The CUORE and CUORE-0 experiments at LNGS

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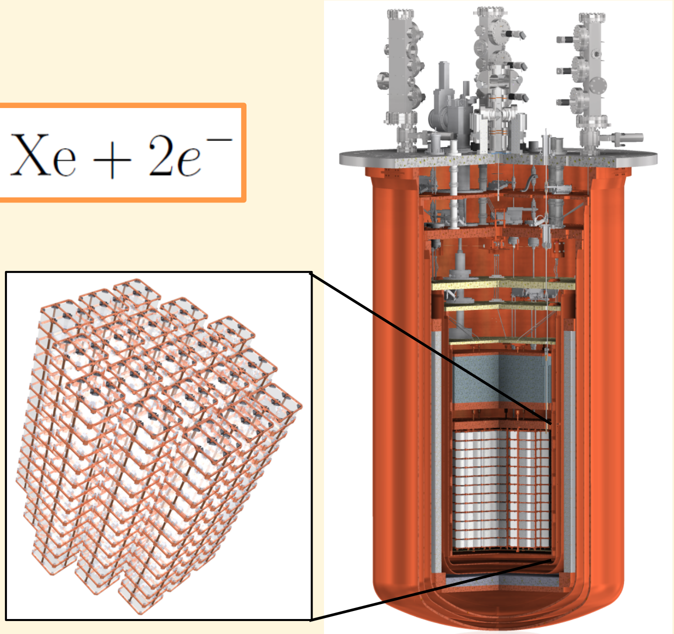
On behalf of the CUORE collaboration

CNNP 2017, October 15–21, Catania (Italy)

The CUORE experiment
Cryogenic Underground Observatory for Rare Events

Primary goal

Search for **0νββ decay of ^{130}Te**: $$^{130}\mathrm{Te} \rightarrow {}^{130}\mathrm{Xe} + 2e^-$$

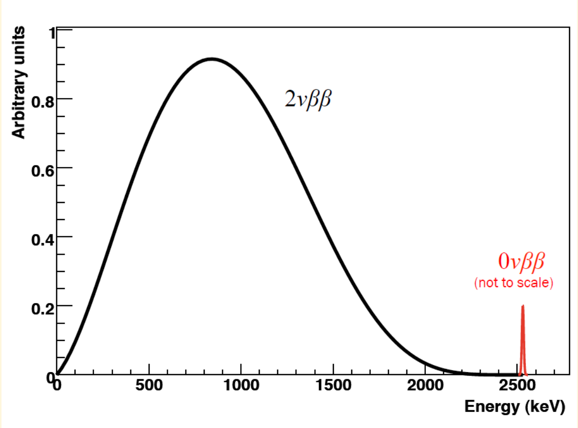


0νββ observation would establish that:

- ✓ lepton number is not conserved;
- ✓ neutrinos are massive Majorana particles;
- ✓ which is the hierarchy and which is the absolute mass scale of neutrinos

Detectors

- Natural TeO_2 crystals as 0νββ source material (^{130}Te is 27% in mass) operated as bolometers
- The signature of the 0νββ decay of ^{130}Te is a peak at the Q-value of the transition (Q = 2527.5 keV).



THE CUORE EXPERIMENT

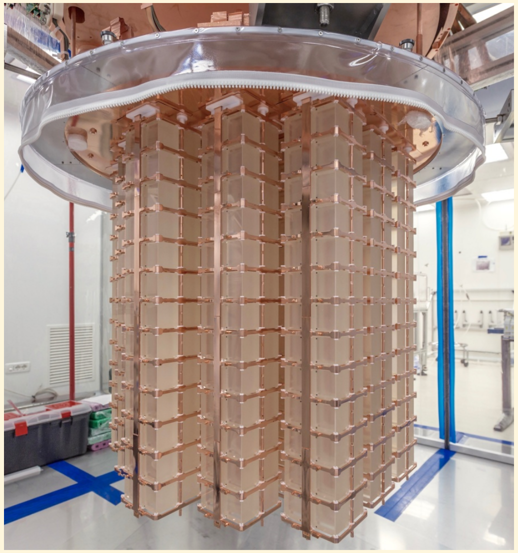
CHALLENGE

$0\nu\beta\beta$ decay is an extremely rare decay ($T_{1/2} \geq 10^{25}$yr)

With background ≠ 0, the experimental sensitivity scales as:

$$T_{1/2}^{0\nu} \propto \eta\, a \sqrt{\frac{M\, t}{b\, \Delta E}}$$

η = efficiency
a = isotopic abundance
M = detector mass
t = livetime
b = background rate
ΔE = energy resolution



CUORE DESIGN PARAMETERS

- Closely packed array of 988 TeO_2 crystals arranged in 19 towers.
- Mass of TeO_2: 742 kg (206 kg of ^{130}Te).
- Low background: 10^{-2} counts/(keV·kg·yr).
- Energy resolution: 5 keV FWHM in the Region Of Interest (ROI)

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

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

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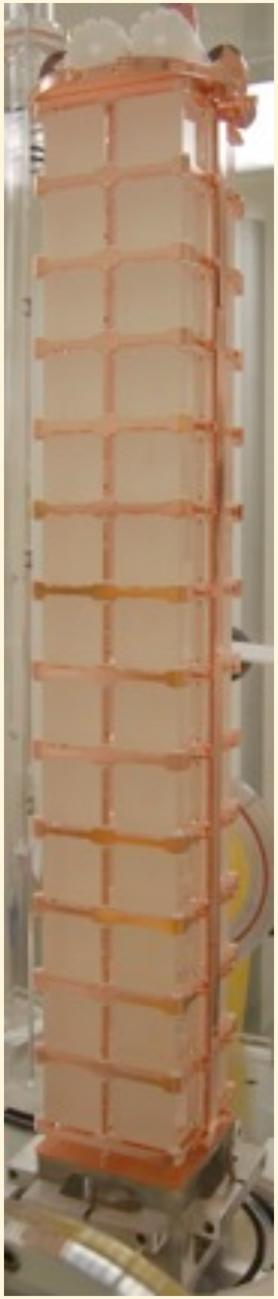
CUORE BOLOMETERS

CUORE TOWER:

Array of 52 independent bolometric detectors

SINGLE BOLOMETER:

- **Absorber:** 5x5x5 cm^3 750g TeO_2 crystal
- **Thermistor:** NTD Ge semiconductor
- **Joule heater** for thermal gain calibration
- **Thermal link:** PTFE holders and gold wires
- **Thermal bath:** Cu structure (cryostat)



