Latest Results from CUORE and Prospects for CUPID

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On behalf of the CUORE & CUPID Collaborations

24th International Workshop on Next Generation Nucleon Decay and Neutrino Detectors

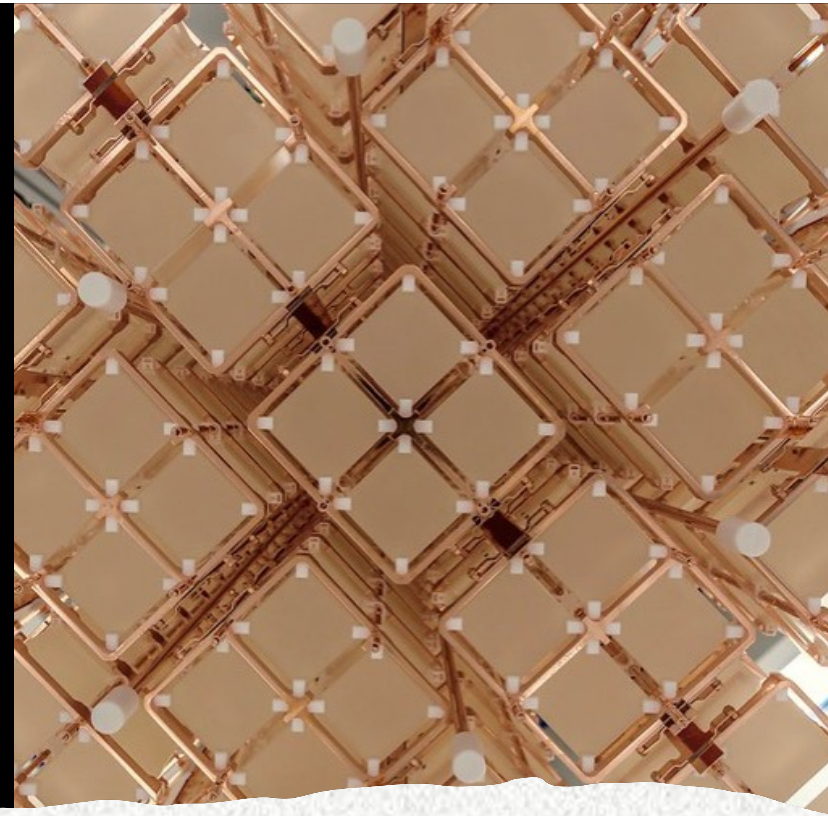
Sudbury, Ontario, Canada

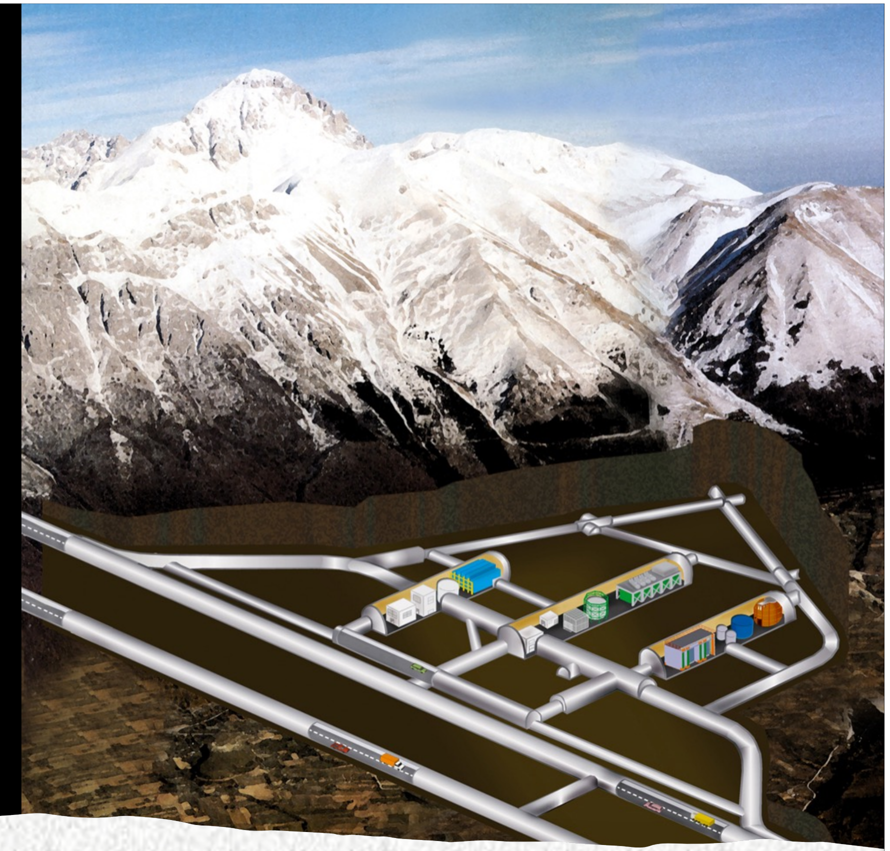
October 1-3, 2025

INFN
Istituto Nazionale di Fisica Nucleare

CUORE

the search for neutrinoless double beta decay



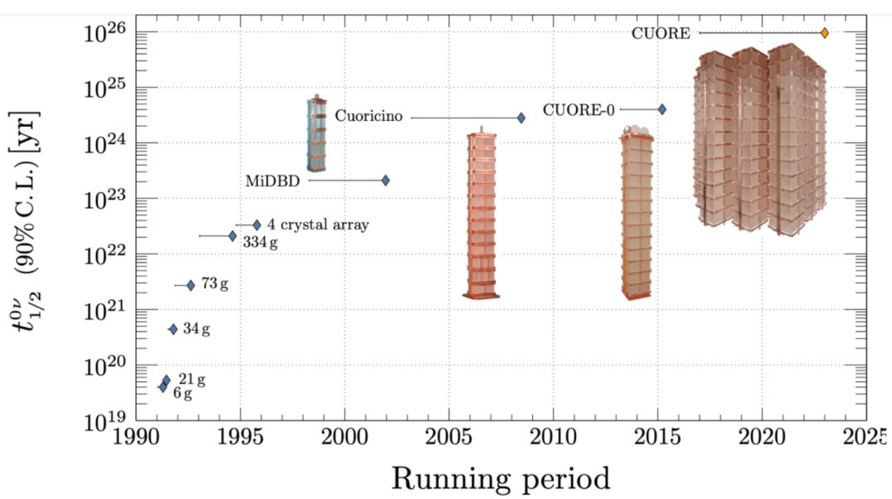


The **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents

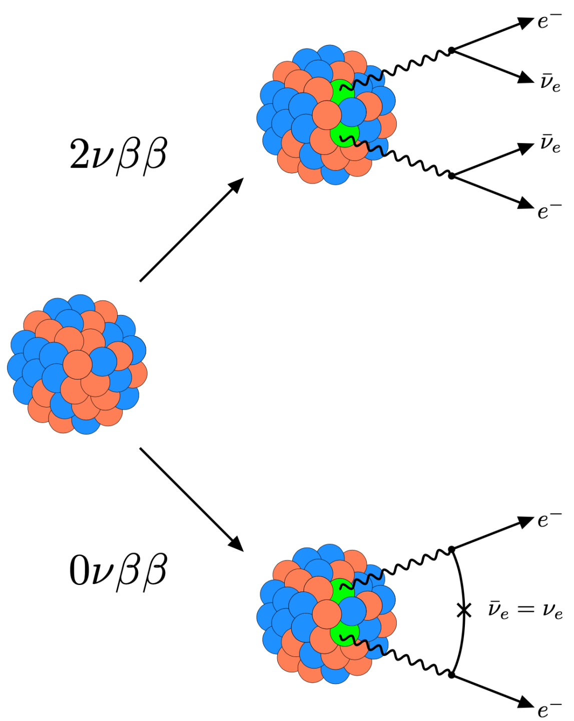
- 742 kg cryogenic bolometric detector
- Designed to search for $0\nu\beta\beta$ of ^{130}Te
- 4500 feet underground in Gran Sasso National Laboratories (LNGS, Italy)
- First science data: Spring 2017. Has collected >2.9 tonne-yr of data
- Search for rare events and physics beyond the standard model

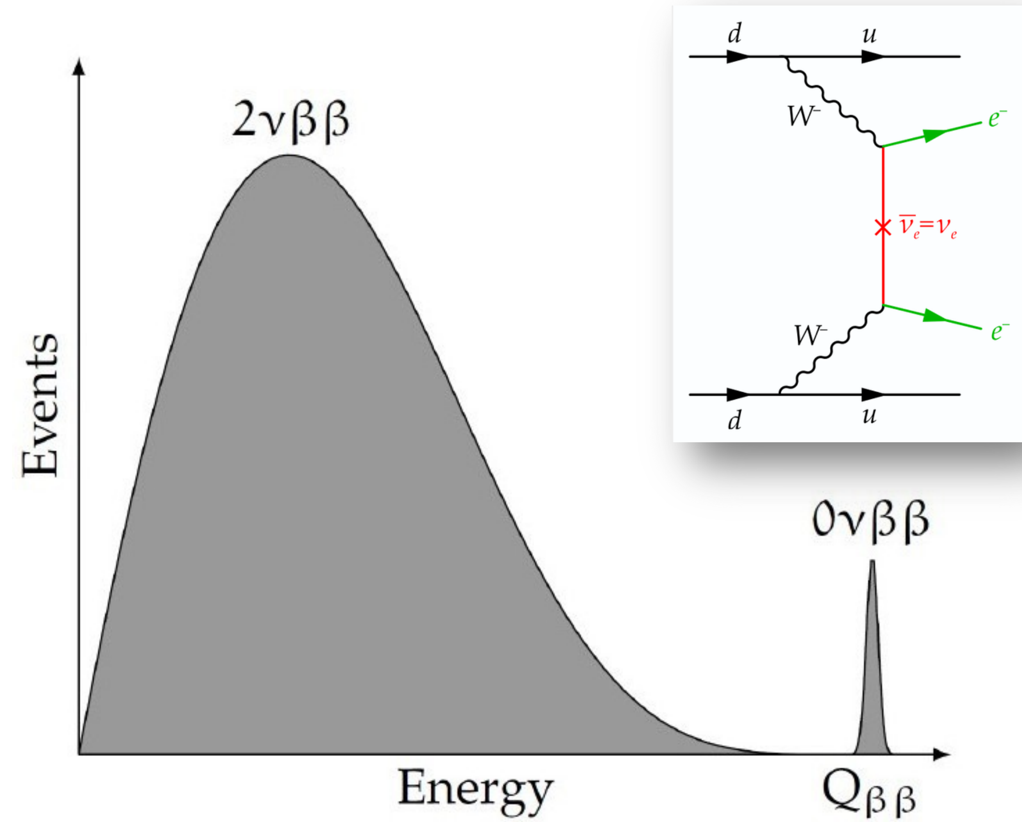
CUORE

- International team of researchers
- >150 Scientists
- 30 Institutions
- 30 years in development!



Neutrinos & Neutrinoless Double-Beta Decay





- [Two neutrino] Double beta decay: allowed in standard model for **even-even** nuclei
- Possible for ~35 naturally occurring isotopes; half lives range from ~10^{18} to 10^{22} years
- **Neutrinoless** double beta decay forbidden in SM; BSM process

- NDBD does not respect lepton number conservation ($\Delta L = 2$)
- Simplest model for NDBD: neutrino as Majorana particle
- Signature: tiny peak at the endpoint of the double beta decay spectrum
- No evidence observed so far; half life $T^{0\nu}_{1/2} > 10^{24}$-10^{26} years

Neutrinoless Double-Beta Decay

- Assuming light Majorana neutrino exchange, one can use the decay rate obtained from the half life limit to extract an effective Majorana mass for the neutrino
- This, in turn, allows constraints on the neutrino mass scale and hierarchy

$$\Gamma_{0\nu\beta\beta} \propto G_{0\nu}(Q,Z)\left|M_{0\nu}\right|^2 \frac{\left|<m_{\beta\beta}>\right|^2}{m_e^2}$$

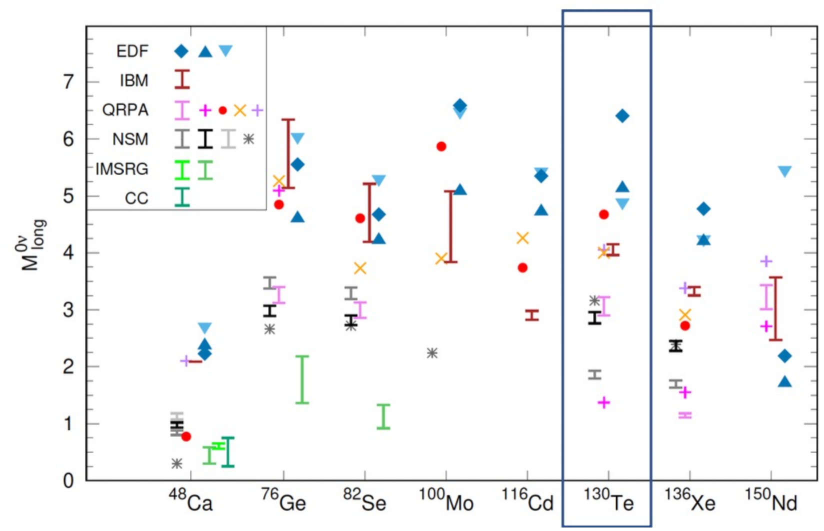
Phase space factor

Nuclear matrix element

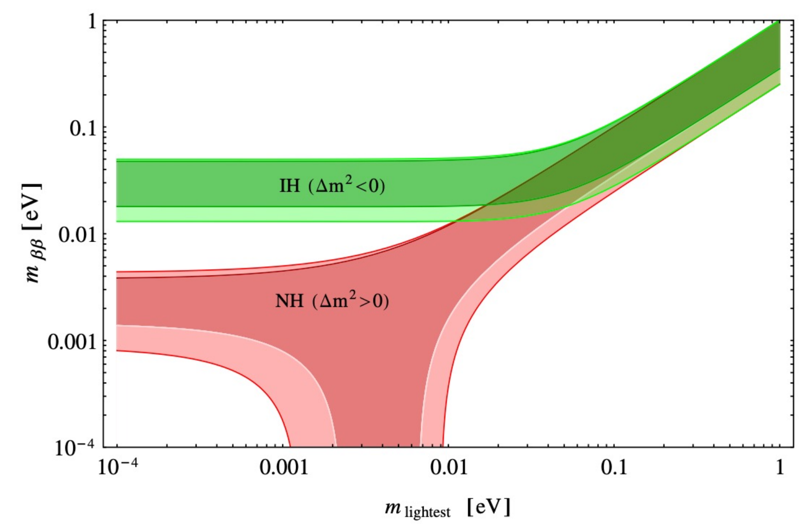
Effective Majorana mass

$$<m_{\beta\beta}> = \left|\sum_{i=1,2,3} |U|_{ei}^2 e^{i\alpha_i} m_i\right|$$

CUORE Talk at TAUP 2025 (A. Campani)



