Searching for neutrinoless double beta decay with Li_2MoO_4 scintillating bolometers

THE CUPID EXPERIMENT

Cuore Upgrade with Particle IDentification

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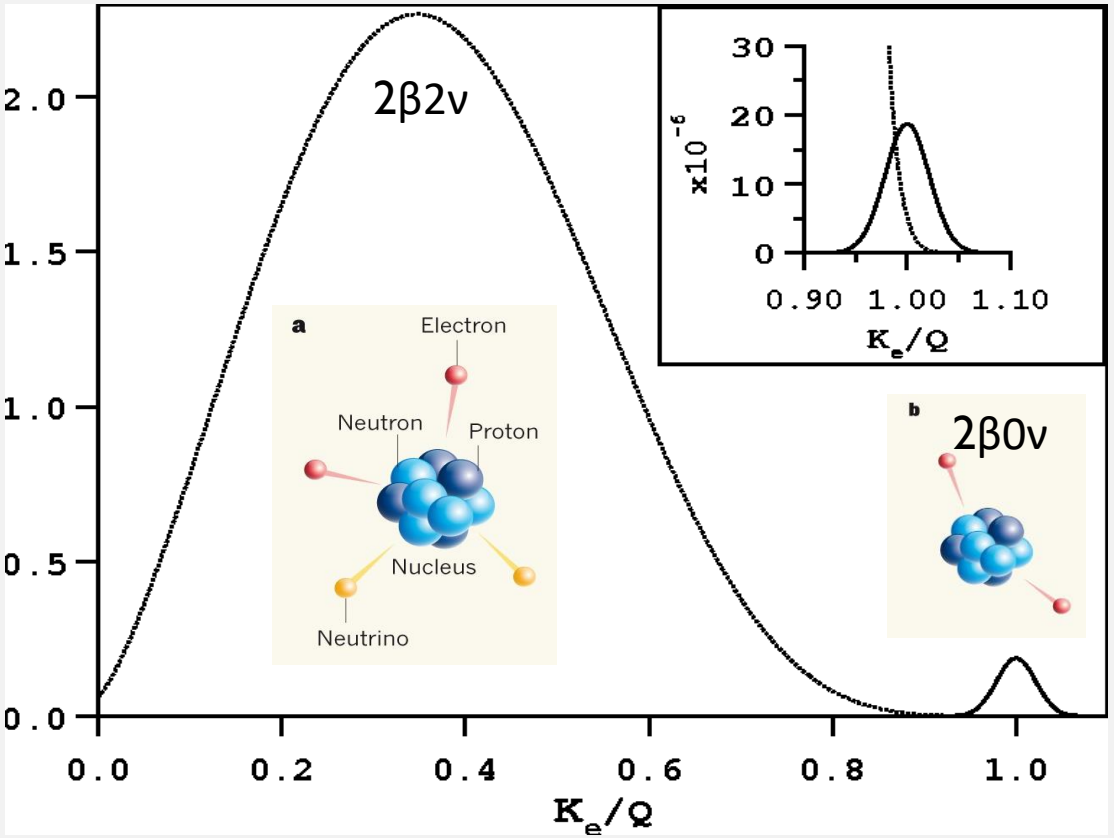
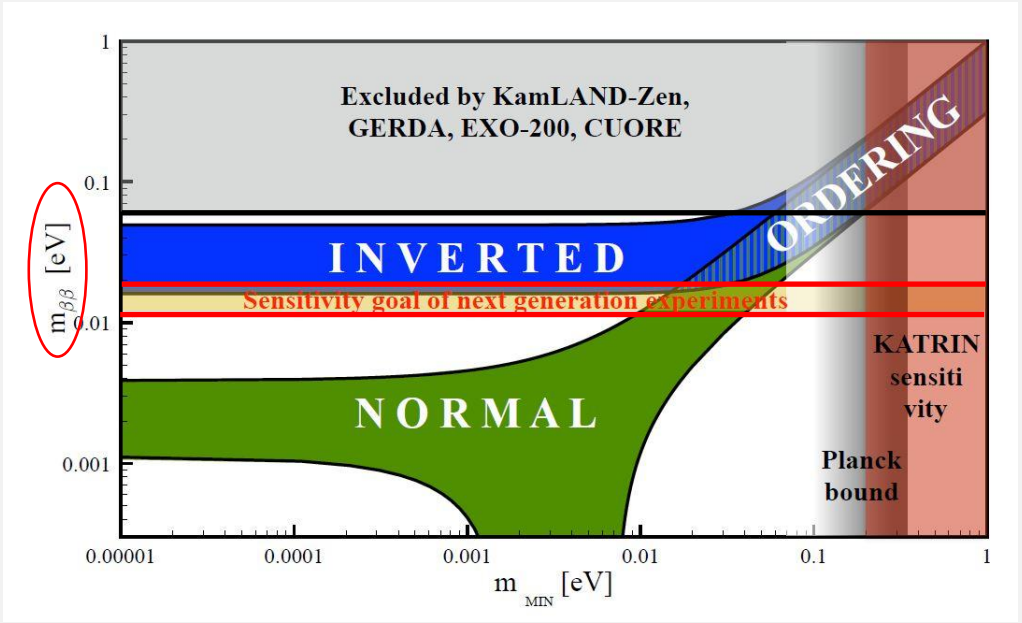
REMINDER : SEARCHING FOR 2β0ν

- An hypothetical decay : $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- Leads to a peak in the sum of e^- energy spectrum
  - Violates the lepton number conservation
- Could prove the Majorana nature of the neutrino ($\nu = \bar{\nu}$)
  - Gives clues about matter/antimatter asymmetry and information on mass hierarchy



An experimental challenge :

