The CUORE detector and results

Irene Nutini
Università degli Studi Milano Bicocca
INFN Milano Bicocca

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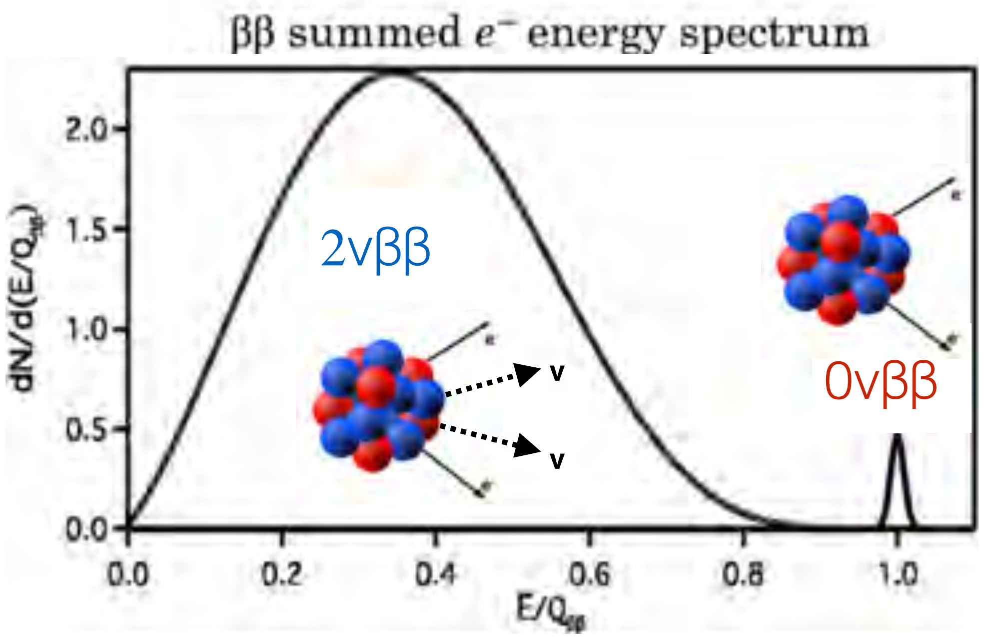
Double beta decay



Experimental 0νββ half-life sensitivity

Finite background

$$S_{0\nu} \propto \eta \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta \cdot B}}$$

Zero background
$(B \cdot \Delta << 1)$

$$S_{0\nu} \propto \eta \cdot \epsilon \cdot M \cdot T$$

Detector performance
- extremely low background
- excellent energy resolution

Detection technology
- Good detection efficiency: ββ source embedded into the absorber

Isotope choice
- High isotopic natural abundance or enrichment

Exposure
- Large active mass (M) detector
- Long live-time

CUORE

Cryogenic Underground Observatory for Rare Events

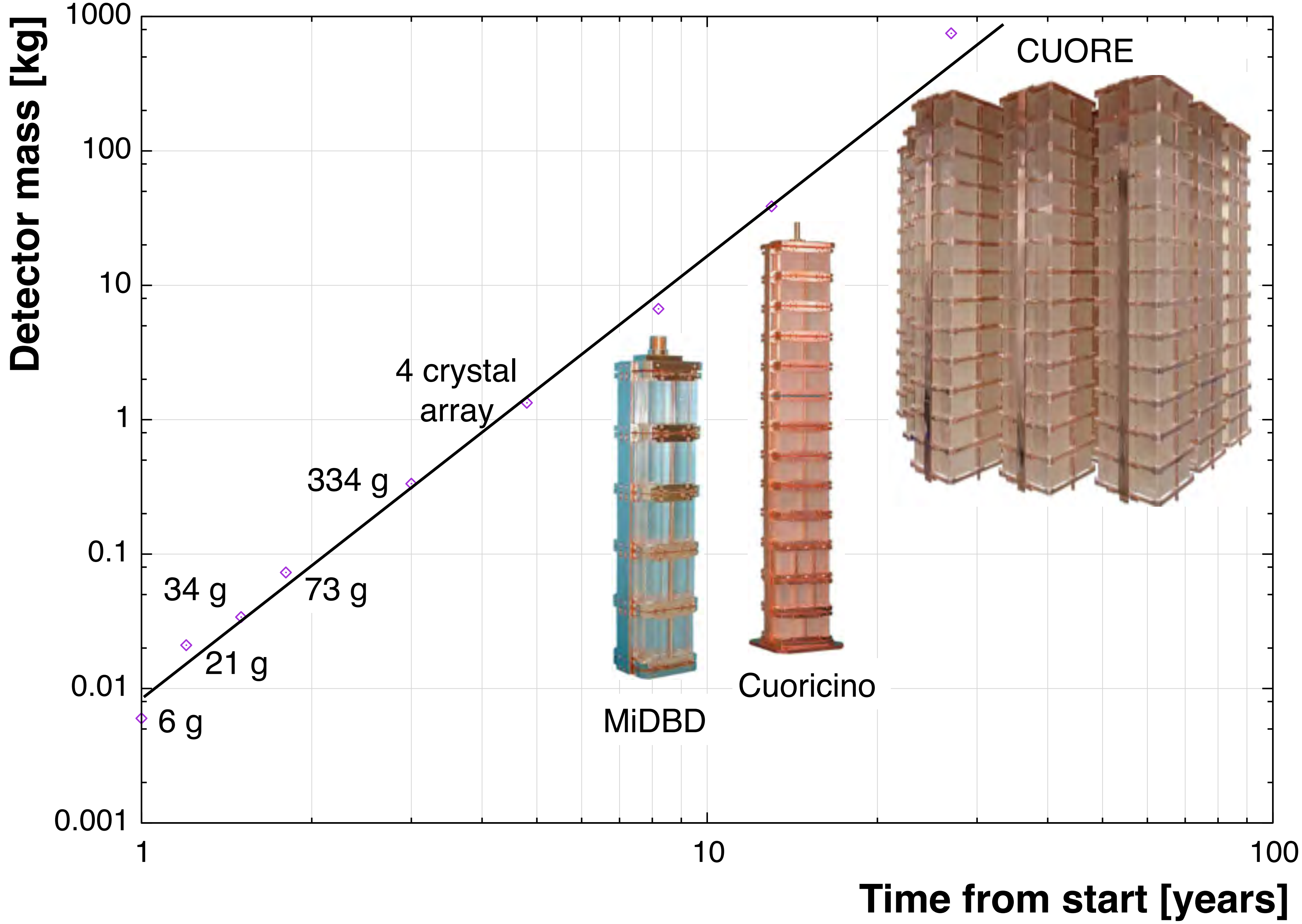
Cryogenic experiment using $^{(nat)}TeO_2$ detectors

- ^{130}Te within the detector absorber of TeO_2 (ε ~ 90%)
- **Detector active mass 742 kg TeO_2 (~206 kg of 130Te)**
- TeO_2 operated as **low temperature macro-calorimters** (~10 mK): **good energy resolution** Δ (~0.2% FWHM/E) , compared to other ββ experiments
- **η(^{130}Te) = 34.167%,** $Q_{\beta\beta}$ (^{130}Te) = 2527.518 keV

Artusa D.R. et al. (CUORE Collaboration), Adv. High Energy Phys. 2015,879871,(2015) http://doi.org/10.1155/2015/879871

The CUORE detector

From few g to 1 tonne TeO_2 calorimeters for double beta decay search



The CUORE detector

CUORE detector

Array of closely packed
988 TeO_2 crystals
arranged in 19 towers
High Mass of TeO_2:
742 kg (206 kg of ^{130}Te)
and high granularity

CUORE tower:
52 crystals
arranged in 13 floors
of 4 crystals each

CUORE-0 experiment:
CUORE-tower demonstrator

CUORE array:
19 towers

The CUORE challenge

CUORE

* **Low background**
  - Deep underground location (LNGS)
  - Strict radio-purity controls on materials and assembly
  - Passive shields (Pb) from external and cryostat radioactivity
  - Detector: high granularity and self-shielding

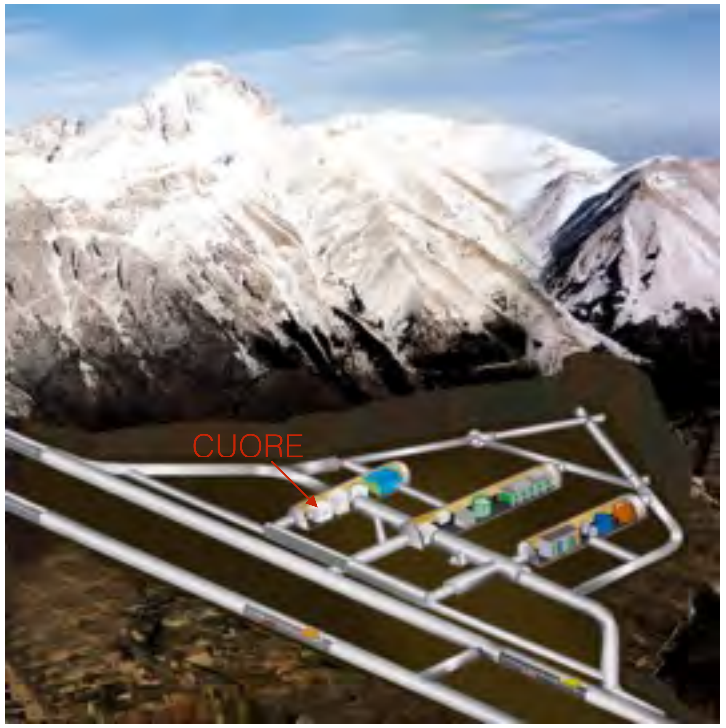
Background goal: 10^{-2} c/(keV·kg·yr)
in the Region Of Interest (ROI) around $Q_{\beta\beta}$

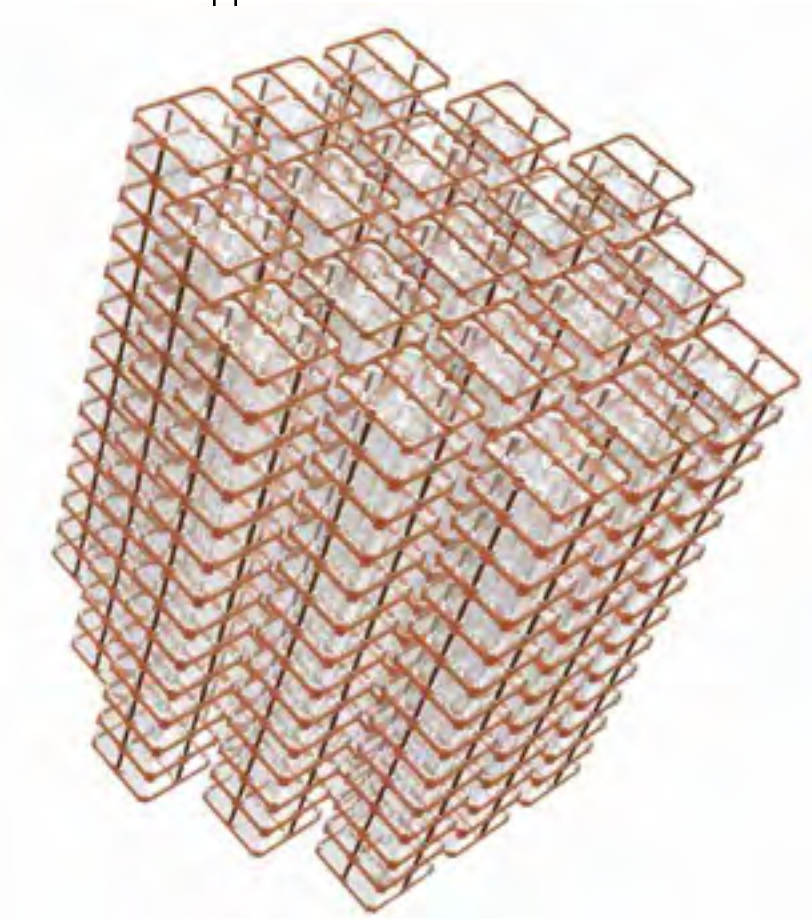
* **Low temperature and low vibrations**

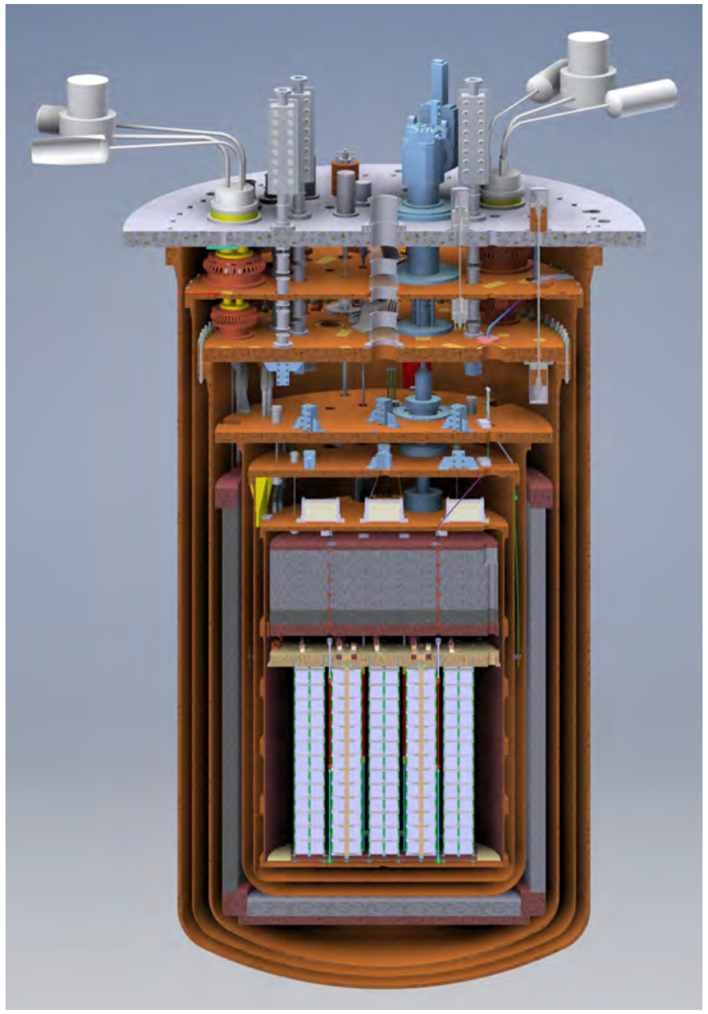
TeO_2 detectors to be operated as calorimeters at temperature ~10 mK: Multistage cryogen-free cryostat