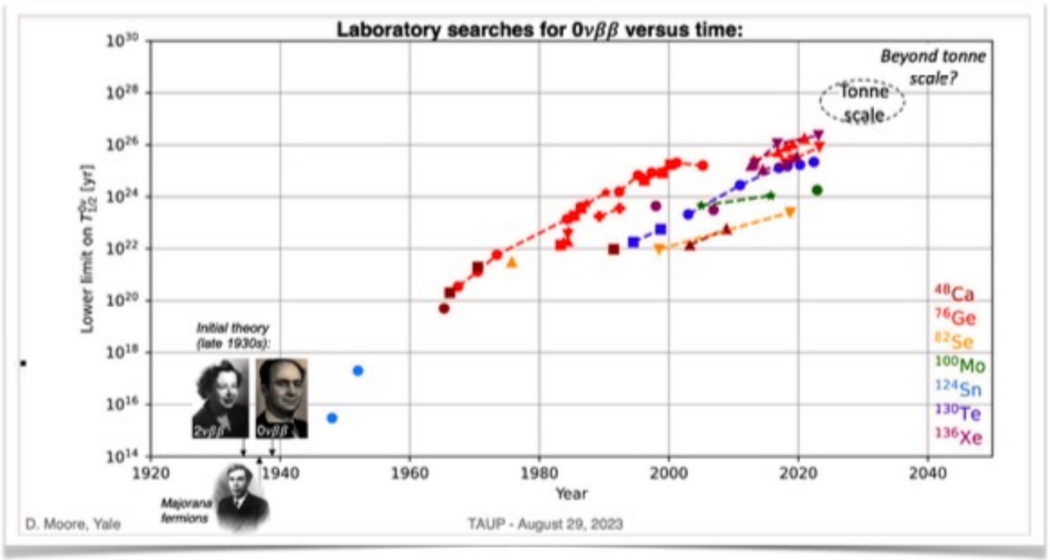
Rev. Mod. Phys. ***95****, 025002*



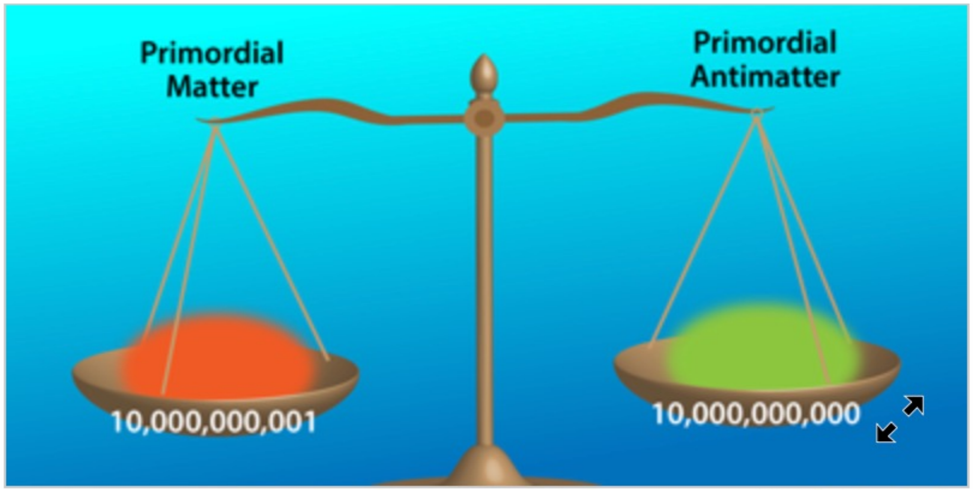
Phys. Rev. D **90**, 033005 (2014)

Beyond the Standard Model

- NDBD→ BSM Process (ΔL = 2)
- Impacts:
  - Existence of LNV processes
  - Presence of a Majorana term for the neutrino mass
- NME uncertainties influence estimates of the effective neutrino mass
  - Important feedback for nuclear physics
- LNV has implications for matter-antimatter asymmetry in the universe
  - Important implications for particle physics & cosmology



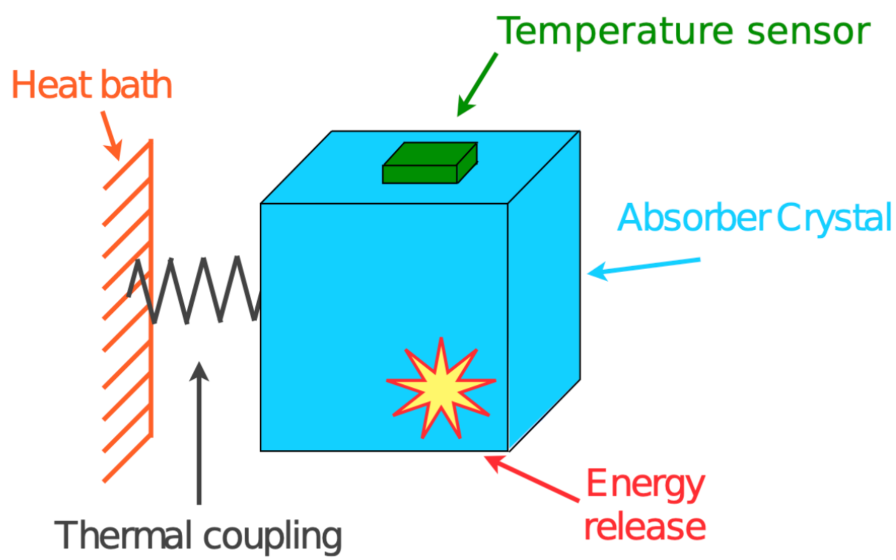
D. Moore @TAUP2023



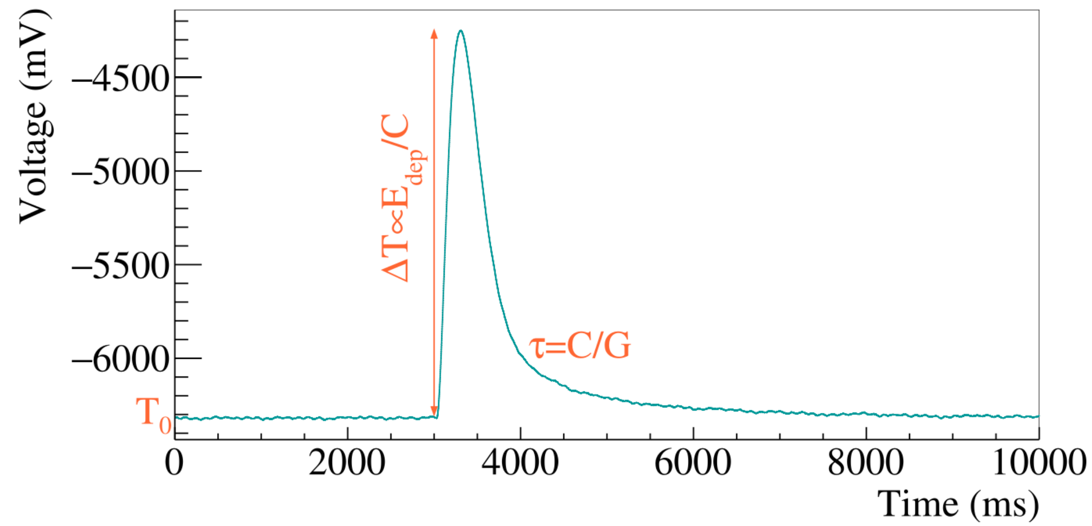
APS/Alan Stonebraker

The CUORE Detector

Nature 604 (2022) 7904, 53-58



I. Nutini, EuNPC 2025, A. Campani , TAUP 2025



- Deposited energy converted into ΔT (phonons)
- Detector acts as ββ source
- Can scale to large, segmented calorimeters (~kg scale)
  - Sensitive from keV to MeV scale
  - Optimal energy resolution ~ 0.1%@MeV

CUORE

- 1 MeV energy release causes ΔT 100 μK For operating temperature 10 mK
- Si heater used to inject stable voltage pulses and do thermal gain stabilization

CUORE Talk at TAUP 2025 (A. Campani)

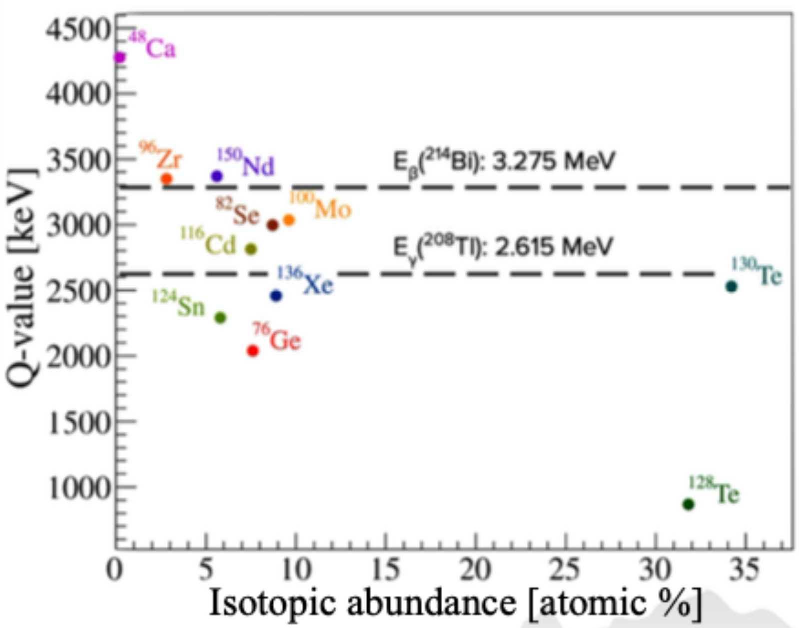
$0\nu\beta\beta$ decay: experimental search and CUORE

- Sensitivity to $0\nu\beta\beta$ scales as†

$\beta\beta$ emitter isotopic fraction
- ^{130}Te ~34%
- TeO_2 crystals with $^{(nat)}Te$

detection efficiency
- source ≡ detector
- total efficiency (all cuts) ~93%

active mass
- tonne-scale detector: 742 (206) kg TeO_2 (^{130}Te)
- close-packed array - 988 crystals



$$S_{0\nu} \propto \eta \cdot \varepsilon \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$$

livetime
- 8 yr continuous operation
- ~50 kg · yr/month

background in the ROI
- $Q_{\beta\beta}$~2528 keV only Tl γ line above
- $(1.42^{+0.03}_{-0.02}) \cdot 10^{-2}$ counts/keV/kg/yr

energy resolution @ $Q_{\beta\beta}$
- ΔE (FWHM)= (7.310 ± 0.024) keV
$\rightarrow \Delta E/E \simeq 0.3\,\%$

TAUP XICHANG

†For zero-background cases $S_{0\nu} \propto M \cdot T$

The CUORE experiment: current status and road ahead

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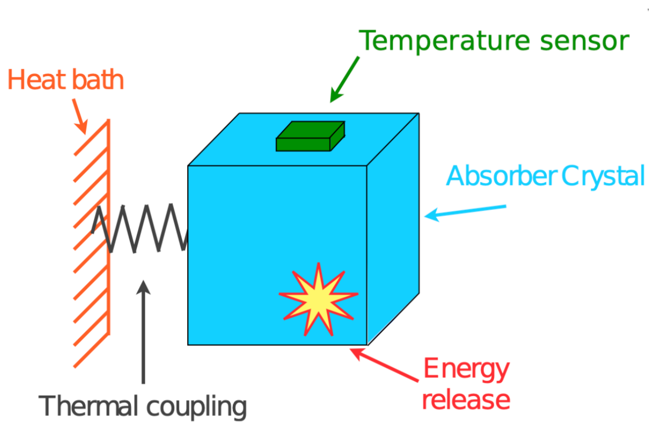
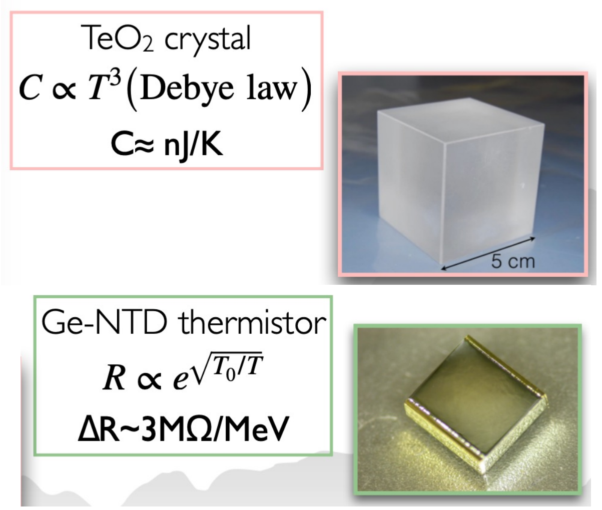
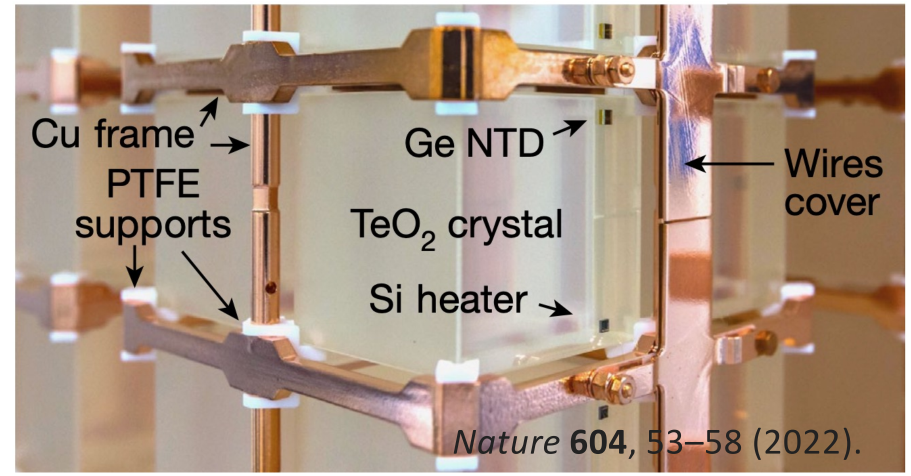
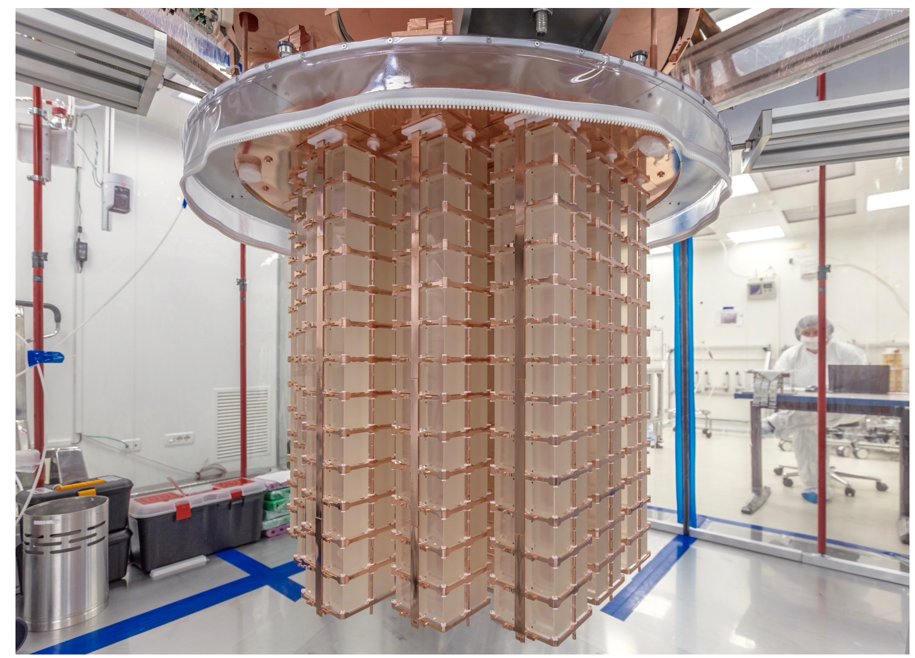
The CUORE Detector

