The CUPID neutrinoless double-beta decay experiment

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Majorana neutrinos

Neutrino Physics

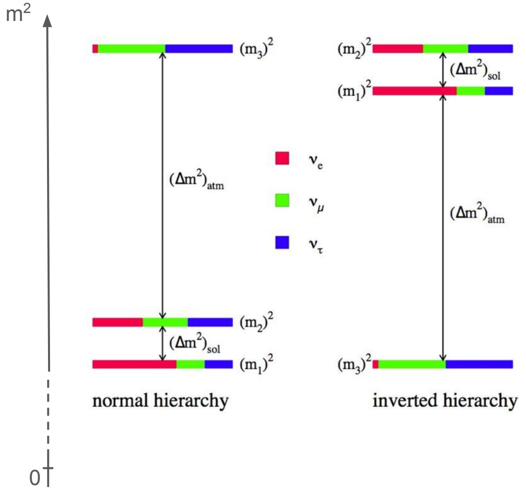
- Neutrinos are the most elusive particles in the Standard Model of Particle Physics
- We know from oscillation experiments that neutrinos have non-zero mass
- Most of the parameters determining neutrino oscillations have been measured

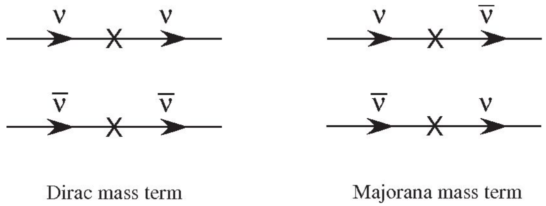
Some things we still don't know

- The absolute mass scale of the neutrino mass
- Whether the normal or the inverted neutrino mass hierarchy holds
- Whether the neutrino is a Dirac or a Majorana particle

Implications of Majorana neutrinos

- The lepton number is not a conserved quantity
- Might explain the smallness of neutrino masses (see-saw mechanism)
- Might explain the matter-antimatter asymmetry in the Universe



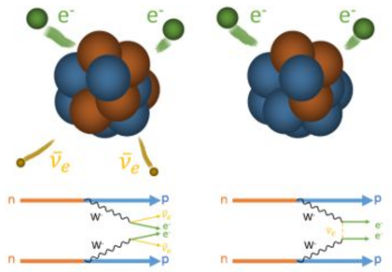


Double beta decay

A spontaneous nuclear decay taking place in some nuclei with an even number of neutrons and protons

Two neutrino double beta decay - 2nuDBD
Allowed by the Standard Model, observed in several isotopes
half-lifes are in the range 10^{18} - 10^{21} y

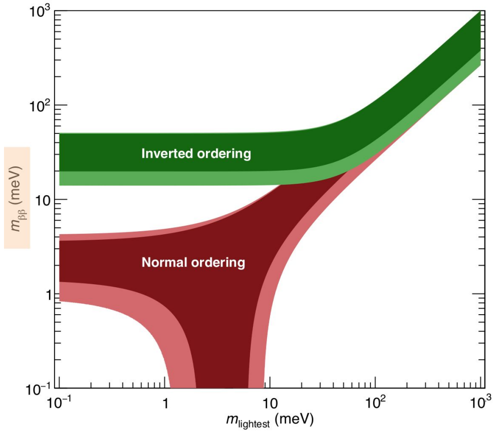
Zero neutrinos double beta decay - 0nuDBD
only allowed if neutrinos are Majorana particles, never observed
half-lifes limits are in the range 10^{25} - 10^{26} y



- The observation of 0nuDBD would imply that neutrino is a Majorana particle
- By measuring the half-life we can infer the effective Majorana mass of the neutrino

Half life — phase space — Nuclear matrix element — Effective Majorana mass

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\,|M^{0\nu}|^2\,\frac{|m_{\beta\beta}|^2}{m_e^2}$$

