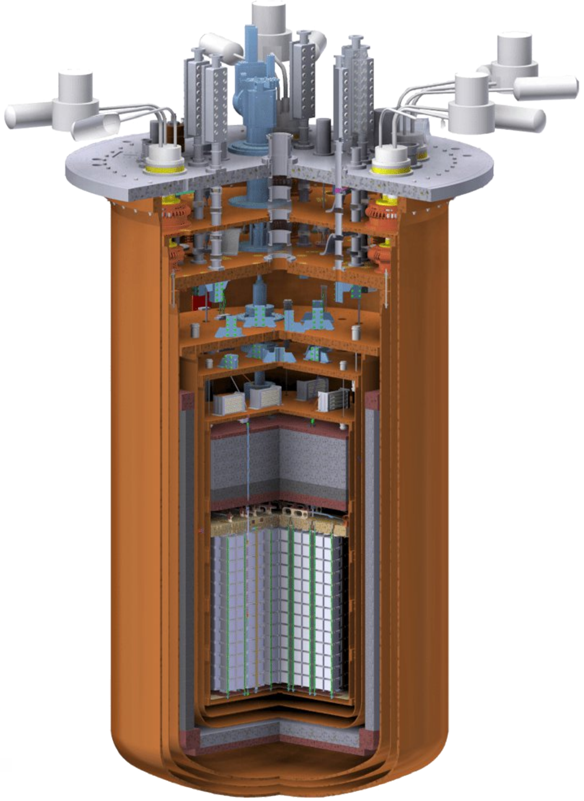
Sensitivity of the CUPID experiment

Pía Loaiza, on behalf of the CUPID collaboration

TAUP 2025, Xichang, China



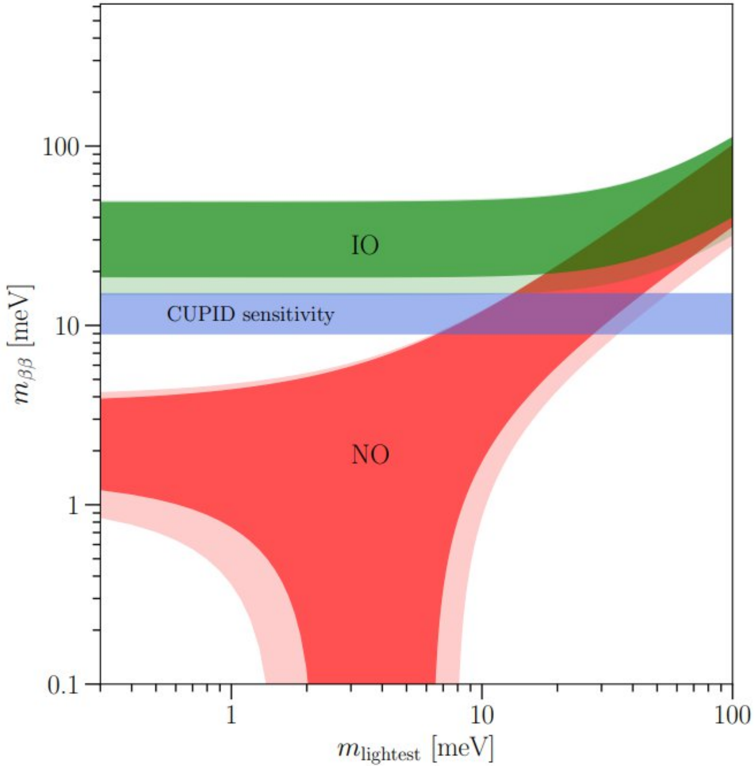
IJCLab, CNRS/IN2P3 Université Paris Saclay

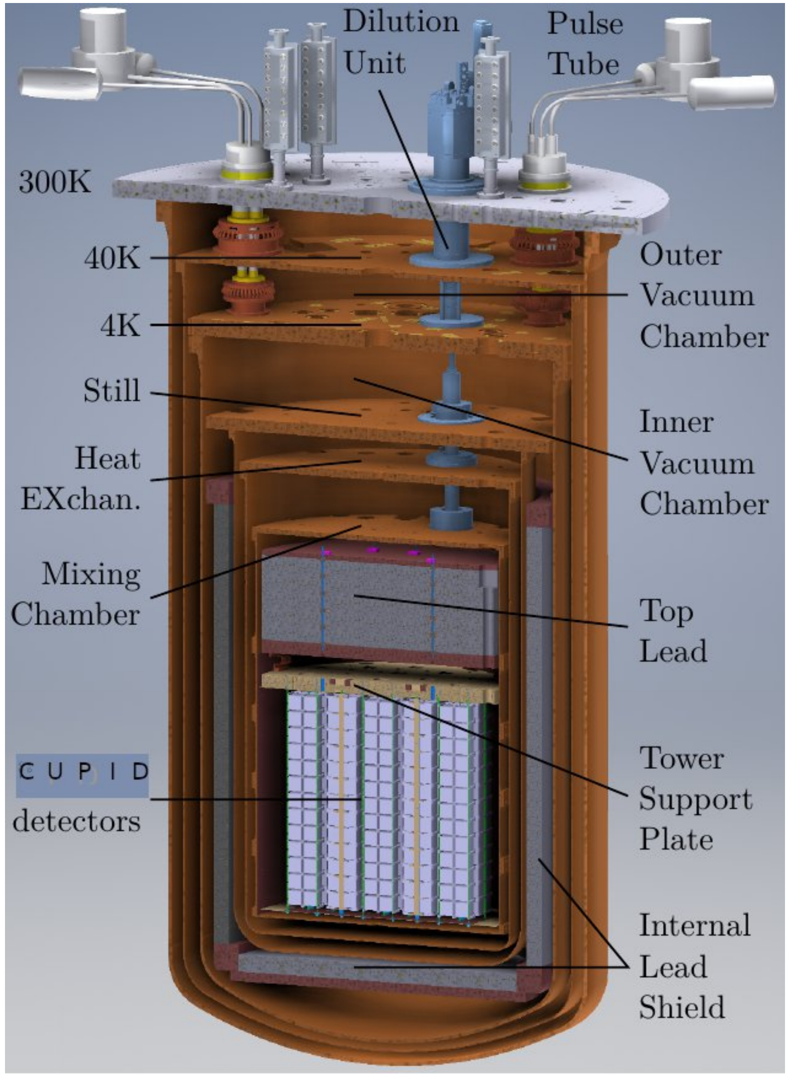
CUPID

CUORE Upgrade with Particle IDentification

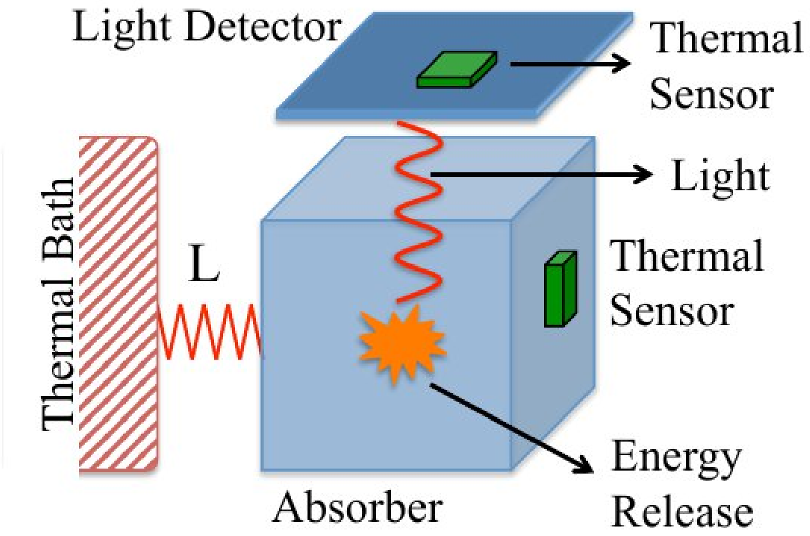
Irene Nutini's talk
#NAP 1A

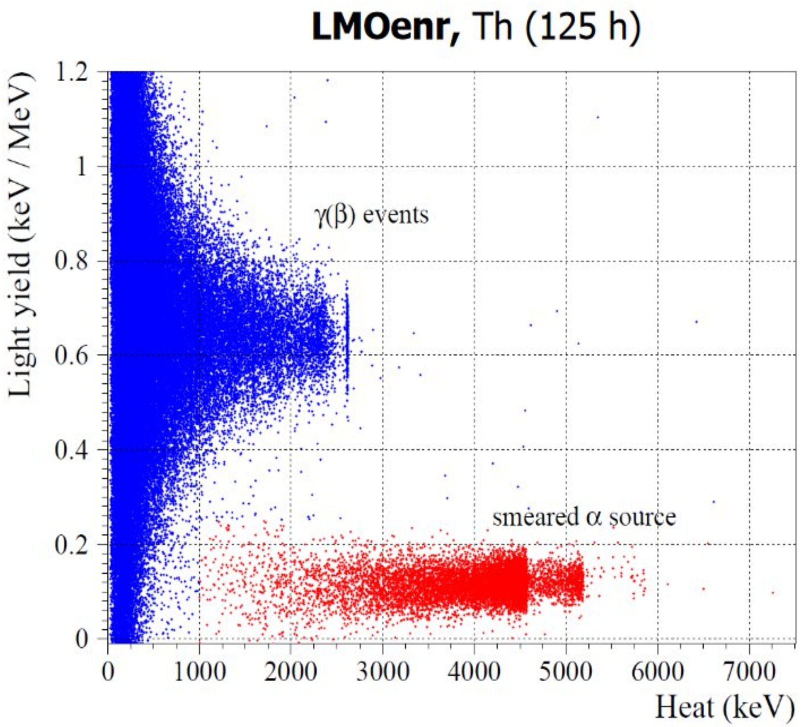
- Near future bolometric $0\nu\beta\beta$ experiment in existing CUORE infrastructure at LNGS
- Li_2MoO_4 scintillating bolometers, ^{100}Mo ($Q_{\beta\beta}$ = 3034 keV)
- Fully explore Inverted-Ordering and part of Normal Ordering region





