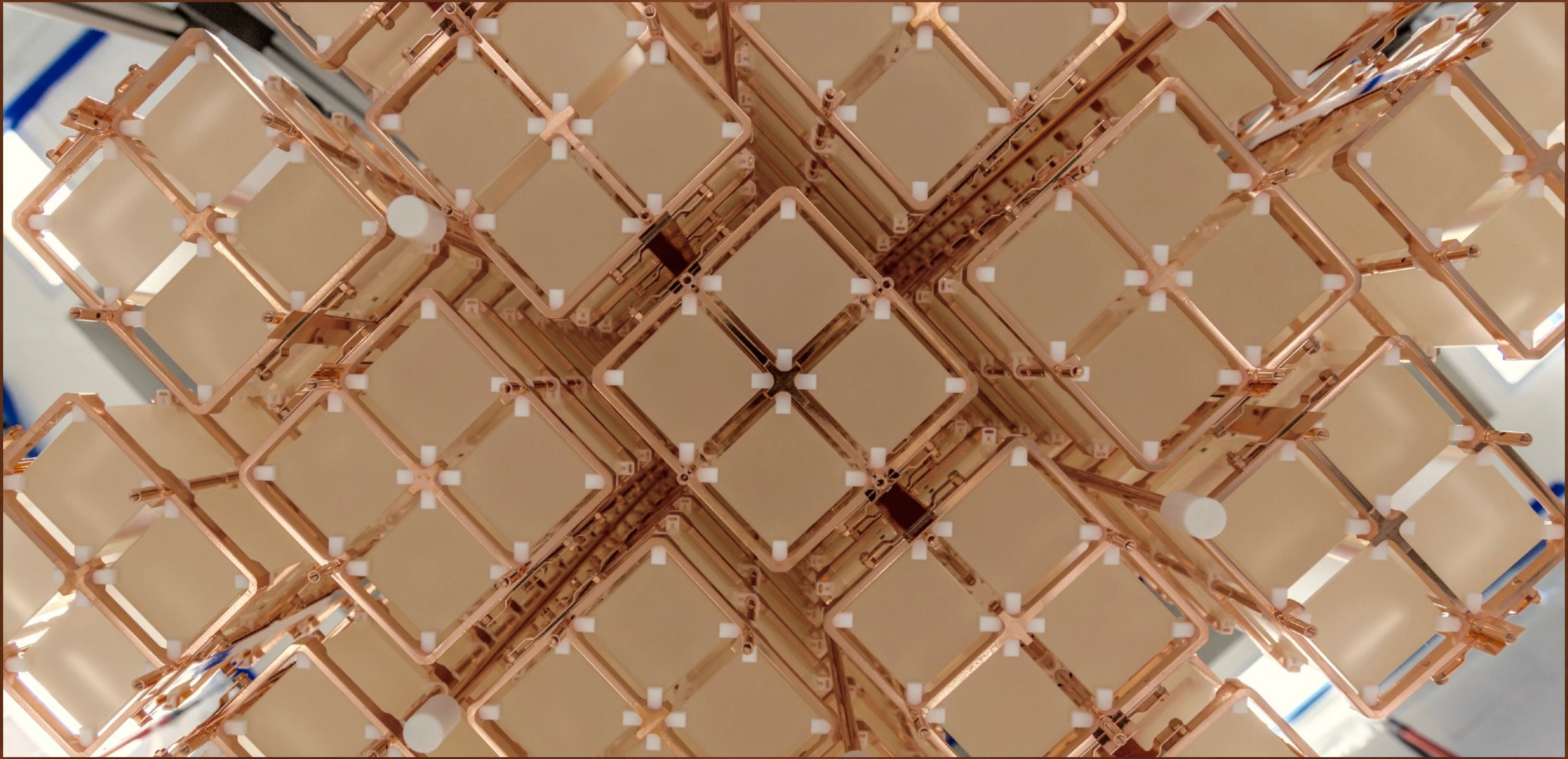
CUORE

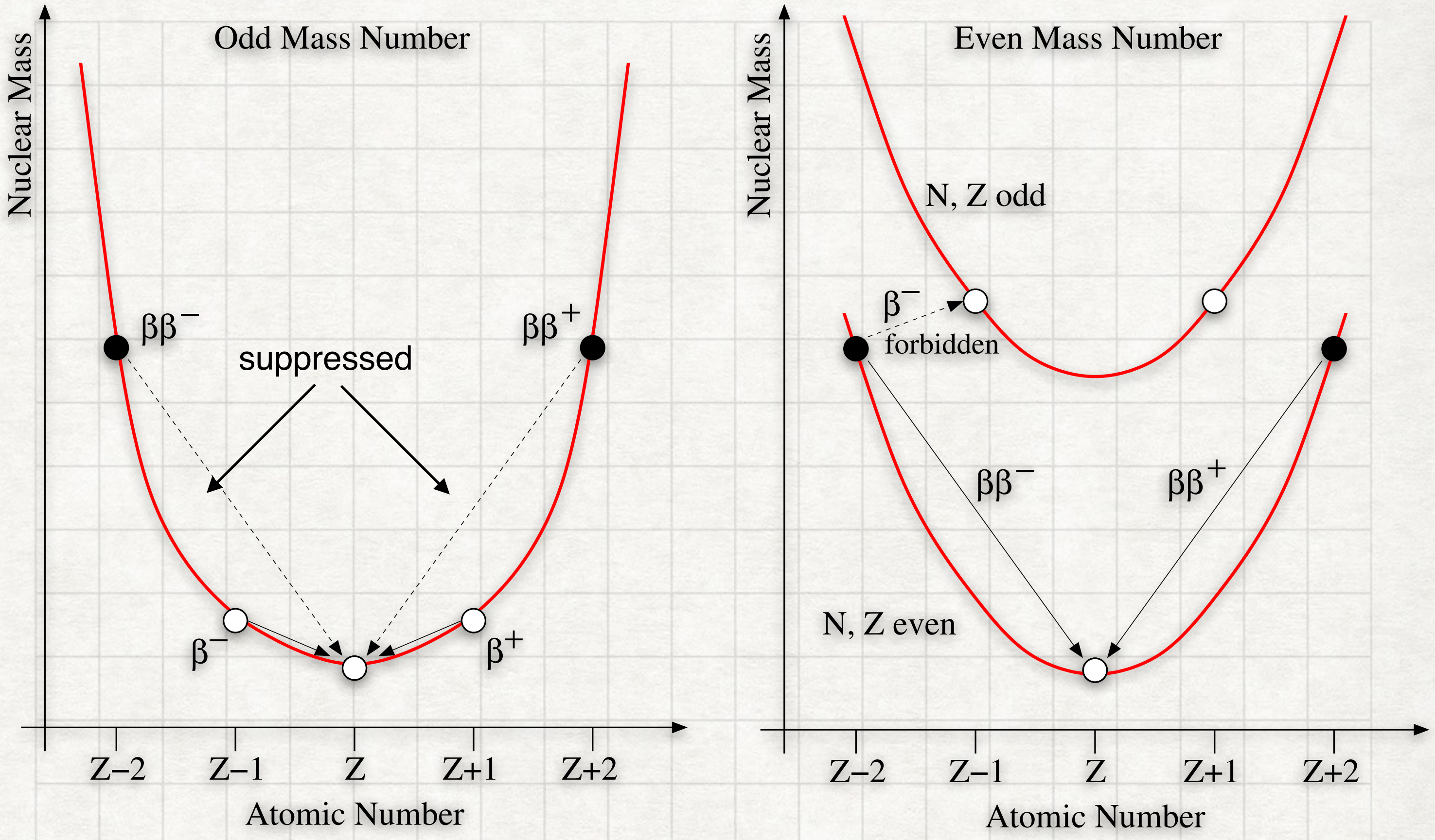
Laura Marini, Università degli studi di Genova and INFN
on the behalf of the Cuore collaboration

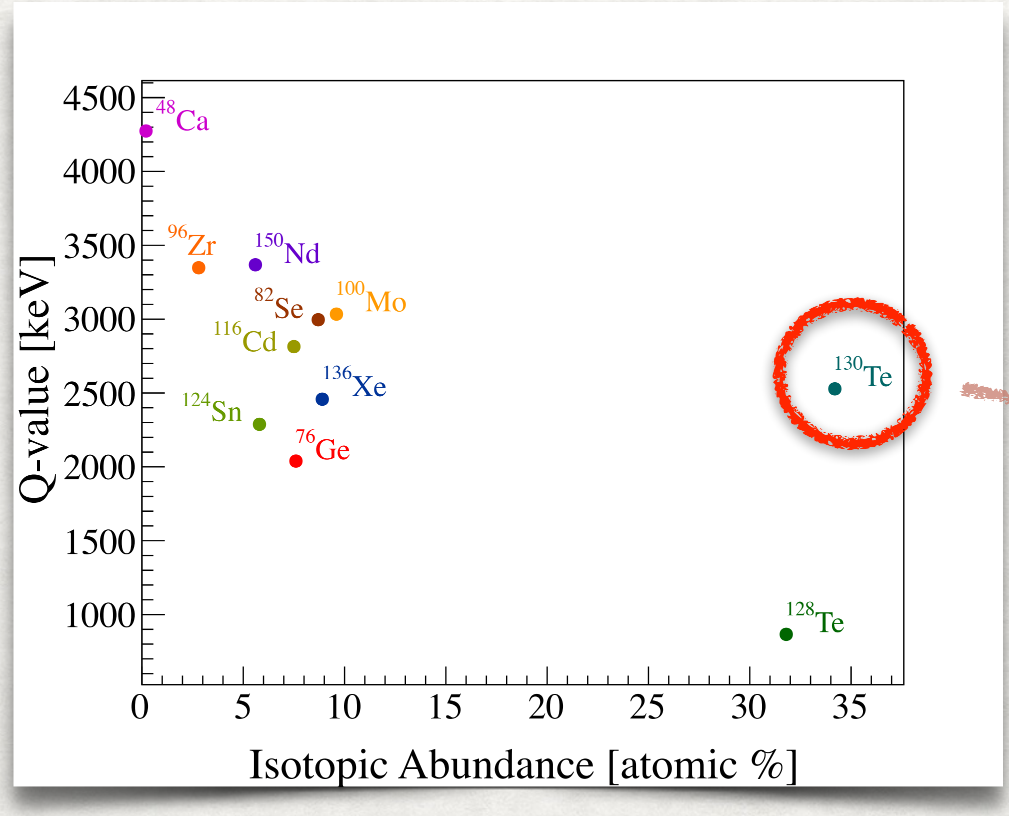


WHAT

DO WE WANT TO SEE

Double Beta Decay is a second order weak interaction, only directly observable for few nuclei, for which the standard Beta Decay is suppressed or forbidden (even - even nuclei)





^{130}Te is chosen for:

- its high isotopic abundance (34.17%)
- ^{130}Te within the detector absorber of TeO_2 (high detection efficiency)
- Q-value of 2527.515 ± 0.013 keV in a region with low beta/gamma background
- reproducible growth of high quality crystals

WHAT

DO WE WANT TO SEE

Why 0vBB?

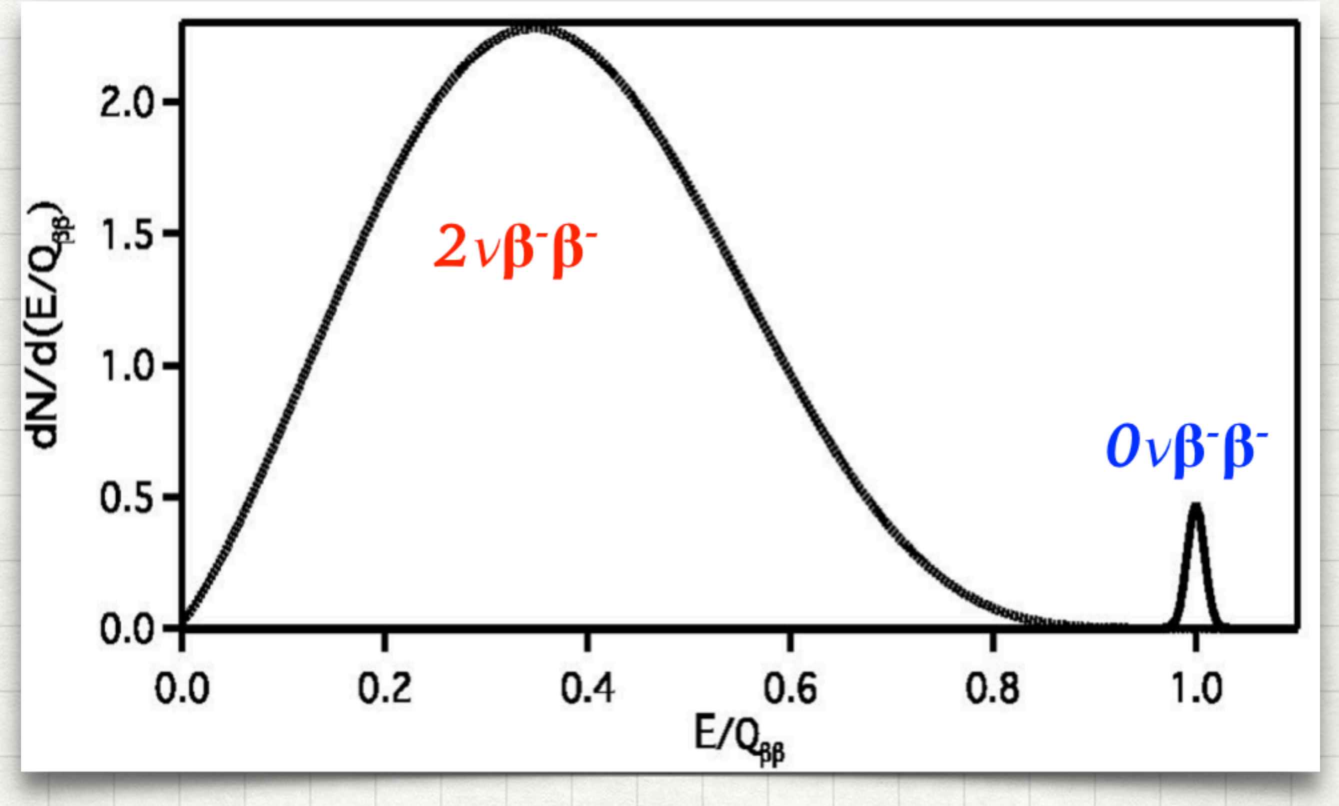
- lepton number violation
- Majorana nature of neutrinos
- constrain the absolute neutrino mass hierarchy and scale

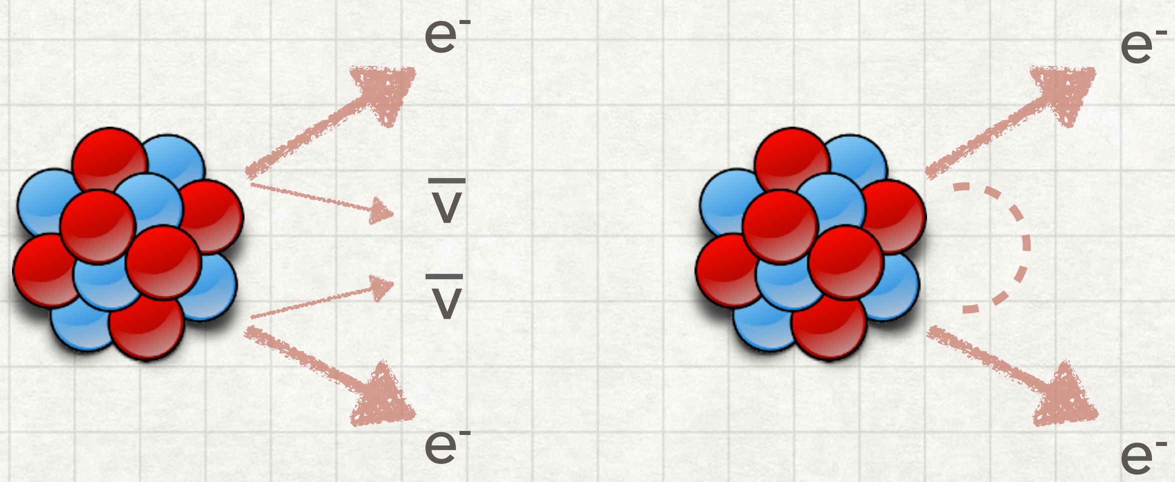
Signature

- peak at the Q-value of ^{130}Te ßß decay (2527.515 ± 0.013)keV

Never observed to date

- Current 0vBB half-life lower limits are in the range 10^{22} – 10^{26} y





CHALLENGES

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{ln2}{n_\sigma}\,\frac{N_A\, i\, \varepsilon}{A}\, f(\Delta E)\boxed{\sqrt{\frac{M\, t}{B\, \Delta E}}}$$

big exposure (mass x time)

- 988 TeO_2 crystal with isotopic abundance of 34.167% for a total mass 206 kg of active material
- foreseen 5 years of data taking

Goal: 5 years

high energy resolution

- noise reduction techniques
- temperature stability
- fine tuning of detectors parameters to optimize the signal to noise ratio

Goal: 5 keV FWHM

low background

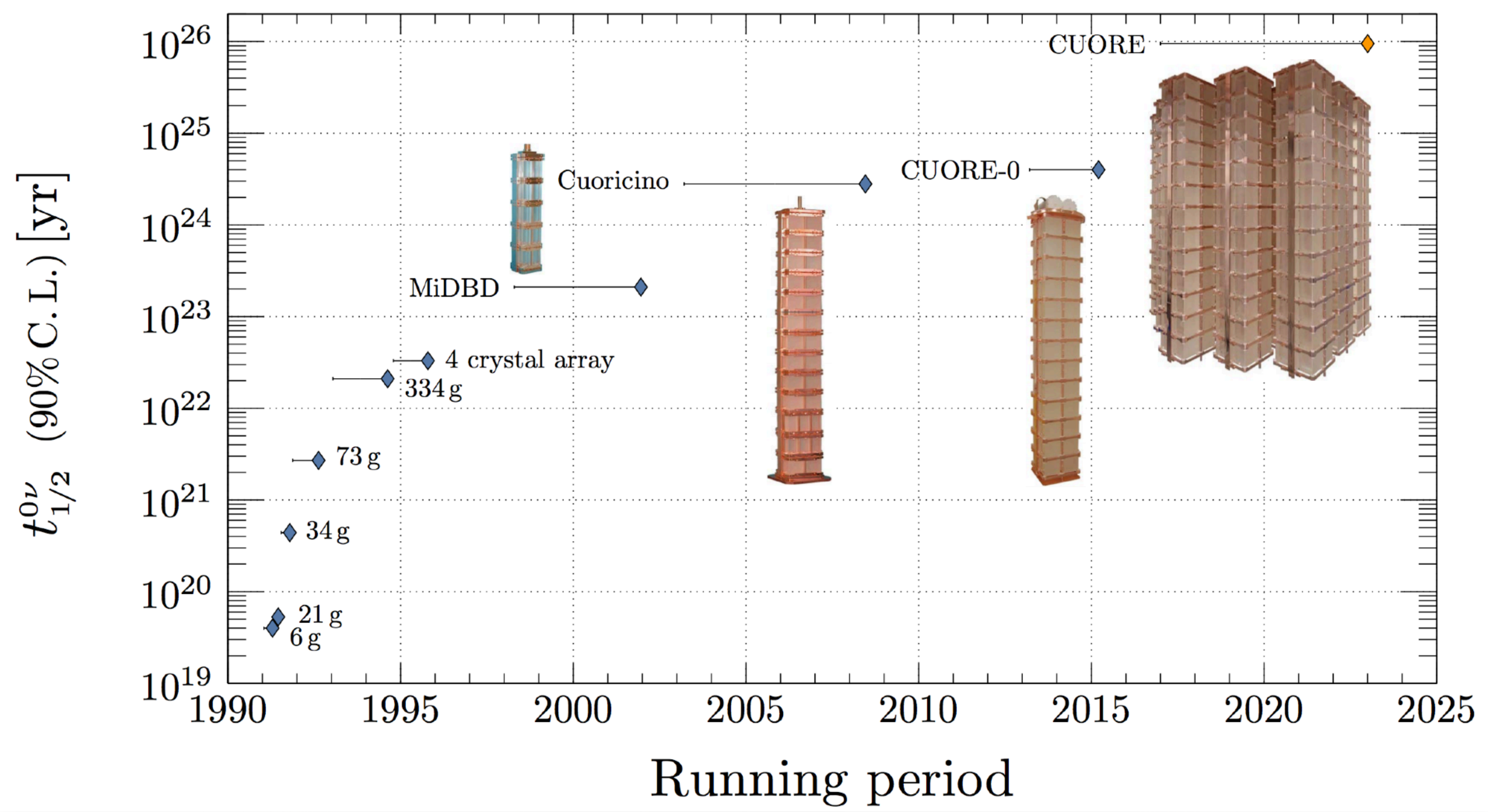
- strict radiopurity selection on materials
- low background assembly environment
- passive shields from external and cryostat radioactivity

