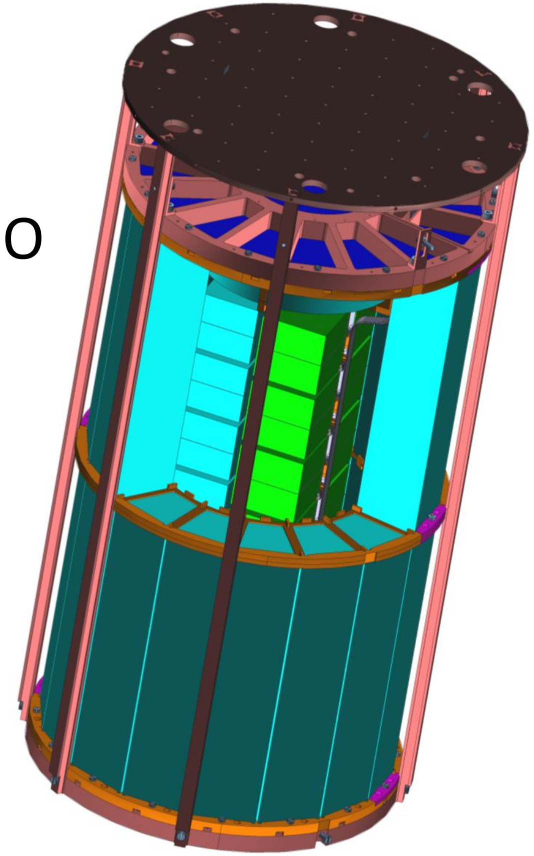


$TeO_2$ energy spectrum of events in coincidence with BGO

BGO energy spectrum of events in coincidence with $TeO_2$

# Status of the veto

- A new veto design is being produced
- Studying the best reflection materials is still ongoing
    - A reflecting material will be added on the lateral side of the veto
    - A reflecting material will be added between the two bars (possibly)
    - On the internal side of veto, facing the crystals
- We have now hints of good providers for the raw materials to make BGO
- Four new trapezoidal bars to be produced by autumn 2023
- A section of the final veto design (two trapezoidal BGO bars) will be measured above-ground in a cryostat to test the mechanics/NL LD/ reflecting materials in September 2023

