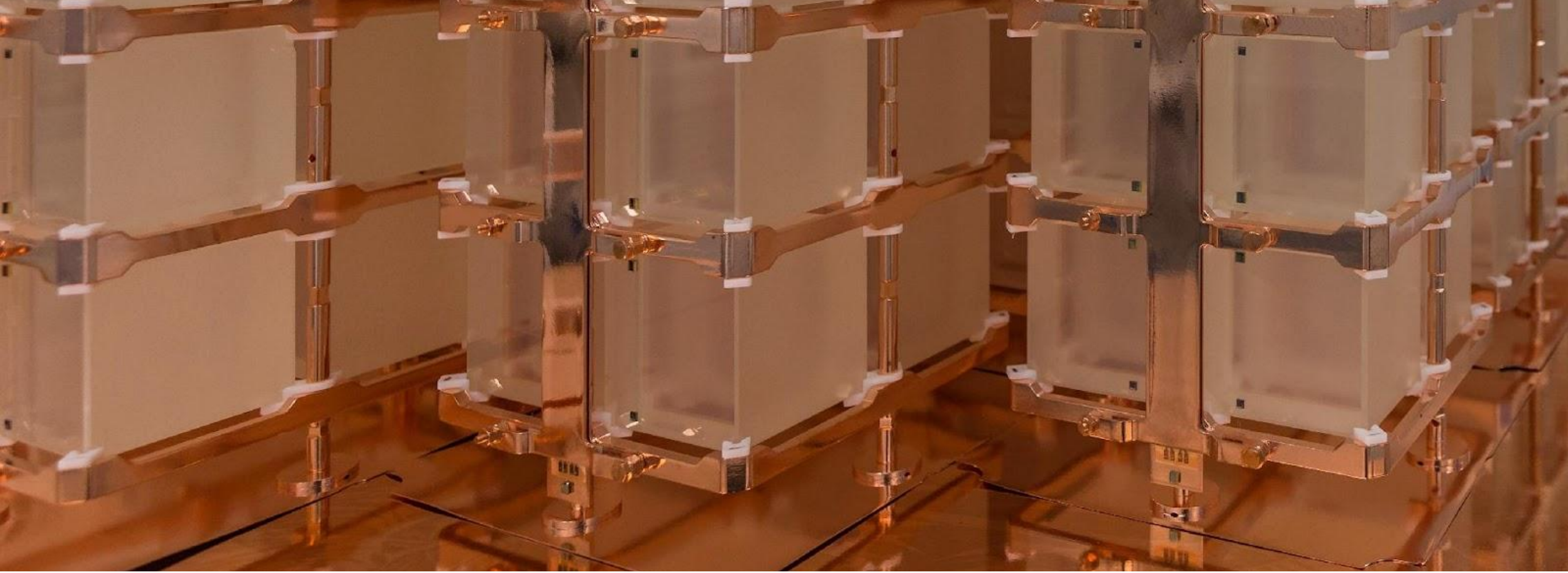


Latest results from the CUORE experiment

Miriam Olmi on behalf of the CUORE collaboration

The 16th International Workshop on Tau Lepton Physics

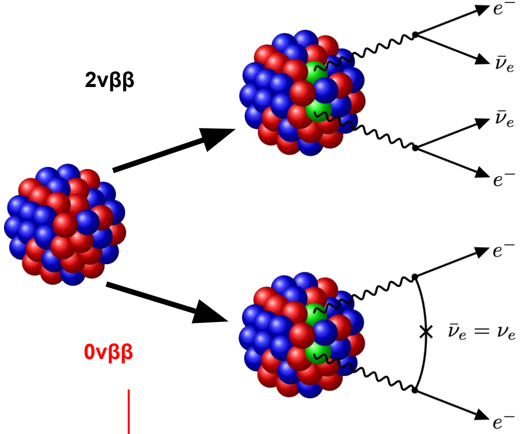
CUORE

INFN
LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

Neutrinoless double beta decay ($0\nu\beta\beta$)

Double beta decay is a rare second order Fermi weak interaction

Two decay channels usually considered:

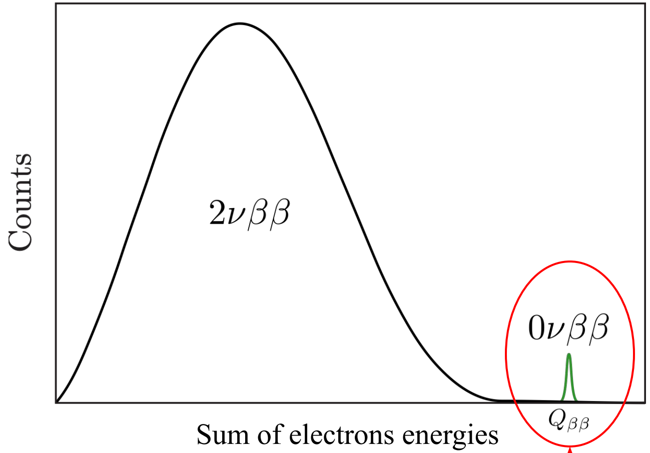


Standard Model allowed, observed in 11 nuclei

Beyond Standard Model, not yet observed

Candidates = even-even nuclei when single β decay energetically forbidden

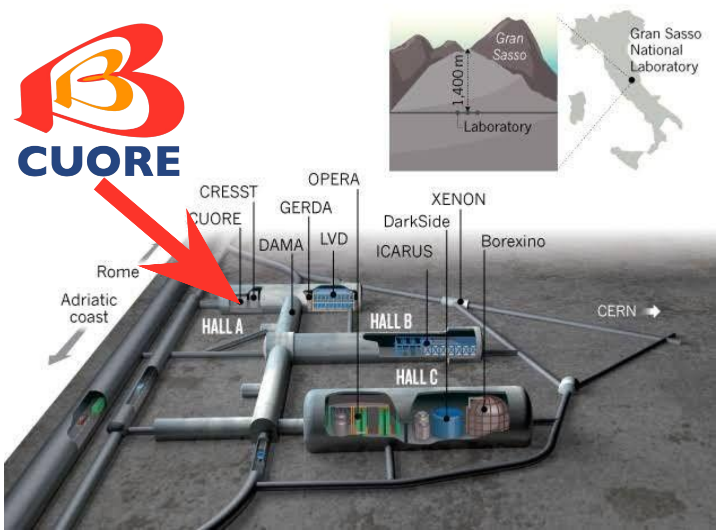
- Lepton number violating process (Δ L=2)
  ⇒ L is not a symmetry of nature
- Only possible if neutrinos have a Majorana component
  ⇒ new possible mechanism for ν mass
- Possible explanation of matter-antimatter asymmetry origin via Leptogenesis

