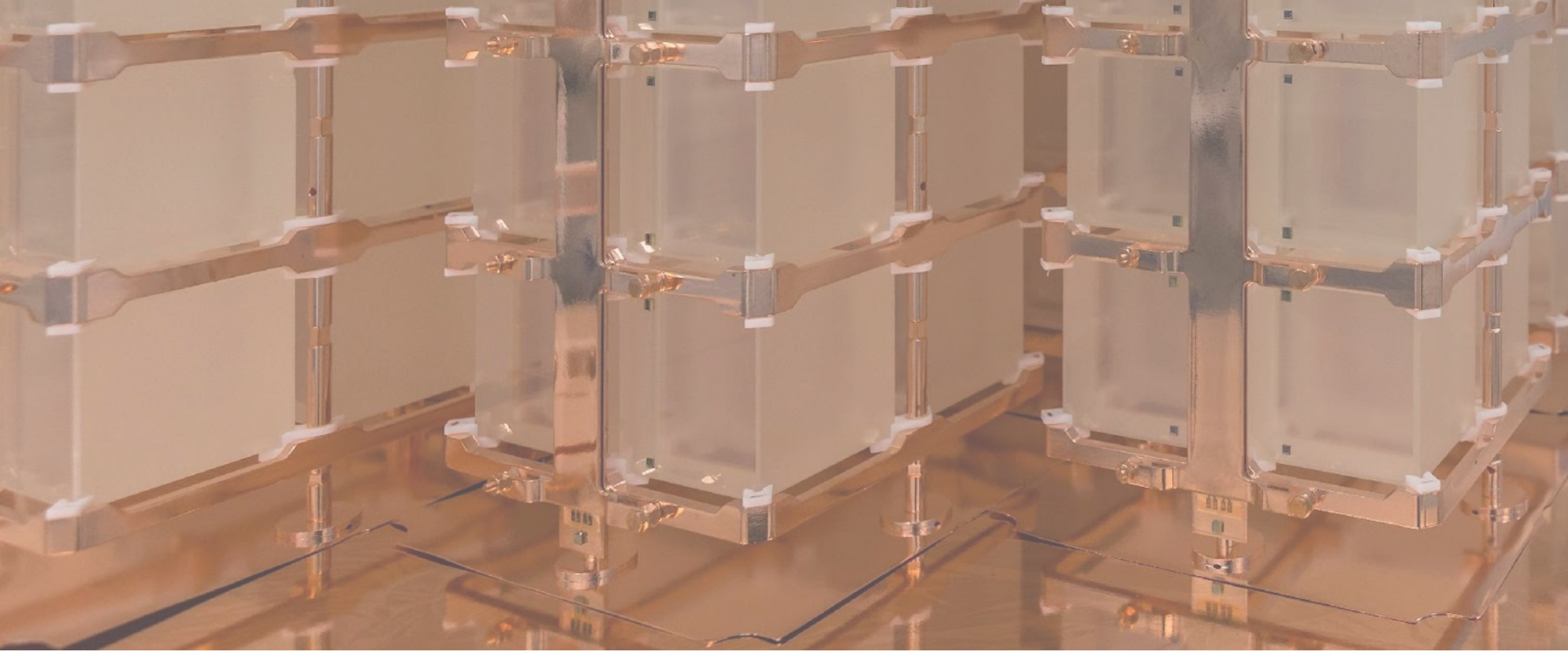


The CUORE latest results and the path towards CUPID

Stefano Di Lorenzo on behalf of the CUORE collaboration

CUORE

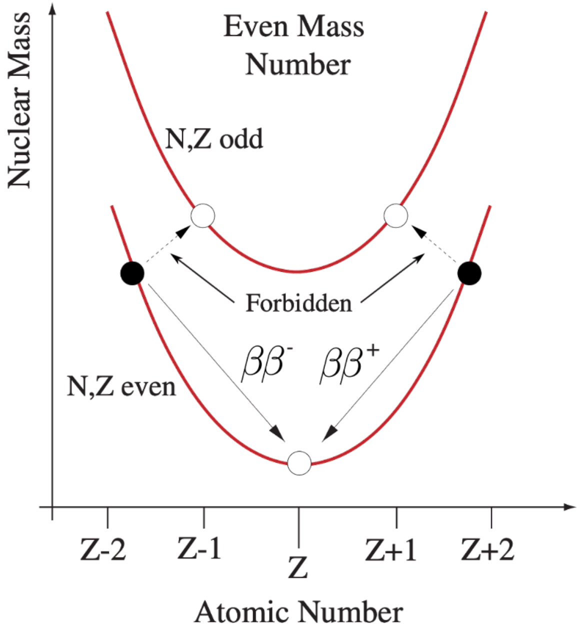
INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso

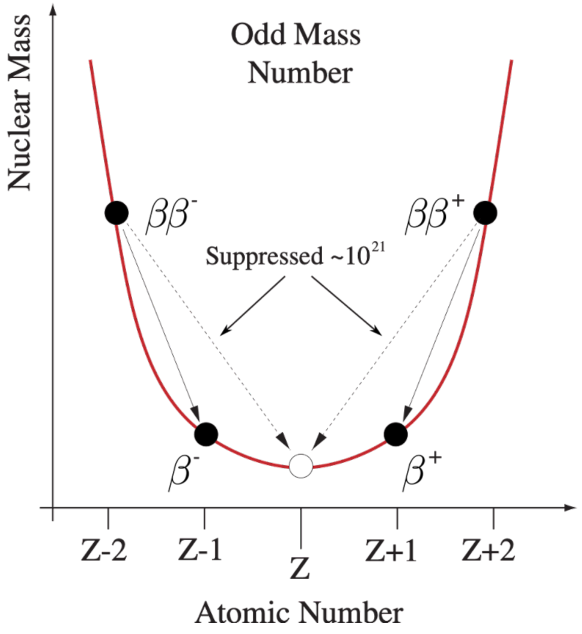
NOW2022, 4-11 September, Ostuni

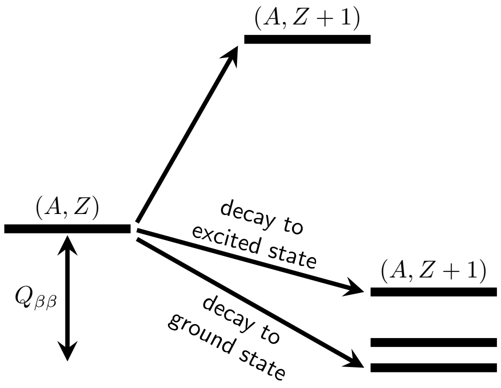
Neutrinoless double beta decay ($0\nu\beta\beta$)

Double beta decay is a rare second order Fermi weak interaction

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

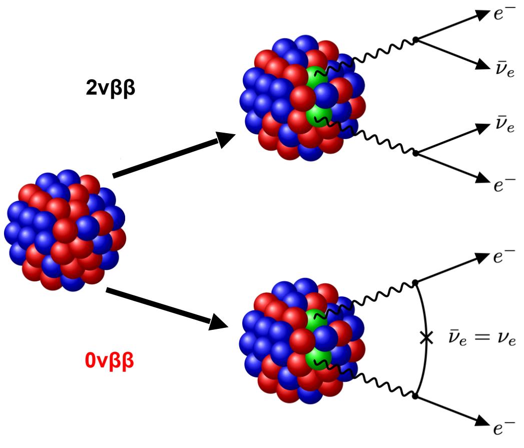






Neutrinoless double beta decay ($0\nu\beta\beta$)

Two decay channels usually considered:

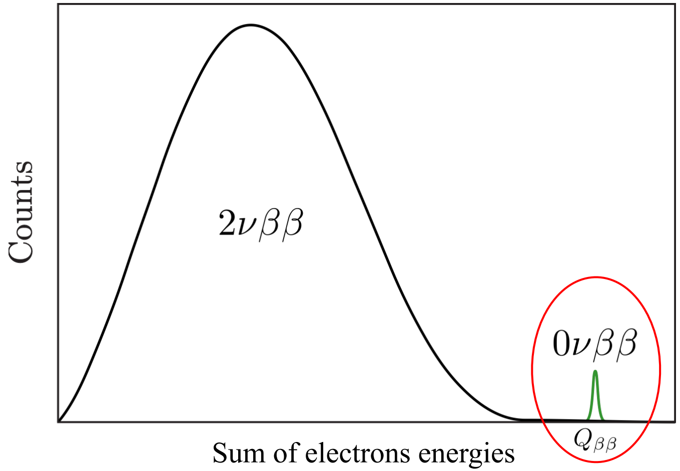


Standard Model allowed, observed in 11 nuclei

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 neutrino mass
- Possible explanation of matter-antimatter asymmetry origin via Leptogenesis

