XIX International Workshop on Neutrino Telescopes

18-26 February 2021

CUPID

CUORE Upgrade with Particle IDentification

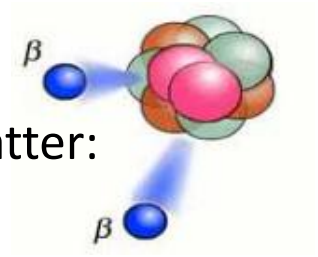
Andrea Giuliani

Orsay, France

On behalf of the CUPID collaboration

Searching for 0ν2β

0ν2β is an inclusive test for the « creation of leptons »:
$2n \rightarrow 2p + 2e^-$ ⇒ LNV



This test is implemented in the nuclear matter:
$(A,Z) \rightarrow (A,Z+2) + 2e^-$

Very rare (**> 10^{26} yr**) - Energetically possible for **35 nuclei**
Experimentally relevant: **^{82}Se**, **^{76}Ge**, **^{100}Mo**, **^{130}Te**, **^{136}Xe**
Enrichement is mandatory, with the exception of ^{130}Te

Signal: **a peak** in the sum-energy specrum of $2e^-$ **at $Q_{2\beta}$**

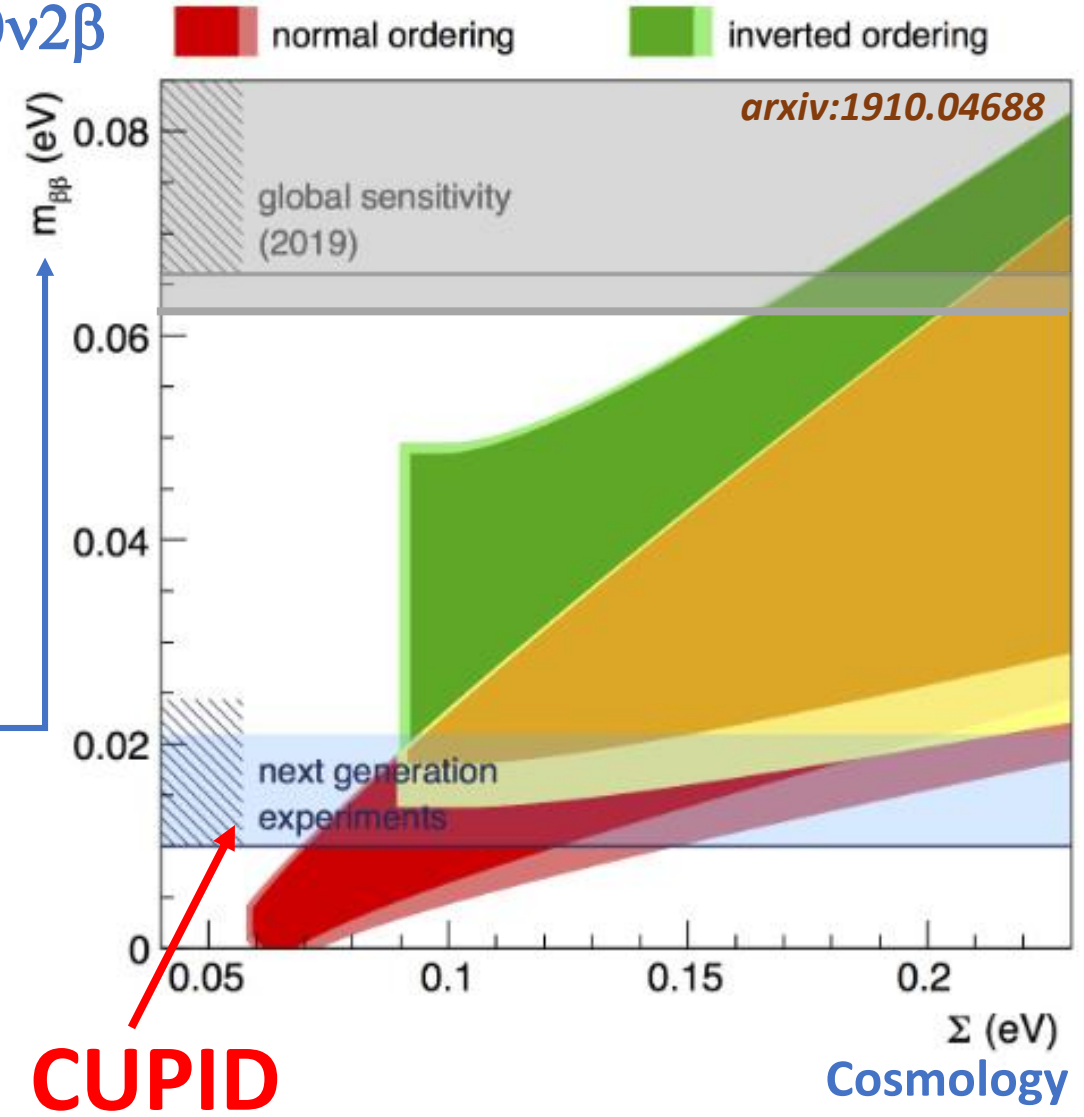
0ν2β

Standard mechanism: neutrino physics
0ν2β is mediated by
light massive Majorana neutrinos
(exactly those which oscillate)

BSM non-standard mechanisms
Not necessarily neutrino physics

F. Ferroni
This conference

0ν2β



CUPID

Cosmology

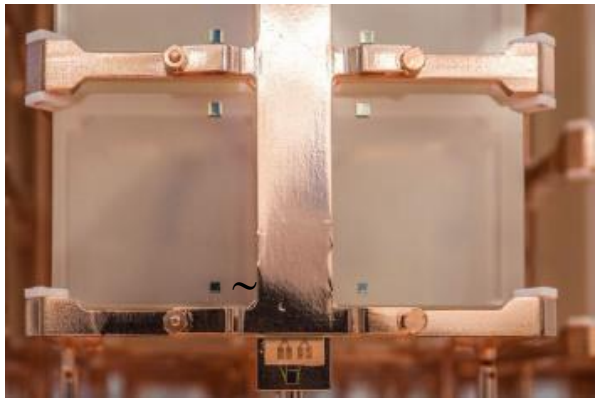
CUORE in a nutshell

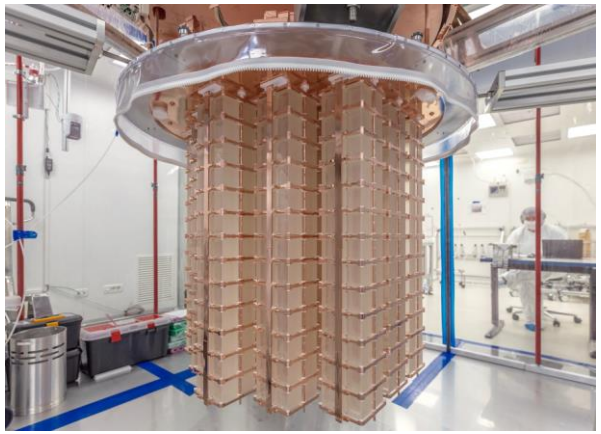
CUORE is an array of **TeO_2 bolometers** searching for $0\nu2\beta$ decay of the **isotope ^{130}Te** and taking data in LNGS (Italy) at **~ 12-15 mK**

G. Fantini
A. Campani
This conference

The largest bolometric experiment ever

- 988 crystals 5x5x5 cm, closely packed
- Arranged in 19 towers of 13 floors each
- 742 kg (206 kg of ^{130}Te)
- Background according to expectations: **$1.38(7)\times10^{-2}$ counts/(keV·kg·yr)**
- Energy resolution close to expectations: **7.0(4) keV FWHM**
- → margins for improvement





One of the most sensitive $0\nu2\beta$ experiments of the current generation

- Exposure for the current limit: **373 kg·y** (collected **> 1 tonne·y**)
- Current limit (^{130}Te $T_{1/2}^{0\nu2\beta}$) : **> 3.2×10^{25} y**
  → $m_{\beta\beta}$ < 75 – 350 meV
- 5 y projected $T_{1/2}$ sensitivity: **~ 9×10^{25} y**
  → $m_{\beta\beta}$ < 60 – 280 meV

