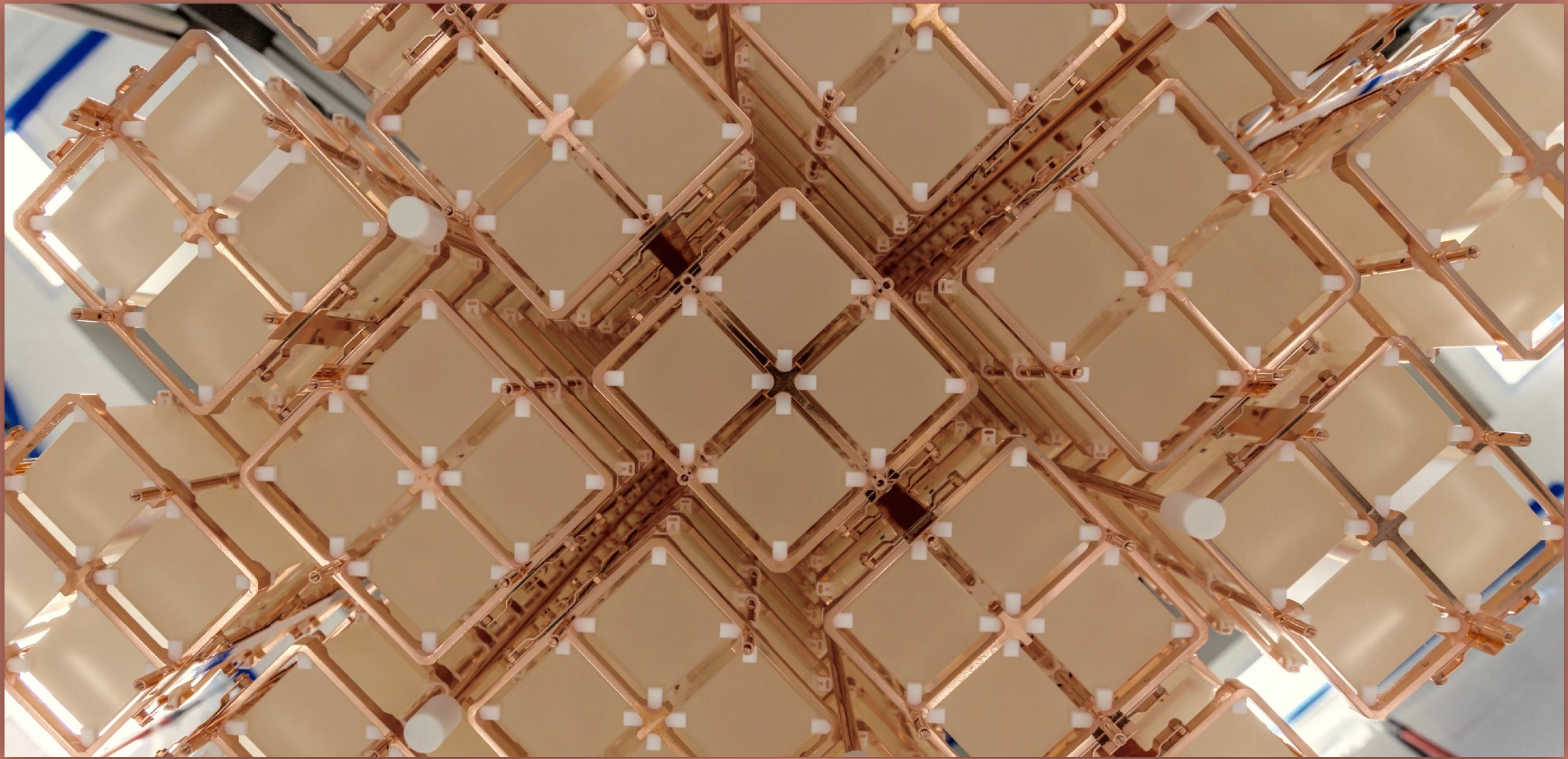
La Thuile 2019 - Les Rencontres de Physique de la Vallée d'Aoste

RESULTS FROM THE CUORE EXPERIMENT

Antonio D'Addabbo

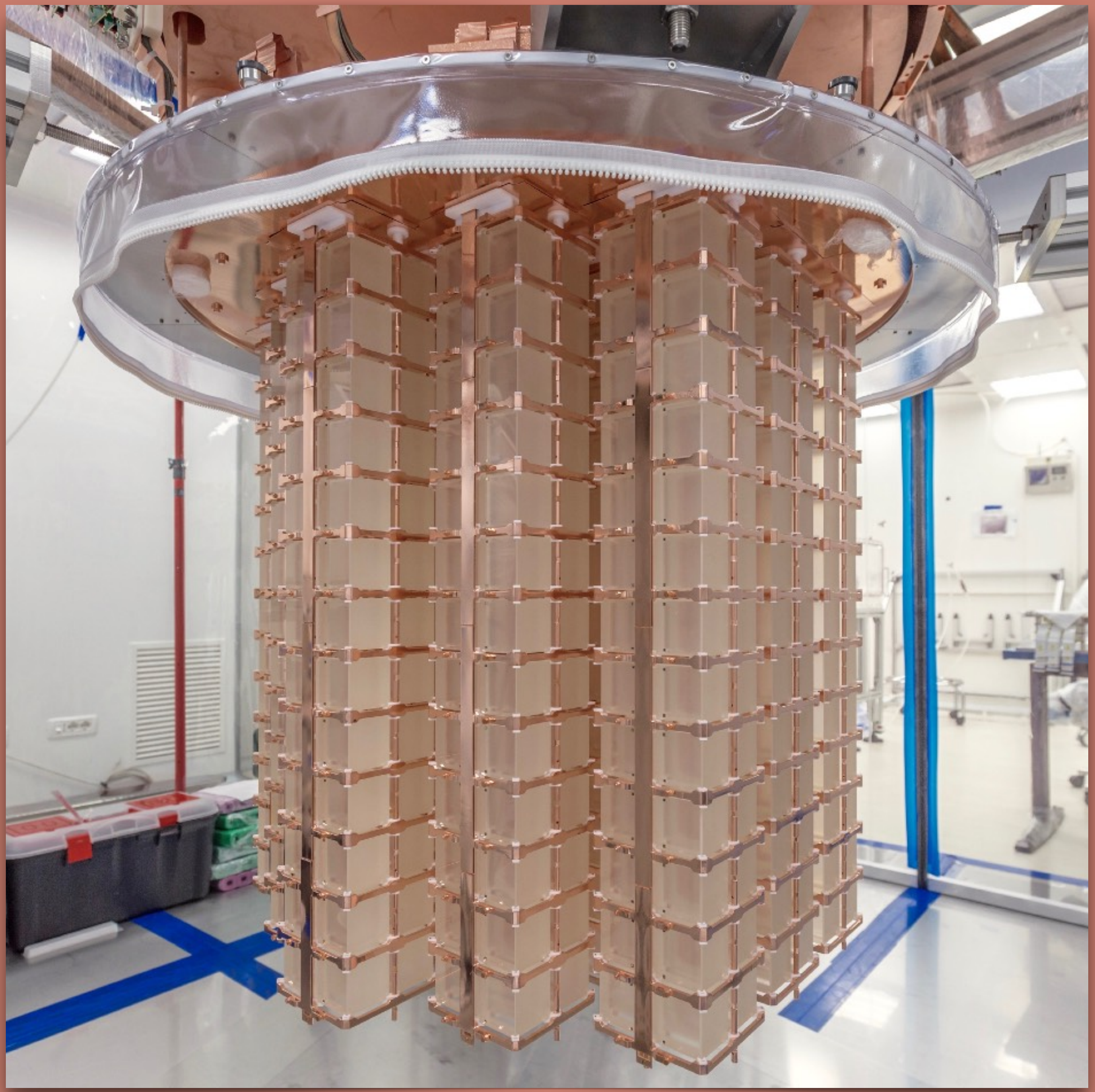
Gran Sasso Science Institute and Laboratori Nazionali del Gran Sasso, on behalf of the CUORE collaboration



OUTLINE

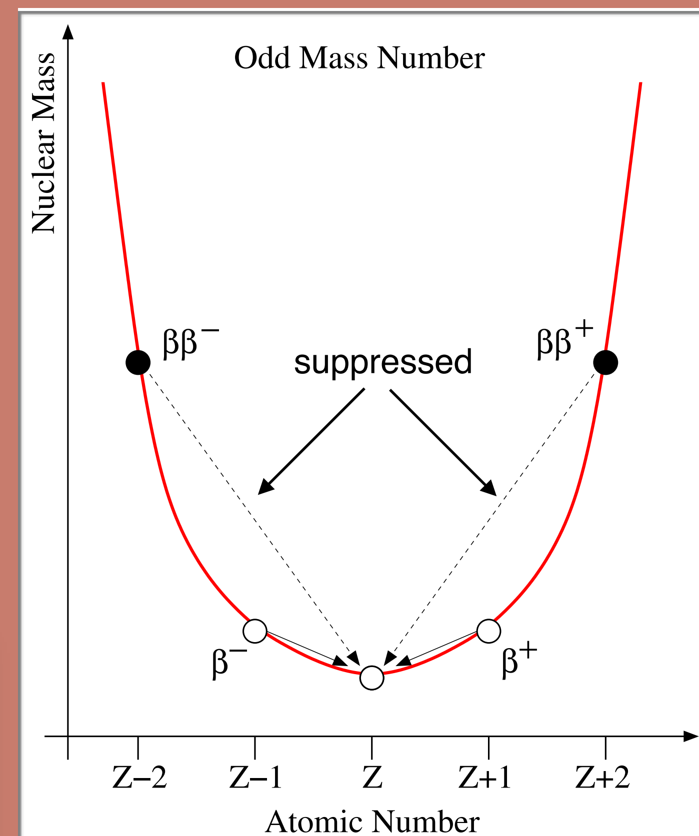
CUORE:
Cryogenic Underground Observatory for Rare Events

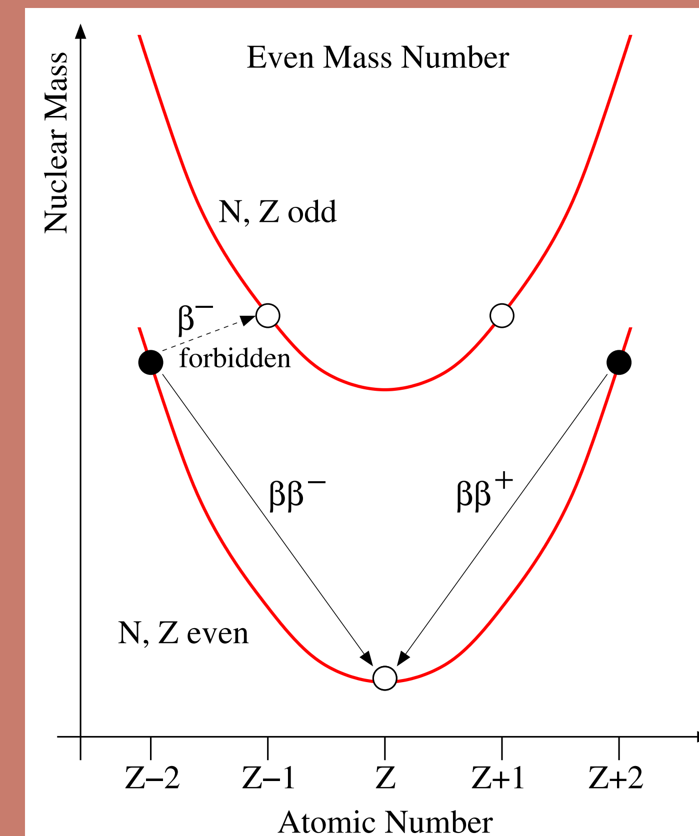
- Double beta decay
- Detector
- Cryostat
- Commissioning
- Detector optimization
- Data analysis
- Results
- Conclusion

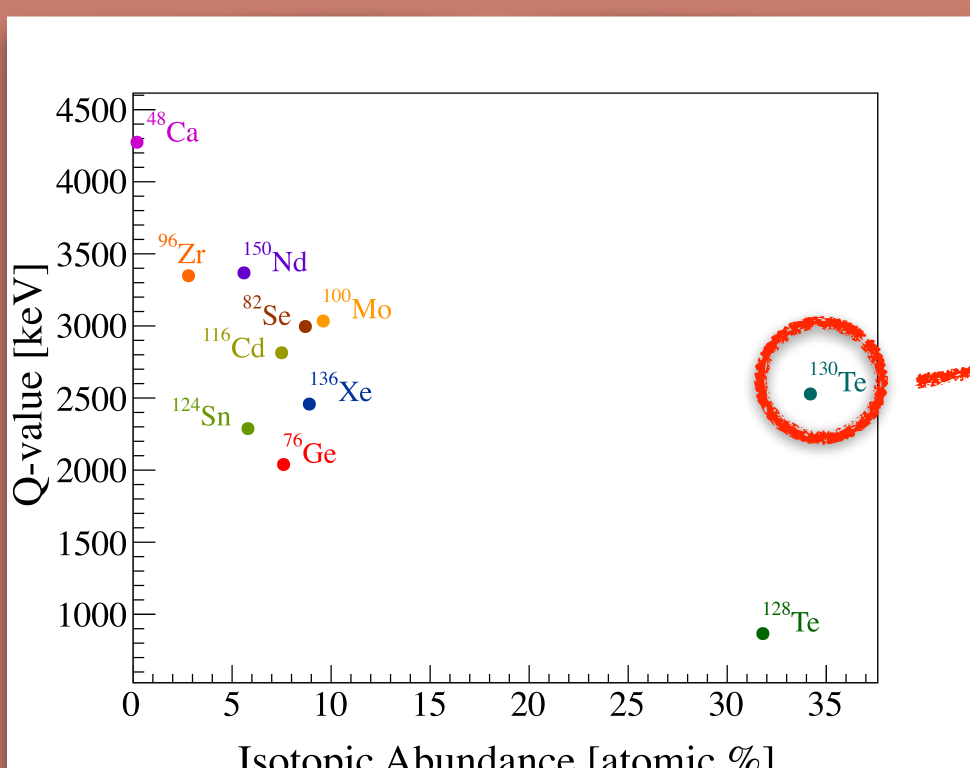


DOUBLE BETA DECAY

Double Beta Decay (ββ) is a second order weak interaction, directly observable only for few nuclei







