«ETTORE MAJORANA» FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE
TO PAY A PERMANENT TRIBUTE TO GALILEO GALILEI, FOUNDER OF MODERN SCIENCE AND TO ENRICO FERMI, THE "ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS

39th Course: NEUTRINOS IN COSMOLOGY, IN ASTRO-, PARTICLE- AND NUCLEAR PHYSICS

ERICE–SICILY: 16 – 24 SEPTEMBER 2017

CUORE

FIRST RESULTS FROM THE CUORE EXPERIMENT

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on behalf of the CUORE collaboration

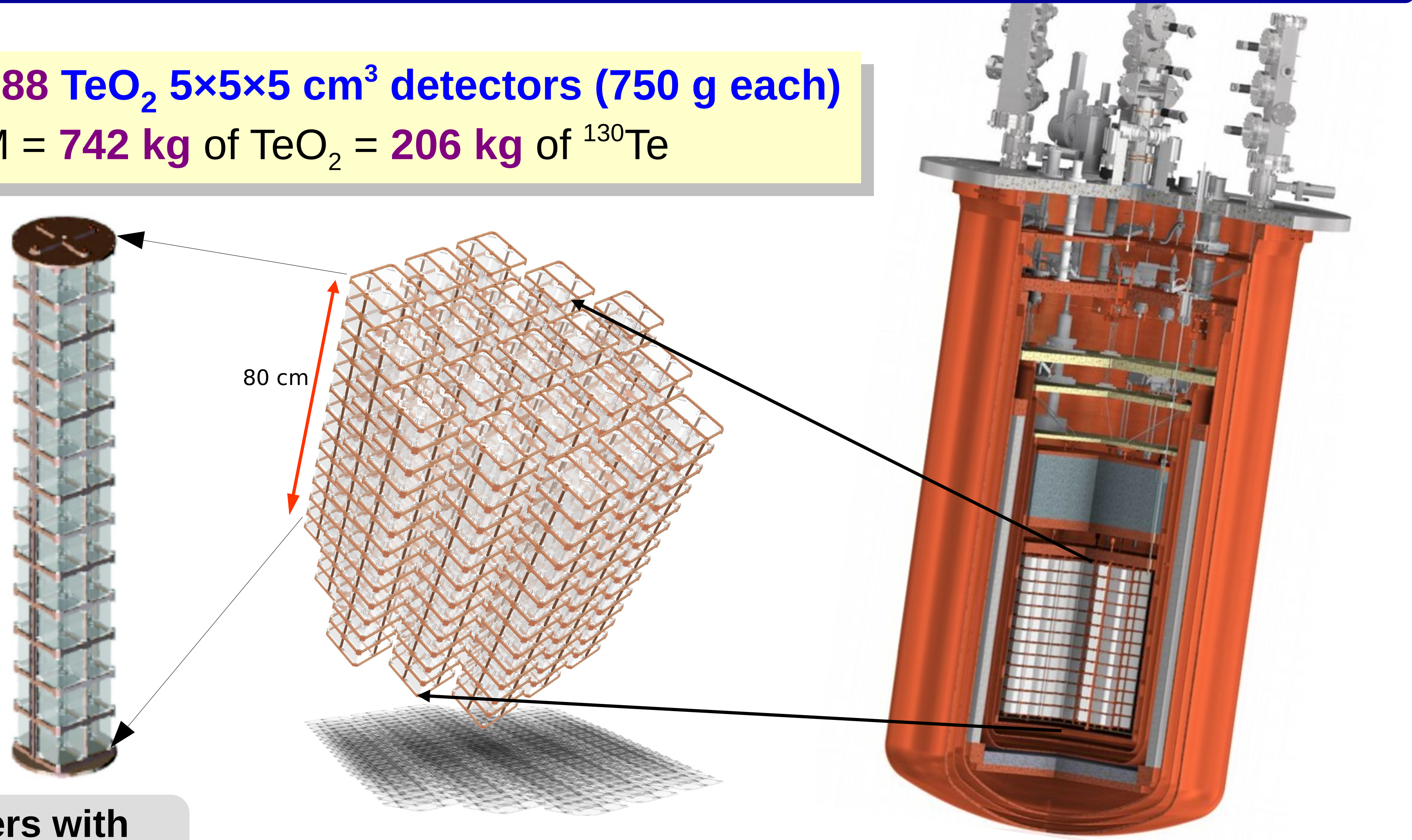
The CUORE experiment

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

Primary goal: search for neutrinoless double beta decay ($0\nu\beta\beta$) of ^{130}Te

Array of 988 TeO_2 5×5×5 cm^3 detectors (750 g each)

M = **742 kg** of TeO_2 = **206 kg** of ^{130}Te



19 towers with
13 planes of
4 crystals each

The CUORE detectors: TeO_2 thermal detectors

Properties of thermal detectors

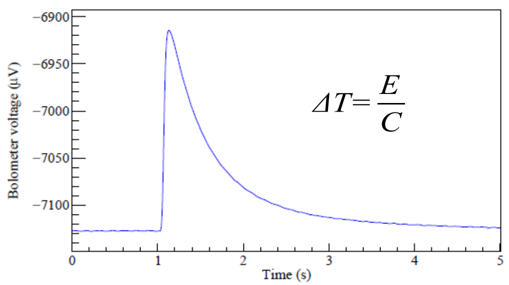
- excellent energy resolution: $(k_B C T^2)^{1/2}$
- large choice of absorber materials
- true calorimeters

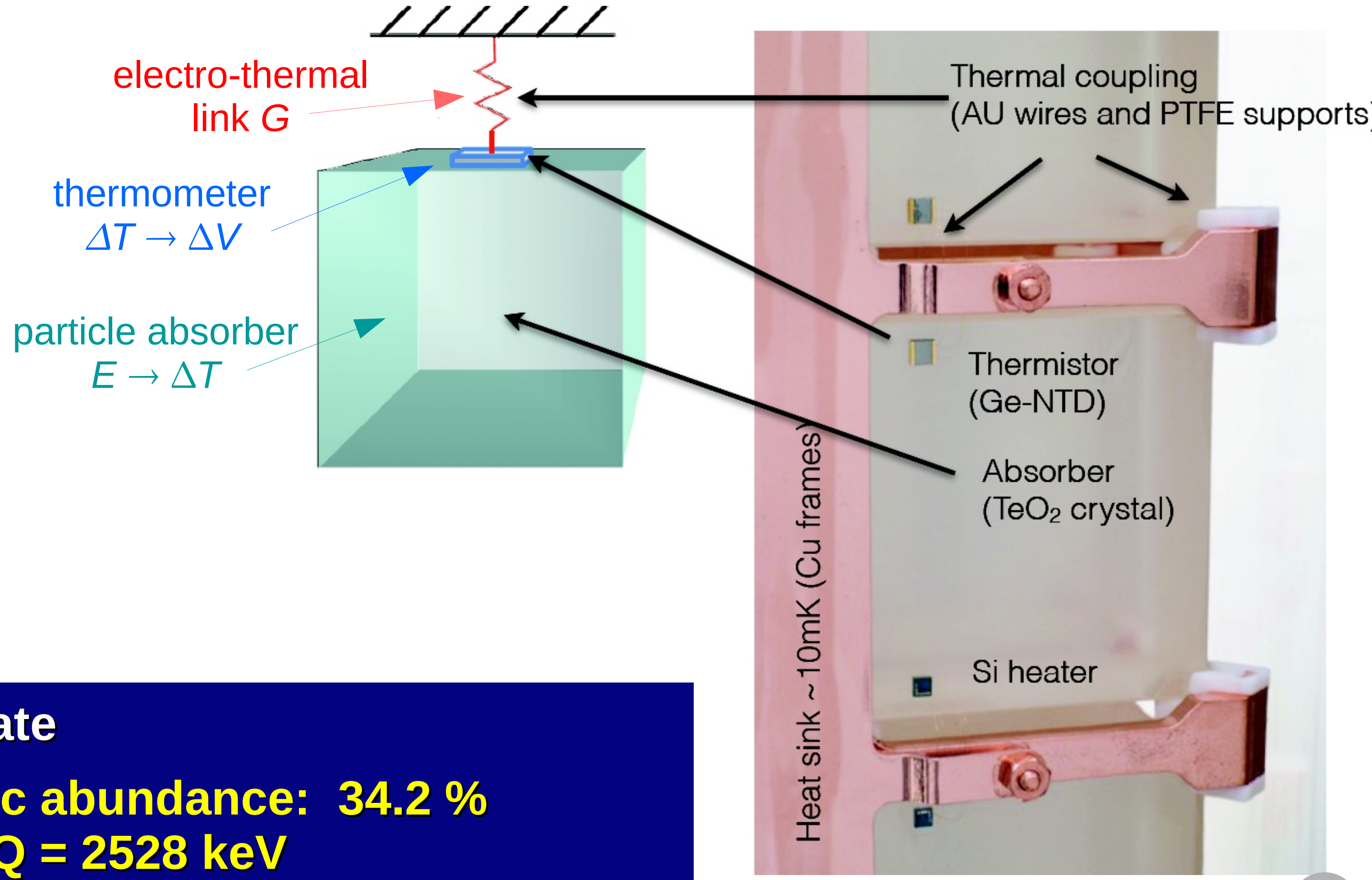
TeO_2 Absorbers

- low specific heat
- large crystals available
- radiopure

TeO2 absorbers + Ge-NTD thermistors:

$T \sim 10$ mK
$\Delta T/\Delta E \sim 0.1$ mK/MeV
$\Delta V/\Delta E \sim 0.3$ mV/MeV
$\tau = C/G \sim 1$ s
$C \sim 2\times10^{-9}$ J/K
FWHM ~ 0.2 %

