Neutrinoless double β decay search with CUORE and CUPID experiments

Alberto Ressa, PhD Seminars 27/04/2022

INFN
Istituto Nazionale di Fisica Nucleare

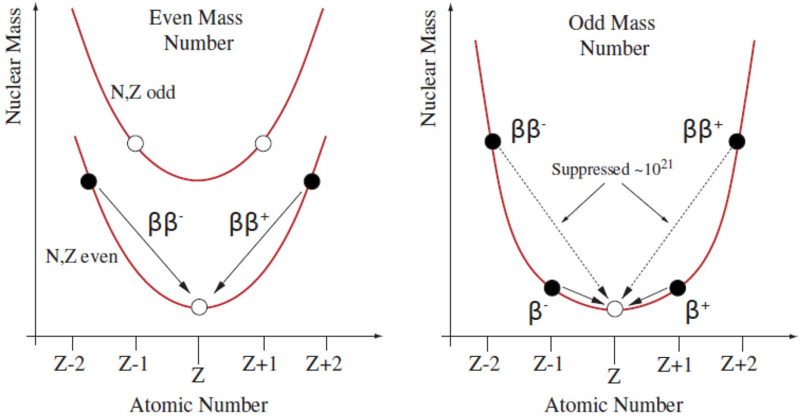
CUORE

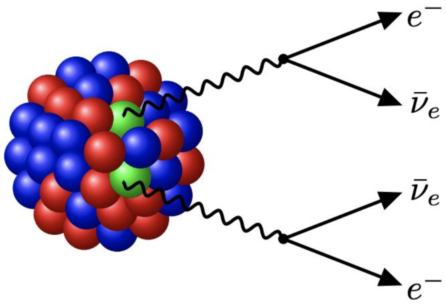
CUPID

SAPIENZA
UNIVERSITÀ DI ROMA

Double β Decay

Standard Model allowed double β decay: **2νββ**
- **Observed** in 11 even-even nuclei in which single β decay is energetically forbidden (very few possible candidates!)





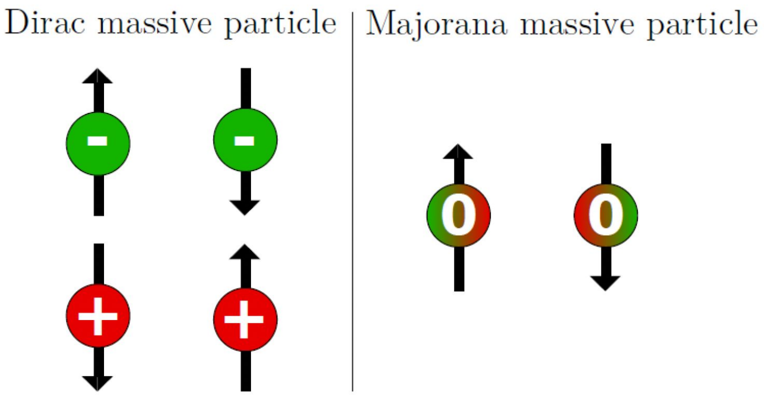
$T_{1/2}$ ~ 10^{18} - 10^{24} years (age of the universe ~ 1.4 × 10^{10} years!)

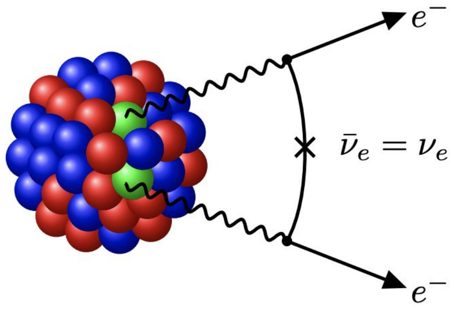
➔ means about equivalent number of candidate nuclides in the detector: tonne-scale experiment

Double β Decay

Neutrinoless Double β decay: **0νββ**

- **Massive neutrino** to flip the chirality (we know it's true because of flavor oscillations observation)
- **Majorana neutrino**: particle and antiparticle have to coincide

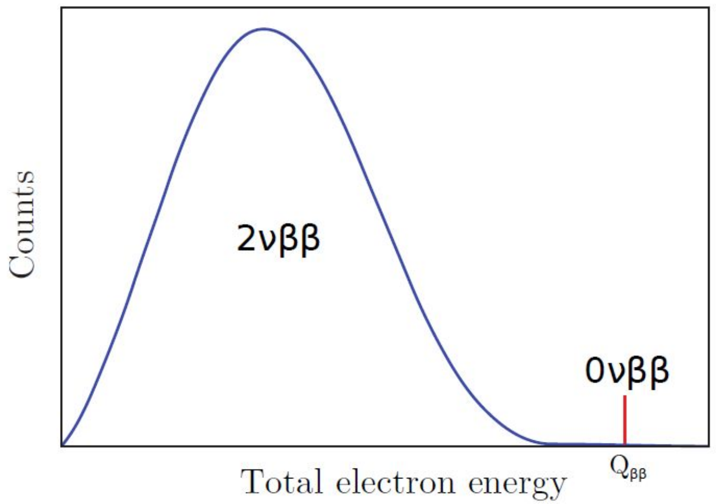




Total Lepton number violated of 2 units:

- not allowed in Standard Model
- Hint to explain lack of antimatter in the universe

Double β Decay



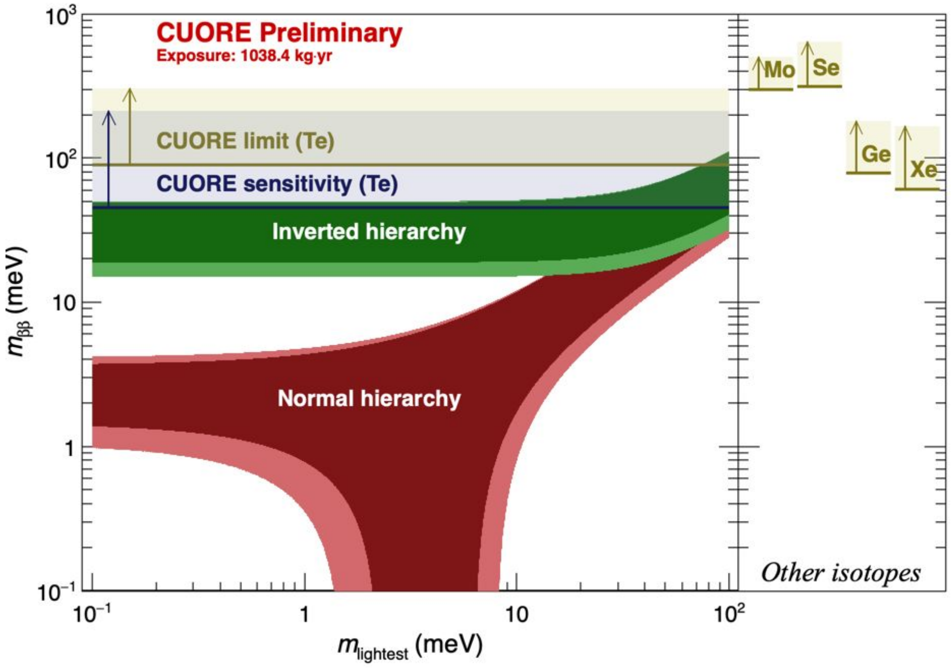
Standard Model allowed double β decay: **2νββ**

➔ 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!)

