International Symposium on Neutrino Physics and Beyond

NPB 2024

Hong Kong - February 19-21, 2024

The Hong Kong University of Science and Technology

HKUST Jockey Club Institute for Advanced Study,
Lo Ka Chung Building, Lee Shau Kee Campus

The CUPID experiment

CUPID

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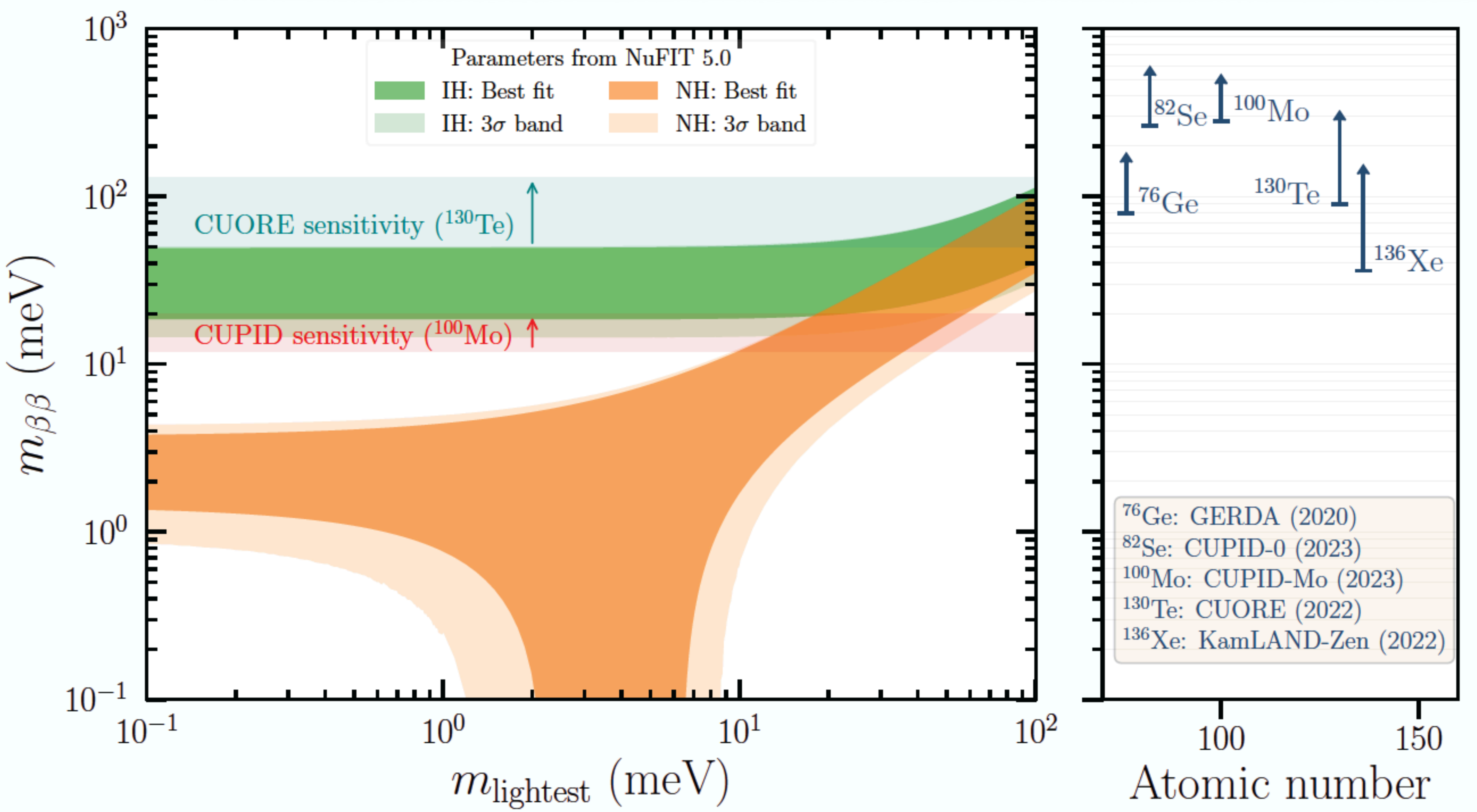
On behalf of the CUPID collaboration

INFN
Istituto Nazionale di Fisica Nucleare

CUPID goal

CUPID: CUORE Upgrade with Particle IDentification

A ton scale high resolution array for the search of $0\nu\beta\beta$ decay of ^{100}Mo with cryogenic detectors



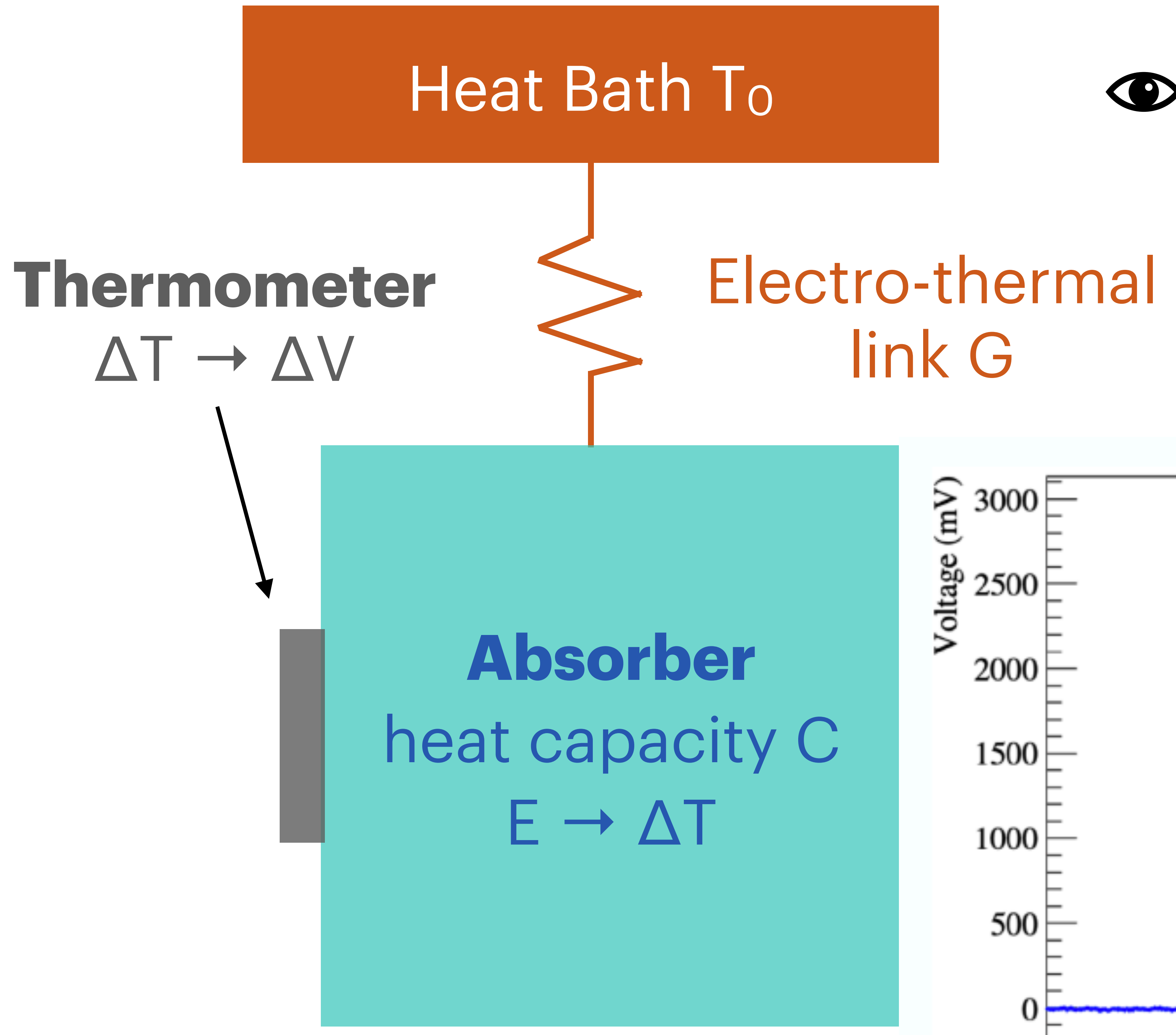
3σ discovery sensitivity:
$m_{\beta\beta}$: [13-21] meV
$T_{1/2} > 10^{27}$ yr

Calorimetric search for $0\nu\beta\beta$ decay

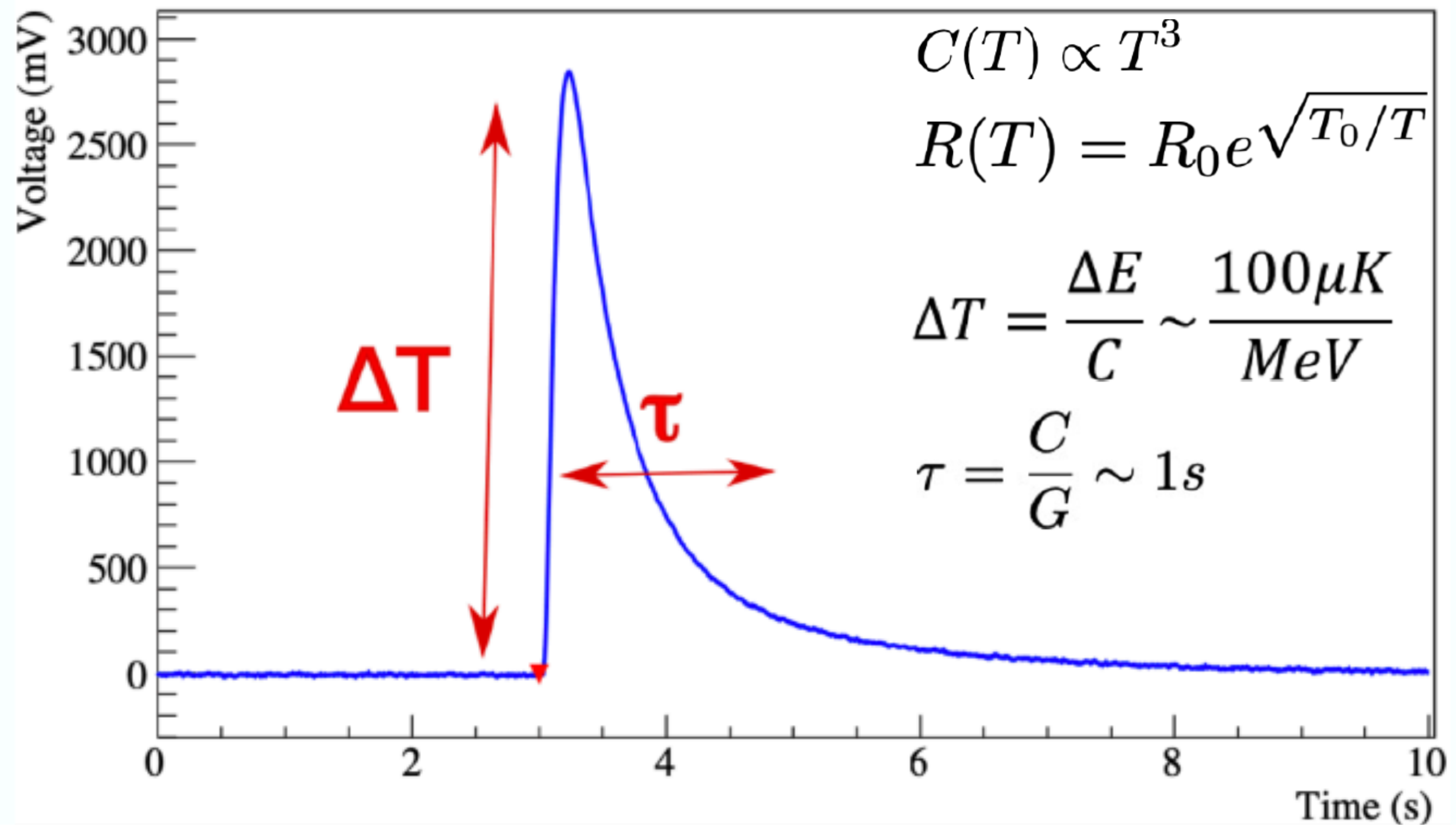
with Cryogenic Detectors (or Bolometers)

Properties of cryogenic detectors

- Excellent energy resolution: $(k_B C T^2)^{1/2}$
- Large choice of absorber materials
- True calorimeters
- Source ≡ Detector: high efficiency



