GDR Deep Underground Physics plenary meeting

DUΦ Deep Underground Physics

9–11 oct. 2024
IP2I

CUPID

Status and prospects

Andrea Giuliani

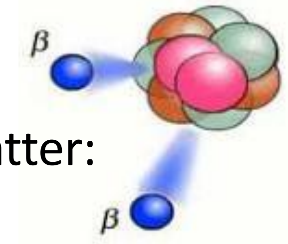
cnrs

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

CUPID

0ν2β in a nutshell

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

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

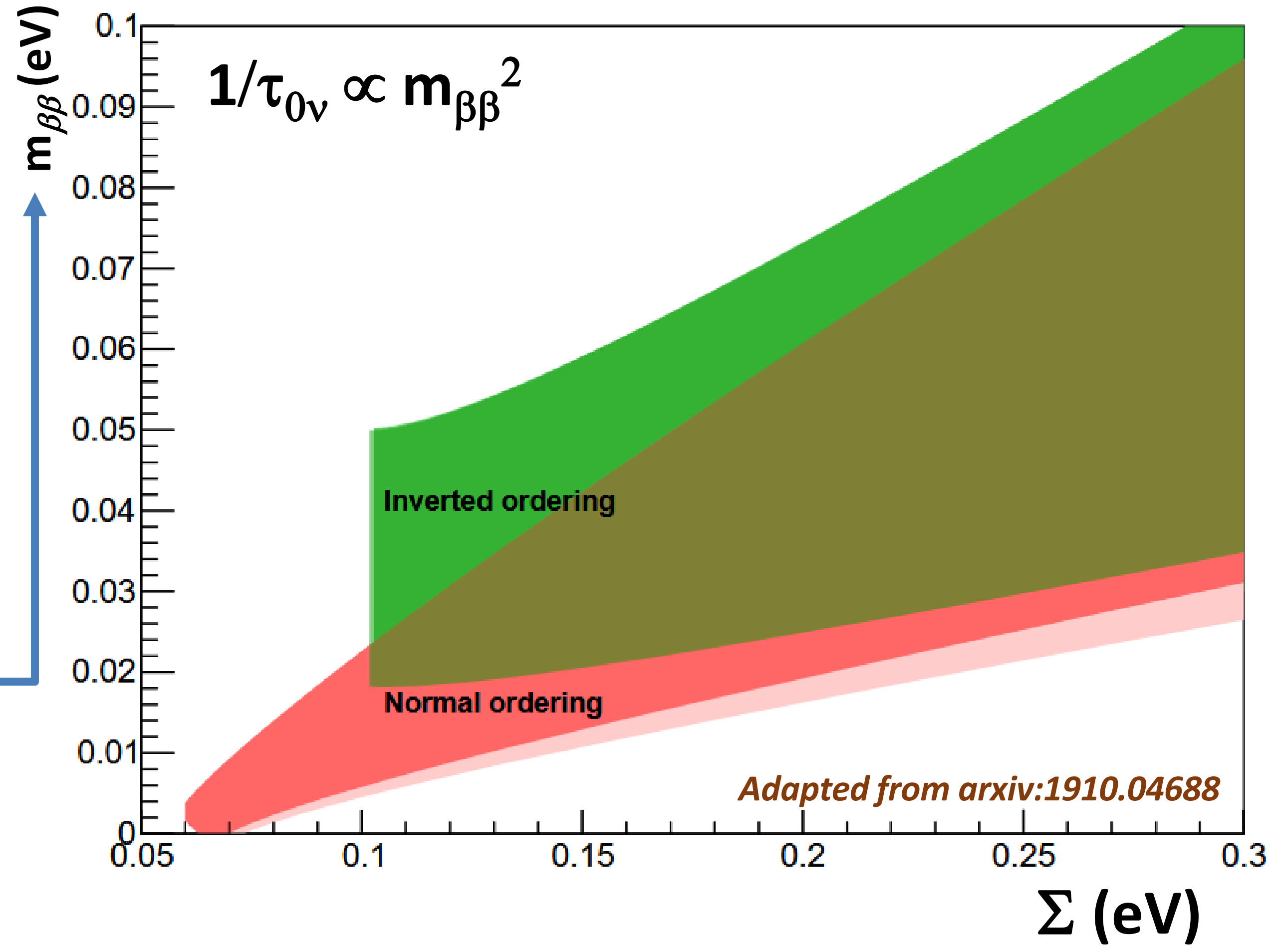
0ν2β

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

BSM non-standard mechanisms
Not necessarily neutrino physics

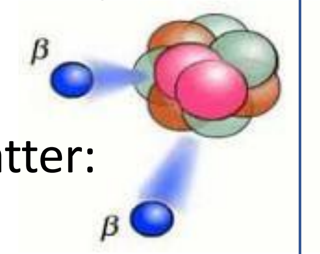
$\Sigma = m_1 + m_2 + m_3$ → Cosmology

$m_{\beta\beta} = ||U_{e1}|^2 m_1 + e^{i\alpha 1}|U_{e2}|^2 m_2 + e^{i\alpha 2}|U_{e3}|^2 m_3|$ → 0ν2β



$0\nu2\beta$ in a nutshell

$0\nu2\beta$ is an inclusive test for the « creation of leptons »:
$2n \rightarrow 2p + 2e^-$ $\Rightarrow$ 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**
Enrichment is mandatory, with the exception of ^{130}Te

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

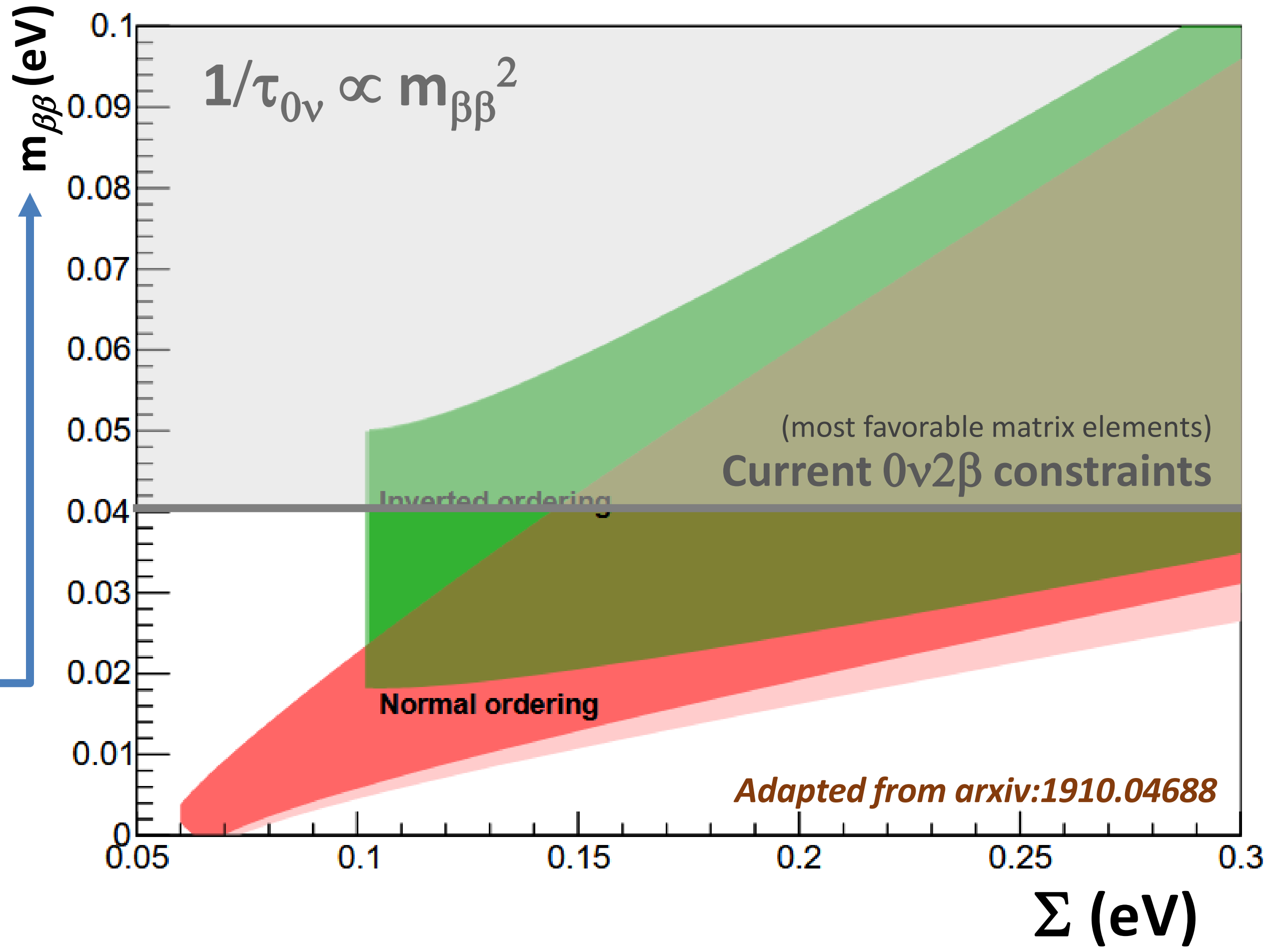
$0\nu2\beta$

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

$\Sigma = m_1 + m_2 + m_3$ $\rightarrow$ **Cosmology**

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



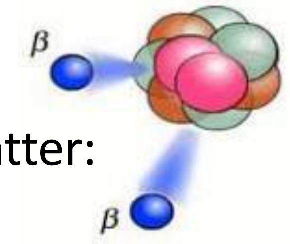
CUPID

0ν2β in a nutshell

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

$m_{\beta\beta} = ||U_{e1}|^2 m_1 + e^{i\alpha 1}|U_{e2}|^2 m_2 + e^{i\alpha 2}|U_{e3}|^2 m_3|$ → 0ν2β