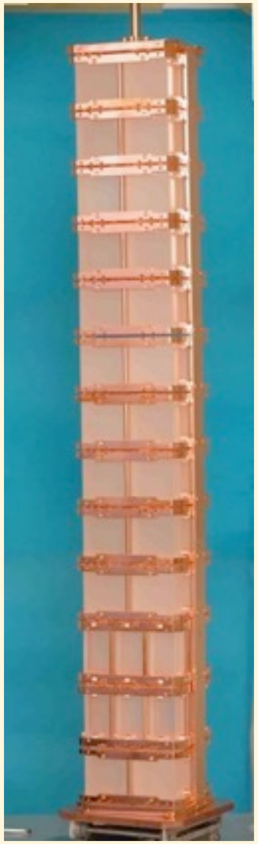
At a working temperature of 10 mK,

C ~ 2 nJ/K

$\Delta T \sim 100\ \mu K$ for 1 MeV energy deposit

Signal decay time ~1 s

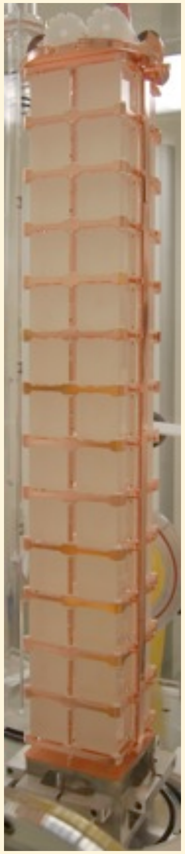
CUORE FAMILY



CUORICINO 2003 – 2008

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

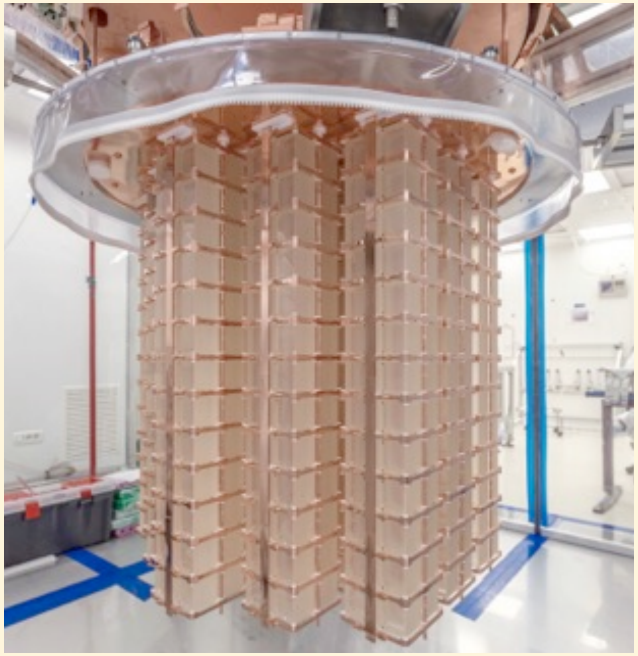
$T_{1/2} > 2.8 \times 10^{24}$ yr
(90% CL)



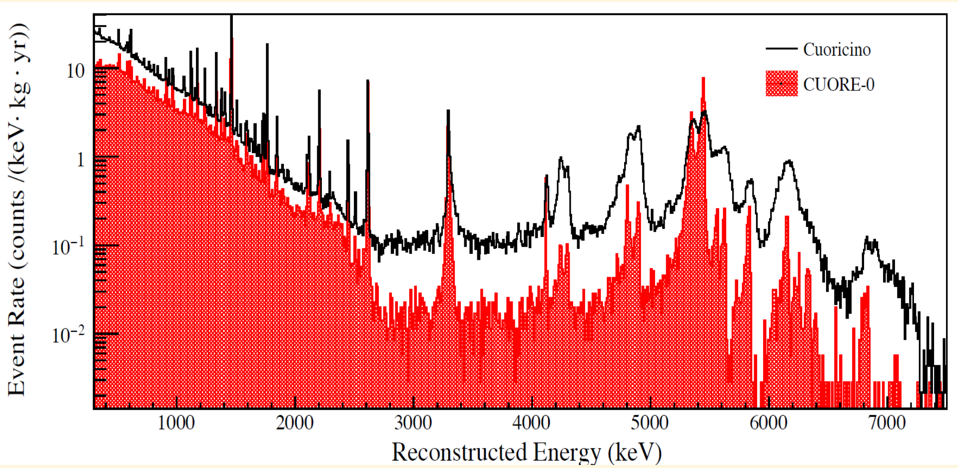
CUORE-0 2013 - 2015

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)



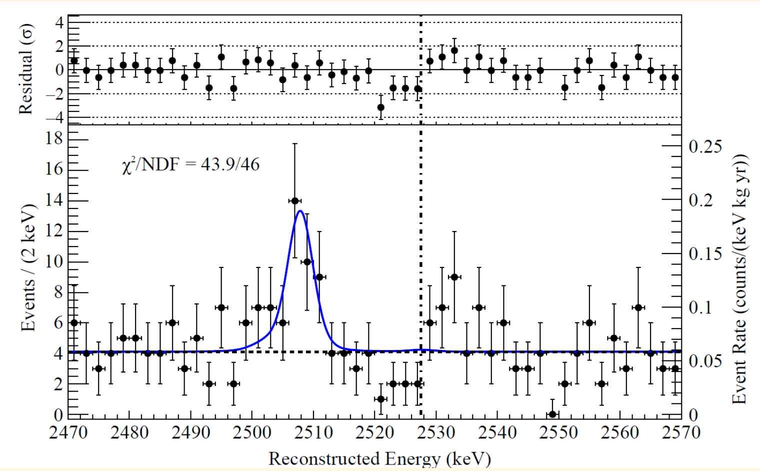
CUORE 2017 - ....

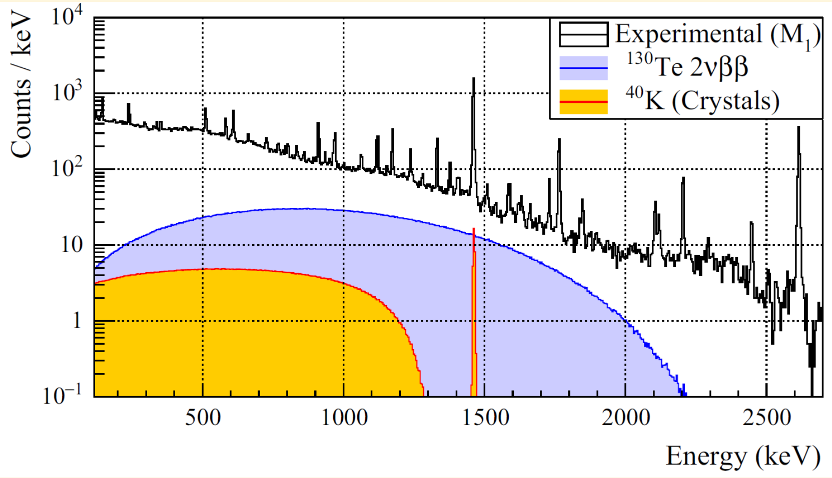


Background reduction with respect to Cuoricino:

- factor 6 for surface contaminations
- factor of ~2.5 in the ROI

Not only the first prototype of a CUORE tower but a small scale experiment





$\tau_{1/2}^{0\nu} > 2.7 \times 10^{24}$ y (90%C.L.)

