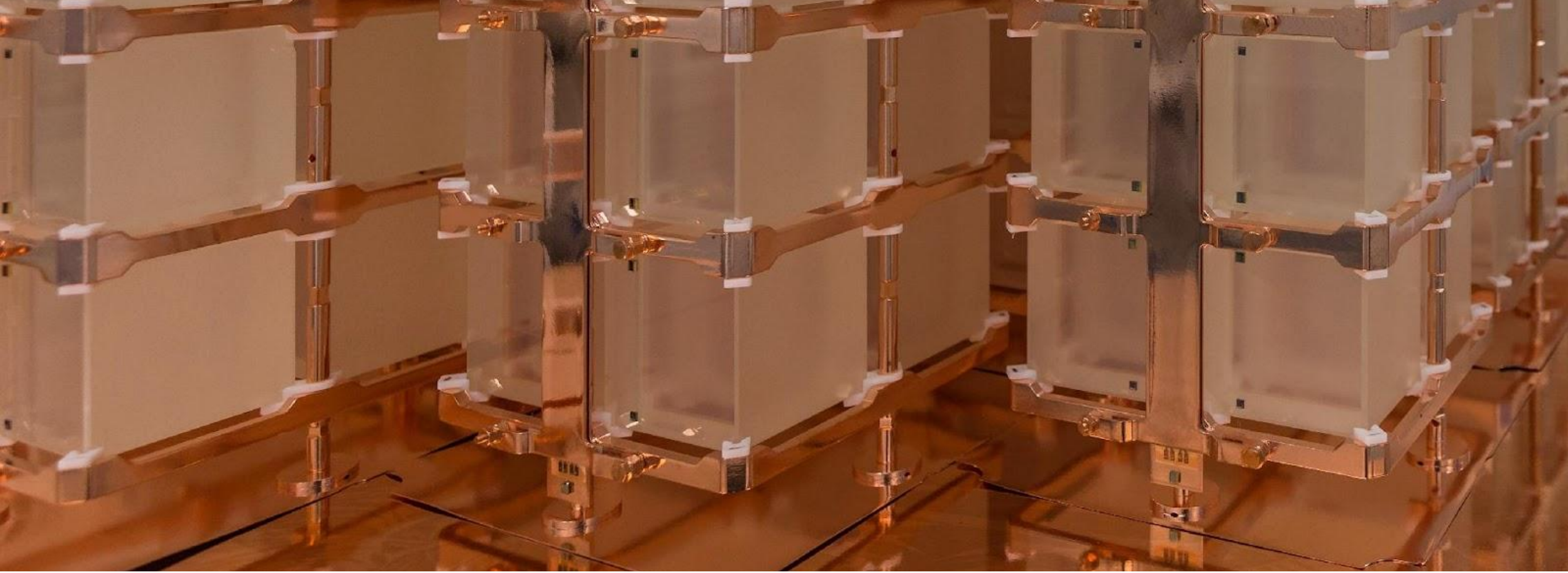


Latest results from the CUORE experiment

Stefano Di Lorenzo on behalf of the CUORE collaboration

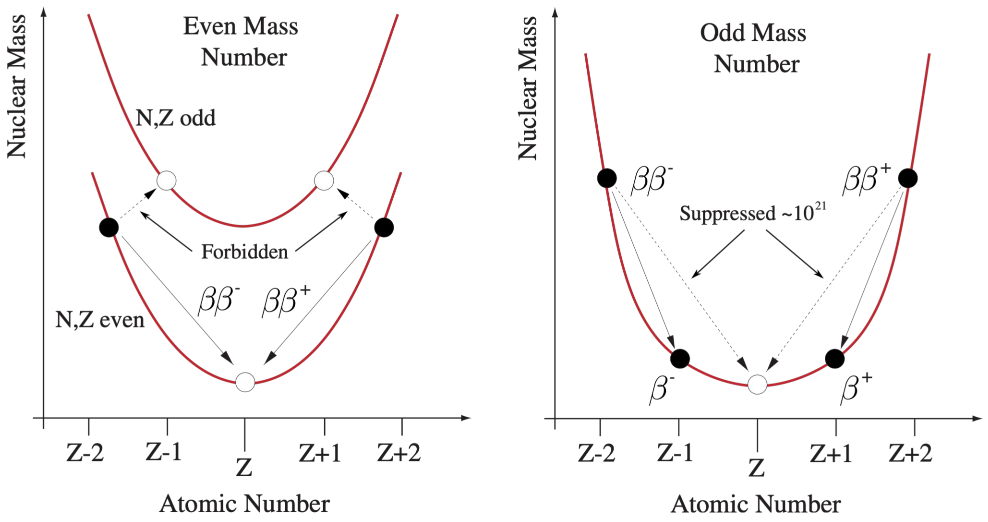
TeV Particle Astrophysics 2021

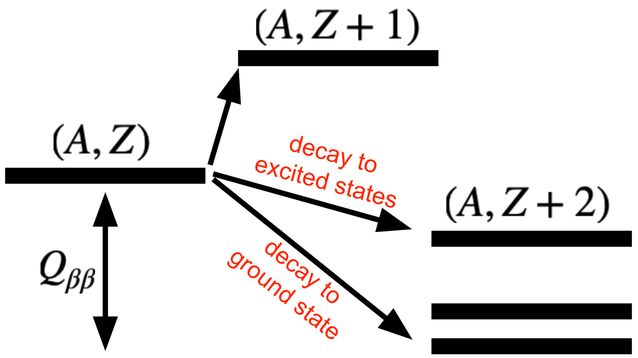
CUORE

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

Double beta decay

$$(A,Z) \longrightarrow (A,Z+2)+X$$



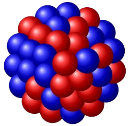


- SM 2nd order weak transition
- even-even nuclei
- half lives 10^{18} - 10^{24} yr

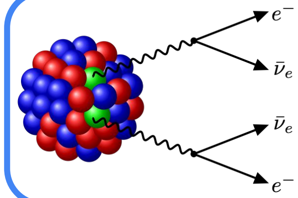
Neutrinoless double beta decay ($0\nu\beta\beta$)

Double beta decay is a rare second order Fermi weak interaction

Two decay channels usually considered:

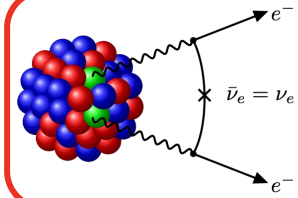


2νββ



Standard Model allowed, observed in 11 nuclei

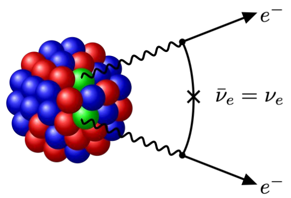
0νββ



Beyond Standard Model, not yet observed

- Lepton number violating process ($\Delta L=2$)
  ⇒ 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

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



Light Majorana neutrino exchange mechanism for 0vββ decay

In this case, we define the Effective Majorana mass $m_{\beta\beta}$

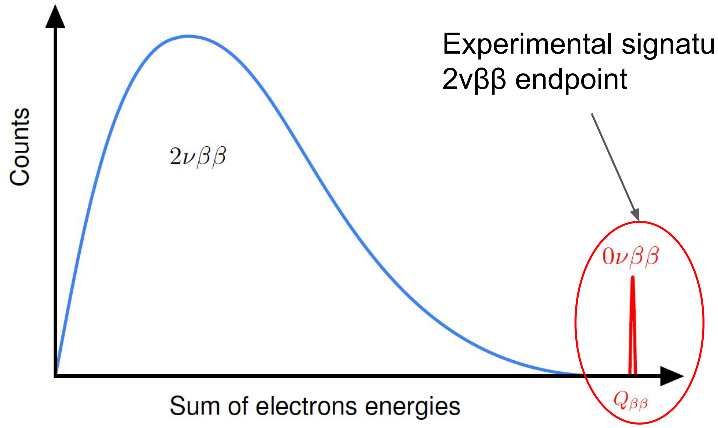
$$m_{\beta\beta} = \sum_{i=1}^{3} m_i U_{ei}^2$$

$$\Gamma_{0\nu} = G_{0\nu} |M_{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

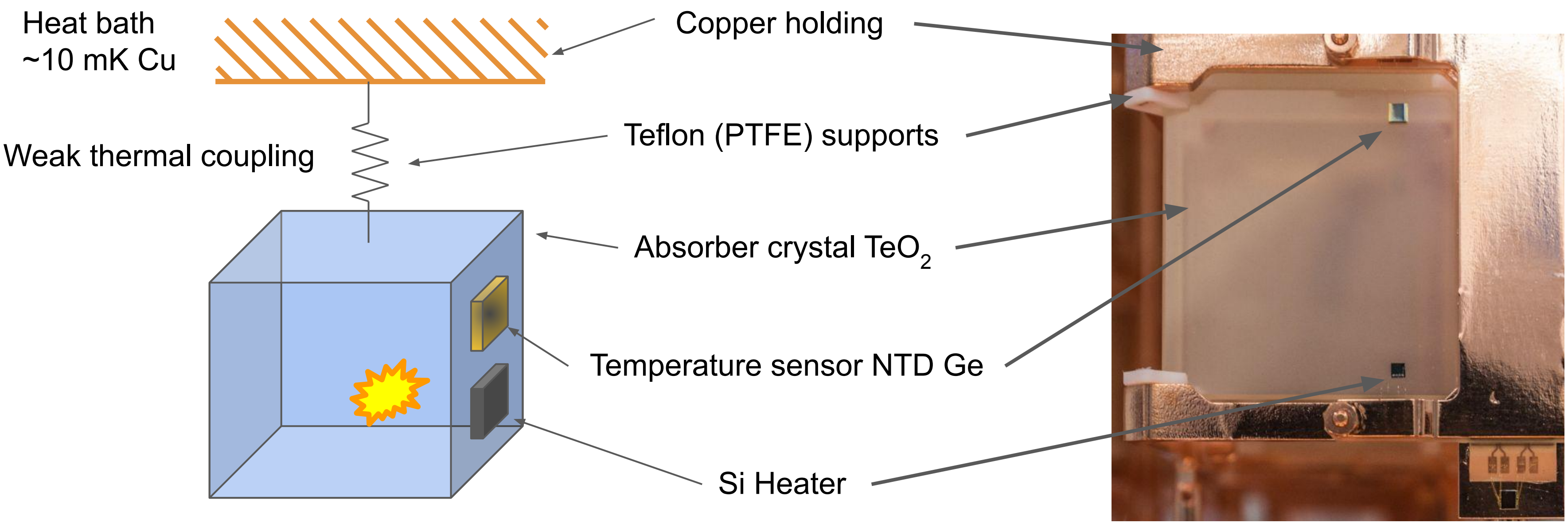
Phase space factor: precisely calculated

Nuclear Matrix Element (NME): source of uncertainty (different numerical calculations from several models)

