CUORE: the first bolometric experiment at the ton scale for rare decay searches

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On behalf of the CUORE Collaboration

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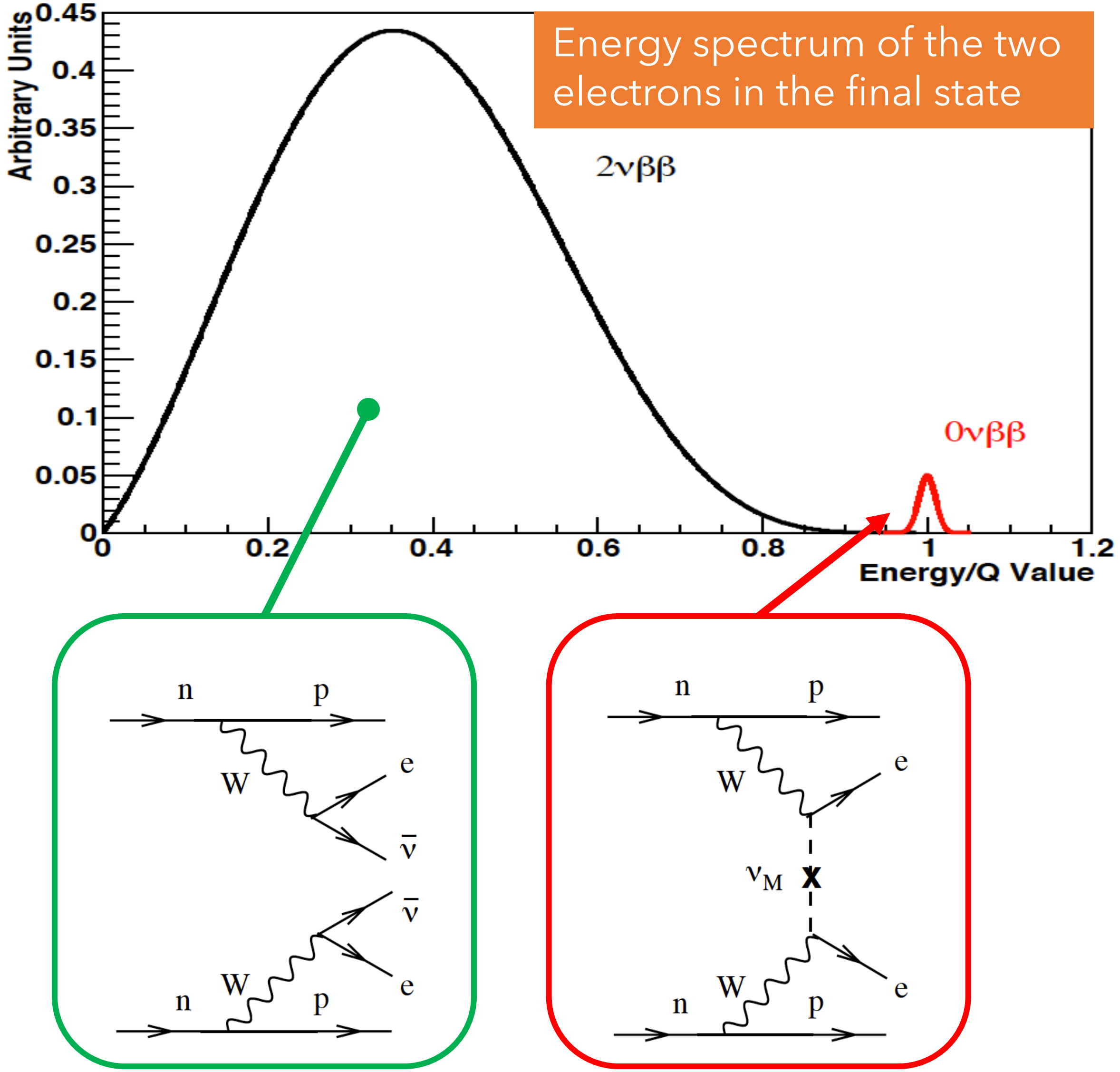
The signal CUORE is searching for

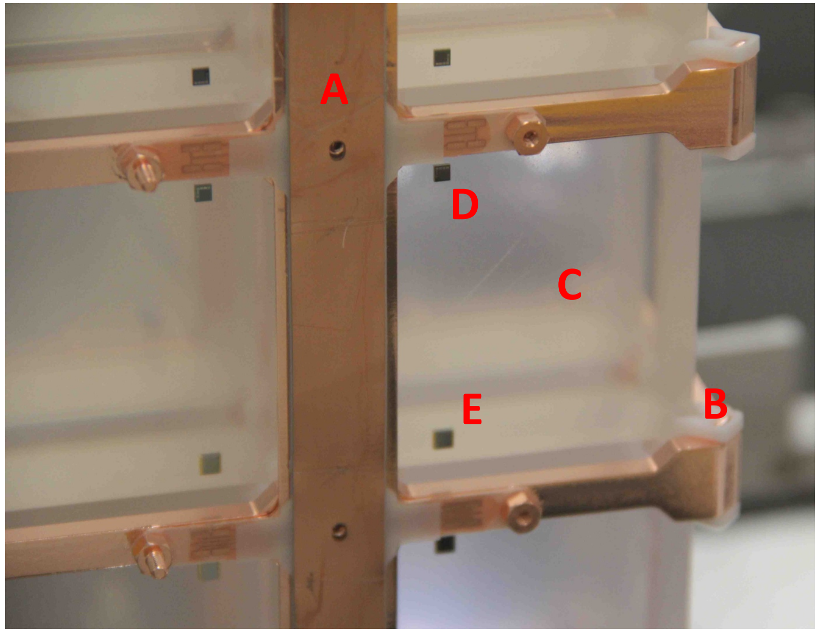


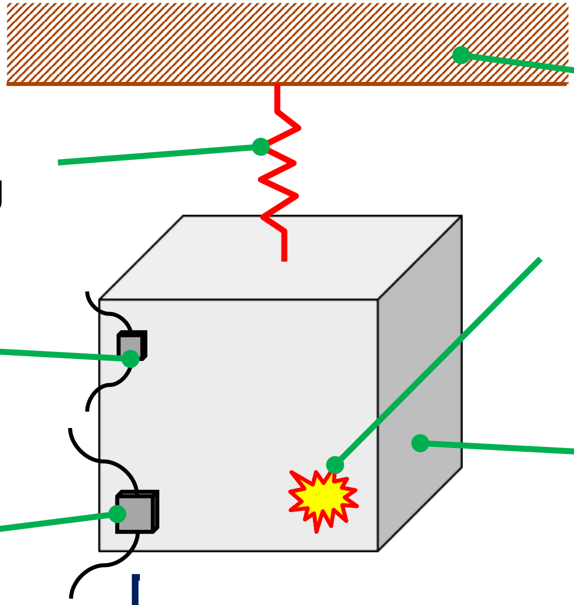
To build a high sensitivity experiment:

$$\left(T_{1/2}^{0\nu}\right)^{sens.} \propto i.a.\cdot\varepsilon\cdot\sqrt{\frac{M\cdot t}{\Delta E\cdot B}}$$

- ***i.a.***: select 0ν DBD candidates with high natural isotopic abundance or enriched;
- ***ε***: high detection efficiency;
- ***M***: high detector mass;
- ***t***: good detector stability over a long period;
- ***ΔE***: extremely high energy resolution;
- ***B***: extremely low background environment;

Bolometric technique in CUORE





(A) Copper frame: 10 mK heat sink

(B) PTFE holders: weak thermal coupling

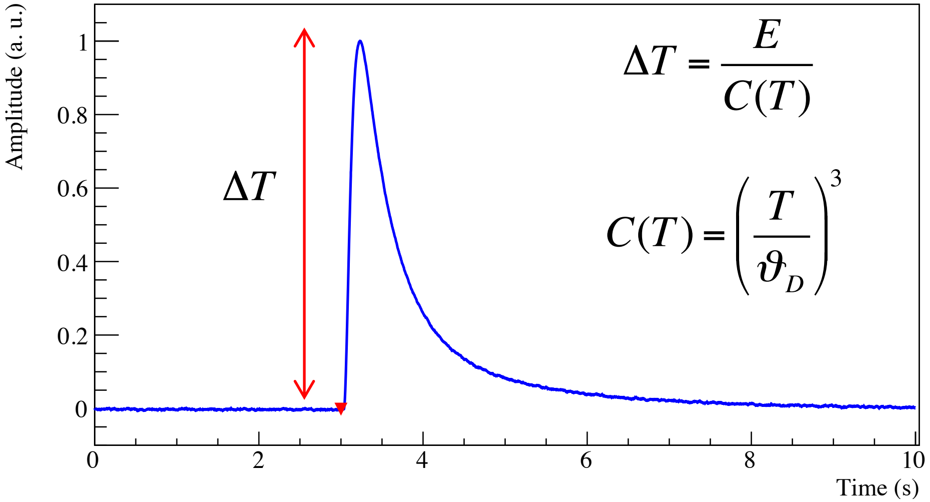
Radiation: energy deposit

(D) Si joule heater: reference pulses

(C) TeO_2 crystal: energy absorber

(E) NTD Ge thermistor: resistive thermometer

Readout



$$\Delta T = \frac{E}{C(T)}$$

$$C(T) = \left(\frac{T}{\vartheta_D}\right)^3$$

Low temperature needed: $@T = 10\ mK$

$$C \sim 10^{-9}\frac{J}{K}; \quad \Delta T = 0.1\frac{mK}{MeV}; \quad \tau \sim 1s$$

- high efficiency;
- excellent energy resolution;
- large masses achievable;
- ^{130}Te high natural isotopic abundance;
- ^{130}Te Q-value 2528 keV;

A rare event search

Searching for a rare event (0ν DBD): $\tau > 10^{24-26}\ yr$

Extremely important to reduce as much as possible backgrounds:

CUORE installed @ LNGS underground laboratories (~3600 m.w.e.)

REDUCTION →

a. natural radioactivity from outside the detector:

- cosmic ray muons induced background;
- neutron and gamma fluxes;

- Strict protocols for crystal production @ SICCAS;
- Cleaning techniques developed @ LNL for copper parts near crystals;
- Strict protocol for assembling and installation;

REDUCTION →

b. natural radioactivity from the detector itself:

- long-lived nuclei (^{40}K, ^{238}U, ^{232}Th);
- anthropogenic radioactive isotopes (^{60}Co, ^{137}Cs, ^{134}Cs);
- cosmogenic radioactive isotopes (^{60}Co);

Suspension/damping systems and new noise cancellation tools

REDUCTION →

c. mechanical vibration noise:

- cryogenic system and seismic noise;

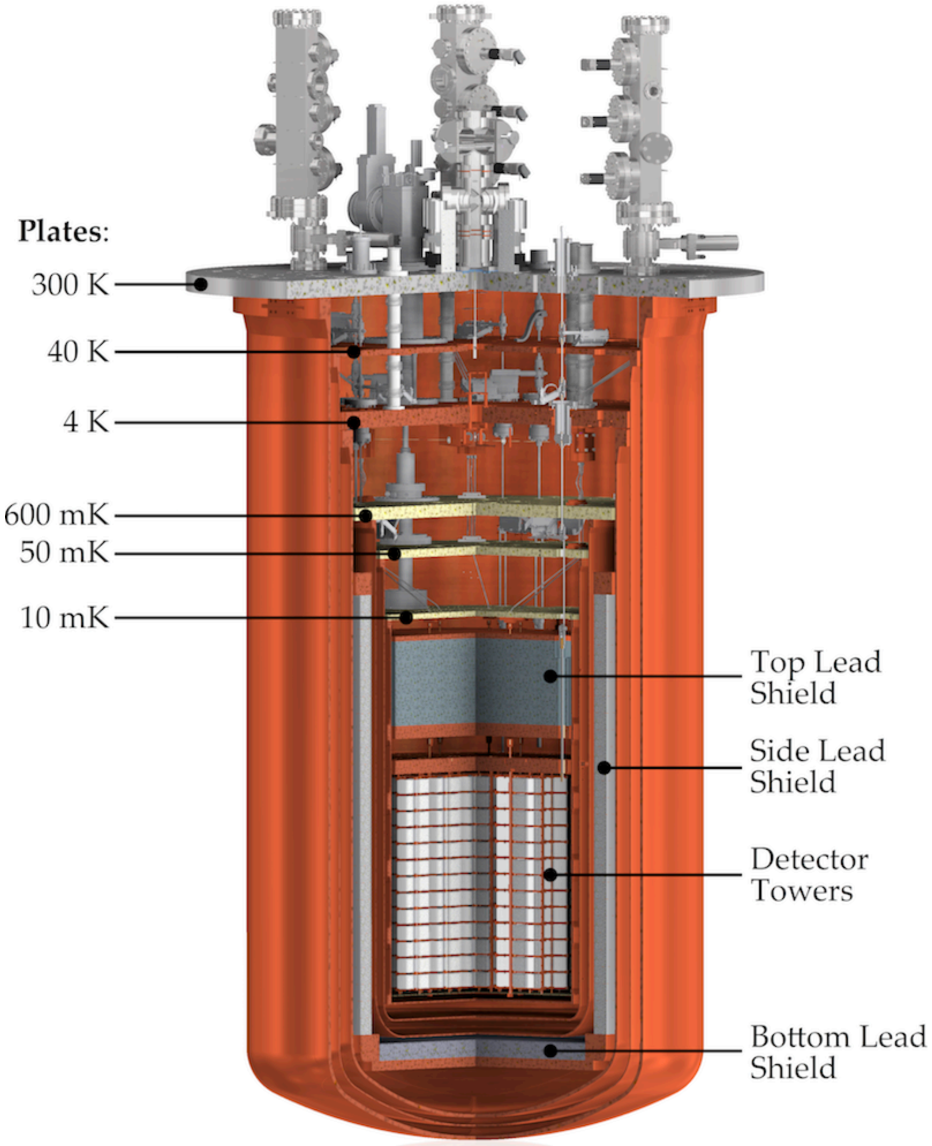
Cryogenic system

Challenging task: cool down ~15 tons @ T < 4 K and ~1.5 tons @ T = 10 mK in a few weeks in a low radioactive environment.

