Enhancing $0\nu2\beta$ detection with the CROSS demonstrator

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The $0\nu2\beta$ decay

2ν double beta decay: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

- Rarest detected nuclear decay: $T_{1/2} \sim 10^{18}$-10^{24} yr
- Observed in 11 nuclei ($Q_{\beta\beta} \sim 2$ - 4 MeV)

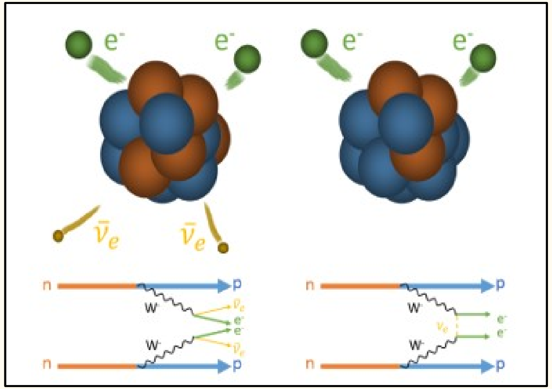
0ν double beta decay: $(A,Z) \rightarrow (A,Z+2) + 2e^-$

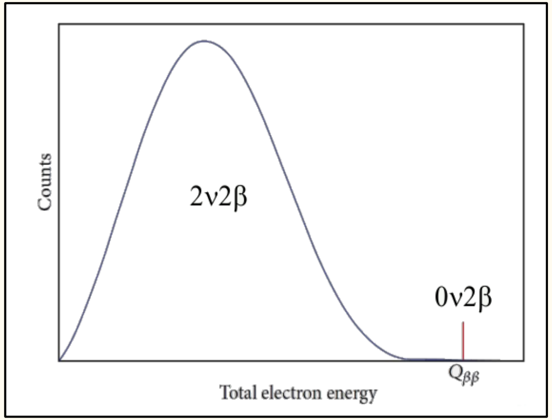
- Forbidden in Standard Model
- Lepton number violation and massive neutrinos
- Not observed yet: $T_{1/2} > 10^{25}$ - 10^{26} yr

The observation of $0\nu2\beta$ would allow us to explore physics beyond SM. Among others:

- **Neutrino nature: $\nu = \bar{\nu}$ (Majorana particle)**
- Leptogenesis
- Matter-antimatter asymmetry
- Information on neutrino masses

The main experimental challenge in $0\nu2\beta$ decay search is background reduction!

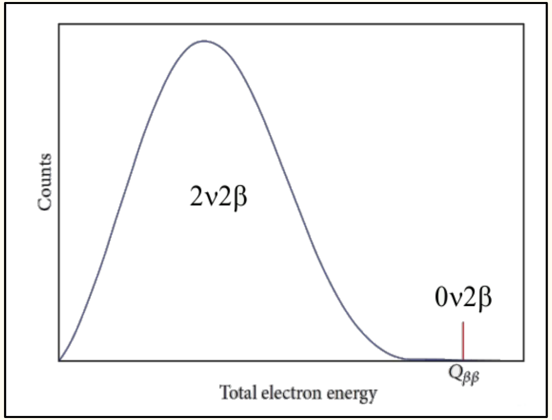




The 0ν2β decay

Experiments searching 0ν2β decay are applying different solutions to reduce the background sources

Background sources	**Solutions**
Cosmic rays	Underground labs
Environmental radioactivity	Radiopure materials
	Shielding (Active & Passive)
	Detect multiple channels to reject α's
	Study isotopes with high Q-value
2ν2β decay from isotope studied	High energy resolution detectors
α and β surface radioactivity	Detectors with impact point identification



→ **As for example, bolometers**

Bolometers and NTD thermistors

Bolometer = heat radiation detector consisting of:

- Absorber
- Connection to a thermal reservoir
- Thermistor

Thermistor = Termometer with an electrical resistance dependent on the temperature

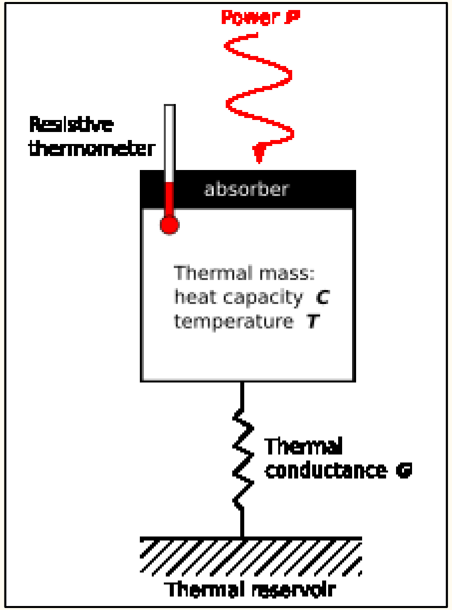
$$\rho = \rho_0 e^{(T_0/T)^\gamma}$$

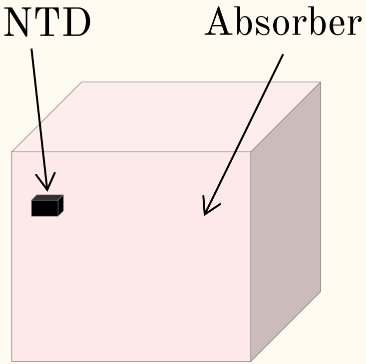
Comonly used as particle detectors

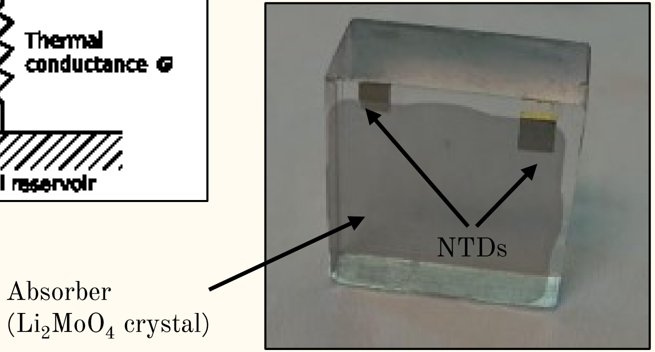
Intrinsic energy resolution of the detector depends on the temperature:

$$\Delta E = \sqrt{k_b C(T) T^2} \qquad C = \frac{12}{5}\pi^4 N_A \frac{m}{M} k_b \left(\frac{T}{\Theta_D}\right)^3$$