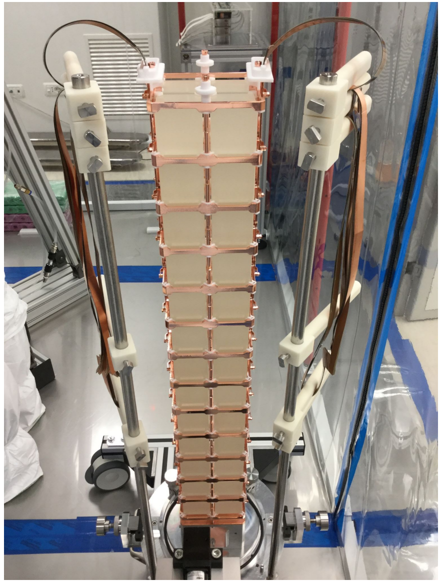


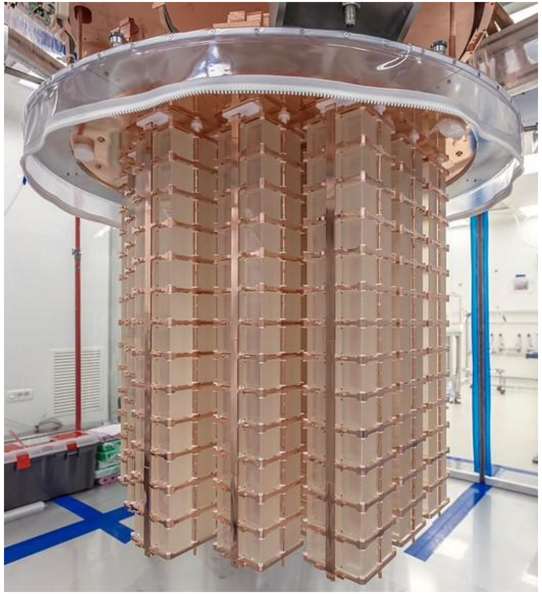
The CUORE experiment

CUORE (**C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents) is located at the underground facility of the Laboratori Nazionali del Gran Sasso.
The experiment is surrounded in every directions by at least 1400m of rocks (∼3600 m.w.e.).

The CUORE experiment

- 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

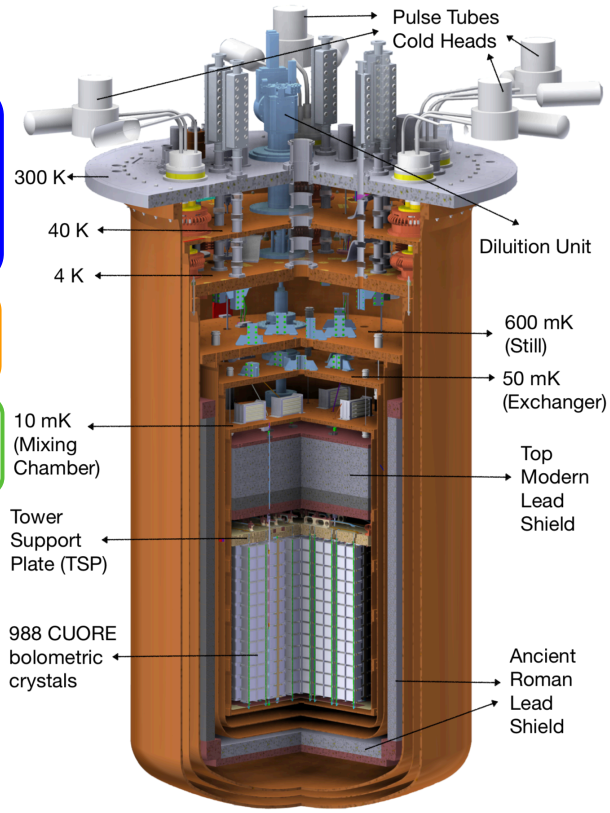




The CUORE cryostat challenges

Requirements:

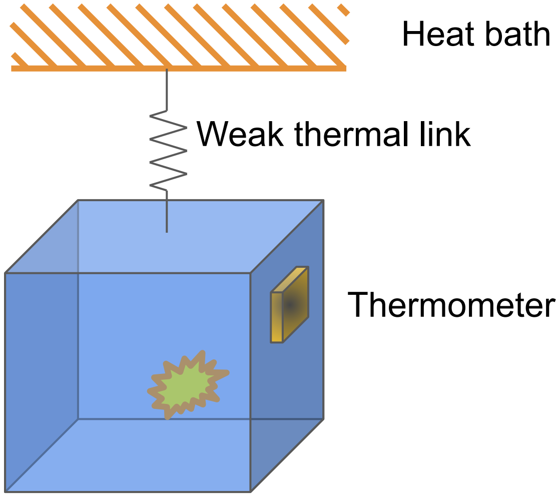
- Ton-scale detector operated a cryogenic temperature (15 tons of Pb, Cu and TeO_2 below 4K)
- Operating temperature ~ 10 mK
- Low background level: goal of 10^{-2} counts/(kev kg yr) at $Q_{\beta\beta}$
- Energy resolution: goal of 5 keV FWHM at ^{130}Te $Q_{\beta\beta}$

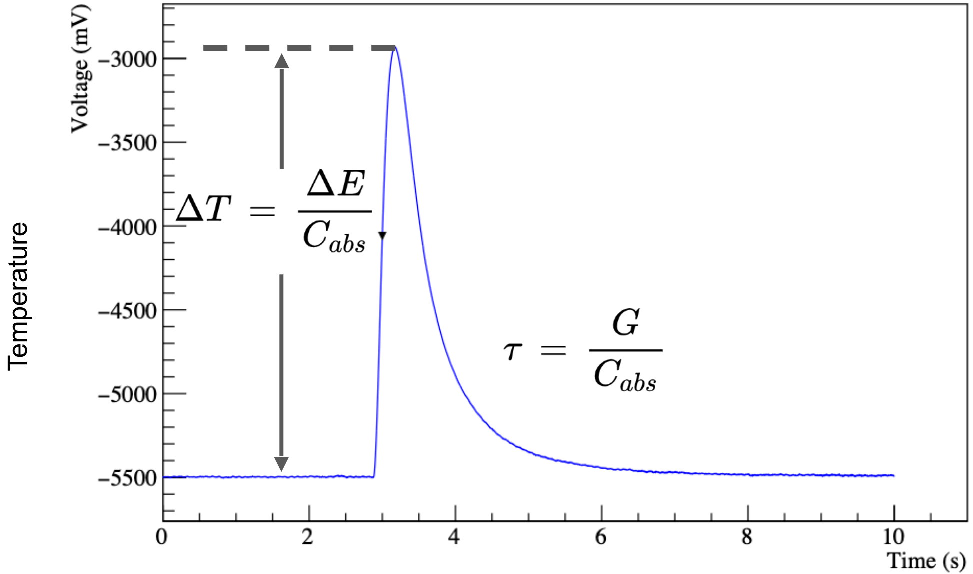


Solutions:

- Cryogen-free cryostat ⟶ lower downtime
- 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 noise active cancellation

The CUORE detector working principle





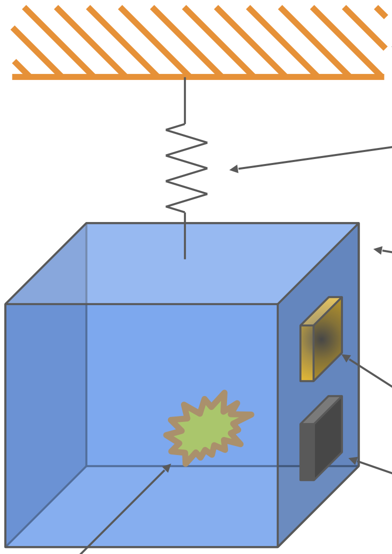
$$\left.\begin{aligned} \Delta T &= \frac{\Delta E}{C_{abs}} \\ C_{abs}(T) &\propto T^3 \end{aligned}\right\} 100\,\mu K/MeV \;\; @T_0 \sim 10\,mK$$

