CUPID, the next-generation 0νββ bolometric experiment

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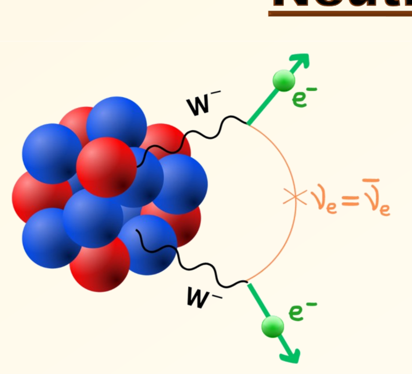
WIN 2025
9-13 June 2025
University of Sussex, Brighton, UK

Neutrinoless double-beta decay



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

Current limits on the half-life:
$T^{0\nu}_{1/2} > 10^{24}$ - 10^{26} yr

Experimental requirements

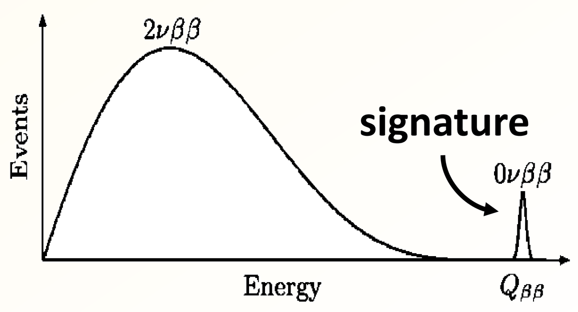
- Large exposure $M \times t$
- Large δ (isotopic abundance)
- Small b (low background index) in the ROI
- Small ΔE (good energy resolution)
- High ε (detection efficiency)

$$T_{1/2} \propto \begin{cases} \delta \times \varepsilon \times \sqrt{\frac{M \times t}{b \times \Delta E}} \rightarrow \text{with background} \\ \delta \times \varepsilon \times M \times t \rightarrow \text{background free} \end{cases}$$

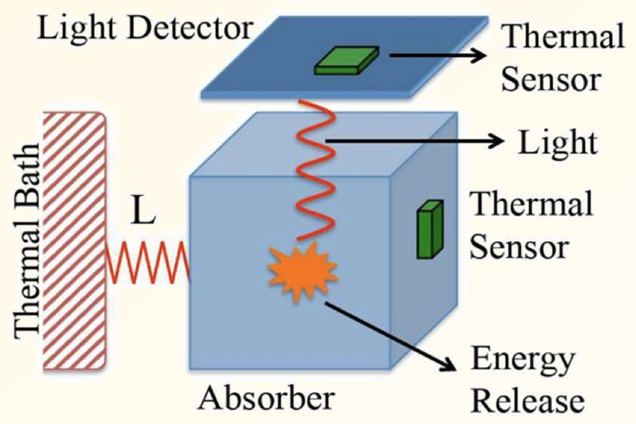
$(b \times \Delta E \times M \times t \ll 1)$

In case of observation:

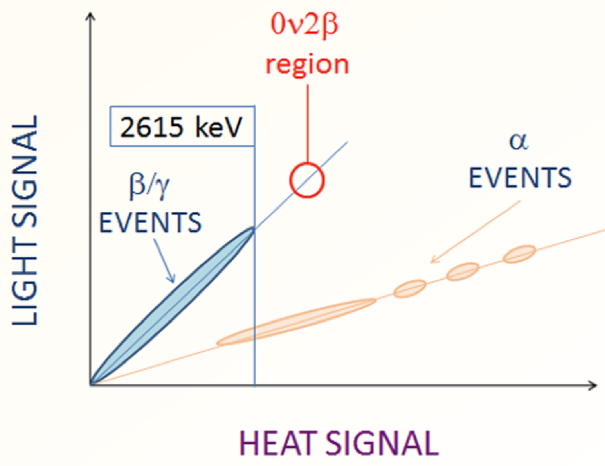
- Lepton number violation
- Majorana nature of neutrinos
- Explanation of matter-antimatter asymmetry



Scintillating bolometers



- $\Delta T = \Delta E / C$ ~ 0.1 mK/MeV
- $C(T) \propto T^3 \Rightarrow$ operating temperatures 10-30 mK
- Good energy resolution: 5-10 keV FWHM at $Q_{\beta\beta}$



