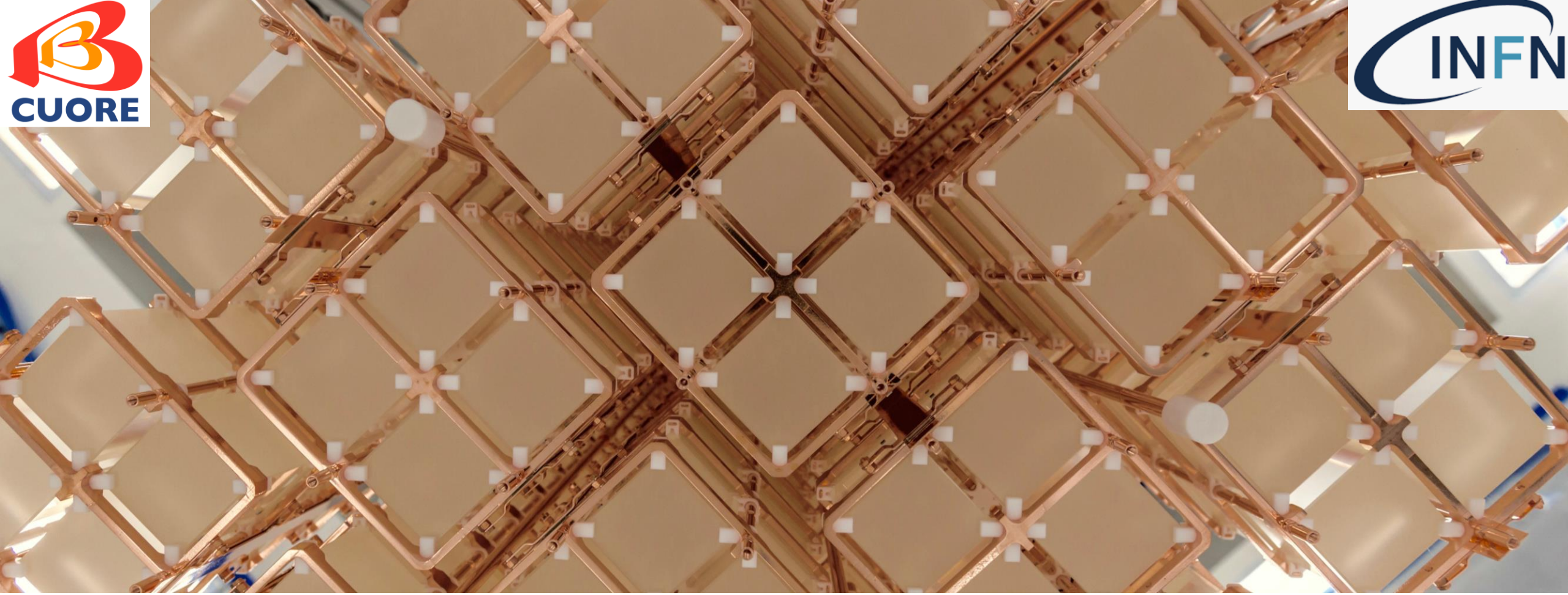


CUORE

CRYOGENIC UNDERGROUND OBSERVATORY FOR RARE EVENTS

VCI 2025

February 17-21, Vienna

Simone Copello on behalf of the CUORE collaboration

INFN - Pavia

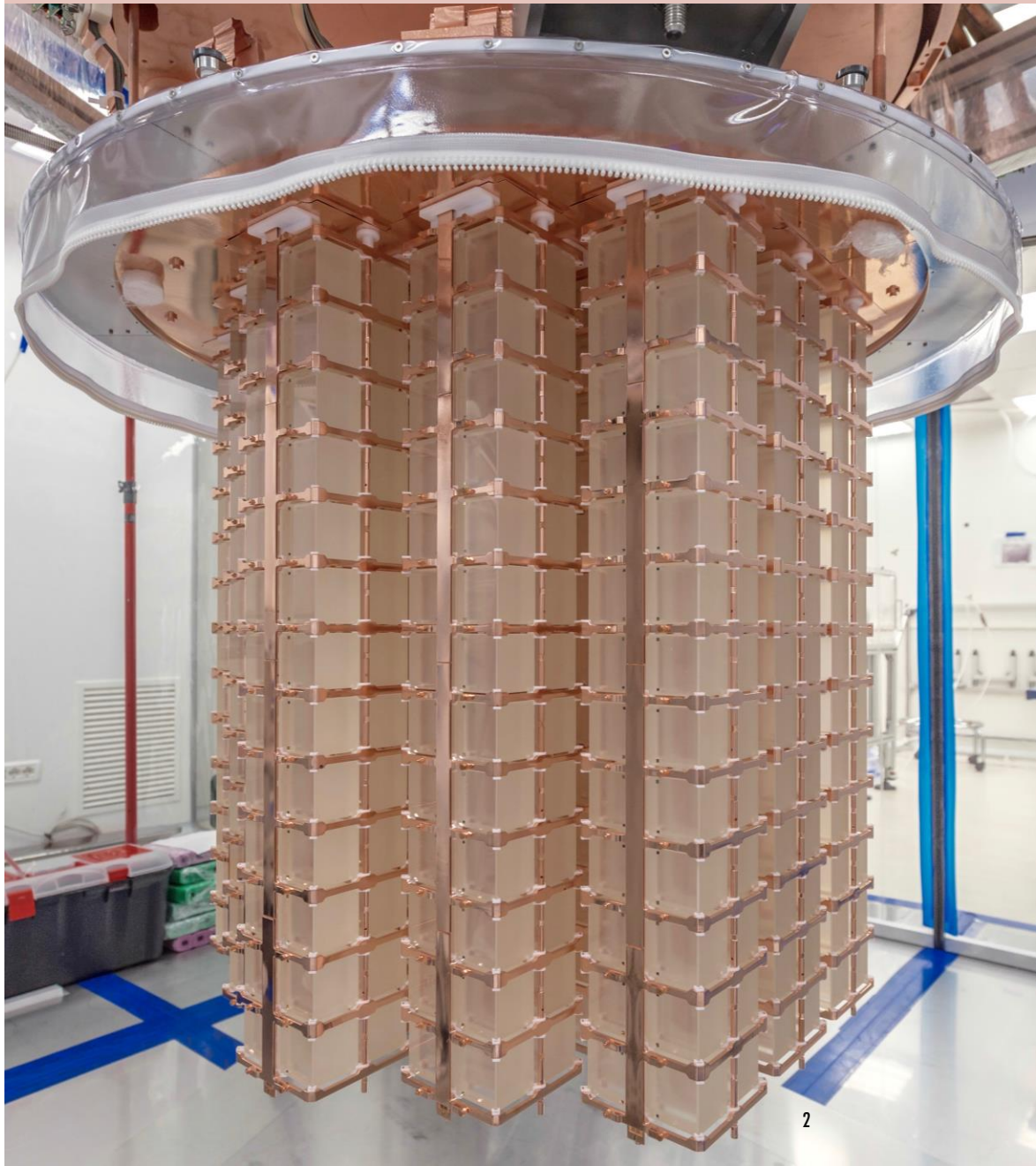
THE CUORE EXPERIMENT

Running at Gran Sasso National Laboratory (Italy)
Data taking started in 2017

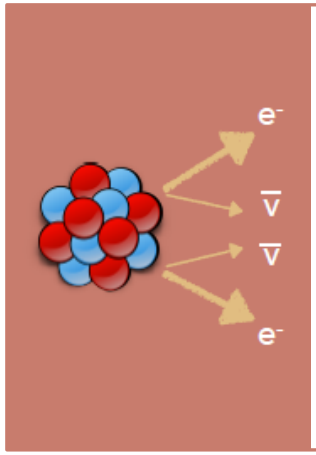
Scientific goal:

Search for rare events and for physics beyond the Standard Model:

- Search for 0νββ decay of ^{130}Te
  - demonstrate lepton number violation
  - establish the Majorana nature of neutrinos
  - constrain the absolute neutrino mass hierarchy and scale
- Measurement of 2νββ decay rate of ^{130}Te
- Study of other rare Te decays: ^{130}Te ββ decay to excited states, 0νββ/2νββ decay of ^{128}Te, 0ν(β+EC) ^{120}Te decay
- Low energy studies: WIMP dark matter, axions, supernova neutrinos…
- Spectral shape studies: 0νββ/2νββ decay with Majoron emission, CPT violation in 2νββ decay



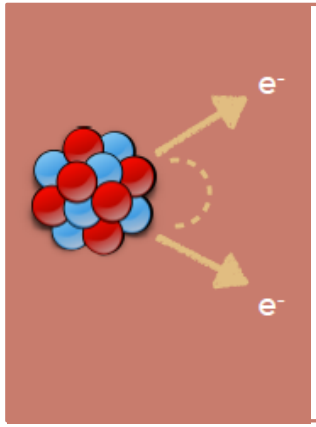
DOUBLE BETA DECAY



Double Beta Decay (ββ)

Is a second order weak interaction, directly observable (and observed) only for few even-even nuclei.