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

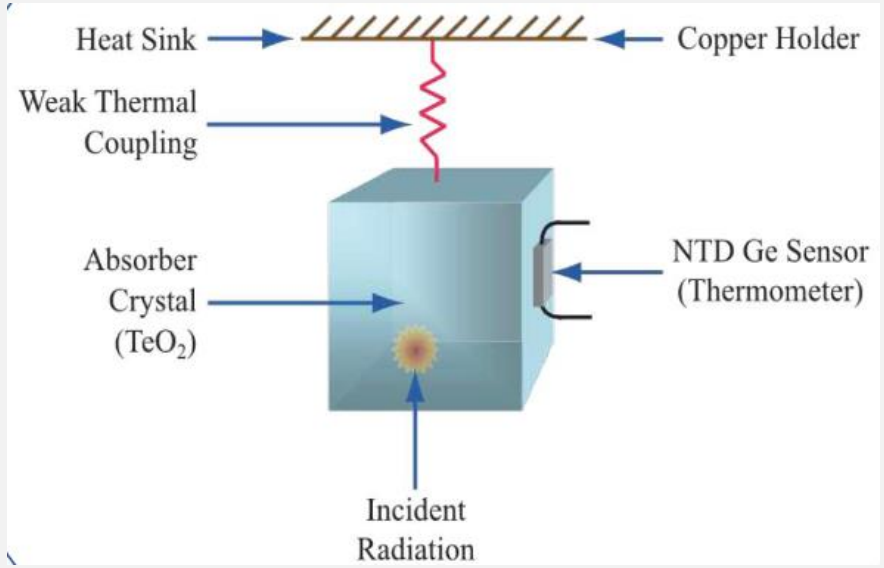


- An extremely rare decay : $T_{1/2}^{0\nu} > 10^{25} - 10^{26}\ yr$
- 35 isotopes able to do the 2β2ν, observed for 12
  - Requires almost 0 background event in the ROI

$$T_{1/2}^{0\nu} \propto a \times \epsilon \times \sqrt{\frac{M \times t}{b \times \Delta E}}$$

REMINDER : How to detect the 2β0ν ? The example of CUORE

The bolometric technique



- Cryogenic detectors : $\Delta T = \frac{E}{C}$ working around 15 mK
- Detector = source

Ideal for 2β0ν search because of :

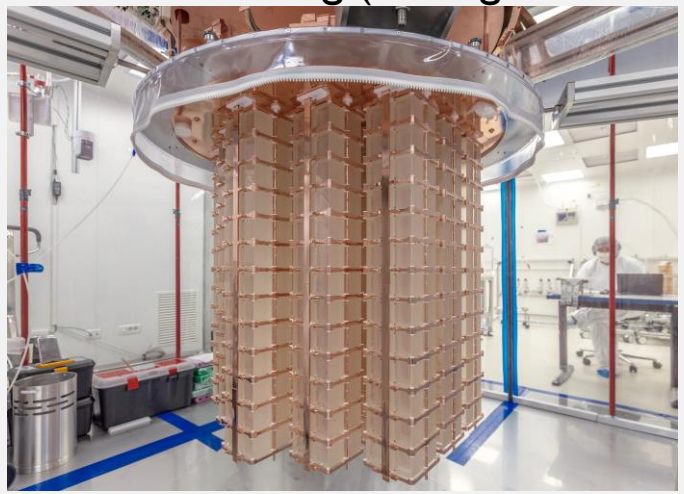
- High energy resolution (<5 keV FWHM in the ROI)
- Large masses achievable by using an array of crystals
- High detection efficiency (80-90%)
- Large isotope choice for the absorber among the 2β0ν candidates

CURRENTLY USED IN

The CUORE experiment in LNGS

2β0ν candidate : ^{130}Te ($Q_{\beta\beta} = 2527\ keV$)

- The LARGEST bolometric experiment ever :
988 5x5x5cm crystals of TeO_2 arranged in 19 towers
Total mass : 742 kg (206 kg of ^{130}Te)



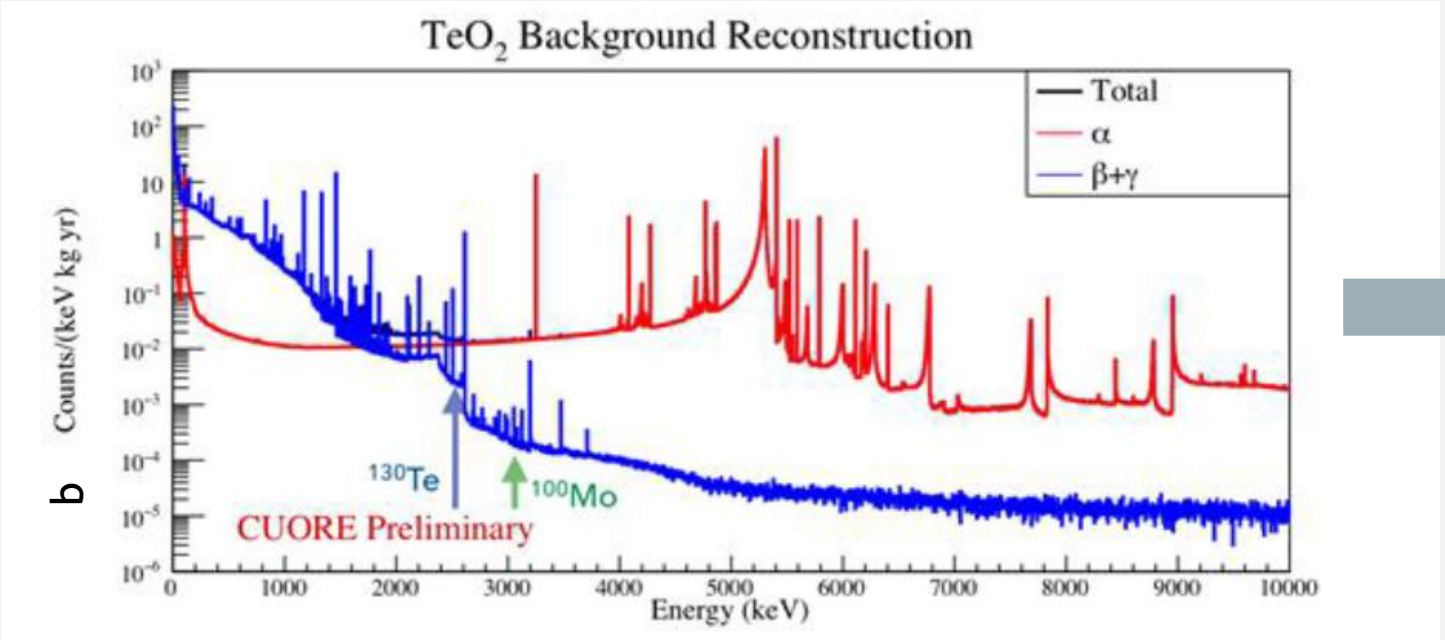
- One of the MOST SENSITIVE current experiment :
Current limit : $T_{1/2}^{0\nu} > 2.2 \times 10^{25}\ yr$
$\rightarrow\ m_{\beta\beta} < 90 - 305\ meV$
Expected limit after 5 years : $T_{1/2}^{0\nu} > 9 \times 10^{25}\ yr$
$\rightarrow\ m_{\beta\beta} < 60 - 280\ meV$

