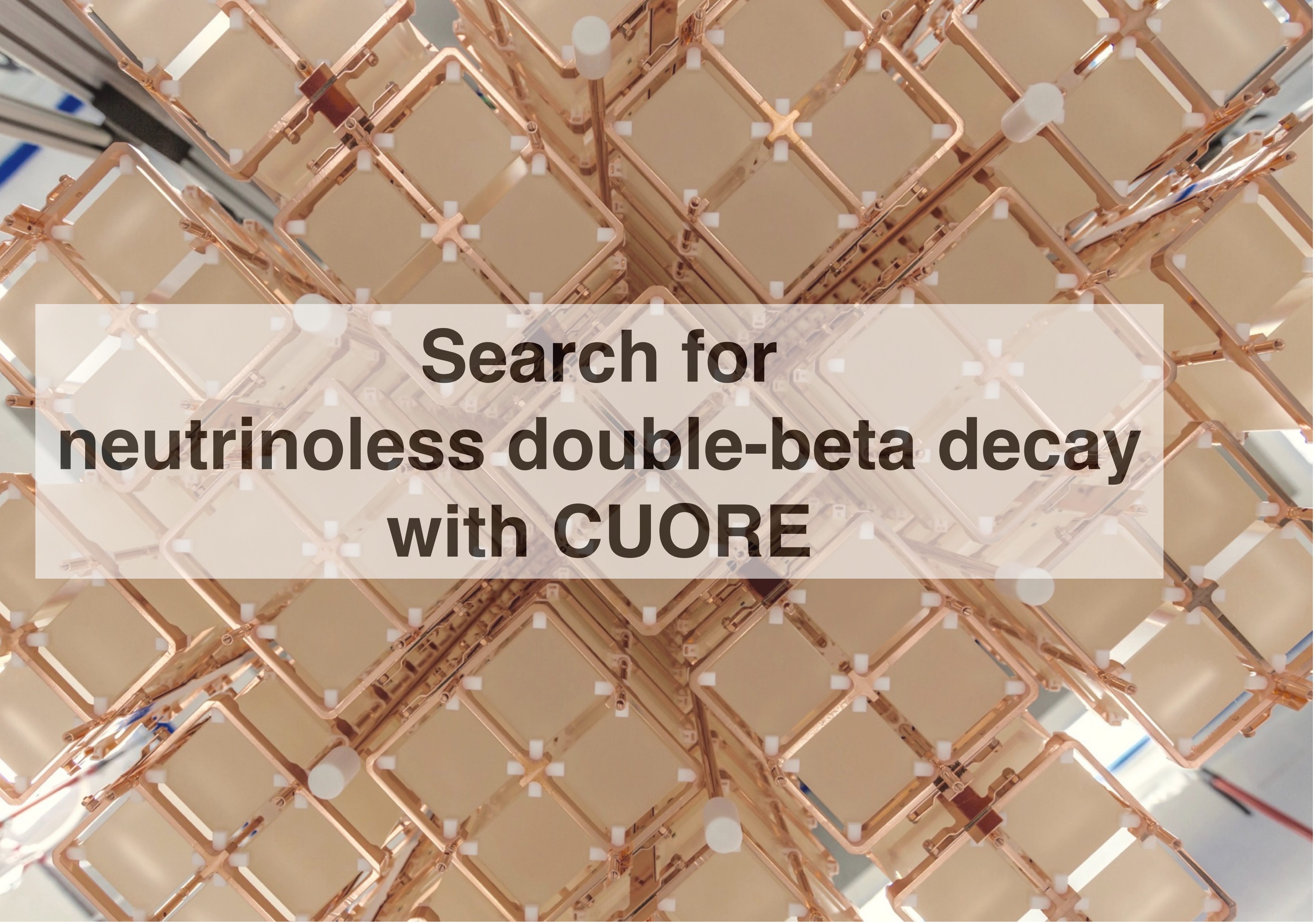


Search for neutrinoless double-beta decay with CUORE

I.Nutini on behalf of the CUORE collaboration
Gran Sasso Science Institute
INFN Laboratori Nazionali del Gran Sasso

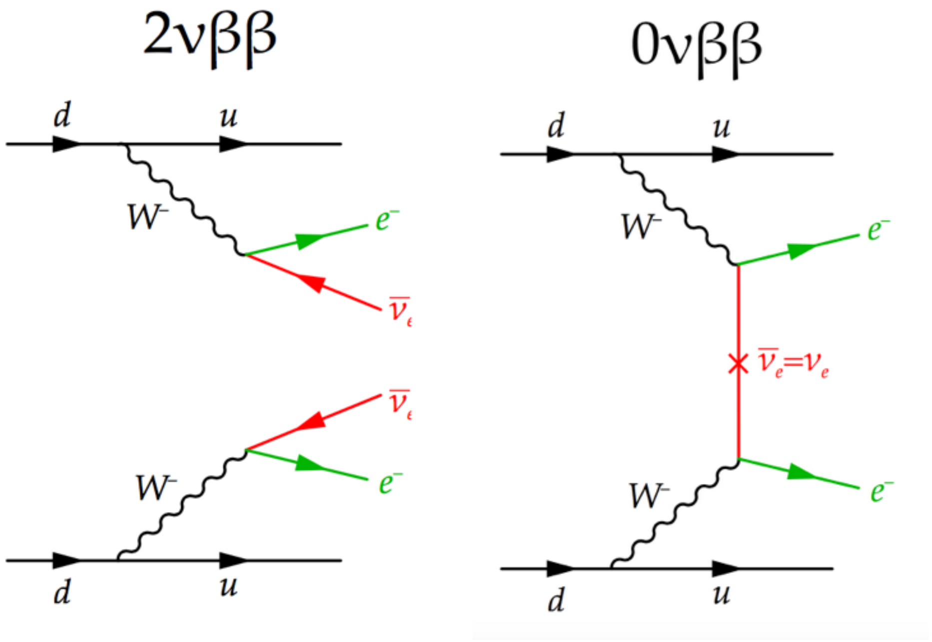
Les Rencontres de Physique de la Vallée d'Aoste
February 26th, 2018

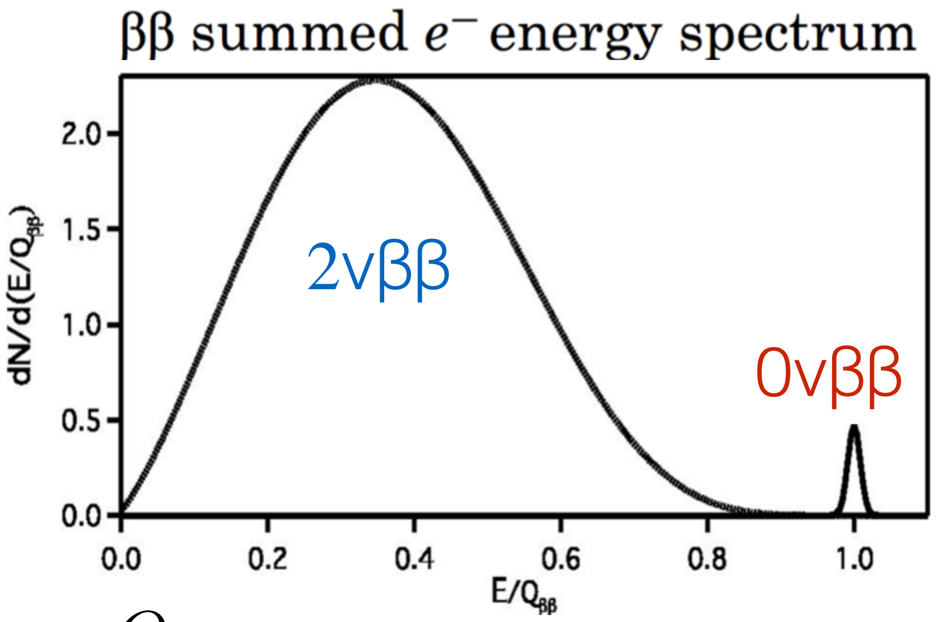
The 0νββ decay search

Double beta decay is a rare nuclear decay
(N,Z) → (N-2, Z+2)

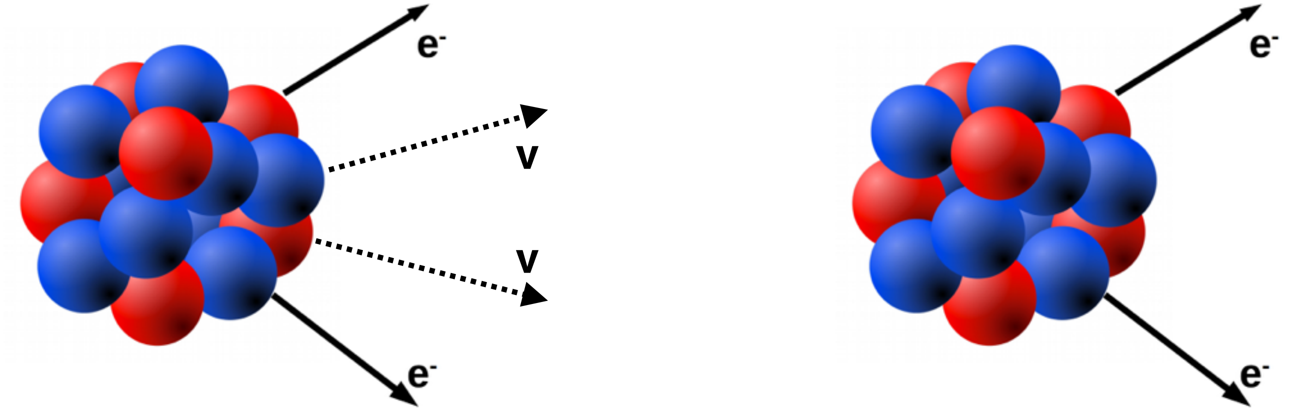
2νββ:
- 2nd order process allowed in SM
- Observed in several nuclei: $\tau \sim 10^{19\text{-}21}$ y

0νββ:
- Lepton number violation process (beyond SM)
- Majorana nature of neutrino
- Constraints on neutrino mass hierarchy and scale
- Not yet observed $\tau > 10^{24\text{-}26}$ y





$Q_{\beta\beta}$ Q-value of the ββ decay

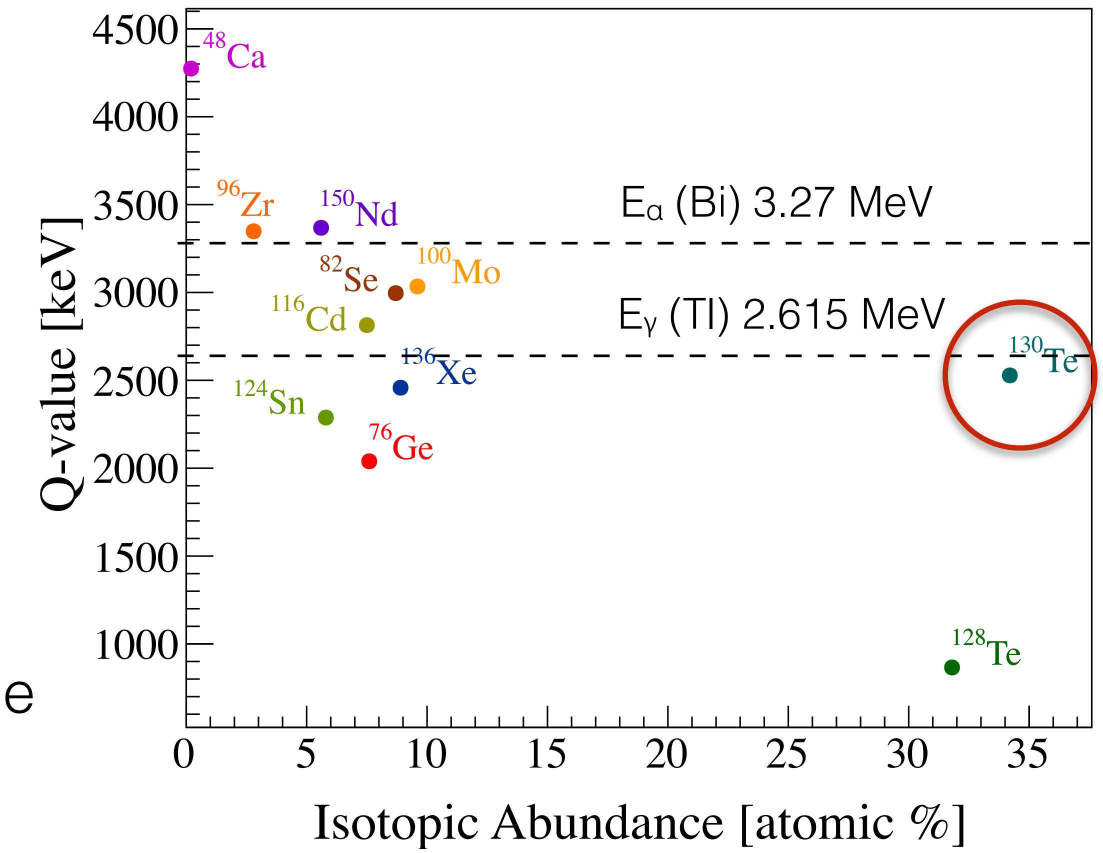


The CUORE experiment and the 0νββ search

Search for neutrino-less double beta (0νββ) decay of ^{130}Te

Why ^{130}Te:

- Transition energy $Q_{\beta\beta}$ (^{130}Te) = 2527.518 keV, above most of the natural radioactivity
- Highest natural isotopic abundance (η = 34.167%)
- ^{130}Te within the detector absorber of TeO_2 (high detection efficiency ε ~ 90%)
- Reproducible growth of large number of high quality crystals; large active mass (M) detector
- Good energy resolution Δ to reduce the 2ν irreducible background around $Q_{\beta\beta}$

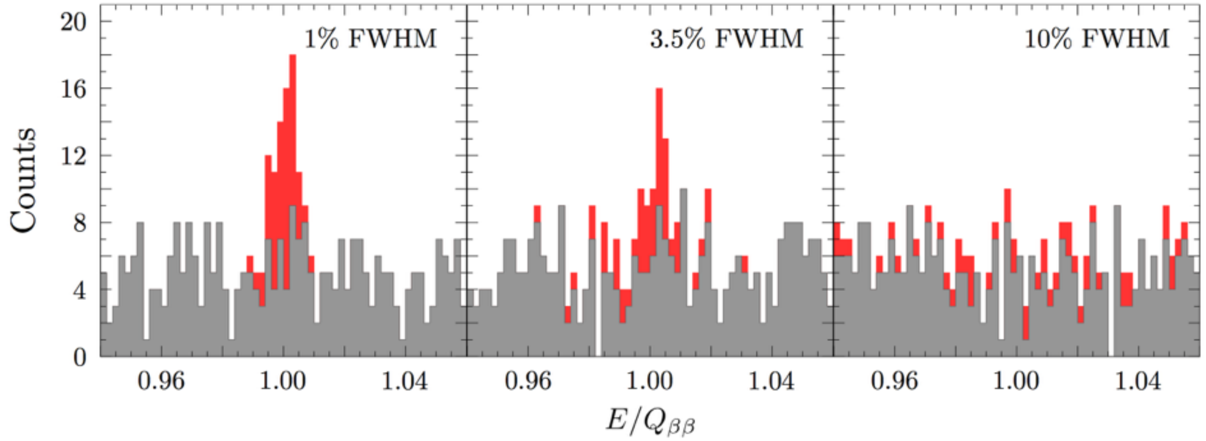


Experimental 0νββ half-life sensitivity:

Present generation experiments

Finite background: M · T · B · Δ > 1

$$\boxed{S^{0\nu}(n_\sigma) = ln2\ \epsilon\ \frac{1}{n_\sigma}\ \frac{x\ \eta\ N_A}{M_A}\sqrt{\frac{M\ T}{B\ \Delta}}}$$

