Search for fractionally charged particles with CUORE

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Contribution #417
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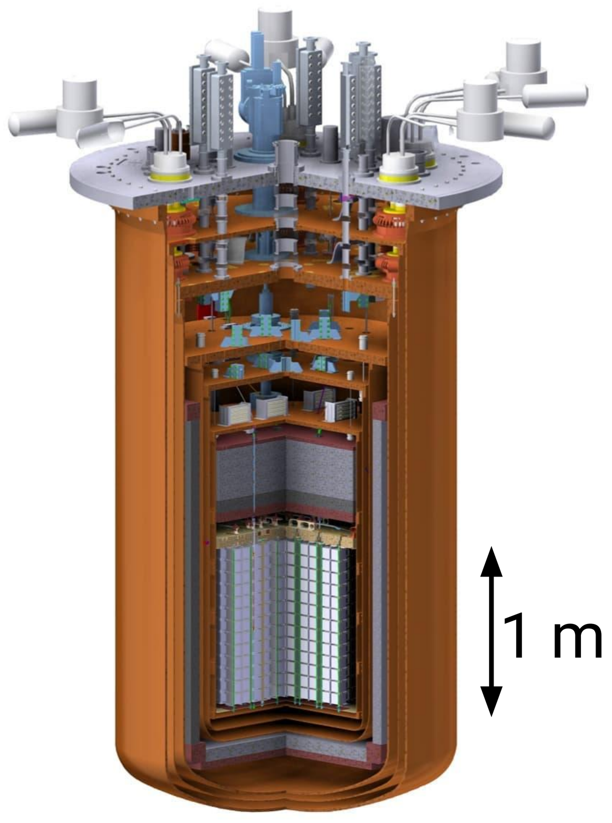
CUORE: the Cryogenic Underground Observatory for Rare Events



Tonne-scale millikelvin detector array comprised by 988 TeO_2 crystals.

- Cryogenic calorimeter technique: resolve thermal pulses from energy deposition within crystal absorber.

Located underground within the Laboratori Nazionali del Gran Sasso in Italy (~3600 m.w.e. overburden).

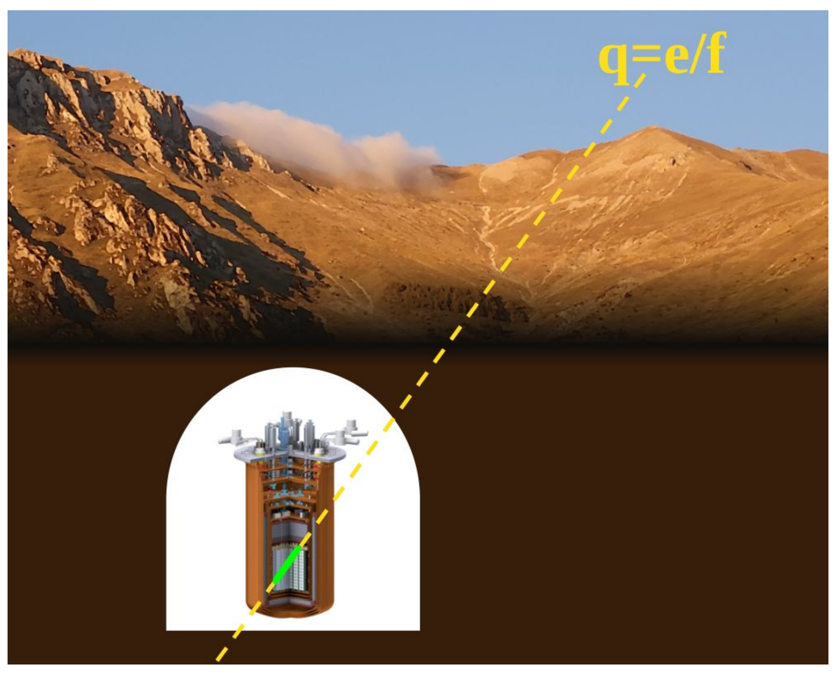
Primarily searching for neutrinoless double-beta decay in ^{130}Te, aided by strong energy resolution and low background conditions.

- Latest 0νββ results: arXiv:2404.04453

Fractionally Charged Particles

Particles with fractional electric charge predicted by various Beyond the Standard Model extensions:

- Hidden-Sector U(1) portals with novel fermions
- Free quarks
- And more!



