INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

The CUORE bolometric detector for neutrinoless double beta decay searches

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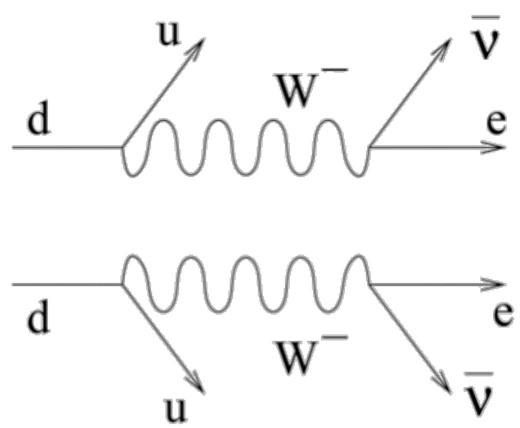
Double beta decay

Double beta decay is a very rare nuclear decay (N,Z) ➞ (N-2, Z+2)

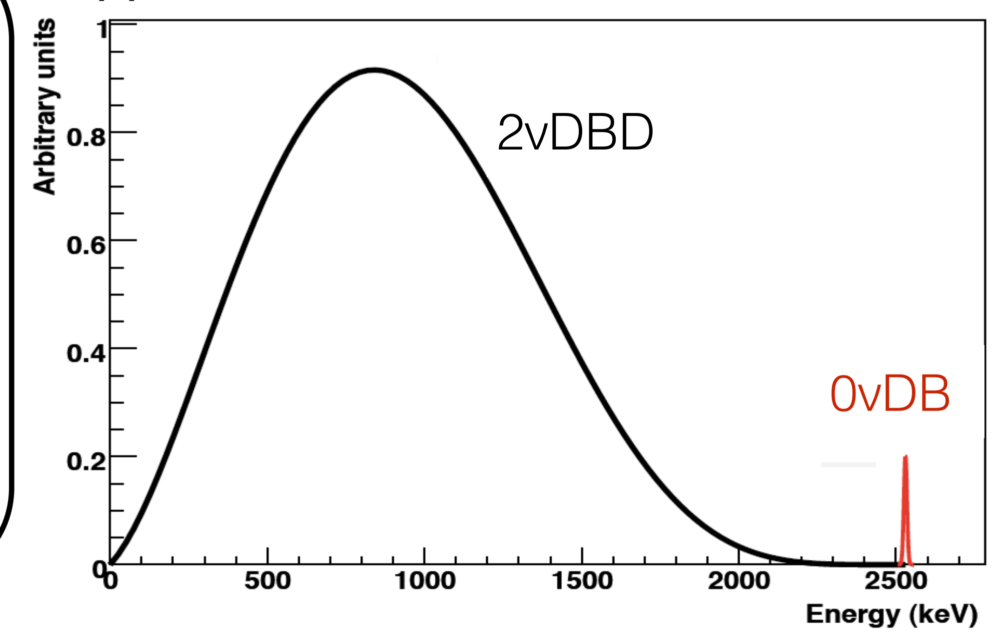
$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}$$

2νββ



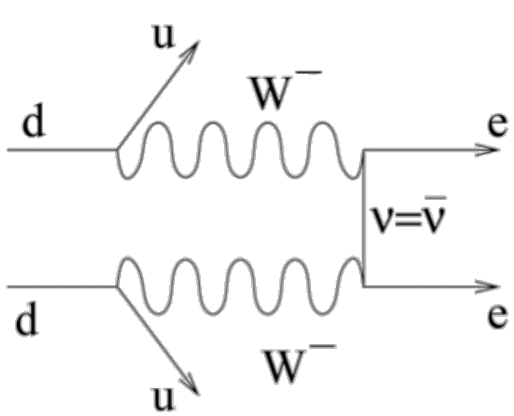
- 2nd order process allowed in SM
- observed in several nuclei
- τ~10[19-21] y

ββ summed e^- energy spectrum



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

0νββ



- Lepton number violation ΔL=2
- exists for Majorana neutrinos $\nu = \bar{\nu}$
- τ>10[24-25] y

Nuclear matrix element

$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q,Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

Phase space integral

Effective neutrino mass

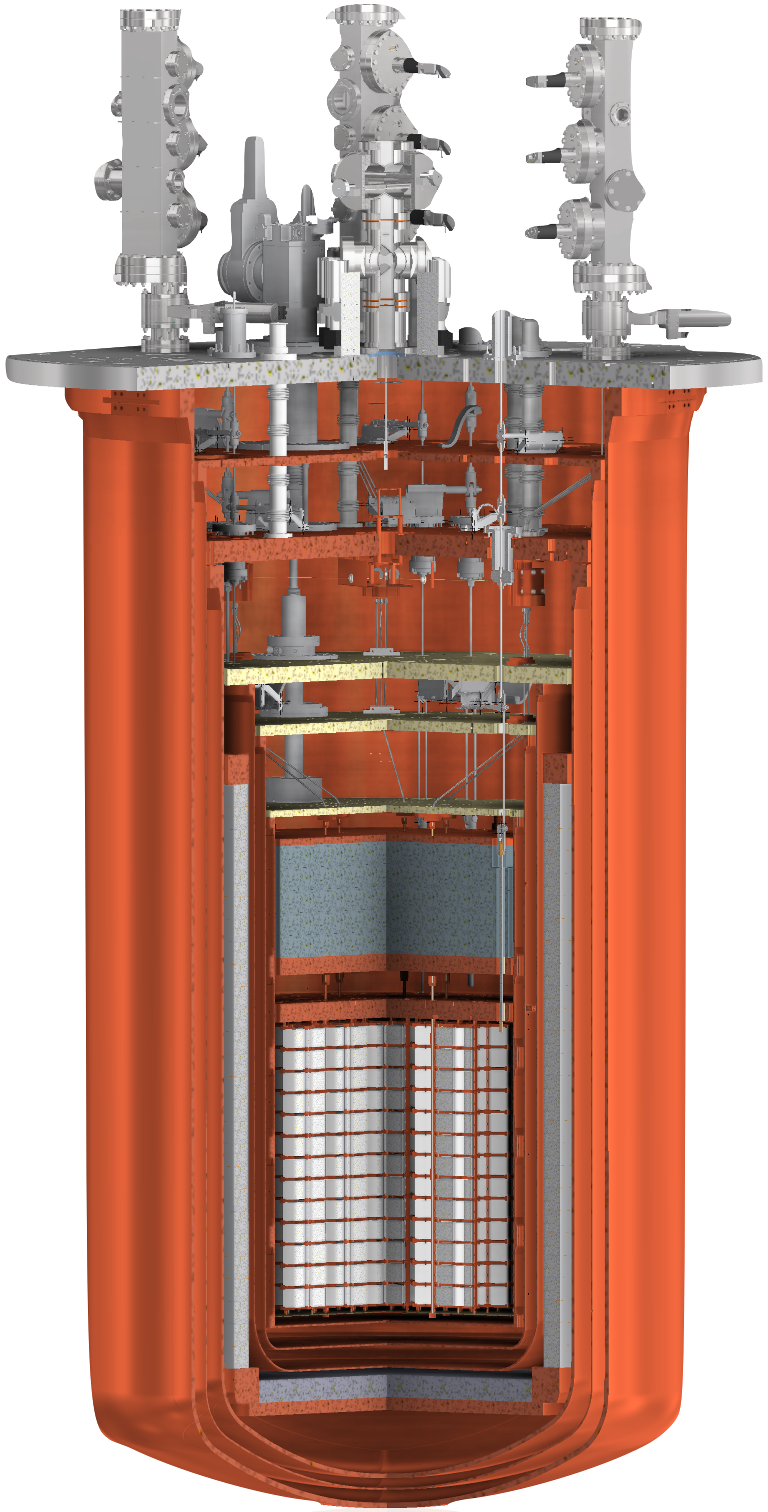
$$m_{\beta\beta} = |\sum_i m_{\nu_i} U^2_{ei}|$$

The CUORE experiment

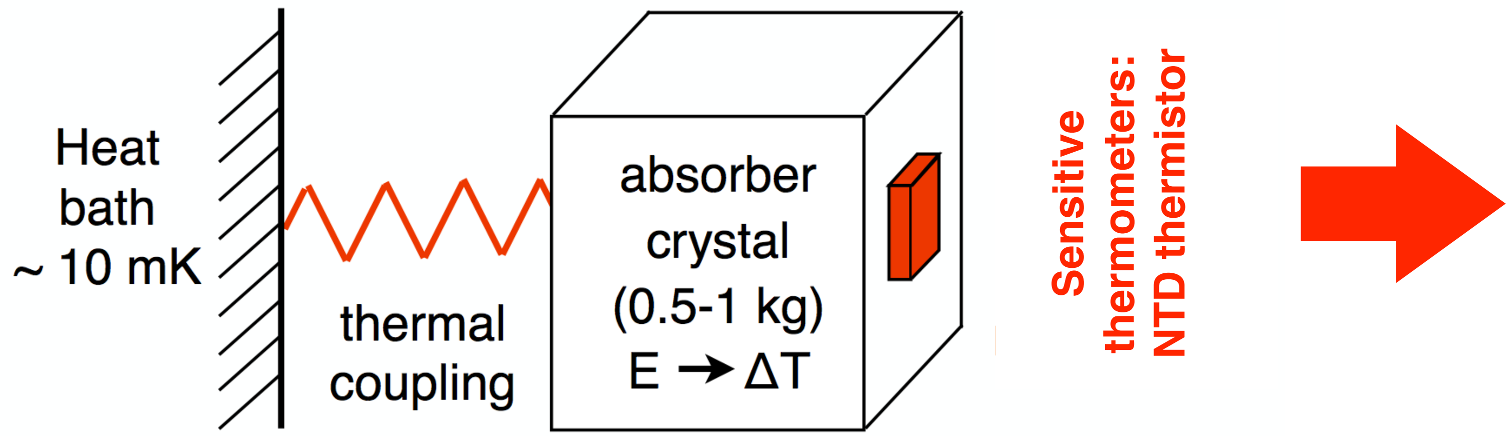
Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

