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Searching for neutrinoless double-beta decay with CUPID

CUPID

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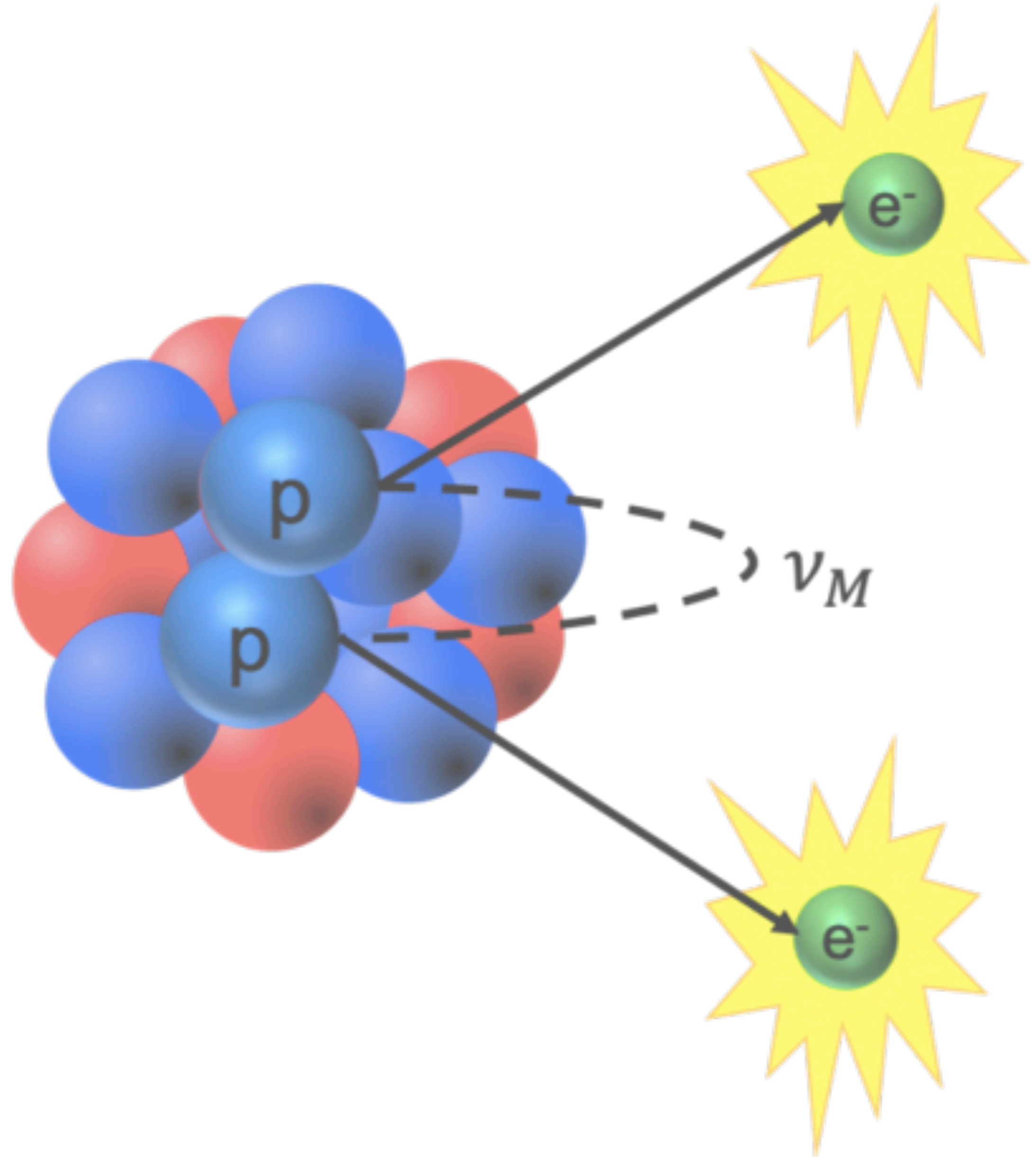
On behalf of CUPID collaboration

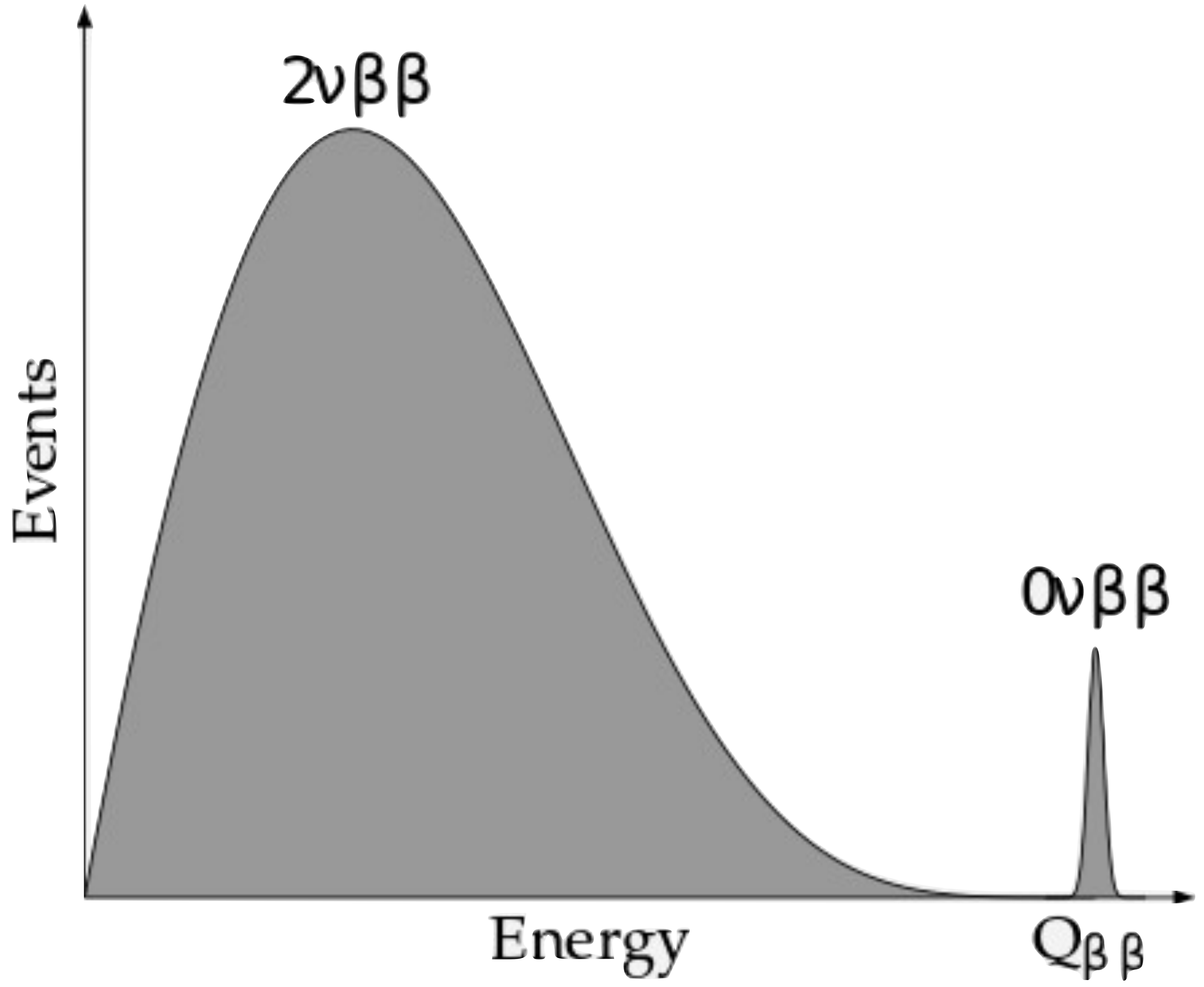


Neutrinoless double-beta decay

- Neutrinoless double-beta decay is an extremely rare ($T_{1/2} > 10^{25} - 10^{26}$ yr) hypothetical process:

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

- Signature - monoenergetic peak at the $Q_{\beta\beta}$ energy



The modern $0\nu\beta\beta$ experiment requires:

- Large exposure $M \times t$ (big mass, long life-time)
- Large a (isotopic abundance)
- Small b (very low background in the ROI)
- Small ΔE (good energy resolution)
- High detection efficiency

