Latest results from the CUORE experiment

Stefano Pozzi (CUORE collaboration)
Università and INFN Milano-Bicocca

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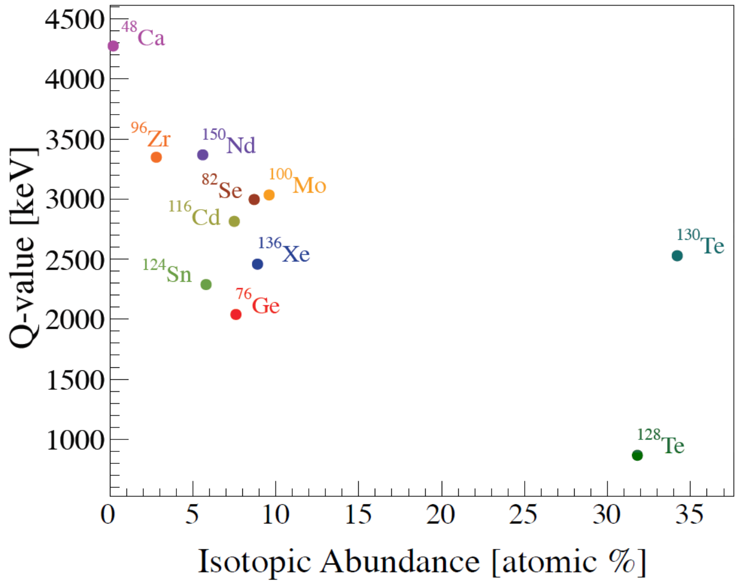
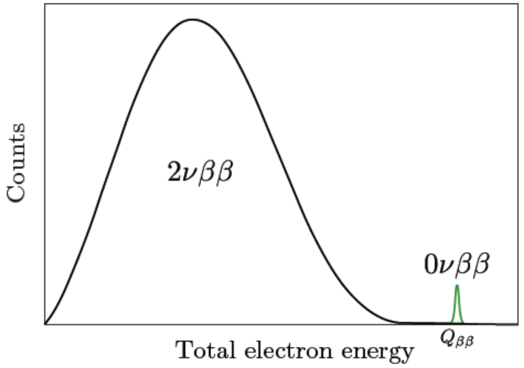
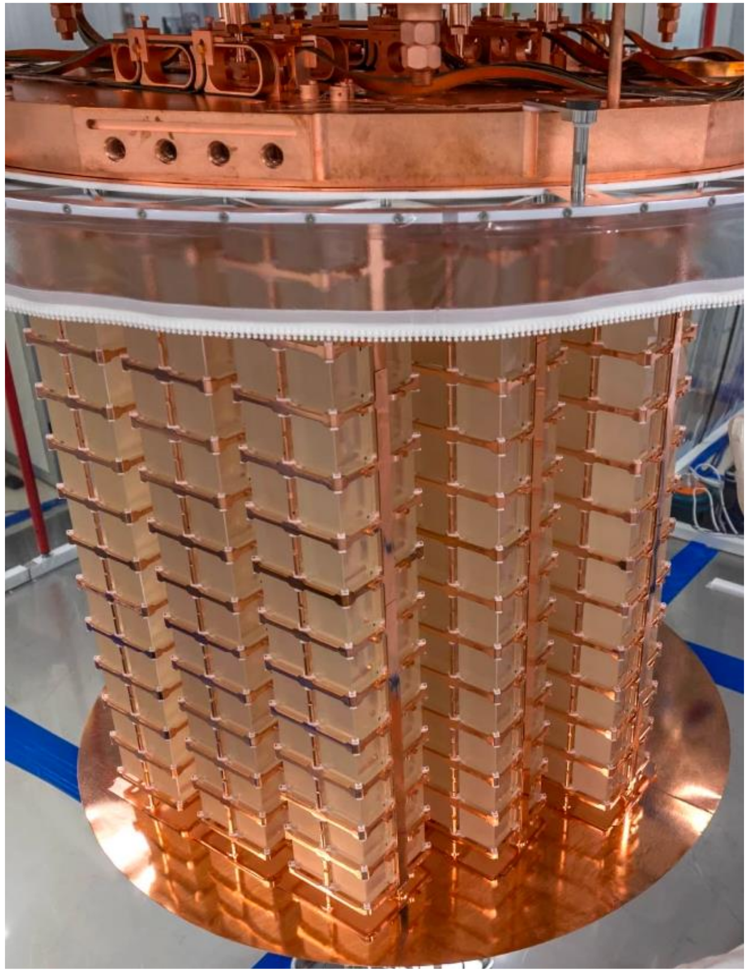
Neutrinoless double beta decay

- Double beta decay (2νββ):
  - Observed on a small number of even-even nuclei
  - Half-lives ~10^{18}-10^{24} yr
- Neutrinoless double beta decay (0νββ):
  - Beyond Standard Model process, never observed
  - Lepton number violation (ΔL = 2)
  - Experimental signature: peak at 2νββ endpoint
  - Requires ultra-low background, excellent energy resolution, high source mass