Goal: 0.01 counts/keV/kg/yr

Goal $T_{1/2}$ (90% C.L.) > 9×10^{25} yr
Goal $\langle m_{\beta\beta} \rangle$ 56 - 160 meV

European Physical Journal C 77.532 (2017)
arxiv: 1705.10816

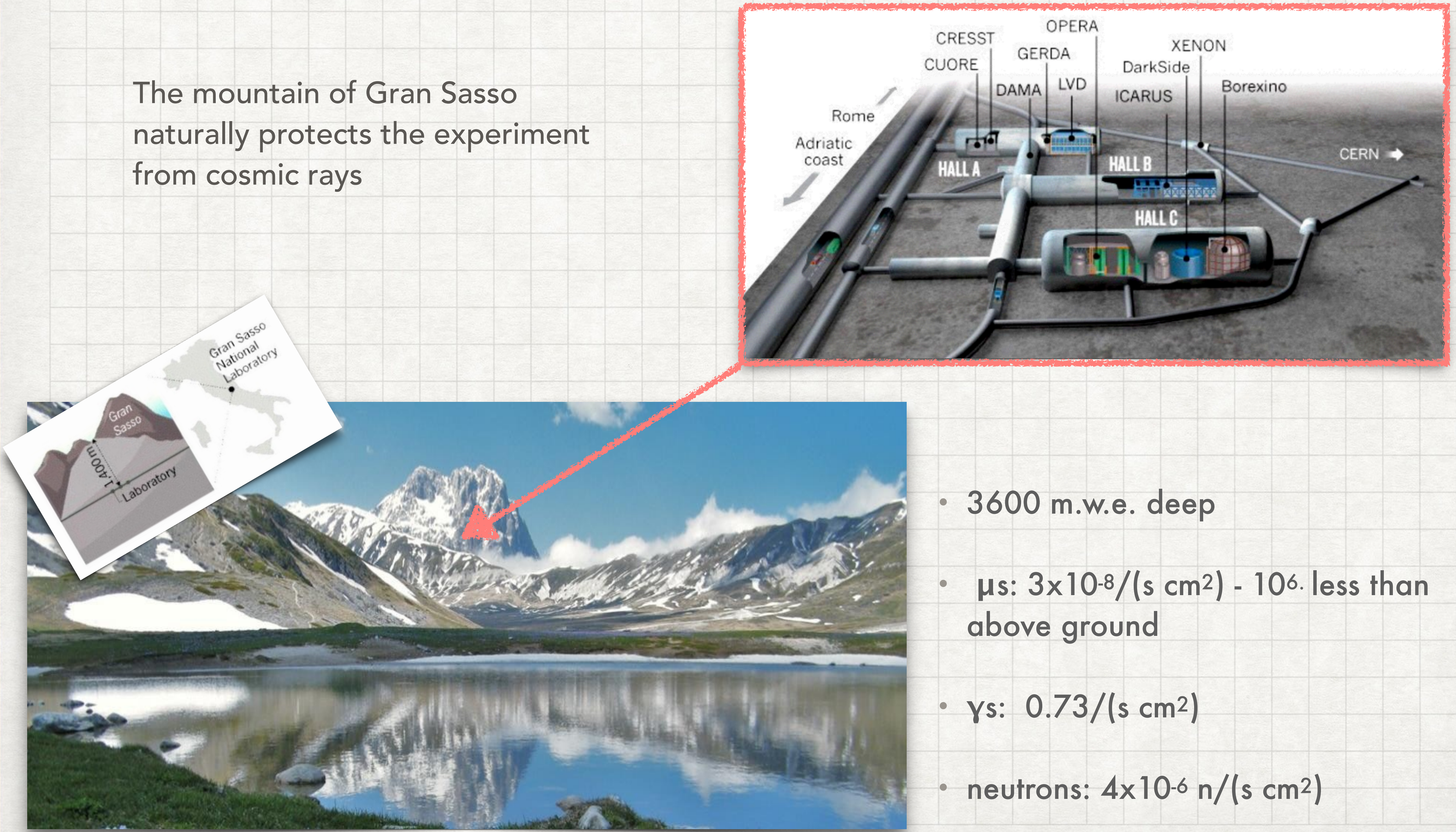
CUORE HISTORY



WHERE

LNGS - GRAN SASSO UNDERGROUND LABORATORY (ITALY)

The mountain of Gran Sasso naturally protects the experiment from cosmic rays



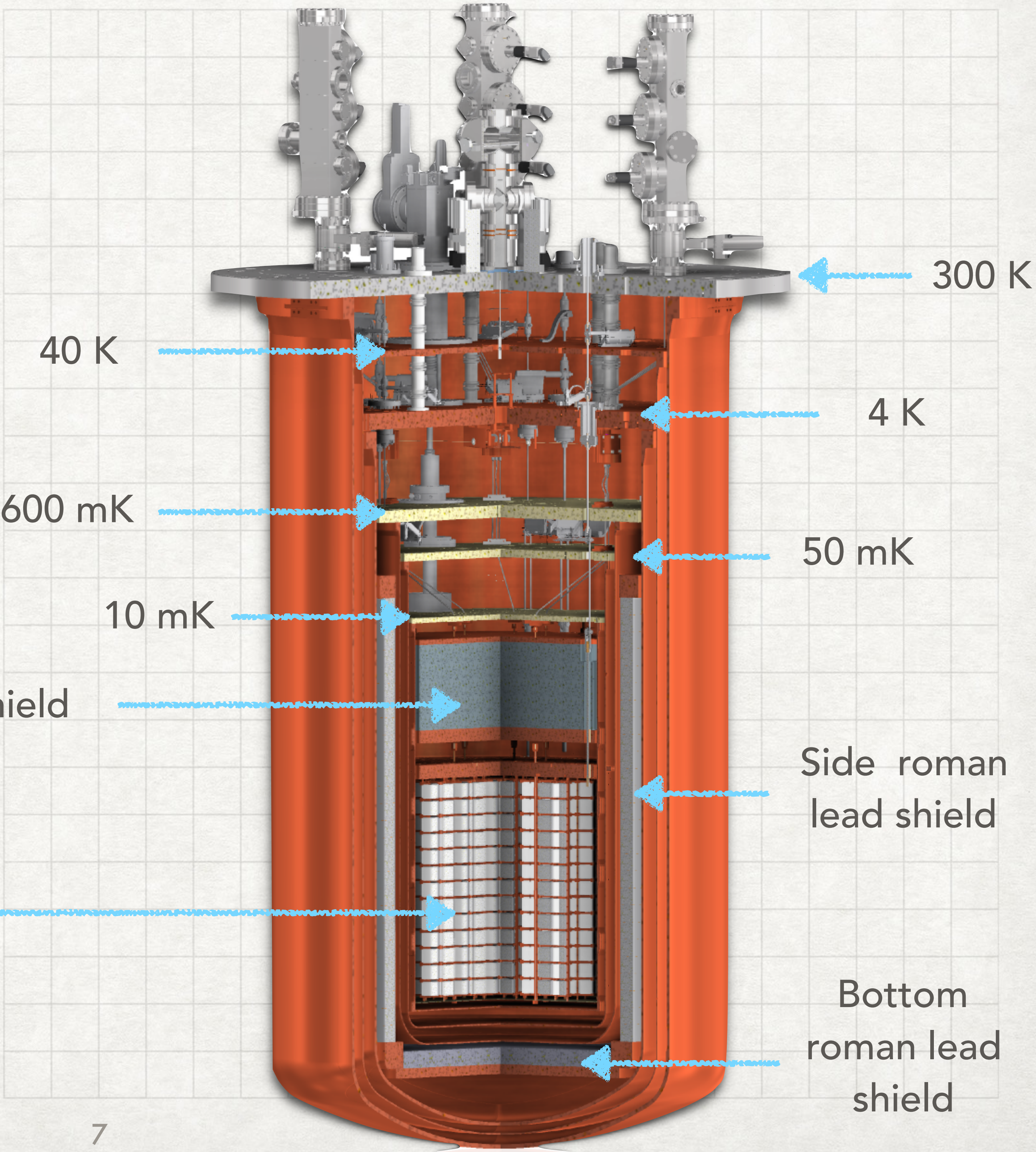
- 3600 m.w.e. deep
- μs: $3\times10^{-8}/(\mathrm{s\ cm}^2)$ - 10^{6} less than above ground
- γs: $0.73/(\mathrm{s\ cm}^2)$
- neutrons: 4×10^{-6} n/(s cm^2)

CUORE

CRYOGENIC UNDERGROUND OBSERVATORY FOR RARE EVENTS

The CUORE detector is hosted in a cryogen-free cryostat:

- Mass to be cooled < 4K: ~15 tons (Pb, Cu and TeO_2)
- Operating temperature 10 mK
- Designed to guarantee extremely low radioactivity and low vibrations environment



300 K

40 K

4 K

600 mK

50 mK

10 mK

Top lead shield

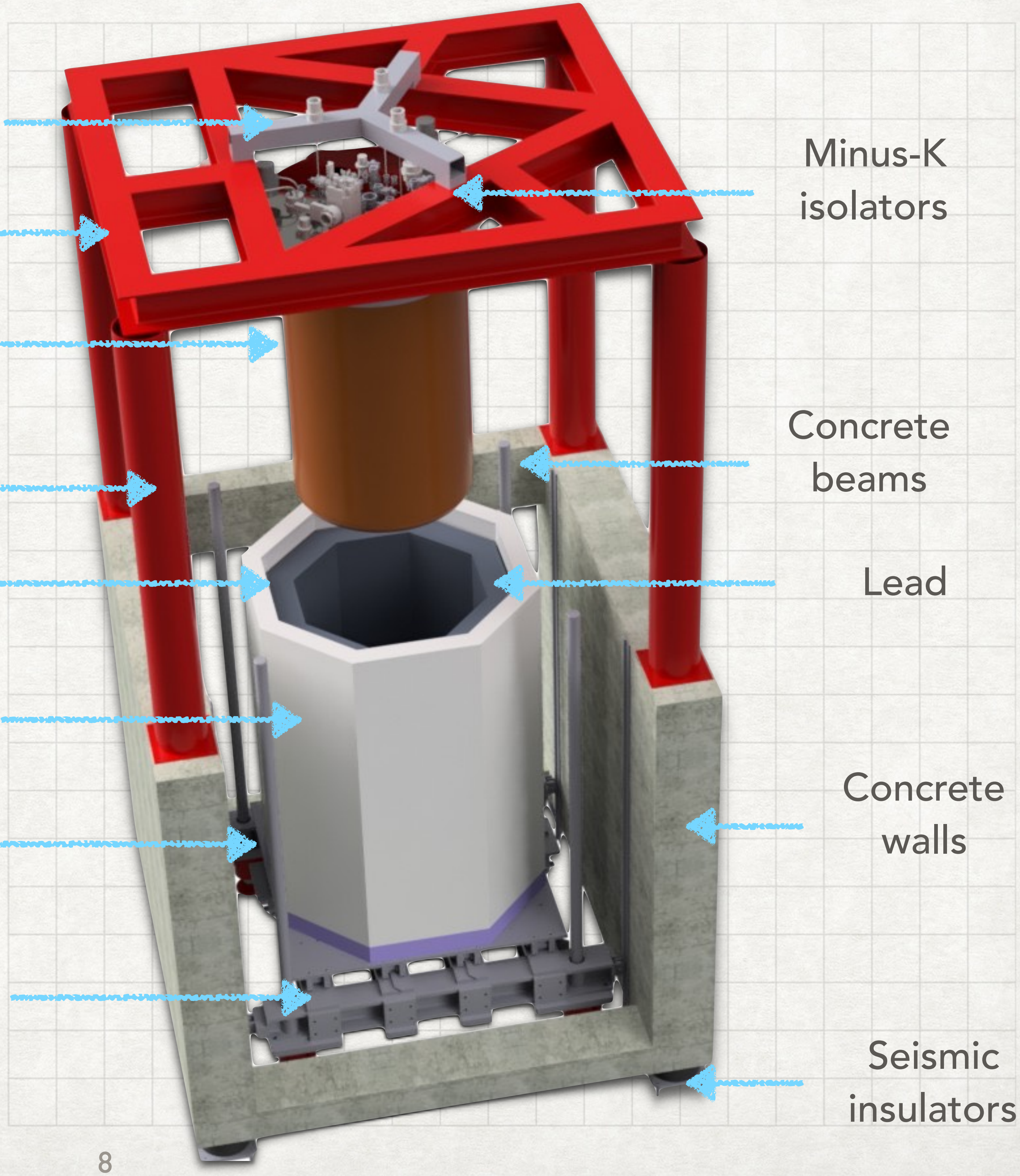
Side roman lead shield

988 TeO_2 crystals (arranged in 19 towers with 13 floors each, 52 5x5x5 cm^3 TeO_2 crystals per tower)

Bottom roman lead shield

CUORE

CRYOGENIC UNDERGROUND OBSERVATORY FOR RARE EVENTS



Y- beam

Main Support Plate

Cryostat

Sand-filled columns

H_3BO_3 panels

Polythylene

Screwjacks

Movable platform

Minus-K isolators

Concrete beams

Lead

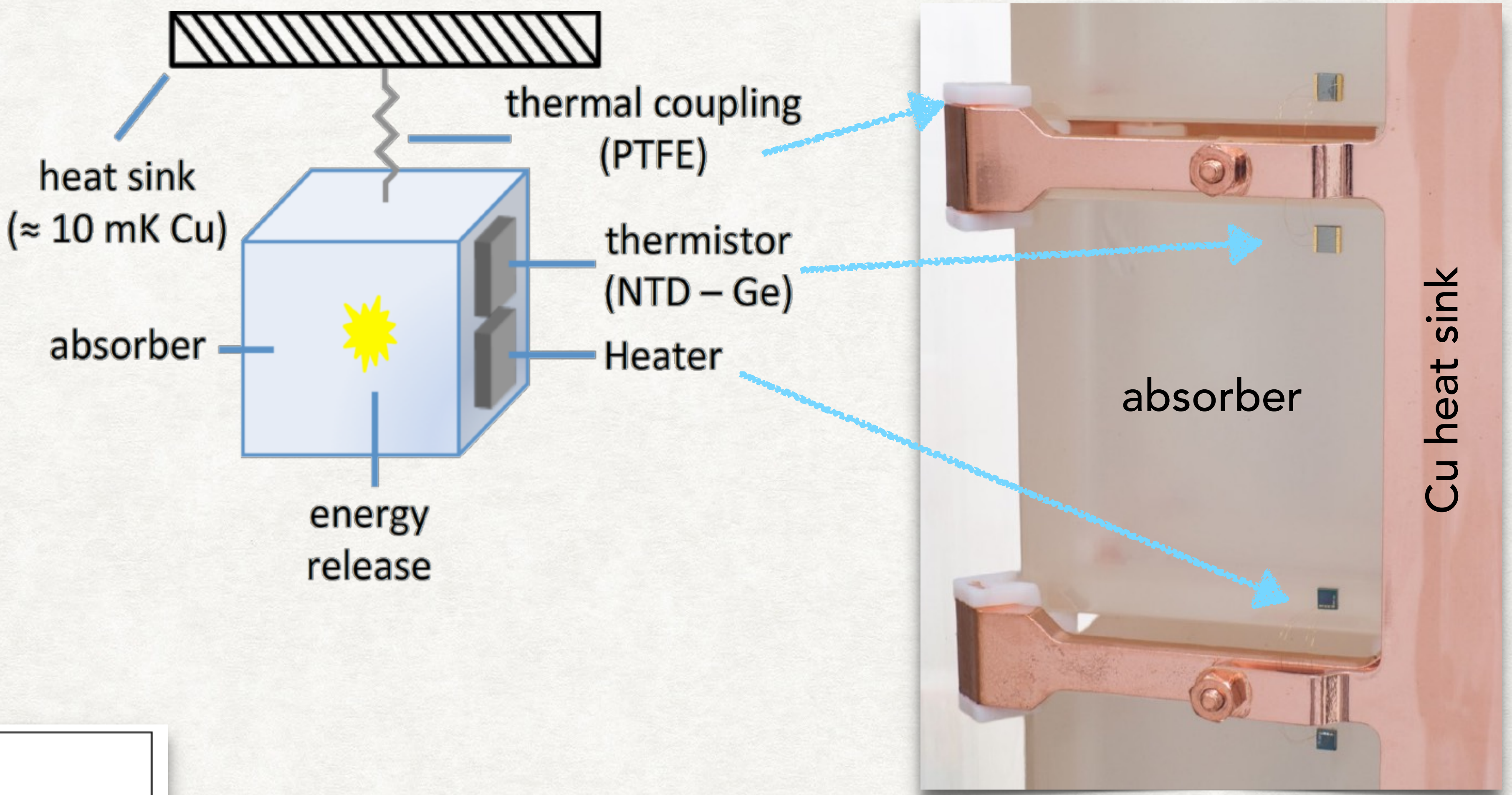
Concrete walls

Seismic insulators

HOW

WE MEASURE PARTICLE INTERACTION WITH BOLOMETERS

A particle interaction in the absorber causes an increase in temperature, measured by the thermistor



heat sink
(≈ 10 mK Cu)

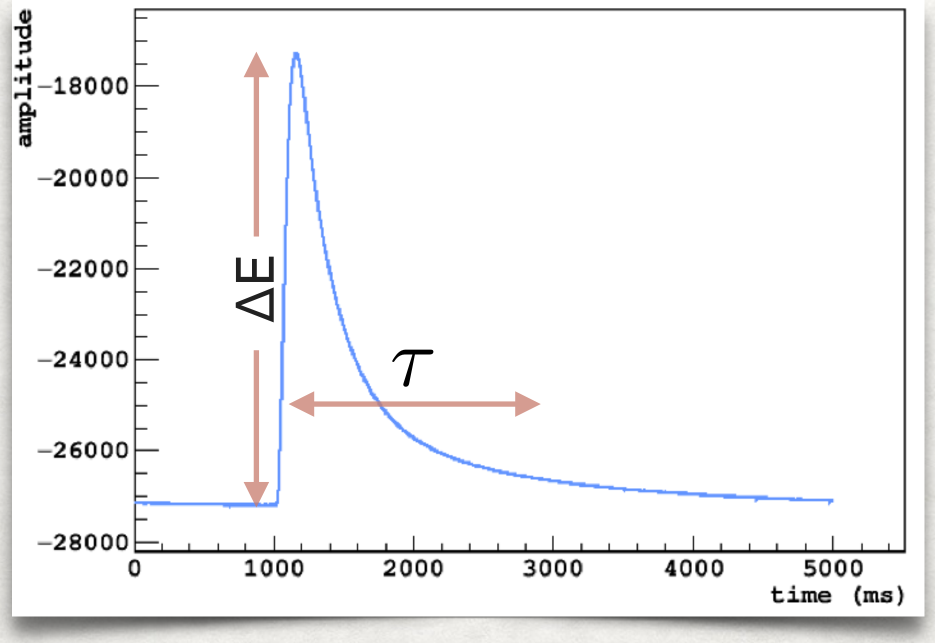
thermal coupling
(PTFE)

thermistor
(NTD – Ge)

