CUPID

A next generation $0\nu\beta\beta$ bolometric experiment

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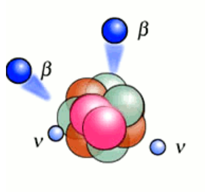
Neutrinoless double-beta decay

Two-neutrino mode: 2νββ

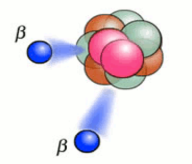
$$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\bar{\nu}_e$$



- 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

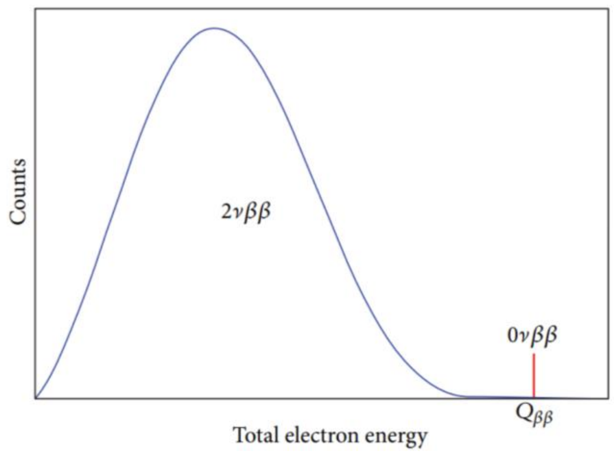
Neutrinoless mode: 0νββ

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

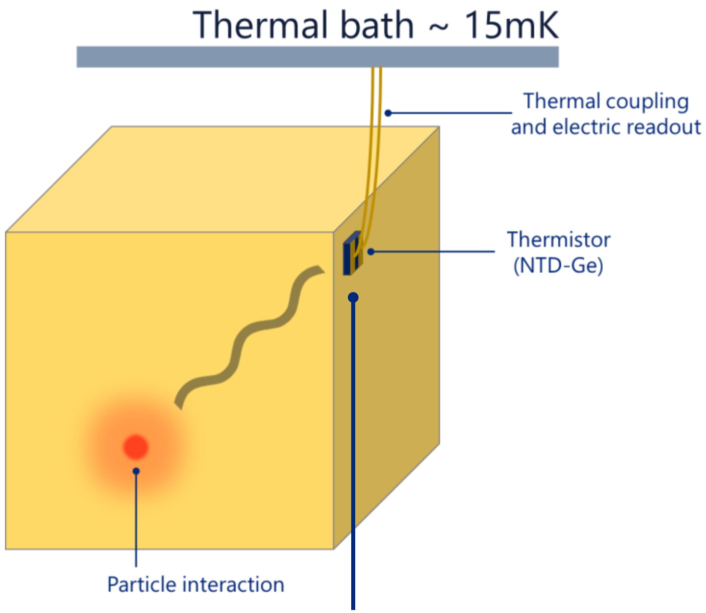


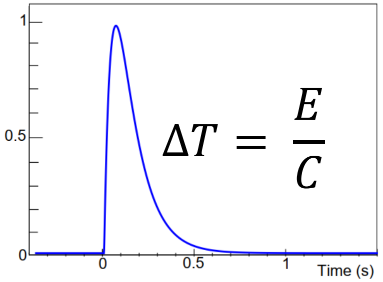
A hypothetical decay, where its observation leads to:

- Affirmation of Lepton number violation
- Neutrinos are Majorana particles ($\bar{\nu} = \nu$)



CUORE in a nutshell

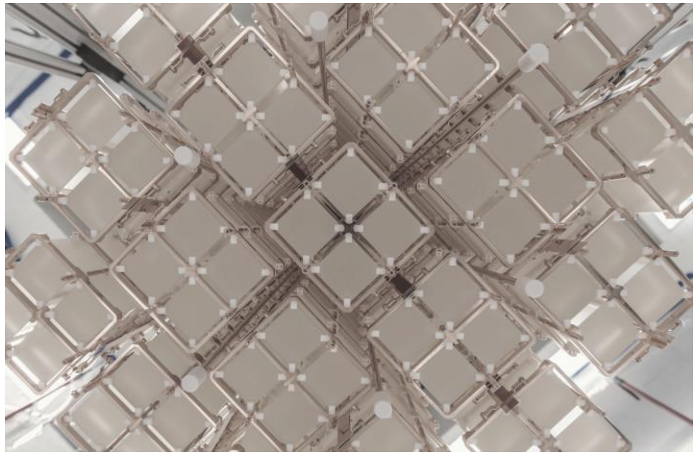




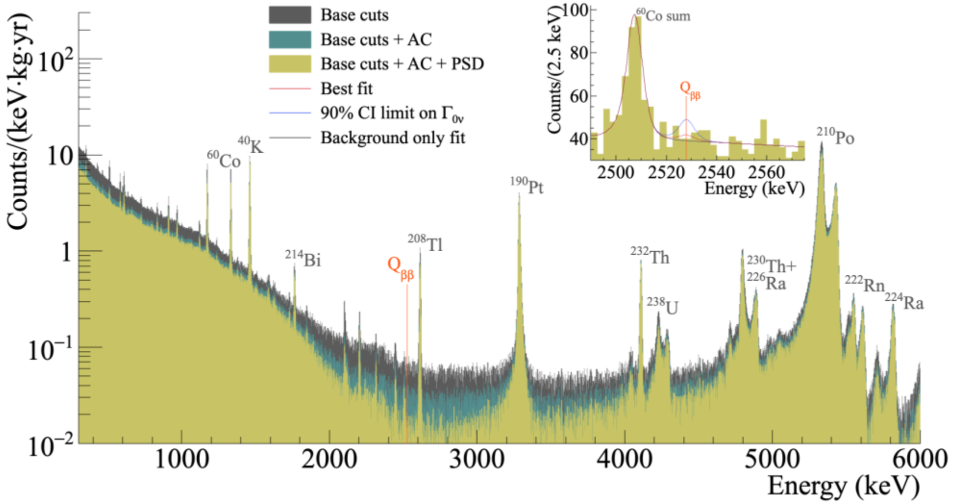
Bolometer features
- High energy resolution
- Full active volume (no dead layer)
- Flexible material choices

