16TH TOPICAL SEMINAR ON INNOVATIVE PARTICLE AND RADIATION DETECTORS

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Latest results from the CUORE experiment

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On behalf of the CUORE collaboration

Scientific goal: search for 0νββ decay

Double beta (ββ) decay is a very rare radioactive decay where the charge of the nucleus changes by two units:

2νββ $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

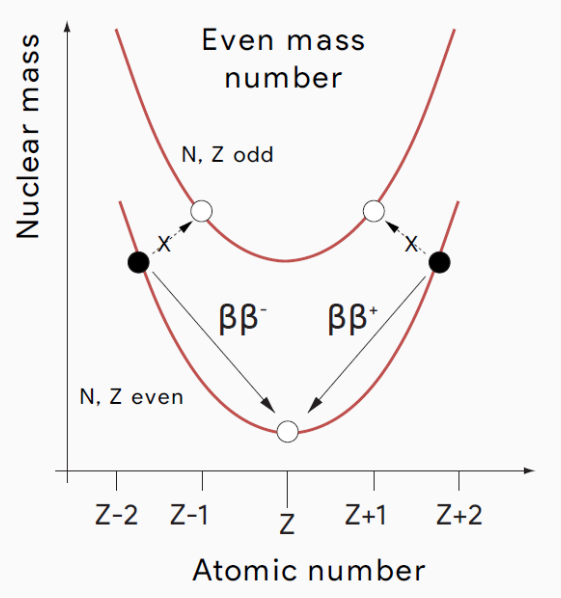
Allowed in the Standard Model and already observed for even-even nuclei (β decay is forbidden) with $T_{1/2} = 10^{18} - 10^{21}$ yr

0νββ $(A,Z) \rightarrow (A,Z+2) + 2e^-$

Forbidden by the Standard Model ($\Delta L = 2$) and, if exists, expected with $T_{1/2}^{0\nu} > 10^{25}$ yr

Gateway to **new physics** and key tool to study neutrinos:

- Lepton number violation (ΔL=2)
- Majorana or Dirac nature ($\nu = \bar{\nu}$ or $\nu \neq \bar{\nu}$)
- Insights on neutrino mass scale and ordering



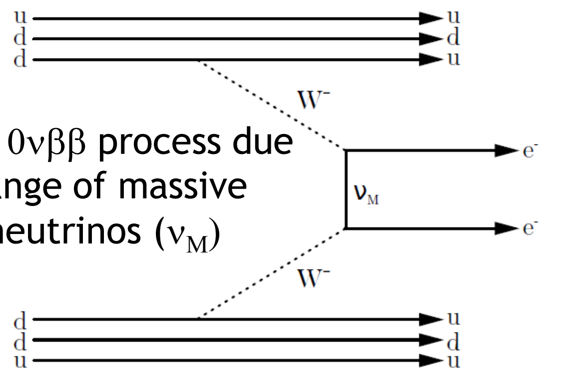


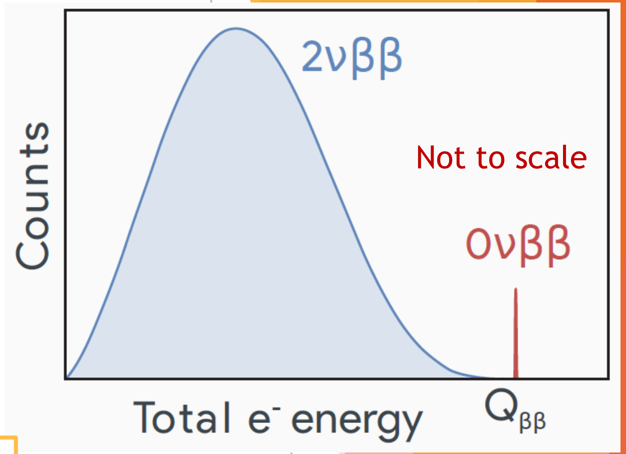
Diagram of the 0νββ process due to the exchange of massive Majorana neutrinos (ν_M)

Experimental search for 0νββ decay

- Detection of the energy of the 2 emitted e^-
- 0νββ signature: monochromatic peak at the Q-value of the decay ($Q_{\beta\beta}$)
- Observable:

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\,|\mathcal{M}|^2\,\left|m_{\beta\beta}\right|^2$$

$G_{0\nu}$ phase space factor
$\mathcal{M}$ nuclear matrix element
$m_{\beta\beta}$ effective Majorana mass



- In the case of the 0νββ peak observation

$$T_{1/2}^{0\nu} = \ln 2\left(\frac{\varepsilon\,T}{n_c}\right)N_{\beta\beta}$$

n_c peak counts
ε efficiency
T data taking time
$N_{\beta\beta}$ number of ββ decaying nuclides

If $T_{1/2}^{0\nu} = 10^{27}$yr
$N_{\beta\beta} = 10^4$ moles
$(M \sim 10^3$ kg)
↓
~ 4 decays/yr

- In the case of not null background, the **sensitivity** is defined as the maximum signal that can be hidden by a background fluctuation $n_B \propto \sqrt{B\,\Delta E\,M\,T}$, scales as:

$$S_{1/2}^{0\nu} \propto \left(\frac{\varepsilon\,T}{n_B}\right)N_{\beta\beta} \xrightarrow{N_{\beta\beta}\,\propto\,\eta\,M} S_{1/2}^{0\nu} \propto \varepsilon\,\eta\sqrt{\frac{M\,T}{B\,\Delta E}}$$

M detector mass
η isotopic abundance
ΔE energy resolution
B background index
→ counts/(keV × kg × yr)

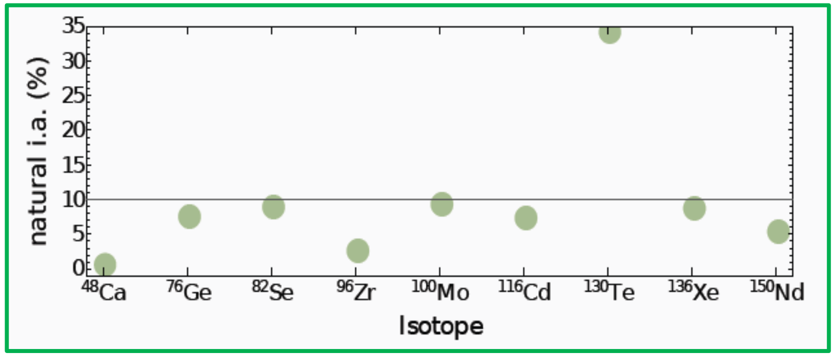
Features of 0νββ detectors

- High efficiency (ε)
  - → Source = Detector
- Large detector mass (M)
  - → Present: tens to several hundreds of kg
  - → Next generation experiments: ton scale to cover the inverted ordering region
- Long data taking time (T)
  - → Steady state operation
- High isotopic abundance (η)
  - → High natural η or enrichment
- Good energy resolution (ΔE)
- Extremely low background (B)
  - → Underground location + shielding
  - → Selection of radio-pure materials for detector and shields
  - → Background discrimination (analysis techniques, veto systems, …)

