Latest Results from CUORE and Progress towards CUPID

Ridge Liu, on behalf of the CUORE and CUPID collaborations

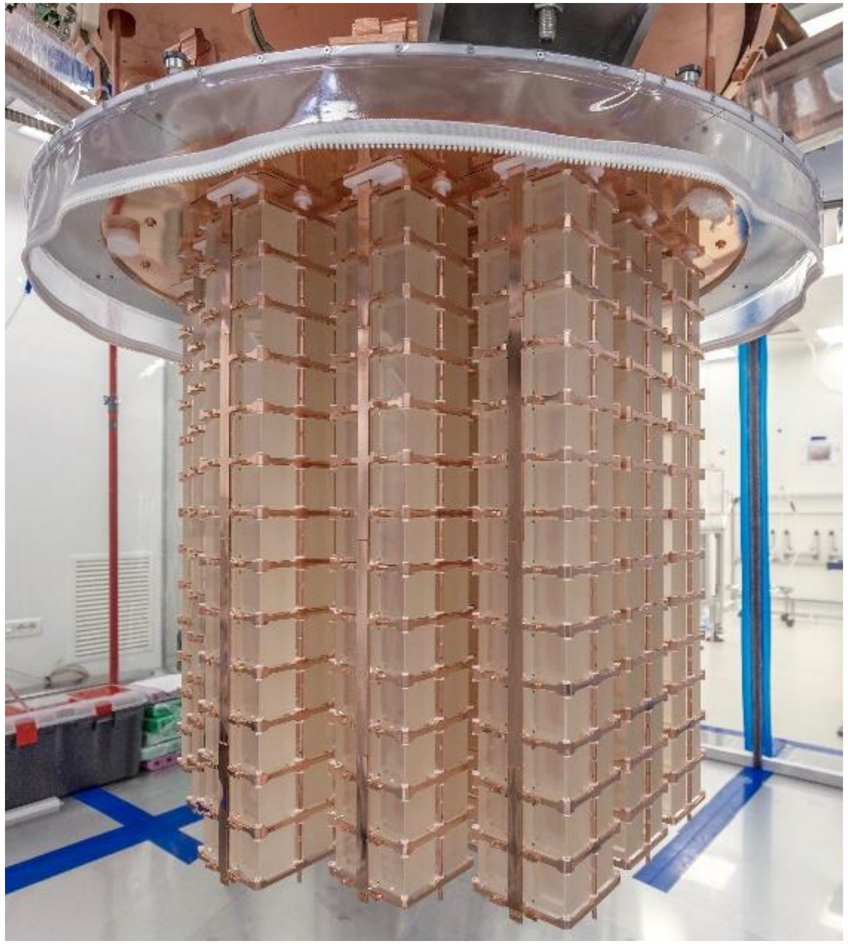
Yale University

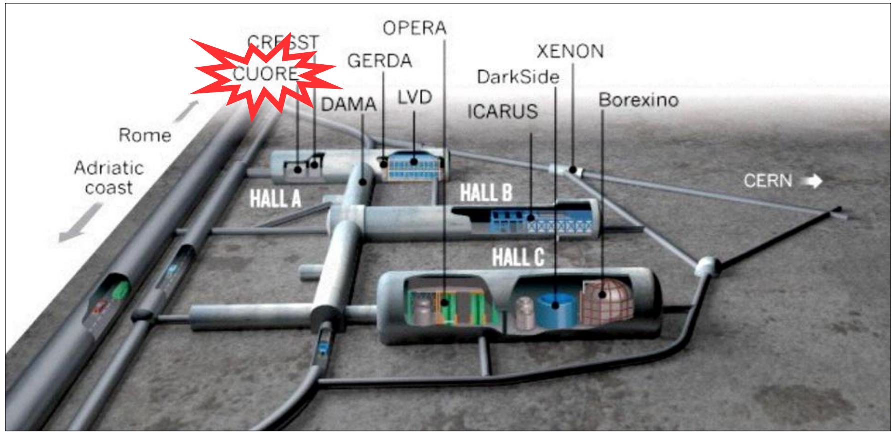
Les Rencontres de Physique de la Vallée d'Aoste

La Thuile, 11 March 2025

Cryogenic Underground Observatory for Rare Events (CUORE)

- Array of 988 TeO_2 crystals (742 kg, 206 kg ^{130}Te)
  - Decay source = detector
  - Unenriched, large isotopic abundance (~1/3)
- Hall A of Laboratori Nazionali del Gran Sasso
  - Rock overburden reduces muon flux by factor of 10^6 relative to sea level (BOREXINO, J. Cosmol. Astropart. Phys., 05:015, 2012)





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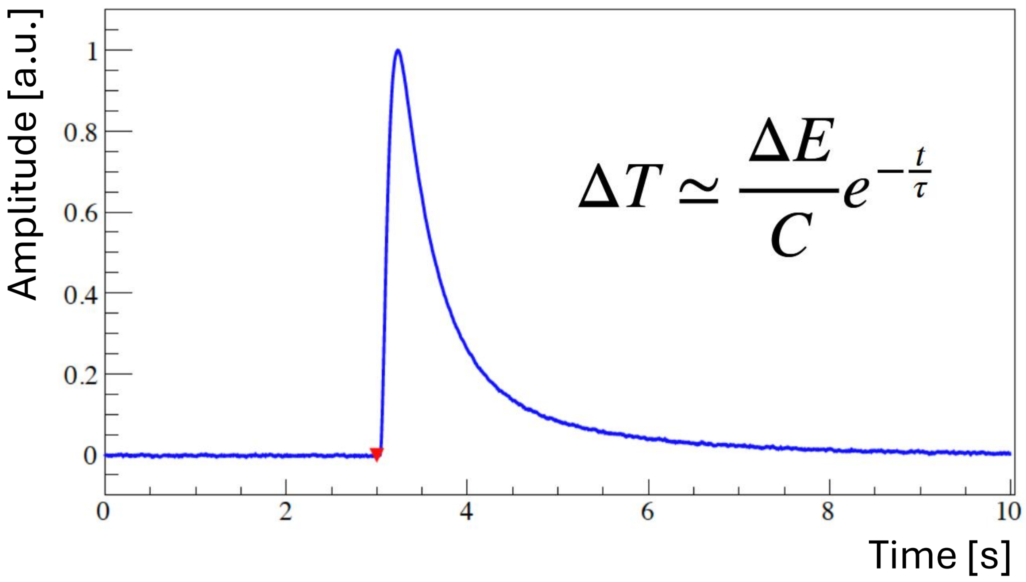
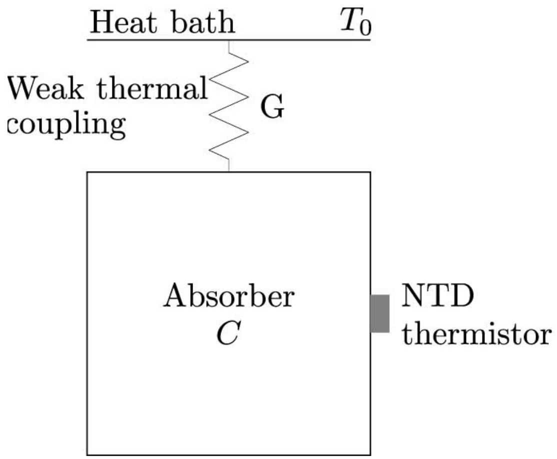
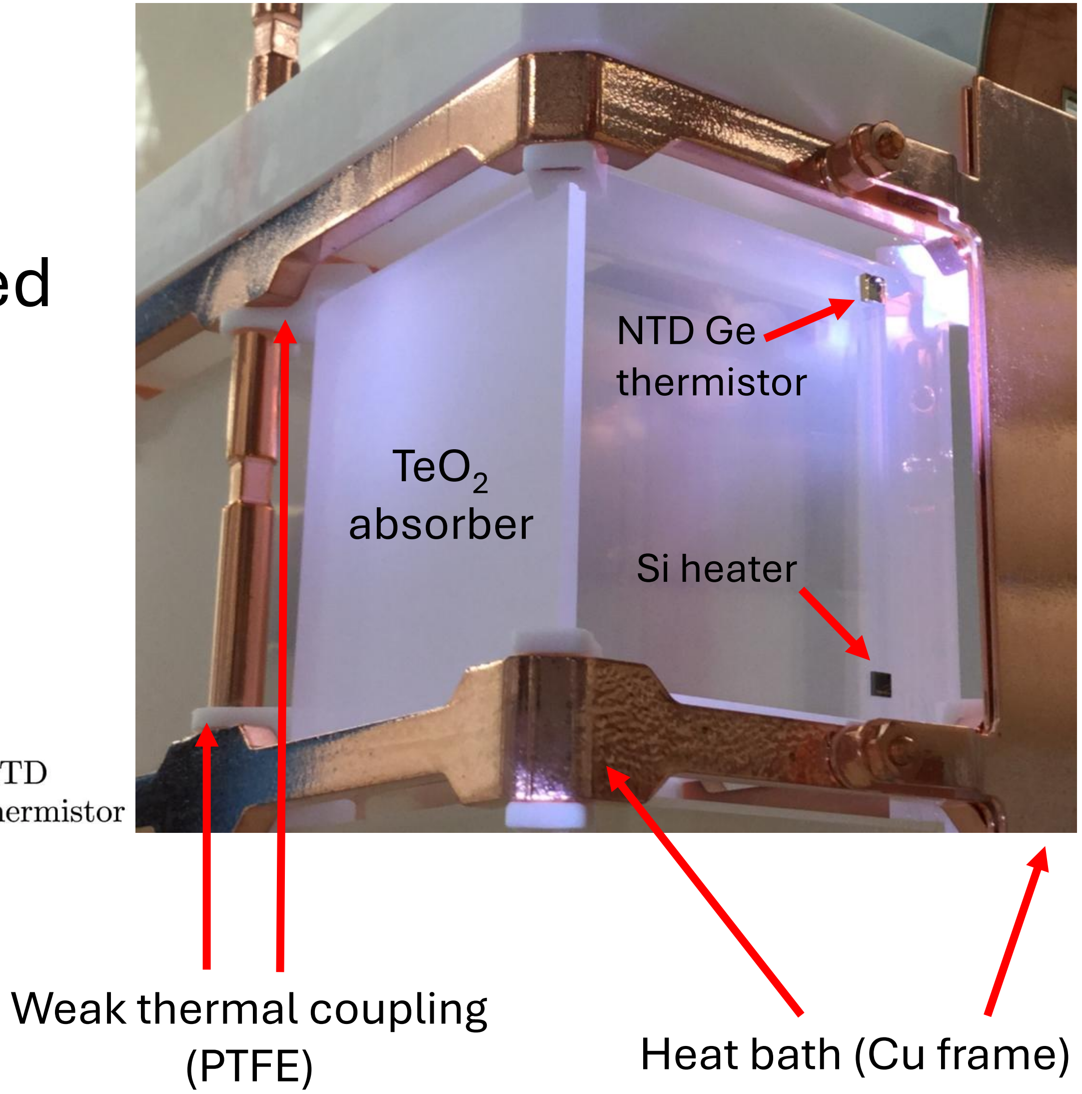
TeO_2 cryogenic calorimeters