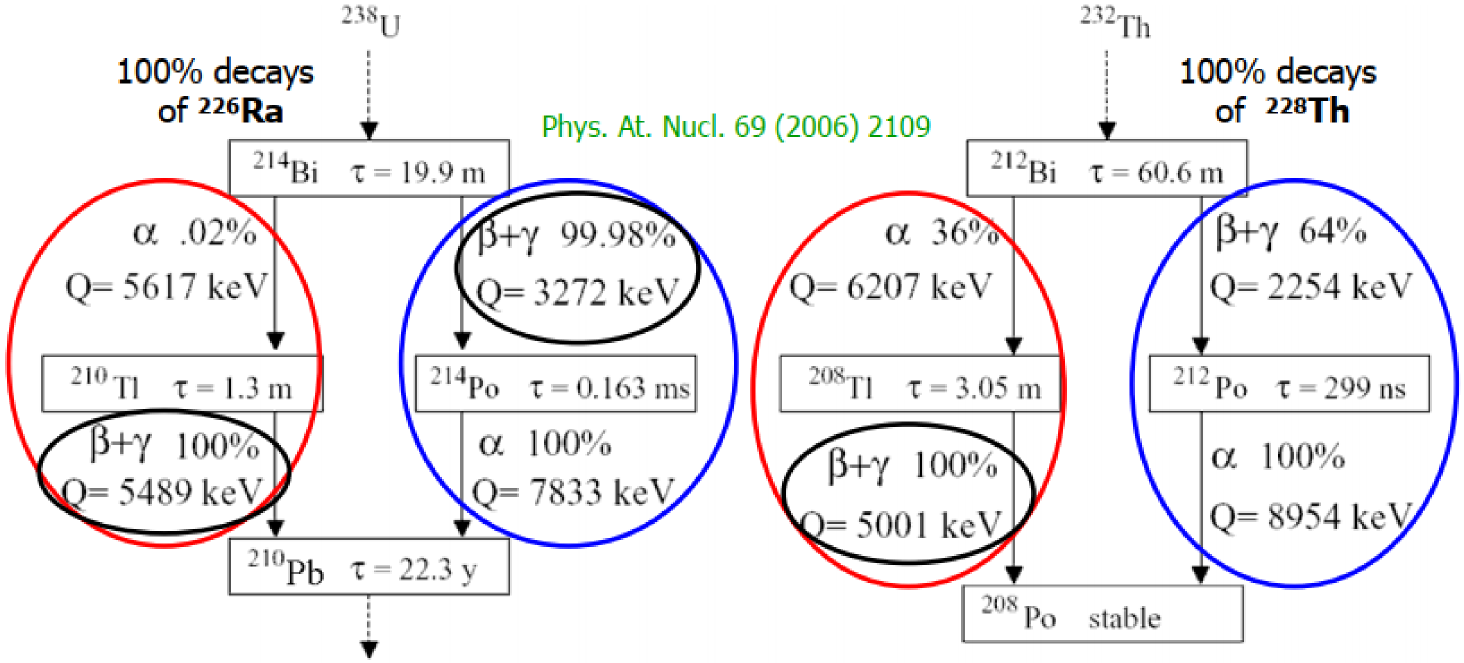


# Conclusions

- BINGO introduces innovative technology for background rejection
- For the first time, an active veto will be developed to surround the double-beta bolometers
- It will be used to reject external gamma radioactivity, in addition to surface radioactivity from the crystals facing the veto
- Prototype tests and MC simulation are still ongoing before moving to the final full geometry