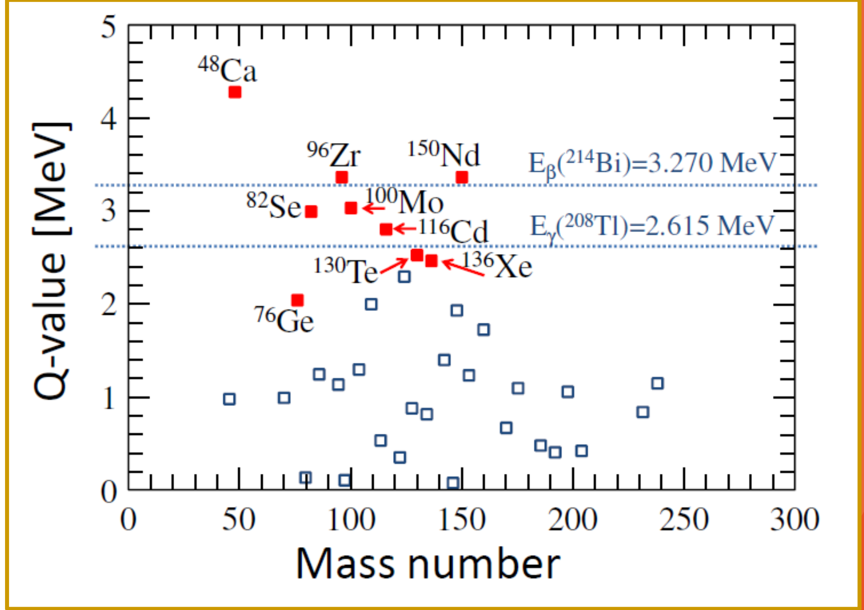
SENSITIVITY

$$S^{0\nu}_{1/2} \propto \varepsilon\, \eta \sqrt{\frac{M\,T}{B\,\Delta E}}$$

$$M\,T \equiv \text{exposure}$$



CHOICE OF THE NUCLIDE



Higher value of $Q_{\beta\beta}$ implies:

- Lower β/γ background in the ROI
- Higher $G_{0\nu}$ (proportional to a 5th degree polynomial in $Q_{\beta\beta}$)

Cryogenic calorimeters

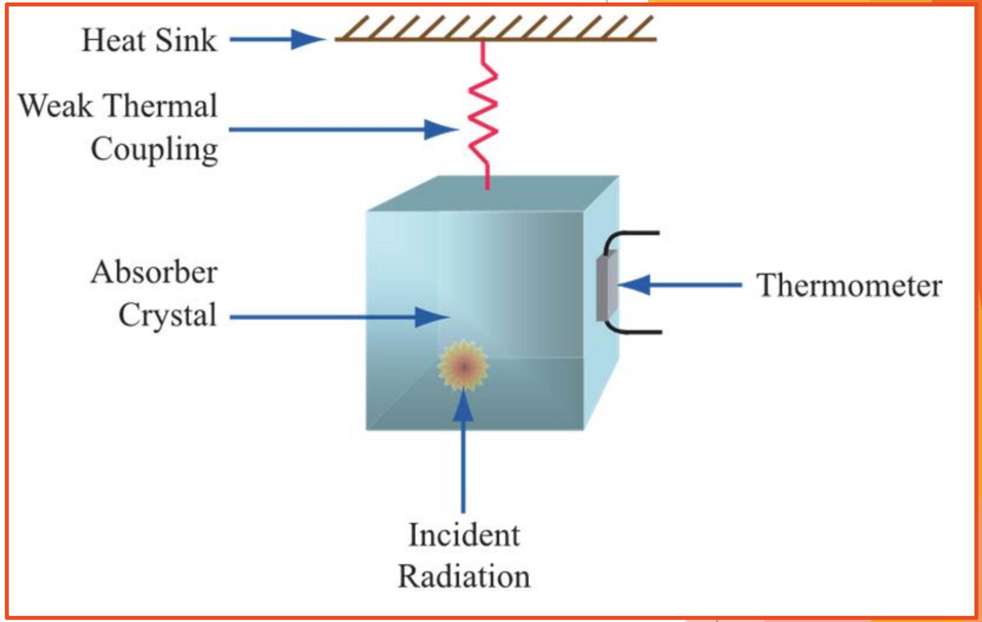
- Cryogenic calorimeters (also called *bolometers*) are detectors capable to measure the energy deposited by a single particle interaction:

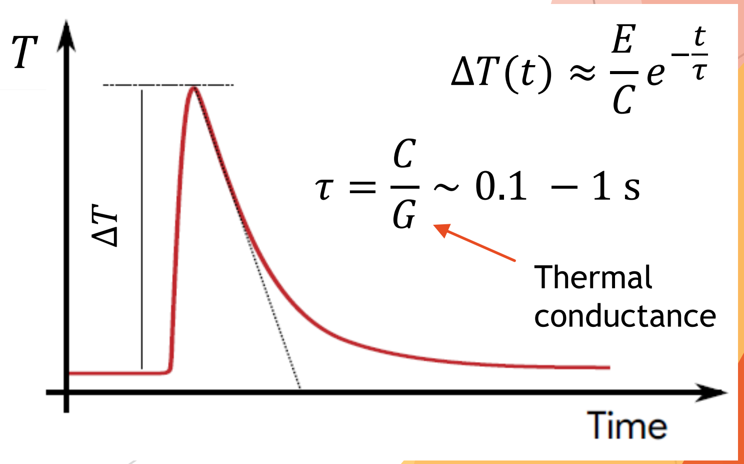
$$\Delta T \propto \frac{E}{C}$$

- Absorbers with very low thermal capacity (C) are needed to get measurable ΔT signals.
- At low temperatures, C of dielectric and diamagnetic crystals follows the Debye's law:

$$C \propto \left(\frac{T}{T_D}\right)^3 \Rightarrow$$ Very low temperature (of the order of $10\ \mathrm{mK}$) is needed

- A thermometer is coupled to the absorber to convert ΔT into an electrical signal.