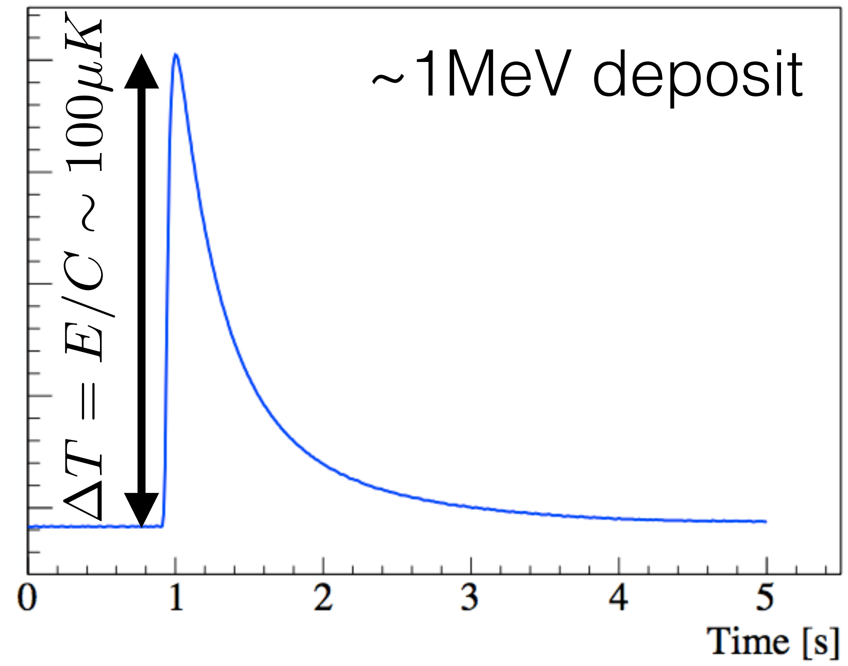
Operate a huge thermal detector array in a low radioactivity and low vibrations environment

- Closely packed array of 988 TeO_2 crystals (19 towers of 52 crystals 5×5×5 cm^3, 0.75 kg each)
- Mass of TeO_2: 742 kg (206 kg of ^{130}Te)
- Energy resolution goal: 5 keV FWHM @ 2615 keV
- Operating temperature: ~10 mK
- Mass to be cooled down: ~15 tonnes (Pb, Cu and TeO_2)
- Background aim: 10^{-2} c/keV/kg/year
- $T_{1/2}$ sensitivity in 5 years (90% C.L.): ~ 9 x 10^{25} yr



TeO_2 bolometers





- $^{nat}TeO_2$ crystals —> source = detector
- NTD-Ge thermistor (R@work ~ 10-100 MΩ)

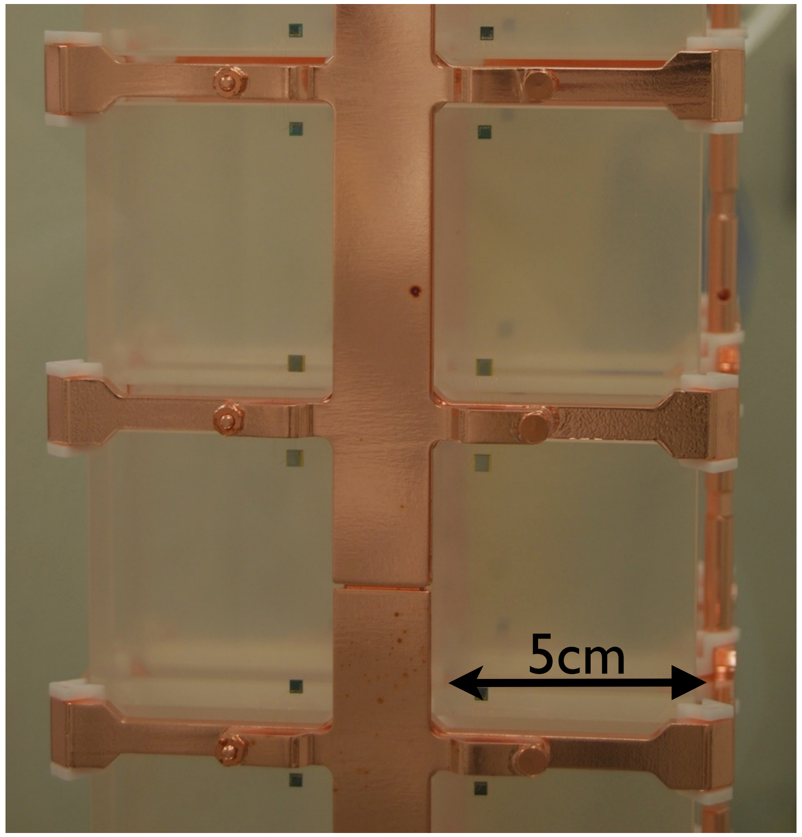
$$R(T)=R_0 \exp\left[\frac{T_0}{T}\right]^{1/2}$$

- Resolution @0νββ energy (2528 keV):

  ΔE= 5-7 keV FWHM

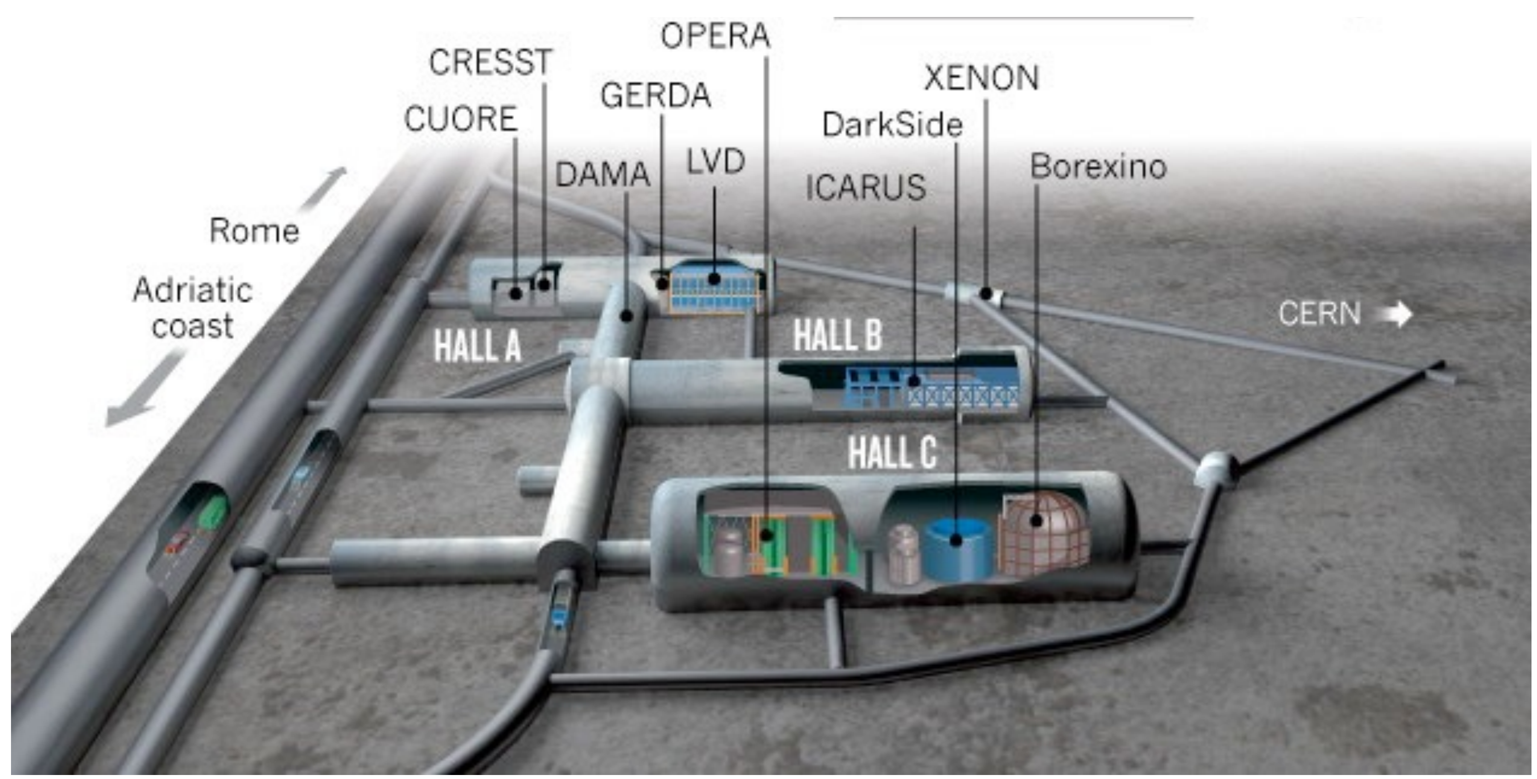
ΔT_{NTD} ~ 10-20 μK/MeV
$\Delta T_{crystal}$ ~ 100 μK/MeV