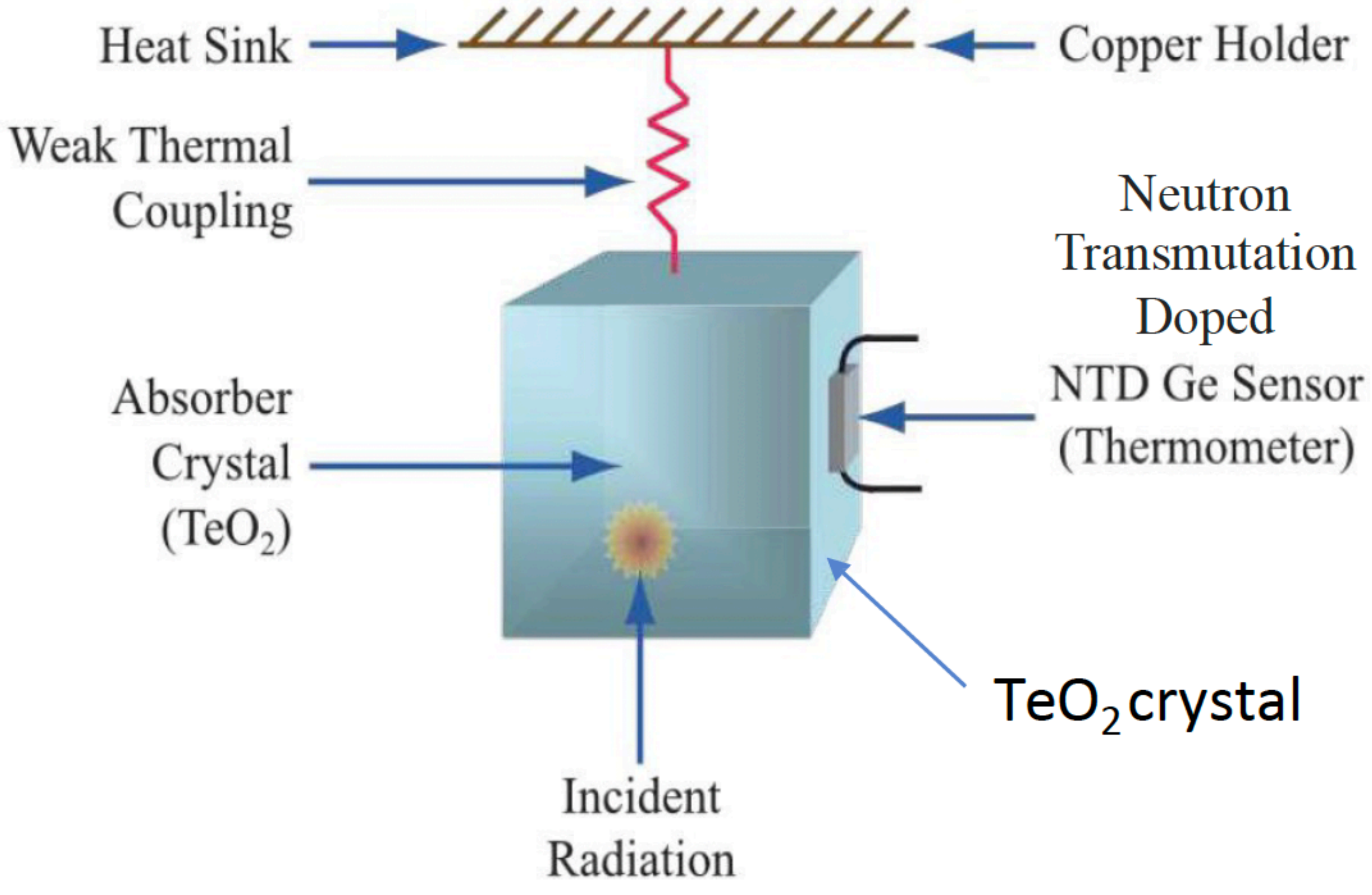
$$T_{1/2} \propto a \times \epsilon \times \sqrt{\frac{M \times t}{b \times \Delta E}}$$

In case of observation:

- Lepton number violation
- Majorana nature of neutrino: $\nu = \overline{\nu}$
- Neutrino mass ordering
- Source for matter-antimatter asymmetry

CUORE

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



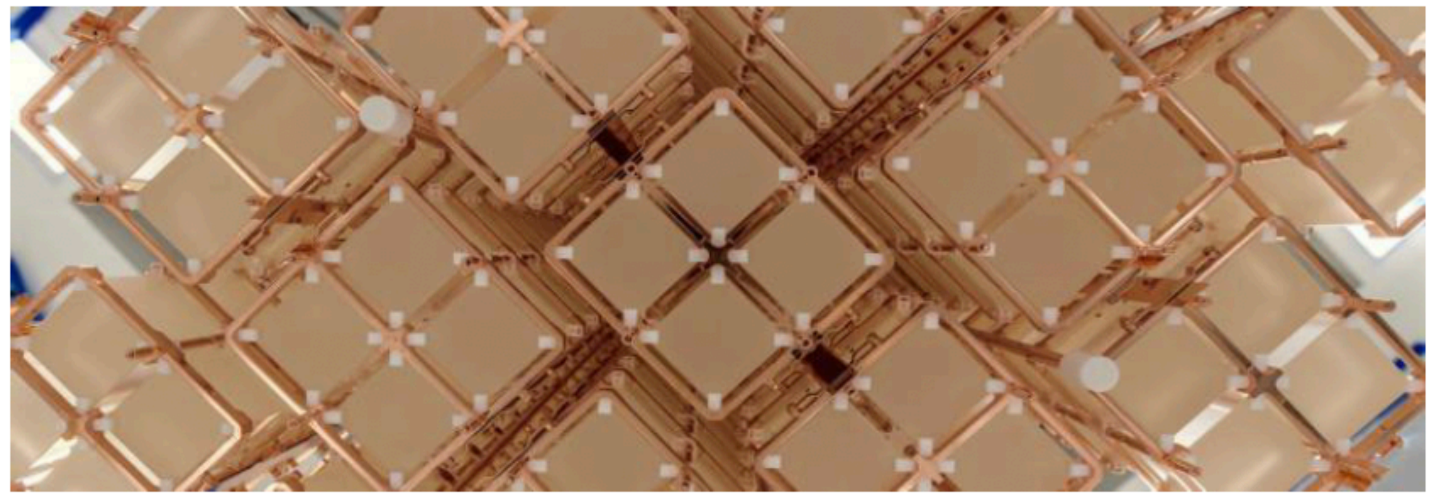
No PID

Q = 2527 keV < 2615 keV

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

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, $5 \times 5 \times 5$ cm^3 each
- Total mass: 742 kg TeO_2 (natural Te)
- ^{130}Te mass: 206 kg
- Current analysed exposure: 2039 kg y
- $T^{0\nu}_{1/2} > 3.8 \times 10^{25}$ **yr at 90% C.I.**
- $m_{\beta\beta} < 70 - 240$ **meV at 90% C.I.**

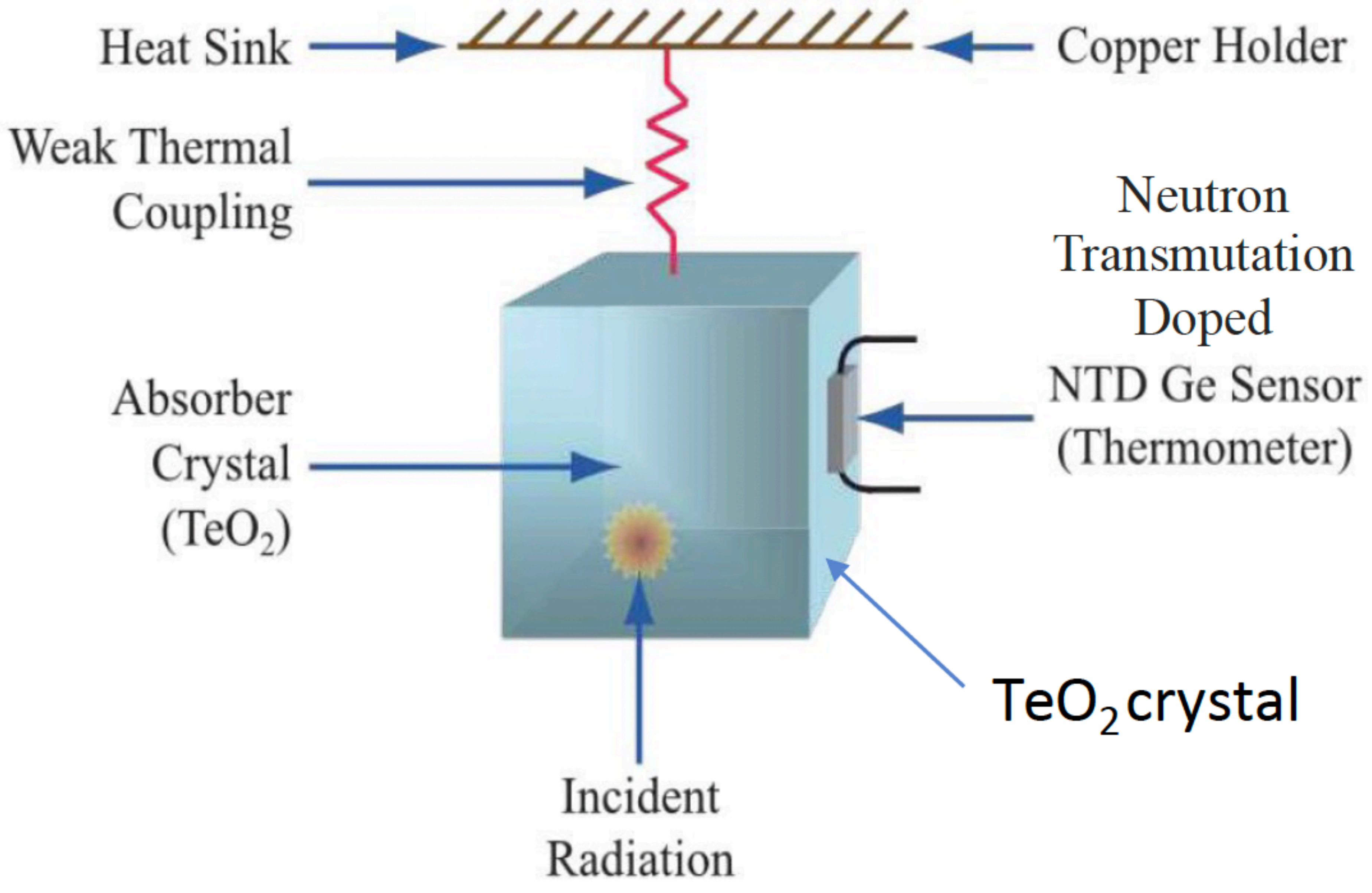


α background → b~10^{-2} c/(keV kg y)

γ background → b~10^{-3} c/(keV kg y)