Phys. Rev. Lett. 115 (2015) 102502

$\tau_{1/2}^{2\nu} = [8.2 \pm 0.2_{stat} \pm 0.6_{sys}] \times 10^{20}$ y

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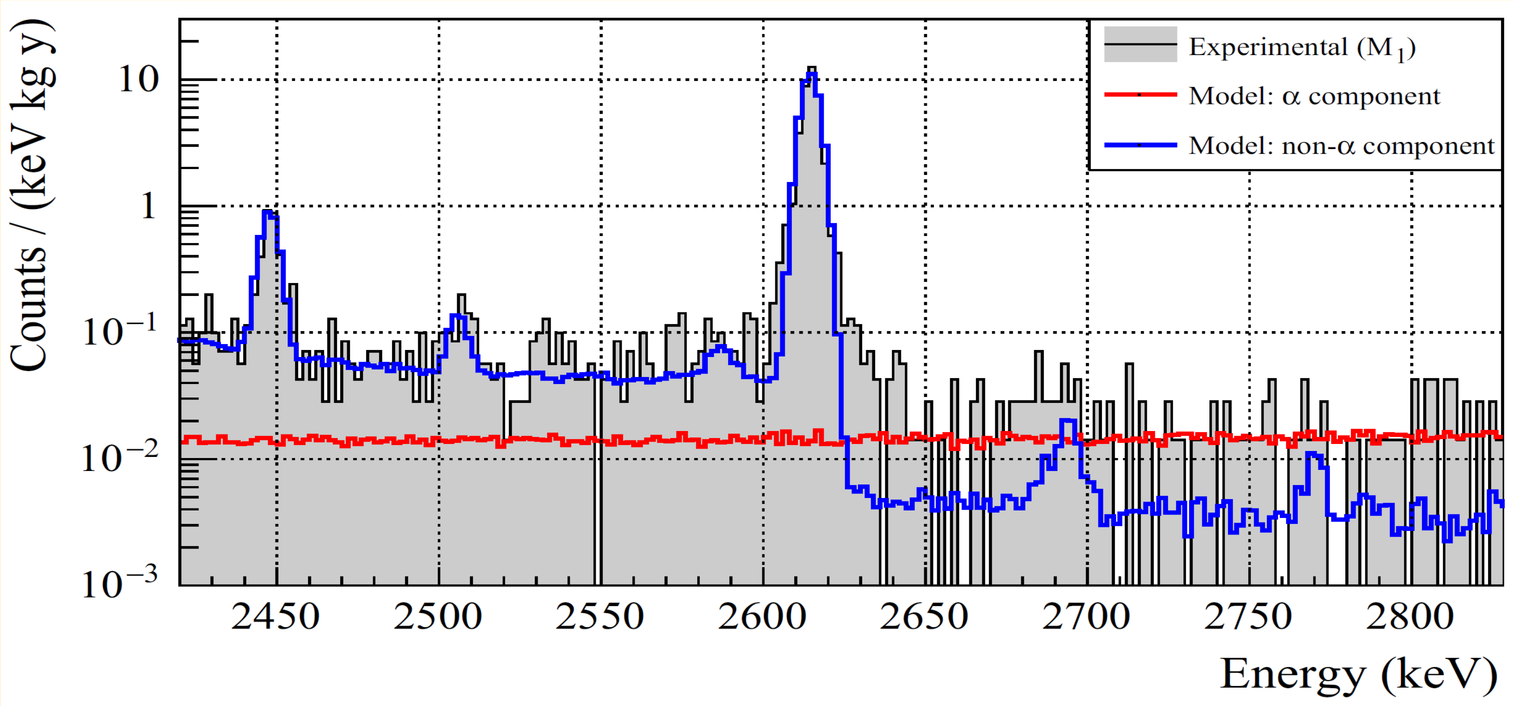
CUORE-0: BACKGROUND MODEL

CUORE-0 background model in the $0\nu\beta\beta$ ROI.

Analysis of the contribution due to α vs non-α particle energy depositions.



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MORE PHYSICS TO COME:

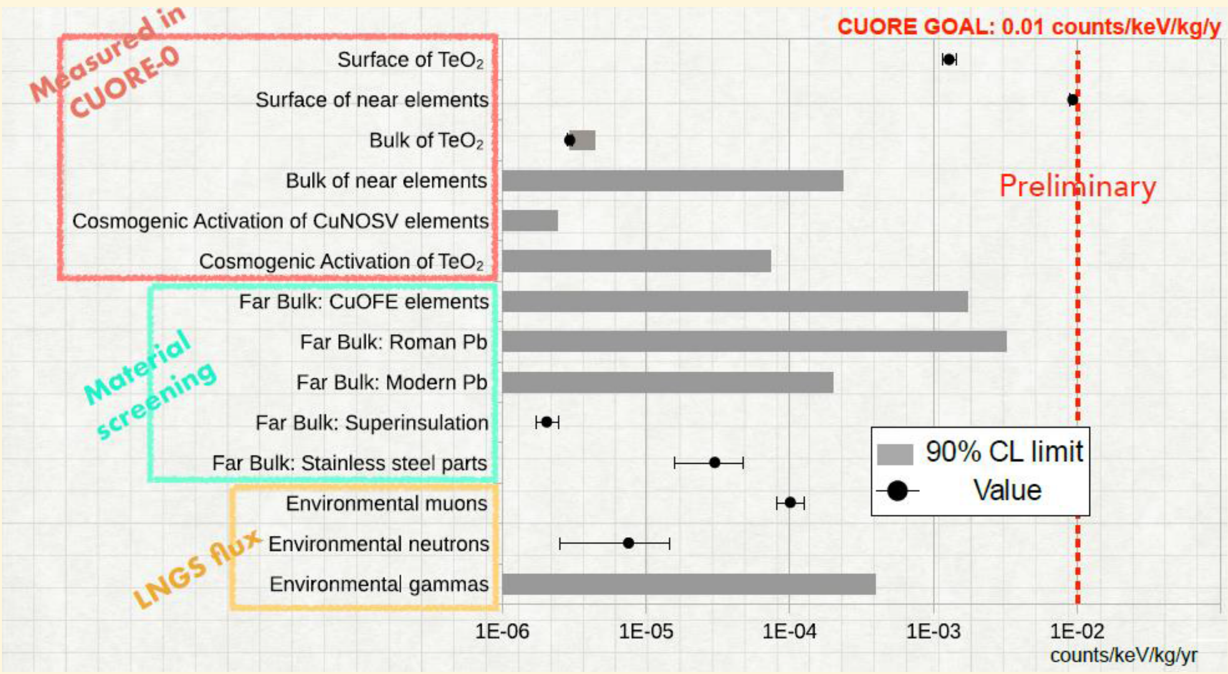
^{120}Te $0\nu(\beta^+EC)$DBD, ^{130}Te 0νDBD on exc. states, Low energy studies (DM?)