ΔV_{NTD} ~ 300 μV/MeV
ΔR_{NTD} ~ 3 MΩ/MeV



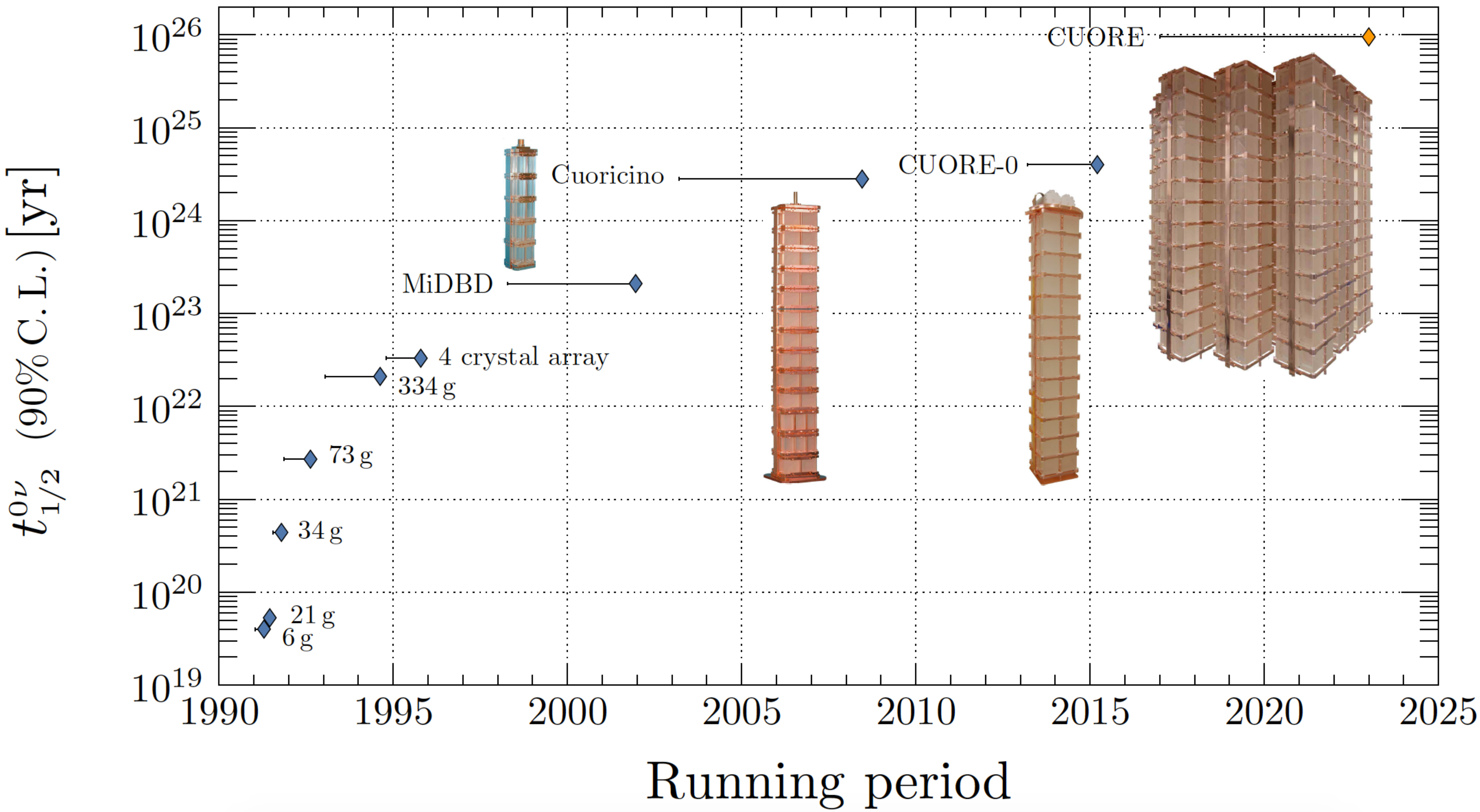
CUORE @ LNGS

- Gran Sasso National Laboratory
- ~3600 m.w.e. deep
- μs: ~3×10^{-8}/(s cm^2)
- γs: ~0.73/(s cm^2)
- neutrons: 4×10^{-6} n/(s cm^2)

