Results and Progress from the CUORE Experiment

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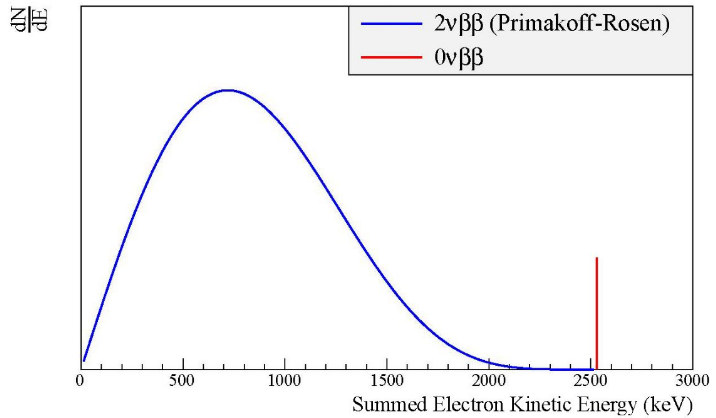
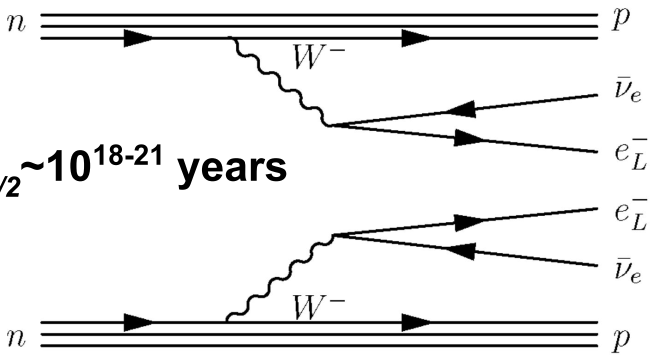
Neutrinoless Double-Beta Decay

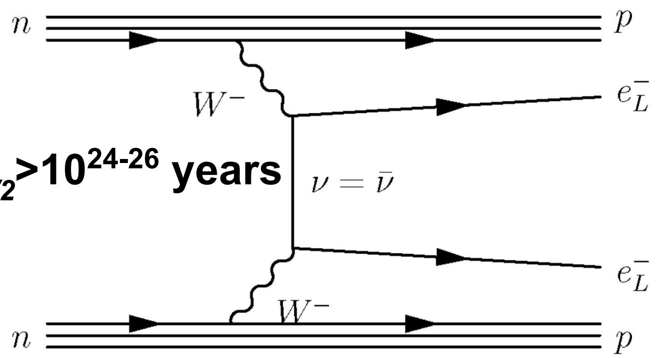
- 2vββ is a rare decay observable in select isotopes
- Hypothesized 0vββ mode provides a nuclear technique to probe the fundamental nature of neutrinos
- A discovery of 0vββ would:
  - Provide evidence of BSM physics
  - Violate *B-L* conservation
  - Imply v's are Majorana particles
- Target isotope for CUORE: ^{130}Te
  - $Q_{\beta\beta}$=2.53 MeV, 34% natural abundance

Experimental Signature: monoenergetic peak at $Q_{\beta\beta}$



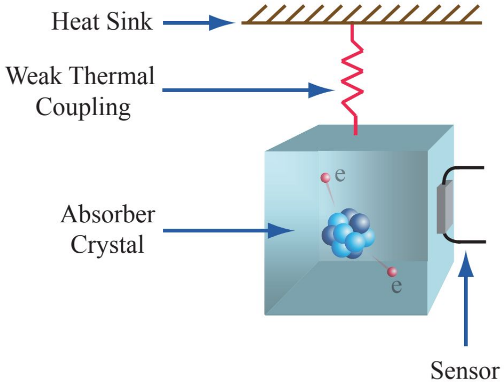


2vββ: $T_{1/2}$~$10^{18\text{-}21}$ years

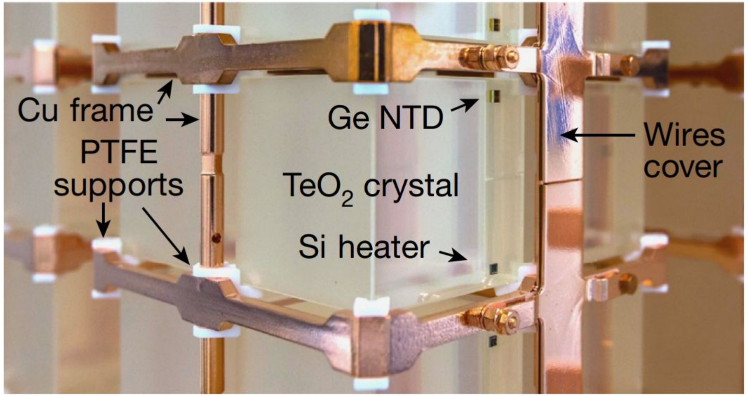


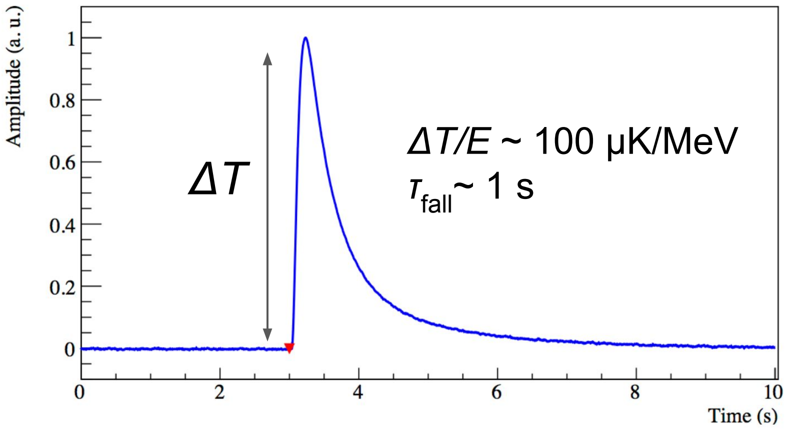
0vββ: $T_{1/2}$>$10^{24\text{-}26}$ years