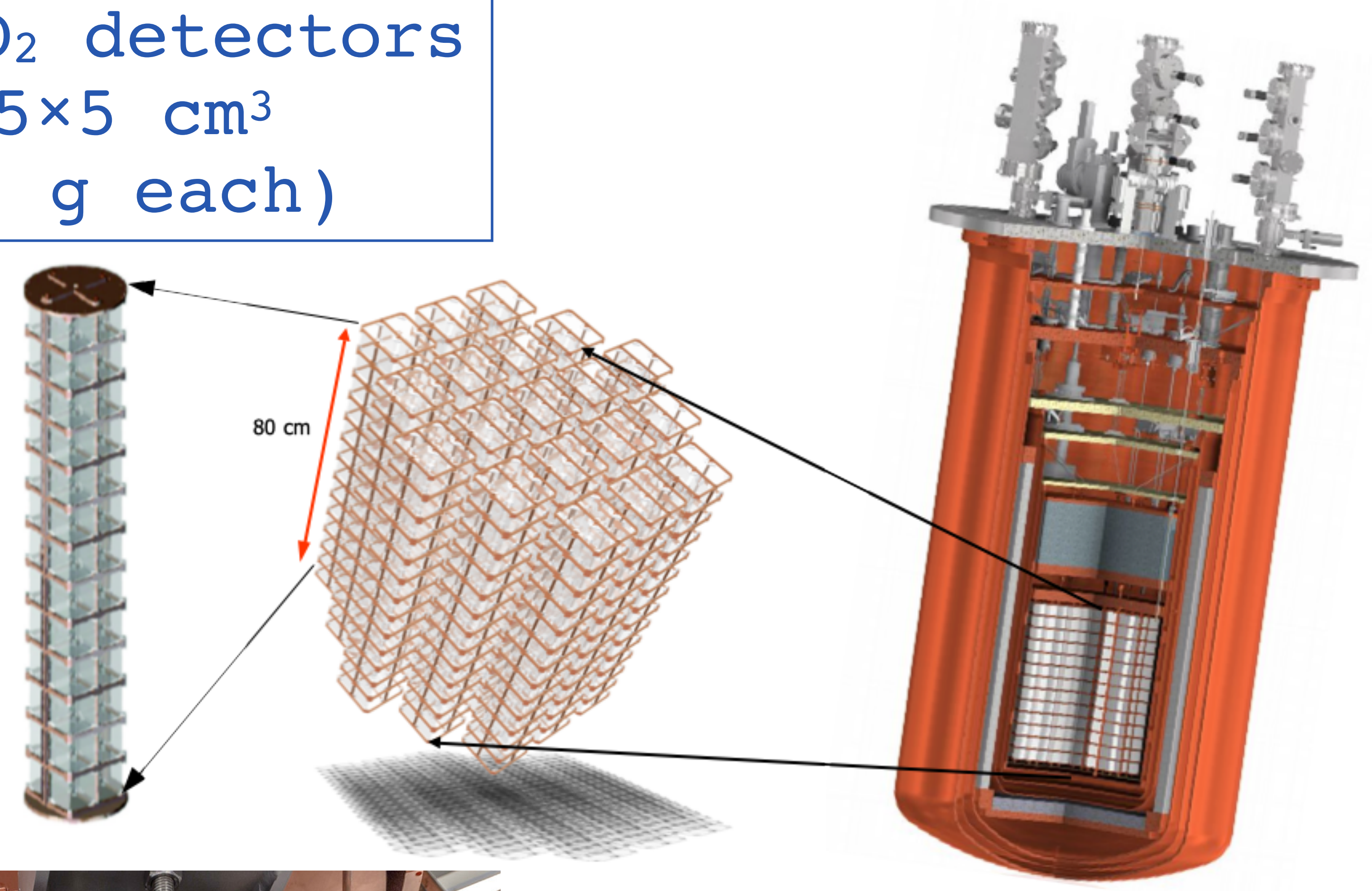
J.Low Temp.Phys.151(2008)5

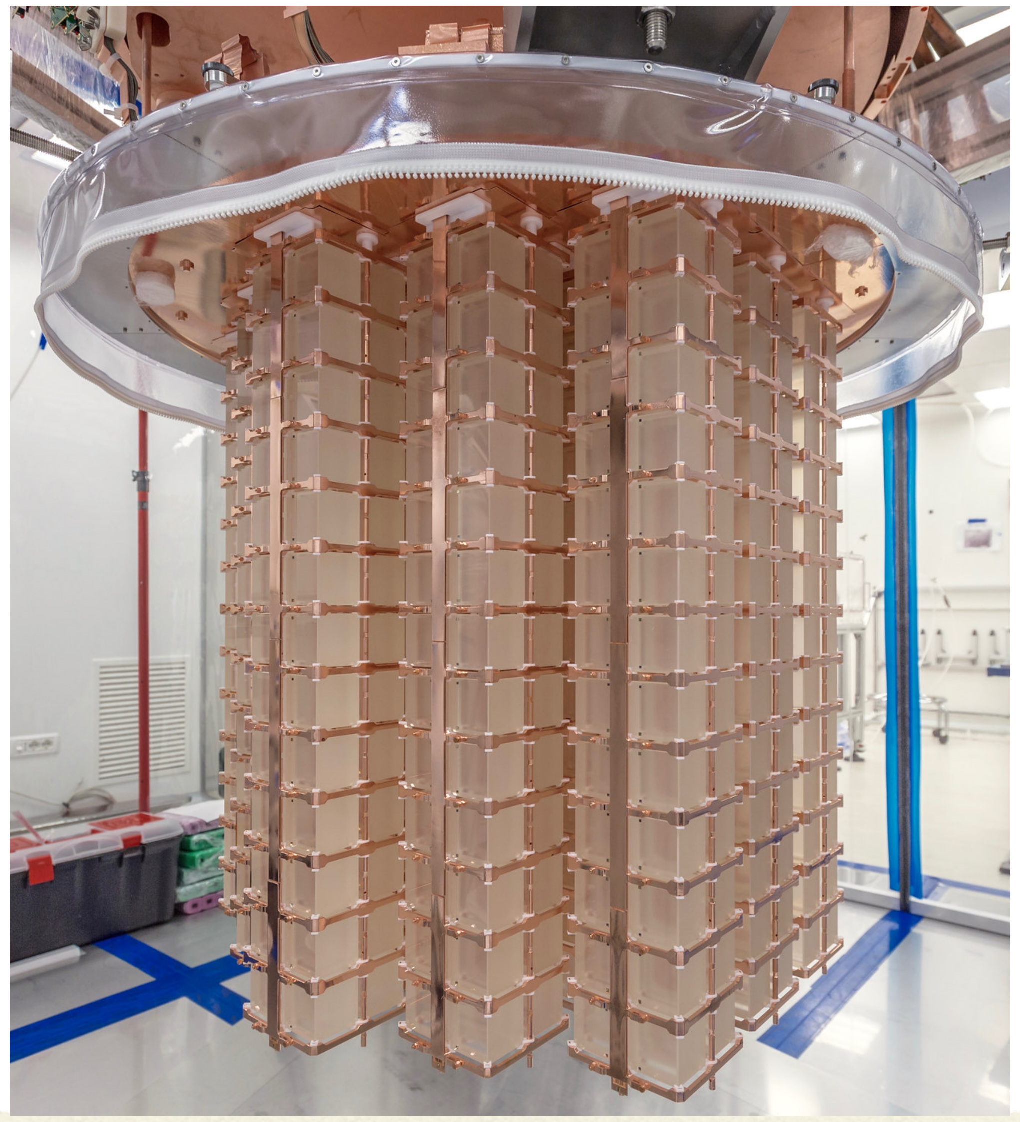


CUORE: The state of the art

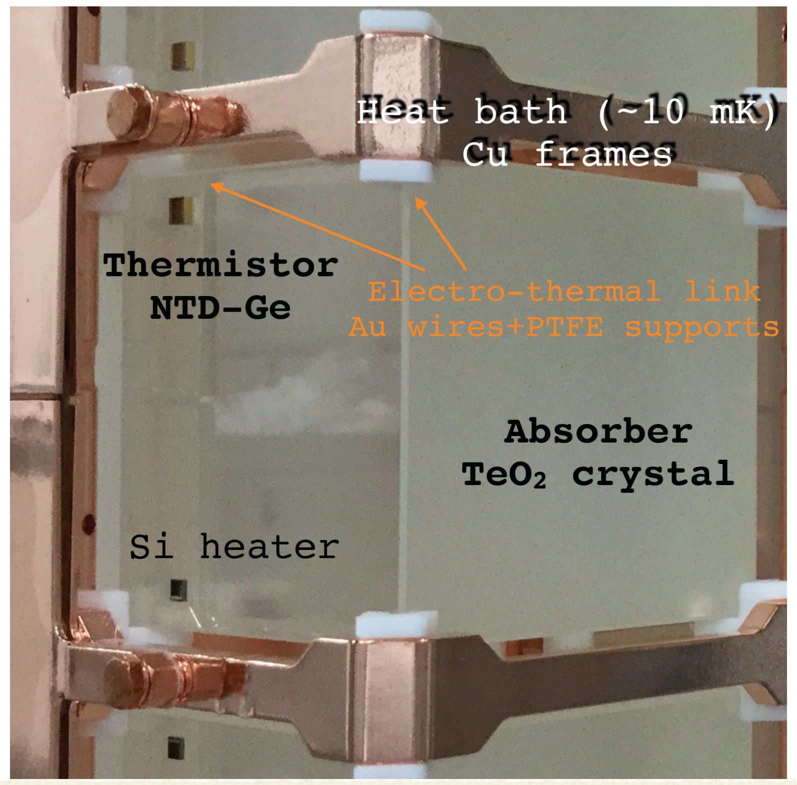
988 TeO_2 detectors
5×5×5 cm^3
(750 g each)

19 towers ×
13 planes ×
4 detectors



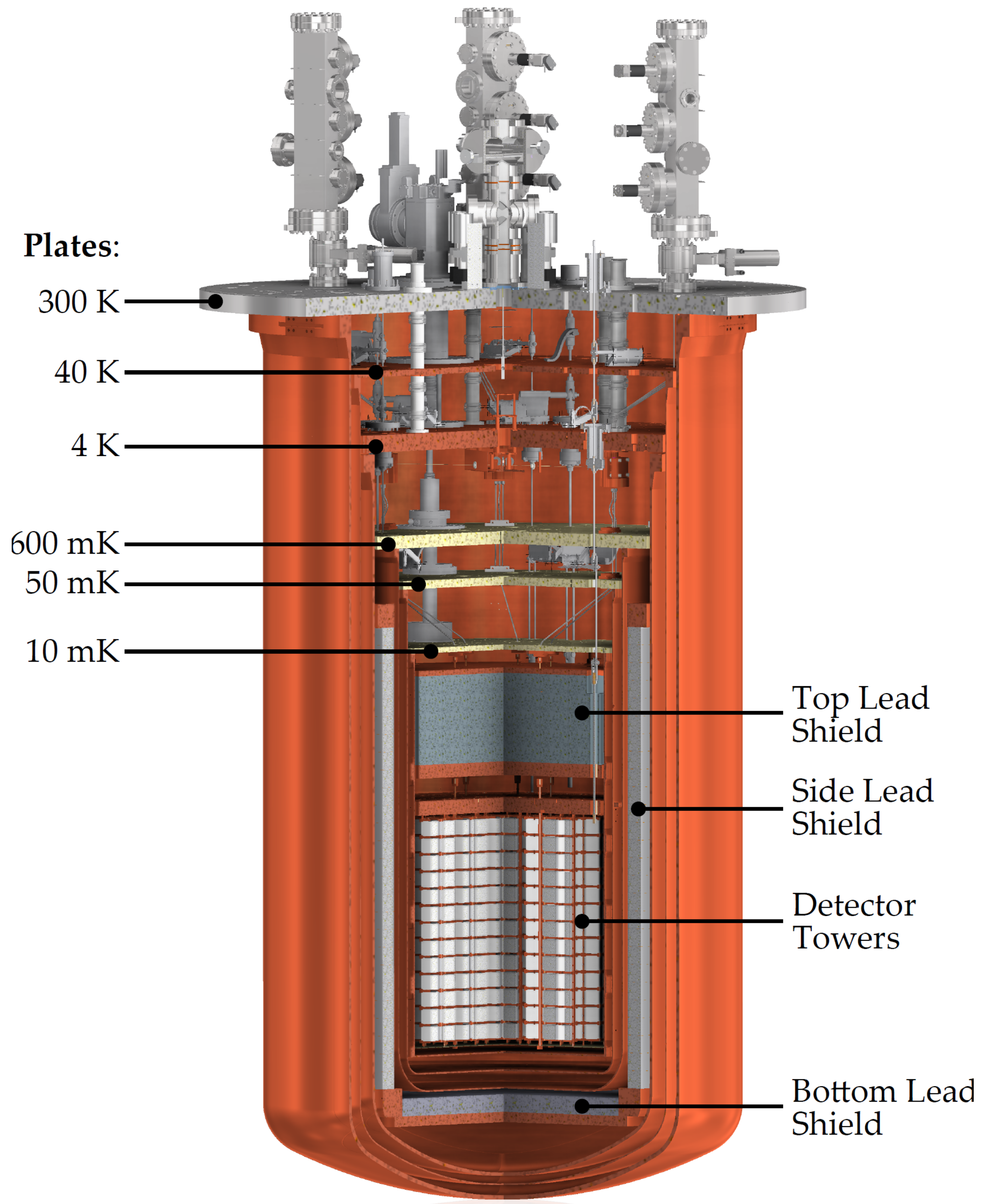


Total mass:
742 kg of TeO_2
206 kg of ^{130}Te



Cryogenic detectors for $0\nu\beta\beta$ decay

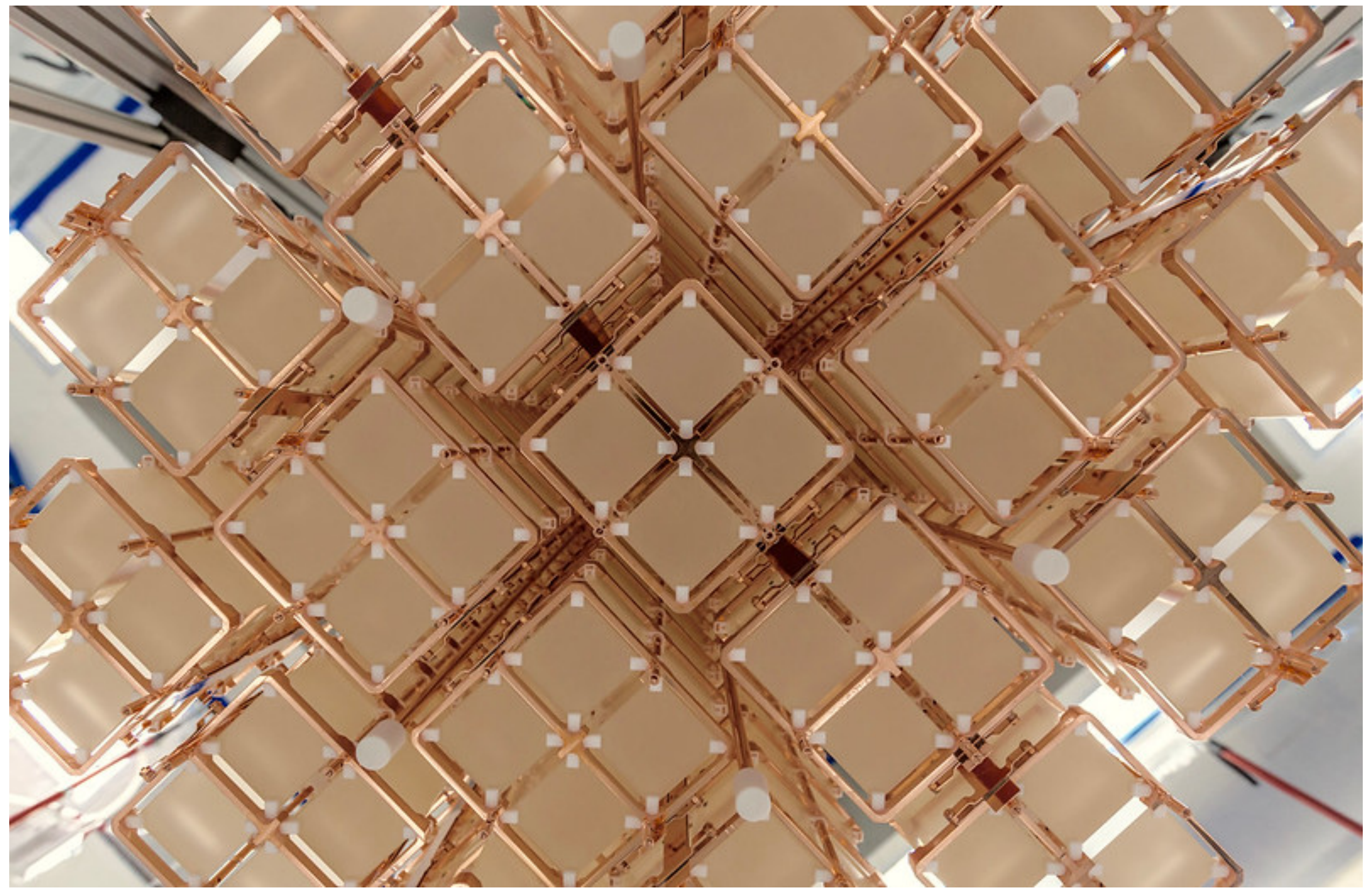
CUORE: from challenge to established technology



- Cryogen free cryostat
- Fast cooling system down to ~50 mK
- 5 pulse tube cryocooler down to ~4 K
- Dilution refrigerator down to ~10 mK.
- Nominal cooling power: 3 μW @ 10 mK

Custom-made cryogenic system

- Designed to cool down ~1 ton detector to ~10 mK.
- Detectors mechanically decoupled for extremely low vibrations.
- Careful selection of materials for low background



TeO_2 crystals kept at 11-15 mK

Cryogenics 102(2019)9

- Cryostat total mass: ~30 ton
- Mass cooled below 4K: ~15 ton
- Mass cooled below 50 mK: ~3 ton (Pb, Cu, TeO_2)

Adv.High.En.Phys(2015)879871

Eur.Phys.J.C77(2017)532

Cryogenic detectors for 0νββ decay

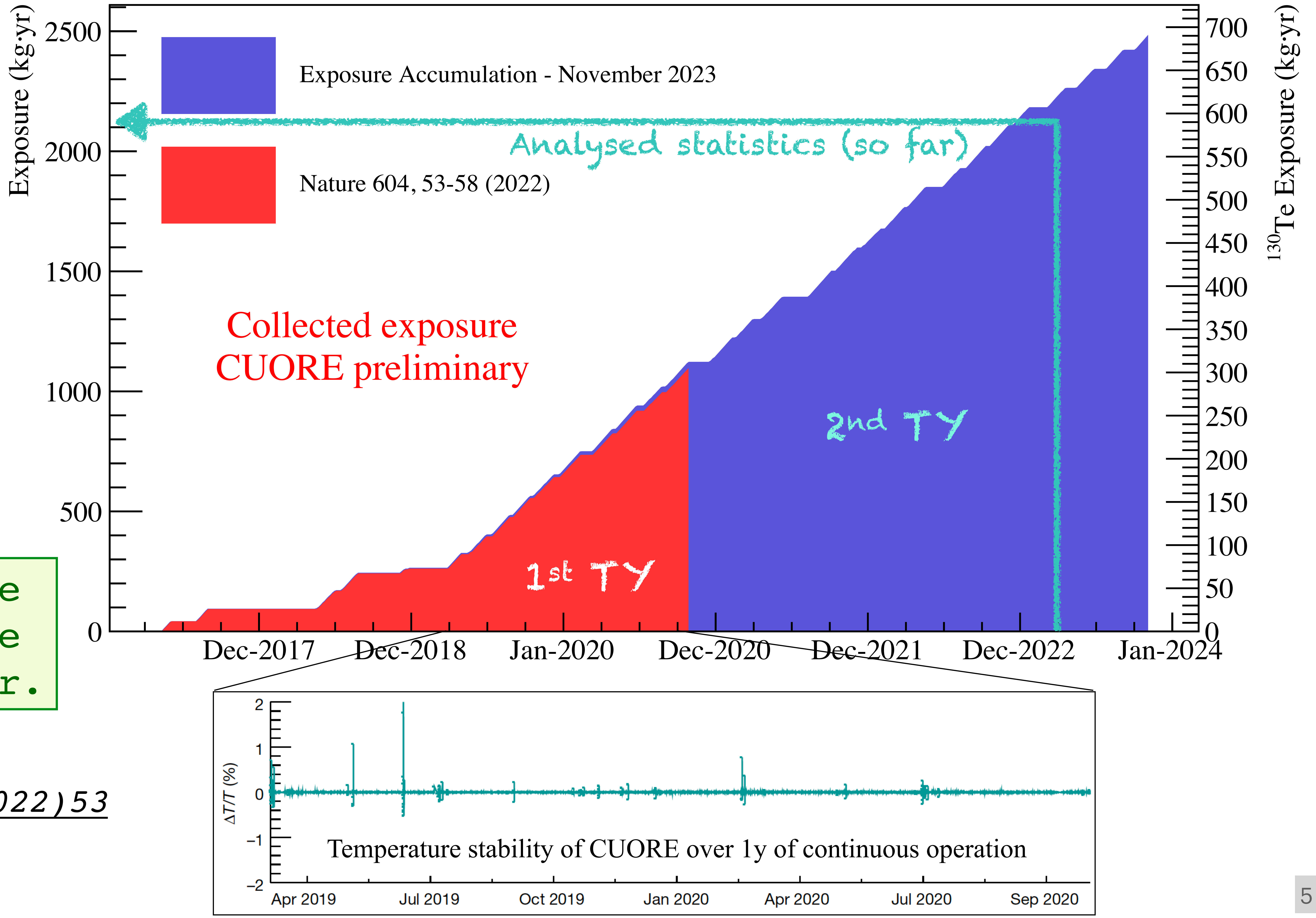
CUORE: from challenge to established technology
→ more than 2 ton•yr of TeO_2 data

Data taking with CUORE

- Continuous data taking since 2017 (with few optimisation campaigns)
- Since March 2019, more than 90% uptime in stable temperature conditions.