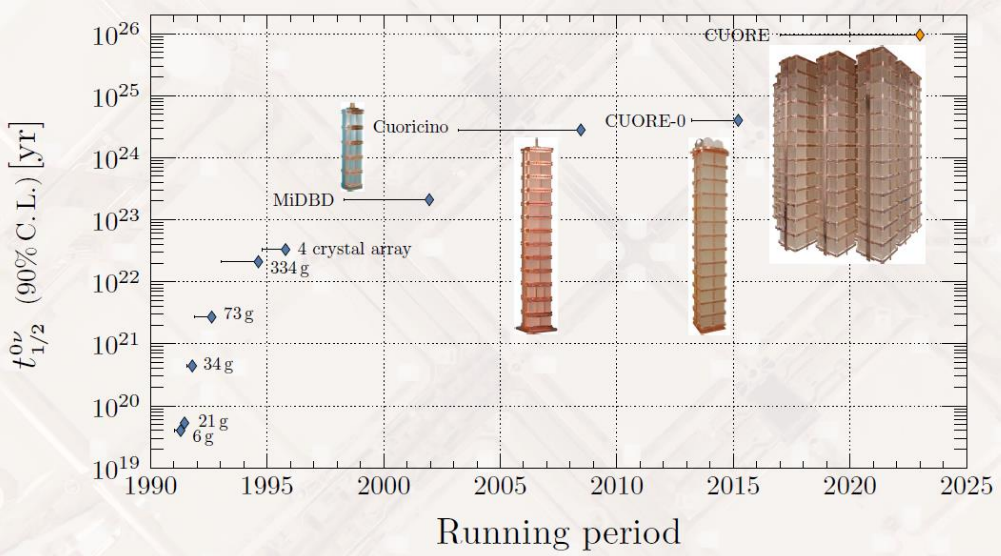
TeO_2 cryogenic calorimeters

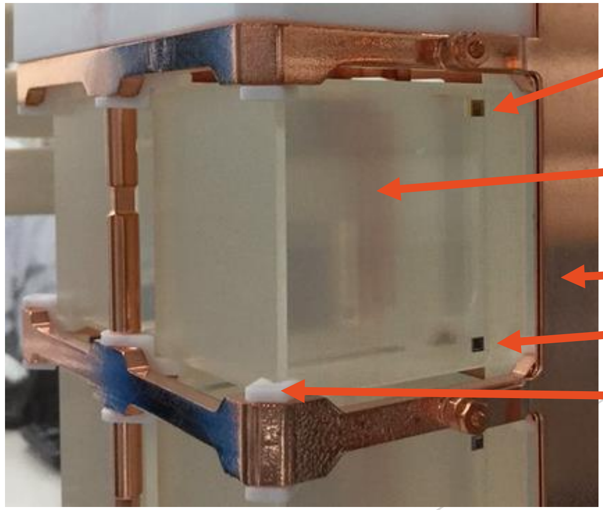
- Searched $0\nu\beta\beta$ decay: $^{130}\mathrm{Te} \rightarrow {}^{130}\mathrm{Xe} + 2e^-$
  - $Q_{\beta\beta} = 2527.5$ keV → just below the endpoint of the main natural γ background
  - High natural $\eta = 34.2$ % → no need for enrichment
- Absorber: $\mathrm{TeO_2}$ crystals
  - Big crystals with low radioactive contaminations can be grown
  - Good mechanical properties
  - Low heat capacity (dielectric and diamagnetic)

$$C \simeq \mathrm{nJ/K} \text{ at } T \simeq 10 \text{ mK} \quad \Rightarrow \quad \frac{\Delta T}{E} \sim \frac{0.1 \text{ mK}}{\text{MeV}}$$

- Thermometer: Neutron Transmutation Doped (NTD)
  - Germanium crystal doped through neutron irradiation
  - Electrical resistance dependent on temperature:

$$R(T) = R_0 \exp\left(\sqrt{T_0/T}\right) \qquad R_0 \sim 1\ \Omega \quad T_0 \sim 4\ \mathrm{K}$$





- Thermometer: NTD Ge thermistor
- Absorber: $\mathrm{TeO_2}$ crystal $5 \times 5 \times 5$ cm^3
- Heat sink: Cu structure
- Si heater (reference pulses)
- Thermal link: PTFE holders and gold wires

The CUORE detector

Cryogenic Underground Observatory for Rare Events

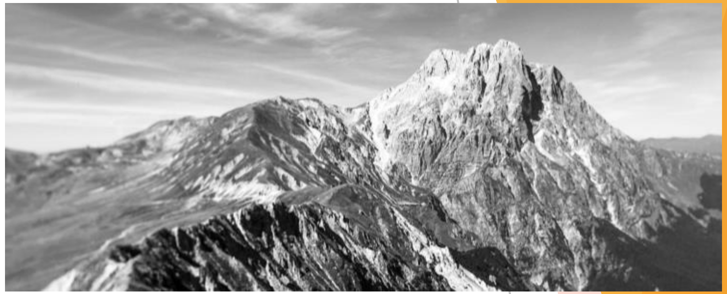
- Largest bolometric detector ever built
- Closely packed modular array of 988 $\mathrm{TeO_2}$ bolometers arranged in 19 towers.
- Mass of $\mathrm{TeO_2}$: $742\ \mathrm{kg}$ ($206\ \mathrm{kg}$ of $^{130}\mathrm{Te}$)
- $0\nu\beta\beta$ containment efficiency: $\varepsilon = 88.35(9)\%$ (Monte Carlo)

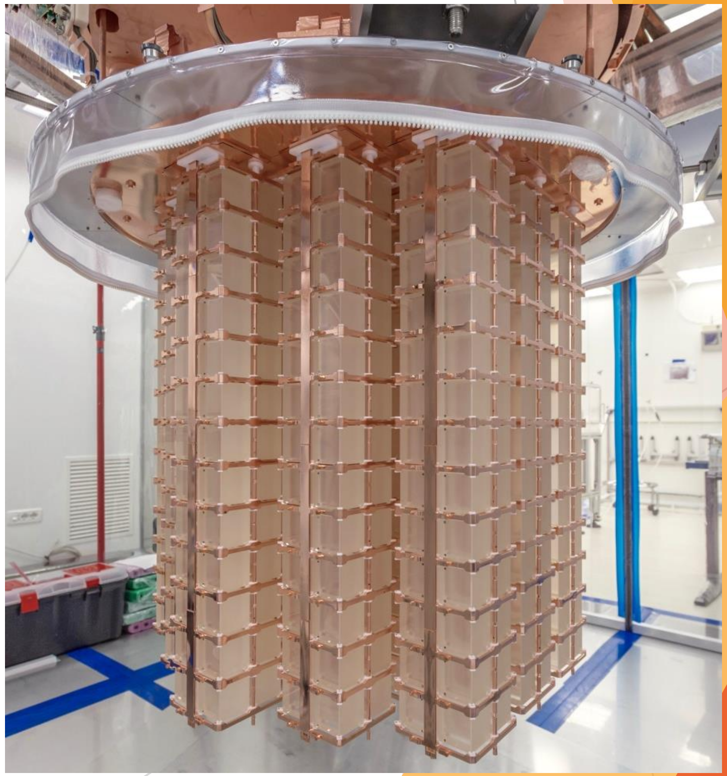
DESIGN PARAMETERS

- Energy resolution: $\mathrm{FWHM} = 5\ \mathrm{keV}$ at $\mathrm{Q}_{\beta\beta}$
- Low background: $10^{-2}\ \mathrm{counts/(keV \times kg \times yr)}$
  - Located at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, 1400 m of rock (~3600 m.w.e.)
  - Strict radiopurity controls
  - Passive shielding