Talk V.Singh

Nominal energy resolution: 5 keV FWHM
in the Region Of Interest (ROI) around $Q_{\beta\beta}$







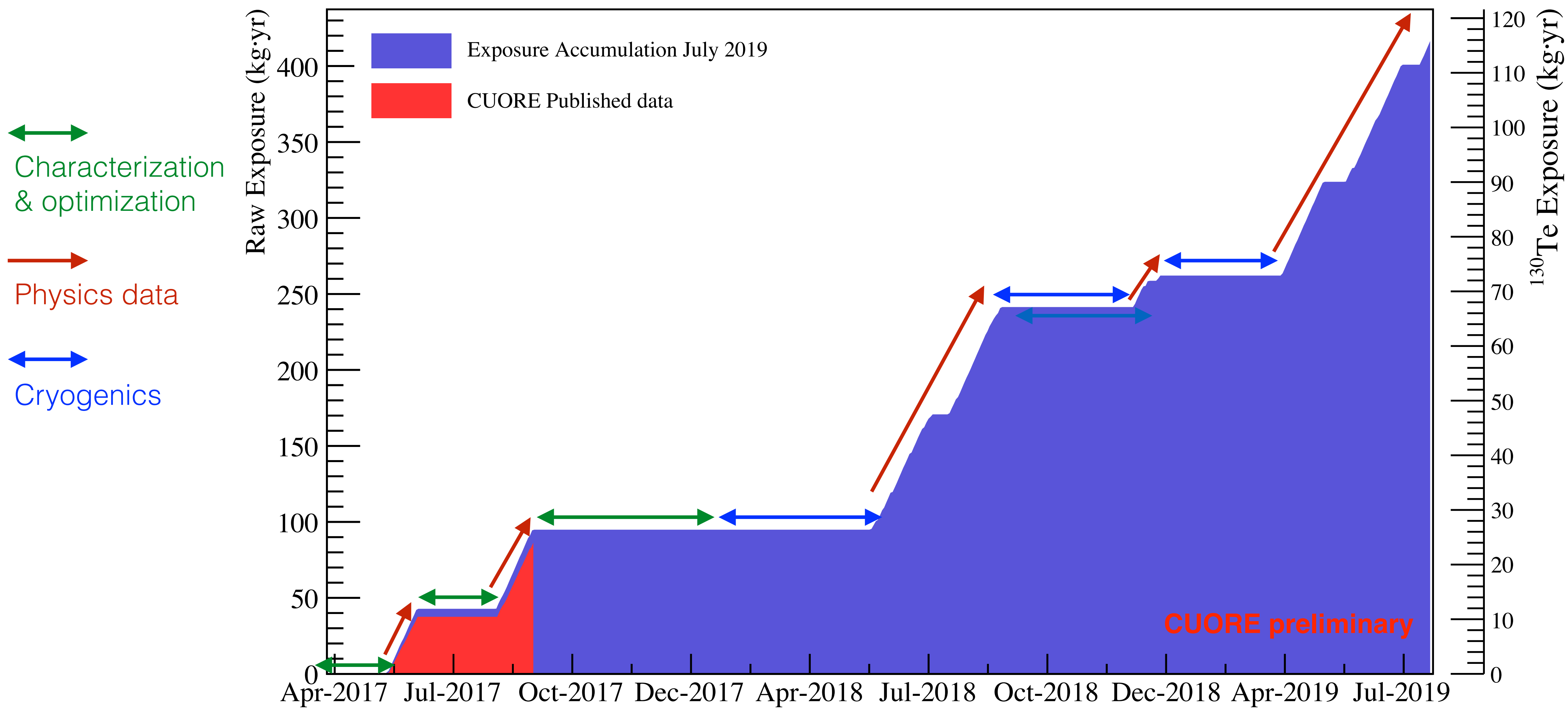
Dell'Oro S. et al., Cryogenics 102, 9, (2019)
https://doi.org/10.1016/j.cryogenics.2019.06.011

CUORE data taking

2017 - First CUORE cool-down (early 2017)
- CUORE detector initial characterization —> Set T = 15 mK
- First CUORE Physics data taking @ 15 mK
- Optimization and test new temperature T = 11 mK (late 2017)

2018 - Warm-up and maintenance of gate valves for the calibration system (early 2018)
- Physics data taking @ 11 mK
- Warm-up and resolution of a leak using the second condensing line (late 2018)

2019 - Warm-up and maintenance of the cryogenic system (early 2019)
- Physics data taking @ 11 mK (ongoing since March 2019)



CUORE optimization

The CUORE experiment started taking data in 2017.

- First time such a **large number of macro-calorimeters (~ 1000)** simultaneously operated in a completely new and unique cryogenic system
- Detector and overall system different compared to previous smaller scale bolometer experiments

Dedicated detector characterization and optimization campaigns performed in order to characterize and improve the detectors and overall system performance.

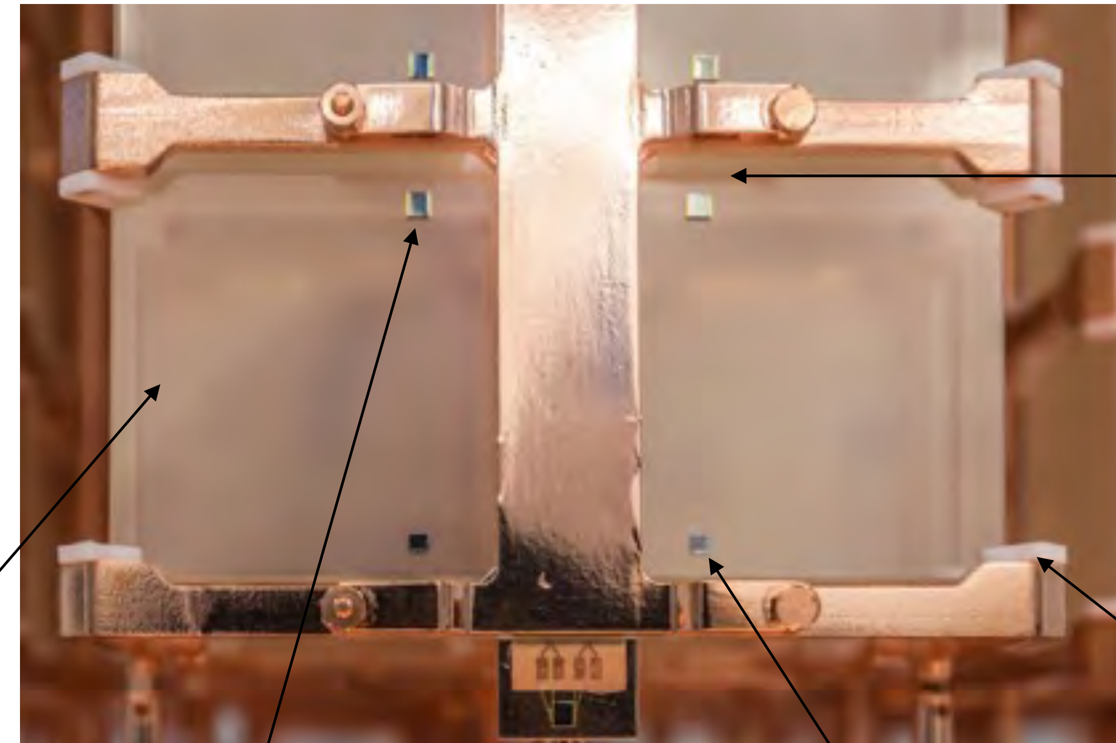
Goal: Improve the energy resolution and reach stable data-taking conditions

- Characterization and tuning of detector operating parameters
- Noise reduction

CUORE instrumented detectors

TeO$_2$ crystals coupled with NTDs

- Macro-calorimeters
- Same detector response for different particles (phonons only)
- Slowness if coupled with NTDs (suitable only for low rate experiments, as rare event searches - 0νββ)



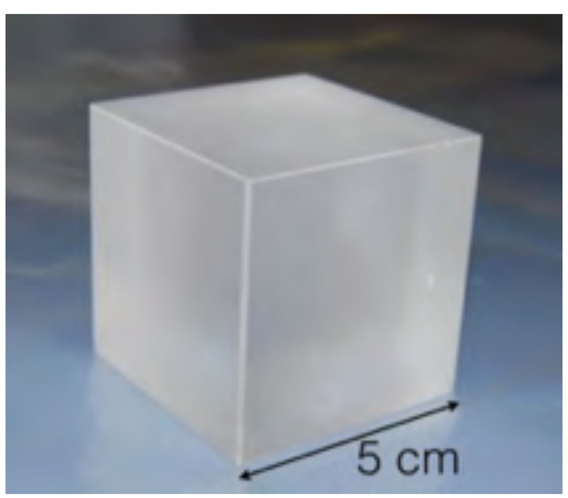
Au-wire bonding to Cu-PEN read-out strips

TeO$_2$ absorber

Ge-NTD

Si-heater

PTFE holders



$^{(nat)}$TeO$_2$ crystal

Absorber = 0νββ source

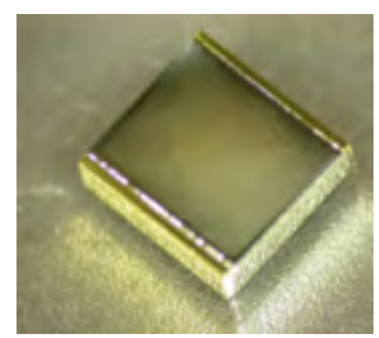
5.0 × 5.0 × 5.0 cm^3

750 g mass

C(T) ~ 2.3 x 10^{-9} J/K (@ 10 mK)

$\Delta T_{crystal}$ ~ 100 μK/MeV

τ ~ 0.1 - 1 s



Ge-NTD thermistor

3.0 x 2.9 x 0.9 mm^3

Working impedance of the thermistors: R_{wp} ~ 100 MΩ -1 GΩ

ΔV_{NTD} ~ 400 μV/MeV (@10 mK)

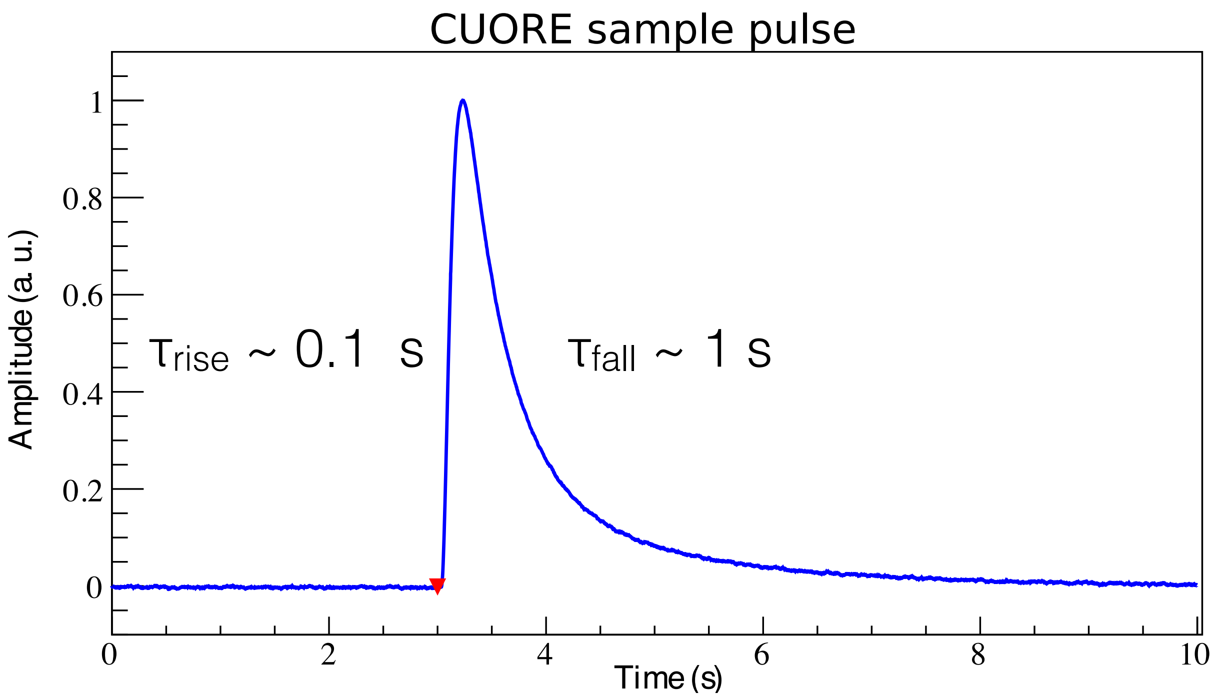
Si heater

2.3 x 2.4 x 0.5 mm^3

Joule heater designed to periodically provide a fixed amount of energy in the crystal

Alduino C. et al. (CUORE collaboration), J. Inst. 11(07), P07009, (2016)
https://doi.org/10.1088/1748-0221/11/07/p07009