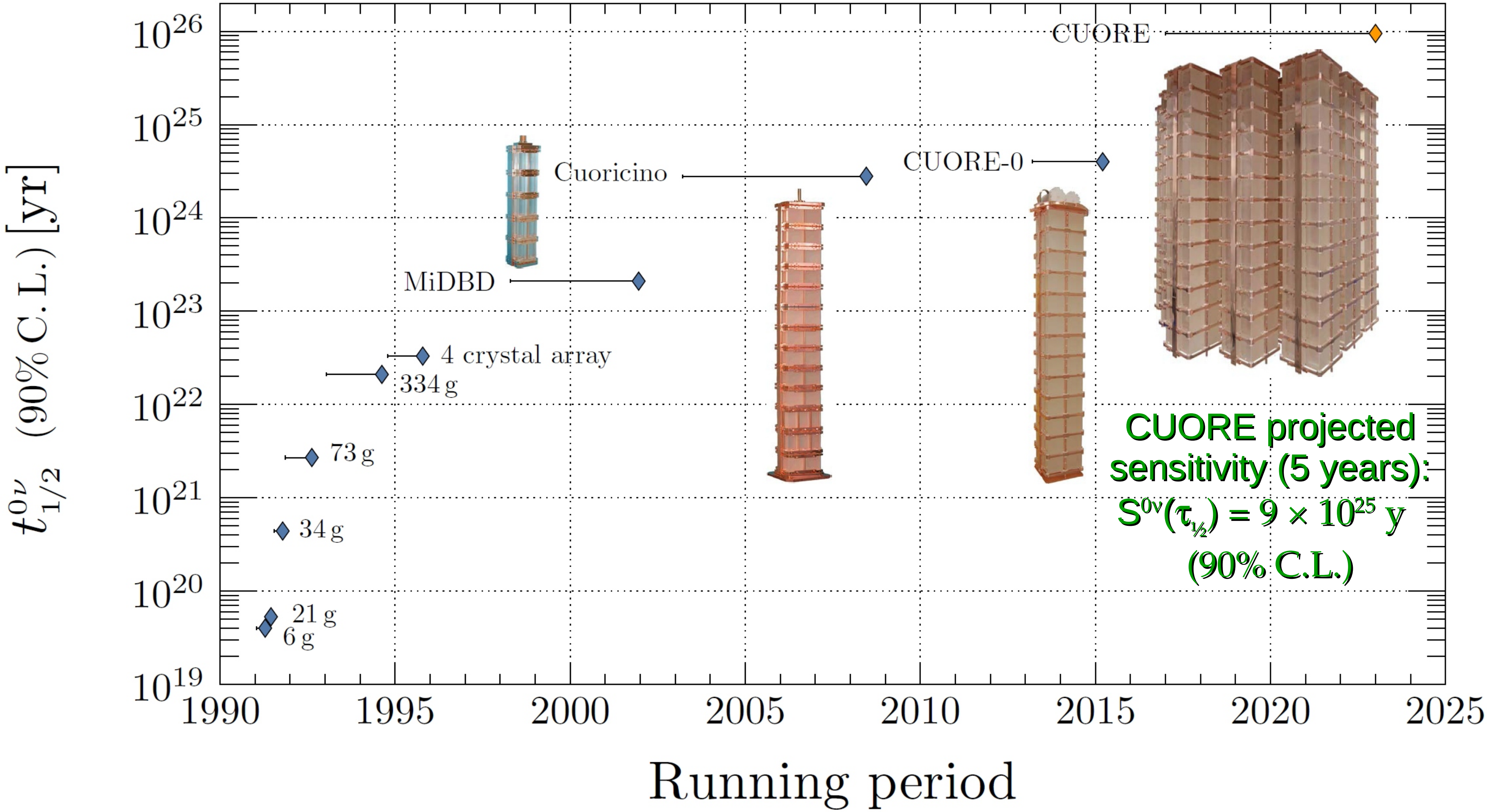




^{130}Te as ββ0ν candidate

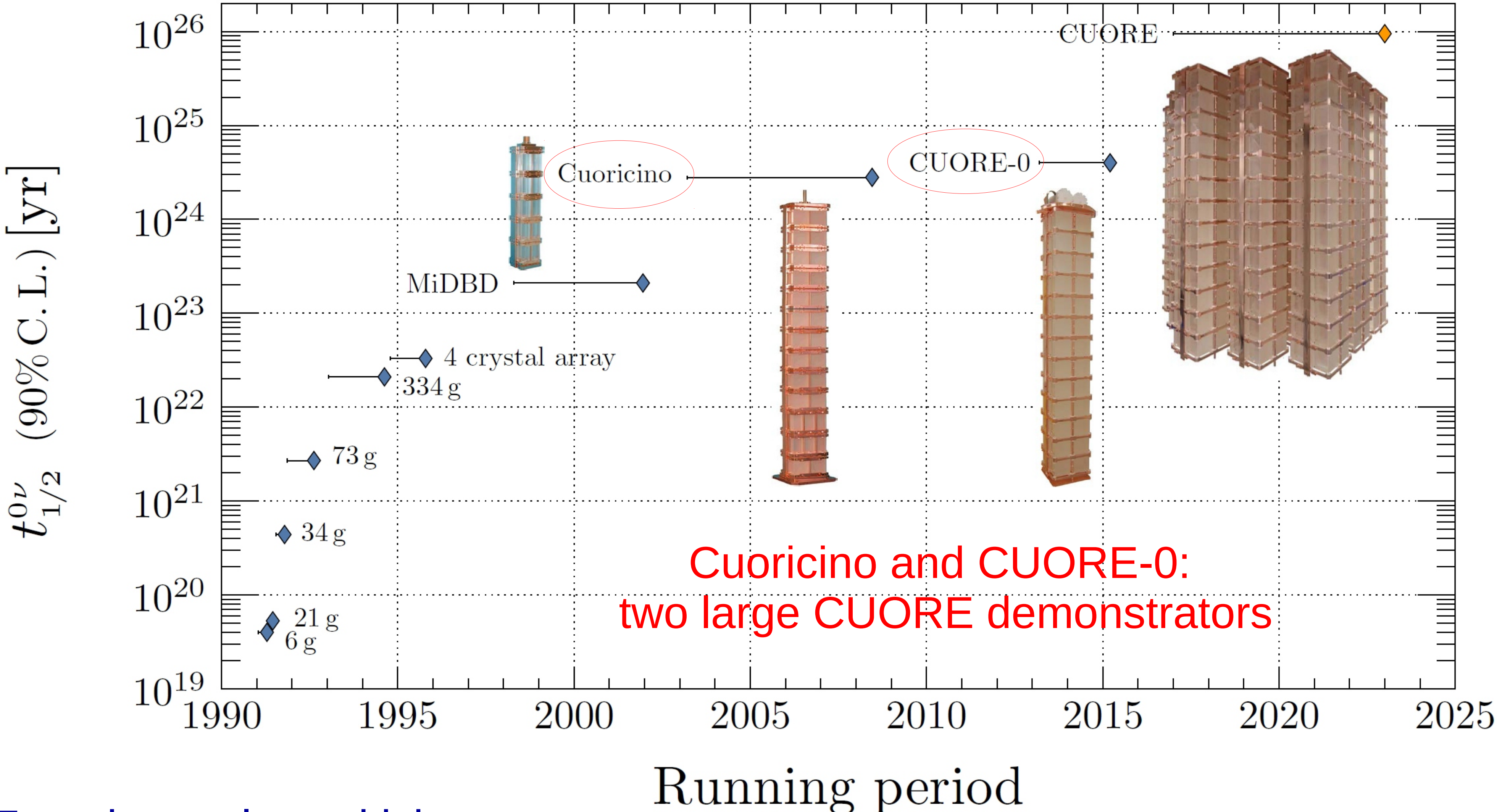
- high natural isotopic abundance: 34.2 %
- transition energy: Q = 2528 keV

TeO_2 arrays evolution



CUORE is the latest evolution of a long series of TeO_2 detector arrays

TeO_2 arrays evolution



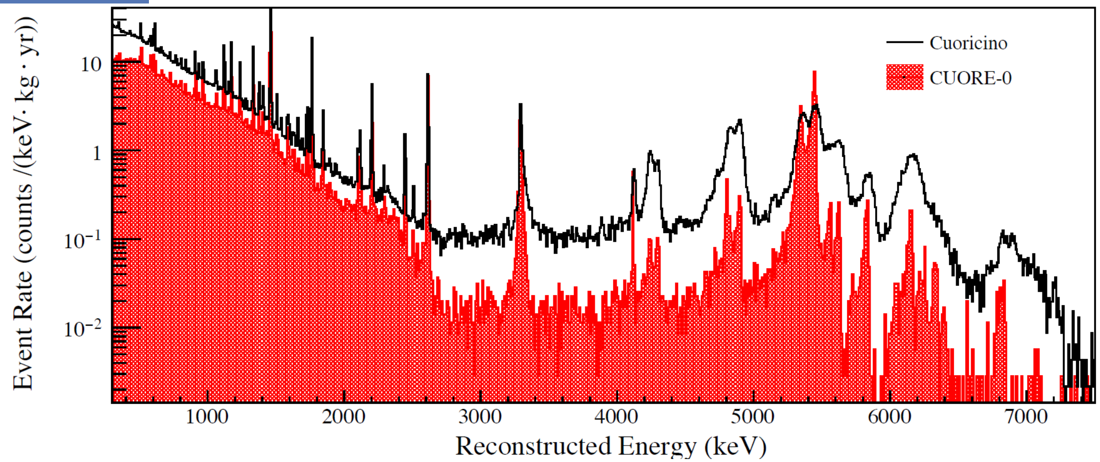
Experimental sensitivity:

$$S^{0\nu}(\tau_{1/2}) \propto \epsilon \cdot \frac{i.a.}{A}\sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}} \qquad bkg \neq 0$$

ε	detector efficiency	**ΔE**	FWHM resolution
i.a.	ββ0ν isotope abundance	**M**	total active mass
A	atomic mass	**t_{meas}**	measuring time

bkg background @ ROI in counts/keV/kg/y

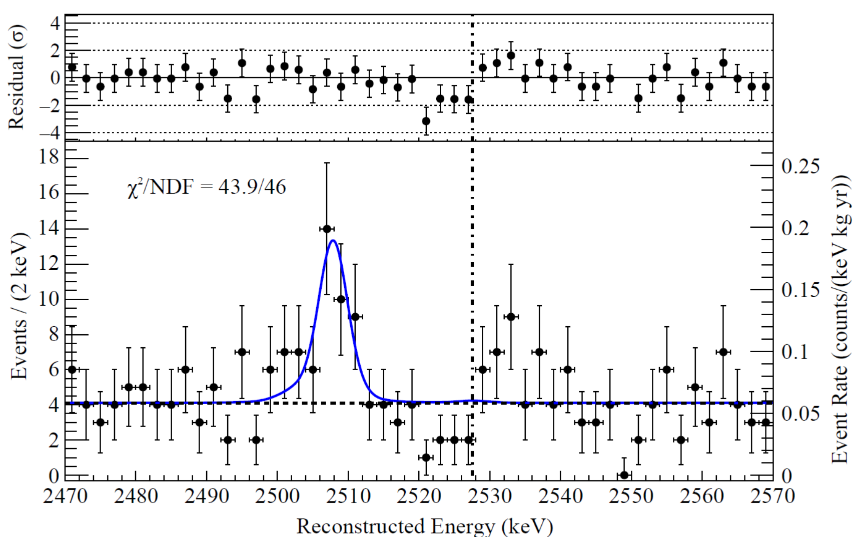
CUORE-0: first step towards CUORE



Background reduction with respect to Cuoricino:

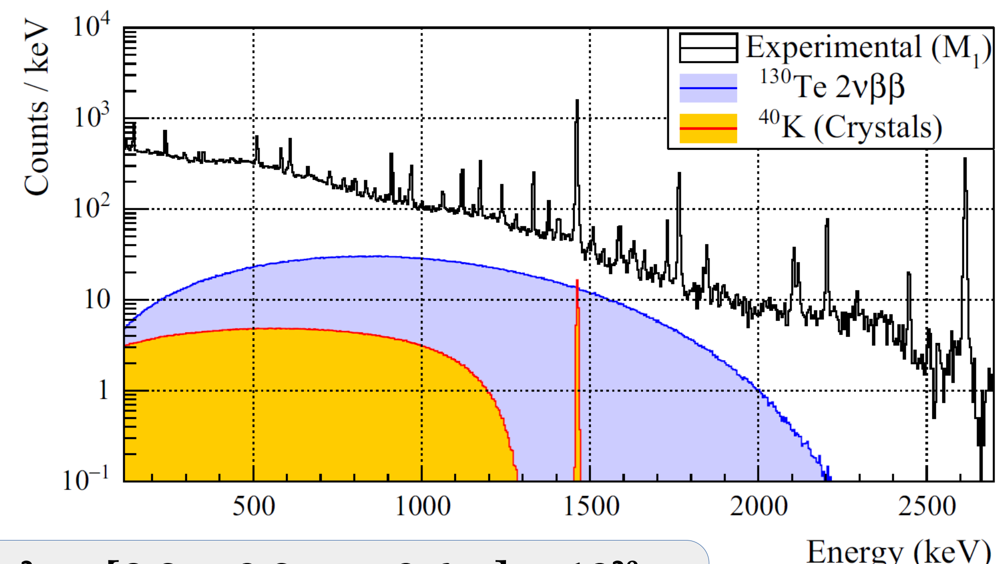
- factor 6 for surface contaminations
- factor of ~2.5 in the ROI

Not only a proof of concept of the CUORE detector 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



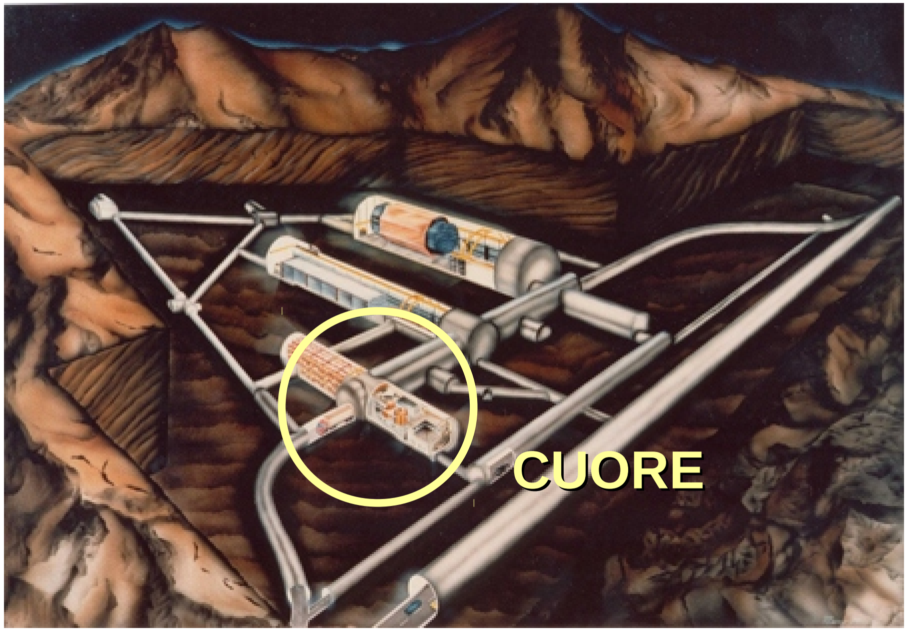
$\tau_{½}^{2\nu} = [8.2 \pm 0.2_{stat} \pm 0.6_{sys}] \times 10^{20}$ y