- Double read-out of heat and light signals
- Particle discrimination using light detectors (LDs): > 99.9% α particles rejection efficiency
- Technology proven in CUPID-0 [1] and CUPID-Mo [2] demonstrators

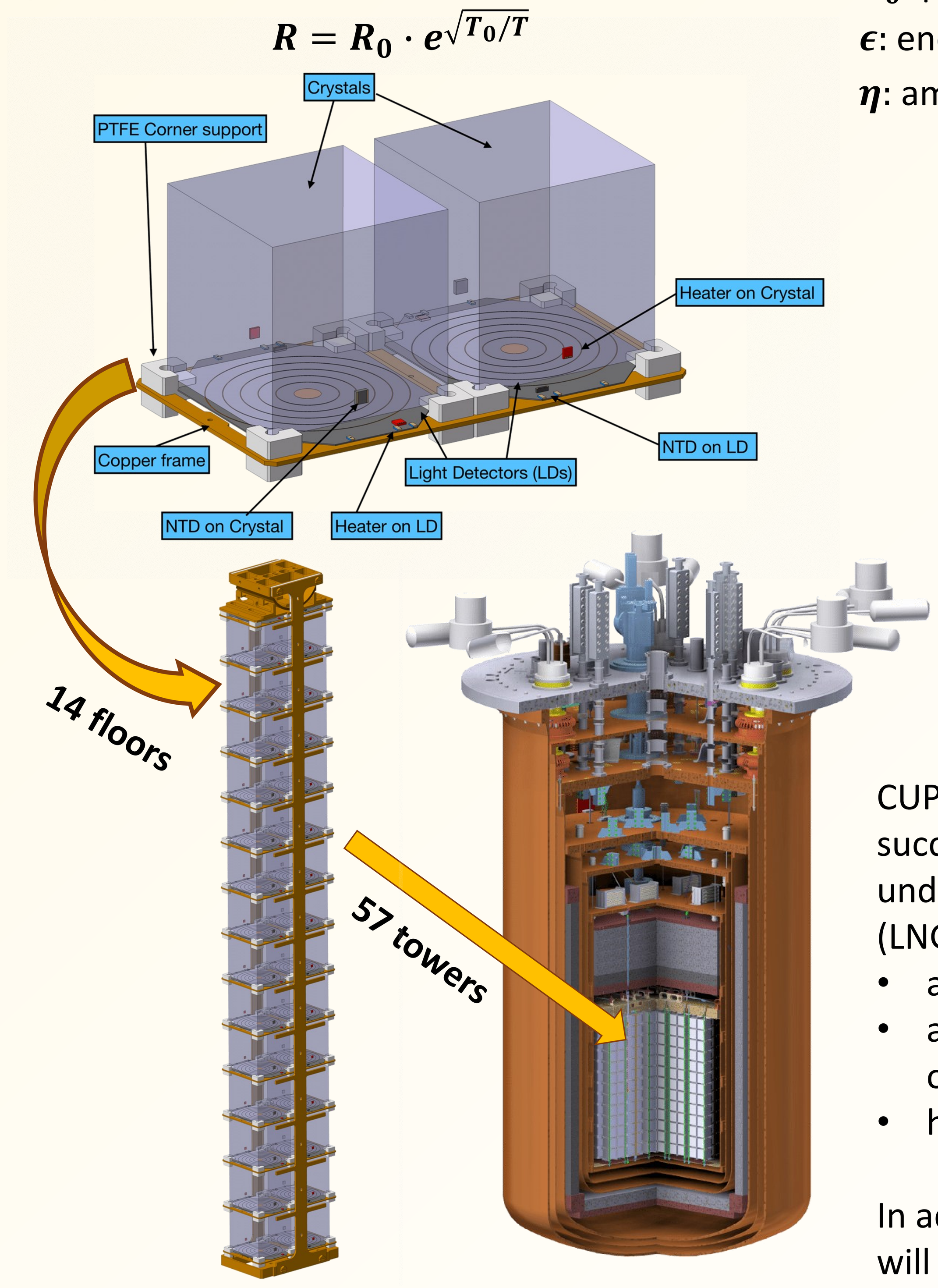
CUORE Upgrade with Particle IDentification [3]

$Li_2{}^{100}MoO_4$ crystals

- Isotope of interest: ^{100}Mo ($Q_{\beta\beta}$ = 3034 keV)
- Enrichment in ^{100}Mo > 95%
- Size of 45 x 45 x 45 mm^3
- Pre-production in China (SICCAS) is ongoing