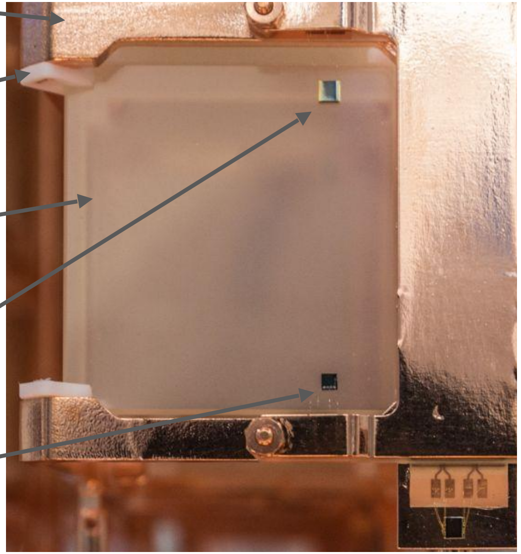
$$\tau = \frac{G}{C_{abs}} \sim 1\,s$$

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

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

The CUORE detector





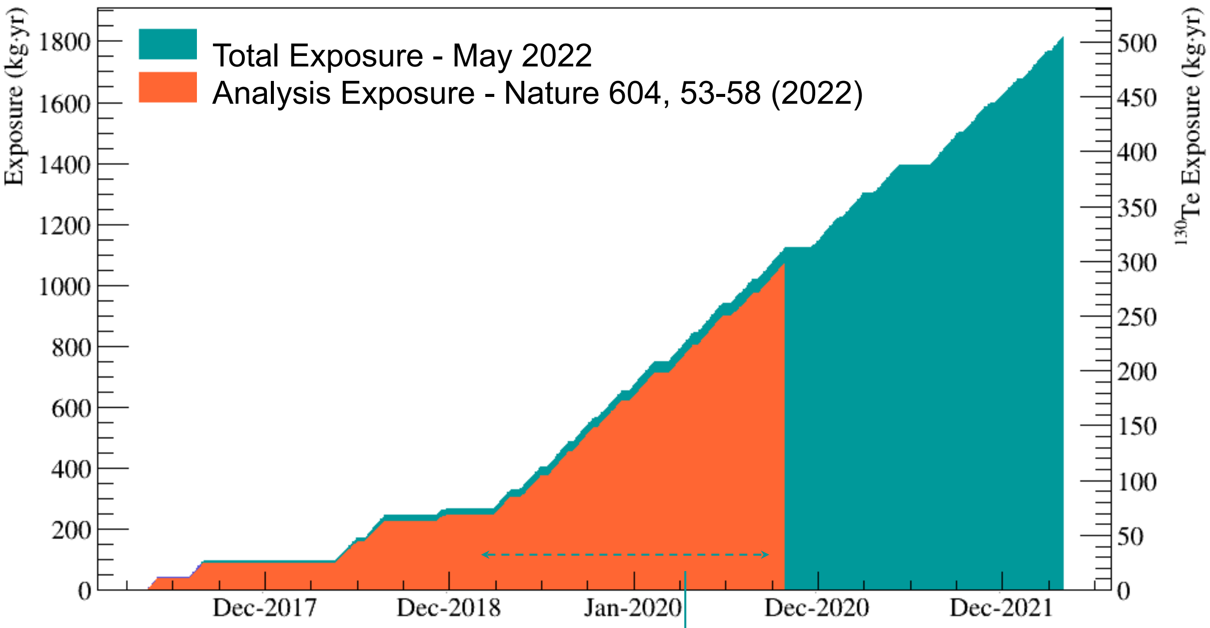
$$R_{NTD}(T) = R_0\, e^{\sqrt{T_0/T}}$$

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

$\Delta E \sim 1$ MeV

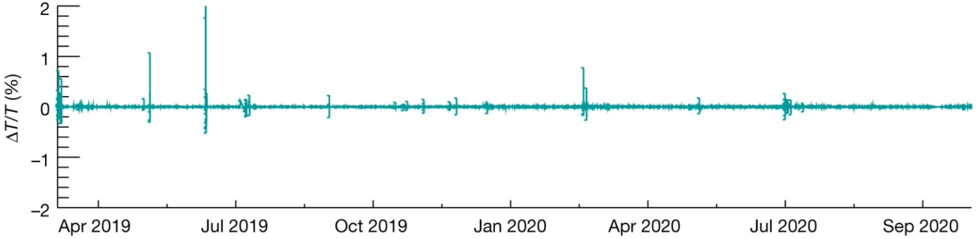
- $\Delta T \sim 10^{-18}$-10^{-15} K @ $T_0 \approx 300$ K
- $\Delta T \sim 0.1$ mK @ $T_0 \approx 10$ mK

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 ~50 kg/month
- > 1.8 tonne yr raw exposure

The CUORE Collaboration. *Nature* **604,** 53–58 (2022).
https://doi.org/10.1038/s41586-022-04497-4

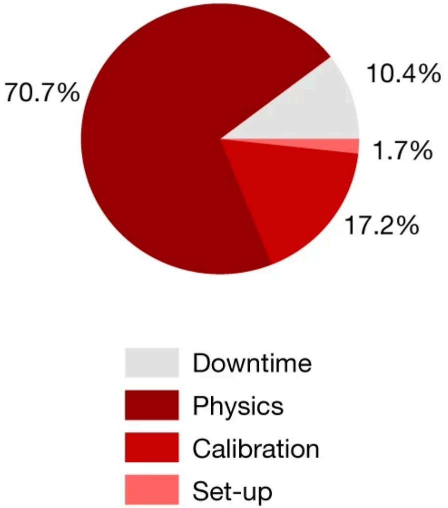


CUORE data taking

CUORE "data set": ~1months of physics data taking

- Calibration runs (few days)
- Background runs
- Calibration runs (few days)

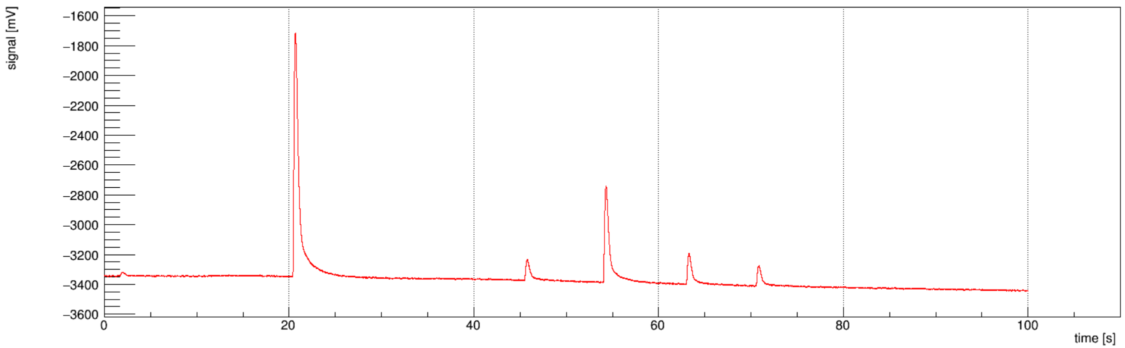
A run ~24h



- Continuous monitoring of detectors resistance/temperature stability and noise minimisation (set-up runs)
- The output from the detectors is sampled at 1 kHz and saved into a data-stream

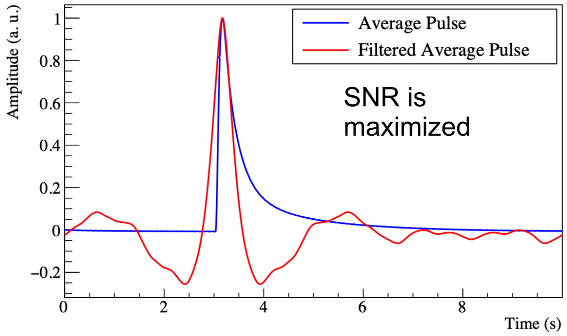
The CUORE Collaboration. *Nature* **604**, 53–58 (2022). https://doi.org/10.1038/s41586-022-04497-4

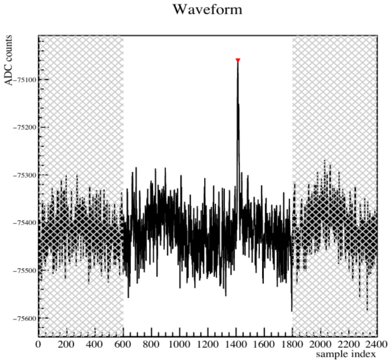
Calibration rate 100-200 mHz
Physics rate < 10 mHz

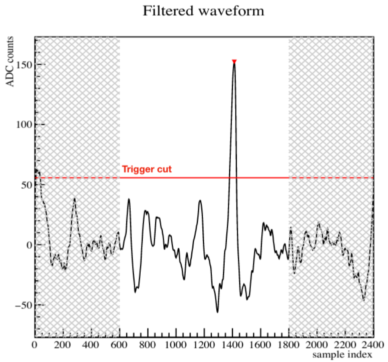


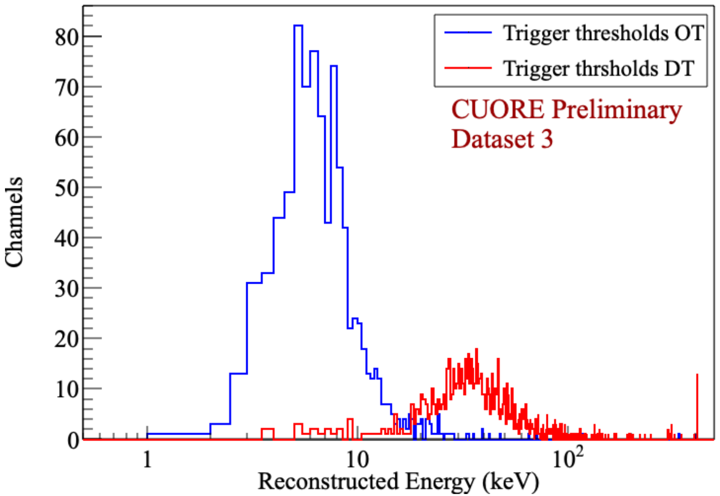
CUORE data trigger

Triggering pulse
- Online Derivative Trigger (DT): threshold on the derivative of the data-stream
- Offline Optimal Trigger (OT): identification of pulses in the filtered data-stream (template filter: expected pulse shape wrt to expected noise)