Eur. Phys. J. C 77 (2017) 13

The CUORE collaboration

CUORE location

INFN LABORATORI NAZIONALI DEL GRAN SASSO



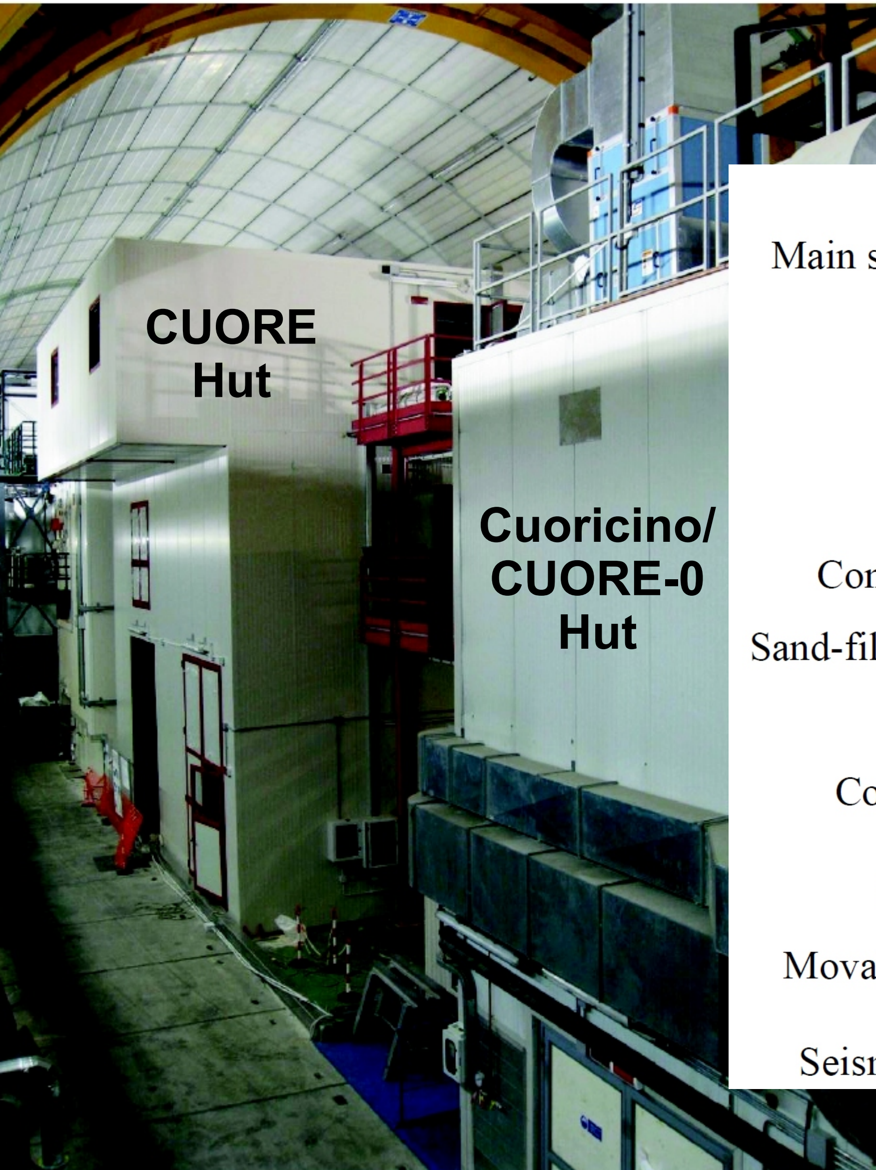
Average depth ~ 3600 m.w.e.

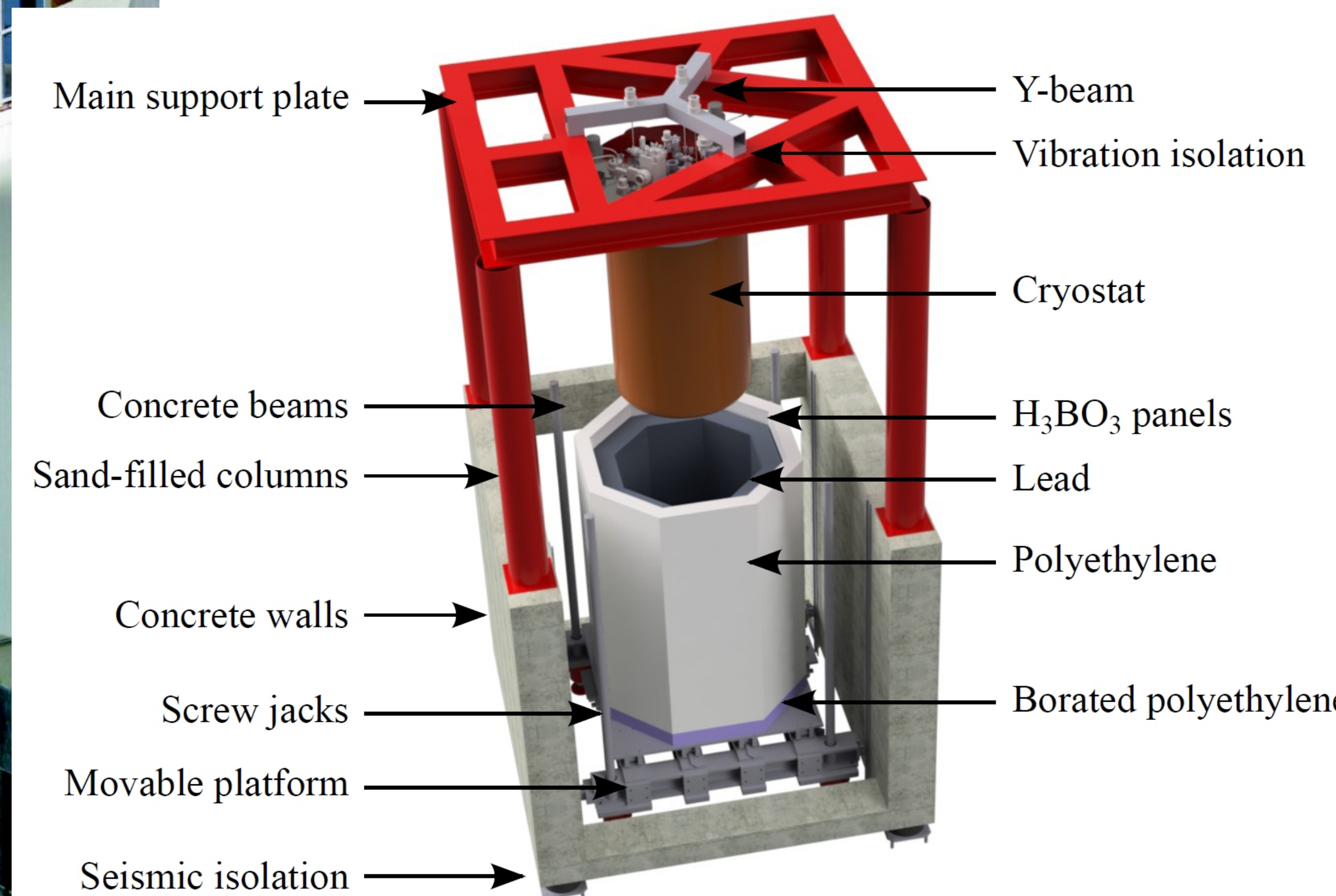
μ flux: ~ 3 $\cdot 10^{-8}$ μ/s/cm^2

n flux <10 MeV: $4 \cdot 10^{-6}$ n/s/cm^2

γ flux < 3 MeV: 0.73 γ/s/cm^2

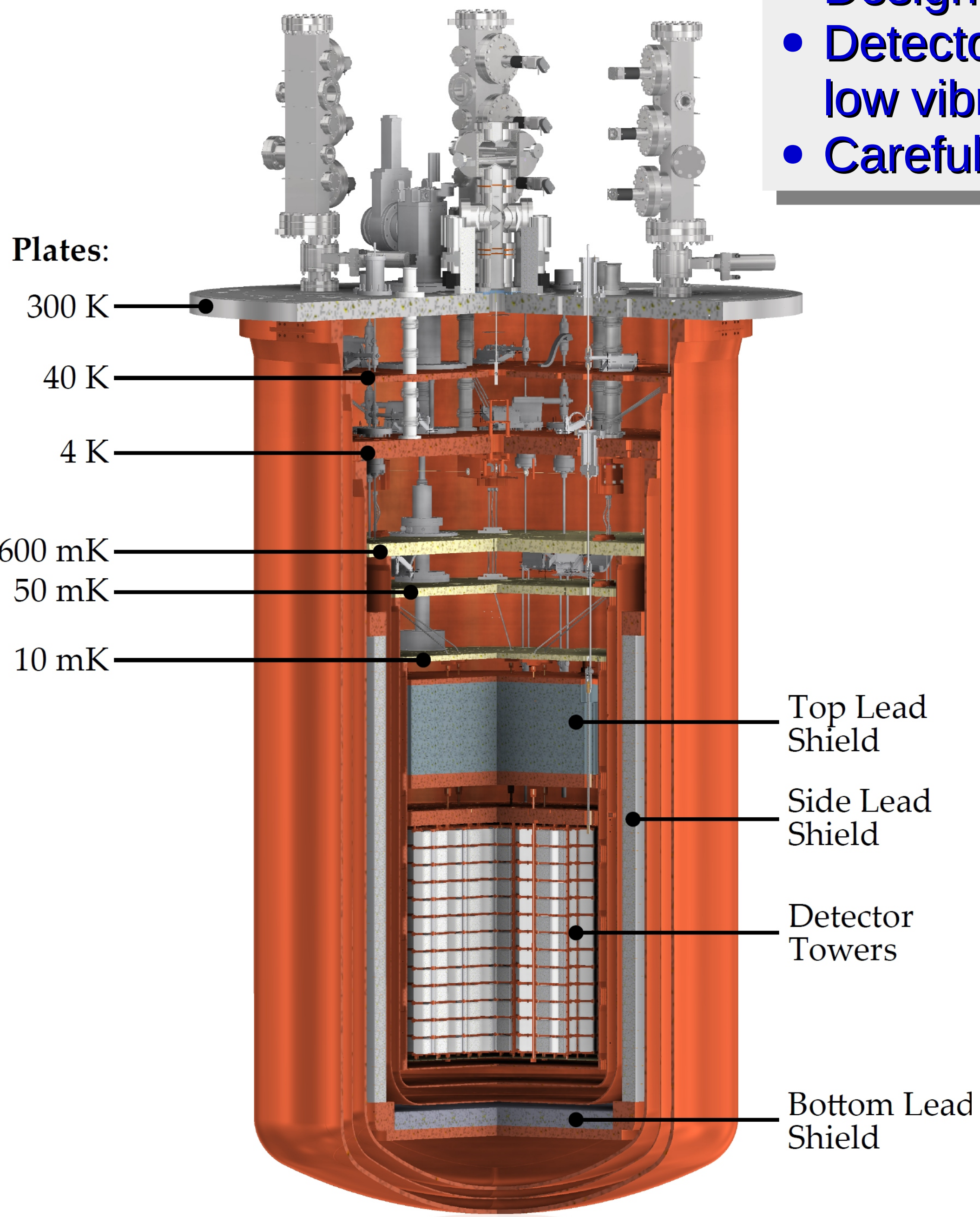
Underground laboratory





CUORE cryogenic system

- Designed to cool down ~ 1 ton detector to ~10 mK
- Detector mechanically decoupled for extremely low vibrations
- Careful selection of materials for low background



- Cryogen free cryostat
- Fast cooling system(4He gas) down to ~50 K
- 5 pulse tube cryocooler down to ~4 K
- Dilution refrigerator down to ~10 mK
- Nominal cooling power: 3 μW @ 10 mK
- Cryostat total mass ~30 ton
- Mass to be cooled below 4 K: ~ 15 ton
- Mass to be cooled below 50 mK: ~ 3 ton (Pb, Cu and TeO_2)

CUORE cryogenic system commissioning

February 2016

everything installed but the CUORE towers:

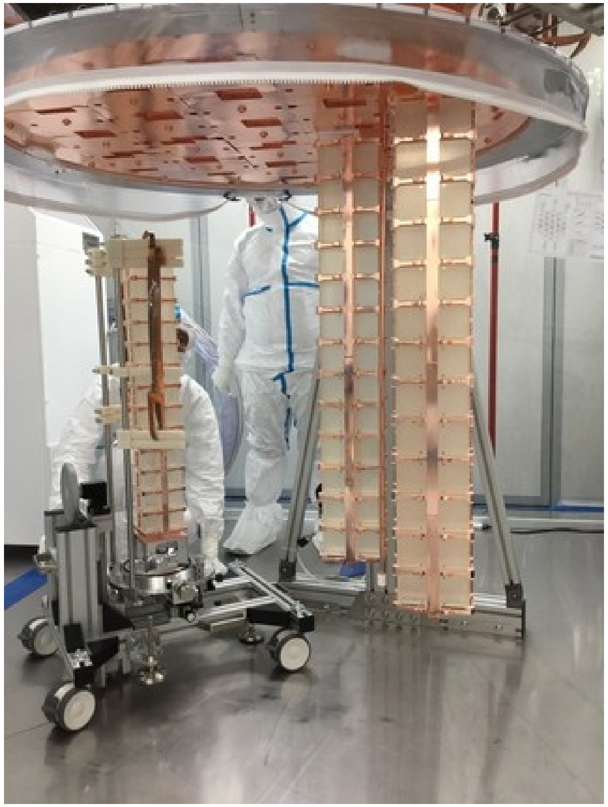
- base T < 7 mK
- stable operation

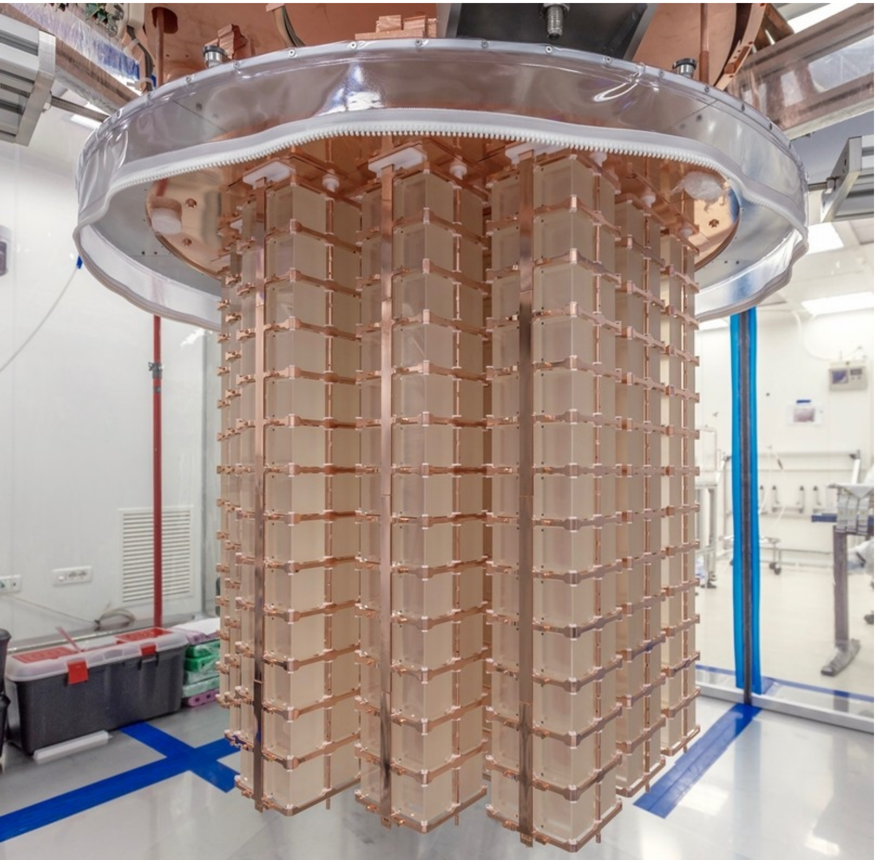
Roman lead lateral shield

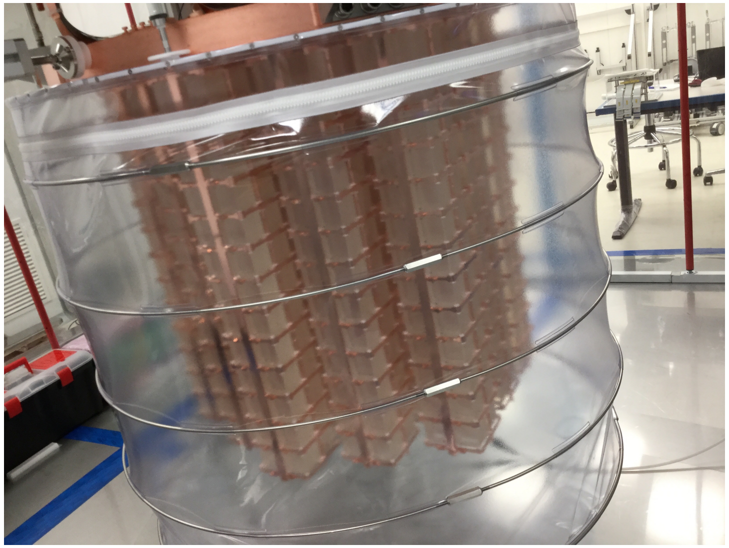
CUORE detector installation

Installation of the 19 CUORE towers:
- Performed in a radon-free environment
- Completed on August 26, 2016

September-November 2016:
- Installation of the cryostat interfaces and radiation shields
- Cryostat closure

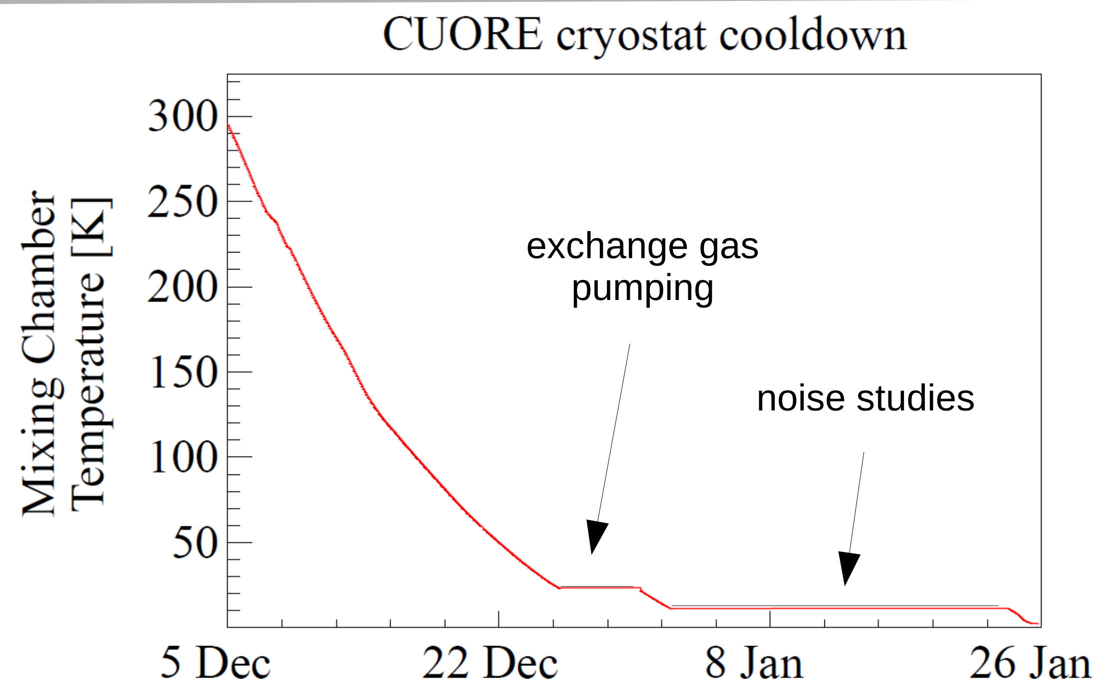


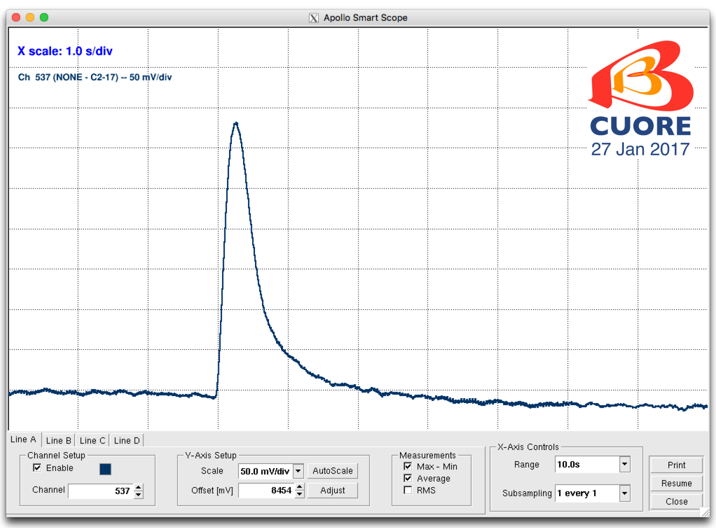




CUORE detector cooldown

- Detector cooldown started on December 5, 2016
- Stable base temperature of ~7 mK reached on January 27, 2017
- Observed first detector pulses right after cooldown





After the successful cooldown, we faced the challenge to operate ~1000 thermal detectors in a completely new system

Pre-operations:

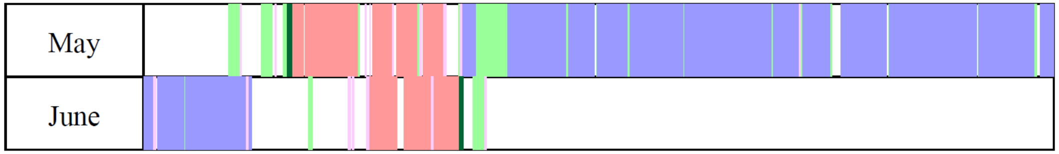
- DAQ and front-end electronics optimization
- Working points optimization
- Impressive results both in terms of temperature stabilization and noise abatement
- Commissioning phase completed in April 2017

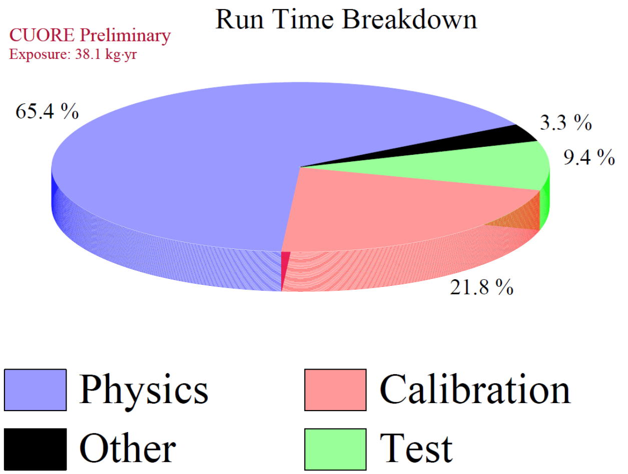
CUORE first science run

Official CUORE data release

- 3 weeks of physics data preceded and succeeded by several days dedicated to calibration data
- Selected working temperature: 15 mK (stable within ~0.25 mK)
- Excellent data taking efficiency
- Much improved detector stability compared to Cuoricino/CUORE-0
- Calibration/physics ratio still to be optimized to maximize 0νββ efficiency

Dataset time breakdown (May 4 – June 11, 2017)





Operational performance:

- **984/988 active detectors (99.6%)**
- for the first analysis: selected 889 best performing detectors (90% of the total)

Acquired statistics for 0νββ decay search:

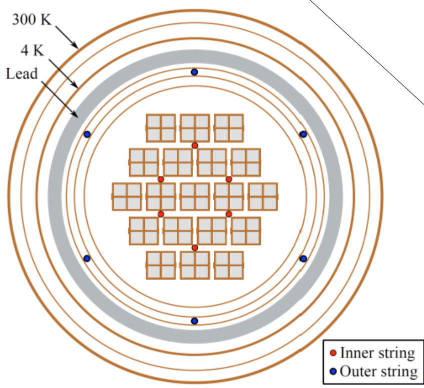
➢ $^{nat}TeO_2$ exposure: 38.1 kg·y

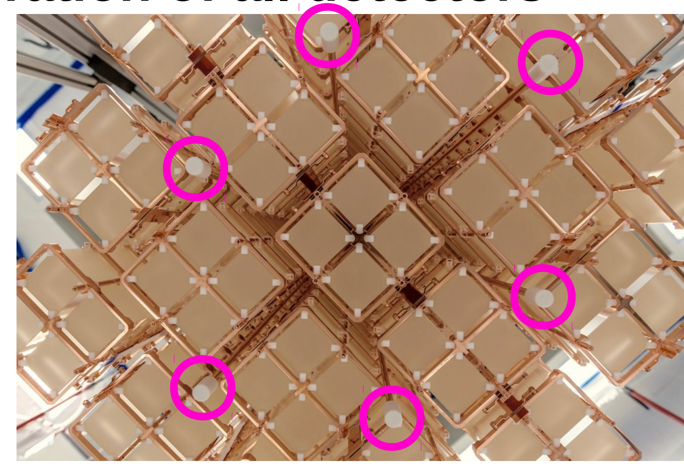
➢ ^{130}Te exposure: 10.6 kg·y

Data taking is going on: more to come!

