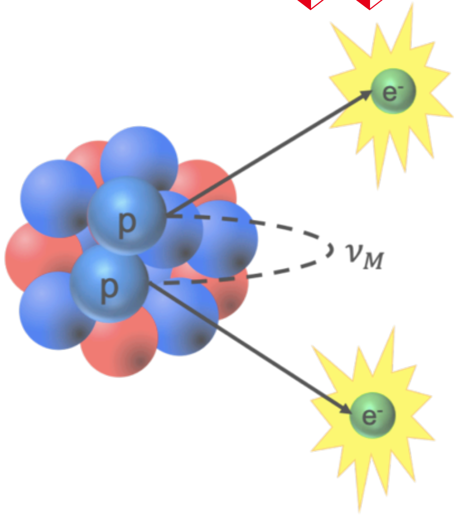


CUPID:
the next generation 0νββ bolometric experiment

Claudia Nones

On behalf of the CUPID collaboration

CUPID

Outline

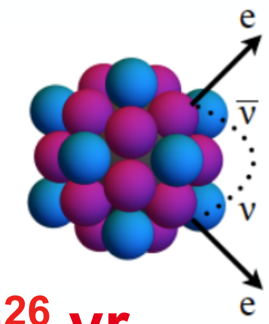
- Double beta decay → promising isotopes
- The bolometric technique → from CUORE to CUPID
- CUPID precursors and CUPID structure
- CUPID experimental tests
- Background and sensitivity
- Conclusions

Nuclear Double Beta Decay

- Double Beta Decay is the **rarest nuclear weak process**
- It takes place between **two even-even isobars**

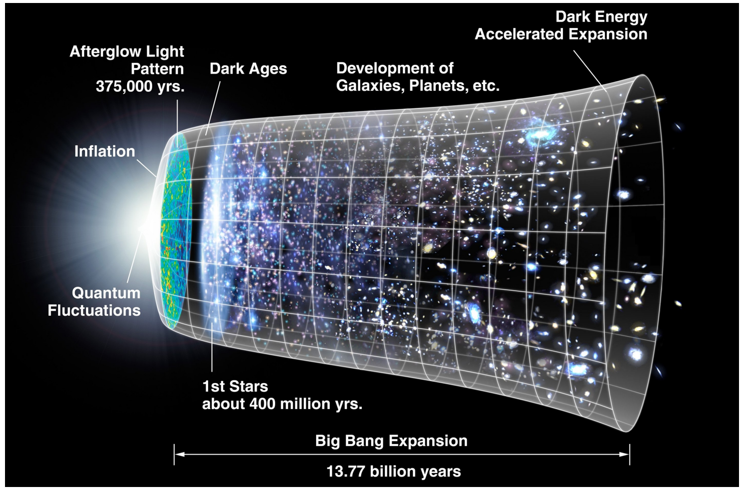
$$(A,Z) \rightarrow (A,Z+2) + 2e^- + (\ldots)$$

If only electrons and nothing else:



- Need to find single events in a ton of isotope x year(s) of exposure!
- 3 x 10^{-11} Bq/kg vs 15 Bq/banana !
- We go to extreme length to limit ubiquitous radioactivity

Half-life larger > 10^{25} yr - 10^{26} yr



x 10^{15}

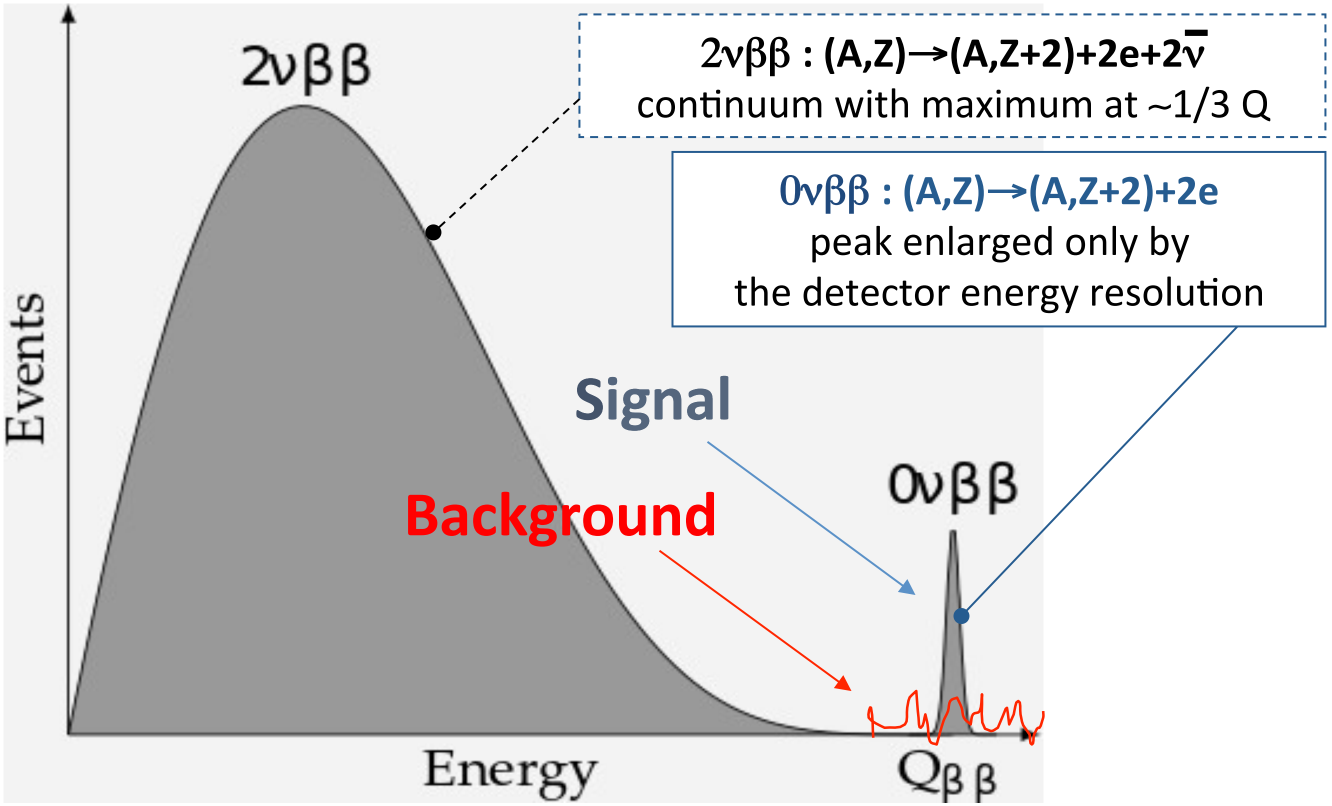
Very hard, but the reward is great:

- Lepton number non conservation
- Creation of matter with no antimatter counterpart
- Majorana nature of neutrinos
- Neutrino mass scale

