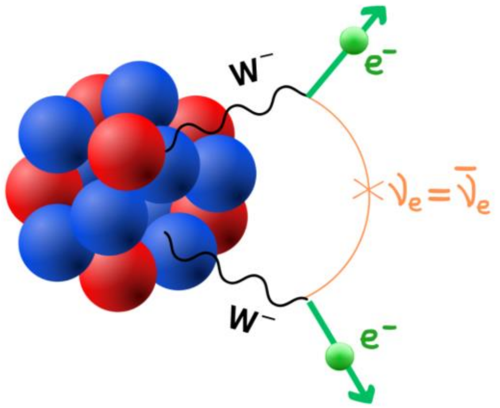
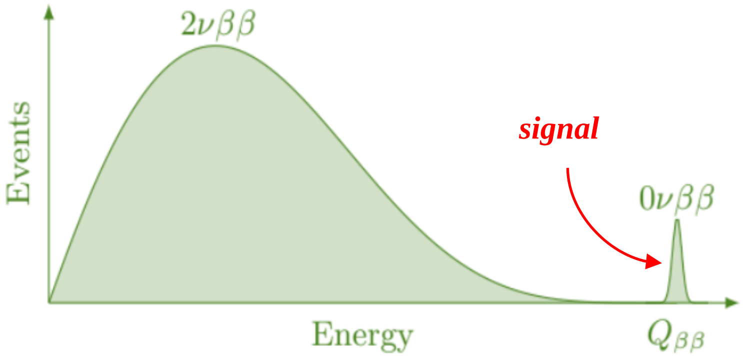
Prospects of the CUPID and CROSS experiments

Mariia Buchynska on behalf of the CROSS and CUPID collaborations

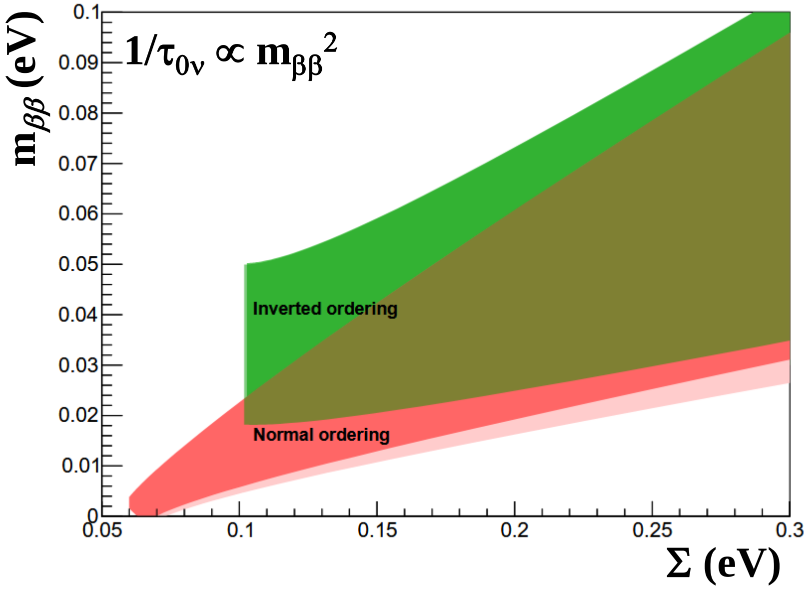
0νββ decay



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



Very rare: $\mathbf{T^{0\nu}_{1/2}}$ > **10²⁴-10²⁶ yr** → low background



$\Sigma = m_1 + m_2 + m_3$ → Cosmology

$m_{\beta\beta} = \left|\,|U_{e1}|^2 m_1 + e^{i\alpha 1} |U_{e2}|^2 m_2 + e^{i\alpha 2} |U_{e3}|^2 m_3\right|$ → 0ν2β

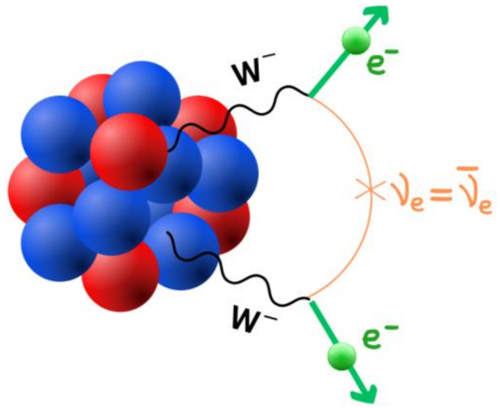
$$\frac{1}{T^{0\nu\beta\beta}_{1/2}} \sim G^{0\nu}(Q,Z) \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_{\beta\beta}\rangle^2$$

(in case of light neutrino exchange mechanism)

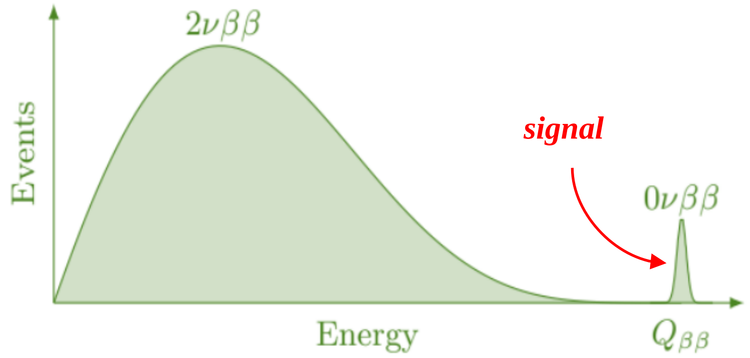
Observation would imply:

- Violation of lepton number conservation ($\Delta L = 2$)
- Majorana nature of neutrinos => provide information of the neutrino mass scale and ordering

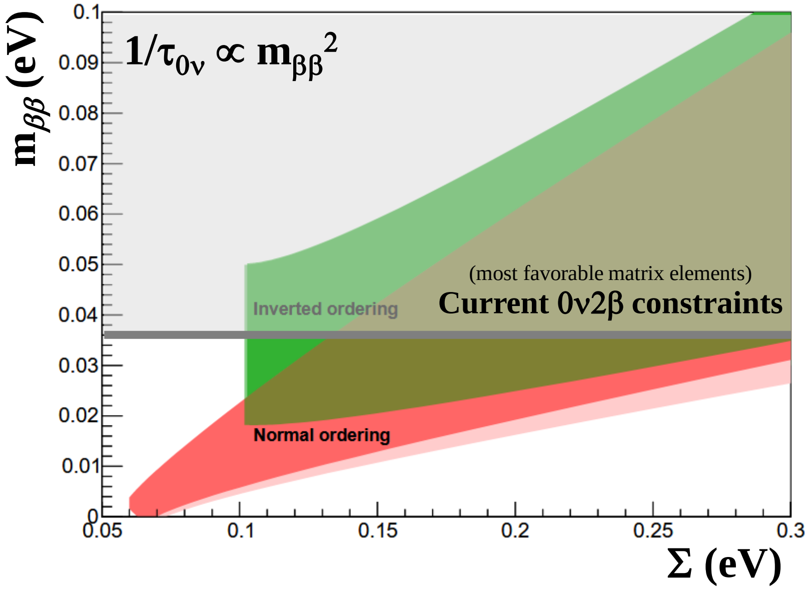
0νββ decay



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



Very rare: $T_{1/2}^{0\nu}$ > **10^{24} -10^{26} yr** → low background



$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} \sim G^{0\nu}(Q, Z) \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_{\beta\beta}\rangle^2$$

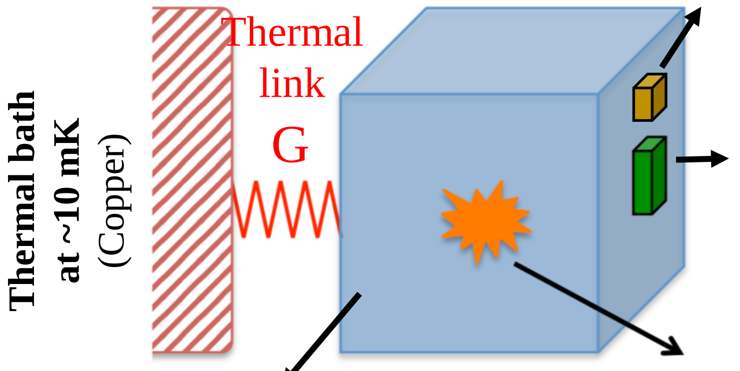
(in case of light neutrino exchange mechanism)

Observation would imply:

- Violation of lepton number conservation ($\Delta L = 2$)
- Majorana nature of neutrinos => provide information of the neutrino mass scale and ordering

Bolometric technique

Heater:
For correction of temperature instabilities



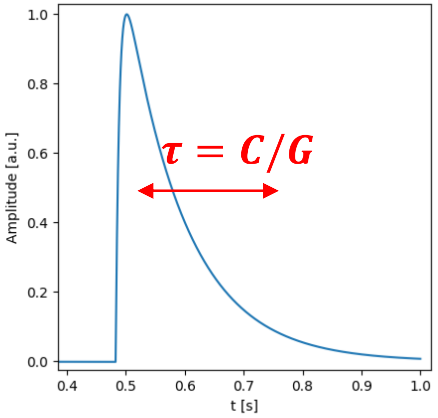
Temperature sensor:
Neutron Transmutation Doped (NTD) Ge thermistor

