CUPID and CROSS status

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on behalf of the CROSS/CUPID collaboration
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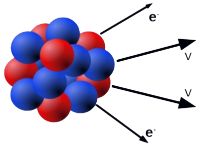
GDR DI2I, 17-19 June 2026

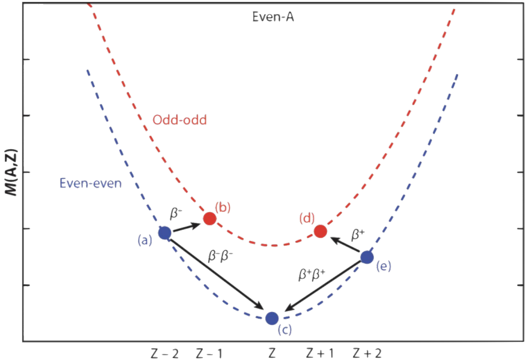
Double beta decay

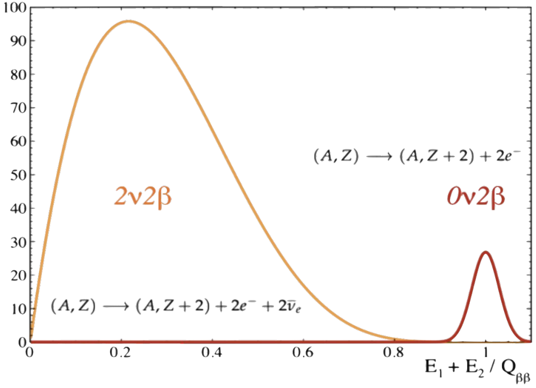
Double beta decay: rare second-order weak process in which a nucleus undergoes two **simultaneous** beta decays

2νββ

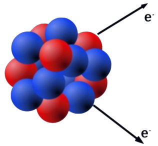


- Predicted by the Standard Model for even-even nuclei **($\Delta L = 0$)**
- First **observed** in 1987 at UC Irvine in ^{82}Se
- Half life $T_{1/2} \sim 10^{18}$ - 10^{22} yr
- Signature: **continuous spectrum** from 0 up to the $Q_{\beta\beta}$





0νββ

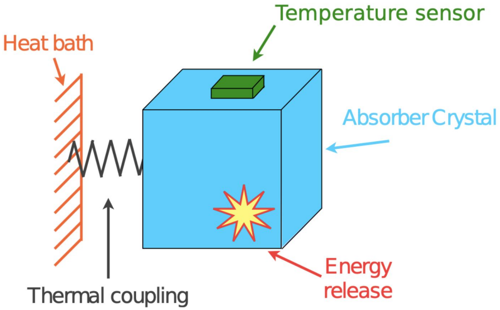


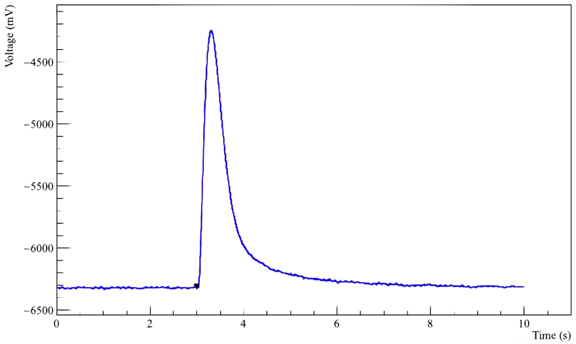
- **Violates** the lepton number symmetry **($\Delta L = 2$)**
- **No experimental evidence** up to now
- Half life $T_{1/2} > 10^{24}$ - 10^{26} yr
- Signature: **peak at the Qββ**
- Could play an important role in the **Matter-Antimatter asymmetry**

Cryogenic Calorimeters

The energy deposited by the particles is converted into **phonons**

↳ Through a **sensor** (Ge-thermistor) the heating of the absorber is measured





→ The absorber is operated at approximately **10 mK**

→ **Slow** signal response (timescale of ~ 1 s)

→ **Excellent** energy resolution (FWHM ≈ 0.1%) at the $Q_{\beta\beta}$

→ **ββ source** is **embedded** within the detector

→ Wide choice of absorber **materials**, allowing the use of many **ββ isotopes**

→ **Scalable** technology (ton-scale experiment)

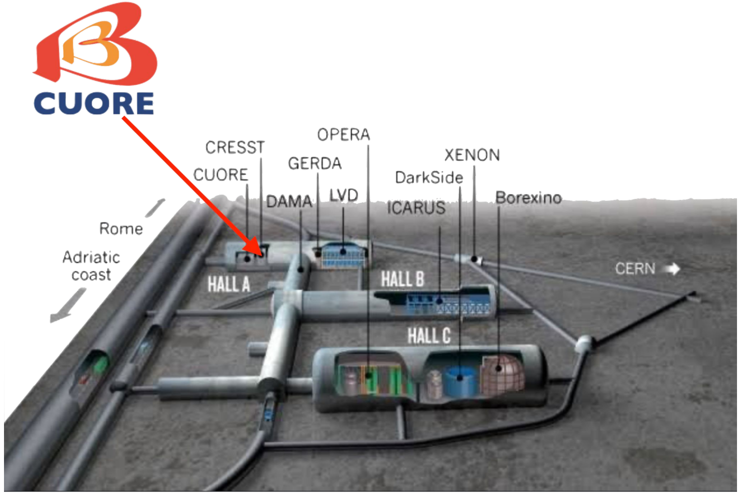
The CUORE experiment

[HEP 879871 (2015)]

CUORE (**C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents) is an experiment located at Gran Sasso National Laboratories (**LNGS)** Abruzzo, Italy. The laboratory is covered by approximately 1400 m of rock (~3400 m.w.e.).

→ Mainly designed for the search of the 0νββ decay of **^{130}Te** [EPJC 77 532 (2017)]

→ Composed of **988 TeO_2** crystals, used as **cryogenic calorimeters** containing the isotope of interest



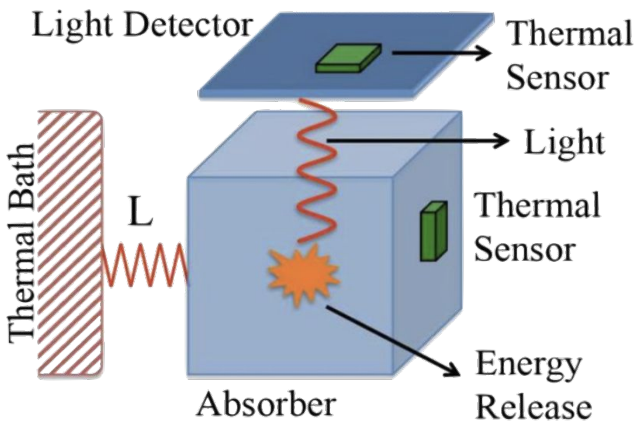
What to improve for a next generation experiment?