- Operated at O(10 mK)
- Energy depositions → temperature change
- Read out using neutron transmutation doped (NTD) Ge thermistors

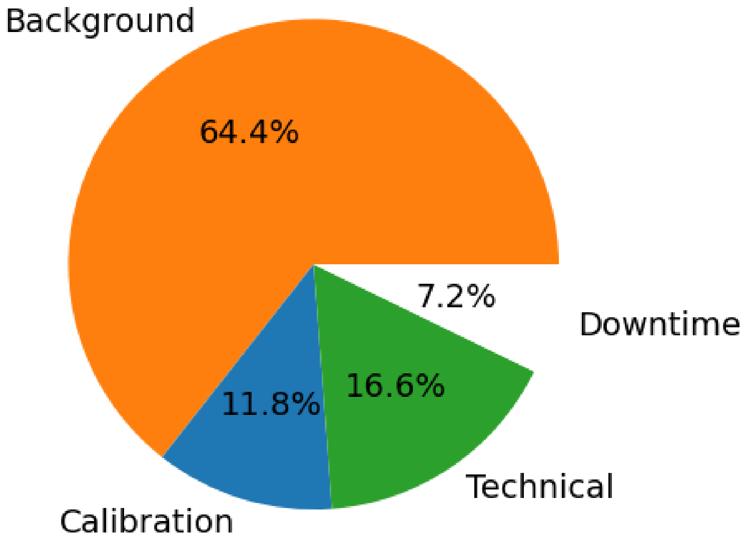


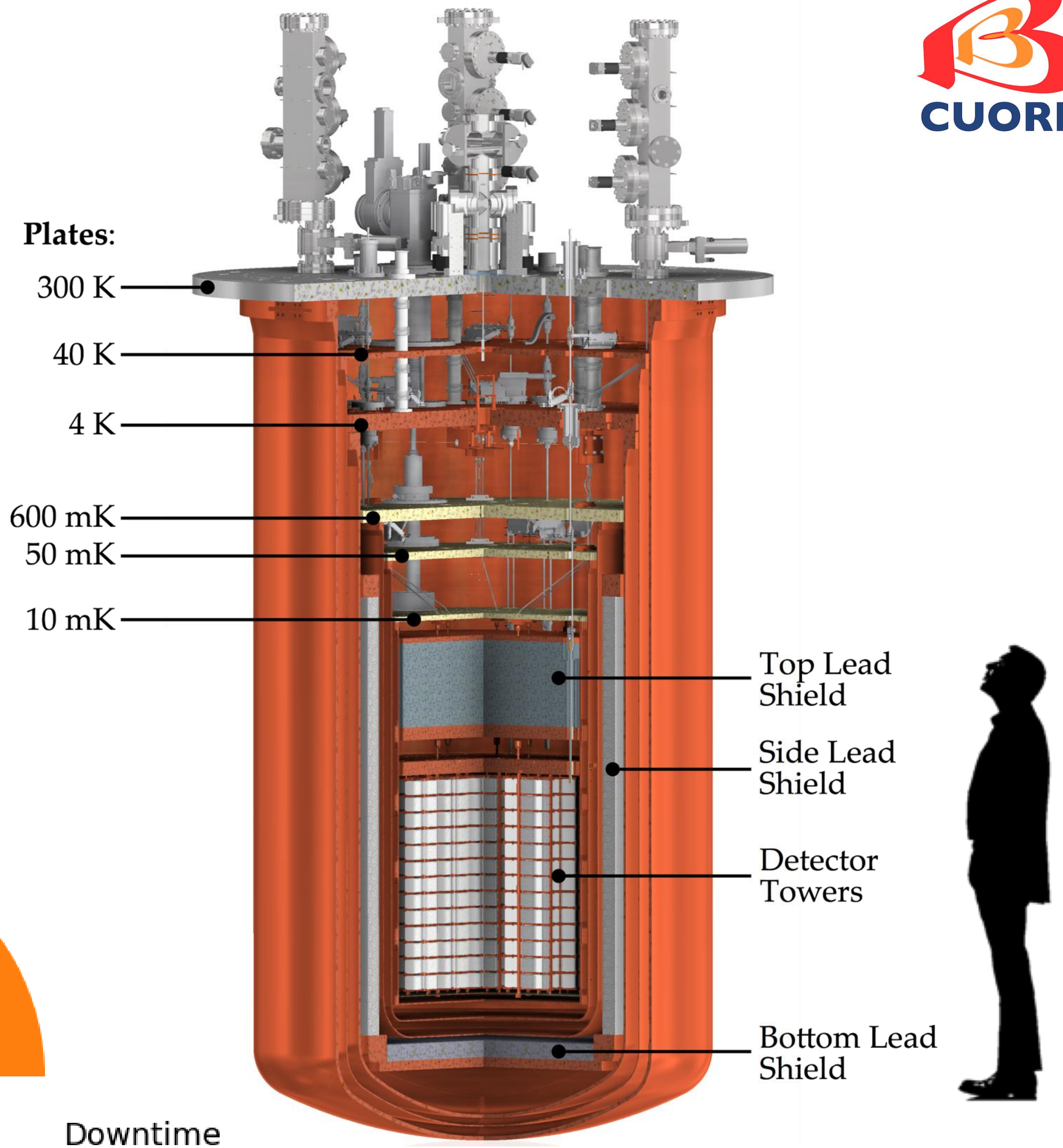




The CUORE cryostat

- Large custom-built dilution refrigerator
  - Cool ~3 tonnes to 50mK
  - 5 pulse tubes, 6 thermal stages
- Over 5 years of stable data-taking, uptime >90%
- Data-taking planned through 2026 before upgrades for CUPID
  - Exposure goal: 3 t-yr TeO_2





J. Low Temp. Phys. 193, 867-875 (2018)

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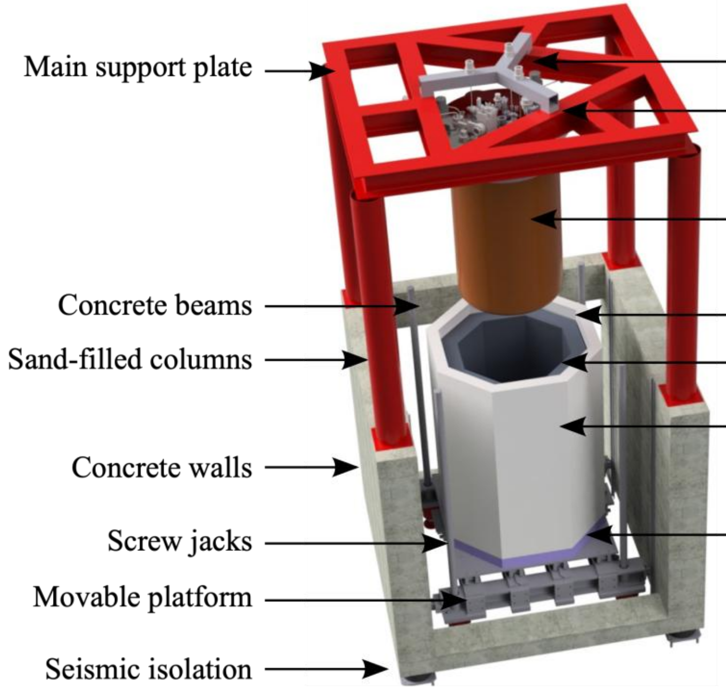
Vibrational isolation and noise cancellation

- Multiple stages of vibrational isolation
- Offline denoising
  - ~40% reduction in total RMS_{noise}
  - Eur. Phys. J. C 84, 243 (2024)
- Good resolution: 0.3% $\delta E/E$ at $Q_{\beta\beta}$ (2.5MeV)
  - arXiv:2404.04453
- Sensitive enough to see sea storm activity!
  - Eur. Phys. J. C 84, 728 (2024)



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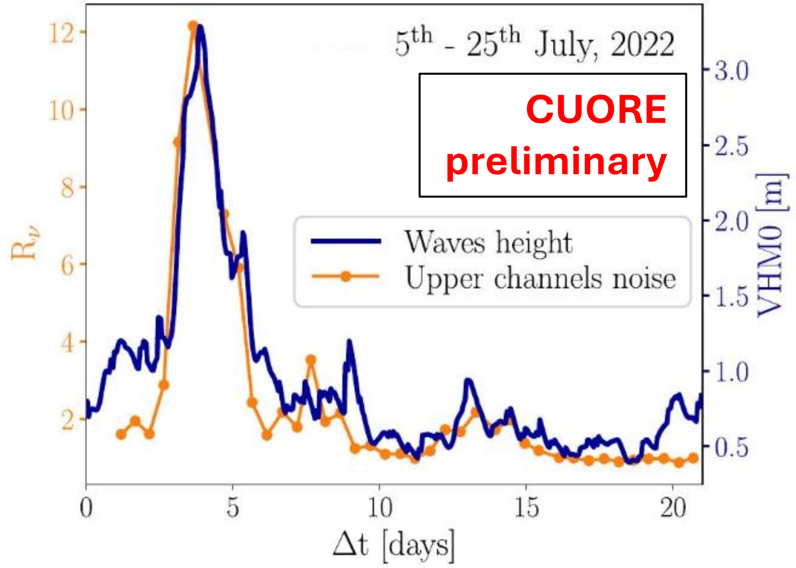

