Direct Neutrino Mass Measurement

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Our goals:

- Model the β decay spectrum of (atomic) Tritium
- Examine effects of non-zero neutrinos masses on the spectrum
- Get a sense of the energy resolution and statistics required to be sensitive to those effects
- Explore sensitivity to neutrino mass scale and mass ordering

Intro and Relevant Theory

$$T \to {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_e$$

$$\left(\frac{d\Gamma}{dE_e}\right)_i = \frac{G_F^2 |V_{ud}|^2}{2\pi^3} |M_{\mathrm{nuc}}|^2 F(Z, E_e) p_e (E_e + m_e)(E_0 - E_e) |U_{ei}|^2 \sqrt{(E_0 - E_e)^2 - m_i^2}\, C(E_e)$$

- β decay spectrum of Tritium is sensitive m_1, m_2, m_3 neutrino mass values
  - non-zero mass values manifest as (small) kinks and shape distortions

Full spectrum: $\left(\frac{d\Gamma}{dE_e}\right) = \sum_{i=1}^{3} \left(\frac{d\Gamma}{dE_e}\right)_i$ For $m_1 \cong m_2 \cong m_3$: $m_{\bar{\nu}}^2 = \sum_i |U_{ei}|^2 m_i^2$

Modeling the β Spectrum

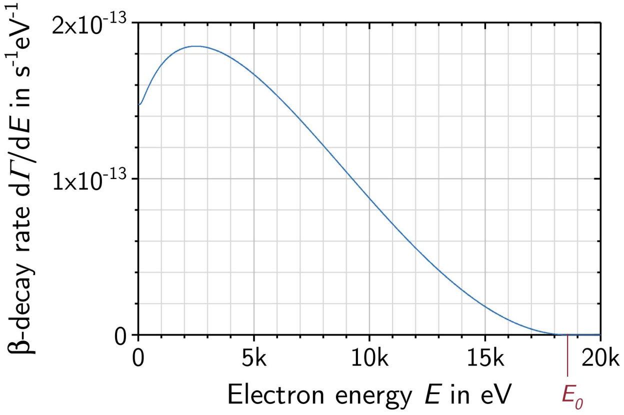
$$m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2$$

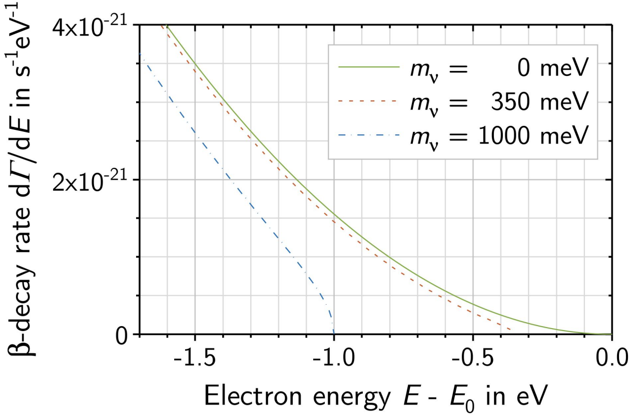
Full β Spectrum

Endpoint β Spectrum

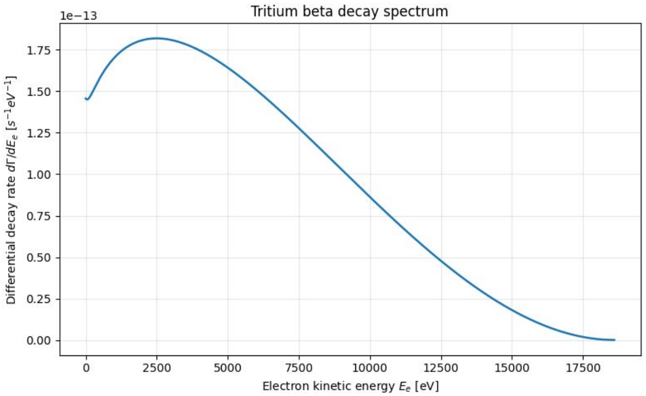
Paper:

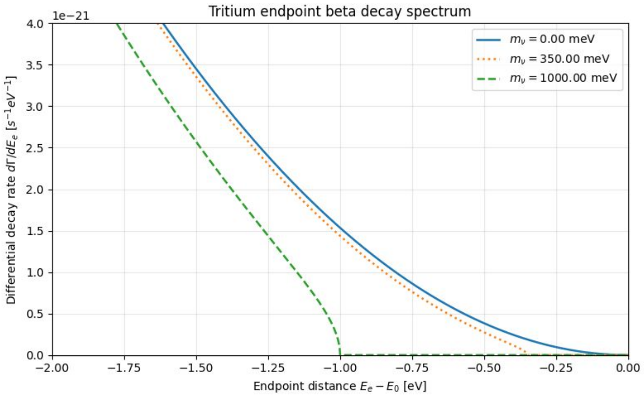
(Eur. Phys. J. C (2019) 79 :204)





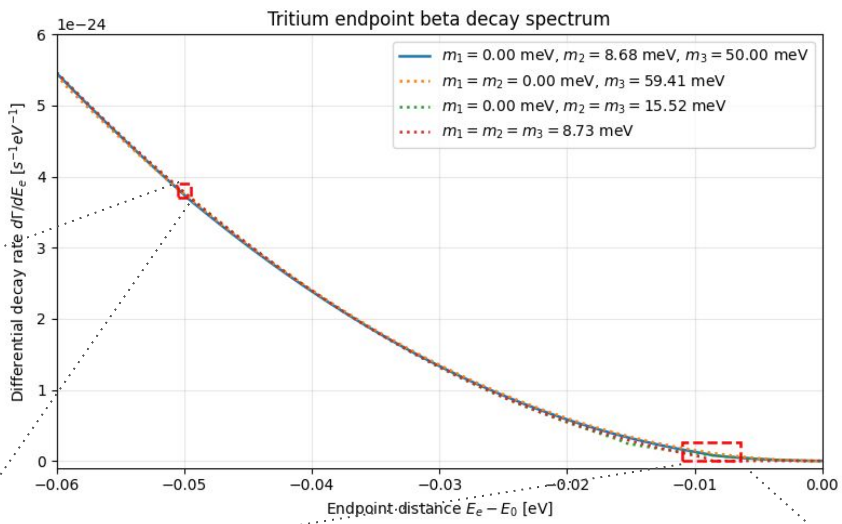
Our Plot:

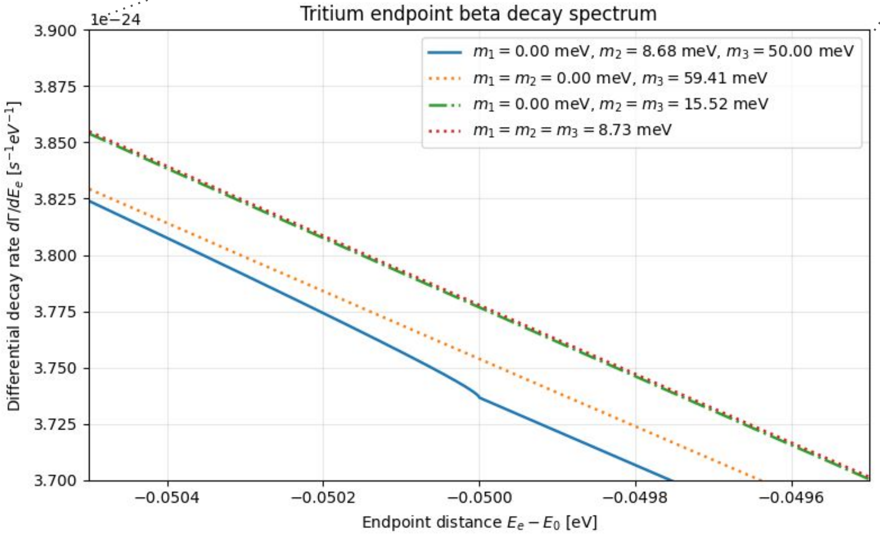


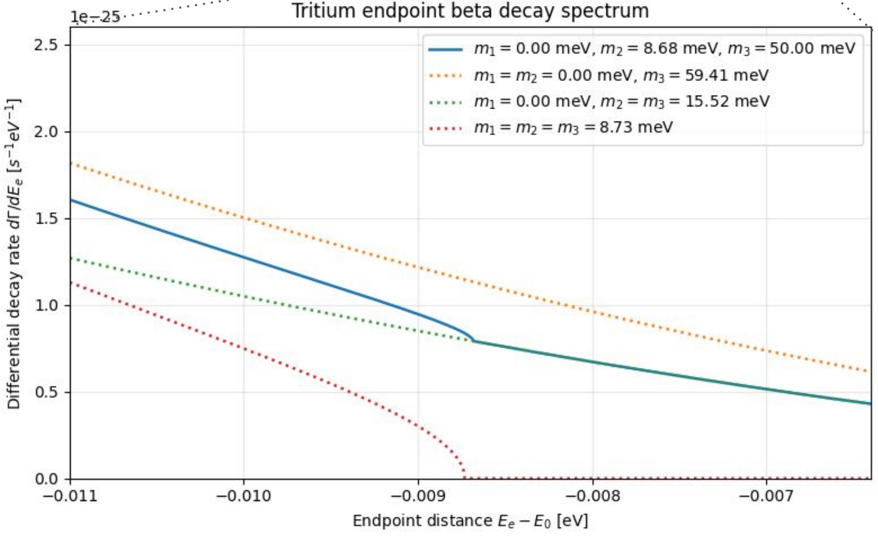


Determining Sensitivity to Mass Splittings

- **Choose Normal Ordering with m_1 = 0** and m_2, m_3 determined by the mass splittings
- Compare with spectra for degenerate mass cases





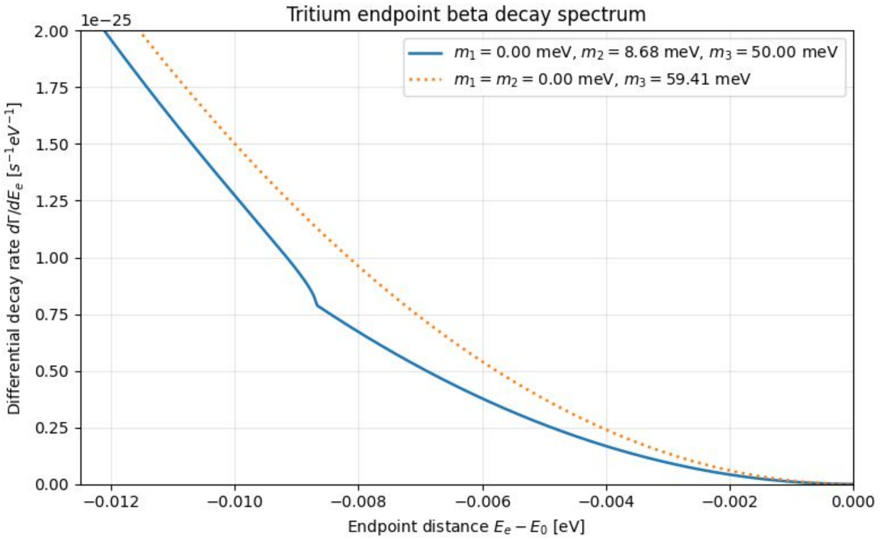


What resolution and number of decays would we need to measure each of the mass splittings at 3σ?

Hypothesis test

True hypothesis
Spectrum with 2 distinctive kinks due to 2 mass splittings (from oscillation experiments)

Null hypothesis
Same total m_β (effective mass), but states *i* and *j* are replaced by a degenerate mass



Two approaches to count events

Integral approach

Cumulative total above a shifting electron threshold.

1: E > E1

2: E > E2 > E1

N: $E > E_n > E_{n-1}$

Adjacent bins -> **correlated counts and spectral distortions get diluted**

Differential approach

Measure decay rate at each discrete energy.

