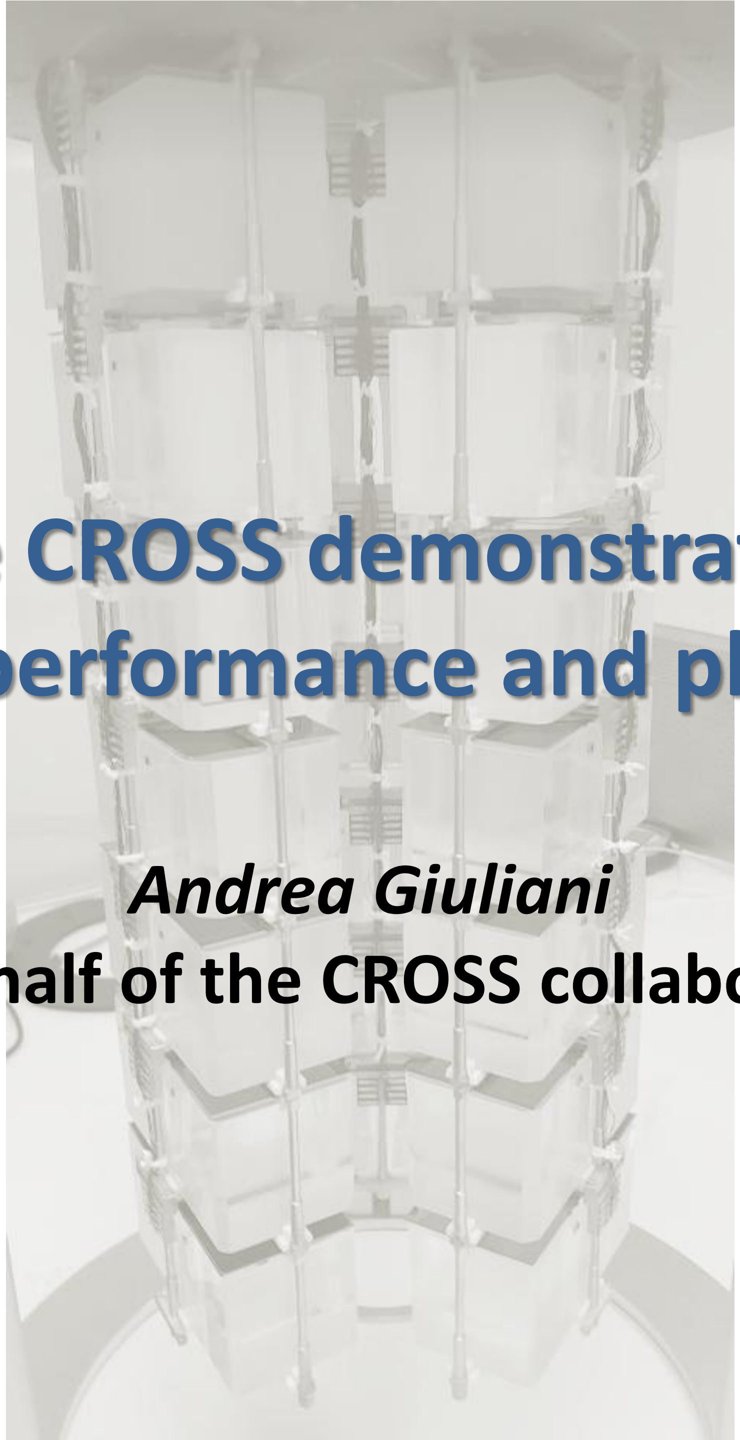
TAUP 2025

Xichang,
August 27th, 2025

# The CROSS demonstrator: structure, performance and physics reach




*Andrea Giuliani*

**on behalf of the CROSS collaboration**

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

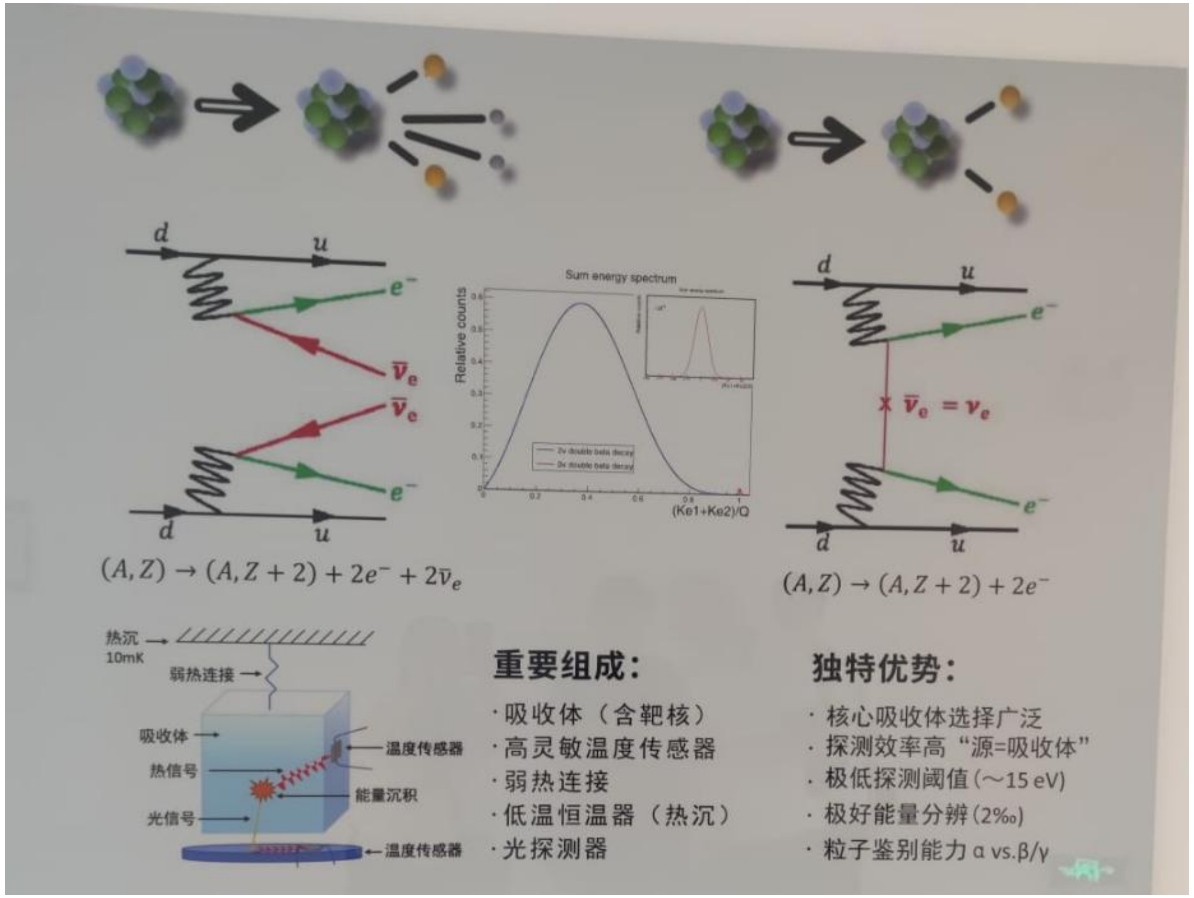
A2C Astroparticles, Astrophysics & Cosmology

université PARIS-SACLAY

# 0ν2β in a nutshell

- 0ν2β is an inclusive test for the « creation of leptons »:
  **2n → 2p + 2e⁻ ⇒ LNV**
- This test is implemented in the nuclear matter:
  **(A,Z) → (A,Z+2) + 2e⁻**
- Very rare (**> $10^{26}$ y**)
- Energetically possible for **35 nuclei**
- Experimentally relevant: **$^{82}$Se**, **$^{76}$Ge**, **$^{100}$Mo**, **$^{130}$Te**, **$^{136}$Xe**
- Signal: **a peak** in the sum-energy spectrum of 2e⁻ **at $Q_{2\beta}$**

