CUORE analysis framework for 988 cryogenic calorimeters
Searching for neutrinoless double-beta decay of ^{130}Te

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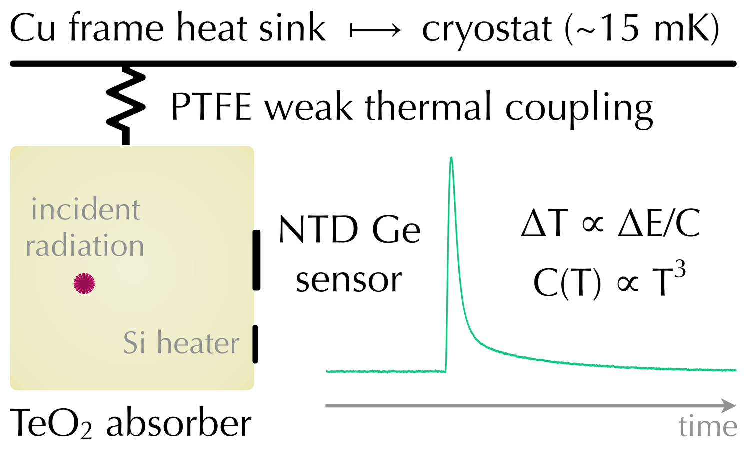
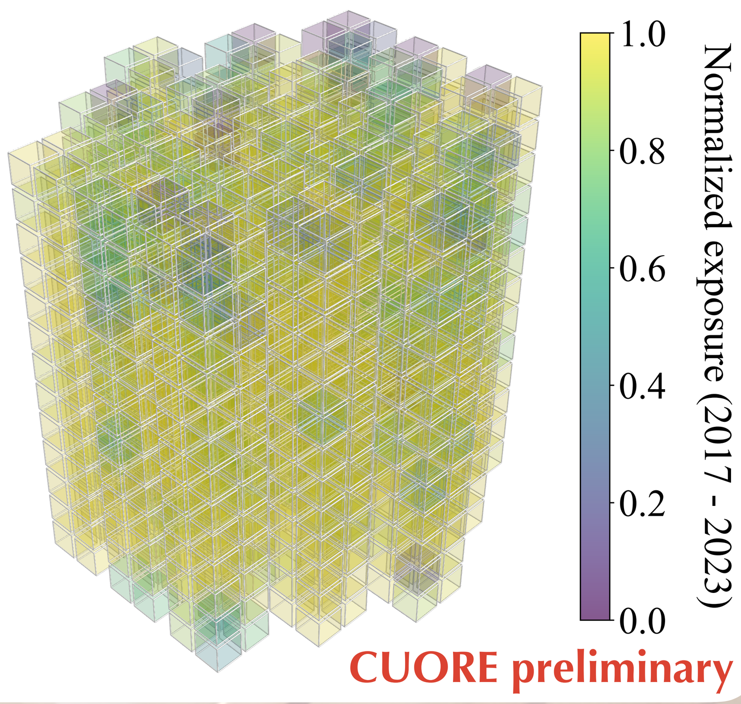
CUORE cryogenic calorimeter

- 742 kg TeO_2 (206 kg ^{130}Te)
- $\delta E/E \sim 0.3\%$ at 2527.5 keV ($Q_{\beta\beta}$)
- BI ~ 10^{-2} counts/(keV·kg·yr)
- non-uniformities in components necessitates individual calorimeter optimization and analysis