Thermal sensor: neutron transmutation doped (NTD) Ge thermistor

$$R = R_0 \cdot e^{\sqrt{T_0/T}}$$

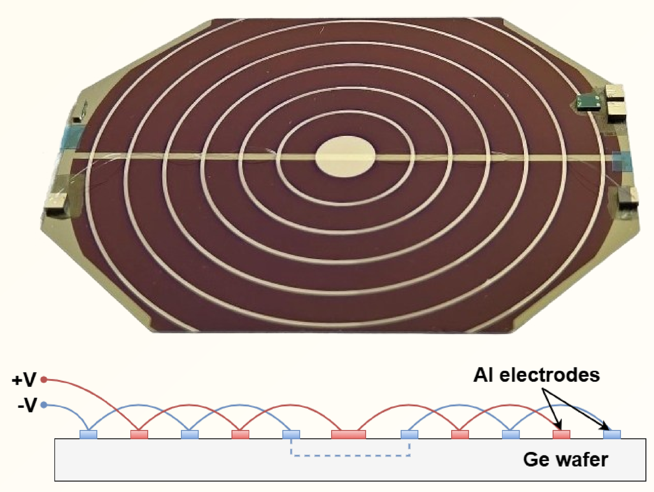


Neganov-Trofimov-Luke (NTL) light detectors [4]

- Ge wafer (operated as a bolometer) with SiO antireflecting coating (enhances light collection by ~ 30%)
- Signal enhancement due to the extra heat produced by the drift of e-h pairs in the electric field (NTL effect)

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

E_0: particle energy; q: e^- charge;
ϵ: energy required to create one of e-h pair;
η: amplification efficiency; G_{NTL}: NTL gain



- 1596 enriched $Li_2{}^{100}MoO_4$ crystals, containing **240 kg of ^{100}Mo** in total
- 1710 LDs (each crystal is facing 2 NTL LDs)

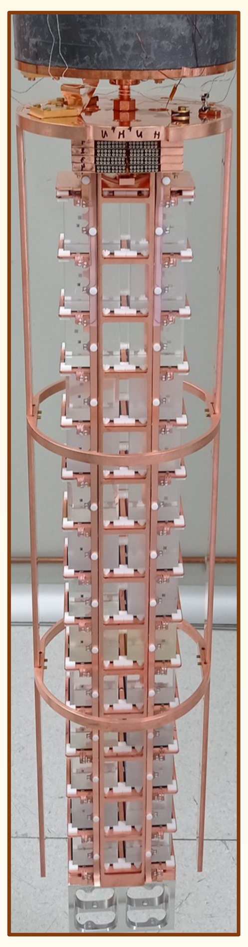
CUPID will reuse much of the technology successfully employed by CUORE located underground at the Gran Sasso National Laboratory (LNGS), Italy:

- a cryostat maintaining 10 mK for years
- a readout/DAQ system optimized for thousands of channels
- highly reliable procedures for radiopurity

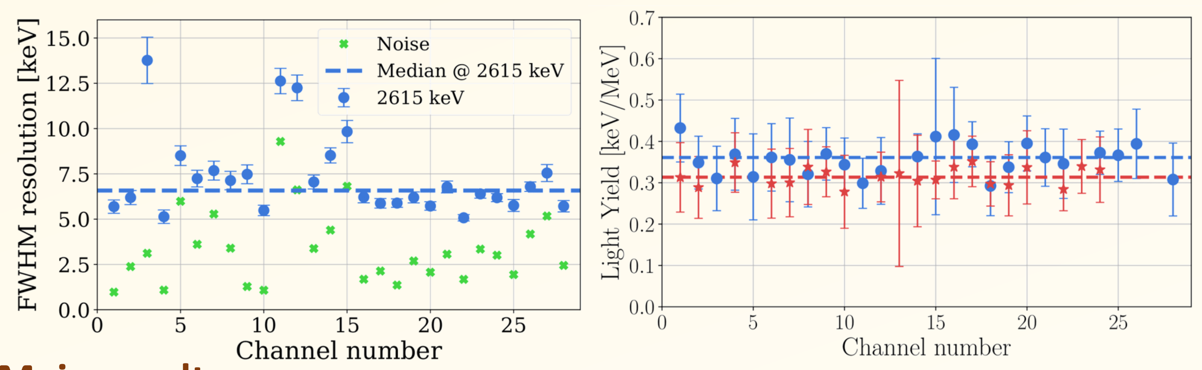
In addition, a muon-veto system & neutron shields will be installed