CUORE detectors characterization



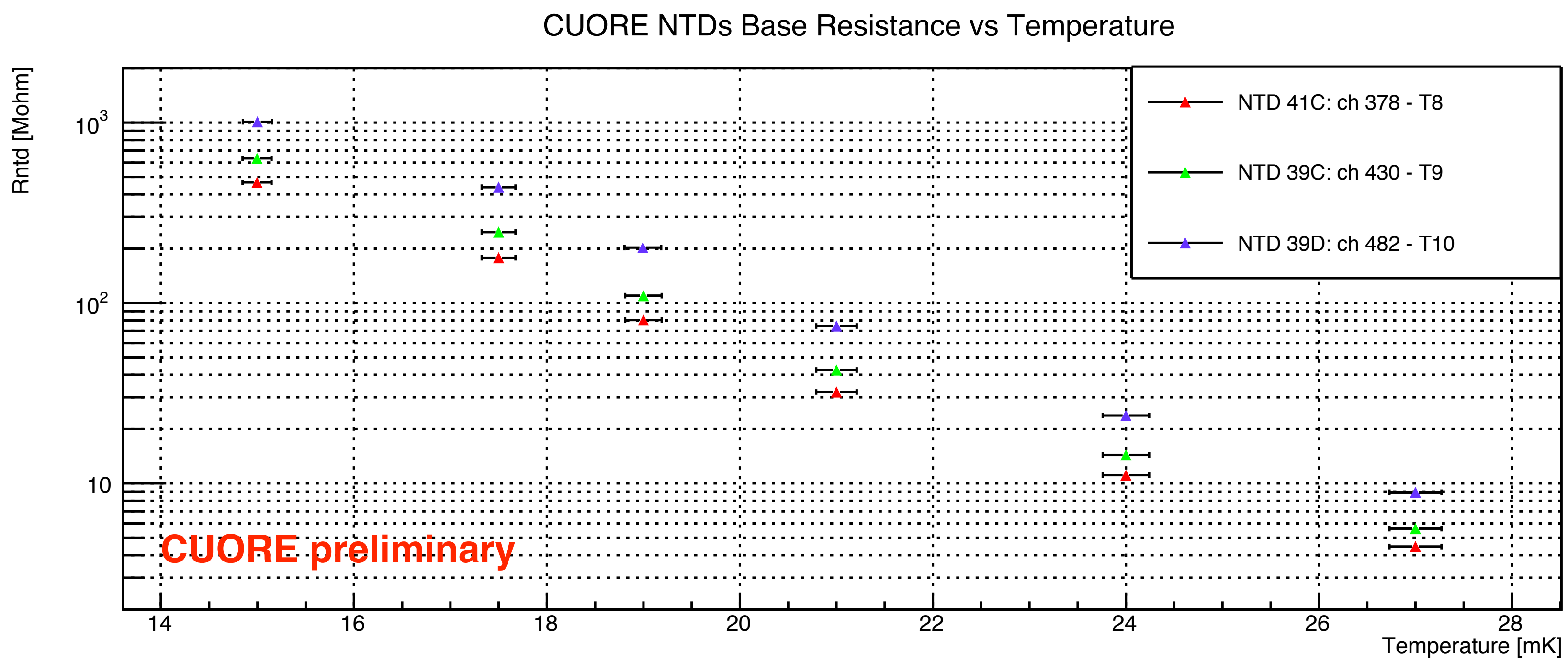
Detector response

RC coupling between the NTD resistance and the parasitic capacitance of the electrical links acts as a low pass filter limiting the signal bandwidth: ~(0 - 10) Hz

Thermistor NTD-Ge

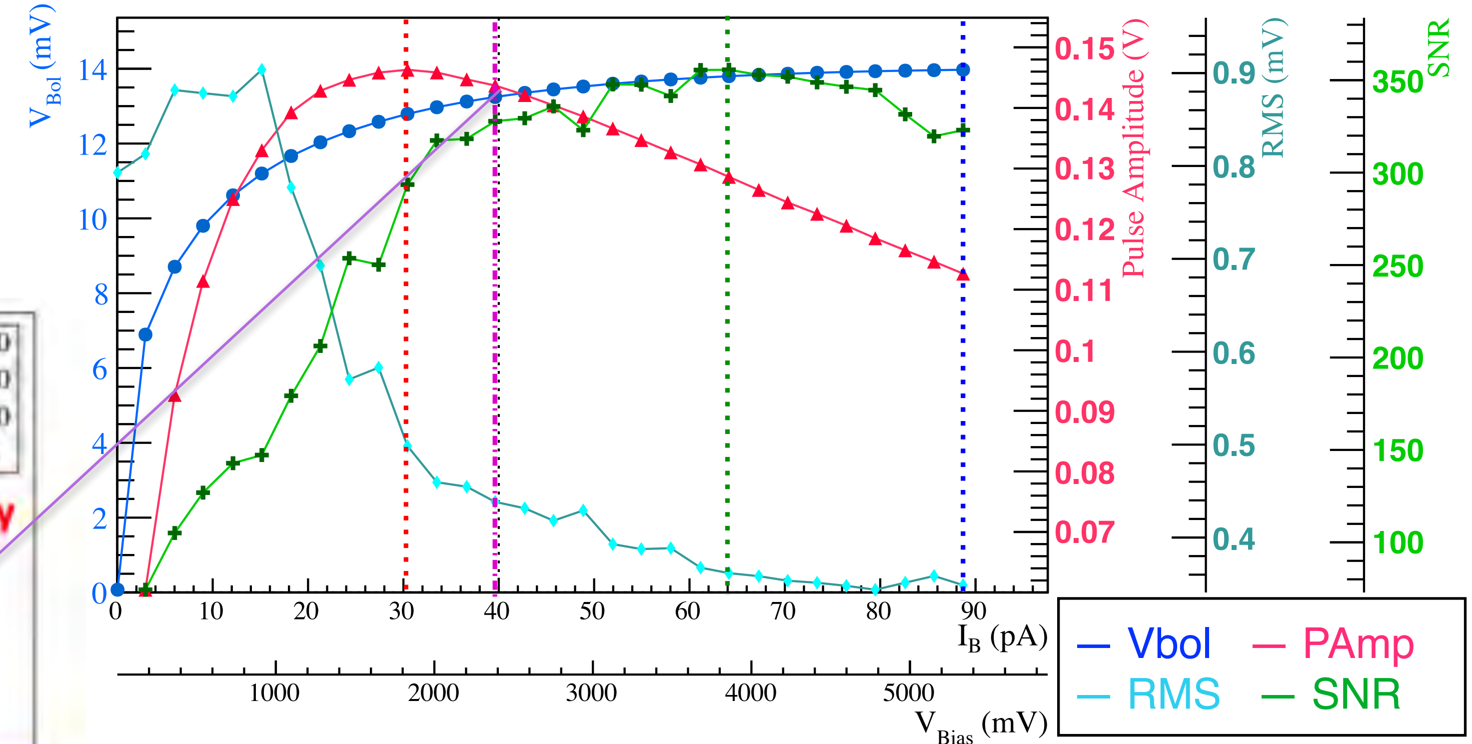
NTDs belonging to different (neutron implantation) batches installed on the CUORE towers: NTD 41C, NTD 39C, NTD 39D

- The three NTD-types have slightly different characteristic parameters of their R(T) curves

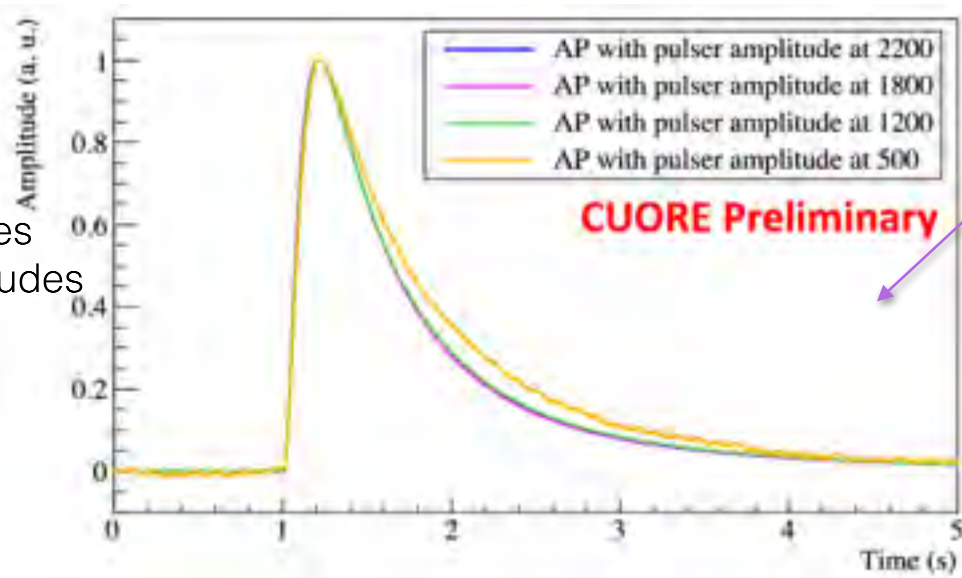


Load Curves analysis and NTDs Working Points selection

Dedicated procedures and algorithms in CUORE to automate the NTDs load curve measurement and the working point identification at each T_{base} for every detector



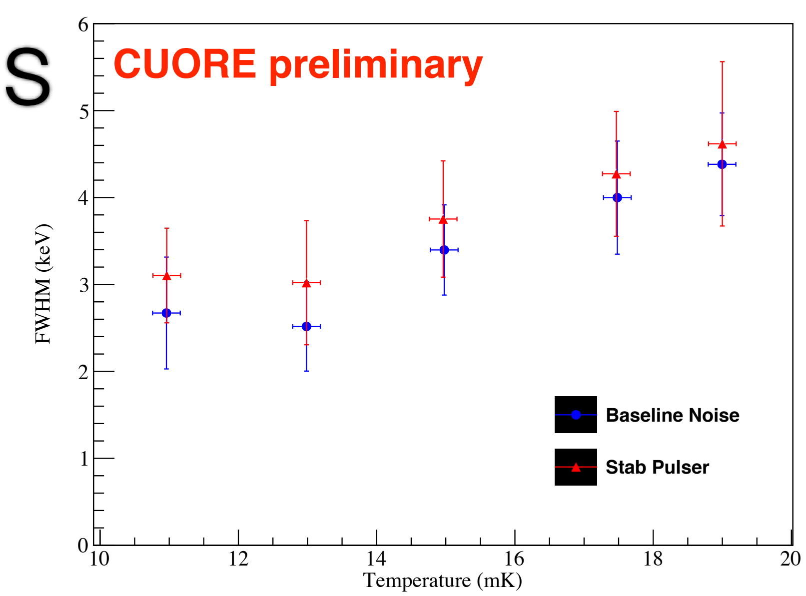
Reference pulses for different amplitudes @ V_{BIAS_WP}