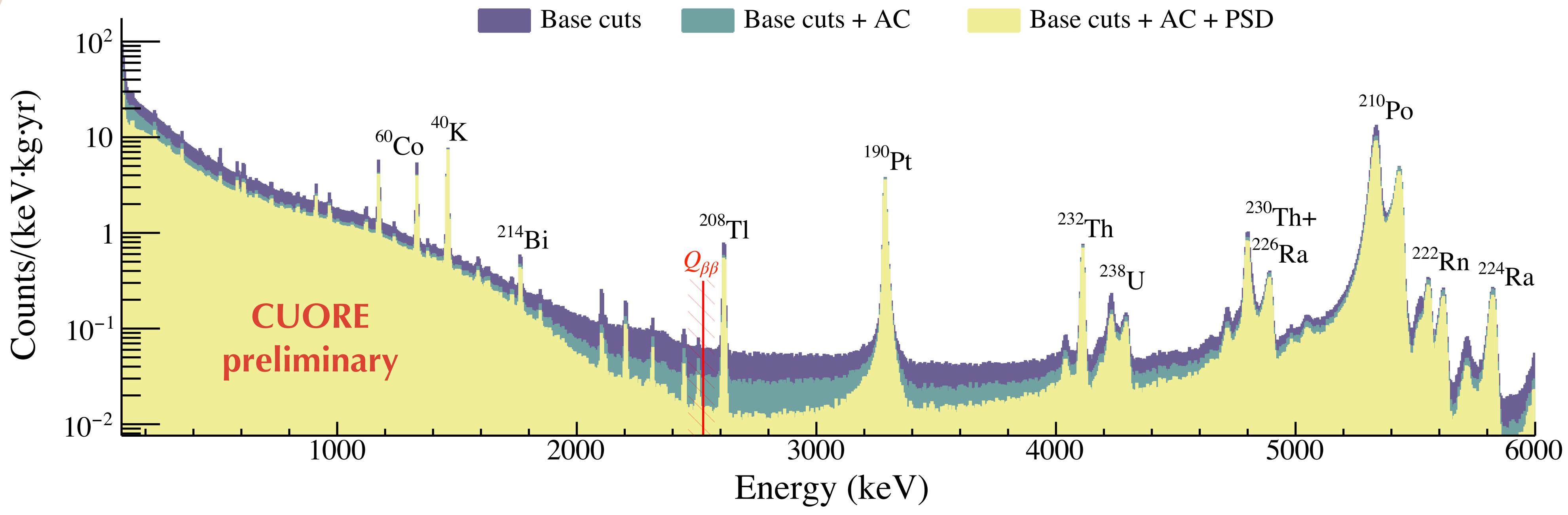


2 tonne·yr TeO_2 exposure

- 28 datasets (each dataset consists of ~1 week initial calibration, ~1.5 month-long physics measurement, and ~1 week final calibration)
- 914 analysis-active calorimeters per dataset on average
- > 90% duty cycle with an exposure rate of ~50 kg·yr TeO_2 per month since 2019 (unprecedented 5 year stable detector operation to date)



Energy spectrum and event selection



- event energy reconstruction is performed independently for each dataset-calorimeter (ds-ch)
- denoising ⟶ OT triggering ⟼ filtering (OF) ⟼ thermal gain stabilization ⟼ calibration
  continuous data stream — event (OT triggered pulse)
- base cuts (BC) reject spurious pulses, the anticoincidence (AC) cut rejects multi-crystal events, and the pulse shape discrimination (PSD) cut rejects pulses with uncharacteristic features

Efficiencies • BC: heater-induced pulses are used to evaluate the probabilities of accurate detection, energy reconstruction, and pile-up rejection • AC: events in the 1461 keV ^{40}K peak are used to evaluate the probability of identifying a single crystal event • PSD: events in the γ peaks are used to evaluate the probability of keeping a physical event at different energies; $\epsilon_{PSD}(Q_{\beta\beta})$ is extrapolated

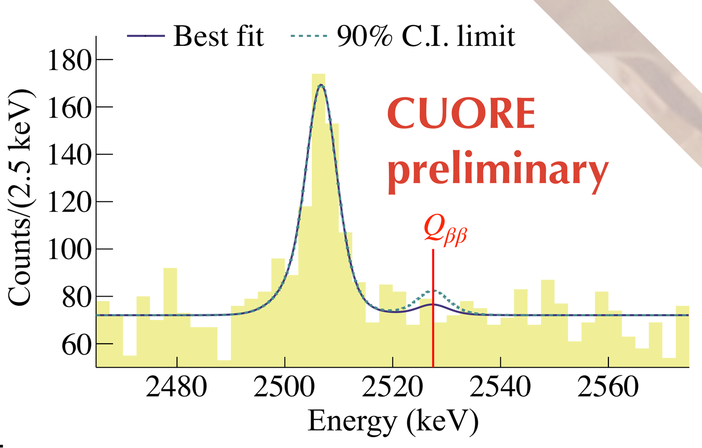
Statistical approach and model

$\Gamma_{0\nu}$ from UEML fit

Perform fit in the BAT* framework to sample the posterior probability distribution function (pdf):

