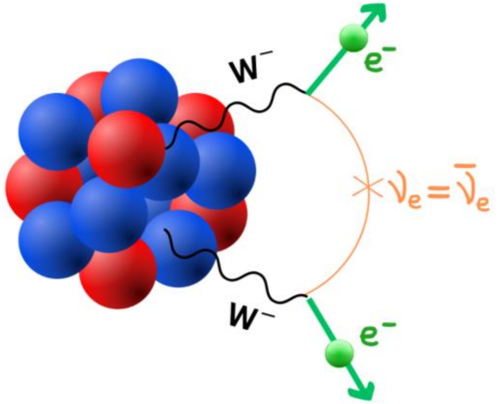
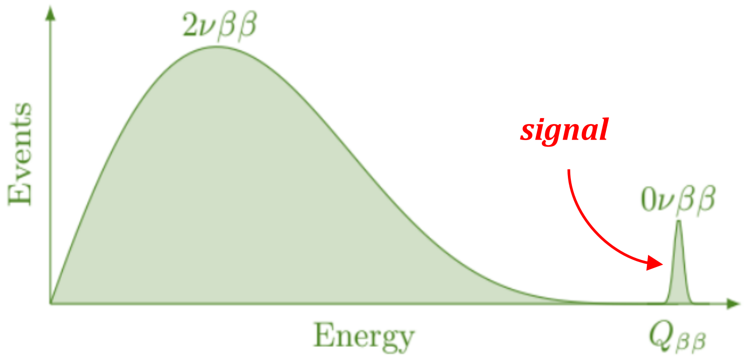
# Status of the CUPID experiment

*Mariia Buchynska on behalf of the CUPID collaboration*

# 0νββ decay




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

$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} \sim G^{0\nu}(Q, Z) \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Phase-space factor → Larger Q-values are preferable

Nuclear matrix element (NME) → Different models for calculations Provide main uncertainties to effective Majorana mass measurements (limits)

Effective Majorana neutrino mass

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1,2,3} U_{e,i}^2 m_i \right|$$

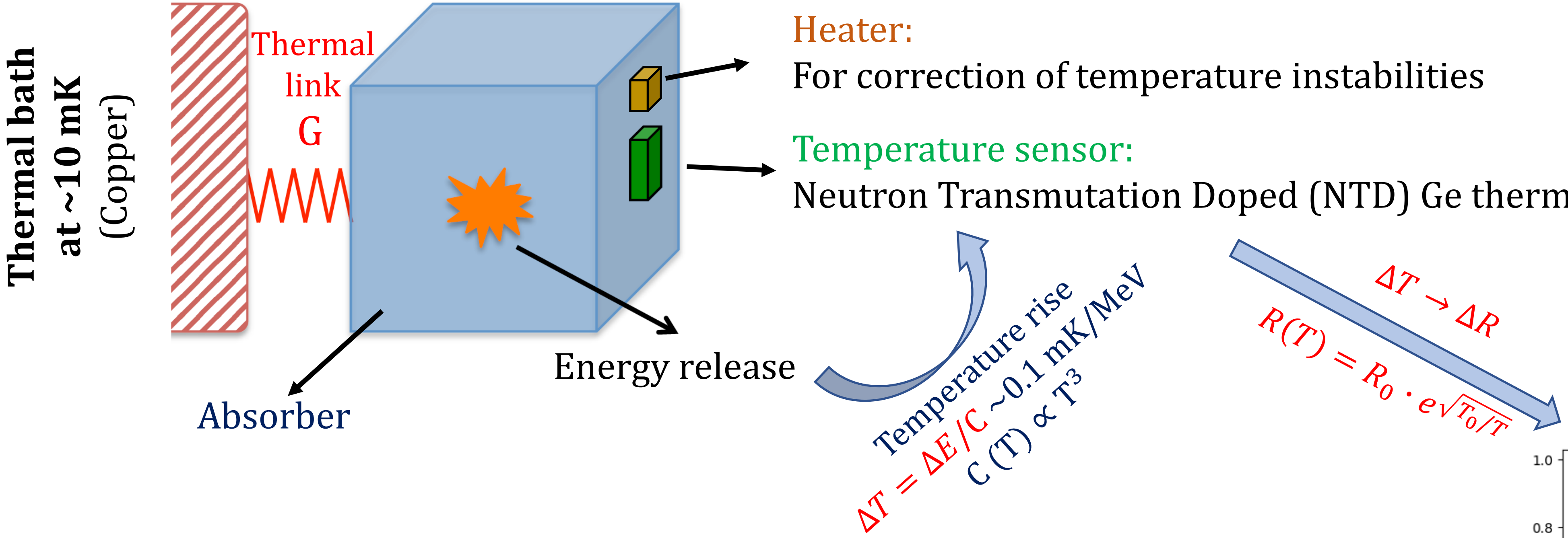
→ Access to the neutrino mass scale

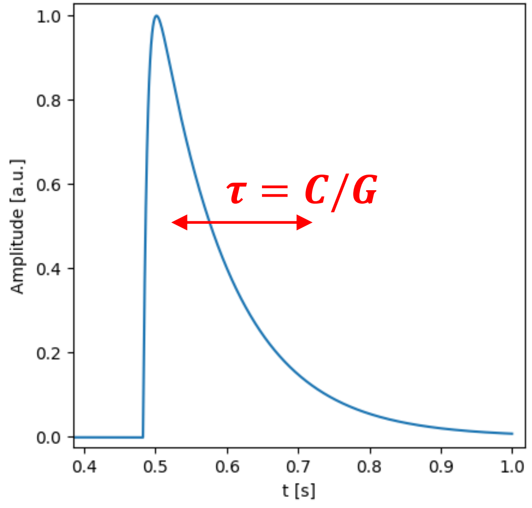
Very rare: $T_{1/2}^{0\nu} > 10^{24}$-$10^{26}$ yr → low background

Observation would imply:

- Violation of lepton number conservation ($\Delta L = 2$)
- Majorana nature of neutrinos => provide information of the neutrino mass scale and ordering