Heater

absorber

energy
release



$$\Delta T = \frac{\Delta E}{C} \sim \frac{100\mu K}{MeV}$$

$$\tau = \frac{G}{C} \sim 1s$$

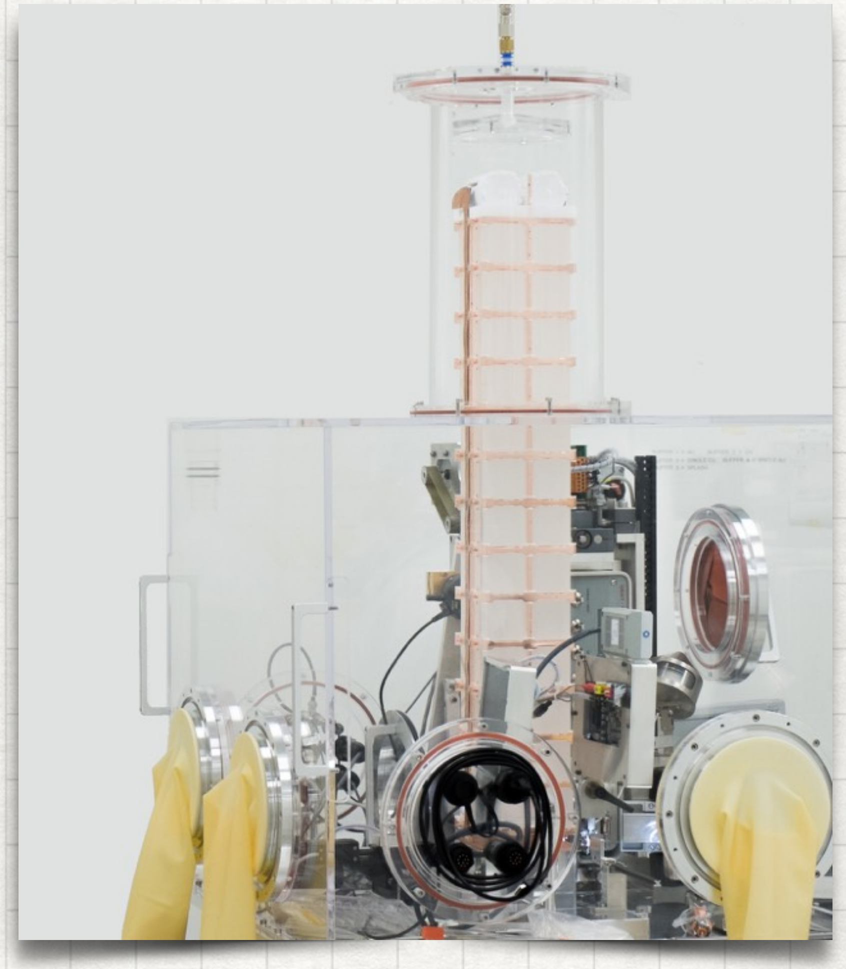
$$C(T) \propto T^3$$

$$R(T) = R_0 e^{\sqrt{T_0/T}}$$

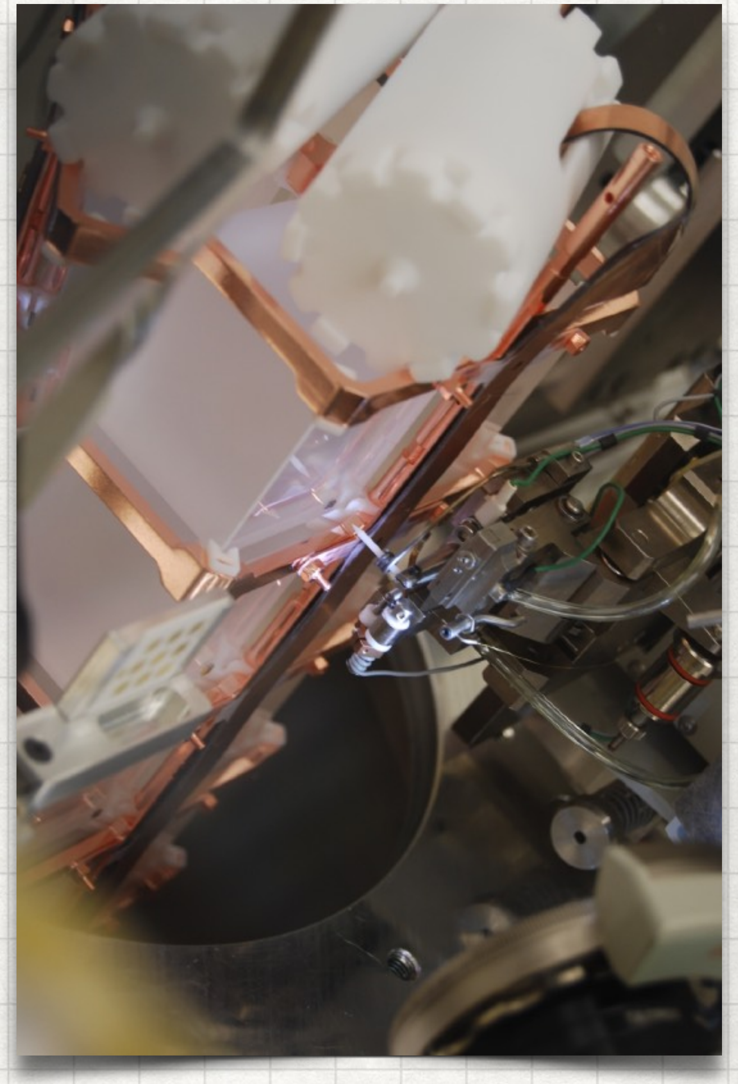
C: absorber capacity
ΔT: temperature variation
ΔE: energy deposition
G: thermal conductance
t: signal decay time

DETECTOR

SENSOR GLUING, TOWER ASSEMBLY AND SENSORS BONDING



Tower assembly performed inside a clean room, using glove boxes under N_2 atmosphere

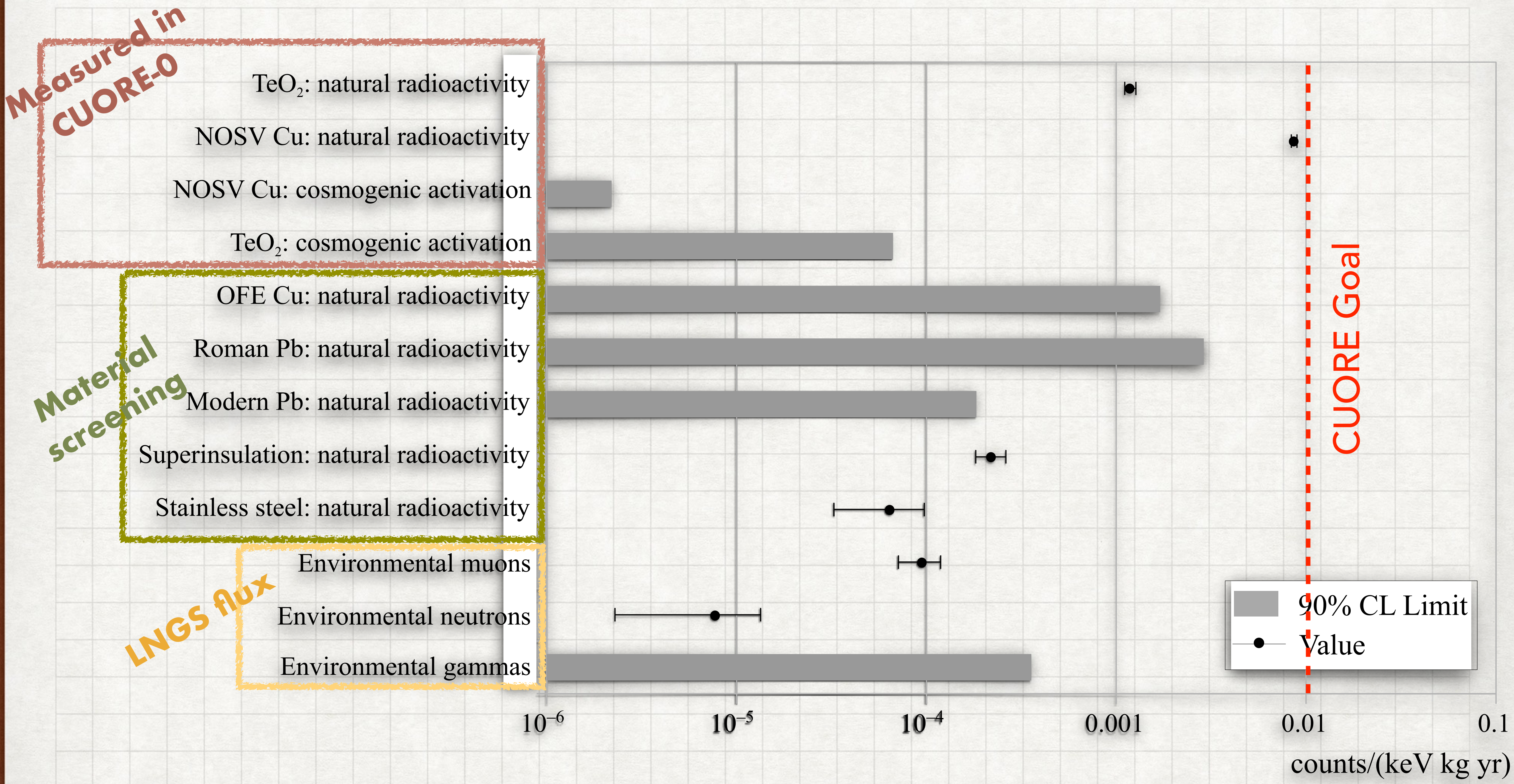


Bonding

The 19 towers have been stored in dedicates cases under N_2 atmosphere

Nuclear Instruments and Methods A 768, 130-140 (2014)
arxiv:1405.0852

BACKGROUND BUDGET



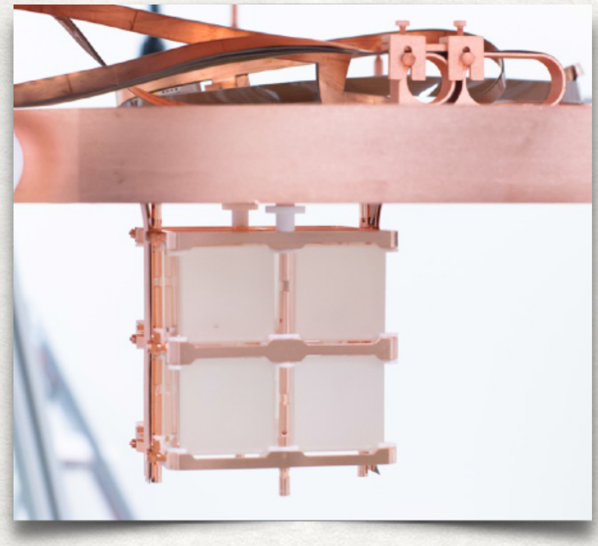
European Physical Journal C 77, 543 (2017)
arXiv:1704.08970

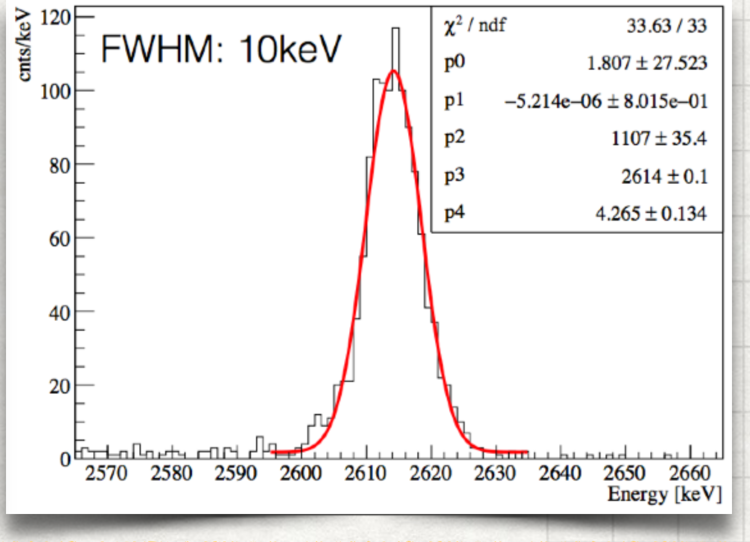
CUORE COMMISSIONING

CRYOGENIC SYSTEM

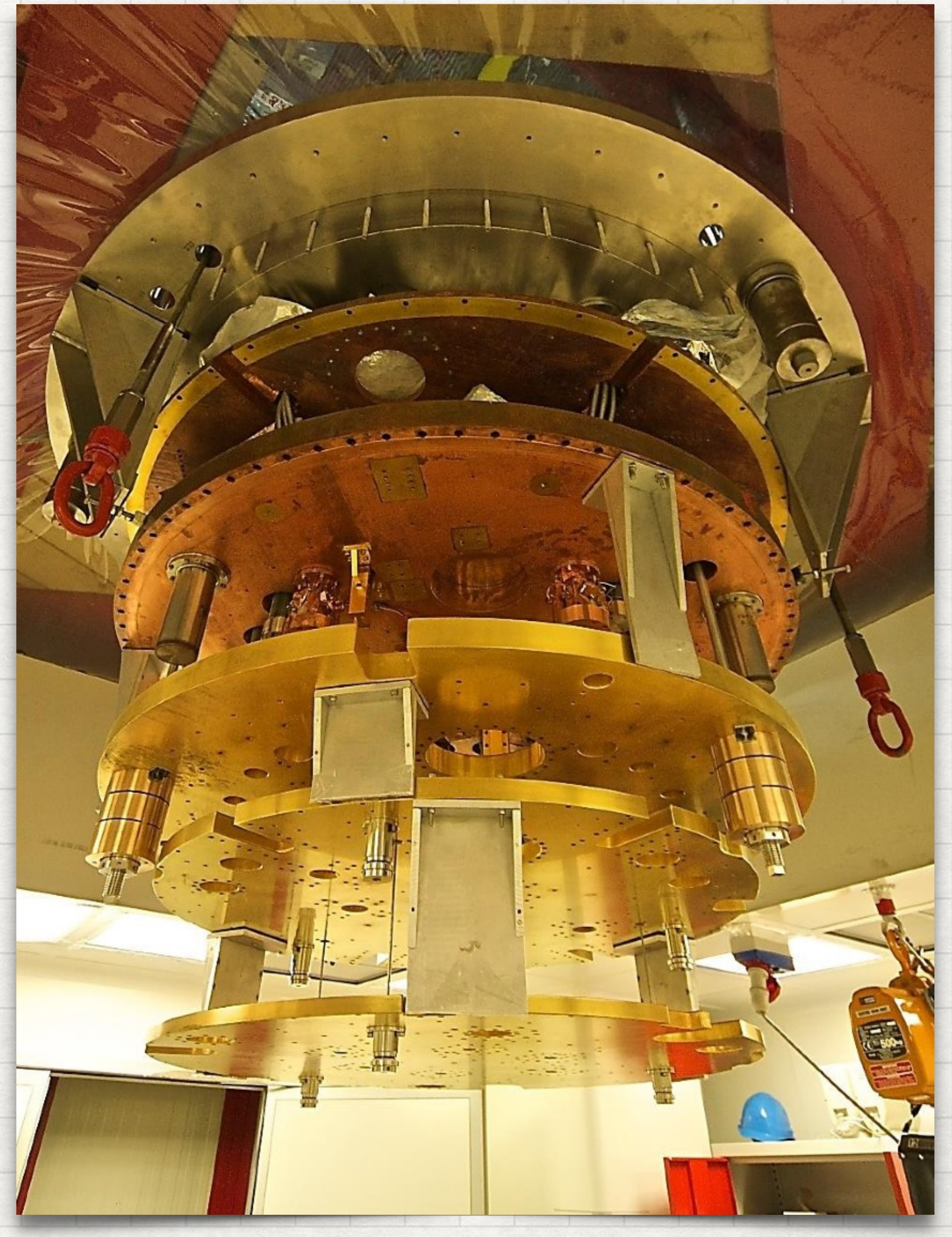
Commissioning completed in March 2016:

- Stable base temperature @ 6.3mK
- Cooling power: > 3μW @10mK
- Test of the full detector readout chain (electronics, DAQ) and temperature stability with the Mini-tower (8 crystal tower)



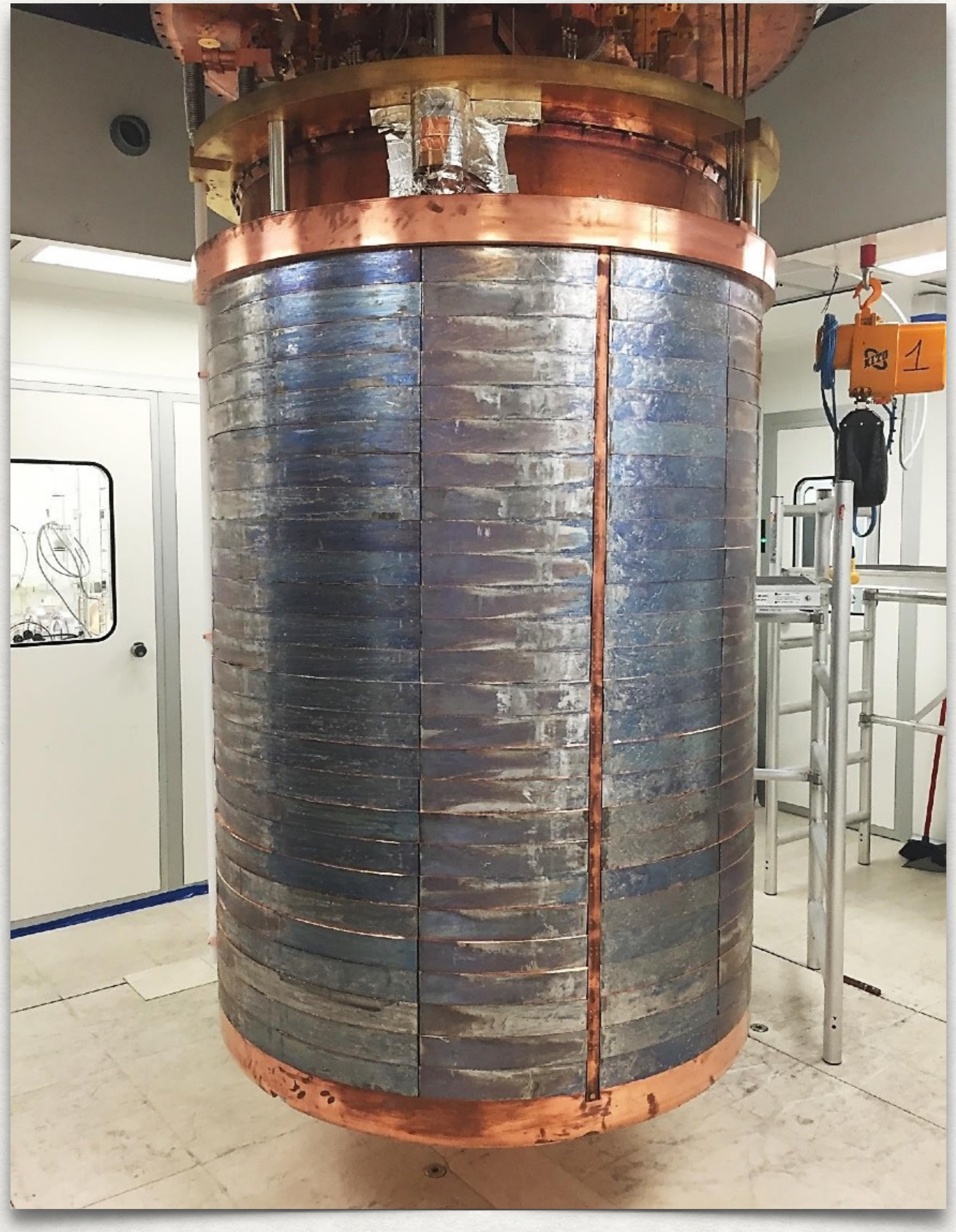


Note: the resolution of the minitower was obtain without any detector or electronic optimization