Bin 1: independent Poisson count

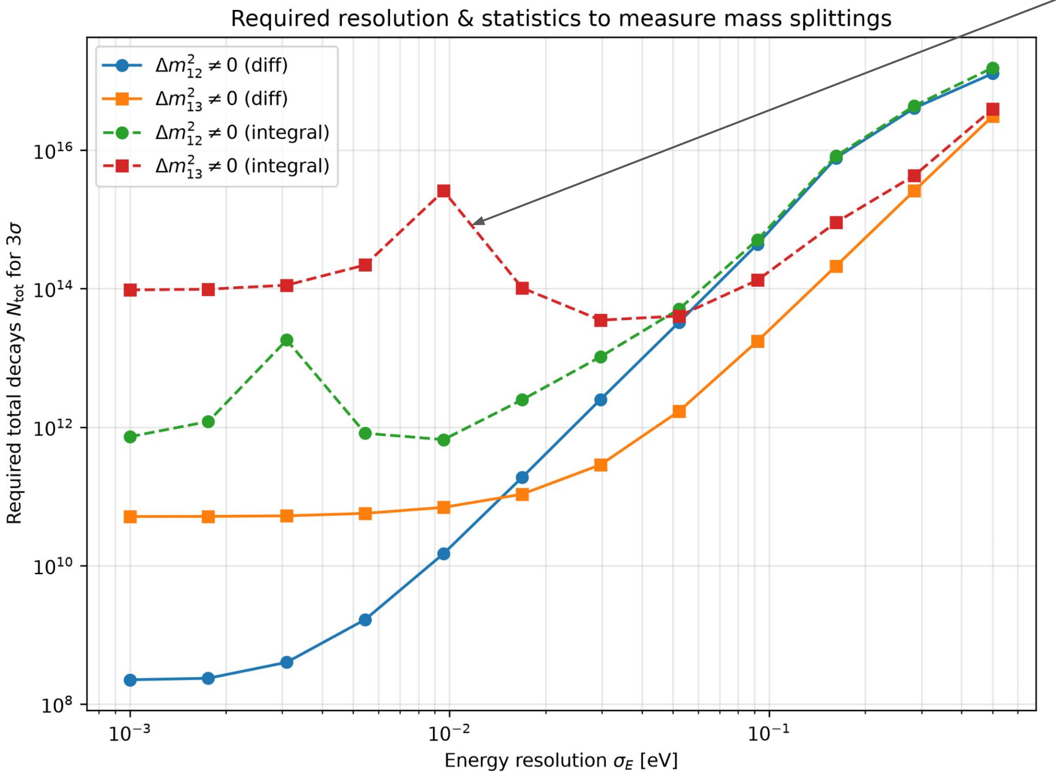
Bin 2: independent Poisson count

Bin N: independent Poisson count

Bins counted **independently** (can use Poisson likelihood ratio)

Two approaches to count events

Due to bin choice here.
General shape of distribution is what is important



Conclusion: many (many) tritium decays and very good resolution are needed for a 3σ measurement of the mass splitting!

Differential vs Integral Spectral Measurements

Integral

- Measures the ***number*** of electrons above a specific threshold of energy.
- Constructs decay spectrum by manually adjusting energy threshold.

Differential

- Measures the energy of ***individual*** electrons.
- Directly constructs decay spectrum.

KATRIN (Integral Approach)

- Experiment commissioned in 2015.
- Located at the Karlsruhe Institute of Technology in Germany.
- First measurements in 2019.
- In April of 2025 Established an upper-bound on m_ν of $m_\nu < 0.45\,\mathrm{eV}$.
- Expected sensitivity of 0.2 eV.

“The main spectrometer of the KATRIN experiment being transported to the Karlsruhe Research Center” [Quanta]
https://www.quantamagazine.org/how-the-neutrinos-tiny-mass-could-help-solve-big-mysteries-20191015/

https://www.energy.gov/science/np/articles/katrin-narrows-down-range-neutrinos-mass

