CUPID and its demonstrators

Background goals for bolometric experiments

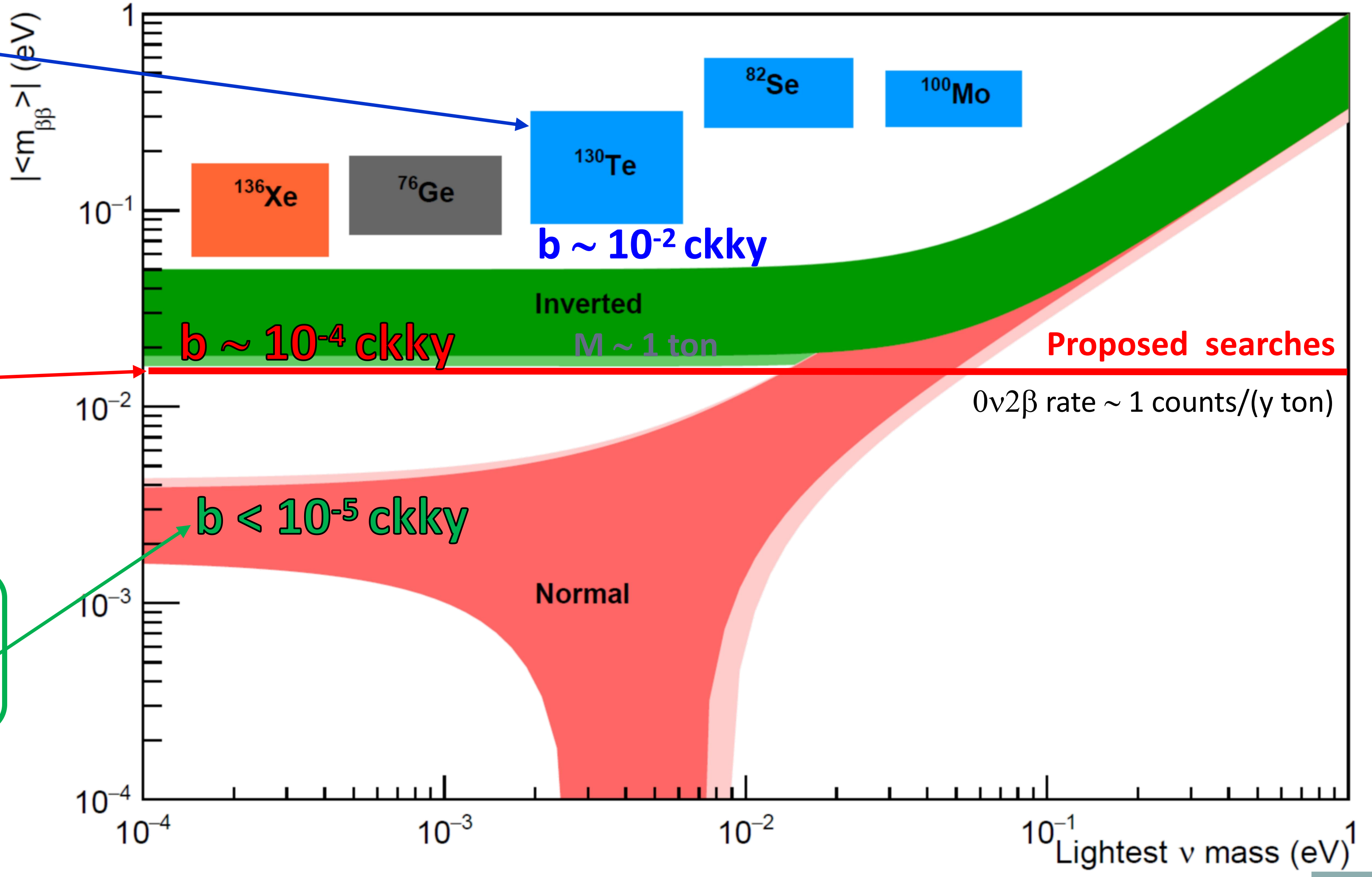
Pure bolometer: CUORE
Background dominated by surface α's

Reject α's + $Q_{2\beta}$>2.6 MeV

Scintillating bolometer: CUPID
Important contribution from β events

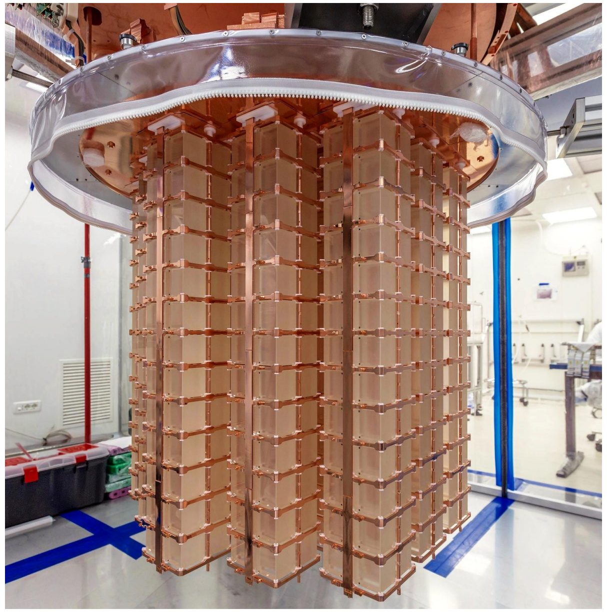
Beyond next phase of 0ν2β experiments

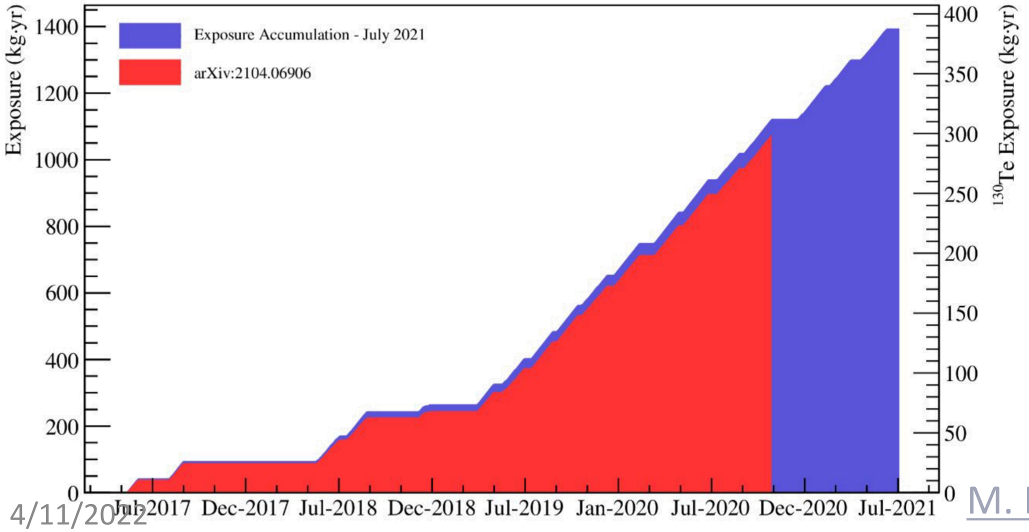
ΔE_{FWHM} ~ **5-10 keV** for bolometers

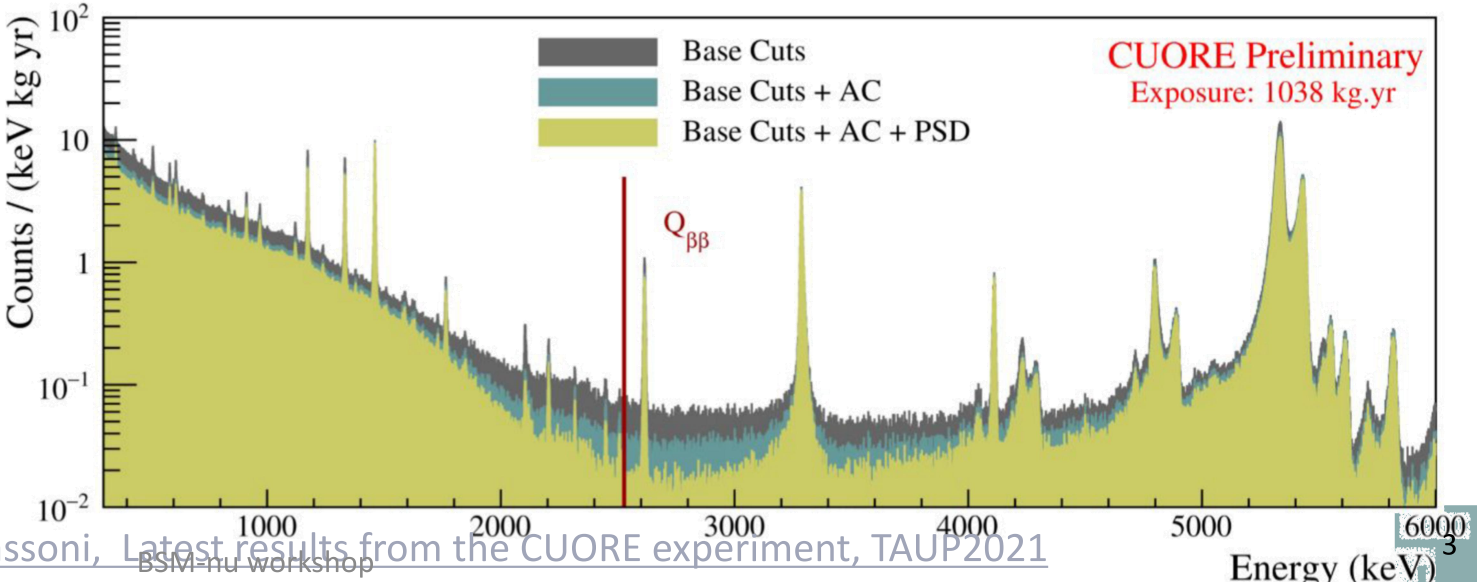


CUORE: the largest bolometric experiment

- **CUORE:** the Cryogenic Underground Observatory for Rare Events
- **First ton scale** array of cryogenic calorimeters: **988 TeO_2 crystals** (0.75 kg each)
- CUORE cryogenic facility is an unprecendented techological challenge, which is now **taking data in steady and reliable conditions** (after 1 yr of optimization)







M. Biassoni, Latest results from the CUORE experiment, TAUP2021

CUORE background

CUORE Background Index:

- $b = 1.49 \times 10^{-2}$ *cnts/keV/kg/yr*

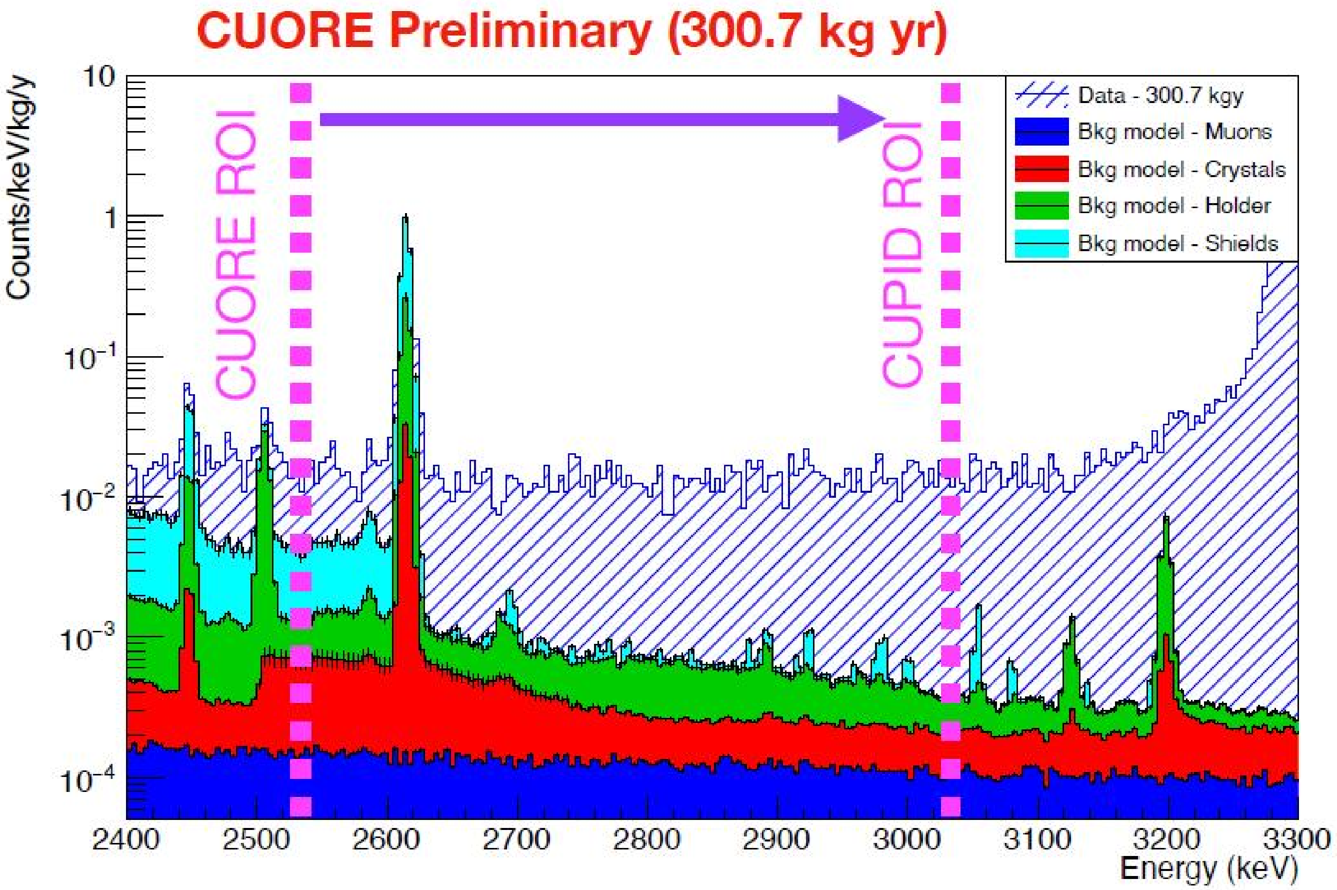
90% Degraded-α background:

- Decays with Q-values in 4-8 MeV range that lose energy in nearby passive materials

10% β/γ background:

- Mostly 2615 keV γ's that scatter before hitting a bolometer
- Also nearby β's from U/Th chains

$\lesssim$ 1% Muons



CUORE upgrade

CUORE: first ton-scale
DBD experiment at 10 mK
No particle ID

CUPID: past and future

CUPID-Mo

CUPID demonstrators:
a rejection with light
Best limits on
^{100}Mo and ^{82}Se 0ν2β

CUPID-0

CUORE: first ton-scale
DBD experiment at 10 mK
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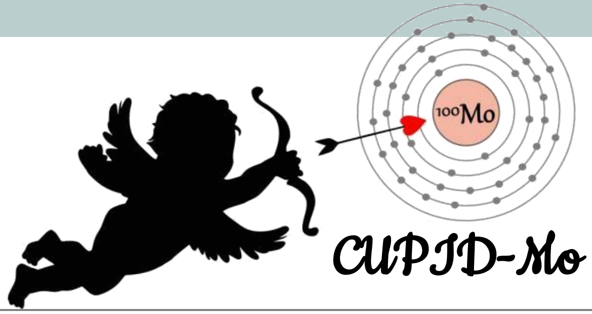

CUPID demonstrators:
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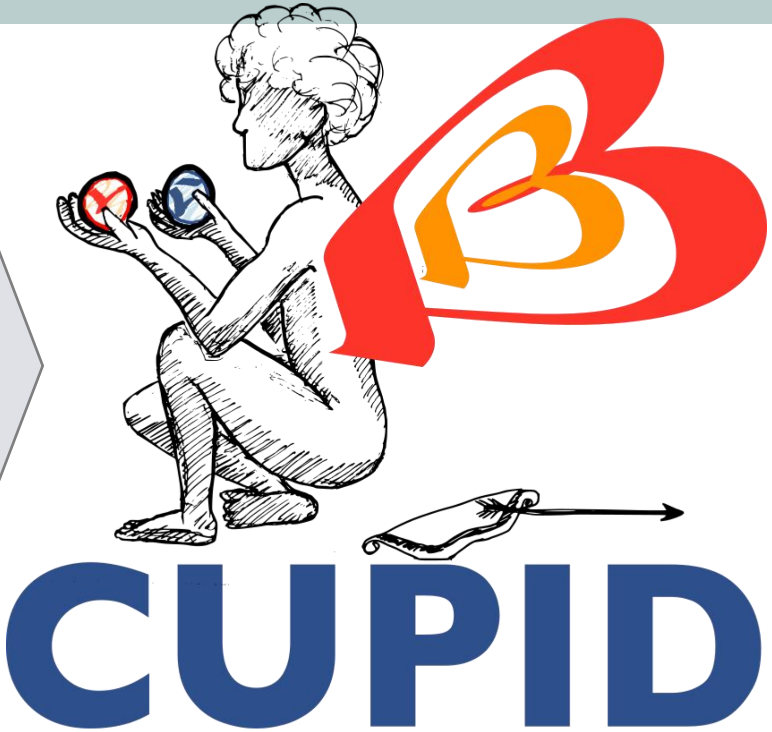

