The CUORE and CUORE-0 experiments

Carlo Bucci

INFN - Laboratori Nazionali del Gran Sasso

Present knowledge about neutrinos

- neutrinos are massive fermions
- there are 3 active neutrino flavors (ν_α)
- neutrino flavor states are mixtures of mass states (ν_k)

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle$$

Pontecorvo–Maki–Nakagawa–Sakata matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric / Accelerator — Reactor / Accelerator — Solar / Reactor

Measurements of neutrino parameters from:

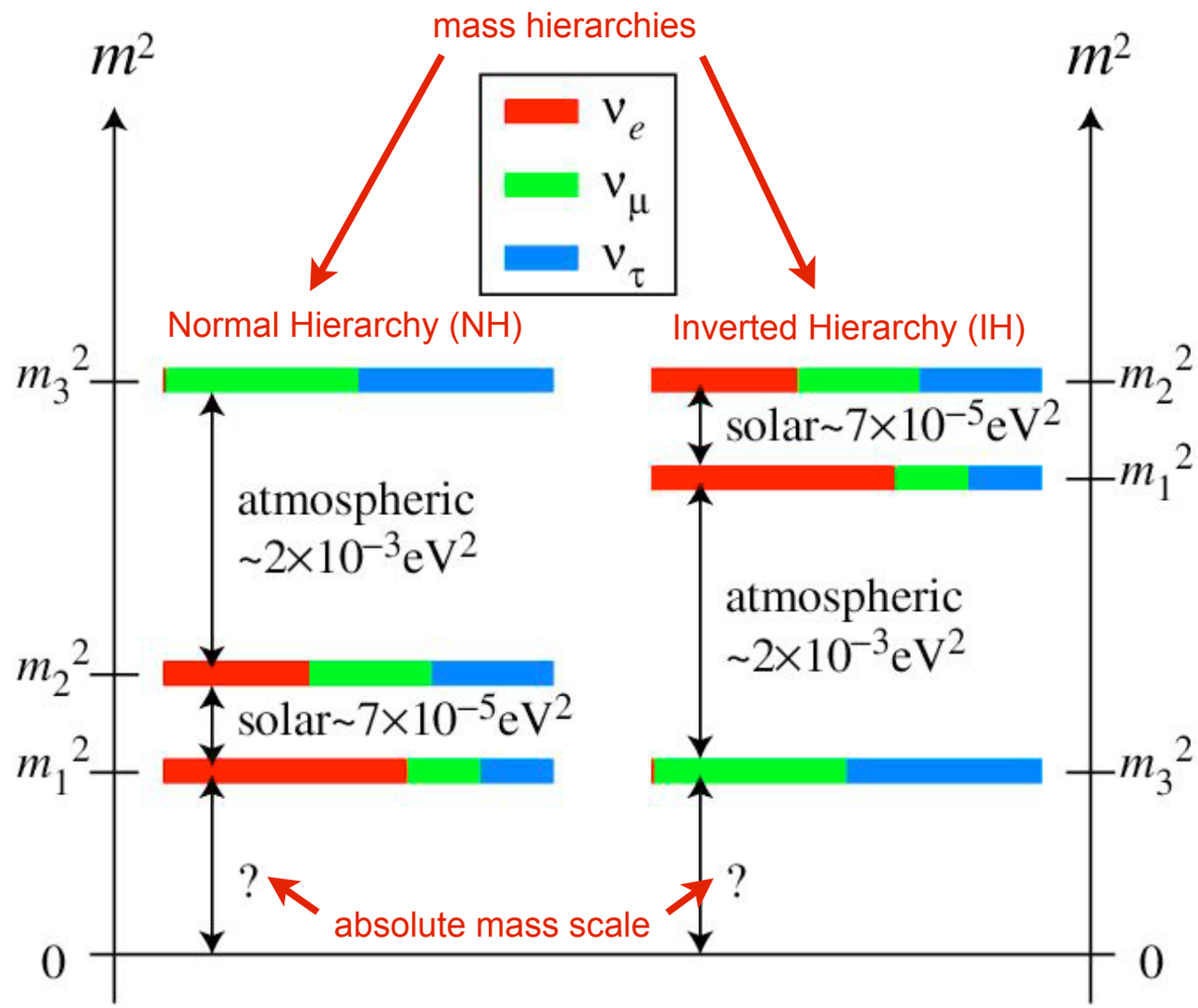
- neutrino oscillations
- single beta decay
- cosmology
- neutrinoless double beta decay

Open questions

Neutrinos are important probes of the Standard Model limits

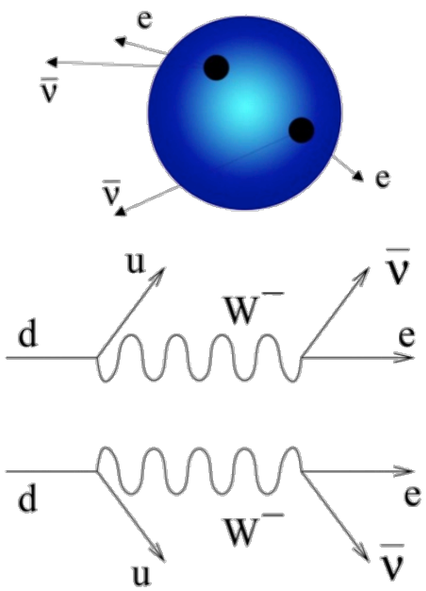
0ν-ββ can give an answer to three open questions:

- Are neutrinos Dirac or Majorana particles?
- What is the absolute neutrino mass scale?
  mass of the lightest ν
- What is the neutrino mass hierarchy?
- (m1 < m2 ≪ m3 or m3 ≪ m1 <m2)



Oscillation experiments can determine the hierarchy but are blind to the other two questions

Double beta decay

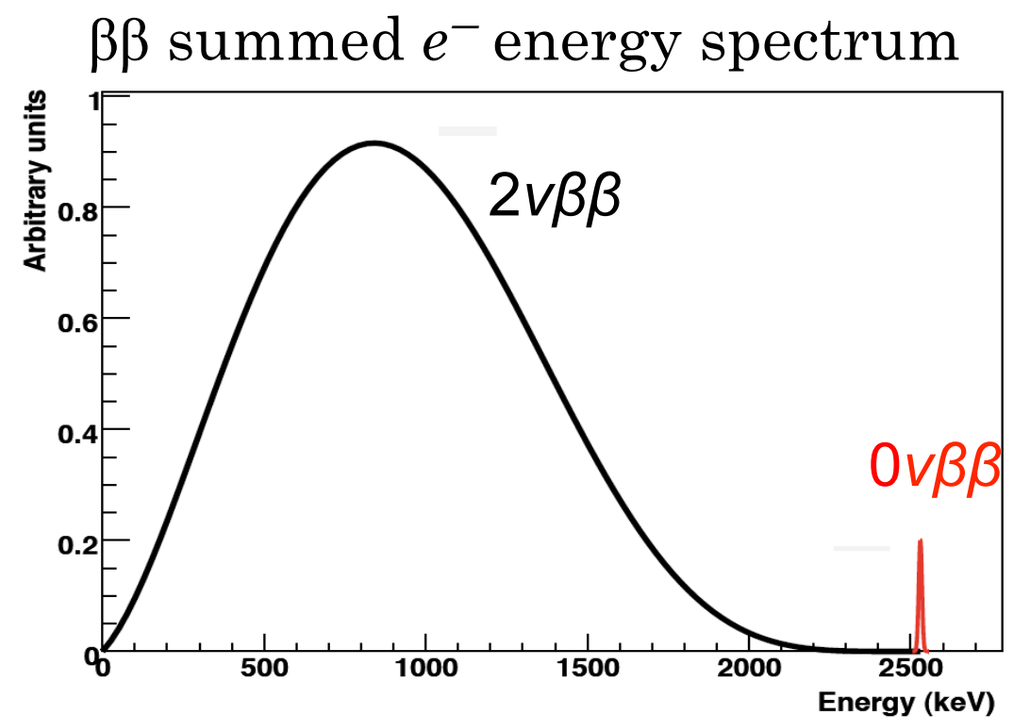


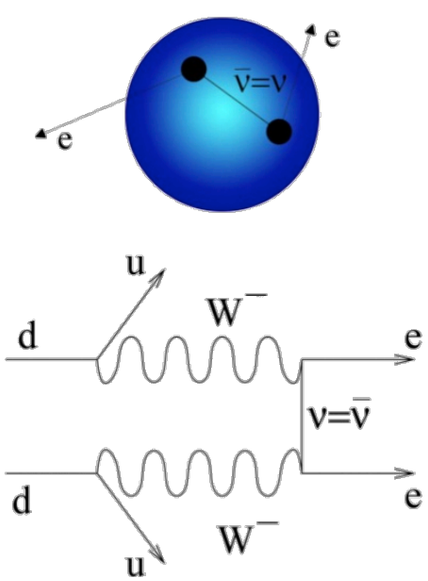
$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\overline{\nu}$$

2ν-DBD

2nd order process allowed in the SM

observed in several nuclei with $\tau^{2\nu} \sim 10^{19}$-10^{21} y





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

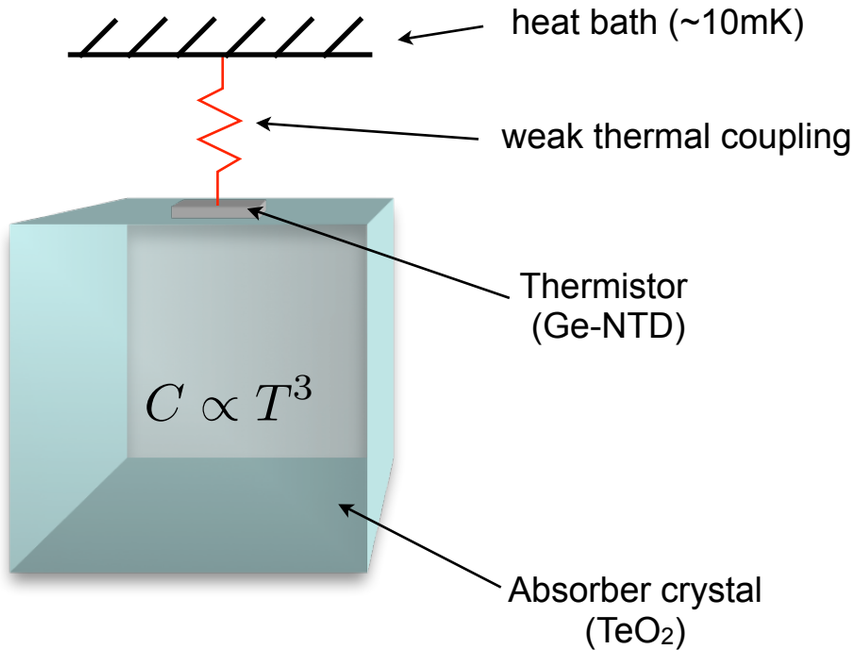
0ν-DBD (implies physics beyond SM)