If realized, fractionally charged particles (FCPs) could be present within cosmic radiation and be observed within underground experiments such as CUORE.

Relativistic FCPs with charge $q=e/f$ ($f>1$) would leave faint track-like signatures across the detector.

Track Reconstruction in CUORE

CUORE demonstrates that bolometric detectors have reached sufficient scale to resolve through-going particle tracks:

- Observe & measure muon flux in LNGS[1]
- Enable exotic physics searches, such as FCPs!

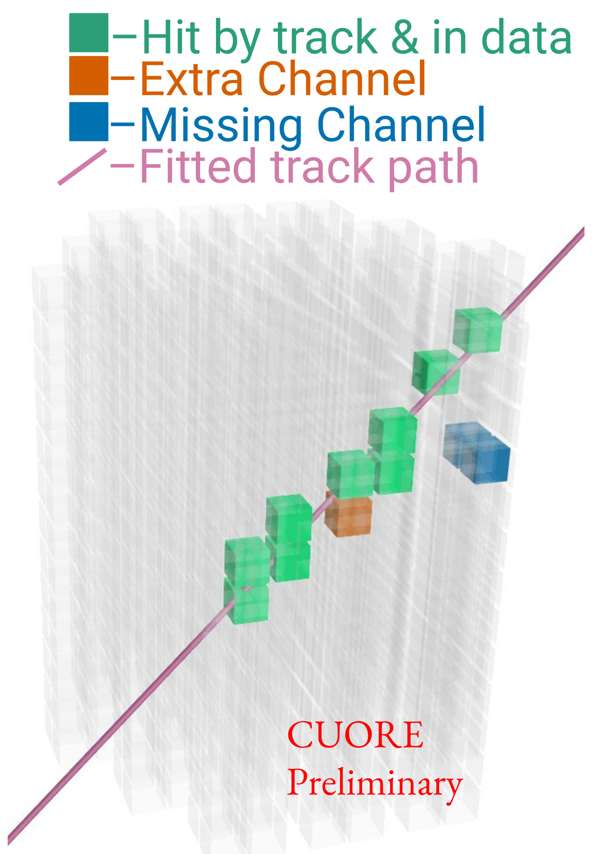
Track-fitting algorithm developed using multi-objective optimization (MOO)[2] to maximize information provided by segmented geometry of CUORE.

MOO algorithm simultaneously minimizes:

 # missing-channels: crystals registering an event in data, but not struck by through-going track.

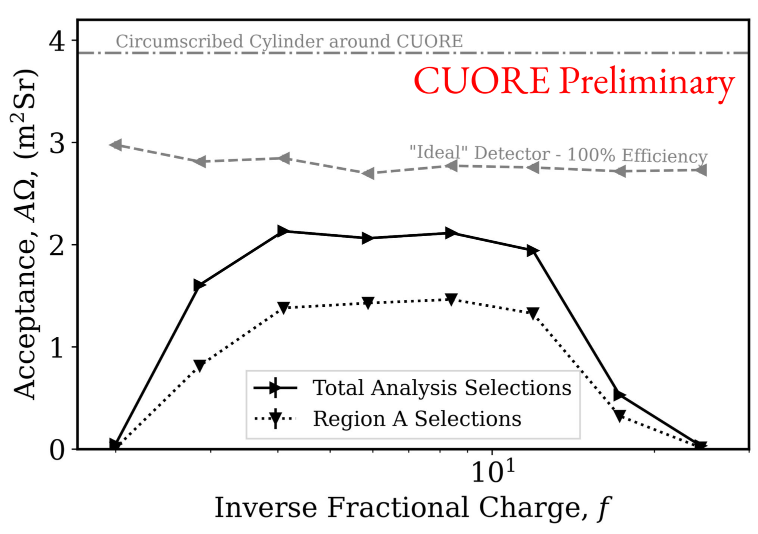
 # extra-channels: crystals struck by through-going track, but do not register an event in data.

Lower counts of extra- and missing-channels indicate a more track-like cluster topology.