CUORE

Cryogenic Underground Observatory for Rare Events

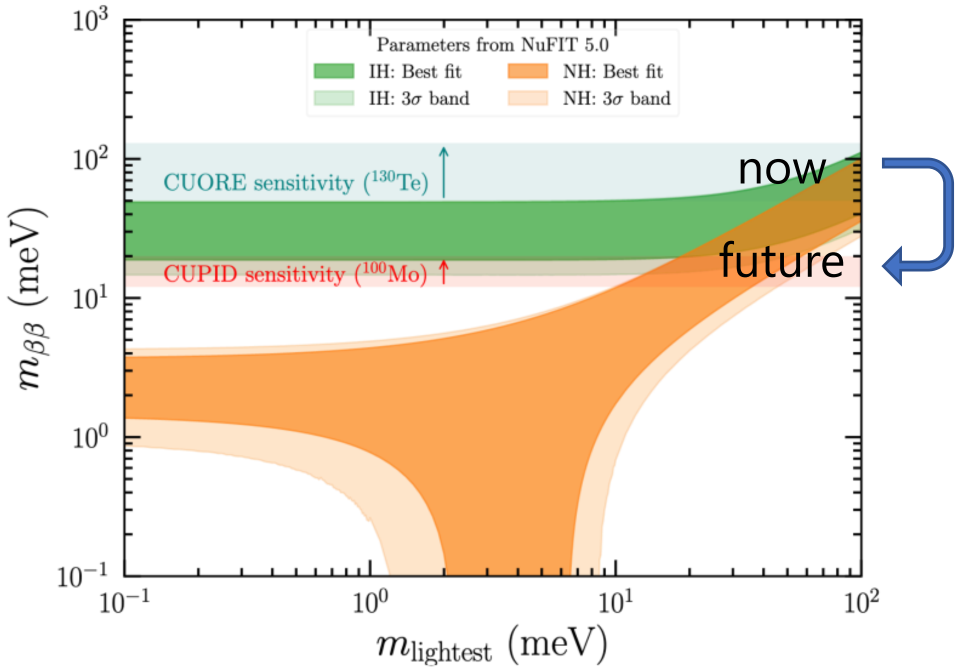


- ^{130}Te with a $Q_{\beta\beta}$ = 2527 keV
- Natural isotopic abundance: 34%
- Embedded in TeO_2 crystal
- 988 crystals
- 19 towers with 13 floors each
- 206 kg of ^{130}Te (total: 742 kg)



- The first tonne-scale bolometric experiment
- Steady data taking since 2017
- Energy resolution FWHM at $Q_{\beta\beta}$ is 7.4 keV
- Bkg index in ROI 1.5×10^{-2} cnts/(keV kg yr):
  - ~ 90% degraded α particles from surface contamination
  - ~ 10% β/γ natural radioactivity
  - < 1% muons

Sensitivity of bolometric experiments



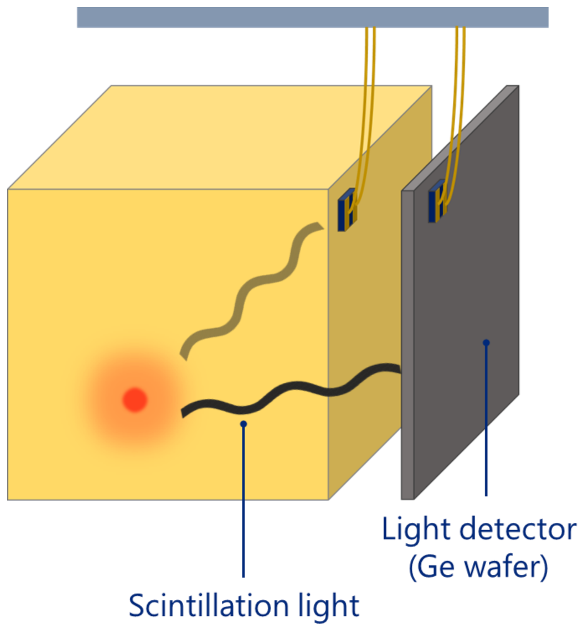
$$b = \frac{\text{number of background counts}}{\boldsymbol{M} \times T \times \Delta\boldsymbol{E}}$$

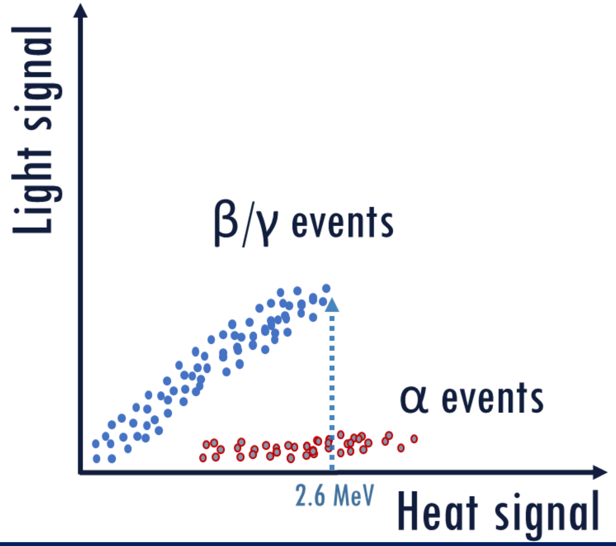
b: background index
M: detector mass
T: time of measurement
ΔE: energy resolution of the detector (FWHM**)**

Increasing the sensitivity on the effective Majorana mass requires learning from past experiences and an extensive R&D:

- Isotope selection?
- Crystal selection?
- α background rejection?
- U/Th chain background rejection?
- Pileup rejection?

From CUORE to CUPID (CUORE Upgrade with Particle IDentification)





Rejection of the α background from surface contamination:

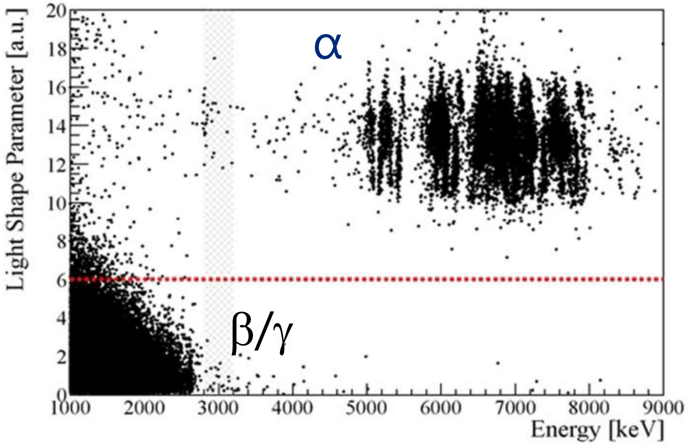
- Use scintillating crystals coupled to light detectors (dual heat-light readout)
- α particle interaction inside the scintillator leads to a different light output compared to β/γ
- Validate the technology in CUPID-0 and CUPID-Mo demonstrators

Choose a different isotope with a $Q_{\beta\beta}$ above the natural γ radioactivity at 2615 keV.