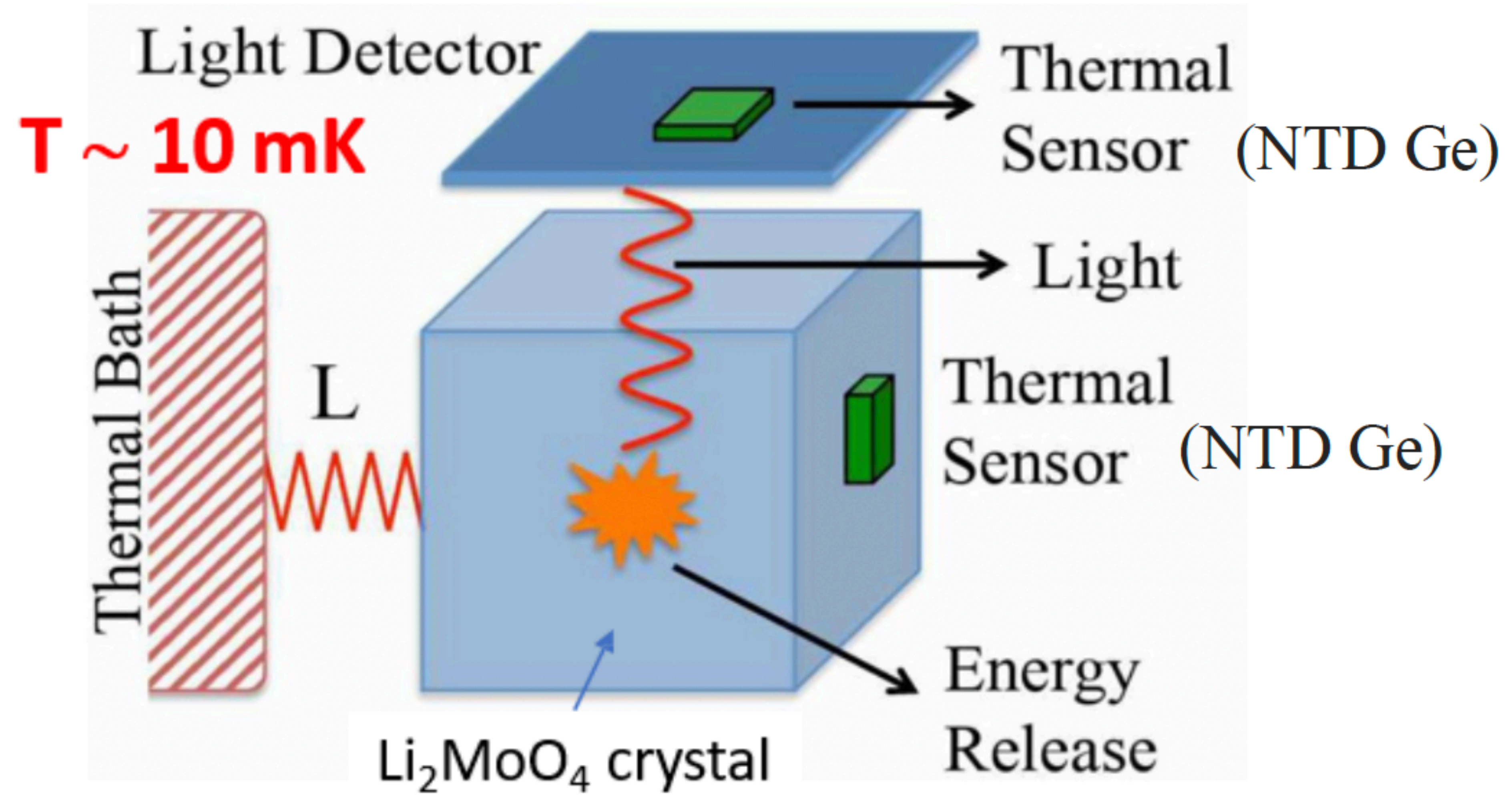
From CUORE to CUPID

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



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

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



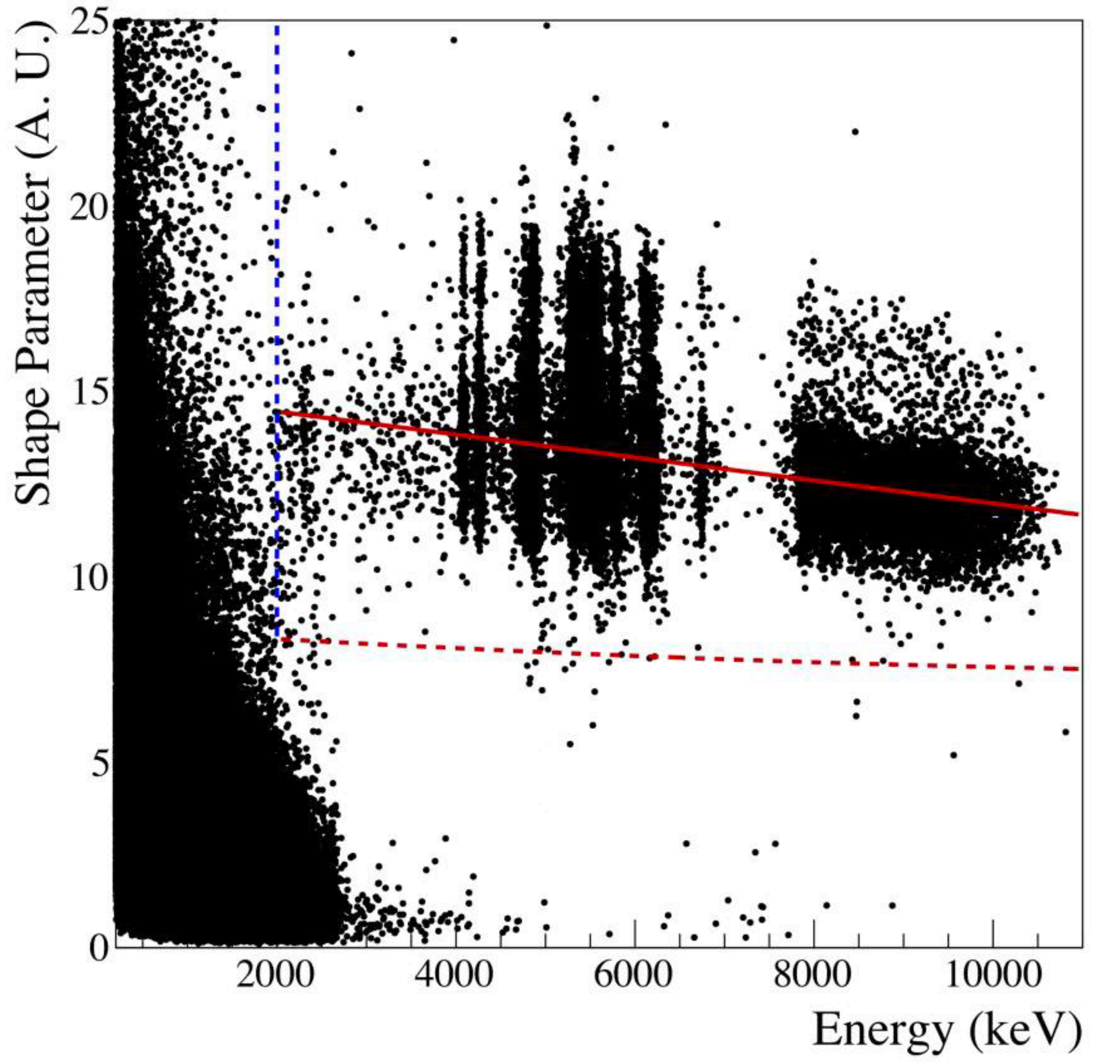
α ~~background~~ ← **PID**
γ ~~background~~ ← **Q = 3034 keV**
> 2615 keV

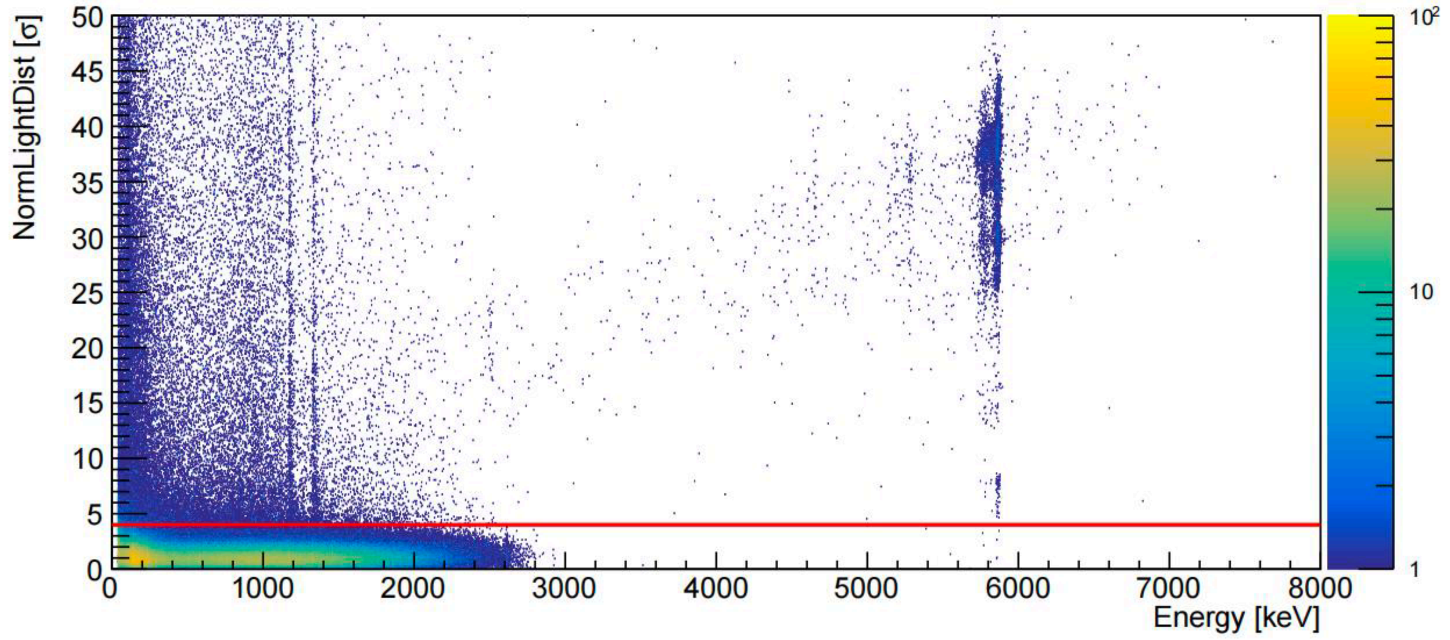
Enrichment in ^{100}Mo is possible on large scale