The isotope of interest for the CUORE experiment is ^{130}Te

- high isotopic abundance (34.17%)
- ^{130}Te within the detector absorber of TeO_2
- reproducible growth of high quality crystals
- Q-value of 2527.515 ± 0.013 keV

DOUBLE BETA DECAY

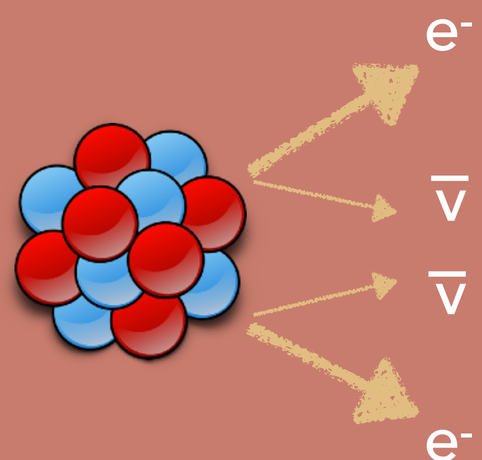
Signature:

peak at the Q-value of ^{130}Te ββ decay

ββ summed e⁻ energy spectrum in ^{130}Te

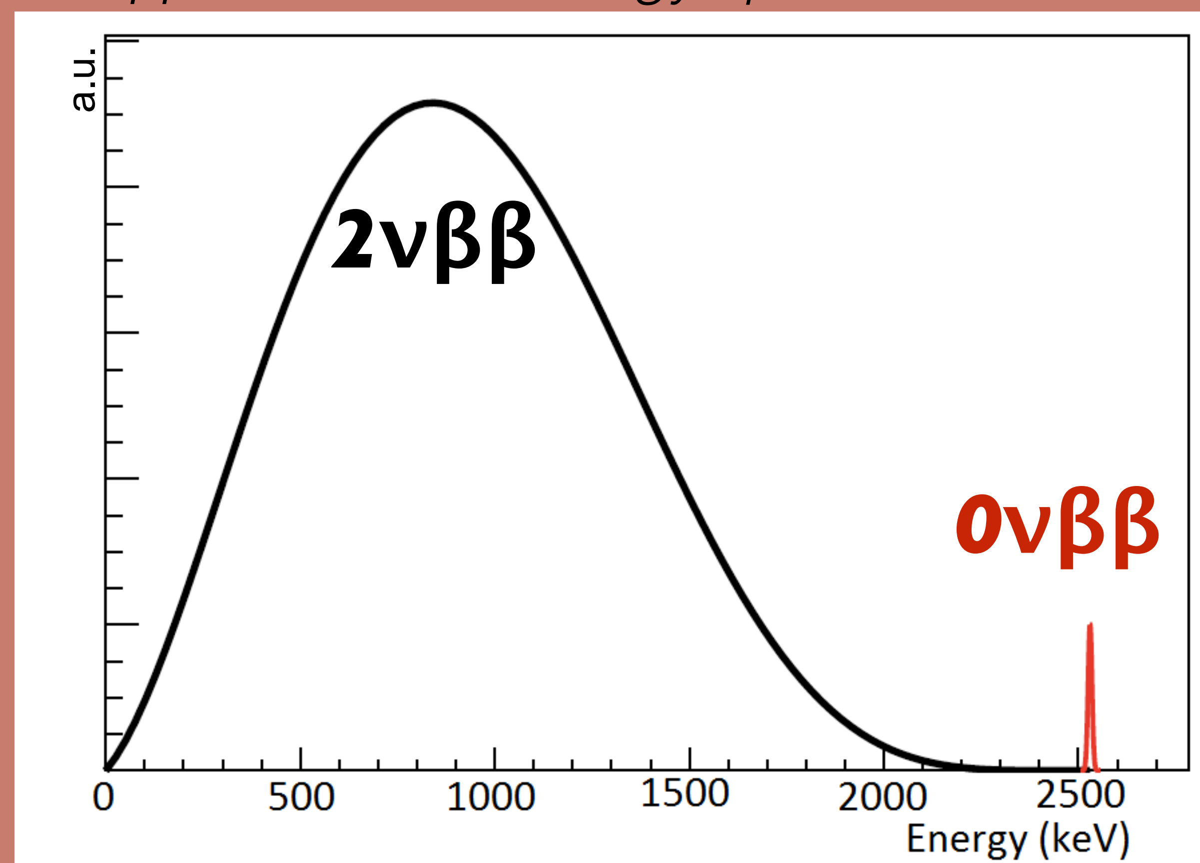
2νββ with neutrinos

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



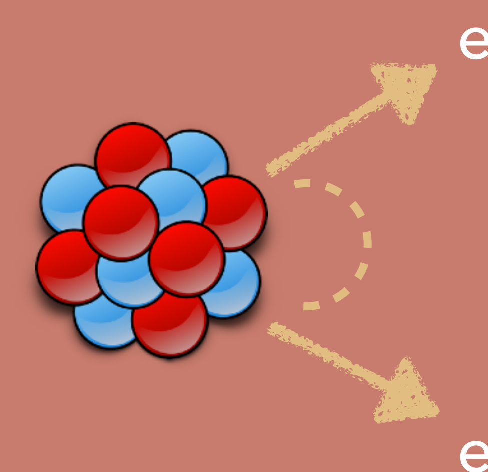
- Allowed by SM (ΔL = 0)
- Observed in several nuclei

$\tau_{1/2} \sim 10^{19\text{-}21}$ years



0νββ neutrinoless

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



- Beyond by SM (ΔL = 2)
- Never observed to date

$\tau_{1/2} > 10^{25\text{-}26}$ years

Implication in 0νββ decay observation:

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

CHALLENGES

Sensitivity: $T_{1/2}^{0\nu} \propto \sqrt{\frac{Mt}{b\Delta E}}$

M: isotope mass
t: live time
b: background index
ΔE: energy resolution

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

high energy resolution

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

low background

- strict radiopurity criteria on material selection and assembly chain
- passive shields from external and cryostat radioactivity

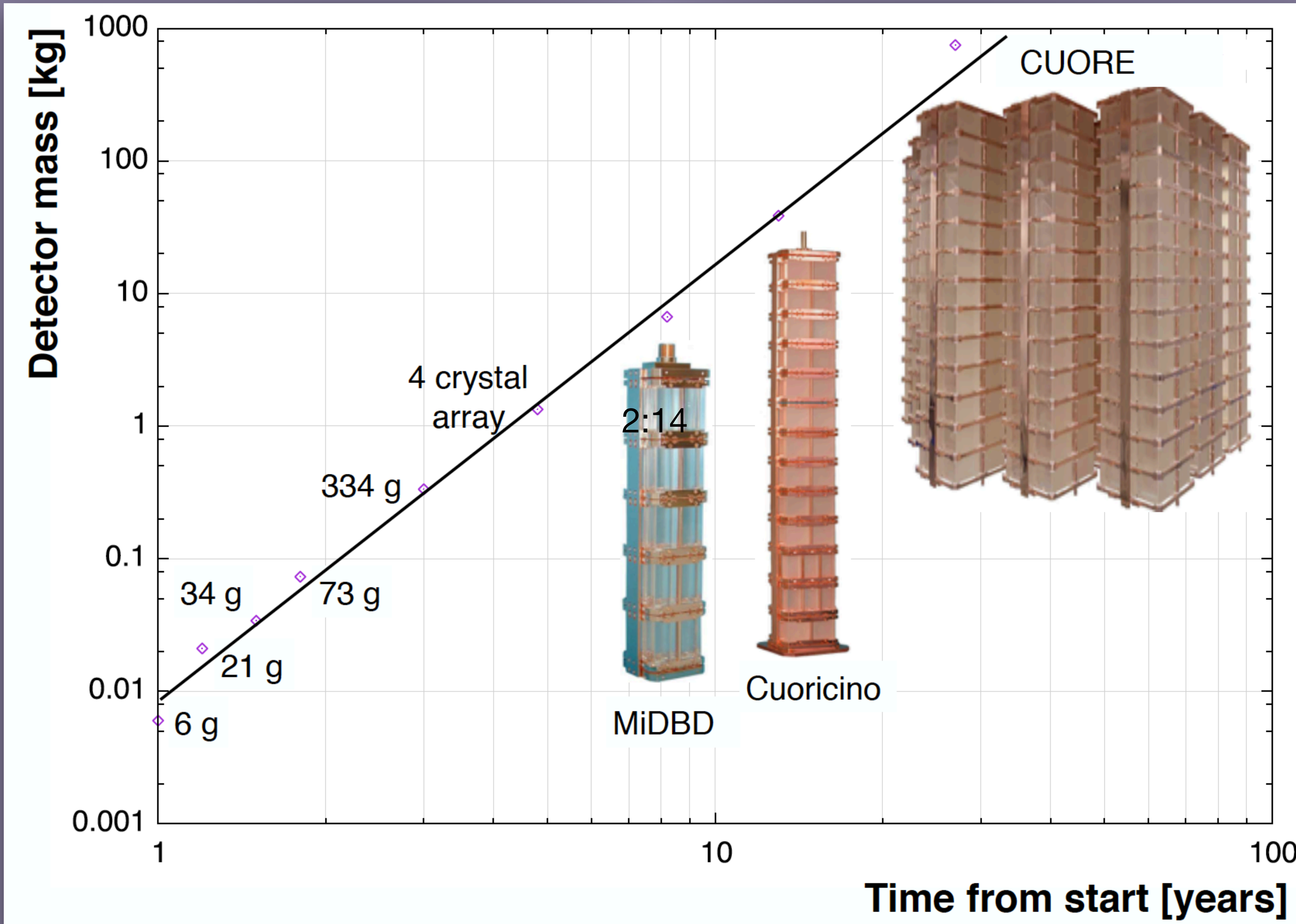
Goals: ~ 1 ton year | 5 keV FWHM | 0.01 counts/keV/kg/yr

$$m_{\beta\beta} \equiv \left| \sum_i U_{ei}^2 m_i \right|$$

Goal: $T_{1/2}$ (90% C.L.) > 9 x 10^{25} yr
$\langle m_{\beta\beta} \rangle$ 45 - 210 meV

European Physical Journal C 77.532 (2017)

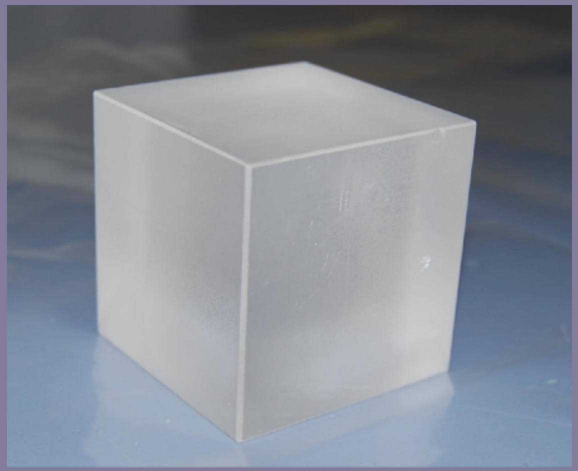
CUORE: A LONG HISTORY



CUORE DETECTOR

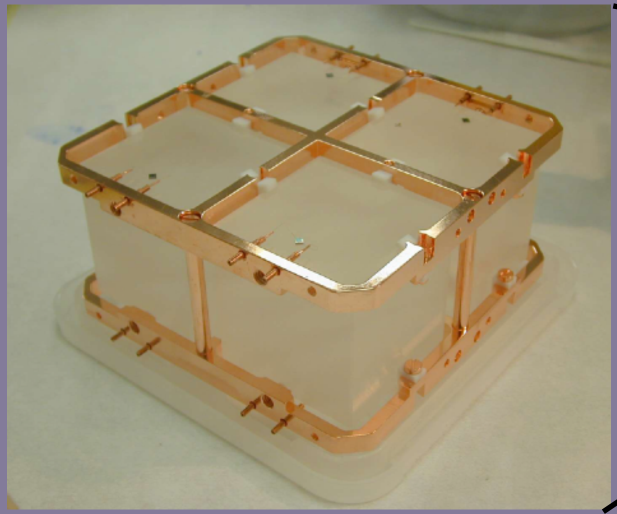
TeO2 cryogenic bolometers

$5 \times 5 \times 5$ cm^3 and 0.75 kg each



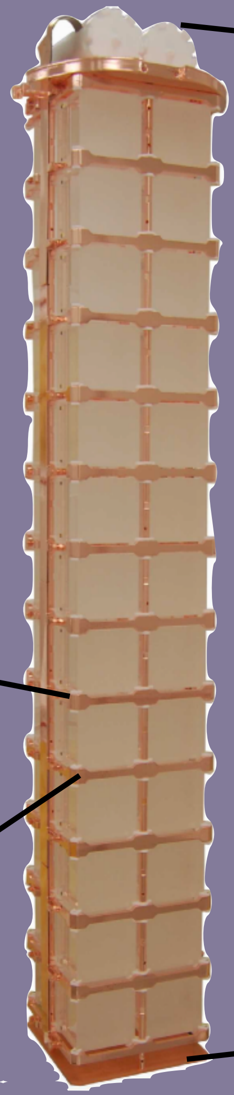
SINGLE TeO_2 CRYSTAL

4 TeO_2 crystals



FLOOR

52 TeO_2 crystals arranged in 13 floors



TOWER (CUORE-0 like)

