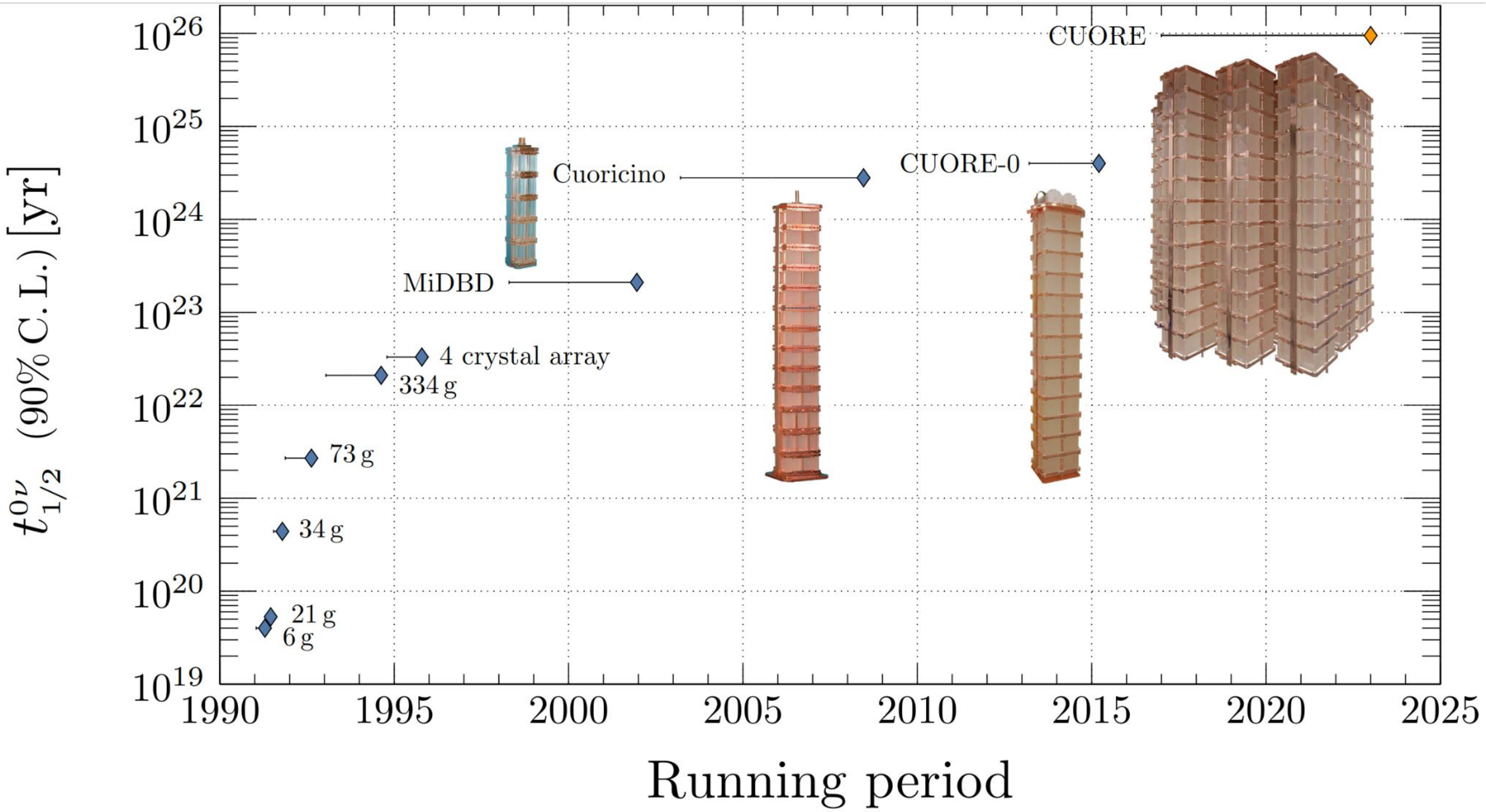
From CUORE to CUPID

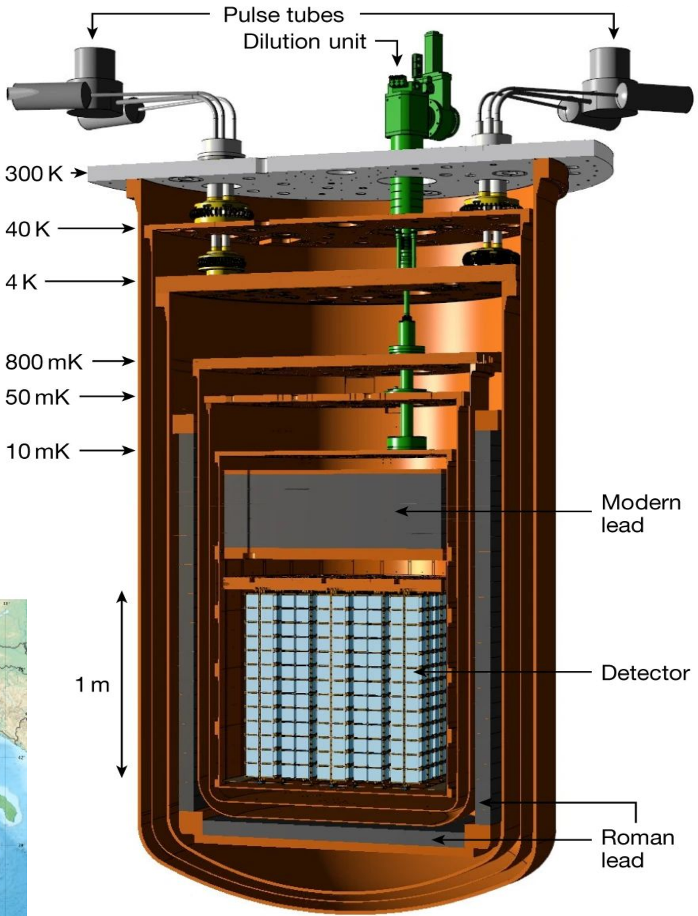

CUORE
CUORE-0
Cuoricino
MiDBD
4 crystal array
334 g
73 g
34 g
21 g
6 g
10^{19}
10^{20}
10^{21}
10^{22}
10^{23}
10^{24}
10^{25}
10^{26}
1990
1995
2000
2005
2010
2015
2020
2025
$t_{1/2}^{0\nu}$ (90% C.L.) [yr]
Running period

CUORE

Cryogenic Underground Observatory for Rare Events

- closely packed array of TeO_2 crystals 750 g each working as cryogenic calorimeters @ 10 mK
- total mass of TeO_2: 742 kg (~206 kg of ^{130}Te)