Nuclear Double Beta Decay

Sum energy spectrum of the two electrons

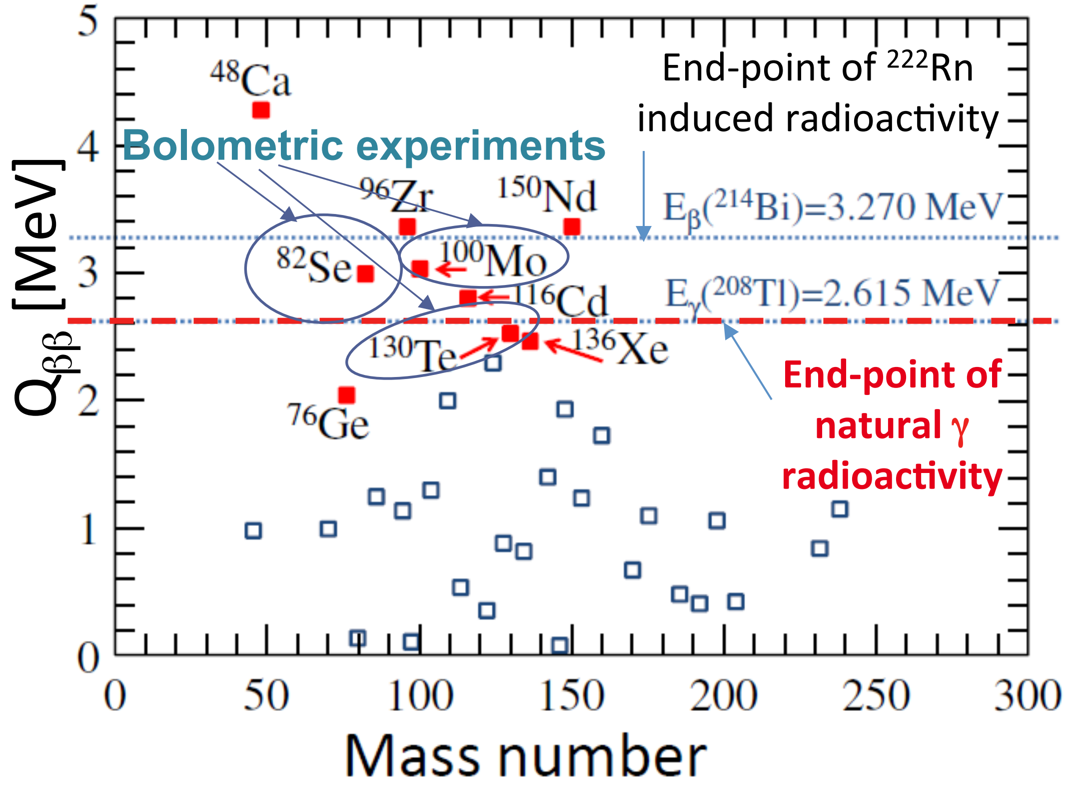
$Q_{\beta\beta}$: energy available for the products



Possible for 35 nuclei

Only **9** are **experimentally relevant**

$Q_{\beta\beta}$ **~ 2-3 MeV** for the most promising candidates



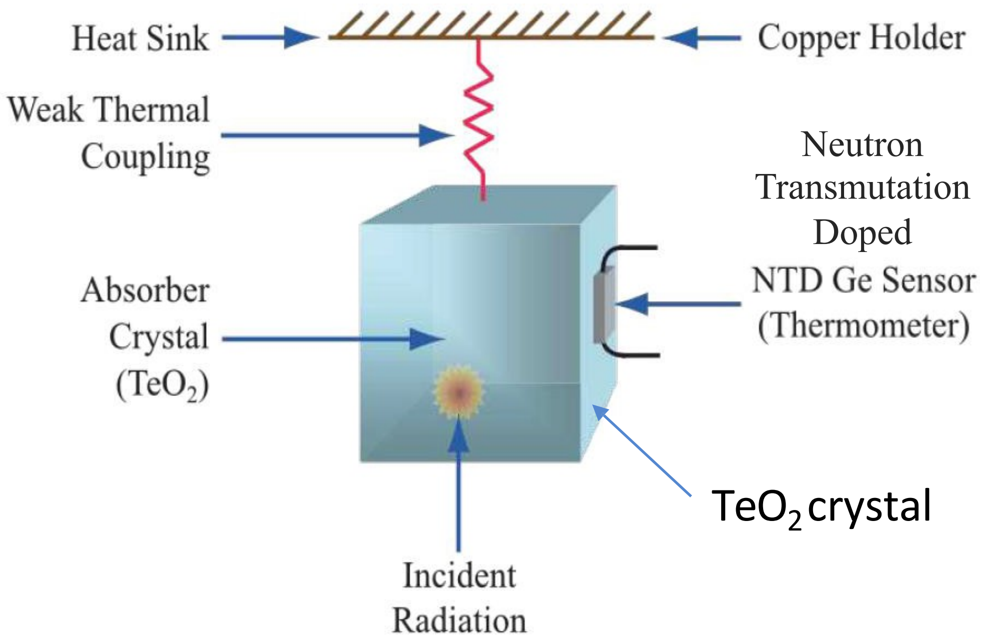
The bolometric technique: CUORE

CUORE ^{130}Te

pure thermal detector

(**bolometer**)

T ~ 10 mK



No PID

Q = 2527 keV < 2615 keV

No enrichment: ^{130}Te I.A. ~34%

The bolometric technique: CUORE

CUORE ^{130}Te

pure thermal detector

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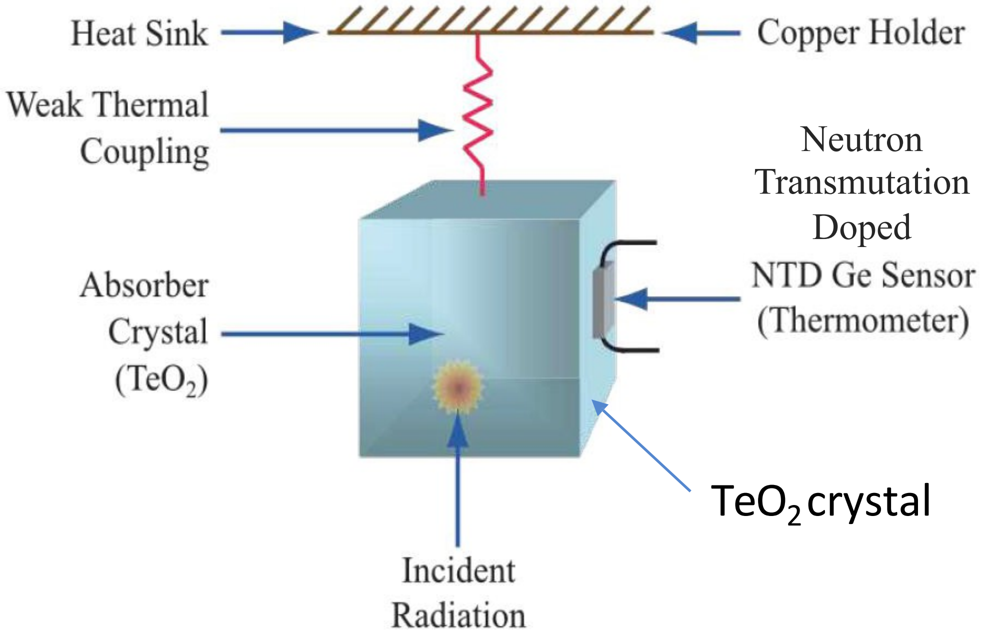
T ~ 10 mK



No PID

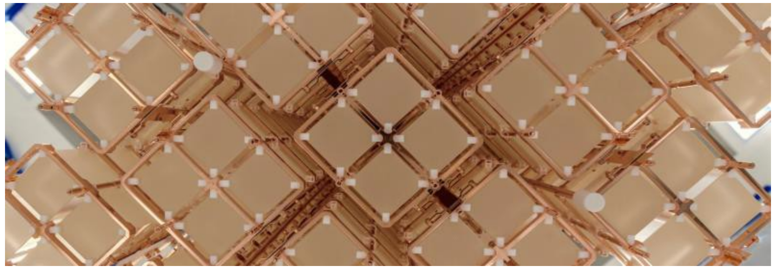
Q = 2527 keV < 2615 keV

No enrichment: ^{130}Te I.A. ~34%

CUORE - Cryogenic Underground Observatory for Rare Events

- Located in Gran Sasso, Italy
- Main objective: $0\nu\beta\beta$ in ^{130}Te
- 988 TeO_2 crystals, 5x5x5 cm^3 each
- Total mass: 742 kg TeO_2 (natural Te)
- ^{130}Te mass: 206 kg
- Current analysed exposure: 2023 kg y
- **$T_{1/2}^{0\nu} > 3.33 \times 10^{25}$ yr at 90% C.I.**
- **$m_{\beta\beta} < 75 - 260$ meV at 90% C.I.**