# backups

# Sources of background



$^{238}U$

100% decays of $^{226}$Ra

$^{214}Bi$ τ = 19.9 m

α .02% Q= 5617 keV

β+γ 99.98% Q= 3272 keV

$^{210}Tl$ τ = 1.3 m

β+γ 100% Q= 5489 keV

$^{214}Po$ τ = 0.163 ms

α 100% Q= 7833 keV

$^{210}Pb$ τ = 22.3 y

Phys. At. Nucl. 69 (2006) 2109

$^{232}Th$

100% decays of $^{228}$Th

$^{212}Bi$ τ = 60.6 m

α 36% Q= 6207 keV

β+γ 64% Q= 2254 keV

$^{208}Tl$ τ = 3.05 m

β+γ 100% Q= 5001 keV

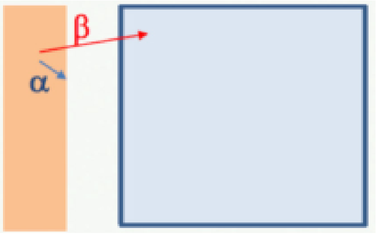
$^{212}Po$ τ = 299 ns

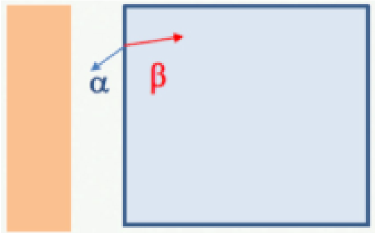
α 100% Q= 8954 keV

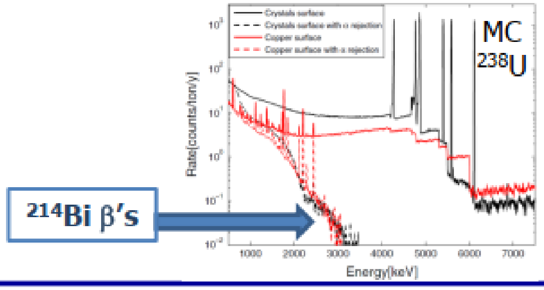
$^{208}Po$ stable

## 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**

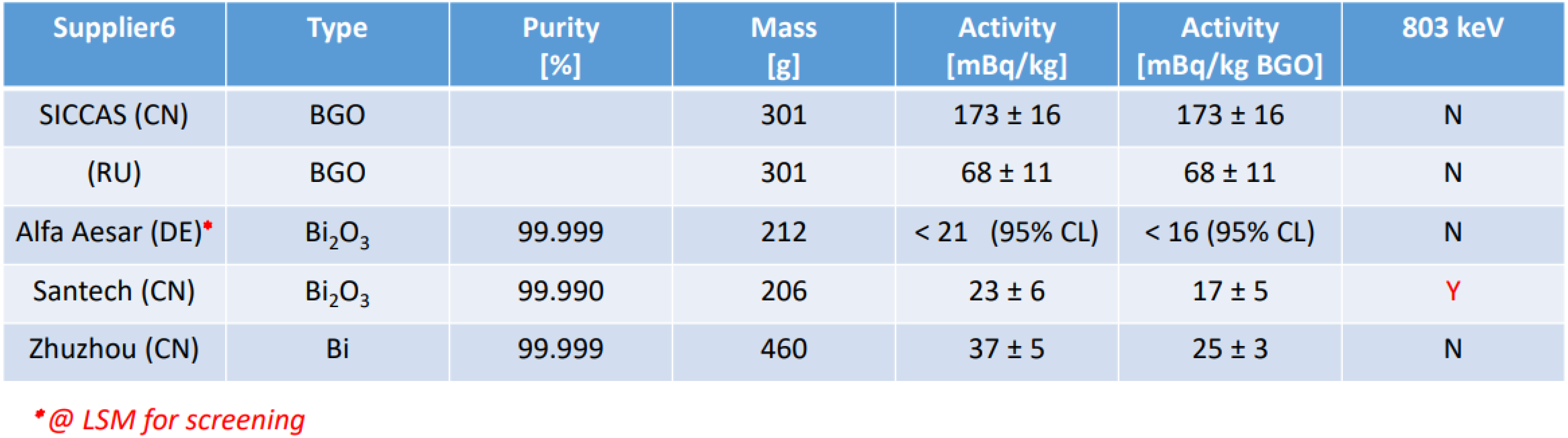






# $^{207}$Bi contamination

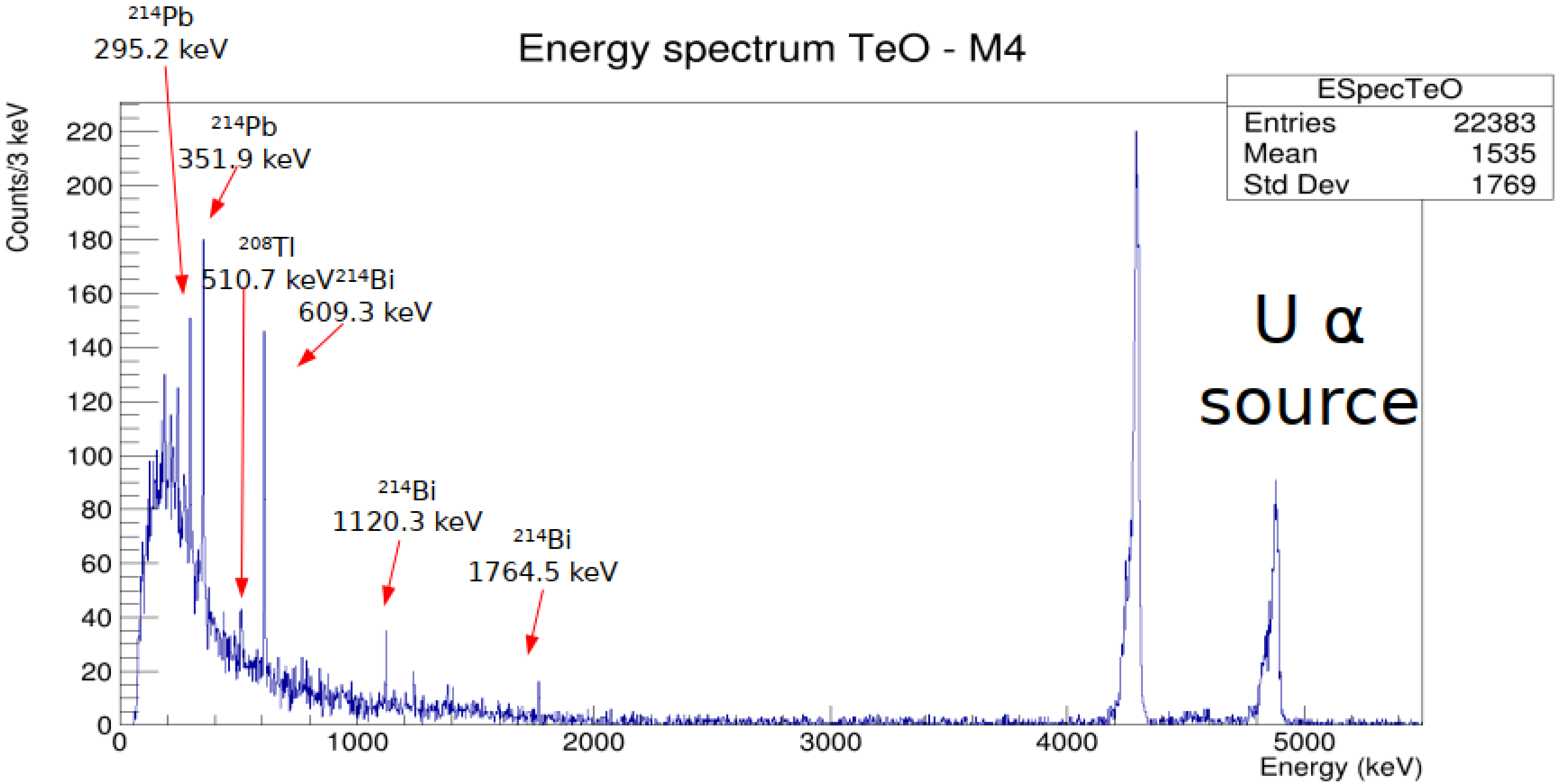
- With 328 mBq/kg, $M_{VETO} = 115$ kg and assuming a 5 ms coincidence time window, dead time is $\sim$17%
- Desirable to reach $< 100$ mBq/kg $\rightarrow$ deadtime is $\sim$6%