$$p(\vec{\theta}\,|\,\vec{E}) \propto \mathscr{L}(\vec{E}\,|\,\vec{\theta}) \cdot \pi(\vec{\theta})$$

where $\mathscr{L}$ is a model of the data in the ROI [2465, 2575] keV and π contains evaluated parameter prior pdfs



$$\mathscr{L} = \prod_{ds,ch} \frac{e^{-\lambda}\lambda^n}{n!} \prod_i \left[\frac{s}{\lambda} f_{0\nu}(E_i\,|\,\vec{\theta}_{0\nu}) + \frac{c}{\lambda} f_{Co}(E_i\,|\,\vec{\theta}_{Co}) + \frac{b}{\lambda \Delta E} \right]$$

$$s = \frac{N_A \cdot I_{^{130}Te}}{M_{TeO_2}} \cdot \Gamma_{0\nu} \cdot \sum_{ds,ch} (m \cdot t) \cdot \epsilon_{sel} \cdot \epsilon_{MC}; \quad b = BI \cdot \Delta E \cdot \sum_{ch} (m \cdot t)$$

Detector response

- define a multi-Gaussian peak shape model (f_{cal}) and fit the 2615 keV ^{208}Tl peak in calibration data to determine calorimeter-dependent energy resolution and bias
  - perform a simultaneous fit over each dataset-tower to constrain low-statistics structures in the spectrum

$$\delta E_{FWHM} = \sum_{ds,ch} (m \cdot t) \Big/ \sum_{ds,ch} \left(\frac{m \cdot t}{2.355 \cdot \sigma_{cal}} \right) = (7.540 \pm 0.024)\,\mathrm{keV}$$

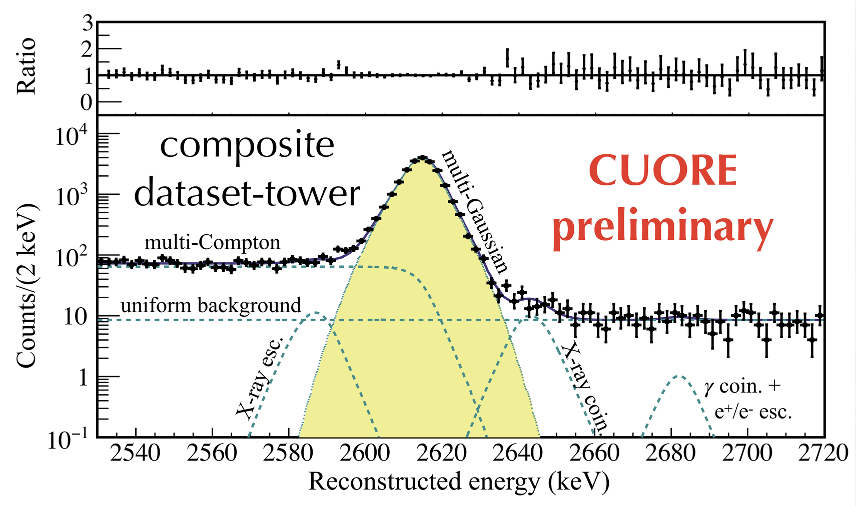
- define an energy-dependent scaling model for the resolution and bias to extrapolate their values to the ROI

