The CUPID $0\nu\beta\beta$ Experiment

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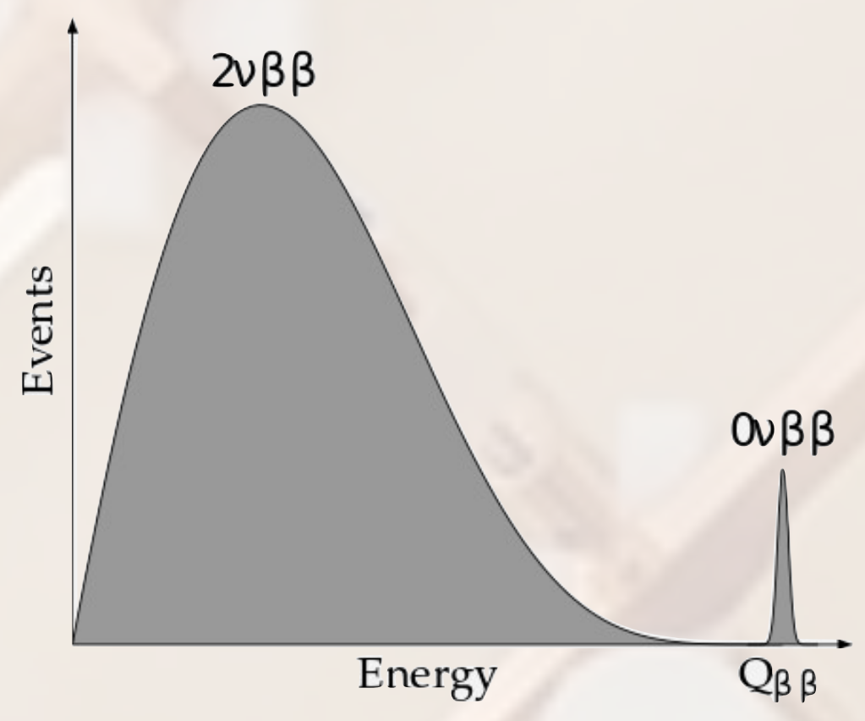
Neutrinoless double-beta decay

- 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



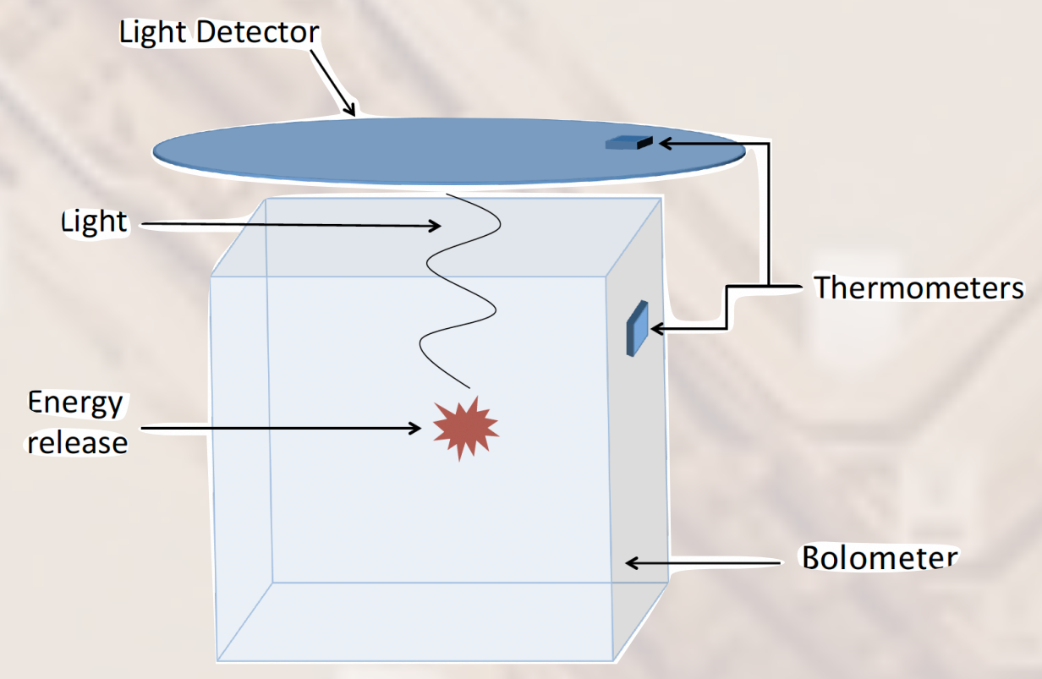
The modern $0\nu\beta\beta$ experiment requires:
- Large exposure $M \times t$ (big mass, long life-time)
- Large a (isotopic abundance)
- Small b (very low background in the ROI)
- Small ΔE (good energy resolution)
- High detection efficiency