The Cryogenic Calorimeter Technique

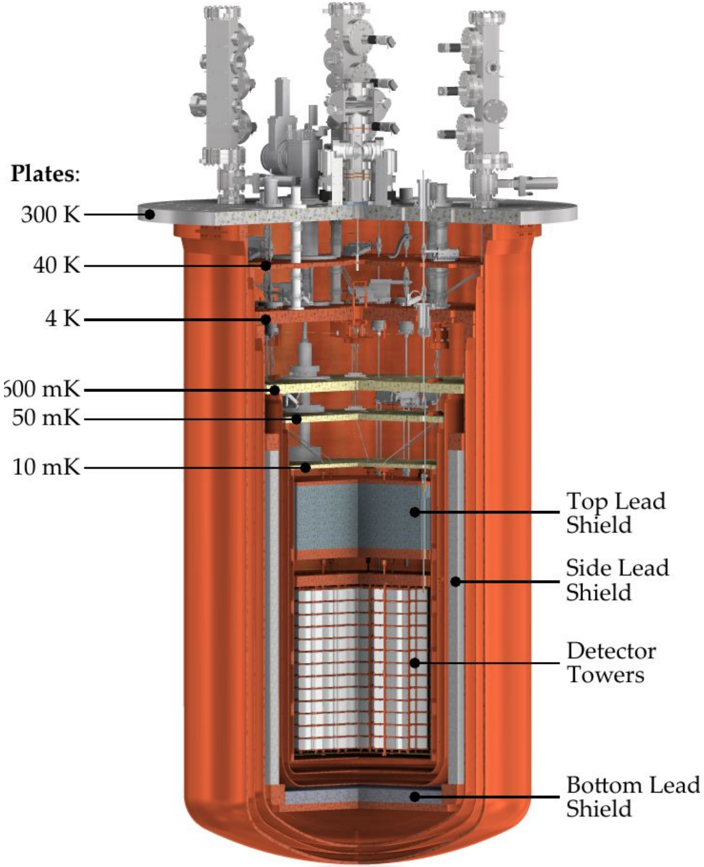


- At milli-kelvin temperatures, thermalized phonons from energy deposition in absorber leads to measurable temperature increase: read out by sensitive thermistor
- Versatile technology capable of strong energy resolution & high detection efficiency
- CUORE: Array of 988 5 cm×5 cm×5 cm TeO_2 crystals each instrumented with NTD thermistor

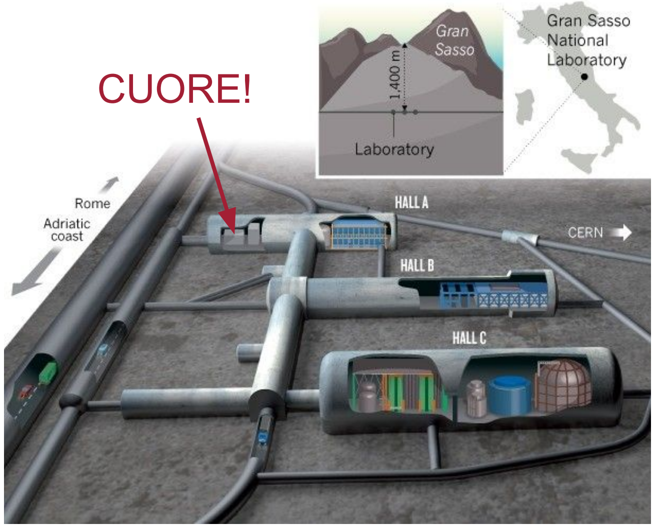




CUORE: Cryogenic Underground Observatory for Rare Events



- First ton-scale operating cryogenic 0νββ experiment
- Total TeO_2 mass of 742 kg (206 kg of ^{130}Te)
- Powerful dilution refrigerator: 3 tons of material at 50 mK or below, 1 ton at base temperature of ~10 mK
- Located at LNGS with 3600 m.w.e. overburden
- Ancient Roman Pb shield & high radiopure materials to reduce backgrounds



In Progress across CUORE…

Low-Energy:
- WIMPs
- Solar axions
- ^{123}Te EC

Rare nuclear decays
- ^{128}Te & ^{130}Te $2\nu\beta\beta$ & $0\nu\beta\beta$
- ^{130}Te decays to excited states
- ^{120}Te β^{+}EC/2EC

High-Multiplicity
- Muon backgrounds
- Exotic track-like particles
- Tri-nucleon decay

Background Model
- *In situ* characterization
- Delayed coincidences

Detector Response
- Electrothermal model
- Denoising
- Seismic correlations

And More!