CUORE: first ton-scale
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No particle ID

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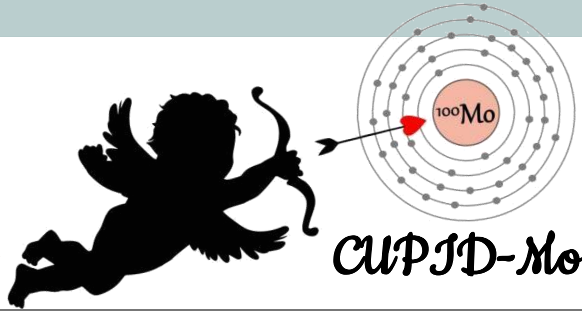
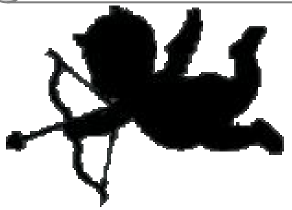
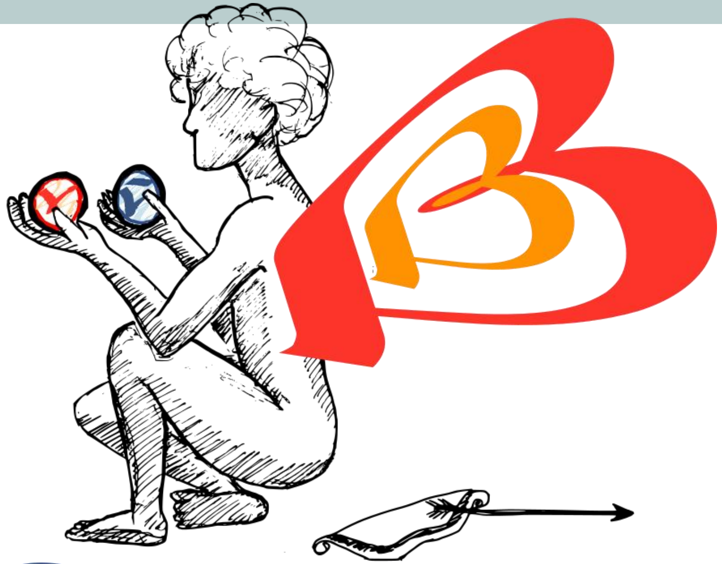


CUPID-Mo

CUPID demonstrators:
a rejection with light
Best limits on
^{100}Mo and ^{82}Se 0ν2β



CUPID-0



CUPID

CUORE: first ton-scale
DBD experiment at 10 mK
No particle ID

New demonstrators for
deeper investigations of
normal mass ordering

BINGO

CROSS

CUPID: past and future

CUORE: first ton-scale
DBD experiment at 10 mK
No particle ID

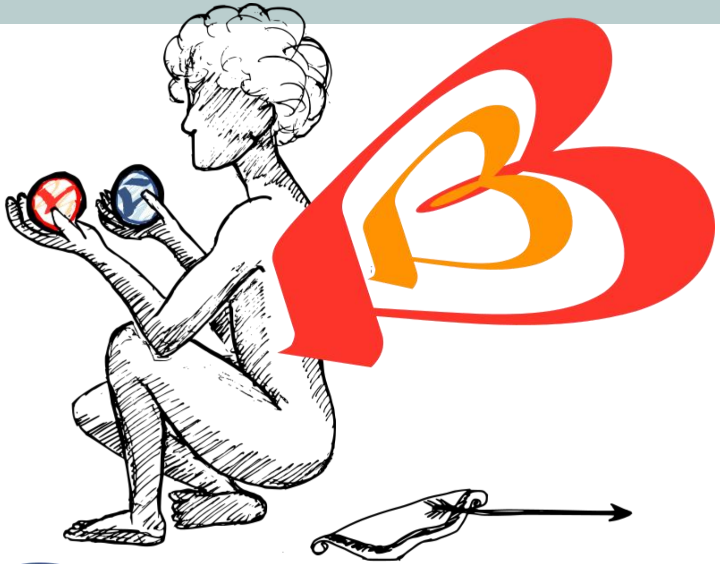
CUPID-Mo

CUPID demonstrators:
a rejection with light
Best limits on
^{100}Mo and ^{82}Se 0v2β

CUPID-0

Phase II

New demonstrators for
deeper investigations of
normal mass ordering

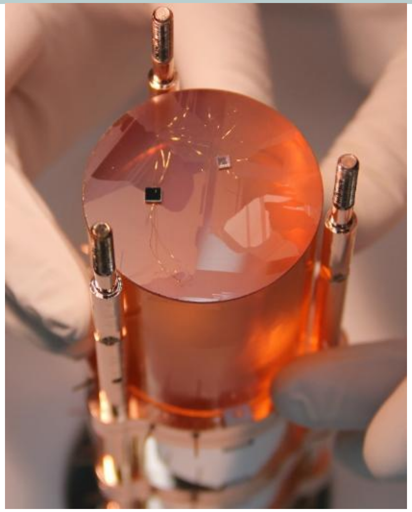


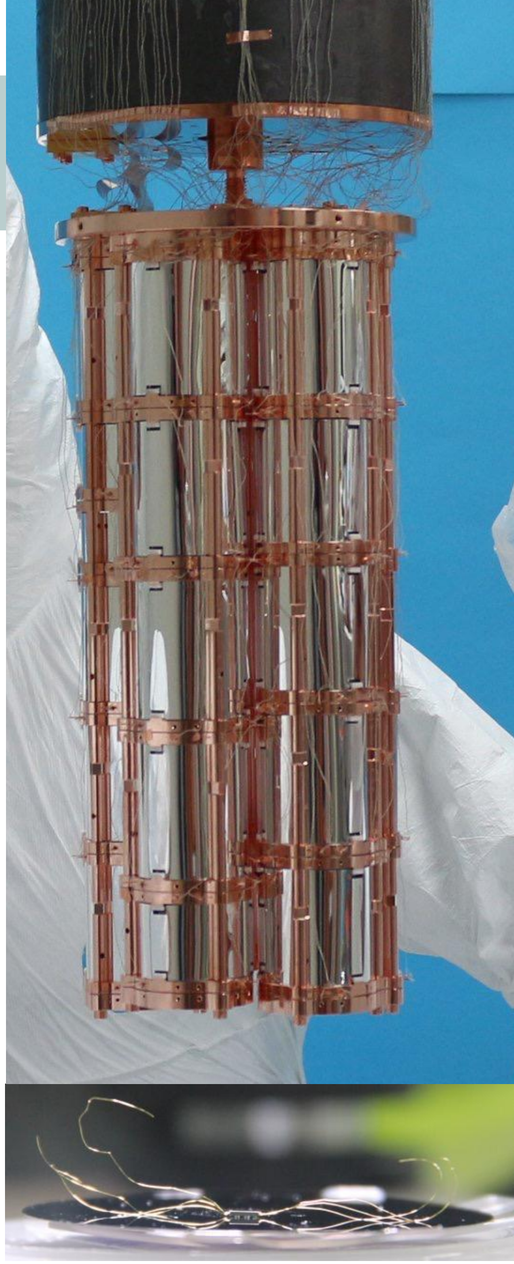
CUPID

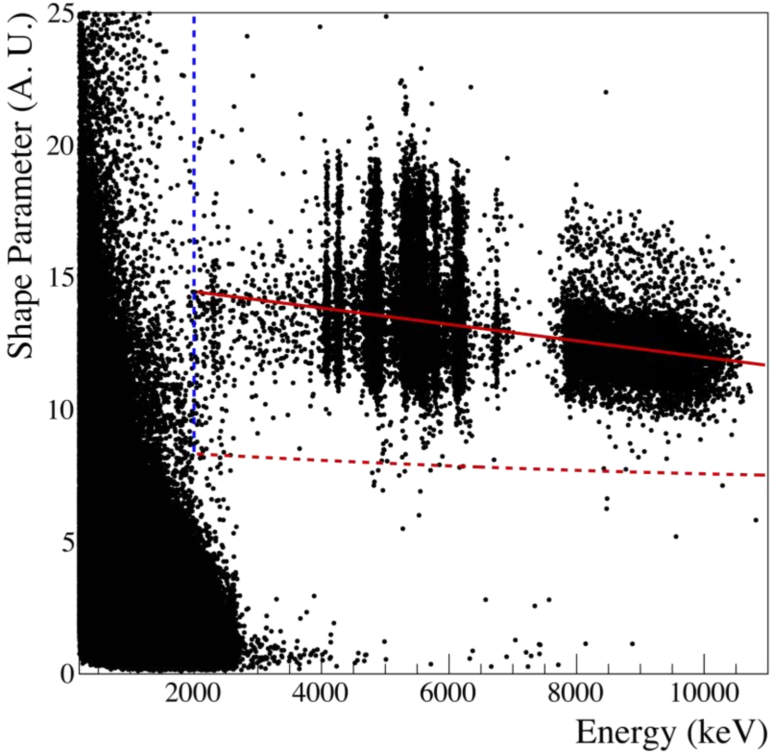
BINGO CROSS

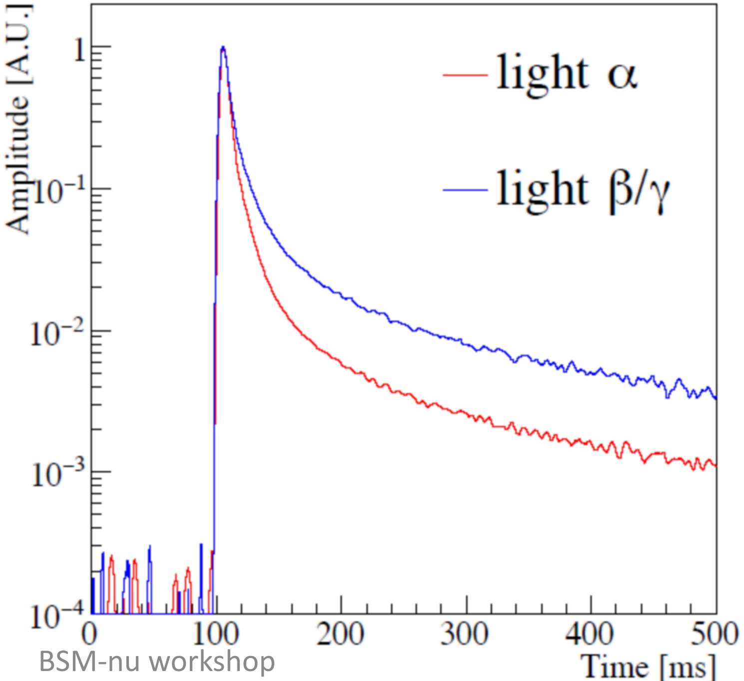
CUPID-0 demonstrator (^{82}Se)

- The first array of scintillating bolometers for the investigation of ^{82}Se 0v2β in LNGS
- 95% enriched $Zn^{82}Se$ bolometers (**5.17 kg of ^{82}Se, $Q_{\beta\beta}$=2998 keV**)







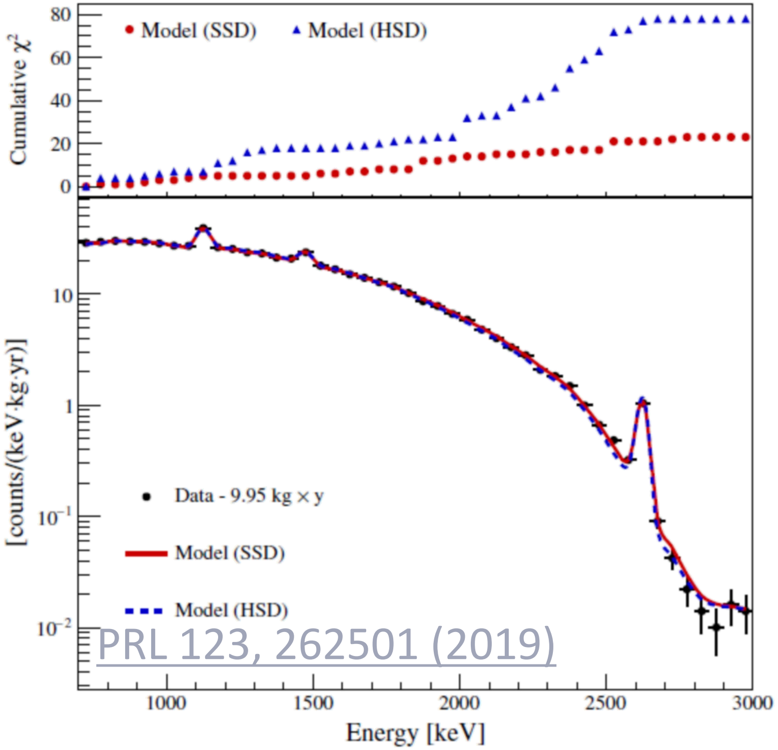


CUPID-0 results

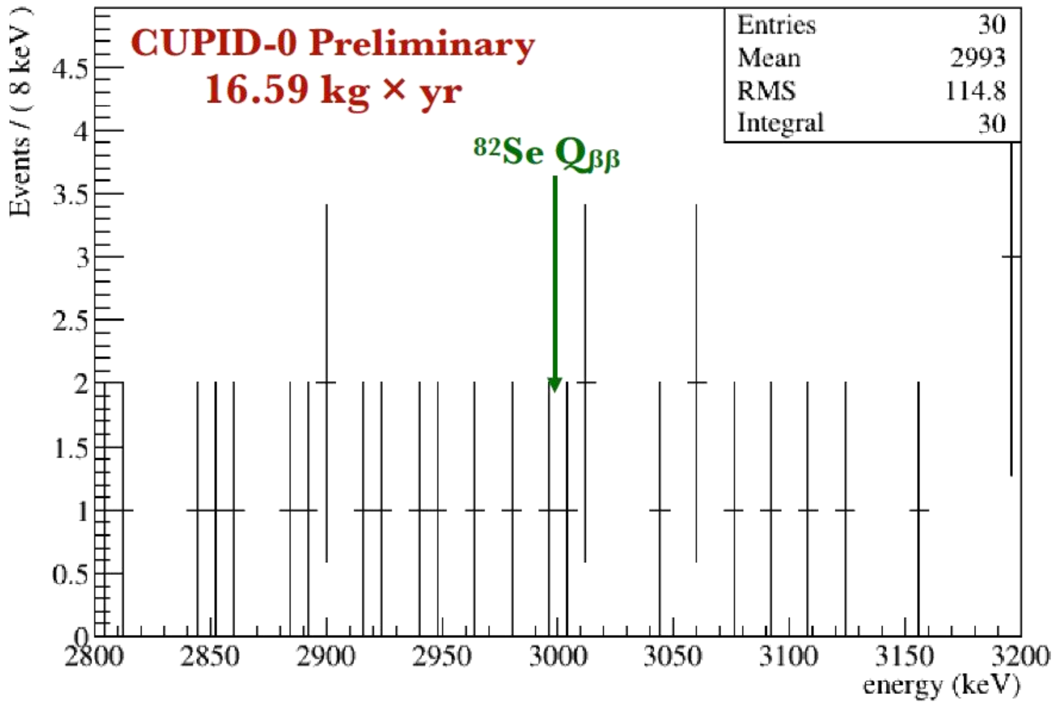
FWHM @ $Q_{\beta\beta}$=20.05 ± 0.34 keV

- Demonstration of advantages of dual-readout technique
- High scientific potential (e.g. best limit on ^{82}Se 0v2β half- life, most precise measurement of ^{82}Se 2v2β, CPT violation search, SSD vs HSD)

$$T_{1/2}^{0v} > 4.7 \times 10^{24} yr \text{ (90\% C. I. limit)}$$

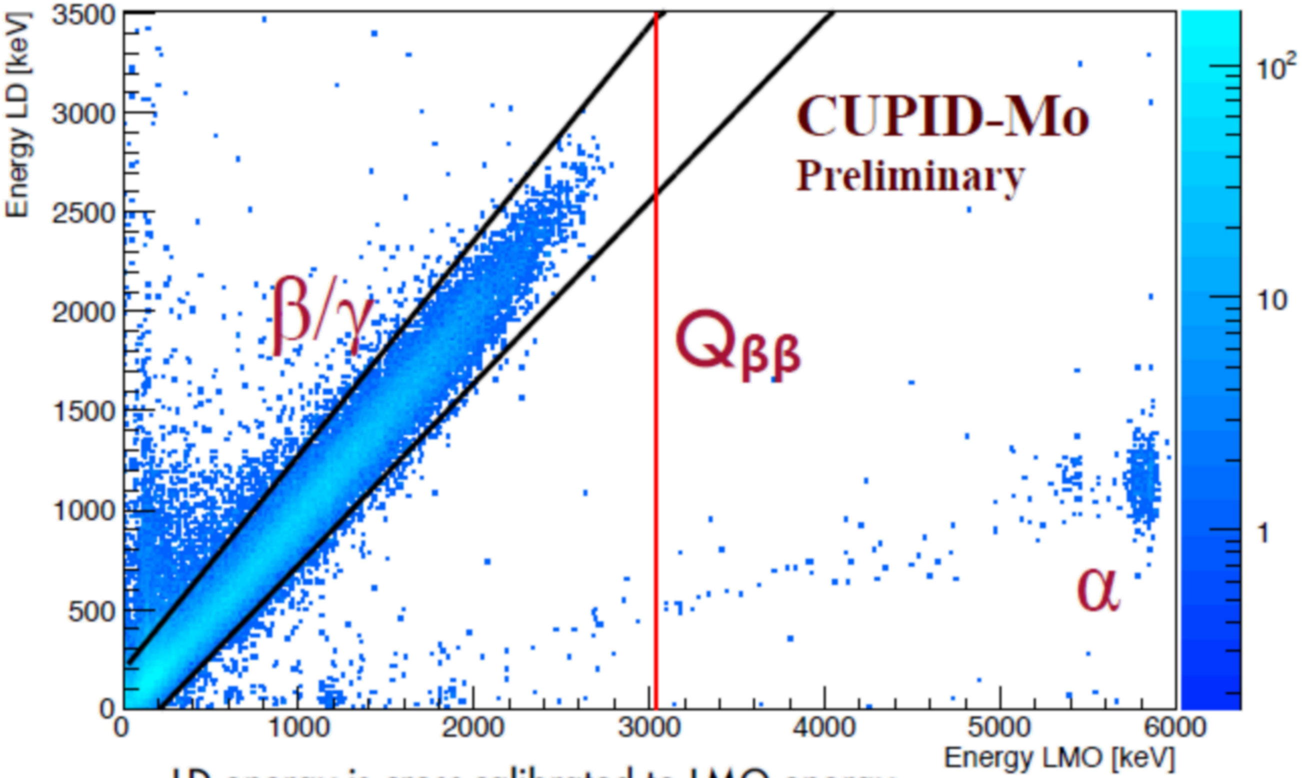


PRL 123, 262501 (2019)