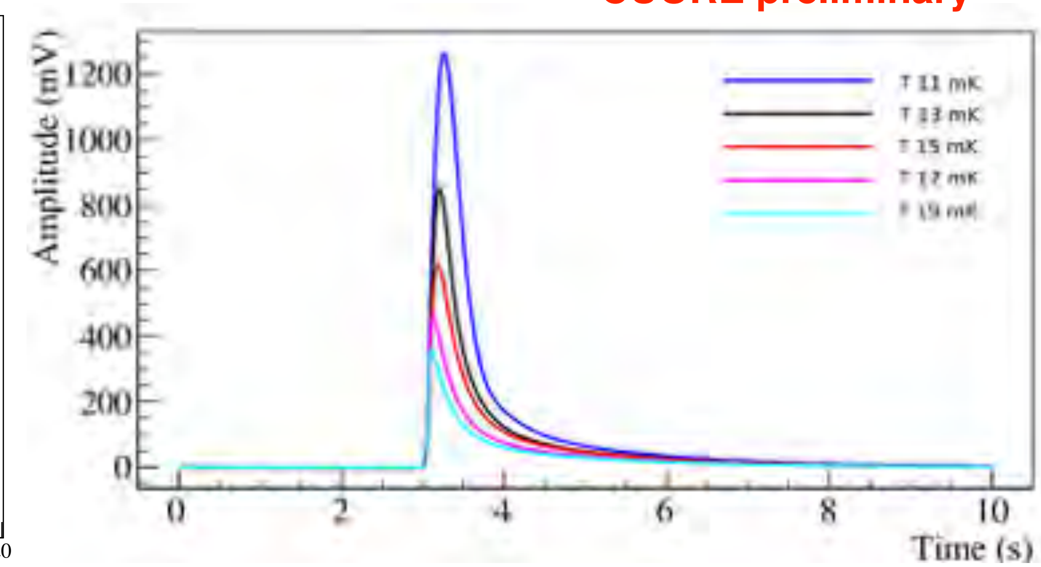
Poster I.Nutini

Temperature Scans

Identify the best operating temperature (T_{base}) for the CUORE detector array



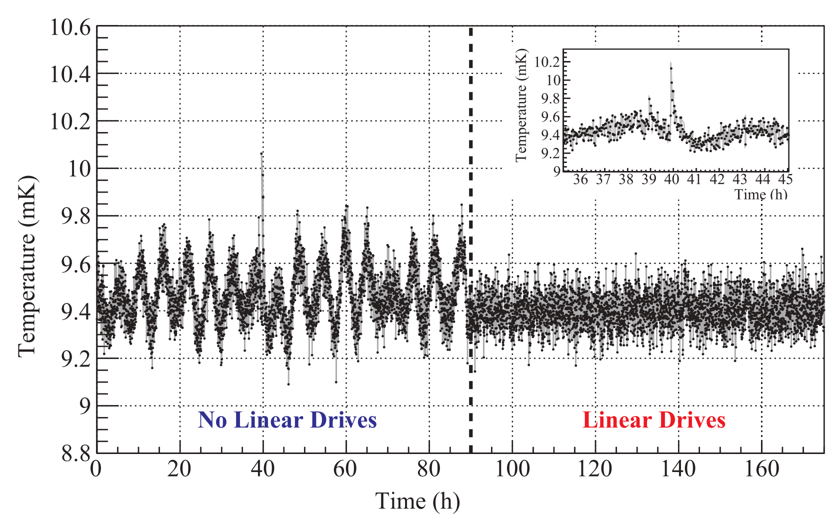
CUORE preliminary

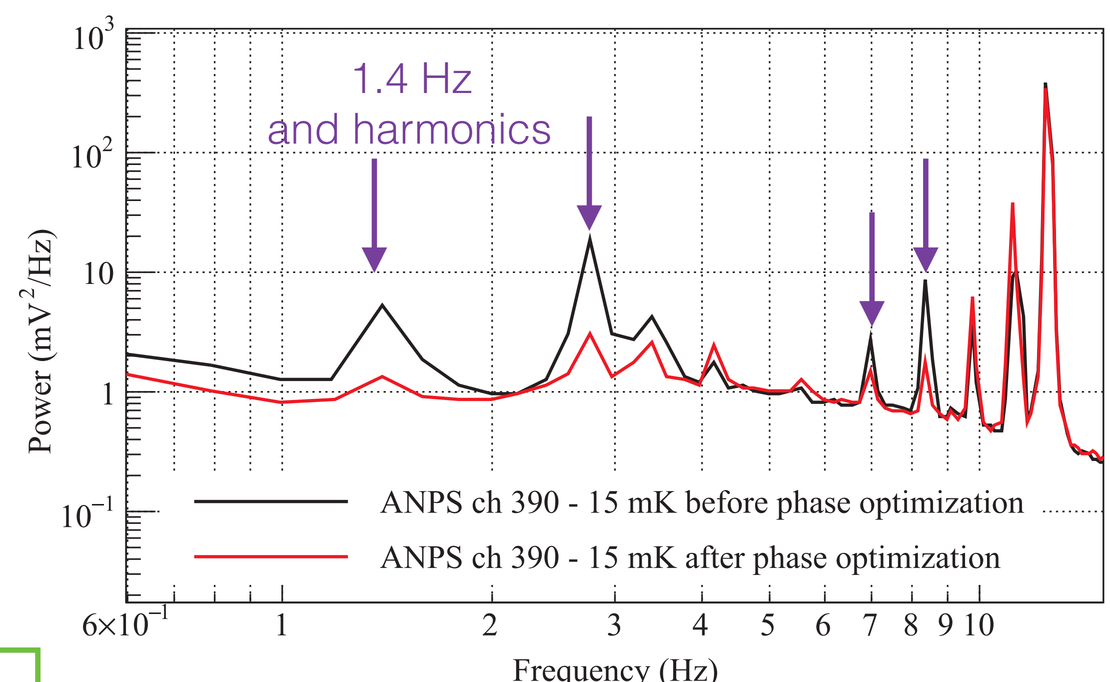


Noise contribution on the CUORE detectors

- Intrinsic Noise sources
  - Thermodynamic noise: thermodynamic energy fluctuation between the absorber and the heat bath ~(20-100) eV
  - Johnson Noise on load resistor R_L: $FWHM_{Johnson}$ ~ 0.8-0.9 keV
- Extrinsic Noise sources
  - Preamplifier noise: boards designed to minimize at negligible level the corresponding noise contribution
  - Vibrational noise: dominant noise contribution - vibrations of the cryogenic apparatus transmitted to the crystals.

Pulse Tubes induced vibrations: **Pulse Tube active noise cancellation**



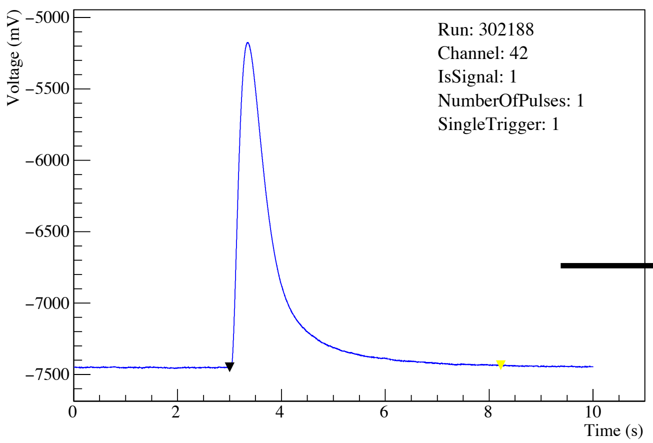


D'Addabbo A. et al.,Cryogenics 93, 55-56, (2018)
https://doi.org/10.1016/j.cryogenics.2018.05.001

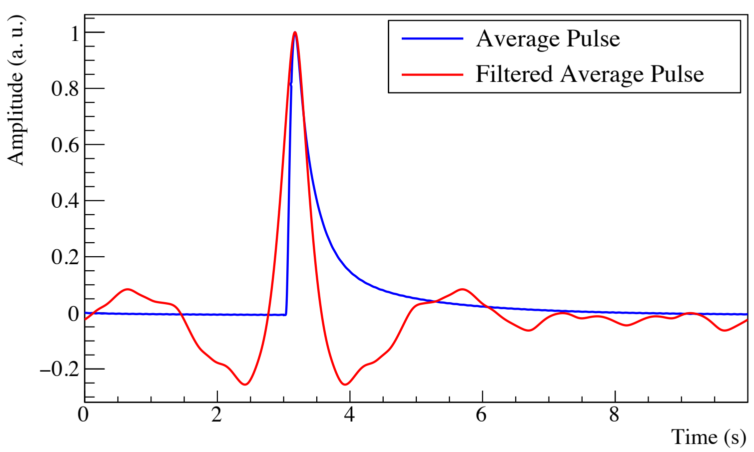
Energy resolution improvement (at Tl 2615 keV peak)
9.0 keV FWHM —> 7.4 keV FWHM

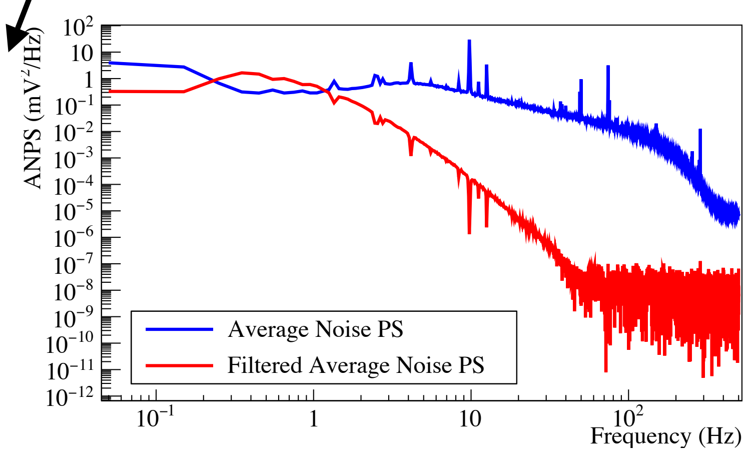
Poster V.Dompè

CUORE raw data processing

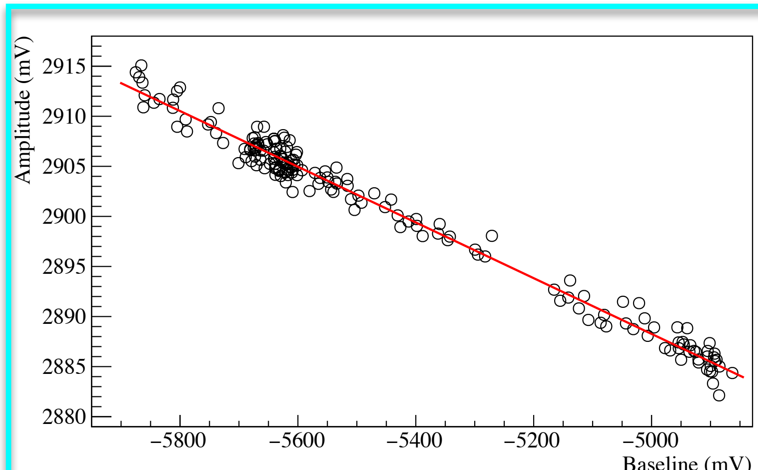


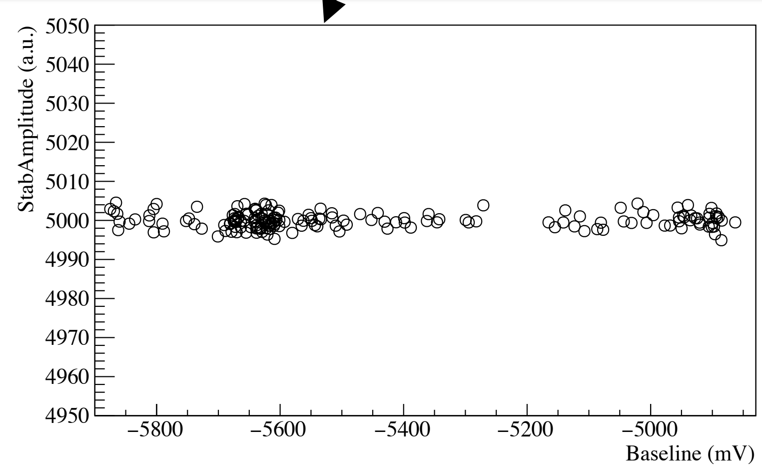
Optimum Filter → Gain Instability Correction → Energy Calibration → Coincidences



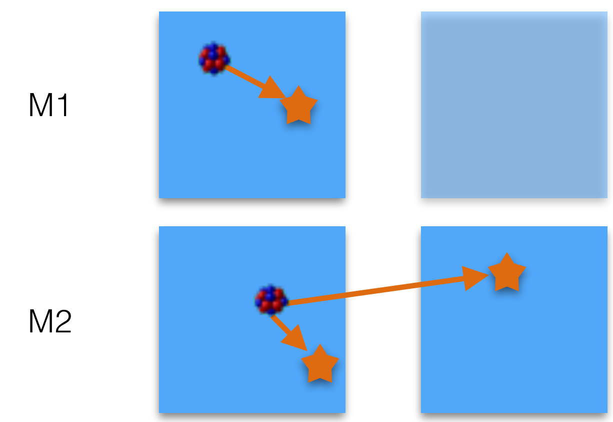


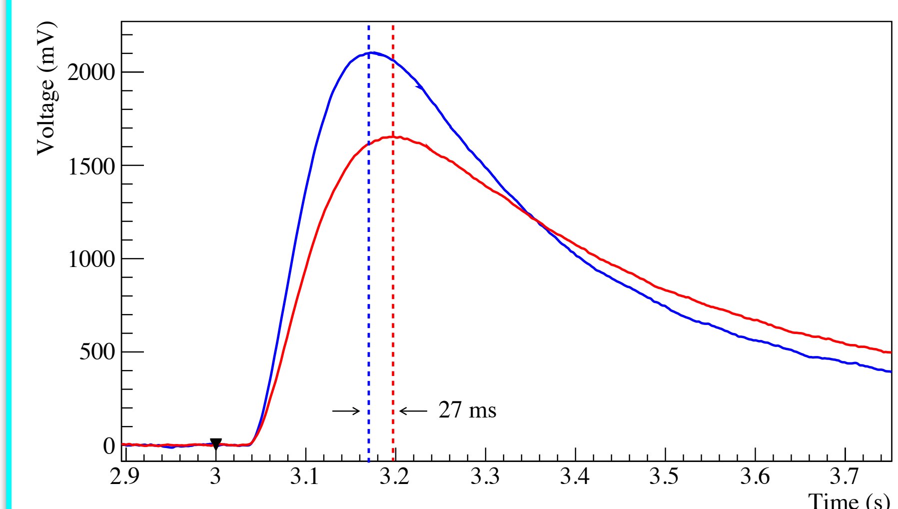
Matched filter that maximizes the signal-to-noise ratio