«High sensitivity neutrinoless double-beta decay search with one tonne-year of CUORE data», CUORE Collaboration, arXiv:2104.06906v1 [nucl-ex] 14 Apr 2021

Performances and limitations of CUORE

- CUORE has proven that a ton-scale experiment is technically possible using bolometers.
- The cryostat holding the experiment shows excellent performances and a really good stability overtime.
- An energy resolution of ~7 keV FWHM is reached in the ROI, so really close to the objective.

- BUT ~50 background counts/year in the ROI, corresponding to b~$10^{-2} ckky$
- Dominated by surface α events + $Q_{\beta\beta}$ of ^{130}Te < 2615 keV
- = Sensitivity limited by the background index



Necessity of an UPDATE to fully explore the inverted hierarchy region :

- Particle identification for α events rejection with **luminescent bolometers**
  - New isotope : ^{100}Mo

($Q_{\beta\beta}$ = 3034 keV > 2615 keV)

=

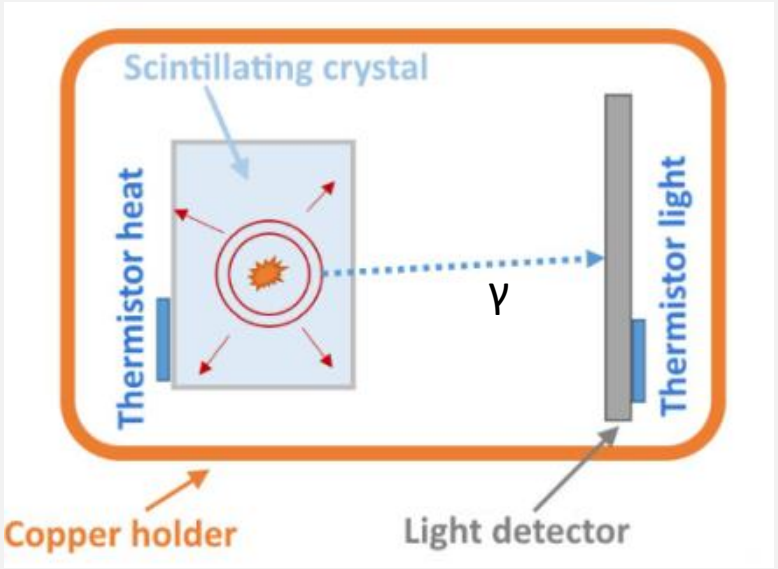
CUPID :

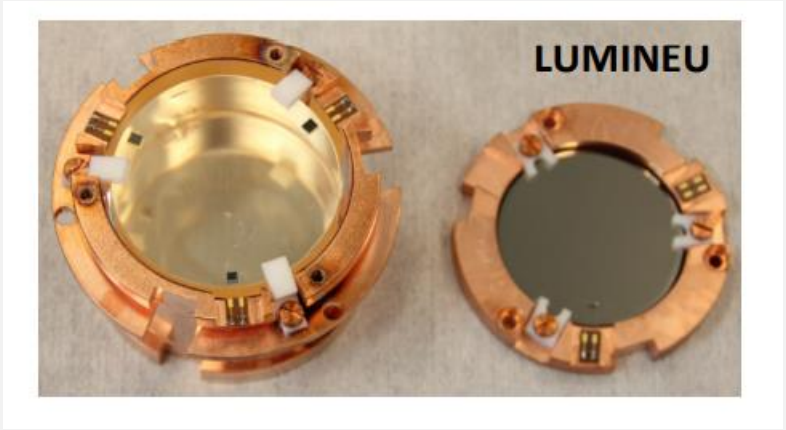
Use of the already existing CUORE infrastructure but with both those improvements (b<10^{-4} ckky achievable)

FROM CUORE TO CUPID : Luminescent bolometers and isotope choice

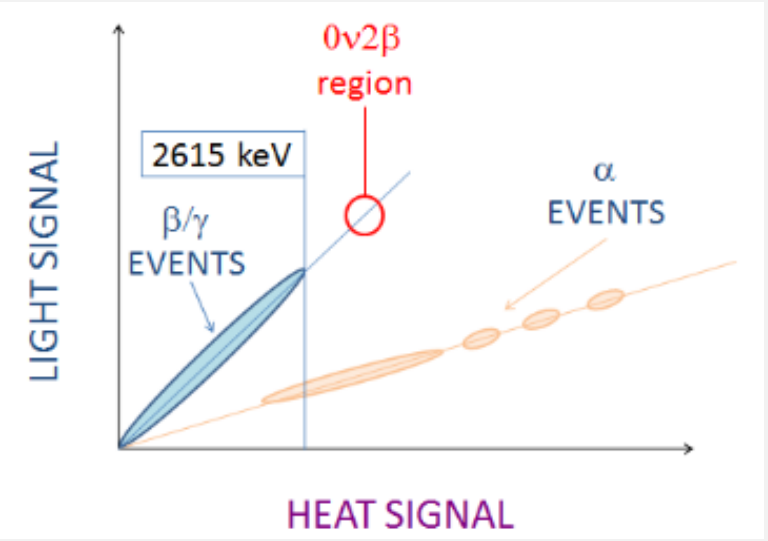
Luminescent bolometers

- Scintillator used for the absorber
- Add of an auxilary Ge bolometer, acting as a scintillation light detector
- Two signal channels : light + heat → dual read-out





Example of a luminescent bolometer with its bolometric light detector (LUMINEU EXPERIMENT)

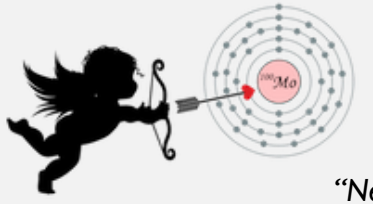


Allows to reject >99% of α events ! <u>No more α background</u>

First demonstrator using this technique : CUPID-0 with ZnSe crystals at LNGS

+ isotope choice : ^{100}Mo ($Q_{\beta\beta} = 3034\ \mathrm{keV} > 2615\ \mathrm{keV}$) <u>γ background reduced + easier to enriched</u>

Tested and validated by CUPID-Mo using Li_2MoO_4 crystals at LSM



New world best limit on ^{100}Mo : $T_{1/2}^{0\nu} > 1{,}5.10^{24}\ yr$ with only 2.34 kg of ^{100}Mo !!