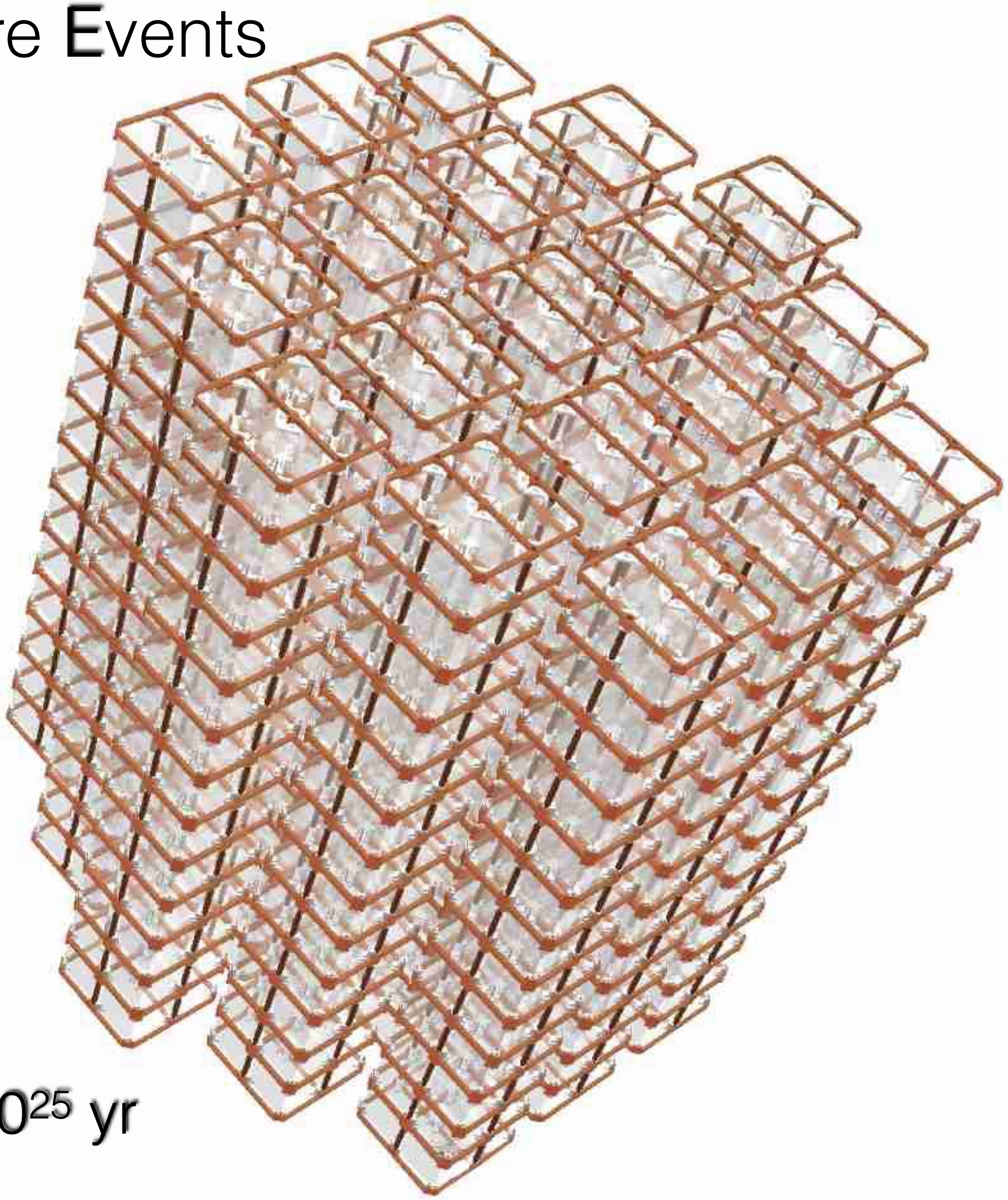


J. J. Gómez-Cadenas and J. Martin-Albo, Phenomenology of neutrinoless double beta decay , Proc. of Science (GSSI14), 004 (2015)

The CUORE experiment and the 0νββ search

The CUORE challenge:

Cryogenic Underground Observatory for Rare Events



Primary goal: Search for 0νββ decay in ^{130}Te

Closely packed array of **988 TeO_2 crystals**

19 towers of 52 crystals 5×5×5 cm^3, 0.75 kg each

High Mass of TeO_2: 742 kg (206 kg of ^{130}Te)
and high granularity

Experiment hosted at
Gran Sasso National Labs (LNGS)

CUORE $S_{0\nu}$ sensitivity in 5 years (90% C.L.): ~ 9×10^{25} yr

The CUORE experiment and the 0νββ search

CUORE

The CUORE challenge:

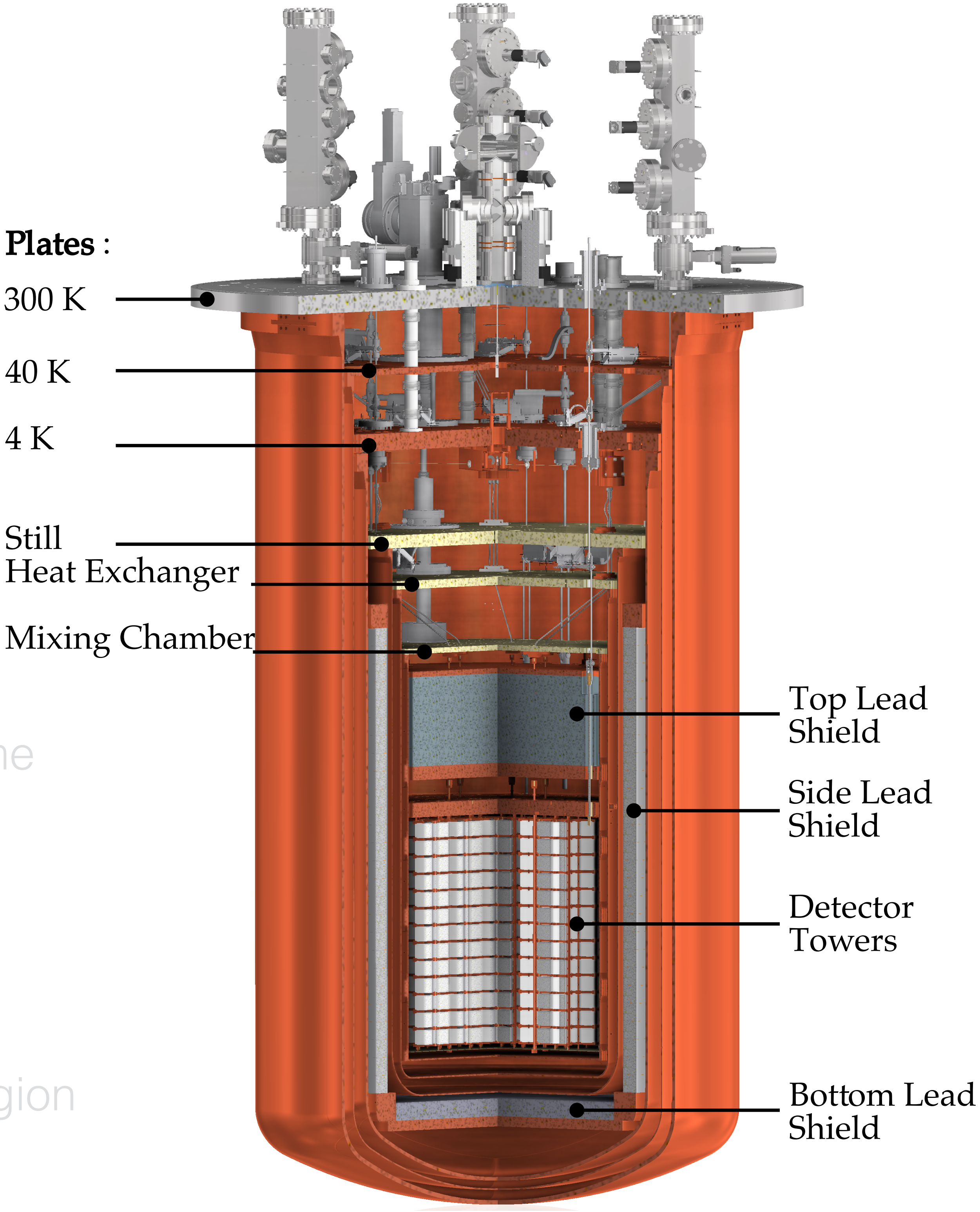
- **Low background**:
  - Deep underground location (Gran Sasso National Labs - LNGS)
  - Strict radio-purity controls on materials and assembly
  - Passive shields (Pb) from external and cryostat radioactivity

  Background goal: 10^{-2} c/(keV·kg·yr)

- **Low temperature and low vibrations**
  - Multistage cryogen-free cryostat:
    - Mass to be cooled < 4K: ~ 15 tons (IVC volume and Cu vessels, Roman Pb shield)
    - Mass to be cooled < 50 mK: ~ 3 tons (Top Pb shield, Cu supports and TeO$_2$ detectors)

  TeO$_2$ detectors operating temperature: ~10 mK
  - Mechanical vibration isolation

  Energy resolution goal: 5 keV FWHM in the Region Of Interest (ROI)



The CUORE experiment and the 0νββ search

The CUORE challenge:

- **Low background**:
  - Deep underground location (Gran Sasso National Labs - LNGS)
  - Strict radio-purity controls on materials and assembly
  - Passive shields (Pb) from external and cryostat radioactivity

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  TeO_2 detectors operating temperature: ~10 mK
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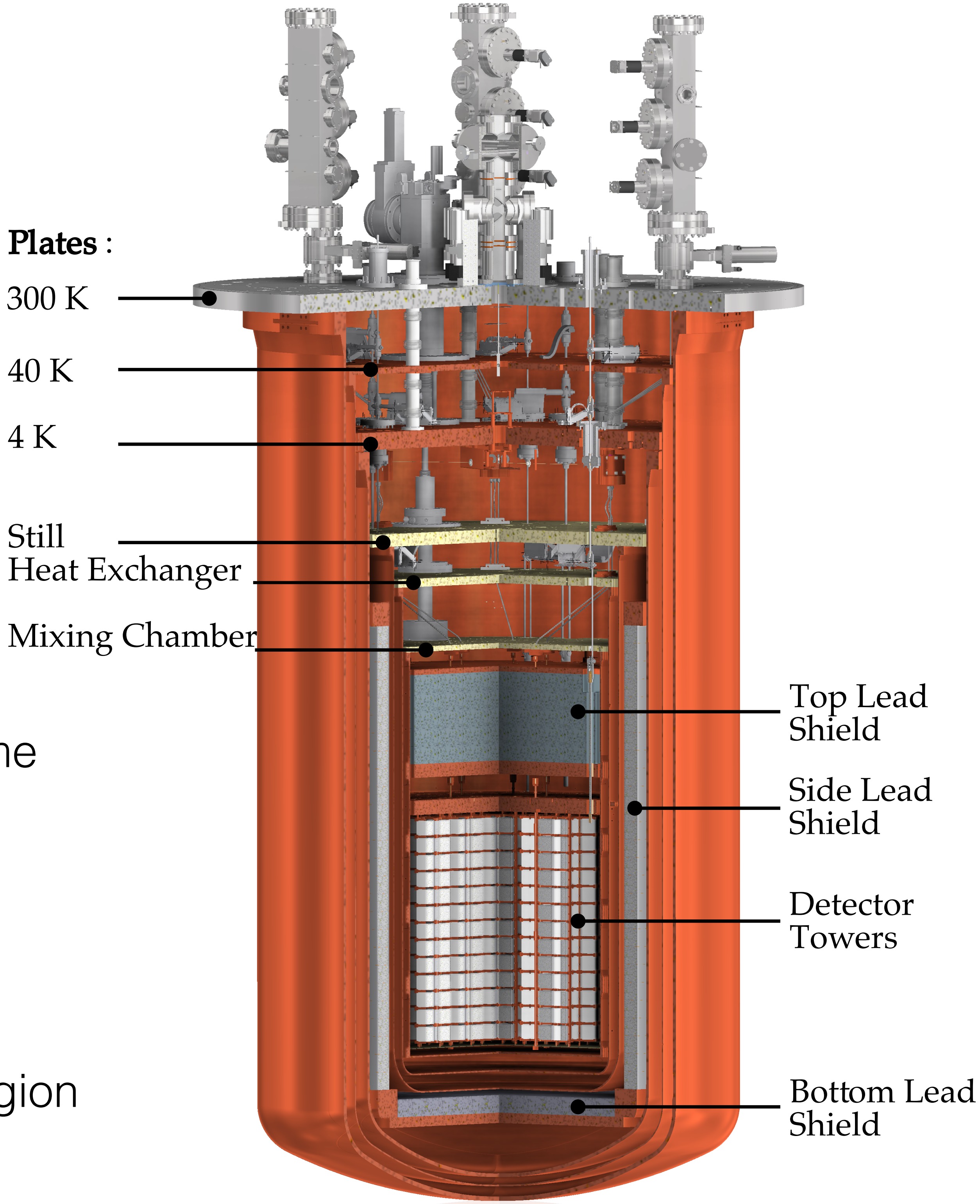
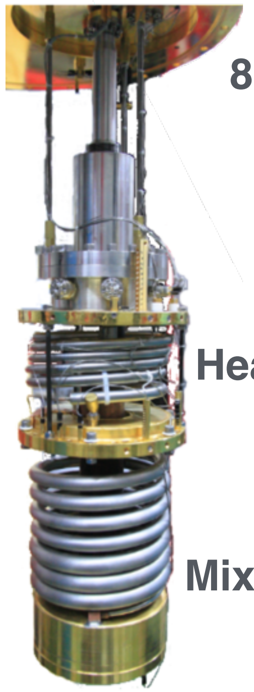
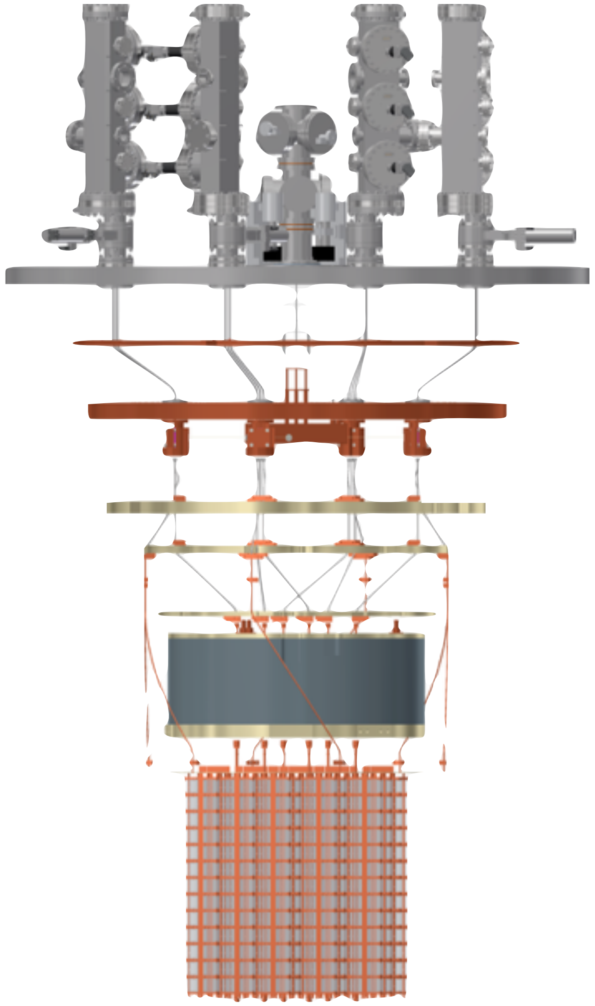
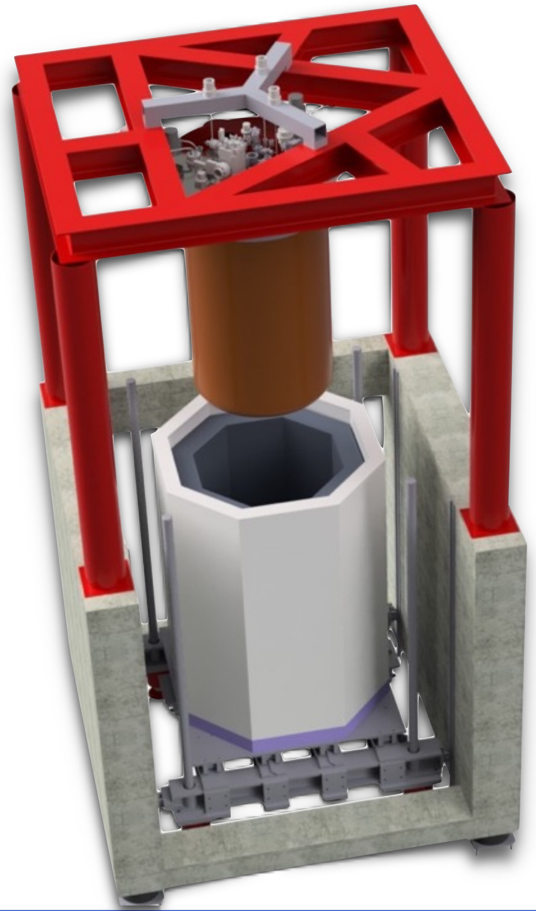


CUORE Cryogenic infrastructure and auxiliary systems

Multistage cryogen-free cryostat:
- Fast Cooling System
- 5 Pulse Tube cryocoolers
- Continuous-cycle 3He/4He dilution refrigerator







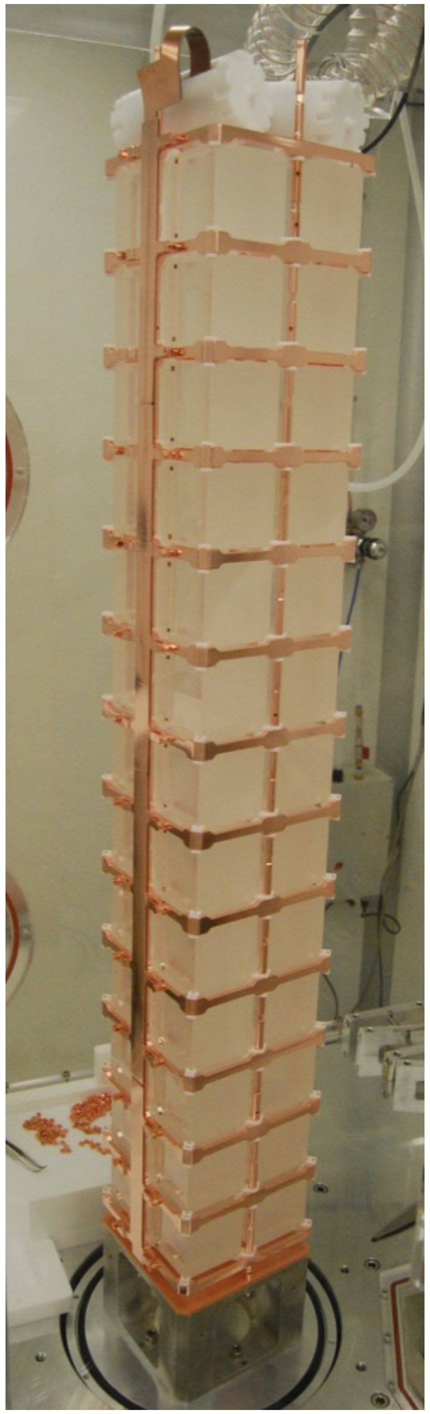
Shieldings
- External lead shielding and concrete support structure
- Internal Ancient Roman Lead Shield (6 cm thick, 5 tons) @ 4K
- Internal Top Lead Shield (30 cm thick, 2.5 tons) @ 50 mK