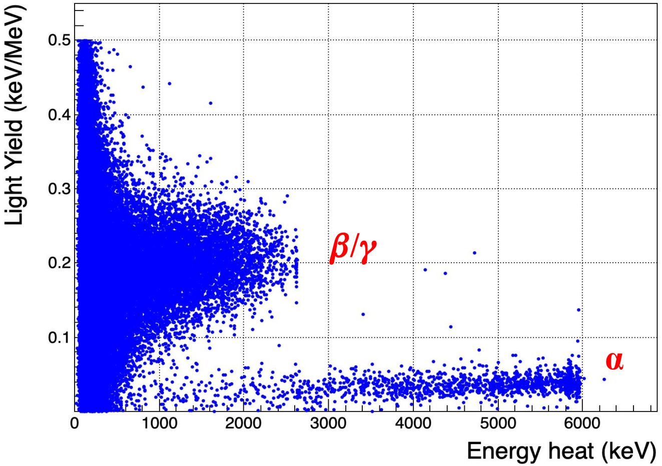
Surface α's dominate the CUORE background → **α rejection is pivotal**

↳ **Scintillating calorimeters** enable α-event rejection due to their **lower light yield** compared to β/γ

→ TeO_2 (CUORE) is non-scintillating. CROSS/CUPID will use Li_2MoO_4 crystals

→ To enhance **SNR** and **discrimination** the **Neganov-Trofimov-Luke** (**NTL**) effect is exploited





$$\mathrm{LY} = \frac{E_{light}}{E_{heat}}$$

Neganov-Trofimov-Luke (NTL) effect

Light detector performance can be enhanced by the **Neganov-Trofimov-Luke effect**:

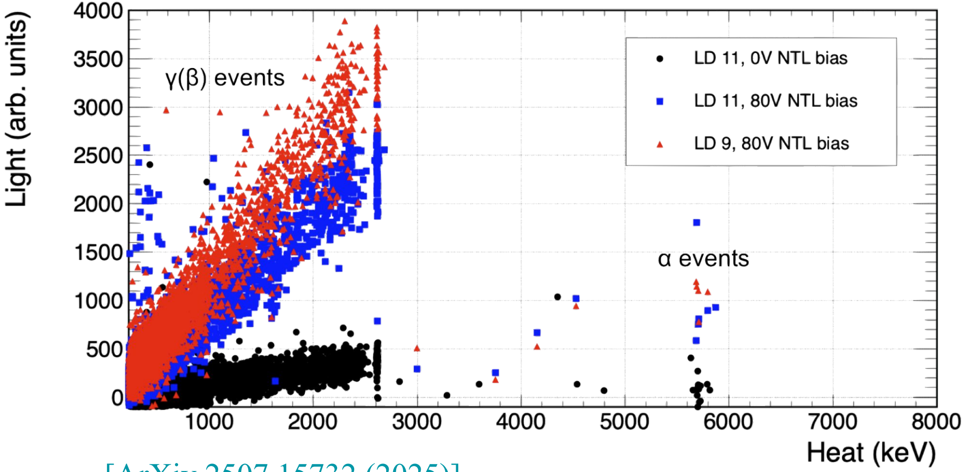
$$E_{tot} = E_0 \left(1 + \frac{q \cdot V_{el} \cdot \eta}{\epsilon}\right)$$

→ Electric field generated applying Voltage (V_{el}) on the **electrodes** deposited on the LD

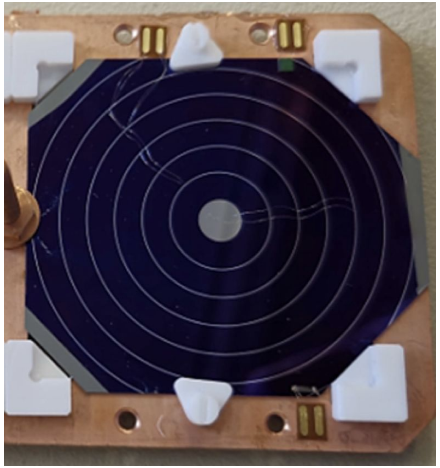
→ Impinging particle generates electron–hole pairs that **drift** through the field ⇒

Extra heat is produced thanks to the drift (increased amplitude)

→ **SNR** can be increased by an order of magnitude



[ArXiv 2507 15732 (2025)]

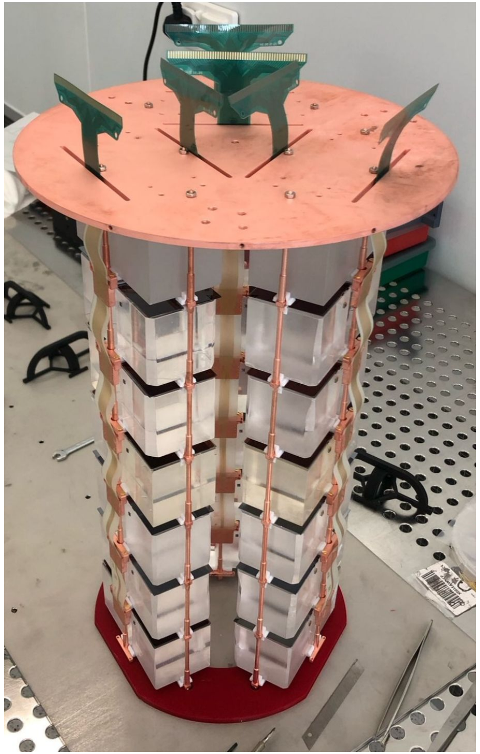


Higher SNR improves **pile-up rejection**.

Crucial for CUPID: Mitigation of background induced by **random coincidences** of ordinary **2νββ** events

The CROSS experiment

CROSS (**C**ryogenic **R**are-event **O**bservatory with **S**urface **S**ensitivity) is hosted in the Canfranc Underground Laboratory (**LSC**) , in Spain at a depth of ~2400 m.w.e.