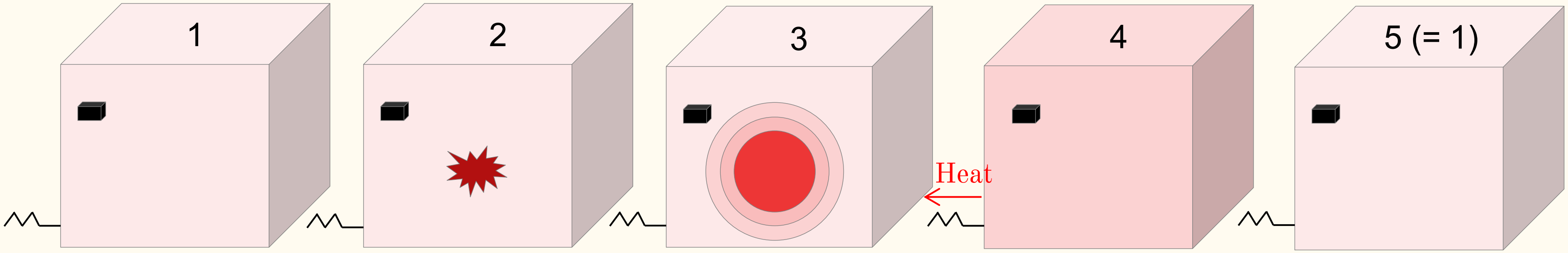
Bolometric particle detectors operates at T ~ 10 mK!

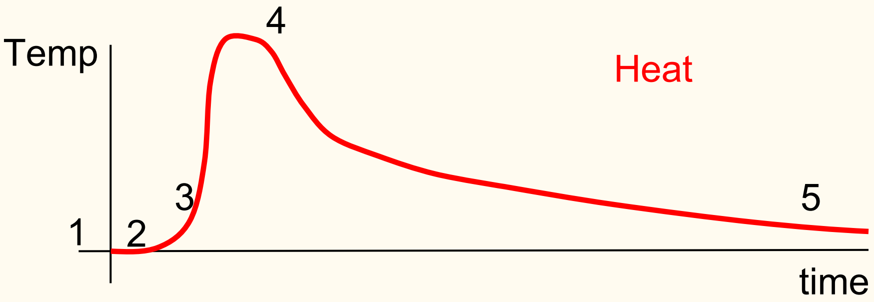




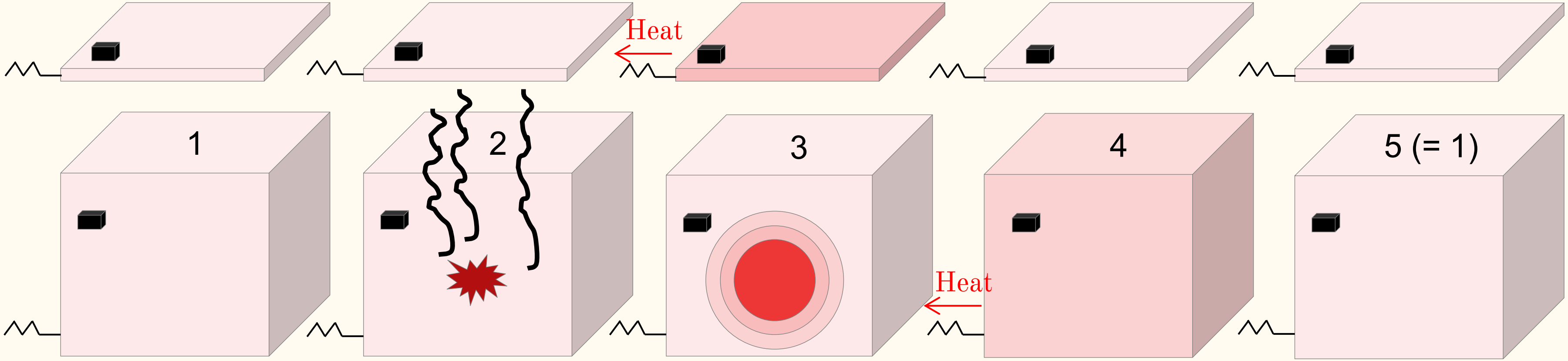


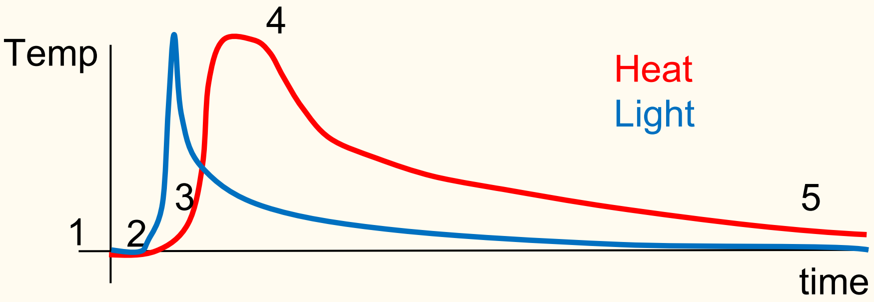
Bolometers as particle detectors

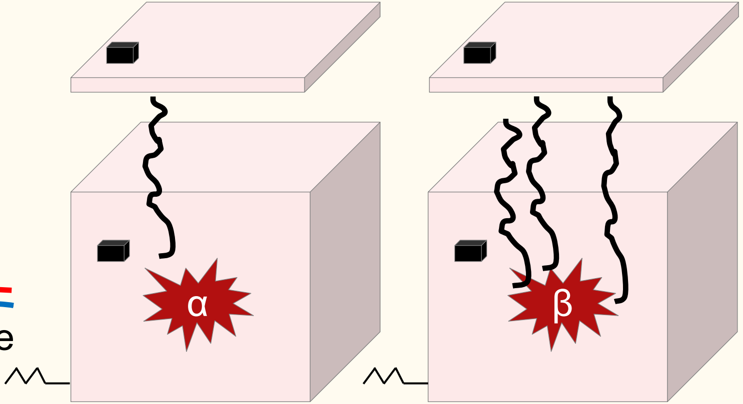




Scintillating bolometers as particle detectors







Multiple read-out allows to reject α's due to the LY difference

The CROSS experiment

CROSS is a bolometric experiment aiming to detect 0ν2β developing new strategies to reduce the background contribution with origin in the surface of the detectors and the surrounding materials

The CROSS approach:

Background sources	Solutions
Cosmic rays	Underground labs
Environmental radioactivity	Radiopure materials
	Shielding (Active & Passive)
	Study isotopes with high Q-value
	Detect multiple channels to reject α's
2ν2β decay from isotope studied	High energy resolution detectors
α and β surface radioactivity	Detectors with impact point identification

Underground cryogenic facility at LSC (Spain)

Use of radiopure materials: Cu, PTPE, PLA, Crystals...