Heater pulses for thermal gain stabilization



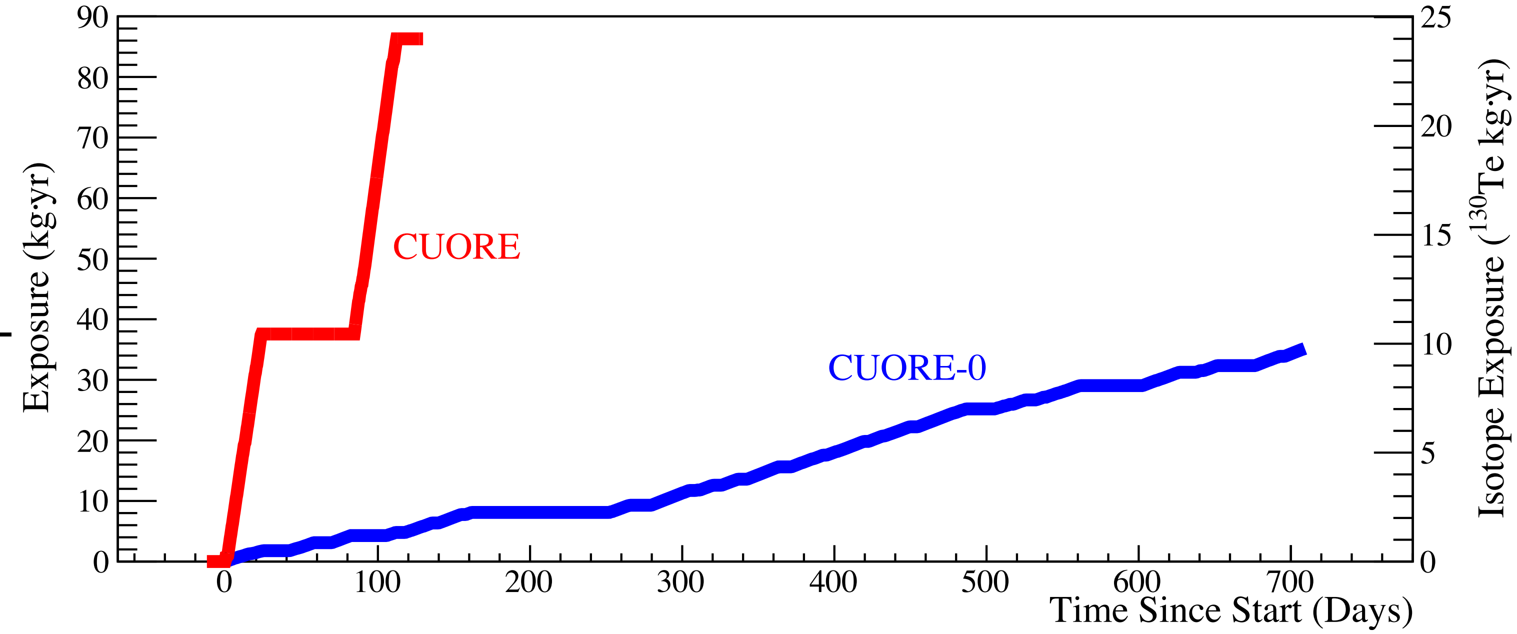


First results from CUORE

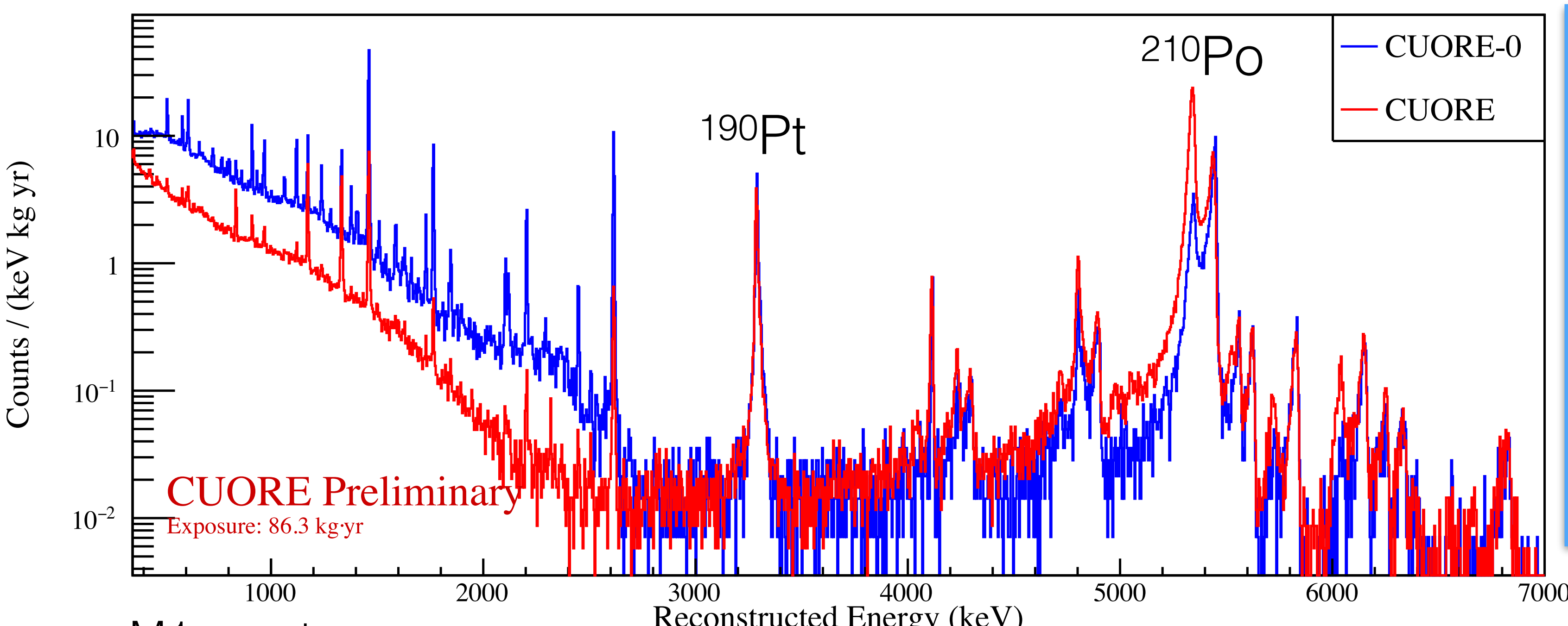
CUORE Physics data 2017

CUORE vs CUORE-0

- In 7 weeks of data taking (2017) CUORE collected more than twice the CUORE-0 total **exposure** (CUORE-0 - single CUORE-like tower - run for almost 2 years)
- **Background reduction** in the γ region by a factor ~ 6
- Alpha background consistent with CUORE-0; unexpected excess of ^{210}Po surface events (5.3 MeV), accounts for < 10^{-4} cts/kev/kg/yr around $Q_{\beta\beta}$



<u>Collected statistic for physics analyses</u> (2017)
$^{nat}TeO_2$ exposure: 86.3 kg yr, ^{130}Te exposure: 24.0 kg yr
(After analysis selections)



M1 events

<u>CUORE Operational performance</u>

- 984/988 operational channels
- Improved cryogenic system and detector stability
- Thresholds: from ~50 keV (average)
- Trigger rate per bolometer:

Calibration 50 mHz, Physics runs: 6 mHz

First results from CUORE

CUORE Physics data 2017

Reconstructed energy resolution at $Q_{\beta\beta}$: (7.7 ± 0.5) keV FWHM

ROI background index (B) ~ 1.4×10^{-2} c/(keV·kg·yr)

0νββ analysis

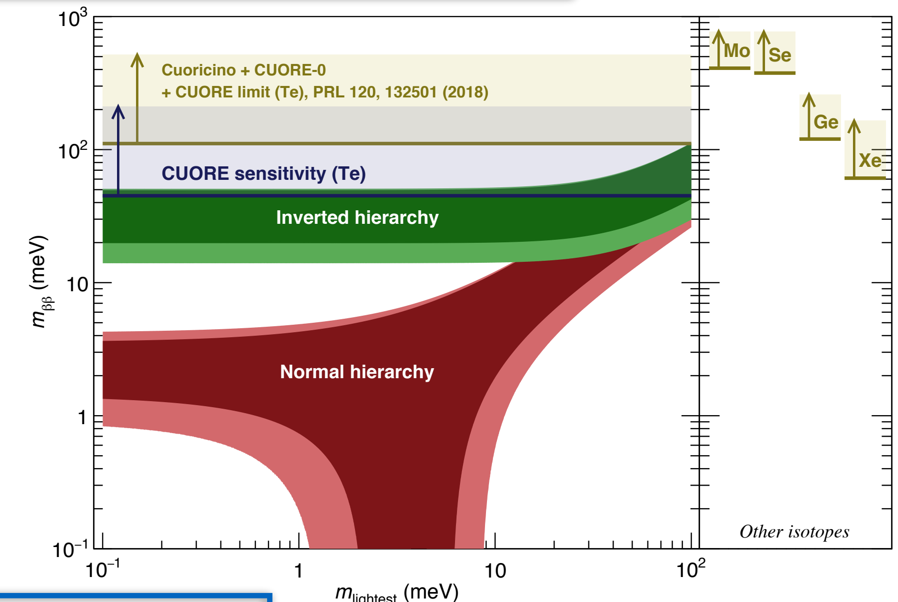
Half-life limit for 0νββ in ^{130}Te (90%C.L including syst.)

$T_{0\nu}^{1/2}$ (^{130}Te) > 1.3×10^{25} yr

Combined data: CUORE + CUORE-0 + Cuoricino

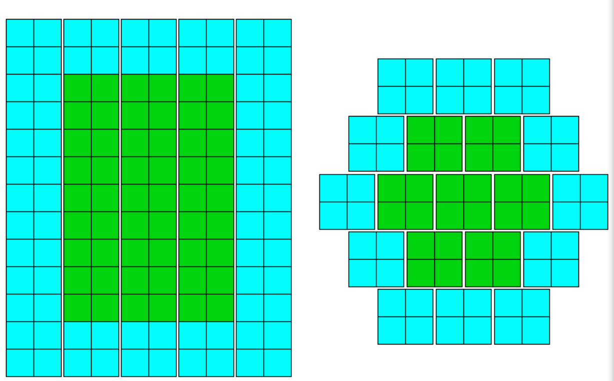
$T_{0\nu}^{1/2}$ (^{130}Te) > 1.5×10^{25} yr

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



Alduino C. et al. (CUORE collaboration), Phys. Rev. Lett. 120, 132501, (2018), https://doi.org/10.1103/PhysRevLett.120.132501

Background model & ^{130}Te 2νββ half-life



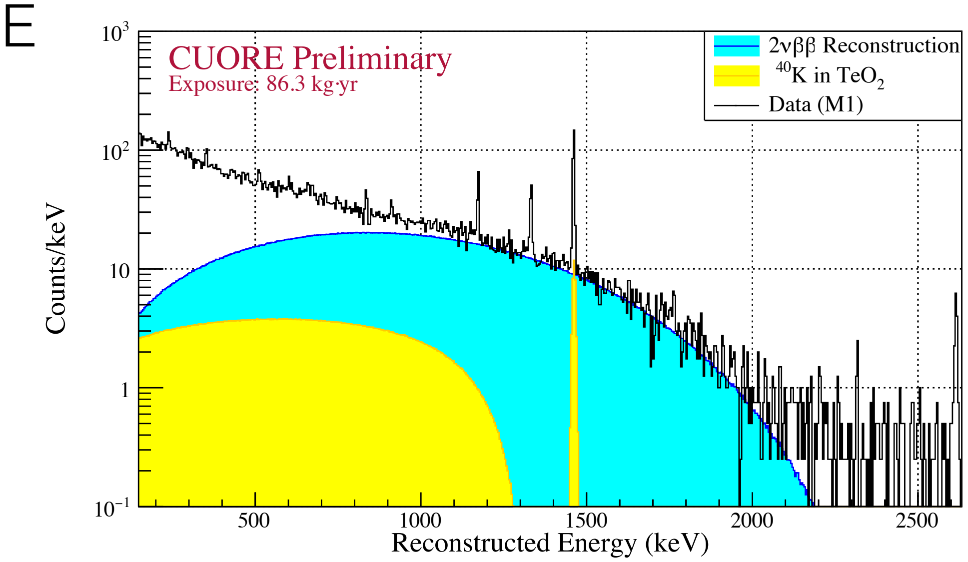
Monte Carlo reconstruction of the CUORE background

Profit of a segmented detector:

- events multiplicity
- background sources location
- inner towers self-shielded from outer contaminants

$T_{2\nu}^{1/2}$ (^{130}Te) =

[7.9 ± 0.1 (stat) ± 0.2 (syst)] × 10^{20} yr



Adams, D. Q. et al. (CUORE Collaboration),"Update on the recent progress of the CUORE experiment" arXiv:1808.10342, (2018)

Conclusions

CUORE

CUORE is the first tonne-scale operating macro-calorimetric $0\nu\beta\beta$ detector.

- First CUORE physics results of $T_{0\nu}$ and $T_{2\nu}$ in ^{130}Te with the physics data collected in 2017
- A total exposure of more than 400 kg yr is already available, updated physics results will be released at TAUP-2019
- The CUORE data taking is currently underway to collect 5 years of live time
- Studying and testing new strategies to improve the detector resolution
- Investigating the potential of the CUORE experiment for the search for rare events and/or for physics beyond the Standard Model other than the $2\nu\beta\beta$ decay of ^{130}Te
- Important feedback from CUORE operations for the future CUPID project (CUORE Upgrade with Particle IDentification)

Thank you on behalf of The CUORE collaboration

CUORE contributions at LTD-18

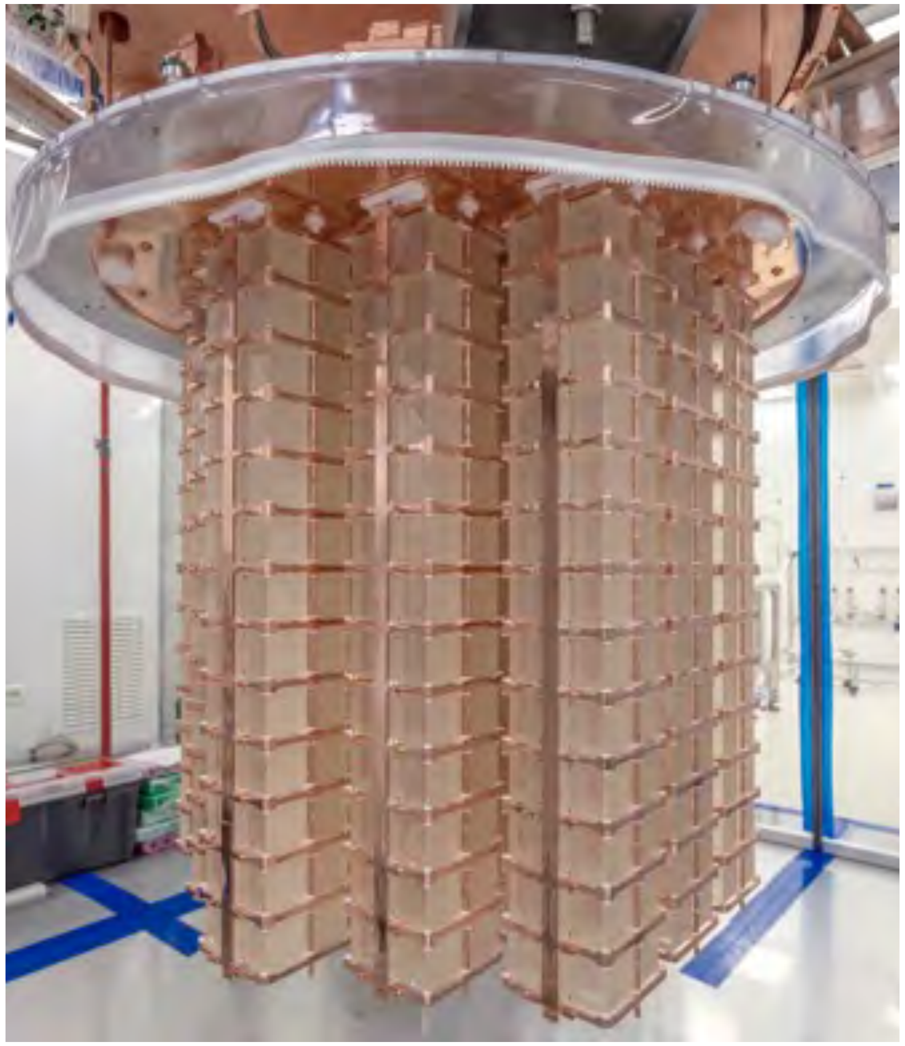
Talks:
- V.Singh, “The CUORE cryostat: the first sub-10 mK 1-ton scale infrastructure for low temperature detectors”
- I.Nutini, “The CUORE detector and results”