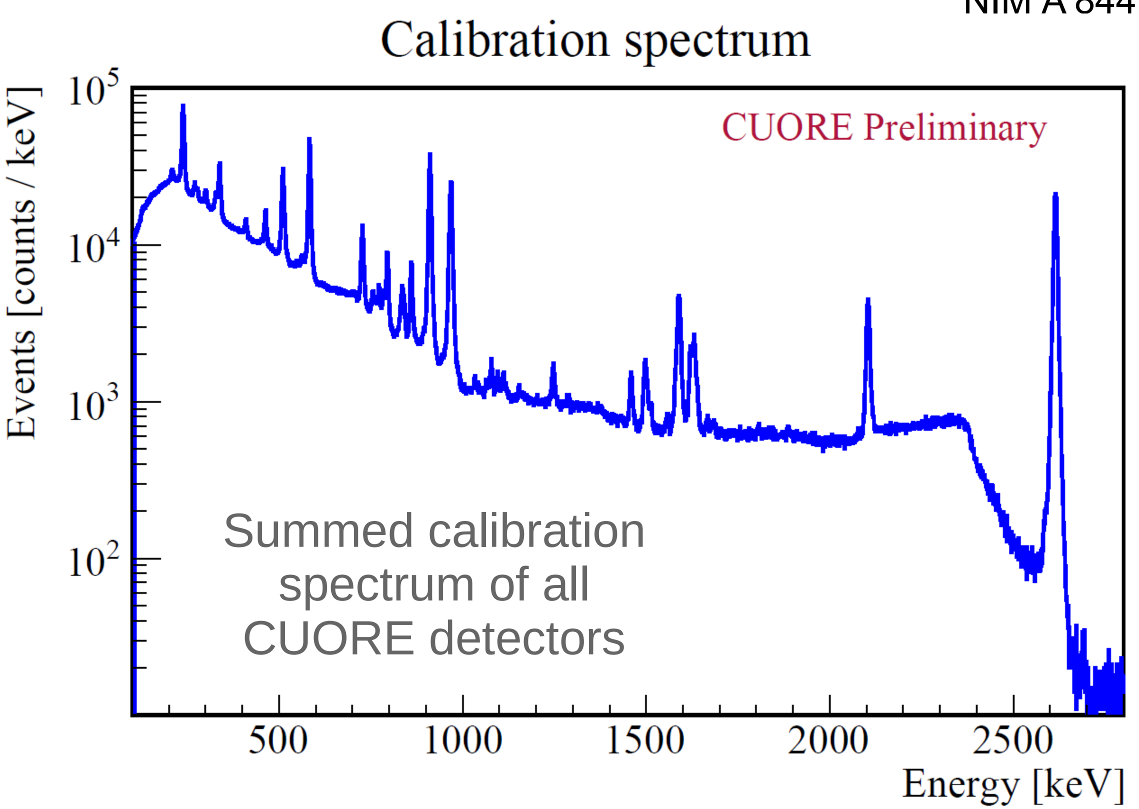
CUORE detector calibration

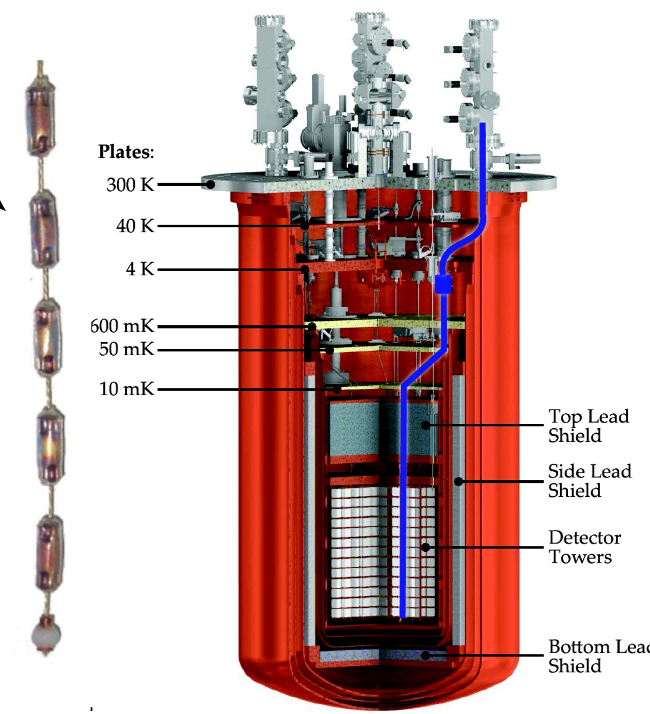
^{232}Th sources (strings) are deployed through the cryostat from room temperature into the detector core, providing a uniform calibration of all detectors





NIM A 844 (2017) 32



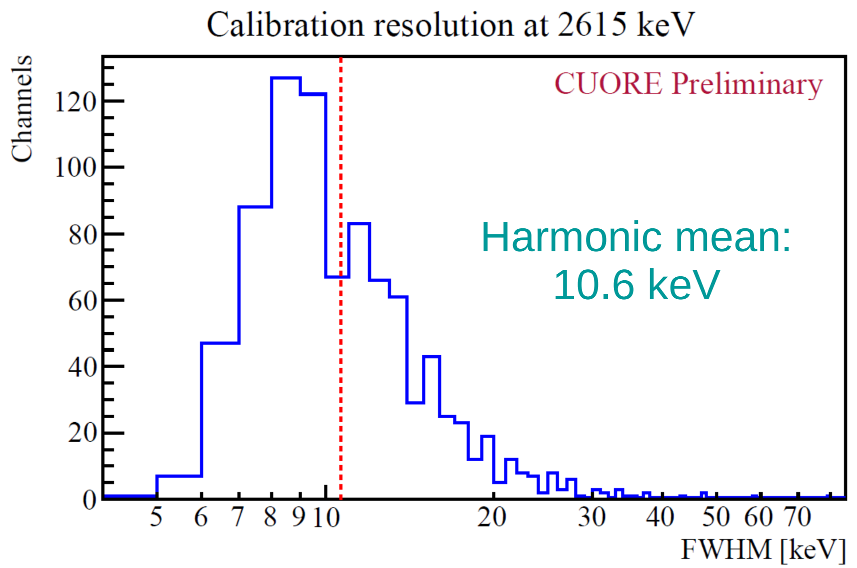


Detector energy resolution

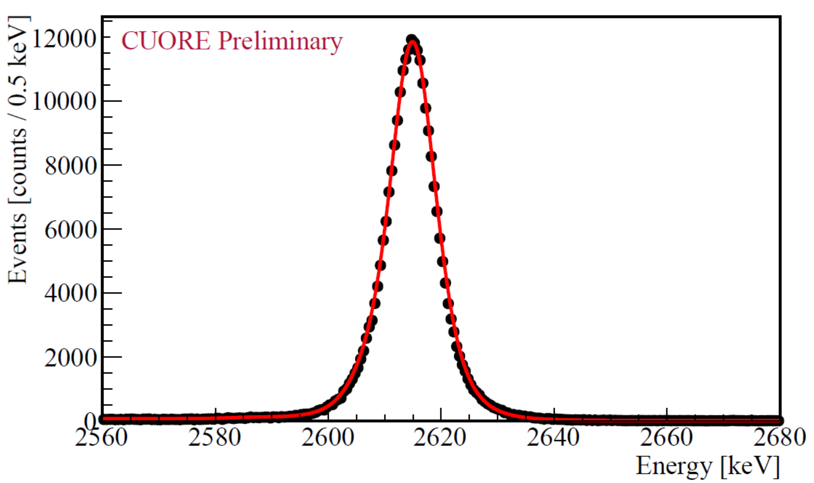
CALIBRATION RUNS

Average (“harmonic mean”) energy resolution:

10.6 keV FWHM @ 2615 keV



Fit of the 2615 keV line in calibration spectrum



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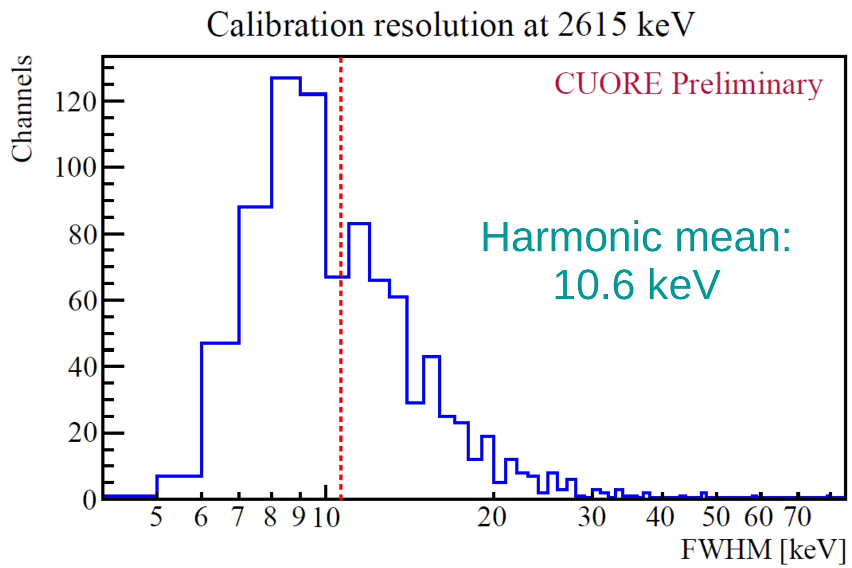

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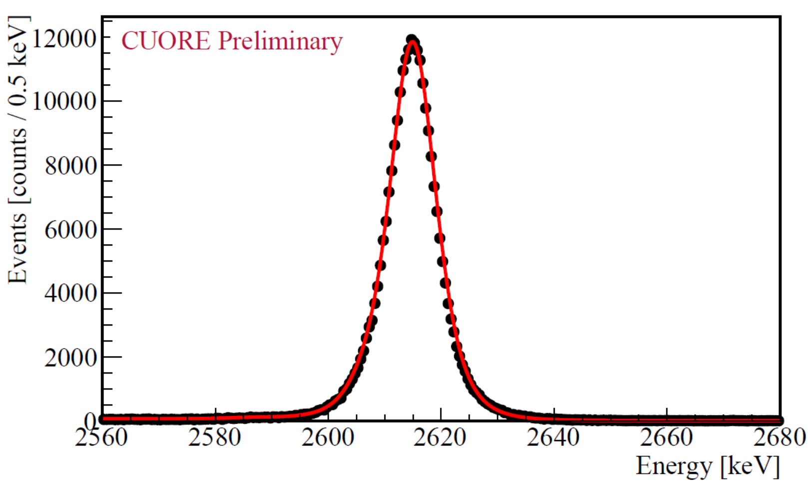
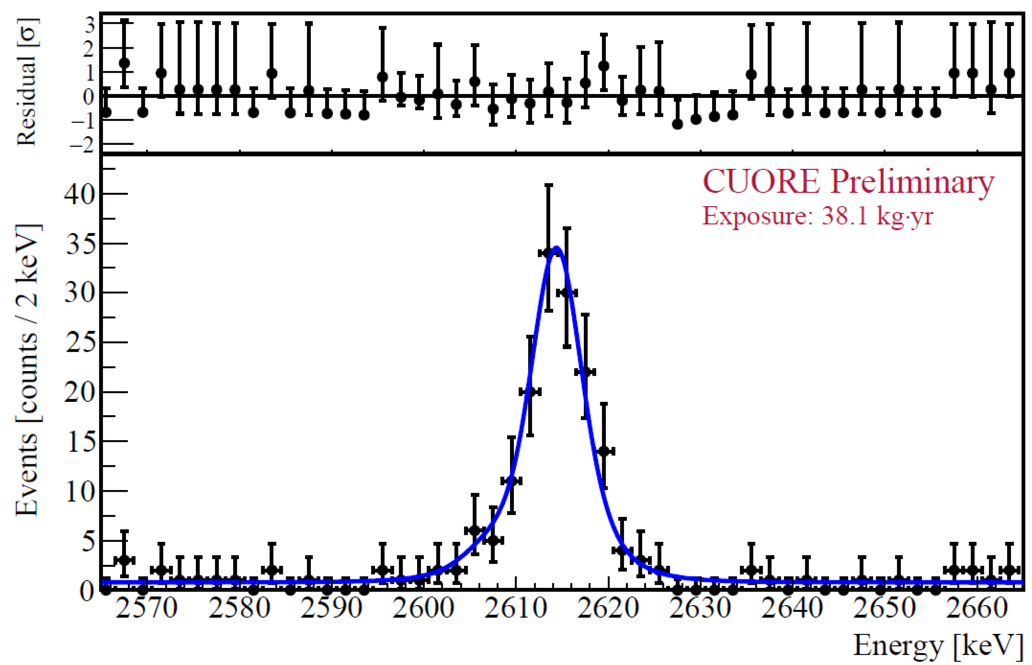


PHYSICS RUNS

Significantly better performance in physics data:
(7.9 ± 0.6) keV FWHM @ 2615 keV

Fit of the 2615 keV background line summed over all detectors

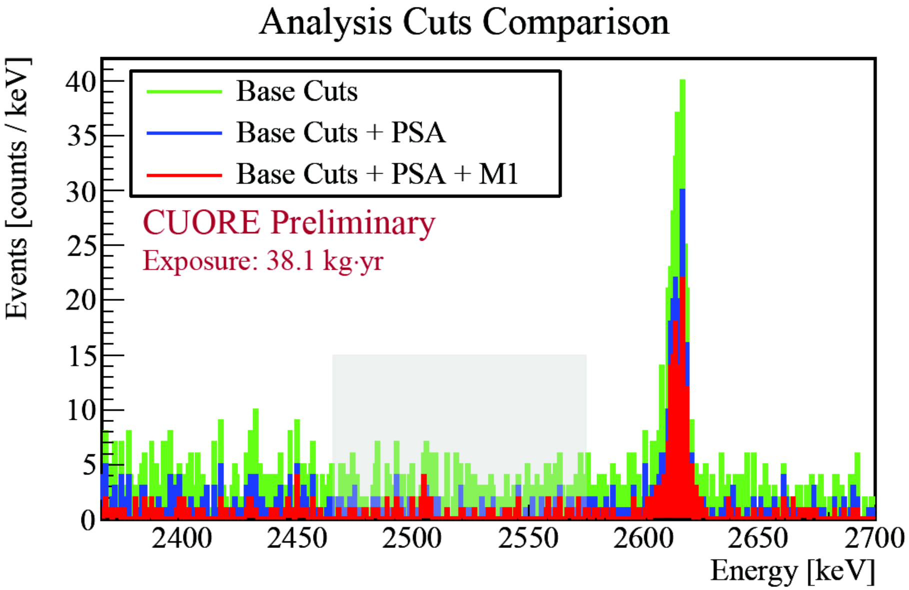


Event selection

BASE CUTS:
remove period of low quality data (1% of the total live time)

