New results from the CUORE experiment

CUORE

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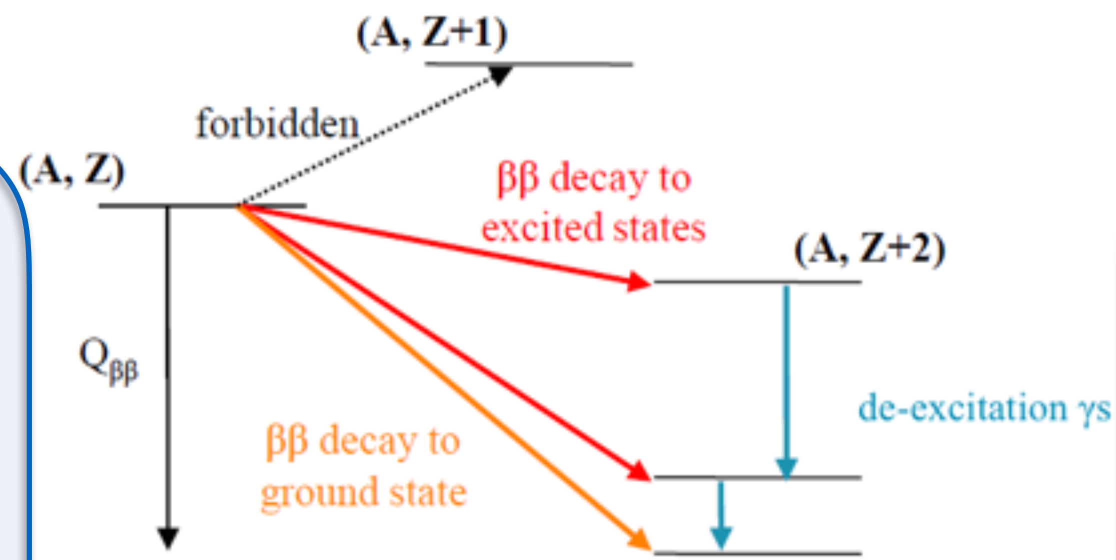
9th International Conference on New Frontiers in Physics (ICNFP 2020)
September 8th, 2020

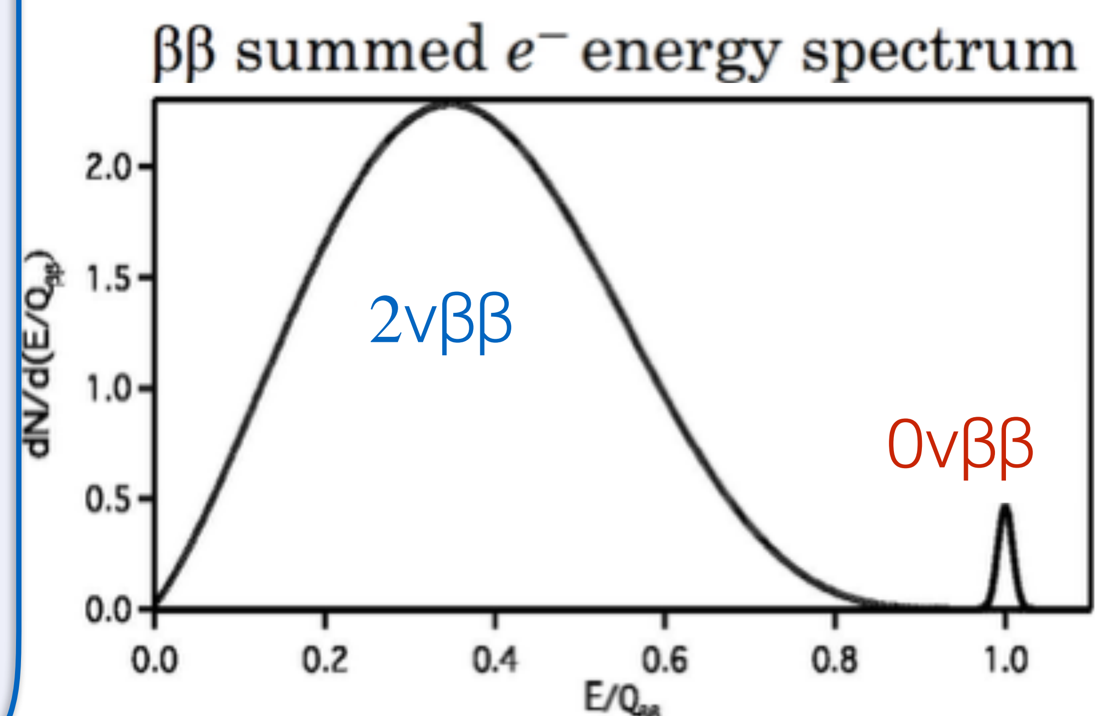
Outlook

- Double beta decay
- The CUORE experiment
- CUORE physics data taking
- New results from CUORE:
  - 0νββ decay search
  - 2νββ decay measurement and background
  - 0νββ/2νββ decay to excited states

Double beta decay

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

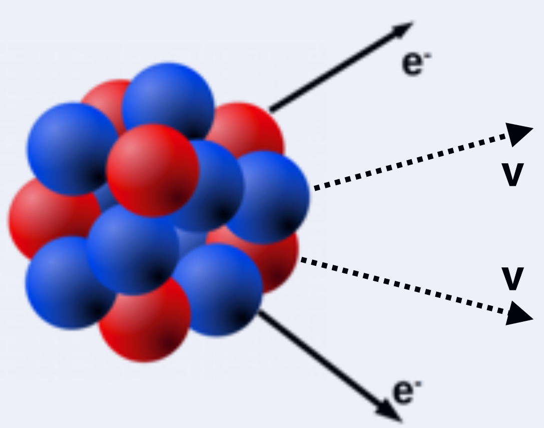




$Q_{\beta\beta}$ Q-value of the ββ decay

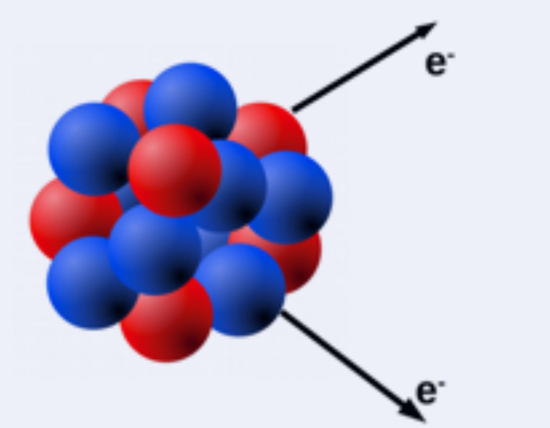
Two neutrino double beta decay (2νββ)

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



Neutrinoless double beta decay (0νββ)

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

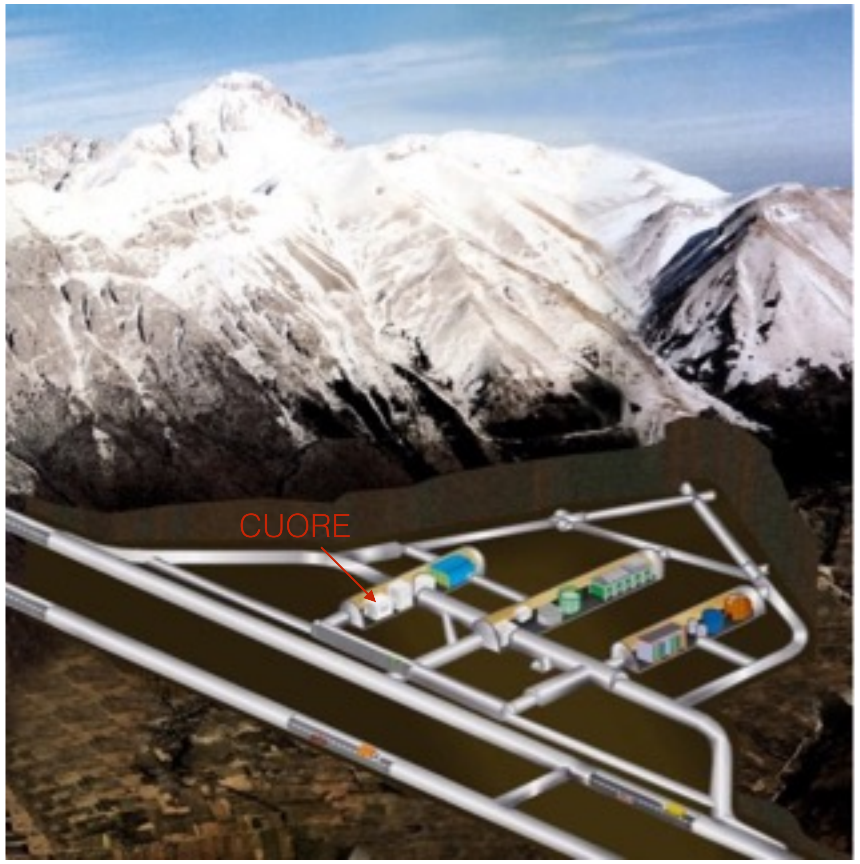


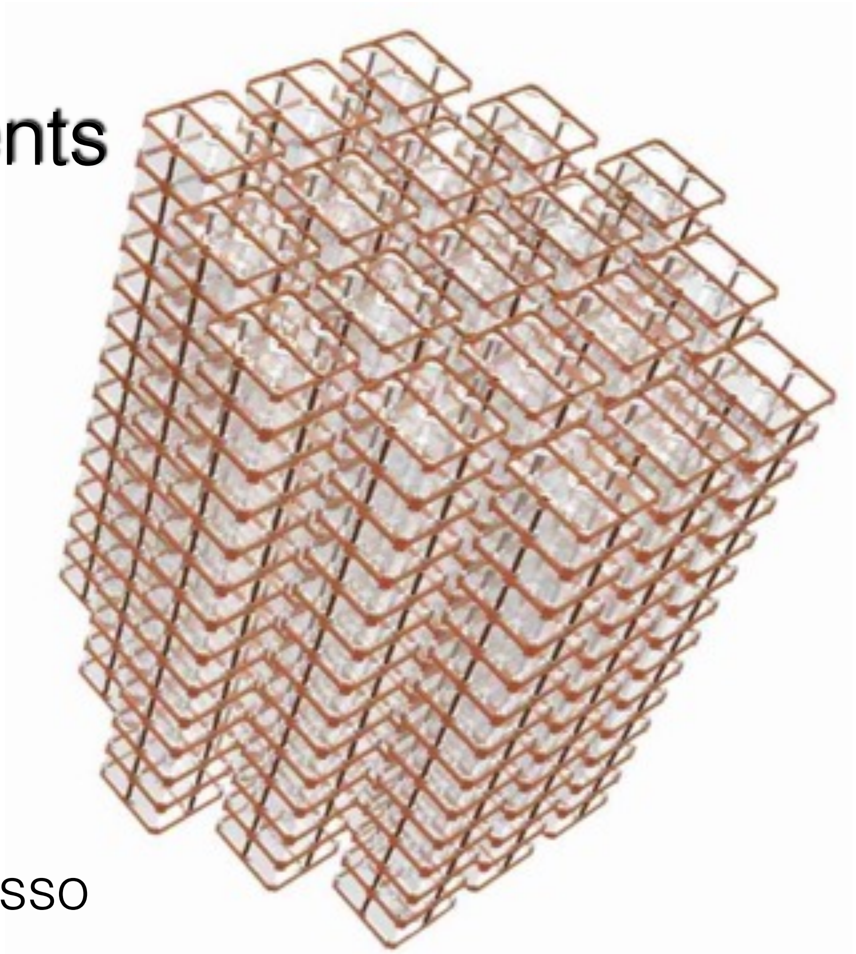
The CUORE experiment

CUORE:

Cryogenic Underground Observatory for Rare Events

Cryogenic experiment: ~1 ton solid state calorimeter
988 $^{(nat)}TeO_2$ crystals operated at ~10 mK
- large mass and high granularity -





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

Experiment located at
Laboratori Nazionali del Gran Sasso
(LNGS), Italy

Primary goal: search for $0\nu\beta\beta$ decay of ^{130}Te
CUORE $0\nu\beta\beta$ projected sensitivity:

$S_{0\nu} \sim 9 \times 10^{25}$ yr (90% C.L.) in 5 years
$m_{\beta\beta} < 50\text{-}130$ meV