+ an excellent energy resolution : ~5-7 keV FWHM

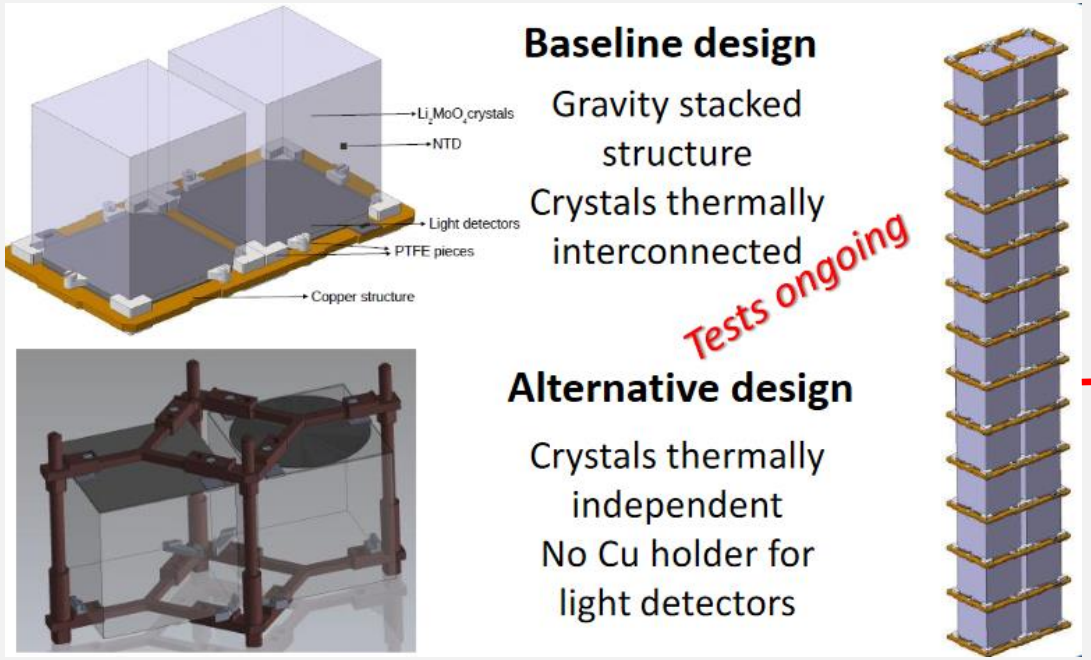
"New Limit for Neutrinoless Double-Beta Decay of 100Mo from the CUPID-Mo Experiment", CUPID-Mo Collaboration, Phys. Rev. Lett. 126, 3 May 2021

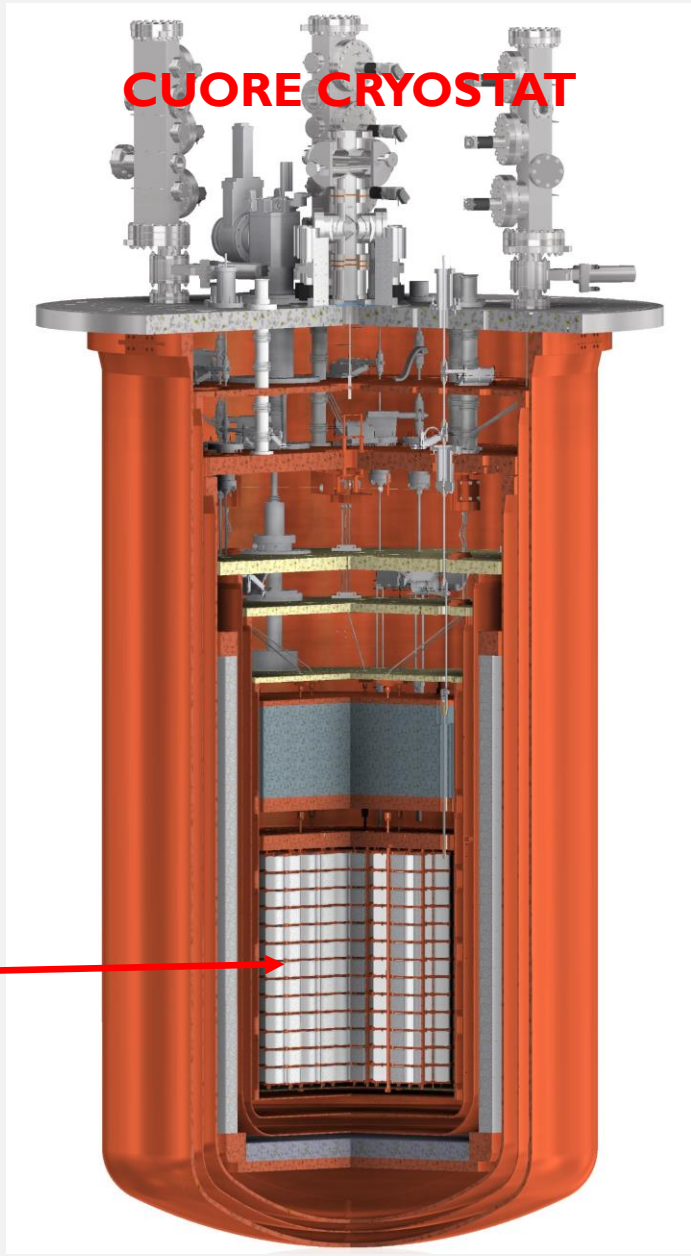
The CUPID configuration

- Use of the CUORE cryostat at LNGS (available in ~2024)