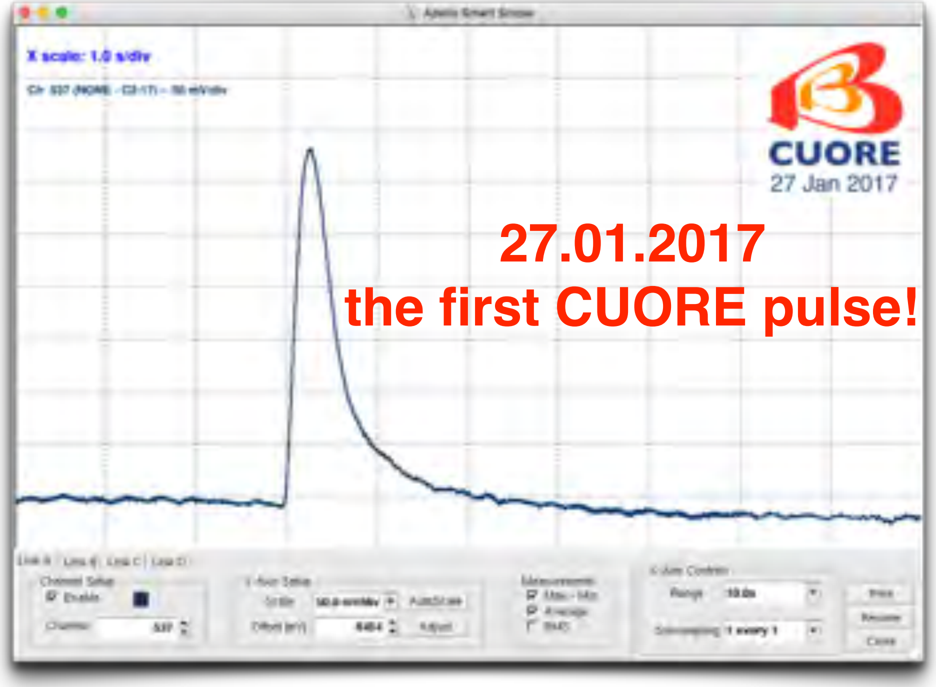
Posters:
- A.Campani, “Lowering the energy thresholds for the CUORE Experiment: a comparison between Optimum Trigger and Derivative Trigger Algorithm performances”
- S.Copello, “The CUORE data acquisition system”
- V.Dompè, “The CUORE pulse tubes noise cancellation technique
- G.Fantini, “Noise reduction techniques for the CUORE experiment”
- I.Nutini, “The CUORE bolometric detectors: pulse shape analysis of the thermal signals”

Backup

CUORE initial operations

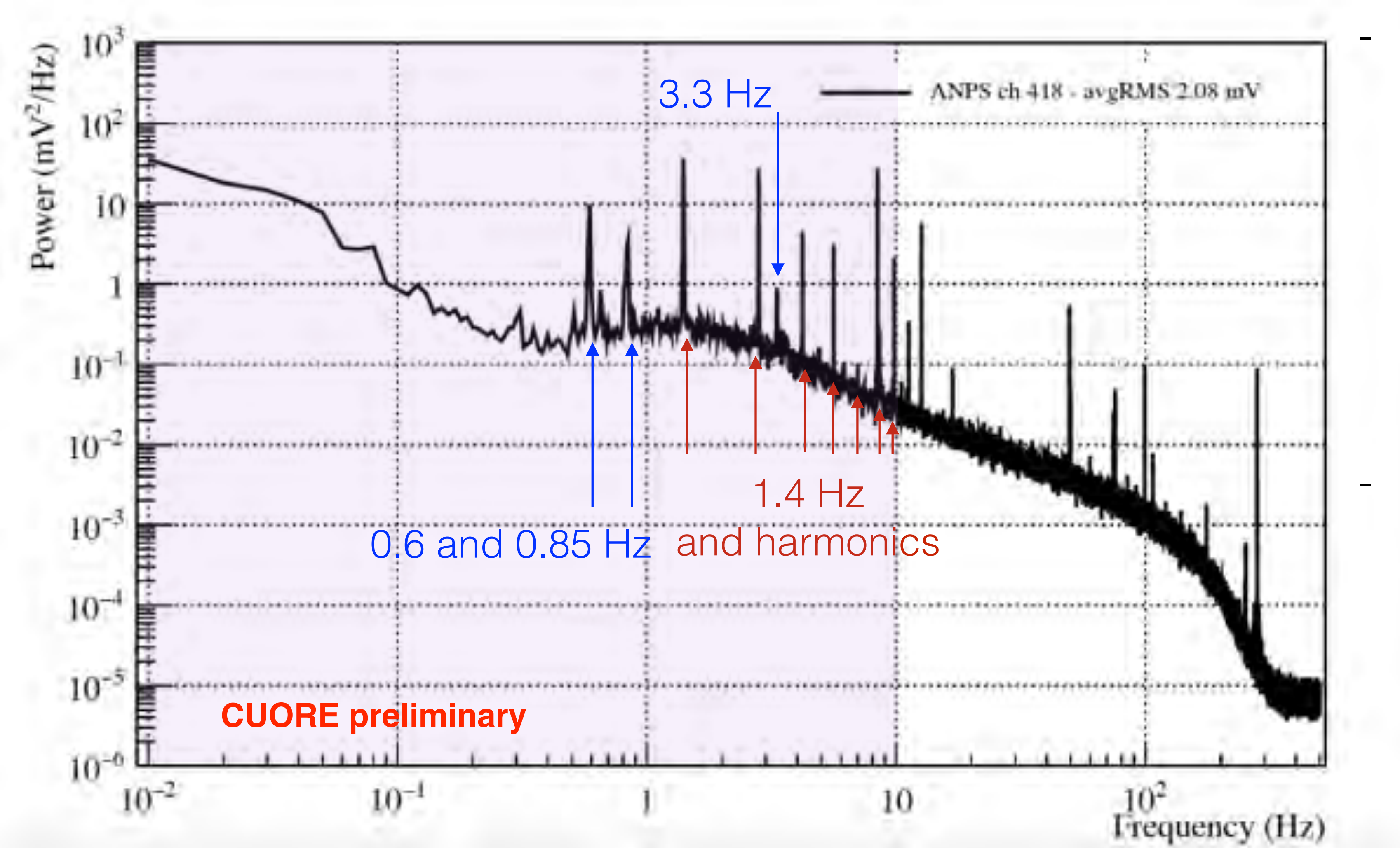
- Cryogenic system commissioning: Completed in Feb.2016
- Detector assembly and installation: Completed at the end of Aug. 2016
- First Detector cool-down: Started at the beginning of Dec. 2016
- First CUORE data and detector initial characterization and optimization: Early 2017





Noise contribution on the CUORE detectors

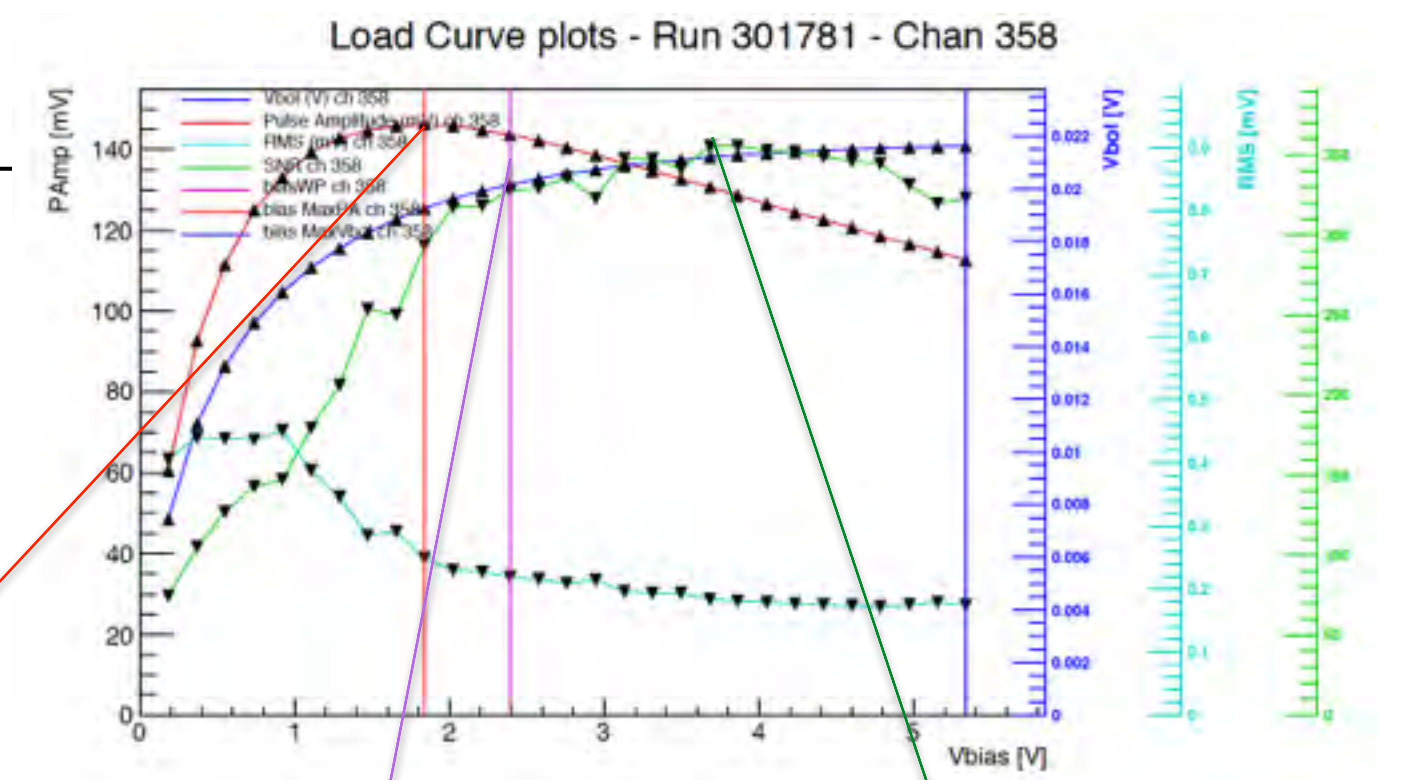
Spectral shape of the noise of the CUORE channels: a very complex spectrum, which is the sum of several contributions.
Transmission of vibrations by the cooling system appeared to be the dominant noise contribution on the bolometers.

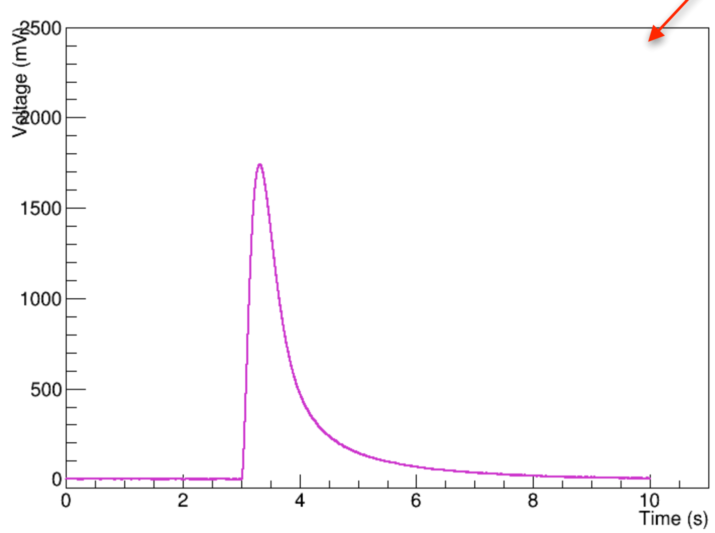


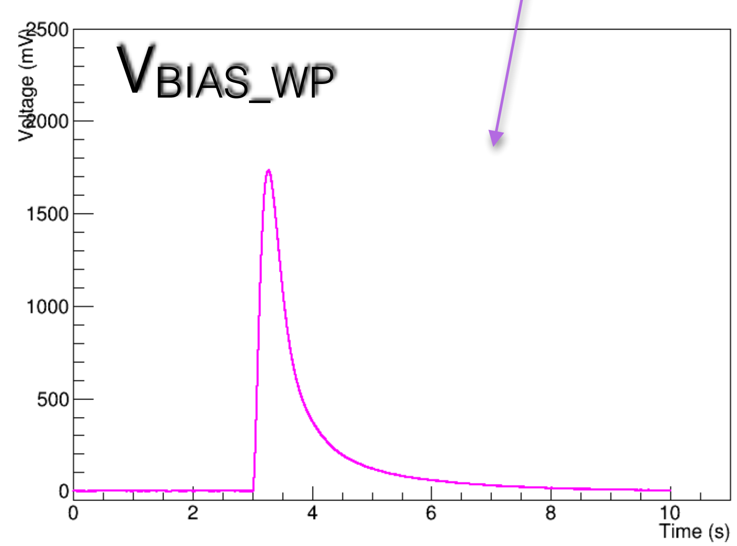
- Pulse Tubes induced vibrations (peaks at 1.4 Hz and its harmonics, which is the frequency of the pressure waves generated by the PTs).
  —> Pulse Tube active noise cancellation
- Residual mechanical vibrations and oscillations related to the suspension and support structure (e.g. 0.6 Hz, 0.85 Hz, 3.3 Hz, ..).
  —> Passive damping systems

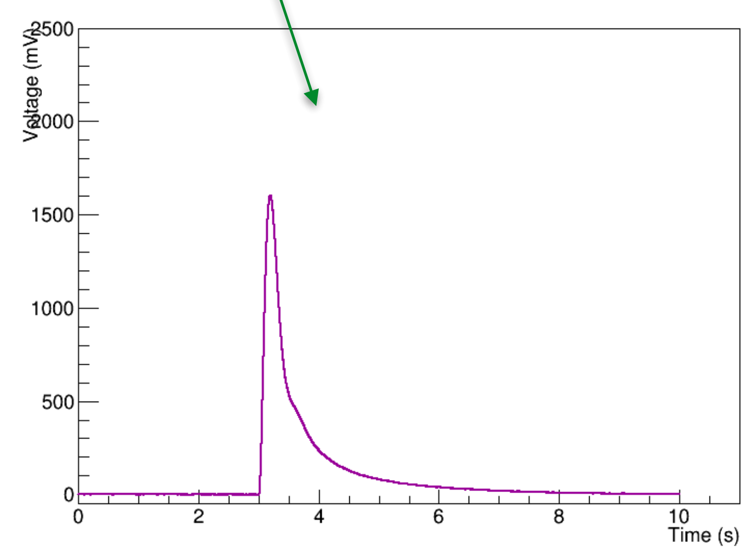
Load Curves analysis and NTDs Working Points selection

- Optimize the sensor response to particles energy deposition maximizing the signal-to-noise ratio.
- Ensure a linear behavior for small temperature variations avoiding pulse deformation.

