Cryogenic Bolometer Experiments for Neutrinoless Double Beta Decay: CUORE and CUPID

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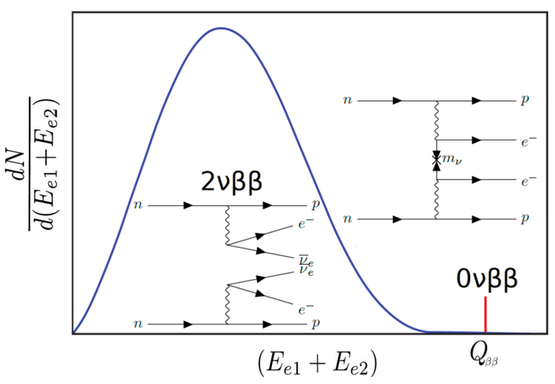
1. Searching for $0\nu\beta\beta$



Neutrinoless double-beta decay

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

$\Delta(B-L) \neq 0$ hypothetical beyond-SM process

$T_{1/2}^{0\nu\beta\beta} > 10^{24-26}$ yr not yet observed and very rare

If detected, it will contribute with:

- An example of leptogenesis mechanism ($\Delta L = 2$)
- Constraints on neutrino mass scale and hierarchy
- Hints on the Majorana nature of neutrinos ($\nu \equiv \bar{\nu}$)

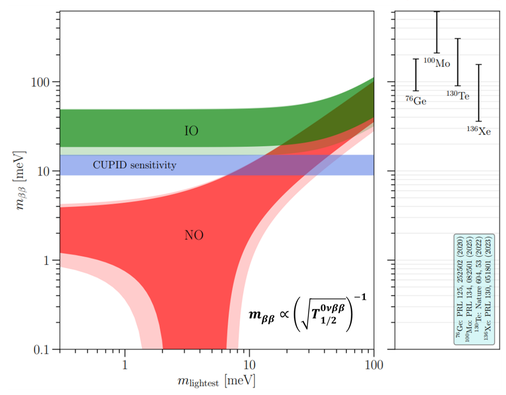
Signature

monoenergetic peak at the $Q_{\beta\beta}$ energy (~ MeV)

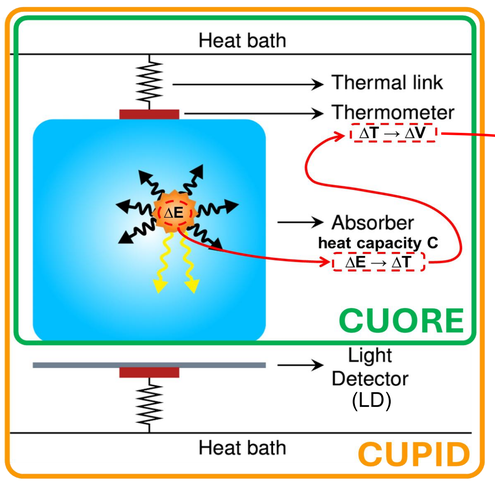
Desired features

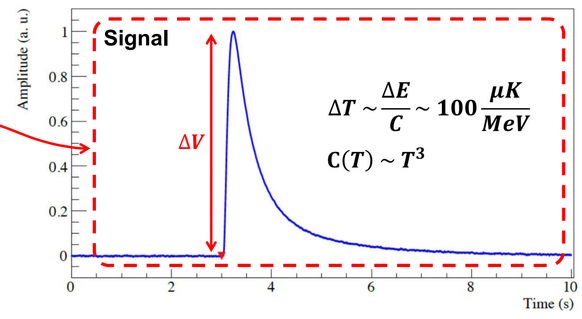
- Large isotopic abundance
- Large exposure (either mass or livetime)
- High detection efficiency
- Small background
- Good energy resolution

Alfonso, K. et al. (CUPID Collaboration), Eur. Phys. J. C 85, 737 (2025)