Phys. Rev. Lett. 124 (2020) 122501

CUORE is not background free

→ **~ 50 counts/y in the ROI**, dominated by **surface alpha background**

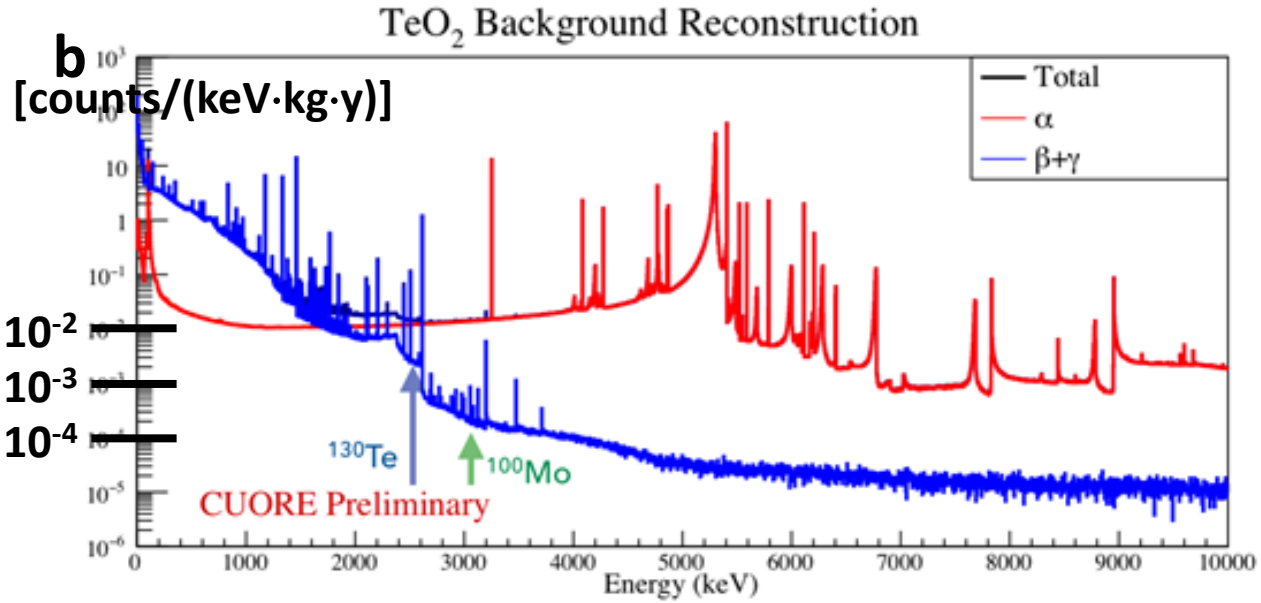
CUORE → CUPID

Three important messages from CUORE

1. **A tonne-scale bolometric detector** is technically feasable
2. **Analysis of ~1000 individual bolometers** is handable
3. **An infrastructure to host a bolometric next-generation $0\nu2\beta$ experiment exists** and will be available at the end of the CUORE physics program (~2023-2024)

CUPID (CUORE Upgrade with Particle ID) is a proposed $0\nu2\beta$ bolometric experiment exploiting the **CUORE infrastructure** and with a **background 100 times lower at the ROI**

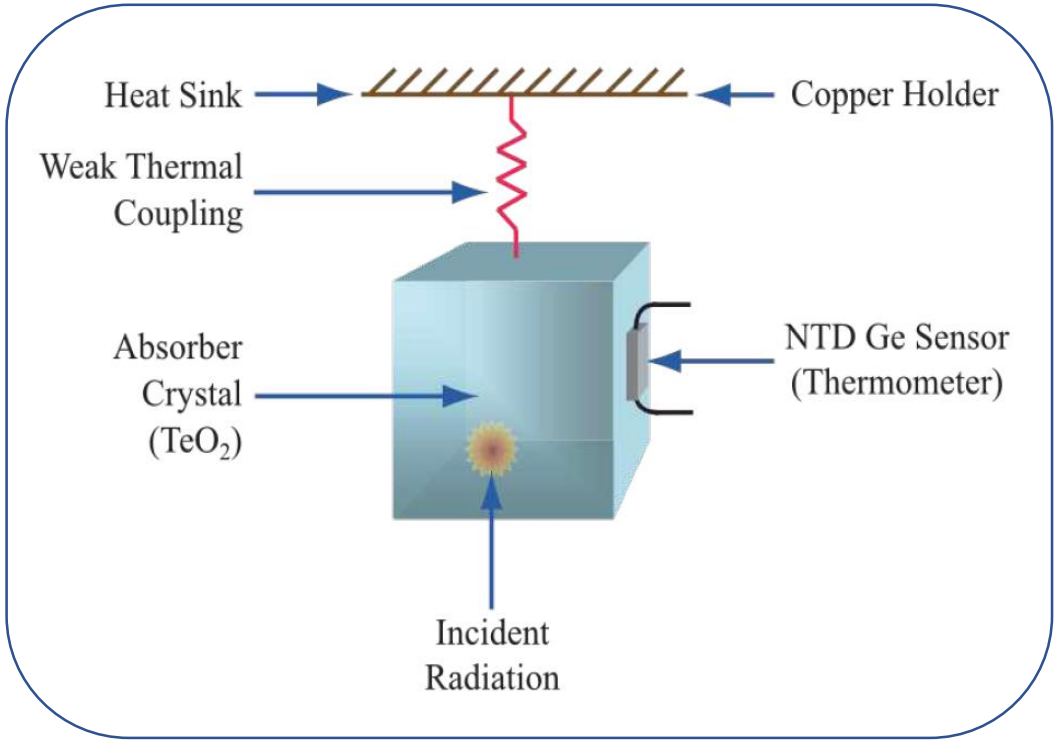
CUORE background model



- Reject α background with **scintillating bolometers**
- Mitigate γ background by **moving to ^{100}Mo**
  - $Q_{2\beta}$: 2527 keV (^{130}Te) → 3034 keV (^{100}Mo)
- Increase isotope mass by **enrichment** (natural isotopic abundance: 9.7%)

CUPID rationale

CUORE ^{130}Te
pure thermal detector
(**bolometer**)

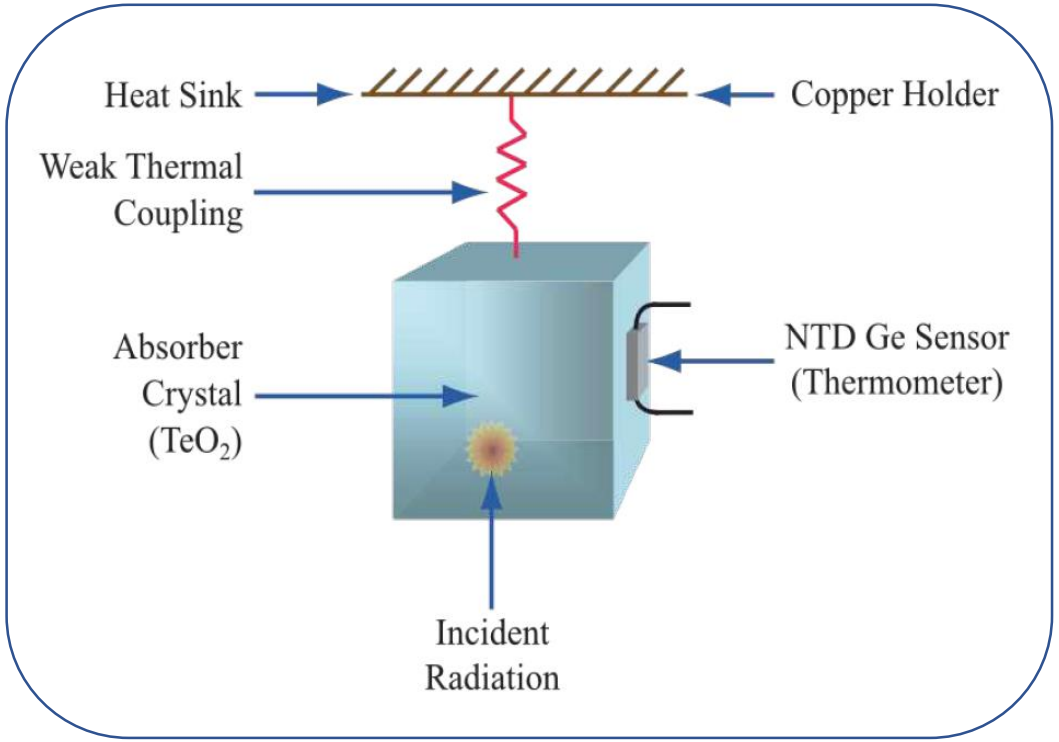


No PID

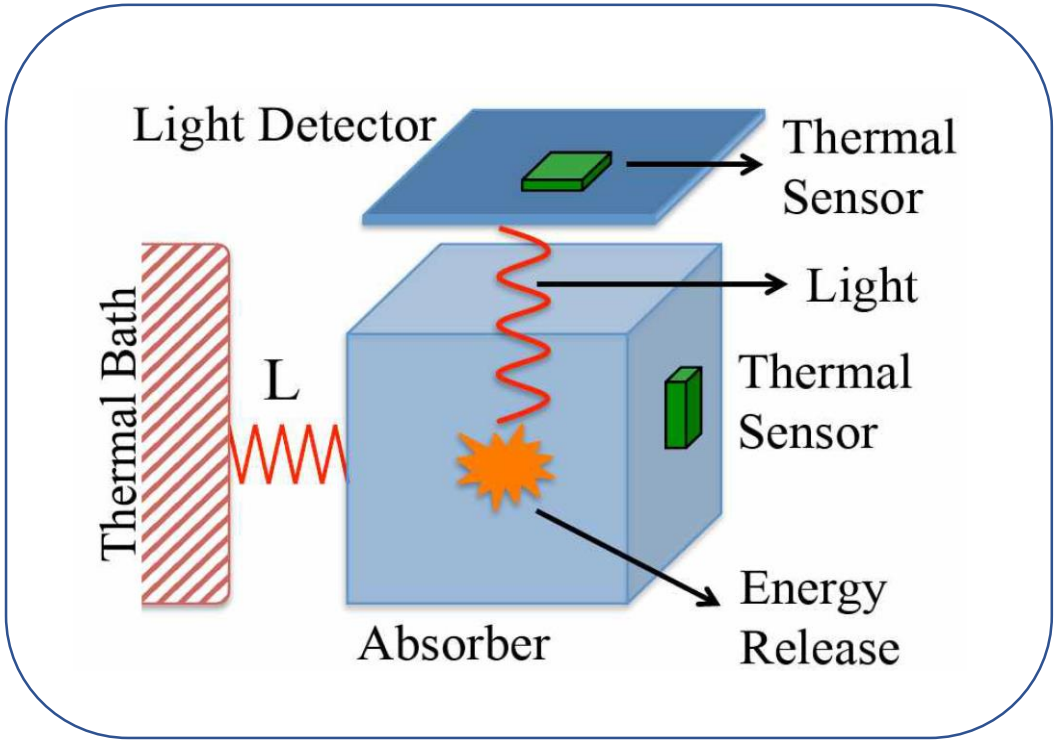
$Q_{2\beta}$ = 2527 keV **< 2615 keV**

CUPID rationale

CUORE ^{130}Te
pure thermal detector
(**bolometer**)