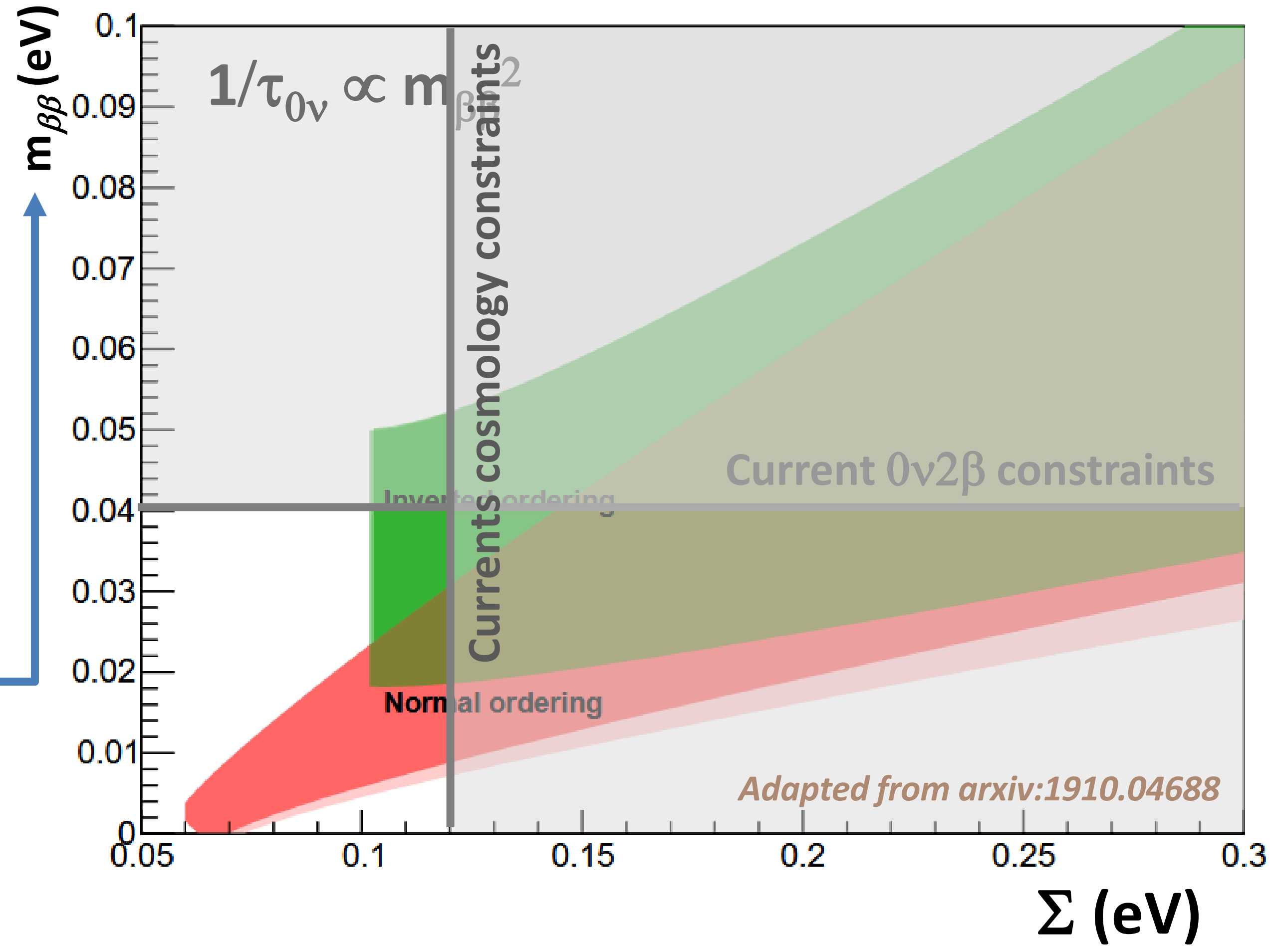
0ν2β is an inclusive test for the « creation of leptons »:
$2n \rightarrow 2p + 2e^-$ ⇒ LNV



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

Signal: **a peak** in the sum-energy spectrum 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

0ν2β in a nutshell

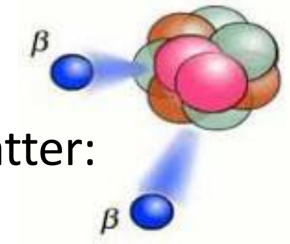
CUPID

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

$m_{\beta\beta} = ||U_{e1}|^2 m_1 + e^{i\alpha 1}|U_{e2}|^2 m_2 + e^{i\alpha 2}|U_{e3}|^2 m_3|$ → 0ν2β

0ν2β is an inclusive test for the « creation of leptons »:

2n → 2p + 2e⁻ ⇒ LNV



This test is implemented in the nuclear matter:

(A,Z) → (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**

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

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

0ν2β

Standard mechanism: neutrino physics

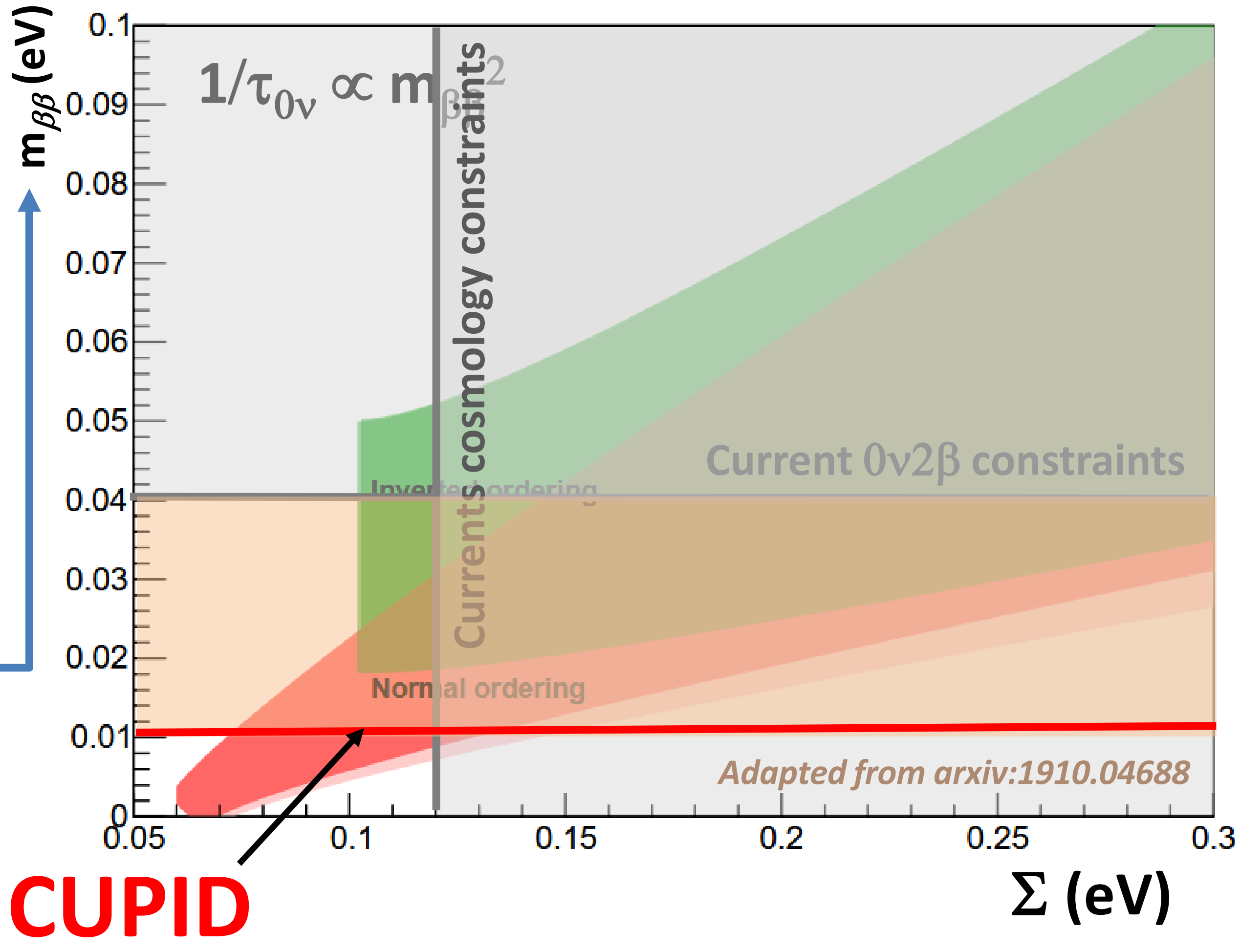
0ν2β is mediated by

light massive Majorana neutrinos

(exactly those which oscillate)

BSM non-standard mechanisms

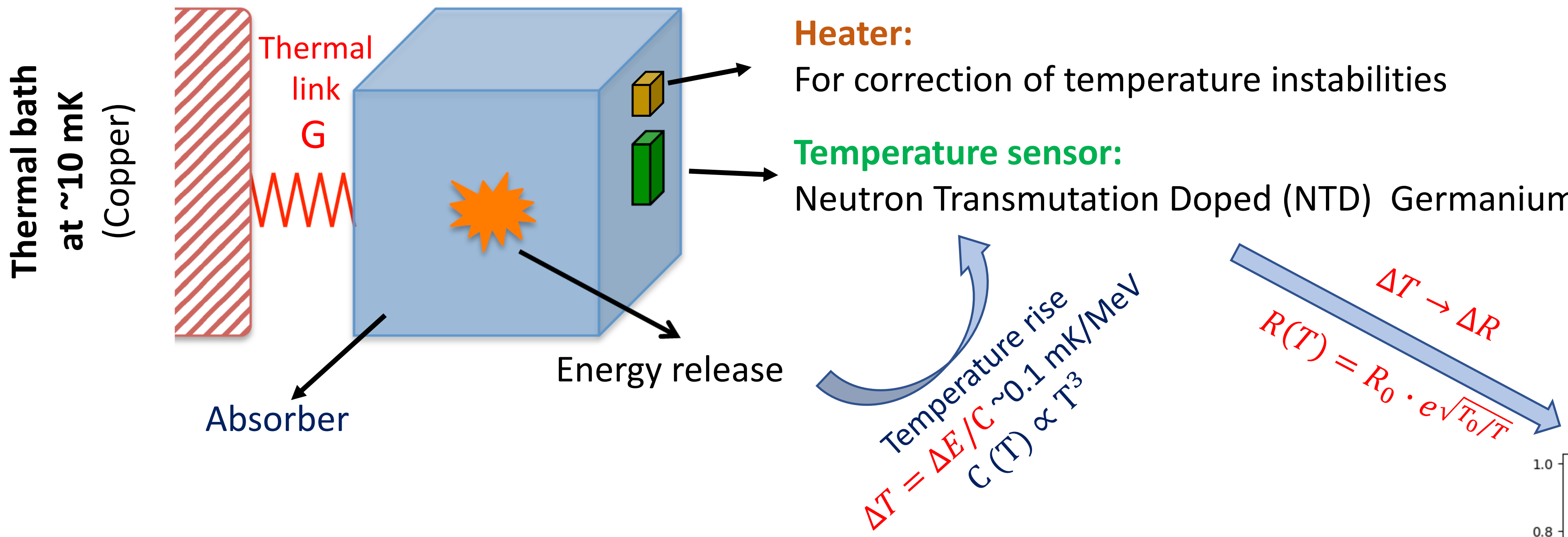
Not necessarily neutrino physics

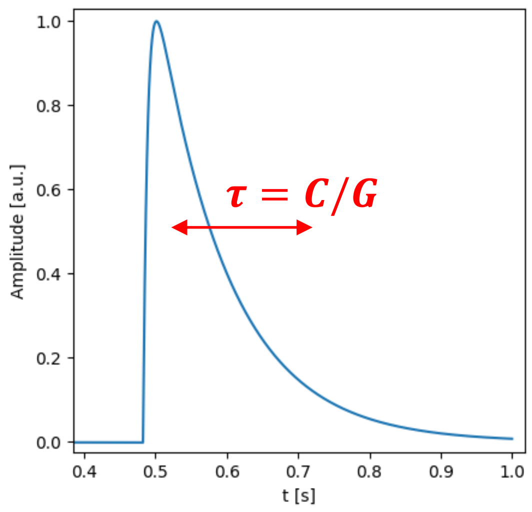


and other next-generation experiments (nEXO, LEGEND, NEXT)