Lead shielding, anti-radon shield and muon veto

Two high Q-value 2β isotopes studied:

- ^{100}Mo: Q-value = 3034 keV
- ^{130}Te: Q-value = 2527 keV

Double read-out (heat & light) using Neganov Trofimov Luke (NTL) Light Detectors

Use of bolometers. They are made of crystals enriched with the 2β isotopes: $Li_2{}^{100}MoO_4$ and $^{130}TeO_2$

Bolometers coated with metal films to identify near-surface interactions (work ongoing)

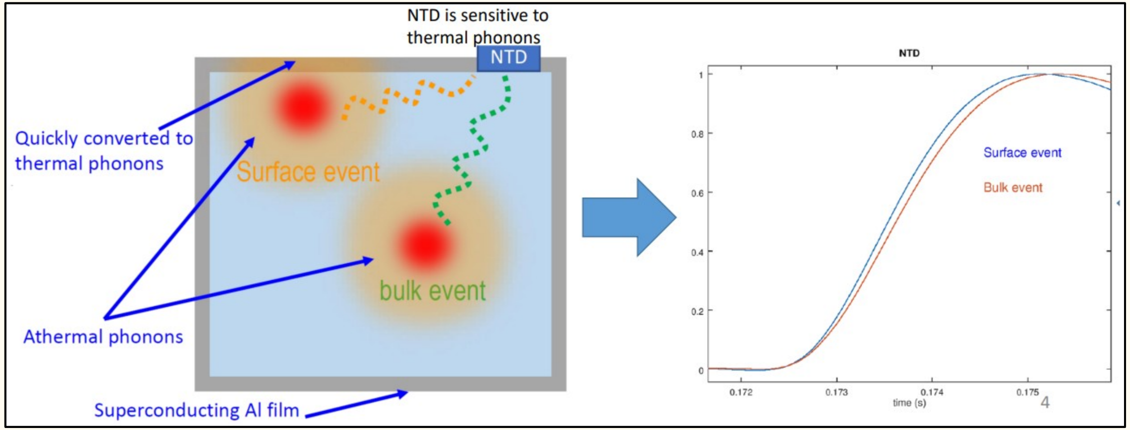
New technologies!

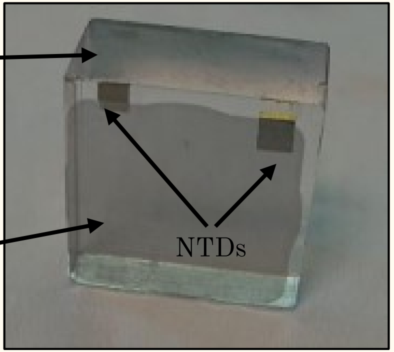
Other experiments searching for 0ν2β decay in ^{100}Mo: CUPID-Mo and AMORE

JHEP 01 (2020) 018

CROSS R&D: Metal-coated bolometers

Objective: Discrimination between bulk and surface α/β events

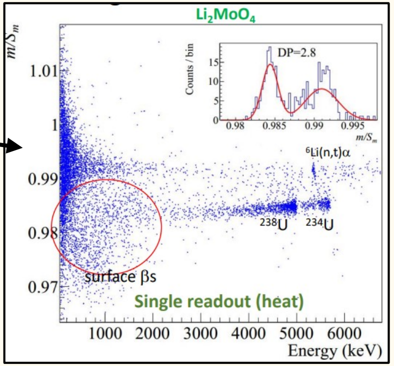




Li_2MoO_4 crystal

NTDs

10 nm Pd coating



Tests with small ($2 \times 2 \times 1$ cm^3) Li_2MoO_4 crystals coated with Al-Pd are promising:

- Discrimination power of surface α's $\geq 4.5\sigma$
- β surface events selection efficiency ~ 93%
- Baseline resolution is not affected

Discrimination power:

$$DP = \frac{|\mu_{\beta/\alpha} - \mu_\alpha|}{\sqrt{\sigma^2_{\beta/\gamma} + \sigma^2_\alpha}}$$

Difficulties in reproducing the same results with larger samples

JHEP 01 (2020) 018, APL 118 (2021) 184105

CROSS R&D: NTL Light Detectors

Objectives:

- Discrimination of α's due to its lower light yield compared to γ(β)
- Rejection of pileup events produced by the random coincidence of two $2\nu2\beta$ events

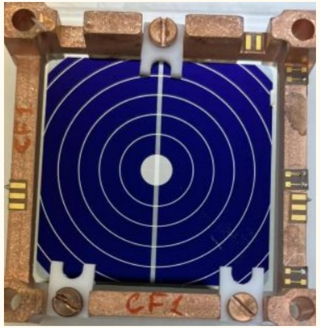
NTL effect: The heat signal is amplified because an extra heat is released by charged carriers drifted in an electric field $S_{Tot} = S_o \cdot Gain_{NTL} \quad Gain_{NTL} \propto V_{NTL}$

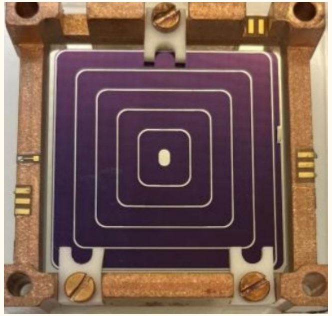
Design:

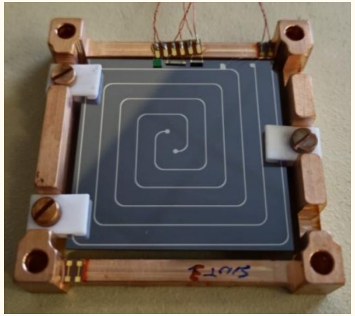
- Ge or Si wafers
- Coated with anti-reflective SiO to increase the light collection in ~ 30 %
- Al electrodes
- NTD glued to the wafer to measure the heat
- Three electrode shapes produced: Circular, Square and Spiral

Parameters to optimize:

- SNR: Improved a factor 10 with NTL effect
- Rise-time: Essential for pile-up rejection







Very promising results! (see later)

NIMA 940 (2019) 320, EPJC 83 (2023) 373

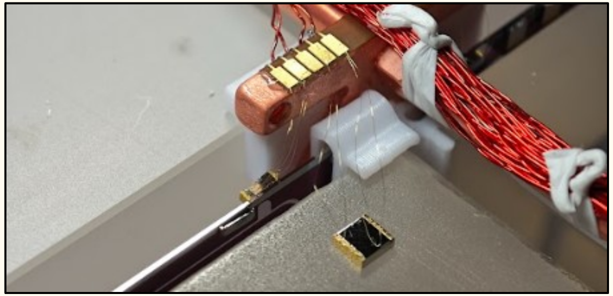
CROSS detector structure

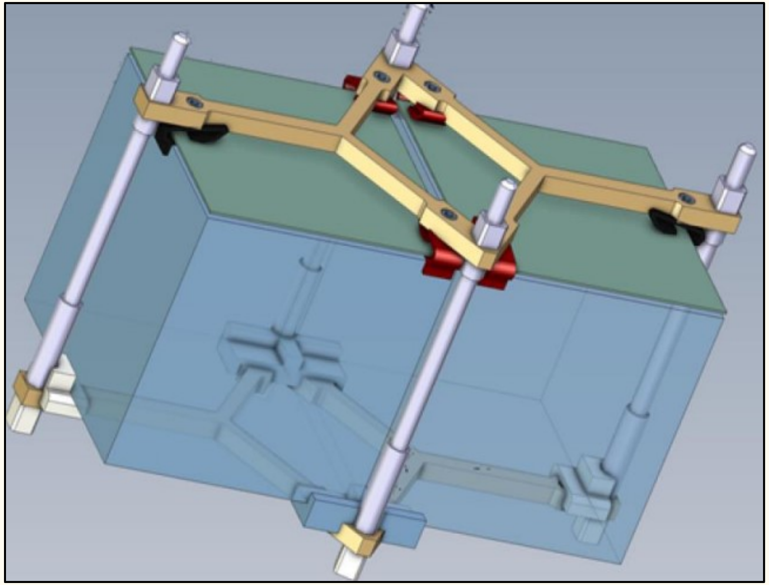
Cubic $Li_2{}^{100}MoO_4$ (LMO) and $^{130}TeO_2$ crystals (45 mm side)

Square Ge wafers (45 mm side x 0.3 mm thick)

Neutron Transmutation Doped (NTD) Ge thermistors glued to crystals and LDs

Structure designed to pile few 2 crystals floors in a "tower"





JINST 19 09, P09013 (2024) JINST 19 09, P09014 (2024)

CROSS underground facility at LSC

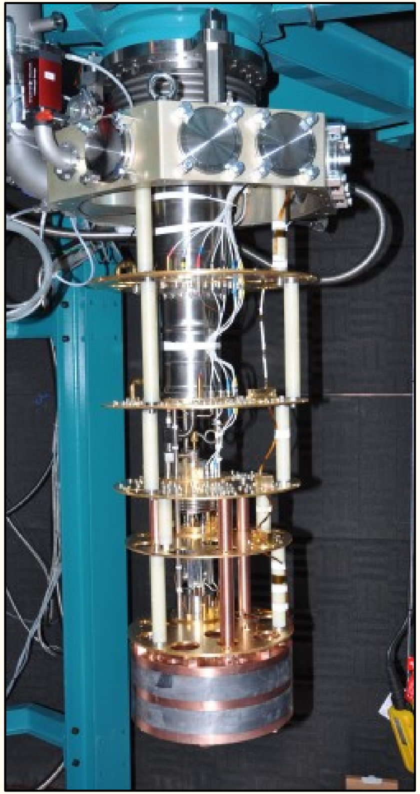
Cryostat installed and commissioned in April 2019

- $>$ 90% duty cycle and high stability

Lead shielding (external + internal) and antiradon box

Facility exploited to develop tests for the characterization and optimization of:

1. LMO crystals in terms of:
   a. Energy resolution
   b. Light yield
   c. Sensitivity
   d. Radiopurity
2. NTL LDs in terms of:
   a. Sensitivity and leakage current
   b. Optimal geometry of electrodes
   c. Studies on pile-ups rejection efficiency



JINST 18 (2023) P06018, JINST 18 (2023) P12004

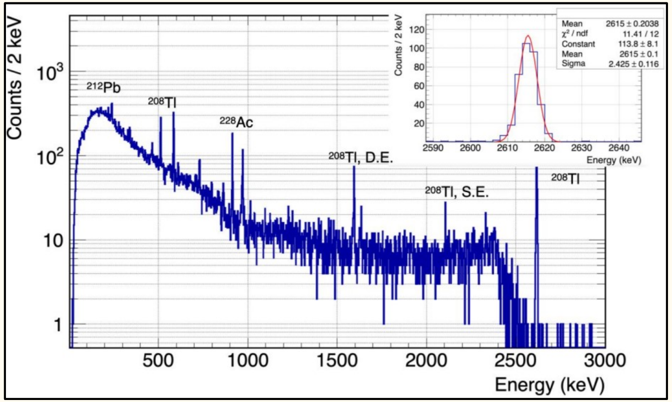
Detectors performance in the last test run

Tower structure:

- 6 LMO + 2 bare $^{130}TeO_2$ + 2 coated $^{130}TeO_2$(Al/Al-Pd)
- 10 NTL LDs with circular electrodes

Bolometer performance:

- Calibration of a LMO

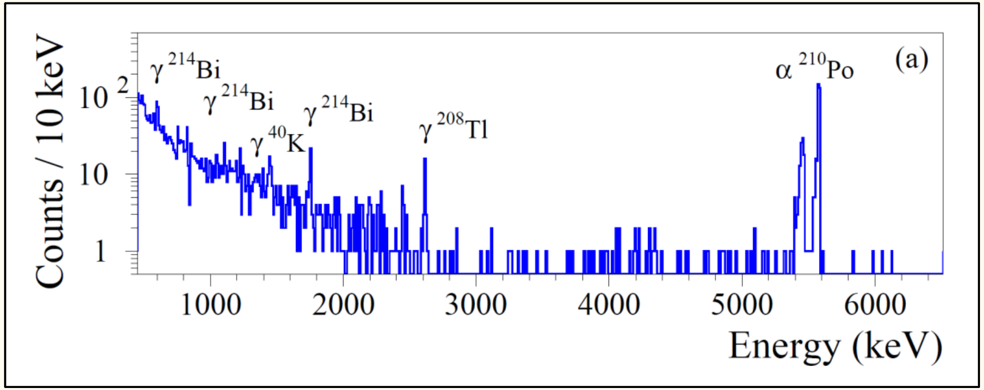


Excellent energy resolution:
ΔE_{FWHM}(2615 keV) = 5.7±0.3 keV

Measurements (performed at 17-27 mK):