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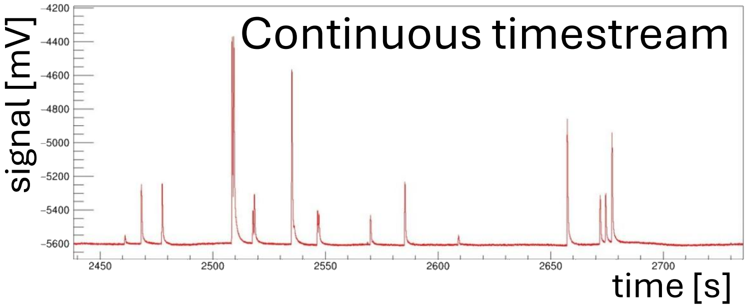
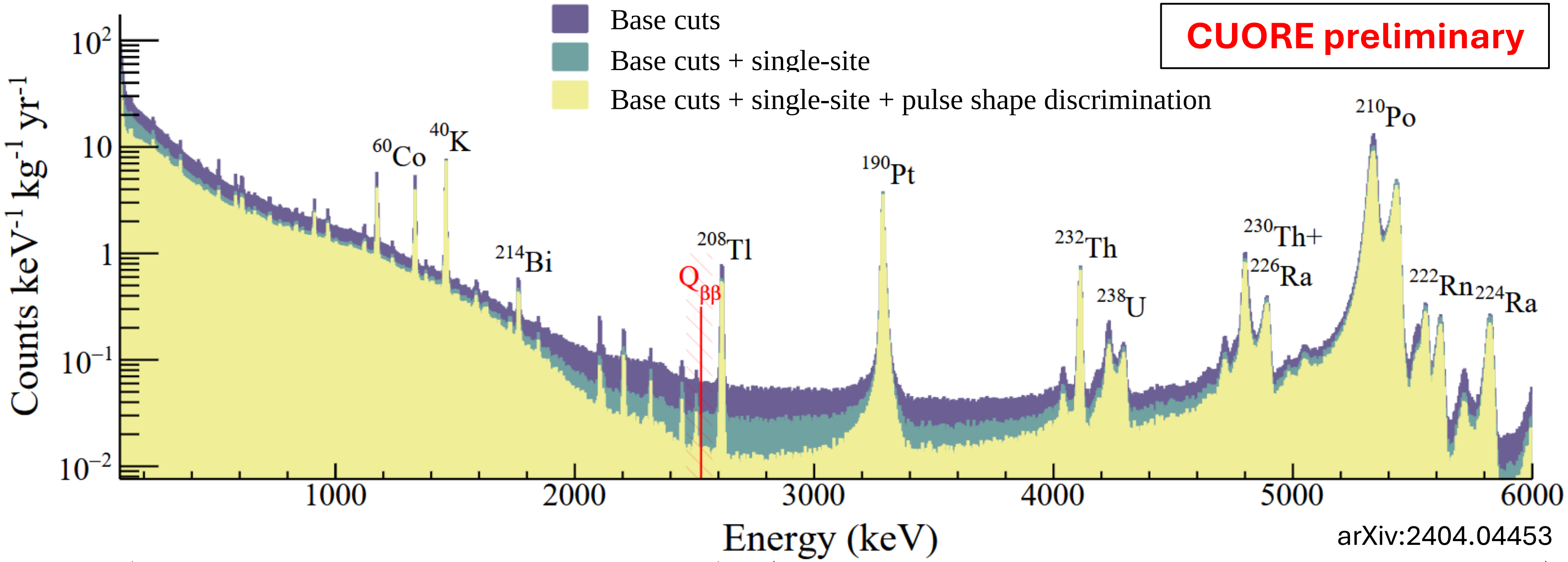
Producing the CUORE spectrum



Triggering → Signal denoising and filtering → Thermal gain stabilization → Energy calibration → Coincidence clustering → Pulse shape discrimination

Latest CUORE spectrum from 2 t-yr of exposure:



gamma region ↔ alpha region

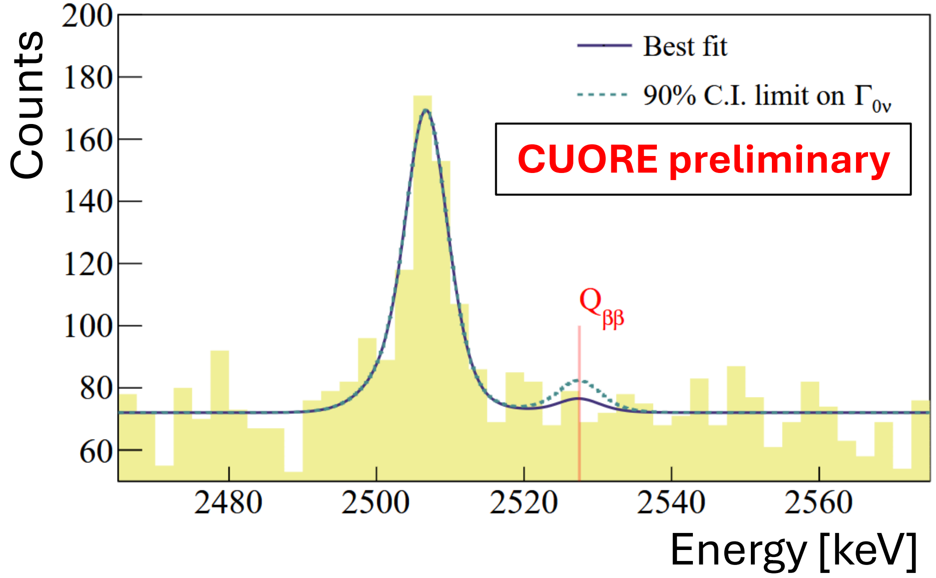
^{130}Te 0νββ search (latest!)

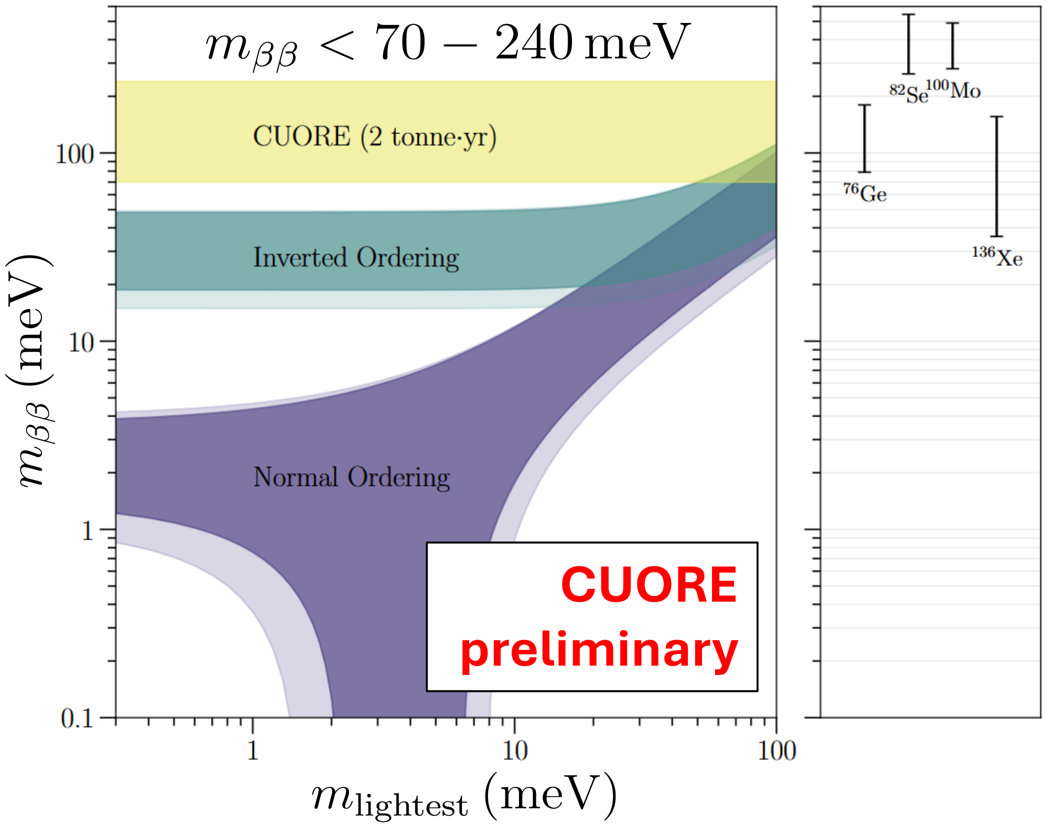
- Bayesian unbinned fit of ROI
  - Flat background
  - ^{60}Co peak
  - 0νββ peak at $Q_{\beta\beta}$
- Resolution @ 2615 keV: ~7.5 keV
- Analysis efficiency: 93.4(18)%

arXiv:2404.04453

- No evidence of 0νββ

$$T^{0\nu}_{1/2} > 3.8 \times 10^{25} \mathrm{yr}\ (90\%\ \mathrm{C.I.})$$





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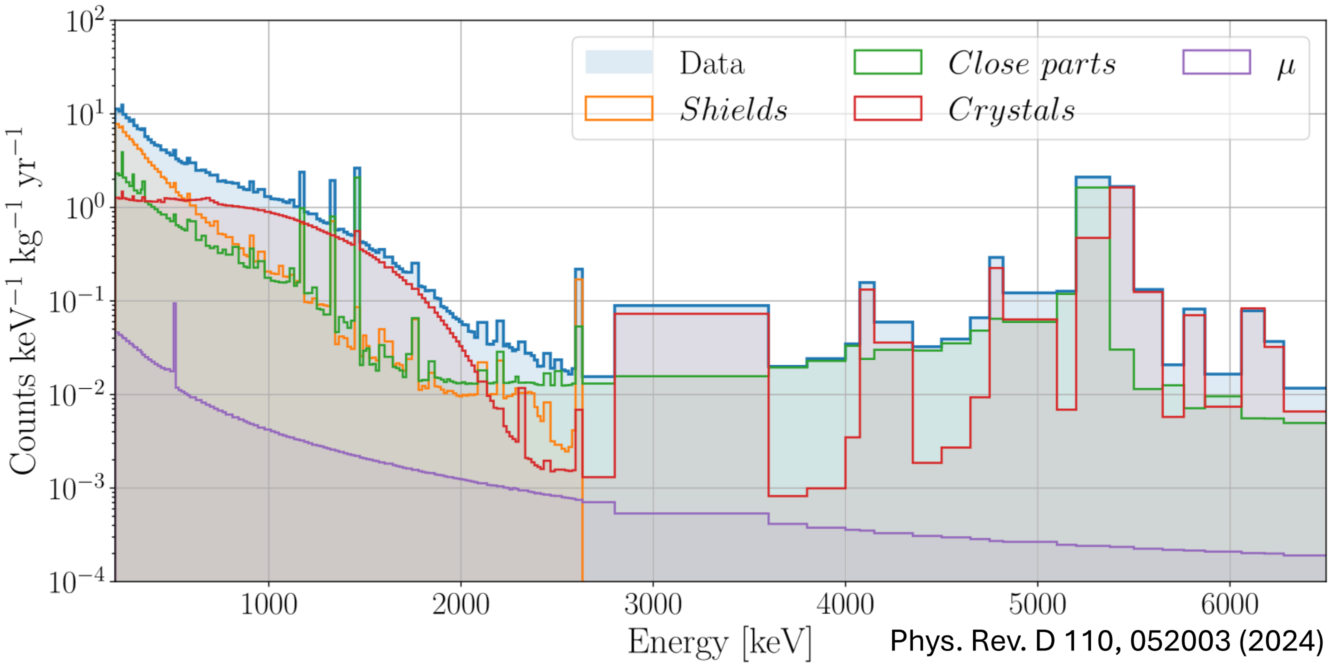
Backgrounds are well-understood