**CROSS** (→ $^{100}$Mo, $^{130}$Te)




**From a poster in USTC, Hefei**

0ν2β →

- **Standard mechanism: neutrino physics**
  0ν2β is mediated by
  **light massive Majorana neutrinos**
  (exactly those which oscillate)
- **BSM non-standard mechanisms**
  Not necessarily neutrino physics

$$m_{\beta\beta} = ||U_{e1}|^2 m_1 + e^{i\alpha 1}|U_{e2}|^2 m_2 + e^{i\alpha 2}|U_{e3}|^2 m_3|$$

$$1/\tau_{0\nu} \propto m_{\beta\beta}^2$$

# CROSS project

## A standalone experiment and a test bench for CUPID

**CROSS (C**ryogenic **R**are-event **O**bservatory with **S**urface **S**ensitivity**): 0ν2β bolometric search**

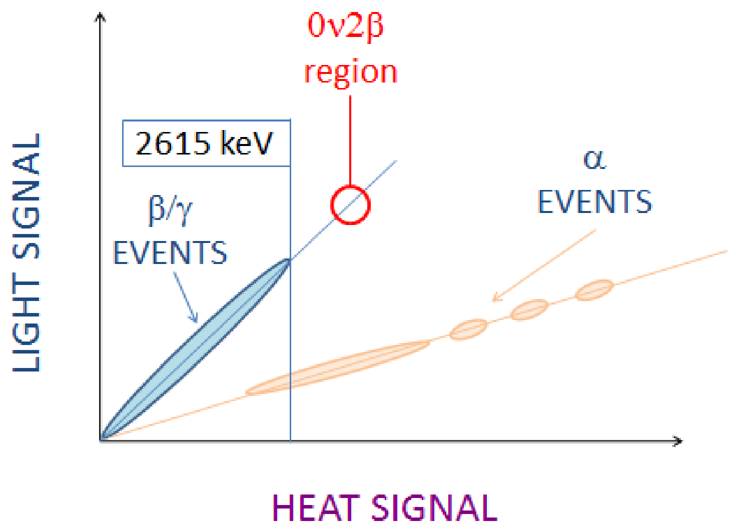
**Two high Q-value isotopes studied** (as in BINGO) → *C. Nones*

- **$^{100}$Mo**: Q-value = 3034 keV (as in CUPID-Mo, CUPID, AMoRE))
- **$^{130}$Te**: Q-value = 2527 keV (as in CUORE)

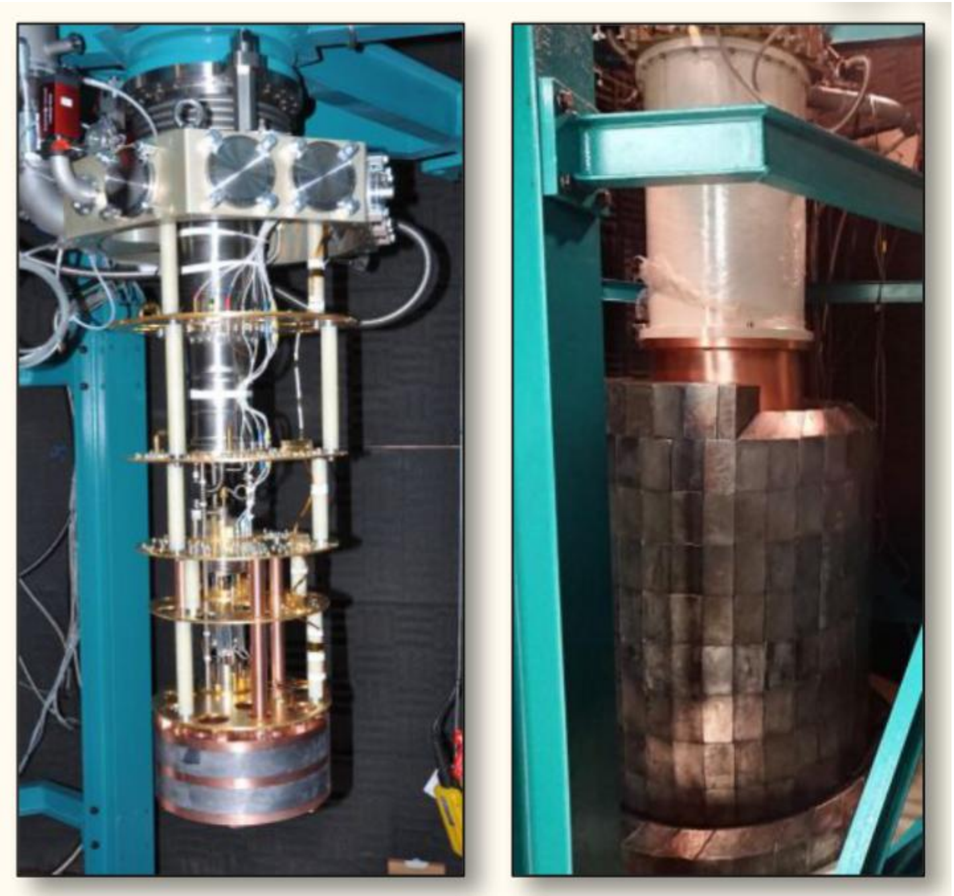
→ *A. Campani* → *B. Schmidt* → *I. Nutini* → *SeungCheon Kim*

**Basic approach**

- Bolometers made of enriched crystals : **$Li_2{}^{100}MoO_4$** and **$^{130}TeO_2$**
- Measurement of heat and light from each event




Rejection of surface α background



**Underground cryogenic facility at LSC (Canfranc, Spain)**

- Lead shielding, anti-radon shield and muon veto

# What's new in CROSS?

**Multi-year program to develop new technologies for background reduction and new radiopure enriched crystal production**

1. **Surface film coating** of crystals to discriminate between bulk and surface events (both $\alpha$'s and $\beta$'s)

2. **Neganov-Trofimov-Luke (NTL) Light Detectors** development and optimization

3. **Novel mechanical structure** that minimizes the amount of passive materials around the detectors

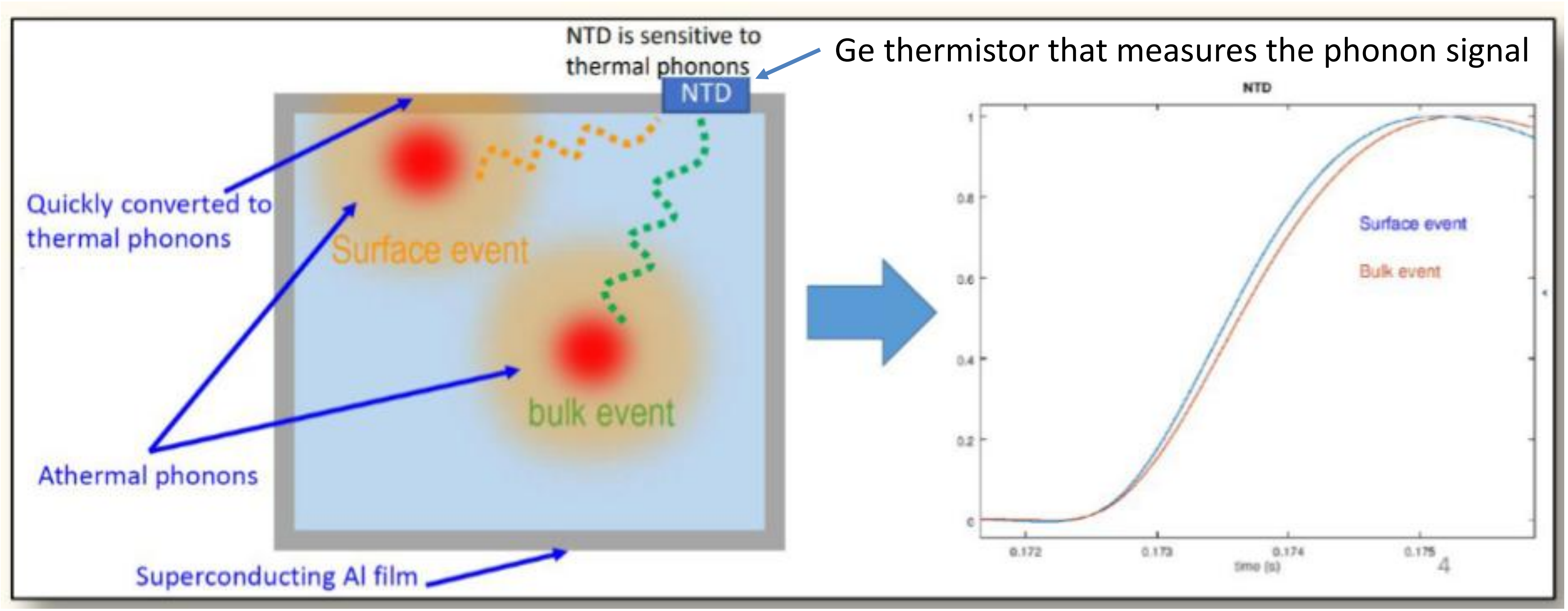
4. **Purification-crystallization** chain for enriched **$^{130}TeO_2$ crystals**