The CUORE challenge

CUORE

- **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

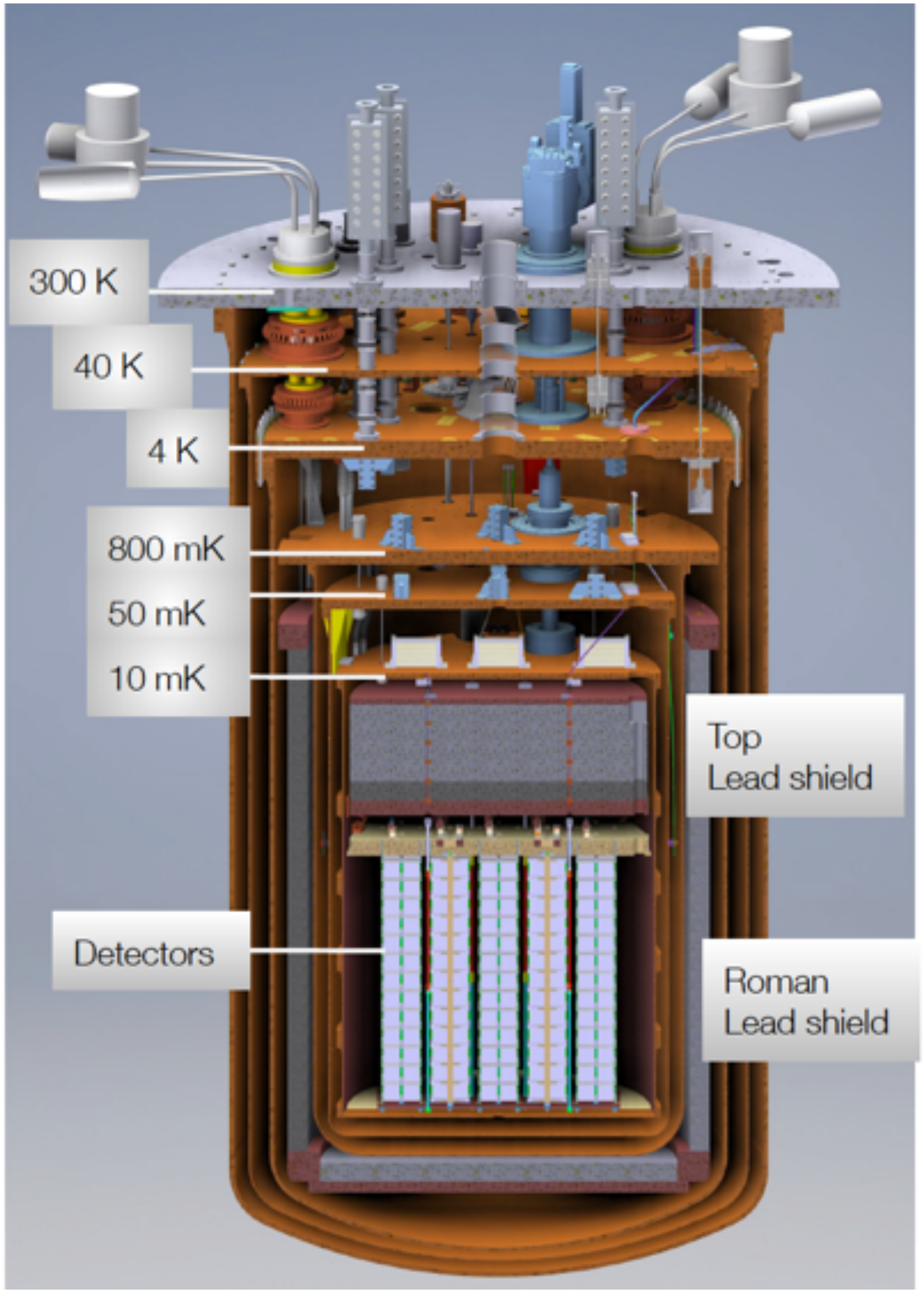
Background goal: 10^{-2} c/(keV·kg·yr)
in the Region Of Interest (ROI) around $Q_{\beta\beta}$

- **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:
  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 $Q_{\beta\beta}$



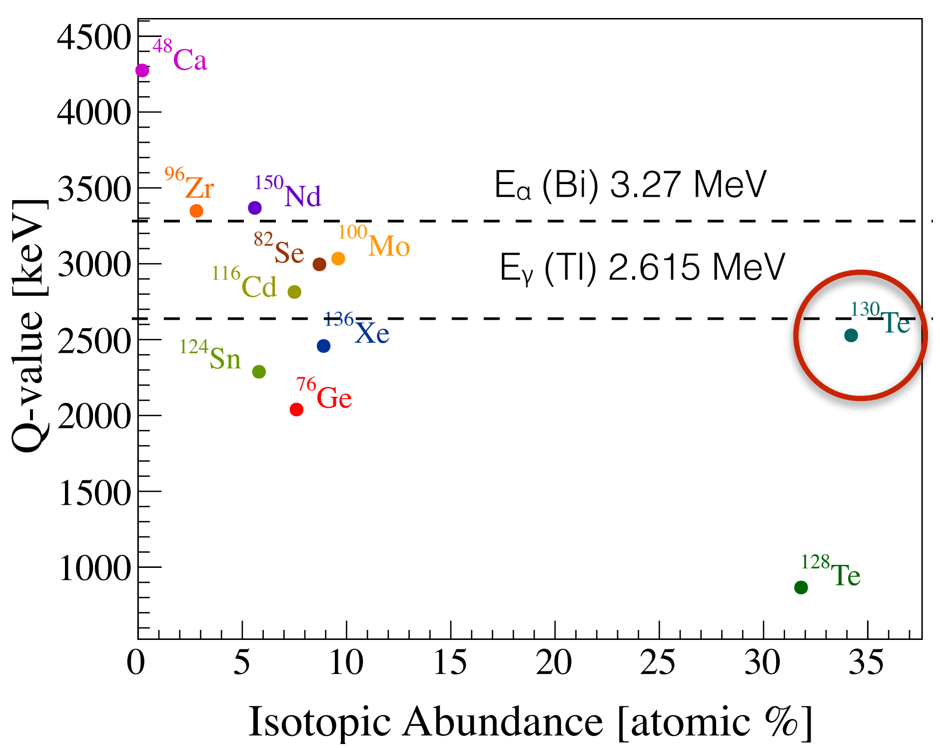
Dell'Oro S. et al., Cryogenics 102, 9, (2019)
https://doi.org/10.1016/j.cryogenics.2019.06.011

Double beta decay with TeO_2 bolometers

CUORE

Benefits of using $^{(nat)}TeO_2$ detectors:

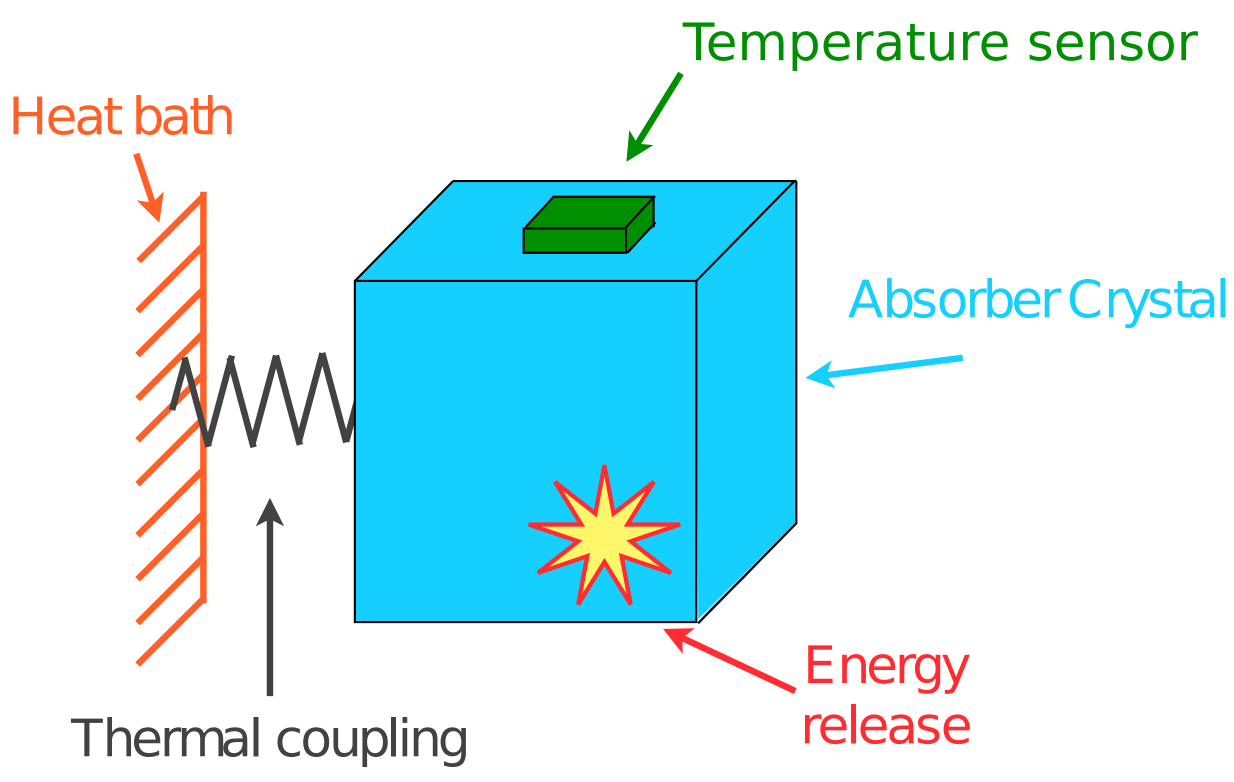
- **^{130}Te natural isotopic abundance η(^{130}Te) = 34.167%,** no need for further enrichment after the growth of natural crystals
- **$Q_{\beta\beta}$ (^{130}Te) = 2527.518 keV**, above most of the natural radioactivity
- **^{130}Te within the detector absorber of TeO_2** (ε ~ 90%)
- Reproducible growth of large number of high quality and high purity crystals; **large active mass detector** (crystals ~ 1kg, ~1000 crystals)
- TeO_2 operated as **low temperature detectors** (~10 mK): **very good energy resolution** Δ (~0.1-0.2% FWHM/E at **$Q_{\beta\beta}$**), allows a better reconstruction of the background spectrum and a reduction of 2νββ decay irreducible background around $Q_{\beta\beta}$



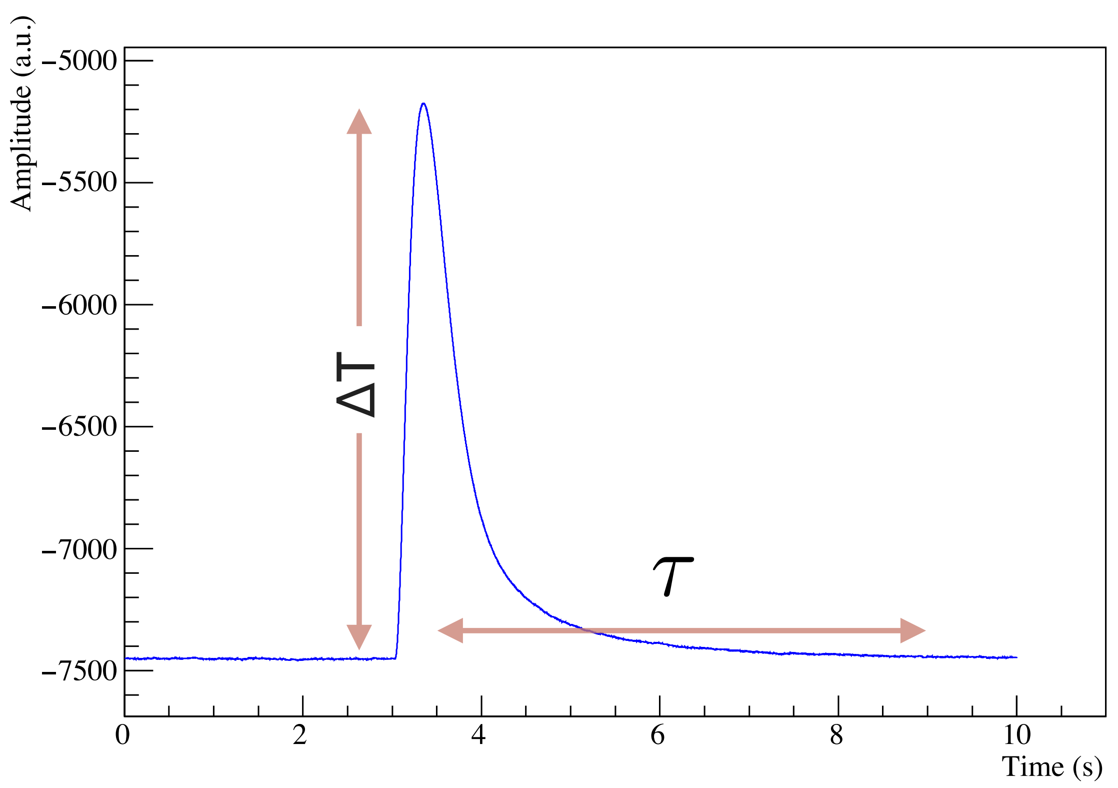
Artusa D.R. et al. (CUORE Collaboration), Adv. High Energy Phys. 2015,879871,(2015)
http://doi.org/10.1155/2015/879871

CUORE and the bolometric technique

CUORE TeO_2 detectors are operated as cryogenic bolometers **sensitive to 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:

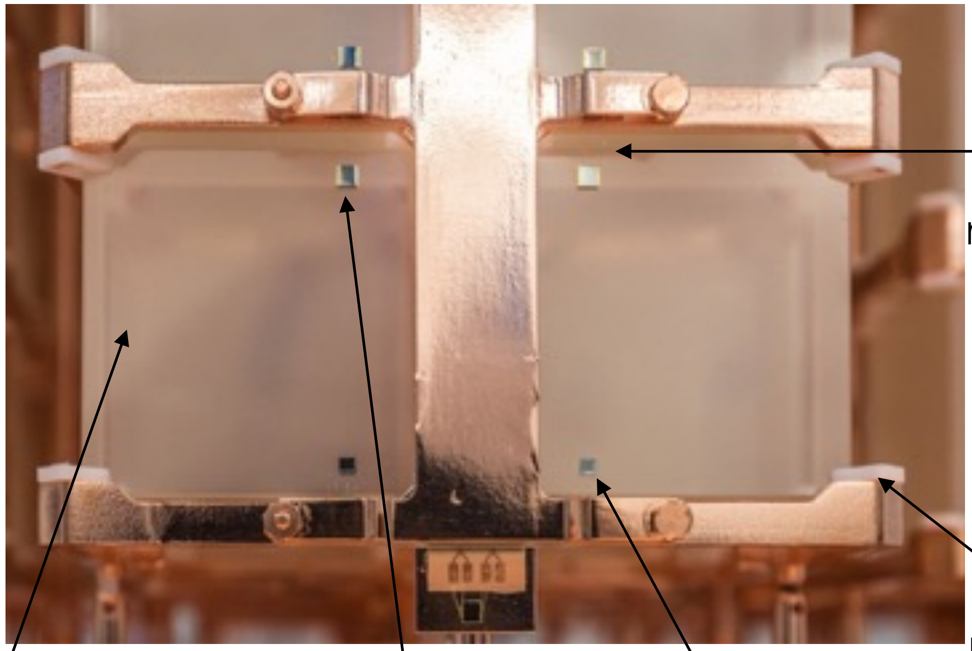
One thermal capacity C (crystal)
One thermal link G (btw crystal/heat bath)

