New results from the CUORE experiment

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Outlook

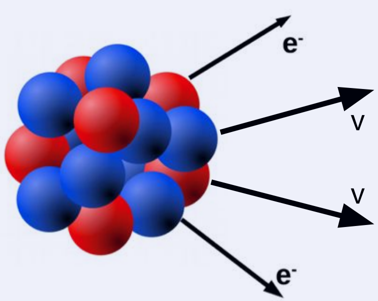
- Neutrinoless double beta decay
- The CUORE experiment
- CUORE initial operations & optimization
- CUORE physics data taking
  - ✦ Data processing
  - ✦ New results from CUORE on search for ^{130}Te 0νββ decay
- Conclusions

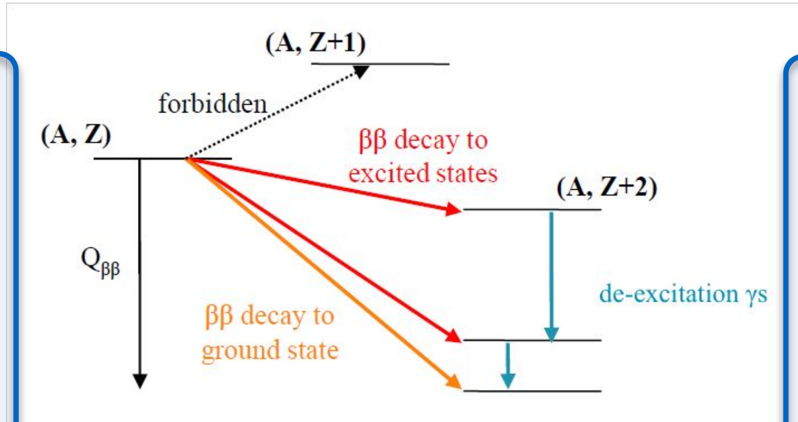
Double beta decay

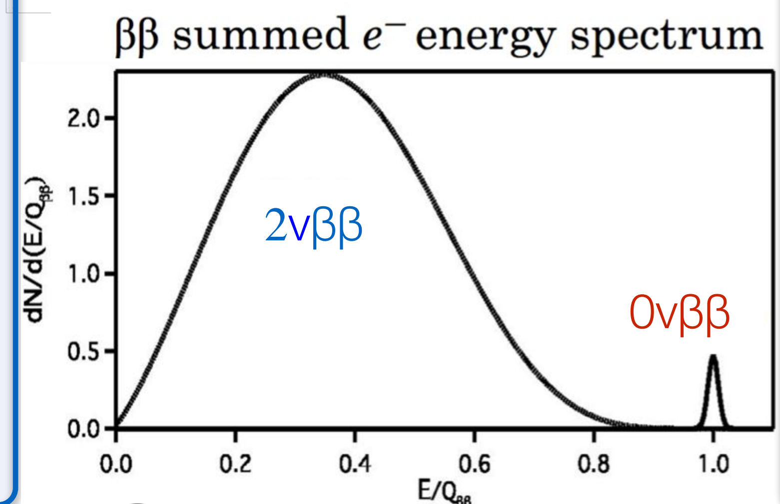
Double beta decay is a rare nuclear decay: (N,Z) → (N-2, Z+2)

Two neutrino double beta decay ($2\nu\beta\beta$)

- 2^{nd} order process allowed in SM ($\Delta L = 0$)
- Observed in several nuclei: $T^{1/2}_{2\nu\beta\beta} \sim 10^{18\text{-}24}$ yr



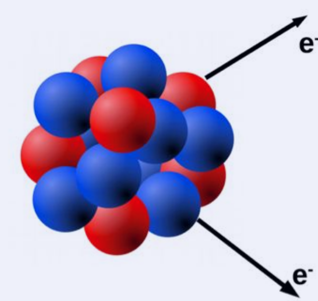




$Q_{\beta\beta}$ Q-value of the ββ decay

Neutrinoless double beta decay ($0\nu\beta\beta$)

- Beyond SM process ($\Delta L = 2$)
- Not yet observed $T^{1/2}_{0\nu\beta\beta} > 10^{24\text{-}26}$ yr



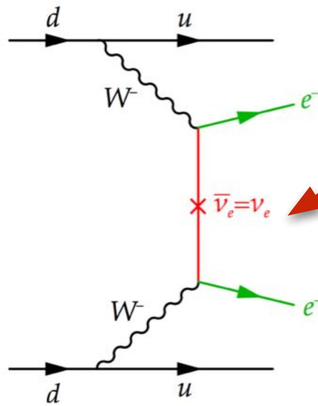
Neutrinoless double beta decay

Observation of **0νββ decay would imply:**

- Lepton number violation
- Hint on origin of matter/anti-matter asymmetry
- Presence of a Majorana term for the neutrino mass
- Constraints on neutrino mass hierarchy and scale

0νββ mechanism:

Light Majorana neutrino exchange



Majorana mass term
coupling
the two neutrinos

From 0νββ decay rate measurements one can infer the effective neutrino mass term

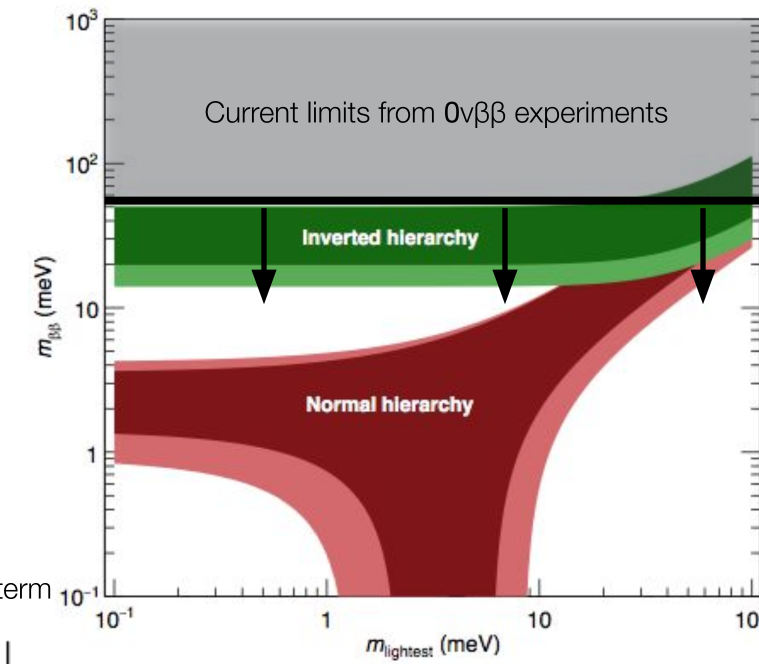
$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

Phase space integral

Nuclear matrix element (NME)

Effective neutrino mass term

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



Experimental 0νββ half-life sensitivity

Finite background

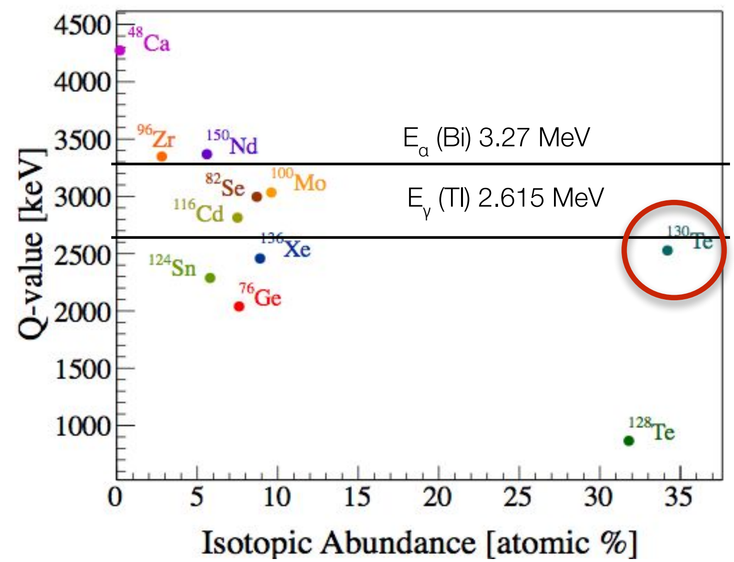
$$S_{0\nu} \propto \eta \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta \cdot B}}$$

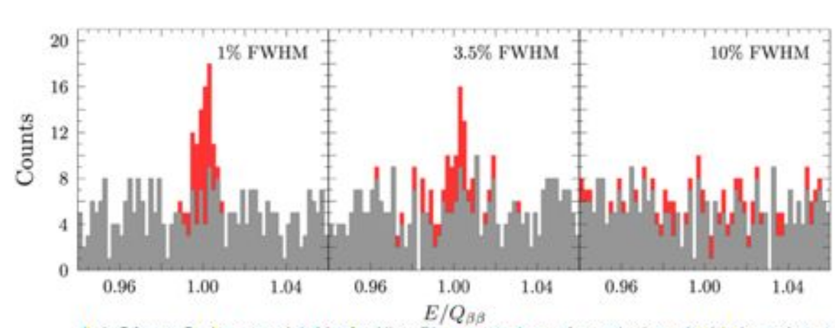
Suitable nuclei for double-beta decay are 48Ca, 76Ge, 82Se, 100Mo, 116Cd, 130Te,128Te,136Xe...

Isotope choice
- High isotopic natural abundance or enrichment
- High $Q_{\beta\beta}$

- Good detection efficiency:
ββ source embedded into the absorber
- Excellent energy resolution

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





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

Search for 0νββ decay of 130Te

CUORE

- ^{130}Te highest natural isotopic abundance **η(^{130}Te) = 34.167%**,
  no detector enrichment
- ^{130}Te within the detector absorber of TeO_2 (**containment efficiency ~ 90%**)
- $Q_{\beta\beta}$ (^{130}Te) = 2527.518 keV, above most of the natural radioactivity
- TeO_2 operated as low temperature macro-calorimeters (~10 mK): good energy resolution **Δ (~0.2% FWHM/E)**, compared to other ββ experiments
- Reproducible growth of large number of high quality detectors; **large active mass detector**: 742 kg TeO_2 (~206 kg of 130Te)

The CUORE experiment

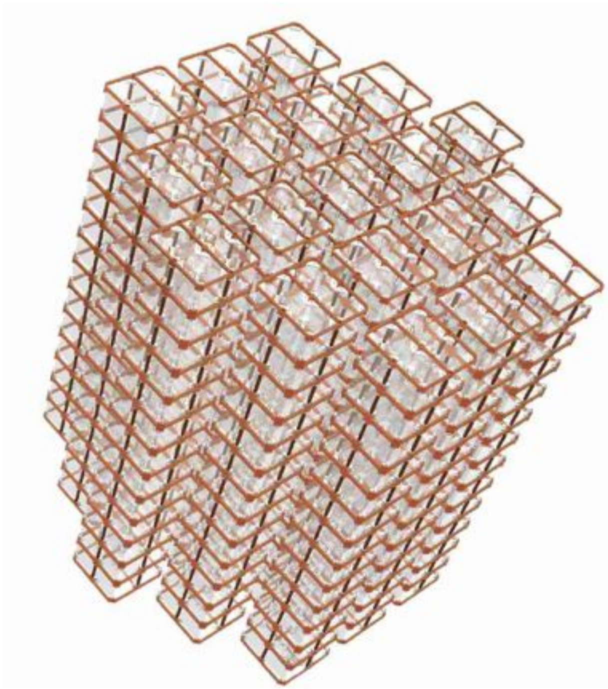
CUORE

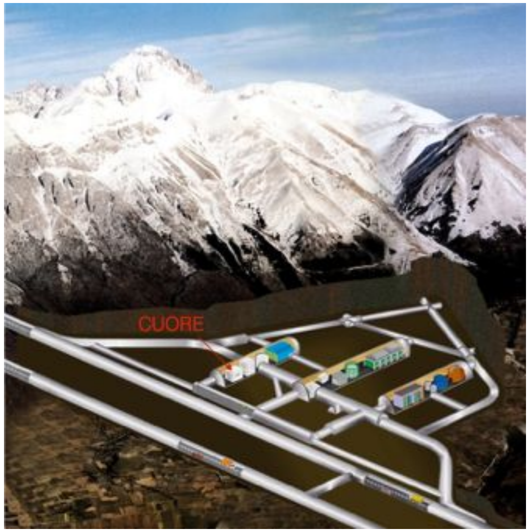
Cryogenic Underground Observatory for Rare Events

Ton-scale cryogenic experiment
using 988 $^{(nat)}TeO_2$ crystals operated at ~10 mK
- large mass and high granularity -

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

Test Majorana nature of neutrino ←→ 0νββ decay





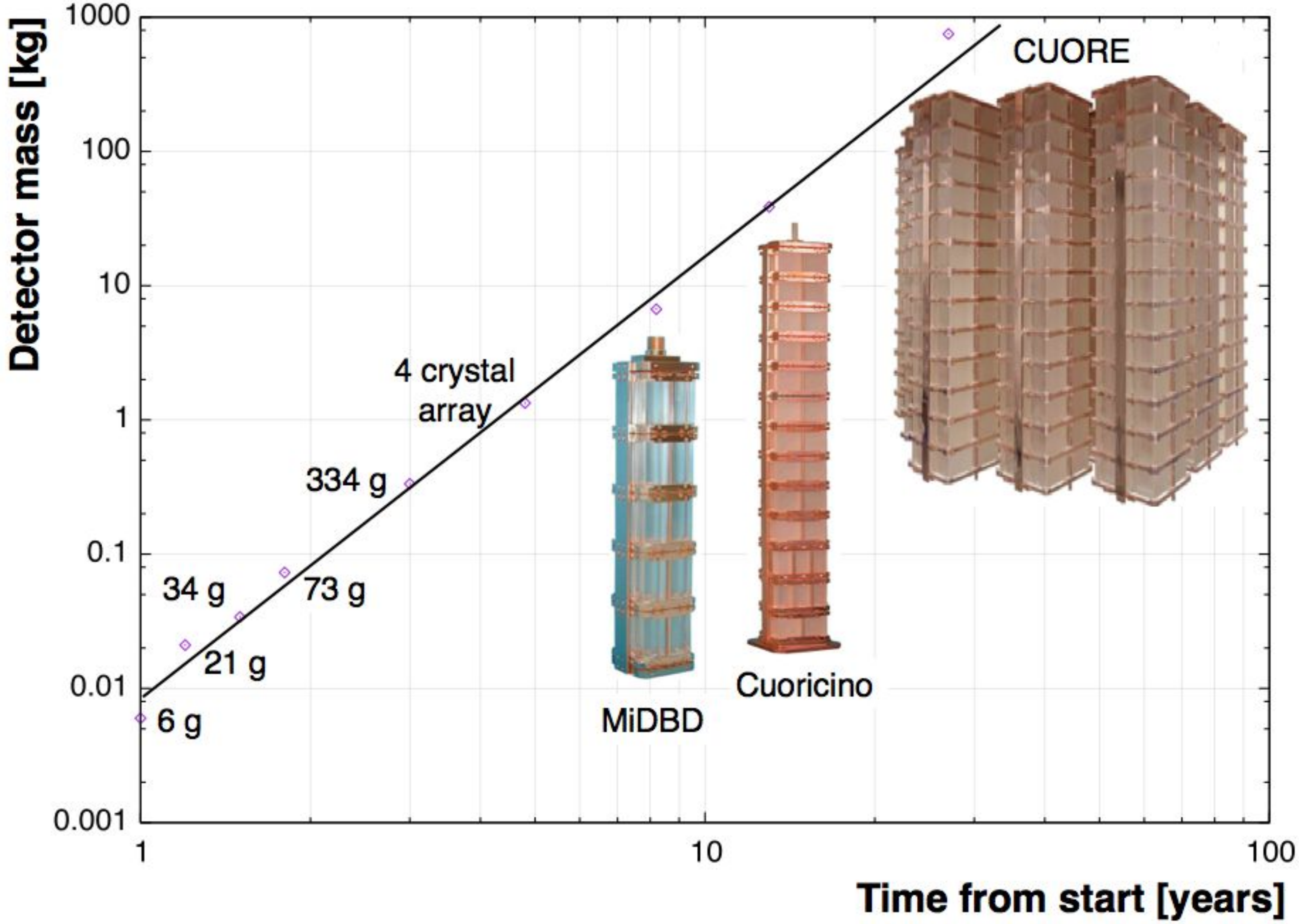
Experiment hosted at
Laboratori Nazionali del Gran Sasso (LNGS)

CUORE ^{130}Te 0νββ projected sensitivity:
$T^{0\nu}_{1/2}$ ~ 9 x 10^{25} yr (90% C.L.) in 5 years
$m_{\beta\beta}$ < 50-130 meV

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

History of TeO_2 macro-calorimeters for 0νββ

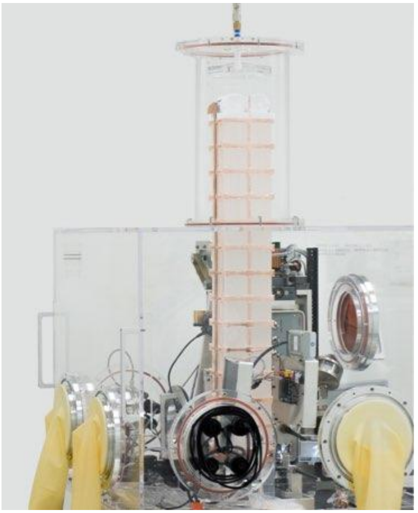
From few g to 1 tonne TeO_2 cryogenic calorimeters for double beta decay search



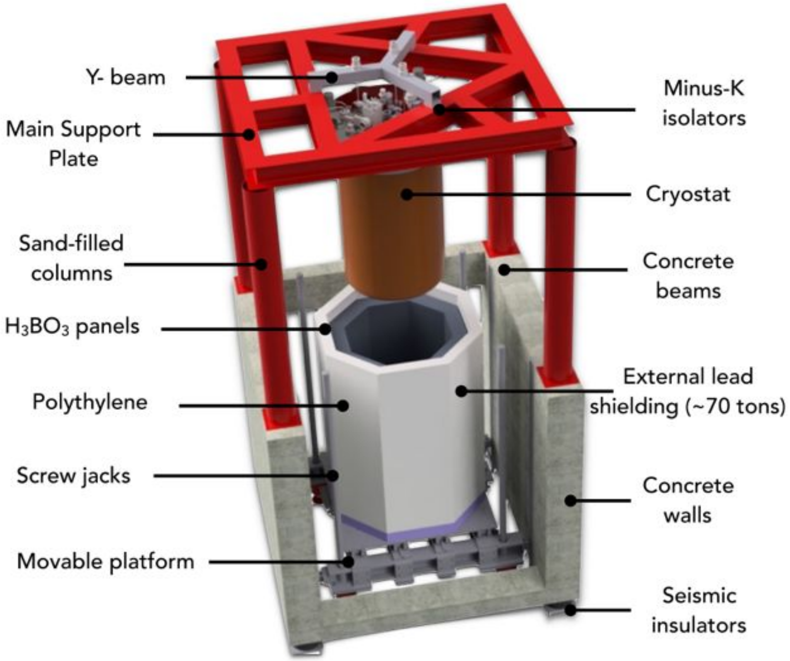
The CUORE challenge

- **Low background**
  - Deep underground location (LNGS)
    Overburden: 1400 m calcareous rock (3600 m.w.e)
    Cosmic ray rate reduction: 10^{-6} relative to the surface
  - 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 $Q_{\beta\beta}$