(most favorable matrix elements)

Bolometric technique





Bolometric detector properties match well the required features for 0ν2β search

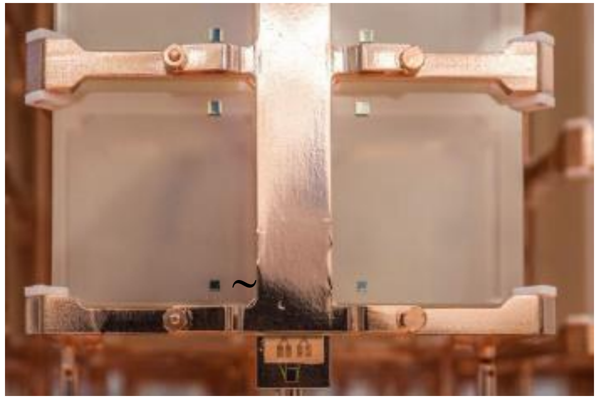
- Good energy resolution ~ 5-10 keV at 2.5 MeV
- Large flexibility in material choice
- Source = detector: high efficiency

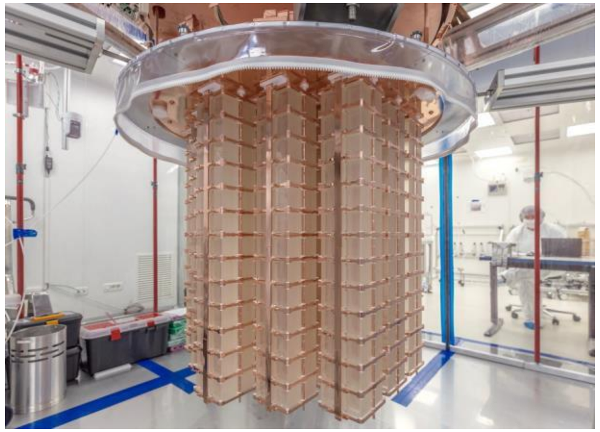
CUORE in a nutshell

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**

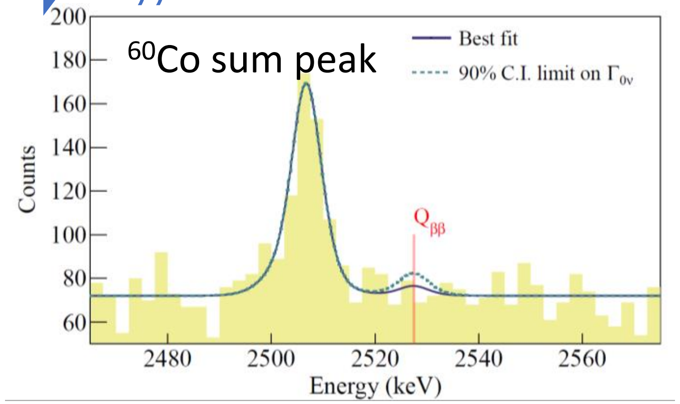




One of the most sensitive $0\nu2\beta$ experiments of the current generation

- Analyzed exposure: **2039.0 kg·y** (567.0 kg·y ^{130}Te)
- Current limit (^{130}Te $T_{1/2}^{0\nu2\beta}$) : **> 3.8 × 10^{25} y**

→ **$m_{\beta\beta}$ < 70 – 240 meV**



CUORE is not background free

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

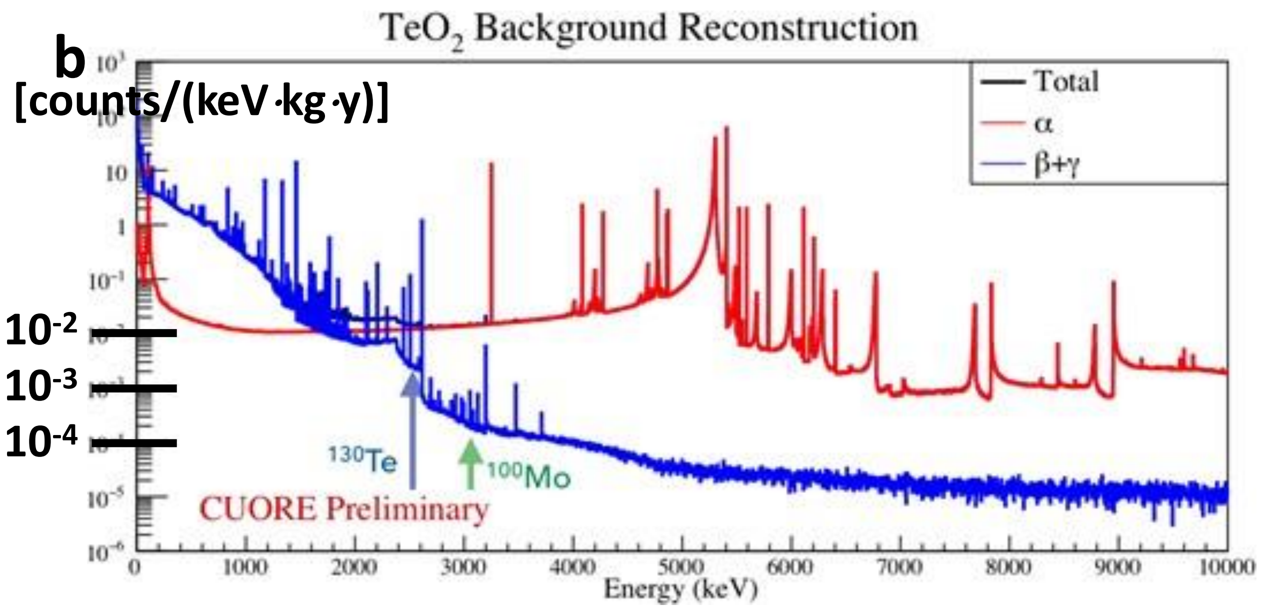
CUORE → CUPID

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 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



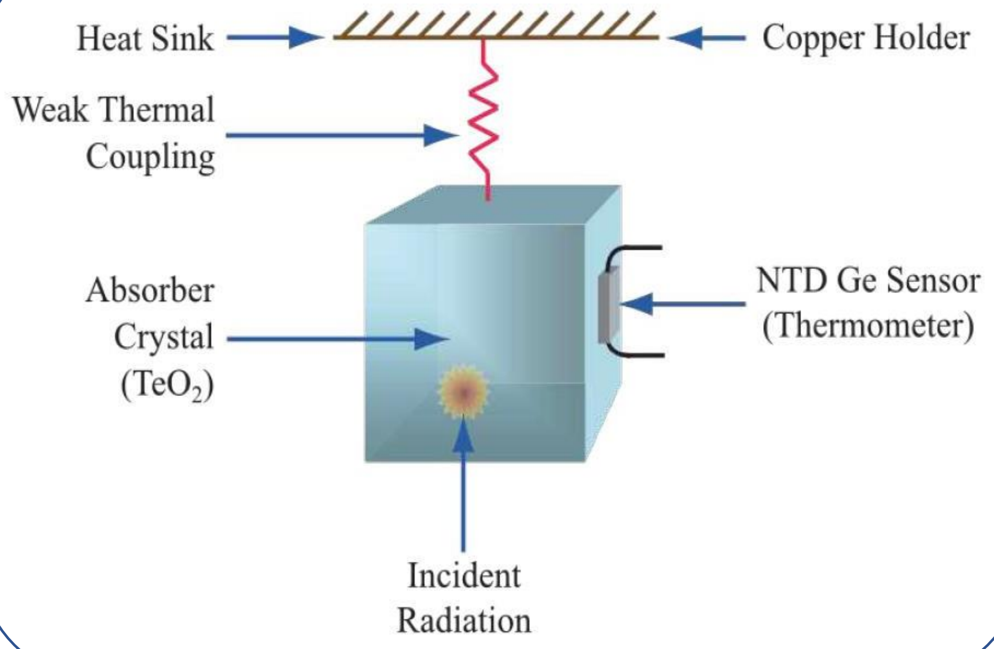
- Reject α background with **scintillating bolometers**
- Mitigate γ background by **moving to ^{100}Mo**

→ $Q_{2\beta}$: 2527 keV (^{130}Te) → 3034 keV (^{100}Mo)

- Increase isotope mass by **enrichment** (natural isotopic abundance: 9.7%)

CUPID rationale

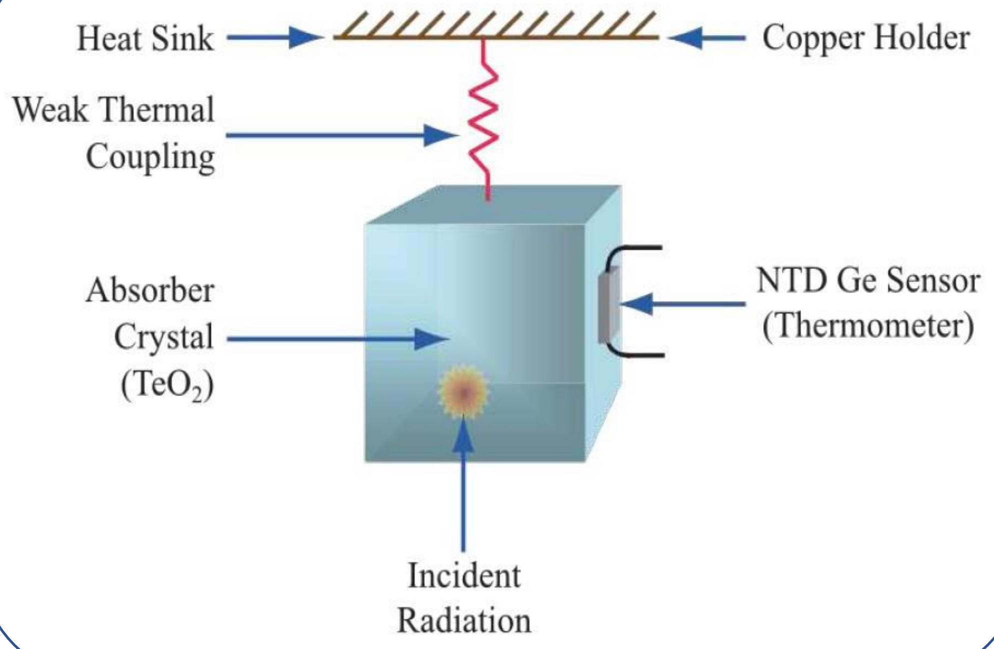
CUORE ^{130}Te
pure thermal detector
(**bolometer**)