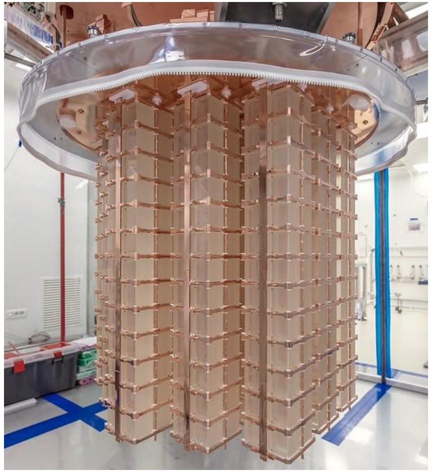


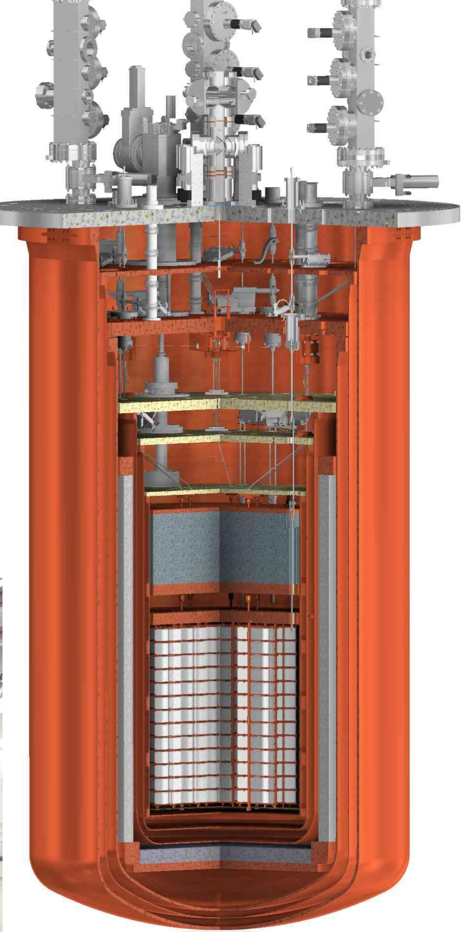
The CUORE experiment

Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

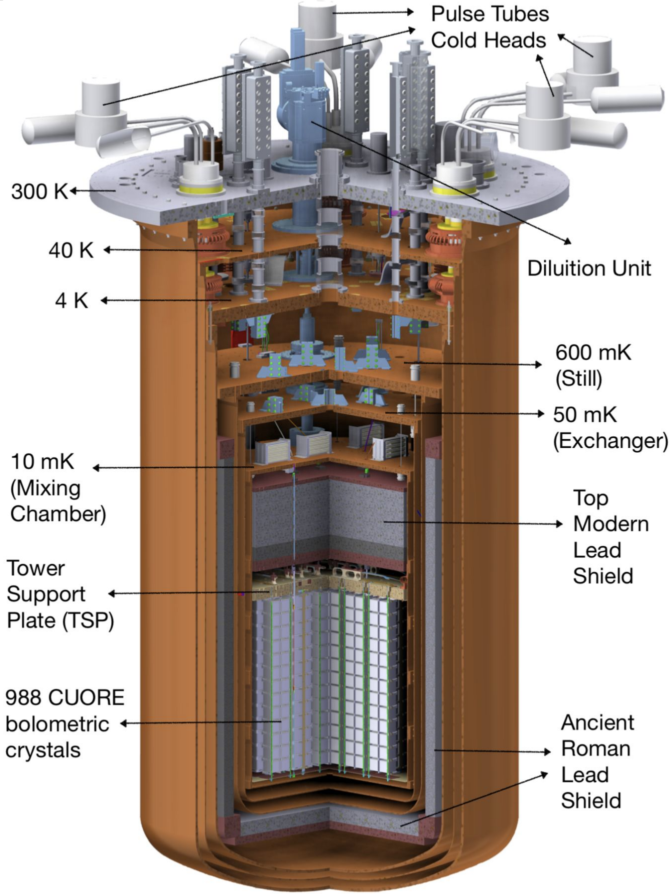
- Located at the LNGS underground facility (3650 m.w.e.)
- Main Physics goal: search for 0νββ decay of ^{130}Te
- $Q_{\beta\beta}$ = 2527.5 keV above (most) natural γ backgrounds
- 988 natural TeO_2 crystals at ~10 mK
- 742 kg of TeO_2 ⇒ 206 kg of ^{130}Te ~90% detection efficiency







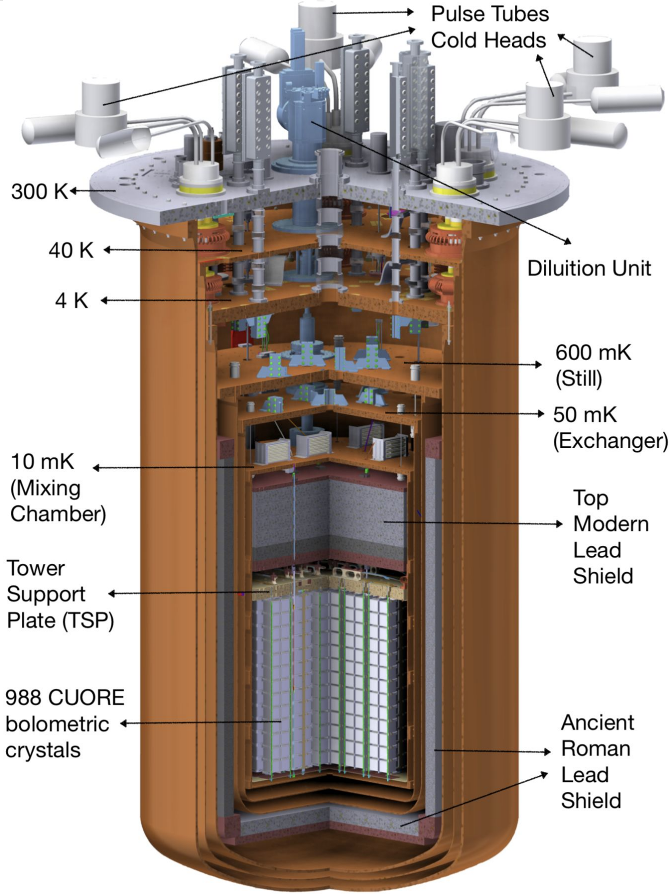
The CUORE cryostat challenges



Requirements:

- Ton-scale detector hosted in a cryogen-free cryostat (mass < 4K: ~ 15 tons of Pb, Cu and TeO_2)
- Operating temperature ~ 10 mK
- Low background level: goal of 10^{-2} counts/(kev kg yr) at $Q_{\beta\beta}$
  - □ Extremely low radioactivity
- Energy resolution: goal of 5 keV FWHM at ^{130}Te $Q_{\beta\beta}$
  - □ Low vibrations environment
- Run for ~5 yr