CUPID-0 and CUPID-Mo demonstrators

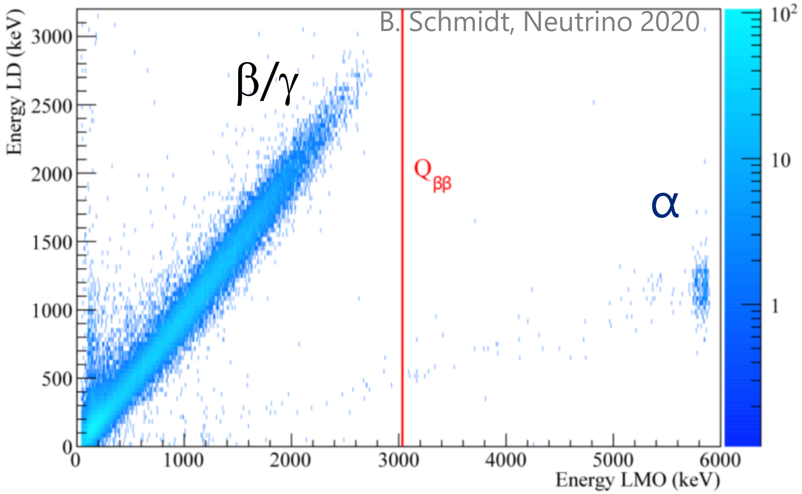
CUPID-0

- The first CUPID demonstrator using the scintillating crystal $Zn^{82}Se$, tested at LNGS (Italy)
- 95 % enrichment in ^{82}Se (5.17 kg)
- $Q_{\beta\beta}$ = 2998 keV
- Demonstrated an excellent α rejection using the dual heat-light readout (> 99.9%)
- Background index (BI) 3.5×10^{-3} cnts/(keV kg yr)
- Energy resolution at $Q_{\beta\beta}$ is 21.8 keV FHWM



CUPID-Mo

- The chosen CUPID demonstrator using the scintillating crystal $Li_2{}^{100}MoO_4$, tested at LSM (France)
- 95 % enrichment in ^{100}Mo (2.34 kg)
- $Q_{\beta\beta}$ = 3034 keV
- Demonstrated an excellent α rejection using the dual heat-light readout (> 99.9%)
- The lowest BI achieved in a bolometric 0νββ experiment 2.7×10^{-3} cnts/(keV kg yr)
- Energy resolution at $Q_{\beta\beta}$ is 7.4 keV FHWM



CUPID-0 and CUPID-Mo demonstrators

CUPID-0

- The first CUPID demonstrator using the scintillating crystal
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- 95 % enrichment in ^{82}Se (5
- $Q_{\beta\beta}$ = 2998 keV
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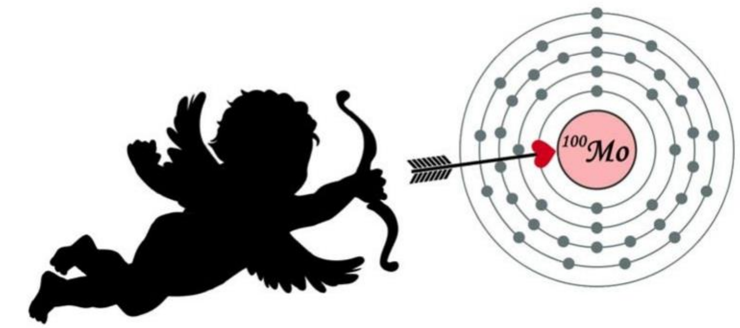
  light readout (> 99.9%)
- Best limit on the $T_{1/2}^{0\nu}$ of ^{82}S
- Energy resolution at $Q_{\beta\beta}$ is

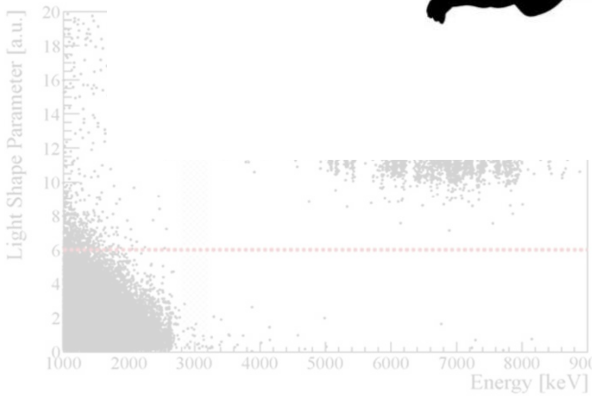
CUPID-Mo

- The chosen CUPID demonstrator using the scintillating
  l (France)
  kg)
  ection using the dual heat-
  1.8 × 10^{24} yr
  V FHWM

demonstrator using the scintillating crystal
at LNGS (Italy)
nt in ^{82}Se (5.17 kg)

Due to the high energy resolution, high internal radiopurity of the crystals and the full α rejection shown by CUPID-Mo, $Li_2{}^{100}MoO_4$ has been chosen for CUPID





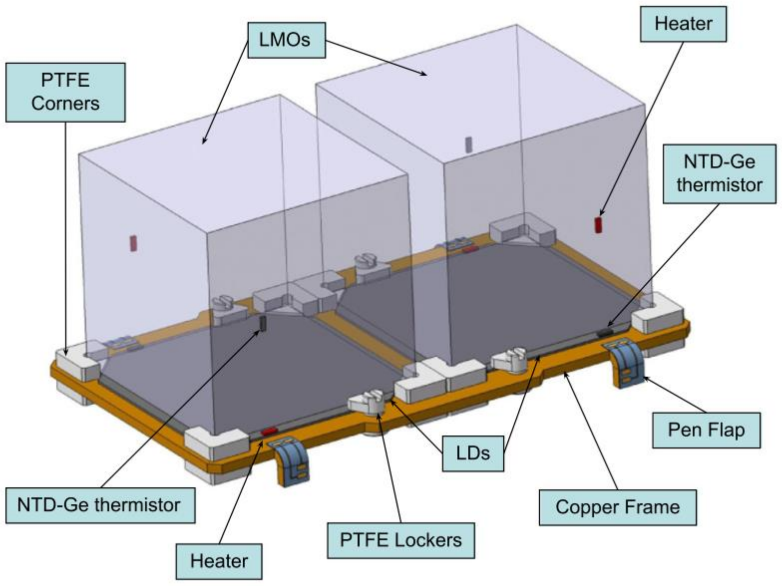
α

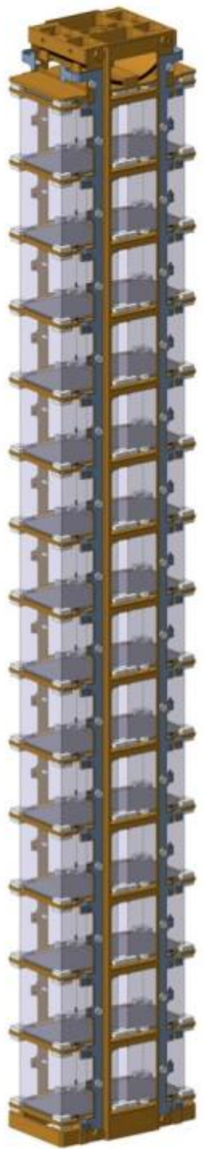
- Demonstrated an excellent α rejection using the dual heat-light readout (> 99.9%)
- Best limit on the $T_{1/2}^{0\nu}$ of ^{82}Se > 4.6 × 10^{24} yr
- Energy resolution at $Q_{\beta\beta}$ is 21.8 keV FHWM