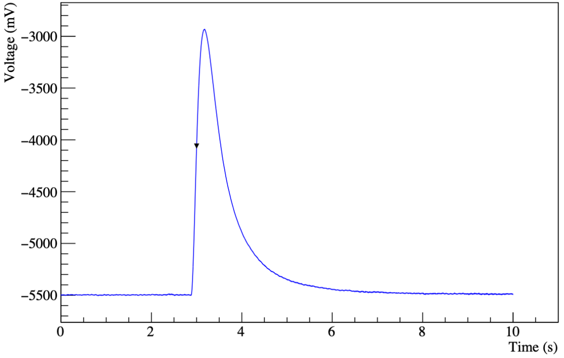


Thresholds: DT ~50 keV, OT <10 keV

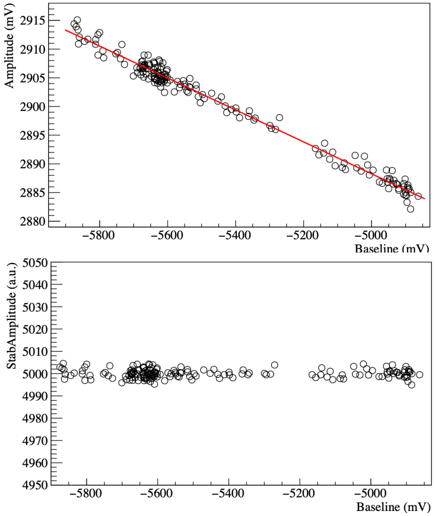
CUORE low thresholds
V Dompè et al 2020 J. Phys.: Conf. Ser. **1643** 012020
doi:10.1088/1742-6596/1643/1/012020

CUORE data processing (1/2)

Amplitude (Optimum Filter)

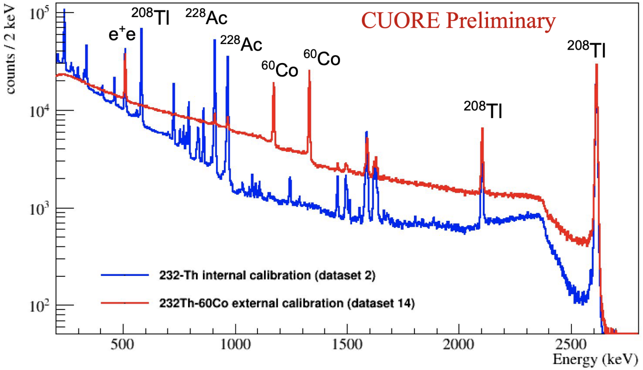


Thermal gain stabilization



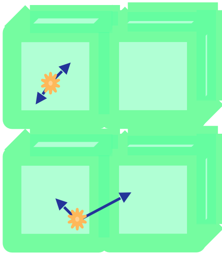
Energy calibration

External calibration system:
^{232}Th+^{60}Co sources



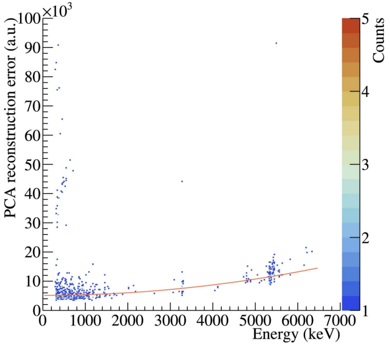
CUORE data processing (2/2)

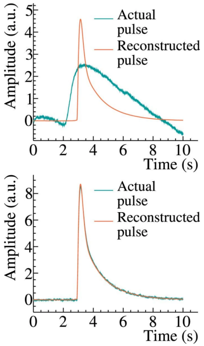
Coincidence → Pulse Shape Discrimination → ROI Blinding & Optimization → Unblinding

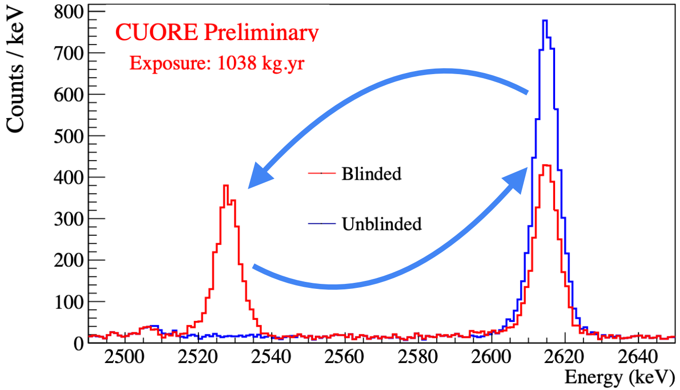


M1 (0νββ expected signature)

M≥2 (background events)





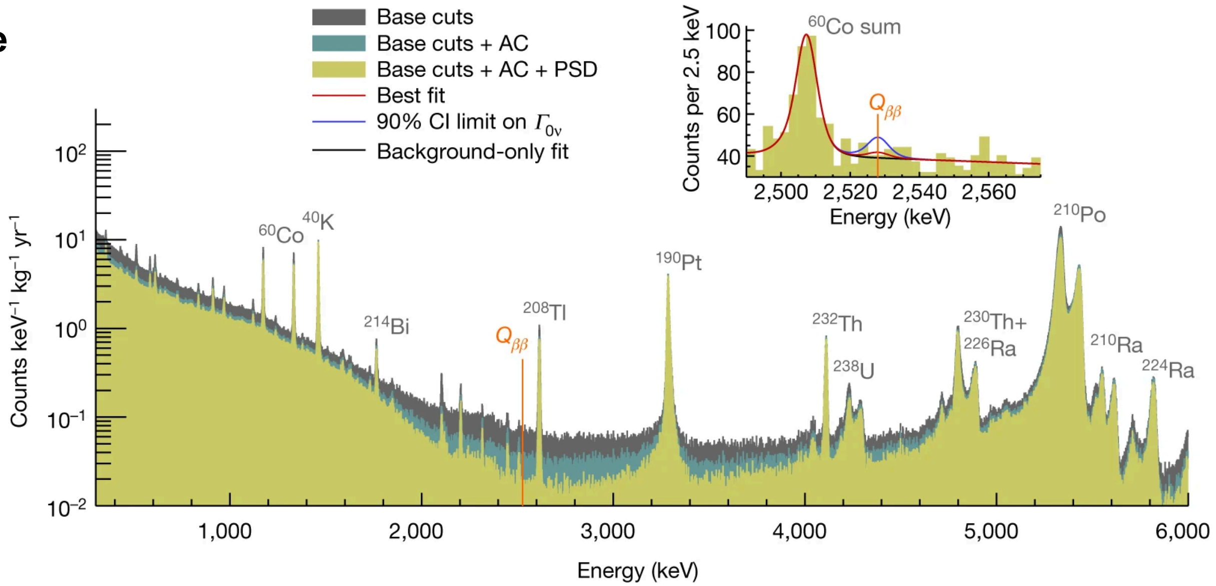


^{130}Te $0\nu\beta\beta$ decay search

Total exposure:
1038.4 kg yr TeO_2, 288 kg yr ^{130}Te
^{130}Te $Q_{\beta\beta}$= 2527.5 keV

Total analysis efficiencies: 92.4(2)%

(evaluated on data) - trigger, energy reconstruction, pile-up rejection, multiplicity (M1), PSA



The CUORE Collaboration. *Nature* **604,** 53–58 (2022) https://doi.org/10.1038/s41586-022-04497-4

^{130}Te $0\nu\beta\beta$ decay search

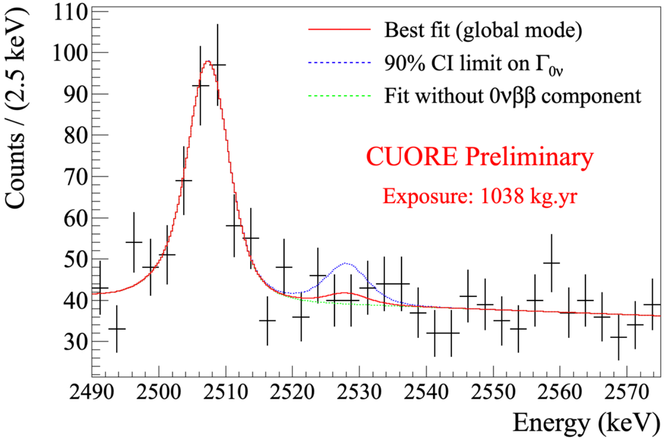
No evidence of signal at Qββ in ROI [2490-2575 keV].

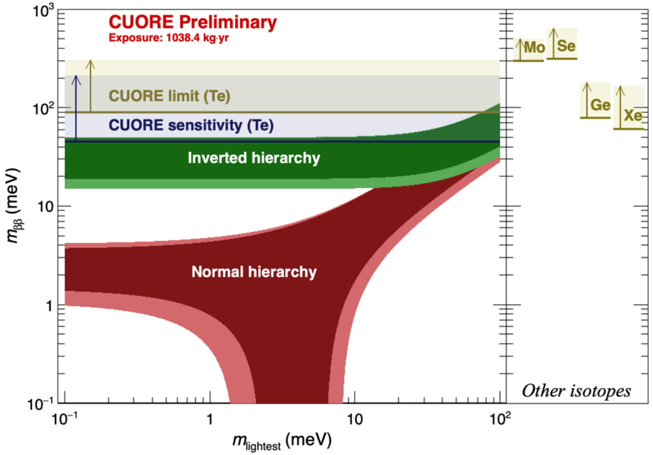
$T_{1/2}^{0\nu}$ (^{130}Te) > 2.2 x 10^{25} yr (90%C.I. including syst.)