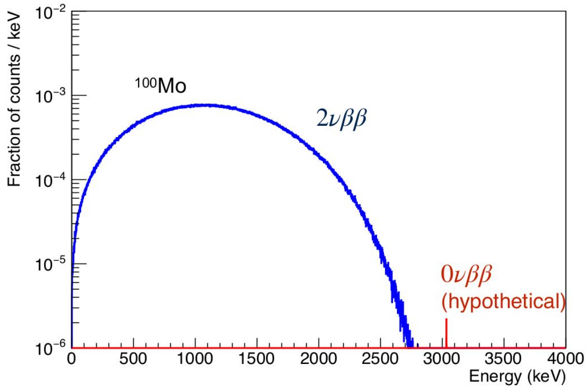


Double-beta decay: experimental searches

- 0nuDBD signature: a peak in the energy spectrum at the Q-value of the decay (2-4 MeV, depending on the isotope)
- In future experiments we expect at most ~ 1-10 signal events per 100 kg of isotope per year
- Experimental requirements
  - Very large source mass
  - Extremely low background
  - Excellent energy resolution
- Background sources
  - Radioactivity in the surrounding environment
  - Radioactivity in the detector components
  - Muons from cosmic rays, and their products
- In background limited experiments the half-life sensitivity scales as

$$S^{0\nu} \sim \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}$$

Isotope mass — meas. time — background index — energy resolution



Isotope	Q [keV]	Half-life limit [10^{25} y]
^{48}Ca	4271	0.0058 (CANDLES)
^{76}Ge	2039	12 (GERDA-II)
^{82}Se	2995	0.44 (CUPID-0)
^{100}Mo	3034	0.17 (CUPID-Mo)
^{130}Te	2528	2.2 (CUORE)
^{136}Xe	2479	23 (KamLAND-Zen)

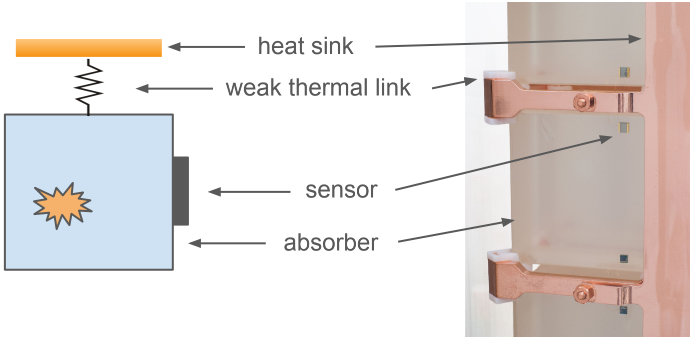
Cryogenic calorimeters for double beta decay

Key features

- Measure the temperature increase of an absorber crystal: $\Delta T = E/C$
- Need very low base temperature: ~10 mK
- Several thermal sensors can be used: NTD, TES, etc.

Pros

- Can be built with a wide range of materials
- Many compounds contain DBD isotopes: TeO_2, ZnSe, Li_2MoO_4…, and some of these scintillate
- Can achieve large absorber masses, superior energy resolution and very low radioactive contaminations

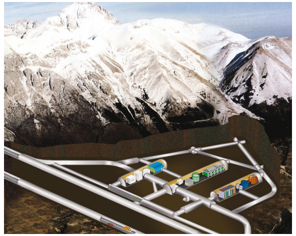


An example: CUORE

Cons

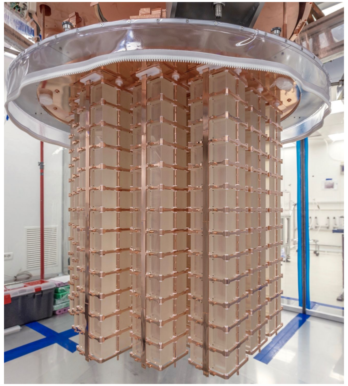
- Cryogenic calorimeters are intrinsically slow
  - not an issue for rare events searches (but…)
- A complex cryogenic infrastructure is necessary, operated for very long time