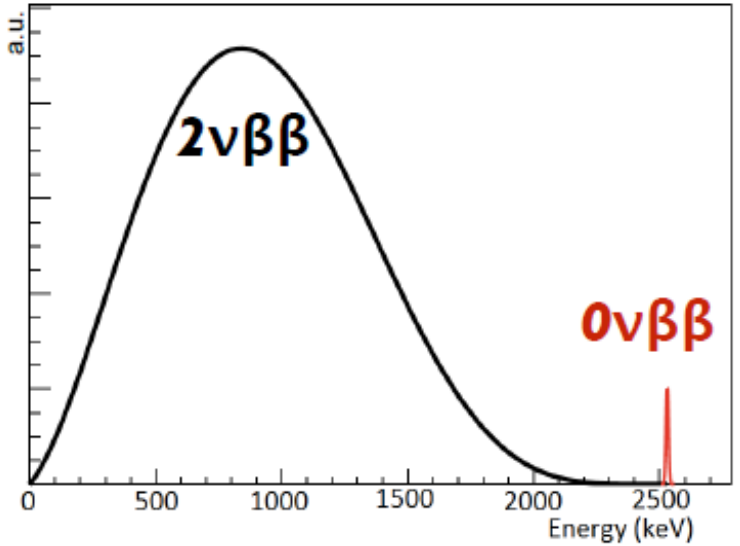
- Allowed by SM ($\Delta L = 0$)
- Observed in several nuclei $\tau_{1/2} \sim 10^{19\text{-}21}$ years

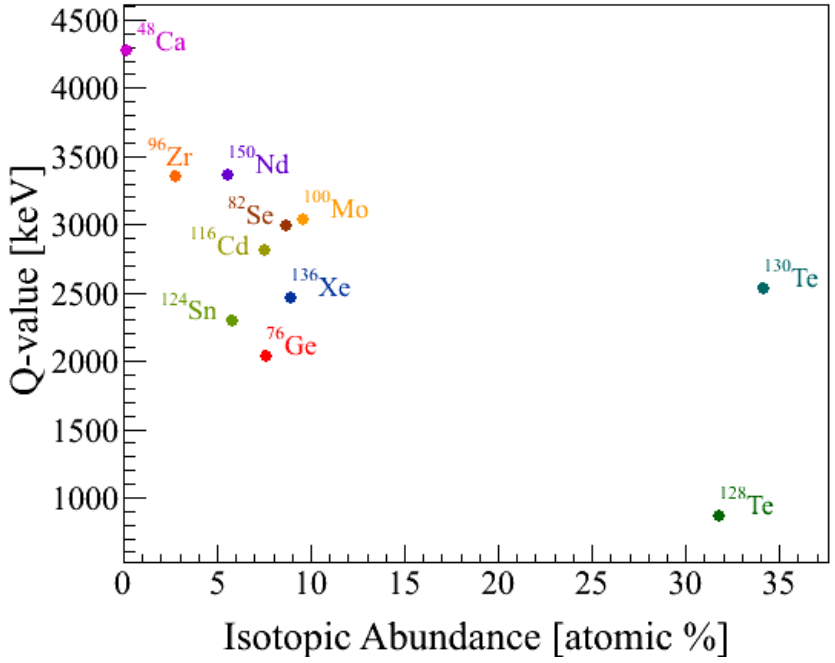


Neutrinoless Double Beta Decay (0νββ)

Is a hypothetical decay with no neutrino emission

- Beyond SM ($\Delta L = 2$)
- Never observed to date $\tau_{1/2} > 10^{25\text{-}26}$ years





THE CUORE EXPERIMENT

Technical requirements

Experimental sensitivity:

$$T_{0\nu} \propto \sqrt{\frac{M\,t}{B\,E}}$$

M = mass (of the candidate isotope): **206 kg of ^{130}Te**

t = live time: **5 years of data taking** in stable conditions

B = background index: **0.01 counts/keV/kg/yr**

E = energy resolution: **5 keV FWHM at 2.5 MeV**

large exposure (M · t)

- 988 TeO_2 crystals with isotopic abundance of 34.2% for a total mass 206 kg of active material
- foreseen 5 years of data taking

high energy resolution

- noise reduction techniques
- temperature stability
- fine tuning of detectors parameters to optimize the signal to noise ratio

low background

- strict radiopurity criteria on material selection and assembly chain
- passive shields from external and cryostat radioactivity
- Underground laboratory LNGS, Italy

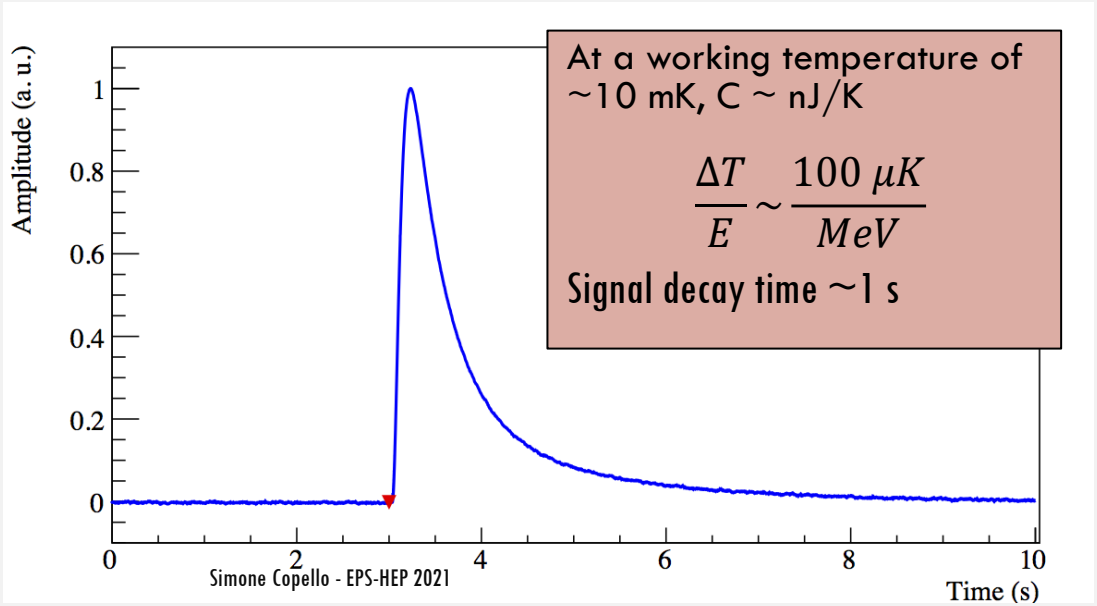
GOAL: $T_{1/2}$ (90% C.L.) > 9 x 10^{25} yr ⟷ $\langle m_{\beta\beta} \rangle$ 50 - 130 meV

Adv. in High Energy Phys. 2015.879871 (2015)

CUORE DETECTOR

A particle interacting in the absorber causes an increase in the absorber temperature, measured by means of the thermistor resistance:

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



At a working temperature of ~10 mK, C ~ nJ/K

$$\frac{\Delta T}{E} \sim \frac{100\ \mu K}{MeV}$$

Signal decay time ~1 s

CUORE is an array of 19 towers

A tower is an array of 52 independent TeO_2 crystals

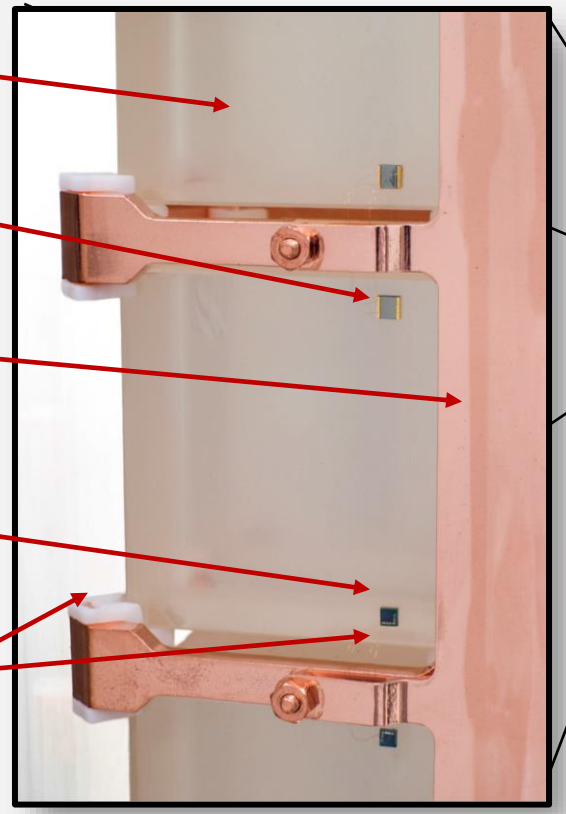
Absorber: 5x5x5 cm^3 TeO_2 crystal

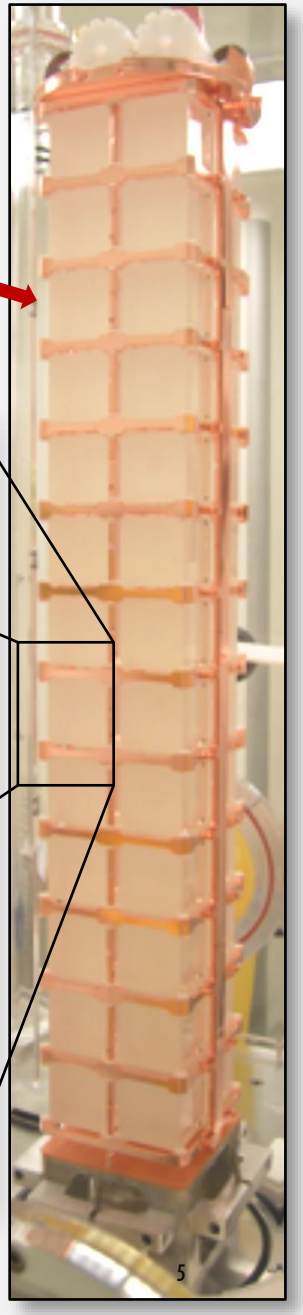
Thermistor: NTD Ge semiconductor

Thermal bath: Cu structure (cryostat)

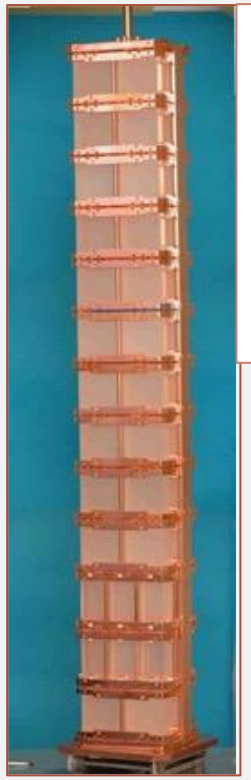
Joule heater for thermal gain stabilization

Thermal link: PTFE holders and gold wires





CUORE PROJECT



Cuoricino 2003 – 2008

Exp = 19.75 kg yr (^{130}Te)
Bkg = 0.169 c/(kg keV yr)

$T_{1/2} > 2.8 \times 10^{24}$ yr
(90% CL)

Astroparticle Phys. 34 Issue 11 pag. 822-831 (2011)

CUORE-0 2013 - 2015

Exp = 9.8 kg yr (^{130}Te)
Bkg = 0.058 c/(kg keV yr)

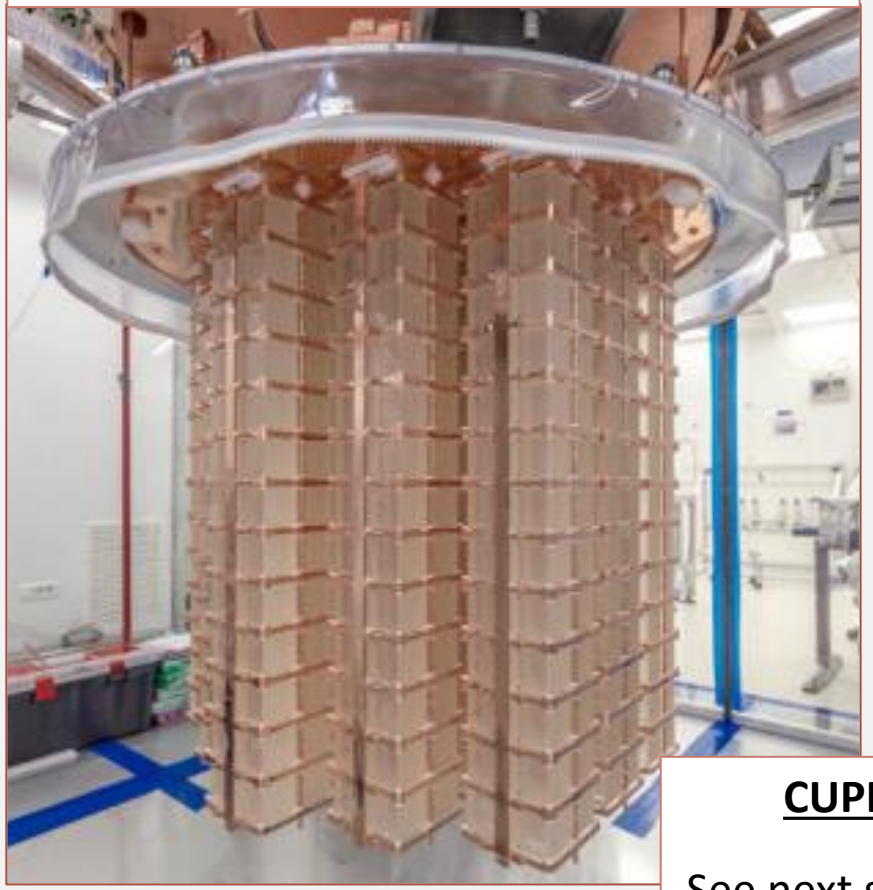
$T_{1/2} > 2.7 \times 10^{24}$ yr
(90% CL)

Phys. Rev. Lett. 115, 102502 (2015)

CUORE 2017 - ….

Array of 988 (750 g) crystals

19 towers - 13 floors - 4 crystals
742 kg total mass - 206 kg of ^{130}Te



CUPID

See next slides…

CRYOGENIC INFRASTRUCTURE

Hall A @ LNGS

The CUORE detector is located at LNGS below ~3600 m water equivalent, and is hosted in a cryogen free cryostat:

- Operating temperature ~ 10-15 mK
- Designed to guarantee extremely low radioactivity and low vibrations environment

The cryostat is suspended inside a clean room, and the external shielding (~70 ton) can be lifted up before the data taking.