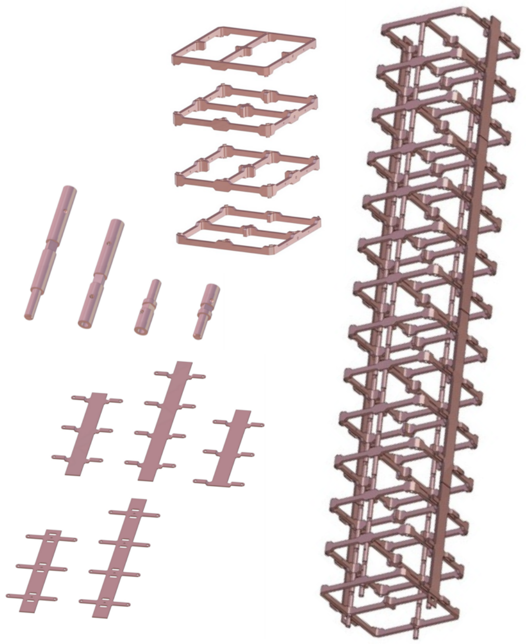


Arrays of TeO_2 bolometers

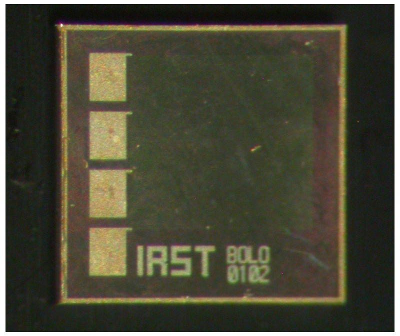
CUORE



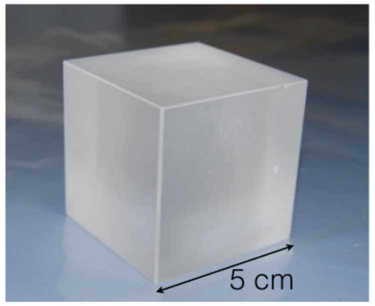
CUORE-module: a tower



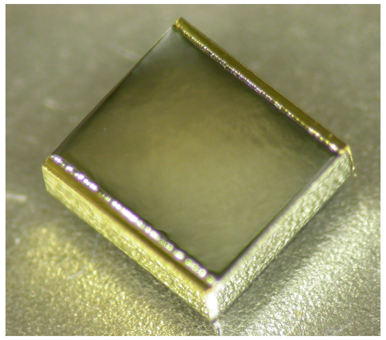
~2000 Cu NOSV components



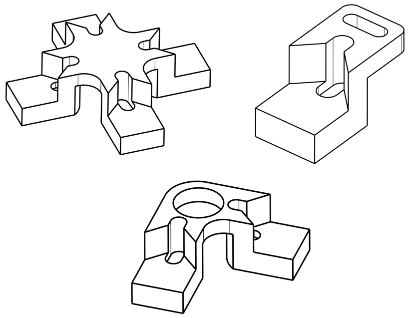
52 Si heaters



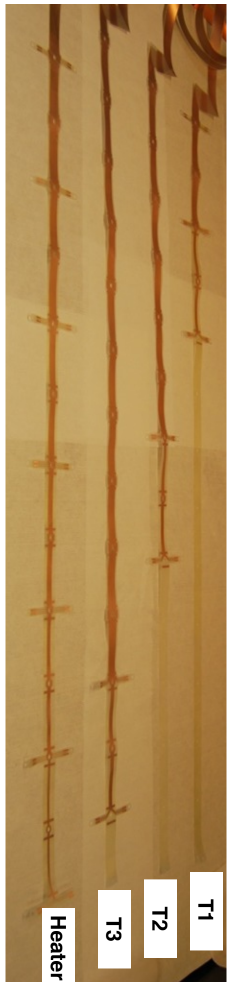
52 TeO_2 crystals



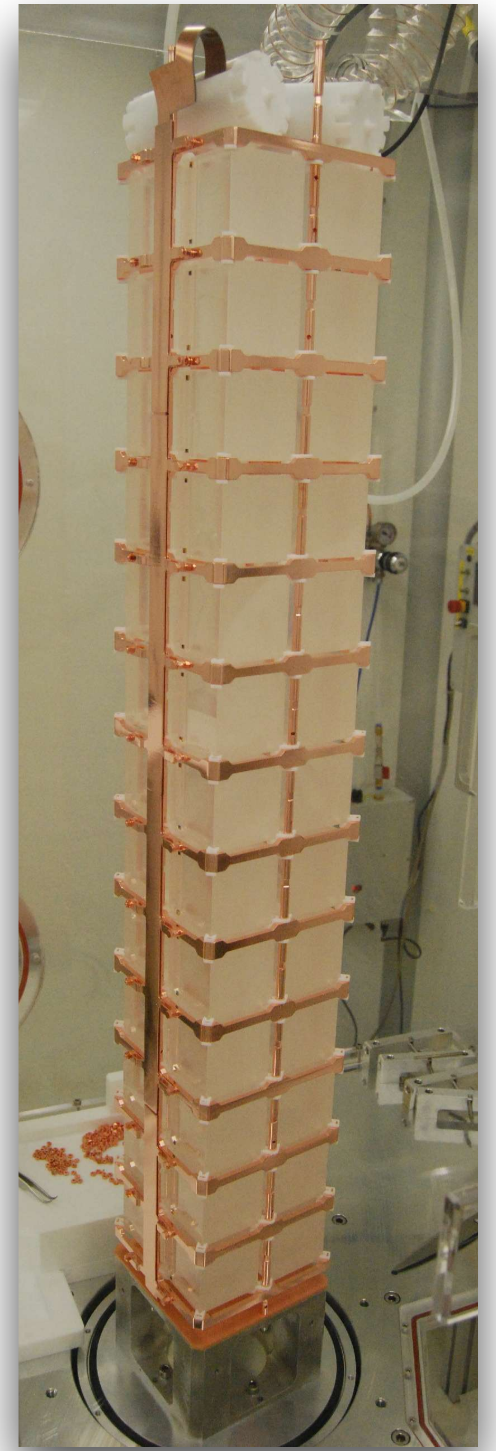
52 Ge NTDs



234 PFTE holders



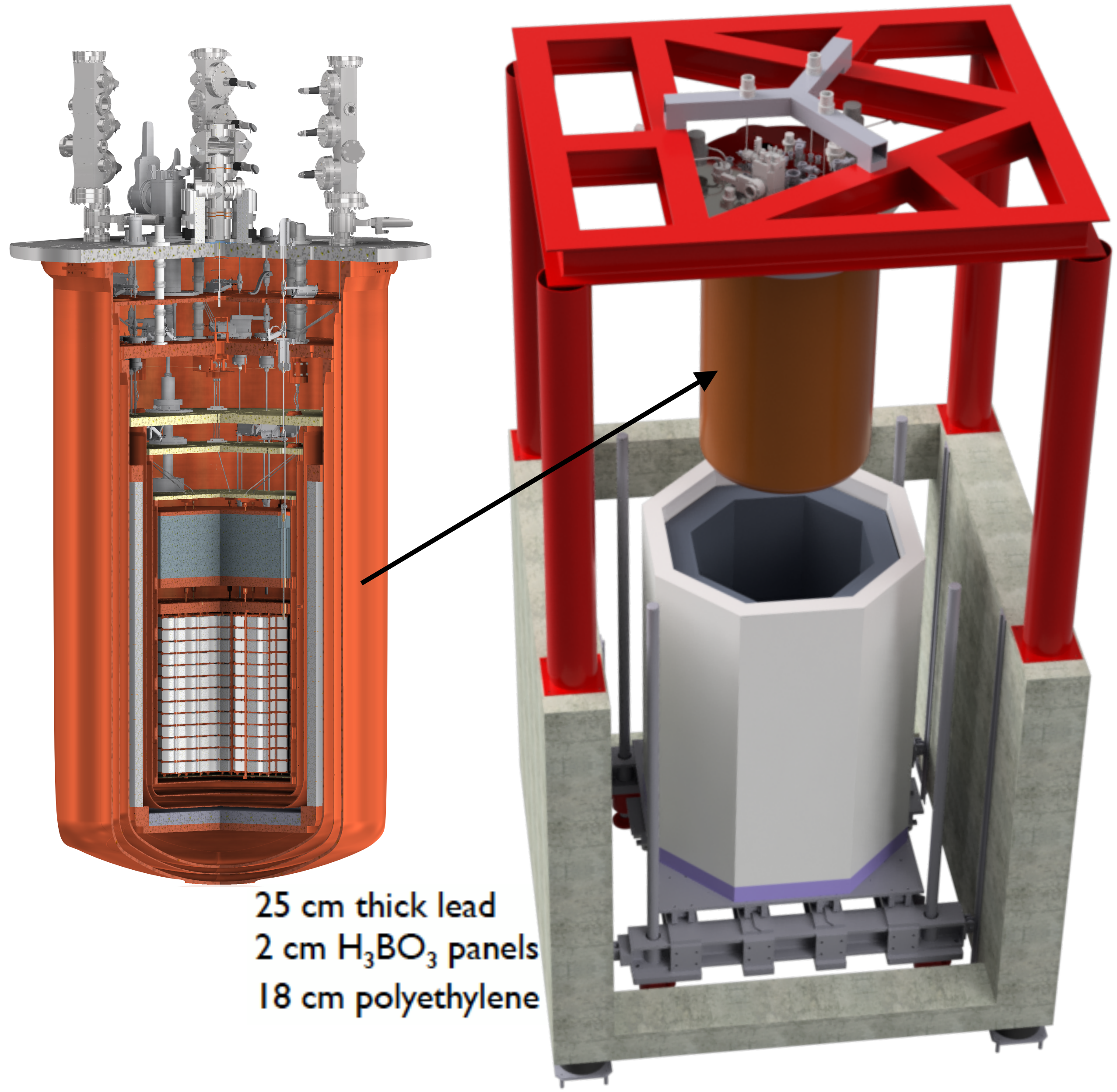
8 Cu-PEN cables



- Strict material selection (e.g. raw materials)
- Strict surface cleaning technique for Cu and TeO_2
- Minimization of Rn exposure (Glove Box assembly)

The cryogenic infrastructure

- Experimental requirements
  - large experimental volume for detector and shielding
  - stable base temperature @ 10mK
  - low radioactive background from the cryogenic apparatus
  - high system reliability to guarantee years of operation
  - low vibration environment

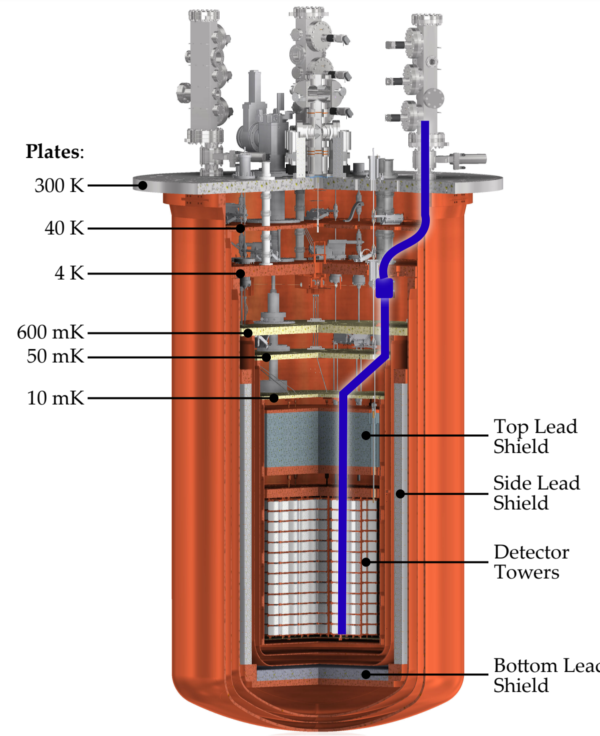


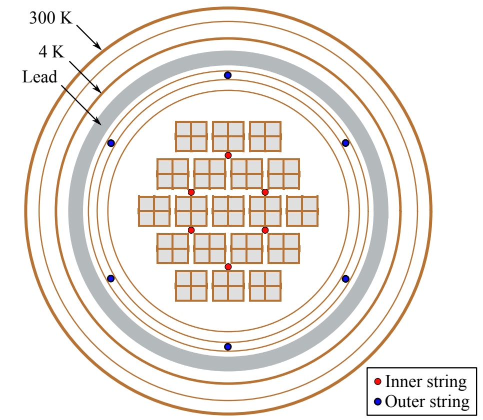
- Cryogen-free cryostat
- Fast Cooling System (4He gas) down to ~50K
- 5 Pulse Tubes cryocooler down to 4K
- Dilution Refrigerator down to operating temperature ~10mK

Cryostat total mass ~30 tons
Mass to be cooled < 4K: ~15tons
Mass to be cooled < 50mK: ~3 tons