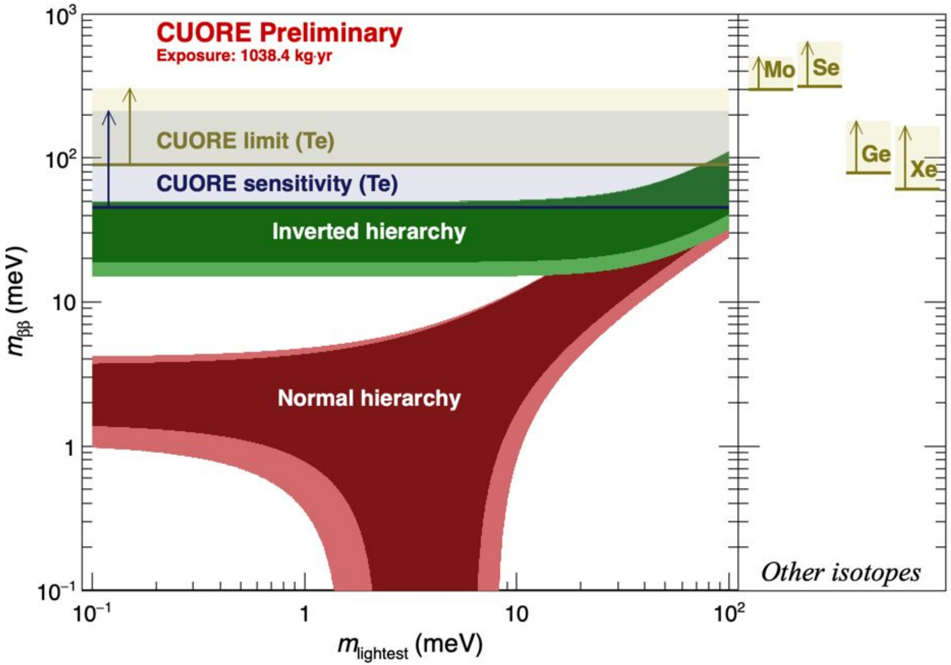
0νββ: where we are now



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

- 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

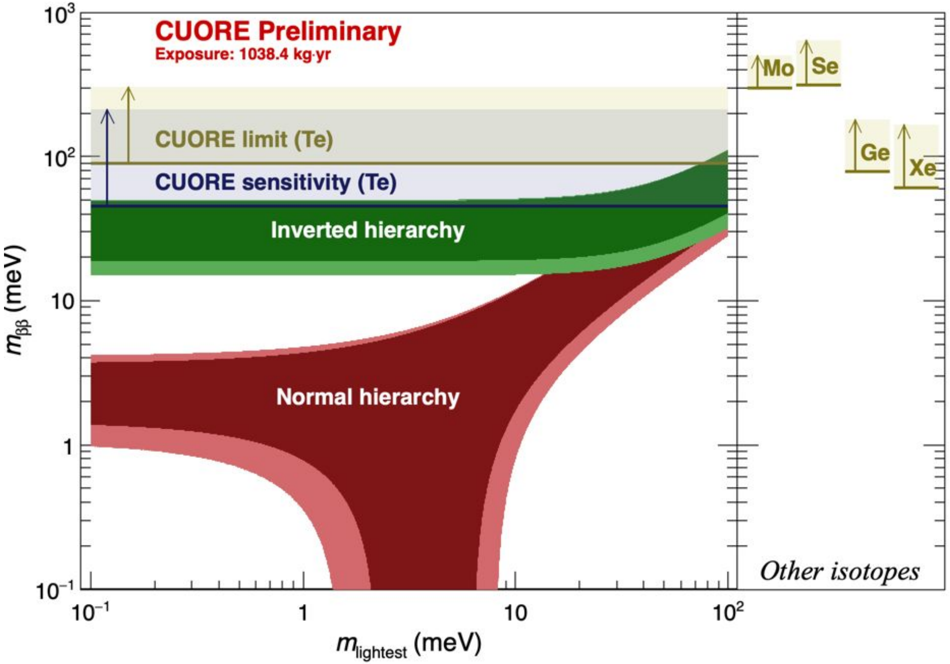


$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

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



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

Contributions from different experiments:

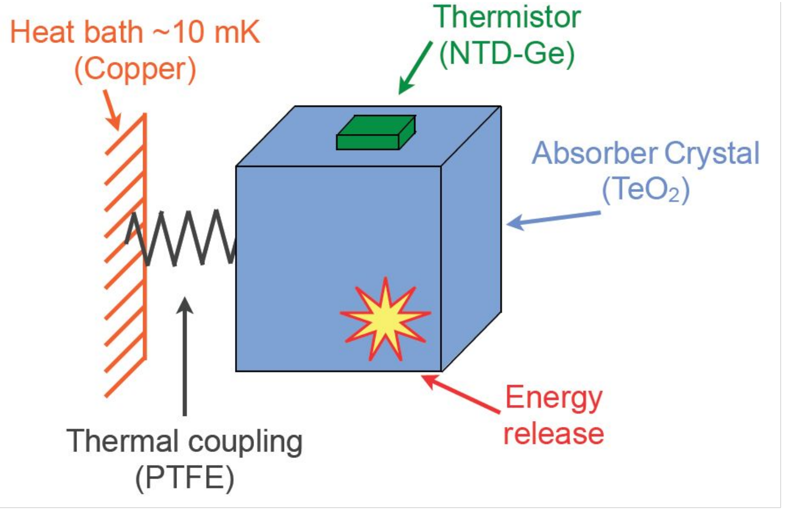
- ^{130}Te: CUORE
- ^{136}Xe: KamLAND-Zen
- ^{76}Ge: GERDA
- ^{82}Se: CUPID-0
- ^{100}Mo: CUPID-Mo

Cryogenic Calorimetric Experiments!