- Cryogen-free (dry) cryostat: high duty cycle:
  - Fast Cooling System (^{4}He gas): T down to ~40 K;
  - 5 Pulse Tubes (PTs) cryocoolers: T down to ~4 K;
- (Custom) Dilution Refrigerator: T operations 10 mK;
- Nominal cooling power: 3 μW @ 10 mK;

Reduction of radioactive background (from detector):

- material screening and accurate selection to ensure radiopurity (mainly pure copper, other material in small amount, limited amount of Multi Layer Insulator);
- lead shielding (Roman and modern Pb);

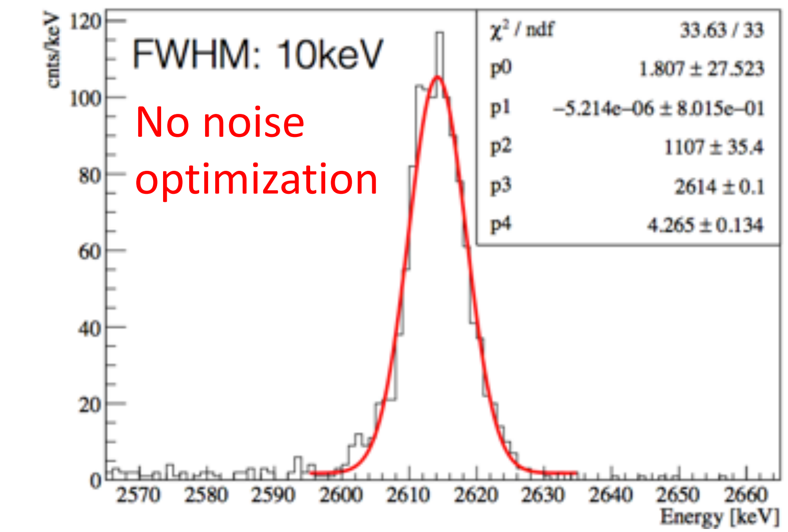


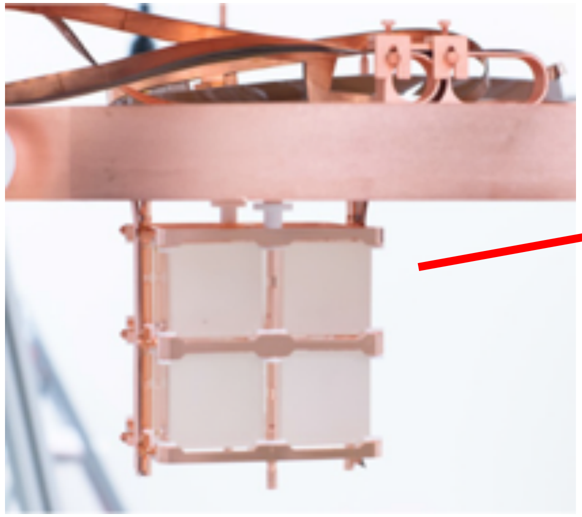
Cryostat commissioning

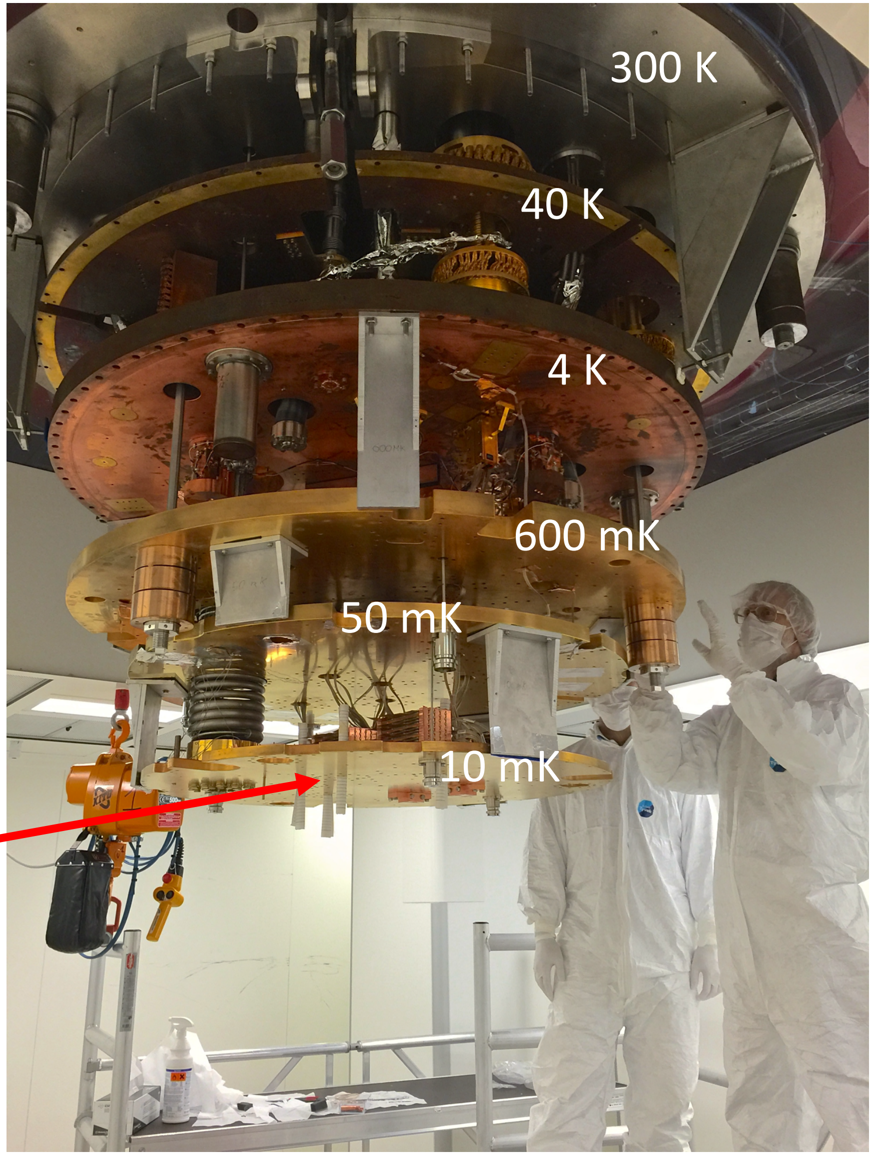
Commissioning completed in March 2016:

- stable base T = 6.3 mK over 70 days (no detector, full load);
- full detector read-out chain (electronics, DAQ) test, temperature stability with Mini-Tower (8 crystal tower);
- successful deployment of the calibration sources at base temperature;

System ready for detector installation.



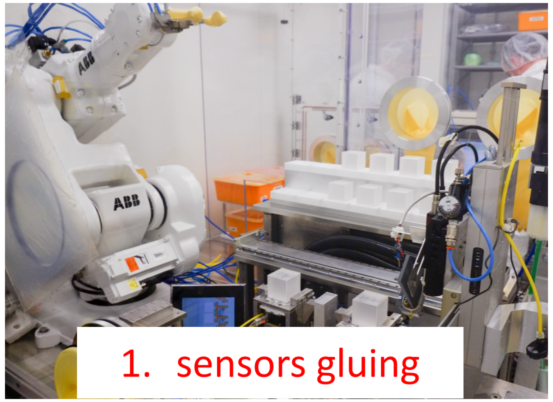




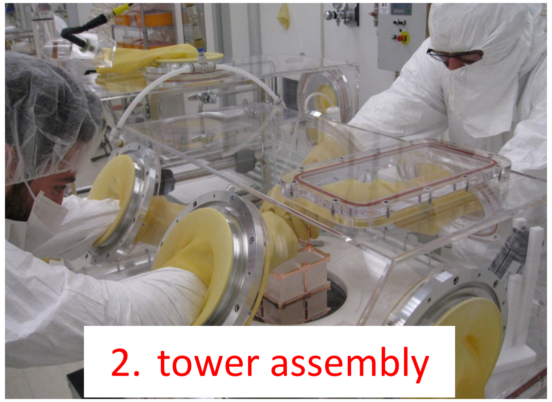
Detector assembling and installation

Strict protocol adopted for each step of assembling/installation (developed and tested in predecessor experiment CUORE0):

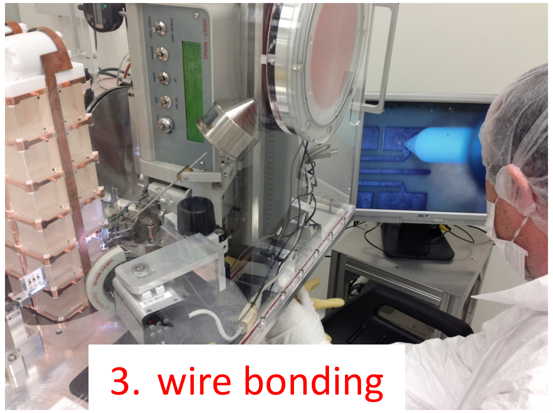
Assembling: in N_2 atmosphere and within glove boxes to avoid radioactive recontamination (between 2013 and 2014);



1. sensors gluing



2. tower assembly



3. wire bonding

4. towers storage

Installation: protected area inside clean room flushed with radon free air; protective bags flushed with N_2 for overnight and emergency storage (started after cryostat commissioning);

5. towers installation

The CUORE "core" installed

Design specifics:

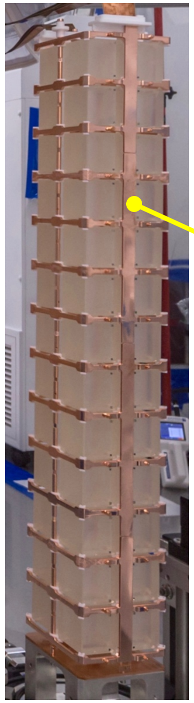
- detector arrangement: 19 towers with 13 floors of 4 crystals each;
- crystals: 988 crystals, 5 cm^3, 750 g each;
- total TeO_2 mass of 742 kg;
- total ^{130}Te mass of 206 kg (all natural abundance);

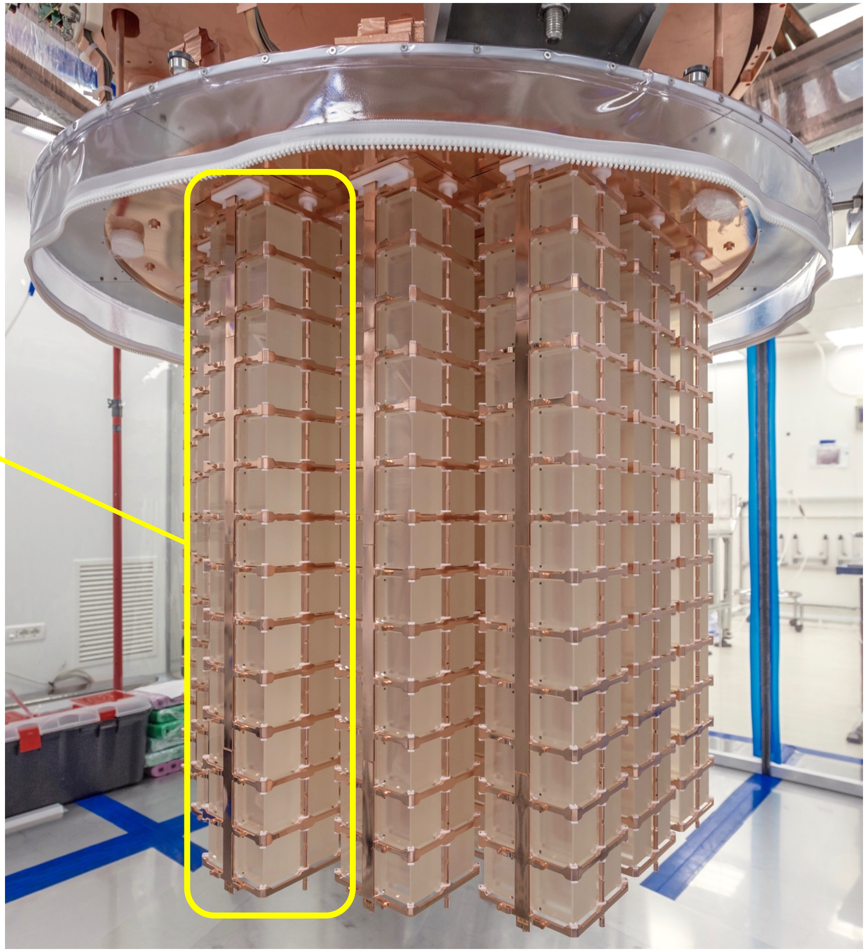
Reduction/control of radioactive background:

- minimization of material/surface facing the crystals;
- closely packed crystal array with high granularity;

GOALS:

- low background of $10^{-2}\ c/(keV \cdot kg \cdot yr)$;
- energy resolution: 5 $keV\ FWHM$ in the Region Of Interest (ROI);
- 0ν-DBD projected sensitivity: $T^{0\nu}_{1/2} = 9 \cdot 10^{25}\ yr$ (5 years, 90% C.L.);