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

Amplitude of the pulse ∝ ΔT ∝ Energy deposition

The CUORE detector

CUORE instrumented bolometers



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)

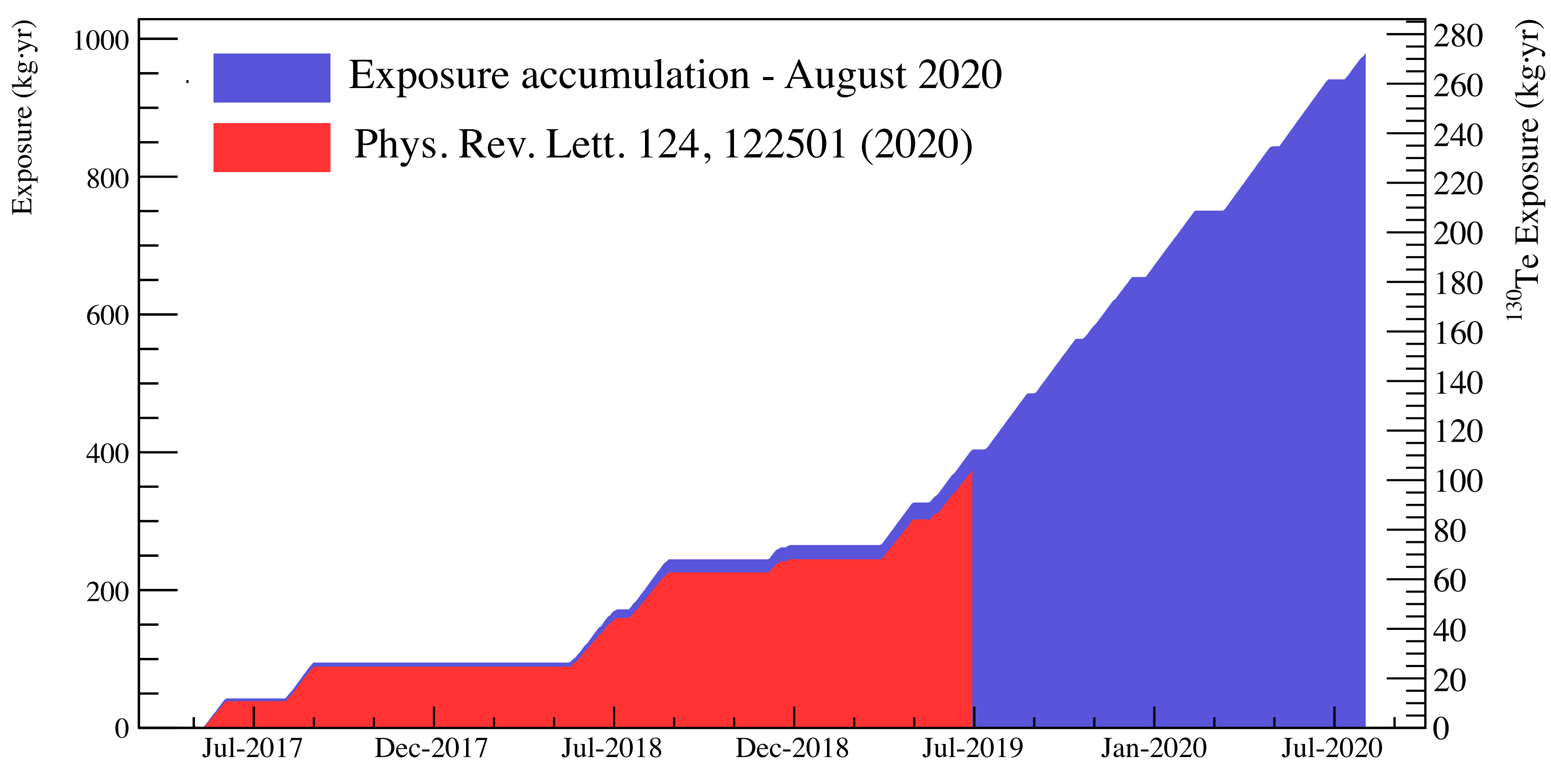
Alduino C. et al. (CUORE collaboration), J. Inst. 11(07), P07009, (2016)
https://doi.org/10.1088/1748-0221/11/07/p07009

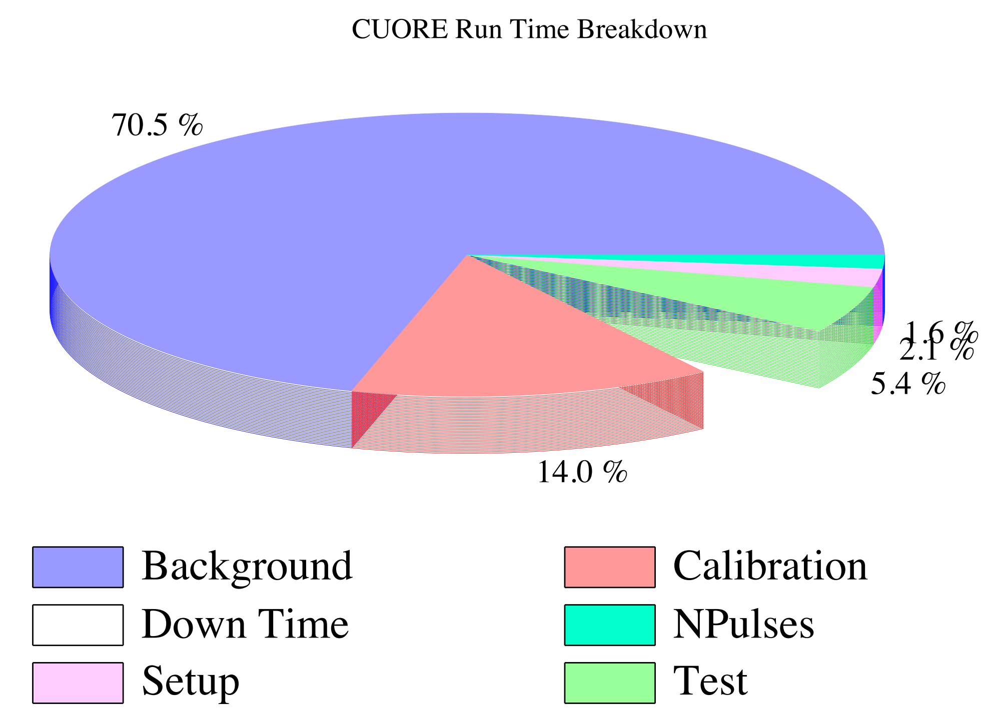
CUORE data taking

- Data taking started in Spring 2017
- After initial data taking phase, significant effort devoted to understanding the system and optimizing data taking conditions
- Since March 2019 data taking is continuing smoothly with > 90% uptime
- CUORE “data set”: ~1 month of background data taking with a few days of calibration at the start and end

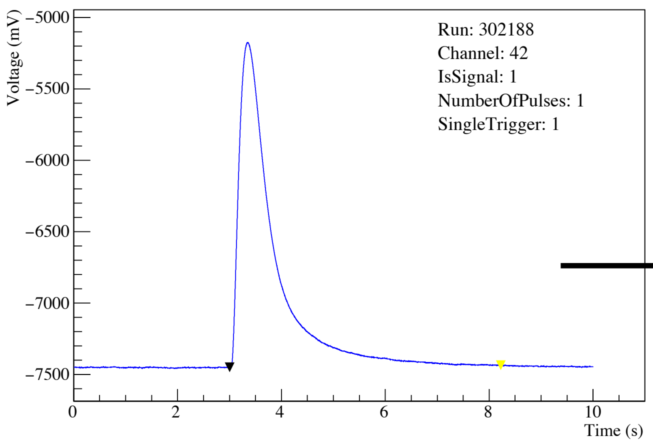
CUORE preliminary

Reached 1 ton yr of raw exposure!

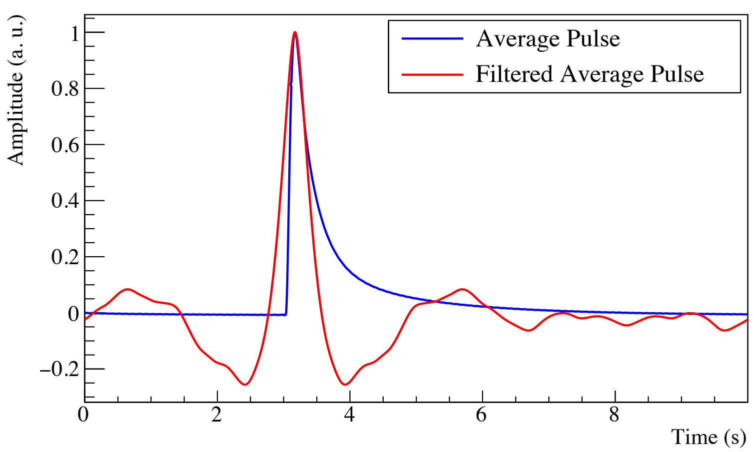


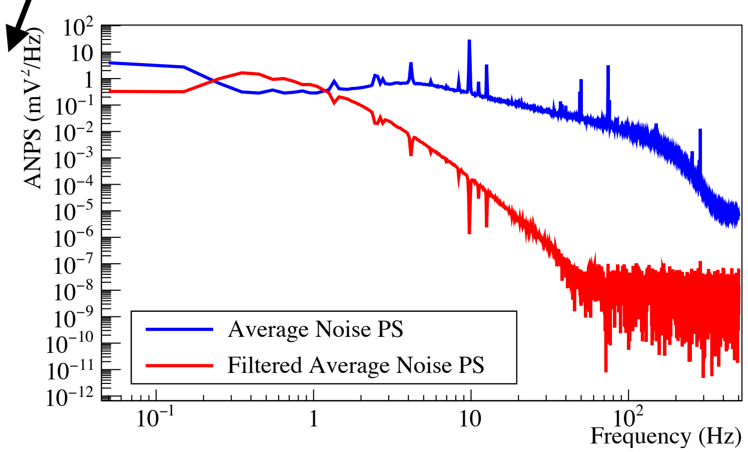


CUORE data processing

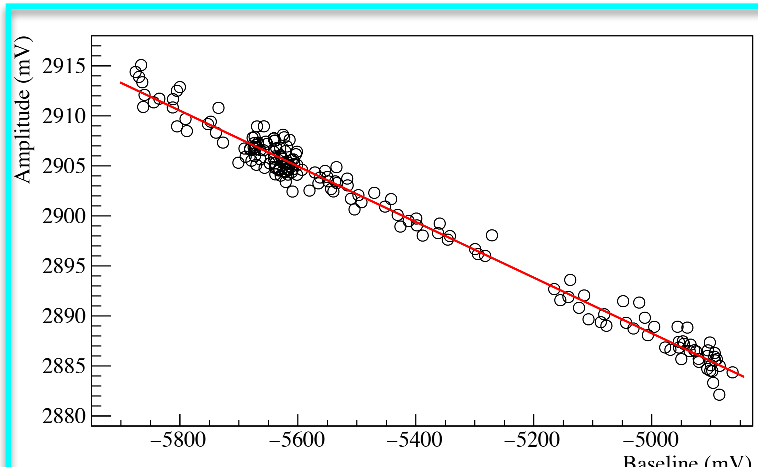


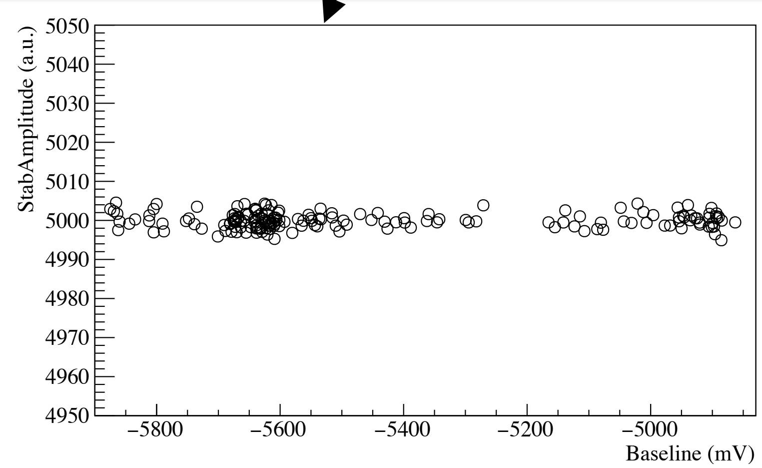
Optimum Filter → Gain Correction → Energy Calibration → Coincidences