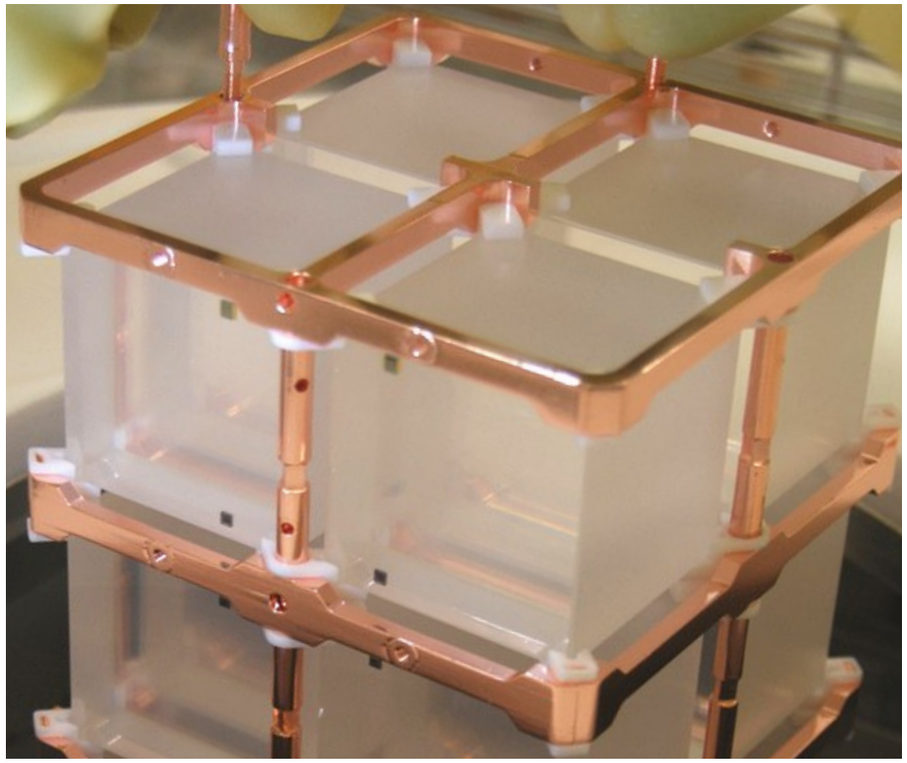
lepton number violating process

$\tau^{0\nu} > 10^{24}$-10^{25} y

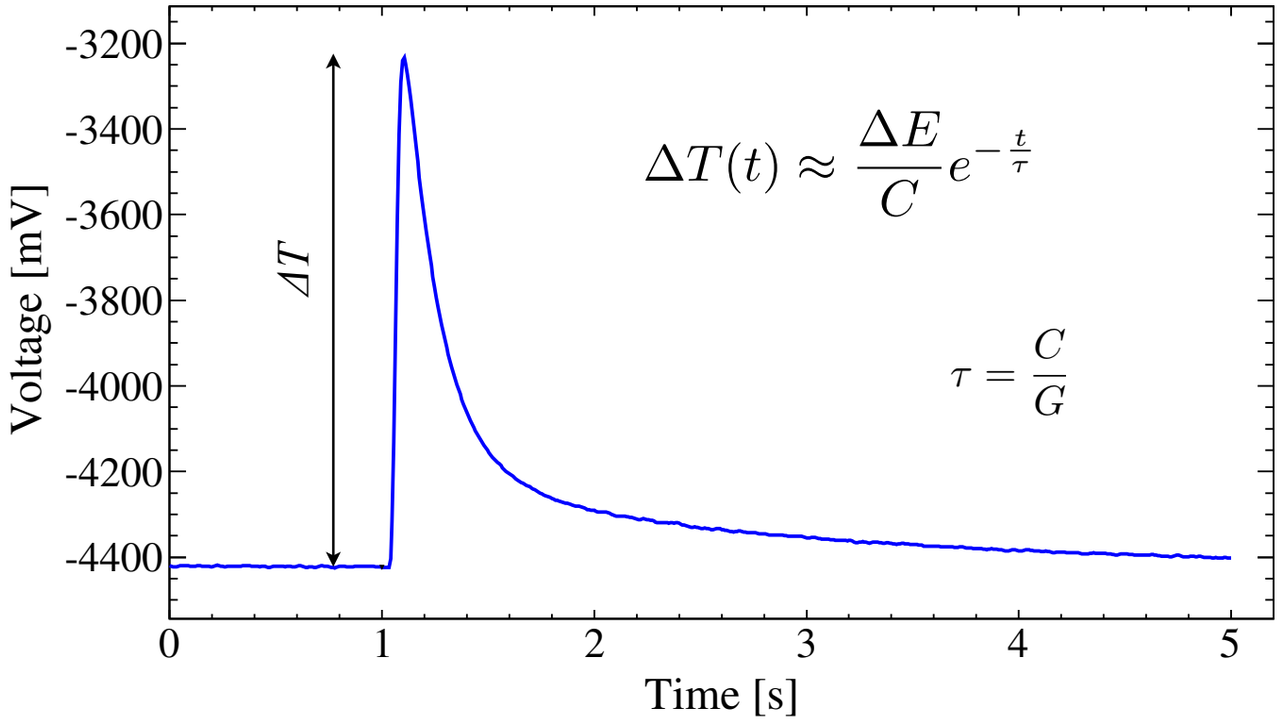
exists if neutrino is a Majorana particle and $m_\nu \neq 0$

Thermal Detectors





- wide choice of detector materials
  - low heat capacity @ T_{work}
- excellent energy resolution (~1 ‰ FWHM)
  - huge number of energy carriers (phonons)
- equal detector response for different particles
  - true calorimeters
- slowness
  - in rare event search doesn't matter

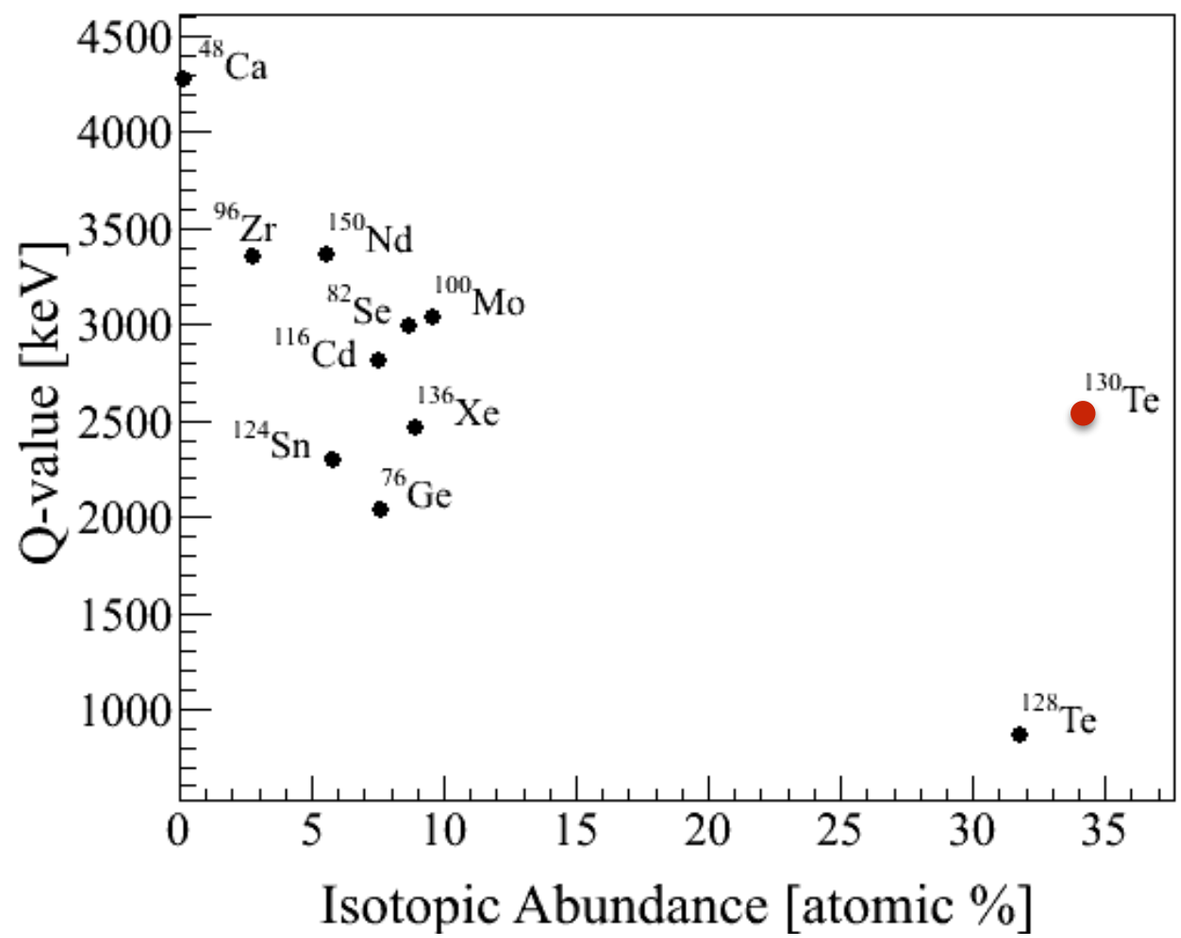


Isotope choice

Not really free, in many cases driven by the detector characteristics.

The advantage of thermal detectors:
first choose the isotope then build the detector having always a good energy resolution

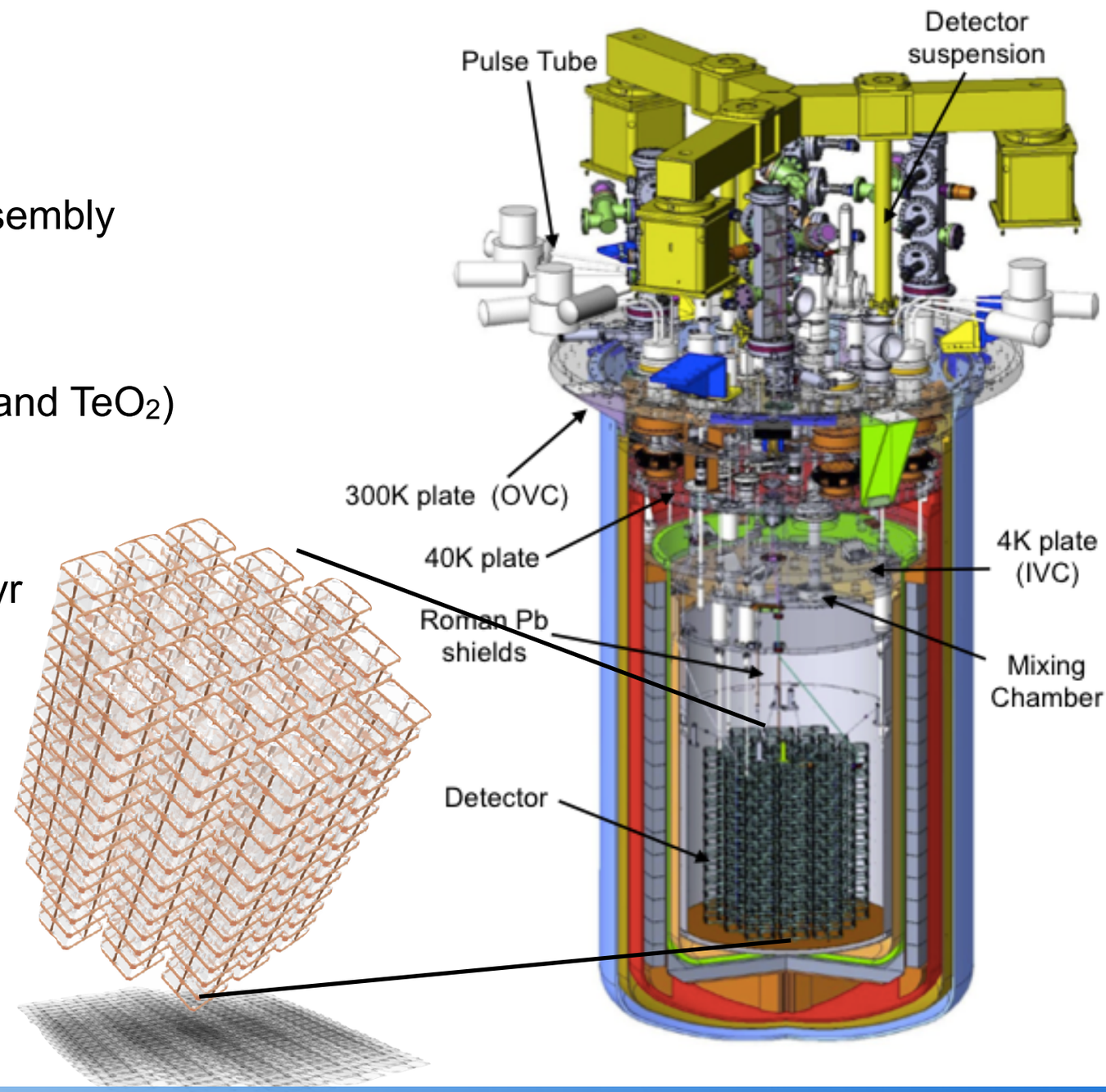
- Isotopic abundance as high as possible
  - money issue
- Q-value as high as possible
  - background
- 2v-DBD half-life as high as possible
  - energy resolution