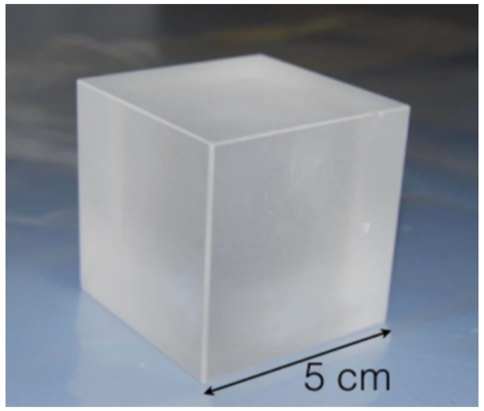
Roman lead shield @4 K

Detector Calibration System
12 ^{232}Th γ-ray sources, cooled to base temperature and lowered into the experimental volume for calibration

CUORE TeO_2 bolometers

CUORE module: a tower

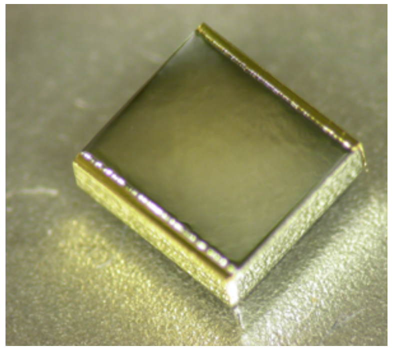




52 $^{(nat)}TeO_2$ crystals

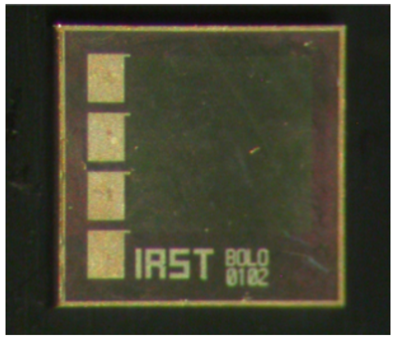
Absorber = 0νββ source

5.0 × 5.0 × 5.0 cm^3



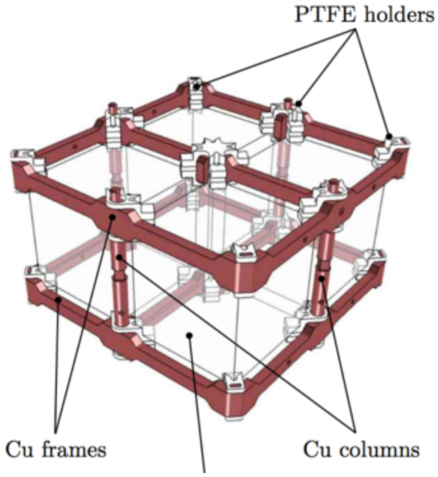
1 Ge NTD thermistor for each crystal

3.0 x 2.9 x 0.9 mm^3



1 Si heater for each crystal

2.3 x 2.4 x 0.5 mm^3



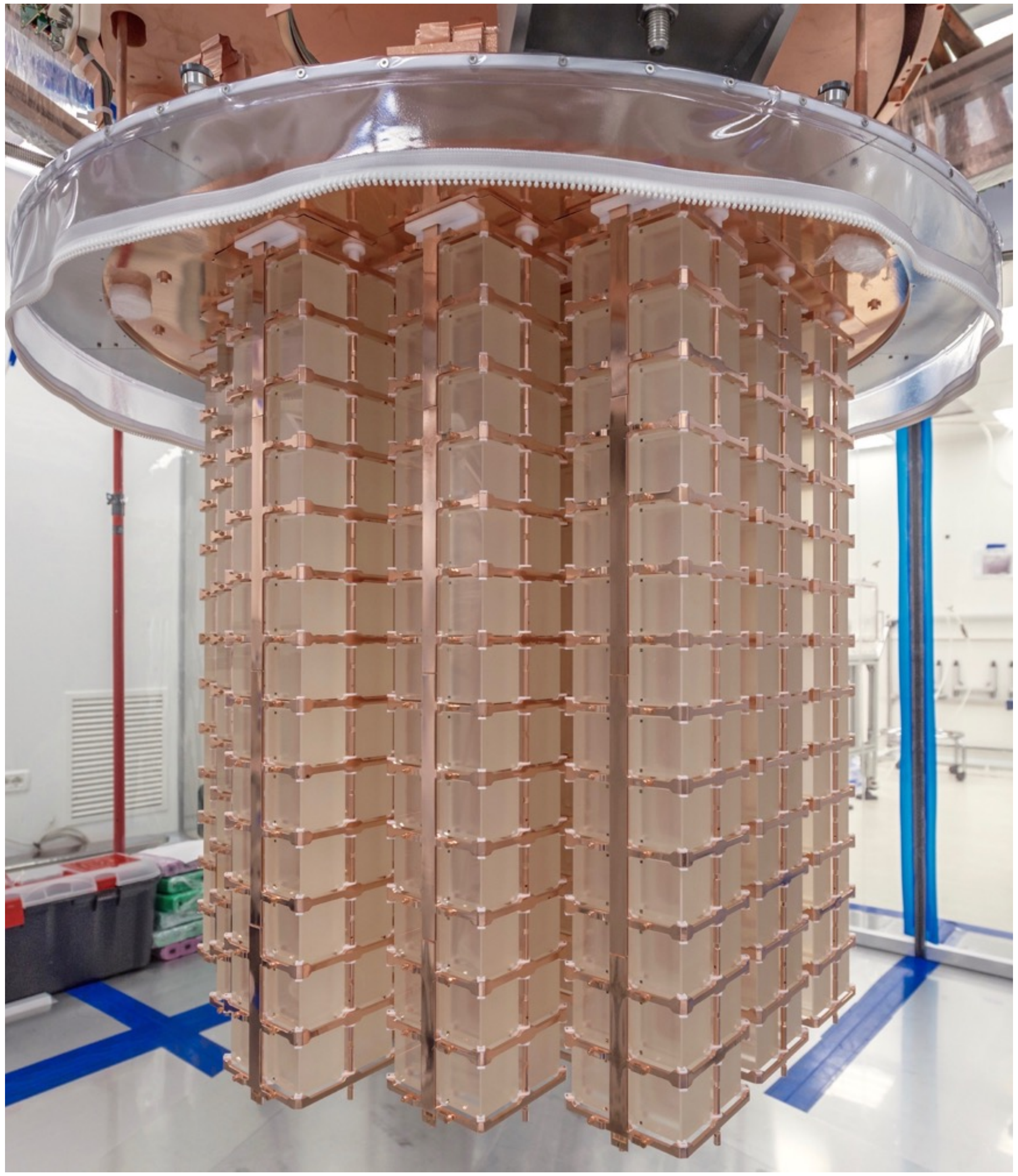
<— Cu frames and PFTE holders

Cu-PEN cables —>

CUORE TeO_2 bolometers

CUORE 19 towers array

Towers installation

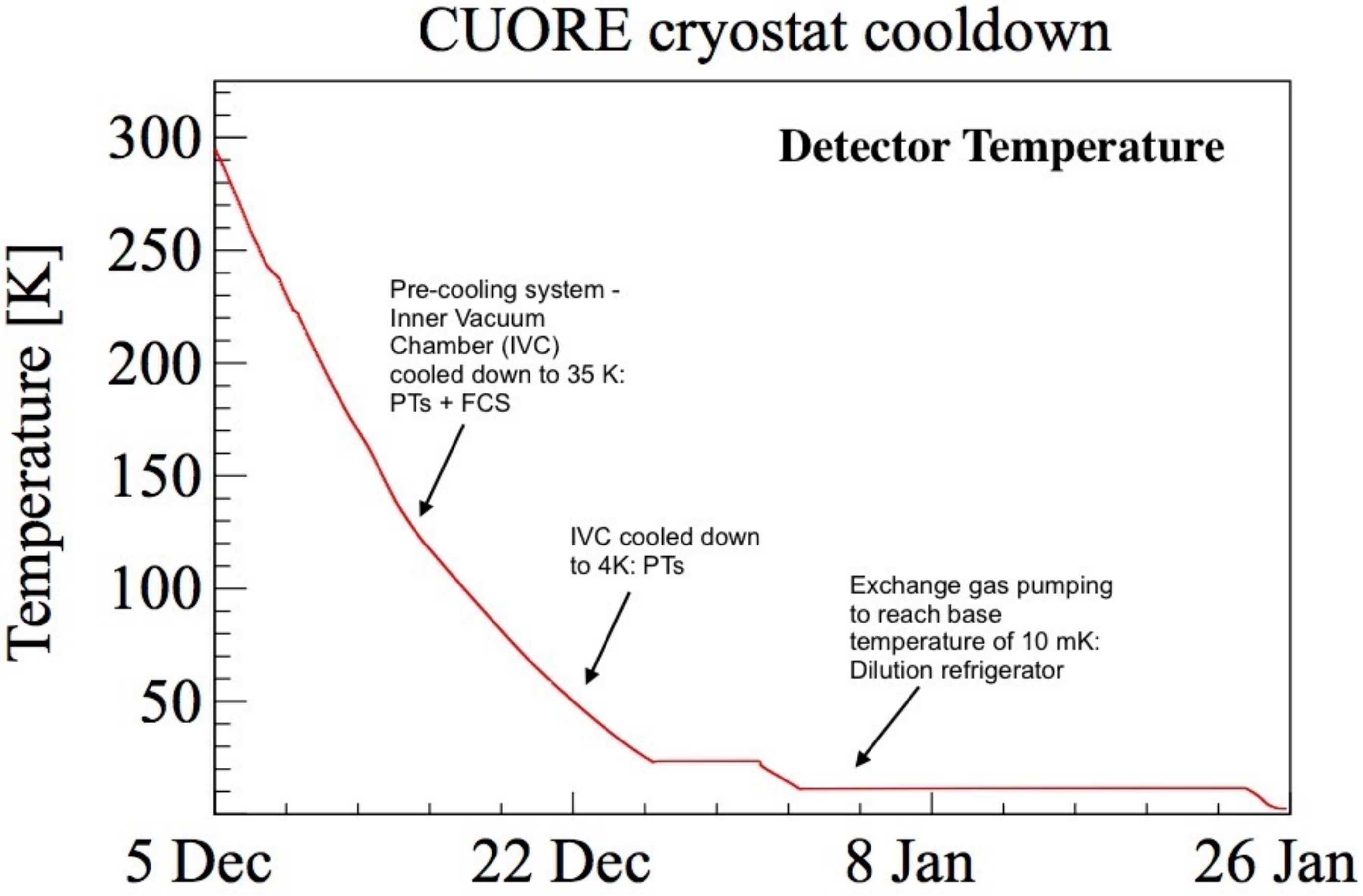


Towers installed,
before the closure of the shields

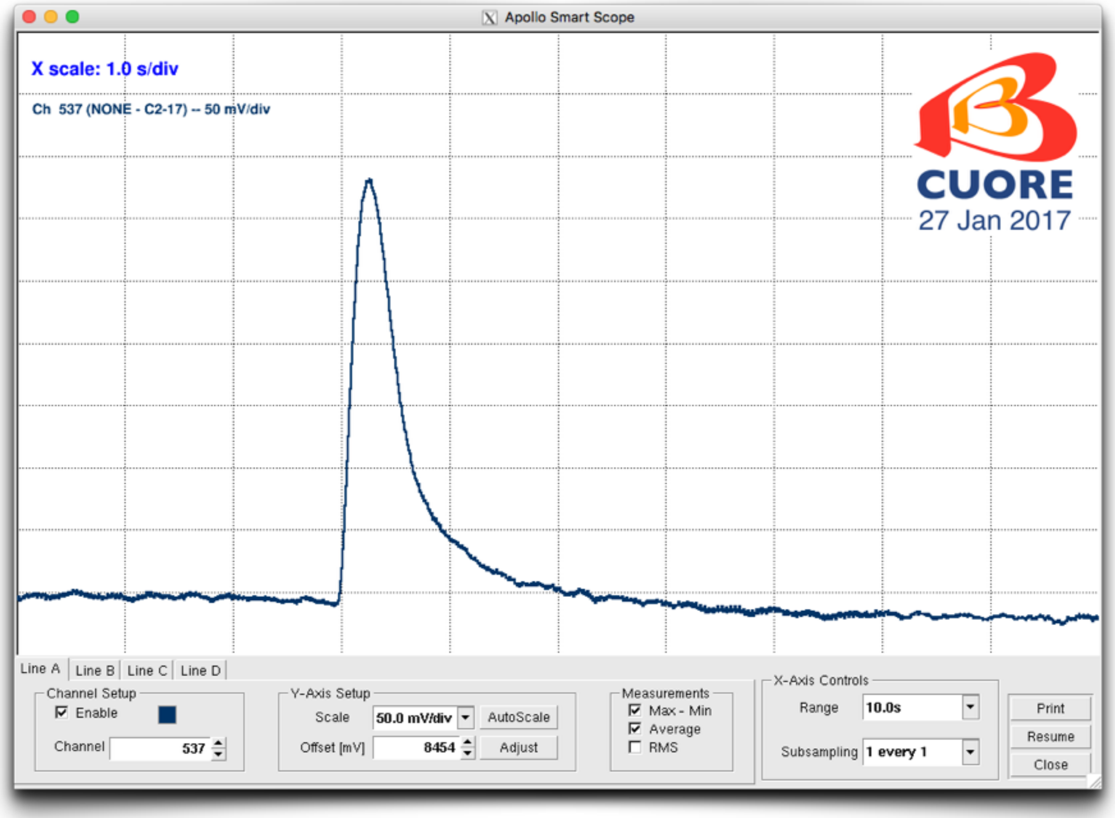
CUORE cooldown

- Cryogenic system commissioning : completed in Feb.2016
- Detector assembly and installation: completed at the end of Aug. 2016
- Detector cooldown: Started at the beginning of Dec. 2016,

Cooldown time: ~ 20 days down to ~3.4 K, ~ 3 weeks pumping the IVC down to vacuum, ~ 1.5 days down to ~10 mK



Observed first detector pulses just after the cool down without any optimization



X scale: 1.0 s/div

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

☑ Enable

Channel 537

Scale 50.0 mV/div

Offset [mV] 8454

☑ Max - Min

☑ Average

☐ RMS

Range 10.0s

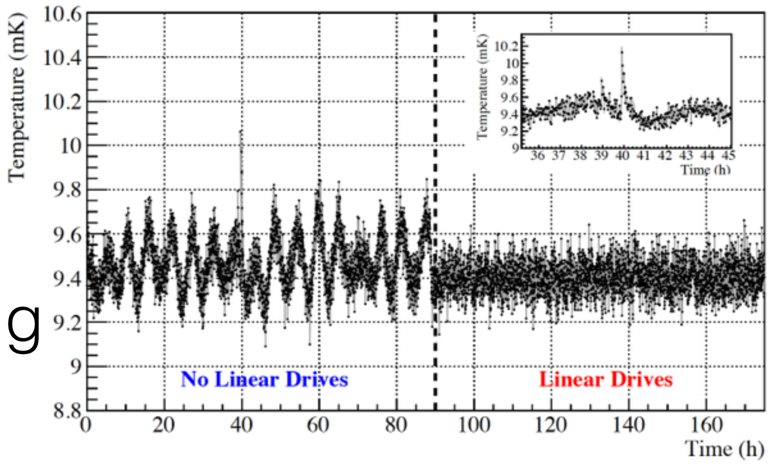
Subsampling 1 every 1

Detector characterization and first physics results

Detector pre-operations and optimization phase (January - April 2017):

Noise optimization:

- Electronics noise attenuation
- Vibrations reduction (detector mechanically isolated)
- Pulse tube phases driven by LD and relative phase shift tuning



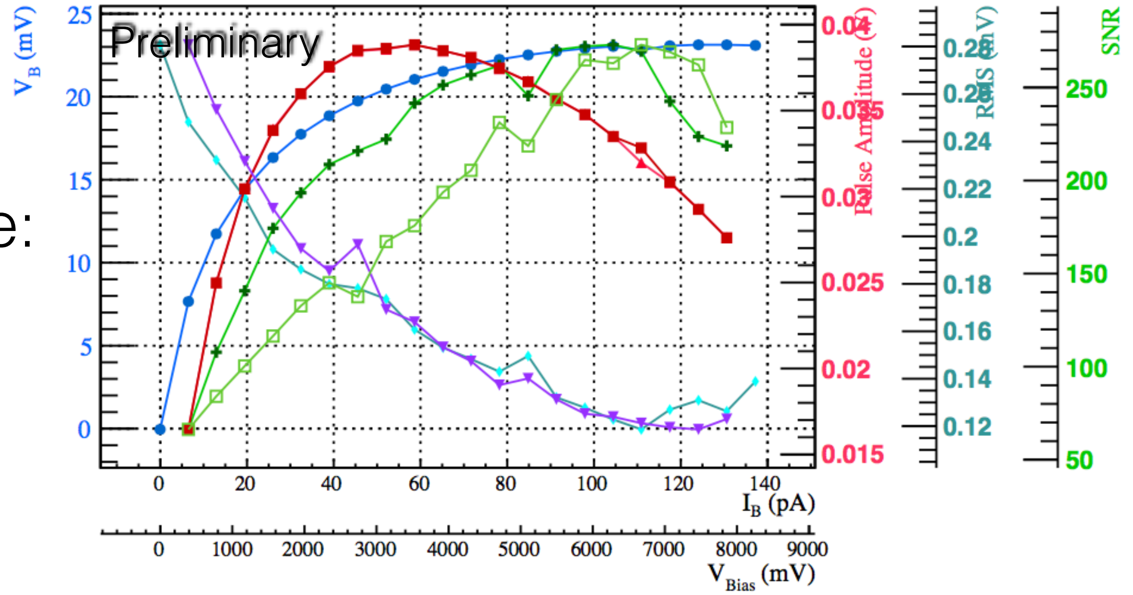
Temperature scan:

Temperature scan around base temperature to choose the one that optimizes the signal, the resolution and at the same time allows to work with a NTD resistance that well matches the readout electronics. Selected working temperature: 15 mK

Setting the working points:

Load curves scan to choose the best bias voltage to feed each channel's NTD at a given temperature:

- linear behavior for small temperature variations
- maximization of signal to noise ratio
- optimization of pulse amplitude



Detector characterization and first physics results

CUORE science runs (May - September 2017):

2 periods of physics data

- Dataset 1: May – Jun 2017 → 37.6 kg·y of TeO_2
- Dataset 2: Aug – Sep 2017 → 48.7 kg·y of TeO_2

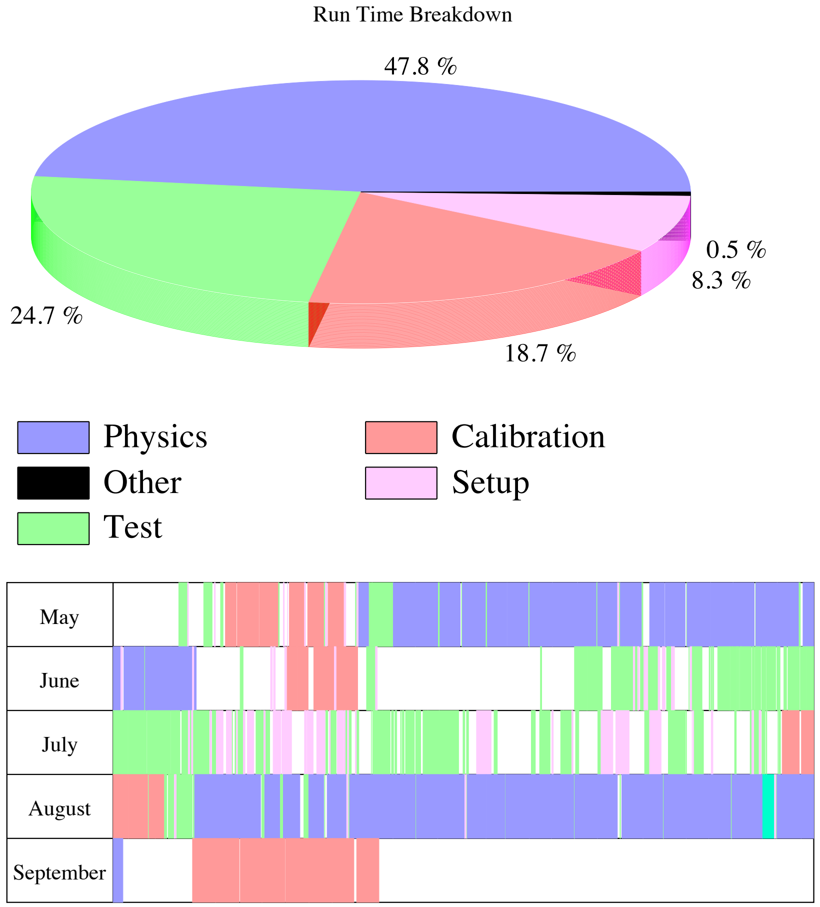
Each dataset is bracketed by an initial and a final calibration

Collected statistic for 0νββ decay search

$^{nat}TeO_2$ exposure: 86.3 kg yr

^{130}Te exposure: 24.0 kg yr

Physics data 2017 - Time breakdown



Operational performance

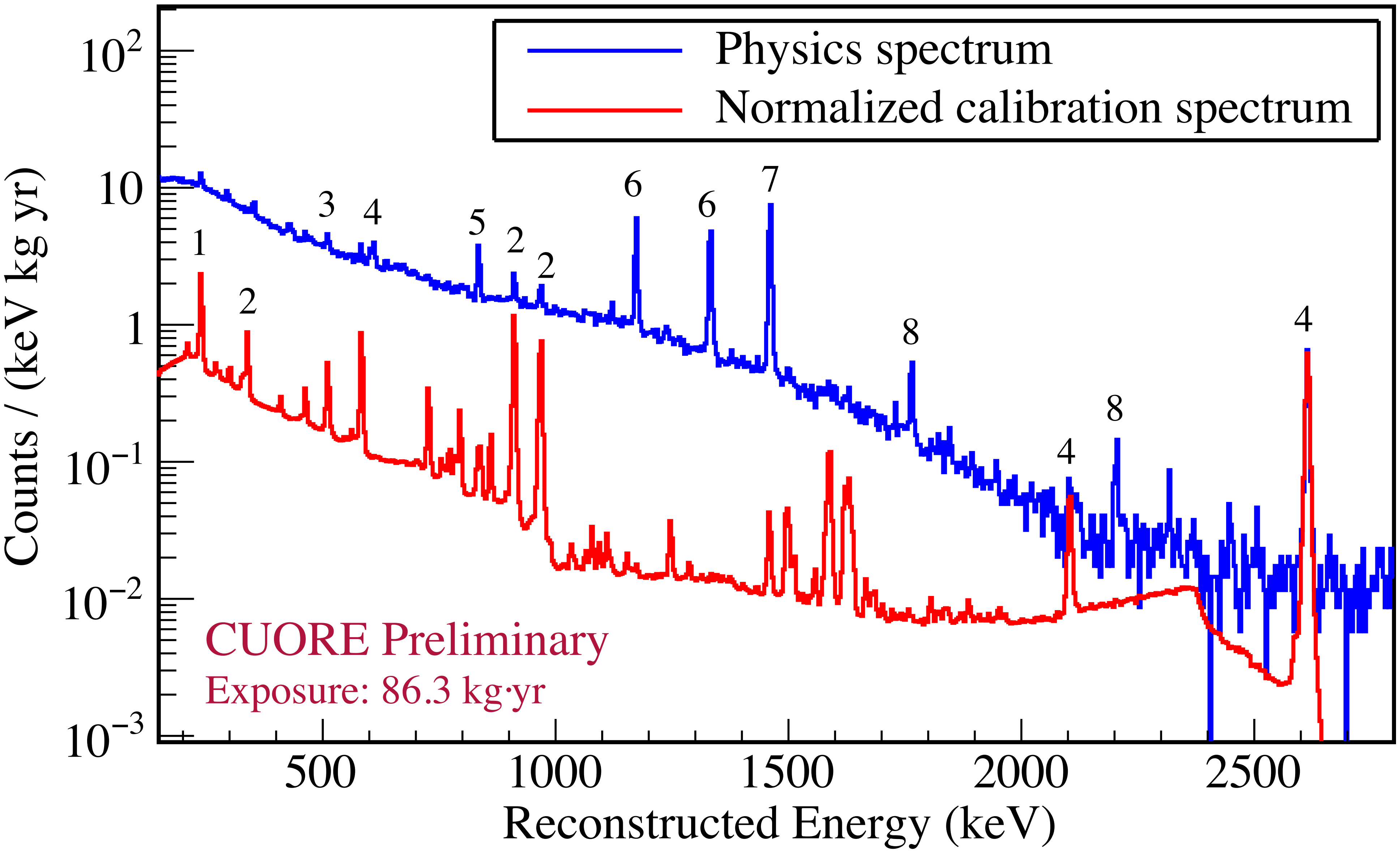
- 984/988 operational channels
- Excellent data-taking efficiency
- Improved detector stability
- Thresholds: from ~20 keV to few hundreds keV
- Trigger rate per bolometer:

Calibration 50 mHz, Physics runs: 6 mHz

Detector characterization and first physics results

CUORE

Calibration and Background spectra



Cumulative energy spectrum
from all the channels selected for the 0νββ initial analysis

Sources of the labeled peaks:
(1)^{212}Pb [239 keV],
(2) ^{228}Ac [338, 911, 969 keV],
(3) e^+ e^- annihilation,
(4) ^{208}Tl [583, 2615 keV],
(5) ^{54}Mn,
(6) ^{60}Co,
(7) ^{40}K,
(8) ^{214}Bi

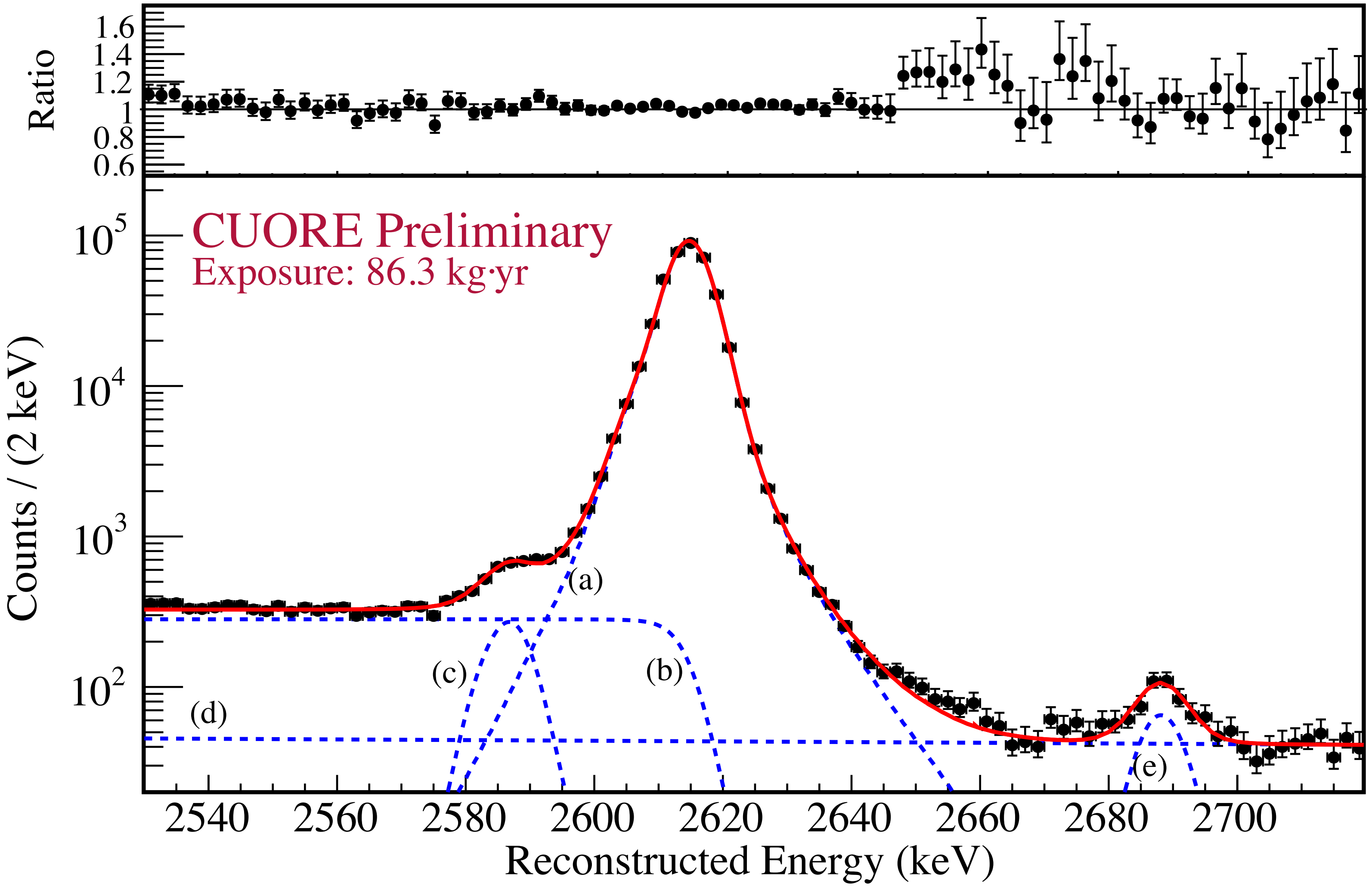
Calibration: ^{232}Th sources deployed inside the CUORE detector

Background - Physics: Spectrum is consistent with the background expectations

Detector characterization and first physics results

Detector performance - Line shape:

Calibration spectrum



**Fit to the 2615 keV line, summed over all channels.*

Fit components:

- a triple gaussian for the main peak (a)
- a step-wise multi-Compton background (b)
- Te X-rays escape peak (combination of gaussian escape lines) (c)
- a linear background (d)
- (2615+583-511) keV peak (e)

Fit on a tower by tower basis

An independent response function is obtained for each channel

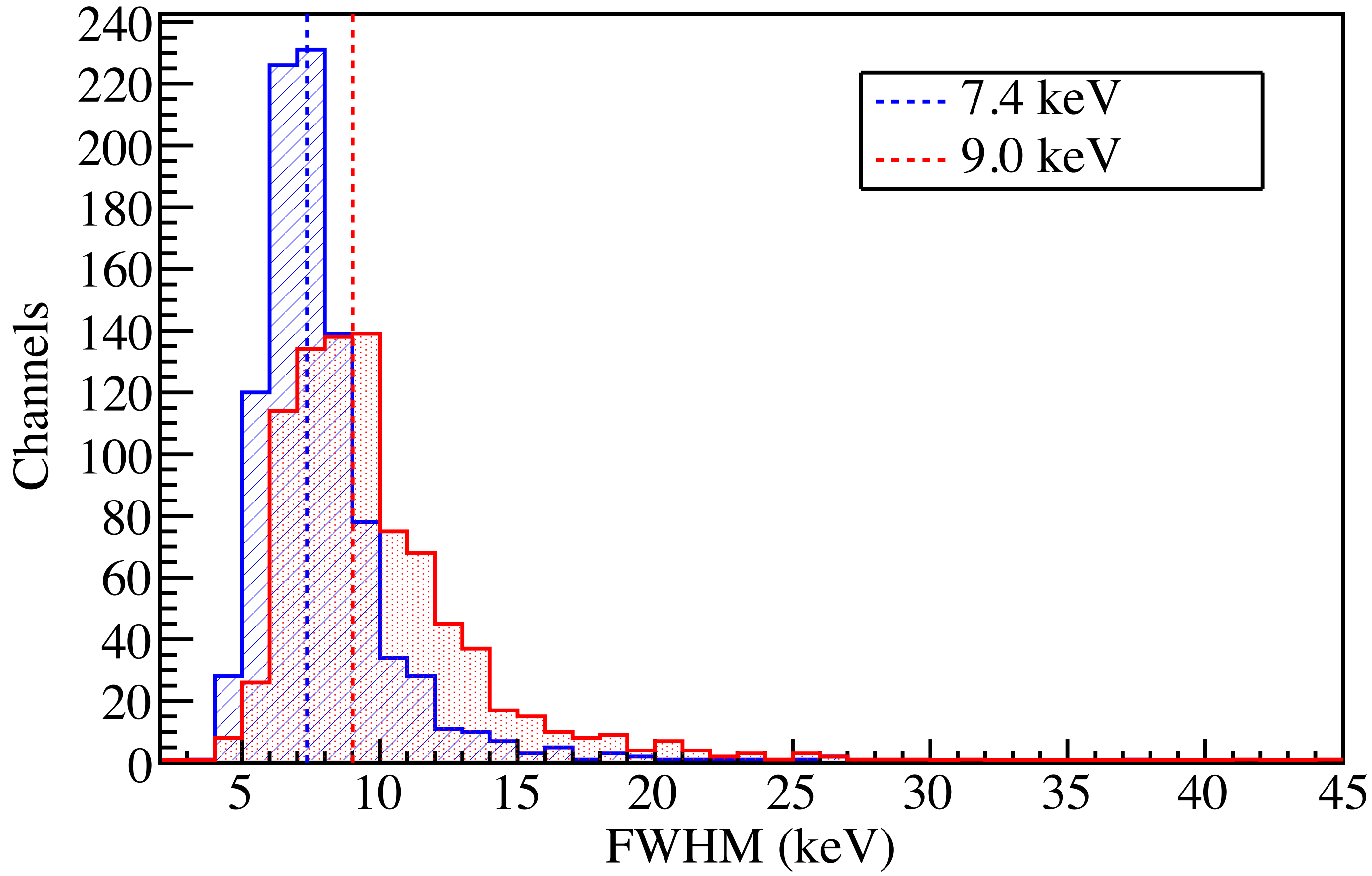
Detector characterization and first physics results

CUORE

Detector performance - Energy resolution:

Calibration spectrum

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



Energy resolution at 2615 keV in calibration

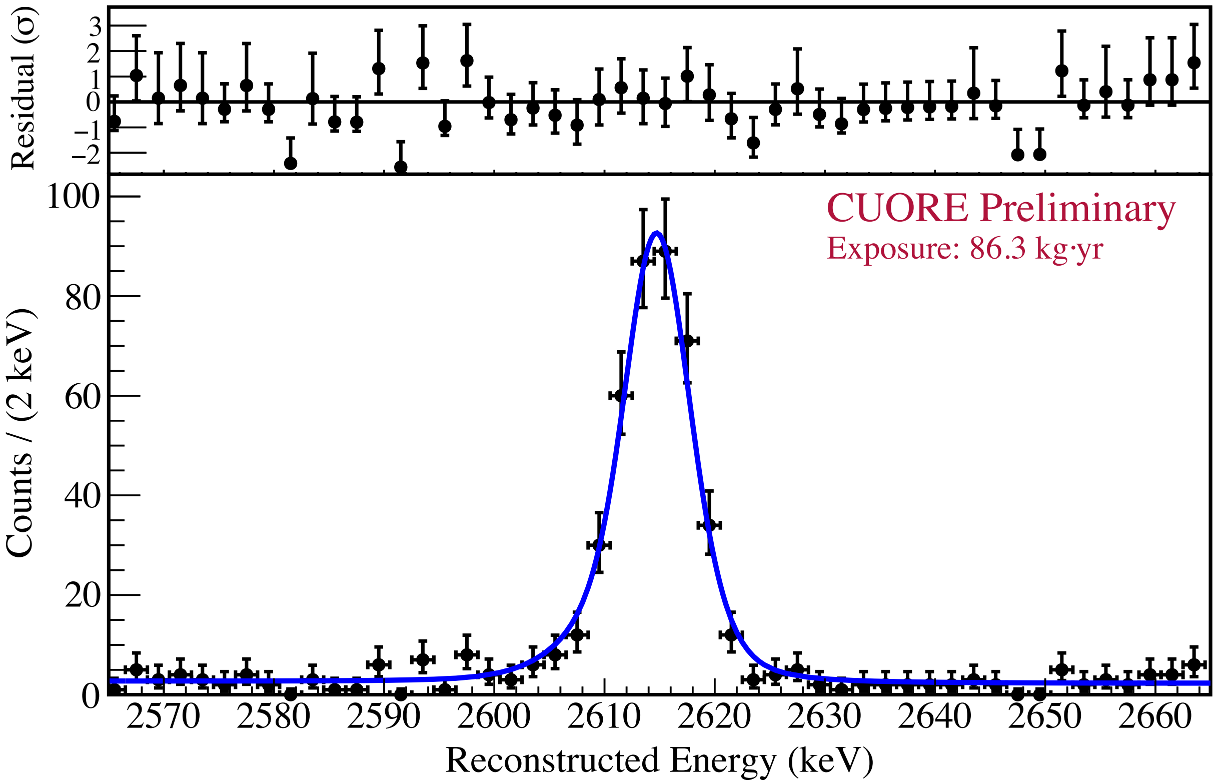
Dataset 1: 9.0 keV FWHM
Dataset 2: 7.4 keV FWHM
Average: **8.0 keV FWHM** - exposure weighted

Detector characterization and first physics results

Detector performance - Energy resolution:

Background spectrum

- Better resolution @^{208}Tl in physics runs.



Applied a scaling factor to the energy resolution evaluated in calibration runs to obtain the correct energy resolution at $Q_{\beta\beta}$

Energy resolution at $Q_{\beta\beta}$ in physics runs

Dataset 1: (8.3 ± 0.4) keV FWHM
Dataset 2: (7.4 ± 0.7) keV FWHM
Average: **(7.7 ± 0.5) keV FWHM** – exposure weighted

Detector characterization and first physics results

Detector performance - Energy resolution:

Energy resolution in physics runs

- 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

- Average FWHM at $Q_{\beta\beta}$: **(7.7 ± 0.5) keV FWHM** – exposure weighted

- CUORE **energy resolution goal** in ROI: **5 keV FWHM**

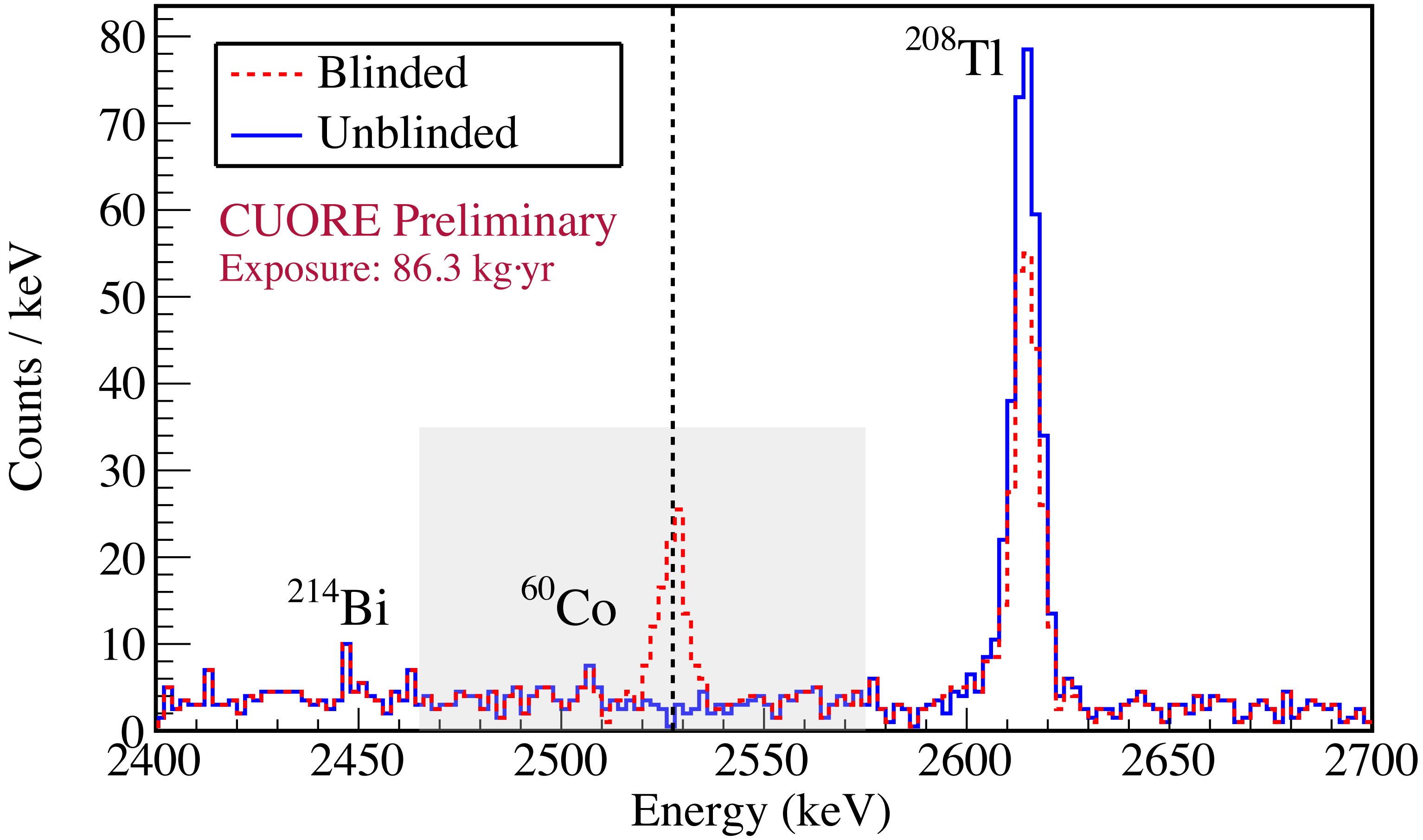
- Further campaign ongoing for resolution optimization, in order to reach the CUORE nominal resolution

Detector characterization and first physics results

0νββ analysis - Blinding of the background spectrum

Blinding procedure:

- Choose a random fraction and move events from +/- 20 keV of 2615 keV to the $Q_{\beta\beta}$ and vice versa
- The blinding algorithm produces an artificial peak around the 0νββ Q-value and blinds the real 0νββ rate of ^{130}Te
- When all data analysis procedures are fixed the data are eventually unblinded



Detector characterization and first physics results

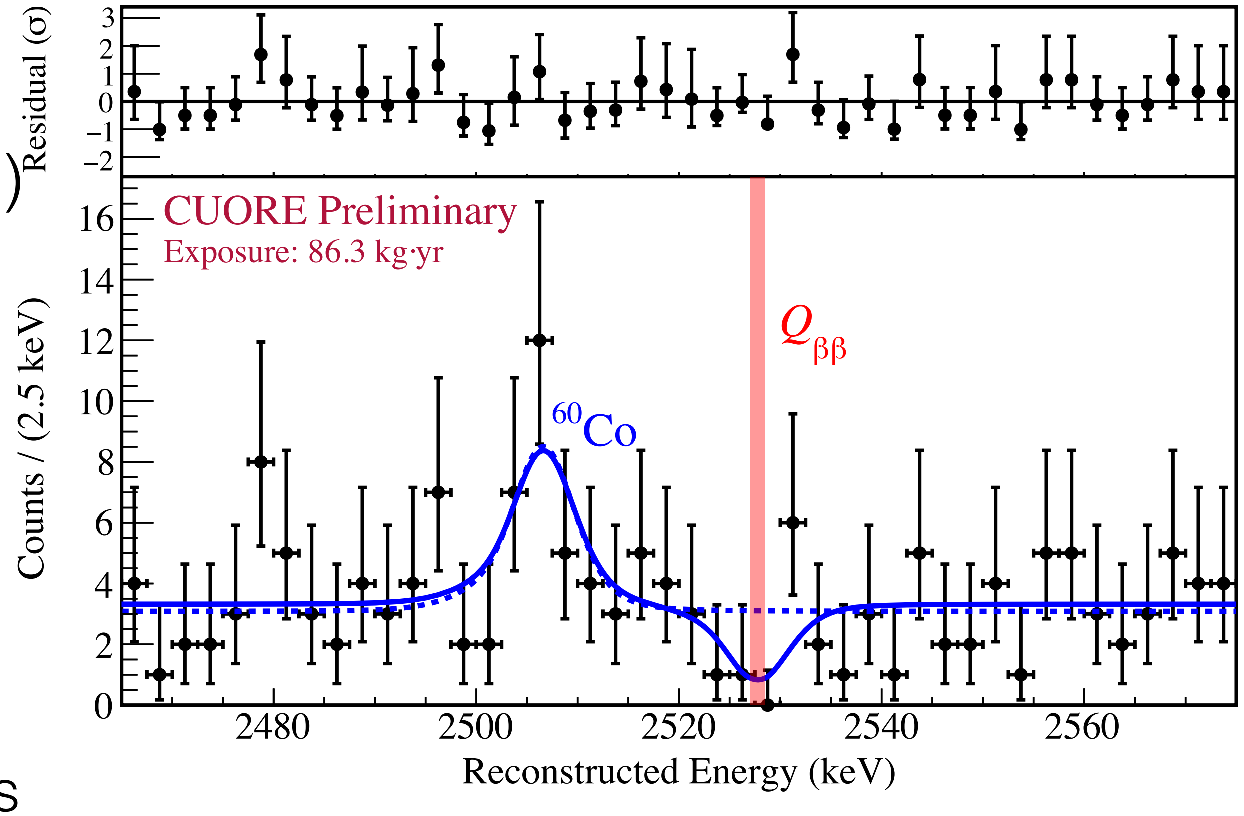
0νββ analysis - Fit in the ROI

Fit to evaluate best fit decay rate for ^{130}Te:

ROI region: **[2465,2575 keV]** around $Q_{\beta\beta}$ (^{130}Te)

Simultaneous unbinned extended maximum likelihood fit:

- Flat background (dataset-dependent)
- ^{60}Co sum peak,
- peak at $Q_{\beta\beta}$ (fixed position, floating rate)



The peaks in each channel-dataset are fitted with its own line shape (fixed from calibration data)

ε : overall signal efficiency
Dataset 1 [ε: (75.7 ± 3.0)%]
Dataset 2 [ε: (83.0 ± 2.6)%]

ROI background index (B):

- Dataset 1

$(1.49_{-0.17}^{+0.18}) \times 10^{-2}$ c/(keV·kg·yr)

- Dataset 2

$(1.35_{-0.18}^{+0.20}) \times 10^{-2}$ c/(keV·kg·yr)

Best fit signal decay rate:

$\Gamma_{0\nu}^{fit} = (-1.0_{-0.3}^{+0.4}(\text{stat.}) \pm 0.1\ (\text{syst.})) \times 10^{-25}$/yr

Detector characterization and first physics results

0νββ analysis - Half life limit

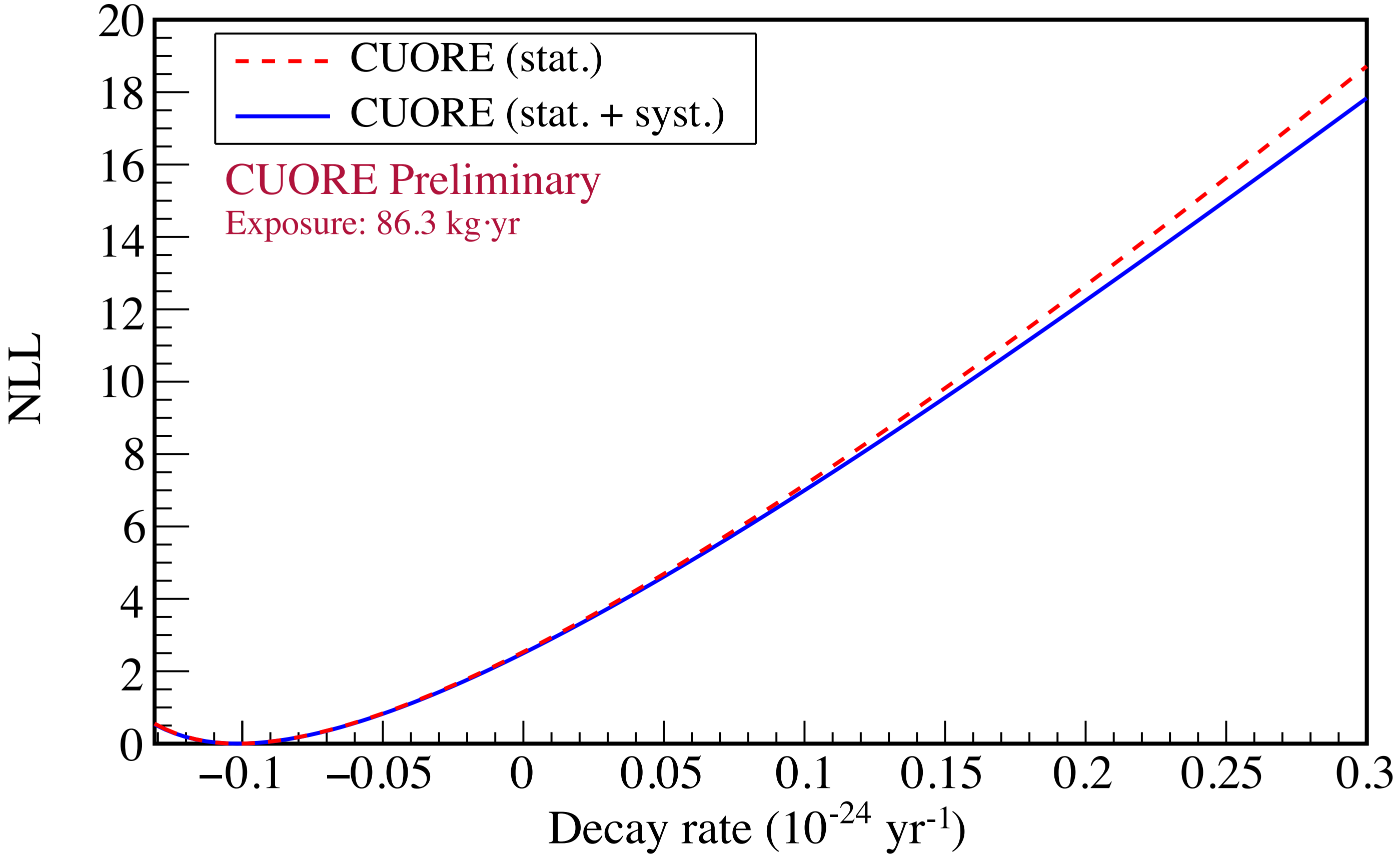
- No evidence of signal -

Limit calculation:

Profile likelihood integrated in the physical region ($\Gamma_{0\nu} > 0$)

Decay rate limit (90% CL, including syst.): $\Gamma_{0\nu} < 0.51 \times 10^{-25}$/ yr

Half-life limit (90%C.L including syst.):
$T_{0\nu}$ (^{130}Te) > 1.3 x 10^{25} yr