The CUORE cryostat challenges



Solutions:

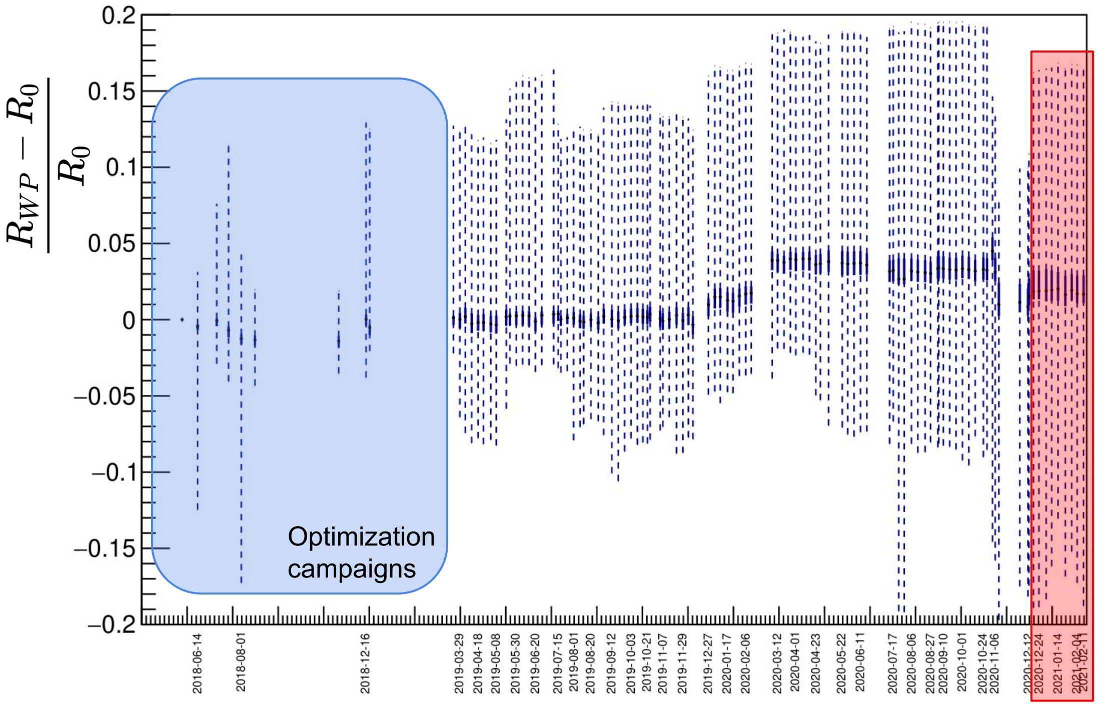
- Cryogen-free cryostat ⟶ lower downtime
- 5 (4) Pulse Tubes (PT) ⟶ down to ~4K
- Custom built Dilution Unit (DU) ⟶ down to ~7mK

- Low-radioactivity materials choice, strict cleaning and assembling protocols
- Roman ^{210}Pb- depleted + modern lead shields
- Neutrons shield: external polyethylene layer with boric acid panels

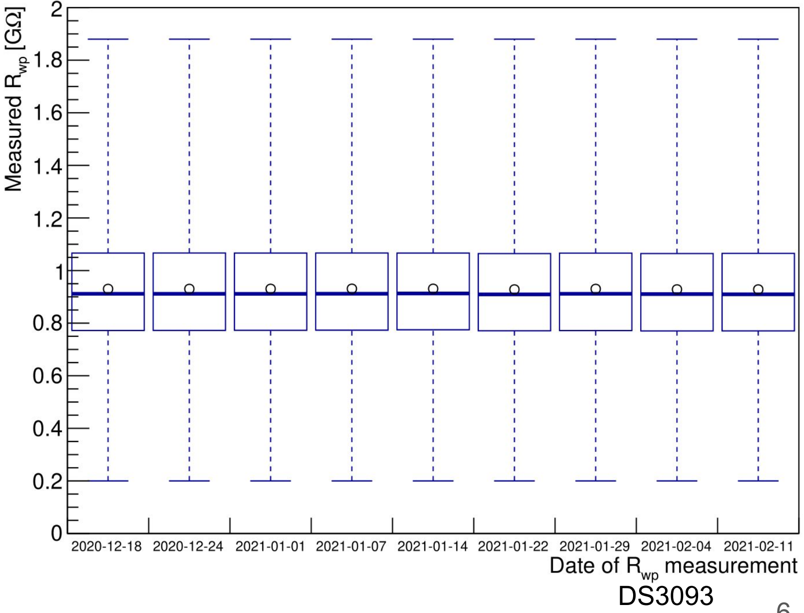
- External support structure mechanically decouples the detectors from the cryostat
- PT phase cancellation

The CUORE cryostat challenges

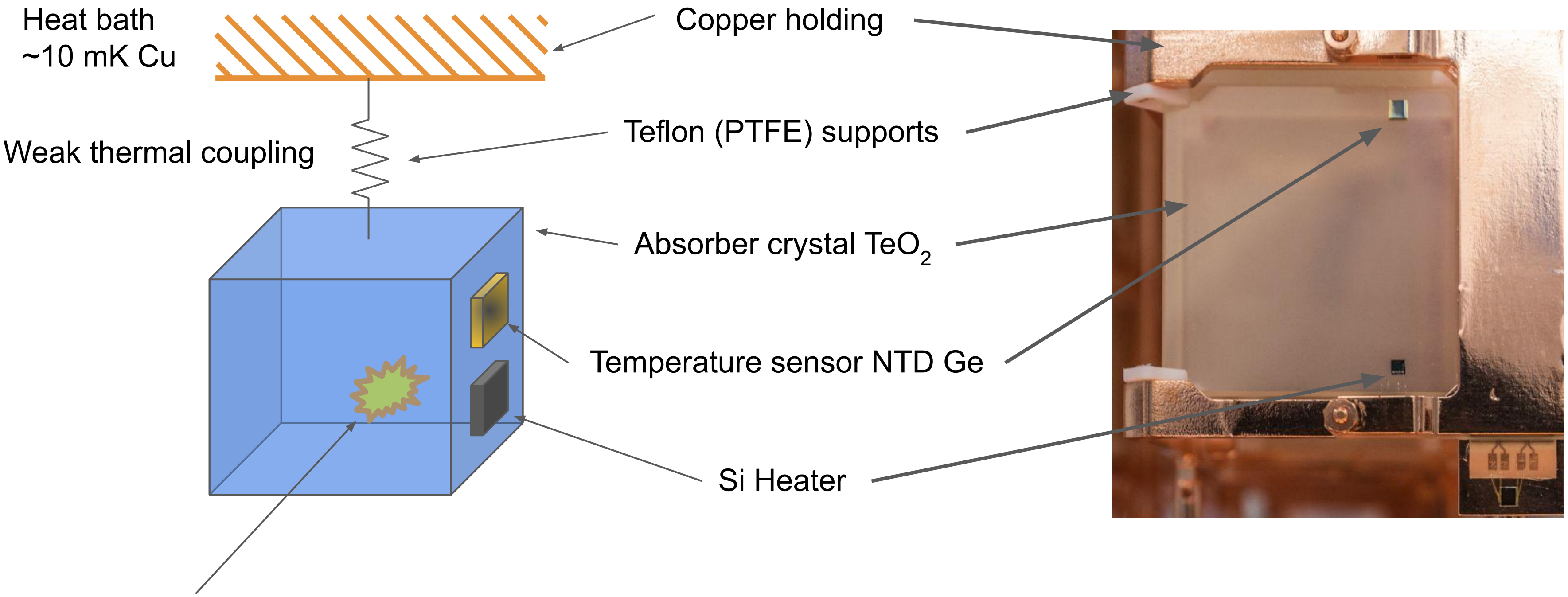
Stability of NTD resistances at WP during the CUORE data taking at 11 mK



