THE CRYOGENIC UNDERGROUND OBSERVATORY FOR RARE EVENTS: STATUS AND PROSPECTS

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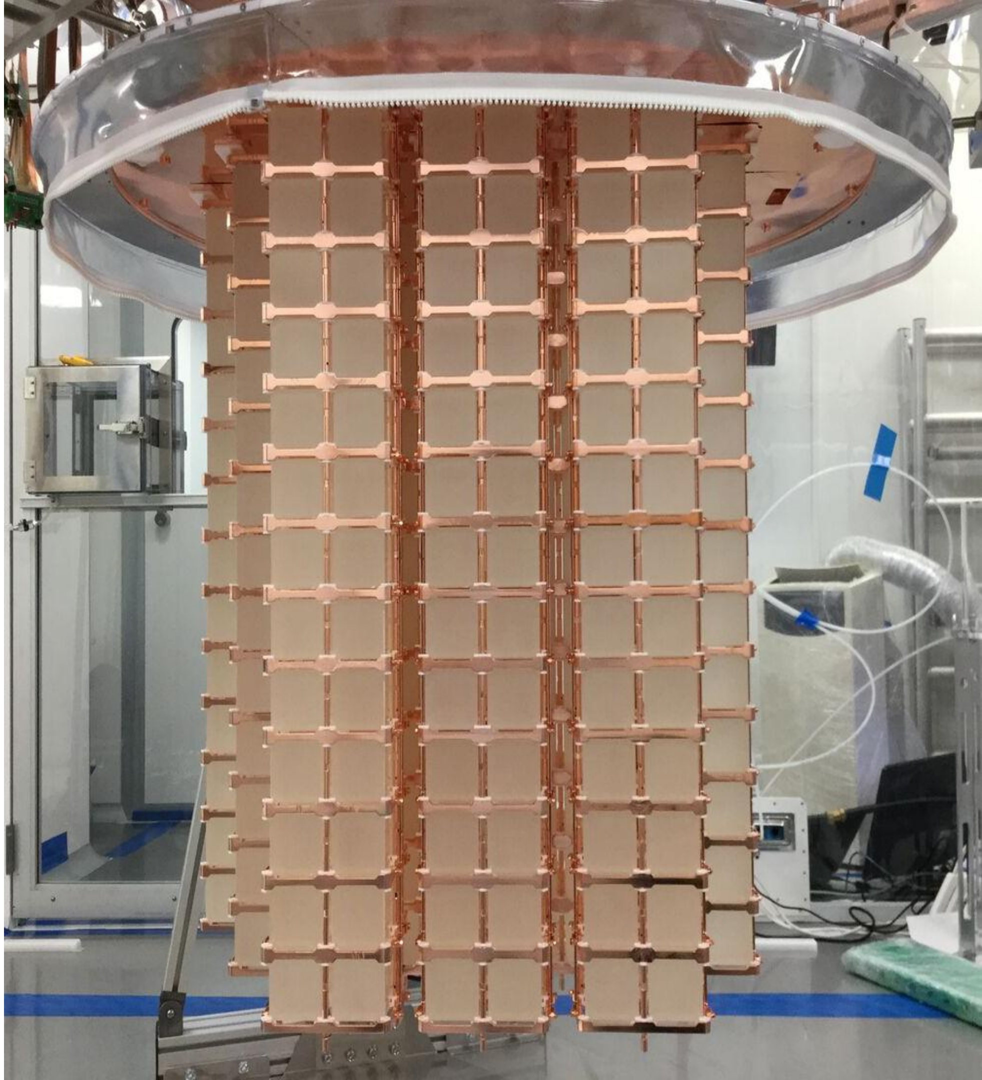


NUCLEAR PHYSICS
IN THE 21ST CENTURY

International Nuclear Physics Conference
INPC 2001

Berkeley, California *30 July - 3 August 2001*

CUORE:
The Cryogenic Underground Observatory for Rare Events

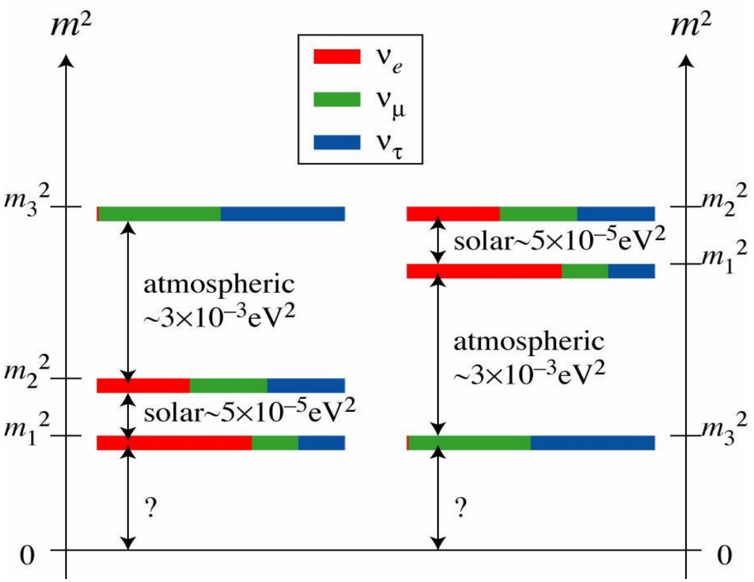
J. W. Beeman[1], E. E. Haller[1,2], R.J. McDonald[1], E. B. Norman[1], A. R. Smith[1], A. Giuliani[3], M. Pedretti[3], G. Ventura[4], M. Balata[5], C. Bucci[5], C. Pobes[5], V. Palmieri[6], G. Frossati[7], A. de Waard[7], C. Brofferio[8], S. Capelli[8], L. Carbone[8], O. Cremonesi[8], E. Fiorini[8], D. Giugni[8], P. Negri[8], A. Nucciotti[8], M. Pavan[8], G. Pessina[8], S. Pirro[8], E. Previtali[8], M. Vanzini[8], L. Zanotti[8], F. T. Avignone III[9], R. J. Creswick[9], H. A. Farach[9], C. Rosenfeld[9], S. Cembrian[10], I. G. Irastorza[9], A. Morales[10]

Recent results in ν physics

Neutrinos undergo flavor-changing oscillations

Neutrinos have finite masses

Neutrino mass hierarchy



At least one ν has m > 55 meV

Open Questions in Neutrino Physics:

What is the absolute scale of ν mass ?

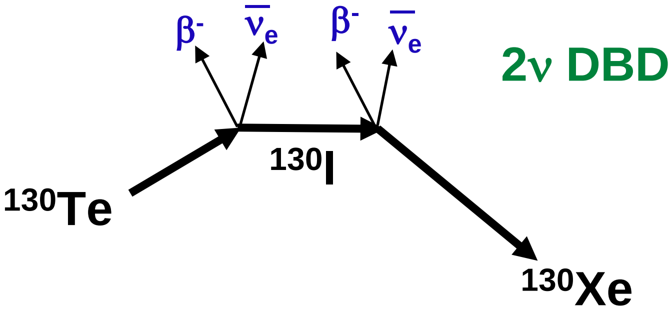
Are ν and $\bar{\nu}$ different particles ?

Alternative mass scheme:

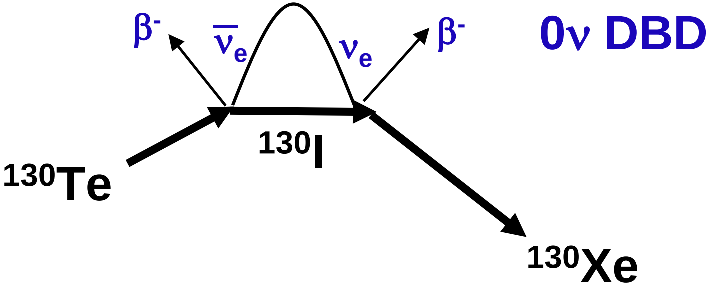
$m_1 \sim m_2 \sim m_3$

All splittings small (degenerate)

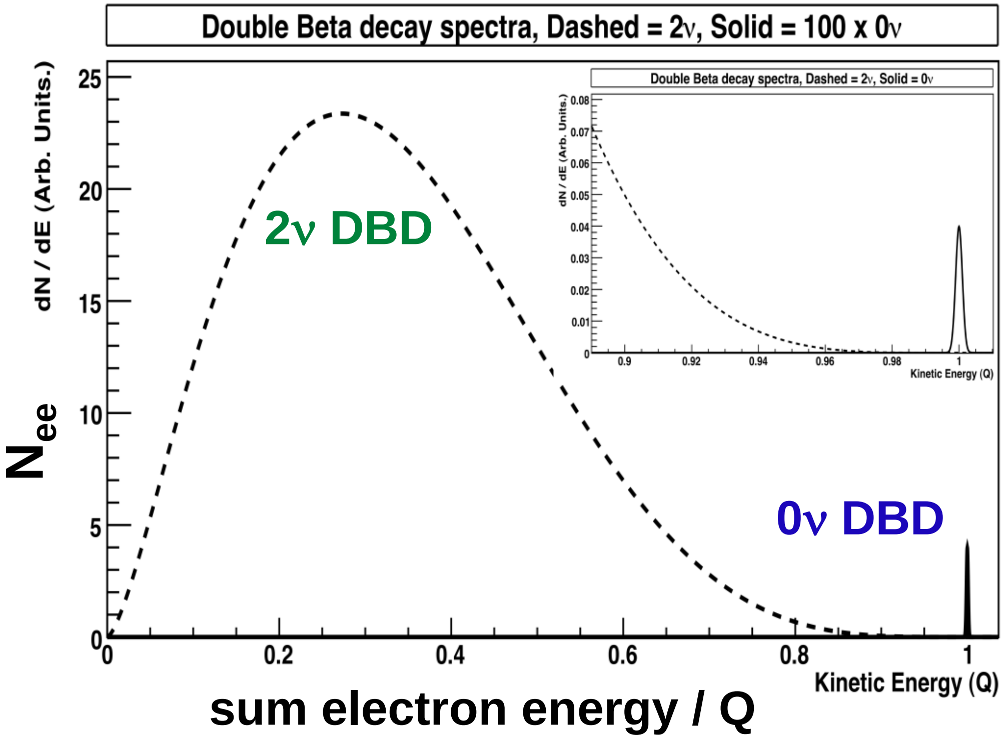
Double Beta Decay



Allowed by Standard Model



Only possible if ν is its own antiparticle



0ν ββ Rate and Neutrino Mass

0ν ββ rate

$$\lambda = 1/\tau = G_F^2\, \Phi(Q,Z)\, |M_{0\nu}|^2\, \langle m_{\beta\beta}\rangle^2$$