CUORE Muon Candidate

Detector Response and Simulation

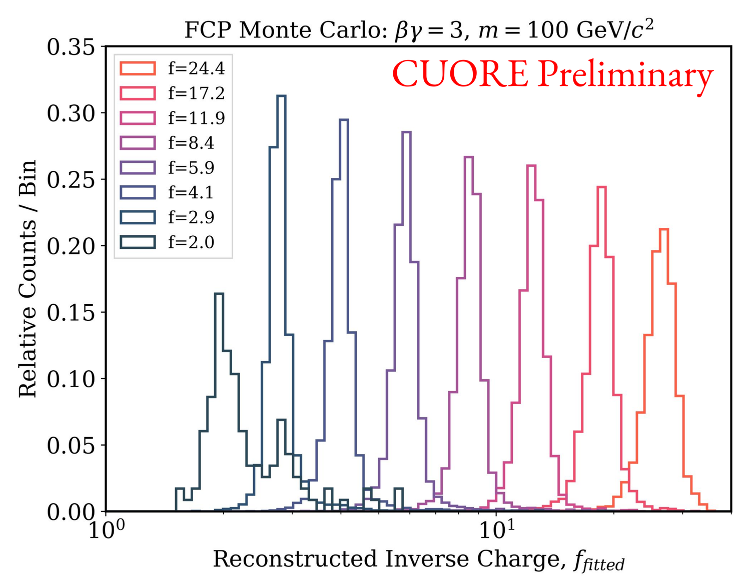


Detector acceptance to relativistic FCPs determined from Monte Carlo simulations of particle interactions with detector, assuming downward-isotropic particle flux.

Analysis selections sensitive to FCPs with charges between $e/2$ to $e/24$.

Track-fitting additionally provides maximum-likelihood estimate of reconstructed inverse charge, f, for each fitted cluster.

FCPs present within underground cosmic-ray flux would produce an excess in the spectrum of reconstructed-f.



Data Selections

Use first tonne-year of CUORE's exposure from *Nature* **604** 53-58 (2022).

- 442.3 days of detector livetime used for this search.

Group together contemporaneous events into detector-wide **clusters** based on their crystal **multiplicity, $\mathcal{M}$.**

- Select per-crystal energy depositions between 20 keV–6 MeV.
- Consider clusters with $\mathcal{M} \geq 6$, and fit with track-reconstruction algorithm.

Reject clusters in coincidence with high-energy events (≥10 MeV) to veto through-going muon candidates.

Likelihood Model

Bin clusters into ABCD regions based on track-reconstruction parameters: **# missing-channels** and **# extra-channels**.