Detector characterization and first physics results

0νββ analysis - Half life limit

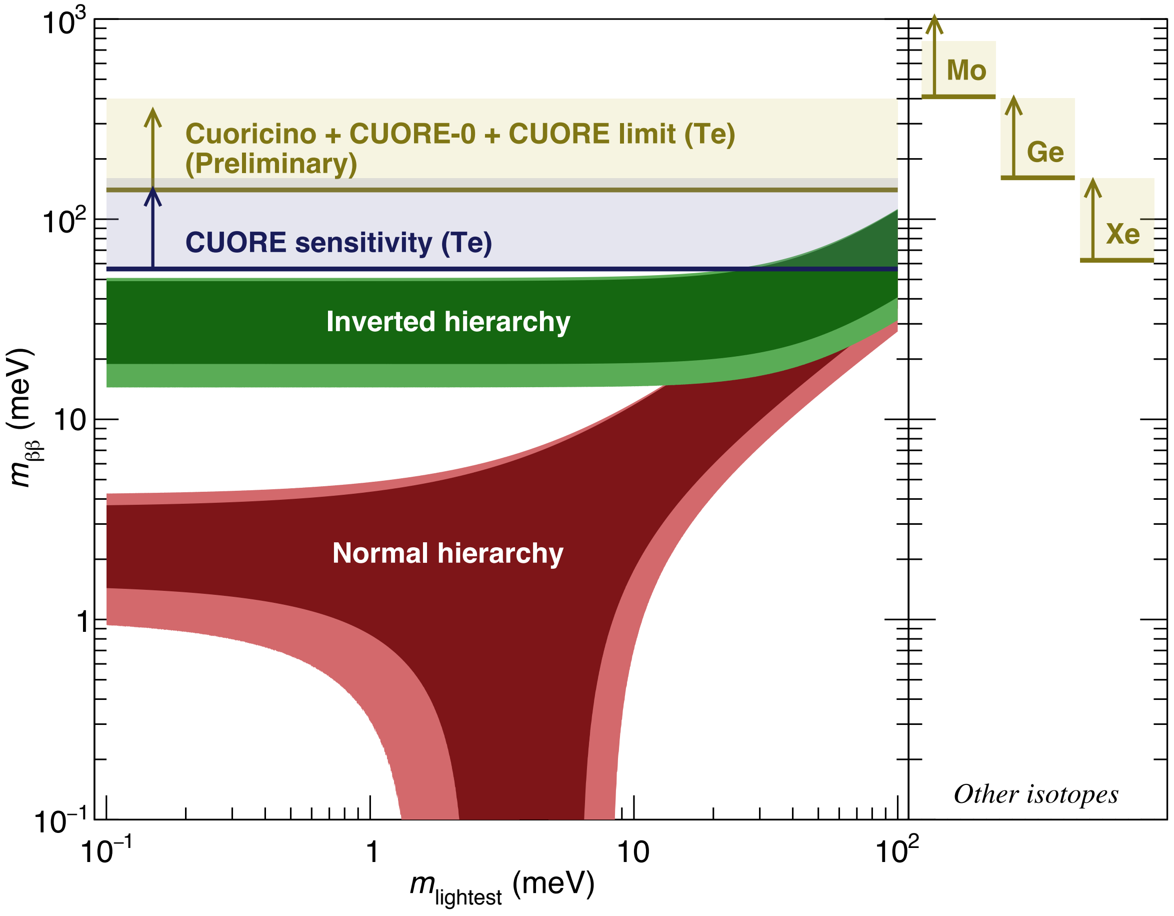
Combined likelihoods: CUORE + CUORE-0 + Cuoricino

Exposure ^{130}Te:
19.75 kg·yr Cuoricino, 9.8 kg·yr CUORE-0,
24.0 kg yr CUORE

Combined half-life limit (90% CL)
$T_{0\nu}$ (^{130}Te) > 1.5 × 10^{25} yr

Limit on $m_{\beta\beta}$:

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



0νββ Decay mechanism:
Light Majorana neutrino exchange

$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

Effective Majorana mass term

Conclusions

CUORE is the first tonne-scale bolometric 0νββ detector.

First months of CUORE operations:

- First CUORE physics results of $T_{0\nu}$ in ^{130}Te with 2 months of collected physics data
- Exceptional cryostat performance and important information on detectors characterization, noise, resolutions and background levels.
- Detector optimization campaign in late 2017 focused on improving the resolution through further noise reduction, followed by a period of maintenance of cryogenics and calibration systems in early 2018
- CUORE cooldown is ongoing and science runs will be starting back soon
- More to come!

Thank you on behalf of The CUORE collaboration

Backup

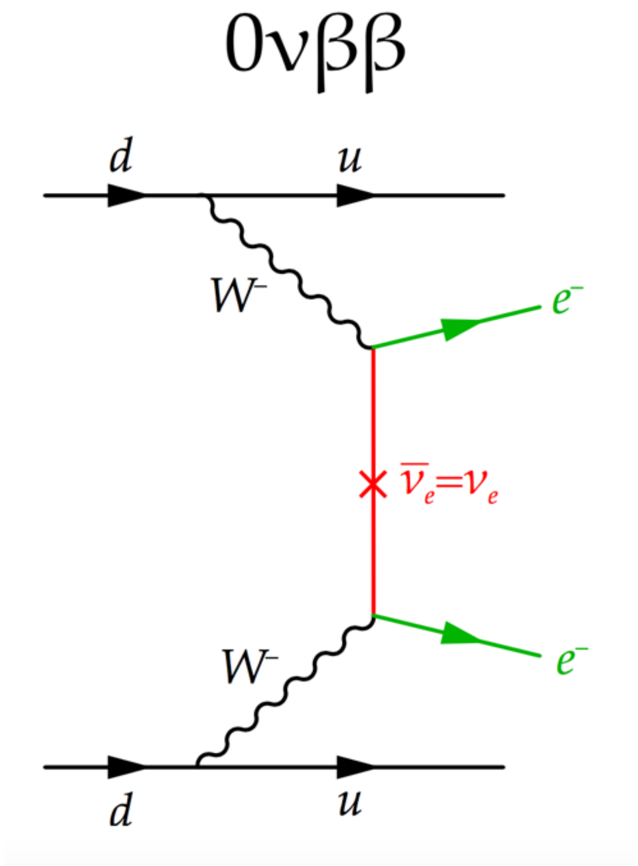
The 0νββ decay search

0νββ:

Majorana nature of neutrino

—> Constraints on neutrino mass hierarchy and scale

0νββ Decay mechanism: Light Majorana neutrino exchange



$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

Phase space integral

Nuclear matrix element

Effective neutrino mass term

$$m_{\beta\beta} = |\Sigma_i m_{\nu_i} U^2_{ei}|$$

The 0νββ decay search

Experimental 0νββ half-life sensitivity:

Present generation experiments - **finite background**: M · T · B · Δ > 1

$$S^{0\nu}(n_\sigma) = ln2\ \epsilon\ \frac{1}{n_\sigma}\ \frac{x\ \eta\ N_A}{M_A}\sqrt{\frac{M\ T}{B\ \Delta}}$$

Future generation experiments - **zero background**: M · T · B · Δ < 1

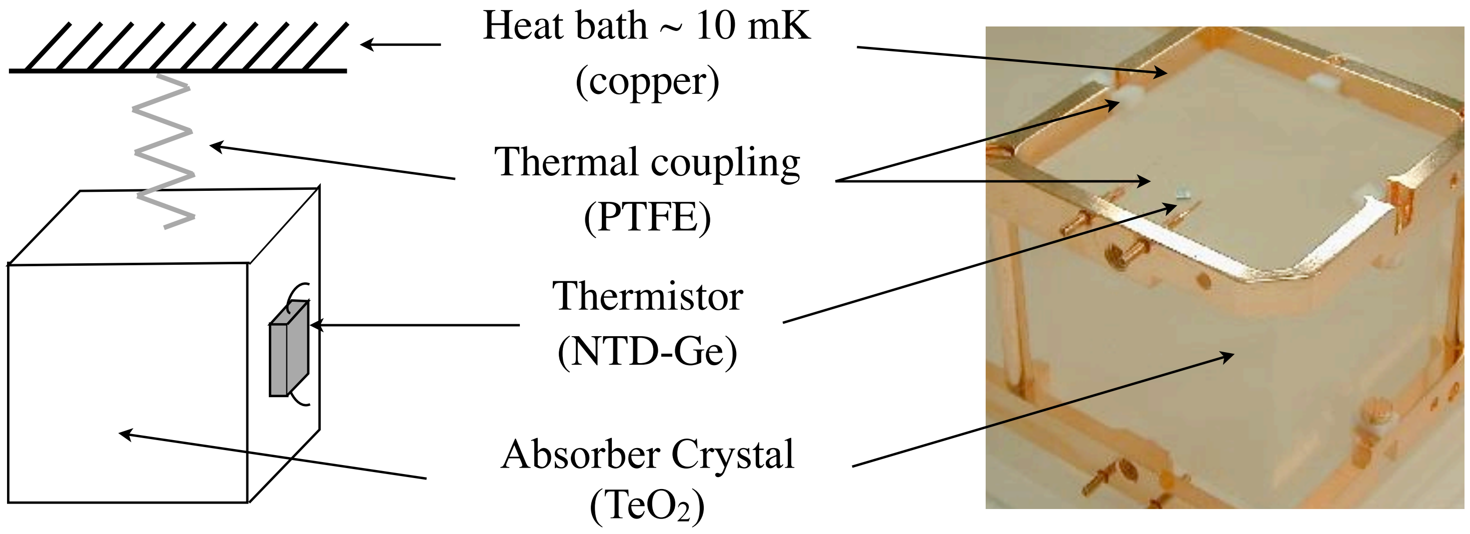
$$S^{0\nu}(n_\sigma) = ln2\ \epsilon\ \frac{1}{n_\sigma}\ \frac{x\ \eta\ N_A}{M_A} M\ T$$

M: total detector mass (kg)
T: measurement time (y)
B: background index in counts/(keV·kg·y)
Δ: energy resolution (keV)

N_A: Avogadro number
x: stoichiometric multiplicity of the element containing the DBD isotope
η: isotopic abundance of DBD isotope
ε: detection efficiency
M_A: molecular mass of the detector compound

CUORE TeO_2 bolometers

Bolometer principle of operation



Absorber crystal $^{(nat)}TeO_2$: 0νββ source

$C(T) \propto T^3$ Lattice specific heat

C(T) ~ 2 x 10^{-9} J/K (@ 10 mK)

Thermistor NTD-Ge

$R(T) = R_0 exp^{(\frac{T_0}{T})^{1/2}}$

R_{wp} ~ 10-100 MΩ

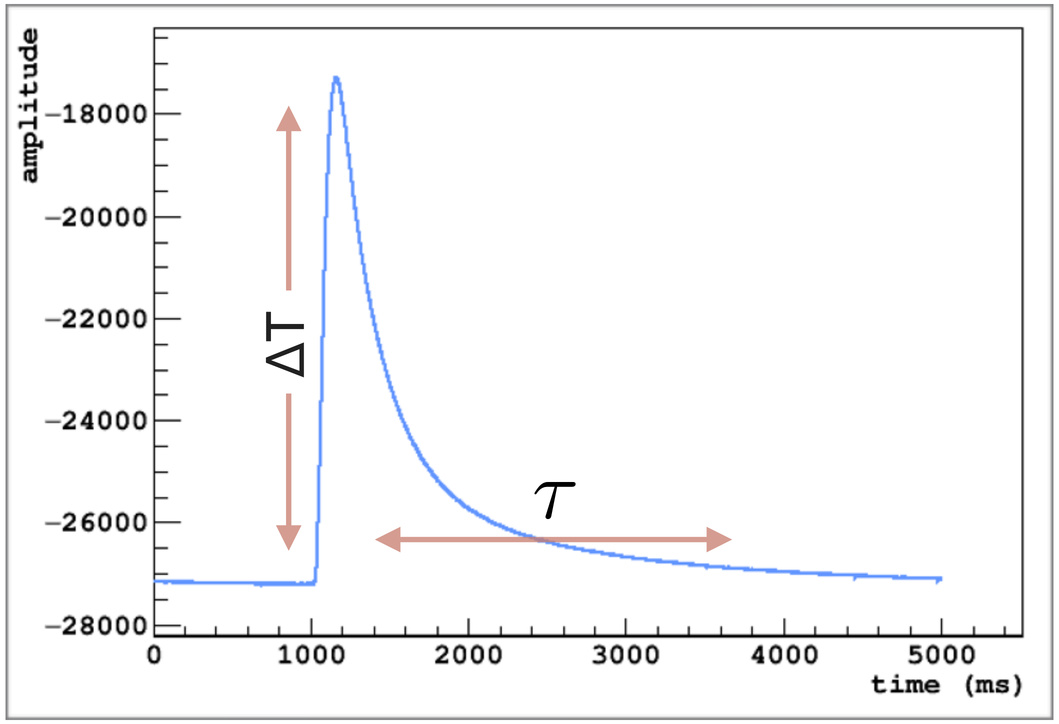
Simplest thermal model:

One thermal capacity (crystal)
One thermal link G (btw crystal/heat bath)

$$\Delta T \propto \frac{E_{dep}}{C} \qquad \tau = \frac{G}{C} \approx 1s$$

Amplitude of the pulse ∝ ΔT ∝ Energy deposit

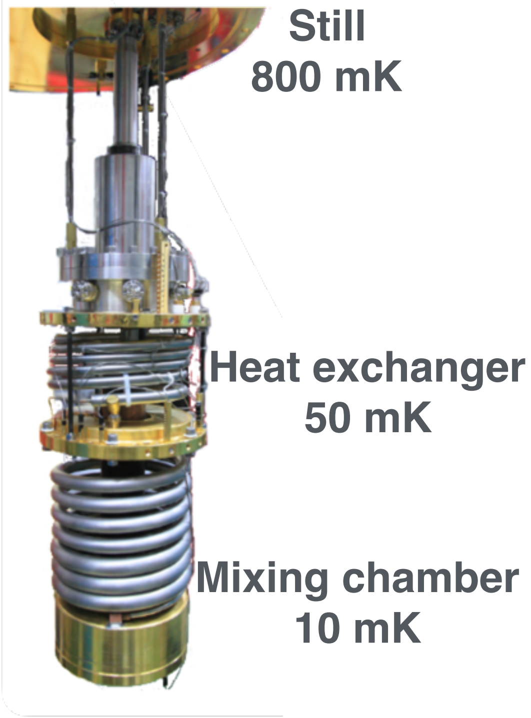
ΔT_{NTD} ~ 10-20 μK/MeV ΔV_{NTD} ~ 300 μV/MeV
$\Delta T_{crystal}$ ~ 100 μK/MeV ΔR_{NTD}~ 3 MΩ/MeV



CUORE cooldown and data-taking

Cryogenic infrastructure and auxiliary systems

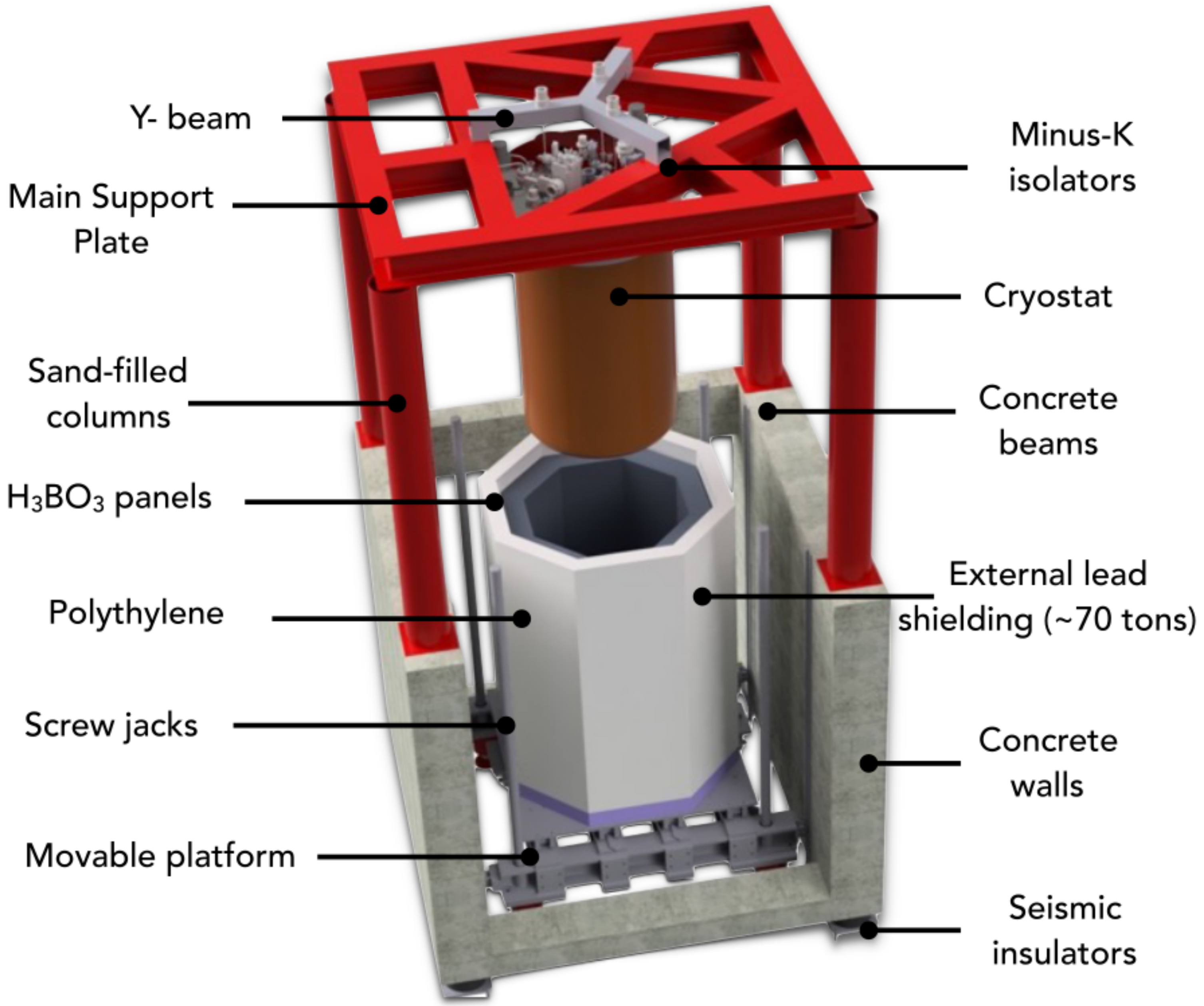
Multistage cryogen-free cryostat:
- Fast Cooling System
- 5 Pulse Tube cryocoolers (down to 4 K)
- Continuous-cycle 3He/4He dilution refrigerator (down to base temperature ~10 mK)