Experimental signature: peak at 2vββ endpoint



The CUORE detector



$$\Delta T = \frac{\Delta E}{C_{abs}} \; ; \; C_{abs} = C(T)$$

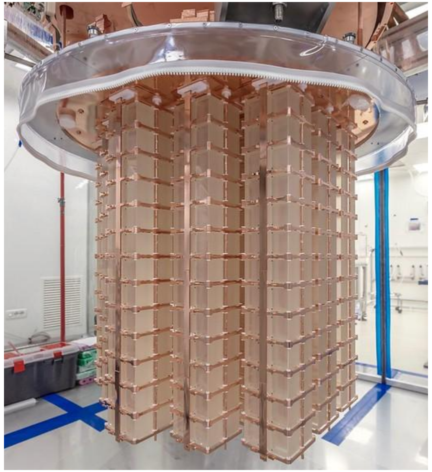
$\Delta E \backsim 1$ MeV

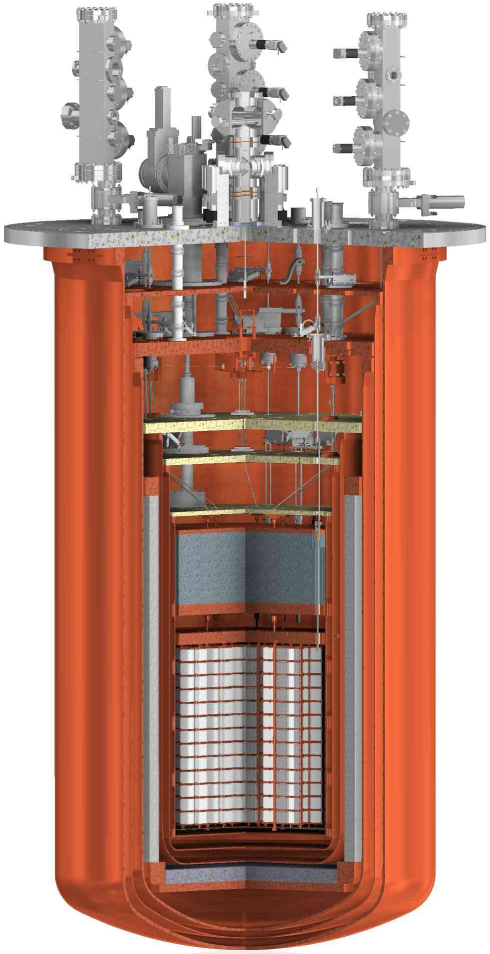
- $\Delta T \sim 10^{-18}$-10^{-15} K @ $T_0 \approx 300$ K
- $\Delta T \sim 0.1$ mK @ $T_0 \approx 10$ mK

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 $0\nu\beta\beta$ 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

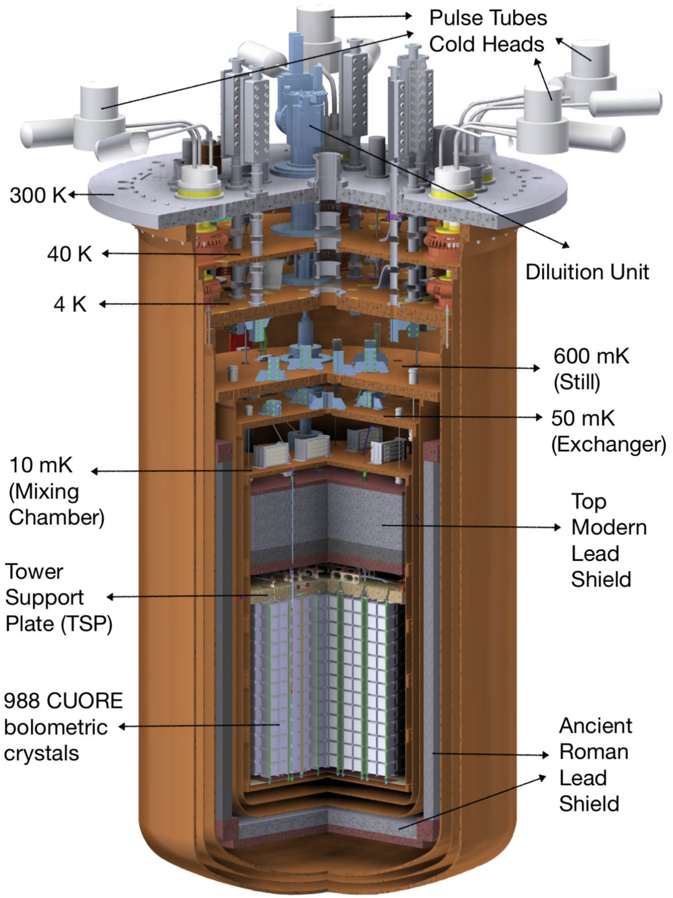




The CUORE cryostat challenges

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



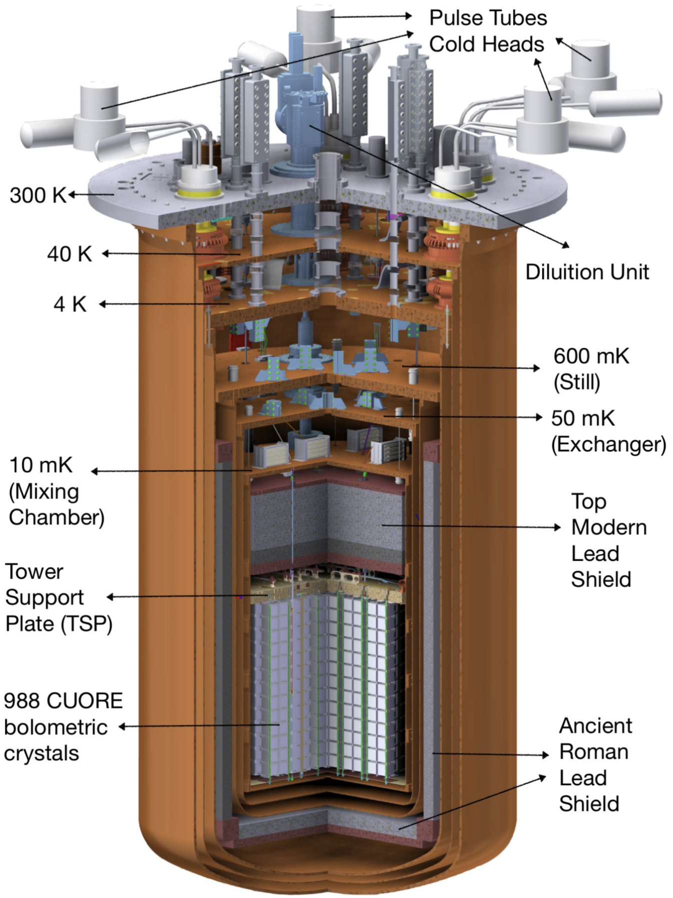
The CUORE cryostat challenges

Solutions:

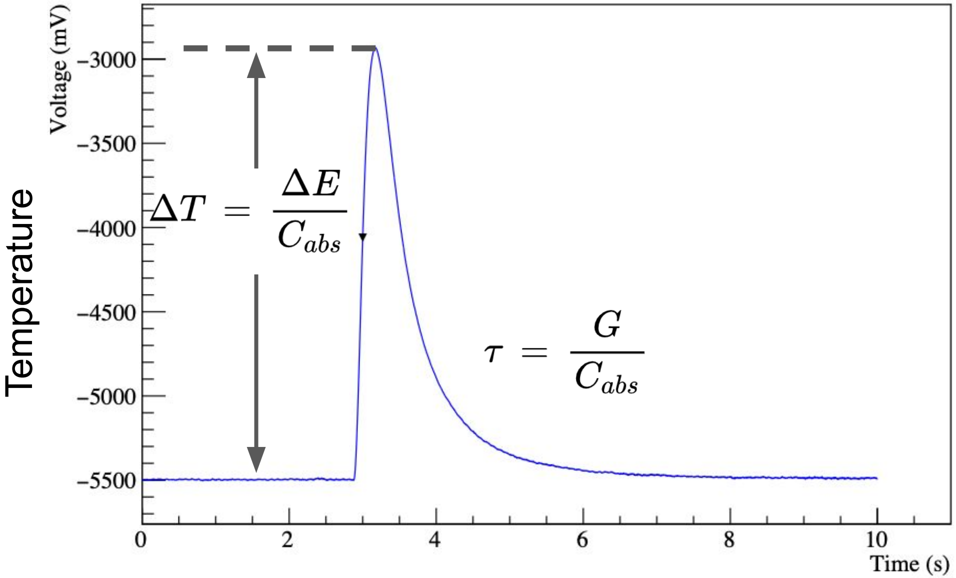
- Cryogen-free cryostat ⟶ lower downtime
- 5 (4) Pulse Tubes (PT) ⟶ down to ~4K
- Custom built Dilution Unit (DU) ⟶ down to ~7mK

- 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 detector working principle