PULSE SHAPE ANALYSIS (PSA) CUTS:
use 6 pulse shape parameters to identify real particle events

ANTI-COINCIDENCE CUTS:
exclude events that trigger more than one channel simultaneously



SIGNAL EFFICIENCY

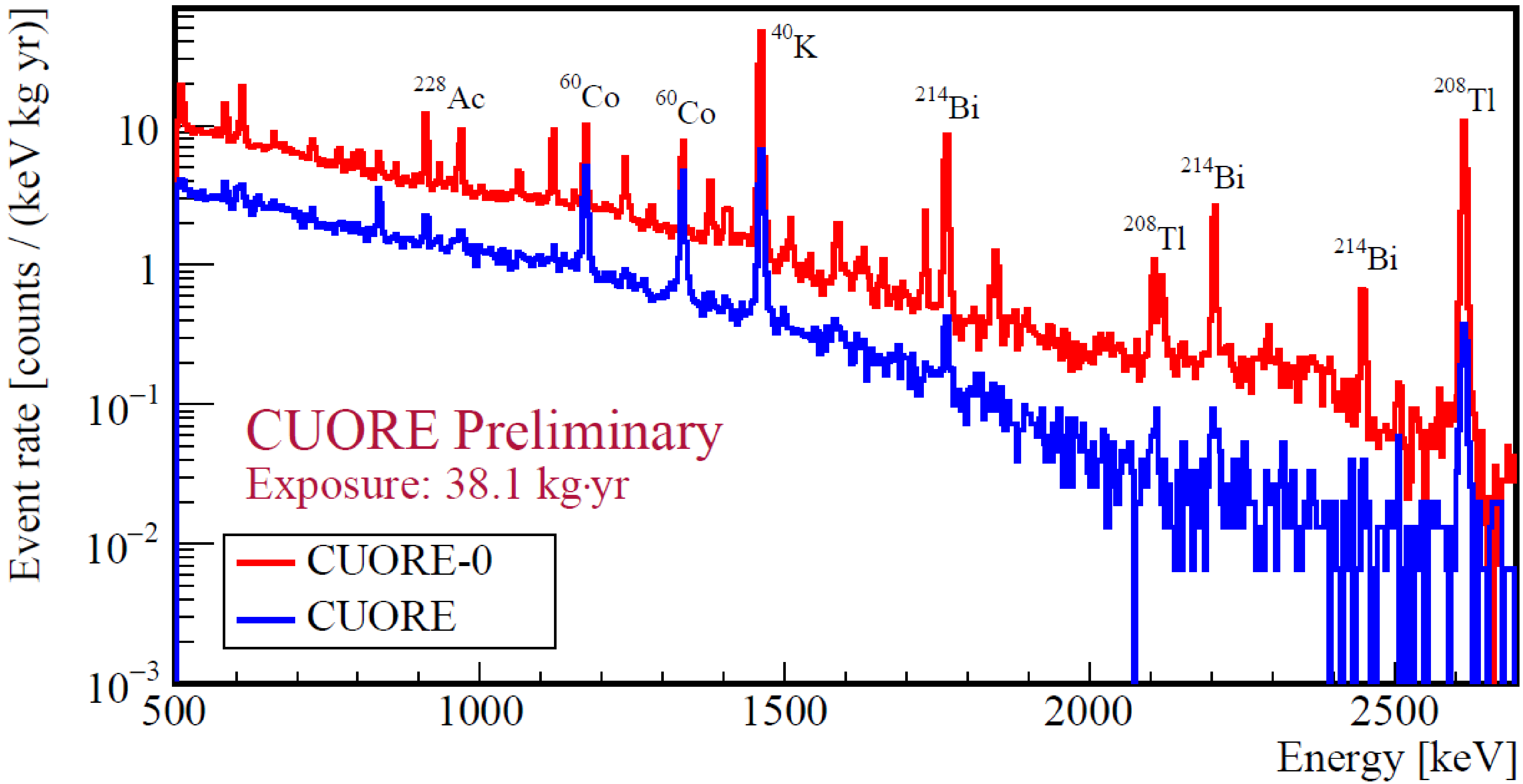
Trigger and energy reconstruction	(98.469 ± 0.009)%
Anti-coincidence	(99.3 ± 0.3)%
PSA	(64 ± 3)%
All cuts except containment	(62.6 ± 3.4)%
$0\nu\beta\beta$ containment	(88.345 ± 0.085)%
Overall signal efficiency	(55.3 ± 3)%

Same procedure developed for CUORE-0:
Phys. Rev. C 93 (2016) 045503

Refining the data analysis to improve that!

CUORE measured background spectrum

Significant reduction of the background rate in the gamma region (as expected)



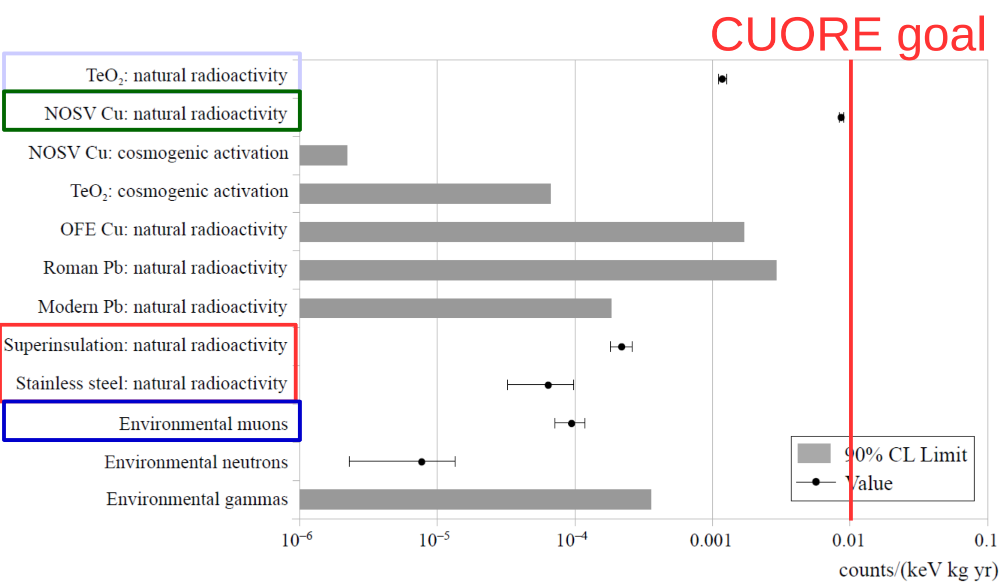
Background sources:

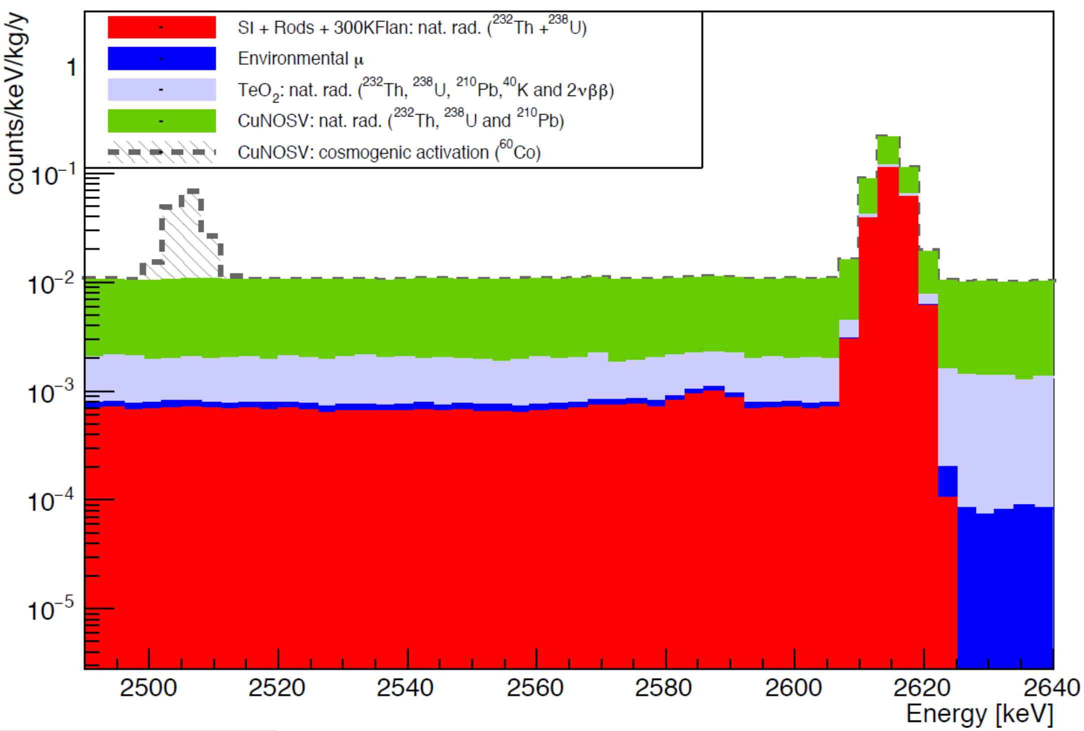
- Long lived natural radionuclides (^{40}K) and decay chains (^{232}Th, ^{238}U)
- Cosmogenically activated nuclides (^{60}Co, ^{125}Sb, …)
- Environmental μ, γ and neutrons

CUORE expected background

CUORE expected counting rates and background spectra in the Region Of Interest (ROI) as obtained by a detailed (Geant4) Monte Carlo simulation of the complete CUORE setup with input information based on:

- radio-assays of the CUORE construction materials
- CUORE-0 background model [Eur. Phys. J. C 77 (2017) 13]





Expected counting rate in the ROI:

$$1.02 \pm 0.03\,(stat)^{+0.23}_{-0.10}\,(syst) \times 10^{-2} \quad \text{counts/keV/kg/y}$$

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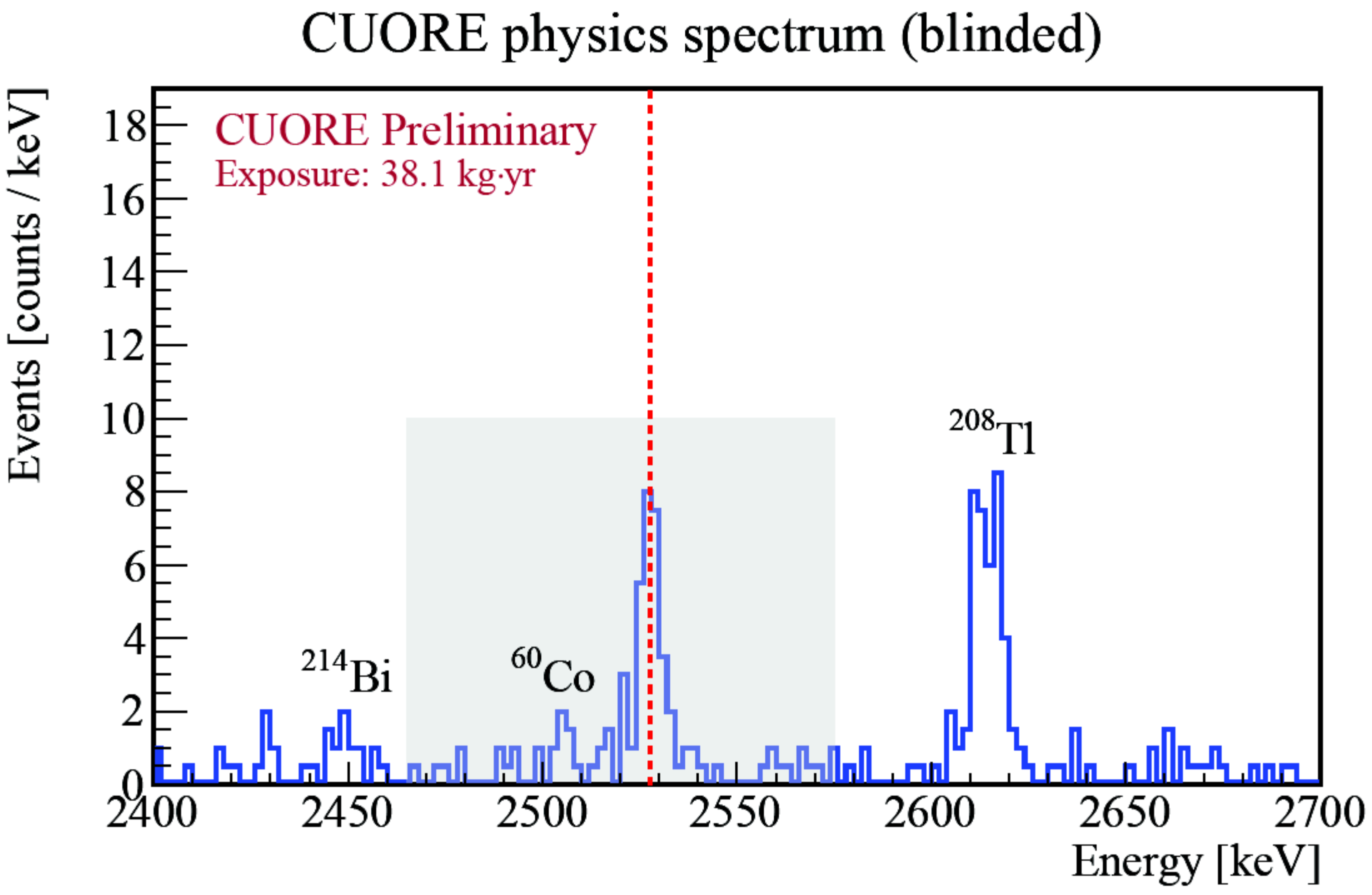
CUORE spectrum in the ROI region

Our blinding procedure produces an artificial peak in the ROI: a small blinded fraction of the events within ±20 keV of the ^{208}Tl 2615 keV peak is exchanged with the events within ±20 keV of the ^{130}Te Q-value.