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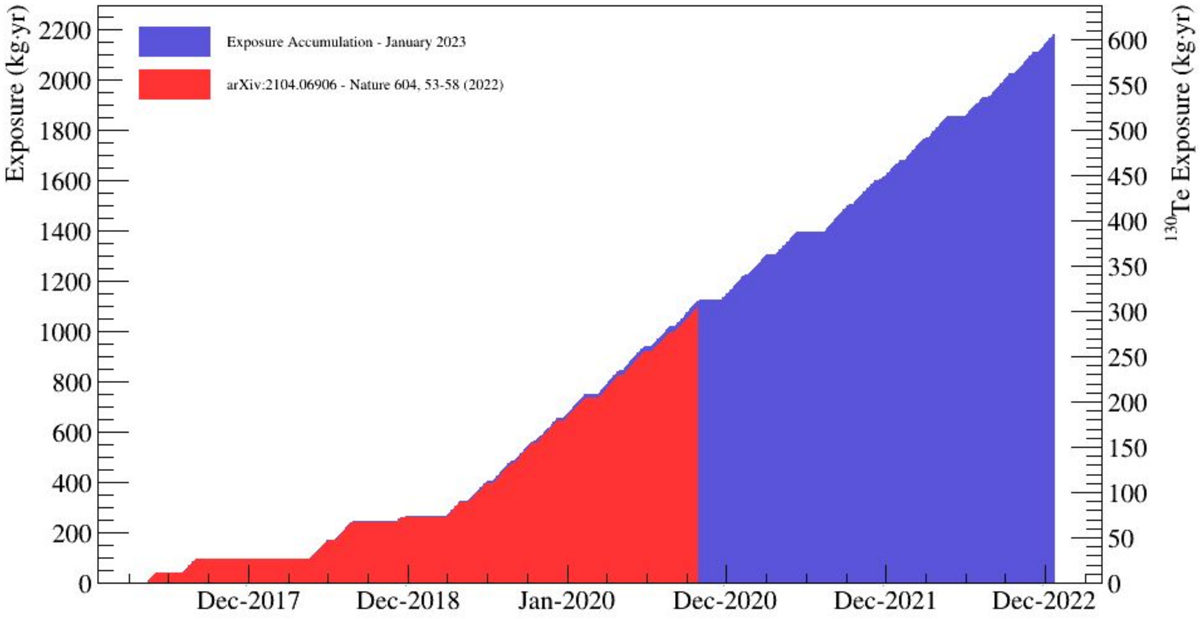
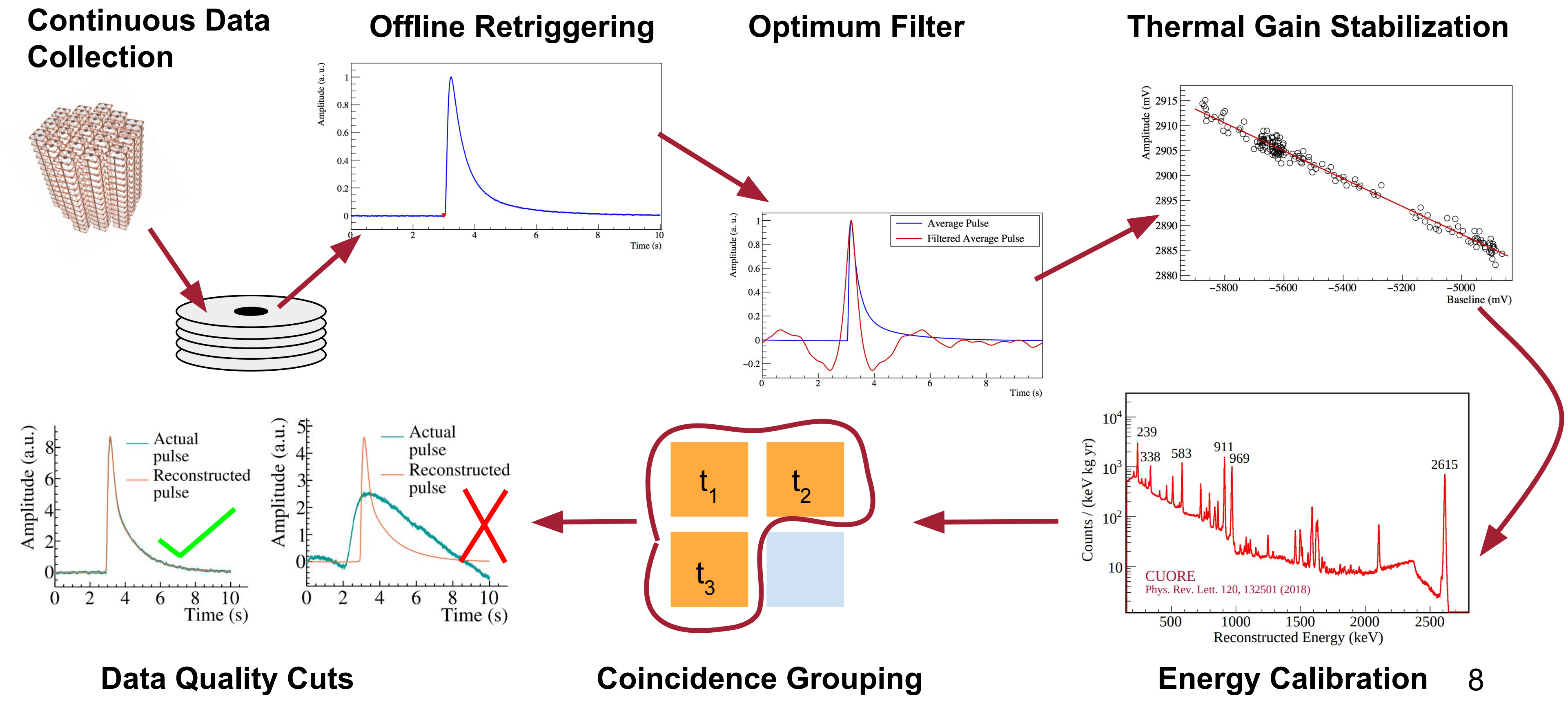
CUORE Data Collection