All 19 towers installed between July-August 2016

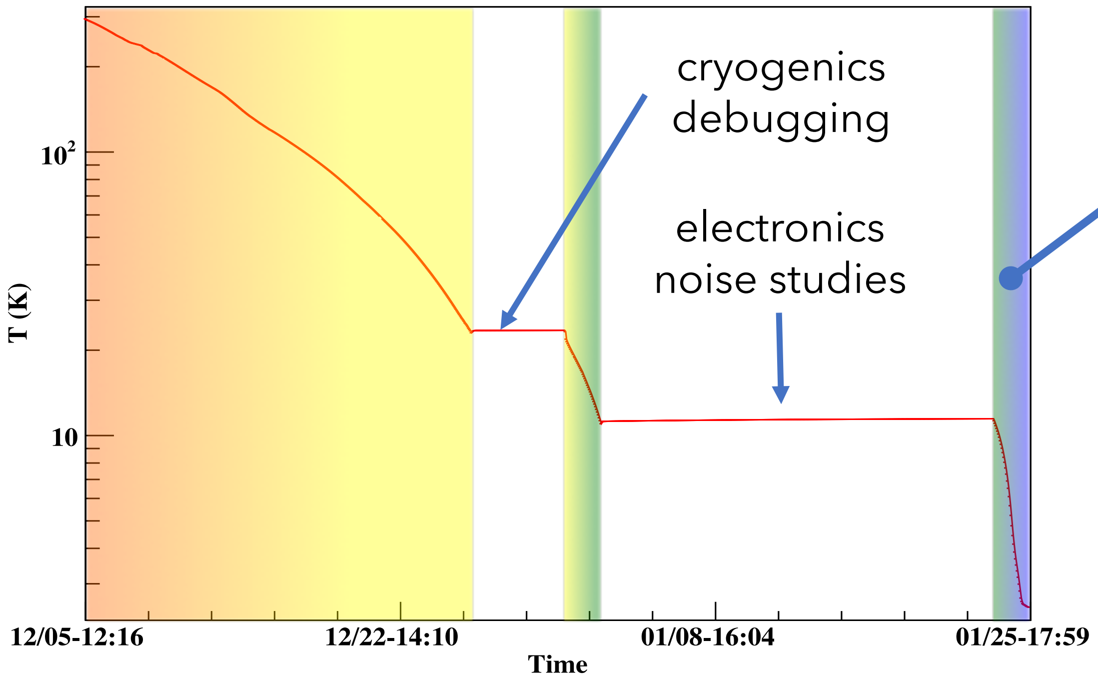
Detector cool down

After towers installation, the cryostat was closed between September-November 2016:

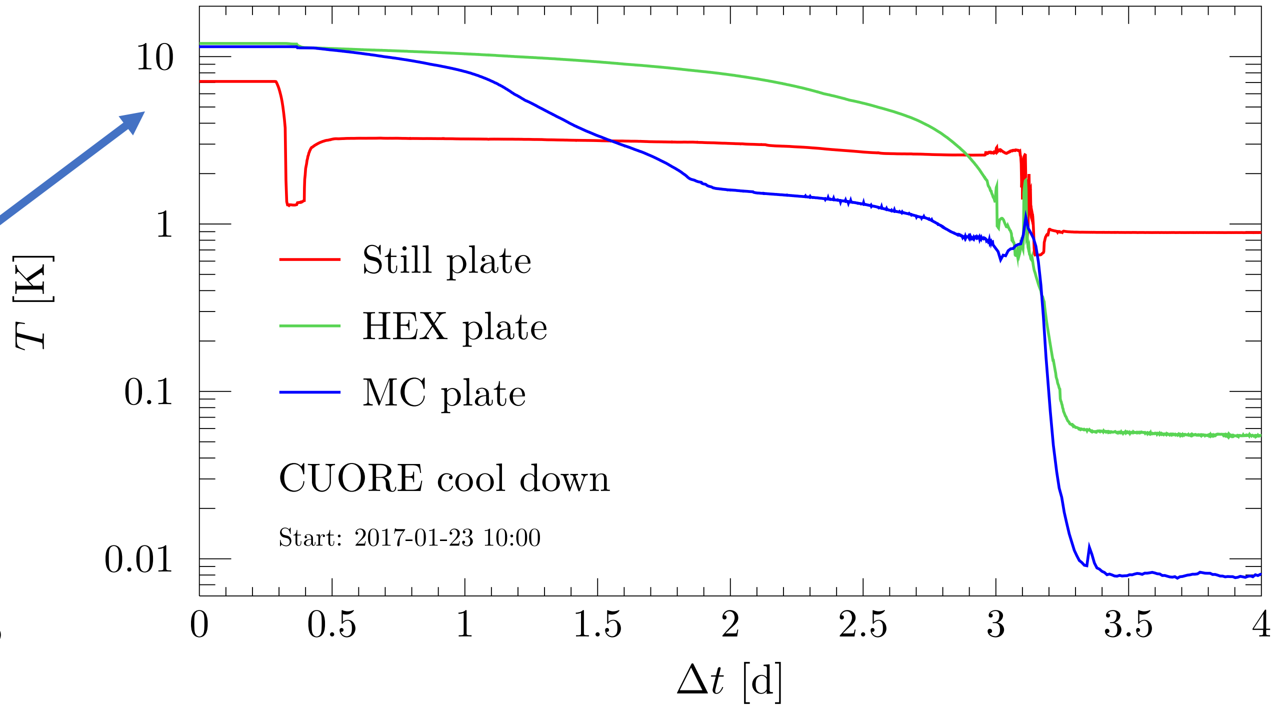
- cooldown started on Dec 5, 2016: lasted ~26 days (without counting technical stops for system debugging);
- on Jan 26, 2017 reached a stable base temperature of T = 7 mK;

After the cooldown started an important phase of detector optimization alternated to data-taking periods

Diode thermometer at 10mK plate



Last 4 days of cooldown: DU switched on

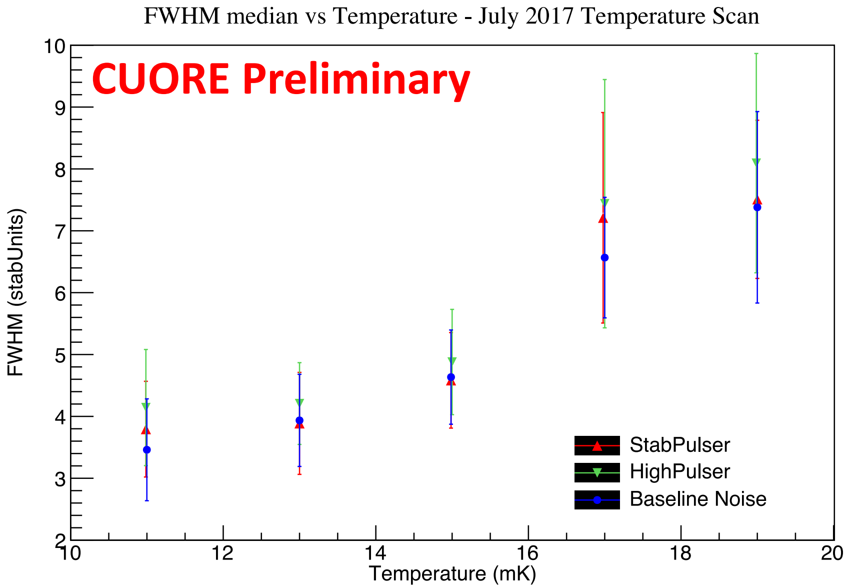


Setting the best working temperature

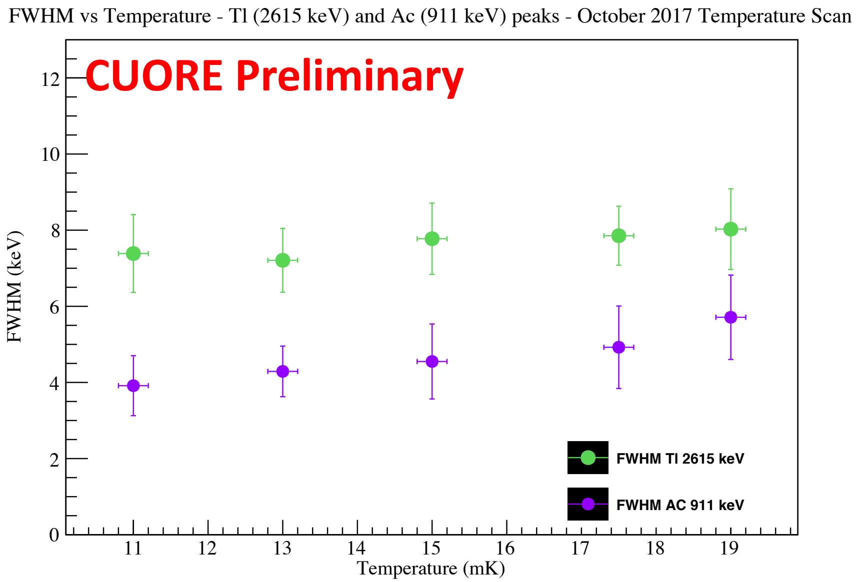
Temperature scans around base temperature to optimize detector resolution and NTDs resistances at design values ($\sim 100\ M\Omega$):

- **First scan** (March 2017): identified the best working temperature of **15 mK** (indications of better resolution at lower T, but higher NTDs resistances then design values);
- **Second scan** (July 2017): check setting from the first scan before starting of new data-taking;
- **Third scan** (September 2017): with calibration sources deployed, confirmed trend of better resolution on physics events at lower T. Set **11 mK** as new working temperature;

Baseline and Pulser resolutions (from July 2017 scan)



Resolutions on physics events (from September 2017 scan)

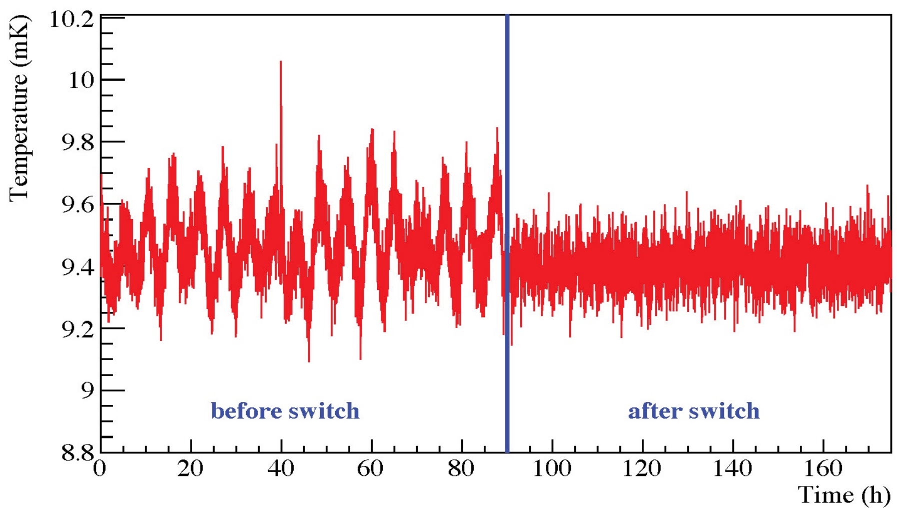


Minimization of vibrational noise

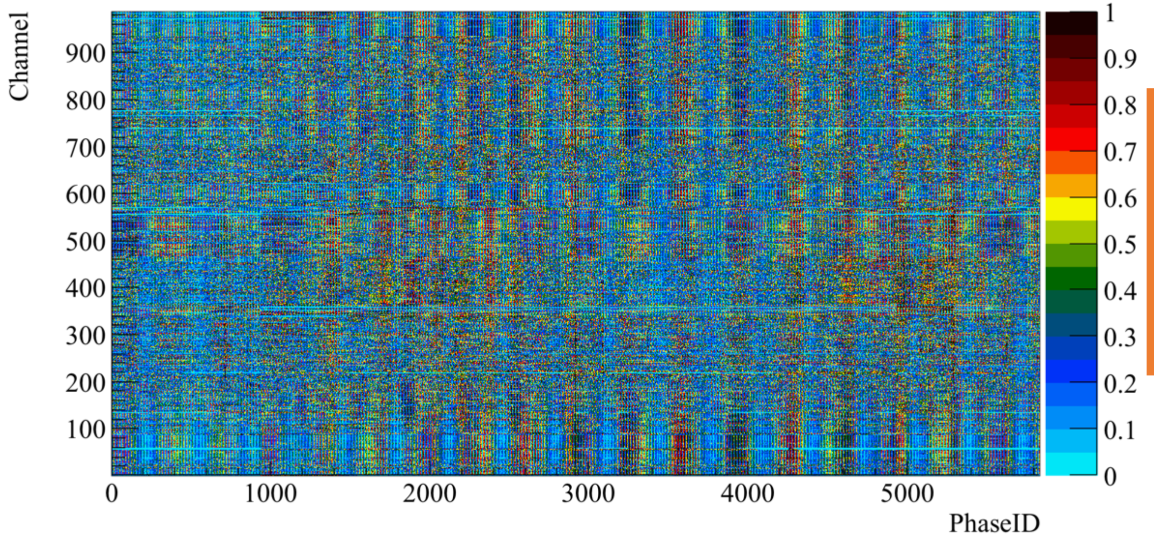
Developed tool to minimize vibrational noise from PTs:

- use linear drives (LD) to control PTs' rotating valves;
- PTs phase scan to find the configuration of minimum noise across the whole detector;

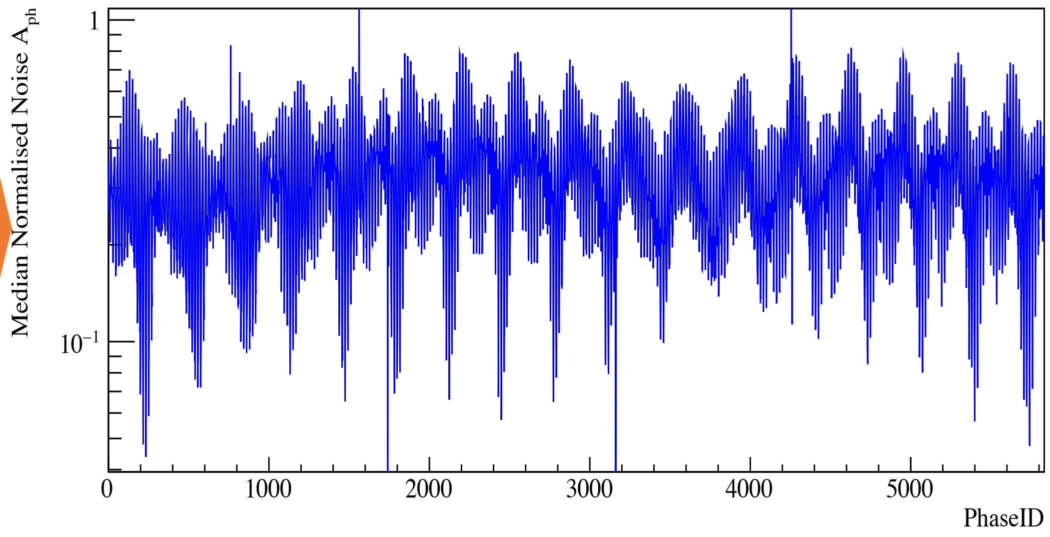
10 mK temperature: before and after LD switch on