- 988 TeO2 crystals, 19 tower array
- 13 floors of 4 crystals in each tower
- Each crystal instrumented with Ge NTD thermistor & Si Heater

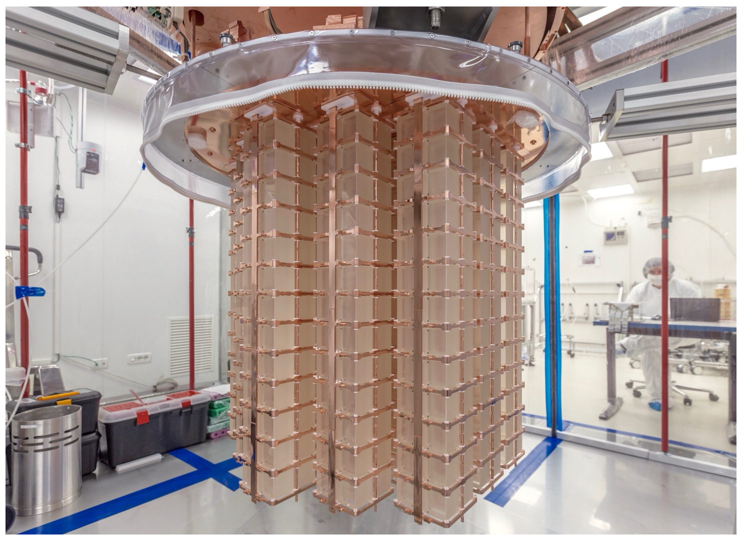


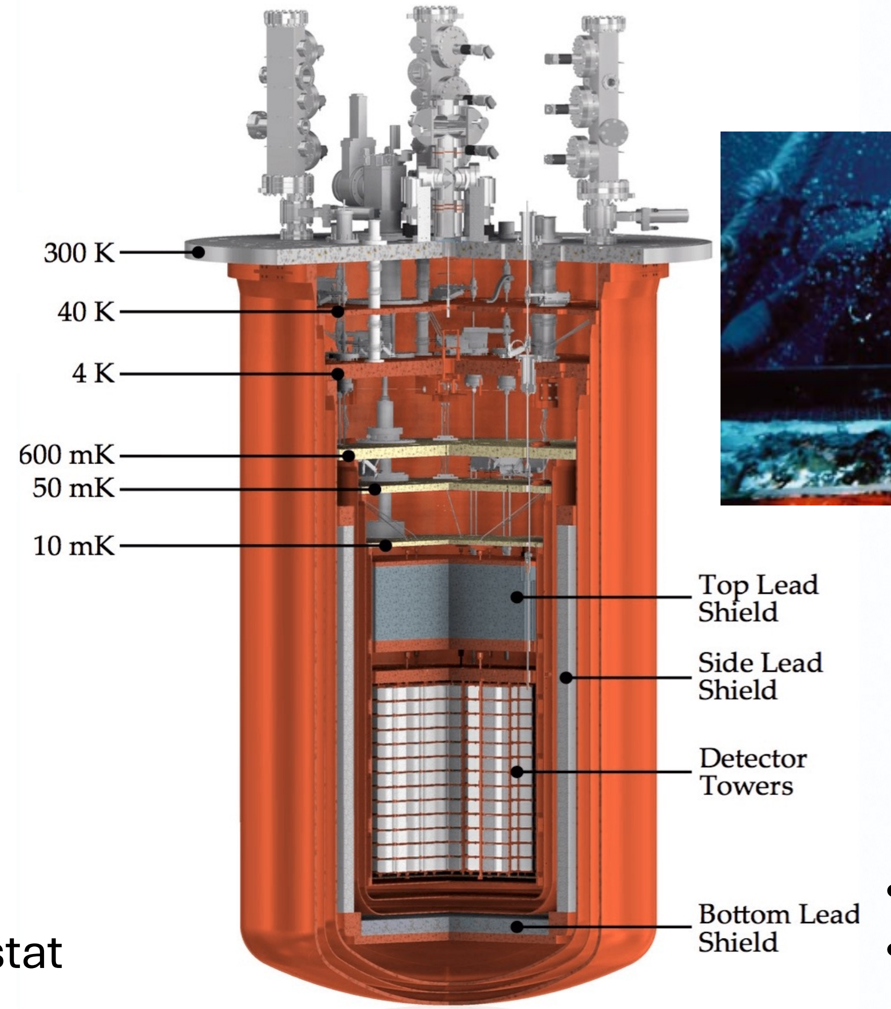






The CUORE Detector

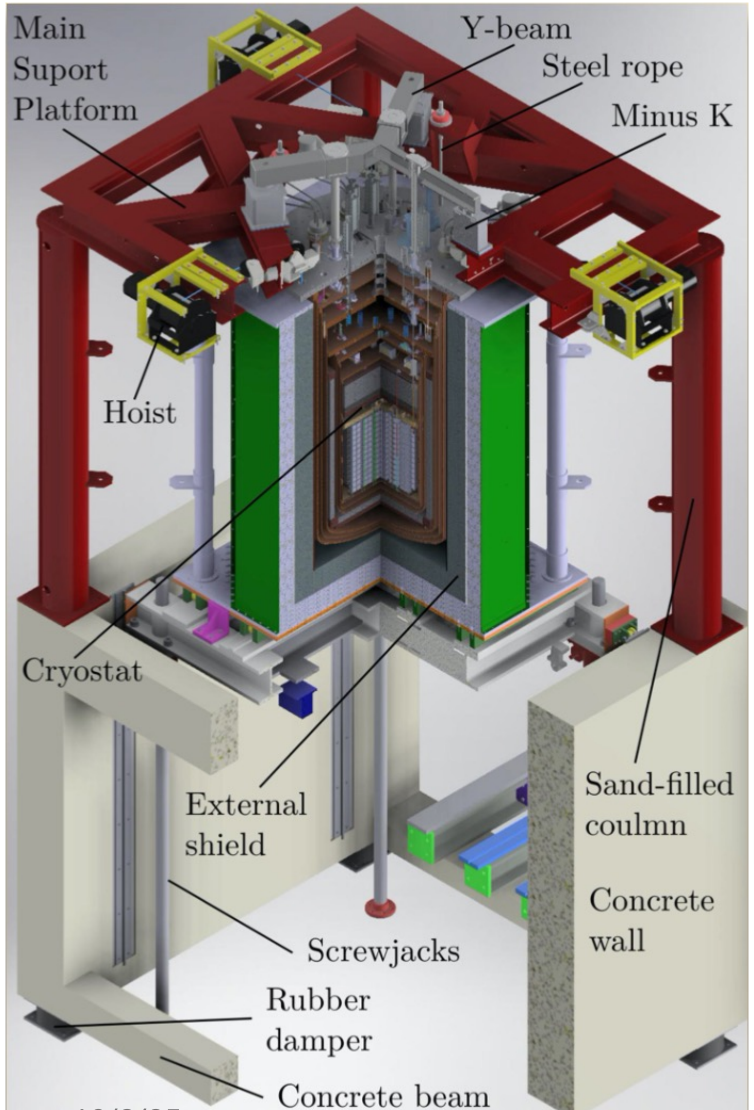




- Custom-made dry dilution cryostat
- Stable ~10 mK over time
- Mechanical vibration isolation: passive & active systems

- ***Top Lead:*** 30 cm of modern lead
- ***Side & Bottom shield:*** 6 cm ancient lead from a shipwreck
  - ^{210}Po < 4 mBq/kg

The CUORE Detector



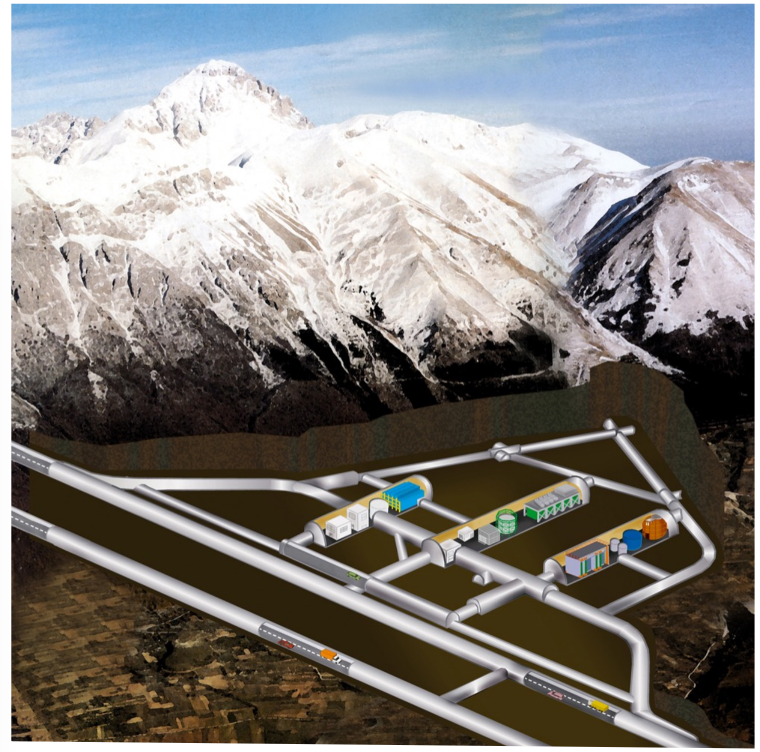
Low temperature and low vibrations
988 TeO_2 detectors (~742 kg) operated as calorimeters at ~10 mK stable over time

- Multistage cryogen-free cryostat
- Mechanical vibration isolation: passive and active systems

Low background

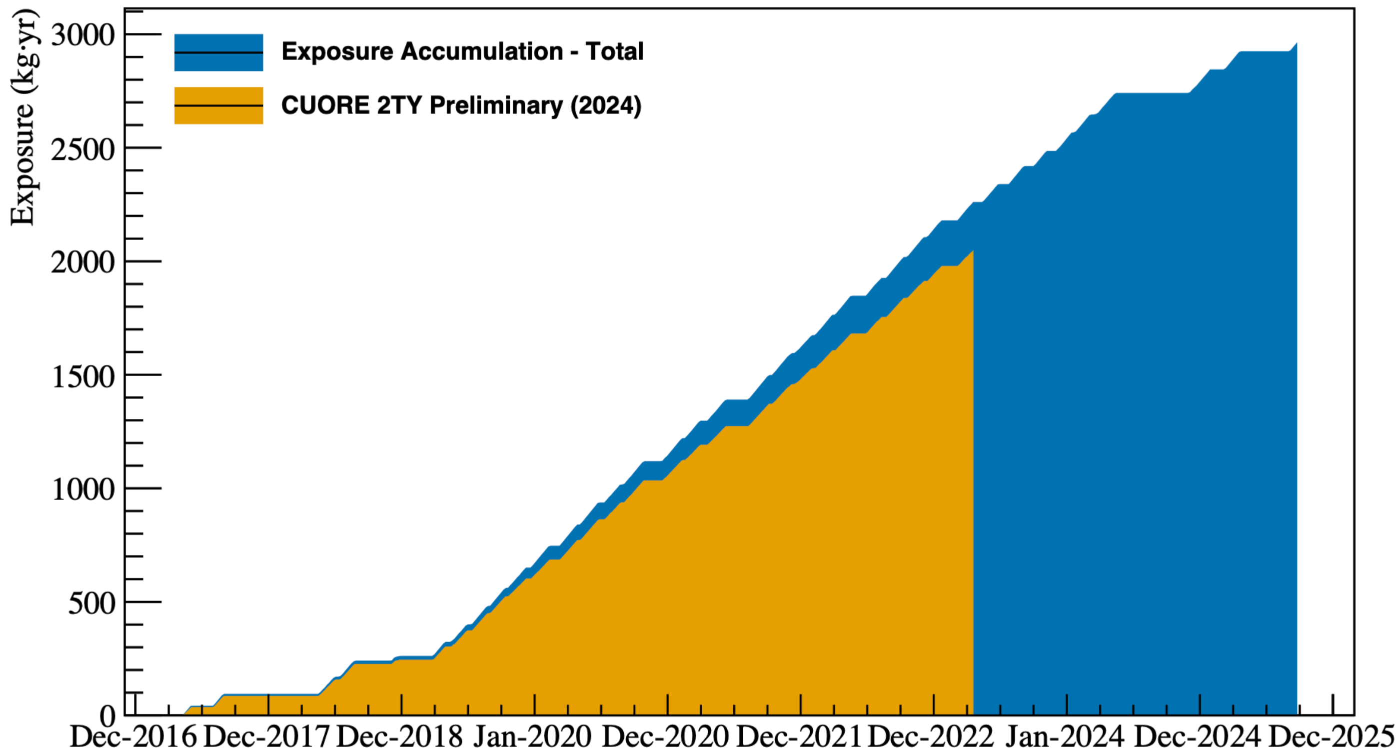
- Deep underground location @LNGS
- Strict radio-purity controls on materials and assembly
- Passive shields from external and cryostat radioactivity
- Detector: high granularity and self-shielding

I. Nutini, EuNPC 2025

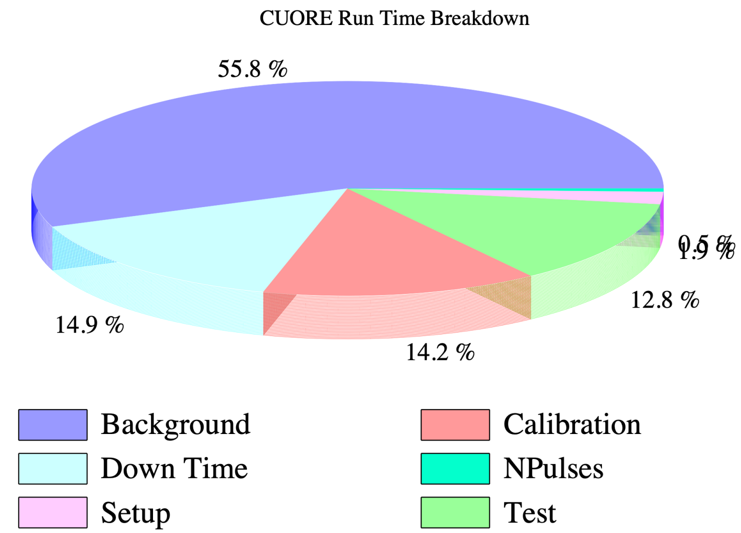


~1400 m rock overburden
→ ~3600 m.w.e.: *Cosmic ray flux reduced by six orders of magnitude compared to the surface*.