Cryostat subsystems

SHIELDINGS

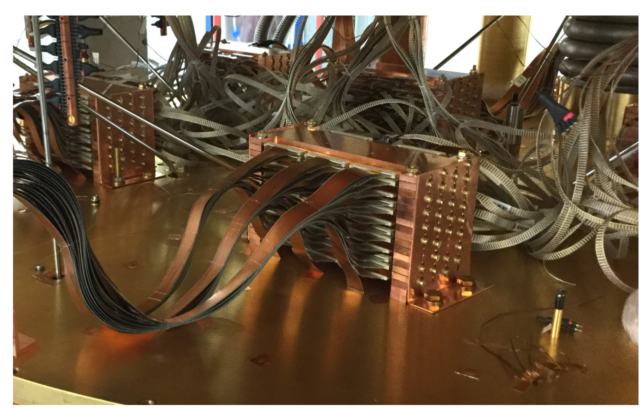


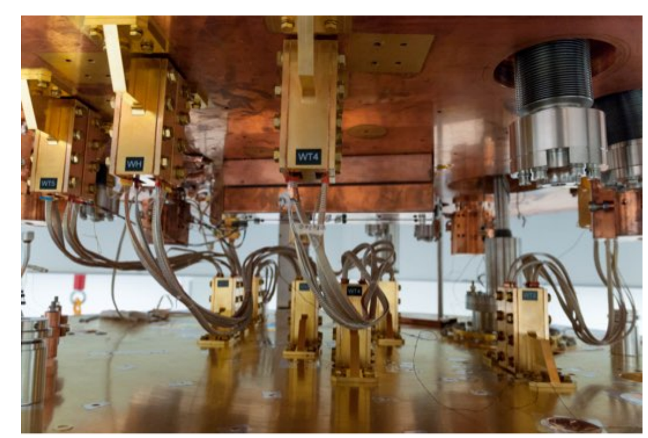


DCS
Detector
Calibration
System

12 ^{232}Th γ-ray sources (thoriated tungsten) are outside cryostat during physics data-taking and lowered into cryostat and cooled to base temperature for calibration

WIRING

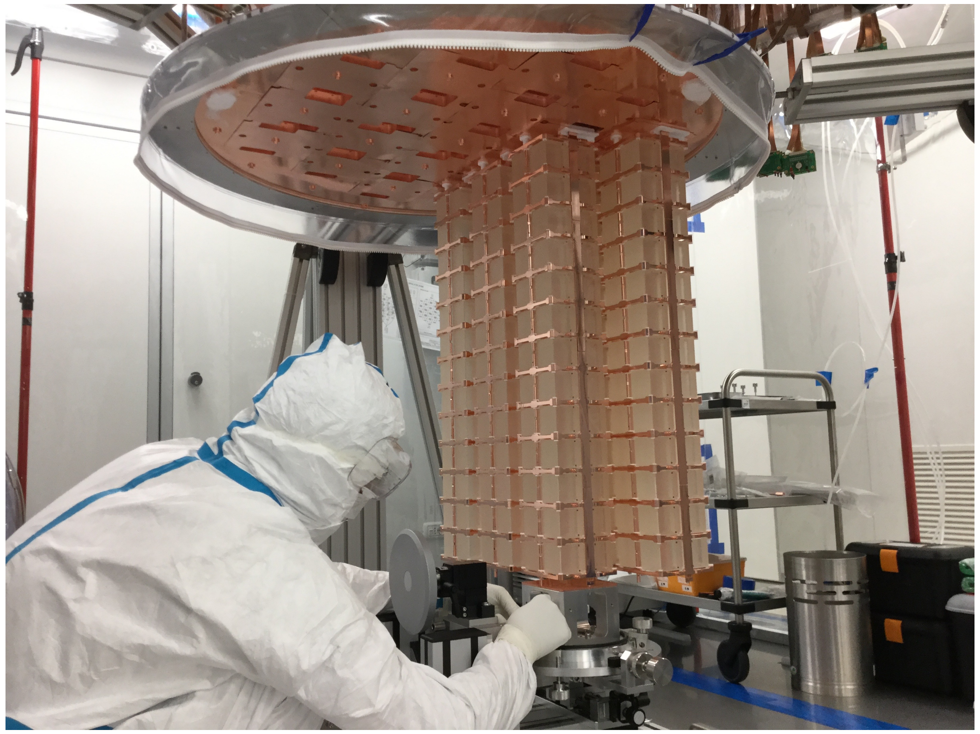


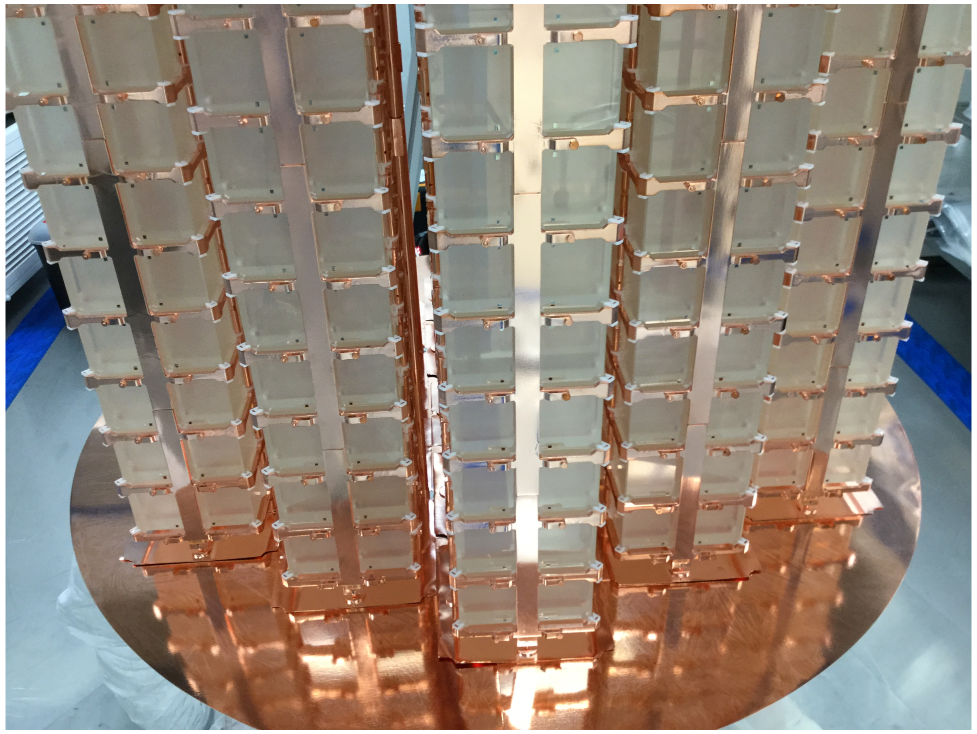


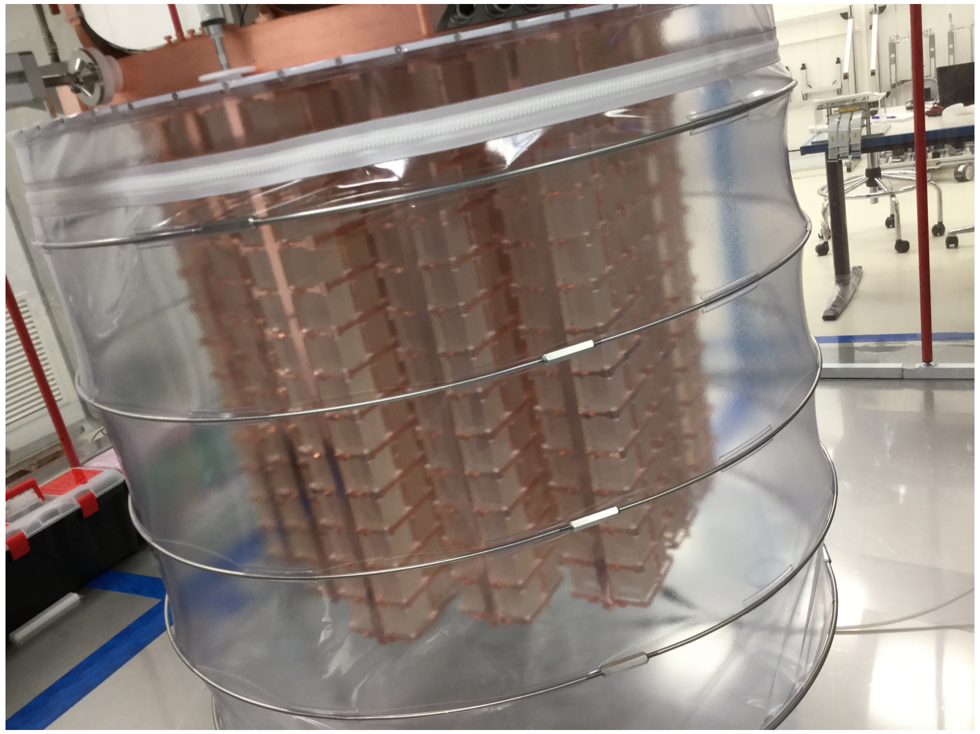
- 2600 wires from 300 K to Mixing Chamber
- 171 PEN-Cu cables from Mixing Chamber to NTDs

Detector installation

- Performed in a radon-free environment:
    - protected area inside the CUORE clean room, flushed with radon-free air (Rn concentration <1 mBq/m^3)
- Completed at the end of August 2016
- Cool down started at the beginning of December 2016. The cryostat reached a stable base temperature of ~7mK on Jan 27, 2017.



