Status and Prospect of Discovery of neutrinoless double β decay with the CUORE Detector

Alberto Ressa on behalf of the CUORE Collaboration

La Thuile 2022 6-12 March

INFN Istituto Nazionale di Fisica Nucleare

CUORE

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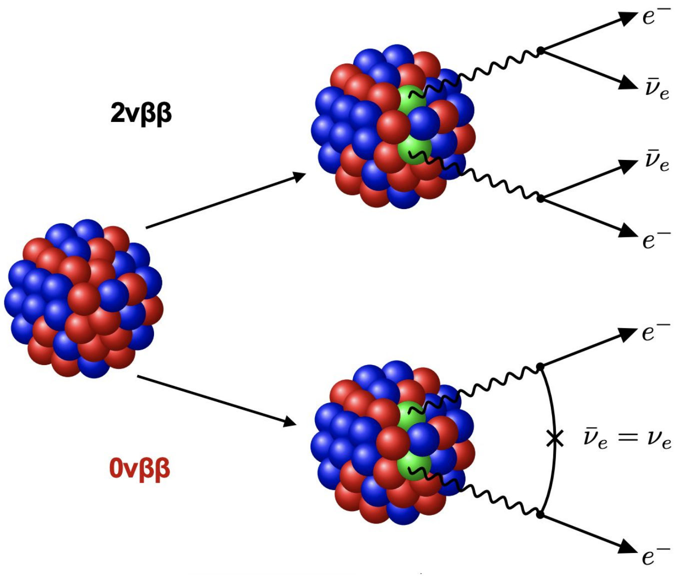
Double β Decay



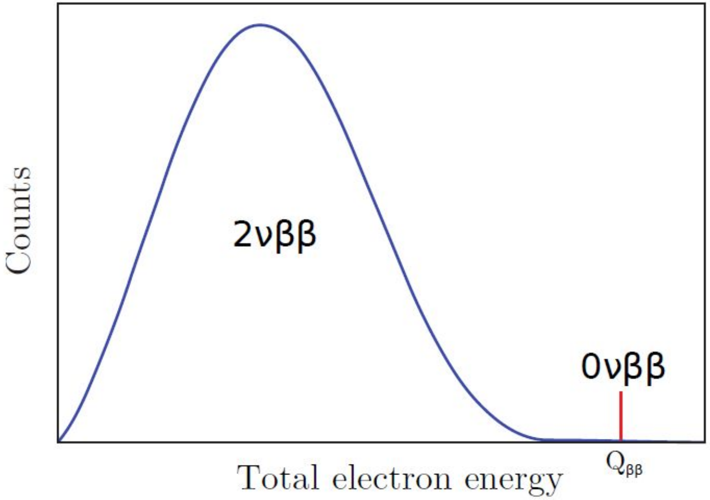
Standard Model allowed double β decay: **2νββ**

- **Observed** in 11 even-even nuclei in which single β decay is energetically forbidden
- **$T_{1/2}$ ~ 10^{18} - 10^{24} years**

Neutrinoless Double β decay: **0νββ**

- **Neutrino Nature**: possible only if neutrino is a Majorana particle (particle and its own antiparticle coincide)
- **Total Lepton number violated of 2 units**: not allowed in Standard Model

Double β Decay



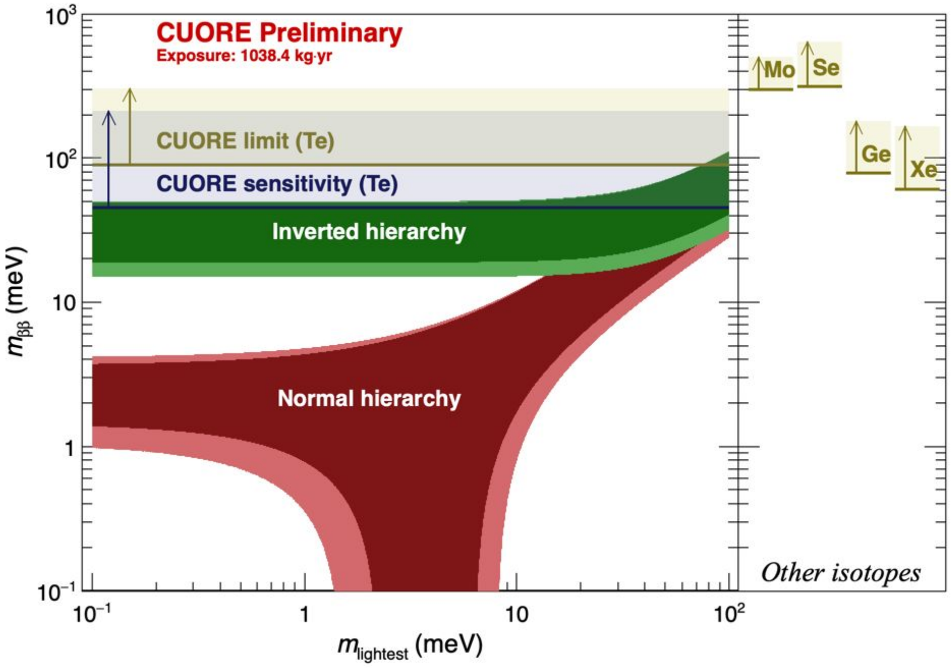
Standard Model allowed double β decay: **2νββ**

➔ continuous spectrum ending at the isotope Q-value

Neutrinoless Double β decay: **0νββ**

➔ Mono-energetic peak at the isotope Q-value (a simple and clear experimental signature!)

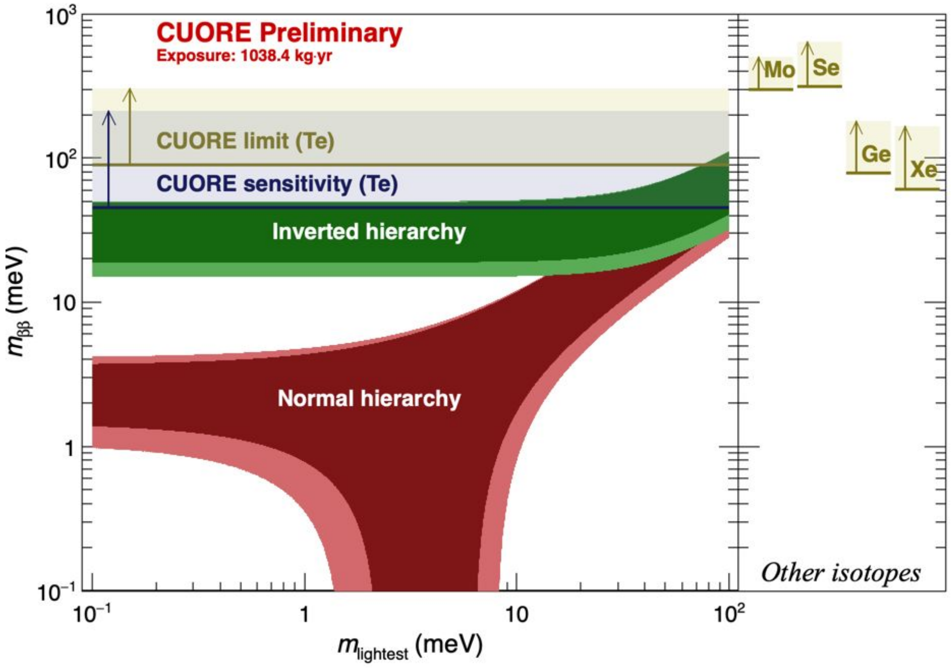
0νββ: where we are now



$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

- Phase Space Factor
- Nuclear Matrix element
- Effective Majorona mass:
  - related to lepton number violating term
  - a weighted sum of ν flavors masses

0νββ: where we are now

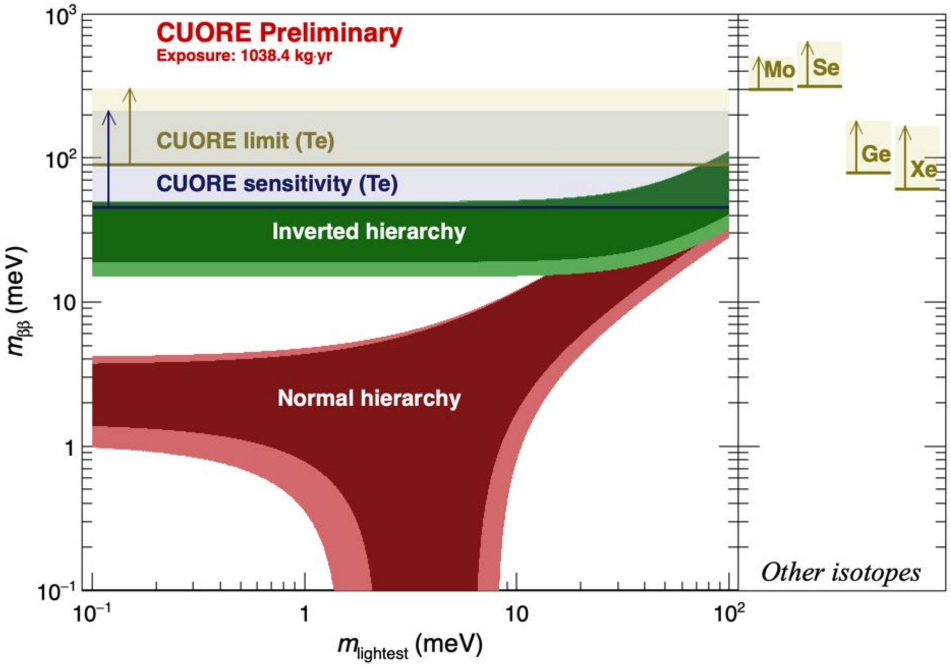


$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Contributions from different experiments:

- ^{130}Te: CUORE
- ^{136}Xe: KamLAND-Zen
- ^{76}Ge: GERDA
- ^{82}Se: CUPID-0
- ^{100}Mo: CUPID-Mo

0νββ: where we are now



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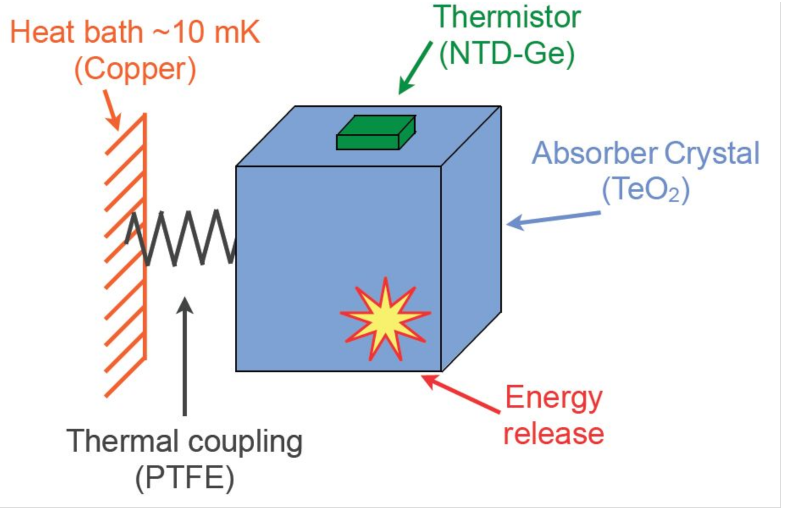
Cryogenic Calorimetric Experiments!

Cryogenic Calorimeters

Crystals containing the isotope candidate for the decay

1. Energy release in the crystal from particle interaction
2. Energy converted into heat (i.e. temperature increase)

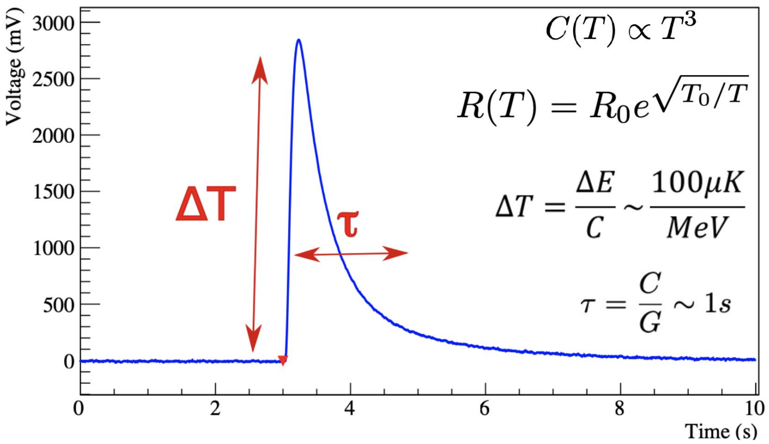


Cryogenic Calorimeters

Crystals containing the isotope candidate for the decay

1. Energy release in the crystal from particle interaction
2. Energy converted into heat (i.e. temperature increase)
3. Cryogenic sensor (**NTD-Ge thermistor**) converts thermal phonons into an electric signal

➔ Cryogenic temperature (about 10 mK) allows to turn the energy deposit in a readable temperature increase



Cryogenic Calorimeters

These detectors perfectly fit to the $0\nu\beta\beta$ search, presenting important features for the decay half-life sensitivity

$$S_{0\nu} \propto \epsilon \sqrt{\frac{MT}{B\Delta}}$$

- ➔ Excellent Energy Resolution (0.3% FWHM)
- ➔ Very good efficiency (80-90%)
- ➔ Flexibility in material choice (detector structure and crystal compounds)

Cryogenic Calorimeters

CUORE

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- ➔ Excellent Energy Resolution (0.3% FWHM)
- ➔ Very good efficiency (80-90%)
- ➔ Flexibility in material choice (detector structure and crystal compounds)

- Select radiopure materials to reduce the background level
- Choice the crystals compounds according to the needs
- Search for $0\nu\beta\beta$ in different isotopes (^{130}Te for CUORE, ^{82}Se for CUPID-0, ^{100}Mo for CUPID-Mo)

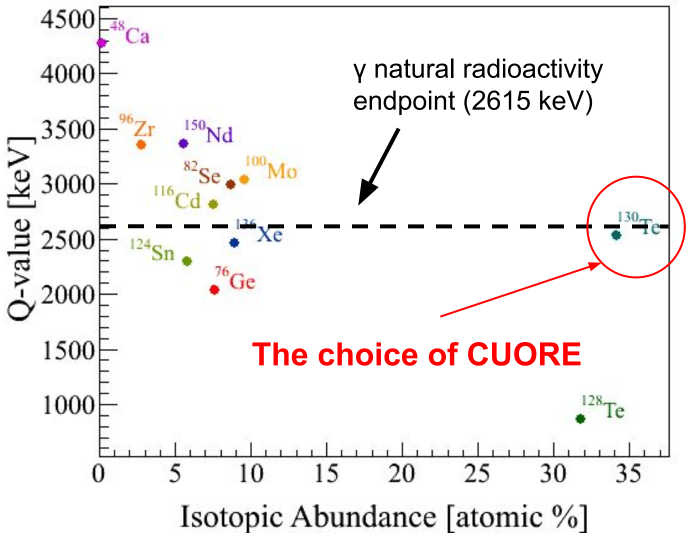
Cryogenic Calorimeters

These detectors perfectly fit to the 0νββ search, presenting important features for the decay half-life sensitivity

$$S_{0\nu} \propto \epsilon \sqrt{\frac{MT}{B\Delta}}$$

Choice an isotope with high Q-value to mitigate the natural radioactivity contribution to the background

High natural abundance (or easy enrichment) for large-scale (e.g. tonne.scale) the experiment

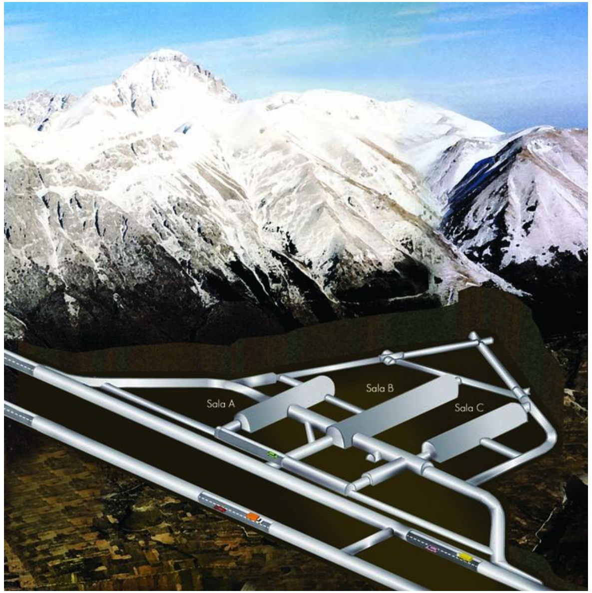


Cryogenic Calorimeters

These detectors perfectly fit to the $0\nu\beta\beta$ search, presenting important features for the decay half-life sensitivity

$$S_{0\nu} \propto \epsilon \sqrt{\frac{MT}{B\Delta}}$$

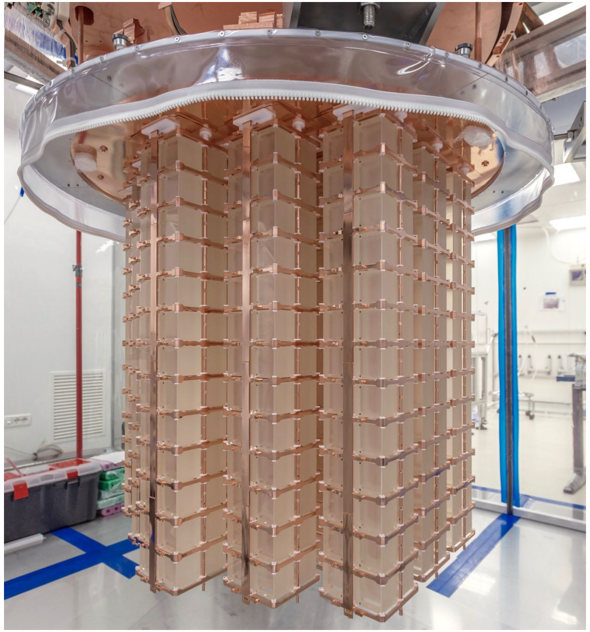
- Operate cryogenic calorimeters in Underground Laboratories (e.g. LNGS) to shield against cosmic rays
- Layered shields against external radioactivity