New released results @TAUP2023

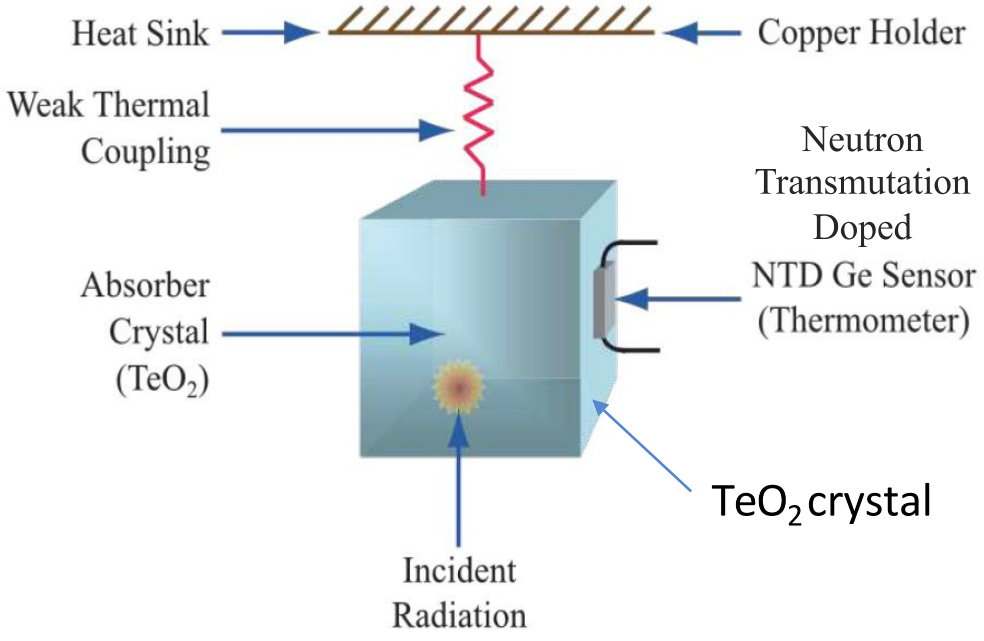


α background → $b \sim 10^{-2}$ c/(keV kg y)

γ background → $b \sim 10^{-3}$ c/(keV kg y)

The bolometric technique: from CUORE to CUPID

CUORE ^{130}Te
pure thermal detector
(**bolometer**)
T ~ 10 mK

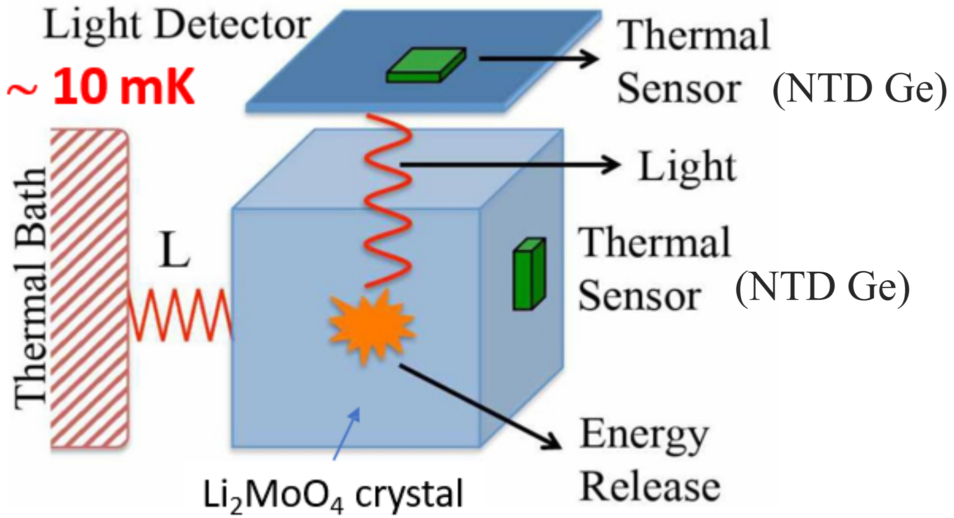


TeO_2 crystal

No PID
Q = 2527 keV < 2615 keV
No enrichment: ^{130}Te I.A. ~34%

CUPID ^{100}Mo
heat + light
(**scintillating bolometer**)

T ~ 10 mK



Li_2MoO_4 crystal

~~α background~~ ← **PID**
~~γ background~~ ← **Q = 3034 keV**
> 2615 keV

Goal: b~10^{-4} c/(keV kg y)
Enrichment in ^{100}Mo is possible on large scale

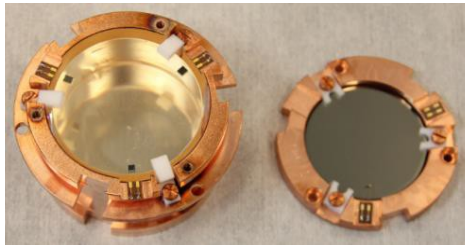
CUPID precursors

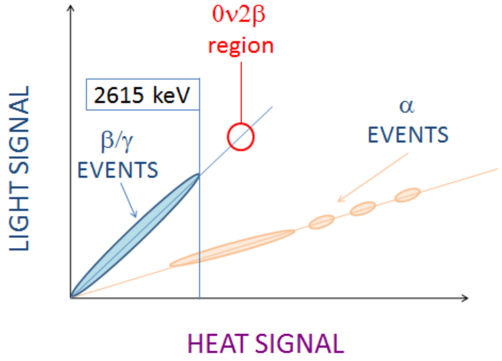
Scintillating bolometers

↓

PID: α particle rejection

Main crystal — Light detector





CUPID-0 – Zn^{82}Se $Q_{2\beta}$ = 2998 keV

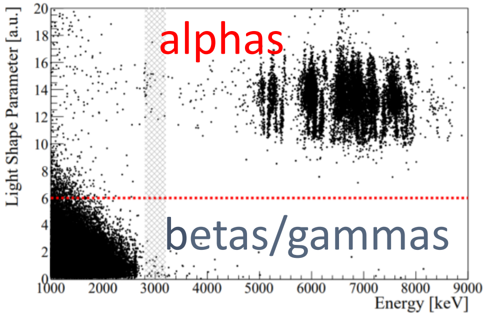
(evolution of LUCIFER erc)

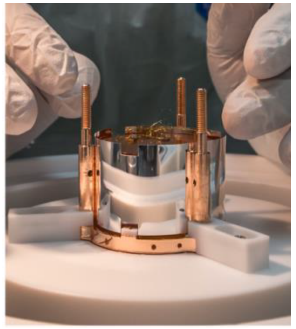
First running demonstrator

24 crystals (enriched in ^{82}Se) – 5.28 kg ^{82}Se

Best limit on ^{82}Se: $T_{1/2} > 4.7\times10^{24}$ y

Energy resolution: **~23 keV FWHM**





LNGS – Italy

b = 3.5 × 10^{-3} counts/(keV·kg·yr)

Useful information for the CUPID background model

Direct proof that α's dominate background above 2.6 MeV

CUPID-Mo – Li$_2$^{100}MoO$_4$ $Q_{2\beta}$= 3034 keV

(evolution of LUMINEU ANR)

Physics data taking: April 2019 – June 2020

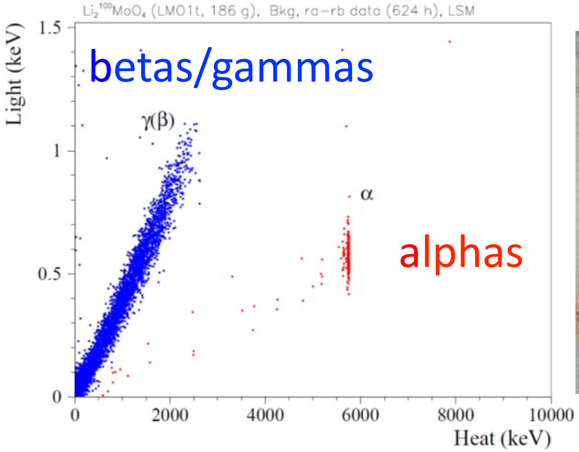
20 crystals (enriched in ^{100}Mo) – 2.34 kg ^{100}Mo