Roman lead shield (210Pb depleted) @ 4K



The CUORE challenge

- **Low temperature and low vibrations**

TeO_2 detectors to be operated as bolometers at ~10 mK

- Multistage cryogen-free cryostat:

  Nested vessels at decreasing temperature

  Cooling systems: Pulse Tubes (PTs) and Dilution Unit (DU)

  -Mass to be cooled < 4K: ~ 15 tons (IVC volume and Cu vessels, Roman Pb shield)

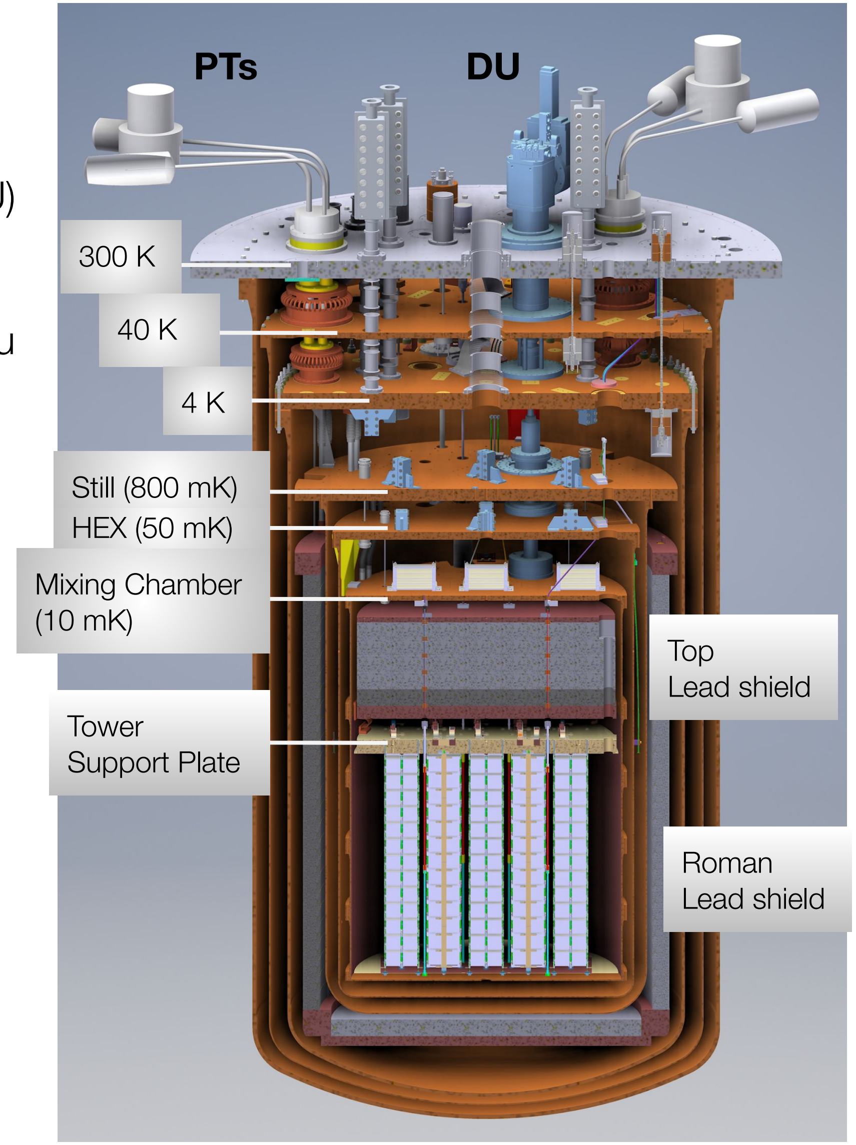
  -Mass to be cooled < 50 mK: ~ 3 tons (Top Pb shield, Cu supports and TeO_2 detectors)

- Mechanical vibration isolation

  Reduce energy dissipation by vibrations

Target energy resolution: 5 keV FWHM

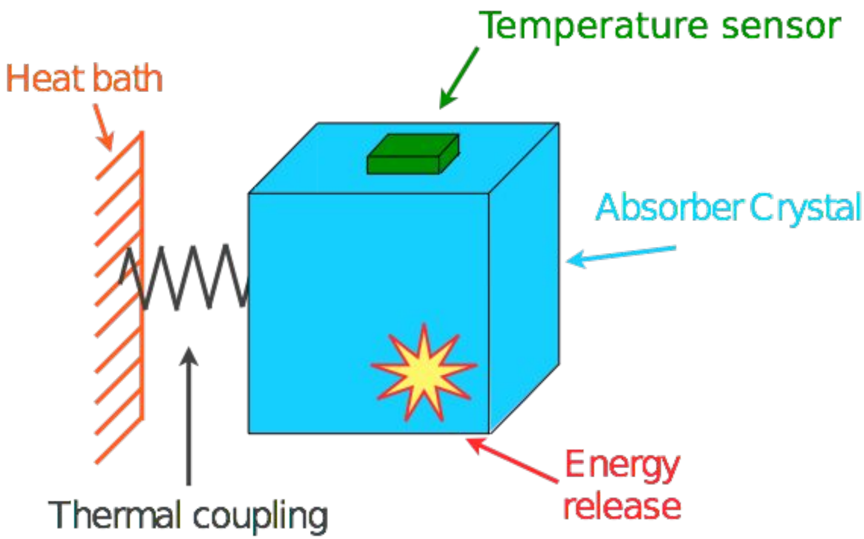
in the Region Of Interest (ROI) around $Q_{\beta\beta}$



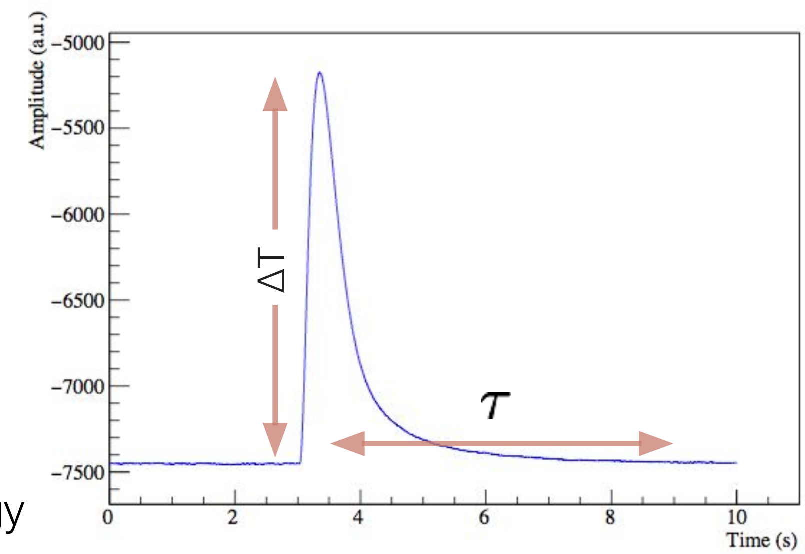
Dell'Oro S. et al., Cryogenics 102, 9, (2019)
https://doi.org/10.1016/j.cryogenics.2019.06.011

CUORE and the bolometric technique

CUORE TeO_2 detectors are operated
as cryogenic bolometers (energy converted into phonons)



- Low heat capacity @ T ~ 10 mK
- Excellent energy resolution (~0.2% FWHM)
- Same detector response for different particles (heat only)
- Slowness if coupled with NTDs (suitable only for rare event searches)



Simplified thermal model:

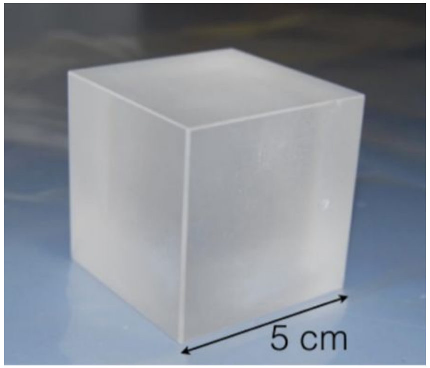
One thermal capacity C (crystal)
One thermal link G (btw crystal/heat bath)

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

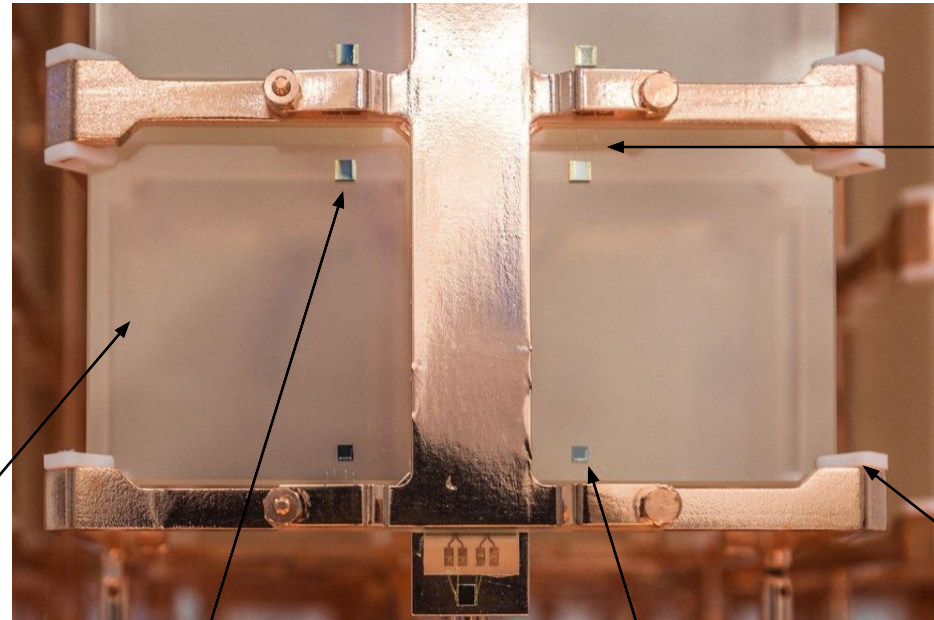
Amplitude of the pulse $\propto$ ΔT $\propto$ Energy deposition

The CUORE detector

CUORE instrumented bolometers



$^{(nat)}TeO_2$ 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



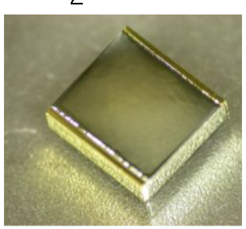
Au-wire bonding to Cu-PEN read-out strips

PTFE holders

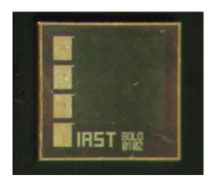
TeO_2 absorber

Ge-NTD

Si-heater



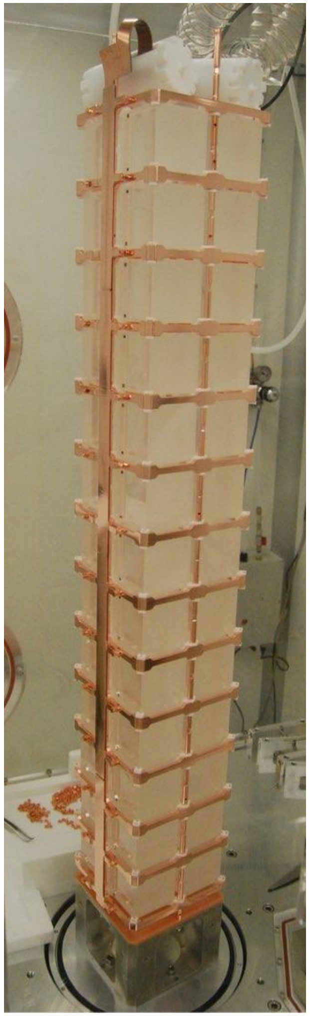
Ge-NTD thermistor
3.0 x 2.9 x 0.9 mm^3
Working impedance of the thermistors:
R_{wp} ~ 100 MΩ -1 GΩ
—> ΔV_{NTD} ~ 400 μV/MeV (@10 mK)



Si heater
2.3 x 2.4 x 0.5 mm^3
Provides periodically a fixed energy for gain stabilization

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

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

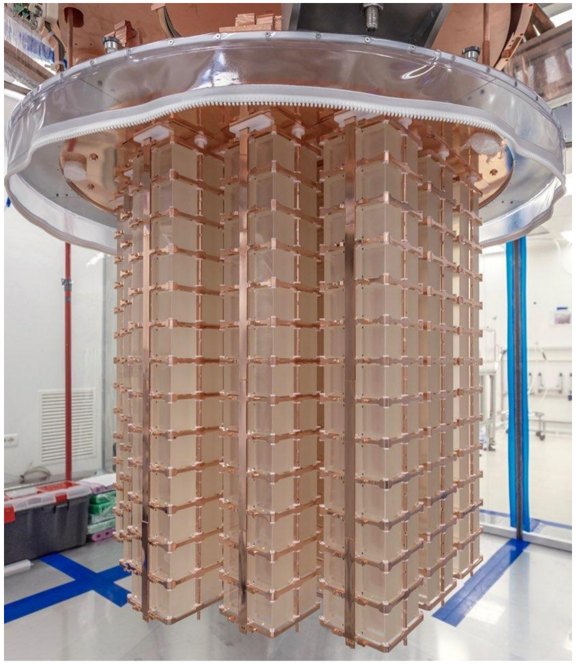
CUORE tower:
52 crystals
arranged in 13 floors
of 4 crystals each

CUORE-0 experiment:
CUORE-tower demonstrator

CUORE array:
19 towers

CUORE commissioning

- Detector assembly: 2012-2014
- Cryogenic system commissioning: Completed in Feb.2016
- Detector installation: Completed at the end of Aug. 2016



CUORE data taking

From early 2017 up to now

- First operation of a large array of macro bolometers
- Completely different detector and cryogenic system

Initial activities:

- Reach low temperature for system and detectors
- Reduce vibrations
- Optimize detectors thermal response
- Collect first physics data (measure background and release first $0\nu\beta\beta$ results)
- Learn how to make effective data analysis on 1000 bolometers

CUORE initial operations

- First Detector cool-down: Started in Dec. 2016

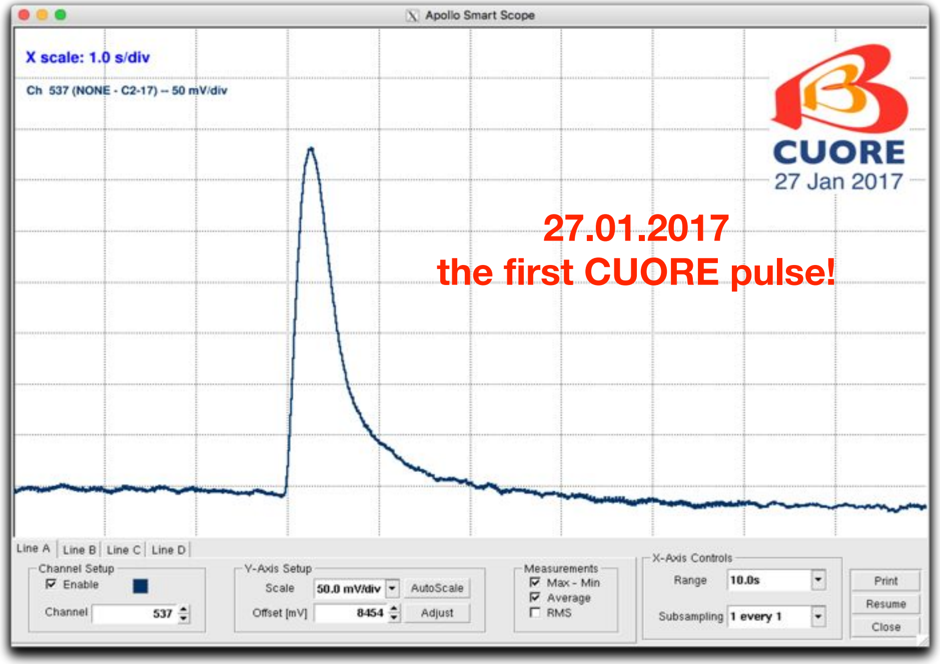
    Cooldown to 4K: ~ 20 days

    Pumping He exchange gas in IVC: ~ 10 days

    Cooldown from 4K to 8 mK: ~ 3 days

Total detector cooldown time from 300K to 10 mK: ~ 1 month

- First CUORE data: Early 2017

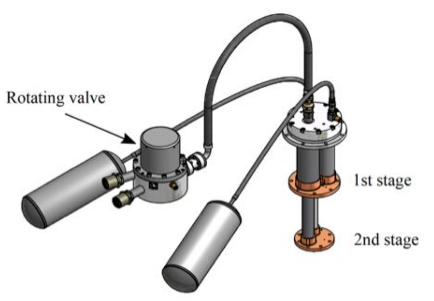


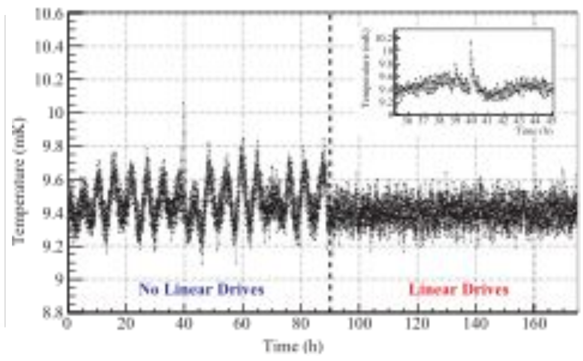
CUORE optimization

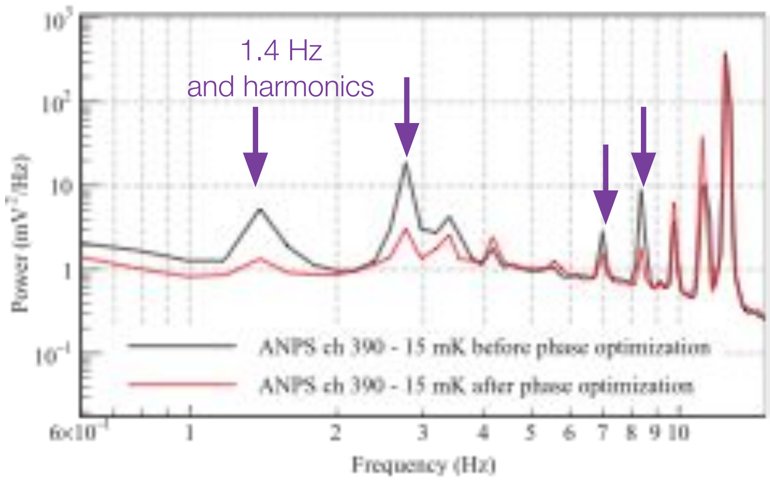
Noise reduction

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

- Linear Drives: precise control of the PTs motor-head rotation frequency
- Control the relative phases of the pressure oscillations in the Pulse Tubes and set the detectors minimum noise phase configuration