CUORE Data Collection



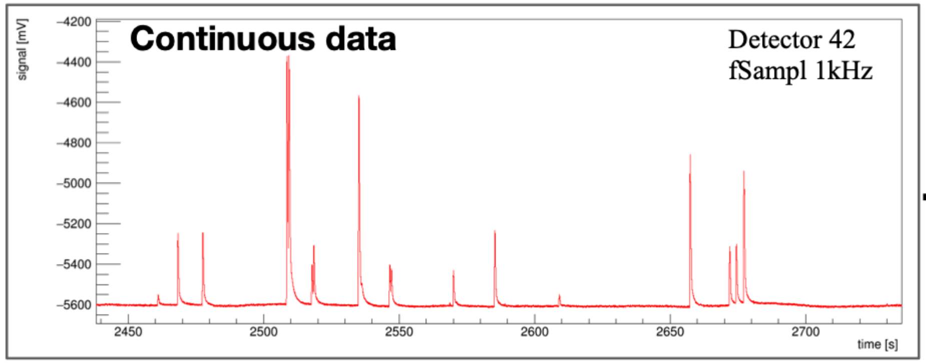
Over 80% up time



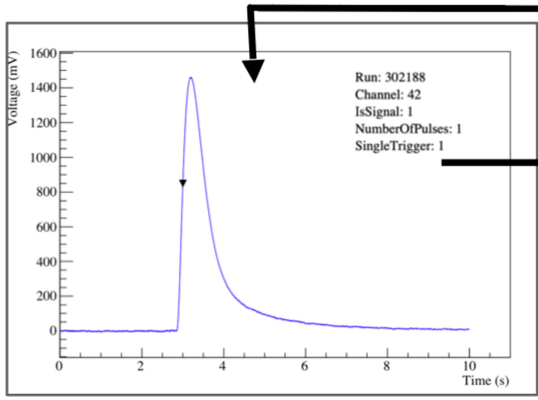
- Almost 3 ton-years of raw cumulative exposure (2TY preliminary was 2039.0 kgyr of TeO_2 exposure)!

The CUORE Analysis Chain

From single detectors waveform data stream



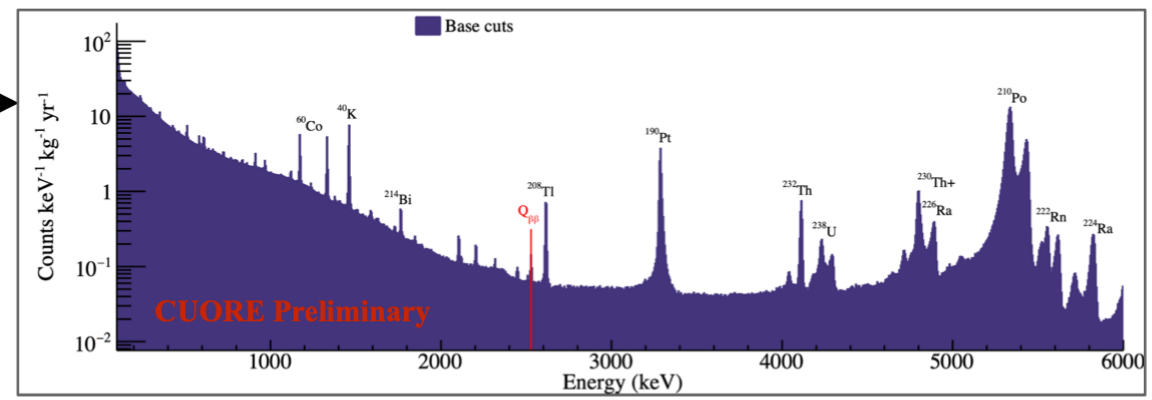
Denoising → Optimum trigger



Event: physics pulse

Optimum Filter → Gain Correction → Energy Calibration → Coincidences → PCA

To a cumulative energy spectrum

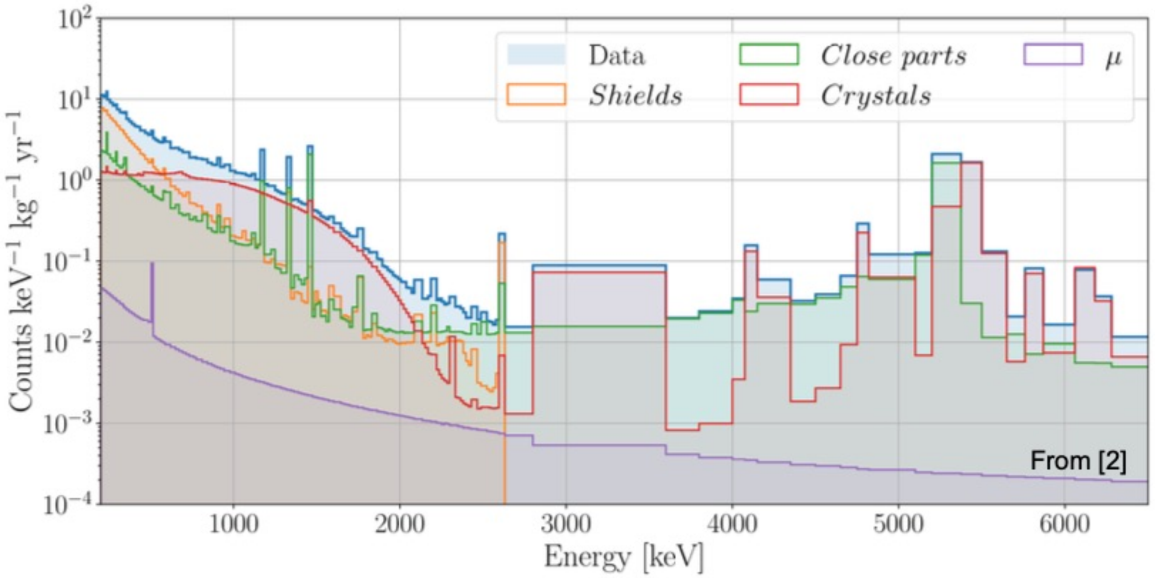


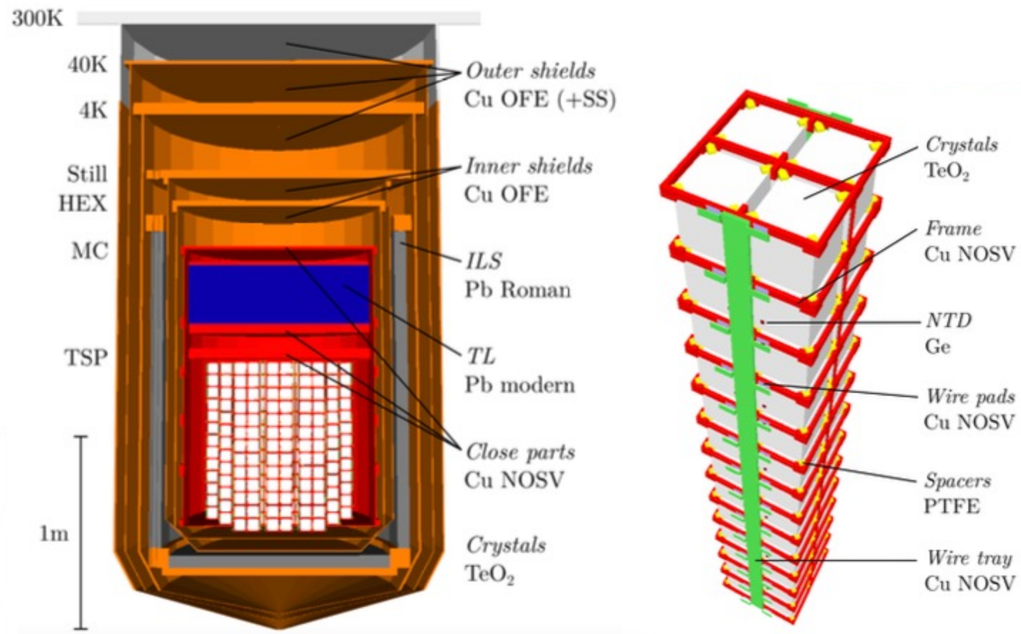
Slide by I. Nutini (ENPC 2025)

CUORE Physics: The Background Model

Reconstruction of the CUORE physics spectrum

- GEANT4 simulation + measured detector response function to produce expected spectra
- Multiple background sources simulated (data-driven), **Bayesian MCMC fit**
- Exploit coincidences & detector self-shielding to constrain location of sources





Total exposure for BM analysis: 1038.4 kg yr

- Sensitivity levels down to 10 nBq kg^{-1} and 0.1 nBq cm^{-2} for bulk and surface contamination
- Main contributions to ROI BI: degraded α particles (~90%), multi-Compton of γs and cosmic muons

Slide by I. Nutini (ENPC 2025)

CUORE Physics: Search for $0\nu\beta\beta$ decay in ^{130}Te

2 ton yr data release

Data from May 2017 to April 2023

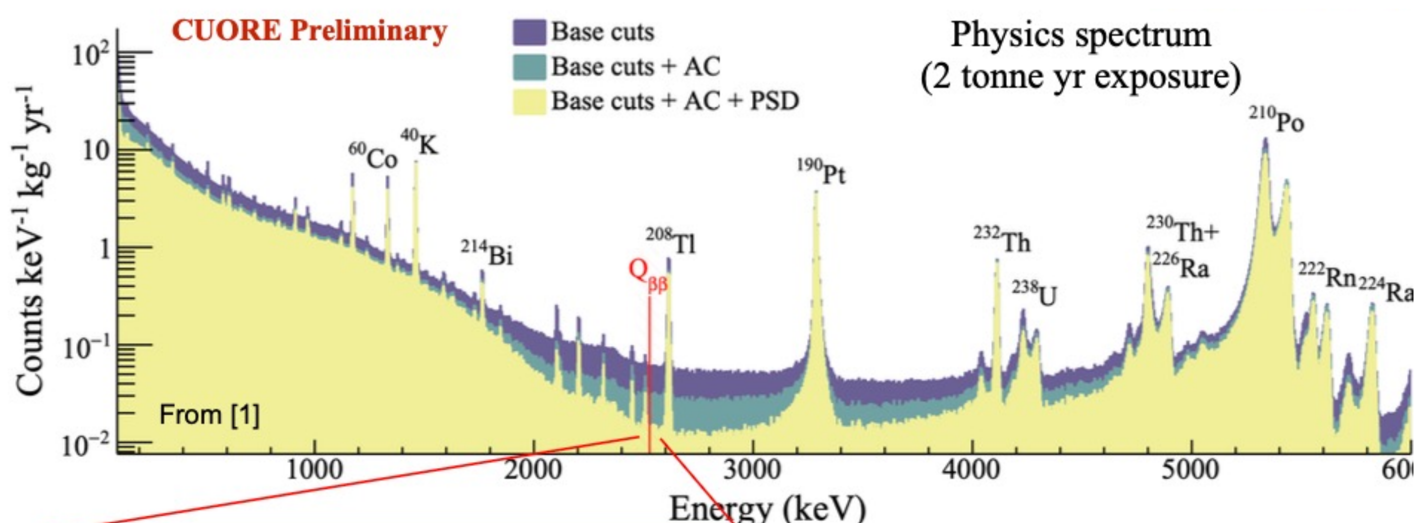
Total exposure for 0νββ decay search:

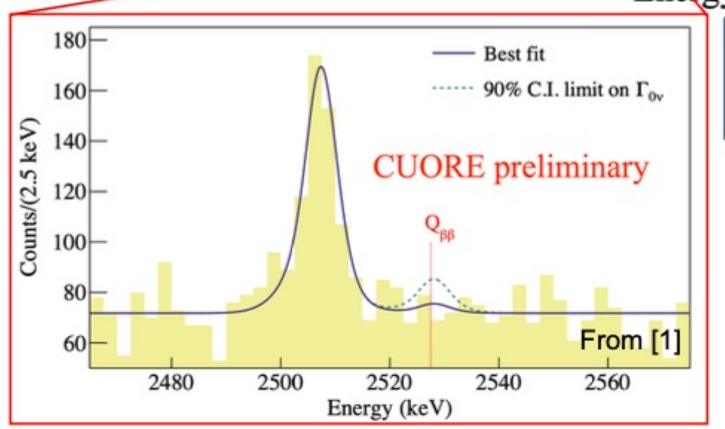
2039.0 kg yr TeO_2, 567.0 kg yr ^{130}Te

Quality cuts for **0νββ search**:

- BaseCuts (trigger, energy reconstruction, pileup rejection)
- Anti-coincidence, AC (only single crystal events)
- Pulse shape discrimination, PSD (only particle-like pulses)

Total efficiency 93.4(2)%





No evidence of signal at $Q_{\beta\beta}$ in ROI

Average background index in the ROI
$(1.42\ ^{+0.03}\ _{-0.02}) \times 10^{-2}$ cts/(keV kg yr)

Pending publication

Slide by I. Nutini (ENPC 2025)

CUORE Physics: Search for $0\nu\beta\beta$ decay in ^{130}Te

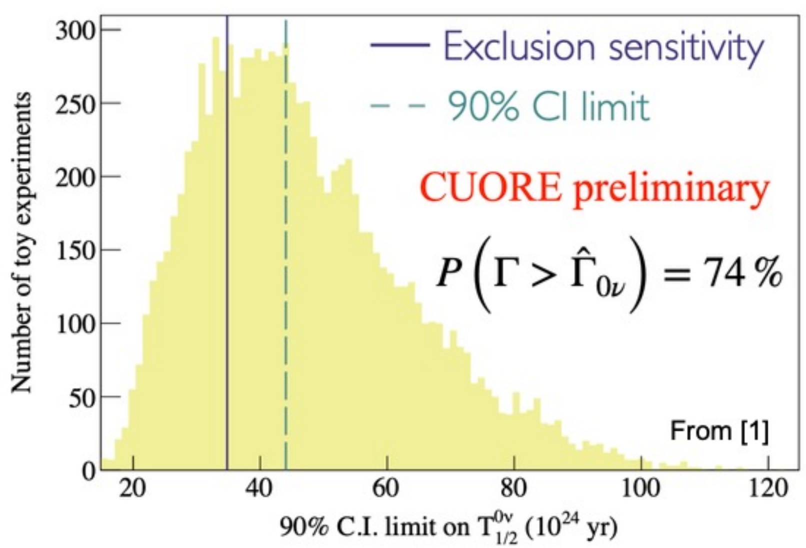
2 ton yr data release

Bayesian fit of the data in the ROI

Lower limit on ^{130}Te $0\nu\beta\beta$ half life:

$T_{0\nu}^{1/2}$ (^{130}Te) > 3.5 x 10^{25} yr (90%C.I.)

Frequentist limit: $T_{1/2} > 3.4 \cdot 10^{25}$ yr (90% C.L.)