PT induced noise on each channel vs PTs phase configuration



median overall channels vs PTs phase configuration



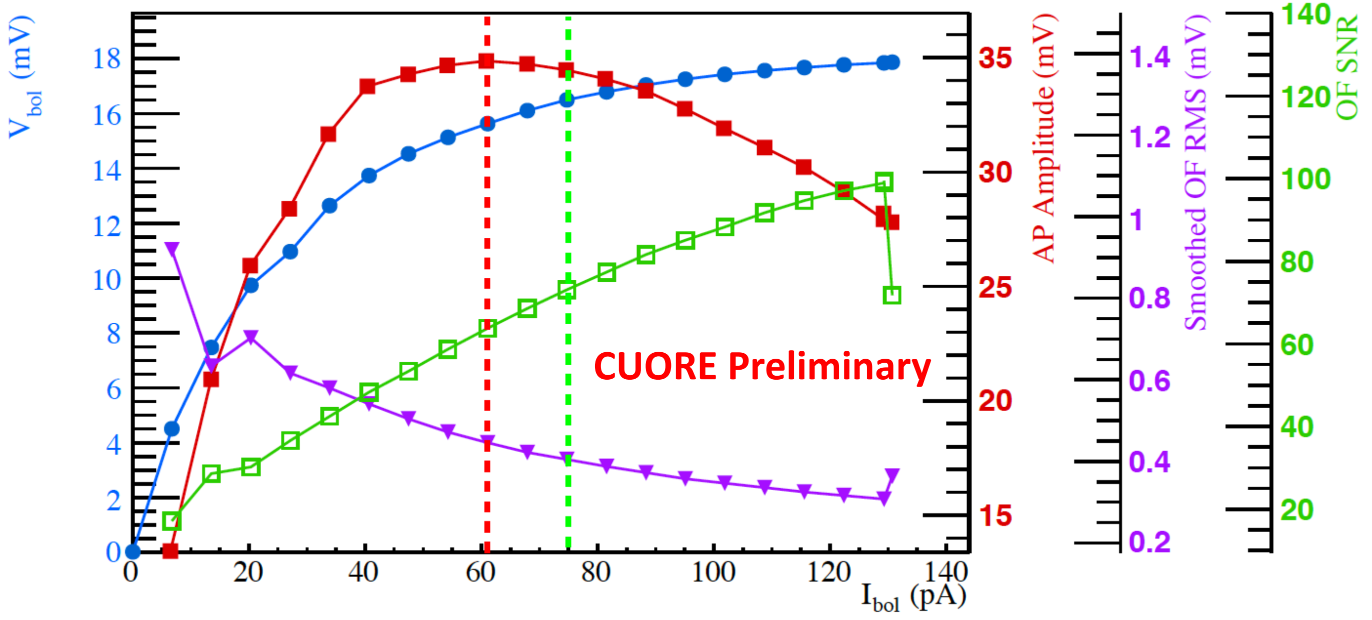
Maximize SNR

Once the NTD resistances have been set by selecting the working temperature, the correct bias currents I_{bias} supplied to the thermistors have been optimized with dedicated measurements:

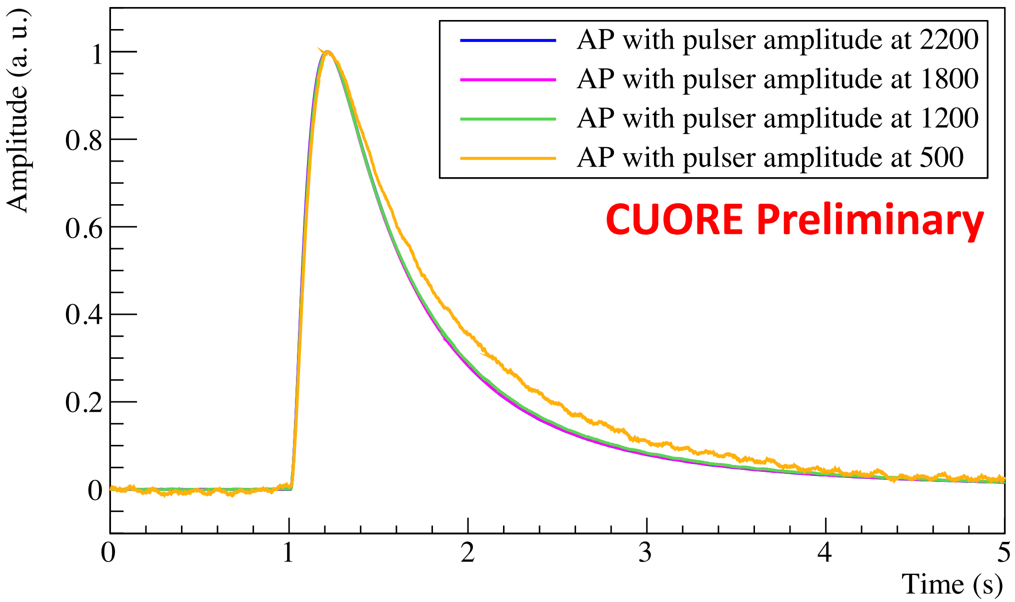
For each bolometer measured:

- characteristic I-V curve: set bias currents lower than values at inversion point (avoid distorted signal shapes);
- reference pulses amplitude, noise RMS and SNR at each (I,V) point: set bias current maximizing SNR;

Example of I-V (Load-Curve) for a channel



Reference pulses for different amplitudes @ I_{bias}



Data taking for physics analysis

Detector optimization ended in April 2017 to start science runs:

- **Dataset 1**: 3 weeks of data bracketed by 2 calibration periods (May - June 2017). TeO_2 exposure $37.6\ kg \cdot yr$;

➢ still room for performance improvements;

Detector optimization restarted in July 2017:

✓ careful investigation/upgrades to the electronics grounding in the CUORE Faraday cage;

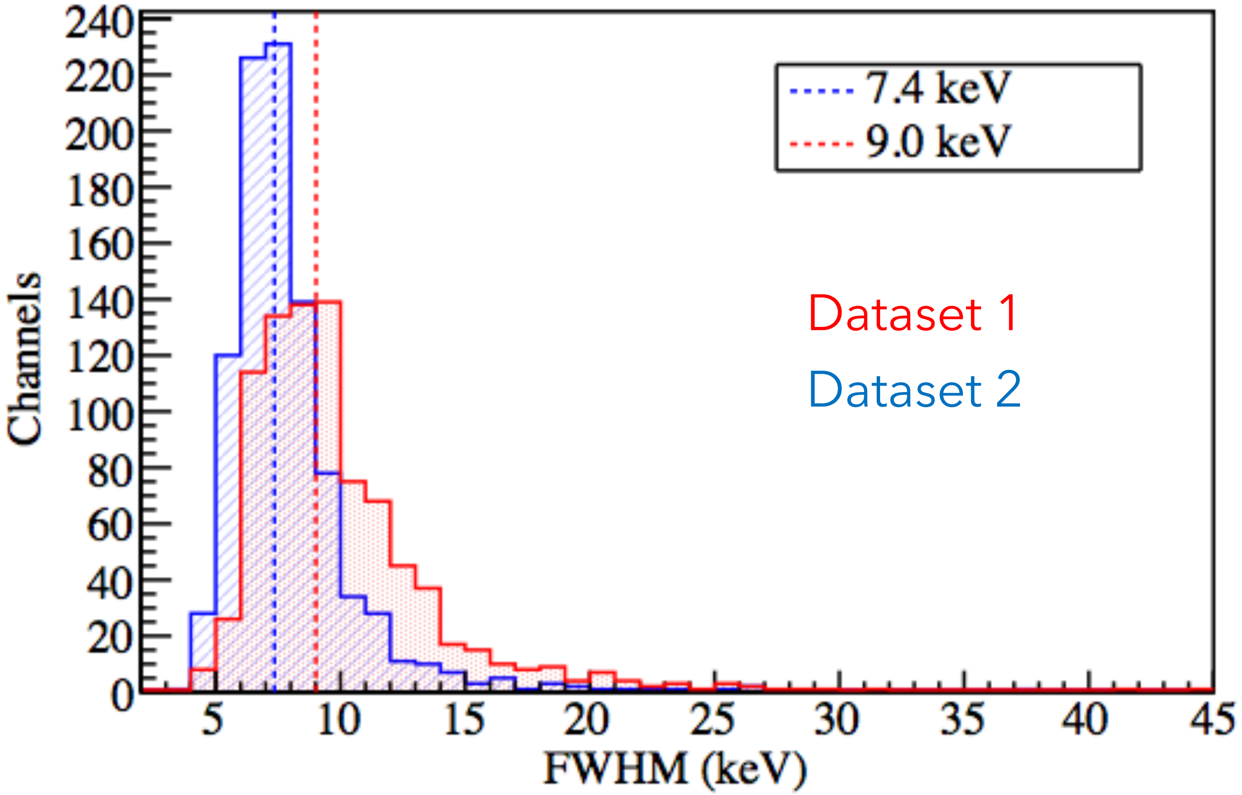
✓ Introduced PTs phase scans to refine the abatement of induced noise;

✓ optimization of the operating temperature and detector working points;

✓ software and analysis upgrades;

After the second optimization phase, resumed data-taking:

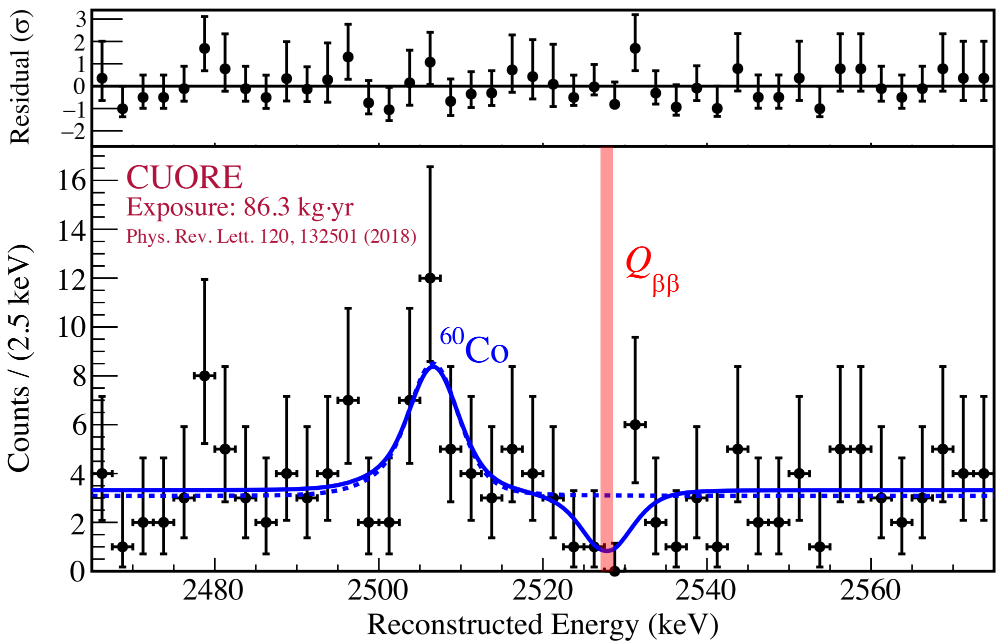
- **Dataset 2**: same procedure as first dataset (August – September 2017). TeO_2 exposure $48.7\ kg \cdot yr$;



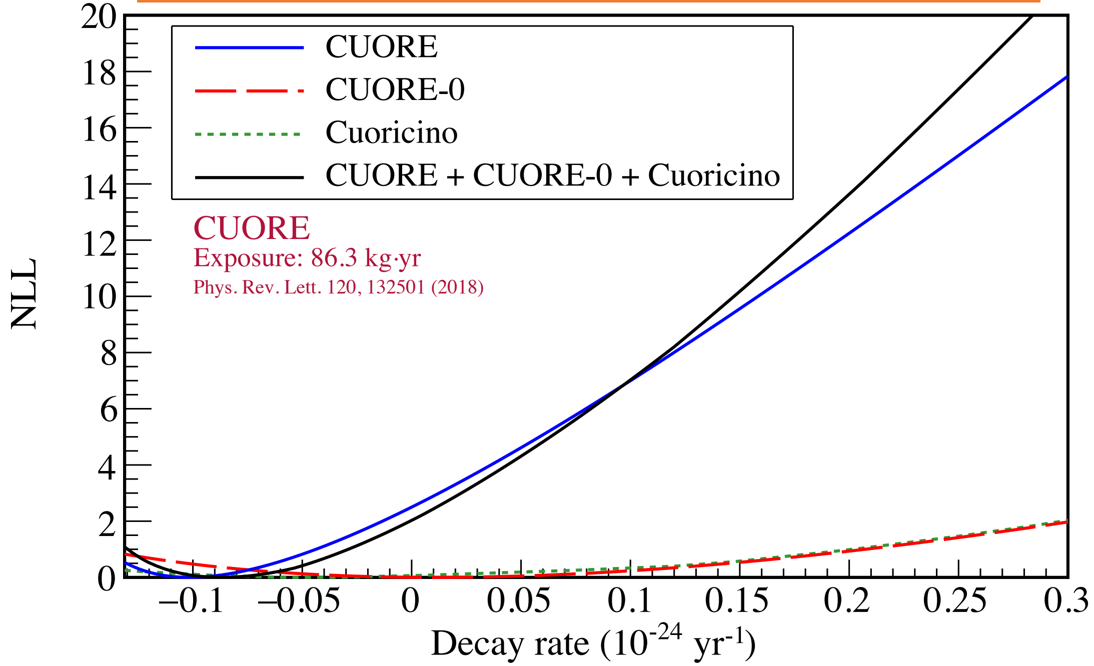
Improved resolution between the two datasets