Closely packed array of 988 TeO_2 crystals arranged in 19 towers

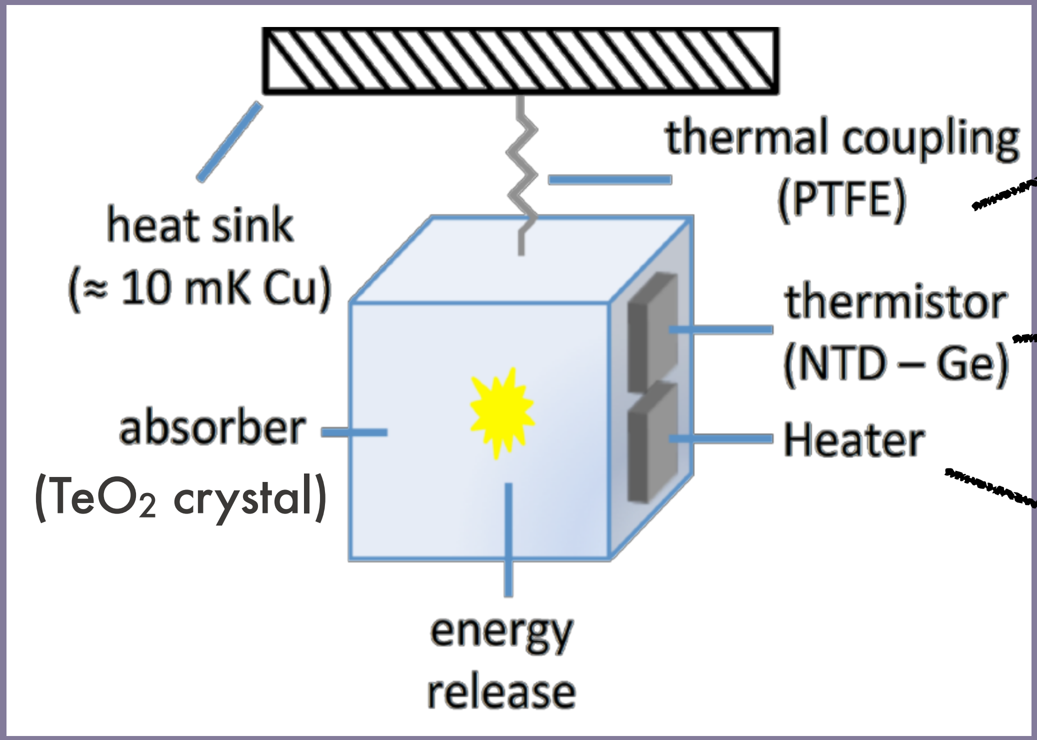
DETECTOR ARRAY

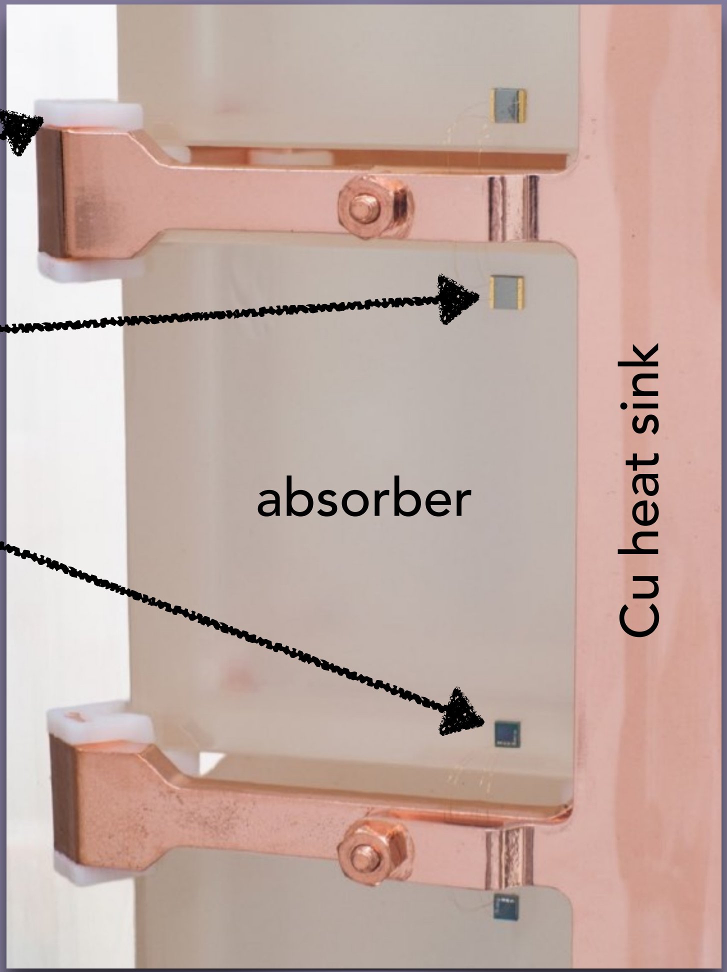
CUORE DETECTOR

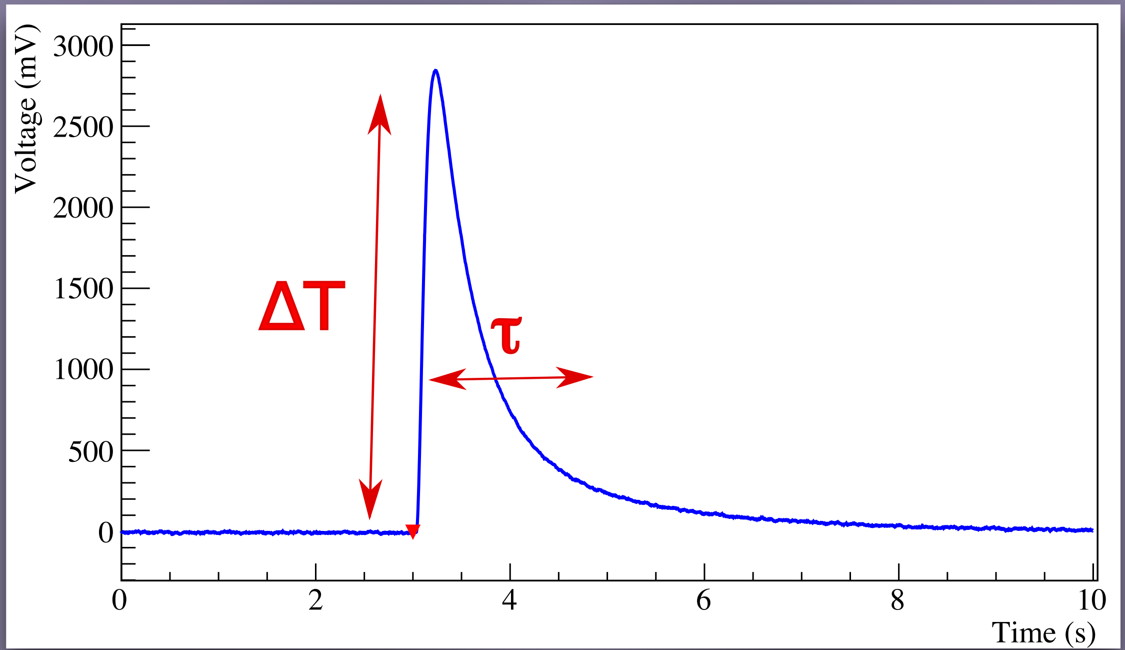
TeO2 cryogenic bolometers

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

The absorber and the thermistor are optimized to work at 10mK







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

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

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

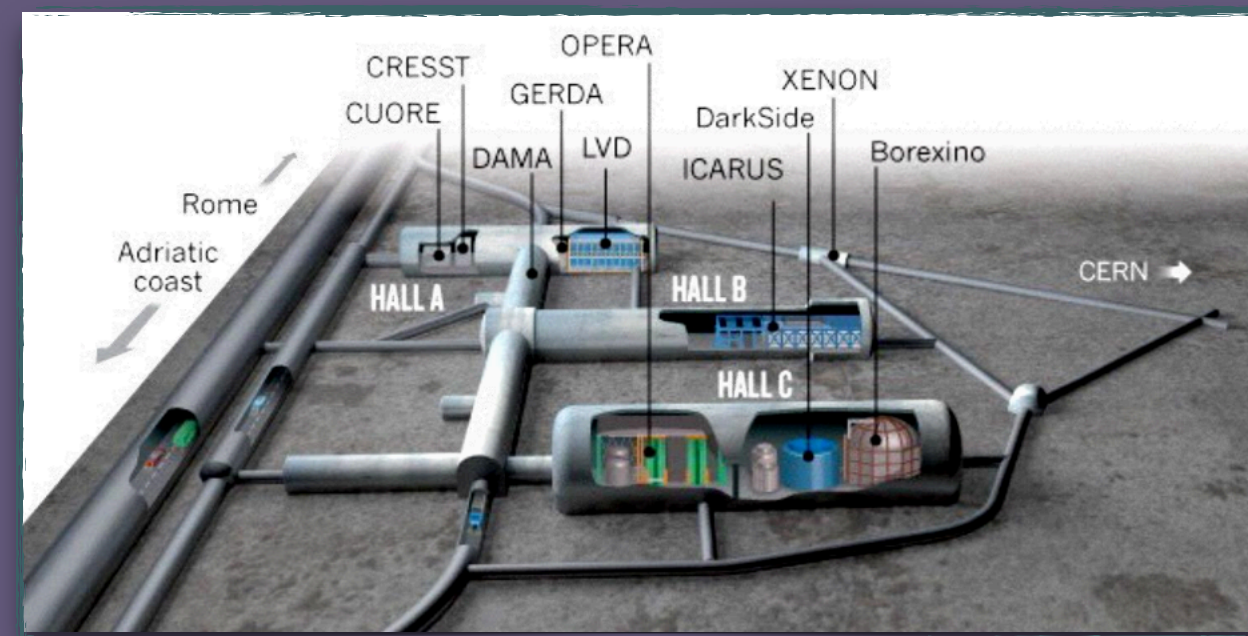
$$R(T) = R_0 e^{\sqrt{T_0/T}}$$

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

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: ~$3x10^{-8}$/(s cm^2) - 10^{6}. less than above ground
- γs: ~0.73/(s cm^2)
- neutrons: < $4x10^{-6}$ n/(s cm^2)