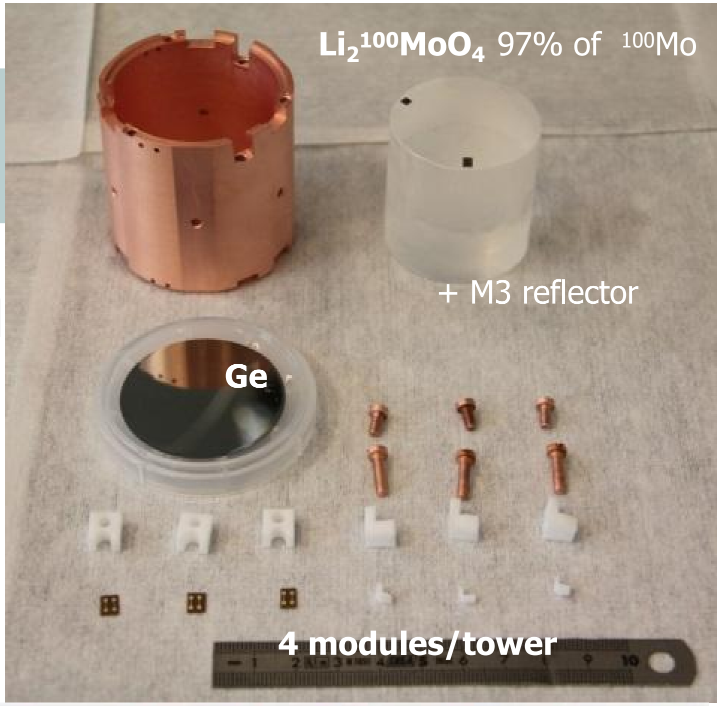


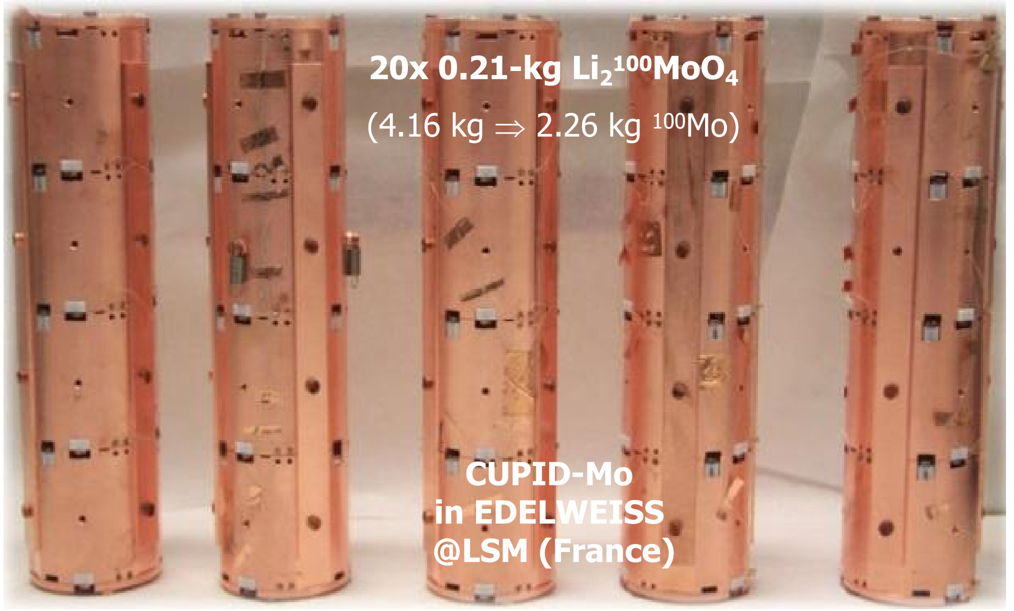
CUPID-Mo

- **$Li_2{}^{100}MoO_4$** scintillating crystals - high energy resolu radiopurity, array of 20 modules
- **Total of 2.26 kg of ^{100}Mo, $Q_{\beta\beta}$ = 3034 keV**



LD energy is cross-calibrated to LMO energy





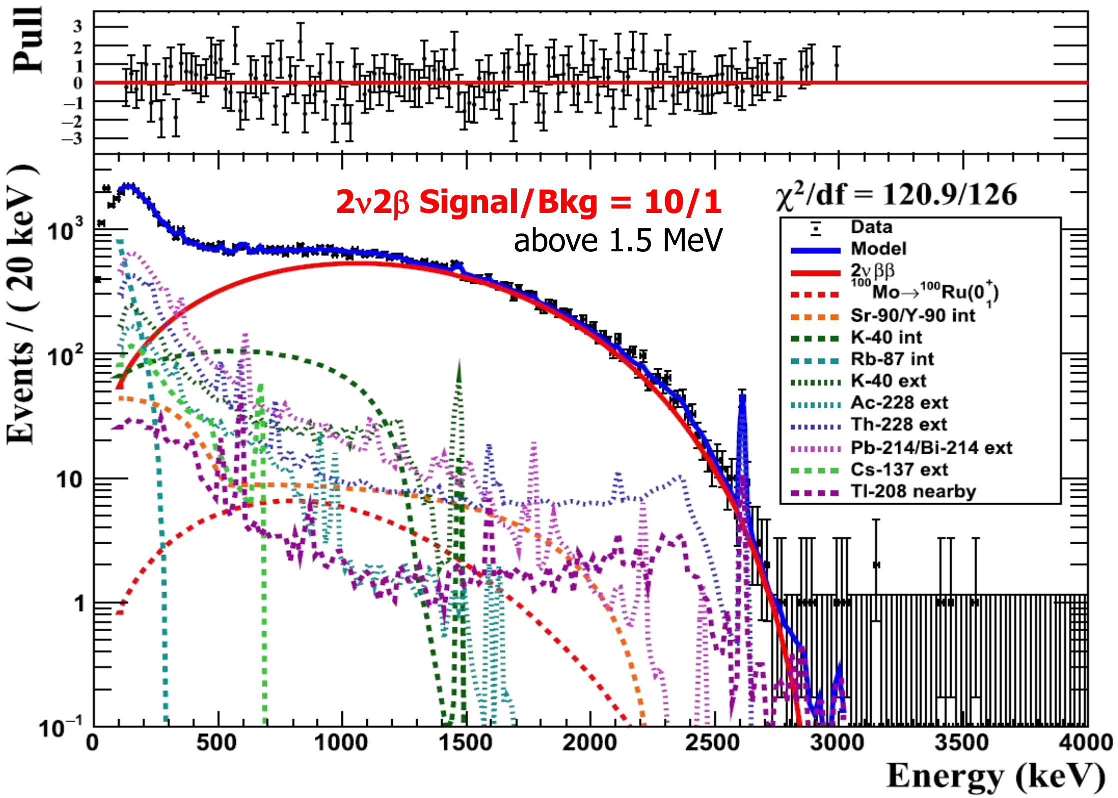
EPJC 80, 44 (2020)

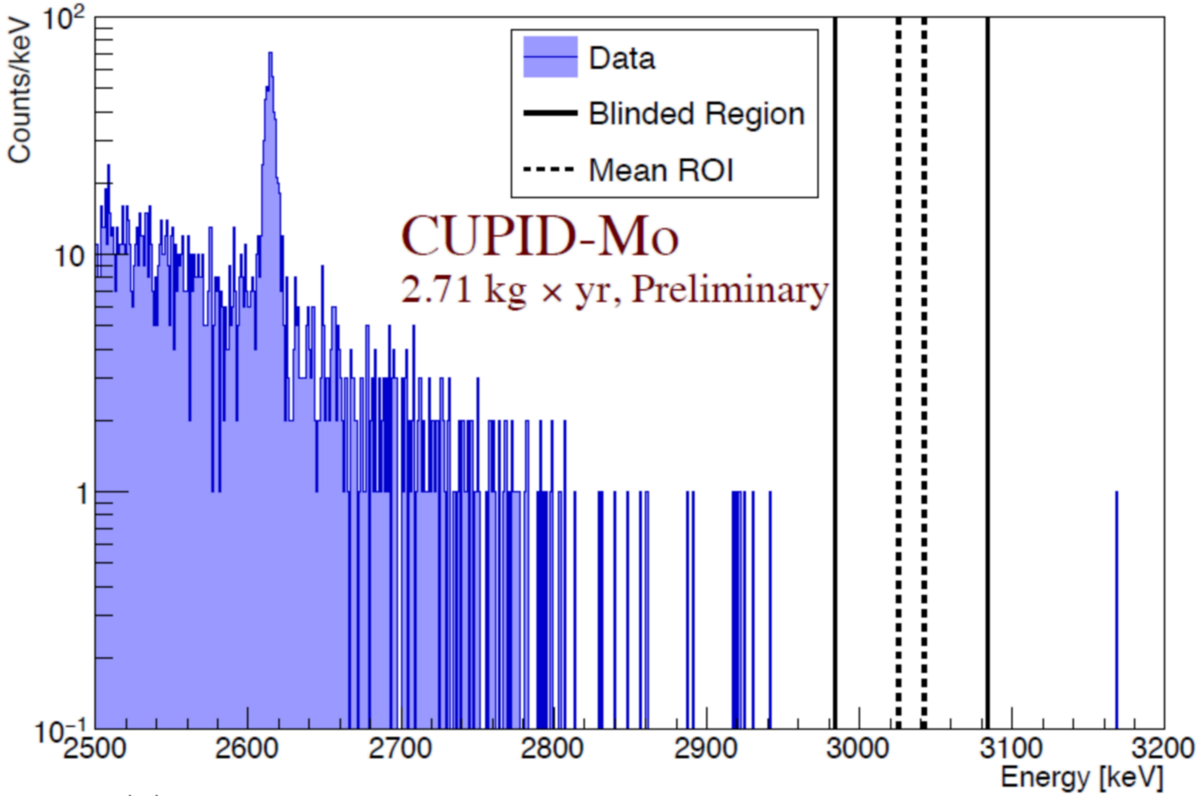
CUPID-Mo results

FWHM @ $Q_{\beta\beta}$=7.38 ± 0.35 keV

- Best limit on ^{100}Mo 0ν2β half- life, most precise measurement of ^{100}Mo 2ν2β

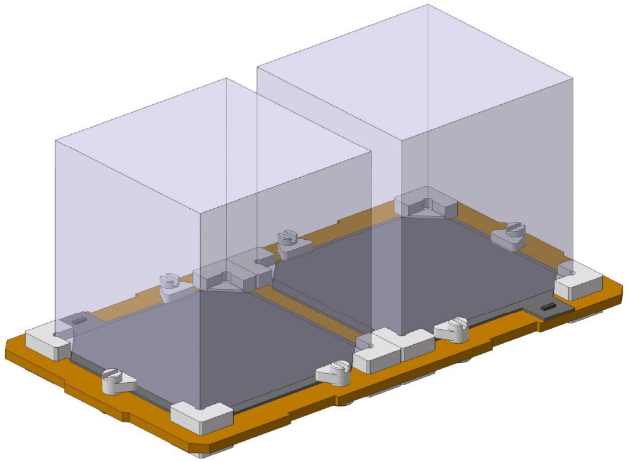
$$T_{1/2}^{0\nu} > 1.8 \times 10^{24} yr \text{ (90\% C. I. limit)}$$

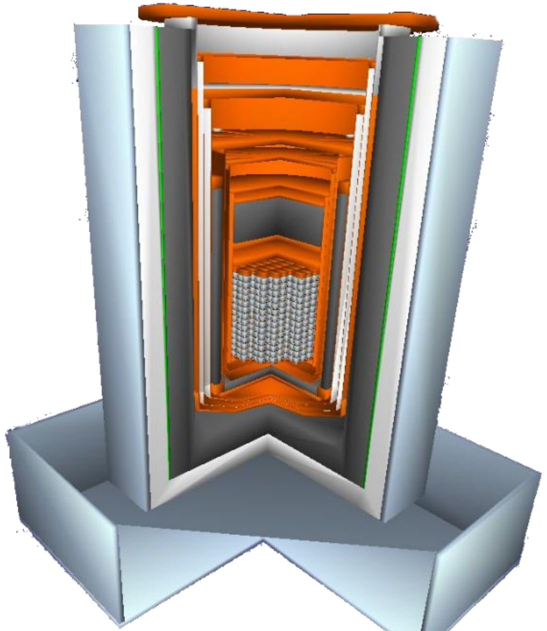


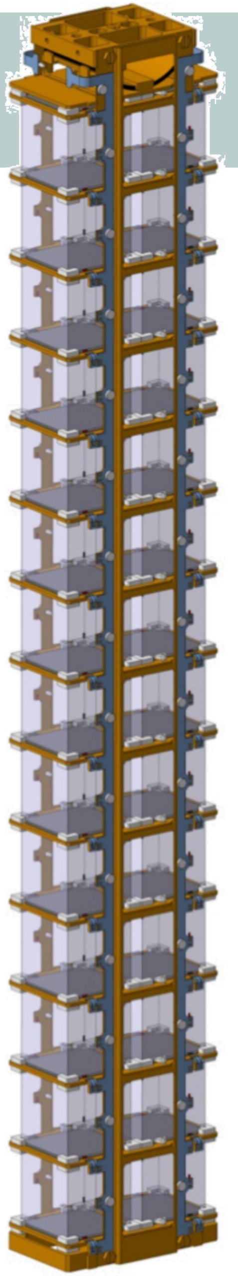


CUPID baseline design

- 1596 **$Li_2{}^{100}MoO_4$** scintillating bolometers
- 95% enrichment: 240 kg of **^{100}Mo**
- Target background index: ~10^{-4} cnts/keV/kg/yr
- Target sensitivity to effective Majorana neutrino mass ~ 10 meV

