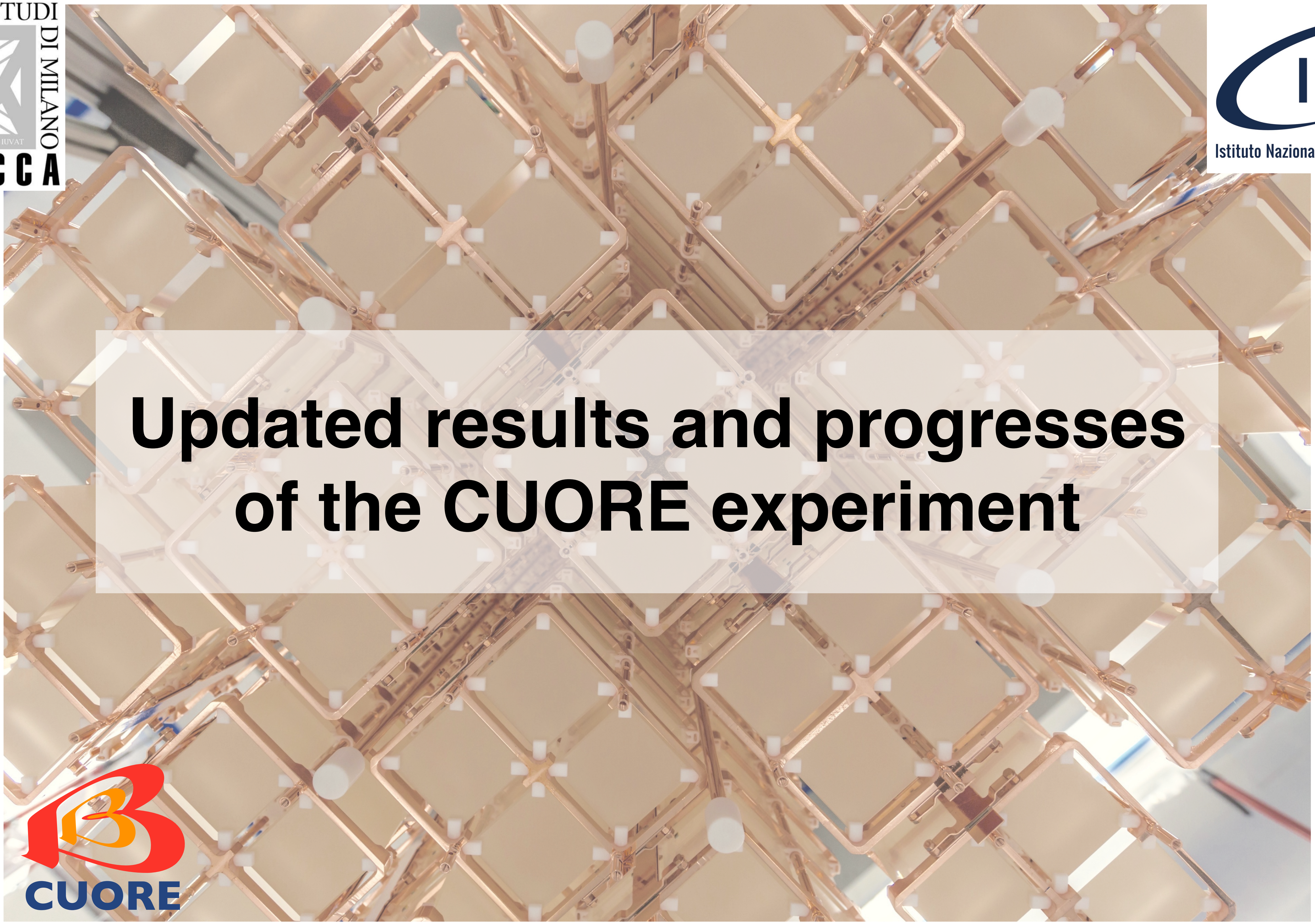


Updated results and progresses of the CUORE experiment

Irene Nutini
Università degli Studi Milano Bicocca
INFN Milano Bicocca

XXX International Conference
on Neutrino Physics and Astrophysics
Seoul (virtual), May 30th - June 4th 2022

Outlook

- The CUORE experiment
  - Technical achievements and data-taking update
  - Data processing
- Physics results from CUORE:
  - ^{130}Te 0νββ decay search
  - ^{130}Te 2νββ decay measurement
  - ^{130}Te ββ decay to excited states
  - ^{120}Te 0νβ^{+}EC decay search
  - ^{128}Te 0νββ decay search
  - Thermal model, background model, low energy - dark matter, …

The CUORE experiment

CUORE

Cryogenic Underground Observatory for Rare Events

Cryogenic experiment at tonne-scale,
utilising $^{(nat)}TeO_2$ thermal detectors operated at ~10 mK
Located at Laboratori Nazionali del Gran Sasso (Italy)

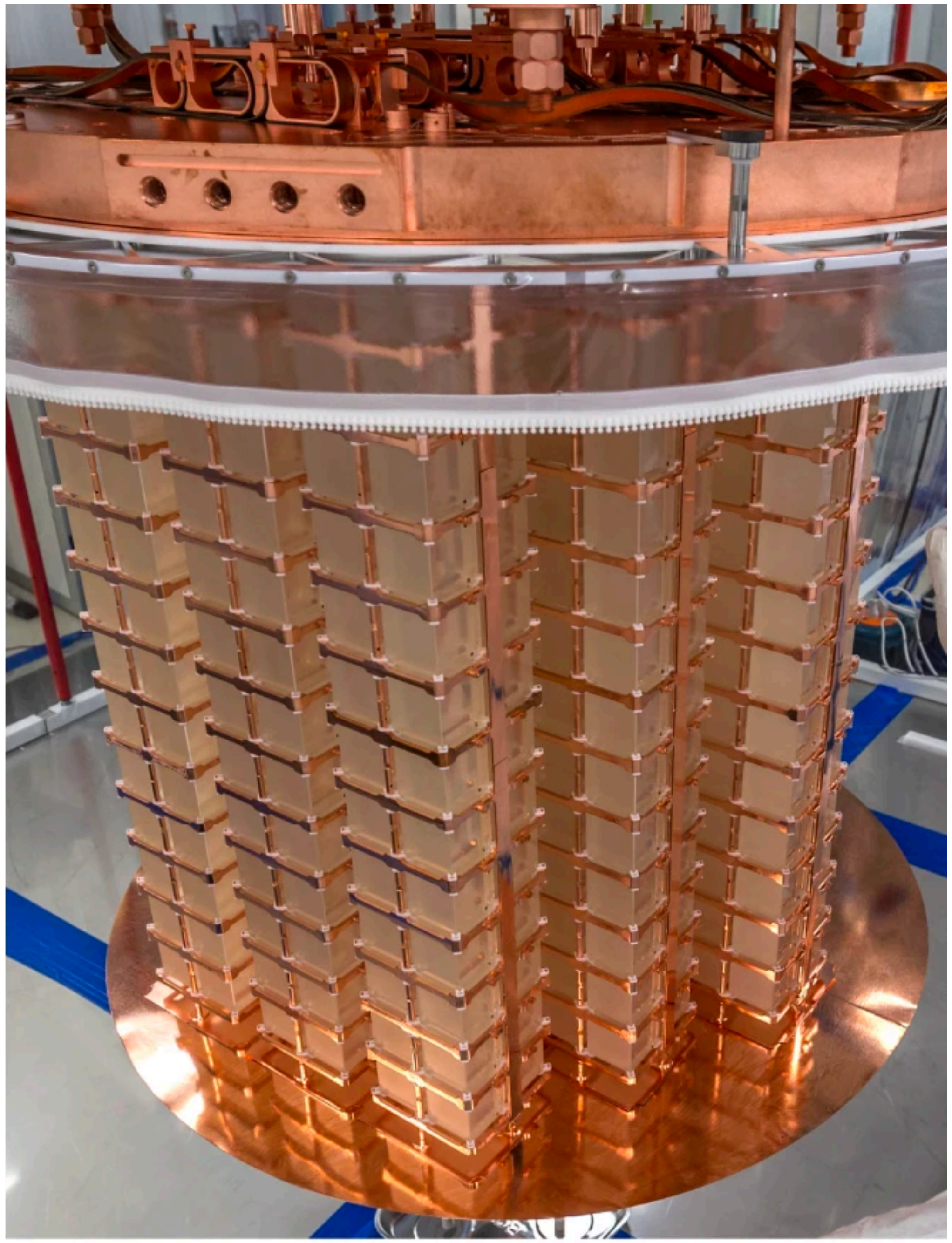
Search for rare events and/or for physics beyond the Standard Model

- Search for $0\nu\beta\beta$ decay of ^{130}Te —> Majorana nature of the neutrino
- Measurement of $2\nu\beta\beta$ decay of ^{130}Te and study of backgrounds
- Study of other rare decays of Te isotopes:
  - ^{130}Te $\beta\beta$ decay to excited states
  - $0\nu\beta\beta$ decay of ^{128}Te
  - $0\nu(\beta^{+}EC)$ ^{120}Te decay
- Low energy studies: dark matter - WIMP, axions, supernova neutrinos…
- Spectral shape studies

Adams D. et al. (CUORE collaboration), *Nature* 604 (2022) 7904, 53-58, https://www.nature.com/articles/s41586-022-04497-4

Adams D. et al. (CUORE collaboration), Prog.Part.Nucl.Phys. 122 (2022) 103902, https://doi.org/10.1016/j.ppnp.2021.103902

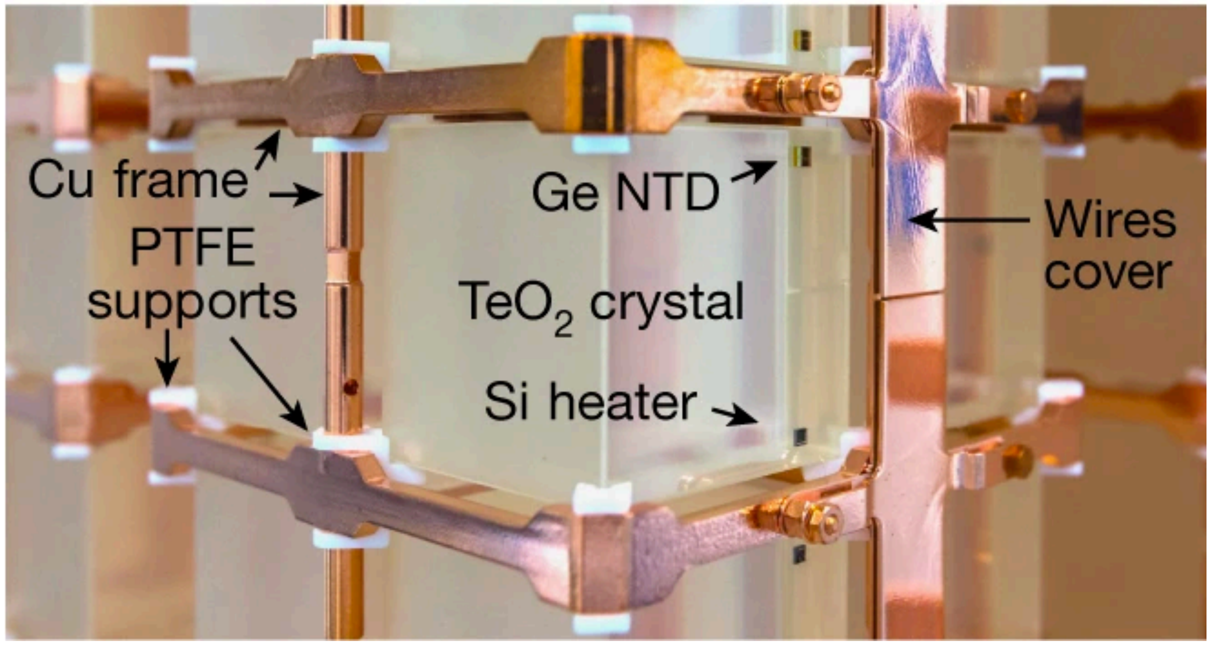
The CUORE detectors



Array of closely packed **988 TeO_2 crystals arranged in 19 towers**

High Mass of TeO_2: **742 kg**

206 kg of ^{130}Te, 188 kg of ^{128}Te, 0.5 kg of ^{120}Te



@10 mK

$\Delta T_{crystal} \sim 100\ \mu K/MeV$; $\Delta V_{NTD} \sim 400\ \mu V/MeV$

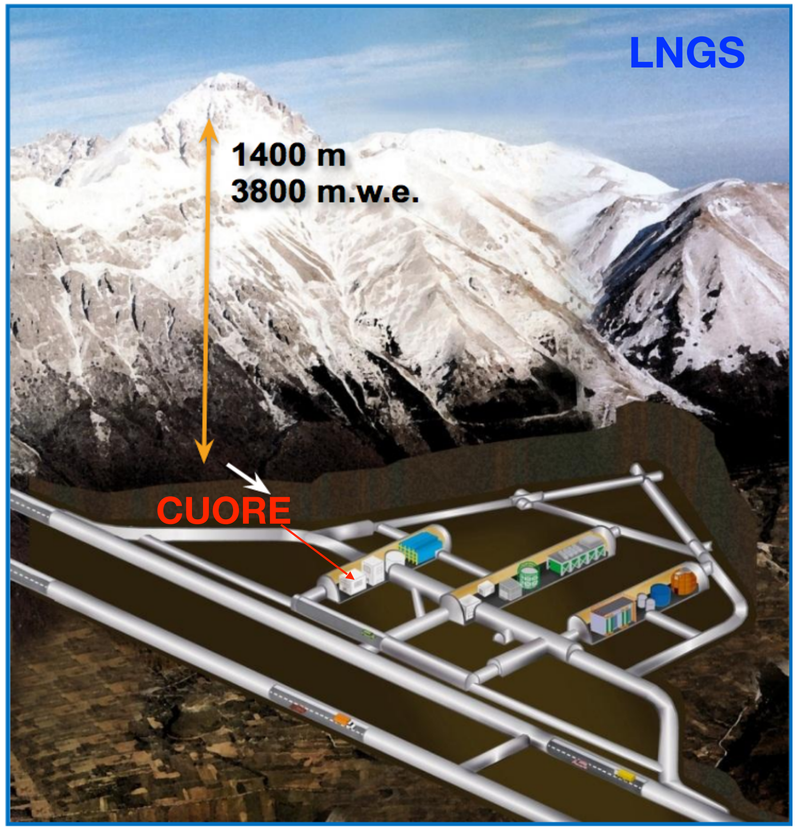
Adams D. et al. (CUORE collaboration), *Nature* 604 (2022) 7904, 53-58, https://www.nature.com/articles/s41586-022-04497-4

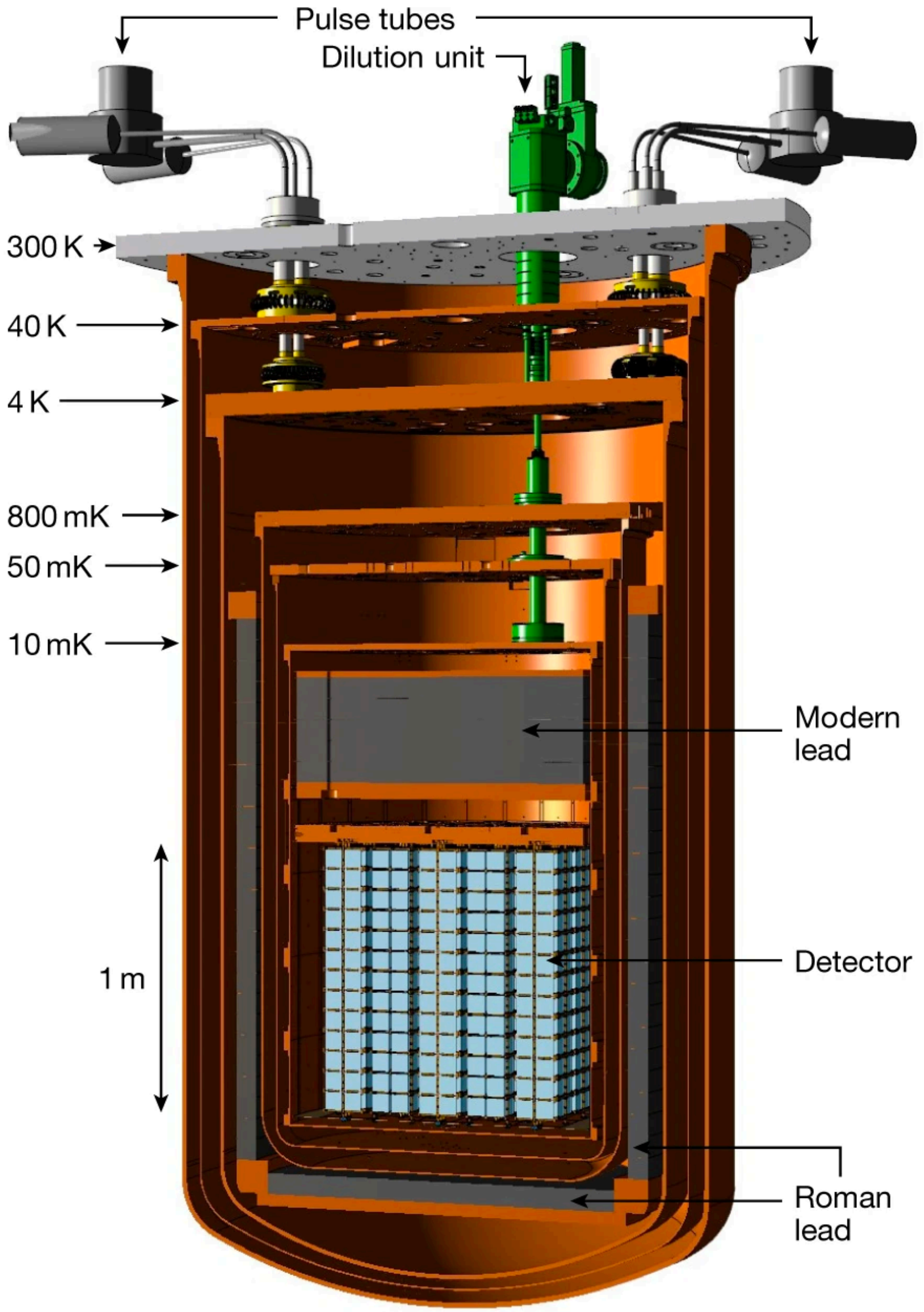
Alduino C. et al. (CUORE collaboration), J. Inst. 11(07), P07009, (2016) https://doi.org/10.1088/1748-0221/11/07/p07009

The CUORE challenge

- **Low temperature and low vibrations**
  TeO_2 detectors operated as calorimeters at ~10 mK stable
  - Multistage cryogen-free cryostat. Nested vessels at decreasing temperature. Cooling systems: Pulse Tubes and Dilution Unit
    - 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