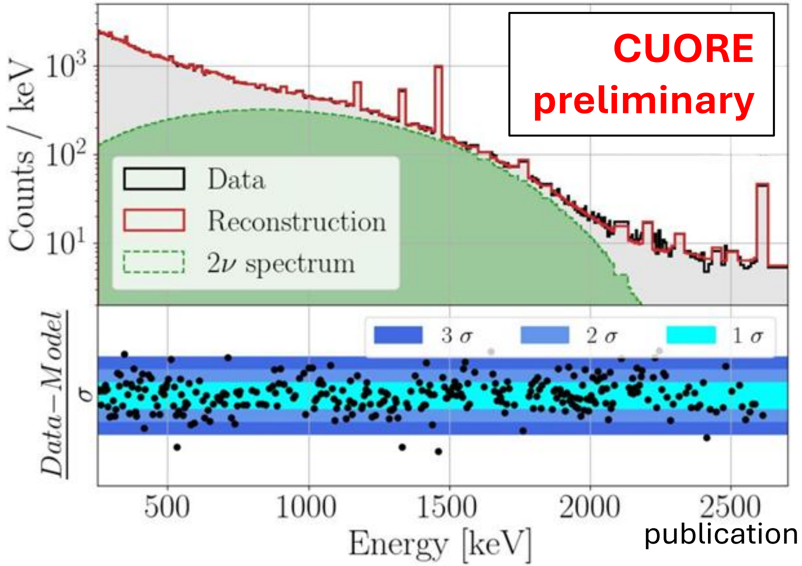
- Good reconstruction of spectral features in [200, 7000] keV
  - Verified by data and simulation
  - Work ongoing for below 200 keV
  - Important for CUPID which will use the same cryostat



Phys. Rev. D 110, 052003 (2024)

- Most precise measurement of 2νββ in ^{130}Te to date (in preparation)

$$T_{1/2}(^{130}\mathrm{Te}) = 9.323^{+0.052}_{-0.037}\ (\mathrm{stat}) \times 10^{20}\ \mathrm{y}$$



publication in preparation

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Beyond 0νββ: new analysis techniques

CUORE

- Leverage good energy collection at keV-scale, detector segmentation, large exposure:

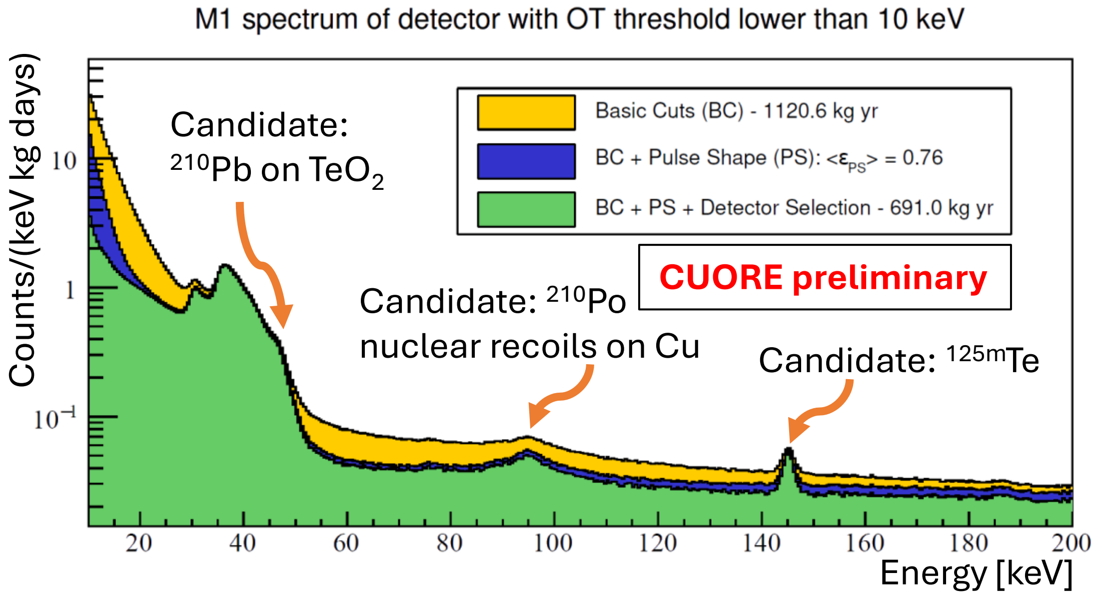
keV-scale "low energy" physics

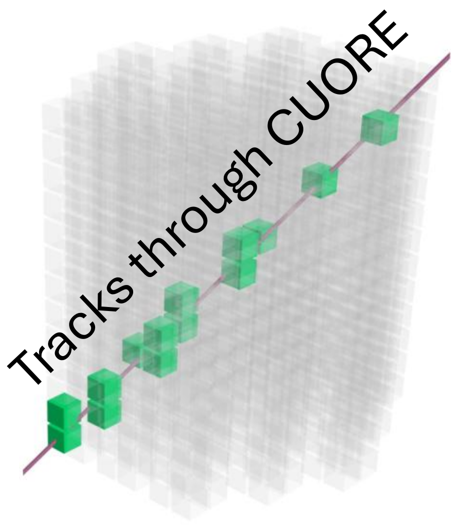
1. Analysis techniques (paper in preparation)
2. Solar axion searches (ongoing)
3. WIMP searches (ongoing)

Coincident multi-site physics

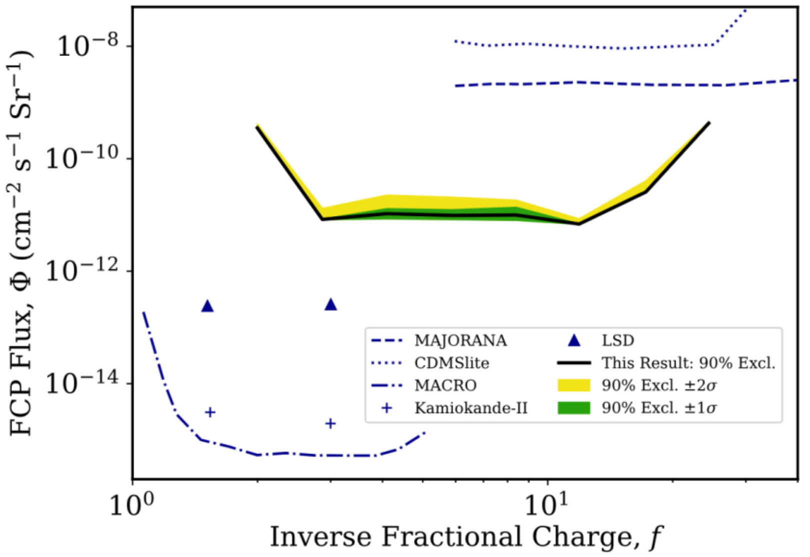
1. Decay to excited state of ^{130}Xe (Eur. Phys. J. C 81, 567 (2021))
2. Neutrinoless electron capture on ^{120}Te (Phys. Rev. C 105, 065504 (2022))
3. Fractionally-charged particles (Phys. Rev. Lett. 133, 241801 (2024))
4. Muon flux measurement (paper in preparation)

...and more!





Fractionally-charged particles



Phys. Rev. Lett. 133,241801 (2024)

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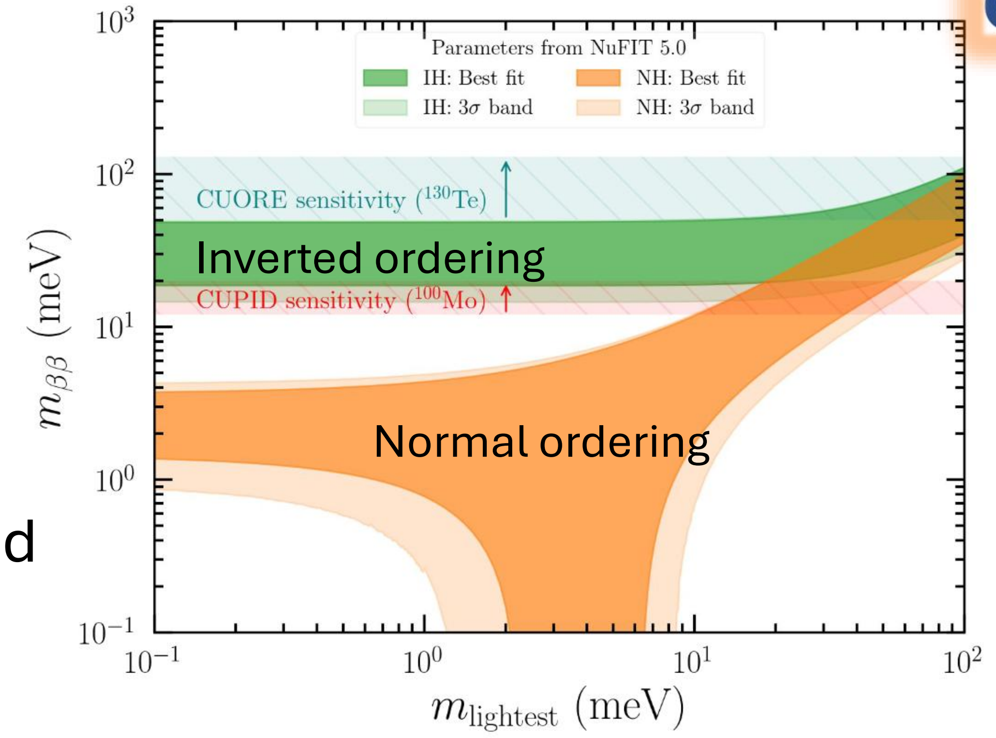
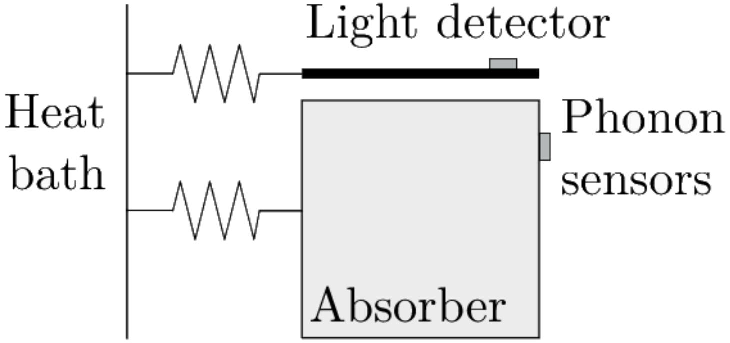
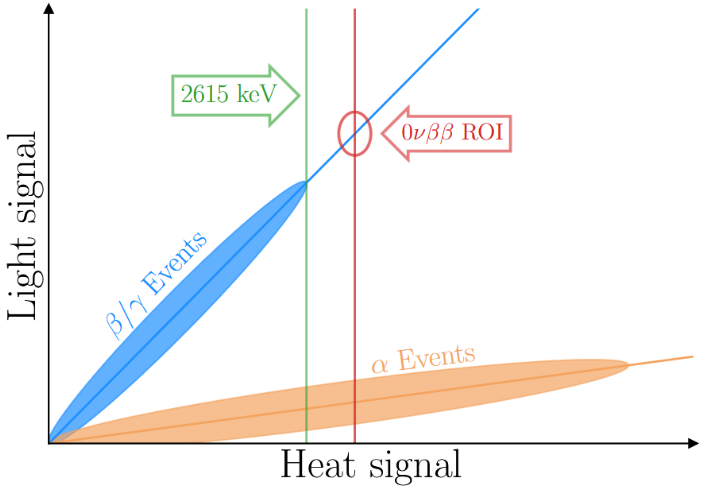
CUORE Upgrade with Particle IDentification