The CUPID-baseline experiment

CUPID will build on the experience of CUORE and use its existing cryogenic infrastructure that will host:

- 1596 Li_2MoO_4 crystals (45×45×45 mm)
  - Arranged in 54 towers of 14 floors
- 1710 Ge wafer light detectors
  - With SiO antireflective coating
- 240 kg of ^{100}Mo (> 95% enrichment)
- Total mass: 450 kg

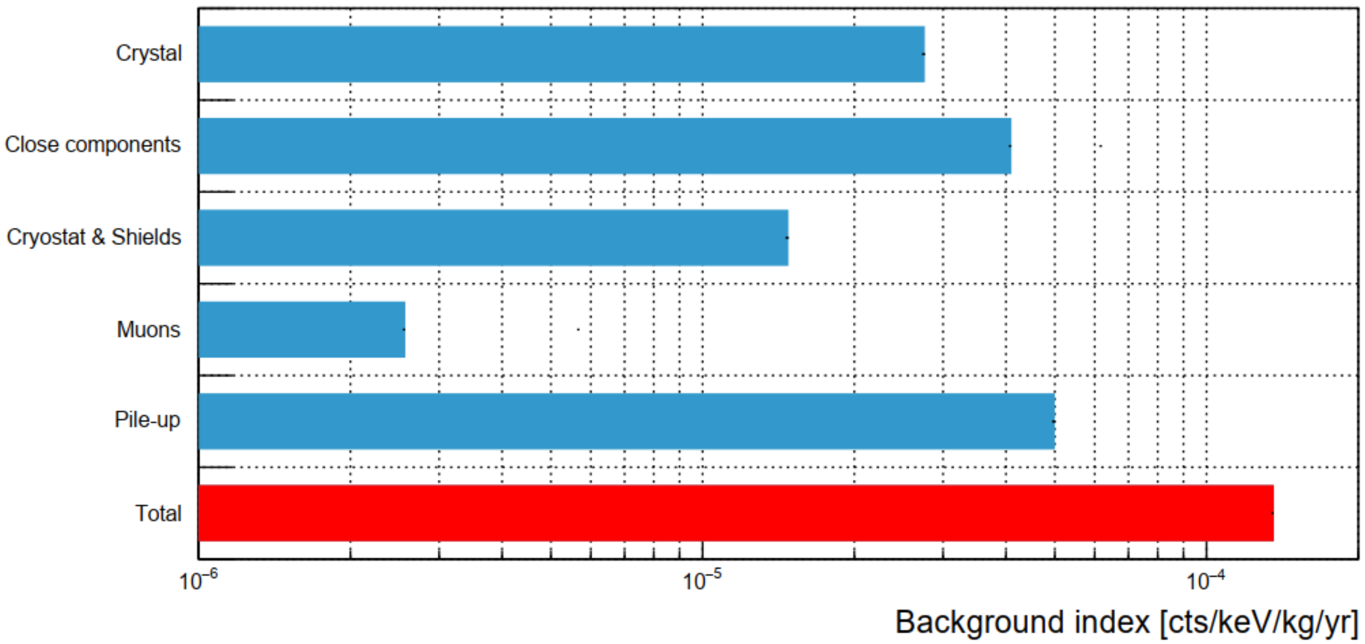




	CUPID-baseline performance aim
Energy resolution at $Q_{\beta\beta}$	5 keV FWHM
Background index	10^{-4} counts/(keV kg yr)
$T_{1/2}^{0\nu}$ exclusion sensitivity (90% C.L.)	1.4×10^{27} yr
LD baseline resolution	< 100 eV RMS
LY	0.3 (keV/MeV)

CUPID-baseline projected background

What we learnt from CUORE, CUPID-Mo and CUPID-0 leads to an expected background index (BI) < 1.36×10^{-4} counts/(kg keV yr)



- > 99.9% of α background rejected by PID
- Muon veto system with 99% geometric efficiency
- β/γ contamination:
  - careful selection of surrounding material, parts cleaning and handling, adding shielding.
  - Perform delayed coincidence cuts to remove background from U/Th chains
- $2\nu\beta\beta$ pileup: faster readout and higher signal to noise ratio in LDs

R&D: Light collection study

Tests on Li_2MoO_4 crystals coupled to LDs were performed at LNGS. These tests are of great importance to assure that the baseline design of CUPID (open structure) guarantees the necessary α rejection

Reflecting foil test

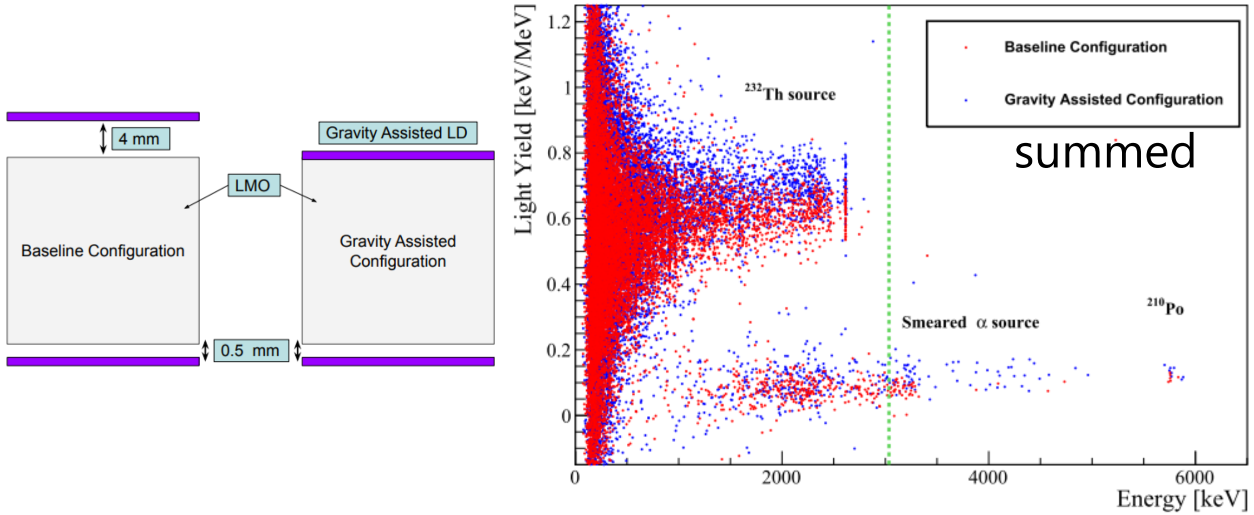
Eur. Phys. J. C (2021) 81:104

- Crystals w/ & w/o reflecting foil
- One LD on top and one on the bottom of each crystal
- No reflecting foil → a sufficient α rejection is guaranteed with a good performing LD (< 100 eV RMS baseline resolution)
- Summing the light collected by the top and bottom LDs allows even a more effective tagging of α
- Conclusion → no reflecting foil is needed to achieve > 99.9% α rejection