Suspension system (minus-K®)
Main Support Plate
Cryostat
External lead shield
Polyethylene
Concrete walls
Seismic isolators

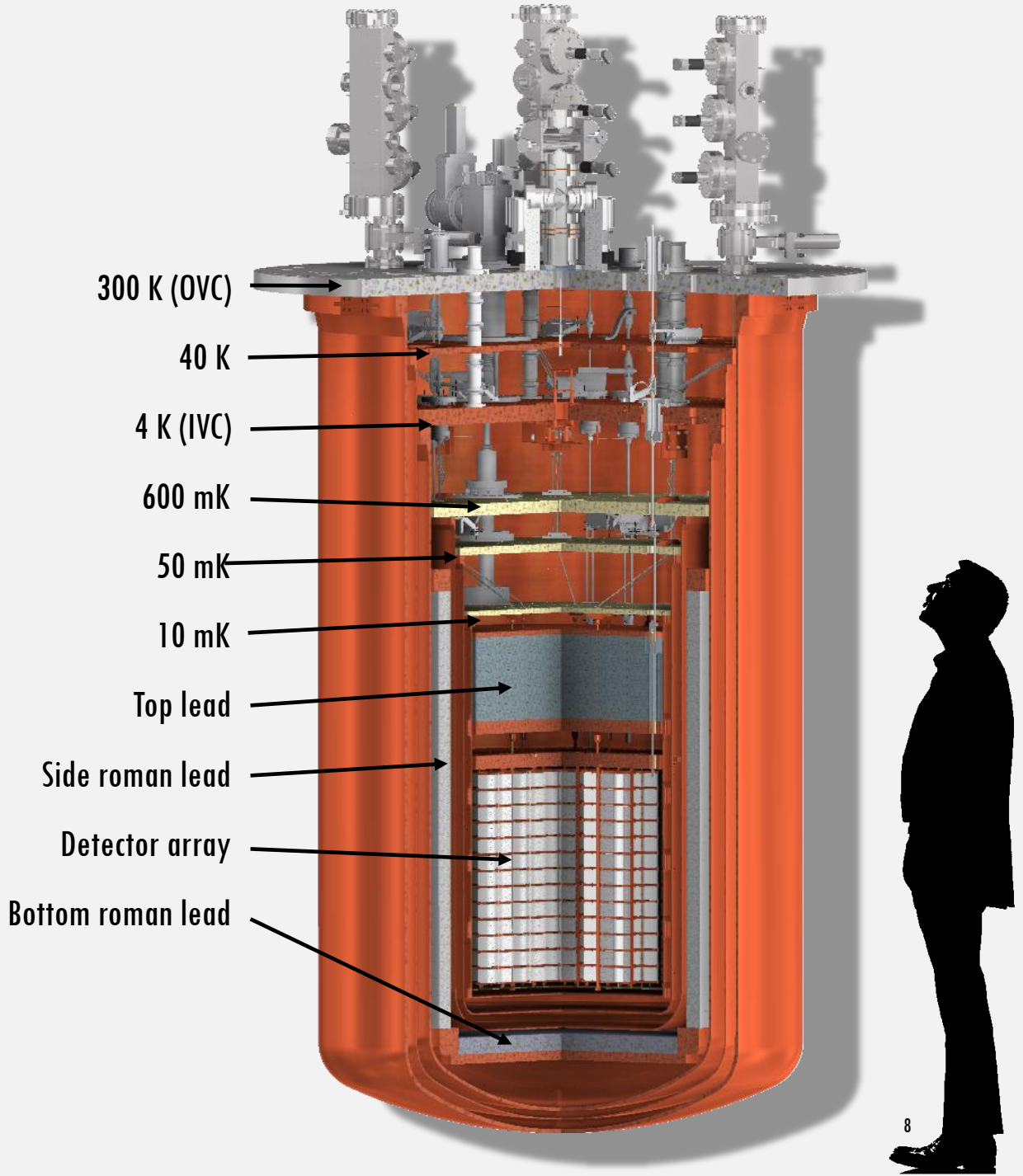
CUORE CRYOSTAT

Total mass: ~30 tons

- Mass < 4K: ~15 tons
- Mass < 50 mK: ~3 tons
- Mass at ~10 mK: ~1 ton

Cool down procedure:

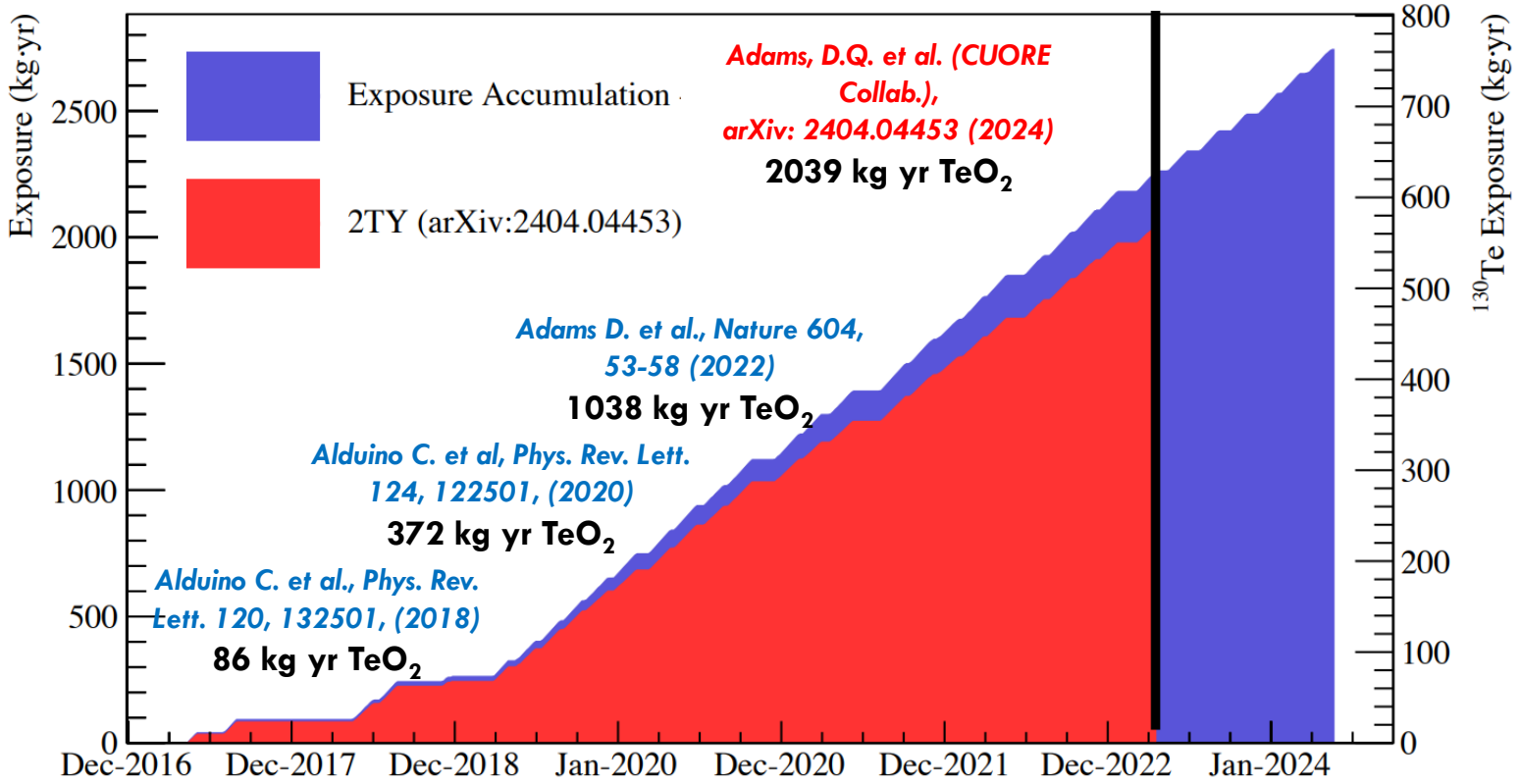
- Fast Cooling System (^{4}He) down to ~150 K
- 5 Pulse Tubes down to ~4 K
- Custom dilution refrigerator (^{4}He + ^{3}He) down to ~10 mK



CURRENT EXPOSURE

Data taking started in Spring 2017

- 984/988 operating channels



CUORE data are divided into Datasets:
about one month of background data taking plus:

- ✓ few days of calibration at the start and end
- ✓ continuous monitoring of detectors stability:
  - Working point measurement (NTD resistance)
  - Pulse Tubes phase scan (minimum noise configuration)

continuous data-stream

- ➢ Online trigger: for monitoring
- ➢ Offline trigger: fine tuned

DETECTOR OPTIMIZATION

Temperature scan:
Choose temperature that optimizes the signal and at the same time allows to work with the designed thermistor