Absorber

Energy release

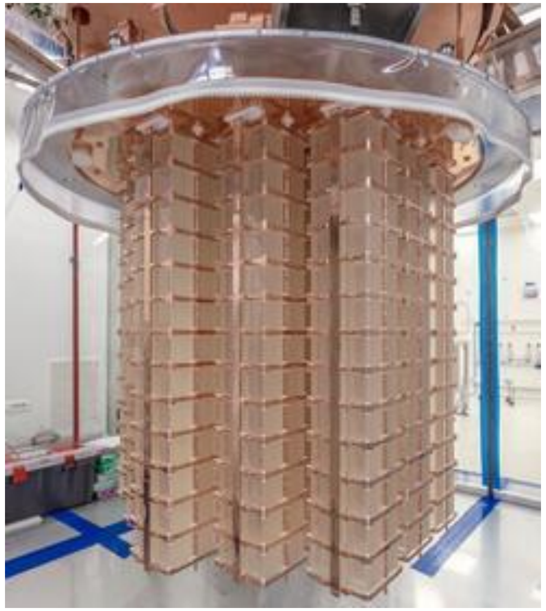
Temperature rise
$\Delta T = \Delta E / C$ ~ 0.1 mK/MeV
C (T) ∝ T^3

$\Delta T \rightarrow \Delta R$
$R(T) = R_0 \cdot e^{\sqrt{T_0/T}}$



CUORE

- located at LNGS ~ 3600 m.w.e.
- 988 TeO_2 crystals arranged in 19 towers
- 742 kg of TeO_2 (natural Te, I.A. ~34%), 206 kg of ^{130}Te
- operation at ~10 mK
- analysed exposure: ~ 2 ton·yr TeO_2 (~0.6 ton·yr ^{130}Te)



no evidence of 0νββ decay

Half life limit: $T^{0\nu}_{1/2} > 3.8 \cdot 10^{25}$yr (90% C.l.)

$m_{\beta\beta}$ < (70–240) meV (depending on NME)

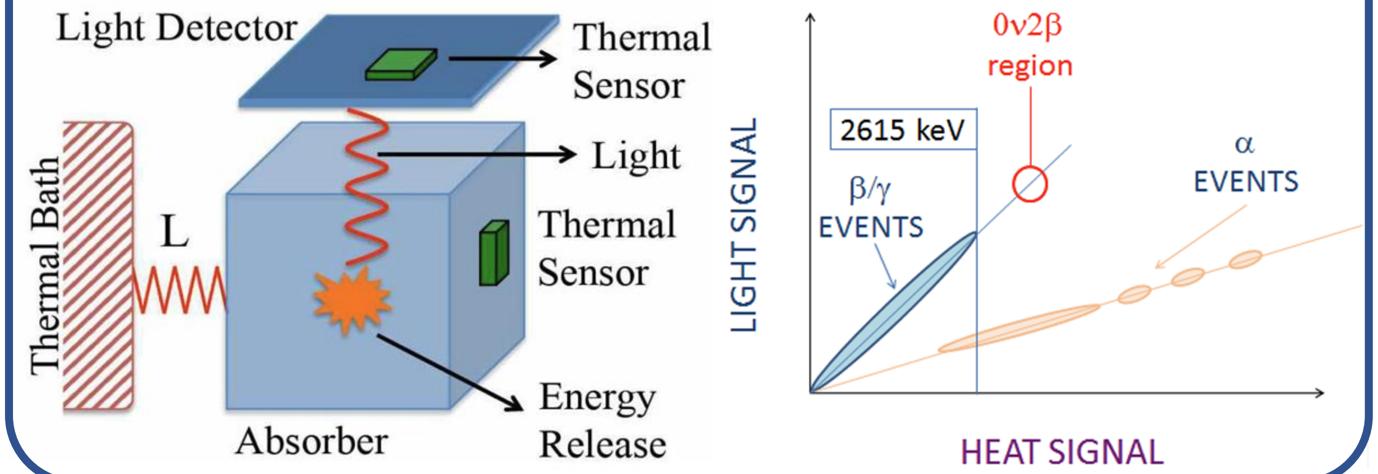
BI = (1.42 ± 0.02) · 10^{-2} ckky -> dominated by contributions of surface α

Proof of the feasibility of the ton-scale bolometric experiment
Available large cryogenic infrastructure

arXiv:2404.04453 [nucl-ex]

From CUORE to CUPID

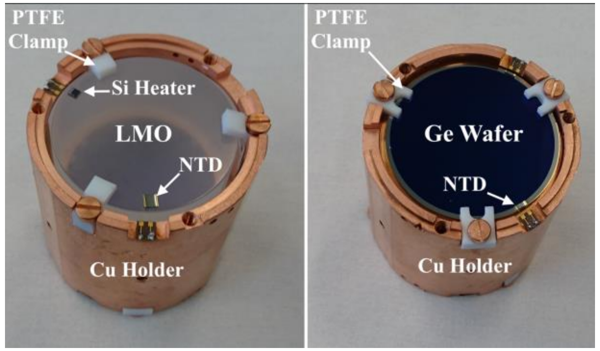
PID with scintillating bolometer



- α events are rejected due to lower light yield of α particles
- moving from ^{130}Te ($Q_{\beta\beta}$ = 2527 keV) to ^{100}Mo ($Q_{\beta\beta}$ = 3034 keV, $Q_{\beta\beta}$ > 2615, endline of natural radioactivity from ^{208}Tl);
  - natural I.A. of ^{100}Mo ~ 9.7% (for TeO ~34%) -> enrichment required

CUPID-Mo

- located in the Laboratoire Souterrain de Modane (France) ~ 4800 m.w.e.
- 20 scintillating bolometers arranged in 5 towers (single module: $Li_2{}^{100}MoO_4$ (~97% ^{100}Mo) and Ge light detector)



- total mass of crystals is ~4.2 kg corresponding to ~2.3 kg of ^{100}Mo
- ~ 1.5 years of data taking

0νββ decay limits	$T^{0\nu}_{1/2} > 1.8 \cdot 10^{24}$ yr (90% C. l.)
	$m_{\beta\beta}$ < (0.28–0.49) eV

Energy resolution (FWHM): **6.6(1) keV** @ 2615 keV

More than 99.9% α particles rejection efficiency

Total BI: $\mathbf{2.7^{+0.7}_{-0.6}(stat)^{+1.1}_{-0.5}(syst) \times 10^{-3}}$ **counts/keV/kg/yr**

$Li_2{}^{100}MoO_4$ scintillating bolometers demonstrate excellent performance and high radiopurity

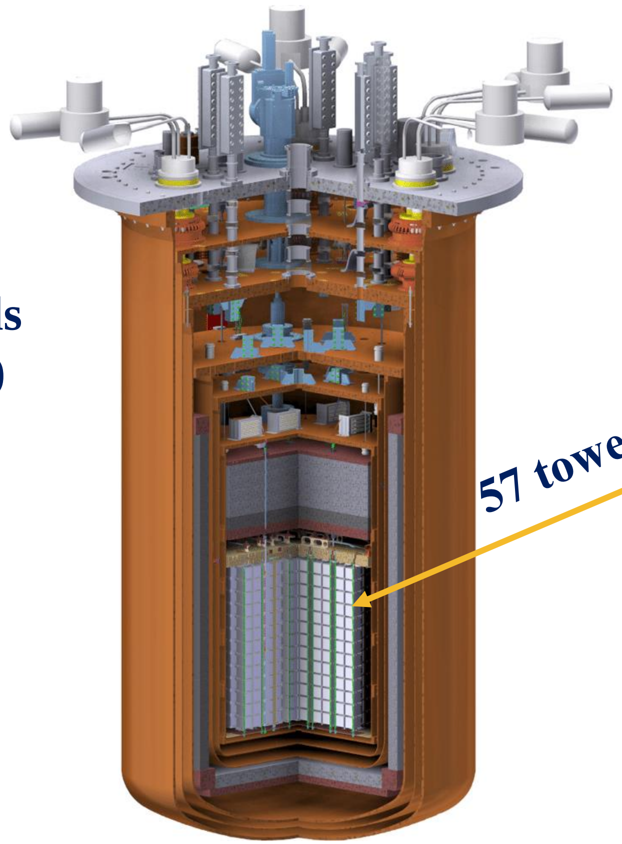
EPJC 82 (2022) 1033   EPJC 83 (2023) 675

CUPID baseline structure

1596 enriched $Li_2{}^{100}MoO_4$ crystals (>95% enrichment)