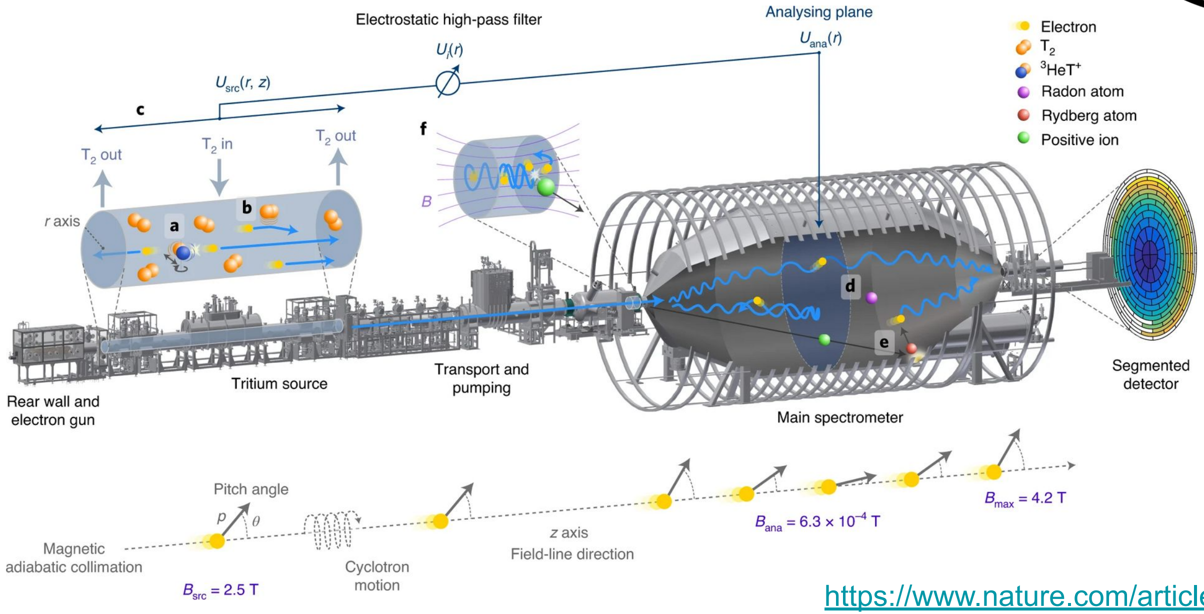
KATRIN (Integral Approach)

also has cool logo

- Uses molecular Tritium as decay source.

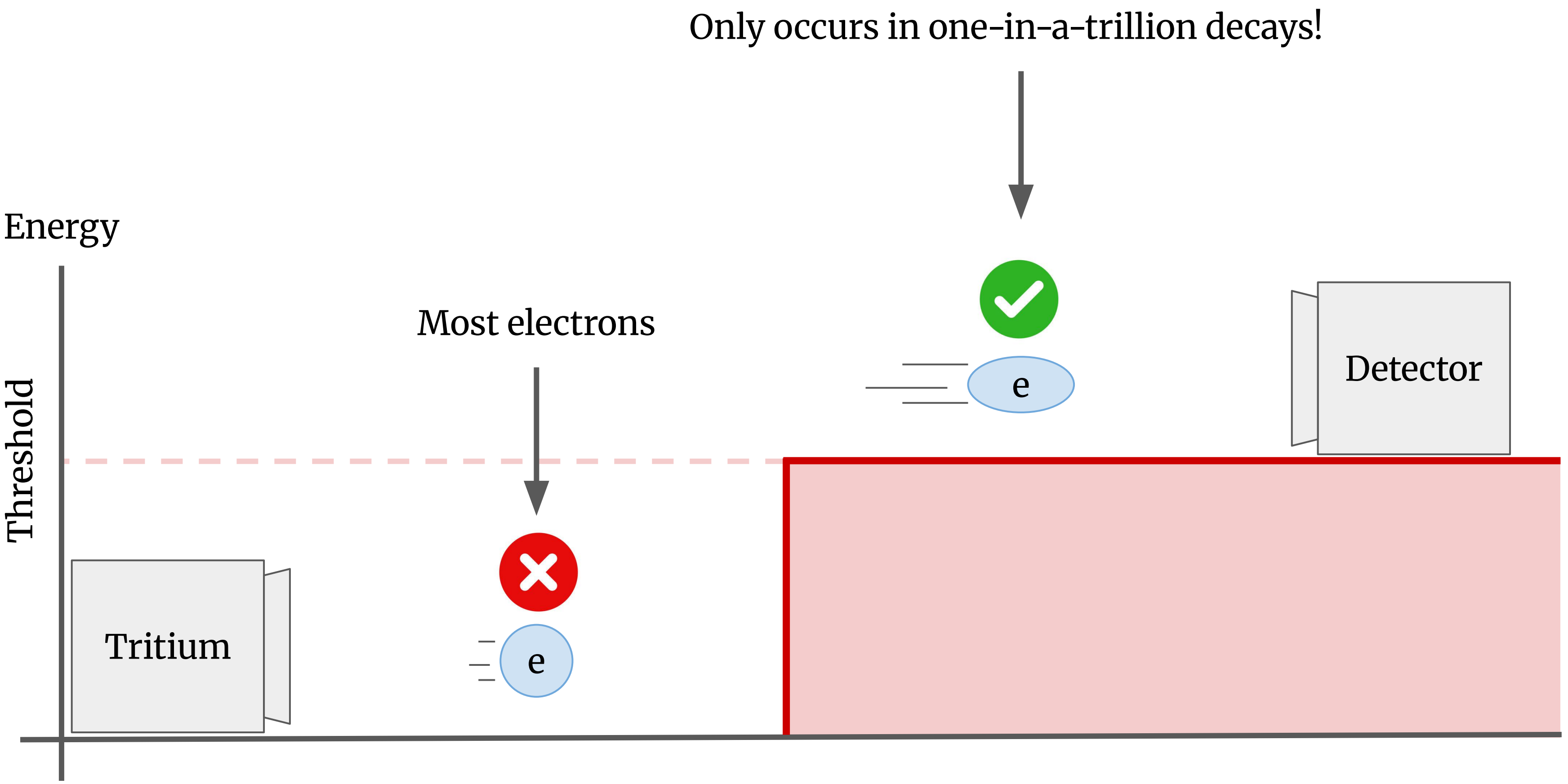
- Uses a retarding potential to filter high energy electrons.