Cryostat stability + PID temperature control guarantee stability of NTD resistance better than 1%



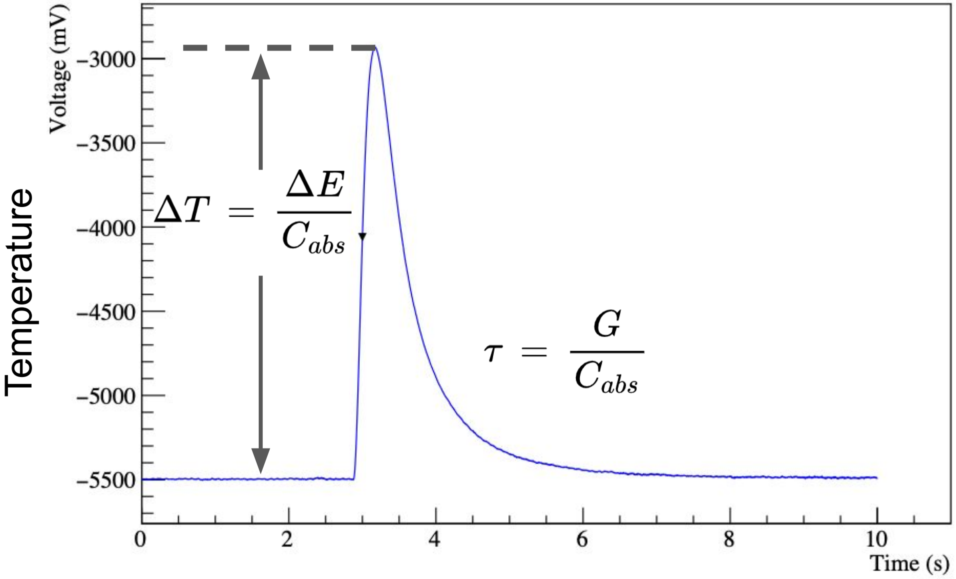
The CUORE detector



Particle interaction

$$\Delta T = \frac{\Delta E}{C_{abs}}\ ;\ C_{abs} = C(T) \longrightarrow \Delta E \backsim 1\ \text{MeV} \begin{cases} \Delta T \sim 10^{-18}\text{-}10^{-15}\ \text{K} & @\ T_0 \approx 300\ \text{K} \\ \Delta T \sim 0.1\ \text{mK} & @\ T_0 \approx 10\ \text{mK} \end{cases}$$

The CUORE detector working principle



$$\Delta T = \frac{\Delta E}{C_{abs}} \Rightarrow \boxed{100\,\mu K/MeV \;\; @\,T_0 \sim 10\,mK}$$

$$\tau = \frac{G}{C_{abs}} \sim 1\,s$$

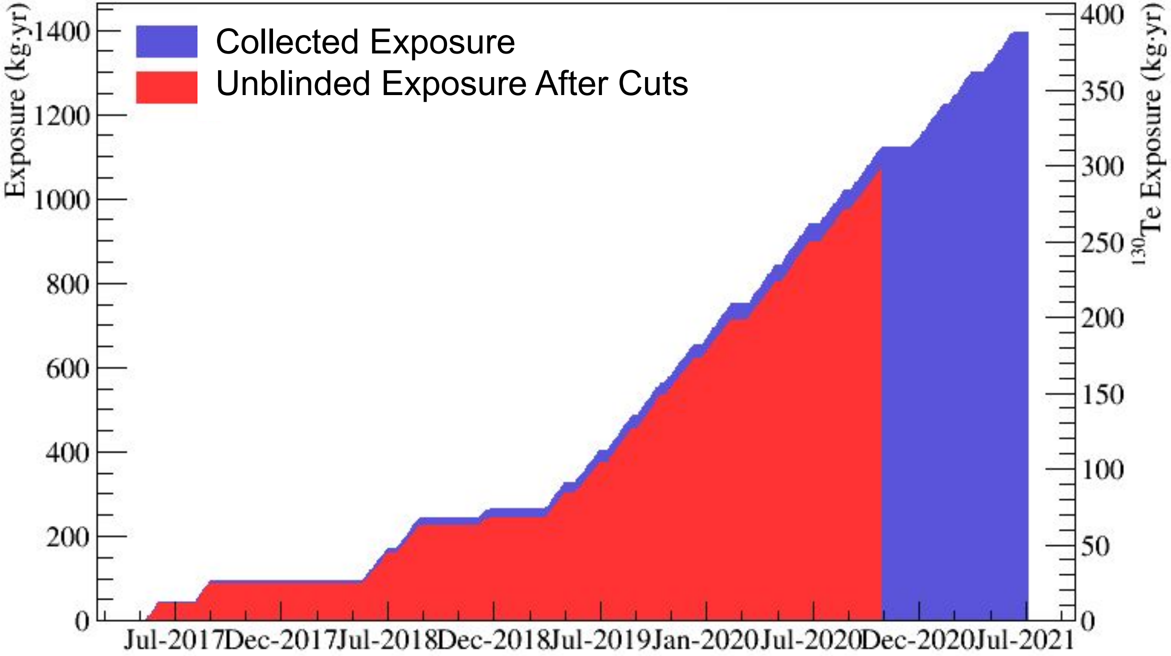
$$C_{abs}(T) \propto T^3$$

$$R_{NTD}(T) = R_0\, e^{\sqrt{T_0/T}}$$

ΔT: temperature variation
ΔE: energy deposition
C_{abs}: absorber capacity
τ: signal decay time
G: thermal conductance
R_0,T_0: NTD parameters