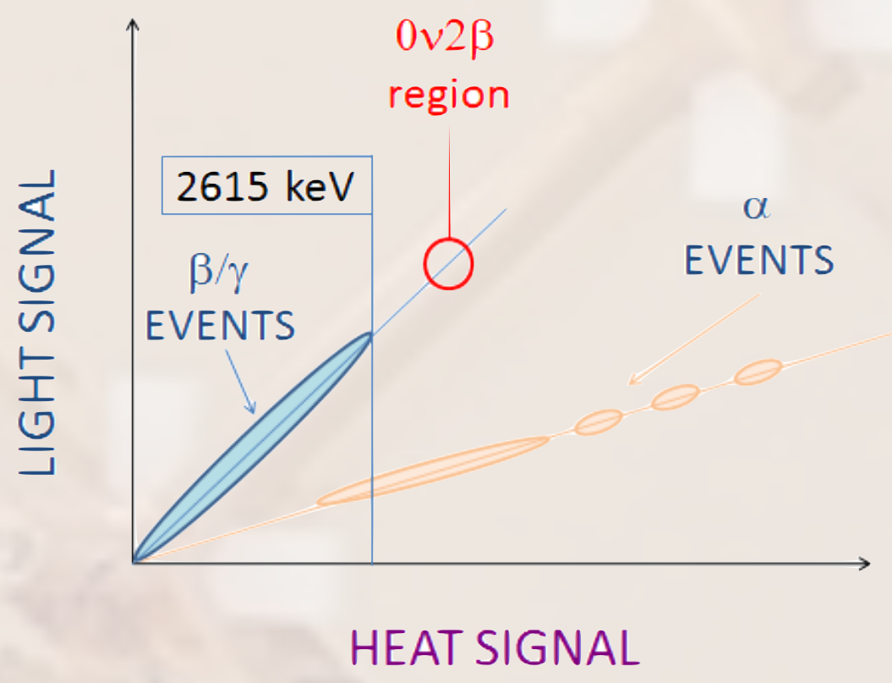
In case of observation:
- Lepton number violation
- Majorana nature of neutrino: $\nu = \bar{\nu}$
- Neutrino mass ordering
- Source for matter-antimatter asymmetry

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

Scintillation bolometers

- Crystal absorber coupled to the temperature sensor: $\Delta T \propto \Delta E_{deposited}$
- Operate at 10-30 mK to be able to detect ΔT in the order of 0.1 mK
- High energy resolution: ~5 keV FWHM (0.2%) at the $Q_{\beta\beta}$