Average data taking rate: ~50 kg×yr/month

CUORE is the first to demonstrate stable operation of a tonne-scale milli-kelvin cryogenic calorimeter.

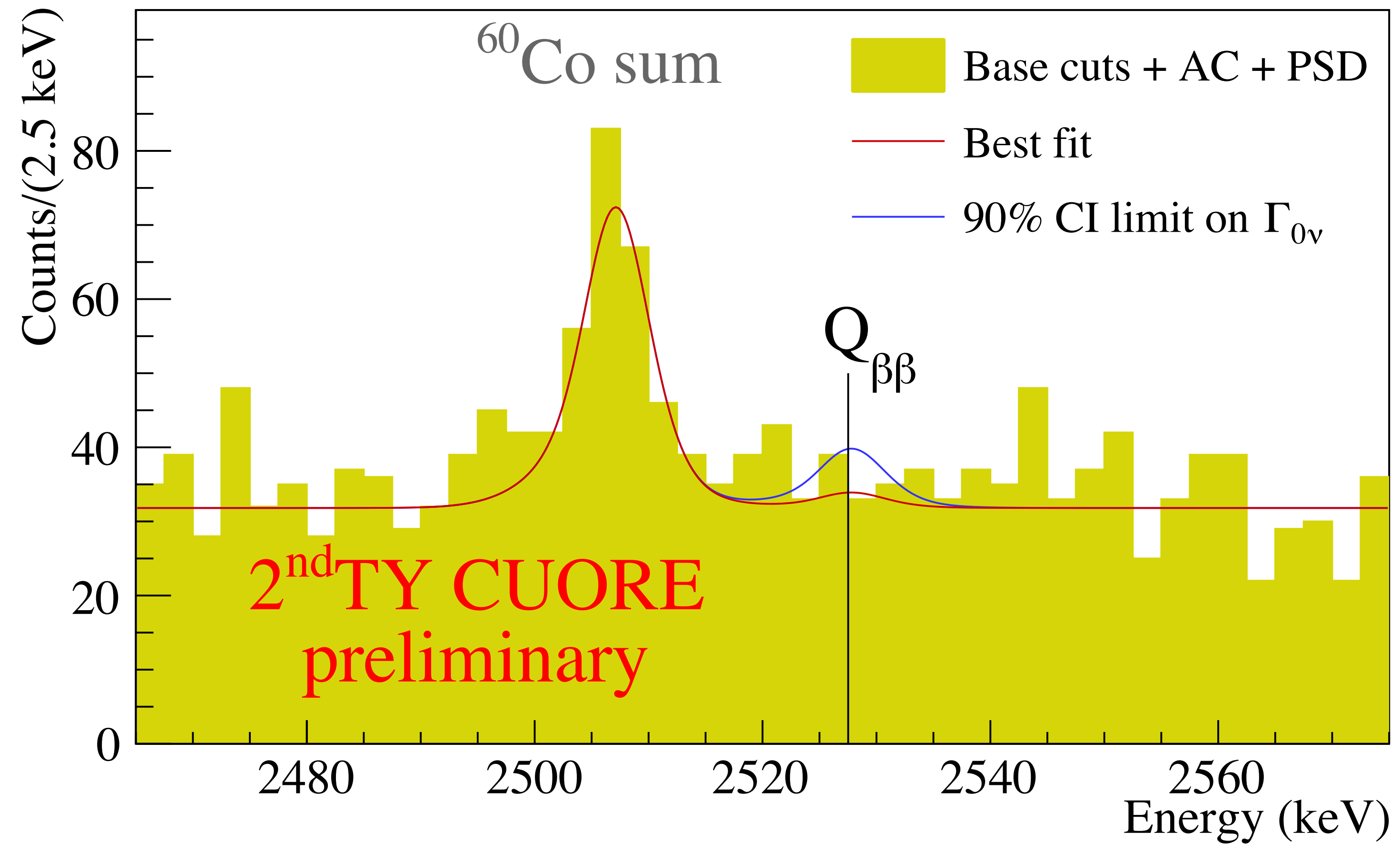


Nature 604(2022)53

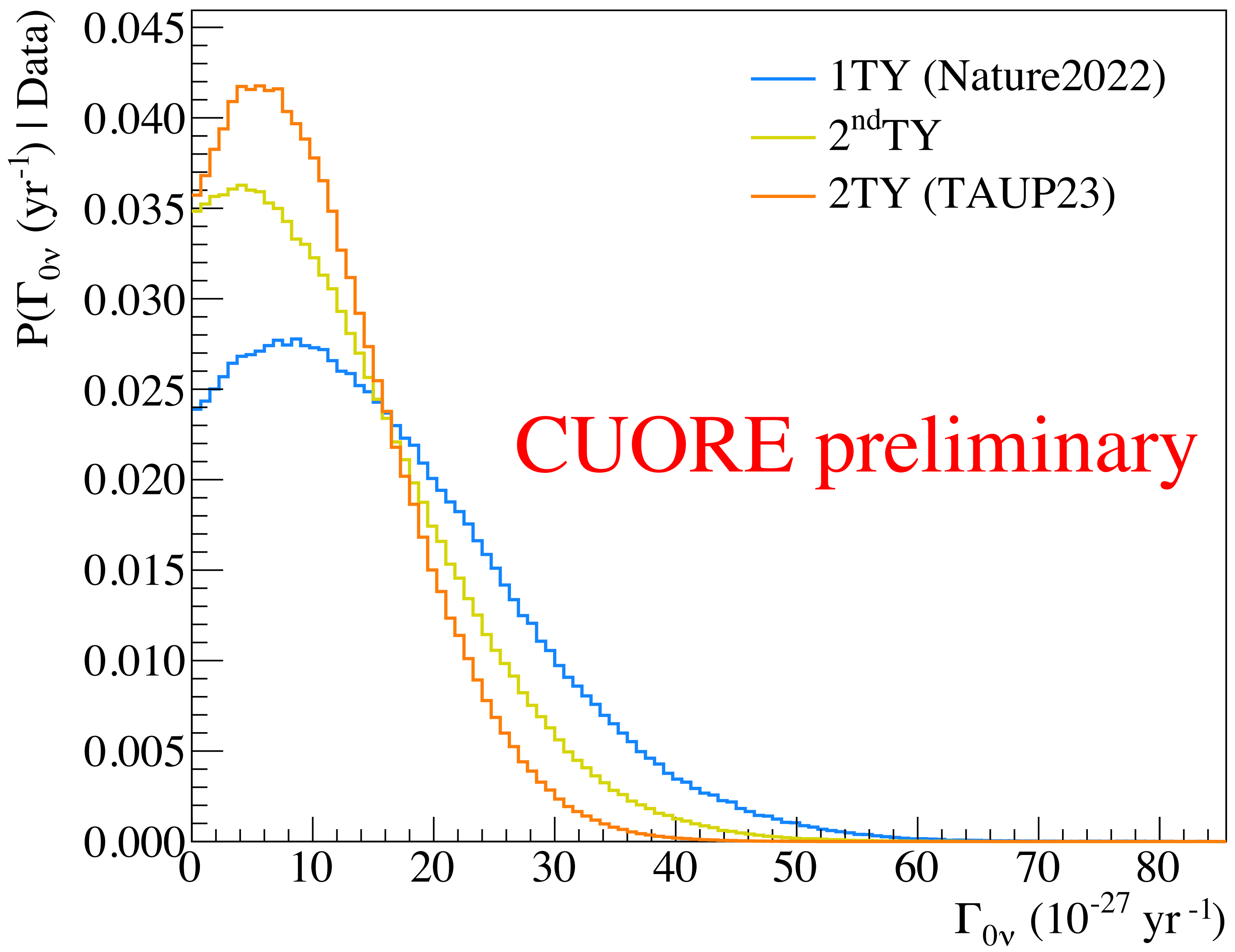
CUORE results

Combining 1st TY and 2nd TY data

- ROI: [2465, 2575] keV
- Fit Model: ^{130}Te $Q_{\beta\beta}$ peak + ^{60}Co sum peak + flat background
  -> rates ($\Gamma_{0\nu}$, Γ_{Co}) and background index (BI) as free parameters
- Unbinned Bayesian fit with $\Gamma_{0\nu} > 0$
- Systematics are treated as nuisance parameters



We combined the posteriors on the $0\nu\beta\beta$ half lives resulting from the analysis of the 1st TY and 2nd TY of CUORE data:



=> **Overall analysed exposure: 2023 kg×yr (TeO_2)**

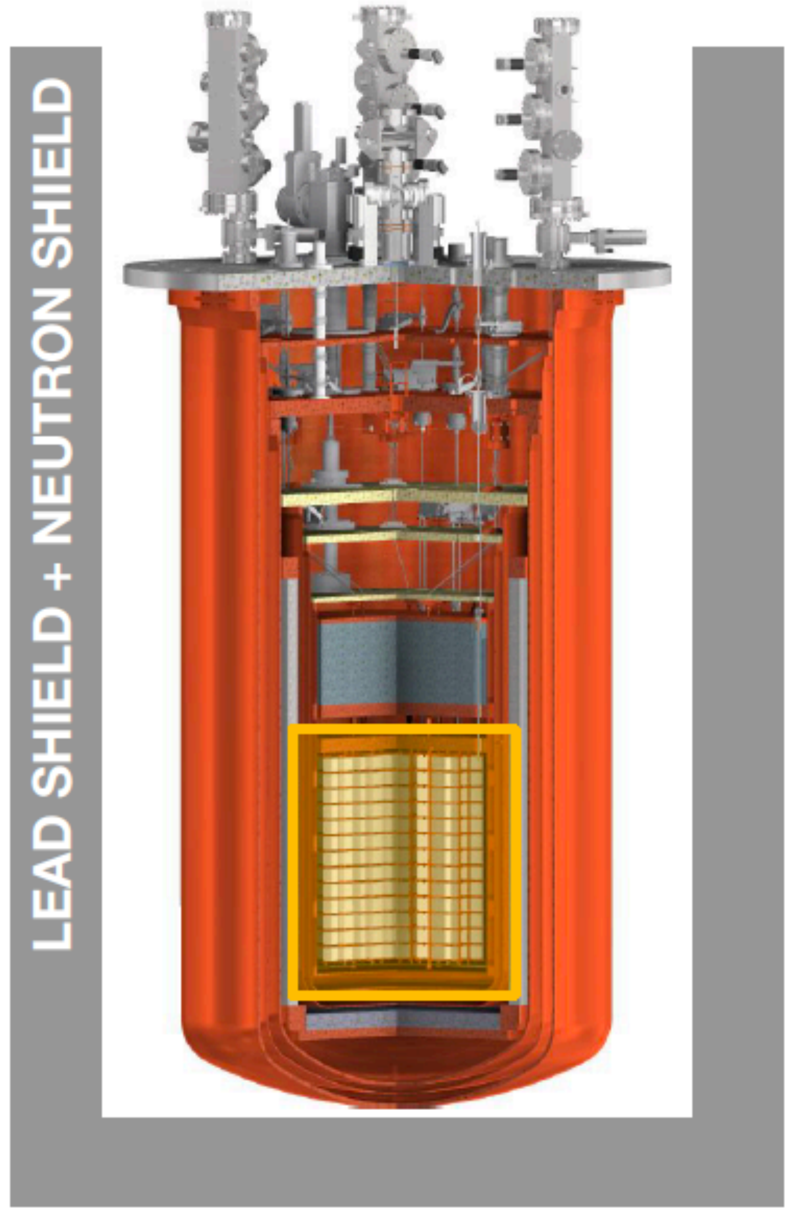
We find no evidence of ^{130}Te $0\nu\beta\beta$ decay

Decay rate limit $\Gamma_{0\nu} < 2.1\times10^{-26}$/yr (90% C.I.)

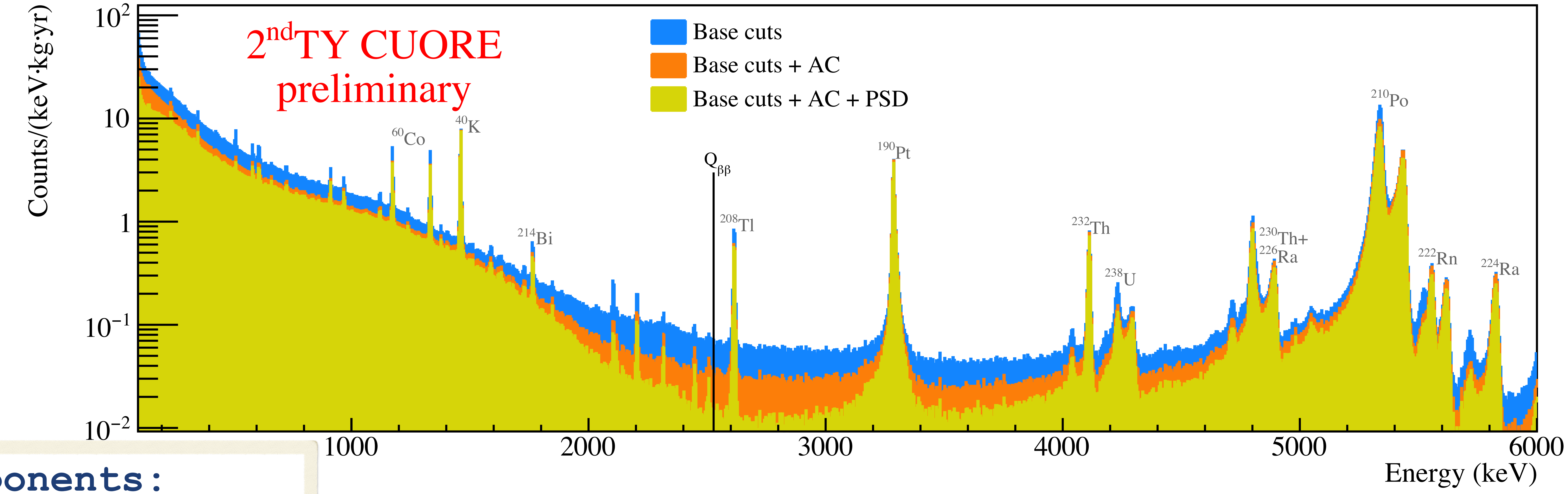
Half life limit $T_{1/2} > 3.3\times10^{25}$ yr (90% C.I.)