Detectors tests and performance

GDPT (Gravity Design Prototype Tower) [5]



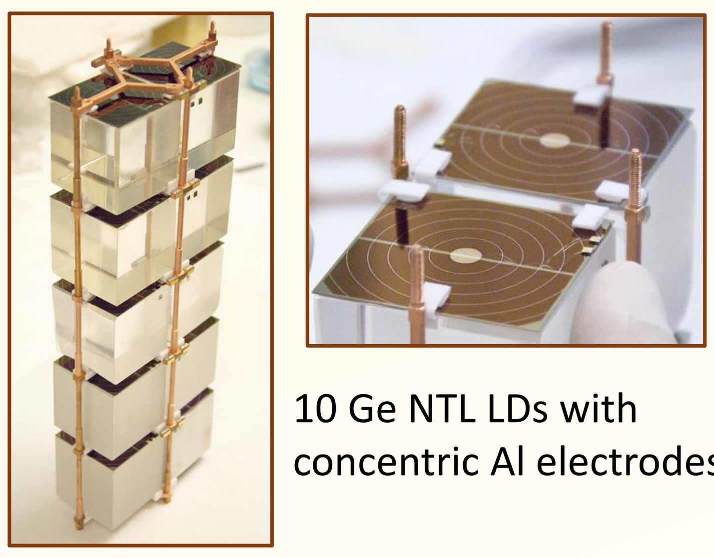
- 28 Li_2MoO_4 crystals (7 of them 98% enriched in ^{100}Mo)
- 30 Ge light detectors (no NTL), SiO coating by evaporation/sputtering
- Tested at LNGS in July-October 2022



Main results

- innovative gravity based approach, copper/LMO ratio < 20%
- good temperature stability (±0.5 mK at 10 mK)
- **(6.6 ± 2.2) keV** median FWHM @2615 keV
  (6.2 ± 1.9) keV FWHM excluding 2 test crystals ⇒ **close to CUPID target: 5 keV @ $Q_{\beta\beta}$**
- **0.36 keV/MeV** light yield (LY) measured by "close" LD
  0.31 keV/MeV LY measured by "far" LD ⇒ **fulfills the CUPID target: 0.35 keV/MeV**

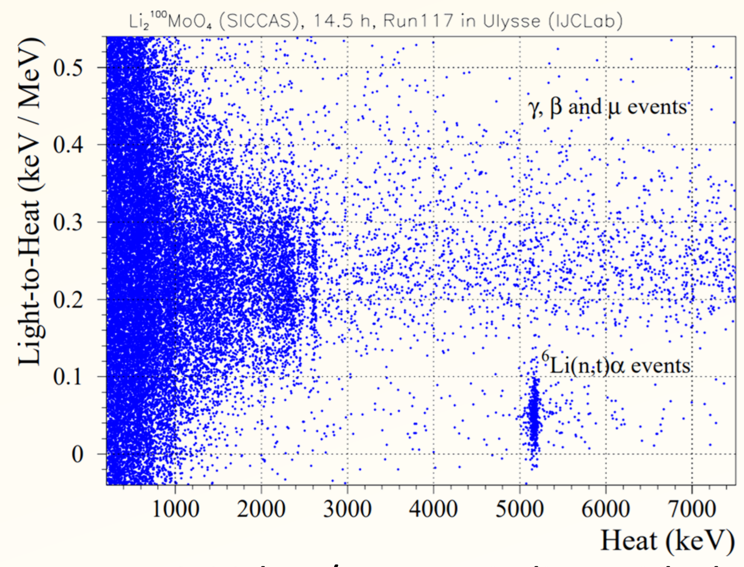
R&D on NTL LDs @ Laboratorio Subterraneo de Canfranc (LSC), Spain



10 Ge NTL LDs with concentric Al electrodes

- 8/9 can be biased > 80 V
- mean value of the effective gain G_{eff} = **8.5 at 80 V** (would be at least ~1.3 larger in CUPID at this voltage thanks to enlarged electrodes coverage)
- fast signals: rise-time close to **0.5 ms** => important for pile-up rejection

Test of 1st enriched SICCAS crystal @ IJCLab, France



Crystal size: 45 x 45 x 21 mm^3

Tested in BINGO assembly [6], with the LD (no NTL)