CUORE projected sensitivity (5 years, 90% C.L.):

$$T_{1/2}^{0\nu} > 9 \times 10^{25}\mathrm{yr}$$



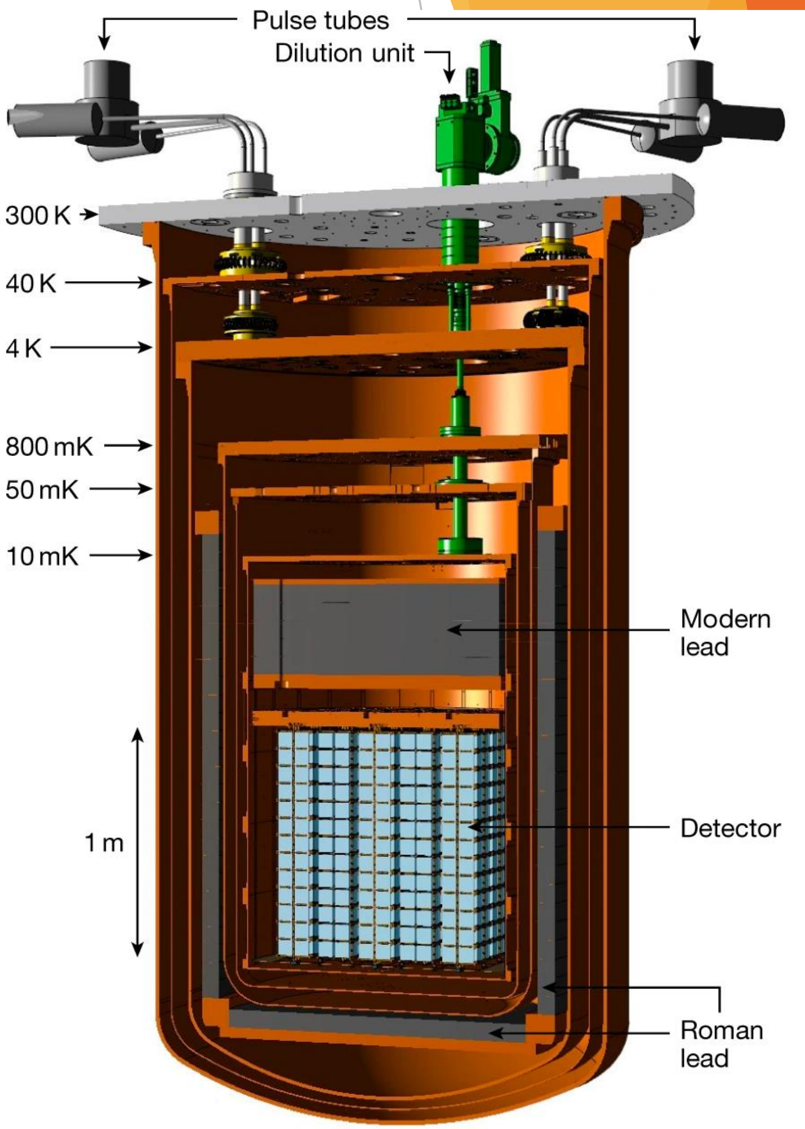


The CUORE cryostat

- Technological challenge and outstanding achievement
- Primary goal: cool down ~1 ton of material @10 mK and keep it stable in low noise environment for 5-10 years

Design parameters

- Cryogen-free cryostat
- 5 pulse tubes cryocooler to 4 K
- Dilution refrigerator to operating temperature ~10 mK
- Nominal cooling power: $4\ \mu W$ @10 mK
- System total mass including room temperature lead shield ~100 tons
- Mass to be cooled < 4 K: ~15 tons
- Mass to be cooled < 50 mK: ~3 tons (Pb, Cu and TeO_2)
- Mechanical decoupling for low vibrations
- Low background materials



Signal processing (offline)

1. **Denoising**

   Remove noise from the continuous data stream through decorrelation algorithms using data from auxiliary devices (accelerometers, antennae, microphones)

2. **Amplitude evaluation**

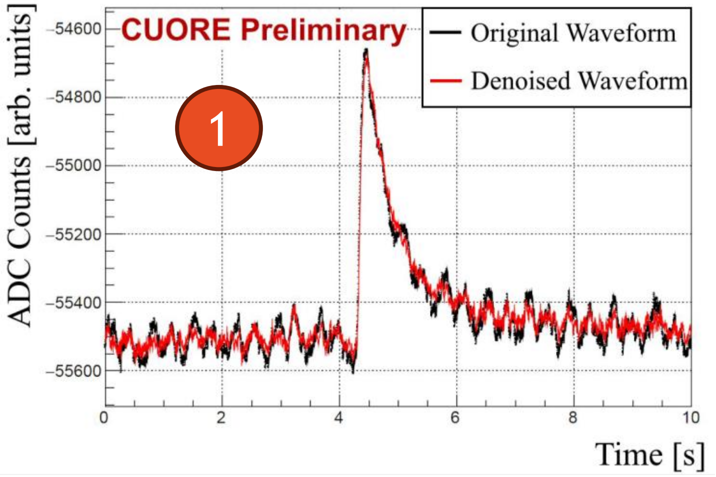
   Digital filter that maximizes the signal-to-noise ratio to estimate the pulse amplitude $A(T, E) = G(T)\, B(E)$

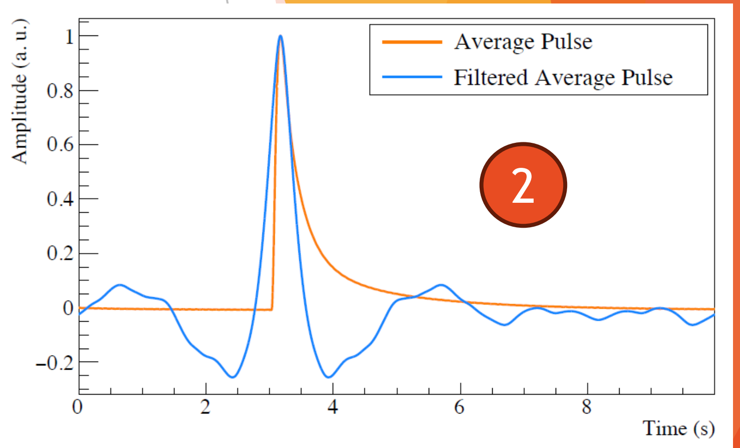
3. **Thermal gain stabilization**

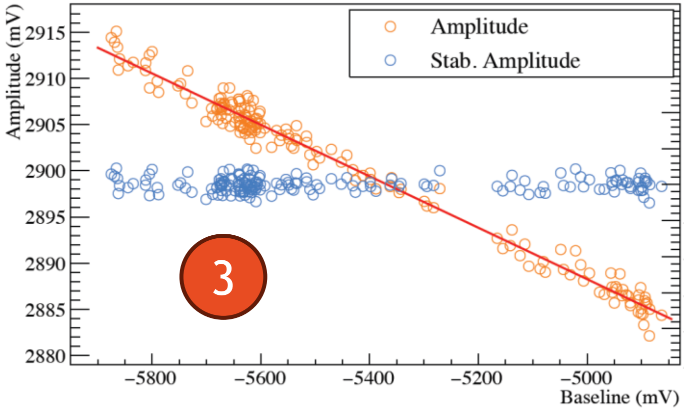
   Based on standardized heat (or energy) pulses to stabilize the amplitude against temperature drifts of the detector