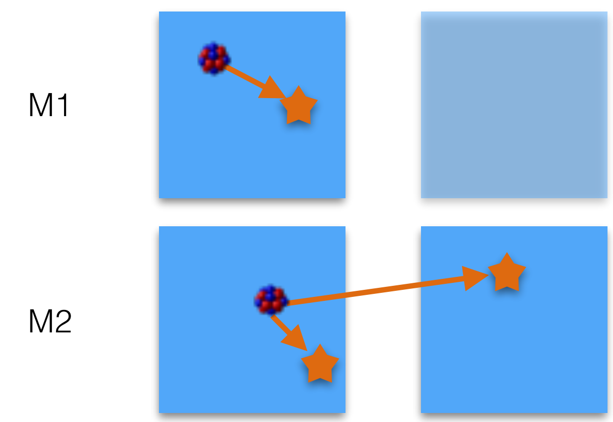


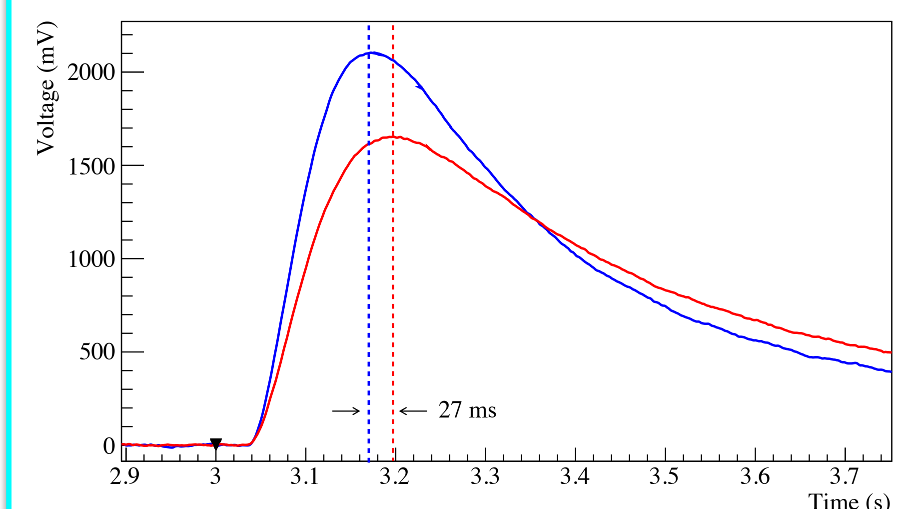
Matched filter that maximizes the signal-to-noise ratio





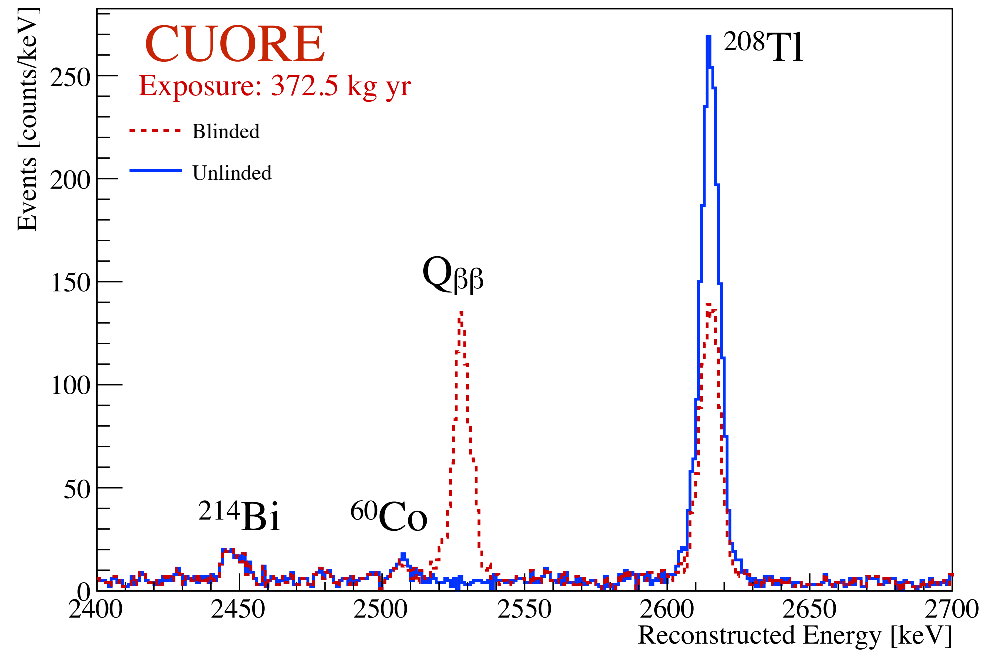
Heater pulses for thermal gain stabilization



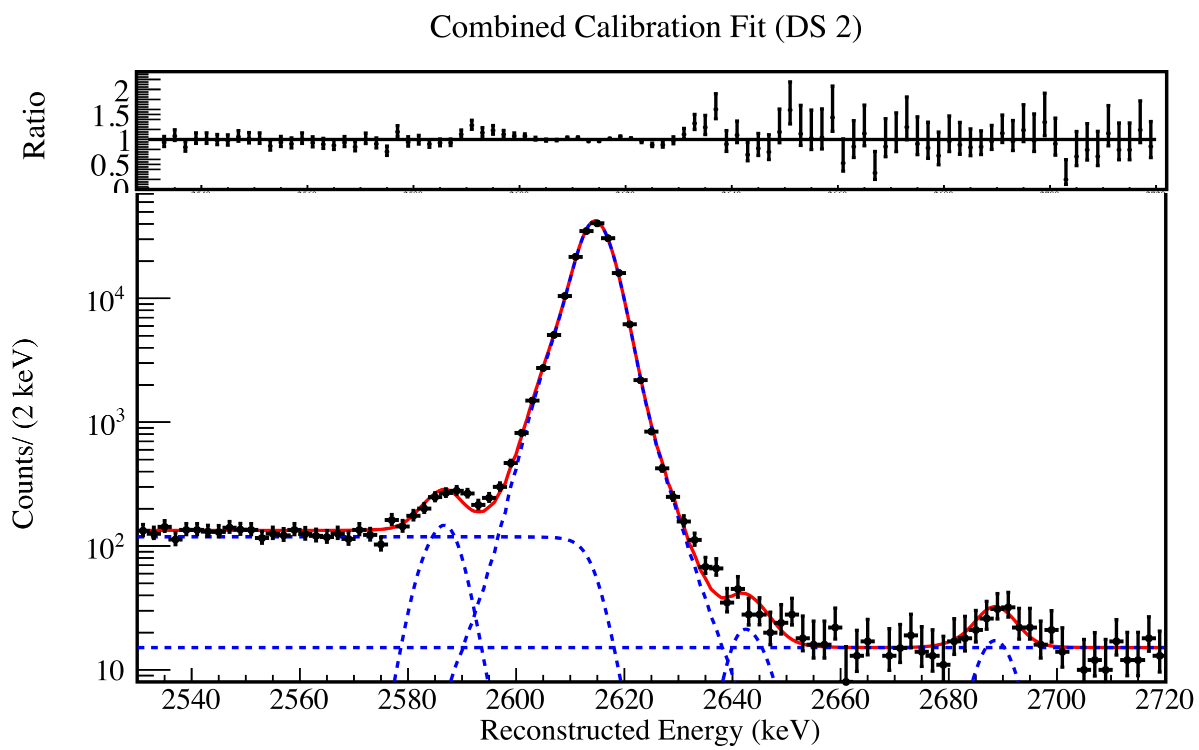


New results from CUORE: 0νββ analysis

Total exposure for 0νββ decay search (PRL2020)
372.5 kg yr $^{nat}TeO_2$, ^{130}Te exposure: 103.6 kg yr
(After analysis selections)



- **Blinding of the background spectrum**: optimization of analysis procedures and selections
- Event selection is performed after discarding periods of low quality data (about 1% of live time)
- Detector response function built on the 2615 keV calibration line. Apply a scaling factor to obtain the correct **energy resolution at $Q_{\beta\beta}$:(7.0 ± 0.4) keV FWHM**
- Containment efficiency for a 0νββ decay to be single site event (evaluated via MC) - (88.350 ± 0.090)%
- Selection efficiencies (evaluated on data): trigger, energy reconstruction, pile-up rejection, multiplicity, PSA - (87.54 ± 0.17)%



Alduino C. et al. (CUORE collaboration), Phys. Rev. Lett. 122, 122501, (2020), https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.122501

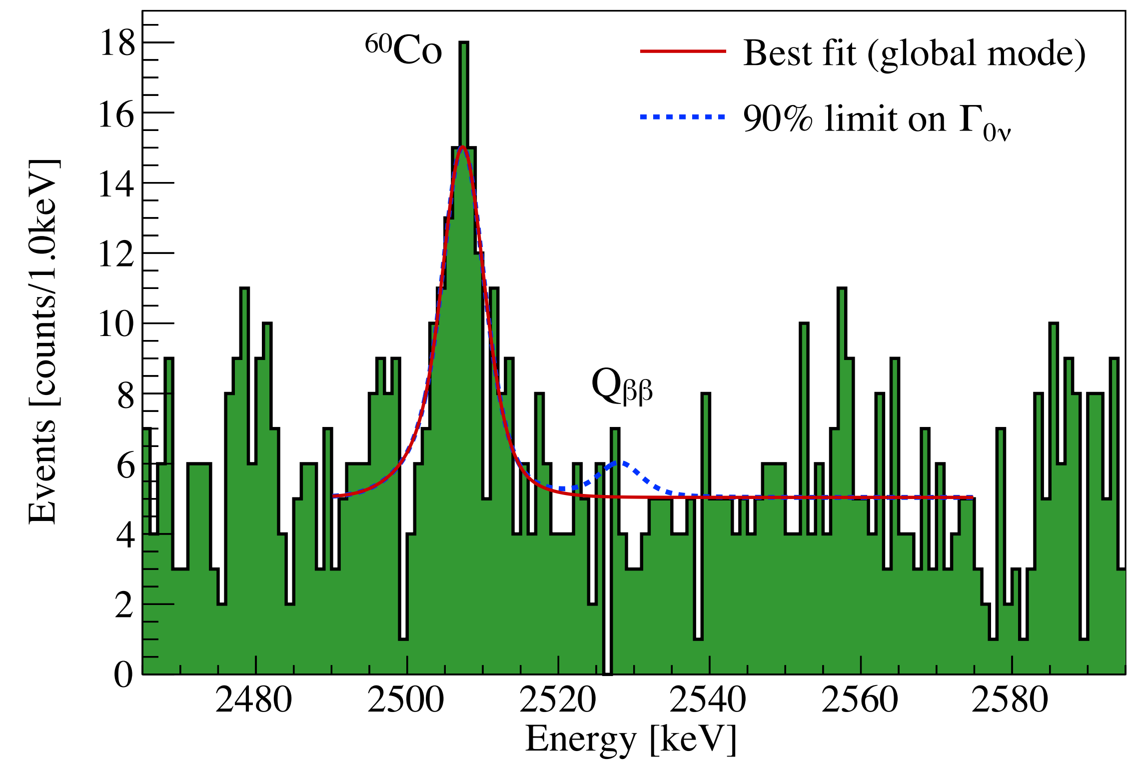
New results from CUORE: 0νββ analysis

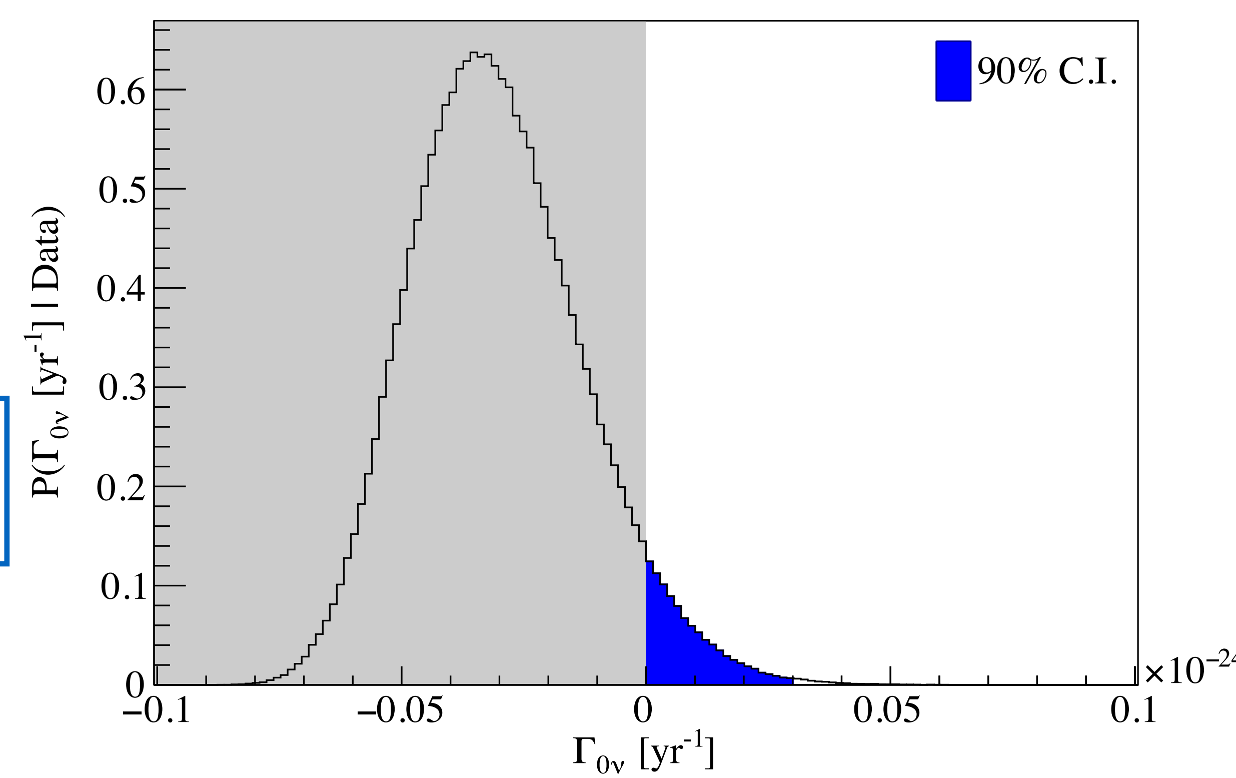
0νββ peak search

- Unblinded data:
  - Bayesian Analysis (BAT)
  - Likelihood model: flat continuum (BI), posited peak for 0νββ (rate), peak for 60Co (rate + position)
  - Unbinned fit in ROI [2490,2575 keV] on physical range (rates non-negative), uniform prior on $\Gamma_{0\nu}$
  - Systematics: repeat fits with nuisance parameters, allow negative rates (<0.4% impact on limit)

No evidence of signal.
Posterior of $\Gamma_{0\nu}$: extract an upper limit on decay rate.