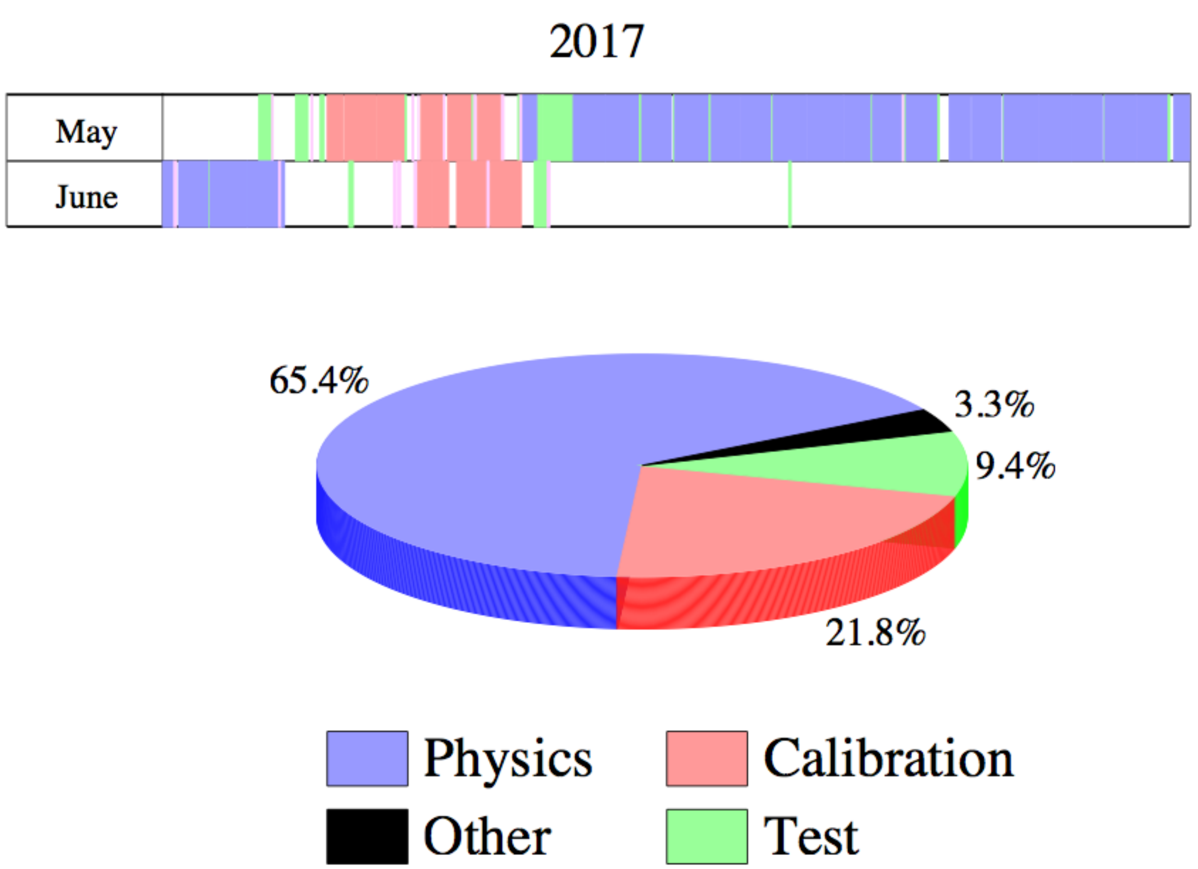




Physics data taking

- Science operations started on April 14th, 2017.
    - Dataset1: very short (identified issue with the thermistor bias on about 1/3 of the channels)
    - Dataset2: 3 weeks of physics data, plus an initial and a final calibration.
- Acquired statistic for 0νββ decay search:
    - $^{nat}TeO_2$ exposure: 38.1 kg yr
    - ^{130}Te exposure: 10.6 kg yr

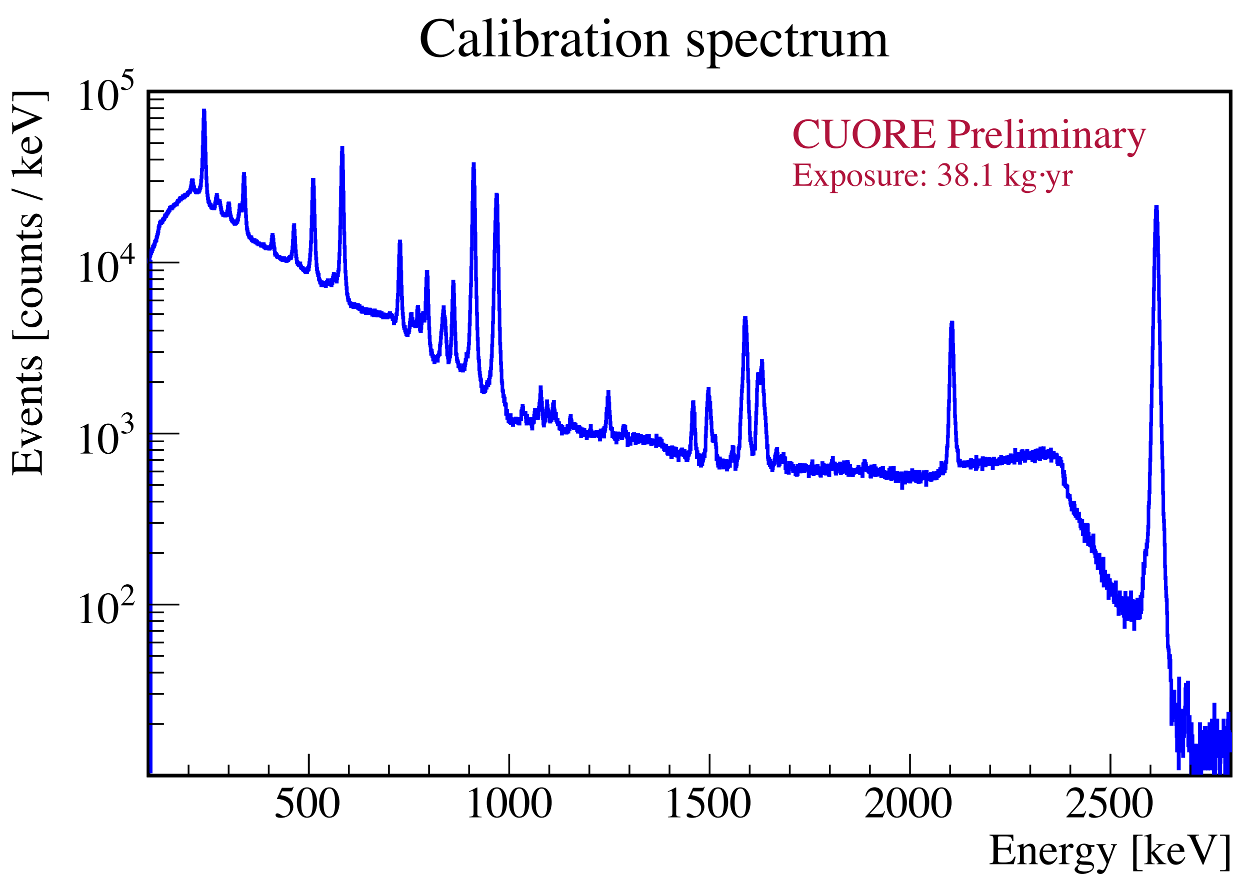
Dataset 2 time breakdown

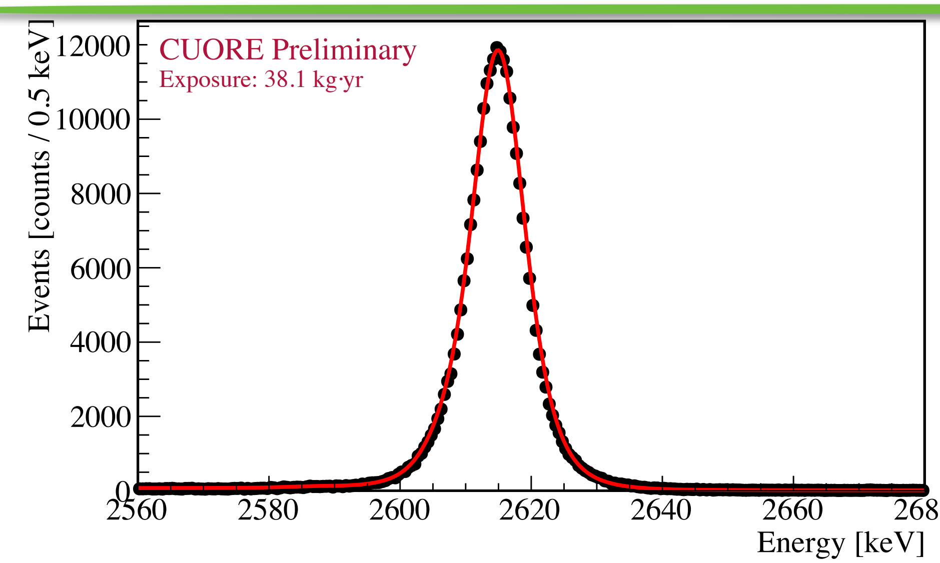


- Operational performance:
    - 984/988 operational channels
    - Excellent data-taking efficiency