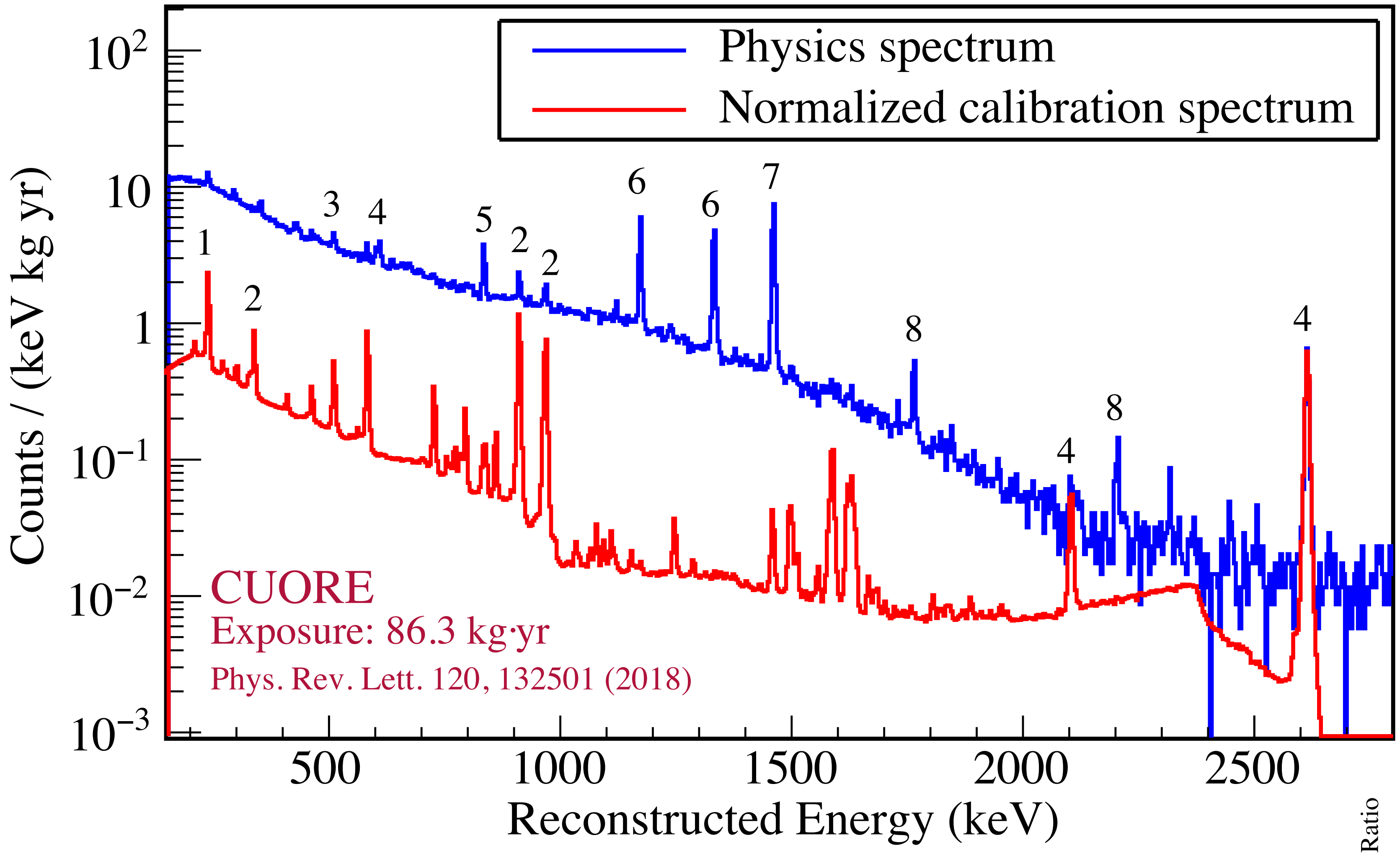








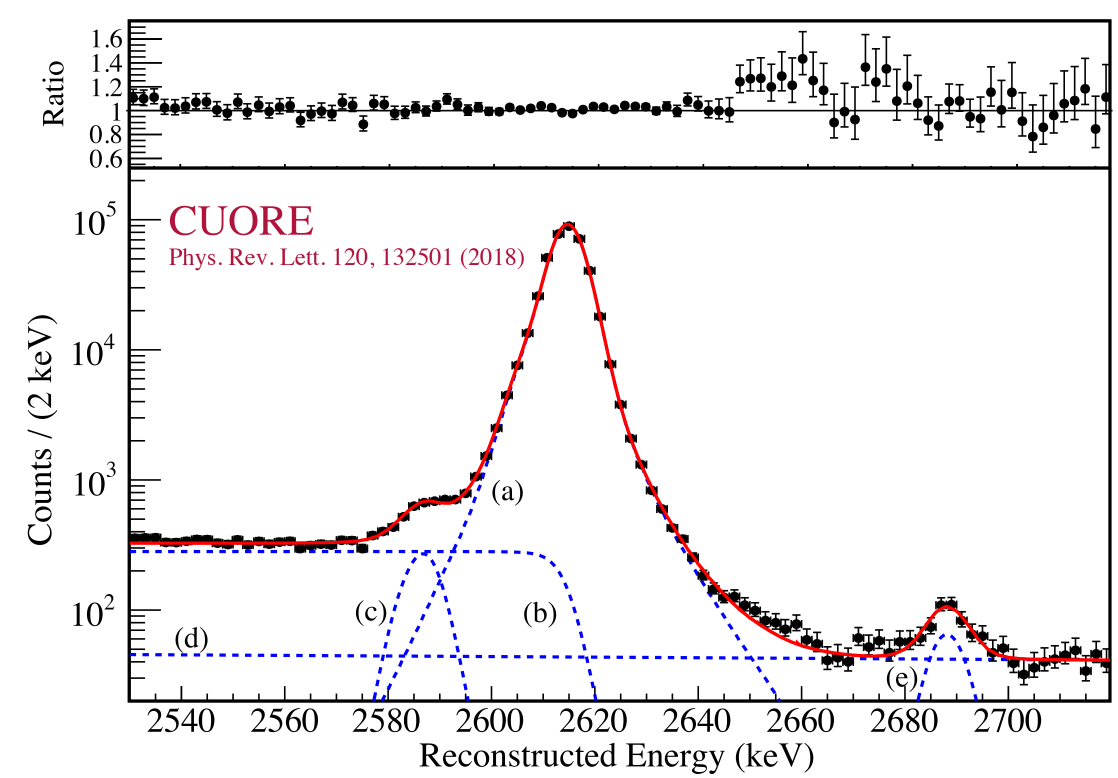
Detector performance - Energy resolution



Detector response function built on the 2615 keV calibration line

Apply a scaling factor to obtain the correct energy resolution at $Q_{\beta\beta}$

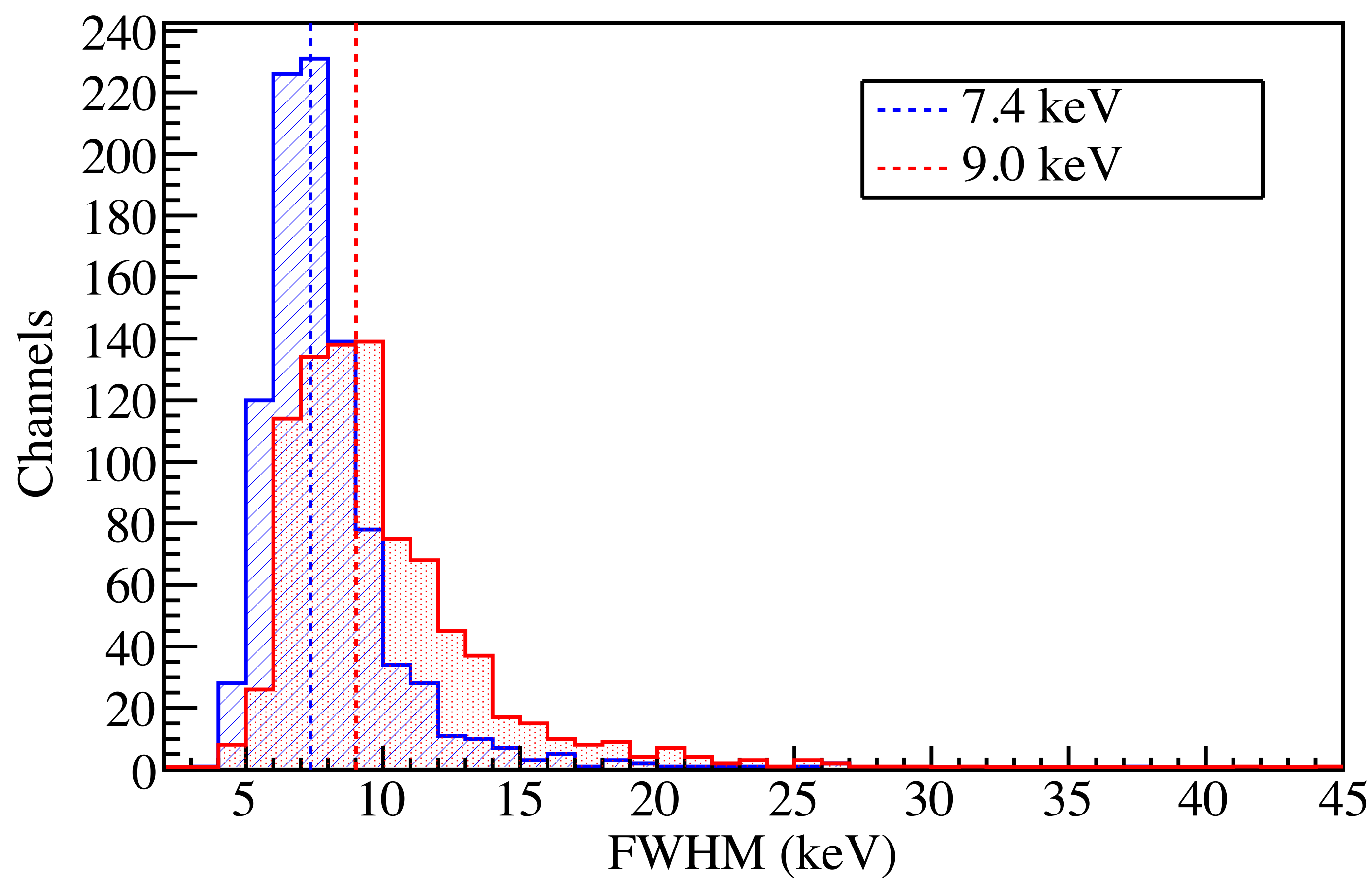
Reconstructed energy resolution at $Q_{\beta\beta}$: (7.7 ± 0.5) keV FWHM



Detector performance - Energy resolution

Calibration spectrum

- Energy resolution in calibration runs @^{208}Tl decay gamma-peak



Energy resolution at 2615 keV in calibration

Dataset 1: 9.0 keV FWHM
Dataset 2: 7.4 keV FWHM
Average: **8.0 keV FWHM** - exposure weighted

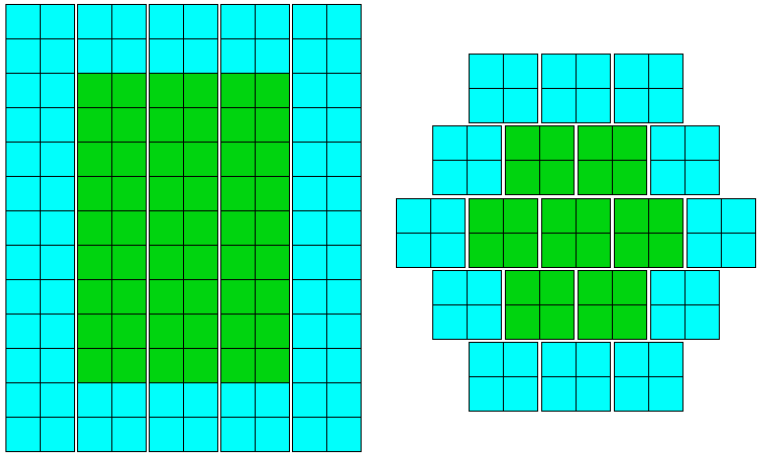
Improved resolution from Dataset 1 to Dataset 2 due to :