3 towers with 7 floors each

- Each floor has 2 crystals + 2 LDs
- Top floors consists of 6 $^{130}TeO_2$ crystals, that will work also as shielding to others crystals due to higher density

36 Li_2MoO_4 (mass of ^{100}Mo: ~ 4.9 kg) and 6 TeO_2 (mass of ^{130}Te: ~ 2.4 kg)

Facility equipped with **lead** shielding, **anti-radon** shield and **muon veto**

CROSS: what's new

CROSS exploited key technologies relevant to next generation neutrinoless double-beta decay experiments:

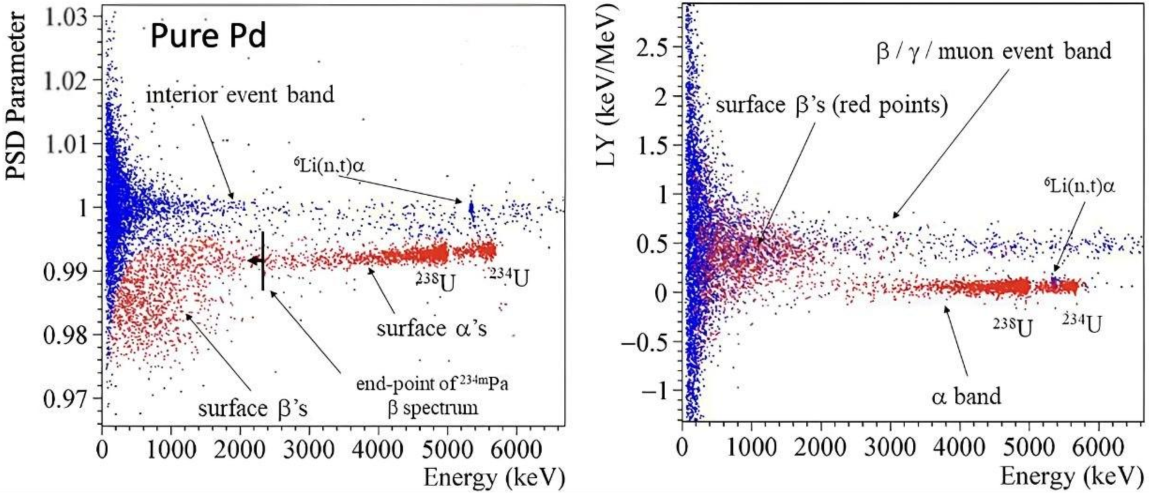
1. **Surface-coated** crystals for bulk/surface event discrimination (α and β)
2. Optimization of Neganov–Trofimov–Luke (**NTL**) light-detector technology
3. Deployment of **Silicon**-wafer NTL light detectors in a **medium-scale** detector array
4. New **low-mass** mechanical structures minimizing **passive material** near the detectors
5. Development of the purification and crystallization process for **enriched $^{130}TeO_2$** crystals

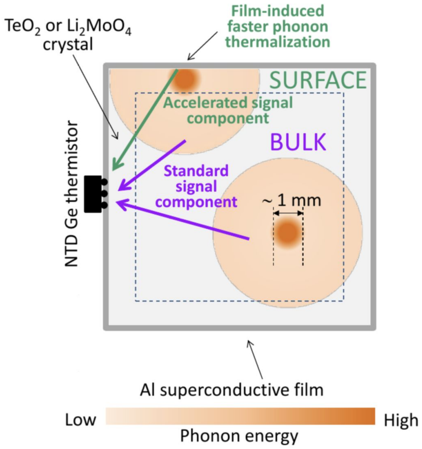
CROSS: Surface Sensitivity

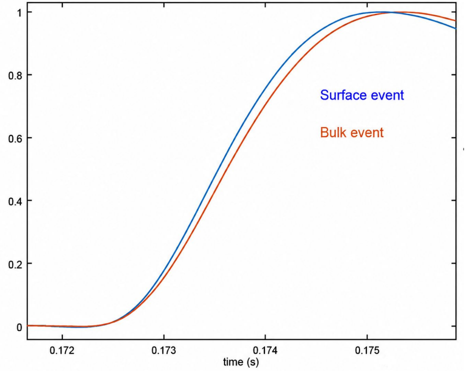
Metal films act as **pulse-shape modifiers** for charged particles depositing energy near the film surface → **Bulk vs Surface event discrimination**

After long R&D with 2×2×1 cm^3 → **Al-Pd bi-layer** was selected

[APL 118 184105 (2021)]





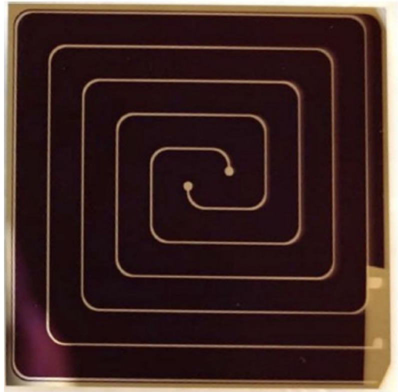


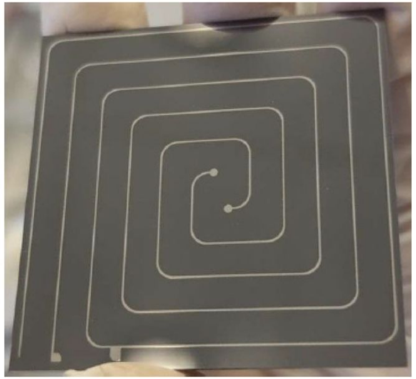
Unfortunately, scaling this technology to large CUPID and CROSS size crystals (4.5 × 4.5 × 4.5 cm^3) has **not yet been successful**

CROSS: Silicon LDs

Silicon wafers may provide a **more practical solution** for a large-scale experiment, as they are significantly less expensive than germanium detectors.

→ Si LDs are ~3 times cheaper than Ge LDs


Germanium


Silicon

The CROSS data will allow us to evaluate:

- NTL amplification performance and **reproducibility**
- **Bolometric** performance of Si LDs
- **Light** collection **efficiency** in Si compared to Ge
- The minimum achievable **rise time**

In addition, the availability of high-purity germanium has become **increasingly limited** in recent years, making large-scale production more challenging and expensive.