Cryogenic Calorimeters

Crystals containing the isotope candidate for the decay

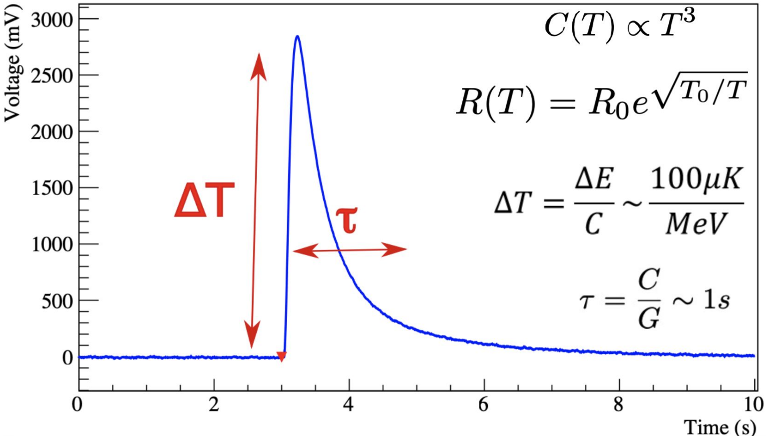
1. Energy release in the crystal from particle interaction
2. Energy converted into heat (i.e. temperature increase)



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 0νββ 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

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)

- 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)

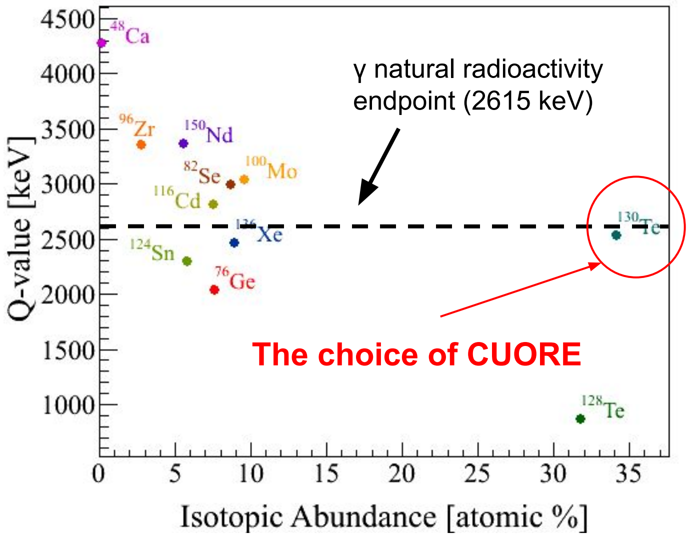
Cryogenic Calorimeters

These detectors perfectly fit to the $0\nu\beta\beta$ 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

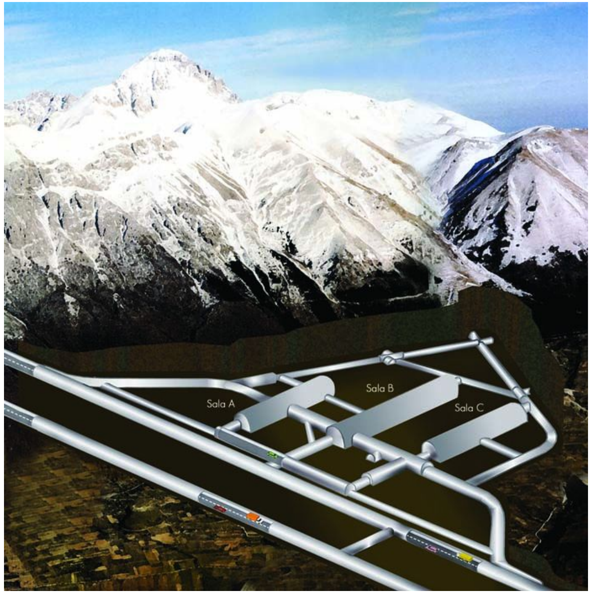


Cryogenic Calorimeters

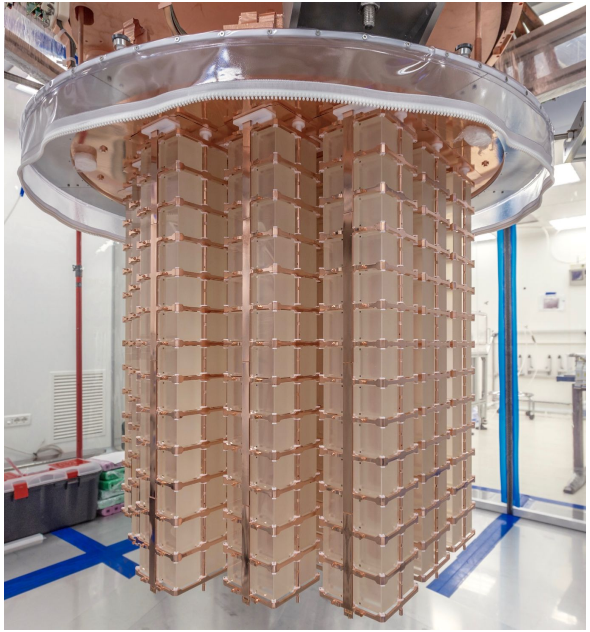
These detectors perfectly fit to the $0\nu\beta\beta$ search, presenting important features for the decay half-life sensitivity