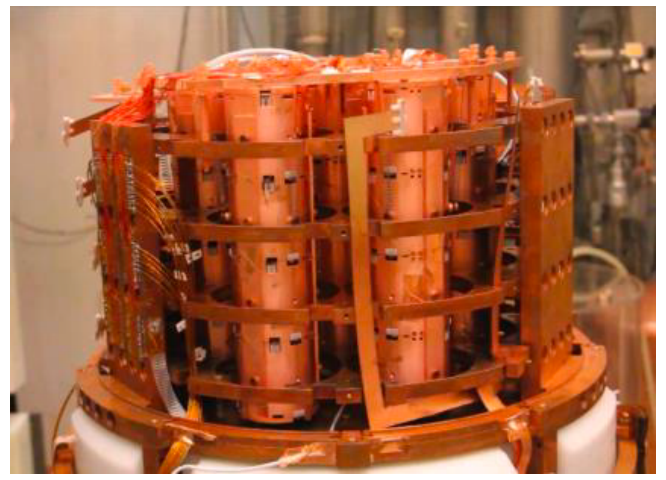
CUPID precursors

- CUPID-0: first pilot experiment for CUPID with scintillating bolometers ($Zn^{82}Se$) in LNGS
- >99.9% α rejection
- ΔE = 21.8 keV @ $Q_{\beta\beta}$ (2998 keV)
- Reached background:

$$b = 3.5 \times 10^{-3} \text{ counts/keV/kg/yr}$$



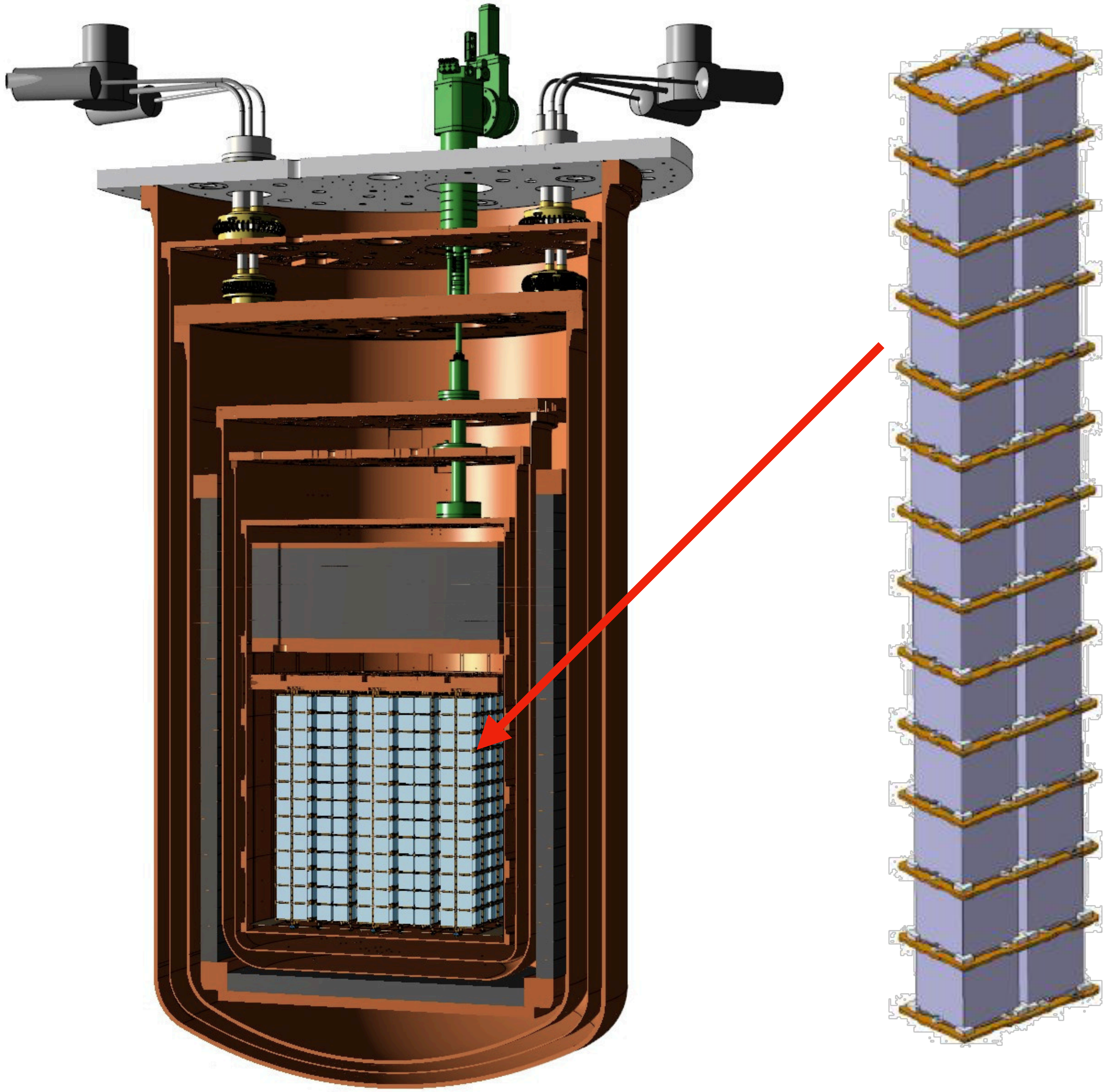




- CUPID-Mo: $Li_2{}^{100}MoO_4$ dual read-out detectors
- >99.9% α rejection
- ΔE = 7.4 keV @ $Q_{\beta\beta}$ (3034 keV)
- Demonstrated best background index reached in bolometric experiments:

$$b = 2.7^{+0.7}_{-0.6} \times 10^{-3} \text{ counts/keV/kg/year}$$

CUPID



- CUPID will use the CUORE cryostat located underground at Gran Sasso National Laboratory
- 1596 $Li_2{}^{100}MoO_4$ crystals (45x45x45 mm3) assembled in 57 towers of 28 crystals each
- 240 kg of ^{100}Mo (>95% enrichment)
- 1710 Neganov-Luke Ge light detectors with SiO anti-reflective coating to maximise light collection
- Neganov-Luke effect will enhance the S/N ratio to reach our pileup rejection capability through PSD.

CUPID projected sensitivity

CUPID requirements

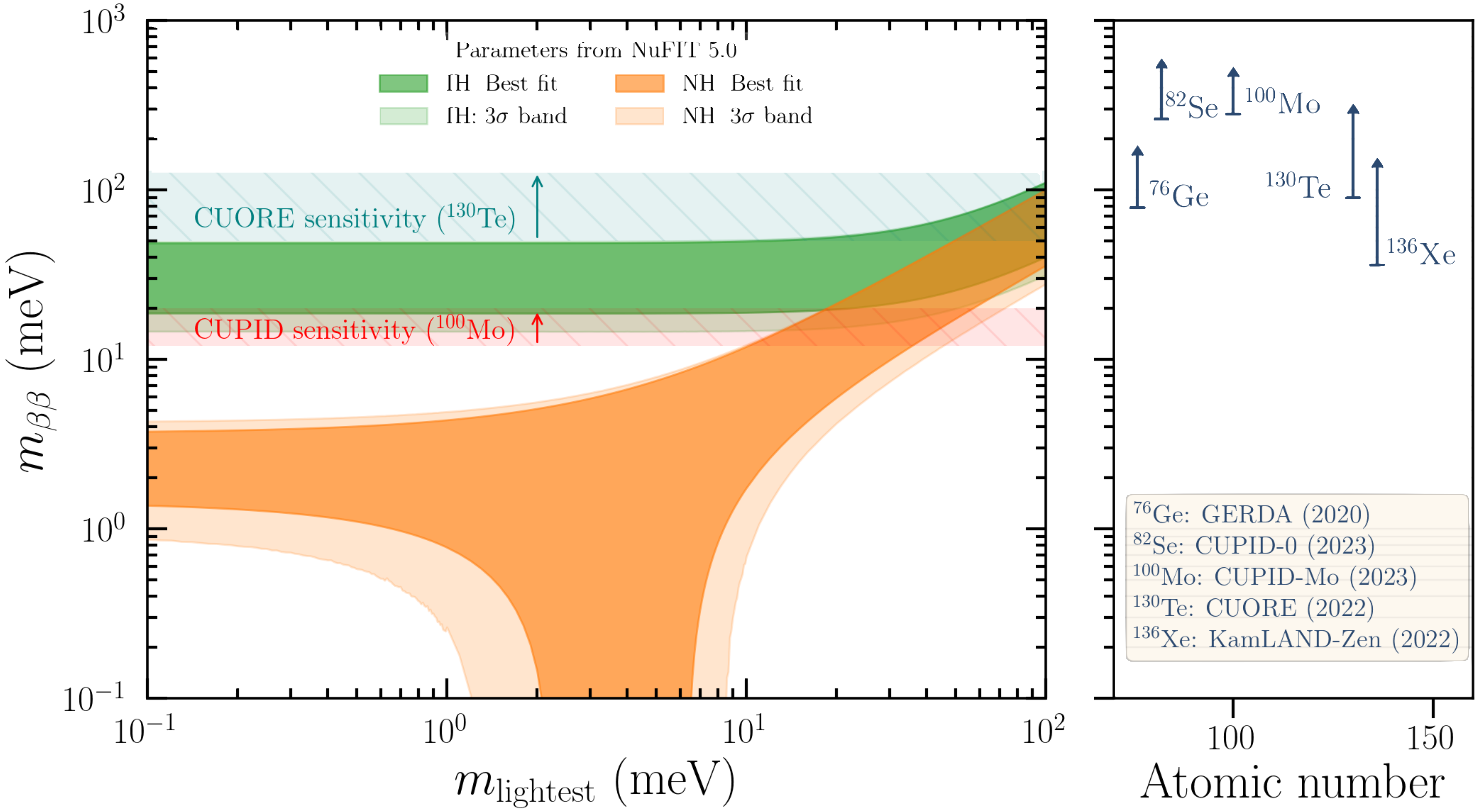
- >99.9% α-rejection efficiency
- Energy resolution: 5 keV FWHM at $Q_{\beta\beta}$
- LD baseline resolution: < 100 eV RMS (for PID)
- Light Yield: 0.3 keV/MeV
- Light detectors timing resolution: <0.17 ms (for pile-up rejection)
- Background index: 1×10^{-4} counts/keV/kg/yr