Phase space α Q^5

Nuclear matrix element

Effective ν mass

Requirements for a 0νDBD experiment

Experimental Sensitivity:

source mass

live time

$$S_{0\nu} \propto \sqrt{\frac{M \cdot T}{\Gamma \cdot b}}$$

background level

energy resolution

→ large source (many nuclei under observation)

→ long time measurements

→ good energy resolution

→ low background

The CUORE experiment

Located at LNGS (Italy), ~3600 m.w.e. shield

Investigate: $^{130}Te \rightarrow {}^{130}Xe + 2e^-$

Array of 988 $^{nat}TeO_2$ detectors, arranged in 19 towers, 13 floors each. Total mass of 206 kg of ^{130}Te

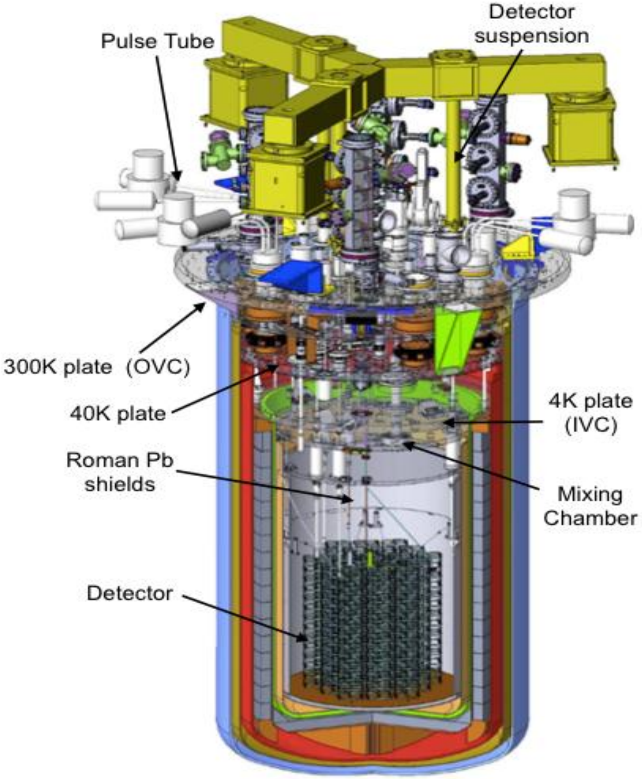
Operated at 10 mK

Energy resolution of 5 keV FWHM at $Q_{\beta\beta}$ (2527 keV)

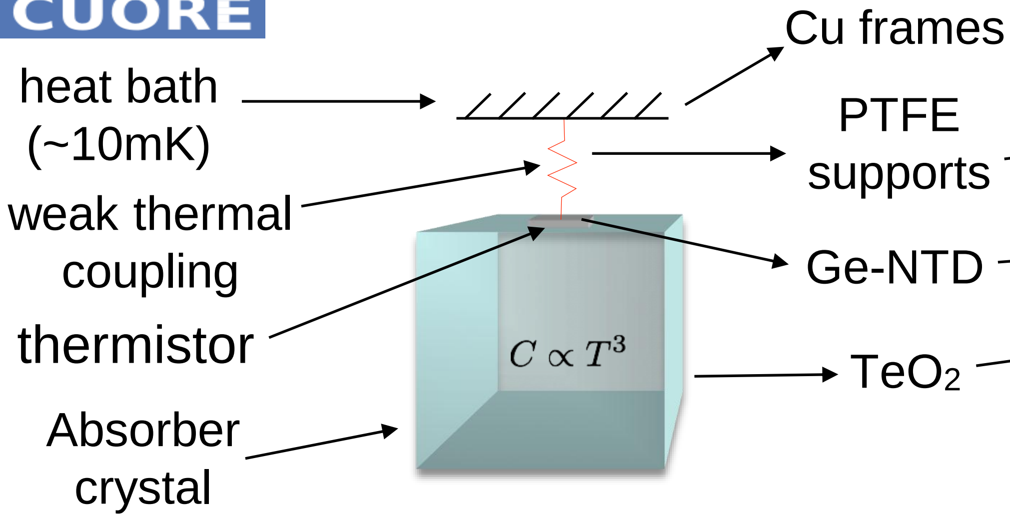
Background goal: 10^{-2} c/keV/kg/year in the ROI.

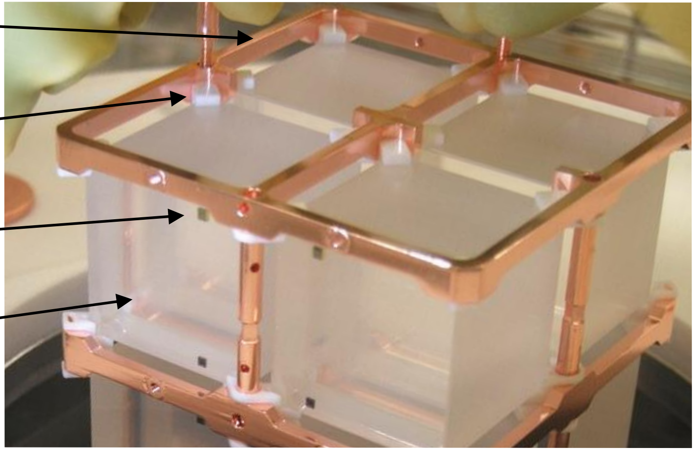
Sensitivity on $m_{\beta\beta}$ (5y, 90% C.L.): 50 - 130 meV

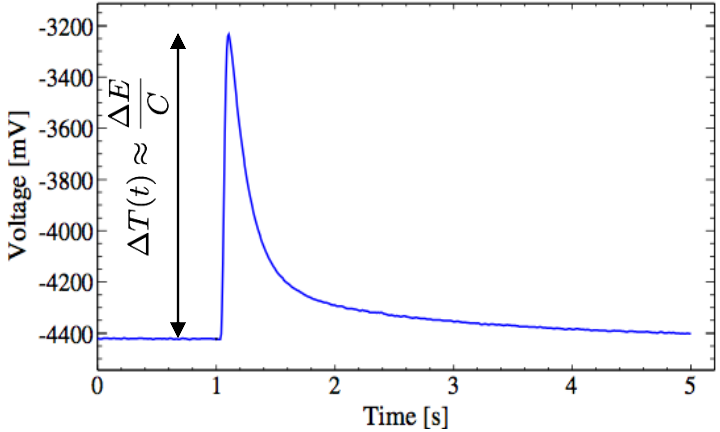
Sensitivity on $0\nu\beta\beta$ $T_{1/2}$ (5y, 90% C.L.): 9.5 x 10^{25} y



CUORE TeO_2 bolometers





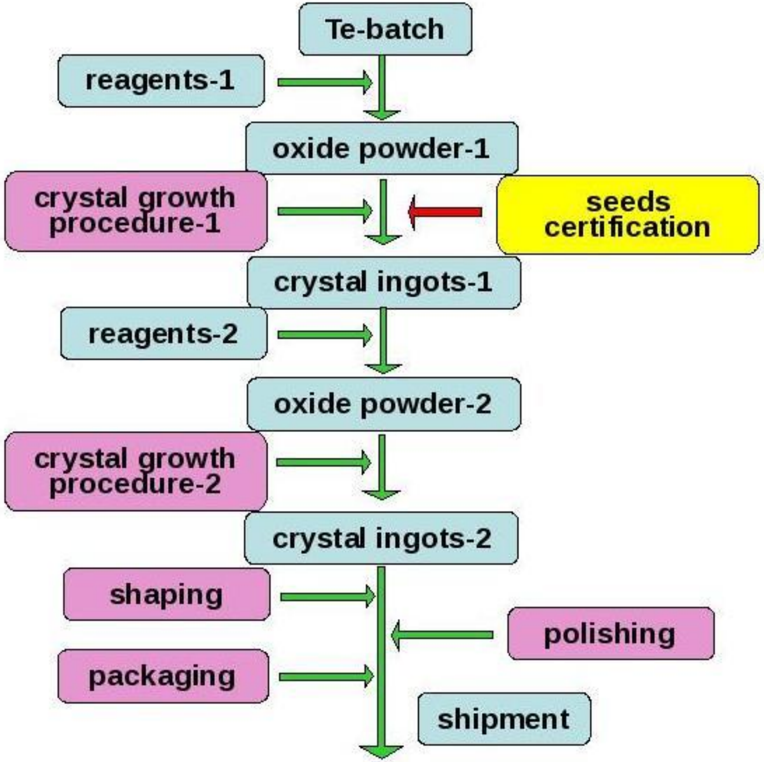


- operated in extreme conditions
- (low T, low noise environment)
- excellent energy resolution (~0.2% FWHM)
- no particle identification
- slow, but ok for rare event searches

TeO_2 crystal production

Shanghai Institute of Ceramics

Material	Category	Contamination limits
Metallic Te	Raw material	$^{238}U < 2 \times 10^{-10}$ g/g $^{232}Th < 2 \times 10^{-10}$ g/g $^{210}Pb < 10^{-4}$ Bq/kg $^{40}K < 10^{-3}$ Bq/kg $^{60}Co < 10^{-5}$ Bq/kg
Water and acids used for TeO_2 powder synthesis	Reagent	$^{238}U < 2 \times 10^{-12}$ g/g $^{232}Th < 2 \times 10^{-12}$ g/g
Water	Consumable	$^{238}U < 2 \times 10^{-12}$ g/g $^{232}Th < 2 \times 10^{-12}$ g/g
TeO_2 powder before crystal growth	Intermediary product	$^{238}U < 2 \times 10^{-10}$ g/g $^{232}Th < 2 \times 10^{-10}$ g/g $^{210}Pb < 10^{-4}$ Bq/kg $^{40}K < 10^{-3}$ Bq/kg $^{60}Co < 4 \times 10^{-5}$ Bq/kg $Pt < 10^{-7}$ g/g $Bi < 10^{-8}$ g/g
TeO_2 crystal, ready-to-use	Final product	$^{238}U < 3 \times 10^{-13}$ g/g $^{232}Th < 3 \times 10^{-13}$ g/g $^{210}Pb < 10^{-5}$ Bq/kg $^{60}Co < 10^{-6}$ Bq/kg
SiO_2 powder for crystal polishing and textile polishing pads	Consumables	$^{238}U < 4 \times 10^{-12}$ g/g $^{232}Th < 4 \times 10^{-12}$ g/g
Gloves, plastic bags, cleaning tissues, etc.	Ancillaries	$^{238}U < 4 \times 10^{-12}$ g/g $^{232}Th < 4 \times 10^{-12}$ g/g



Journal of Crystal Growth **312** (2010) 2999

Crystal Validation

4% of crystals tested as bolometers

Bulk contamination of TeO_2

Upper limits at 90% C.L. on the activity and on the bulk contamination of uranium and thorium decay chains in the hypothesis of secular equilibrium.