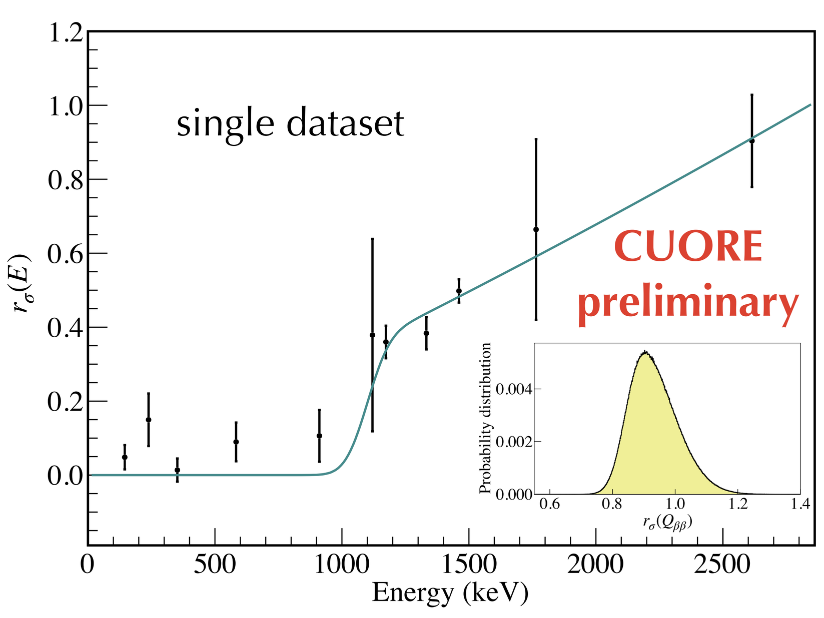
$$\sigma_{phys}(E) = \sqrt{\delta^2_{phys} + r_\sigma(E) \cdot (\sigma^2_{cal} - \delta^2_{cal})}, \quad \mu_{phys}(E) = r_\mu(E)\mu_{cal}$$

- fit the peak shape model to individual dataset-peaks over all calorimeters to determine $r_{\sigma/\mu}(\vec{E})$
  - for each dataset, fit $r_{\sigma/\mu}(E)$ in BAT and use $r_{\sigma/\mu}(Q_{\beta\beta})$ posteriors as priors in the ROI fit

$$\delta E(Q_{\beta\beta}) = (7.320 \pm 0.024)\,\mathrm{keV}$$

*Bayesian Analysis Toolkit





Priors

Parameter (θ)	Prior (π)/Dependence
$\Gamma_{0\nu}$	Uniform/Global
E_{sum} (^{60}Co)	Uniform/Global
Γ_{Co}	Uniform/Dataset
BI	Uniform/Dataset
^{130}Te $Q_{\beta\beta}$	Gaussian/Global
Isotopic abundance	Gaussian/Global
Containment eff.	Gaussian/Global
Energy bias	Multivariate/Dataset
Energy resolution	Multivariate/Dataset
Total selection eff.	Multivariate/Dataset

AC/PSD selection efficiencies: fit the number of events above background in a dataset-peak region that pass and fail the cut in BAT, then sample their posteriors to evaluate $\epsilon_{AC/PSD}$ pdfs for the ϵ_{sel} prior

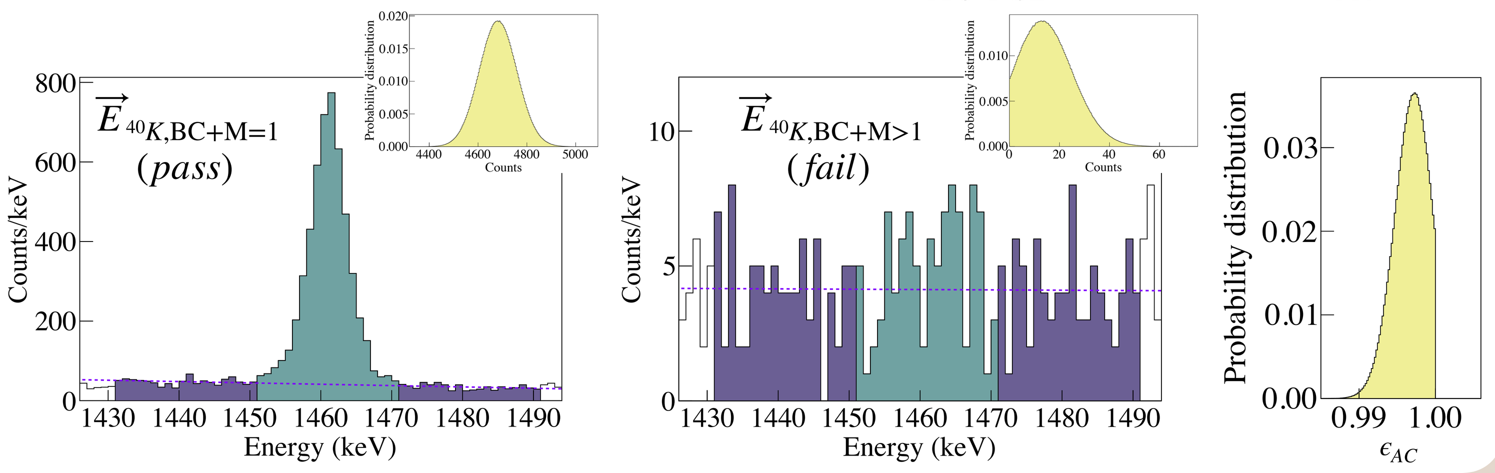
Bayesian counting analysis:

$$\mathscr{L}_{eff} = \prod_{i=l,c,r} \frac{e^{-\lambda_i}\lambda_i^{n_i}}{n_i!}; \quad \lambda_i = \int_{E_{i,1}}^{E_{i,2}} f(b)dE + S_i$$

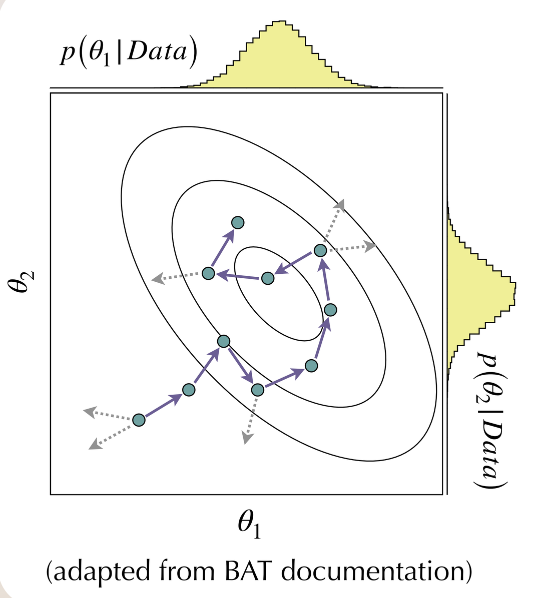
$$N_{pass/fail} = p(S_c\,|\,\vec{E}_{pass/fail}) \rightarrow Random()$$

$$\epsilon_{dataset-peak} = \frac{N_{pass}}{N_{pass} + N_{fail}}$$

CUORE preliminary — single dataset ϵ_{AC} example (right):



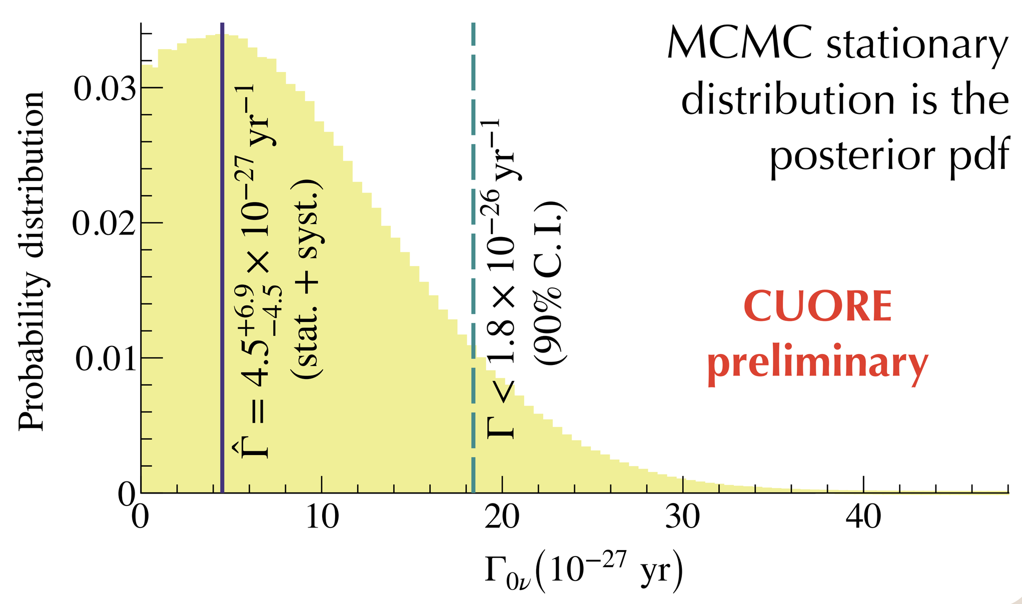
Posterior via Markov Chain Monte Carlo (MCMC)