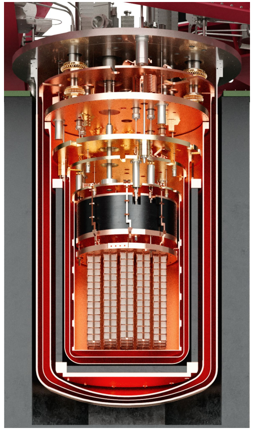
The CUORE experiment

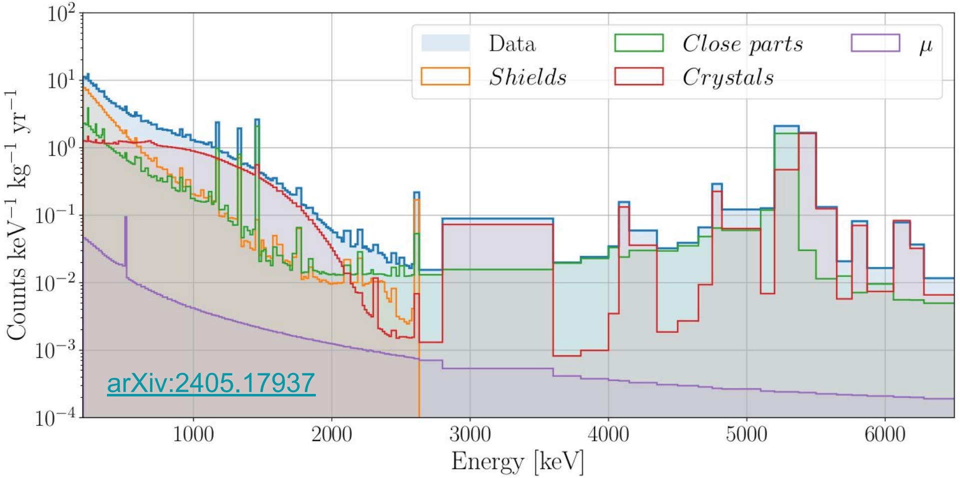


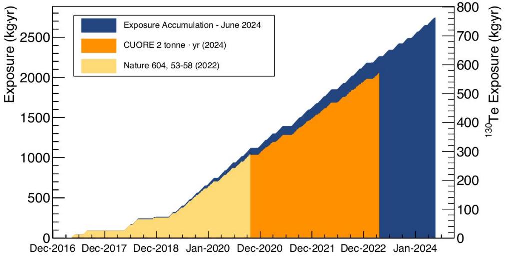
- An array of 988 cubic TeO_2 crystals (~0.75 ton) operated as cryogenic calorimeters
- Taking data at the Laboratori Nazionali del Gran Sasso since 2017
- Complex cryogenic infrastructure, few tons of material kept at 10 mK

- First demonstration of a ton scale cryogenic experiment running for several years
- Te-130 0nuDBD half-life limit: $3.8 \cdot 10^{25}$ y (arXiv:2404.04453)
- Background index in the ROI: $1.42 \cdot 10^{-2}$ counts/(keV·kg·y)
- We have a very good understanding of the CUORE background