# Bolometric technique

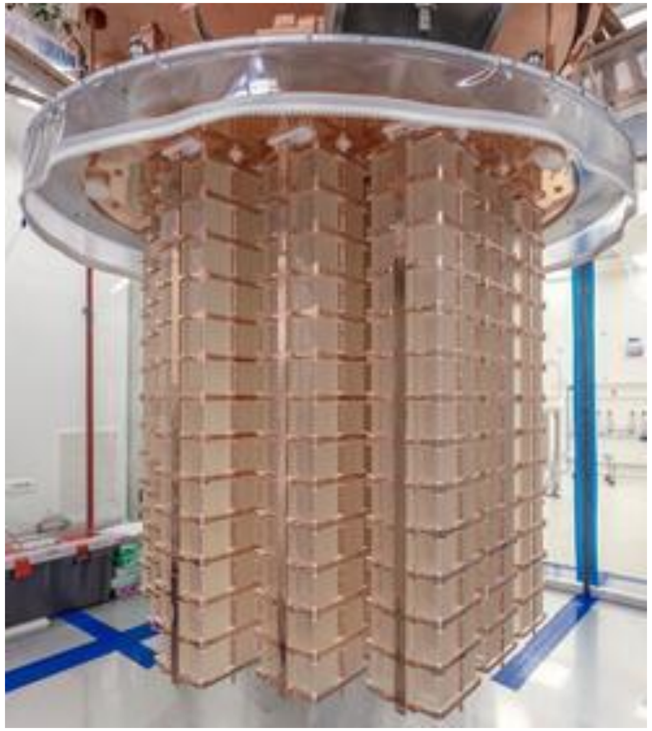


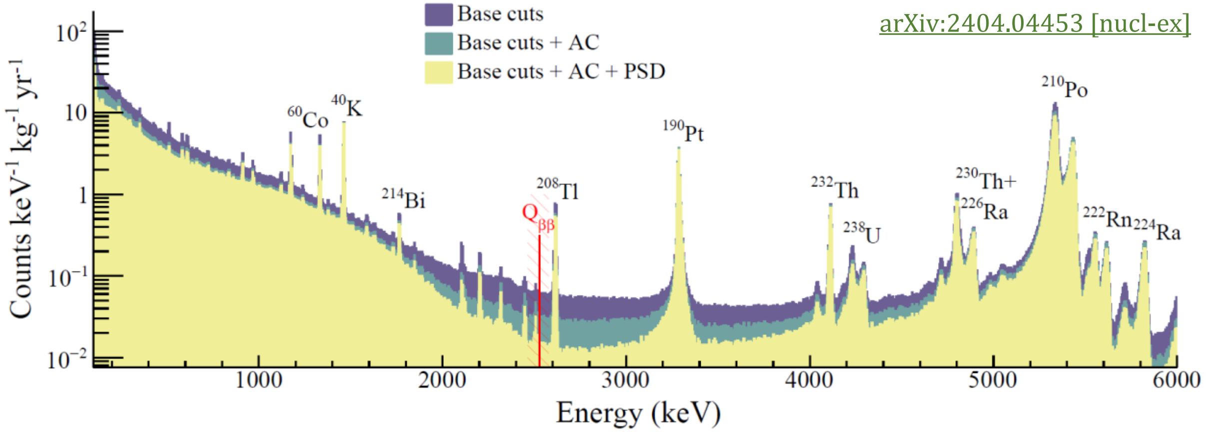

Cryogenic detectors properties

- Good energy resolution ~ 5-10 keV at Q-value (3 MeV)
- Source = detector: high efficiency

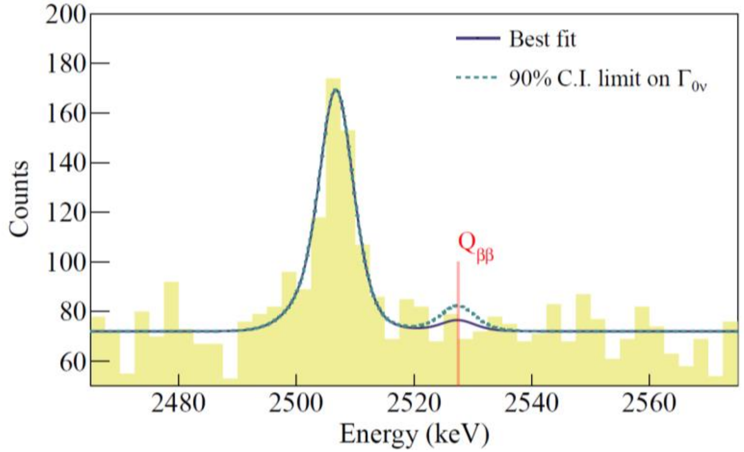
# CUORE results



- located at LNGS ~ 3600 m.w.e.
- 988 $TeO_2$ crystals arranged in 19 towers
- 742 kg of $TeO_2$ (natural Te, I.A. ~34% ), 206 kg of $^{130}Te$
- operation at ~10 mK
- analysed exposure: ~ 2.04 ton·yr $TeO_2$ (~0.6 ton·yr $^{130}Te$)




