IRN Neutrino meeting

November 16-17 2022

16-17 novembre 2022 IJCLab Paris

CUPID

CUORE Upgrade with Particle IDentification

Andrea Giuliani

On behalf of the CUPID collaboration

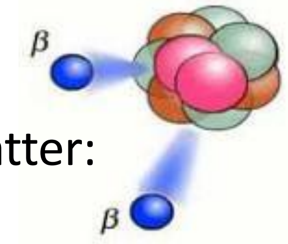
$0\nu2\beta$ in a nutshell

$\Sigma = m_1 + m_2 + m_3$ → Cosmology

$m_{\beta\beta} = \left| |U_{e1}|^2 m_1 + e^{i\alpha 1} |U_{e2}|^2 m_2 + e^{i\alpha 2} |U_{e3}|^2 m_3 \right|$ → $0\nu2\beta$

$0\nu2\beta$ 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: **^{76}Ge**, **^{82}Se**, **^{100}Mo**, **^{130}Te, ^{136}Xe**

Enrichment is mandatory, with the exception of ^{130}Te

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

$0\nu2\beta$

Standard mechanism: neutrino physics

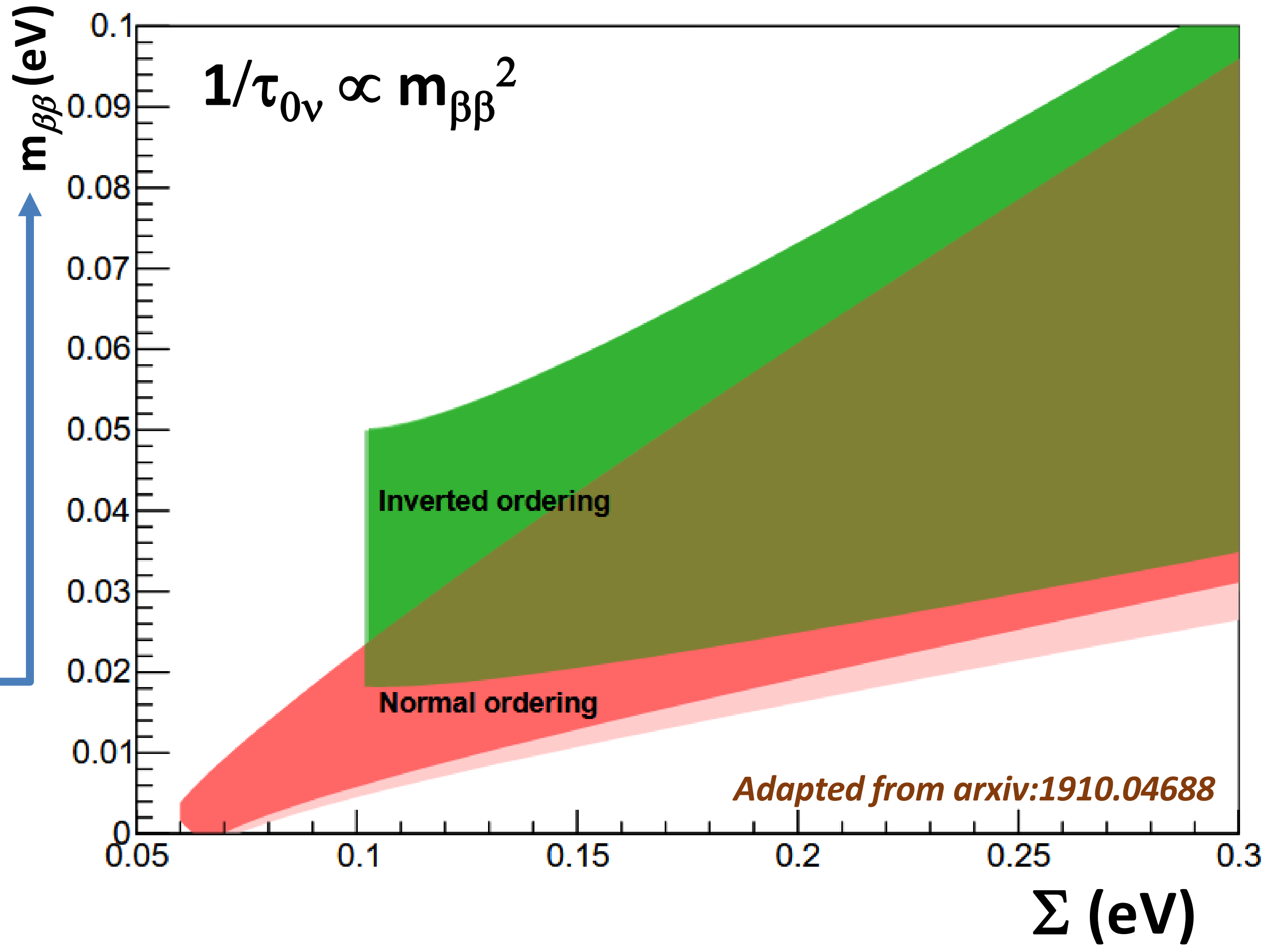
$0\nu2\beta$ is mediated by

light massive Majorana neutrinos

(exactly those which oscillate)

BSM non-standard mechanisms

Not necessarily neutrino physics



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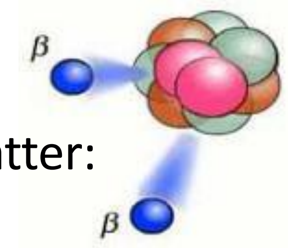

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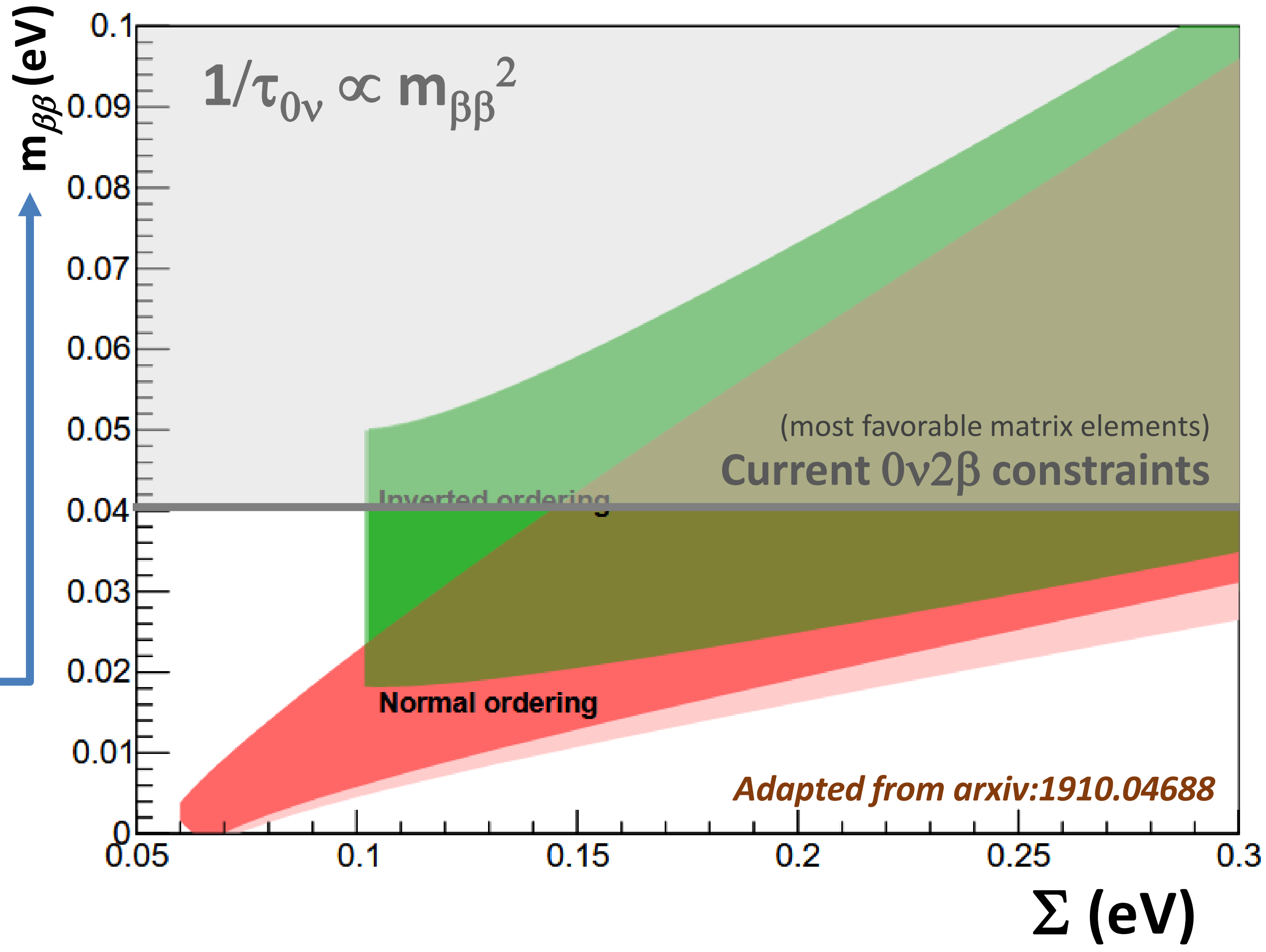

0ν2β in a nutshell

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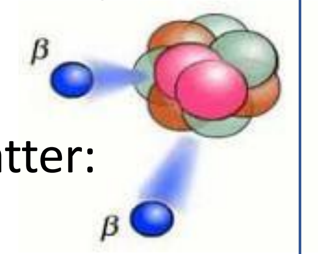