The CUORE Detector

Searching for Neutrinoless Double-Beta Decay of 130Te with CUORE
https://doi.org/10.1155/2015/879871

CUORE



Cryogenic
Underground
Observatory for
Rare
Events

The CUORE Detector

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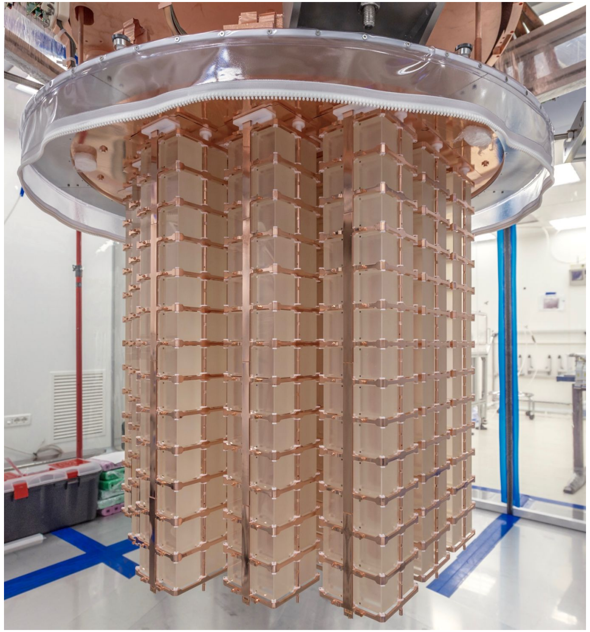
CUORE



Cryogenic
Underground
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- ➔ MT > 1 ton x yr (unblinded!)
- ➔ ΔE < 8 keV at $Q_{\beta\beta}$
- ➔ ϵ ~ 88 %
- ➔ B ~ 10^{-2} counts/ kg/ keV/ yr

- ➔ 988 TeO_2 cubic 5x5x5 cm^3 crystals arranged in 19 towers
- ➔ 742 kg of TeO_2 / 206 kg of ^{130}Te
- ➔ ^{130}Te: $Q_{\beta\beta}$ ~ 2527 keV, natural isotopic abundance 34%

The CUORE Cryostat

[Searching for Neutrinoless Double-Beta Decay of 130Te with CUORE](https://doi.org/10.1155/2015/879871)
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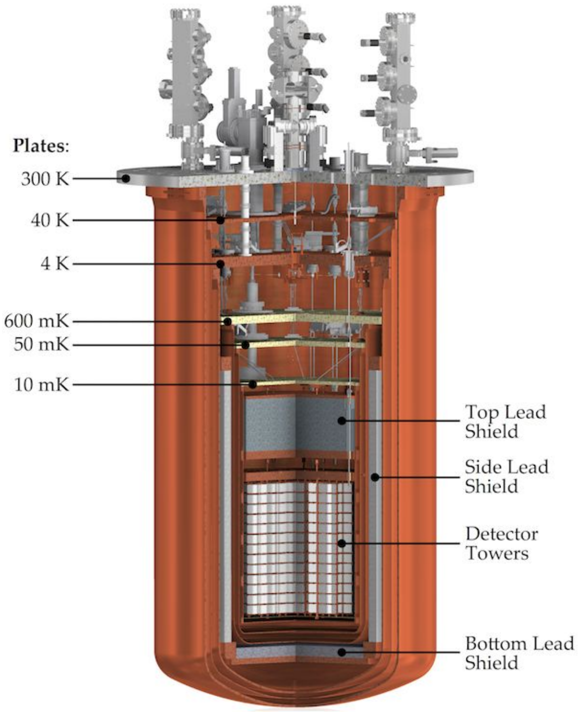
CUORE



"The coldest cubic meter in the known universe": world leading cryostat in terms of power and size

- Dilution Refrigerator: keep TeO_2 crystals at ~ 10 mK
- 5 Pulse Tube cryocoolers for cooling to 4K
- Nested co-axial copper vessels at decreasing temperatures
- Ancient roman Lead shielding

➔ 15 tons cooled below 4K
➔ 3 tons cooled below 50mK
➔ Stable data taking for over 2 yr

CUORE Data Taking

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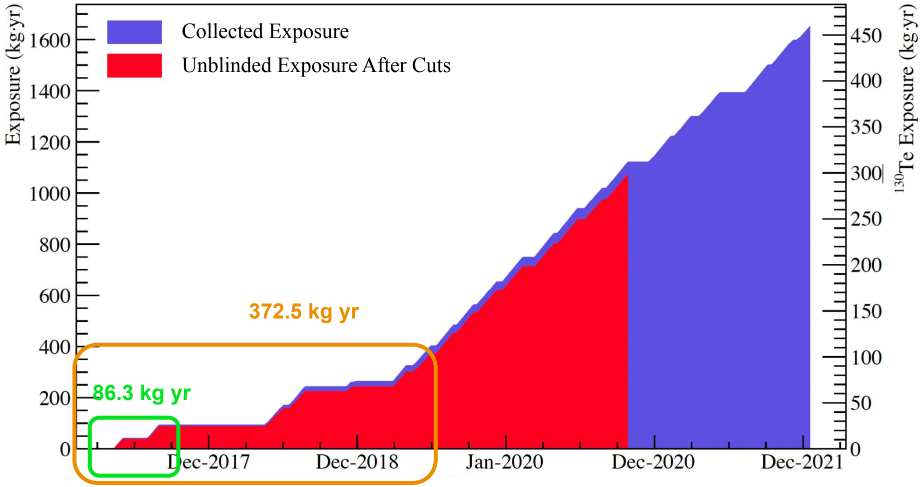


First Results from CUORE: A Search for Lepton Number Violation via $0\nu\beta\beta$ Decay of ^{130}Te
https://doi.org/10.1103/PhysRevLett.120.132501

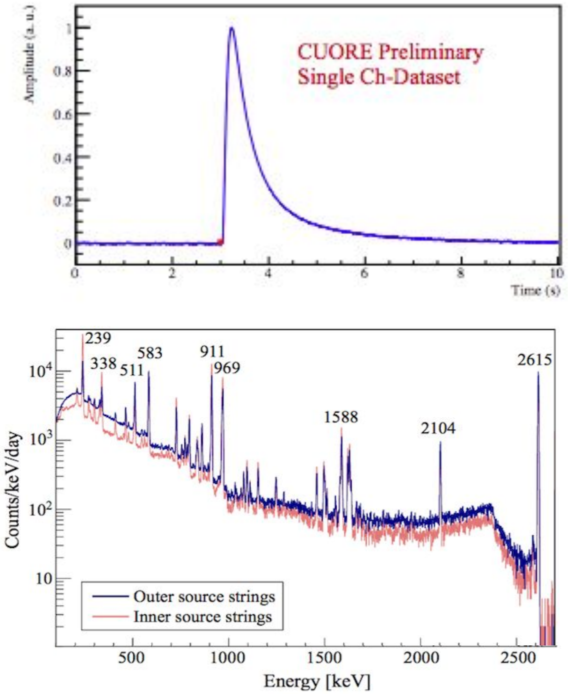
Improved Limit on Neutrinoless Double-Beta Decay in ^{130}Te with CUORE
https://doi.org/10.1103/PhysRevLett.124.122501

Data taking started in 2017.
From march 2019 higher than 90% uptime:
Background data taking > 67%

➔ Raw exposure collected is higher than **1670 kg × year**

CUORE is the first tonne-scale cryogenic calorimetric experiment

CUORE Event Reconstruction



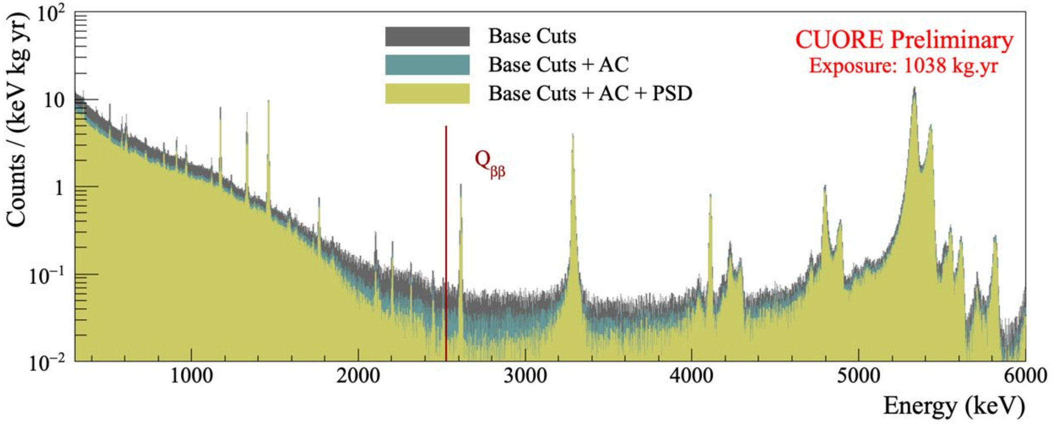
1. **Trigger**:
   Online + Offline to improve energy threshold

2. **Optimum Filter**:
   Suppress frequencies most affected by the noise

3. **Thermal Gain Correction**:
   Correct amplitude dependence on the operating temperature instabilities

4. **Calibration**:
   Exploits peaks from external ^{232}Th - ^{60}Co sources.