- LY = 0.22 keV/MeV => in line with the CUPID goal when considering the assembly configuration
- Voltage to energy conversion complies with CUPID goal

Future tests

VSTT (Vertical Slice Tower Test)

Similar to GDPT, but with NTL LDs and some modification to design to mitigate noise, under preparation

CROSS (Cryogenic Rare-event Observatory with Surface Sensitivity)

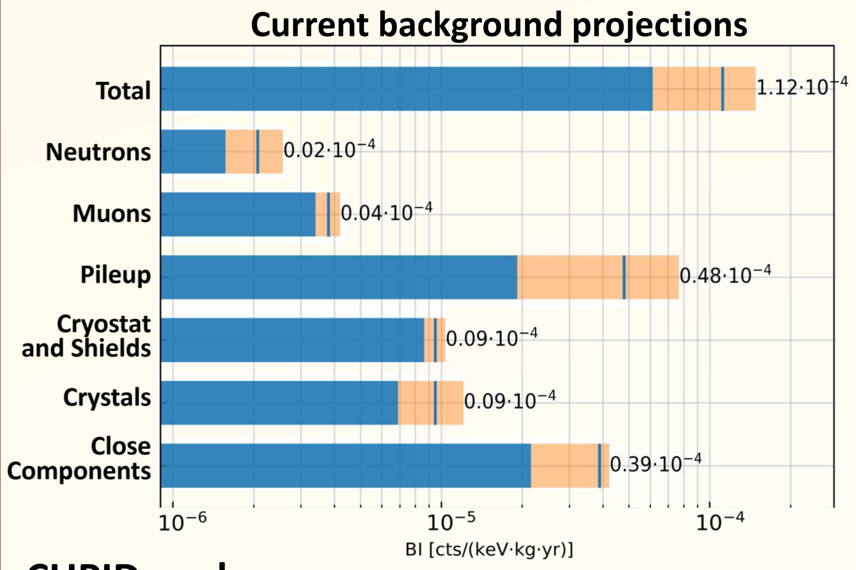
26 Ge NTL LDs will be tested, commissioning this year

CUPID background and sensitivity

Background sources and rejection

- **99.9% rejection efficiency of α particles** due to scintillating bolometers technique
- **High $Q_{\beta\beta}$ value (3034 keV)** above the bulk of γ environmental background

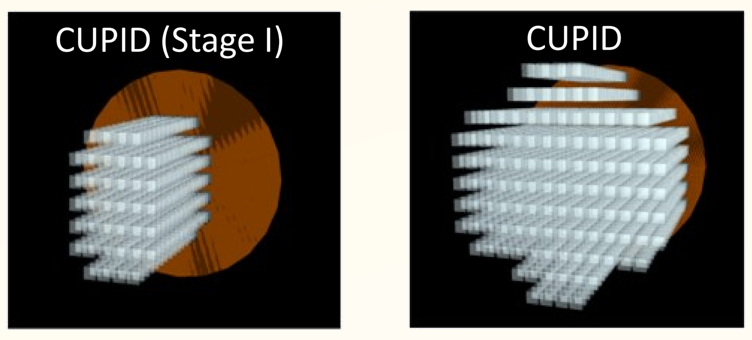
Current background projections



CUPID goal:
Background index: 1 × 10^{-4} counts/keV/kg/yr

- **Random coincidences of 2νββ events**
  $T^{2\nu\beta\beta}_{1/2}(^{100}Mo) = 7.1 \times 10^{18}$ yr is relatively fast; expected background 3.3×10^{-4} ckky ⇒ can be suppressed to 0.5×10^{-4} ckky by pulse shape discrimination of NTL LD signals [7]
- **Environmental radiation (μ, n, γ)** ⇒ reduced by LNGS overburden (3600 m. w. e.) + muon veto, shielding and anti-coincidence cut
- **Close components (detector holders, dominated by surface contamination)** ⇒ cleaning, reduction of the machining operations due to design changes
- **Crystals (dominated by surface contaminants)** ⇒ targeting zero exposure to air, anti-coincidence cut