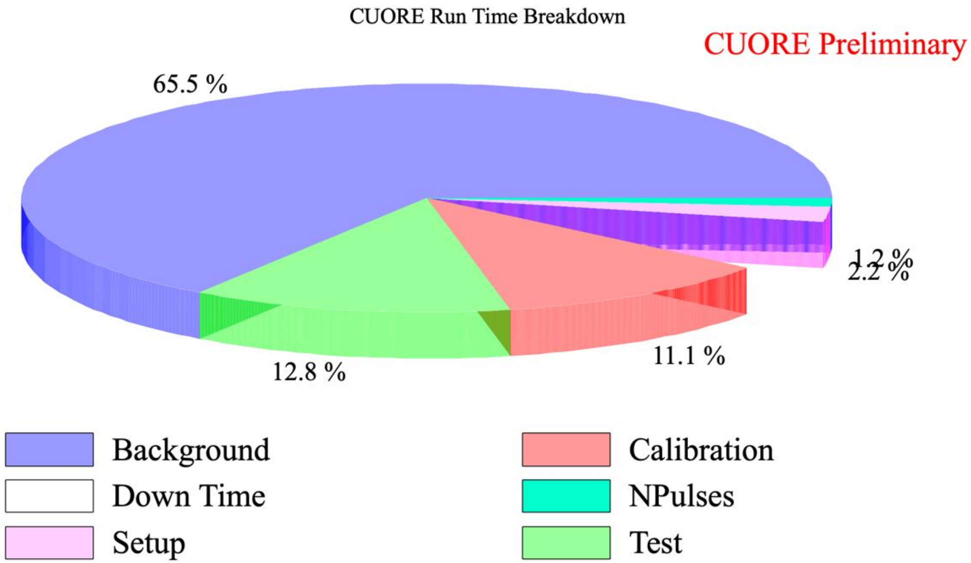
- Low heat capacity @ T_0
- Excellent energy resolution (~1‰ FWHM)
- Equal detector response for different particles
- Slowness (suitable for rare event searches)

CUORE data taking

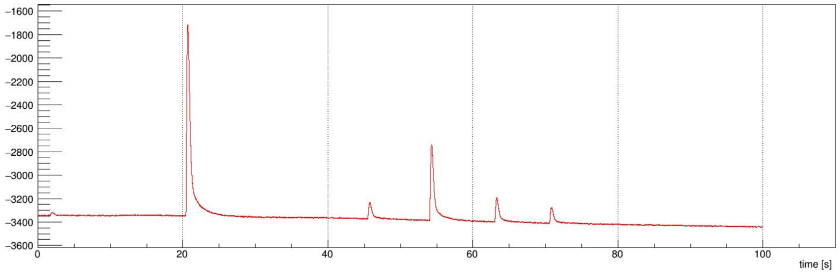


- data taking started in 2017
- 2017-2019: optimization campaigns to improve understanding and stability of the experiment
- since march 2019 steady data taking with >90% uptime
- steadily collecting data at an average rate of ~ 69 kg yr / month
- > 1.29 tonne yr raw exposure

CUORE data taking

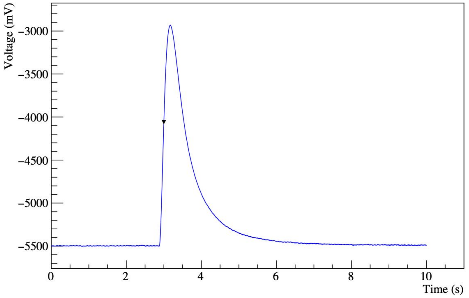


- Voltage output continuously sampled (1 kHz) and stored on disk
- Periods with unstable data taking conditions excluded (e.g. earthquakes)



- CUORE “data set”: 1 month of background (physics) data taking, few days of calibration before and after

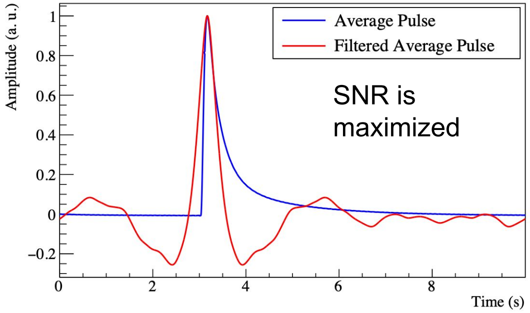
CUORE data processing

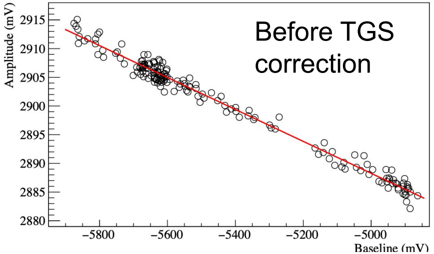


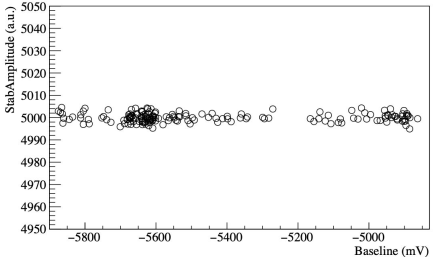
Amplitude (Optimum Filter)

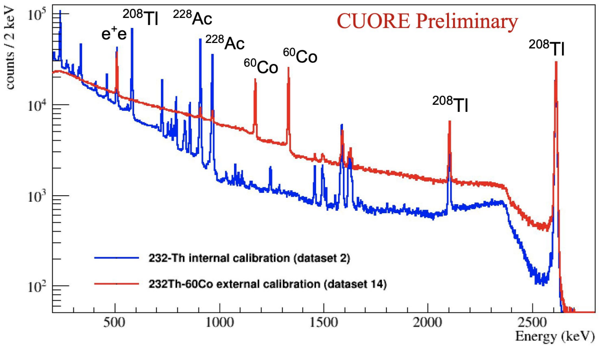
Thermal gain stabilization

Energy calibration









Stabilized amplitude is converted in Energy

Coincidences

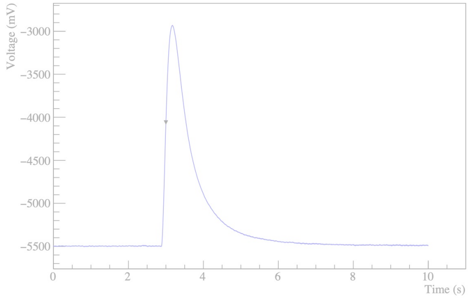
Pulse Shape Discrimination

ROI blinding

ROI fit optimization

Unblinding

CUORE data processing

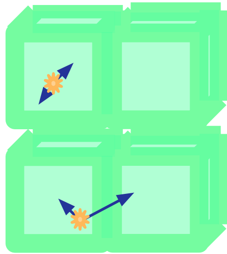


Amplitude (Optimum Filter)