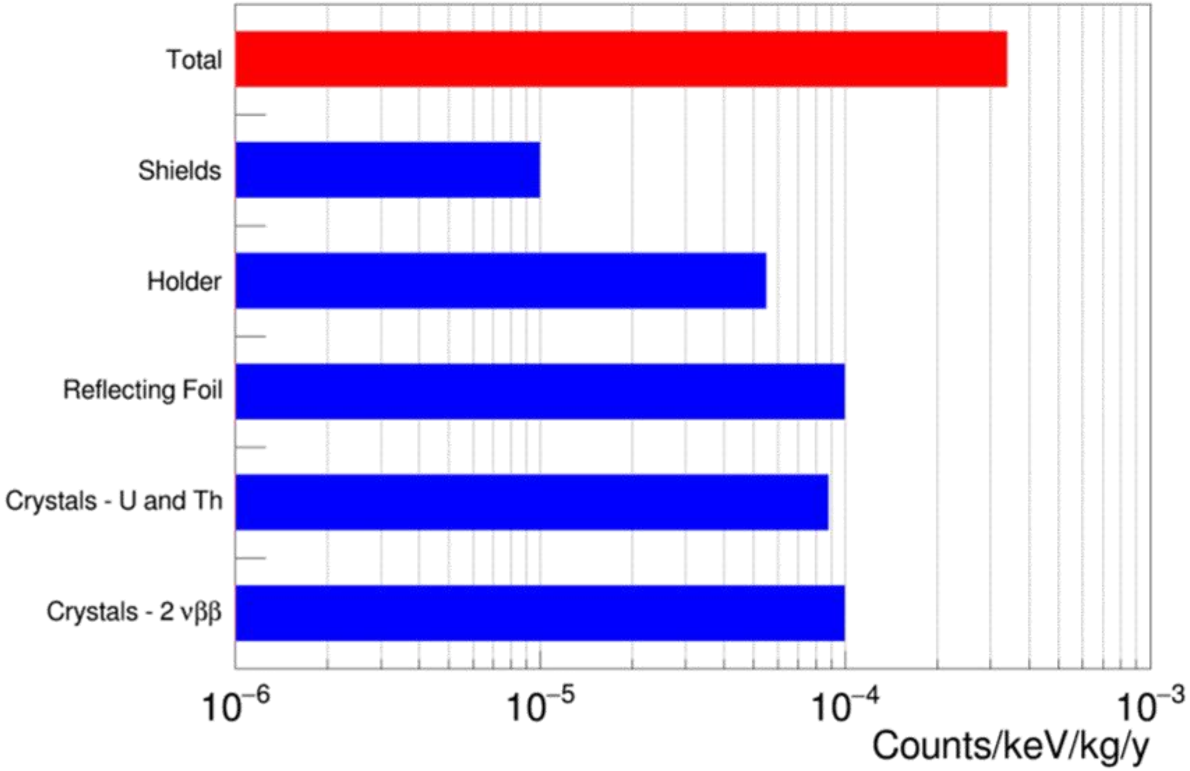






CUPID background model

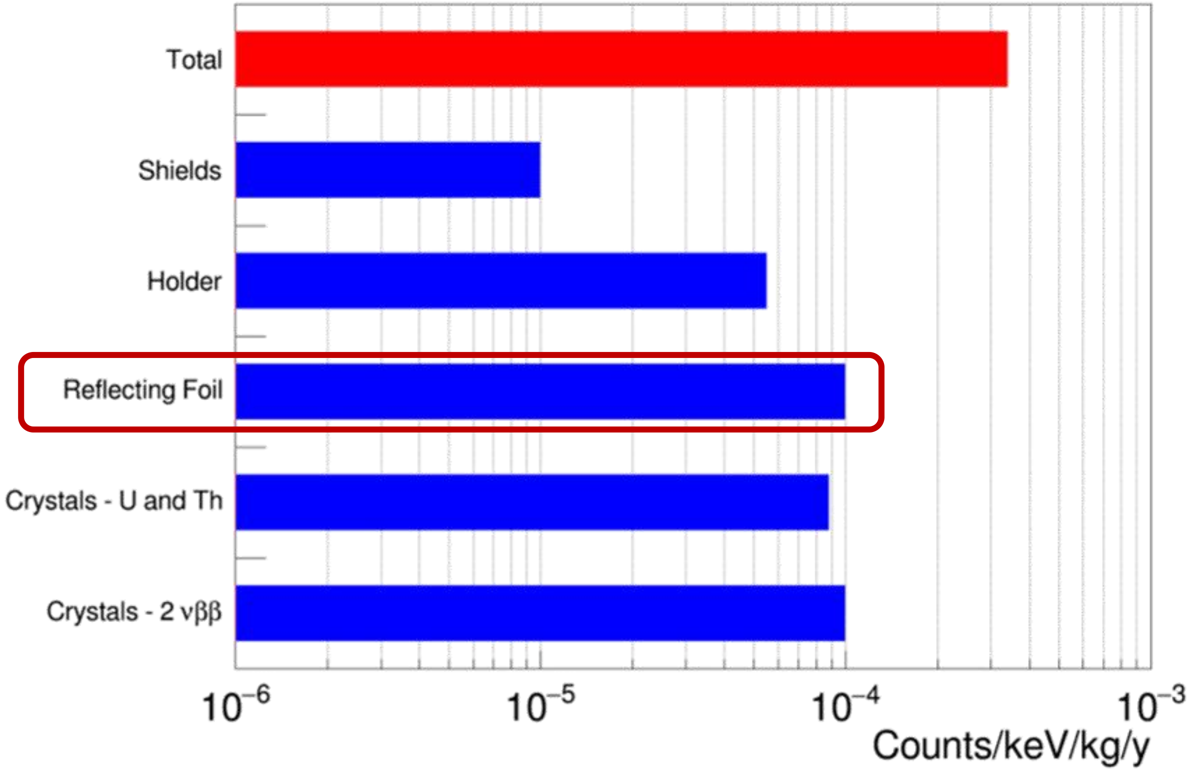
α background effectively eliminated by PID

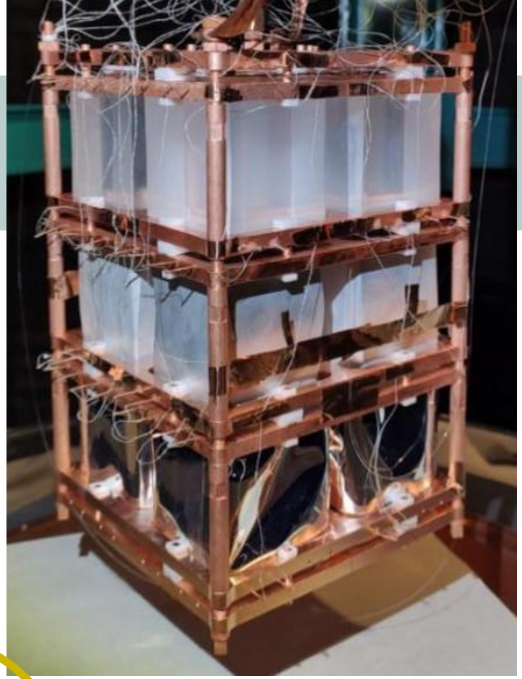


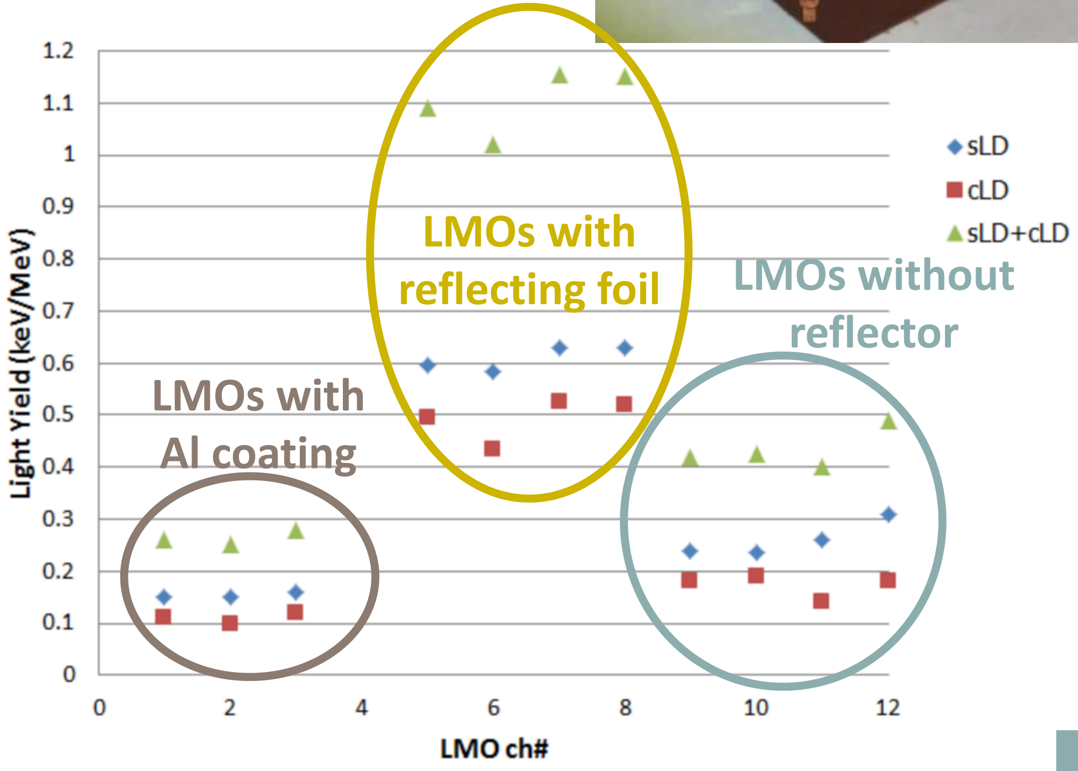
CUPID background model

α background effectively eliminated by PID

High preformance of light detectors is required to eliminate the reflecting foil







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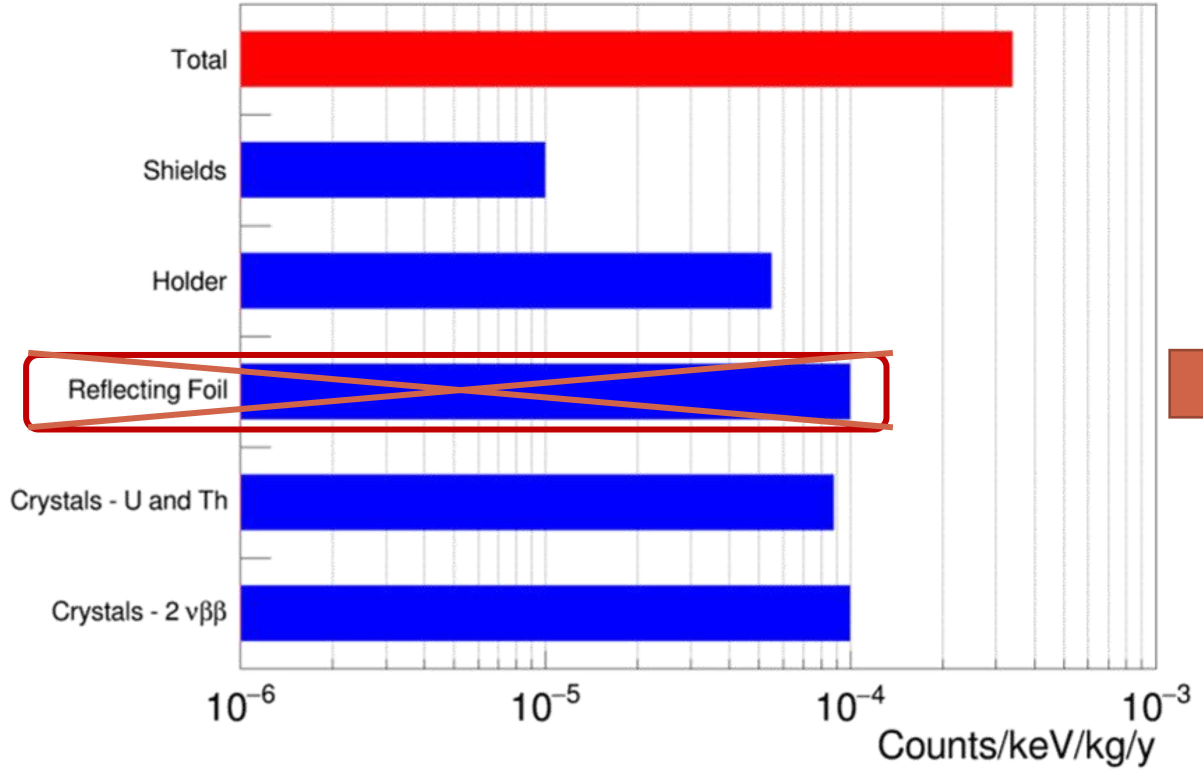

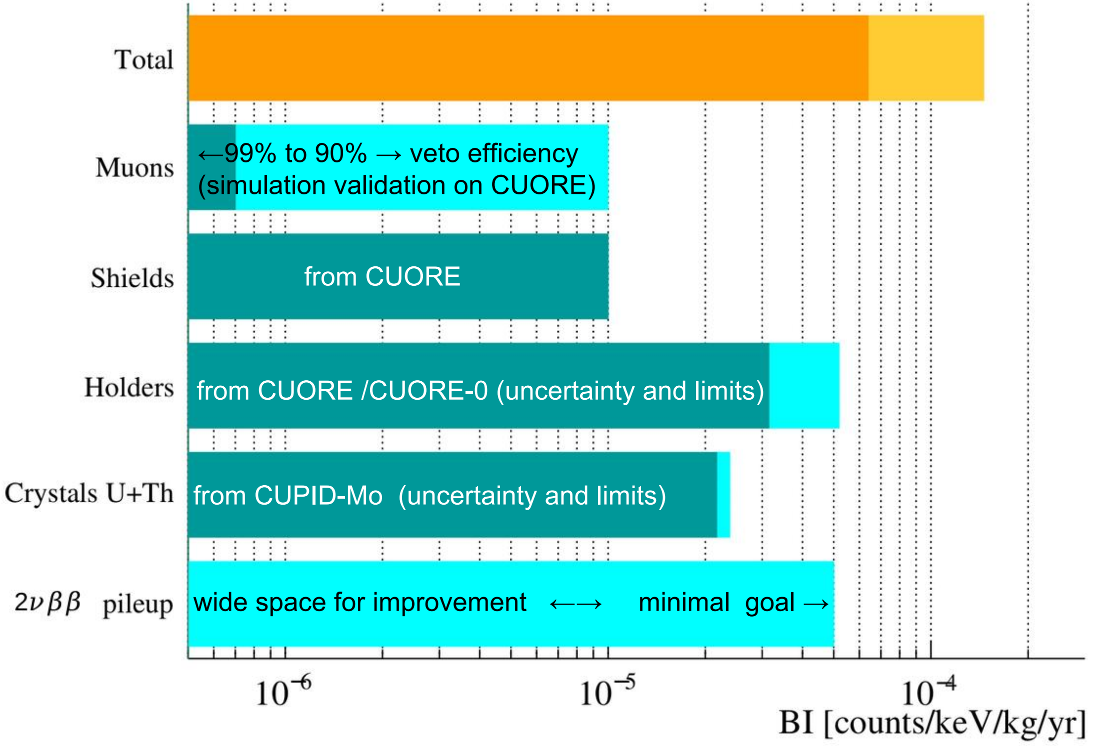

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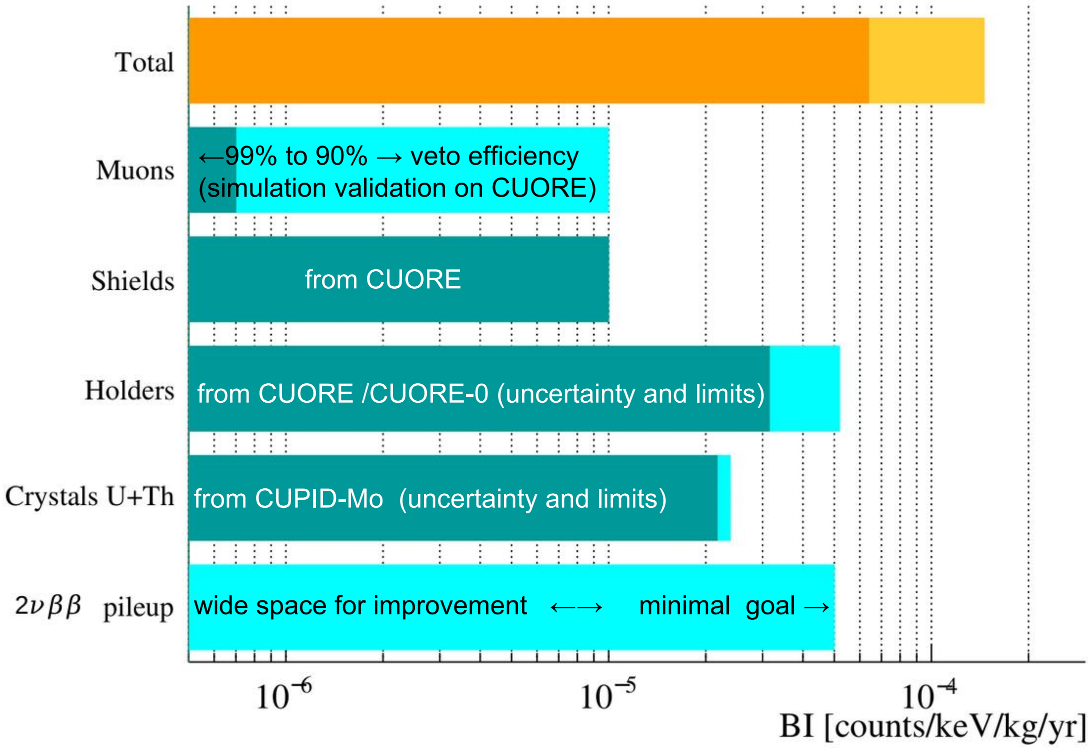
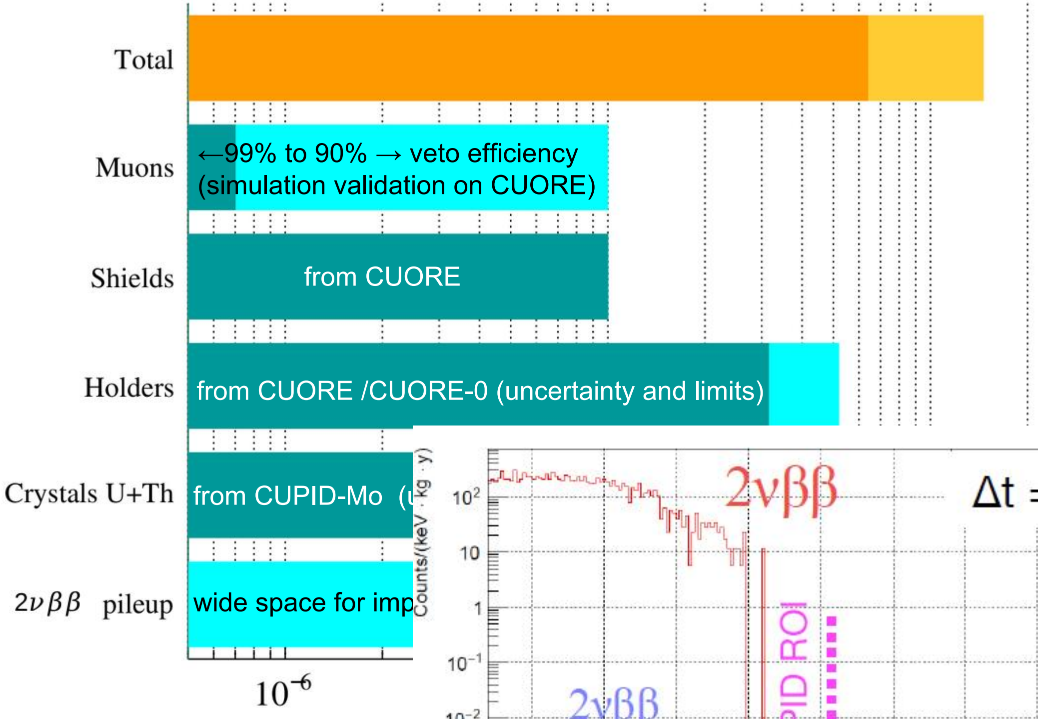