- **1596** 45x45x45mm Li_2MoO_4 crystals of ~280g each
  - Arranged in 57 towers of 14 floors
  - Total mass : **~240 kg** of ^{100}Mo thanks to a >95% enrichment

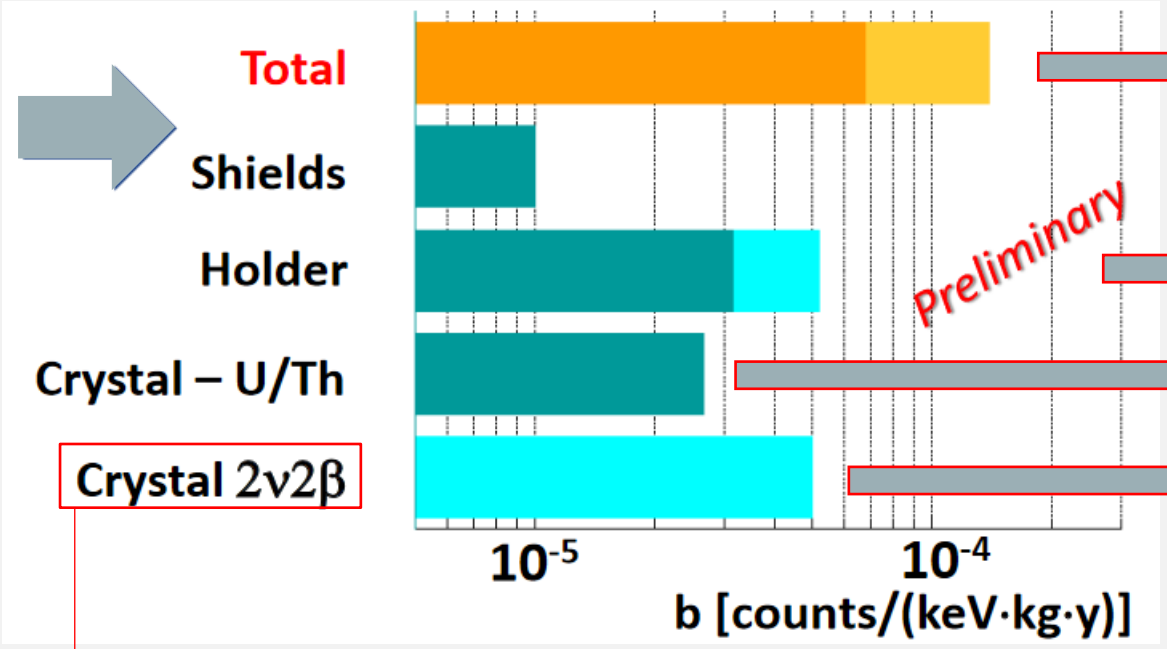
- SEVERAL TESTS DONE AND ON GOING FOR THE BASELINE DESIGN :





CUPID BACKGROUND MODEL

Using the results and acquired knowledge from CUORE and CUPID R&D demonstrators :



Total around **b~10^{-4}** $ckky$ for the baseline design

Depends on the structure and on the design

Well known thanks to CUPID-Mo

Due to ^{100}Mo « fast » 2β2ν decay ($T_{1/2}^{2\nu} = 7.1 \times 10^{18}\ yr$)

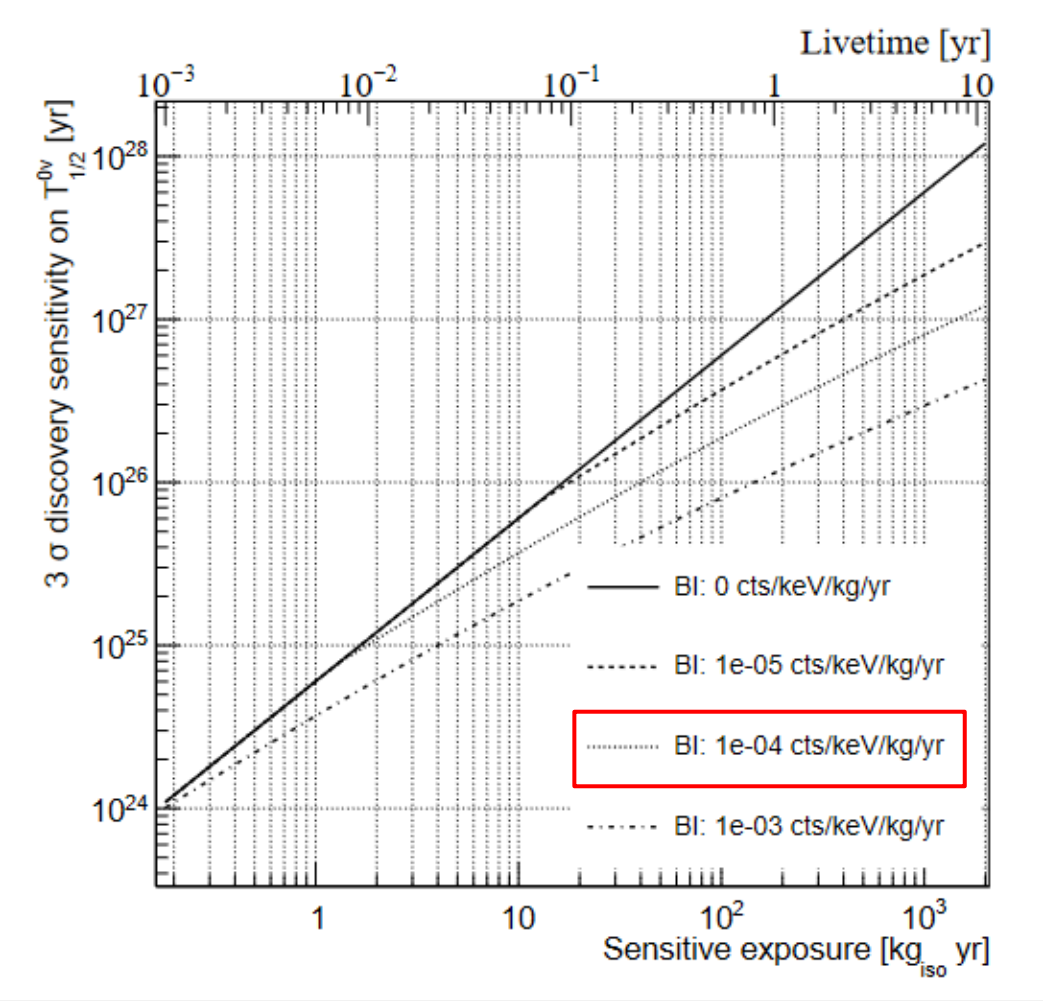
\+ * Neutron background : b<10^{-5}ckky,