Open structure experiment → anticoincidence analysis for surface contamination rejection

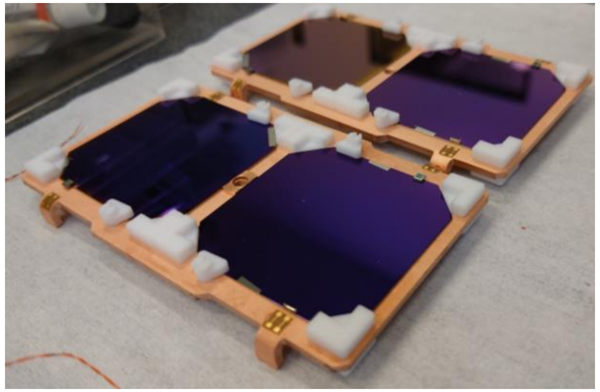
Light detector position test

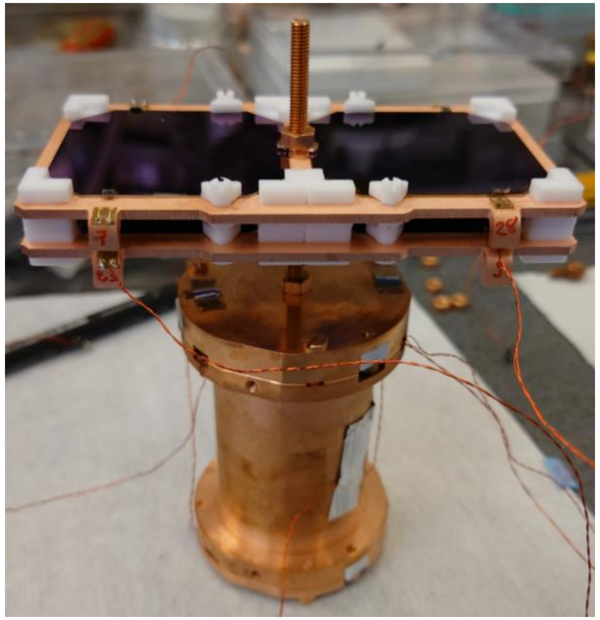
Eur. Phys. J. C (2022) 82:810



- Good performing LDs: 35-70 eV RMS
- > 99.9% α rejection achieved
- The light collection gain with the gravity assisted configuration is not worth the additional technical complication

Light detectors test in a pulsetube cryostat

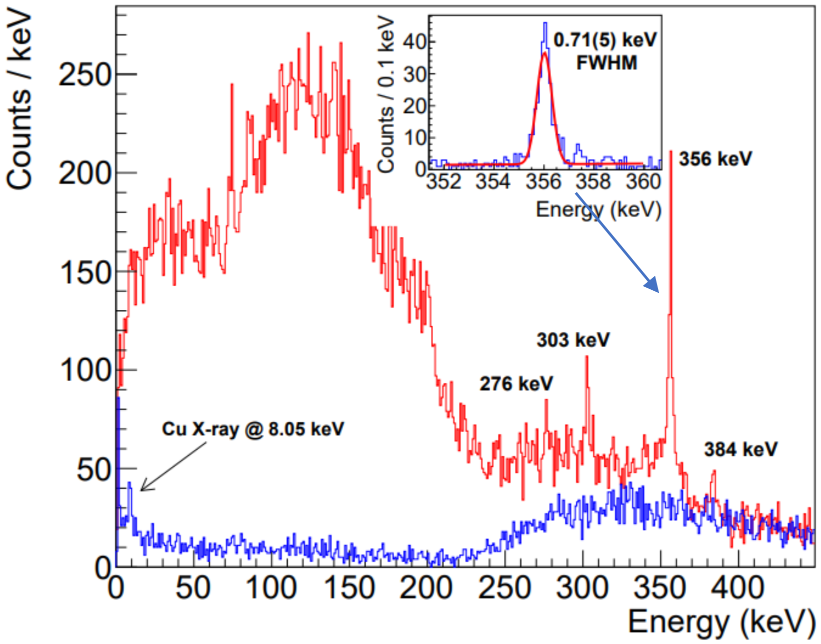




- Validation of the new CUPID-baseline LD assembly was performed in a pulse-tube cryostat at IJCLab
- Check the bolometric performance
- 2 Cu frames with 2 LDs each (0.5 mm in thickness) mounted on top of each other
- Baseline energy resolution **70-90 eV RMS**

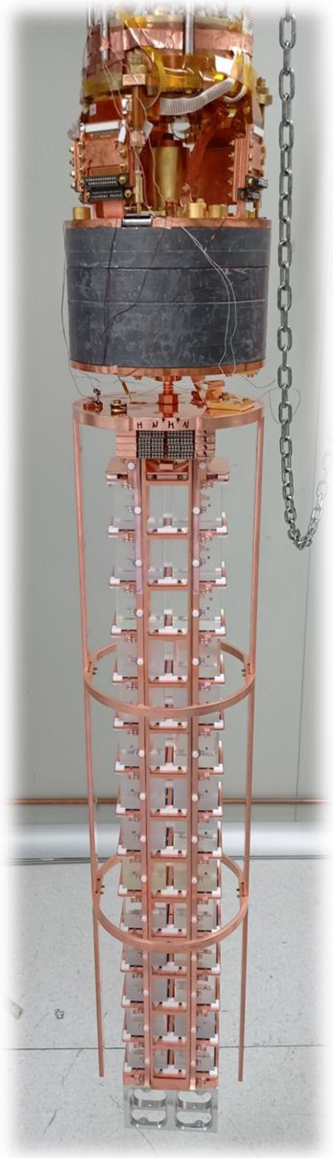
A very important result to achieve the required α rejection in a pulsetube cryostat (as CUORE)

JINST **18** P06033



With ^{133}Ba source calibration we achieved an excellent energy resolution of 0.71 keV FWHM at 356 keV

R&D: ongoing



Baseline Design Prototype Tower (BDPT), is the first tower of CUPID-baseline being tested at LNGS (Italy):