CUORE EXPECTED BACKGROUND

We developed a detailed MC (Geant4) simulation of the CUORE setup and we used the information from:

- CUORE-0 background model,
- radio-assays of the CUORE construction materials,
- LNGS environmental fluxes

to provide an estimate of the expected counting rates and background spectra.



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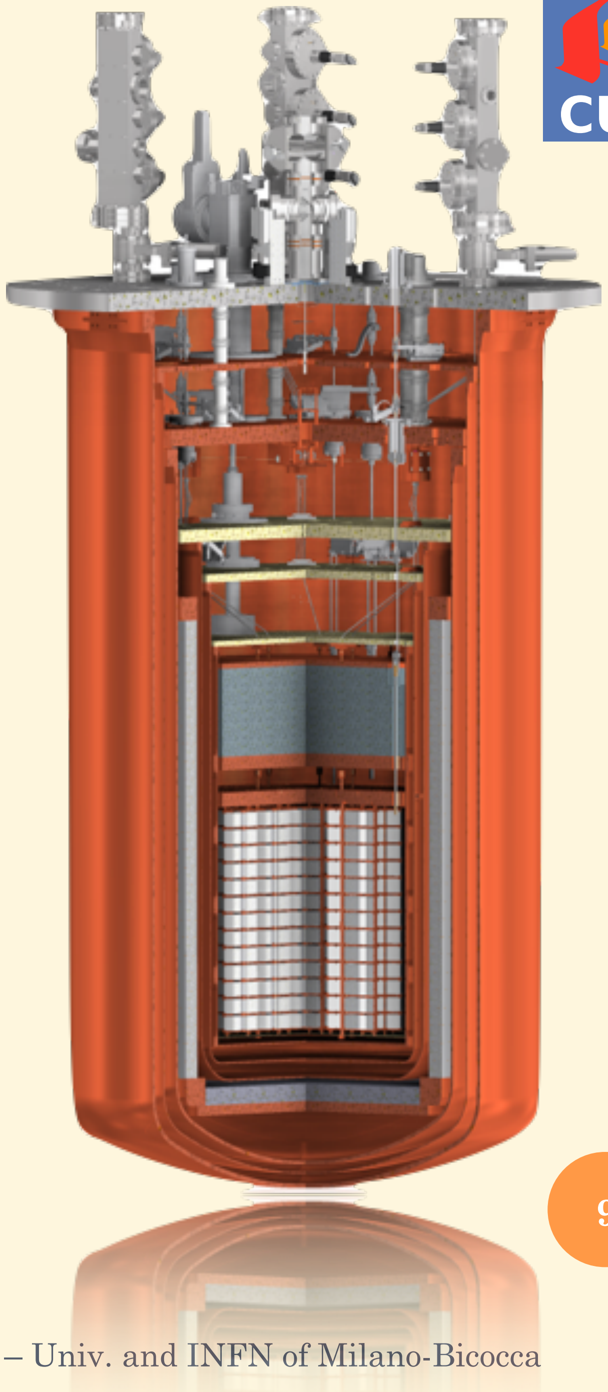
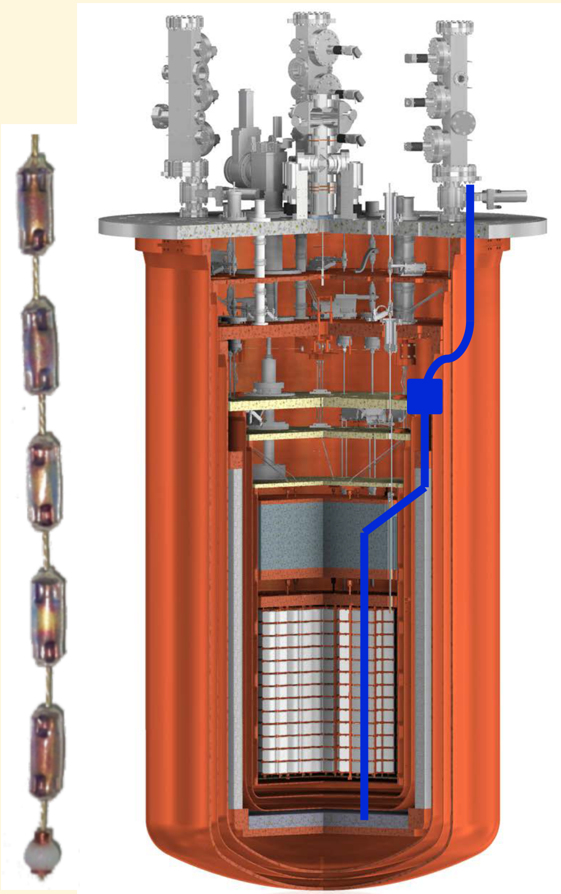
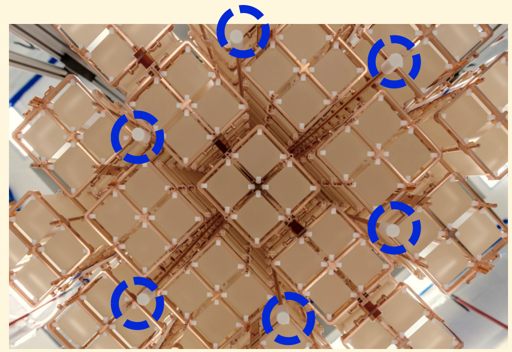
CUORE CRYOSTAT

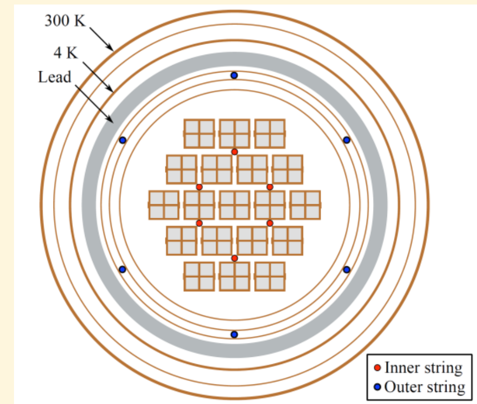
- Cryogen-free
- Base temperature <10 mK
- Experimental vol: ⌀ 900 mm × h 1370 mm
- Massive (10t) Pb shielding close to detector
- High cooling power
- Strict material selection
- Low mechanical vibration input on detector
- Independent detector suspension



Detector Calibration







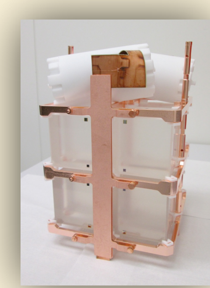
CHALLENGES

- Provide a uniform calibration of all the CUORE detectors
- Deployment of ^{232}Th sources (sausage-like strings) through the cryostat, from room temperature into the detector core