**Total analysis efficiency: 93(2)%** **BI = (1.42 ± 0.02) · $10^{-2}$ ckky**




**no evidence of 0νββ decay**

**Half life limit: $T_{1/2}^{0\nu} > 3.8 \cdot 10^{25}$yr (90% C.I.)**

**$m_{\beta\beta}$ < (70–240) meV (depending on NME)**

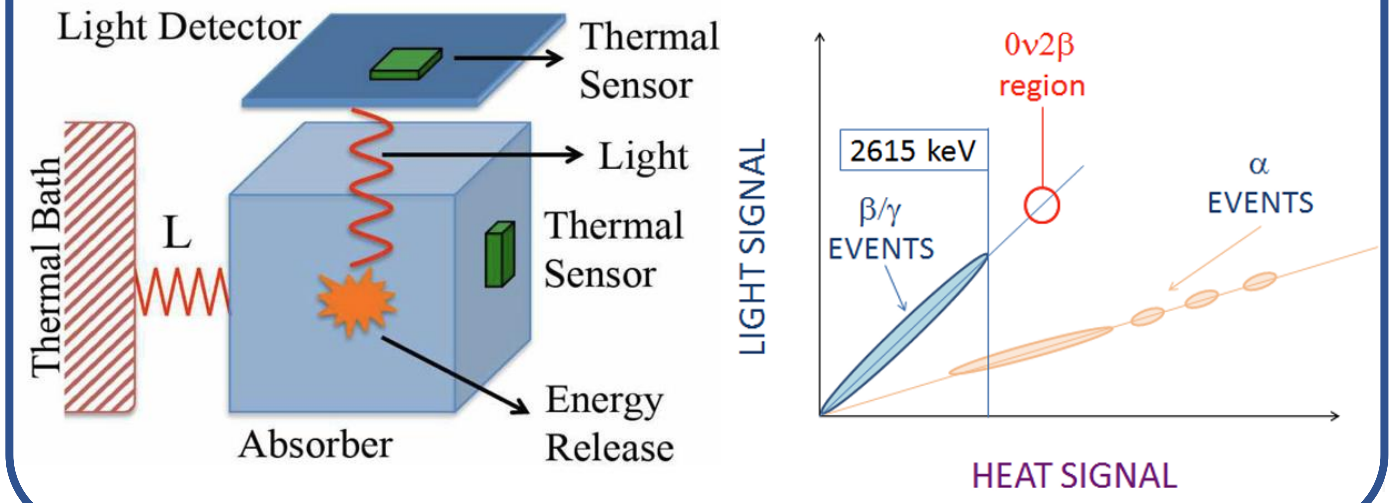
**Proof of the feasibility of the ton-scale bolometric experiment**
**Available large cryogenic infrastructure**

# CUORE limitations and CUPID approach

**No PID**

main background - α events ~75% of BI

**PID with scintillating bolometer**

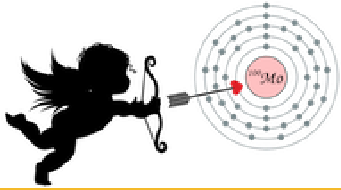



**$Q_{\beta\beta}$ ($^{130}$Te)= 2527 keV < 2615 keV**
(endline of natural radioactivity from $^{208}$Tl)

contribution of natural γ radioactivity to the BI

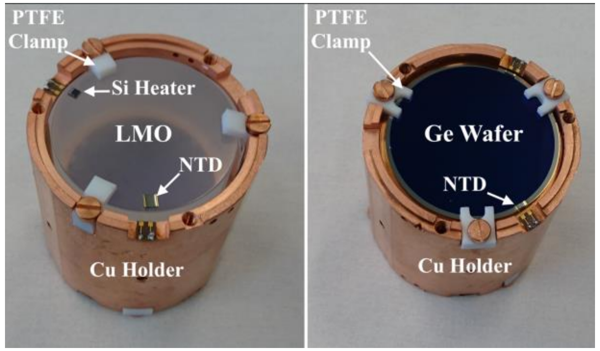
moving to $^{100}$Mo with $Q_{\beta\beta}$ = 3034 keV;
natural I.A. ~ 9.7% -> enrichment required

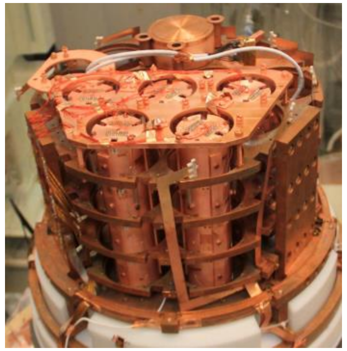
# CUPID-Mo



## CUPID-Mo experiment

- located in the Laboratoire Souterrain de Modane (France) ~ 4800 m.w.e.
- 20 scintillating bolometers arranged in 5 towers (single module: $Li_2{}^{100}MoO_4$ (~97% $^{100}Mo$ ) and Ge light detector)
- total mass of crystals is ~4.2 kg corresponding to ~2.3 kg of $^{100}Mo$
- ~ 1.5 years of data taking



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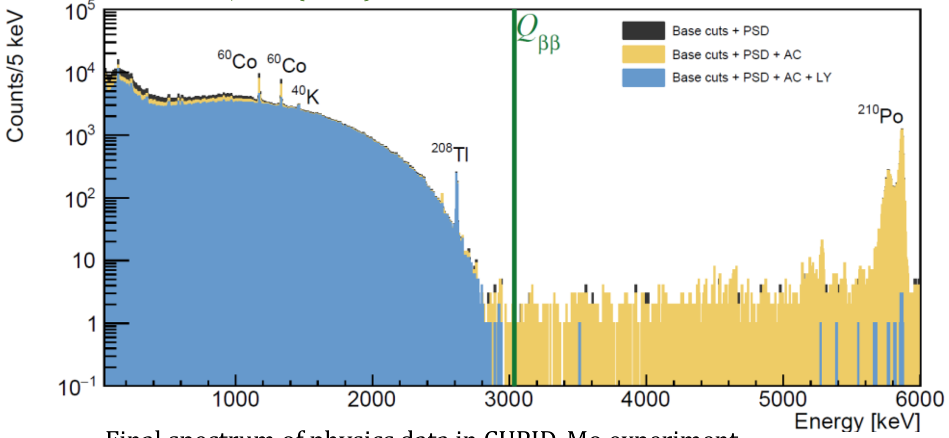
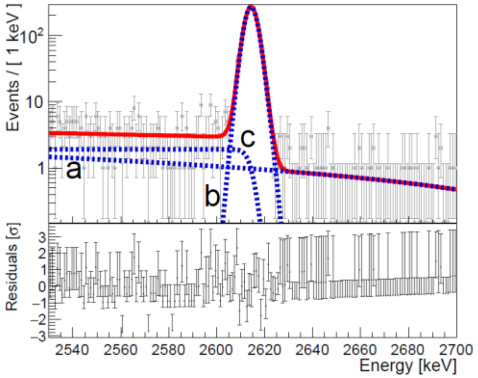



Final spectrum of physics data in CUPID-Mo experiment




Fit of Tl peak at 2615 keV

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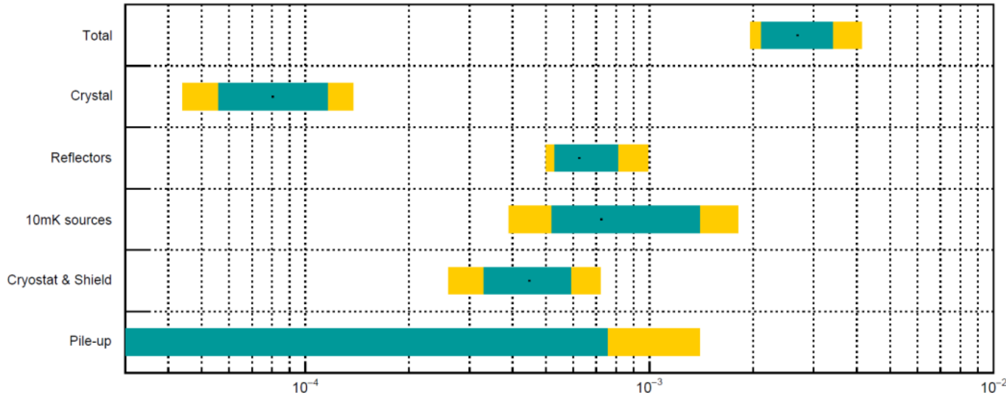