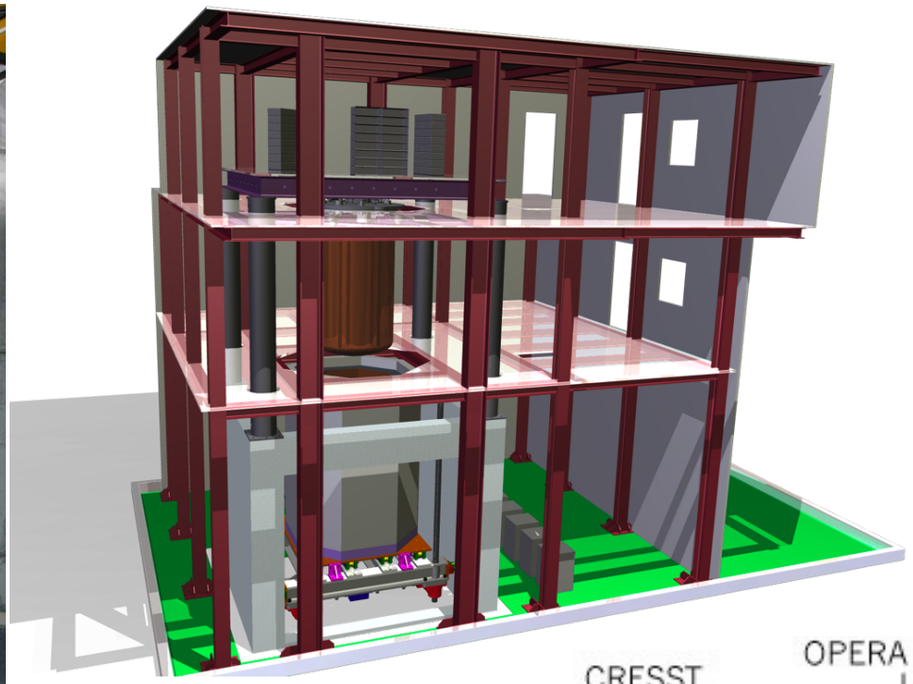
The CUORE challenge

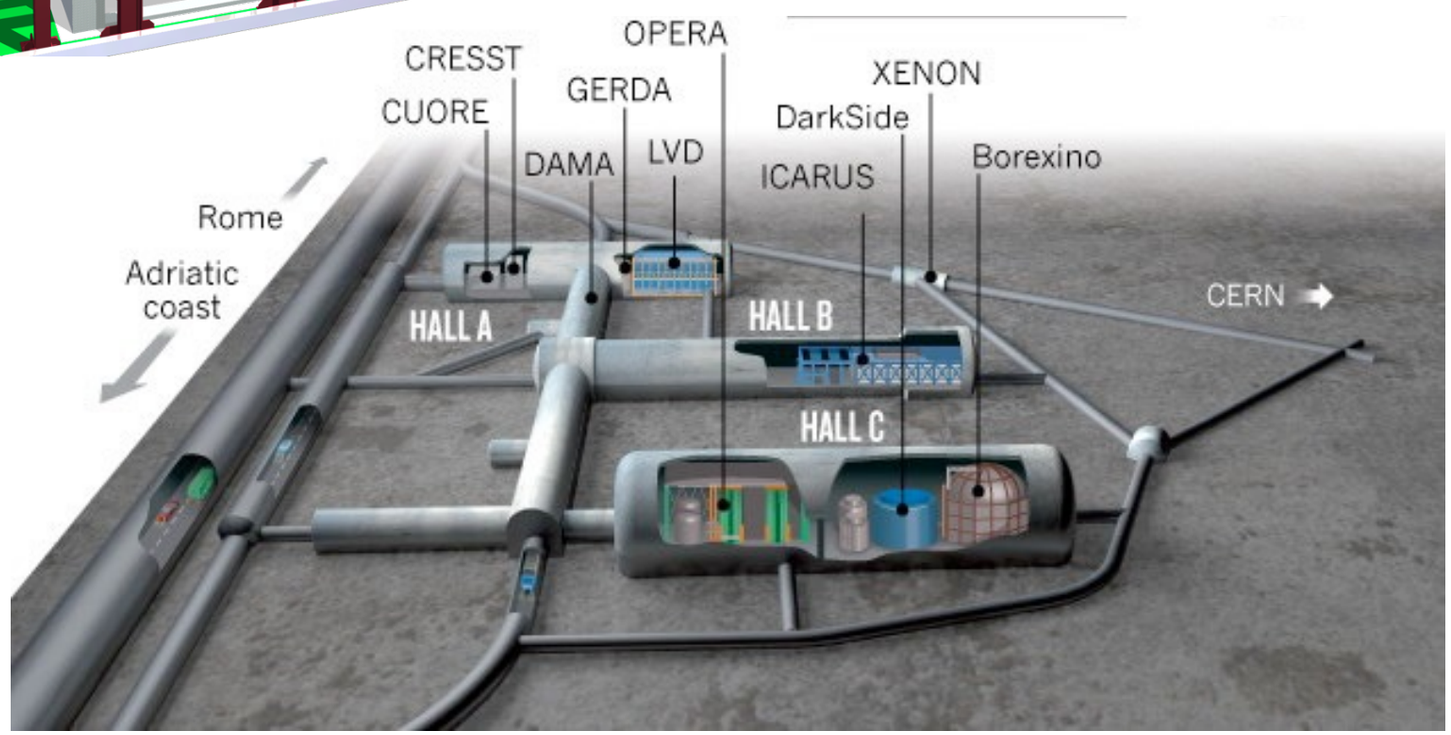
Operate a huge thermal detector array in a extremely low radioactivity and low vibrations environment

- 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: 741 kg (~206 kg of ^{130}Te)
- Energy resolution: 5 keV @ 2615 keV (FWHM)
- Stringent radiopurity controls on materials and assembly
- Operating temperature: ~ 10 mK
- Mass to be cooled down: ~ 15 tons (lead, copper and TeO_2)
- Background aim: 10^{-2} c/keV/kg/year
- $T_{1/2}$ sensitivity in 5 years (90% C.L.): ~ 9.5 x 10^{25} yr



CUORE @ LNGS

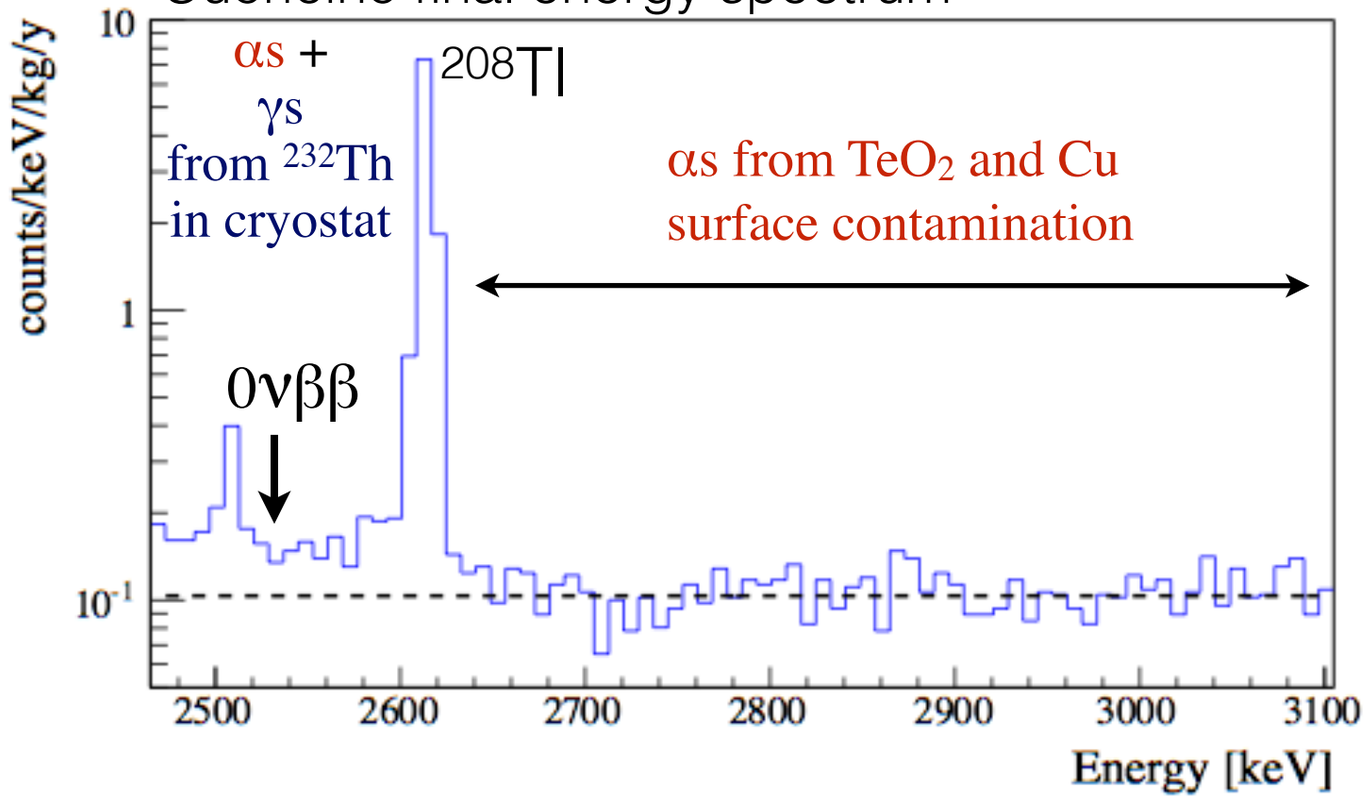




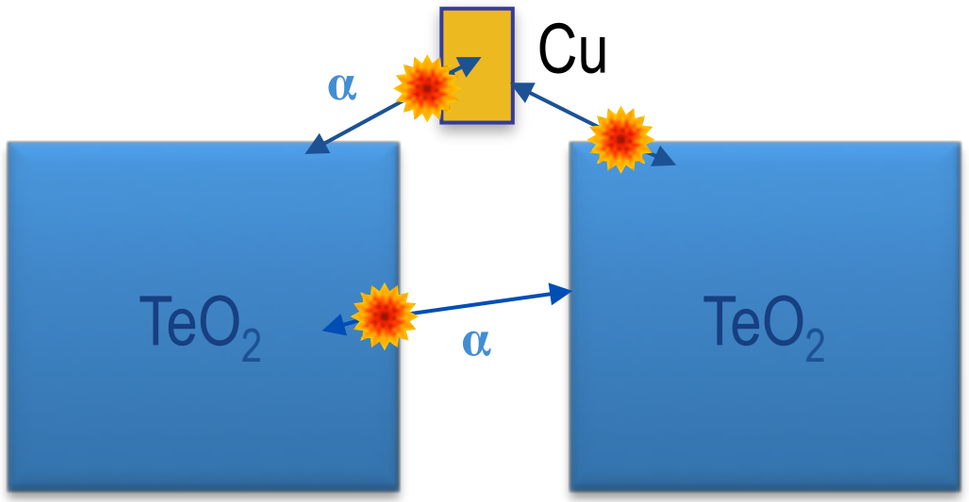
- ~3600 m.w.e. deep
- μ_S: ~3×10^{-8}/(s cm^2)
- γ_S: ~0.73/(s cm^2)
- neutrons: 4×10^{-6} n/(s cm^2)

Cuoricino background

Cuoricino final energy spectrum



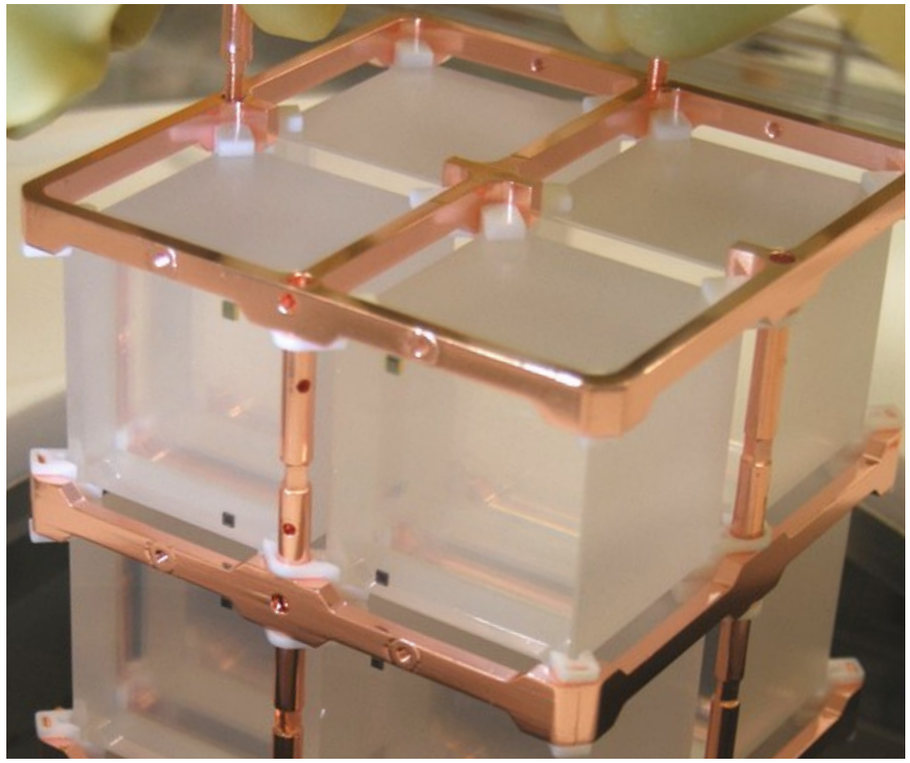
Background @ 0vDBD Q-value:
0.161 c keV^{-1} kg^{-1} y^{-1}