# Bulk vs. surface event discrimination

- Reject **surface events** by **Pulse Shape Discrimination assisted by metal film coating**

Metal films work as **pulse-shape modifiers** for charged particles that release energy close to the film → phonon and superconductivity physics

*J. High Energ. Phys. 2020, 18 (2020)*



# Bulk vs. surface event discrimination

After a long R&D with 2×2×1 cm to fix the best coating material, **AlPd bi-layer** was selected

- Al is superconductive with $T_C$=1.2 K – Pd is a normal metal
- **Pd(10 nm) on the crystal – Al(100 nm) on top of Pd** → $T_C \sim 0.7$ K (proximity effect)

*H. Khalife PhD thesis*
*https://theses.hal.science/tel-03168547*

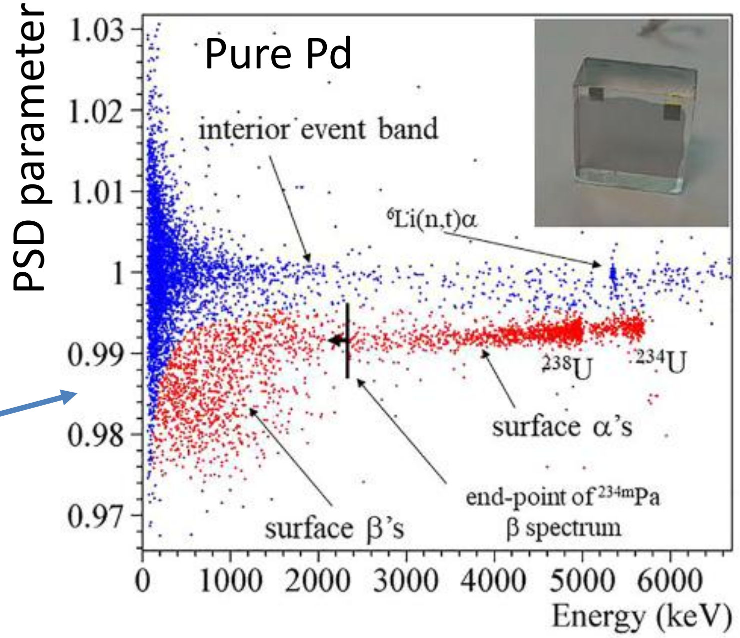
Best compromise between:

- Efficient thermalization of surface events
- Low specific heat
- Easy deposition by evaporation

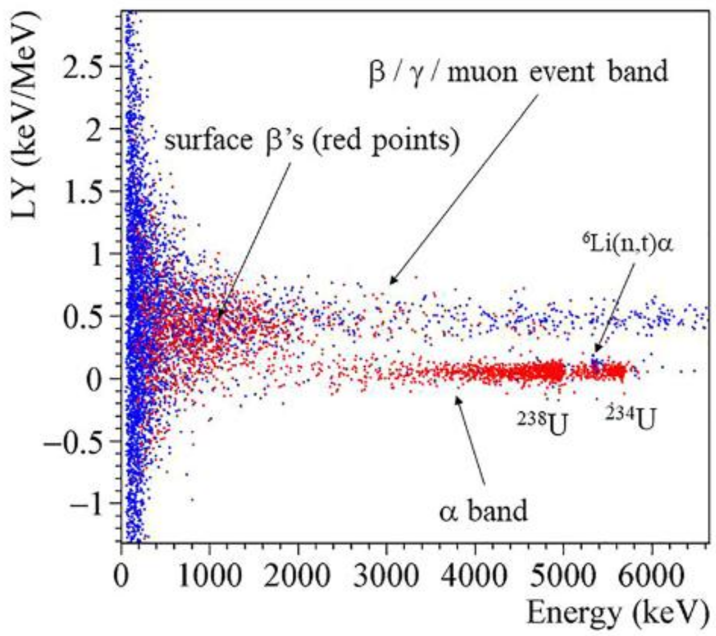
The sample is irradiated with an U source providing both α (4.2 and 4.7 MeV) and β (end-point at 2.2 MeV)

For redundancy, also scintillation light is detected

*APL 118 (2021) 184105*




Both surface α's and β's are discriminated by the metallic film




Only surface α's are discriminated by a light-yield cut

**Unfortunately, technology transfer to large CUPID- and CROSS-size crystals (4.5 × 4.5 × 4.5 cm$^3$) failed so far**

# Enhanced-performance light detectors

**Light detectors** are essential to **reject surface α background**

→ H. Khalife Poster #77

→ In CROSS, light detector performance is enhanced by the **Neganov-Trofimov-Luke effect (NTL)**

- **Improve pile-up rejection**
- Mitigation of background induced by **random coincidences of ordinary 2ν2β events** → crucial for CUPID

→ I. Nutini, P. Loaiza

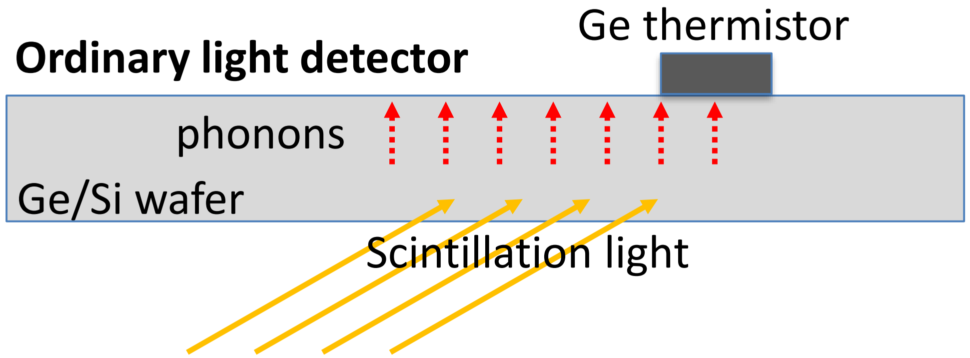
## NTL effect applied to light detectors