This method of blinding the data preserves the integrity of the possible 0νββ events while maintaining the spectral characteristics with measured energy resolution and introducing no discontinuity in the spectrum.

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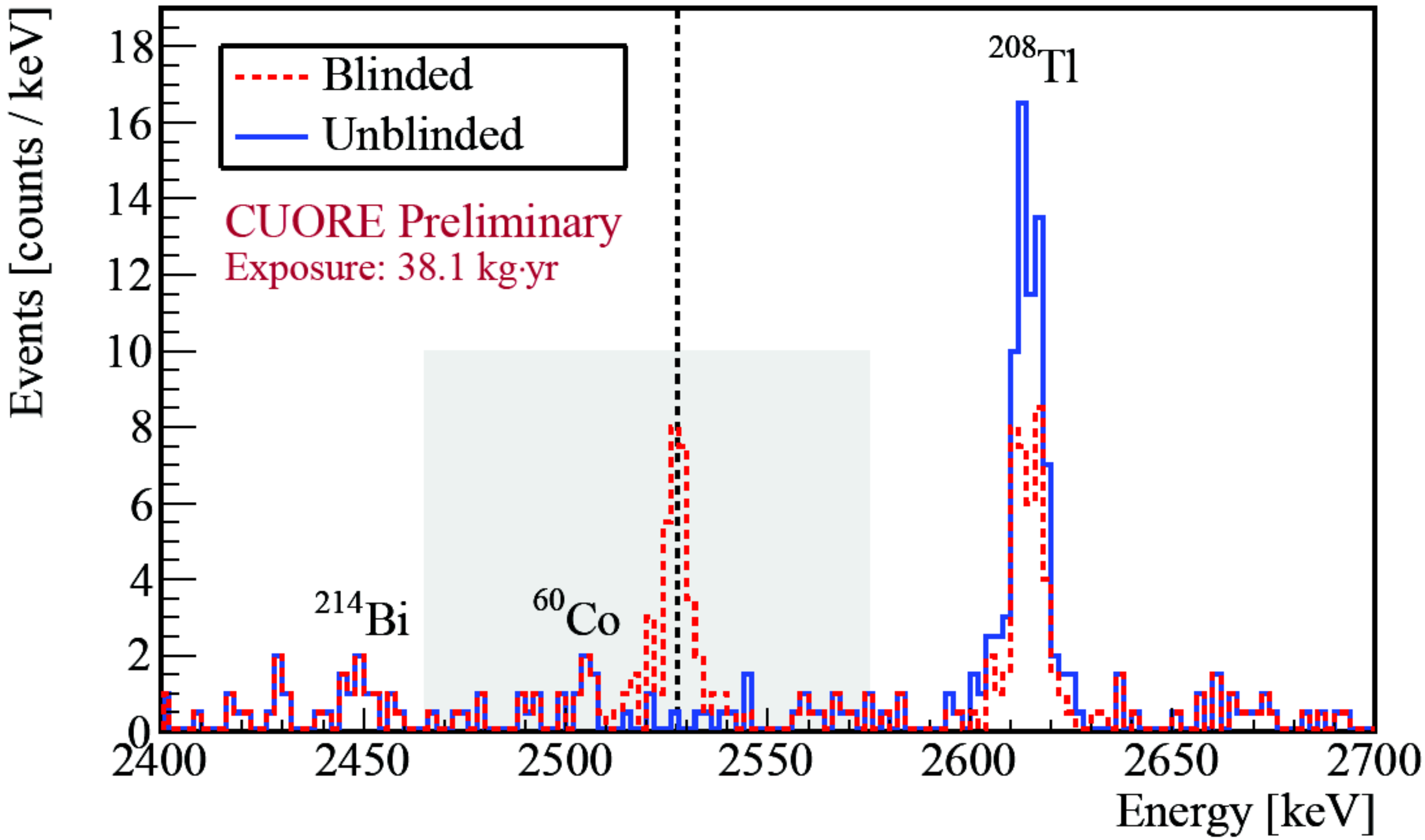

When all data analysis procedures are fixed the data are eventually unblinded.

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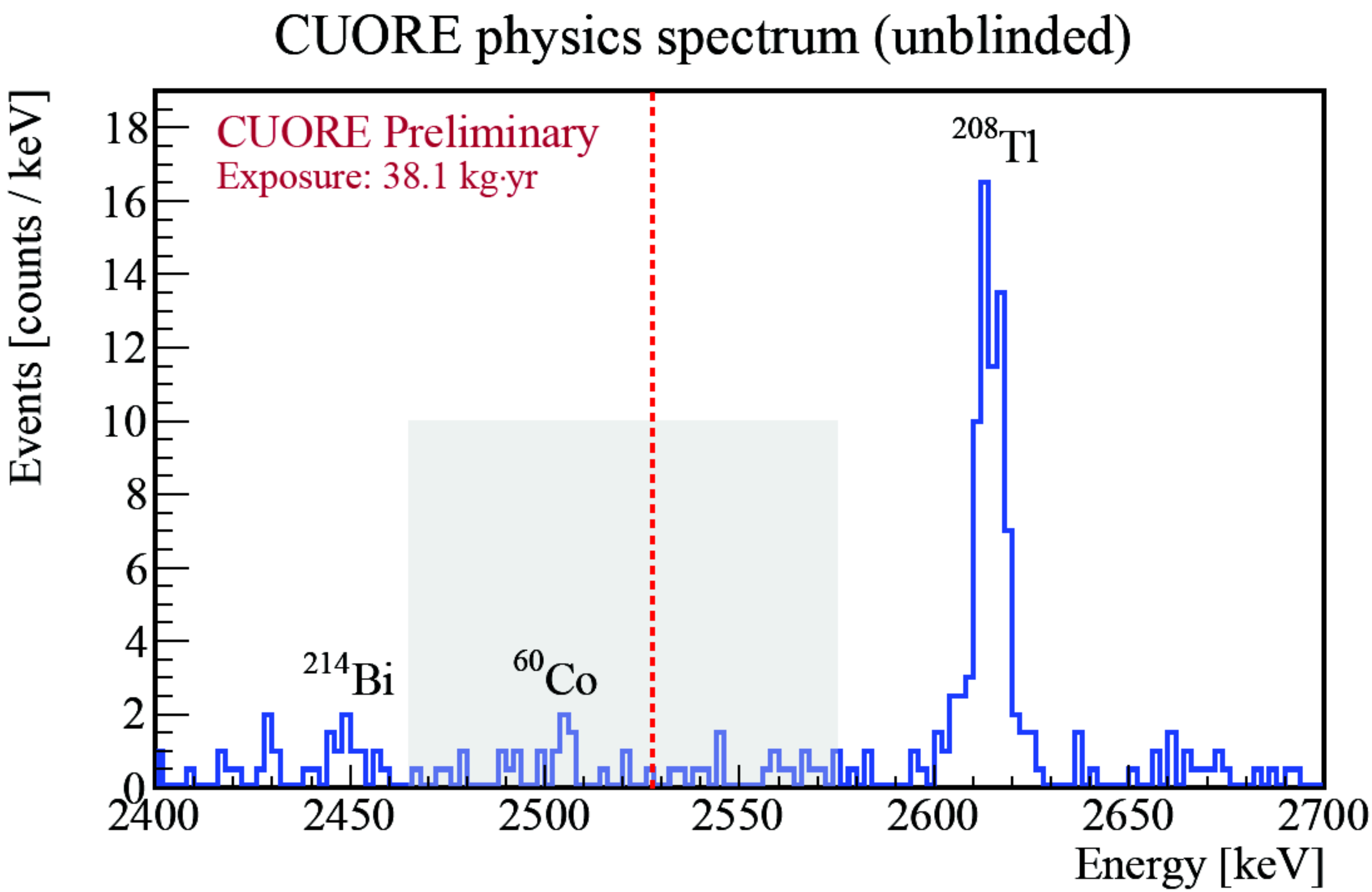


When all data analysis procedures are fixed the data are eventually unblinded.

CUORE spectrum in the ROI region: fit

To determine the yield of 0νββ events we perform a simultaneous Unbinned Extended Maximum Likelihood fit in the ROI (2465 keV – 2575 keV) using a procedure similar to that of CUORE-0 [Phys. Rev. C 93 (2016) 045503].

The fit ha 3 components:

- **a posited peak at the ^{130}Te Q-value**
- **a floating peak to account for the ^{60}Co sum gamma peak (2505 keV)**
- **a constant continuum background, attributed to multi-scatter Compton events from ^{208}Tl and to degraded alpha events (from surface contaminations)**

FIT RESULTS

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

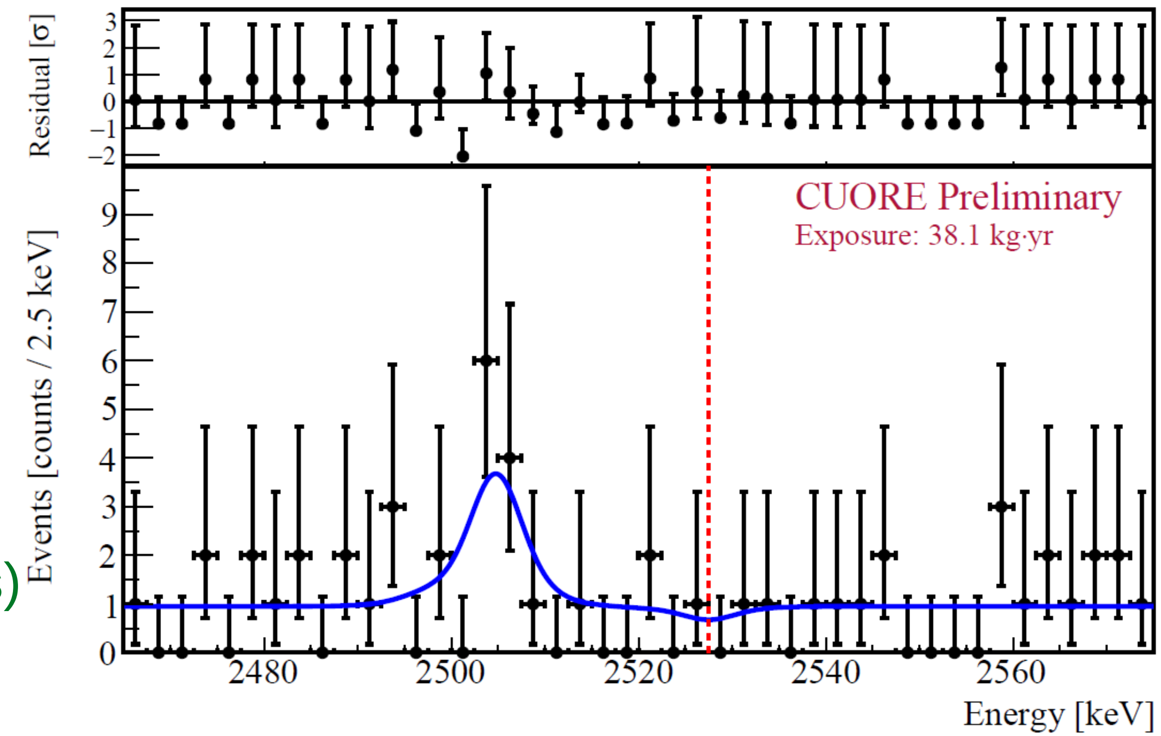
$$9.8^{+1.7}_{-1.5} \times 10^{-3} \;\; \text{counts/keV/kg/y}$$

- Best fit decay rate:

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

- Half life limit (including systematics)