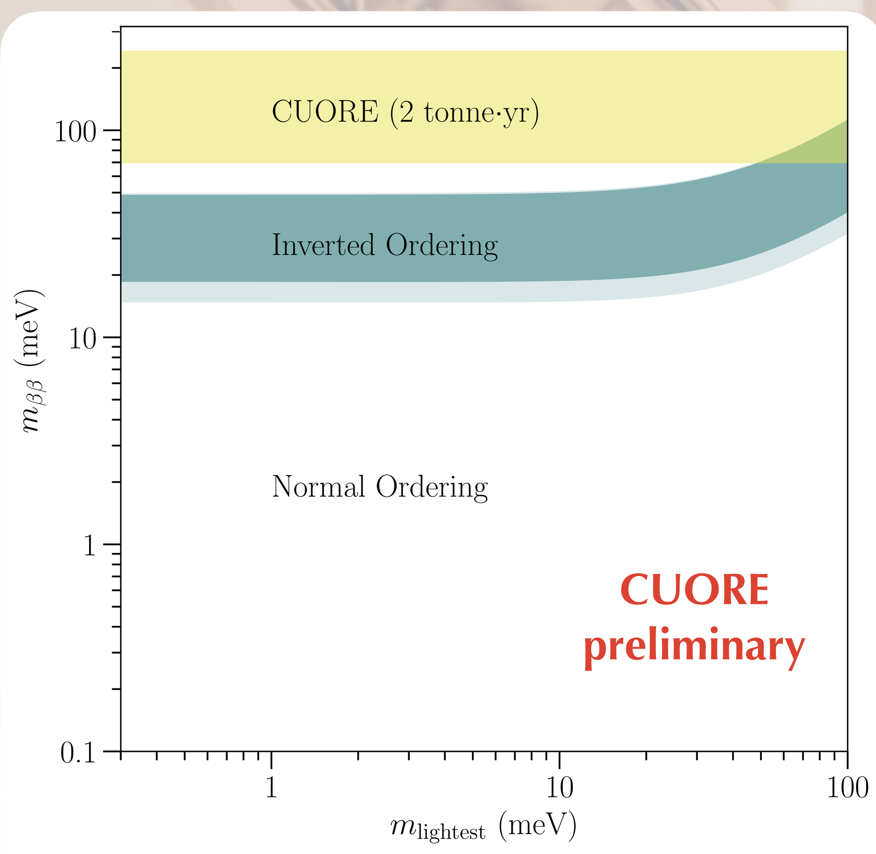
(adapted from BAT documentation)

- MCMC determines a sequence of random model parameter coordinates using a limiting distribution proportional to the posterior pdf
- fundamentally, each coordinate in the sequence only depends on the previous one
- Metropolis-Hastings algorithm accepted coordinates (●):

$$\frac{p(\vec{\theta}_{next}\,|\,Data)}{p(\vec{\theta}_{current}\,|\,Data)} > U[0,1]$$



Result



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

$$m_{\beta\beta} < 70 - 240\ \mathrm{meV}$$

CUORE will continue collecting data until reaching 3 tonne·yr TeO_2 analyzed exposure, after which new cryogenic hardware will be installed to benefit our phase II low-energy investigations.

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