Half-life limit for 0νββ in ^{130}Te
$T_{0\nu}^{1/2}$ (^{130}Te) > 3.2 × 10^{25} yr (90%C.I including syst.)





Alduino C. et al. (CUORE collaboration), Phys. Rev. Lett. 122, 122501, (2020), https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.122501

New results from CUORE: 0νββ analysis

Repeating the fit in the ROI, without the 0νββ decay contribution

ROI background index (B) = (1.38 ± 0.07) × 10^{-2} c/(keV·kg·yr)

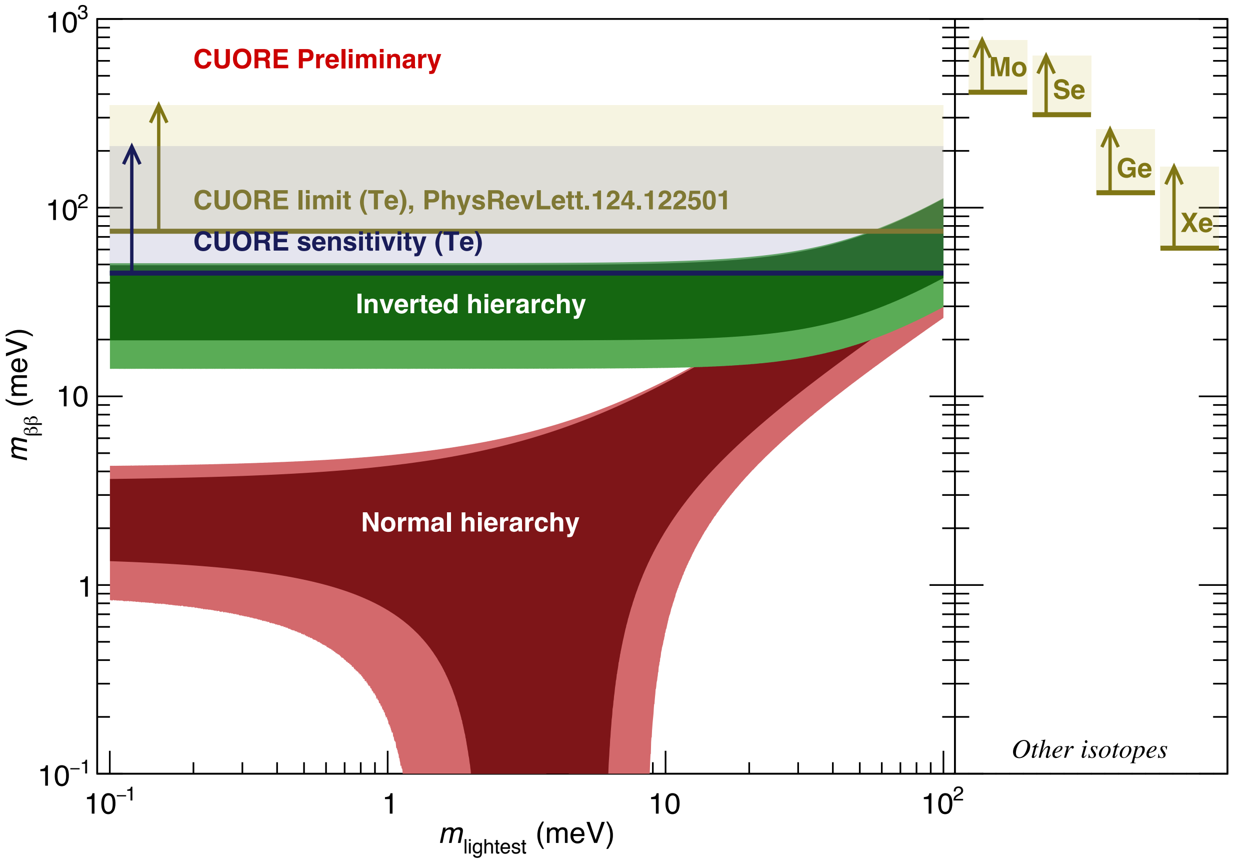
Exclusion sensitivity for 0νββ decay:

Generate pseudo-experiments with bkg-only hypothesis, fit the ROI with bkg+signal hypothesis

CUORE median exclusion sensitivity on ^{130}Te halflife: $T_{0\nu}^{1/2}$ (^{130}Te) = 1.7 × 10^{25} yr

Probability to get a more stringent limit given the current sensitivity: 3.2%.

Limit on 0νββ decay half life and interpretation in context of light Majorana neutrino exchange:
$m_{\beta\beta}$ < 75 - 350 meV at 90% C.I.



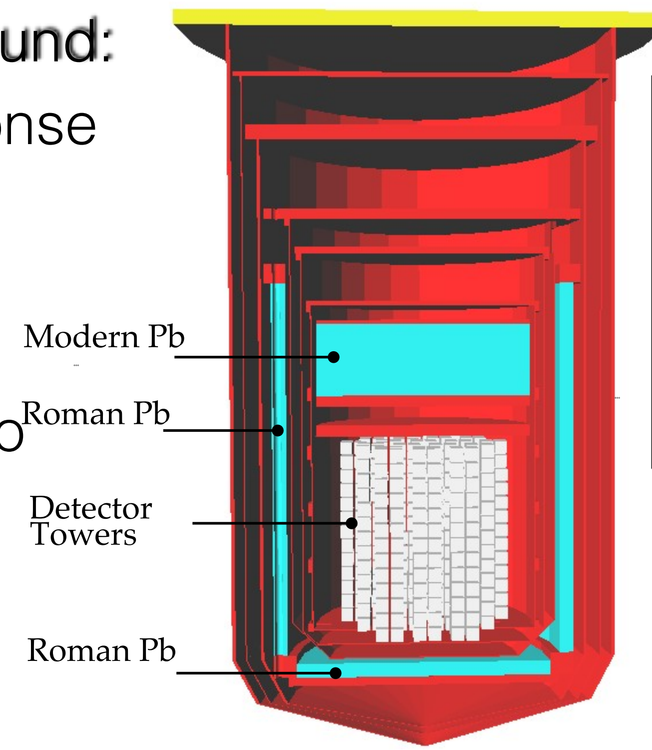
Alduino C. et al. (CUORE collaboration), Phys. Rev. Lett. 122, 122501, (2020), https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.122501

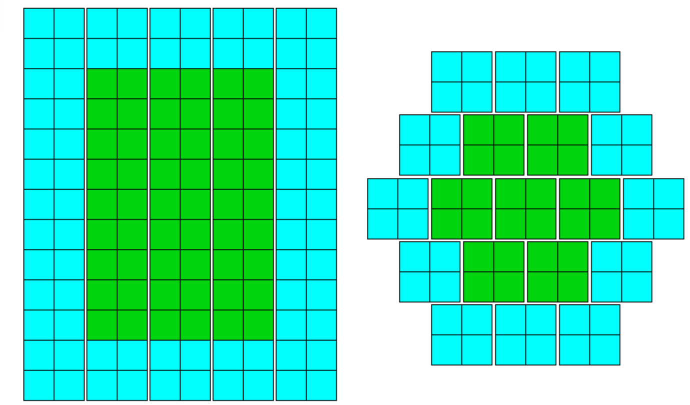
New results from CUORE: 2νββ decay

Reconstruction of the CUORE continuum background:

- GEANT4 simulation + measured detector response function to produce expected spectra
- 61 background sources simulated, bayesian MCMC fit with uniform priors (except muons)
- Exploit coincidences & detector self-shielding to constrain location of sources

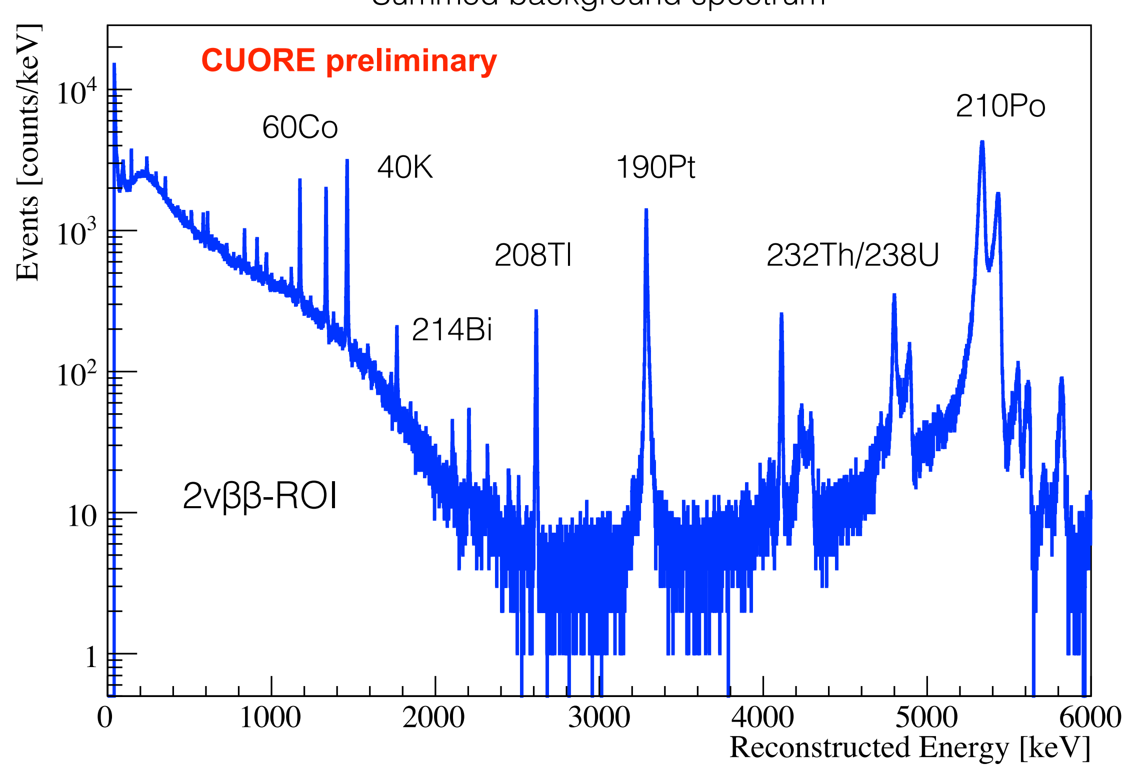
Total exposure for 2νββ analysis: 300.7 kg yr



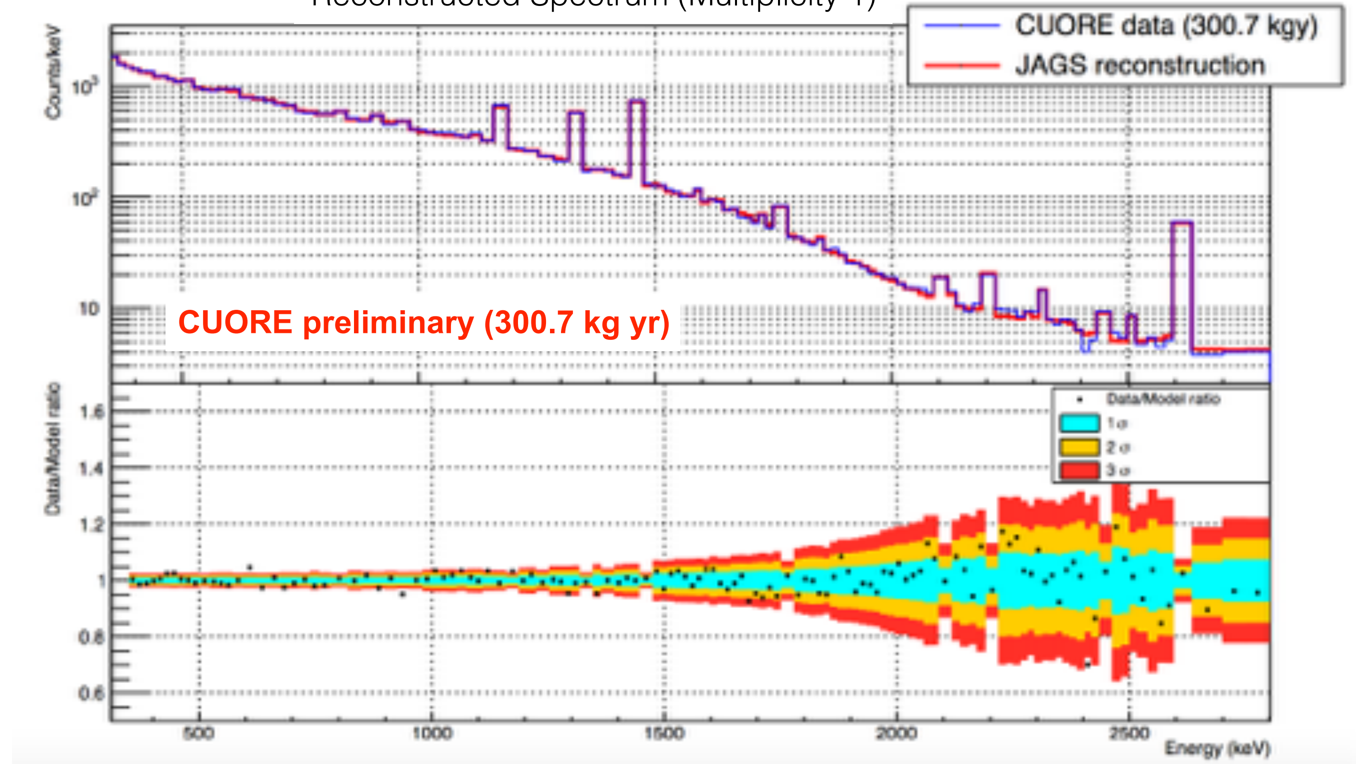


Adams, D. Q. et al. (CUORE Collaboration),"Update on the recent progress of the CUORE experiment" arXiv:1808.10342, (2018)