Effective Majorana mass limit $m_{\beta\beta} <$ 75-255 meV

CUORE limitations



Modeling CUORE background index BI



CUORE background components:

- ***Bulk contaminations in the materials of the experimental setup:***
  - Main decay chains: ^{232}Th, ^{238}U, ^{235}U
  - Ubiquitous contaminants: ^{40}K, ^{60}Co
  - Fallout: ^{137}Cs, ^{90}Sr, ^{207}Bi
  - Activation: ^{125}Sb, ^{54}Mn, ^{110m}Ag, ^{108m}Ag
  - Others: ^{147}Sm, ^{190}Pt (crystal growing)
- ***Surface contaminations of copper and crystals from main decay chains***
- ***Muons and muon induced background***

Average BI in CUORE ROI [2465,2575]keV for 2nd TY data:

1.30(3) × 10^{-2} c/keV/kg/y

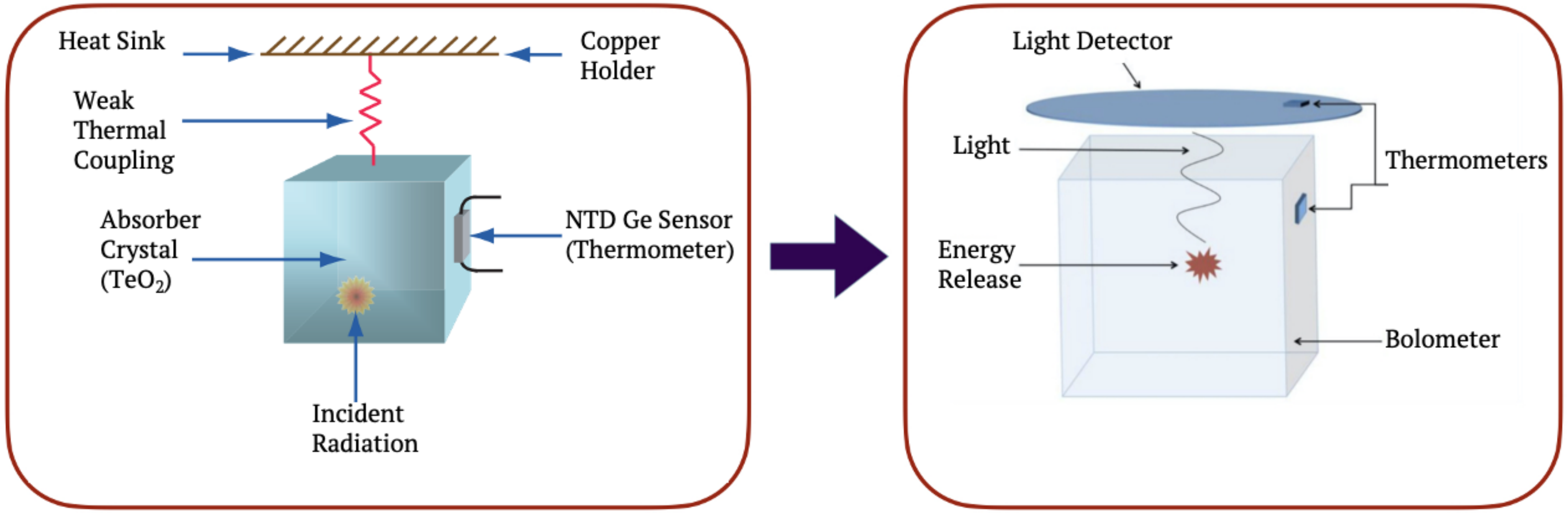
https://indico.cern.ch/event/1199289/contributions/5447161/

CUPID concept

A new detector concept to lower the background index

CUORE ^{130}Te Bolometer

CUPID ^{100}Mo Scintillating Bolometer



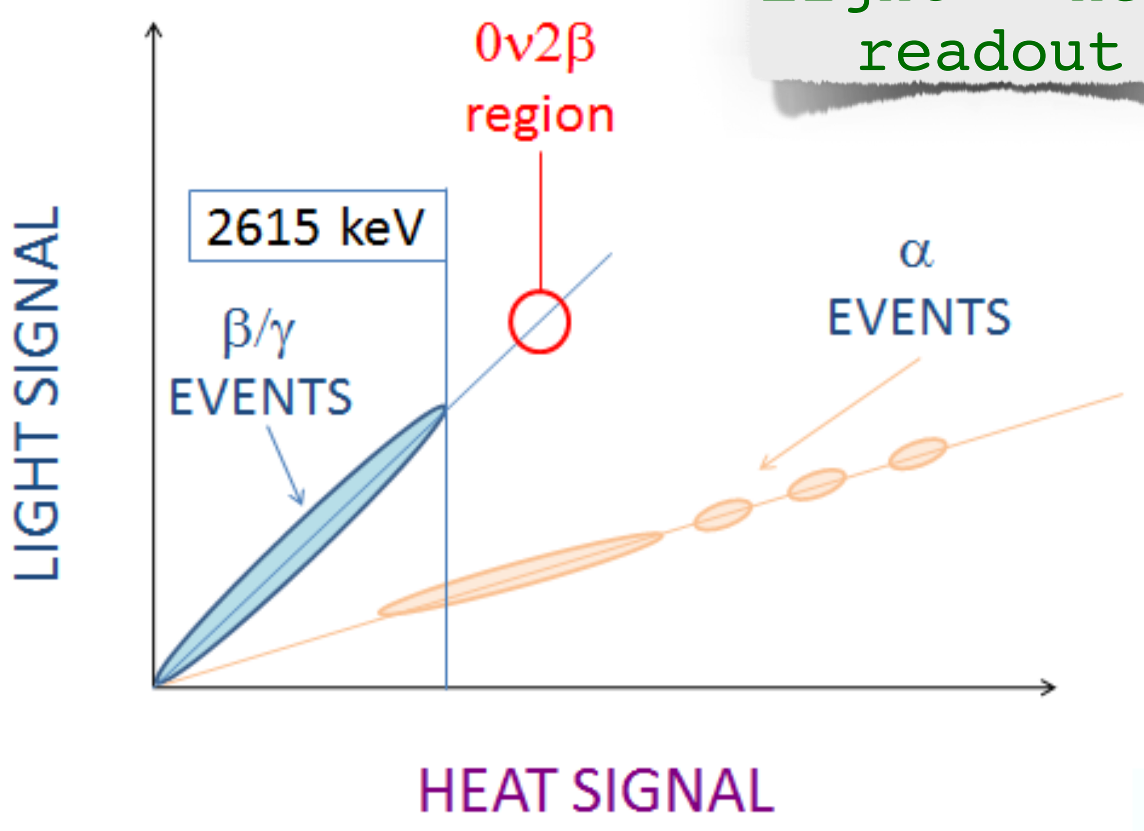
CUORE: no PID

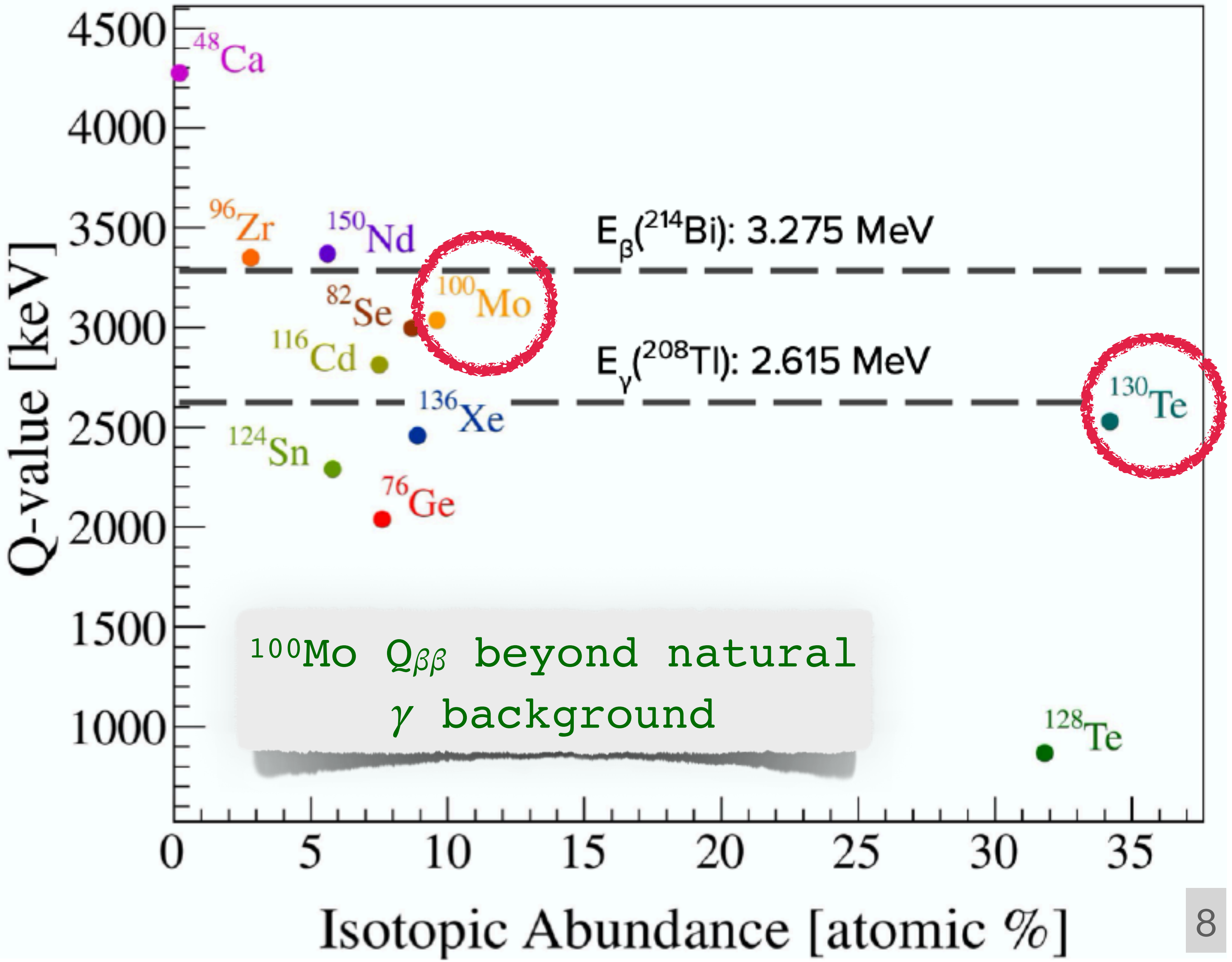
CUPID: PID allows to separate β/γ from α events

A Li_2MoO_4 (LMO) scintillating cryogenic detector to search for the $0\nu\beta\beta$ decay of ^{100}Mo

Particle Identification

Light + heat readout





👁 *CUPID Pre-CDR*

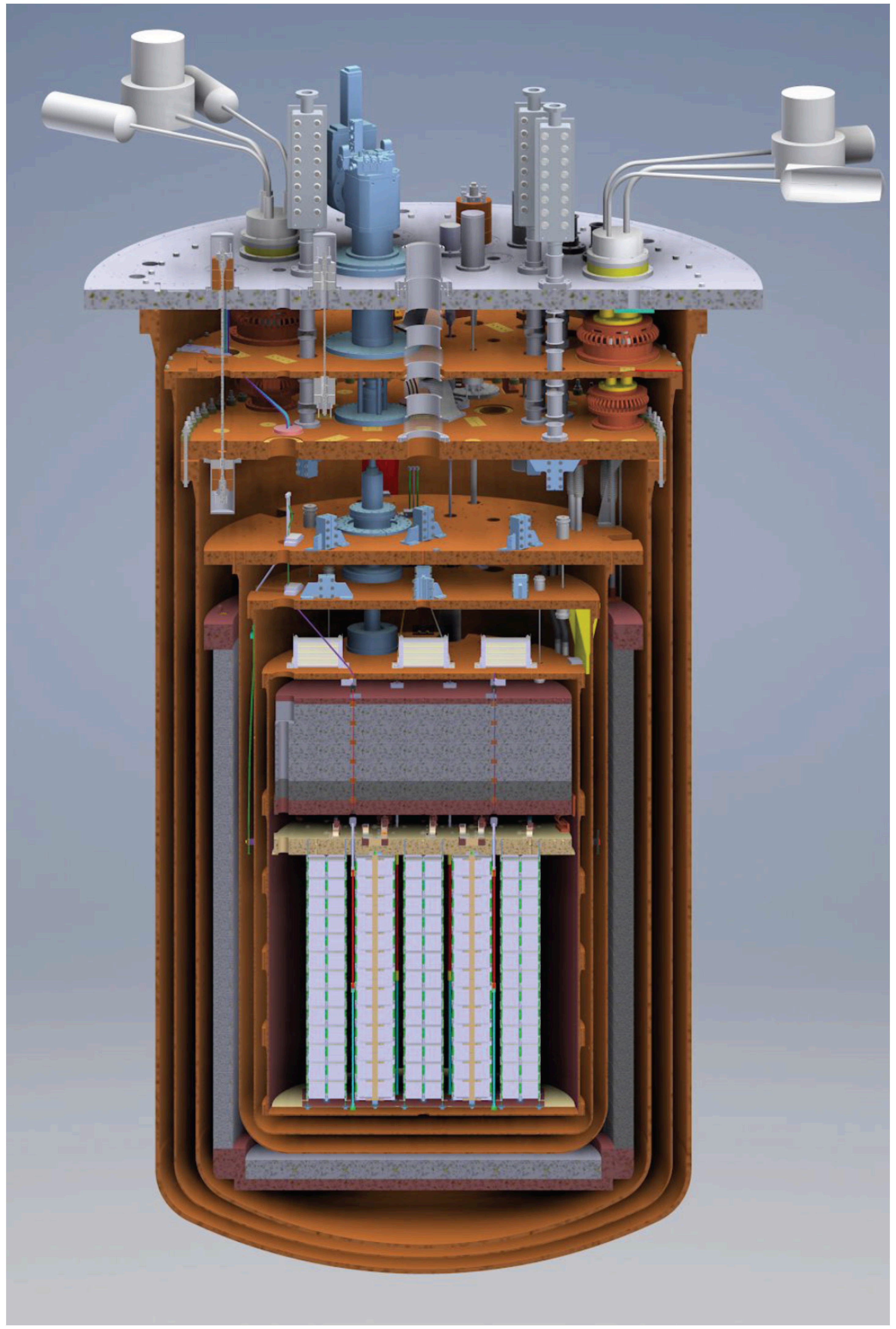
CUPID strategy

A ton scale high resolution array for the search of $0\nu\beta\beta$ decay

- Re-use CUORE infrastructure
- Replace CUORE $^{nat}TeO_2$ detectors with an array of $Li_2{}^{100}MoO_4$ enriched at 95% in ^{100}Mo

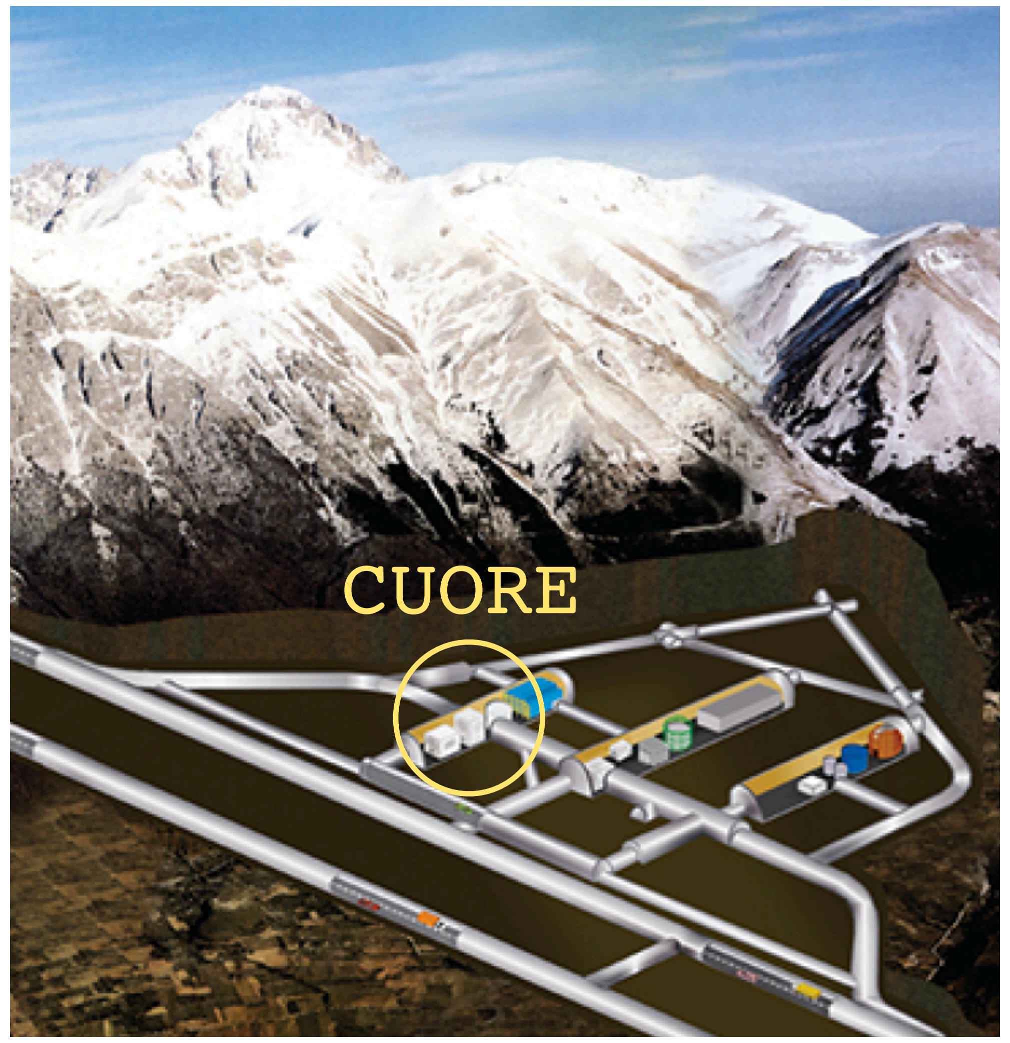
Enough to take a leap forward in sensitivity because background reduces dramatically (~ ×100):

- ^{100}Mo has higher $Q_{\beta\beta}$ (3034 keV) than ^{130}Te: lower γ-induced background, more favourable phase space and matrix element factors
- New detector with α particle rejection: removes the dominant background of CUORE