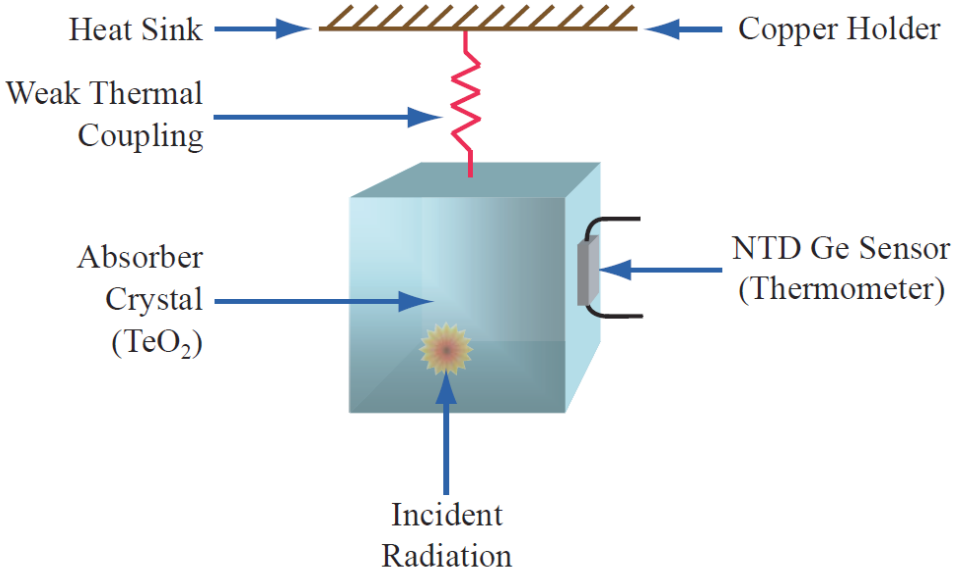
CUORE

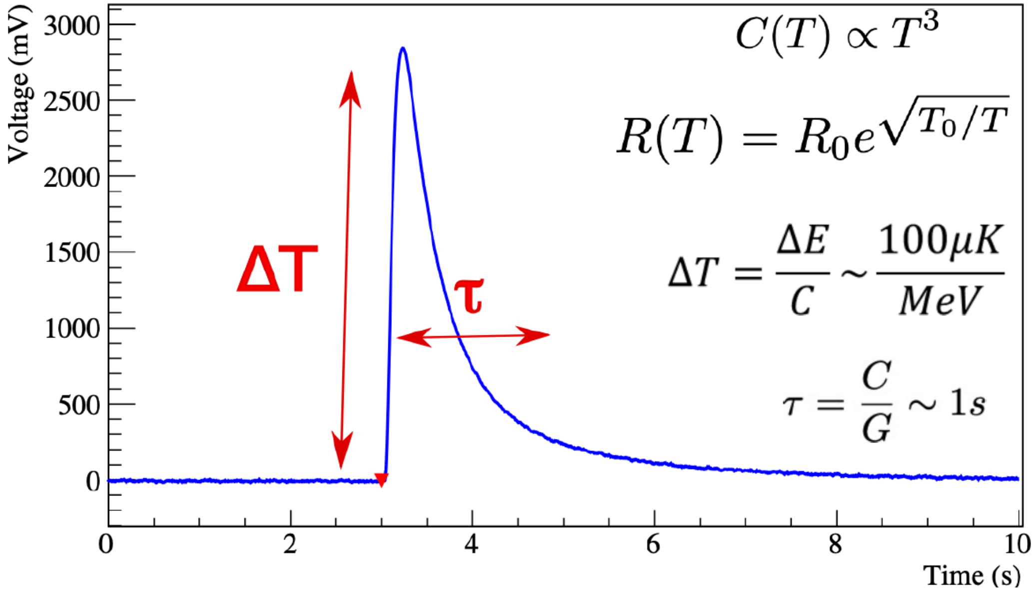


- **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents
- Main objective: search for 0νββ in ^{130}Te
- $Q_{\beta\beta}$ ~2527 keV
    - Above most natural γ backgrounds, with the exception of ^{208}Tl
- 988 cubic TeO_2 crystals
    - Natural Te (~34% A.I. ^{130}Te)
    - 742 kg TeO_2, 206 kg ^{130}Te
- Thermal detectors in a cryostat @10mK

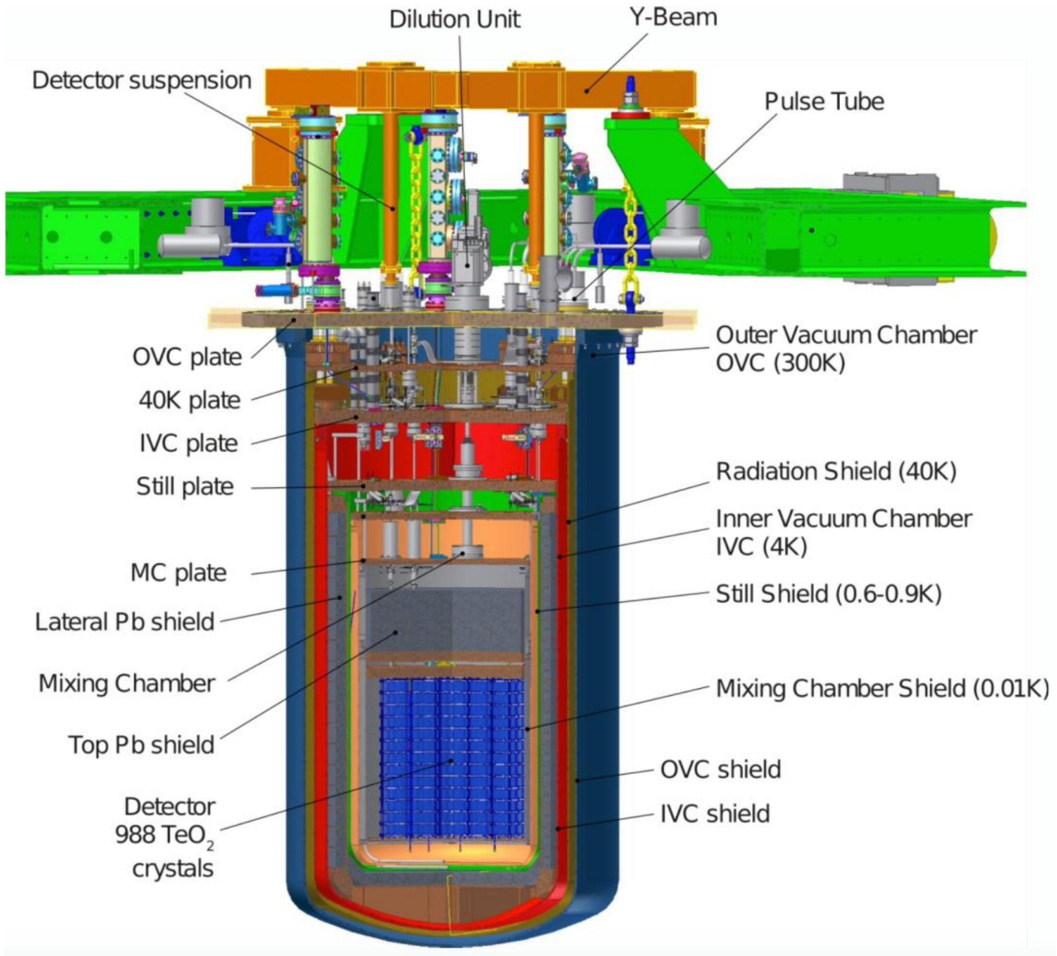
Cryogenic calorimeters

- Energy deposition converted into a temperature increase: $\Delta T \propto$ **E/C(T)**
- Need to work at extremely low temperatures: **C(T)$\propto$T^3**
- Signal readout with an NTD Ge sensor
- Heat dissipated to the Cu holder; base temperature restored in a few seconds



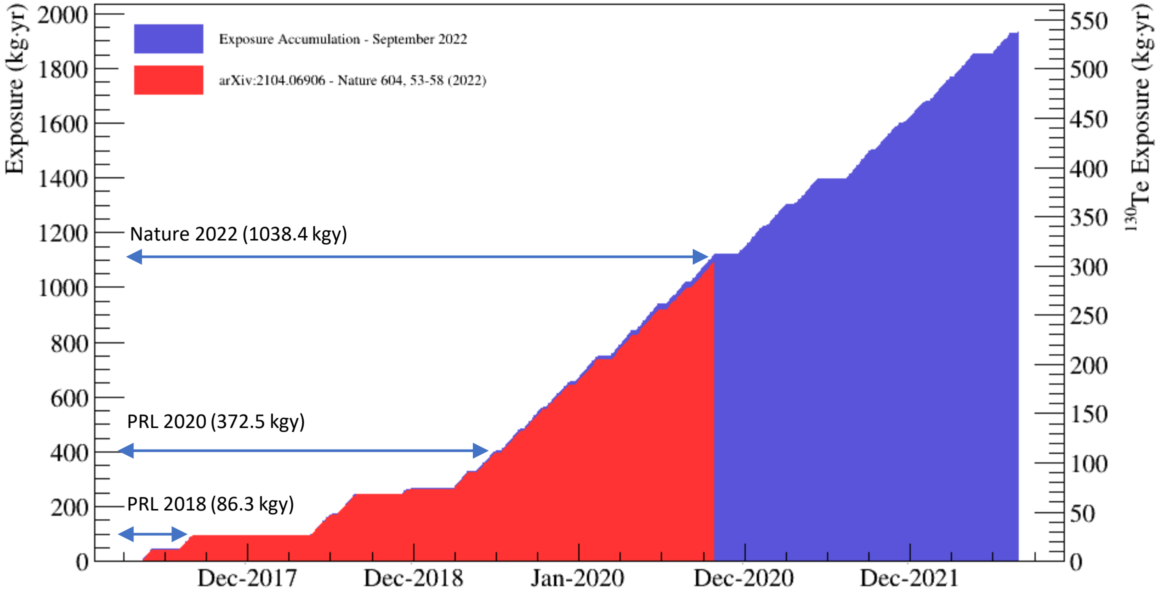


The CUORE cryostat



- Custom-made dilution refrigerator, capable of stable operation at ~10mK
- Nested copper vessels at decreasing temperatures
- Ultra-pure materials used in the whole assembly, with special attention for parts facing the detector
- Shielding:
  - 25 cm modern Pb @300K
  - 6cm roman Pb (low 210Bi/210Po) @4K
  - 30cm modern Pb @50mK
  - 20cm borated polyethylene @300K