Contribution of the different sources to the BI

**More than 99.9% α particles rejection efficiency**

**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**

Energy resolution (FWHM)
**6.6(1) keV** @ 2615 keV
**7.4(4) keV** @ $Q_{\beta\beta}$ (3034 keV)

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

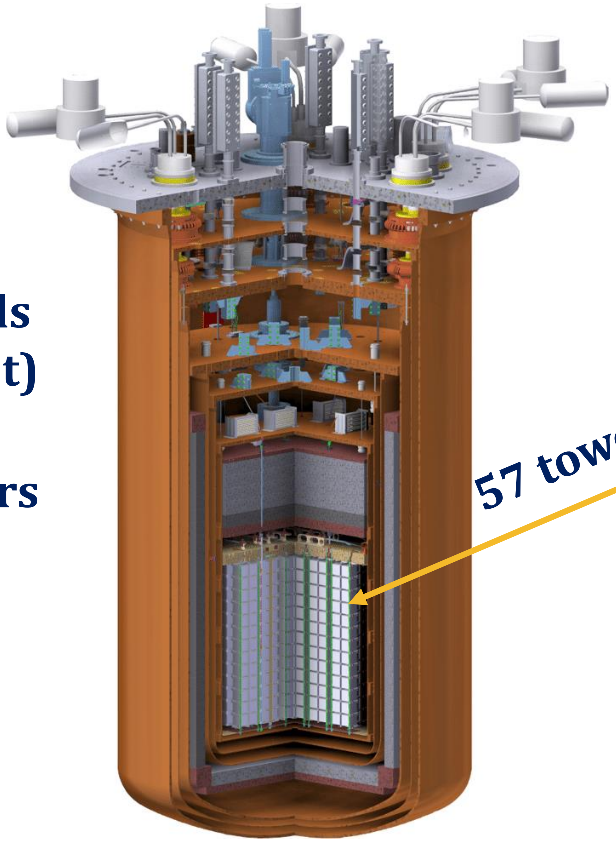
**$Li_2{}^{100}MoO_4$ scintillating bolometers demonstrate excellent performance and high radiopurity**

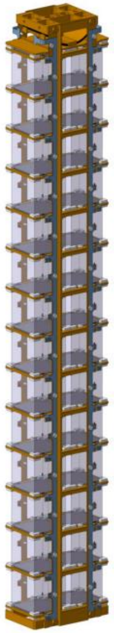
# CUPID baseline structure

1596 enriched $Li_2{}^{100}MoO_4$ crystals (>95% enrichment)

1710 light detectors

240 kg of $^{100}$Mo




CUORE cryostat and shielding

+ additional muon-veto system & neutron shields

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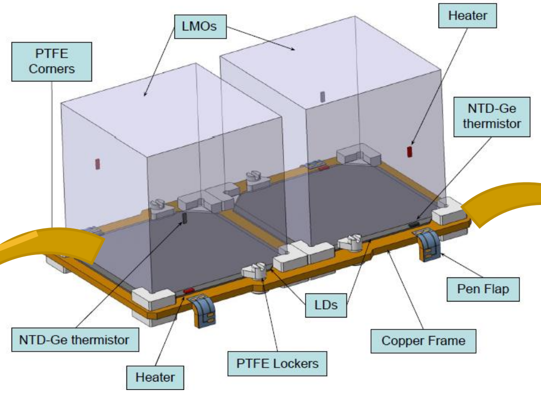



**$Li_2{}^{100}MoO_4$ crystal**

- 45 x 45 x 45 mm$^3$
- Thermal sensor: NTD Ge thermistor

**Ge light detector**

- Thin Ge wafer (<1 mm thickness)
- Thermal sensor: NTD Ge thermistor
- SiO antireflective coating (enhances light collection by ~ 30 %)
- Exploiting Neganov-Trofimov-Luke effect for signal amplification

CUPID pre-CDR arXiv:1907.09376

# Status of crystals procurement

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

Possible suppliers:

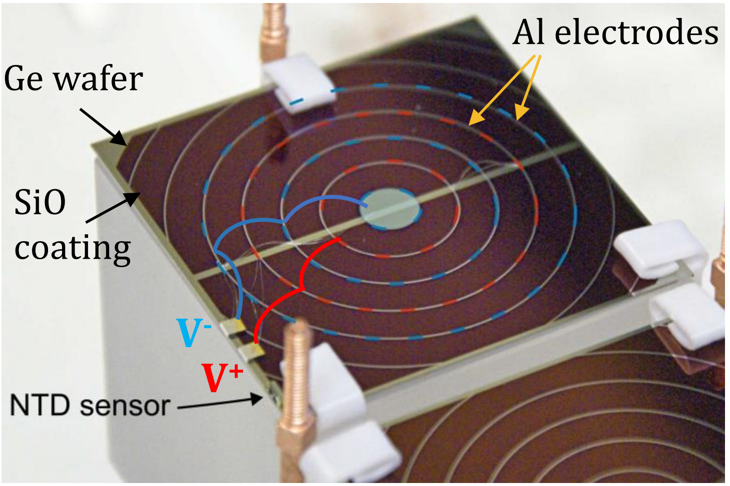
- **Most probable candidate: SICCAS (Shanghai, China)**
  - Already produced 988 $TeO_2$ crystals for CUORE
  - Is ready to produce 1596 $Li_2^{100}MoO_4$ crystals with 95% enrichment
  - The first sample of isotope were measured by ICP-MS at LNGS
  - Pre-production is ongoing:
    - set of several natural crystals was tested in cryogenic facility in LNGS and in Orsay
    - we are expecting to receive 6 enriched crystals by the end of 2024 in Orsay
    - additional enriched crystals are being purchased by INFN
- **Investigating opportunities for production in France:**
  - We received first natural $Li_2MoO_4$ crystal from Matias Velázquez (Univ. Grenoble Alpes, CNRS, Grenoble INP, SIMAP, France) and performed first tests in Orsay cryogenic facility
  - The first $Li_2MoO_4$ crystals from Luxium Solutions (France) were grown, we should receive them by the end of 2024