$$\Delta T = \frac{\Delta E}{C_{abs}}$$

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

$$100\,\mu K/MeV \;\; @\, T_0 \sim 10\,mK$$

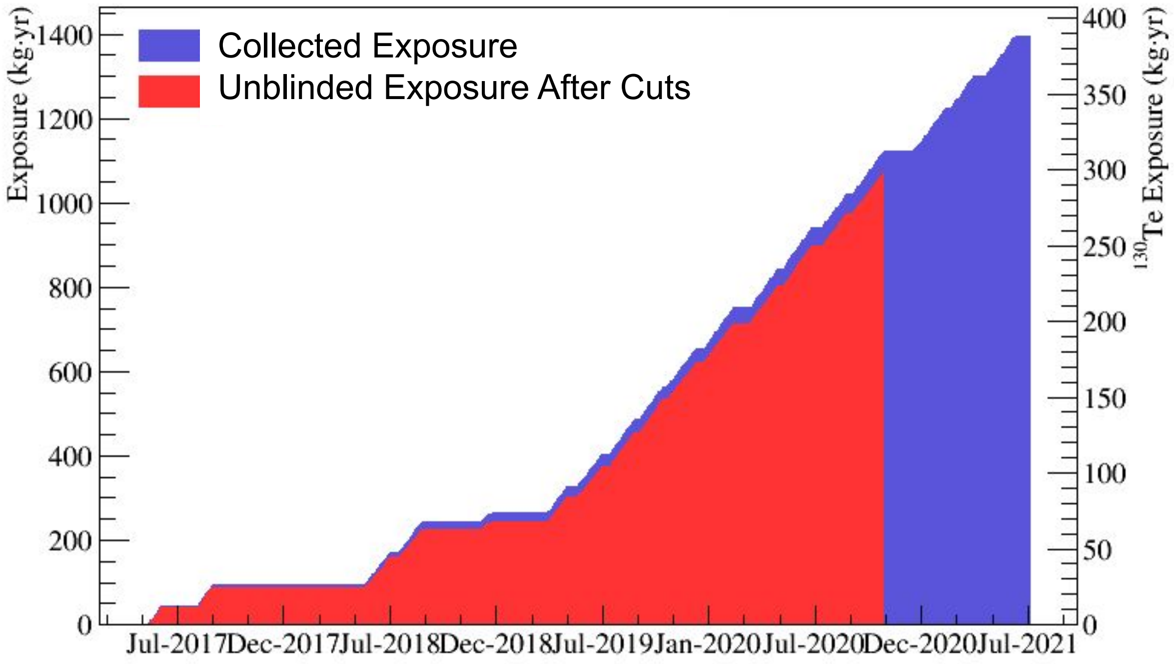
$$\tau = \frac{G}{C_{abs}} \sim 1\,s$$

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

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

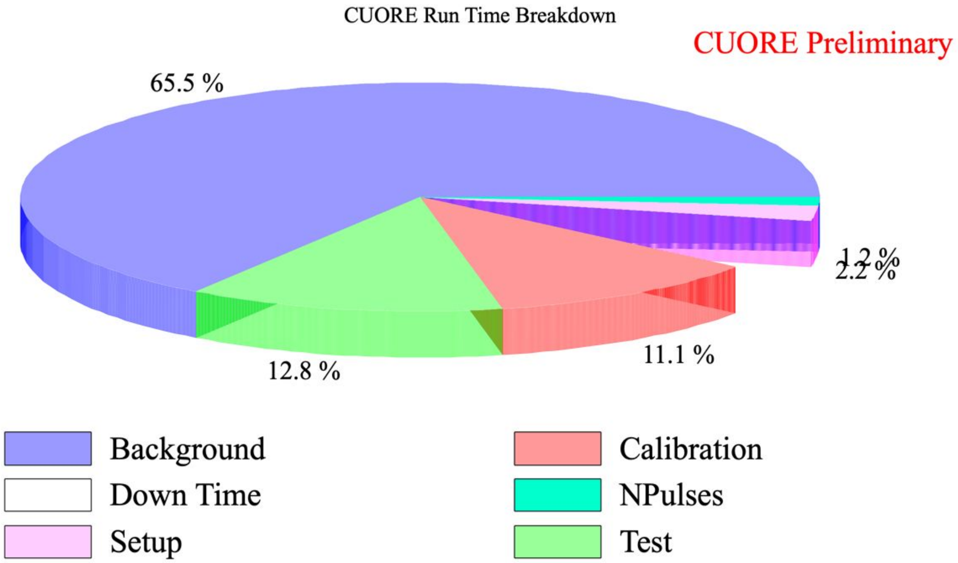
- Low heat capacity @ T_0
- Excellent energy resolution (~1‰ FWHM)
- Equal detector response for different particles
- Slowness (suitable for rare event searches)

CUORE data taking

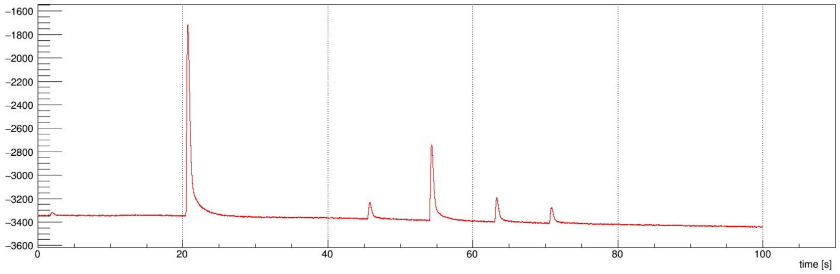


- data taking started in 2017
- 2017-2019: optimization campaigns to improve understanding and stability of the experiment
- since march 2019 steady data taking with >90% uptime
- steadily collecting data at an average rate of ~ 69 kg yr / month
- > 1.29 tonne yr raw exposure

CUORE data taking



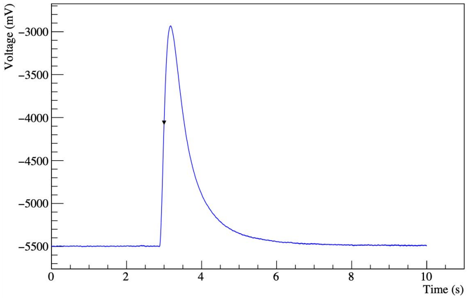
- Voltage output continuously sampled (1 kHz) and stored on disk
- Periods with unstable data taking conditions excluded (e.g. earthquakes)

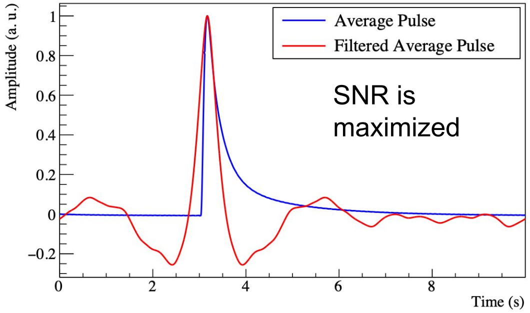


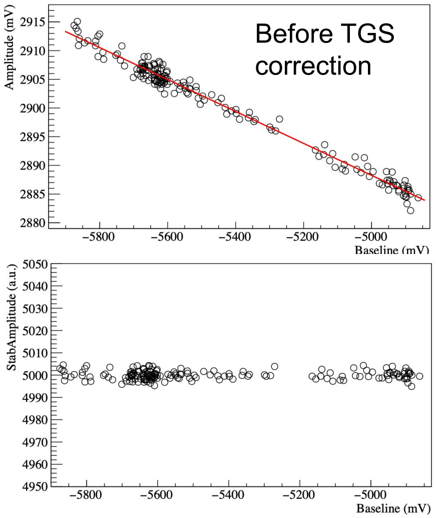
- CUORE "data set": 1 month of background (physics) data taking, few days of calibration before and after

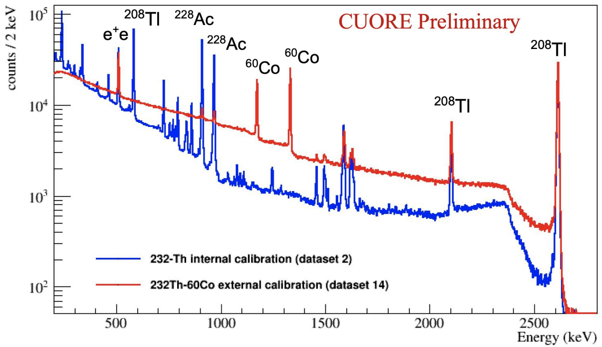
CUORE data processing

Amplitude (Optimum Filter) → Thermal gain stabilization → Energy calibration





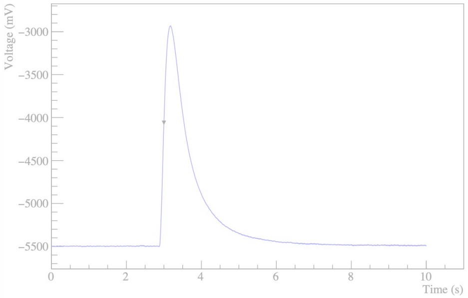




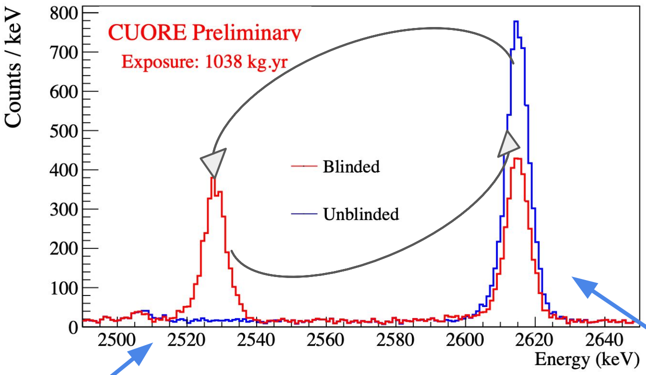
Stabilized amplitude is converted in Energy

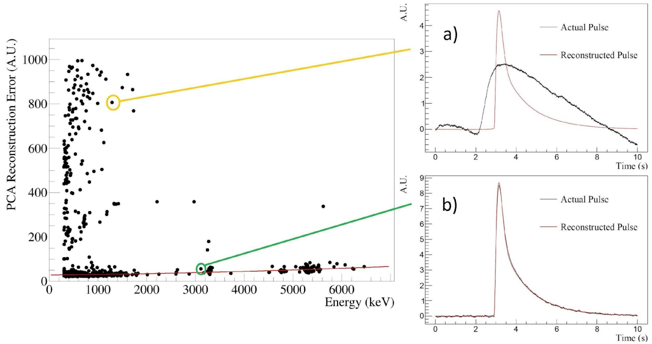
Coincidences ← Pulse Shape Discrimination ← ROI blinding ← ROI fit optimization ← Unblinding

CUORE data processing

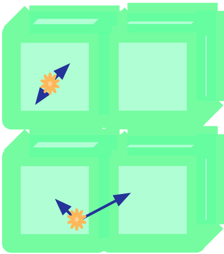


Amplitude (Optimum Filter) → Thermal gain stabilization → Energy calibration





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



M1 (0νββ expected signature)

M≥2 (background events)

Time/space-based coincidences calculation and event multiplicity assignment

Coincidences → Pulse Shape Discrimination → ROI blinding → ROI fit optimization → **Unblinding**

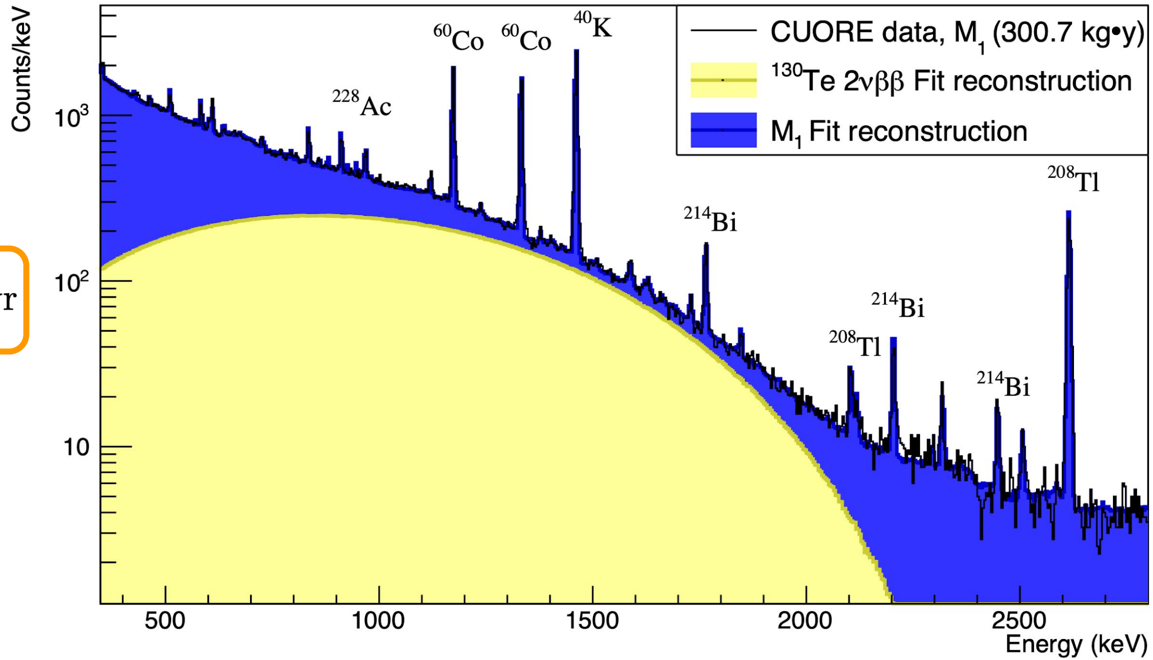
CUORE background model: Measurement of $2\nu\beta\beta$ decay of ^{130}Te