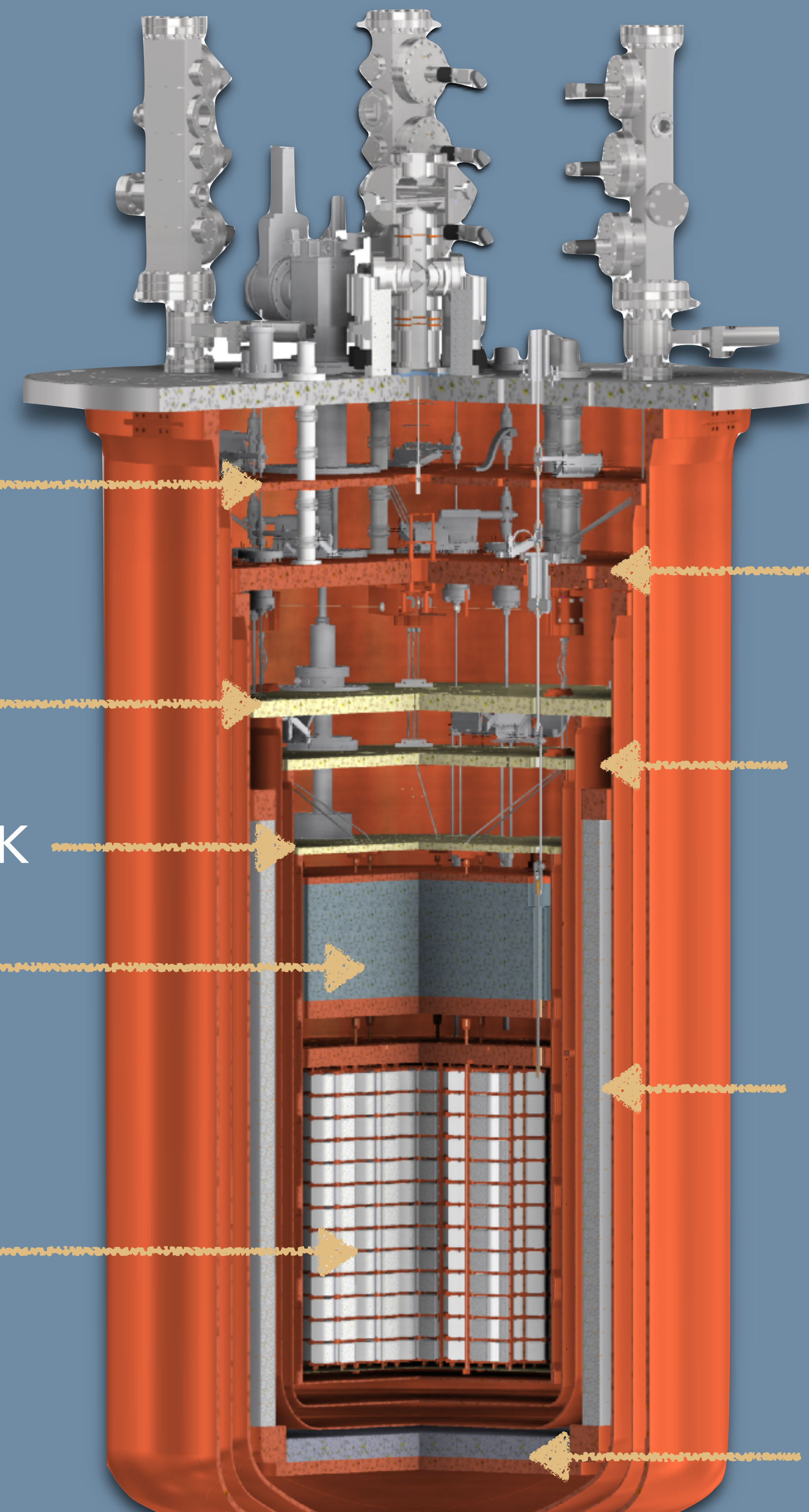
CUORE

CRYOGENIC INFRASTRUCTURE

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

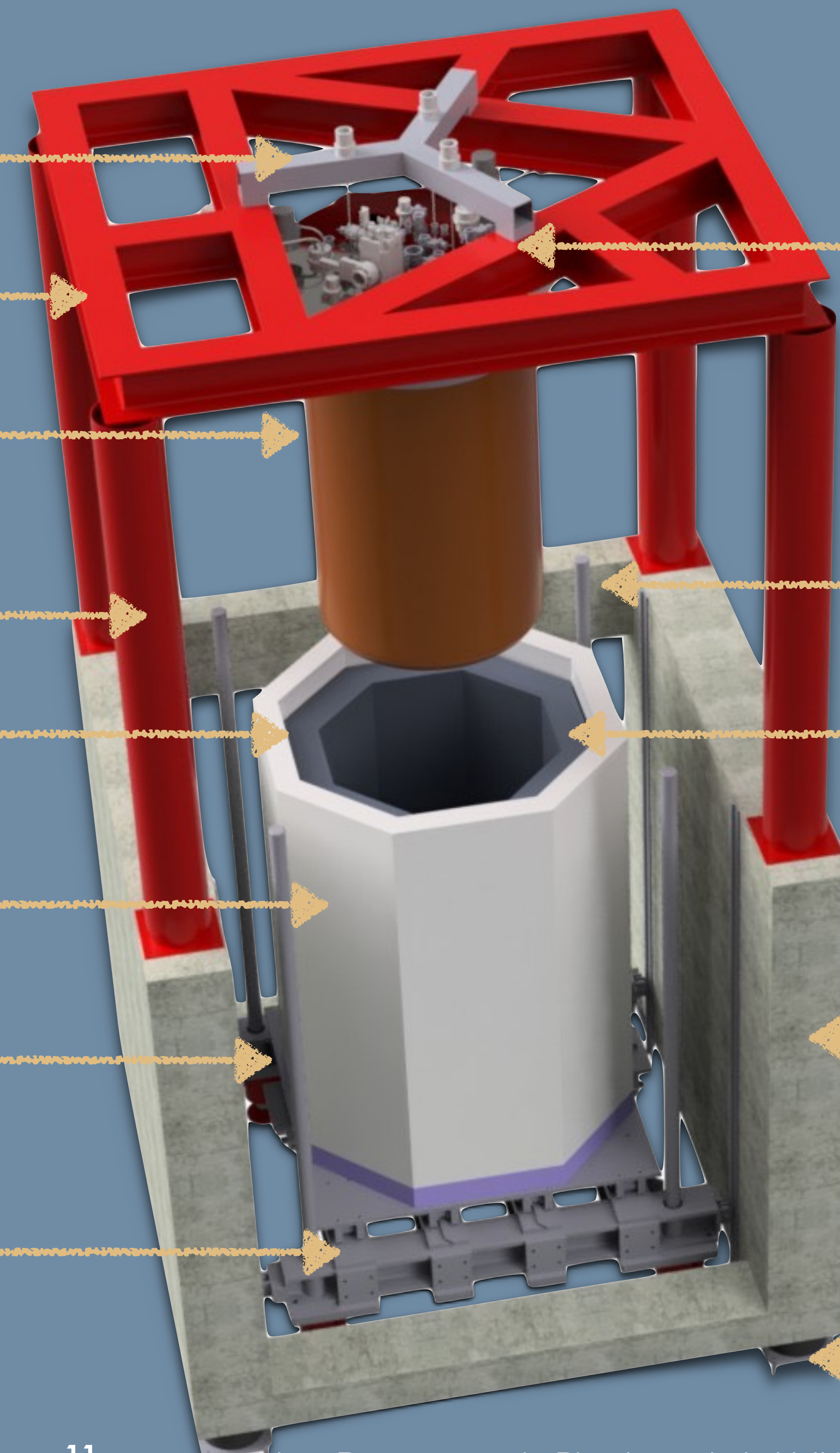
- Mass to be cooled < 4K: ~15 tons (Pb, Cu and TeO_2)
- Operating temperature 10 mK
- Designed to guarantee extremely low radioactivity and low vibrations environment
- Biggest dilution cryostat in the world

paper in preparation

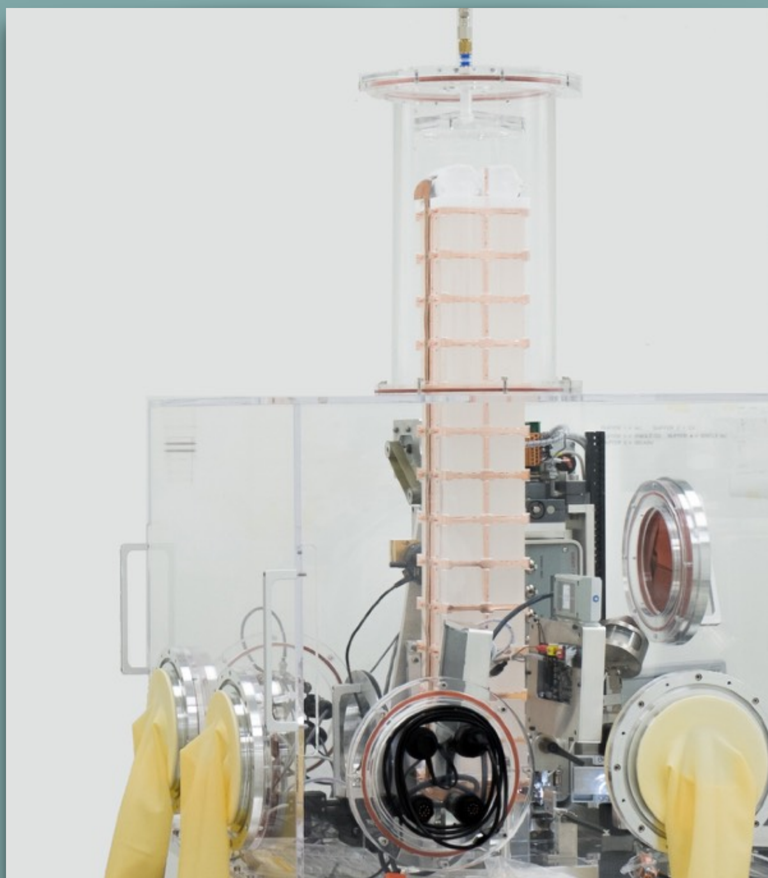


CUORE

CRYOGENIC INFRACTRUCTURE



COMMISSIONING

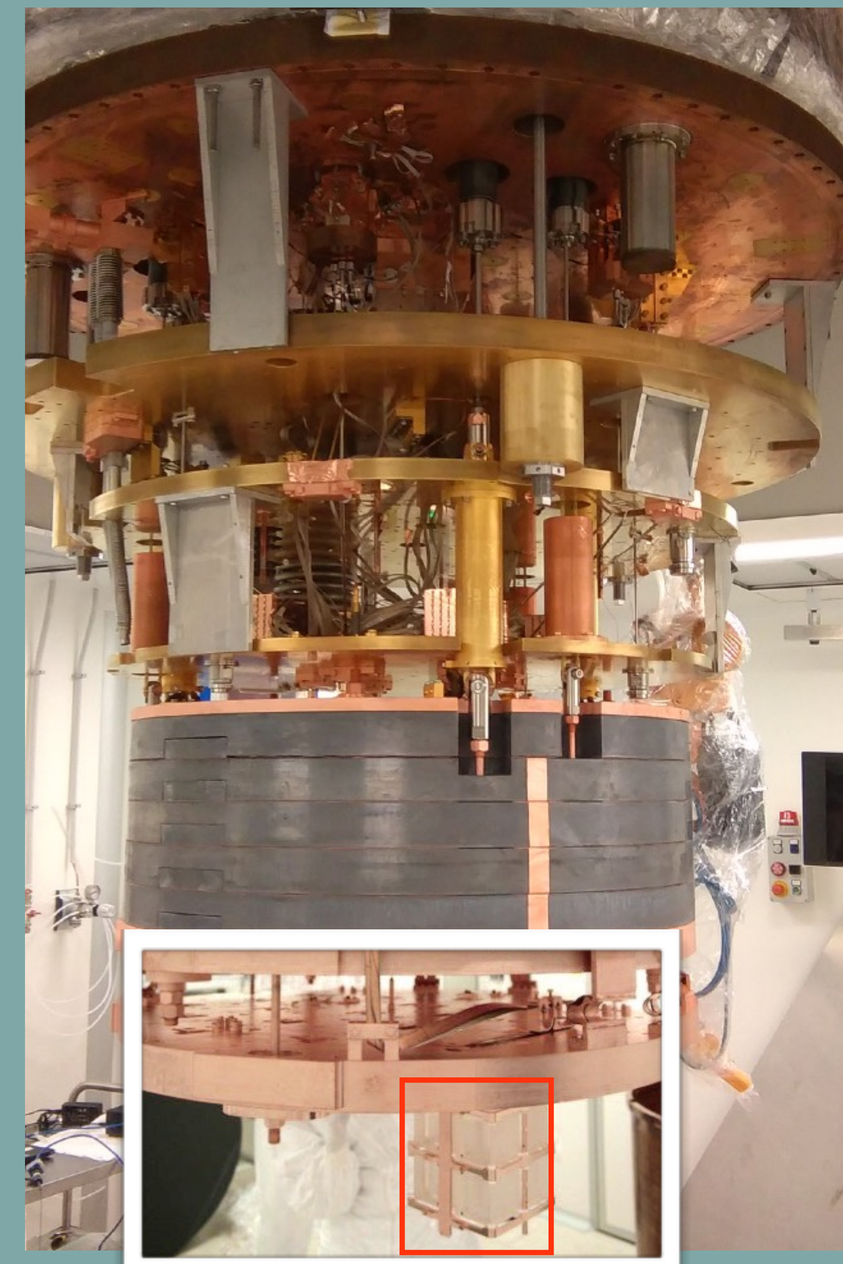


Tower assembly performed in N_2 atmosphere to prevent contamination from Rn

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

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

The ingots stayed under water for centuries, loosing their radioactive components. The ingots have been recasted in a clean environment.

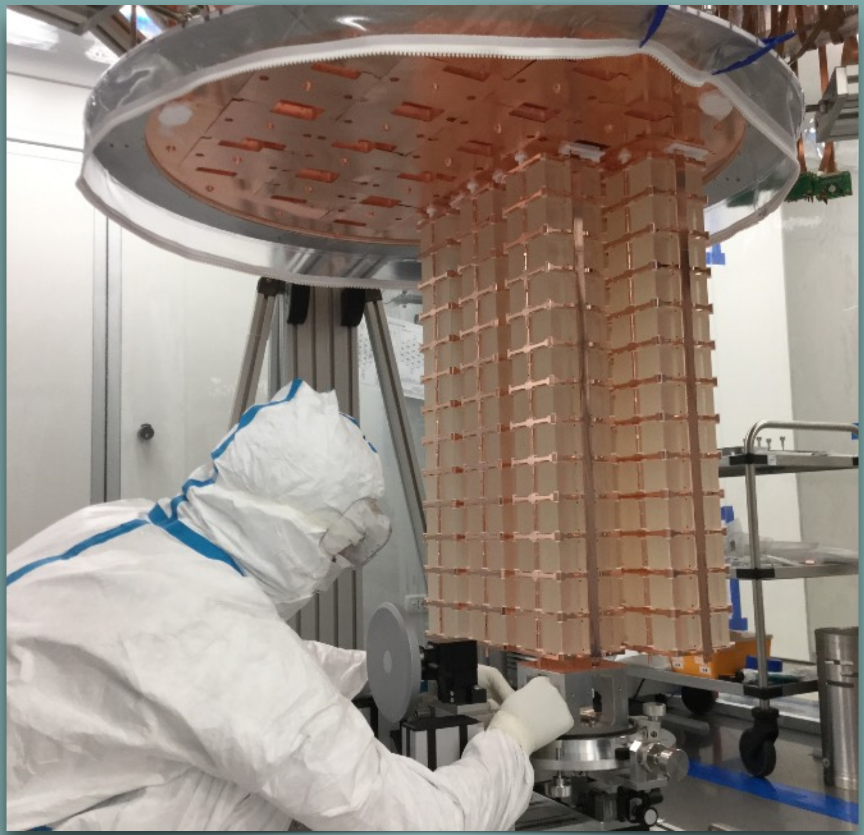


Cryogenic system commissioning completed in March 2016:

- Stable base temperature @ 6.3mK
- Cooling power: > 3μW @10mK

COMMISSIONING

towers installation
July - August 2016



The 19 towers were installed in a radon free clean room.
It took about one month.
Only 4 out of 988 channels were lost during the installation.
In September 2018 we were ready to cool down.