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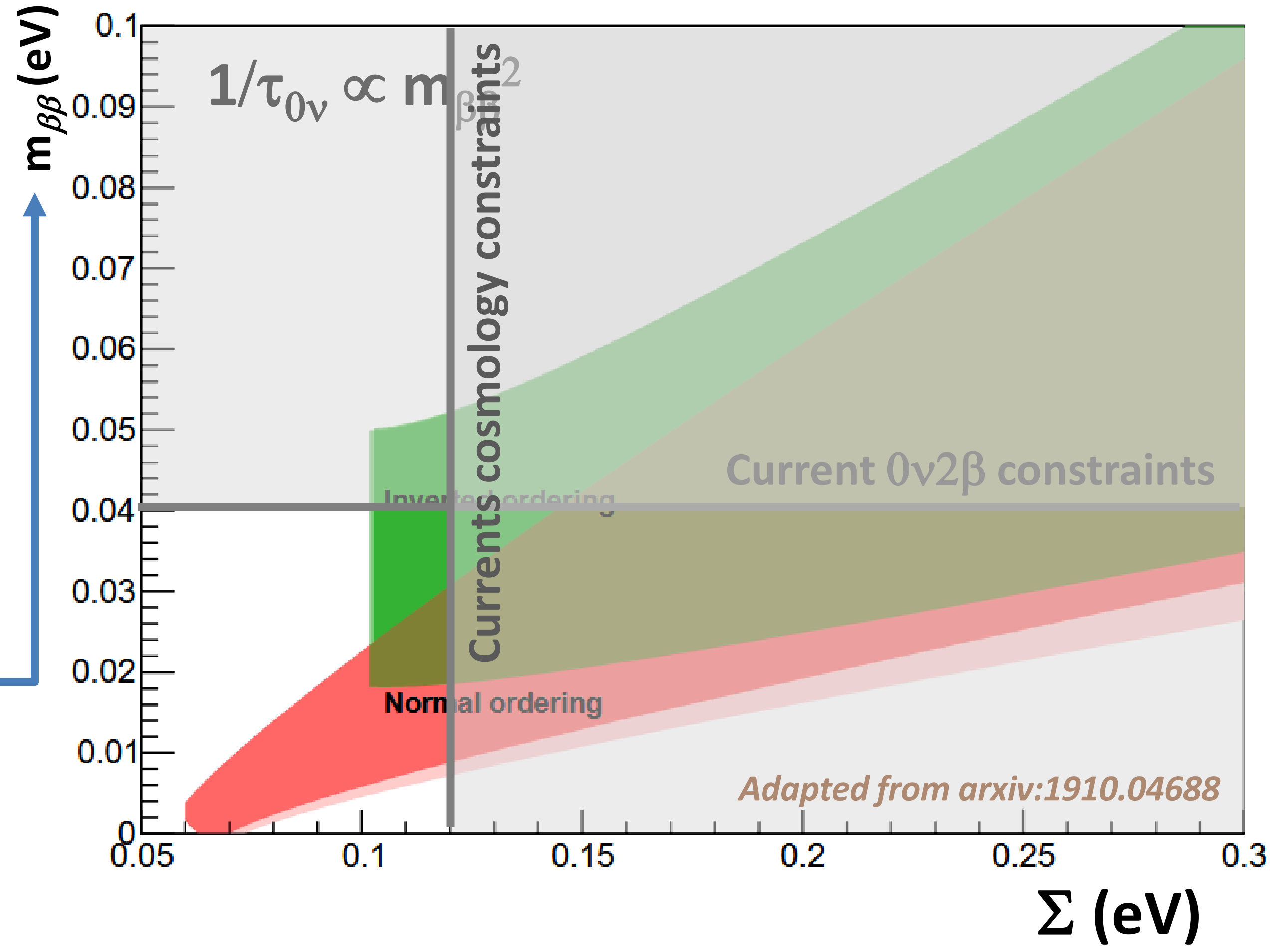

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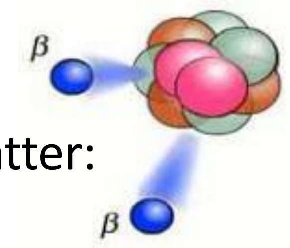

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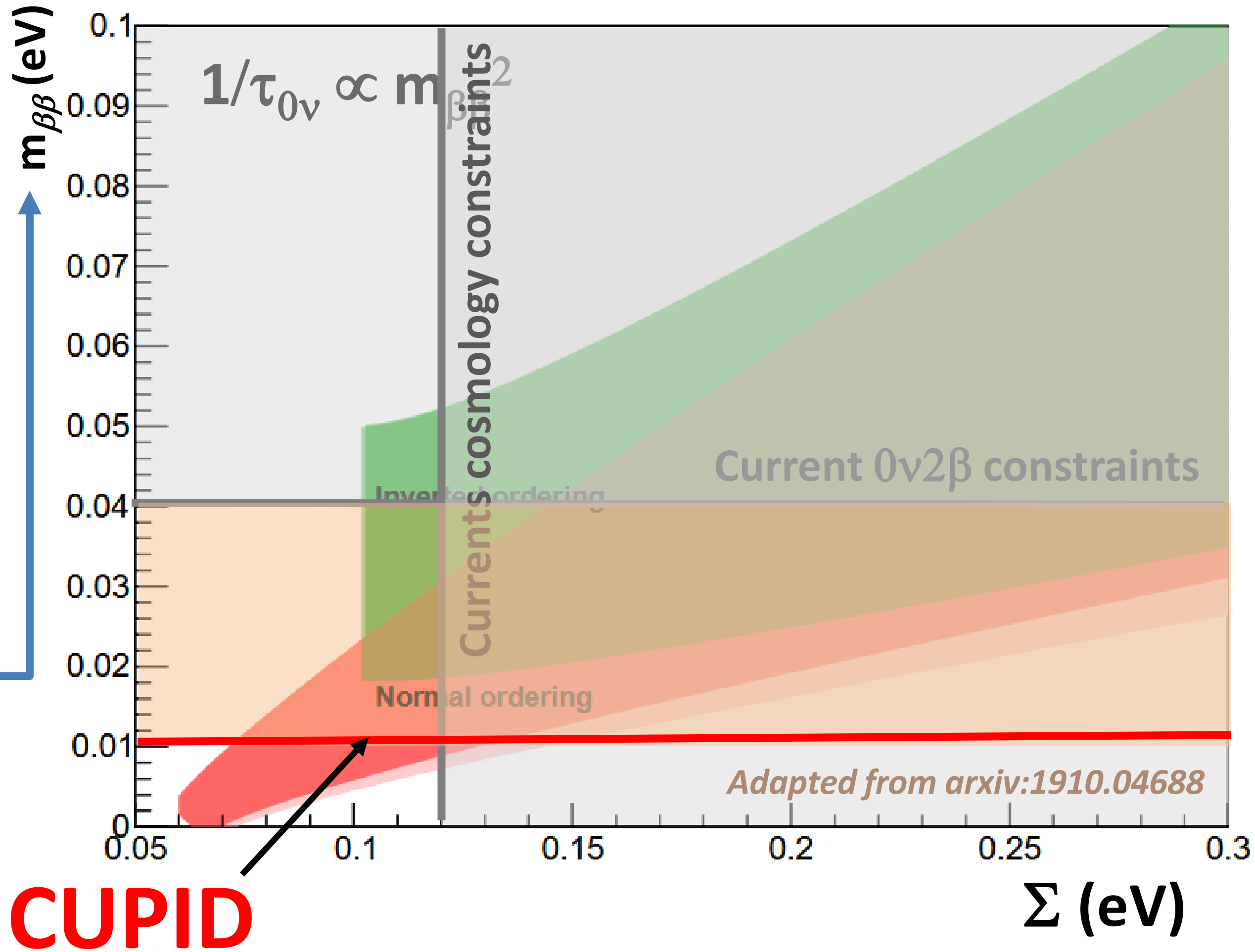


CUPID

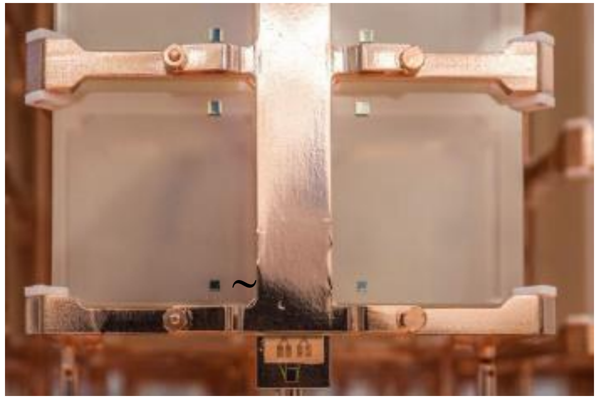
and other next-generation experiments (nEXO, LEGEND, NEXT)
(most favorable matrix elements)

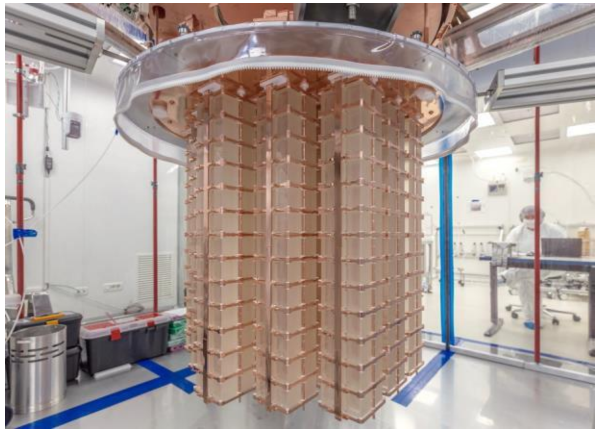
CUORE in a nutshell

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**

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
- **$1.49(4)\times10^{-2}$ counts/(keV·kg·y)**
- Energy resolution (at 2615 keV) close to expectations: **7.78(3) keV FHWM**





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

- Exposure for the current limit: **1038.4 kg·y (> 1.8 tonne·y collected!!)**
- Current limit (^{130}Te $T_{1/2}^{0\nu2\beta}$) : **> 2.2×10^{25} y**
  → **$m_{\beta\beta}$ < 90 – 305 meV**
- 5 y projected $T_{1/2}$ sensitivity: **~9×10^{25} y**
  → **$m_{\beta\beta}$ < 50 – 130 meV**

Nature 604 (2022) 53-58

CUORE is not background free

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

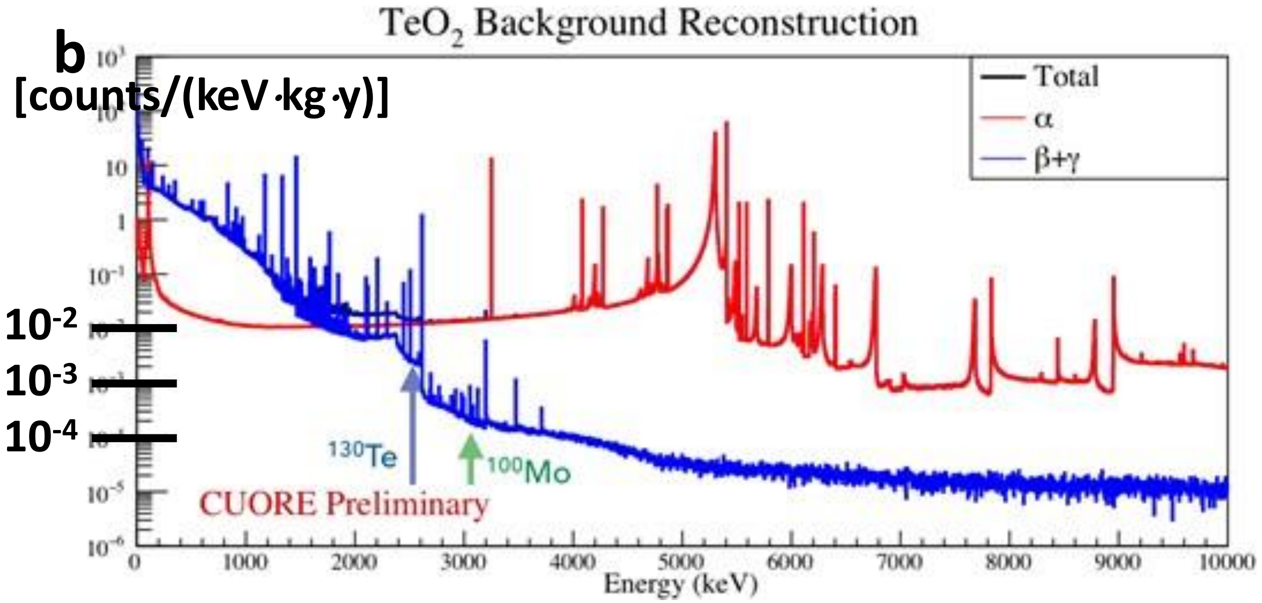
CUORE $\rightarrow$ CUPID

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 0ν2β experiment exists** and will be available at the end of the CUORE physics program (~2024)