Dominant component of the observed 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 $2\nu\beta\beta$ decay half-life to date

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

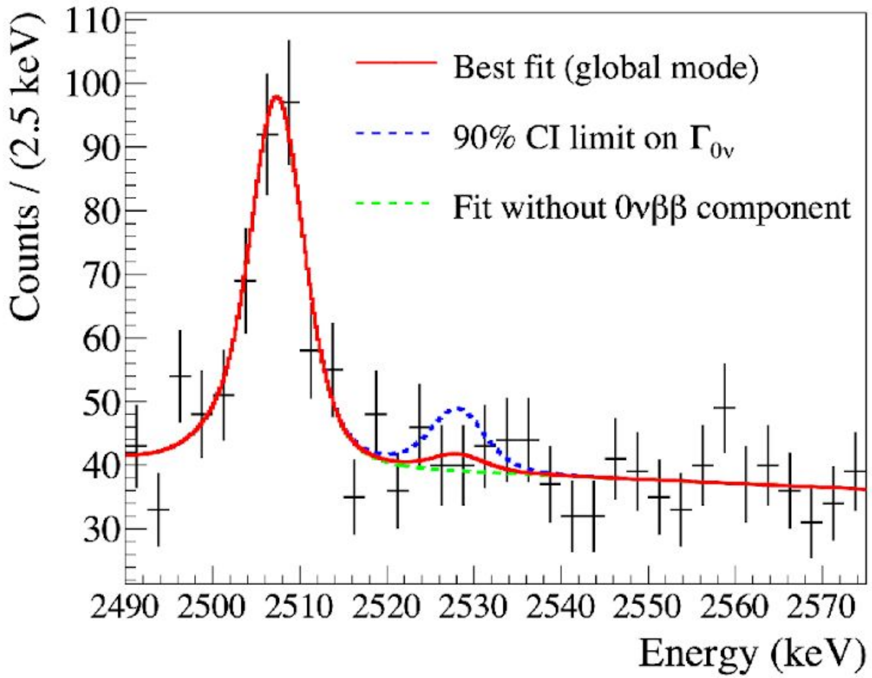


Results of $0\nu\beta\beta$ decay of ^{130}Te

ROI: [2490 - 2575] keV

Total TeO_2 exposure: **1038.4 kg • yr** (15 datasets)

No evidence of ^{130}Te $0\nu\beta\beta$ decay is observed



Best Fit : $\Gamma_{0\nu} = (0.9 \pm 1.4) \cdot 10^{-26}\ yr^{-1}$

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

Background Index: BI = $(1.49 \pm 0.04) \cdot 10^{-2}$ cts/keV/kg/yr

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

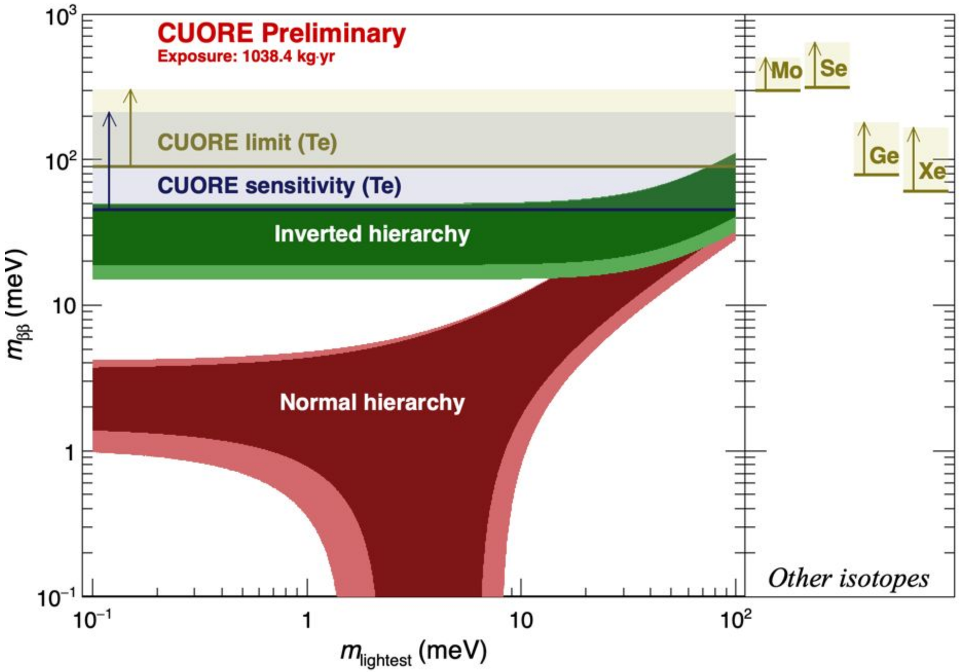
In the assumption that the 0νββ decay is mediated by the exchange of a light Majorana neutrino:

$$\Gamma_{0\nu} = G_{0\nu} |M_{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

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

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

arXiv:2104.06906 (2021)



Armengaus, E. et al. (CUPID-Mo Collaboration),Phys. Rev. Lett. 126, 181802 (2021) https://doi.org/10.1103/PhysRevLett.126.181802

Agostini, M. et al. (GERDA Collaboration), Phys. Rev. Lett. 125, 252502 (2020) https://doi.org/10.1103/PhysRevLett.125.252502

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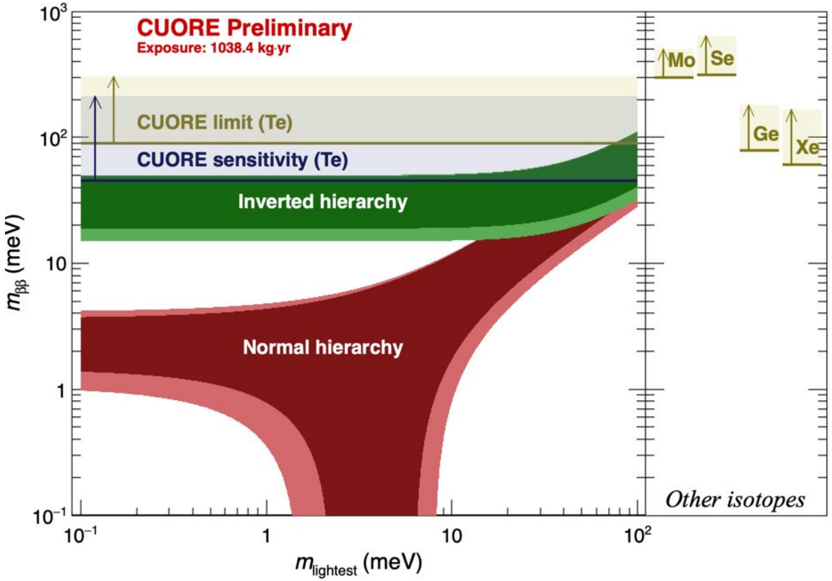
Gando, A. et al. (KamLAND-Zen Collaboration), Phys. Rev. Lett. 117, 082503 (2016) https://doi.org/10.1103/PhysRevLett.117.082503

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



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What's next?

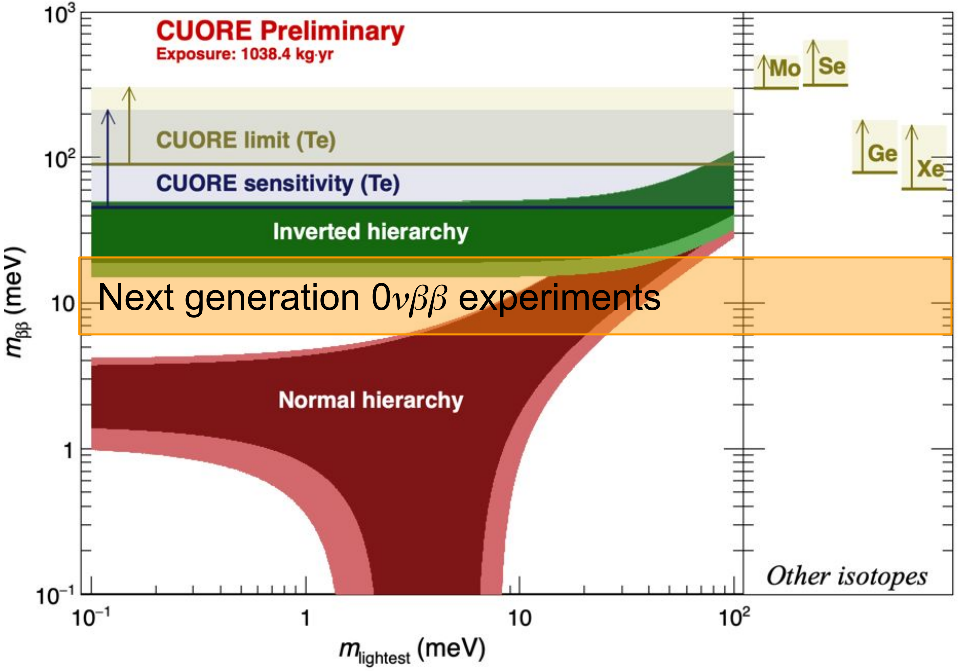
Next generation $0\nu\beta\beta$ decay experiments seek to be sensitive to the full Inverted Hierarchy region:

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

To reach these sensitivities:

I. Reach the "zero background" regime
⇒ lower the background and improve energy resolution in the ROI

II. Larger active mass



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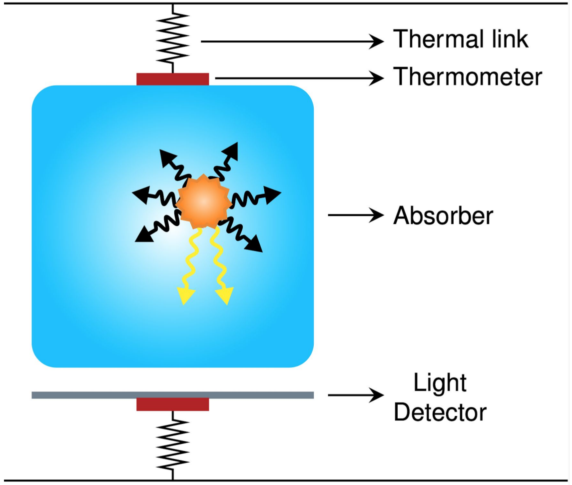
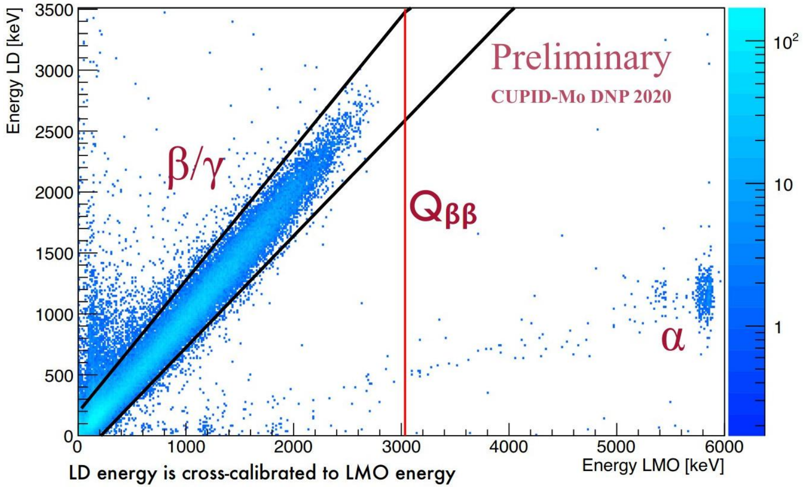
CUPID

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



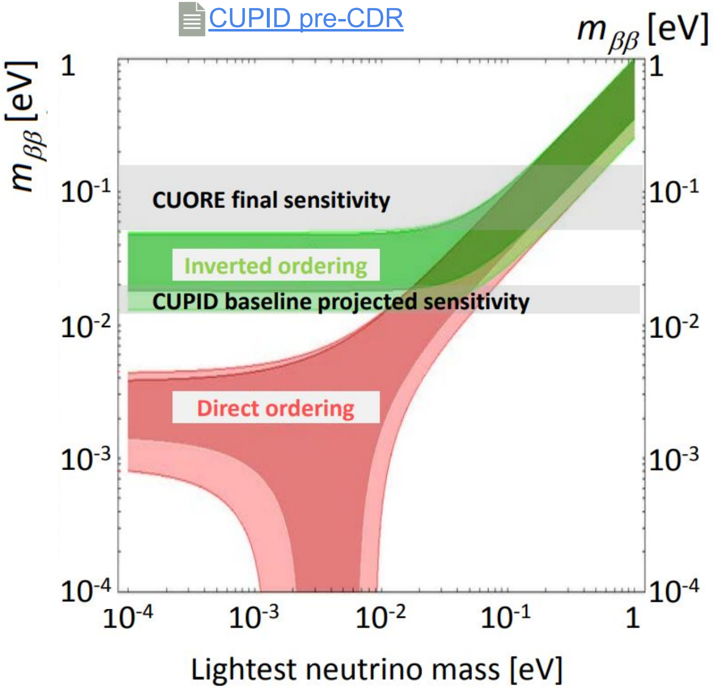


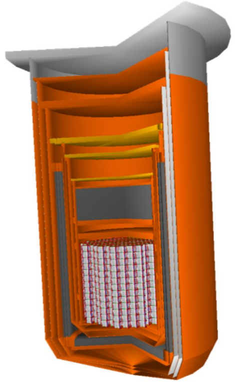
Courtesy of the CUPID-Mo Coll.

CUPID

CUORE Upgrade with Particle IDentification

CUPID pre-CDR





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

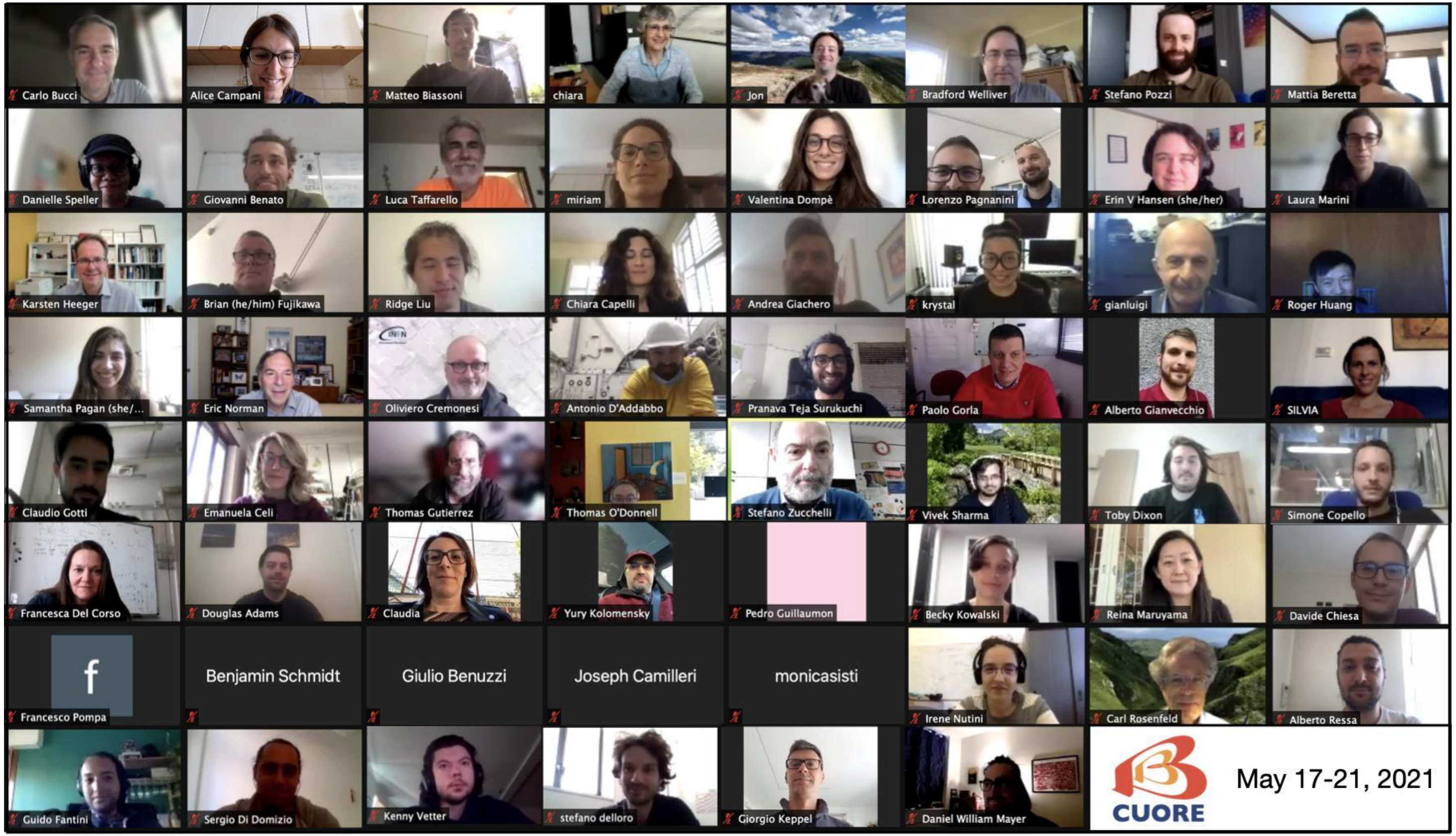
- Particle ID (α vs β/γ) with scintillation light
- Possible discrimination of $2\nu\beta\beta$ pile-up from pulse shape
- Background reduction: underground location at LNGS, passive shields (Pb/Cu), high-radiopurity in assembly and storage of detectors and materials, muon veto, profit of detector high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

Summary & Conclusions

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

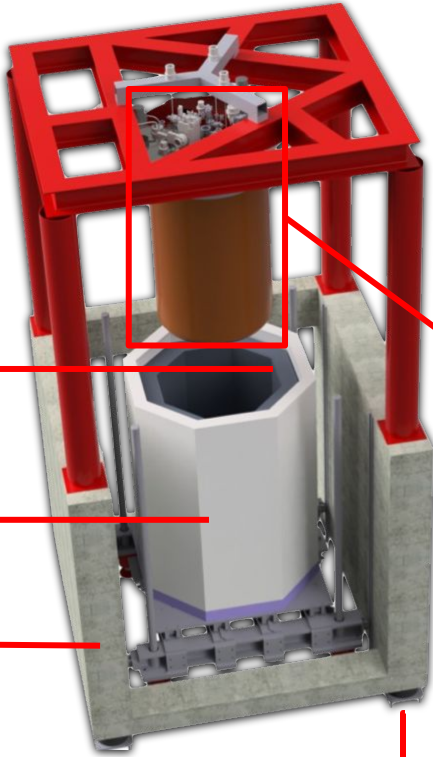
  ⇒ stable operation for ton-scale cryogenic detector is possible
- Data taking is smoothly ongoing aiming at 5 years live time
- New results on ^{130}Te 0νββ decay (1038.4 kg · yr exposure): most stringent half-life limit to date
  arXiv:2104.06906 (2021)
- New results on ^{130}Te 2νββ decay (300.7 kg · 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)