Working point and Load Curves:
Scan bias current to feed each channel thermistor:

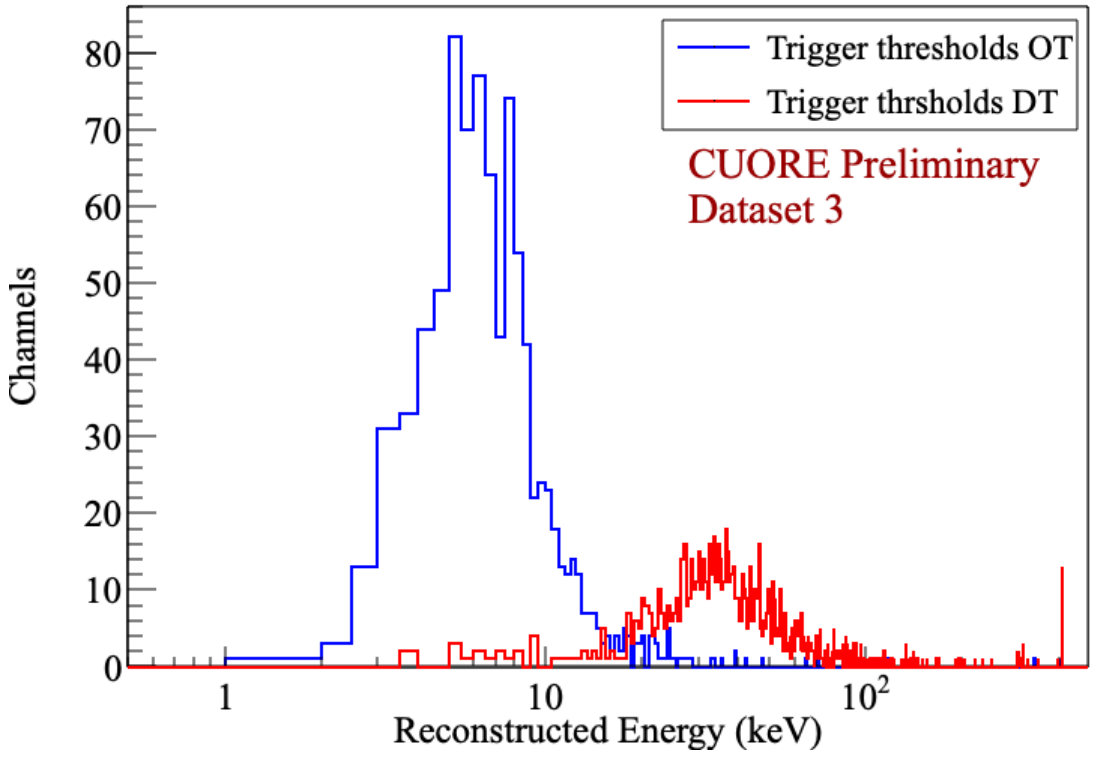
- linear behaviour for small temperature variations,
- maximization of signal to noise ratio

Alfonso K. et al., Nucl. Instr. Meth. A, Vol 1008 (2021), 165451

Attenuation of Pulse tube induced vibrations:
The 4 active Pulse Tubes are synchronized in the minimum noise phase-configuration

D'Addabbo A. et al., Cryogenics 93 (2018) 56–65

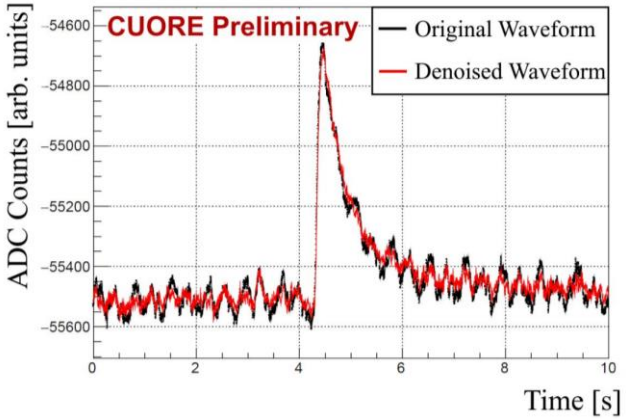
Optimization of online trigger thresholds:
20 keV to a few hundred keV

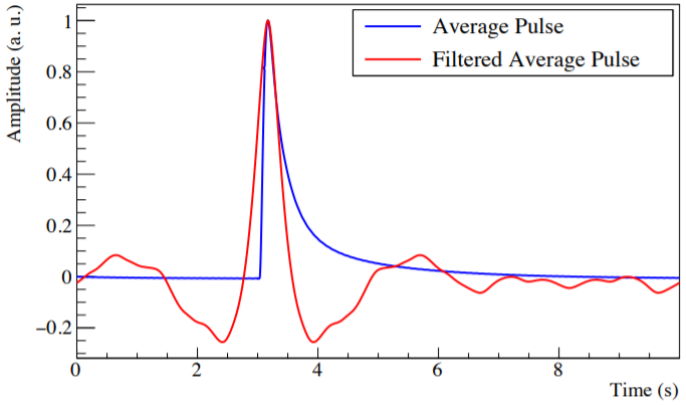


ANALYSIS

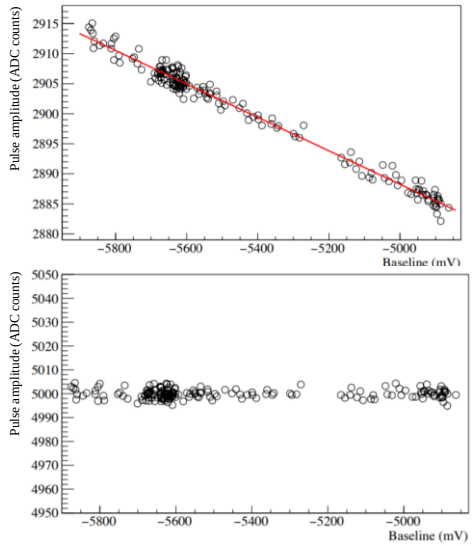
Main steps are:

- Signal denoising and filtering
- Amplitude Evaluation
- Thermal gain stabilization
- Energy calibration
- Multiplicity (M) selection
- Principal Component Analysis
- *Data blinding*

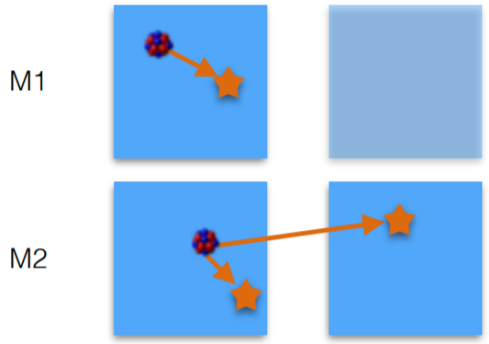




- Denoising by means of auxiliary devices (microphones, accelerometers, seismometers, antennas) *(poster at TAUP 2023)*
- Optimum filter



The amplitudes of **reference pulses** (produced by Jules heater) are correlated to the base temperature.