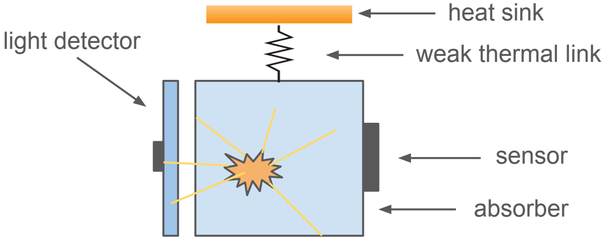


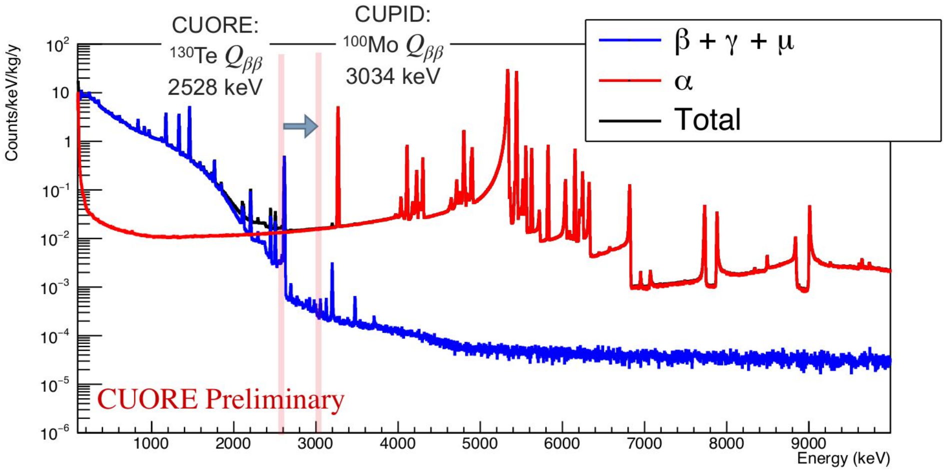


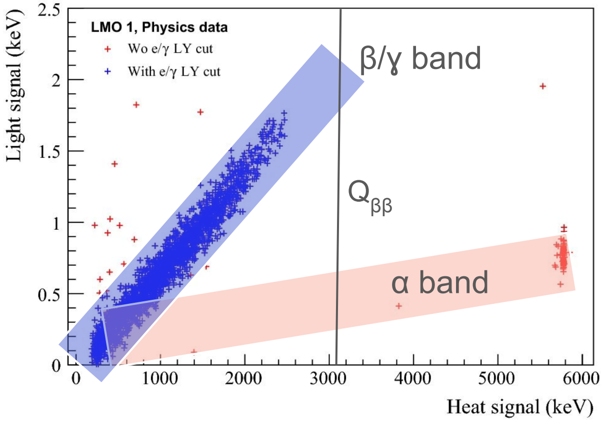


CUPID: CUORE Upgrade with Particle IDentification

- Change isotope: $^{130}Te \rightarrow ^{100}Mo$
  - Higher Q-value, lower intrinsic gamma background
- Use a scintillating compound containing Mo: Li_2MoO_4 (LMO)
- Reject alpha background with dual heat+light readout
- Introduce a muon veto and improved neutron shield





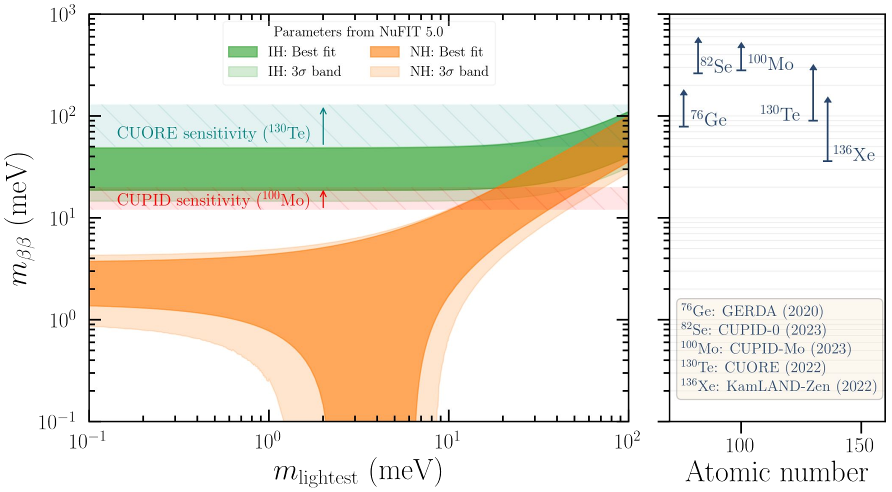


The CUPID project

Goal: fully explore the inverted hierarchy region of the effective Majorana neutrino mass using an array of Li_2MoO_4 cryogenic calorimeters