- main goal: assess the Majorana nature of neutrinos by searching for 0νββ in ^{130}Te

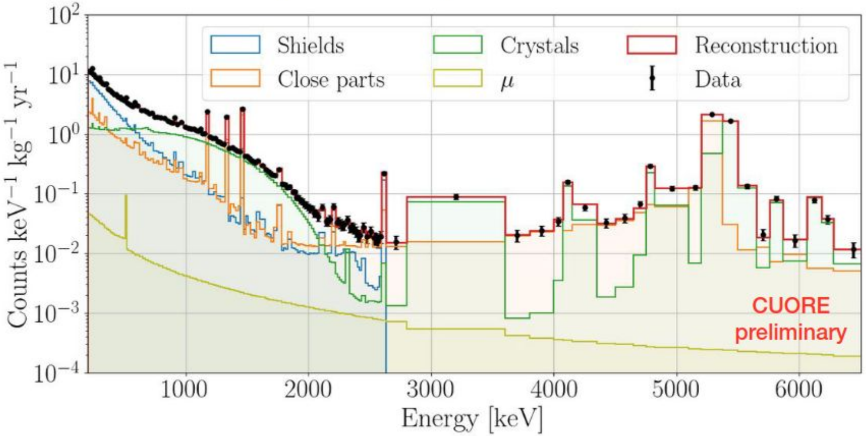
In operation since 2016 @ **LNGS** (L'Aquila Italy)

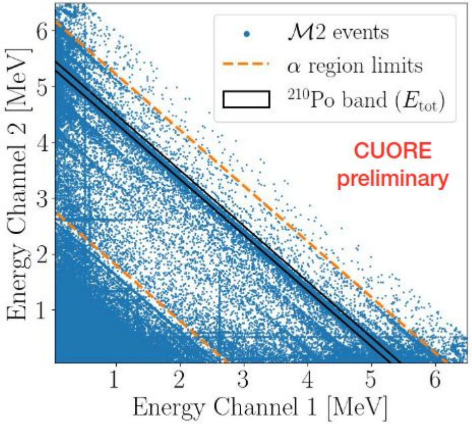


CUORE - Background Model

Accurate Geant4-based background model

- Detailed geometry
- Simulation of ~80 different sources
- Takes advantage of the high granularity of the detector
- Bayesian simultaneous fit of M1 and M2 spectra with a linear combination of the background sources
- Priors given by radioassays and previous experiments