Limit on the effective neutrino mass, assuming light Majorana-neutrino exchange:

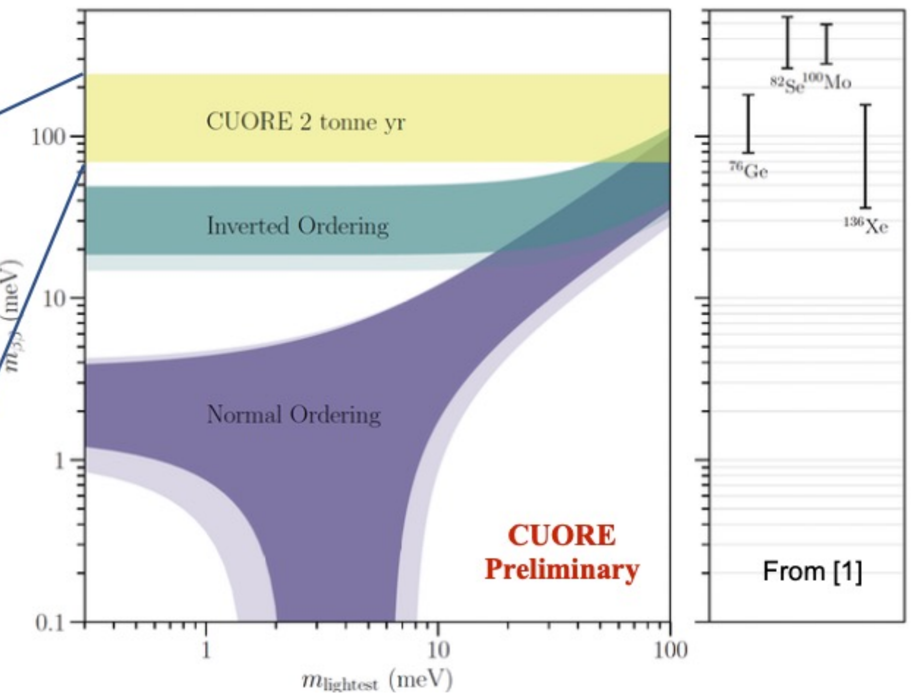
$m_{\beta\beta}$ < 70-250 meV

NME ^{130}Te

(3.9, 6.4)

Nuclear models considered: QRPA, ISM, IBM, NREDF

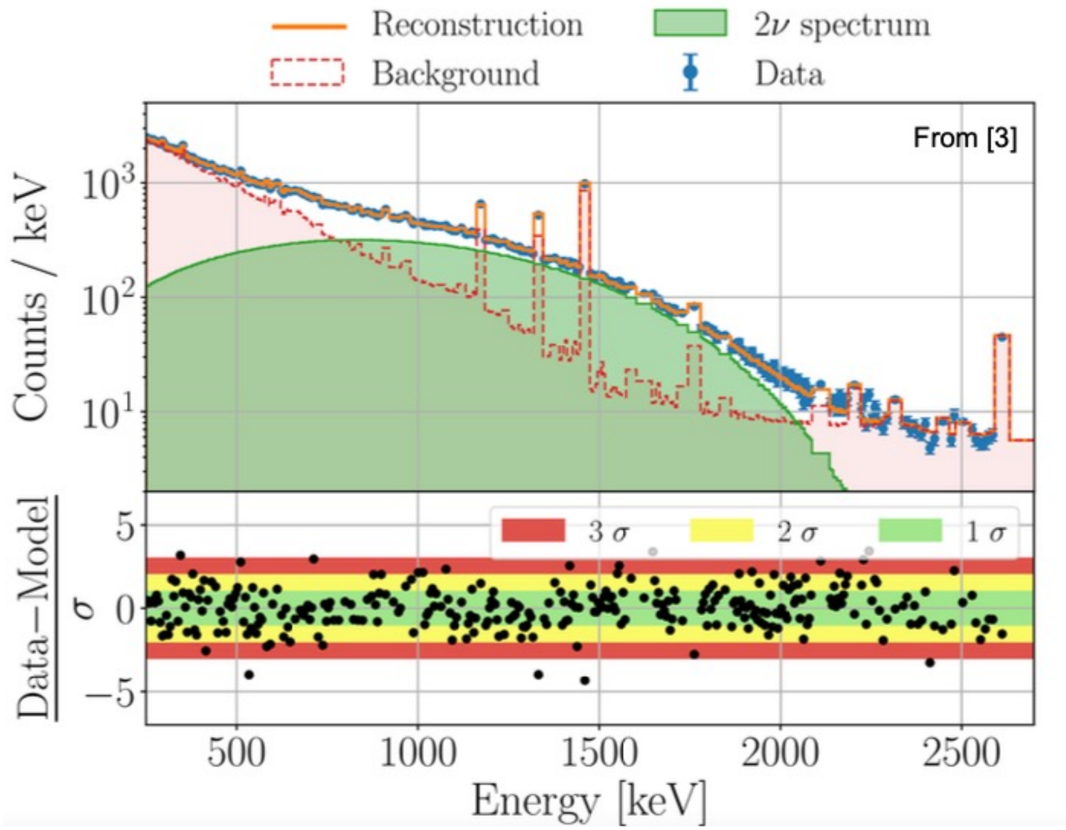
Pending publication



Slide by I. Nutini (ENPC 2025)

CUORE Physics: $2\nu\beta\beta$ decay in ^{130}Te

^{130}Te 2νββ decay: dominant component of the observed single-site physics spectrum between ~ 1 to 2 MeV



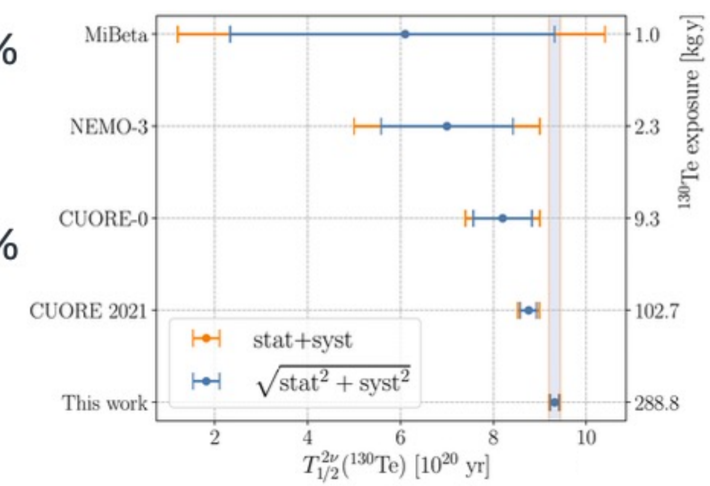
→ **Precise 2νββ half-life measurement**

Choice of the nuclear model
Single-state dominance (SSD), with leading contribution from 1⁺ state of intermediate nucleus
- Selected as reference
- Preferred to higher-state dominance (HSD) model

$T_{2\nu}^{1/2}$ (^{130}Te) = [9.32 $^{+0.05}_{-0.04}$(stat) $^{+0.07}_{-0.07}$(syst)] x 10^{20} yr

- Statistical uncertainty ~0.5%
- Contribution from nuisance parameters ~0.01%
- Multiple sources of systematic uncertainties < 1%

Also! Improved formalism and fit to $2\nu\beta\beta$ spectral shape. See Phys. Rev. Lett. 135, 082501 (2025)



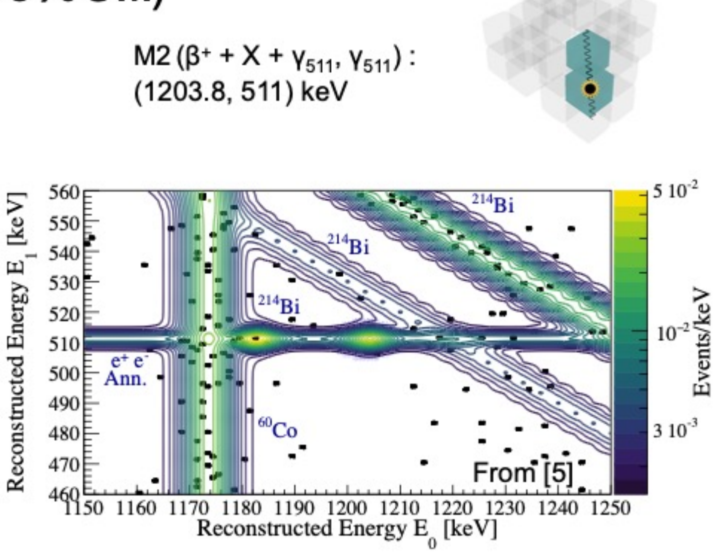
Phys. Rev. Lett. 135, 082501 (2025)

Slide by I. Nutini (ENPC 2025)

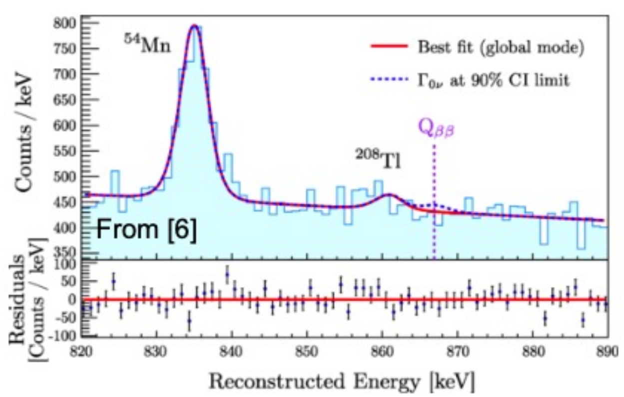
CUORE Physics Analyses (Selected)

Decays of other Te isotopes

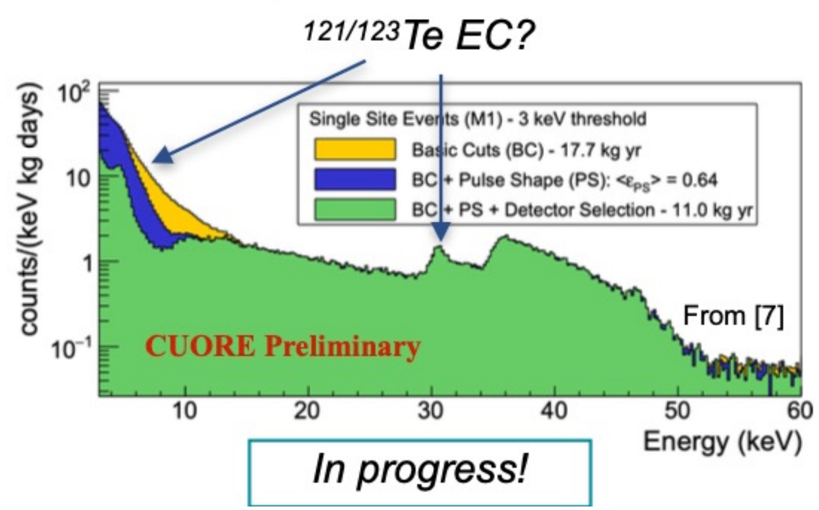
^{120}Te 0νβ^{+}EC decay
$Q_{\beta\beta}$= 1714.8 keV, natural abundance: 0.09%
Clear signature from e+e- annihilation and ^{120}Sn de-excitation via X-ray/Auger electrons emission
$T_{0\nu}$ $^{1/2}$ (^{120}Te) > 2.9 × 10^{22} yr (90%C.I.)



^{128}Te 0νββ decay
$Q_{\beta\beta}$= 866.7 keV, natural abundance: 31.74%
$T_{0\nu}$ $^{1/2}$ (^{128}Te) > 3.6 × 10^{24} yr (90%C.I.)
Improved limit of over a factor 30 wrt to previous direct search results, and exceeded the results from geochemical experiments



Low energy spectrum
- Specific low-energy variables & event-level cuts to optimise sensitivity at keV-scale
- Investigation of spectral features potentially related to **^{121}Te,^{123}Te,^{125m}Te decays** (not yet measured)



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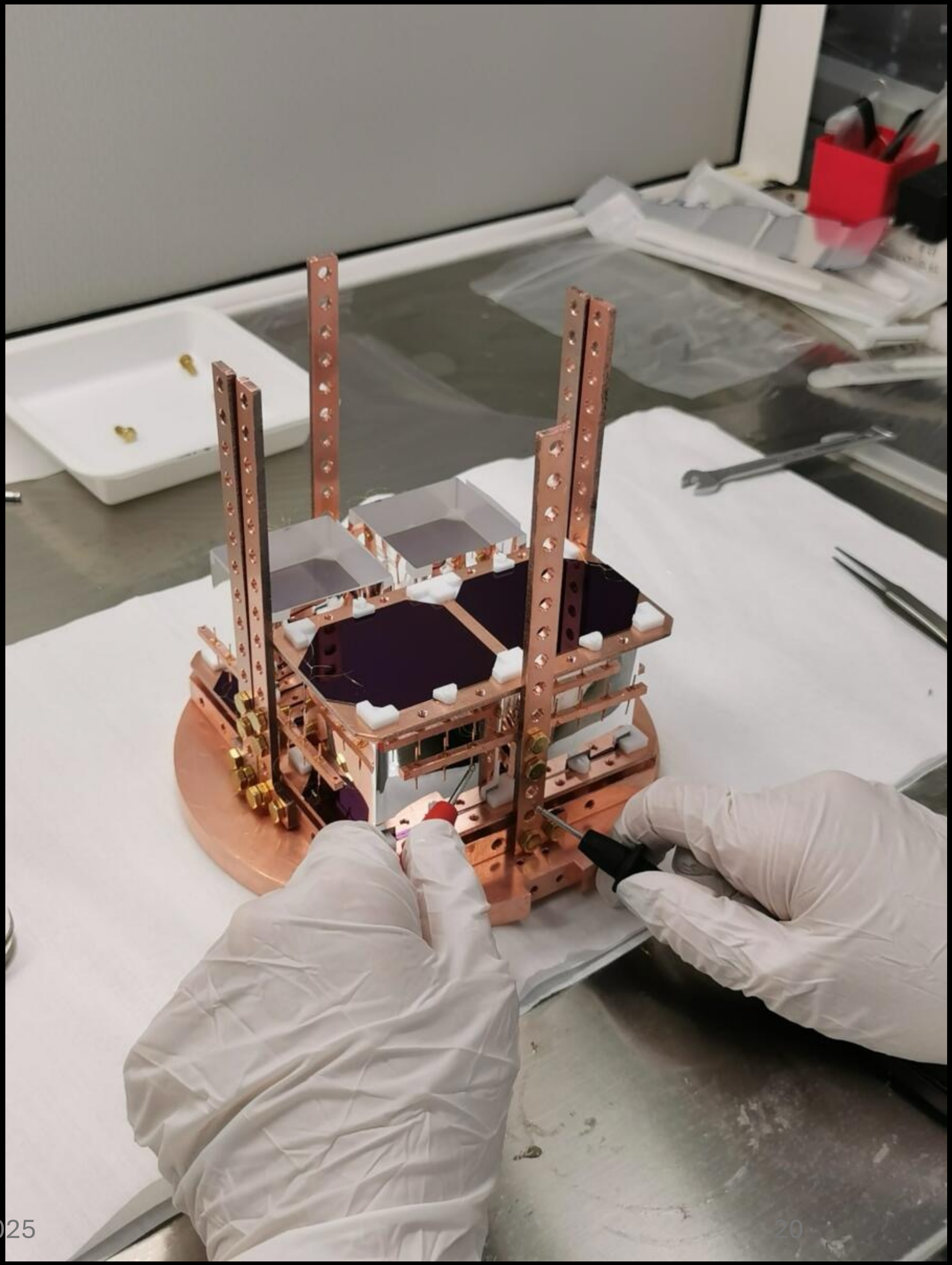
CUPID



CUPID

CUPID Program

Next generation $0\nu\beta\beta$ decay search.