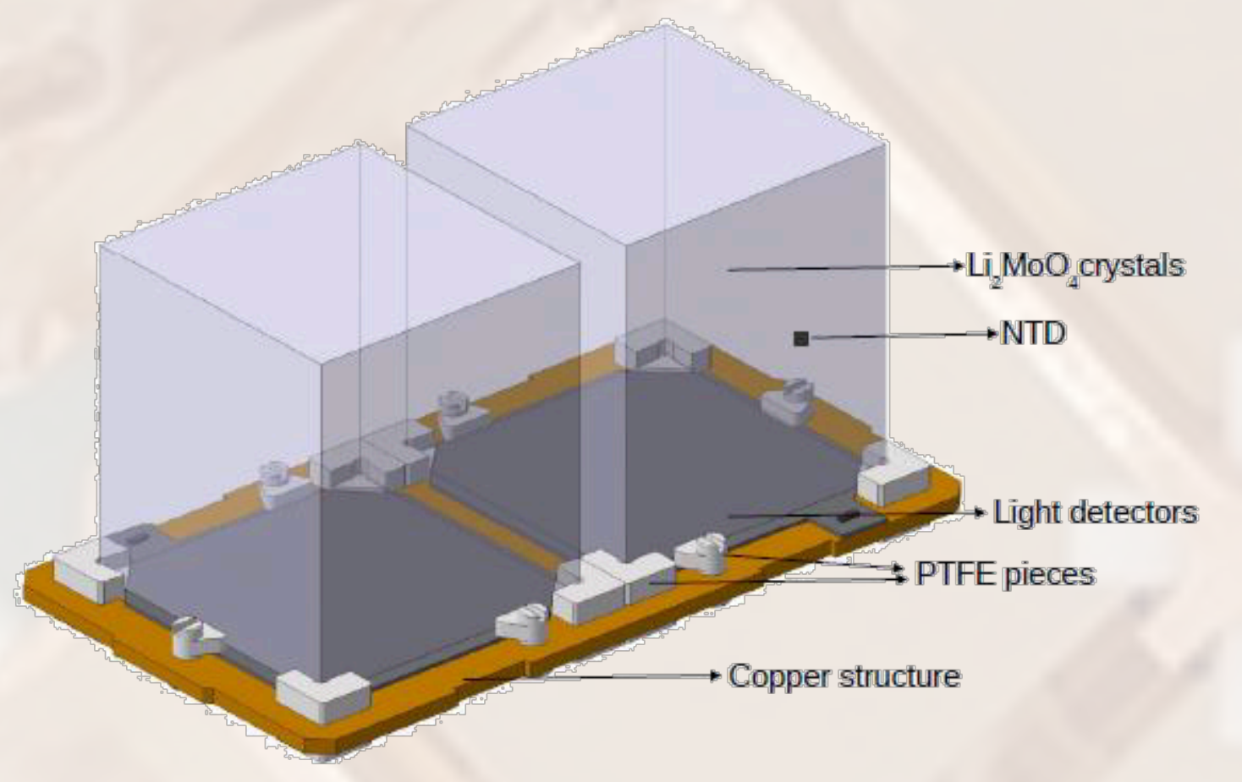




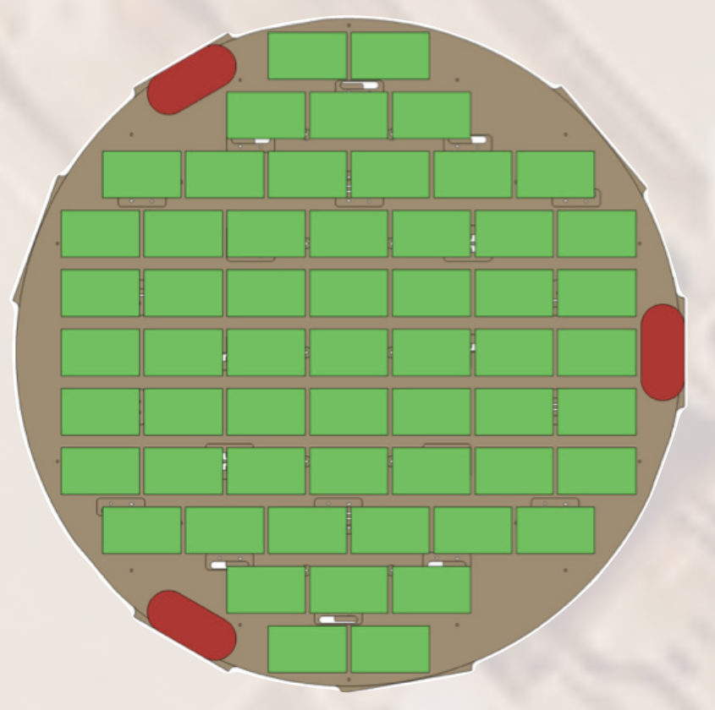
- Double read-out of heat and light signals
- Particle discrimination using light detectors (LD): >99.9% α-rejection
- Technology proven in CUPID-0 and CUPID-Mo demonstrators

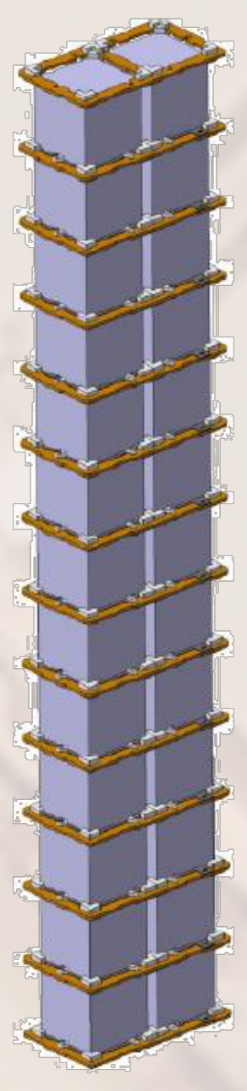
CUPID baseline design

- Gravity-assisted structure [3] (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