$0\nu DBD$: fit results and half-life limits

Fit in the region of interest (2465-2575 keV)



Profile negative-log-likelihood curves



Signal decay rate best-fit:

$$\Gamma_{0\nu} = \left(-1^{+0.4}_{-0.3}\,(stat.)\ \pm 0.1\,(syst.)\right) \times 10^{-25} yr^{-1}$$

Background index best-fit (datasets average):

$$BI = (0.014 \pm 0.002)\ counts/(keV \cdot kg \cdot yr)$$

Combined (CUORE+CUORE0+Cuoricino) limit on the half-life:

$$T^{0\nu}_{1/2} > 1.5 \cdot 10^{25}\ yr\ (90\%\ C.L.)$$

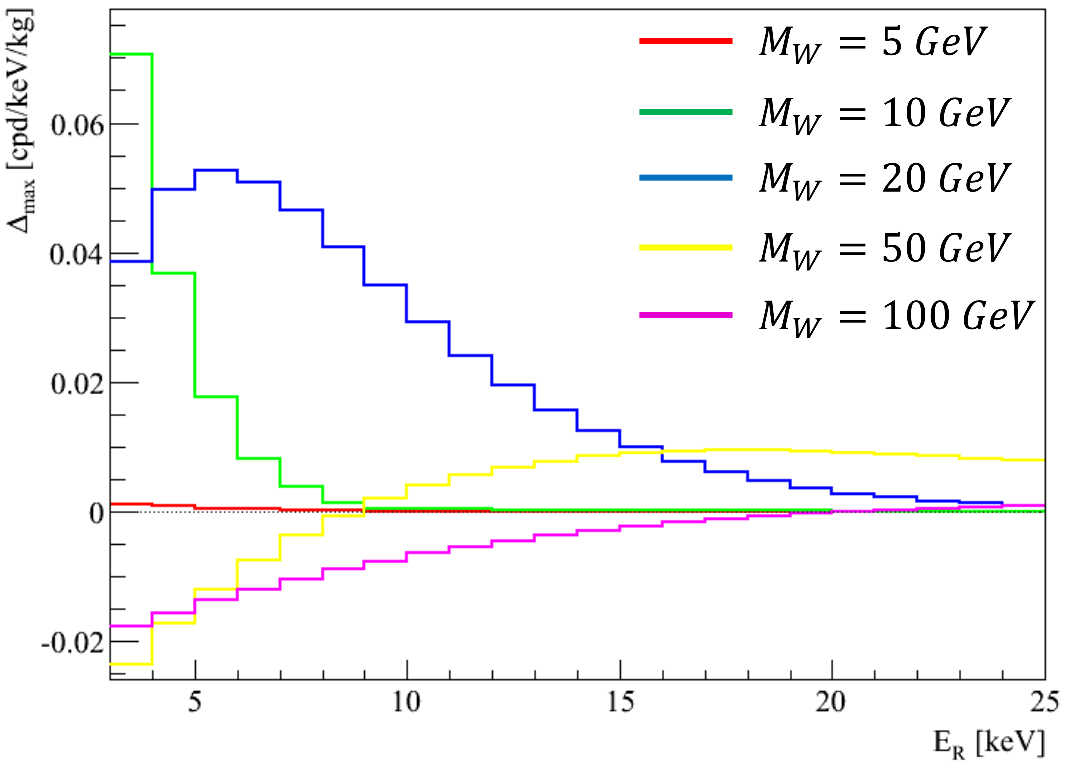
Effective Majorana mass limit:

$$m_{\beta\beta} < 110 - 520\ meV$$

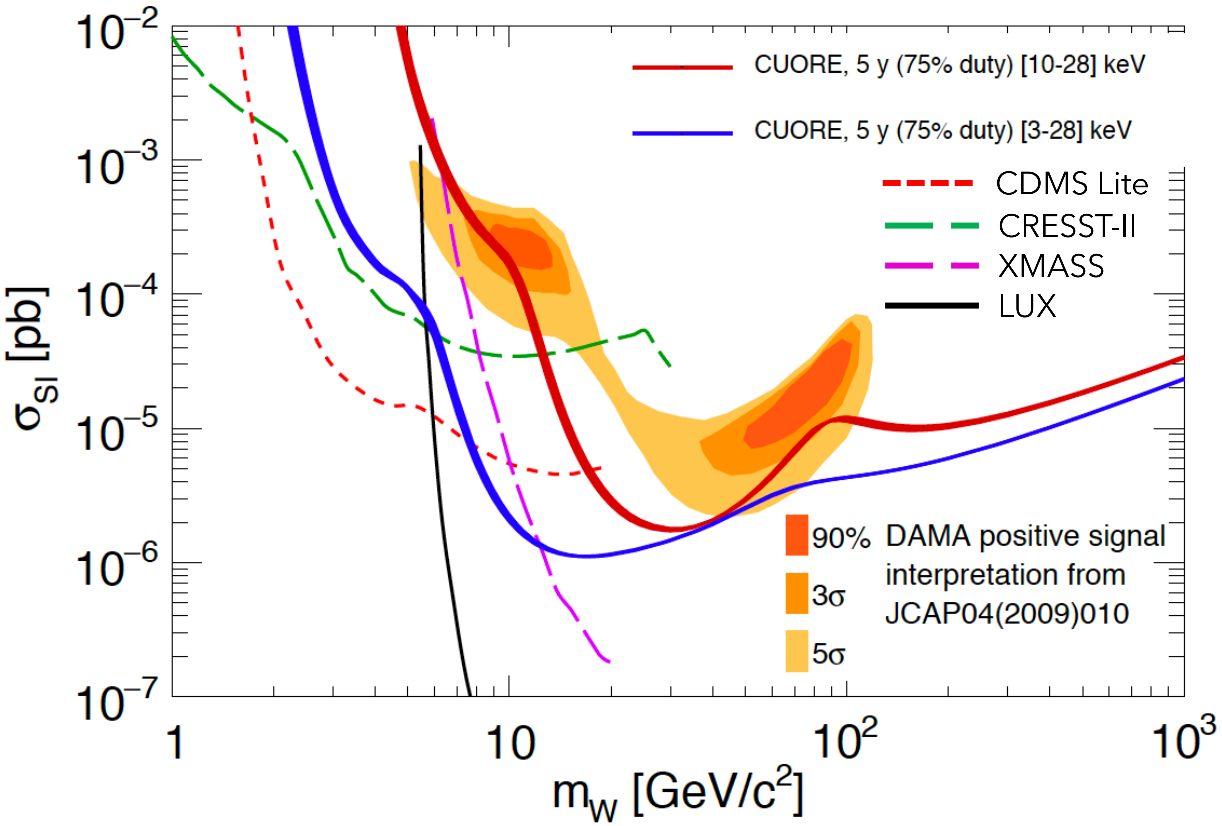
Trigger thresholds & other searches

Could CUORE search also for very low energy events (like Dark Matter induced signals)?

Expected WIMP modulation amplitude (max – min) in TeO_2 for $\sigma_{SI} = 10^{-5} pb$



Projected 90% C.L. sensitivity on the spin-independent elastic WIMP-nucleon cross section



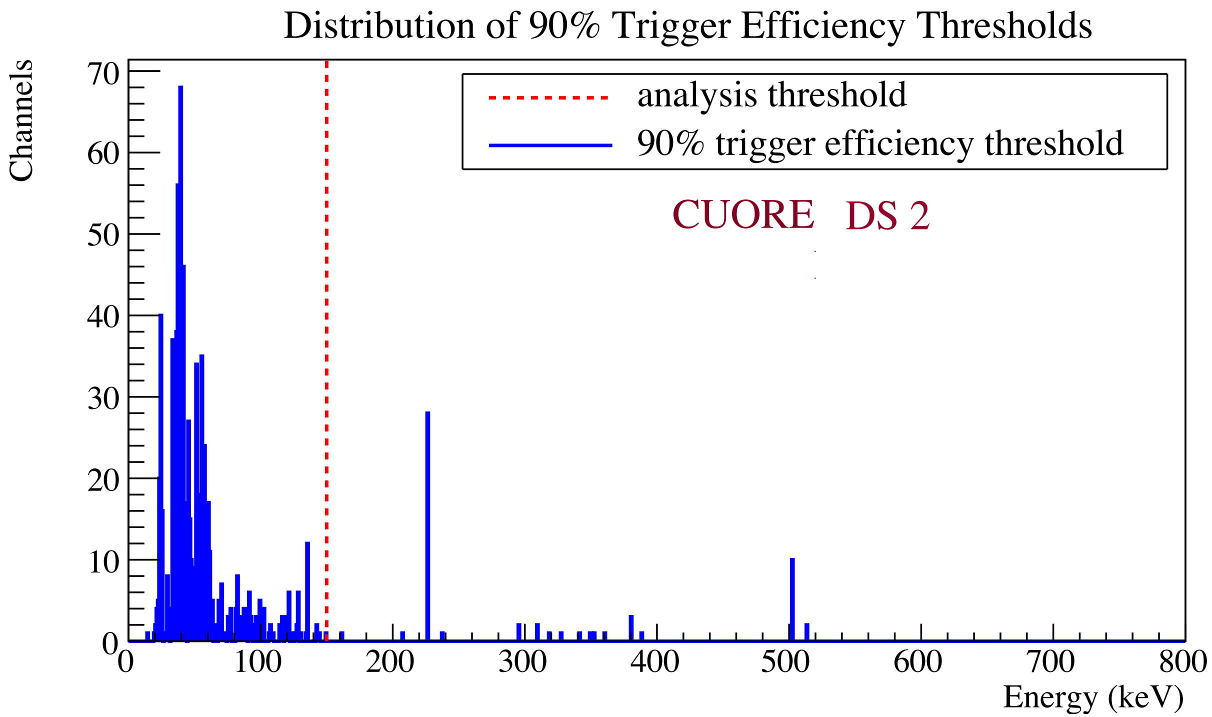
Trigger thresholds & other searches

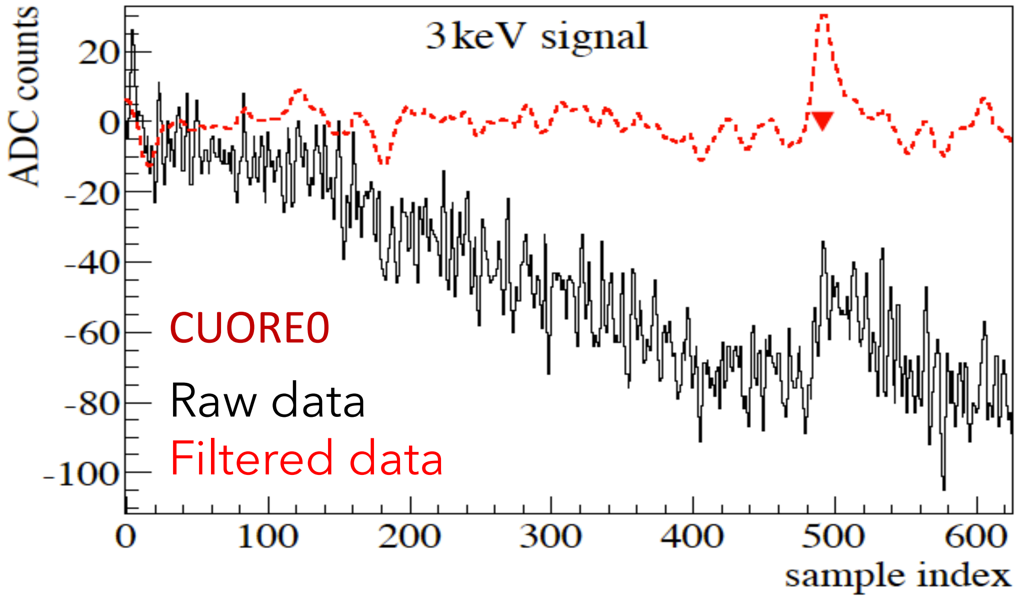
Lower the trigger thresholds for low energy event tagging:

- currently working on testing a trigger based on the Optimal Filter technique (Optimum Trigger);

Current trigger thresholds ranging from 20 keV to ~100 keV. How to lower them?