- Calibration with ^{232}Th source
- Background

- Background measurement with a 550 g TeO_2 for 116 h at 27 mK



Confirmation of the radiopurity of the crystals
~ 1 mBq/kg activity of ^{210}Po

JINST 19 09, P09013 (2024)

Detectors performance in the last test run

Tower structure:

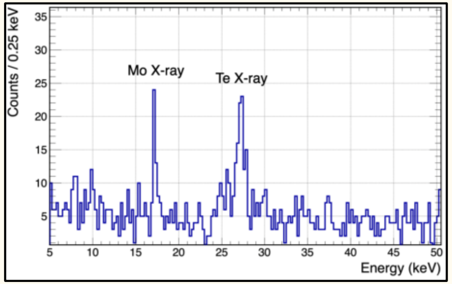
- 6 LMO + 2 bare $^{130}TeO_2$ + 2 coated $^{130}TeO_2$(Al/Al-Pd)
- 10 NTL LDs with circular electrodes

Measurements (performed at 17-27 mK):

- Calibration with ^{232}Th source
- Background

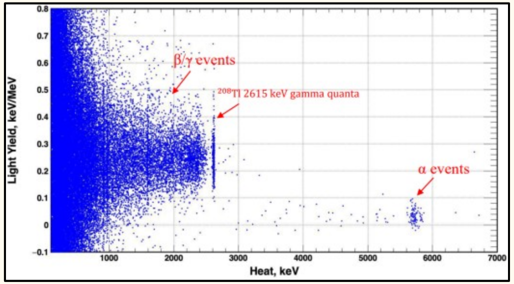
NTL LD performance:

- LD Calibration with Mo and Te X-rays



Excellent energy resolution

- $\alpha/\beta(\gamma)$ discrimination at $V_{NTL} = 0$ V



All LDs have $\sigma_{bsl} < 150$ eV when $V_{NTL} = 0$ V

99.9% α rejection

- Maximum NTL bias across the electrodes without developing leakage current was 95 V
- Mean values for the 10 LDs: $\sigma_{bsl} = (12 \pm 4)$ eV, $G_{NTL} \sim 11$ and SNR = 89
- Only 56% of surface is covered by the electrodes, so we expect $\sigma_{bsl} = 6.8$ eV and SNR = 152 for 100% coverage
- Mean rise-time of 0.55 ± 0.11 ms working at ~ 1 MOhm resistances of LD NTDs
- The gain obtained when light impinges on the electrode side of the Ge wafer is 2.5 higher than in back side

The CROSS demonstrator

3 towers with 7 floors each

Test of different LDs in each tower

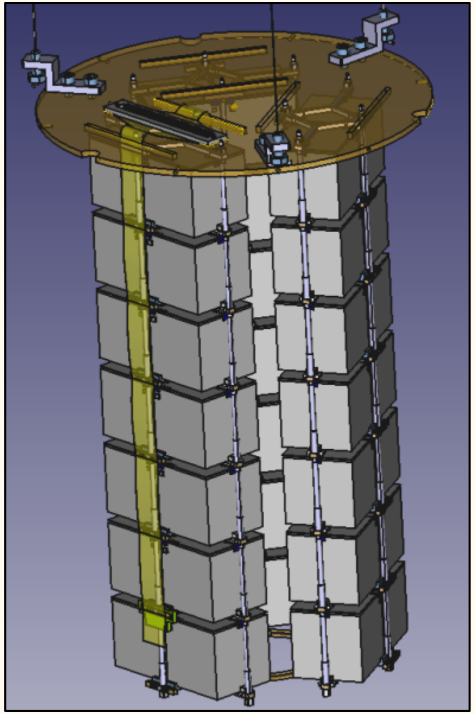
In total:

- **32 $Li_2{}^{100}MoO_4$**
- **2 $Li_2{}^{100depl}MoO_4$**
- **2 R&D Li_2MoO_4**
- **6 $^{130}TeO_2$**

- **Total mass of ^{100}Mo: 4.7 kg**
- **Total mass of ^{130}Te: 2.6 kg**

Detector assembly already started

Installation and commissioning in early 2025 and will be taking data for 2 years



The muon veto system for CROSS demonstrator

Made of plastic scintillators (Luminofores in PST)

SiPMs as light detectors

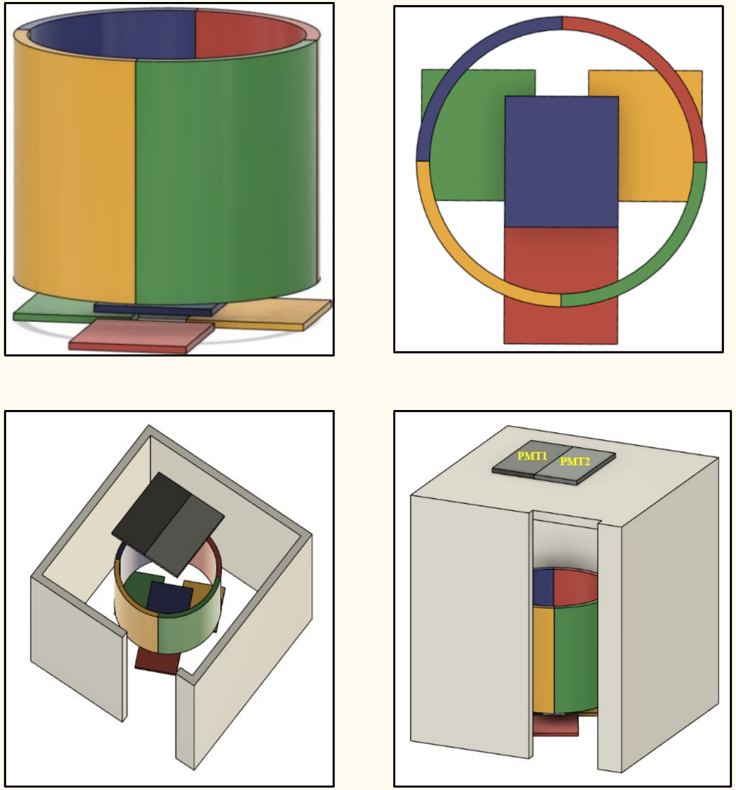
9 sectors (4 lateral + 4 bottom + 1 top)