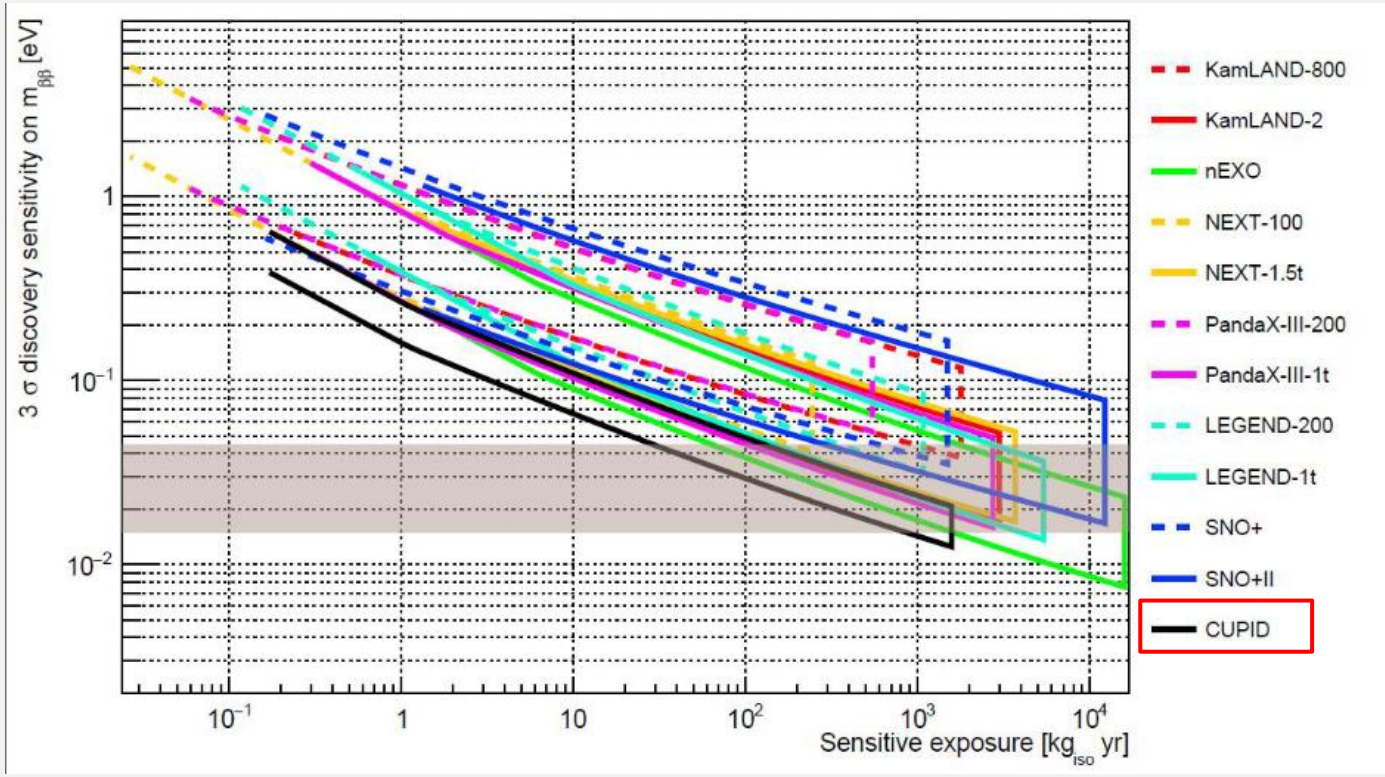
* Muon background : b~$10^{-4} ckky$, can be reduced with a veto

* Random coïncident 2ν2β events :
Once again due to ^{100}Mo « fast » 2β2ν decay → Approximately b~$3.10^{-4} \times \tau[ms]\ ckky$ with τ the temporal resolution between 2 signals.

WORK **IN PROGRESS** TO IMPROVE τ : Increase sampling rate, reduce baseline noise, new rejection parameters, exploit the light channel.. + Offline rejection → Last results : 90% rejection efficiency for PU with $\Delta t > 2ms$

CUPID sensitivity and discovery potential





With b=10^{-4}ckky, 5 keV FWHM in the ROI and a 10 years exposure :

Half-life 3σ discovery sensitivity :

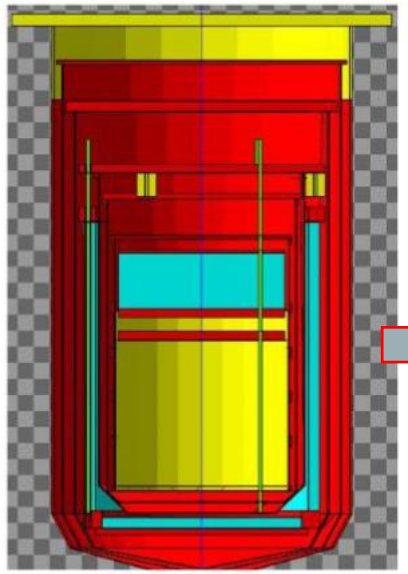
$$T^{0\nu}_{1/2} > 1.10^{27}\ yr \rightarrow m_{\beta\beta} < 12 - 20\ meV$$

ONE of the most promising next generation experiment !!

CUPID : What's next ?