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



No PID

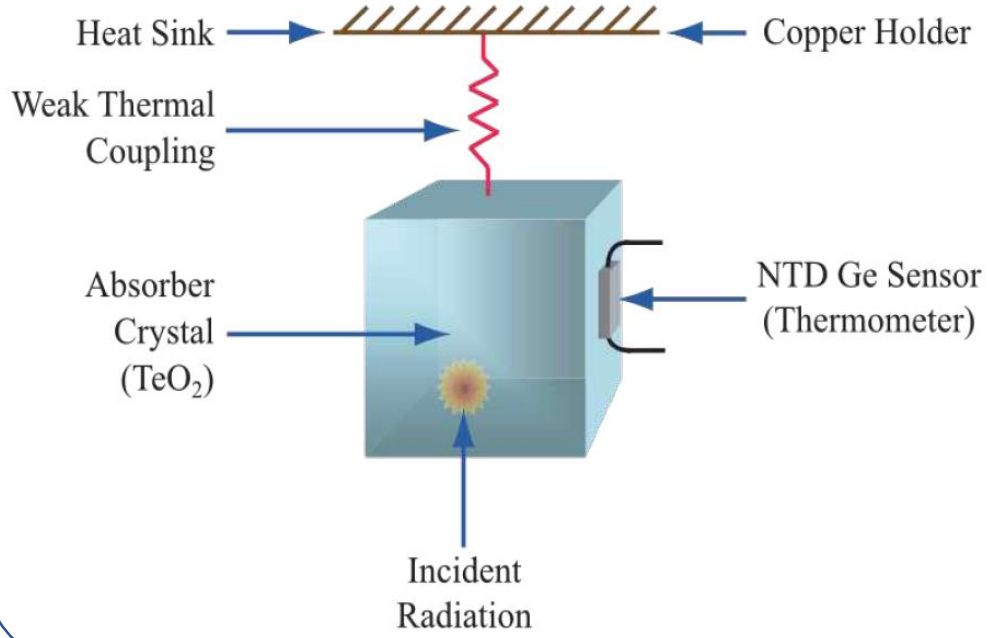
$Q_{2\beta}$ = 2527 keV **< 2615 keV**

α background

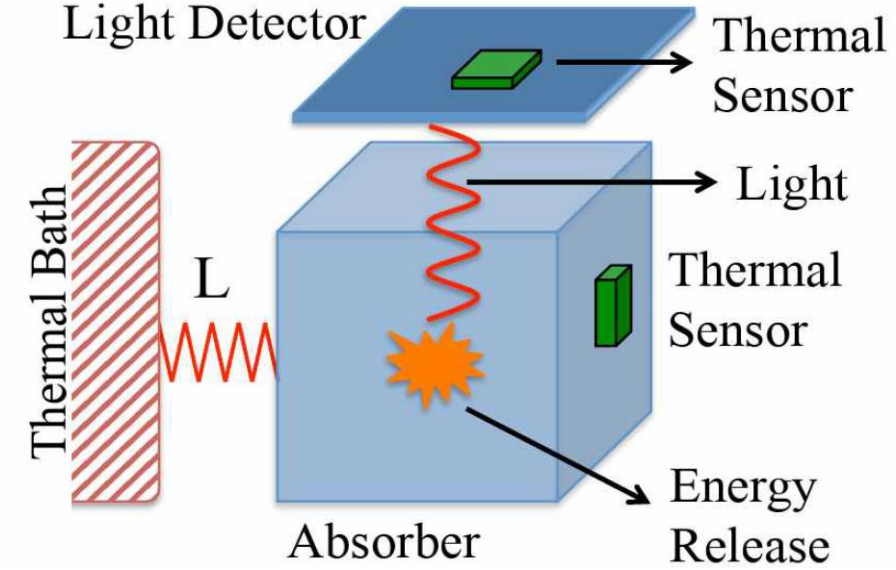
γ background

CUPID rationale

CUORE ^{130}Te
pure thermal detector
(**bolometer**)



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



No PID

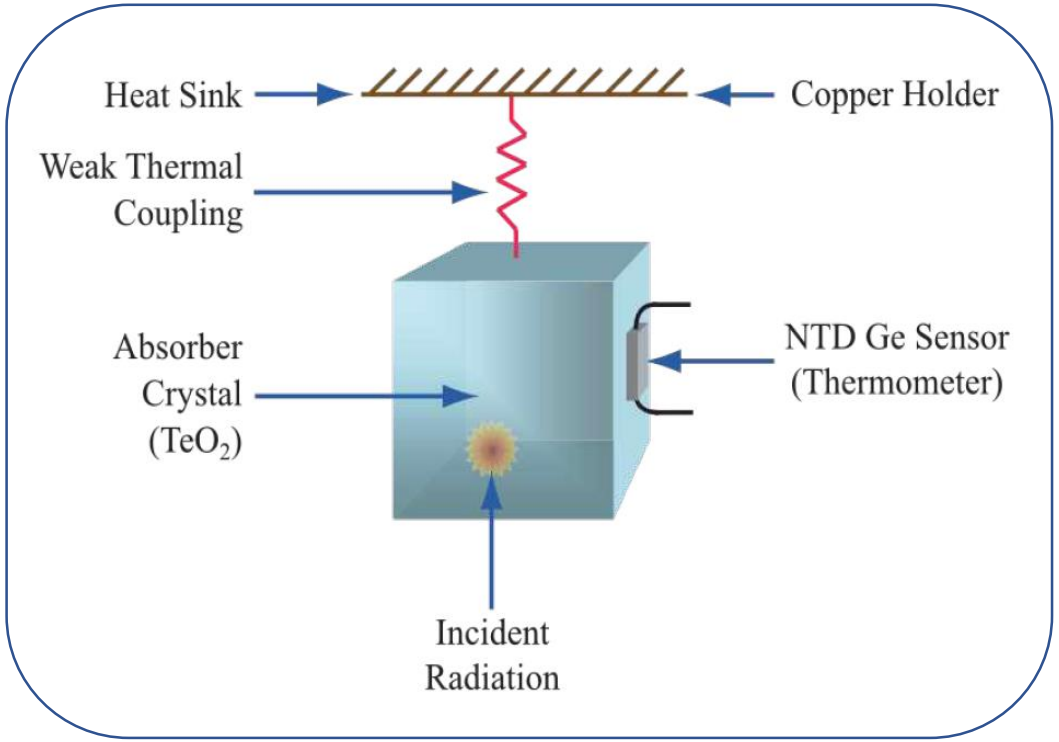
$Q_{2\beta}$ = 2527 keV **< 2615 keV**

~~α background~~ ← **PID**

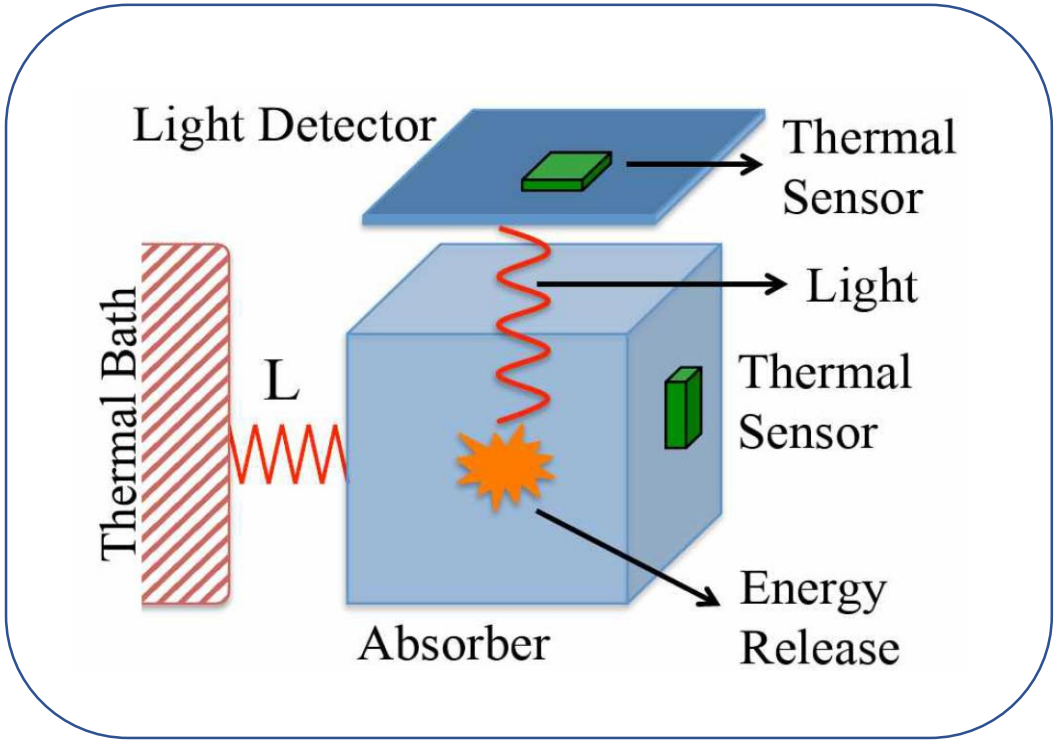
γ background

CUPID rationale

CUORE ^{130}Te
pure thermal detector
(**bolometer**)