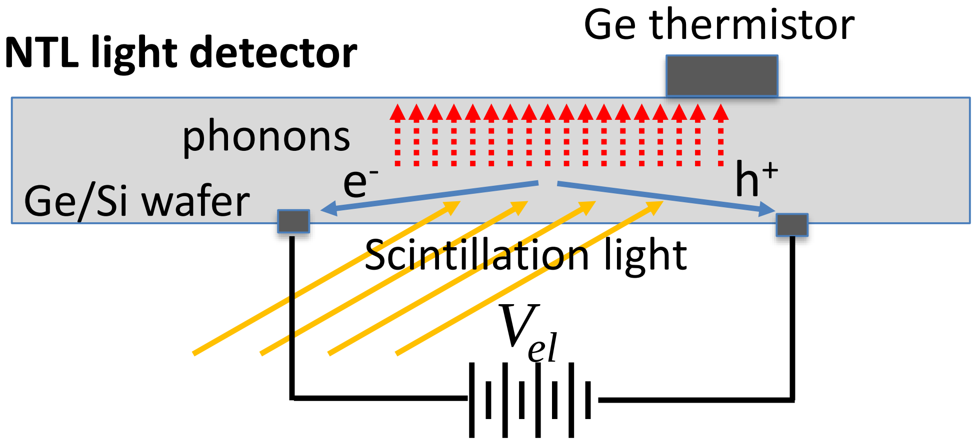
*NIMA 940, 320 (2019)*

- Establish an **electric field** in the light detector wafer via **a set of Al electrodes**
- Electron-hole pairs created by scintillation light absorption drift in the field and produce **additional heat**
- An **amplification of the thermal signal** by a factor 10-20 is technically possible
- **SNR is increased by an order of magnitude**