Repeating the fit in the ROI,
without the 0νββ decay contribution
ROI background index (B):
1.49(4) × 10^{-2} c/(keV·kg·yr)

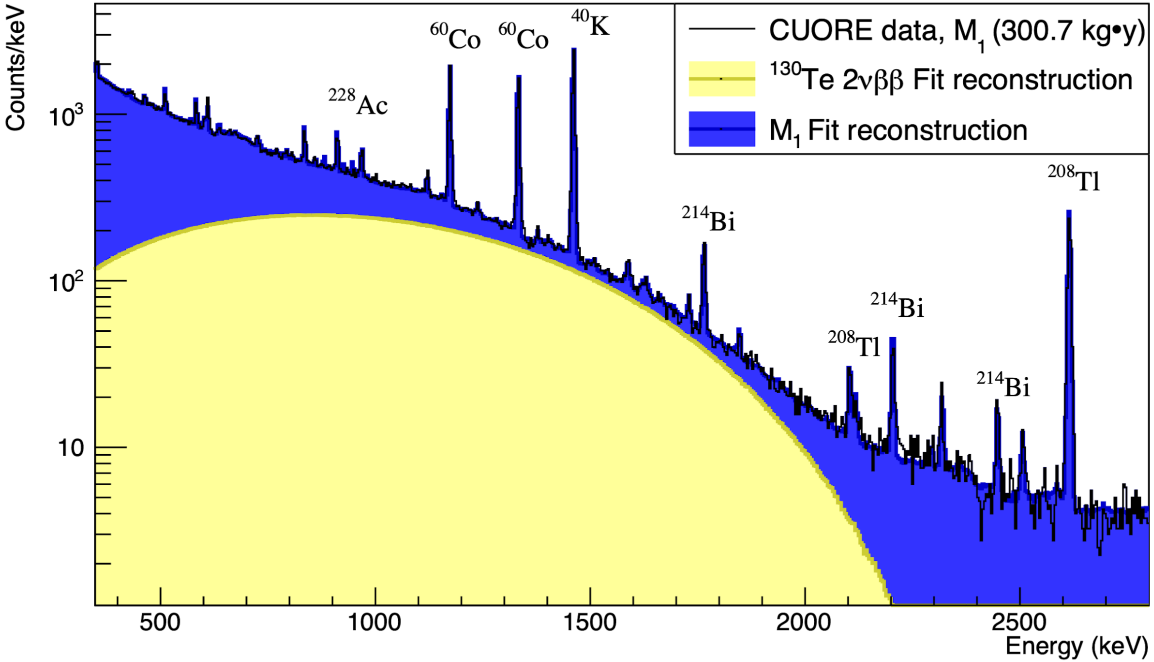
Limit on 0νββ decay half life and interpretation in context of light Majorana neutrino exchange:

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





^{130}Te $2\nu\beta\beta$ decay



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 2νββ decay half-life to date

The CUORE Collaboration. *Phys. Rev. Lett.* **126**:171801 (2021)
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.171801

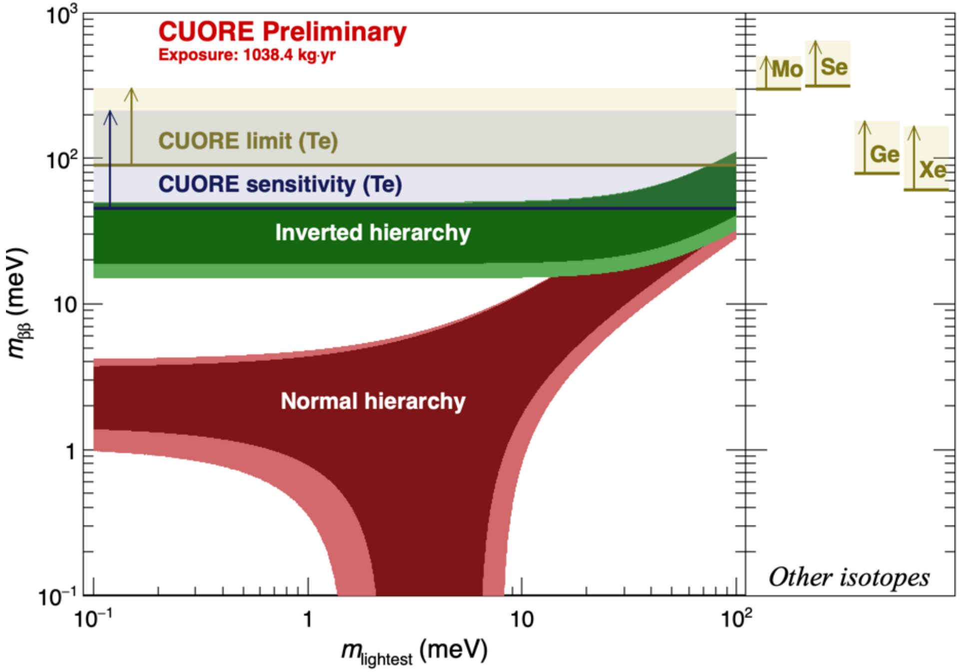
CUORE projected sensitivity

$0\nu\beta\beta$ decay exclusion sensitivity in 5 yr (90% C.L.): $S_{0\nu}$~ $9 \cdot 10^{25}$ 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

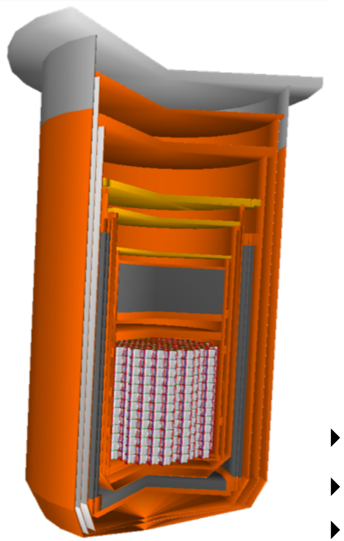
CUORE sensitivity limited by TeO_2 detectors background:

- **Degraded α particles**
  - from radioactive decays close to the detectors or on their surface
  - 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? **CUPID**

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



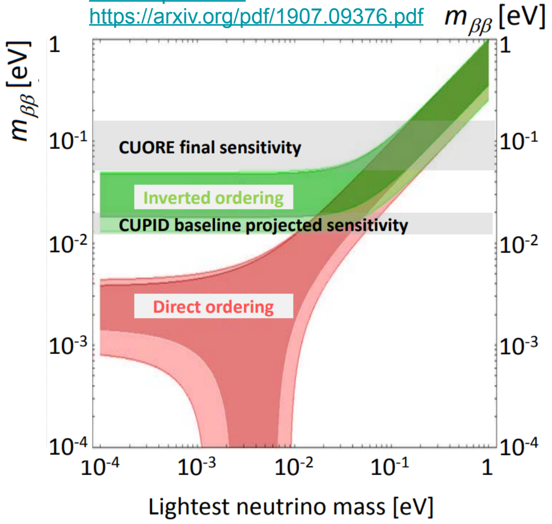
1 tonne of scintillating detectors

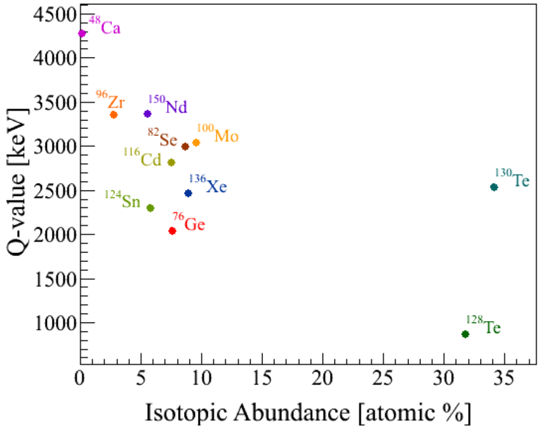
- **GOAL :** fully probe the "Inverted Hierarchy" region
- Will Operate in the same cryostat that currently houses CUORE

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: high-radiopurity in assembly and storage of detectors and materials, muon veto, higher Q value