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



No PID

$Q_{2\beta}$ = 2527 keV **< 2615 keV**

~~α background~~ ← **PID**

~~γ background~~ ← $Q_{2\beta}$ = 3034 keV **> 2615 keV**

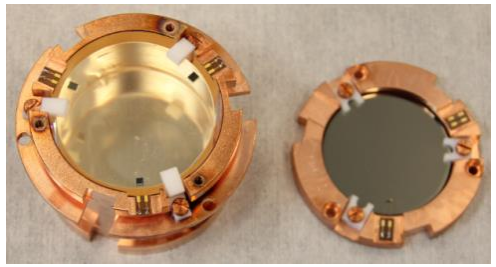
Choice of the isotope and compound

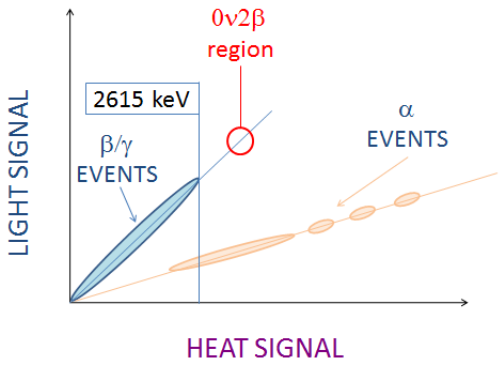
Scintillating bolometers

↓

α particle rejection

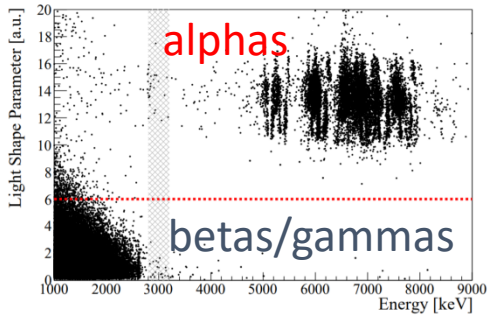
Main crystal | Light detector



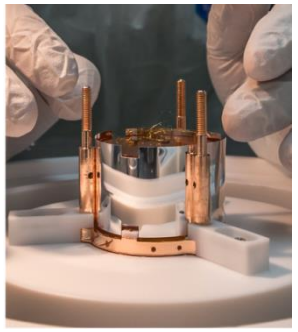


CUPID-0 – $Zn^{82}Se$ $Q_{2\beta}$ = 2998 keV
(evolution of **LUCIFER** erc)
First running demonstrator
24 crystals (enriched in ^{82}Se) – 5.28 kg ^{82}Se
Best limit on ^{82}Se: $T_{1/2} > 3.5\times10^{24}$ y
Energy resolution: **~23 keV FWHM**

E. Celi This conference



Phys. Rev. Lett. 123 (2019) 032501



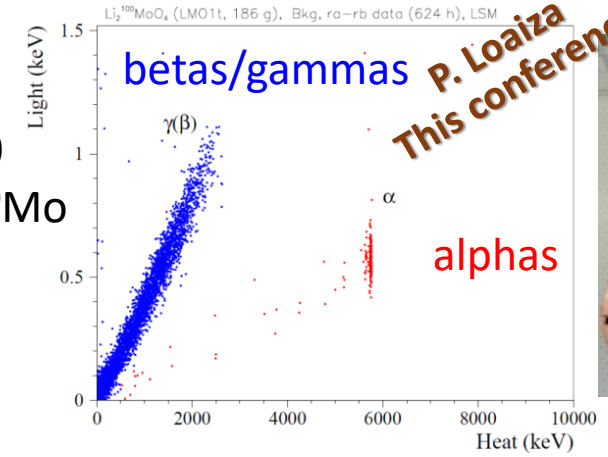
LNGS – Italy b = 3.5×10^{-3} counts/(keV·kg·yr)

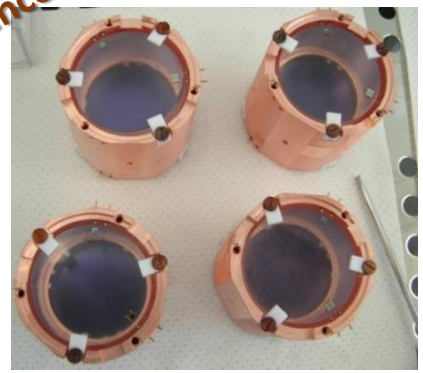
Useful information for the CUPID background model

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: $T_{1/2} > 1.5\times10^{24}$ y
Full α rejection
Radiopure crystals: U/Th ≤ 1 μBq/kg

P. Loaiza This conference





LSM – France

Zero background experiment at LSM

CUPID requirements met

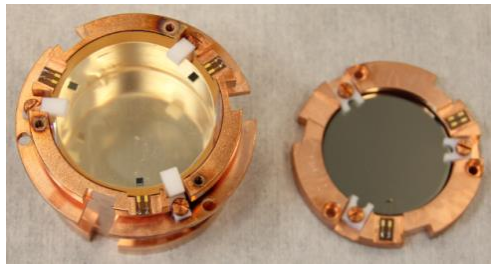
arXiv:2011.13243v1 – submitted to PRL

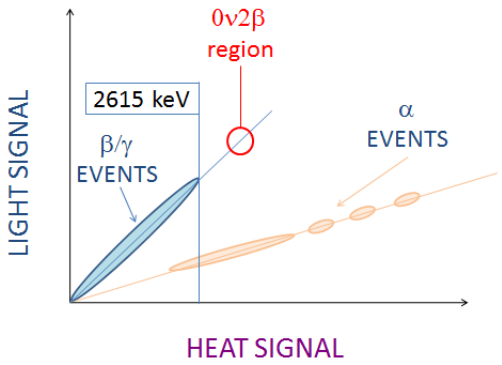
Choice of the isotope and compound

Scintillating bolometers

α particle rejection

Main crystal | Light detector





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

(evolution of **LUCIFER** erc)

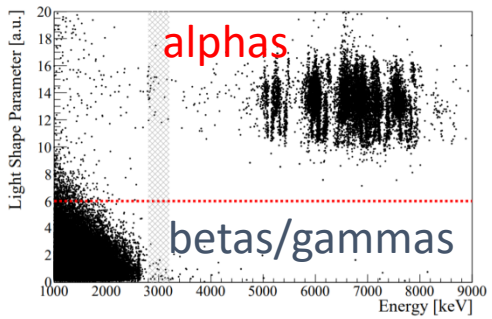
First running demonstrator

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

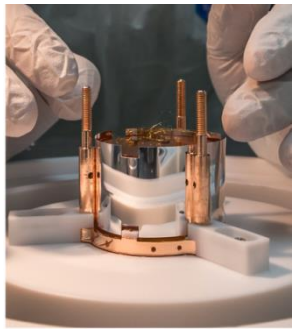
Best limit on ^{82}Se: $T_{1/2} > 3.5\times10^{24}$ y

Energy resolution: **~23 keV FWHM**

E. Celi This conference



Phys. Rev. Lett. 123 (2019) 032501



LNGS – Italy $b = 3.5 \times 10^{-3}$ 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

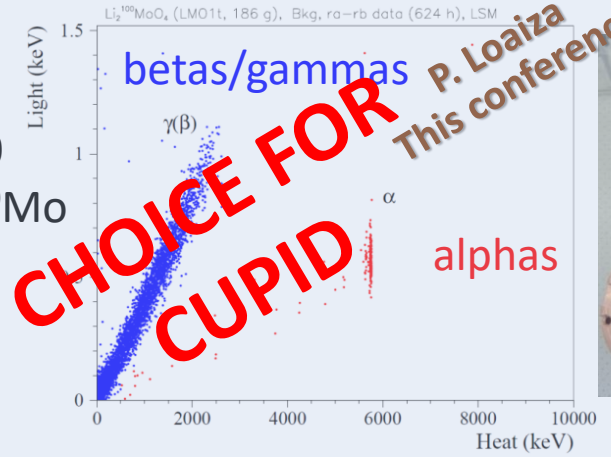
20 crystals (enriched in ^{100}Mo) – 2.34 kg ^{100}Mo