Chain	Nuclide	Upper limit [Bq/kg]	Upper limit [g/g]
^{238}U	^{238}U	2.5E−07	2.0E−14
	^{234}U	4.7E−07	3.6E−14
	^{230}Th	5.7E−07	4.4E−14
	^{226}Ra	6.7E−07	5.3E−14
	^{218}Po	1.6E−07	1.3E−14
^{232}Th	^{232}Th	1.3E−07	3.1E−14
	^{212}Bi	8.4E−07	2.1E−13

Preliminary

Bulk contamination contributes < 3×10^{-6} cts/keV/kg/yr to CUORE background

Surface contamination contributes < 1.5×10^{-3} cts/keV/kg/yr to CUORE background

Surface contamination of TeO_2

Upper limits at 90% C.L. for surface contamination, for different penetration length values. See text for details on the calculation of confidence intervals.

Depth	Nuclide	Upper limit 90% C.L. [Bq/cm^2]
0.01 μm	^{238}U	3.1E−09
	^{226}Ra	6.3E−09
	^{232}Th	1.6E−09
0.1 μm	^{238}U	3.2E−09
	^{226}Ra	6.6E−09
	^{232}Th	1.6E−09
0.2 μm	^{238}U	3.8E−09
	^{226}Ra	7.6E−09
	^{232}Th	2.0E−09
1 μm	^{238}U	3.7E−09
	^{226}Ra	8.9E−09
	^{232}Th	1.9E−09
5 μm	^{238}U	2.0E−09
	^{226}Ra	5.4E−09
	^{232}Th	1.0E−09
10 μm	^{238}U	1.7E−09
	^{226}Ra	4.4E−09
	^{232}Th	8.3E−10

Astroparticle Physics **35** (2012) 839

Cosmogenic activation of TeO_2

Bin	Bin range	Integrated neutron flux $((cm^2\ s)^{-1})$	Cross section (mb)		Contribution to R (s^{-1})	
			^{110m}Ag	^{60}Co	^{110m}Ag	^{60}Co
1	1.25–800 MeV	$(3.7 \pm 1.3) \times 10^{-3}$	0.28 ± 0.04	<0.0016	$(2.9 \pm 1.1) \times 10^{-6}$ (80%)	$<(1.7 \pm 0.6) \times 10^{-8}$ (<37%)
2	800 MeV to 1.4 GeV	$(5.3 \pm 1.9) \times 10^{-5}$	3.95 ± 0.40 [a] [43]	0.09 ± 0.04 [19]	$(5.9 \pm 2.2) \times 10^{-7}$ (16%)	$(1.4 \pm 0.8) \times 10^{-8}$ (>30%)
3	1.4–23 GeV	$(2.6 \pm 1.0) \times 10^{-5}$	1.9 ± 0.3 [19]	0.20 ± 0.04 [19]	$(1.4 \pm 0.6) \times 10^{-7}$ (3.9%)	$(1.5 \pm 0.6) \times 10^{-8}$ (>33%)
4	23–150 GeV	$(1.6 \pm 0.6) \times 10^{-7}$	0.88 ± 0.59 [19]	0.75 ± 0.08 [19]	$(4.0 \pm 3.1) \times 10^{-10}$ (0.01%)	$(3.4 \pm 1.3) \times 10^{-10}$ (>0.8%)

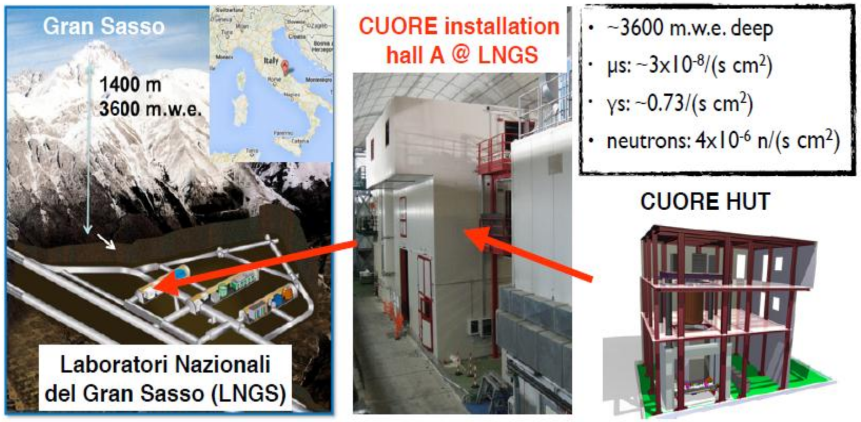
Cosmogenic activation of TeO_2 contributes $< 10^{-4}$ cts/kev/kg/yr to CUORE background

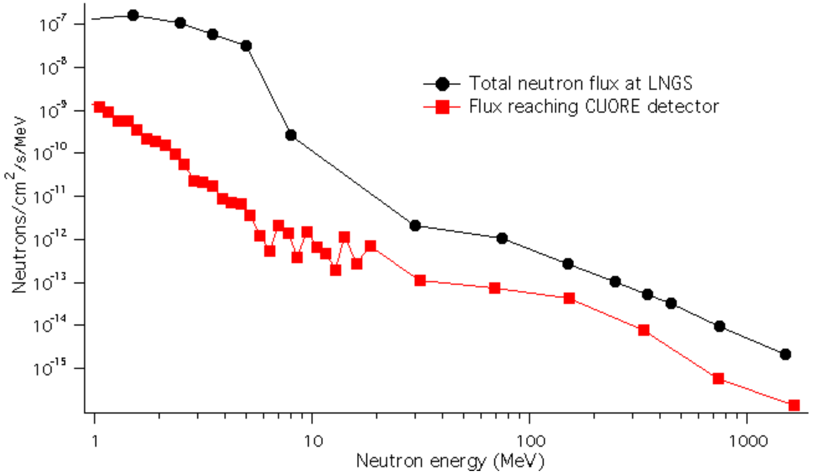
NIM B **295** (2013) 16
Phys. Rev. C **92** (2015) 024620

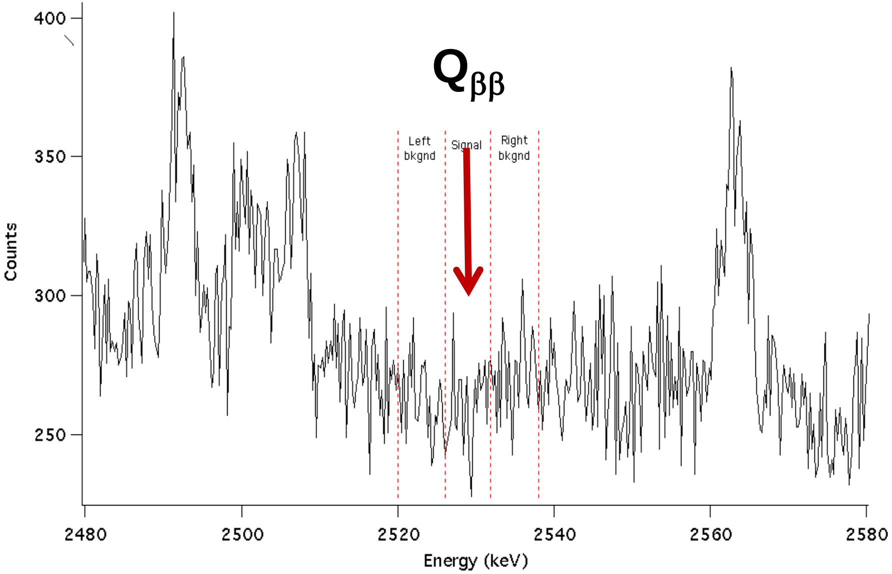
CUORE: Cryogenic Underground Observatory for Rare Events

primary goal: search for neutrino less double beta ($0\nu\beta\beta$) decay in ^{130}Te

Gamma-ray production cross sections from neutron-induced reactions on tellurium (Poster NN1)