CUORE COMMISSIONING

ROMAN LEAD SHIELD

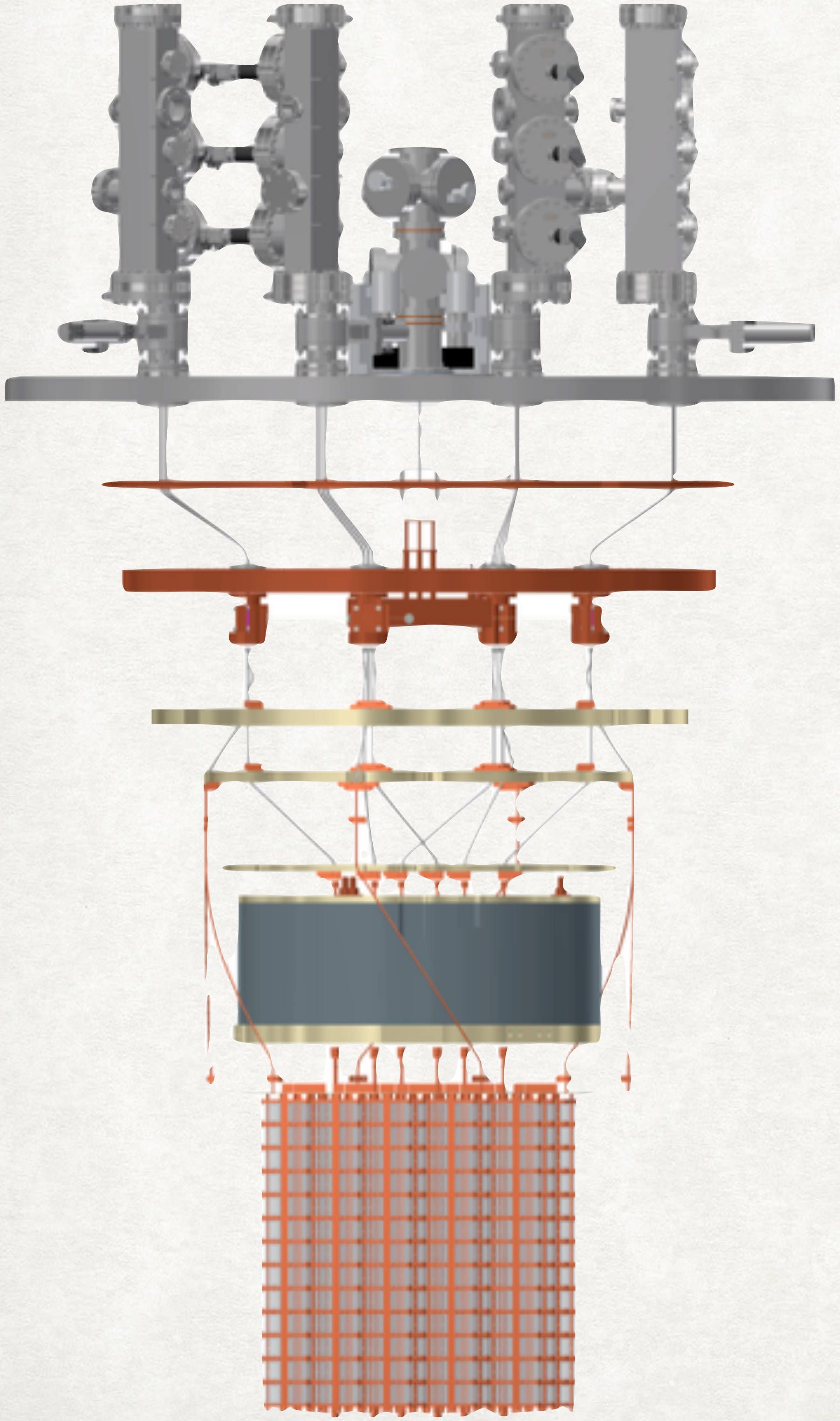


Lateral and bottom shielding with 6cm - thick ^{210}Pb - depleted roman lead

The ingots stayed under water for centuries, loosing most of their radioactive component (es. cosmogenic activated lead isotopes)

The ingots have been melted in a clean environment without the using any additive that could have contaminated the lead during the melting process

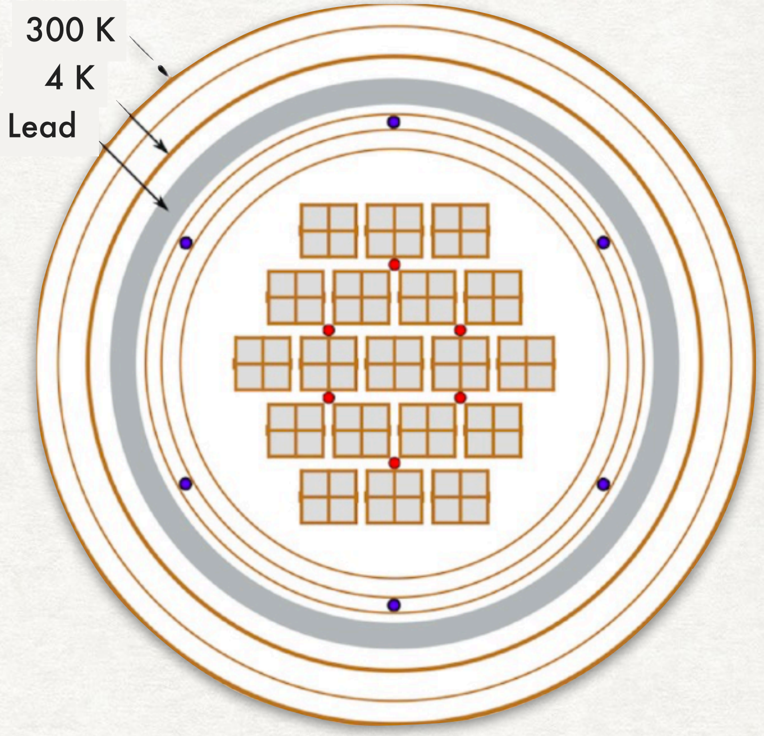
CALIBRATION SYSTEM

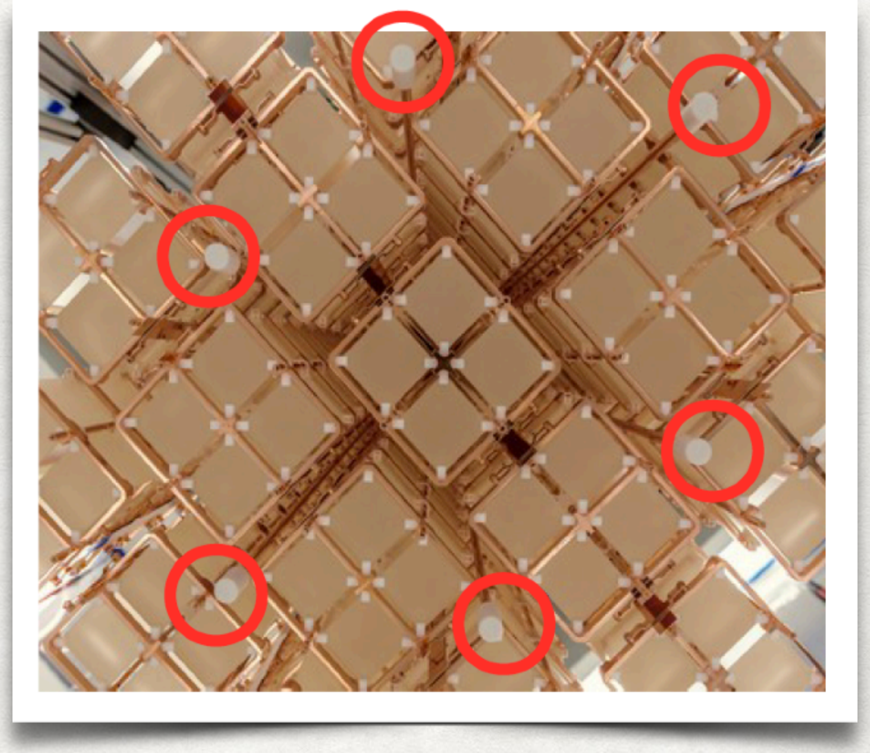


A series of tubes in the cryostat guide 12 strings that can be inserted within the detector towers.

- the strings contain ^{232}Th γ-ray sources that produce peaks from 239 keV to 2615 keV
- Usually these strings are kept outside the detector and lowered once a month for calibration
- Outer strings have a higher activity in order to compensate for the two inner cryostat Cu vessels

Nucl. Instrum. Methods A 844 (2017) 32-44
arXiv:1608.01607v2

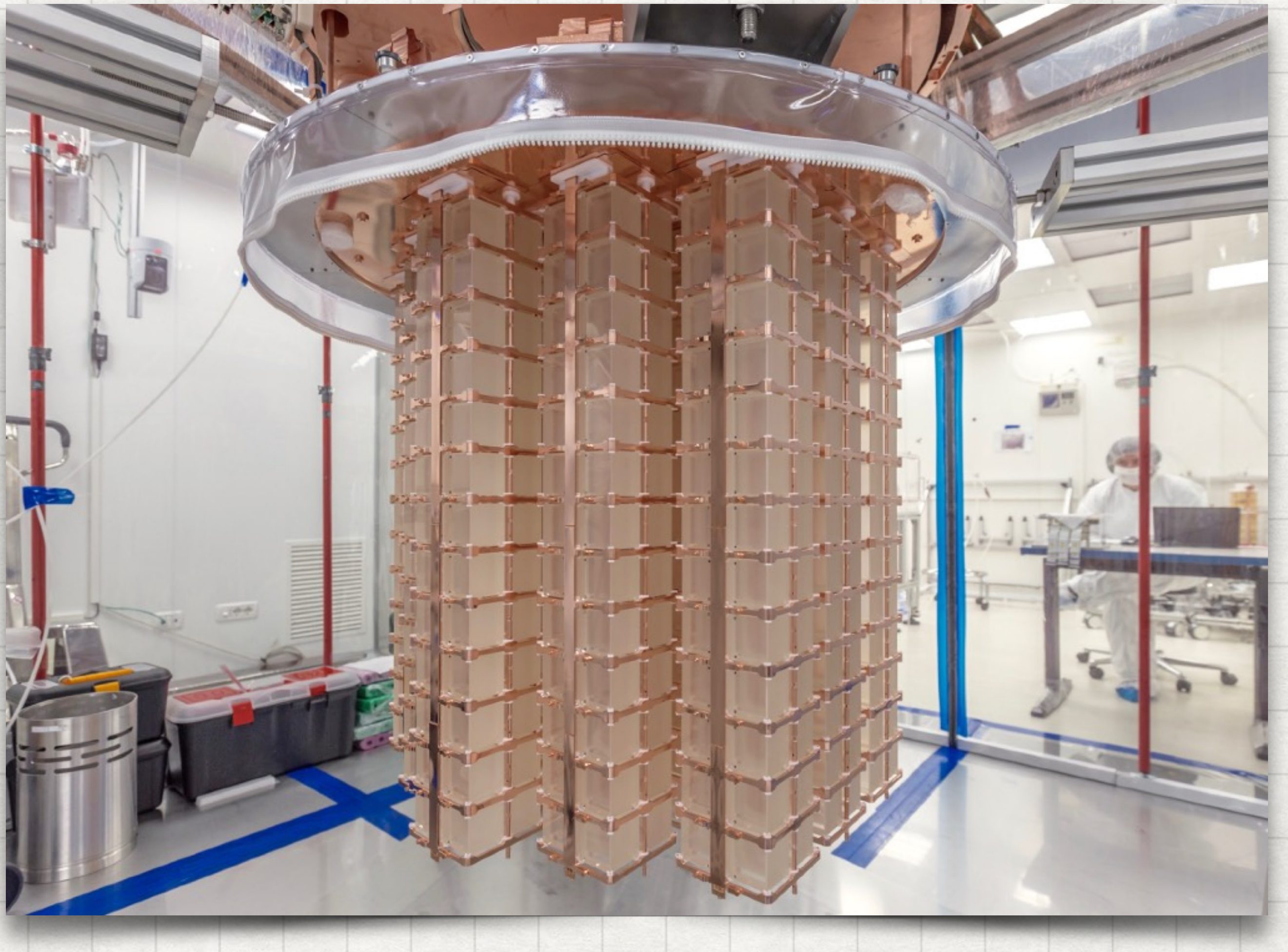




CUORE COMMISSIONING

TOWERS INSTALLATION

towers installation
July - August 2016



The 19 towers were installed in a radon free clean room.
It took about one month.

CUORE COOL DOWN

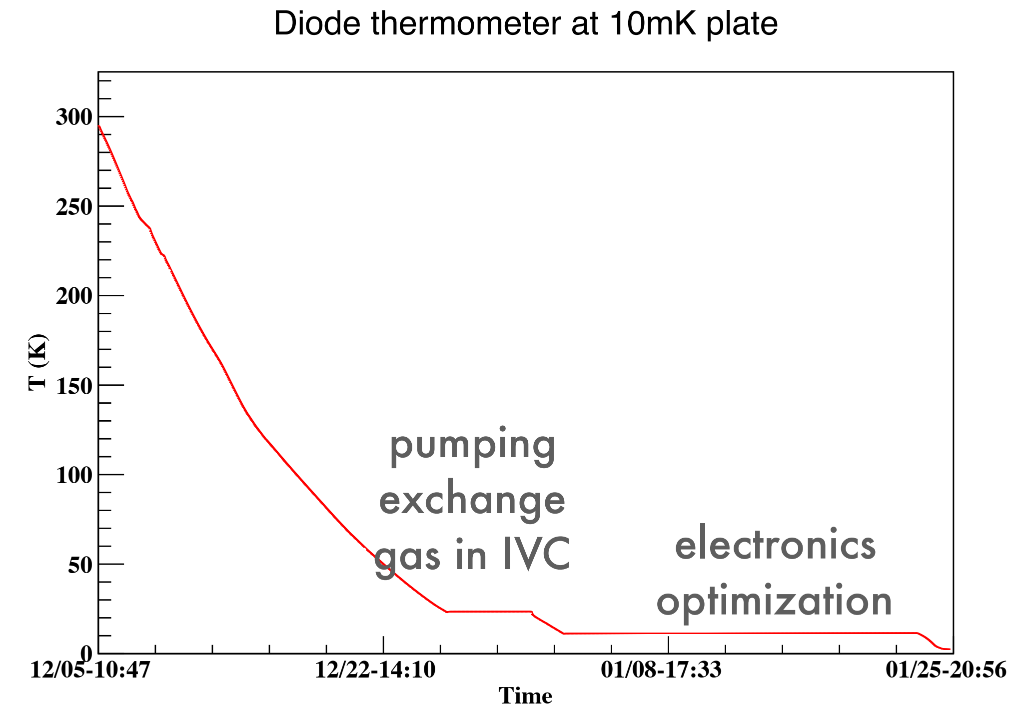
The cool down of the cryostat started in December 2016

First phase with dedicated fast cooling system, introduction of He exchange gas prior to the start of pulse tubes, then pulse tubes only.

Last phase after the pause dedicated to electronics optimisation was achieved with the dilution unit, down to base temperature (~7mK).

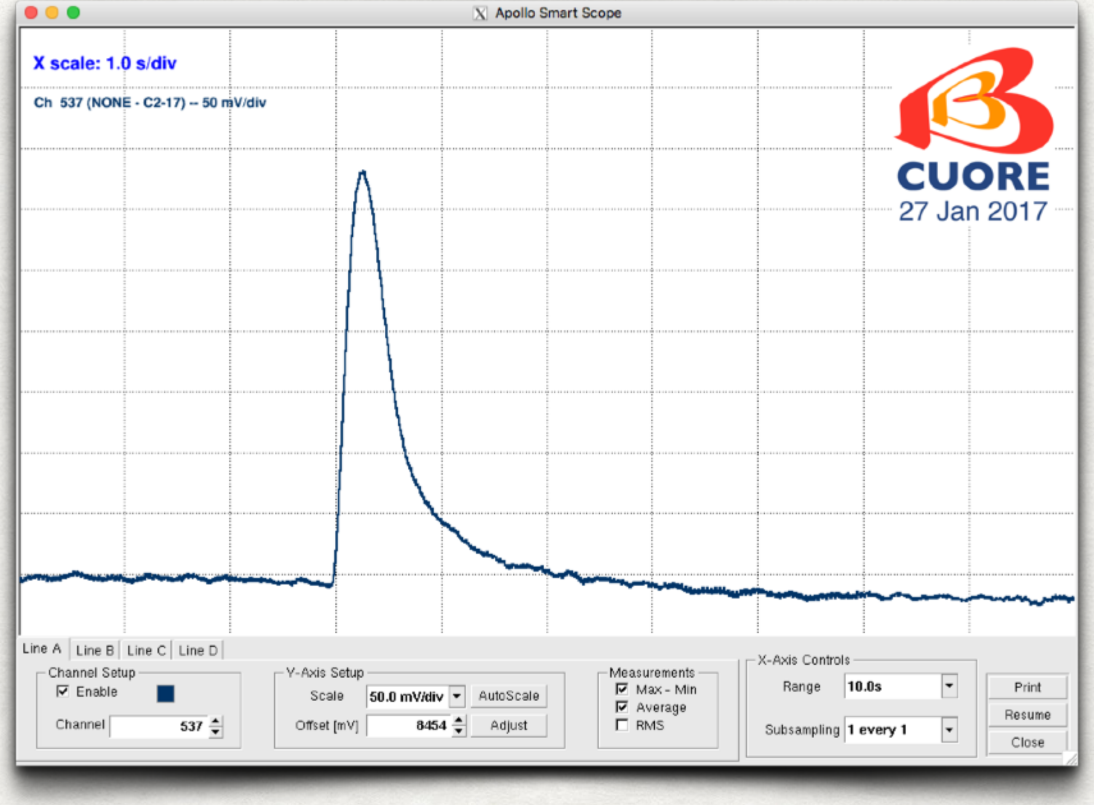
26.01.2017
Base temperature 7 mK

27.01.2017
As soon as we reached base temperature we observed the first pulse!



pumping exchange gas in IVC

electronics optimization


Apollo Smart Scope

X scale: 1.0 s/div

Ch 537 (NONE - C2-17) -- 50 mV/div

CUORE
27 Jan 2017

Line A | Line B | Line C | Line D

Channel Setup
☑ Enable
Channel 537

Y-Axis Setup
Scale 50.0 mV/div
Offset [mV] 8454

Measurements
☑ Max - Min
☑ Average
☐ RMS

X-Axis Controls
Range 10.0s
Subsampling 1 every 1

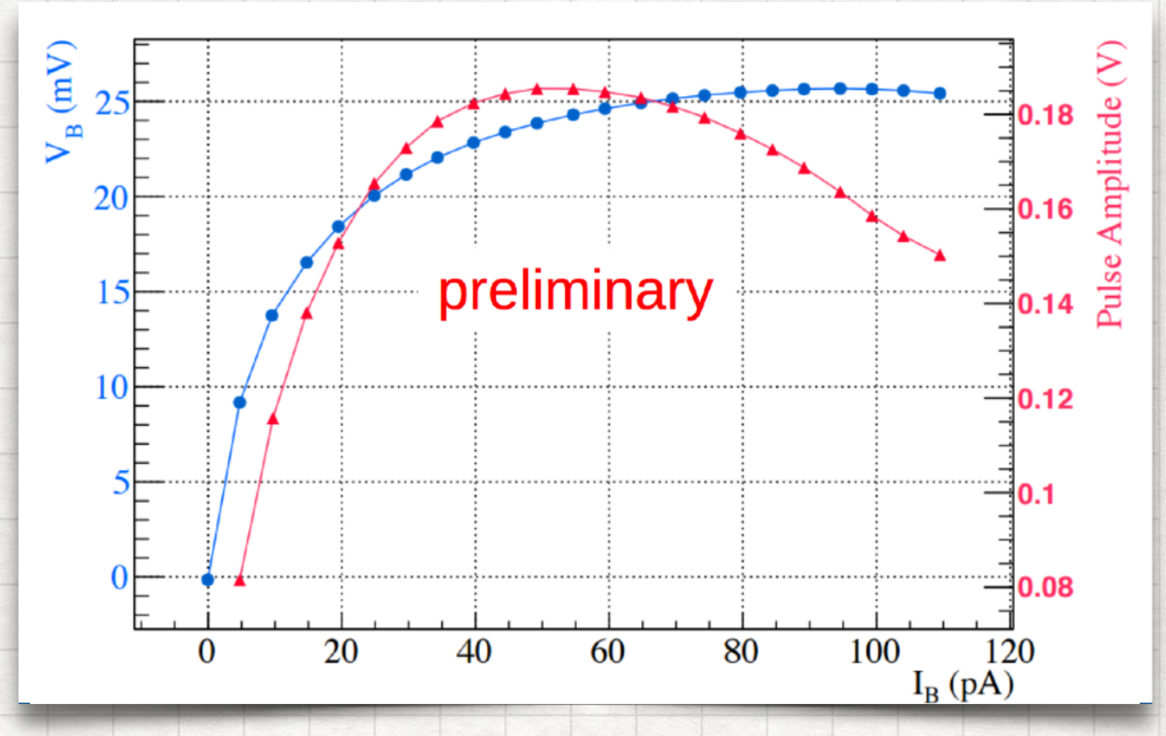
DETECTOR OPTIMIZATION

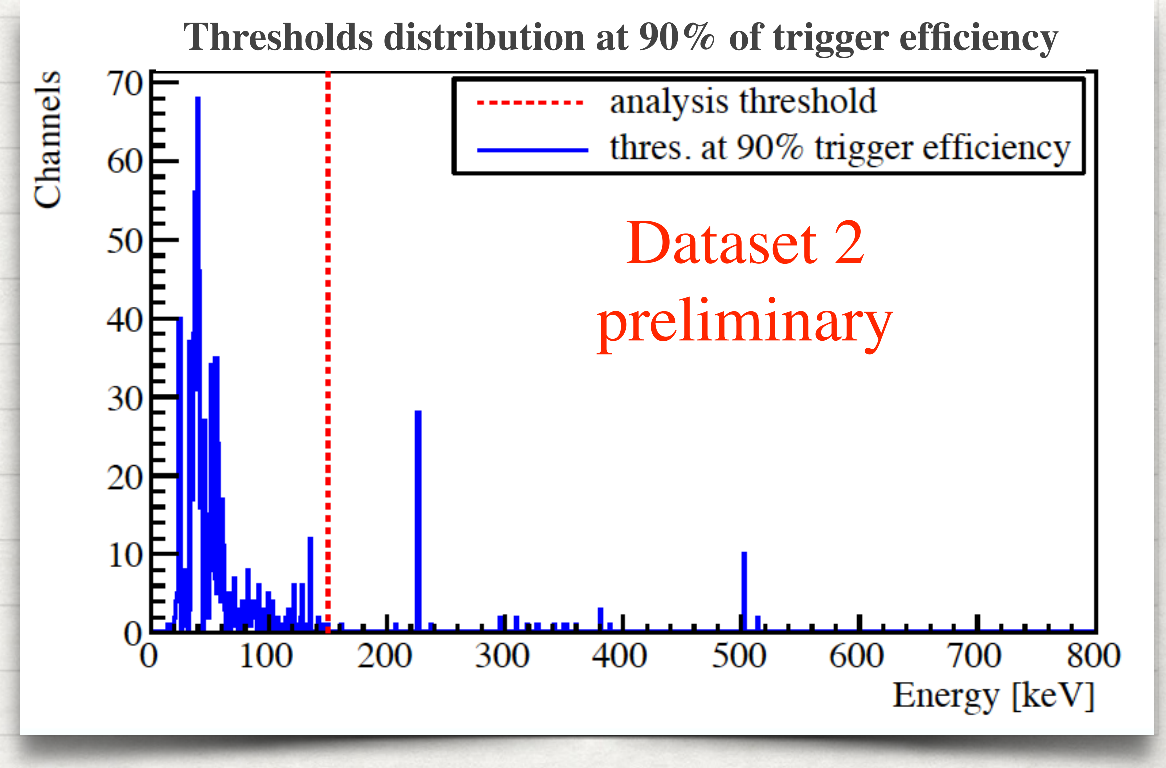
Electronics and DAQ debugging
Noise and vibrations optimizations