Scintillating bolometers





- Heat and light detection allows α rejection > 99.7%

CUPID detectors

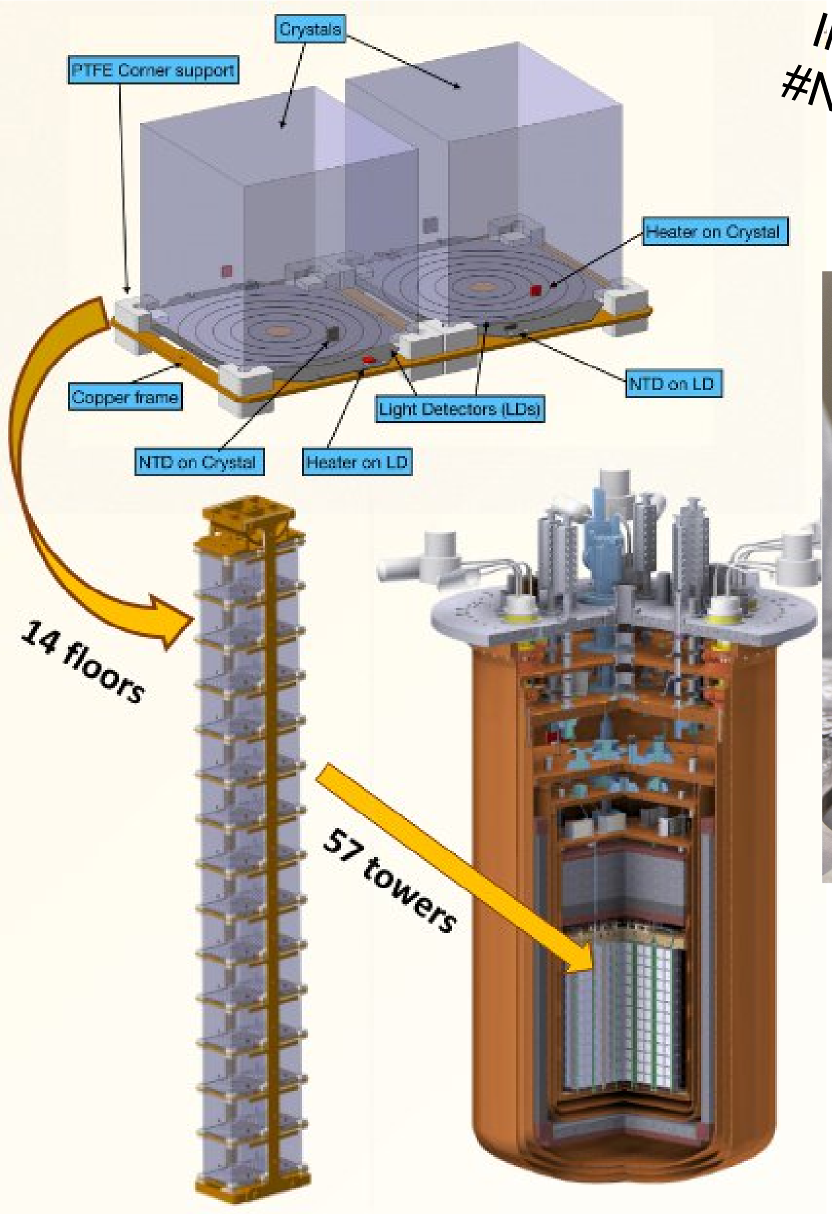
- 450 kg Li_2MoO_4
- 240 kg ^{100}Mo (95% enrichment)
- 57 towers, each with 14 x 2 crystals
- Two light detectors for each crystal
  - 1596 Li_2MoO_4 crystals
  - 1710 Ge NTL Light Detectors

Physics goal:

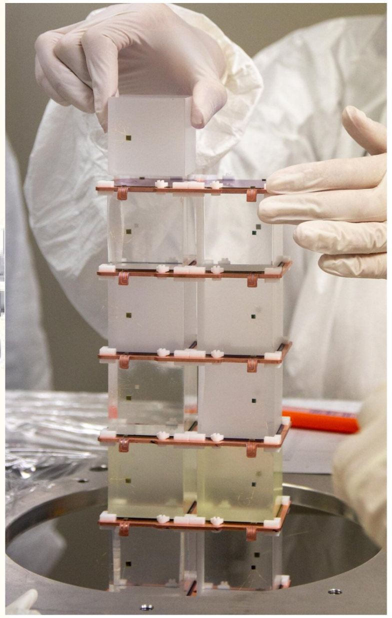
- $\tau_{1/2} \sim 10^{27}$ years $\rightarrow$ discovery in $m_{\beta\beta} \sim 10$ meV

Requires:

- Background Index: $1.0 \cdot 10^{-4}$ counts/(keV·kg·y)
- Energy resolution: 5 keV FWHM at $Q_{\beta\beta}$
- 10 years livetime



Irene Nutini's talk
#NAP 1A



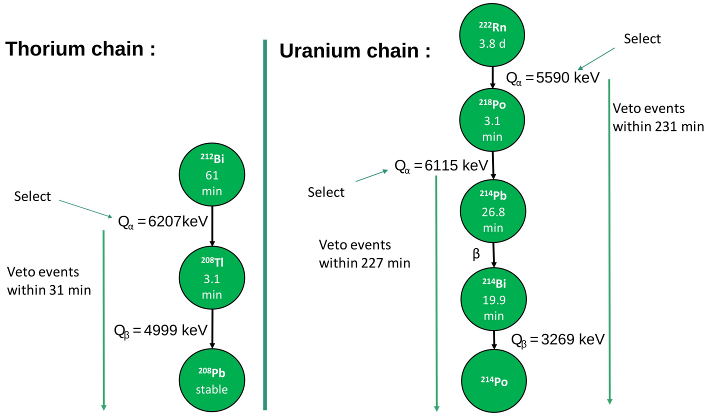
Prototype tower

M. Girola's talk
#UL 5

Can we do it?

Background projections from CUORE and CUPID-Mo background models and detailed simulations:

1. GEANT-4 simulations: implemented detailed geometry of CUORE cryostat and detector towers according to baseline design
2. Simulate detector response: energy resolution, light yield, NTL light detector response in light and ionization
3. Selection cuts:
   - Light yield: remove α particles
   - Delayed coincidences: remove events from ^{214}Bi and ^{208}Tl decays



   - Events with energy deposit in only one crystal

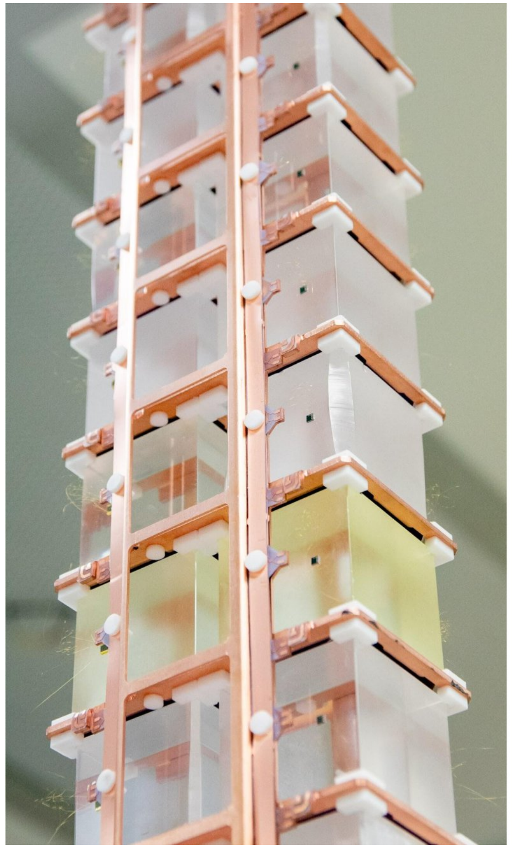
Select events in ROI: (3034 ± 15) keV
(avoid 3000 keV and 3053 keV γ's from ^{214}Bi)