Thermal gain stabilization

Energy calibration

Coincidences

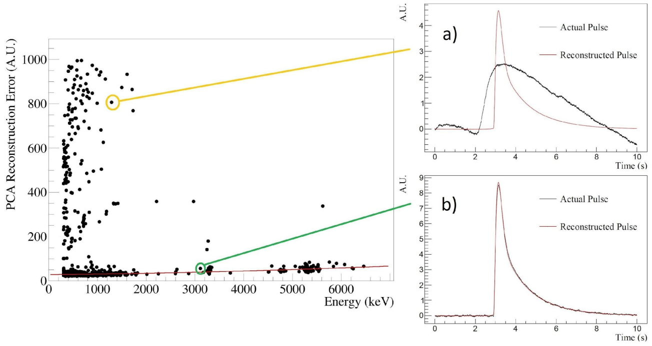


M1 (0νββ expected signature)

M≥2 (background events)

Time/space-based coincidences calculation and event multiplicity assignment

Pulse Shape Discrimination

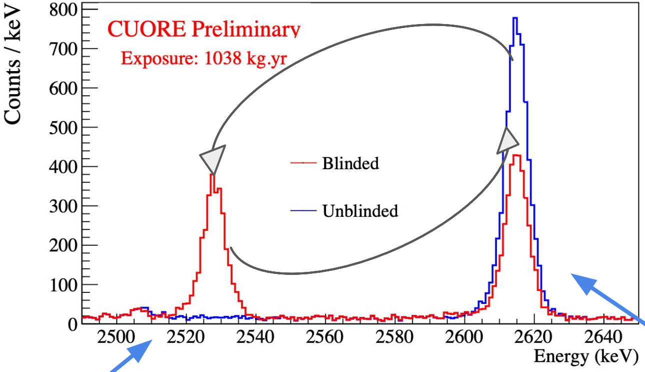


Principal Component Analysis: waveforms deviating from the average pulse (leading principal component) are poorly reconstructed and rejected

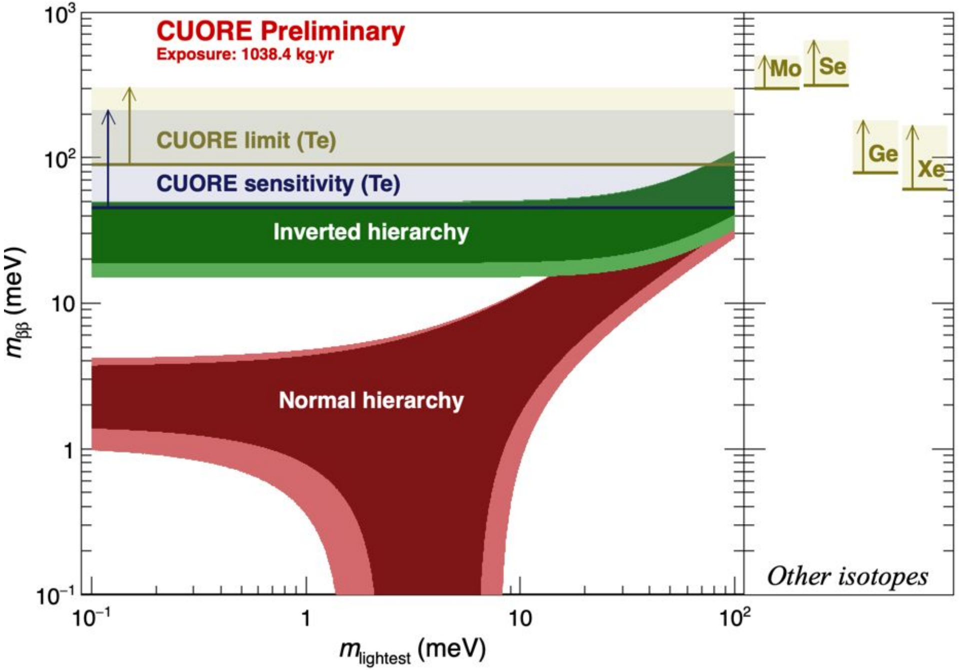
ROI blinding

ROI fit optimization

Unblinding



Limit on effective Majorana mass ($m_{\beta\beta}$)



In the assumption that the 0νββ decay is mediated by the exchange of a light Majorana neutrino:

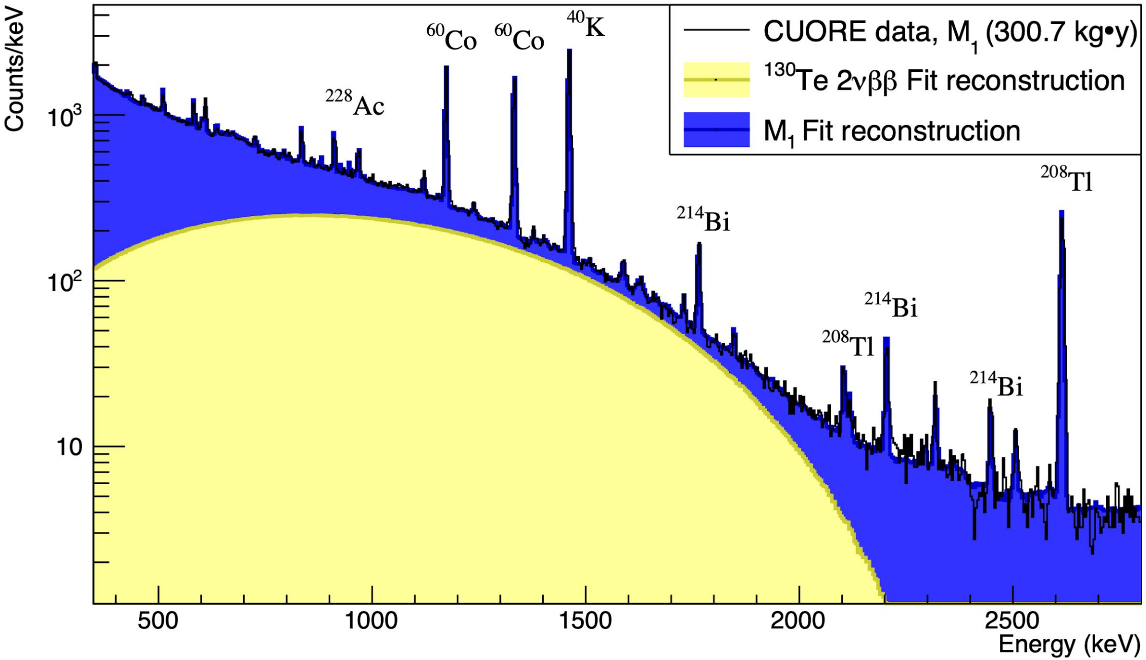
$$\Gamma^{0\nu} = G^{0\nu} \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

$T_{1/2} > 2.2 \cdot 10^{25}$ yr (limit 90% C.I.)