Summed background spectrum



Reconstructed Spectrum (Multiplicity 1)



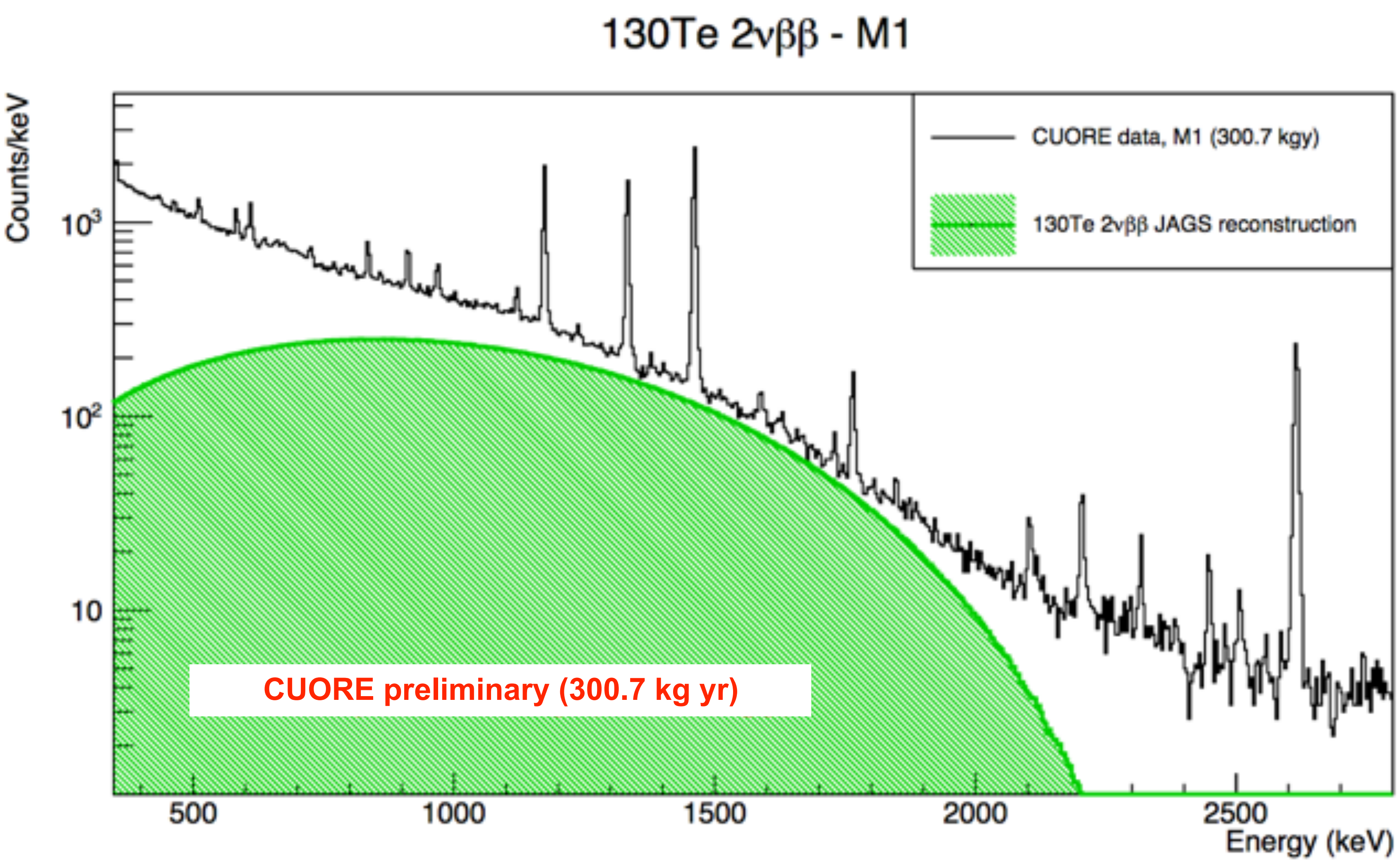
“CUORE Results and the CUPID Project” at Neutrino 2020 conference, https://indico.fnal.gov/event/43209/contributions/187866/attachments/129542/159294/CUORE_CUPID_Nu2020.pdf

Paper in preparation

New results from CUORE: $2\nu\beta\beta$ decay

$2\nu\beta\beta$ decay: dominant component of the observed M1 spectrum between ~ 1 to 2 MeV, due to reduced γ backgrounds and self shielding of outer TeO_2 towers

Measurement of the $2\nu\beta\beta$ half-life of ^{130}Te
$T_{2\nu}^{1/2}$ (^{130}Te) = [7.71 $^{+0.08}_{-0.06}$(stat) $^{+0.17}_{-0.15}$(syst)] x 10^{20} yr



Systematic uncertainties:
- Data selection: geometric splitting, time splitting, fit range
- Choice of $2\nu\beta\beta$ spectrum (SSD vs HSD)
- Unconstrained fallout products (90Sr)

"CUORE Results and the CUPID Project" at Neutrino 2020 conference, https://indico.fnal.gov/event/43209/contributions/187866/attachments/129542/159294/CUORE_CUPID_Nu2020.pdf

Paper in preparation

New results from CUORE: excited states

CUORE

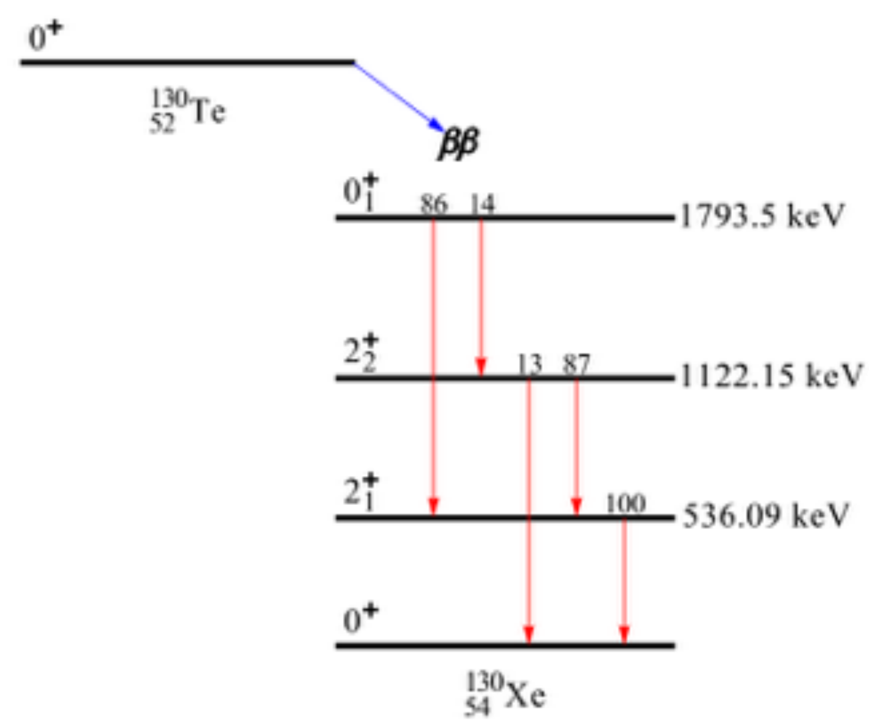
Search for 0νββ and 2νββ decays of ^{130}Te to the first 0^+ excited state of ^{130}Xe

- Double beta decay can proceed also through transitions to the various excited states of the daughter nucleus
- 2νββ decay to the 0^+ excited state observed in ^{100}Mo and ^{150}Nd, with half lives of the order of few 10^{20} yr
- Previous attempts of measuring the ββ decay of ^{130}Te to the first 0^+ excited state of ^{130}Xe made by both CUORICINO and CUORE-0:
  $(T^{1/2})^{0\nu}{}_{0+} > 1.4 \times 10^{24}$ yr (90% C.L.), $(T^{1/2})^{2\nu}{}_{0+} > 2.5 \times 10^{23}$ yr (90% C.L.)

Signature of the decay:

Cascade of de-excitation γs in coincidence with βs

- multi-site signatures
- background reduction with respect to the corresponding transitions to the ground state, especially in case of a high detector granularity



Pattern	BR [%]	Energy γ_1	Energy γ_2	Energy γ_3
A	86%	1257 keV	536 keV	-
B	12%	671 keV	586 keV	536 keV
C	2%	1122 keV	671 keV	-

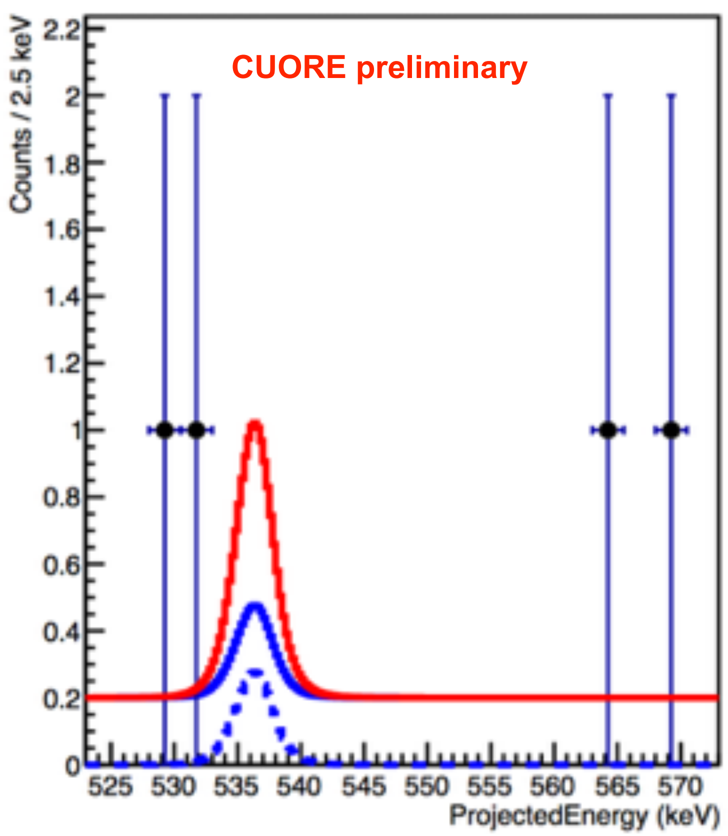
New results from CUORE: excited states

Considering only fully contained events for the analysis

Experimental signatures considered for the analysis:
- 2A0-2B1: Multiplicity 2, crystal1= ββ + γ(536) & crystal2 = γ(1257)
- 2A2-2B3: Multiplicity 2, crystal1= γ(536) & crystal2 = ββ + γ(1257)
- 3A0: Multiplicity 3, crystal1= ββ & crystal2= γ(536) & crystal3 = γ(1257)

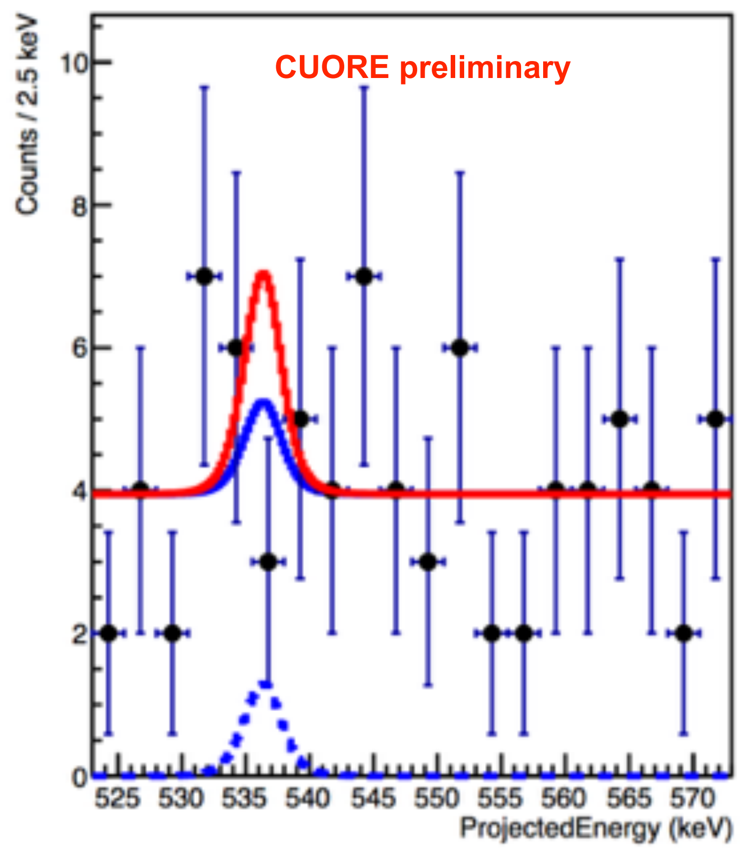
These are the signatures which contribute the most to the discovery sensitivity in the ββ decay rate

0νββ, sig. 2A2-2B3



crystal1 ~ E in[523, 573], γ (536)
crystal2 ~ E in[1981, 2001], ββ (734) + γ (1257)

2νββ, sig. 2A2-2B3



crystal1 ~ E in[523, 573], γ (536)
crystal2 ~ E in[1360, 1990], ββ (0-734) + γ (1257)

No evidence of signal for both 0νββ and 2νββ decays of ^{130}Te to ^{130}Xe 0^+ excited state

0νββ:
$(T^{1/2})^{0\nu}_{0+} > 5.9 \times 10^{24}$ yr (90% C.I.)

