Bayesian Analysis of Project 8's Sensitivity to the Neutrino Mass Scale and Ordering

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PROJECT 8

We devised a **model of the tritium β spectrum** suited to **Bayesian inference**, then employed it to study **Project 8's sensitivity**.

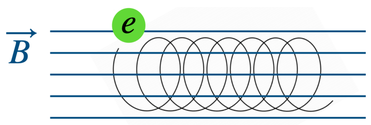
For a **design scenario** under consideration, Project 8 can achieve its goal of measuring the **neutrino mass within 40 meV**—with **90%** credibility and coverage.

For masses >500 meV, we project **~5meV sensitivity** in this scenario.

A kinematic neutrino mass measurement using cyclotron radiation

Even with a known neutrino mass hierarchy, the absolute mass scale m_β will still be unknown. Project 8 aims to determine m_β from the shape of the tritium beta decay spectrum.

Electron cyclotron frequencies are converted to energies, enabling very high precision.



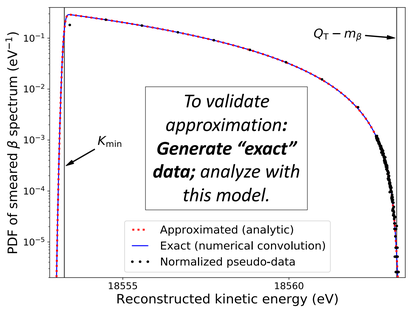
Validating a new β spectrum model for Bayesian inference

Bayesian likelihood models are probability densities (PDFs). Thus, they must be **normalized.**

Such models can be coded in **Stan MCMC** Bayesian software.

While the full (broadened) β-decay spectrum is not analytically normalizable, it is with an approximation:

Expand in $\frac{m_\beta^2}{(Q-K_e)^2}$, then convolve with a Gaussian.



Model-based calibration

Calibrations involve asking:

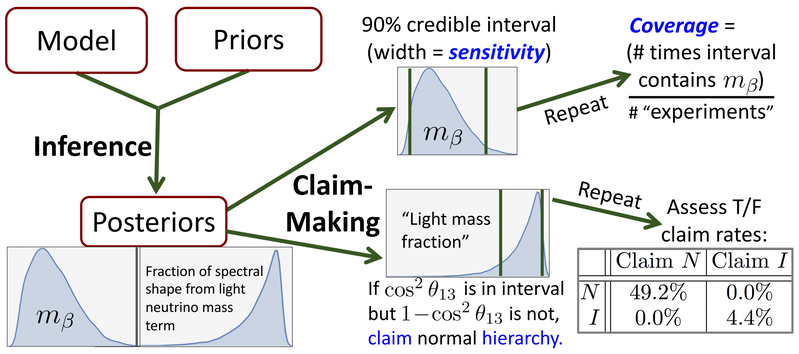
Given many likely pseudo-data sets, what fraction (coverage) of the time is the result of some analysis procedure consistent with the "truth"?

This reveals biases due to assumptions made during inference.

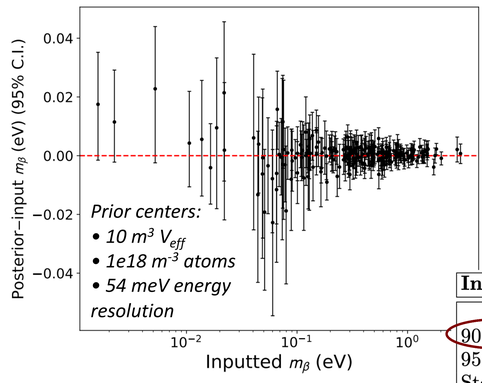
By comparing coverages for different definitions of "*consistent with the truth,*" we can assess the impacts of our procedure for claiming a result.

Bayesian inference

Bayesian methods are uniquely suited to such calibration because they **separate "inference" from "claim-making."**



Mass scale sensitivity & calibration results



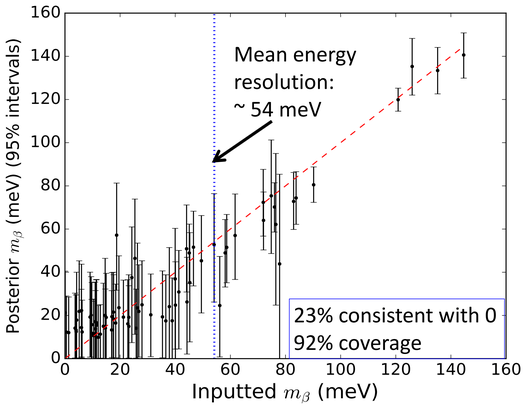
90% interval widths: 3-50 meV, depending on m_β; statistical fluctuations.

Coverage is consistent with credibility! → posteriors are reliable.

Interval	Sensitivity (eV)		Coverage
	Median	Mean	
90% C.I.	0.0071	0.0112	90.0%
95% C.I.	0.0084	0.0133	93.2%
Stdev.	0.0022	0.0034	70.1%

To calibrate a claim of nonzero m_β:

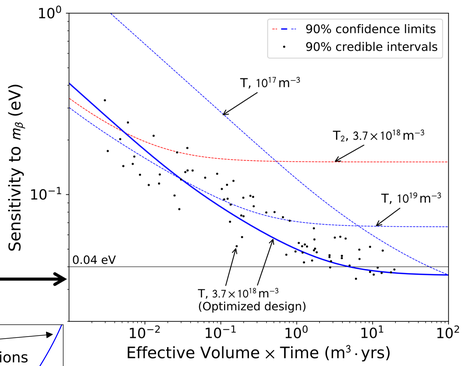
1. **Remove:** oscillations-based lower bound on m_β.
2. **Ask:** "*Is the interval's low-mass end at 0?*"
3. **Calibrate:** When true mass is 0, confirm the analysis determines it is consistent with 0.

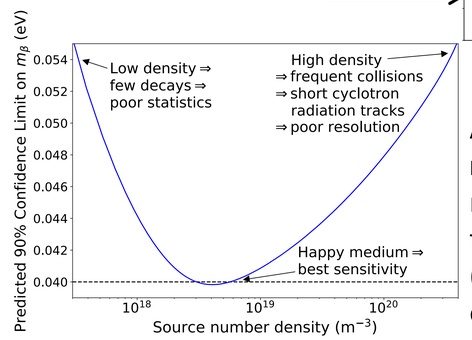


For a true mass of zero, m_β is consistent with zero **93% of the time**, implying a **successful calibration**.

Optimizing sensitivity inputs

Bayesian sensitivity points from pseudo-data (for smallest allowed m_β) validate analytic predictions.





At a source density of **3.7e18 m^{-3}**, uncertainty on m_β is minimized. This corresponds to an energy resolution of **(115 ± 2) meV** and sensitivity of **40 meV.**

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