CUPID (CUORE Upgrade with Particle ID) is a proposed 0ν2β bolometric experiment exploiting the **CUORE infrastructure** and with a **background 100 times lower at the ROI**

CUORE background model

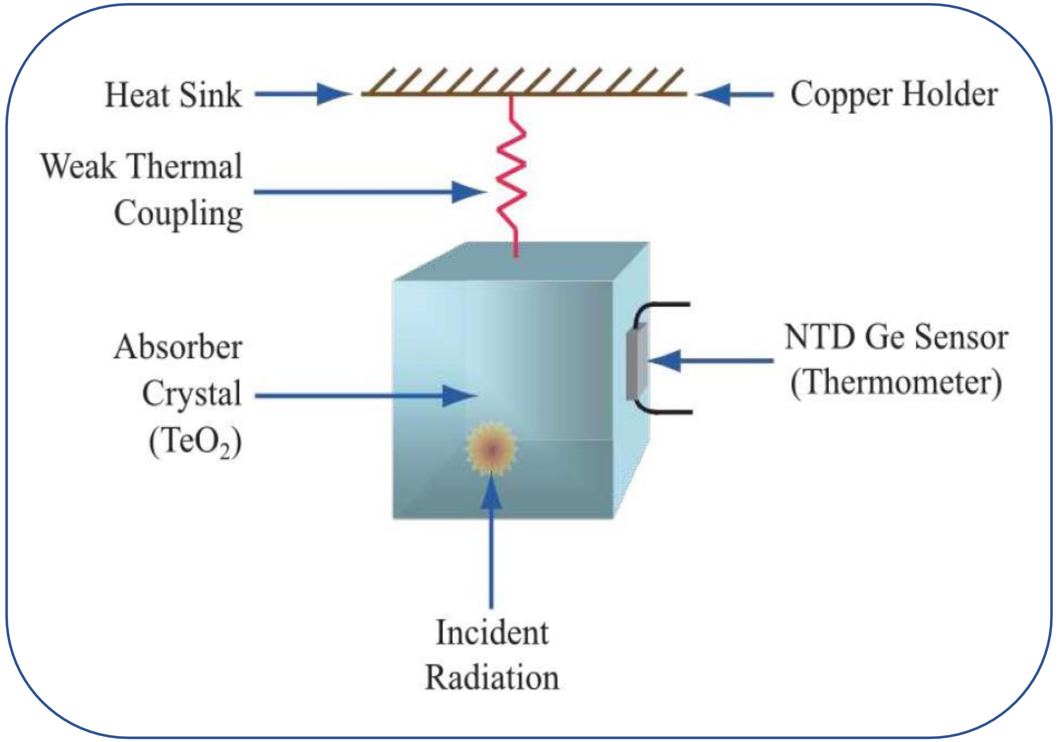


- Reject α background with **scintillating bolometers**
- Mitigate γ background by **moving to ^{100}Mo**

  → $Q_{2\beta}$: 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

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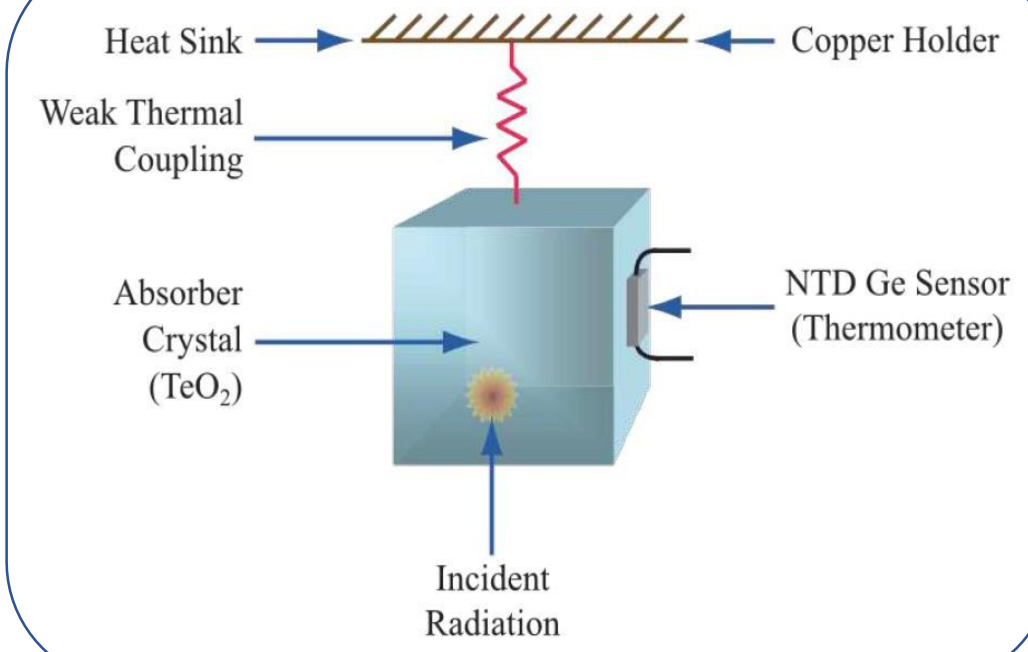
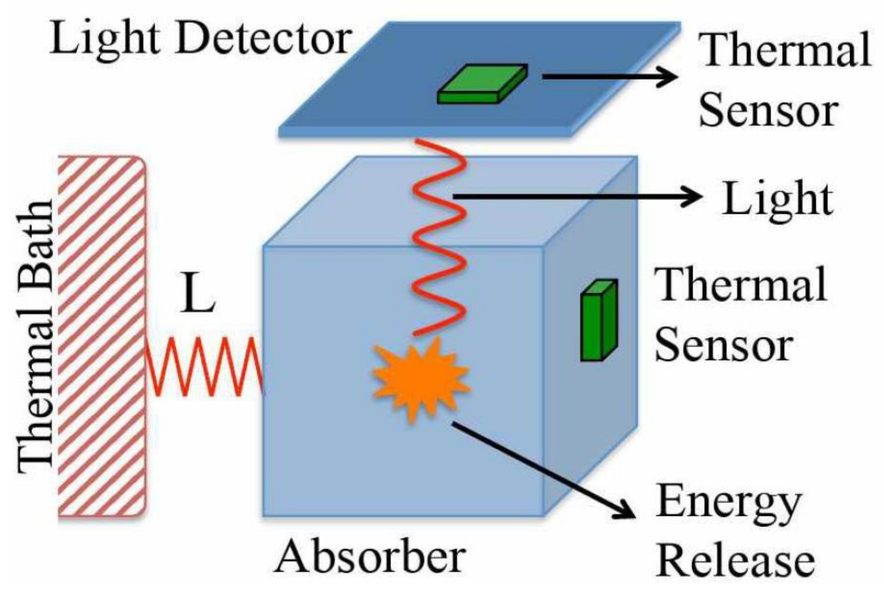


CUPID ^{100}Mo
heat + light
(**scintillating bolometer**)



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α background
γ background

CUPID rationale

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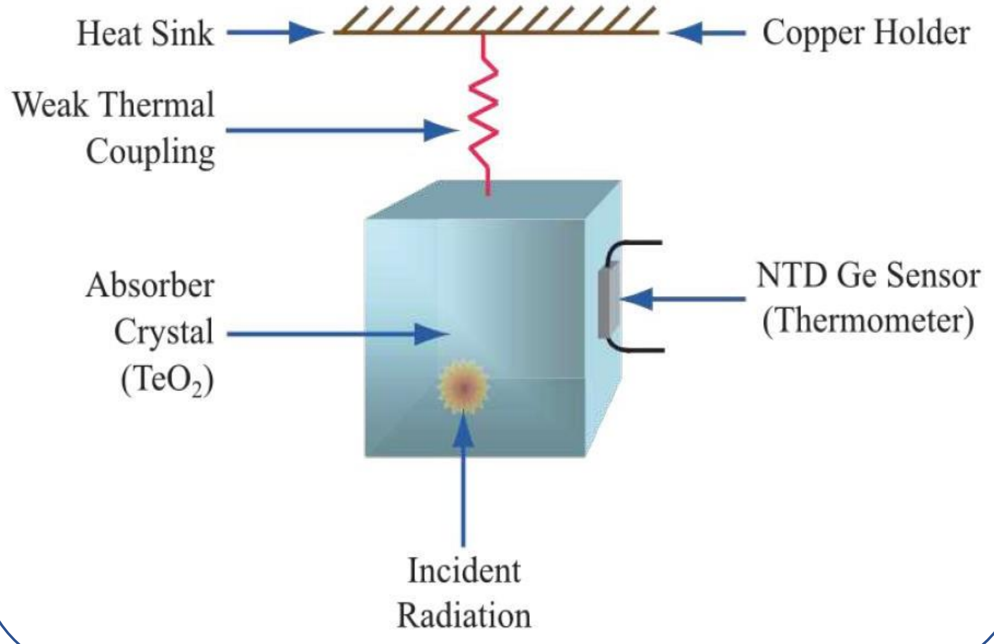

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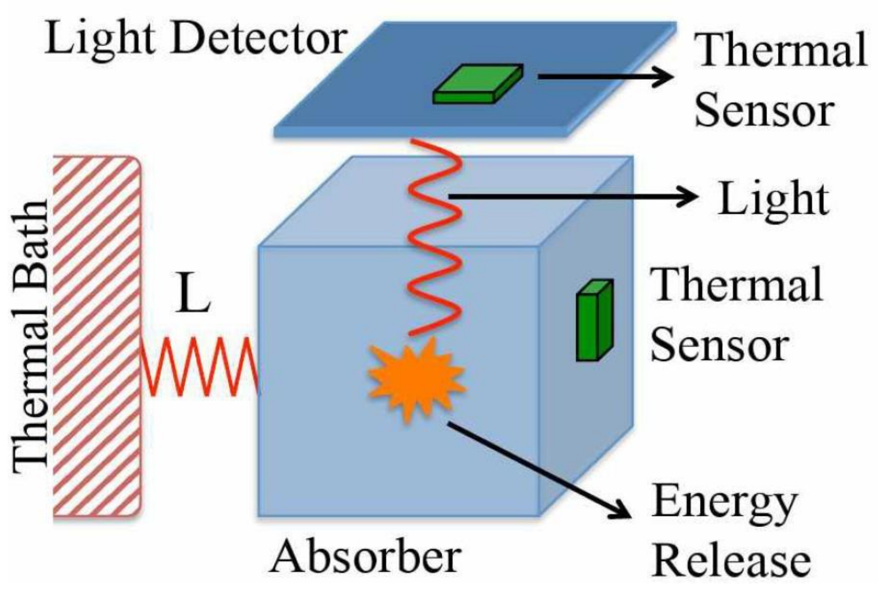