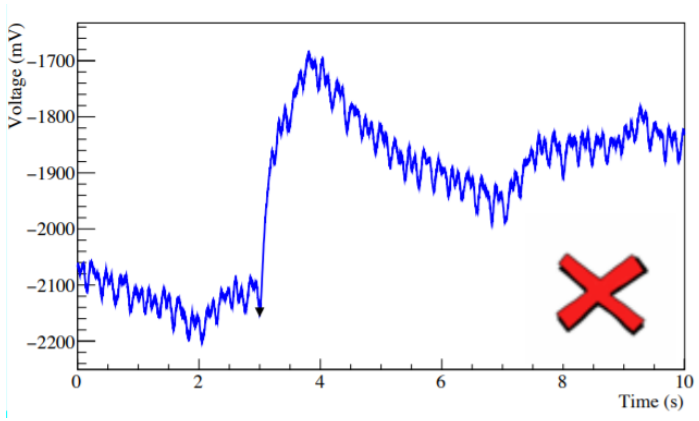


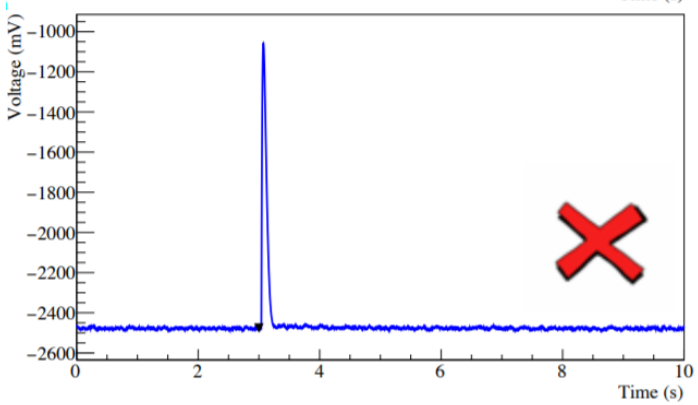
Single site events: 88% of $0\nu\beta\beta$ decays are contained

ANALYSIS

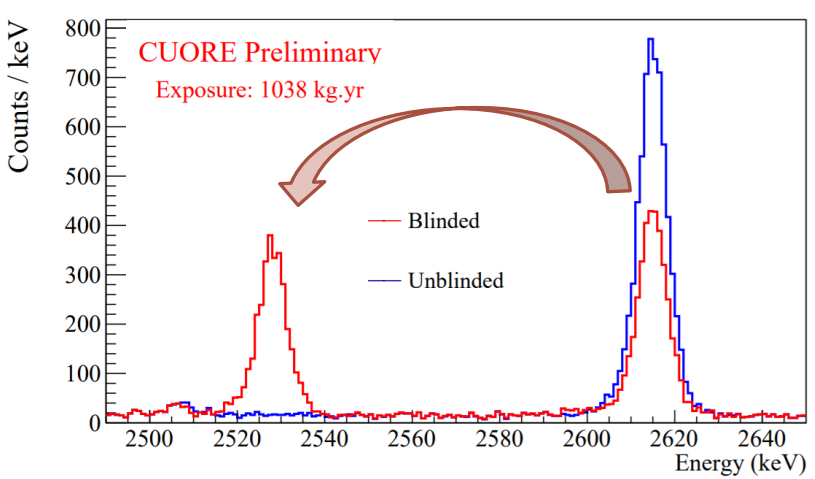
Main steps are:

- Signal denoising and filtering
- Amplitude Evaluation
- Thermal gain correction
- Energy calibration
- Multiplicity (M) selection
- Principal Component Analysis
- *Data blinding*





Spurious events are removed



Event from ^{206}Tl peak are randomly moved to the ROI, and vice-versa.
This creates a fake peak at $Q_{\beta\beta}$

LATEST RESULTS

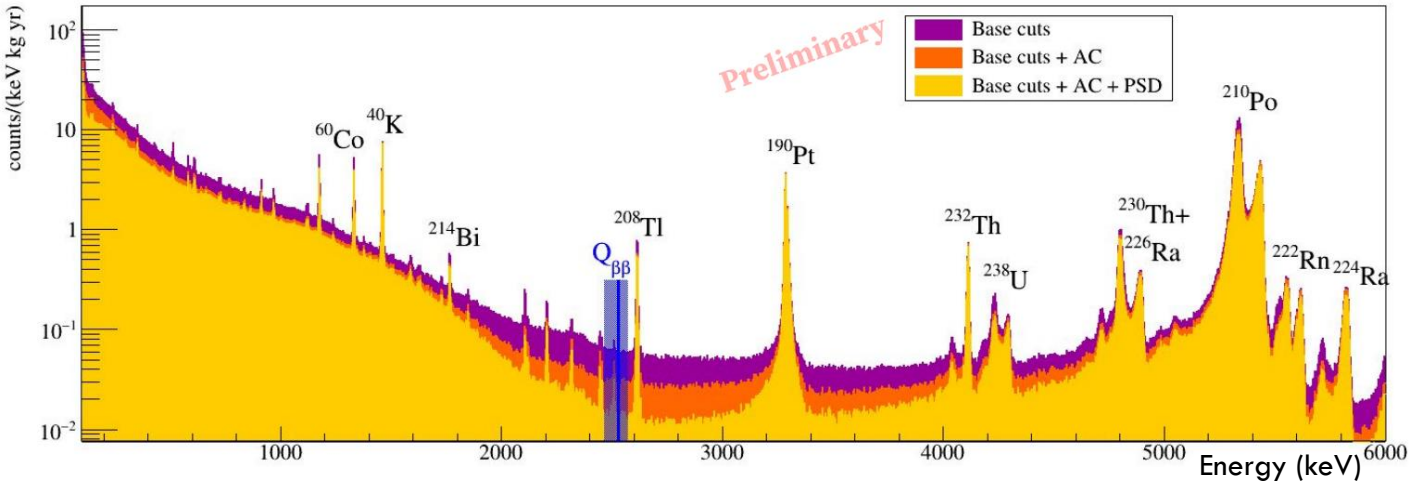
SPECTRUM AND 2νββ

Background model

Good background reconstruction is made possible by detector segmentation:

- events multiplicity
- background sources location
- inner towers self-shielded from outer contaminants

Phys. Rev. D 110, 052003 (2024)

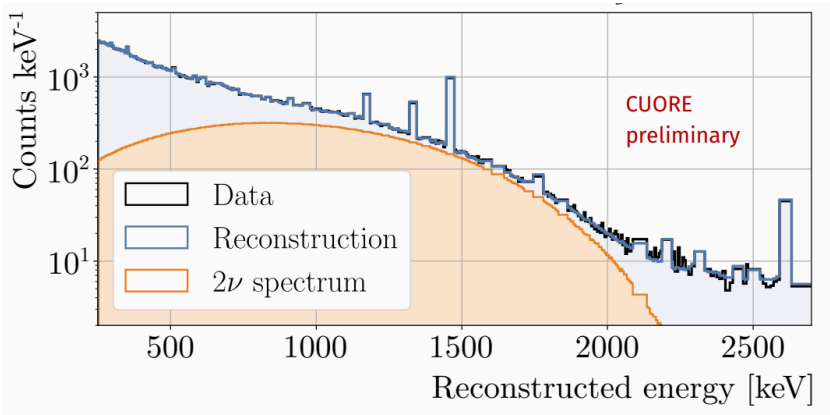


^{130}Te 2νββ half-life

Total exposure: **2039 kg yr TeO_2** (567 kg yr ^{130}Te)

- ^{130}Te 2νββ most precise measurement to date: **$T^{2\nu}_{1/2}$ = 9.3 x 10^{20} yr**

(publication in preparation)



LATEST RESULTS
NEUTRINOLESS DOUBLE BETA DECAY

(arxiv:2404.04453)

Fit strategy

Extendex maximum likelihood fit in the ROI (2465, 2575) keV:

- flat background (mainly due to degraded-α particles)
- ^{60}Co γ-peak @ 2505.7 keV
- $Q_{\beta\beta}(^{130}\text{Te}) = 2527.5$ keV

Detector performance

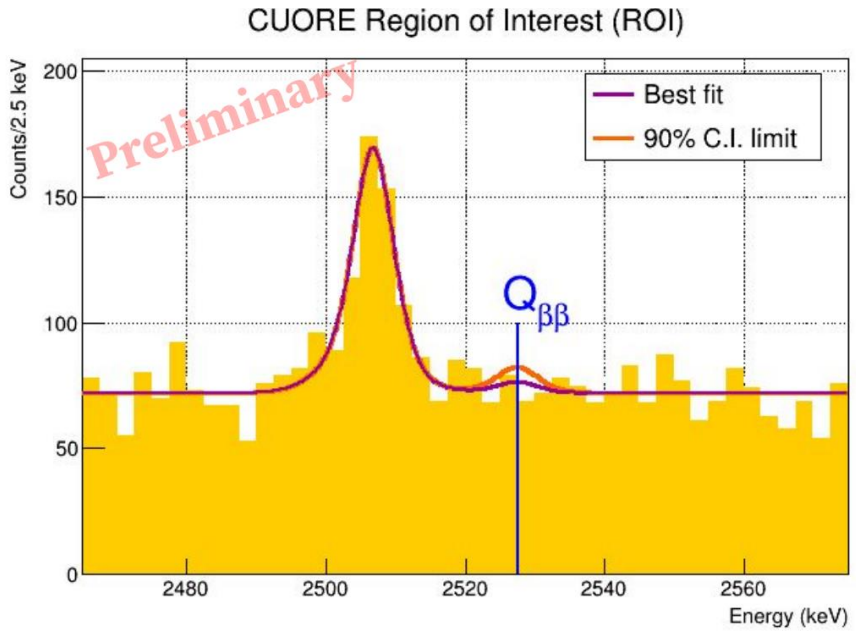
- Energy resolution at $Q_{\beta\beta}$ **7.3 keV** FWHM
- ROI background index **1.42×10^{-2} counts/(keV·kg·yr)**