**Amplified heat** ($E_{tot}$) — **Initial heat** ($E_0$) — **Voltage at the electrodes** ($V_{el}$)

$$E_{tot} = E_0 \left(1 + \frac{q \cdot V_{el} \cdot \eta}{\epsilon}\right)$$

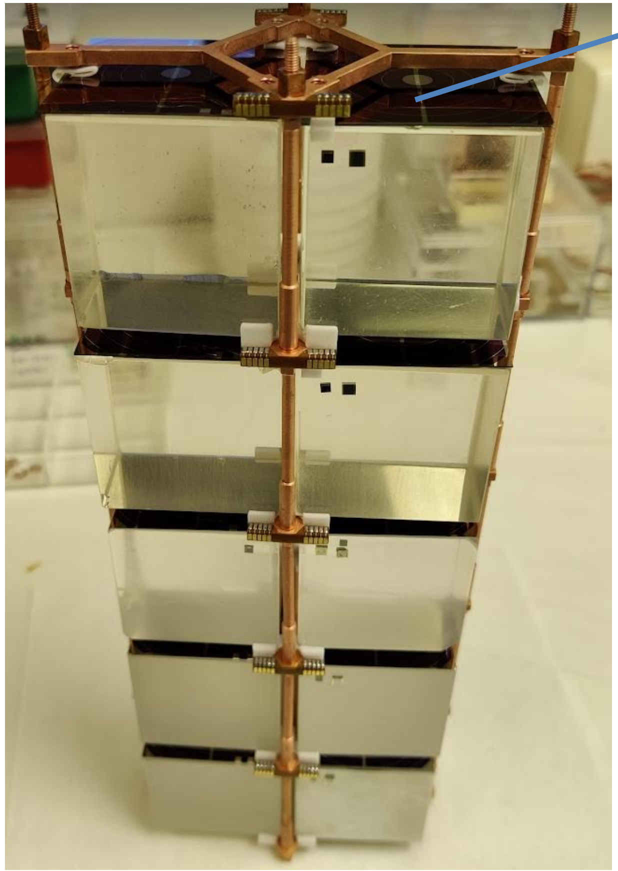


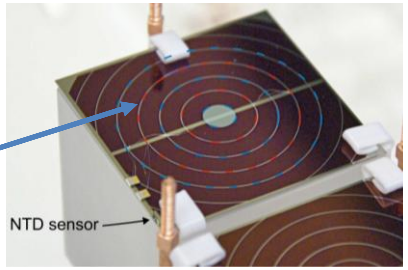



# Enhanced-performance light detectors

**NTL test in a CROSS prototype**

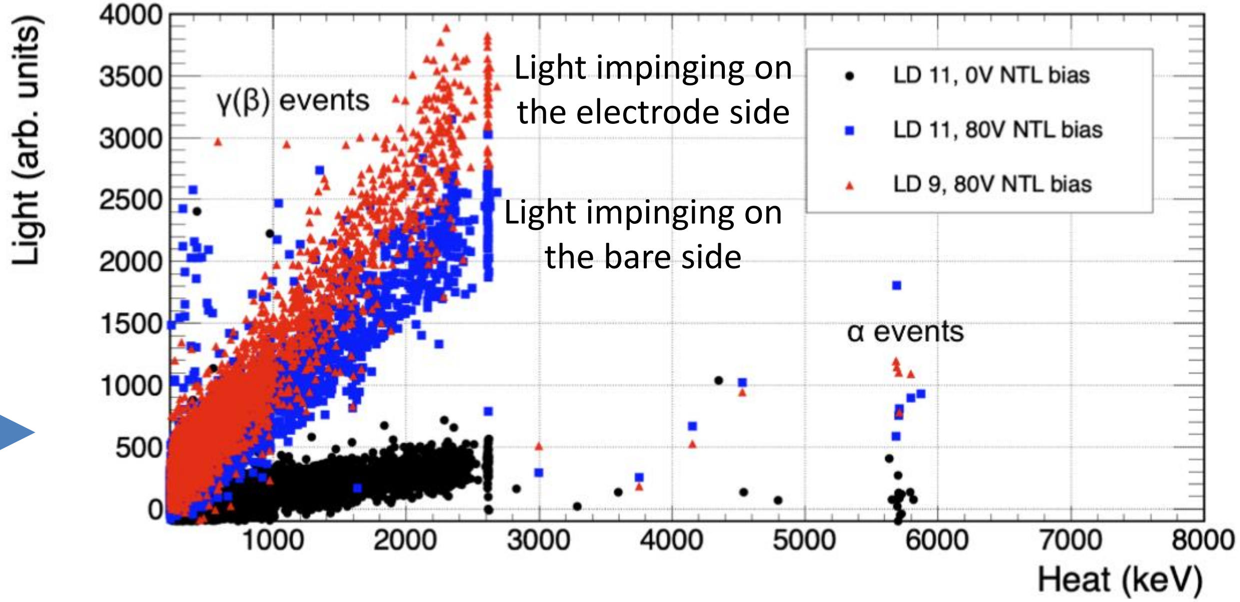
**10 scintillating bolometers**



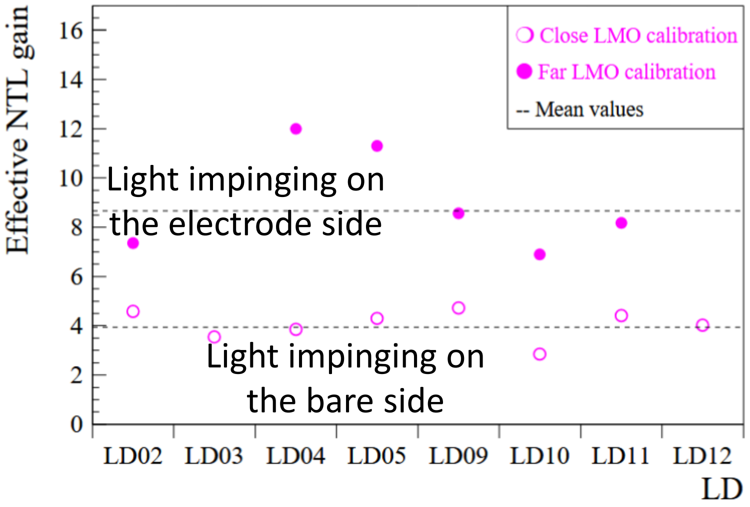



*arXiv:2507.15732*

**Enhancement of light signal**




**Gain at $V_{el}$=80 V on 8 light detectors in parallel**




**$\sigma_{baseline}$ [$V_{el}$=0 V] ~ 100 eV**

↓

**$\sigma_{baseline}$ [$V_{el}$=80 V] ~ 12 eV**

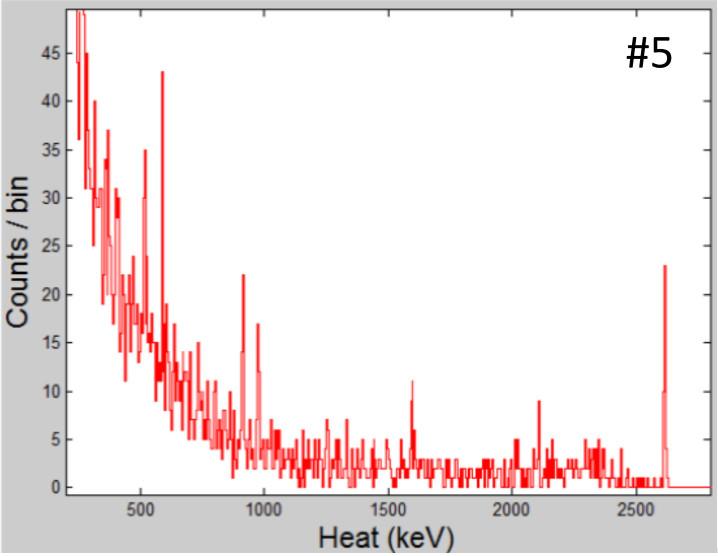
# Final facility validation

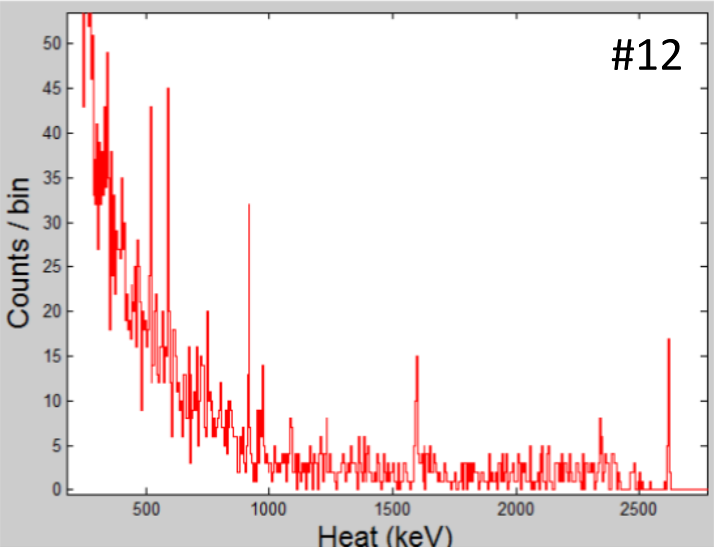
We routinely obtained **5-7 keV FWHM energy resolution @2615 keV** in $Li_2MoO_4$ crystals in previous LSC runs

The facility in the final configuration was tested using **two CUPID-Mo modules** [two 210 g $Li_2MoO_4$ scintillating bolometers]
**Wiring, electronics, DAQ, suspension and all ancillary systems exactly as in the demonstrator**



**$^{232}Th$ calibration**




**The performance of the CUPID-Mo modules are reproduced in the Canfranc facility**

**Crystal performance**

| | Detector | FWHM @2615 keV (keV) |
|---|---|---|
| CROSS | LMO-5 | 5.7(13) |
| | LMO-12 | 5.2(11) |
| CUPID-Mo | mean: 6.6 ± 0.1 | |

**LDs performance**

| | Detector | $\sigma_{baseline}$ (eV) |
|---|---|---|
| CROSS | LD-5 | 64 |
| | LD-12 | 72 |
| CUPID-Mo | LD-5 | 66 |
| | LD-12 | 69 |

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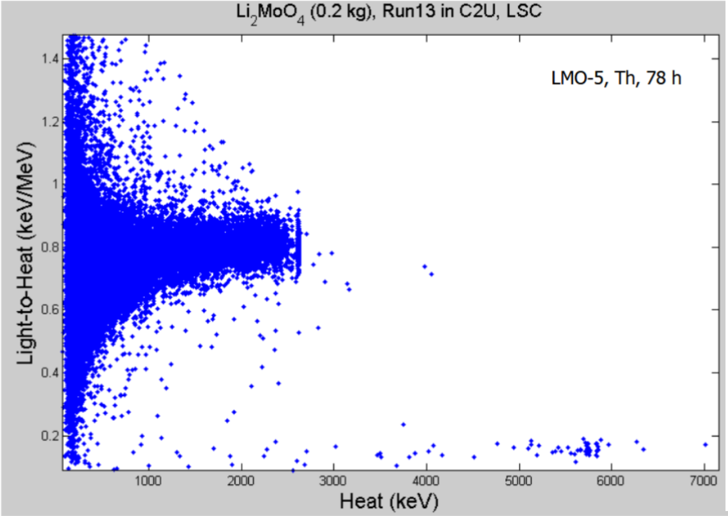
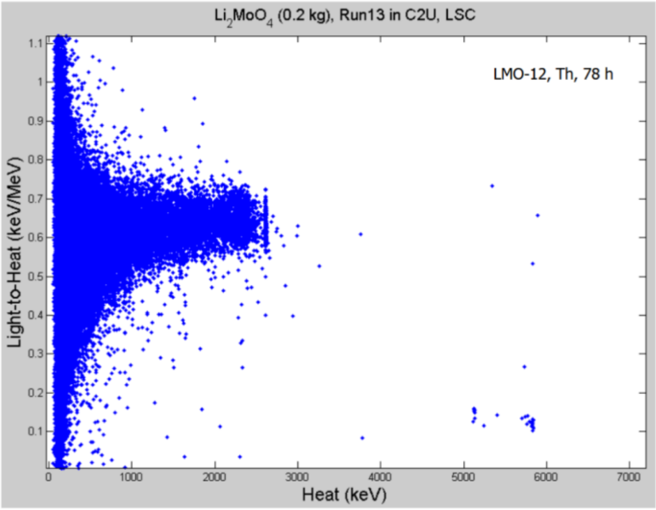
**α/β separation via LY plot**

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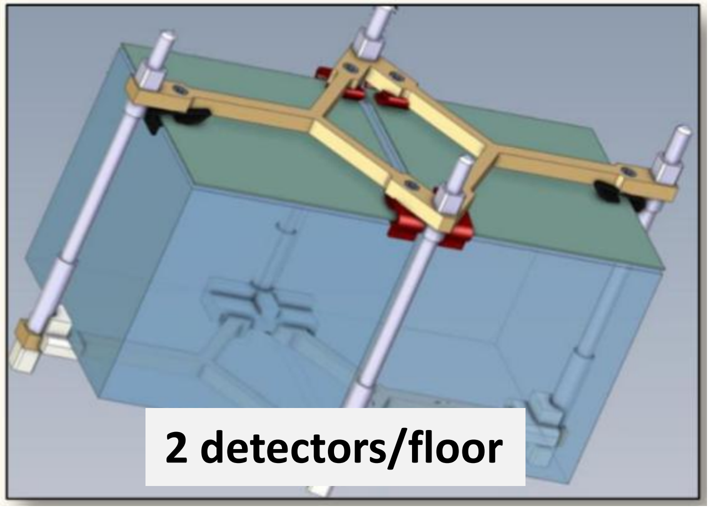
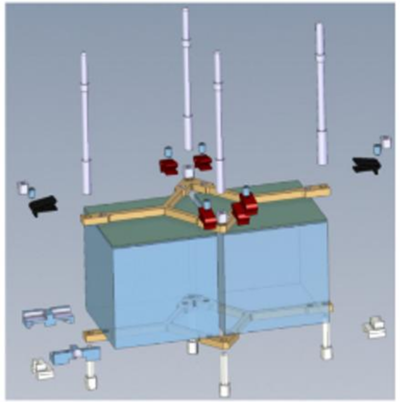
# CROSS demonstrator: structure