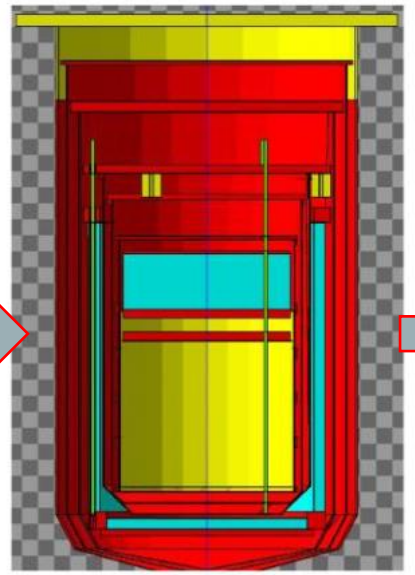
TECHNICALLY READY

CUPID Baseline



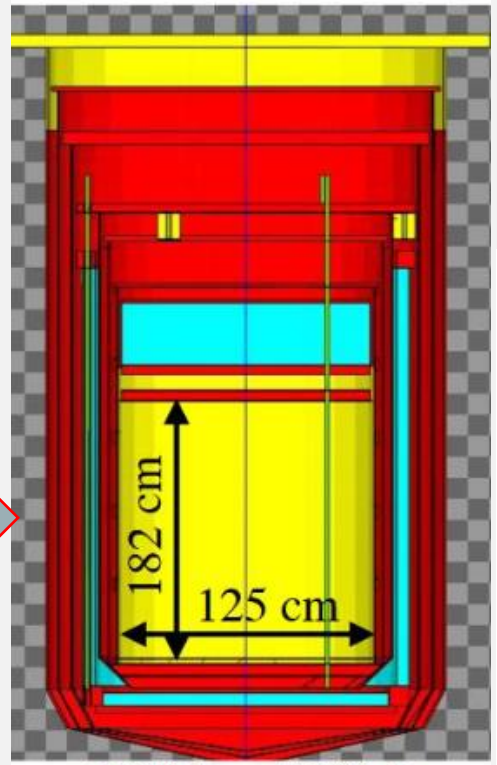
250 kg of ^{100}Mo
CUORE cryostat
Bkg 1×10^{-4} ckky
Excl. sensitivity:
$T_{1/2} > 1.4 \times 10^{27}$ y

CUPID-reach

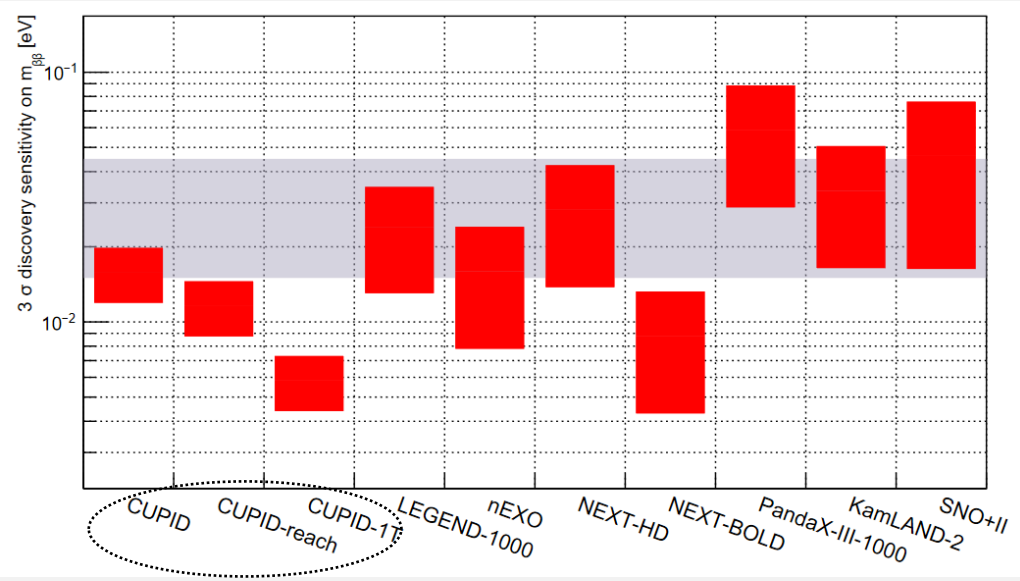


250 kg of ^{100}Mo
CUORE cryostat
Bkg 2×10^{-5} ckky
Excl. sensitivity:
$T_{1/2} > 2.2 \times 10^{27}$ y

CUPID-1T



1000 kg of ^{100}Mo
New cryostat
Bkg 5×10^{-6} ckky
Excl. sensitivity:
$T_{1/2} > 9.1 \times 10^{27}$ y



CONCLUSION AND SUMMARY

- CUPID is one of the **most promising next generation experiment** for the 2β0ν search thanks to the bolometers

- The first phase is **technically ready** : Li_2MoO_4 are well known and it is proven that they fulfill the requirements of CUPID (excellent energy resolution, mass production, radiopurity, good light yield for α rejection…)

- **The cryogenic infrastructure already exists** and is well-tested and optimized since it is used for CUORE

- **A background index of 10^{-4} $ckky$** expected in the ROI with a robust background model

- **Cost effective**

- Aims to **fully explore the inverted mass hierarchy** region of neutrino masses

REFERENCES

1. A. Armatol et al. [CUPID Collaboration], *Characterization of cubic $Li_2{}^{100}MoO_4$ crystals for the CUPID experiment*, Eur.Phys.J.C **81**, 104 (2021)
https://doi.org/10.1140/epjc/s10052-020-08809-8

2. A. Armatol et al. [CUPID and CROSS Collaborations], *A CUPID $Li_2{}^{100}MoO_4$ scintillating bolometer tested in the CROSS underground facility*, JINST **16**, P02037 (2021);
https://doi.org/10.1088/1748-0221/16/02/P02037

3. [CUPID Collaboration], A novel technique for the study of pile-up events in cryogenic bolometers
https://arxiv.org/abs/2011.11726