# Neganov-Trofimov-Luke light detectors

Enhancement of signal is needed to suppress random coincidences of $2\nu\beta\beta$ events

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

## NTL light detectors




Total heat:

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

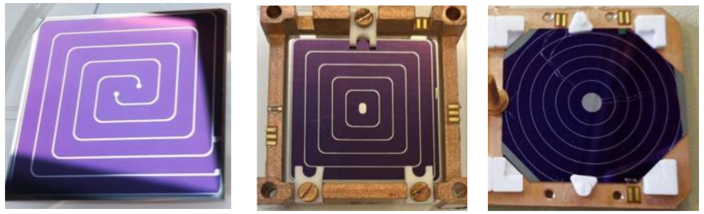
## Typical parameters

- $G_{eff}$ ~ 10 ($V_{bias}$ = 80 V )
- SNR ~ 90 ($V_{bias}$ = 80 V )
- rise-time: were possible to reach 0.42 ms mean value at the best WP (0.55 ± 0.11) ms
- Leakage current: 8/9 NTL LDs were able to stand > 90 V

Results from recent tests in Canfranc

## Work in progress

- optimization of light detectors and electrodes geometry

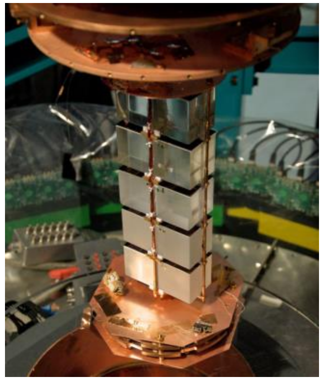


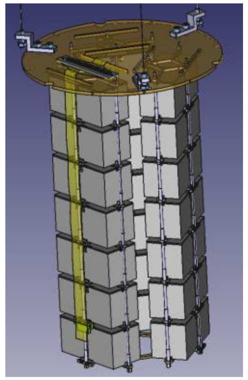
- optimization of gluing procedure to prevent leakage current (increase maximum voltage bias)
- tests of Si wafers
- studies on pile-ups rejection efficiency

## Tests of NTL LDs

**Orsay cryostat:**
small experimental volume, suitable for quick tests

**LSC, Canfranc, Spain**



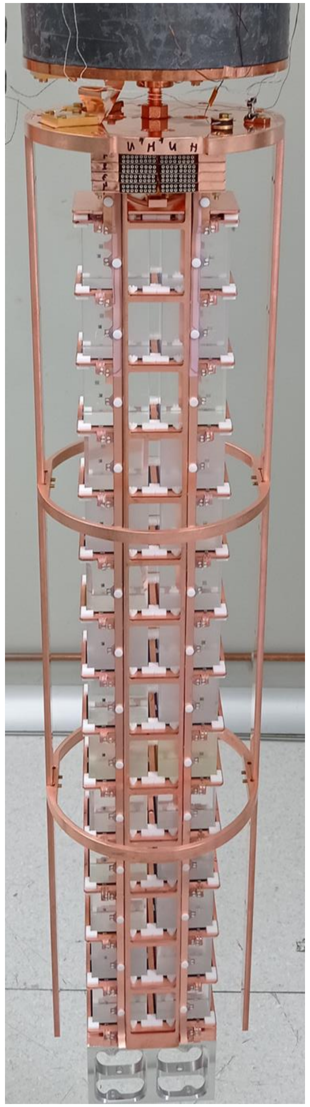


**CROSS demonstrator**
(commissioning in early 2025)

42 scintillating bolometers
High statistic test for CUPID NTL LD

**Tests at LNGS, Italy** -> see next slide

# Tests of the CUPID tower



**BDPT**

**(baseline design prototype tower)**

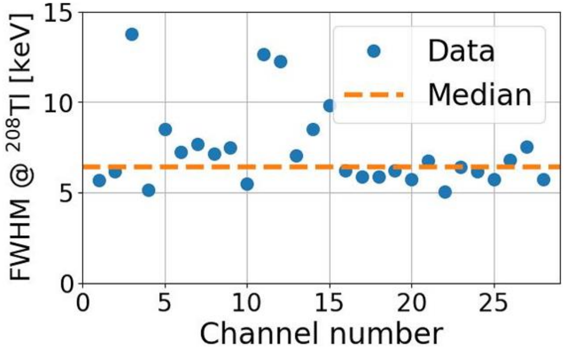
- 28 LMOs
- 30 Ge light detectors without NTL effect
- Tested at LNGS, Italy in July-October, 2022

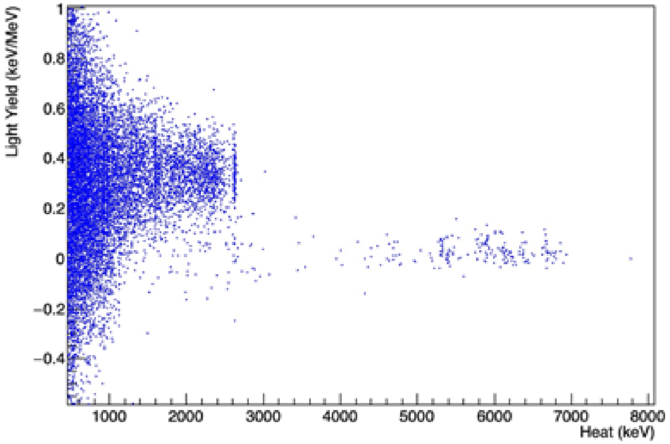
**Results:**

- ➢ 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
- ➢ $\alpha$ vs $\beta,\gamma$ discrimination capability:

$$DP = \frac{|LY_{\beta,\gamma} - LY_{\alpha}|}{\sqrt{\sigma^2_{\beta,\gamma} + \sigma^2_{\alpha}}} = 3.2$$