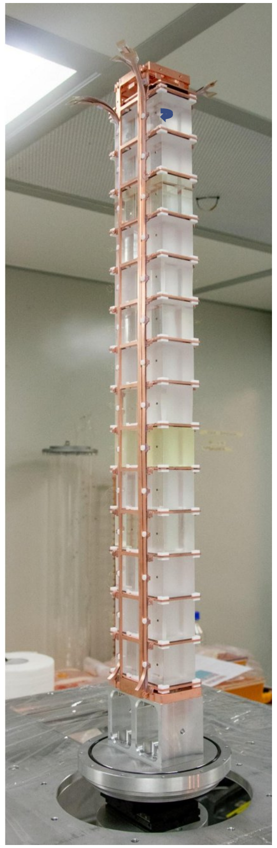
GEANT-4 renderings of the CUPID detector geometry

Background sources

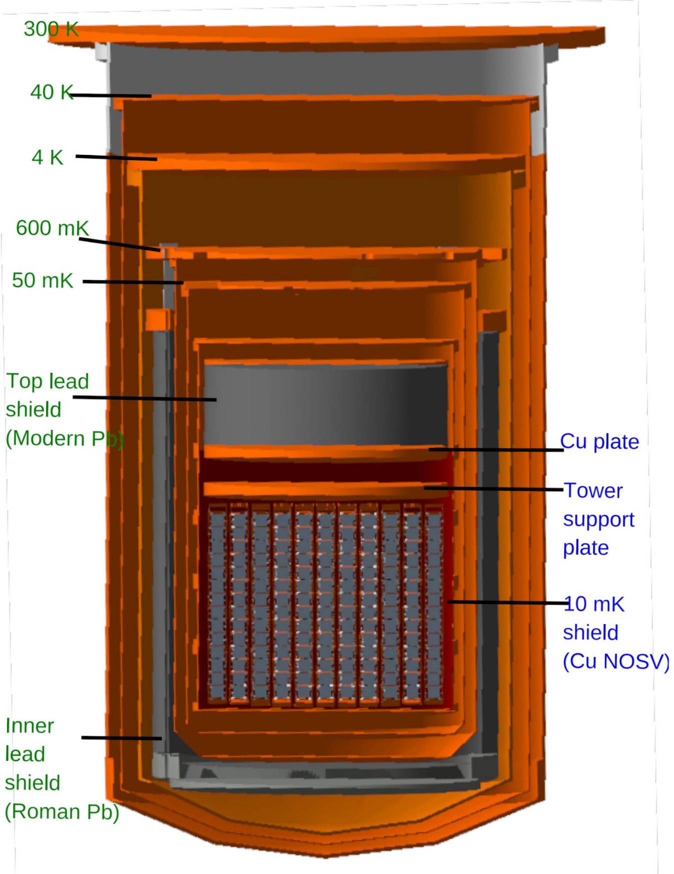
From radioactivity

- Crystals
- Holders: Cu frames, PTFE supports, CuPEN readout





- 10 mK components
- Cryostat shields and infrastructure



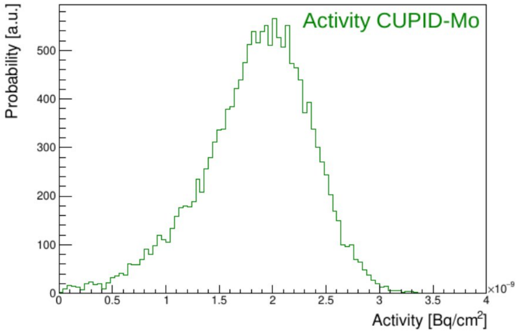
- **Muons**
- **Neutrons**
- **$2\nu\beta\beta$ pile-up**

Backgrounds from radioactivity : Method

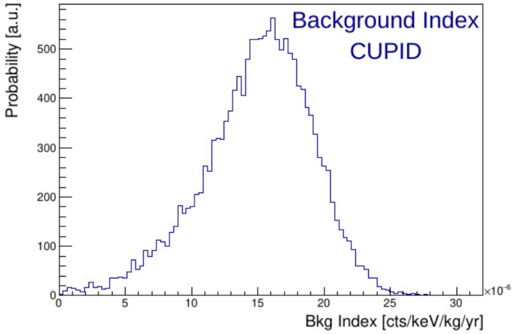
- Use probability density functions of the activities from CUORE/CUPID-Mo background models w_j
- Sample full posterior distribution for each step in the Markov Chain:

$$b_i = \sum_{j=1}^{\mathrm{Nsources}} \mathrm{Pois}(N_j) \frac{w_{i,j}}{\Delta E \times N_{gen}}$$

- Translate the activity pdf to Background index pdf using N_j and N_{gen}, the number of events in the ROI and the number of generated events from CUPID simulation



CUPID MC



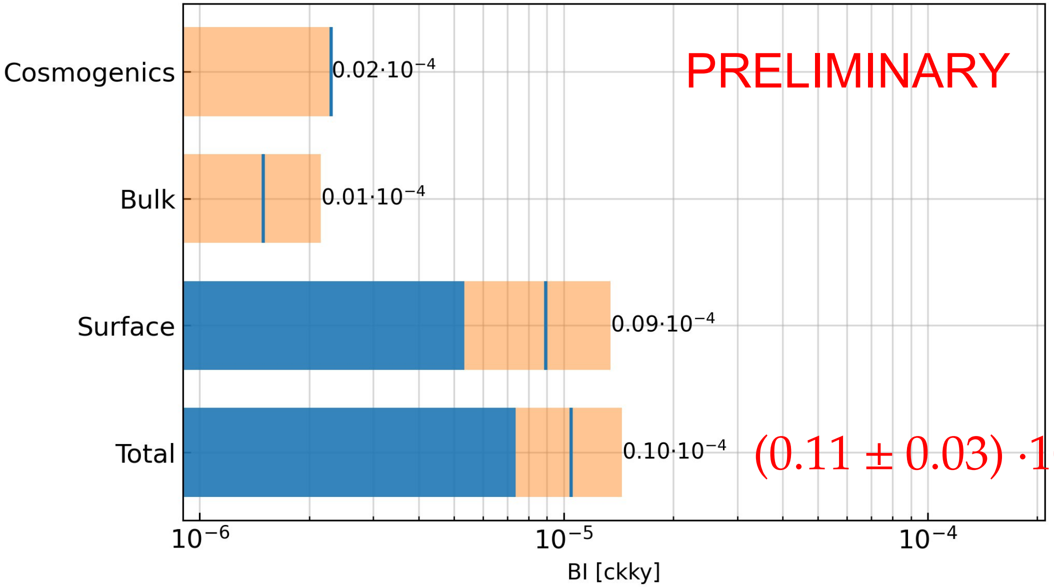
- Obtain the marginalised posterior as the mode ± smallest 68% interval

Projected background from crystals

- Probability density functions from CUPID-Mo background model `[EPJC 83, 675 (2023)]`

- ^{226}Ra/^{228}Th bulk : <0.2 μBq/kg / 0.4 ± 0.2 μBq/kg → (1.4 ± 0.6)·10^{-6} counts/(keV·kg·y)
- ^{226}Ra/^{228}Th surface: 2 ± 0.5 nBq/cm^2 / < 2.5 nBq/cm^2 → (9.0 ± 4)·10^{-6} counts/(keV·kg·y)

- Cosmogenics: 90 days at sea level and 1 year cooling down (ACTIVIA). ^{42}K, ^{82}Rb, ^{88}Y, ^{56}Co → 2.1 · 10^{-6} counts/(keV·kg·y)

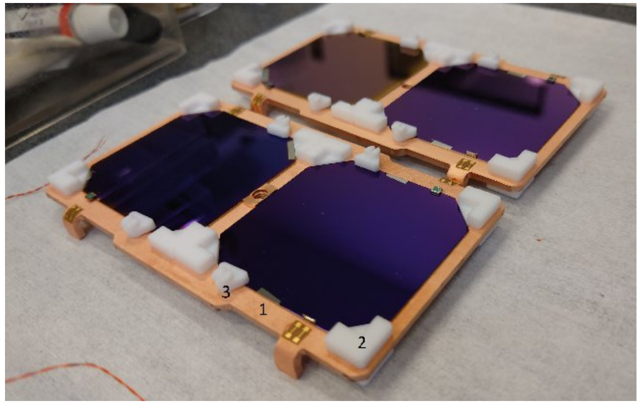


(0.11 ± 0.03) ·10^{-4} ckky

The dominant background in the ROI is the surface contamination.
Can be further decrease improving polishing and handling

Projected background from close components

- Probability density functions from CUORE background model [PRD 110, 052003(2024)]

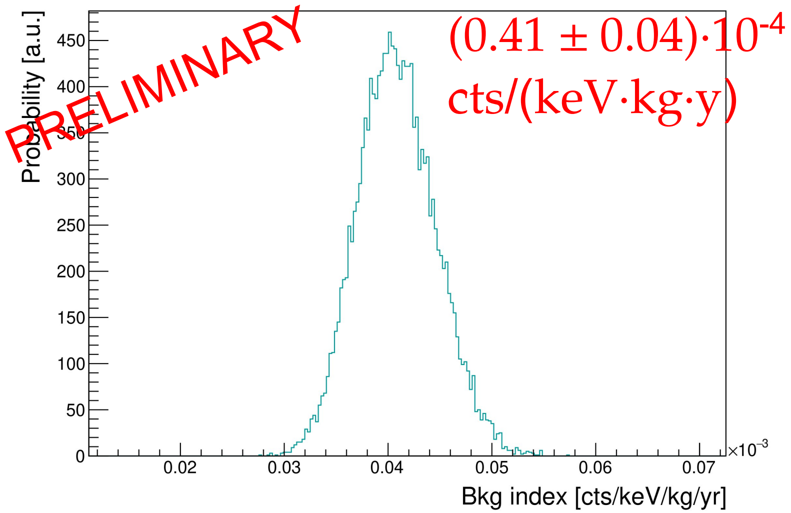


NOSV copper + PTFE spacers + CuPEN readout

- ^{226}Ra < 0.5 μBq/kg — 8.4 ± 0.7 nBq/cm^2
- ^{228}Th < 0.4 μBq/kg — 11.5 ± 0.5 nBq/cm^2