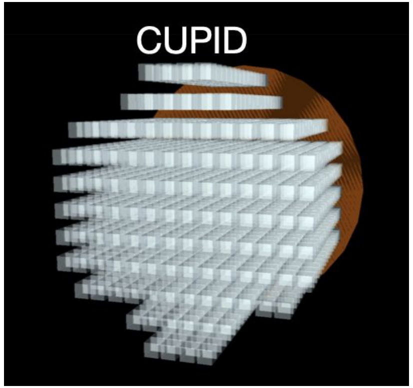
The CUPID experiment

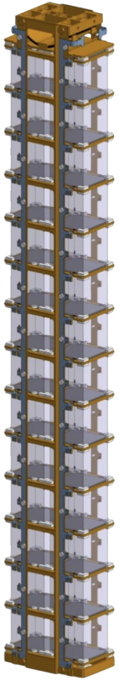
CUPID (**C**UORE **U**pgraded with **P**article **ID**entification) will be hosted in CUORE cryogenic infrastructure

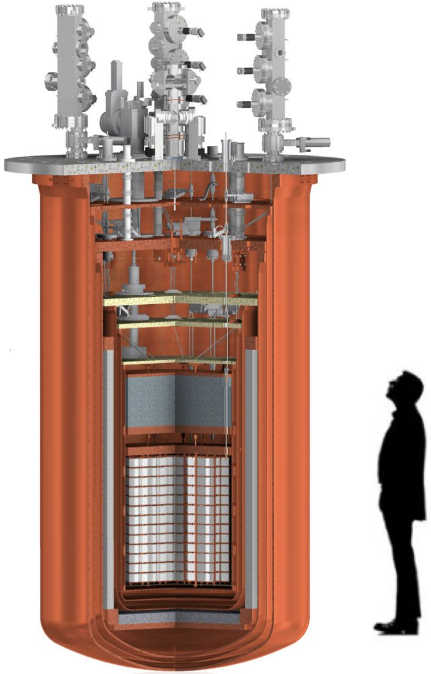
57 towers with 14 floors each

→ 1596 Li_2MoO_4 scintillating crystals (280 g each)

→ 1710 light detectors







CUPID's goals:

→ Mo enrichment > 95% in ^{100}Mo (η)

→ 450 kg (240 kg) $Li_2{}^{100}MoO_4$(^{100}Mo) (M)

→ Background Index ~ 10^{-4} cts/(keV kg yr) (b)

→ ~ 5 keV FWHM at $Q_{\beta\beta}$ (ΔE)

→ Live Time ~ 10 yrs (T)

The sensitivity to **0νββ** can be expressed as:

With Background: $S_{0\nu} \propto \eta \cdot \varepsilon \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$

Zero Background: $S_{0\nu} \propto M \cdot T$

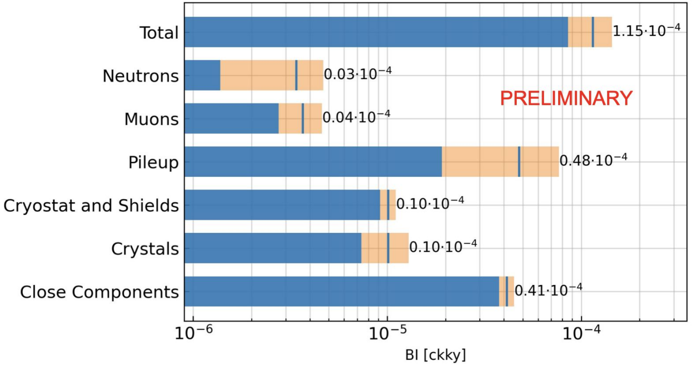
CUPID projections

From simulations, the **dominant background** contributions are expected to be:

→ **Muons & neutrons:** mitigated by a *muon veto* and *neutron shielding*

→ **Cryostat, shields, close components and crystals:** addressed through the use of *high-radiopurity* materials

→ **Pile-up:** random coincidence of the ordinary 2νββ events. Suppressed thanks to the *Light Detectors* (fast signals)



With **BI = 10^{-4}** ckky, **10-years exposure** yields the Bayesian exclusion sensitivity (90% C.I.)

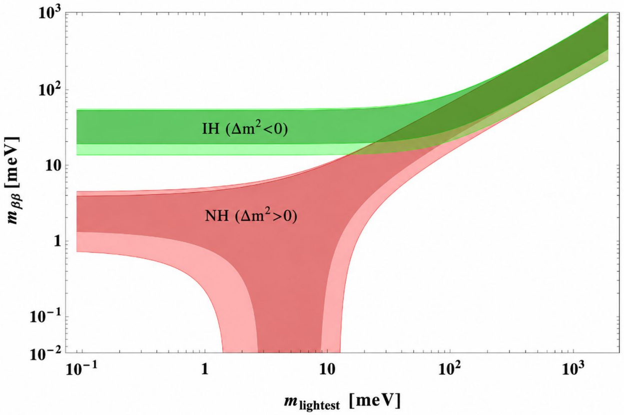
$$T_{1/2} > 1.6^{+0.6}_{-0.5} \times 10^{27}\, yr$$

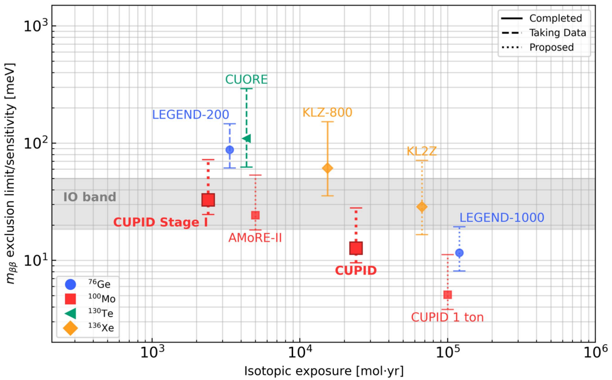
$$m_{\beta\beta} < 9.6 - 28\, meV$$

and the Frequentis discovery sensitivity (3σ)