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

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



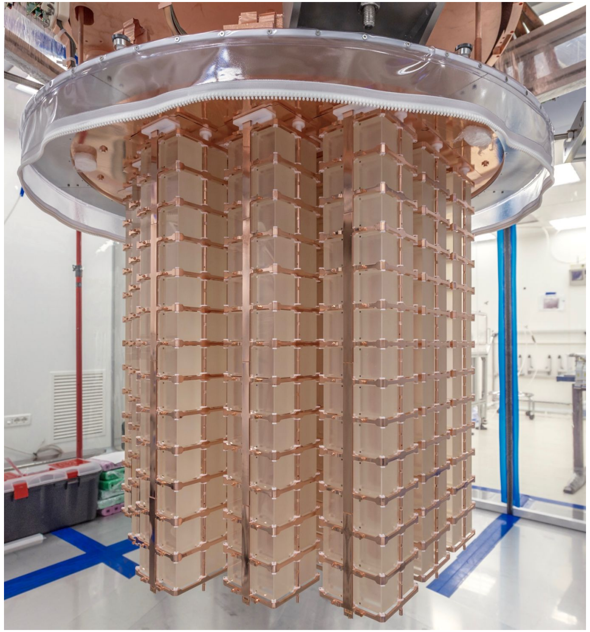
The CUORE Detector



Cryogenic
Underground
Observatory for
Rare
Events

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

The CUORE Detector



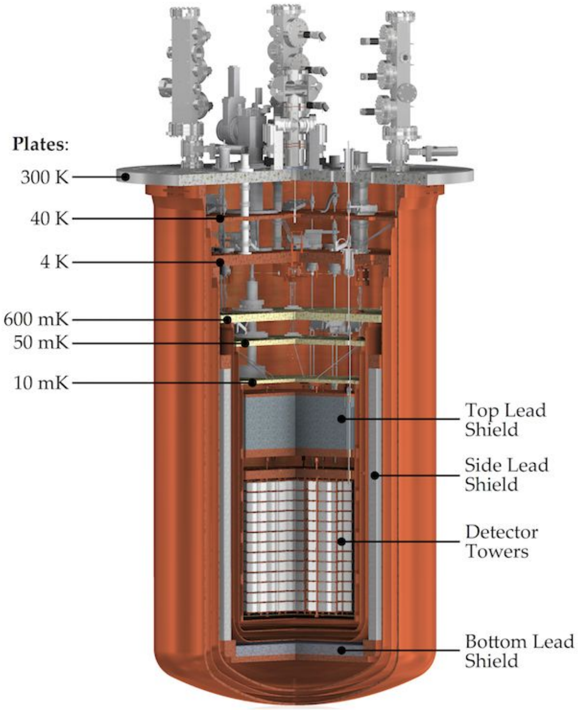
Cryogenic
Underground
Observatory for
Rare
Events

- ➔ MT > 1 ton x yr (unblinded!)
- ➔ $\Delta E < 8$ keV at $Q_{\beta\beta}$
- ➔ $\epsilon \sim 88$ %
- ➔ 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: $Q_{\beta\beta} \sim 2527$ keV, natural isotopic abundance 34%

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

The CUORE Cryostat



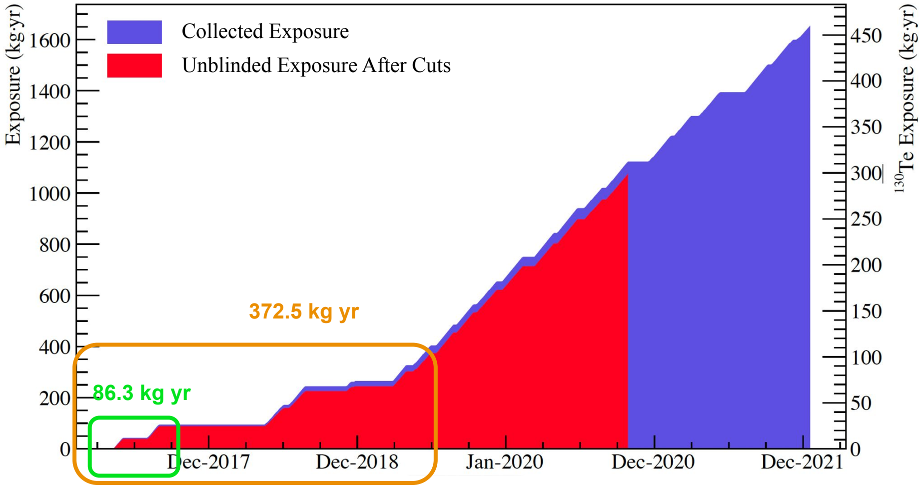
"The coldest cubic meter in the known universe": world leading cryostat in terms of power and size

- 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**

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

CUORE Data Taking



[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)
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)
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**

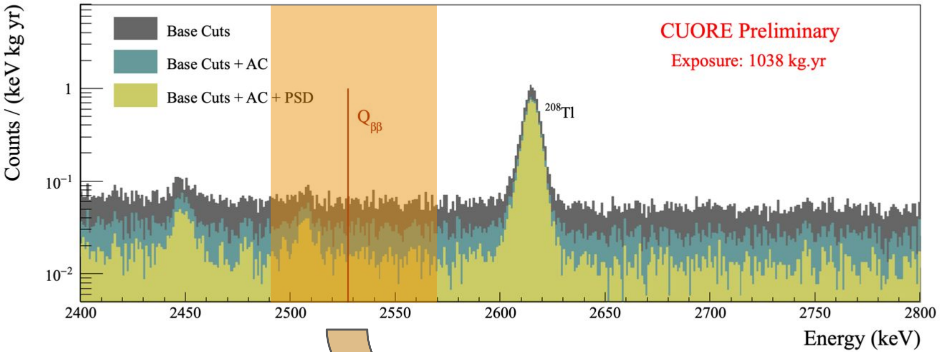
CUORE is the first tonne-scale cryogenic calorimetric experiment

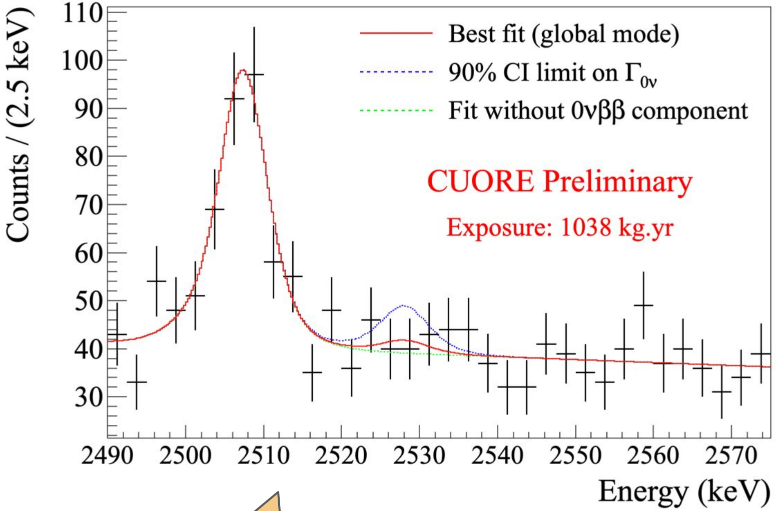
Searching for Neutrinoless Double-Beta Decay of 130Te with CUORE
https://doi.org/10.1155/2015/879871

0νββ Analysis

Fit the Region Of Interest to search the 0νββ:

➔ **Window**: [2490, 2575] keV





$0\nu\beta\beta$ Analysis

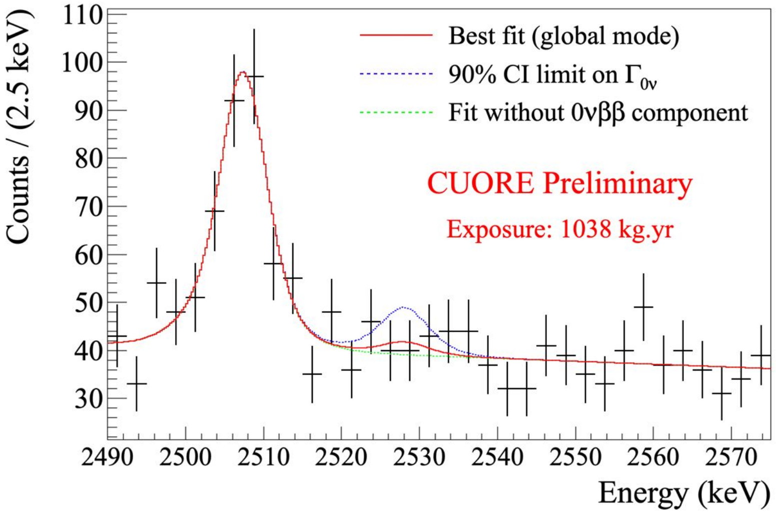
[High sensitivity neutrinoless double-beta decay search with one tonne-year of CUORE data](https://arxiv.org/abs/2104.06906)
https://arxiv.org/abs/2104.06906

Fit the Region Of Interest to search the $0\nu\beta\beta$:

➔ **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 $0\nu\beta\beta$ and ^{60}Co ($\Gamma_{0\nu}$, Γ_{Co}), Background Index and slope



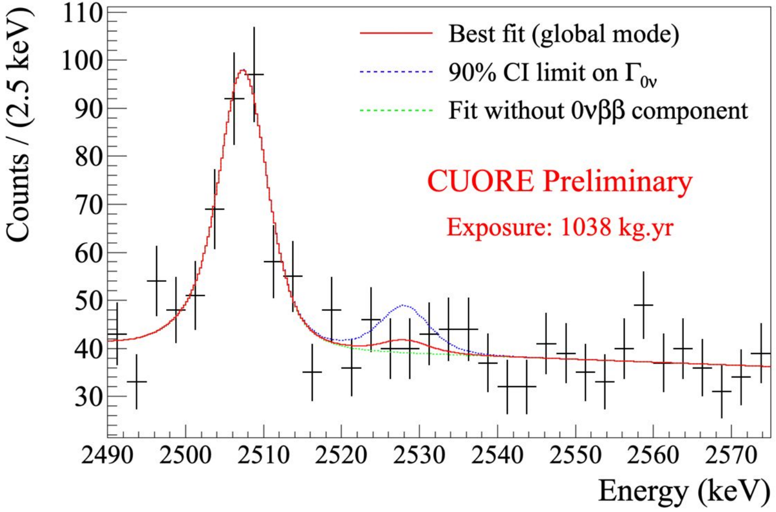
0νββ Analysis

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

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}



No significant Signal observed:

➔ **Set Limit from the posterior**

0νββ Analysis

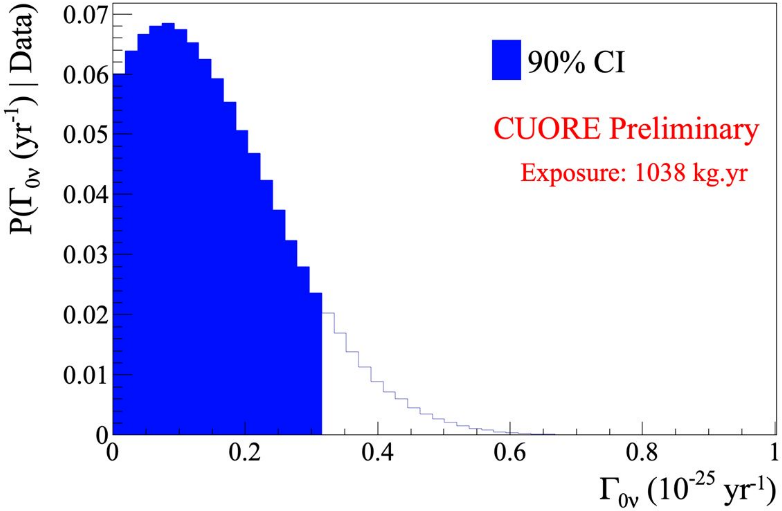
High sensitivity neutrinoless double-beta decay search with one tonne-year of CUORE data
https://arxiv.org/abs/2104.06906

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}

Half-life Limit of ^{130}Te 0νββ

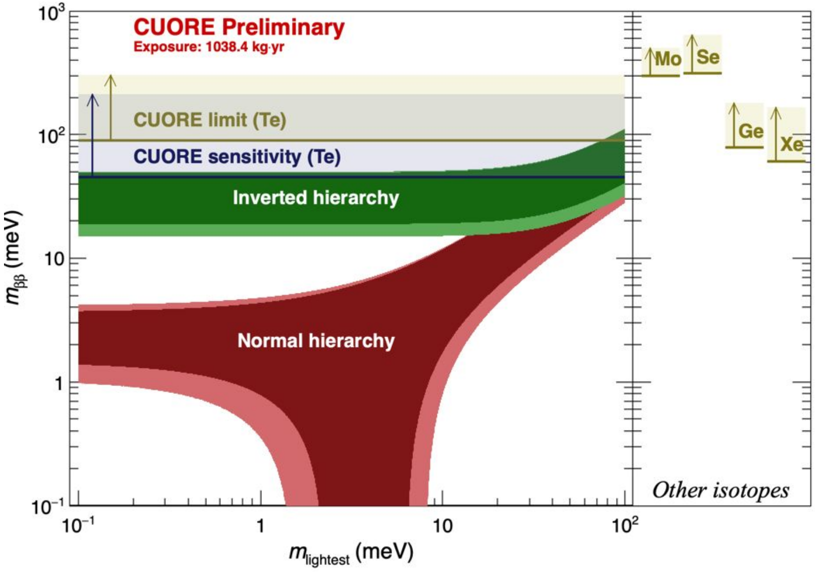
$$T^{0\nu}_{1/2} > 2.2 \times 10^{25}\ \mathrm{yr}\ (90\,\%\,\mathrm{C.I.})$$