Key parameters

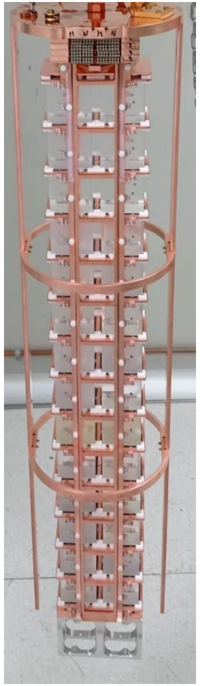
- 240 kg of ^{100}Mo
- 5 keV FWHM energy resolution at 3034 keV
- 10^{-4} counts/(keV·kg·y) background index at 3034 keV
- $1.4 \cdot 10^{27}$ y half-life sensitivity after 10 years

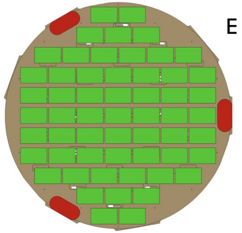


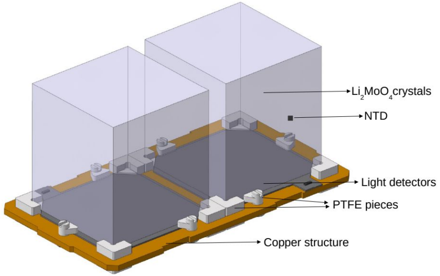
Approach: exploit existing infrastructures and already established technologies to maximize the chances of success

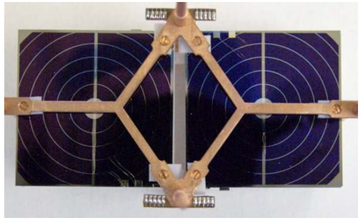
- Reuse the CUORE cryogenic infrastructure, add muon veto and improve the neutron shield
- Use absorber crystals containing enriched isotope: 250 kg of ^{100}Mo (>95% enrichment)
- Exploit the experience about scintillating detectors gained with the CUPID-0 and CUPID-Mo experiments
- Use a data-driven background model based on the results of the CUORE, CUPID-0 and CUPID-Mo experiments

The CUPID detector









Mechanical structure

- The detectors are arranged in 57 towers
- High-purity copper structure, PTFE supports
- Simplified assembly with respect to CUORE

Absorber crystals

- 1596 $Li_2{}^{100}MoO_4$ crystals read out by NTD sensors
- Each crystal is a cube with 4.5cm side and weighs 280g

Light detectors

- 1710 light detectors (2 per LMO crystal)
- Light detectors are Ge wafers read out by NTD
- Anti-reflective SiO coating to improve light collection

Performances (based on past measurements)

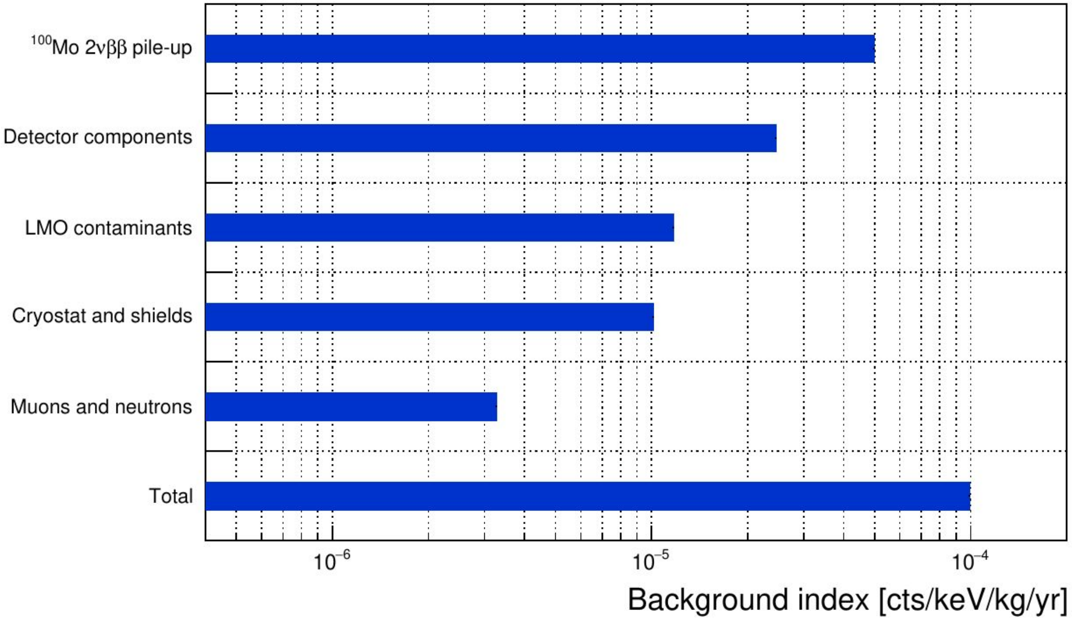
- α background rejection > 99.9%
- Energy resolution at 3034 keV: 7.4 keV FWHM
- Light yield: 0.3 keV/MeV
- Light detector baseline resolution: < 100 eV RMS