Temperature scan:
Chose temperature that optimises the signal and at the same time allows to work with the designed thermistor resistance

Working point and Load Curves:
scan to choose the best bias current to feed to each channel thermistor:
linear behaviour for small temperature variations
maximisation of signal to noise ratio
optimization of pulse amplitude

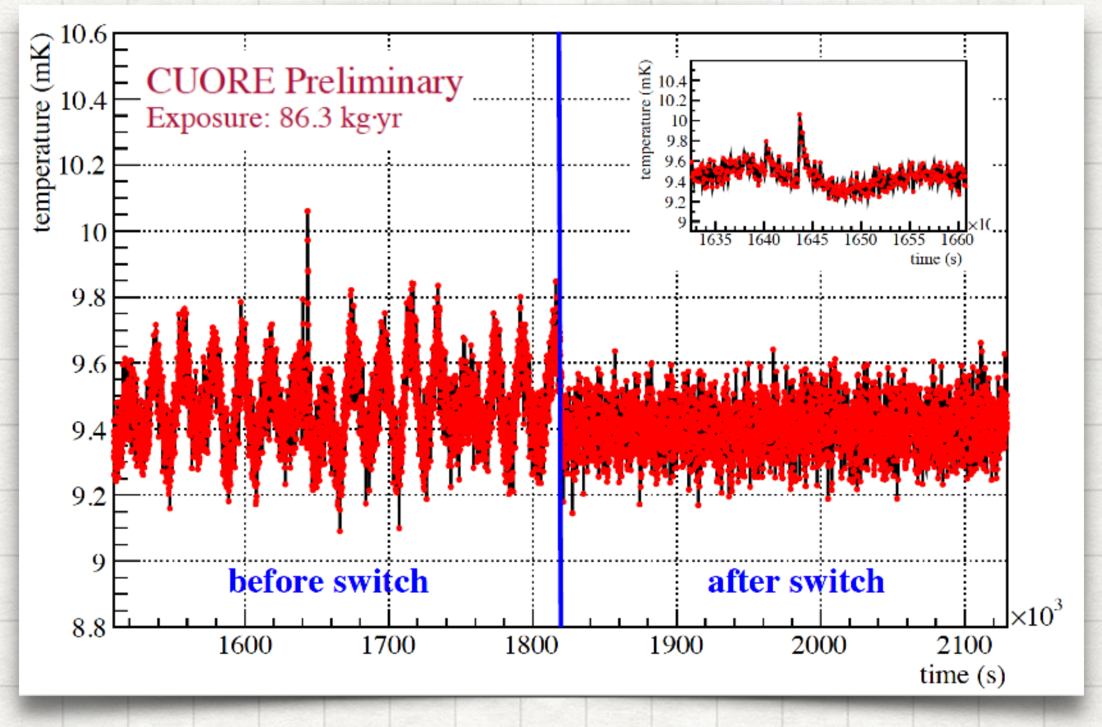
Optimization of trigger thresholds:
Trigger thresholds ranging from 20 to a few hundred keV





DETECTOR OPTIMISATION

The Cryostat is cool down to 3K by 5 Pulse Tubes (4 active - 1 backup) that induce vibrations at 1.4 Hz and harmonics.



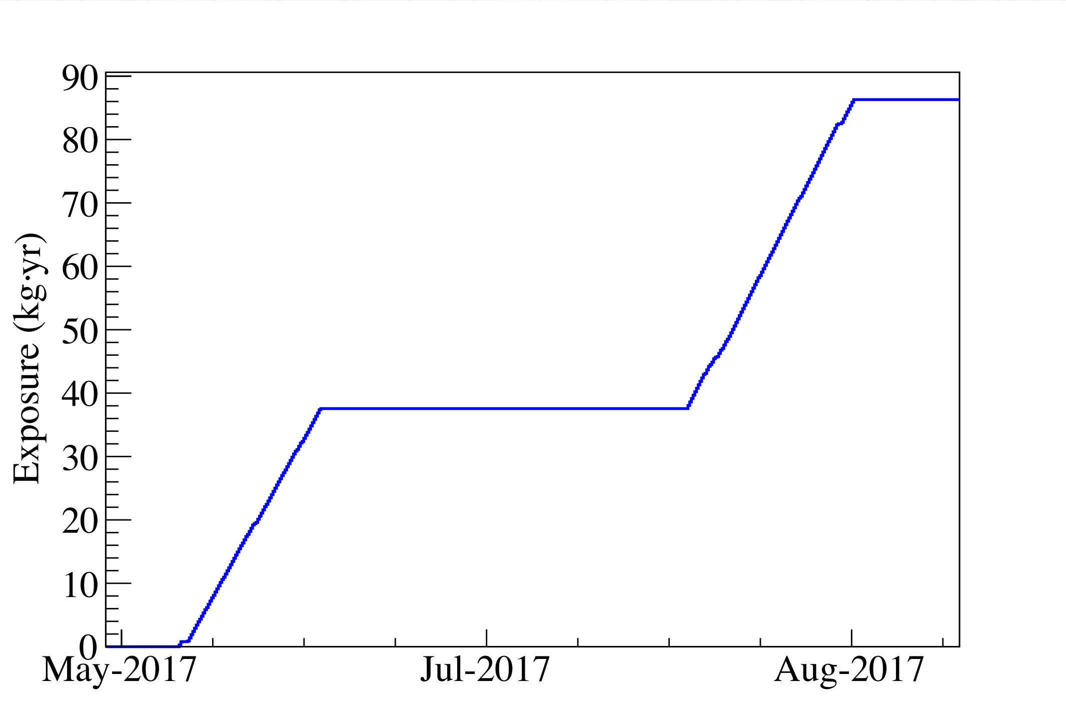
Attenuation of Pulse tube induced vibrations:

(1) Switch to Linear Drives to control PT motor heads -> reduce temperature variations on the Mixing Chamber

(2) PT phase scan to find the phase configuration that actively minimize the PT induced vibrations

Example of the PT induced noise for three different PT phase configurations

DATA TAKING



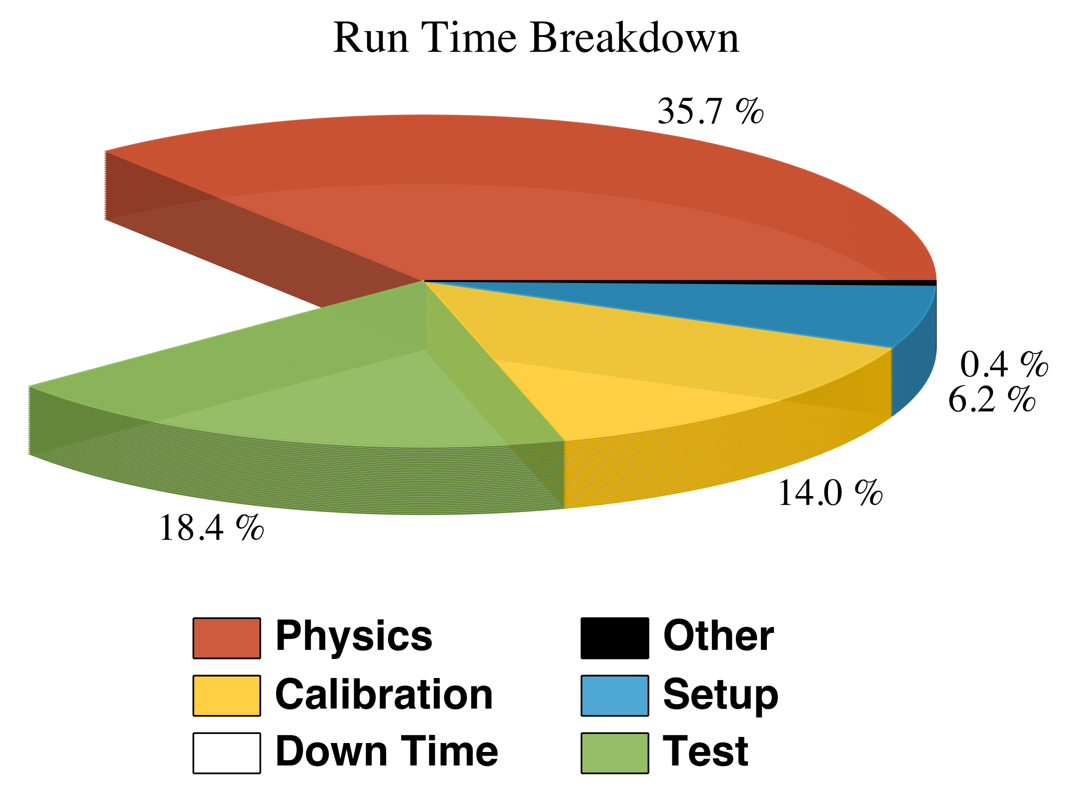
984/988 active channels (99.6%)

Average Rates (per channel):

- *Calibration:* ~50 mHz
- *Physics:* ~6 mHz

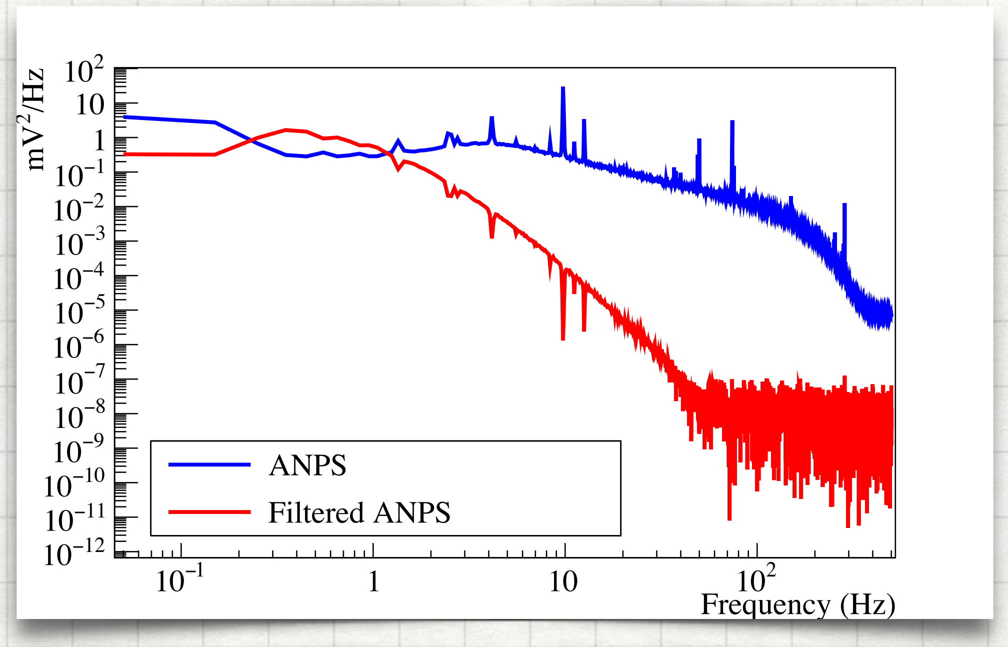
Up to now CUORE had two month-long of steady data collection, bridged by a detector optimization period

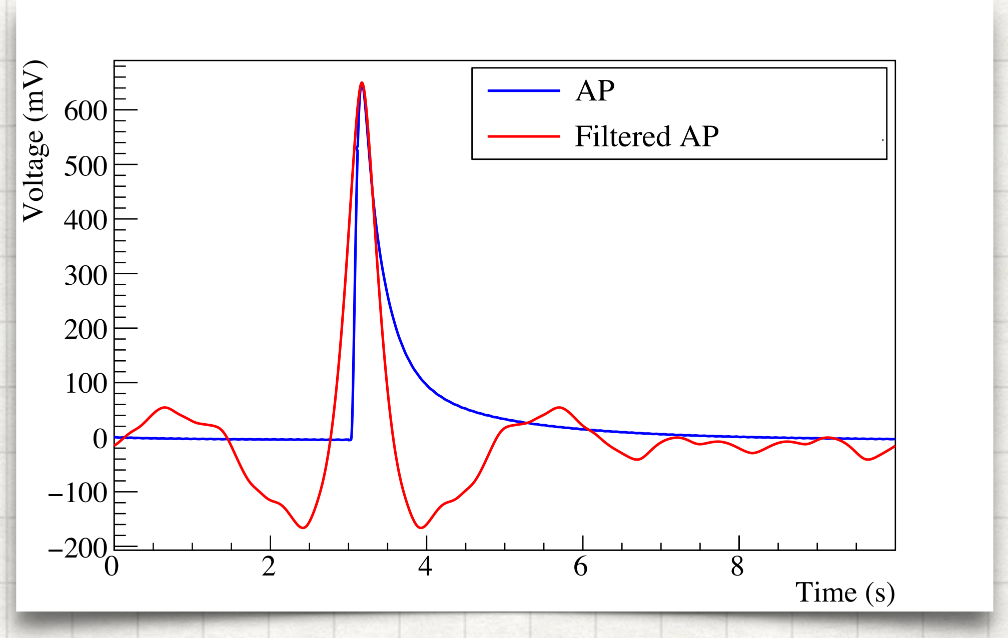
- Dataset 1 - May 2017
- Dataset 2 - August 2017


Run Time Breakdown

FIRST LEVEL ANALYSIS

- **Amplitude Evaluation**

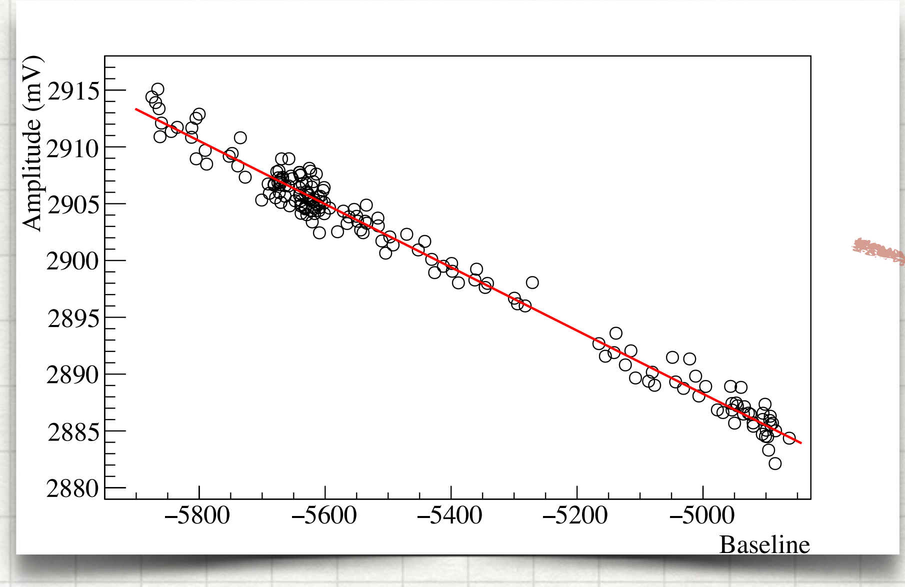


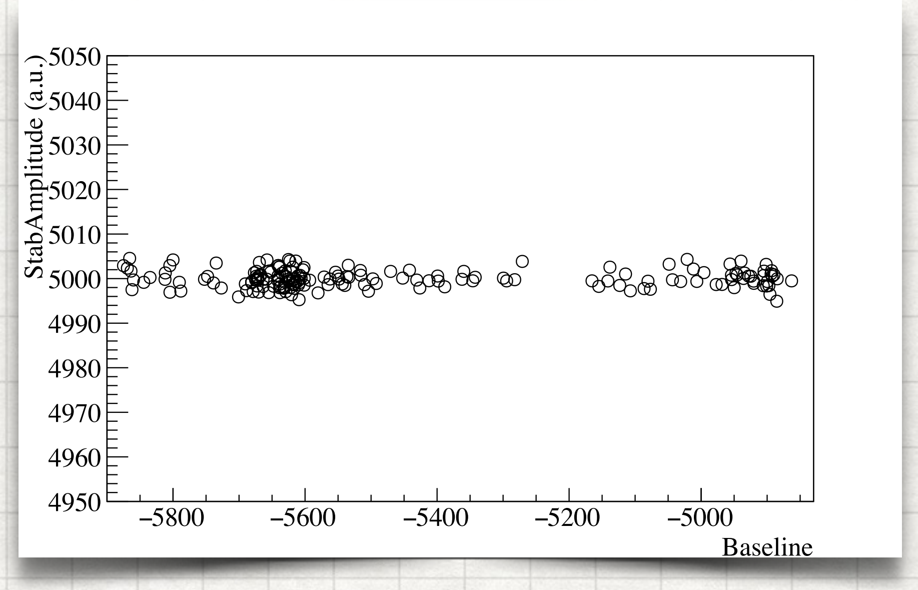


We evaluate the amplitude of pulses using a matched filter that maximizes the signalto-noise ratio.

FIRST LEVEL ANALYSIS

- **Amplitude Evaluation**
- **Thermal gain stabilization**

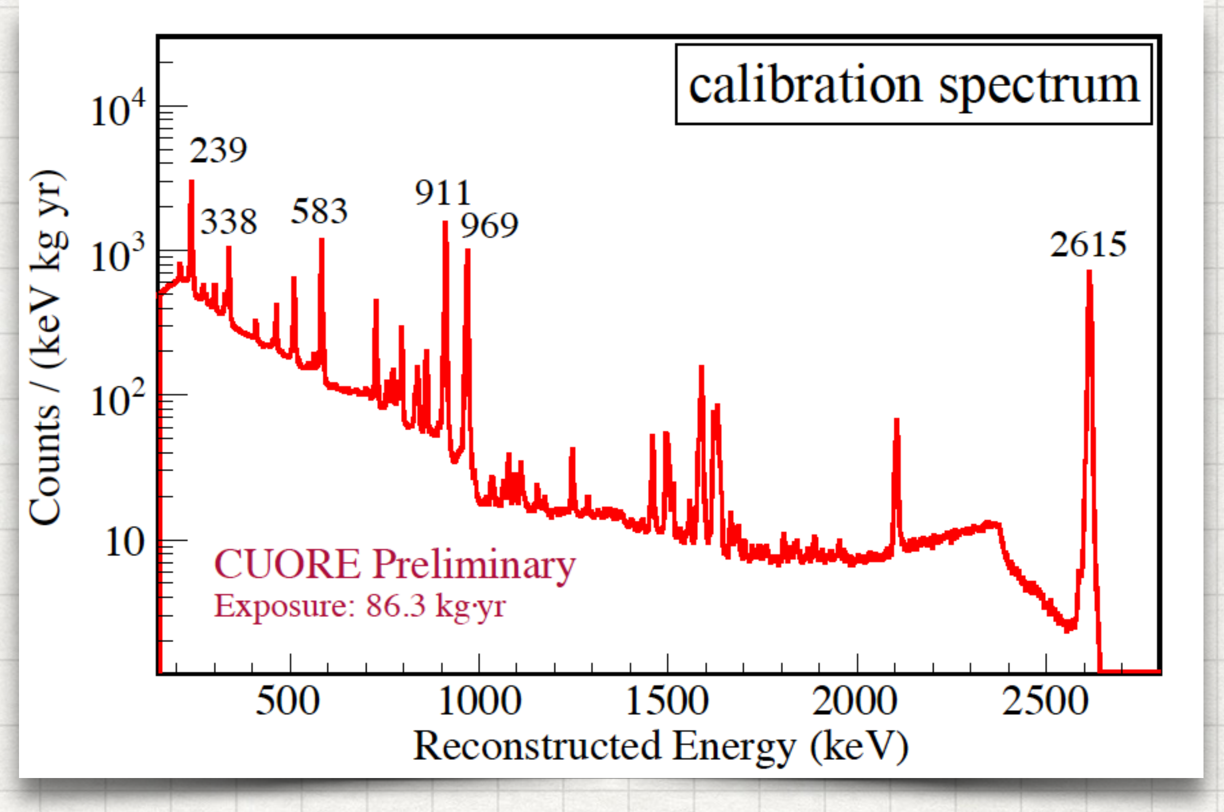




We use heater events at a fixed energy to study the amplitude dependence for small variations of the operating temperature.
Then we correct the amplitude gain variations.