↓ Bulk — ↓ Surface

< 1.0 ·10^{-6} counts/(keV·kg·y) — (4.1 ± 0.4)·10^{-5} counts/(keV·kg·y)



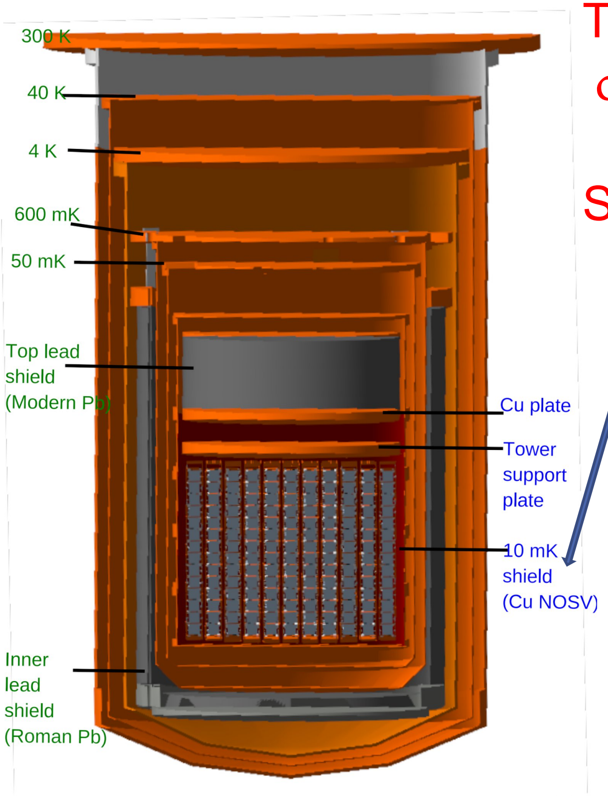
Dominated by surface copper frames.
Improvements in progress:

- Cleaner machining practices
- More effective cleaning and storage conditions

Projected background from radioactivity

Cryostat and shields

• Probability density functions from CUORE background model [PRD 110, 052003 (2024)]



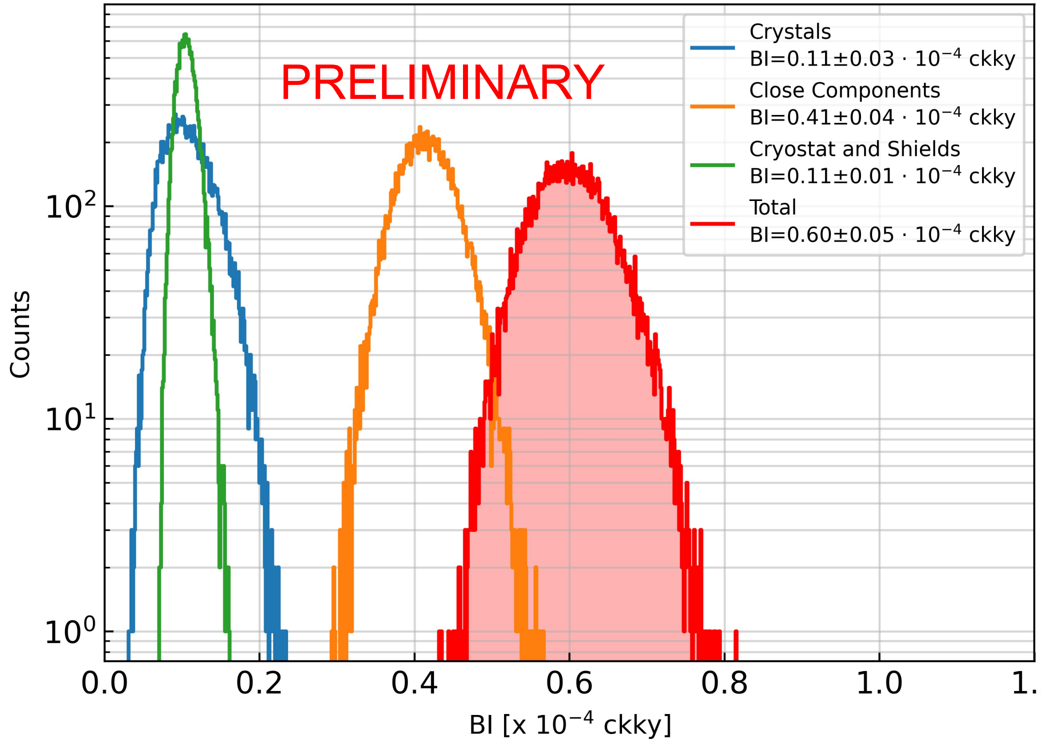
Total: $(0.11 \pm 0.01) \cdot 10^{-4}$ counts/(keV·kg·y)

Subdominant

Primary contribution ^{226}Ra and ^{228}Th on surfaces of 10 mK shield

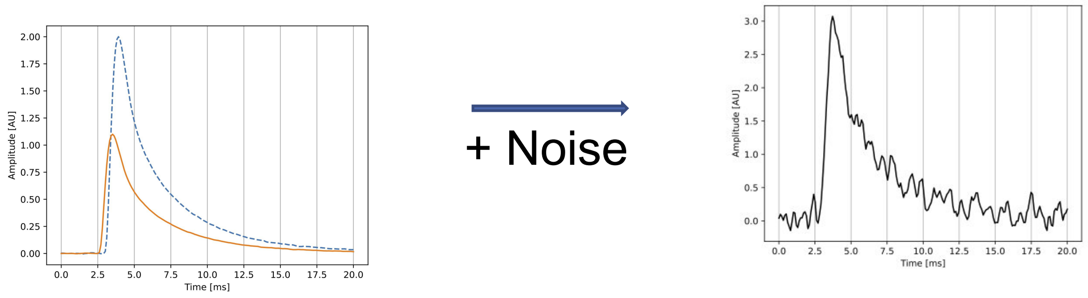
Other cryostat shields: background from bulk