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

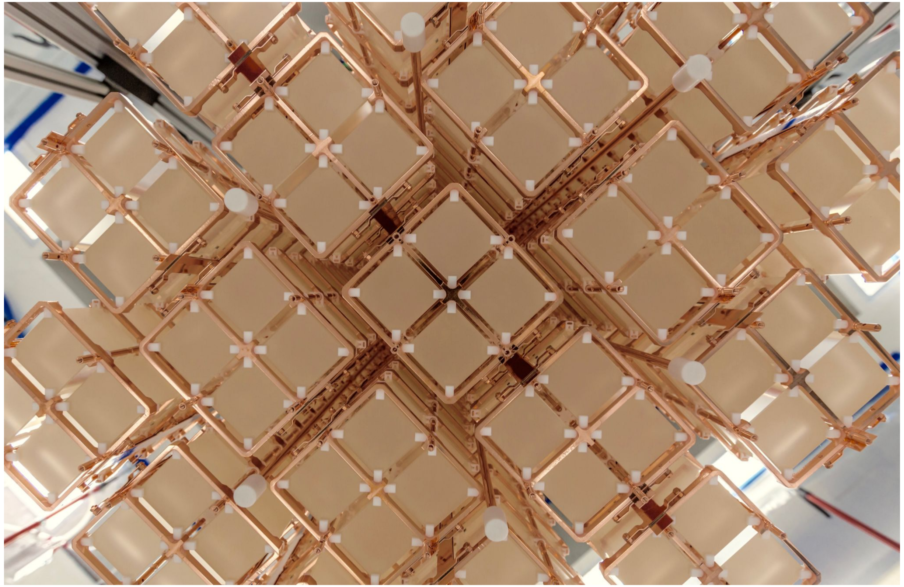
CUORE

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

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

Beyond 0νββ:

- **^{130}Te 2νββ precision measurement**
- **^{130}Te 0ν/2νββ to excited states**
- **^{128}Te 0ν/2νββ**
- **^{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

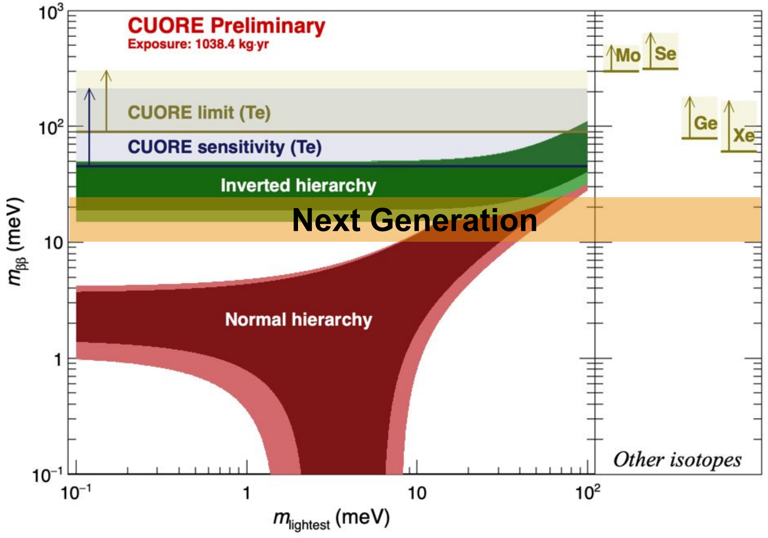
https://doi.org/10.1140/epjc/s10052-021-09317-z

Future of CUORE

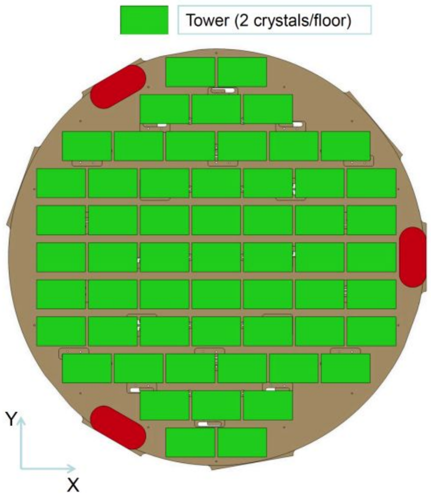
CUORE
Upgrade with
Particle
IDentification

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

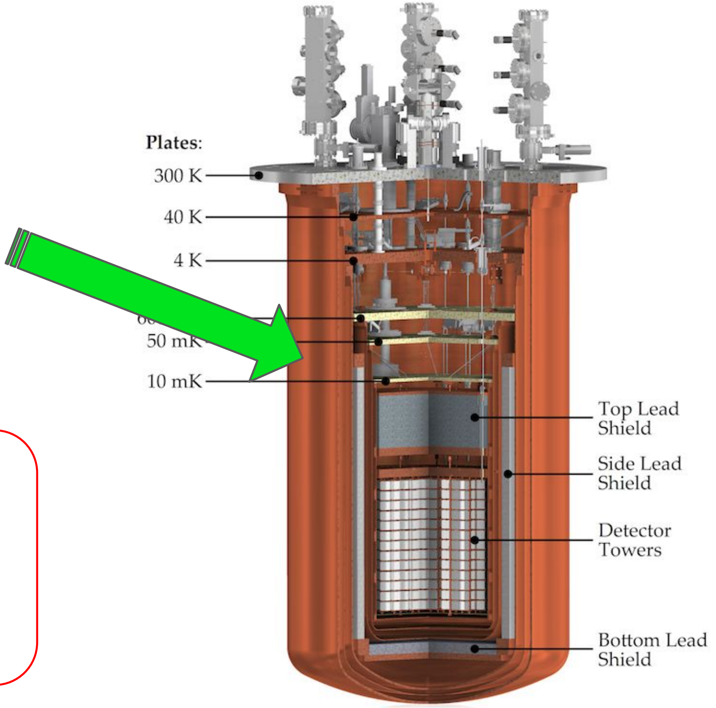


Future of CUORE



https://arxiv.org/abs/1907.09376

CUORE
Upgrade with
Particle
IDentification



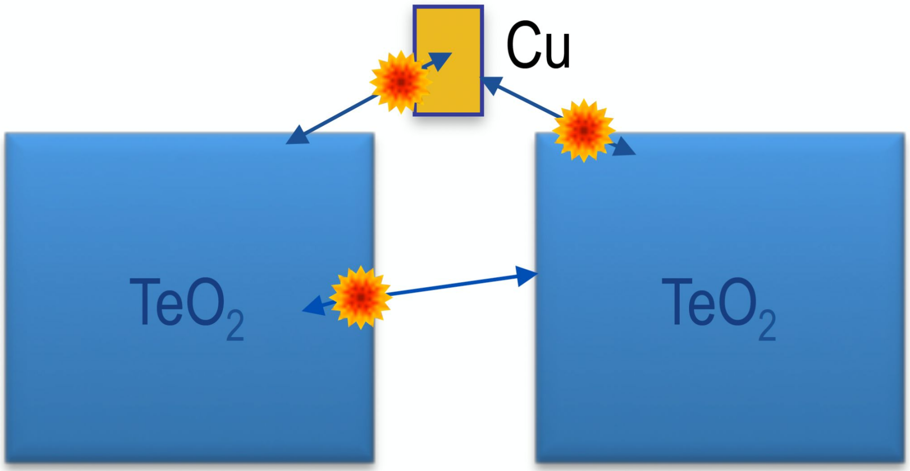
CUORE set a milestone for future cryogenic calorimetric experiments