1710 light detectors

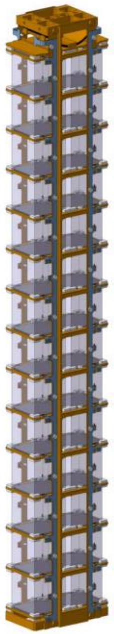
240 kg of ^{100}Mo



CUORE cryostat and shielding

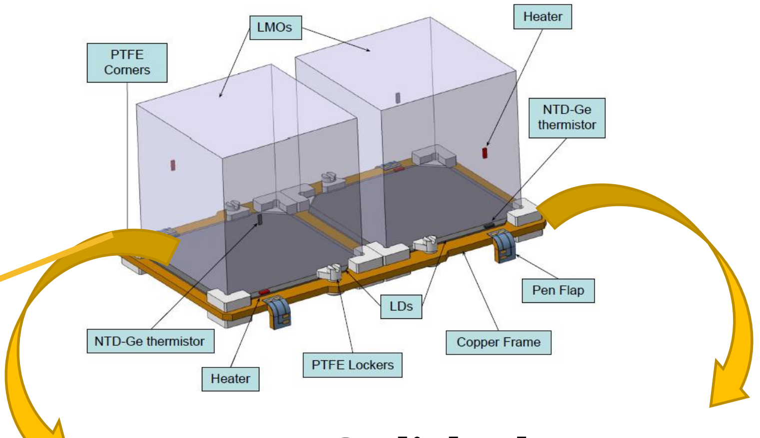
+ additional muon-veto system & neutron shields

57 towers



14 floors each with 2 crystals

EPJC **82** (2022) 810



$Li_2{}^{100}MoO_4$ crystal

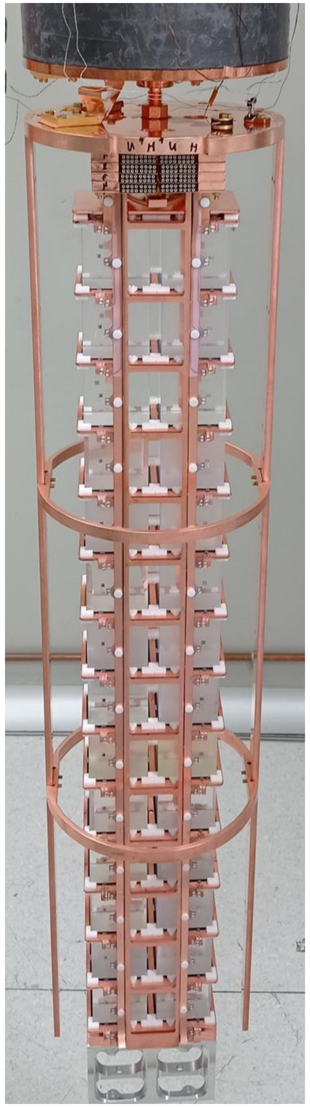
- 45 x 45 x 45 mm^3
- Thermal sensor: NTD Ge thermistor

Ge light detector

- Thin Ge wafer (<1 mm thickness)
- Thermal sensor: NTD Ge thermistor
- SiO antireflective coating (enhances light collection by ~ 30 %)
- Exploiting Neganov-Trofimov-Luke effect for signal amplification

CUPID pre-CDR arXiv:1907.09376

Test of the CUPID tower



BDPT

(baseline design prototype tower)

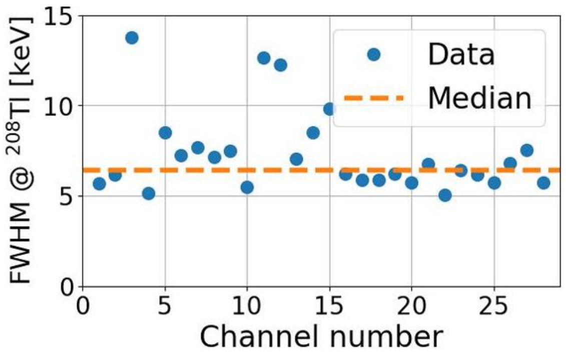
- 28 LMOs
- 30 Ge light detectors without NTL effect
- Tested at LNGS, Italy in July-October, 2022

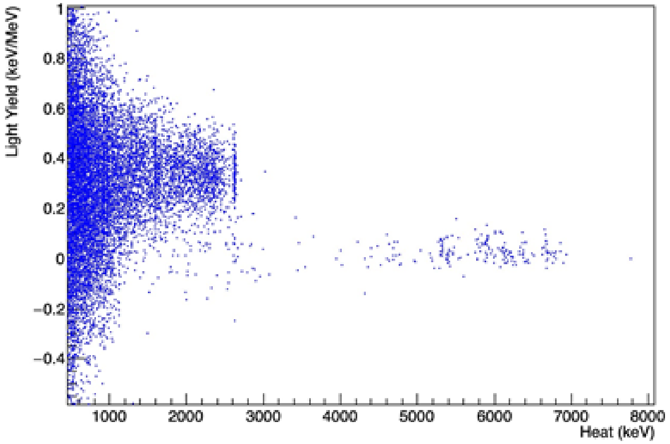
Results:

- Detectors successfully reached baseline temperature ~15 mK
- Baseline stable over the time
- LMO performance:
  median $FWHM_{2615\ keV} = 6.2$ keV
- median light yield: 0.34 keV/MeV
- α vs β,γ discrimination capability:

$$DP = \frac{|LY_{\beta,\gamma} - LY_{\alpha}|}{\sqrt{\sigma^2_{\beta,\gamma}+\sigma^2_{\alpha}}} = 3.2$$

- some excess noise on the LD -> changes to the LD assembly structure for the next test





S. Quitadamo, S. Ghislandi. Evaluation of the CUPID First Tower Prototype performance. Poster presented at Neutrino 2024; June 16-22, 2024; Milano; Italy

Next test: VSTT (Vertical Slice Test Tower)

- Preparation for the new test are currently ongoing

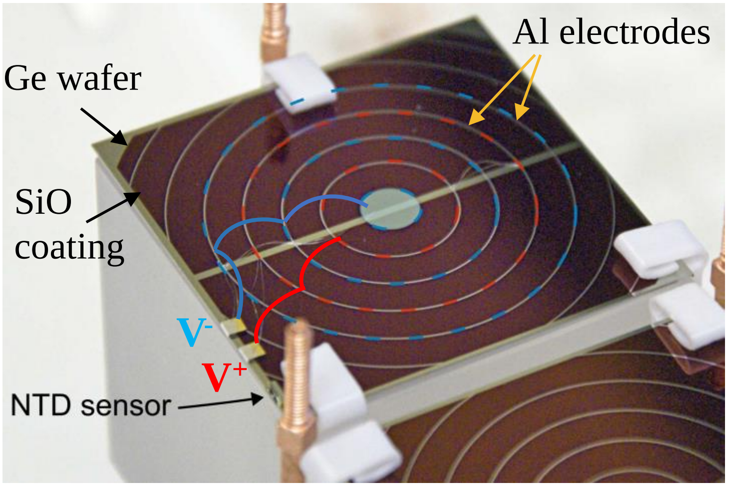
What's new?

- Light detectors with NTL amplification
- Changes to the LD holding system to mitigate the noise

Neganov-Trofimov-Luke light detectors

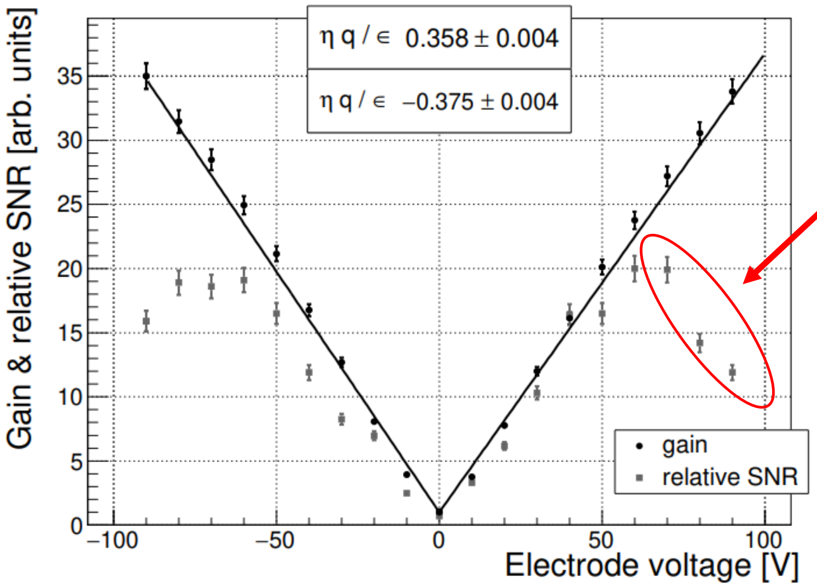
One of the dominant background source in CUPID are random coincidences of $2\nu\beta\beta$ events (pile-up events)

For rejection of the pile-up events we need
- fast signals → rise time can be reduced to 0.5ms by choosing optimal working point on the light detector
- high signal-to-noise ratio → **exploit the Neganov-Trofimov-Luke (NTL) effect for signal amplification**



Total heat: $E_{tot} = E_0\left(1+\frac{q \cdot V_{el} \cdot \eta}{\epsilon}\right) = E_0 \cdot G_{NTL}$, where

ϵ – average energy to create electron-hole pair
q – elementary charge
η – amplification efficiency
$V_{el} = V^+ - V^-$ - potential between the electrodes
E_0 – energy of the ionizing particle
G_{NTL} - gain



Dependence of the gain on the applied voltage

NIMA 940 (2019) 320

Operation challenges

- Extra noise production after certain voltage threshold → need to search for the optimal V_{el}
- Limitation of the applied voltage: after certain threshold of V_{el} there is leakage current and we heat up the cryostat

CROSS (Cryogenic Rare-event Observatory with Surface Sensitivity)

Aims at the development of a new bolometric technique to search for 0νββ decay in ^{100}Mo and ^{130}Te nuclei using $Li_2{}^{100}MoO_4$ and $^{130}TeO_2$ crystals.