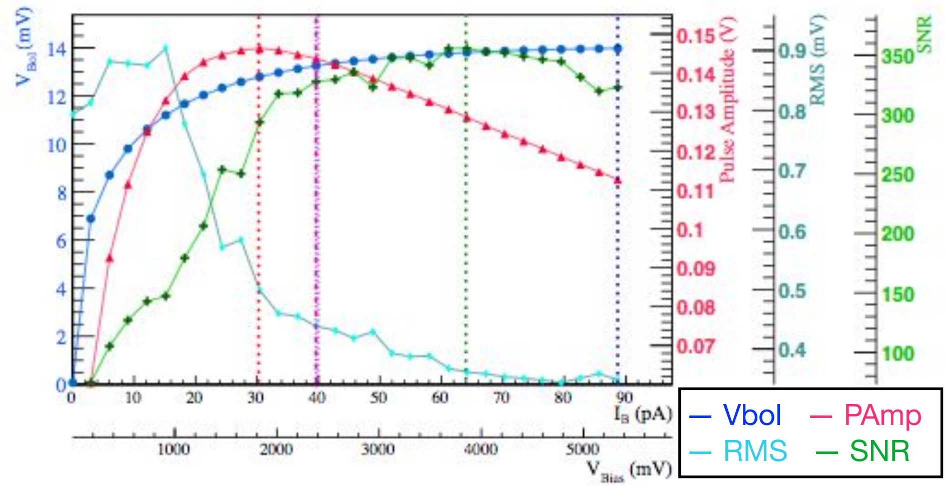
D'Addabbo A. et al.,Cryogenics 93, 55-56, (2018)
https://doi.org/10.1016/j.cryogenics.2018.05.001

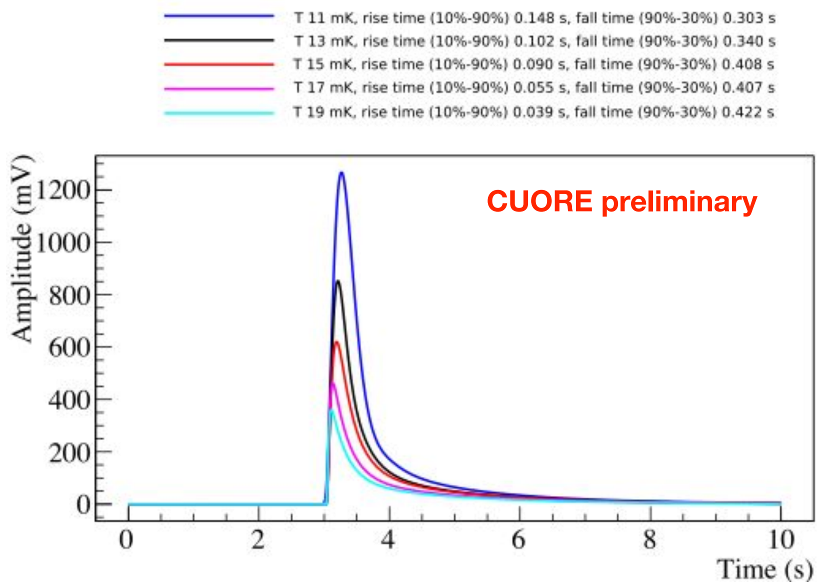
CUORE optimization

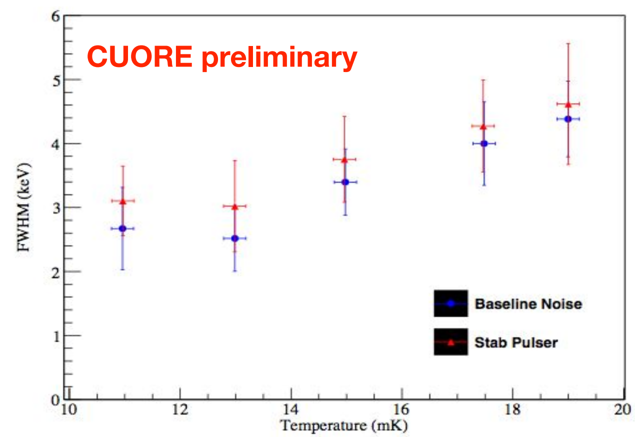
Load Curves, Working Points & Temperature scans

Achieve high quality detector readout with a good signal-to-noise ratio

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

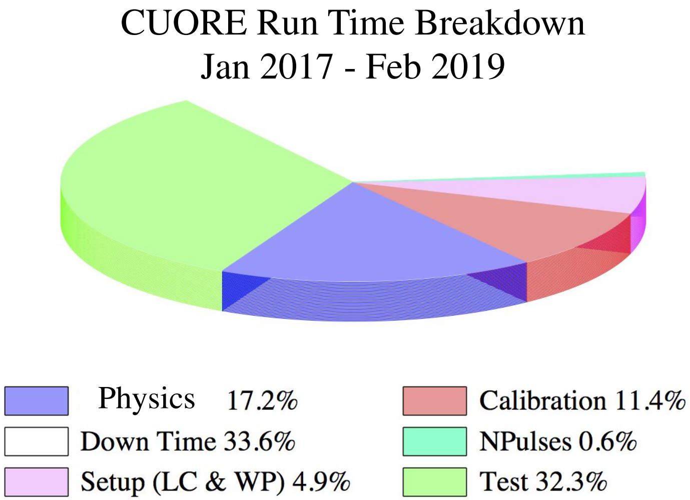






CUORE data taking

Data taking up to March 2019



The duty cycle of the system was poor, dominated by down-time (short warm-ups and cool-downs) and technical runs.
We concentrated our efforts on improving the reliability of the overall system and the stability of the data-taking.

- Performed a major maintenance of the cryogenic system (early 2019)
- Performed an upgrade of the calibration system (2018)
- Improved the data processing and analysis techniques
- Focussed on physics data-taking

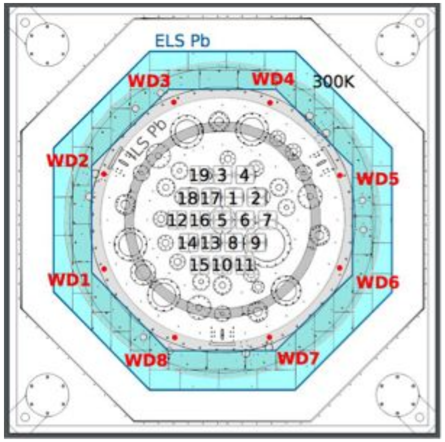
CUORE data taking: improvements

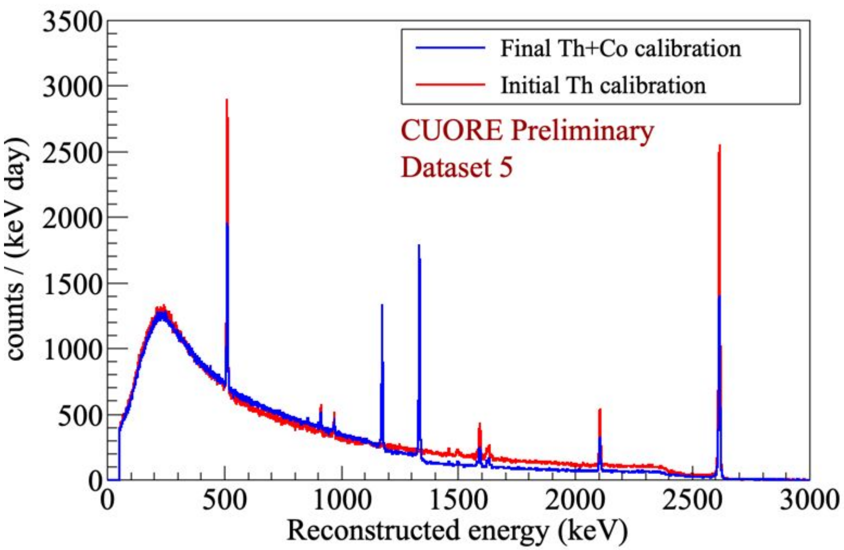
External Detector Calibration System (EDCS)

Internal Detector Calibration System: strings of ^{232}Th γ-ray sources reaching the detectors down to 10 mK, complex procedure for deployment and interference with the cryogenic system operation

→ Installation of External Detector Calibration System (EDCS)

EDCS: ^{232}Th+^{60}Co γ-ray sources, strings positioned in between the 300K vessel and the external Lead Shield

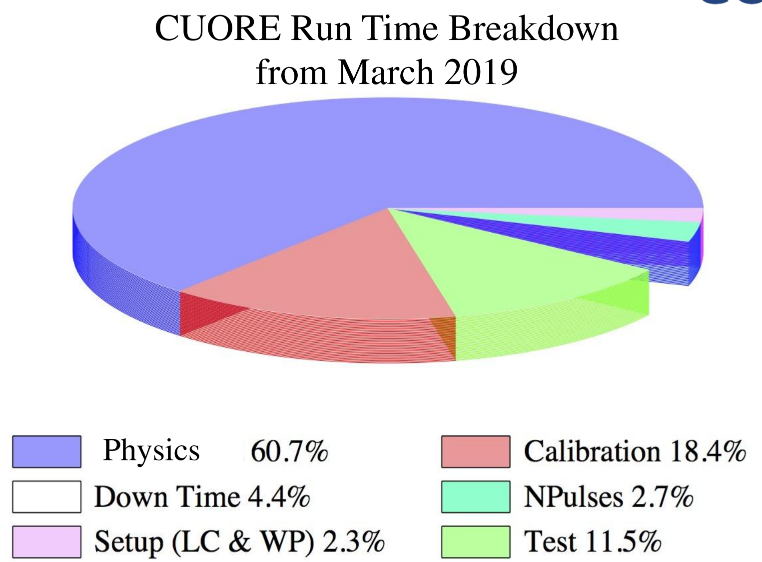


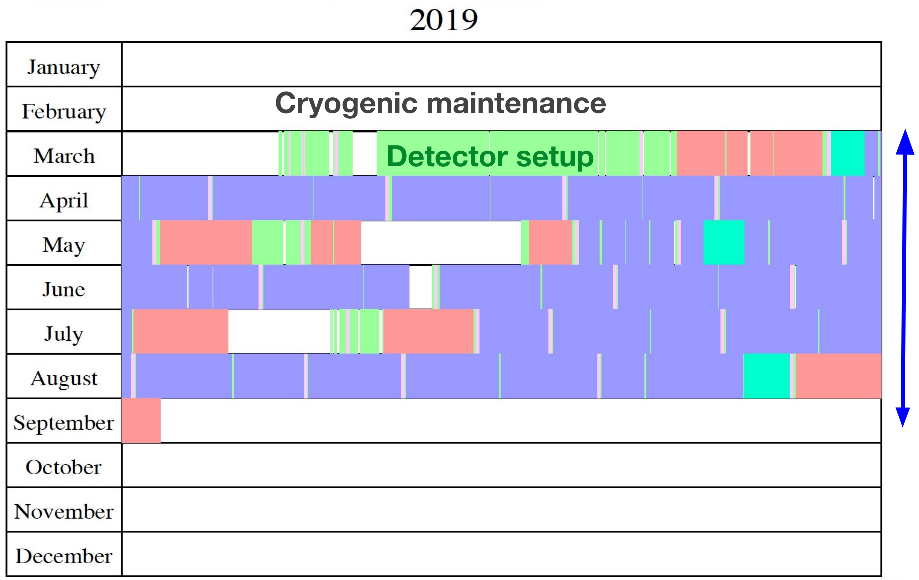


CUORE data taking

Data taking from March 2019 on

- **Reached stable data-taking with high duty cycle**
- Physics data bracketed by initial and final calibrations
- Calibration with EDCS
- Only short maintenance operations at dataset closure; checks for noise and thermal response consistency after the activities
- 3 complete consecutive datasets acquired, new dataset started in these days
- Priority is data taking - no further optimizations in the near future

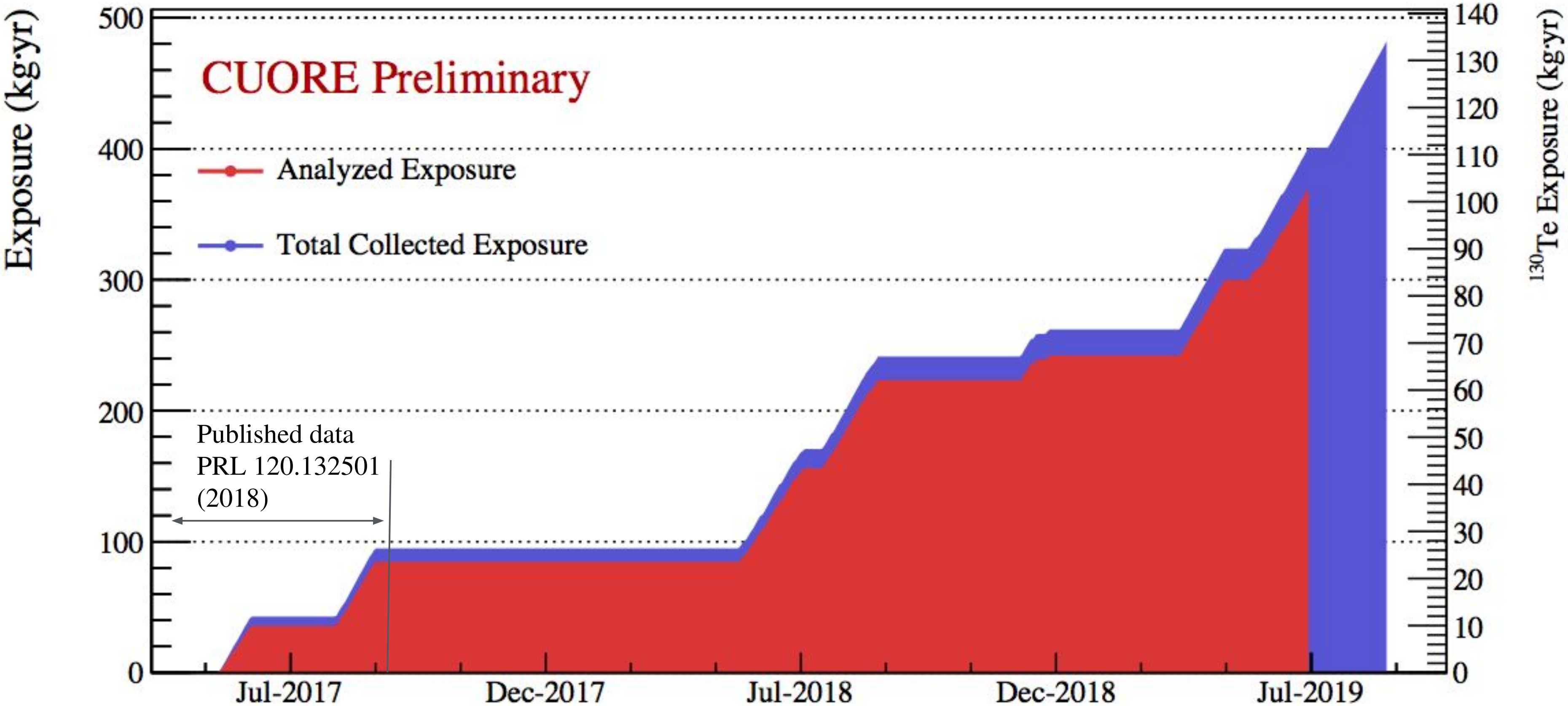




CUORE data taking

Current CUORE exposure

Collected Background exposure (TeO_2): 400. 9 kg yr
Analyzed Background exposure (TeO_2): 369.9 kg yr
^{130}Te exposure: 102.9 kg yr



CUORE first results

CUORE published results - Data from 2017

984/988 operational channels

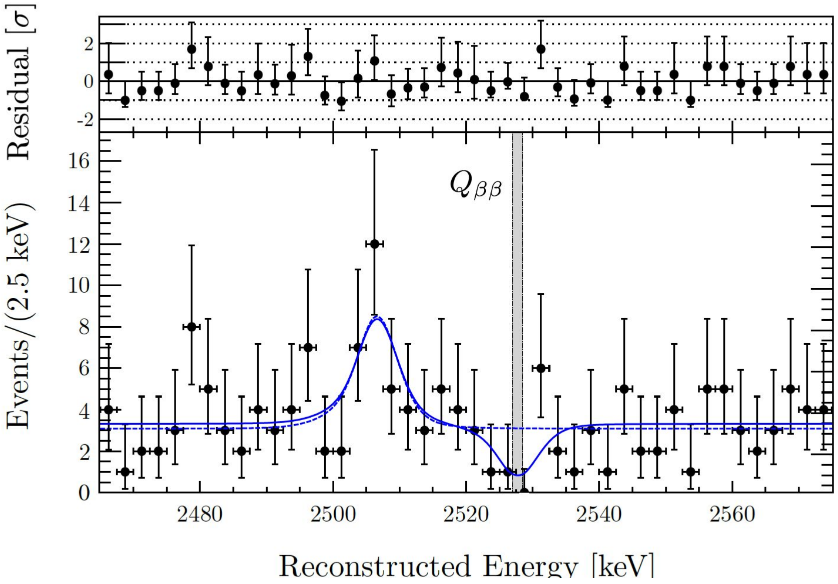
7 weeks of physics data taking (Dataset 1, Dataset 2)
$^{nat}TeO_2$ exposure: 86.3 kg yr,
^{130}Te exposure: 24.0 kg yr