**3 towers - 7 floors/tower - 2 detectors/floor**

**→ 42 crystals (45x45x45 mm) and light detectors (45x45 mm)**

**M[$Li_2MoO_4$] ~ 280 g**
**M [$TeO_2$] ~ 550 g**

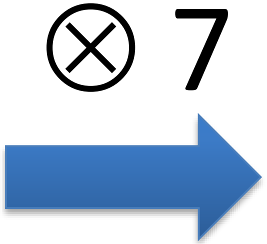


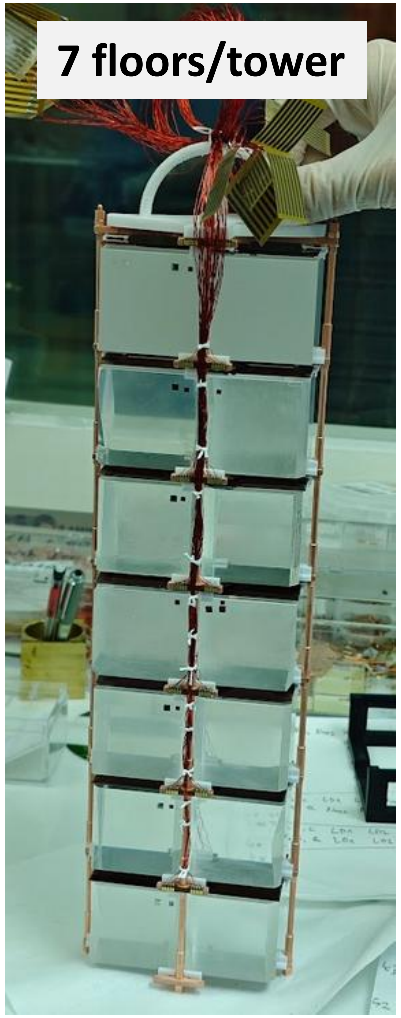



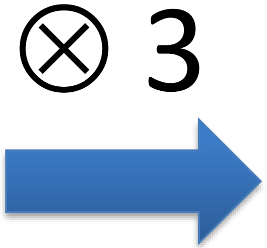
No Cu holder for light detector wafer

**Low (6%) Cu/$Li_2MoO_4$ mass ratio**

***2024 JINST 19 P09013***

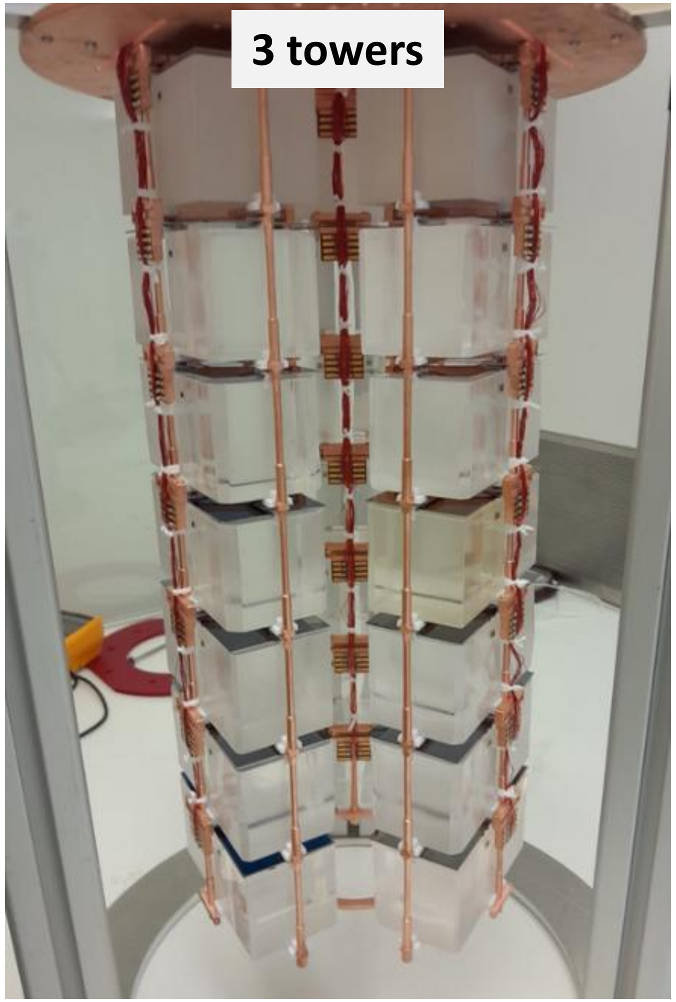



***M. Buchynska, WIN 2025***

**Assembled CROSS demonstrator**



# CROSS demonstrator: composition and status

## Molybdenum sector

- $36x\ Li_2MoO_4 \rightarrow$ **32 $^{100}$Mo-enriched (~97.5%)** , 2 $^{100}$Mo-depleted (~0.01%), 2 naturals
- **Total mass of $^{100}$Mo: 4.9 kg**

NIIC, Novosibirsk, Russia *J. Mater. Sci. Eng. B 2017, 7, 63*
Superior quality and radiopurity, < 1 μBq/kg $^{226}$Ra, $^{228}$Th

## Tellurium sector

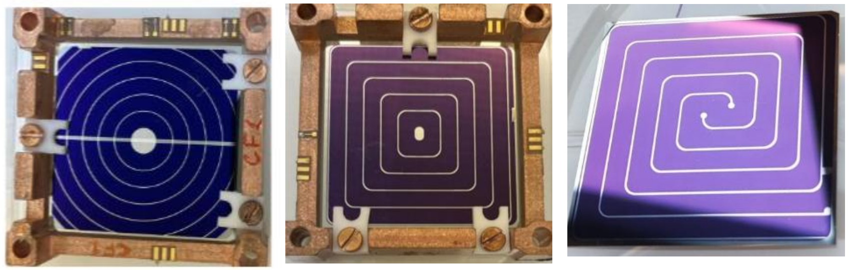
- $6x\ TeO_2 \rightarrow$ **$^{130}$Te-enriched (~91.4%)**
- **Total mass of $^{130}$Te: 2.6 kg**

5N, Canada (purification) – G&H, USA (crystallization) *2024 JINST 19 P09014*
Excellent quality and radiopurity, < 10 μBq/kg $^{226}$Ra, $^{228}$Th

## Test of different light detectors

- Ge wafers with circular electrodes
- Ge wafers with square/spiral electrodes
- Si wafers with spiral electrodes