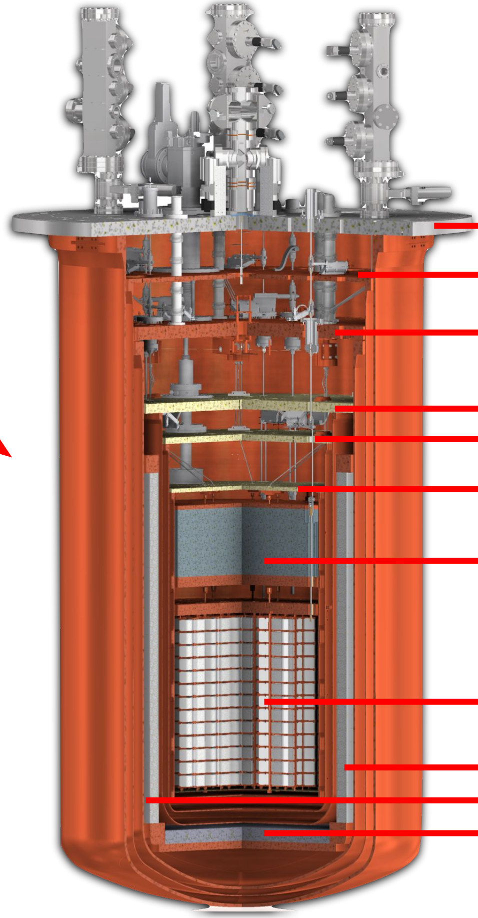
Thank you for the attention



Spare slides

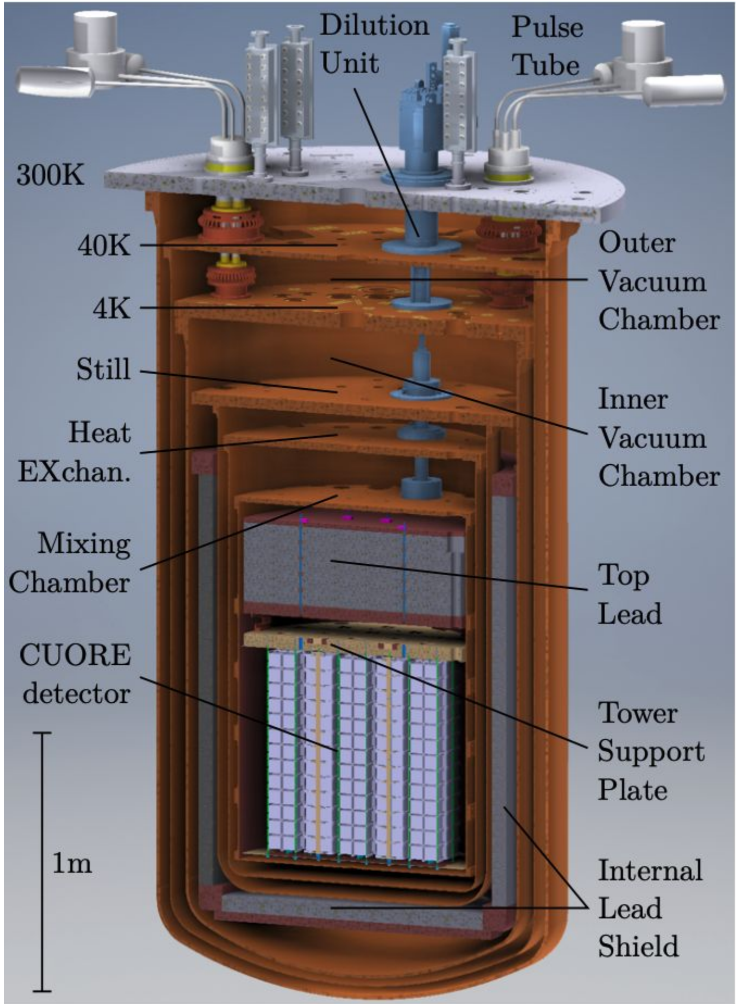
The CUORE experiment



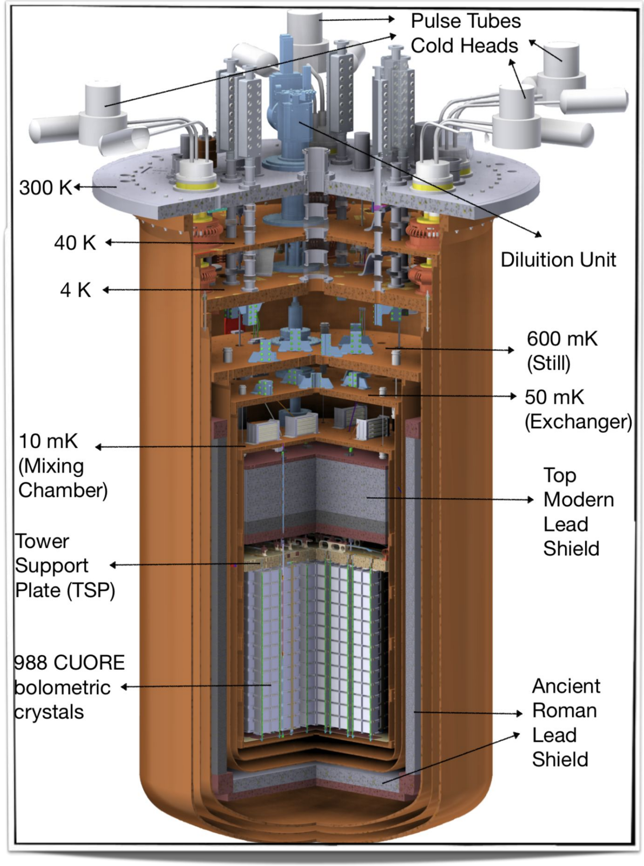


The CUORE experiment

- Custom made dilution refrigerator
  ~ 10 mK base temperature
- 5 pulse tube cryocoolers (no helium bath)
- Nested copper vessels at decreasing temperatures
- Low temperature lead shielding (top)
- Low temperature roman lead shielding (side, bottom)

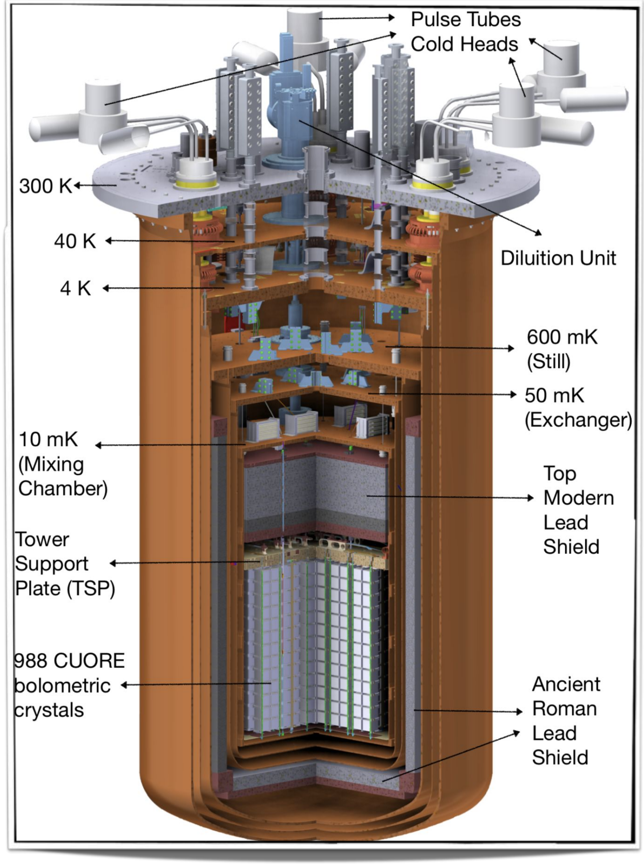


CUORE challenges



- Ton-scale infrastructure cooled down by a custom built cryogen-free structure: 5 pulse tubes + $^{3}He/^{4}He$ Dilution Refrigerator
- Operational T ~ 10 mK stable over years
- Background level goal of 10^{-2} counts/(kev kg yr)
  - 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
- Energy resolution goal of 5 keV FWHM at ^{130}Te $Q_{\beta\beta}$
  - Minimization of vibrational noise: external support structure mechanically decouples the detectors from the cryostat

CUORE challenges



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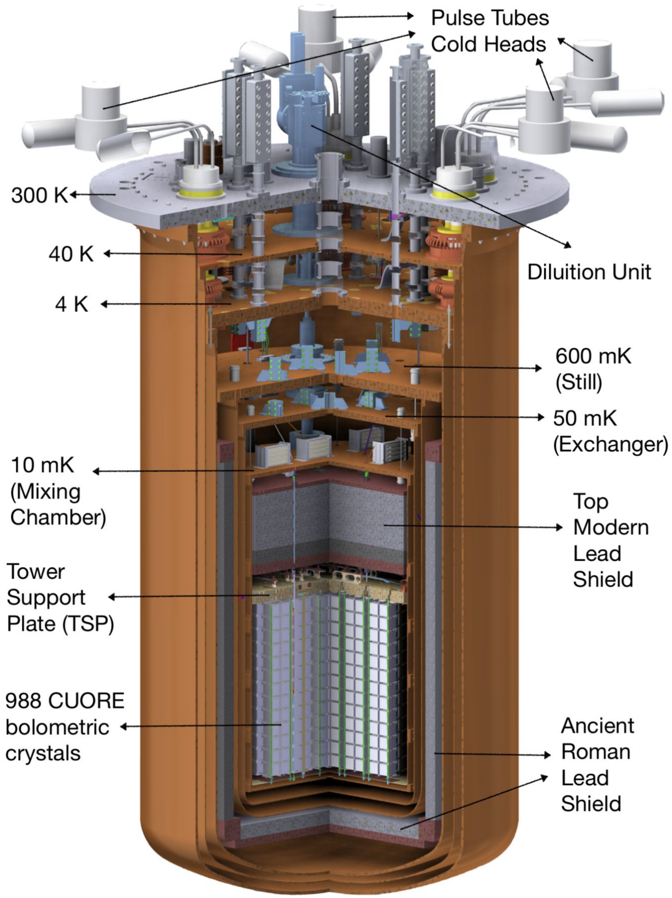
The CUORE cryostat



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

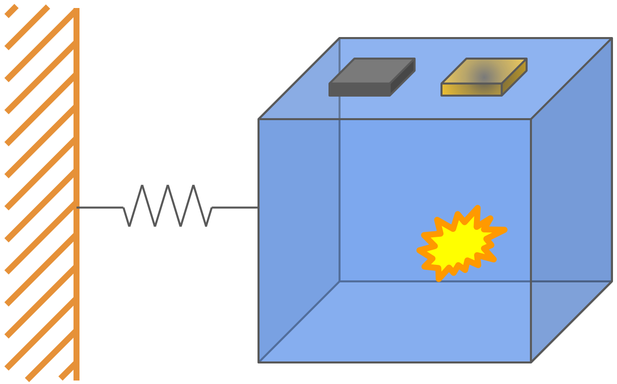
Solutions:

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

The CUORE detector

Heat bath
~10 mK Cu

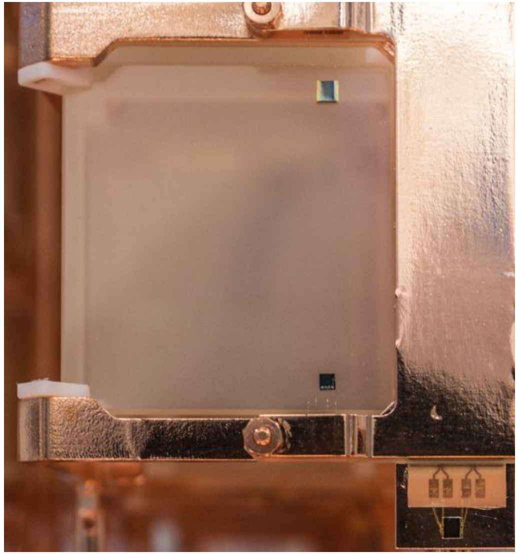
Thermal coupling



Temperature sensor
NTD Ge

Si Heater

Absorber crystal TeO_2



Particle interaction

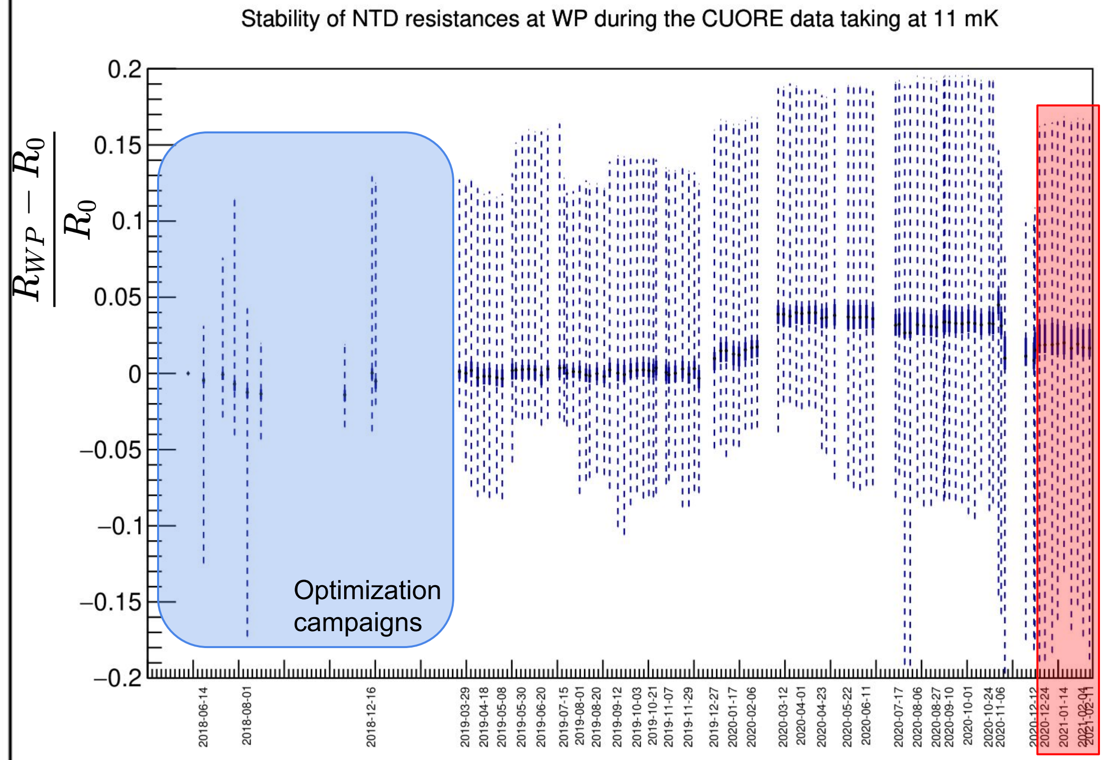
$$\Delta T = \frac{\Delta E}{C_{abs}} \; ; \; C_{abs} = C(T)$$

$\Delta E \backsim 1$ MeV

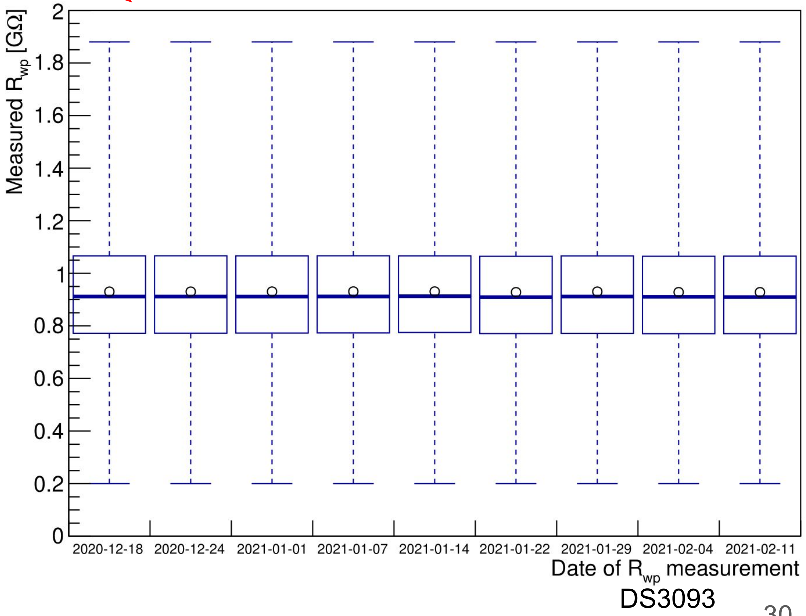
$\Delta T \sim 10^{-18}$-10^{-15} K @ $T_0 \approx 300$ K

$\Delta T \sim 0.1$ mK @ $T_0 \approx 10$ mK

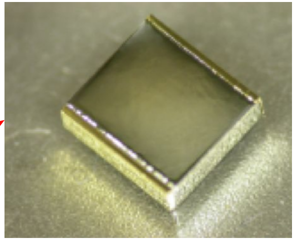
The CUORE cryostat challenges



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



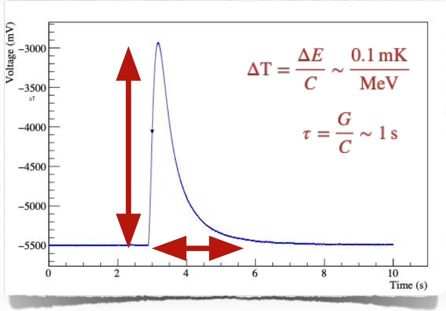
The CUORE sensors

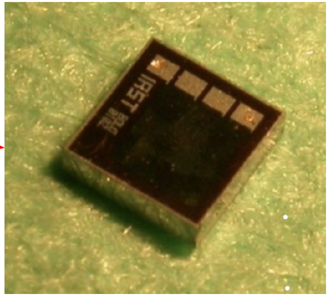


NTD = Neutron Transmutation Doped Ge thermistor

$$R(T) = R_0 e^{\sqrt{\frac{T_0}{T}}}$$

biased with a constant current, converts ΔT to voltage signal



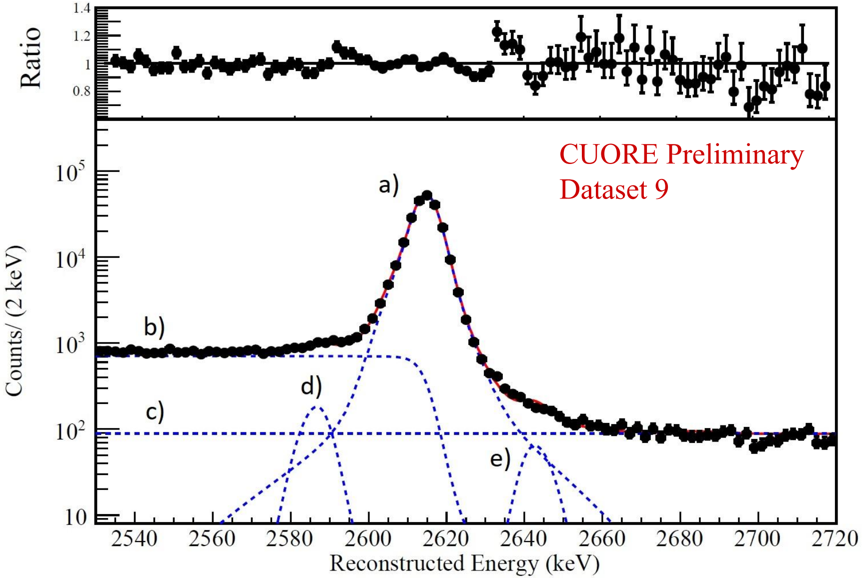


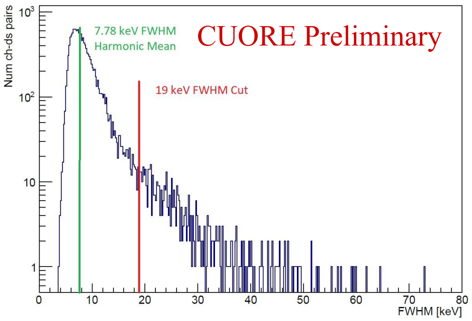
Silicon heater

Periodically fires a pulse at a fixed energy to measure the detector's gain and correct the effect of thermal instabilities (stabilization)

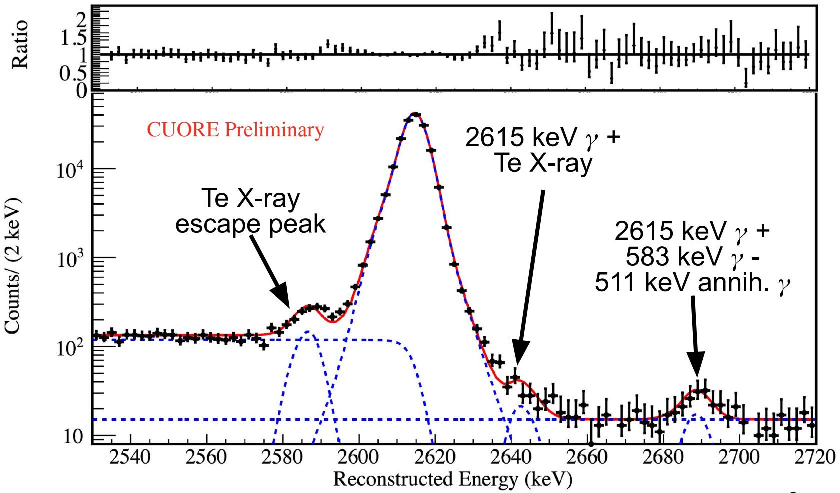
CUORE detector response function

- Fit 2615 keV calibration peak for each channel
  a) 3-Gaussian signal peak
  b) Compton background
  c) Flat background
  d) 30 keV X-ray escape peak (background)
  e) 30 keV X-ray sum peak (background)
- Detector response function is just component (a)
- Excluded channels with FWHM > 19 keV for this analysis