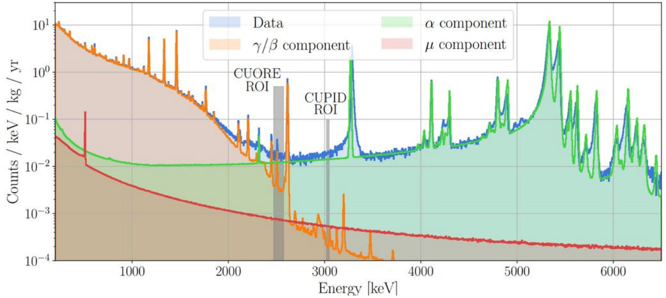


ArXiv:2405.17937

CUORE - Background Model

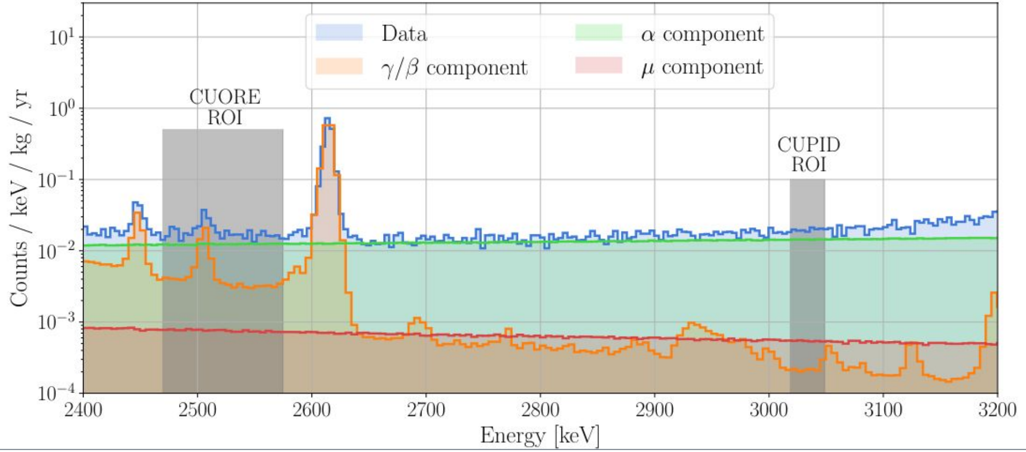
particle-based background composition suggests the path toward a new generation 0nbb experiment with bolometers:

- muon-veto
- alpha rejection



residual bkg is:

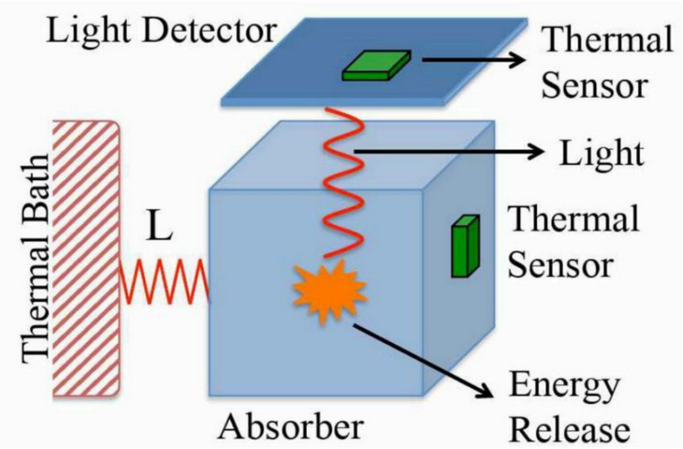
- ~ 3 10^{-3} ckky in ^{130}Te ROI
- ~ 2 10^{-4} ckky in ^{100}Mo ROI

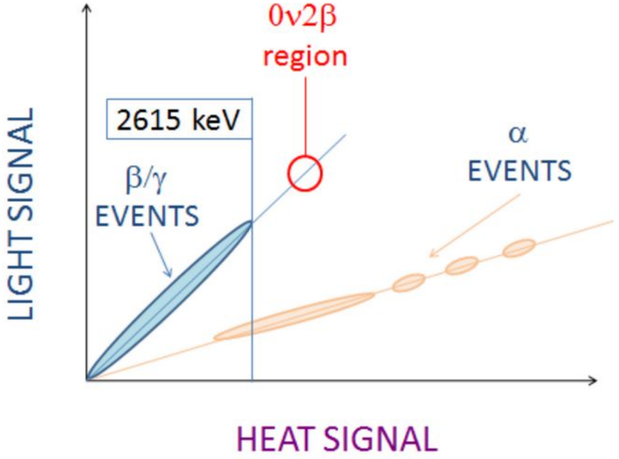


CUPID: scintillating bolometers

Idea: use scintillation for alpha vs. beta-gamma discrimination

Scintillating bolometers: double read-out
- heat (LMO crystal)
- light (Ge light detector)





CUPID - project

replace CUORE **TeO_2** detector with an array of **$Li_2{}^{100}MoO_4$** scintillating bolometers

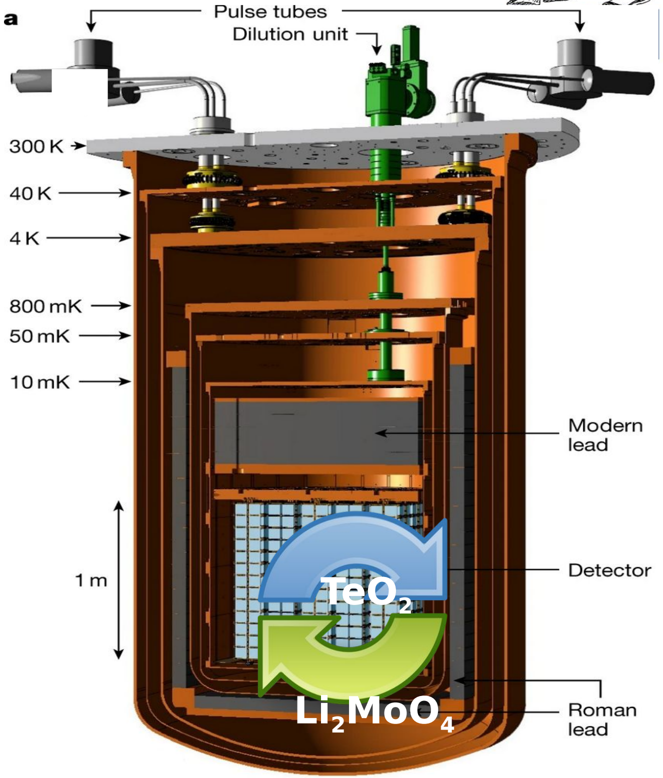
- ^{100}Mo ($Q_{\beta\beta}$ = 3034 keV) → lower BI & better phase space compared to ^{130}Te