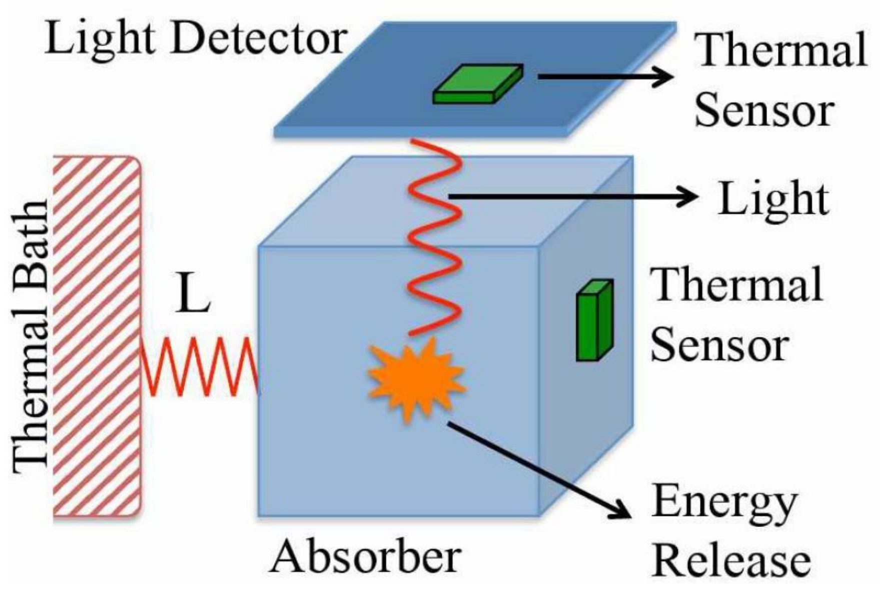
No PID
$Q_{2\beta}$ = 2527 keV **< 2615 keV**

CUPID rationale

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



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

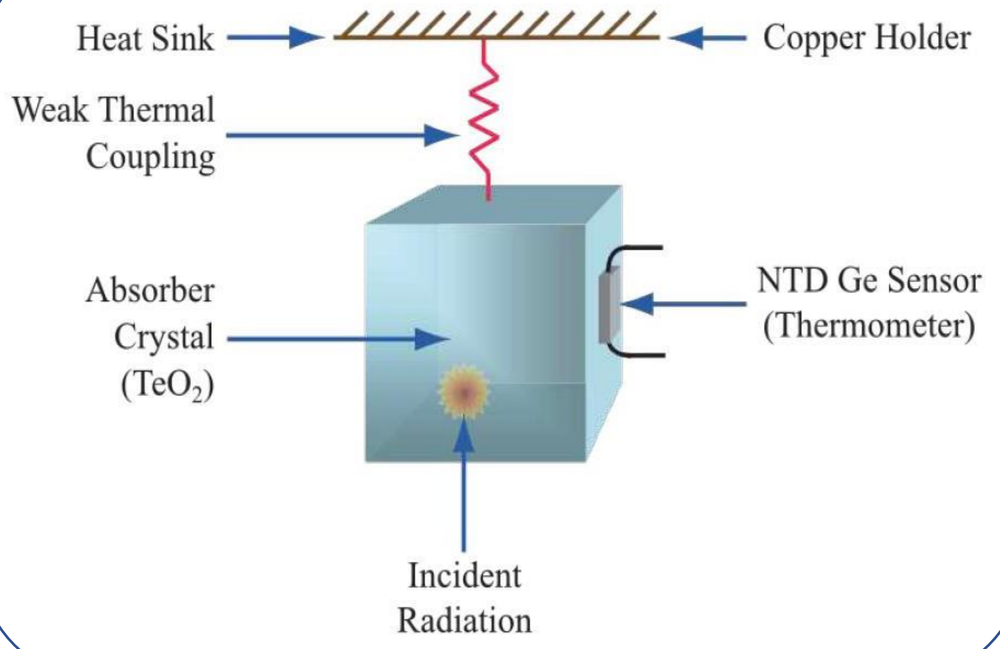


No PID
$Q_{2\beta}$ = 2527 keV **< 2615 keV**

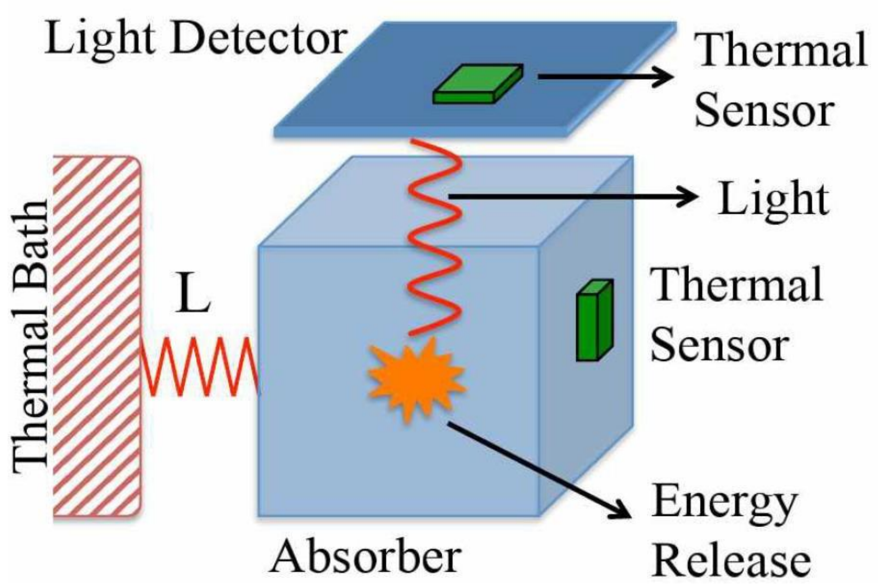
α background
γ background

CUPID rationale

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



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

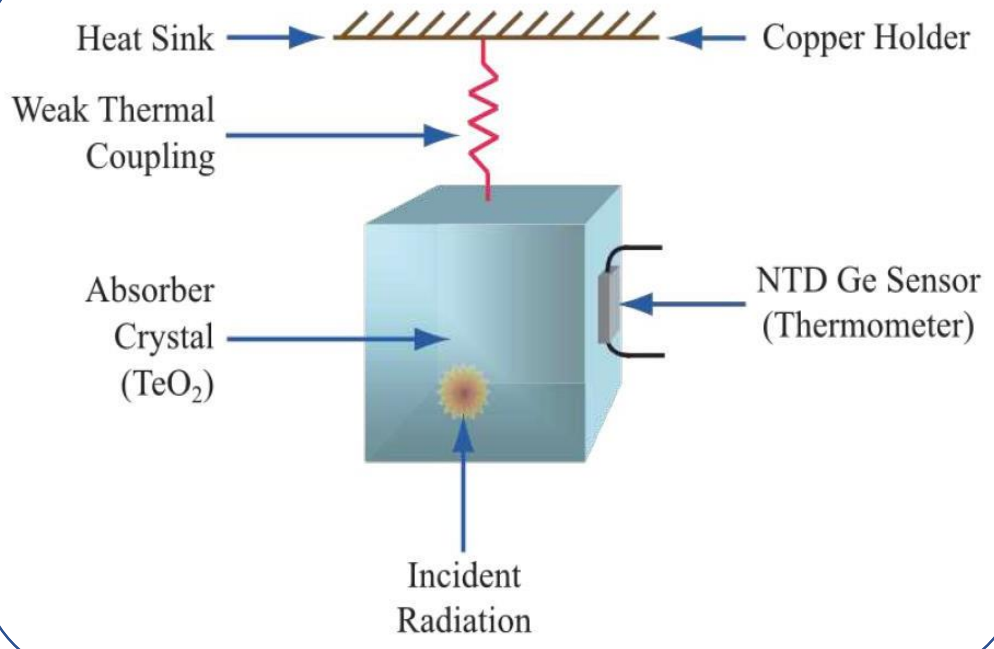


No PID
$Q_{2\beta}$ = 2527 keV **< 2615 keV**

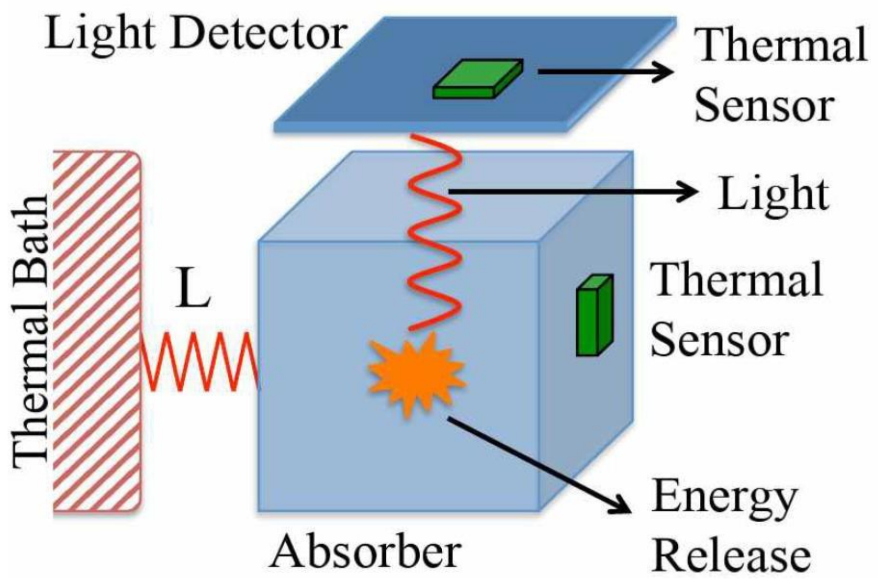
~~α background~~ ← **PID**
γ background

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**

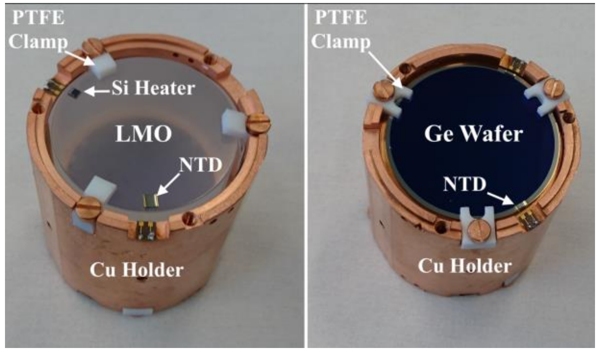
~~α background~~
~~γ background~~

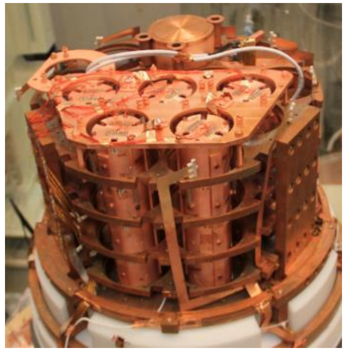
PID
$Q_{2\beta}$ = 3034 keV **> 2615 keV**