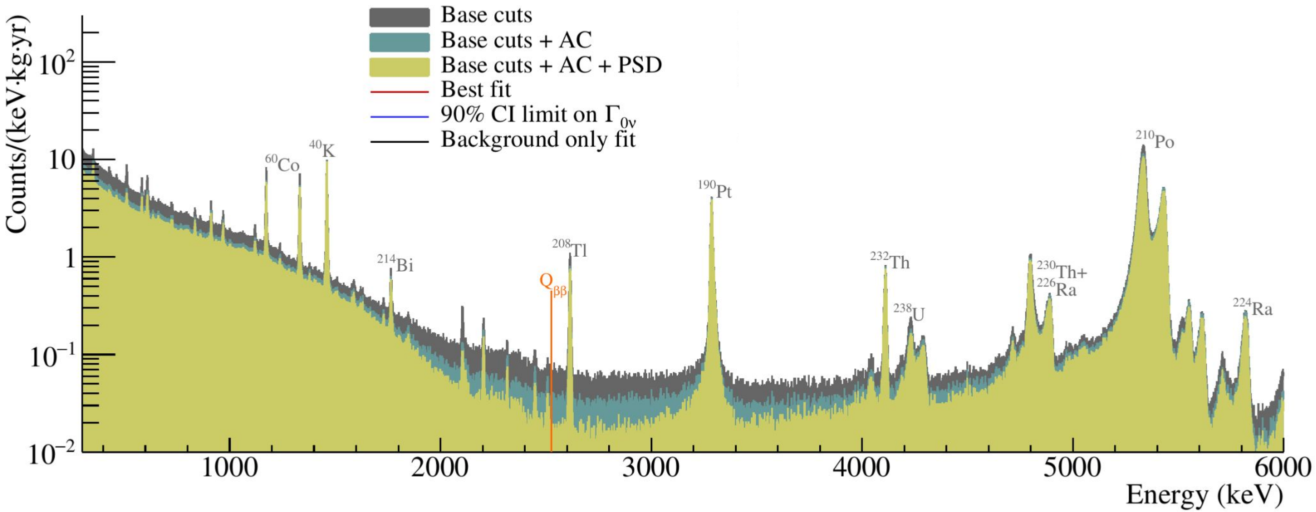
- Online since mid-2017
- Steady data-taking since ~early 2019 following cryogenic interventions and optimizations
  - Continued over pandemic without interruption!
- Data collection ongoing at ~50 kg yr/month of raw exposure
- Background datasets of 1-2 months, with calibration periods at beginning and end with external sources
- Approx. ½ of current collected data analyzed in latest $0\nu\beta\beta$ search



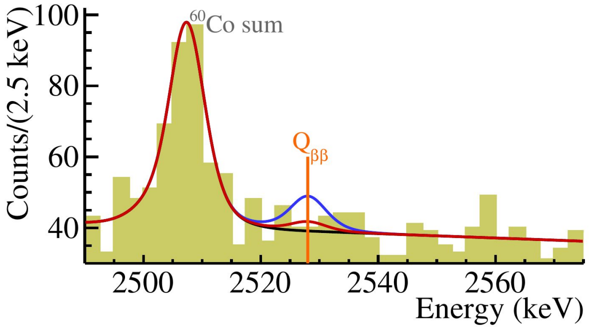
CUORE Data Processing: 1 ton year data release



Latest 0νββ Results: *Nature* **604** 53-58 (2022)



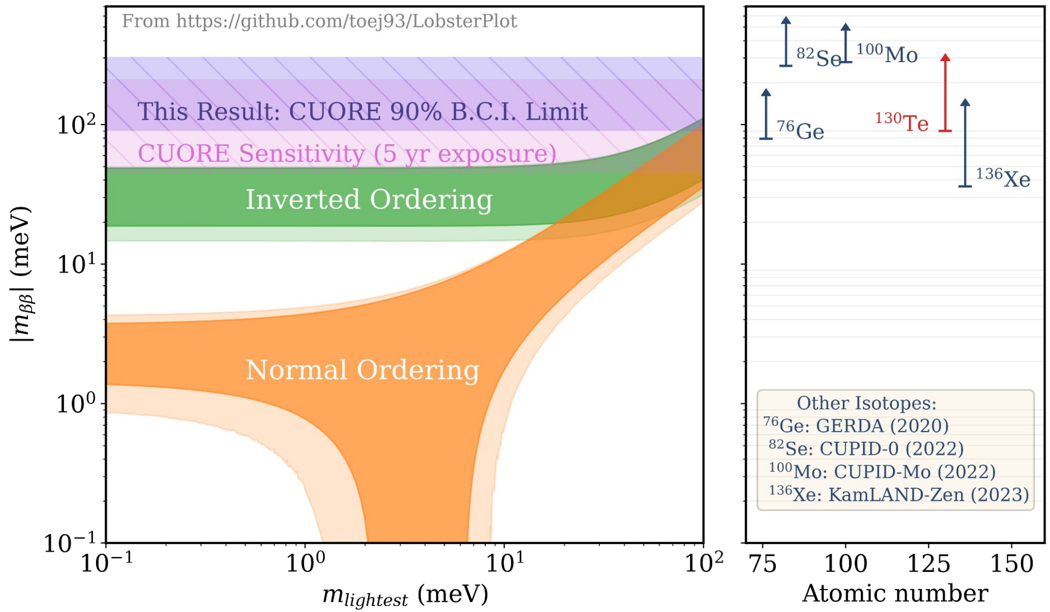
0νββ ROI:

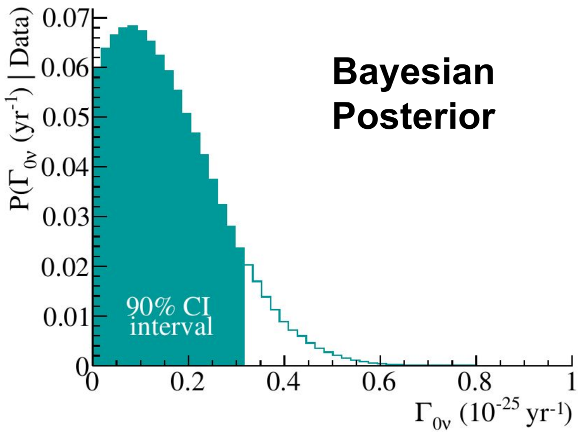


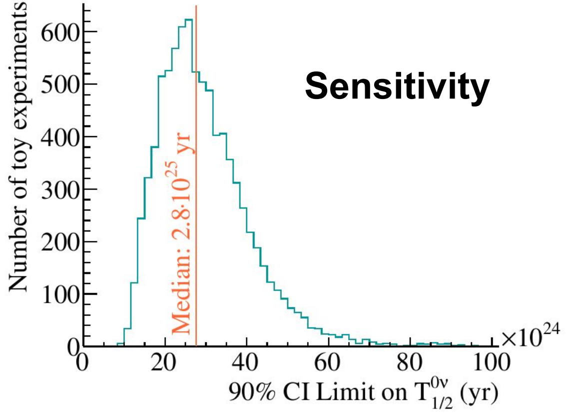
- Search with >1 t yr of total TeO_2 exposure
- 88% of 0νββ events would occur in only 1 crystal:
  - Apply anti-coincidence cut to veto events with crystal multiplicity greater than one
- No particle identification: dominant background in ROI is from degraded alphas

Detector Parameter	Value
TeO_2 Exposure	1038.4 kg yr
^{130}Te Exposure	288.8 kg yr
FWHM at 2615 keV (calibration)	7.78(3) keV
FWHM at $Q_{\beta\beta}$ (physics data)	7.8(5) keV
Total analysis efficiency (data)	92.4(2)%
Containment efficiency (MC)	88.35(9)%
Average background index at $Q_{\beta\beta}$	$1.49(4)\cdot10^{-2}$ ckky

Latest $0\nu\beta\beta$ Results: *Nature* **604** 53-58 (2022)







- **No evidence of decay**
- Best-fit rate: $\Gamma^{0\nu}$ **= (0.9±1.4)·10^{-26} yr^{-1}**
- Bayesian 90% Credibility Interval: $T_{1/2}^{0\nu}$ **> 2.2·10^{25} yr**
- Most-sensitive search in ^{130}Te to-date
  - Median exclusion sensitivity: **2.8·10^{25} yr**
- Corresponding limit: **$m_{\beta\beta}$< (90 - 305) meV**

Latest 0νβ… 8 (2022)

March

Neuroimaging

Brain changes after COVID revealed by imaging

In 2020, the UK Biobank (a large-scale biomedical database and research resource) launched a COVID-19 repeat-imaging study, in which participants who had completed a medical-imaging session before the pandemic returned for an identical, second scan session. Douaud *et al.* explored these data, comparing scans pre- and post-pandemic. Participants who had tested positive for SARS-CoV-2 between the two scans exhibited changes in the brain cortex that are often associated with worsening brain health. This group also displayed increases in markers of tissue damage in brain regions connected to smell and taste. There is much more work to be done to extract all the useful information from this valuable data set. The UK Biobank's data sharing and Douaud and colleagues' release of their analysis code serve as an open invitation to join the effort.

Randy L. Gollub writing in *Nature* **604**, 633–634 (2022).
Original research: *Nature* **604**, 697–707 (2022).

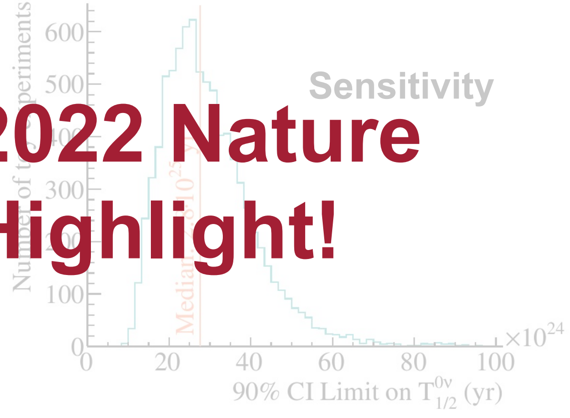
April

Nuclear physics

Cryogenic mastery aids bid to spot matter creation

Astrophysical observations reveal that the Universe is made almost entirely of matter, with nearly no antimatter in sight. However, laboratory and particle-collider experiments have so far observed the creation of matter and antimatter in equal parts. Big Bang theories that aim to explain the cosmic-matter imbalance predict that matter could be generated without antimatter in a 'little bang', during an ultra-rare nuclear process called neutrinoless double-β decay. The CUORE Collaboration reports the most sensitive search yet for this type of decay using isotopes of tellurium. The decay was not observed, but the engineering feat was remarkable – requiring the stable operation of more than one tonne of experimental apparatus, at cryogenic temperatures close to 10 millikelvin, over several years. The CUORE refrigerator is unofficially referred to as the coldest cubic metre in the known Universe.

Jason Detwiler writing in *Nature* **604**, 42–43 (2022).
Original Research: *Nature* **604**, 53–58 (2022).