Total background from radioactivity

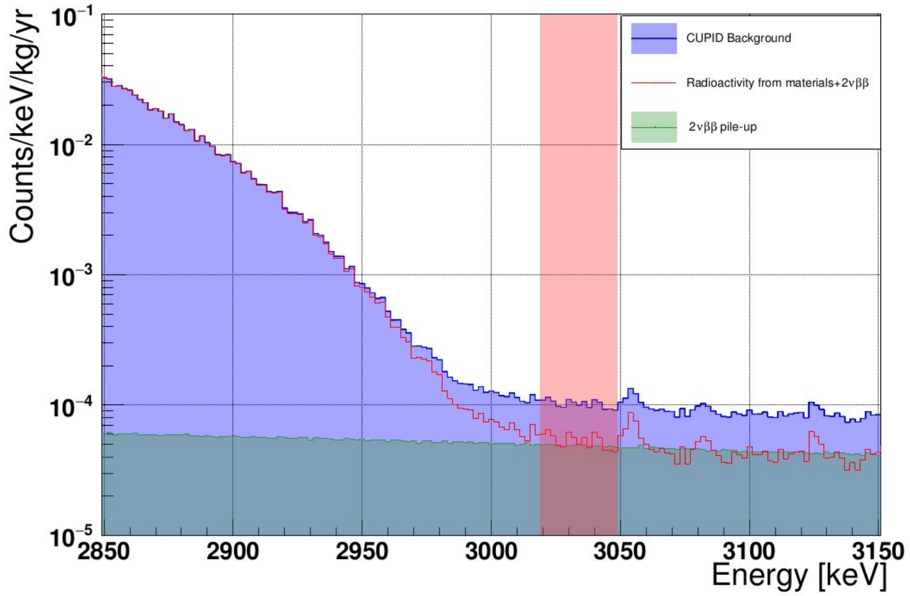


2νββ Pile-up

- Random coincidence of 2νββ decay of ^{100}Mo can populate the ROI

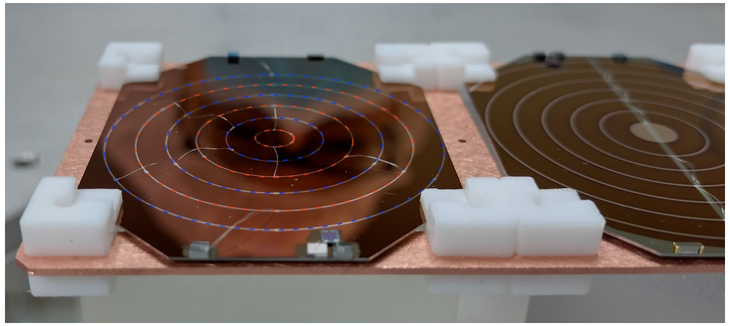


- Rejection via pulse shape analysis of Light Detector signals



Hawraa Khalife poster
ID 77

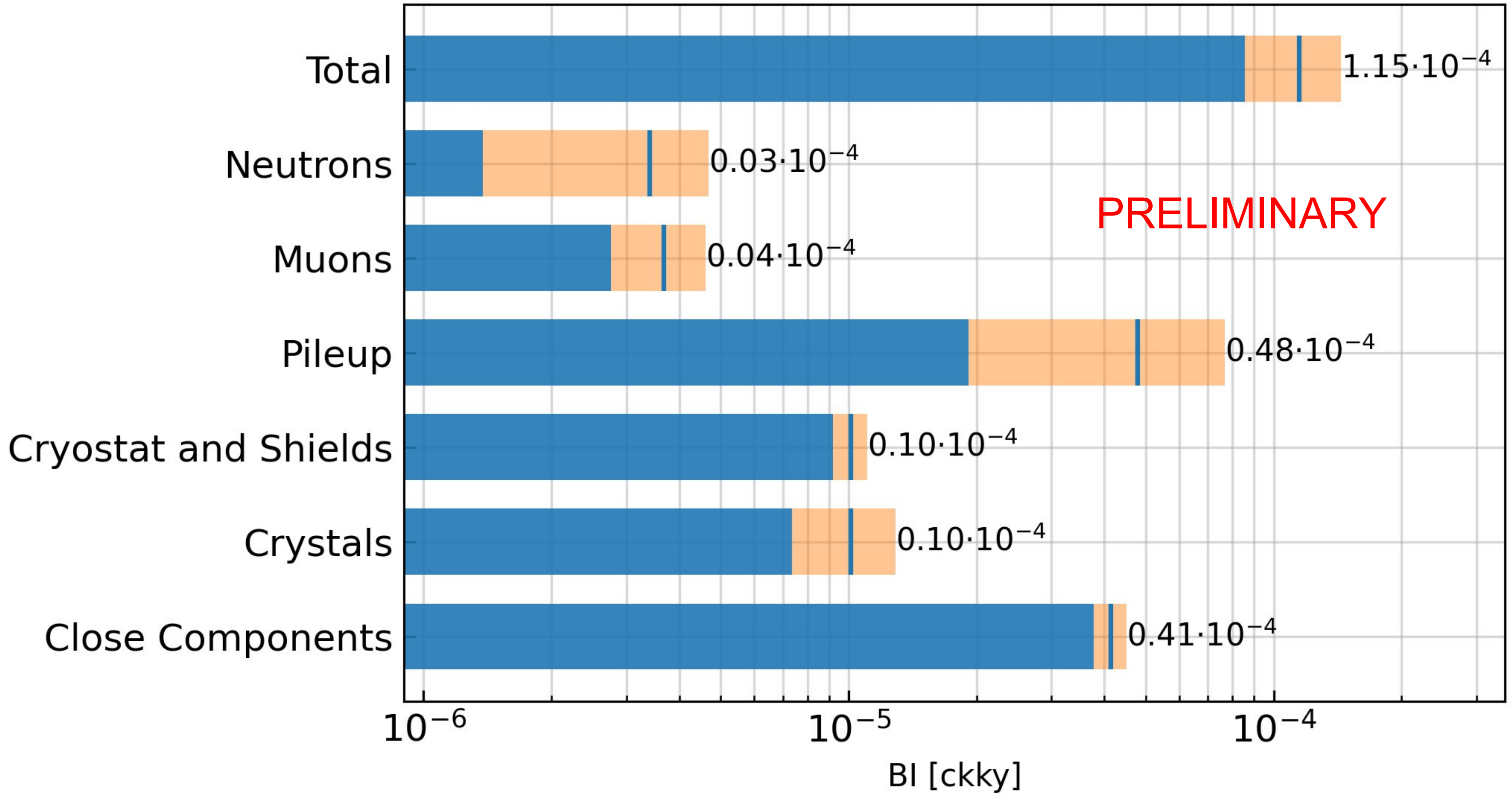
- Pulse shape cut to reject pile-up
  - Profit from faster Light Detector pulse
  - Improve Signal to Noise ratio through Neganov-Trofimov-Luke effect



- Current performances of NTL Light Detectors

→ Pile -up background ~ $0.5 \cdot 10^{-4}$ counts/(keV·kg·y)

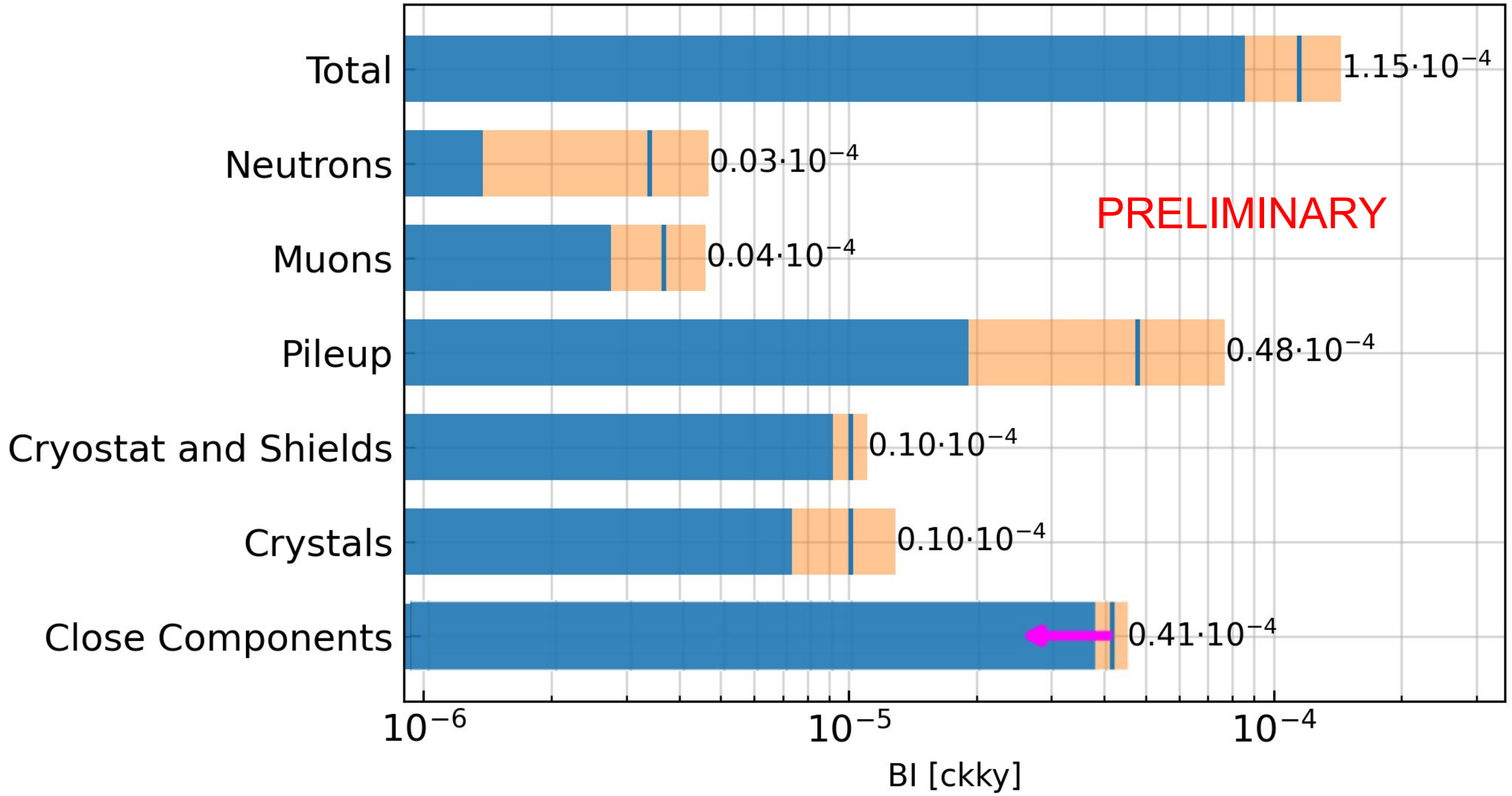
CUPID Background projection from simulations



BI = $1.15 \cdot 10^{-4}$ counts/(keV·kg·y)

68% interval =
(0.86, 1.44) · 10^{-4} counts/(keV·kg·y)