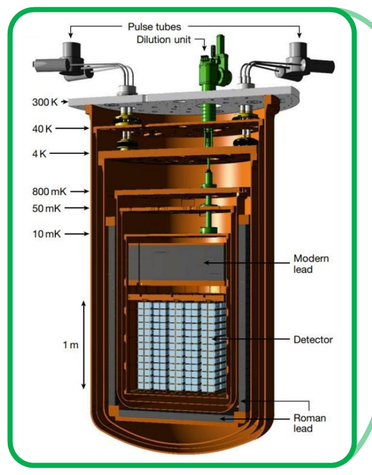
2. Bolometers



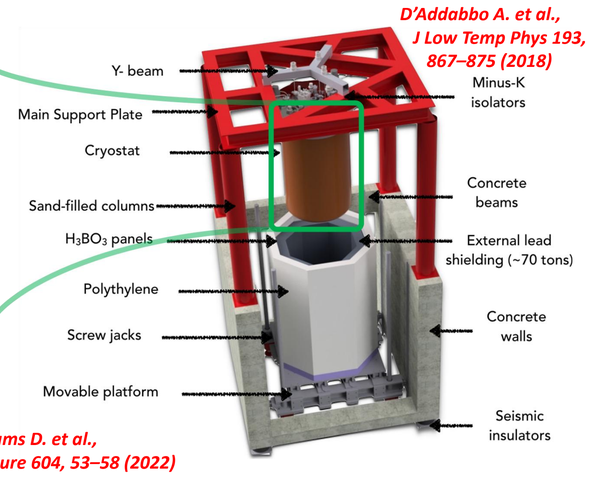


CUORE/CUPID is an ongoing/next-generation cryogenic experiment at tonne-scale searching for 0νββ decay and other rare events. They deploy ~1000 crystals kept at very low temperatures (~10 mK), acting both as sources and detectors.

3. Infrastructure



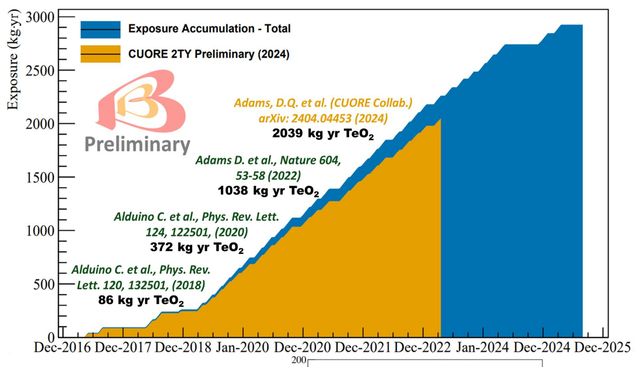
Adams D. et al., Nature 604, 53–58 (2022)

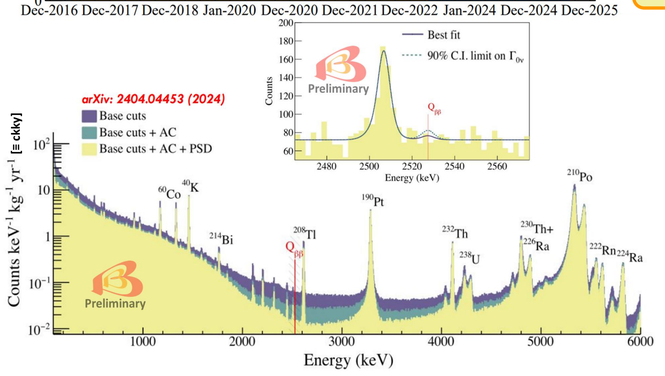


D'Addabbo A. et al., J Low Temp Phys 193, 867–875 (2018)

CUORE's custom-built dry dilution cryostat is located underground, at the INFN Gran Sasso National Laboratory (Italy), providing ~3600 m.w.e. of natural shielding from cosmic rays. Similarly, CUPID will use the same infrastructure and cryostat. However, to achieve the desired performance, it will undergo several upgrades in the following years.

4. The CUORE Experiment





- ^{130}Te isotope, $Q_{\beta\beta}$ = 2527.5keV
- TeO_2 natural crystals
- 988 instrumented crystals
  - ➔ 206 kg of ^{130}Te
- Ge-NTD sensor glued to the crystal
  - ➔ sensitive from keV to MeV
  - ➔ $\Delta E/E \sim 0.3\%$ @ $Q_{\beta\beta}$
- Background index ~ 10^{-2} ckky

$T_{1/2}^{0\nu\beta\beta} > 3.8 \times 10^{25}$ yr (90% C.I.) *arXiv:2404.04453* 2 tonne-yr limit

Low-Frequency Noise

Vibrational noise and noise instabilities play an important role in the low-frequency range where the thermal pulses live, ~Hz

- raise the energy threshold
- worsen the energy resolution
- induce non-physical events at low energies

➔ denoising technique and filters

Reliable Background Model

CUORE backgrounds are well understood but they are also its limitation: mainly due to degraded α.