- Goal: fully explore inverted ordering parameter space
  - Reduce backgrounds in ROI by 100x
- 1596 scintillating crystals of $Li_2{}^{100}MoO_4$
  1710 Ge light detectors
  - ^{100}Mo higher Q-value → less β/γ background
  - Less scintillation light for α's
- Benefit from CUORE expertise
  - Same facilities and cryostat as CUORE







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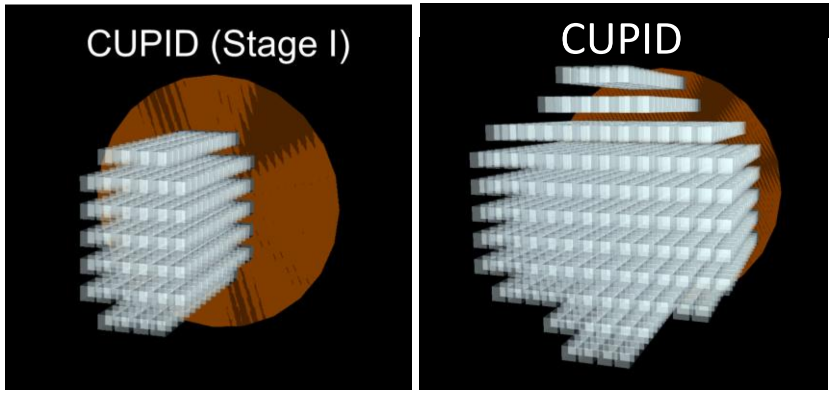
CUORE upgrades and CUPID R&D

arXiv:2503.02894
arXiv:2503.04481

- CUORE data-taking through 2026
  - Plans for dedicated "low-energy" runs
- Cryogenic upgrades planned for 2026

- CUPID full baseline tower R&D test underway
- Staged deployment for CUPID: physics data by 2030
  - Stage I: 532 crystals (1/3 of total array)
  - Stage II: full array



Test tower assembly

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Summary and outlook

- CUORE has taken data stably since 2019
- World-leading limit on ^{130}Te 0νββ half-life: >3.8×10^{25} yr
- Wide variety of physics possible to explore
- CUPID will improve on CUORE with background rejection using scintillation light detection
- CUPID benefits from CUORE experience:
  - Background model, operating procedures, etc.
- Upgrades expected in 2026 – stay tuned!

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Thank you!

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- The authors acknowledge Advanced Research Computing at Virginia Tech for providing computational resources and technical support that have contributed to the results reported within this paper. URL: https://arc.vt.edu/.The CUPID 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, the Italian Ministry of University and Research (Italy), the European Research Council and European Commission, the US Department of Energy (DOE) Office of Science, the DOE Office of Science, Office of Nuclear Physics, the National Science Foundation (USA), the National Research Foundation (Ukraine), and the Russian Science Foundation (Russia). This research used resources of the National Energy Research Scientific Computing Center (NERSC). This work makes use of both the DIANA data analysis and APOLLO data acquisition software packages, which were developed by the CUORICINO, CUORE, LUCIFER and CUPID-0 Collaborations.

CUORE

CUPID

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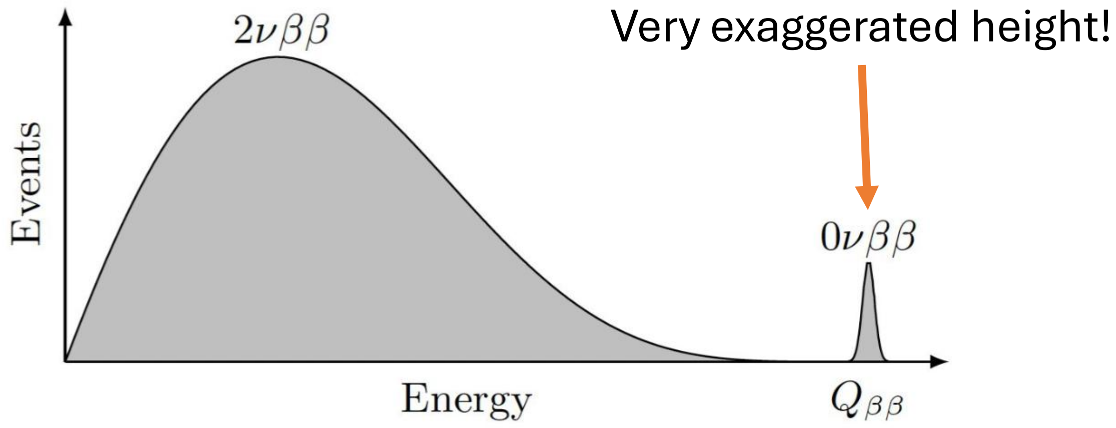
Backup

Double beta decay experiment design

- Peak in energy spectrum at tail of two-neutrino double-beta decay (2νββ)
- Half-life limits > $10^{22} – 10^{26}$ yr
- Sensitivity of experiment depends on:
  - Number of signal events you can see
    - Amount of active isotope
    - Runtime
    - Efficiency
  - Amount of background in ROI
    - Background index
    - Energy resolution (~width of ROI)



exposure = mass × runtime

$$T^{0\nu}_{1/2} \propto \epsilon \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

efficiency

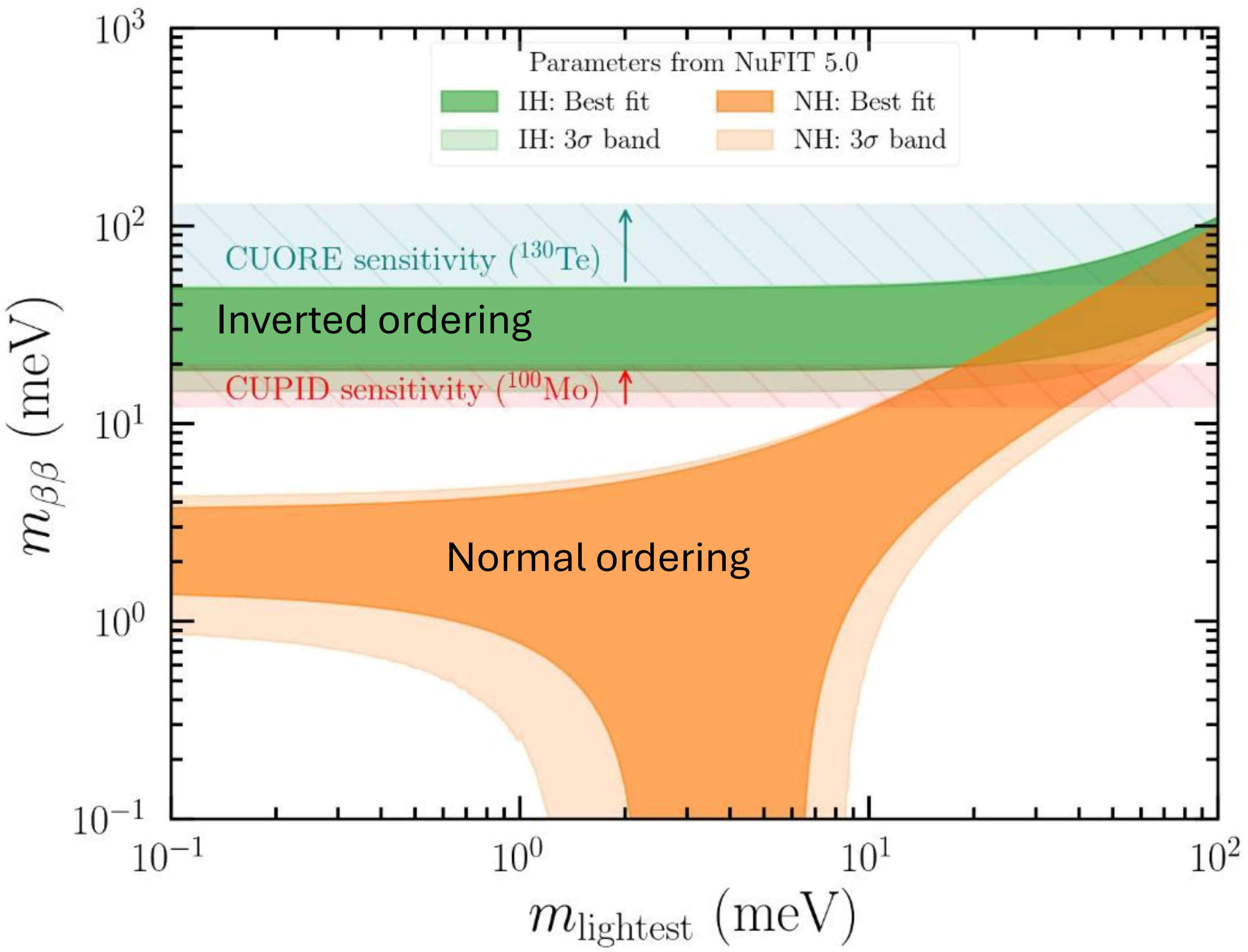
background index

energy resolution

Effective neutrino mass

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} |U_{ei}|^2 e^{i\phi_i} m_i \right|$$

$$T_{1/2}^{0\nu} = \left[G_{0\nu} |\mathcal{M}|^2 \frac{m_{\beta\beta}^2}{m_e^2} \right]^{-1}$$