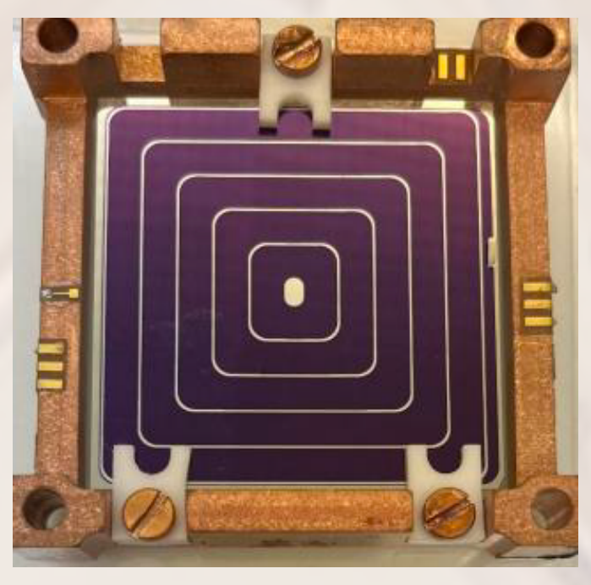


LMO crystals
- SICCAS* (Shanghai, China) has the capability to produce the enriched crystals, procuring the isotope from a Chinese manufacturer
- Crystal pre-production is ongoing
- Tests at LNGS and LSC to validate performance/radio purity and assess contamination
- Strategies to further reduce background level by improving crystal surface cleaning are being developed
- Full production at a large scale for CUPID is viable and currently under negotiation.





Light detectors
- Testing of the LDs with NTD readout in the new baseline holder design was performed [2].
- Baseline energy resolution 70-90 eV RMS which complies with CUPID requirement
- 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