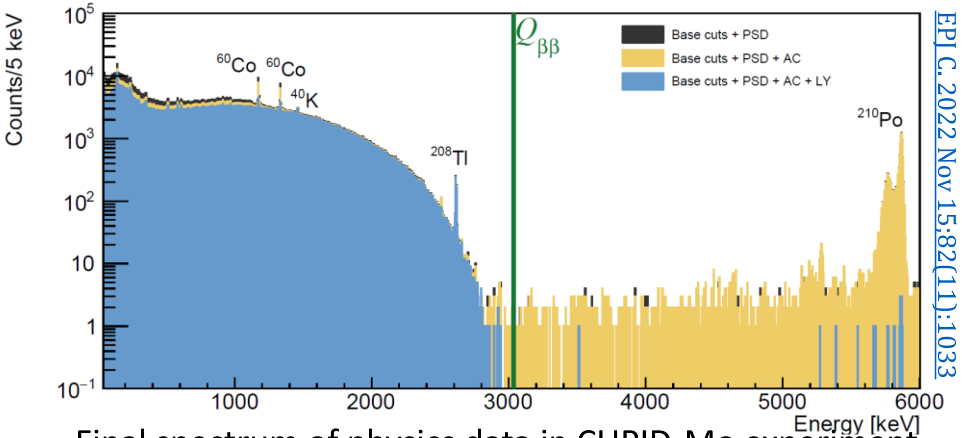
CUPID-Mo

CUPID-Mo experiment

- 20 scintillating bolometers arranged in 5 towers
- each scintillating bolometer consists of $Li_2{}^{100}MoO_4$ enriched crystal (~ 97% enrichment level) and Germanium light detector
- total mass of crystals is 4.16 kg corresponding to 2.26 kg of ^{100}Mo
- ~ 1.5 years of data taking
- located in the Laboratoire Souterrain de Modane (France) ~ 4800 m.w.e.

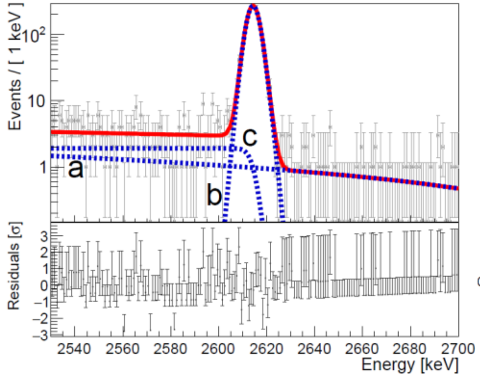






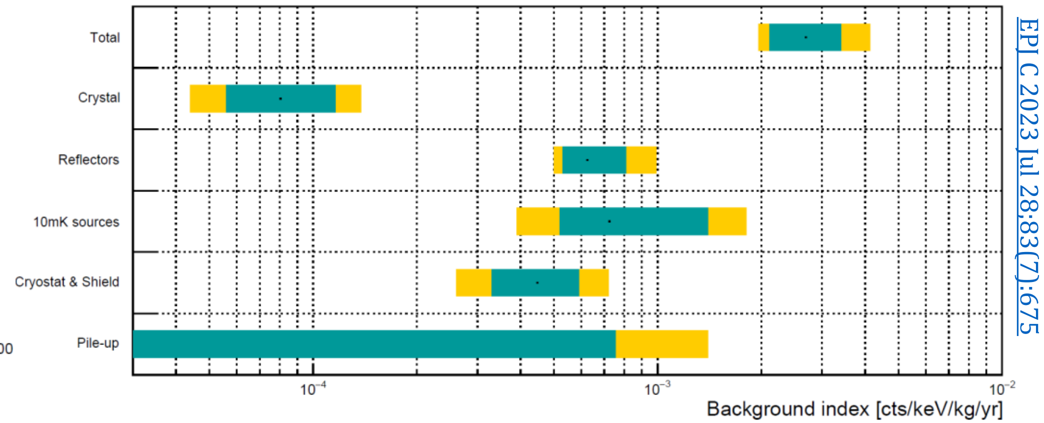
Final spectrum of physics data in CUPID-Mo experiment

99.9% α particles rejection efficiency



Fit of Tl peak at 2615 keV

Energy resolution (FWHM)
6.6 ± 0.1 keV @ 2615 keV
7.4 ± 0.4 keV @ $Q_{\beta\beta}$ (3034 keV)



Contribution of the different sources to the BI

Total BI:
$$2.7^{+0.7}_{-0.6}(\text{stat})^{+1.1}_{-0.5}(\text{syst}) \times 10^{-3}\ \text{counts/keV/kg/yr}$$

0νββ decay limits $T^{0\nu}_{1/2} > 1.8 \cdot 10^{24}$ yr (90% C. l.)
$m_{\beta\beta} < (0.28 - 0.49)$ eV

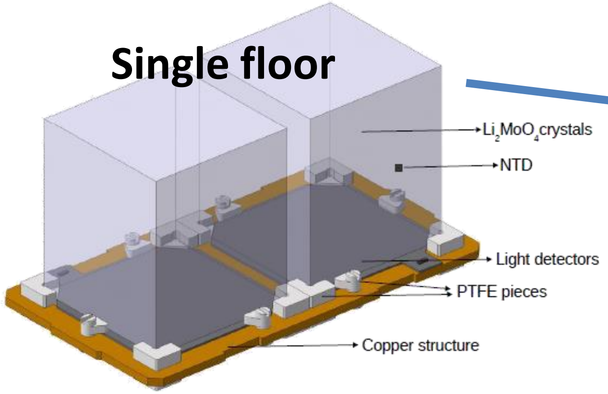
$Li_2{}^{100}MoO_4$ scintillating bolometers adopted as CUPID technology

CUPID structure

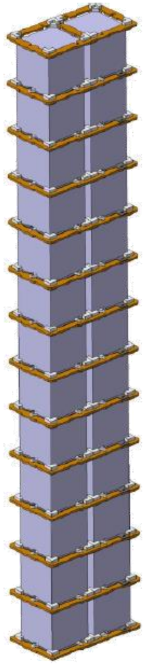
CUPID pre-CDR *arXiv:1907.09376*

- Single crystal 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

Single floor



Single tower



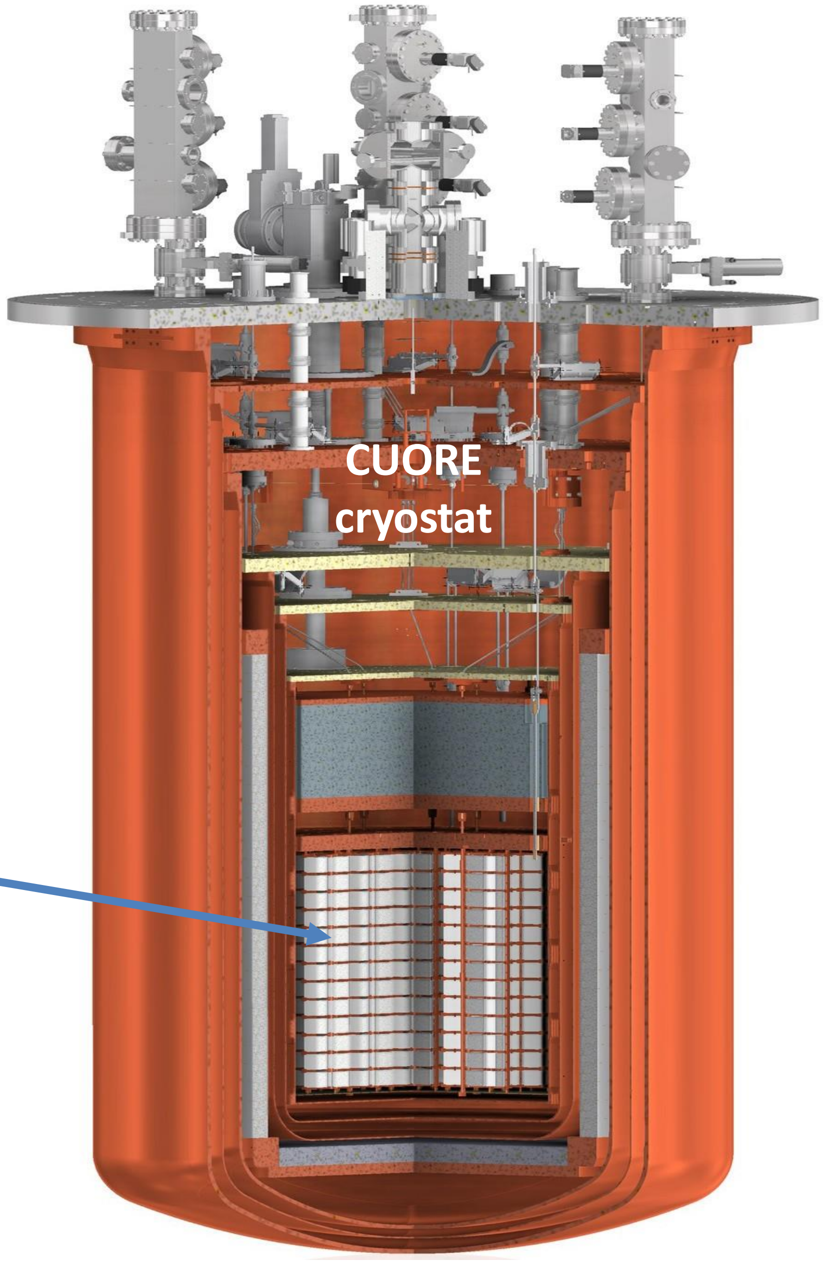
Baseline design

Gravity stacked structure

1710 Ge light detectors with SiO antireflective coating (each crystal has top and bottom LD)

- No reflective foil
- Exploitment of the Neganov-Trofimov-Luke effect

Muon veto and **neutron shield**



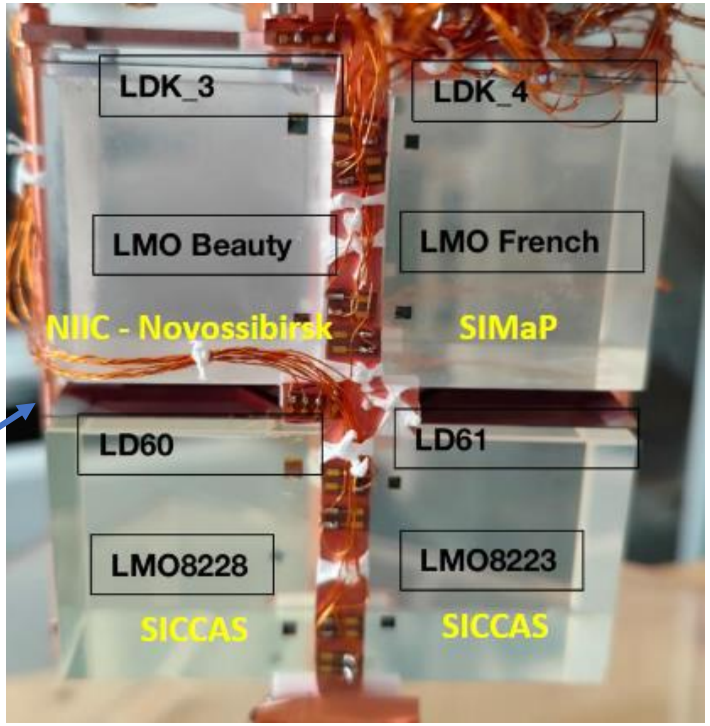
Status of crystal procurement

Because of the war against Ukraine the procurement of enriched crystals from Russia is impossible