- Scintillating bolometer technology.
- Extremely good energy resolution, flexible choice of isotope.

CUPID builds on CUORE, the largest bolometric array ever built.

- Established and well understood infrastructure and environment.
- CUORE has demonstrated stable and reliable operation over multiple years of exposure.

Particle identification with scintillating Li_2MoO_4 bolometers has been demonstrated in the CUPID-Mo pilot experiment. *

- Isotopic enrichment and crystals growth has been demonstrated and can be done at scale. *

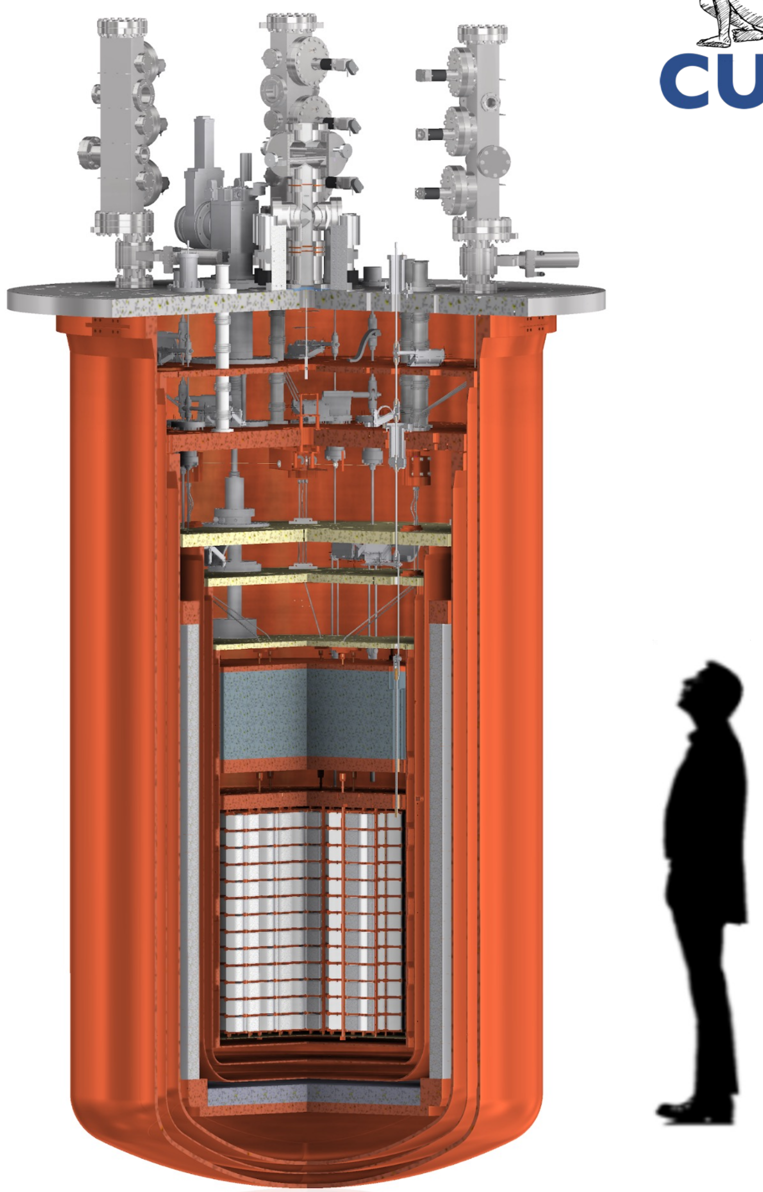
Background index goal of $<10^{-4}$ counts/(keV·kg·yr).

- Data driven based on CUORE, CUPID-0, and CUPID-Mo experiments. *

Probe the full Inverted Hierarchy region down to $m_{\beta\beta}<12$ meV (3σ, favorable NME).

- Using only 240 kg of ^{100}Mo.

Next-next generation CUPID-1T capable of probing into Normal Hierarchy, or multiple isotope precision measurements in Inverted Hierarchy.



*arXiv:1907.09376, PRL 126, 181802 (2021)

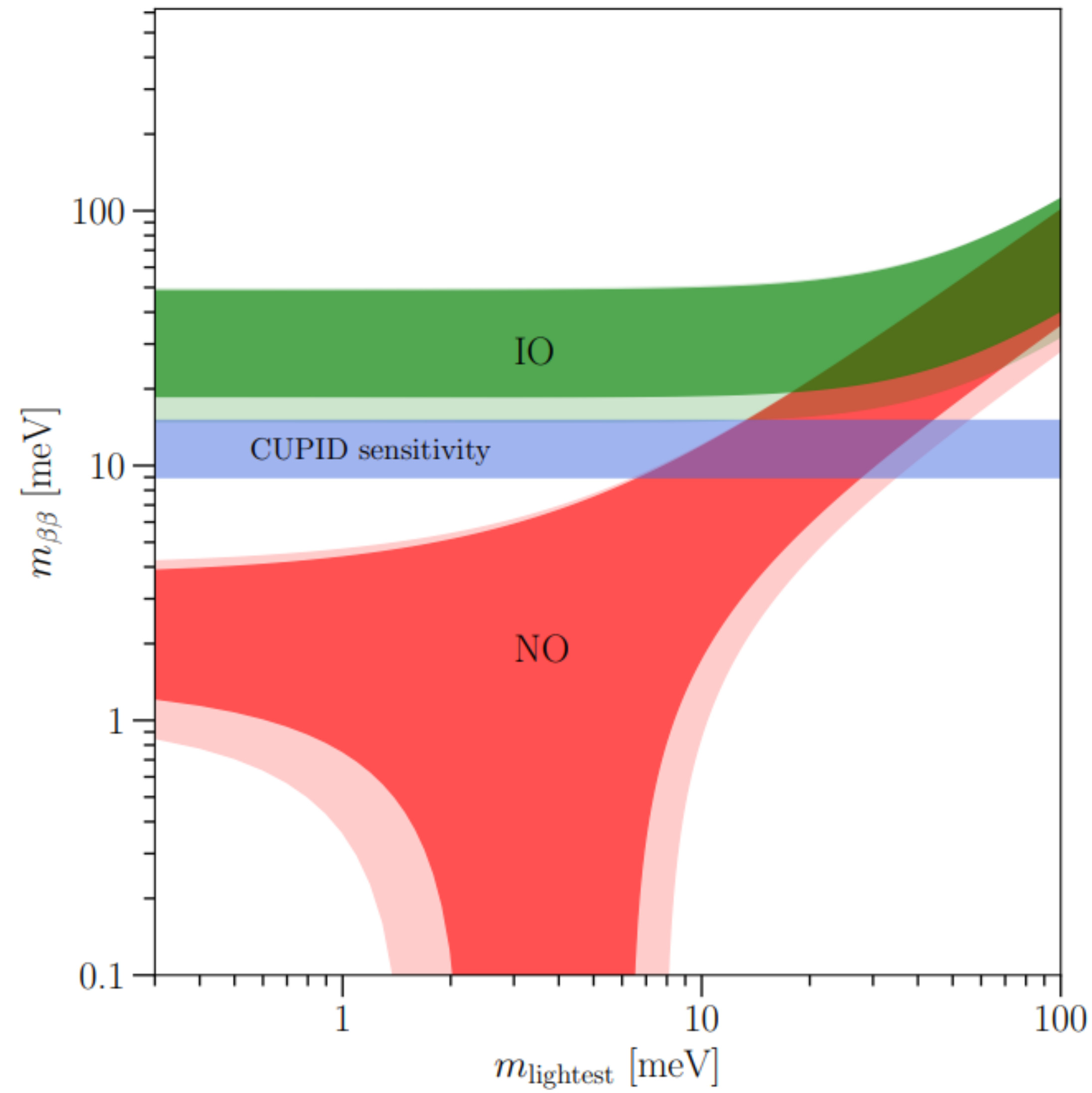
CUORE Upgrade With Particle Identification

CUPID Experiment

- Will operate in the same cryostat that currently houses CUORE
- Goal: Fully probe the "Inverted Hierarchy" region. Improve exclusion sensitivity to $m_{\beta\beta}$ by factor of ~5 relative to CUORE

Improved Sensitivity from Background Reduction

- Particle identification
- Muon veto
- Increased Q value for reduced γ/β backgrounds



arXiv:2503.02894, arXiv:2504.14369

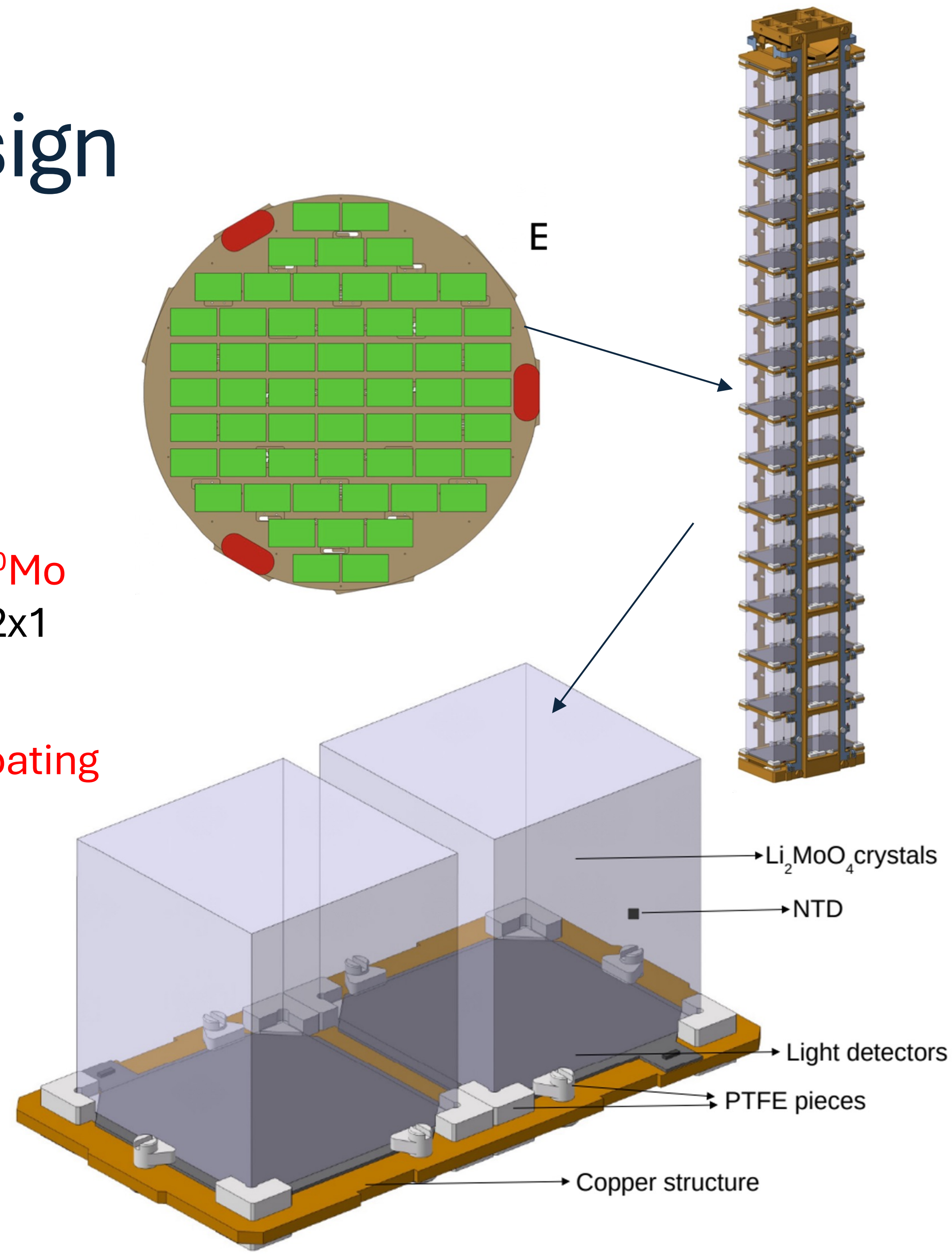
CUPID Baseline Design

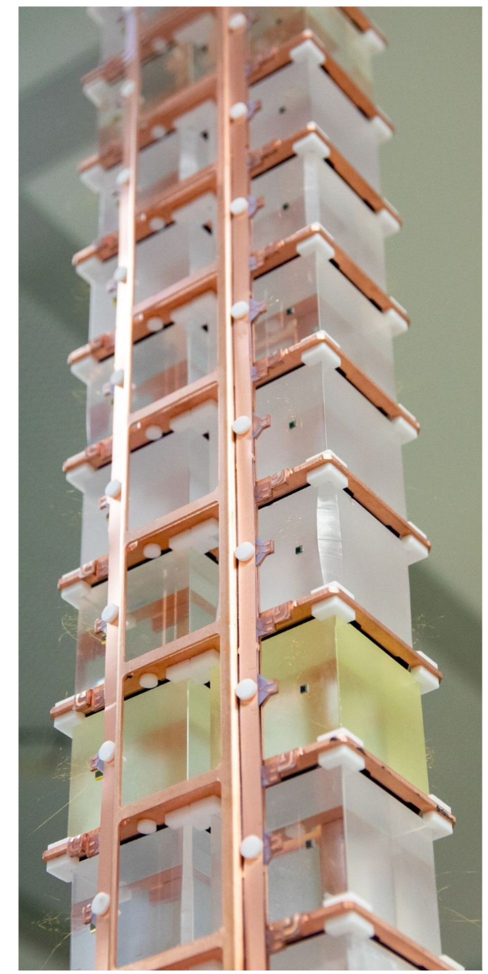
45 x 45 x 45 mm^3 Li$_2$^{100}MoO$_4$ crystals
- Crystal mass: 280 g

1596 total crystals
- 450 kg of Li$_2$^{100}MoO$_4$
- 95% enrichment in ^{100}Mo: 240 kg of ^{100}Mo
- 57 towers of 28 crystals. 14-floors of 2x1 crystal pairs. Gravity-assisted design

Ge light detectors with SiO anti-reflective coating
- Each crystal has top and bottom light detectors
- No reflective foils