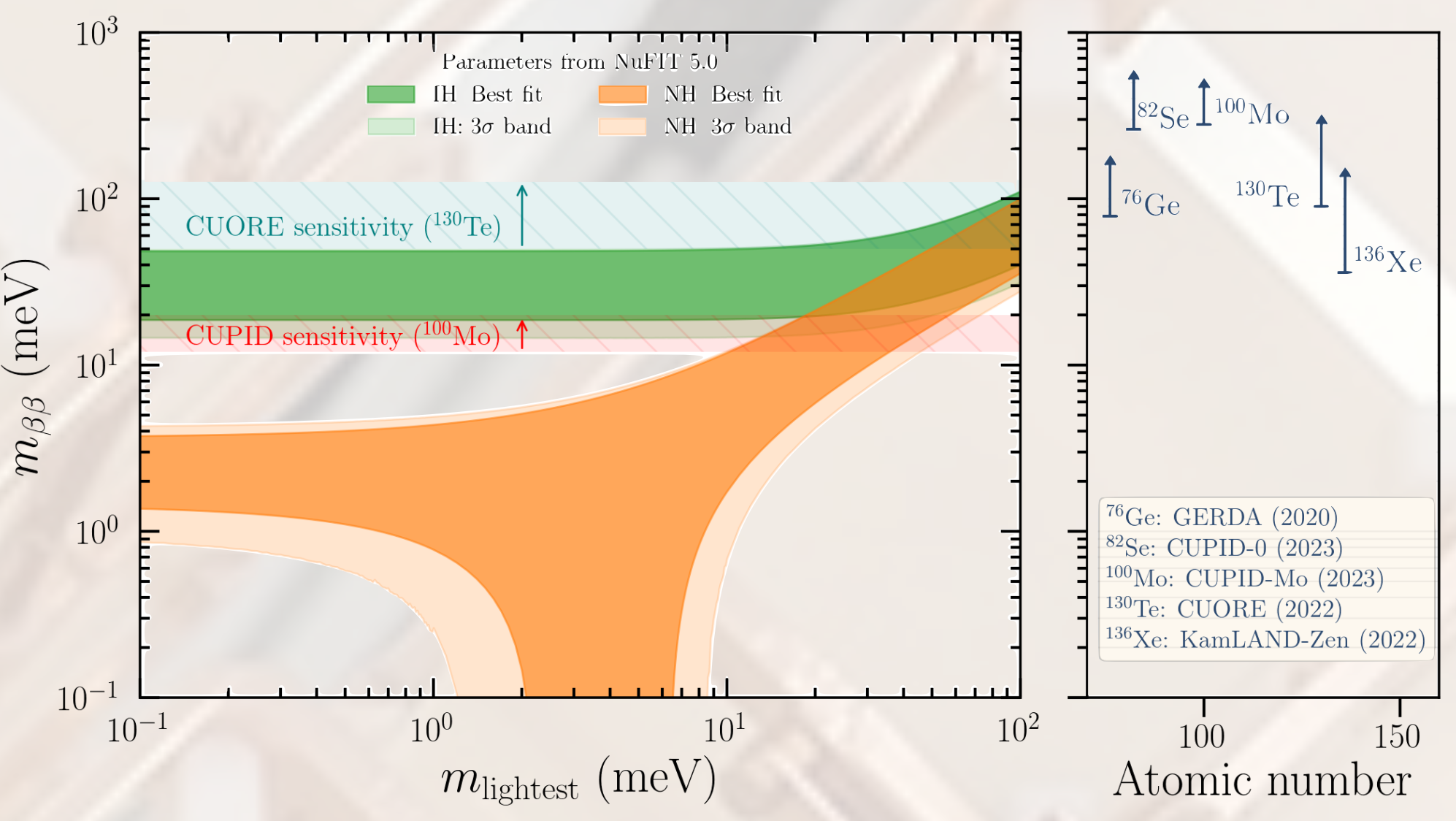


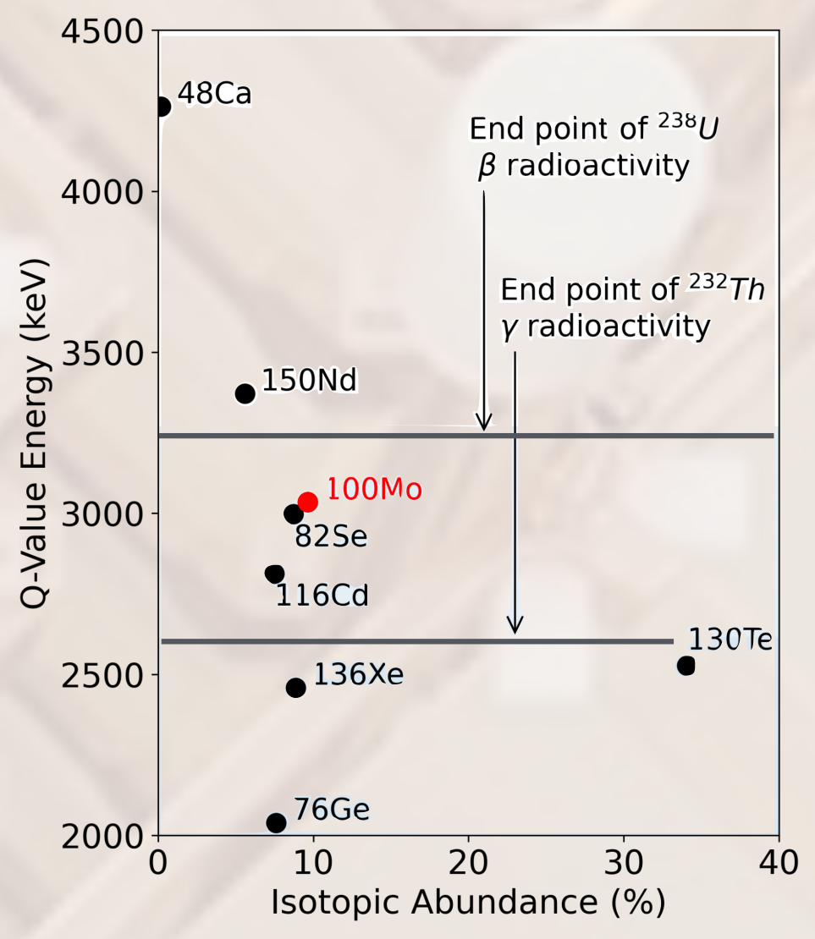
References

[1] CUPID pre-CDR. CUPID Collaboration • W.R. Armstrong (Argonne (main)) et al. e-Print: 1907.09376
[2] A first test of CUPID prototypal light detectors with NTD-Ge sensors in a pulse-tube cryostat. CUPID Collaboration • K. Alfonso (Virginia Tech.) et al. JINST 18 (2023) 06, P06033. DOI 10.1088/1748-0221/18/06/P06033
[3] Optimization of the first CUPID detector module. CUPID Collaboration., Alfonso, K., Armatol, A. et al. Eur. Phys. J. C 82, 810 (2022). DOI: 10.1140/epjc/s10052-022-10720-3
[4] Toward CUPID-1T. CUPID Collaboration • A. Armatol (IRFU, Saclay) et al. e-Print: 2203.08386