new detector array

- 1596 Li_2MoO_4 scintillating crystals (280 g each)
- 1700 light detectors → scintillation signal read-out
- Mo enriched > 95% in ^{100}Mo

additional needs

- upgrade the cryostat for a 1600 double read-out array
- improve external n-shield & add a μ-veto



CUPID – sensitivity goal

$T_{1/2}$=1 x 10^{27} yr

$m_{\beta\beta}$= 12-20 meV

mass:

450 kg (**240 kg**) $Li_2{}^{100}MoO_4$ (**^{100}Mo**)

livetime:

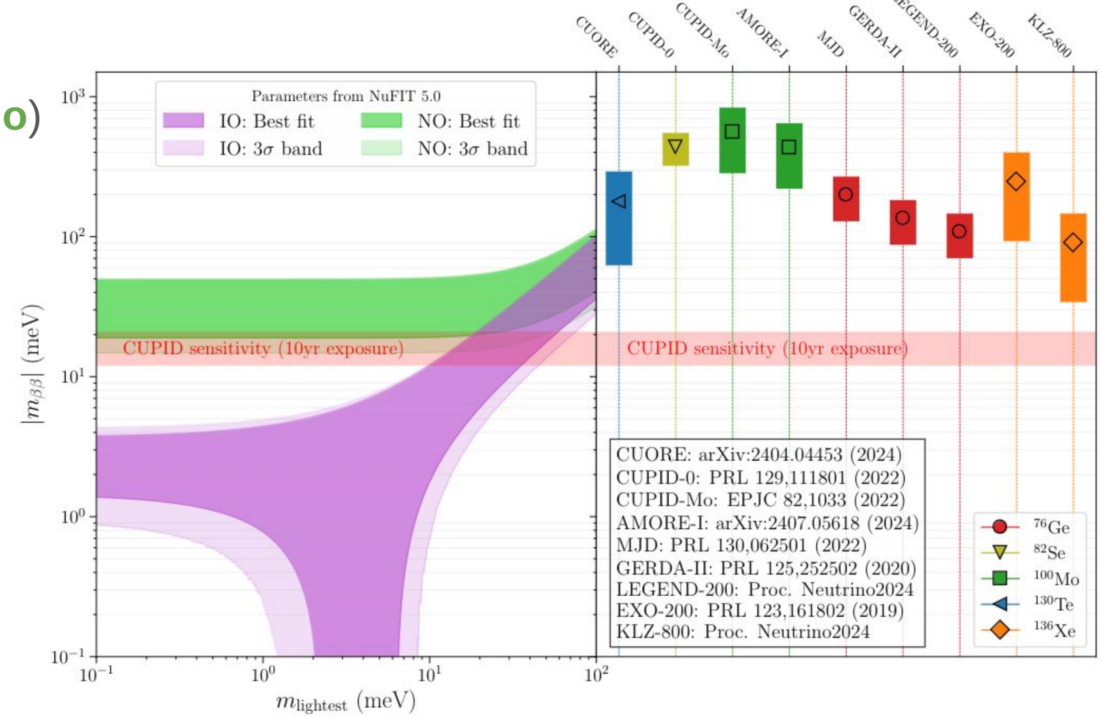
10 yr

energy resolution:

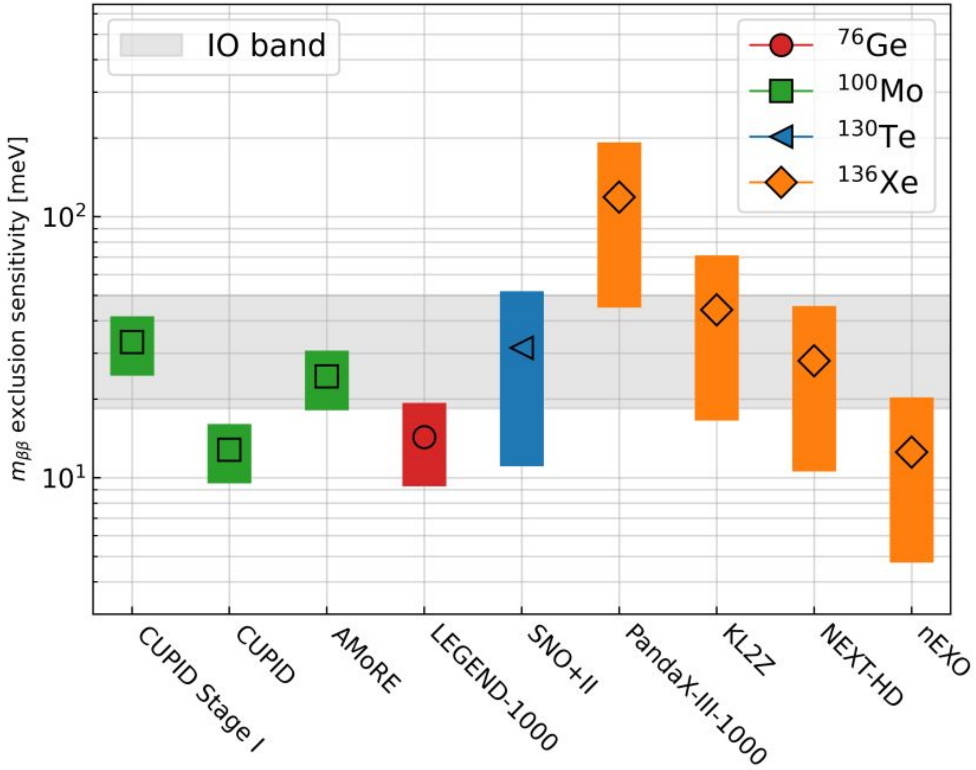
5 keV FWHM

background index:

BI< 10^{-4} cts/(keV kg yr)



CUPID sensitivity vs other experiments



CUPID - activities: crystals

Requirements:

- Enrichment ~ 95%
- Radiopurity < 0.4 nBq/kg U & Th
- Performances
  - Heat energy FWHM ~ 5 keV @ 3 MeV
  - Light Yield > 0.36 keV/MeV

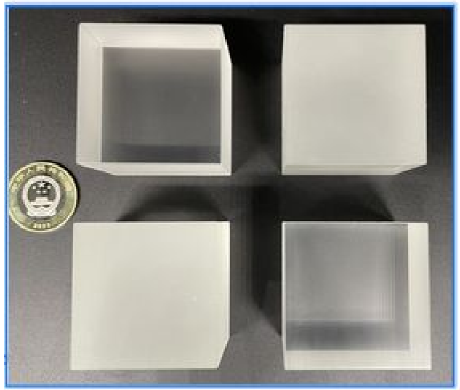
Baseline:

- ^{100}Mo isotope producer = IPCE (Tianjin China)
- **$Li_2{}^{100}MoO_4$** crystal producer (SICCAS Shanghai China)

Critical points

- Carefully controlled production chain able to ensure reproducibility in radiopurity & optical performances

- Reduce to a minimum isotope loss during crystal production: recycling and re-use of leftover material from various stages of crystal production chain



CUPID - activities: crystals

Pre-production: joint INFN+IN2P3 activity

- 4 kg ^{100}Mo produced by IPCE during 2024
- ICP-MS screening to certify U/Th and K (same samples measured in China, Italy, USA)
- work in progress to define the crystal growth procedure and material recovery efficiency

Element	Requirement
^{232}Th	< 0.8 mBq/kg
^{238}U	< 2.5 mBq/kg
^{40}K	< 50 mBq/kg

Powder Radioactivity Requirements

Expected results are:

- protocol for mass production: crystal growth, cutting and final treatment. Certified reproducibility of crystal quality (radiopurity and performances) & production yield.
- certified ^{100}Mo recycling efficiency and certified reproducibility in crystal production.
- timeline and price for the crystal production for CUPID experiment (~1600 LMO crystals).

CUPID - activities: crystals

Bulk Radioactivity Requirements

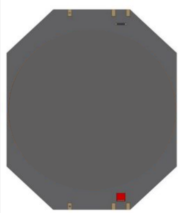
$$^{238}\mathrm{U}\text{ and }^{226}\mathrm{Ra} < 0.4\ \mu\mathrm{Bq/kg}$$
$$^{232}\mathrm{Th}\text{ and }^{228}\mathrm{Th} < 0.4\ \mu\mathrm{Bq/kg}$$
$$^{40}\mathrm{K} < 1\ \mathrm{mBq/kg}$$

Note:

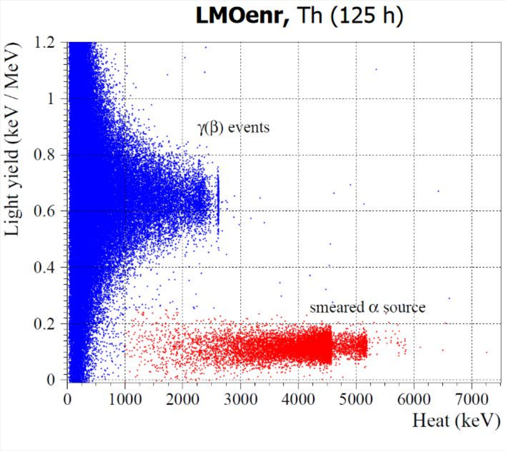
- requirements on ^{226}Ra and ^{228}Th that are the two isotopes in the U and Th chains always in secular equilibrium with ^{214}Bi and ^{208}Tl (extremely dangerous background source for CUPID)
- the concentration of these isotopes by ICP-MS, also in precursors, is unknown (ICP-MS can't be used) we rely on U and Th concentrations but we know that often secular equilibrium is broken
- assuming secular equilibrium, we aim at an impurity reduction from crystallization > 1000 on U/Ra and Th
- Bolometric tests at LNGS for each production batch to verity that crystals meet requirements