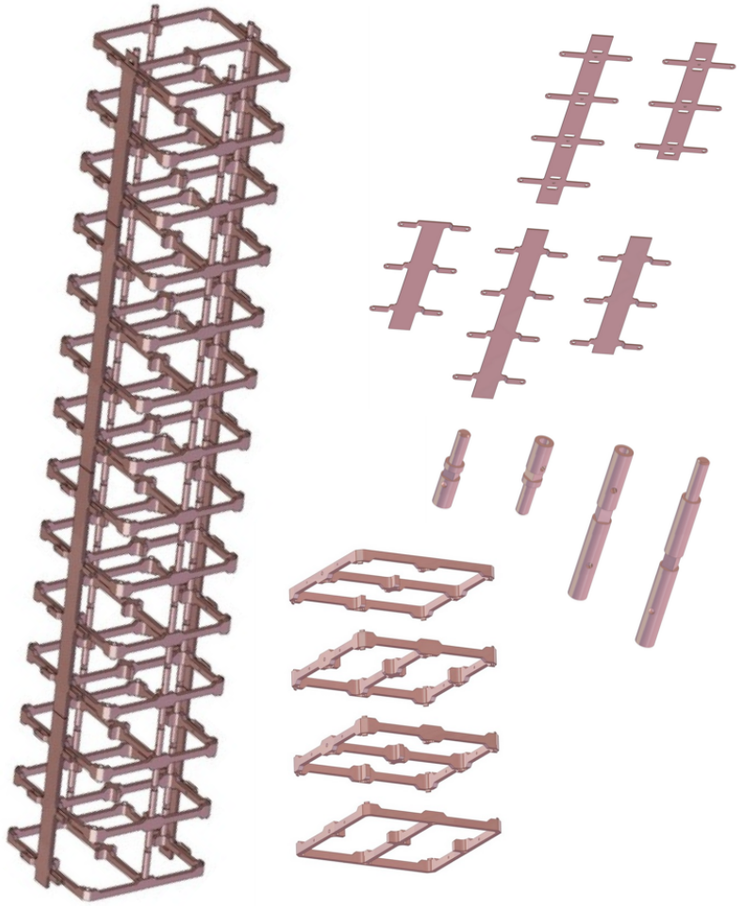


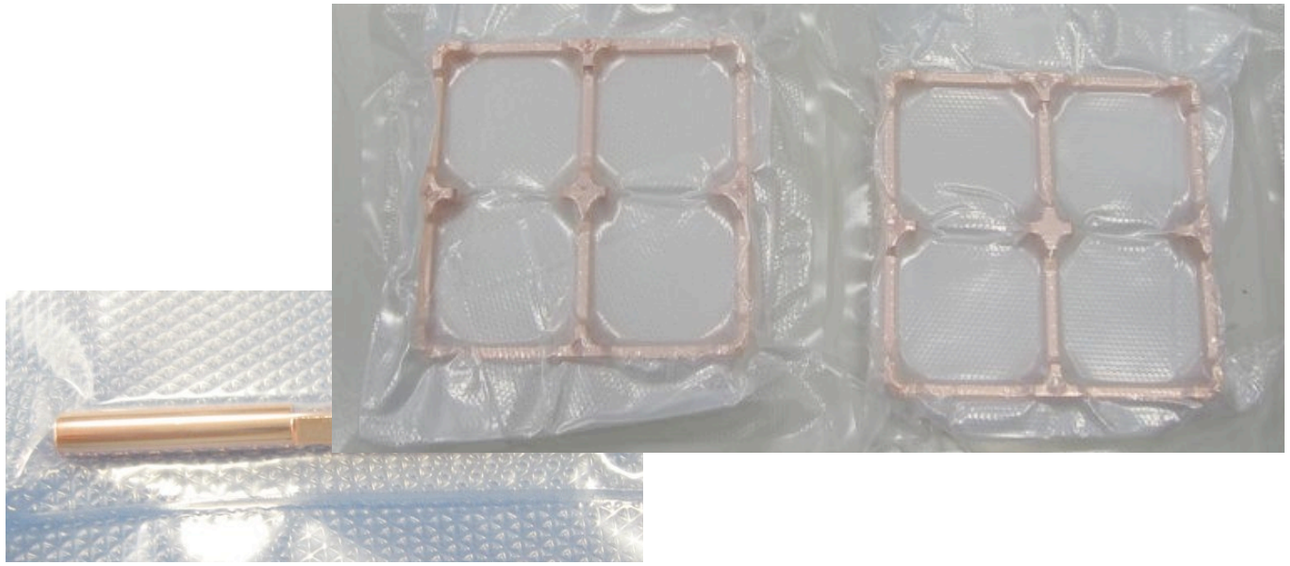
Source	^{208}Tl	$\beta\beta(0\nu)$ region	3-4 MeV region
TeO_2 ^{238}U and ^{232}Th surface contamination	-	10± 5%	20± 10%
Cu ^{238}U and ^{232}Th surface contamination	~15%	50± 20%	80± 10%
^{232}Th contamination of cryostat Cu shields	~85%	30± 10%	-

From Cuoricino to CUORE

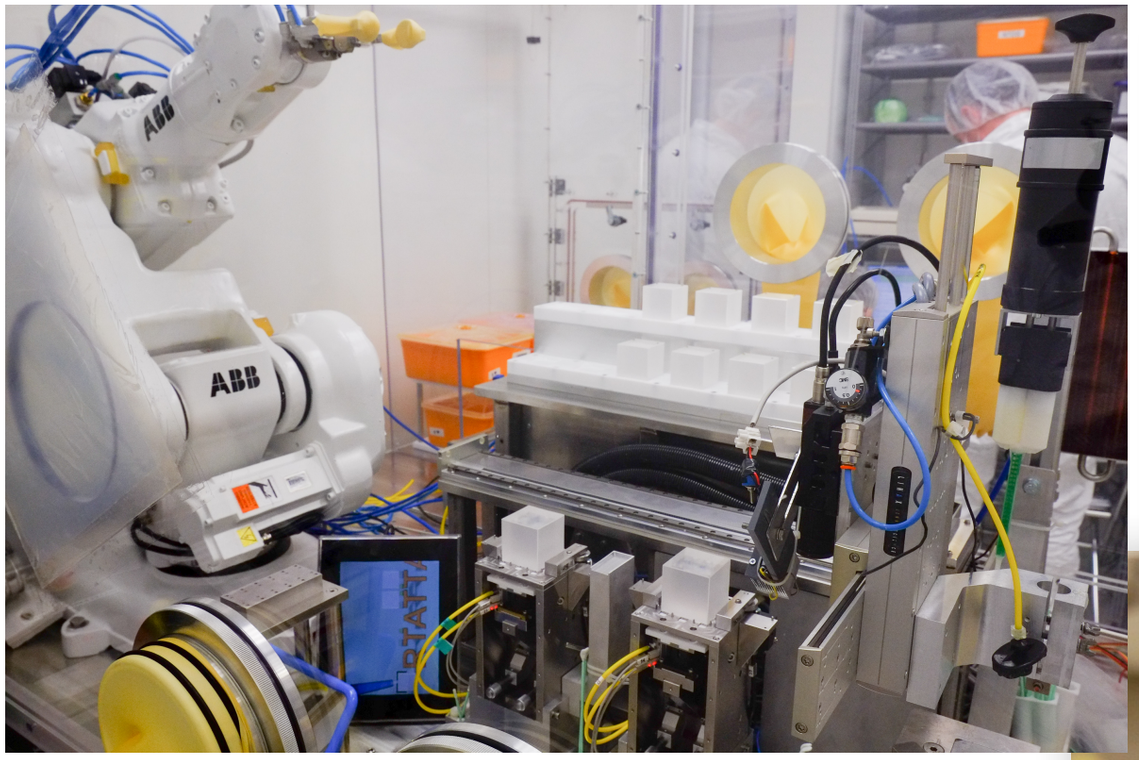
- Strict material selection
- New lighter detector design structure
- Reduced overall copper surfaces by a factor ~2
- New surface cleaning technique
- Strict production protocols for TeO_2 surface contamination
- Minimization of Rn exposure (N_2 glove box assembly)