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



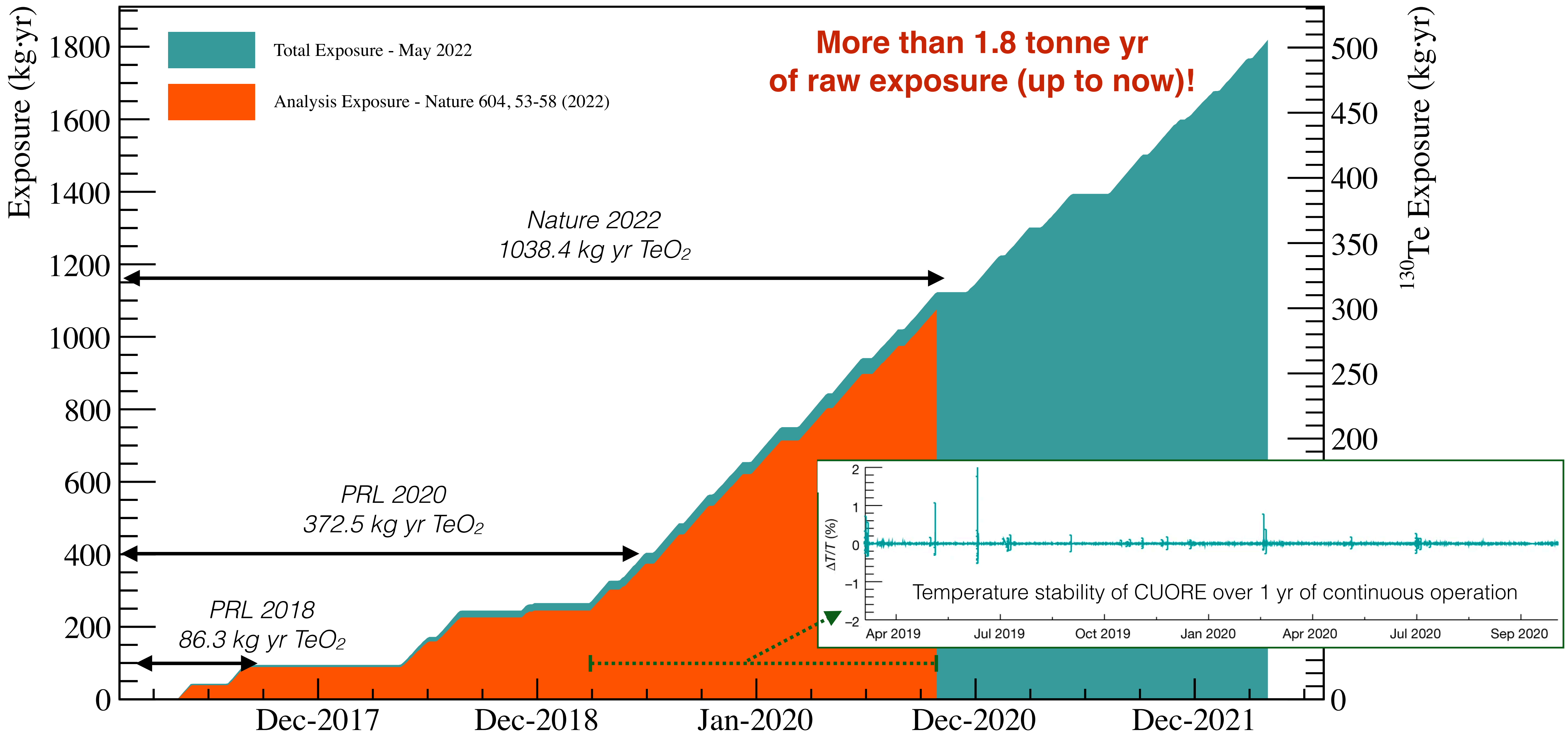


Dell'Oro S. et al., Cryogenics 102, 9, (2019)
https://doi.org/10.1016/j.cryogenics.2019.06.011

Adams D. et al. (CUORE collaboration), Prog.Part.Nucl.Phys. 122 (2022) 103902,
https://doi.org/10.1016/j.ppnp.2021.103902

CUORE data-taking

- Data taking started in Spring 2017: detector commissioning and optimisation
- Physics data taking since early 2019, at operating temperature 11-15 mK. **Uptime ~90%**. Data taking rate ~50 kg/month



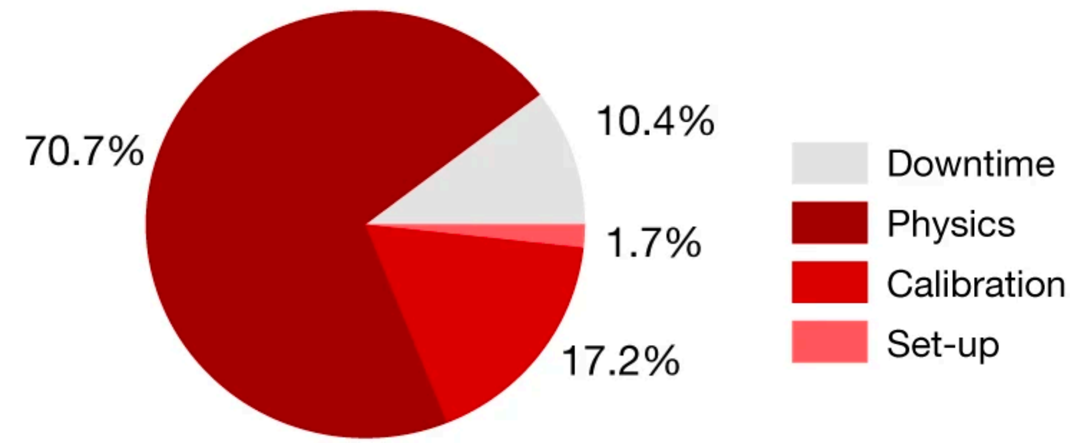
Alduino C. et al. (CUORE collaboration), Phys. Rev. Lett. 120, 132501, (2018), https://doi.org/10.1103/PhysRevLett.120.132501

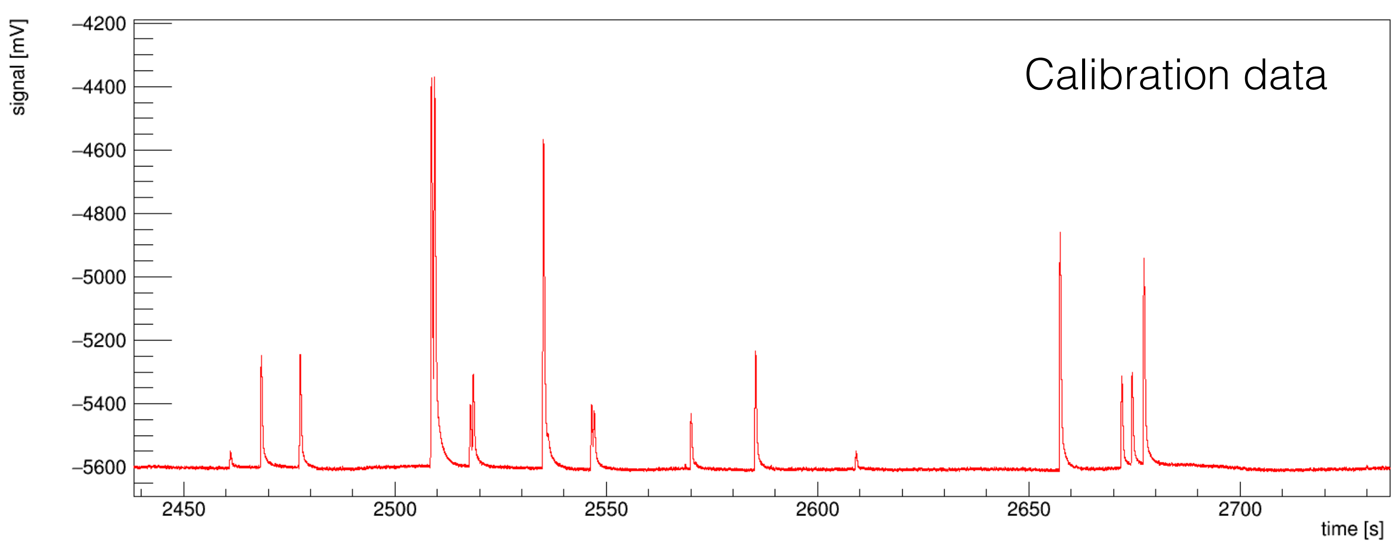
Alduino C. et al. (CUORE collaboration), Phys. Rev. Lett. 124, 122501, (2020), https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.122501

Adams D. et al. (CUORE collaboration), *Nature* 604 (2022) 7904, 53-58, https://www.nature.com/articles/s41586-022-04497-4

CUORE physics runs

- CUORE "data set": ~1 month of physics data taking with a few days of calibration at the start and end
- Continuous monitoring of detectors resistance/temperature stability and noise minimisation (set-up runs)
- Operational performance: 983/988 operational channels
- The voltage output from the detectors is sampled at 1 kHz (the BW of the detectors is a few tens of Hz) and saved into a data-stream
- The analysis procedure aims to trigger the signal pulses, measure their amplitude (energy) and reject spurious events



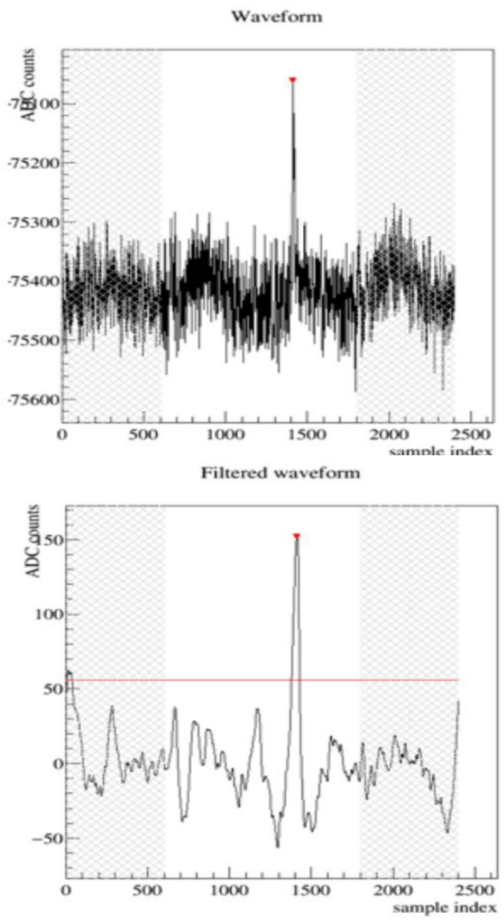


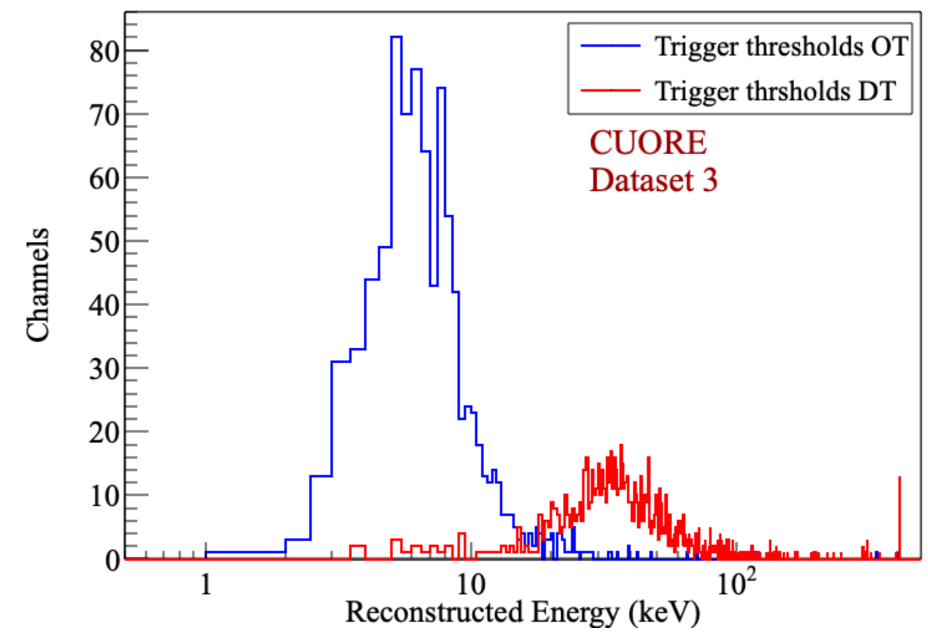
Calibration rate 100-200 mHz
Physics rate < 10 mHz

CUORE data-processing

Triggering pulses

- Online Derivative Trigger (DT): threshold on the derivative of the data-stream
- Offline Optimal Trigger (OT): identification of pulses in the filtered data-stream (template filter: expected pulse shape wrt to expected noise)



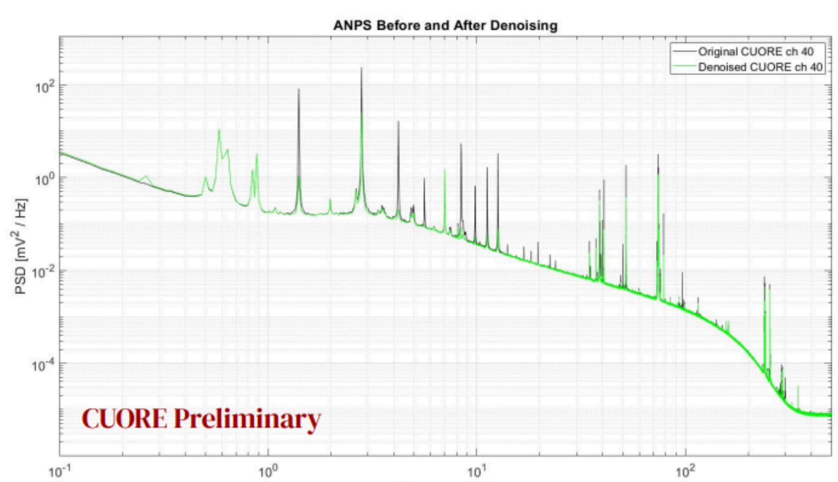


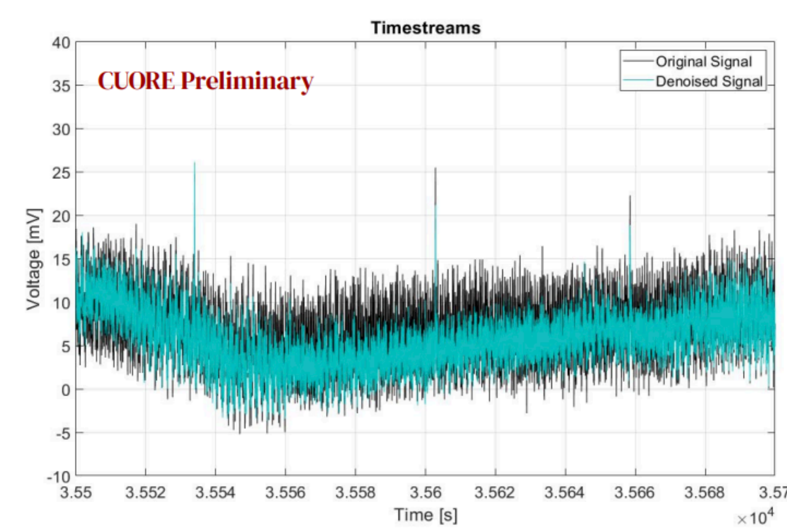
Thresholds: DT ~50 keV, OT <10 keV

CUORE low thresholds

Denoising the continuous data

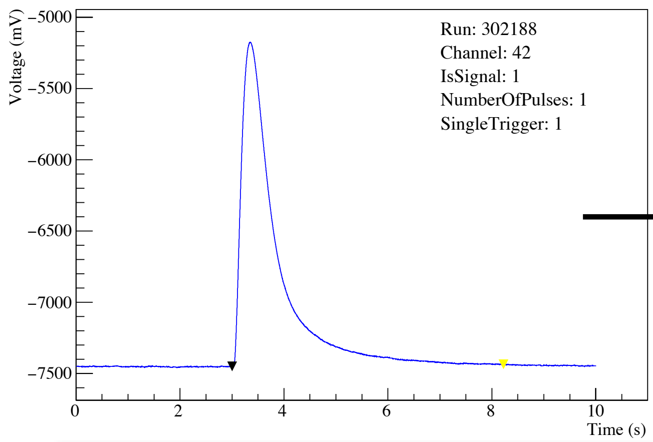
Remove noise from calorimeter channels utilising diagnostic devices (accelerometers, antennae, microphones) which can identify and measure the noise sources.



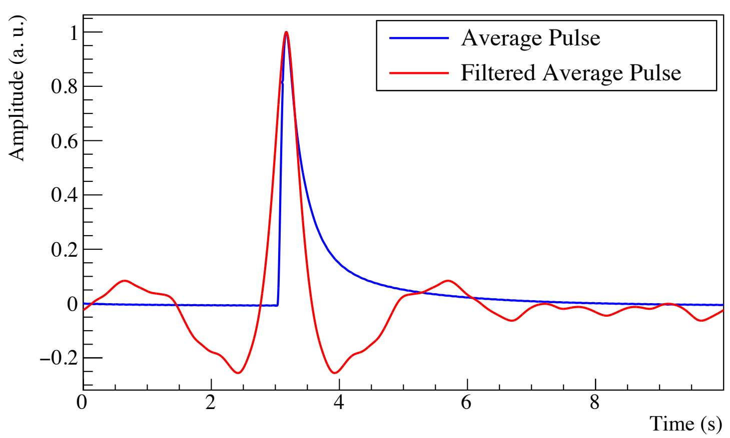


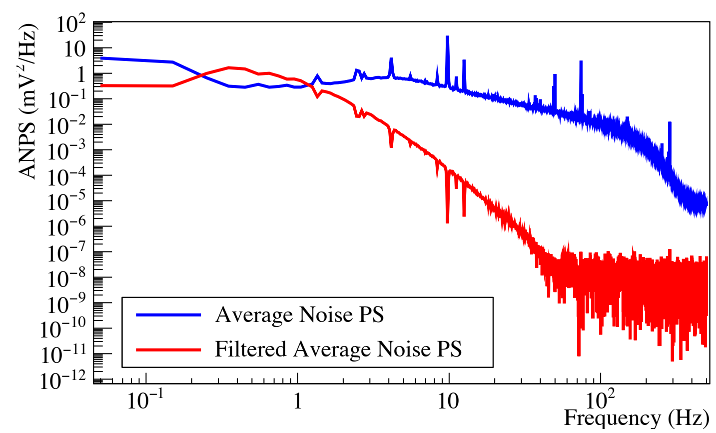
CUORE denoising @DNP 2021

CUORE data-processing

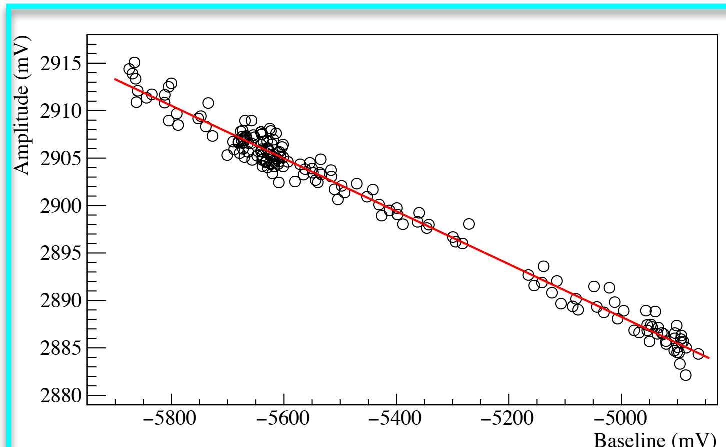


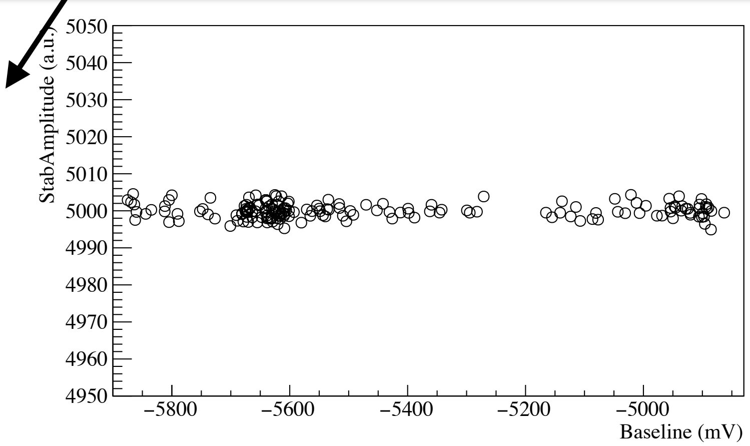
Optimum Filter → Gain Correction → Energy Calibration → Coincidences → PCA