**26 Ge detectors**
**16 Si detectors**

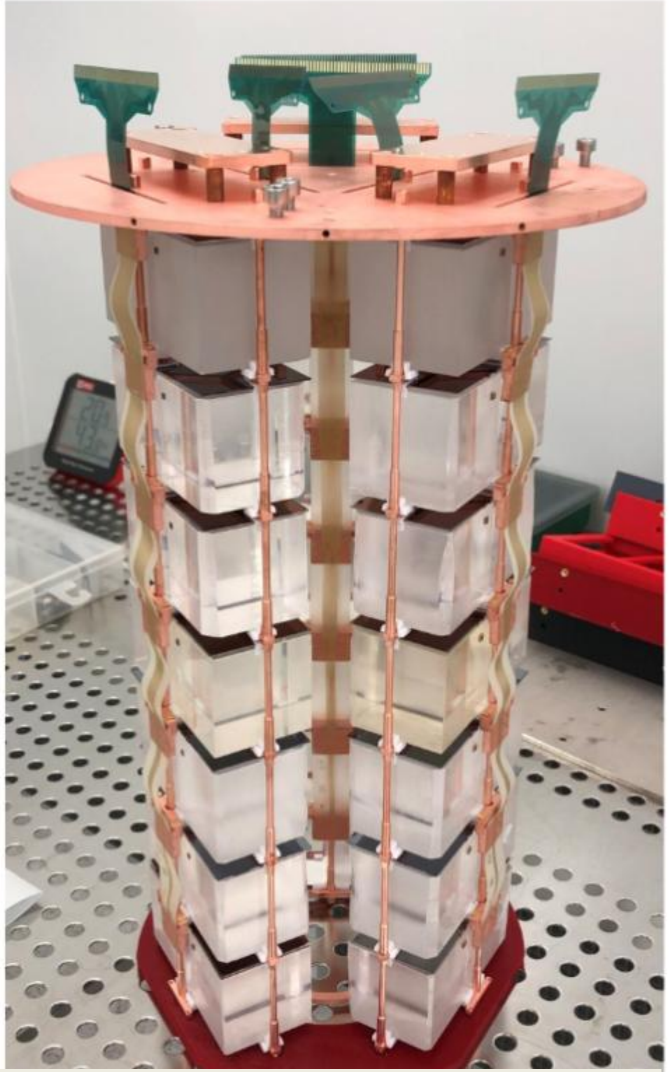


## Detectors now installed in the Canfranc underground laboratory

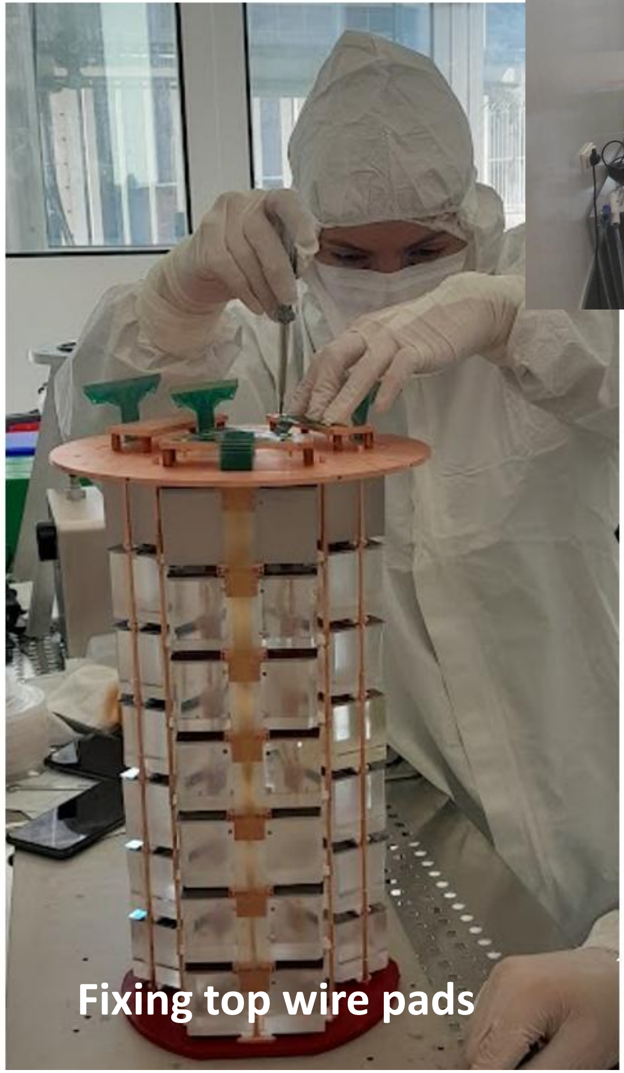
Cryostat ready to be cooled down

- **Commissioning in September 2025**
- **Data taking to be started in October 2025**

# CROSS demonstrator: assembly

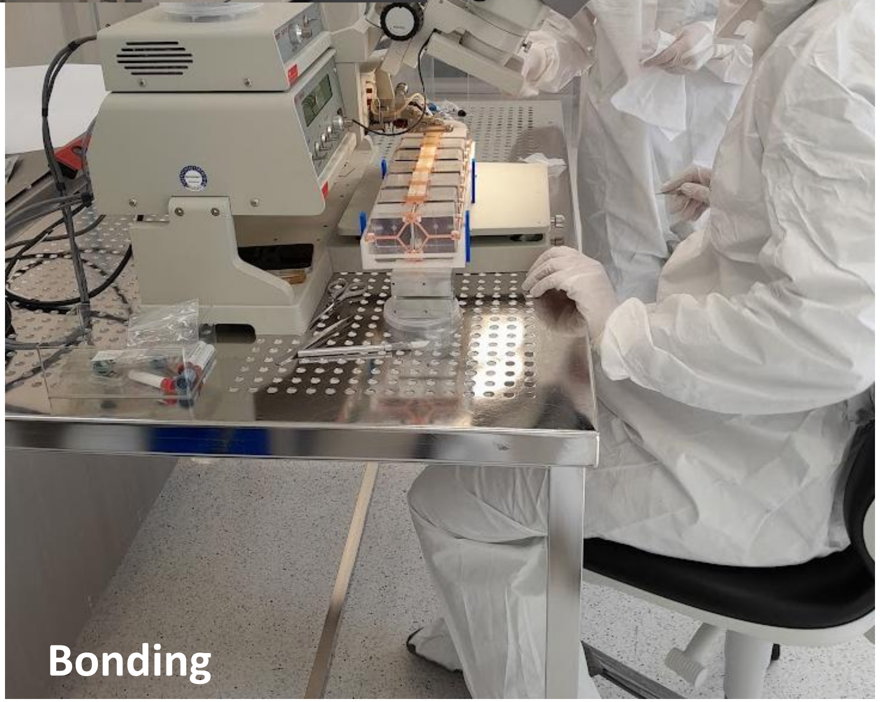


Assembled demonstrator
(baseline version of the cabling)