2νββ:
$(T^{1/2})^{2\nu}_{0+} > 1.3 \times 10^{24}$ yr (90% C.I.)

"CUORE Results and the CUPID Project" at Neutrino 2020 conference, https://indico.fnal.gov/event/43209/contributions/187866/attachments/129542/159294/CUORE_CUPID_Nu2020.pdf

Paper in preparation

Conclusions

CUORE

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

- New CUORE physics results of ^{130}Te $0\nu\beta\beta$ and $2\nu\beta\beta$ decays to ground and excited states with the physics data collected in 2017-2019
- A raw exposure of ~ 1 ton yr has been achieved and data-taking is proceeding, updated results for 1 ton yr total exposure (after analysis cuts) will be released soon!
- The CUORE data taking is currently underway to collect 5 years of run time
- Important feedback from CUORE operations for the future CUPID project (CUORE Upgrade with Particle IDentification)

Thank you on behalf of The CUORE collaboration

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UCLA

SINAP

University of South Carolina

CUORE

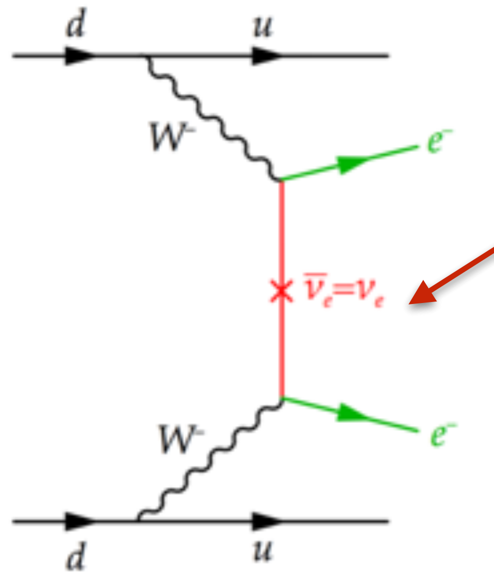
Backup

Neutrinoless double beta decay

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

- Lepton number violation
- presence of a Majorana term for the neutrino mass
- Constraints on neutrino mass hierarchy and scale

0νββ favorite 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

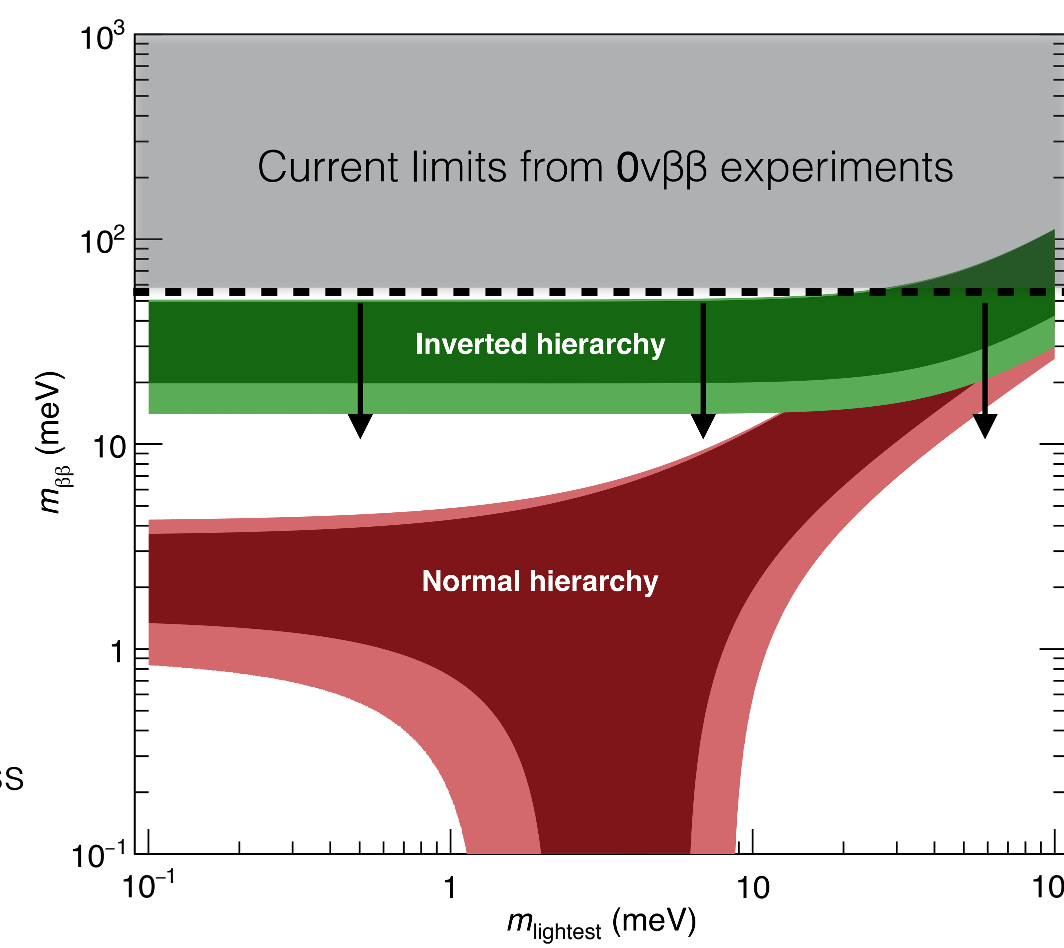
$$\frac{1}{T_{1/2}^{0\nu}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2 |m_{\beta\beta}|^2$$

Phase space integral

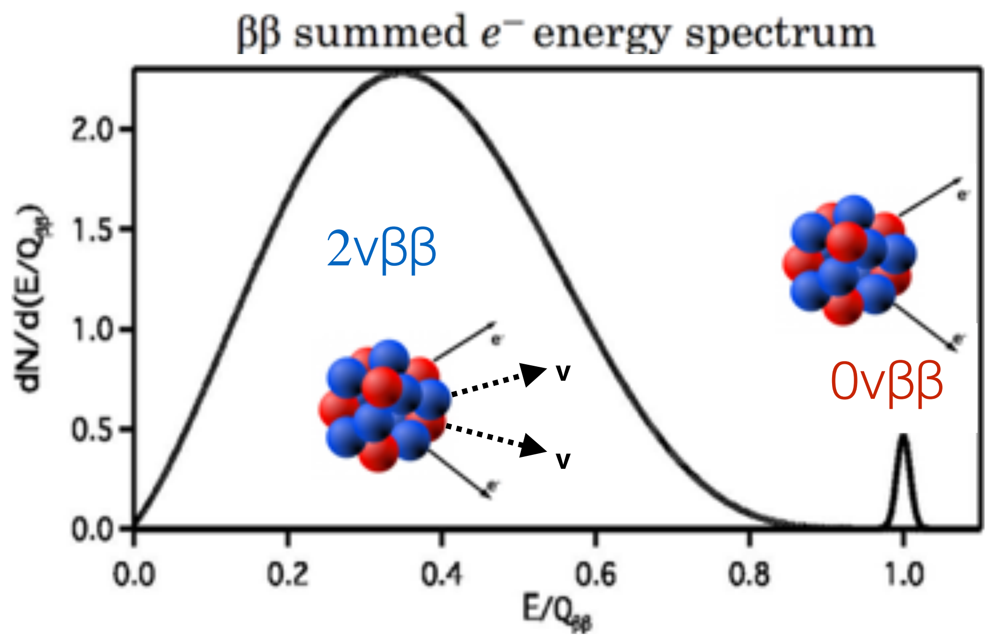
Nuclear matrix element (NME)

Effective neutrino mass term

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



Neutrinoless double beta decay



Experimental 0νββ half-life sensitivity

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

Finite background

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

Detector performance
- extremely low background
- excellent energy resolution

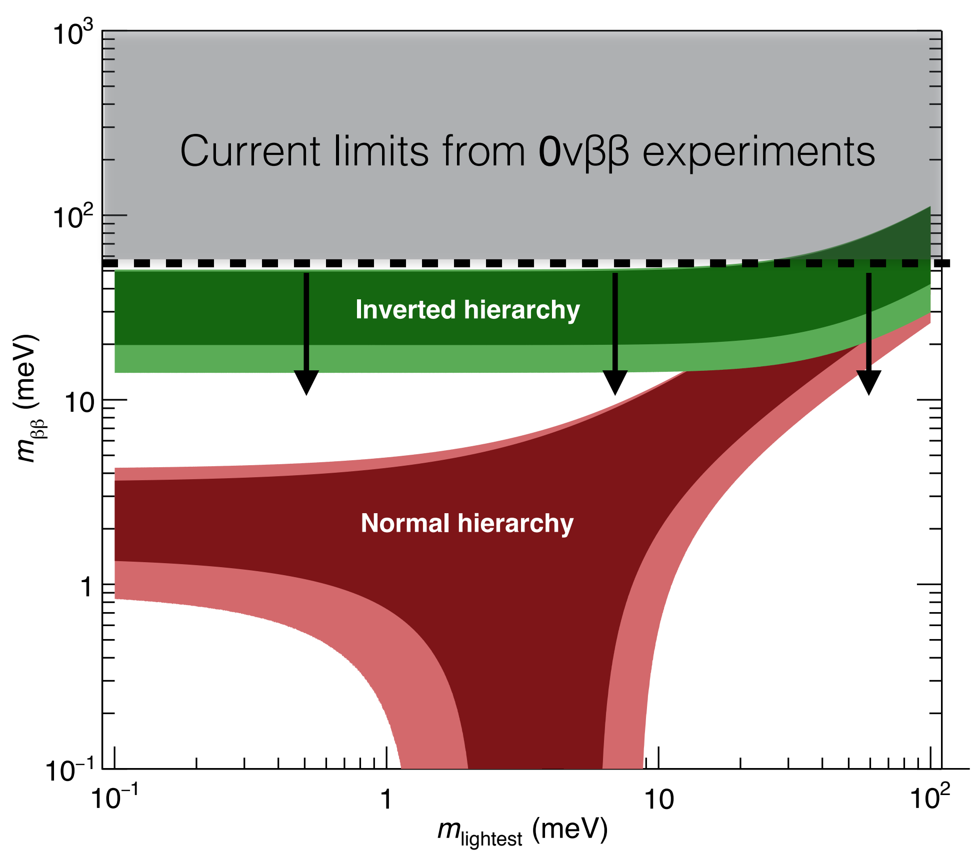
Detection technology
- Good detection efficiency: ββ source embedded into the absorber

Isotope choice
- High isotopic natural abundance or enrichment

Background free (B · Δ << 1)

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

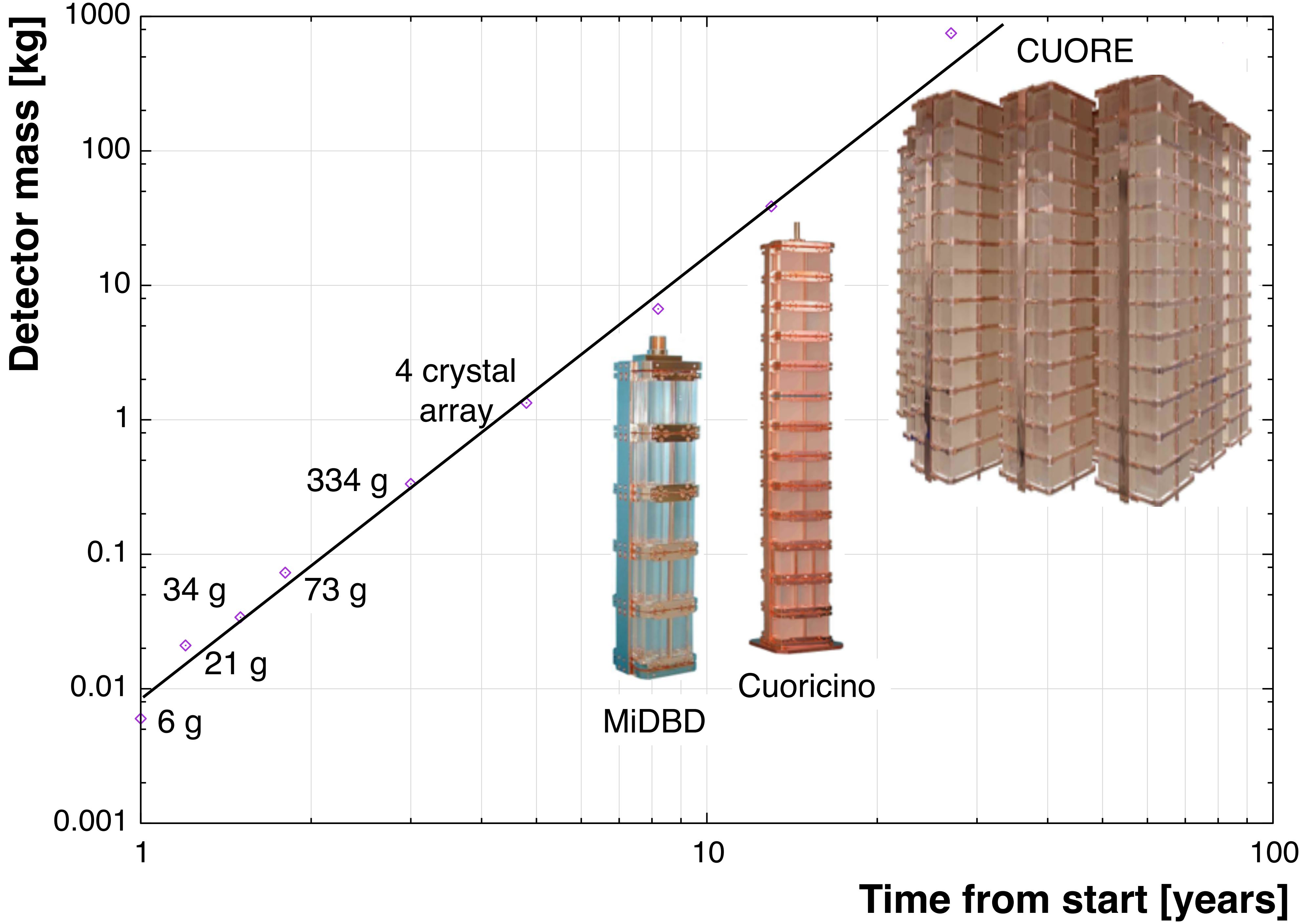
Exposure
- Large active mass (M) detector
- Long live-time