CUPID - activities: light detectors

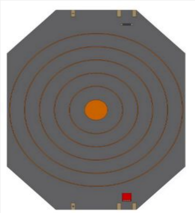
scintillation light collected with a Ge wafer + NTD thermistor

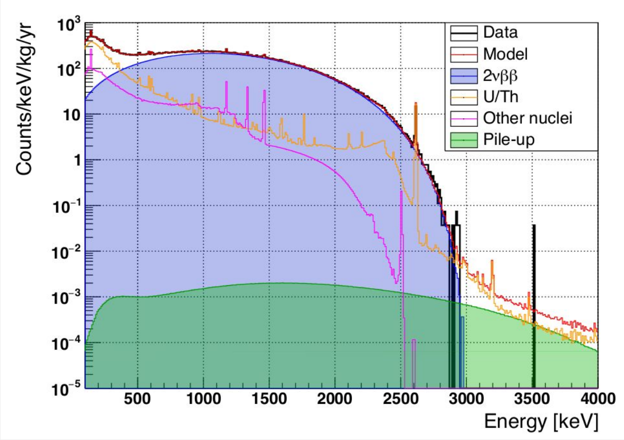


- collected light ~ 0.3 keV/MeV
- **99.7% rejection α particles**



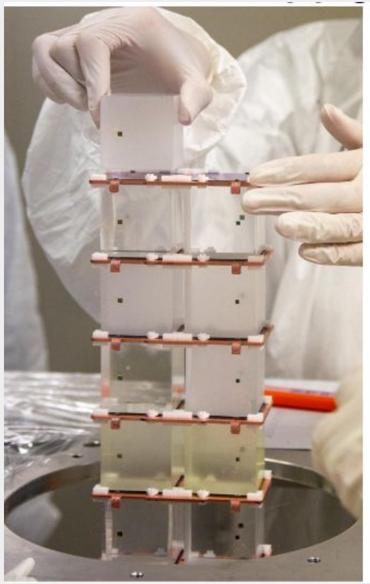
Neganov-Truminof-Luke amplification used to **improve S/N and reject $2\nu\beta\beta$ pile-up** ^{100}Mo $2\nu\beta\beta$ ~ 2.6 mHz





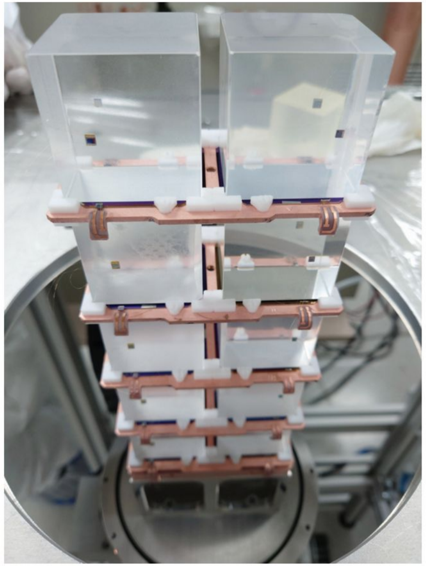
CUPID - activities: light detectors

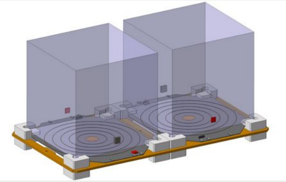
CUPID - activities: gravity assisted assembly



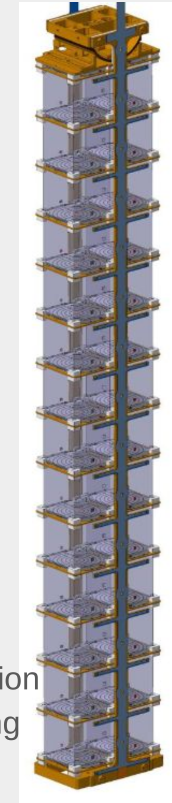
step 0: design. Crystals stacked and hold in place by their own weight. Fast assembly and improved radiopurity.