CUORE data-taking

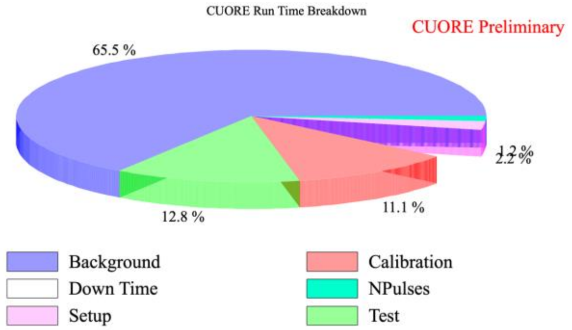


Nature 2022 (1038.4 kgy)

PRL 2020 (372.5 kgy)

PRL 2018 (86.3 kgy)

- Data taking started in 2017
- Optimization campaigns improved the stability of the experiment
- Stable data taking with >90% uptime since March 2019
- >1.8 tonne x yr accumulated raw exposure
- Data splint in datasets (1-2 months), with initial and final calibration runs



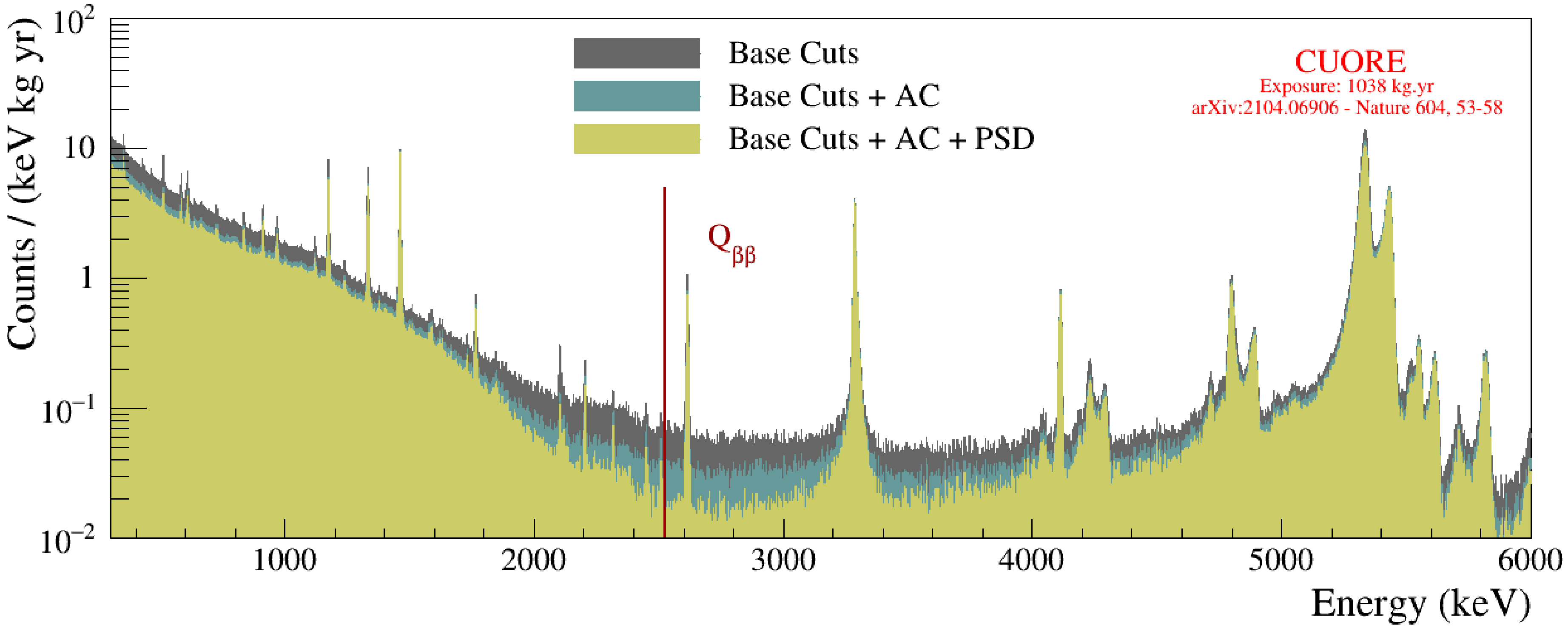
Alduino C. et al. (CUORE collaboration), Phys. Rev. Lett. 120, 132501, (2018), https://doi.org/10.1103/PhysRevLett.120.132501

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

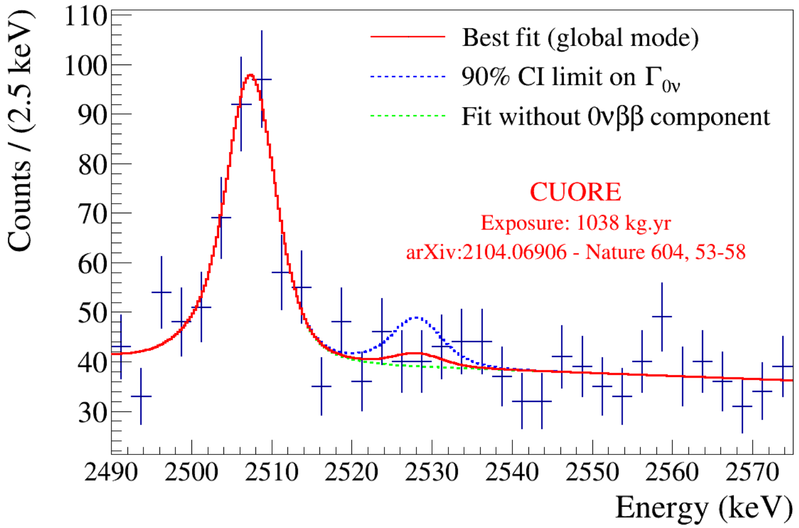
Adams D. et al. (CUORE collaboration), *Nature* 604 (2022) 7904, 53-58, https://www.nature.com/articles/s41586-022-04497-4

0νββ search

- Total exposure: **1038.4 kg yr TeO_2**
- Selection efficiency: 92.4(2)%
- $Q_{\beta\beta}$: 2527.5 keV
- Energy resolution @$Q_{\beta\beta}$: 7.8(5) keV