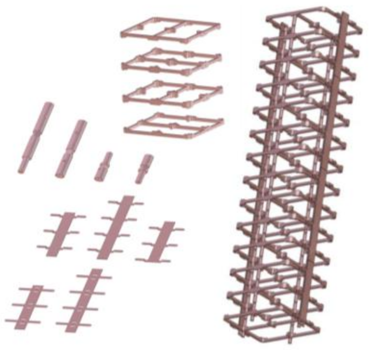




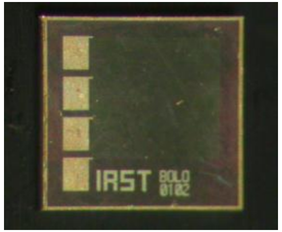


Environmental neutrons contribute $< 10^{-5}$ cts/keV/kg/yr to CUORE background

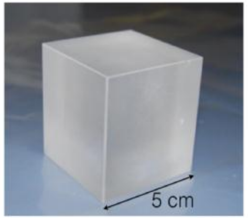
CUORE-module: a tower



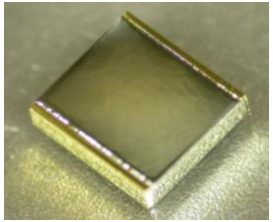
~2000 Cu components



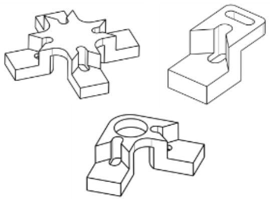
52 Si heaters



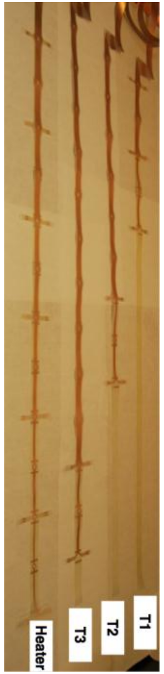
52 TeO_2 crystals



52 Ge NTDs



234 PFTE holders



8 Cu cables

New detector design structure

Strict material selection (e.g. raw materials)

Strict surface cleaning technique for Cu and TeO_2

Minimization of Rn exposure (Glove Box assembly)

CUORE-0

- **CUORE-0 was the first tower produced from the CUORE assembly line:**

  52 TeO_2 5x5x5 cm^3 crystals (~750 g each)

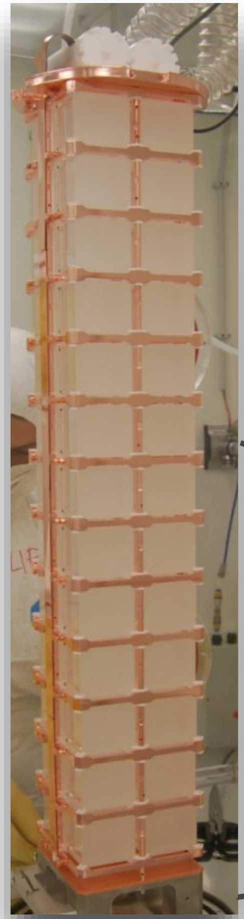
- **Total detector mass: 39 kg TeO_2 (10.9 kg of ^{130}Te)**

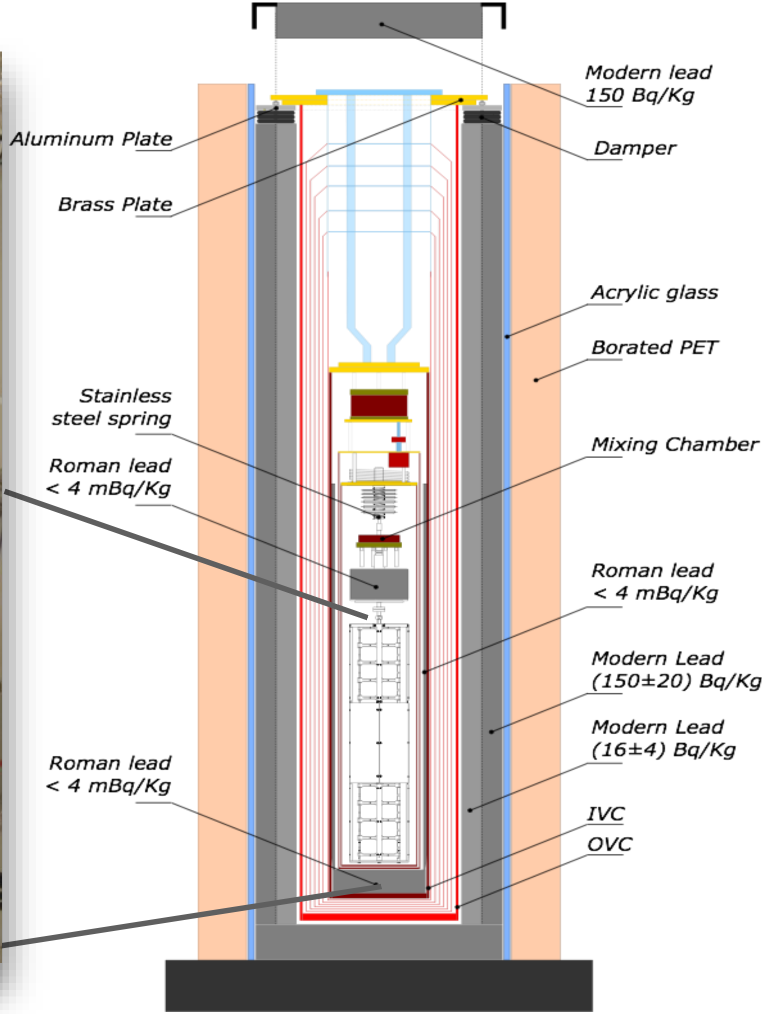
- **Operated in Gran Sasso National Laboratory from March 2013 to March 2015**

- **Statistics accumulated: 9.8 kg·yr ^{130}Te**

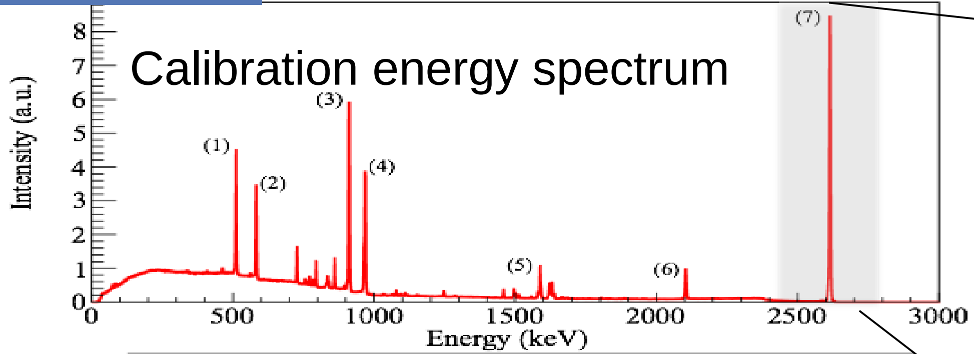
- **Duty cycle: 78.6%**

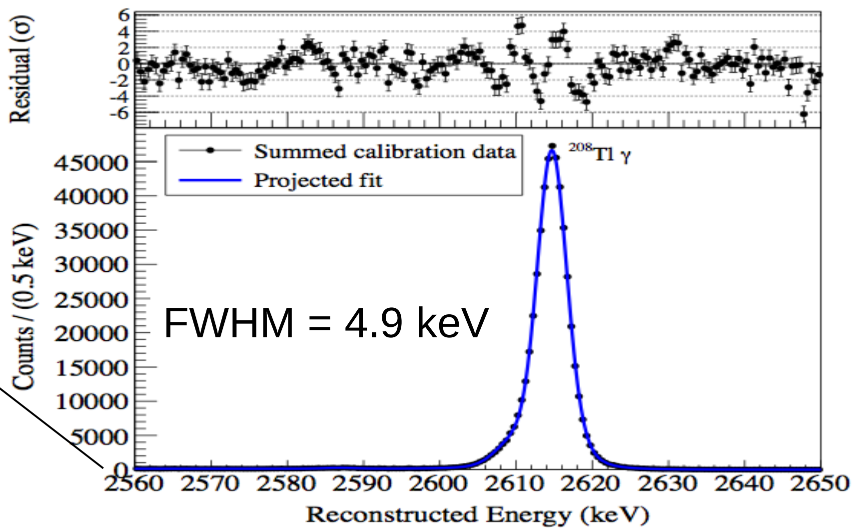
https://arxiv.org/abs/1604.05465

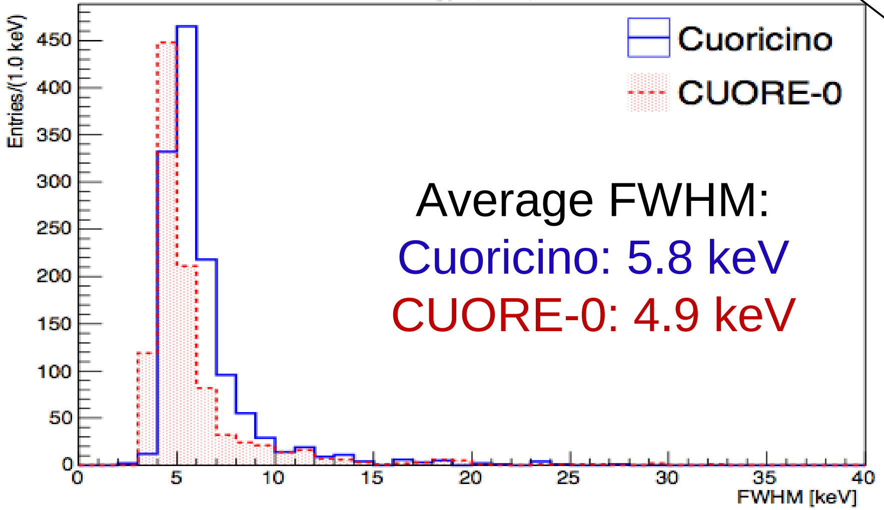




CUORE0 performance

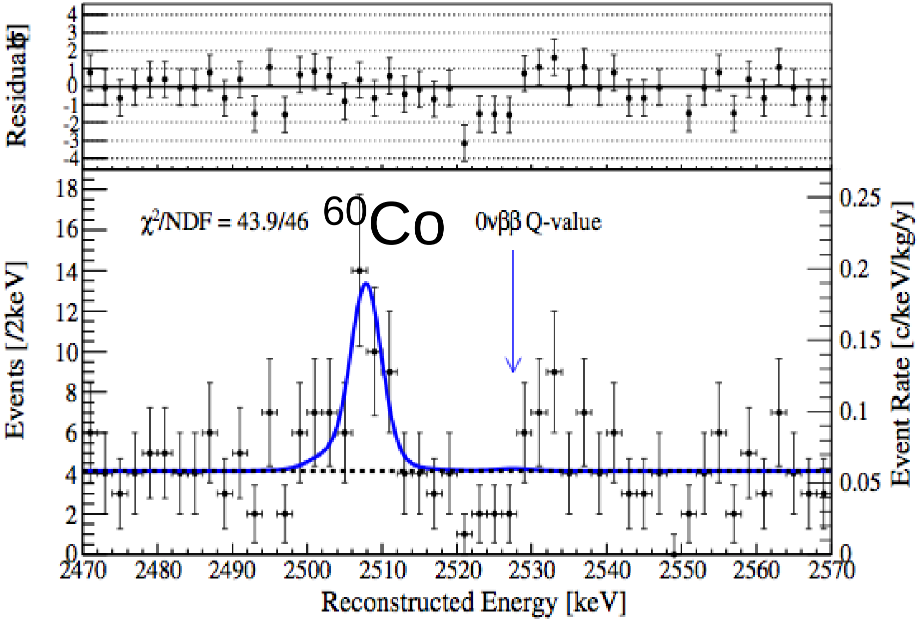






The 5 keV CUORE goal has been reached

CUORE-0 0νββ result



CUORE-0 Final Limit (90% C.L.)