CUPID pre-CDR
https://arxiv.org/pdf/1907.09376.pdf

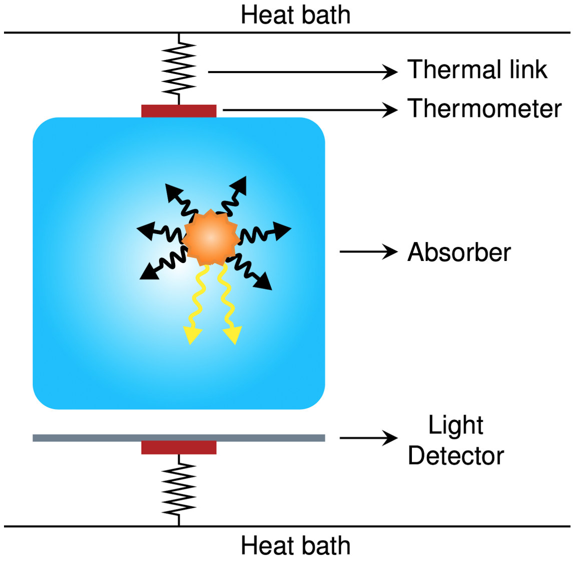




What's next? **CUPID**

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

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

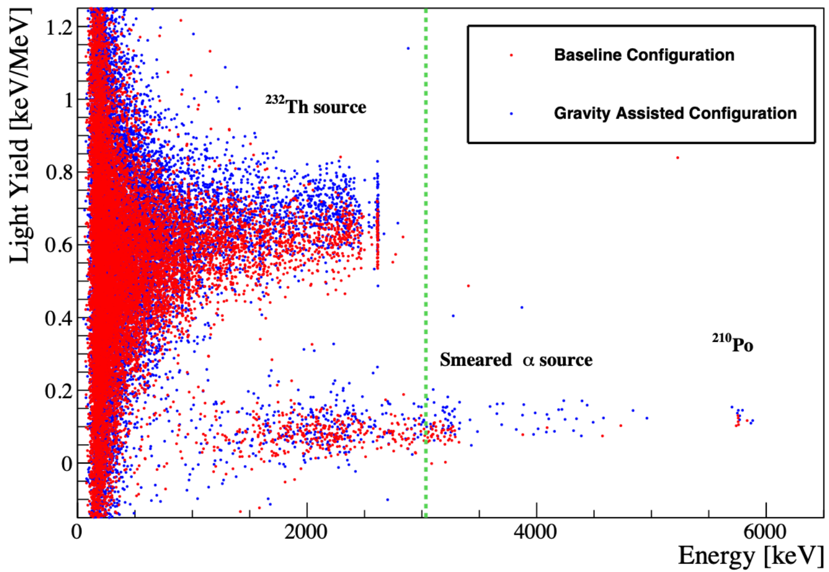


100Mo $\beta\beta$ decay candidate: Q$\beta\beta$ ~3034 keV

Readout of both heat and scintillation light with thermal sensors

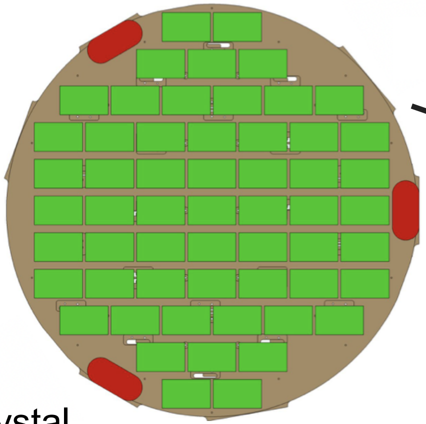
Alpha-particle rejection using light signal

CUPID



https://arxiv.org/pdf/2202.06279.pdf

CUPID Baseline Design



45 x 45 x 45 mm3 $Li_2{}^{100}MoO_4$ crystals

- Crystal mass: 280 g

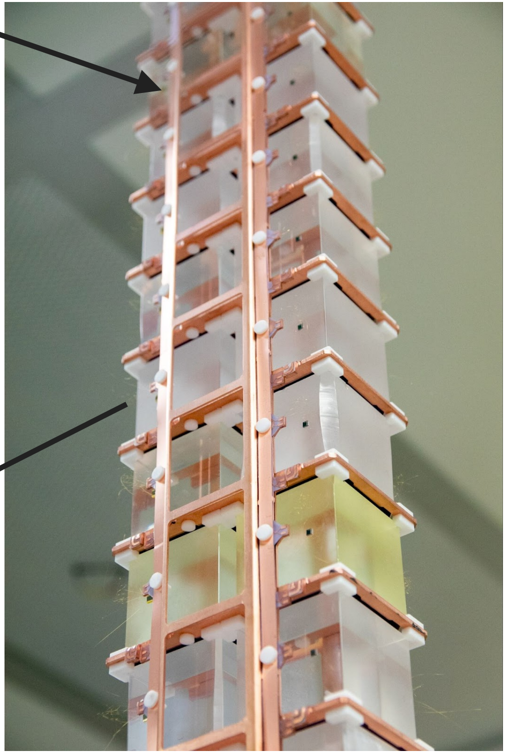
1596 total crystals

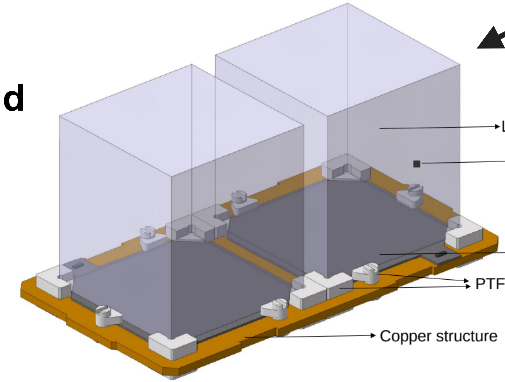
- 450 kg of $Li_2{}^{100}MoO_4$
- 95% enrichment in ^{100}Mo: **240 kg of ^{100}Mo**
- 57 towers of 28 crystals. 14-floors of 2x1 crystal pairs. Gravity-assisted design

Ge light detectors

- Each crystal has top and bottom light detectors
- No reflective foils

Muon veto for muon-induced background suppression





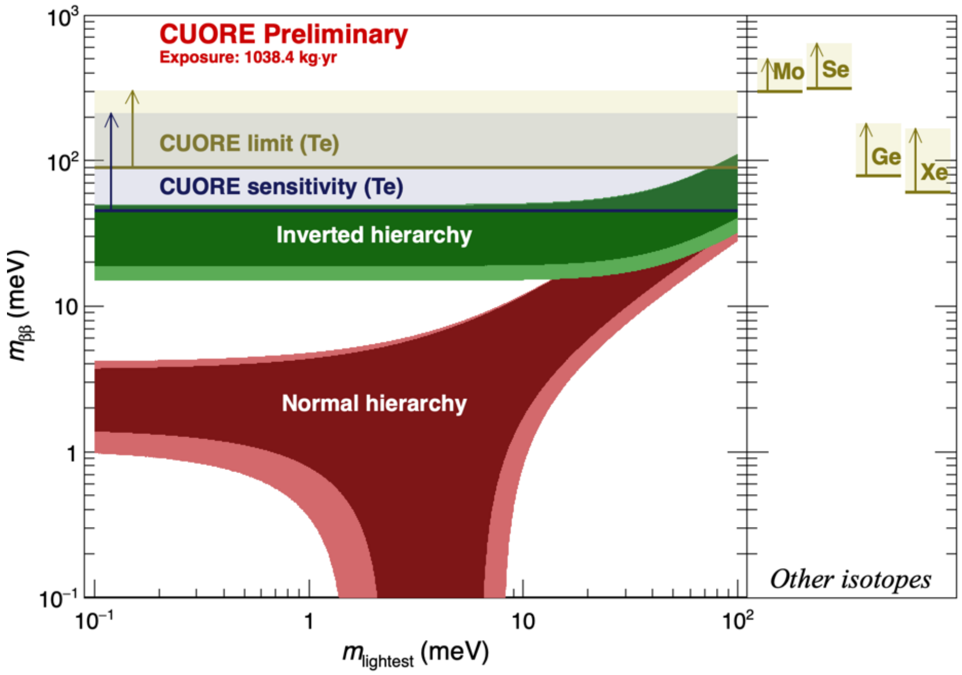
Summary & Conclusions

- CUORE demonstrates the feasibility of a tonne-scale experiment employing cryogenic calorimeters, for the search of the $0\nu\beta\beta$ decay and rare events
- The CUORE experiment operation is proceeding with 90% uptime. A raw exposure of more than 1.8 tonne yr TeO_2 has been achieved as of today!
- CUORE released physics results of ^{130}Te $0\nu\beta\beta$ decay, utilising 1 tonne yr TeO_2 data; this achieved ambitious goal was published on Nature!
- CUORE obtained the most precise half-life measurement for the $2\nu\beta\beta$ decay of ^{130}Te. Many more physics analyses are ongoing!
- The CUORE data taking is currently underway to collect up to 3 tonne yr TeO_2 exposure (1 tonne yr ^{130}Te)
- CUORE future is CUPID, next generation tonne-scale cryogenic calorimeters for $0\nu\beta\beta$ decay searches with ^{100}Mo
- CUPID is a Next-Generation detector suitable to fully explore the “inverted hierarchy” region

Thank you for the attention

Spare slides

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



Observation of 0νββ decay would imply:

- Lepton number violation
- Presence of a Majorana term for the neutrino mass
- Constraints on neutrino mass hierarchy and scale
- Hint on origin of matter/anti-matter asymmetry