$m_{\beta\beta} < 90 - 305$ meV (90% C.I.)

arXiv:2104.06906 (2021)

CUORE background model: $2\nu\beta\beta$ decay of ^{130}Te



Dominant component of the observed M1 spectrum between ~1 to 2 MeV, due to reduced γ background and self shielding of outer TeO_2 towers

$$T^{2\nu}_{1/2} = 7.71^{+0.08}_{-0.06}\,(\text{stat})^{+0.12}_{-0.15}(\text{syst}) \cdot 10^{20}\ \text{yr}$$

Most precise measurement of ^{130}Te 2vββ decay half-life to date

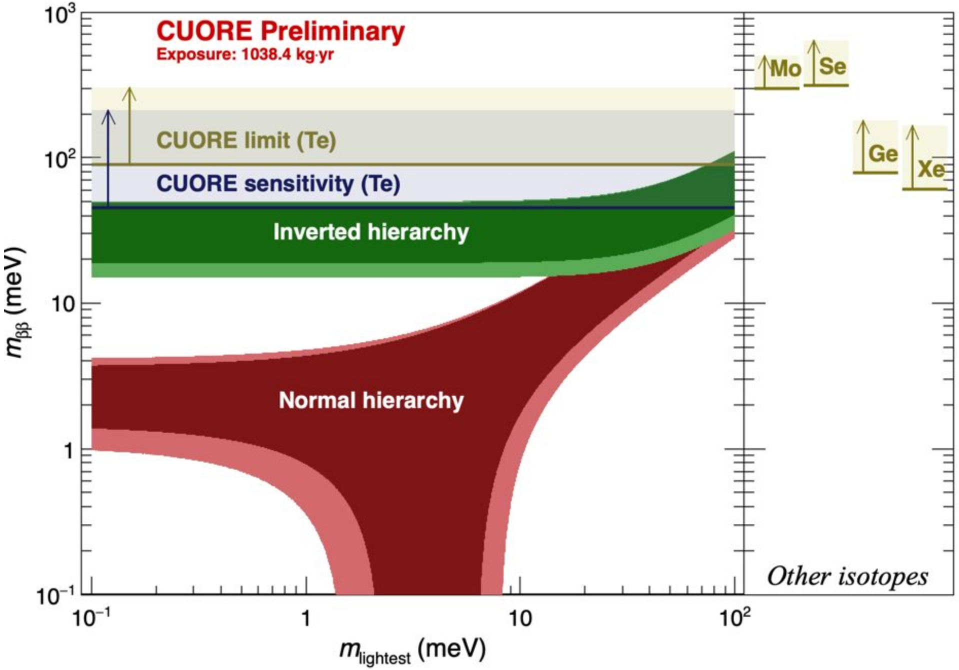
Phys. Rev. Lett., 126:171801, 2021

CUORE sensitivity

$0\nu\beta\beta$ decay exclusion sensitivity in 5 yr (90% C.L.): $S_{0\nu} \sim 9 \cdot 10^{25}$ yr, $m_{\beta\beta}$<50-130 meV
with nominal background B: 10^{-2} c/(keV·kg·yr) and nominal energy resolution of 5 keV FWHM in the ROI

CUORE TeO_2 detectors background:

- Degraded α particles
  - from radioactive decays close to the detectors or on their surface
  - deposit part of their energy in the detectors
  - constitute the main (~90%) contribution to the CUORE background index in the ROI
- Multi-Compton of γ
  - by the ^{232}Th/^{239}U chains and cosmic muons
  - constitute the remaining background contribution



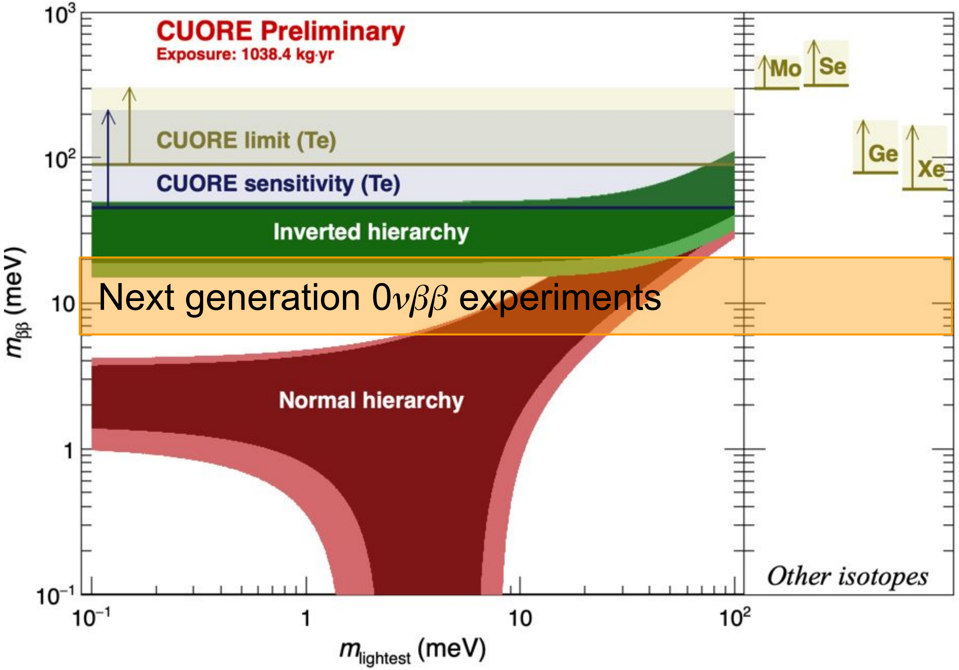
What’s next?