CUPID Background projection from simulations

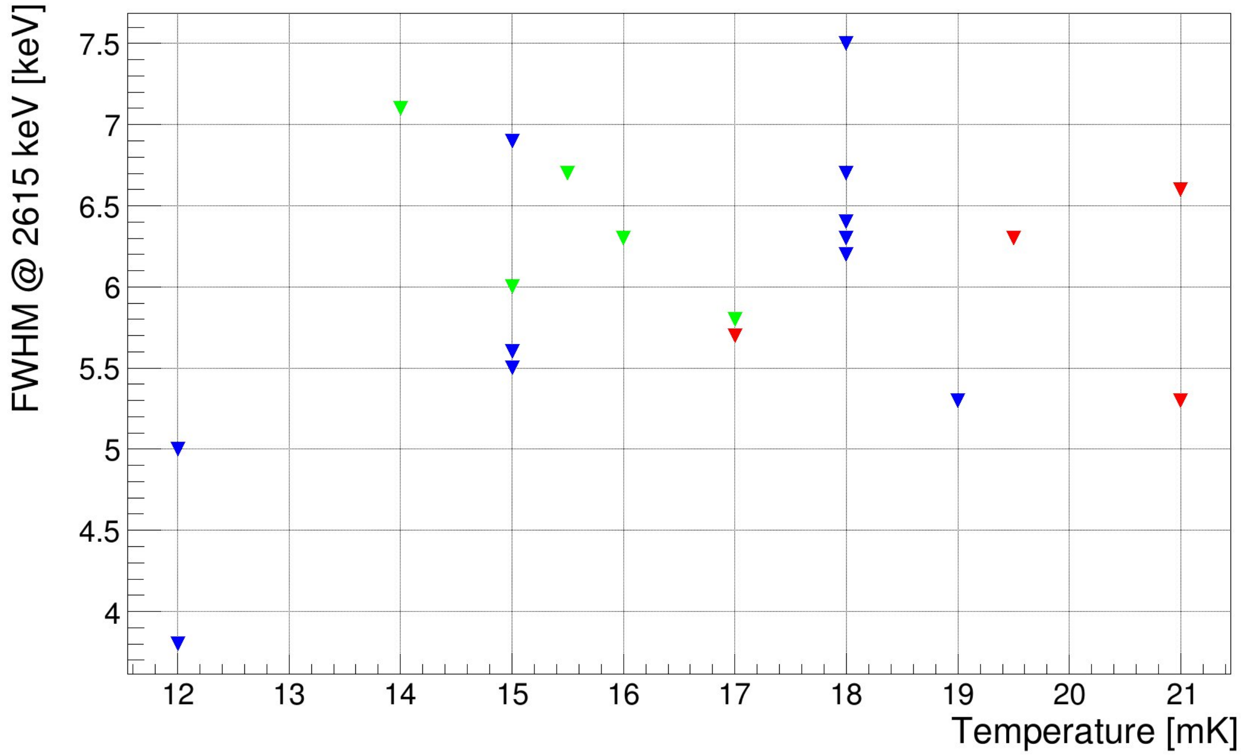


BI = $1.15 \cdot 10^{-4}$ counts/(keV·kg·y)

68% interval = (0.86, 1.44) $\cdot 10^{-4}$ counts/(keV·kg·y)

We are testing an improved version of the tower geometry → expect background reduction on surface contamination from close components

Energy resolution of Li_2MoO_4 crystals



- Preselection baseline < 6 keV
- Measurements in several cryostats
- Mean : 6.0 keV FWHM at 2615 keV
- Improvement through optimization of thermal sensor dimensions and coupling to the crystals plus cryostat upgrade

EPJC 77, 785 (2017)
AIP Conf. Proc. 1894 020017 (2017)
EPJC 80, 44 (2020)
JINST 16 P02037 (2021)
JINST 18 P06018 (2023)

Sensitivity calculation: Parameters and method

Parameters to evaluate CUPID baseline sensitivity

arXiv: 2504.14369

Crystal mass = 450 kg
Isotope enrichment = 95%

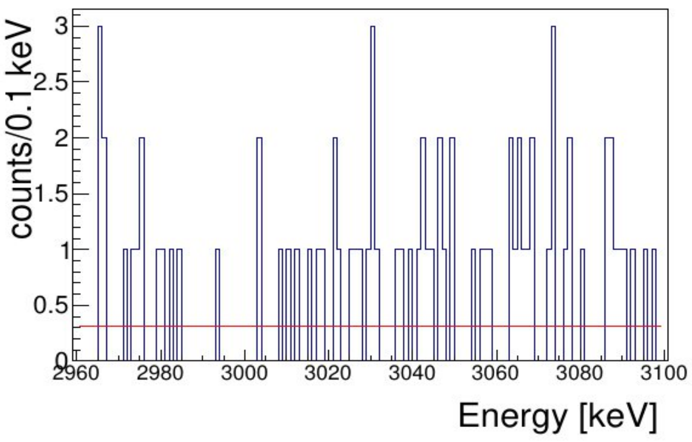
Livetime = 10 years
Containment efficiency = 77.8 % (from simulations)
Analysis efficiency = 92 %

Background Index = $1.0 \cdot 10^{-4}$ counts/(keV·kg·y)
Energy resolution, FWHM = 5 keV at Qββ

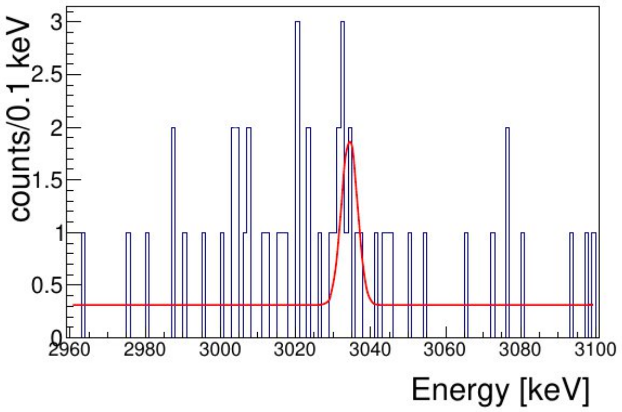
Method

- Frequentist and Bayesian analysis based on likelihood
- Generate pseudo-experiments:
  - Background
  - Signal

Example of toy with 0 signal



Example of toy with $T_{1/2} = 10^{27}$ yr



Discovery sensitivity in Frequentist analysis

- We have two hypothesis. H_0 : decay rate $\Gamma = 0$ and H_1: $\Gamma > 0$

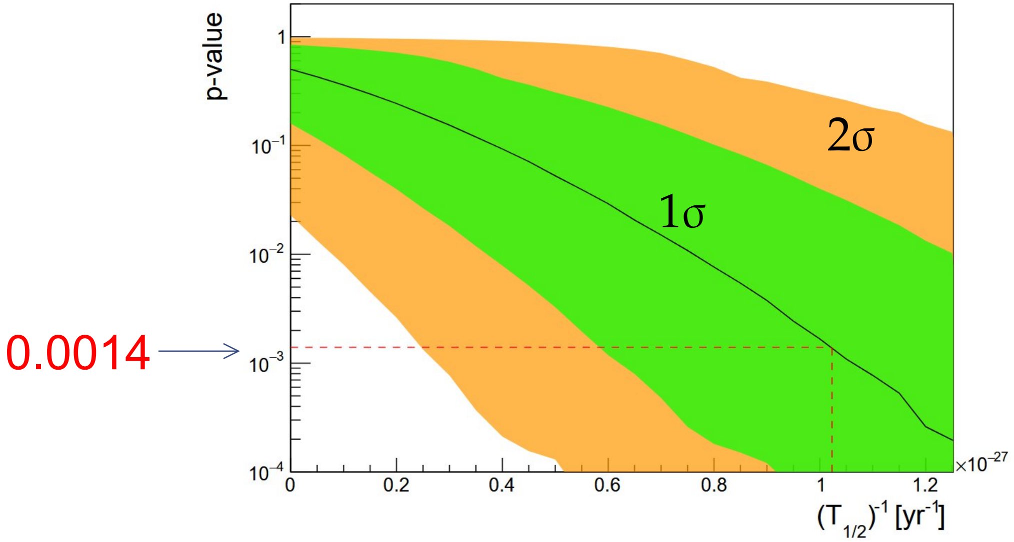
arXiv: 2504.14369

- Define the test statistic comparing the likelihoods

$$t_P(\Gamma = 0) = -2 \ln \frac{H_0}{H_1} = -2 \ln \left(\frac{\mathcal{L}(0)}{\mathcal{L}(\hat{\Gamma})} \right)$$

→ Background-only hypothesis

- Generate pseudo-experiments for different values of Γ and compute the background-only p-value. A discovery can be claimed if *p* is smaller than some cutoff.