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 from surface contamination (**e.g. from the copper structure or other crystals)

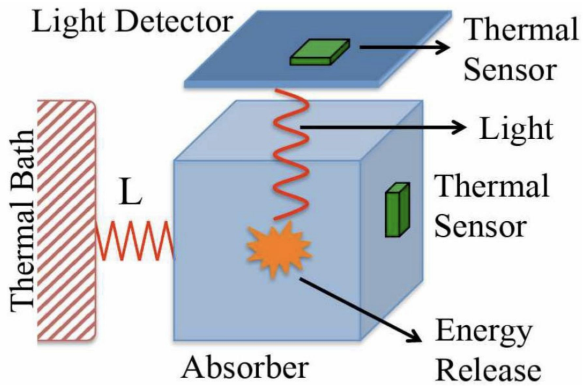


Release only a fraction of the energy in the crystal, falling in the ROI even if the α-decay Q value is higher (e.g. ^{210}Po in U/Th chain ha 5.4 MeV of Q value)

CUPID

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

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)



- Scintillating crystals containing the candidate isotope (ZnSe, Li_2MoO_4)
- Light detectors (LD) coupled to crystals: (thin Ge bolometers)

CUPID

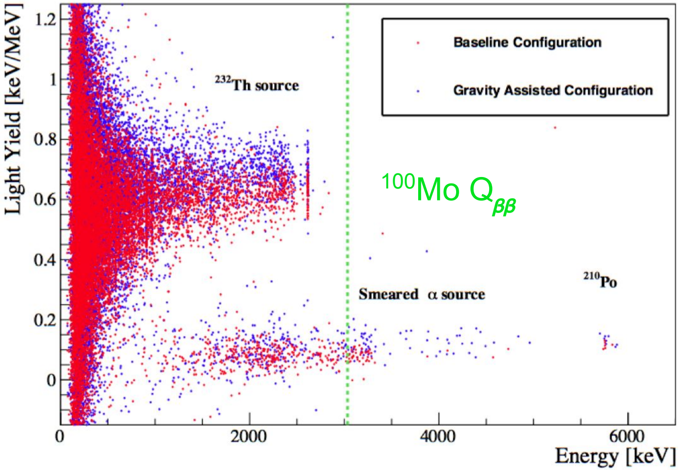
https://arxiv.org/abs/2202.06279

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

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)

Light Yield =
Energy from scintillation photons (LD)
/ Energy from heat (crystals)

α particles has a quenched number of scintillation photons produced in the crystal

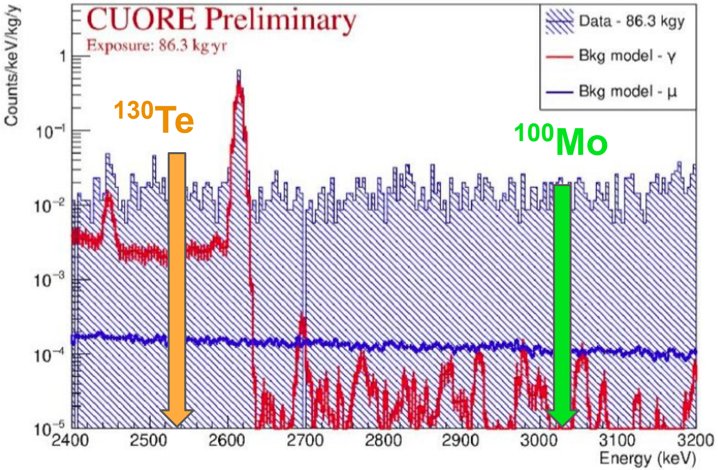


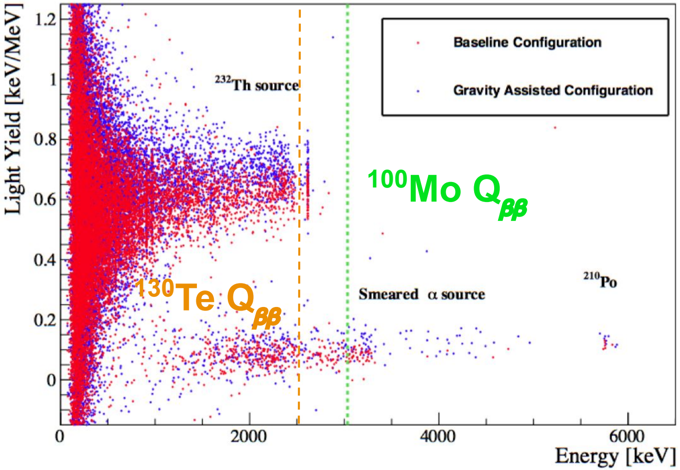
CUPID

https://arxiv.org/abs/2202.06279

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)



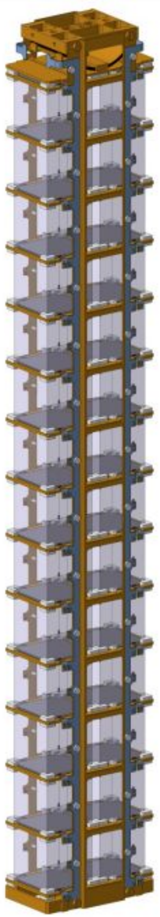


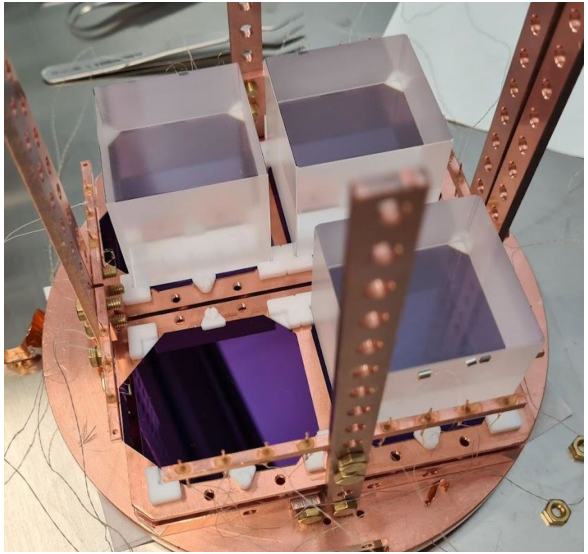
CUPID

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





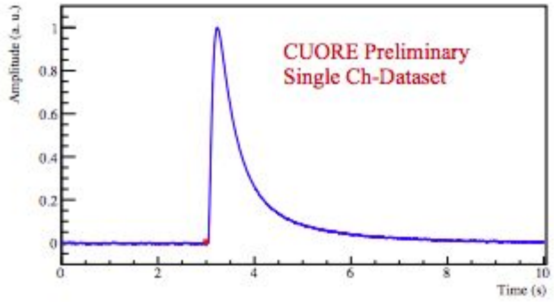
Thanks for your attention!