COOL DOWN

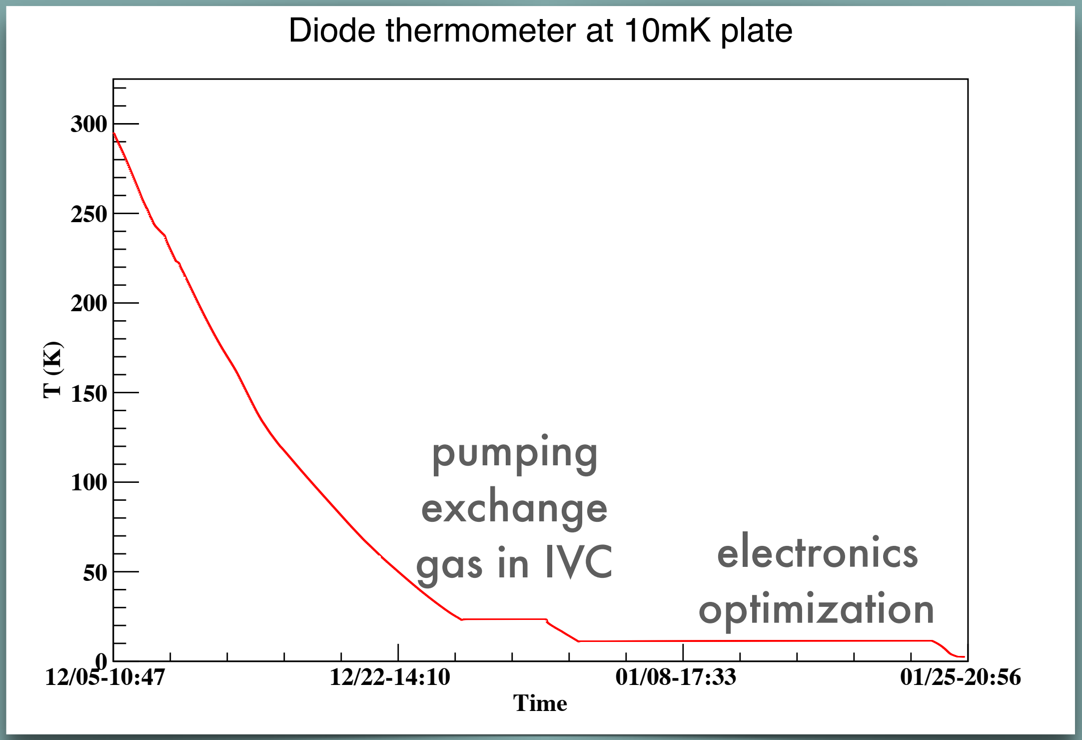
The cool down of the cryostat started in December 2016

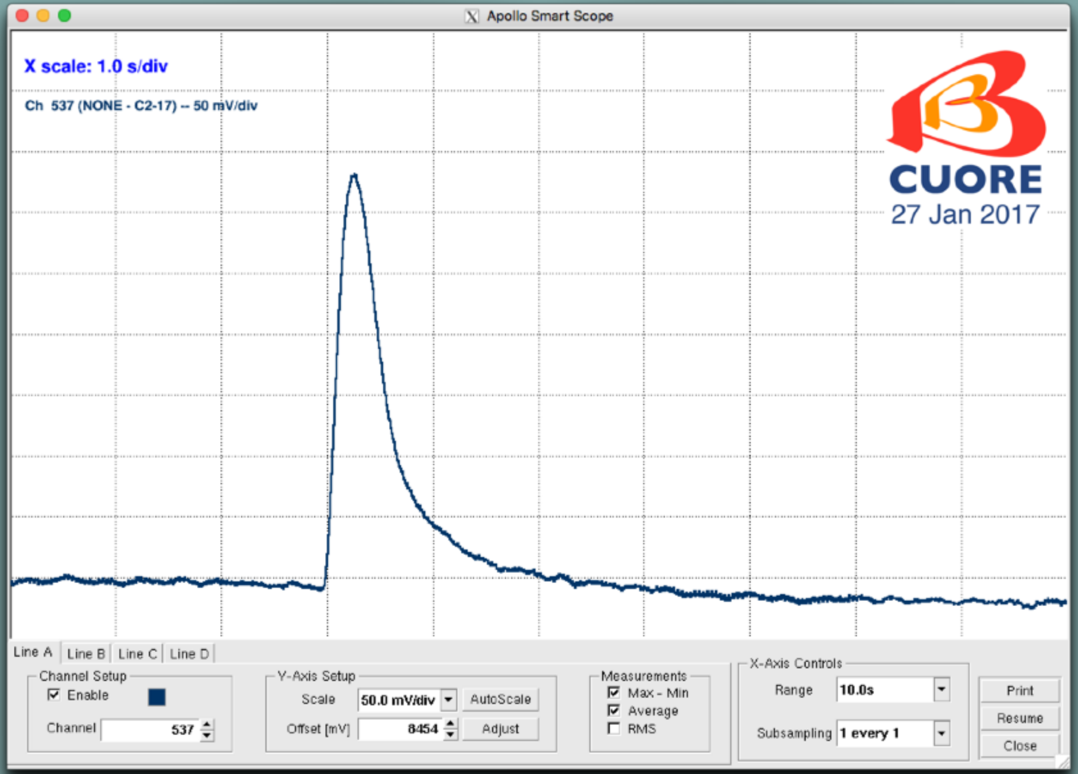
First phase with dedicated Fast Cooling System, introduction of He exchange gas prior to the start of Pulse Tubes, then pulse tubes only.

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!



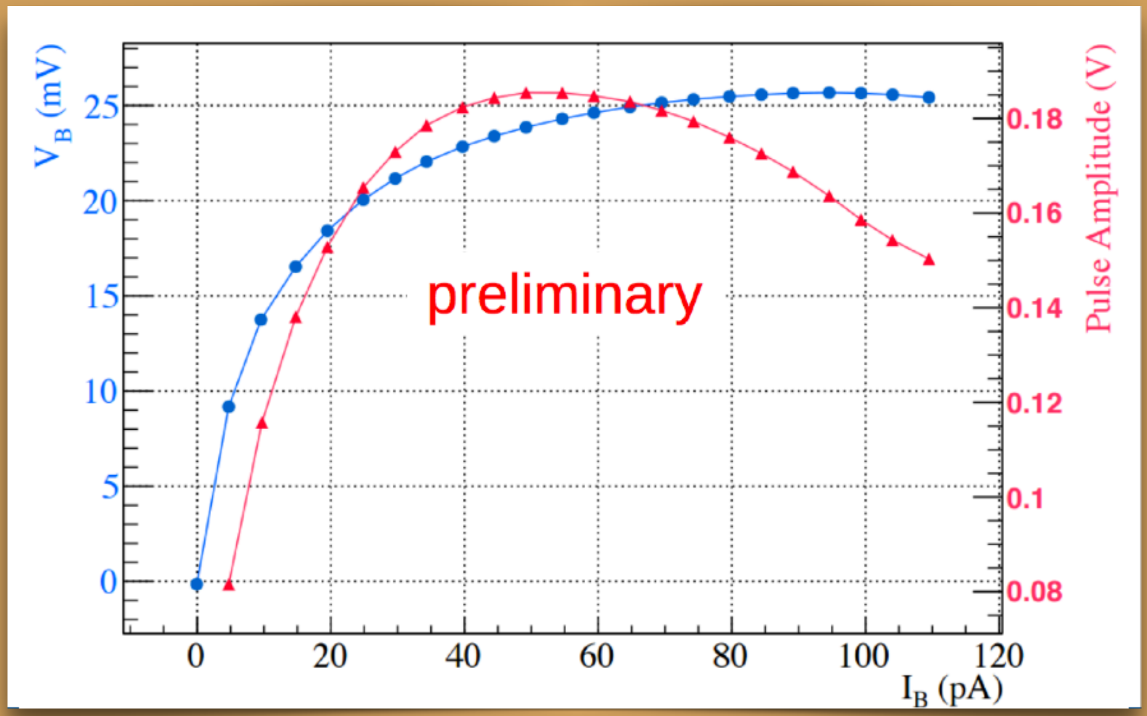


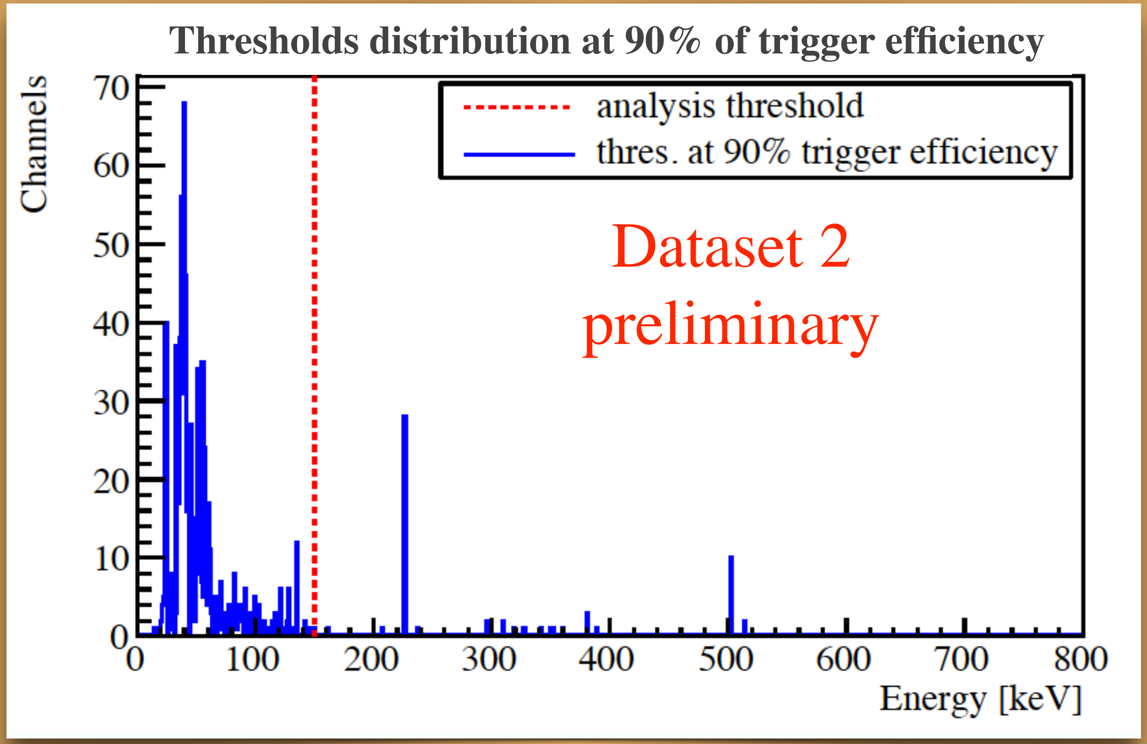
DETECTOR OPTIMIZATION

Temperature scan:
Chose temperature that optimises the signal and at the same time allows to work with the designed thermistor resistance
(this analysis @ **15 mK**)

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





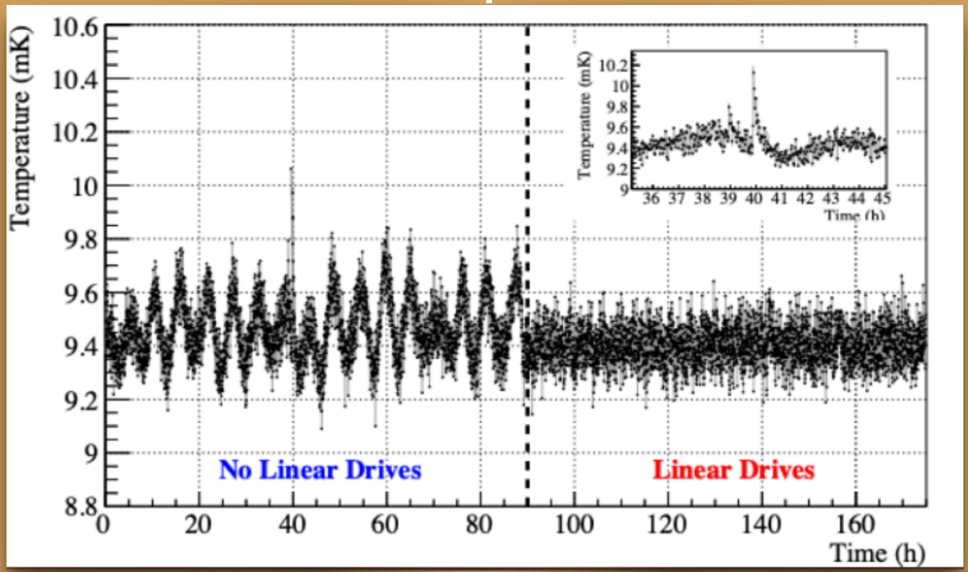
DETECTOR OPTIMIZATION

The Cryostat is cool down to 4K by 5 Pulse Tubes that induce vibrations at 1.4 Hz and harmonics.

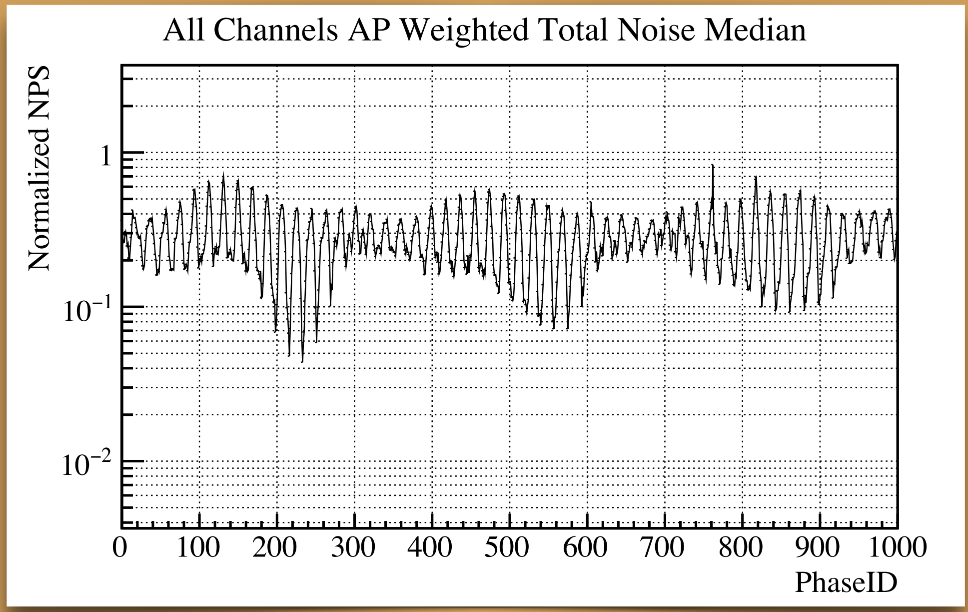
Attenuation of Pulse tube induced vibrations:

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
3. Drive the PT at the minimum noise phase configuration