FIRST LEVEL ANALYSIS

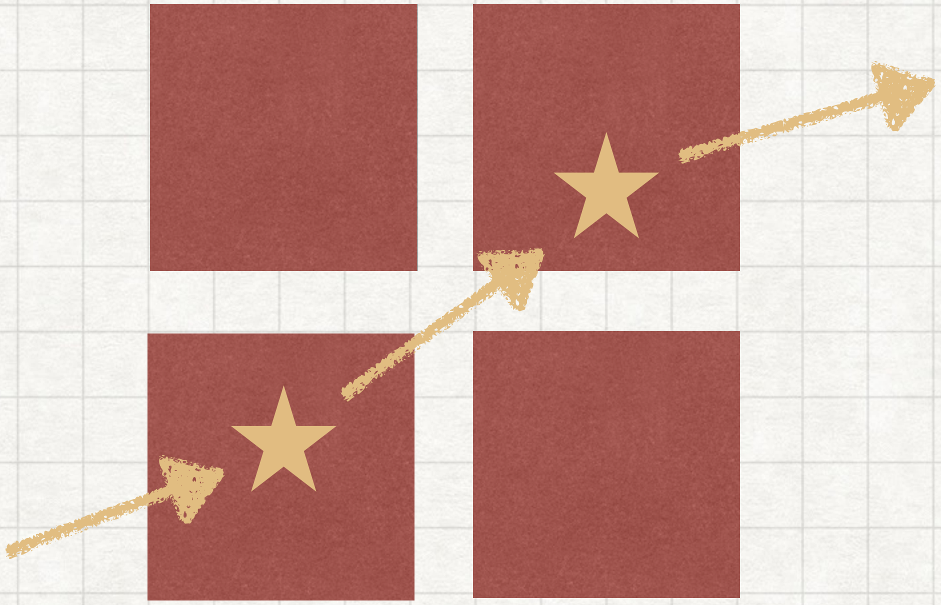
- **Amplitude Evaluation**
- **Thermal gain stabilization**
- **Energy calibration**



Calibration data is taken at the beginning and at the end of each dataset.
Calibration uses the 6 strongest peaks from ^{232}Th source to build, for each bolometer, an amplitude to energy conversion function.

FIRST LEVEL ANALYSIS

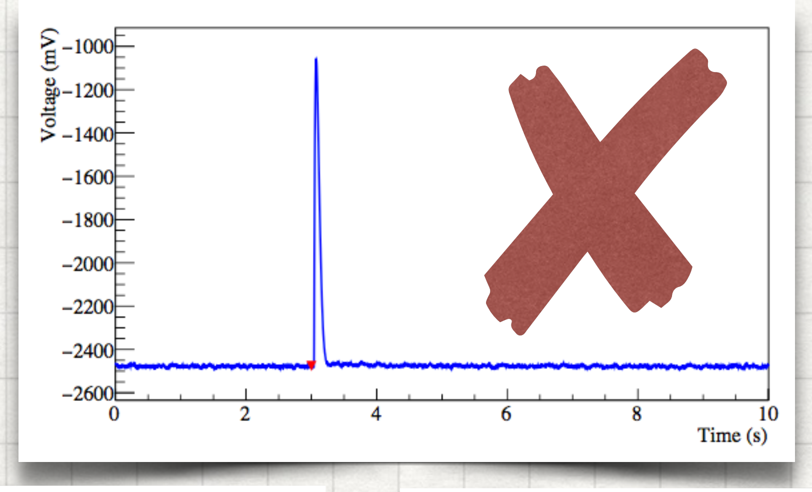
- **Amplitude Evaluation**
- **Thermal gain stabilization**
- **Energy calibration**
- **Select events with multiplicity=1**

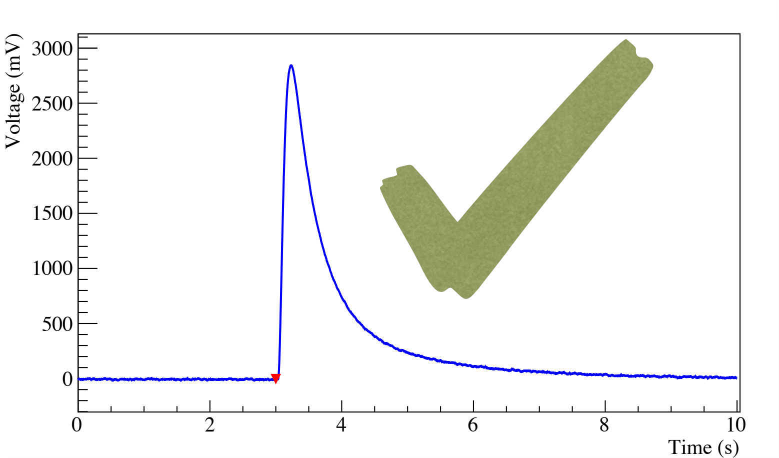


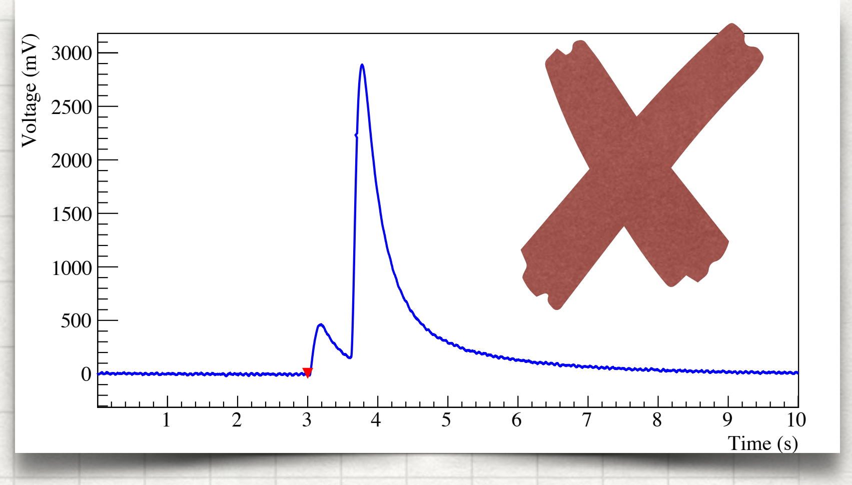
When more than one bolometer fires in a small time window, the event is likely to be due to radioactive contaminations.
We assign multiplicity and total energy to such events and select only the ones that do not have other signals in coincidence.

FIRST LEVEL ANALYSIS

- **Amplitude Evaluation**
- **Thermal gain stabilization**
- **Energy calibration**
- **Select events with multiplicity=1**
- **Pulse shape analysis**





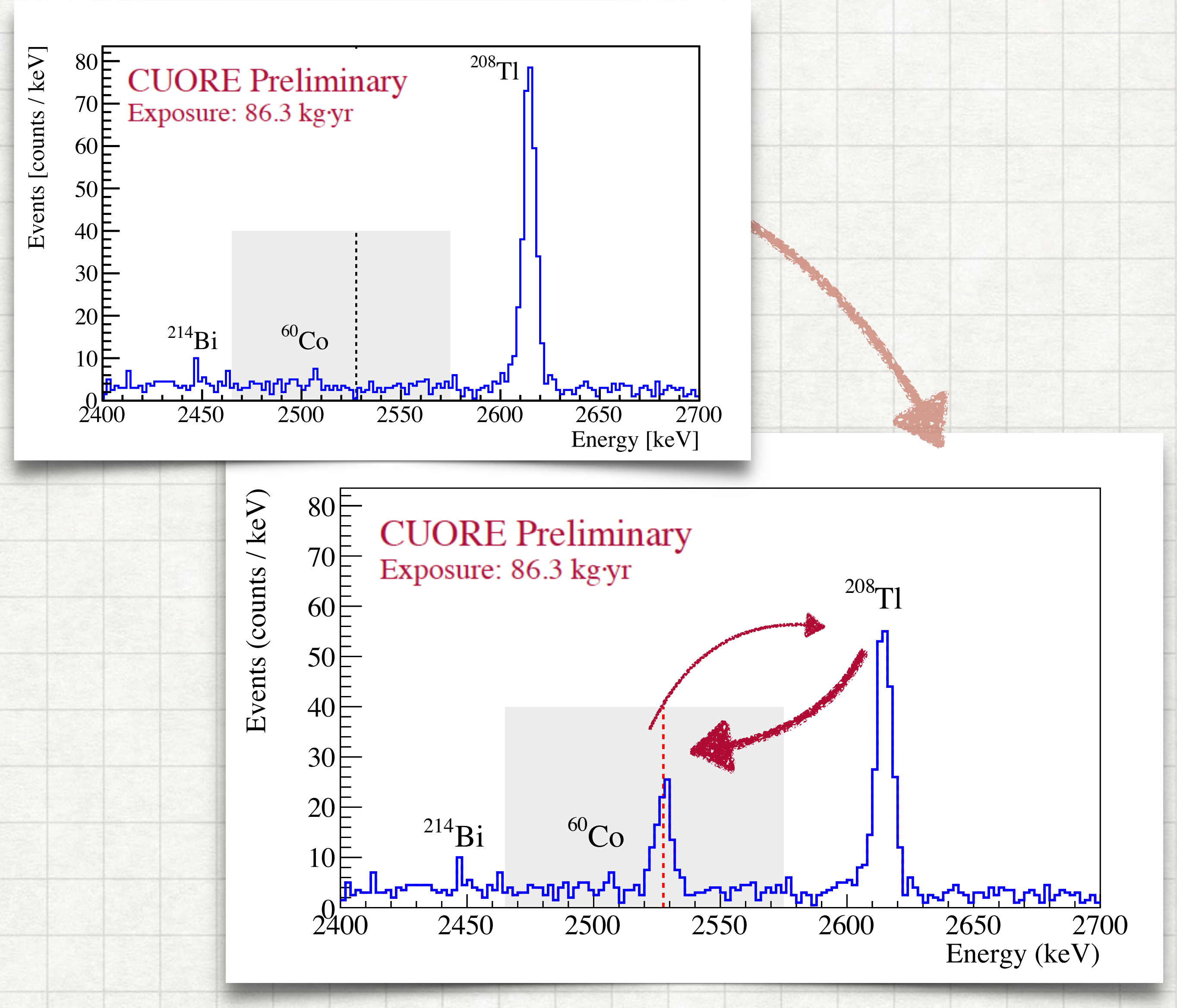


Pulse shape analysis allow us to identify and then remove pulses with features that deviates from the average signal: noise spikes, pile-up…

We define a distance in the multi-dimensional space of six pulse shape parameters. Accept or discard events which distance from the centroid of the distribution is above the threshold that maximizes the experimental sensitivity.

FIRST LEVEL ANALYSIS

- **Amplitude Evaluation**
- **Thermal gain stabilization**
- **Energy calibration**
- **Select events with multiplicity=1**
- **Pulse shape analysis**
- **Blinding**

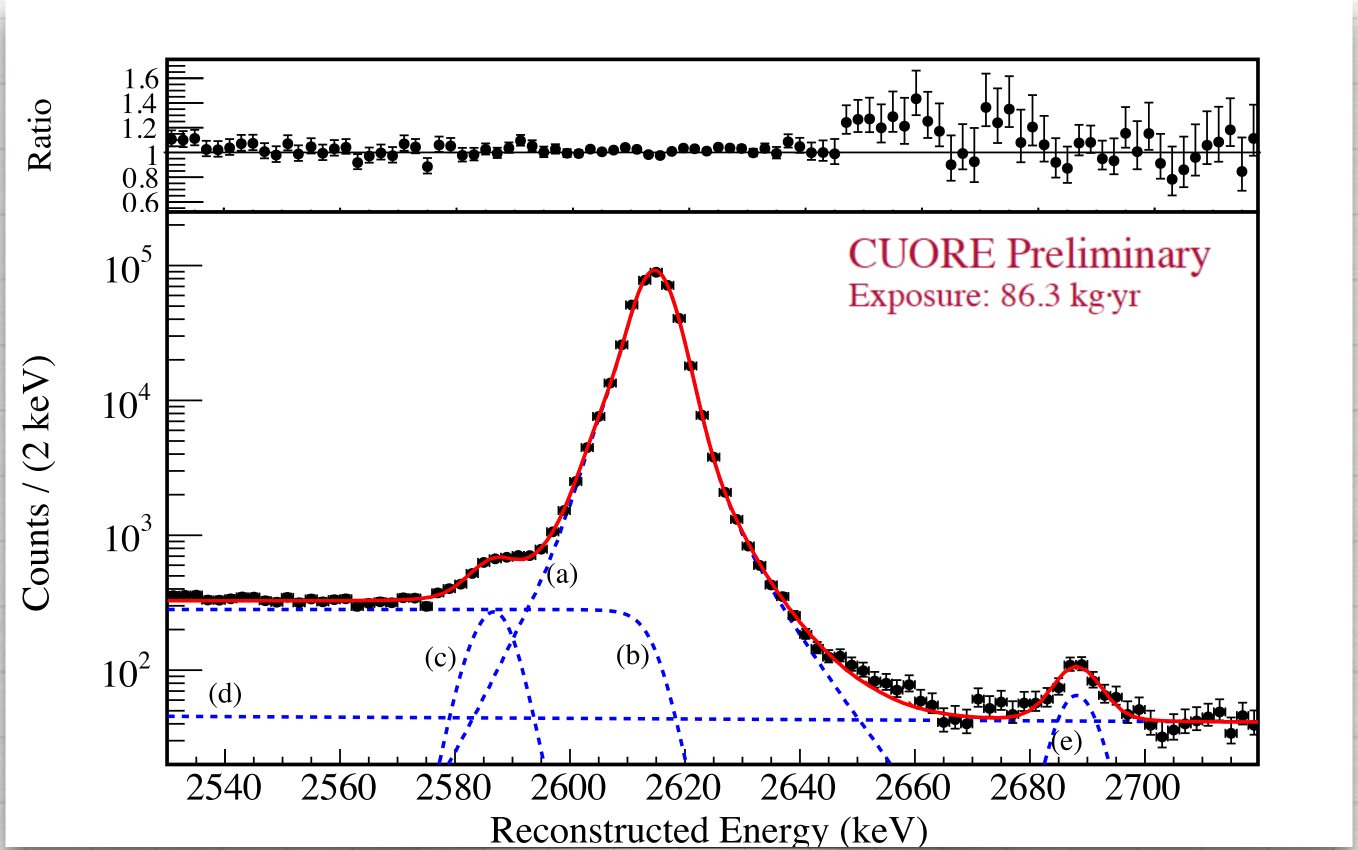


The blinding algorithm takes a fraction of the events from the ^{208}Tl line and shift them around the $Q_{\beta\beta}$ and vice versa.
The original energies remain encrypted until unblinding.
The unblinding occurs only after the full analysis procedure has been fixed.

DETECTOR RESPONSE

arXiv:1710.07988 (submitted to PRL)

Sum on all towers of the line shape fit



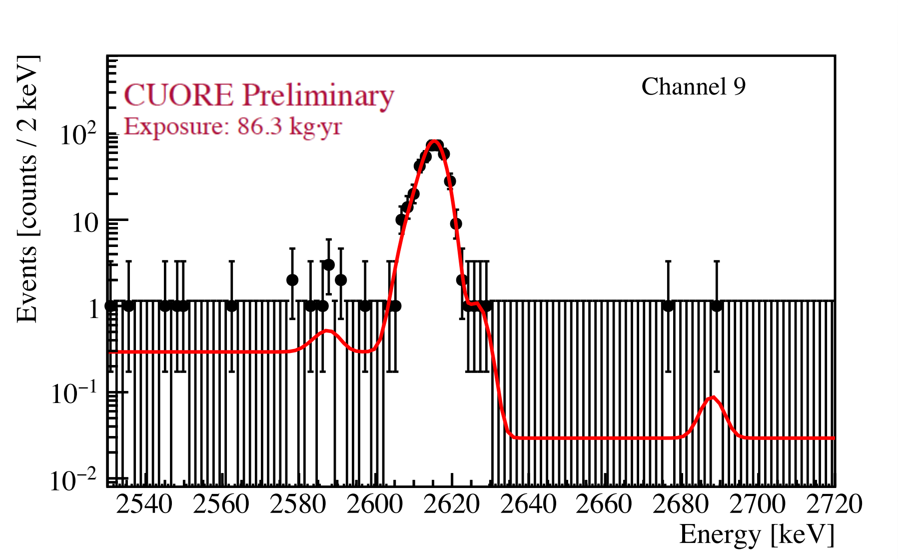
(a) Photopeak
(b) Compton
(c) 30 keV X-Ray escape
(d) Linear background
(e) (2615 + 538 - 511) keV coincidence

We study the detector response of each channel by fitting the 2615 keV ^{208}Tl calibration line.

We perform an UEML simultaneous fit over all the channel-dataset.

The detector response is given by the photopeak component of the fit, modelled by the sum of 3 Gaussians.