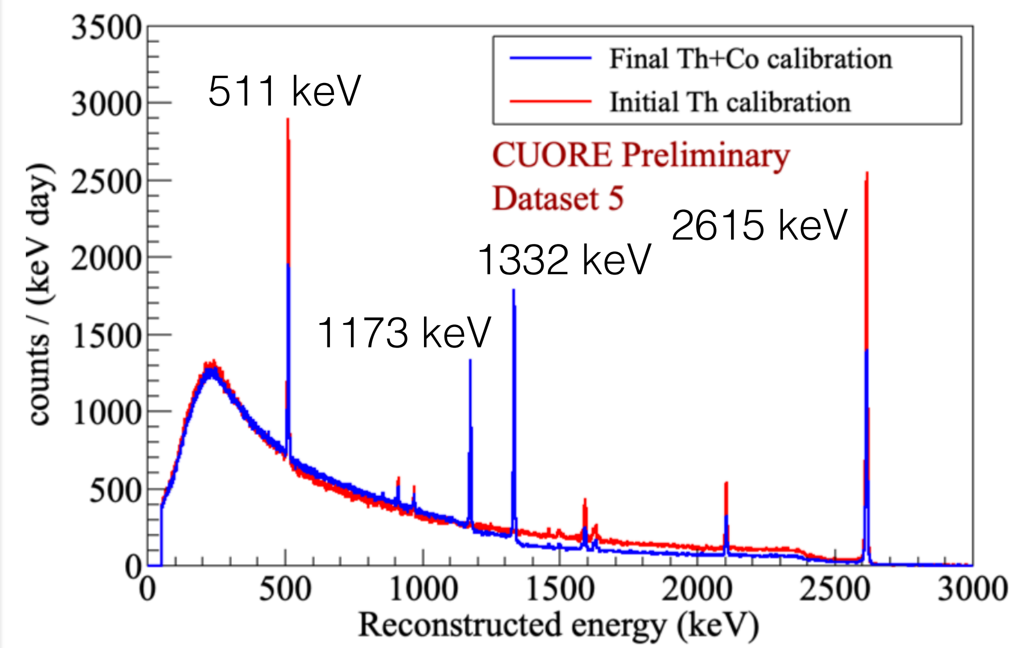
Matched filter that maximizes the signal-to-noise ratio





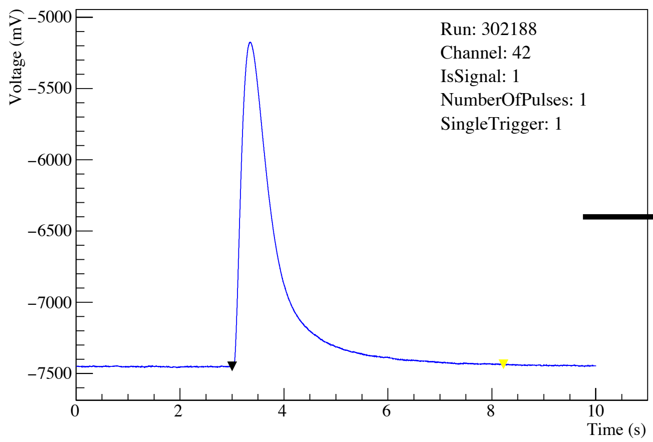
Heater pulses for thermal gain stabilization

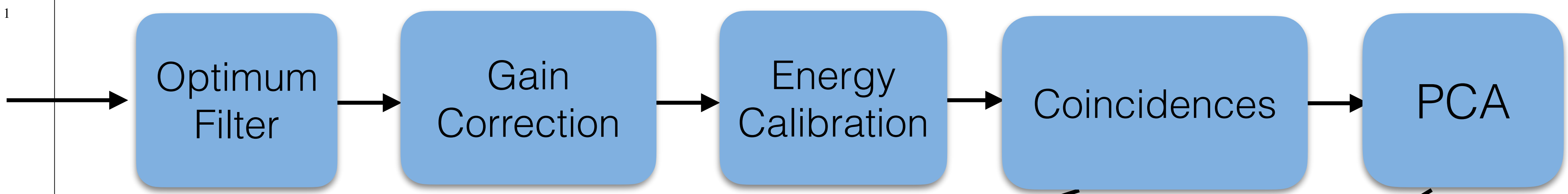
Convert amplitudes to energies

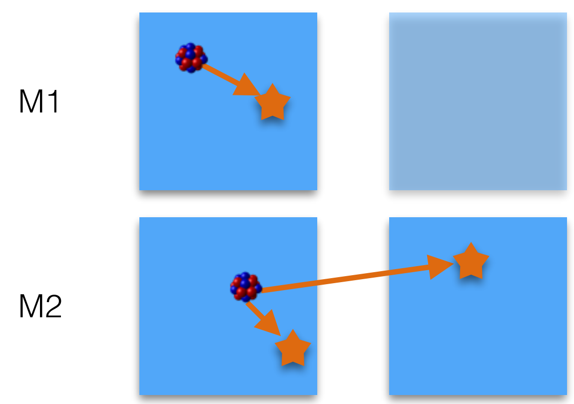


External calibration system:
^{232}Th+^{60}Co sources

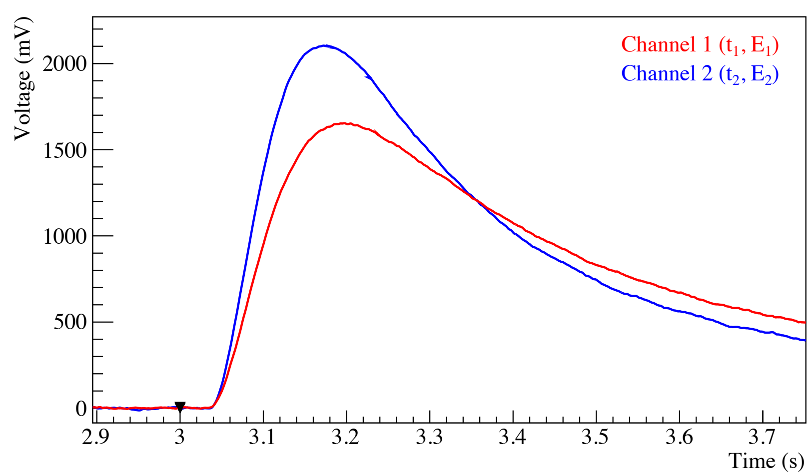
CUORE data-processing

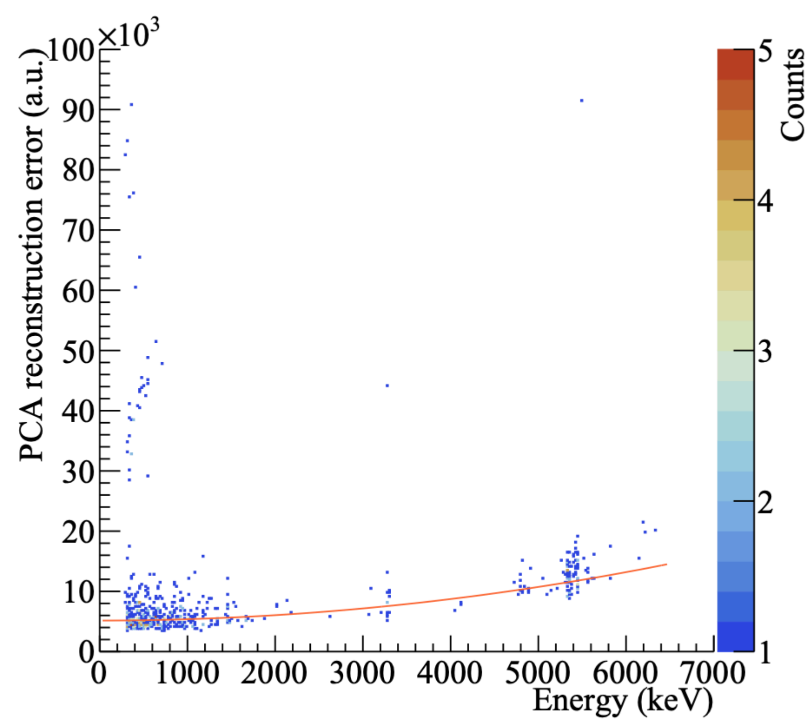


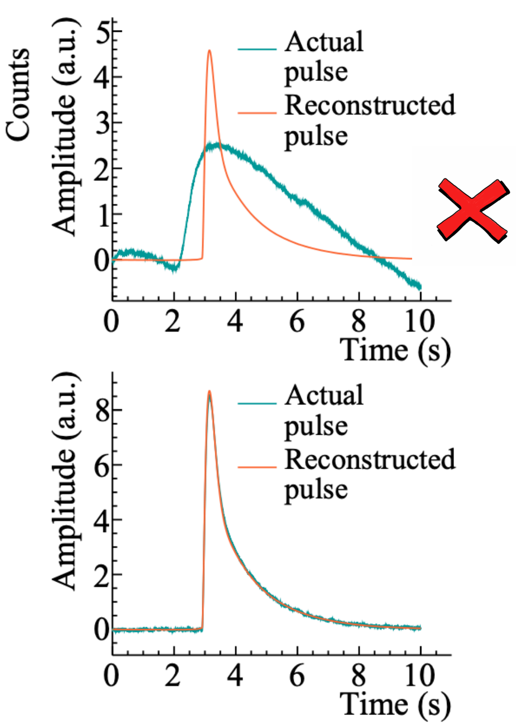




Identify events at different multiplicities







Principal Component Analysis
to reject spurious pulses in a wide energy range

^{130}Te 0νββ decay search

Total exposure:
1038.4 kg yr TeO$_2$, 288 kg yr ^{130}Te
Selection efficiencies: 92.4(2)%

^{130}Te $Q_{\beta\beta}$= 2527.5 keV

Reconstructed energy resolution at $Q_{\beta\beta}$:

7.8(5) keV FWHM

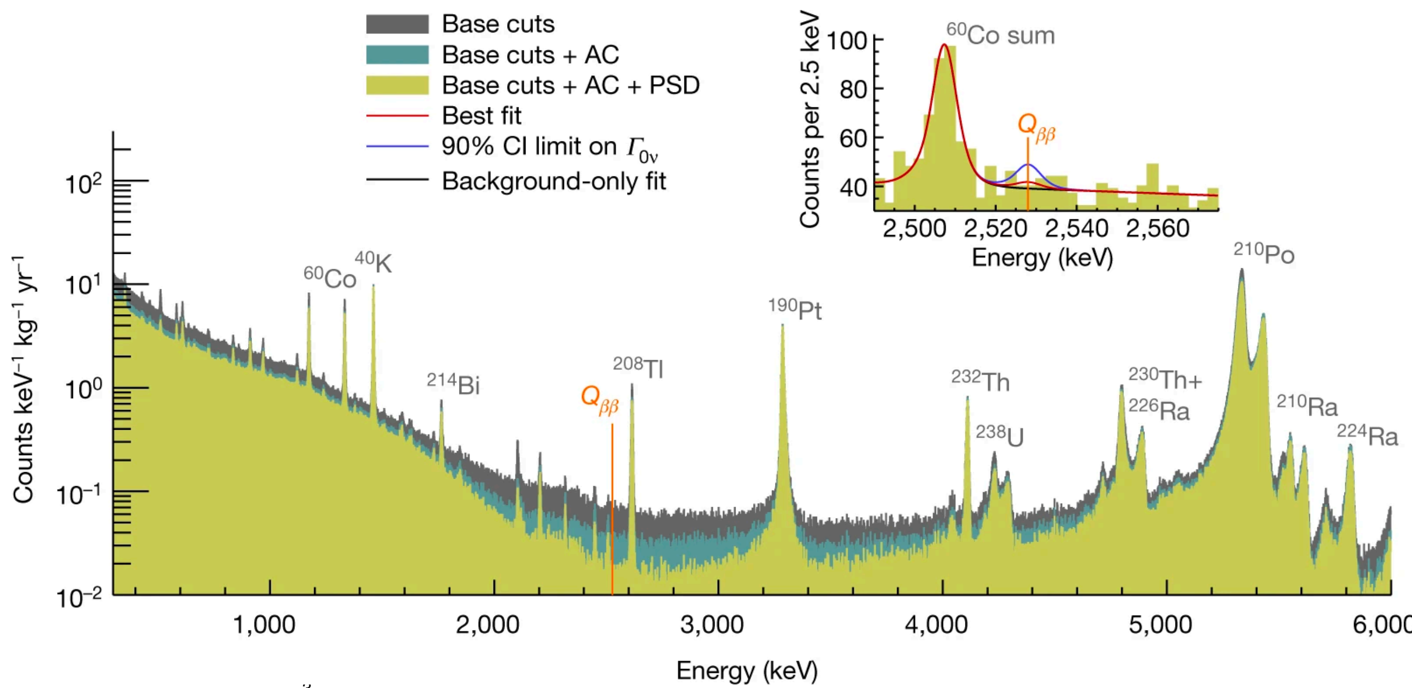
ROI background index (B)
~ 1.49(4) × 10^{-2} c/(keV·kg·yr)

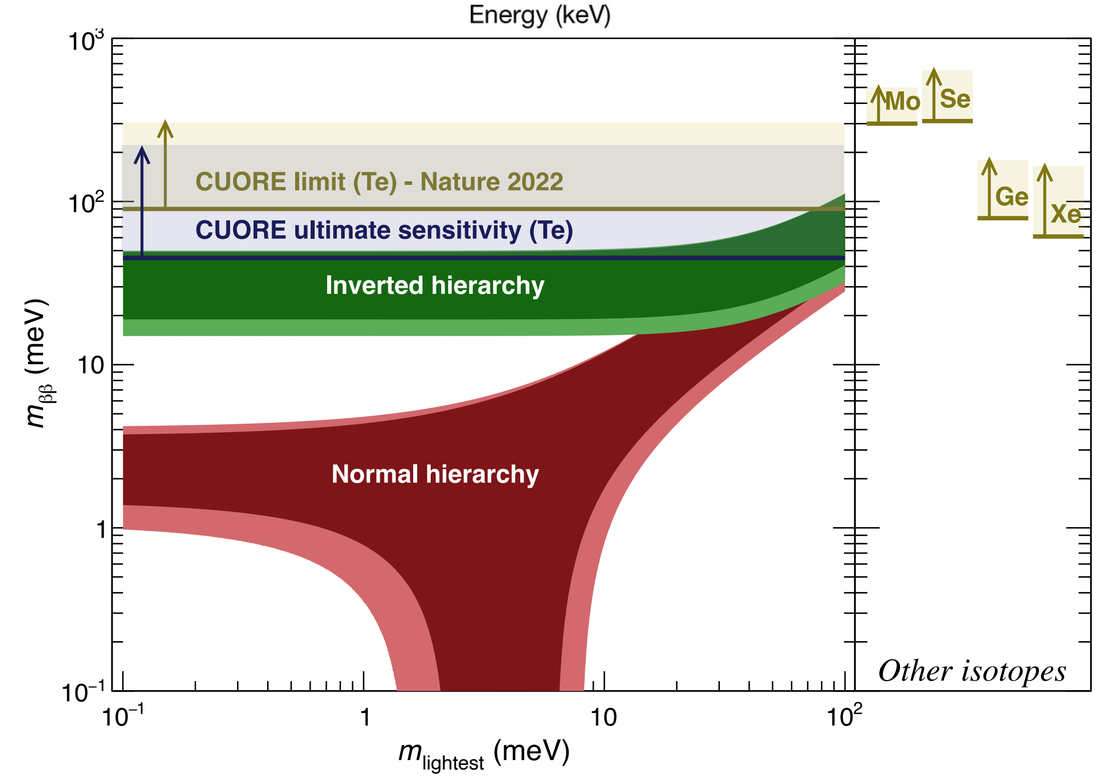
0νββ analysis

Half-life limit for 0νββ in ^{130}Te (90%C.I. including syst.)
$T_{0\nu}^{1/2}$ (^{130}Te) > 2.2 x 10^{25} yr

$m_{\beta\beta}$ < 90 - 305 meV

Result published on Nature (2022)!





Adams D. et al. (CUORE collaboration), *Nature* 604 (2022) 7904, 53-58, https://www.nature.com/articles/s41586-022-04497-4

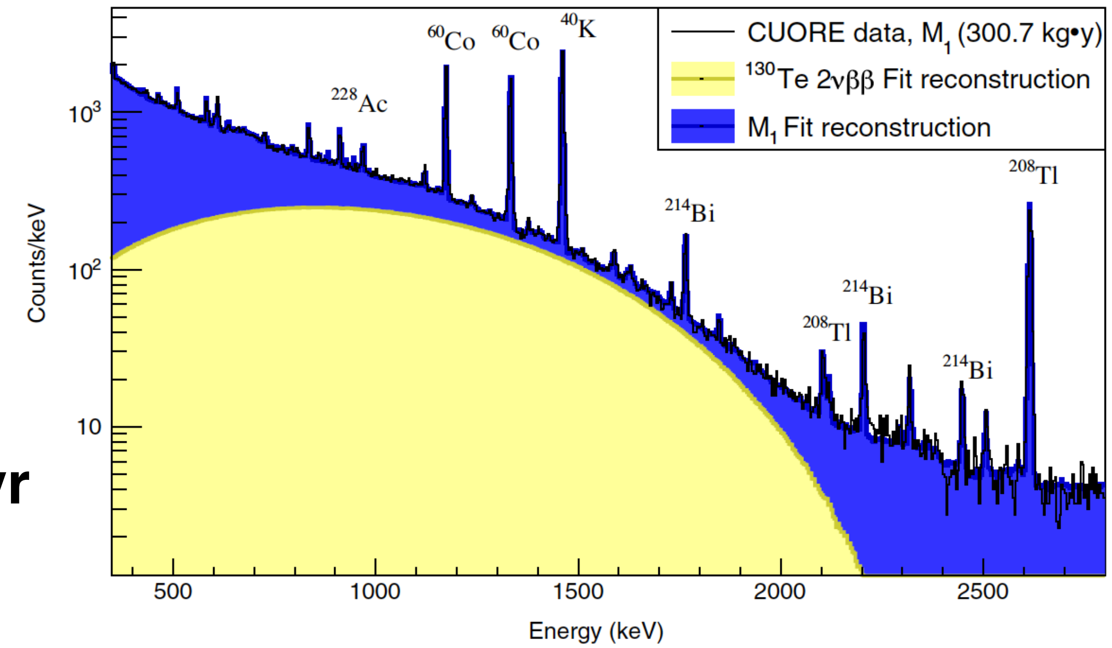
^{130}Te ββ decay

^{130}Te 2νββ half-life measurement

Monte Carlo reconstruction of the CUORE background, profiting from a segmented detector.