Possible **alternative suppliers**:

Baseline candidate: SICCAS (Shanghai, China)

- Already produced 988 TeO_2 crystals for CUORE
- It is ready to produce 1596 $Li_2^{100}MoO_4$ crystals with 95 % enrichment
- The first sample of isotope, measured by ICP-MS at LNGS, fully matches radiopurity requirements
- Pre-production is ongoing:
  - set of several natural crystals was tested in cryogenic facility in LNGS and in Orsay
  - we are expecting to receive 6 enriched crystals within the end of 2024 in Orsay
  - additional enriched crystals are being purchased by INFN



Investigating opportunities for production in France:

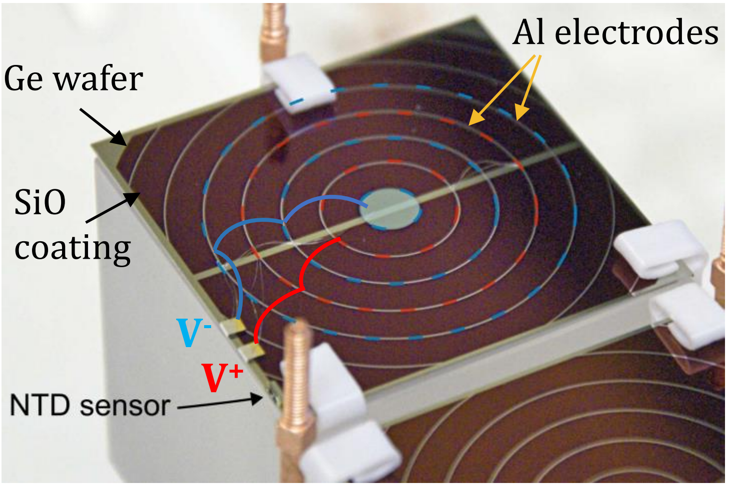
- We received a first natural Li_2MoO_4 crystal from Matias Velázquez (Univ. Grenoble Alpes, CNRS, Grenoble INP, SIMaP, France) and performed the first tests in Orsay cryogenic facility
- The first Li_2MoO_4 crystals from Luxium Solutions were grown, we will receive them within the end of 2024

Neganov-Trofimov-Luke light detectors

Enhancement of signal is needed to suppress the dominant background source in CUPID (**random coincidences of 2νββ events**)

Exploit the Neganov-Trofimov-Luke (NTL) effect for signal amplification

NTL light detectors



Total heat:

$$E_{tot} = E_0 \cdot G_{NTL} \propto V_{bias} = V^+ - V^-$$

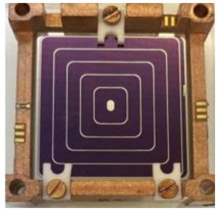
Typical parameters

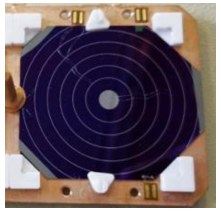
Results from recent tests in Canfranc

- G_{eff} ~10 (V_{bias} = 80 V)
- SNR ~ 90 (V_{bias} = 80 V) @ ββ energy
- rise-time: 0.4 – 0.7 ms range
- Leakage current: 8/9 NTL LD were able to stand > 90V

Work in progress

- optimization of light detectors and electrode geometry



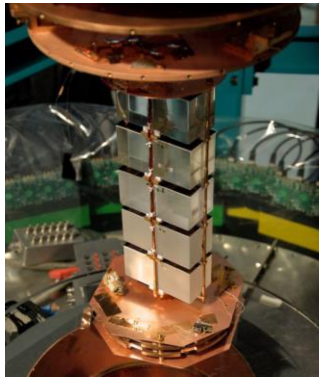


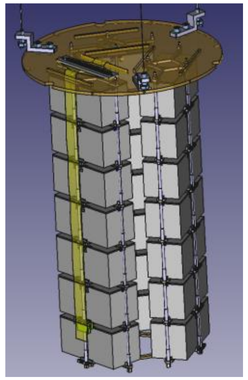
- optimization of gluing procedure to prevent leakage current
- (increase maximum voltage bias)
- tests of Silicon wafers
- studies on pile-ups rejection efficiency

Tests of NTL LDs

Orsay cryostat:
small experimental volume, suitable for quick tests

LSC, Canfranc, Spain





CROSS demonstrator
(commissioning in early 2025)

- 42 scintillating bolometers
- High statistic test for CUPID NTL LD

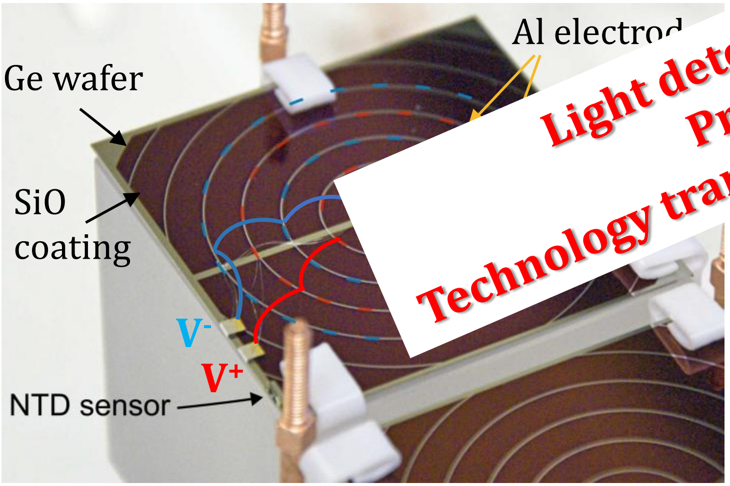
Tests at LNGS, Italy -> see next slide

Neganov-Trofimov-Luke light detectors

Enhancement of signal is needed to suppress the dominant background source in CUPID (**random coincidences of 2νββ events**)

Exploit the Neganov-Trofimov-Luke (NTL) effect for signal amplification

NTL light detectors



Total heat:

$E_{tot} = E_0 \cdot G_{NTL} \propto V_{bias} = V^+ - V^-$

Typical parameters

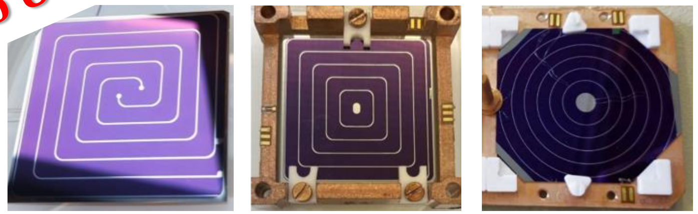
Results from recent tests in Canfranc

- G_{eff} ~10 (V_{bias} = 80 V)
- SNR ~ 90 (V_{bias} = 80 V) @ ββ energ
- rise-time: 0.4 – 0.7 ms range
- Leakage current: 8/9 N
  stand > 90V

Light detector production is coordinated by IJCLab and CEA/IRFU
Production of half of light detectors is a French scope
Technology transfer to US (Argonne, Berkeley) for the production of the other half

ss

ght detectors and
geometry



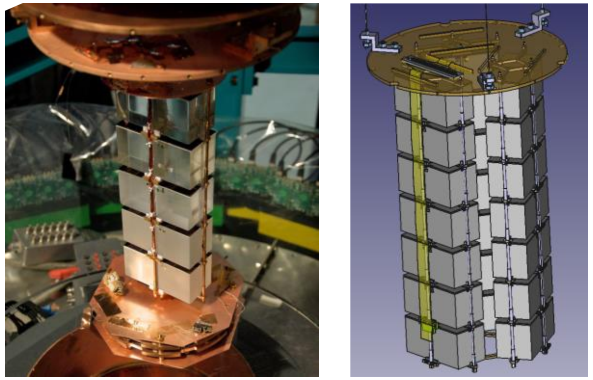
- optimization of gluing procedure to prevent leakage current
- (increase maximum voltage bias)
- tests of Silicon wafers
- studies on pile-ups rejection efficiency

Tests TL LDs

Orsay

e,
sts

anfranc, Spain

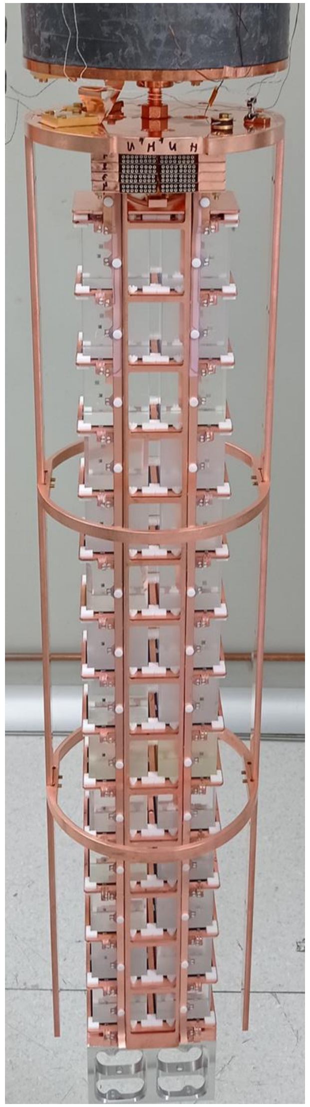


CROSS demonstrator
(commissioning in early 2025)

- 42 scintillating bolometers
- High statistic test for CUPID NTL LD

Tests at LNGS, Italy -> see next slide

Test of CUPID towers at LNGS



BDPT

(baseline design prototype tower)

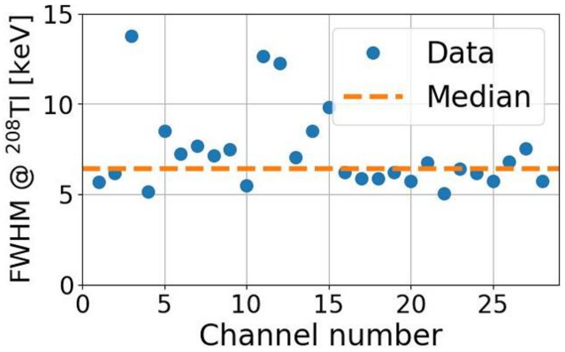
- 28 LMOs
- 30 Ge light detectors **without NTL effect**
- Tested at LNGS, Italy in July-October, 2022

Results:

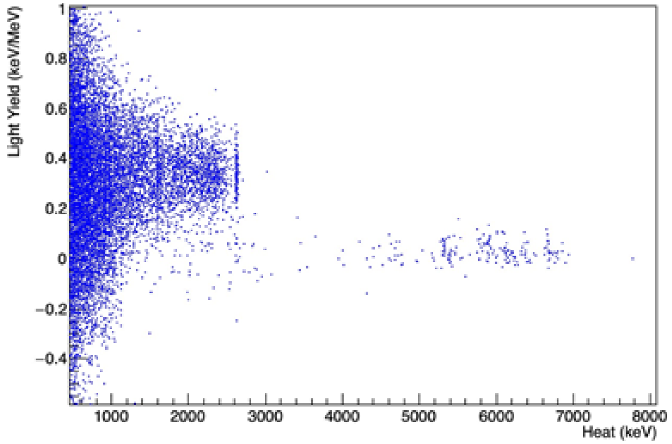
- Detectors successfully reached baseline temperature ~15 mK
- Baseline stable over the time
- LMO performance:
  median $\mathrm{FWHM}_{2615\ \mathrm{keV}}$ = 6.2 keV
- median light yield: 0.34 keV/MeV
- α vs β,γ discrimination capability:

$$DP = \frac{|LY_{\beta,\gamma} - LY_{\alpha}|}{\sqrt{\sigma^2_{\beta,\gamma} + \sigma^2_{\alpha}}} = 3.21$$

- some excess noise on the LD -> changes to the LD assembly structure for the next test



Example of α/β separation in a low noise channel



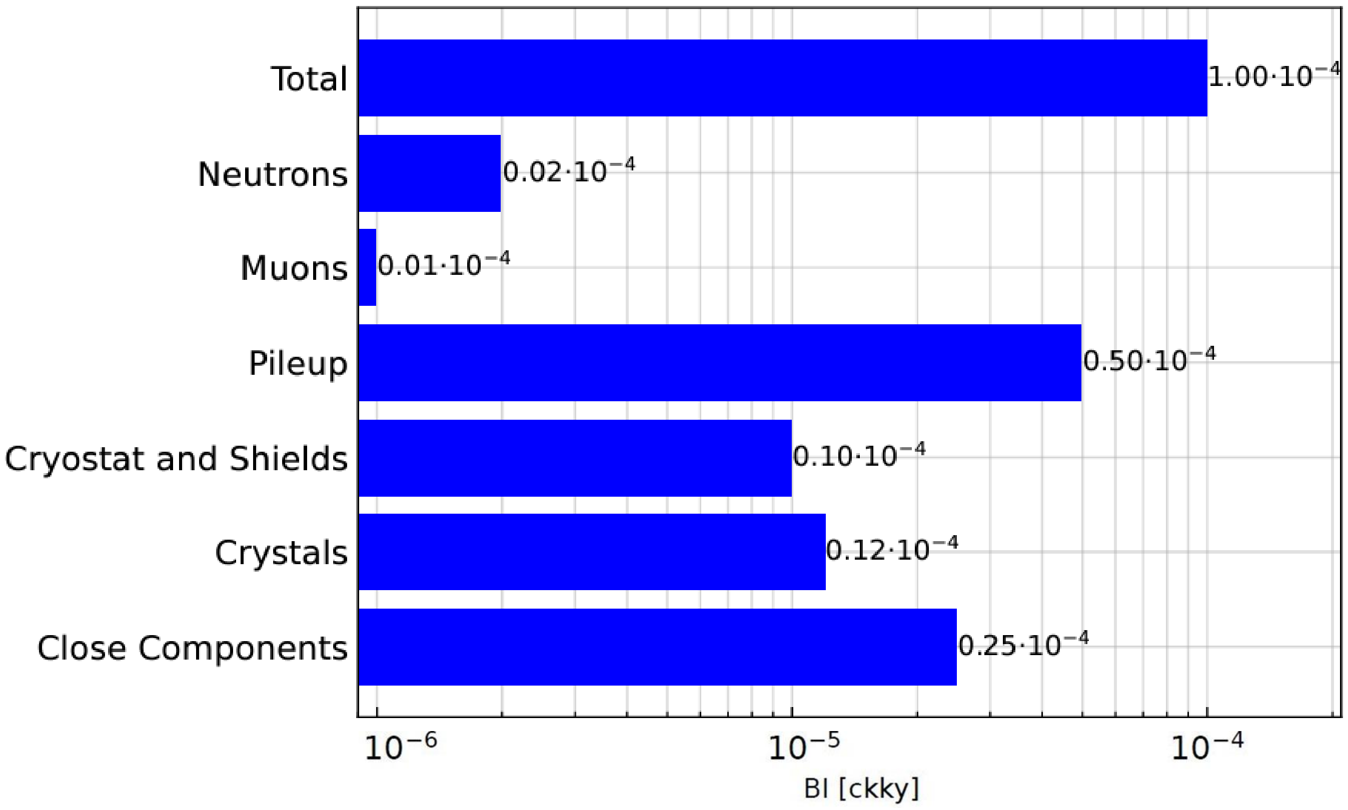
Next test: VSTT (Vertical Slice Test Tower)

- Preparation for the new test are currently ongoing

What's new?

- Light detectors with NTL amplification
- Changes to the LD holding system to mitigate the noise

CUPID background budget



CUPID background goal:
BI = 10^{-4} counts/keV/kg/year

Dominant contribution: pile-up events
(random coincidences of ordinary $2\nu\beta\beta$ events)

Data driven: based on CUORE and CUPID-Mo background models

Phys. Rev. D 110 (2024) 052003

Eur. Phys. J. C 83 (2023) 675

Pile-up rejection

$T_{1/2}^{2\nu\beta\beta}(^{100}Mo) = 7.1 \cdot 10^{18}$ years ⇒

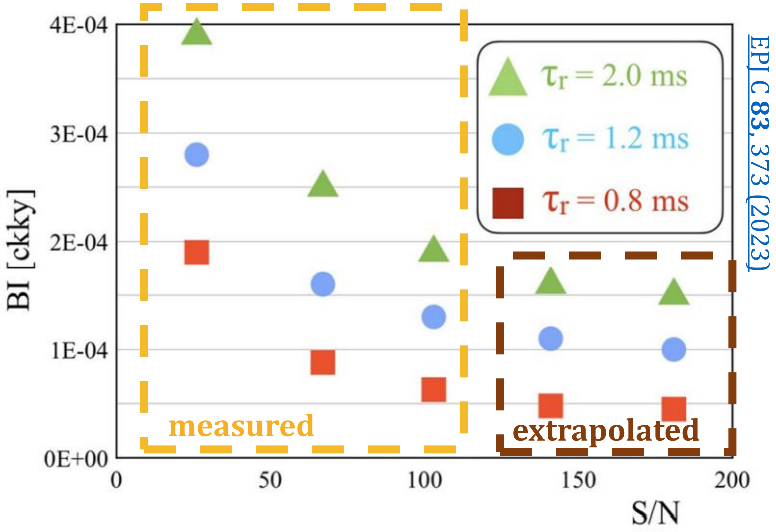
Eur. Phys. J. C **72, 1989 (2012)**

assuming time resolving capability **1 ms** BI due to random coincidence: $\mathbf{3.3 \cdot 10^{-4}}$ **counts/(keV kg y)** -> resolving time must be decreased to **0.17 ms** to meet CUPID background target

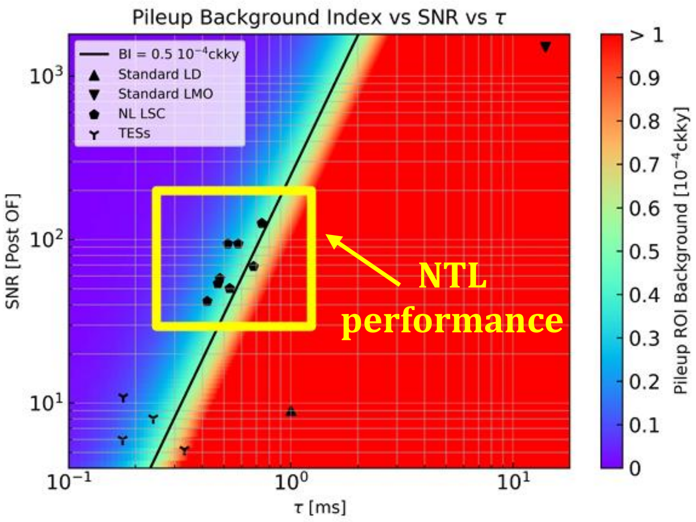
Crucial parameters for pile-up events rejection

- Signal-to-noise ratio ⇒ Improved by **factor ~10** using NTL amplification
- Rise-time ⇒ Can be reduced to **0.5 ms** by choosing properly the working point

Work at IJCLab is ongoing to study the rejection capability of the pile-up events



BI as a function of S/N ratio for different rise-times (from simulations based on real data from 1 NTL LD)



NTL performance obtained from recent tests projected on the BI plot

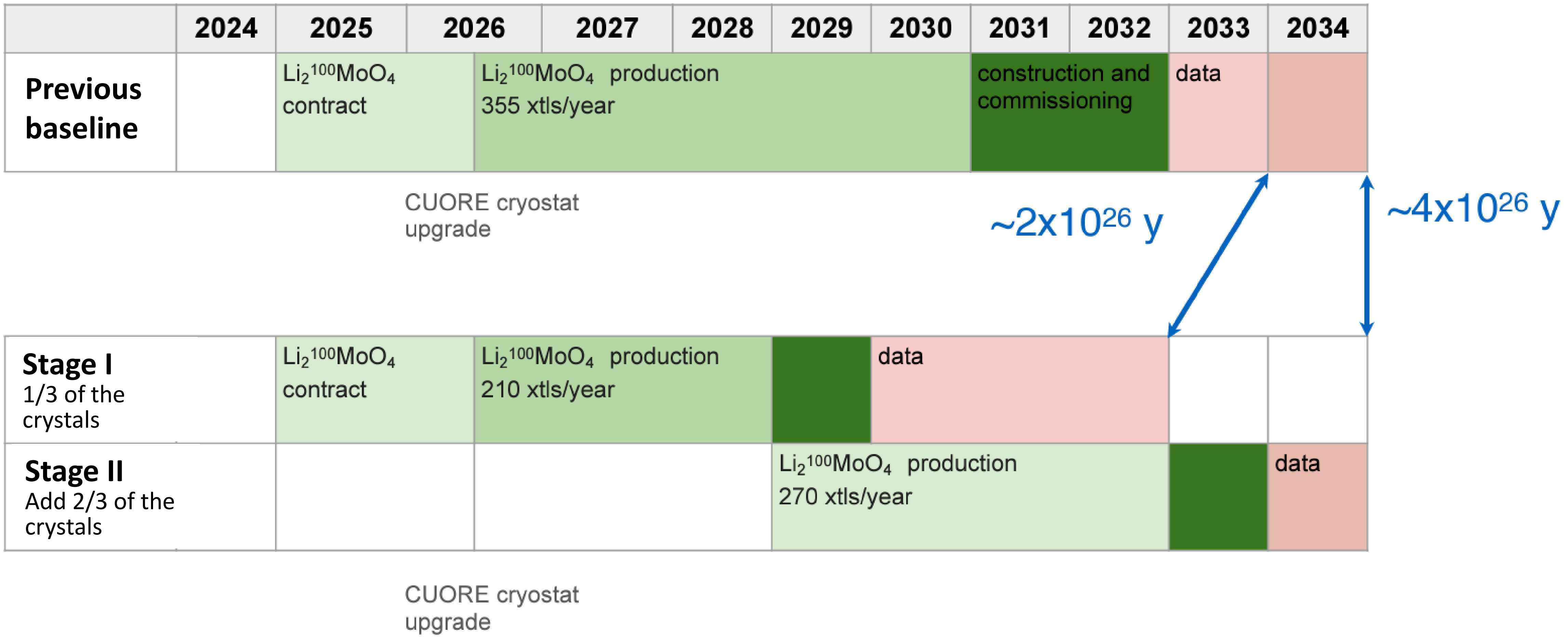
On average < 0.5 $\cdot 10^{-4}$ counts/(keV kg y)