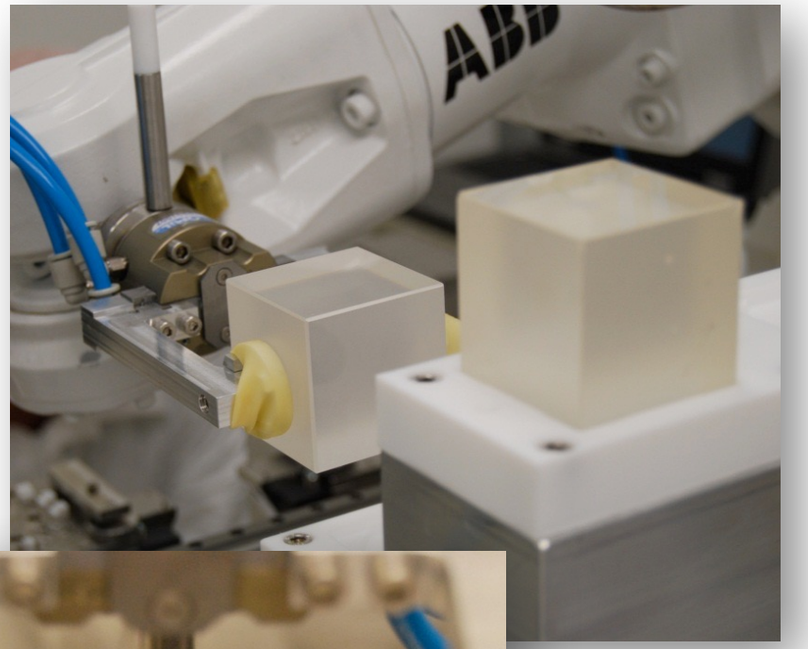


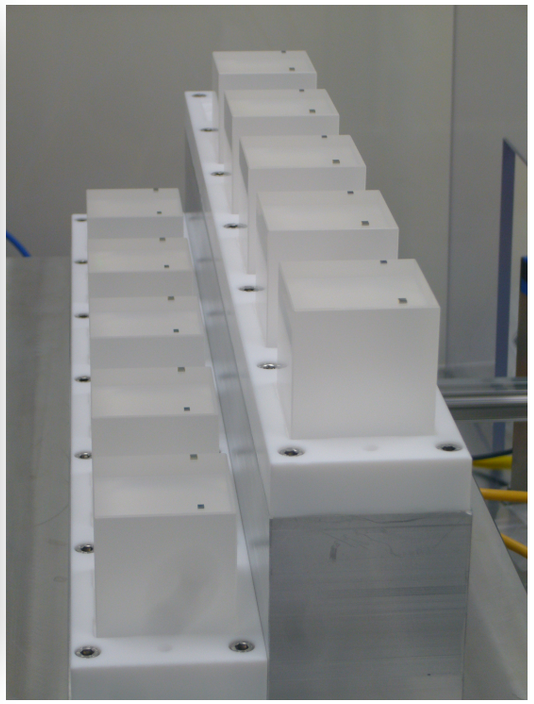


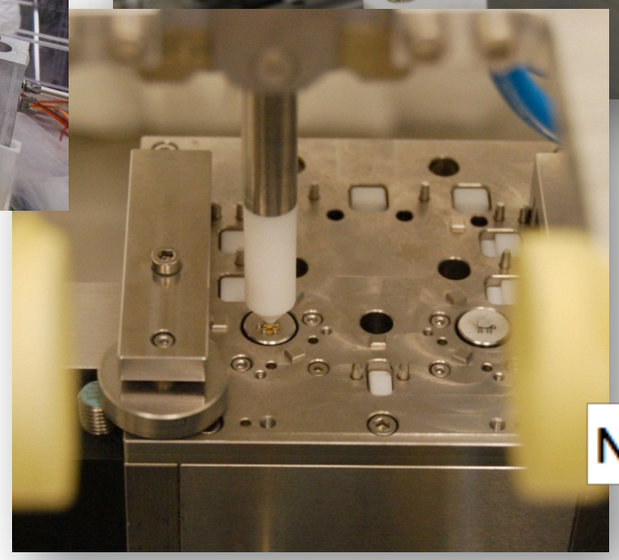


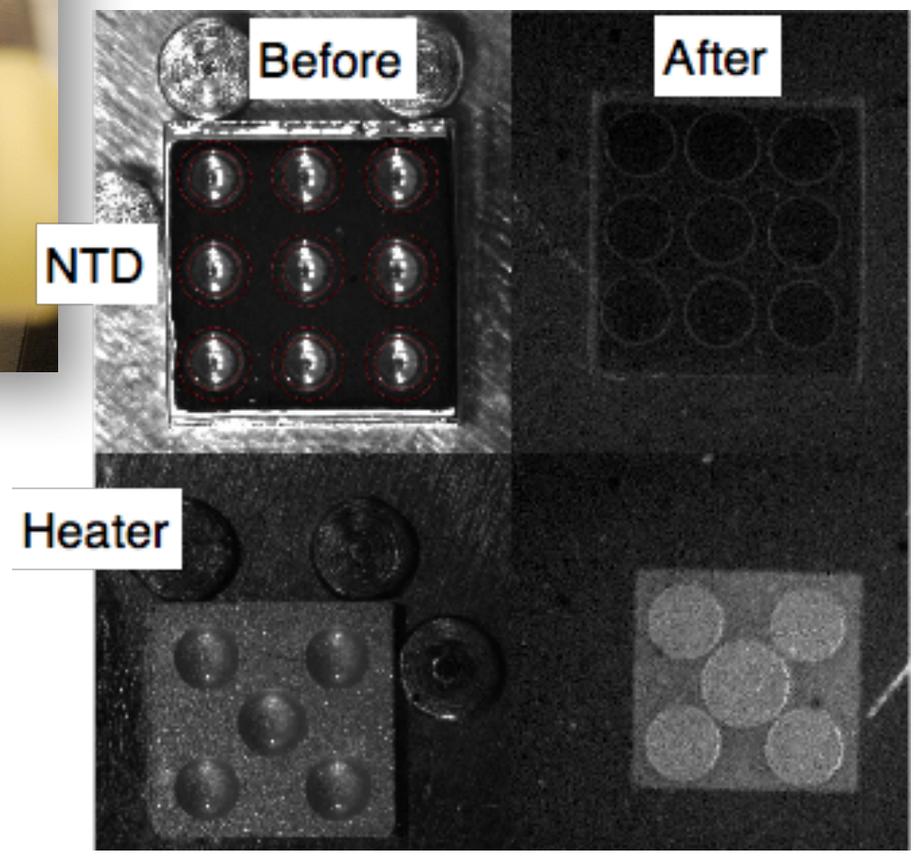
Thermistors & Heaters coupling







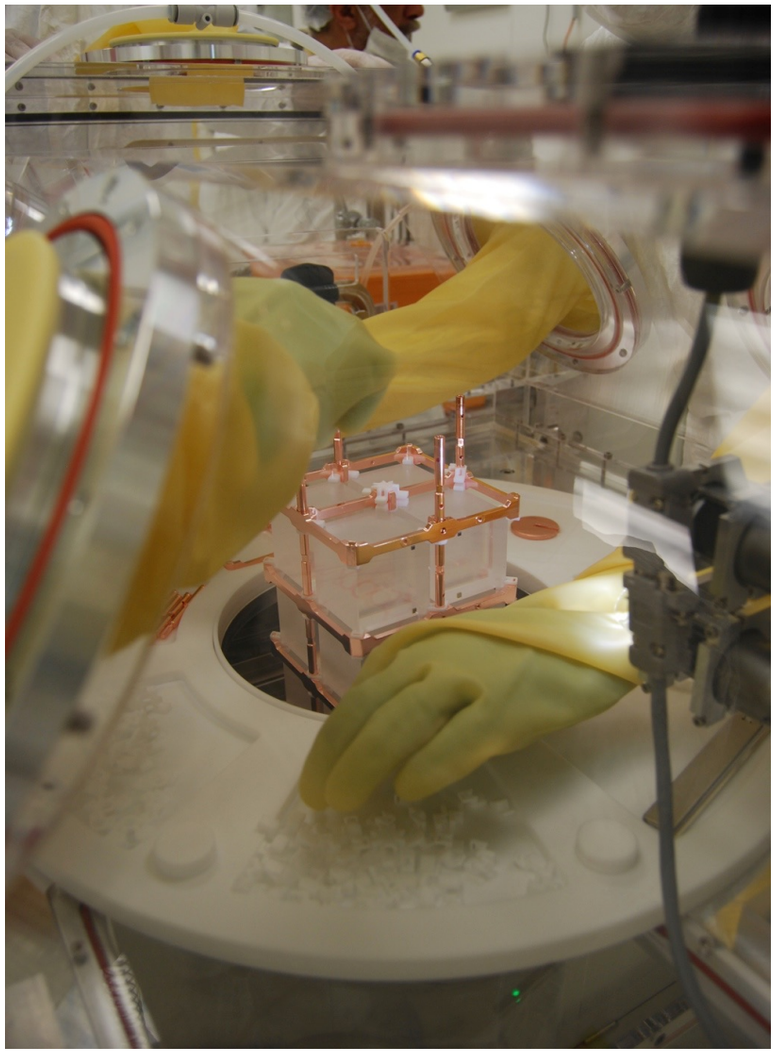


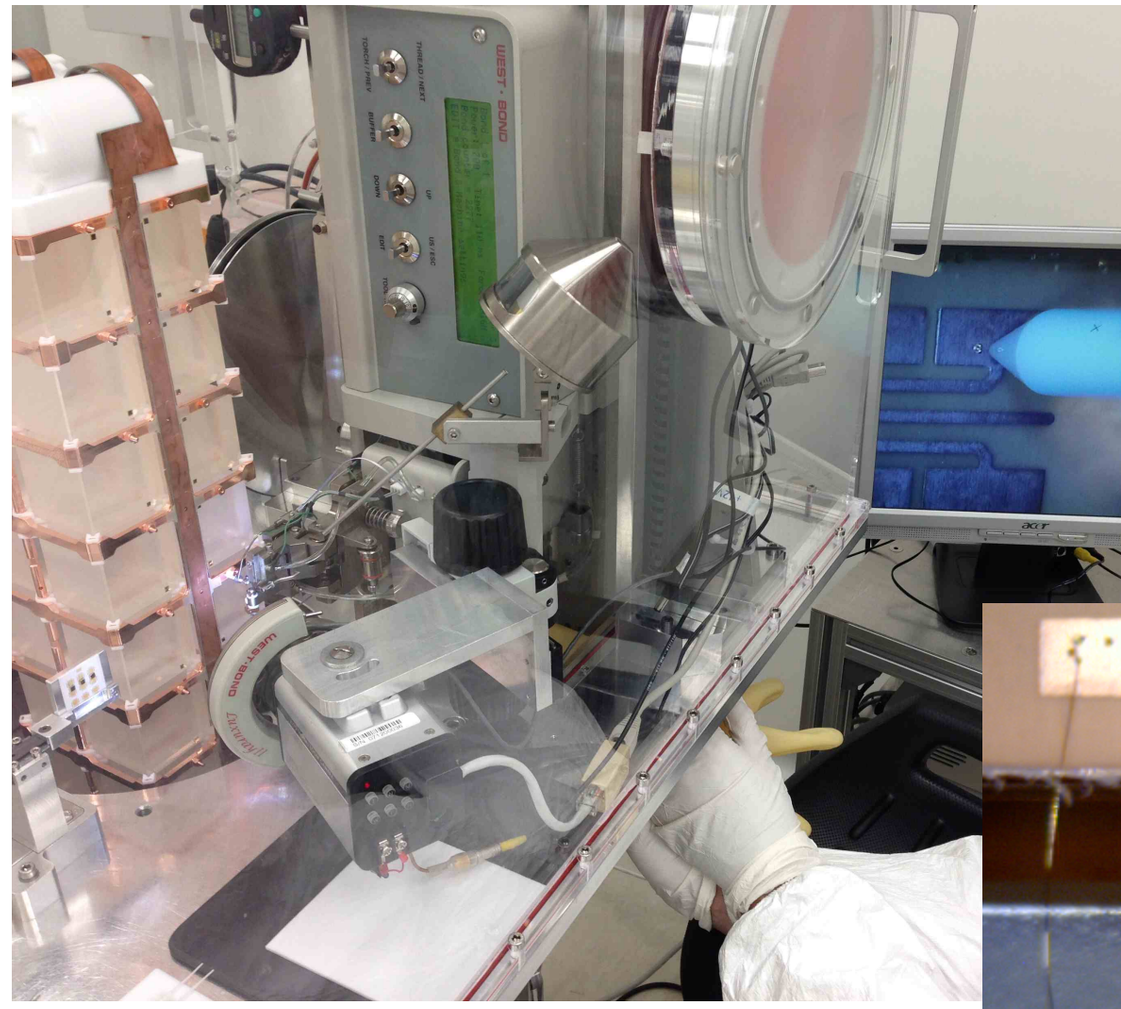


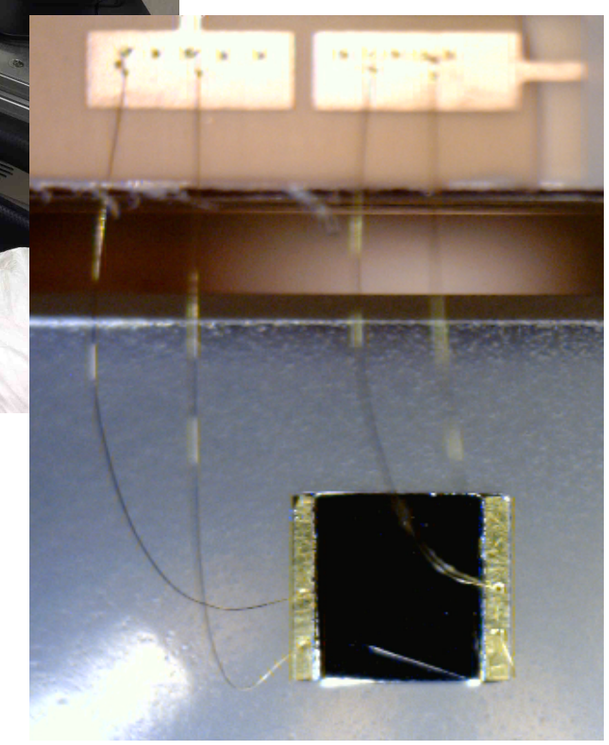
Features:

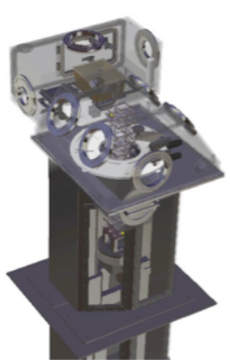
- new semi-automatic system
- highly-reproducible
- fully performed under N_2 atmosphere to minimize radioactive recontamination.

CUORE-0 Assembly & Bonding

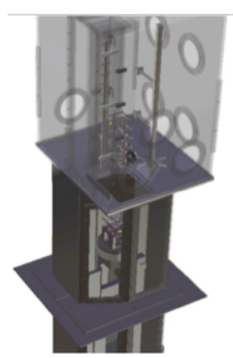




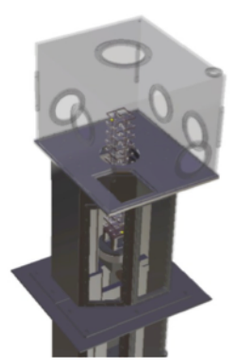




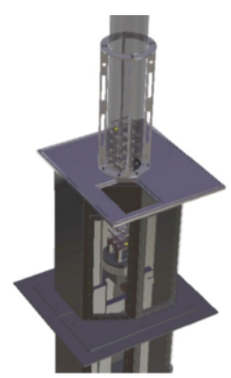
1. Assembly box



2. Cabling box



3. Bonding box



4. Storage box

CUORE-0

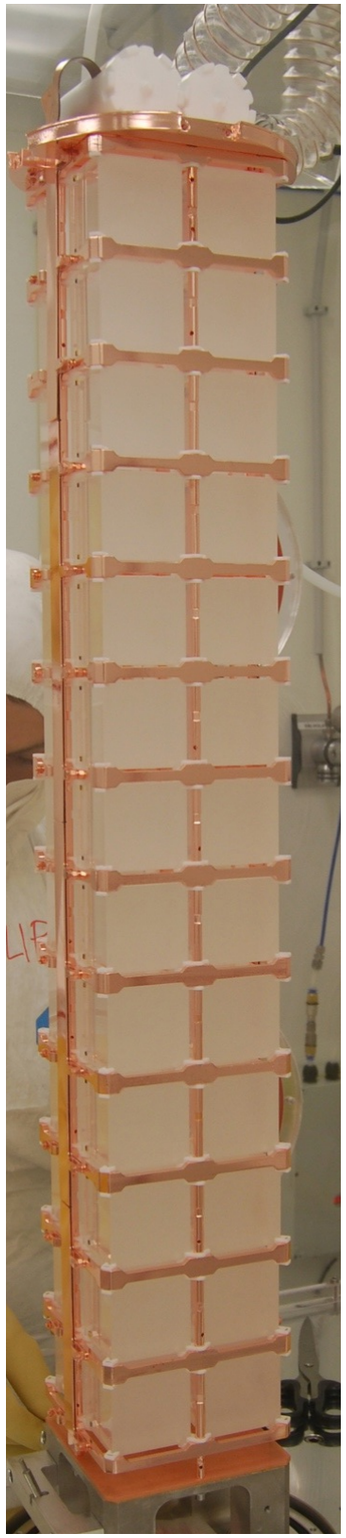
CUORE-0 is the first tower produced out of the CUORE assembly line.

- 52 TeO_2 5x5x5 cm^3 crystals (~750 g each)
- 13 floors of 4 crystals each
- total detector mass: 39 kg TeO_2 (10.9 kg of ^{130}Te)

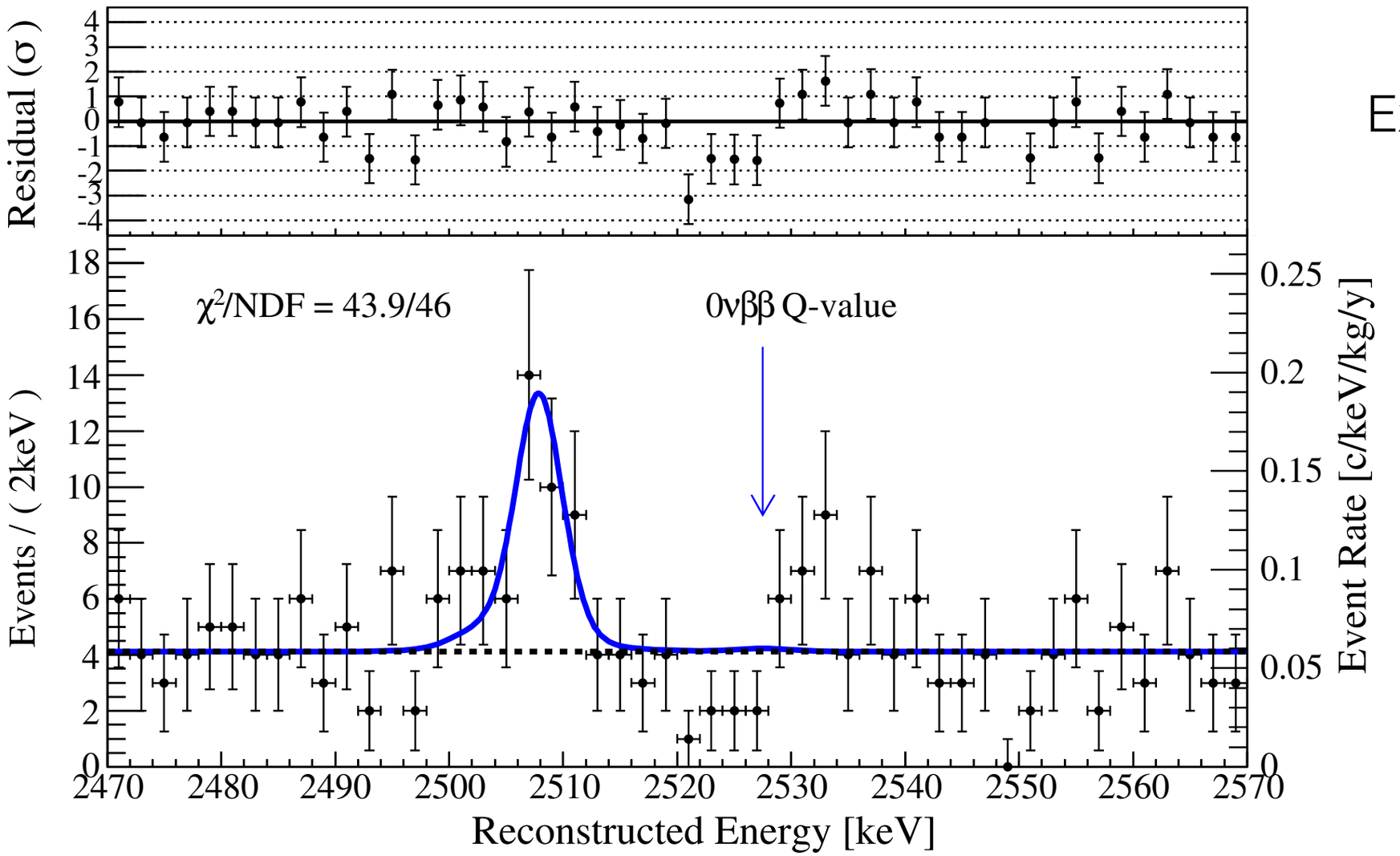
CUORE-0 has been taking data since March 2013 in the 25 year old Cuoricino cryostat.