CUORE cooldown and data-taking

Cryogenic infrastructure and auxiliary systems

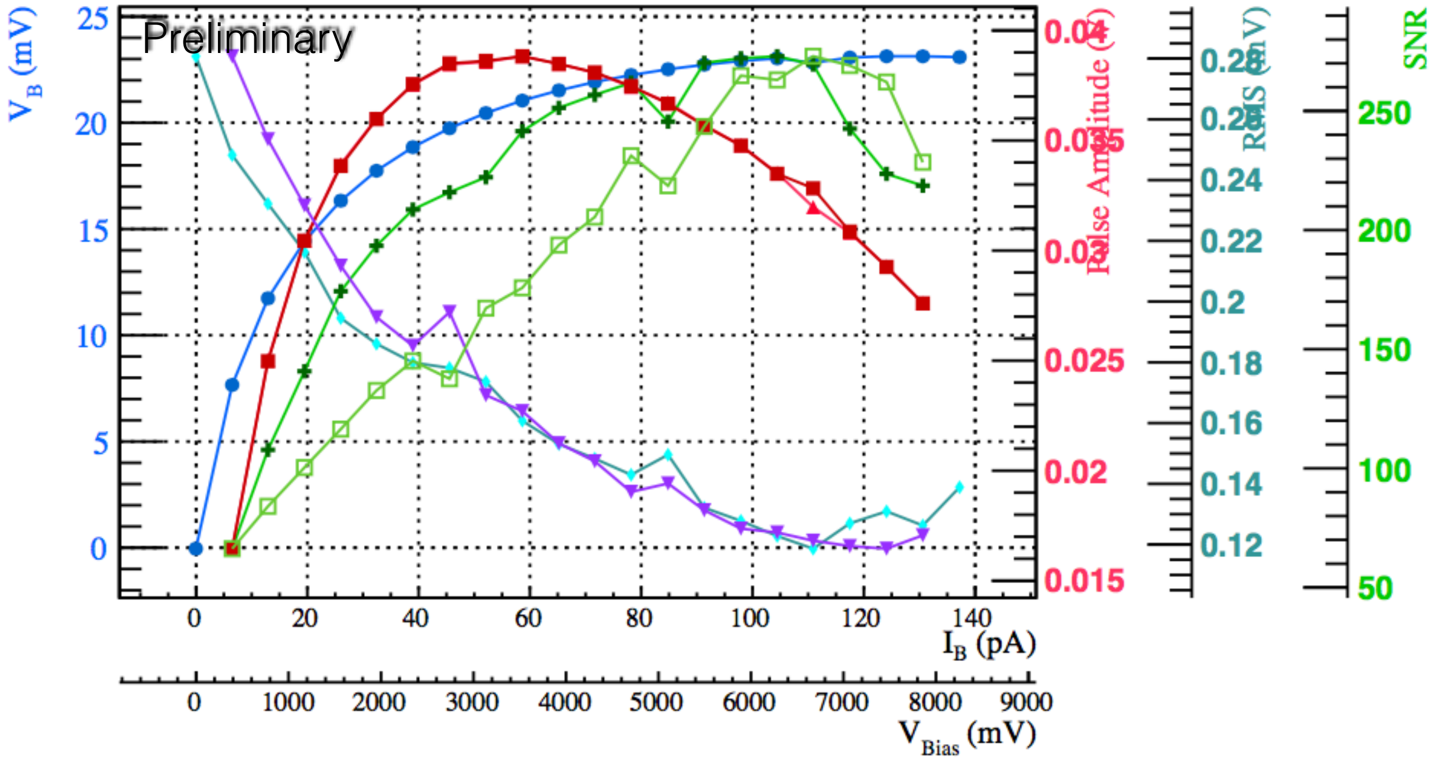
Cryostat support structure



Detector characterization and first physics results

Setting the detector working points

From **Load Curves analysis**.
Set operation conditions of the bolometer&NTD for a fixed T$_{base}$ to have best signal response and lowest noise



The optimal working point is chosen to be where the signal-to-noise ratio (SNR), defined as the ratio of the amplitude of the reference pulse to the baseline noise RMS, is maximized and at the same time the detector has a linear behavior for small temperature (amplitude) variations.

Developed an **automated tool** to provide Working Point bias voltage to be set to all the 988 channels of the CUORE experiment

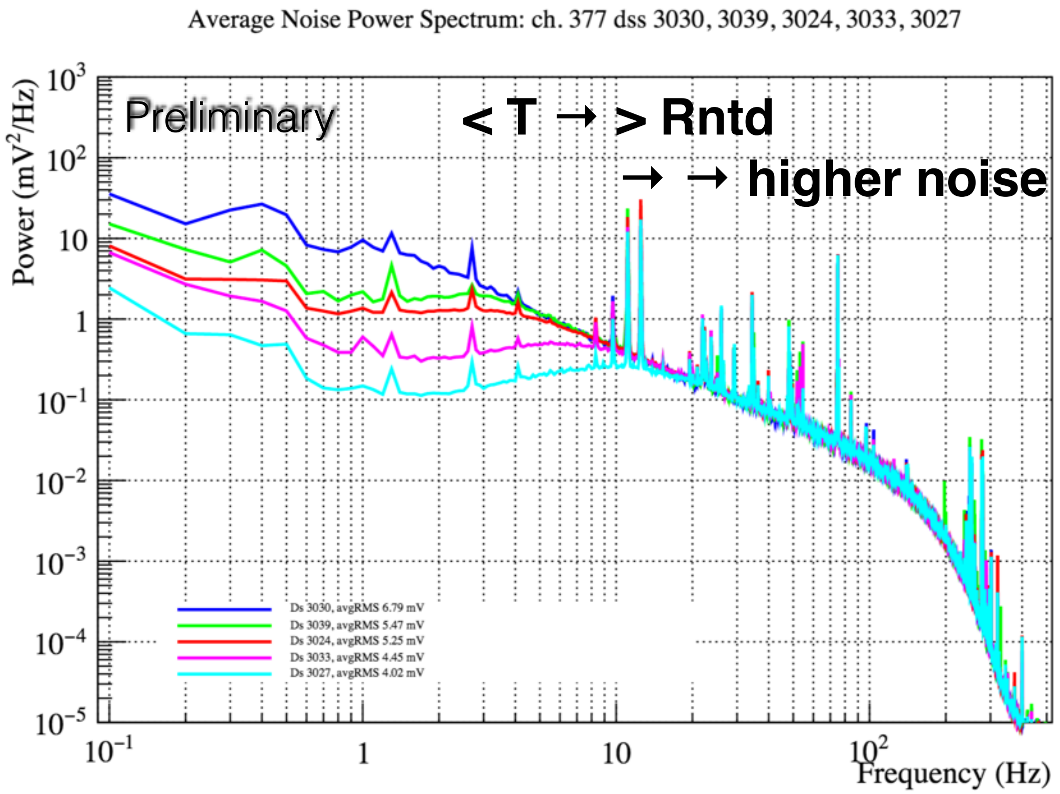
Detector characterization and first physics results

Temperature scans

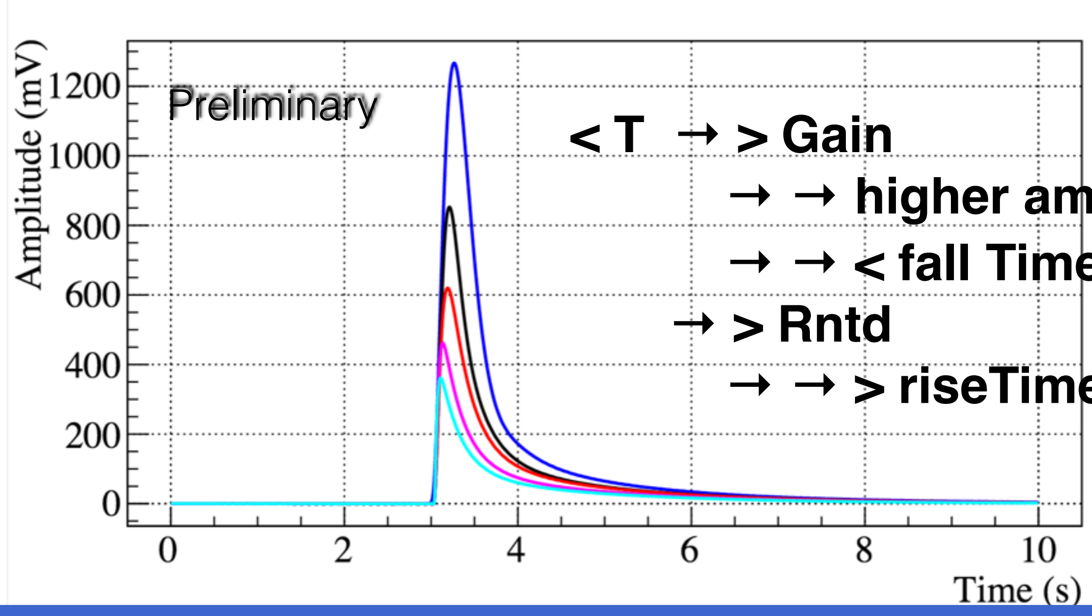
Focus on 78 active channels during the temperature scan:
26 ch- NTD 41C, 26 ch - NTD 39 D, 26 ch - NTD 39 C;

different NTDs types <—> different Rntd

- February 2017 - **From 9 to 15 mK**
  Background + pulsers (2 pulsers)
- July 2017 - **From 11 to 27 mK**
  Background + pulsers (2 pulsers)
- October 2017 - **From 11 to 19 mK**
  Calibration + pulsers (3 pulsers)



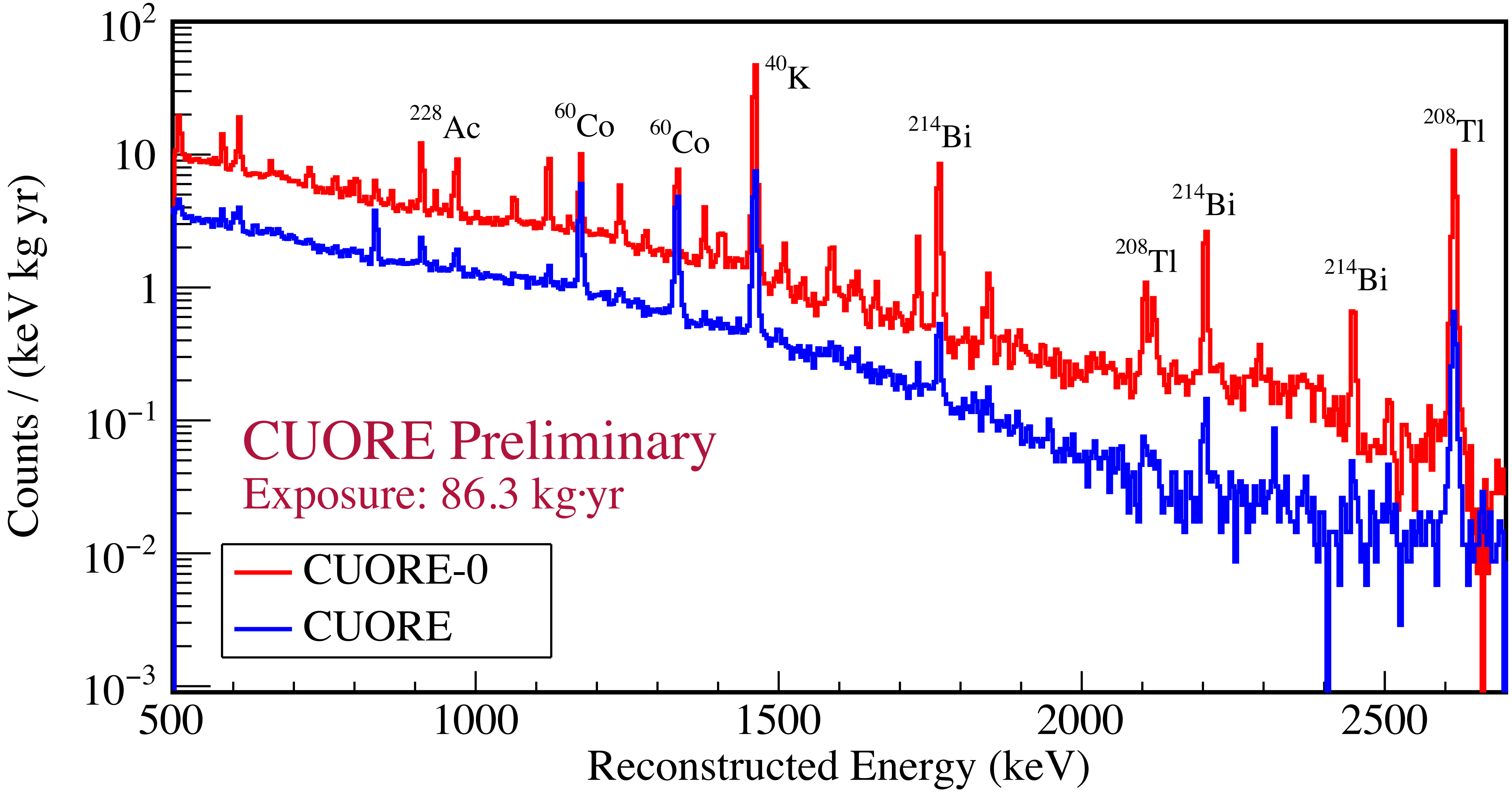
< T → > Rntd
→ → higher noise



< T → > Gain
→ → higher amplitude pulses
→ → < fall Time signal
→ > Rntd
→ → > riseTime signal (RC)

Detector characterization and first physics results

Background spectrum



Background - Physics: Significant reduction in the γ region with respect to CUORE-0 (CUORE-like tower experiment), Spectrum is consistent with the background expectations

Detector characterization and first physics results

0νββ analysis

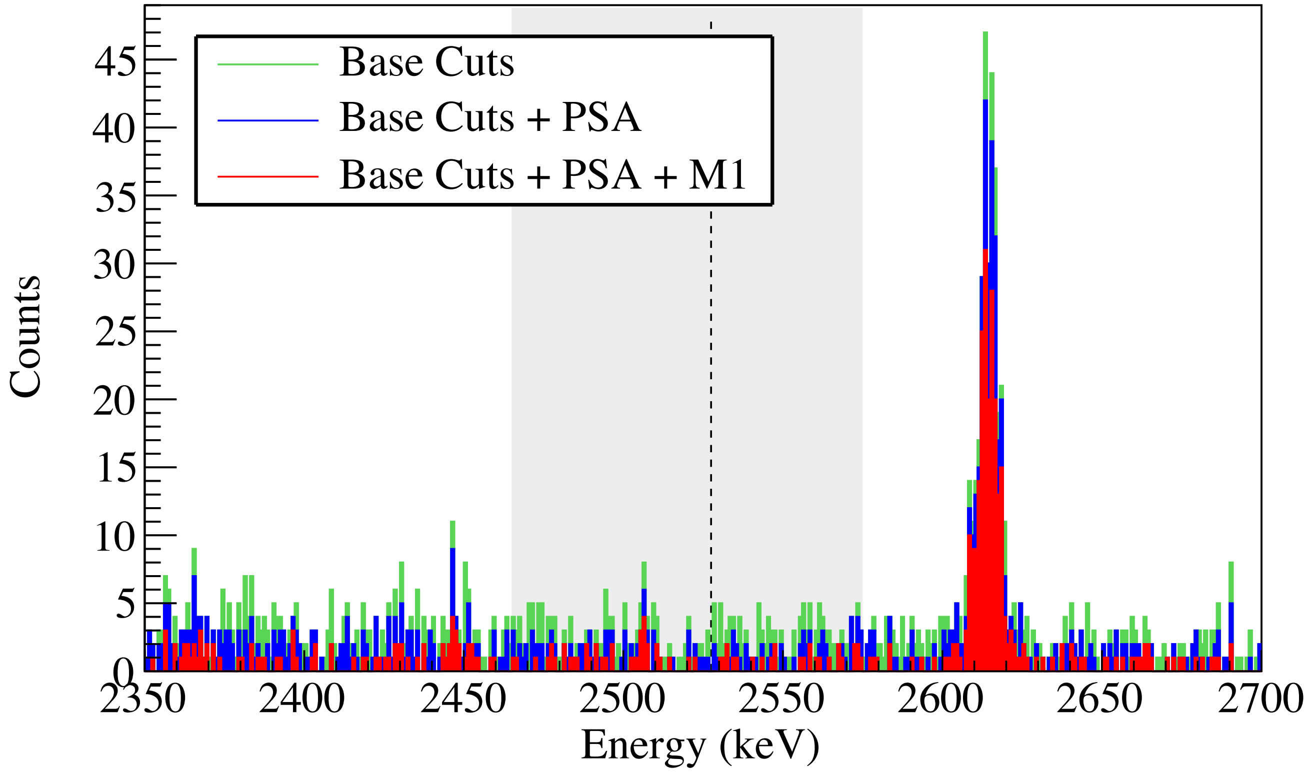
Selection efficiencies

Event selection is performed after discarding periods of low quality data (about 1% of live time)

The 0νββ containment efficiency is evaluated from Monte Carlo simulations

All other efficiencies are evaluated on data.