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




S. Quitadamo, S. Ghislandi. Evaluation of the CUPID First Tower Prototype performance. Poster presented at Neutrino 2024; June 16-22, 2024; Milano; Italy

**Next test: VSTT (Vertical Slice Test Tower)**

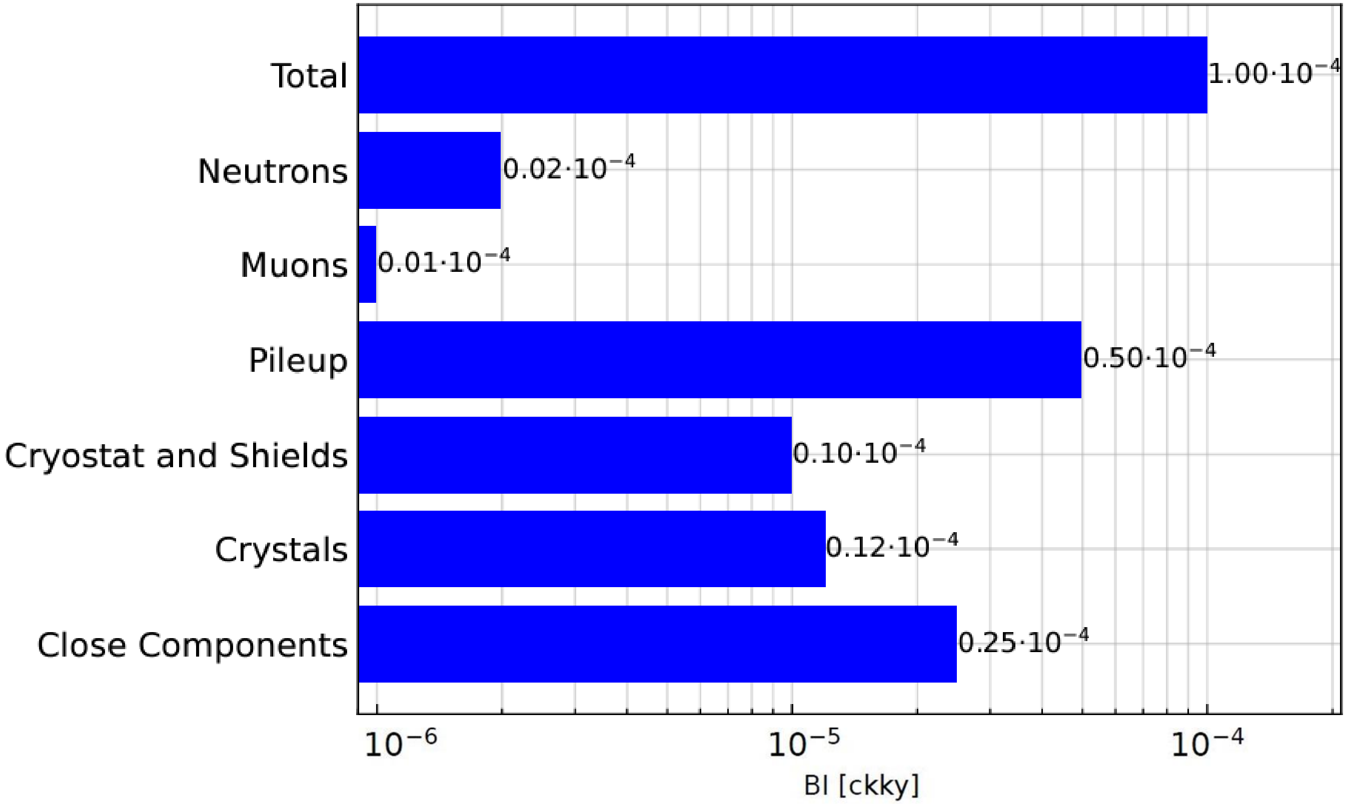
- ➢ Preparation for the new test are currently ongoing

What's new?

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

# CUPID background goal

P. Loaiza. Backgrounds of the CUPID experiment. LRT 2024 talk, Krakow Poland




CUPID background goal:
**BI = $10^{-4}$ counts/keV/kg/year** in the ROI

One of the most important contribution:
pile-up events
(random coincidences of ordinary $2\nu\beta\beta$ events)

# Pile-up events

$T_{1/2}^{2\nu\beta\beta}(^{100}Mo) = 7.1 \cdot 10^{18}$ years ⟹ assuming time resolving capability **1 ms,** BI due to random coincidence: $\mathbf{3.3 \cdot 10^{-4}}$ **ckky** ->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 optimal working point

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

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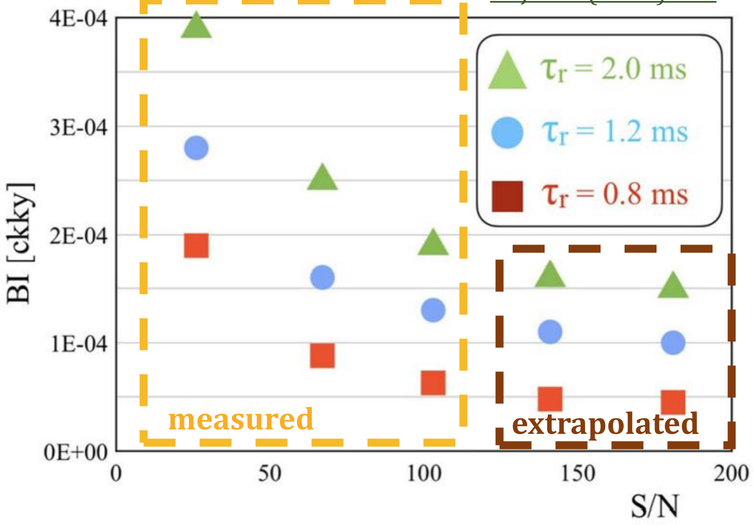
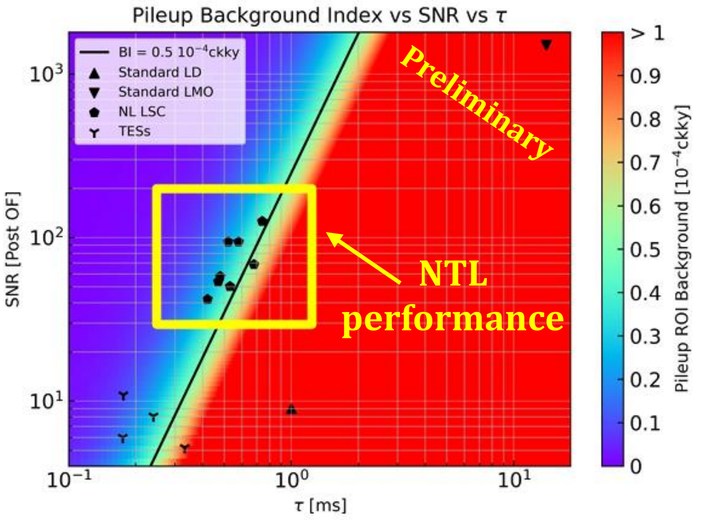