Main objectives:

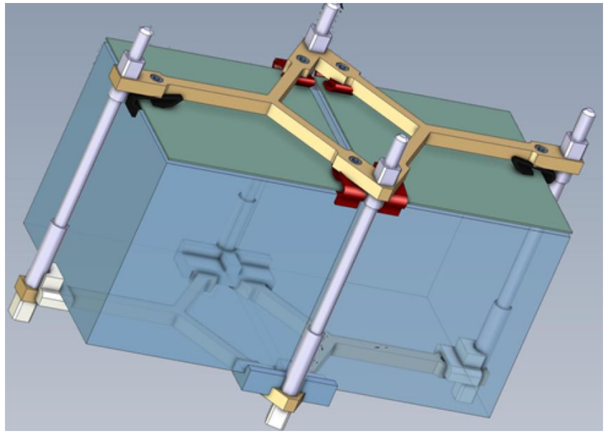
- production and use of $Li_2{}^{100}MoO_4$ crystals
- protocol for the production of radiopure ^{130}Te-enriched TeO_2 bolometers
- R&D on metal-coated bolometers for discrimination between bulk and near surface interactions
- R&D on NTL Light Detectors
- Development of fully equipped underground facility to test advanced bolometers

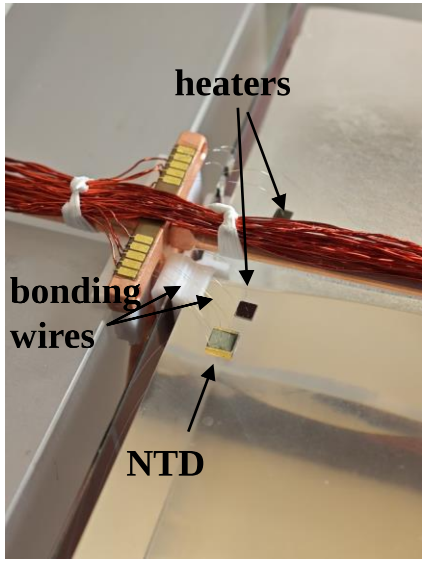
Location and underground facility

- LSC (Laboratorio Subterráneo de Canfranc), Canfranc, Spain
- A pulse tube based dilution refrigerator was installed and commissioned in April 2019
  - Can provide baseline temperature ~10 mK
  - Experimental volume of 60 cm length and 30 cm diameter
- External and internal lead shielding
- Anti-radon system
- Muon veto

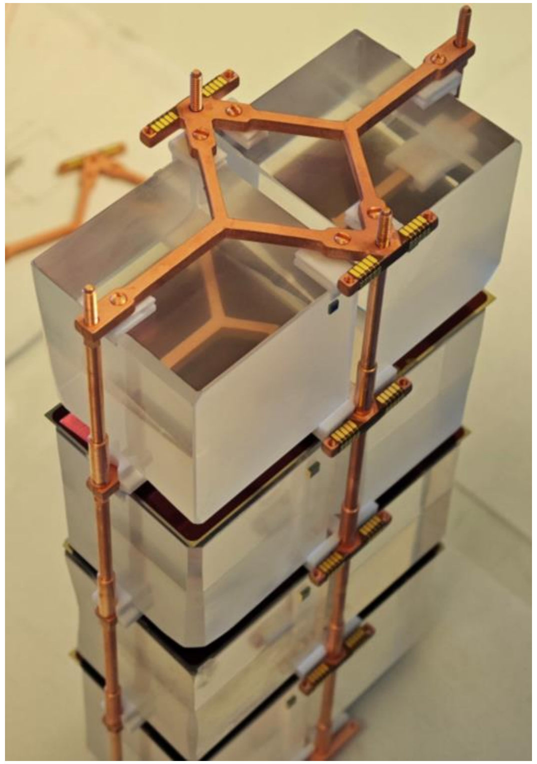
CROSS detectors structure

- Cubic $Li_2{}^{100}MoO_4$ (LMO) and $^{130}TeO_2$ crystals (45 mm side) and square Ge or Si wafers (45 mm side, thickness < 1 mm)
- Temperature sensors: (NTD) Ge thermistors glued at crystals and Ge wafers with bi-component epoxy or UV-cured glue
- Light detectors are kept with 3D-printed polylactic acid (PLA) clamps on the crystal
- Cu-to-LMO mass ratio is minimized to 6% to decrease radioactivity from surface of close elements
- Heaters are glued on the crystals with bi-component epoxy and used to inject pulses of the same amplitude to optimize and stabilize detectors
- The electrical contacts to the sensors are provided with thin (25 um or 50 um) Au or Al bonding wires

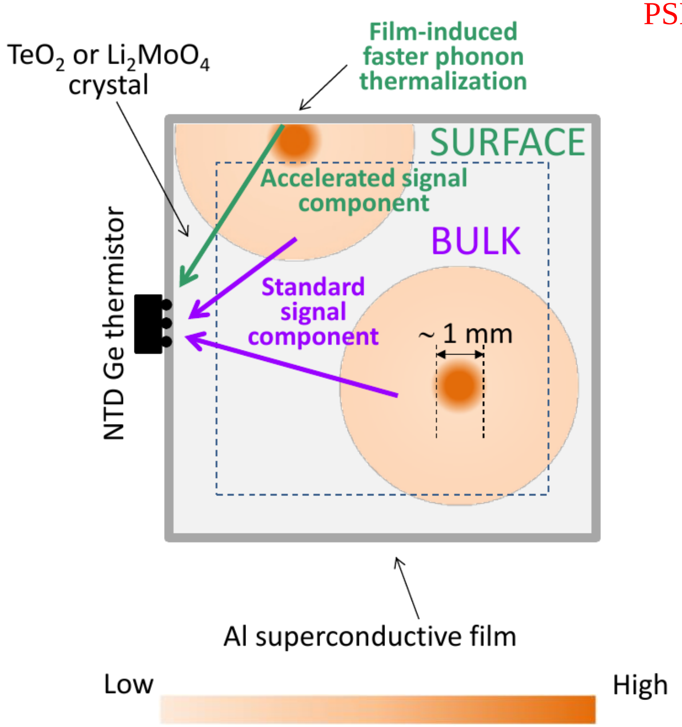




arXiv:2405.18980 (2024)

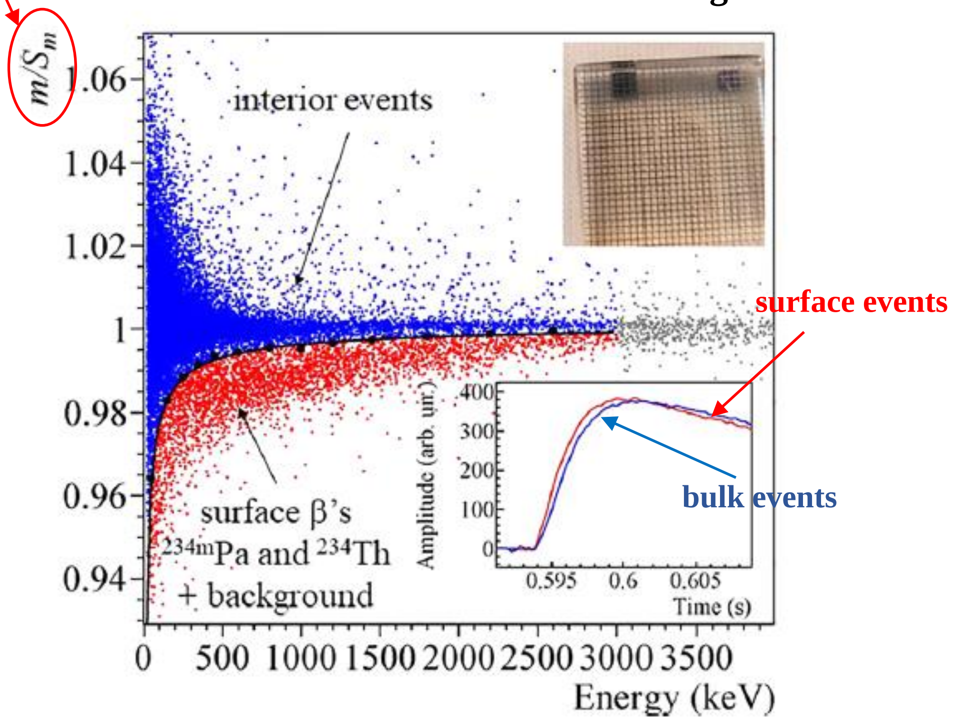


Metal coating for surface events discrimination



JHEP 01 (2020) 018

Example of surface/bulk events discrimination with Al-Pd coating



Appl. Phys. Lett. 118, 184105 (2021)

Tests performed with Al, Pd, and Al-Pd coatings

<u>Results for small crystals (2 × 2 × 1 cm^3 Li_2MoO_4 crystal with Al-Pd grid)</u>

- discrimination power of surface α-s: DP $\geq 4.5\sigma$
- β surface events selection efficiency (with Al-Pd): ~93%
- baseline resolution is not affected and remains at keV level (with Al-Pd)