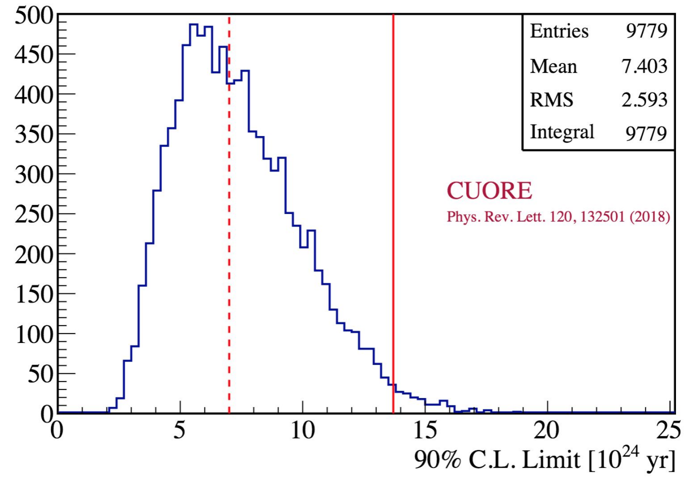
ROI background index (B) ~ 1.4×10^{-2} c/(keV·kg·yr)

UEML fit performed in the ROI [2465,2575 keV]
to evaluate best fit decay rate for 0vββ of 130Te

No evidence of signal

Half-life limit for 0vββ in 130Te (90%C.L including syst.)
T_{0v} (130Te) > 1.3 x 10^{25} yr





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

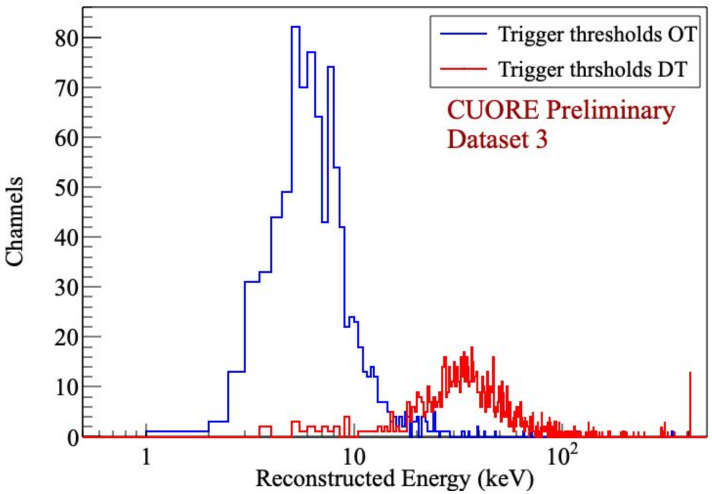
CUORE trigger algorithm

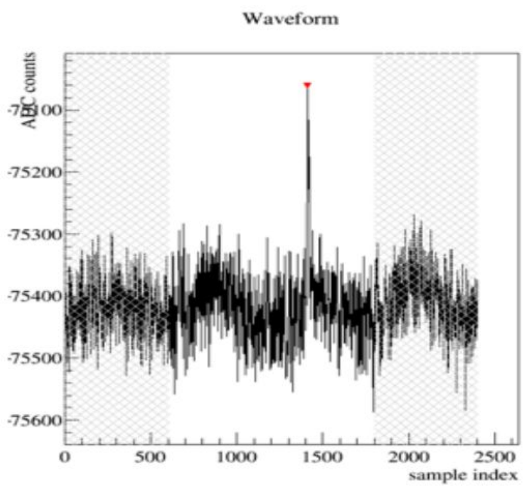
OT trigger

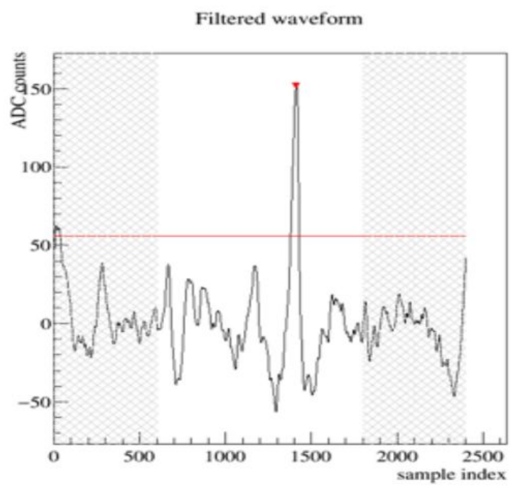
Disentangle low energy signals from fake signals produced by noise, lower the detectors trigger thresholds

→ Optimum Trigger (OT) algorithm: identifies a signal when the amplitude of the filtered signal waveform exceeds a configurable threshold

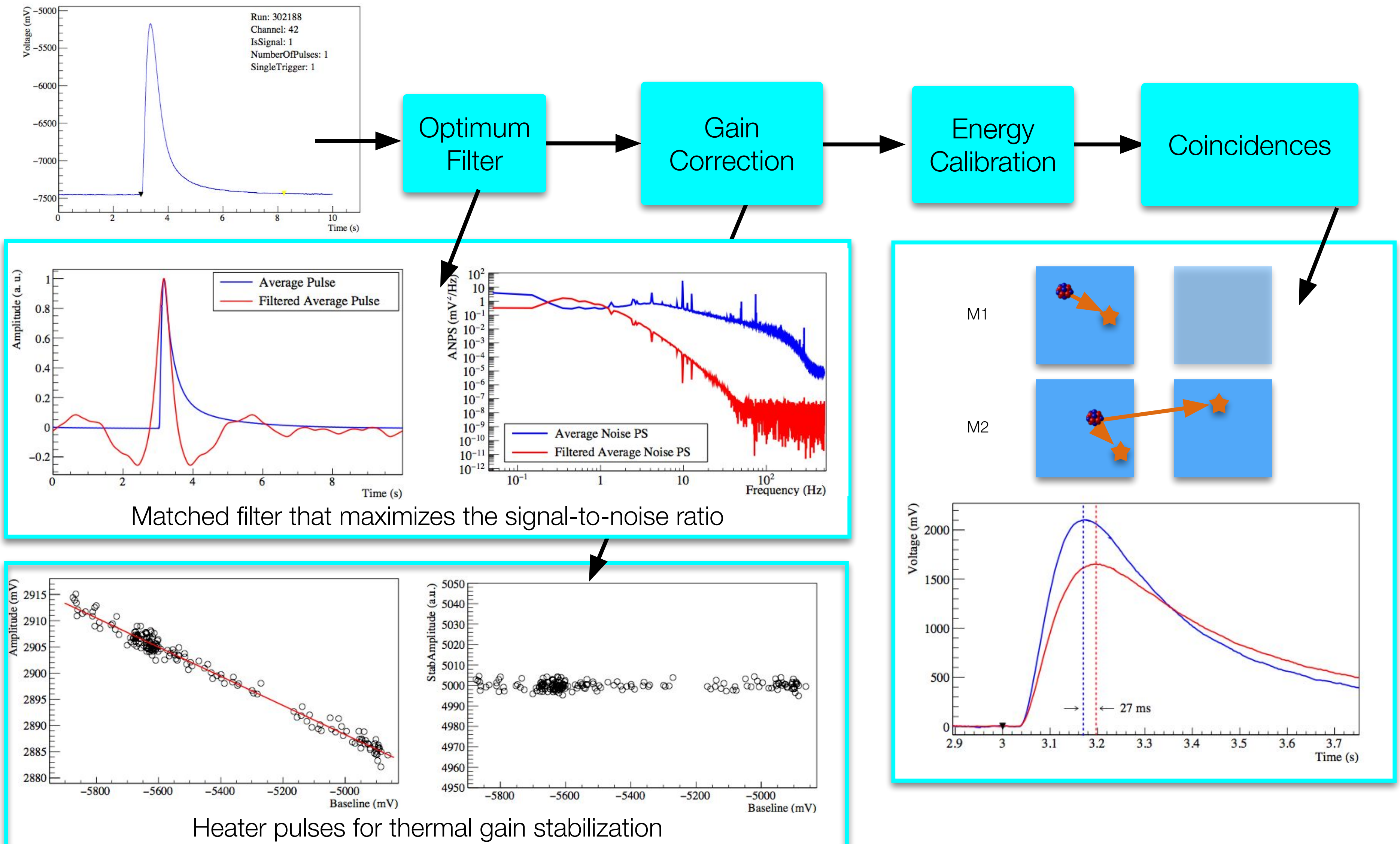
- OT trigger applied for offline re-triggering of the continuous recorded stream of data



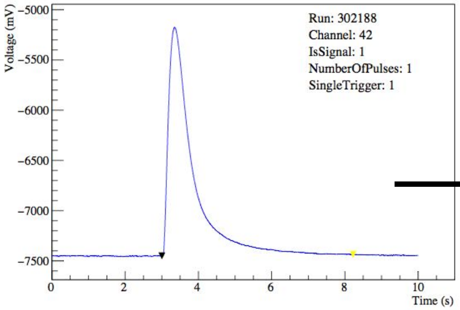




CUORE data processing

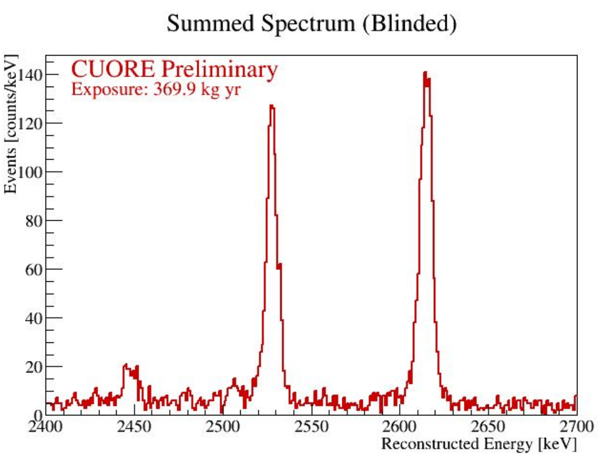


CUORE data processing

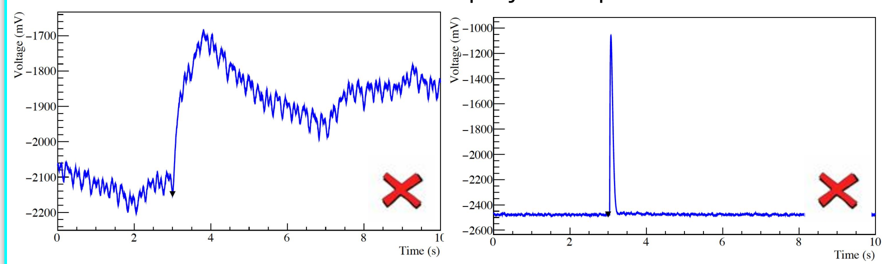


Optimum Filter → Gain Correction → Energy Calibration → Coincidences → PSA → Blinding of the ROI → Data quality selections → Unblinding

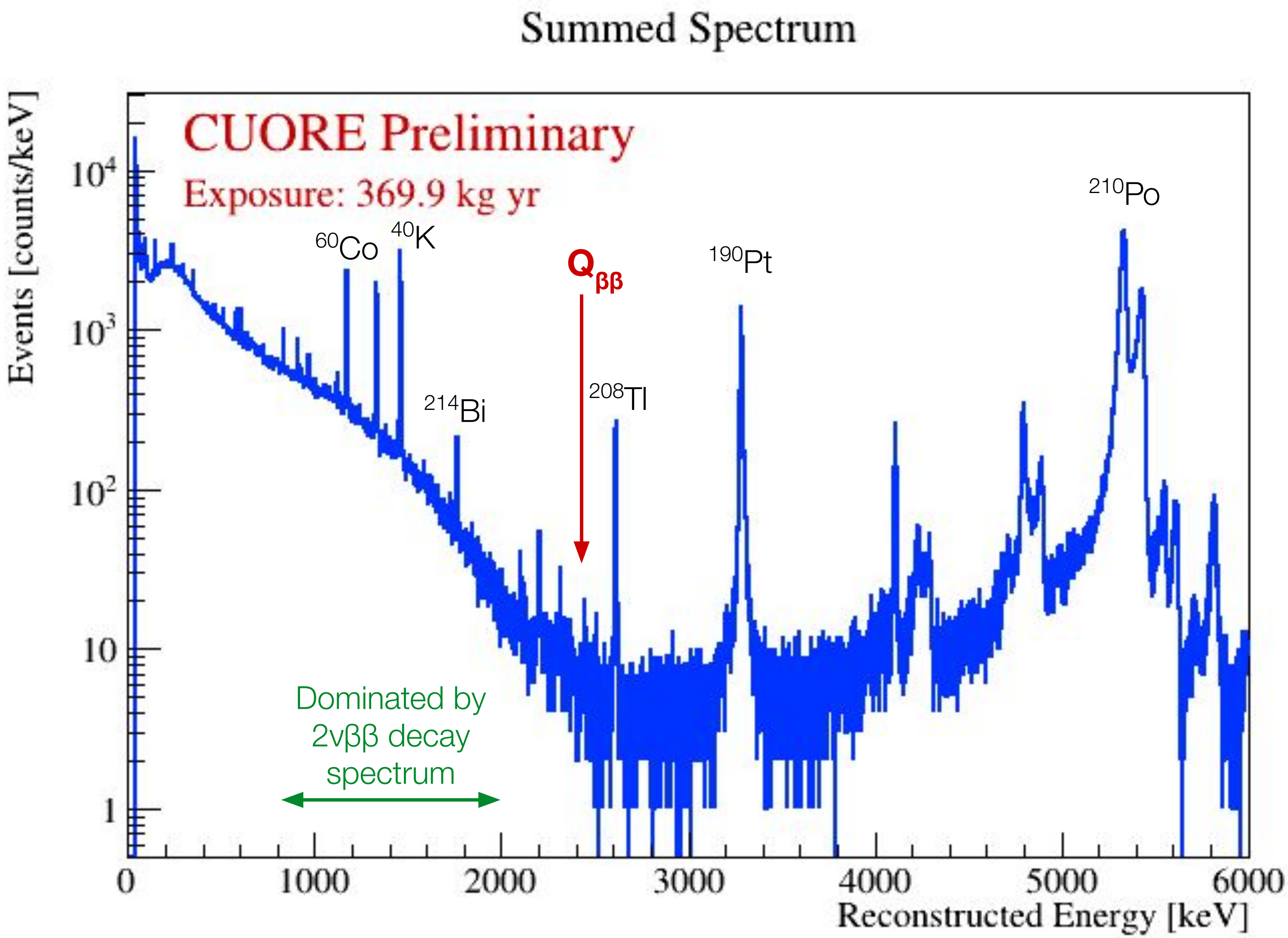
- Optimization of data quality cuts on Blinded data



Reject non-physical pulses



CUORE data



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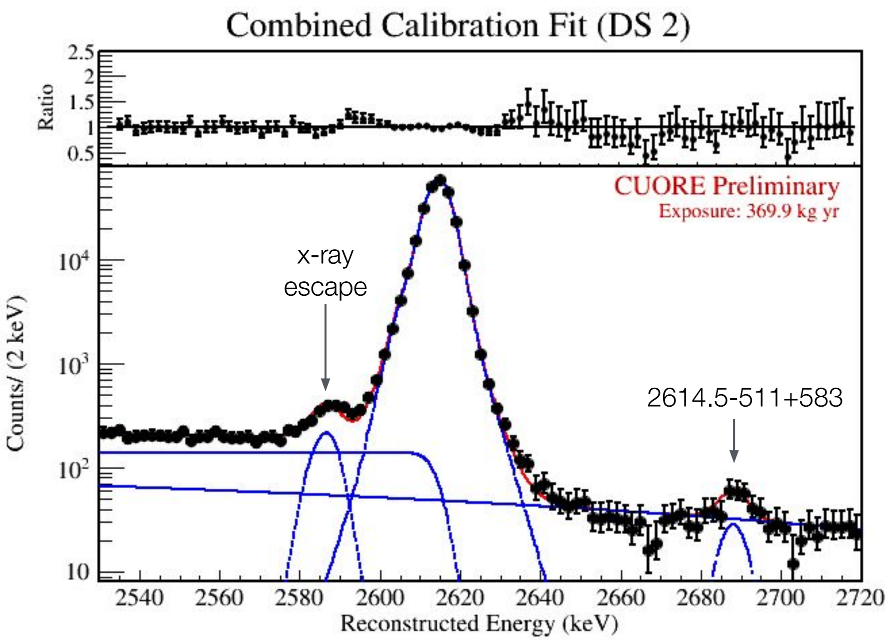
Lineshape

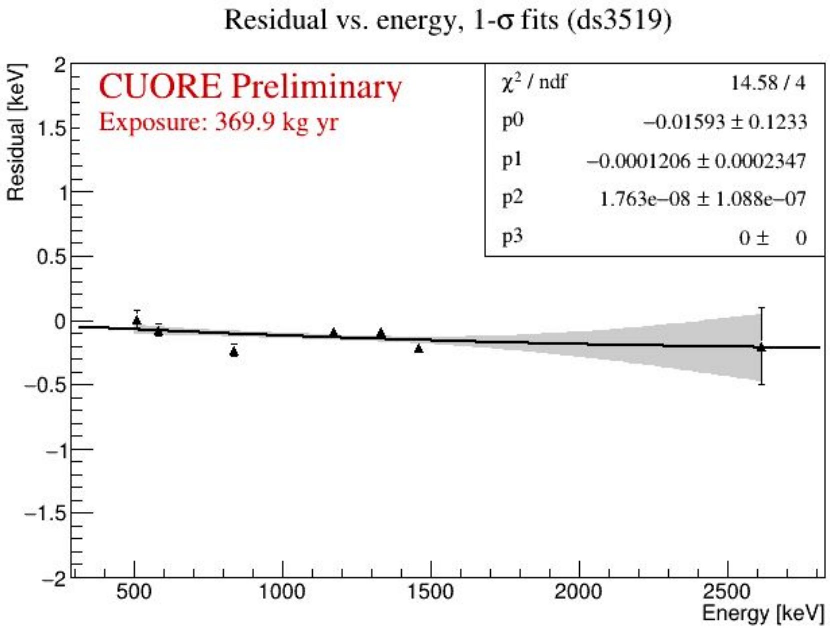
Lineshape fit

- Fit ^{208}Tl line at 2614.5 keV in calibration spectra to precisely evaluate lineshape
- Main peak parameterized with sum of 3 Gaussian
- Fit run on single tower simultaneously for multiple datasets



Bias of peak position in physics data

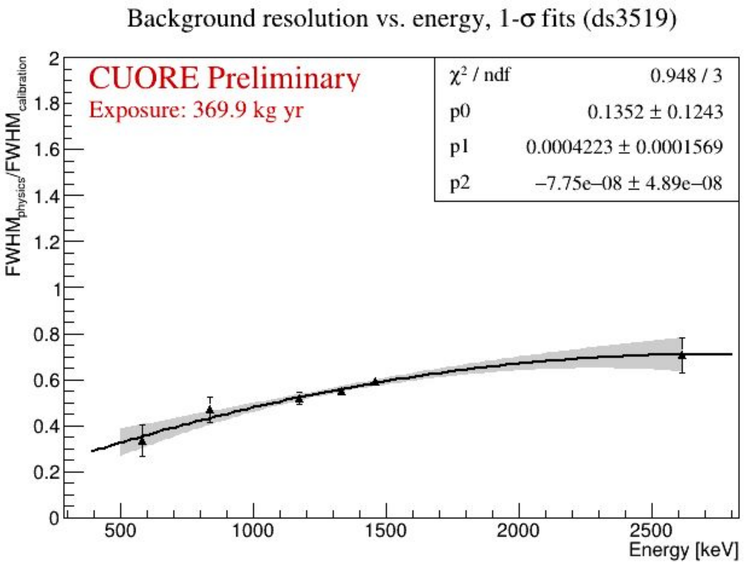
- Fit peaks in physics spectrum with 3-Gaussian
- Compute residuals from literature values
- Fit residuals vs energy with 2nd order polynomial → Systematics!