Muon veto for muon-induced background suppression

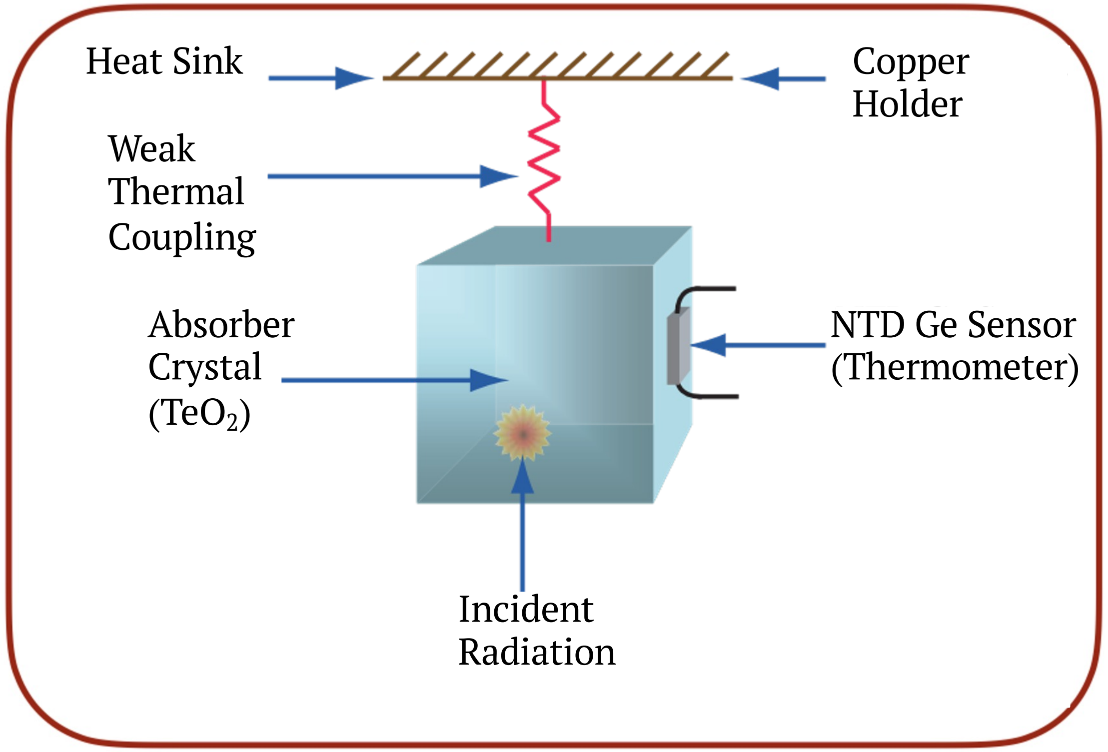




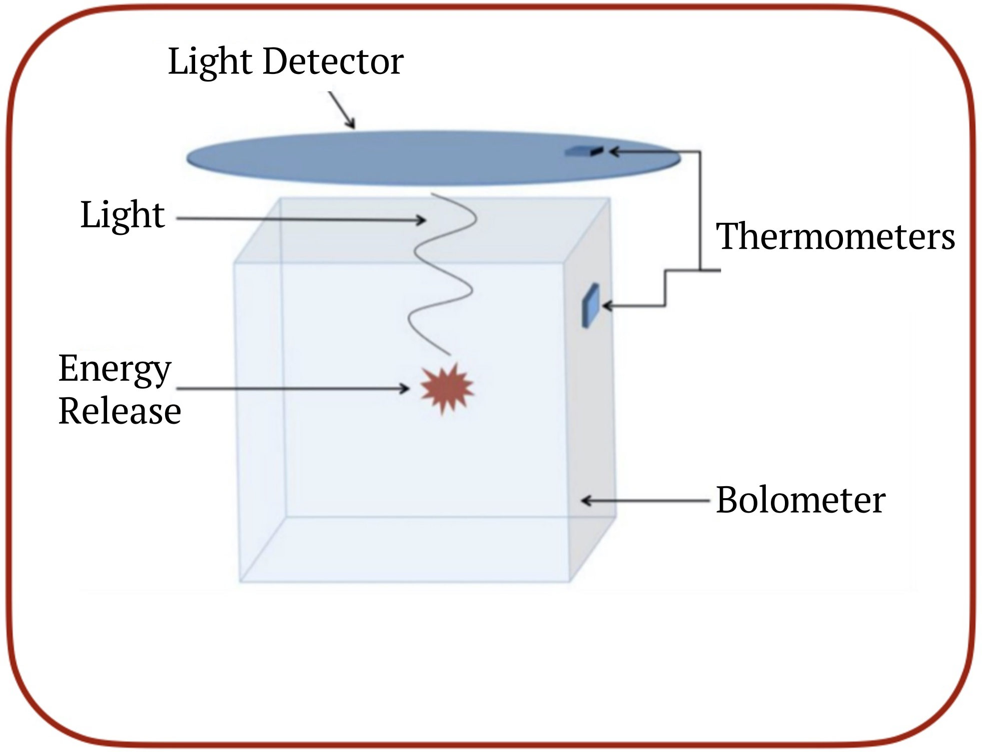
arXiv:2503.04481

CUPID Technology

CUORE ^{130}Te Bolometer



CUPID ^{100}Mo Scintillating Bolometer



$Q_{\beta\beta}$ = 2527 keV < 2615 keV peak
Measure only heat
No particle ID

$Q_{\beta\beta}$= 3034 keV: Most β/γ backgrounds reduced
Measure both heat + light
Particle ID to actively discriminate **α** particles

CUPID-1T: A Next-Next Generation Detector

CUPID-1T

- 4x scale up
- 1871 kg of $Li_2{}^{100}MoO_4$ for 1000 kg of ^{100}Mo

Cryogenics are achievable with current technology

- Distributed multi-cryostat setup
- Or single large cryostat and dilution refrigerator (comparable cooling power to CUORE)

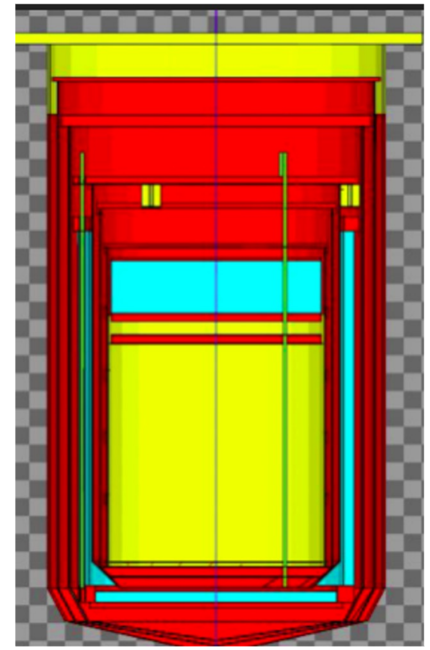
Quantum sensors

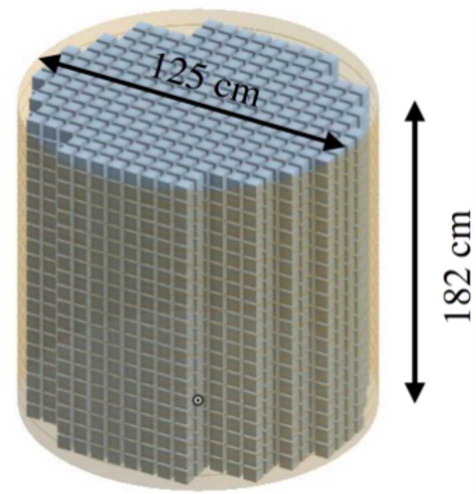
- Would require low-noise, high-bandwidth TES or mKIDs superconducting sensors
- Reasonable level of multiplexing
- Active R&D toward background reduction

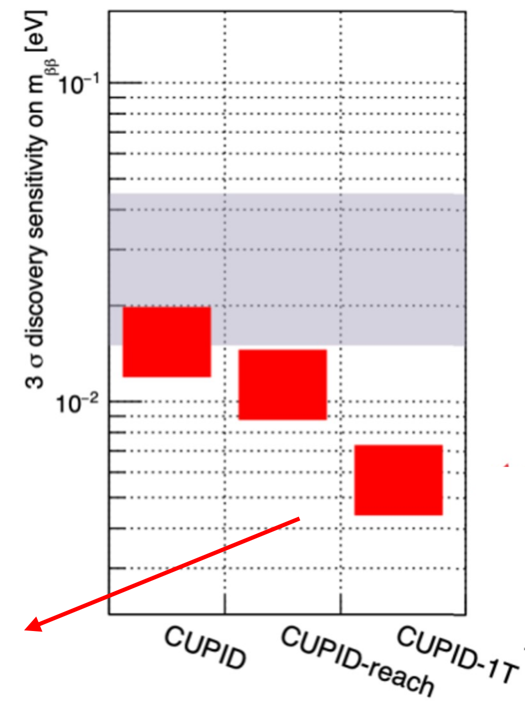
Background goal of 5×10^{-6} counts/(keV · kg · yr)

- Reduce background μ, β/γ, α discrimination
- Consider pileup and subdominant backgrounds

CUPID-1T is an Inverted Hierarchy precision measurement device across multiple isotopes or a Normal Hierarchy explorer



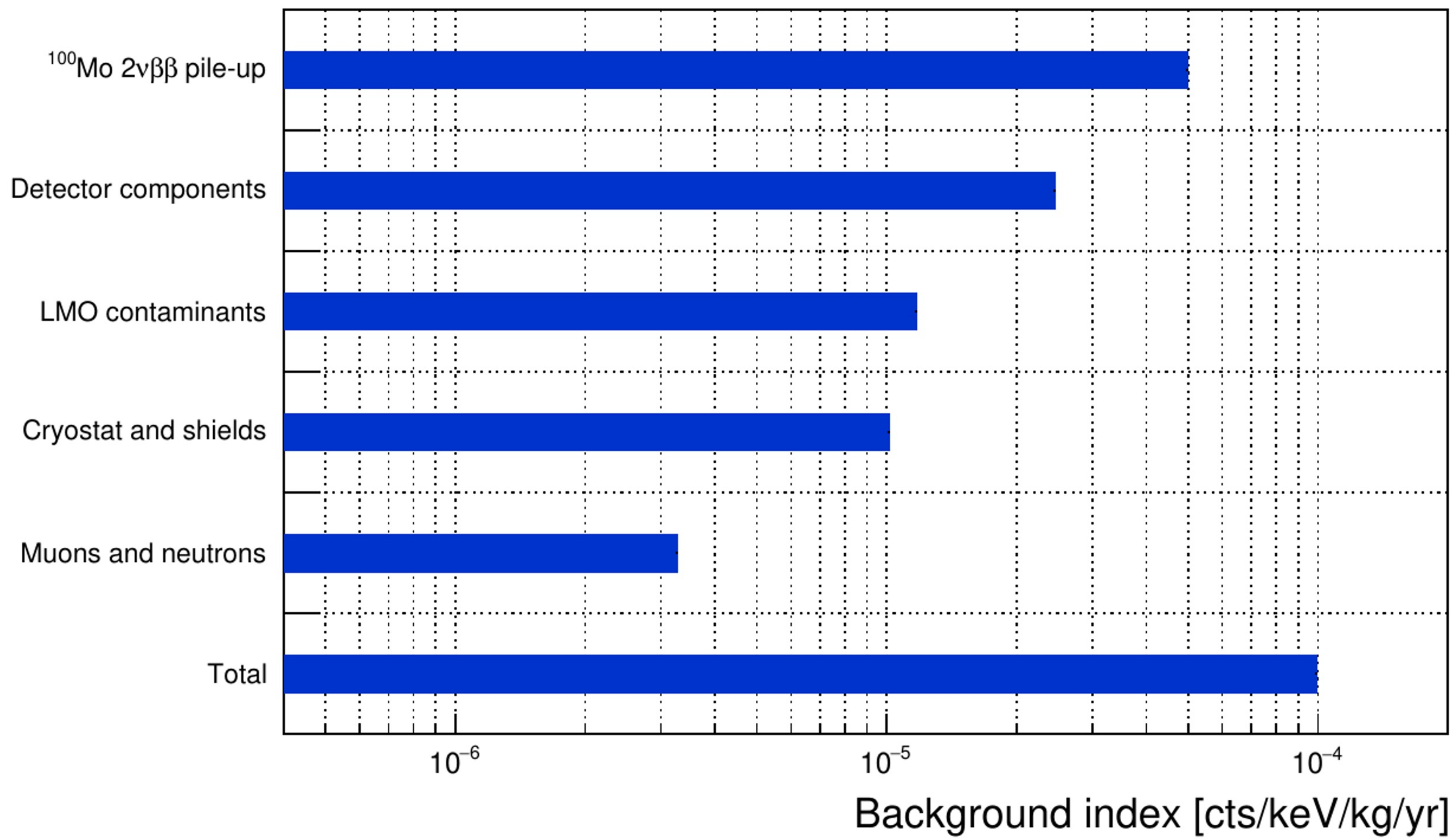




CUPID Background budget

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

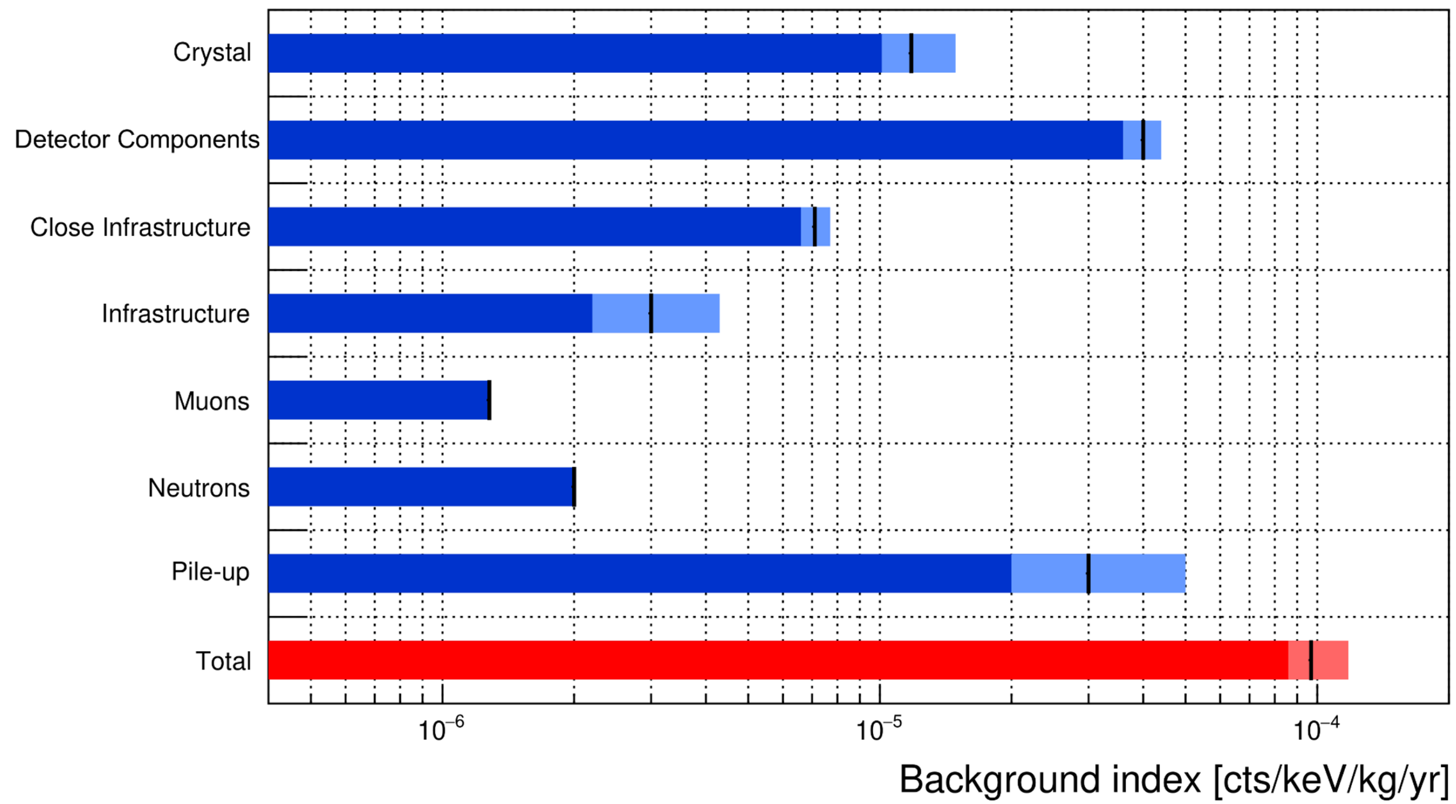
- **LMO ^{100}Mo pile-up:** demonstrated performance on baseline NTL detectors
- **Detector components:** surface driven
- **LMO contaminants**: surface driven
- **Cryostat & shields:** bulk
- **Muons and neutrons**