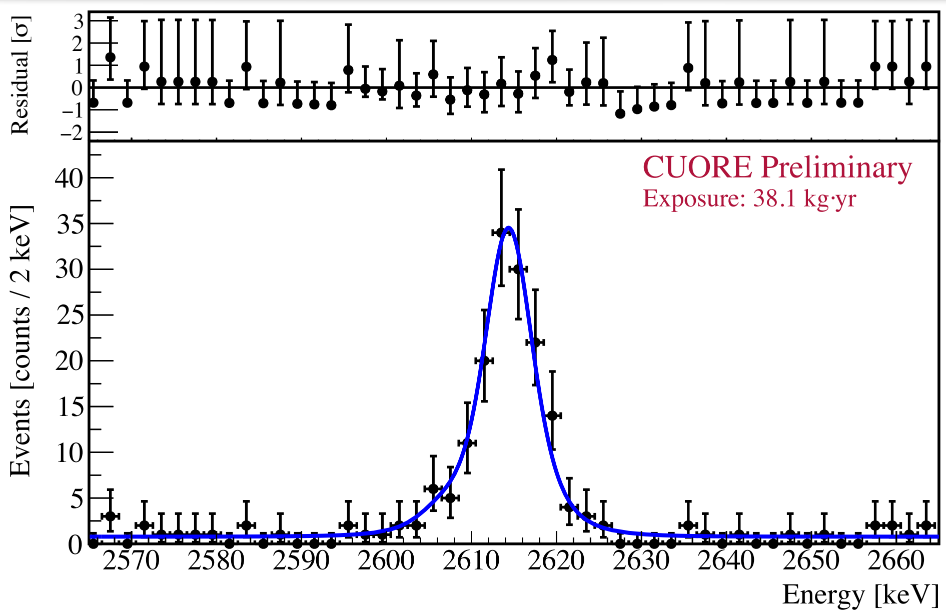
Calibration spectrum

- ^{232}Th sources deployed inside the CUORE detector
- Energy spectrum of the CUORE detectors (899 channels selected for analysis: 90% best performing channels for initial analysis)