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

Best limit on ^{100}Mo: $T_{1/2} > 1.5\times10^{24}$ y

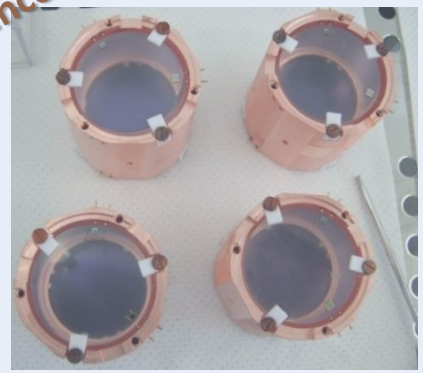
Full α rejection

Radiopure crystals: U/Th ≤ 1 μBq/kg



CHOICE FOR CUPID

P. Loaiza This conference



LSM – France

Zero background experiment at LSM

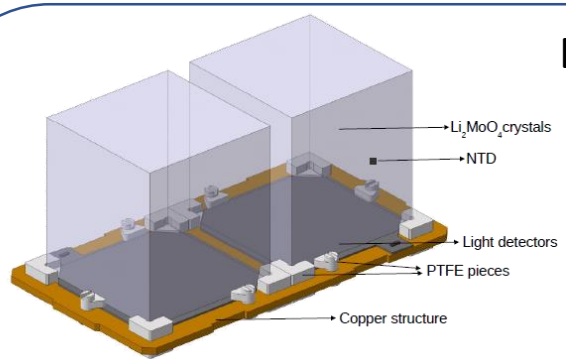
CUPID requirements met

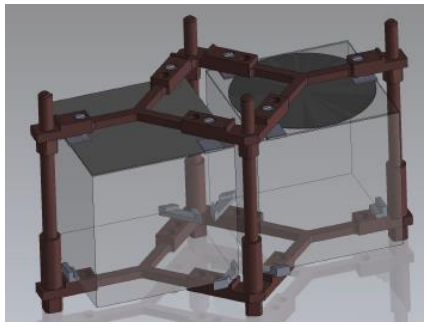
arXiv:2011.13243v1 – submitted to PRL

CUPID structure

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

- Single module: $Li_2{}^{100}MoO_4$ **45×45x45 mm – ~ 280 g**
- 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
- No reflecting foil
- Ge light detector as in CUPID-Mo, CUPID-0





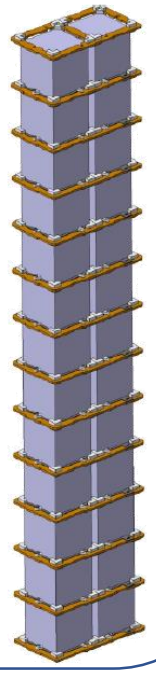
Baseline design

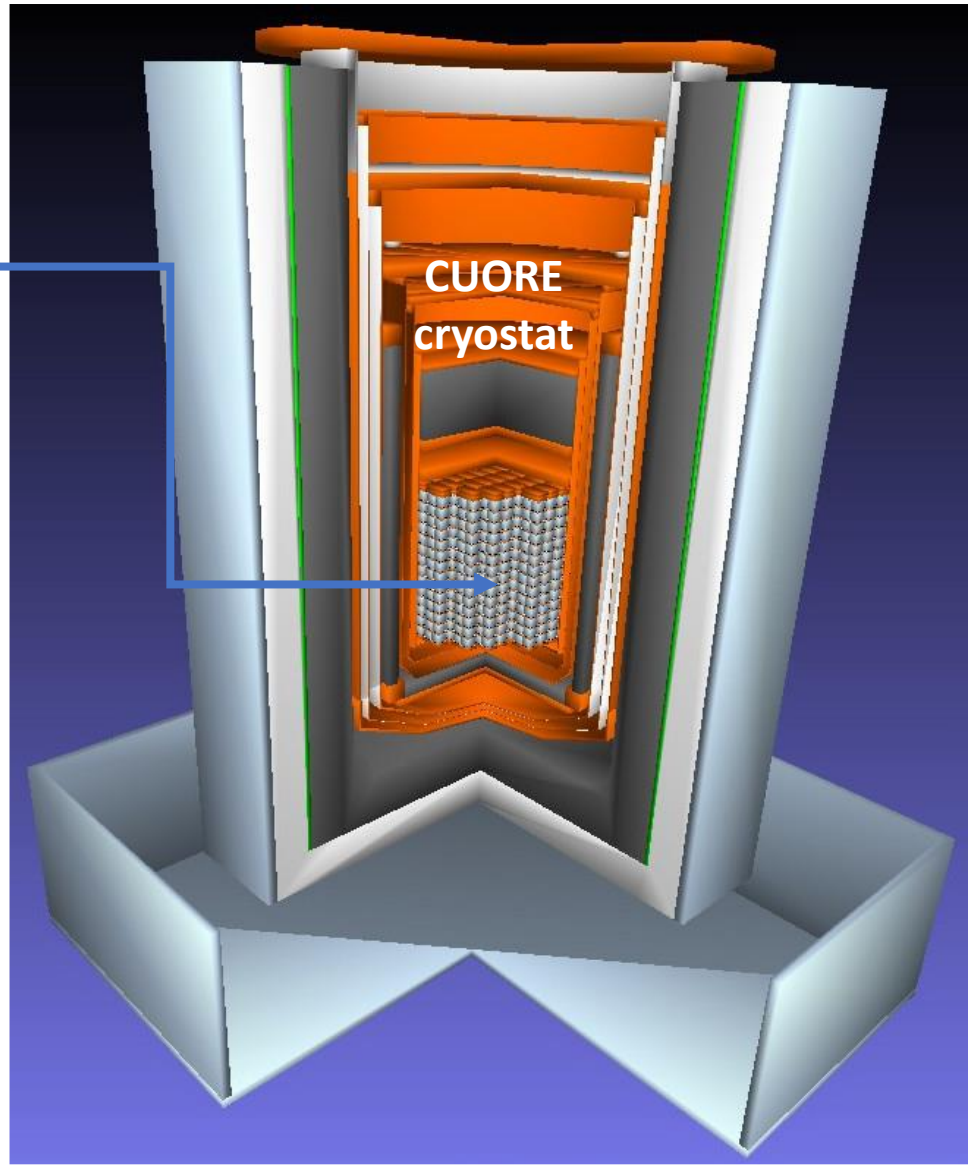
Gravity stacked structure
Crystals thermally interconnected

Tests ongoing

Alternative design

Crystals thermally independent
No Cu holder for light detectors

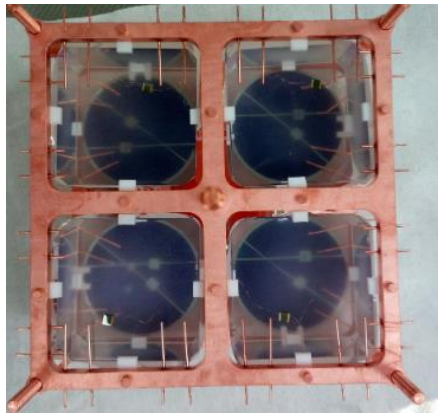




CUPID tests on cubic crystals

Satisfactory results on **cubic crystals with final CUPID size**, grown from enriched molybdenum, have been obtained

LNGS test – Hall C facility



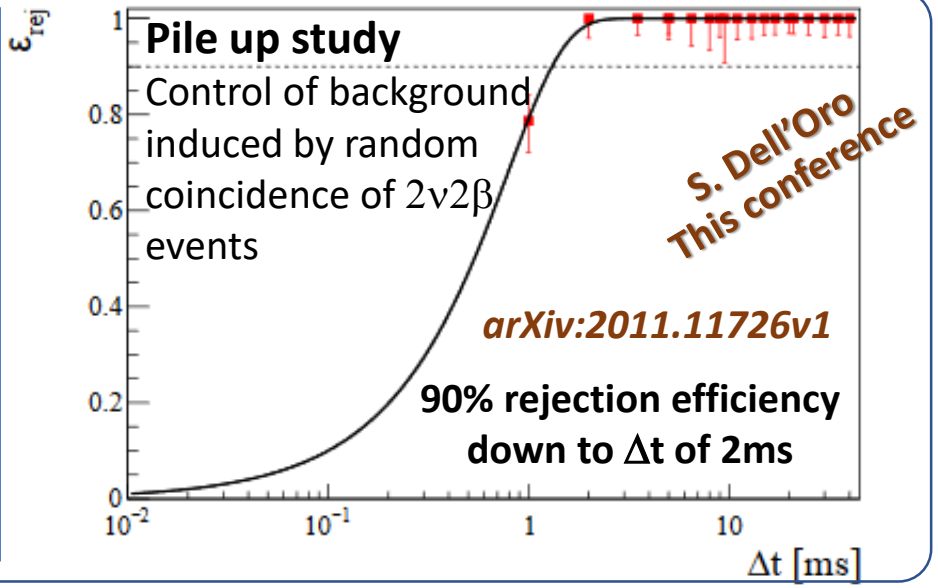
8 crystal array (4 without reflective foil)
12 round light detectors ∅ 44 mm (as CUPID-Mo)

- with reflective foil → **α/β separation at 8-10σ**
- without reflective foil → **α/β separation > 4σ**