J. S. Cushman et al. NIM A 844 (2017) 32

CUORE COMMISSIONING

A 2y-long commissioning process

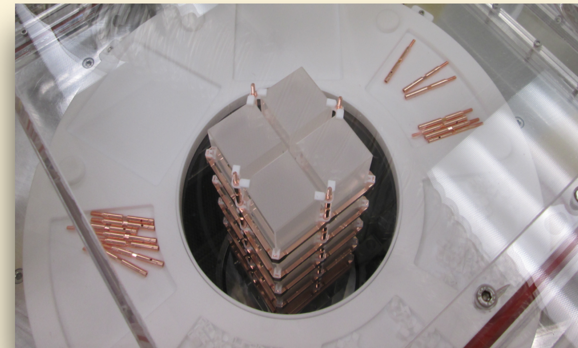
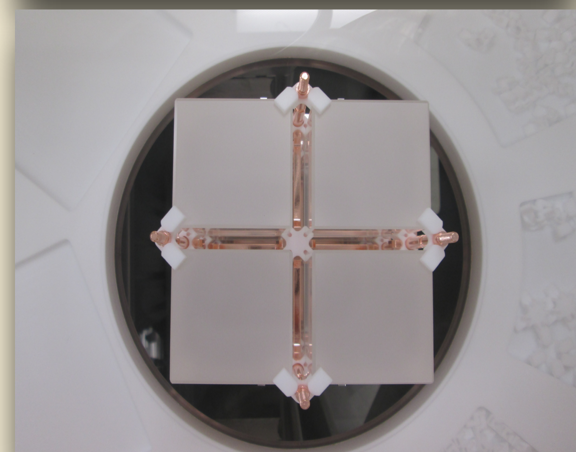
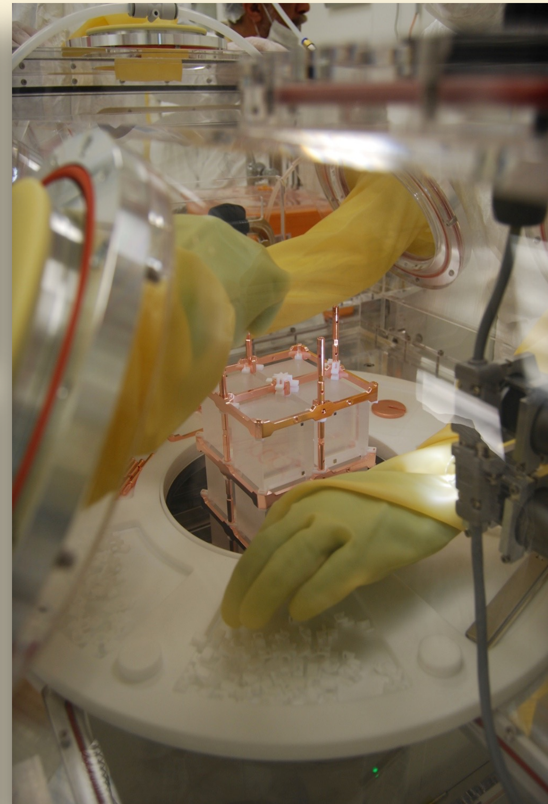


Insertion of few TeO_2 detectors

↓

Cryostat + Dilution Unit → Wiring → Top Pb shield / Detector Calibration System / Towers support plate / Fast Cooling System → lateral roman Pb shield

CUORE TOWERS ASSEMBLY

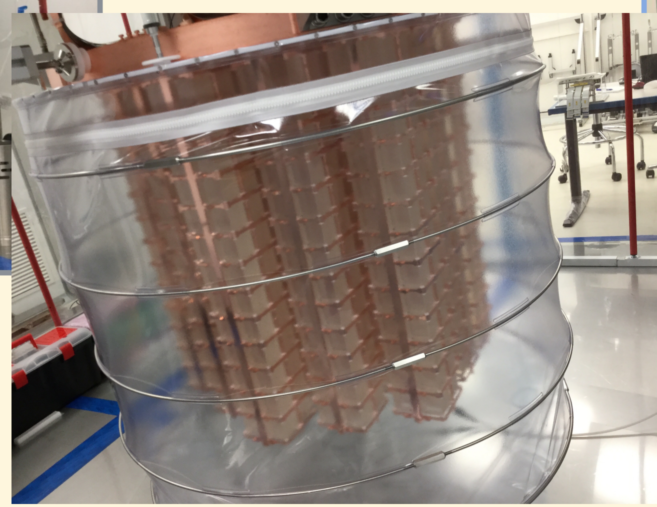





- Floor-by-floor construction in nitrogen flushed glove box.
- Minimize radon contamination at every step of the detector assembly.

CUORE DETECTOR INSTALLATION

- Performed in a custom-made CR flushed with Rn-free air (<0.1 Bq/m^3)
- Installation of the 19 towers completed on August 26, 2016.
- 984/988 operational channels.
- September-October 2016: installation of the cryostat interfaces and radiation shields.

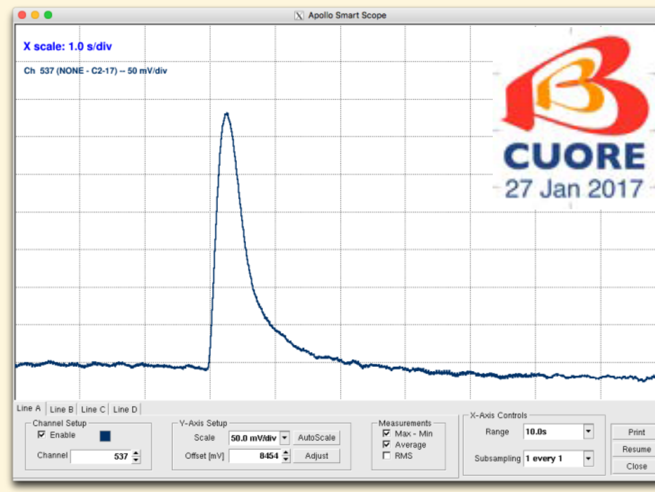
Detector "protective bag" flushed with nitrogen during installation stops



8 tons of internal Pb shielding

Detector cool down and pre-operation

- Cool down started at the beginning of December 2016.
- A stable temperature of ~7 mK was reached on January 27, 2017.
- We observed the first detector pulses just after the cool down.