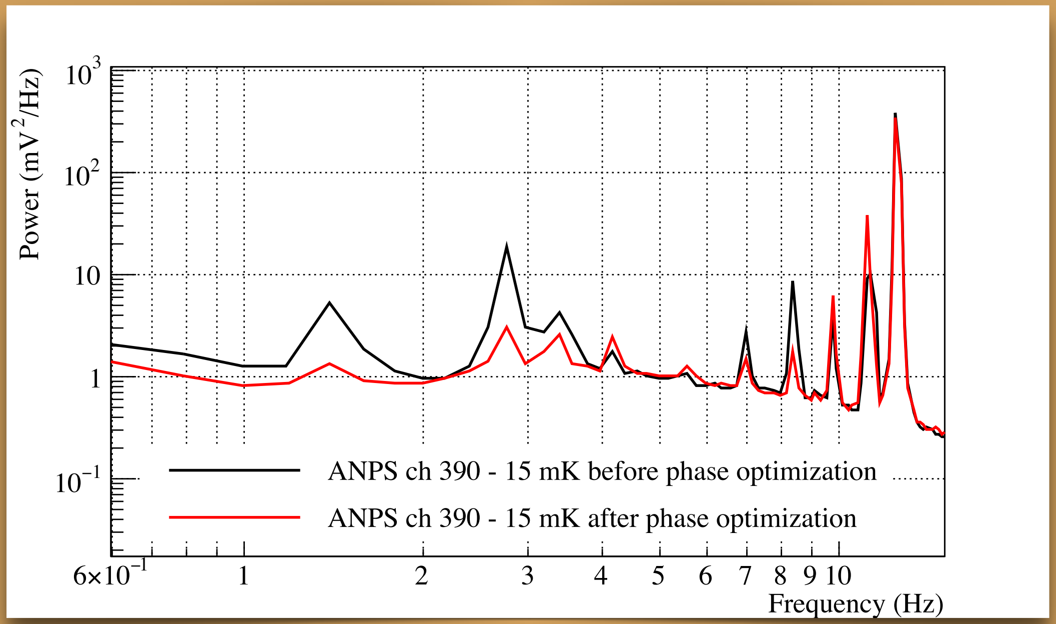
Base temperature



Noise level on the detector



Single channel NPS comparison

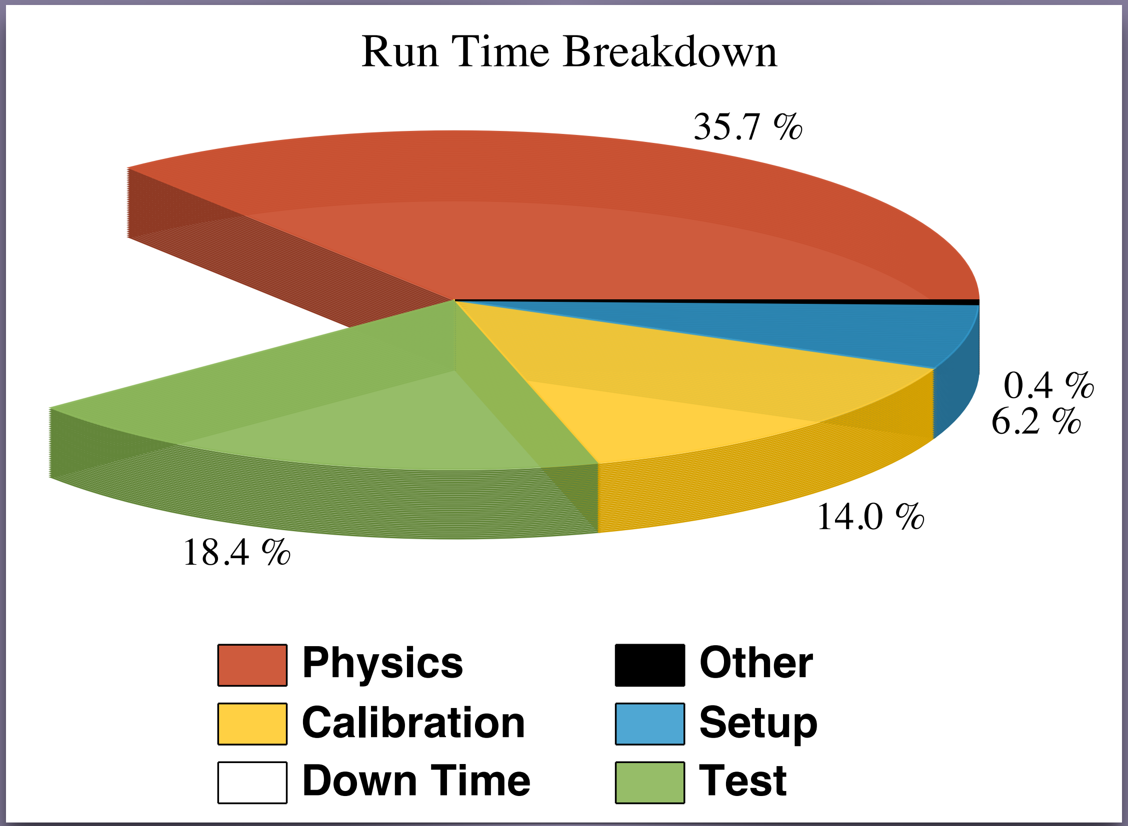


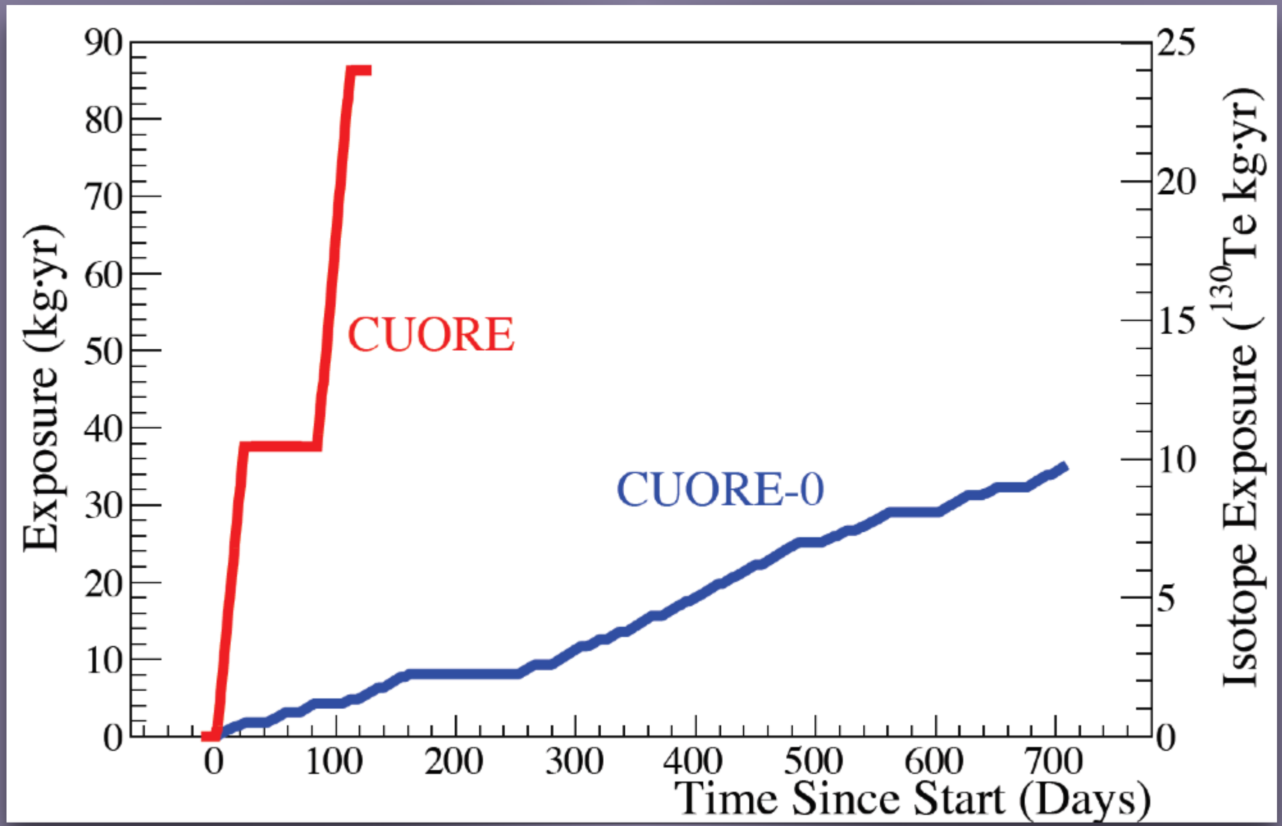
PT phase optimization changes noise by an order of magnitude!

Cryogenics 93 (2018) 56–65

DATA TAKING

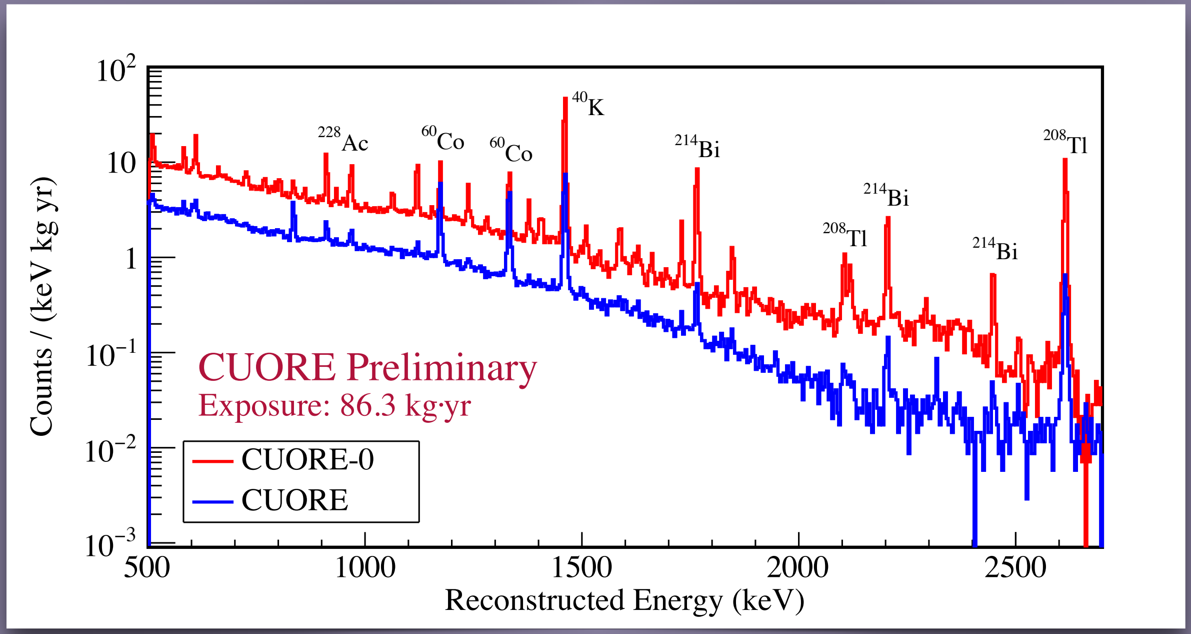
- CUORE surpassed CUORE-0 exposure in about 3 weeks of data taking
- Collected 86.3 kg·yr of TeO_2 over 7 weeks in summer 2017 (splitted in two datasets)
- 99.6% of channels active (984/988)
- 92% of channels passing analysis cuts
- Energy resolution of 7.7 keV FWHM
- Signal efficiency of ~80%
- Average rates per channel:
  calibration: ~50 mHz, physics: ~6 mHz