$$T_{1/2} > 1.0^{+0.7}_{-0.3} \times 10^{27}\, yr$$

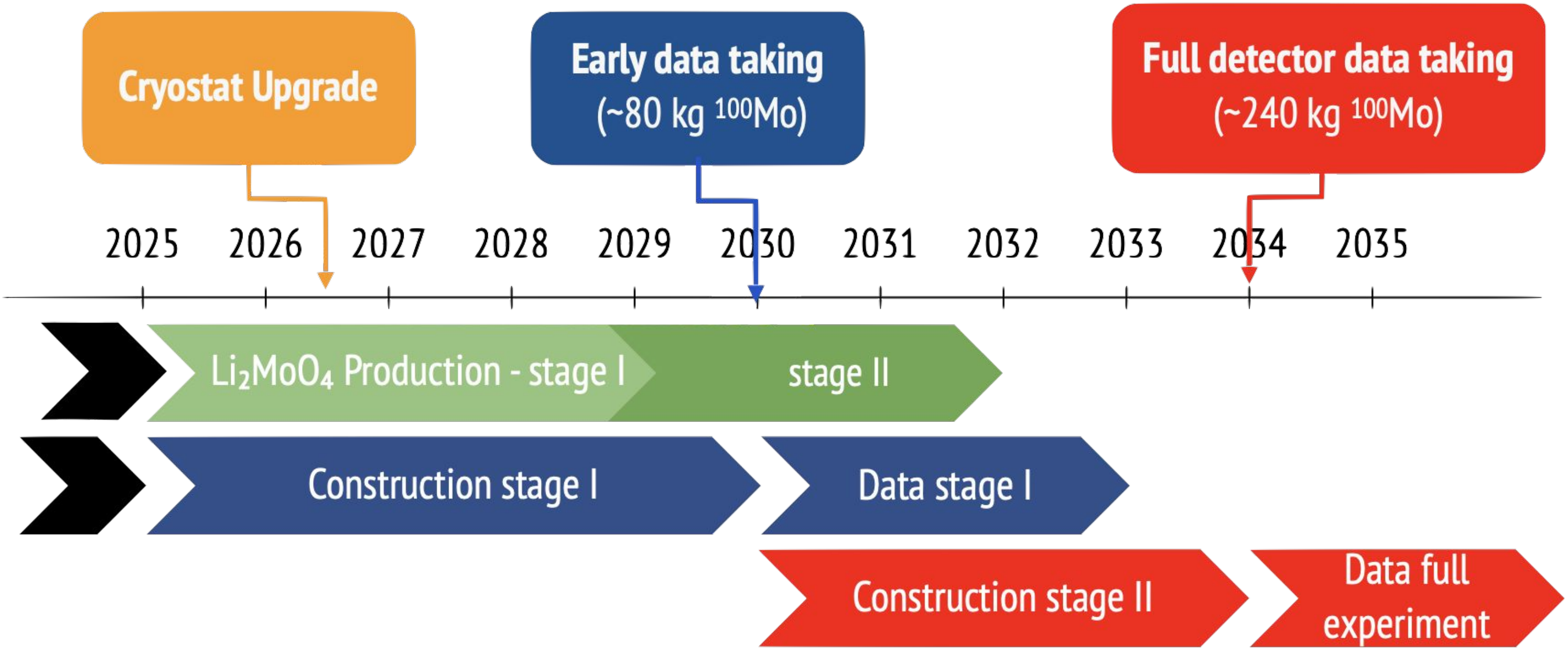
$$m_{\beta\beta} < 12 - 36\, meV$$





[EPJC 86 633 (2026)]

CUPID timeline



Summary

→ CROSS is demonstrating the technology over an extended period of time

→ Silicon could serve as a good, **lower-cost alternative** to germanium

→ Proven path for isotope enrichment, procurement, and crystal growth

→ Final technical integration and **LD optimization** ongoing

→ CUPID infrastructure is already well established (CUORE provides the world's **largest bolometric facility**)

→ Sensitivity covering the full **inverted ordering** region (down to $m_{\beta\beta} \approx 10$ meV for the most favorable NME)

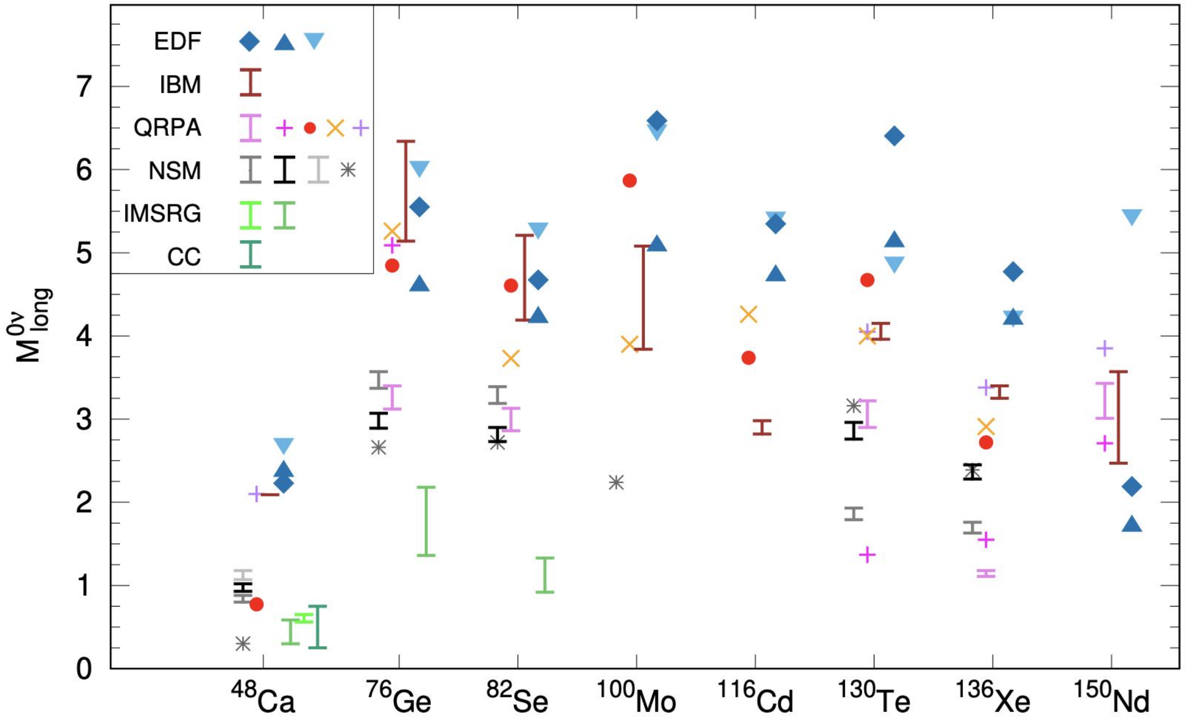
→ Collaboration preparing for **CUPID Stage-I** construction