<u>Difficulties with transfering this technology to larger samples (4.5 × 4.5 × 4.5 cm^3)</u>

- dramatic reduction of the sensitivity and a modification of the pulse shape for all the pulses for LMO crystals
- for TeO_2 sensitivity and pulse shape of the pulses are almost unaffected, but no discrimination capability

For now, this technology is discarded from the final demonstrator

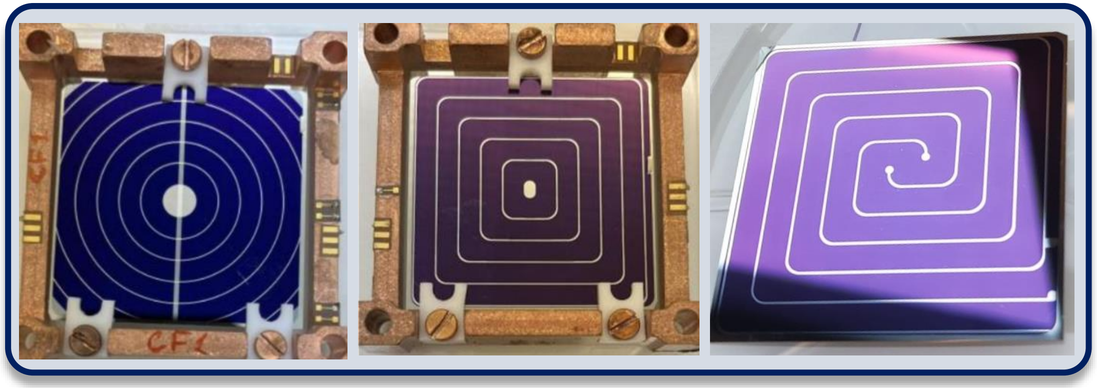
R&D on NTL Light Detectors

Objectives

- Discrimination of α's
- Rejection of pileup events produced by the random coincidence of two 2ν2β events

Effective area (area under the electrodes)

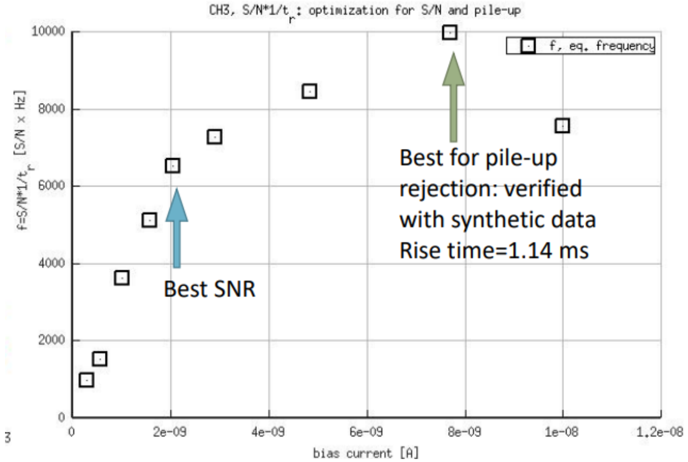
56% **≈100%** **≈100%**



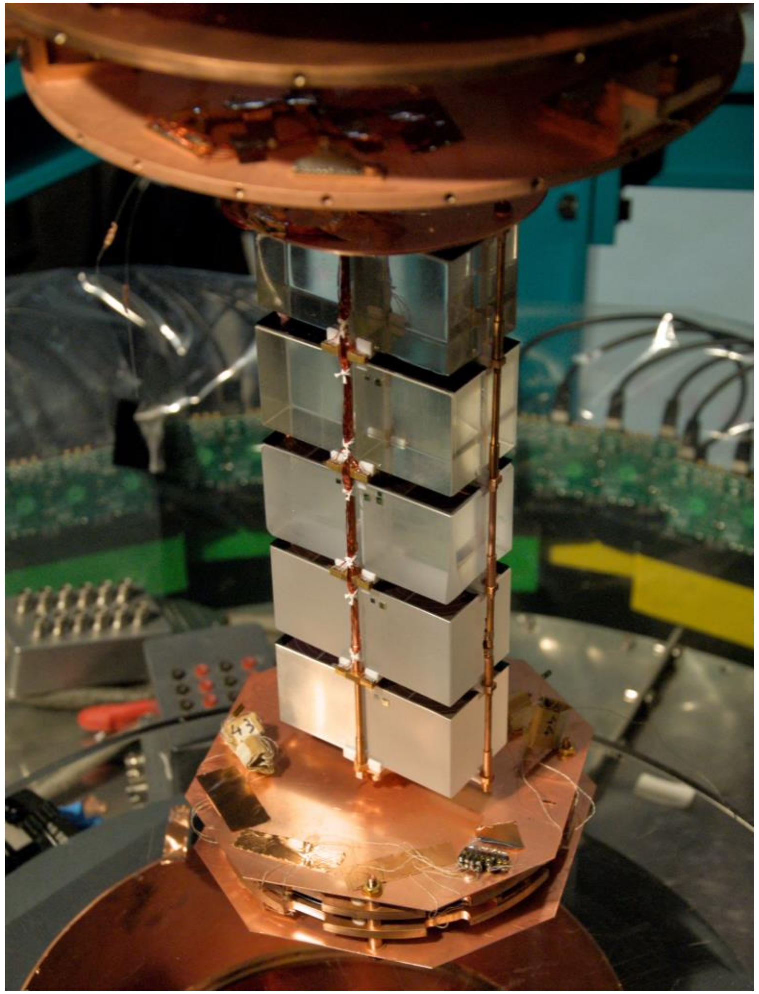
Factor ~ 1.7 difference in gain at the same voltage

Current tests

- optimization of the electrodes geometry
- tests of Si wafers
- estimation of detector performance: leakage current, signal-to-noise ratio
- work on the pile up rejection:
  - searching for the best working point for pile-up events rejection
  - estimation of pile-up rejection capability based on detectors performance



Recent test in Canfranc. Detectors structure



10-crystal structure:

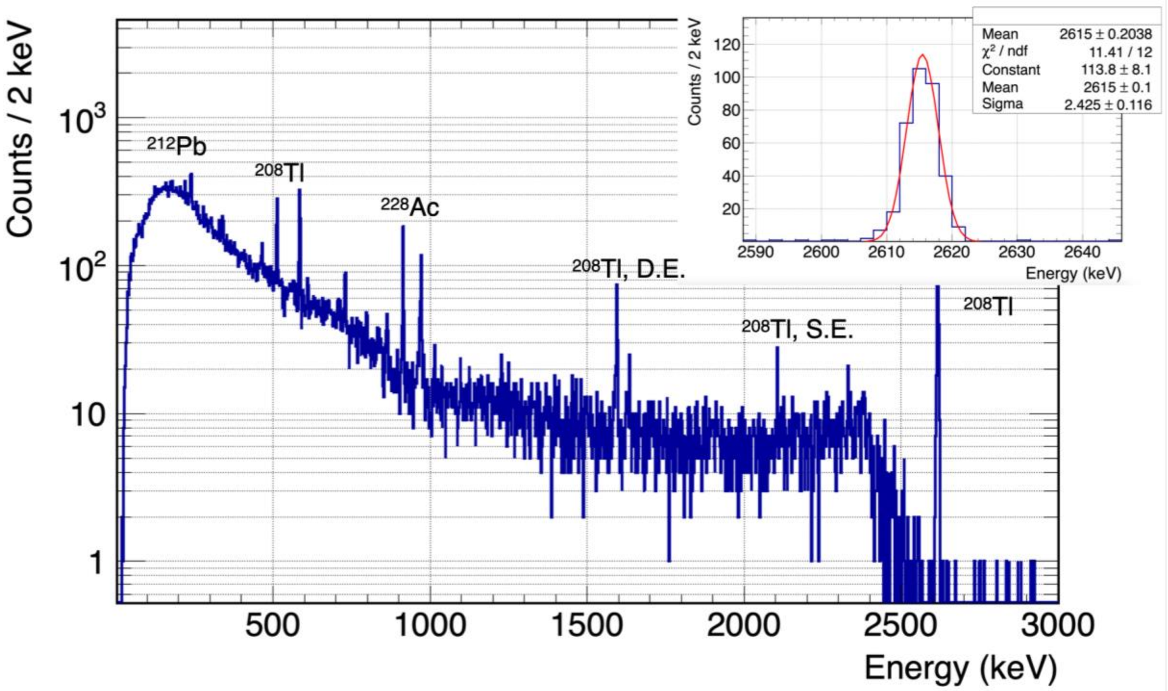
- 6 Li_2MoO_4 crystals (2 reference high purity $Li_2{}^{100}MoO_4$ crystals and 4 natural crystals from a US company that are under investigation)
- 2 bare $^{130}TeO_2$ crystals
- 2 $^{130}TeO_2$ crystals with thin metallic coating (Al for one and Al-Pd for other)
- 10 NTL light detectors with circular electrodes geometry

Operation temperatures: 17–27 mK

Measurements:

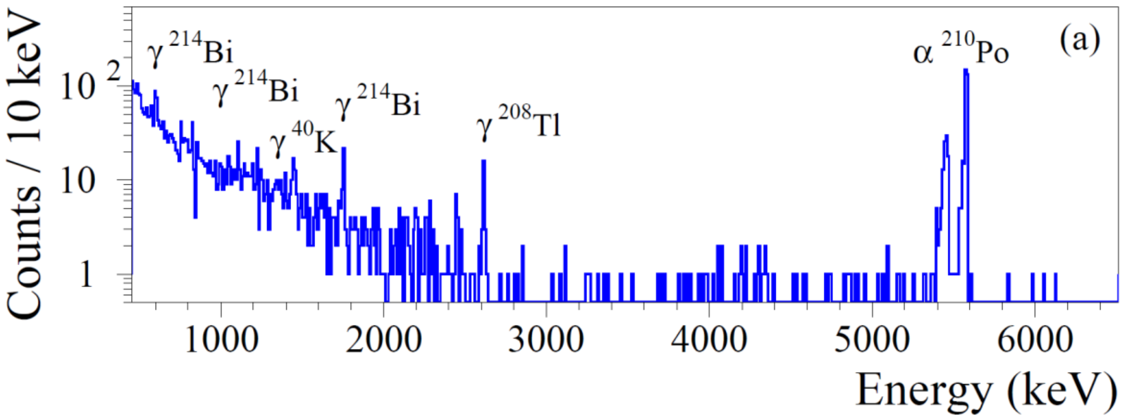
- Calibration measurements with ^{232}Th source
- Background measurements
- Tests on pile-up rejection capability

Recent test in Canfranc. Crystals performance



Energy spectrum of the reference $Li_2{}^{100}MoO_4$ crystal.
Energy resolution @ 2615 keV ^{208}Tl line is (5.7 ± 0.3) keV

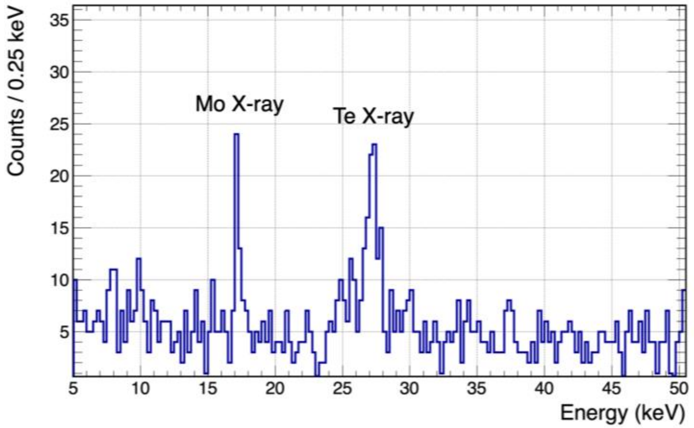
arXiv:2406.01444 (2024)



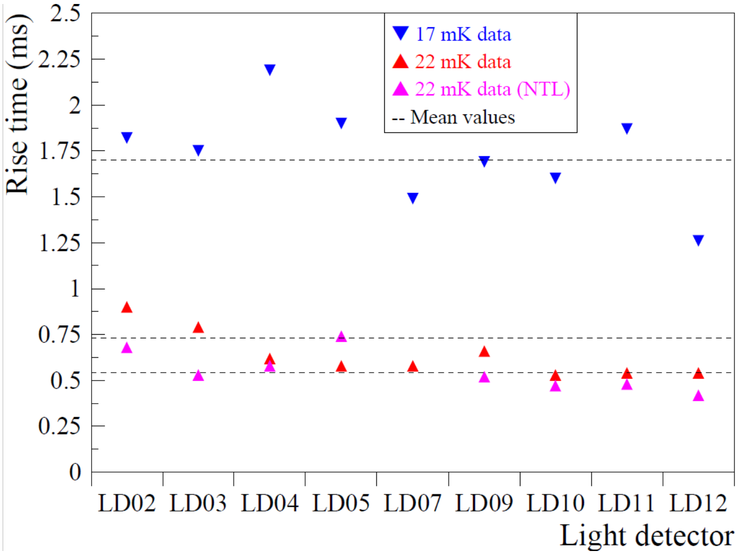
Background spectrum measured by a 0.55 kg $^{130}TeO_2$ bolometer (116 h at 27 mK)

Confirmation of the radiopurity of the TeO crystals (~1 mBq/kg activity of ^{210}Po) by bolometric measurements together with excellent energy resolution

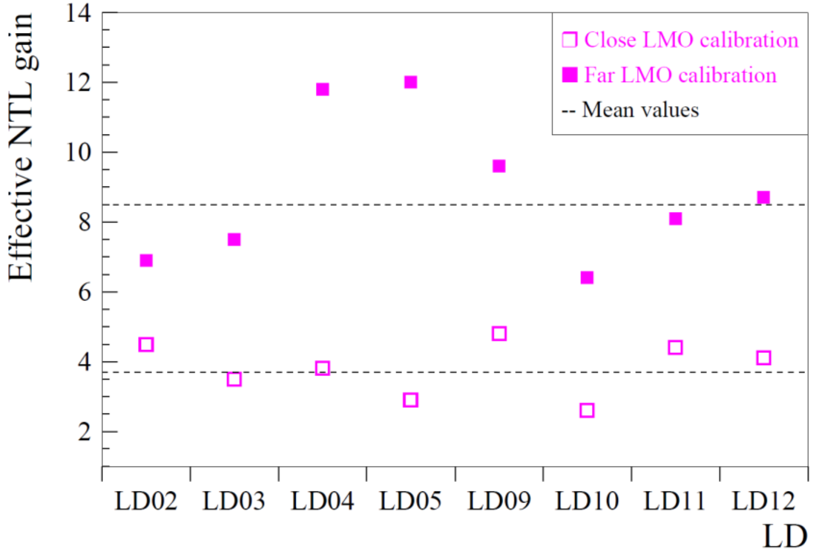
Recent test in Canfranc. NTL LD performance



Energy spectrum accumulated by NTL LD after 93 h of calibrations with a Th source at 17 mK



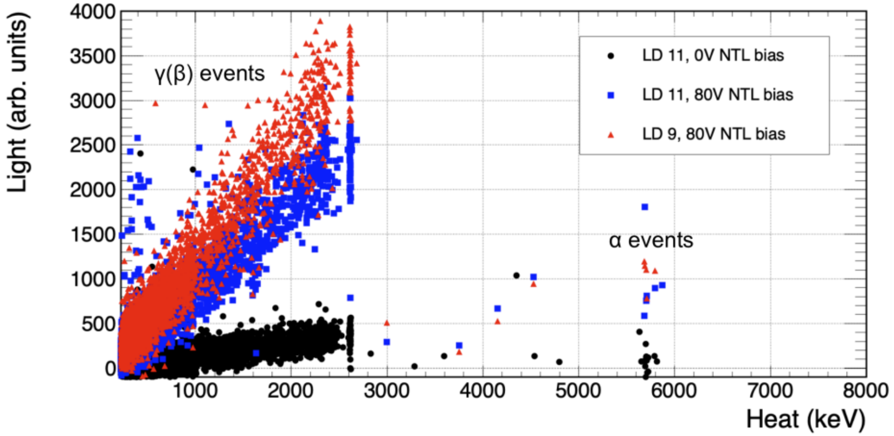
Mean value of the risetime: 0.54 ms
(for measurements at 22 mK)



Effective NTL gain for NTL LD at 22mK, 80 V NTL bias

Mean values of the effective gain:

- **G = 8.5** when light impinges on the electrode side
- **G = 3.7** when light impinges on the opposite side



Energy detected in the top and bottom LDs facing the LMO crystal vs energy detected in the LMO (T = 22 mK)

With scaling to the CUPID geometry with these parameters **BI =** $\mathbf{6.5 \cdot 10^{-5}}$**ckky** from the pile-up events

CROSS demonstrator

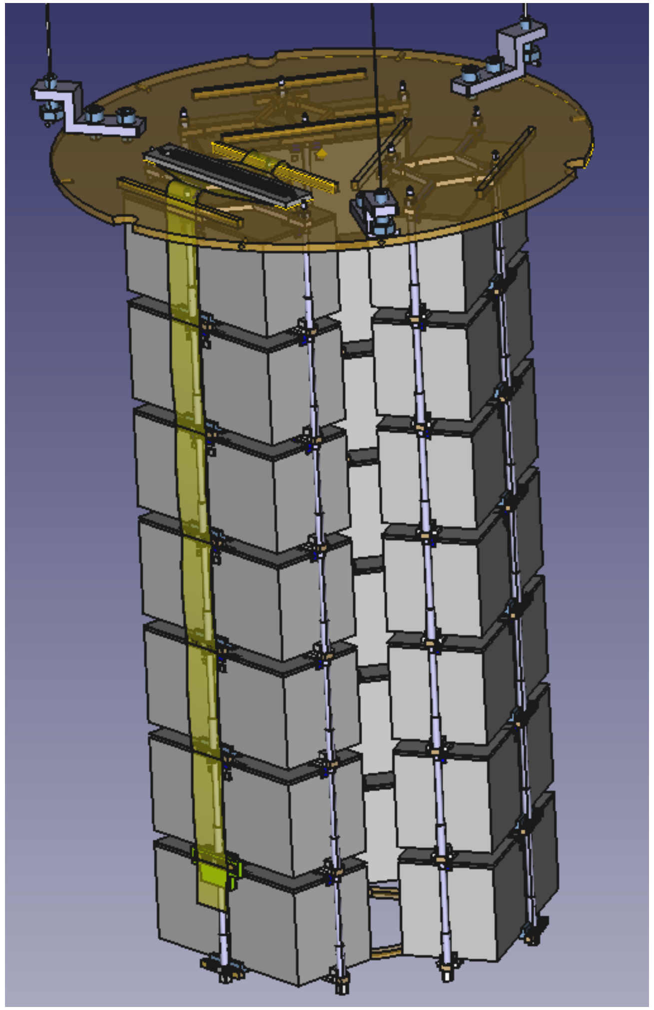
<u>**Structure**</u>

- 3 towers with 7 floors each
- each floor has 2 crystal + 2 NTL-LD
- each crystal, except the bottom ones, will face 2 NTL-LD
- top floor consists of TeO_2 crystals, that will work also as shielding to others crystals due to higher density