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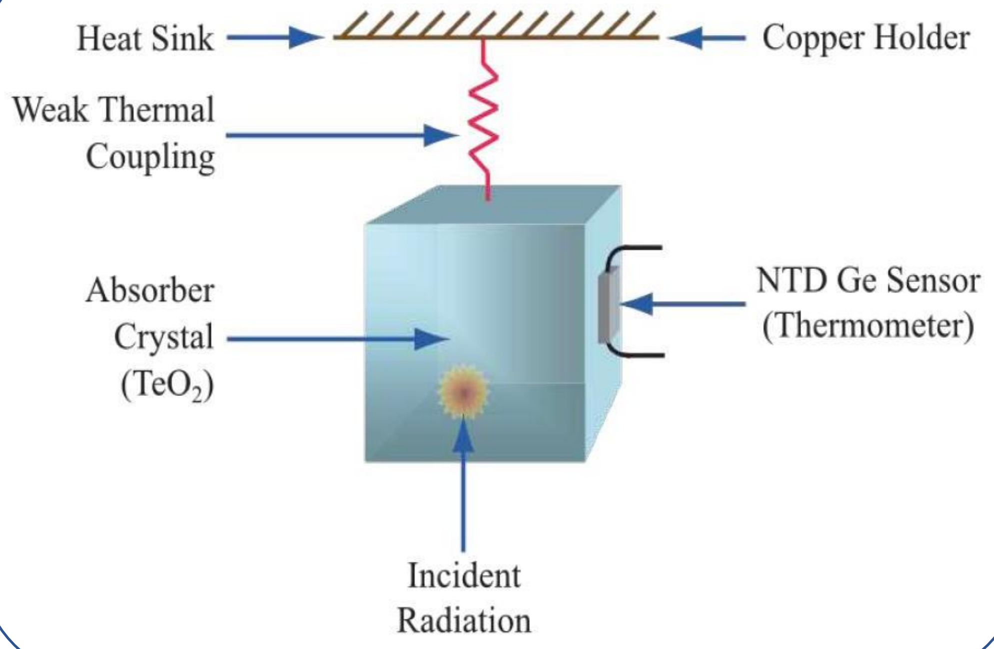
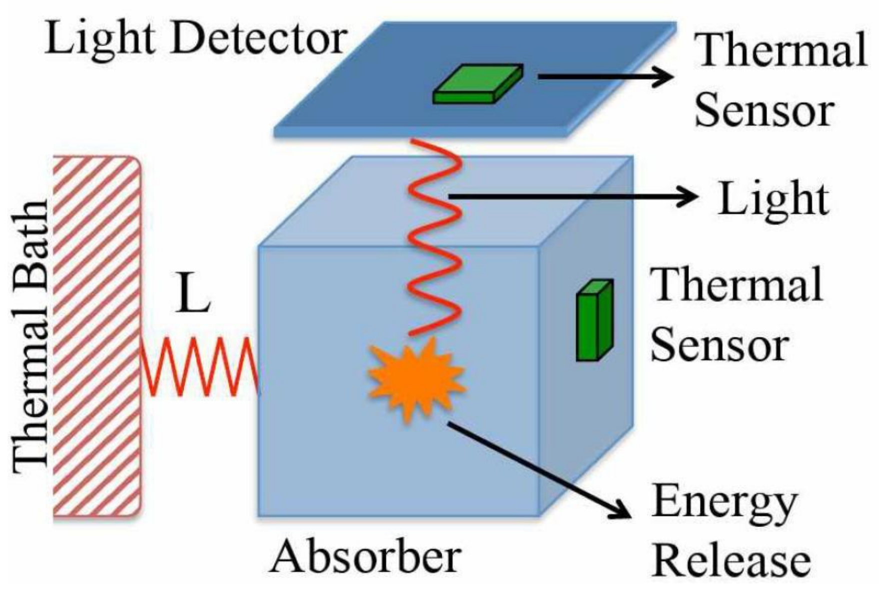
~~α background~~ ← **PID**
γ background

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~~
~~γ background~~

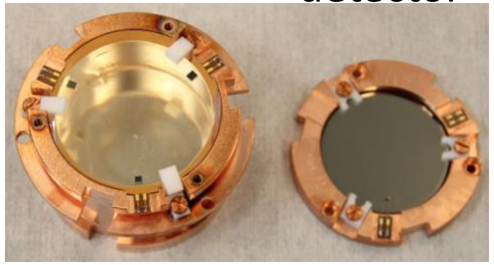
PID
$Q_{2\beta}$ = 3034 keV **> 2615 keV**

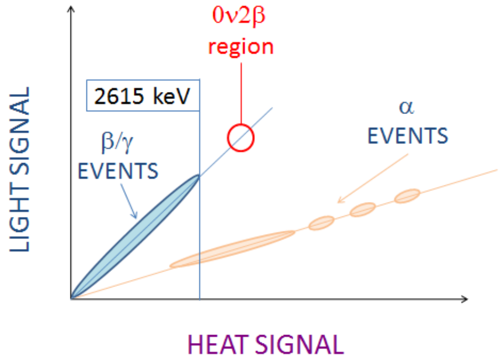
Choice of the isotope and compound

Scintillating bolometers

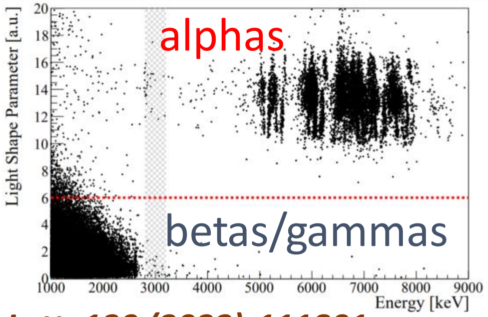
↓

α particle rejection

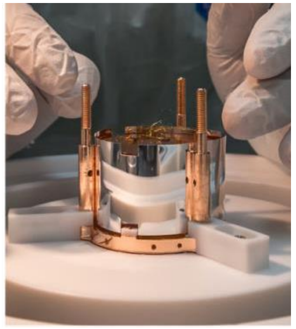




CUPID-0 – Zn^{82}Se $Q_{2\beta}$ = 2998 keV
(evolution of **LUCIFER** erc)
First running demonstrator (2017-2020)
24 crystals (enriched in ^{82}Se) – 5.28 kg ^{82}Se
Best limit on ^{82}Se: $T_{1/2} > 4.6\times10^{24}$ y
Energy resolution: ~**23 keV FWHM**

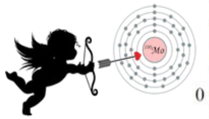


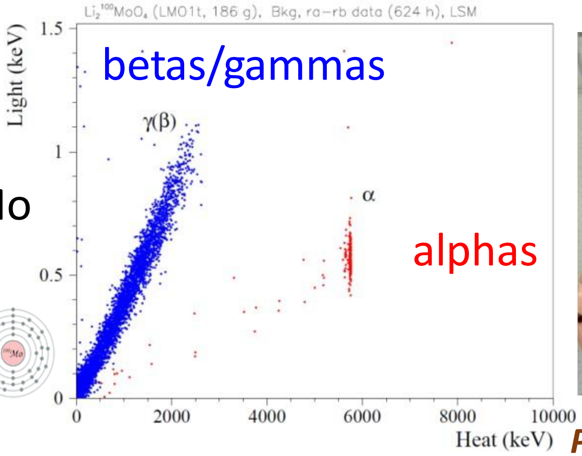
Phys. Rev. Lett. 129 (2022) 111801

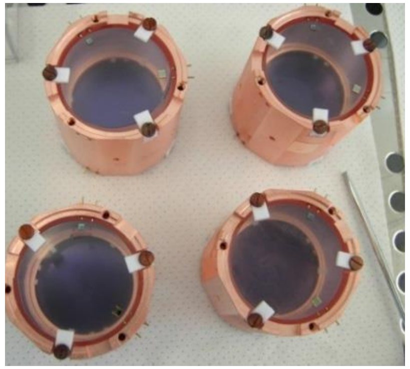


LNGS – Italy
b = 3.5 × 10^{-3} counts/(keV·kg·yr)
Useful information for the CUPID background model
Direct proof that α's dominate background above 2.6 MeV

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
Conceived and built at IJCLab
Zero background in ROI
Essential CUPID requirements met

Phys.Rev.Lett. 126(2021)181802-Eur.Phys.J. C 82,1033(2022)

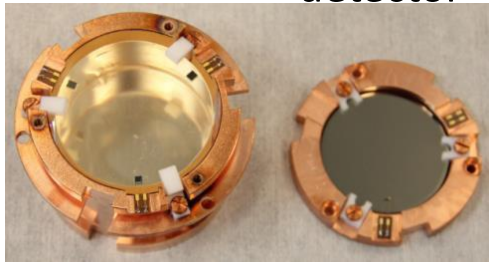
Choice of the isotope and compound

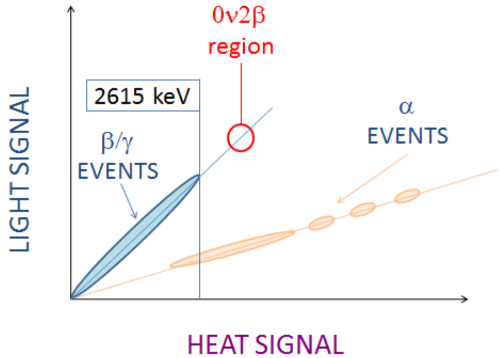
Scintillating bolometers

↓

α particle rejection

Main crystal | Light detector





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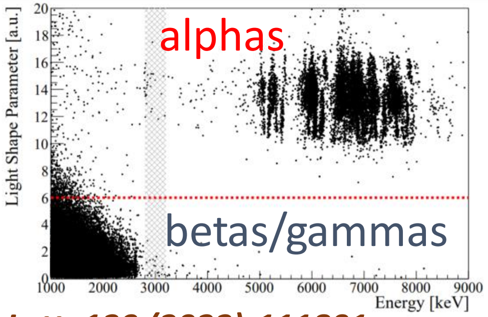
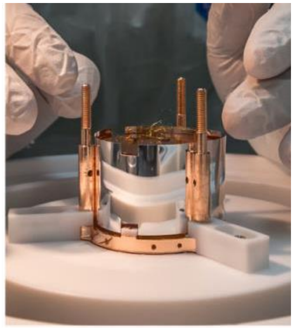


Phys. Rev. Lett. 129 (2022) 111801



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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

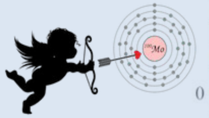
20 crystals (enriched in ^{100}Mo) – 2.34 kg ^{100}Mo

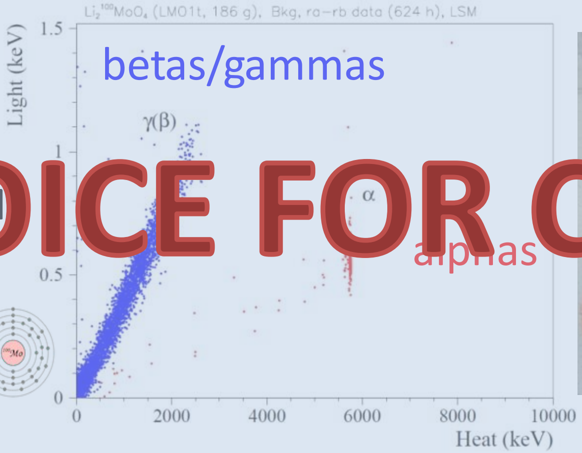
Energy resolution: ~**5-7 keV FWHM**

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

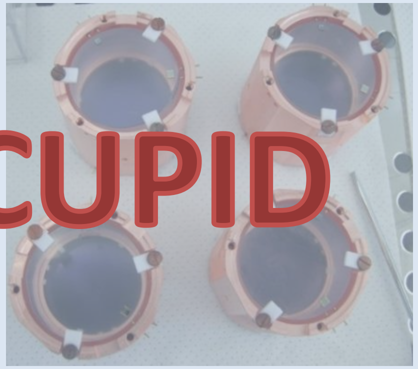
Full α rejection

Radiopure crystals: U/Th ≤ 1 μBq/kg





CHOICE FOR CUPID



LSM – France

Conceived and built at IJCLab

Zero background

Essential CUPID requirements met

Phys. Rev. Lett. 126 (2021) 181802 - arXiv:2202.08716v1

CUPID structure

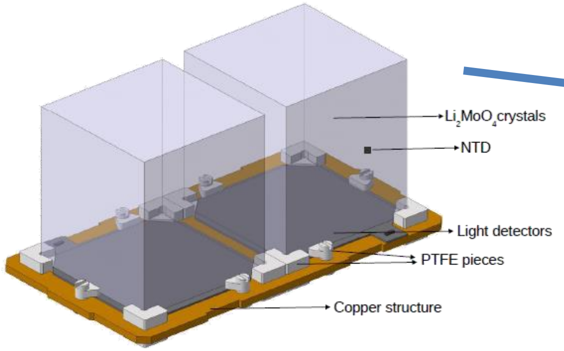
CUPID pre-CDR *arXiv:1907.09376* **TDR ready**