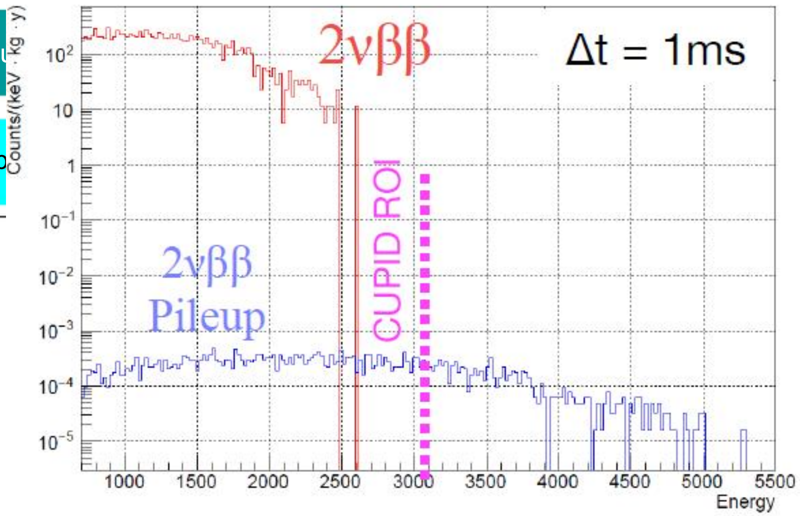
β/γ backgrounds reduced to < 5×10^{-5} cnts/(keV·kg·yr):

- Achievable with existing material selection, parts cleaning and handling, cryostat shielding
- Delayed coincidence cuts remove backgrounds from U/Th decay chains

CUPID background model

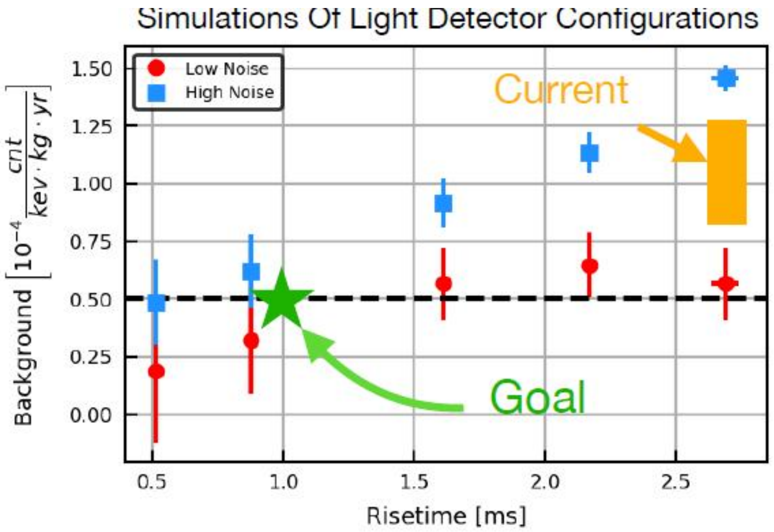
α background effectively eliminated by PID





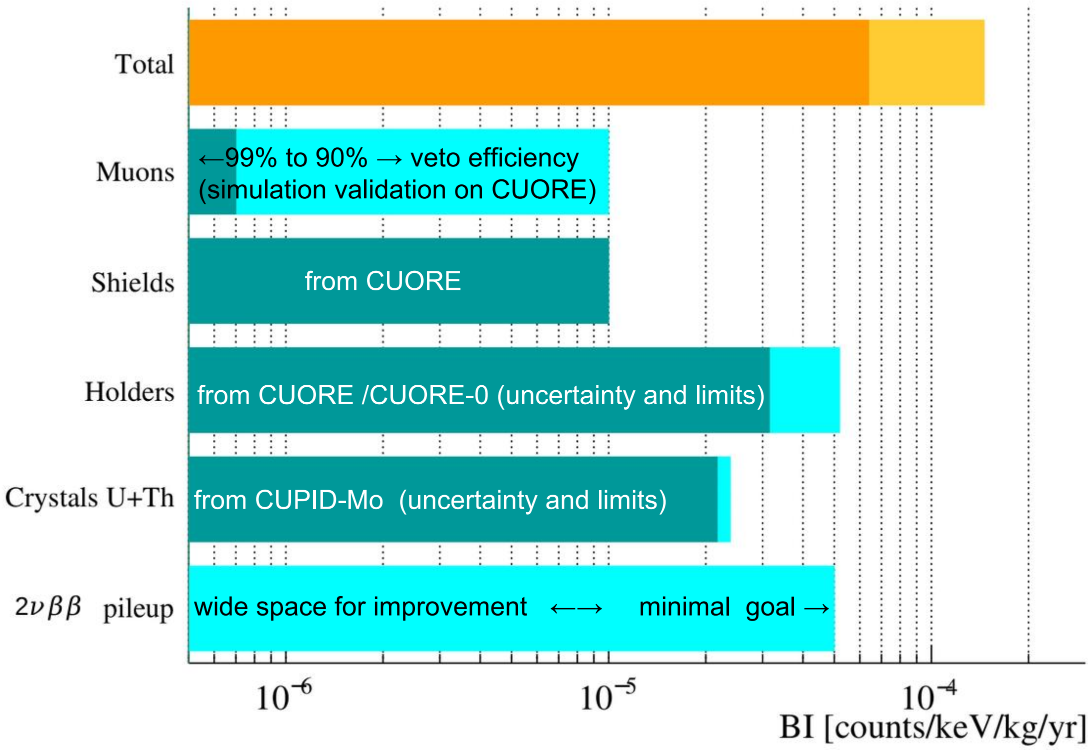
2νββ decay pileup reduced to < 5×10^{-5} cnts/(keV·kg·yr):

- Requires high light detector timing resolution
- Higher sampling rate, wider bandwidth electronics, lower noise, new NTDs, machine learning techniques
- Requires hardware improvements of factor of ~2 on light detectors



CUPID background model

α background effectively eliminated by PID

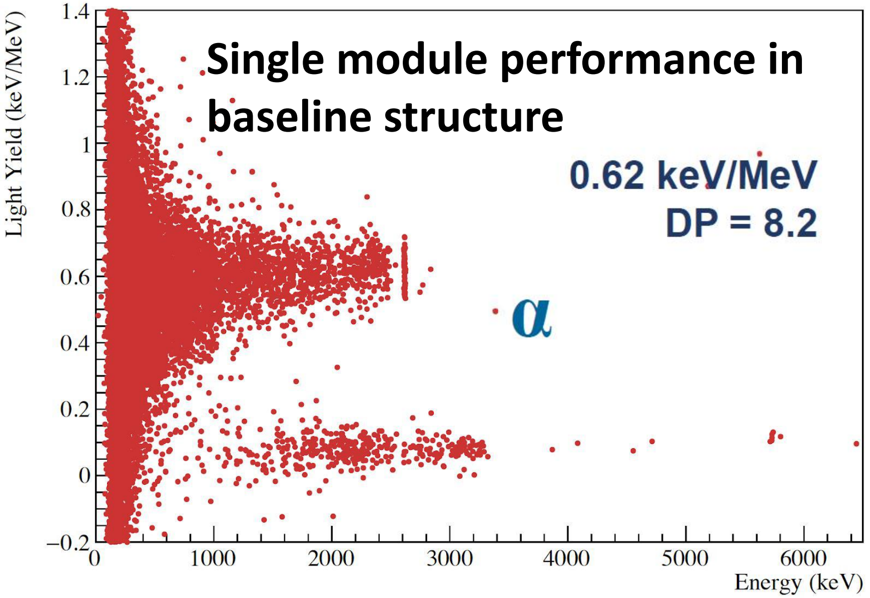


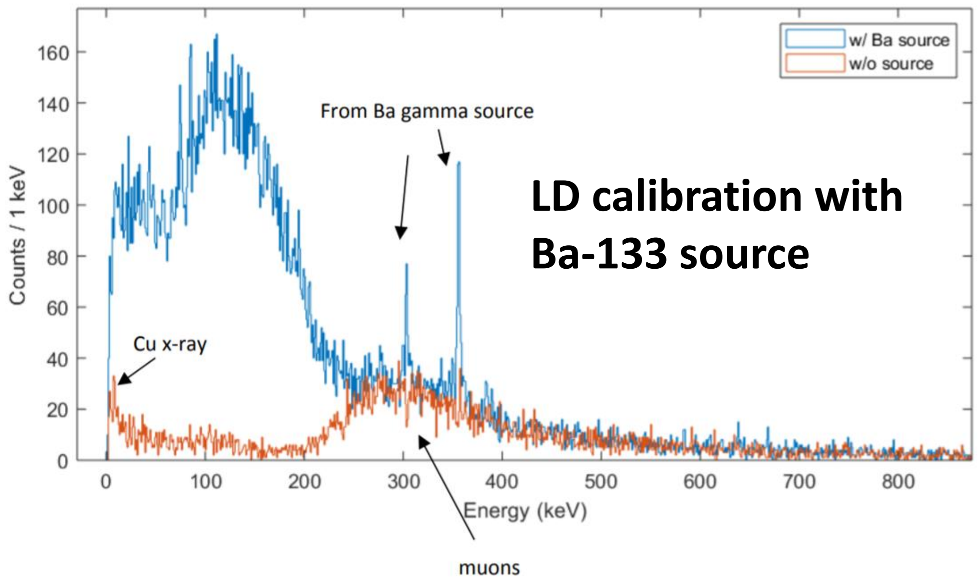
Muons reduced by an order of magnitude:

- Muon veto system with 99% geometric efficiency

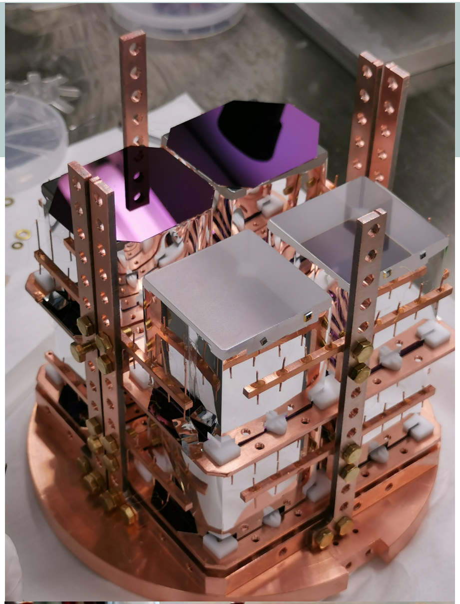
CUPID detectors prototypes

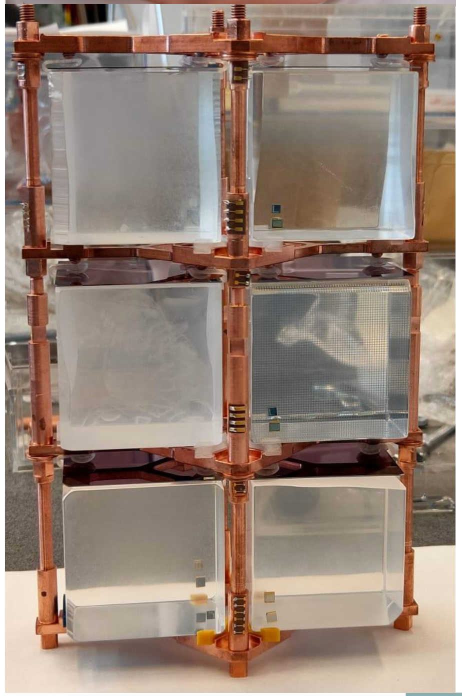
- Tests with few modules are concluded
- Two structures (baseline and alternative) were designed
- Reflecting foil is eliminated, LD performance is within requirements