step 1: conceptual validation.
Test of mechanical and thermal properties



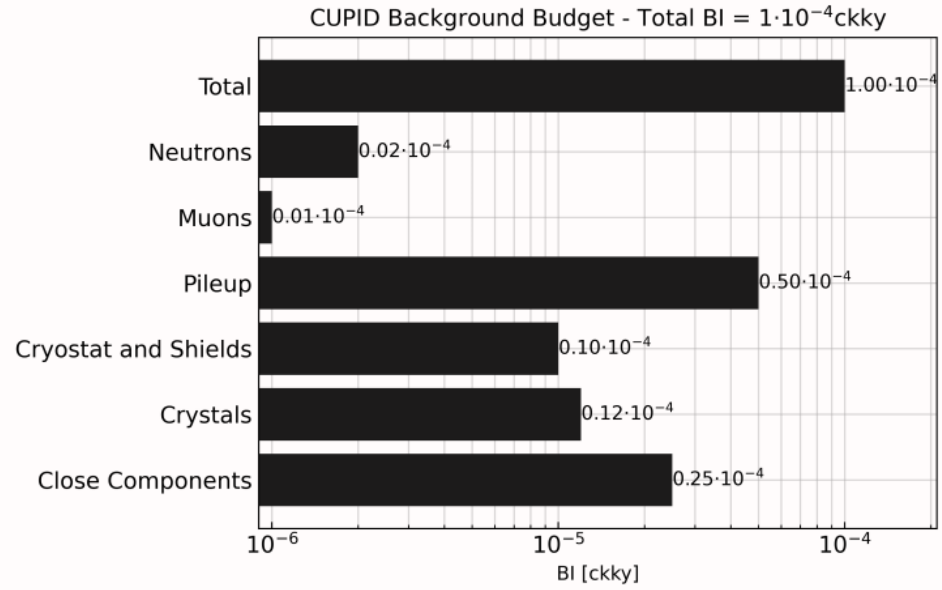


step 2: full-scale prototype. Construction in progress, test during 2025.

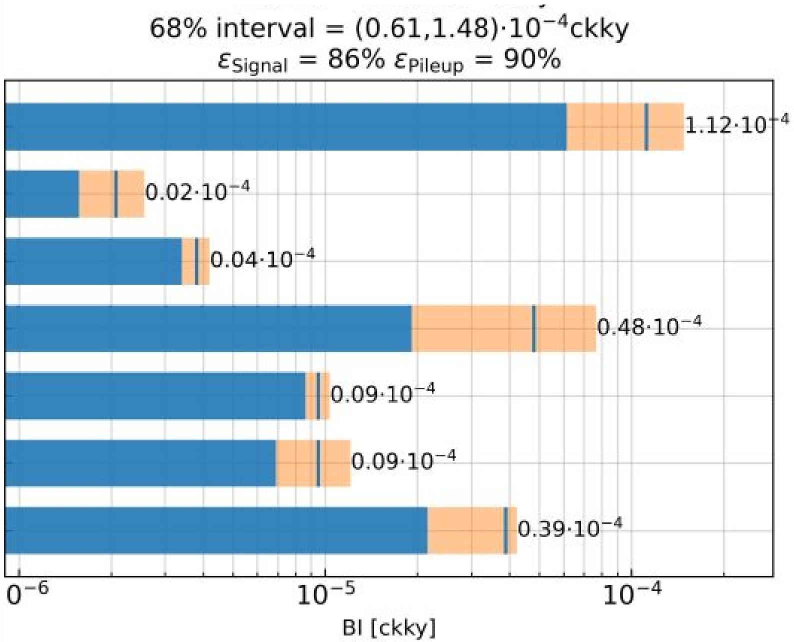


CUPID – background

Background Budget (our goal)
BI = **1 10^{-4}** c/(keV kg y)



Background Projections (our status)
BI = **1.2 10^{-4}** c/(keV kg y)