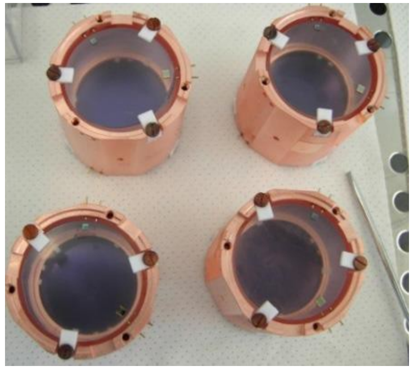
Energy resolution: ~ **5-7 keV FWHM**

Best limit on ^{100}Mo: $T_{1/2} > 1.8\times10^{24}$ y

Full α rejection

Radiopure crystals: U/Th ≤ 1 μBq/kg





LSM – France

b = 2.7 × 10^{-3} counts/(keV·kg·yr)

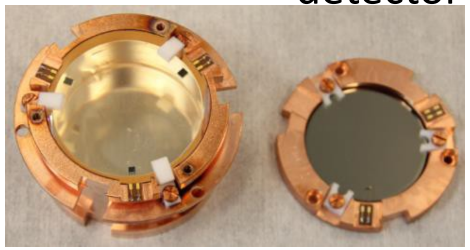
In non-optimized cryostat

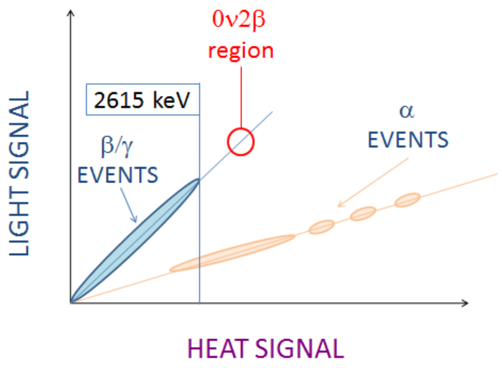
CUPID precursors

Scintillating bolometers

↓

PID: α particle rejection





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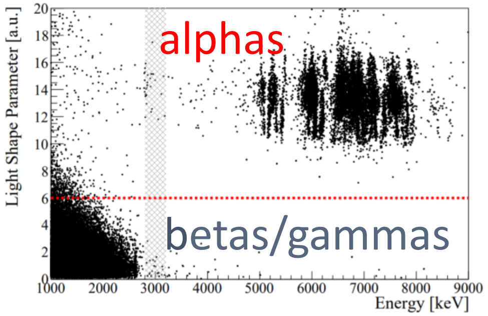
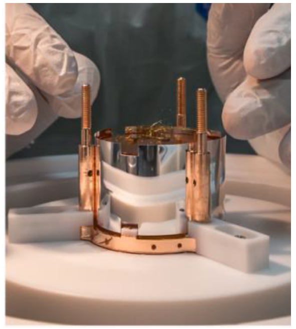




LNGS – Italy

b = 3.5 × 10^{-3} counts/(keV·kg·yr)

Useful information for the CUPID background model

Direct proof that α's dominate background above 2.6 MeV

CUPID-Mo – Li$_2$^{100}MoO$_4$ $Q_{2\beta}$= 3034 keV

(evolution of LUMINEU)

Physics data taking: April 2019 – June 2020

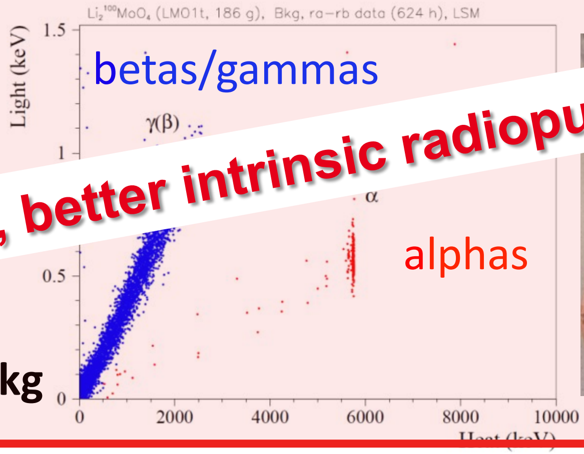
20 crystals (enriched in ^{100}Mo) – 2.34 kg ^{100}M

Energy resolution: ~ **5-7 k**

Best limit ... 10^{24} y

... **Radiopure crystals: U/Th ≤ 1 μBq/kg**

Choice for CUPID: better energy resolution, better intrinsic radiopurity, mature crystal technology



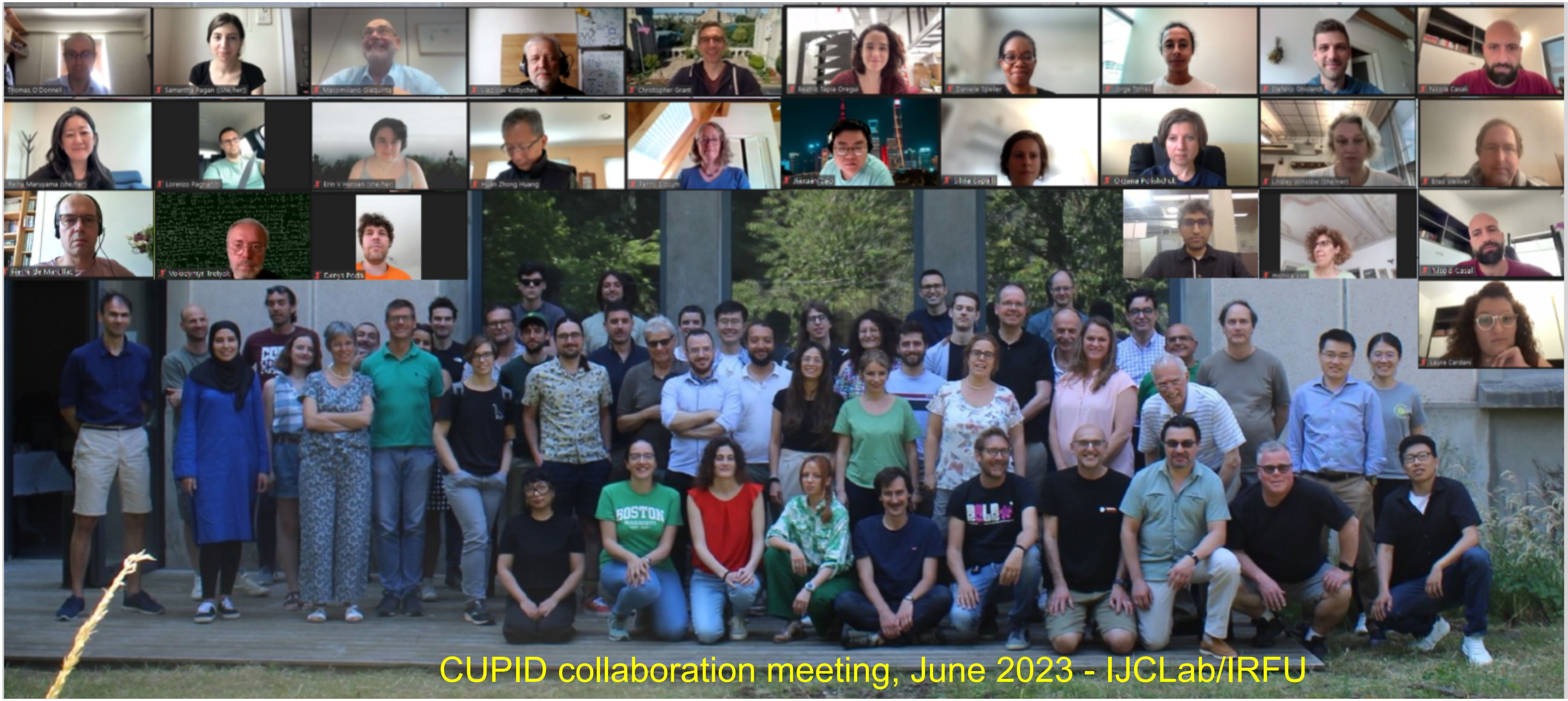
LSM – France

b = 2.7 × 10^{-3}

In non-optimized cryostat

The CUPID collaboration

7 countries
~180 members



The CUPID experiment in a nutshell

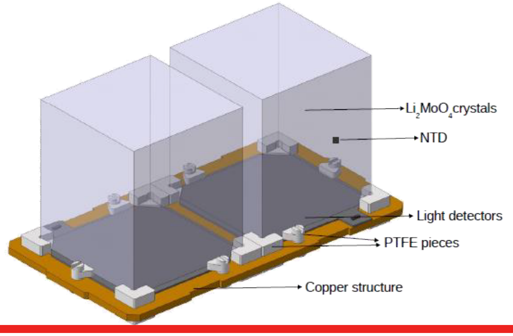
CUPID pre-CDR ***arXiv:1907.09376*** **upgrade to CDR ongoing**