- **0νββ** half-life limit with ^{130}Te:

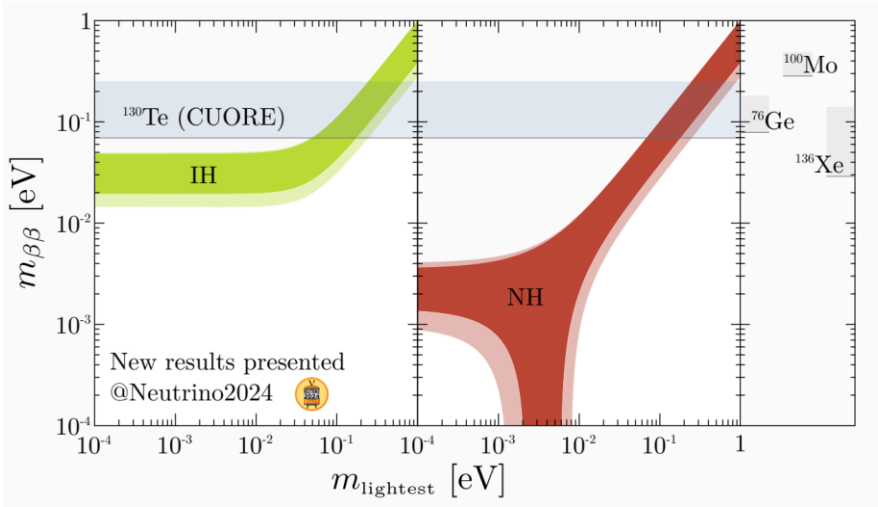
  $T^{0\nu}_{1/2} > 3.8 \times 10^{25}$ yr (90% C.I.)

- Corresponding to effective Majorana mass:

  $m_{\beta\beta} < 70 - 240$ meV



$$T^{0\nu}_{1/2} = \left[G_{0\nu} g_A^4 |M_{0\nu}|^2 \frac{m_{\beta\beta}^2}{m_e^2} \right]^{-1}$$



LATEST RESULTS
OTHER DECAYS

- **0νβ⁺EC of ^{120}Te** ($Q_{\beta\beta}$= 1714.8 keV)
  - $^{120}Te + e^- \rightarrow {}^{120}Sn^* + \beta^+$
    $\rightarrow {}^{120}Sn + X + \beta^+$
    $\rightarrow {}^{120}Sn + X + 2\,\gamma_{511}$
  - multiple signatures in M1, M2 and M3
  - limit: $T^{0\nu}_{1/2} > 2.9 \times 10^{22}$ yr @ 90% C. I.

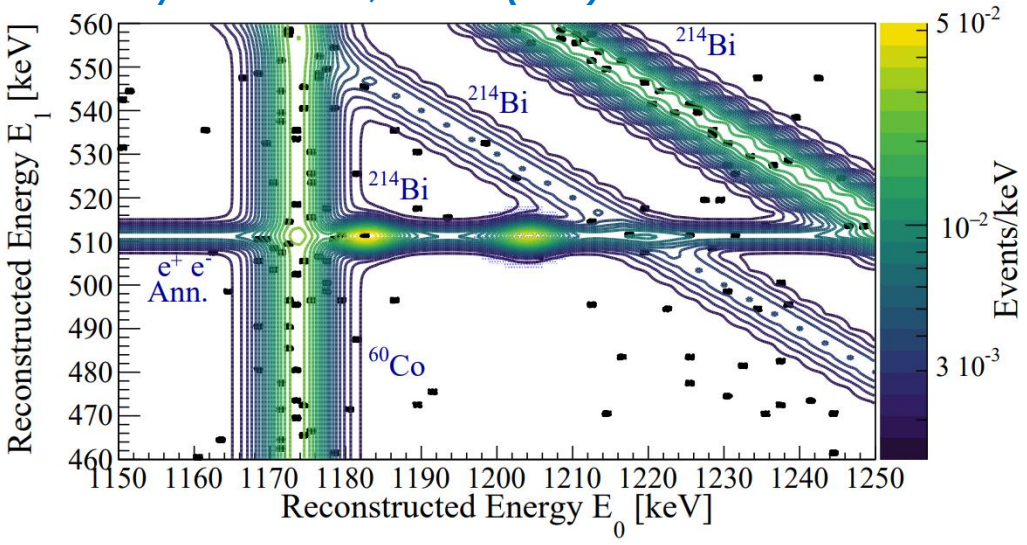
  Exposure: 0.24 kg yr of ^{120}Te (^{120}Te/natTe = 0.09%)

- **0νββ of ^{128}Te** ($Q_{\beta\beta}$= 866.7 keV)
  - limit: $T^{0\nu}_{1/2} > 3.6 \times 10^{24}$ yr @ 90% C. I.

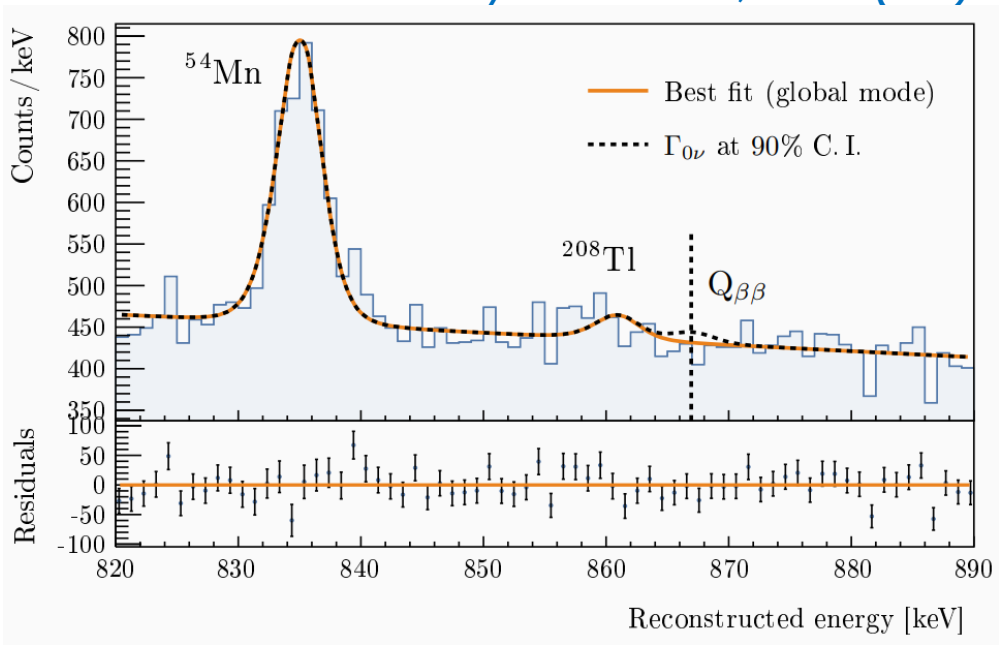
- ββ decays of ^{130}Te to **excited states of ^{130}Xe**
  - search for de-excitation γ's
  - $(T_{1/2})^{0\nu} > 5.9 \times 10^{24}$ yr @ 90% C. I.
  - $(T_{1/2})^{2\nu}_{0^+_2} > 1.3 \times 10^{24}$ yr @ 90% C. I.