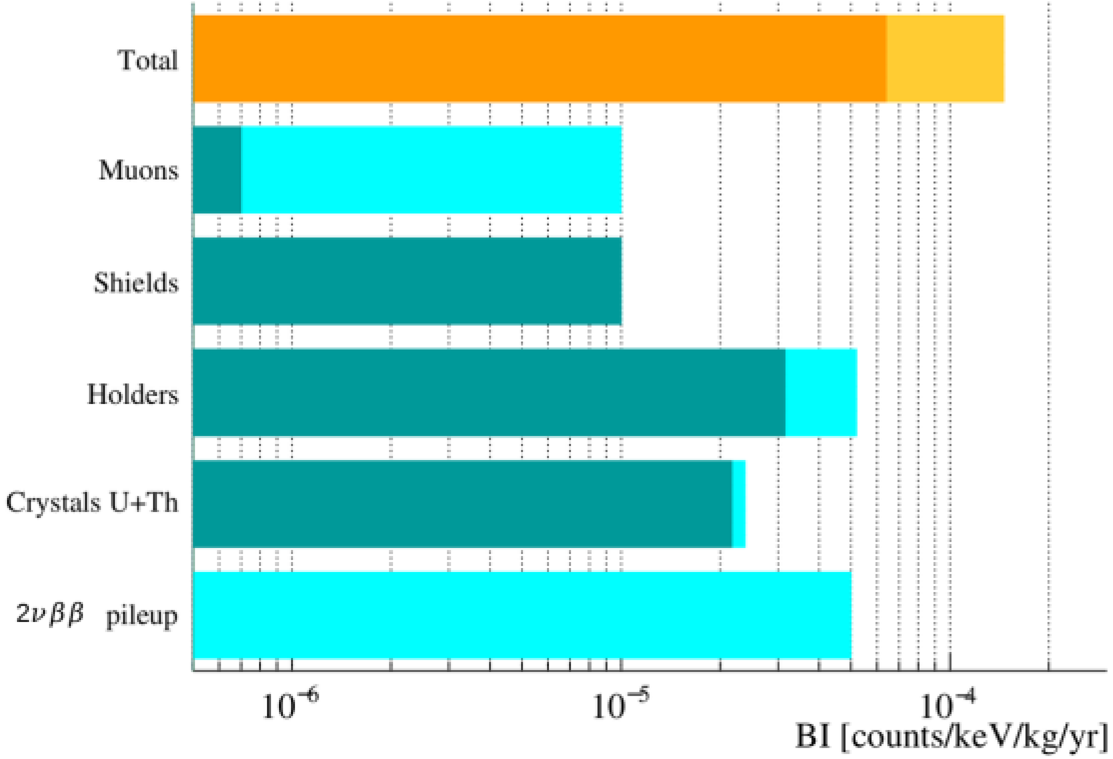


| Supplier6 | Type | Purity [%] | Mass [g] | Activity [mBq/kg] | Activity [mBq/kg BGO] | 803 keV |
|---|---|---|---|---|---|---|
| SICCAS (CN) | BGO | | 301 | 173 ± 16 | 173 ± 16 | N |
| (RU) | BGO | | 301 | 68 ± 11 | 68 ± 11 | N |
| Alfa Aesar (DE)* | $Bi_2O_3$ | 99.999 | 212 | < 21 (95% CL) | < 16 (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