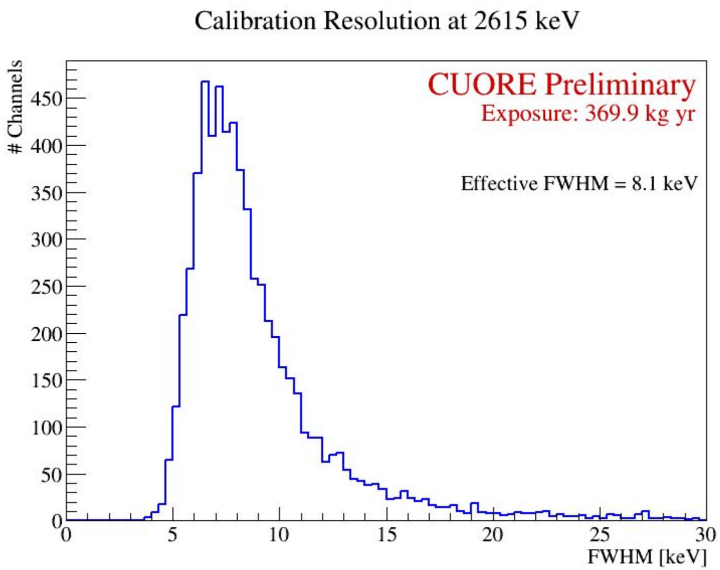


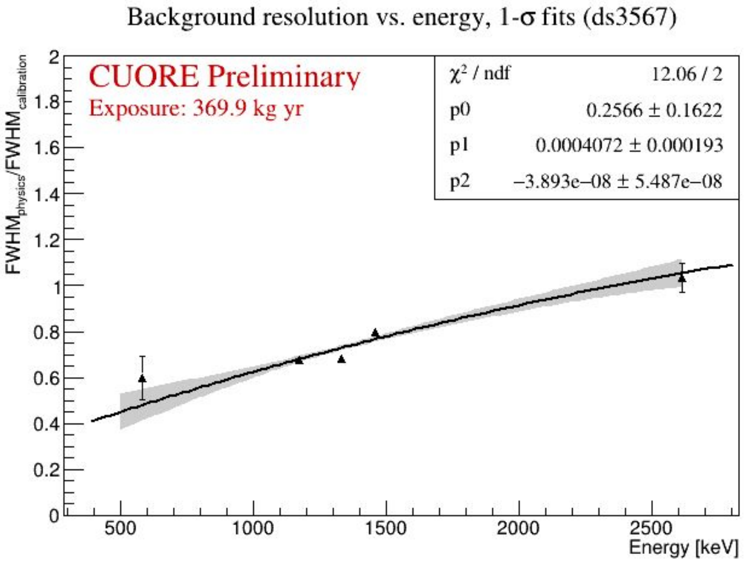
Lineshape

Scaling of resolution to physics data

- Extract FWHM from peak fit in physics spectra
- Fit ratio of FWHM in physics and calibration data as a function of energy
- Extrapolate to $Q_{\beta\beta}$

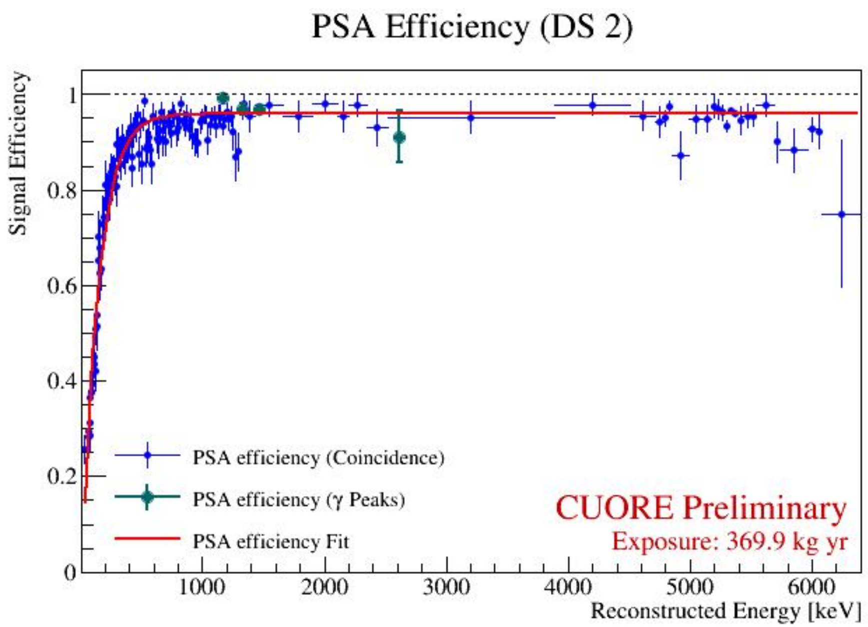






Efficiencies

Reconstruction efficiency	Comprises: → trigger → event reconstruction → pile-up identification
Anti-coincidence efficiency	Quantifies the probability of properly identifying a single-site event
Pulse-Shape Analysis efficiency	Fraction of events passing a multi-dimensional cut on 6 pulse-shape variables



Parameters for the analysis

CUORE

Parameter	Value
Number of datasets	7
Number of channels	842-948 (depending on dataset)
TeO_2 exposure	369.94 kg·yr
FWHM at 2615 keV in calibration data	8.1 keV
FWHM at $Q_{\beta\beta}$ in physics data	8.7 keV
Reconstruction efficiency	(95.9578 ± 0.0033)%
Anti-coincidence efficiency	$(98.95^{+0.15}_{-0.16})\%$
PSA efficiency	(92.04 ± 0.11)%
Tot. analysis efficiency	(87.41 ± 0.18)%
Syst. on analysis efficiency	±1.9%
Containment efficiency	(88.350 ± 0.090)%

Statistical approach

CUORE

Bayes theorem: $$P\left(\vec{\theta}|\vec{E}\right) = \frac{\mathcal{L}\left(\vec{E}|\vec{\theta}\right)\cdot\pi\left(\vec{\theta}\right)}{\int_{\Omega}\mathcal{L}\left(\vec{E}|\vec{\theta}\right)\cdot\pi\left(\vec{\theta}\right)d\vec{\theta}}$$

Likelihood: $$\mathcal{L}\left(\vec{E}|\vec{\theta}\right) = \prod_{dataset}\prod_{channel}\left[\frac{e^{-\lambda}\lambda^{n}}{n!}\prod_{event\ i}\left(\frac{s}{\lambda}pdf_{0\nu\beta\beta}\left(E_i|\vec{\theta}\right) + \frac{c}{\lambda}pdf_{^{60}Co}\left(E_i|\vec{\theta}\right) + \frac{b}{\lambda}\frac{1}{\Delta E}\right)\right]$$

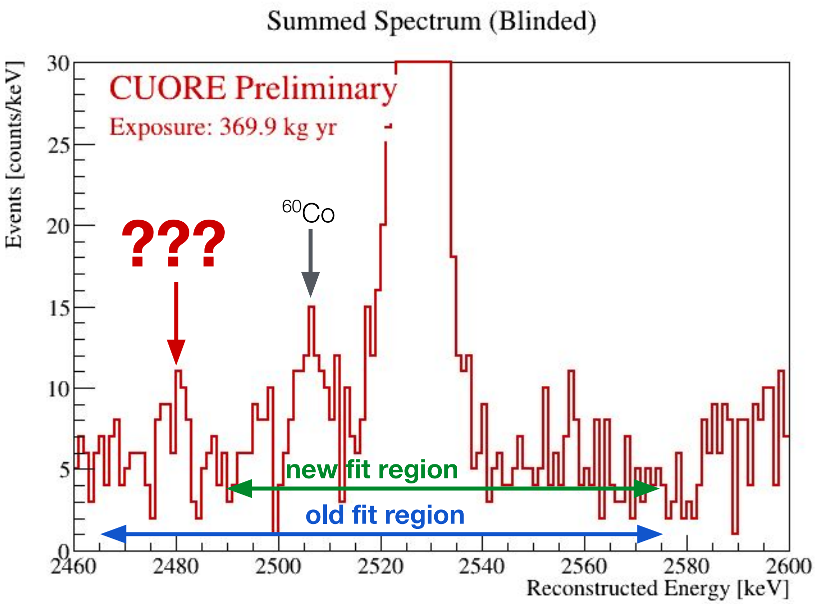
Expectation value: $\lambda=s+c+b$

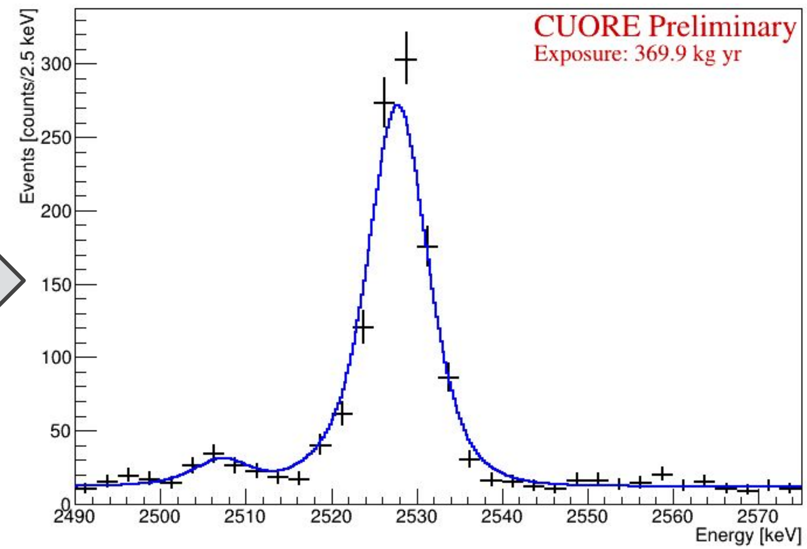
Width of fit region: ΔE

Systematics implemented as nuisance parameters

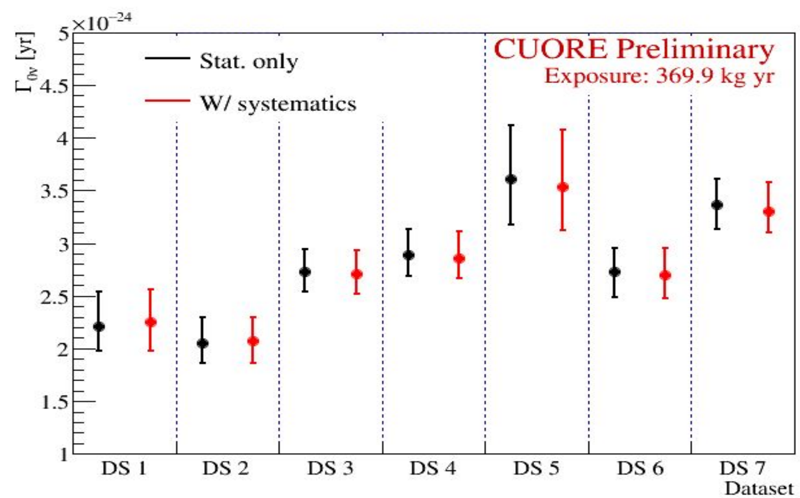
Parameter	Dependence	Method
Analysis efficiency I	Dataset	Gaussian
Analysis efficiency II	Global	Flat in [0.981, 1.021] range
Energy bias	Dataset	Fit residuals of peaks in physics spectrum from literature values with 2^{nd} order polynomial
Energy resolution	Dataset	Fit ratio of FWHM in physics and calibration data with 2^{nd} order polynomial
$\mathbf{Q_{\beta\beta}}$	Global	Gaussian, 2527.518(13) keV
^{130}Te isotopic fraction	Global	Gaussian, 34.1668(16)%

Blinded fit

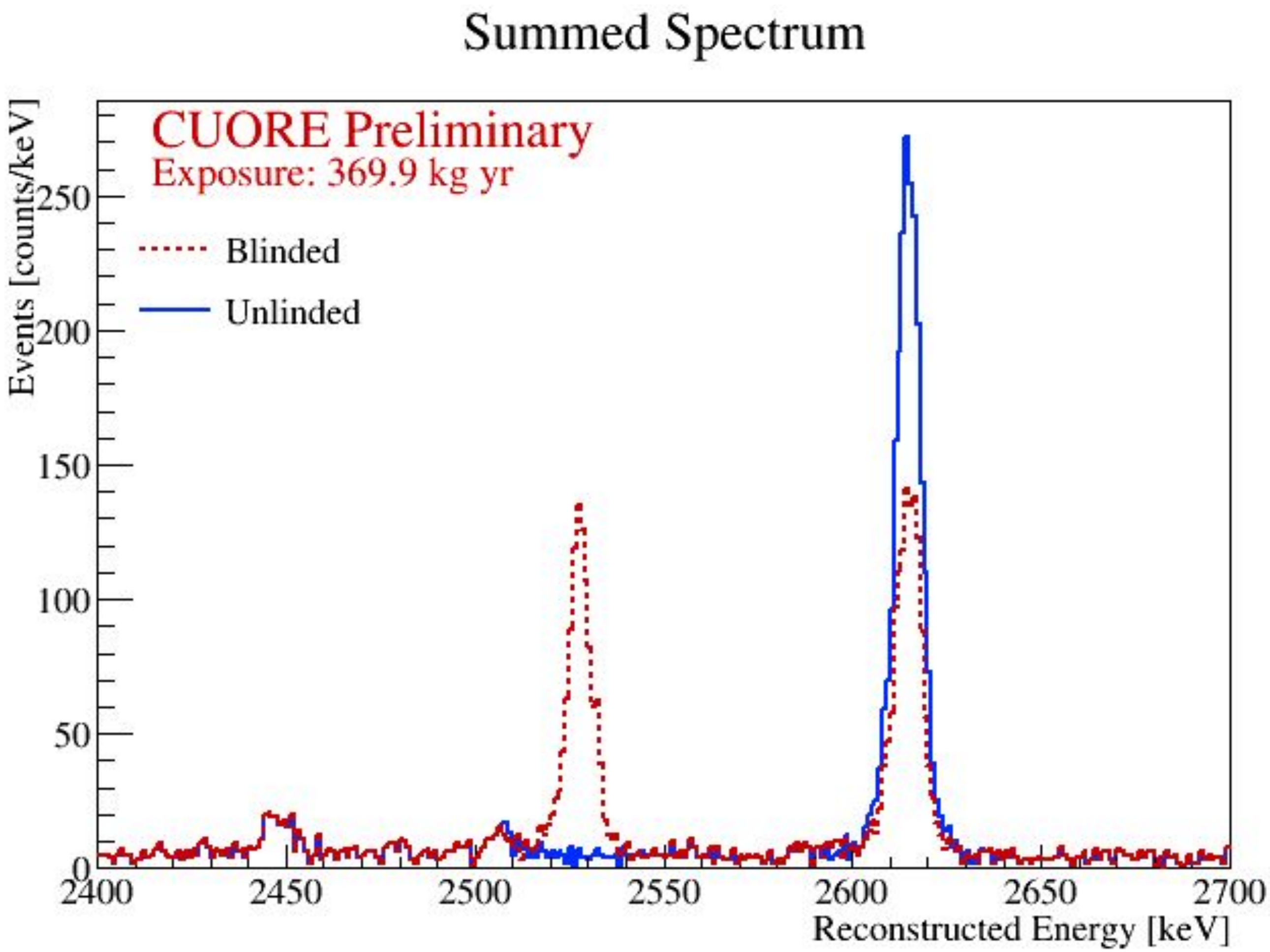




- Fit range: [2490, 2575] keV
- Components: flat background, ^{60}Co peak, 0νββ peak
- Fit run independently for each dataset and tested w/ and w/o additional nuisance parameters for systematics
  → 0νββ consistent in both cases for all datasets



Unblinding



Summed Spectrum
CUORE Preliminary
Exposure: 369.9 kg yr
Blinded
Unlinded
Events [counts/keV]
0
50
100
150
200
250
2400
2450
2500
2550
2600
2650
2700
Reconstructed Energy [keV]