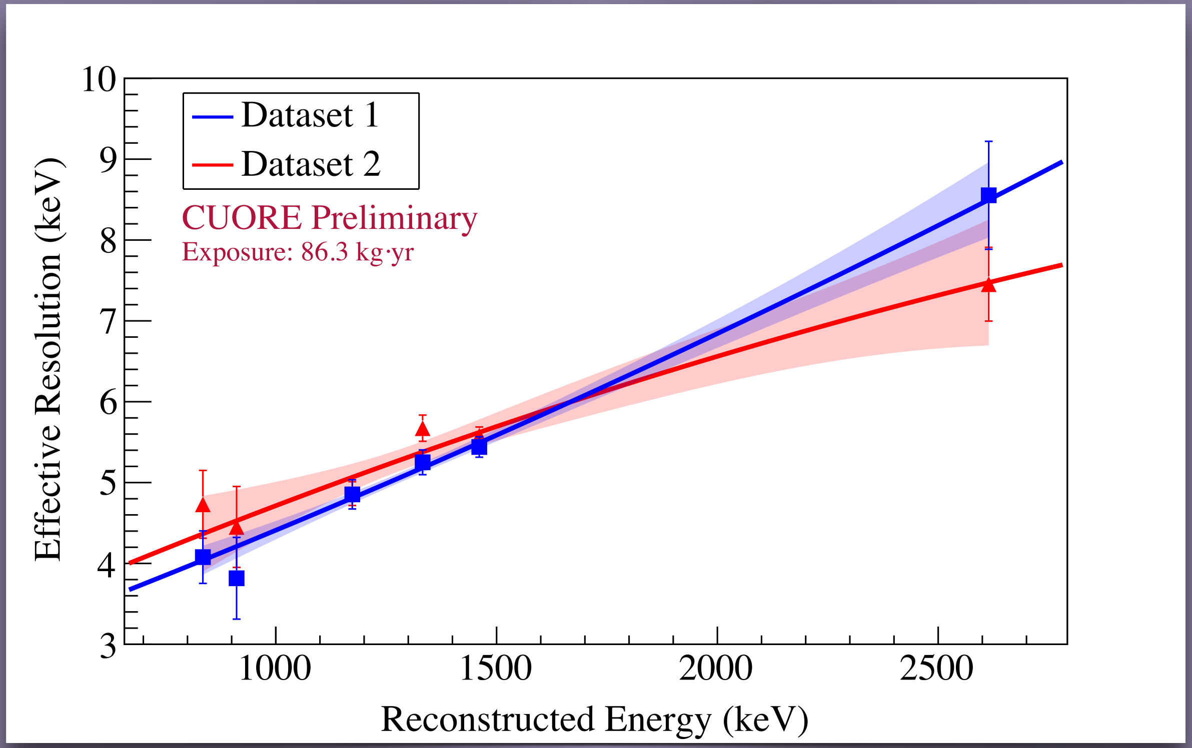


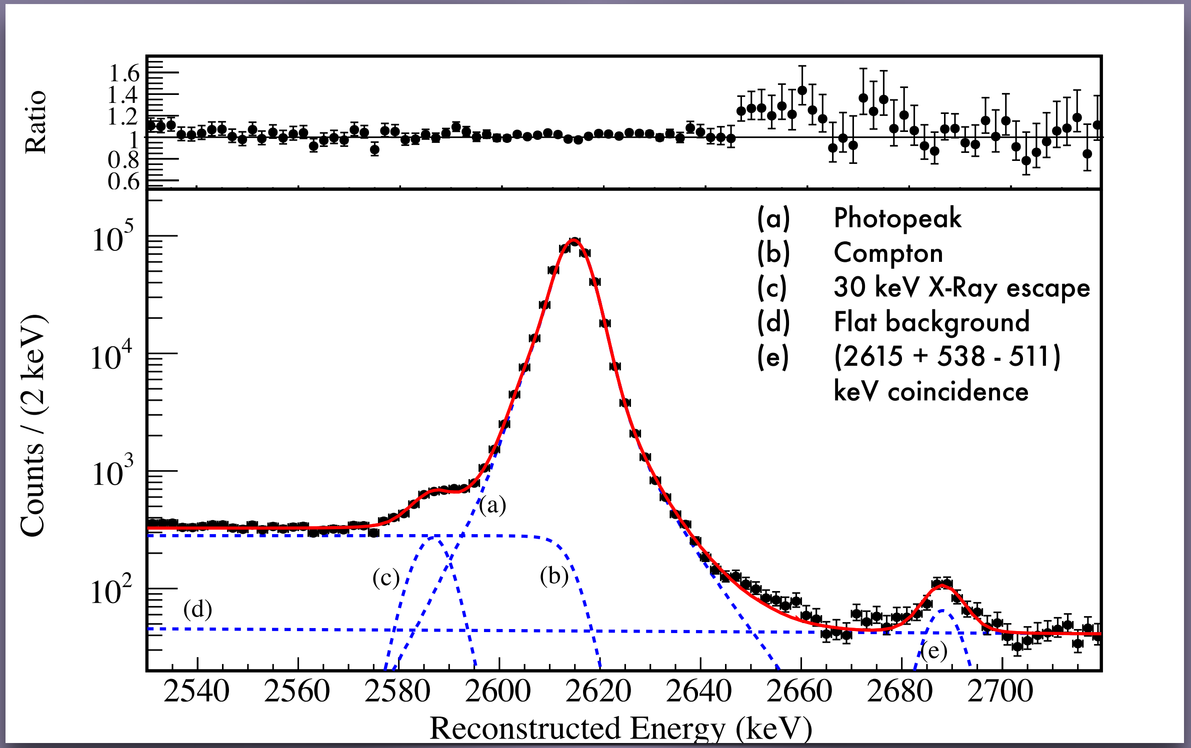
DATA ANALYSIS

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



Sum on all towers of the line shape fit



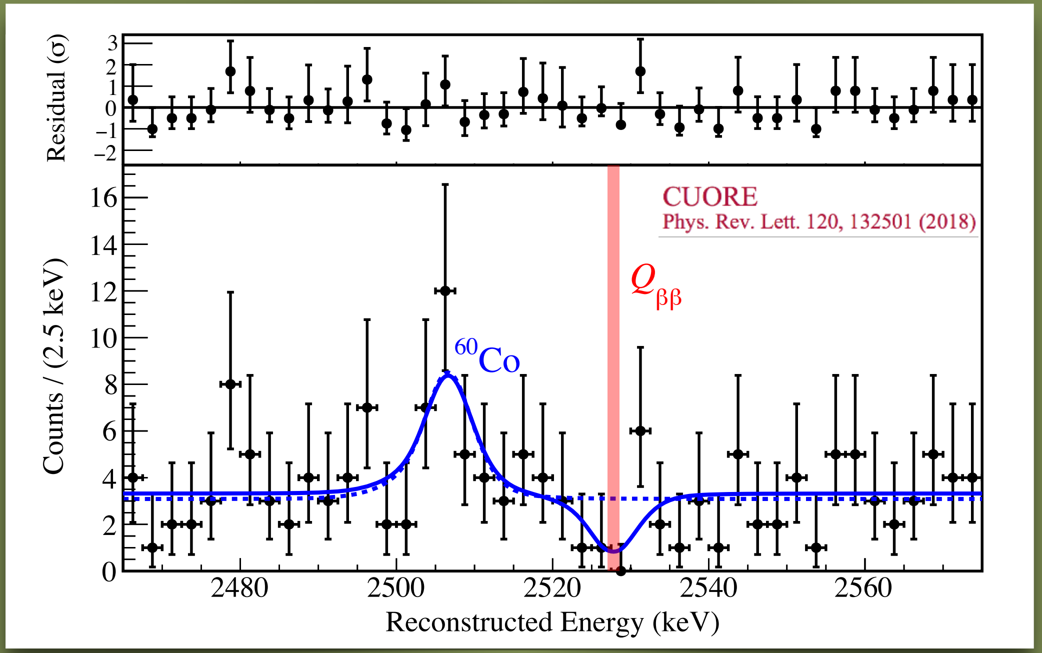


RESULTS

Search for 0νββ of ^{130}Te

UEML fit in the ROI (2465 - 2575) keV:

- ^{60}Co peak position: (2506.4 ± 1.2) keV
- Background index is consistent with expectations (1.4 ± 0.2) x 10^{-2} cnts/(keV·kg·yr)
- Median expected sensitivity $T^{0\nu}_{1/2}$ = 7.0 x 10^{24} yr
- Signal decay rate best fit: $\Gamma_{0\nu} = (-1.0\ ^{+0.4}_{-0.3}\ (stat) \pm 0.1\ (syst)) \times 10^{-25}\ yr^{-1}$



Combined limit (CUORE+CUORE-0+Cuoricino):

$T^{0\nu}_{1/2} > 1.5 \times 10^{25}$ yr

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

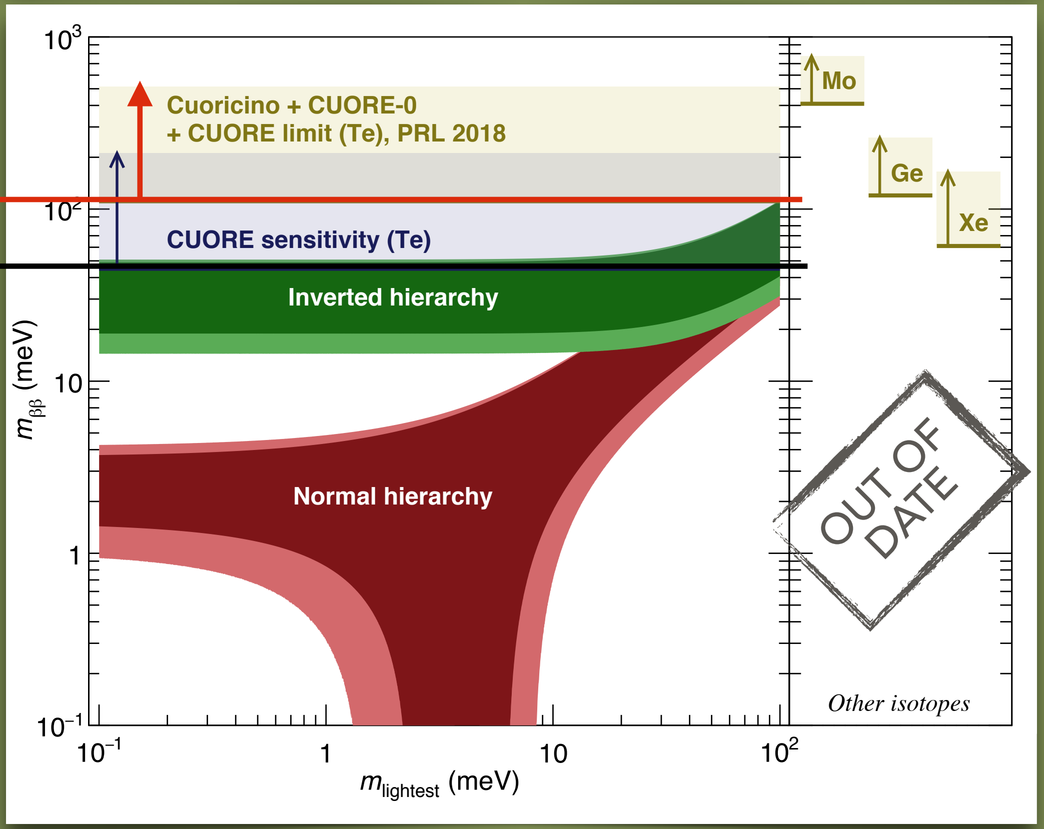
PRL 120, 132501 (2108)

$$m_{\beta\beta} \equiv \left| \sum_i U_{ei}^2 m_i \right|$$

CUORE sensitivity in 5 yr:

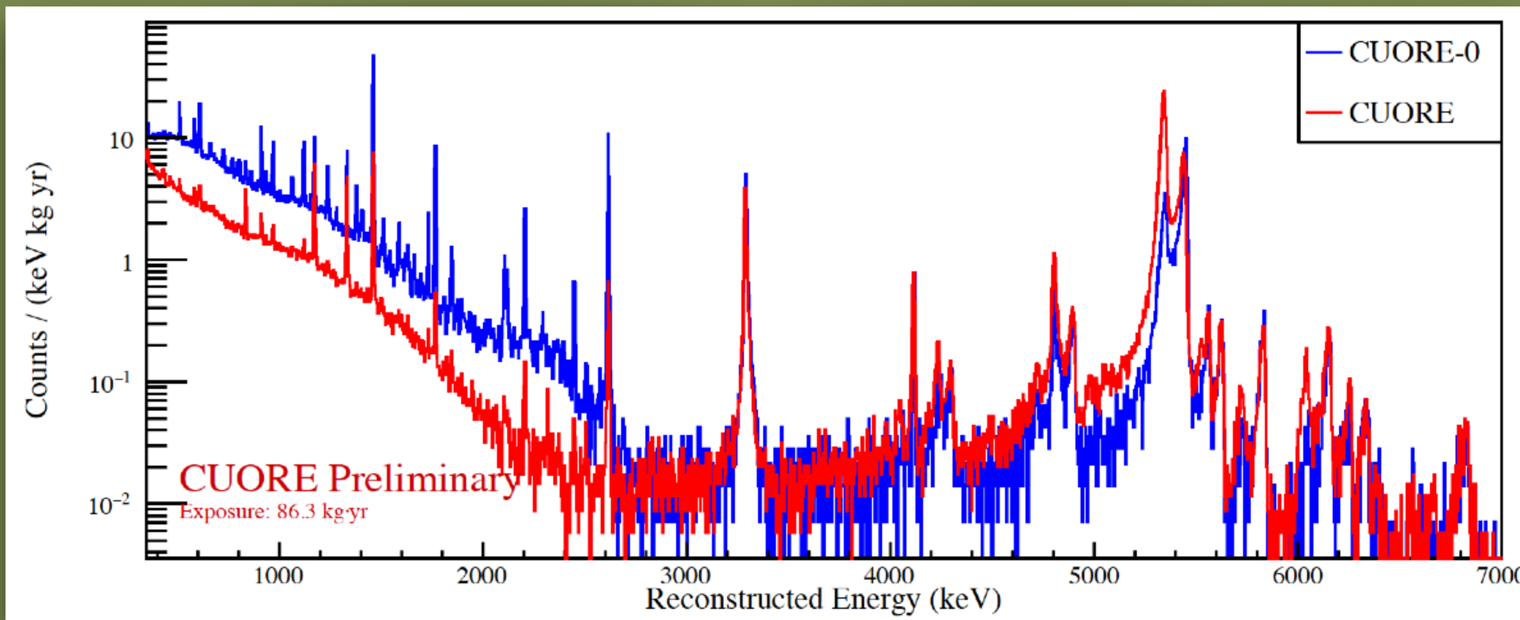
$T^{0\nu}_{1/2} > 9.0 \times 10^{25}$ yr