Each sector divided in channels (174 channels in total):

- 28 for lateral
- 15 for bottom
- 2 for top

Trigger: coincidence between at least two sectors in a 250 ns time window

New trigger strategies are being considered for the future CROSS demonstrator (see later)



Background modeling with Monte Carlo simulations

Objectives:

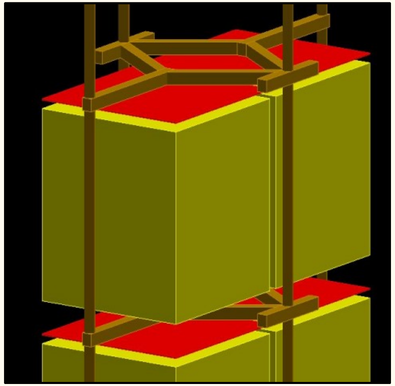
- Calculate the background index (BI) in the ROI considering known backgrounds (radioactive decays, muon-related events, etc)
- Reduce BI by applying event selections across different detectors
- Assess the experiment's sensitivity

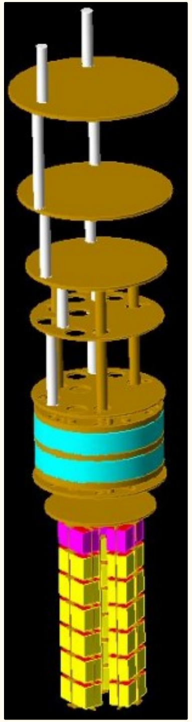
Performed Geant4-based Monte Carlo (MC) simulations

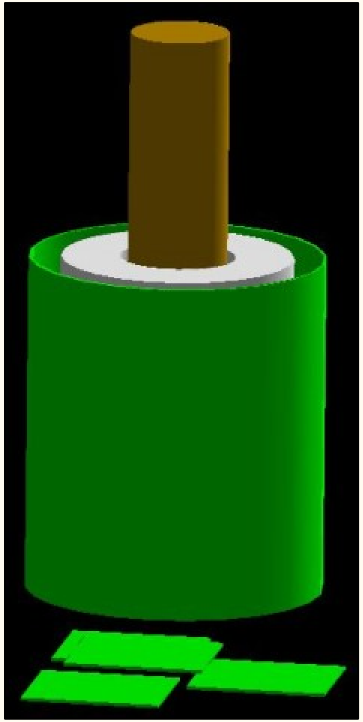
Most of the volumes are simulated

Information provided by the simulations:

- Δt between energy deposits among detectors
- Multiplicity among detectors for the same simulated event
- Energy deposited in each detector (Vetos, Crystals or LDs)







Backgrund simulations

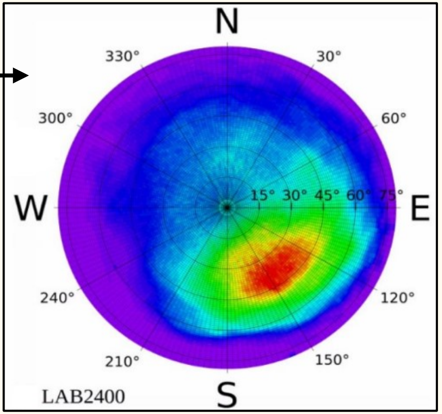
Muons:

- Momentum: From angular distribution measured at LSC
- Energy: From an approach for $E_\mu > 100$ GeV above ground, then calculated underground with the rock depth:

$$\frac{dN_\mu}{dE_\mu d\Omega} \approx \frac{0.14\, E_\mu^{-2.7}}{\mathrm{cm}^2\ \mathrm{s\ sr\ GeV}} \times \left\{ \frac{1}{1+\frac{1.1 E_\mu \cos\theta}{115\,\mathrm{GeV}}} + \frac{0.054}{1+\frac{1.1 E_\mu \cos\theta}{850\,\mathrm{GeV}}} \right\}$$

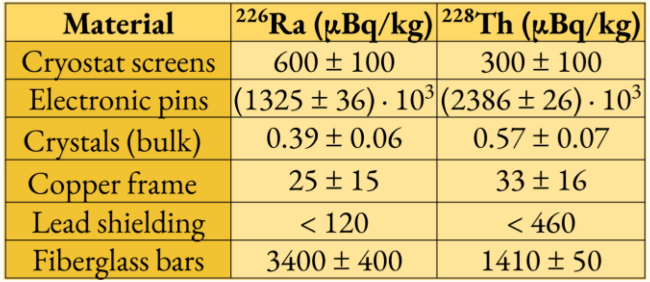
$$E_{\mu,0} = (E_\mu + \epsilon)e^{bX} - \epsilon$$

- Activity normalized with flux measured at LSC: 18.9 ± 0.8 μ/m2/h



Radioactive decays:

- Chains of ^{226}Ra (down to ^{210}Pb) and ^{228}Th homogeneously distributed in all volumes surrounding the detectors
  - Activities measured with HPGe or in CUPID-Mo experiment
- 2ν2β of ^{100}Mo considering the most accurate decay rate measurement up to date done by CUPID-Mo
- Pile-up of 2ν2β of ^{100}Mo



Material	^{226}Ra (μBq/kg)	^{228}Th (μBq/kg)
Cryostat screens	600 ± 100	300 ± 100
Electronic pins	$(1325 \pm 36) \cdot 10^3$	$(2386 \pm 26) \cdot 10^3$
Crystals (bulk)	0.39 ± 0.06	0.57 ± 0.07
Copper frame	25 ± 15	33 ± 16
Lead shielding	< 120	< 460
Fiberglass bars	3400 ± 400	1410 ± 50

EPJC 79, 721 (2019) PDG, Cosmic Rays (2021) EPJC 83, 675 (2023) PRL 131, 162501 (2023) EPJC 83, 373 (2023)