  Eur. Phys. J. C 81, 567 (2021)

Phys. Rev. C 105, 065504 (2022)



Phys. Rev. Lett. 129, 222501 (2022)



CUPID

CUORE UPGRADE WITH PARTICLE IDENTIFICATION

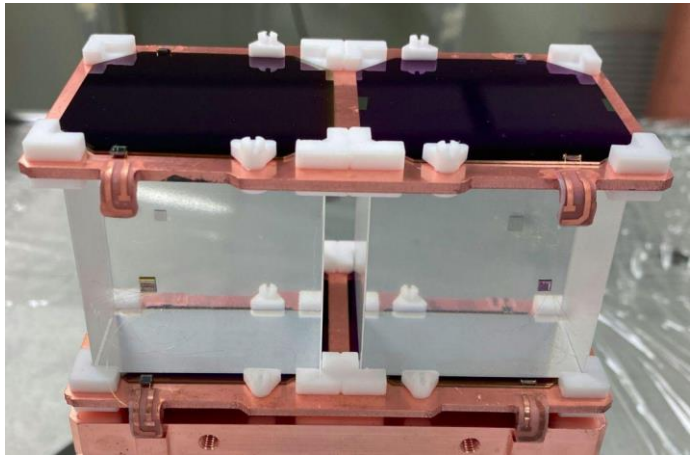
- **Scintillating crystals: $Li_2{}^{100}MoO_4$** (~1600 bolometers → 240 kg of ^{100}Mo):
  - $Q_{\beta\beta}(^{100}Mo) = 3034$ keV → reduced γ background
  - Scintillating crystals → dual readout for α rejection
  - Projected background in the ROI of 10^{-4} counts/(keV·kg·yr)
  - 95% enriched in ^{100}Mo

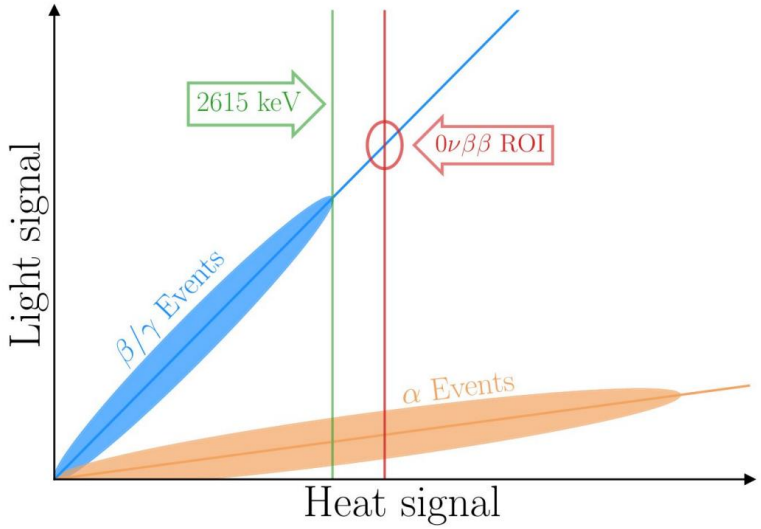
- Ge light detectors equipped with NTDs and Neganov-Trofimov-Luke amplification

- Reuse proven **CUORE cryogenic infrastructure** at LNGS after a few upgrades → CUORE phase 2

- 0νββ decay sensitivity:
  - $T^{0\nu}_{1/2}(^{100}Mo) > 10^{27}$ yr (10 yr of data taking)
  - effective Majorana mass: $m_{\beta\beta} \sim 12 - 20$ meV
  - explore the entire inverted hierarchy region of neutrino masses.

(Pre-CDR arxiv:1907.09376)





CONCLUSIONS

2 tonne year TeO_2 exposure reached

- results released for ^{130}Te $0\nu\beta\beta$
- demonstrates good stability and reliability after 8 years of data taking

Scientific:

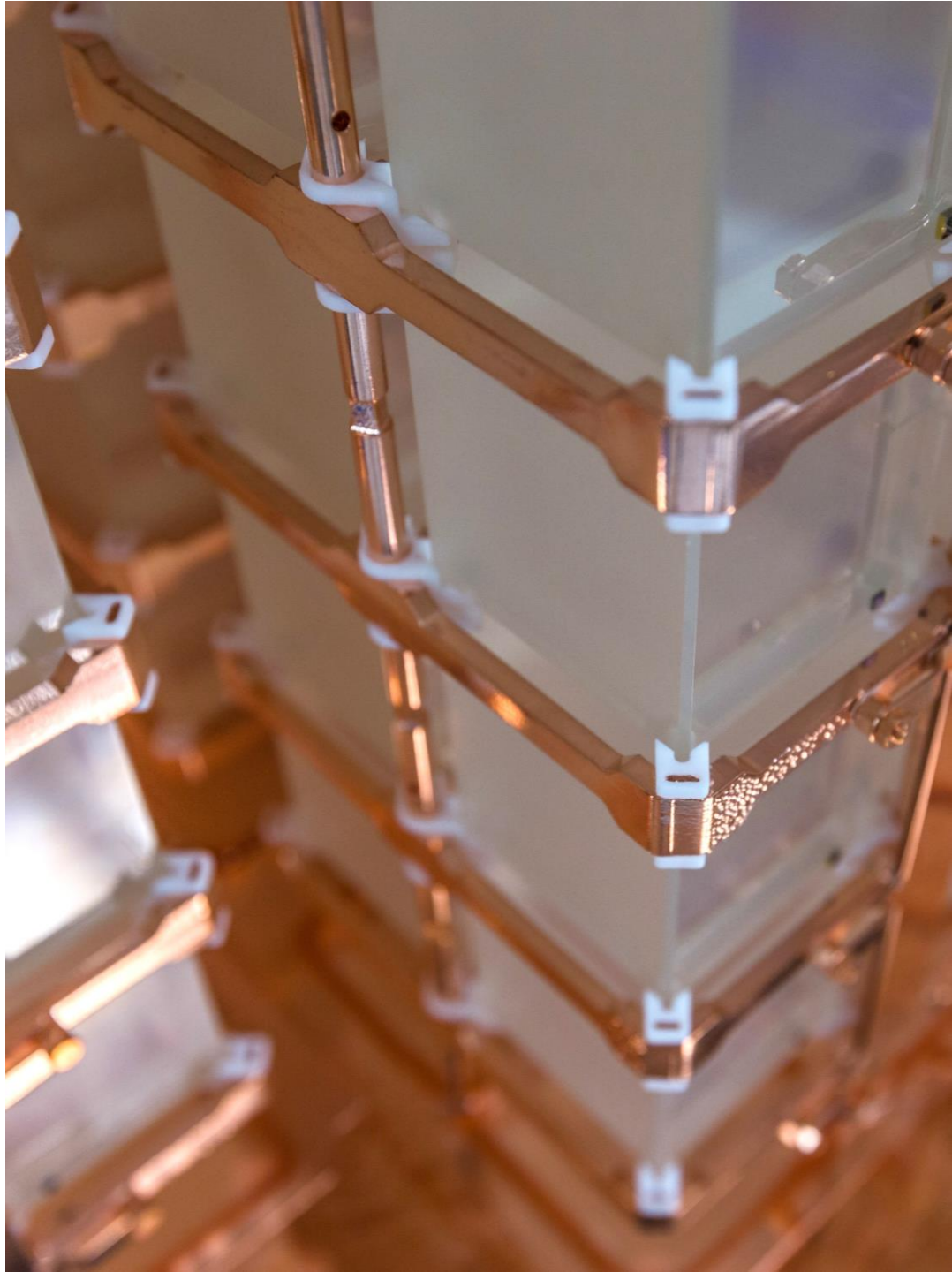
- most stringent limit on $0\nu\beta\beta$ decay half-life of ^{130}Te to date
- most accurate measurements of $2\nu\beta\beta$ decay half-life of ^{130}Te

Technical:

- operation of the world's first ton-scale bolometric detector
- construction and operation of one of the largest and most powerful dilution refrigerator

The future:

- More exposure planned (up to ~3 tonne year)
- CUORE run-II with upgraded cryogenics and energy threshold improvements
- Next generation: CUPID



THANK YOU!