Extrapolated energy resolution at $Q_{2\beta}$
6.7(6) keV FWHM

EPJC 81 (2021) 104

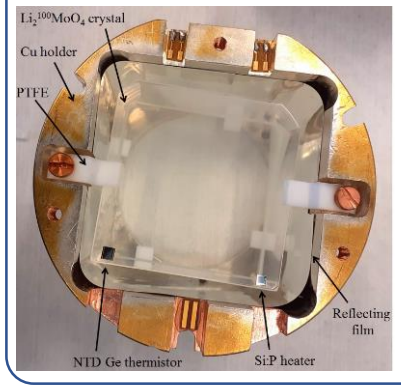
A. Ressa This conference



Canfranc test – CROSS erc facility

Accepted by JINST
arXiv:2011.13806v1

Run 1



1 crystal + 1 round light detector

- with reflective foil

→ **α/β separation at 8σ**

Extrapolated energy resolution at $Q_{2\beta}$
6.0(5) keV FWHM

Confirmed CUPID-Mo crystal radiopurity

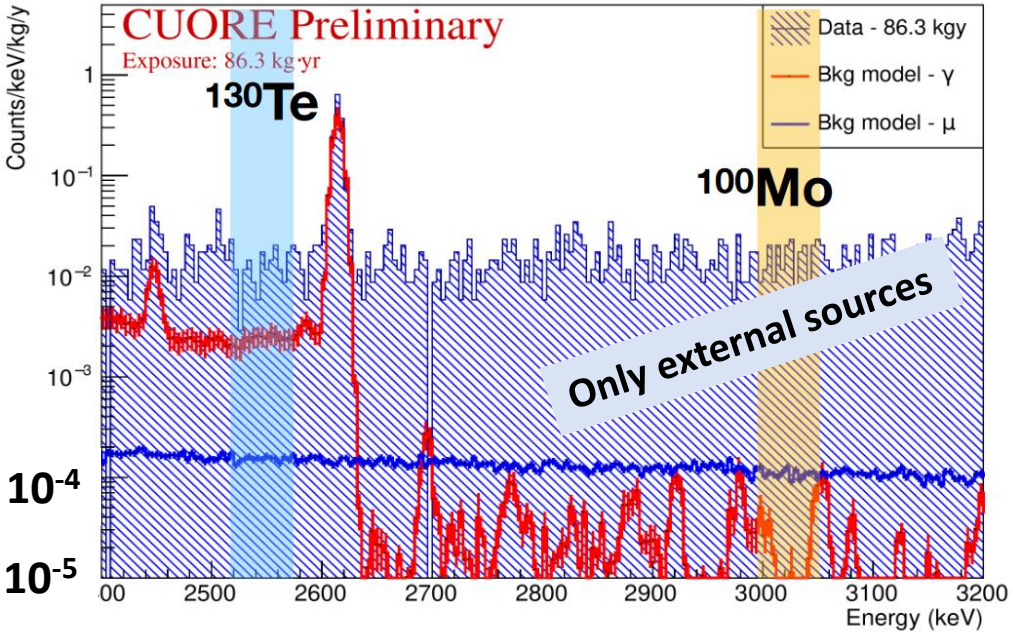
Run 2

12 crystal array
16 light detectors

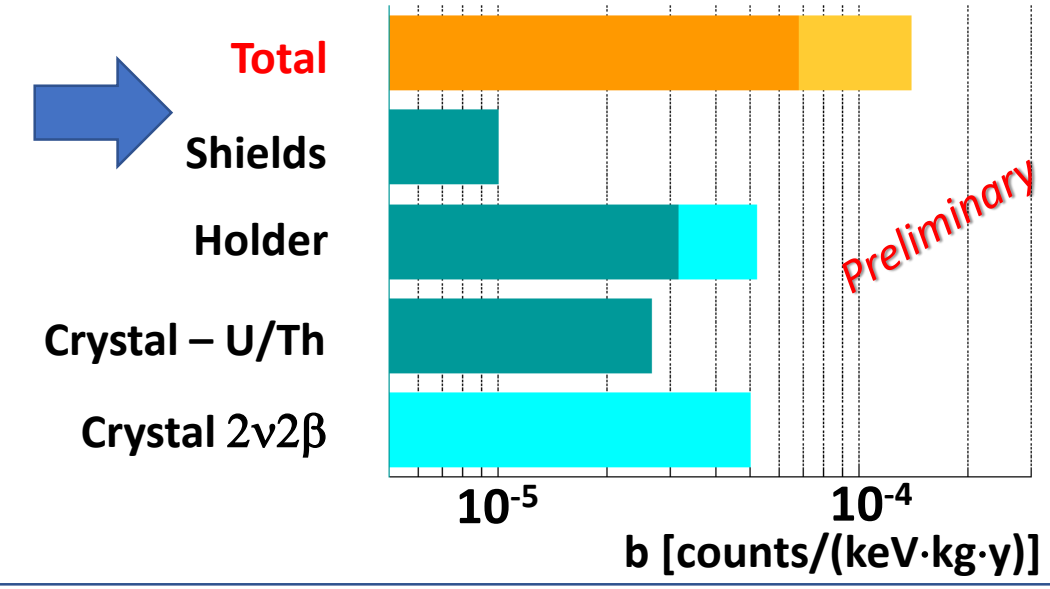
- Comparison of light collections with different approaches
- Confirmation of previous performance for configurations with/without reflector
- **First validation of square (45x45 mm) light detectors** → ⬆ ~20% light collection

CUPID background

CUORE + CUPID-0 + CUPID-Mo ⇒ **CUPID background model**



Dedicated simulation for CUPID assuming the current baseline structure ⇒



Neutron background: $< 1 \times 10^{-5}$ counts/(keV kg y)

Muon-induced background: $\sim 1 \times 10^{-4}$ counts/(keV kg y) in the current configuration – suppressed by a factor 10 with veto

Random coincidence of $2\nu2\beta$ events

($T^{2\nu2\beta} = 7.1 \times 10^{18}$ yr → 3 mHz in a CUPID crystal)

Pulse shape discriminaiton to reject pile-up

Improvement of background rejection by a factor ~ 4 with respect to the current state of the art

⇒

- Improve noise level in the heat channel
- Widen electronics bandwidth and increase sampling rate
- Investigate machine learning techniques
- **Exploit light signal** improving S/N and/or speed of light detectors

→ **promising technological solutions: Neganov-Luke or TES**

Work in progress

CUPID sensitivity

Energy resolution

5 keV FWHM

Backgroud index

1×10^{-4} counts/(keV·kg·y)