Matched filter technique: transfer function maximizing SNR (applied in frequency domain)



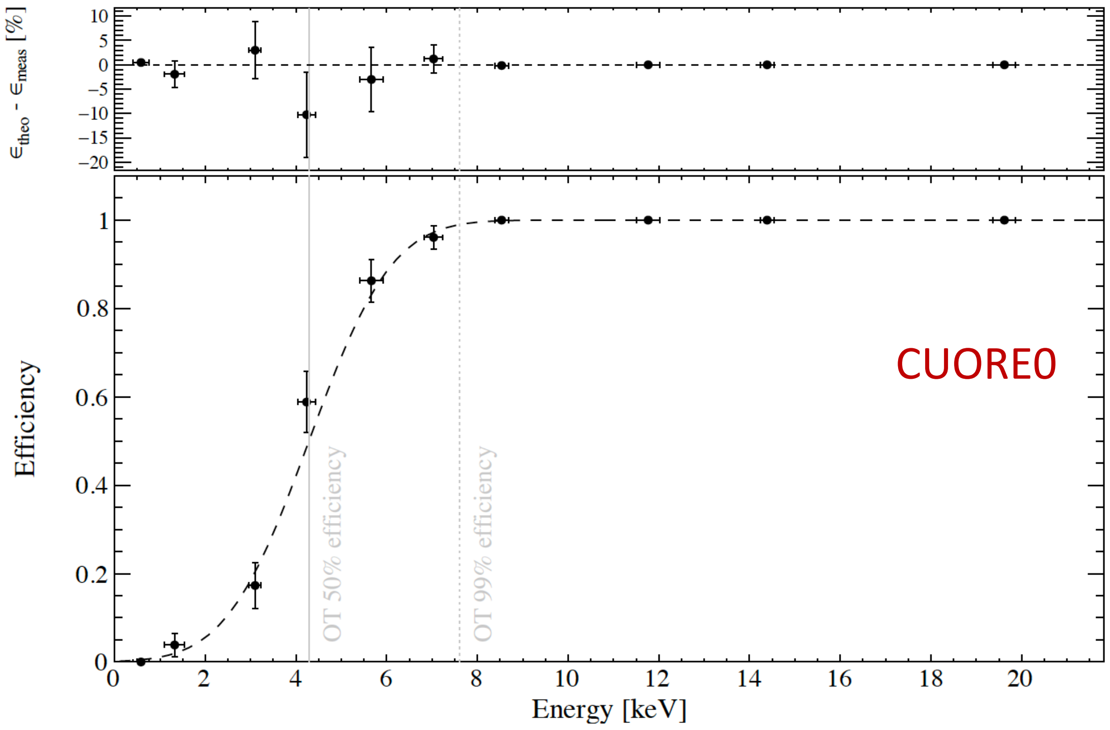


- filtered pulses are less noisy;
- lower thresholds could be achievable;

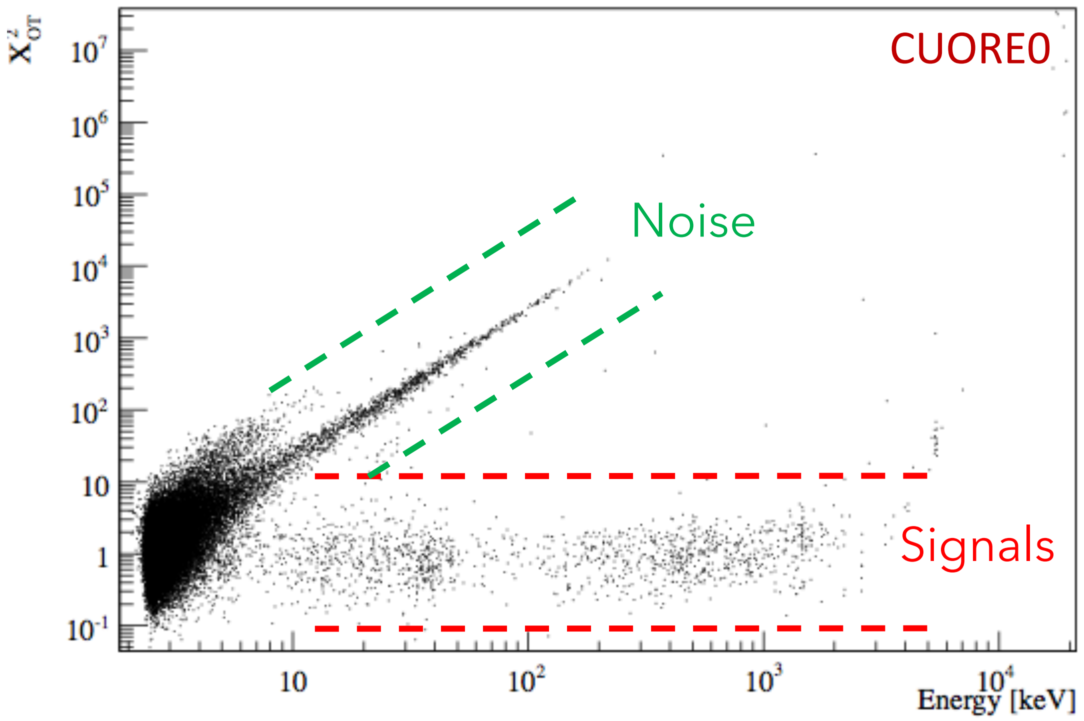
Trigger thresholds & other searches

Optimum Trigger: what has been achieved in CUORE-0

Obtained trigger thresholds range from 4 keV up to 12 keV



Signal/Noise shape discriminator: χ^2 of triggered filtered pulses w.r.t. ideal one



Conclusions

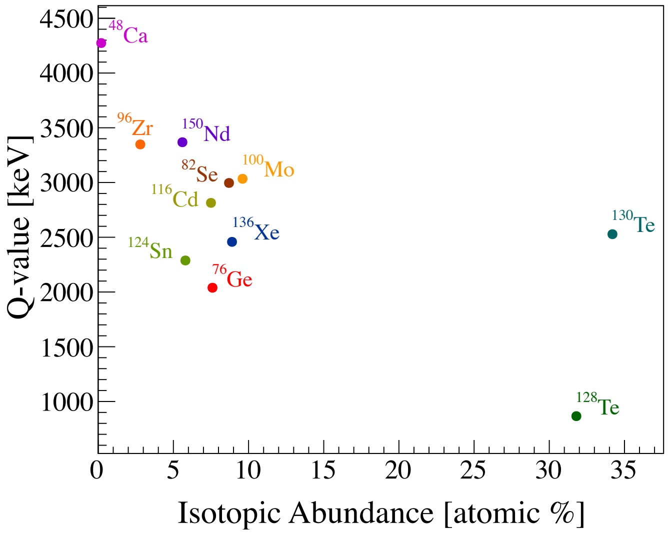
- **Best limit on 0ν DBD half-life of ^{130}Te;**
  - ✓ first CUORE result published in PRL;
- **Technological achievements:**
  - ✓ first ton scale bolometric detector in operation;
  - ✓ largest and most powerful dilution refrigerator in operation;
  - ✓ developed new methods to reduce noise and set best working conditions for the detector;
- **Work in progress:**
  - ❖ after acquiring the first two datasets for physics, a new optimization phase started;
  - ❖ resumed data-taking in May 2018;
  - ❖ exploring the possibility to lower the trigger thresholds to perform DM searches;

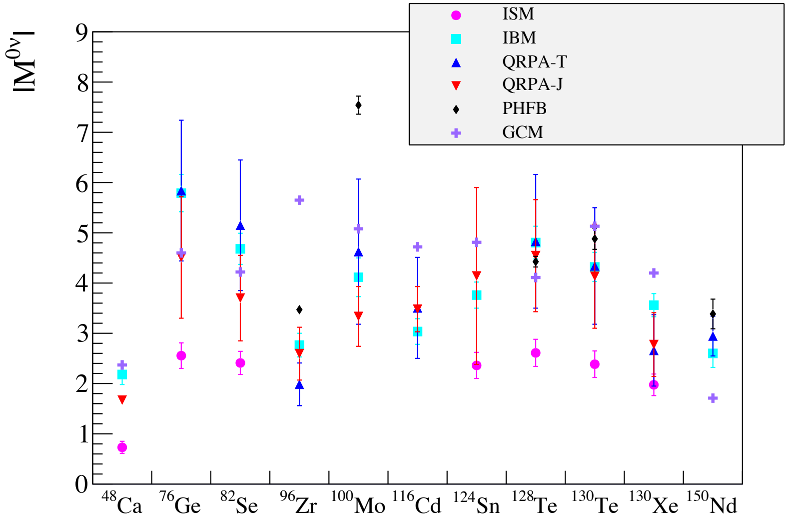
List of references

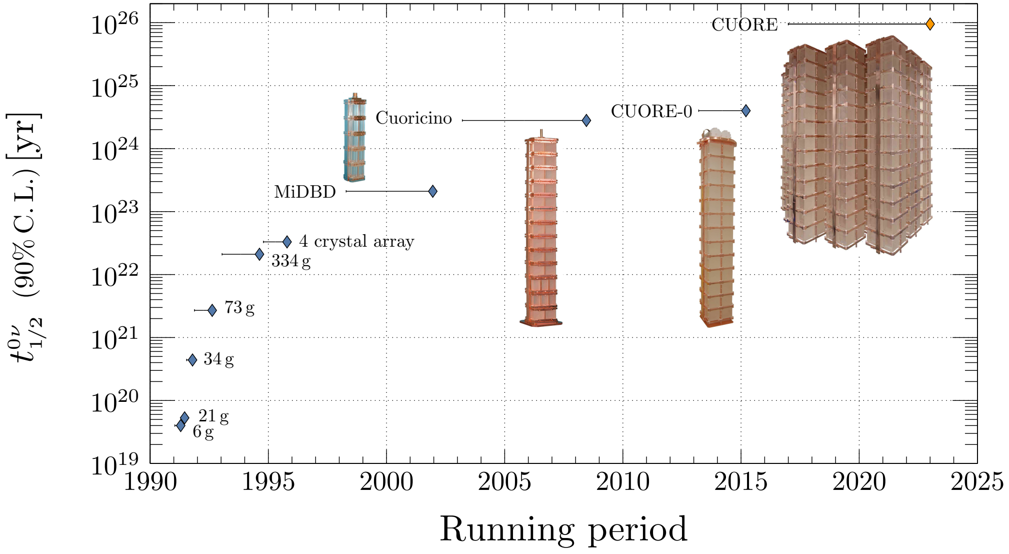
- CUORE Collaboration, First Results from CUORE: A Search for Lepton Number Violation via $0\nu\beta\beta$ Decay of ^{130}Te, Phys. Rev. Lett. 120, 132501 (2018);
- A. D'Addabbo, C. Bucci, L. Canonica, S. Di Domizio, P. Gorla, L. Marini, A. Nucciotti, I. Nutini, C. Rusconi, B. Welliver, An active noise cancellation technique for the CUORE Pulse Tube Cryocoolers, arXiv:1712.02753 [physics.ins-det];
- CUORE Collaboration, Low Energy Analysis Techniques for CUORE. *European Physical Journal C* 77, 857 (2017);
- Sergio Di Domizio, Filippo Orio, Marco Vignati, Lowering the energy threshold of large-mass bolometric detectors, JINST 6 (2011) P02007;
- S. Dell'Oro, Optimization of the CUORE detector during the commissioning phase, Ph.D. thesis, Gran Sasso Science Institute (2017);
- L. Marini, The CUORE experiment: from the commissioning to the first $0\nu\beta\beta$ limit, Ph.D. thesis, Università degli Studi di Genova (2018);

Additional material

Bolometric technique: ^{130}Te







Bolometric detectors: detector also the source of 0ν DBD:

- high efficiency;
- excellent energy resolution;
- large masses are achievable;

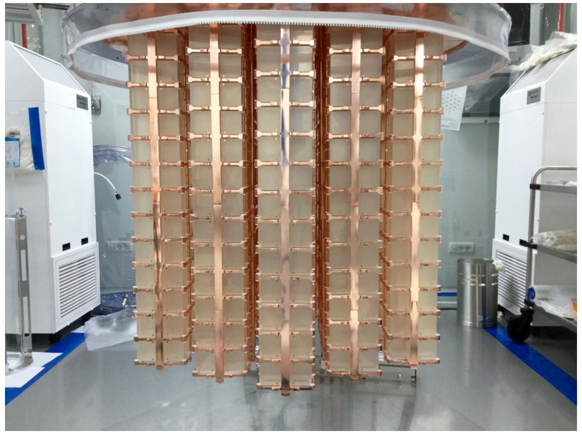
^{130}Te: a good candidate source for 0νDBD:

- high natural isotopic abundance;
- Q-value (2528 keV) above most of the natural radioactivity;
- nuclear matrix elements and phase space on average;

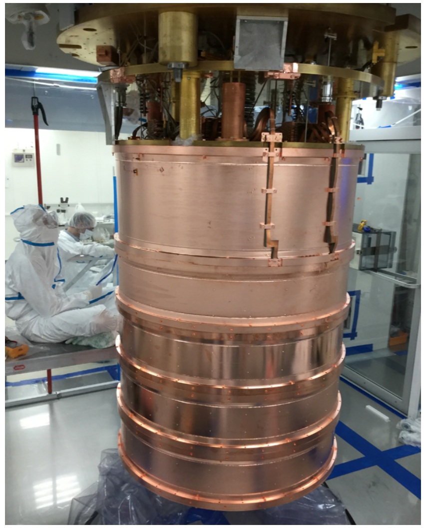
Last phases of CUORE installation

Aug 2016

Towers installation completed



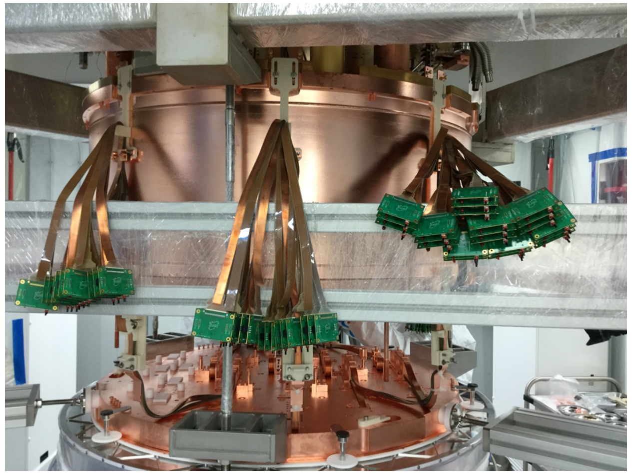
10 mK Cu shield closed



Lead shield installed

Sep – Nov 2016

Cables routing



Cryostat closed

Nov 2016

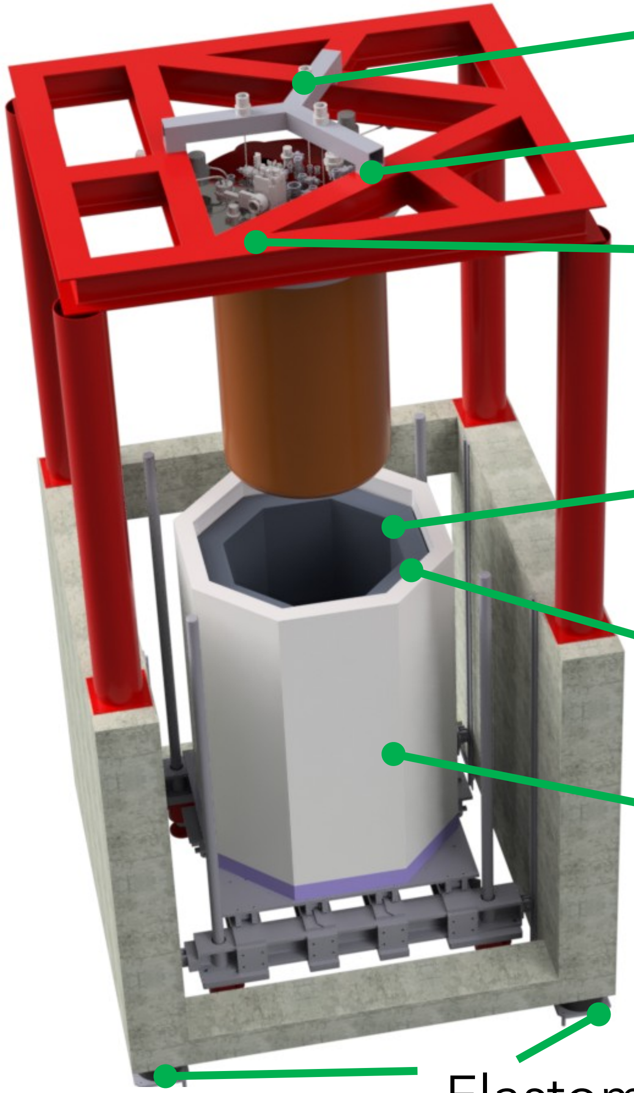
Suspension system

Abatement of vibrations: mechanical decoupling from the outside environment:

- detector suspension independent from that of cryogenic and calibration systems:
  - detector hung by the Y-Beam through cables made of stainless steel tie bars, Kevlar ropes and copper bars (damping the horizontal oscillations);
  - 3 minus-K springs connect the Y-Beam to the Main Support Plate, MSP (attenuating the noise of ~35 dB);
- elastometers at the structure basis (seismic isolators);

Reduction of radioactive background (from outside):

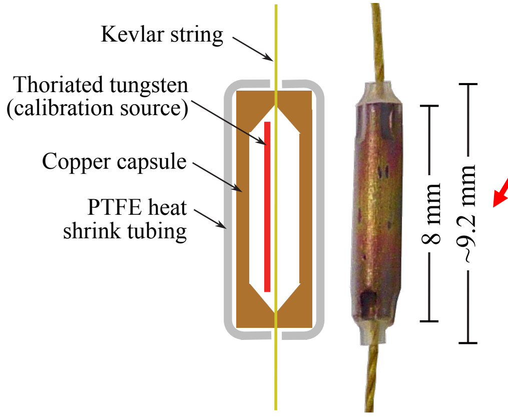
- outer neutron shield: polyethylene + borated powder;
- outer gamma shield: lead shield;

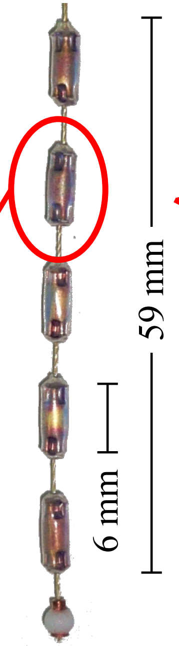


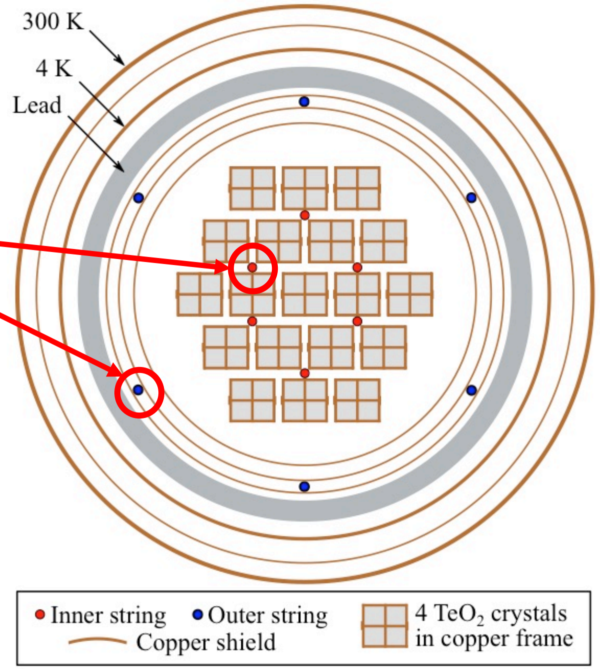
Calibration system

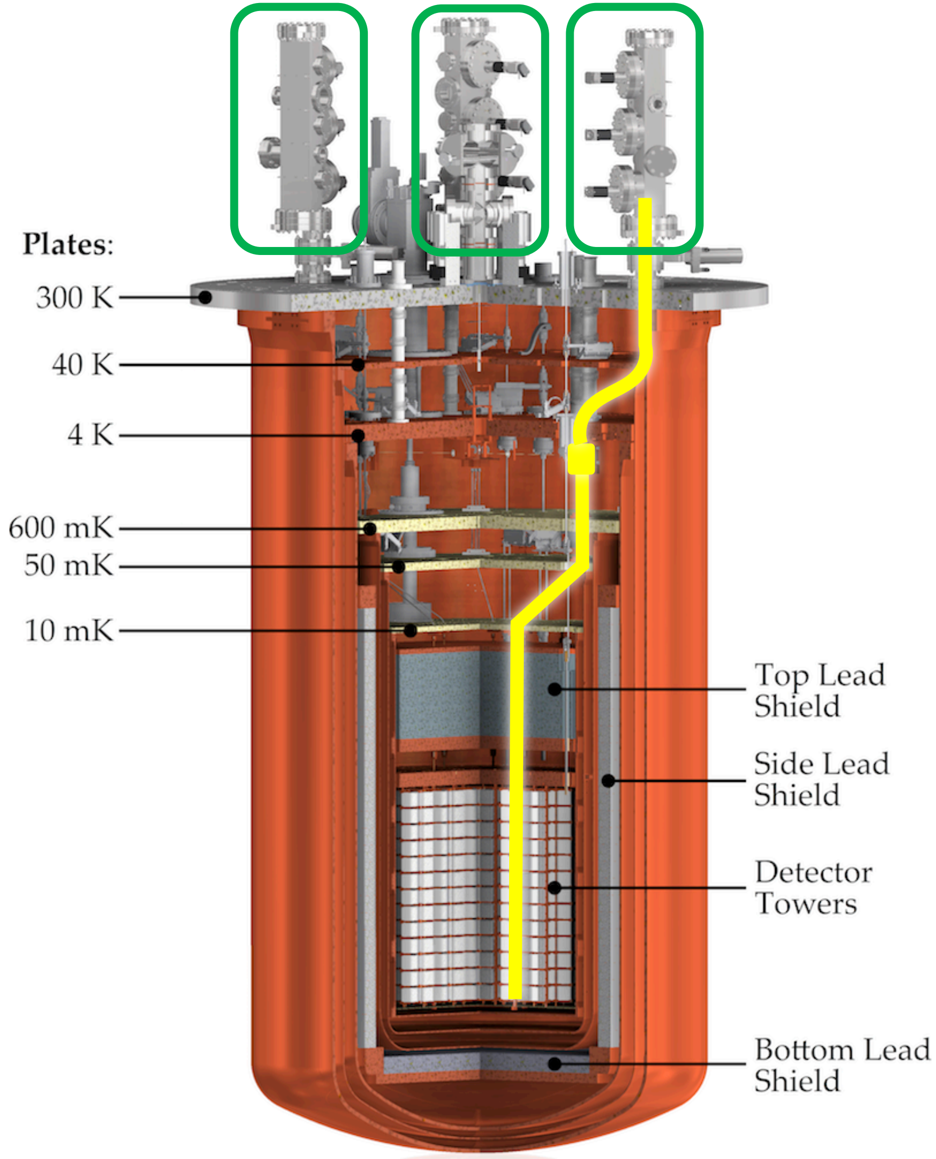
Bolometers require independent *in situ* energy calibration:

- ^{232}Th γ-ray sources every ~month (239 keV to 2615 keV);
- sources are outside cryostat during physics data-taking and lowered into cryostat and cooled to 10 mK for calibration;
- sources are put on strings, lowered under their own weight;
- a series of tubes in the cryostat guides the strings;









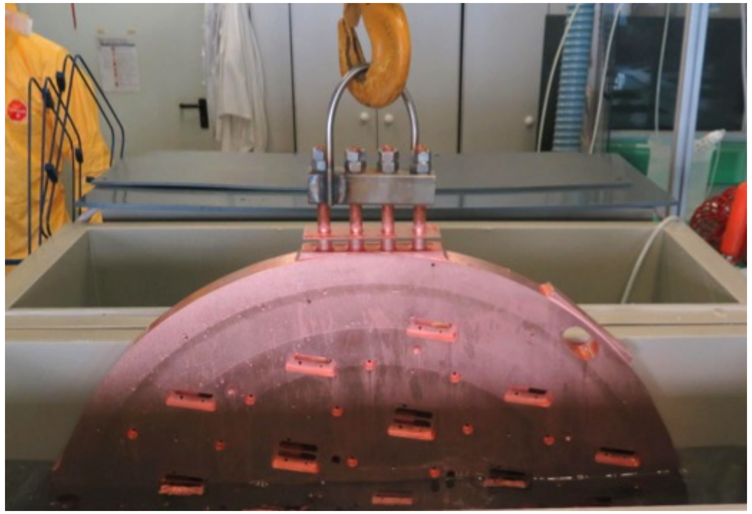
Crystals production and copper cleaning

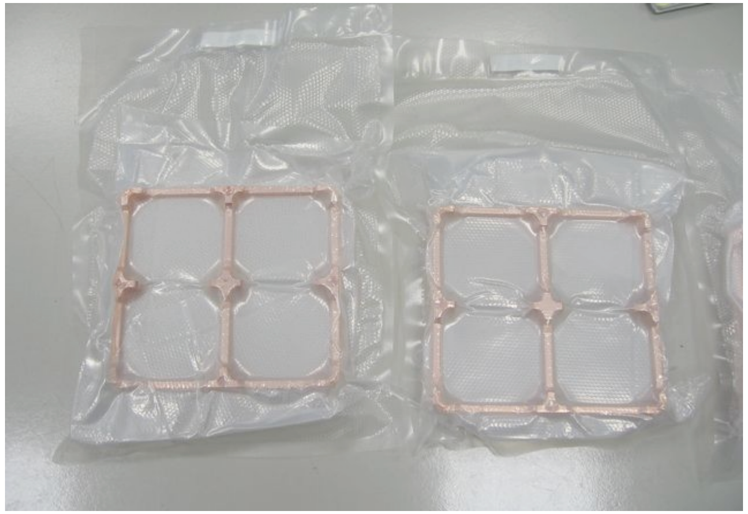
Production of the TeO_2 crystals:

- by Shanghai Institute of Ceramics, Chinese Academy of Science (SICCAS);
- all operations performed in a dedicated clean room and following strict controls to limit radioactive contamination;

Cleaning of copper surfaces (tower parts and 10 mK cryostat shield):

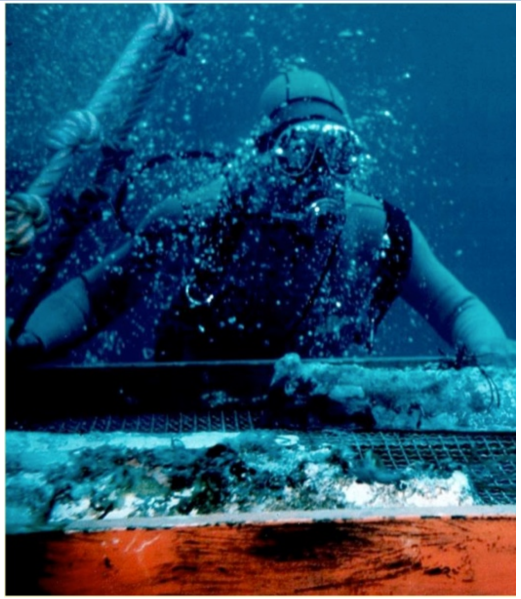
- new cleaning techniques developed at LNL;
- tumbling, electropolishing, chemical etching, magnetron plasma aimed at the removal of a thin layer of material (from 1 μm to 100 μm);





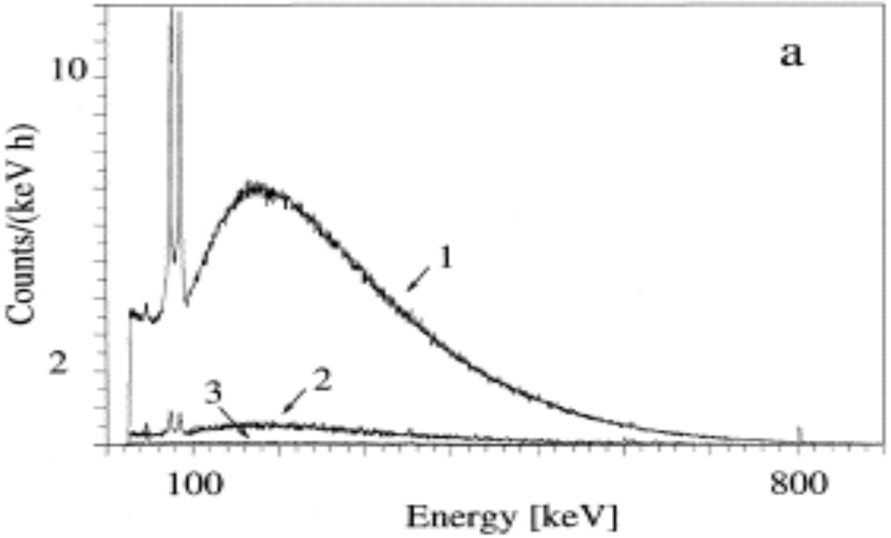
Roman Lead

- Ancient Roman lead bricks for low-activity shielding;
- Recovered in late '80s from shipwreck off Sardinian coast;
- Obtained through agreement between INFN and Italian historical society;
- 270 bricks, 33 kg each = 7 tons (after inscriptions removed);