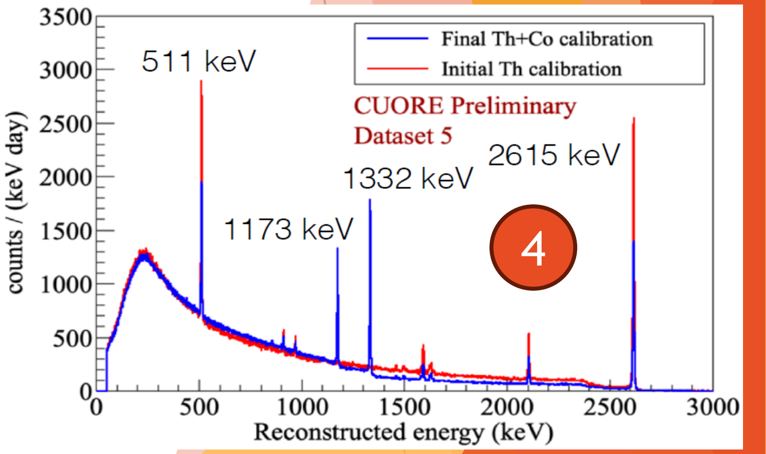
4. **Calibration**

   Determine $B(E)$ through dedicated runs with ^{232}Th and ^{60}Co sources at the beginning/end of each physics dataset



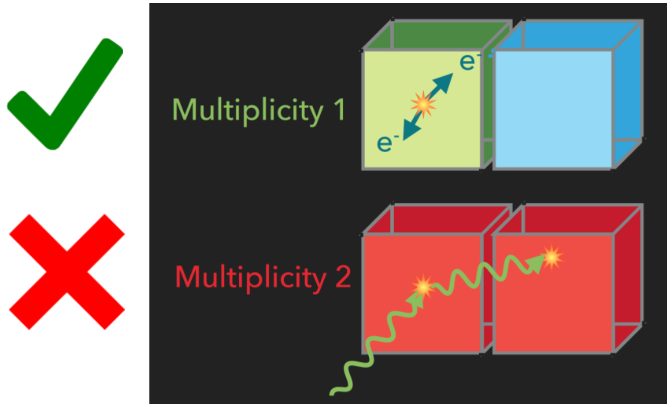


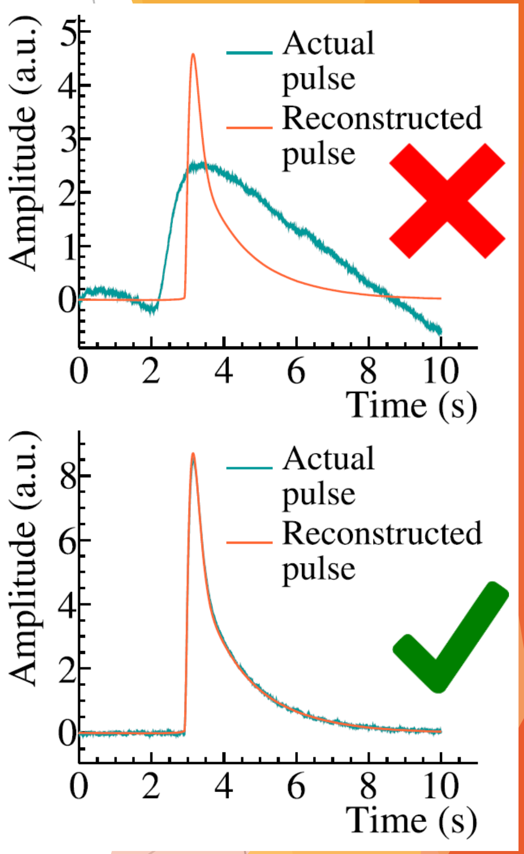


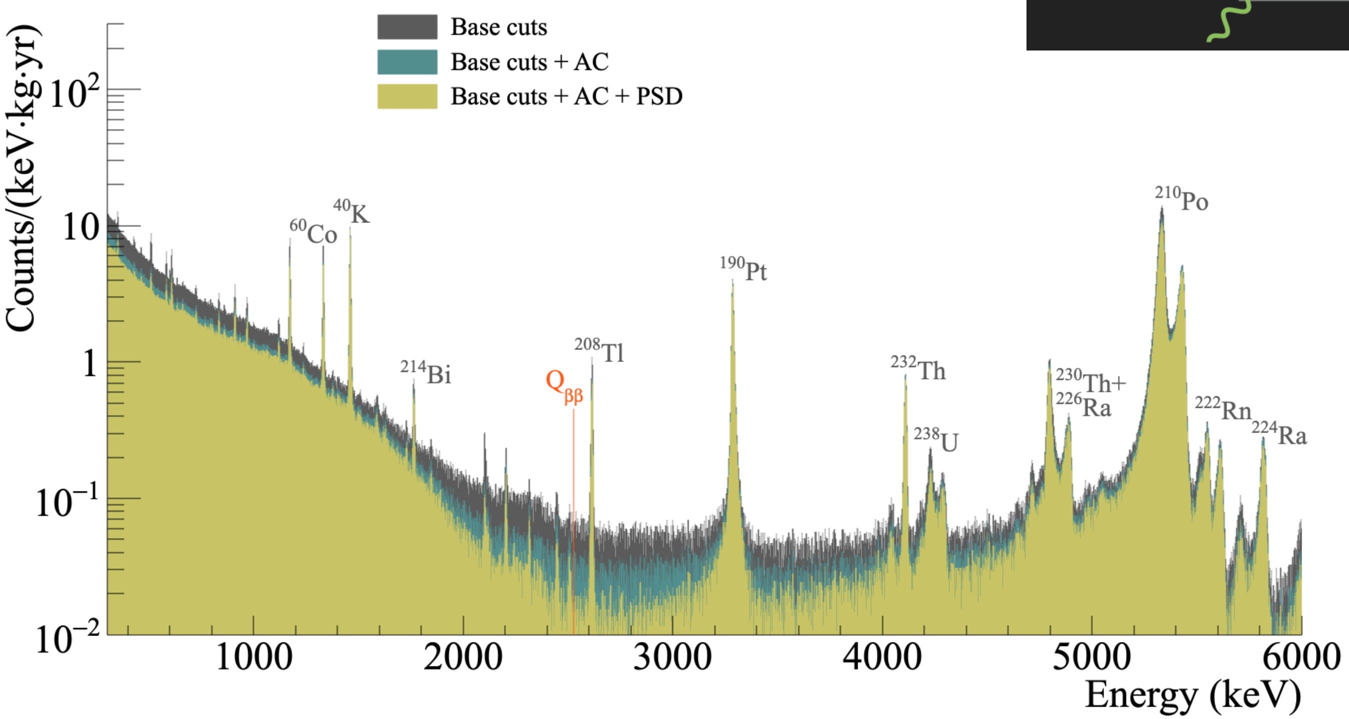


Data selection

- **Anticoincidence (AC)**: reject background events simultaneously triggering more than one crystal
- **Pulse Shape Discrimination (PSD)**: principal component analysis to reject spurious pulses (pile-up, non-physical shape, …)