Background in α region and at $Q_{\beta\beta}$

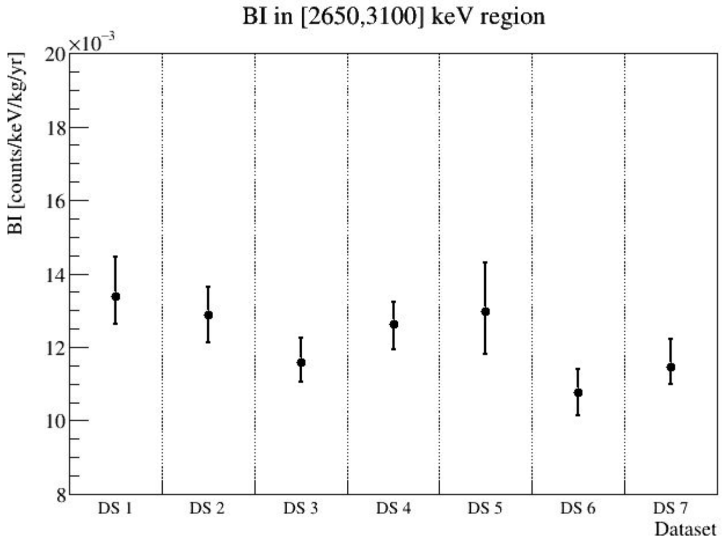
α region

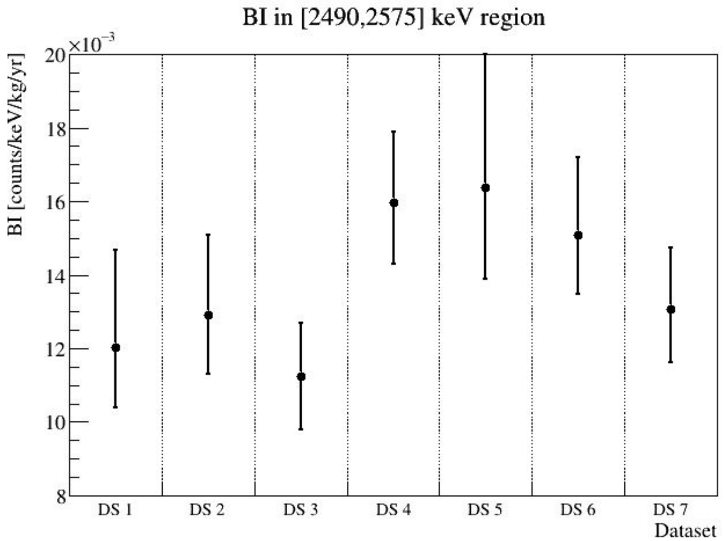
- Fit flat background in [2650,3100] keV region
- Average α background: $1.210(28)\cdot10^{-2}$

$Q_{\beta\beta}$ region

- Fit with flat background + ^{60}Co peak in [2490,2575] keV region
- Average BI: $1.369(69)\cdot10^{-2}$ cts/keV/kg/yr

Dataset	BI [$\times10^{-2}$ counts/keV/kg/yr]
1	$1.20^{+0,26}_{-0.17}$
2	$1.29^{+0.22}_{-0.16}$
3	$1.11^{+0.15}_{0.14}$
4	$1.60^{+0.19}_{-0.17}$
5	$1.64^{+0.44}_{-0.25}$
6	$1.51^{-0.21}_{-0.16}$
7	$1.13^{+0.17}_{-0.14}$

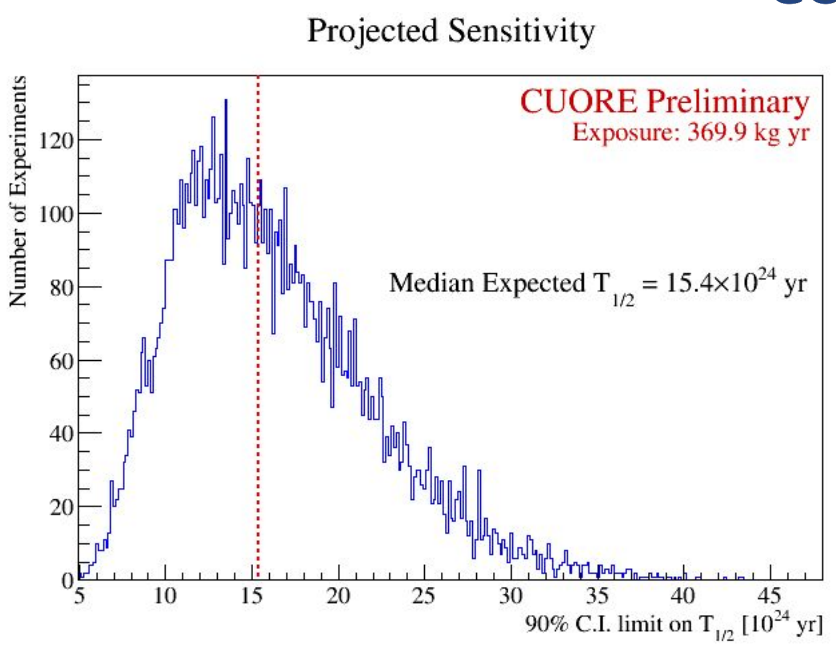




Sensitivity

Method

- Fit unblinded data with flat background and ^{60}Co components only (no $0\nu\beta\beta$)
- Generate set of 10^4 toy-MC data-sets according to bkg-only model
- Fit toy-MC with signal+bkg model
- Extract distribution of 90% C.I. halflives limits



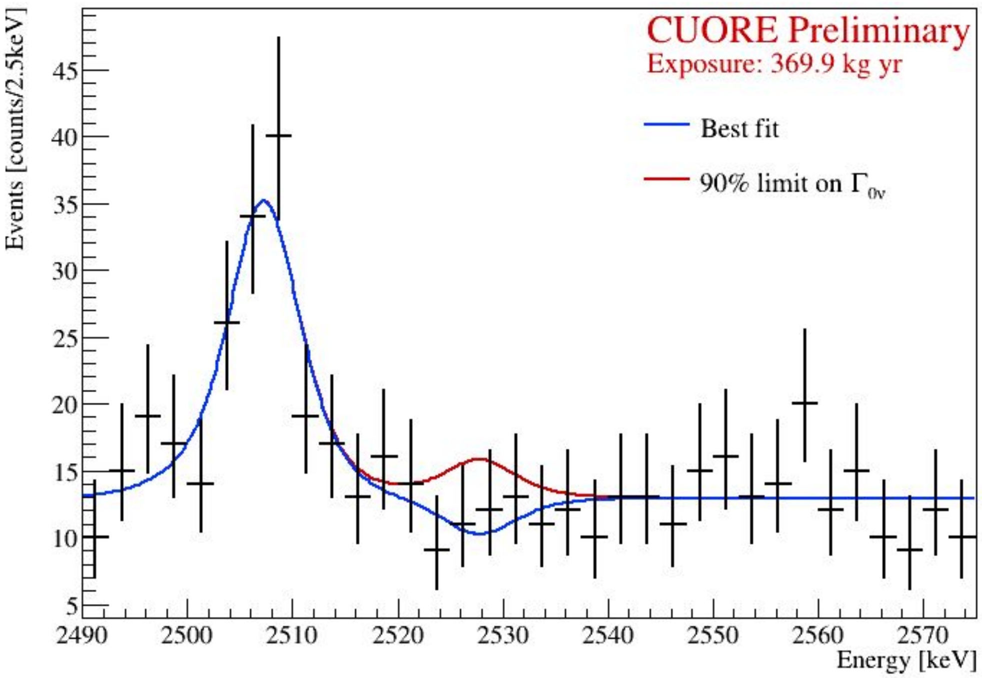
Details for NERDs

- Posterior for background index (BI) and ^{60}Co rate from bkg-only fit have uncertainties larger than corresponding Poisson uncertainty
  → Sample from enlarged distribution: TRandom3::PoissonD(B^2/σ^2)$\cdot\sigma^2/B$
- ^{60}Co peak generated using same 3-Gaussian lineshape used for the fit

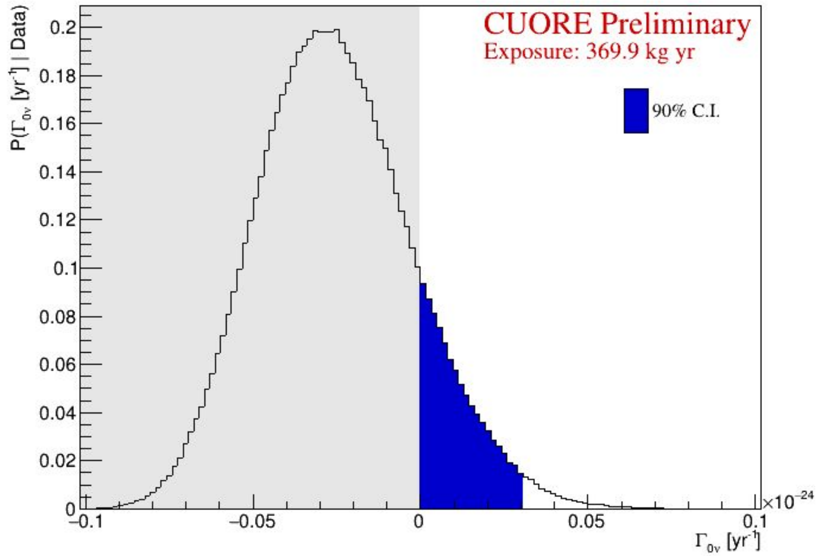
Unblinded fit

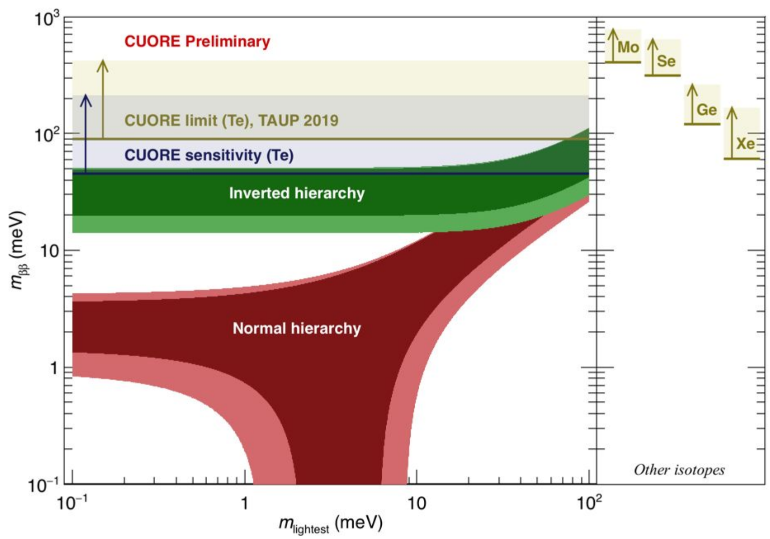
Method

- Bayesian analysis based on BAT
- Allow negative non-physical range for $\Gamma_{0\nu}$ to evaluate the amplitude of possible background under-fluctuations
- Repeat fit on physical range only
  → Results on $\Gamma_{0\nu}$ obtained from this!
- Free params: 60Co peak rate & position, $\Gamma_{0\nu}$ rate, background
- Repeat fit with additional nuisance parameters to account for systematics



Results





PRELIMINARY Results

- No evidence for 0νββ decay 😢
- Background under-fluctuation yields a best-fit value of: $\Gamma_{0v}=-3.0^{+2.8}_{-1.8} \cdot 10^{-26}$ yr $^{-1}$
- Marginalized limit computed on physical range: $\Gamma_{0v} < 3.0 \cdot 10^{-26}$ yr $^{-1}$

$T^{0v}_{1/2} > 2.3 \cdot 10^{25}$ yr at 90% C.I.

- Systematics affect the limit by ~1%
- Probability of getting a stronger limit: 13%
- Assuming the light neutrino exchange:

mββ < 0.09-0.42 eV at 90% C.I.

- Starting to work on a publication

Conclusions

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

- New CUORE physics results of $T_{0\nu}$ in ^{130}Te with increased exposure (370 kg yr TeO2)
- The CUORE data taking is currently underway to collect 5 years of run time
- Investigating the potential of the CUORE experiment for the search for rare events and/or for physics beyond the Standard Model other than the 2νββ decay of 130Te

Thank you on behalf of The CUORE collaboration

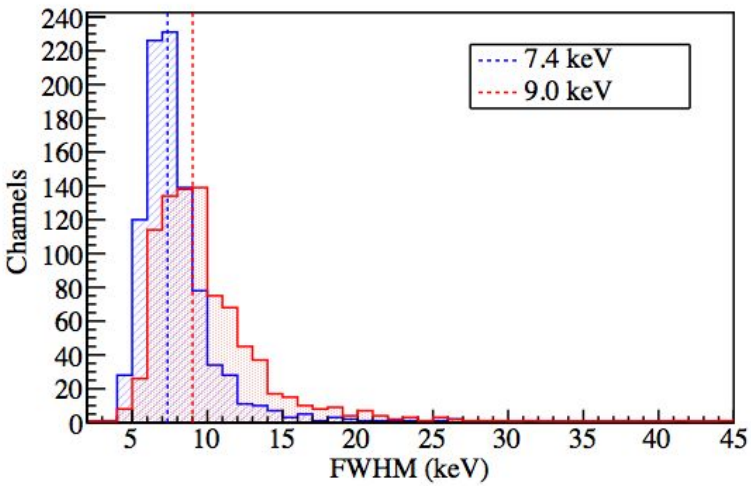
Backup

CUORE optimization & first physics data

Improved Detector performance during optimization in 2017

- Energy resolution in calibration runs @^{208}Tl decay gamma-peak (2615 keV)

Dataset 1: 9.0 keV FWHM
Dataset 2: 7.4 keV FWHM



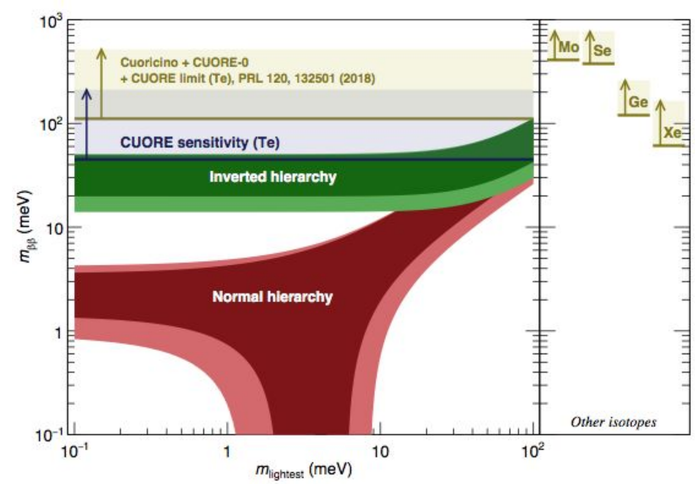
Improved resolution from Dataset 1 to Dataset 2 due to:

- 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 CUORE physics data

984/988 operational channels
7 weeks of physics data taking (Dataset 1, Dataset 2)
$^{nat}TeO_2$ exposure: 86.3 kg yr, ^{130}Te exposure: 24.0 kg yr

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



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

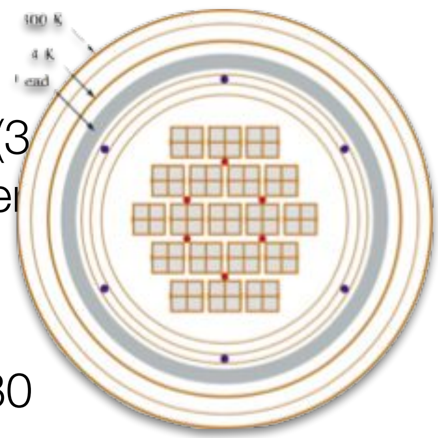
CUORE auxiliary systems

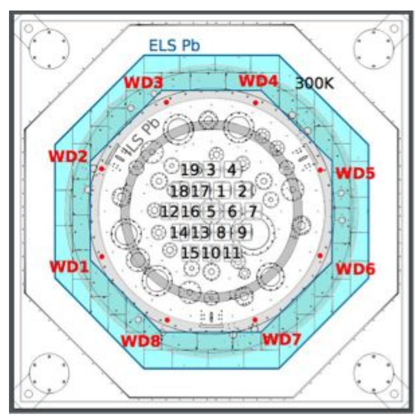
Detector Calibration Systems

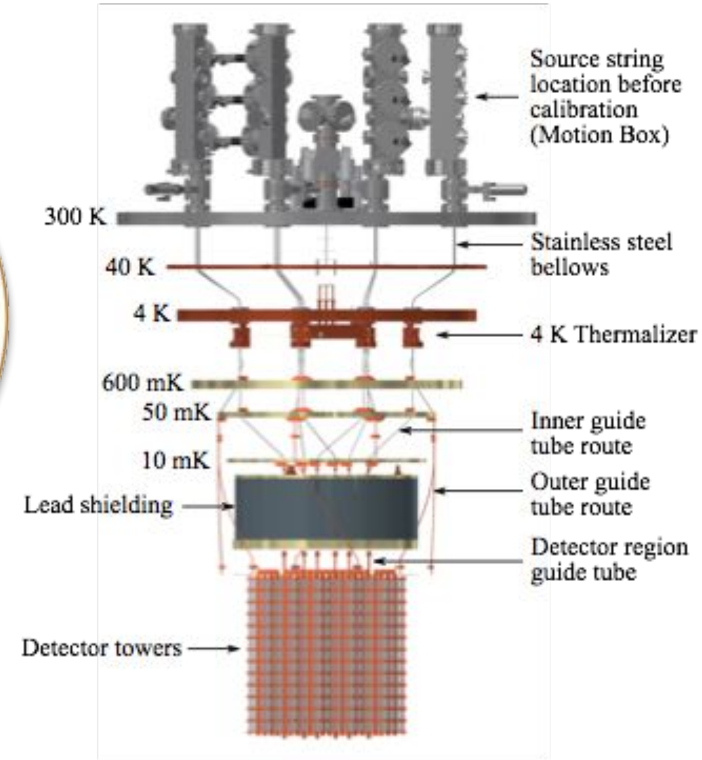
^{232}Th γ-ray sources

- Internal DCS: 12 strings (3 Bq for 6 inner str, 19.4 Bq for 6 outer str)

- External DCS: 8 strings (80 kBq total)