$T_{1/2} > 2.7 \times 10^{24}$ yr

CUORE-0 Background:

b = 0.058 ± 0.004 ± 0.002 cts/keV/kg/yr in the region of interest

Combining the limit with Cuoricino experiment (90% C.L.):

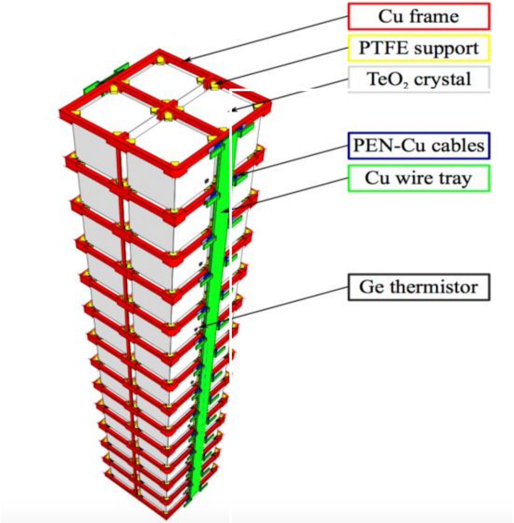
$T_{1/2} > 4.0 \times 10^{24}$ yr

Phys. Rev. Lett. **115** (2015) 102502
Phys. Rev C **93** (2016) 045503

CUORE-0 background model

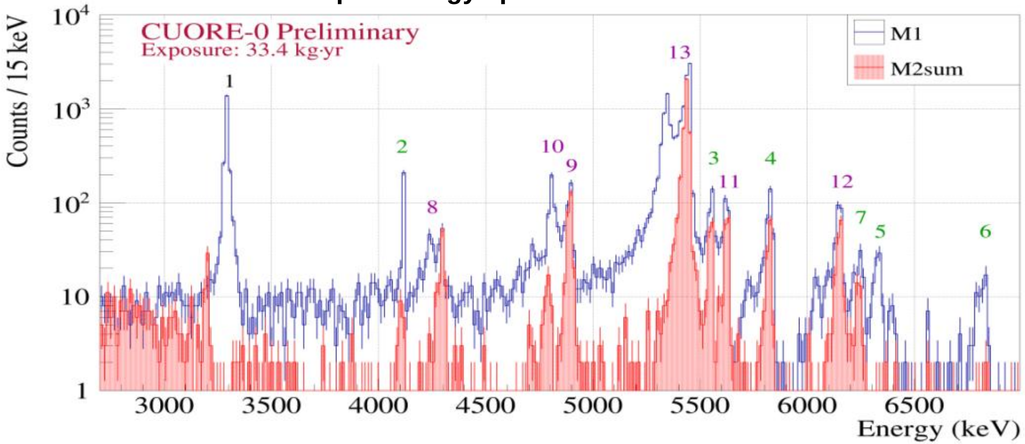
Developed for understanding of bkgd contribution in the ROI

1) **Identification of bkg sources:**
   I. CUORE-0 analysis
   II. radio-assay measurements
   III. cosmogenic activation analysis



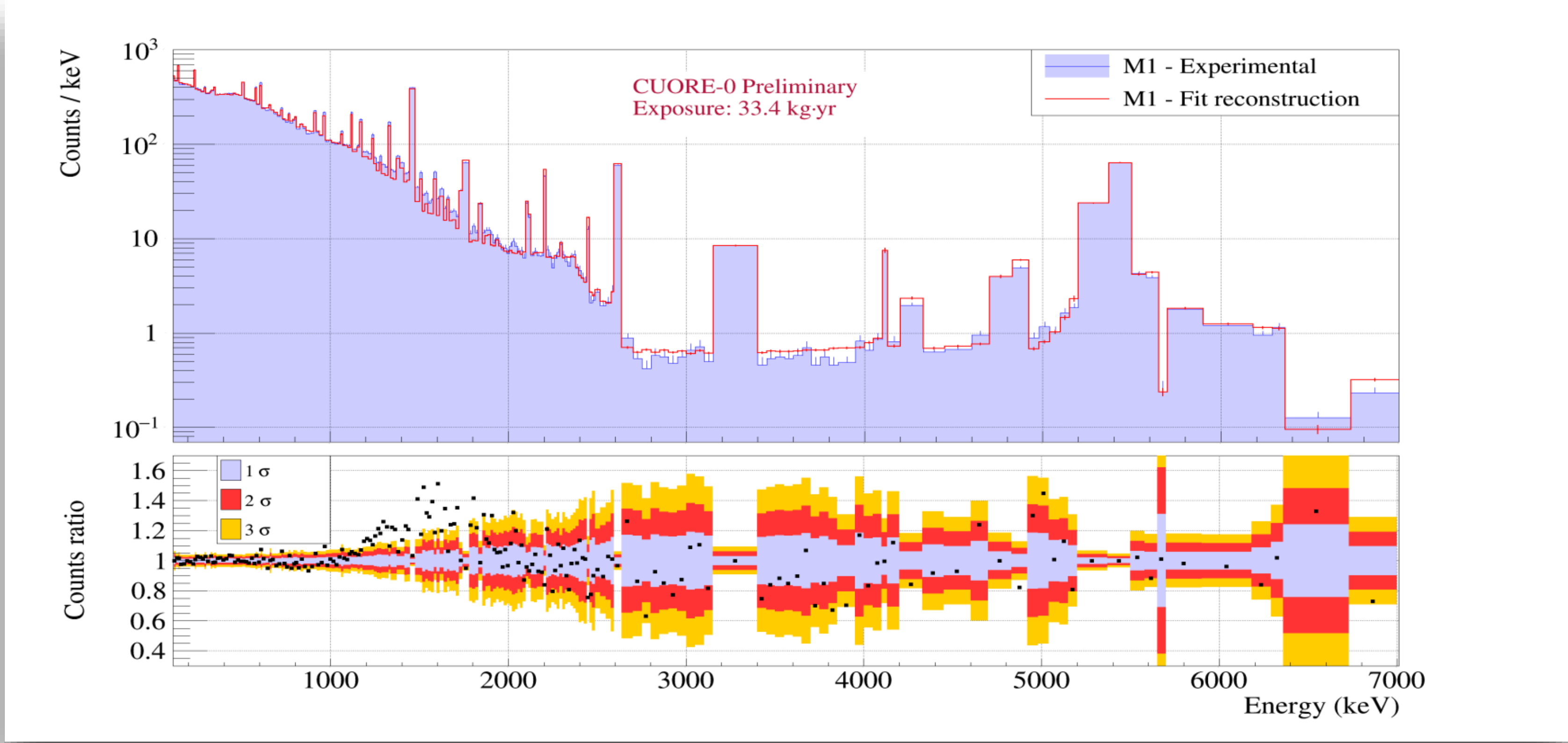
1 ^{190}Pt
2-7 ^{232}Th decay chain
8-13 ^{238}U decay chain