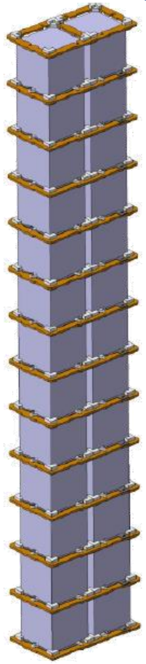
- Single module: $Li_2{}^{100}MoO_4$ **45×45x45 mm – ~280 g**
- 57 towers of 14 floors with 2 crystals each - **1596 crystals**
- **~240 kg of ^{100}Mo** with >95% enrichment
- **~1.6×10^{27}** ^{100}Mo atoms

Baseline design

Gravity stacked structure

Crystals thermally interconnected

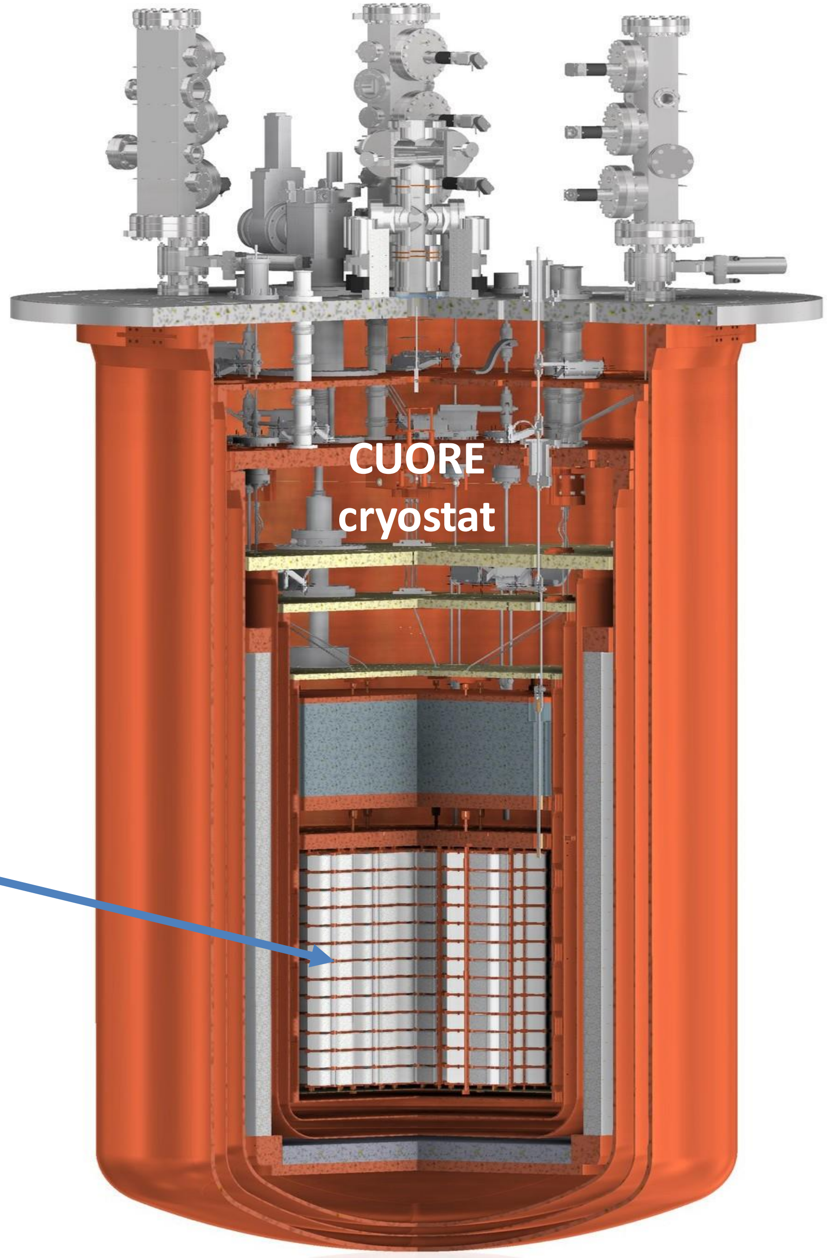




Ge light detectors with SiO antireflective coating (each crystal has top and bottom LD)

No reflective foil

Muon veto for muon induced background suppression



CUPID experimental tests

Tests are ongoing to **validate the CUPID detector structure** and investigate some **critical points of the background model**

Several above-ground facilities and **three underground facilities** are in use ➡

1. **Canfranc CROSS facility** (Spain) erc ← ICJLab-led
2. **LNGS Hall C facility** (Italy)
3. **LNGS Hall A facility** (Italy) (former CUORICINO, CUORE-0, CUPID-0 cryostat)

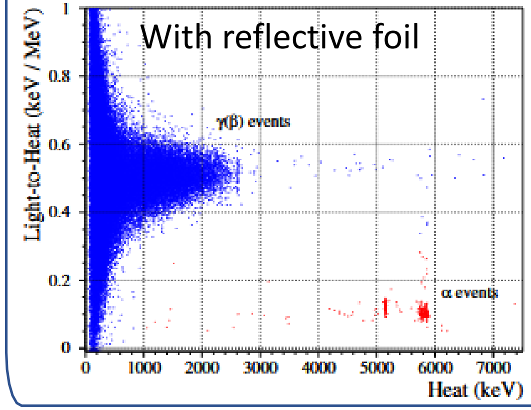
Canfranc CROSS facility

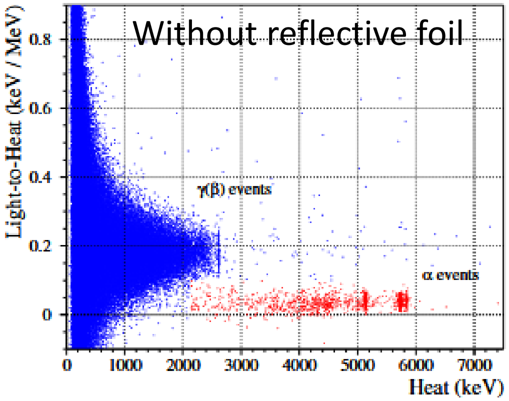
12 crystal array
16 light detectors

- 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

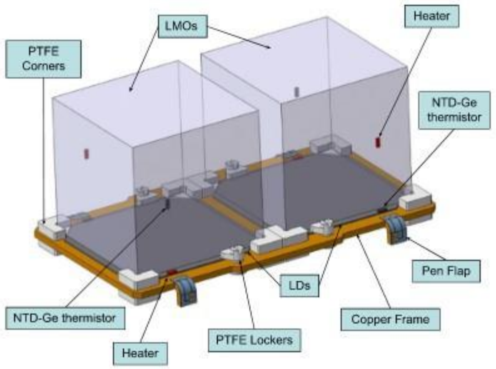
Validation of no-reflective-foil approach





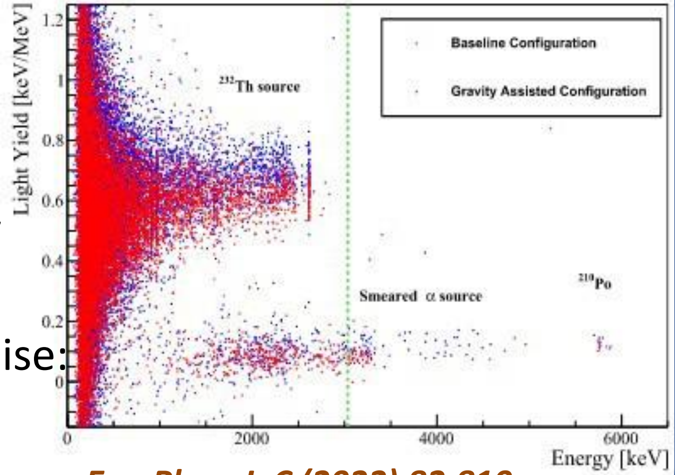
LNGS Hall C facility

First test and validation of the baseline CUPID module



8 crystal array
12 light detectors

- Energy resolution: **5.9 keV FWHM** at **3034 keV** ($Q_{\beta\beta}$)
- Light detector baseline noise: 35 – 70 eV FWHM
- **α rejection: > 99.9%**

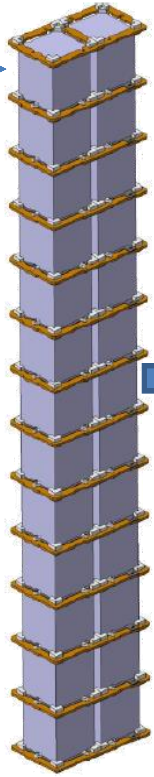


Eur. Phys. J. C (2022) 82:810

CUPID Baseline-Design Prototype Tower

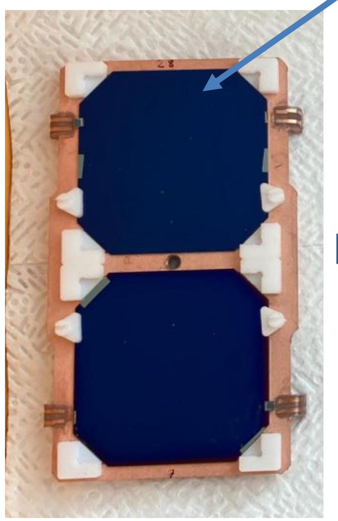
A **full CUPID tower** was fabricated (**IJCLab** and LNGS) and tested (LNGS Hall A facility)

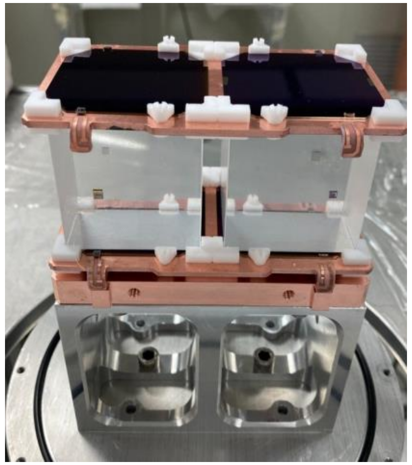
This tower has exactly the structure currently envisaged for the final 57 CUPID towers →