	Dataset 1	Dataset 2
Trigger	(99.766 ± 0.003) %	(99.735 ± 0.004) %
Energy reconstruction	(99.168 ± 0.006) %	(99.218 ± 0.006) %
Base cuts (pile-up, global data quality)	(95.63 ± 0.01) %	(96.69 ±0.01) %
Anti-coincidence	(99.4 ± 0.5) %	(100.0 ± 0.4) %
Pulse shape analysis	(91.1 ± 3.6) %	(98.2 ± 3.0) %
All cuts except containment	(85.7 ± 3.4) %	(94.0 ± 2.9) %
0νββ containment	(88.35 ± 0.09) %	
Total	(75.7 ± 3.0) %	(83.0 ± 2.6) %



Detector characterization and first physics results

$0\nu\beta\beta$ analysis

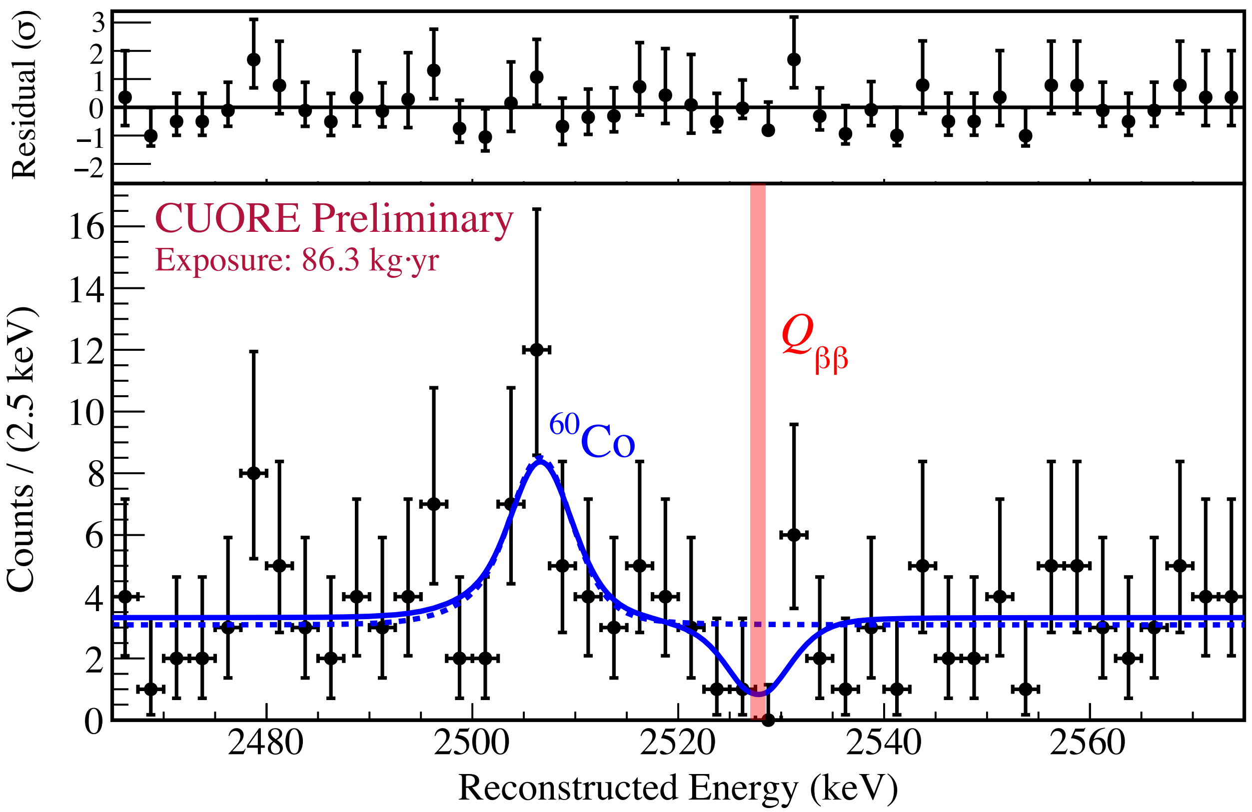
ROI Fit to evaluate **best fit decay rate** for ^{130}Te: Simultaneous unbinned extended maximum likelihood (UEML) fit based on RooFit

ROI region: [**2465,2575 keV]** around $Q_{\beta\beta}$ (^{130}Te).

The fit has 3 components:

- a peak at the Q-value of ^{130}Te - fixed position at 2527.518 keV, floating rate common to all channel-dataset pairs
- a peak to account for the ^{60}Co sum gamma line (2506 keV) - floating peak position and rate, rate common to all channel-dataset pairs
- a constant flat background, attributed to multi scatter Compton events from ^{208}Tl and surface alpha events - common to all channels, but dataset-dependent

The peaks in each channel-dataset are fitted with its own line shape (fixed from calibration data)



- Solid blue line: Best-fit model from the UEML fit overlaid on the spectrum of **$0\nu\beta\beta$** decay candidates observed in CUORE. The normalized residuals of this model and the binned data are shown in the top panel.
- Dashed blue line: Best-fit for a model with **no $0\nu\beta\beta$** decay component.
- Vertical band: centered at $Q_{\beta\beta}$, the width of the band reflects the systematic uncertainty on the reconstructed energy.

Detector characterization and first physics results

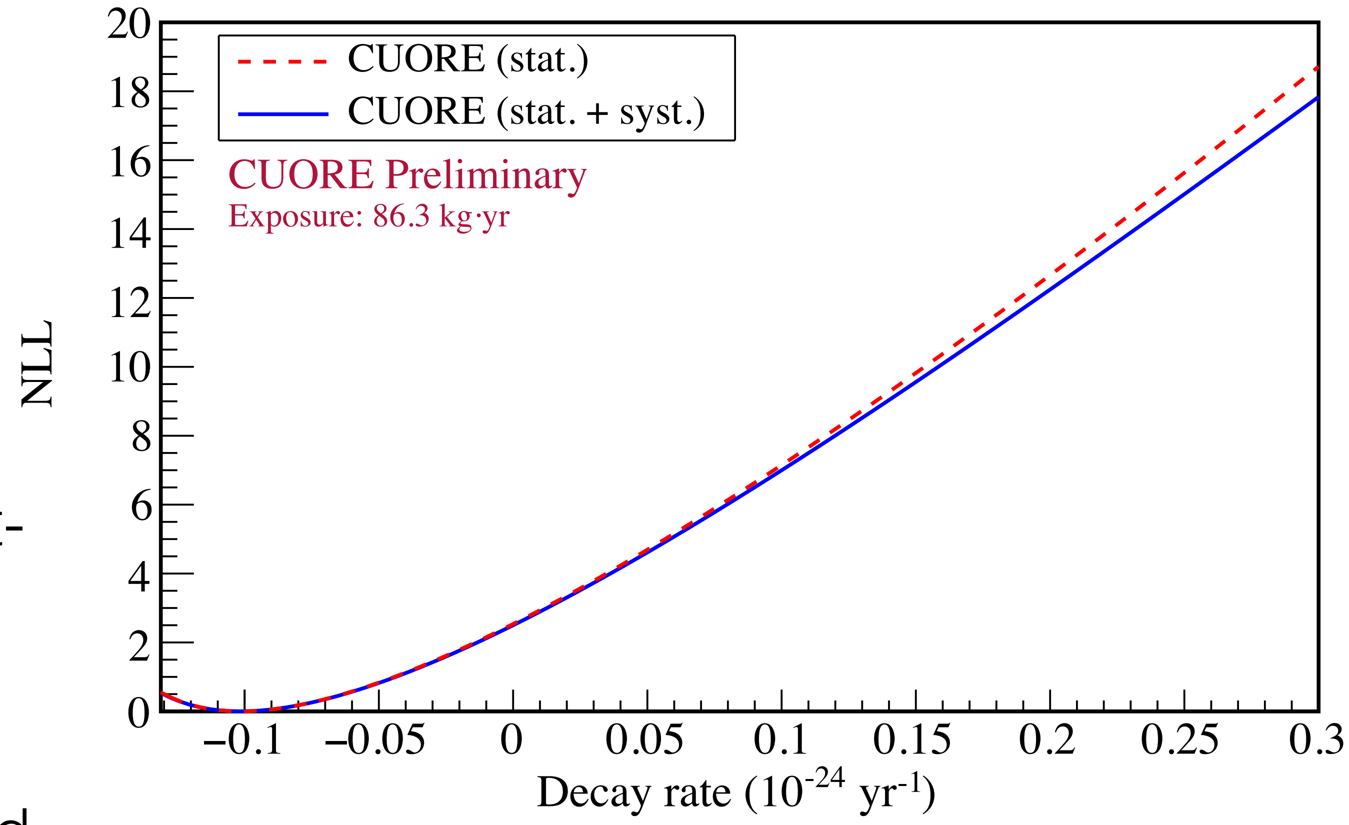
CUORE

0νββ analysis - Half life limit

Evaluate the goodness of fit:

- Prepare large set of pseudo-experiments
  - number of events determined by a Poisson distribution with a mean of 155 (number of events in CUORE data ROI)
  - energy distributed according to the best-fit zero-signal model.
- Repeat 0νββ decay search fit on each of the pseudo-experiments
- 68% of them yield a negative log likelihood (NLL) larger than that obtained with data

- No evidence of signal at 3 σ -



Limit calculation:

Profile likelihood integrated in the physical region ($\Gamma_{0\nu} > 0$)

Detector characterization and first physics results

0νββ analysis - Half life limit

Evaluating systematics

Uncertain parameters of the model that can affect the result are considered as potential source of systematic errors:

- FWHM, energy resolution (± 1 σ)
- Q-value (± 0.5 keV from energy scale uncertainty)
- No sub-peak in the detector response
- Linear background (± 1 σ)

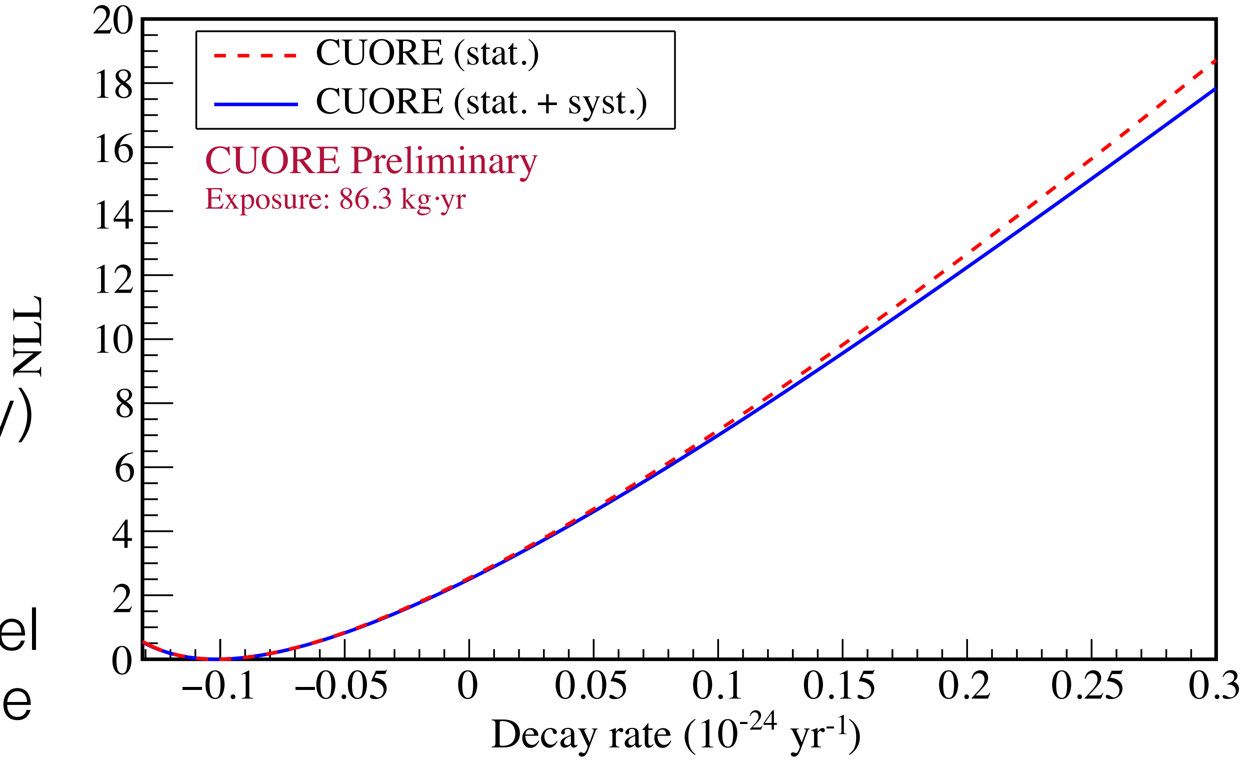
Toy-MC experiments generated starting from a model where the signal rate $\Gamma_{0\nu}$ is changed from 0 to a large value, and the parameter of interest had been changed.

Each pseudo-experiment is fitted with the full 0νββ model.

Parametrize the bias as:

$\Gamma_{0\nu}^{fitted} = p0\ (\text{additive}) + p1 \cdot \Gamma_{0\nu}^{true}\ (\text{scaling})$

Deviations from 0 in p0 and from 1 in p1 considered as systematic errors and added in quadrature and propagated to NLL and to the limit



Limit calculation:

Profile likelihood integrated in $\Gamma_{0\nu} > 0$

Decay rate limit (90% CL, including syst.):

$\Gamma_{0\nu} < 0.51 \times 10^{-25}$/ yr

Half-life limit (90%C.L including syst.):

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

Detector characterization and first physics results

0νββ analysis - Half life limit

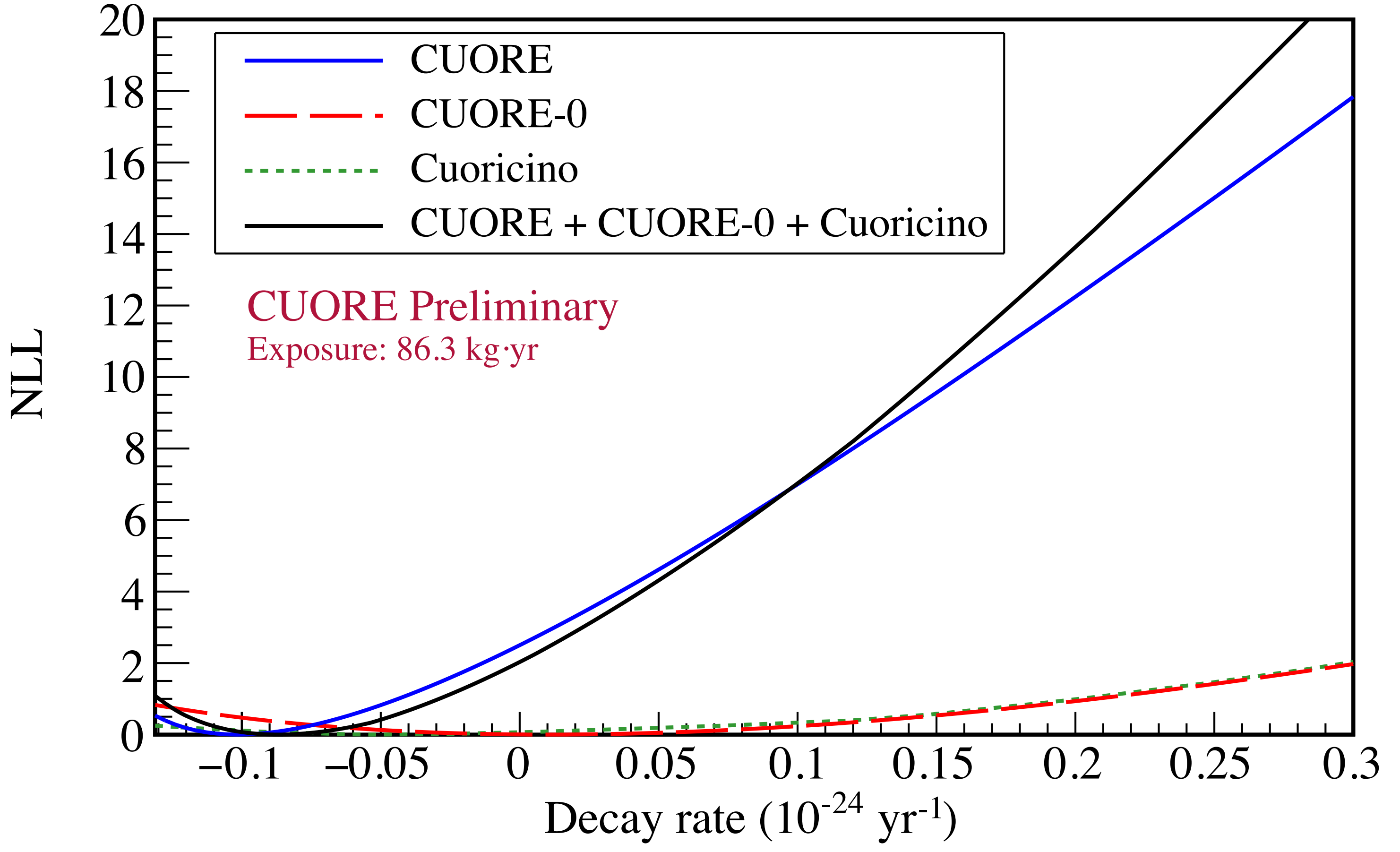
Combined likelihoods: CUORE + CUORE-0 + Cuoricino

Exposure ^{130}Te:
19.75 kg·yr Cuoricino,
9.8 kg·yr CUORE-0,
24.0 kg yr CUORE

Combined half-life limit (90% CL)
$T_{0\nu}$ (^{130}Te) > 1.5 × 10^{25} yr

Limit on $m_{\beta\beta}$:

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



Detector characterization and first physics results

CUORE

CUORE background budget