Single channel-dataset



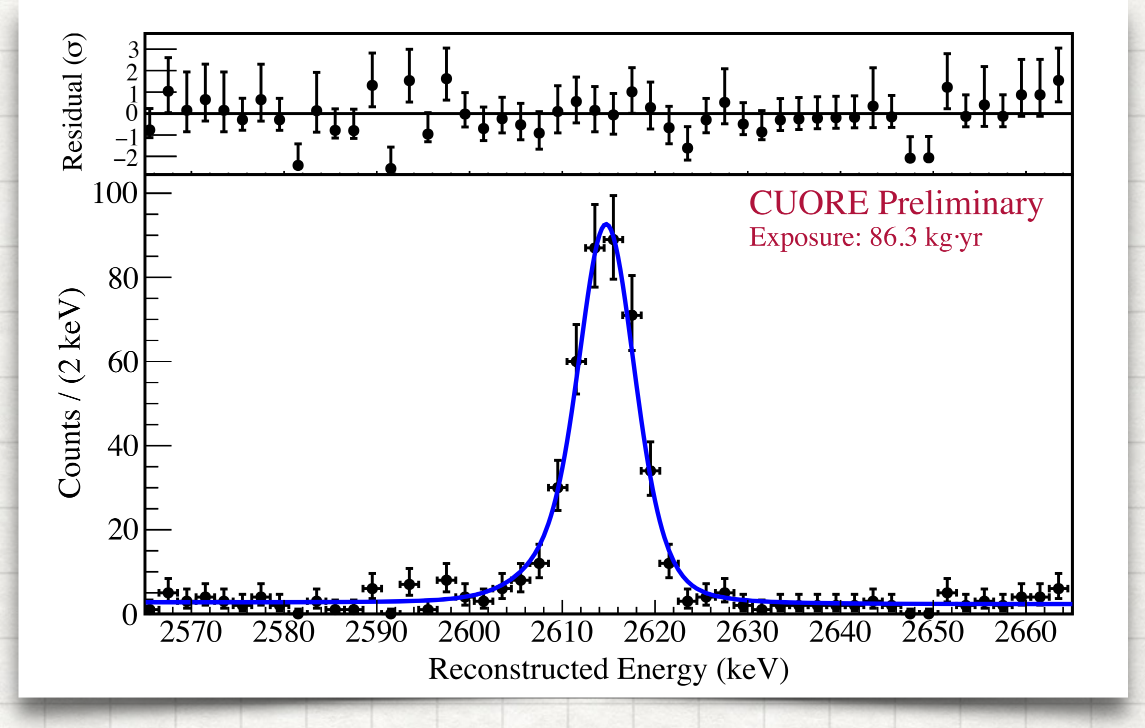
ENERGY RESOLUTION

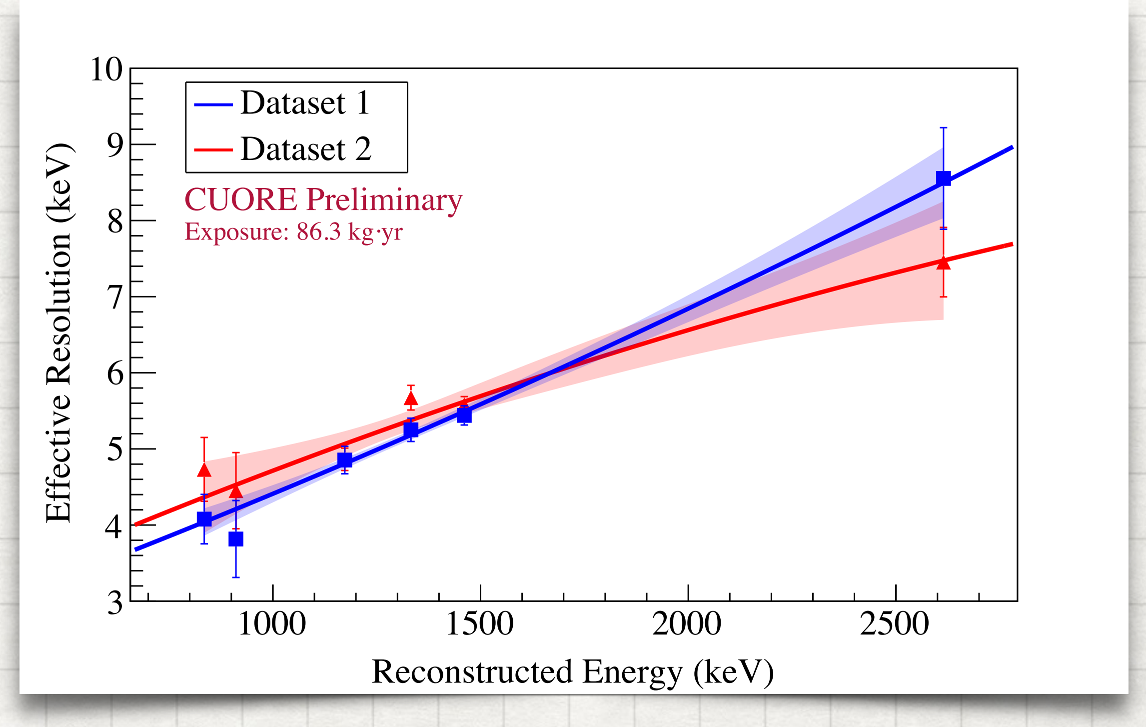
arXiv:1710.07988 (submitted to PRL)

The energy resolution is evaluated for each bolometer-dataset in calibration runs, because of higher statistics on a bolometer-dataset level

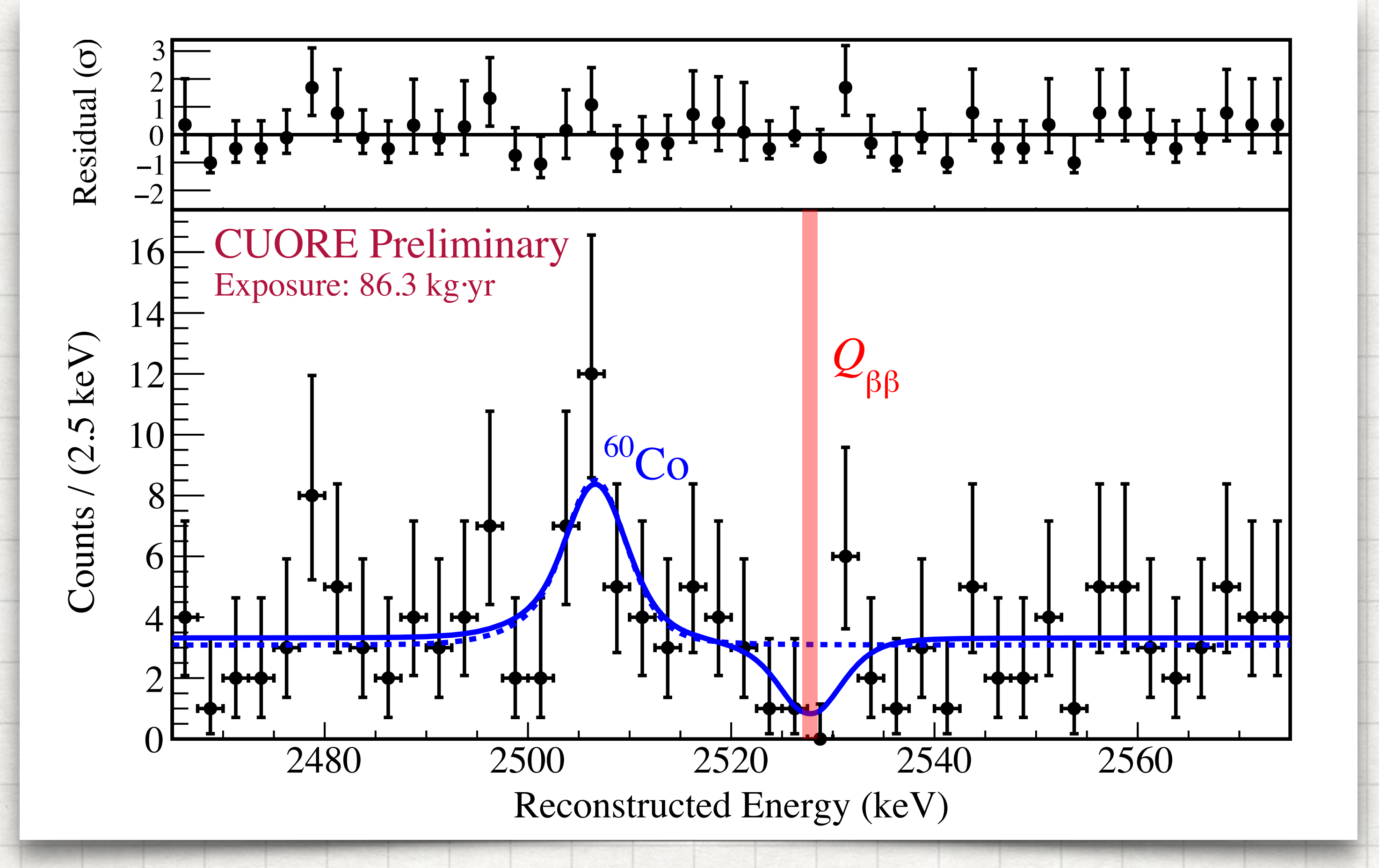
A **scaling factor** is obtained by fitting 6 spectral lines from physics runs and its value is extrapolated at $Q_{\beta\beta}$

The scaling factor is applied to the energy resolution evaluated in calibration runs to obtain the correct energy resolution at $Q_{\beta\beta}$





ROI FIT



arXiv:1710.07988 (submitted to PRL)

We perform in the ROI (2465 - 2575) keV an Unbinned Extended Maximum-Likelihood (UEML) fit based on RooFit

Flat background:

- common to all channels
- dataset-dependent

^{60}Co sum peak:

- floating peak position
- rate common to all channel-dataset pairs

Peak at $Q_{\beta\beta}$:

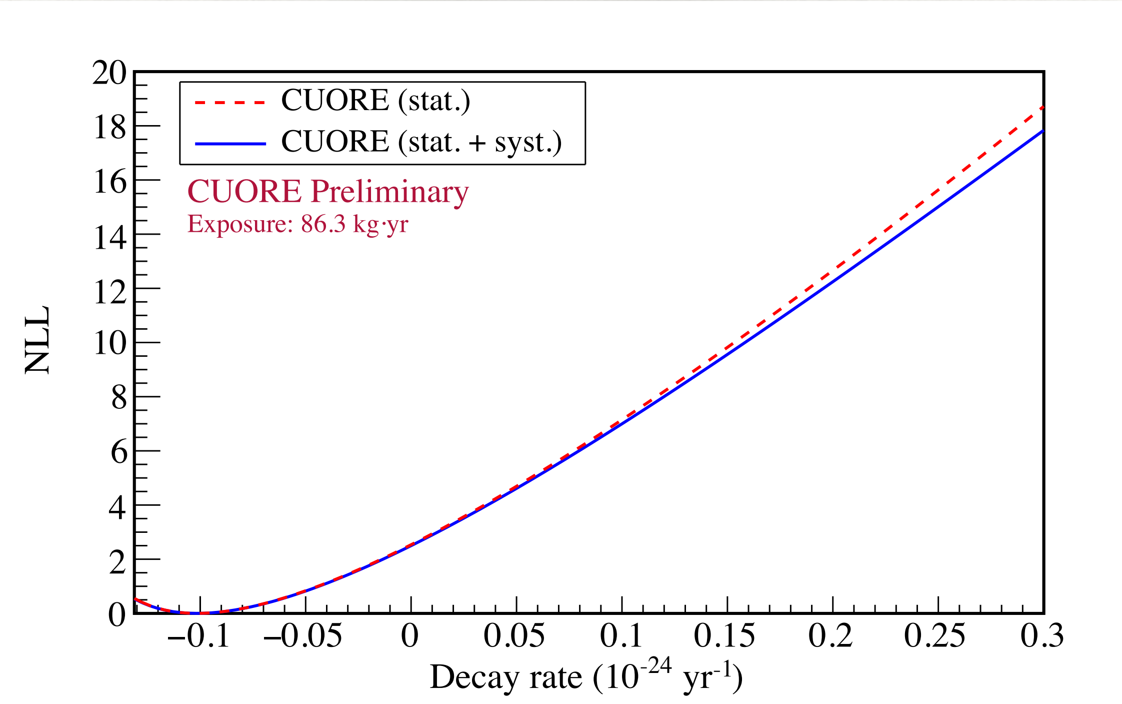
- fixed position
- floating rate, common to all channel-dataset pairs

signal decay rate best fit: $\Gamma_{0\nu} = (-1.0^{+0.4}_{-0.3}$ (stat) ± 0.1 (syst)) 10^{-25} yr^{-1}

^{60}Co peak position: (2506.4 ± 1.2) keV

RESULTS

arXiv:1710.07988 (submitted to PRL)

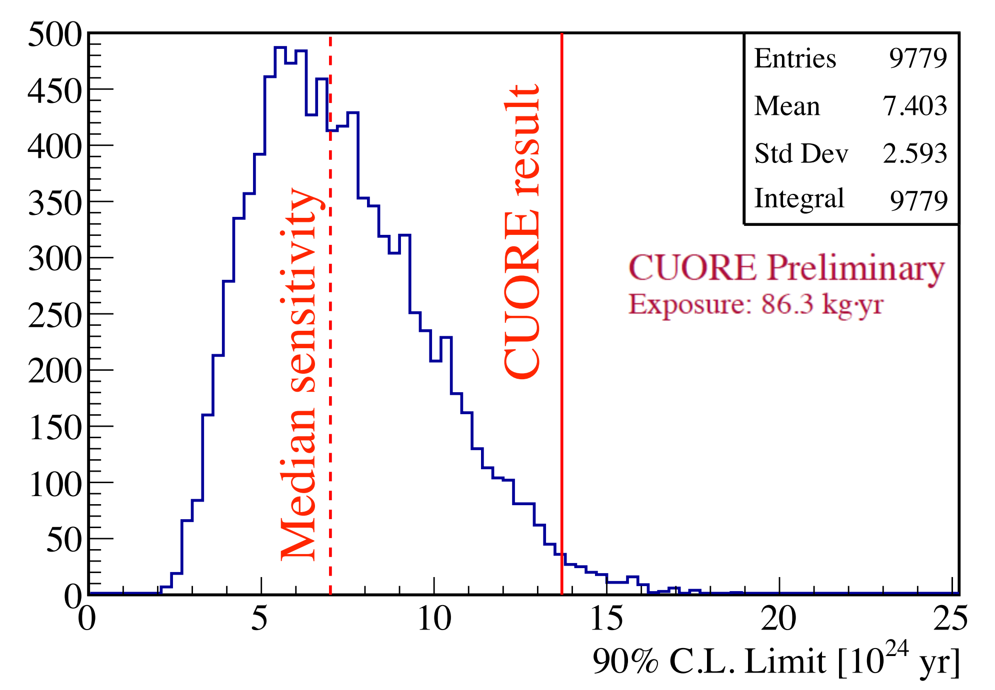


To get the half-life limit we integrate the profile likelihood in the physical region (decay rate > 0)

$T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr (90% CL, syst. included)

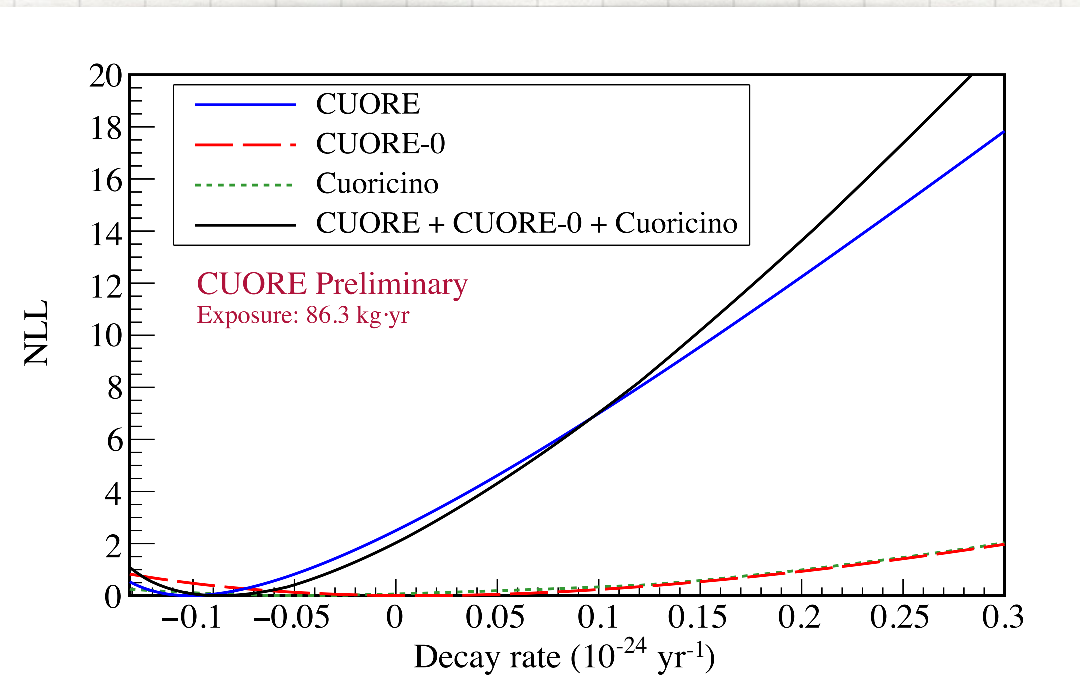
Distribution of 90% C.L. half-lives from 10000 Toy MC experiments:

- The limit is evaluated from the same ROI fit used with real data
- There is a 2% probability to get a better limit (more negative decay rate)



RESULTS

arXiv:1710.07988 (submitted to PRL)



Combine CUORE result with CUORE-0 and Cuoricino

$T^{0\nu}_{1/2} > 1.5 \times 10^{25}$ yr (90% CL, syst. included)

CUORE surpassed CUORE-0 exposure in about 3 weeks of data taking

This result:

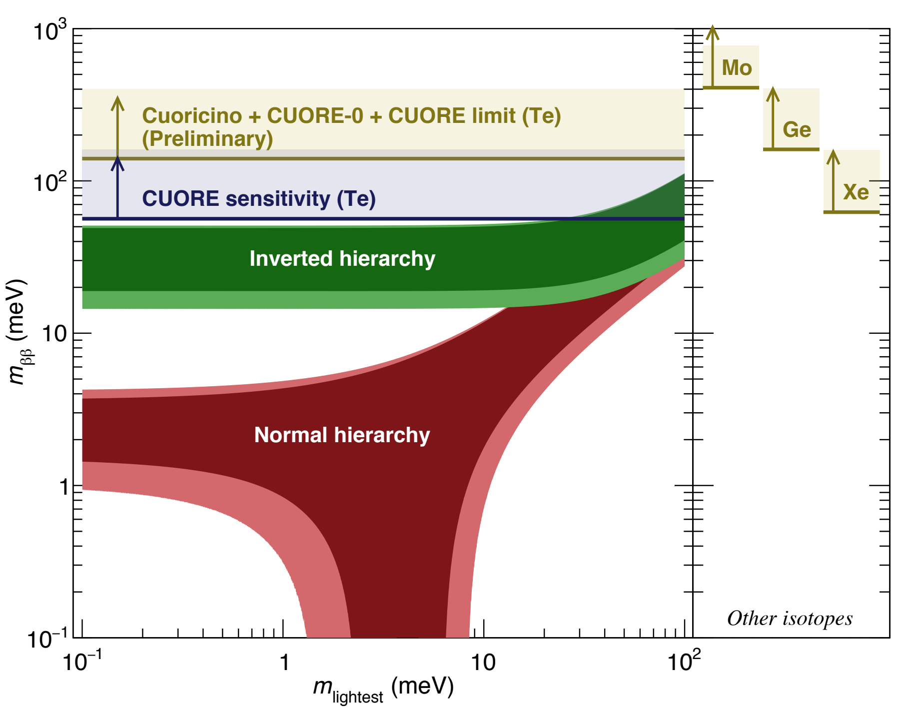
$T_{1/2} > 1.5 \times 10^{25}$ yr

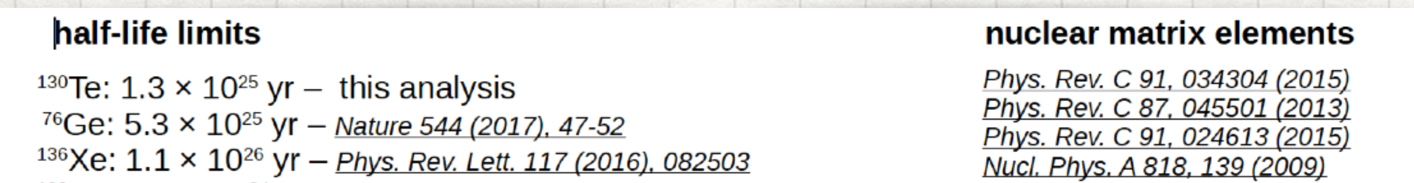
$m_{\beta\beta} < 140 - 400$ meV

CUORE sensitivity in 5 yr:

$T_{1/2} > 9.0 \times 10^{25}$ yr

$m_{\beta\beta} < 56 - 160$ meV





half-life limits

^{130}Te: 1.3 × 10^{25} yr – this analysis

^{76}Ge: 5.3 × 10^{25} yr – *Nature 544 (2017), 47-52*

^{136}Xe: 1.1 × 10^{26} yr – *Phys. Rev. Lett. 117 (2016), 082503*

^{100}Mo: 1.1 × 10^{24} yr – *Phys. Rev. D 89 (2014) , 111101*

nuclear matrix elements

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)

IMPROVEMENTS

DATASET 1

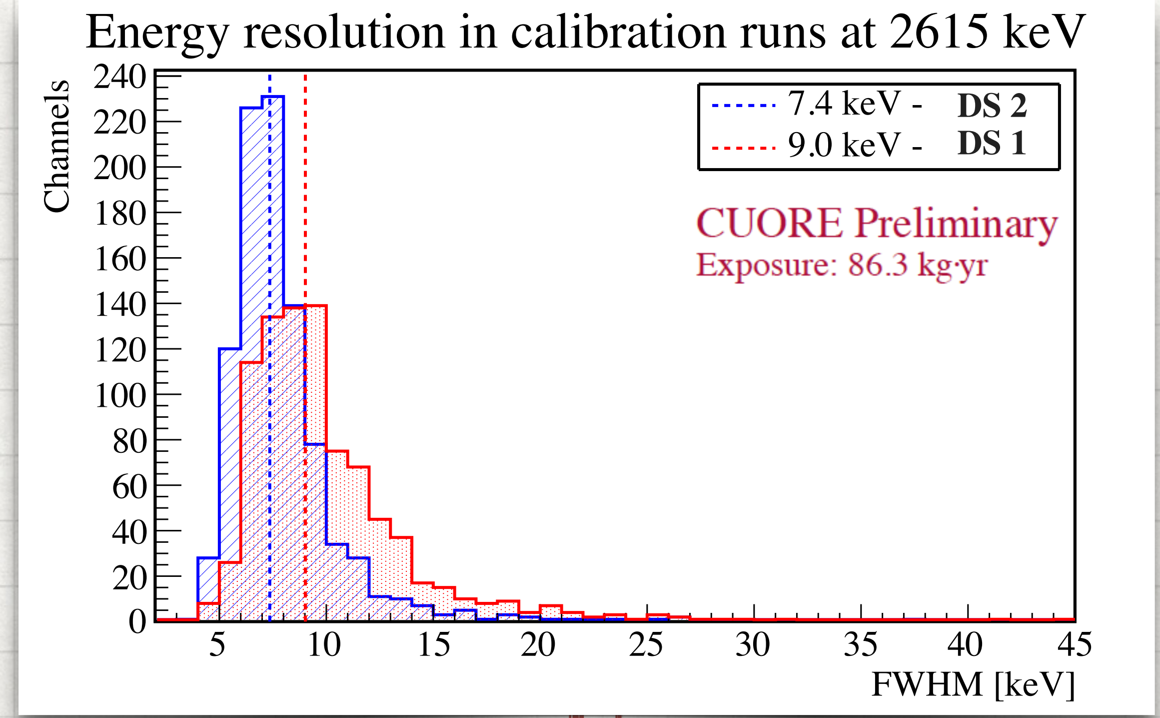
- FWHM in calib data@ 2615: 9.0 keV
- FWHM in physics data@ Q-value: 8.3 keV
- Channels used: 876
- 0VBB Signal Efficiency: (75.69 ± 3.02)%
- Exposure TeO_2: 37.6 kg·yr
- Background: $(1.49 \pm 0.18) 10^{-2}$ c/(keV·kg·yr)