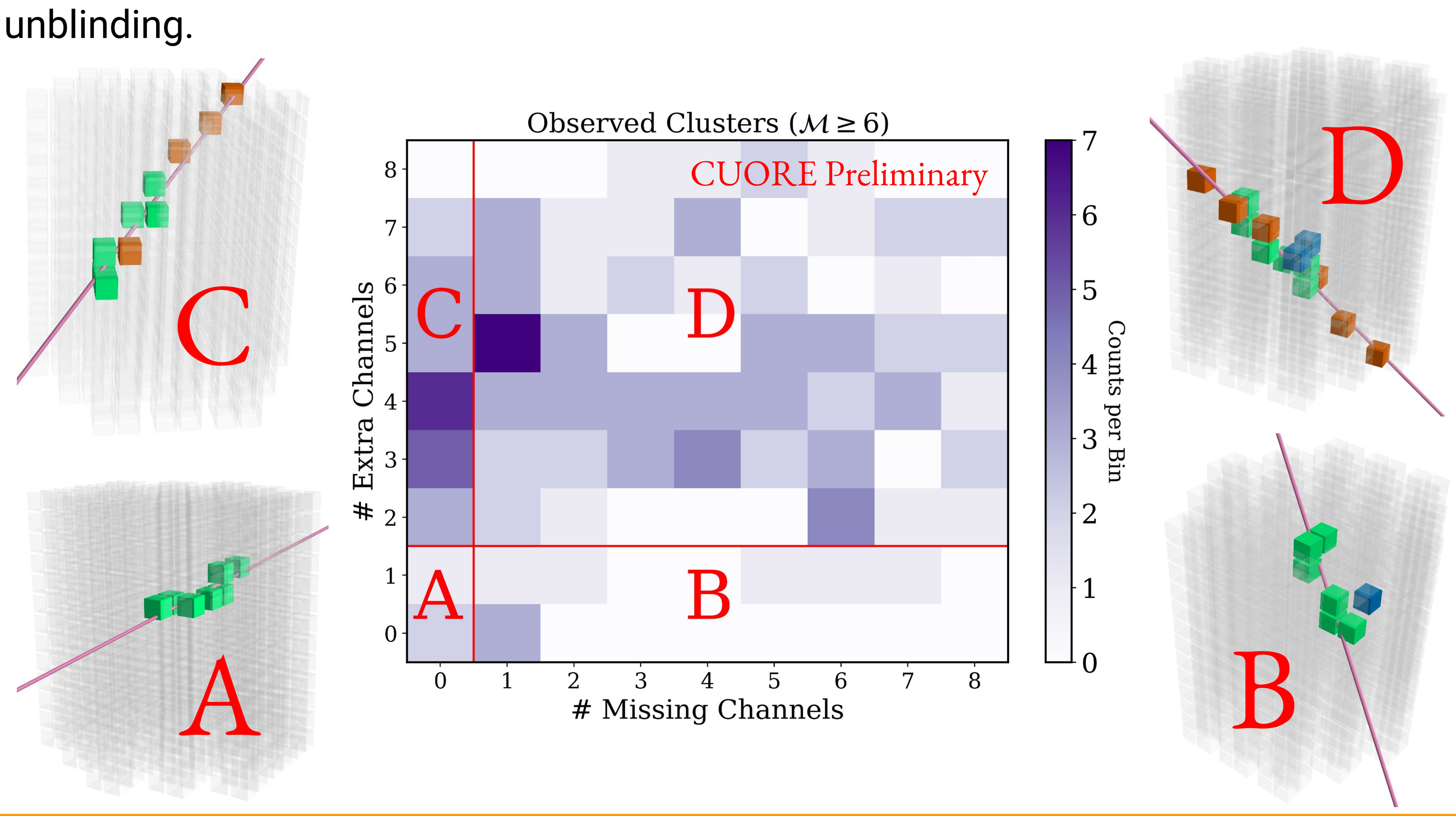
Have signal-preferred Region A, background-dominated Region D, and control Regions B & C.

Data-driven background modeling with binned ABCD likelihood:

$$-2\log\mathcal{L} = \sum_{i\in f\text{ bins}} \sum_{j\in\{A,B,C,D\}} -2\log\mathrm{Pois}\left(k_{ij}; N_{ij}\right) \quad \text{where} \quad \begin{aligned} N_{iA} &= \epsilon_{iA} n^{\mathrm{Sig}} + n_i^{\mathrm{Bgd}}, \\ N_{iB} &= \epsilon_{iB} n^{\mathrm{Sig}} + \tau_{iB} n_i^{\mathrm{Bgd}}, \\ N_{iC} &= \epsilon_{iC} n^{\mathrm{Sig}} + \tau_{iC} n_i^{\mathrm{Bgd}}, \\ N_{iD} &= \epsilon_{iD} n^{\mathrm{Sig}} + \tau_{iB}\tau_{iC} n_i^{\mathrm{Bgd}}. \end{aligned}$$

k_{ij} – Observed data in bin-i and Region j.
ϵ_{ij} – Signal template, from FCP Monte Carlo.
τ_{ij} – Background transfer functions.
n^{Sig} – Signal counts parameter.
n_i^{Bgd} – Region A background counts.

Model assumes that **# extra-channels** and **# missing-channels** are independently distributed for background clusters: validated with Region D inset prior to full search unblinding.