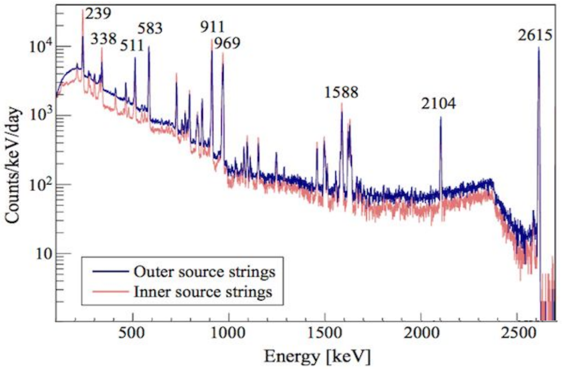
Alberto Ressa, PhD Seminars 27/04/2022

Istituto Nazionale di Fisica Nucleare

Backup Slides

CUORE Event Reconstruction





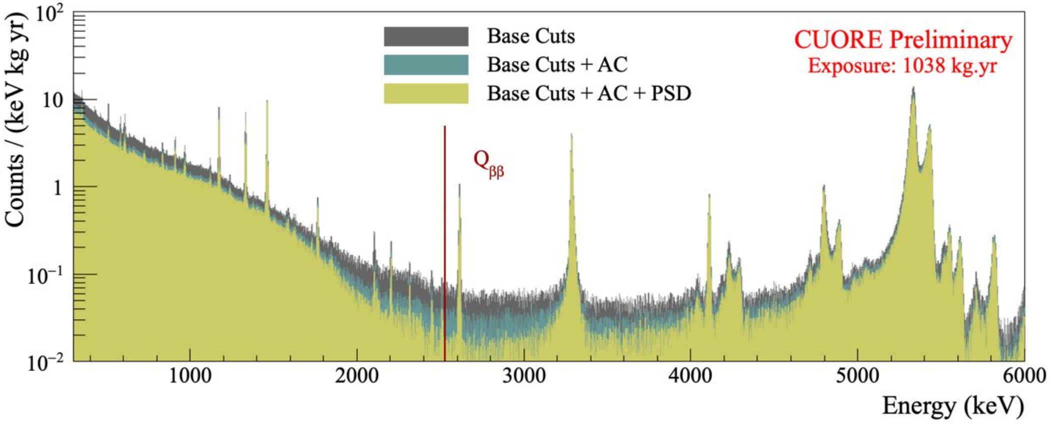
1. **Trigger**:
   Online + Offline to improve energy threshold

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

0νββ Analysis

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

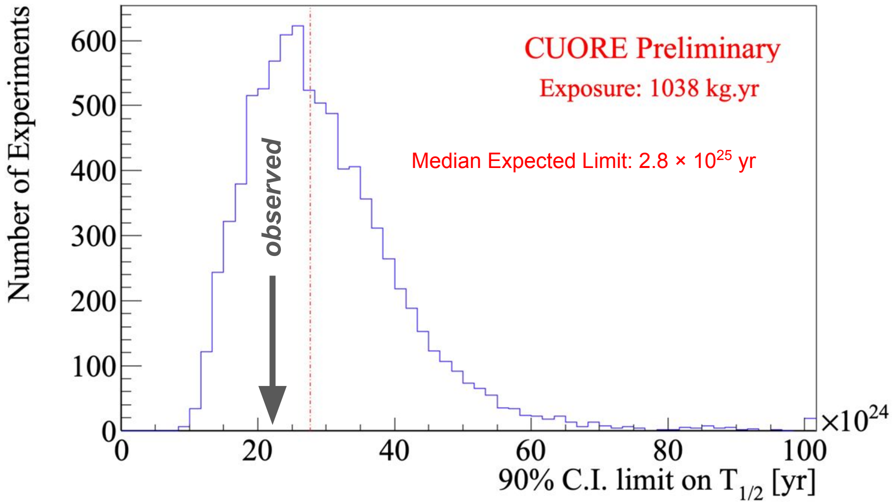
CUORE

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}

Half-life Limit of ^{130}Te 0νββ

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



Median Expected Sensitivity:

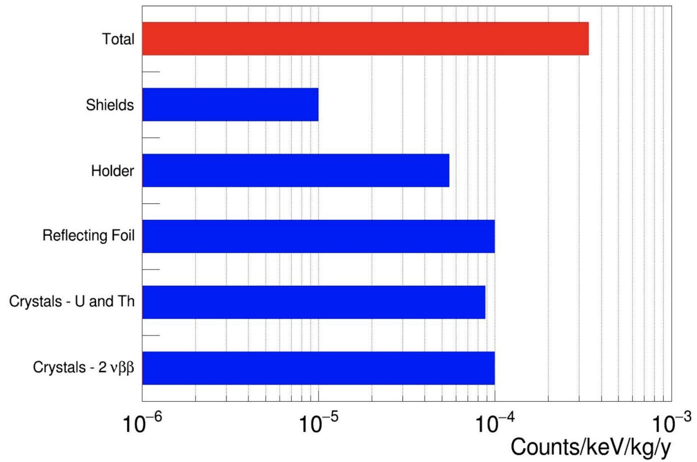
➔ **2.8 × 10^{25} year**
➔ evaluated from toy experiments in background-only hypothesis using real data fit results
➔ 72% of chance to obtain a stronger limit

CUPID

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

“Background-Free” Environment: the sensitivity grows linearly with the exposure!

Suppose **10 yr** of livetime, 5 keV of resolution, and 1 ton of material
CUORE 10^{-2} counts/ (kg keV yr) : 500 events
CUPID $<10^{-4}$ counts/ (kg keV yr) : <5 events



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