Most precise measurement of $T_{2\nu}^{1/2}$ (^{130}Te):

$T_{2\nu}^{1/2}$ (^{130}Te) = [7.71 $^{+0.08}_{-0.06}$(stat) $^{+0.12}_{-0.15}$(syst)] x 10^{20} yr

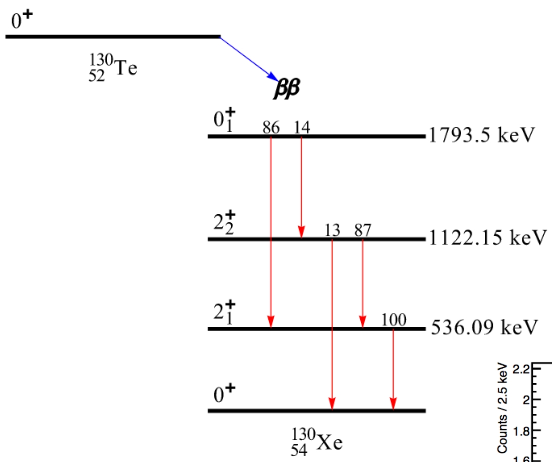


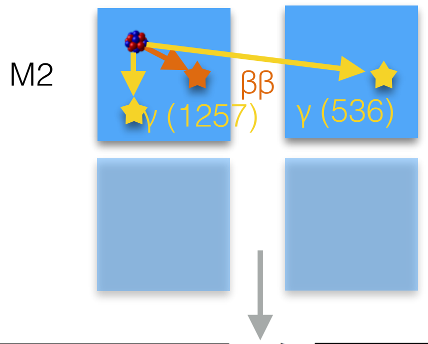
Adams D. et al. (CUORE collaboration), Phys. Rev. Lett. 126, 171801 (2021)
https://doi.org/10.1103/PhysRevLett.126.171801

^{130}Te ββ to first 0+ excited state of ^{130}Xe

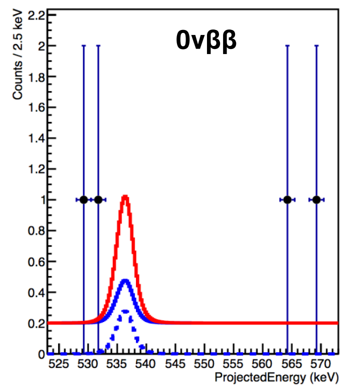
Cascade of de-excitation γs in coincidence with βs
- Multi-site signatures
- Analysis of only fully contained events

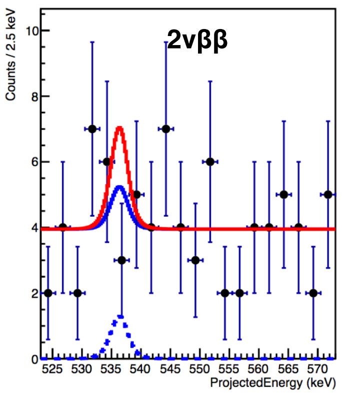
Half-life limits @90%C.I.
0νββ: $(T^{1/2})^{0\nu}_{0+} > 5.9 \times 10^{24}$ yr
2νββ: $(T^{1/2})^{2\nu}_{0+} > 1.3 \times 10^{24}$ yr





Exposure:
372.5 kg·yr TeO_2,
103.6 kg·yr ^{130}Te





Adams D. et al. (CUORE collaboration), Eur. Phys. J. C (2021) 81:567
https://doi.org/10.1140/epjc/s10052-021-09317-z

Decays of other Te isotopes

CUORE

^{120}Te 0vβ+EC decay

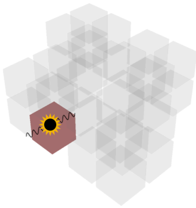
$Q_{\beta\beta}$= 1714.8 keV, natural abundance: 0.09%
Clear signature from e+e- annihilation and ^{120}Sn de-excitation via X-ray/Auger electrons emission

Half-life limit @90%C.I.

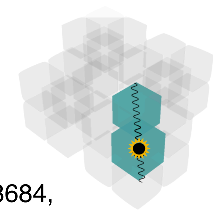
$T_{0\nu}^{1/2}$ (^{120}Te) > 2.9 × 10^{22} yr

Exposure: 355.7 kg·yr TeO_2, 0.2405 kg·yr ^{120}Te

Adams D. et al. (CUORE collaboration), arXiv:2203.08684, https://doi.org/10.48550/arXiv.2203.08684

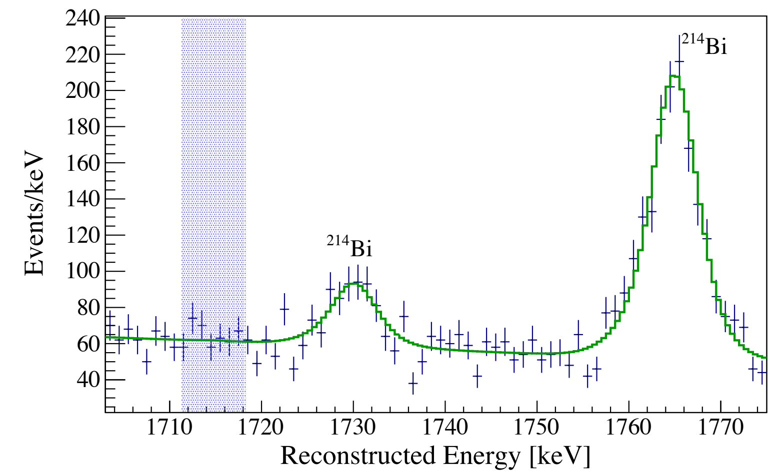


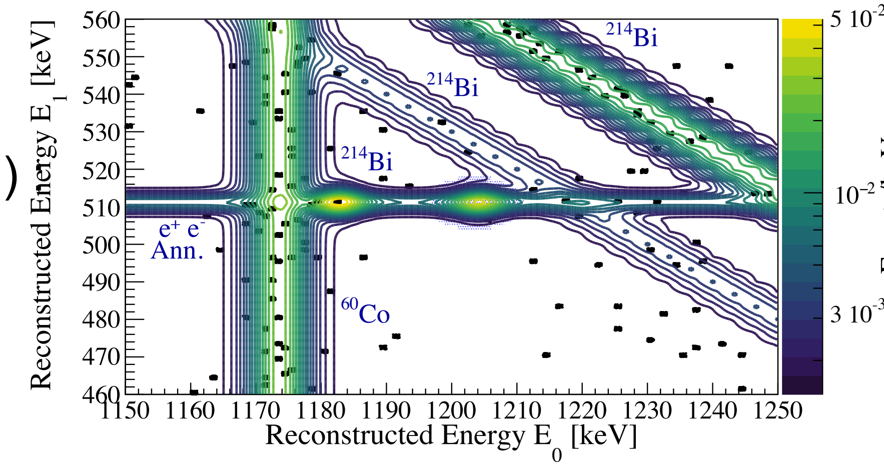
M1
$\beta^+ + X + 2\,\gamma_{511}$:
1714.8 keV



M2
($\beta^+ + X + \gamma_{511}$, γ_{511})
(1203.8, 511) keV

See CUORE poster P0209 (A.Campani)





^{128}Te 0vββ decay

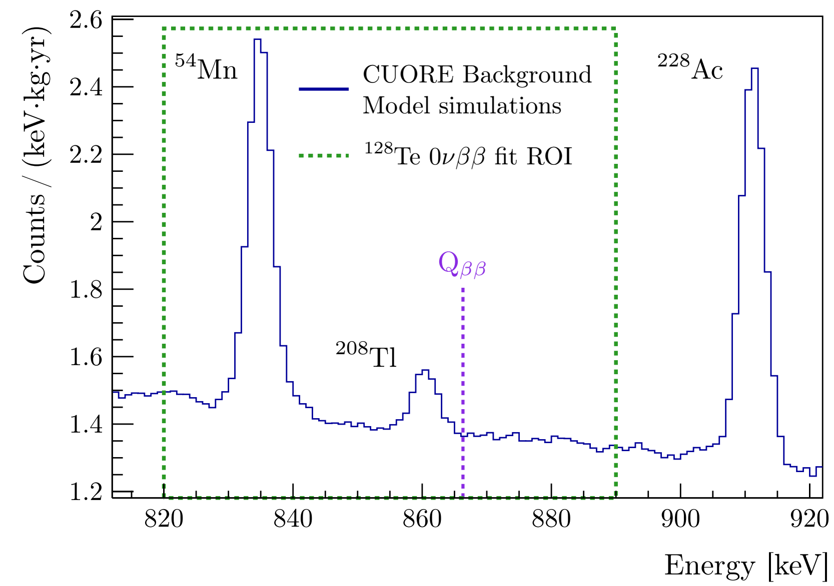
$Q_{\beta\beta}$= 866.7 keV, natural abundance: 31.74%

Half-life limit @90%C.I.

$T_{0\nu}^{1/2}$ (^{128}Te) > 3.6 × 10^{24} yr

Improved limit of over a factor 30 wrt to previous direct search results, and exceeded the results from geochemical experiments

Adams D. et al. (CUORE collaboration), arXiv:2205.03132, https://doi.org/10.48550/arXiv.2205.03132



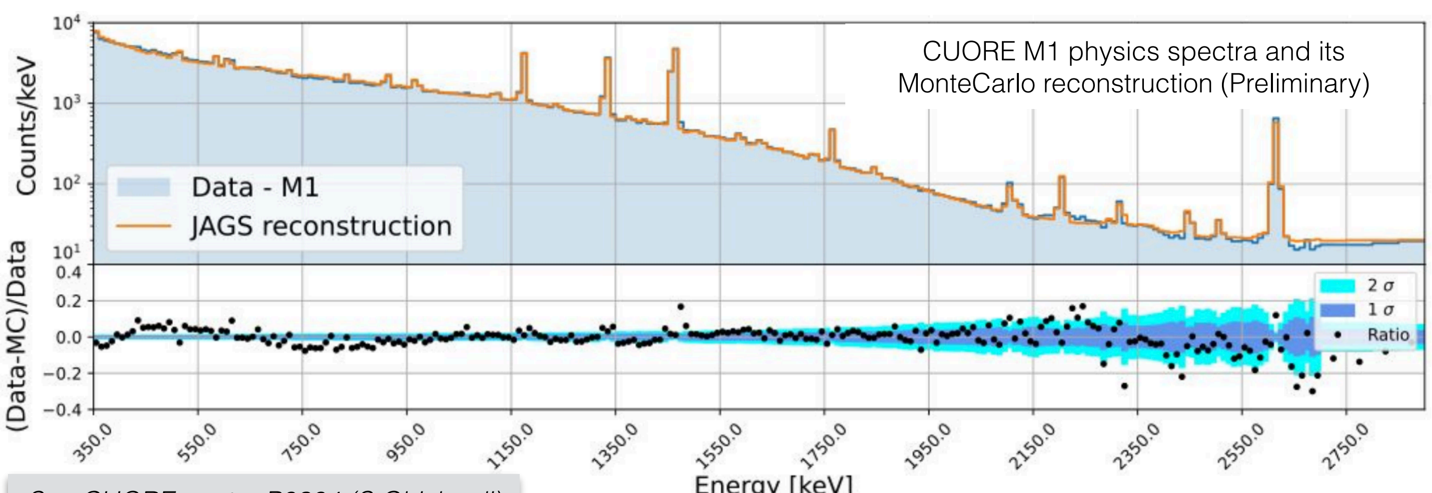
See CUORE poster P0537 (V.Dompè)

Exposure:
309.33 kg·yr TeO_2,
78.56 kg·yr ^{128}Te

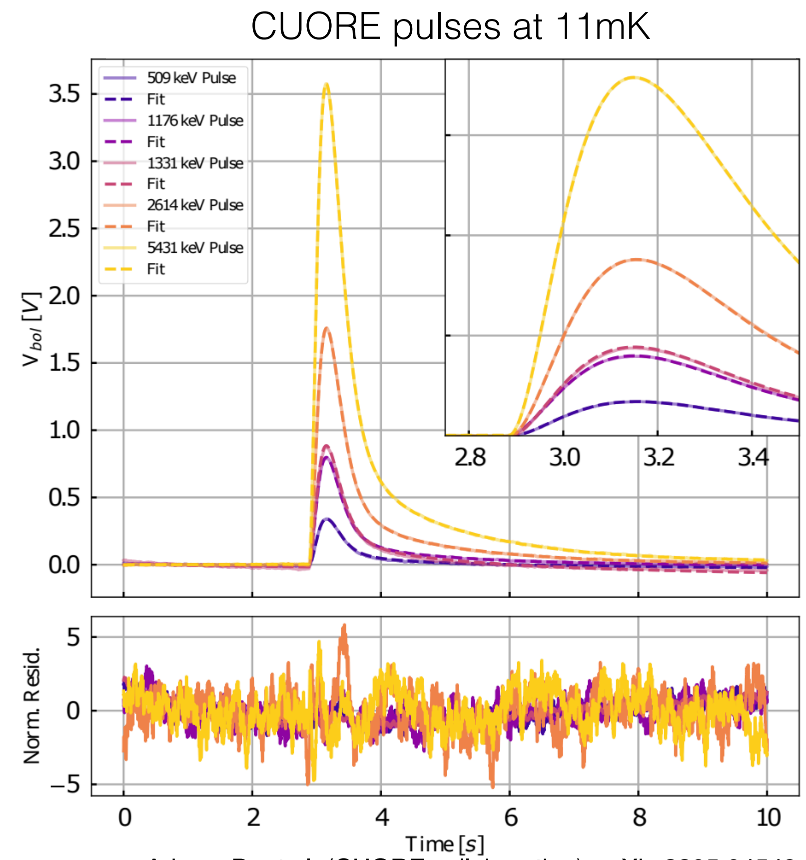
Other physics analyses

Several analyses are ongoing to study the CUORE physics spectra and detectors response:

- Background model
- Model of the CUORE detectors thermal response
- Study of environmental and anthropic vibrational sources and correlation with detectors noise



See CUORE poster P0304 (S.Ghislandi)



Adams D. et al. (CUORE collaboration), arXiv:2205.04549, https://doi.org/10.48550/arXiv.2205.04549

Moreover CUORE is exploring the search for rare events and/or for physics beyond the Standard Model other than the ββ decay of Te isotopes

- Spectral shape studies: HSD/SSD in 2νββ, ββ decay with Majoron emission, CPT violation in 2νββ decay,…
- Low energy: dark matter (WIMPs, axions,..)
- High-multiplicity events, muons…

Conclusion

- CUORE demonstrates the feasibility of a tonne-scale experiment employing cryogenic calorimeters, for the search of the 0νββ decay and rare events
- The CUORE experiment operation is proceeding with 90% uptime. A raw exposure of more than 1.8 tonne yr TeO_2 has been achieved as of today!

- CUORE released physics results of ^{130}Te 0νββ decay, utilising 1 tonne yr TeO_2 data; this achieved ambitious goal was published on Nature!
- CUORE has a rich science program of searches for rare decays of different Te isotopes: new results on ^{128}Te and ^{120}Te decay searches were released. Many more physics analyses are ongoing!

- The CUORE data taking is currently underway to collect up to 3 tonne yr TeO_2 exposure (1 tonne yr ^{130}Te)
- CUORE paves the road to the CUPID project (CUORE Upgrade with Particle IDentification) for next generation tonne-scale cryogenic calorimeters for 0νββ decay searches

Next talk:
CUPID and its demonstrators (A. Zolotarova)

Thank you on behalf of the CUORE collaboration

CUORE Posters @ Neutrino 2022

- Alice Campani - P0209 - *Recent results of the search for neutrinoless positron emitting electron capture of ^{120}Te with CUORE*
- Valentina Dompè - P0537 - *First results on the search for ^{128}Te 0vbb decay with the CUORE TeO2 cryogenic crystals*
- Stefano Ghislandi - P0304 - *Status and perspectives of the CUORE background model*
- Shihong Fu - P0249 - *The CUORE cryostat: current performance and future upgrade towards CUPID*

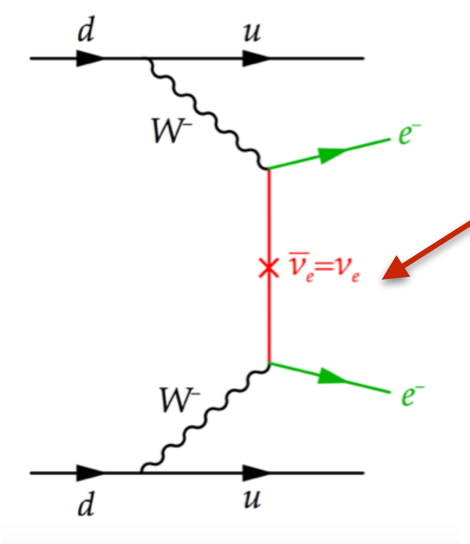
Acknowledgements

The CUORE Collaboration thanks the directors and staff of the Laboratori Nazionali del Gran Sasso and the technical staff of our laboratories. This work was supported by the Istituto Nazionale di Fisica Nucleare (INFN); the National Science Foundation under Grant Nos. NSF-PHY-0605119, NSF-PHY-0500337, NSF-PHY-0855314, NSF-PHY-0902171, NSF-PHY-0969852, NSF-PHY-1307204, NSF-PHY-1314881, NSF-PHY-1401832, and NSF-PHY-1913374; the Alfred P. Sloan Foundation; the University of Wisconsin Foundation; and Yale University. This material is also based upon work supported by the US Department of Energy (DOE) Office of Science under Contract Nos.DE-AC02-05CH11231, DE-AC52-07NA27344, DE-SC0012654, and DE-SC0020423 ; by the DOE Office of Science, Office of Nuclear Physics under Contract Nos. DE-FG02-08ER41551 and DE-FG03-00ER41138; and by the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No 754496. This research used resources of the National Energy Research Scientific Computing Center (NERSC). This work makes use of the DIANA data analysis and APOLLO data acquisition software which has been developed by the CUORICINO, CUORE, LUCIFER and CUPID-0 collaborations.