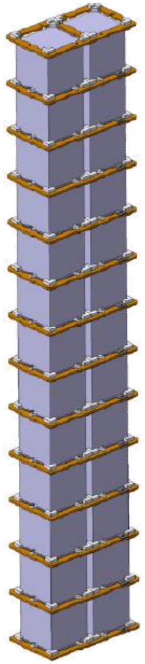
- Single module:
  - 2 x $Li_2{}^{100}MoO_4$ **45×45x45 mm – ~ 280 g**
  - 2 x Ge light detectors
- 57 towers of 14 floors with 2 crystals each - **1596 crystals**
- **~240 kg of ^{100}Mo** with >95% enrichment (**~1.6×10^{27}** ^{100}Mo atoms)
- **1710 Ge light detector** (CUPID-Mo, CUPID-0 basic technology + Neganov-Trofimov-Luke effect)

Baseline design

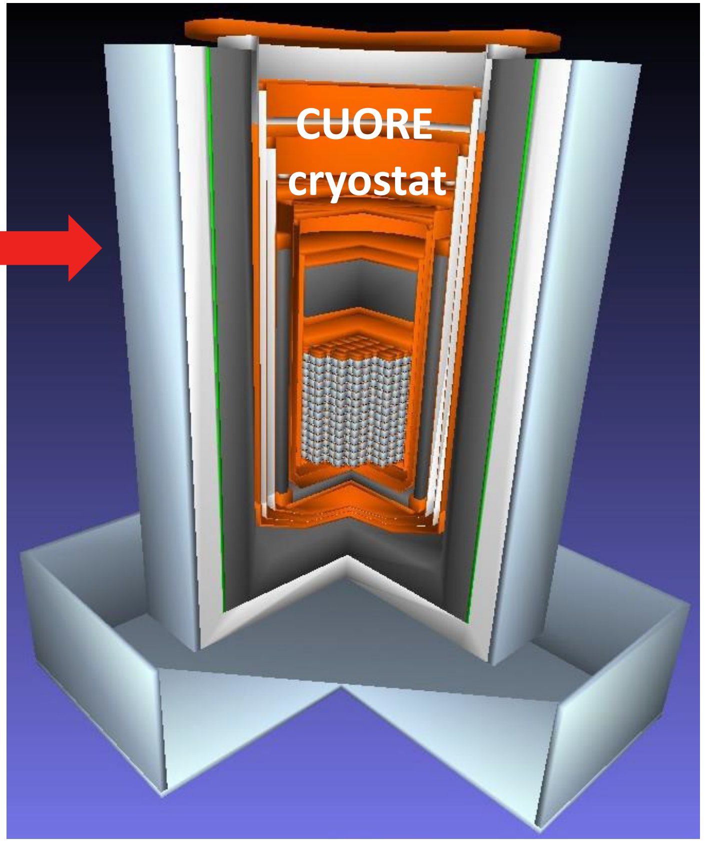
Gravity stacked structure

(innovative approach with respect to CUORE and CUPID precursors)





Ton-scale array of high-resolution cryogenic calorimeters to search for $0\nu\beta\beta$ and other rare events



CUPID objectives

- Energy resolution at $Q_{\beta\beta}$: ≤ 5 keV FWHM
- Light signal: 0.3 keV/MeV
- Light detector baseline resolution: ≤ 100 eV RMS (for PID)
- Light detector timing resolution: ≤ 0.17 ms (for pile-up)
- Background index: ≤ 10^{-4} counts/(kg keV yr)
- $0\nu\beta\beta$ half-life exclusion sensitivity (90% C.L.): 1.4×10^{27} yr

Test of the tower structure

A prototype single CUPID tower was cooled down in July and October 2022 in LNGS

The tower was installed in the Cuoricino-CUORE0-CUPID-0 cryostat

- **Primary goal**: validate the tower structure in terms of assembly procedure, **detector temperature values and distribution**
- **Secondary goals**: Analysis of **detector performance** - Study of the **crystal radiopurity** – Dependence of detector behavior on **glue type**, **crystal origin**, **light-detector coating** method

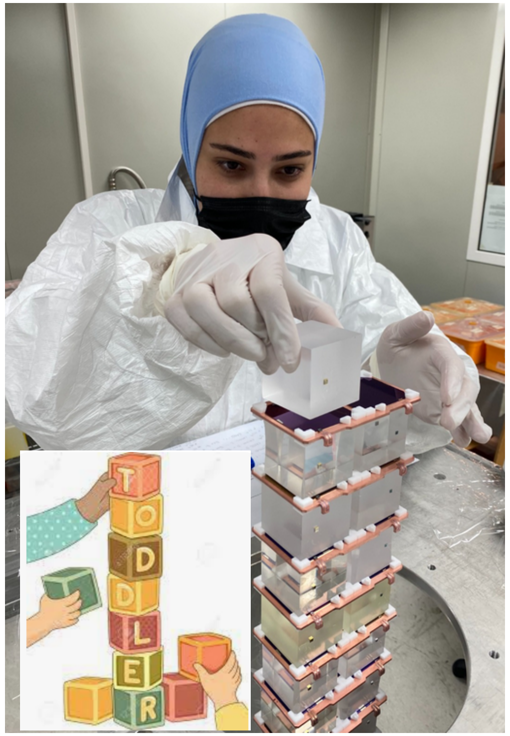
14-floor tower run

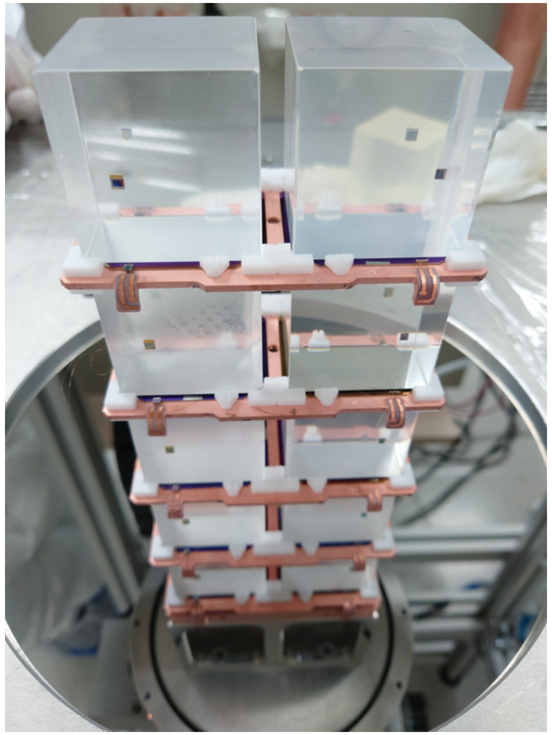
- 28 LMO crystals
- 30 Ge light detectors

The primary goal is achieved - All the channels cool down without problems with a reasonably narrow temperature distribution and no dependence on the position in the tower

→ **The thermal scheme of the tower is validated**

LMO: 7-8 keV FWHM @$Q_{\beta\beta}$
LD: 180 eV median RMS
New test in the coming months