PRL 129 (2022), 111801
EPJC 82 (2022), 1033
JINST 18 (2023), P06033
EPJC 82 (2022), 810
EPJC 81 (2021), 104

CUPID background budget

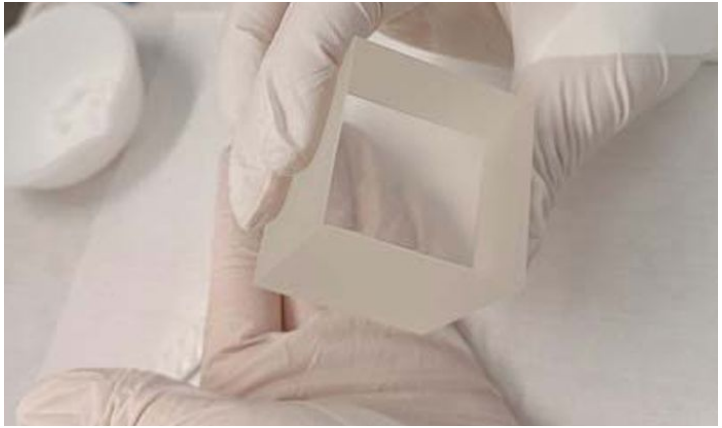
CUPID background budget is based on results from precursor experiments (CUORE and CUPID-Mo) and on improved new design.

- **LMO ^{100}Mo pile-up:** demonstrated performance on baseline NTL detectors
- **Detector components:** surface driven
- **LMO contaminants**: surface driven
- **Cryostat & shields:** bulk
- **Muons and neutrons**