Backup

Neutrinoless double beta decay (0νββ)

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
- Hint on origin of matter/anti-matter asymmetry



Majorana mass term coupling the two neutrinos

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

0νββ favorite mechanism:
Light Majorana neutrino exchange

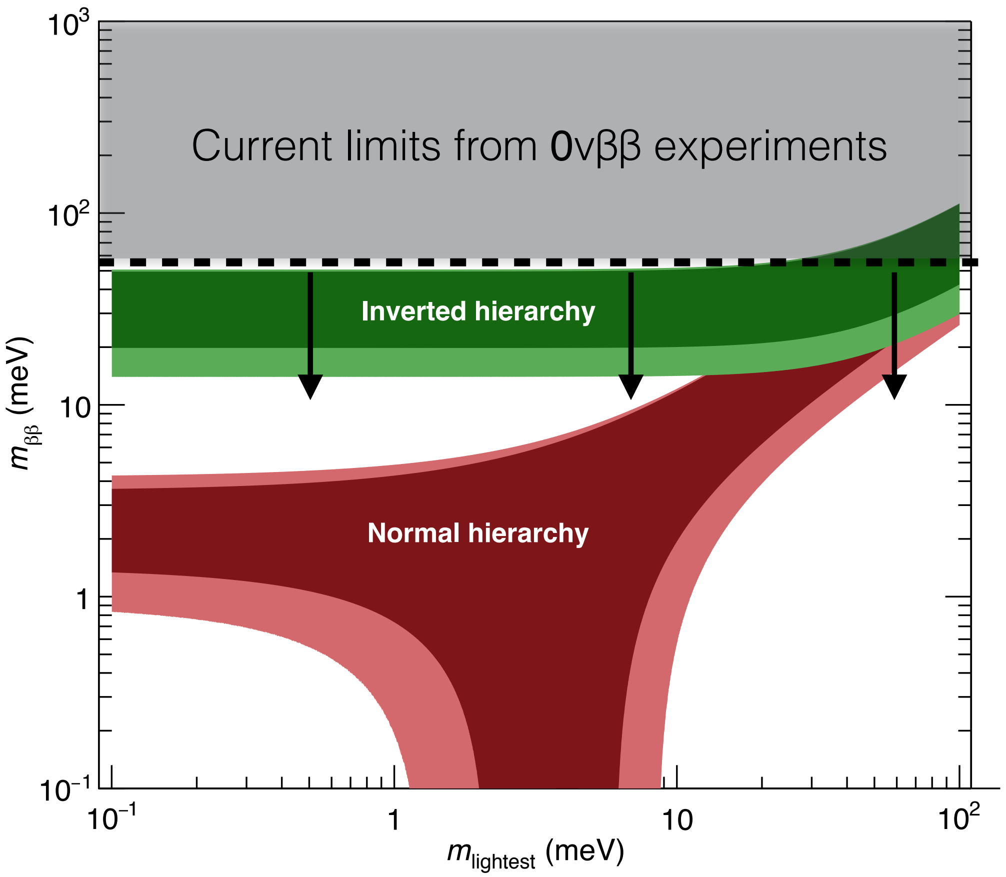
$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

Phase space integral

Nuclear matrix element (NME)

Effective neutrino mass term

$$m_{\beta\beta} \equiv \left|\Sigma_i m_{\nu_i} U_{ei}^2\right| = \left|e^{i\alpha_1}|U_{e1}^2|m_1 + e^{i\alpha_2}|U_{e2}^2|m_2 + |U_{e3}^2|m_3\right|$$



Experimental 0νββ sensitivity

The number of observable 0νββ decays is limited by the fluctuations of the background counts around $Q_{\beta\beta}$ (region of interest, ROI)

'Finite background'

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

'Zero background' (B · Δ · M · T) << 1

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

<u>Isotope choice</u>

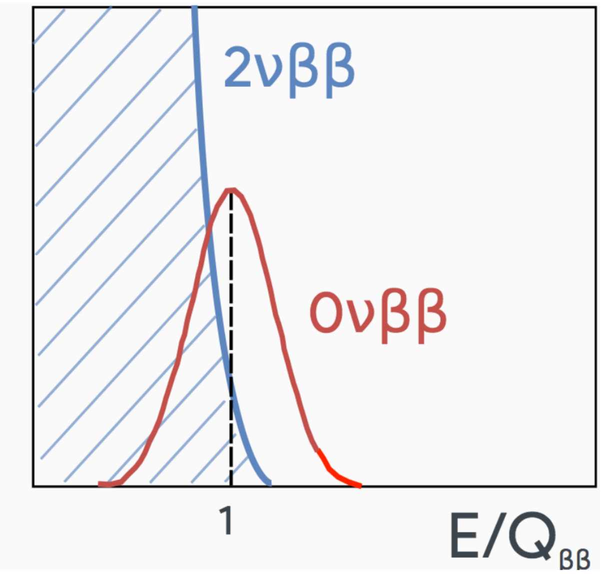
- High isotopic natural abundance or enrichment, η
- High Q-value, $Q_{\beta\beta}$

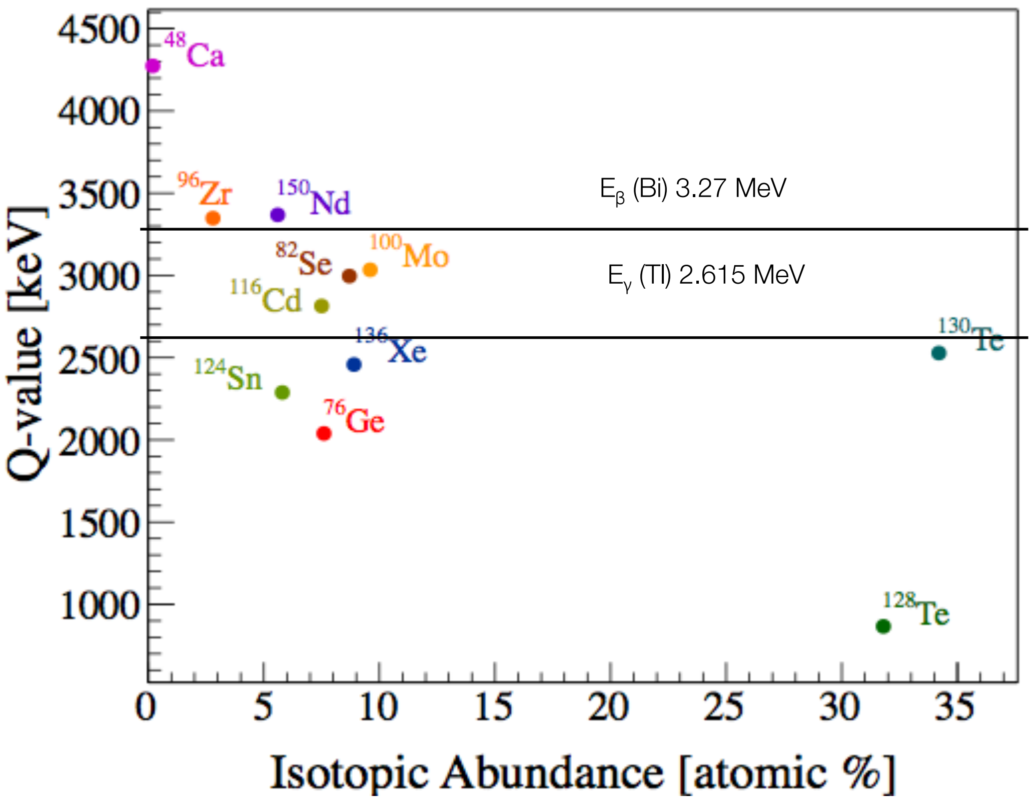
<u>Detection technology</u>

- Good detection efficiency (ε): ββ source embedded into the absorber
- Excellent energy resolution (Δ)

<u>Exposure</u>

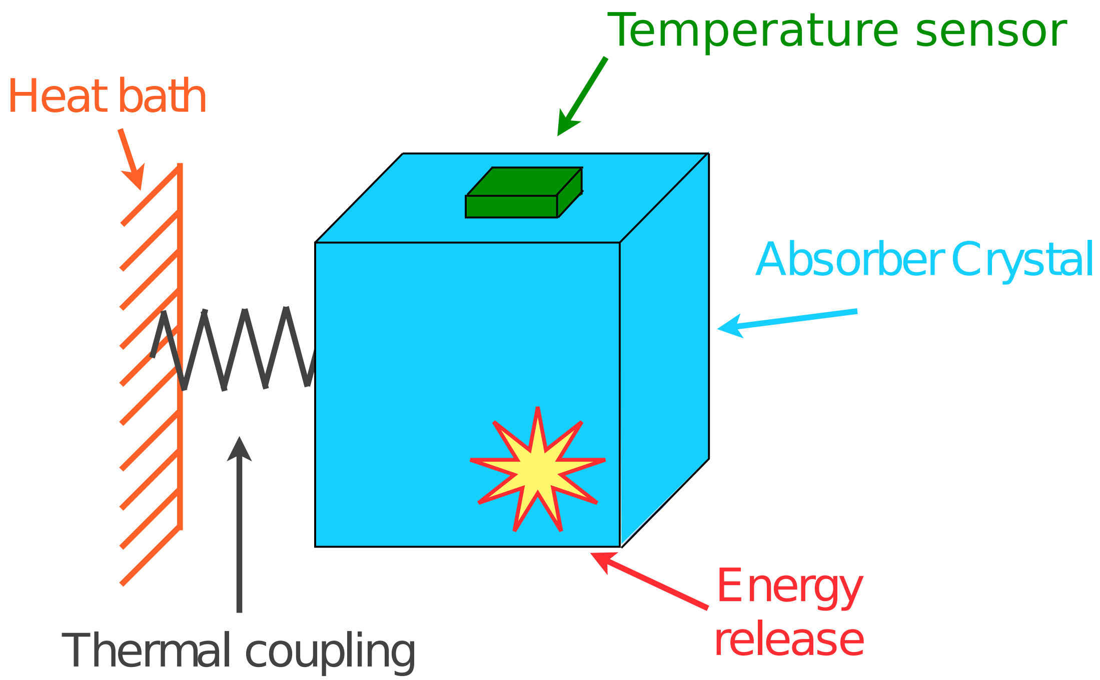
- Large active mass (M) detector
- Long live-time (T)





Low temperature detectors

Cryogenics calorimeters. An absorber crystal is connected to an ‘heat bath’ at ~few mK. It is instrumented with a sensor measuring the temperature variation in the crystal induced by a small energy release (~keV/MeV). The deposited energy is converted into phonons - heat.



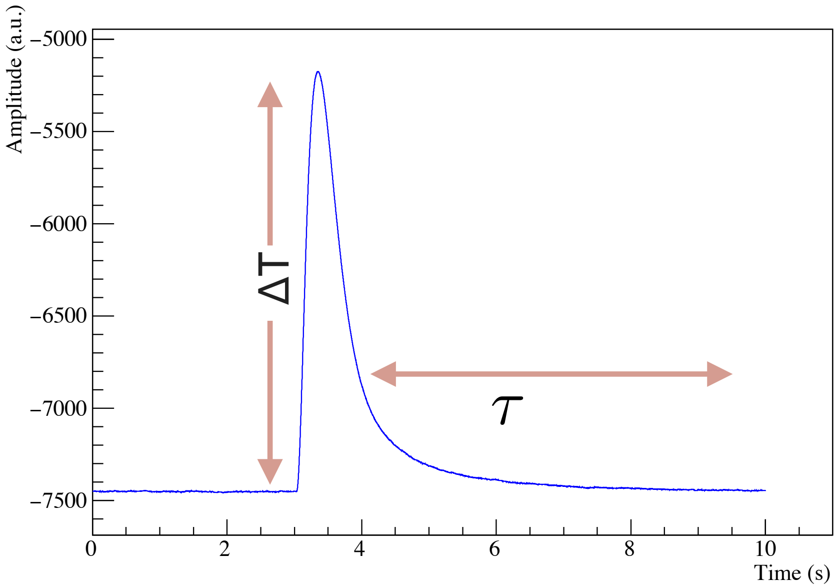
- Absorber at T~ 10 mK
- Energy deposition in the absorber (E_{dep}): particles scattering on electrons and nuclei → production of athermal phonons → energy degradation → thermal phonons/heat → ΔT
- Phonon sensor - NTD thermistor: large resistance variation with T (ΔR) → generation of an electrical pulse signal with amplitude proportional to the energy of the excess phonons

Simplified thermal model:

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

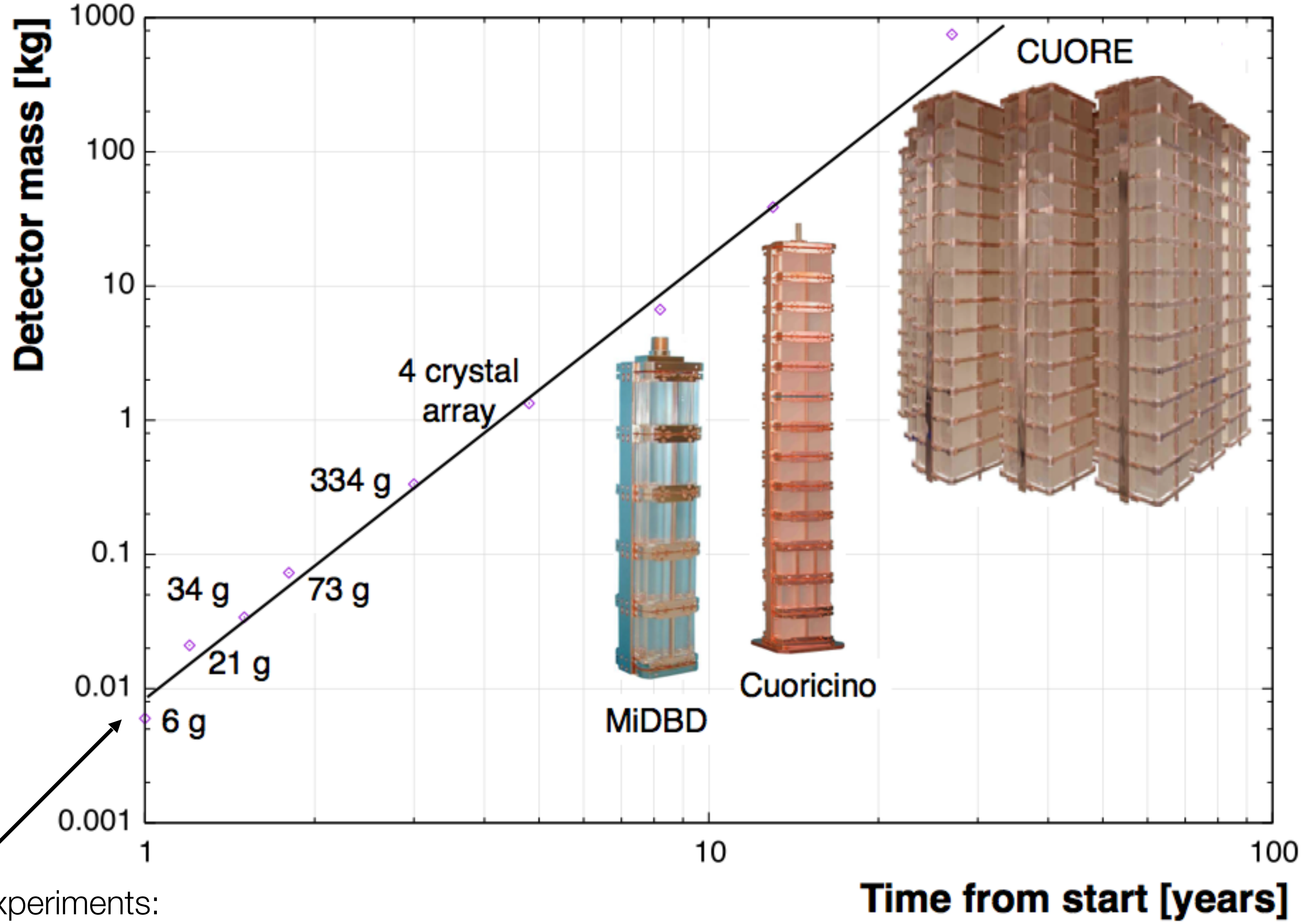
$$\Delta T \propto \frac{E_{dep}}{C}$$

$$\tau = \frac{G}{C}$$



Towards the CUORE experiment

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

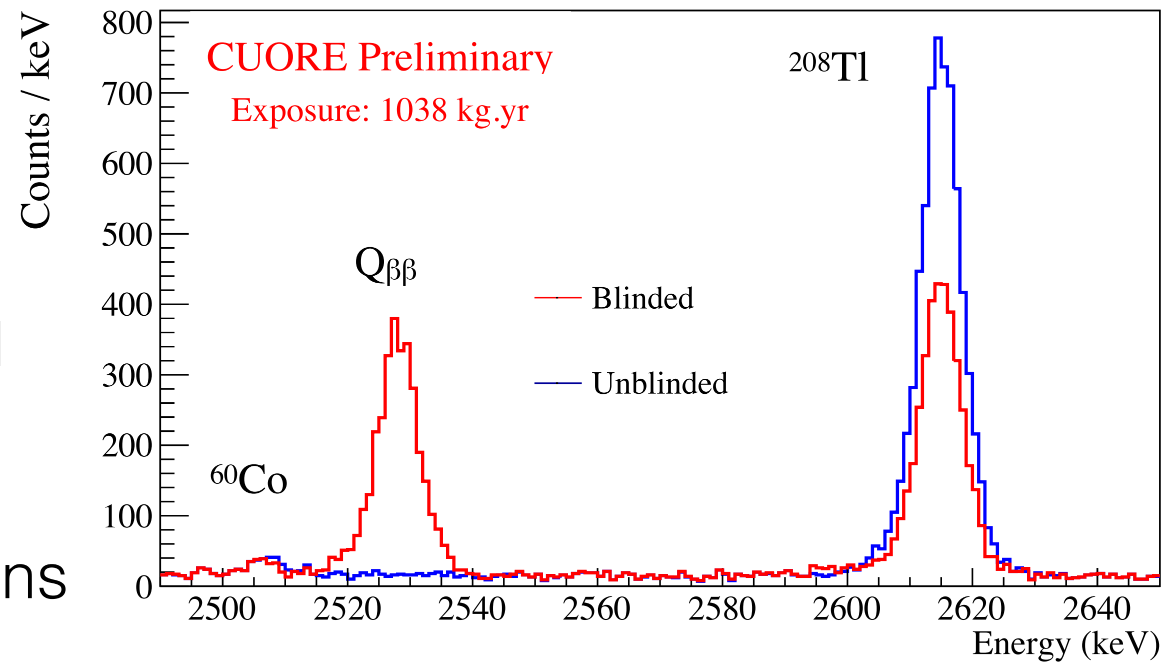


Pioneering experiments:
E.Fiorini group in Milano in the 1980s

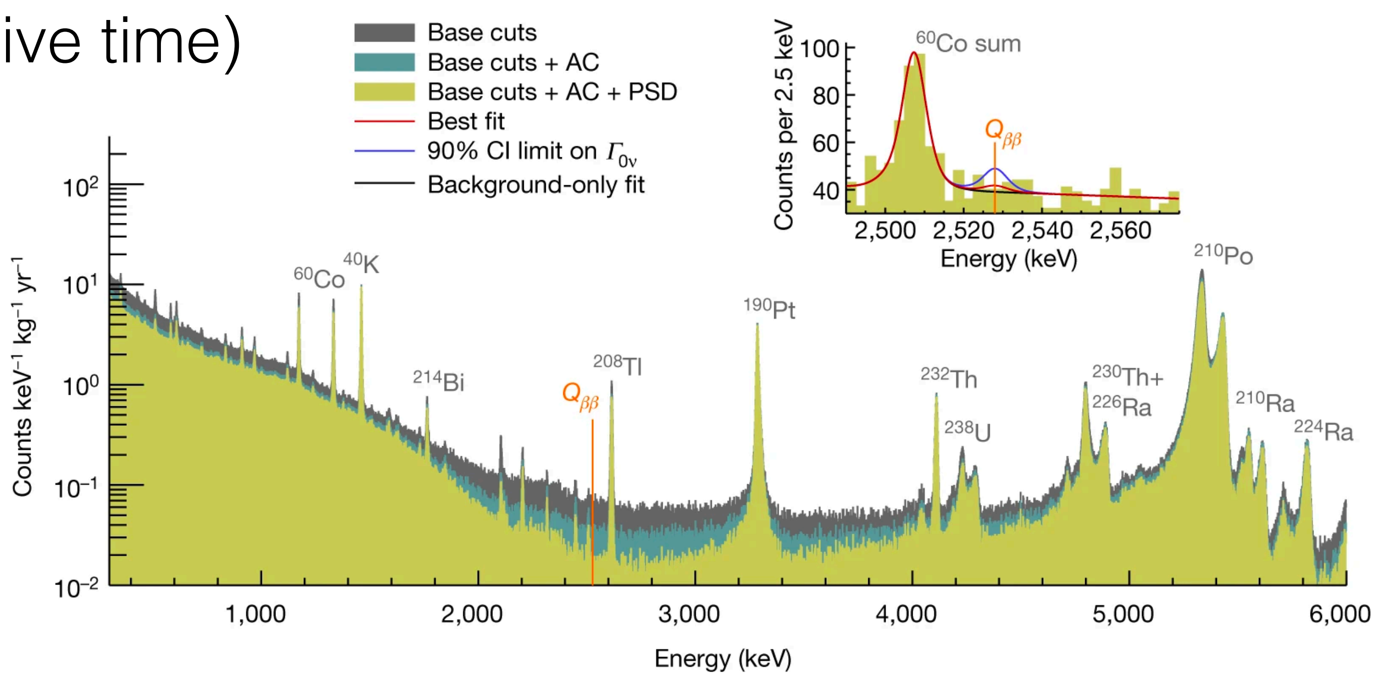
^{130}Te 0νββ decay search

Total exposure for 0νββ decay search (nature-2022)
1038.4 kg yr TeO_2, 288 kg yr ^{130}Te
Num channels after analysis cuts: ~934