- **3σ discovery if p < 0.14%**
- **$T_{1/2} = 1.0 \cdot 10^{27}$ y**

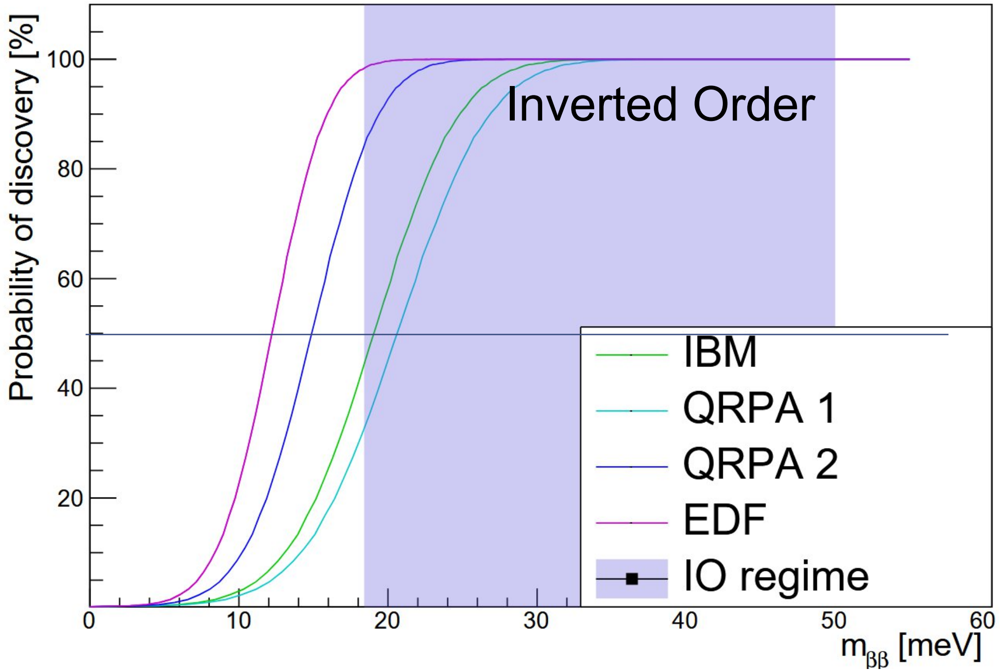
$M_{\beta\beta}$ discovery sensitivity

$$T_{1/2}^{-1} = g_A^4 G_{0\nu} |M_{0\nu}^2| m_{\beta\beta}^2 / m_e^2$$

arXiv: 2504.14369

Model	NME	Reference
pn-QRPA	3.90	P.R.C 91, 024613(2015)
pn-QRPA	5.850	P.R.C 87, 045501 (2013)
IBM-2	4.22	P.R.C 91, 034304 (2015)
EDF	6.58	P.R.L. 111, 142501 (2013)
	6.588	P.R.C 91, 024316 (2015)

- **$T_{1/2} = 1.0 \cdot 10^{27}$ y**
- **$m_{\beta\beta}$ = 12.2 – 20.6 meV**



Discovery: Probability = 50%

Model	NME	Reference
Shell (effective operator)	2.240	PRC 105 (2022) 3, 034312
Shell (bare operator)	3.962	

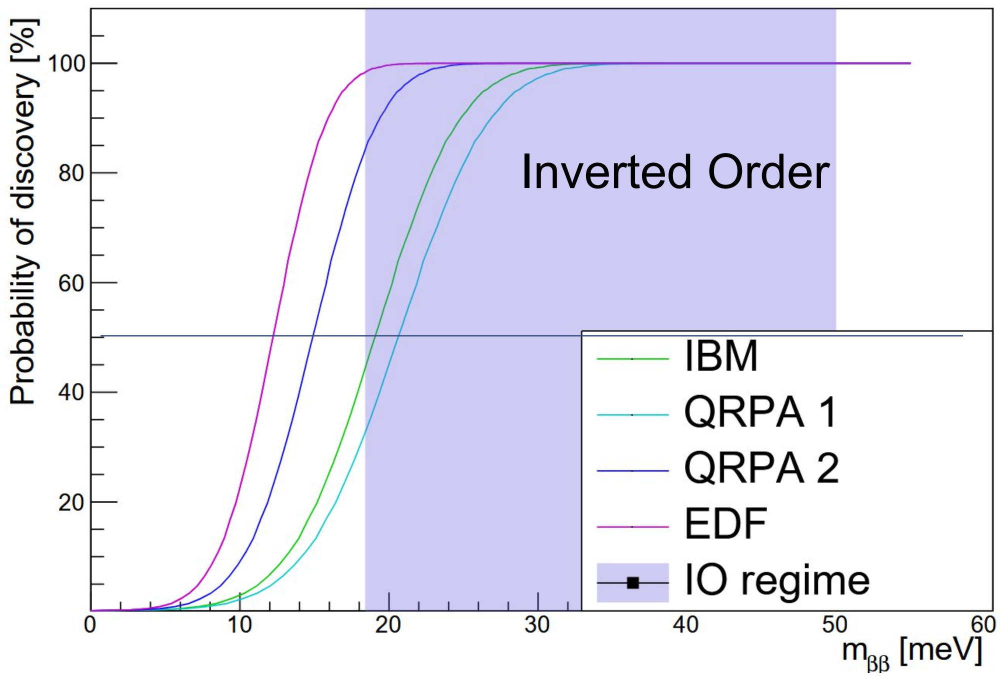
$M_{\beta\beta}$ discovery sensitivity: Shell model and M_S

arXiv: 2504.14369

Model	NME	$m_{\beta\beta}$
Shell (effective operator)	2.240	35.9 meV
Shell (bare operator)	3.962	20.3 meV