Staged approach

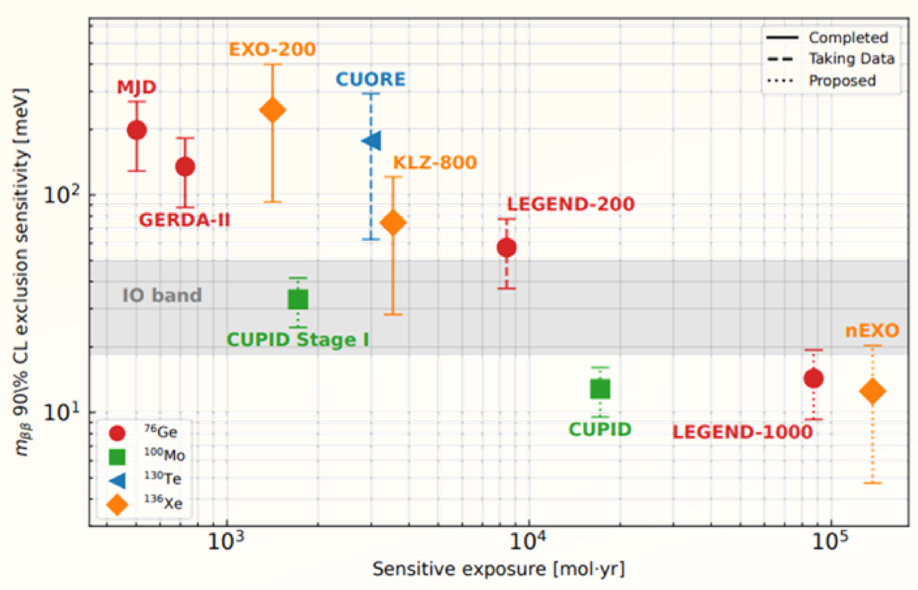


- Start of data taking with 1/3 of all crystals by 2030. Data taking for 3 years
- Start of data taking with full CUPID in 2034

Taking into account its well-established technology and robust, data-driven background predictions, **CUPID Stage I has world-leading scientific reach.**

CUPID is a ton scale experiment with competitive sensitivity and possibility of scaling (CUPID-1T [8])

Sensitivity [9]



3σ discovery sensitivity: $T^{0\nu\beta\beta}_{1/2} = 1 \cdot 10^{27}$yr, corresponding to $m_{\beta\beta} = (12 - 21)$ meV

Exclusion sensitivity (at 90% C.L.): $T^{0\nu\beta\beta}_{1/2} > 1.8 \cdot 10^{27}$yr, corresponding to $m_{\beta\beta} < (9 - 15)$ meV

References and acknowledgements

[1] Final Result on the Neutrinoless Double Beta Decay of ^{82}Se with CUPID-0 CUPID Collaboration • O. Azzolini et al. Phys.Rev.Lett. 123 (2019) 3, 032501 DOI: 10.1103/PhysRevLett.123.032501
[2] Final results on the $0\nu\beta\beta$ decay half-life limit of ^{100}Mo from the CUPID-Mo experiment. C. Augier et al. Eur.Phys.J.C 82 (2022) 11, 1033 DOI: 10.1140/epjc/s10052-022-10942-5
[3] CUPID, the CUORE Upgrade with Particle Identification. CUPID Collaboration • K. Alfonso et al. (2025) e-Print: 2503.02894
[4] Charge-to-heat transducers exploiting the Neganov-Trofimov-Luke effect for light detection in rare-event searches. V.Novati et al. NIMA 940 (2019) 320-327 DOI: 10.1016/j.nima.2019.06.044
[5] Innovating Bolometers' Mounting: A Gravity-Based Approach. CUPID Collaboration • K. Alfonso et al. (2025) e-Print: 2503.04481
[6] BINGO innovative assembly for background reduction in bolometric 0νββ experiments. A. Armatol et al. NIMA 1069, 169936 (2024) DOI:10.1016/j.nima.2024.169936
[7] Enhanced light signal for the suppression of pile-up events in Mo-based bolometers for the $0\nu\beta\beta$ decay search. A. Ahmine et al. Eur.Phys.J.C 83 (2023) 5, 373. DOI: 10.1140/epjc/s10052-023-11519-6
[8] Toward CUPID-1T. CUPID Collaboration • A. Armatol et al. (2022) e-Print: 2203.08386
[9] Sensitivity of the CUPID experiment to 0νββ decay of ^{100}Mo. CUPID Collaboration • K. Alfonso et al. (2025) e-Print: 2504.14369

This work was supported by the INFN, MUR (Italy); IN2P3, CEA, ANR (France); ERC; DOE, NSF(USA); RSF (Russia); NRF(Ukraine).