- 28 Li_2MoO_4 crystals arrange in 14 floors, 2 crystals each
- 30 Ge light detectors

The main goals are:

- Validation of the assembly procedure ✓
- Study the effect of glue type of NTD thermistor
- Validate the bolometric performance of LDs and Li_2MoO_4
- Vibration effect on LD
- Thermalization on each floor

Run 1 (July-Aug 2022): spring loaded
Run 2 (Sep-Oct 2022): spring unloaded to see effect on LD performance
Run 3: preparation ongoing, further tests on vibrations, thermalization and glue type

Pileup rejection studies

Relatively fast decay rate of ^{100}Mo ($T_{1/2}^{2\nu} = 8.1 \times 10^{18}\, yr$) + the slow pulses in heat channel

↓

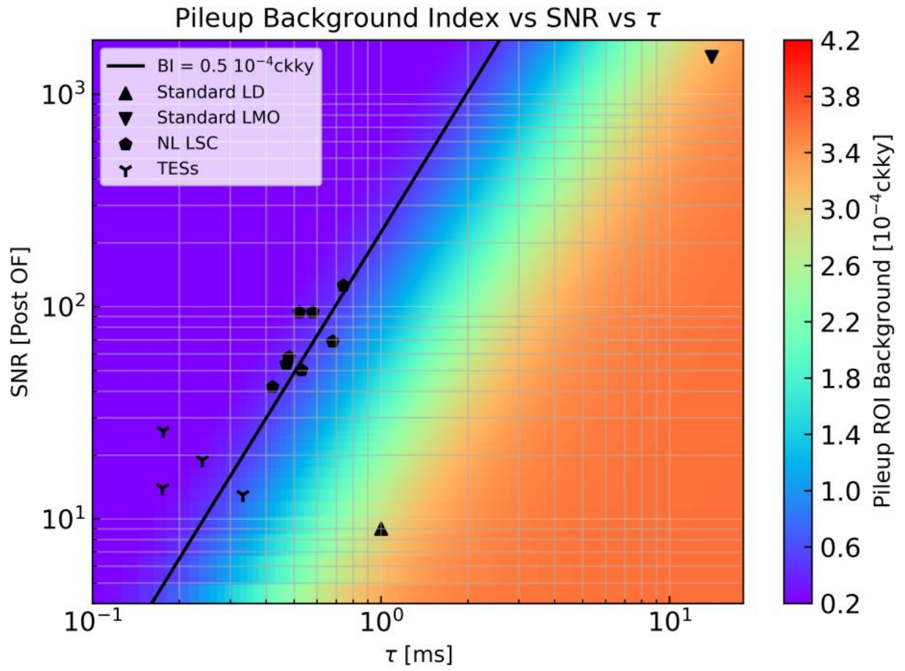
Random coincidences of 2νββ decay in ROI

↓

Rely on light channel which is faster and can be further improved to fight this critical source of background

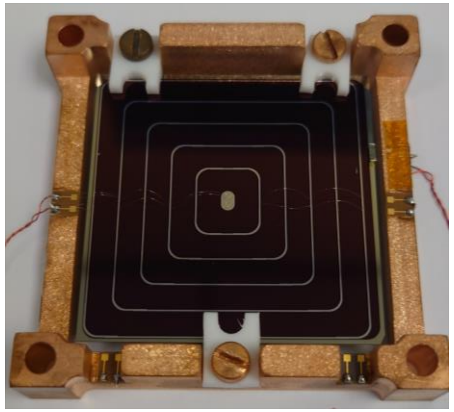
Shorten rise-time

- Use a faster sensor such as TES
- Reduce the sensor size to decrease the heat capacity
- Optimizing the detector working point (bias current)



Increase signal-to-noise ratio

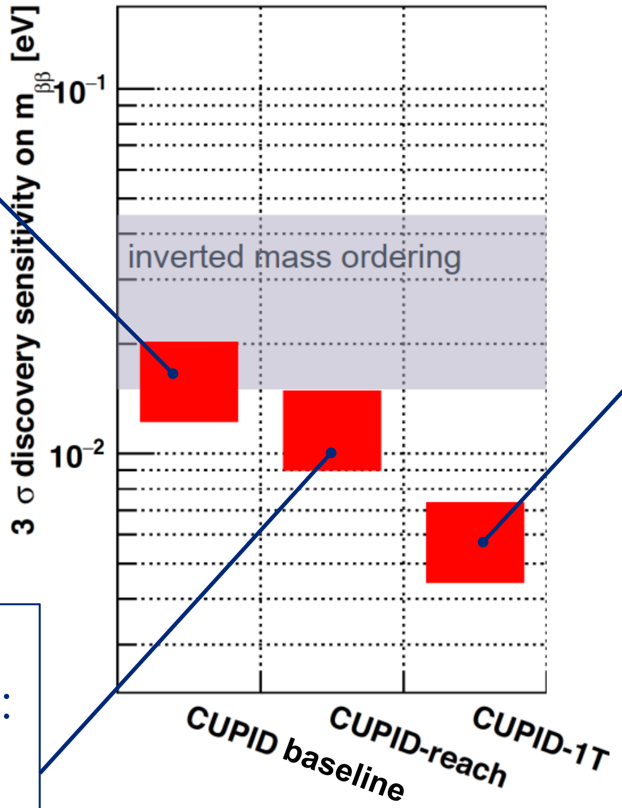
- Use LDs with Neganov-Trofimov-Luke effect which results in a LD with a higher signal-to-noise ratio



CUPID future sensitivity

Next target:
- 240 kg of ^{100}Mo
- $T_{1/2}^{0\nu} > 1.4\times10^{27}$ yr
- BI< 10^{-4} counts/(keV kg yr)