In total: 36 $Li_2{}^{100}MoO_4$ (32 ^{100}Mo-enriched) and 6 TeO_2 (all ^{130}Te-enriched)
Total mass of ^{100}Mo: 4.7 kg

<u>**Main objectives**</u>

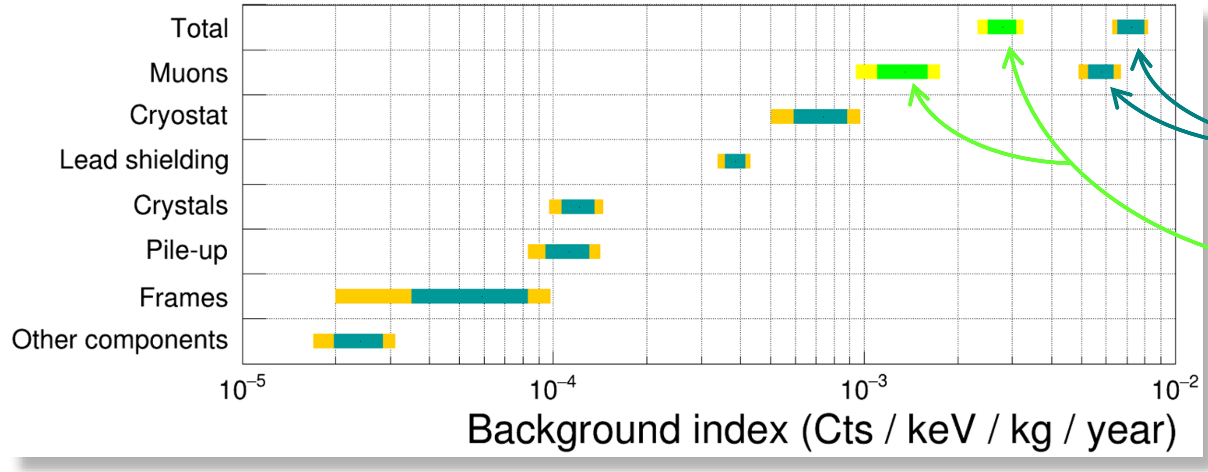
- Test the performance of LMO and TeO_2 crystals
- Test the performance of light detectors with different geometry and made from different material
  - Si NTL LD with spiral electrodes geometry
  - Ge NTL LD with spiral electrodes geometry
  - Ge NTL LD with circular electrodes geometry
- Studies on pile-up events rejection efficiency
- Probe of the assembly structure

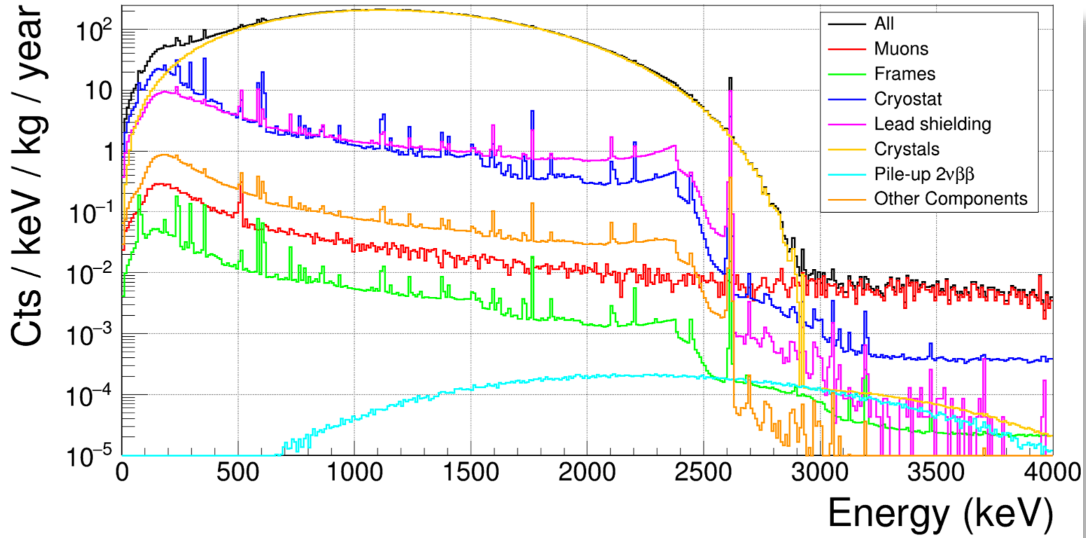


Preparation for the demonstrator is ongoing
Installation and commissioning in early 2025. Data taking is planned for 2 years

CROSS background and sensitivity

Background predicted by MC simulations





One of the dominant contributions to the BI are muon induced events → BI index highly depends on the way these events are rejected

- With rejection only events that have coincidences between 2 muon veto sectors **BI = (7.2±0.9)·10^{-3} ckky**
- With additional rejection of the events that were detected in 1 muon veto sector and 1 bolometer **BI = (2.8±0.5)· 10^{-3} ckky**

Sensitivity

Assuming 2 years live time of the experiment, the CROSS experiment will be able to set a limit (at 90% confidence level) on the ^{100}Mo 0νββ decay:

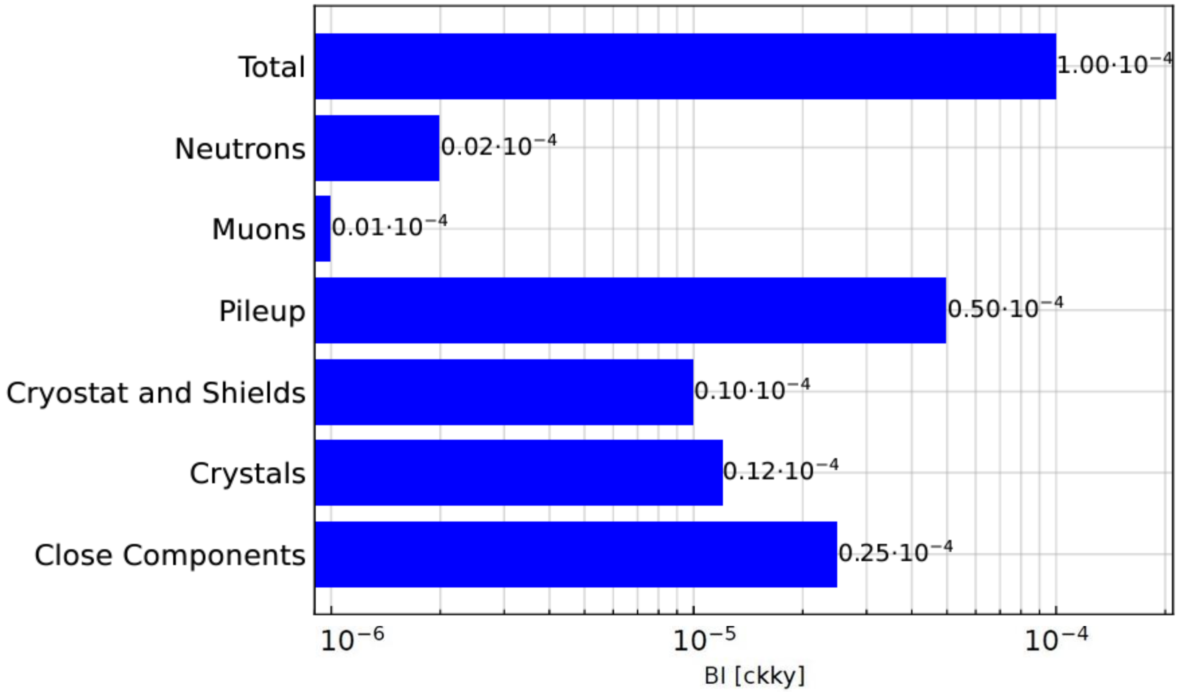
- half-life $\mathbf{T^{0\nu}_{1/2} > 8.5 \cdot 10^{24}}$ **yr** and $\langle m_{\beta\beta} \rangle <$ **(0.131–0.221) eV** (assuming BI = 10^{-3} ckky)
- half-life $\mathbf{T^{0\nu}_{1/2} > 1.2 \cdot 10^{25}}$ **yr** and $\langle m_{\beta\beta} \rangle <$ **(0.110–0.186) eV** (assuming BI = 10^{-2} ckky)