- Containment efficiency for a 0νββ decay to be single site event (evaluated via MC) - (88.350 ± 0.090)% —> background spectrum with only M1 events
- **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)



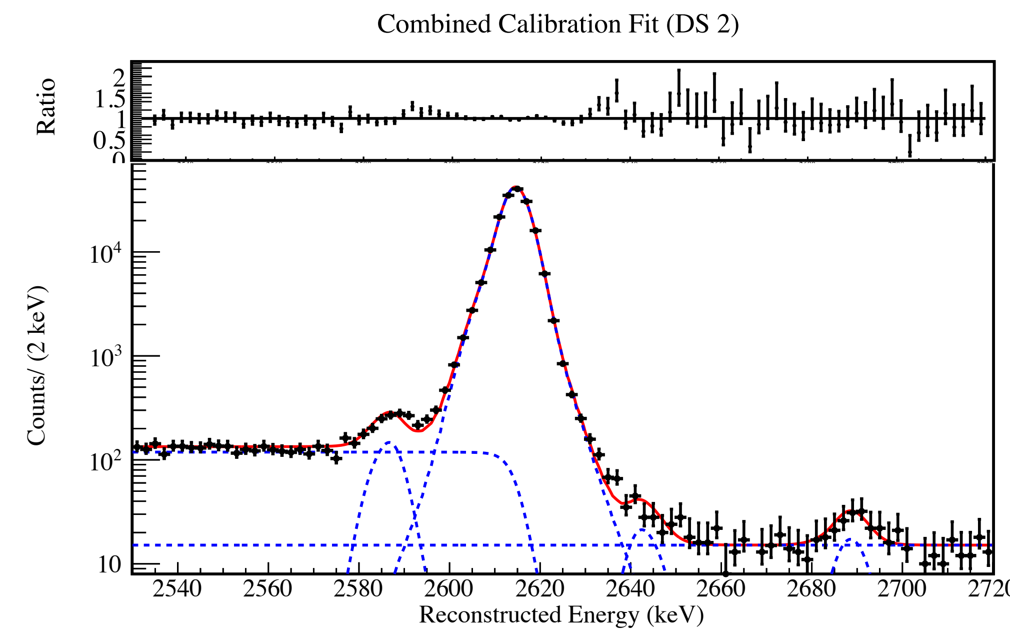
Selection efficiencies: 92.4(2)% (evaluated on data) - trigger, energy reconstruction, pile-up rejection, multiplicity (M1), PSA



Adams D. et al. (CUORE collaboration), *Nature* 604 (2022) 7904, 53-58, https://www.nature.com/articles/s41586-022-04497-4

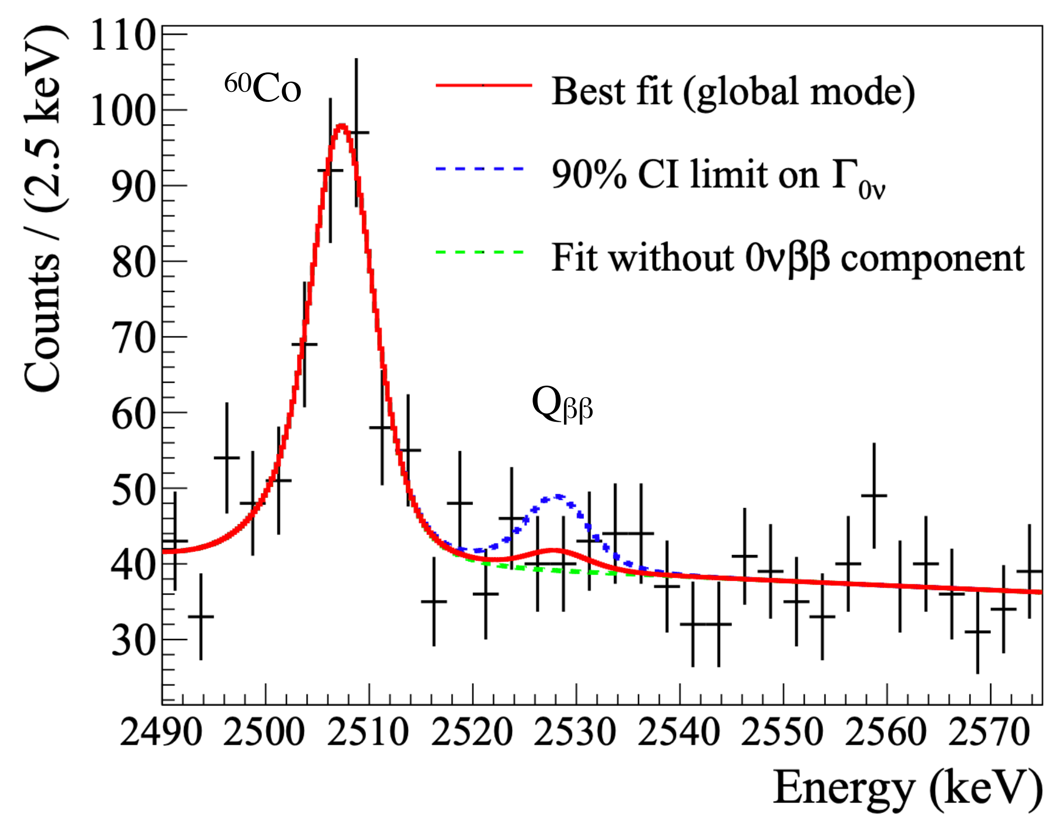
^{130}Te 0νββ decay search

Detector response function built on the 2615 keV calibration line.
Apply a scaling factor to obtain the correct **energy resolution at $Q_{\beta\beta}$:7.8(5) keV FWHM**



0νββ peak search on 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)



Adams D. et al. (CUORE collaboration), *Nature* 604 (2022) 7904, 53-58, https://www.nature.com/articles/s41586-022-04497-4

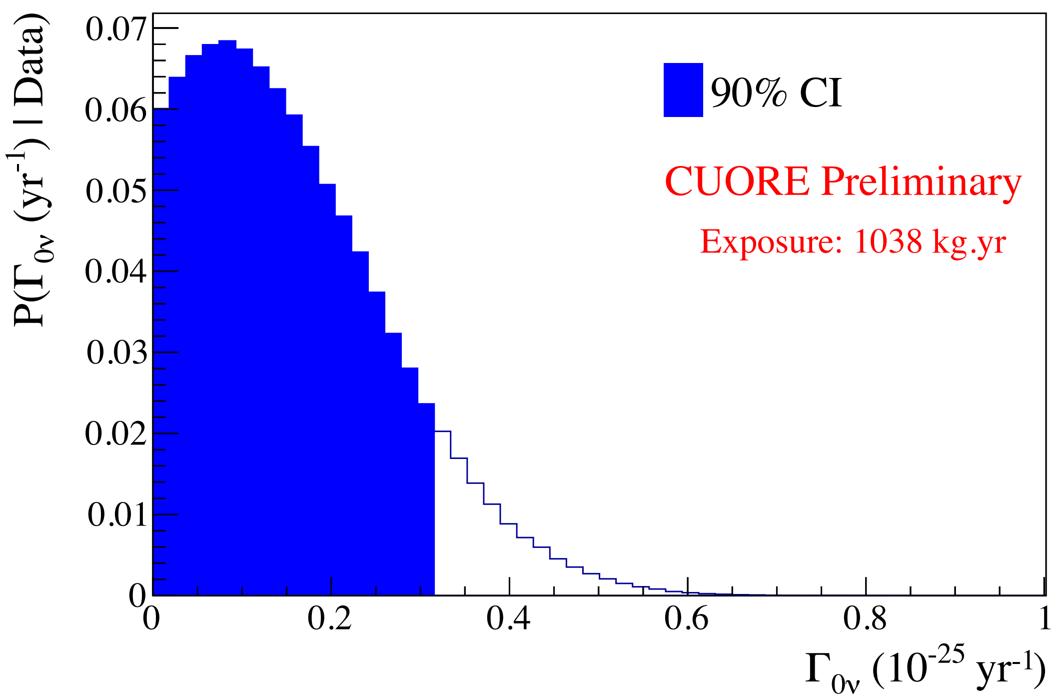
^{130}Te $0\nu\beta\beta$ decay search

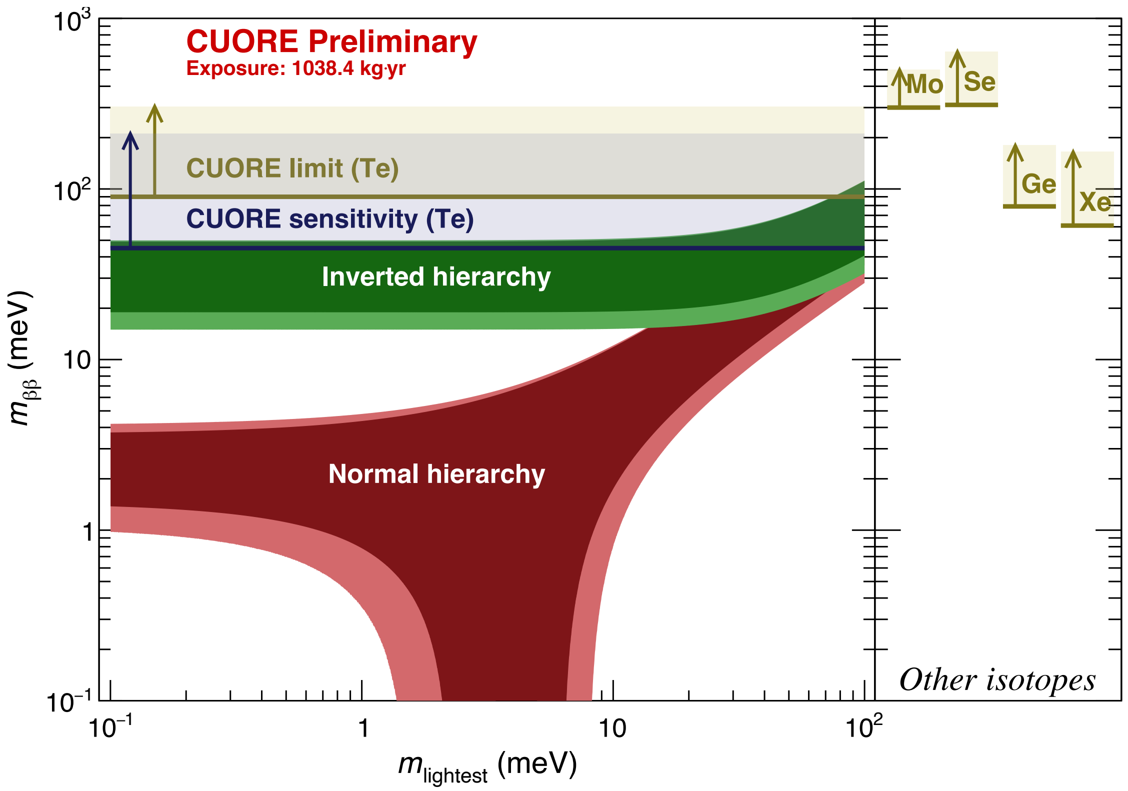
No evidence of signal at $Q_{\beta\beta}$ in ROI.
Posterior of $\Gamma_{0\nu}$: extract an upper limit on decay rate.

Half-life limit for $0\nu\beta\beta$ in ^{130}Te (90%C.I. including syst.)
$T_{0\nu}^{1/2}$ (^{130}Te) > 2.2 x 10^{25} yr

Repeating the fit in the ROI,
without the $0\nu\beta\beta$ decay contribution
ROI background index (B)
1.49(4) × 10^{-2} c/(keV·kg·yr)

Limit on $0\nu\beta\beta$ decay half life and interpretation in context of light Majorana neutrino exchange:
$m_{\beta\beta}$ < 90 - 305 meV at 90% C.I.



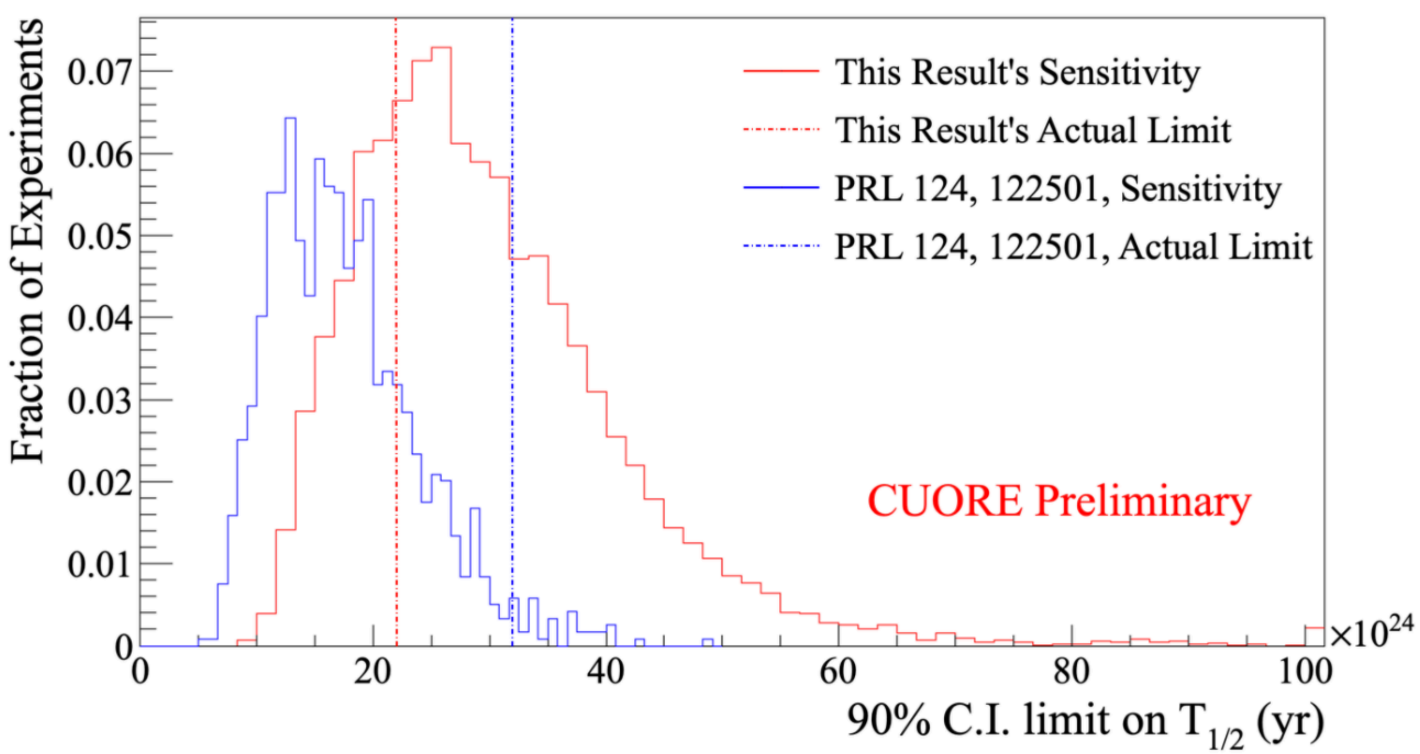


Adams D. et al. (CUORE collaboration), *Nature* 604 (2022) 7904, 53-58,
https://www.nature.com/articles/s41586-022-04497-4

^{130}Te 0νββ decay search

Exclusion sensitivity for 0νββ decay and CUORE results:

- PRL 2020 (372.5 kg yr TeO2): $T_{0\nu}^{1/2}$ (^{130}Te) > 3.2 x 10^{25} yr; $S_{0\nu}^{1/2}$ (^{130}Te) = 1.7 × 10^{25} yr; Probability to get a more stringent limit given the current sensitivity: 3%; $m_{\beta\beta}$ < 75 - 350 meV
- arXiv 2021 (1038.4 kg yr TeO_2): $T_{0\nu}^{1/2}$ (^{130}Te) > 2.2 x 10^{25} yr; $S_{0\nu}^{1/2}$ (^{130}Te) = 2.8 × 10^{25} yr; Probability to get a more stringent limit given the current sensitivity: 72%; $m_{\beta\beta}$ < 90 - 305 meV



Alduino C. et al. (CUORE collaboration), Phys. Rev. Lett. 124, 122501, (2020), https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.122501

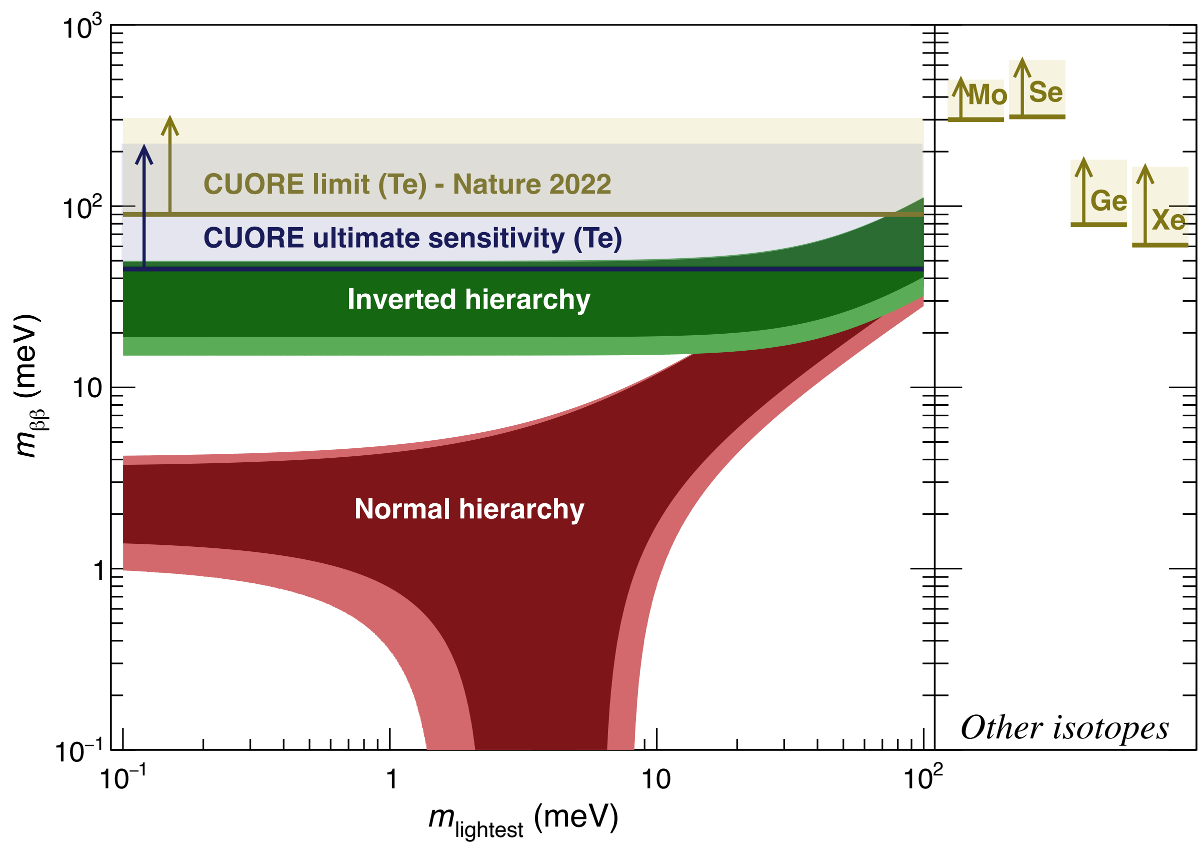
Adams D. et al. (CUORE collaboration), arXiv:2104.06906 (2021), https://arxiv.org/abs/2104.06906