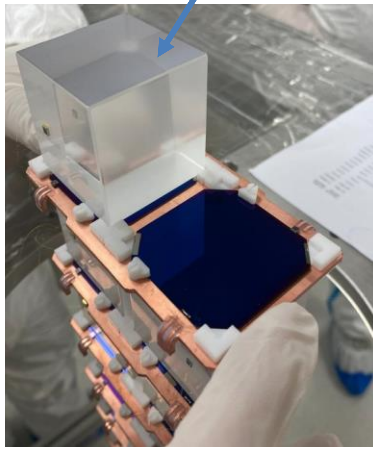


- 14 modules stacked in a tower
- 28 Li_2MoO_4 crystals of different origin (45x45x45 mm)
  - 6 natural crystals from BINGO ← CEA/IRFU-led
  - 8 enriched crystals from CROSS ← ICJLab-led
  - 8 natural crystals previously tested in hall C
  - 6 natural crystal from Chinese providers
  - Russian provider (same as CUPID-Mo)
- 30 Ge light detectors
  - Half of Ge wafers SiO-coated in Argonne, USA, by sputtering
  - Half of Ge wafers SiO-coated in IJCLab, France, by evaporation

Easy, fast and safe assembly procedure → **Needs to be tested: bolometrically unconventional assembly scheme**



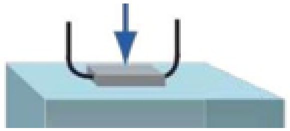




Ongoing tests

CUPID Baseline-Design Prototype Tower

Critical operation in assembly: **temperature-sensor gluing** → detector sensitivity, speed and reproducibility

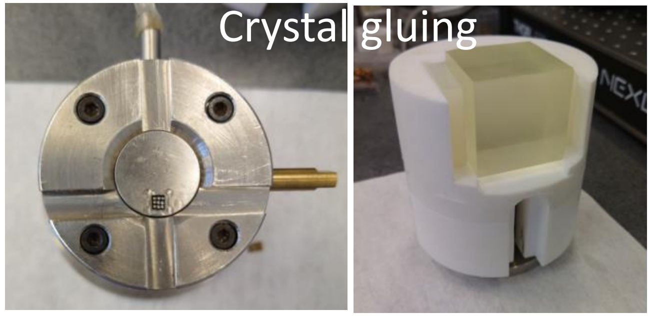


Fast bi-component epoxy | Slow bi-component epoxy | UV-curing glue

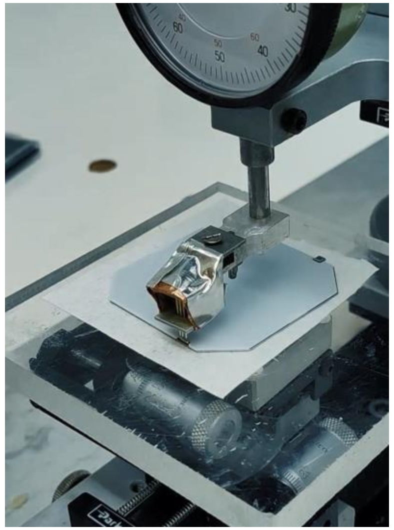
9 separated glue spots | Thin homogeneous layer

The baseline tower will allow us to compare different types of glues for Li_2MoO_4 crystals – Fast epoxy is used for light detectors

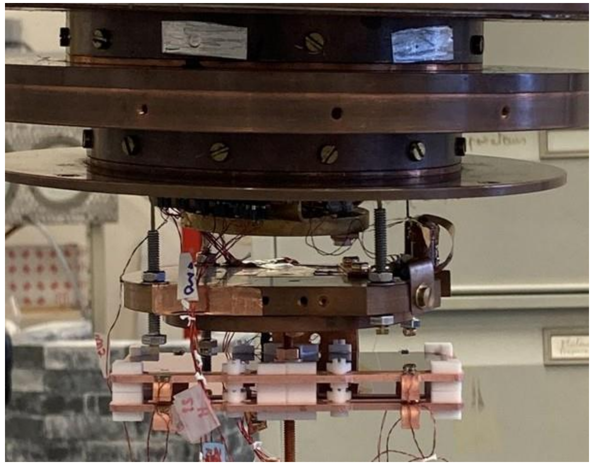
All **gluing operations** and **light-detector assembly** were performed at **IJCLab** by a **CUPID-France team**



Light detector gluing operation



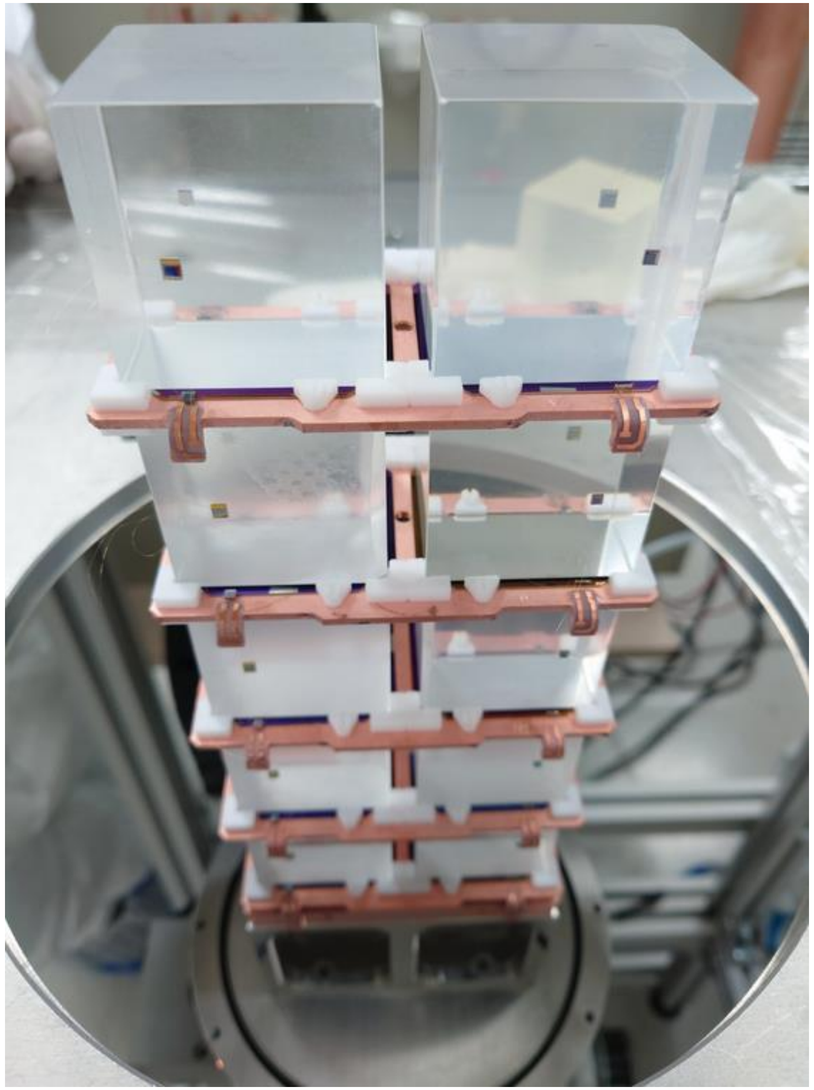
Four light detectors were preliminarily and successfully tested **above ground at IJCLab**



Ongoing tests

CUPID Baseline-Design Prototype Tower

Final tower assembly at LNGS



CUPID Baseline-Design Prototype Tower

The prototype tower was cooled down in July and October 2022

Primary goal: validate the tower structure in terms of **detector temperature values and distribution**

Secondary goals: Analysis of **detector performance** - Study of the **crystal radiopurity** – Dependance of detector behavior on **glue type**, **crystal origin**, **light-detector coating** method
(analysis still ongoing and results very preliminary)

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

Estimated **detector temperature range without readout current** (base temperature)

11 – 15 mK

Estimated **detector temperature range with readout current** (operation point)