- Discovery sensitivity:

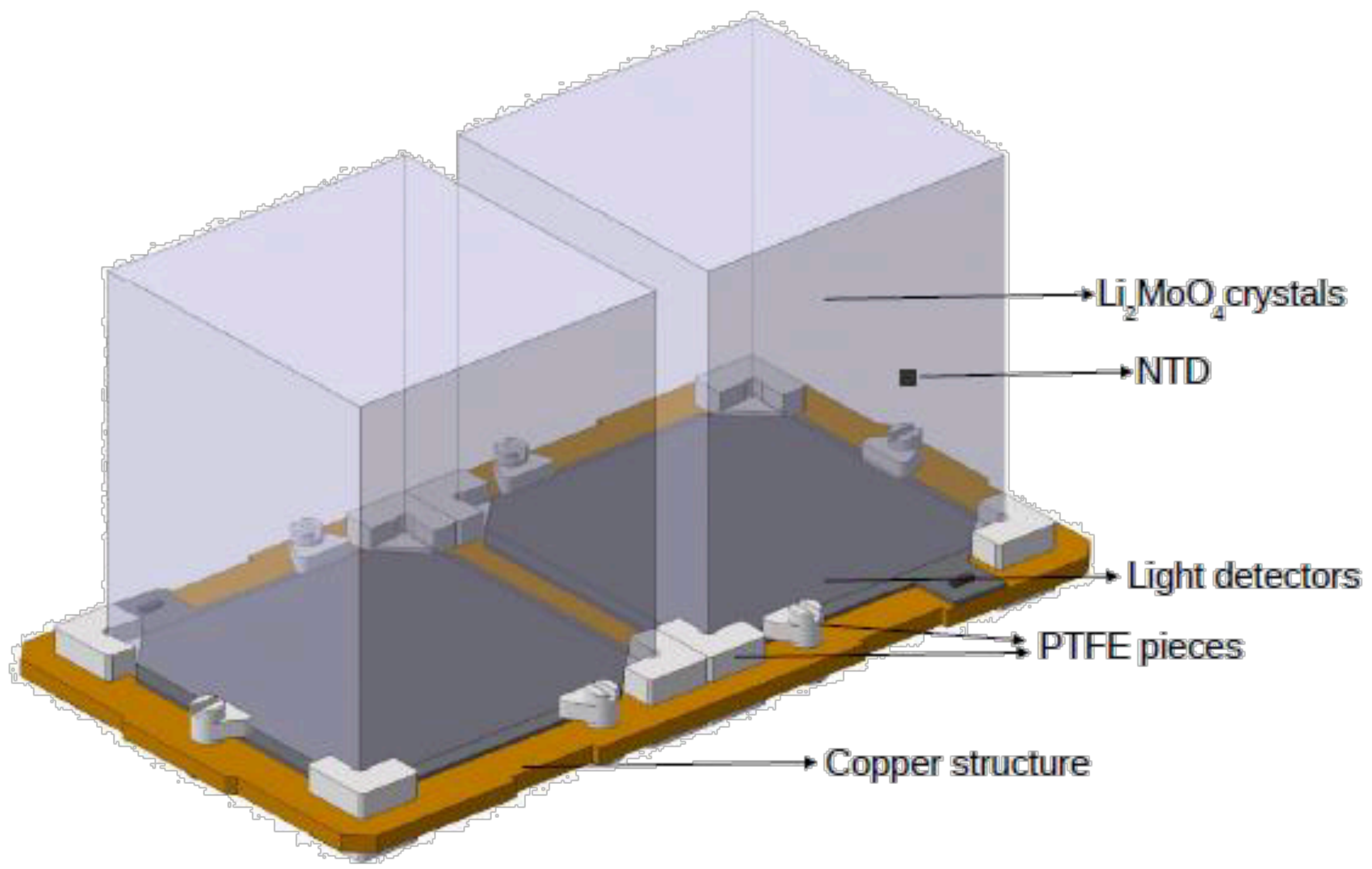
$T_{1/2} > 1.4 \times 10^{27}$ **yr**

$m_{\beta\beta}$ **= (12 - 20) meV**

- Probing the full Inverted Hierarchy region



Baseline design



- Gravity-assisted structure (innovative approach with respect to CUORE and CUPID precursors)
- Light detectors lying directly on the copper structure fixed by PTFE pieces
- Easy and fast assembly
- More effective cleaning

The first baseline tower prototype was tested in July and October 2022 in LNGS

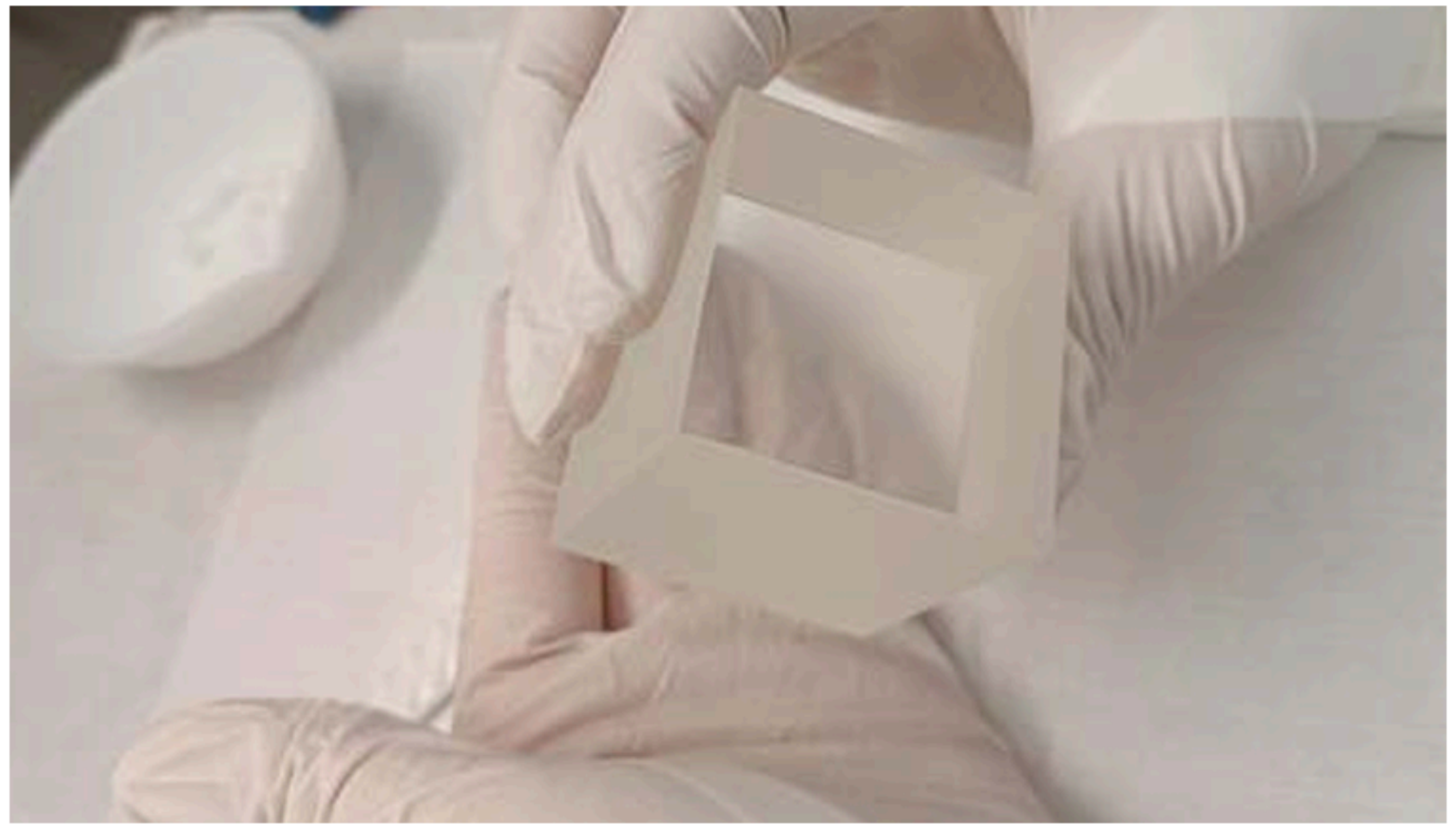
Goals:

- Validate assembly procedure, thermalization, and mechanical structure
- Study of glue type effects on NTD thermistor
- Validate performance of LMOs and light-detectors
- Tests on vibrations