CUORE Data Selection



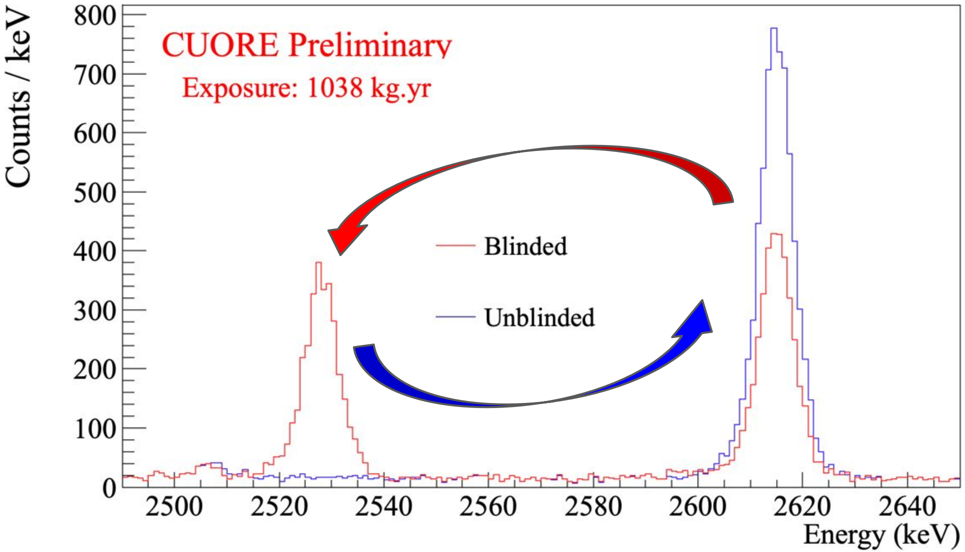
Base Cuts:
remove events to ensure high data quality (bad resolution channels, earthquake related events…)

Coincidences:
discard events involving more than 1 crystal ($0\nu\beta\beta$ events deposit all the energy in a single crystal)

Pulse Shape Discrimination:
reject pulses with anomalous shape

Blinding

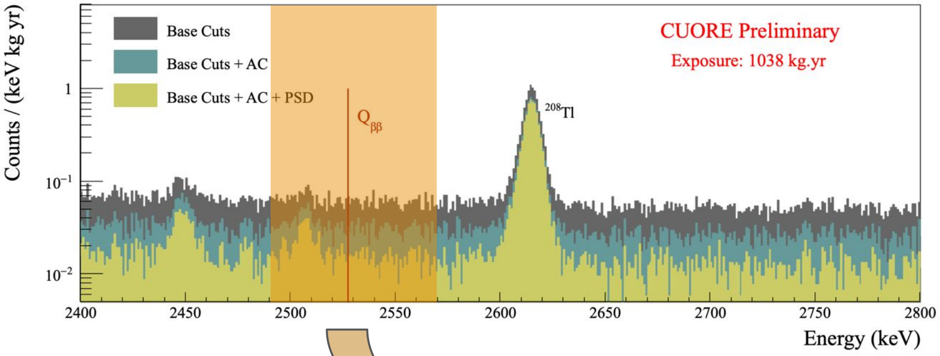
- Random fraction of events shifted from ^{208}Tl line to $Q_{\beta\beta}$ and vice versa
- Original energies stay encrypted until unblinding
- Unblinding happens only after full analysis procedure is finalized

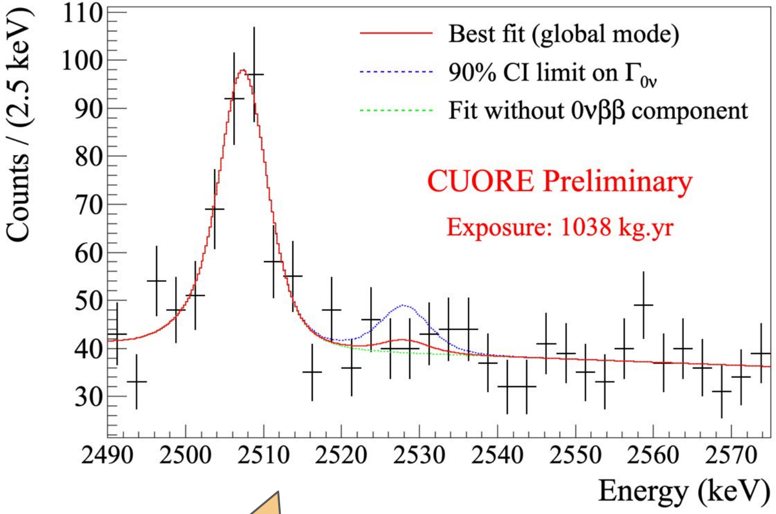


0νββ Analysis

Fit the Region Of Interest to search the 0νββ:

➔ **Window**: [2490, 2575] keV





0νββ Analysis

[High sensitivity neutrinoless double-beta decay search with one tonne-year of CUORE data](https://arxiv.org/abs/2104.06906)
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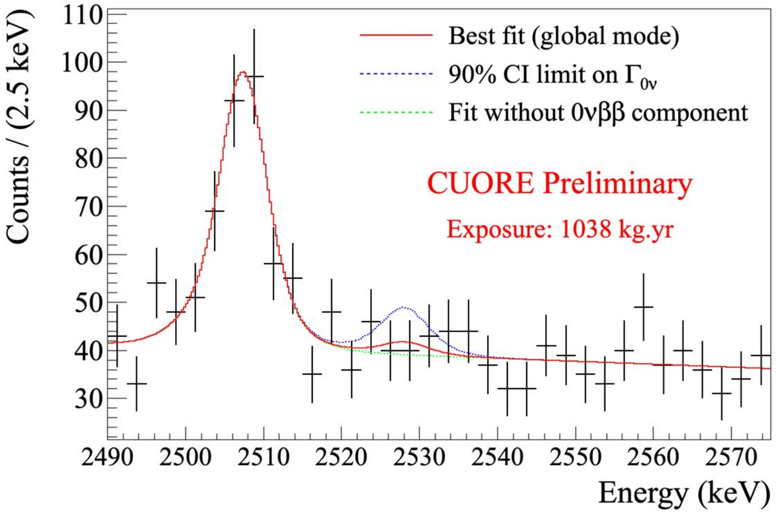
CUORE

Fit the Region Of Interest to search the 0νββ:

➔ **Window**: [2490, 2575] keV

➔ **Model**:
- Peak at $Q_{\beta\beta}$ (Signal)
- ^{60}Co peak
- Linear Background (degraded α particles background)

➔ **Free parameters**: half-life of 0νββ and ^{60}Co ($\Gamma_{0\nu}$, Γ_{Co}), Background Index and slope



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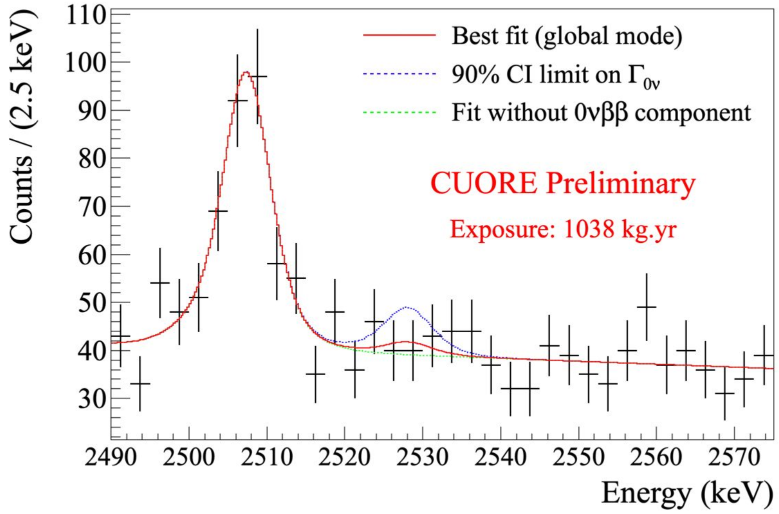
CUORE

Fit the Region Of Interest to search the 0νββ:

- **Systematics as nuisance parameters**: Efficiencies (analysis cuts and containment), Energy scale, $Q_{\beta\beta}$, Resolution, ^{130}Te isotopic abundance

- Fit performed with BAT (Bayesian Analysis Toolkit): software based on MCMC for posteriors sampling