Livetime

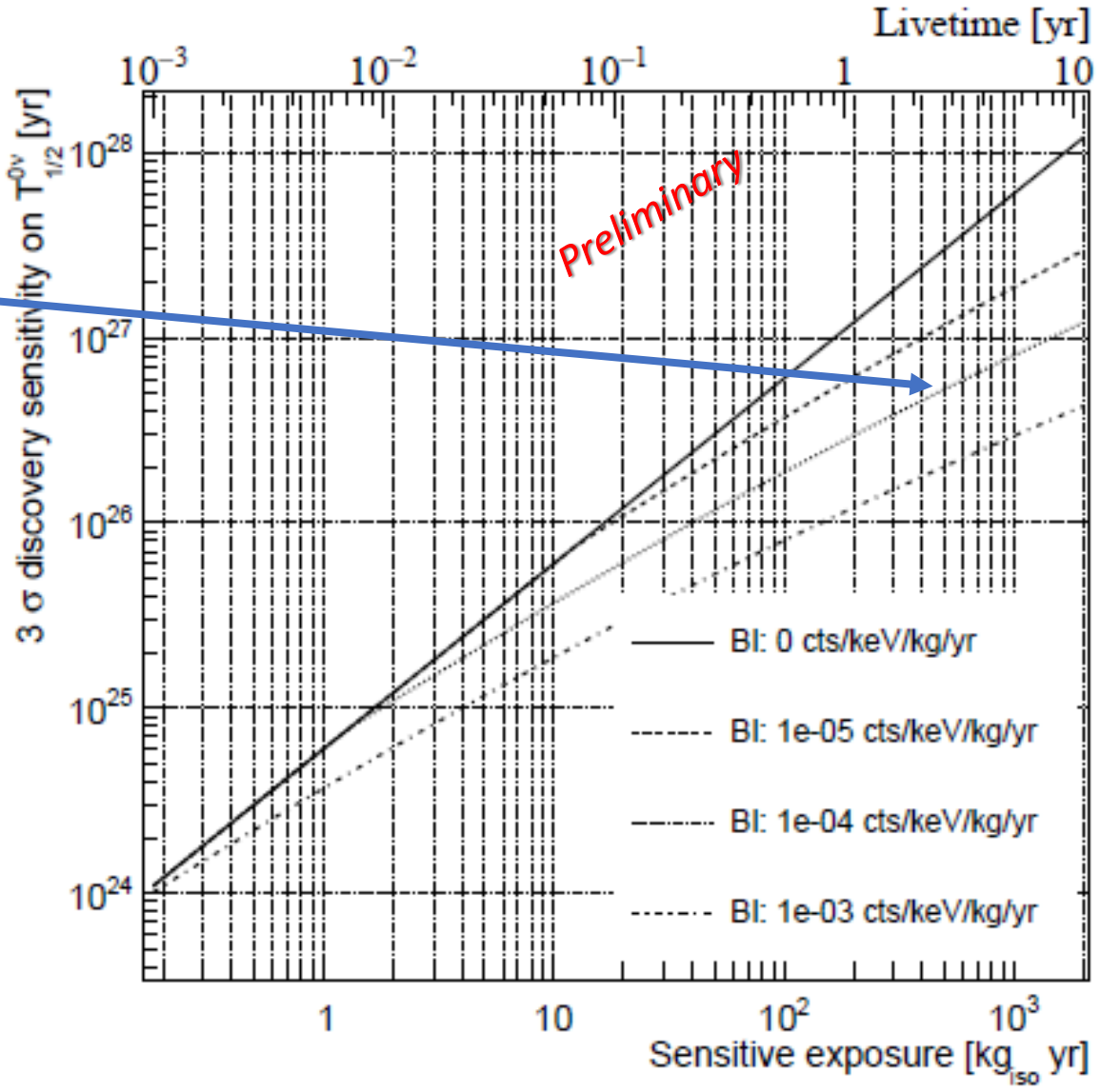
10 y

Half-life exclusion sensitivity

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

Half-life 3σ discovery sensitivity

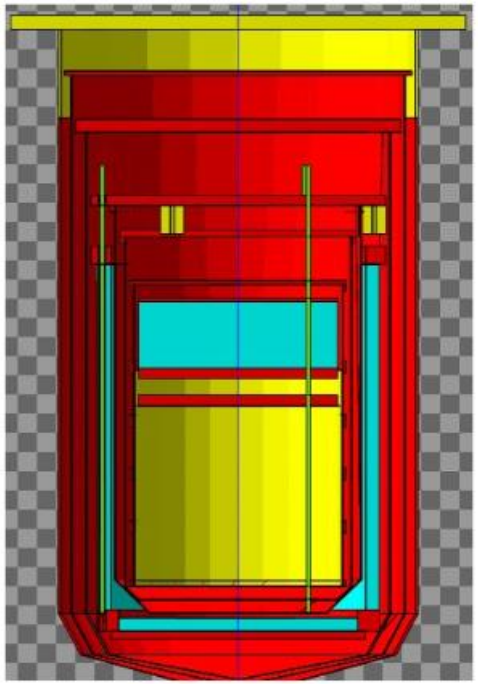
1×10^{27} y – $m_{\beta\beta}$ < 12-20 meV



Phased approach

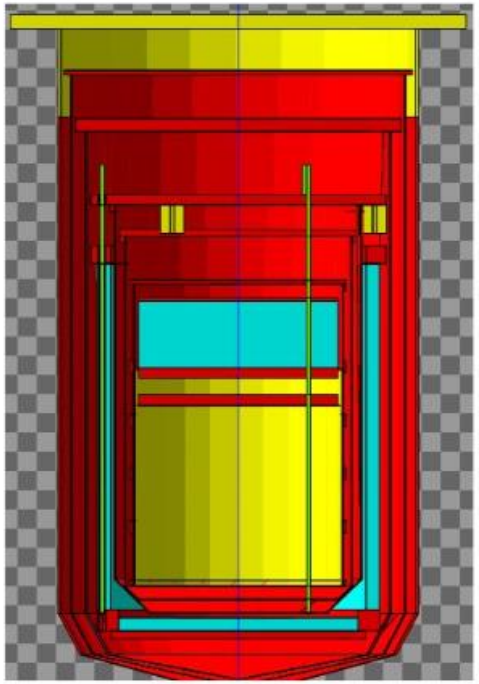
Technically ready

CUPID Baseline



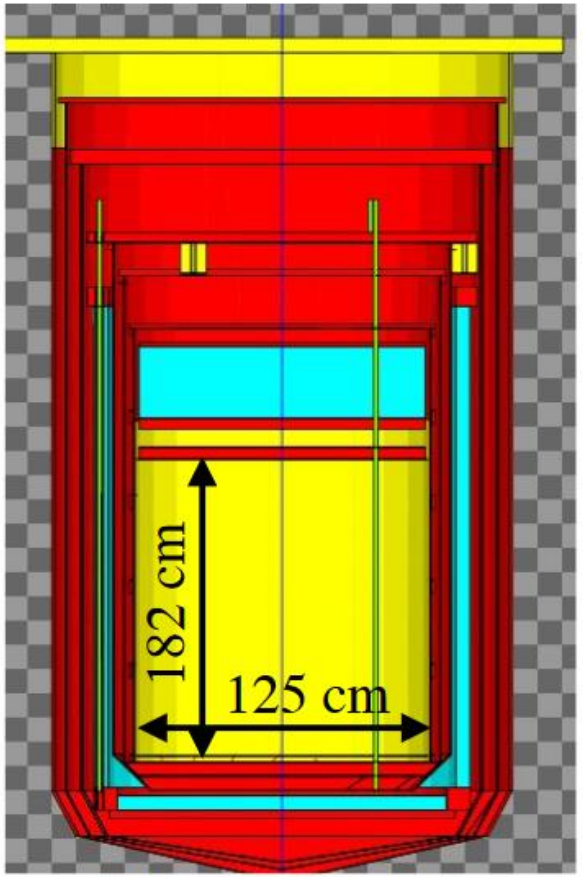
250 kg of ^{100}Mo
CUORE cryostat
Bkg 1×10^{-4} ckky
Excl. sensitivity:
$T_{1/2} > 1.4 \times 10^{27}$ y

CUPID-reach



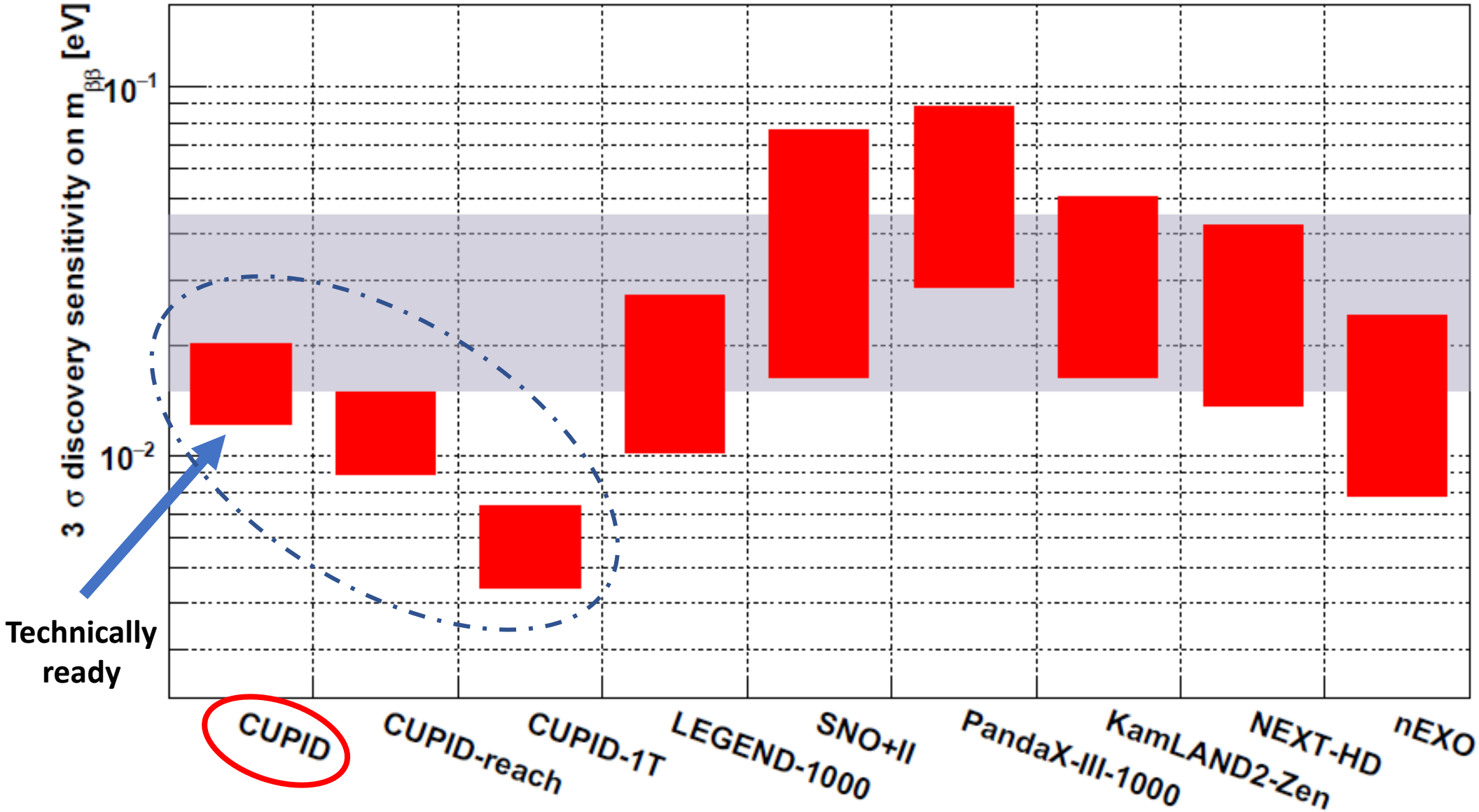
250 kg of ^{100}Mo
CUORE cryostat
Bkg 2×10^{-5} ckky
Excl. sensitivity:
$T_{1/2} > 2.2 \times 10^{27}$ y