2nd baseline tower test is planned for the end 2024 - beginning 2025

LMO crystals status

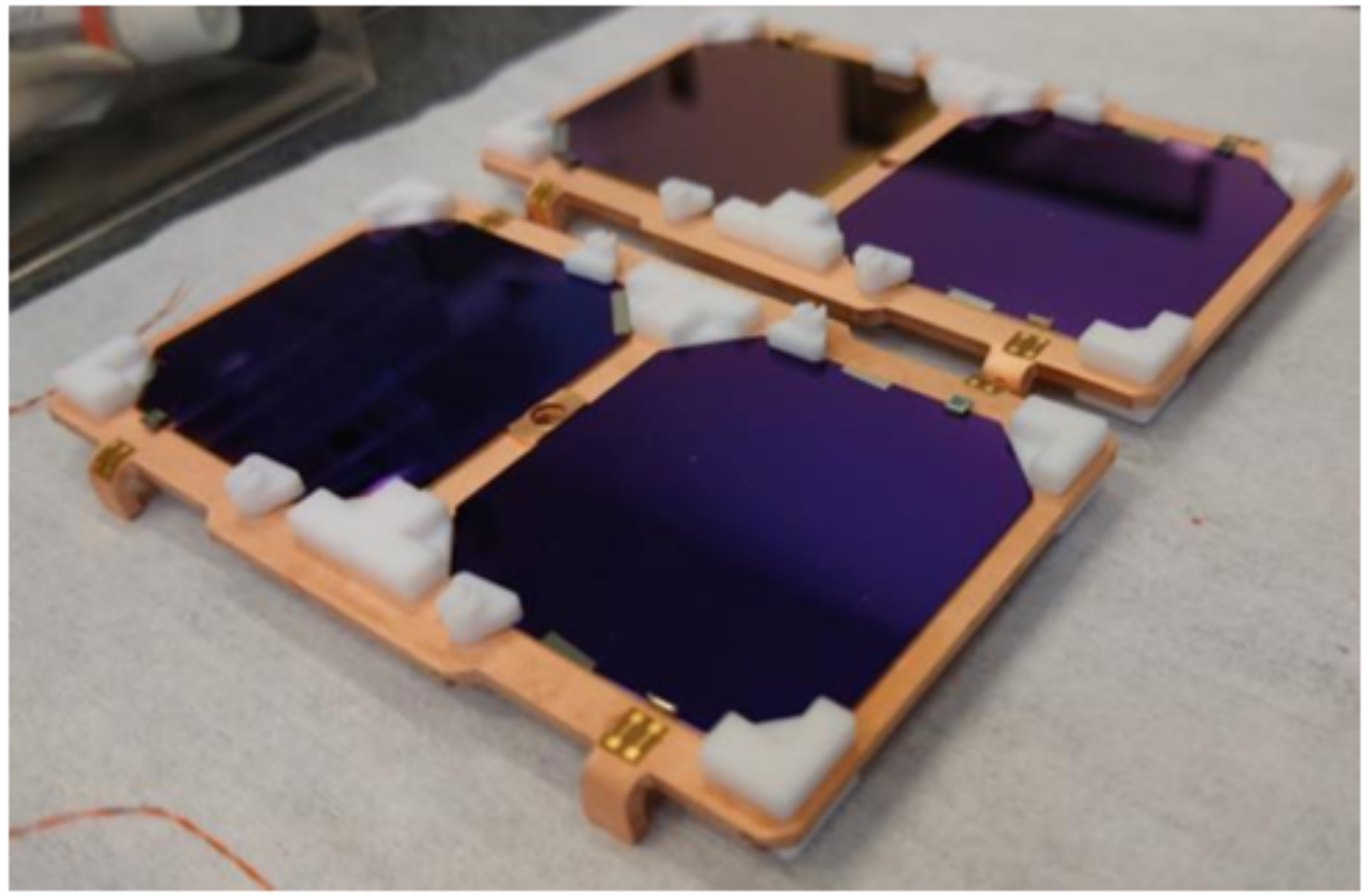
- CUPID has established a supply chain for producing 1596 $Li_2{}^{100}MoO_4$, crystals grown with ~95% enriched ^{100}Mo.
- SICCAS* (Shanghai, China) has the capability to produce the enriched crystals, procuring the isotope from a Chinese manufacturer. The first sample of isotope, measured by ICP-MS at LNGS, fully matches radiopurity requirements.



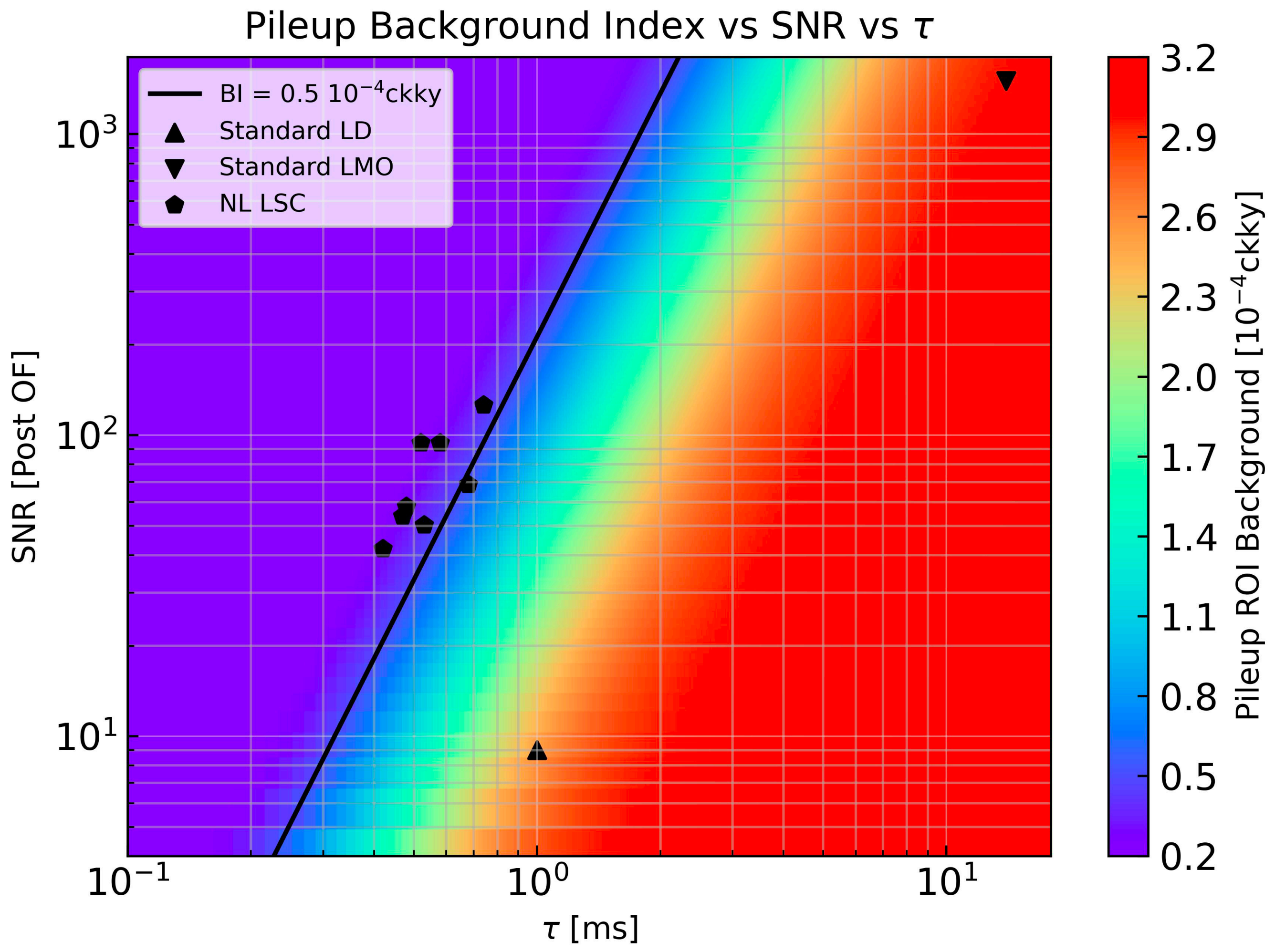
- Crystal pre-production is ongoing
- Tests at LNGS and LSC to validate performance/ radio purity and assess contamination
- Strategies to further reduce background level by improving crystal surface cleaning are being developed
- Full production at a large scale for CUPID is viable and currently under negotiation.