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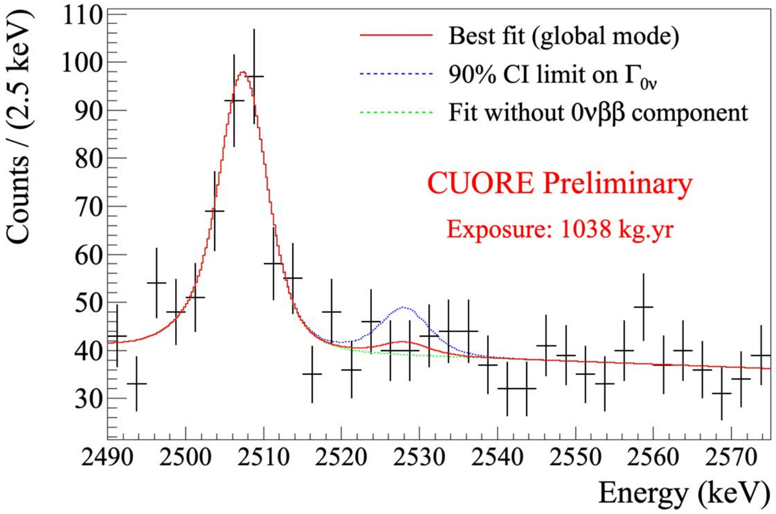
CUORE

Fit the Region Of Interest to search the 0νββ:

- **Background Index:**
  $1.49(4) \times 10^{-2}$ counts /(keV kg year)
- **Best-Fit Signal Rate:**
  $(0.9 \pm 1.4) \times 10^{-26}$ year^{-1}



No significant Signal observed:

➔ **Set Limit from the posterior**

0νββ Analysis

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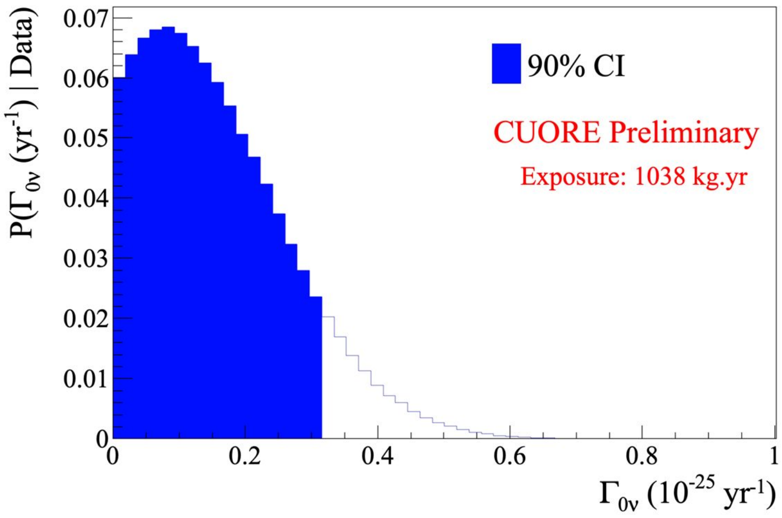
Half-life Limit of ^{130}Te 0νββ

$$T^{0\nu}_{1/2} > 2.2 \times 10^{25}\ \mathrm{yr}\ (90\,\%\ \mathrm{C.I.})$$



0νββ Analysis

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CUORE

Fit the Region Of Interest to search the 0νββ:

- **Background Index**:
  1.49(4) × 10^{-2} counts /(keV kg year)
- **Best-Fit Signal Rate**:
  (0.9 ± 1.4) ×10^{-26} year^{-1}

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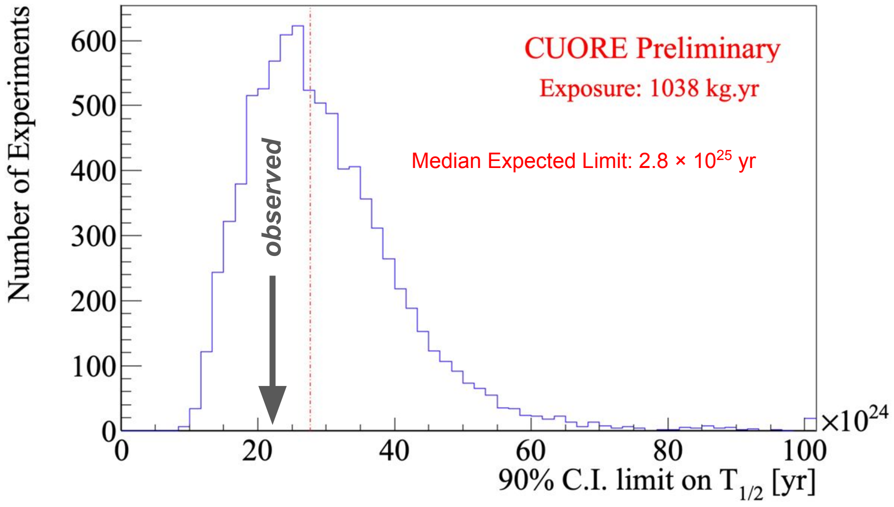
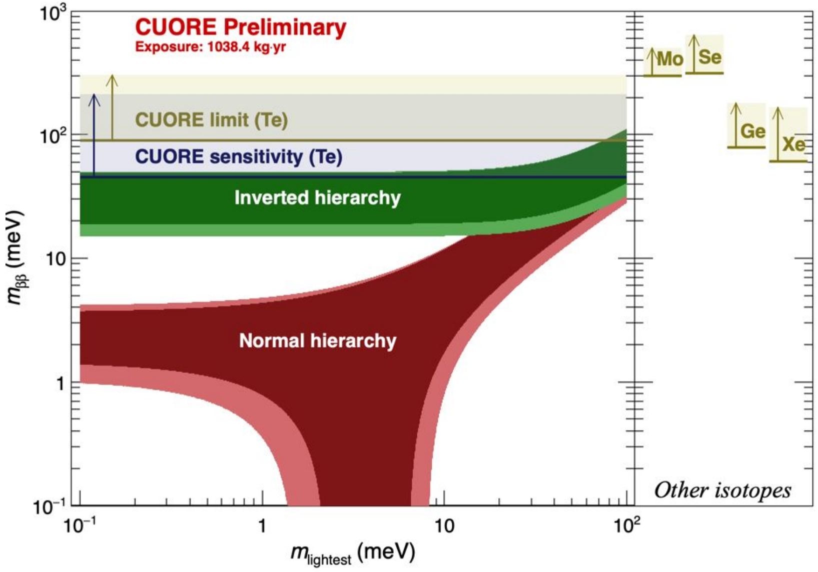


Median Expected Sensitivity:

➔ **2.8 × 10^{25} year**
➔ evaluated from toy experiments in background-only hypothesis using real data fit results
➔ 72% of chance to obtain a stronger limit

Search for 0νββ



Turn the result in terms of 0νββ effective neutrino mass (***m***$_{\beta\beta}$) to compare the result with half-life limit on other isotopes (from other experiments).

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Actual CUORE limit:

$$m_{\beta\beta} < 90 - 305 \text{ meV}$$

Future of CUORE

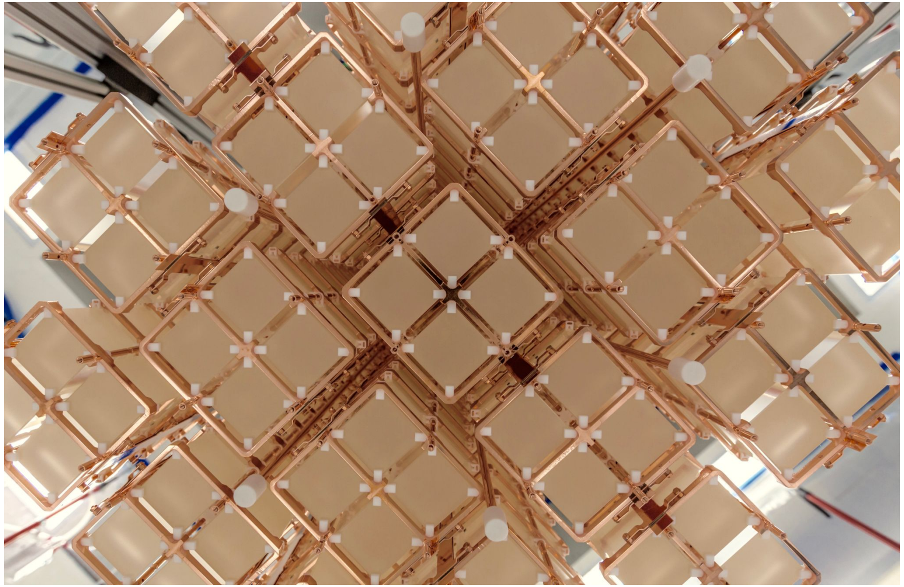
CUORE

Ultimate Exposure Goal **> 3 ton × yr**

Target Sensitivity: $\boldsymbol{m_{\beta\beta}}$ **< 50 - 130 meV**

Beyond $0\nu\beta\beta$:

- **^{130}Te $2\nu\beta\beta$ precision measurement**
- **^{130}Te $0\nu/2\nu\beta\beta$ to excited states**
- **^{128}Te $0\nu/2\nu\beta\beta$**
- **^{120}Te β+β+/β+EC/ECEC**
- Low Energy: Dark Matter, Solar Axions
- Investigate Noise reduction techniques

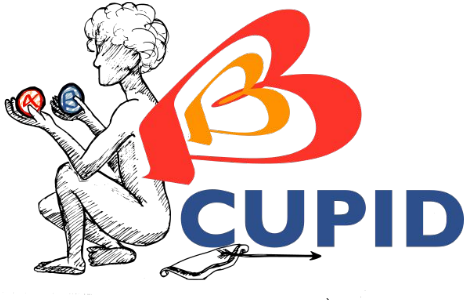


https://doi.org/10.1103/PhysRevLett.126.171801

https://doi.org/10.1140/epjc/s10052-021-09317-z

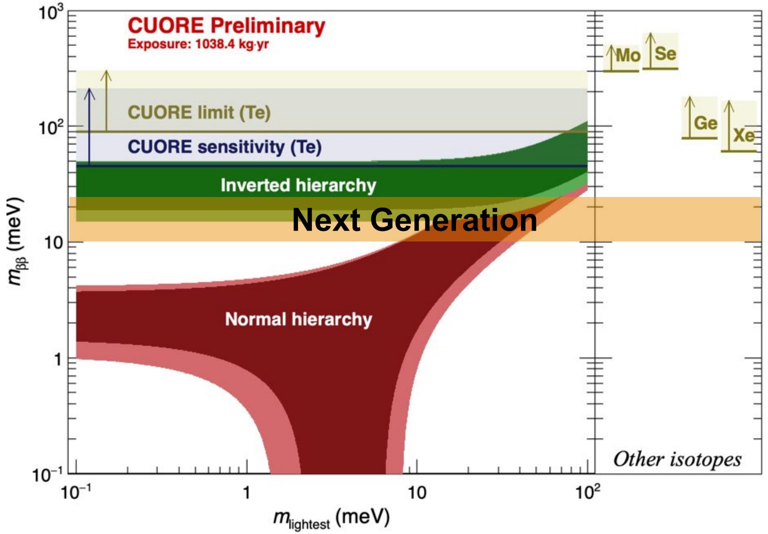
Future of CUORE

CUORE
Upgrade with
Particle
IDentification



Next Generation experiment searching for $0\nu\beta\beta$ with cryogenic calorimeters

CUPID aims to explore the IH region of the effective Majorana mass by reaching a "background-free" environment



Future of CUORE

https://arxiv.org/abs/1907.09376

CUORE

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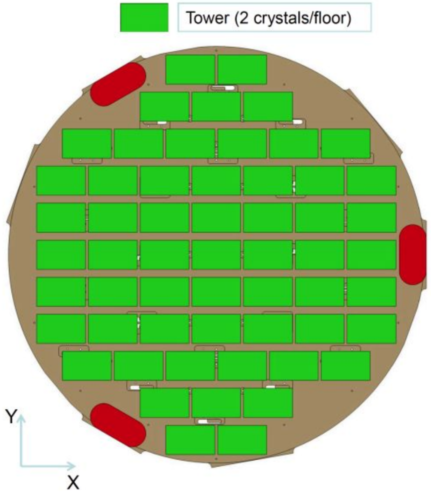
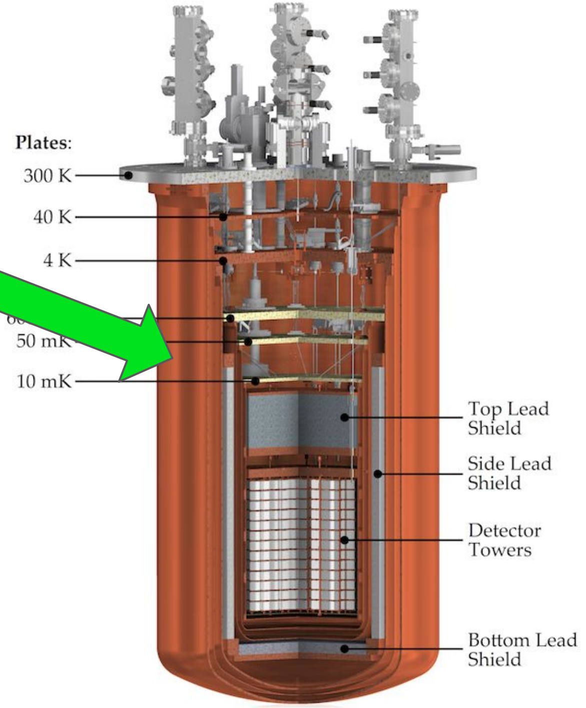




CUORE set a milestone for future cryogenic calorimetric experiments

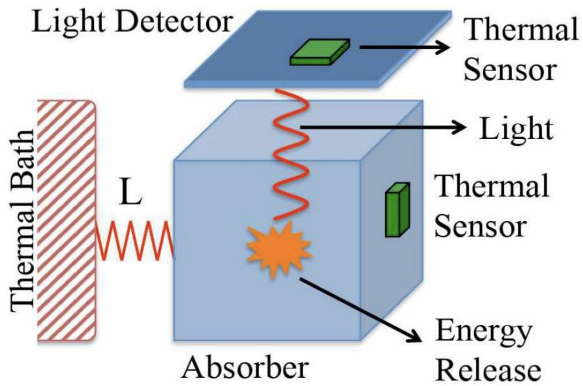
CUPID is based on CUORE expertise and it will be hosted in the same cryogenic facility

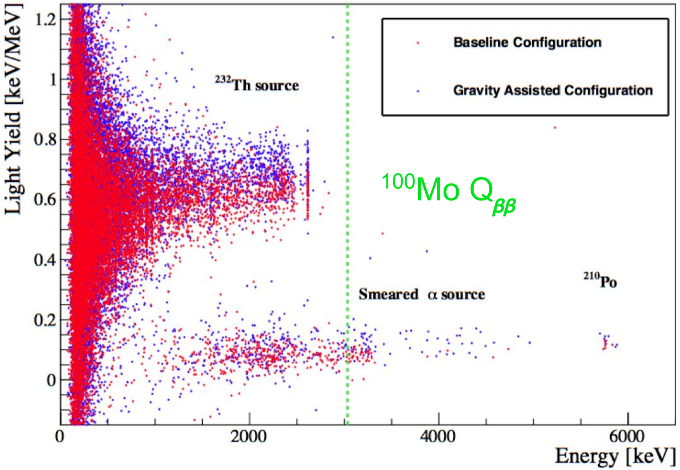
CUPID

https://doi.org/10.1140/epjc/s10052-018-5896-8

Main limit of CUORE: background in the ROI dominated by **α particles**

CUPID will perform particle identification by heat and scintillation light dual read-out (technology proved by the CUPID-0 and CUPID-Mo medium-mass demonstrators)

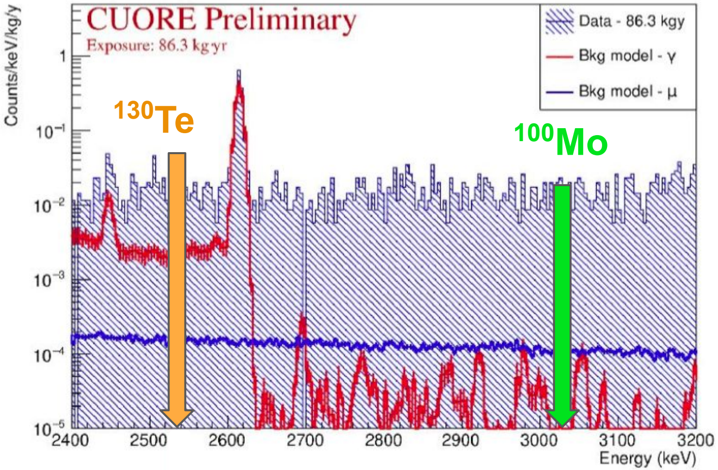


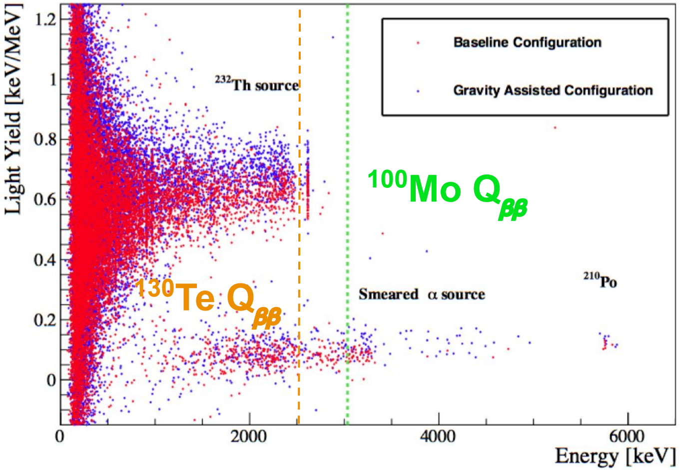


CUPID

https://doi.org/10.1140/epjc/s10052-019-7578-6

γ background further reduced by using higher Q-value emitter ^{100}Mo (first tested by CUPID-Mo and then in LNGS/Canfranc R&D tests)