CUPID location

LABORATORI NAZIONALI DEL GRAN SASSO

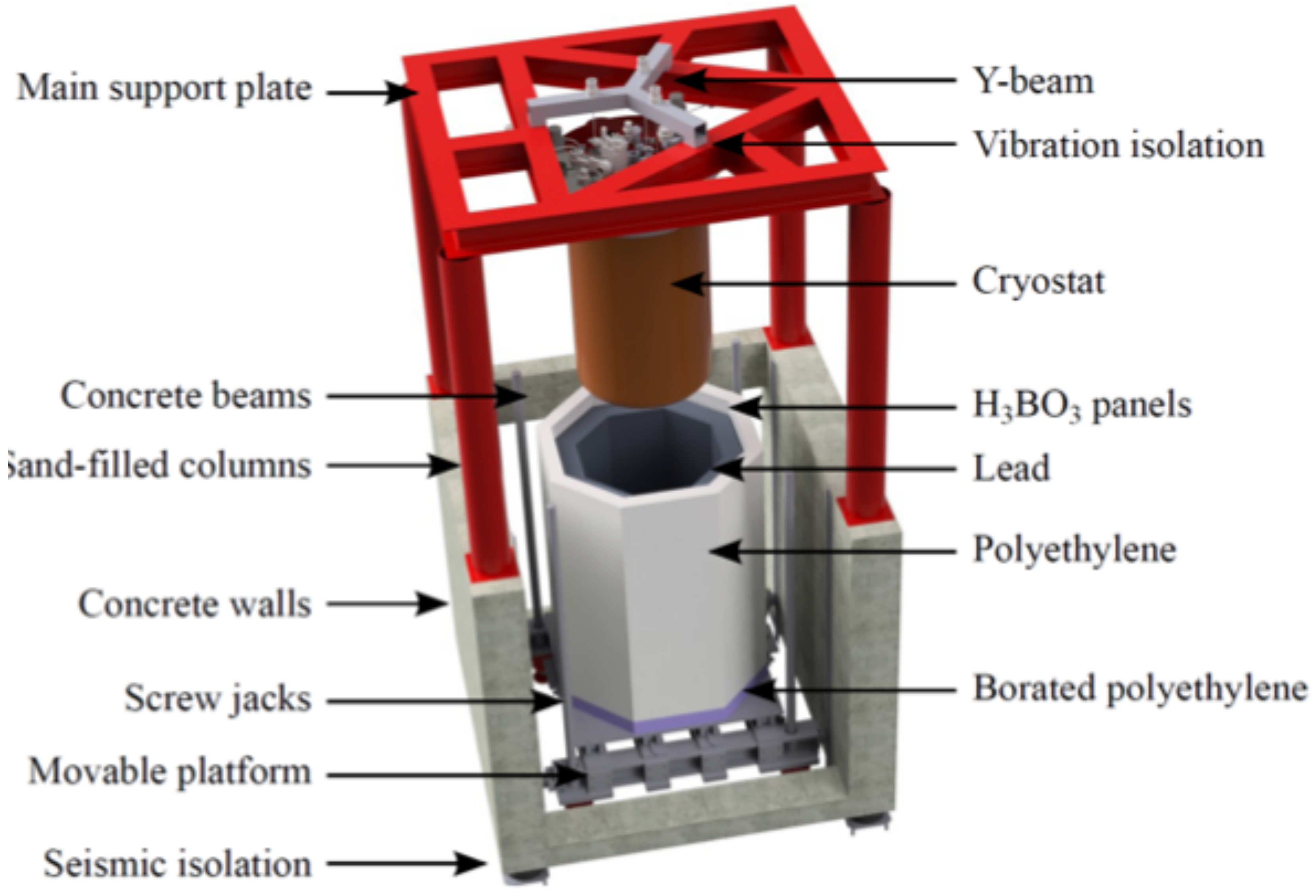


Average depth ~ 3600 m.w.e.

μ flux: 3×10^{-8} $\mu/s/cm^2$

n flux: 4×10^{-6} $n/s/cm^2$ < 10 MeV

γ flux: ~0.73 $\gamma/s/cm^2$ < 3 MeV



- 25 cm of Lead
- 20 cm of Borated Polyethylene and boric acid

CUORE data taking will be stopped in 2025

The goal is to reach 3TY TeO_2 exposure (1TY ^{130}Te exposure)

CUPID collaboration

~180 collaborators from 7 different countries

Major participants: Italy (~60), USA (~40), France (~25)
Other participants: Ukraine, Russia, China, Spain

https://cupid.lngs.infn.it/

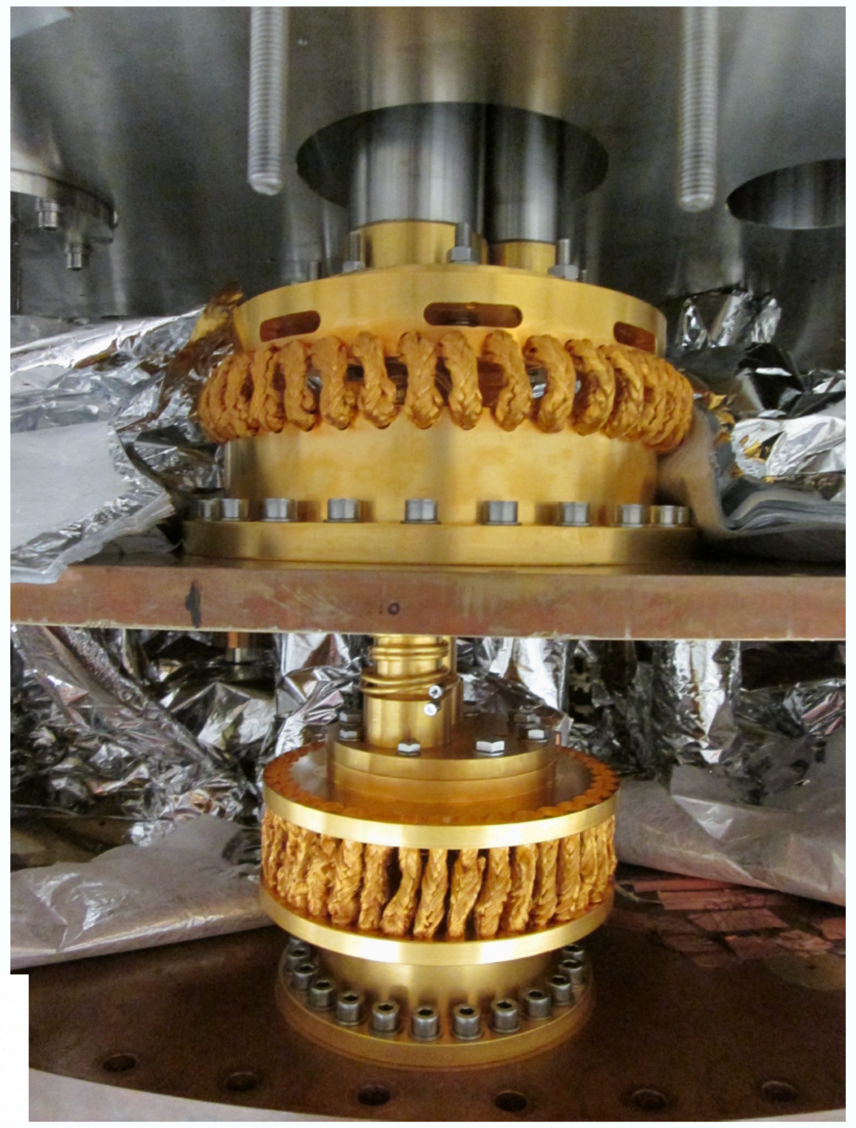
Leverages previous collaborative experience:

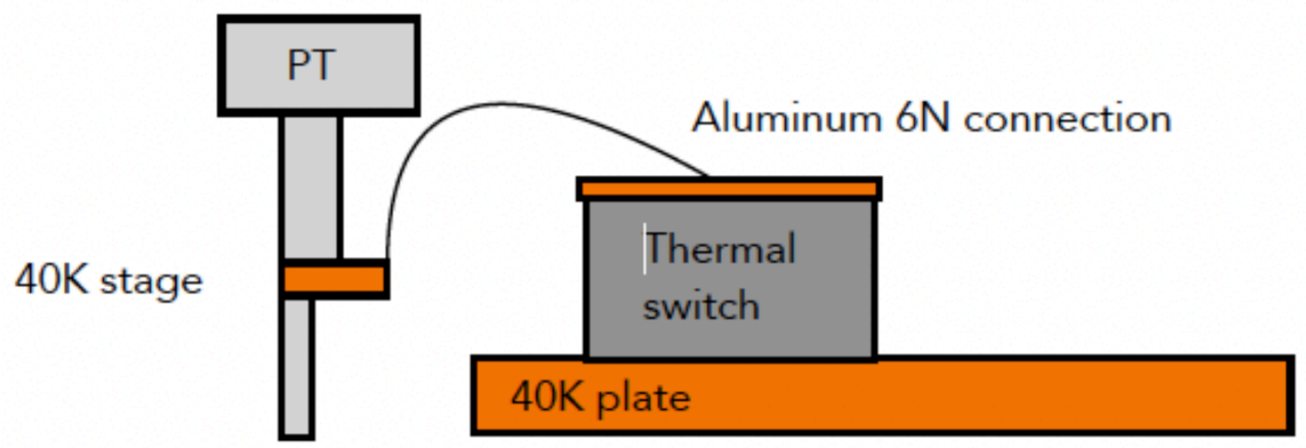
- CUORE
- CUPID-0
- Cupid-Mo

CUORE infrastructure beyond 2025

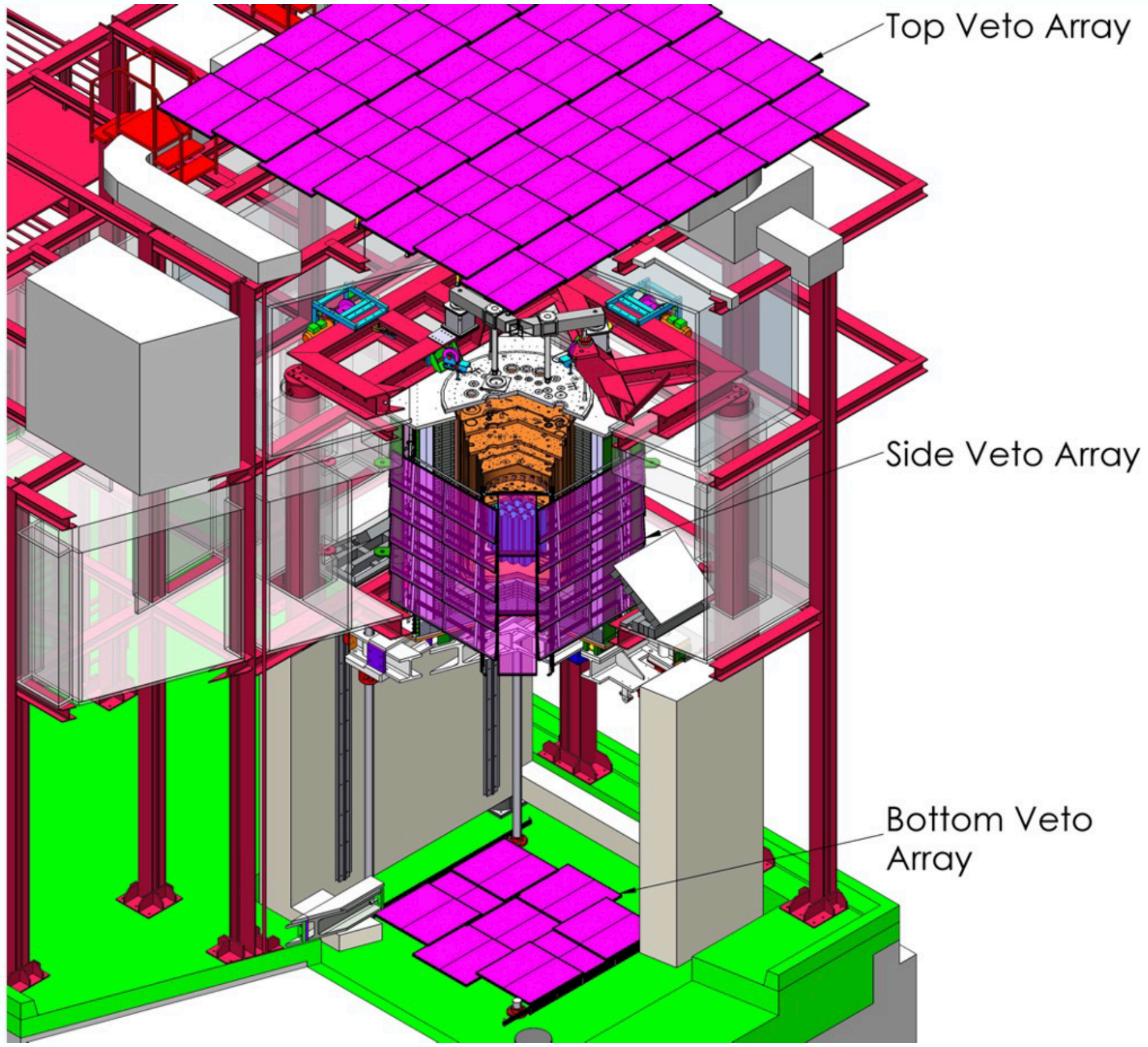
Planned upgrades in view of CUPID

Cryogenic upgrades
- new pulse tubes
- new thermalisation





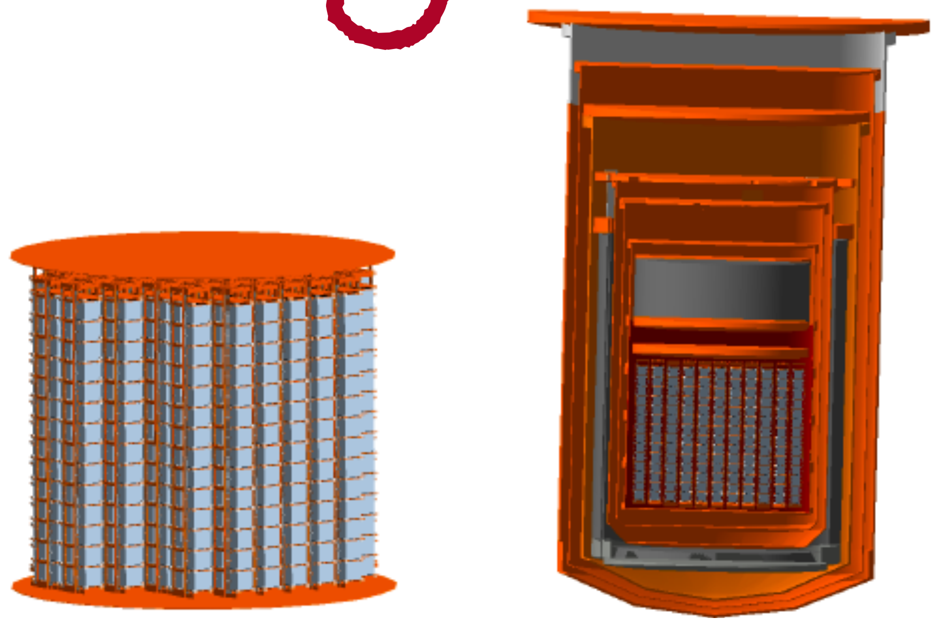
Muon tagger system

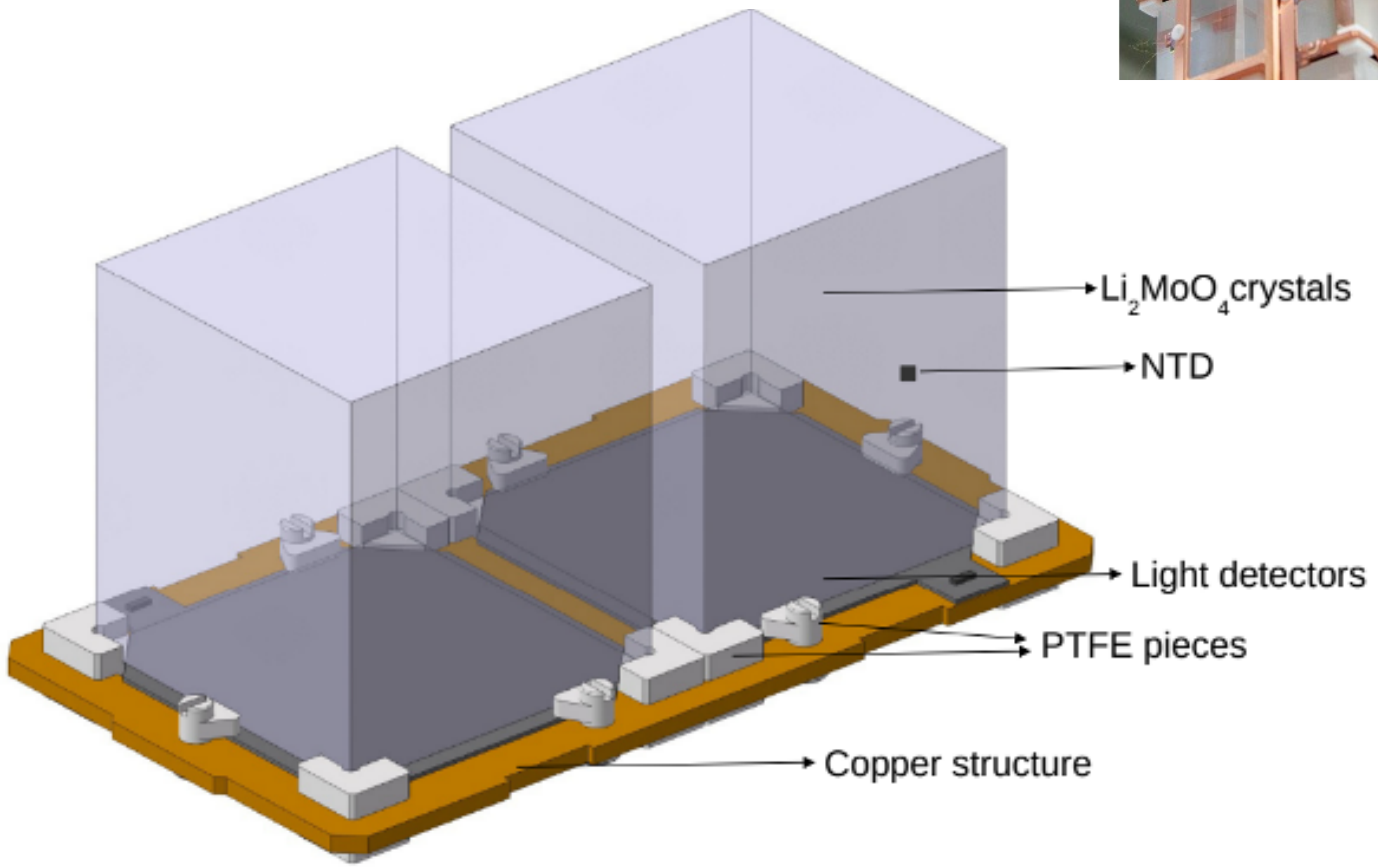


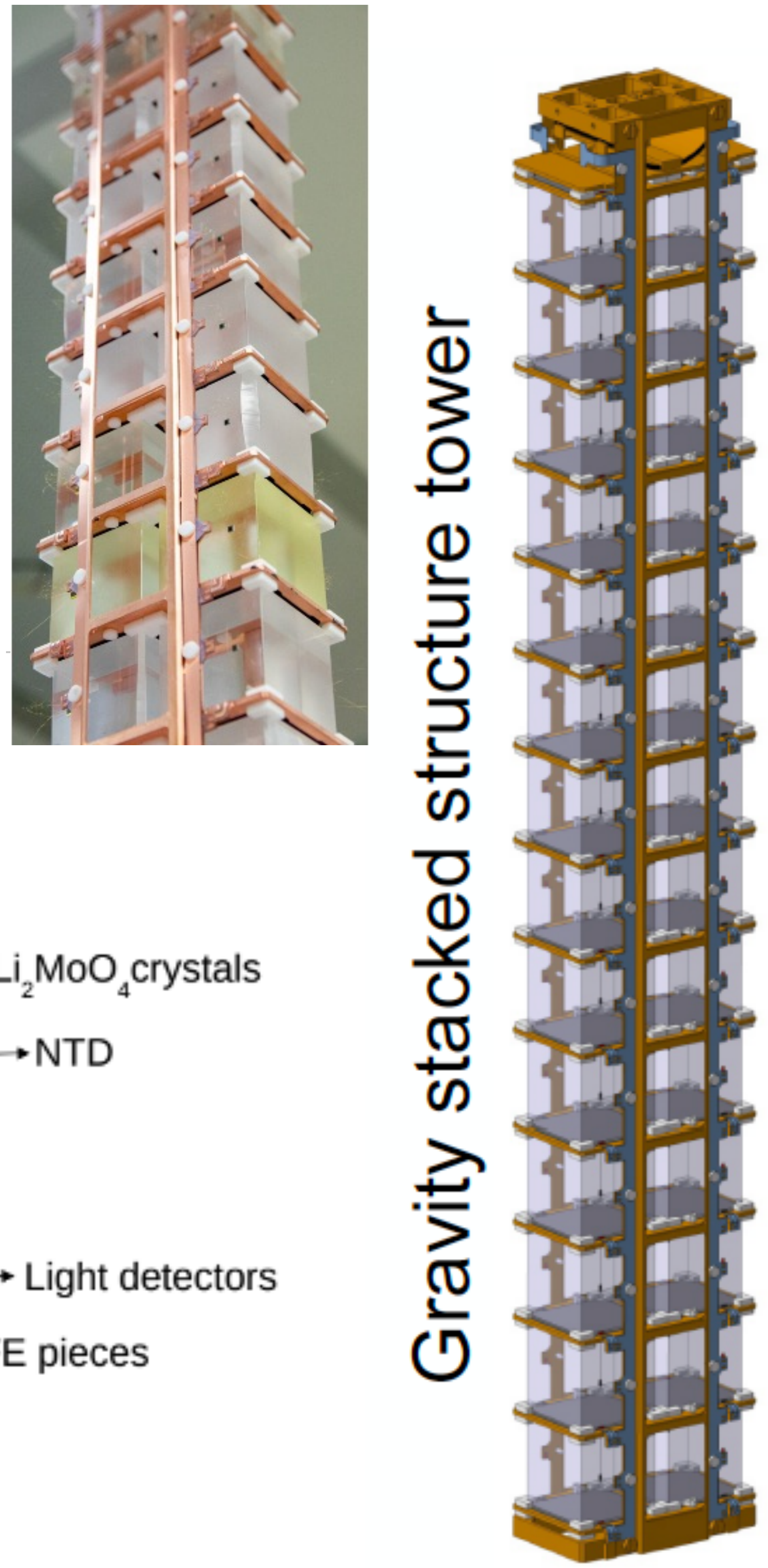
CUPID detector array

The baseline design

- **$45\times45\times45$ mm^3 $Li_2{}^{100}MoO_4$ crystals:**
  - Single crystal mass: 280 g
- **1596 crystals in the array**
  - 450 kg of $Li_2{}^{100}MoO_4$
  - 95% enrichment in ^{100}Mo: 240 kg of ^{100}Mo
  - 57 towers of 28 crystals each. 14-floors of 2×1 crystal pairs. Gravity assisted design
- **Ge light detectors (LD) with SiO anti-reflective coating.**
  - Top and bottom light detectors for each crystal: 1710 light detectors
  - No reflective foils
- **Muon veto for muon-induced background suppression**







- **CUPID performance goal**
  - Energy resolution: 5 keV FWHM
  - Light Yield: 0.3 keV/MeV
  - LD: $\sigma_{baseline}$ ~100 eV for PID
  - Background: 10^{-4} ckky (counts/keV/kg/y)

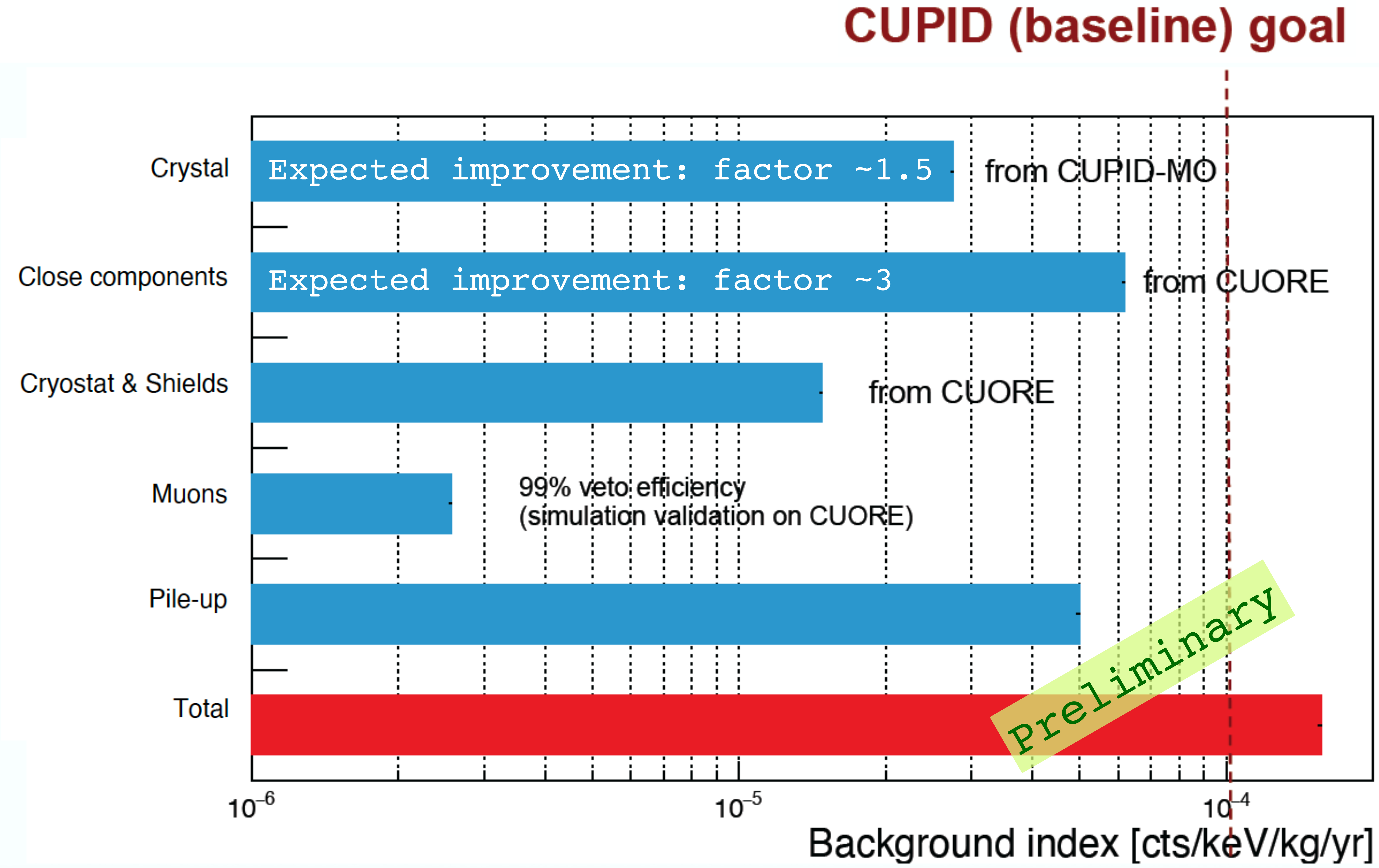
Eur.Phys.J. C82(2022)810

CUPID background budget

The expected background rate in the ROI

CUPID background budget is designed on the basis of results inferred by precursors experiments:

- **CUORE background model validates:**
  - The β/γ background contribution from the cryogenic system and the detector holders at ~3 MeV
- **CUPID-Mo confirms:**
  - α tagging
  - Energy resolution
  - Crystal radiopurity
- **CUPID-0 confirms:**
  - α rejection
  - β/γ bkg from detector holders

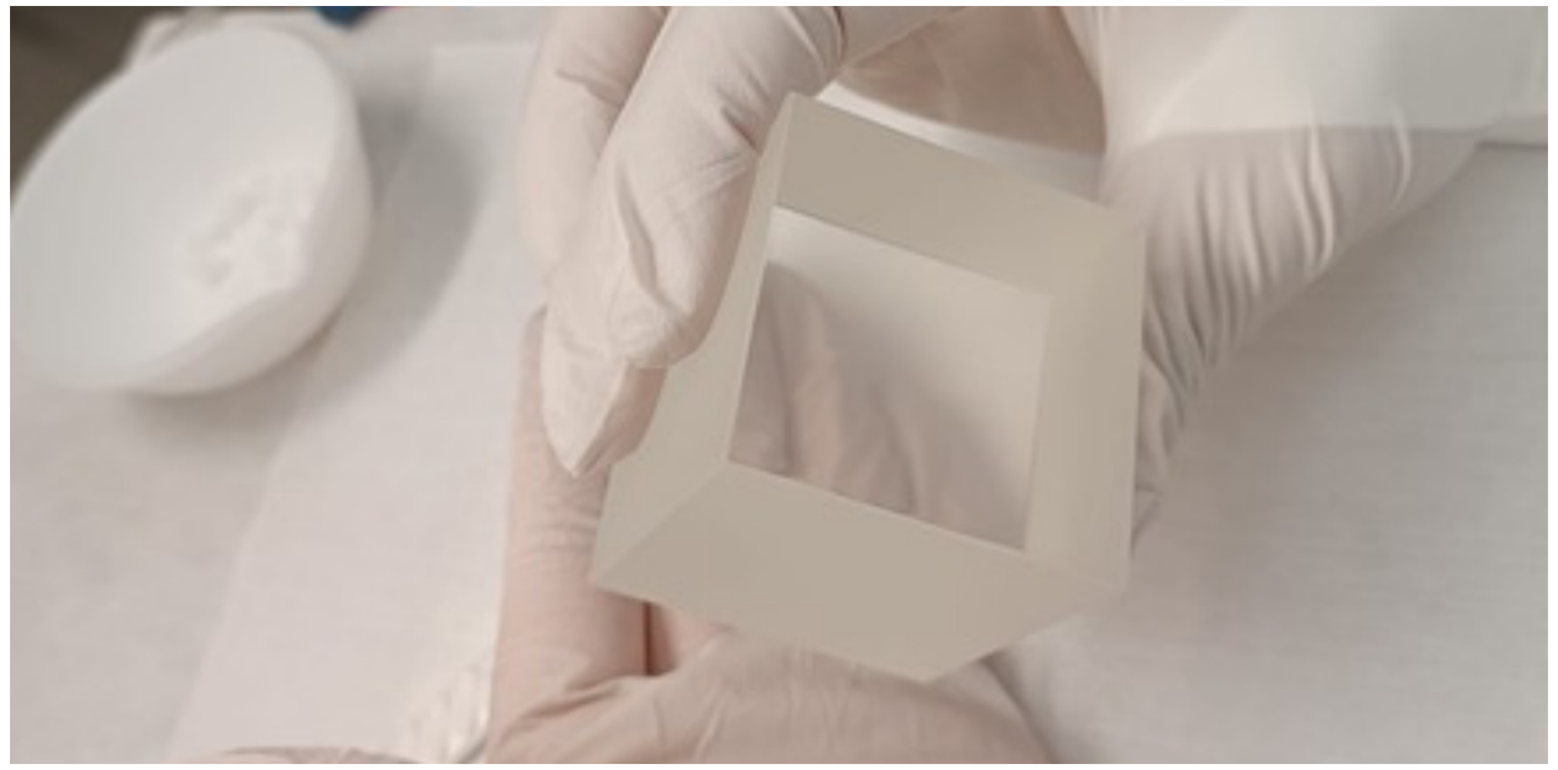


Using past experiment achievements, the total estimated background in CUPID ROI ([3034 ± 15] keV) is: ~1.4×10^{-4} ckky
⇒ expected improvements will lead to the background goal of 10^{-4} ckky

On the way to CUPID

Enriched LMO crystal production

- Enriched LMO crystal pre-production is ongoing in China at SICCAS (Shanghai), funded by INFN (Italy) and CNRS (France).
- SICCAS is a highly reliable producer, having already made the CUORE crystal array.



CUPID LMO natural crystals by SICCAS

- Sequential crystal tests at the Gran Sasso CUPID facility are being conducted to assess performance and analyse residual radioactivity.
- In parallel, we are working on the strategies to improve the surface cleaning of crystals and close components, to reach the 10^{-4} ckky baseline bkg goal.
- Production at large scale of the entire CUPID array at SICCAS is feasible. INFN is presently negotiating with SICCAS the full purchase.