Pre-operation

- DAQ and front-end electronics optimization.
- 984 Working point selections
- Mechanical/electrical noise reduction

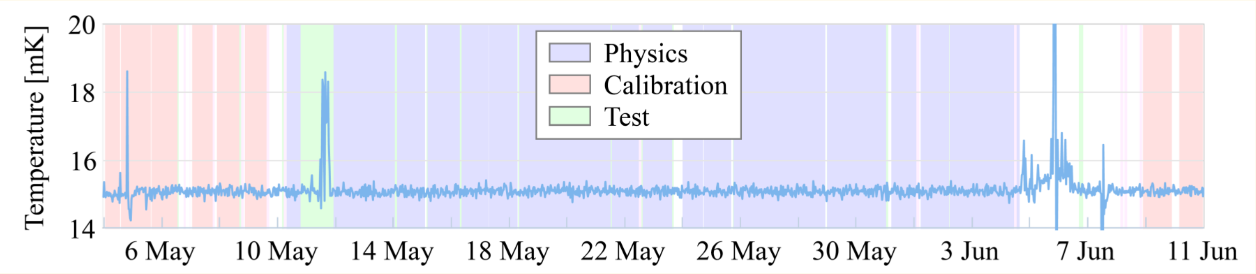
End of March 2017:

- optimization not yet complete
- decision to start calibrations and science runs

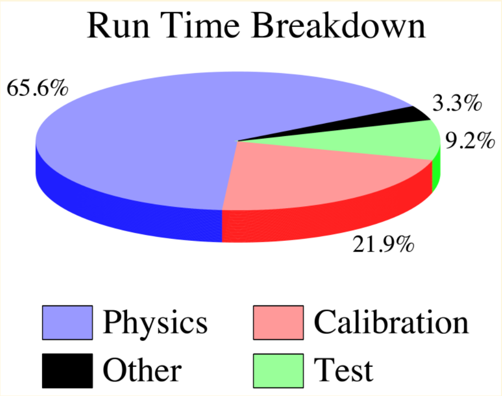
Debugging of the data QA and then first Physics data set

First Dataset

- 3 weeks of physics data bracketed by 2 calibration periods (May 4 - June 11, 2017)



- Detector temperature stable to within ~0.25 mK during data taking.
- Excellent data-taking efficiency.
- Much improved detector stability, compared to Cuoricino/CUORE-0.



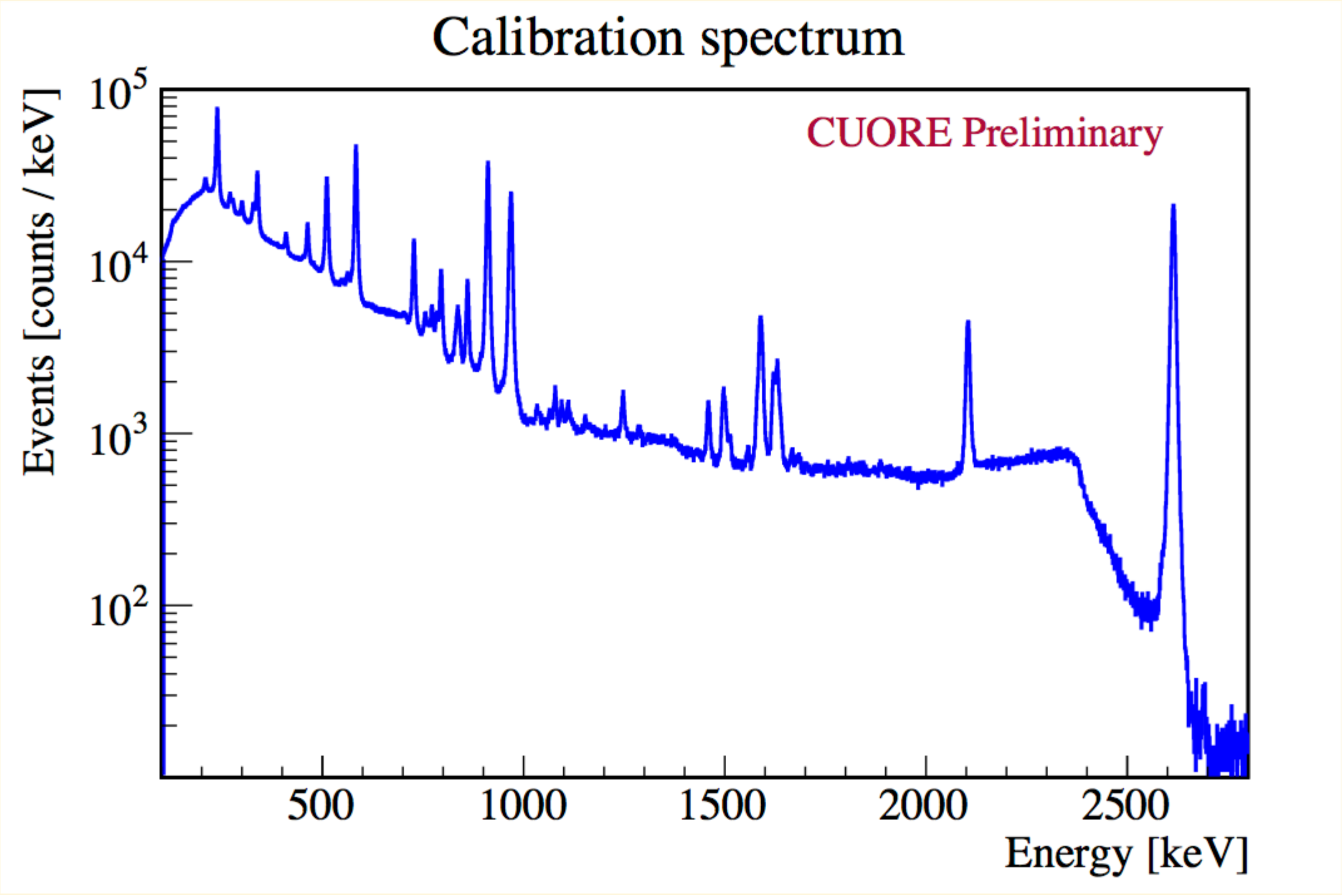
The first analysis was performed with 889 bolometers (90%).