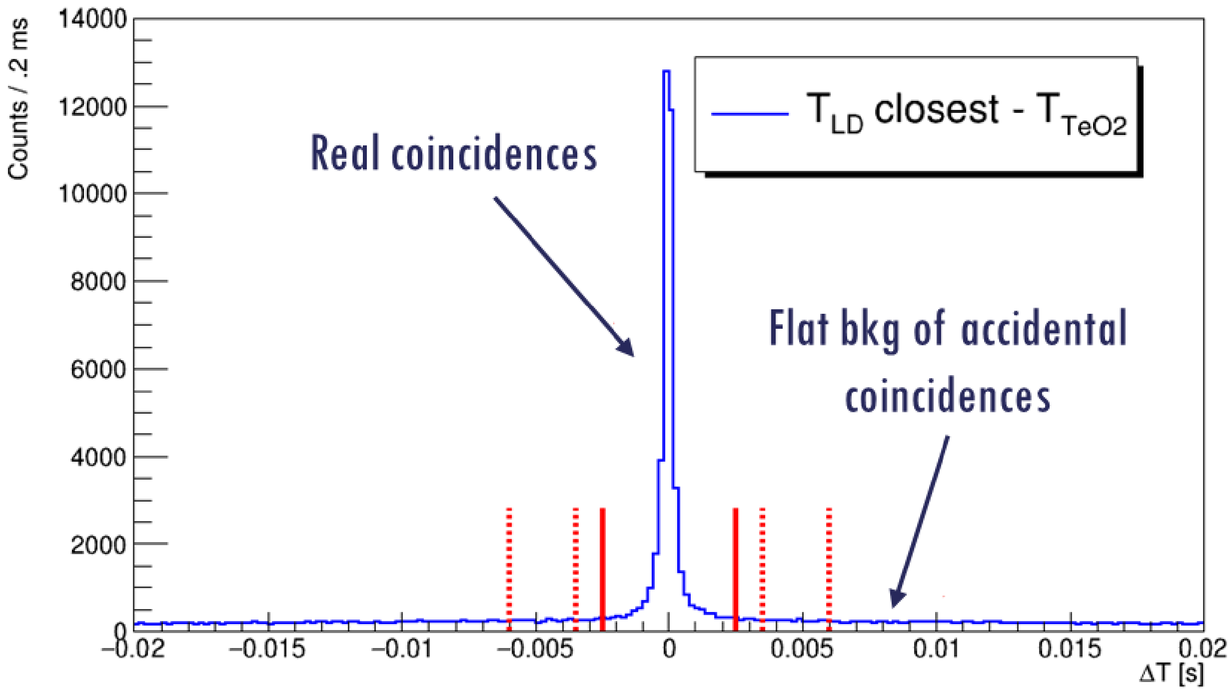
## $Li_2MoO_4$

- 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



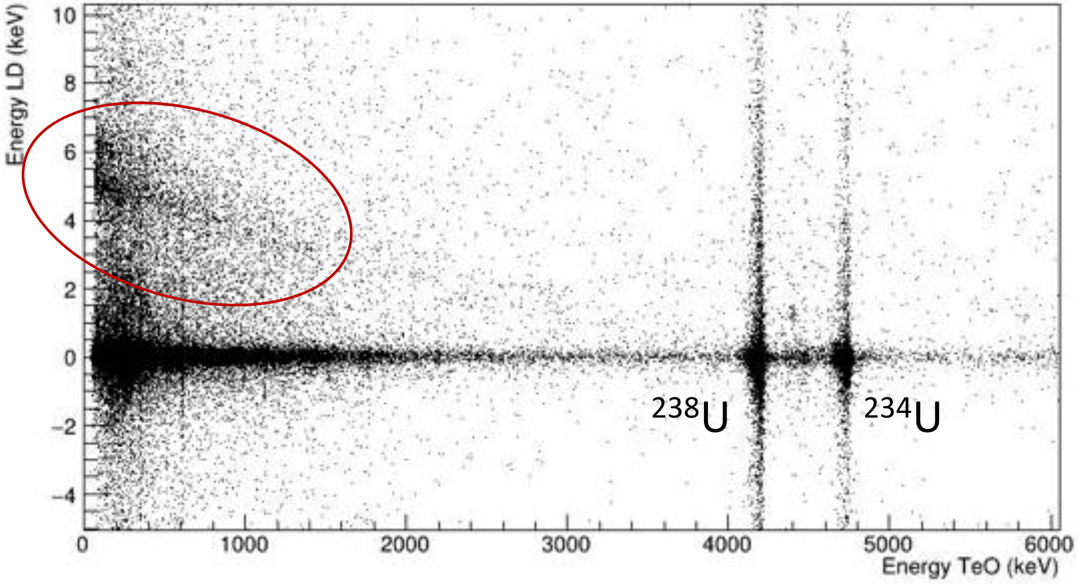
Real coincidences

Flat bkg of accidental coincidences

- 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 $TeO_2$