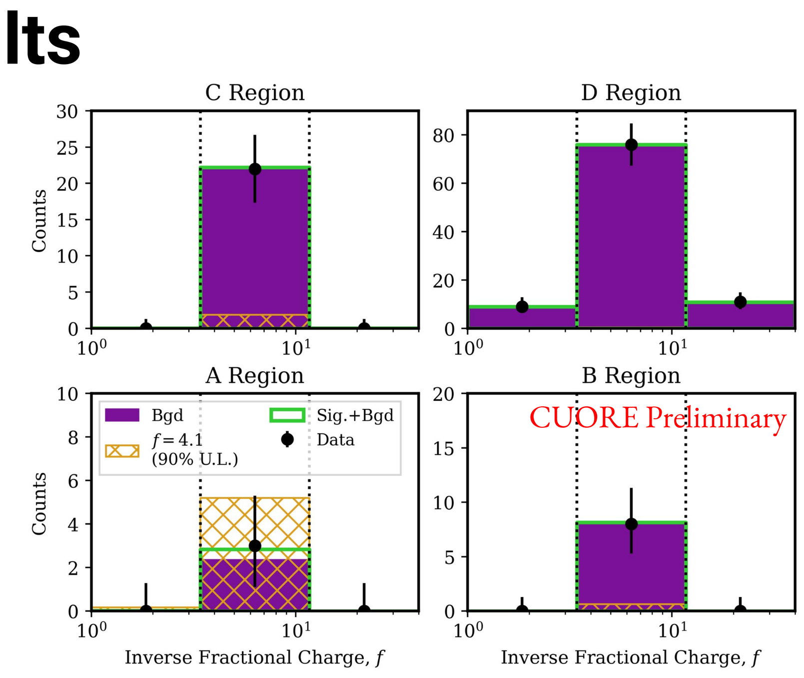


Fit Results

Test background-only vs signal-plus-background hypotheses with profile likelihood ratio, scanning across f=2 to f=24.

No excess observed over background: compatible with background-only hypothesis within 1σ local significance at all test points.

Set upper limits at 90% C.L. on possible FCP signal strength using confidence brackets derived from toy experiments.



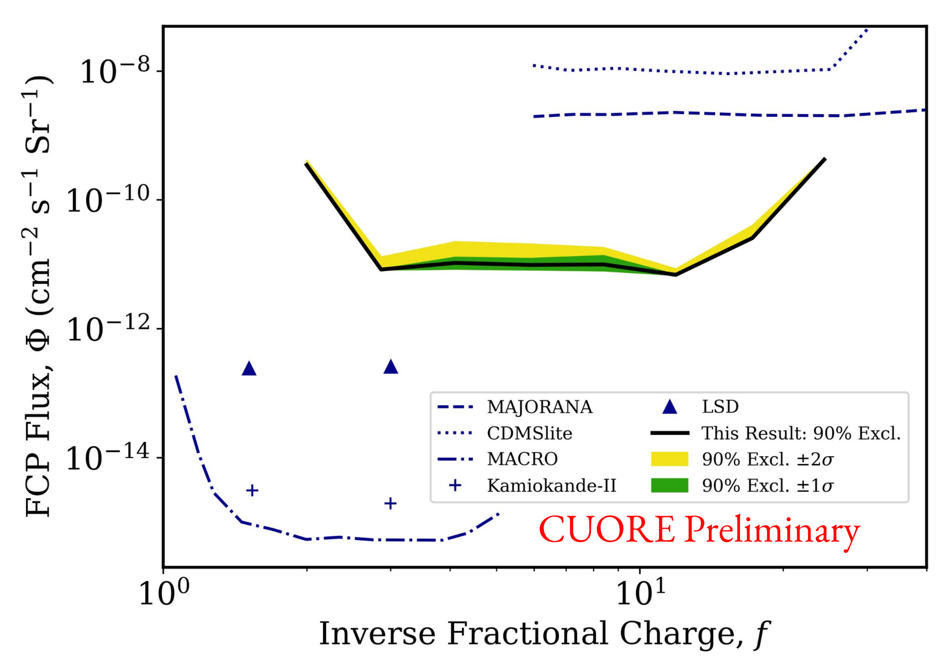
Flux Limits

Exclusions converted into underground flux limits:

$$\Phi(f) = \frac{n^{\mathrm{Sig}}}{T_{\mathrm{livetime}} \cdot (A\Omega)_{\mathrm{selection}} \cdot \epsilon_{\mathrm{cluster}}}$$

Minimum flux exclusion at f=11.9, assuming half-isotropic angular distribution:

$$\Phi < 6.9 \cdot 10^{-12}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{Sr}^{-1}\ (90\%\ \mathrm{C.L.})$$



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Manuscript in preparation!

[1]-See J.A. Torres & D. Mayer, Contribution #269

[2]-Full algorithm details: J. Yocum, D. Mayer *et al.* J. Instrum. **17** (07), P07004