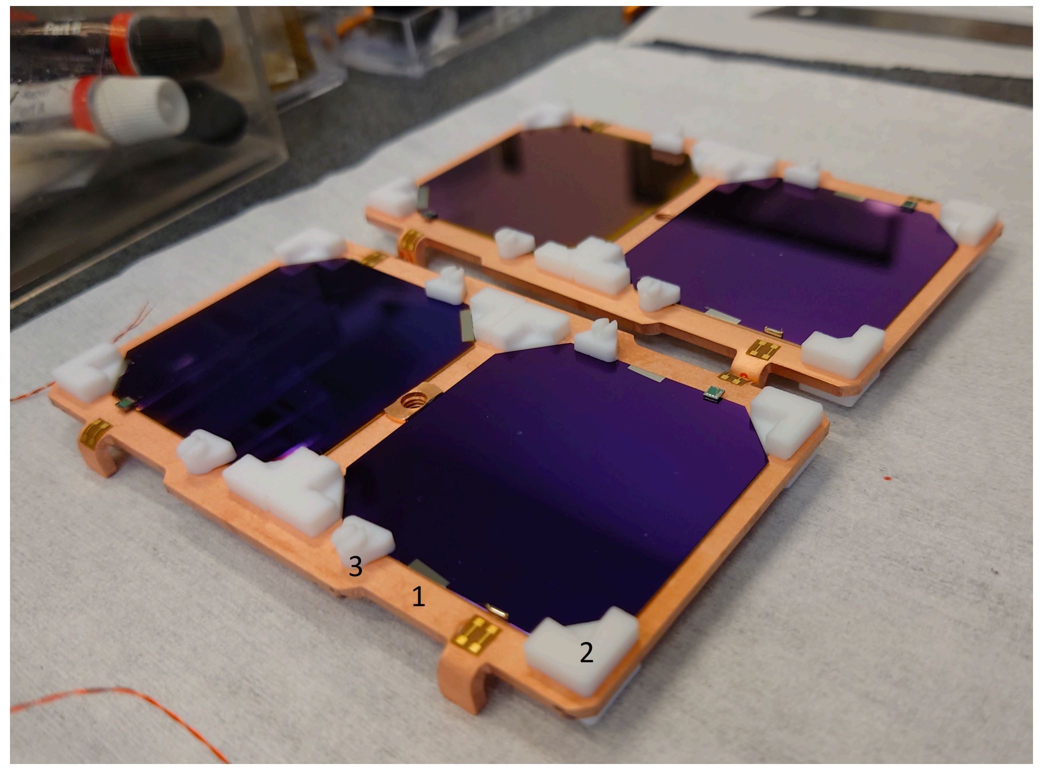
On the way to CUPID

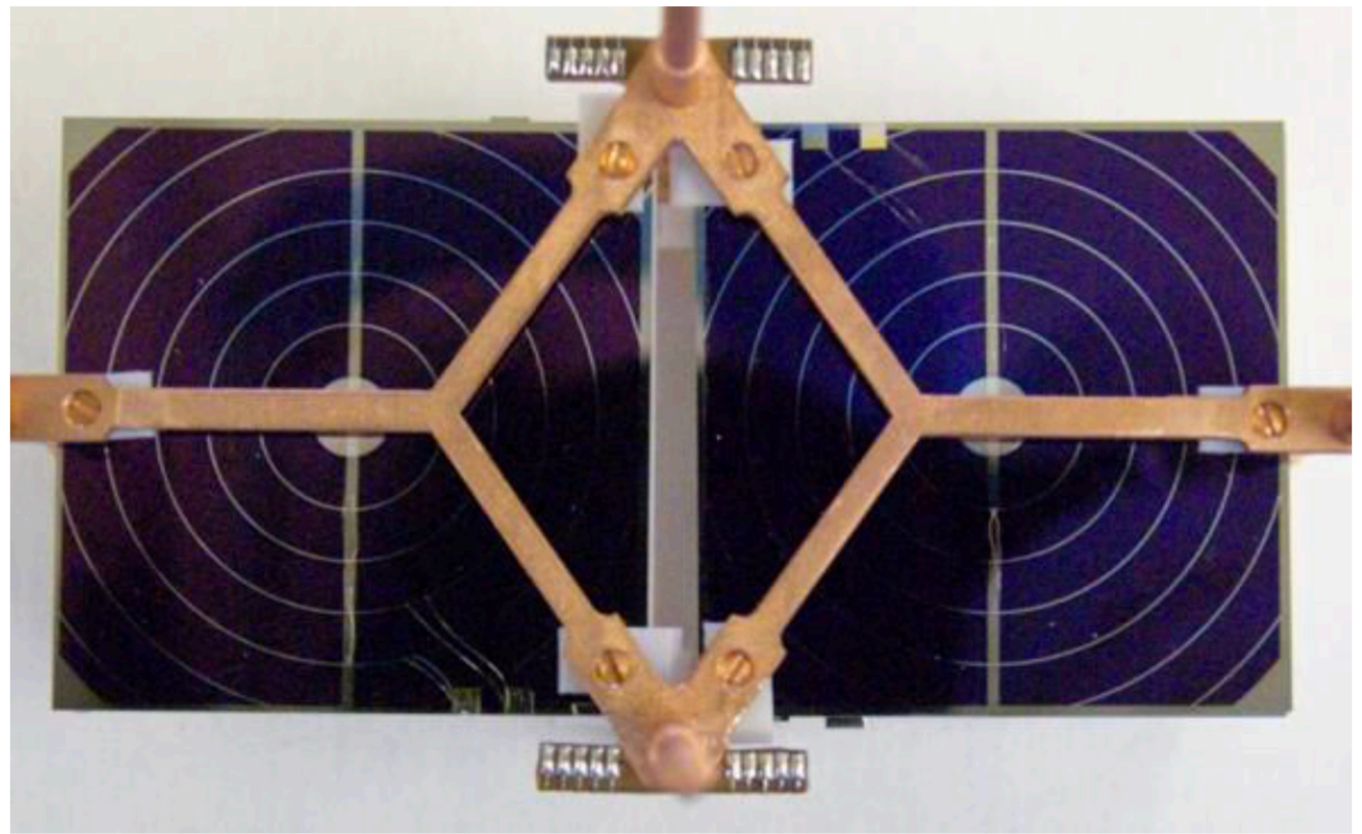
CUPID enhanced light detectors

- Relatively fast ^{100}Mo 2ν double beta decay ($^{2\nu}T_{1/2} = 7.1\times10^{18}$ y) leads to the possibility of two 2ν decays to sum up in the ROI -> it is the ultimate background for $0\nu\beta\beta$ experiments.
- CUPID goal for pile-up background contribution: 5×10^{-5} ckky
- Light detectors made of high-purity Ge wafer with SiO anti-reflective coating and NTD readout are a robust technology already used in several small-medium scale prototypes.
  The use of the NTL (Neganov-Trofimov-Luke) amplification enables their use for pile-up rejection, fulfilling CUPID requirements.

Assembled light detectors for test in a Pulse Tube cryostat at IJCLab

JINST 18 P06033



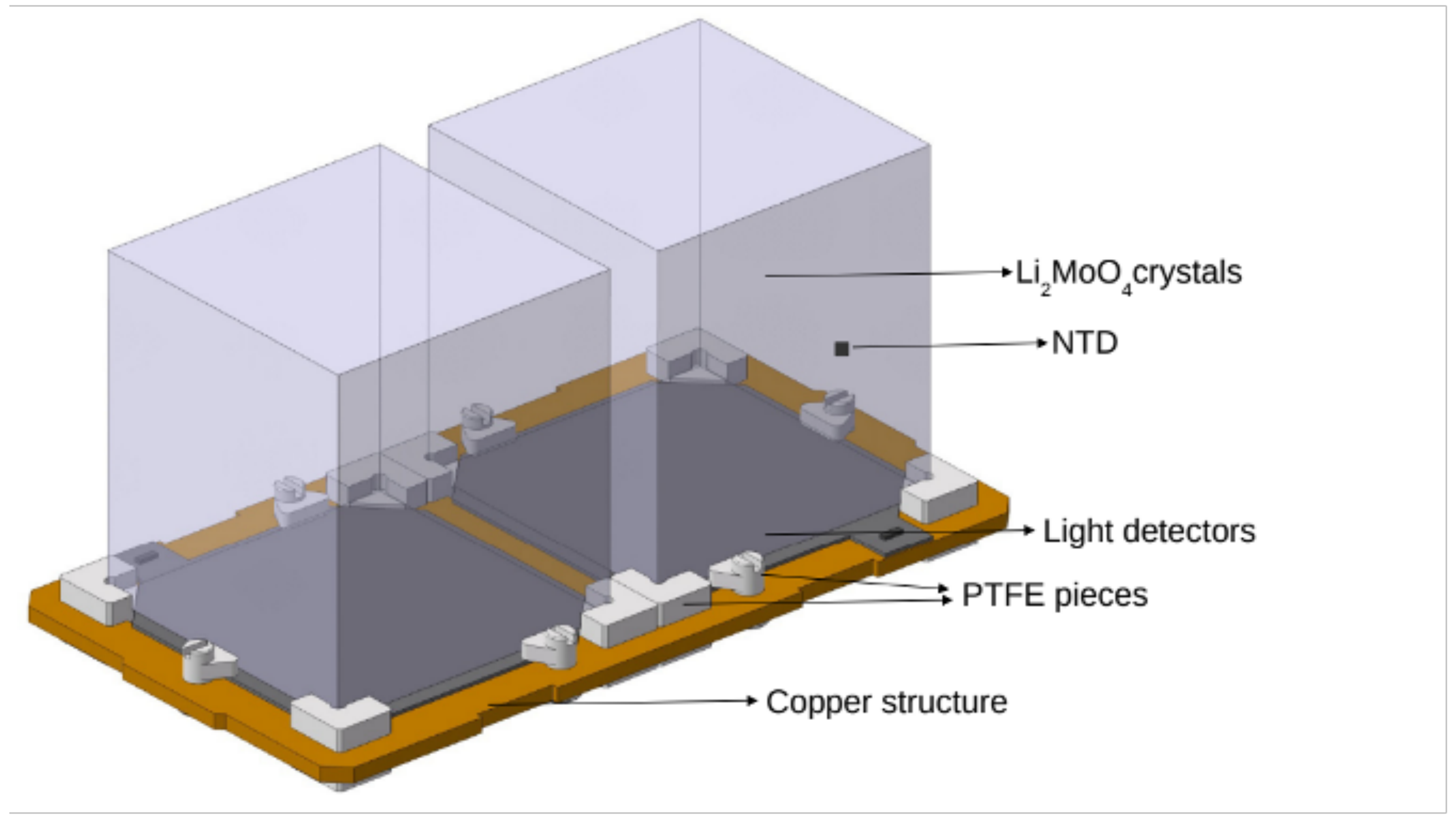


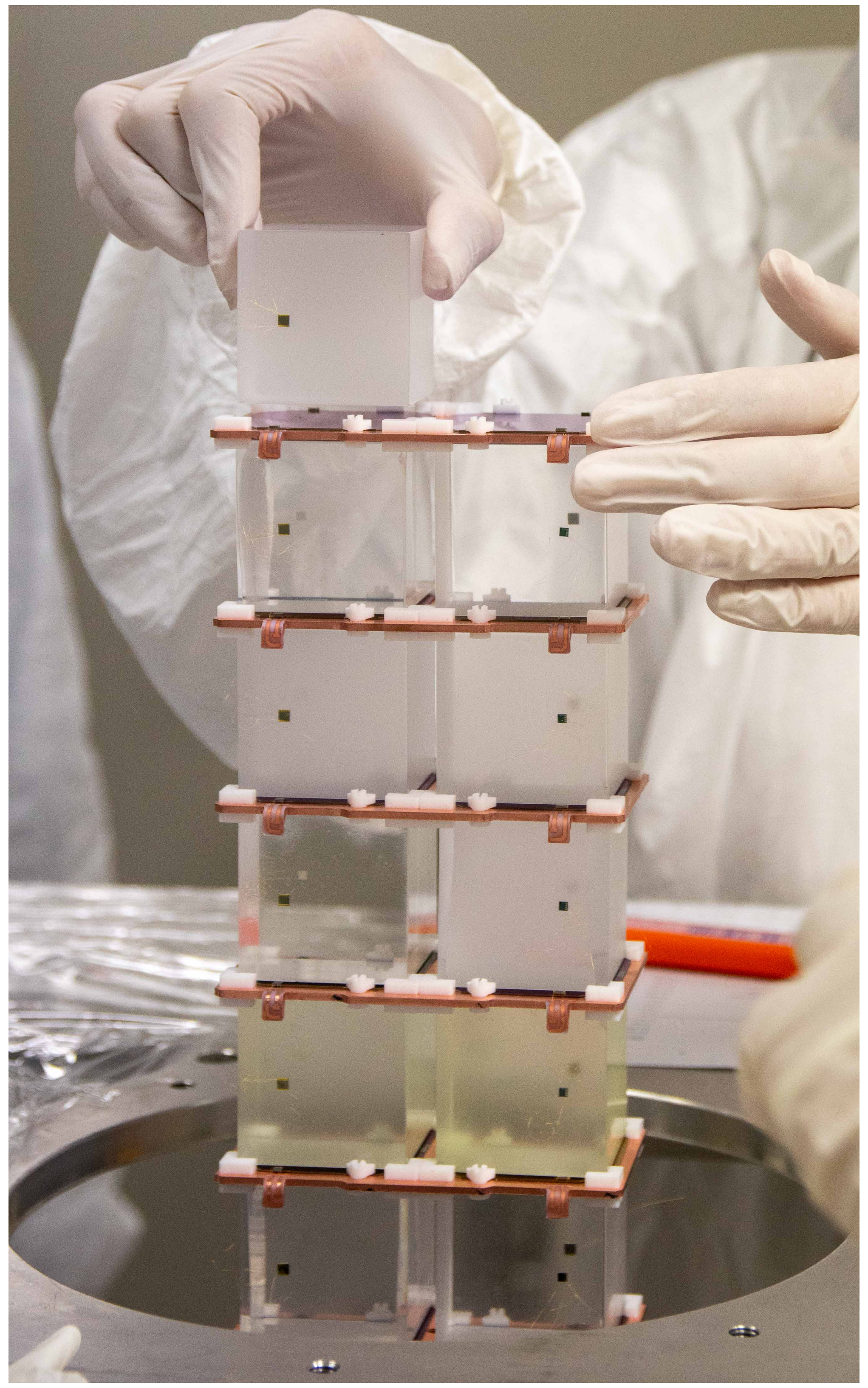
NTL-based light detectors

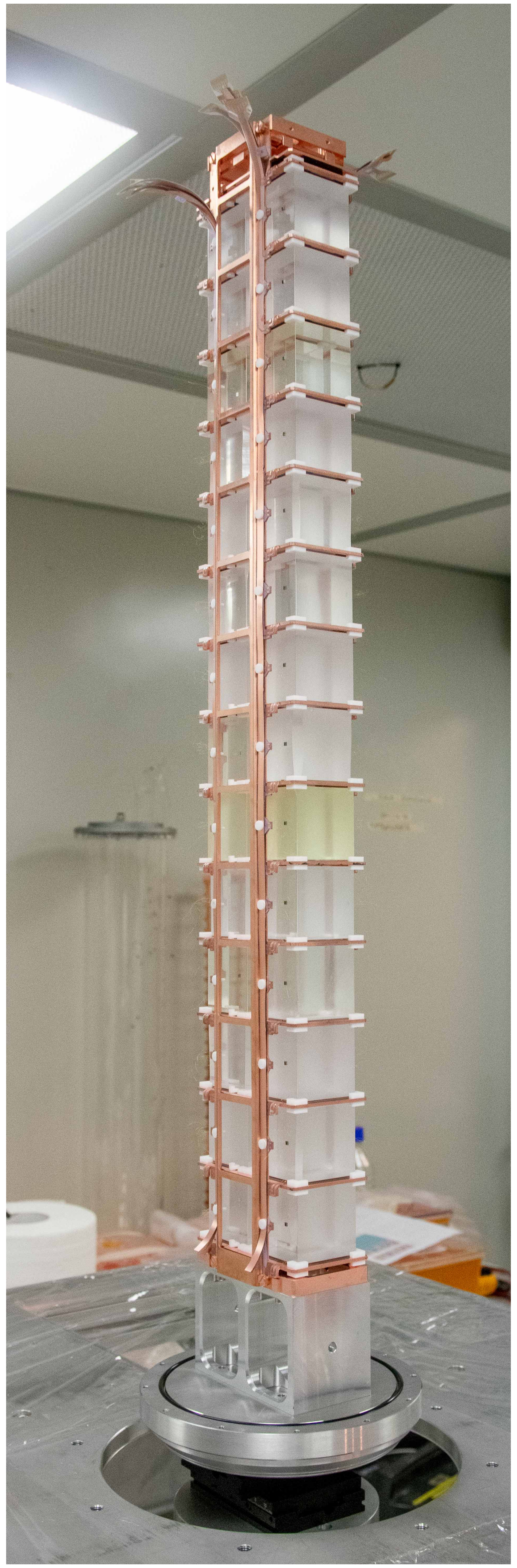
On the way to CUPID

Tests on new tower design

- Prototype towers to optimise the new assembly design are being tested in one of the LNGS test cryostats.
- Main parameters under study are noise performance and FWHM resolutions.