Next generation $0\nu\beta\beta$ decay experiments seek to be sensitive to the full Inverted Hierarchy region:

$$S_{0\nu} \sim 10^{27}\ \text{yr},\ m_{\beta\beta} < 6\text{-}20\ \text{meV}$$

To reach these sensitivities:

I. Reach the “zero background” regime ⇒ lower the background and improve energy resolution in the ROI
II. Larger active mass

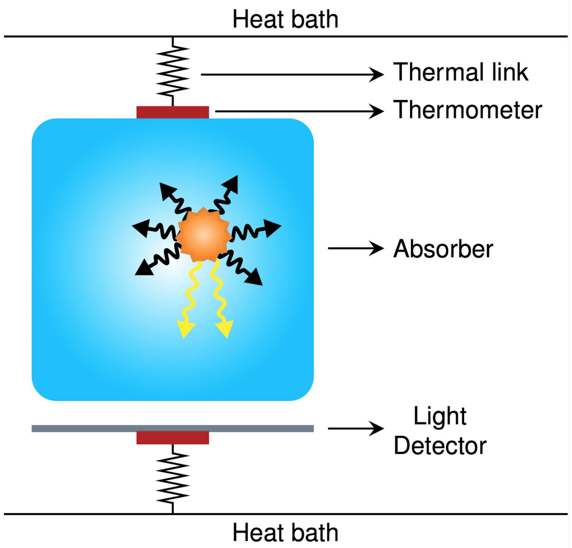


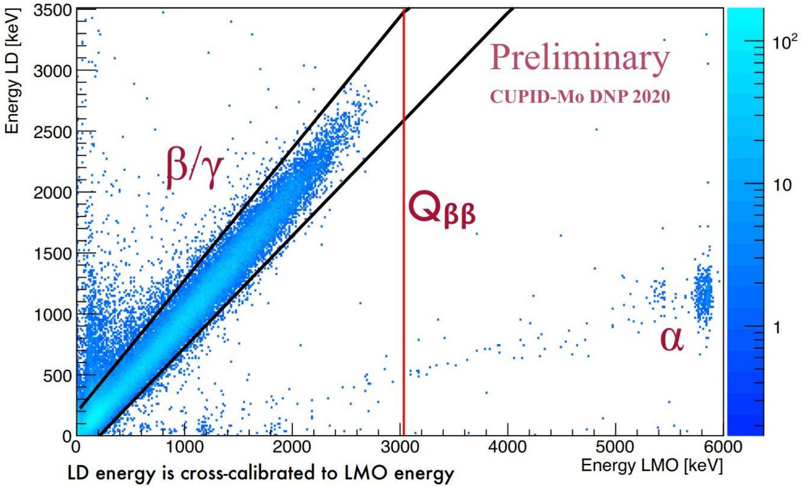
CUPID

CUORE **U**pgrade with **P**article **ID**entification

- ^{100}Mo $\beta\beta$ decay candidate: $Q_{\beta\beta}$ ~3034 keV
- Readout of both heat and scintillation light with thermal sensors
- Alpha-particle rejection using light signal

$Li_2{}^{100}MoO_4$ scintillating crystals

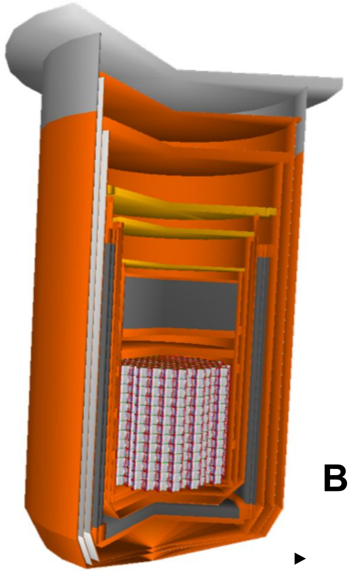




Courtesy of the CUPID-Mo Coll.

CUPID

CUORE **U**pgrade with **P**article **ID**entification



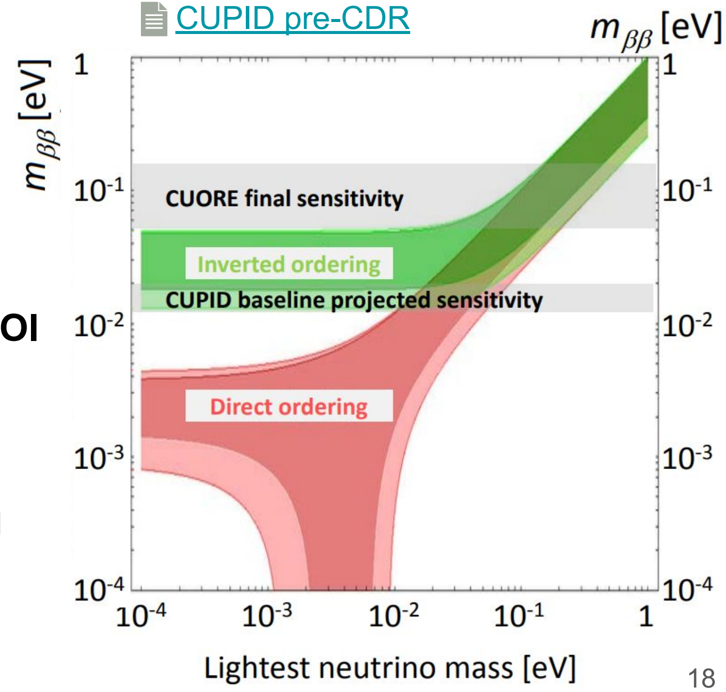
1 tonne of scintillating $LiMoO_4$ detectors

- ~1500 calorimeters, each cubic crystal ~300g
- Crystal enriched >95% in ^{100}Mo (~250 kg of ^{100}Mo)
- Ge light detectors
- LMO and LD read via NTD
- CUPID detector hosted in CUORE cryostat

Background goal B < 10^{-4} c/(keV·kg·yr) in the ROI

- Particle ID (α vs β/γ) with scintillation light
- Possible discrimination of $2\nu\beta\beta$ pile-up from pulse shape
- Background reduction: underground location at LNGS, passive shields (Pb/Cu), high-radiopurity in assembly and storage of detectors and materials, muon veto, profit of detector high granularity

CUPID pre-CDR



Summary & Conclusions

- CUORE is the first ton-scale experiment for double beta decay search operating cryogenic detectors
- 1 ton · yr analyzed data milestone achieved

  ⇒ stable operation for ton-scale cryogenic detector is possible

- Data taking is smoothly ongoing aiming at 5 years live time
- New results on ^{130}Te $0\nu\beta\beta$ decay (1038.4 kg · yr exposure): most stringent half-life limit to date

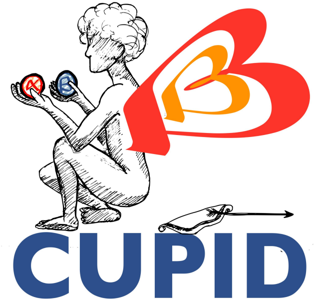
  arXiv:2104.06906 (2021)

- New results on ^{130}Te $2\nu\beta\beta$ decay (300.7 kg · yr exposure): most precise half-life measurement to date

  Phys. Rev. Lett., 126:171801, 2021

- CUORE demonstrates the potential for large-scale bolometric detectors. The same technology and infrastructure will be used for the CUPID experiment.

  arXiv:1907.09376 (2019)



Thank you for the attention