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

Phase space integral

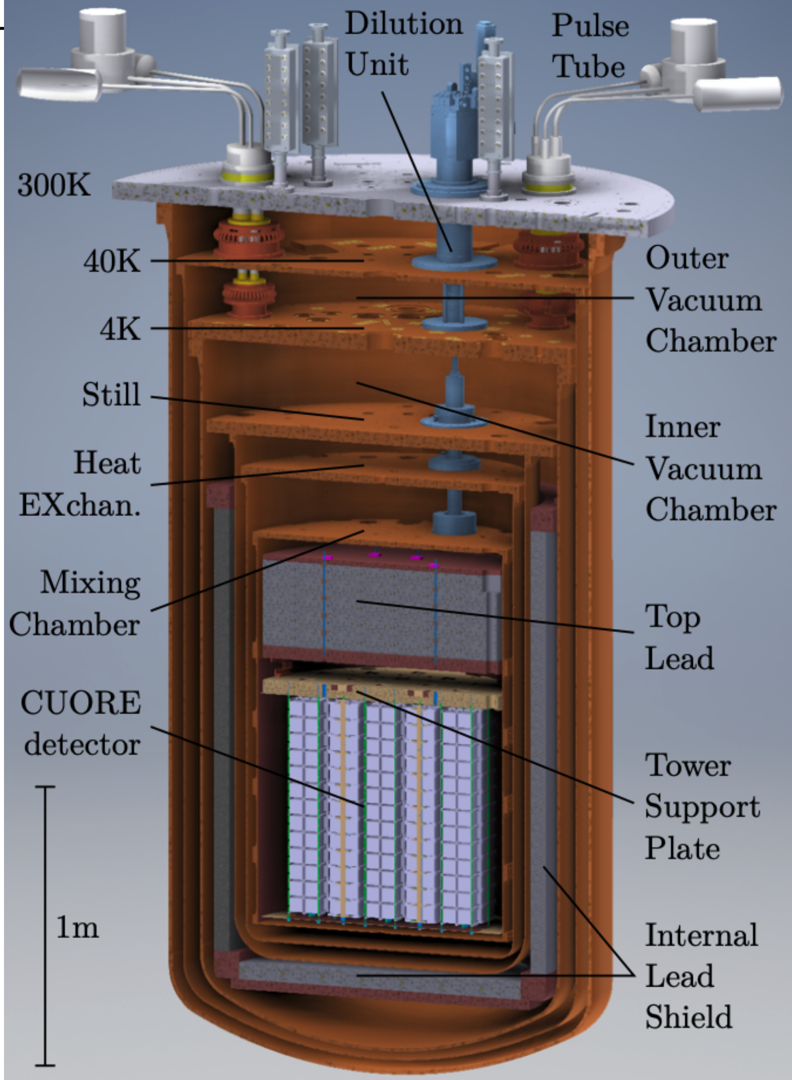
Nuclear matrix element

Effective neutrino mass term

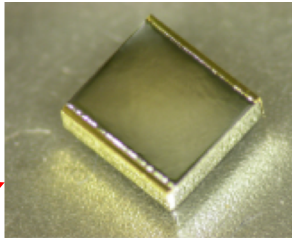
$$m_{\beta\beta} = \left| \Sigma_i m_{\nu_i} U_e i^2 \right| = \left| e^{i\alpha_1} \left| U_{e1}^2 \right| m_1 + e^{i\alpha_2} \left| U_{e2}^2 \right| m_2 + e^{i\alpha_3} \left| U_{e3}^2 \right| m_3 \right|$$

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)



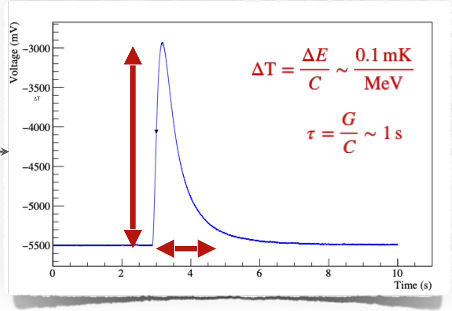
The CUORE sensors

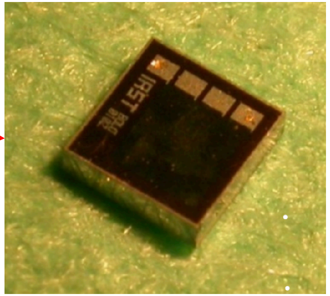


NTD = Neutron Transmutation Doped Ge thermistor

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

biased with a constant current, converts ΔT to voltage signal





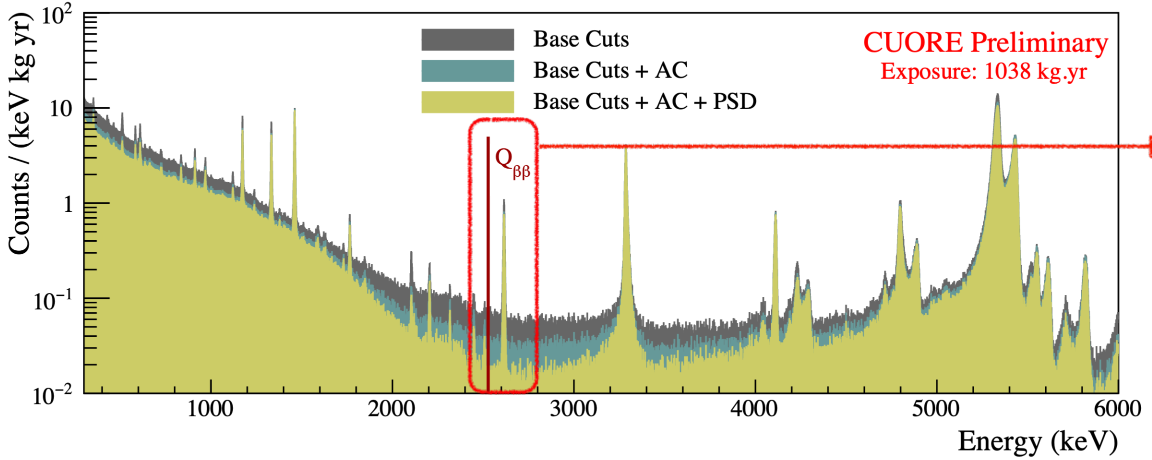
Silicon heater

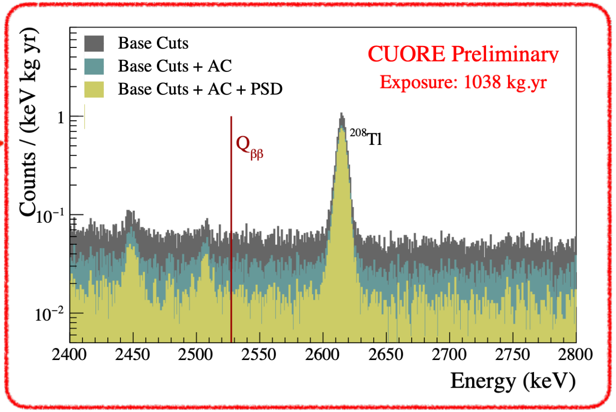
Periodically fires a pulse at a fixed energy to measure the detector's gain and correct the effect of thermal instabilities (stabilization)

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 $0\nu\beta\beta$	**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)%**

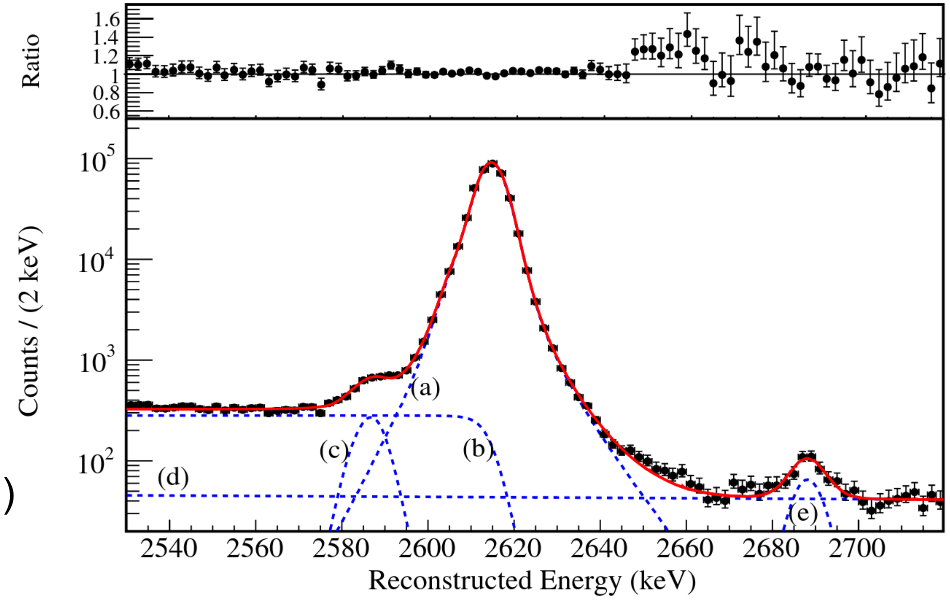




CUORE detector response function

- 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) from which the line shape is evaluated

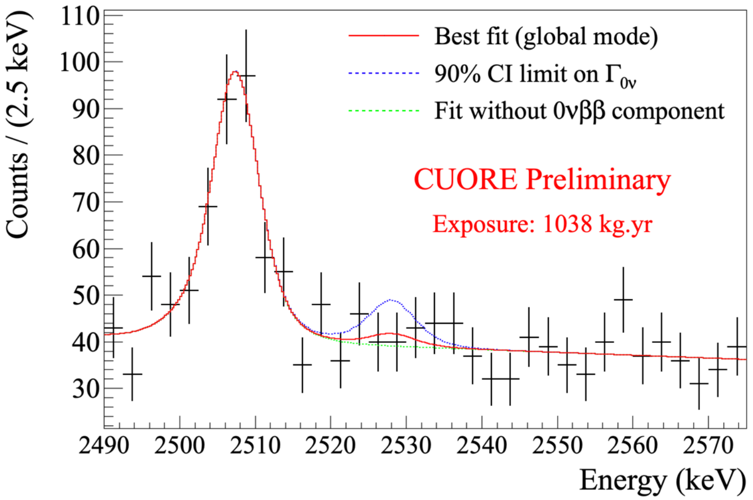


CUORE Collaboration. Phys. Rev. Lett. 120, 132501 (2018)
https://doi.org/10.1103/PhysRevLett.120.132501

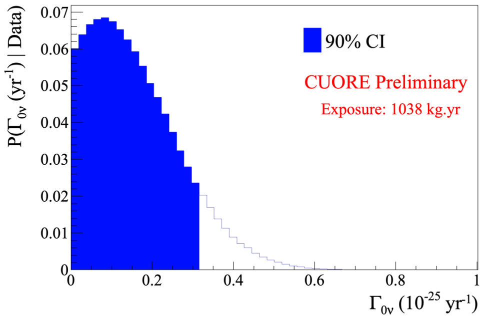
ROI fit: new results on $0\nu\beta\beta$ decay of ^{130}Te

- 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)



0vββ decay signal rate Γ0v marginalized posterior



NEW RESULTS!