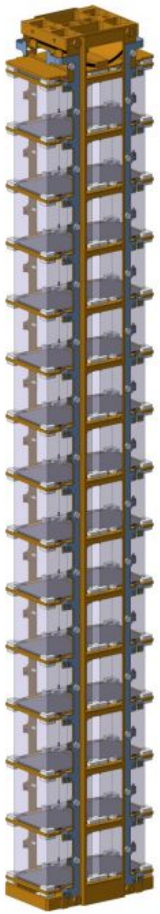


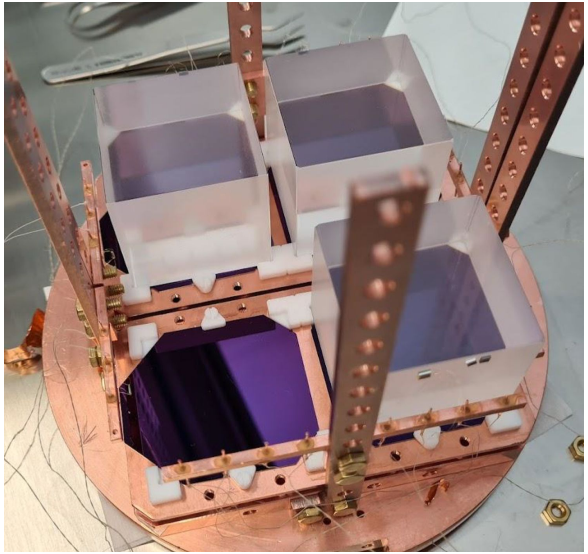
CUPID

Status:

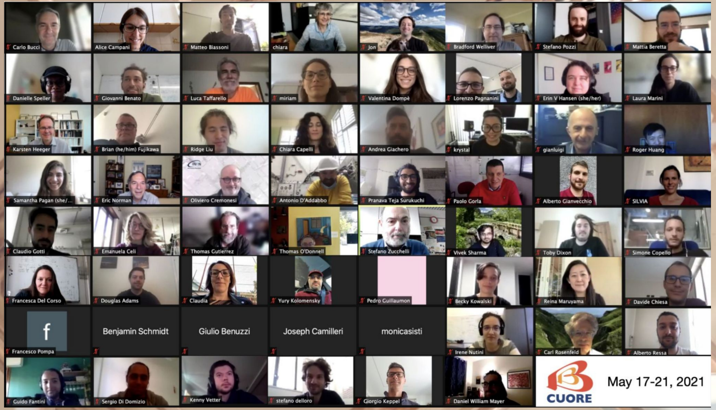
- extensive R&D on light yield enhancement and detector module design concluded
- testing of enriched crystals from official producers: measurements ongoing
- technical test of the Baseline Design Prototype Tower: planned within the first half of 2022

https://doi.org/10.48550/arXiv.2202.06279





Thanks for your attention!



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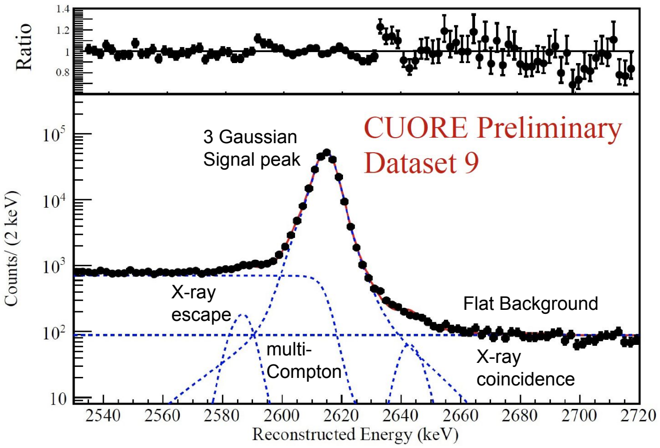
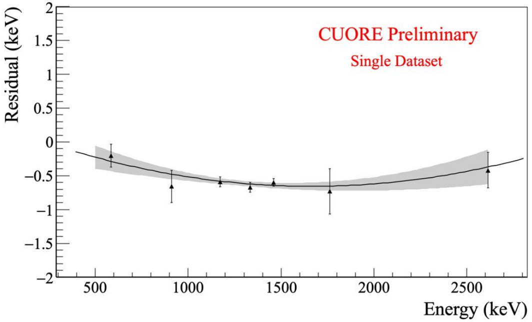
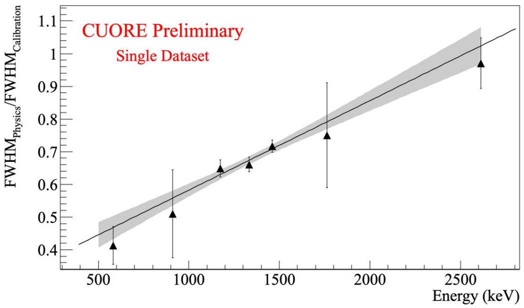
Backup Slides

CUORE Detector Response

1. Study the lineshape of the ^{208}Tl peak at 2615 keV.
   Fit includes 3 Gaussians + Flat and multi-Compton backgrounds + 30 keV coincidence/escape X-ray peaks
2. Scale the result to lower energy background peaks
3. Determine Energy Resolution and Energy Bias at the $Q_{\beta\beta}$



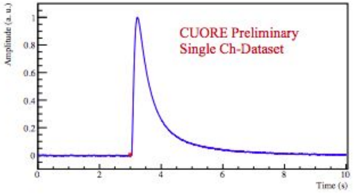




➔ **Energy Bias at $Q_{\beta\beta}$ < 0.7 keV**

➔ **FWHM at $Q_{\beta\beta} \simeq$ 7.8 keV**

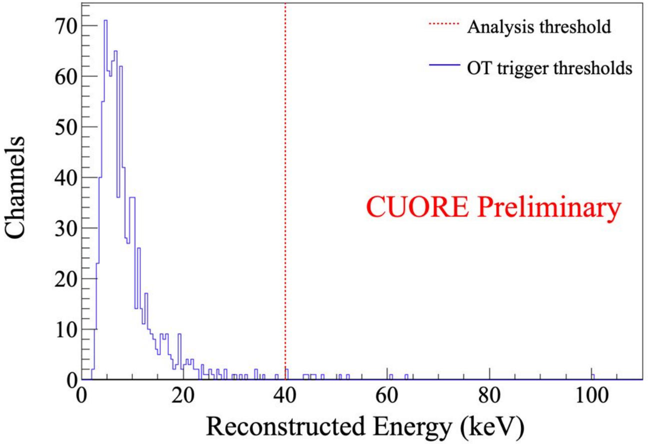
CUORE Event Reconstruction



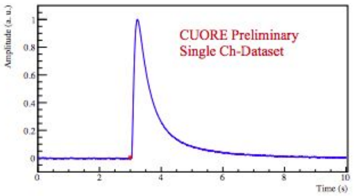
Trigger → Optimum Filter → Thermal Correction → Calibration

Trigger:

- Online derivative trigger for quick data quality feedback.
- Offline re-triggering after suppressing low SNR frequencies (Optimum Trigger) to improve energy threshold

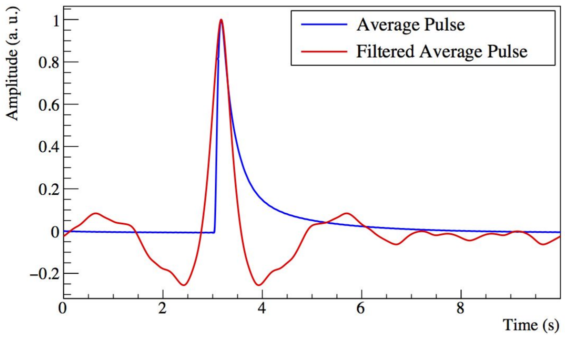


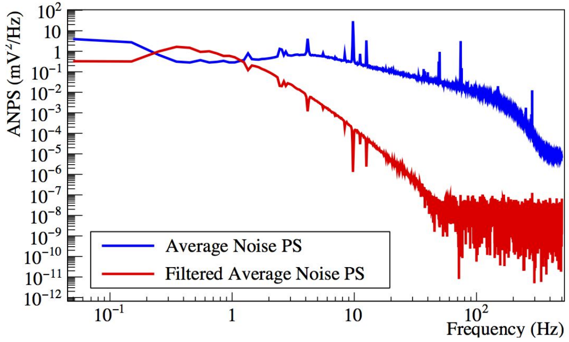
CUORE Event Reconstruction



→ Trigger → Optimum Filter → Thermal Correction → Calibration

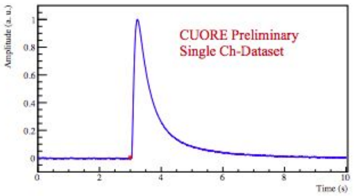
Optimum Filter:
Exploits a signal template (average pulse) and an average noise power spectrum to suppress the frequencies most affected by the noise.