0νββ fit result

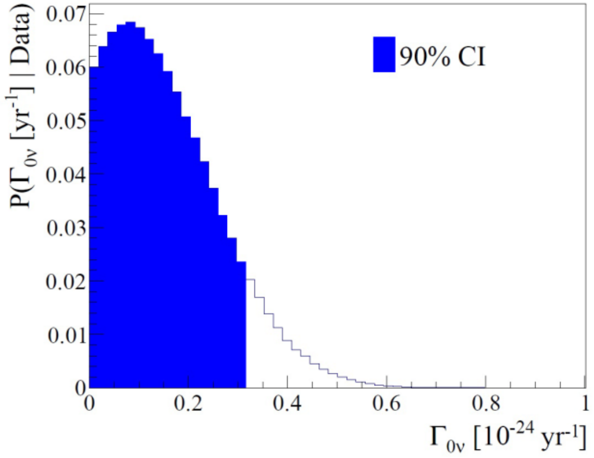


Mean background rate (90% due do degraded alphas):

$$b = (1.49 \pm 0.04) \times 10^{-2} \text{ (c/keV/kg/yr)}$$

- Unbinned bayesian fit of the ROI (2490-2575 keV)
  - Linear background
  - ^{60}Co sum peak @2505.7 keV
  - Signal peak @$Q_{\beta\beta}$
- No evidence of ^{130}Te 0νββ

$$T_{1/2}^{0\nu\beta\beta} > 2.2 \times 10^{25} yr \text{ (90\% C.I.)}$$



0vββ sensitivity

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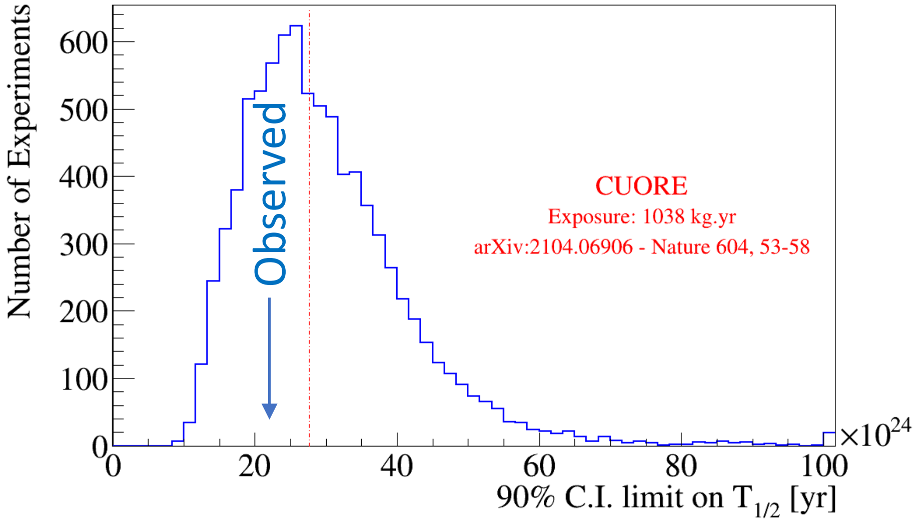
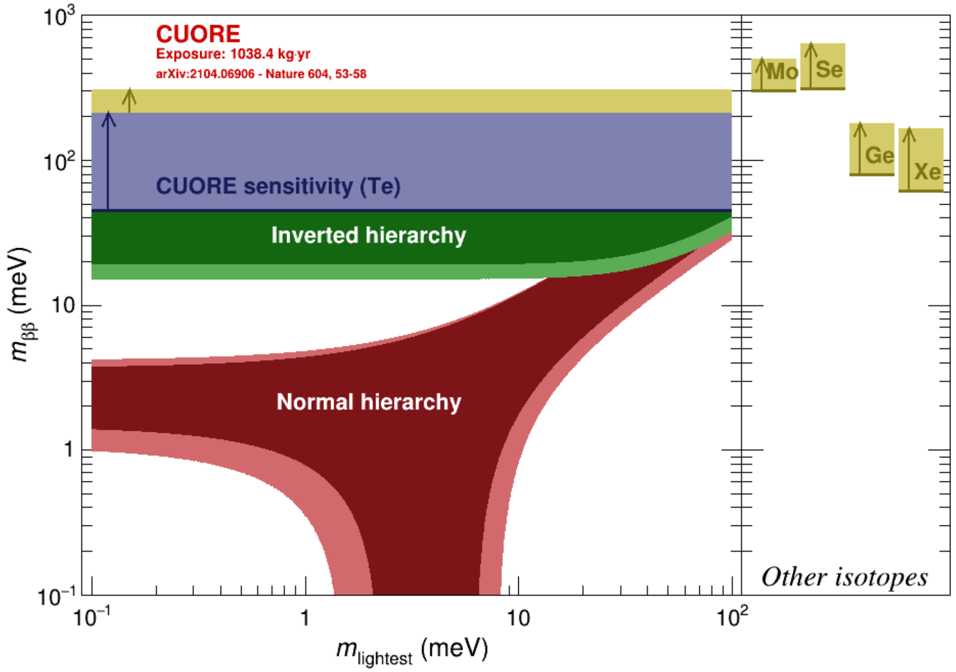
Median exclusion sensitivity:

$$\boxed{T_{1/2}^{0\nu\beta\beta} = 2.8 \times 10^{25} yr \text{(90\% C.I.)}}$$

72% chance of obtaining a stronger limit than the one observed

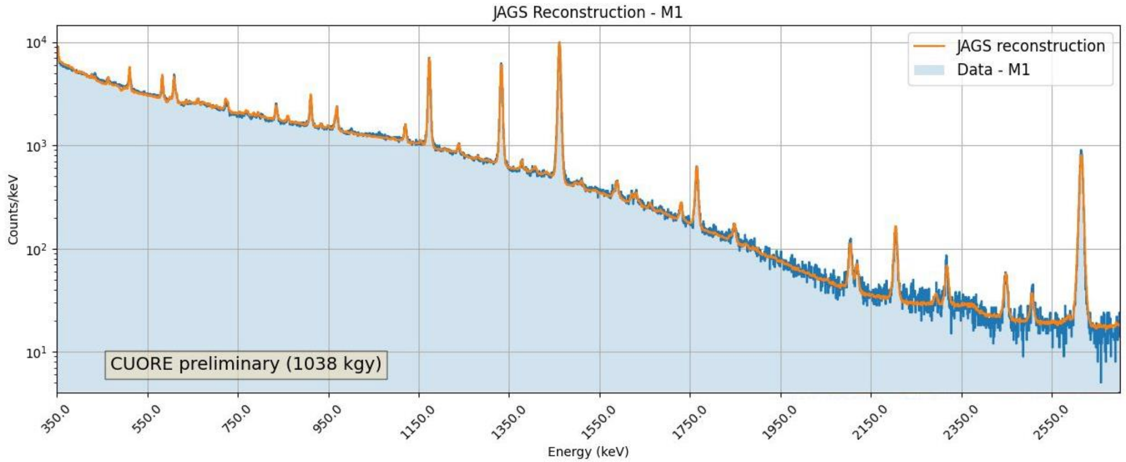


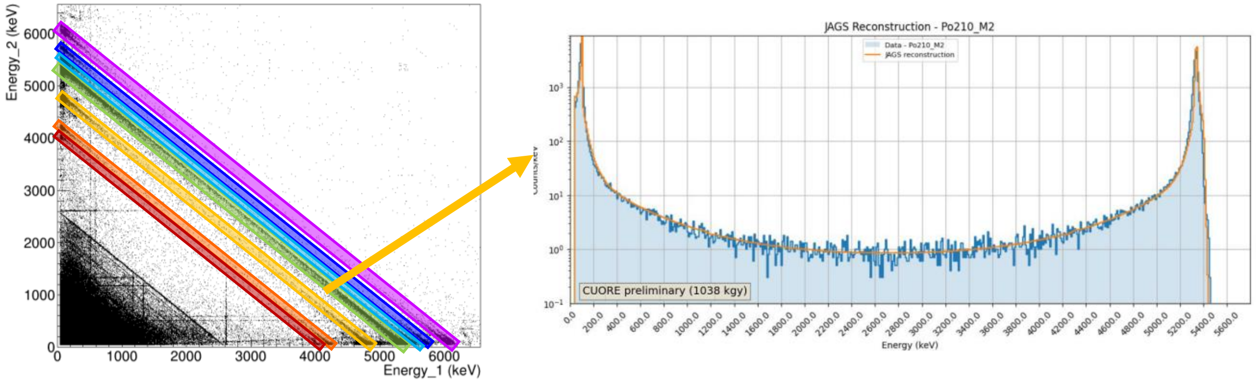


If 0vββ is mediated by light neutrino exchange:

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

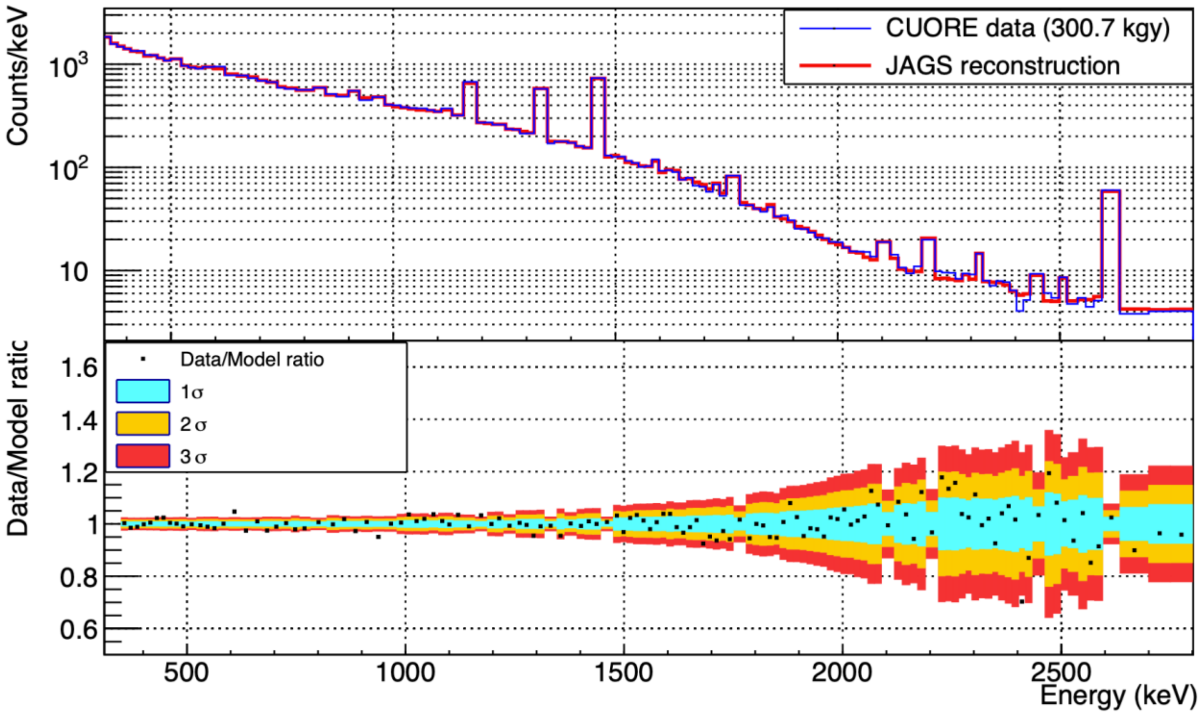
CUORE background model





- CUORE background model: combination of Monte Carlo simulations to match the observed spectra
- ~60 simulation sources (combination of source volume and radioisotope) , processedto match detector response: resolution, efficiency, timing, …
- Binned MCMC Bayesian fit
- Target spectra:
  - M1 – single crystal events
  - M2 – simultaneous hit on two crystals

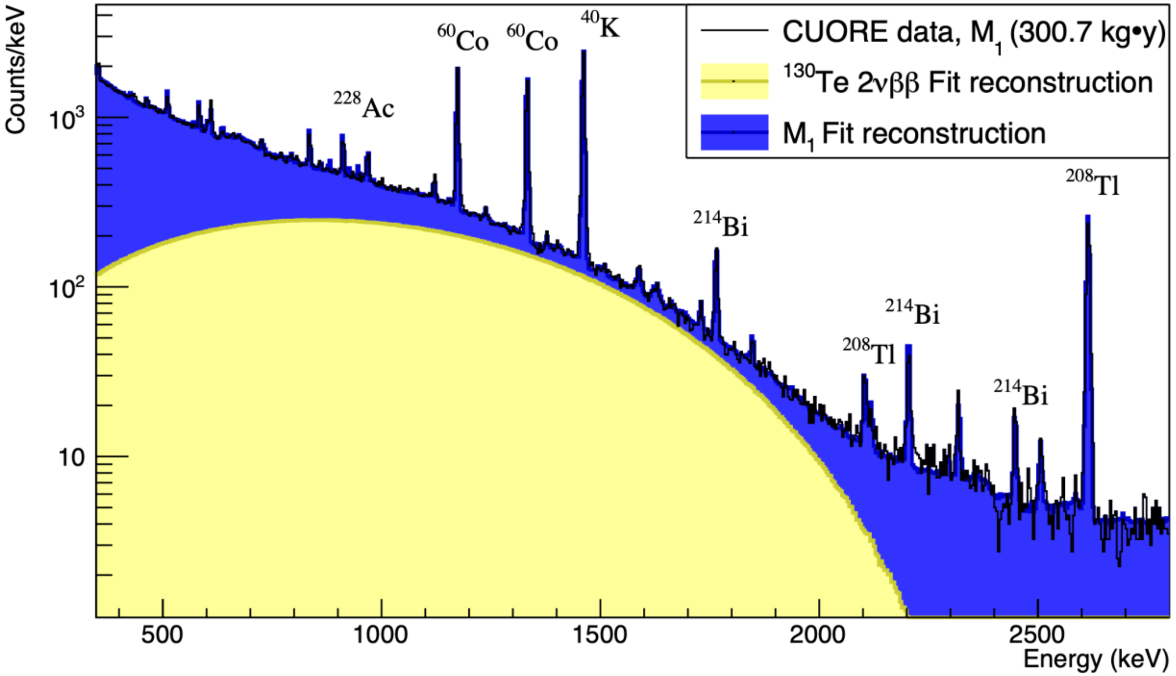
2νββ measurement



- Background model based on the second data release (~300 kg yr)
- Partial energy range (only up to 2.7 MeV)
  - Ignore alpha contributions, irrelevant for 2νββ
- Not used to estimate other contaminations

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

2νββ measurement



Systmatic uncertainties:

- 2νββ model (SSD-HSD)
- Energy threshold (300-800 keV)
- Detector geometrical splitting
- ^{90}Sr inclusion in the source list
- Stability during data taking