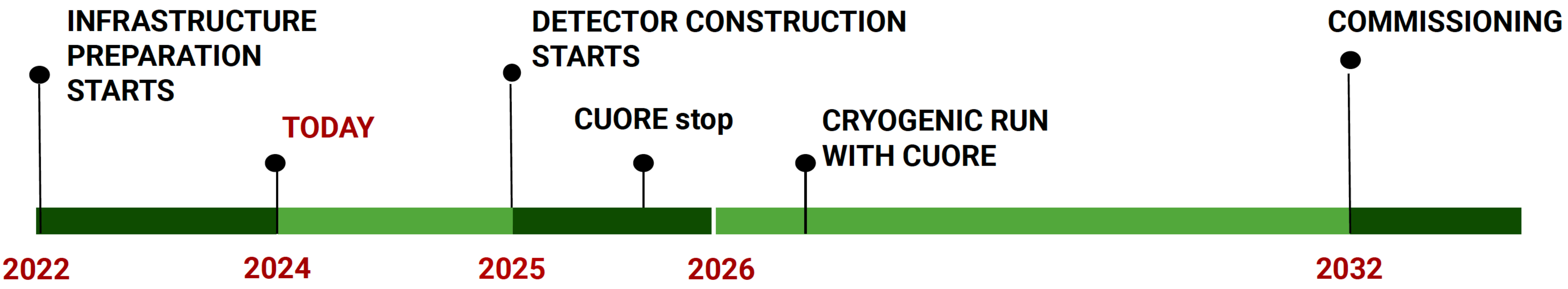






CUPID timeline

Present schedule



★ $Li_2{}^{100}MoO_4$ pre-production

★ $Li_2{}^{100}MoO_4$ production

★ detector design prototype and test
★ infrastructure preparation
(clean-room, assembly line, cryogenic test facilities at LNGS …)

★ cryostat upgrade and commissioning

★ detector assembly

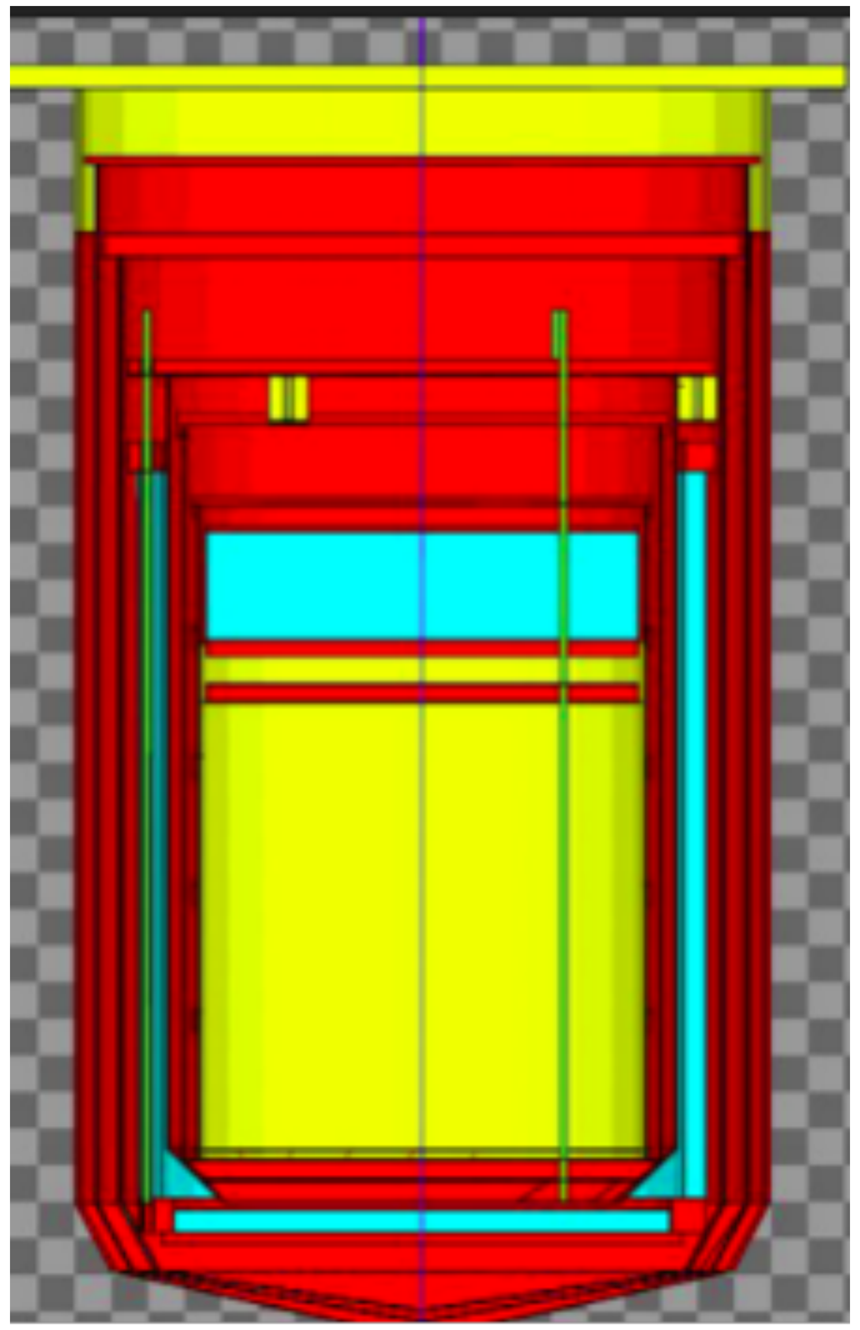
CUPID scenarios

CUPID baseline

240 kg ^{100}Mo
CUORE cryostat
Bkg: 10^{-4} ckky

$T_{1/2} > 1\times10^{27}$ yr
$m_{\beta\beta}$: [13–21] meV

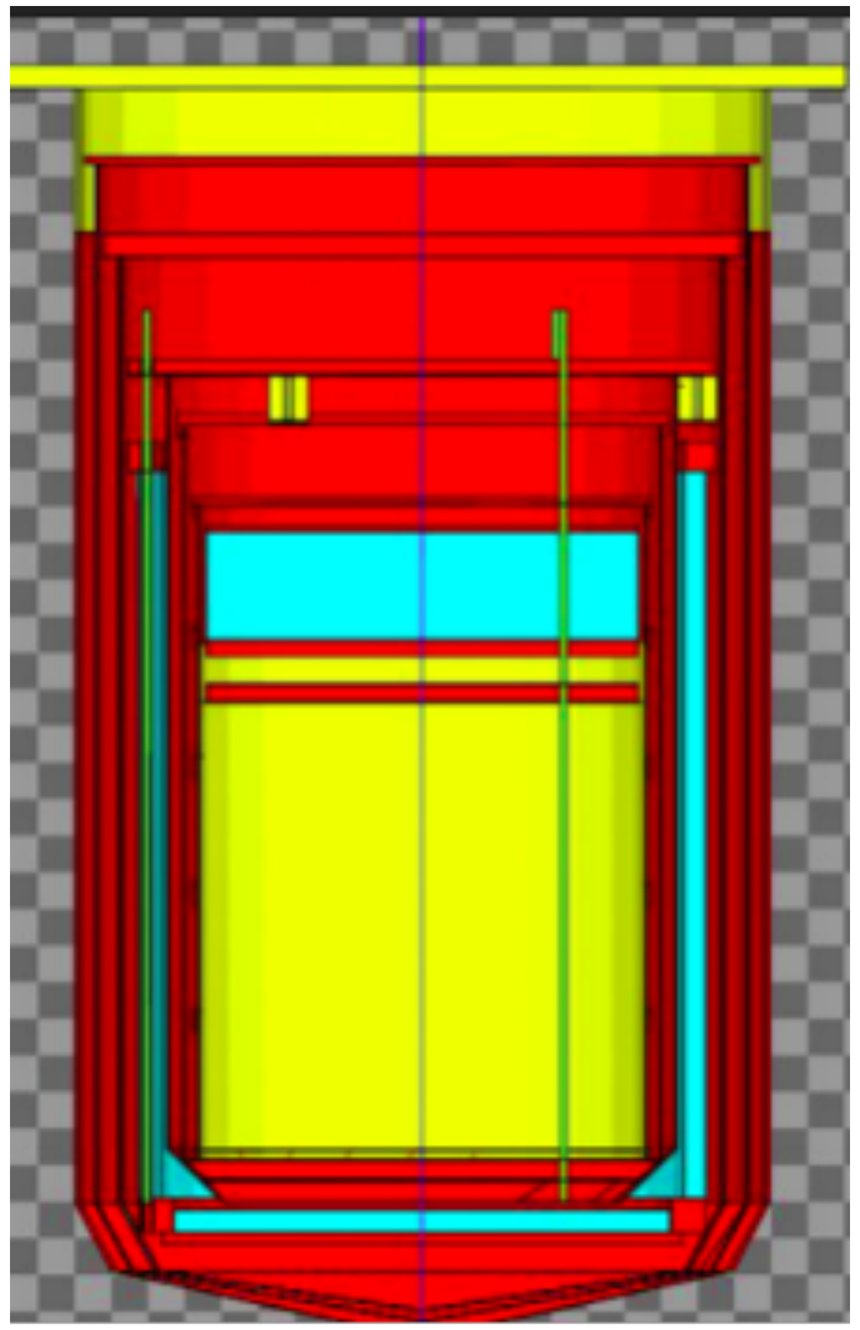
CUPID Reach



240 kg ^{100}Mo
CUORE cryostat
Bkg: 2×10^{-5} ckky

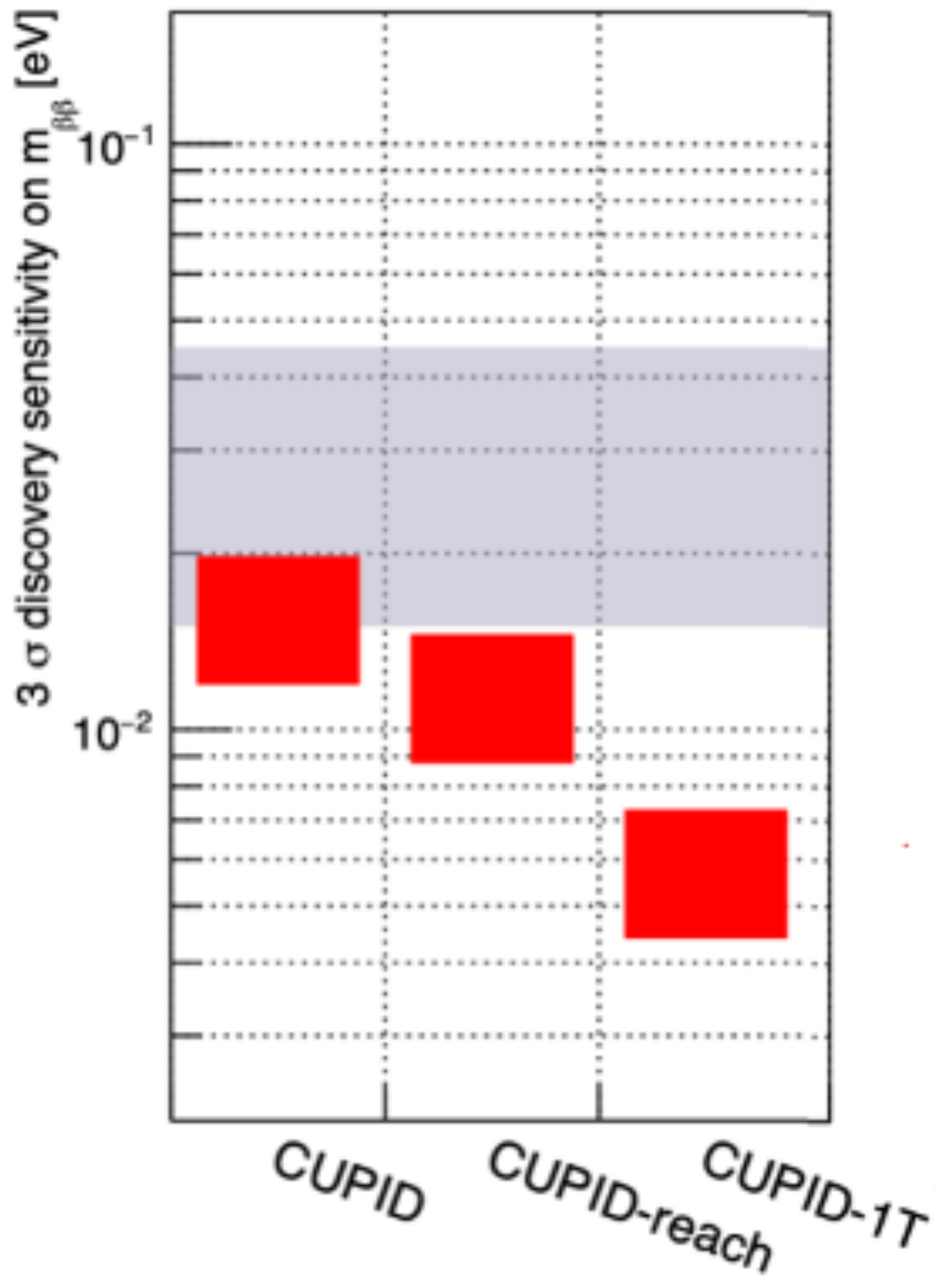
$T_{1/2} > 2\times10^{27}$ yr
$m_{\beta\beta}$: [9–15] meV

CUPID 1 ton



1000 kg ^{100}Mo
NEW cryostat
Bkg: 5×10^{-6} ckky

$T_{1/2} > 9\times10^{27}$ yr
$m_{\beta\beta}$: [4–7] meV



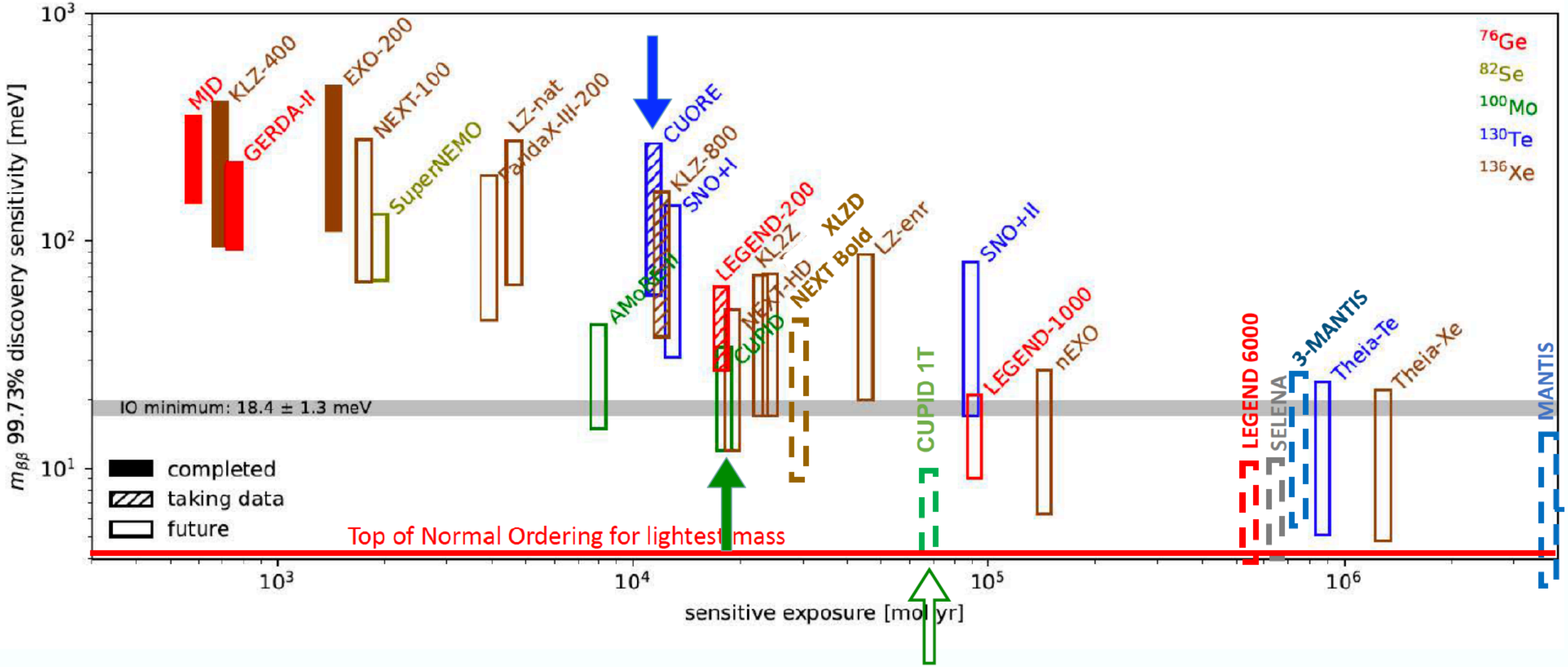
Conclusions and outlook

- CUPID builds on an existing and well-established international collaboration.
- We have operational experience of ton-scale cryogenic experiments and will use the CUORE infrastructure (cost effective, leverages international investments).
- Data-driven background model indicates a background level of ~ 10-4 ckky
- Test production of the first enriched LMO crystals is ongoing. Mass production of the entire CUPID array is feasible and under negotiation.
- The collaboration is working on getting ready for CUPID.

https://cupid.lngs.infn.it/

BACK UP slides

Discovery sensitivity of CUORE and CUPID



From: Fundamental Symmetries, Neutrons, and Neutrinos (FSNN): Whitepaper for the 2023 Nuclear Science Advisory Committee Long Range Plan: arXiv:2304.03451iv:2304.03451