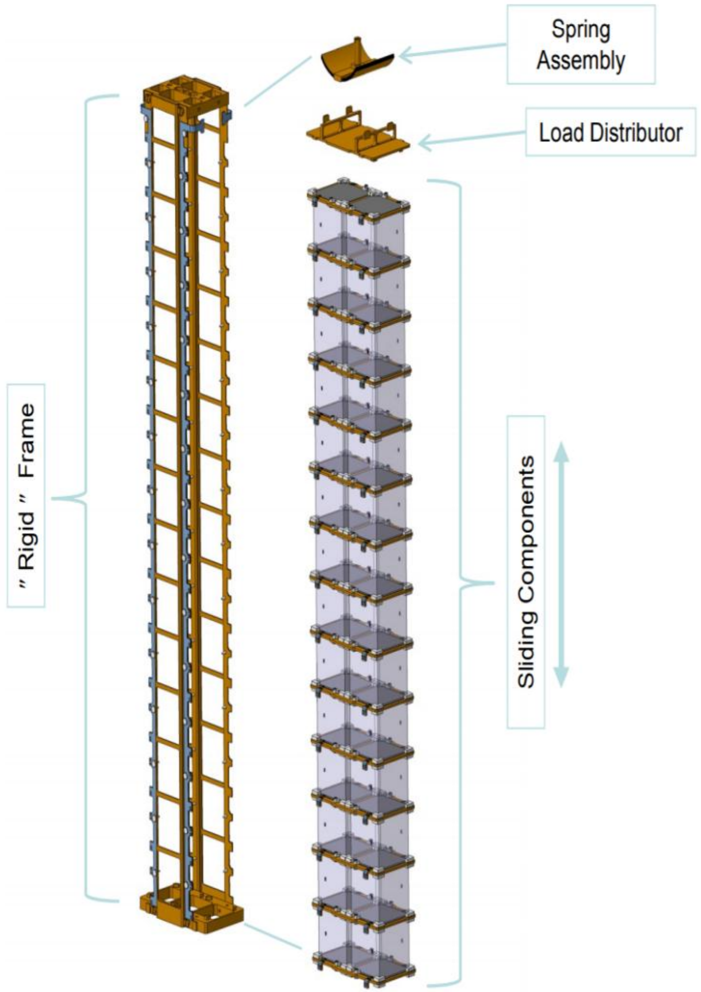
LD calibration with Ba-133 source

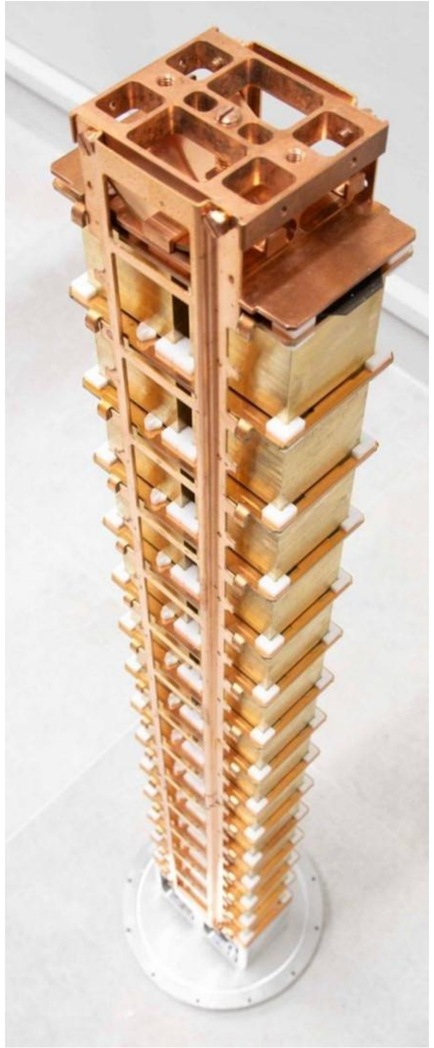




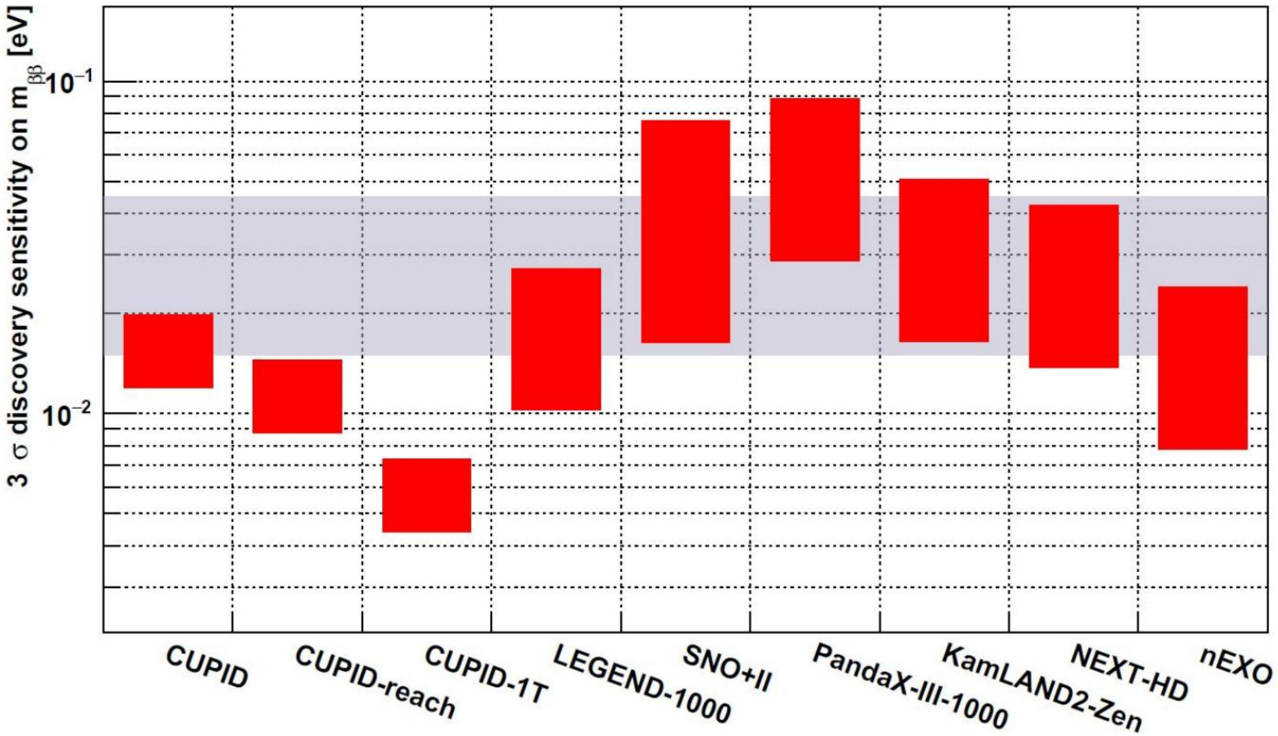
CUPID single tower

- The preparation of 28 modules assembly is ongoing
- The measurement will take place at LNGS underground lab
- Main objectives:
  - Validation of thermal and vibrational characteristics
  - Performance validation
  - Comparison of several types of sensors coupling





CUPID: sensitivity



- CUPID: Exactly what we could start building today: **10^{-4}** cts/keV/kg/yr
- CUPID-reach: improvements before construction: **2×10^{-5}** cts/keV/kg/yr
- CUPID-1T: 1 ton ^{100}Mo in new cryostat: **5×10^{-6}** cts/keV/kg/yr

CUPID demonstrators for CUPID-REACH

- Two projects are ongoing, both strongly tied with CUPID

CROSS

Development of **surface sensitive bolometers** for rejection of both α and β backgrounds

BINGO

Implementation of **cryogenic veto**, **Neganov-Luke** light detectors and **reduction of passive elements** around detectors

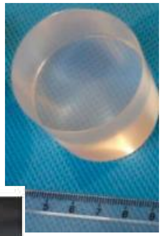
Isotope choice for demonstrators

^{100}Mo - first choise: Q = 3034 keV > 2615 keV A.I.: 9.7%

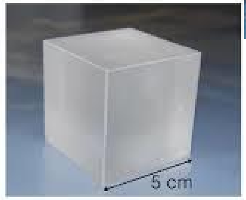
^{130}Te - kept as an option: Q = 2527 keV < 2615 keV A.I.: 34%

Crystals:

Li_2MoO_4 - basic choise for CUPID



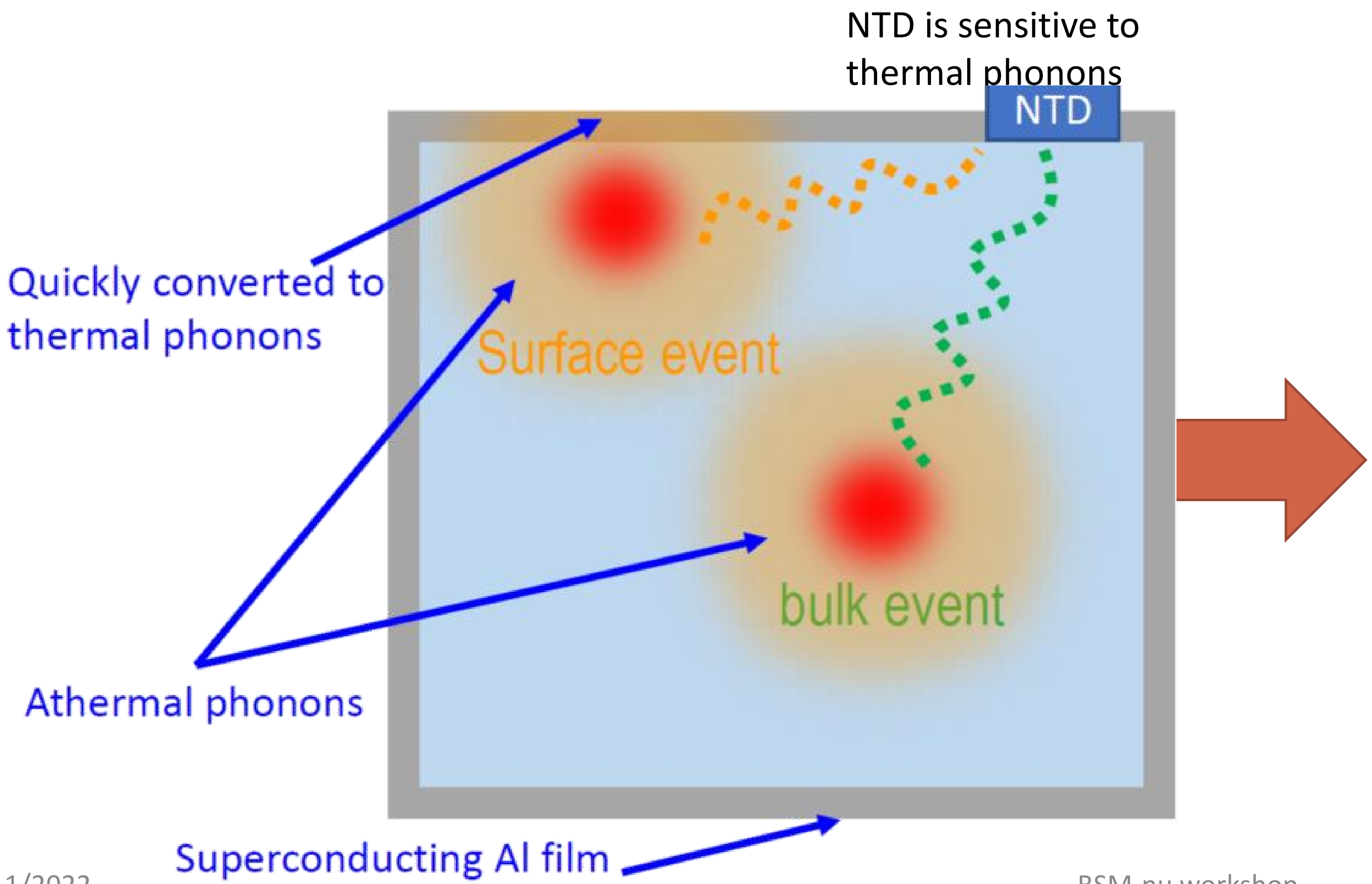
TeO_2 - CUORE compound

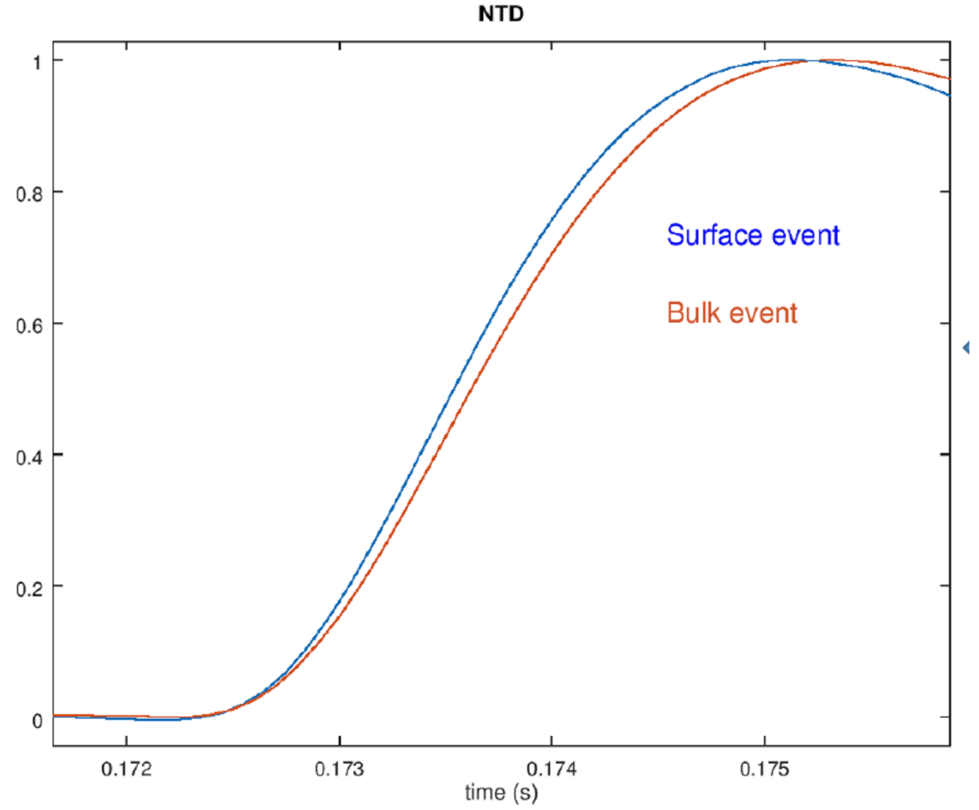


Excellent bolometric properties
High radiopurity
Extensively tested

CROSS technology: surface sensitivity

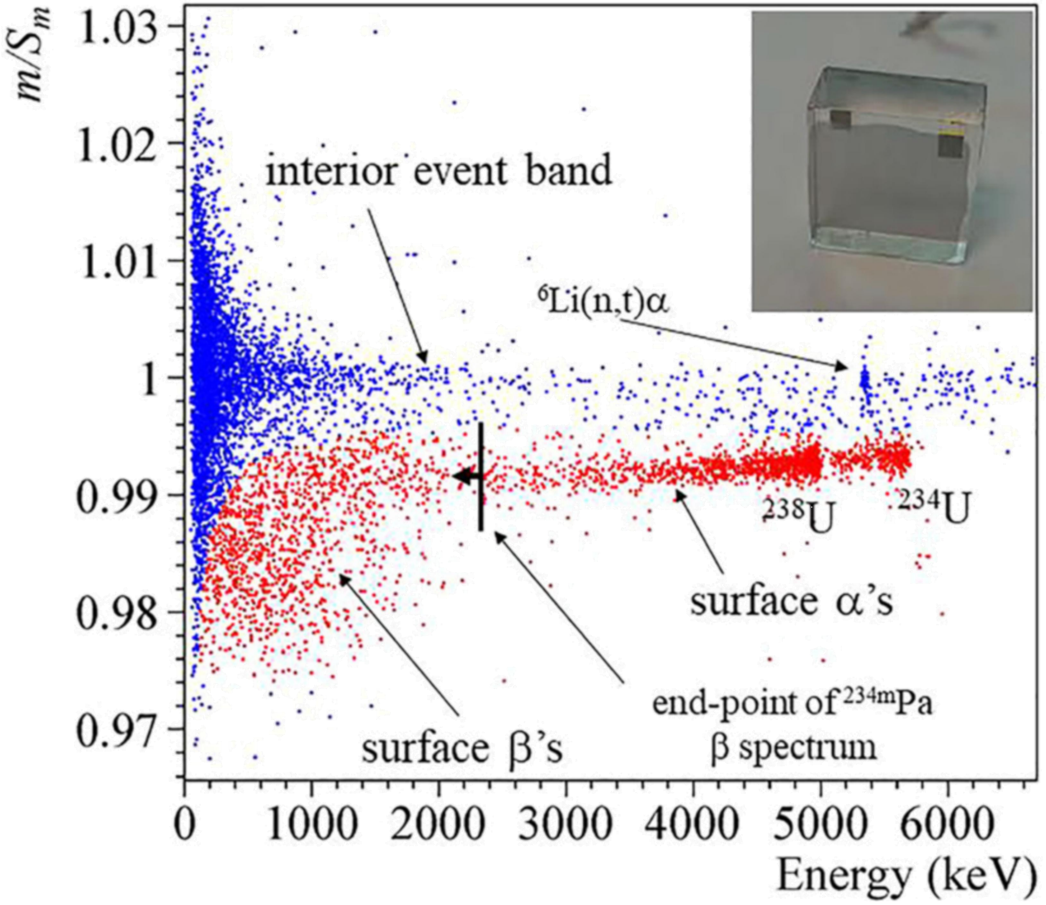
- Bolometers coated with metal films to identify near-surface events (No light detector is needed and advanced particle ID)



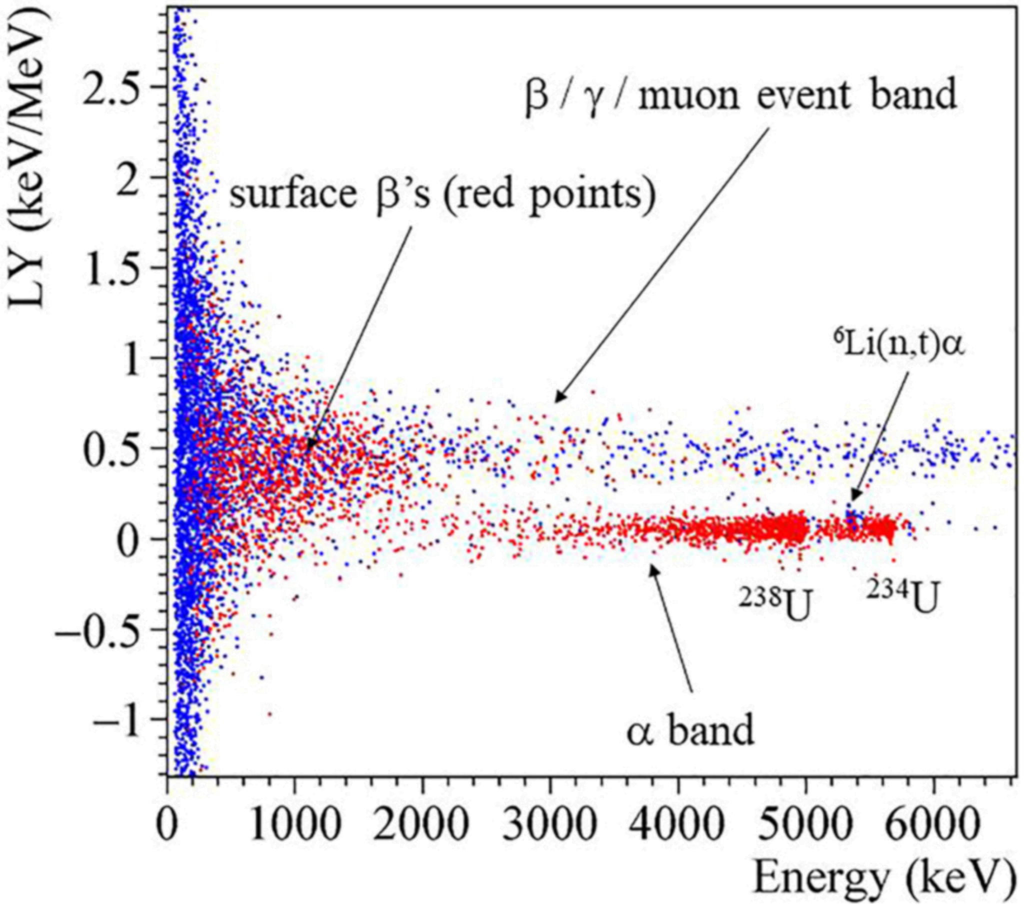


CROSS prototypes

CROSS technology: single read-out



CUPID technology: dual read-out



Li_2MoO_4

Appl. Phys. Lett 118, 184105 (2021)