$M_L^{0\nu}+M_S^{0\nu}$: PRC 107 (2023) 4, 044305

Model	NME	$m_{\beta\beta}$
pn-QRPA	4.07 –7.36	19.8 - 10.9 meV

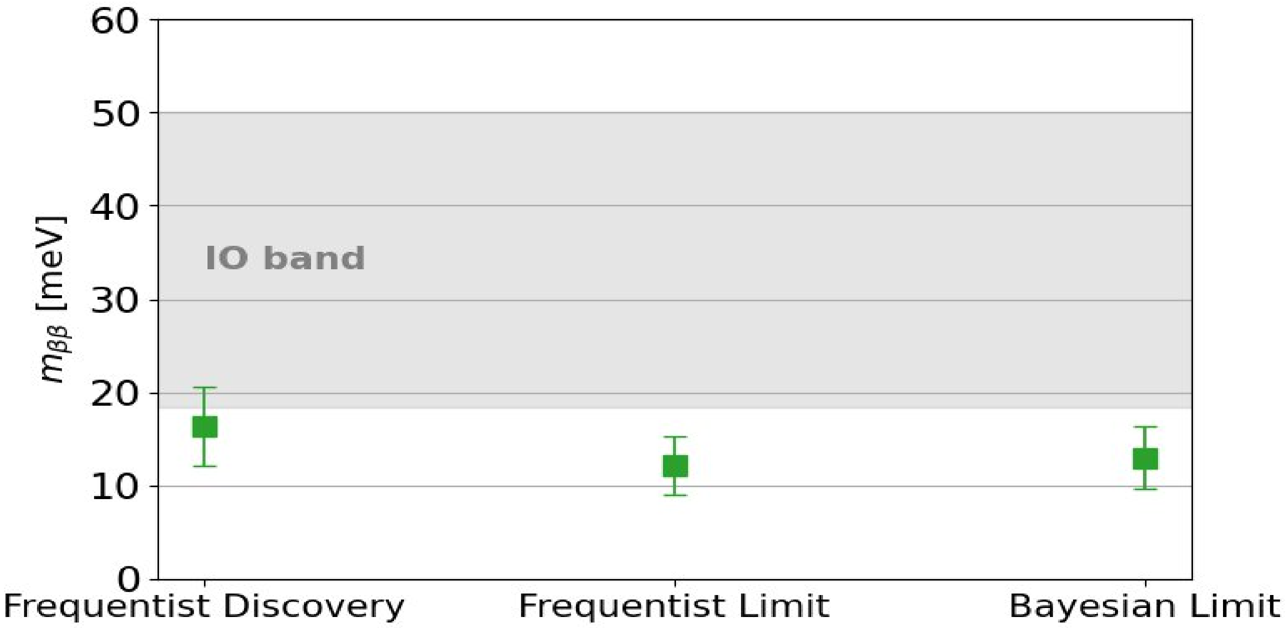


Discovery: Probability = 50%

- $T_{1/2} = 1.0 \cdot 10^{27}$ y
- $m_{\beta\beta} = 12.2 - 20.6$ meV

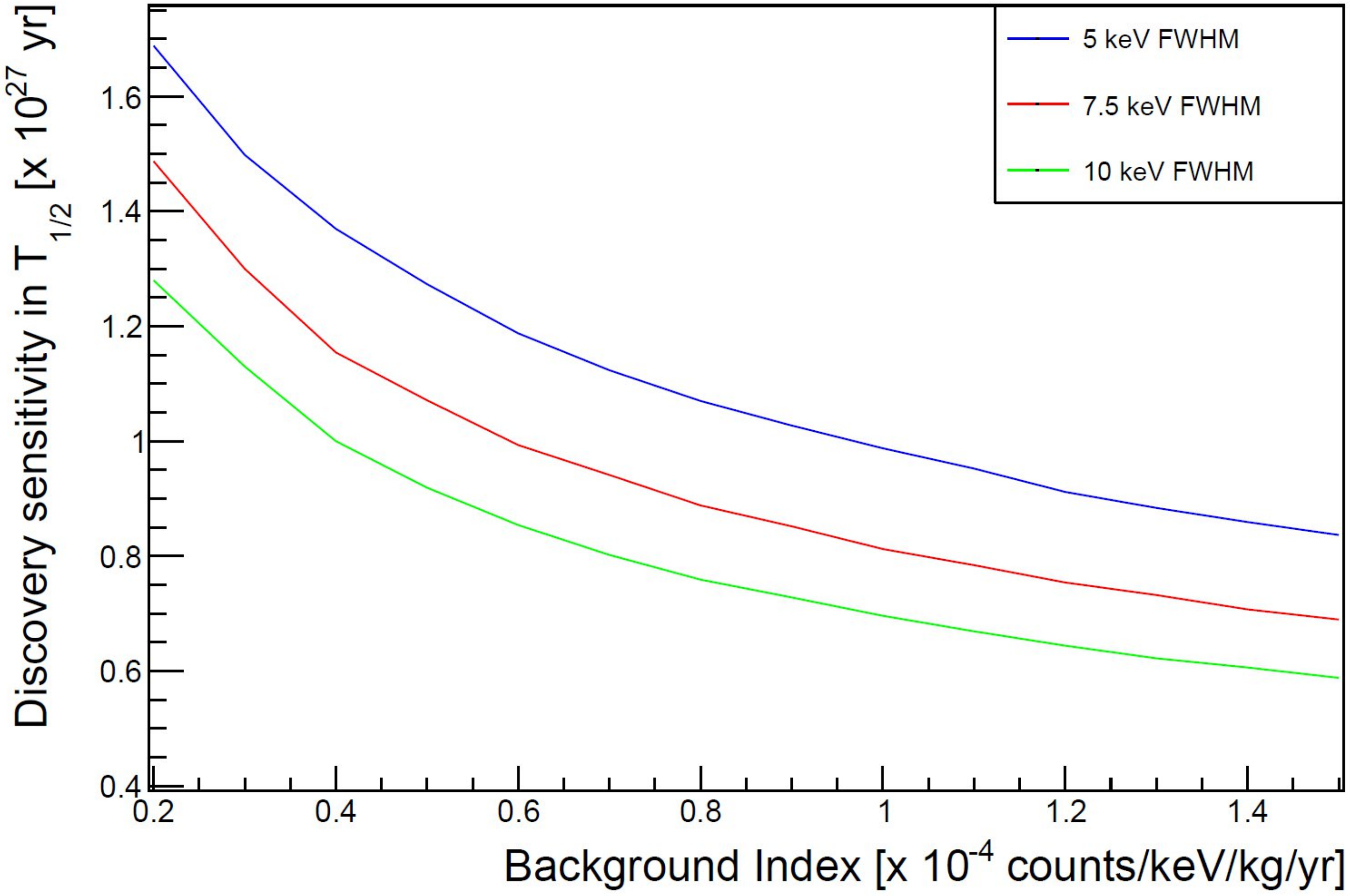
Sensitivity for CUPID baseline

Parameter	3σ Frequentist Discovery	Frequentist Limit (90 % C.L.)	Bayesian Limit (90 % C.I.)
$T_{1/2}$	1.0 x 10^{27} yr	> 1.8 x 10^{27} yr	> 1.6 x 10^{27} yr
$m_{\beta\beta}$	12.2 - 20.6 meV	< 9.0 - 15.2 meV	< 9.6 - 16.3 meV



Impact of Background Index and energy resolution on $T_{1/2}$ sensitivity

arXiv: 2504.14369



Summary

- CUPID Background projections are based on CUORE and CUPID-Mo background models and detailed simulations. The prediction is compatible with the Background Index goal : $1.0 \cdot 10^{-4}$ counts/(keV·kg·y)

- We developed a Frequentist and Bayesian frameworks and compute the discovery and exclusion sensitivity of CUPID to $0\nu\beta\beta$.

- CUPID will be able to fully explore the inverted hierarchy region with a discovery sensitivity:
  - $T_{1/2} = 1.0 \cdot 10^{27}$ y
  - $m_{\beta\beta} = 12.2 - 20.6$ meV

- CUPID can rule out the Inverted Hierarchy of neutrino masses in a majority of nuclear models

- A discovery is very likely for most favorable nuclear models for the smallest $m_{\beta\beta}$ values in the IH

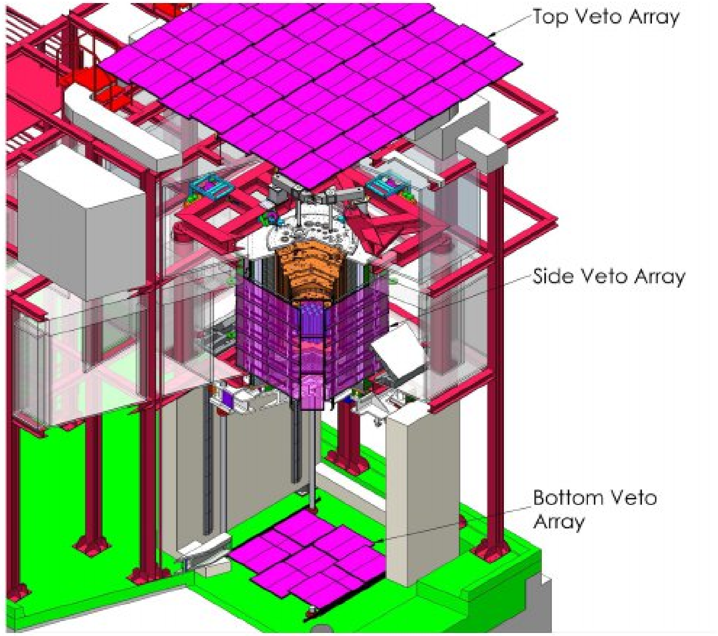
Background from muons and neutrons

Muons

- Additional muon veto. Construction on-going
- From simulations, muon rejection efficiency ~98 % → $1.3 \cdot 10^{-6}$ cts/(keV·kg·y)

Neutrons

- Neutron shielding to be expanded to mitigate (n,γ) reactions in Mo and Cu
- With additional 10 cm of polyethylene on the top and at sides, neutron backgrounds suppressed to $\sim 2 \cdot 10^{-6}$ cts/(keV·kg·y)



Exclusion Sensitivity in Bayesian framework

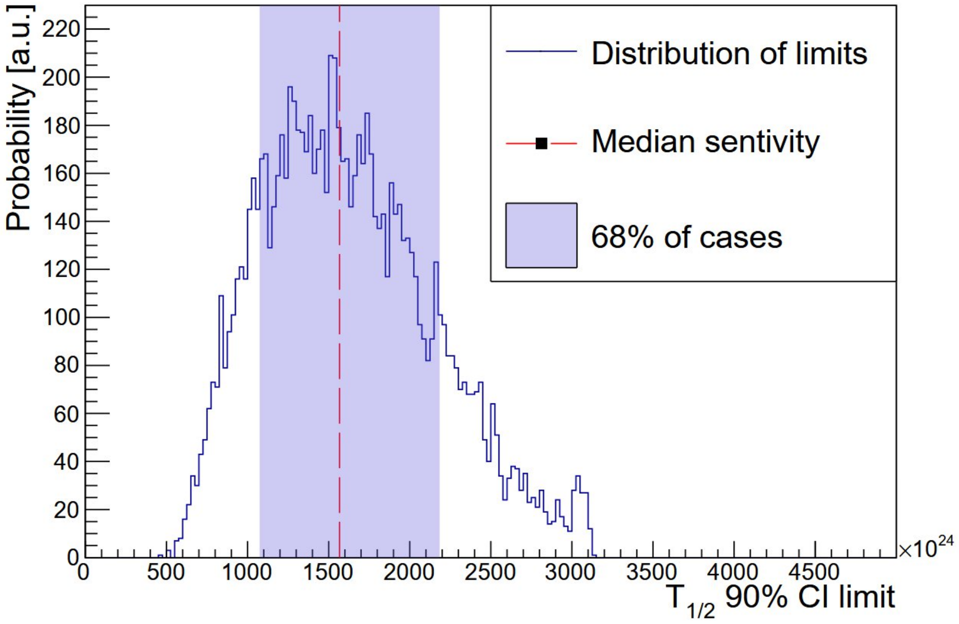
- Extract directly the likelihood distribution of the decay rate for each pseudo-experiment (with BAT), in which we injected zero signal

$$p(\Gamma|\mathcal{D}) = \int_{\Omega} p(\Gamma, \vec{\nu}|\mathcal{D}) d\vec{\nu}$$

arXiv: 2504.14369

- Flat prior on the decay rate, Γ

- Extract the 90% c.i for each pseudo-experiment



- $T_{1/2} > 1.6 \cdot 10^{27}$ y (90% c.i)
- $m_{\beta\beta} < 9.6 - 16.3$ meV

- $m_{\beta\beta} < 9.6 - 28.2$ meV (including shell model)

Impact of Background Index and energy resolution on $T_{1/2}$ sensitivity

Background index $\times 10^{-4}$ [counts/keV/kg/yr]	$\hat{T}_{1/2}$ 10^{27} [yr]	$\hat{m}_{\beta\beta}$ [meV]
1.5	0.8	13.2–22.2
1.0	1.0	12.2–20.6
0.6	1.2	11.0–18.7
0.2	1.7	9.3–15.7

Energy resolution FWHM [keV]	$\hat{T}_{1/2}$ 10^{27} [yr]	$\hat{m}_{\beta\beta}$ [meV]
10	0.7	14.4–24.3
7.5	0.8	13.4–22.6
5	1.0	12.2–20.6