CUORE-0 alpha energy spectrum



2) **MC model of the detector to simulate background sources**

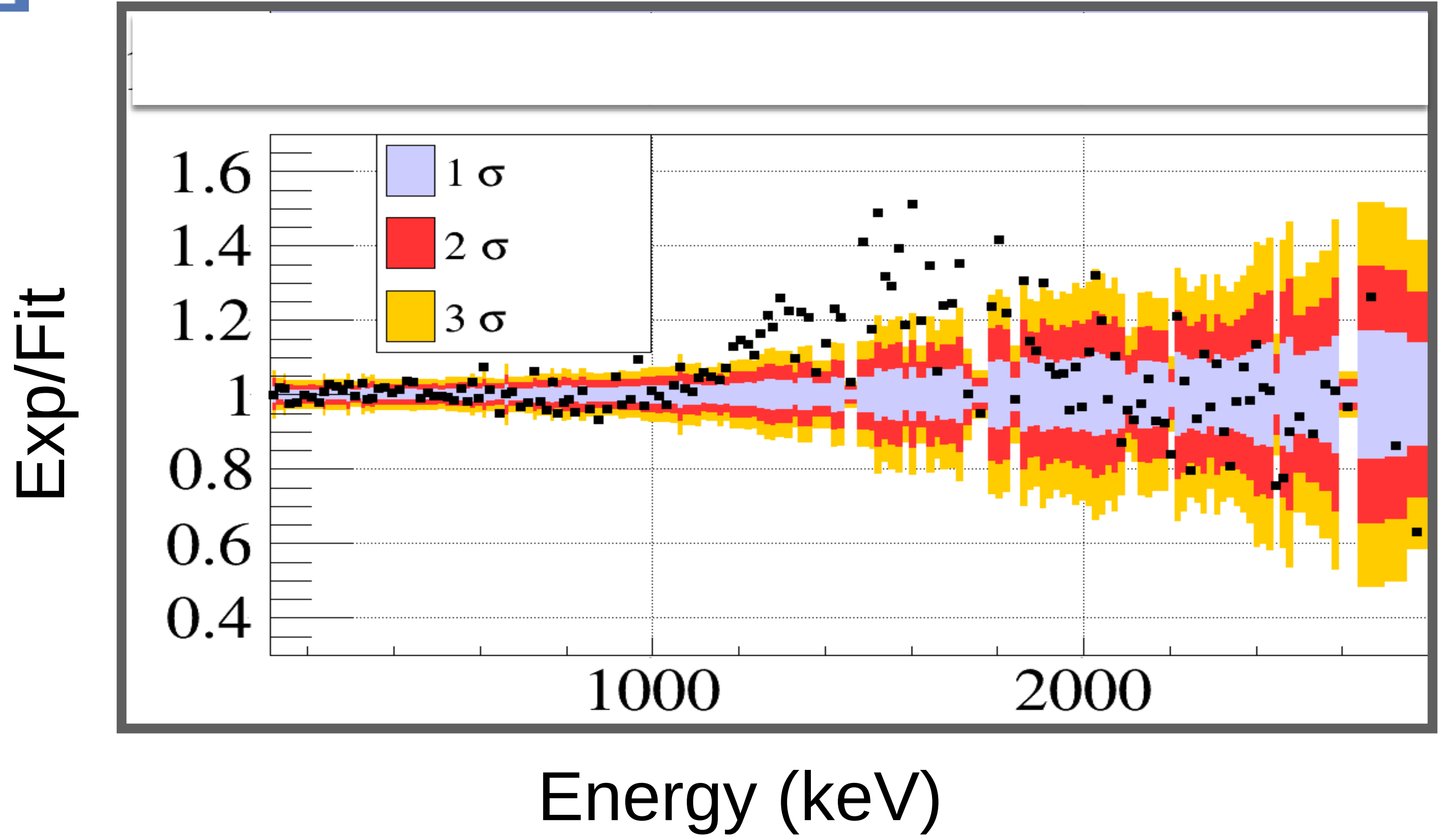
Fit CUORE0 spectrum w/o 2νββ



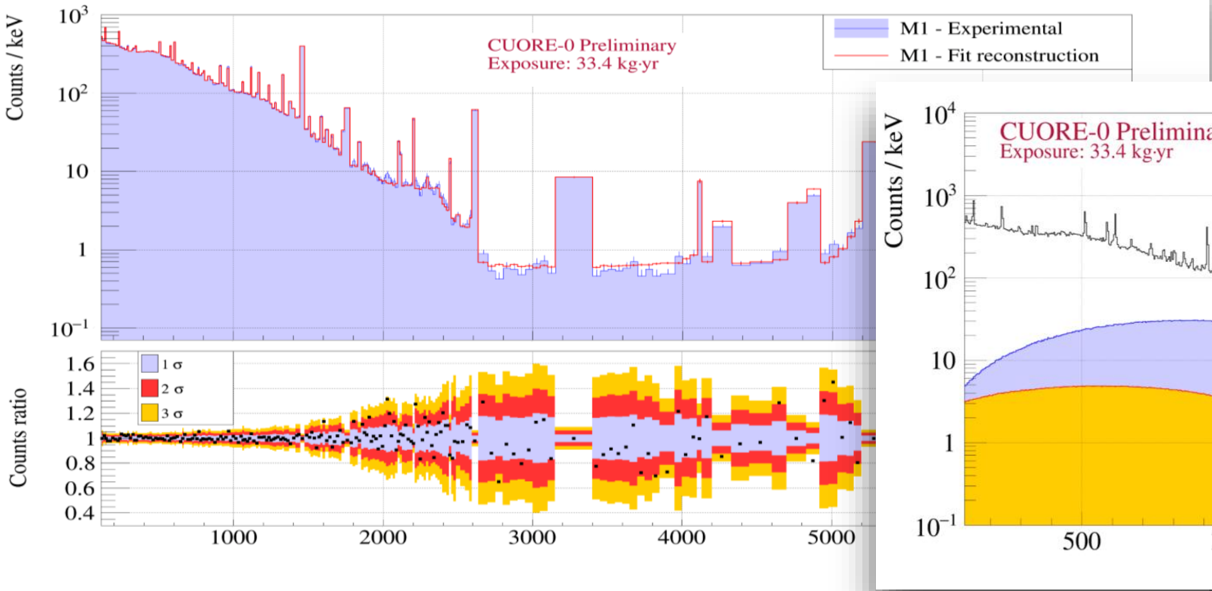
Full reconstruction between: 118 keV - 7 MeV

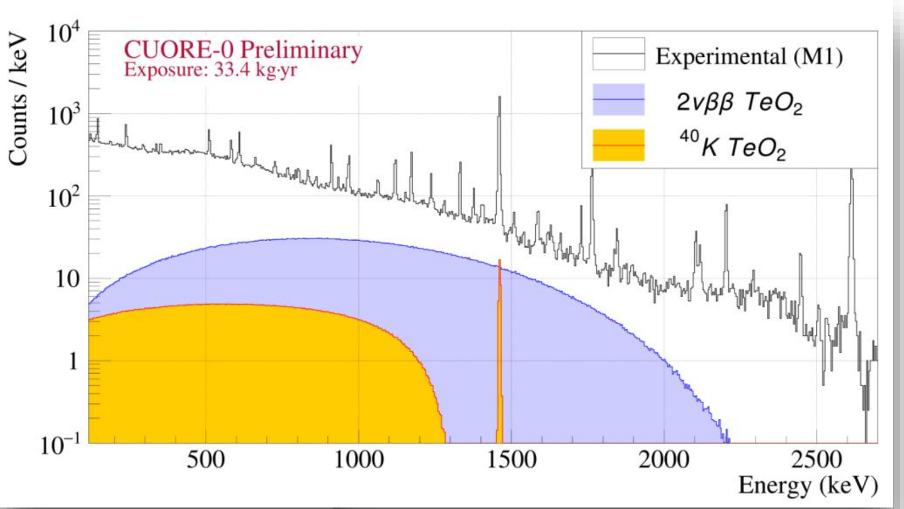
Reconstruction within 3σ range for most bins

Fit CUORE0 spectrum w/o 2νββ



Fit CUORE0 spectrum with 2νββ





$$\text{CUORE-0: } T^{2\nu}_{1/2} = [8.2 \pm 0.2\ (\text{stat.}) \pm 0.6\ (\text{syst.})] \times 10^{20}\ \text{y}$$

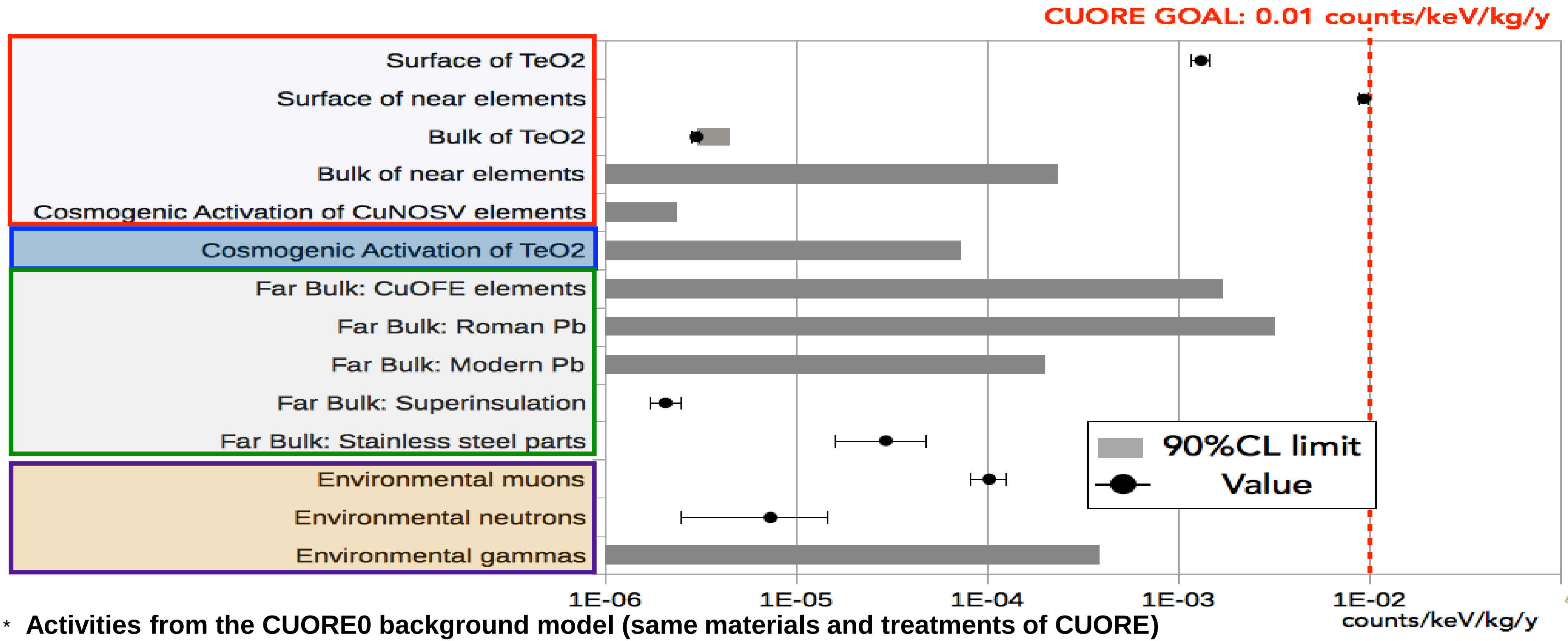
Preprint at: arXiv:1609.01666

$$\text{NEMO: } T^{2\nu}_{1/2} = [7.0 \pm 0.9\ (\text{stat.}) \pm 1.1\ (\text{syst.})] \times 10^{20}\ \text{y}$$

$$\text{MiDBD: } T^{2\nu}_{1/2} = [6.1 \pm 1.4\ (\text{stat.})\ ^{+2.9}_{-3.5}\ (\text{syst.})] \times 10^{20}\ \text{y}$$