CROSS demonstrator

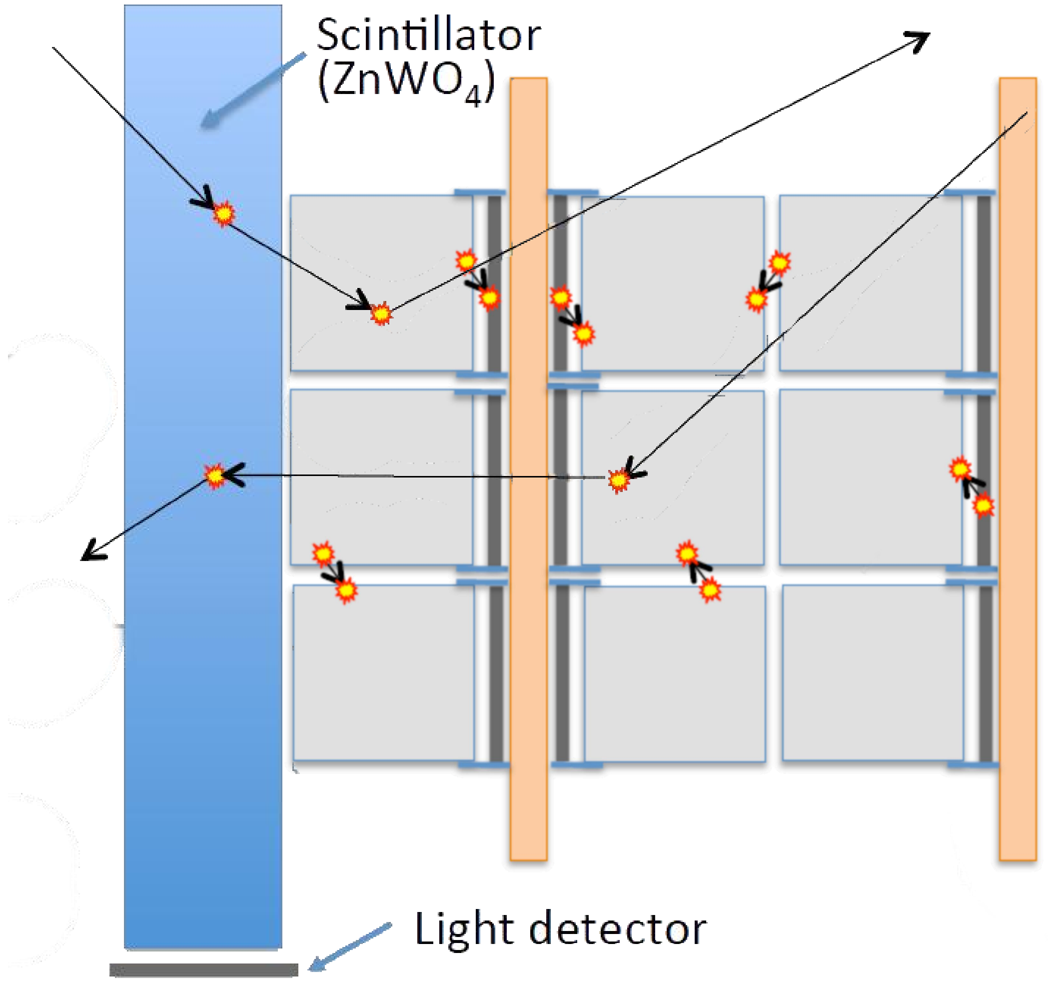
- CROSS-CUPID entanglement: joint tests are in progress, several improvements applied for CUPID

- Scaling from small (20x20x10 mm, 12 g) to large (45x45x45 mm, 280 g) crystals: not straight forward, measurements are ongoing

- Demonstrator with 42 $Li_2{}^{100}MoO_4$ cubic (45^3 mm) crystals with CROSS technology + 20 CUPID-Mo crystals: **6.6 kg of ^{100}Mo**
- With BI=10^{-3} cnts/keV/kg/yr and 2 yr livetime: $T_{1/2}$ limit ~ $2{\times}10^{25}$ yr, **$m_{\beta\beta}$ ~(86-149) meV**

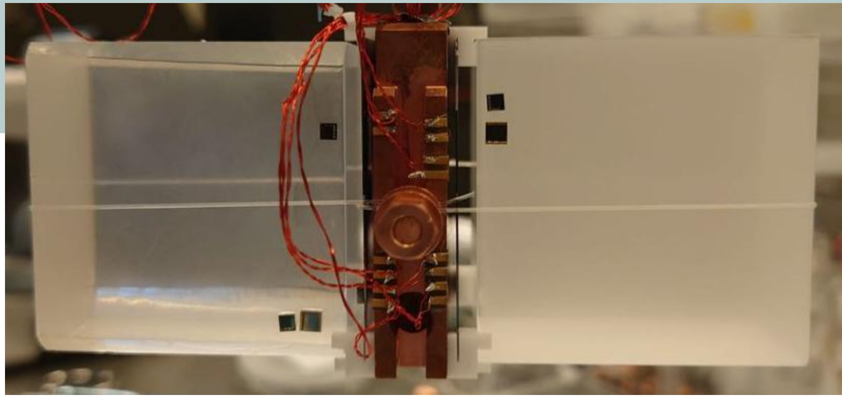
BINGO experiment: gamma bkg reduction

- Surface events discrimination: detectors will "see" only active elements
- Internal **active veto**: $ZnWO_4$(or BGO) scintillators, bolometric light read-out
- Light detectors with **Neganov-Luke technology** to reach 10 eV rms baseline
- Both Li_2MoO_4 and TeO_2 compounds

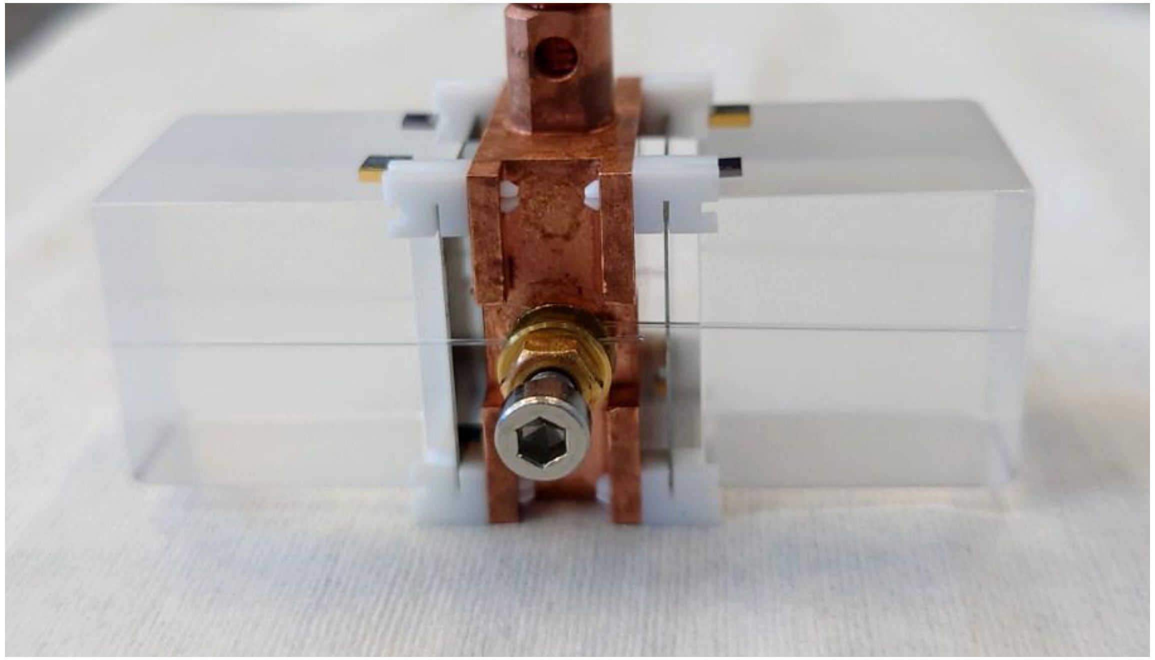


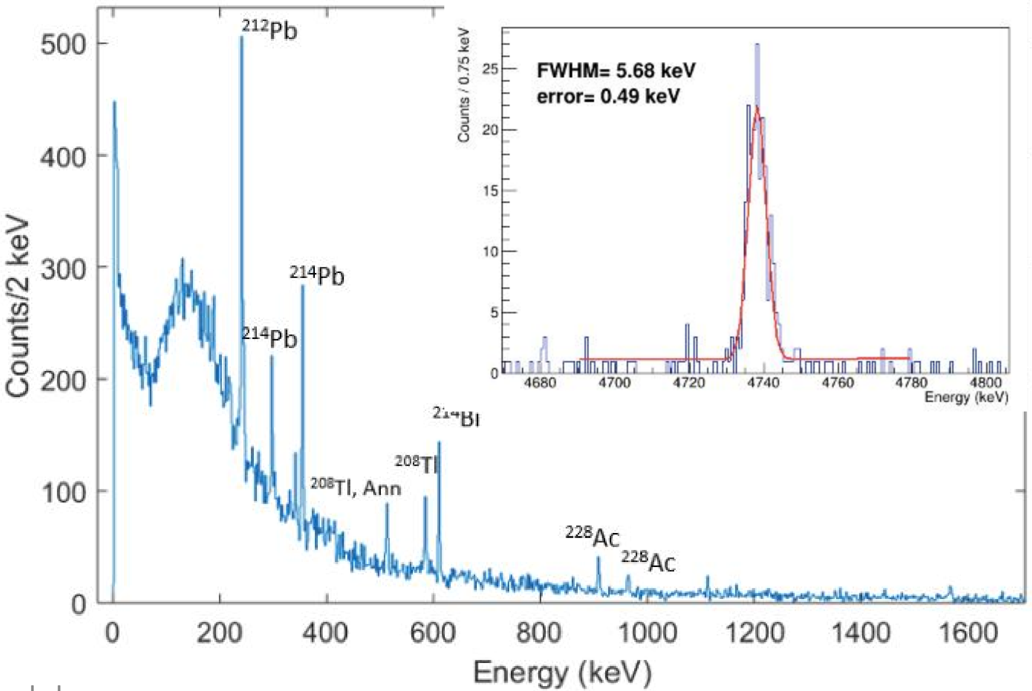
Technology for bkg index in ROI:
~10^{-5} cnts/keV/kg/yr

BINGO prototypes: assembly



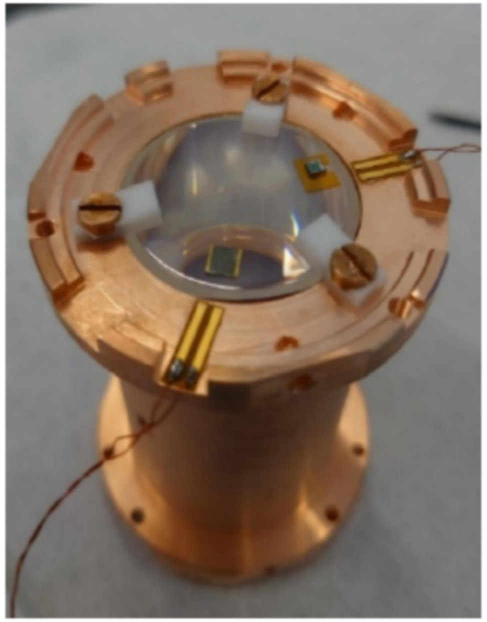
- First prototypes: 20x20x20 mm Li_2MoO_4 crystals
- Excellent performance and energy resolution
- The best energy resolution ever obtained on the ^{7}Lin capture line
- Full scale prototypes to be tested underground soon