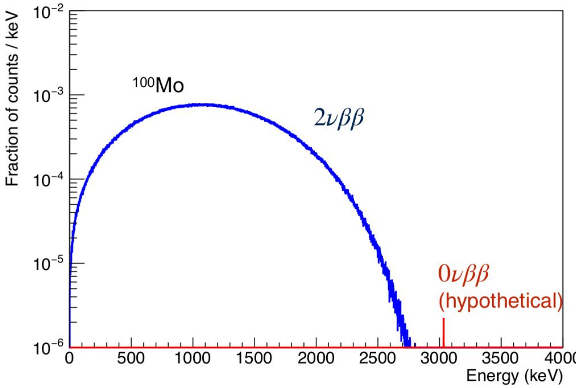
Enriched crystals procurement

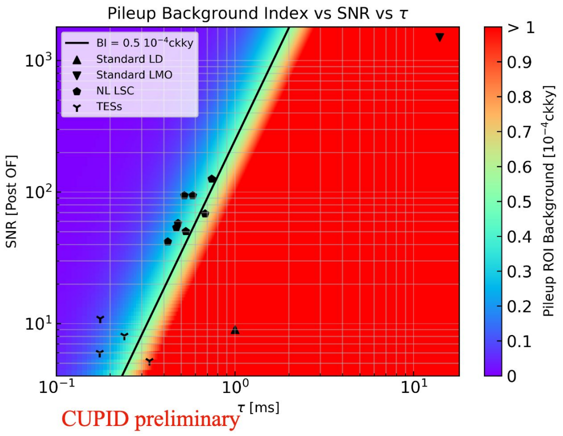
- CUPID has established a supply chain for producing 1596 Li_2MoO_4, crystals grown with ~95% enriched ^{100}Mo
  - SICCAS has the capability to produce the enriched crystals, procuring the isotope from a Chinese manufacturer
  - SICCAS already produced all the CUORE crystals with radiopurity requirements similar to CUPID
  - The first sample of isotope fully matches radiopurity requirements.
- Pre-production is on-going
  - reduce to a minimum material (isotope) loss during growth and cut
  - check and optimize radiopurity
  - optimize light yield and transmission (surface quality)
- Cryogenic tests performed at LNGS CUPID facility
  - Assess performances as cryogenic detectors
  - Analyse residual radioactivity

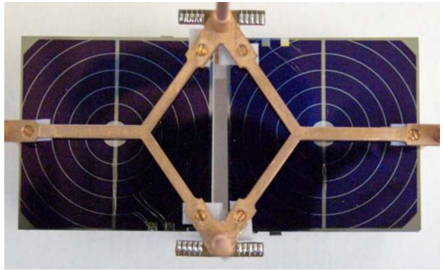


2nuDBD pile-up background

- The 2nuDBD half-life of ^{100}Mo is relatively short ($7 \cdot 10^{18}$ y), moreover cryogenic calorimeters are slow
- Events from 2nuDBD can pile-up and end up in the 0nuDBD energy region of interest
- Need light detectors with good time resolution to keep this background below $0.5 \cdot 10^{-4}$ counts/(keV kg y)
- Baseline: use Neganov-Trofimov-Luke effect to improve the SNR of the LDs
- As a complementary approach faster sensors for the readout of the LDs (TES instead of NTD)

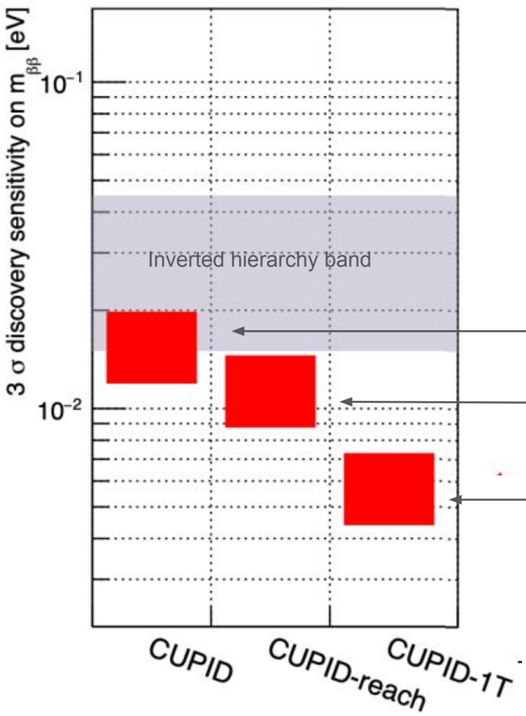






CUPID-like LDs with NTL electrodes

CUPID-1T



CUPID-1T is a possible extension of CUPID with enhanced sensitivity

- 4x mass scale up → 1000 kg of ^{100}Mo
- Background abatement by a factor 20 →$5 \cdot 10^{-6}$ counts/(keV kg y)
- 5x improvement in half-life sensitivity

CUPID baseline: achievable with already demonstrated technologies

CUPID-Reach: achievable achievable if a reduction in the 2nu pile-up and other backgrounds will be obtained

CUPID-1T: requires both background reduction and an increase in the detector mass

Conclusion

- CUPID will explore the inverse-hierarchy region of the Majorana mass with an array of cryogenic calorimeters
- The experiment will use scintillating Li_2MoO_4 crystals to perform background rejection by particle discrimination
- The design of the experiment and the projected sensitivity are based on already demonstrated technologies
- CUPID-1T is a possible future stage of the experiment with enhanced sensitivity