→ CUPID aims to be a leading experiment in **future 0νββ search**

Backup

Backup

[Rev. Mod. Phys. 95 025002 (2023)]



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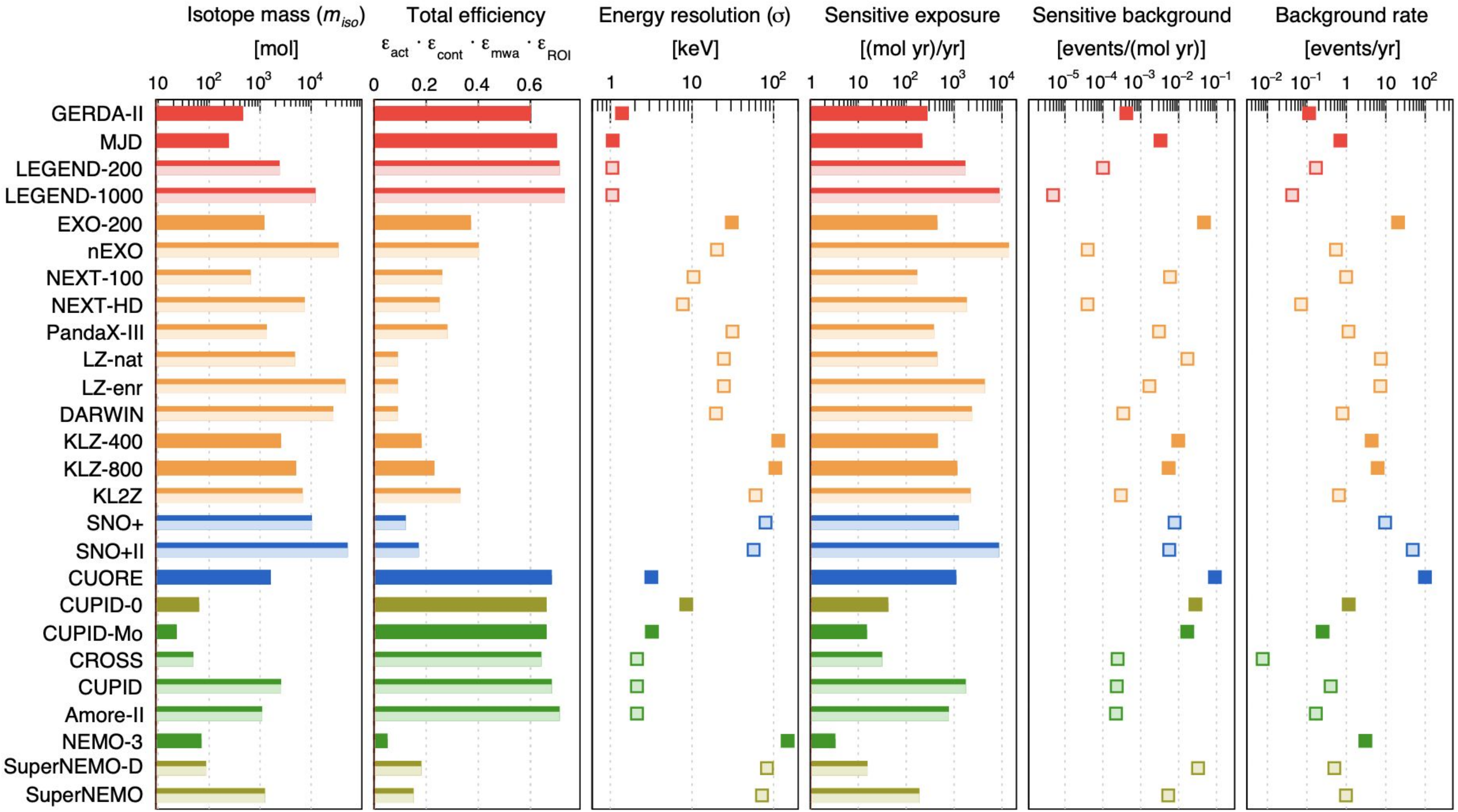

[Rev. Mod. Phys. 95 025002 (2023)]

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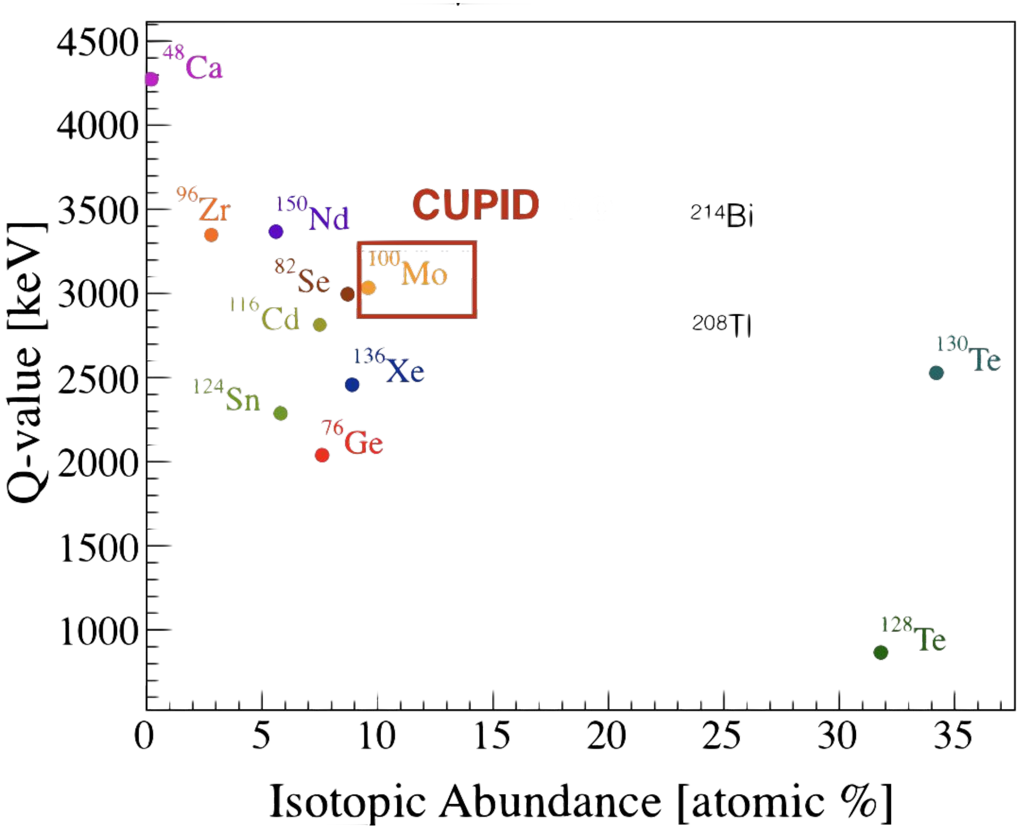
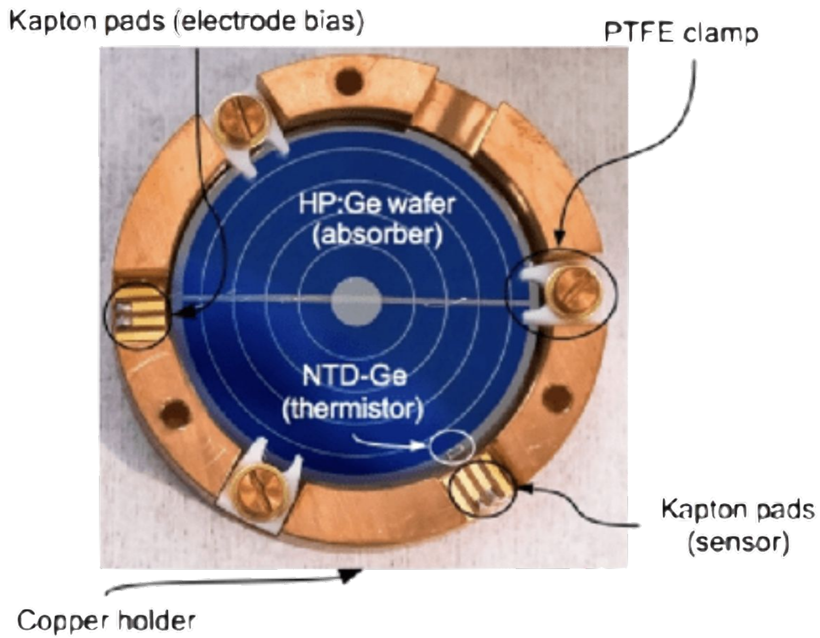