Current status of background estimations

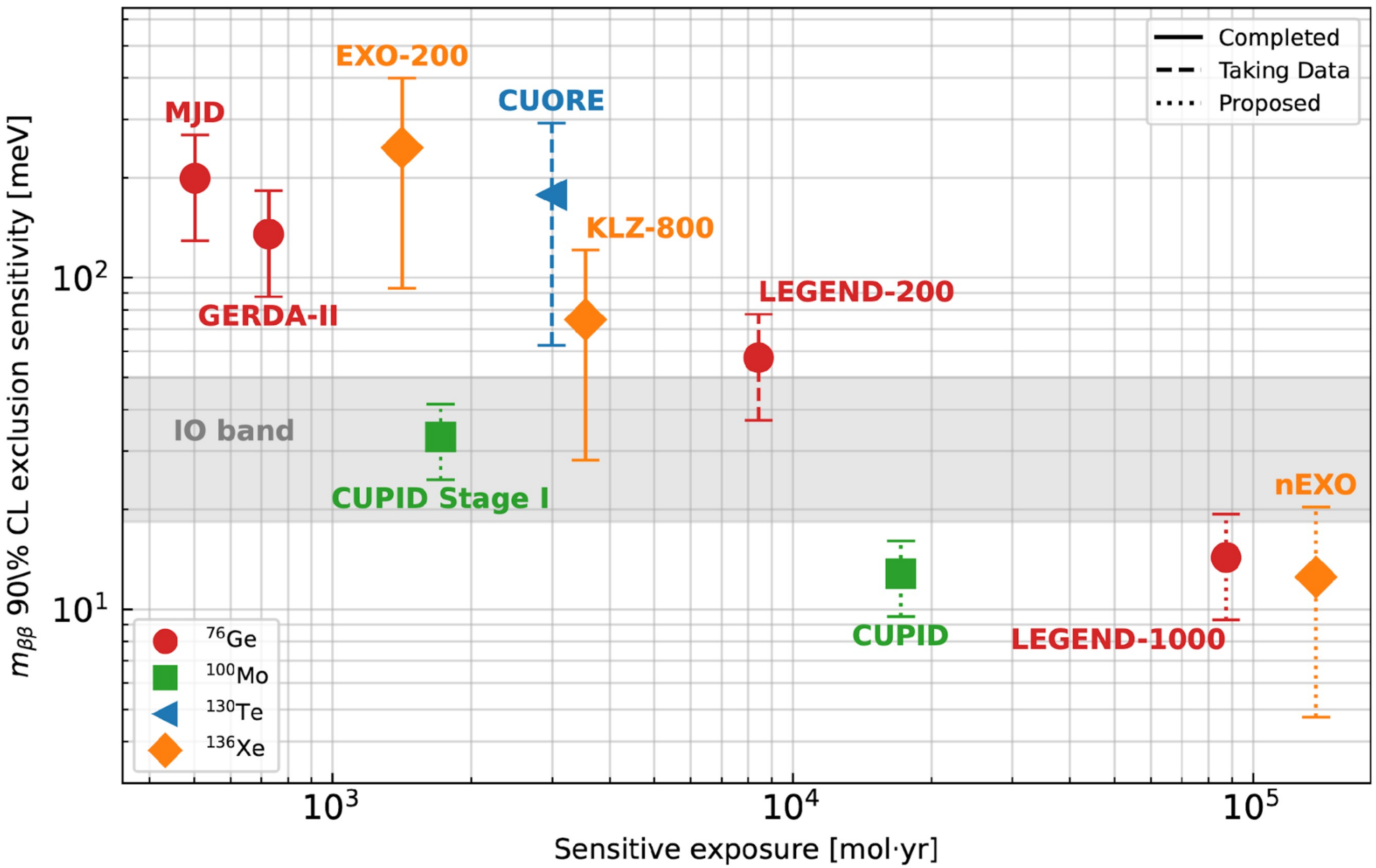
CUPID background estimates are based on measured contaminations in CUORE and CUPID-Mo

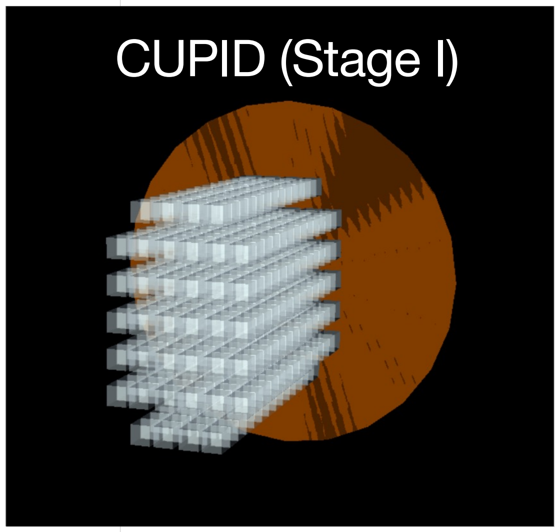
- **LMO ^{100}Mo pile-up:** extrapolated from measured performances of NTL light detectors
- **Detector components:** holders. Surface driven.
- **LMO crystal contaminants**: surface driven. Includes bulk and cosmogenic
- **Cryostat & shields:** bulk
- **Neutrons and muons:** based on initial design and MC simulation

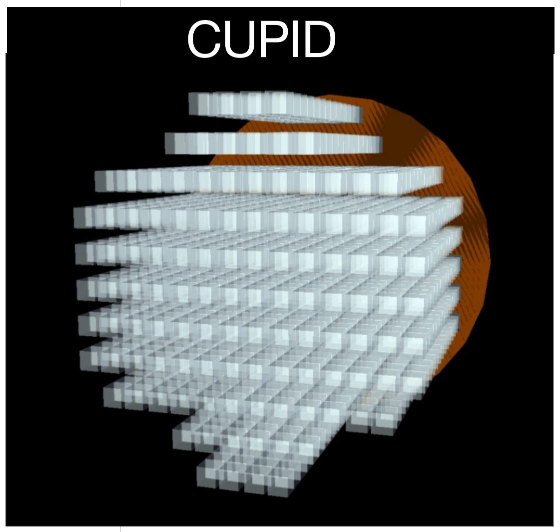


Work continues on further improvements in the overall background level

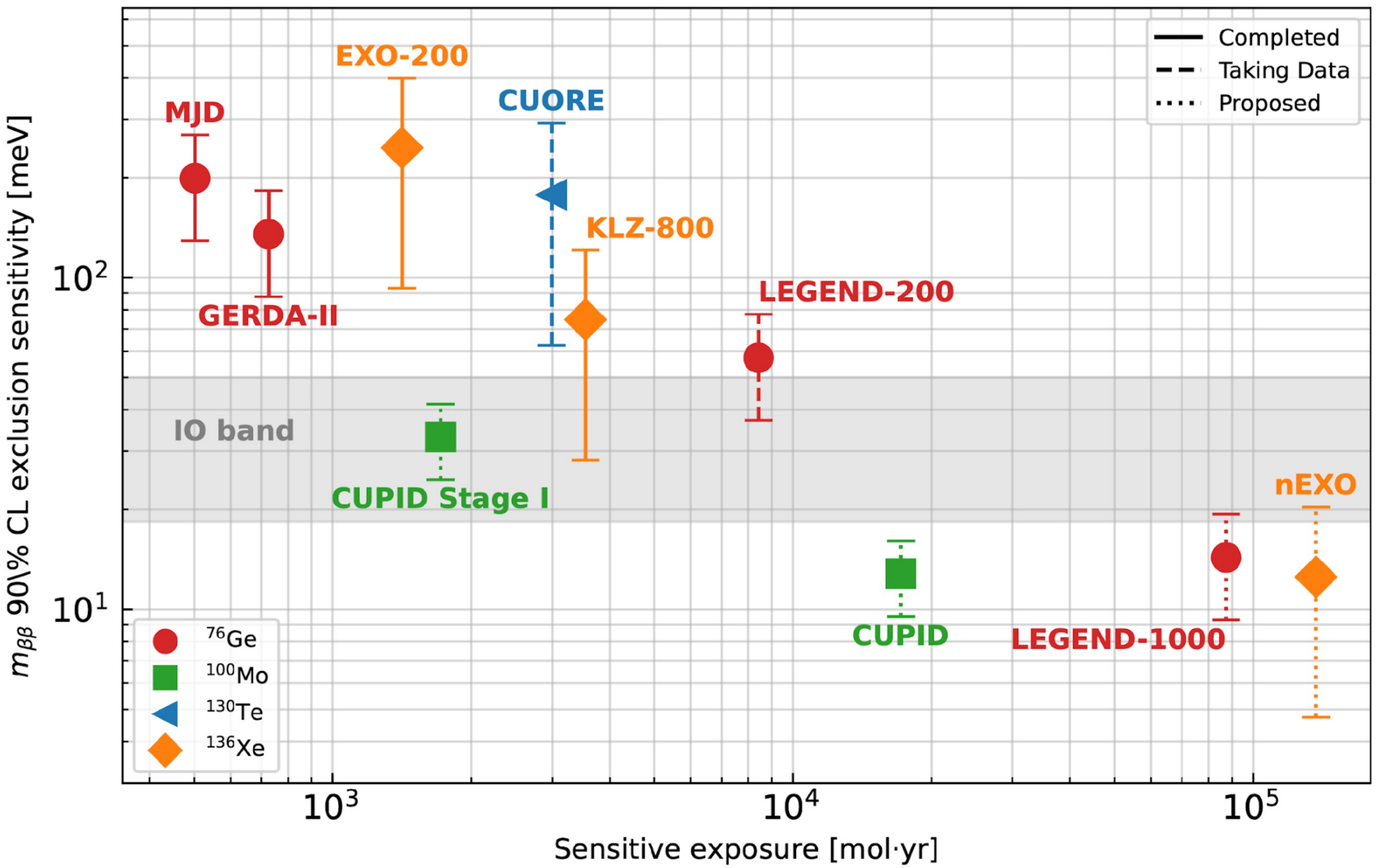
CUPID Sensitivity







CUPID Sensitivity



CUPID Stage I has world-leading science reach

CUPID is a ton-scale experiment with competitive sensitivity

The Path Toward CUPID

CUORE Phase-I (current)

Continue data taking until meeting goal
~ 3 ton yr TeO_2
(1 ton yr ^{130}Te)

Estimate end of data taking in mid-2026

Large statistics to perform high sensitivity searches in several channels (ββ decay, dark matter, exotic phenomena, …)

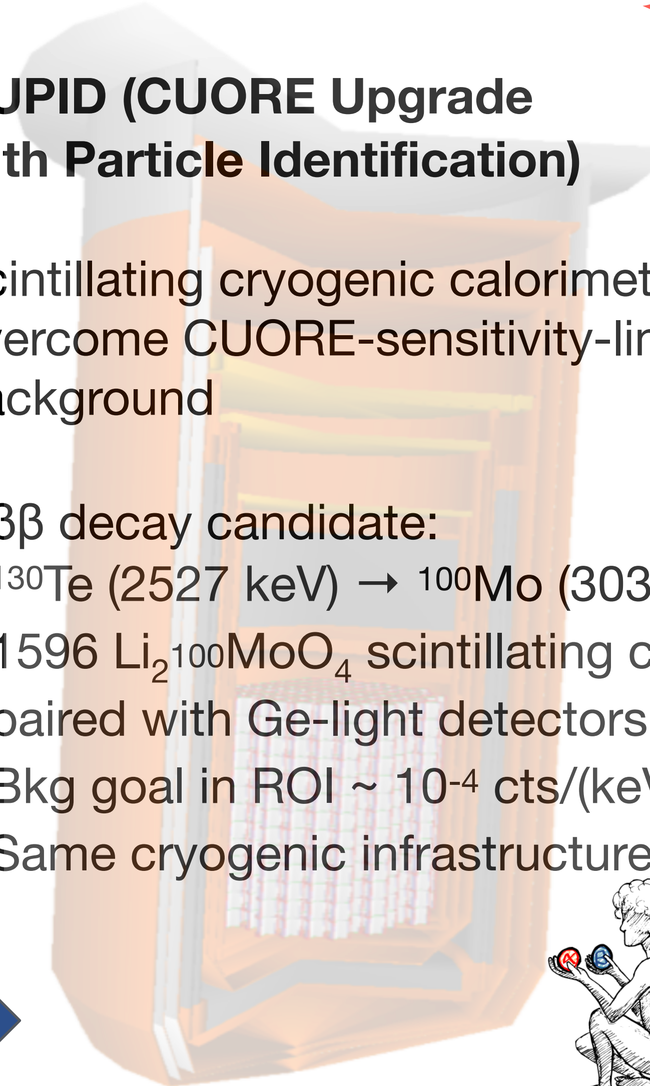
CUORE Phase-II

Upgrade of the cryogenic system to improve cooling power and reduce vibrational noise

Plan to resume data-taking in 2027

Lower thresholds high sensitivity low energy studies (axions, WIMPS, …)

CUPID (CUORE Upgrade with Particle Identification)



Scintillating cryogenic calorimeters to overcome CUORE-sensitivity-limiting α background

- ββ decay candidate:
  ^{130}Te (2527 keV) → ^{100}Mo (3034 keV)
- 1596 $Li_2{}^{100}MoO_4$ scintillating crystals paired with Ge-light detectors
- Bkg goal in ROI ~ 10^{-4} cts/(keV kg yr)
- Same cryogenic infrastructure