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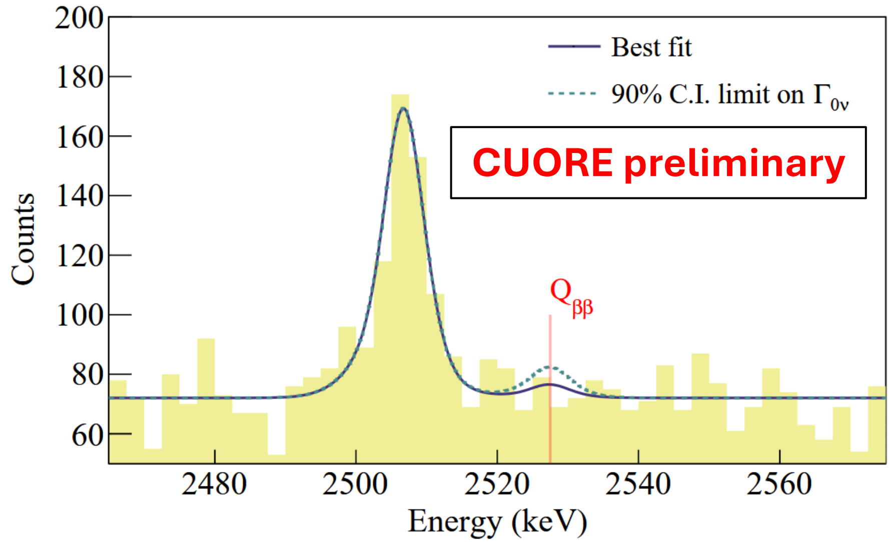
^{130}Te 0νββ search (latest!)

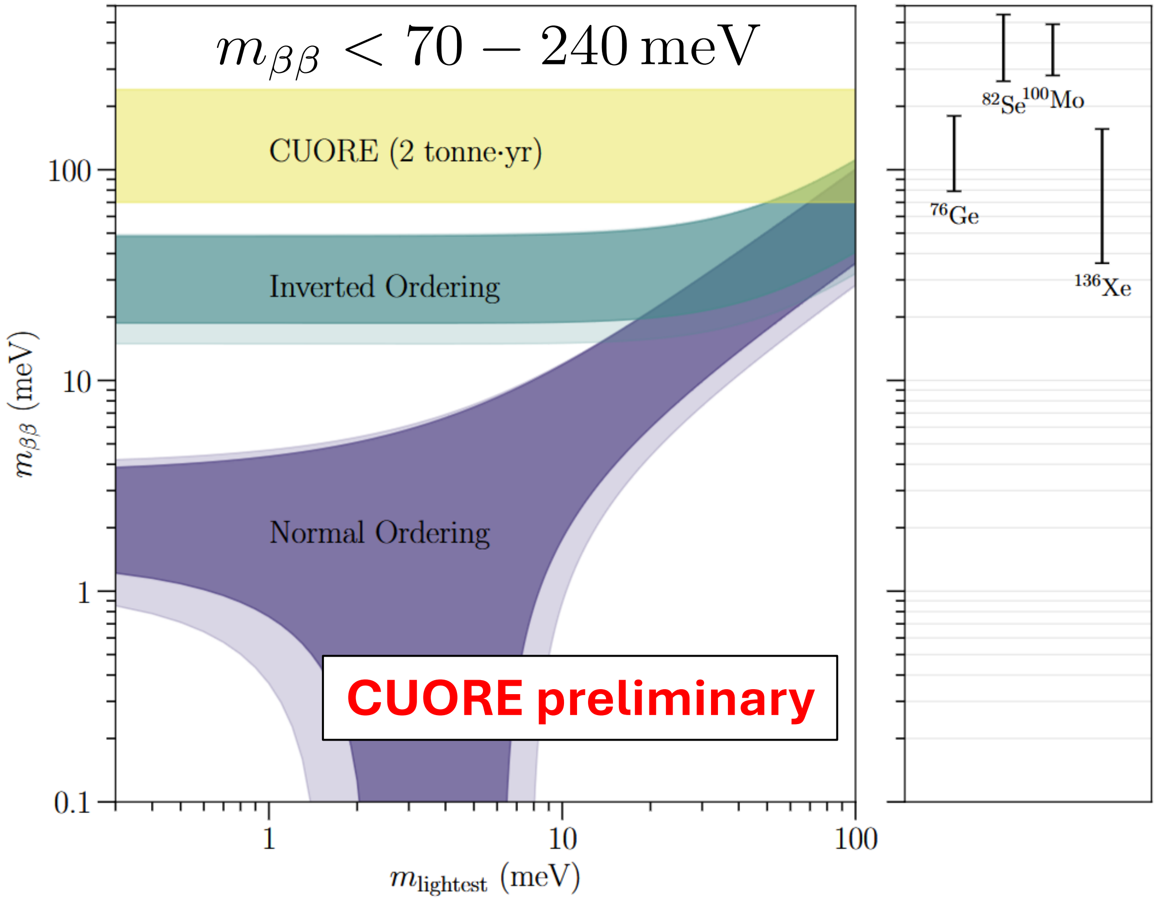
- Bayesian unbinned fit of ROI
  - Flat background
  - ^{60}Co peak
  - 0νββ peak at $Q_{\beta\beta}$

arXiv:2404.04453

Number of datasets	28
TeO_2 exposure	2039.0 kg·yr
^{130}Te exposure	567.0 kg·yr
FWHM at 2615 keV in calibration data	7.540(24) keV
FWHM at $Q_{\beta\beta}$ in physics data	7.320(24) keV
Total analysis efficiency (data)	93.4(18)%
Reconstruction efficiency	95.624(16)%
Anti-coincidence efficiency	99.80(5)%
PSD efficiency	97.9(18)%
Containment efficiency (MC)	88.35(9)% [34]