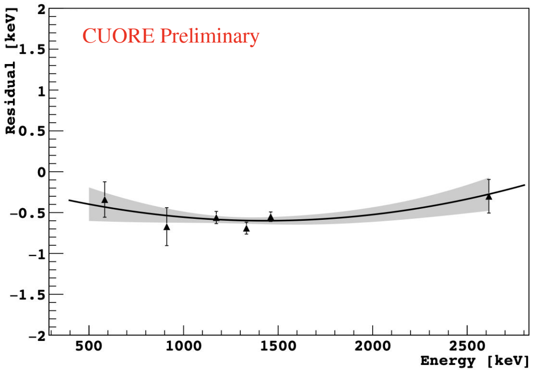


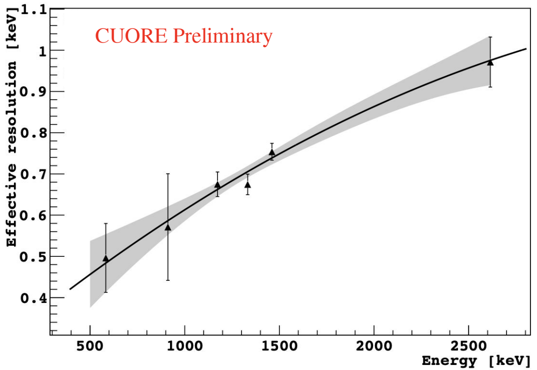
CUORE detector response function (lineshape)



- TeO_2 detectors exhibit a slightly non-gaussian response function
- Lineshape evaluated on the 2615 keV line in calibration: fit with 3 Gaussian for each detector-dataset
- Energy resolution in calibration is extracted (7.8(5) keV)

- Lineshape in physics data: most prominent peaks fitted
- Resolution appears energy dependent, small bias on energy reconstruction
- 2nd order polynomial fit to extract the resolution and bias energy dependence

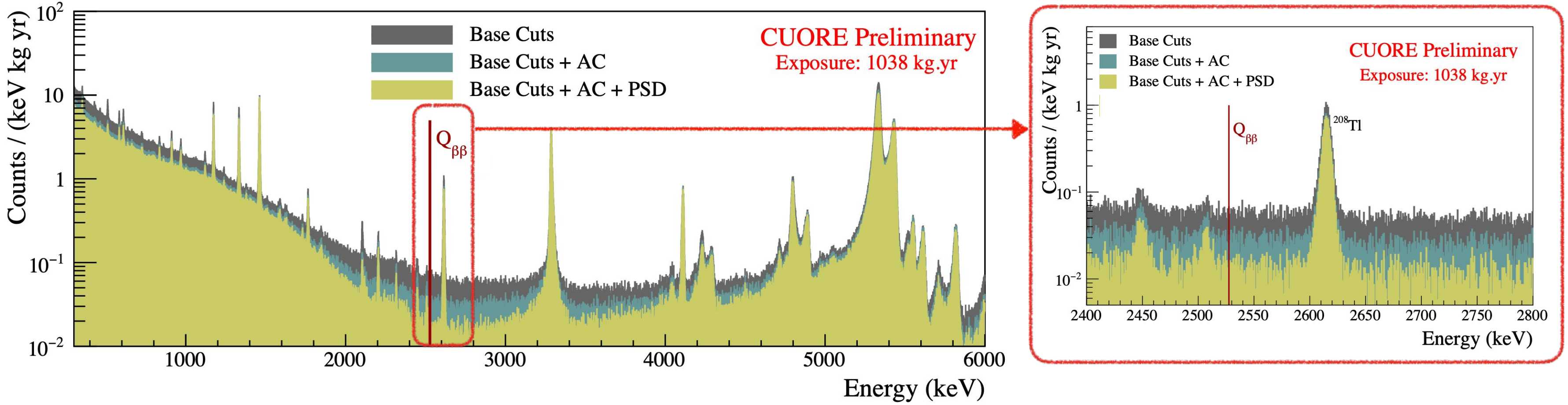




Cuts and Efficiencies

- ***Base cuts***: periods of time with high noise level, processing failures, poor resolution detectors are excluded
- ***Anti-coincidence cut (AC)***: events within ± 5ms from another triggered event at > 40 keV in a distinct crystal are excluded
- ***Pulse shape discrimination cut (PSD)***: abnormal pulse shape events (pile-up, non-physical pulses) are excluded

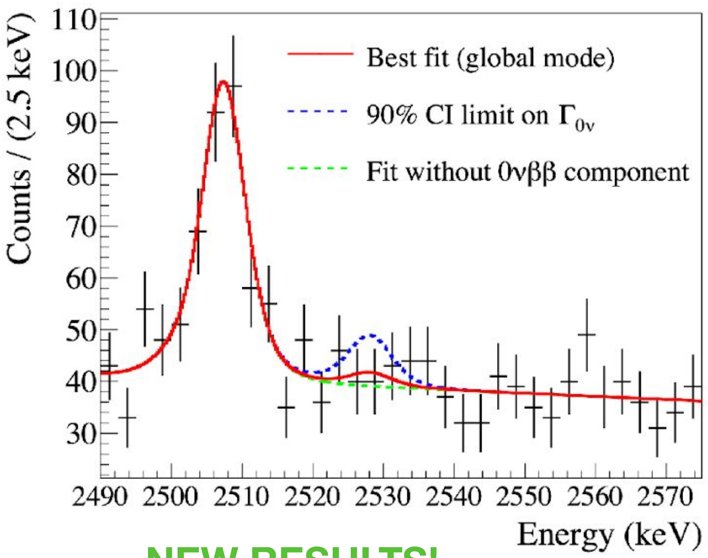
Containment efficiency	Single-hit event probability for 130Te 0νββ	**88.35(9)%**
Reconstruction efficiency	Probability that a signal event is triggered and not rejected by base cuts, the energy is properly reconstructed	**96.418(2)%**
AC efficiency	Probability that a signal event is not cut due to an accidental coincidence with an unrelated event	**99.3(1)%**
PSD efficiency	Probability of a physical event to survive the PSD cut	**96.4(2)%**



ROI fit: new results on $0\nu\beta\beta$ decay of ^{130}Te

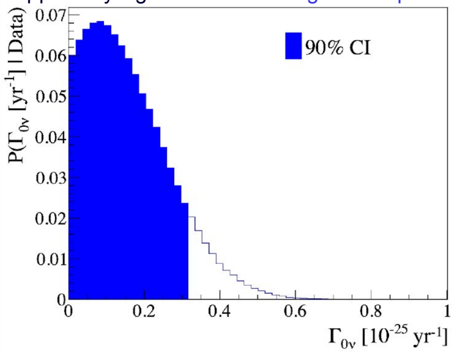
- Unbinned Bayesian fit simultaneously performed for each detector-dataset with BAT samples from the posterior distribution of all the parameters of the model with a Markov Chain Monte Carlo
- Uniform prior on the signal rate $\Gamma_{0\nu}$
- ROI: [2490 - 2575] keV
- Total TeO_2 exposure: 1038.4 kg • yr (15 datasets)
- No evidence of ^{130}Te $0\nu\beta\beta$ decay is observed
- Systematics effects as nuisance parameters in the Bayesian fit (0.8% total effect on the $\Gamma_{0\nu}$ limit):

- ***Efficiencies*** (reconstruction, anti-coincidence, PSD, containment)
- ***^{130}Te isotopic abundance***
- ***$Q_{\beta\beta}$***
- ***Lineshape parameters*** (energy bias and resolution scaling)



NEW RESULTS!

0νββ decay signal rate Γ0ν marginalized posterior



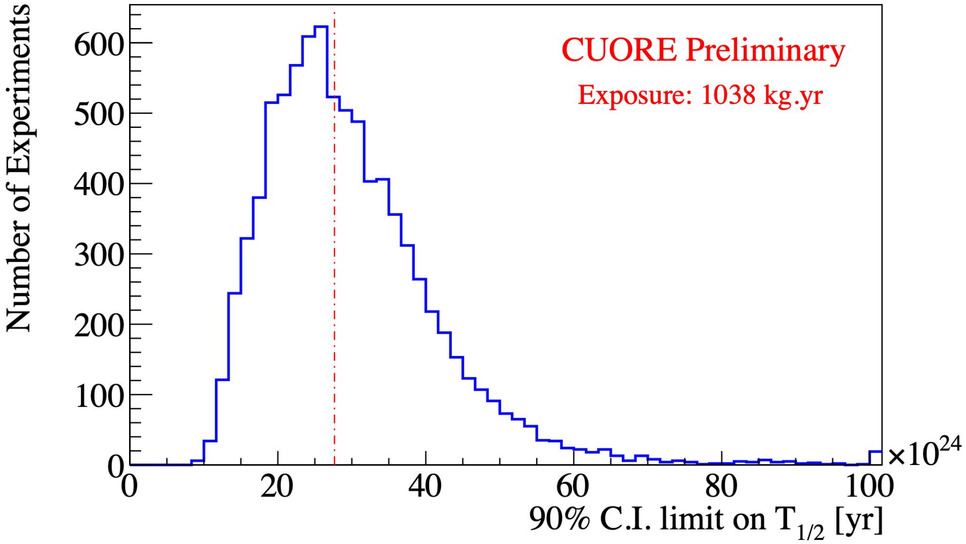
Best fit: $\Gamma_{0\nu} = (0.9 \pm 1.4) \cdot 10^{-26}\ yr^{-1}$

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

Background Index: BI = $(1.49 \pm 0.04) \cdot 10^{-2}$ cts/keV/kg/yr

Exclusion sensitivity on the ^{130}Te $0\nu\beta\beta$ half-life

- 10^4 toyMC with background components only (no signal), floating the parameters extracted from the fit on data
- Bayesian fit with signal + background components independently run on each toyMC
- Extraction of the 90% C.I. half-life limit from each of the 10^4 Bayesian fits
- Exclusion Sensitivity = median of the half-life limits distribution



$T_{1/2}$ = 2.8 • 10^{25} yr

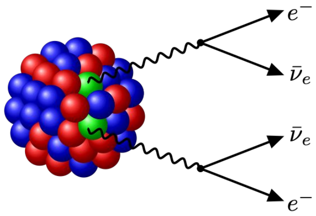
Median expected $T_{1/2}$ 90% C.I. limit

90% C.I. $T_{1/2}$ from the fit on CUORE data:
$T_{1/2}$ > 2.2 • 1025 yr

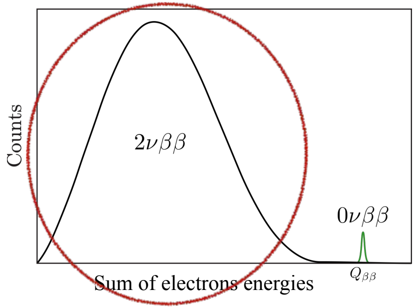
72% probability to get a more stringent limit given the obtained sensitivity distribution

arXiv:2104.06906 (2021)

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



$2\nu\beta\beta$ contribution to the CUORE spectrum can be disentangled through the Background Model fit



- Detailed GEANT4 MC simulation of the background sources
- Bayesian fit on experimental data with a linear combination of the MC simulations
- Fit on 350 keV - 2.8 MeV energy region (dominated by $2\nu\beta\beta$ decay of ^{130}Te)
- Fit parameters: a normalization factor for each source is extracted and used to obtain the activity of the contaminants and half-lives of processes (e.g. $2\nu\beta\beta$ decay $T_{1/2}$)