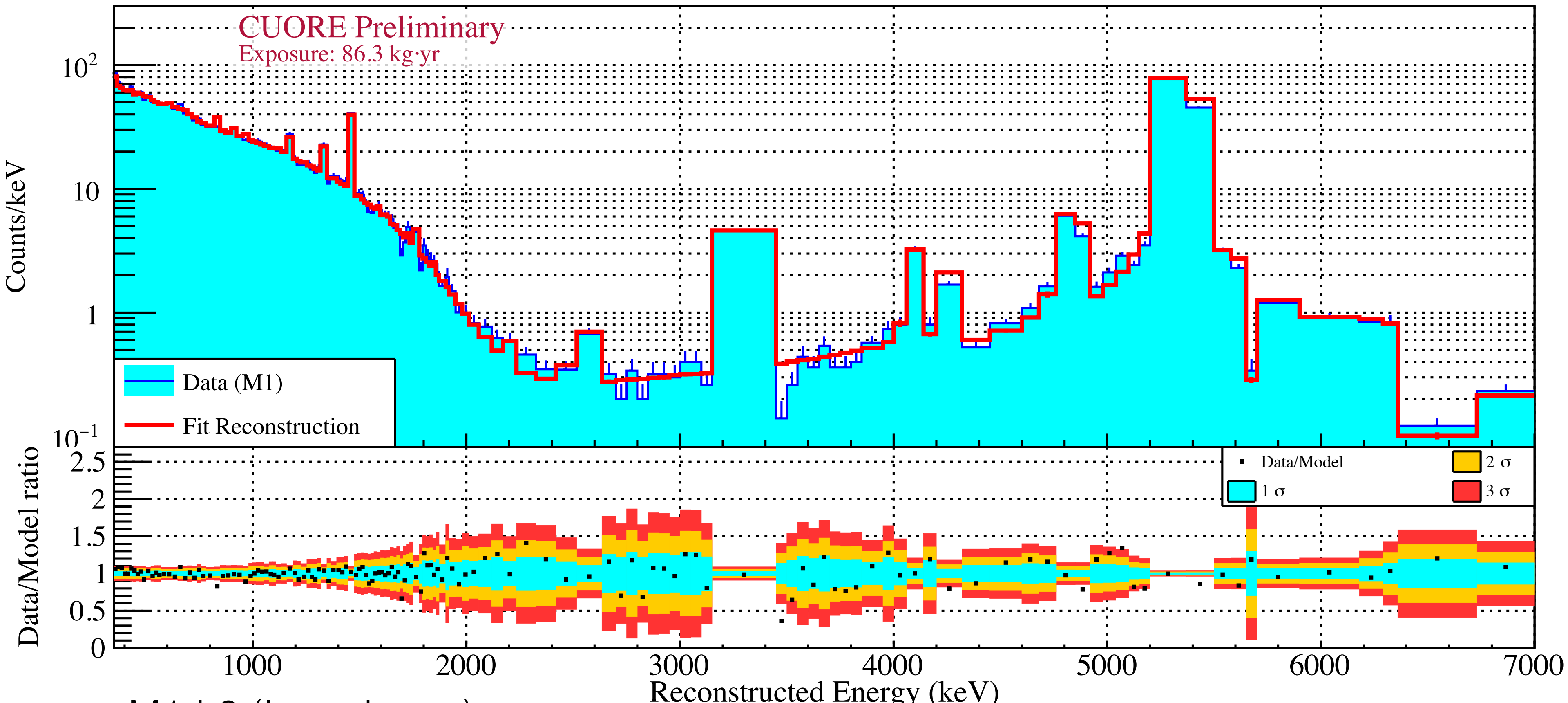
- Investigation and upgrades to the electronics grounding
- **Active cancellation of the PT-induced noise**
- **Optimization of the operating temperature and detector working points**
- Software and analysis upgrades

First results from CUORE: Background model

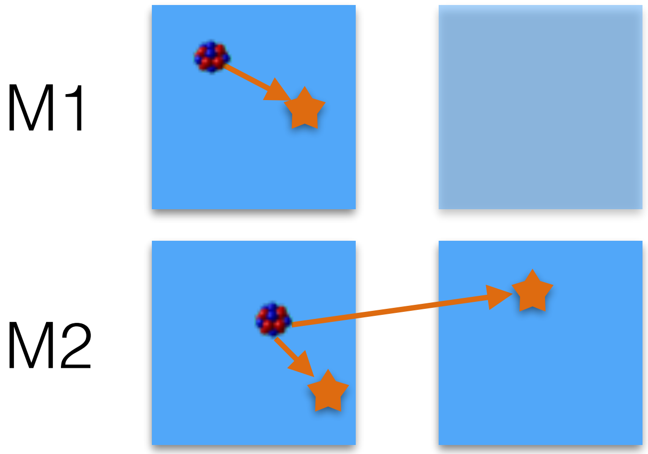
Monte Carlo reconstruction of the CUORE background: the bayesian approach

- Data split into four types of energy spectra:
  - by-layer: L0 inner, L1 outer
  - by-multiplicity: Multiplicity 1 (M1), Multiplicity 2 (M2)
- 60 background sources simulated
- MCMC fit with uniform priors (except muons)

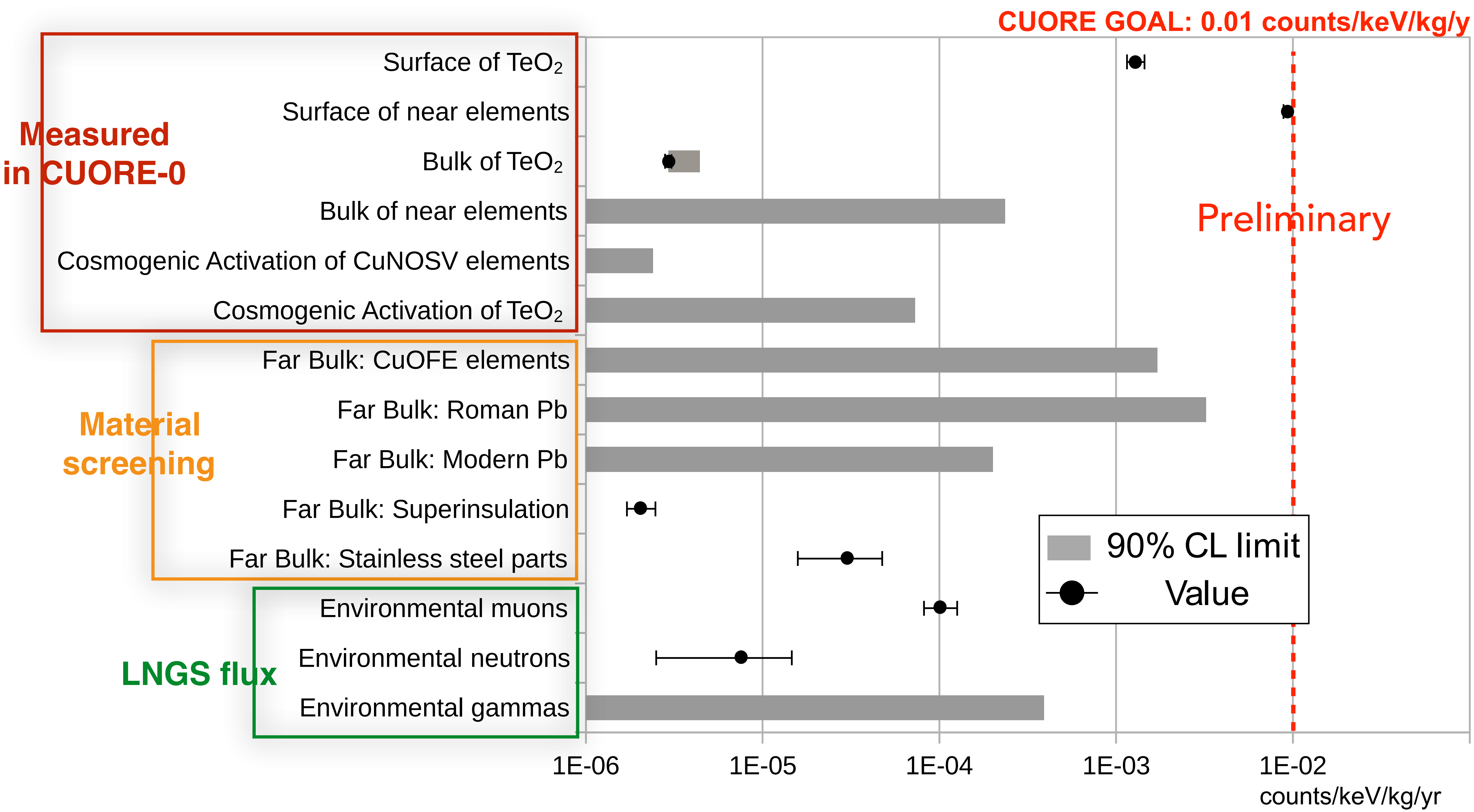




M1-L0 (Inner Layer)



CUORE background budget



CUORE sensitivity and perspectives

CUORE 0νββ exclusion sensitivity in 5 years (90% C.L.):

$S_{0\nu}$ ~ 9 x 10^{25} yr

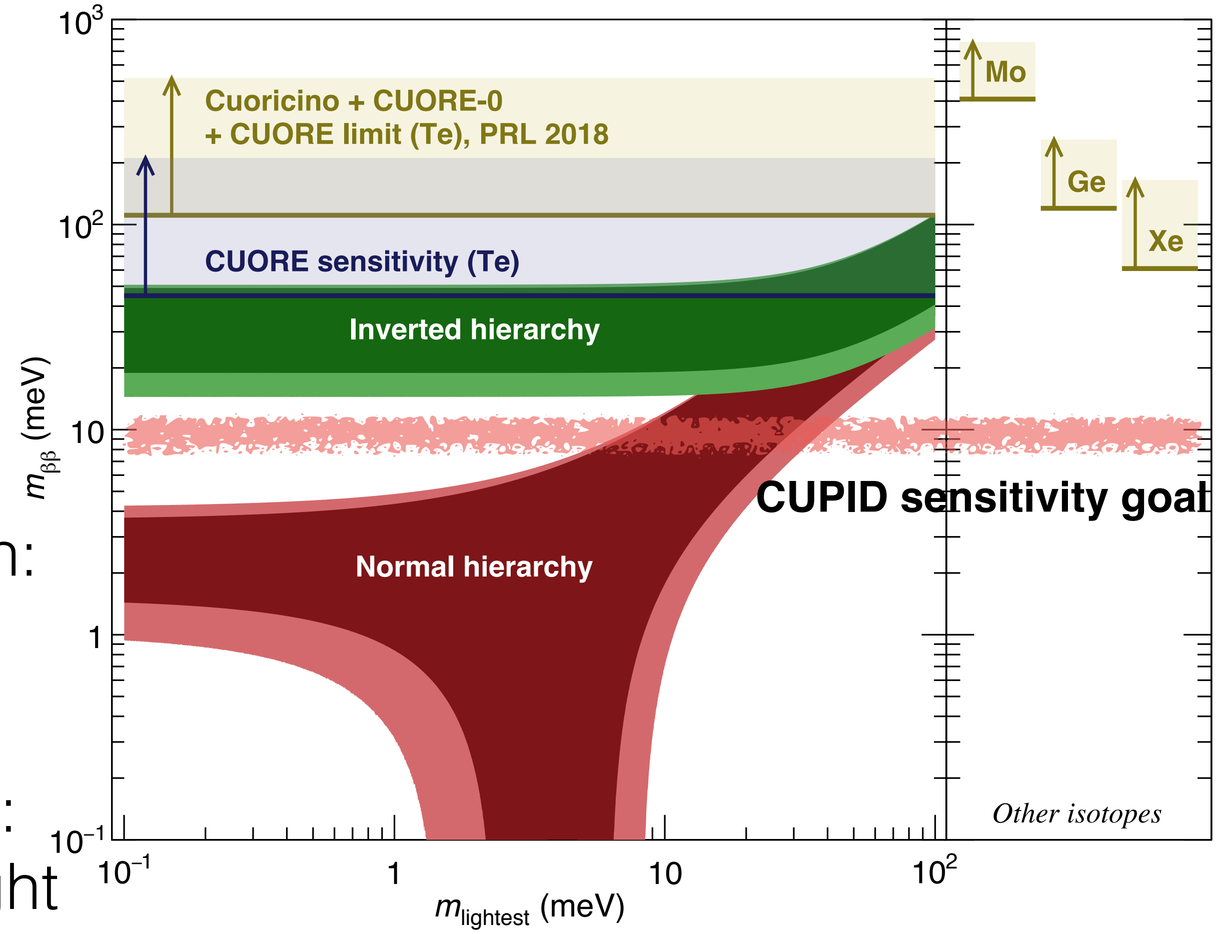
wiith

nominal background: 10^{-2} c/(keV·kg·yr)

and

nominal energy resolution : 5 keV FWHM

in the Region Of Interest (ROI)



Next generation of 0νββ decay experiments seek to be sensitive to the full Inverted Hierarchy region:

Sensitivity **$S_{0\nu}$ ~10^{27} yr, $m_{\beta\beta}$ ~ 6 - 20 meV**

CUPID (CUORE Upgrade with Particle ID) project: build a future experiment with ~ 1500 enriched light emitting bolometers mounted in the CUORE cryostat, reaching nearly zero background goal, Bkg < 10^{-4} c/(keV·kg·yr)