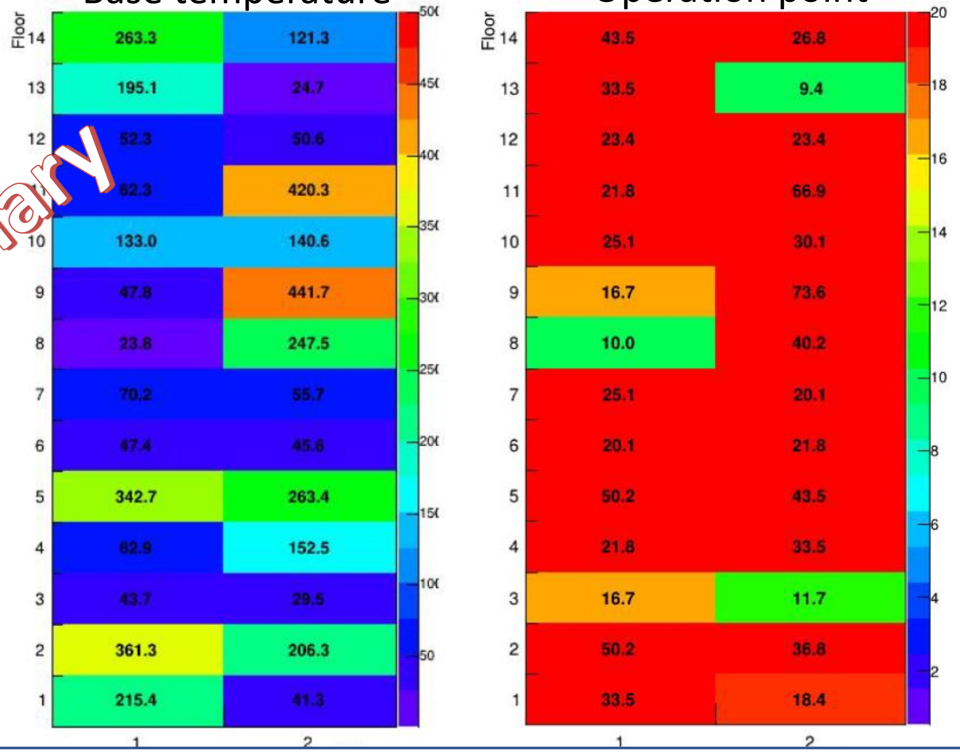
14 – 17 mK

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

Preliminary

Sensor resistance distribution along the tower

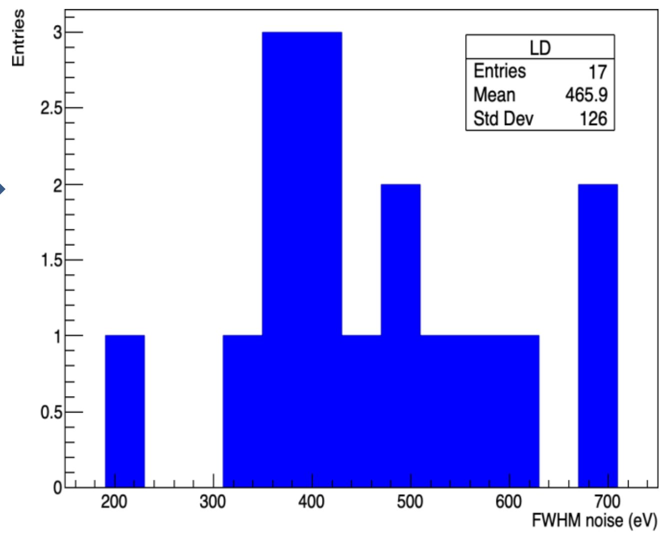
Base temperature | Operation point



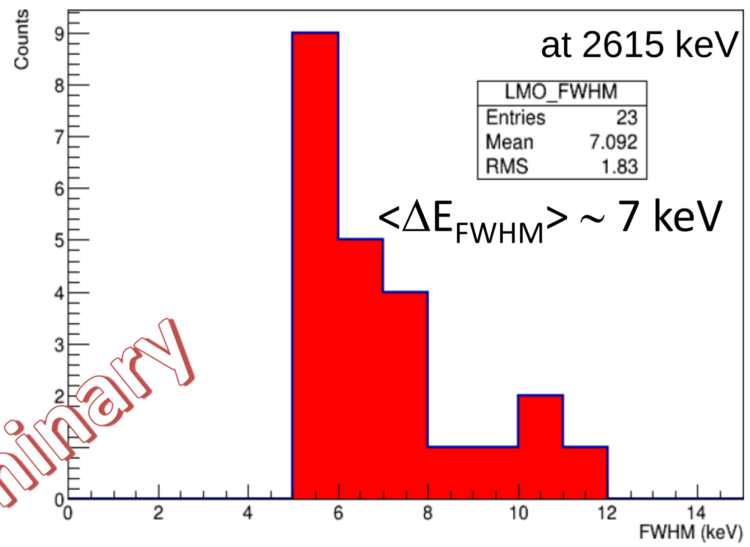
CUPID Baseline-Design Prototype Tower

Distribution of the energy resolutions of light and heat channels

FWHM baseline width of light detectors



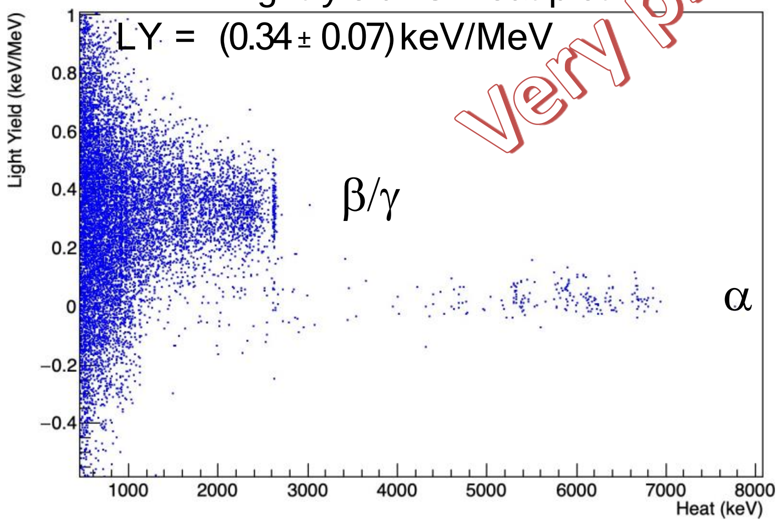
FWHM energy resolution of heat detectors



Very preliminary

Example of alpha rejection in a light channel

Light-yield vs. heat plot

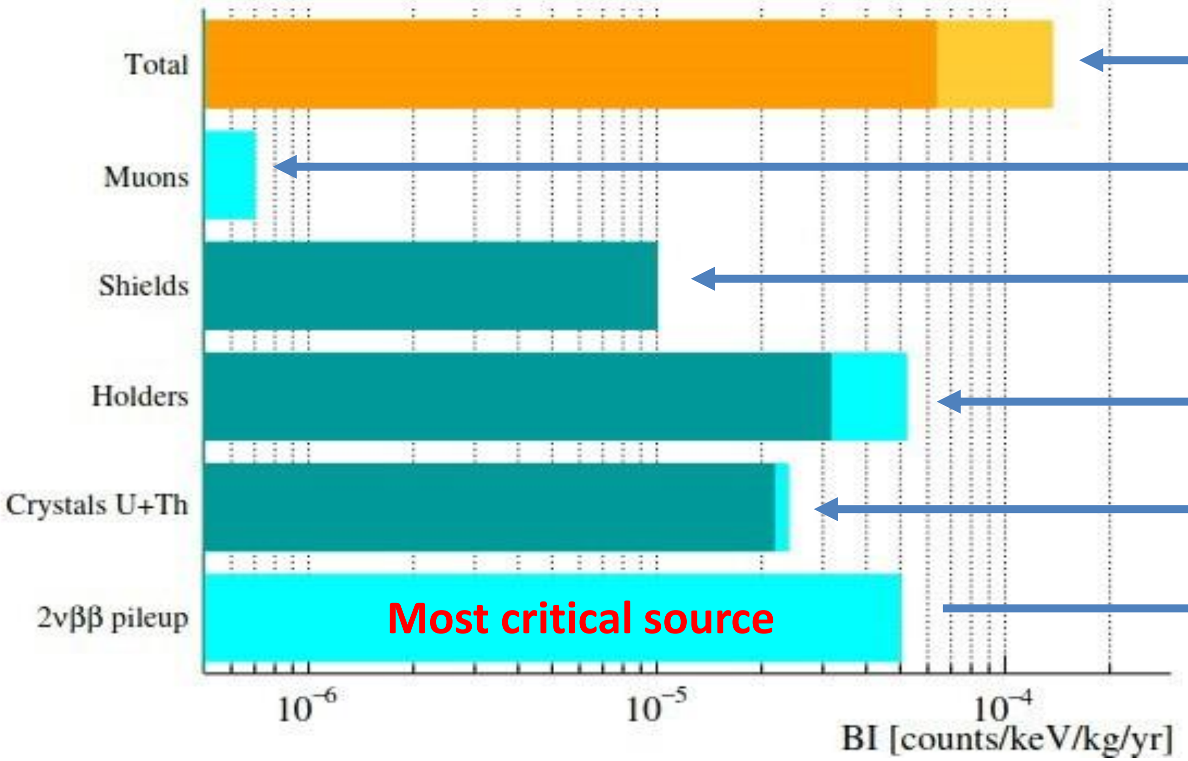


The energy resolution of the heat channels is **satisfactory** and close to CUPID goals

Light detectors are affected by excess noise which is under investigation. Despite that, many channels exhibit **the required discrimination power for CUPID** (> 99.9% α rejection)

CUPID background

Robust background model based on CUORE, CUPID-0, CUPID-Mo – the background in the hosting infrastructure is well-known

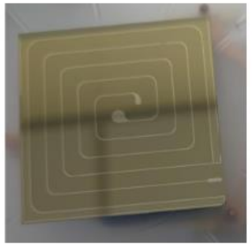


Projected background index: **b=1x10^{-4} counts/(keV·kg·yr)**

Muon veto is required and it is under design

Well-known from previous experiments

Validated by CUPID-Mo
(CUPID-Mo background model developed at IJCLab)



Major expertize in IJCLab

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 both **heat** and **light** channels

Higher S/N — Faster

- Improve noise level in the heat and light channels
- Improve sensitivity and speed acting on sensor features
- Widen electronics bandwidth and increase sampling rate
- Investigate machine learning techniques
- Improve S/N and/or speed of light detectors by technological upgrades
  → **promising technological solutions: Neganov-Trofimov-Luke or TES**

Work in progress

CUPID sensitivity

Energy resolution

5 keV FWHM

Background index

1 × 10^{-4} counts/(keV·kg·y)

Livetime

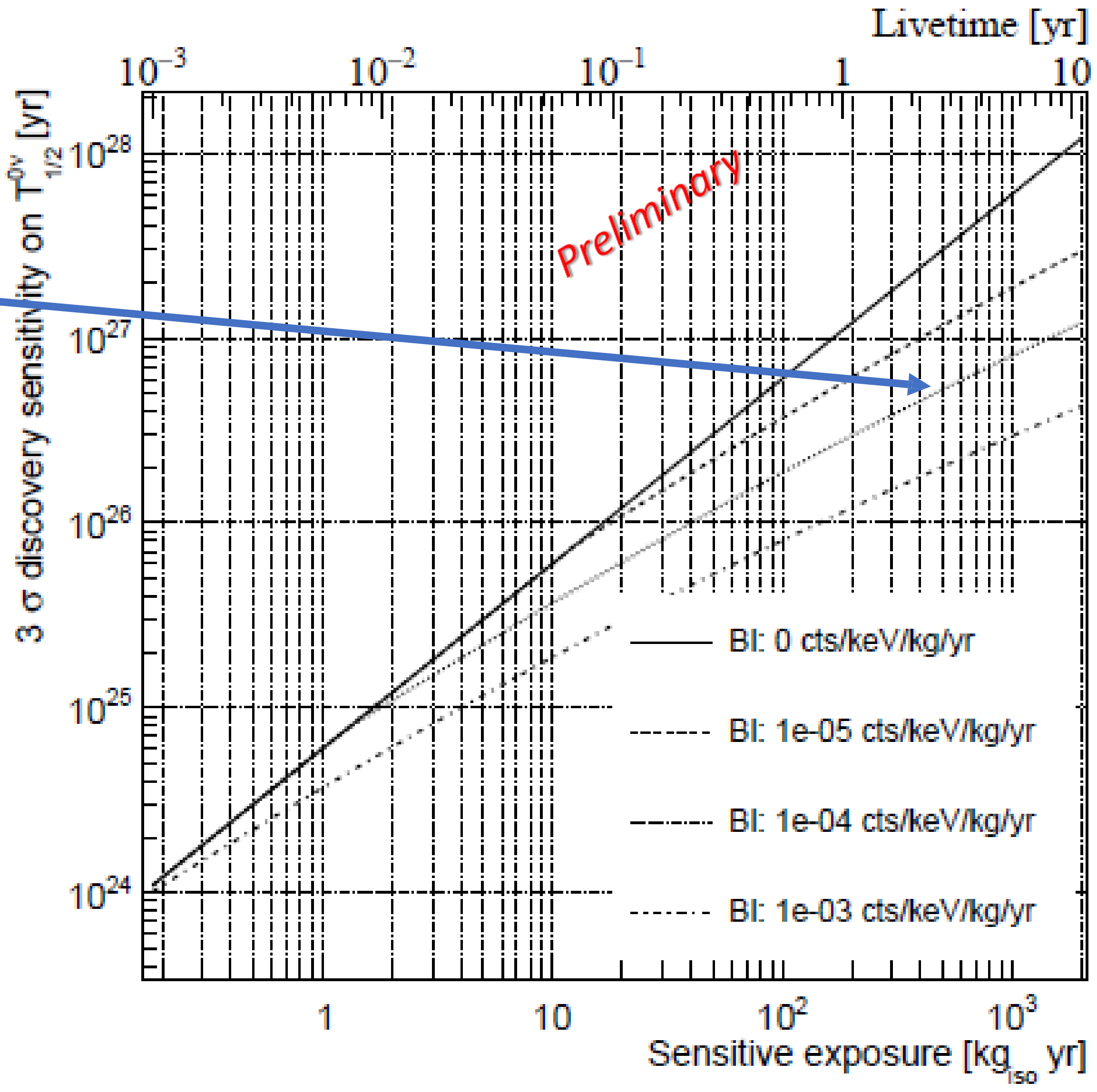
10 y

Half-life exclusion sensitivity

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

Half-life 3σ discovery sensitivity

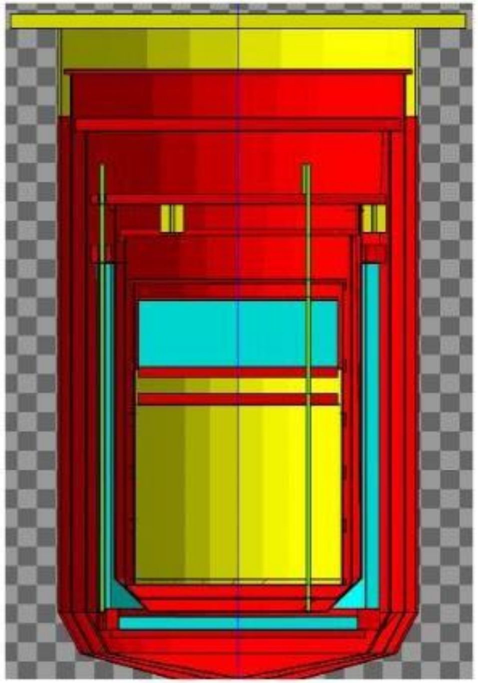
1 × 10^{27} y – $m_{\beta\beta}$ < 12-20 meV