2022 Nature Highlight!

- No evidence
- Best-fit rate:
- Bayesian 90
- Most-sensitiv
  - Media
- Correspondin

Other Rare Nuclear Searches in Te

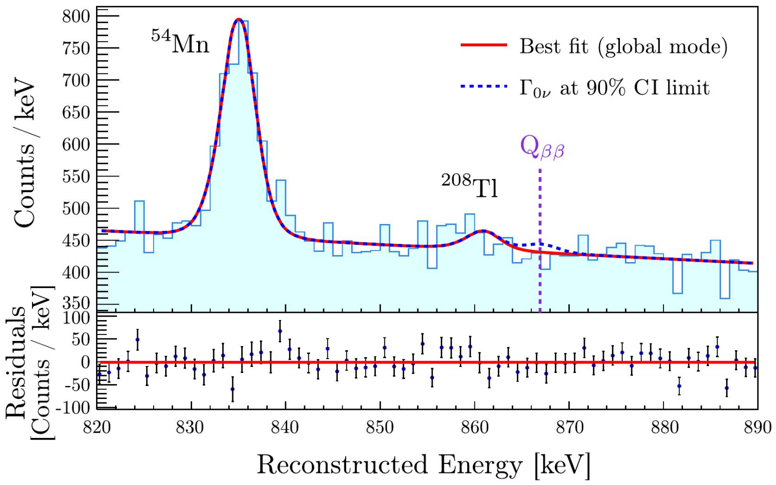
Isotope	Natural Abundance	Decay Mode
^{120}Te	0.09%	β^+EC/2EC
^{122}Te	2.55%	stable
^{123}Te	0.89%	EC
^{124}Te	4.74%	stable
^{125}Te	7.07%	stable
^{126}Te	18.84%	stable
^{128}Te	31.74%	$\beta^-\beta^-$
^{130}Te	34.08%	$\beta^-\beta^-$

- Beyond ^{130}Te, natural tellurium contains several isotopes with rare or possible weak and doubly-weak decay modes
- 0v mode: In event of a discovery, provide complimentary information on possible mechanisms for Lepton number violation
- 2v mode: Searches for Standard Model decay modes can help benchmark and improve nuclear modelling in these rare-decay systems

Other Rare Nuclear Searches in Te

$0\nu\beta\beta$ in ^{128}Te

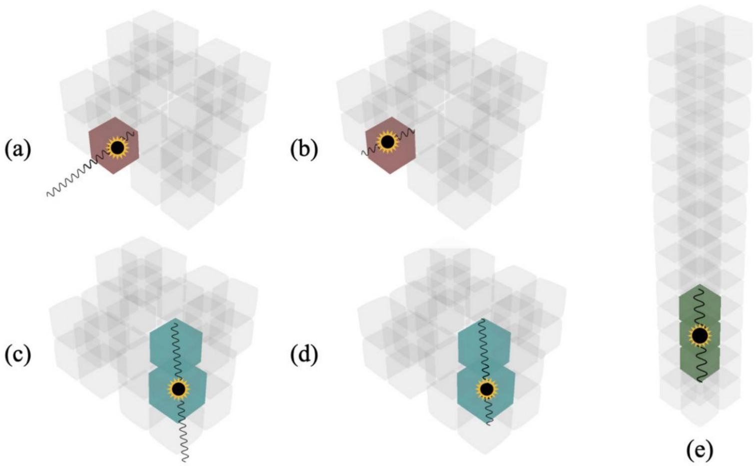
Phys. Rev. Lett **129**, 222501 (2022)



- Low Q-value at 866.7 keV makes search challenging
- 309.33 kg yr TeO_2 exposure (78.56 kg yr ^{128}Te)
- New limit: $T_{1/2}^{0\nu} > 3.6 \cdot 10^{24}$ yr 90% B.C.I.
- Direct limit surpasses geochemical experiments for the first time!

$0\nu\beta^+$EC in ^{120}Te

Phys. Rev. C **105**, 065504 (2022)



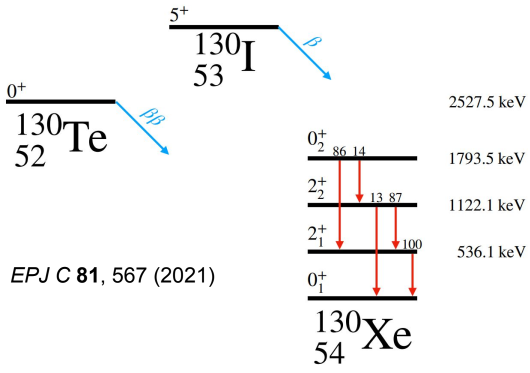
- Very small natural abundance: 0.2405 kg yr of ^{120}Te in 355.7 kg yr total exposure
- Search at Q-value for signatures from e^+e^- annihilation γ's
- No evidence of signal: $T_{1/2}^{0\nu} > 2.9 \cdot 10^{22}$ yr 90% B.C.I.
- 10× improvement in sensitivity over previous searches

Intermediate & High Multiplicity Work

- Focus on expanding CUORE analysis suite towards intermediate & high-multiplicity events: energy deposited across several different crystals

2νES Decays

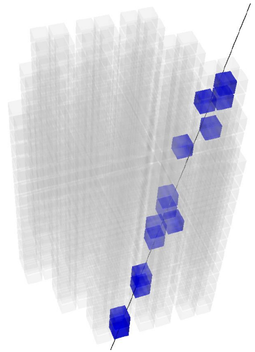
- ββ and 1-3 γ's spread across 2-6 crystals
- Latest search in CUORE:
  EPJ C **81**, 567 (2021) set 90% B.C.I. limit on 2ν mode of $2.1 \cdot 10^{24}$ yr with 372.5 kg yr exposure
- Larger exposure now available, exploring expanded event selections



EPJ C **81**, 567 (2021)

Track-Like Events

- Cross-detector events
- Multi-objective optimization algorithm for track reconstruction*
- Forthcoming search for exotic fractionally-charged particles
- *In situ* muon characterization