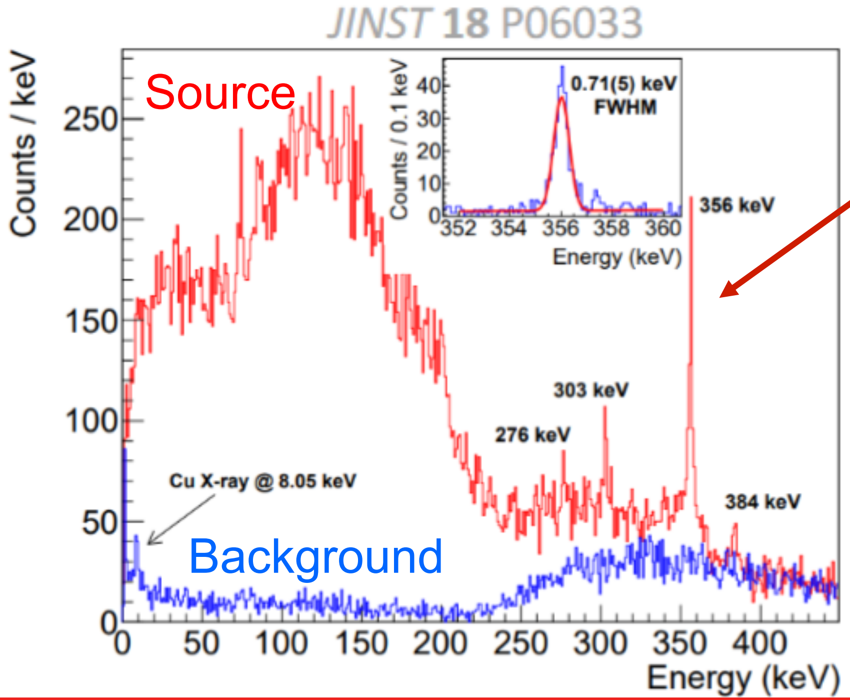


Test of the light-detector structure

The **validation of the new CUPID-baseline light-detector assembly** performed in a pulse-tube cryostat at IJCLab (Orsay)

→ Similar vibrational noise as in CUORE/CUPID cryostat

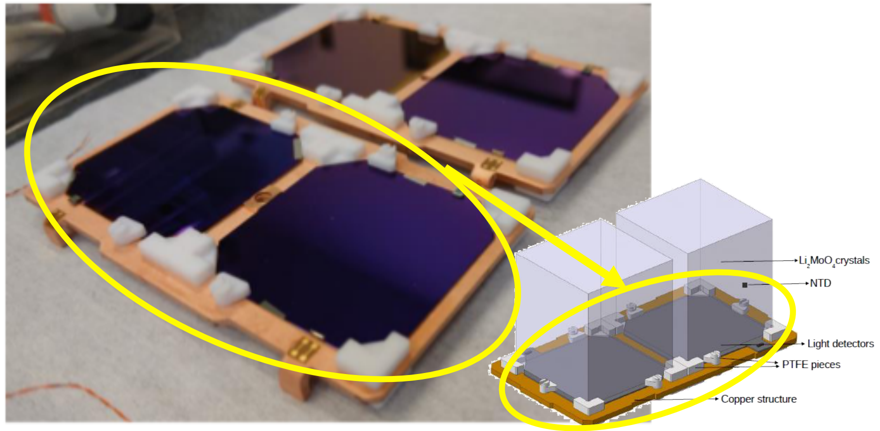
- 2 Cu frames with 2 light detectors each (0.5 mm in thickness) mounted on top of each other (CUPID configuration)
- Check of the bolometric performance
- **Baseline energy resolution 70-90 eV RMS (CUPID goal for PID met)**

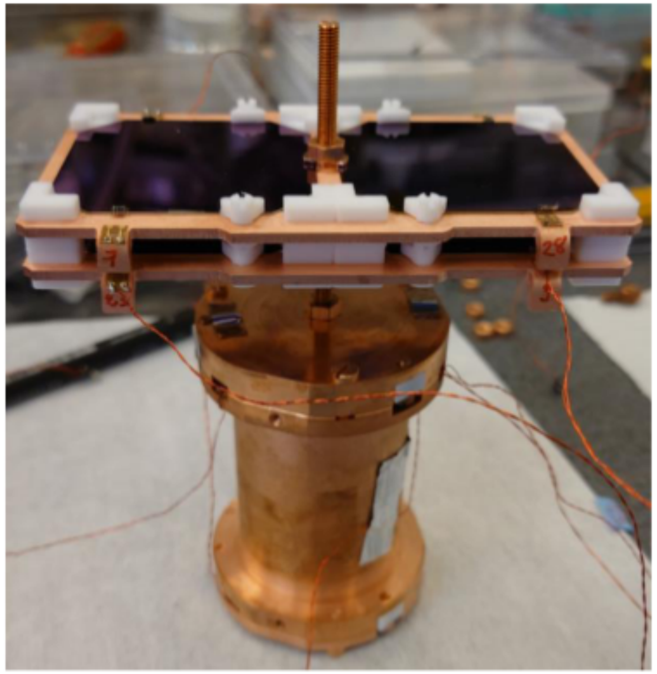


Light detector calibration

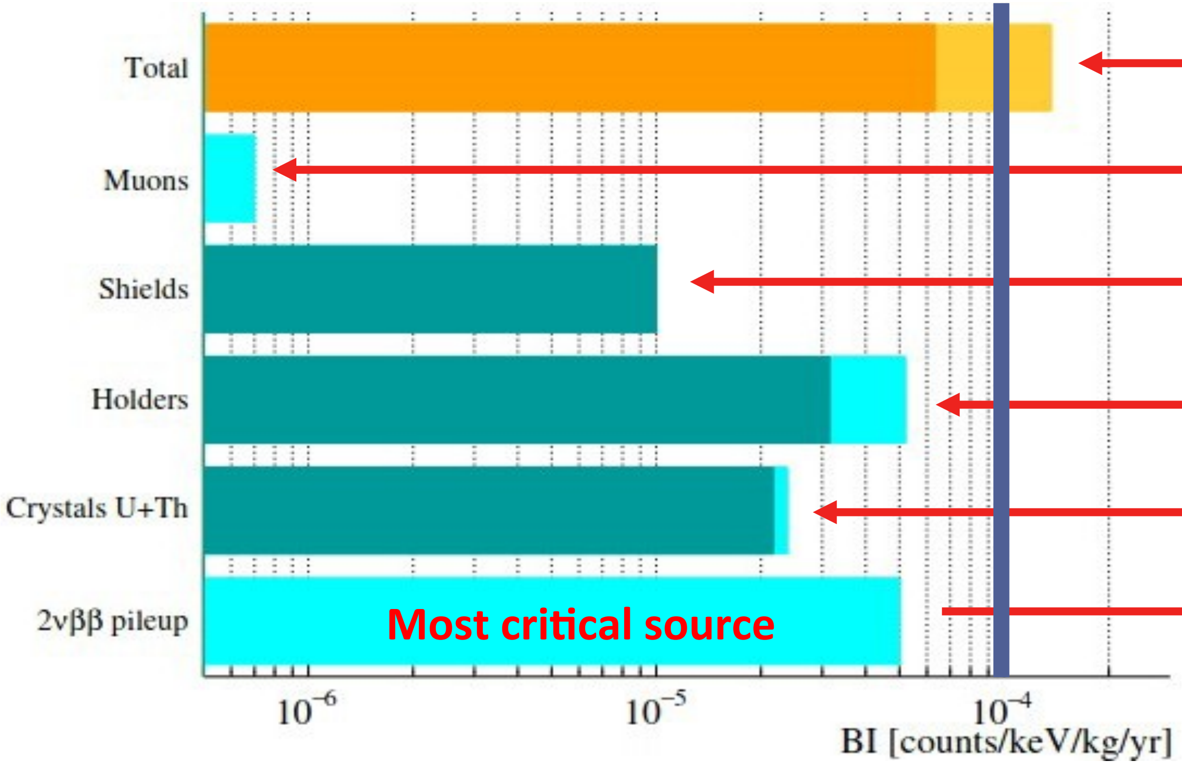
Irradiating the detector with a ^{133}Ba source we achieved an outstanding energy resolution:

0.71 keV FWHM at **356 keV**





CUPID background

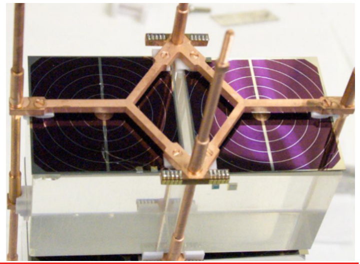


Projected background index: **b=1x10^{-4} counts/(keV·kg·yr)**

Muon veto is required and it is **under design**

Well-known from CUORE and CUPID precursors
(infrastructure background measured in situ by CUORE)

Validated by **CUPID-Mo background model**



Random coincidence of 2ν2β events
($T_{1/2}^{2\nu2\beta}$ = 7.1×10^{18} y → 3 mHz in a CUPID crystal)
Pulse shape discrimination to reject pile up
Exploit faster light channels

- **CUPID light-detector baseline: standard light detector with signal enhanced x10 by Neganov-Trofimov-Luke effect (IJCLab, Orsay)**
  Required performance demonstrated on 8 light detectors in Canfranc
  Baseline energy resolution ~ 6 eV RMS – Risetime ~ 0.5 ms
  → Correspond to pile-up resolution of **~ 0.17 ms (CUPID goal)**
- **Alternative option for light detectors: TES readout (Berkeley)**

CUPID sensitivity

Energy resolution: **5 keV FWHM**

Background index: **1 × 10^{-4} counts/(keV·kg·y)**

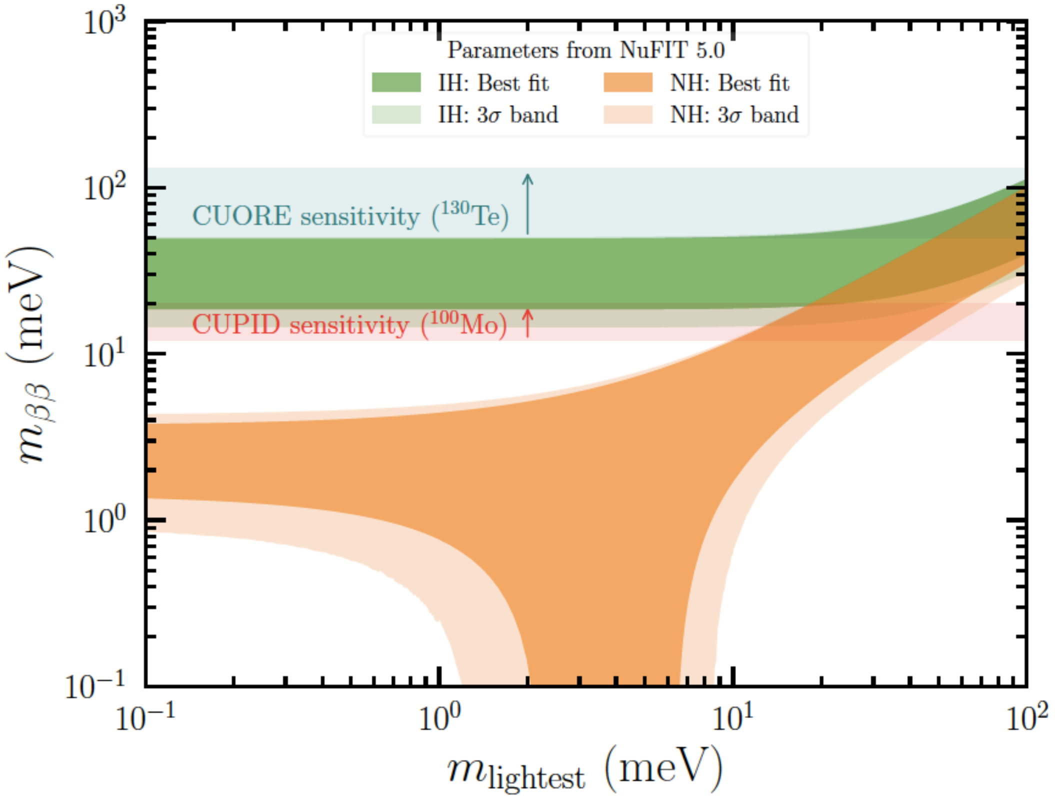
Livetime:**10 y**

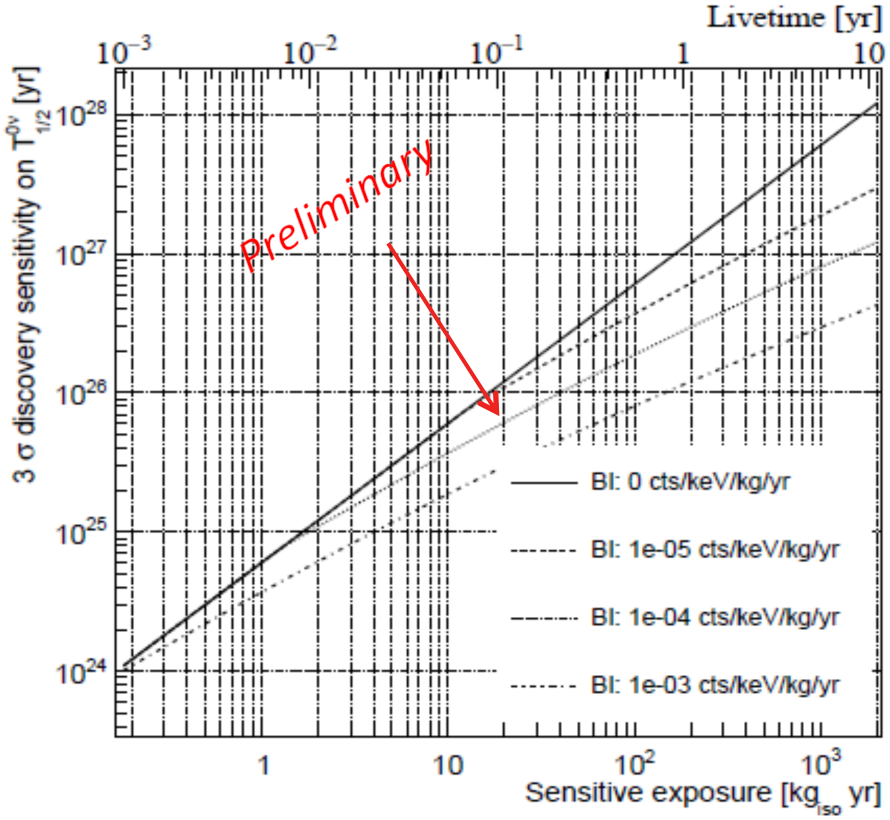
Half-life exclusion sensitivity

1.4 × 10^{27} y – m$_{\beta\beta}$ < 10-17 meV

Half-life 3σ discovery sensitivity

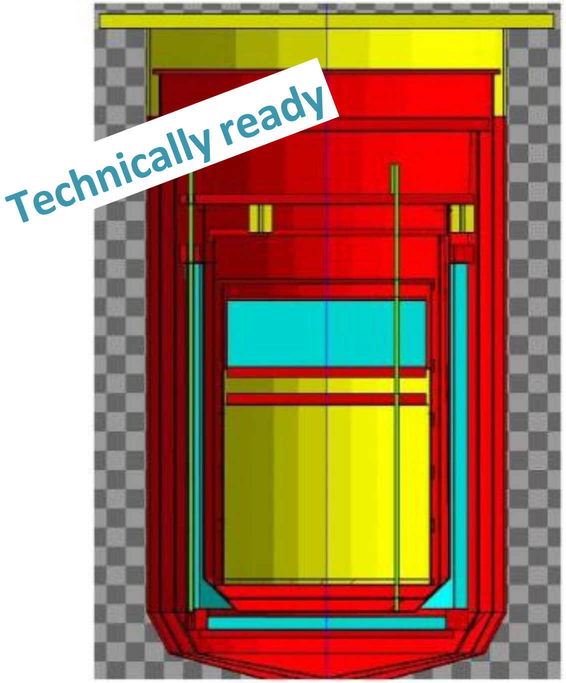
1 × 10^{27} y – m$_{\beta\beta}$ < 12-20 meV