CUORE Upgrade with Particle IDentification

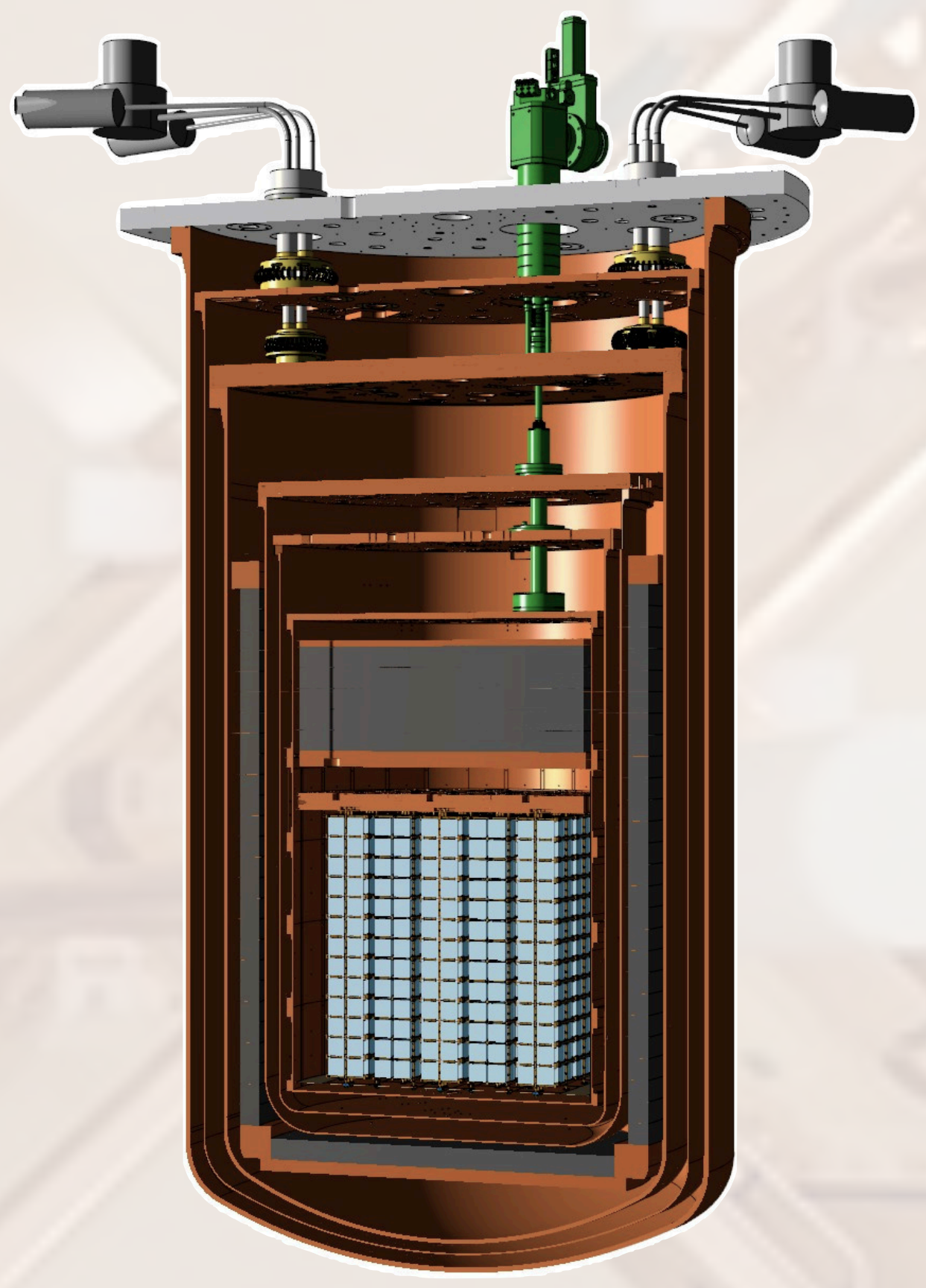
Upgrade to existing CUORE experiment
- Discovery sensitivity:
  - Sensitivity: $T_{1/2} > 1.4 \times 10^{27}$ yr
  - $m_{\beta\beta}$ = (12 - 20) meV
- Probing the full Inverted Hierarchy region
- New technology to decrease background and increase sensitivity