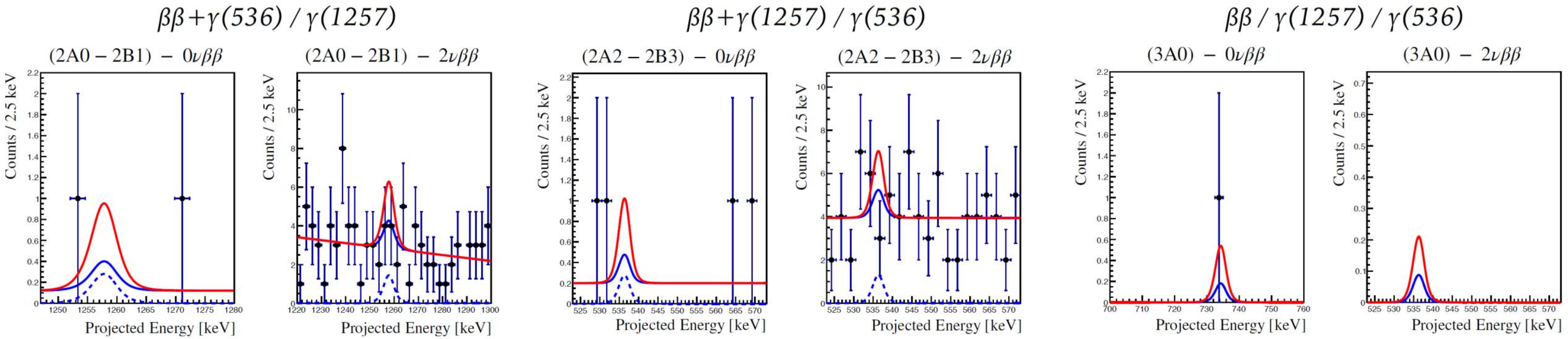
$$\boxed{T_{1/2}^{2\nu} = 7.71^{+0.08}_{-0.06}(stat.)^{+0.12}_{-0.15}(syst.)\ 10^{20}\ yr}$$

Decay to excited states

130Te decay to the first 0+ excited state of 130Xe

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

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



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

Other rare decay searches

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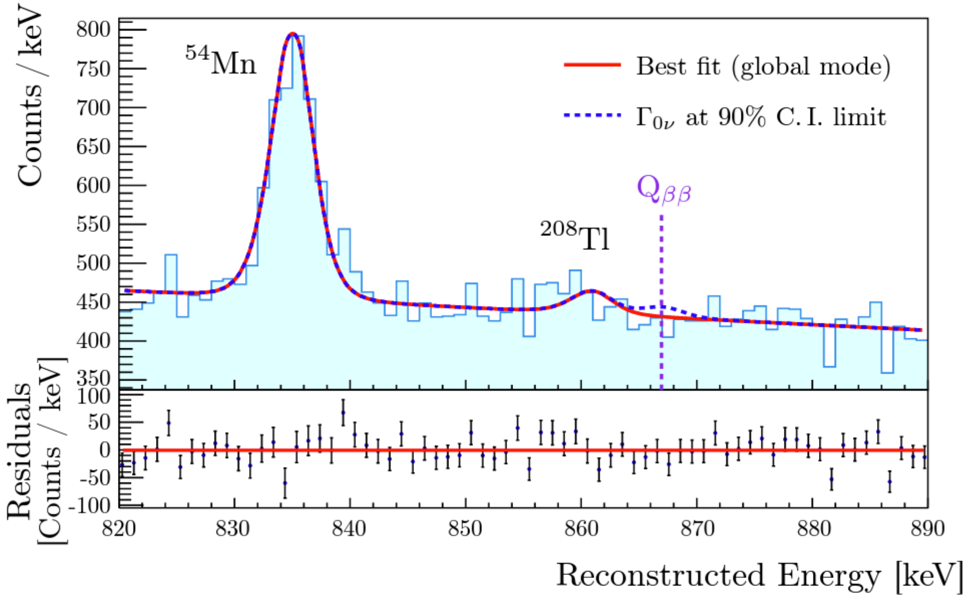
^{128}Te 0νββ

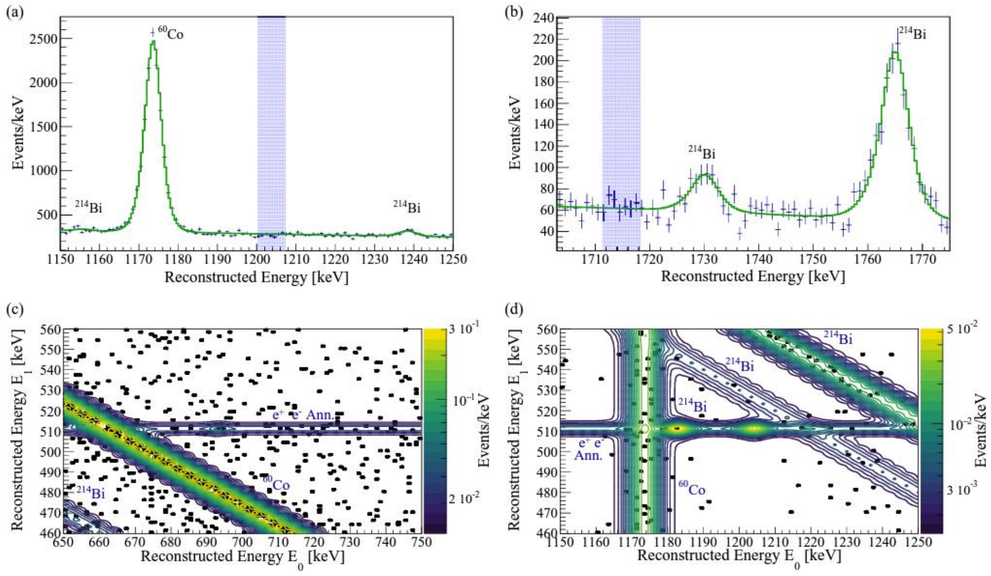
$$T_{1/2}^{0\nu\beta\beta}(^{128}Te) > 3.6 \times 10^{24}\ yr\ (90\%\ C.I.)$$



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

^{120}Te β+/EC

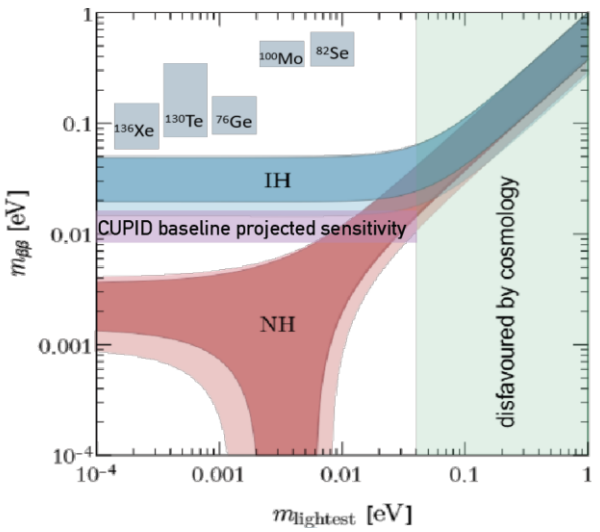
$$T_{1/2}^{0\nu\beta^{+}EC}\left(^{120}Te\right) > 2.9 \times 10^{22}\ yr\ (90\%\ C.I.)$$