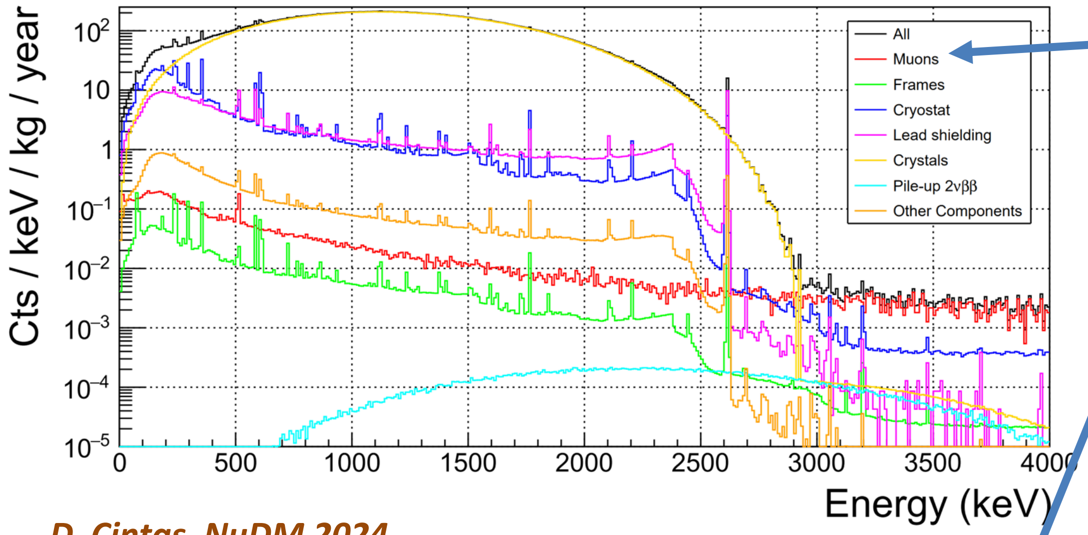
**Fixing top wire pads**

IJCLab-Orsay
ISO5 clean room

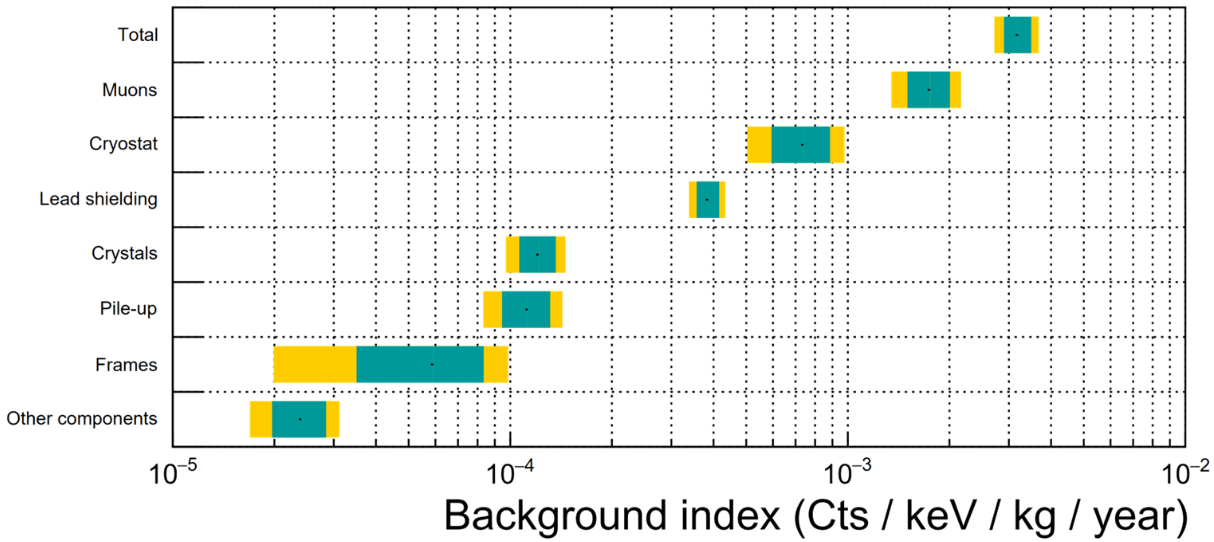


**Bonding**

# Background simulation




*D. Cintas, NuDM 2024*




**Dominant component: muons**
Depth of LSC: 2450 mwe

**Importance of the muon veto**

Extruded scintillators
Wavelength-shifter fibers
SiPMs

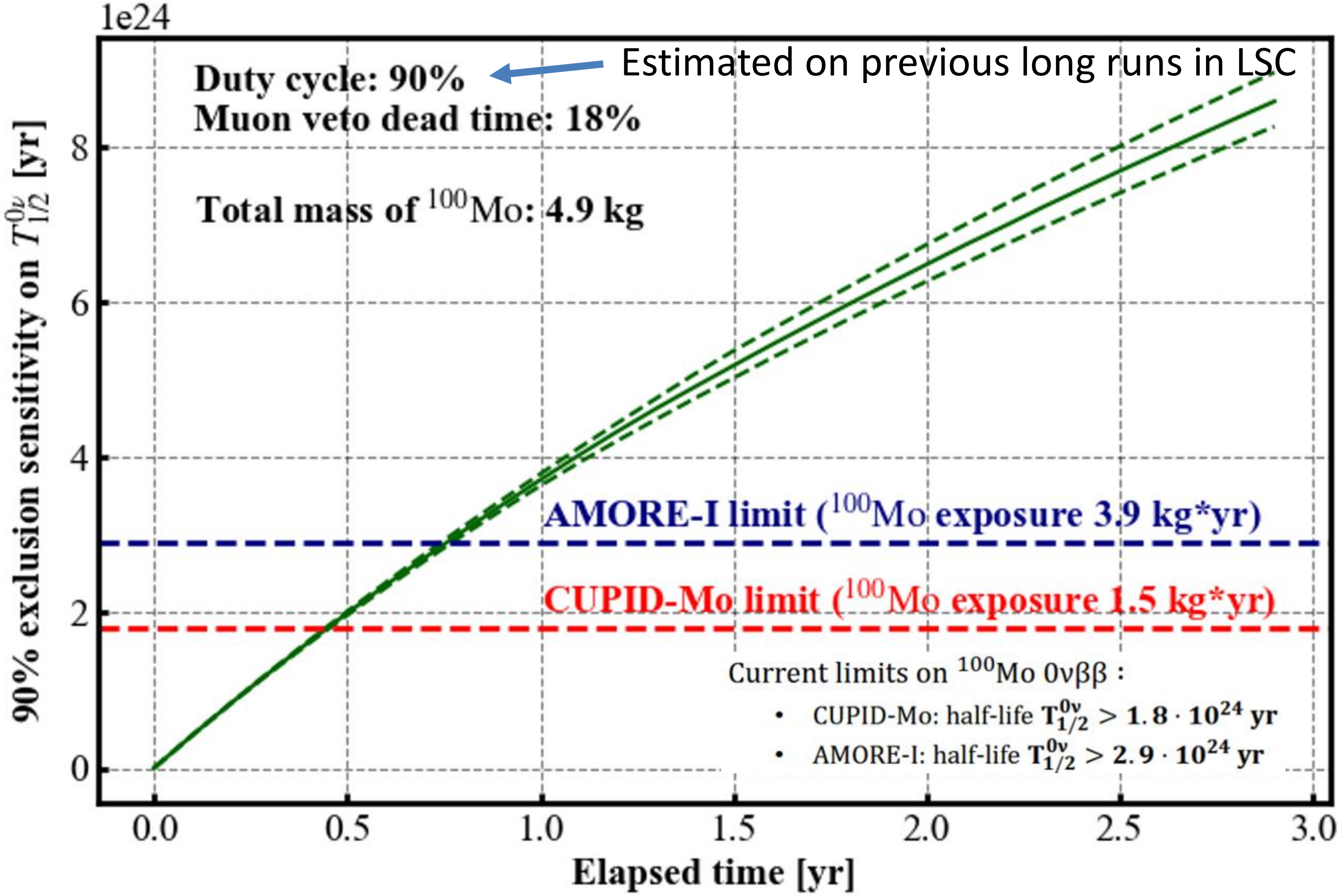
174 channels
grouped in 9 sectors

Rejection of events in coincidence between one veto sector and light detectors

**Total veto rate: 80-90 Hz**
**Dead time: 18 %**

**Total BI: $(3.2\pm0.5)\times10^{-3}$ counts/(keV kg y)**

# Sensitivity




**Assumptions**:

Resolution: **7 keV FWHM @ Qββ**

**ROI: 17.1 keV**
(from CUPID-Mo analysis)
**BI: (3.2±0.5)x10$^{-3}$ counts/(keV kg y)**

**Number of $^{100}$Mo nuclei: 2.95x10$^{25}$**

**Efficiency 70.2%**
- Containment efficiency: 78%
- Cut efficiency 90%

We expect to reach a sensitivity on $^{100}$Mo $T^{0\nu}_{1/2}$ of **3.5x10$^{24}$ y before the end of 2026**

# Conclusions

- The CROSS multi-year program has enabled us to:
  - Investigate and develop new technologies for the reduction of radioactive background
  - In particular, the Neganov-Trofimov-Luke light detector technology is of crucial importance for CUPID
  - Acquire ultrapure crystals of $Li_2MoO_4$ and $TeO_2$ enriched in the relevant isotopes $^{100}Mo$ and $^{130}Te$
  - Develop a fully equipped underground cryogenic facility (LSC) to host a pilot experiment (CROSS demonstrator) based on these technologies
  - Develop the electronics and the DAQ for this pilot experiment
- The CROSS demonstrator has now been assembled, installed at LSC, and is ready for data-taking, scheduled to begin in October 2025
- It has the potential to improve the current limit on $0\nu2\beta$ decay of $^{100}Mo$ before the end of 2026