CUORE BACKGROUND BUDGET

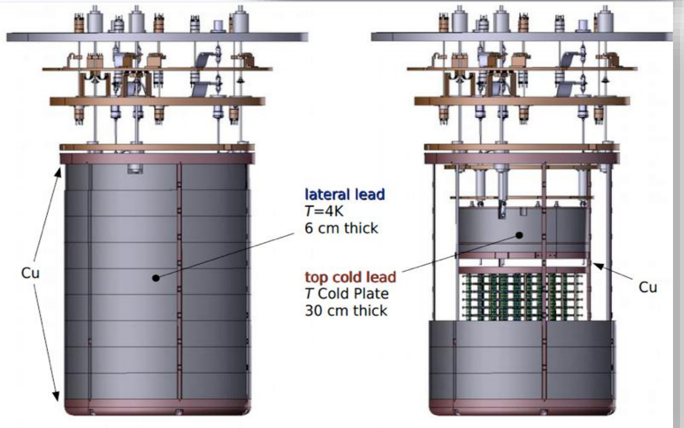
Preliminary



- Activities from the CUORE0 background model (same materials and treatments of CUORE)
- [D.Chiesa talk at 28th Rencontres the Blois]
- Activities from new calculation with the most recent radionuclide production cross sections measured for Te [PRC92(2015)024620]
- Activities from measurements with HPGe and NAA (some are new)
- γ, μ, n fluxes at LNGS from measurements/calculations [Astrop. Phys. 33(2010)169]

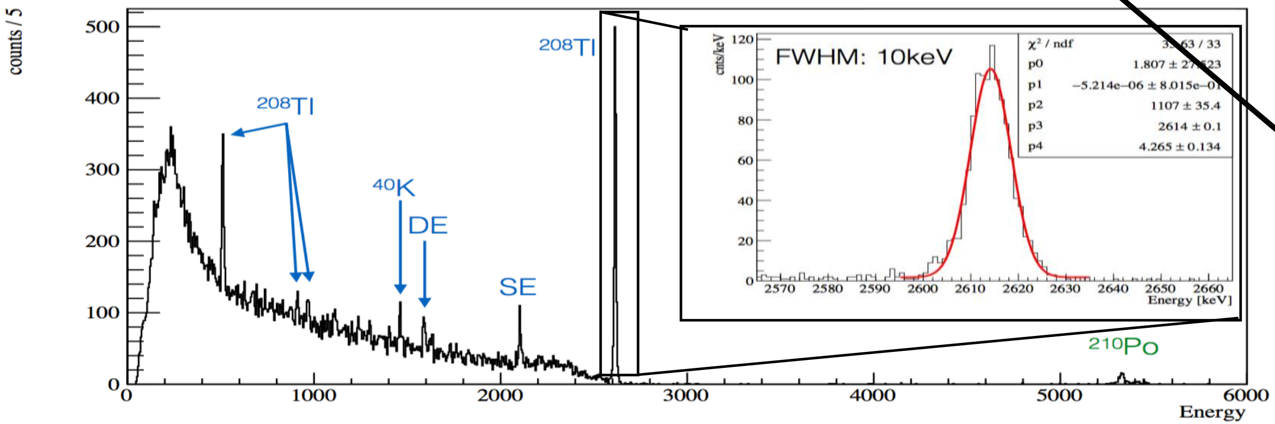
CUORE cryostat commissioning

- *Shielding*
- *Fast Cooling System*: cool down detector to 4K in ~3 weeks
- *Detector calibration system*: ^{232}Th calibration sources deployed from 300 K to 10 mK
- *Stable base temperature* @ 6.3 mK over more than 70 d
- *Cooling power*: 3μW @ 10 mK

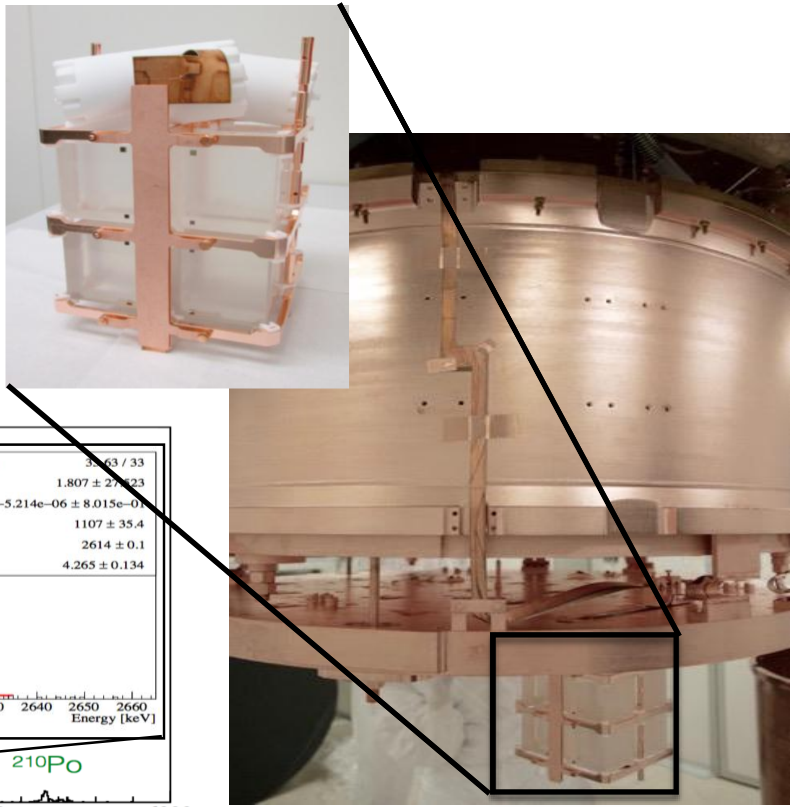


Mini Tower Test Run

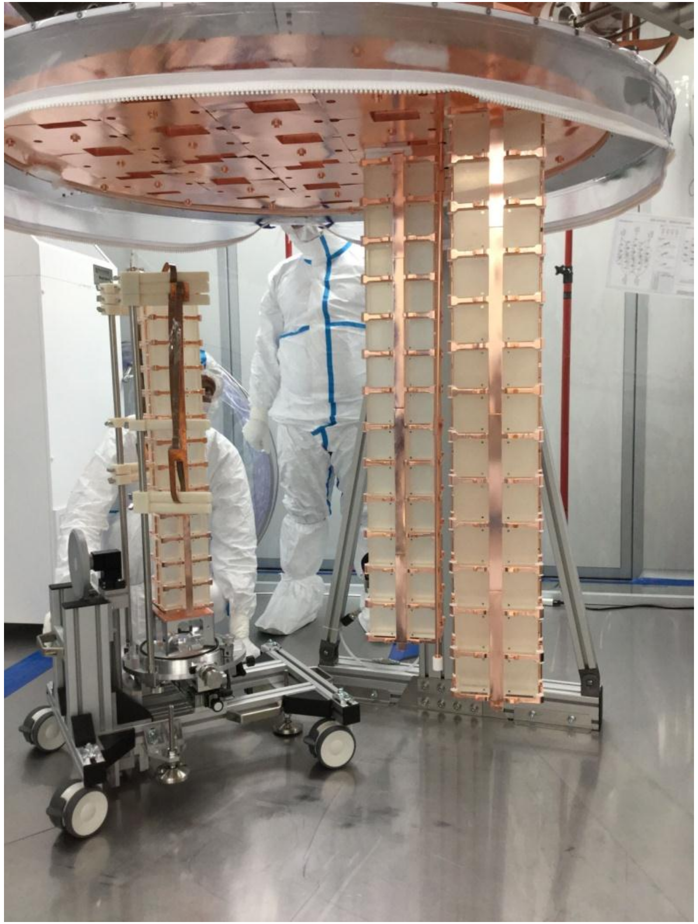
- 8 TeO_2 bolometers (Mini-Tower) have been operated in CUORE cryostat to validate performance.
- Stable base temperature during operations
- Good detector performance (energy resolution).
- No indications of unaccounted-for bkg sources.
- Successful test of electronics, DAQ, temperature stabilization, and detector calibration systems.