Technically ready in terms of technology and infrastructure



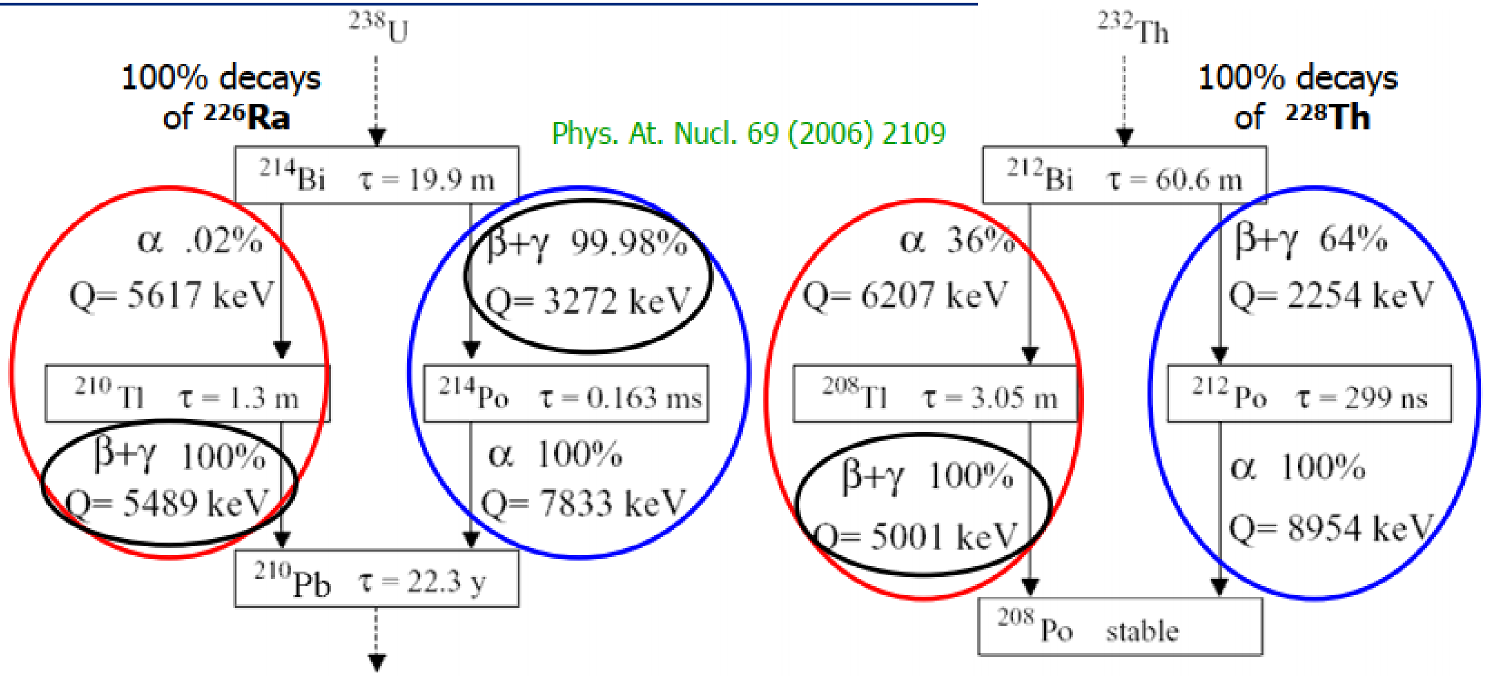
- 1000 kg of ^{100}Mo
- New cryostat(s)
- $T_{1/2}^{0\nu} > 9.1\times10^{27}$ yr
- BI< 5×10^{-6} counts/(keV kg yr)

Same experiment as CUPID-baseline, but with a factor 5 improvement on background:
- $T_{1/2}^{0\nu} > 2.2\times10^{27}$ yr
- BI< 2×10^{-5} counts/(keV kg yr)

Summary

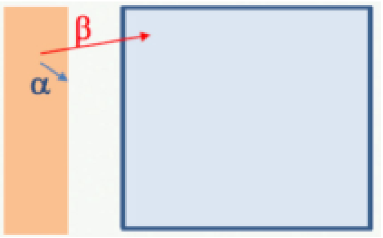
- The envisioned background index will allow CUPID to be among the world-leading $0\nu\beta\beta$ experiments by exploring the full inverted ordering region
- Built on the experience and knowledge gained from CUORE and CUPID demonstrators, CUPID-0 and CUPID-Mo
- It aims with its baseline experiment to reach a BI < 10^{-4} cnts/(keV kg yr)
- R&D test are still ongoing to define the final design

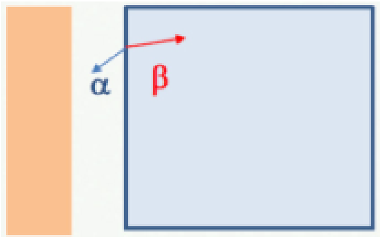
Backups

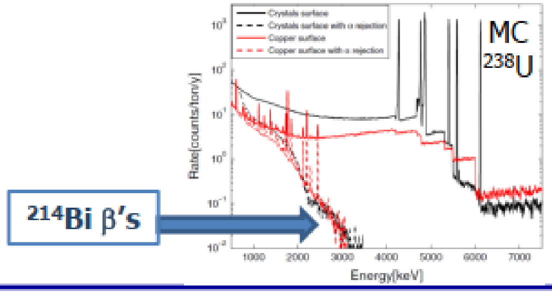


For DBD bolometers with particle ID:

- **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**





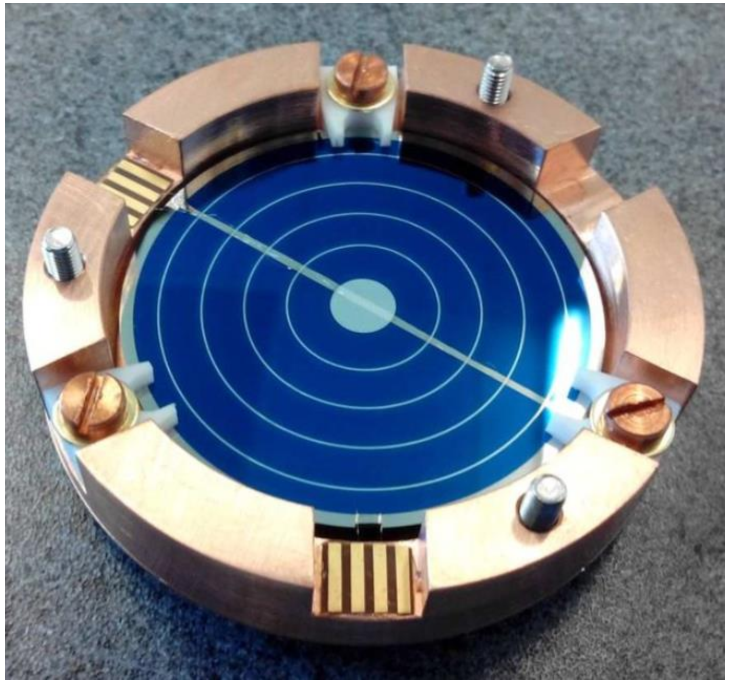


From CUPID-baseline to CUPID-reach

- Reducing the bulk and surface backgrounds from the crystals (e.g. by an additional purification stage of the LMO crystals and the elimination of surface backgrounds by pulse shape discrimination)
- Replacing some of the cryogenic vessels and shields with cleaner materials
- Reducing the $2\nu\beta\beta$ pile-up background to below 10-5 counts/(keV·kg·yr)