Acquired statistics for $0\nu\beta\beta$ decay search:

- $^{nat}TeO_2$ exposure: 38.1 kg yr
- ^{130}Te exposure: 10.6 kg yr

CALIBRATION SPECTRUM

Summed energy spectrum of all the CUORE detectors



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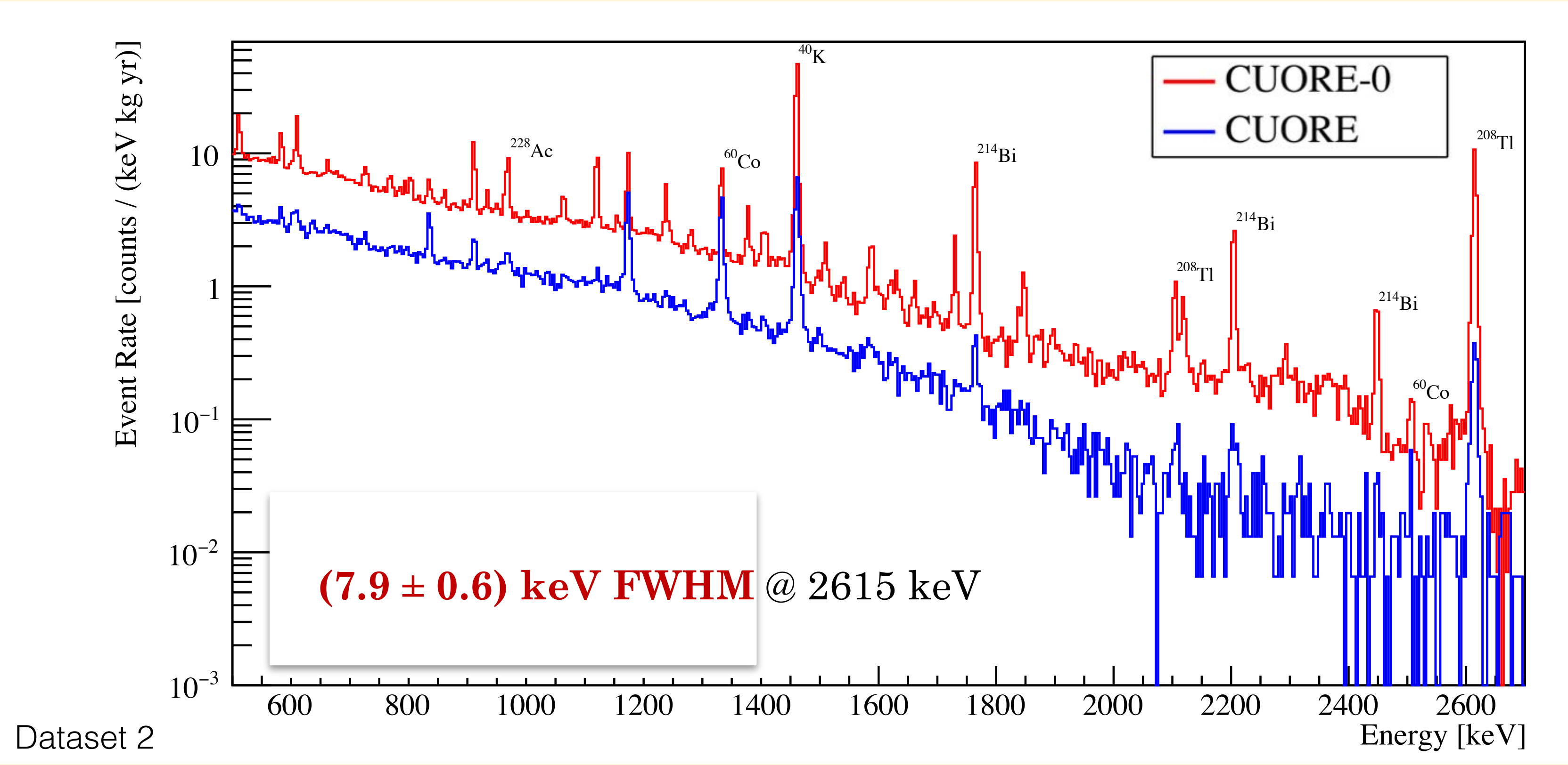
Background spectrum

Significant reduction of the background rate in the γ-region with respect to CUORE-0



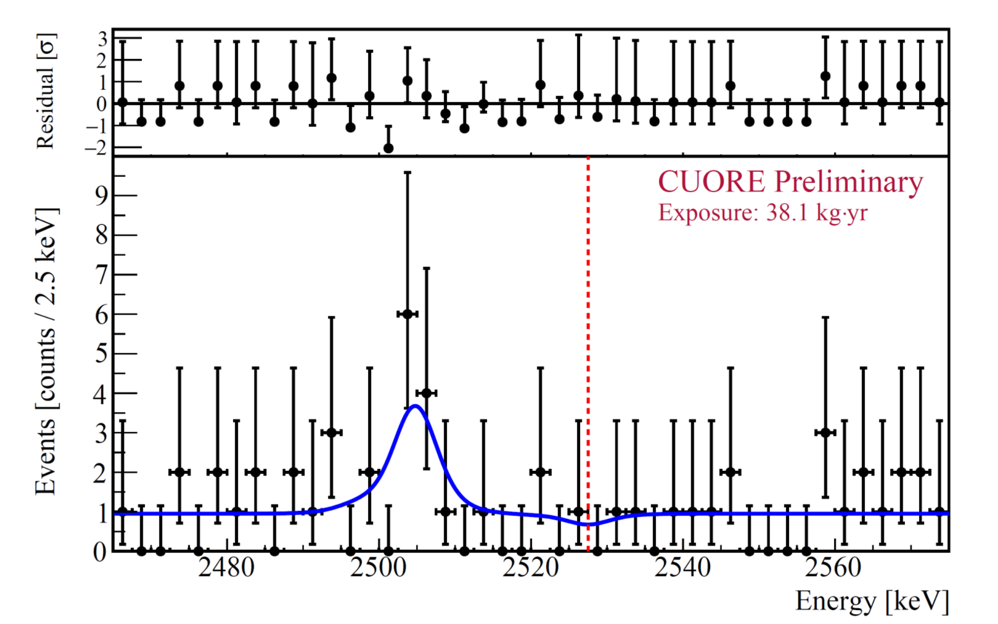
- Contaminations of the experimental setup: ^{232}Th, ^{238}U (and their daughters) and ^{40}K natural contaminations + cosmogenic activation (^{60}Co, …);
- Environmental μ, γ and neutrons.

Fit in the ROI

- We perform the fit in [2465 - 2575] keV, using a procedure similar to CUORE-0

Phys. Rev. C 93 (2016) 045503

- The fit has 3 components:
  - a posited peak at the Q-value of ^{130}Te
  - a floating peak to account for the ^{60}Co sum gamma line (~2505 keV)
  - a constant continuum background



Results

- Events in the ROI: 50
- ROI background index:

$$9.8^{+1.7}_{-1.5} \times 10^{-3}\,\text{c} / (\text{keV kg yr})$$

- Best fit decay rate:

$$(-0.03^{+0.07}_{-0.04}(\text{stat}) \pm 0.01(\text{syst})) \times 10^{-24}\,\text{yr}^{-1}$$