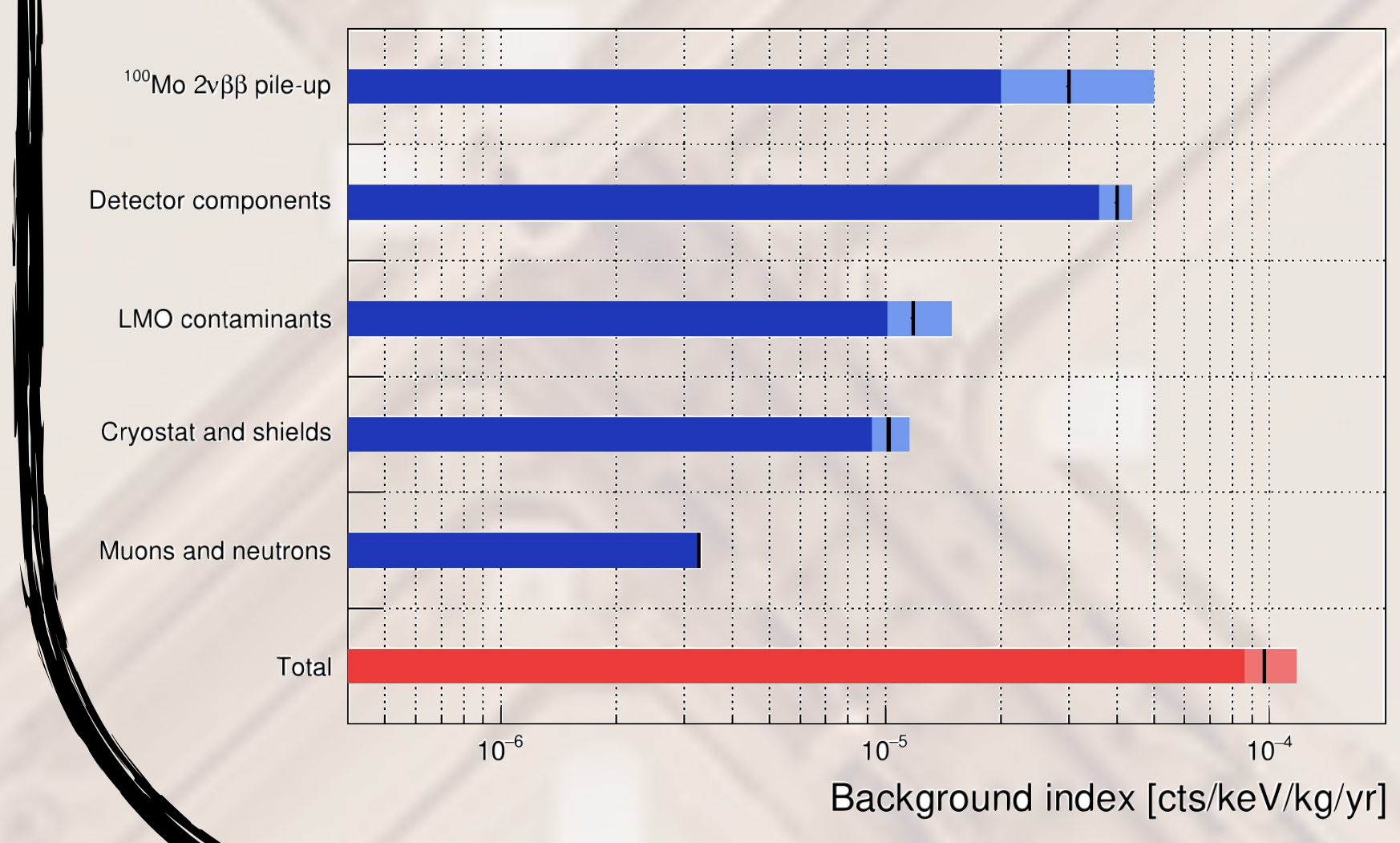
^{100}Mo as the studied isotope
- High $Q_{\beta\beta}$ value (3034 keV) above the bulk of γ environmental background
- Ease of embedding into scintillating crystals
- Possible enrichment
- Good scintillator (important for particle identification PID)
- Relatively fast $2\nu\beta\beta$ decay of ^{100}Mo: $T_{1/2} = 7.1 \times 10^{18}$ yr, but could be rejected by pulse shape