$$T_{1/2}^{0\nu} > 3.8 \times 10^{25} \text{yr} \, (90\% \, \text{C.I.})$$





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CUORE

Analysis framework

Triggering

Signal denoising and filtering

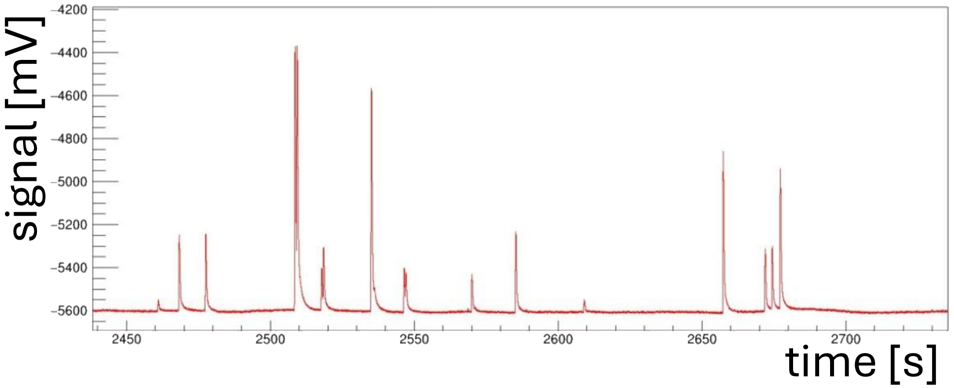
Thermal gain stabilization

Energy calibration

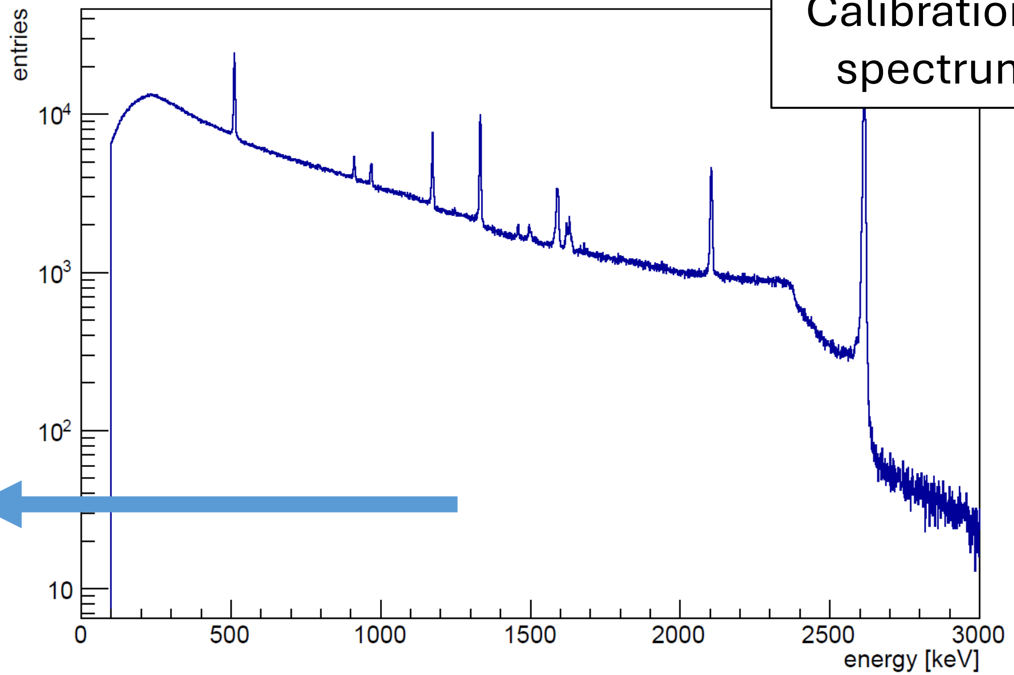
Coincidence clustering

Pulse shape discrimination

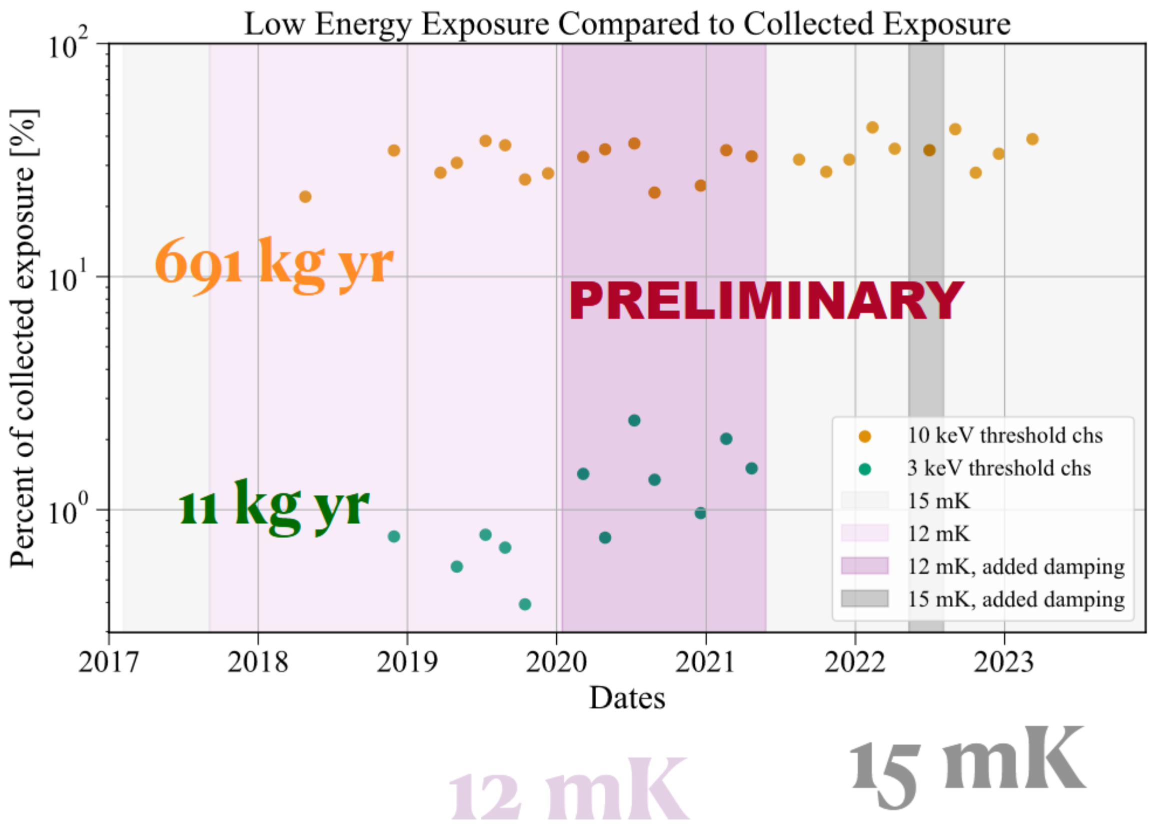
Continuous timestream



Calibration spectrum

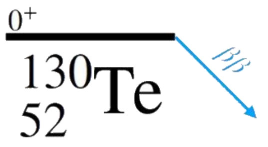


keV-scale "low energy" physics runs



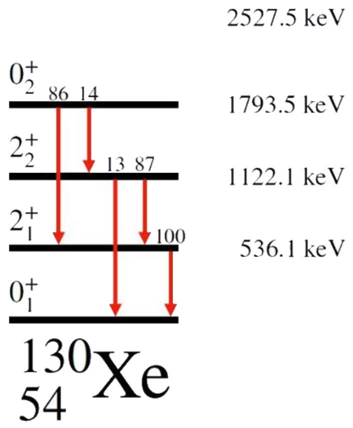
Sensitive to detector operating conditions

CUORE as a segmented detector

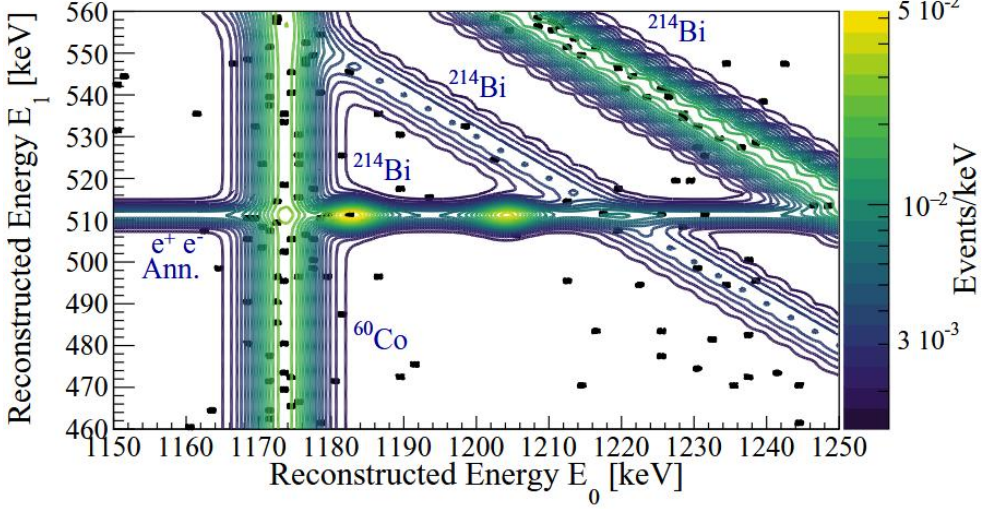


Decay to excited final state
Eur. Phys. J. C 81, 567 (2021)

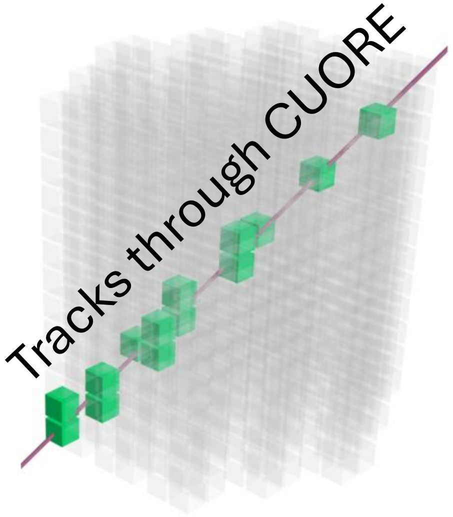
Updated analysis ongoing!



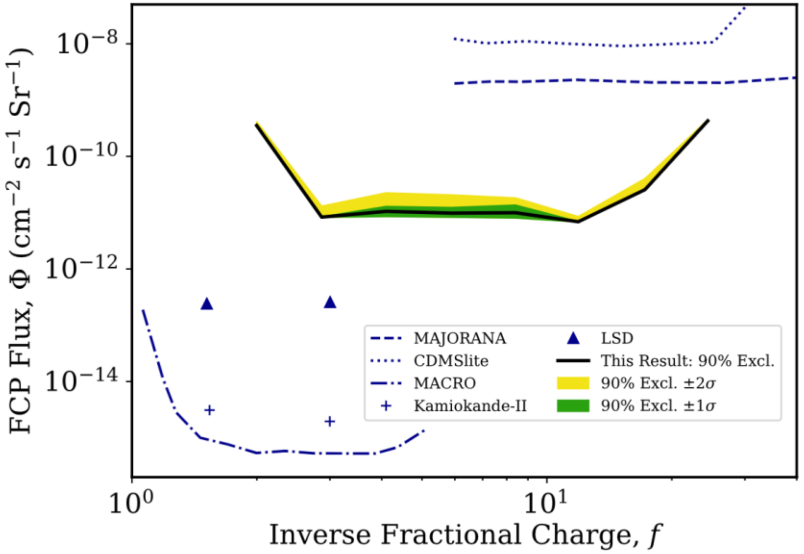
0νβ+EC of ^{120}Te



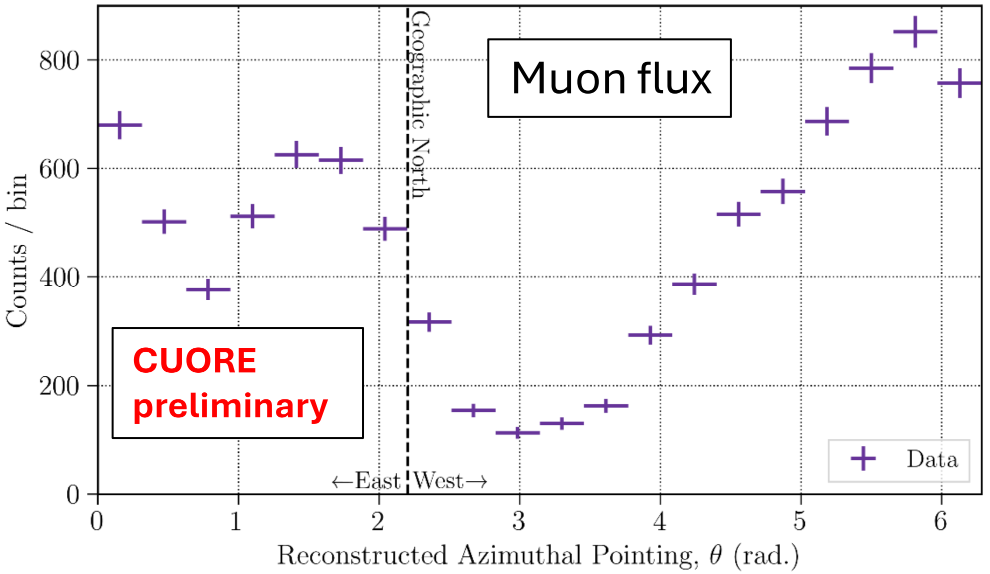
Phys. Rev. C 105, 065504 (2022)



Fractionally-charged particles



Phys. Rev. Lett. 133, 241801 (2024)