CUORE 0νββ sensitivity and perspectives

CUORE ^{130}Te 0νββ decay search

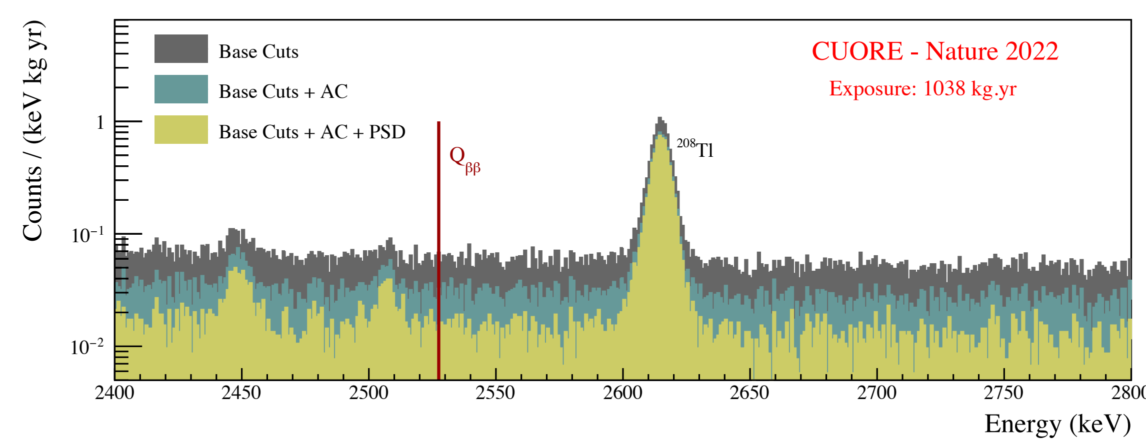
^{130}Te 0νββ decay exclusion sensitivity in 5 years

$S_{0\nu}$ ~ 9 x 10^{25} yr (90% C.L.), $m_{\beta\beta}$ < 50-130 meV with
nominal ROI background B: **10^{-2} c/(keV·kg·yr)**



CUORE TeO_2 detectors background in ROI:

- **Degraded α particles**, produced from radioactive decays close to the detectors or on their surface, which deposit part of their energy in the detectors - ~90% contribution
- Multi-Compton of γ emitted by the $^{232}Th/^{238}U$ chains and cosmic muons - <10% contribution



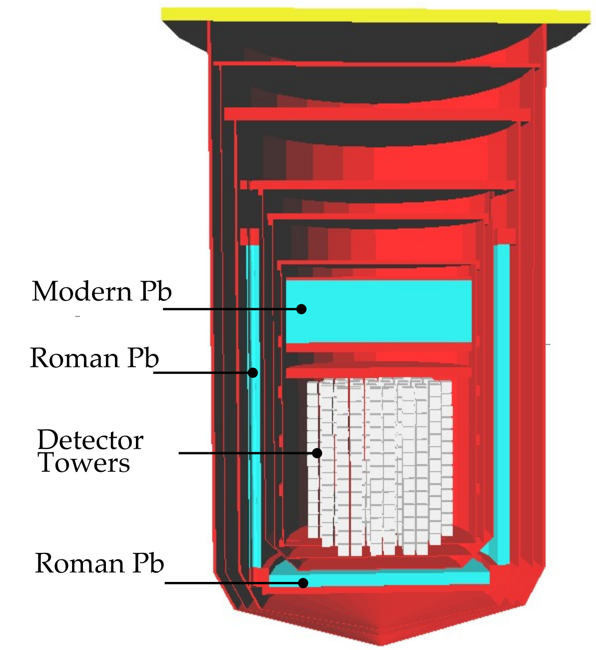
2νββ decay and background analysis

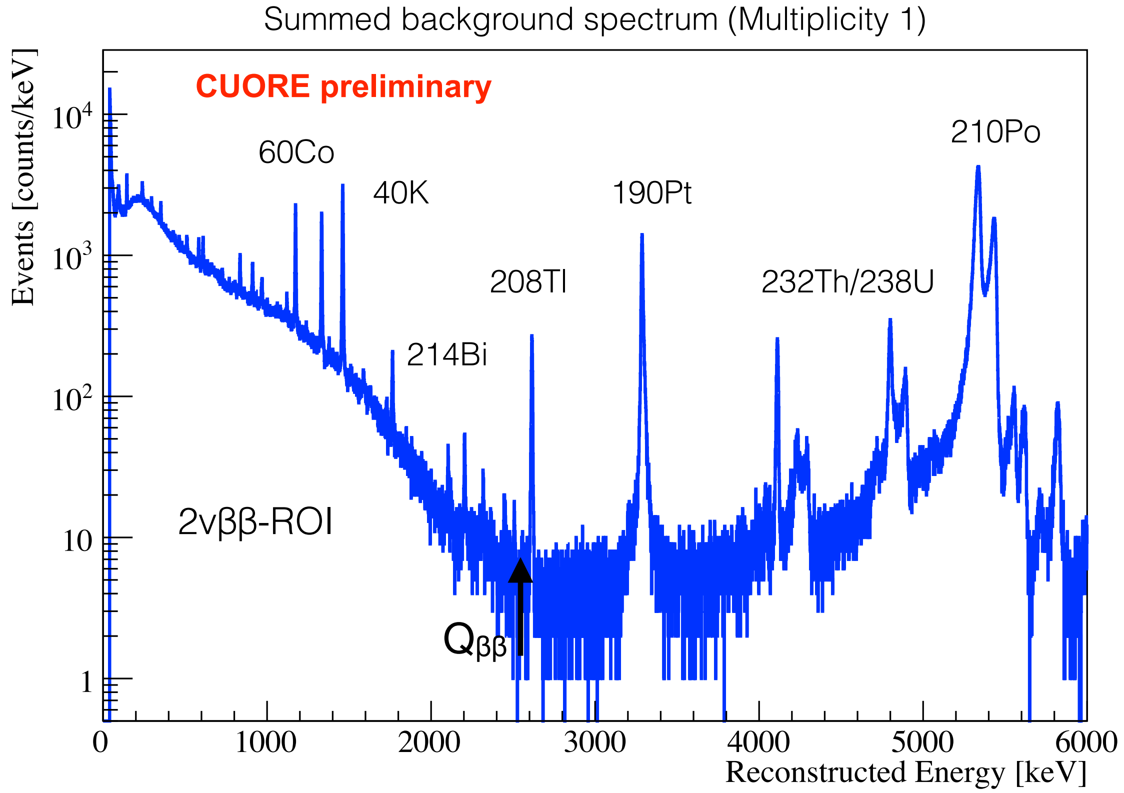
Monte Carlo Reconstruction of the CUORE background

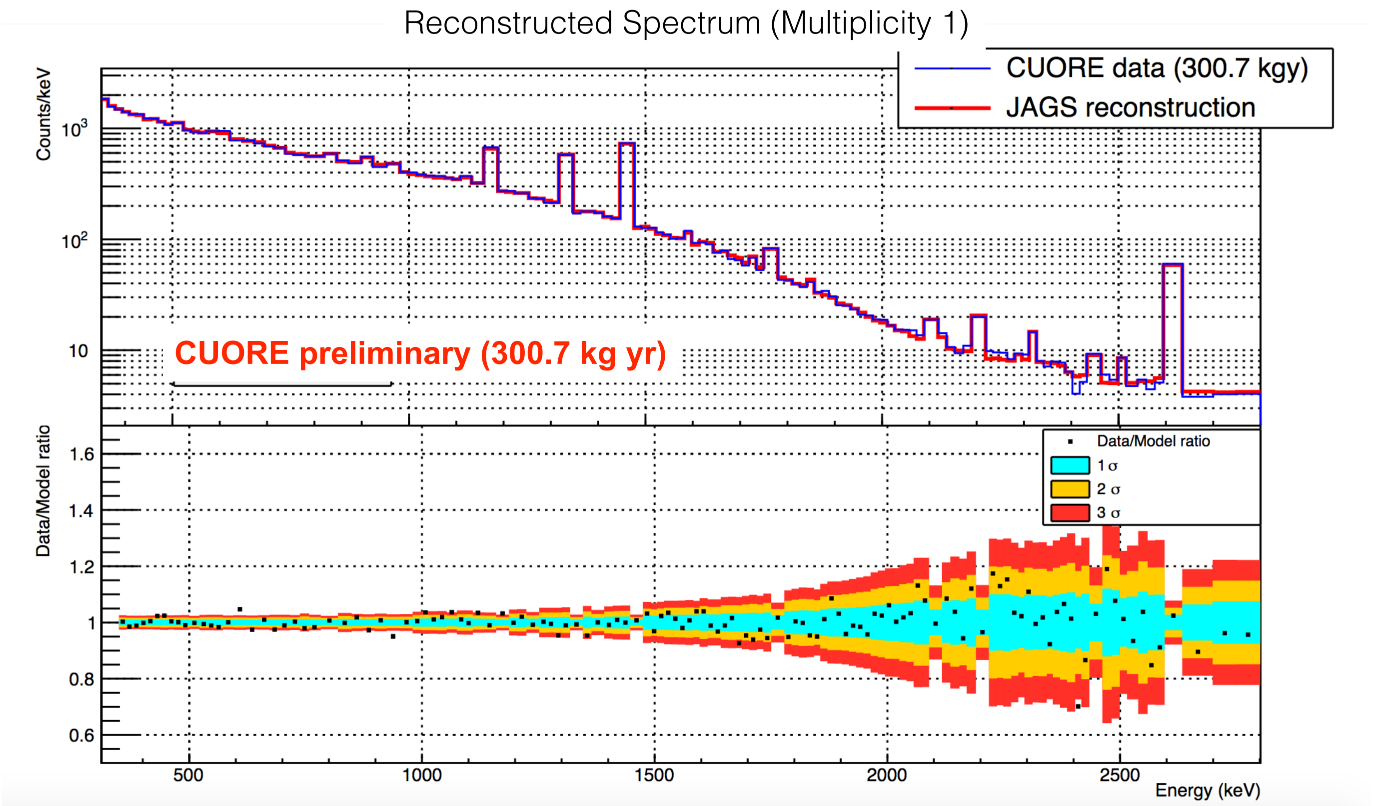
- GEANT4 simulation + measured detector response function to produce expected spectra
- 61 background sources simulated, bayesian MCMC fit with uniform priors (except muons)

Profit of a segmented detector: events multiplicity, background sources location, inner towers self-shielded from outer contaminants

Total exposure for 2νββ analysis: 300.7 kg yr







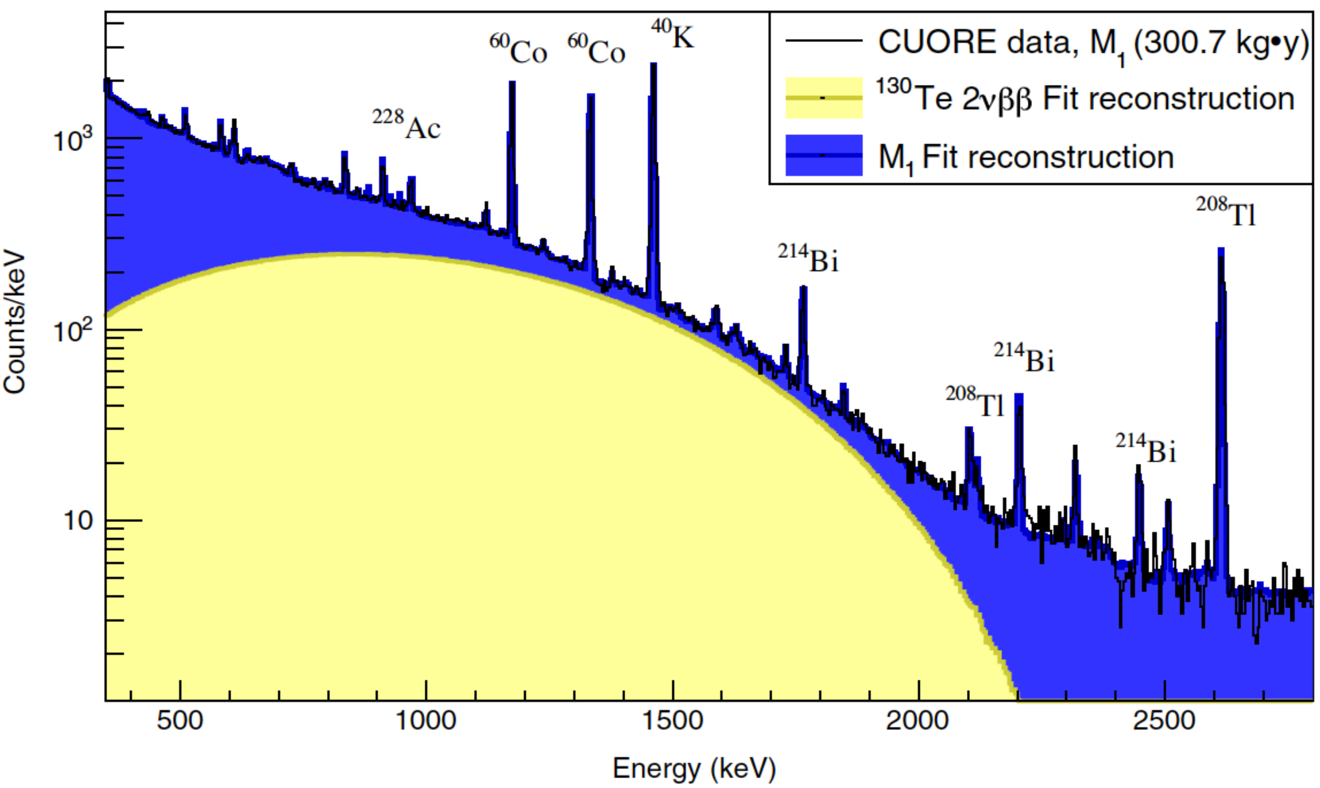
Adams D. et al. (CUORE collaboration), Phys. Rev. Lett. 126, 171801 (2021)
https://doi.org/10.1103/PhysRevLett.126.171801

2νββ decay and background analysis

2νββ 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 2νββ half-life of ^{130}Te

$T_{2\nu}^{1/2}$ (^{130}Te) = [7.71 $^{+0.08}_{-0.06}$(stat) $^{+0.12}_{-0.15}$(syst)] x 10^{20} yr



Exposure: 300.7 kg yr TeO_2, 102.7 kg yr ^{130}Te

	$T_{1/2}^{2\nu}$ (10^{20} yr)	Relative uncertainty	Reference
MiBeta	$6.1 \pm 1.4^{+2.9}_{-3.5}$	57%	2003 [51]
NEMO-3	$7.0 \pm 0.9 \pm 1.1$	20%	2011 [50]
CUORE-0	$8.2 \pm 0.2 \pm 0.6$	7.7%	2016 [39]
CUORE	$7.71^{+0.08+0.12}_{-0.06-0.15}$	2.0%	(This result)

Systematic uncertainties (~2%):

- Choice of 2νββ spectrum (SSD vs HSD)
- Data selection: energy threshold, geometric splitting, time splitting, fit range
- Unconstrained fallout products (90Sr)

Adams D. et al. (CUORE collaboration), Phys. Rev. Lett. 126, 171801 (2021)
https://doi.org/10.1103/PhysRevLett.126.171801

ββ decay to excited states analysis

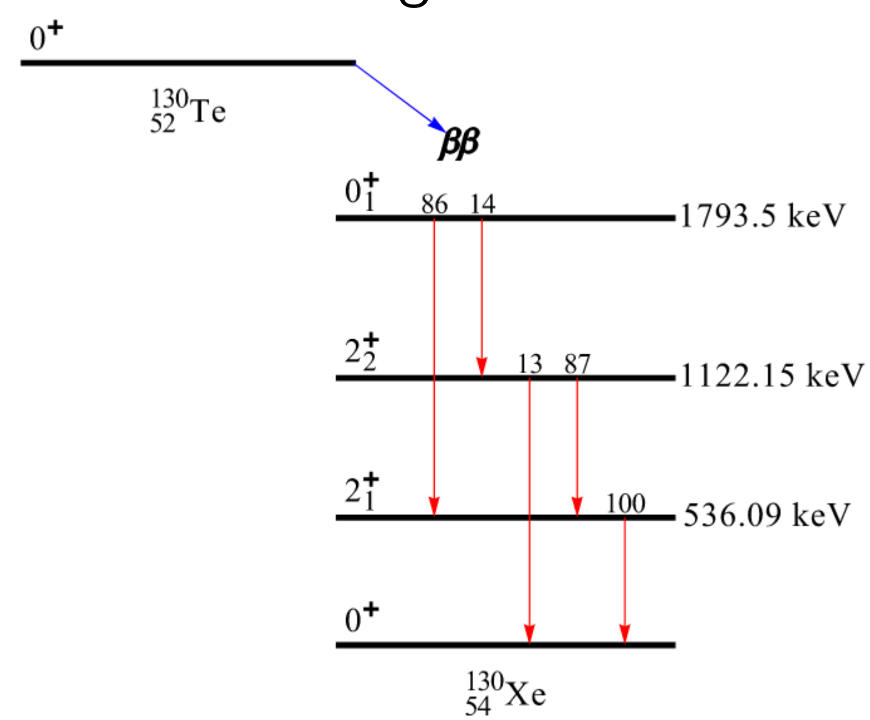
Search for 0νββ and 2νββ decays of ^{130}Te to the first 0+ excited state of ^{130}Xe

- 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: no evidence of signal

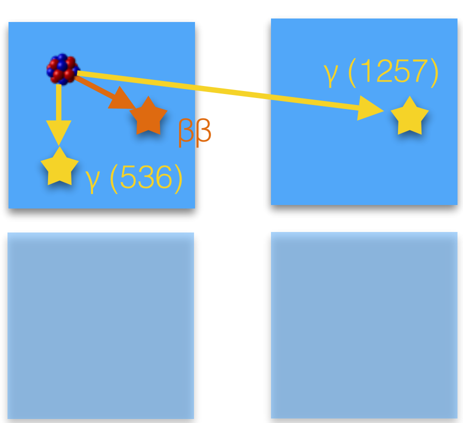
Signature of the decay:

Cascade of de-excitation γs in coincidence with βs

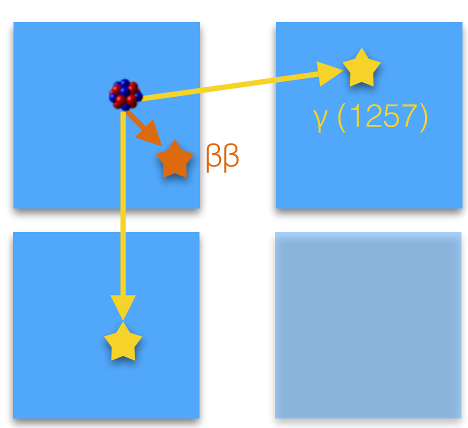
- multi-site signatures
- background reduction with respect to the corresponding transitions to the ground state, especially in case of a high detector granularity