CUPID-1T



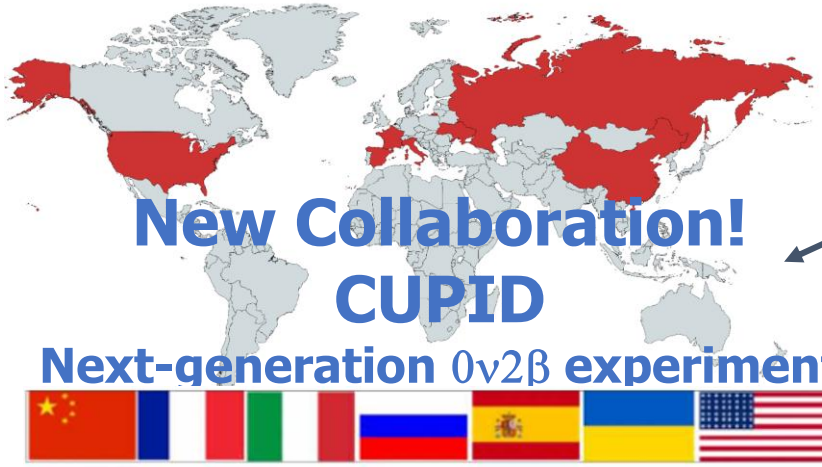
1000 kg of ^{100}Mo
New cryostat
Bkg 5×10^{-6} ckky
Excl. sensitivity:
$T_{1/2} > 9.1 \times 10^{27}$ y

CUPID in the international landscape



CUPID collaboration

Best world limit on ^{130}Te
$T_{1/2}^{0\nu} > 3.2 \times 10^{25}$ y @90% CI



New Collaboration!
CUPID
Next-generation $0\nu2\beta$ experiment

7 countries
~180 members

FRESH FORCES!

Best world limit on ^{100}Mo
$T_{1/2}^{0\nu} > 1.5 \times 10^{24}$ y @90% CI

Best world limit on ^{82}Se
$T_{1/2}^{0\nu} > 3.5 \times 10^{24}$ y @90% CI

Summary and final considerations

Advantages of CUPID

- The **infrastructure** already **exists** (**CUORE** cryostat, **LNGS**, Italy)
- The **required performance** of the single module is demonstrated

  The objectives are achieved in terms of
  - Internal radiopurity
  - Alpha rejection factor
  - Energy resolution
- **Crystallization** and **enrichement** at large scale are **possible and demonstrated**
- **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
- **Cost effective**

Uniquely favorable position when compared to other next-generation $0\nu2\beta$ searches

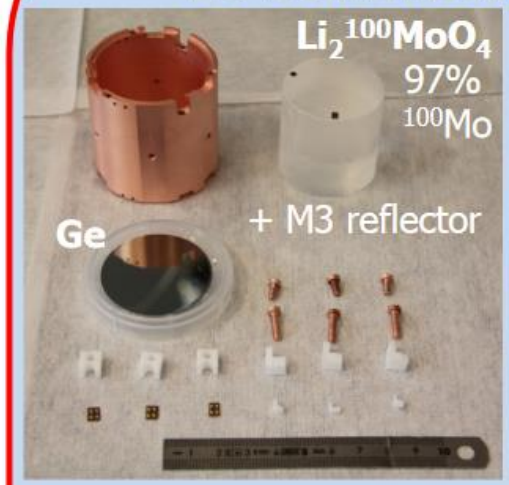
BACK UP

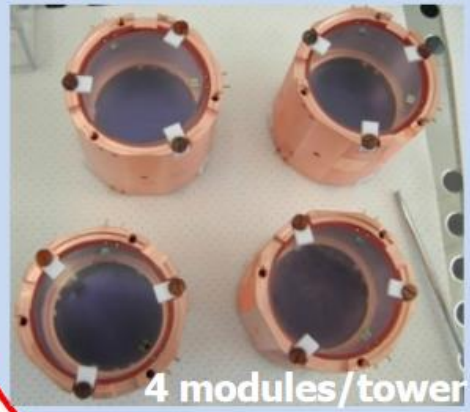
CUPID-Mo in a nutshell

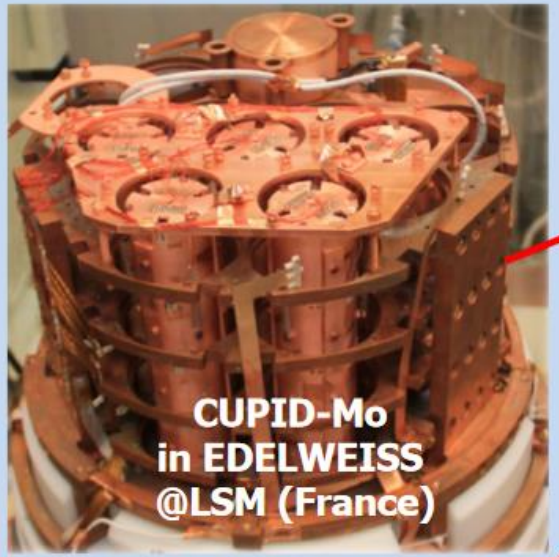
P. Loaiza
This conference

CUPID-Mo

20-scintillating-bolometer array

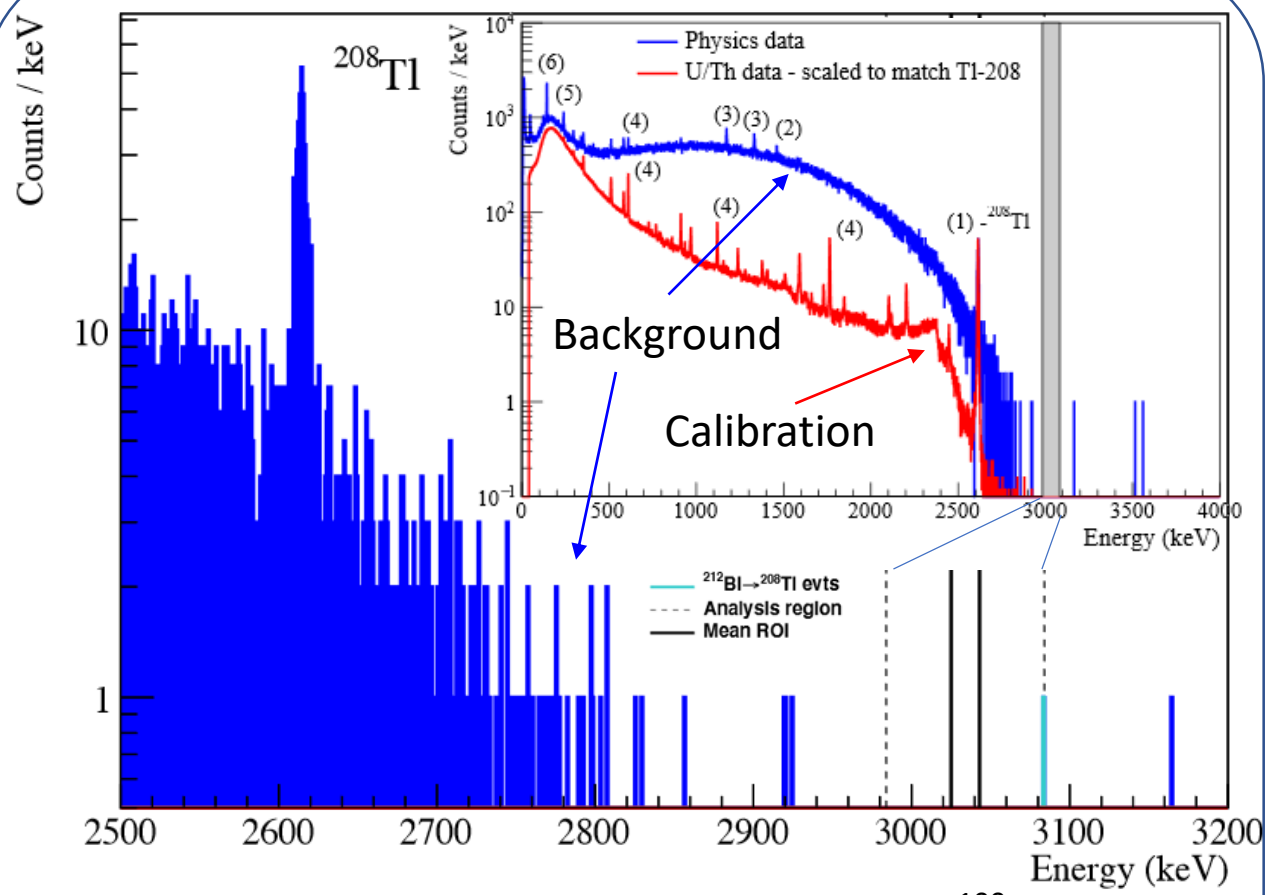






EPJC 80 (2020) 44

arXiv:2011.13243v1 – submitted to PRL



New world leading limit on $0\nu2\beta$ of ^{100}Mo

$T_{1/2} > 1.5\times10^{24}$ y

Crystal contamination in ^{238}U/^{232}Th and daughters

~ (0.2 - 1) μBq/kg

an order of magnitude better than CUPID goal