* See J. Yocum, D. Mayer *et al* 2022 *JINST* **17** P07004

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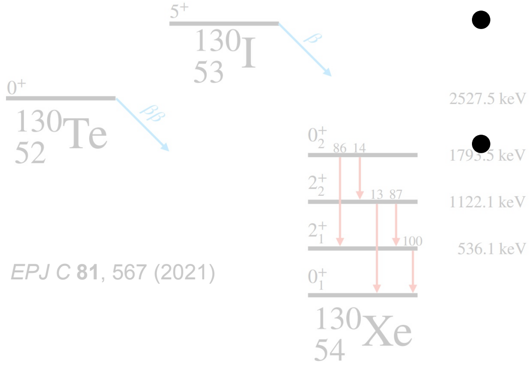

EPJ C **81**, 567 (2021)

- **Increased understanding of multi-crystal backgrounds**
- **Fully leverage CUORE as a segmented detector**
- **Selections and efficiencies optimized for coincidence analyses**
- **Multivariate techniques to maximize physics extraction & sensitivity**

Track-Like Events

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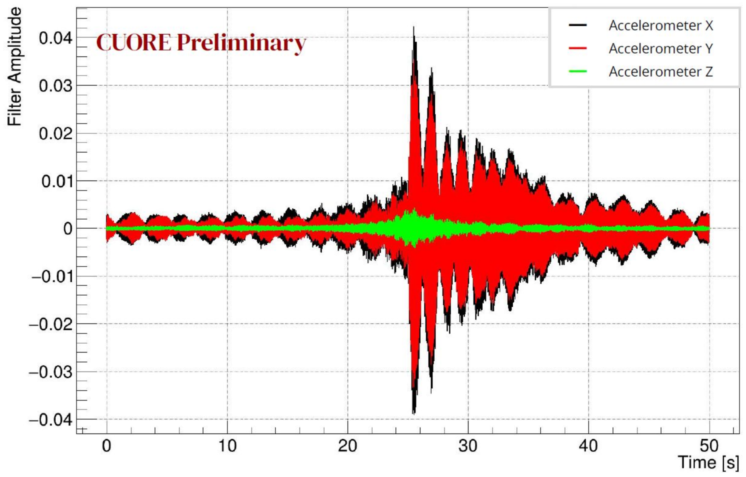
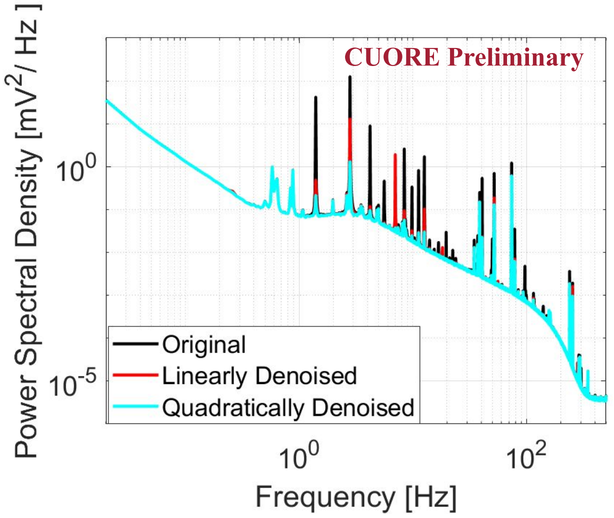
Upcoming: Denoising with Auxiliary Devices

- Use auxiliary devices (accelerometers, microphones) around CUORE to remove coherent noise from calorimeter channels
  - Procedure builds time-dependent transfer function to individual calorimeter channels to predict noise
- Can be applied offline to reprocess all data for which an auxiliary device was present

Denoising weights





Summary

- Strong detector performance in primary search for $0\nu\beta\beta$ in ^{130}Te with 1 t yr of data
  - Most sensitive search in ^{130}Te to-date
- Leading sensitivity in additional searches for other rare/possible nuclear decays in tellurium
- Stable cryogenic operations: >2 t yr of exposure collected
  - 2-6 × exposure of searches to-date
- Data being analyzed with new processing techniques, including denoising with auxiliary devices
- Rich physics program is underway to maximize the reach of CUORE, and pave the way for future ton-scale cryogenic $0\nu\beta\beta$ experiments

Thank You!

Backup: Sensitivity to 0νββ

Half-Life (experiment with background)

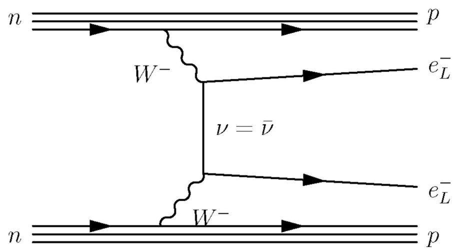
$$T_{1/2}^{0\nu} \propto a\varepsilon\sqrt{\frac{Mt}{B\Delta E}}$$

- a - isotopic abundance of decay candidate
- ε - detection efficiency
- M - target mass
- t - exposure time
- B - background index (typically counts / (keV kg yr)
- ΔE - energy resolution of detector
- Background-free experiments have linear sensitivity to half-life with exposure

Underlying Physics (light Majorana ν exchange)

$$T_{1/2}^{0\nu} = \left(G|\mathcal{M}|^2\langle m_{\beta\beta}\rangle^2\right)^{-1}$$

- G - phase space of decay ($\propto Q^5$)
- M - nuclear matrix element
- $m_{\beta\beta}$ - effective Majorana mass (coherent sum with PMNS matrix elements)
- Different mechanism may have different relation to half-life