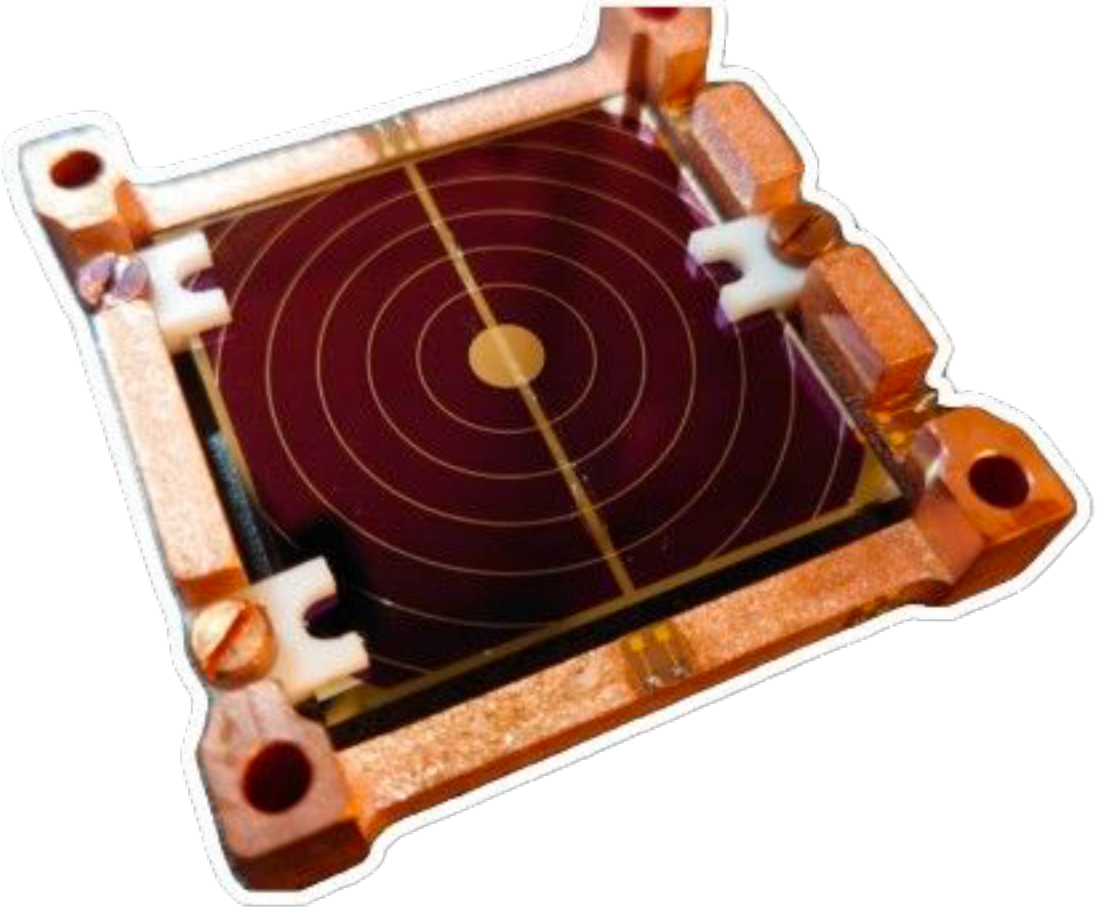
* SICCAS produced the 988 TeO2 crystals used by CUORE that have a radiopurity similar to CUPID requirements for LMO

Light detectors status



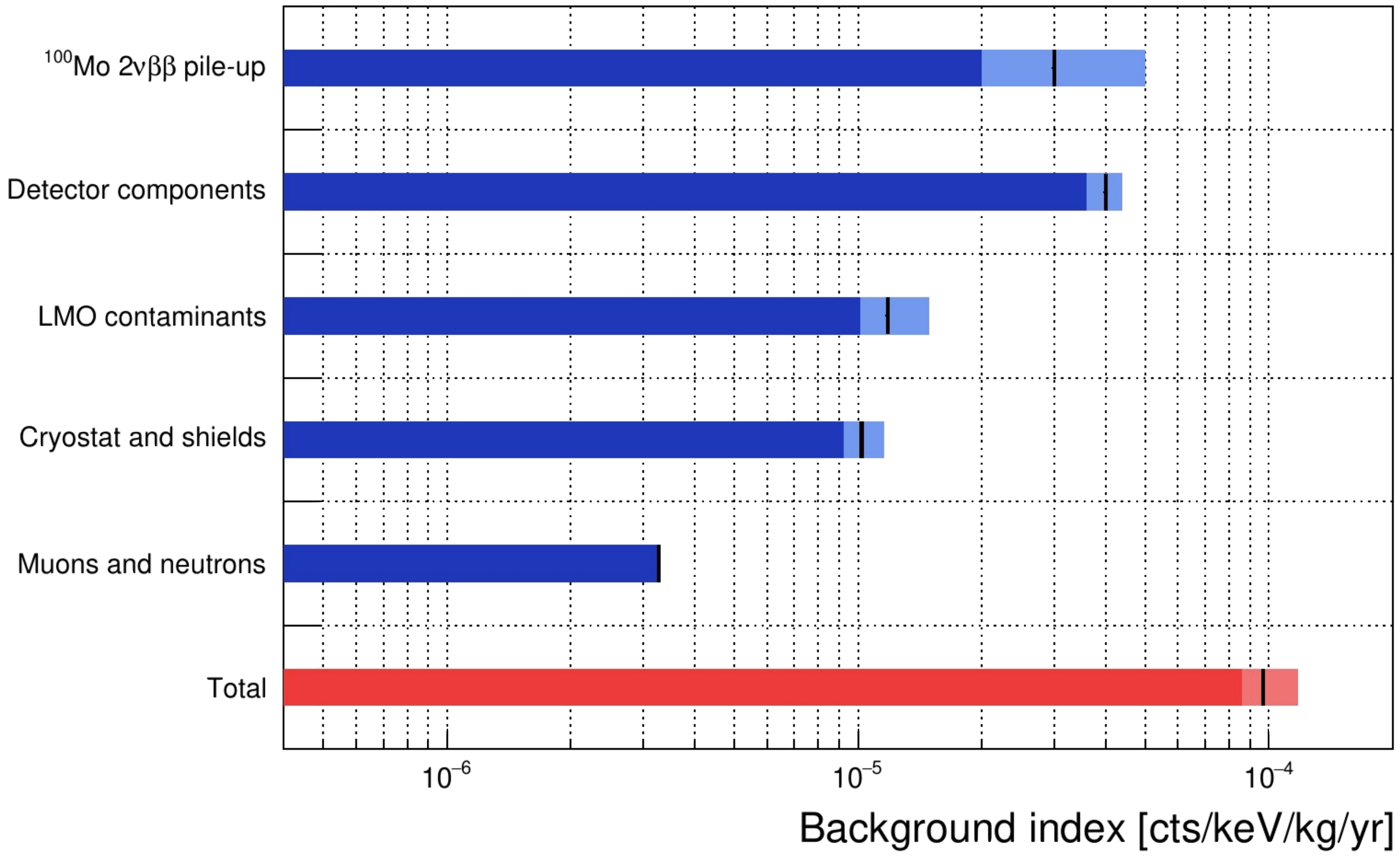
- Performed studies with Ge wafer with anti-reflective SiO coating and NTD readout for CUPID baseline
- Obtained baseline energy resolution 70-90 eV RMS
- Results show that CUPID baseline meets necessary α-rejection capabilities





- 10 Neganov-Luke light detectors were tested underground and demonstrated that a pile-up background index of 0.5×10^{-4} counts/keV/kg/yr is reachable

CUPID background



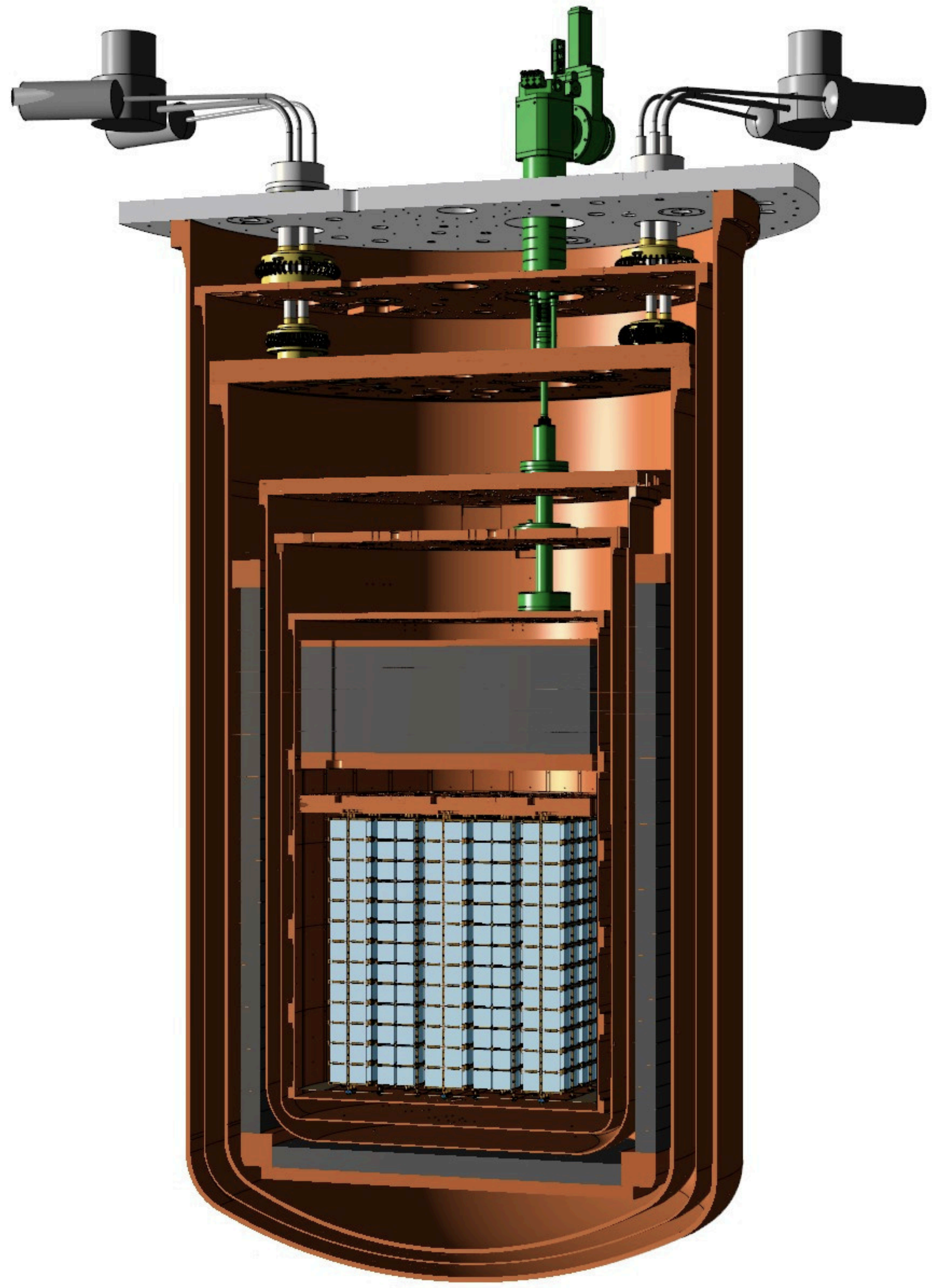
Background mitigation:

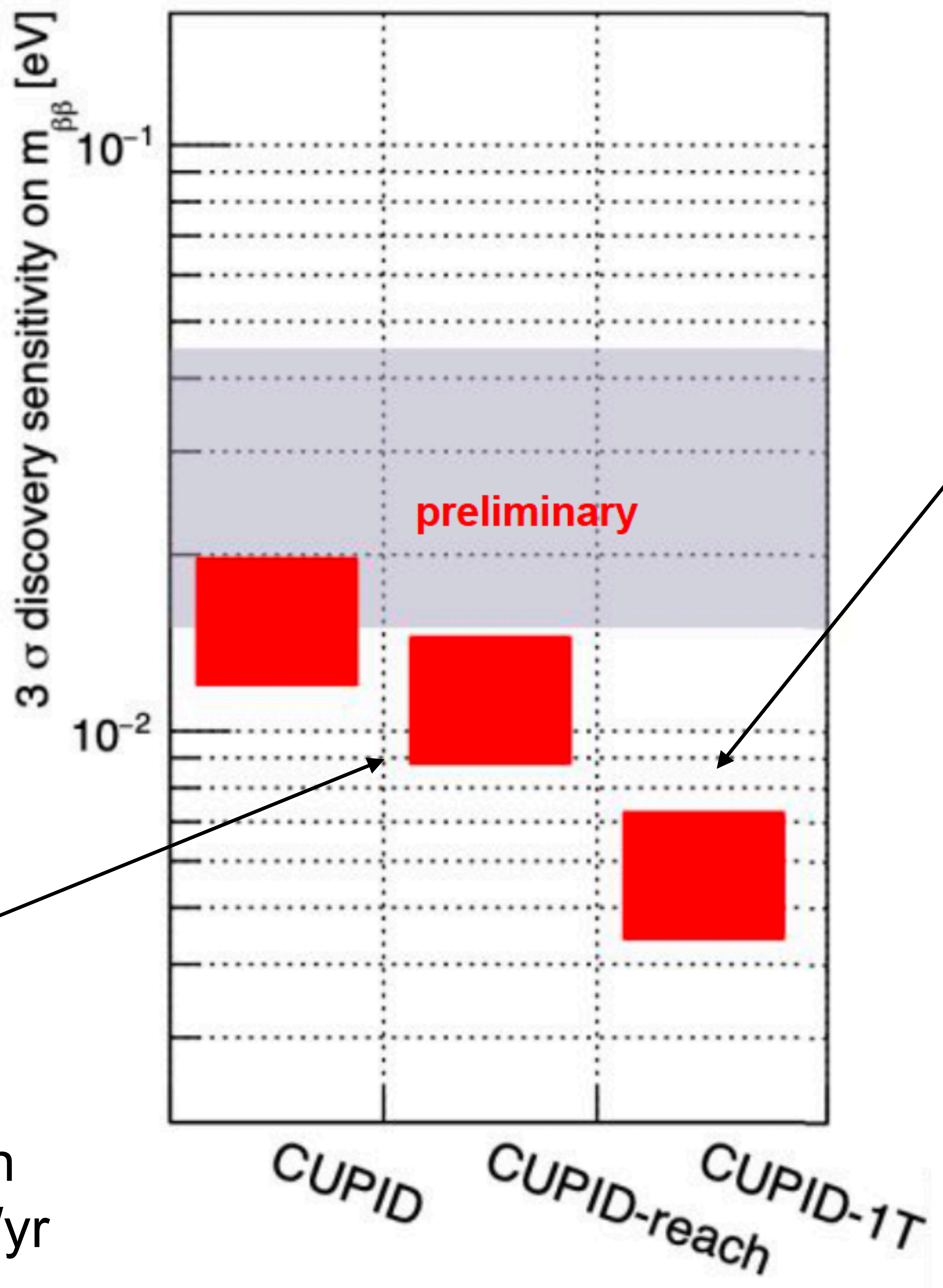
- Muon veto
- Material selection, cleaning, shielding
- Delayed coincidence cuts (U/Th chains).
- Lower noise, higher bandwidth electronics.
- Improved light-detector timing resolution/ SNR

Total expected background:

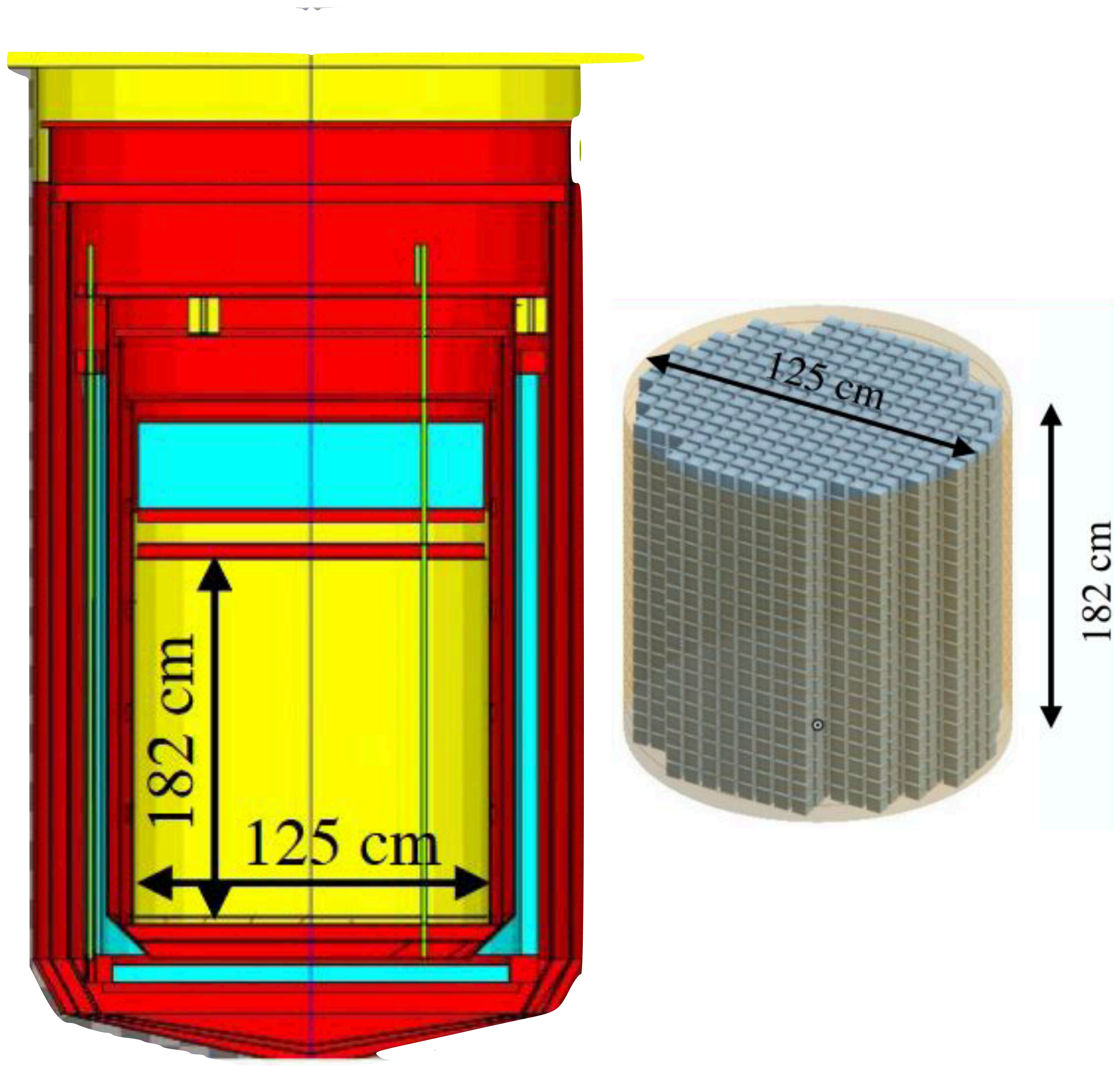
$b = 0.97^{+0.21}_{-0.11} \times 10^{-4}$ counts/keV/kg/yr

What's next?





CUPID-1T:
- New cryostat → Better shielding
- 1000kg of ^{100}Mo
- Background index: 5×10^{-6} counts/keV/kg/yr
- Sensitivity: $T_{1/2} > 9.2 \times 10^{27}$ yr



CUPID-reach:
- Same CUORE cryostat
- The same amount of ^{100}Mo (250 kg)
- New technologies for background reduction
- Background index: 2×10^{-5} counts/keV/kg/yr
- Sensitivity: $T_{1/2} > 2.3 \times 10^{27}$ yr

Summary

- CUPID will be an **upgrade of the existing CUORE experiment** and its infrastructure
- Scintillating bolometer technology, as a **powerful tool for alpha background rejection**, was successfully demonstrated in CUPID-Mo and CUPID-0
- LMO crystals **pre-production is ongoing**; crystals quality validation runs at LNGS and LSC are foreseen
- **Light detectors were tested** in the pulse-tube cryostat and showed the required performance
- Background mitigation strategy is well-defined and the total **background level of** 10^{-4} **counts/keV/kg/yr is reachable**
- Planning to start **data-taking by the end of the decade**
- CUPID is a **competitive double-beta decay experiment with a high discovery potential**, work on the possible improvements is ongoing

The CUPID collaboration

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Thank you for your attention!