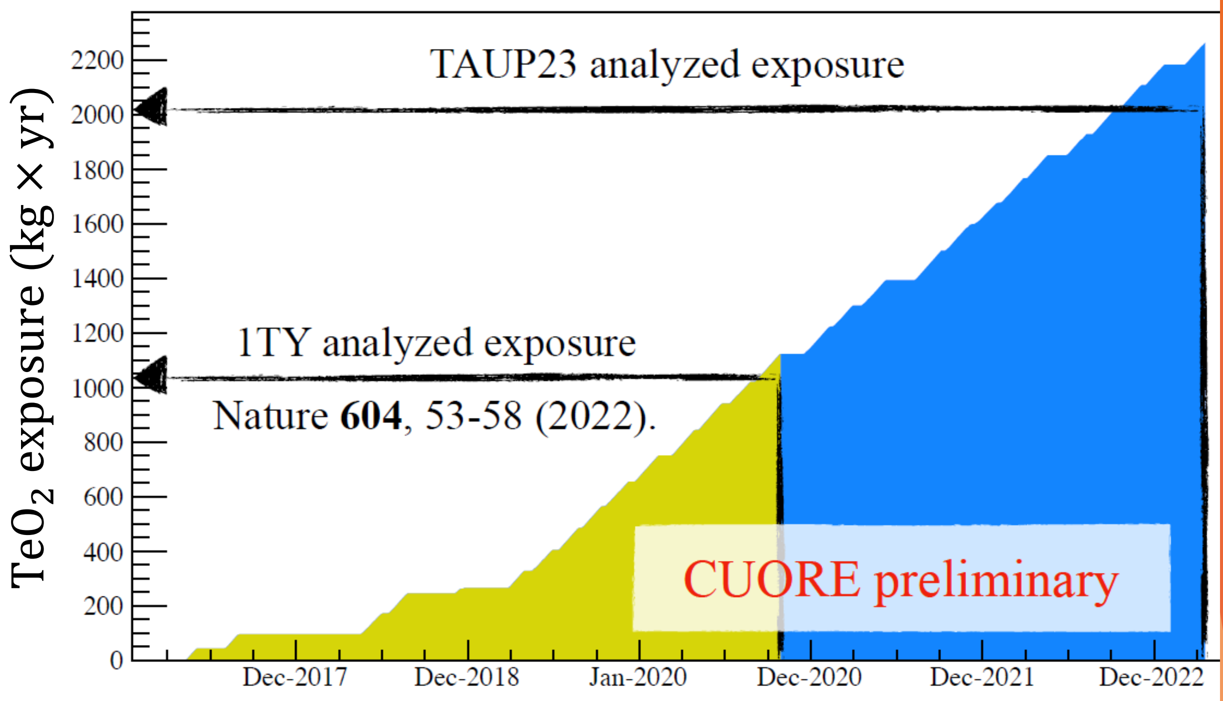


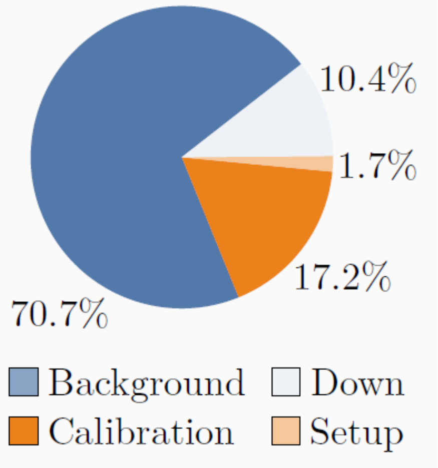




CUORE data taking and performance

- Start of data taking in April 2017, followed by an initial period of detector optimization
- 99.5% active channels (984/988)
- $\sim$ 90% duty cycle since 2019, with an average exposure increase of $\sim 50\ \text{kg} \times \text{yr}$ per month
- $\sim$1 ton $\times$ yr last published data release
- $>$ 2 ton $\times$ yr collected, new data release presented last month at the TAUP 2023 conference





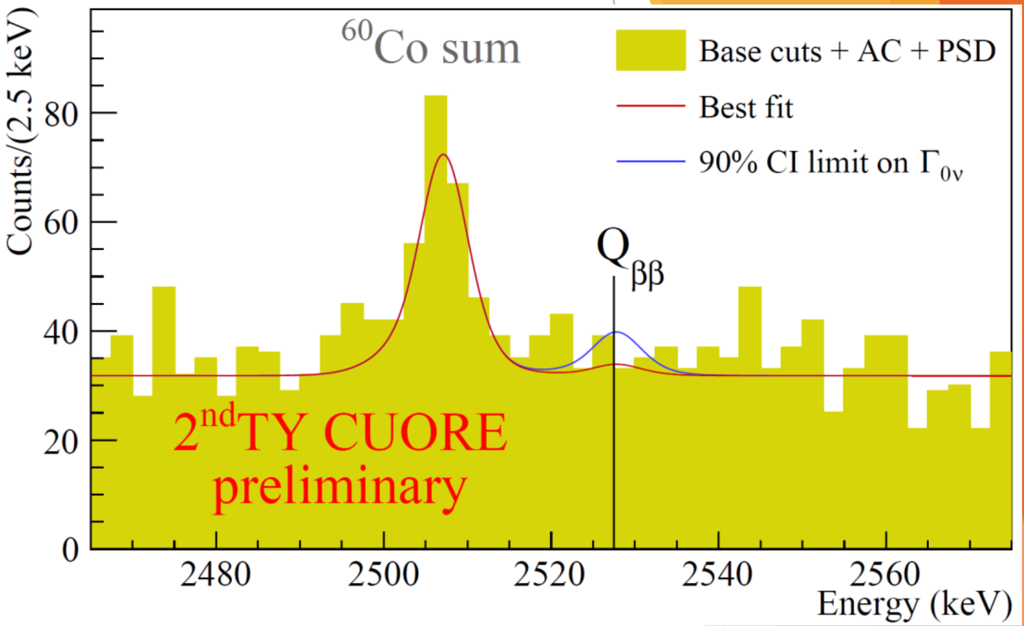
Parameter	1^{st} ton $\times$ yr	2^{nd} ton $\times$ yr
ΔE (FWHM)	(7.8 ± 0.5) keV	(7.3 ± 0.5) keV
B at $Q_{\beta\beta}$ (*)	$(1.49 \pm 0.04) \times 10^{-2}$ ckky	1.3×10^{-2} ckky
Selection ε	$(92.4 \pm 0.2)\%$	93.2%

(*) ckky $\equiv$ counts/(keV $\times$ kg $\times$ yr)