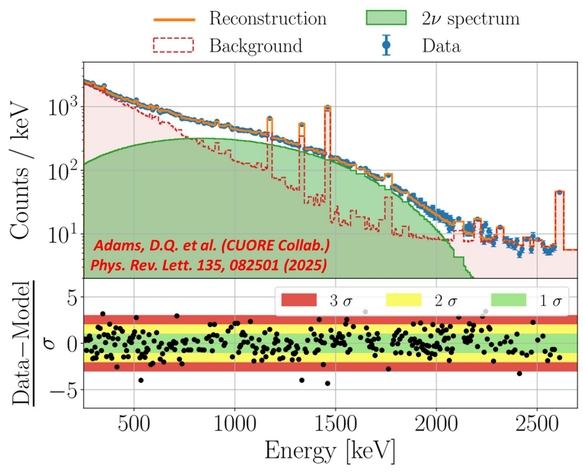
The detector segmentation enables:

- event multiplicity tag
- source location

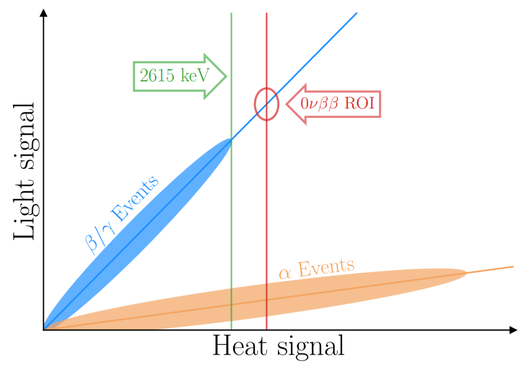
➔ A recent result is the most precise measurement of $T_{1/2}^{2\nu\beta\beta}$ for ^{130}Te so far

$T_{1/2}^{2\nu\beta\beta} = \left(9.32\ ^{+0.05}_{-0.04}\ \text{stat.}\ ^{+0.07}_{-0.07}\ \text{syst.}\right) \times 10^{20}$ yr

Spectrum reconstructed by simultaneous fit of data with MC simulated sources, CUORE geometry and detector response



5. The CUPID Experiment



CUPID baseline

- Different Isotope: ^{100}Mo
- Double Readout (heat+light)
  - ➔ 1596 scintillating bolometers Li_2MoO_4 with NTD sensors 95% enriched in ^{100}Mo (240 kg of ^{100}Mo)
  - ➔ 1710 Ge-wafer LDs NTL amplification
- 10 yr of livetime
- ΔE of 5keV FWHM @ $Q_{\beta\beta}$
- Background index ~10^{-4} ckky
- $T_{1/2}^{0\nu\beta\beta} > 1.0 \times 10^{27}$ yr (90% C.L.)

Reducing the background index

A value ~ 10^{-4} ckky is achievable with:

- Upgrades
  - ➔ New muon tagger veto detectors
  - ➔ Pulse tubes upgrade and thermalisation optimisation
  - ➔ New diagnostic devices
- α vs. β/γ discrimination
  - ➔ requires LY ~ 0.3 keV/MeV
- pile-up rejection from $2\nu\beta\beta$ random coincidences
  - ➔ $T_{1/2}^{2\nu\beta\beta} = 7.1 \times 10^{18}$ yr
- lower γ-induced background
  - ➔ $Q_{\beta\beta}$ = 3034 keV

6. Pavia Group Activities

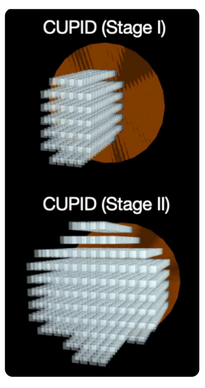
Optical Injection System for CUPID

- Onsite/Offsite shift
- Simulations
- Data Analysis
- R&D

Data analysis for the 3TY of CUORE

- Mid-level Analysis

7. The Road Ahead



2026 CUORE - 3 tonne·yr limit
Cryogenic system upgrades
CUORE phase 2 ➔ higher sensitivity for low energy signatures
➔ test of the upgrades

2030 CUPID Stage I ➔ deployment of 1/3 of the total crystals

2034 CUPID Stage II ➔ full array deployment

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