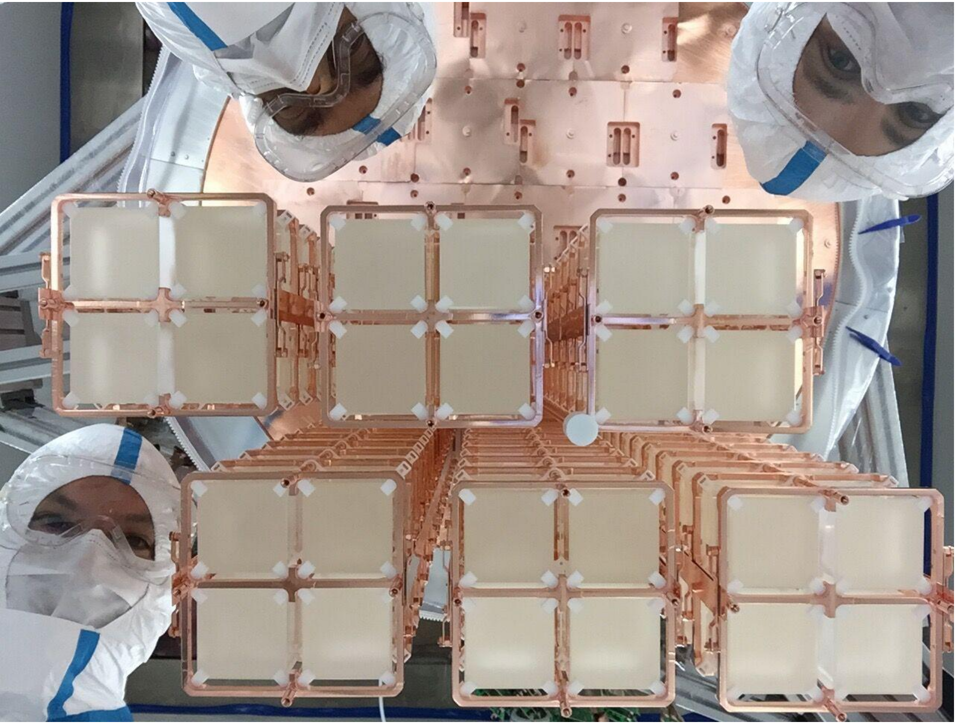
Calibration energy spectrum

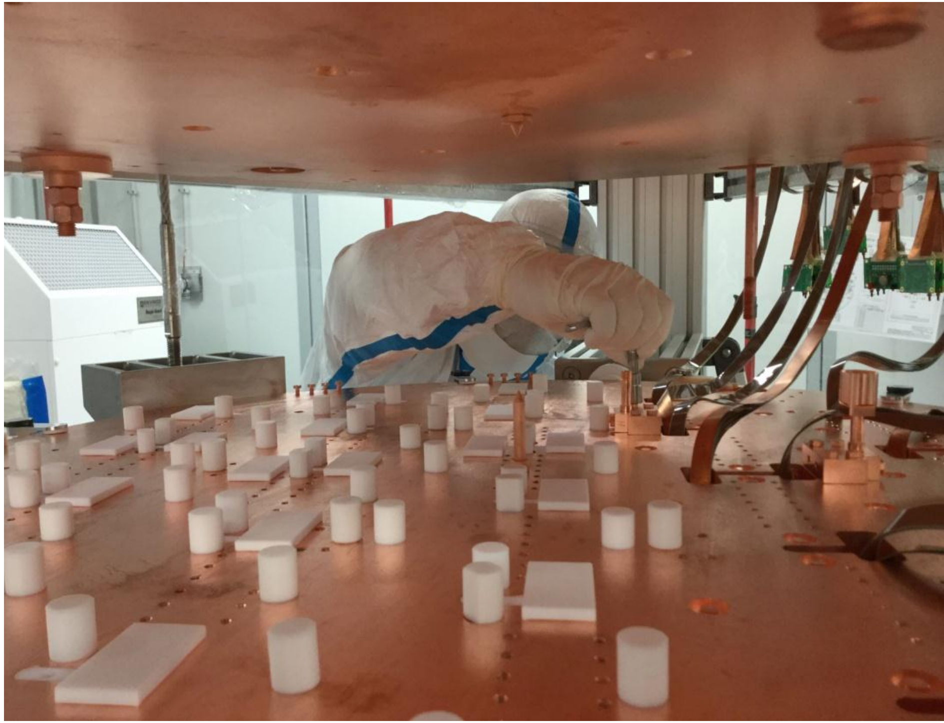


CUORE tower installation



CUORE tower installation





Summary

- TeO_2 bolometers offer a well-established and competitive technology for $0\nu\beta\beta$ decay investigation.

- CUORE-0 demonstrated that the CUORE sensitivity is within the reach.

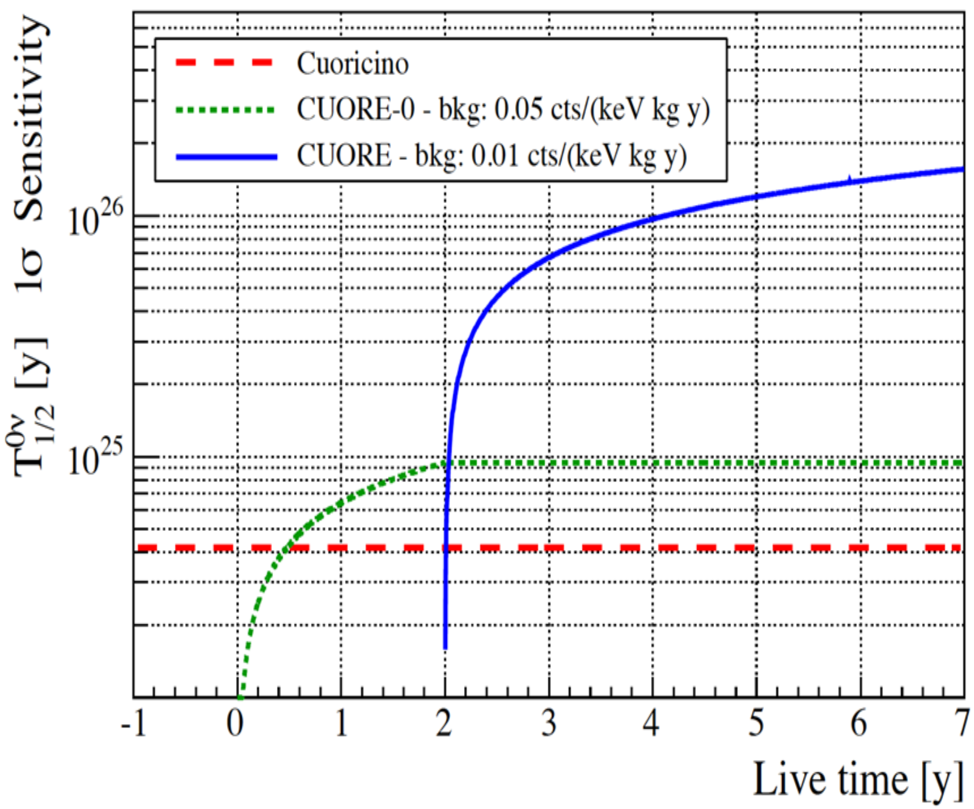
    - CUORE-0 result, combined with Cuoricino, currently sets the best limit on $0\nu\beta\beta$ $T_{1/2}$ of ^{130}Te.

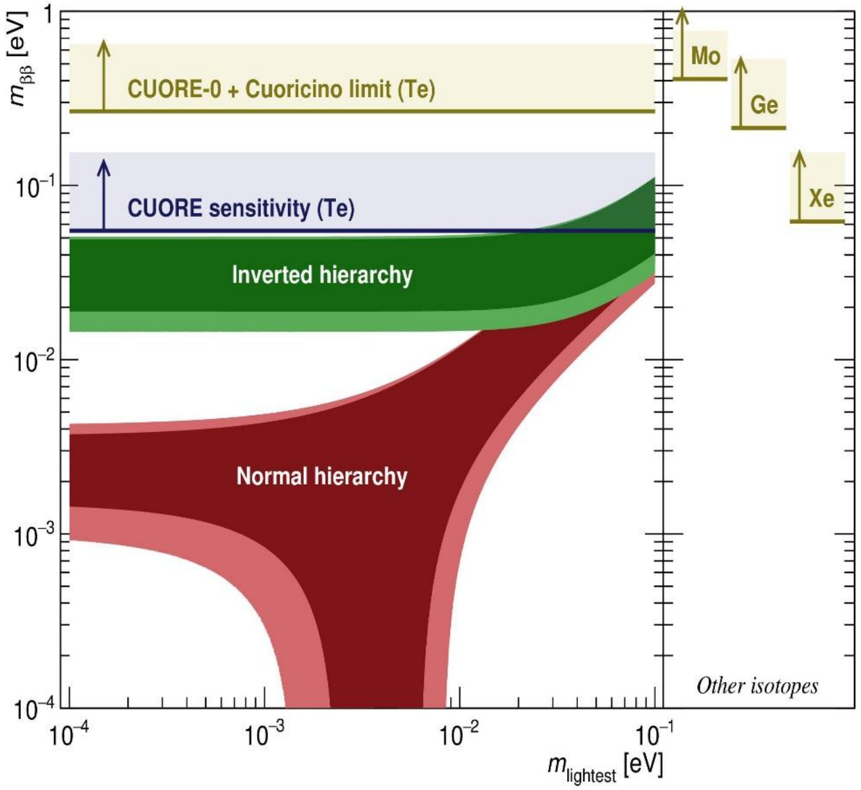
    - ^{130}Te $2\nu\beta\beta$ half-life has been measured (paper submitted to EJPC).

- The 19 CUORE towers have been installed in the cryostat.

CUORE operations will start by the end of this year.

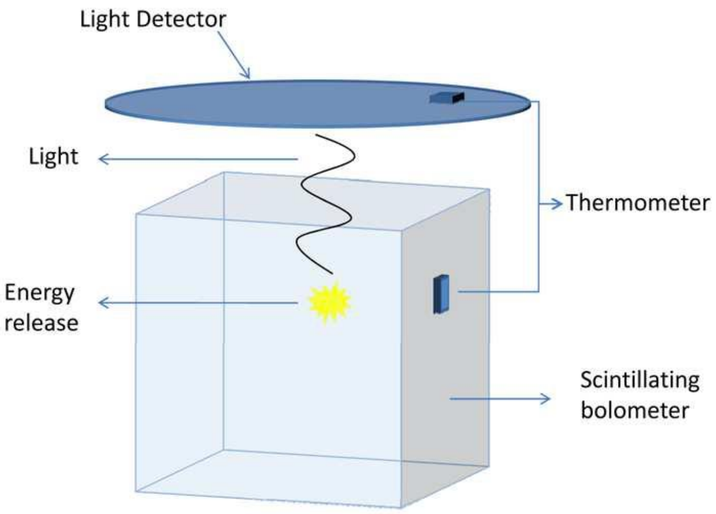
CUORE Sensitivity





Plans for the future: CUORE Upgrade with Particle ID **(CUPID)**

Goal: build a large bolometric 0νββ experiment with ~1 ton of isotope and nearly zero background.



arxiv.org/abs/1504.03599

- Based on the CUORE design, CUORE cryogenics
- Enrichment (^{130}Te, ^{82}Se, ^{116}Cd, ^{100}Mo)
- Background rejection (scintillating bolometers, Cherenkov tagging, surface rejection, improved resolution…)
- Active vetoes

- Goal: reach sensitivity to entire IH region:
  - Half-life sensitivity (2-5)x10^{27} y in 10 y
  - $m_{\beta\beta}$ sensitivity 6-20 meV

Several R&D activities to select the highest performing one

Thank you
on behalf of the CUORE Collaboration