Phased approach

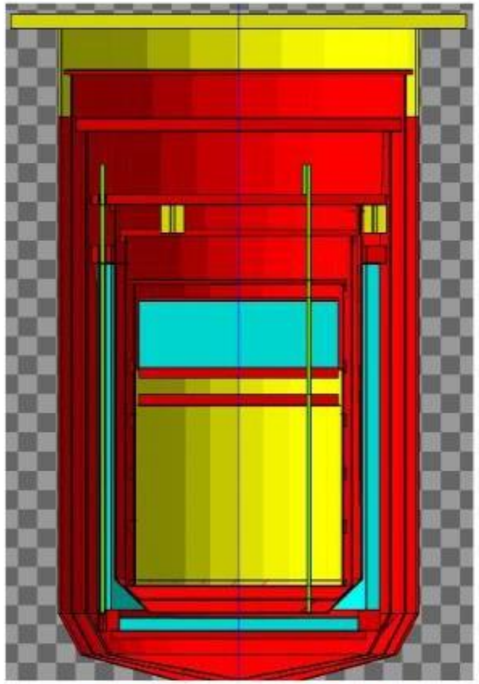
Technically ready

CUPID Baseline



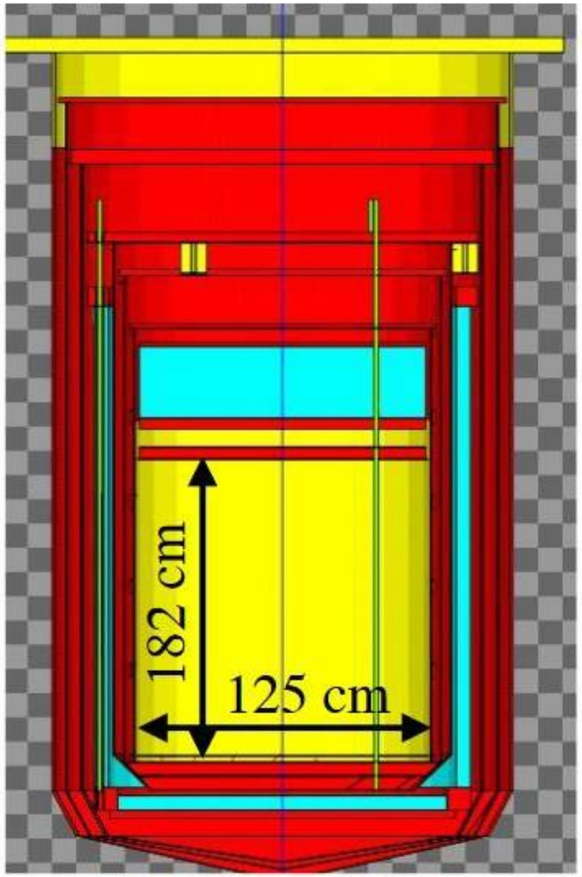
250 kg of ^{100}Mo
CUORE cryostat
Bkg 1×10^{-4} ckky
Excl. sensitivity:
$T_{1/2} > 1.4 \times 10^{27}$ y

CUPID-reach



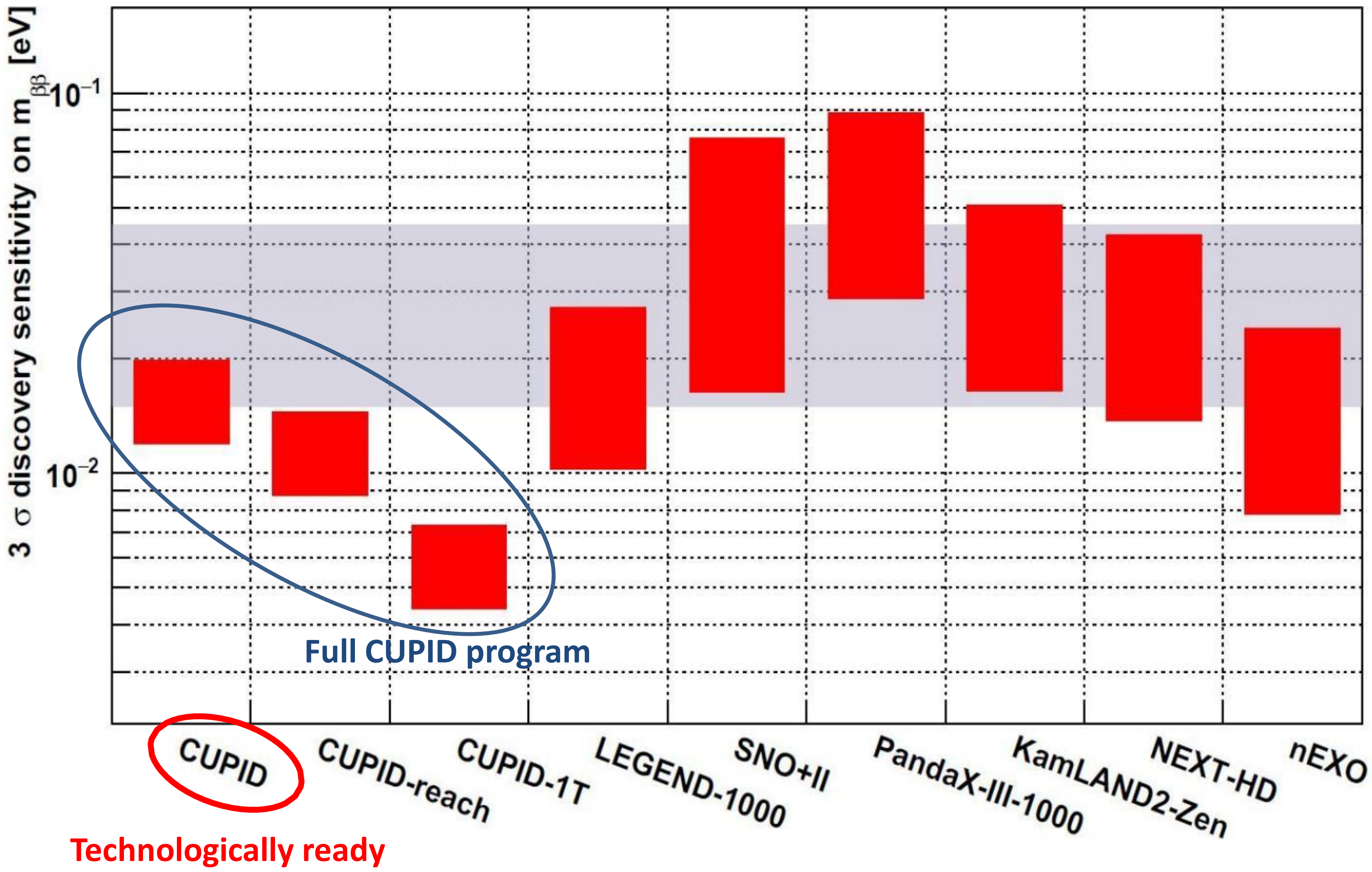
250 kg of ^{100}Mo
CUORE cryostat
Bkg 2×10^{-5} ckky
Excl. sensitivity:
$T_{1/2} > 2.2 \times 10^{27}$ y

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

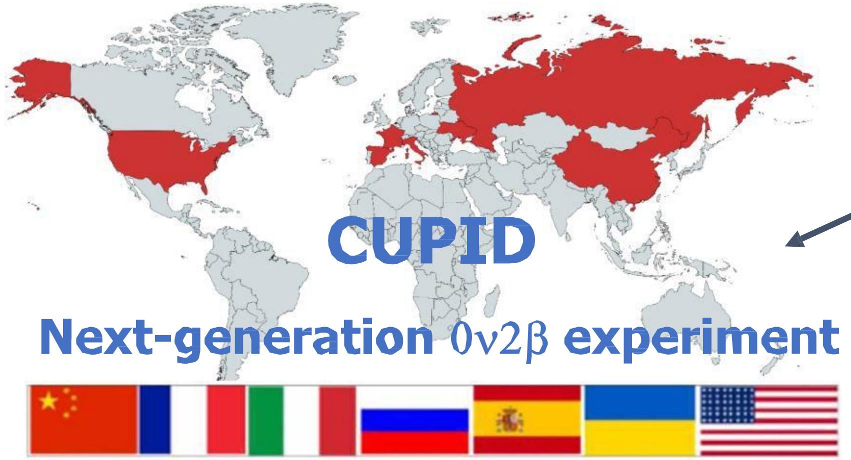
CUPID in the international landscape



CUPID collaboration

Best world limit on ^{130}Te

$T_{1/2}^{0\nu} > 2.2 \times 10^{25}$ y @90%CI



7 countries

~180 members

FRESH FORCES!

Best world limit on ^{100}Mo

$T_{1/2}^{0\nu} > 1.8 \times 10^{24}$ y @90%CI

Best world limit on ^{82}Se

$T_{1/2}^{0\nu} > 4.6 \times 10^{24}$ y @90%CI

Summary and final considerations

Advantages of CUPID

- The **infrastructure** already **exists** (**CUORE** cryostat, **LNGS**, Italy)
- **Basic technology** demonstrated in **CUPID-Mo** (EDELWEISS cryostat, **Modane**, France)
- The **performance** of the single module and of the basic tower are under test with promising results
- **Crystallization** and **enrichement** at large scale are **possible and demonstrated**
- **Data-driven background model** indicates **b$\sim$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, **mass scaling** and potential **multi-isotope approach**

CUPID collaboration

BACK UP

Isotopic enrichment

- **Russia** is by far the main isotope provider for current experiments
  $\rightarrow$ **reliable and high-quality supply chain**
- Some $0\nu\beta\beta$ isotopes procured from a **European producer** (^{82}Se, ^{76}Ge)
- **War against Ukraine** $\rightarrow$ impossible to procure isotopes from Russia for Western countries
- **Intense contacts** with a European producer for a Russia-alternative isotope supply (^{76}Ge,^{100}Mo, ^{136}Xe)
- **Chinese-led projects** could continue to procure $0\nu\beta\beta$ isotopes from Russia
- Experiments using or considering to use **natural isotopic composition** sources:
  Te (34% ^{130}Te): CUORE, SNO+, THEIA, JUNO
  Xe (8.9 % ^{136}Xe): DARWIN