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

The CUORE Collaboration. *Nature* **604**, 53–58 (2022)
https://doi.org/10.1038/s41586-022-04497-4

Experimental $0\nu\beta\beta$ sensitivity

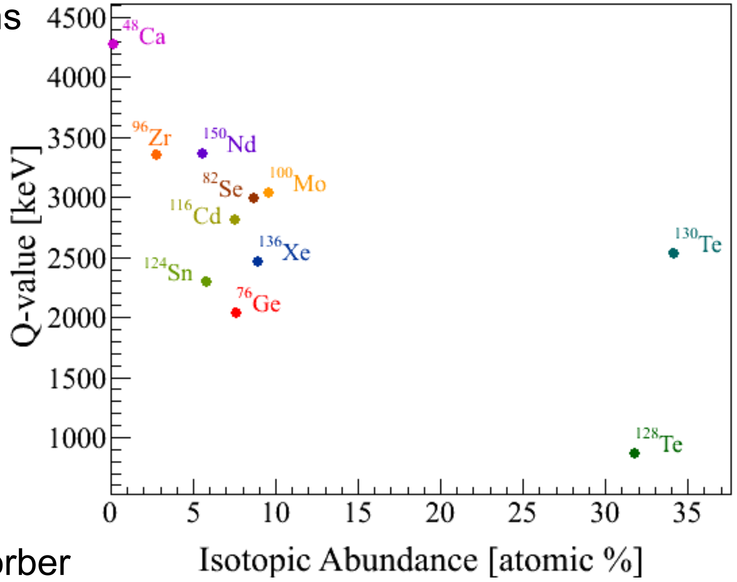
The number of observable 0νββ decays is limited by the fluctuations of the background counts around Qββ (region of interest, ROI)

Finite background

$$S_{0\nu} \propto \eta \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta \cdot B}}$$

Zero background (B·Δ·M·T)<<1

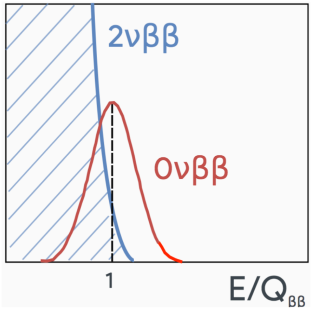
$$S_{0\nu} \propto \eta \cdot \epsilon \cdot M \cdot T$$



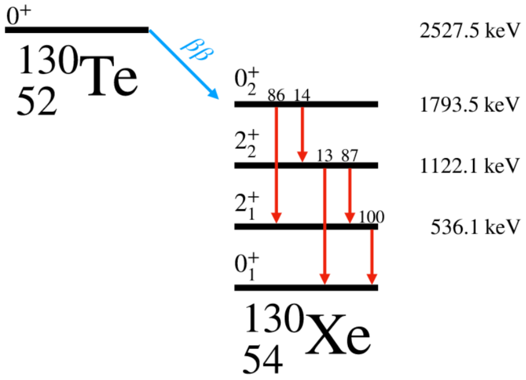
Isotope choice
- High isotopic natural abundance or enrichment, η
- High Q-value, Qββ

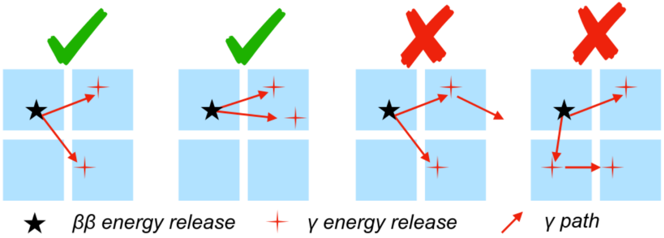
Detection technology
- Good detection efficiency (ε): ββ source embedded into the absorber
- Excellent energy resolution (Δ)

Exposure
- Large active mass (M) detector
- Long live-time (T)

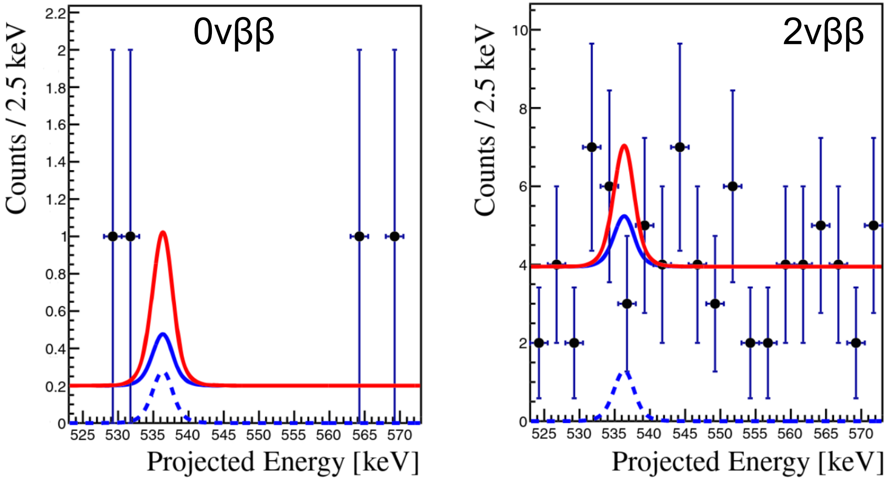


^{130}Te $\beta\beta$ decay to 0^+ excited states of ^{130}Xe





Cascade of de-excitation γs in coincidence with βs
- Multi-site signatures
- Analysis of only fully contained events



Half-life limits @90%C.I.
0νββ: $(T_{1/2})^{0+} > 5.9 \times 10^{24}$ yr
2νββ: $(T_{1/2})^{0+} > 1.3 \times 10^{24}$ yr

Adams D. et al. (CUORE collaboration), Eur. Phys. J. C (2021) 81:567
https://doi.org/10.1140/epjc/s10052-021-09317-z

Other physics analyses

^{120}Te 0νβ+EC decay

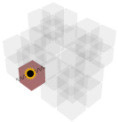
$Q_{\beta\beta}$= 1714.8 keV, natural abundance: 0.09%
Clear signature from e+e- annihilation and ^{120}Sn de-excitation via X-ray/Auger electrons emission

Half-life limit @90%C.I.

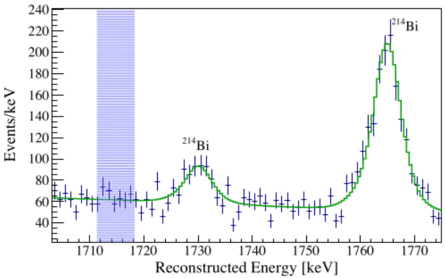
$T_{0\nu}^{1/2}$ (^{120}Te) > 2.9 × 10^{22} yr

Exposure: 355.7 kg·yr TeO_2, 0.2405 kg·yr ^{120}Te

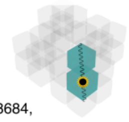
Adams D. et al. (CUORE collaboration), arXiv:2203.08684, https://doi.org/10.48550/arXiv.2203.08684



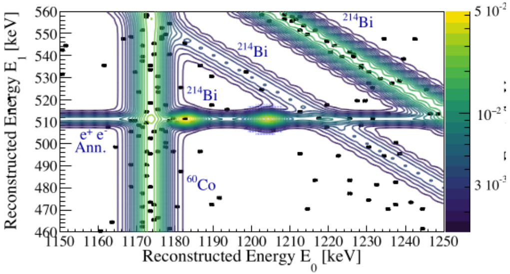
M1
$\beta^+ + X + 2\gamma_{511}$:
1714.8 keV



See CUORE poster P0209 (A.Campani)



M2
($\beta^+ + X + \gamma_{511}$, γ_{511})
(1203.8, 511) keV



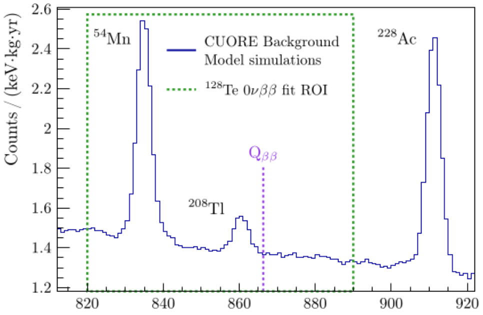
^{128}Te 0νββ decay

$Q_{\beta\beta}$= 866.7 keV, natural abundance: 31.74%
Half-life limit @90%C.I.

$T_{0\nu}^{1/2}$ (^{128}Te) > 3.6 × 10^{24} yr

Improved limit of over a factor 30 wrt to previous direct search results, and exceeded the results from geochemical experiments

Adams D. et al. (CUORE collaboration), arXiv:2205.03132, https://doi.org/10.48550/arXiv.2205.03132



Exposure:
309.33 kg·yr TeO_2,
78.56 kg·yr ^{128}Te