- Proof of concept of CUORE detector in all stages
- Test and debug of the CUORE tower assembly line
- Test of the CUORE DAQ and analysis framework
- Check of the radioactive background reduction
- Sensitive 0vDBD experiment

see posters by
L. Canonica
&
G. Piperno



CUORE-0 results



Exposure: 9.8 kg·yr ^{130}Te

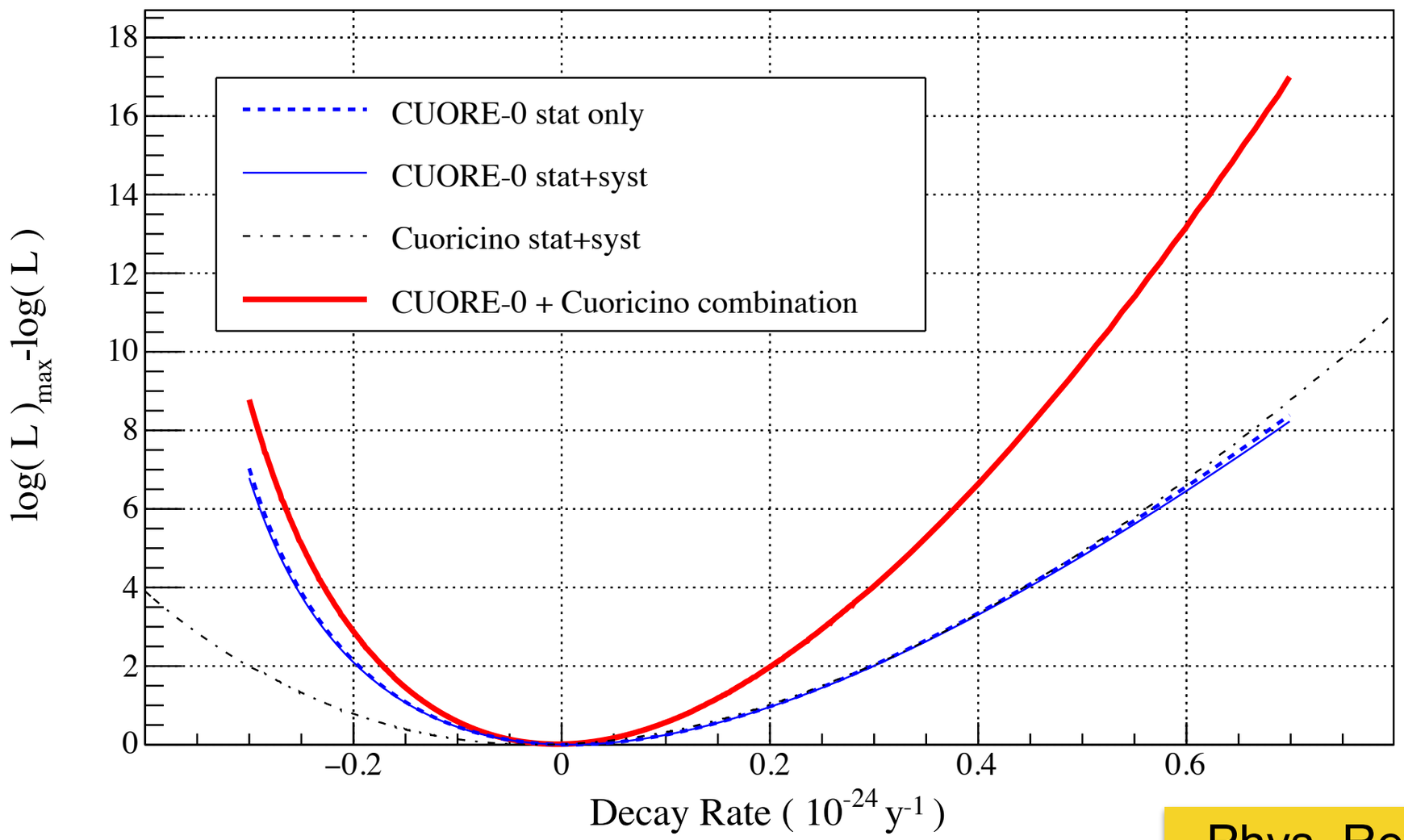
- We determined the yield of 0νDBD events by performing a simultaneous UEML fit in the energy region 2470-2570 keV
- The fit has 3 components:
  - a peaked peak at the Q-value of ^{130}Te
  - a peak floating around 2505 keV, attributed to the sum gamma events from ^{60}Co in the nearby copper
  - a flat continuum background, attributed to multi scatter Compton events from ^{208}Tl and surface alpha events

Background index: 0.058 ± 0.004 (stat.) ± 0.002 (syst.) c keV^{-1} kg^{-1} yr^{-1}

0νDBD ^{130}Te Bayesian 90% C.L. limit: $T_{1/2} > 2.7 \times 10^{24}$ yr

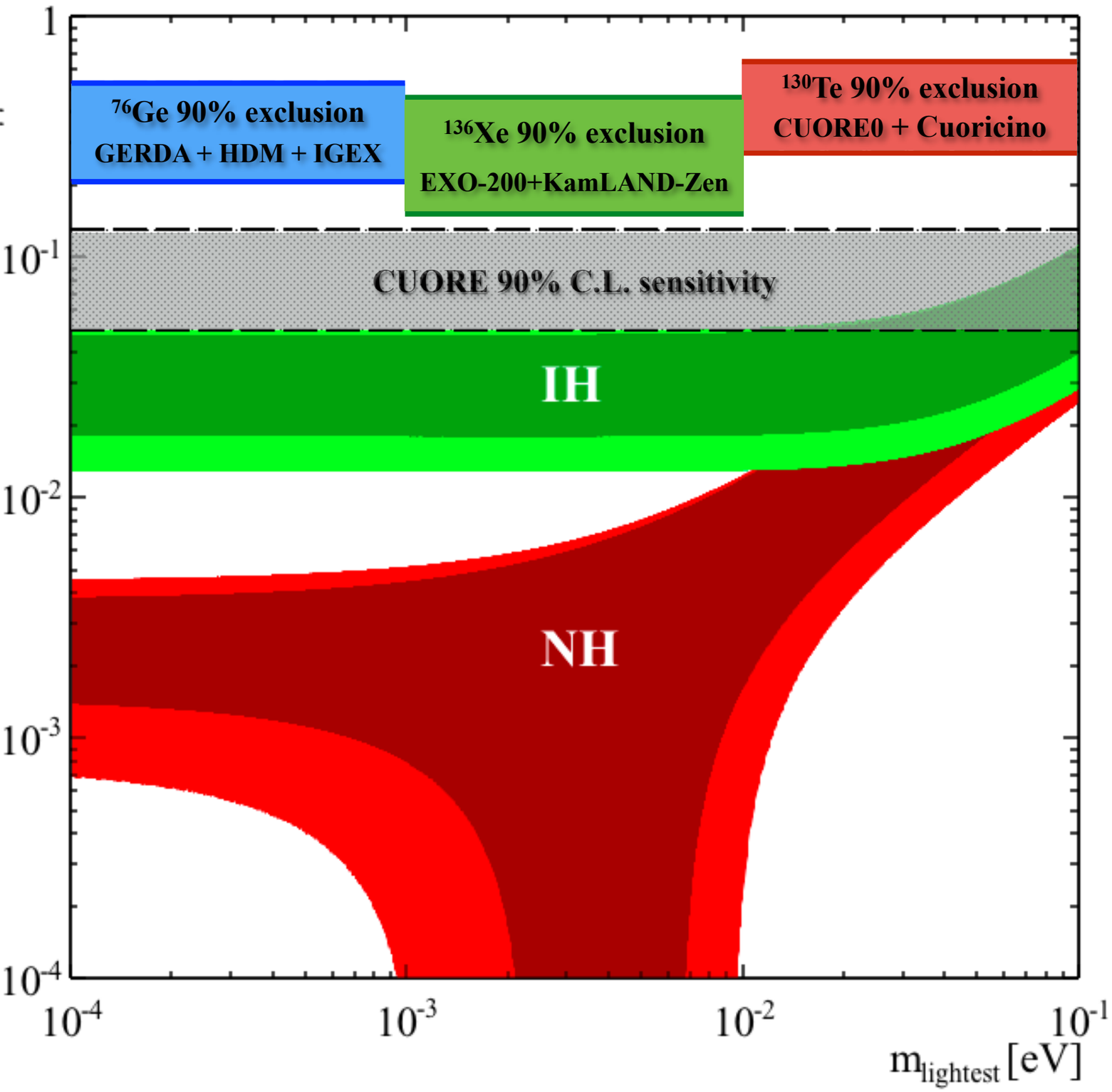
Combining CUORE-0 and Cuoricino

- Combination of the CUORE-0 result with the existing 19.75 kg · yr of ^{130}Te exposure from Cuoricino
- The combined 90% C.L. limit is $T_{1/2} > 4.0 \times 10^{24}$ yr.



Phys. Rev. Lett. 115, 102502

Limit on the effective Majorana mass



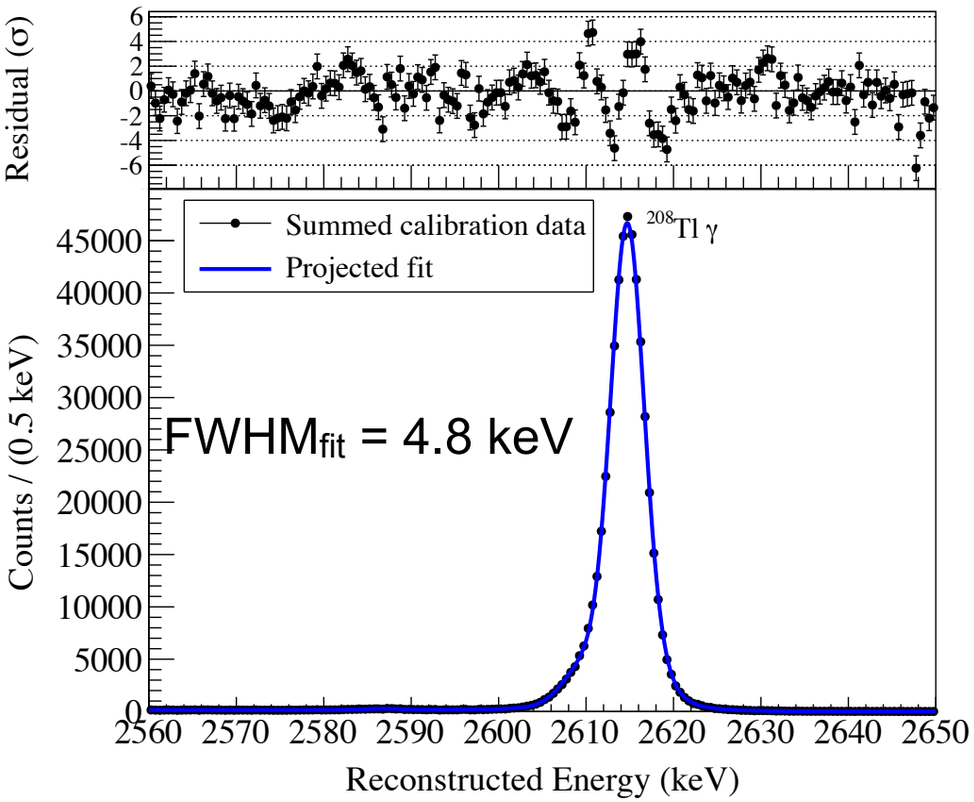
The combined result gives a limit on the effective Majorana neutrino mass:

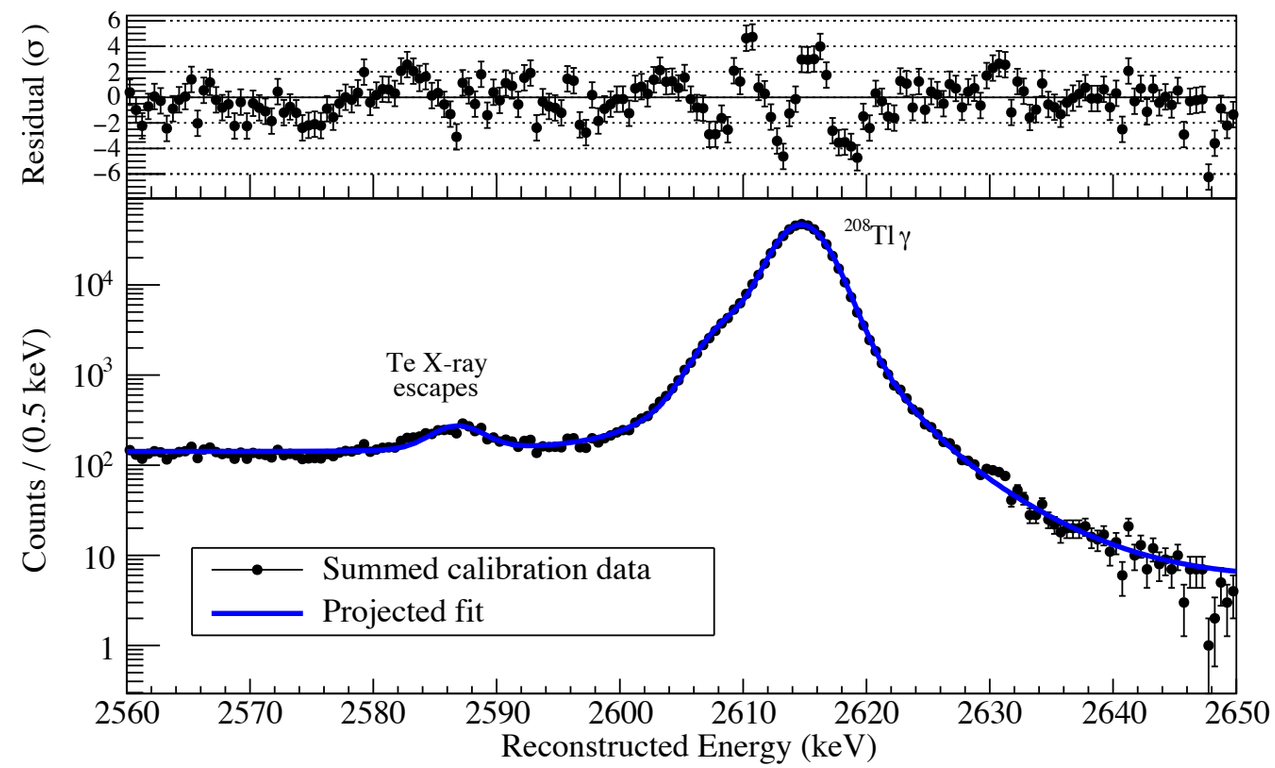
$<m_{\beta\beta}>$ < (270-650) meV

IBM-2 Phys. Rev. C 91, 034304 (2015)
QRPA-TU Phys. Rev. C 87, 045501 (2013)
pnQRPA Phys. Rev. C 91, 024613 (2015)
ISM Nucl. Phys. A 818, 139 (2009)
EDF Phys. Rev. Lett. 105, 252503 (2010)

CUORE-0 calibration resolution

Total fit on the 2615 keV line



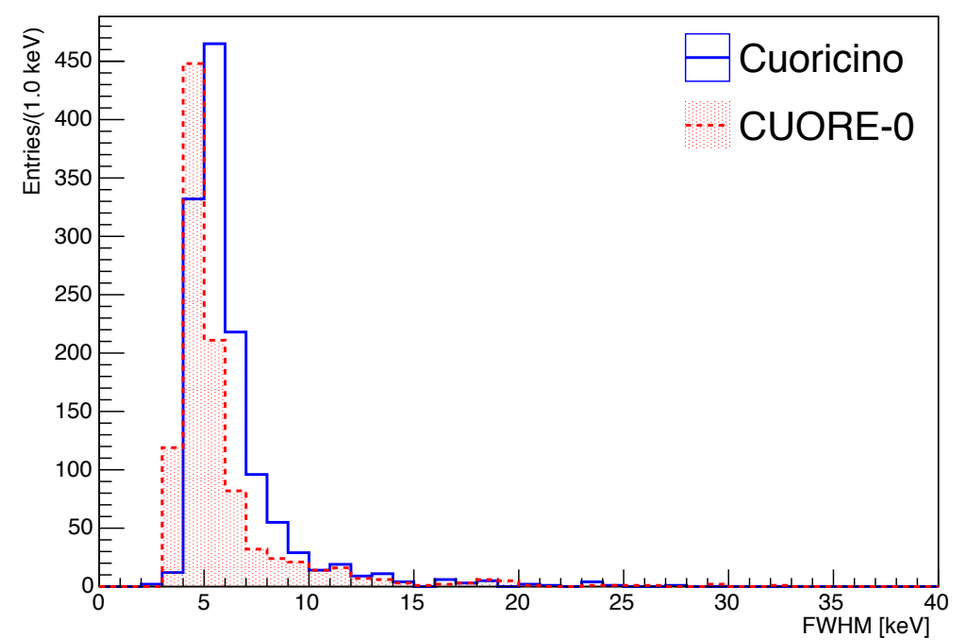


The 5 keV CUORE goal has been reached

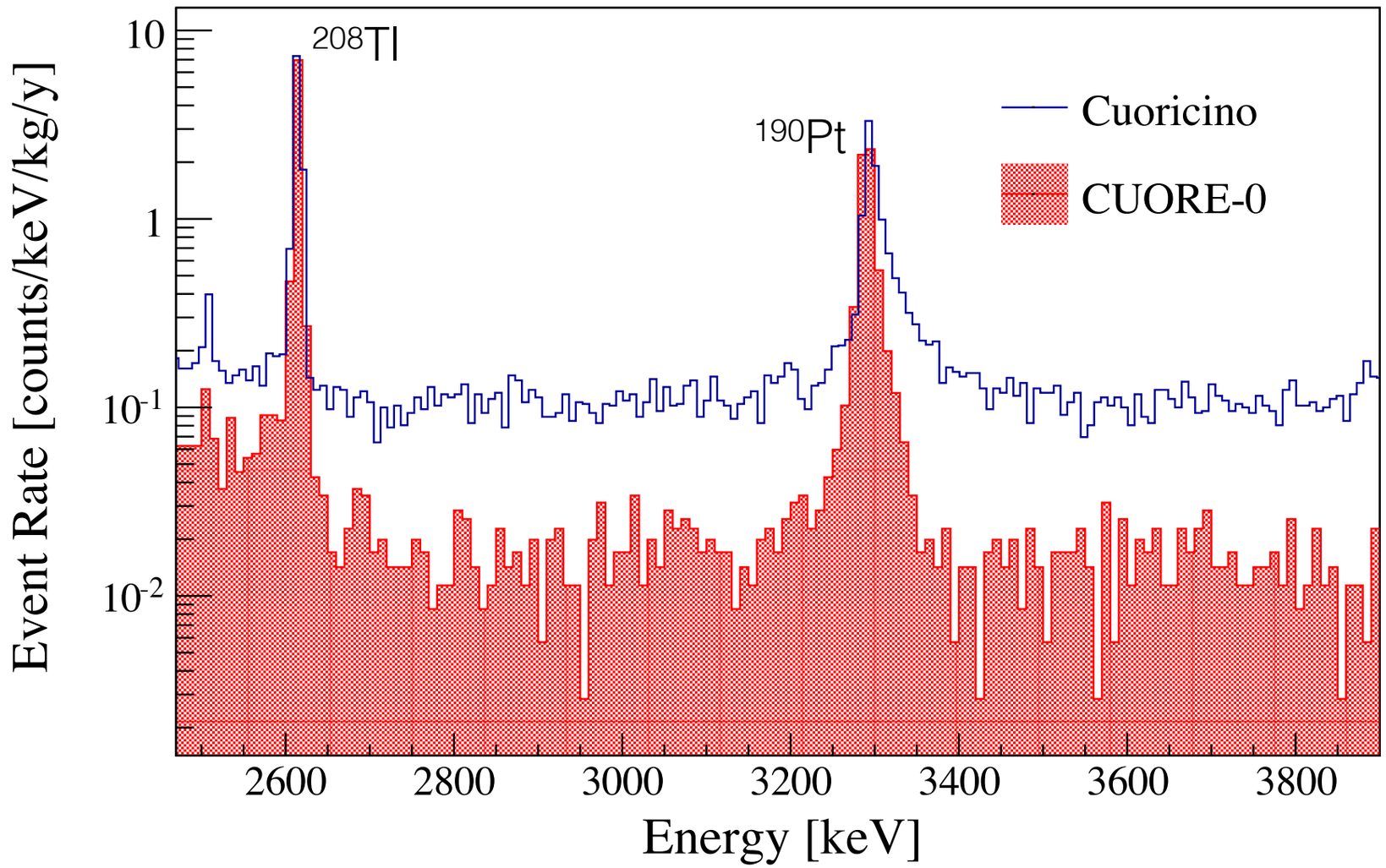
Physics-exposure-weighted harmonic mean

	Average FWHM [keV]	RMS of FWHM [keV]
Cuoricino	5.8	2.1
CUORE-0	4.9	2.9

Distribution of energy resolution @ 2615 keV



CUORE-0 background



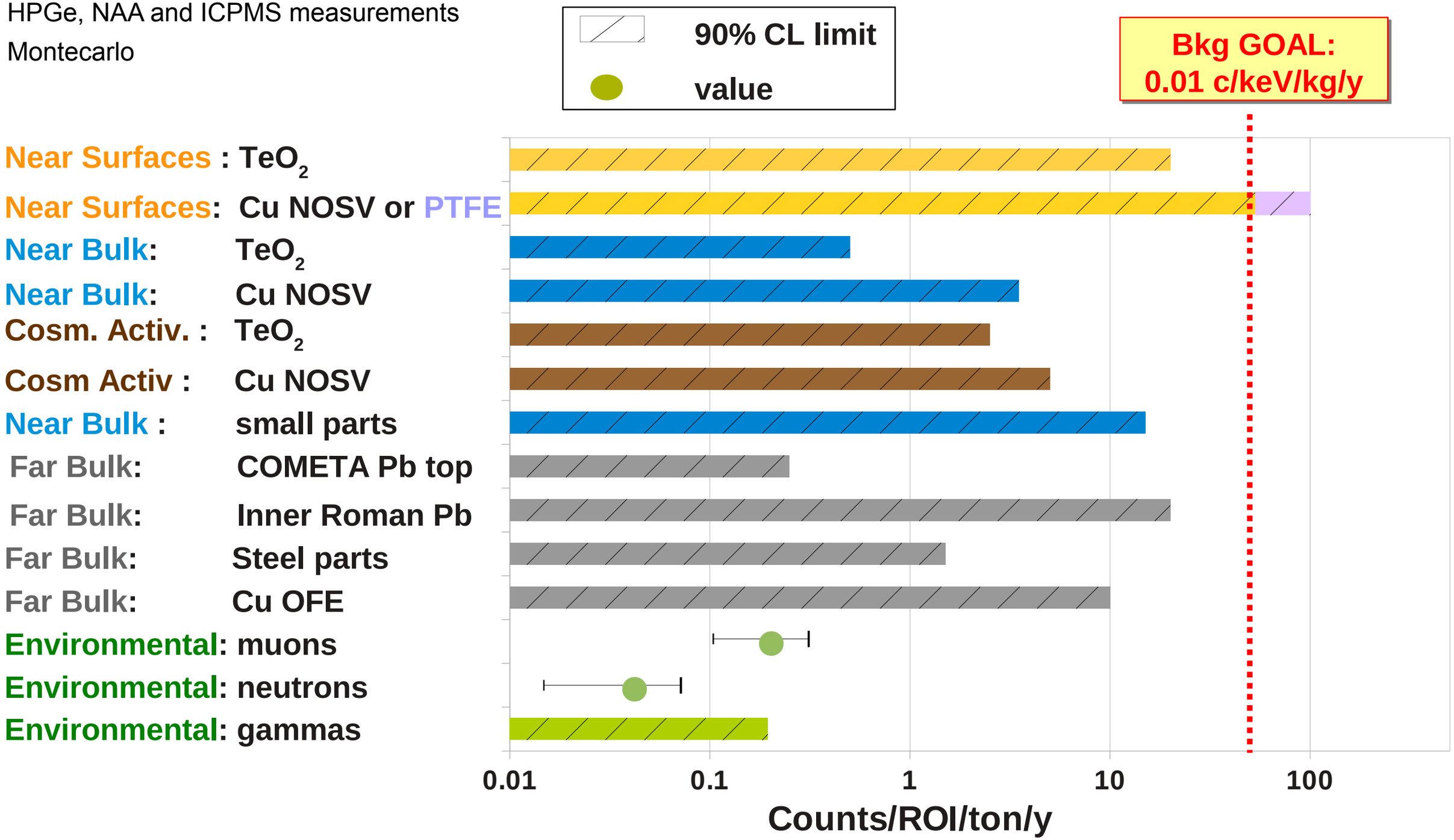
	2.7-3.9 MeV	ROI
CUORE-0	0.016 ± 0.001	0.058 ± 0.004
Cuoricino	0.110 ± 0.001	0.169 ± 0.006