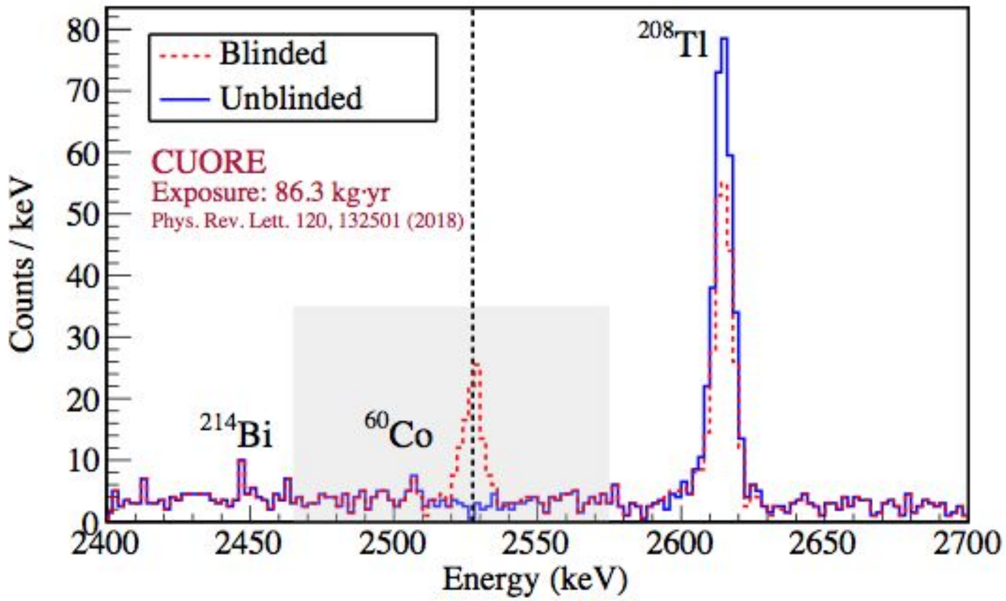


First results from CUORE: 0νββ analysis

Blinding of the background spectrum

Blinding procedure:

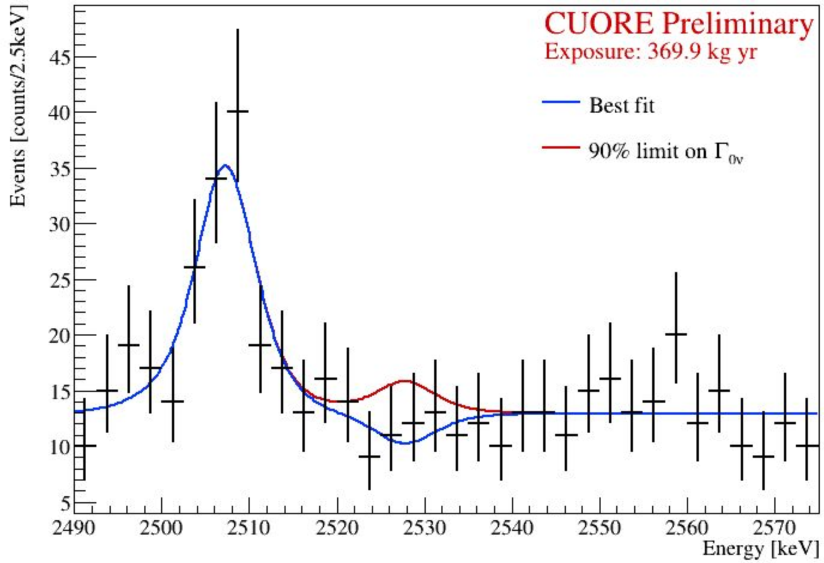
- Choose a random fraction and move events from +/- 20 keV of 2615 keV to the $Q_{\beta\beta}$ and vice versa
  - The blinding algorithm produces an artificial peak around the 0νββ Q-value and blinds the real 0νββ rate of ^{130}Te
  - When all data analysis procedures are fixed the data are eventually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

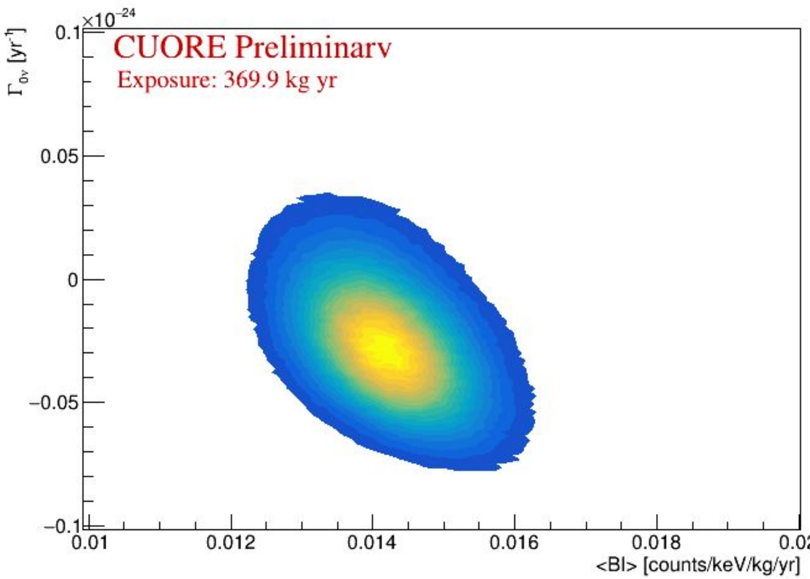


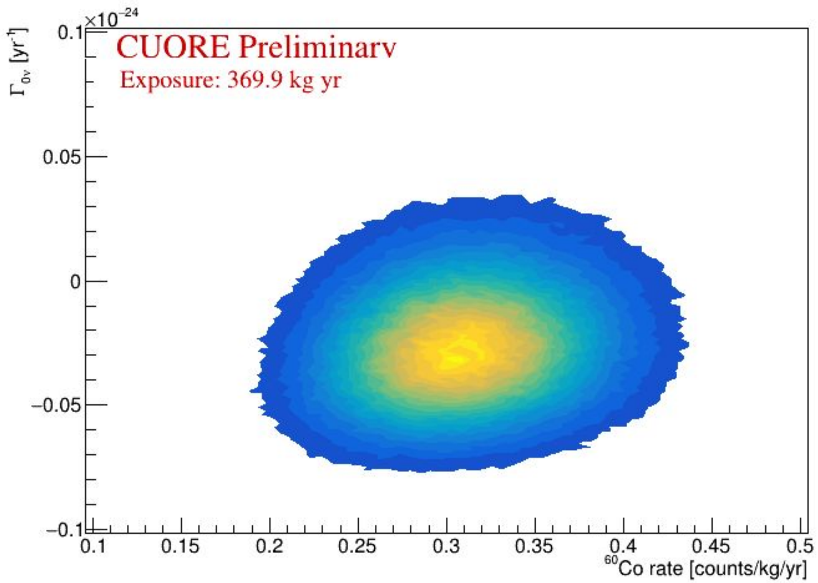
Unblinded fit

Method

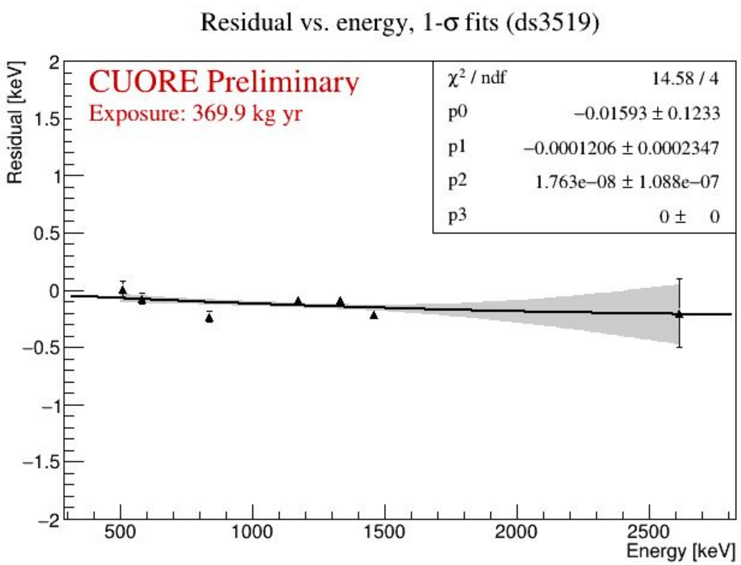
- Bayesian analysis based on BAT
- Allow negative non-physical range for $\Gamma_{0\nu}$ to evaluate the amplitude of possible background under-fluctuations
- Repeat fit on physical range only
  → Results on $\Gamma_{0\nu}$ obtained from this!
- Repeat fit with additional nuisance parameters to account for systematics

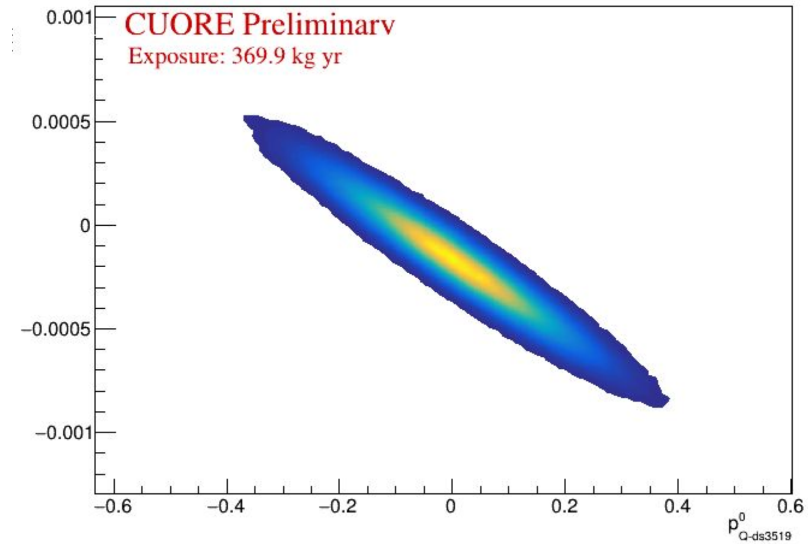


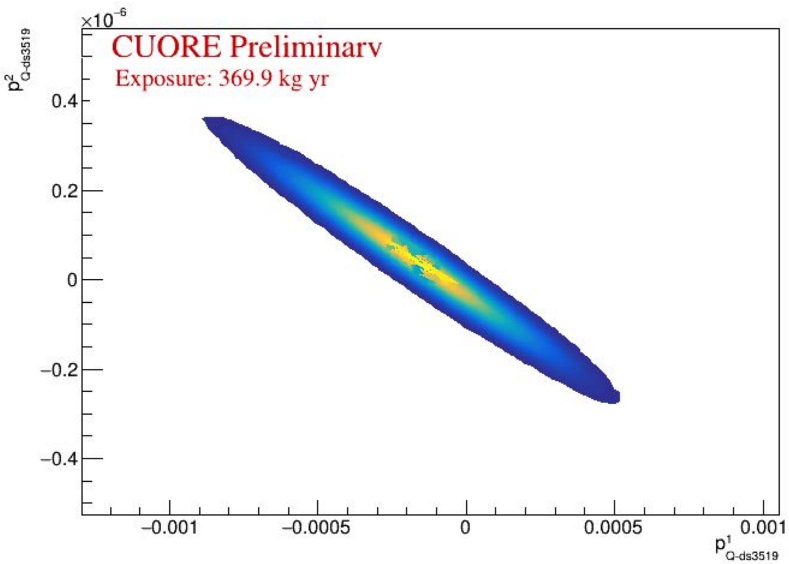


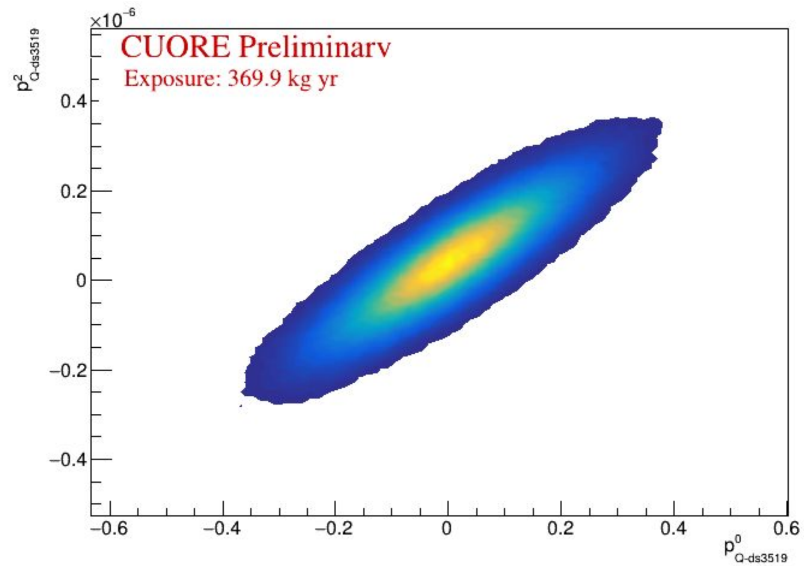


Unblinded fit: systematic on lineshape









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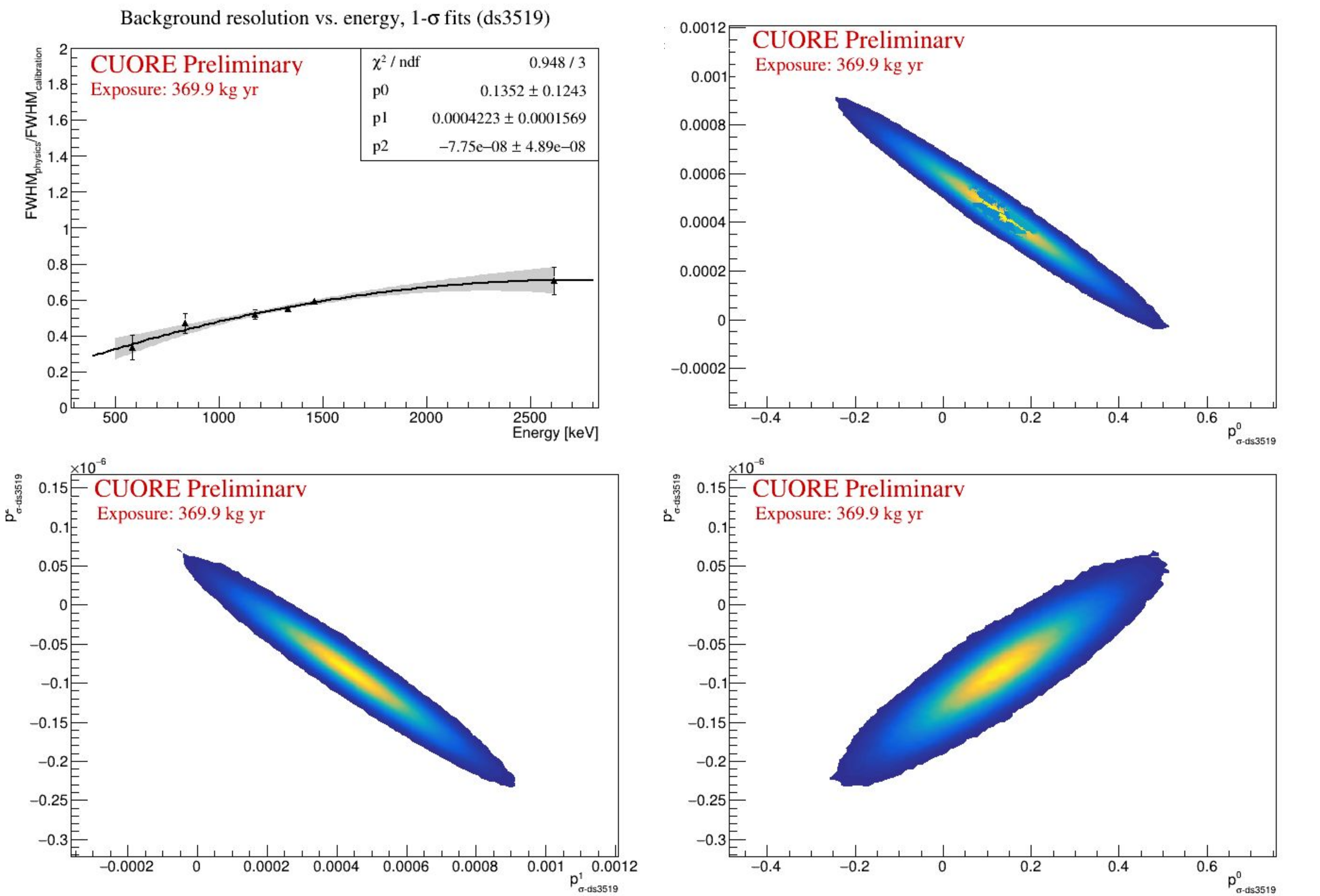
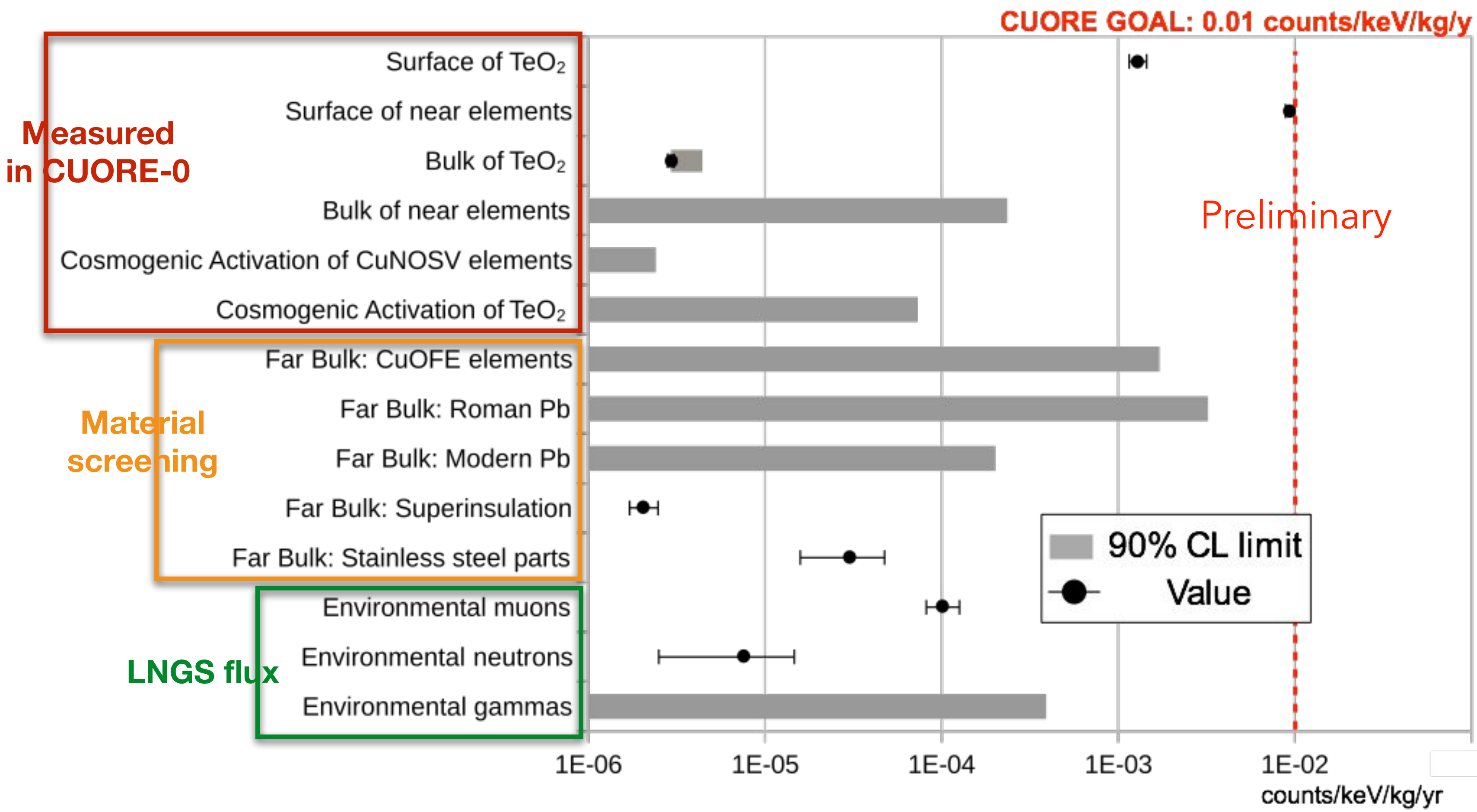