- CUPID will use the CUORE cryostat located underground at Gran Sasso National Laboratory
- 1596 Li$_2$^{100}MoO$_4$ crystals (45x45x45 mm^3) 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 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

CUPID background

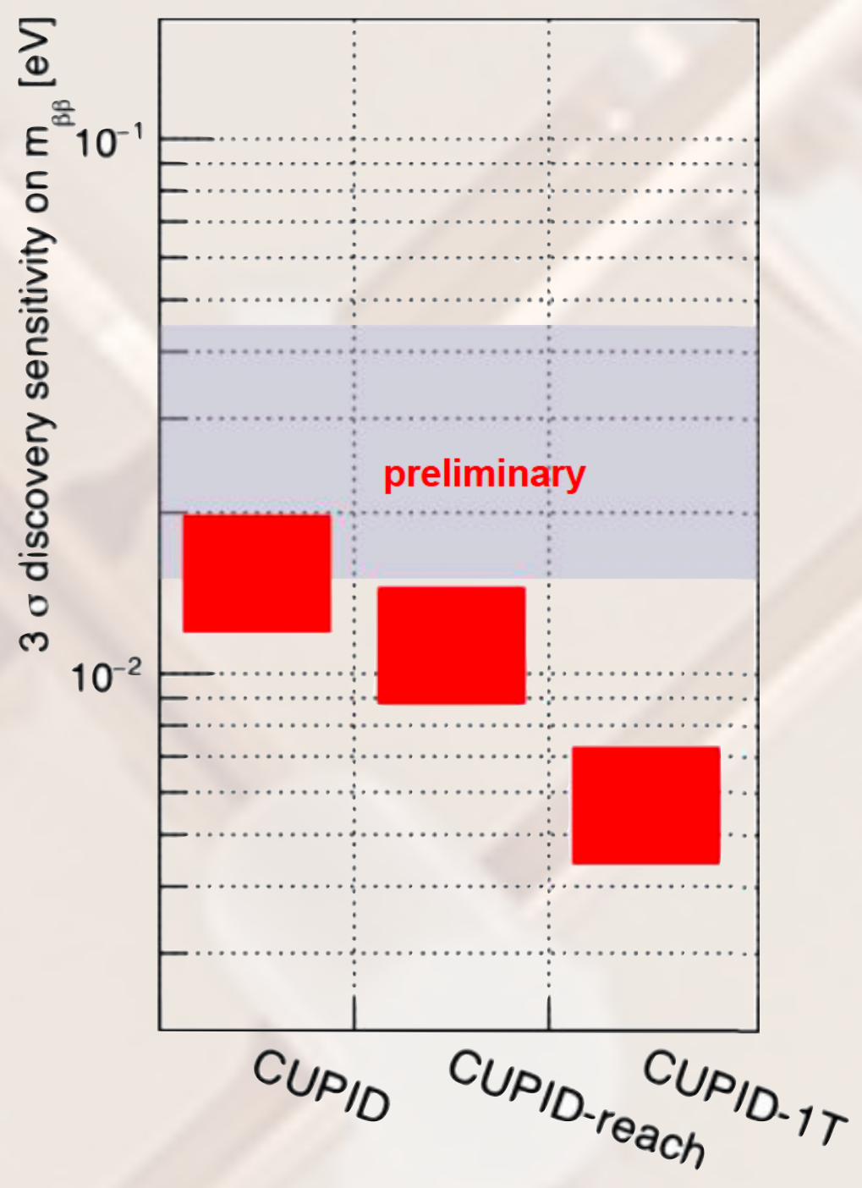


- Muon veto
- Material selection, cleaning, shielding.
- Delayed coincidence cuts (U/Th chains).
- Lower noise, higher bandwidth electronics.
- Improved light-detector timing resolution/ SNR
- Total expected background:
  $b = 0.97^{+0.21}_{-0.11} \times 10^{-4}$ counts/keV/kg/yr

Beyond CUPID

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

CUPID-1T [4]:
- 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



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