M2



M3



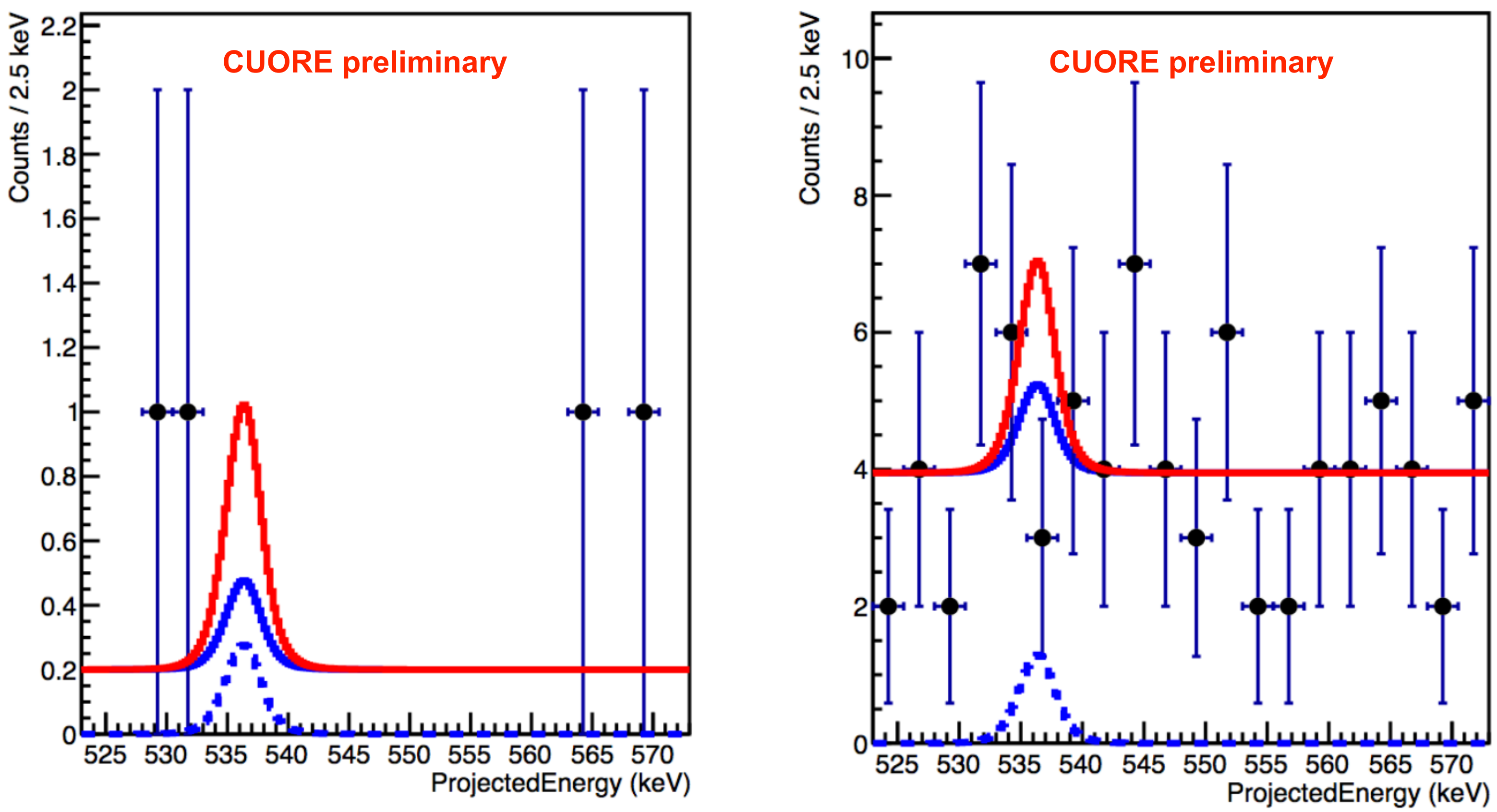
Pattern	BR [%]	Energy γ_1	Energy γ_2	Energy γ_3
A	86%	1257 keV	536 keV	-
B	12%	671 keV	586 keV	536 keV
C	2%	1122 keV	671 keV	-

ββ decay to excited states analysis

CUORE

Considering only fully contained events for the analysis
Selected a set of experimental signatures for the analysis (M2, M3 events), the ones which contribute the most to the discovery sensitivity in the ββ decay rate

0νββ, sig. 2A2-2B3 **2νββ**, sig. 2A2-2B3



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

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.)

Adams D. et al. (CUORE collaboration), Eur. Phys. J. C (2021) 81:567
https://doi.org/10.1140/epjc/s10052-021-09317-z

^{120}Te 0νβ+EC decay search

^{120}Te could potentially decay to ^{120}Sn via 0νECEC and 0νβ+EC.
We did not investigate the former channel as this mode is expected to be suppressed except in the case of the existence of a resonance condition.

Limits on ^{120}Te β+EC half life:
$T_{1/2}^{0\nu} > 2.7 \times 10^{21}$ yr (90% C.I.) - Cuoricino + CUORE-0
$T_{1/2}^{2\nu} > 7.6 \cdot 1019$ yr (90% C.L.) - Cuoricino

The 0νβ+EC decay of 120Te can be expressed as:

$$\begin{aligned} {}^{120}\mathrm{Te} + e_b^- &\to {}^{120}\mathrm{Sn}^* + \beta^+ \\ &\to {}^{120}\mathrm{Sn} + X + \beta^+ \\ &\to {}^{120}\mathrm{Sn} + X + 2\gamma_{511} \end{aligned}$$

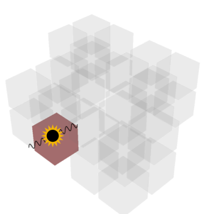
The CUORE analysis of 0νβ+EC decay of 120Te exploits the high granularity of the detector to reconstruct event topologies via a coincidence analysis, thereby minimizing contributions from background sources and optimising our sensitivity to the decay.

Signature	Particles Detected	Signal Peak Position [keV]	Multiplicity	Energy range [keV] ΔE$_0$	ΔE$_1$	ΔE$_2$	Containment efficiency ε_{mc} [%]
(a)	$\beta^+ + X + \gamma_{511}$	1203.8	1	[1150,1250]			12.8(5)
(b)	$\beta^+ + X + 2\gamma_{511}$	1714.8	1	[1703,1775]			13.1(5)
(c)	$(\beta^+ + X,\ \gamma_{511})$	(692.8, 511)	2	[650,750]	[460,560]		4.10(20)
(d)	$(\beta^+ + X + \gamma_{511},\ \gamma_{511})$	(1203.8, 511)	2	[1150,1250]	[460,560]		13.8(6)
(e)	$(\beta^+ + X,\ \gamma_{511},\ \gamma_{511})$	(692.8, 511, 511)	3	[650,750]	[460,560]	[460,560]	2.15(9)

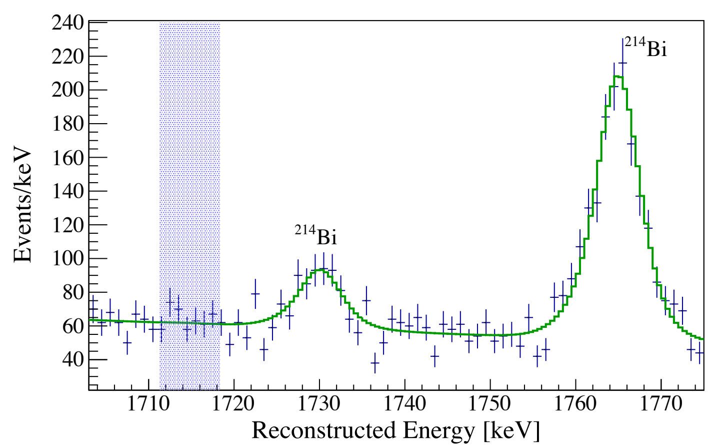
Adams D. et al. (CUORE collaboration), arXiv:2203.08684,
https://doi.org/10.48550/arXiv.2203.08684

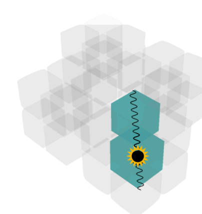
^{120}Te 0νβ$^+$EC decay search

Analysis of only fully contained events

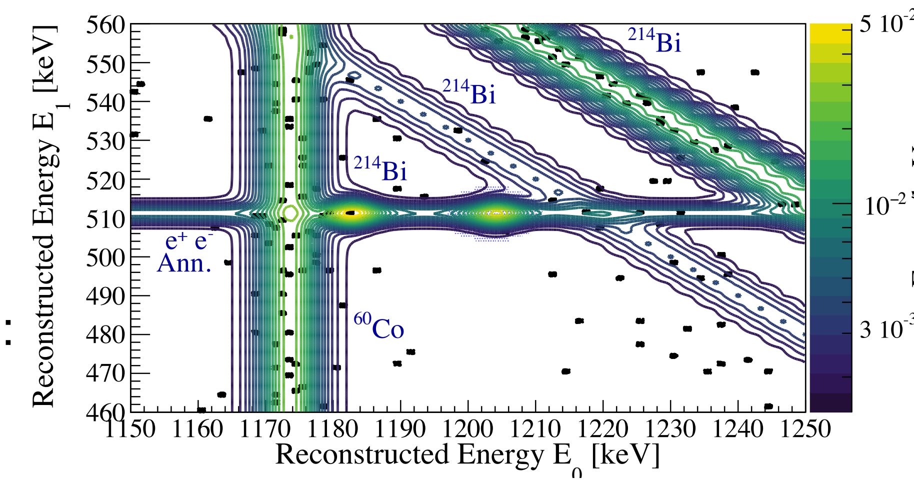


M1
$\beta^+ + X + 2\,\gamma_{511}$:
1714.8 keV

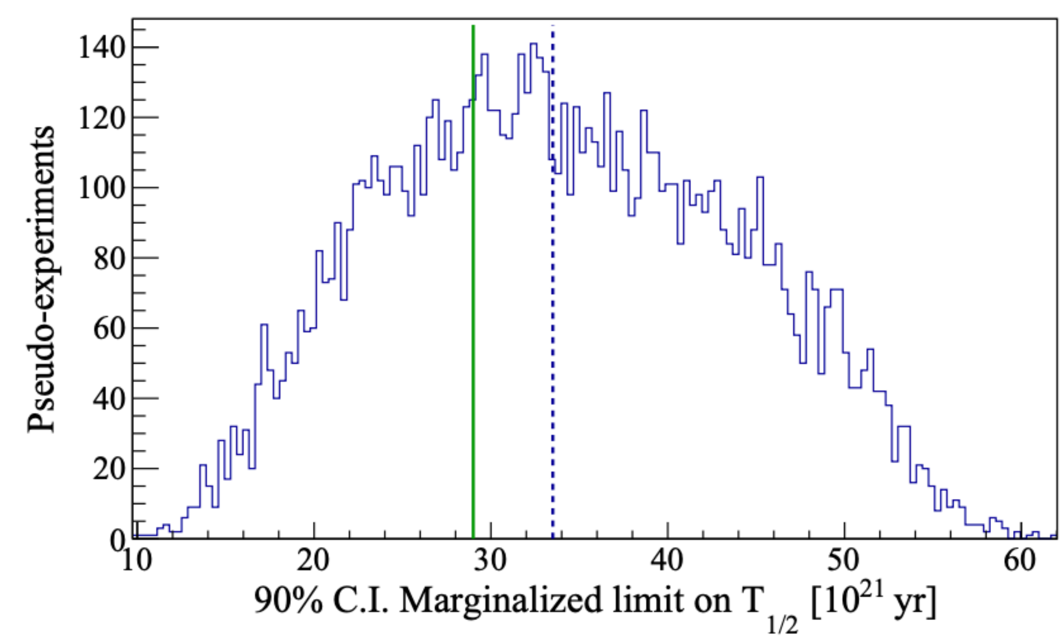




M2
$(\beta^+ + X + \gamma_{511}, \gamma_{511})$:
(1203.8, 511) keV



Half-life limit @90%C.I. **$T_{0\nu}^{1/2}$ (^{120}Te) > 2.9 × 10^{22} yr**
Median exclusion sensitivity: $S_{0\nu}^{1/2}$ (^{120}Te) = 3.4 × 10^{22} yr



Exposure: 355.7 kg·yr TeO_2, 0.2405 kg·yr ^{120}Te

Adams D. et al. (CUORE collaboration), arXiv:2203.08684,
https://doi.org/10.48550/arXiv.2203.08684

^{128}Te 0νββ decay search

^{128}Te has high abundance in CUORE (nat)TeO2 detectors, but direct search of ^{128}Te ββ decay is challenging due to the low $Q_{\beta\beta}$ value of (866.7±0.7) keV, lying in a region of the energy spectrum dominated by 2νββ decay of ^{130}Te and γ backgrounds from other natural radioactivity.

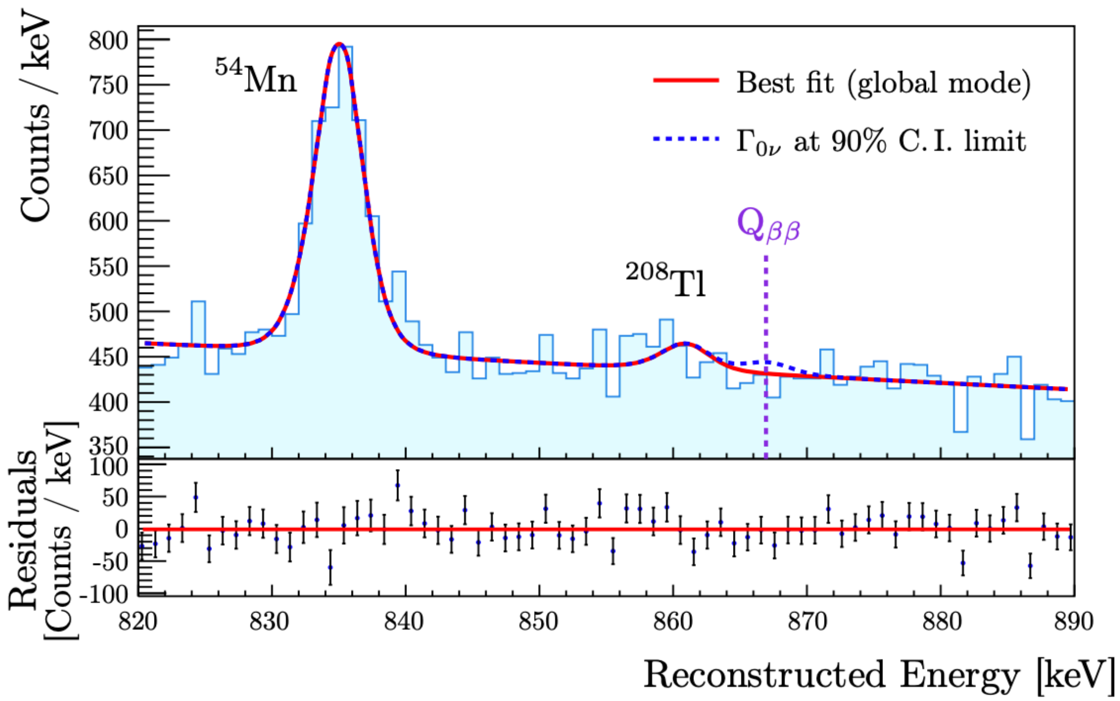
^{128}Te 0νββ decay half-life limit - direct search: $T_{1/2}^{0\nu} > 1.1 \times 10^{23}$ yr - MiDBD

Geochemical measurements: evaluate the presence of the ββ decay products accumulated in geological mineral samples of known age via the assessment of the parent/daughter nuclei ratio; sensitive to the sum of all the possible decays, but 2νββ expected to be dominant.

^{128}Te 2νββ decay half-life, based on the ratio $T_{1/2}^{2\nu}(^{130}Te)/T_{1/2}^{2\nu}(^{128}Te) = (3.52 \pm 0.11) \times 10^{-4}$
$T_{1/2}^{2\nu} = (2.25 \pm 0.09) \times 10^{24}$ yr - weighted avg of $T_{1/2}^{2\nu}(^{130}Te)$ CUORE-0 and CUORE
$T_{1/2}^{2\nu} = (2.19 \pm 0.07) \times 10^{24}$ yr - from $T_{1/2}^{2\nu}(^{130}Te)$ CUORE [this analysis]

Adams D. et al. (CUORE collaboration), arXiv:2205.03132,
https://doi.org/10.48550/arXiv.2205.03132

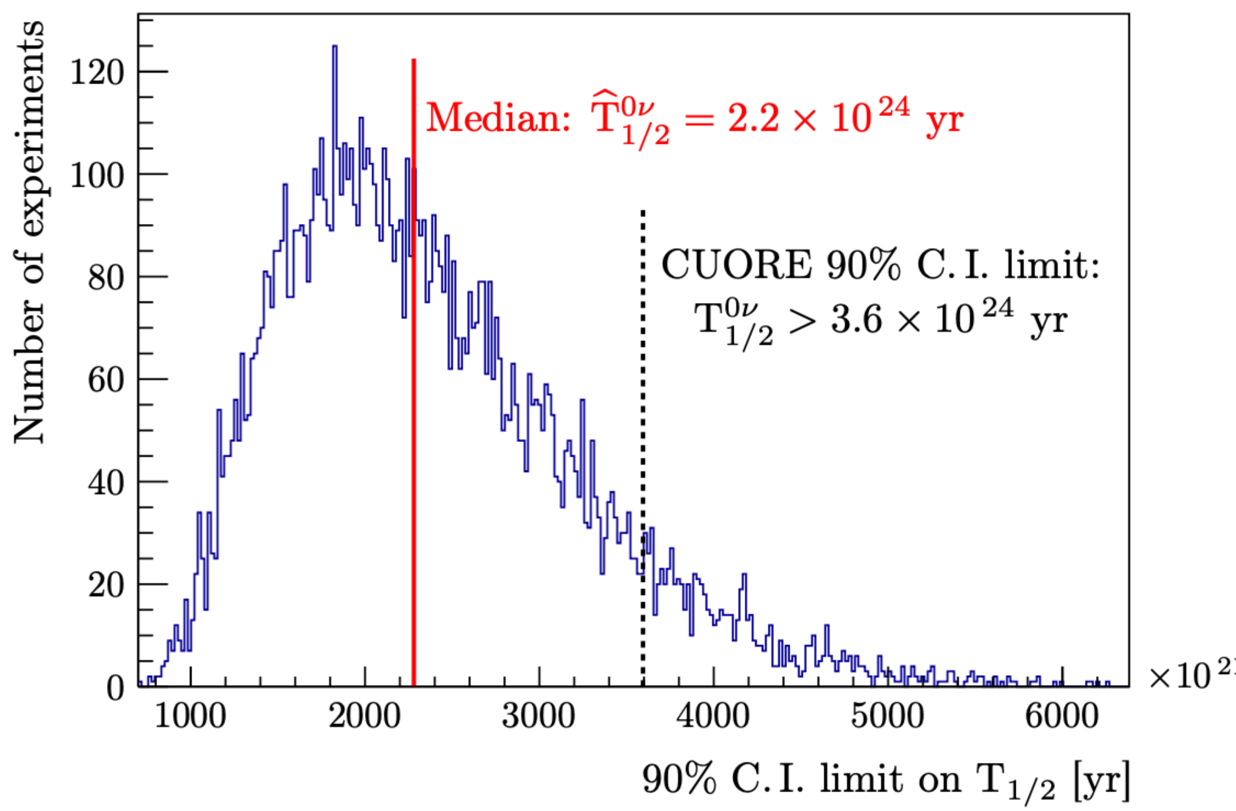
^{128}Te 0νββ decay search



Selection of M1 events
Fit of the Region of Interest [820,890] keV:
peak $Q_{\beta\beta}$ (866.7 ± 0.7) keV + ^{54}Mn and ^{208}Tl peaks + linear background

Half-life limit @90%C.I. **$T_{0\nu}^{1/2}$ (^{128}Te) > 3.6 × 10^{24} yr**
Median exclusion sensitivity: $S_{0\nu}^{1/2}$ (^{128}Te) = 2.2 × 10^{24} yr

Exposure: 309.33 kg·yr TeO_2, 78.56 kg·yr ^{128}Te



Adams D. et al. (CUORE collaboration), arXiv:2205.03132,
https://doi.org/10.48550/arXiv.2205.03132