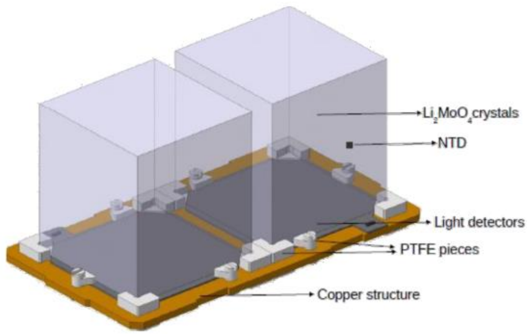


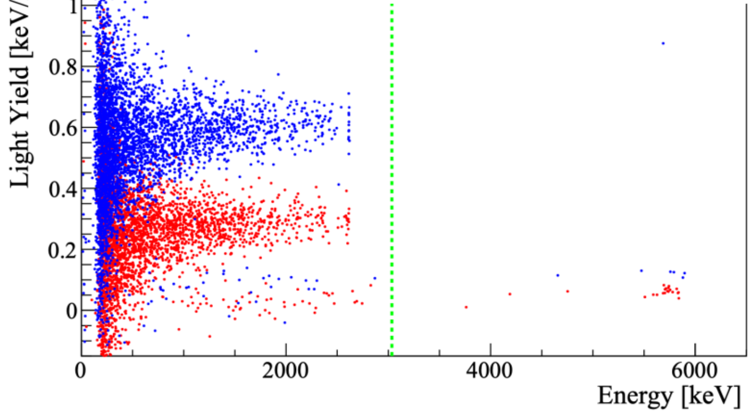
Adams, D.Q. et al. (CUORE Collaboration) Phys.Rev.C 105 (2022) 065504
https://doi.org/10.1103/PhysRevC.105.065504

Next generation: CUPID

- CUORE Upgrade with Particle Identification
- Goal: fully explore the inverted hierarchy parameter space
- New detector technology: scintillating calorimeters
    - Scintillation light: >99% α/β discrimination
    - ~1600 Li2MoO4 crystals
    - High energy resolution (~5 keV)
- Robust technology, proved by CUPID-0 and CUPID-Mo, in the CUORE cryogenic infrastructure







Conclusion

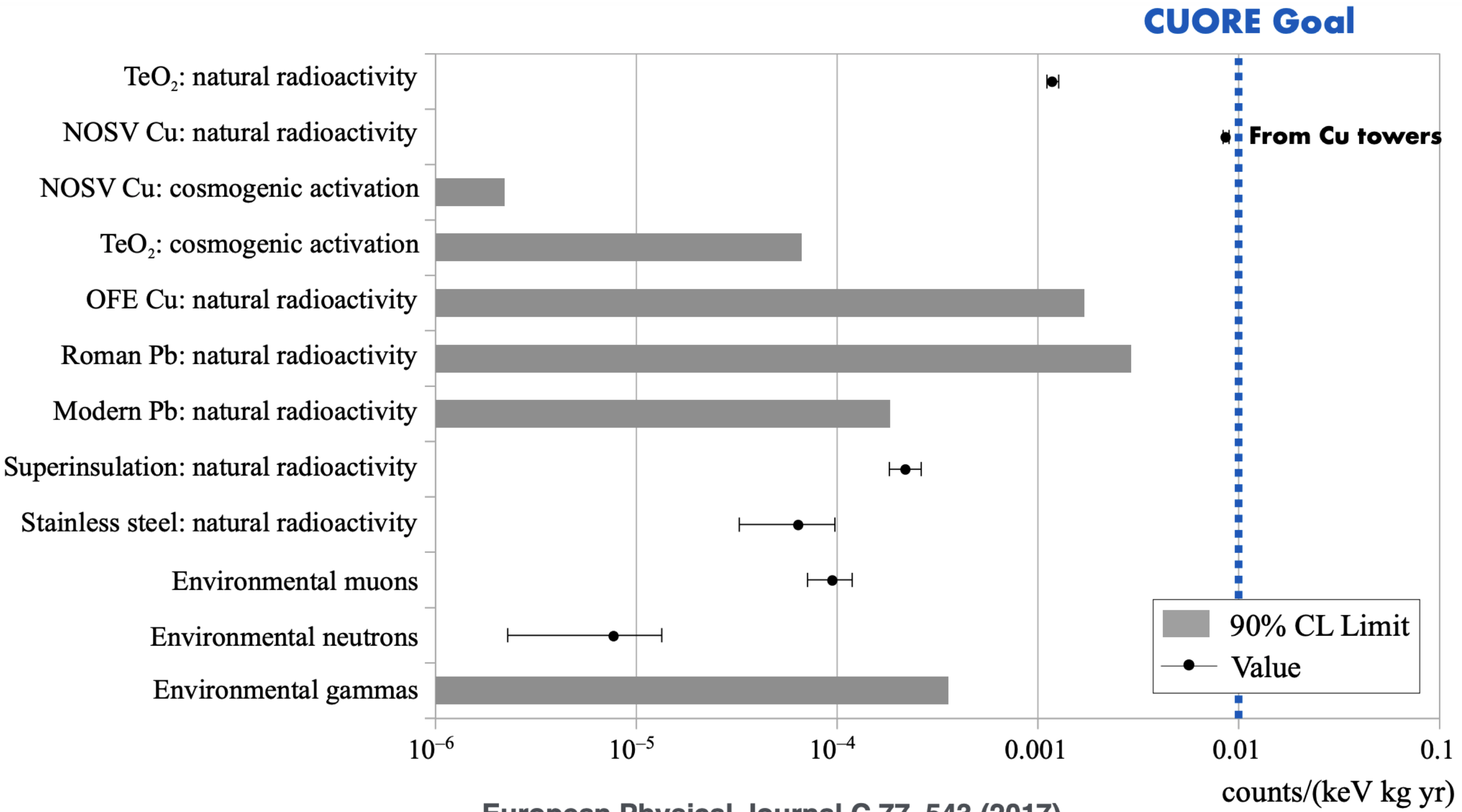
- CUORE has exceeded 1 tonne year of exposure and continues its data taking
- No evidence of 0νββ decay with 1038 kg yr of data
    - Bayesian 90% C.I. limit: $T_{1/2}^{0\nu\beta\beta} > 2.2 \times 10^{25} yr$ (90% C.I.)
    - Effective Majorana mass limit: $m_{\beta\beta} < 90 - 305\, meV$

- Most precise evaluation of 130Te half-life to date: $T_{1/2}^{2\nu} = 7.71_{-0.06}^{+0.08}(stat.)_{-0.15}^{+0.12}(syst.)\ 10^{20}\ yr$

- Many other results on rare decays already published, and many to come
- Proves feasibility of large-scale cryogenic detectors: CUPID