CUORE background budget

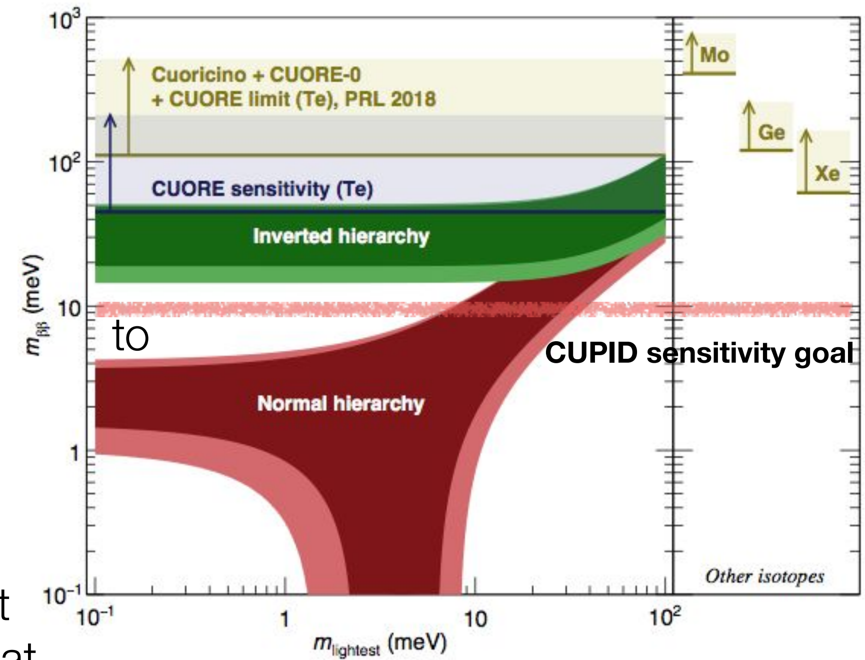


CUORE sensitivity and perspectives

CUORE 0νββ exclusion sensitivity in 5 years (90% C.L.):
$S_{0\nu} \sim 9 \times 10^{25}$ yr
with
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 $S_{0\nu} \sim 10^{27}$ yr, $m_{\beta\beta} \sim$ 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)



The CUORE challenge

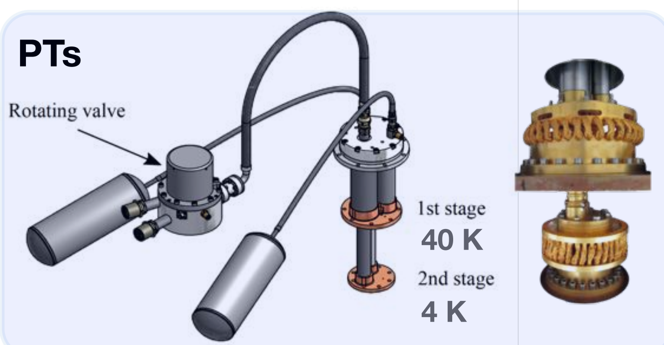
•Low temperature and low vibrations

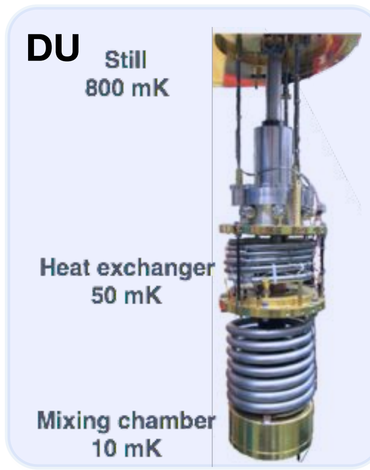
TeO_2 detectors to be operated as bolometers at temperature ~10 mK: need for cryogenic infrastructure

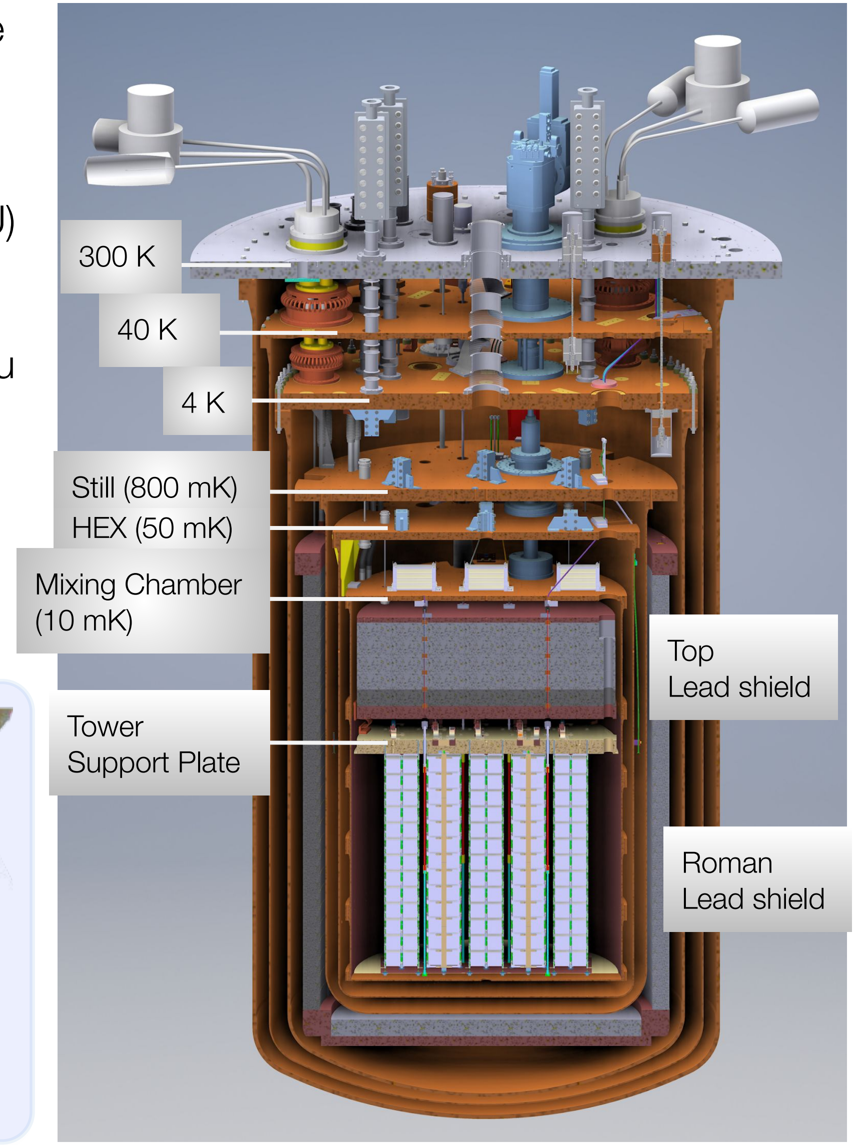
- •Multistage cryogen-free cryostat:
  Nested vessels at decreasing temperature
  Cooling systems: Pulse Tubes (PTs) and Dilution Unit (DU)
  -Mass to be cooled < 4K: ~ 15 tons (IVC volume and Cu vessels, Roman Pb shield)
  -Mass to be cooled < 50 mK: ~ 3 tons (Top Pb shield, Cu supports and TeO_2 detectors)
- Mechanical vibration isolation

  Reduce energy dissipation by vibrations

Target 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

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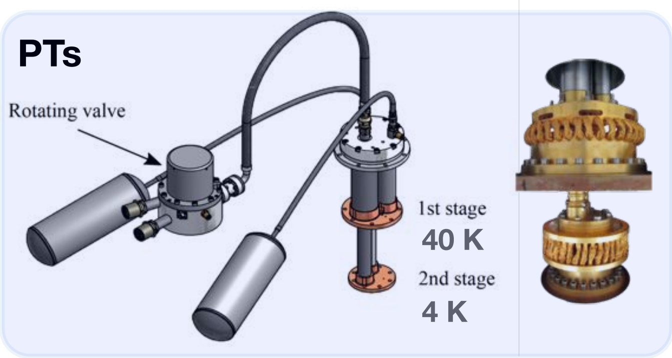
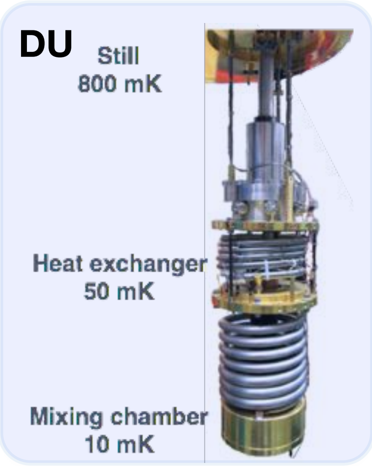
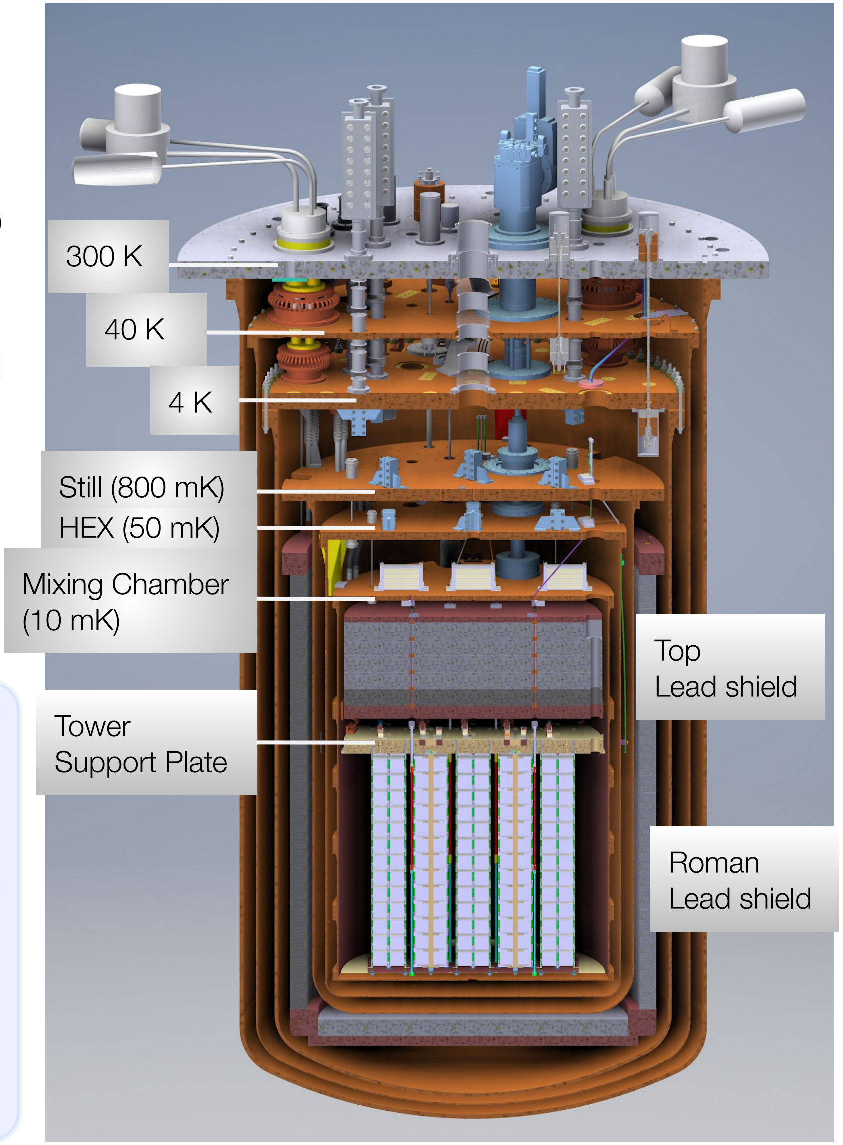




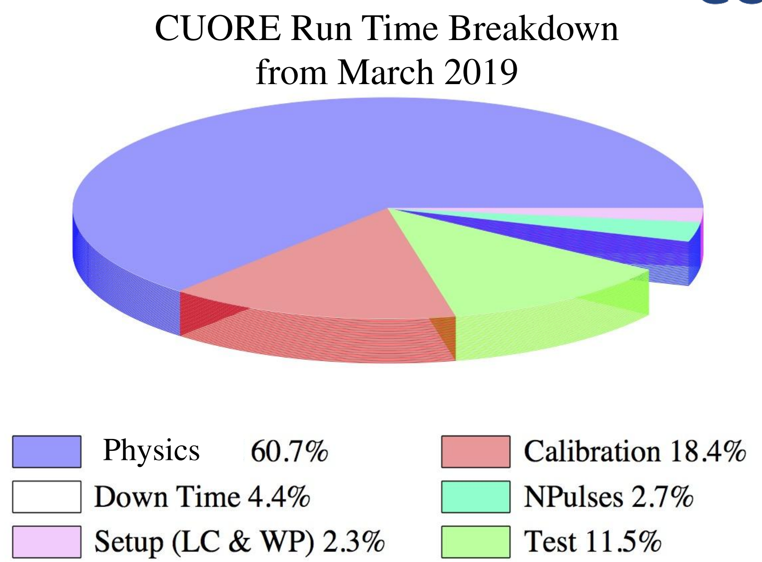


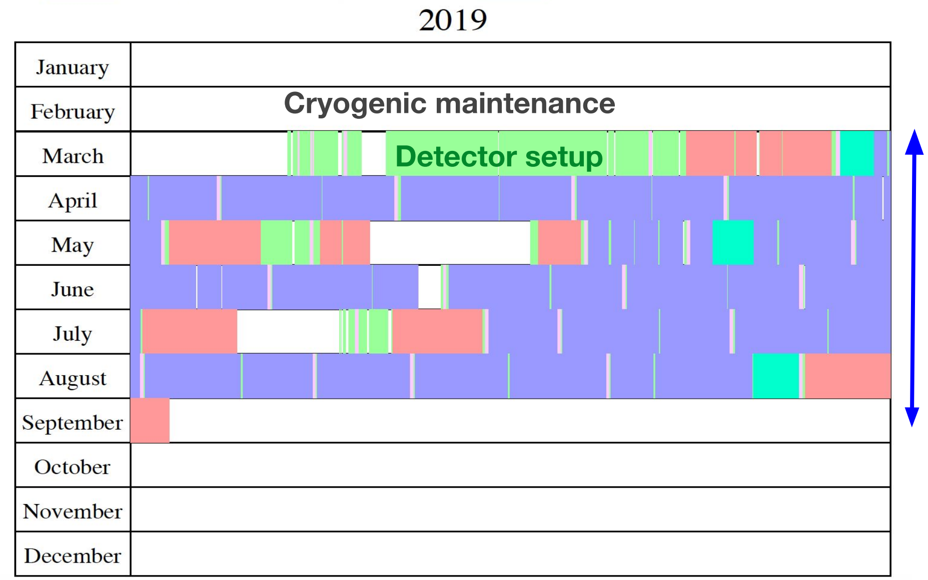
Dell'Oro S. et al., Cryogenics 102, 9, (2019)
https://doi.org/10.1016/j.cryogenics.2019.06.011

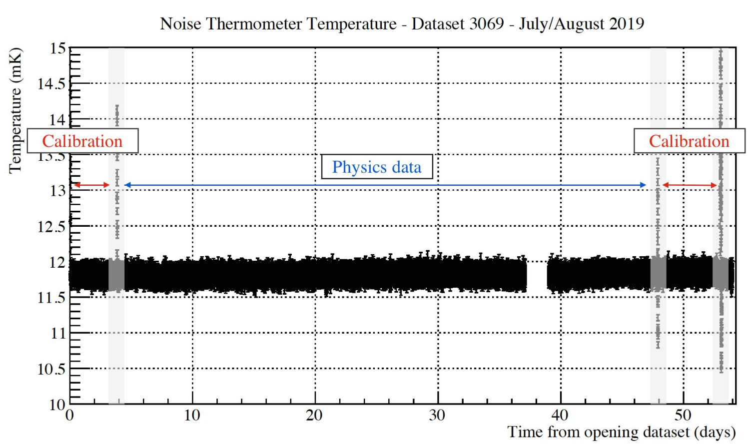
CUORE data taking

Data taking from March 2019 on

- **Reached stable data-taking with high duty cycle**
- Physics data bracketed by initial and final calibrations
- Calibration with EDCS
- Only short maintenance operations at dataset closure; checks for noise and thermal response consistency after the activities
- 3 complete consecutive datasets acquired, new dataset started in these days
- Priority is data taking - no further optimizations in the near future







Open questions about neutrinos

CUORE

- The Minimal Standard Model (MSM) assumes massless neutrinos; need to extend it to accommodate for massive neutrinos
- Neutrino mass hierarchy
- Neutrino mass absolute values
- Why neutrino mass is so small?
- Neutrinos are Dirac or Majorana particles?

Experimental searches:

- Neutrino flavor oscillation parameters precision measurements: Super-K, SNO, KamLAND, Daya Bay, T2K, NoVA
- Sum of neutrinos masses from cosmological and astrophysical data: PLANCK,…
- Direct neutrino mass measurement from β-decay spectral shape: KATRIN (3H), HOLMES and ECHO (163Ho)
- Majorana nature of neutrino via neutrinoless double beta decay: CUORE, GERDA, EXO-200, NEMO…; CUPID, LEGEND, Kamland-Zen, SNO+,…

Neutrinoless double beta decay: unique tool to probe the Majorana nature of neutrino