$m_{\beta\beta} < 45 - 210$ meV

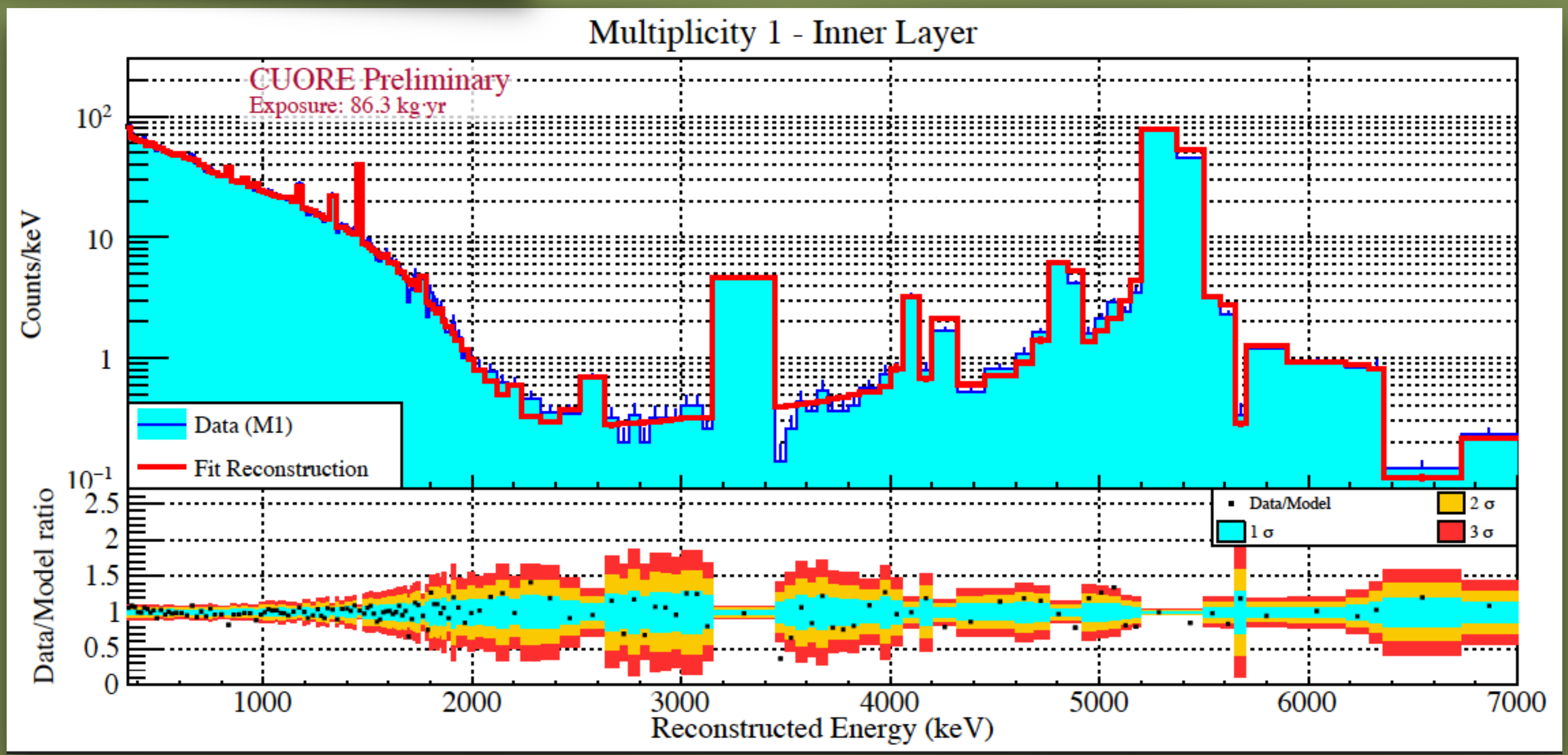


RESULTS

Background model



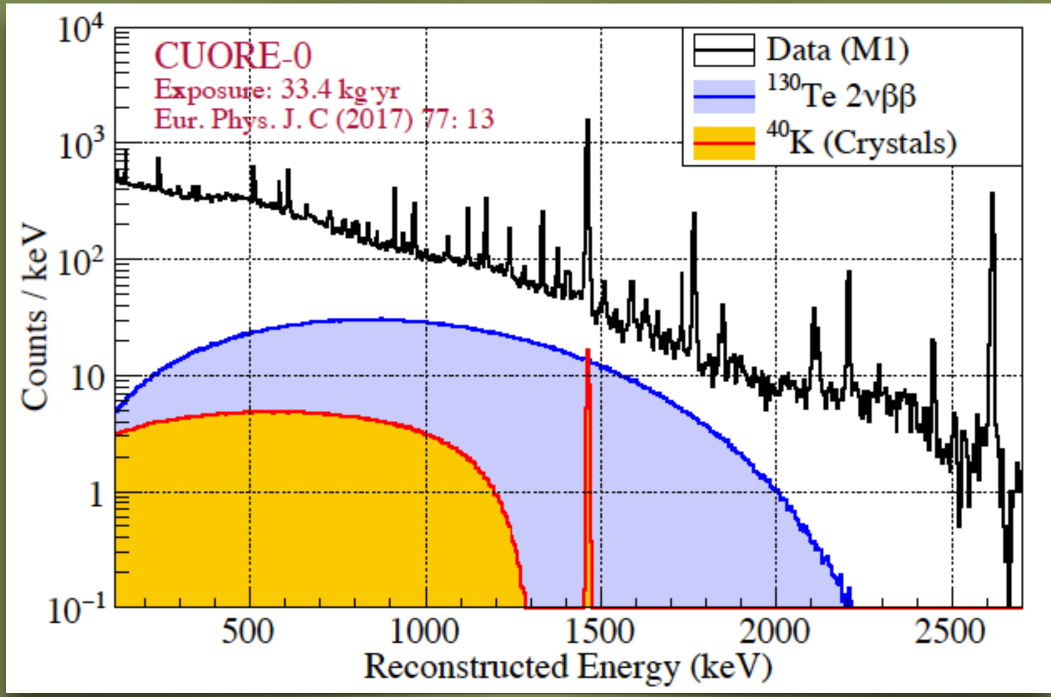
- γ background significantly reduced
- Most α background consistent
- Backgrounds consistent with expectations
- ^{210}Po excess appears to be from shallow contamination in copper around the detectors
  - Current estimated contribution to ROI at the level of ~ 10^{-4} cnts/(keV kg yr)



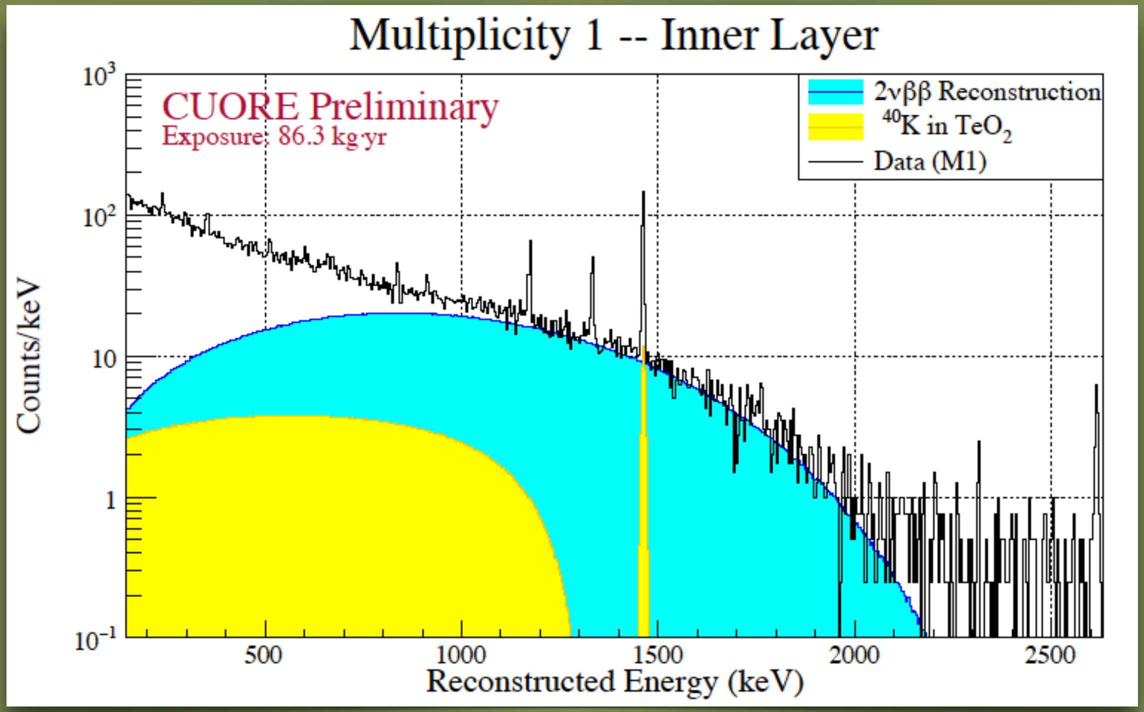
The background model is able to reconstruct the major features of the observed spectrum in CUORE

RESULTS

Measurement of the $2\nu\beta\beta$ half life of Te^{130}



In CUORE-0, $2\nu\beta\beta$ decay spectrum accounts for ~20% of the signal in the range 1-2 MeV



In CUORE, $2\nu\beta\beta$ decay spectrum accounts for nearly all of the signal in the range 1-2 MeV

$T^{2\nu}_{1/2}$ = [7.9 ± 0.1 (stat.) ± 0.2 (syst.)] x 10^{20} yr

paper in preparation

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

NEMO: $T^{2\nu}_{1/2}$ = [7.0 ± 0.9 (stat.) ± 1.1 (syst.)] x 10^{20} yr

CONCLUSION

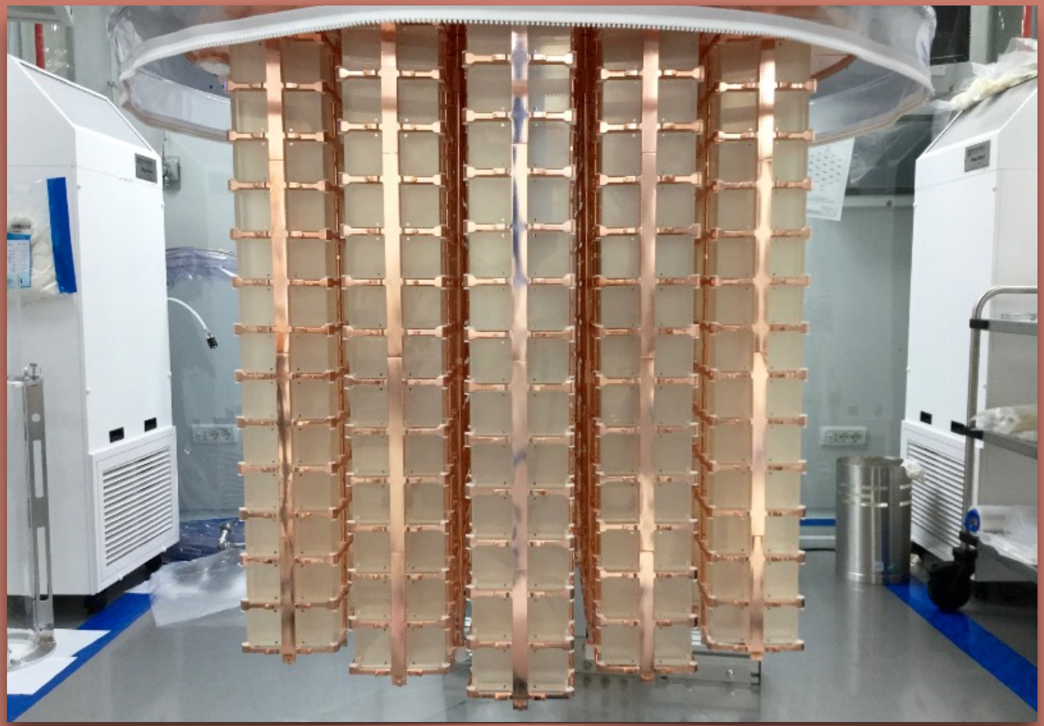
The first result from the CUORE experiment
- Published in 2018 on PRL 120, 132501

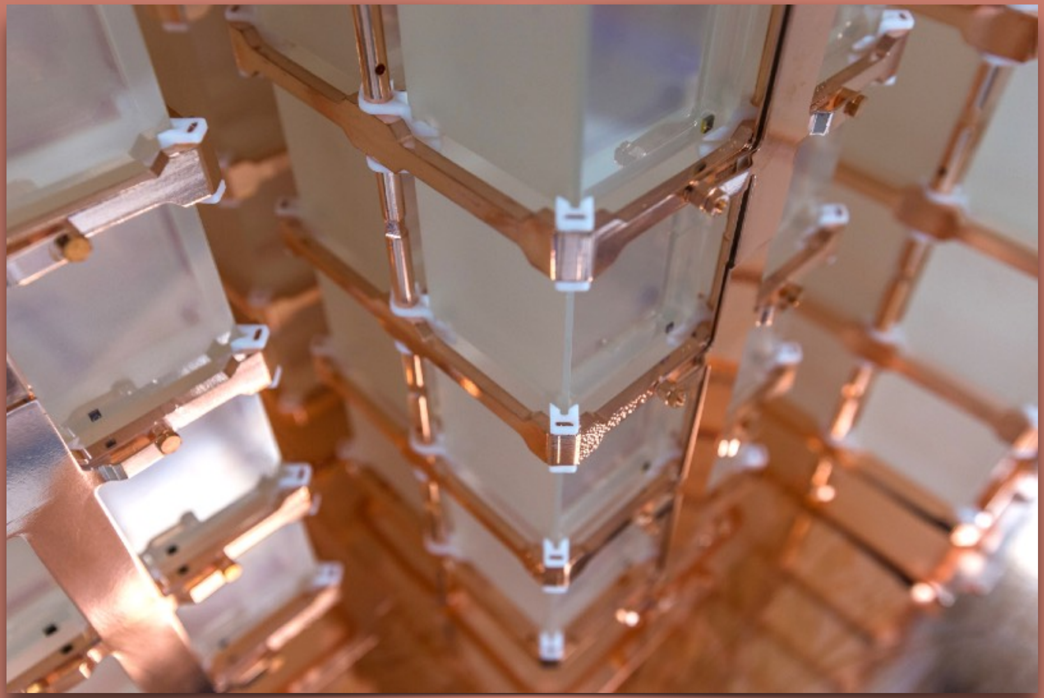
Scientific:
- Most stringent limit on 0νββ decay half-life of ^{130}Te to date
  $T^{0\nu}_{1/2} > 1.5 \times 10^{25}$ yr $m_{\beta\beta} < 110 - 520$ meV
- Most precise and accurate measurements of 2νββ decay half-life of ^{130}Te [7.9 ± 0.1 (stat.) ± 0.2 (syst.)] x 10^{20} yr

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 present:
- Analysis ongoing on the data collected in 2018 at 11mK
- New 2019 dataset is going to start in few weeks

The future:
- 5 years of live time planned
- New analyses (dark matter, axions...)
- CUPID (CUORE Upgrade with Particle Identification)





THANK YOU

CSNSM

Yale

Universitas Studii Paduani MCCXXII

INFN Istituto Nazionale di Fisica Nucleare

Berkeley Lab

Cal Poly San Luis Obispo

The University of California 1868 Let There Be Light

Massachusetts Institute of Technology

Lawrence Livermore National Laboratory

VirginiaTech Invent the Future® 1872

Studivm Vrbis

Sapienza Università di Roma

Università degli Studi di Milano Bicocca

Shanghai Jiao Tong University 1896

Alma Mater Studiorum A.D. 1088

Università degli Studi di Cassino e del Lazio Meridionale Sol per noctem 1979

UCLA

SINAP

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CUORE