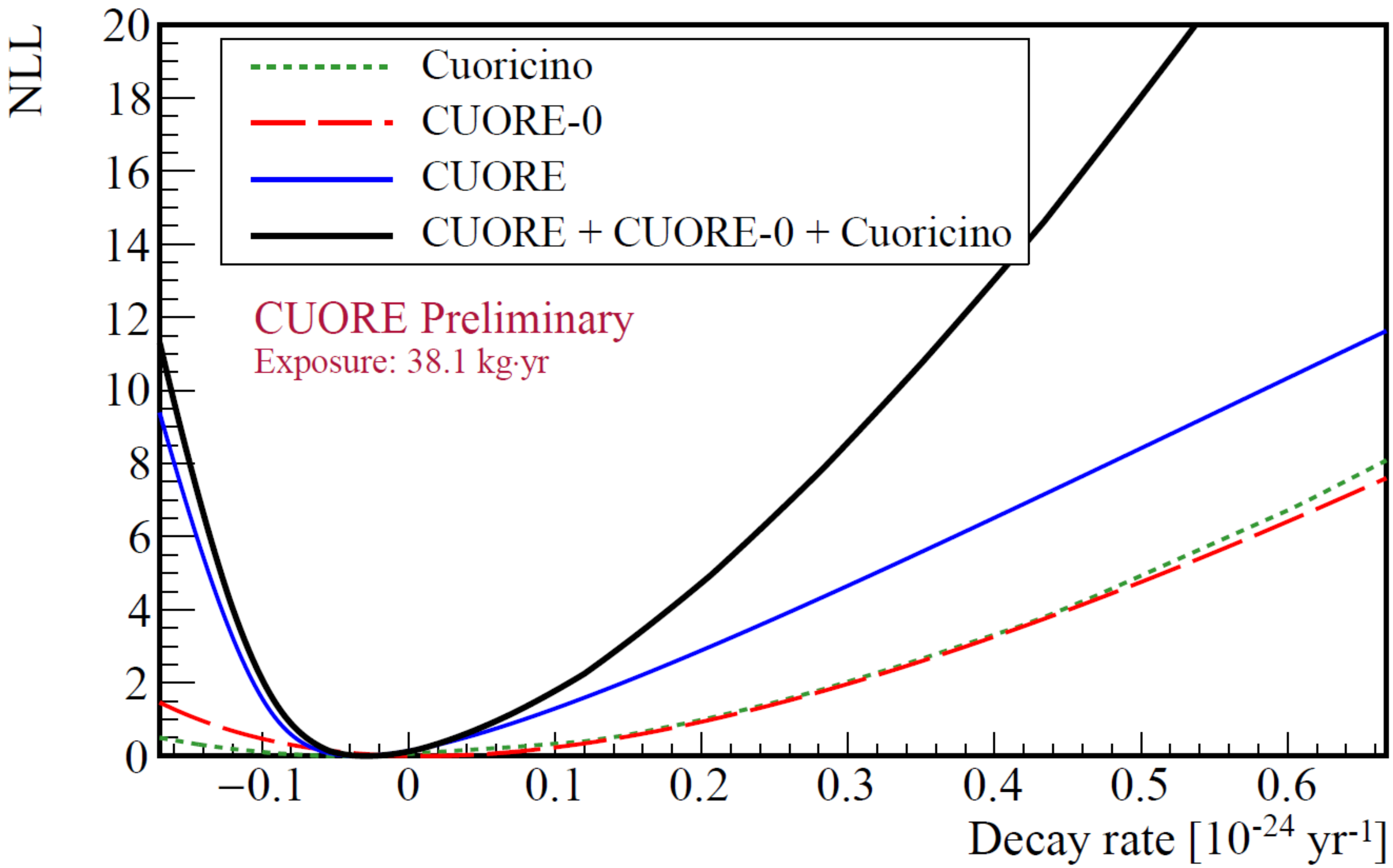
$$\tau_{1/2}^{0\nu} > 4.5 \times 10^{24}\ \text{y}\ \ (90\%\text{C.L.})$$



Combination with previous results

We combined the CUORE result with the previous ones from Cuoricino and CUORE-0, obtaining the best lower limit to date on ^{130}Te 0νββ half life:

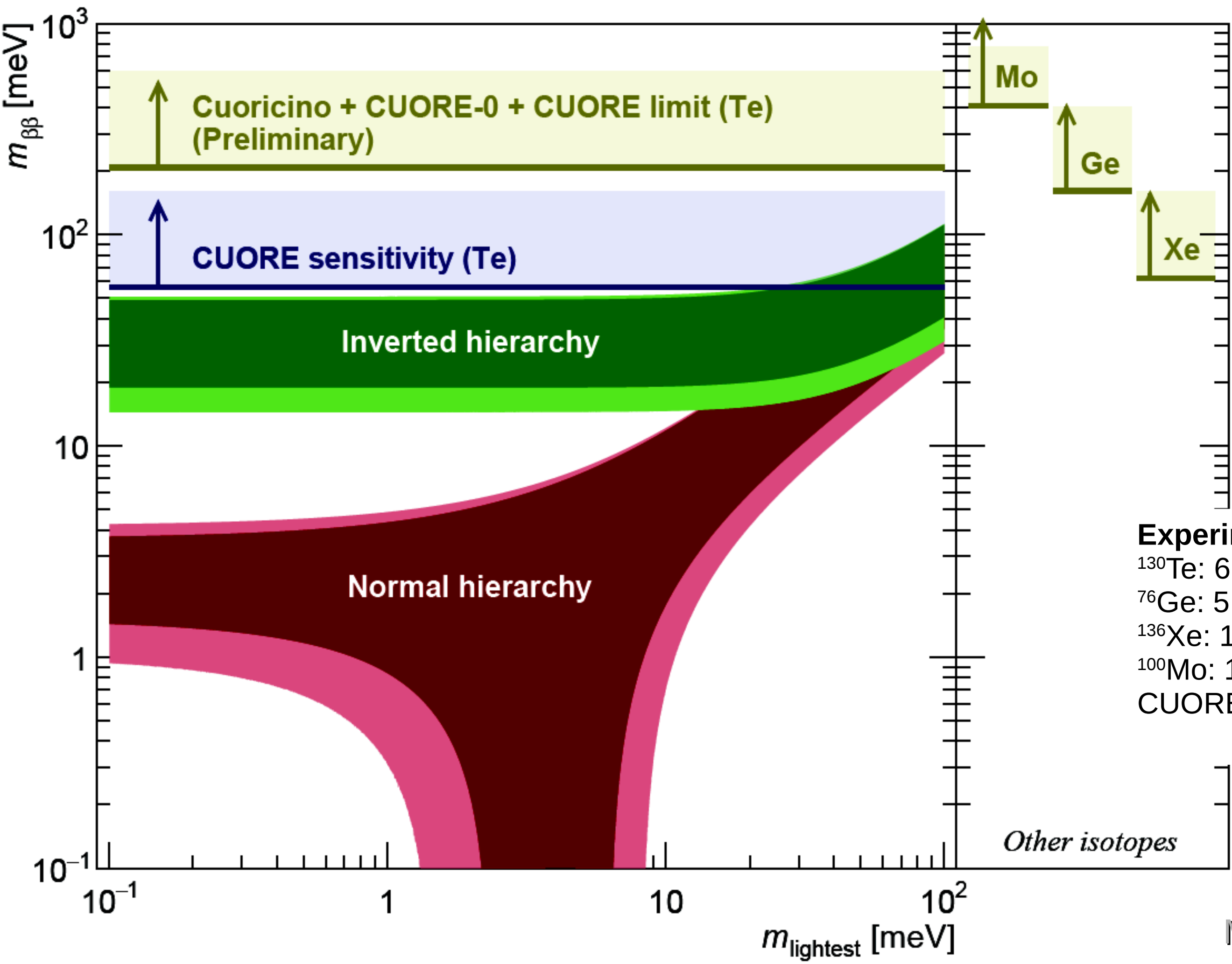
$$\tau_{1/2}^{0\nu} > 6.6 \times 10^{24}\ \mathrm{y}\ \ (90\%\mathrm{C.L.})$$



Combination with previous results

Depending on the Nuclear Matrix Element (NME) calculations, this translates in the following upper limit range for the effective Majorana mass:

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



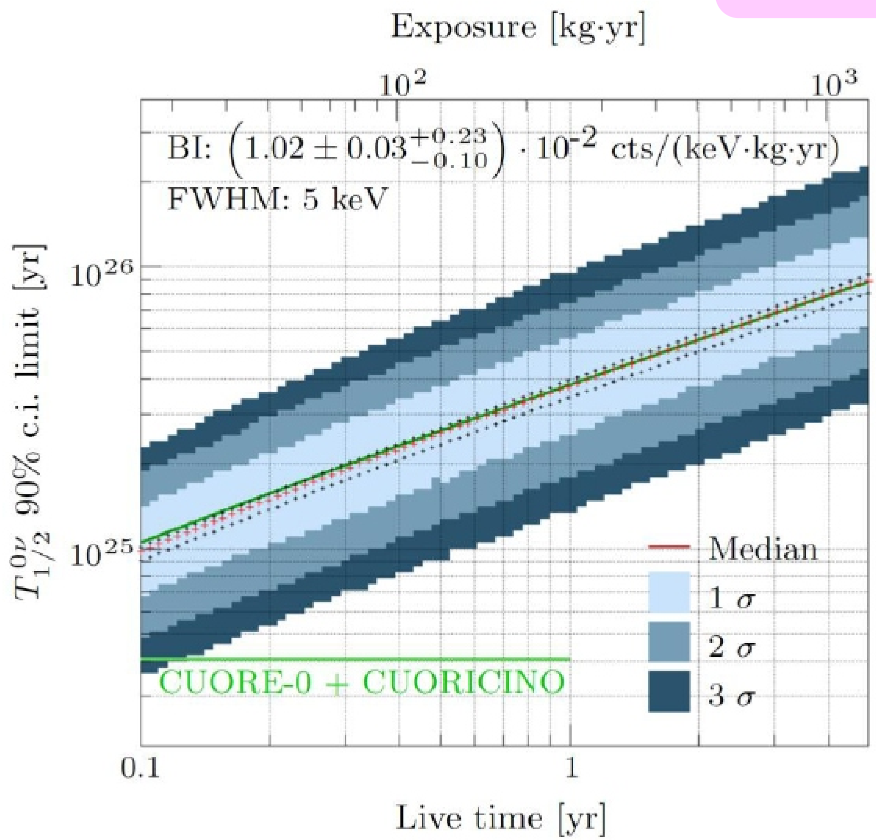
NME
Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 91, 024613 (2015)
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. Lett. 105, 252503 (2010)

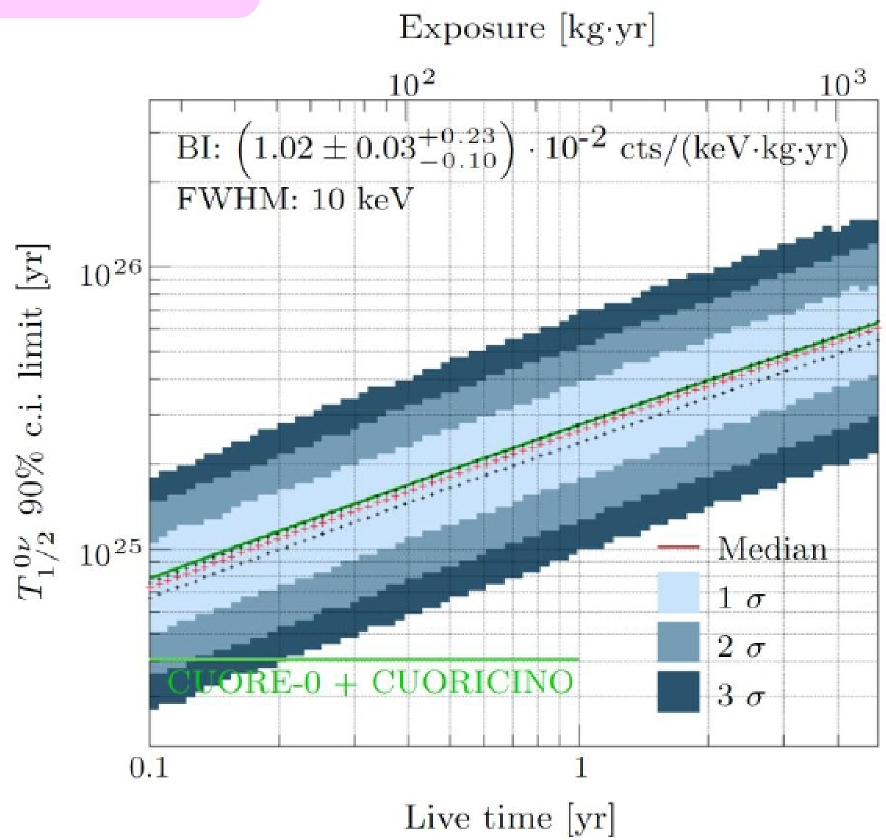
Experiments
^{130}Te: 6.6×10^{24} yr from this analysis
^{76}Ge: 5.3×10^{25} yr from Nature 544, 47–52 (2017)
^{136}Xe: 1.1×10^{26} yr from Phys. Rev. Lett. 117, 082503 (2016)
^{100}Mo: 1.1×10^{24} yr from Phys. Rev. D 89, 111101 (2014)
CUORE sensitivity: 9.0×10^{25} yr

Conclusions

- CUORE is the first ton scale $0\nu\beta\beta$ experiment with thermal detectors
- The cryostat is working spectacularly well
- With 3 weeks of physics data we have surpassed the CUORE-0&Cuoricino limit
- Background rates are consistent with the background model and our predicted sensitivity remains unchanged

More to come!





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CUORE

Thanks!

CUORE official inauguration: October 23, 2017 @ LNGS

Visit our web page: https://cuore.lngs.infn.it