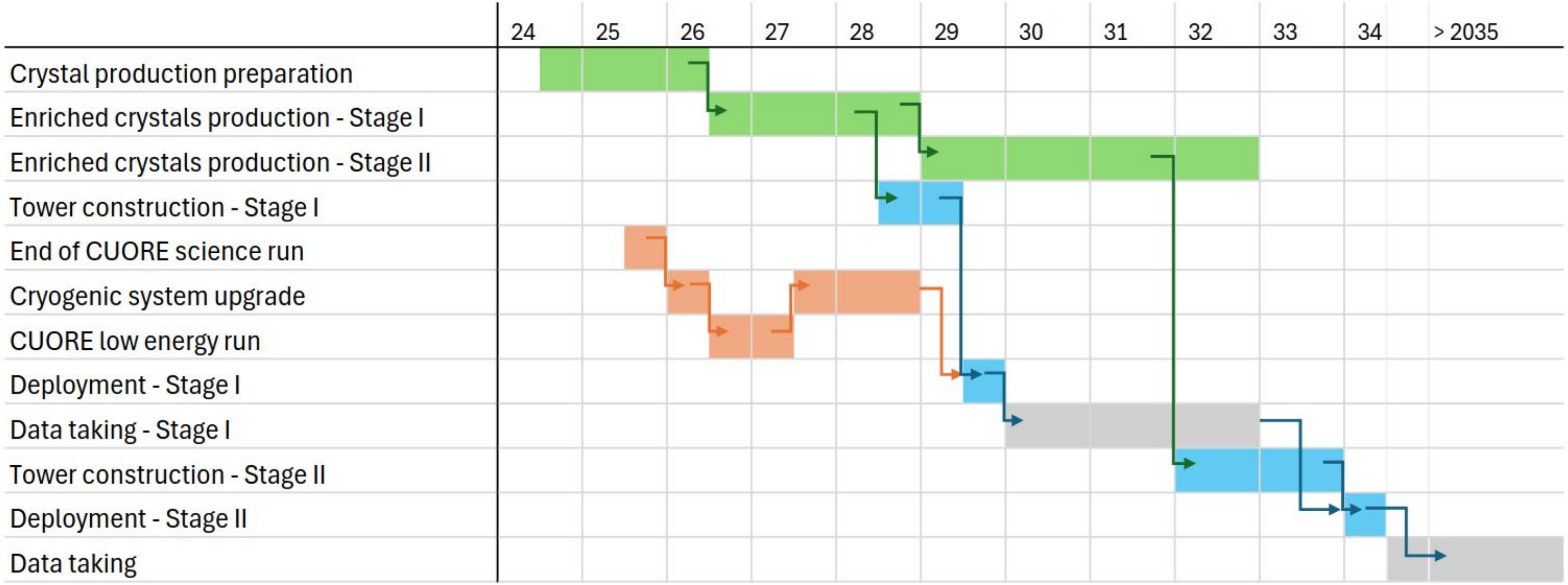


CUPID – timeline and staged deployment

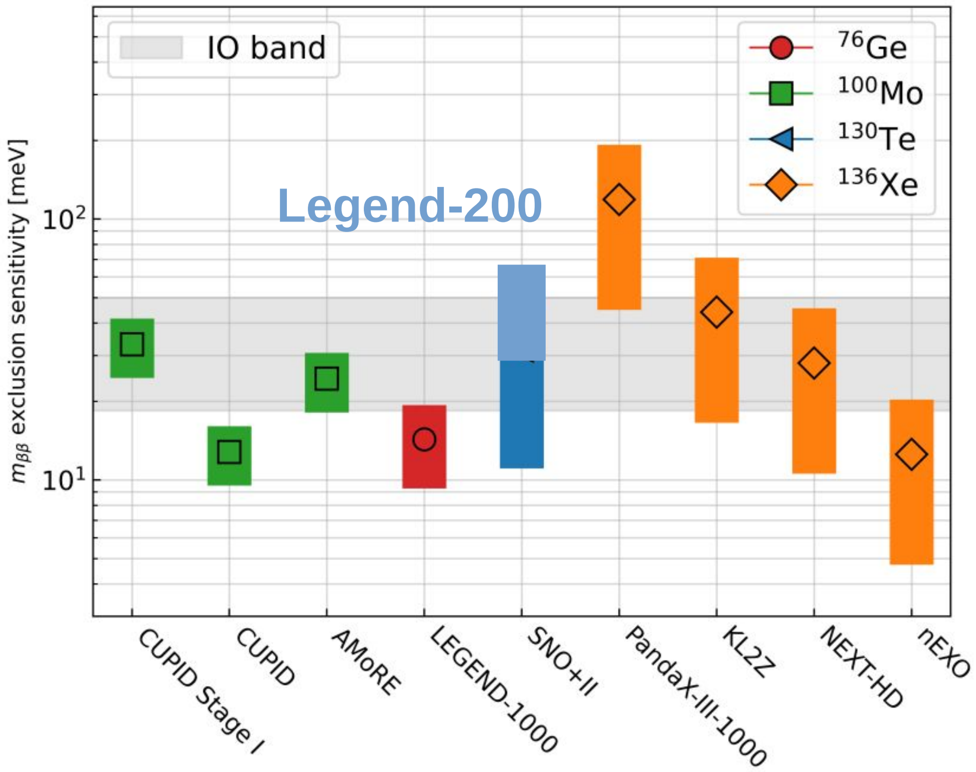
We opted for a staged deployment:

- CUPID-I = 1/3 of the crystals & 3 year data-taking
  - early data (small gap between CUORE shut down and first CUPID data), sensitivity in time to be competitive with Legend-200
  - risk mitigation (early identification of issues)
- CUPID-II → full array= add the remaining 2/3 of the crystals & full data-taking
  - Enrichment and crystal growth will proceed in parallel with stage I data-taking

Timeline: from CUORE to CUPID



CUPID sensitivity vs other experiments



CUPID – Summary & Outlook

2024 milestones

- first 4 kg of isotope produced, enriched crystal pre-production started
- optimization of light detector technology in progress – goal is to achieve $2\nu\beta\beta$ pile-up rejection corespongin to a ROI BI < 5 10^{-4} counts/(keV kg y)
- VSTT tower under construction

2025 goals

- **complet**e enriched crystal pre-production meeting all the requirements (final test of all the crystals @ LNGS
- operate VSTT full validation of all the systems (assembly, assembly line, electronics …)
- INFN review (to be scheduled likely in June) to discuss achievements and next steps

CUPID – Summary & Outlook

CUPID-China contribution in the next years will be essential for the success of CUPID project