$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} \sim g_A^4 \cdot G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

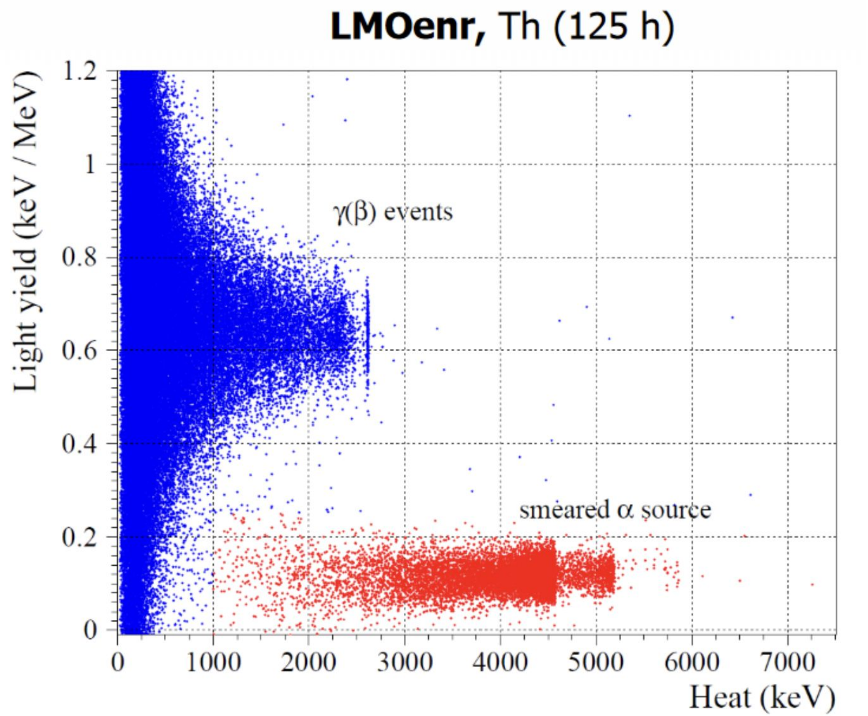
Effective Majorana mass:

$$\langle m_{\beta\beta} \rangle = | \sum_{i=1,2,3} U_{e,i}^2 m_i |$$

Backup

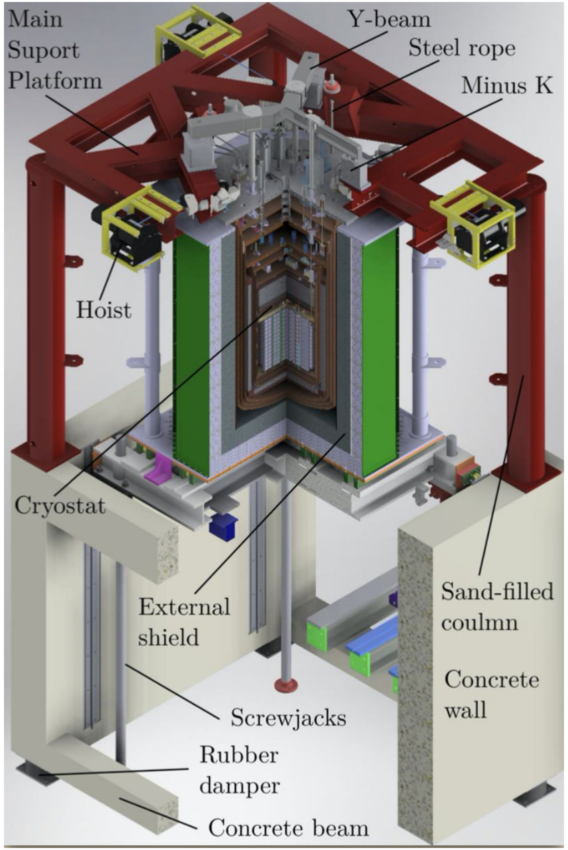


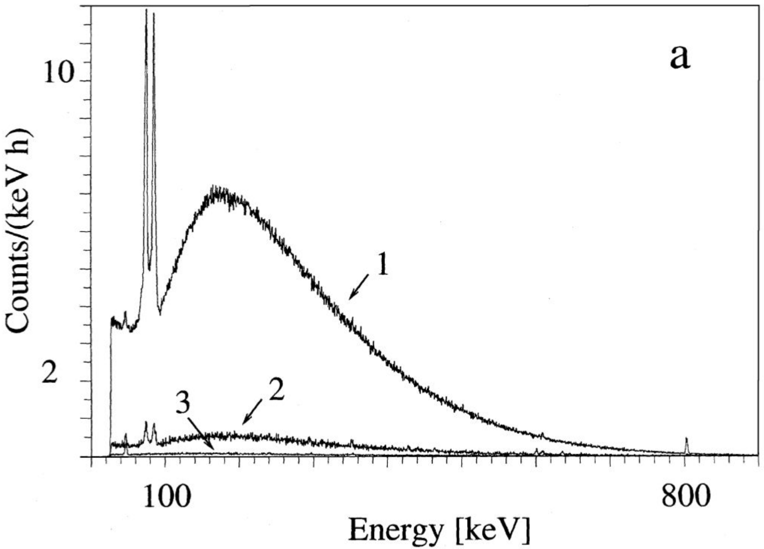
Kapton pads (electrode bias)
PTFE clamp
HP:Ge wafer
(absorber)
NTD-Ge
(thermistor)
Kapton pads
(sensor)
Copper holder



LMOenr, Th (125 h)
Light yield (keV / MeV)
Heat (keV)
γ(β) events
smeared α source
0
0.2
0.4
0.6
0.8
1
1.2
0
1000
2000
3000
4000
5000
6000
7000

Backup





[NIMB 142 163-172 (1998)]

Spectra in the region to 900 keV recorded with shields made with various types of lead:

1. common moadern lead;
2. modern lead with a certied content of less that 20 Bq kg^{-1} of ^{210}Pb

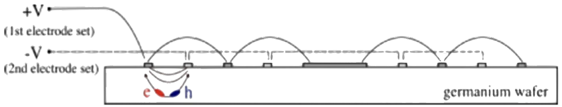
3: roman lead

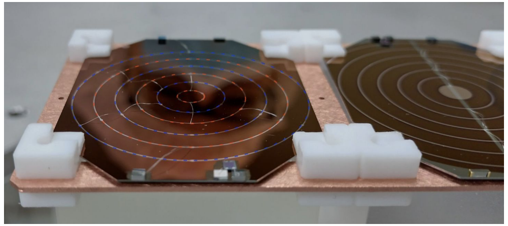
The CUPID detectors

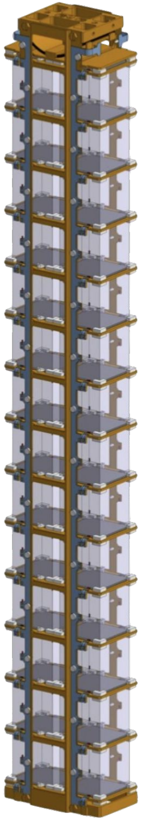
Each floor is composed of 2 $Li_2{}^{100}MoO_4$ (LMO) and 2 Germanium Light Detector (LD)
Both detectors are read out with Ge-NTDs (thermistor)

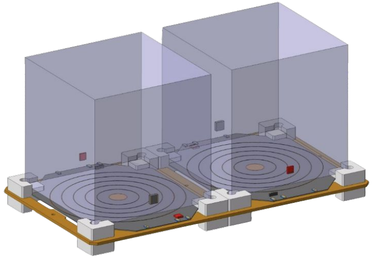
LMO crystals:
→ Controlled LMO production chain (SICCAS): optical properties, radiopurity and minimal isotope loss
→ Sequential crystal testing at LNGS (CUPID Hall C, crystal validation runs): performance at 10 mK and residual radioactivity assessment (ongoing)

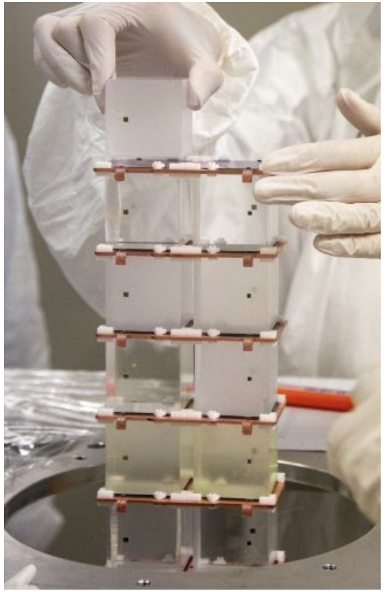
Light detectors:
Ge wafer with electrodes exploiting the **NTL effect**:
→ Signal amplification enables efficient $2\nu\beta\beta$ pile-up rejection
→ Enables α / $\beta\gamma$ discrimination









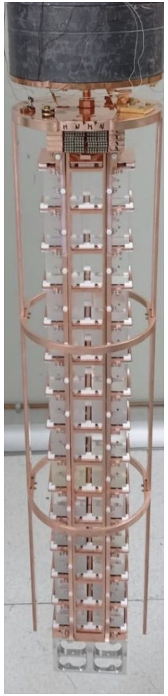


LMOs and LDs performance has already been tested at mid-scale in **CUPID-Mo**, **CROSS** and other **CUPID demonstrators**.

[EPJC 80 44 (2020)] [EPJC 85 935 (2025)] [EPJC 78 428 (2018)]

CUPID towers prototypes

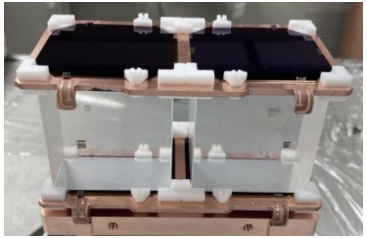
Two CUPID **tower demonstrators** were built to test an innovative assembly design that improves production, cleaning, and the ease and speed of detector construction.



GDPT (Gravity Detector Prototype Tower)

Test of the new tower mechanical assembly conducted at the CUPID Hall A facility at LNGS in 2022.

The first full tower test was successful
The LDs showed limited SNR and correlated noise.



No NTL

[EPJC 85 935 (2025)]

VSTT (Vertical Slice Test Tower)

Full integrated test at the CUPID Hall A facility, LNGS (2025):

→ Upgraded tower mechanical assembly
→ Optical fibers along the tower
→ New electronics and DAQ

Cooled down in early August 2025 (WIP)

With NTL