Backup: 0νββ Systematics

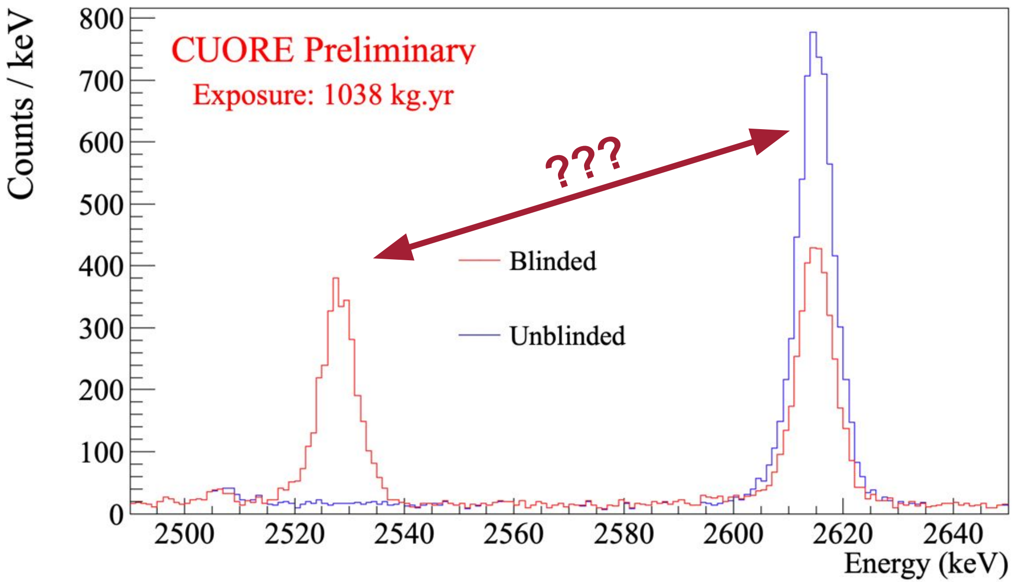
Fit parameter systematics			
Systematic	Prior	Effect on the Marginalized $\Gamma_{0\nu}$ Limit	Effect on $\hat{\Gamma}_{0\nu}$
Total analysis efficiency I	Gaussian	0.2%	$< 0.1\%$
Analysis efficiency II	Gaussian	0.3%	$< 0.1\%$
Containment efficiency	Gaussian	0.2%	$< 0.1\%$
Isotopic abundance	Gaussian	0.2%	$< 0.1\%$
$Q_{\beta\beta}$	Gaussian	$< 0.1 \cdot 10^{-27}$ yr^{-1}	$< 0.1 \cdot 10^{-27}$ yr^{-1}
Energy bias and Resolution scaling	Multivariate	$0.2 \cdot 10^{-27}$ yr^{-1}	$0.1 \cdot 10^{-27}$ yr^{-1}

Upper parameters: affect limit directly

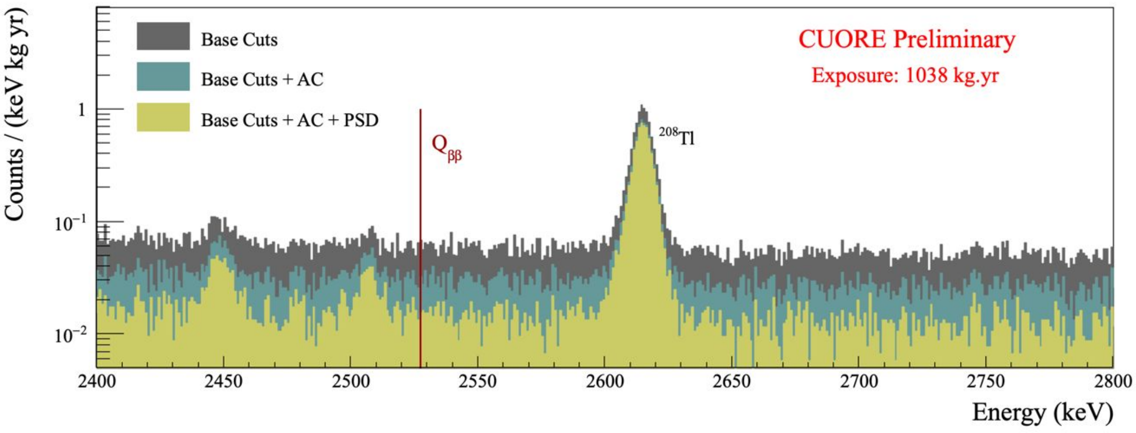
Lower parameters: nuisance parameters within Bayesian fit

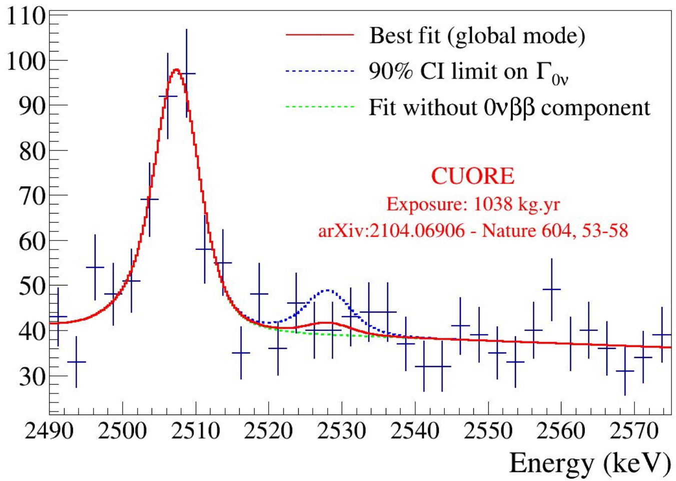
Backup: Blinding

- Salt ROI with unknown fraction of events from nearby ^{208}Tl peak
- True spectrum revealed after freezing analysis



Backup: 0νββ ROI





- ~90% of background in ROI from degraded alphas, ~10% multi-Compton from 2615 keV line
- Average background index of 1.49(4) x 10^{-2} ckky about $Q_{\beta\beta}$