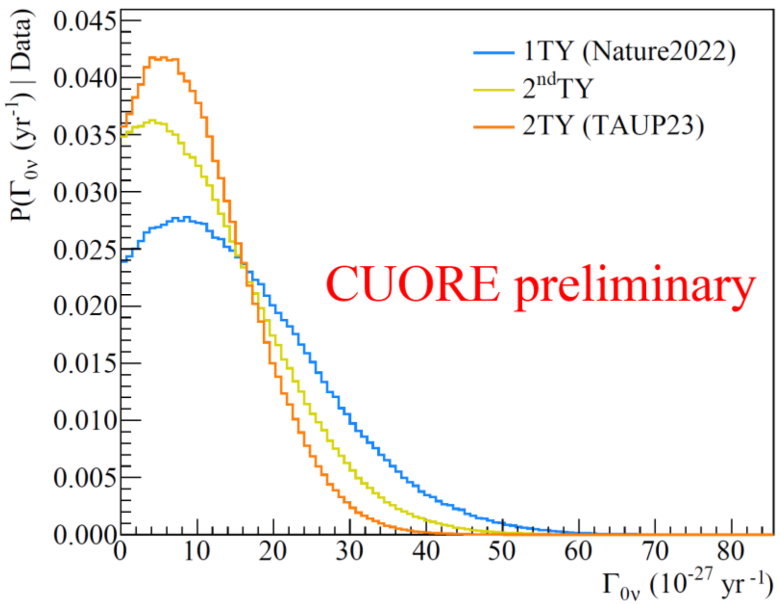
Latest results from CUORE

- **No evidence for $0\nu\beta\beta$ decay**
- We run an unbinned Bayesian fit with uniform non-negative priors on background and decay rates to set a limit on $T^{0\nu}_{1/2}$
- The fit function has 3 components:
  - a posited peak at the $Q_{\beta\beta}$ of ^{130}Te
  - a peak to account for the ^{60}Co sum gamma line
  - a constant continuum background

ROI: $[2465 - 2575]$ keV



$$\Gamma_{0\nu} \equiv \frac{\ln(2)}{T^{0\nu}_{1/2}}$$



Combining the $\Gamma_{0\nu}$ Posterior from the 2^{nd} ton $\times$ yr (TY) data analysis with that from the 1^{st} ton $\times$ yr (Nature 604, 53-58 (2022))

$$T^{0\nu}_{1/2} > 3.3 \times 10^{25}\ \text{yr}\ (90\%\ C.I.)$$

Exposure: 2.023 ton $\times$ yr

Beyond CUORE…

Current CUORE limit:
$m_{\beta\beta} < 75 - 255$ meV

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

- Next generation experiments aim at discovering the $0\nu\beta\beta$ decay if $m_{\beta\beta} > 10$ meV, to fully explore the *inverted ordering* region.
- For this purpose, the background in the ROI must be reduced so that:

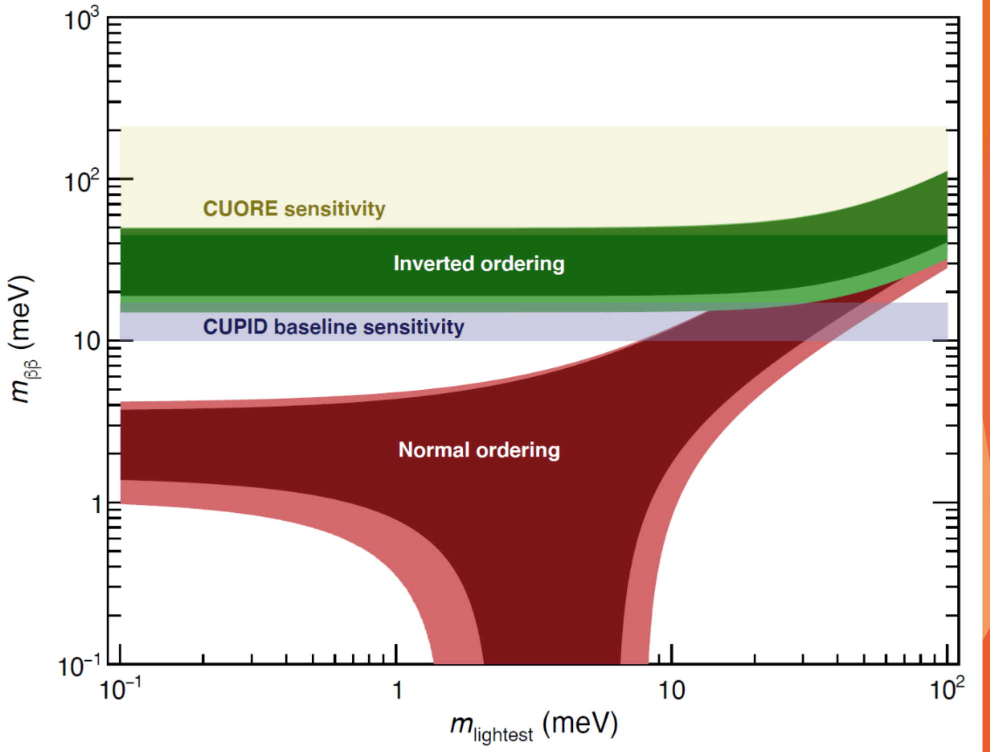
$$B\ \Delta E\ M\ T \leq \mathcal{O}(1)$$

  - → no events are expected in the ROI
  - → the sensitivity scales linearly with the exposure
- CUPID aims at reaching this condition by lowering the background index down to:

$$B \sim 10^{-4}\ \text{counts}/(\text{keV} \times \text{kg} \times \text{yr})$$

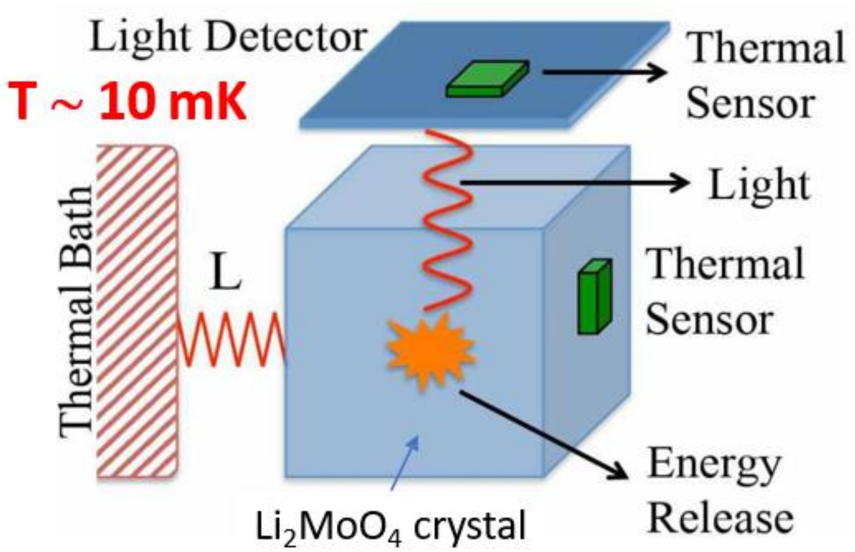
- From the CUORE background model we know that:
  - α background $\sim 10^{-2}$ counts/(keV × kg × yr) → Particle ID
  - γ background $\sim 10^{-3}$ counts/(keV × kg × yr) → Higher $Q_{\beta\beta}$