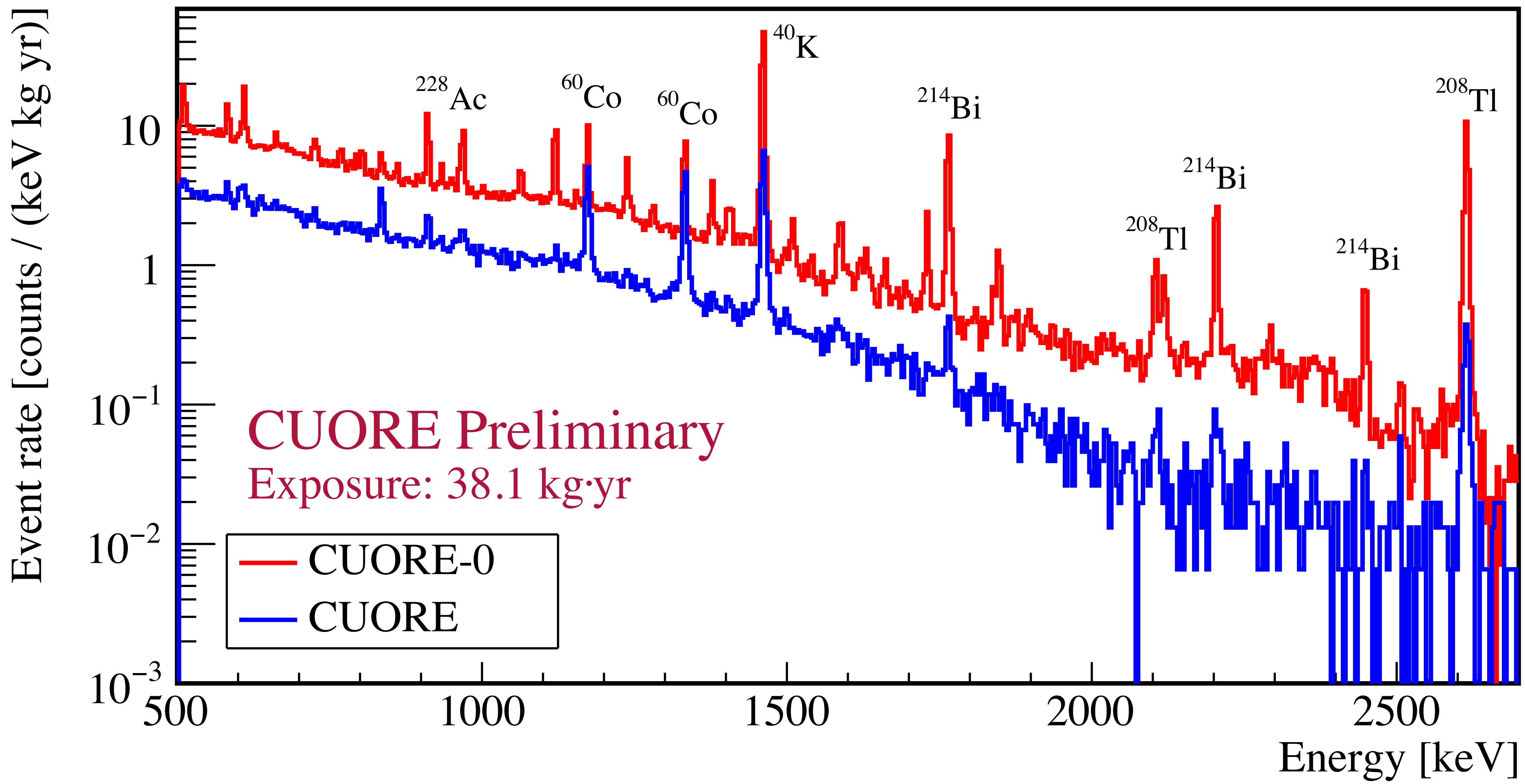


Average ("harmonic mean") energy resolution in calibration runs:
10.6 keV FWHM



Better performance in physics data:
(7.9 ± 0.6) keV FWHM

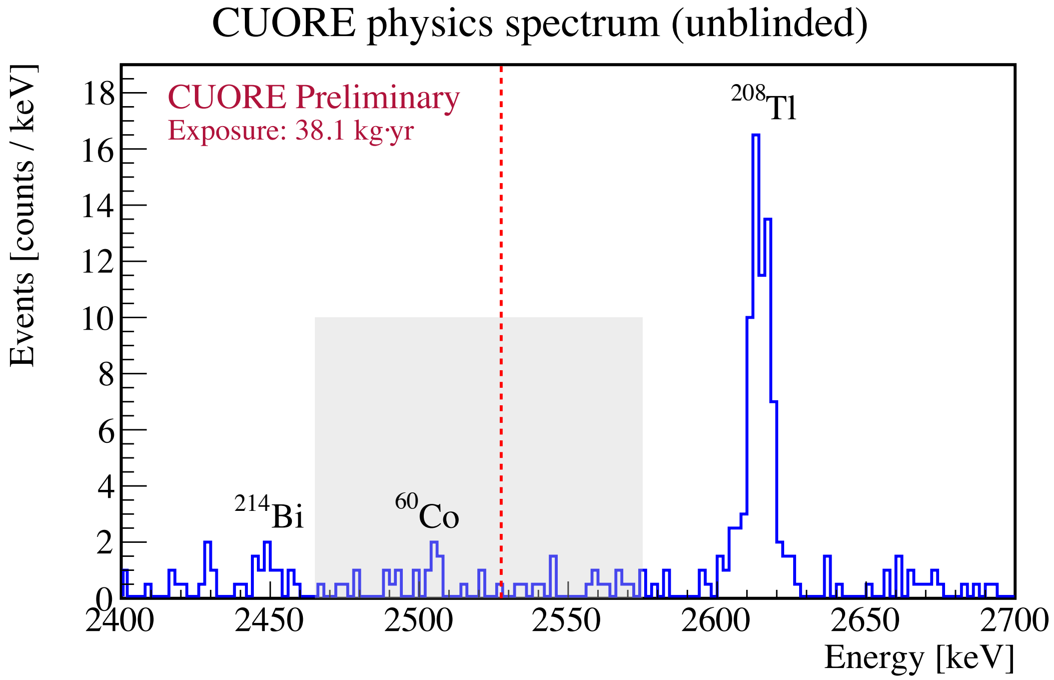
CUORE Background Spectrum

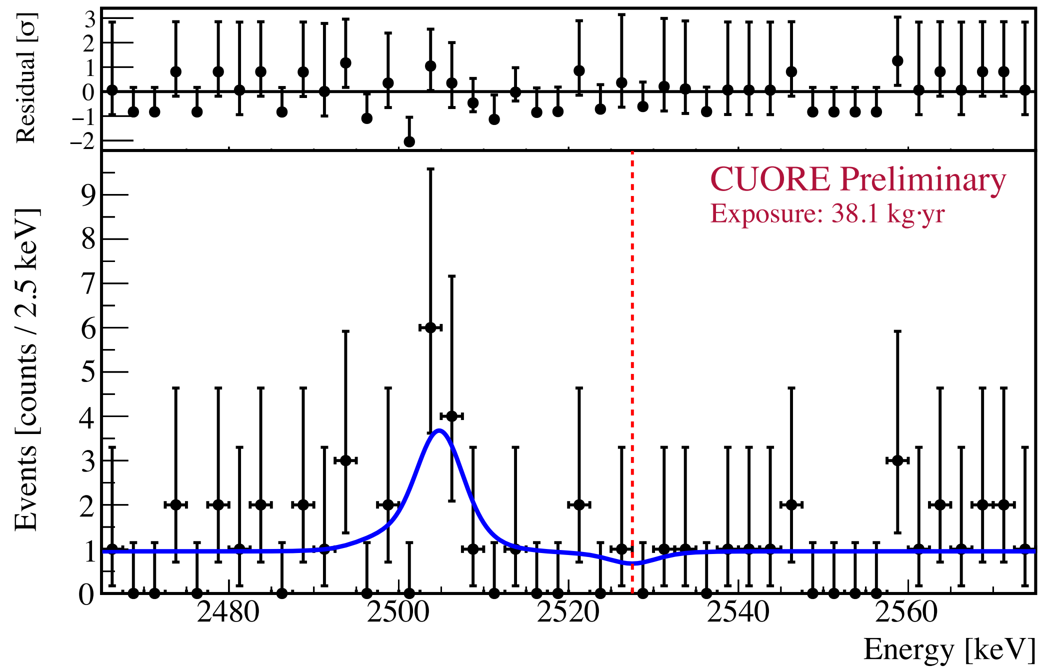


- Significant reduction in the γ region with respect to the prototype CUORE-0 (as expected)
- Spectrum is consistent with the background expectations

0νββ analysis

- Simultaneous unbinned extended maximum likelihood fit in [2465-2575] keV
- 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, (multi-Compton γ from ^{208}Tl and surface α events)





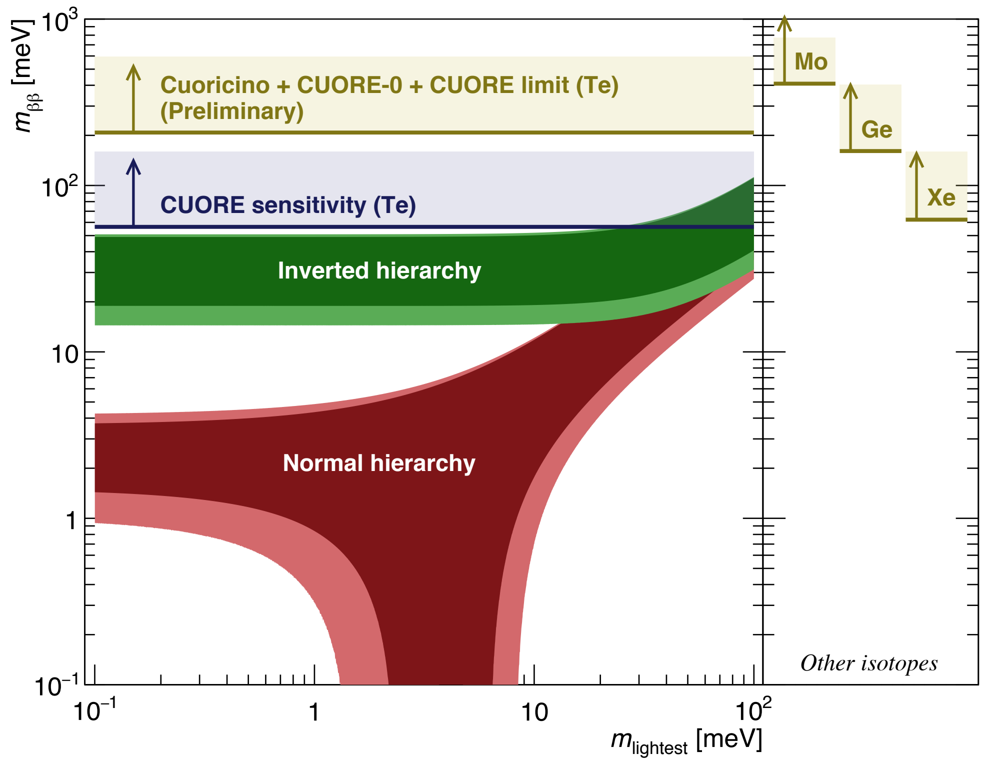
FIT RESULT:

ROI background index:
$(9.8_{-1.5}^{+1.7}) \times 10^{-3}$ c/(keV kg yr)

Half-life limit (90%C.L including syst.):
> 4.5 x 10^{24} yr

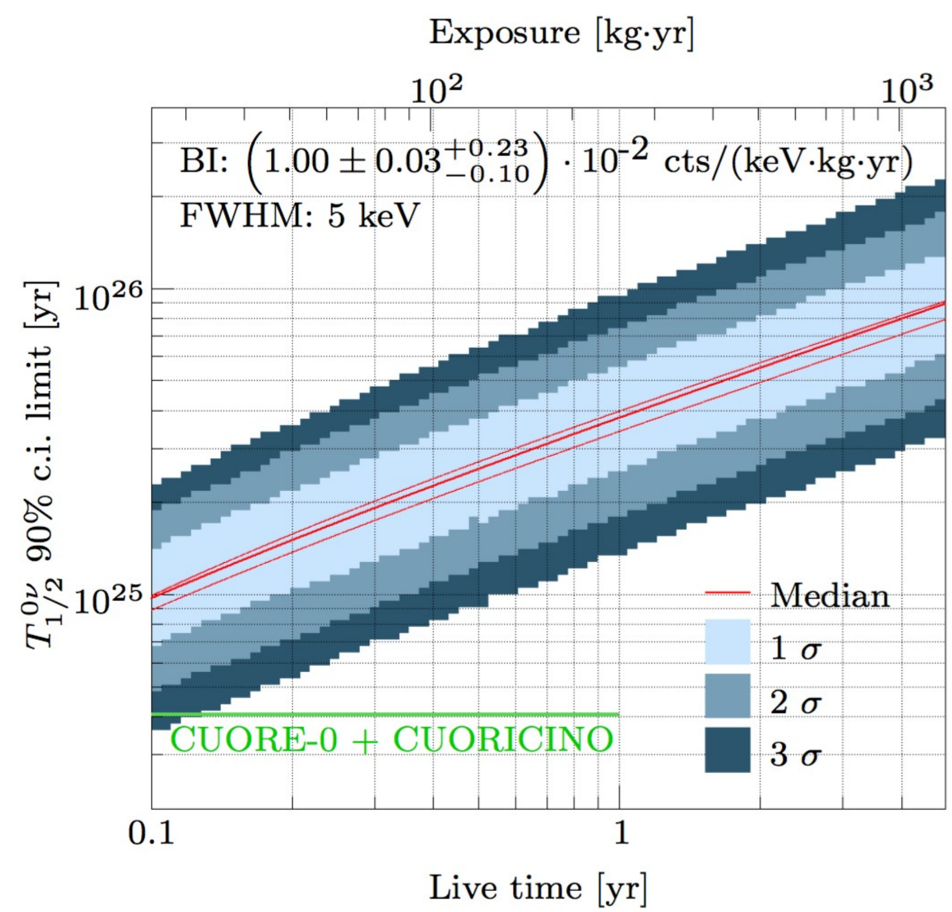
Outlook

- We combined the CUORE result with the existing ^{130}Te exposure: 19.75 kg·yr of Cuoricino and 9.8 kg·yr of CUORE-0



$T_{0\nu}(^{130}Te) > 6.6 \times 10^{24}$ yr

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



FWHM: 5keV

exclusion sensitivity (90% C. L.):

- $2 \cdot 10^{25}$ yr after 3 months
- $9 \cdot 10^{25}$ yr after 5 yr

discovery potential (3σ)

- $7 \cdot 10^{24}$ yr after 3 months
- $4 \cdot 10^{25}$ yr after 5 yr

Conclusion

- CUORE is the first tonne-scale bolometric $0\nu\beta\beta$ detector.
- The cryogenic system works exceptionally well.
- CUORE is most sensitive ^{130}Te experiment to date after just 3 weeks of data taking
- Invaluable operational experience, information on detector performance and backgrounds, end-to-end analysis
- Background rates consistent with expectations
- A further optimization of detector performance is possible.
- Data taking has restarted at the end of July 2017, more results will come shortly —> Stay tuned!

The CUORE Collaboration