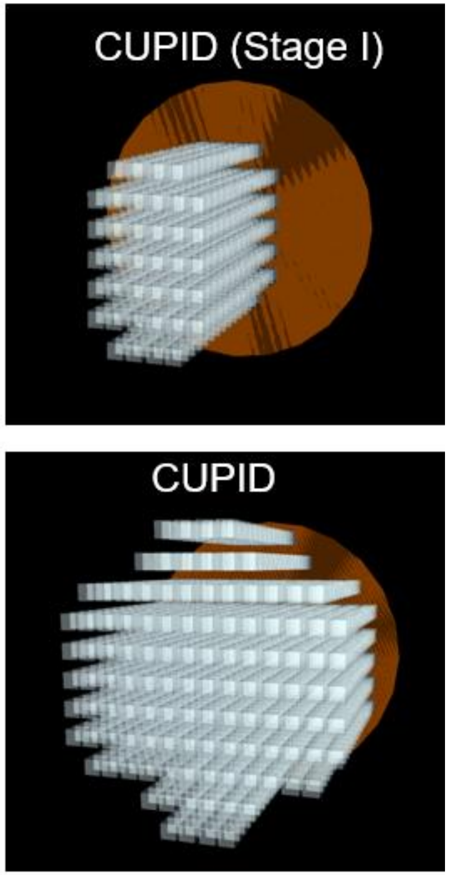

BI as a function of S/N ratio for different rise-times (from simulations based on real data from 1 NTL LD)

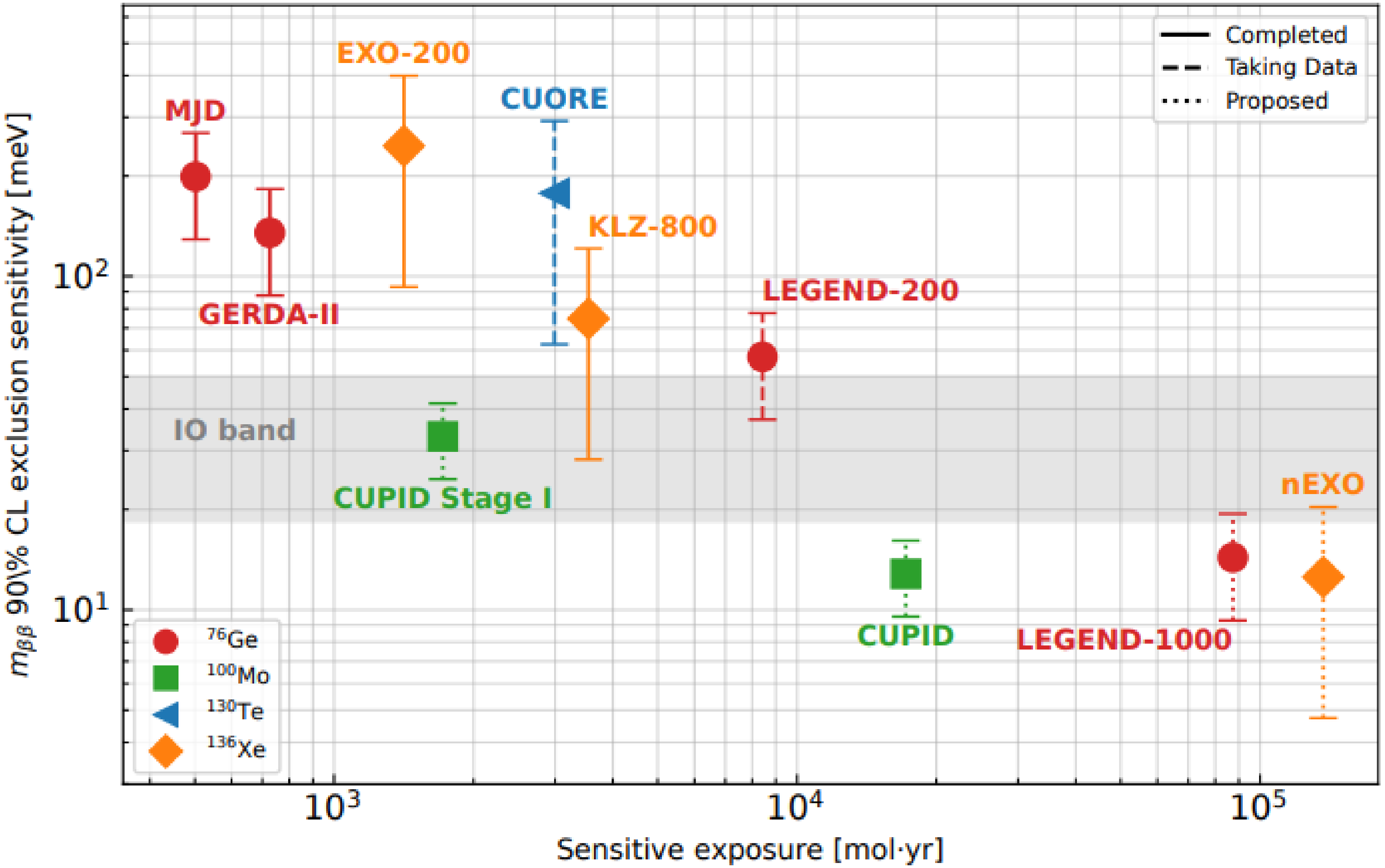



NTL performance obtained from recent tests projected on the BI plot

On average < 0.5 $\cdot 10^{-4}$ ckky!