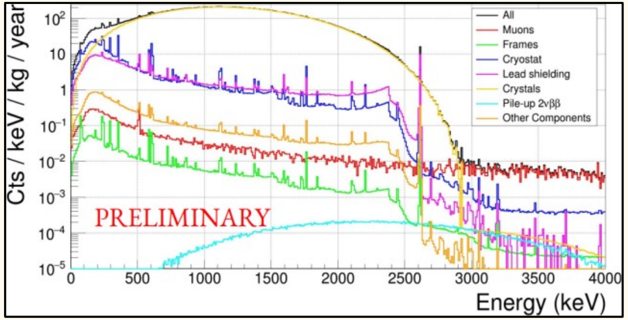
Preliminary background model

Event selections to minimize BI and maximize acceptance of 0ν2β (similar to the experiment):

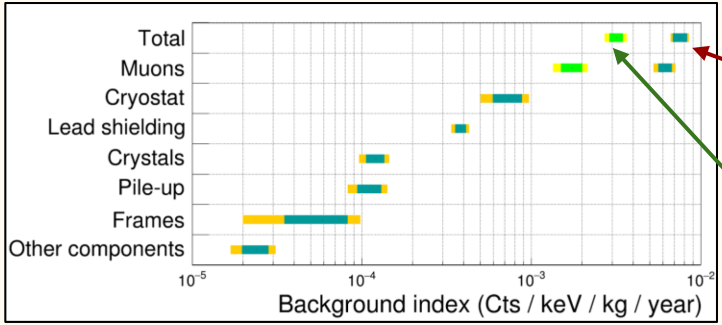
- Crystal multiplicity = 1
- No coincidence in veto sectors within Δt = 2 ms
- Event in the β/γ band: LY ∈ [150,450]

Main contribution (80%) from muon induced events

- γs produced around crystals after muon interactions
- Current muon event trigger is based on coincidences of two veto sectors, but 43% of events trigger only a single veto sector
- Rejecting coincidences between crystals and a single veto sector can reduce the BI by a factor of 2.4



Preliminary BI calculated in the ROI for ^{100}Mo (3034 keV):



Current event selection:

BI = (7.6±0.9)·10^{-3} ckky

Rejecting coincidences between crystals and single veto:

BI = (3.2±0.5)·10^{-3} ckky

Sensitivity prospects

According to the previous estimations, the BI is expected to be between 10^{-2} and 10^{-3} ckky

The lifetime of the experiment is assumed to be 2 years

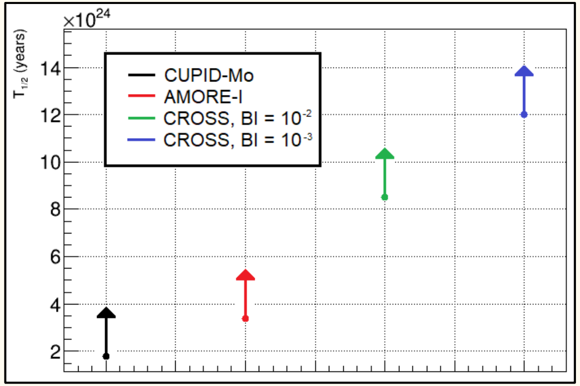
Therefore, the limits (at 90% confidence level) on the ^{100}Mo 0ν2β decay are:

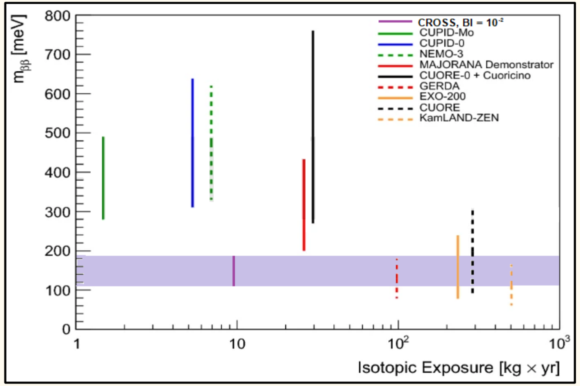
- BI = 10^{-2} → $T_{1/2}(0\nu) > 8.5 \cdot 10^{24}$ yr, $m_{\beta\beta} < (0.131—0.221)$ eV
- BI = 10^{-3} → $T_{1/2}(0\nu) > 1.2 \cdot 10^{25}$ yr, $m_{\beta\beta} < (0.110—0.186)$ eV

Current limits on ^{100}Mo 0ν2β decay:

- CUPID-Mo: $T_{1/2}(0\nu) > 1.8 \cdot 10^{24}$ yr, $m_{\beta\beta} < (0.28—0.49)$ eV
- AMORE: $T_{1/2}(0\nu) > 3.4 \cdot 10^{24}$ yr, $m_{\beta\beta} < (1.2—2.1)$ eV

The CROSS demonstrator will have higher sensitivity on the ^{100}Mo 0ν2β than the best current limits established by CUPID-Mo and AMoRE experiments





EPJC 82 11, 1033 (2022) EPJC 79 9, 791 (2019) H.B. Kim. Result of AMoRE-I Experiment. TAUP 2023

Summary

- **CROSS** is developing cutting-edge **technologies to reduce background** in $0\nu2\beta$ decay detection using **scintillating bolometers**
- Advanced **cryogenic photodetectors**, NTL LDs, demonstrate **excellent baseline energy resolution** ($\sigma_{bsl} = 12$ eV) and **effective pile-up rejection** (rise time ~ 0.5 ms, SNR ~ 90) with optimized designs **improving sensitivity**
- **Excellent energy resolution** ($\Delta E_{FWHM} = 5.7$ keV at 2615 keV) and **high radiopurity of crystals** operated as bolometers are confirmed in recent tests
- Monte Carlo **simulations** accurately **replicate experimental conditions**. It allows to optimize event selection to **reduce the background index to ~ 10^{-3} ckky**
- **CROSS aims to achieve $T_{1/2} > 1.2 \cdot 10^{25}$ yr for ^{100}Mo $0\nu2\beta$ decay, exceeding current experimental limits on that isotope**

THANKS FOR YOUR ATTENTION

IJCLab
Irène Joliot-Curie
Laboratoire de Physique
des 2 Infinis

CROSS

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BACKUP SLIDES

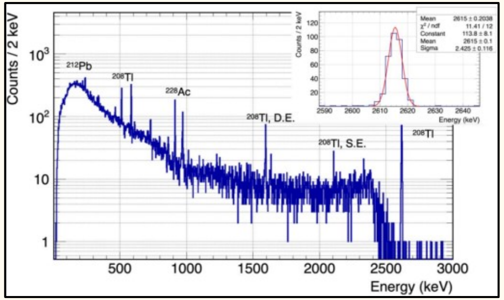
Background modeling with Monte Carlo simulations