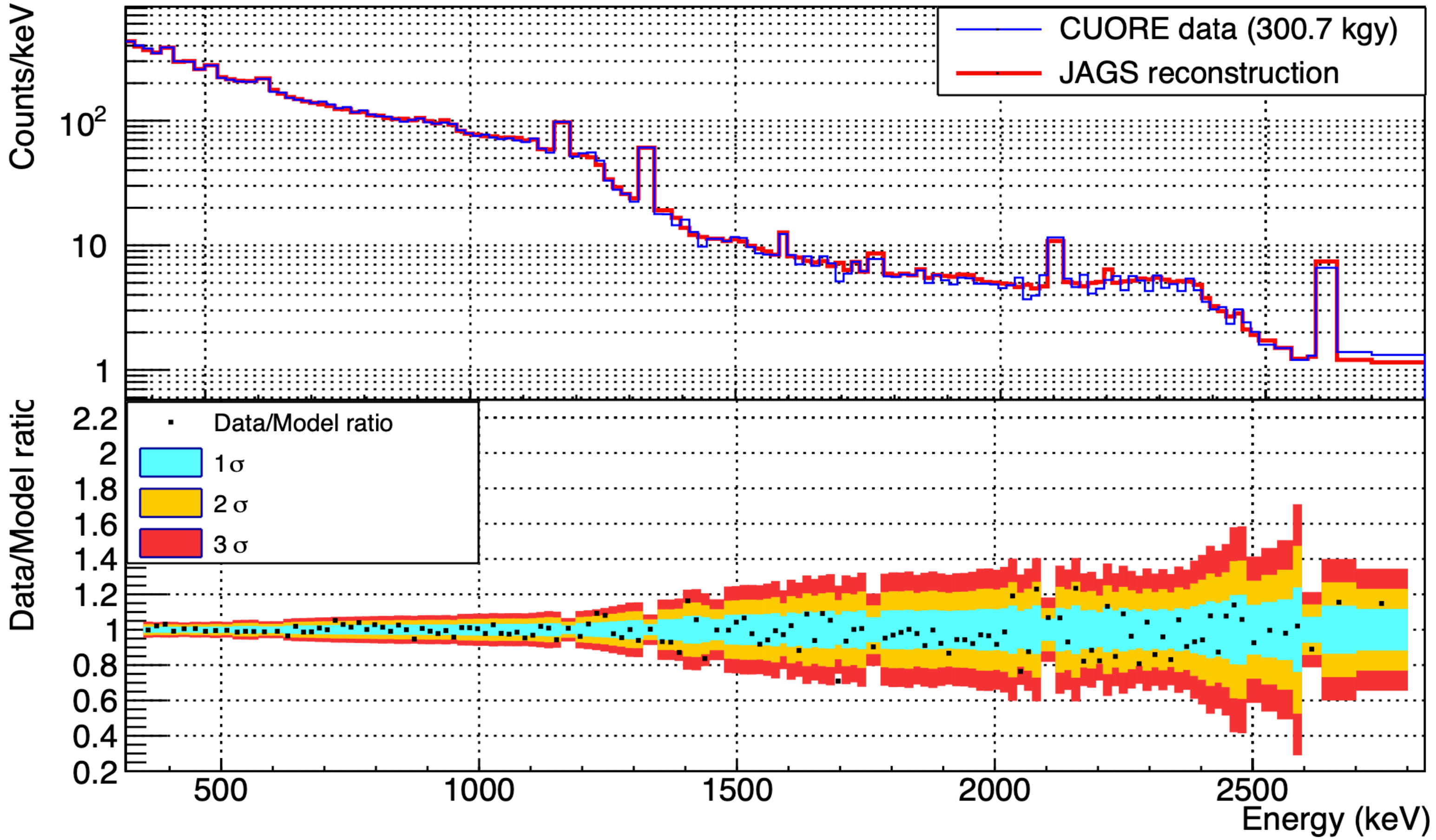
BACKUP

CUORE background budget

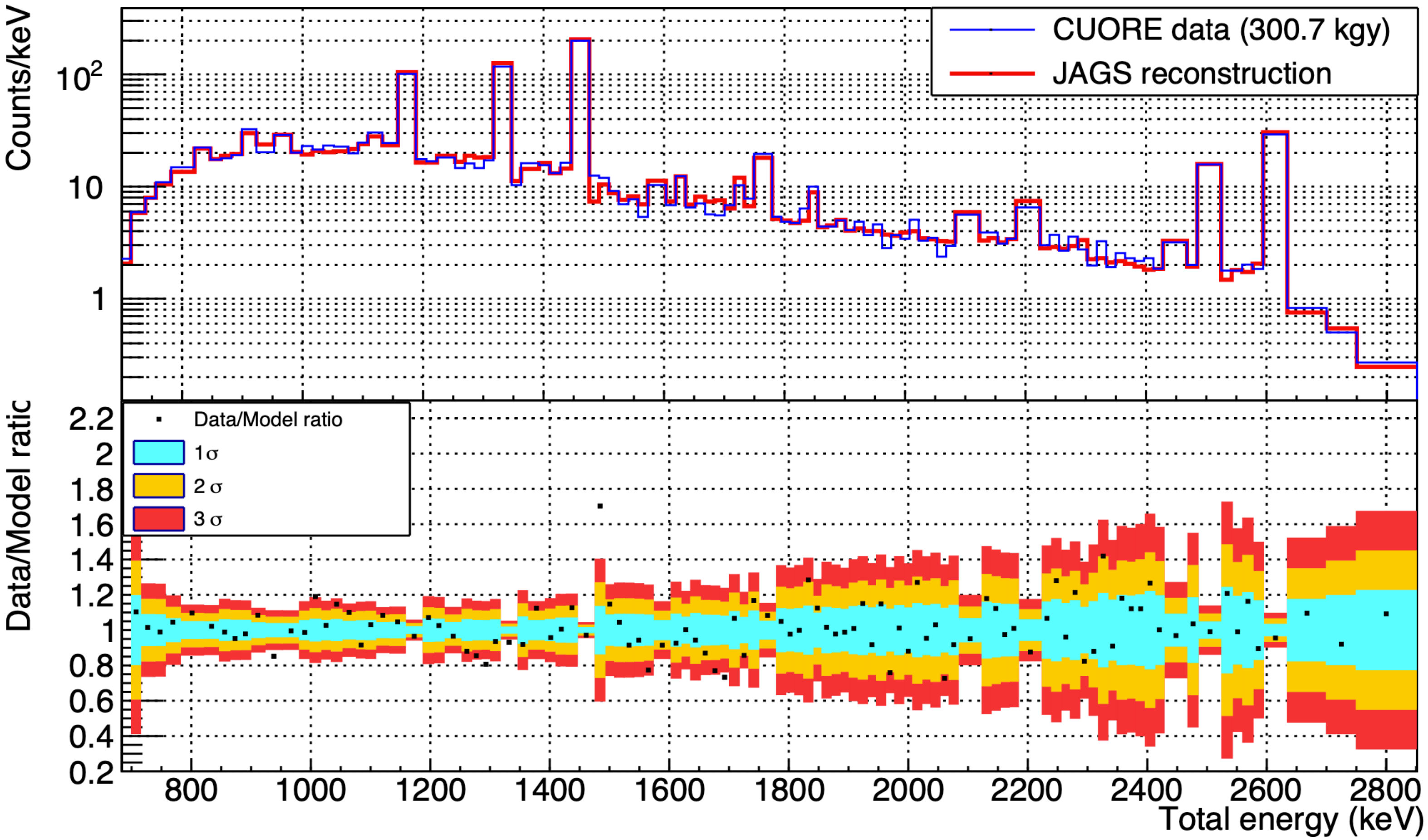


European Physical Journal C 77, 543 (2017)

2νββ measurement – M2 spectrum



2νββ measurement – M2sum spectrum



2νββ measurement – 90Sr