0νββ favorite mechanism:
Light Majorana neutrino exchange

The CUORE detector

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



CUORE optimization

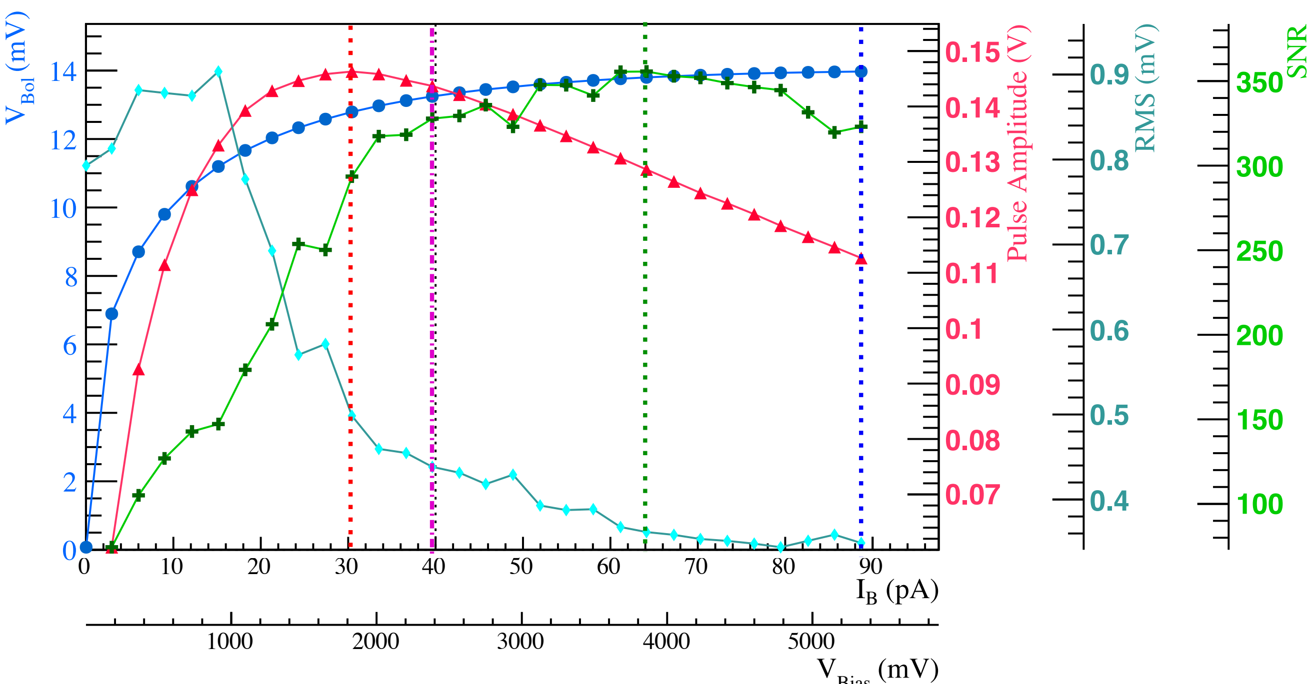
The CUORE experiment started taking data in 2017.

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

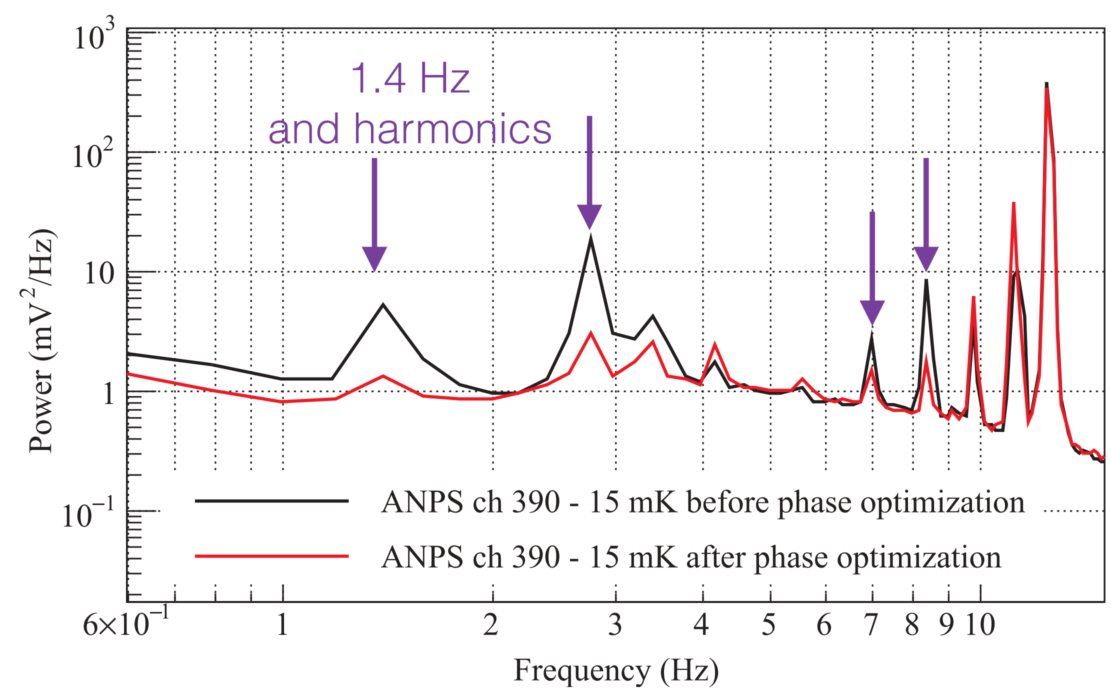
Dedicated detector characterization and optimization campaigns performed in order to characterize and improve the detectors and overall system performance.

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

- Characterization and tuning of detector operating parameters
- Noise reduction



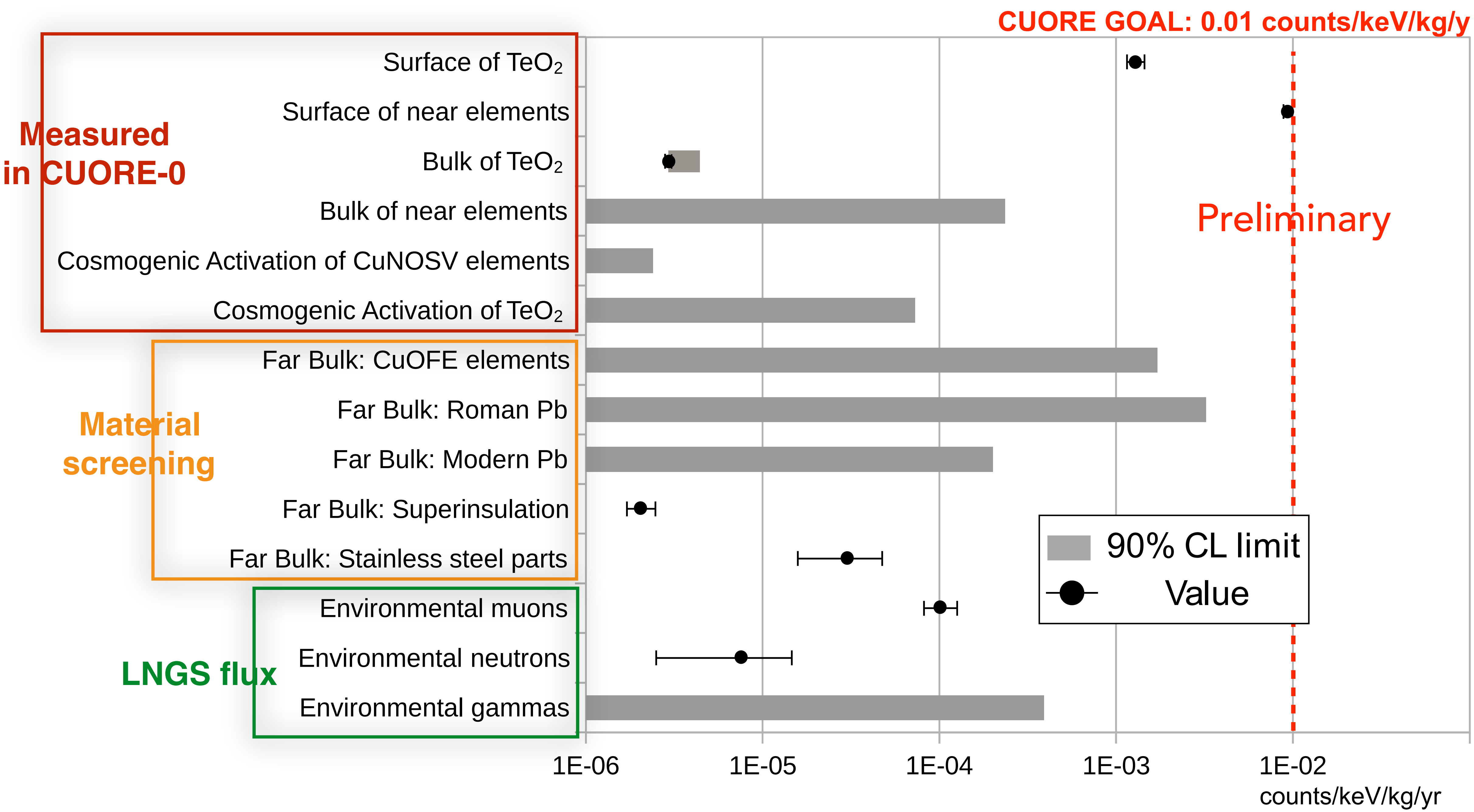
Load curves and set detectors WP



Pulse Tubes active noise cancellation

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

CUORE background budget



CUORE sensitivity and perspectives

CUORE $0\nu\beta\beta$ exclusion sensitivity in 5 years (90% C.L.):

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

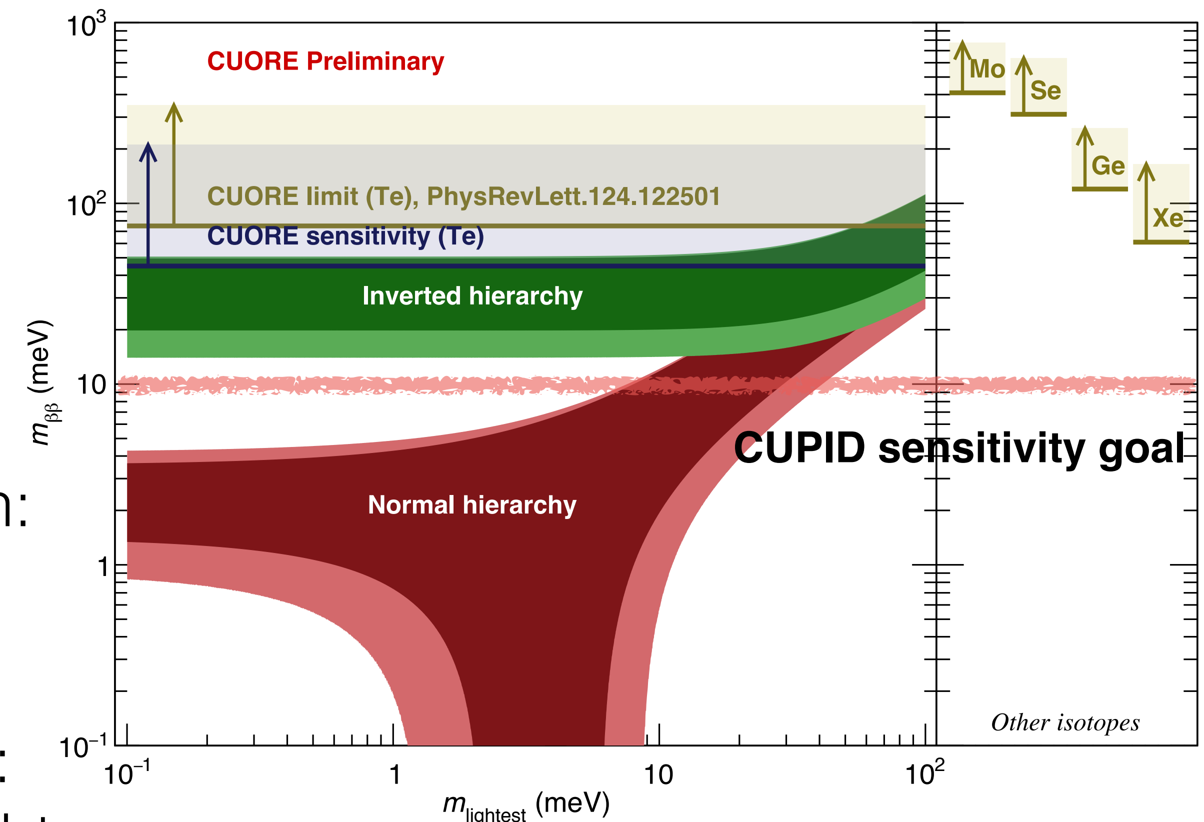
with

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

and

nominal energy resolution : 5 keV FWHM

in the Region Of Interest (ROI)



Next generation of $0\nu\beta\beta$ 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)