DATASET 2

- FWHM in calib data@ 2615: 7.4 keV
- FWHM in physics data@ Q-value: 7.4 keV
- Channels used: 935
- 0VBB Signal Efficiency: (83.01 ± 2.56)%
- Exposure TeO_2: 48.7 kg·yr
- Background: $(1.35 \pm 0.19)\ 10^{-2}$ c/(keV·kg·yr)

Optimization campaign:

- Electronic noise
- Vibrations
- Energy thresholds



CUORE first results on arXiv: 1710.07988 [nucl-ex]

CONCLUSION

The first result from the CUORE experiment

- On the arXiv: arXiv:1710.07988 [nucl-ex]
- Submitted to PRL

Scientific:

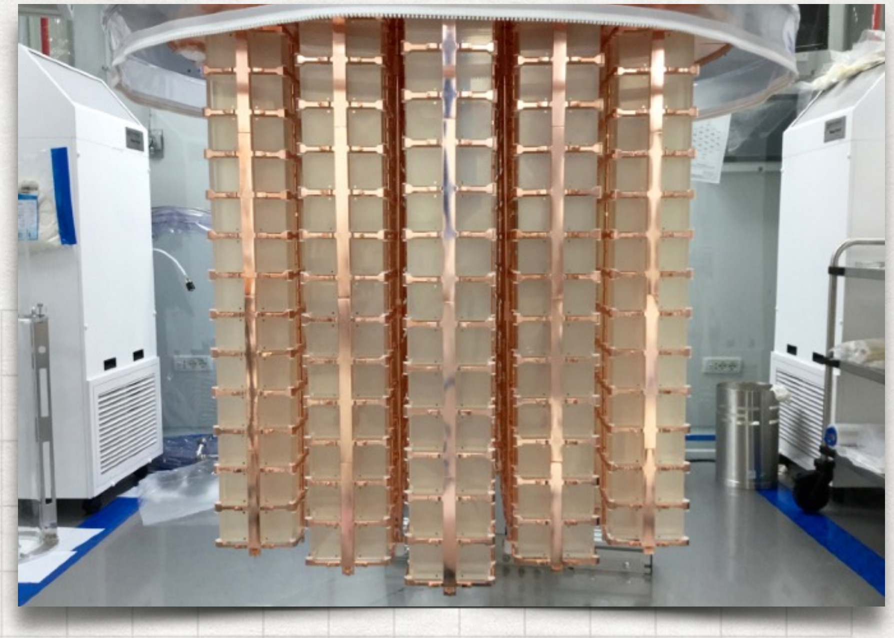
- The most stringent limit on $0\nu\beta\beta$ decay half-life of ^{130}Te to date

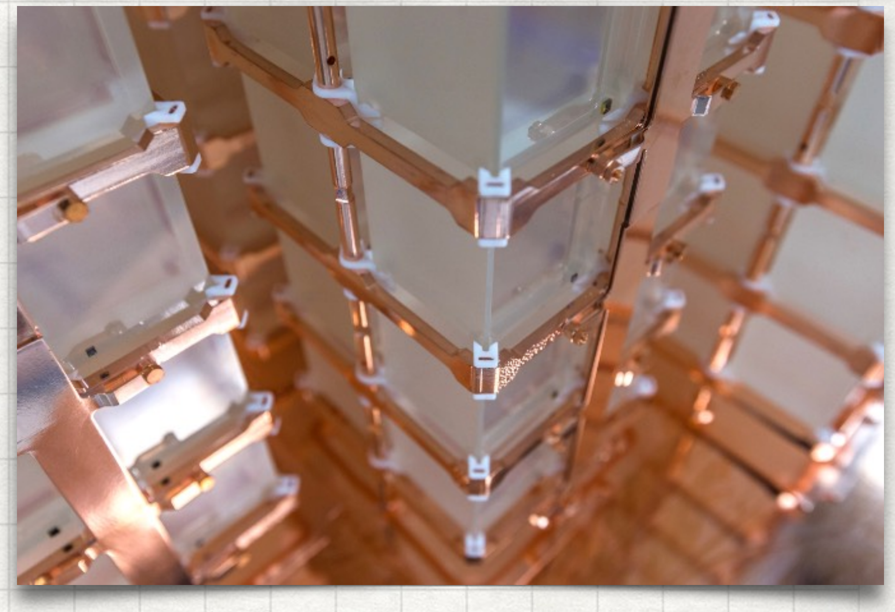
Technical:

- operation of the world's first ton-scale bolometric detector
- construction and operation of the world's largest and most powerful dilution refrigerator

The future:

- 5 years of live time planned
- Further detector performance optimization
- New analyses ($2\nu\beta\beta$, other isotopes, dark matter, axions…)
- CUPID (CUORE Upgrade with Particle Identification)





THANK YOU

CSNSM

Yale

INFN Istituto Nazionale di Fisica Nucleare

Berkeley Lab

Cal Poly San Luis Obispo

Massachusetts Institute of Technology

Virginia Tech Invent the Future®

Lawrence Livermore National Laboratory

Sapienza Università di Roma

Università degli Studi di Milano Bicocca

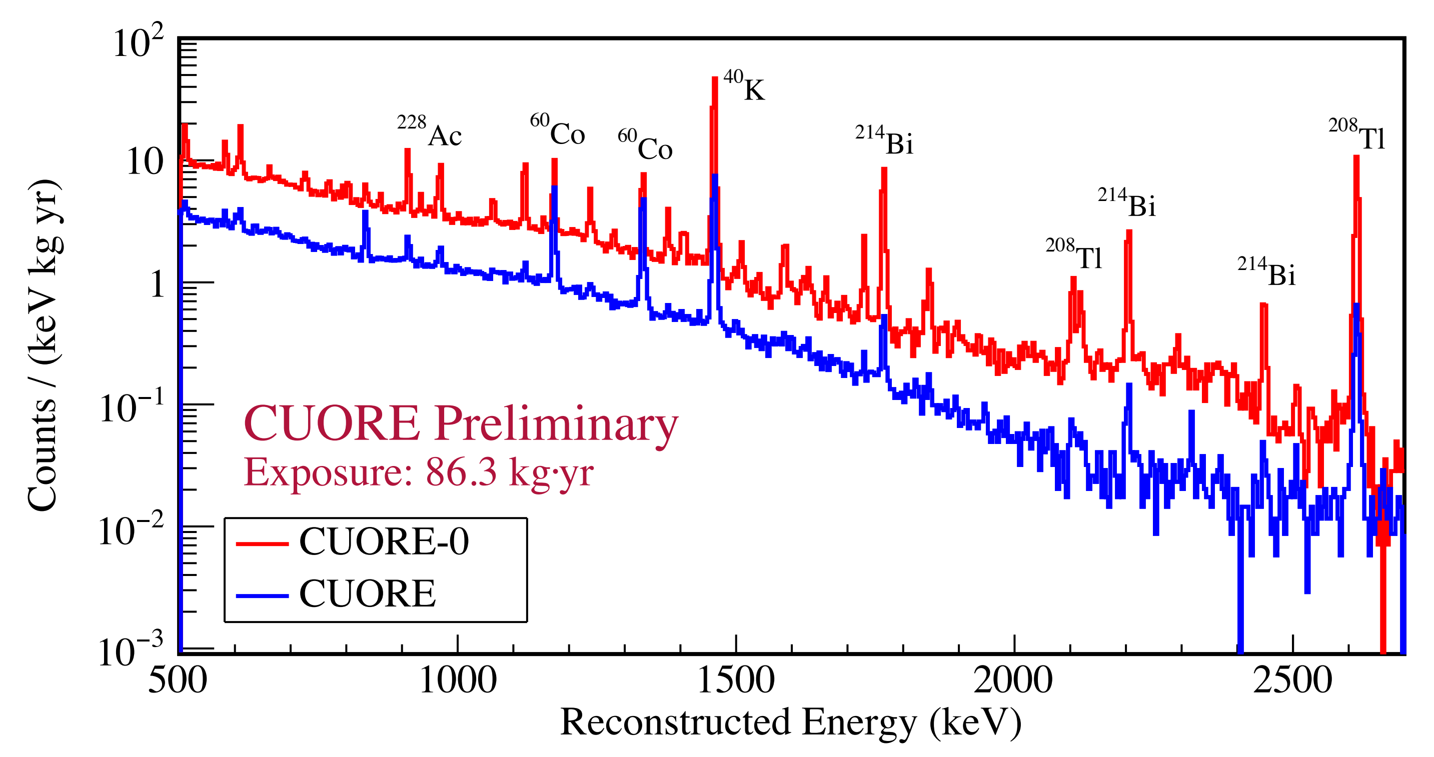
UCLA

SINAP

University of South Carolina

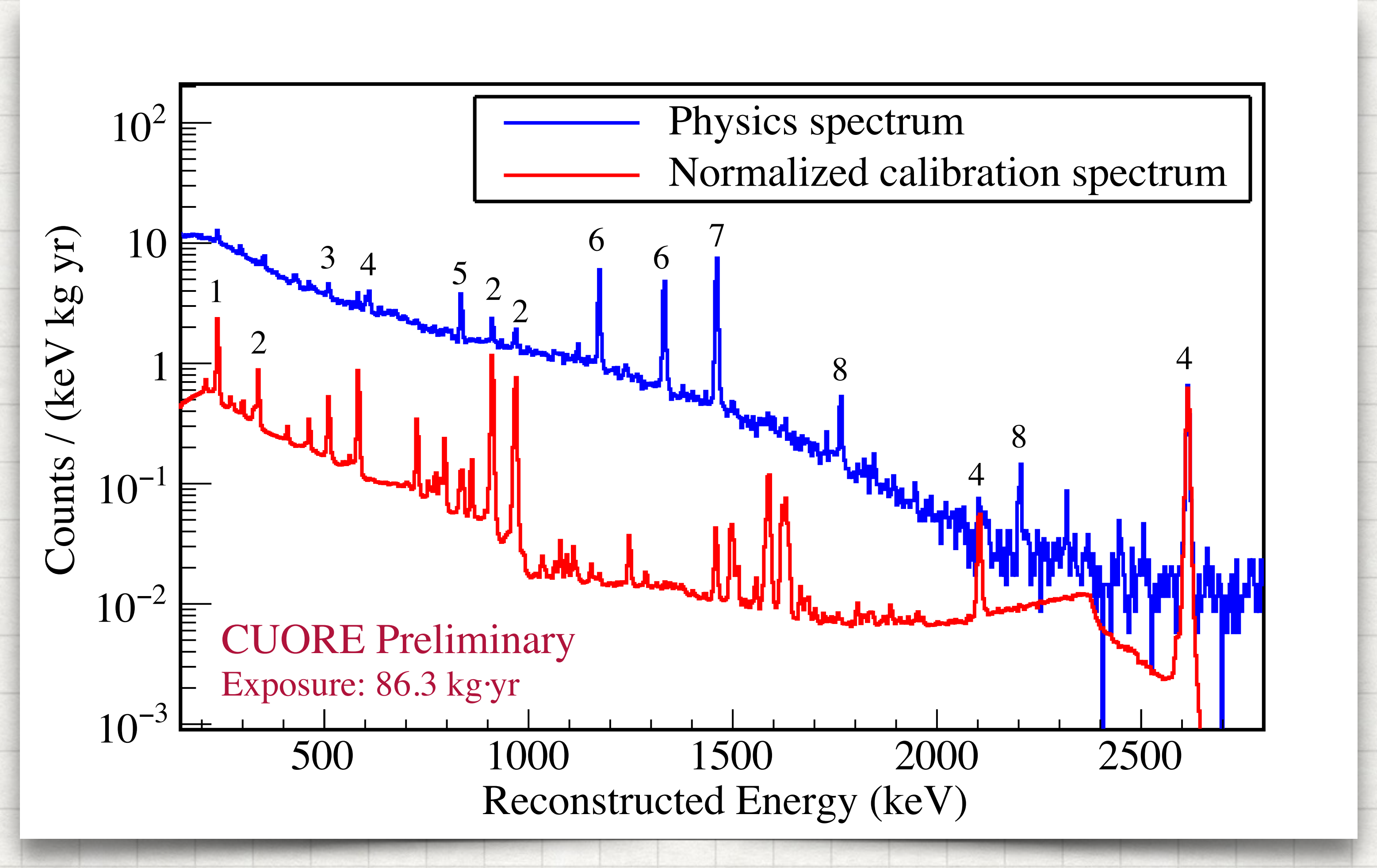
CUORE

BACKUP



CUORE vs CUORE-0 spectrum comparison

BACKUP



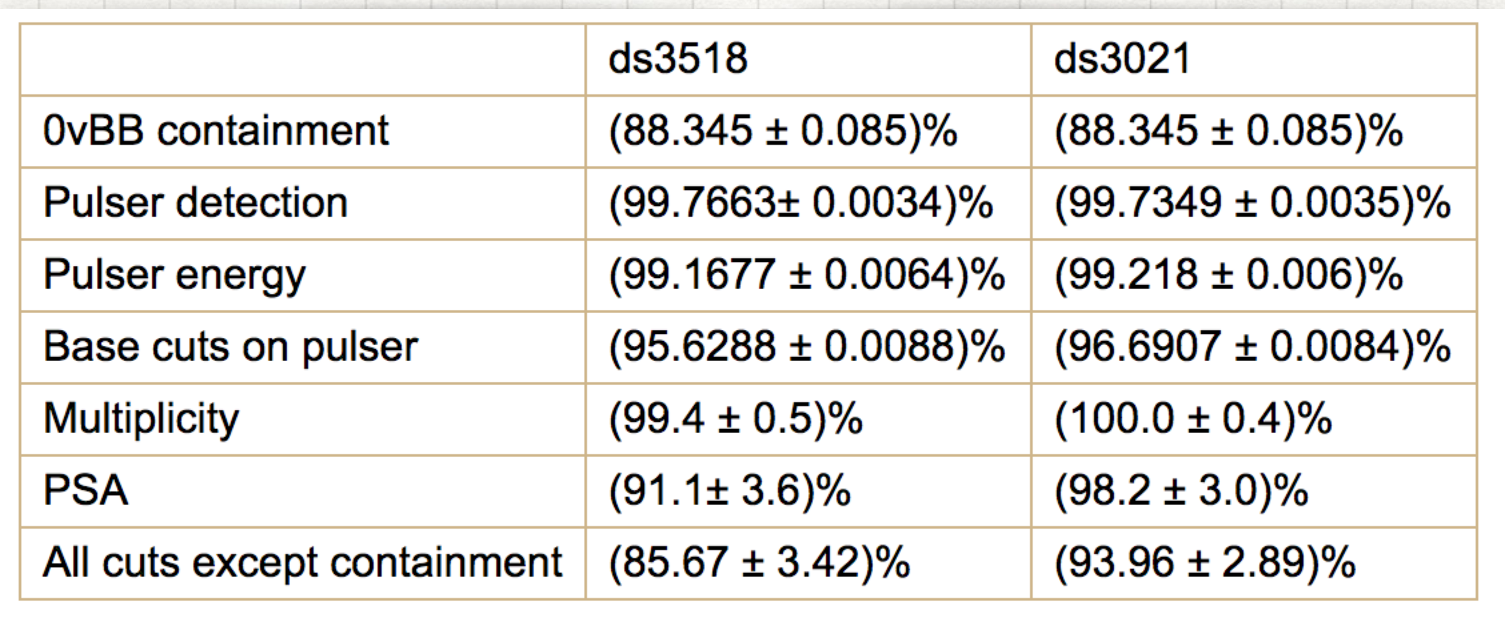
CUORE: comparison between calibration and background spectrum (calibration is normalised to the background ^{208}Tl line)

BACKUP

ROI pulses

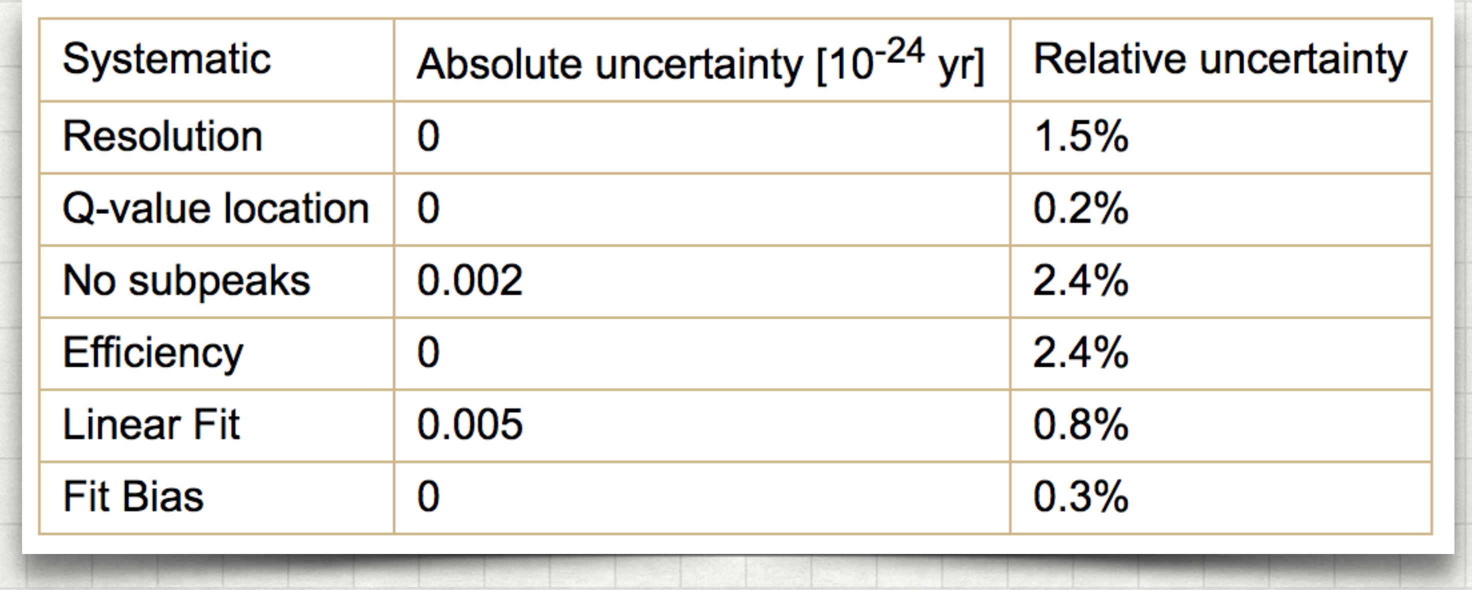
BACKUP

Efficiencies



	ds3518	ds3021
0vBB containment	(88.345 ± 0.085)%	(88.345 ± 0.085)%
Pulser detection	(99.7663± 0.0034)%	(99.7349 ± 0.0035)%
Pulser energy	(99.1677 ± 0.0064)%	(99.218 ± 0.006)%
Base cuts on pulser	(95.6288 ± 0.0088)%	(96.6907 ± 0.0084)%
Multiplicity	(99.4 ± 0.5)%	(100.0 ± 0.4)%
PSA	(91.1± 3.6)%	(98.2 ± 3.0)%
All cuts except containment	(85.67 ± 3.42)%	(93.96 ± 2.89)%

Systematics



Systematic	Absolute uncertainty [10^{-24} yr]	Relative uncertainty
Resolution	0	1.5%
Q-value location	0	0.2%
No subpeaks	0.002	2.4%
Efficiency	0	2.4%
Linear Fit	0.005	0.8%
Fit Bias	0	0.3%