- ~ factor 6 reduction in the alpha continuum region

CUORE background budget

Based on

- Cuoricino & CUORE-0 data
- HPGe, NAA and ICPMS measurements
- Montecarlo



CUORE Towers Assembly

- Assembly of all the 19 CUORE towers completed in 2014

Assembly line improved after CUORE-0

CUORE-0

51/52 NTD connected

51/52 heaters connected

CUORE

988/988 NTD connected

988/988 heaters connected

- Also a mockup tower for the Detector installation phase and a minitower to be used during the cryostat commissioning runs were produced

Cryogenic system commissioning

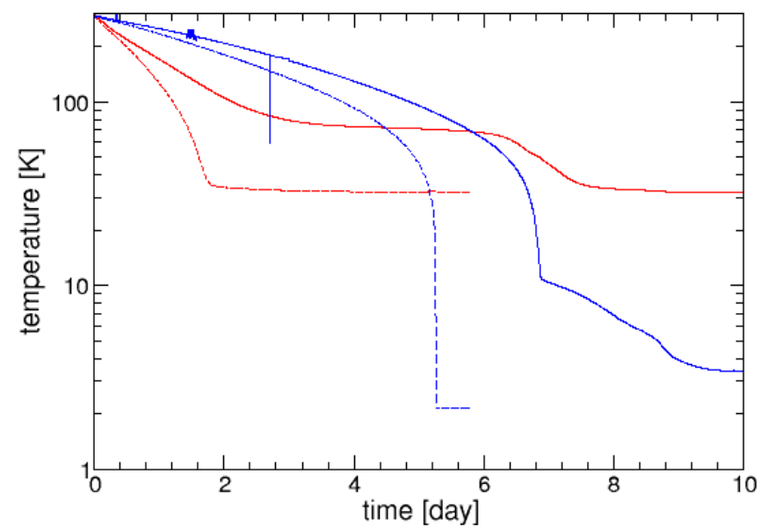
Phased commissioning adding complexity at each step

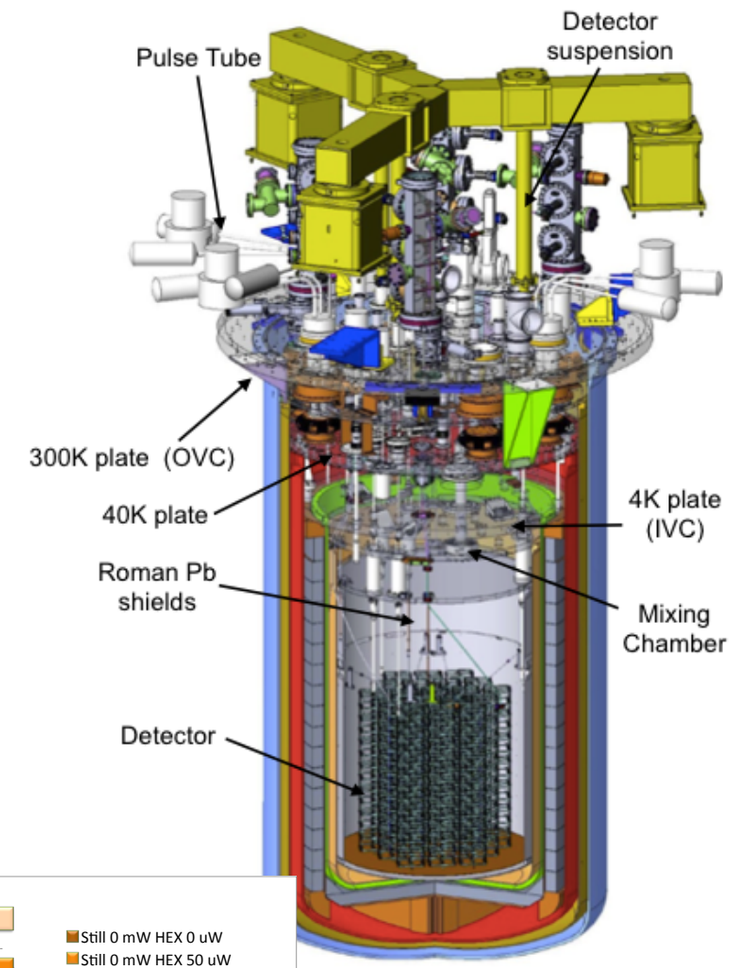
- Phase I: individual systems test
  - Outer/Inner vacuum chamber
  - Cryostat

    Final temperatures:

    32 K at the 40K stage

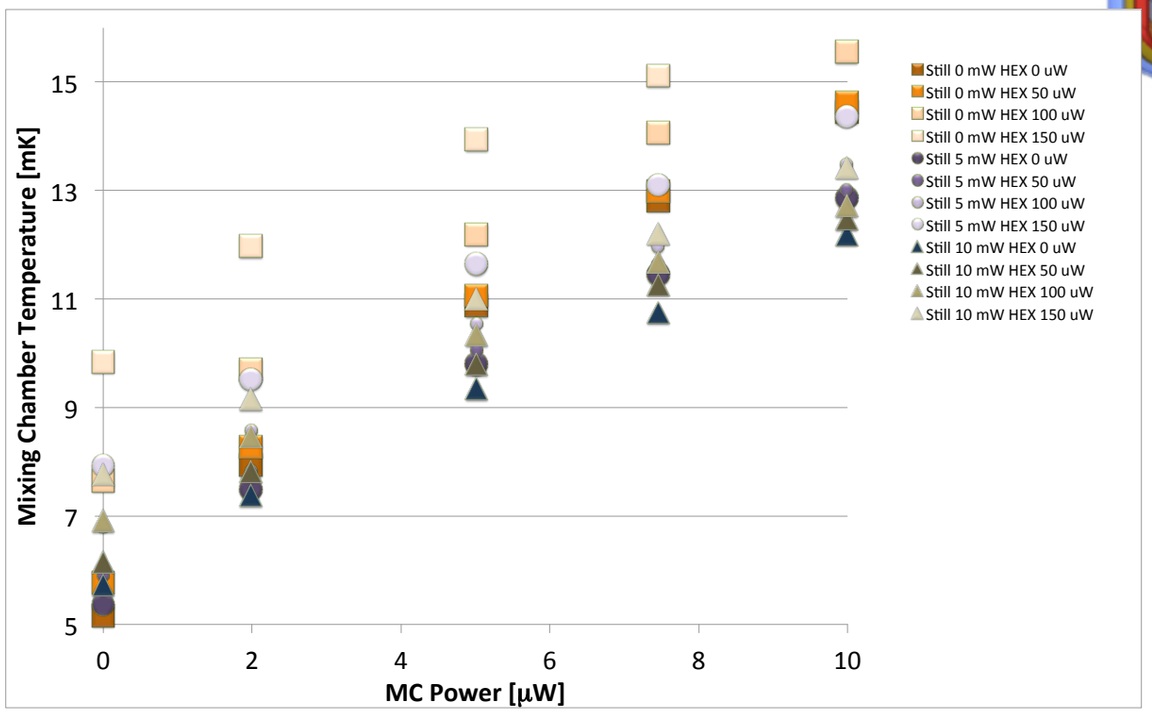
    3.3 K at the 4K stage





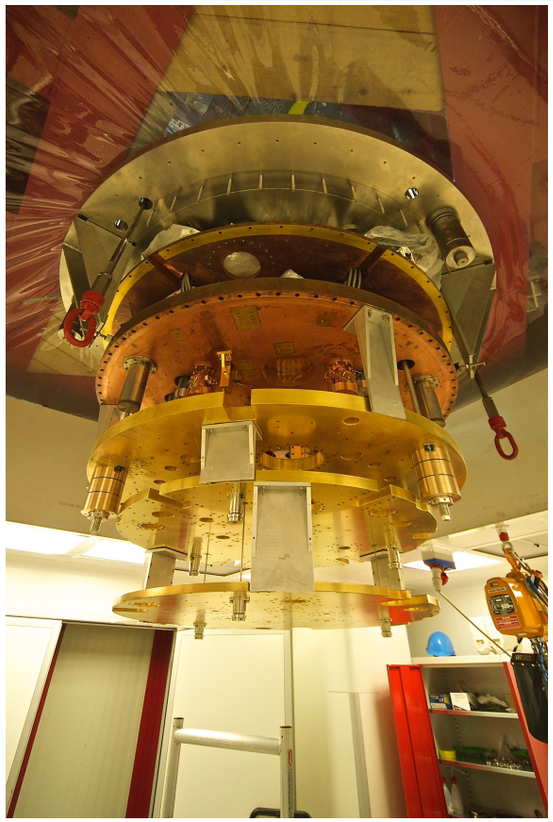
  - Dilution Unit

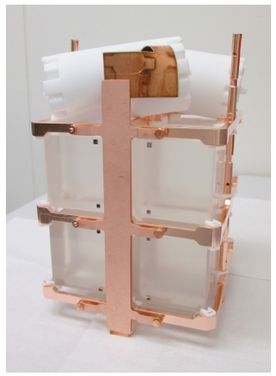
    Lowest temperature: 4.95 mK

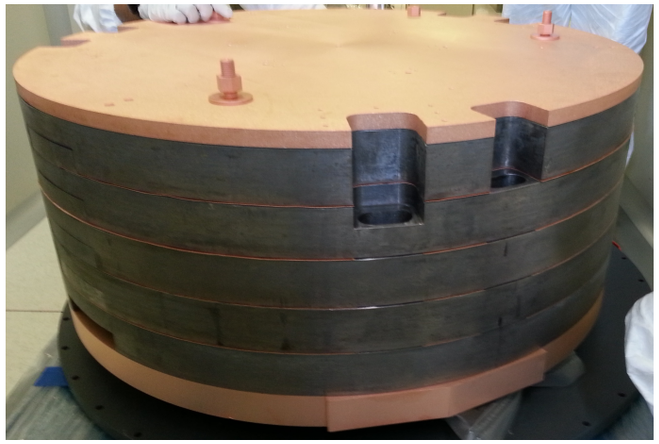


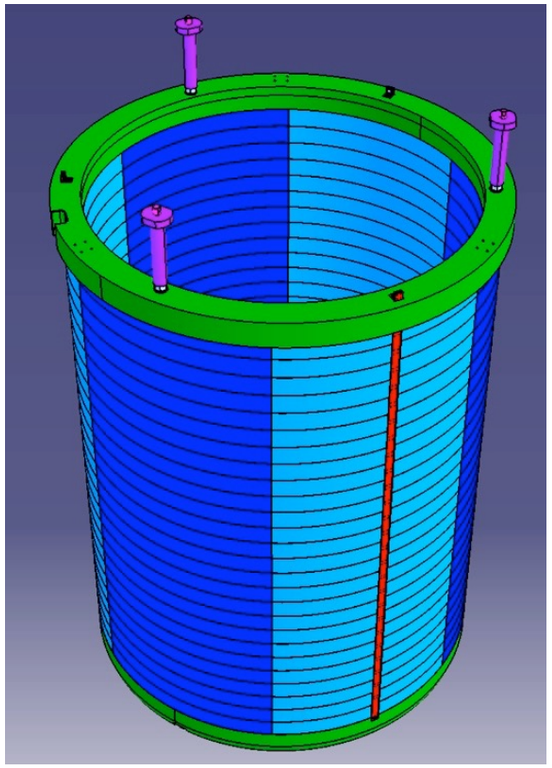
- Phase II: system integration

Cryogenic system commissioning: phase 2









Insertion of few TeO_2 detectors

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

see poster by V. Singh

Coldest m^3

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CUORE: The Coldest Heart in the Known Universe

The CUORE collaboration at the INFN Gran Sasso National Laboratory has set a world record by cooling a copper vessel with the volume of a cubic meter to a temperature of 6 milliKelvins: it is the first experiment ever to cool a mass and a volume of this size to a temperature this close to absolute zero (0 Kelvin). The cooled copper mass, weighing approx. 400 kg, was the coldest cubic meter in the universe for over 15 days.

CUORE is an international collaboration involving some 130 scientists mainly from Italy, USA, China, Spain, and France. CUORE is supported by the Istituto Nazionale di Fisica Nucleare (INFN) in Italy; the Department of Energy Office of Science (Office of Nuclear Physics), the National Science Foundation, and Alfred P. Sloan Foundation in the United States.

Conclusions

CUORE-0

- Achieved its energy resolution and background level objectives
- Did not find evidence of 0vDBD decay.
- Indicated CUORE sensitivity goal is within reach.
- Results published by PRL
- Two additional papers in preparation (detector and background)

CUORE

- Assembly of the 19 CUORE towers is complete.
- CUORE cryostat reached base temperature of ~ 6 mK in Run 1
- The completion of the cryogenic system commissioning is close and will be followed by the detector installation
- CUORE operation expected early in 2016