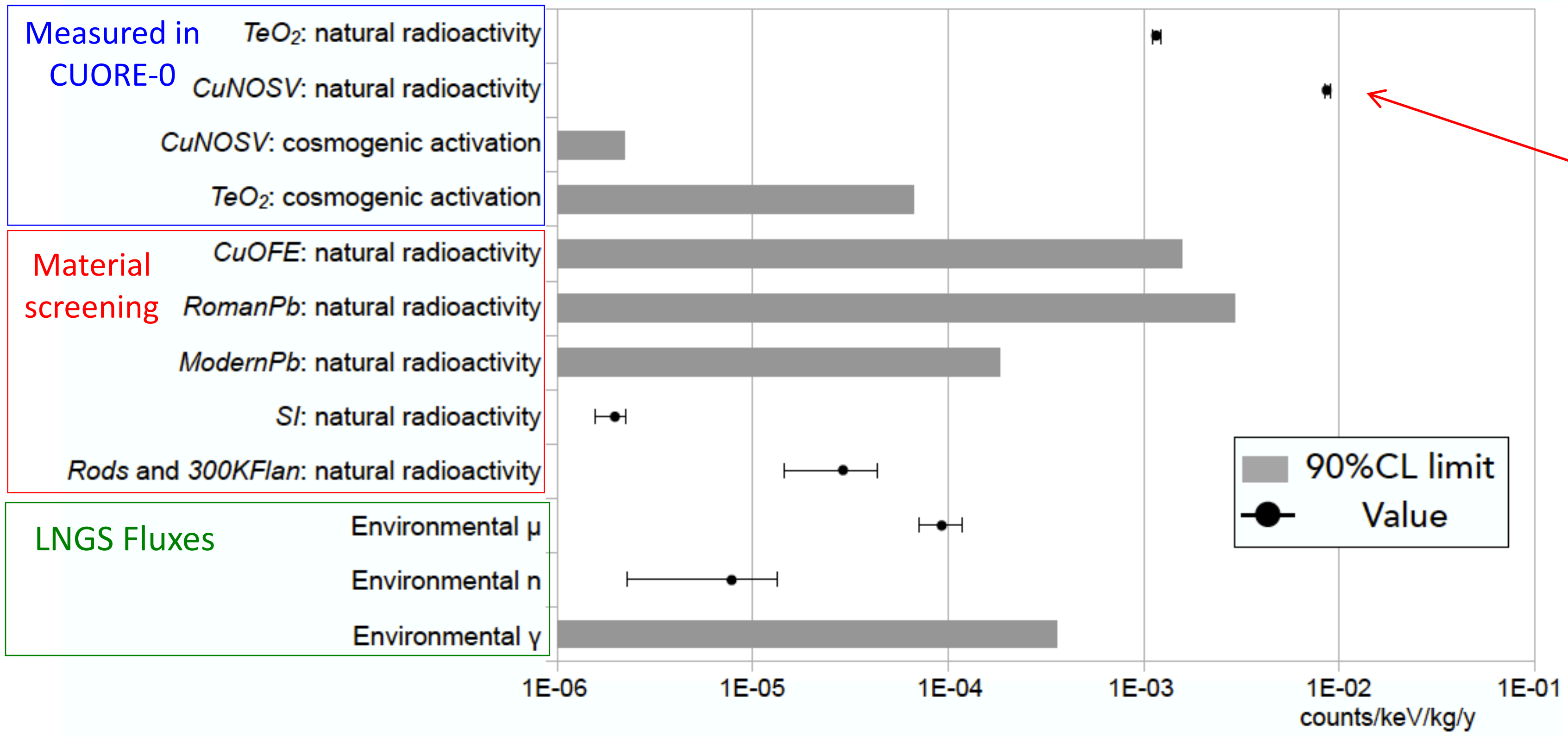
Normally Pb contains ^{210}Pb with 10-1000 Bq/kg (half life ~ 22 y)

^{210}Pb in roman Pb < 4 mBq/kg

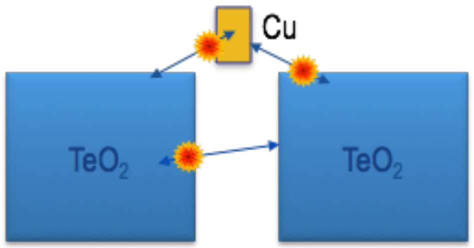


CUORE background projection

Main background index in the 0ν DBD region expected for the various components of CUORE



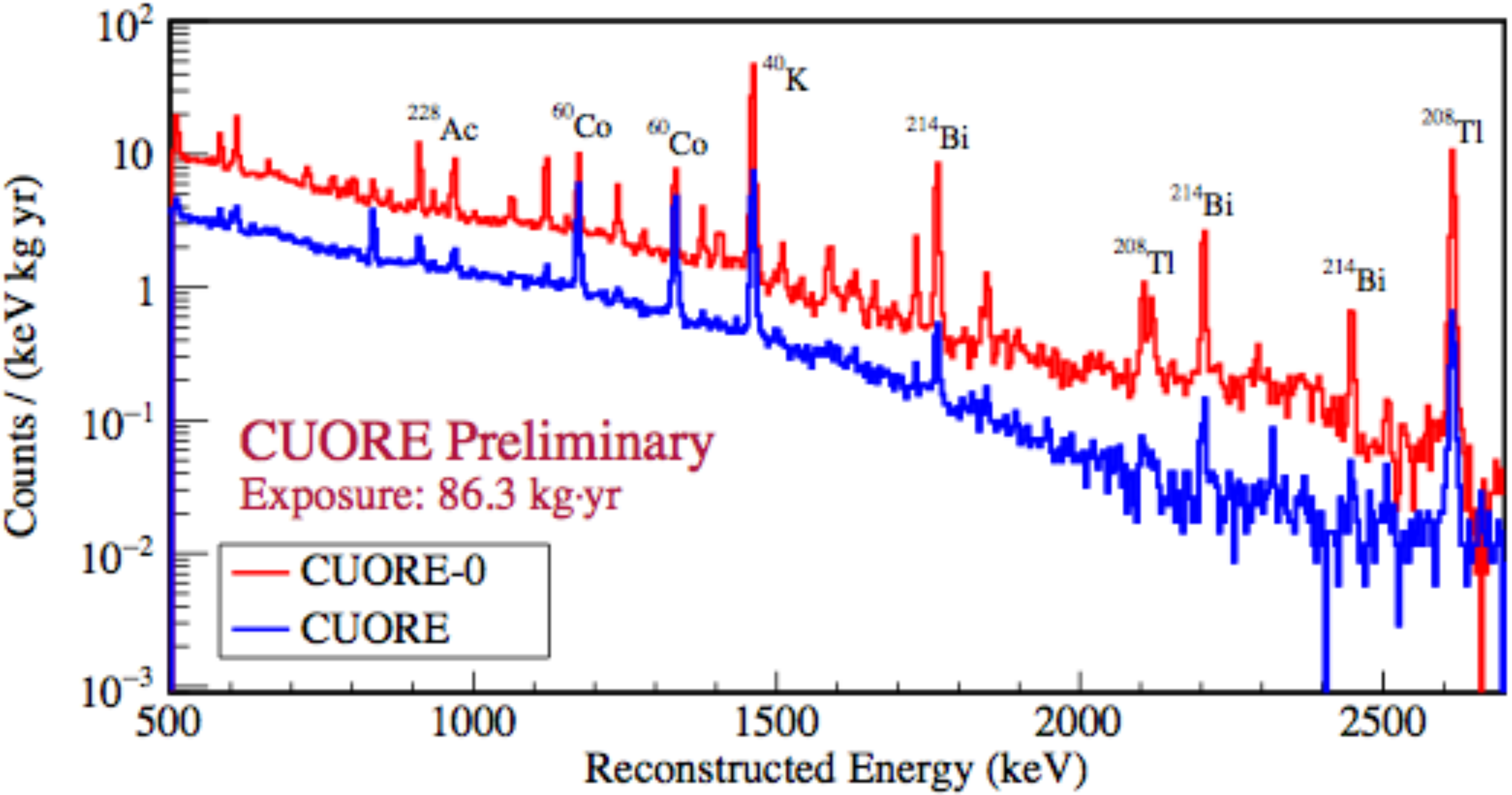
expected dominant contribution from the Cu of the towers structure

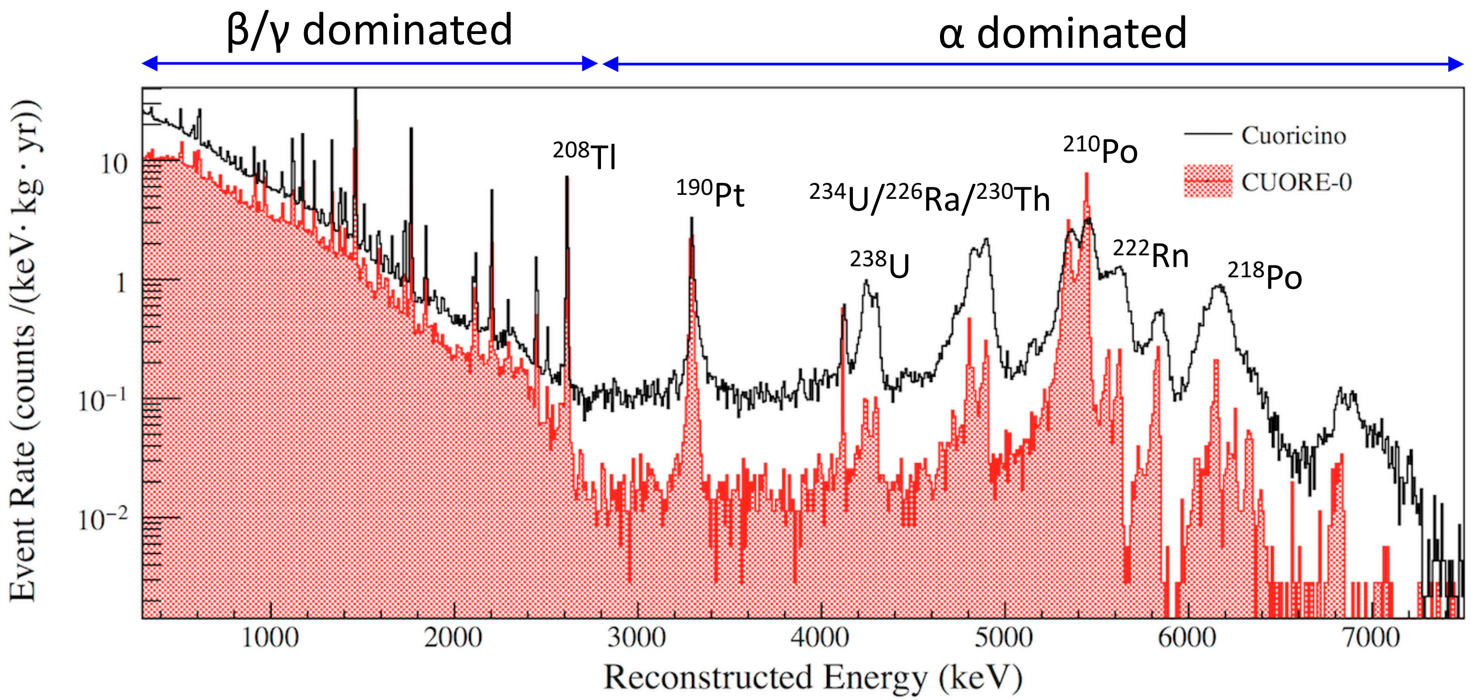


Projected total BI in the 0ν DBD region is consistent with CUORE background goal (10^{-2} counts/(keV•kg•yr)):

$$BI = (1.02 \pm 0.03(stat.)^{+0.23}_{-0.10}(syst.)) \cdot 10^{-2} \frac{counts}{kev \cdot kg \cdot yr}$$

Physics spectrum compared to CUORE-0 (γ region)





Comparison of the background in Cuoricino and CUORE-0

Background indexes (counts/(keV•kg•yr))

	0ν DBD region (2.47-2.58 MeV)	α region (2.7-3.9 MeV)
Cuoricino	0.169 ± 0.006	0.110 ± 0.001
CUORE-0	0.058 ± 0.004	0.016 ± 0.001

- Material cleaning: ^{238}U and ^{232}Th α lines reduced (~ factor of 7);
- Tower assembly in N_2 atmosphere: ^{238}U γ lines reduced (~ factor 2/3);
- Same Cuoricino cryostat: ^{232}Th γ lines not reduced;

Effective Majorana mass limit

Interpreting the combined half-life limit as a limit on the effective Majorana neutrino mass:

- framework of models where the 0ν DBD is mediated by an exchange of a light Majorana neutrino;

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Combined 90% limit:

$$m_{\beta\beta} < 110 - 520\ meV\ (exposure: 86.3\ kg \cdot yr)$$

Half-life limits:

- ^{130}Te: 1.5 × 10^{25} yr from this analysis PRL 120, 132501 (2018)
- ^{76}Ge: 8.0 × 10^{25} yr from PRL 120, 132503 (2018)
- ^{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)

Nuclear Matrix elements from:

- JHEP02 (2013) 025
- Nucl. Phys. A 818, 139 (2009)
- Phys. Rev. C 87, 045501 (2013)
- Phys. Rev. C 87, 064302 (2014)
- Phys. Rev. C 91, 034304 (2015)
- Phys. Rev. C 91, 024613 (2015)
- Phys. Rev. C 91, 024309 (2015)
- Phys. Rev. Lett. 105, 252503 (2010)
- Phys. Rev. Lett. 111, 142501 (2013)

$g_A \cong 1.27$