Paper in collaboration review

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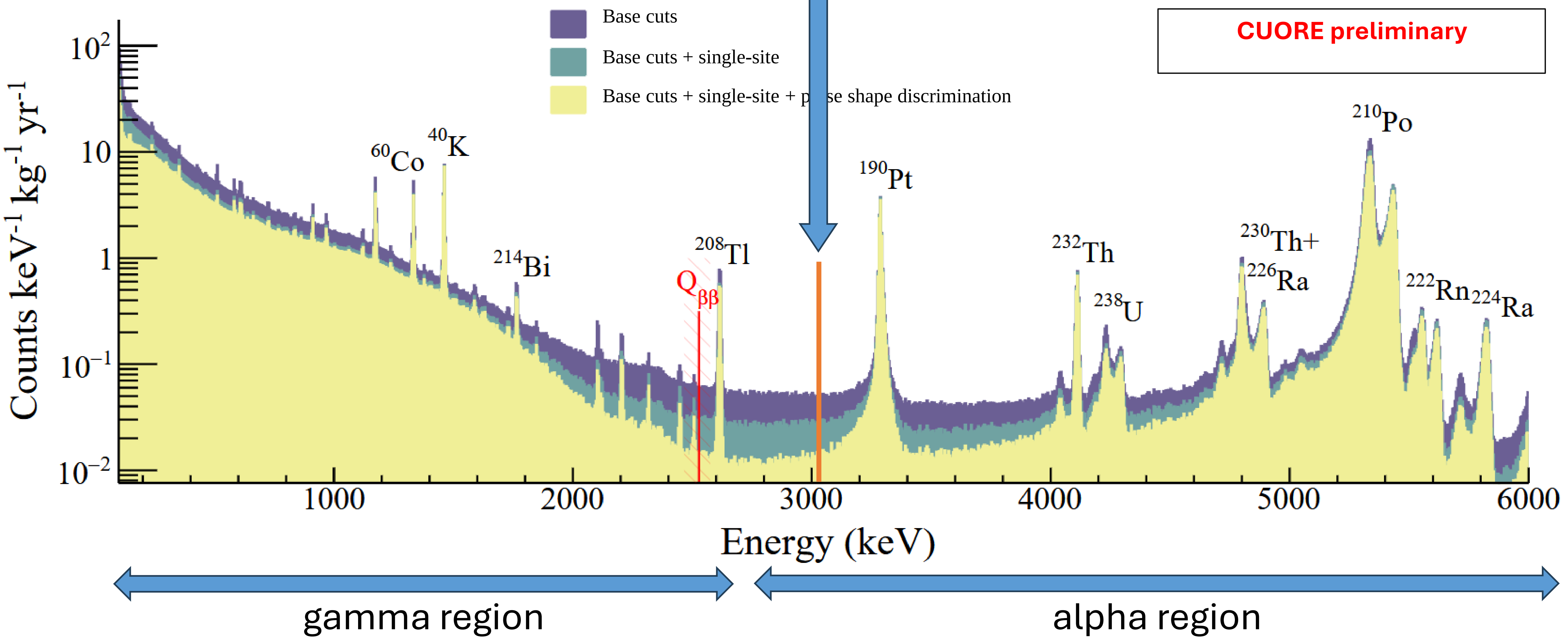
$^{100}Mo\ Q_{\beta\beta}$ 3034keV



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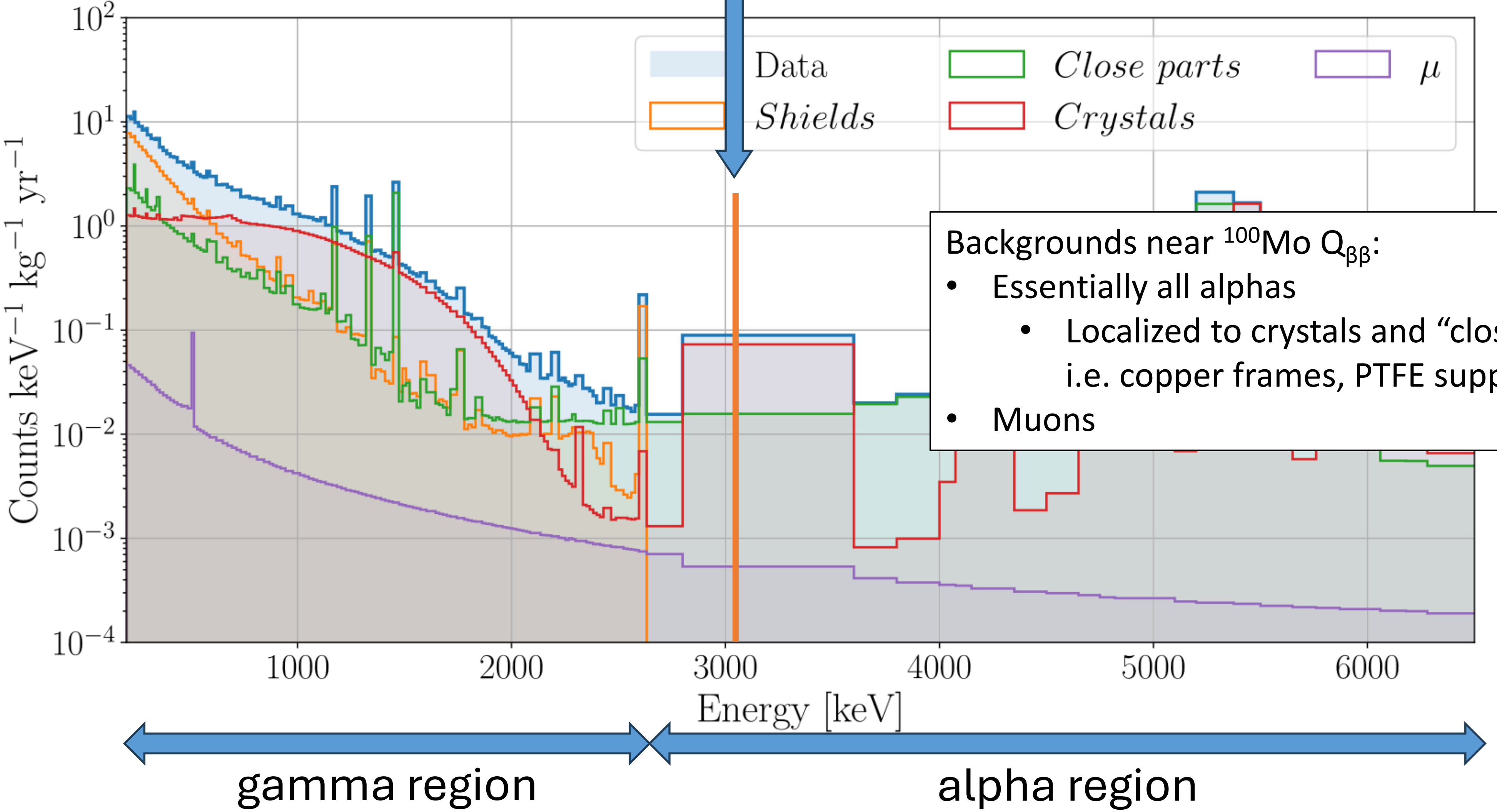

Backgrounds near $^{100}Mo\ Q_{\beta\beta}$:

- Essentially all alphas
  - Localized to crystals and "close parts," i.e. copper frames, PTFE supports
- Muons

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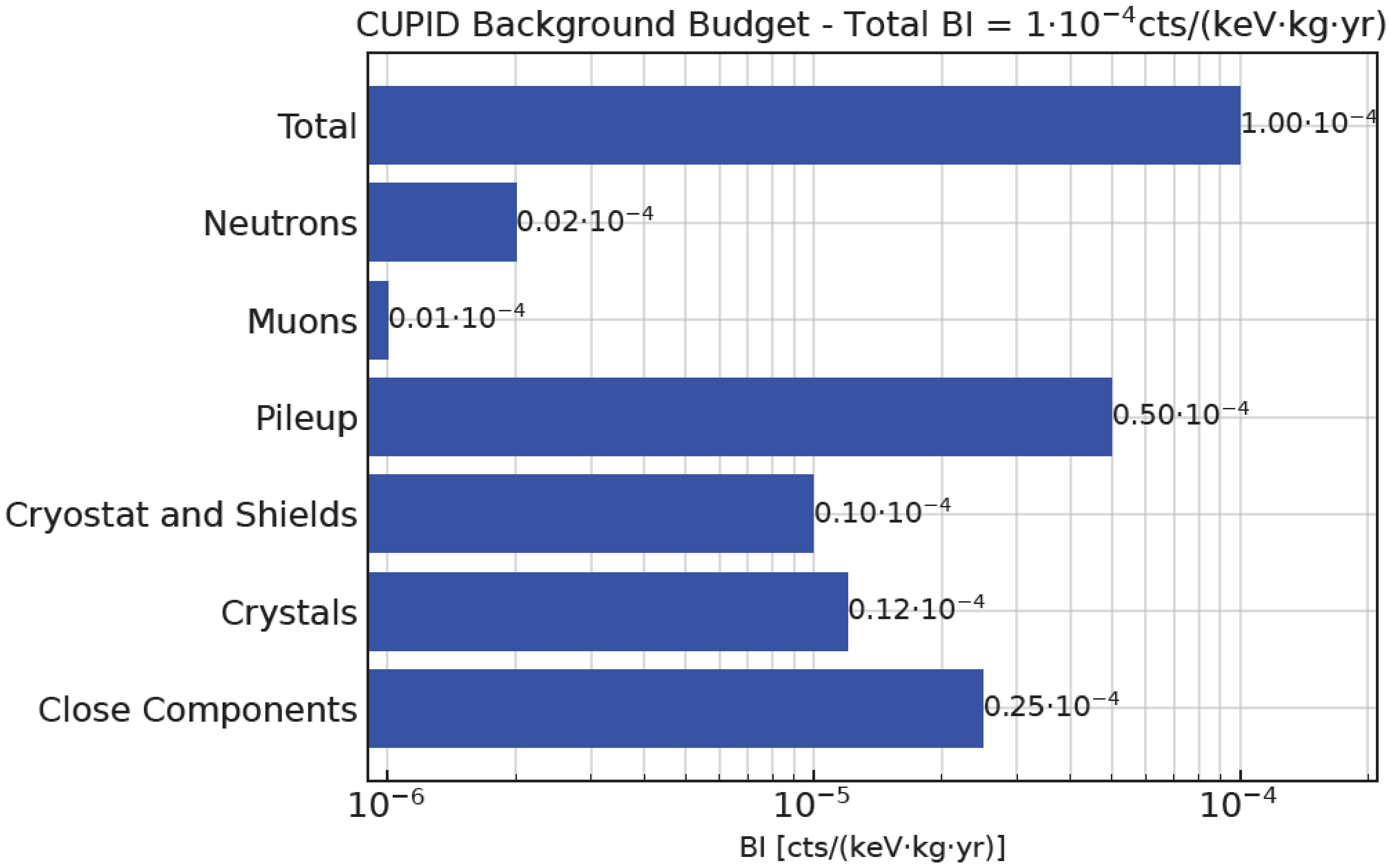
CUORE

Phys. Rev. D 110, 052003 (2024)



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