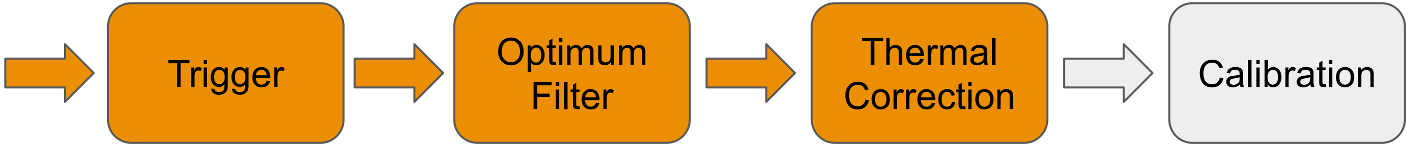




CUORE Event Reconstruction

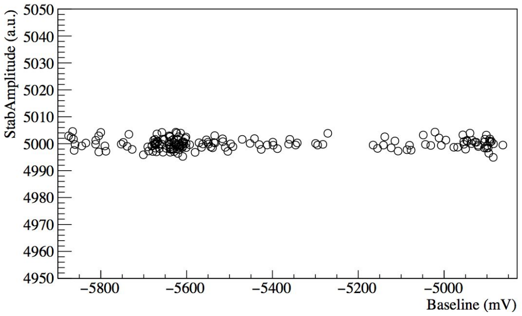
CUORE

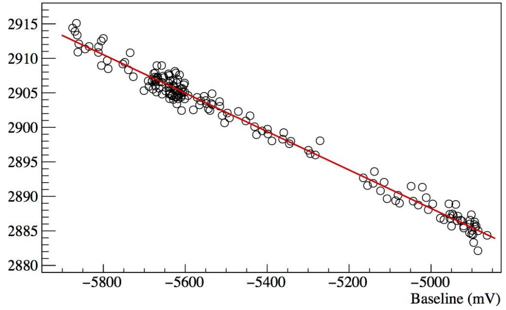




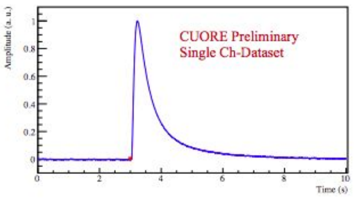
Thermal Gain Correction:
Correct amplitude dependence on the operating temperature instabilities

It exploits a heater injecting fixed energy pulses.



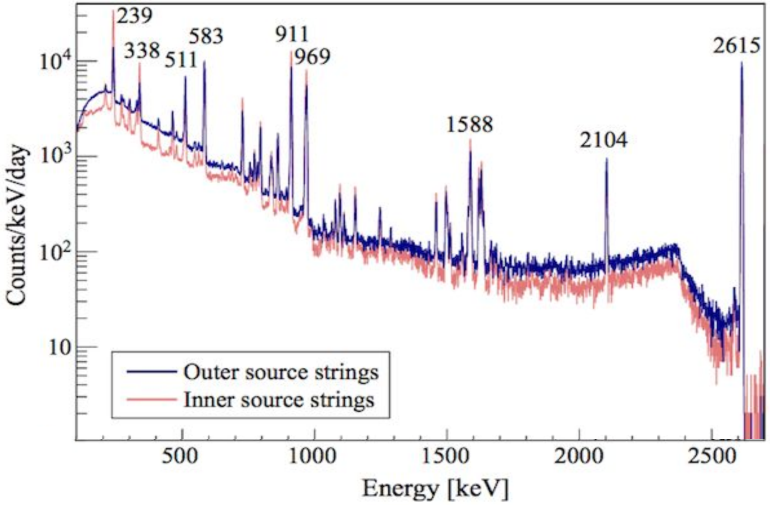


CUORE Event Reconstruction



Trigger → Optimum Filter → Thermal Correction → Calibration

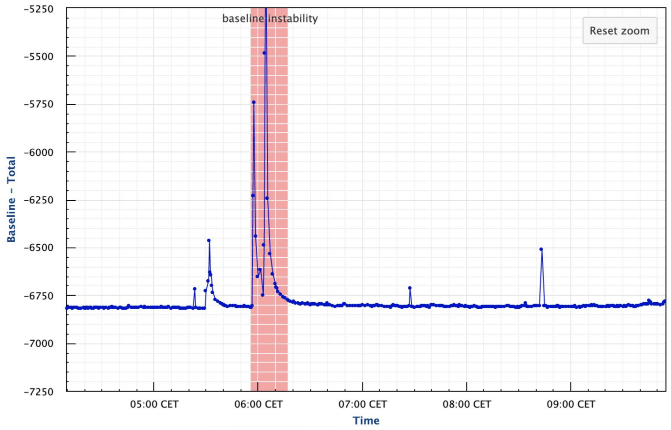
Energy Calibration:
First 3 dataset calibrated with an internal source.
Now data are calibrated by using external ^{232}Th - ^{60}Co sources.
Exploited peaks at 511, 1173, 1333, 2615 keV.



CUORE Data Selection

Base Cuts:

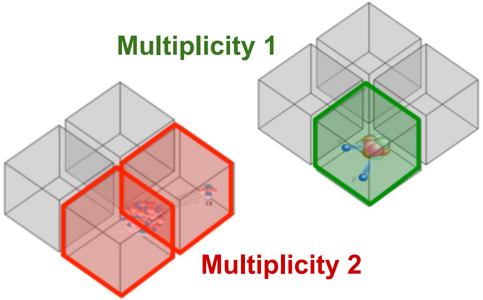
- data presenting excessive noise (due to external events, e.g. earthquake)
- events with more than 1 pulse in the 10 s window
- channels-dataset failing one of the reconstruction steps
- channels-datasets with energy resolution FWHM > 19keV



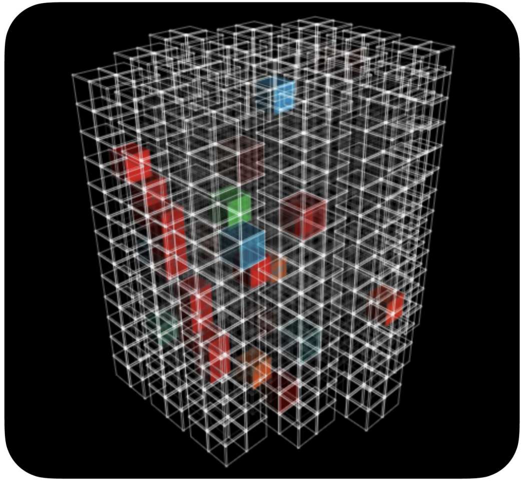
Base Cuts → Coincidences → Pulse Shape Discrimination

CUORE Data Selection

Coincidences:
If more than one cryogenic calorimeter fires in a small time window, a multiplicity higher than 1 is assigned to that event.
Multiplicity is the number of crystals involved in the interaction.

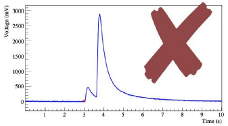
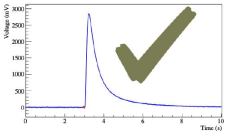
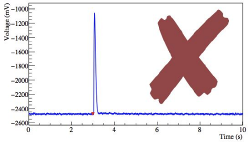


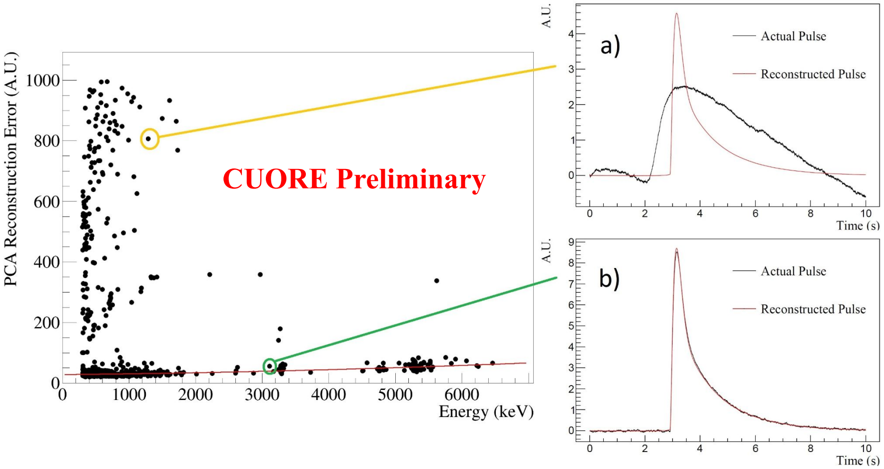
- ➔ $0\nu\beta\beta$ events deposit all the energy in a single crystal
- ➔ events with higher multiplicity are rejected as background for this analysis



CUORE Data Selection

Pulse Shape Discrimination:
PCA (Principal Component Analysis) consists of treating the average pulse as a principal component.
Select data on the bases of the reconstruction error found for each event.



Base Cuts → Coincidences → Pulse Shape Discrimination