# Phased approach




**CUPID Stage I has world-leading science reach**

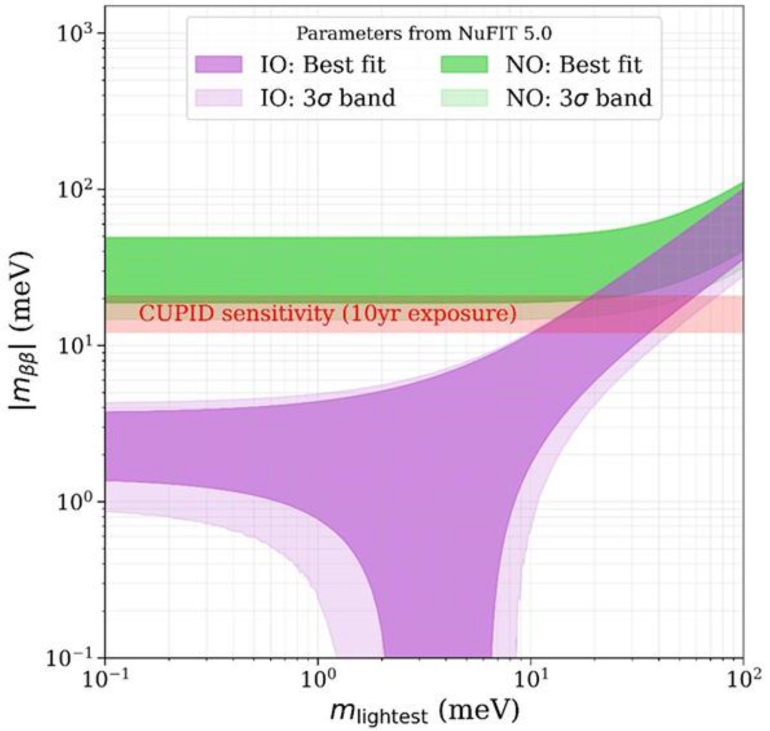
# Conclusions and future prospects

## Preparation in progress

- Enriched $Li_2{}^{100}MoO_4$ crystals pre-production is ongoing, enrichment and crystallization on large scales are possible
- Technologies for single $Li_2{}^{100}MoO_4$ module are validated, R&D on NTL LDs is in progress
  - Test in Canfranc of the 42 NTL LDs in the CROSS demonstrator
  - Full CUPID tower test with NTL LDs

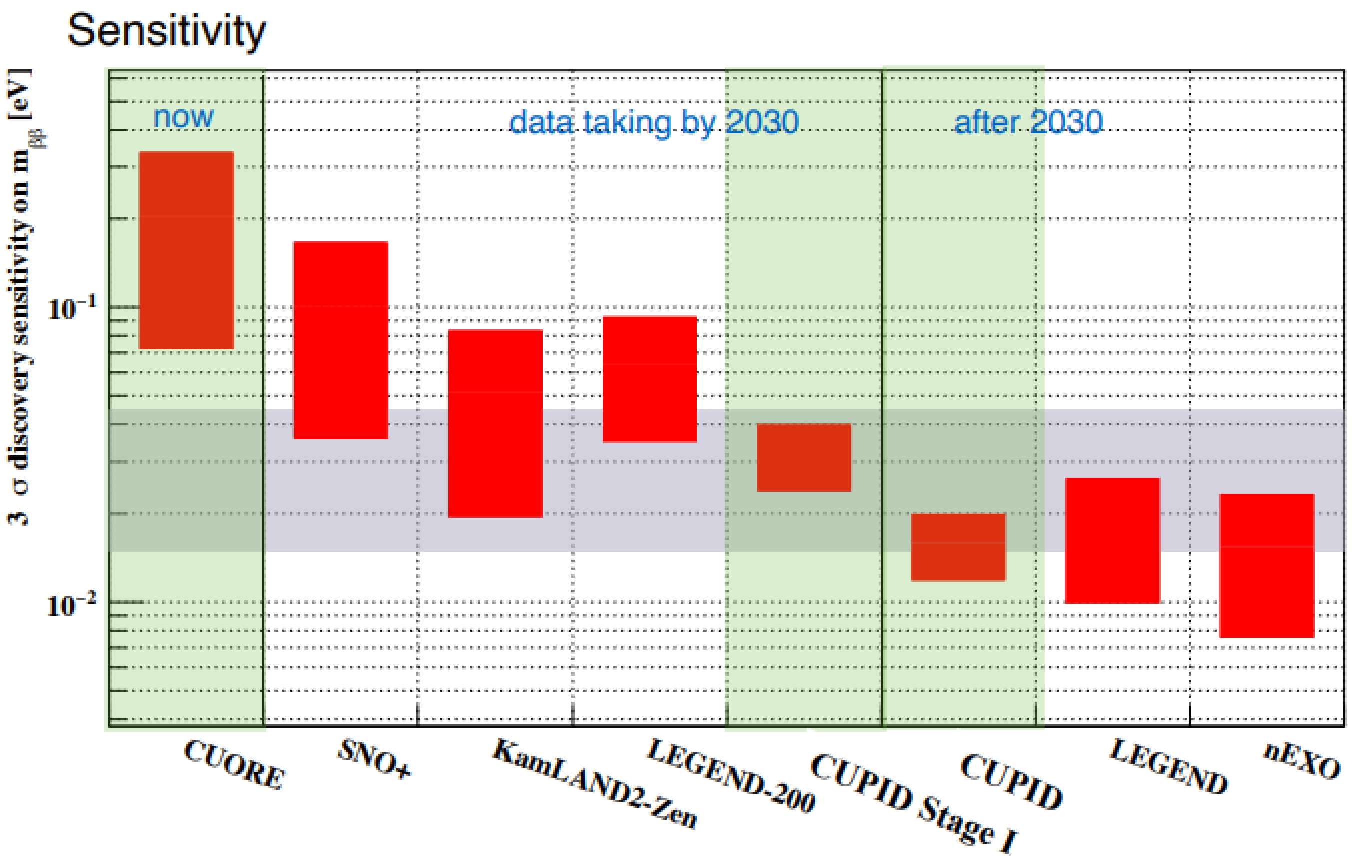
## CUPID advantages

- early competitive physics results with phased approach
- full exploration of the inverted ordering region and normal ordering region for $m_{lightest}$ > 10 meV
- low background: BI = $10^{-4}$ ckky in the ROI region
- on a longer time scale mass-scaling is possible



# CUPID collaboration

# CUPID 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