can significantly reduce the background index

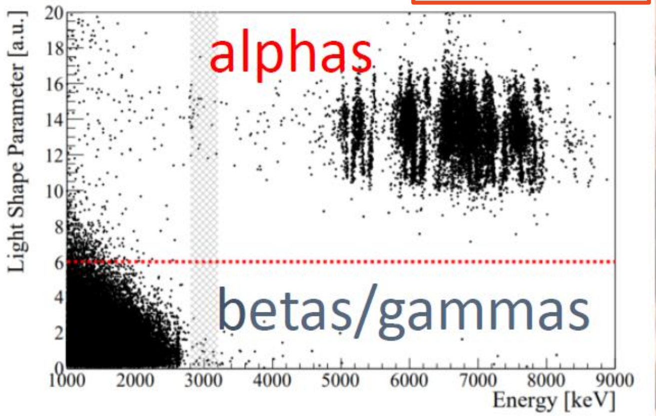


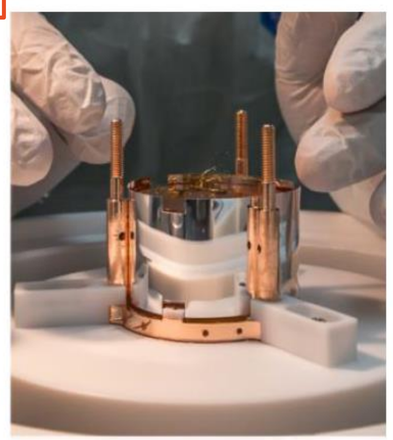
Scintillating bolometers

- Particle identification through dual readout of heat/light signal in scintillating crystals → full α background rejection.

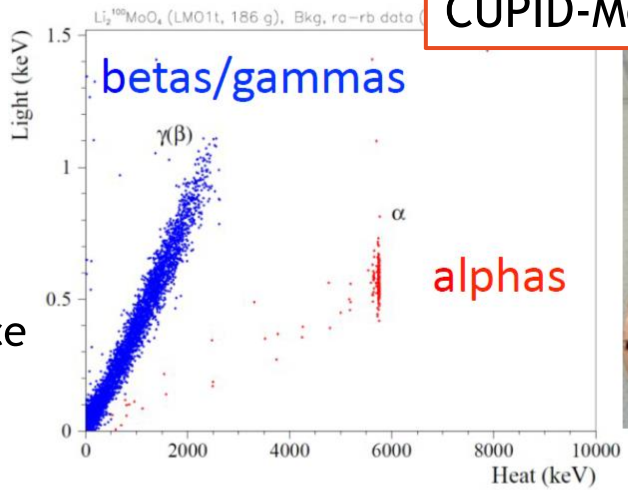


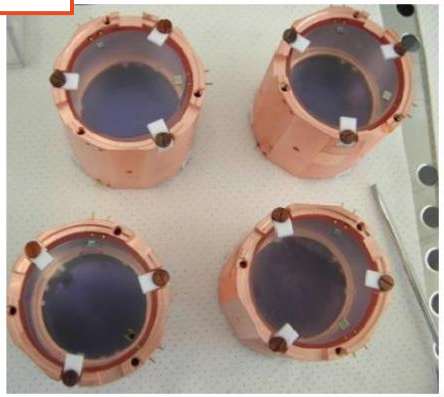
CUPID-0





CUPID-Mo





In the last years, the precursor experiments:

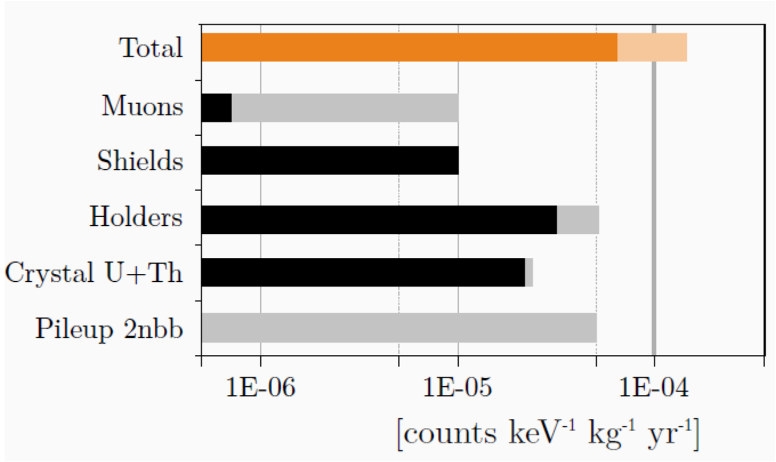
- CUPID-0: 24 ZnSe crystals enriched in ^{82}Se, LNGS-Italy
- CUPID-Mo: 20 Li_2MoO_4 crystals enriched in ^{100}Mo, LSM-France

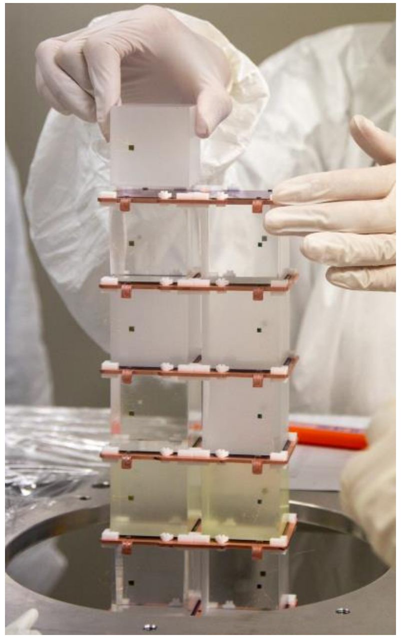
have demonstrated the potential of this technology

CUPID

CUORE Upgrade with Particle IDentification

- Tonne-scale array of scintillating bolometers for the search of the $0\nu\beta\beta$ of ^{100}Mo ($Q_{\beta\beta} = 3034$ keV, above the endpoint of main γ background)
- Keep CUORE cryogenic infrastructure: cost-effective + low risk
- Rich R&D program with multiple cryogenic facilities operational (Italy, France, US)





CUPID DESIGN PARAMETERS

- Detector mass: 450 kg (~240 kg of ^{100}Mo)
- 1596 Li_2MoO_4 crystals $45 \times 45 \times 45\ \mathrm{mm}^3$ enriched in ^{100}Mo to $\eta > 95\%$ (quite expensive, but available at industrial scale)
- Livetime: 10 yr
- Energy resolution: 5 keV FWHM at $Q_{\beta\beta}$
- Background index: 10^{-4} counts/(keV × kg × yr)

$0\nu\beta\beta$ sensitivity:

- $T_{1/2}^{0\nu} > 10^{27}$ yr
- $m_{\beta\beta} < 10 - 17$ meV

Conclusions

- CUORE is the first experiment to demonstrate stable operation of a tonne-scale milli-kelvin cryogenic calorimeter
- CUORE has analyzed 2TY of data setting the most stringent limit on ^{130}Te $0\nu\beta\beta$ half life: $T^{0\nu}_{1/2} > 3.3 \times 10^{25}$ yr (90% *C.I.*)
- Other physics searches:
  - precise measurement of $2\nu\beta\beta$ half-life
  - $2\nu\beta\beta$ spectral shape studies for CPT violation, Majoron emissions, …
  - low-energy spectrum analysis for Dark Matter searches
- CUORE is taking data stably, and aims at reaching 3TY TeO_2 (1TY ^{130}Te) exposure
- CUORE demonstrates the potential for large-scale bolometric detectors. The same technology and infrastructure will be used for the CUPID experiment.

Thanks for your attention

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