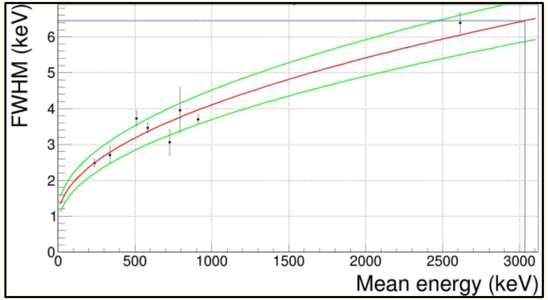
Experimental information provided to the simulations:

- Light Yield (LY) for each kind of particle →
- Light and Heat energy resolution functions ($\sigma = a + b\sqrt{E}$)

Particle	Bottom crystal	Top crystal
β/γ	300	200
α	50	30

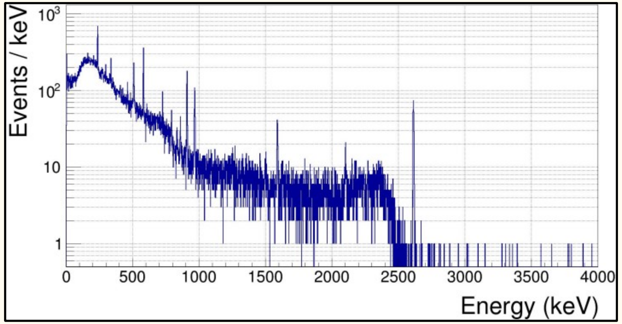
LY units in eV(Light) / keV (Heat)





Example of simulated spectrum:

^{232}Th calibration measurement



Information provided by the simulations:

- Δt between energy deposits among detectors
- Multiplicity among detectors for the same simulated event
- Energy deposited in each detector (Vetos, Crystals or LDs)
  - Scintillation light energy added to energy deposited in LDs using the LY measured experimentally
  - Convolved with the energy resolution functions

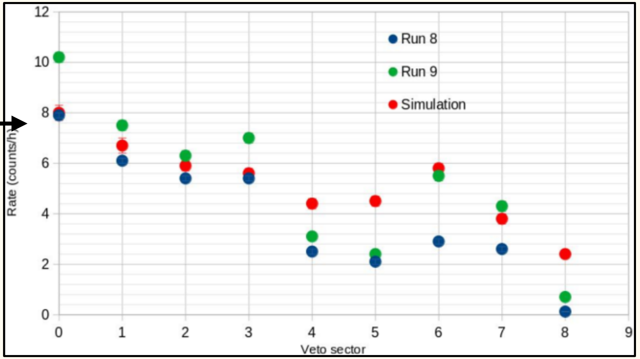
Validation of the simulation

Muons validated with the experimentally measured rates:

- In each veto sector in coincidence with other sector(s) (for two different cryogenic runs)
- In bolometers for events with E $>$ 10 MeV

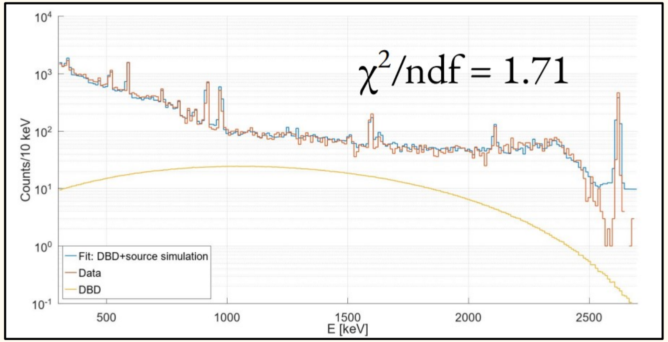
  Exp: 1.44 $\pm$ 0.22 μ/day

  Sim: 1.49 $\pm$ 0.05 μ/day



Validation of radioactive decays simulation:

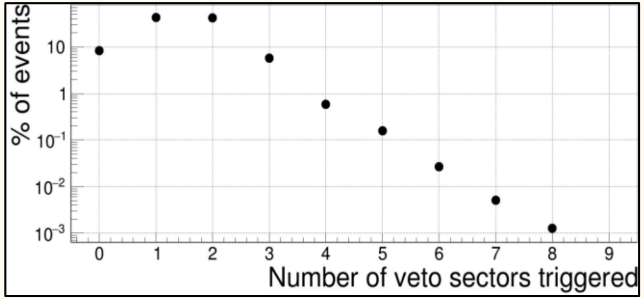
- MC spectrum obtained in ^{232}Th calibration fitted to experimental data
- 2ν2β of ^{100}Mo simulated and included in the fit, as it is the main background contribution
- Good agreement between spectra indicates accurate simulation of geometry and detector response



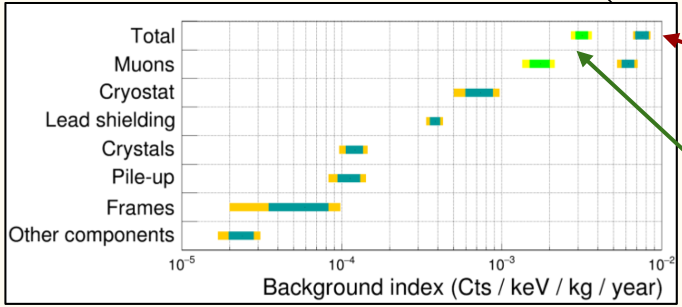
Strategy to reduce the BI

Event selection optimization to reduce muon-induced background:

- Current muon event trigger is based on coincidences of two veto sectors, but 43% of events trigger only a single veto sector
- Rejecting coincidences between crystals and a single veto sector can reduce the BI by a factor of 2.4



Preliminary BI calculated in the ROI for ^{100}Mo (3034 keV):



Current event selection:

BI = $(7.6\pm0.9)\cdot10^{-3}$ ckky

Rejecting coincidences between crystals and single veto:

BI = $(3.2\pm0.5)\cdot10^{-3}$ ckky

We designed an acquisition strategy to:

- Ensure the same energy threshold in all veto channels
- Avoid high trigger rate in each channel to limit dead time

Will be tested soon