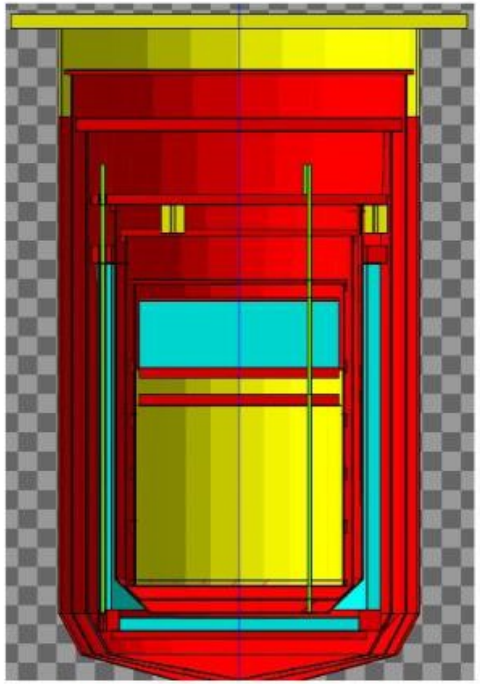
CUPID sensitivity: a phased approach

CUPID Baseline



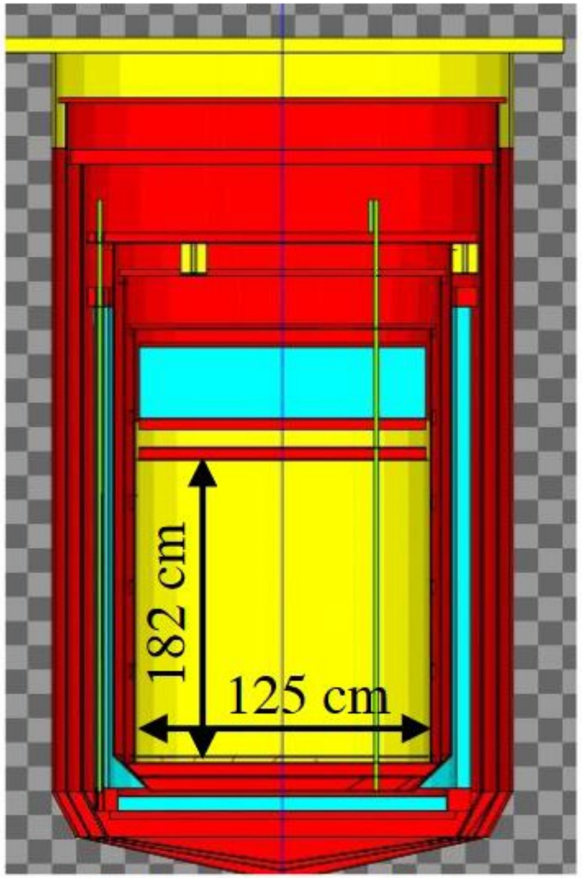
240 kg of ^{100}Mo
CUORE cryostat
Bkg 1×10^{-4} ckky
Excl. sensitivity:
$T_{1/2} > 1.4 \times 10^{27}$ y

CUPID-reach

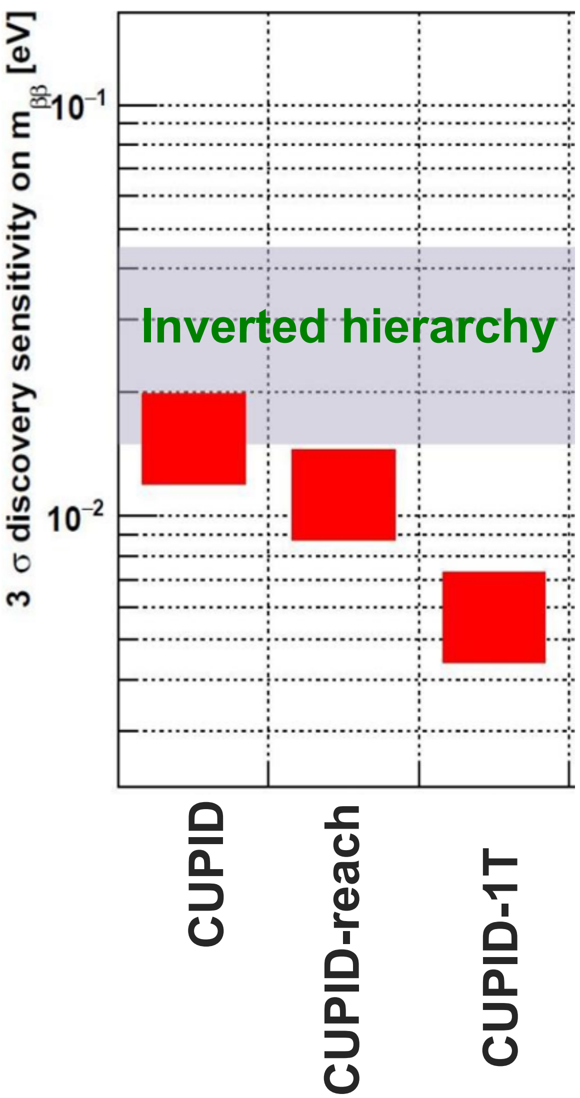


240 kg of ^{100}Mo
CUORE cryostat
Bkg 2×10^{-5} ckky
Excl. sensitivity:
$T_{1/2} > 2.2 \times 10^{27}$ y

CUPID-1T



1000 kg of ^{100}Mo
New cryostat
Bkg 5×10^{-6} ckky
Excl. sensitivity:
$T_{1/2} > 9.1 \times 10^{27}$ y



Conclusions

- The **CUPID infrastructure** already **exists** (**CUORE** cryostat, **LNGS**, Italy)
- **Scintillating bolometer Li_2MoO_4 technology** demonstrated in **CUPID-Mo**
- **Crystallization** and **enrichement** at large scale are **possible and demonstrated**
- The **performance** of the basic tower and of the single module are under test with promising results
- **Data-driven background model** indicates **b~ 10^{-4} counts/(keV·kg·y)**
- **Fully explore the inverted ordering region**
  → down to $m_{\beta\beta}$ = 10 meV for the most favorable nuclear model
- **The collaboration is working on getting ready for CUPID**
- On a longer time scale, **detector mass scaling** and potential **multi-isotope approach**

Related CUORE/CUPID/CUPID-Mo/CUPID-0

Recent progress on BSM and dark matter searches in CUORE
Alberto Ressa
Aug 28, 2023, 6:30 PM (#395)

First results from the CUORE background model
Stefano Ghislandi
Aug 29, 2023, 4:45 PM (Audimax)

Denoising Algorithms for the CUORE Experiment
Kenny Vetter
Aug 30, 2023, 3:30 PM (#216)

Impact of marine macroseisms on the response of the CUORE cryogenic calorimeters
Simone Quitadamo
Aug 30, 2023, 3:30 PM (#233)

Analysis techniques for the search of neutrinoless double-beta decay of Te-130 with CUORE
Krystal Alfonso
Aug 30, 2023, 3:30 PM (#557)

Final results of the CUPID-Mo 0νββ experiment
Léonard Imbert
Aug 29, 2023, 2:00 PM (Audimax)

Latest results from the CUORE experiment
Krystal Alfonso
Aug 29, 2023, 2:15 PM (Audimax)

Backgrounds and sensitivity of the CUPID experiment
Pia Loaiza
Aug 30, 2023, 3:30 PM (#183)

Development of enhanced light detectors for CUPID experiment
Vladyslav Berest, Anastasiia Zolotarova
Aug 30, 2023, 3:30 PM (#372)

Novel techniques for thermal detectors and applications for rare events physics
Irene Nutini
Aug 30, 2023, 3:30 PM (#396)

The Progress of Superconducting Transition Edge Sensor (TES) for Photothermal Detection System in Cupid-China 0νββ Experiment
Shasha Lv et al.
Aug 30, 2023, 3:30 PM (#628)

BINGO: investigation of the Majorana nature of neutrinos at a few meV level of the neutrino mass scale
Vladyslav Berest
Aug 30, 2023, 5:45 PM (Audimax)

Final results of the CUPID-0 combined background model
Emanuela Celi and Lorenzo Pagnanini
Aug 30, 2023, 6:15 PM (Audimax)