CUPID

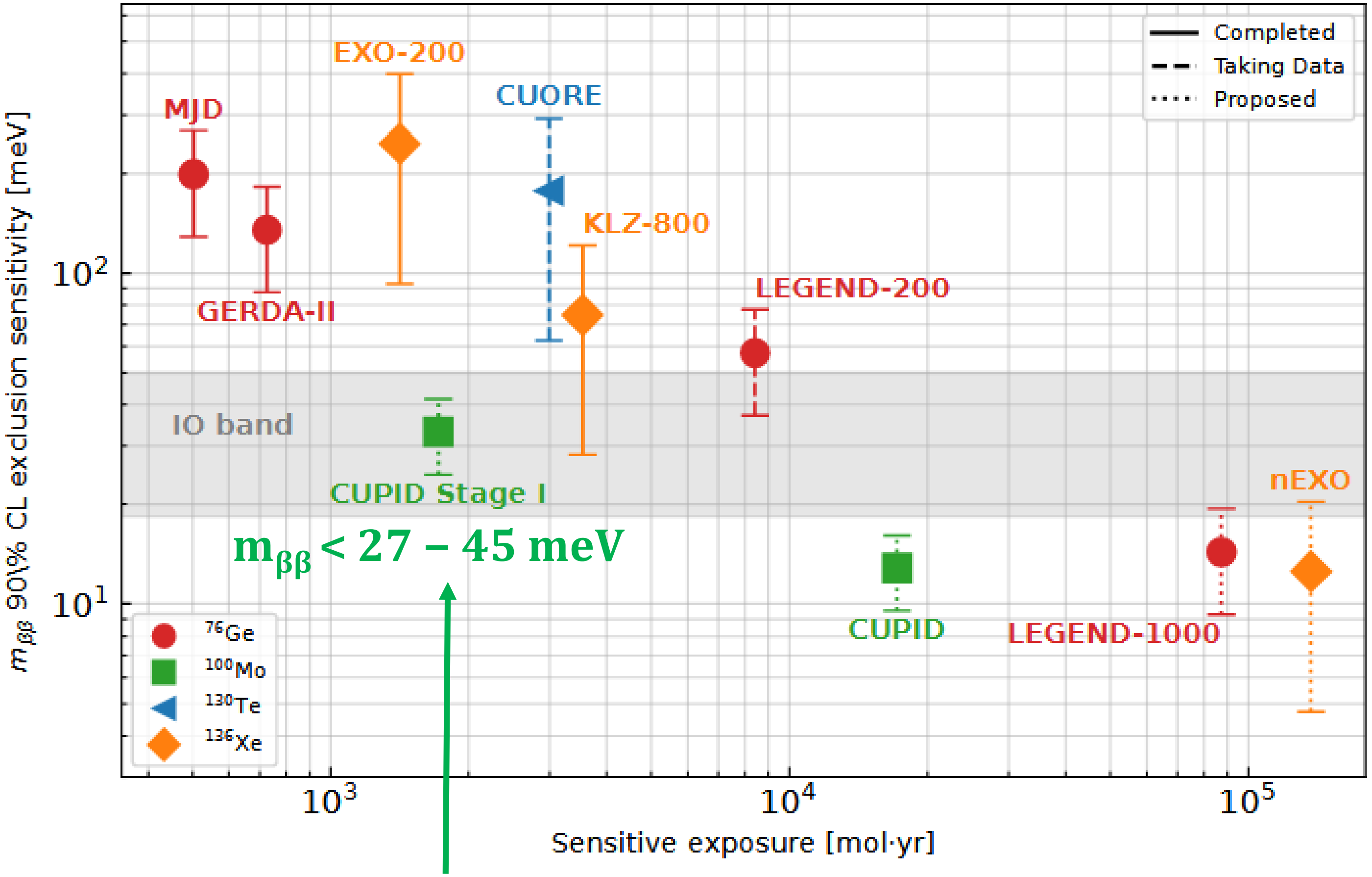
Staged deployment

NEW

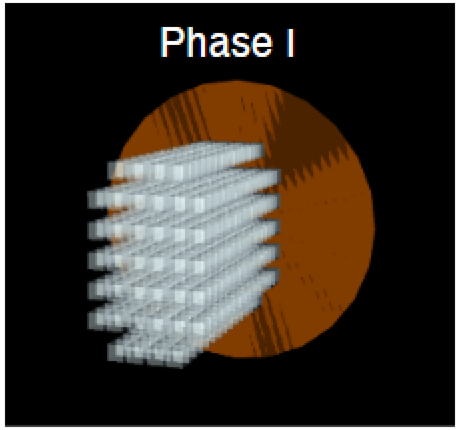
The collaboration decided to move to a **staged deployment** for CUPID implementation

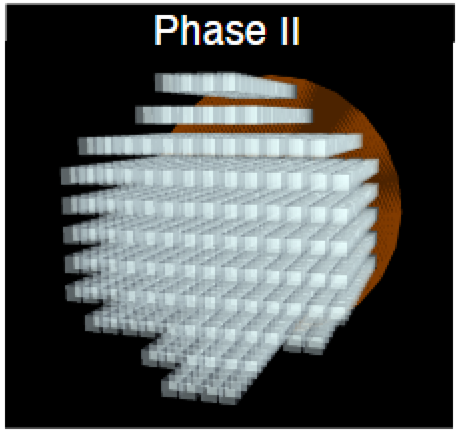


Staged deployment



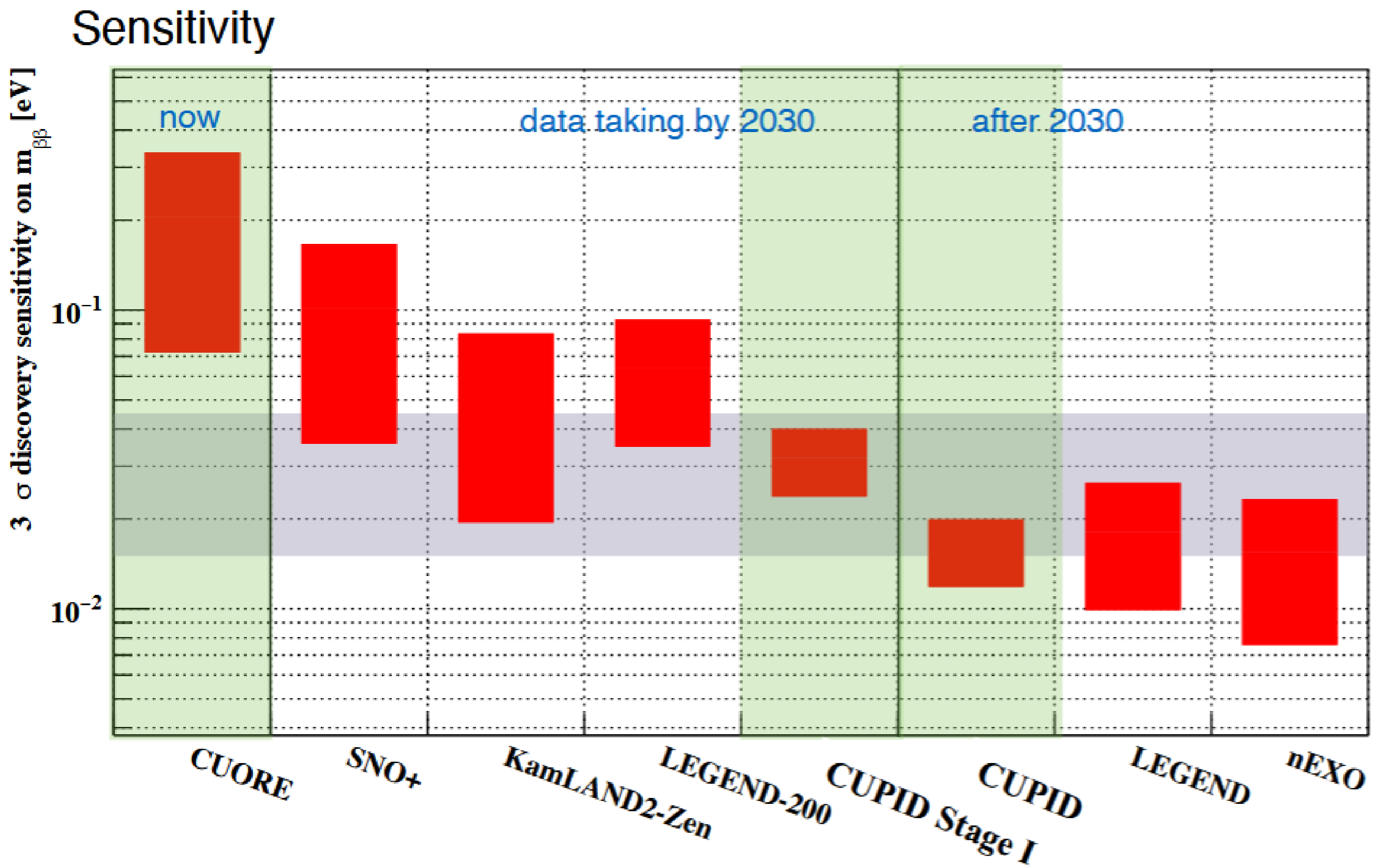
$m_{\beta\beta} < 27 - 45$ meV





The most sensitive experiment worldwide at the beginning of the next decade

CUPID discovery sensitivity



CUPID is critical to the discovery program at LNGS.

Staged deployment enables first science data by 2030 with CUPID Stage I

Ton-scale experiment with competitive sensitivity

Summary and final considerations

- The **infrastructure for CUPID** 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** (new producers)
- **Data-driven background model** indicates **b$\sim 10^{-4}$ counts/(keV·kg·y)**
- **Neganov-Trofimov-Luke light detector** can mitigate the most challenging background
- **Fully explore the inverted ordering region**

  down to $m_{\beta\beta}$ = 10 meV for the most favorable nuclear model
- **Staged deployment: CUPID Stage-I** can take data at the end of this decade and has **world leading science reach**
- On a longer time scale, **mass scaling** and potential **multi-isotope approach**

Collaboration