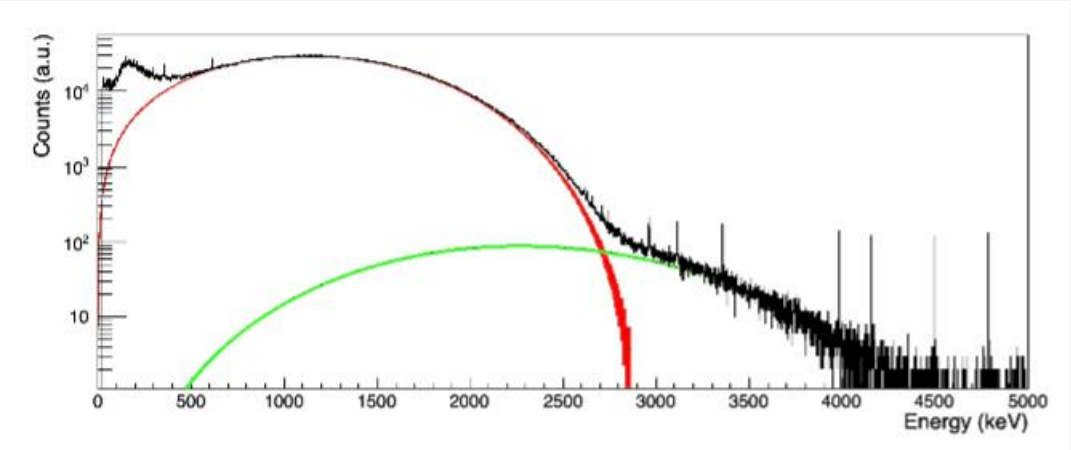
4- CUPID pre-CDR: https://arxiv.org/abs/1907.09376

CEA is looking for a POST-DOC in the CUPID group !!

Contact claudia.nones@cea.fr for more infos

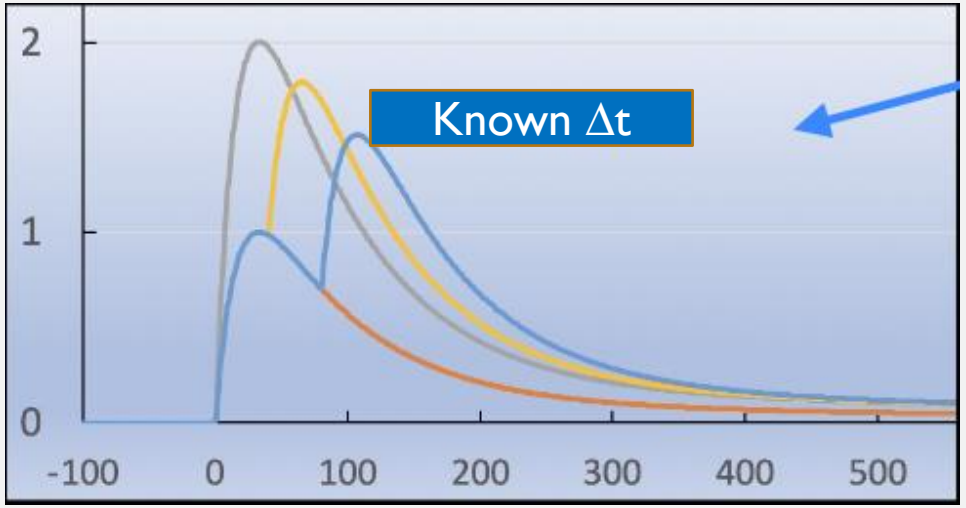
BACK UP SLIDE : PILE UPS REJECTION

BRUT FORCE METHOD



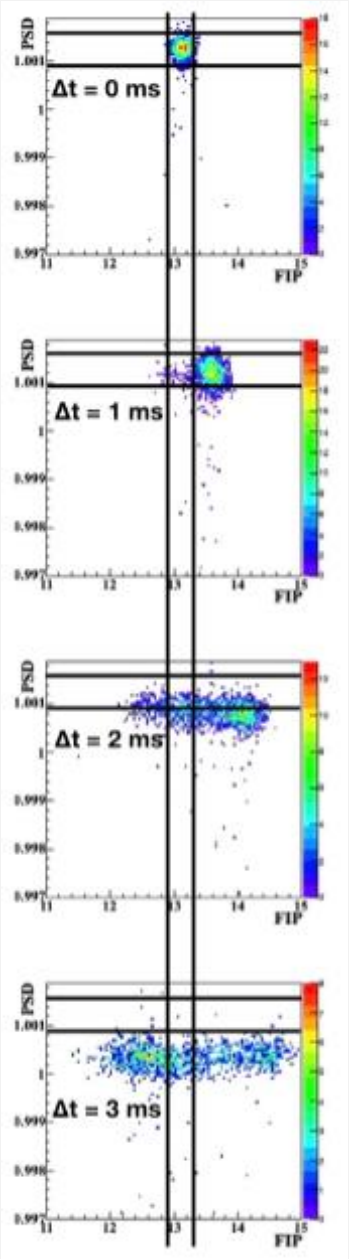
- Injecting mean pulses on a background from a real measurement in Canfranc
- Simulate a x70 decay rate (0.2Bq) and ~7 years of data taking (1.8 To)
- The PU spectrum is appearing, allows to apply cuts and to test rejection efficiency
- Obtain the b[ckky] by normalizing the spectrum

SURGICAL METHOD



- Draw two energies in the DBD spectrum for a sum energy at the $Q_{\beta\beta} \pm 50\ keV$ value
- Build a PU event with a known Δt
- Inject the PU on a real background
- Test cut for each Δt
- Obtain the b[ckky]

BACK UP SLIDE : PILE UPS REJECTION



2 parameters combined are showing a good rejection efficiency : PSD and Fast Integral (FI)

With BRUT FORCE method :

3σ cut -> b=$2.8 \times 10^{-4}\ ckky$ 95 % DBD acceptance

2σ cut -> b=$1.8 \times 10^{-4}\ ckky$ 90 % DBD acceptance

With SURGICAL method :

3σ cut -> b=$2.6 \times 10^{-4}\ ckky$ 95 % DBD acceptance

2σ cut -> b=$1.6 \times 10^{-4}\ ckky$ 87 % DBD acceptance

The two methods give similar results !!

Δt (ms)	0.0	0.1	0.2	0.3	0.4	0.5	1.0	1.5	2.0	2.5	3.0
PSD cut	0.91	0.91	0.87	0.84	0.88	0.90	0.83	0.63	0.28	0.03	0.005
FIP cut	0.94	0.95	0.84	0.69	0.59	0.55	0.06	0.08	0.16	0.18	0.14
PSD + FIP	0.87	0.86	0.75	0.58	0.52	0.49	0.05	0.04	0.05	0.003	0.0007