- Half life limit (90% CL):

$$T^{0\nu}_{1/2} > 4.5 \times 10^{24}\,\text{yr}$$

Combined result with CUORICINO and CUORE-0

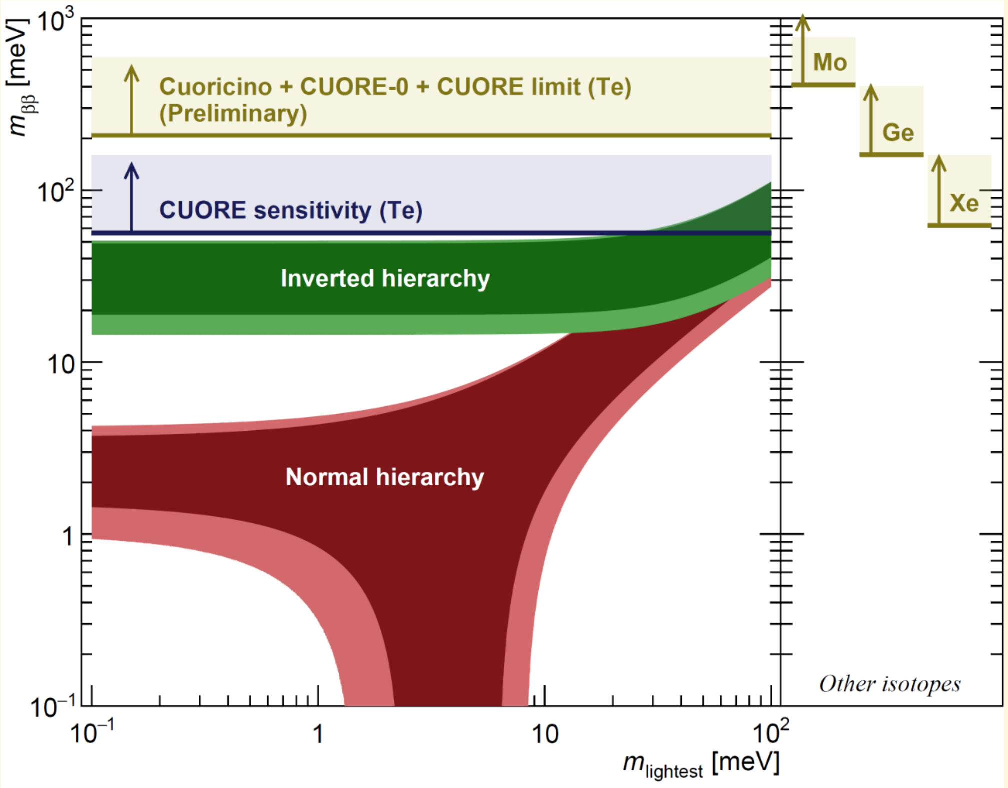
$$T^{0\nu}_{1/2} > 6.6 \times 10^{24}\,\text{yr (90\% CL)}$$

Combination with previous results

The new limit of ^{130}Te $0\nu\beta\beta$ half-life results in a **effective Majorana mass** limit in the following range, depending on the Nuclear Matrix Element (NME) used for calculation:

Effective Majorana mass limit:

$$m_{\beta\beta} < 210 - 590 \text{ meV}$$



NME:
Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 91, 024613 (2015)
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. Lett. 105, 252503 (2010)

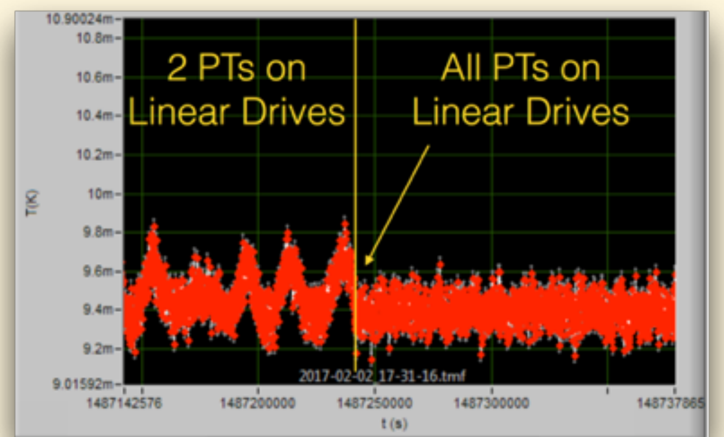
Experiments:
^{130}Te: 6.5×10^{24} yr from this analysis
^{76}Ge: 5.3×10^{25} yr from Nature 544, 47–52 (2017)
^{136}Xe: 1.1×10^{26} yr from Phys. Rev. Lett. 117, 082503 (2016)
^{100}Mo: 1.1×10^{24} yr from Phys. Rev. D 89, 111101 (2014)
CUORE sensitivity: 9.0×10^{25} yr

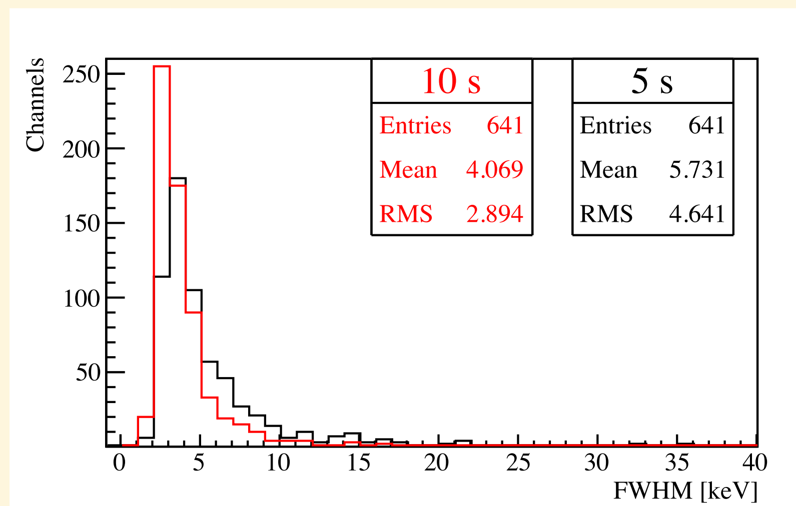
SECOND DET. OPTIMIZATION CAMPAIGN

Detector commissioning stopped in April to start science runs.
But there was still room for improvements

Detector optimization campaign restarted in June-July:

- Careful investigation/upgrades to the electronics grounding in the CUORE Faraday cage
- Active cancellation of the PT-induced noise
- Optimization of the operating temperature and detector working points
- Optimization of software bandwidth for pulse amplitude analysis
- Extend software trigger window from 5s to 10s
- Improved "baseline resolution" (energy resolution for 0 keV pulses) by ~25%





Second Dataset

1 full month of physics data (August)

RESULTS?

(PRL) Paper to appear on arXiV next week

THE EMBARGO IS UNTIL Oct. 23, 1 p.m. CEST

CUORE INAUGURATION @LNGS ON THAT SAME DAY

SUMMARY

- CUORE is the first ton scale bolometric 0νββ detector.
- The cryostat is working spectacularly well.
- With 3 weeks of physics data we have surpassed the CUORE-0+Cuoricino limit.
- Important information on detector performance (noise, resolutions, background).
- Background rates are consistent with the expectations.
- New dataset results will be presented at CUORE inauguration next Monday.

ON STREAMING