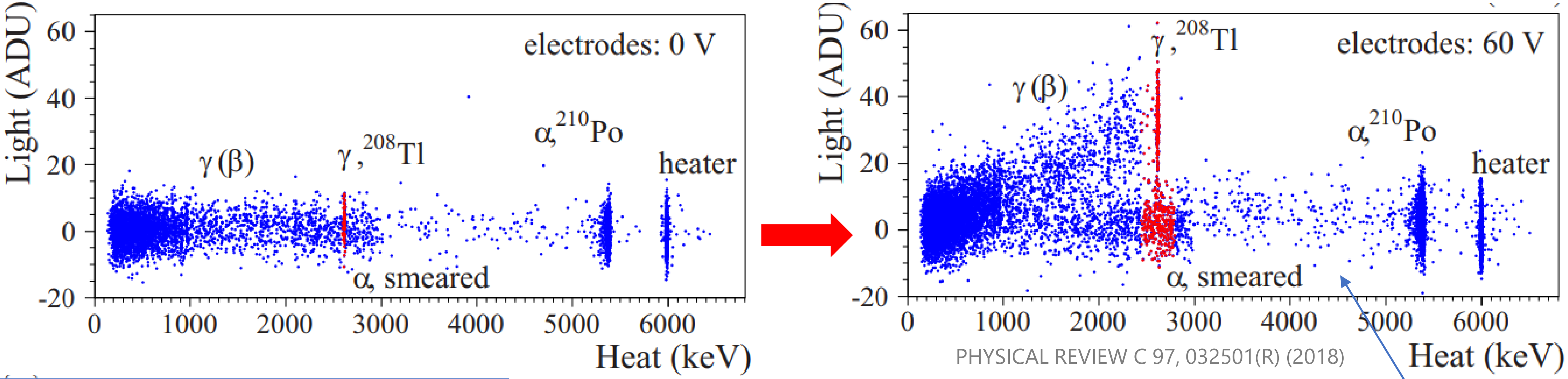
Neganov-Trofimov-Luke LD

- 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)



Effect of NTL

CUORE-size TeO_2 bolometer ($5\times5\times5$ 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

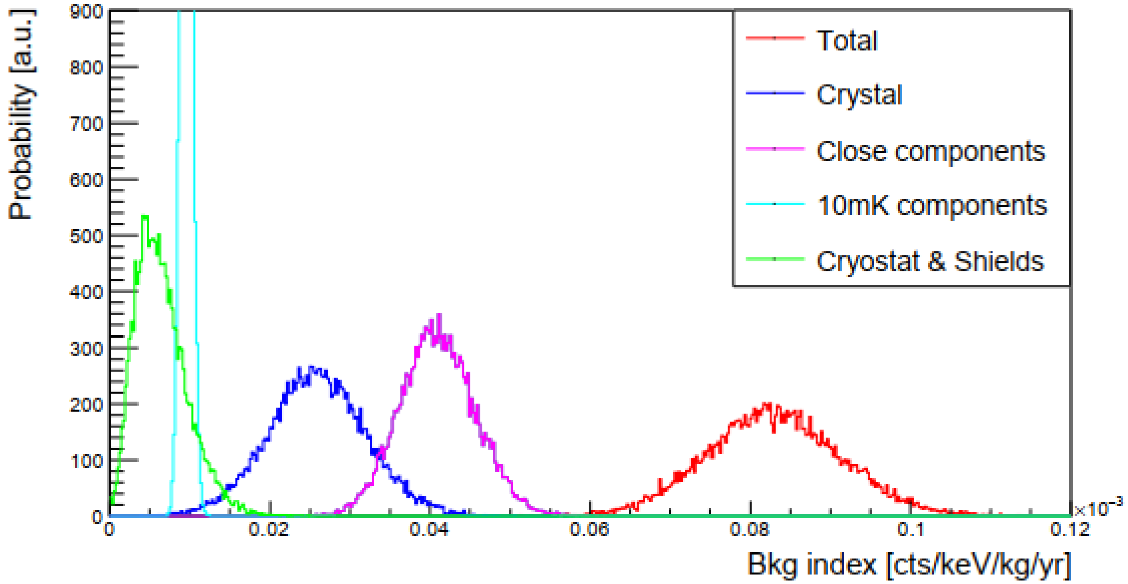
Amplification factor ~ 13
Rms baseline noise = 10±2 eV

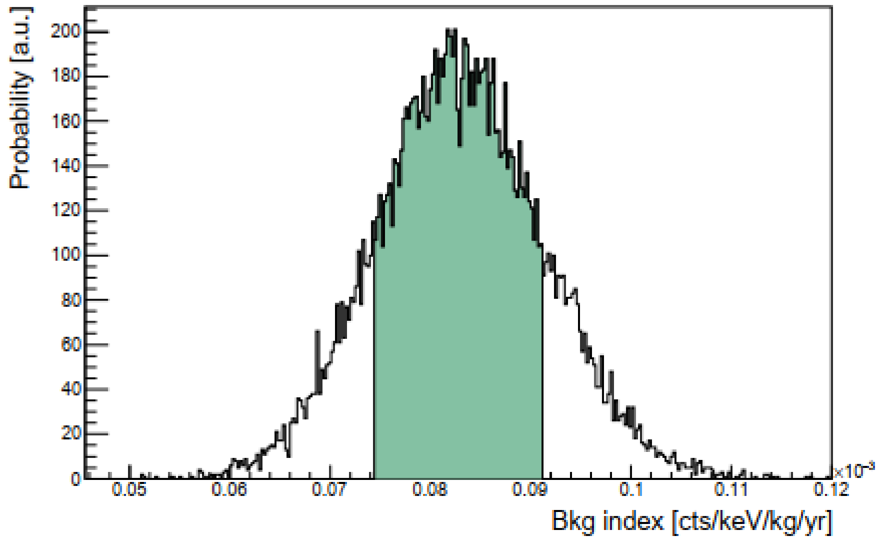
Alpha rejection is achieved

We need to further prove that this concept can be applied to large scale experiment

CUPID background index

Estimated backgrounds from detector components





- Total from radioactivity in materials: $8.3 \pm 0.9 \times 10^{-5}$ cts/(keV·kg·y)
- The driving contributions are contaminations on the surface mainly from close components, Cu frames, PTFE, CuPEN

CUPID-0 background

Based on the results from previous experiments [10,25,26], the sources of background expected in CUPID-0 are:
– the $2\nu\beta\beta$ decay of ^{82}Se;
– contaminations of the experimental setup (including the detector itself, the cryostat and the shielding) due to ubiquitous natural radioisotopes of ^{232}Th, ^{238}U and ^{235}U decay chains, and ^{40}K;
– isotopes produced by cosmogenic activation of detector materials, such as ^{60}Co and ^{54}Mn in copper and ^{65}Zn in ZnSe;
– cosmic muons, environmental γ -rays and neutrons

CUPID-Mo background