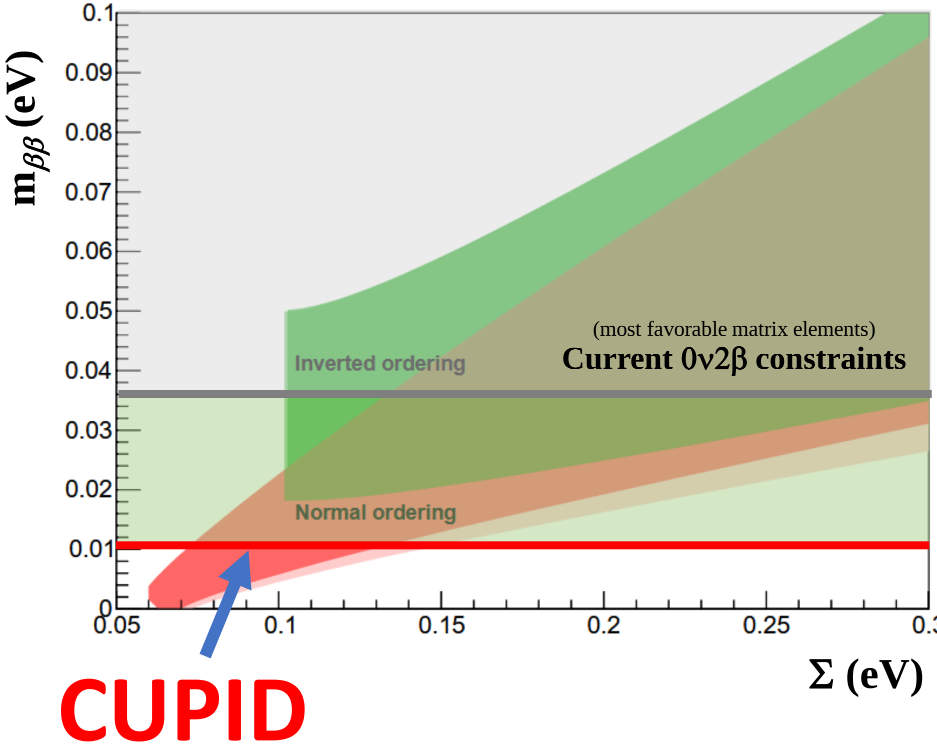
Current limits on ^{100}Mo 0νββ :

- CUPID-Mo: half-life $\mathbf{T^{0\nu}_{1/2} > 1.8 \cdot 10^{24}}$ **yr**
- AMORE-I: half-life $\mathbf{T^{0\nu}_{1/2} > 2.9 \cdot 10^{24}}$ **yr**

arXiv:2407.05618 (2024)

CUPID background and sensitivity





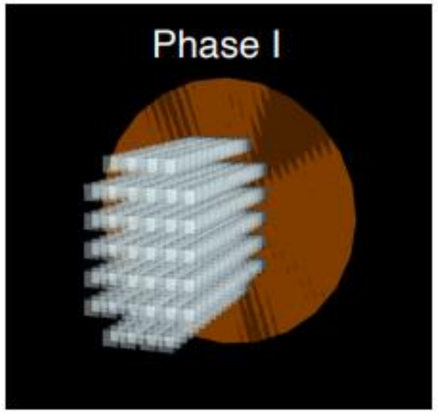
CUPID background goal:

BI = 10^{-4} counts/keV/kg/year in the ROI

CUPID: phased approach

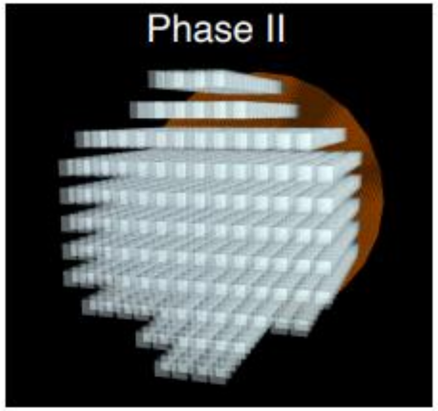
1/3 of all crystals

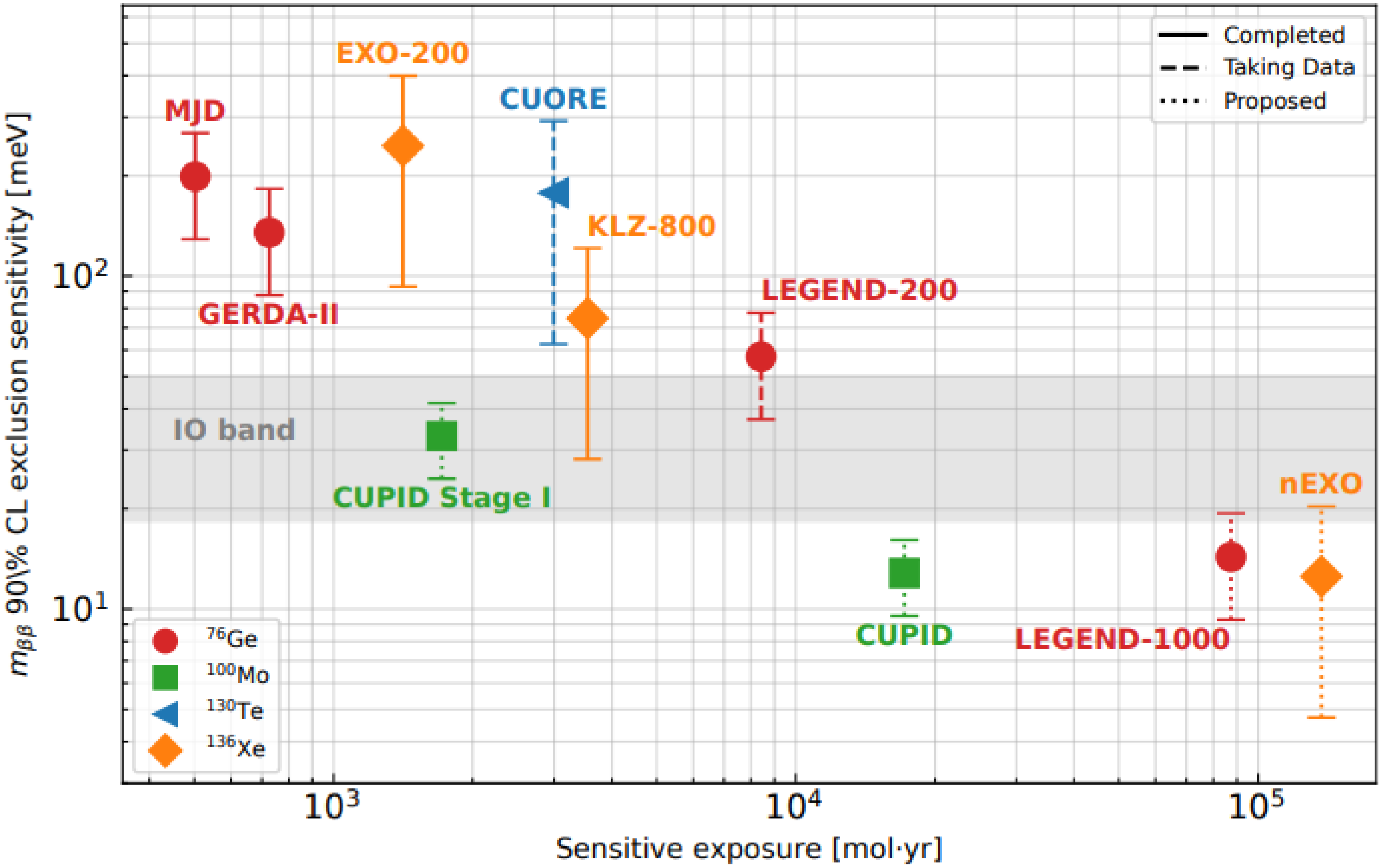
Start of data taking in 2030



Full CUPID

Start of data taking in 2034





CUPID Stage I has world-leading science reach

Conclusions

CROSS is developing cutting-edge technologies to reduce background noise in $0\nu2\beta$ decay detection using bolometers and advanced NTL light detectors

NTL LDs

- demonstrate excellent energy resolution: σ_{bsl} = 10 eV
- good discrimination of α's
- signals with the rise time ~ 0.5ms were achieved, that together with high SNR due to NTL effect and geometry improvement allows to better reject pile-up events

Crystals

- LMOs show excellent energy resolution (FWHM = 5.7 keV at 2615 keV)
- high radiopurity of TeO_2 crystals together with good energy resolution is confirmed

CROSS demonstrator is competitive experiment on the ^{100}Mo 0νββ

Preparation for the CUPID experiment is ongoing: technologies for single $Li_2^{100}MoO_4$ module are validated, R&D on NTL LDs is in progress

- ➢ 42 NTL LDs will be tested in the CROSS demonstrator
- ➢ full CUPID tower test with NTL LDs is planned at LNGS

- ➢ **CUPID experiment allows us to fully explore the inverted ordering region and normal ordering region for $m_{lightest}$ > 10 meV**
- ➢ with the phased approach we can obtain early competitive physics results
- ➢ on a longer time scale mass-scaling is possible (CUPID-1T)

Thank you for your attention!