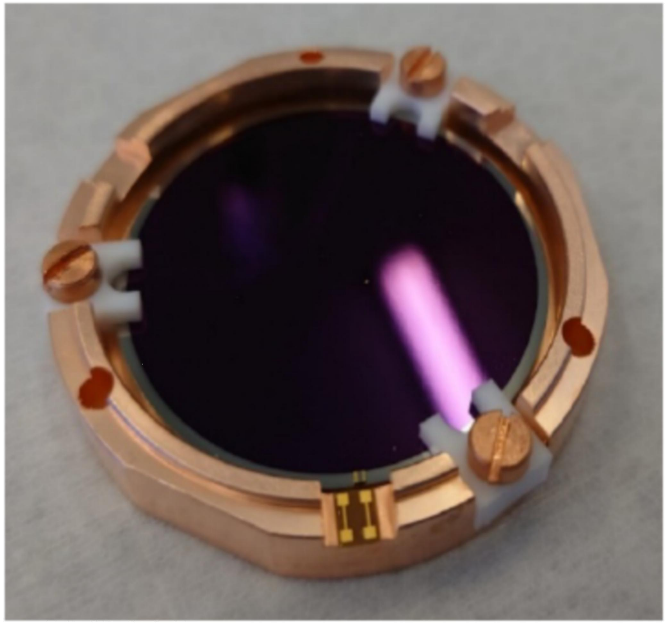


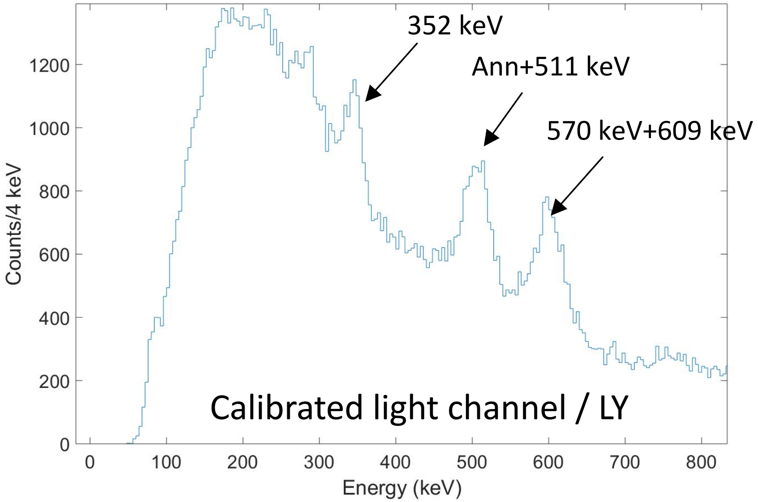


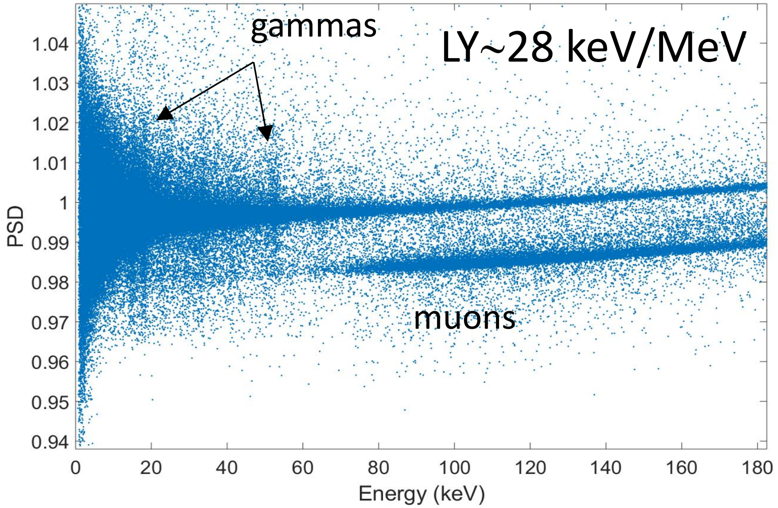
BINGO prototypes: veto

- Veto prototype: Very low energy threshold of the light detector is required





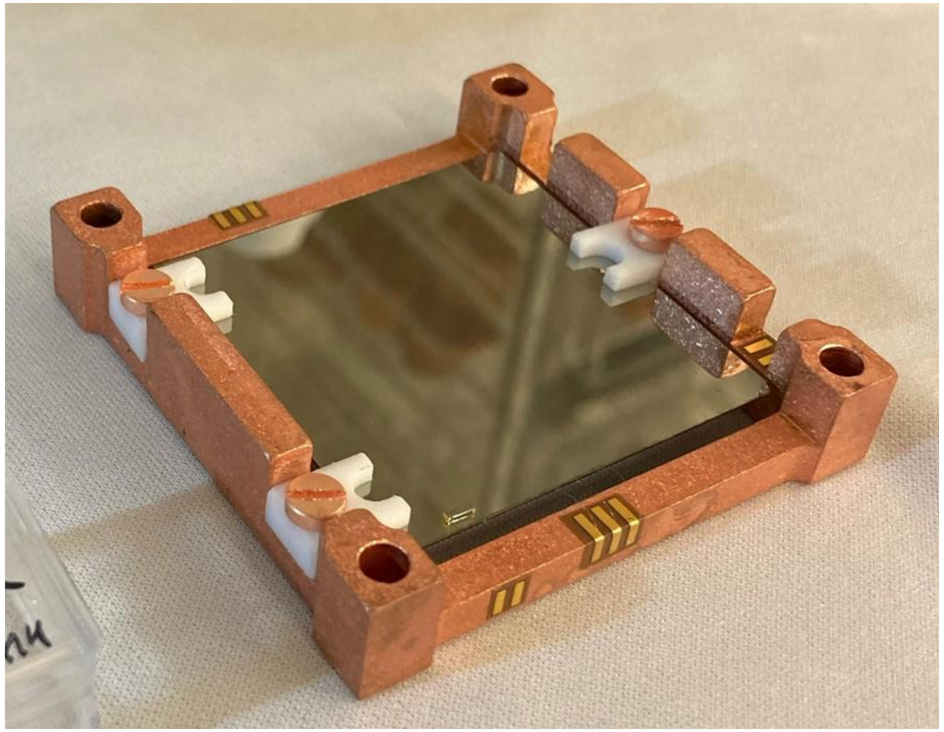


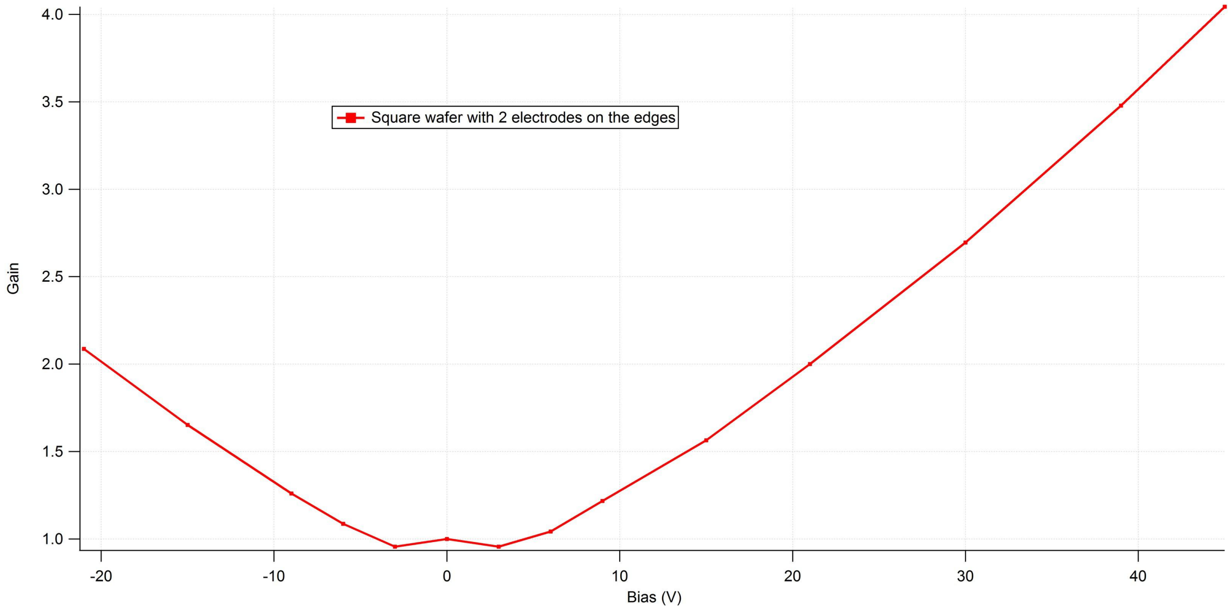


More details on cryogenic veto in the next talk

BINGO prototypes: Neganov-Luke detectors

- New electrodes and shape design
- Can be implemented in CUPID for pile-up reduction

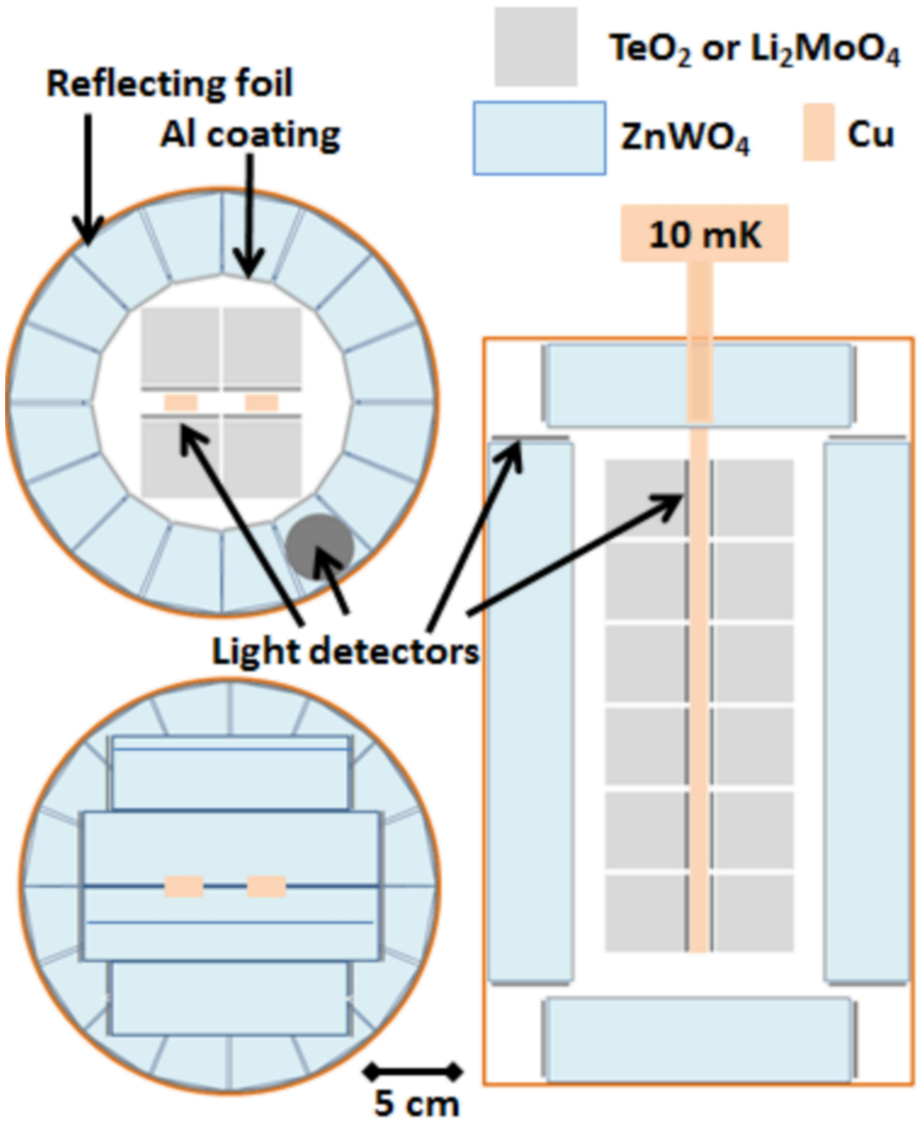




BINGO demonstrator

- MINI-BINGO will be installed in Modane Underground Laboratory
- 2x12 crystal towers
- Crystals will see nothing else that is not active

Scale high enough to demonstrate
b ≤ 10^{-4} cnts/keV/kg/yr
in 1 yr data taking



CUPID

CUPID is an outstanding next-generation experiment:

- **technologically ready:** $Li_2{}^{100}MoO_4$ detectors are well-studied and ready for mass production;
- **data driven:** precise background model of the cryostat; significant experience with data analysis of large arrays of bolometers;
- **based on existing infrastructure**, which is already optimized and well-tested in CUORE;
- **cost effective**

CUPID aims to cover completely inverted and part of normal hiearchy regions

Backups

Background sources and isotope choice

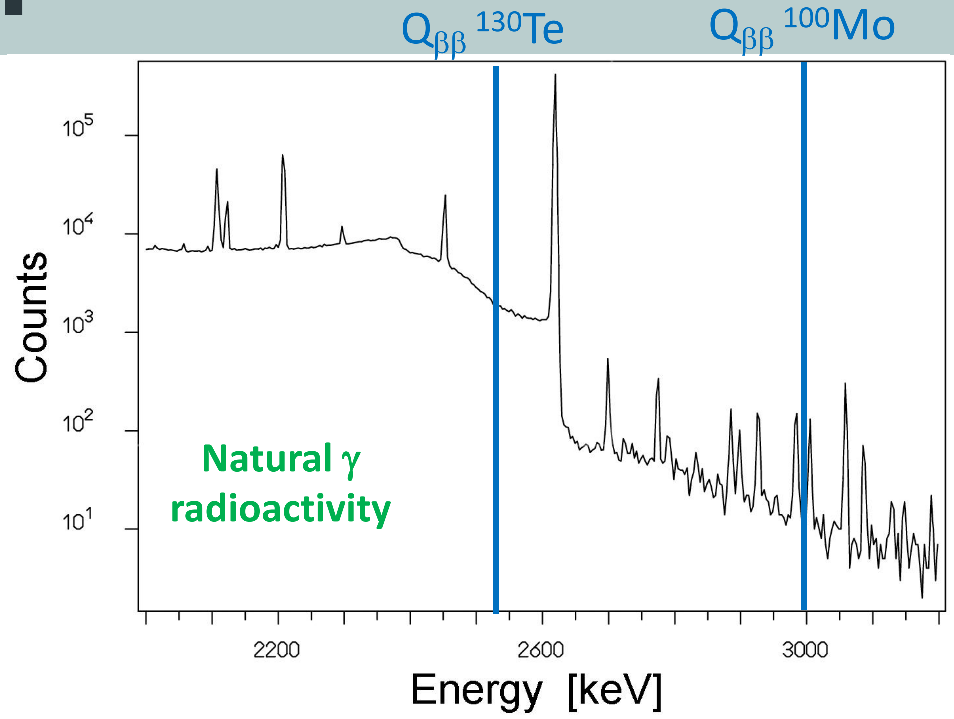
- Cosmic muons, neutrons
- Environmental γ's, α's and β's
- $2\nu2\beta$ decay

Underground lab
Radiopurity
Shielding

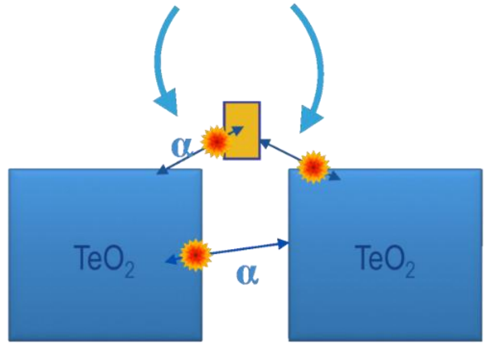
High energy resolution (**bolometers**)

Choose **high $Q_{\beta\beta}$-value** (> 2.6 MeV) isotopes

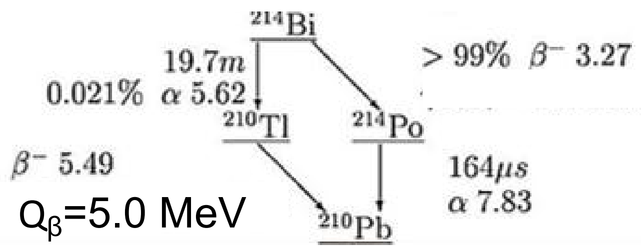
Develop **advanced bolometers** with particle and impact-point identification



Energy degraded α events

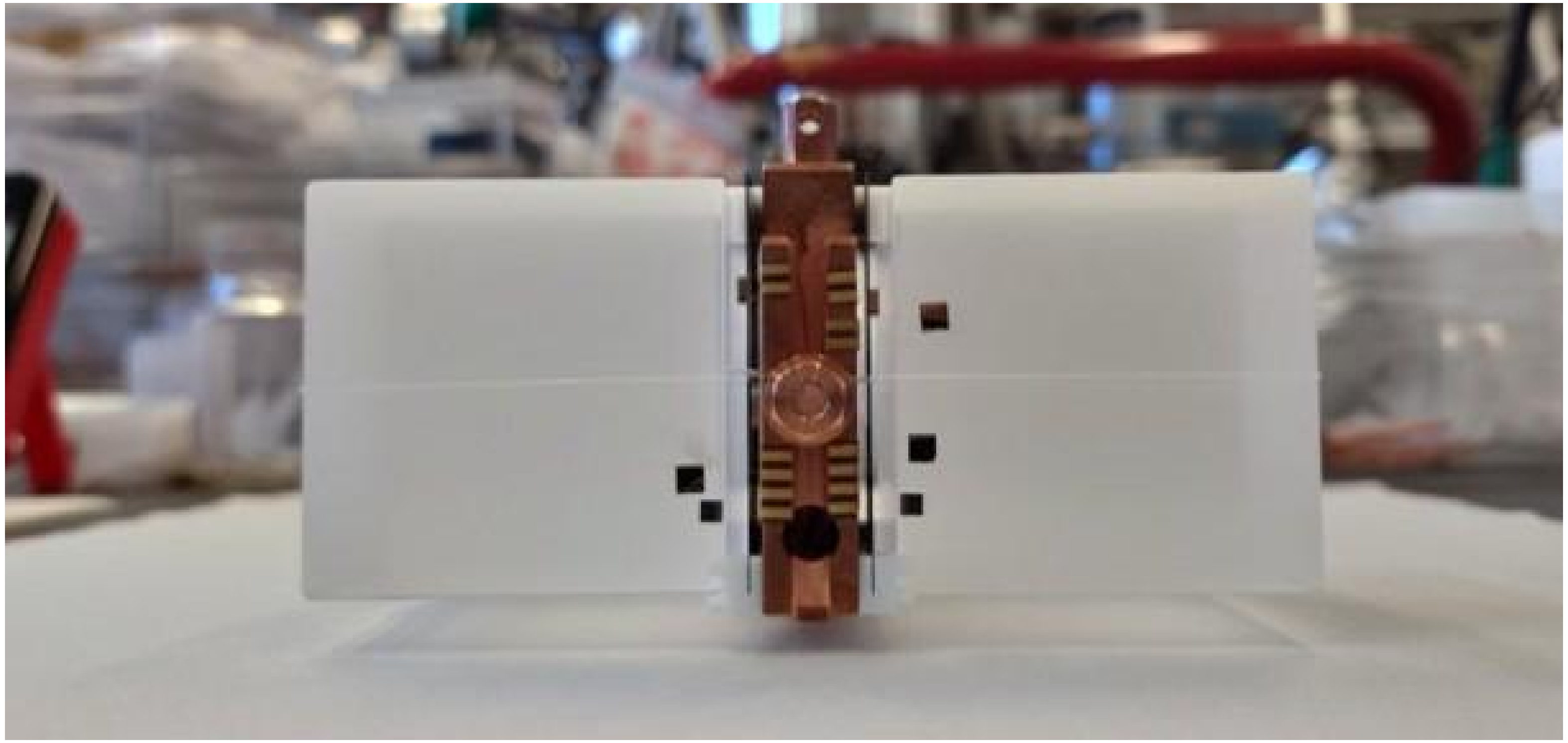


High energy β decays



BINGO prototypes

- Tests with 45x45x45 mm crystals



β surface radioactivity

^{238}U chain → ^{214}Bi Q_β = 3.3 MeV
(^{210}Tl Q_β value: 5.5 MeV; 0.02% ^{214}Bi)

$^{214}Bi \xrightarrow{\beta} {}^{214}Po \xrightarrow{\alpha} {}^{210}Pb$
164 μs

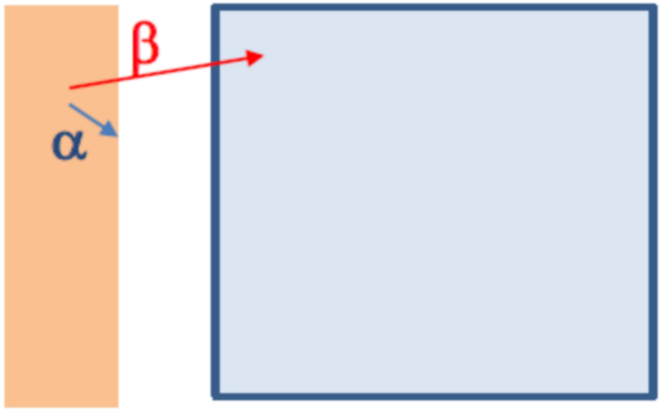
Harmless in the crystal bulk
Mixed α/β event

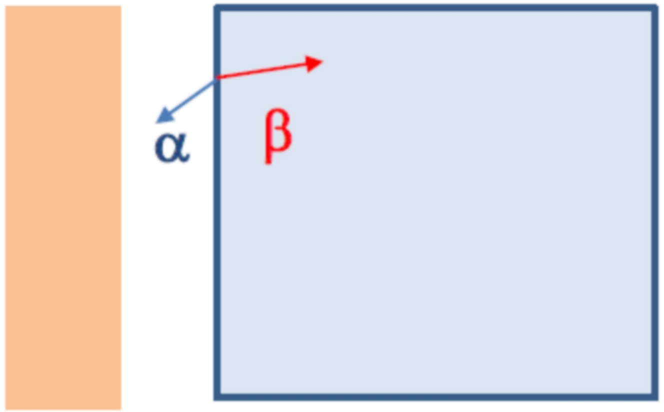
^{232}Th chain → ^{208}Tl Q_β = 5.0 MeV

$^{212}Bi \xrightarrow{\alpha} {}^{208}Tl \xrightarrow{\beta} {}^{208}Pb$
3.053 min

Under control in the crystal bulk
Delayed coincidence

These processes become challenging at the surface → it may happen that α escapes detection and β is (partially) absorbed





Scintillating bolometer technology

- **Source is embedded** in a crystal → high detection efficiency **(~90%)**
- **0.1-0.5 kg** typical crystal mass, scalability to a large-mass array
- Detectors are operated at **~10 mK,** the deposited **energy** is measured as a **temperature increase** in a crystal
- **Scintillator** → Particle discrimination using light: **>99.9 % α background rejection**
- **High energy resolution**: **~5 keV FWHM** (~0.2%) at the $Q_{\beta\beta}$

Typical signal**: 0.1 mK/MeV**, converted to **0.1-0.2 mV/MeV**