- Counts number of electrons with energy greater than a given threshold.



https://www.nature.com/articles/s41567-021-01463-1

KATRIN (Integral Approach)



Project 8 (Differential Approach)

- Proposed in 2009.
- Uses novel technique: ***Cyclotron Radiation Emission Spectroscopy*** (CRES)
- Technique experimentally verified in 2015.
- Projected sensitivity of $0.04\,\mathrm{eV}$.
- Currently in Phase III (out of 4).

Project 8 (Differential Approach)

Google

Project 8

Wikipedia
https://en.wikipedia.org › wiki › Tony_Hawk's_Project_8

Tony Hawk's Project 8

Tony Hawk's Project 8 is a 2006 skateboarding video game and the eighth installment in the Tony Hawk's series. Read more

Project 8 Collaboration
https://www.project8.org

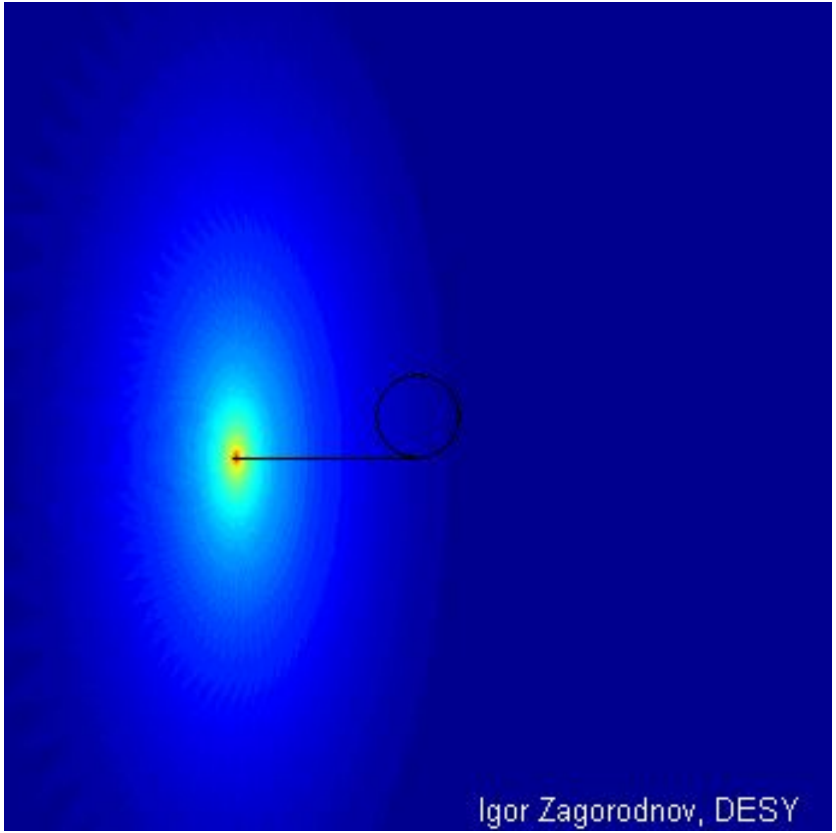
The Project 8 Experiment

Project 8 is a neutrino mass experiment. Navigate through this website to find out more about who we are and the science that we do. Read more

About | Publications | Public Talks | People

PROJECT 8 $\stackrel{?}{=}$

Project 8 (Differential Approach)



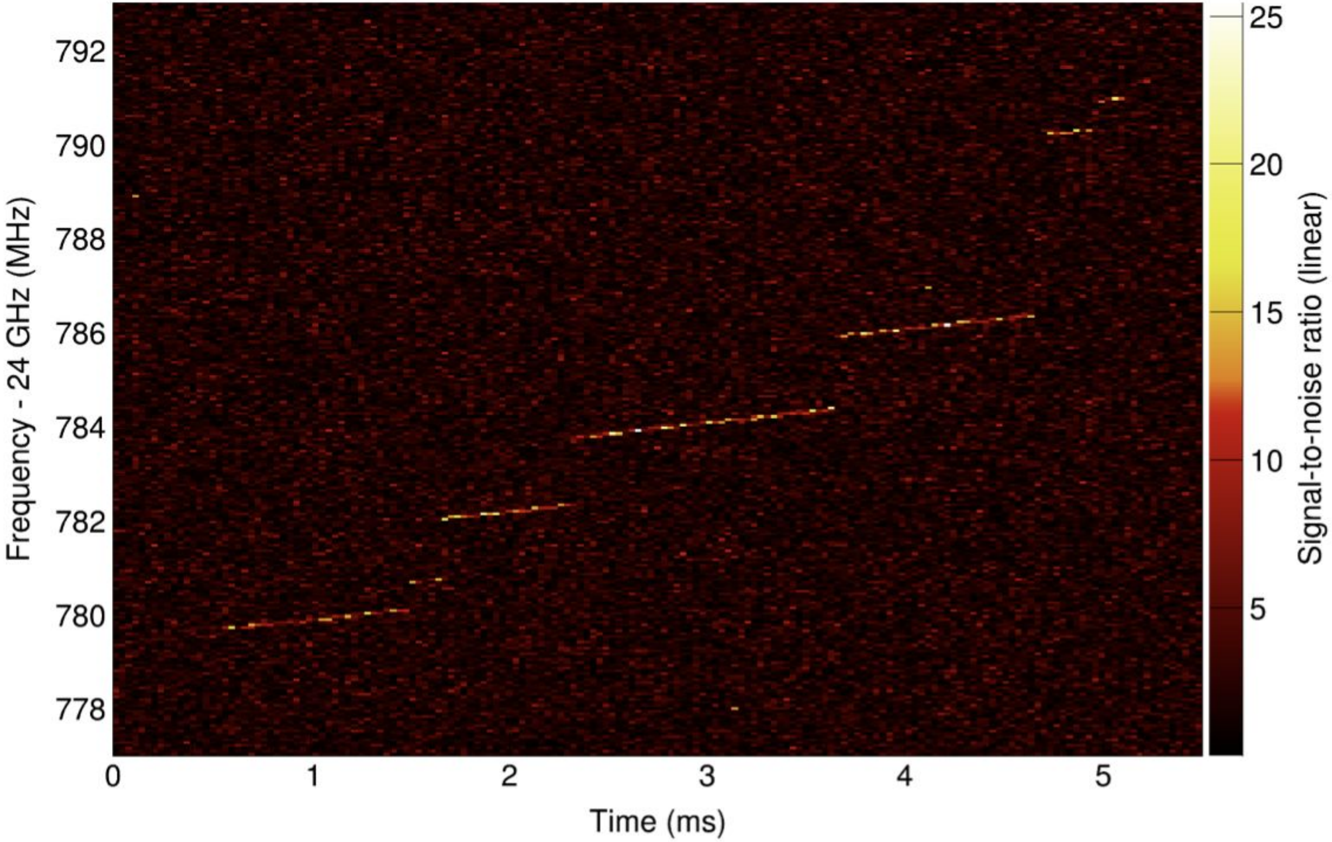
Measure frequency → Determine Energy using:

$$f_\gamma = \frac{1}{2\pi}\frac{eB}{m_e + K_e/c^2}$$

For B = 1 T, an 18.6 keV electron will radiate power of order **1 fW**. (***femto***watts!!!)

Project 8 (Differential Approach)

- First event observed using CRES method.
- Upward slope due to radiation energy loss.
- Jumps caused by electron inelastically scattering with background gas.
- Initial frequency gives initial energy.



Sensitivity to neutrino-mass scale and mass ordering

A. Ashtari Esfahani et al., Bayesian analysis of a future β decay experiment's sensitivity to neutrino mass scale and ordering. Phys. Rev. C 103 (6): 065501 (2021) , 2012.14341

Sensitivity study

- Bayesian modeling to perform a sensitivity study for a physics experiment
- Model of an experiment's measurement process developed (beta spectra with Project 8)
- Statistical modeling done using Bayesian framework with PyStan package.
- Use the model to repeatedly generate and analyze pseudo data
  - Parameters sampled from the prior distributions
  - Analyze posterior distributions
  - Expectations and intervals computed from the posteriors, yielding sensitivity results
- Calibration done to assess the accuracy of the analysis
  - Inject the true values and see if the model accurately predicts the true values with reasonable accuracy

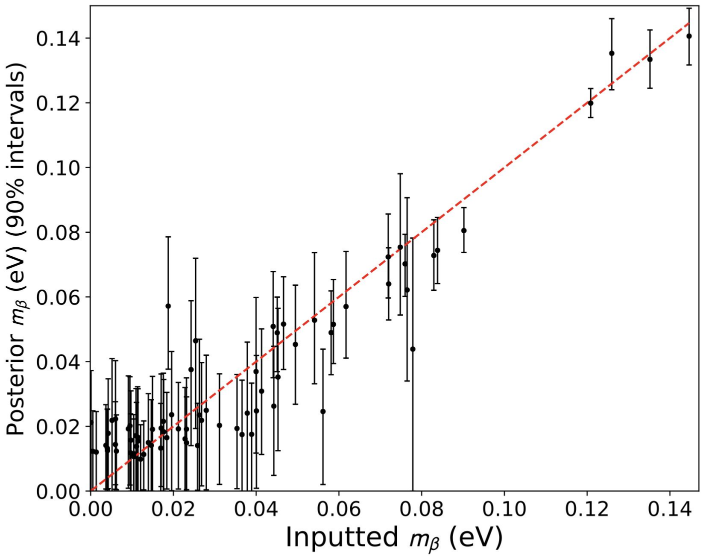
Inputs and Results

- Priors needed for Bayesian modeling
  - Project 8's experimental design parameters fed
  - Other parameters come from measurement
    - Reactor neutrino measurements used as well

	Prior	Model	Prior Source
Q_T	$\mathcal{N}([18563.25, 0.07]\ \mathrm{eV})$	1, 2	Measured
σ_{dopp}	$\gamma(59.82, 2868\ \mathrm{eV}^{-1})$	1, 2	Measured
σ_{inst}	$\mathcal{N}(\mu_{\mathrm{inst}}, \delta_{\mathrm{inst}})$	1, 2	Design
K_{min}	$\mathcal{N}([Q_T - m_{\beta,L}–10, 0.01]\ \mathrm{eV})$	1, 2	Design
A_b	$\mathrm{lognorm}(-27.31, 0.5678)$	1, 2	Design
N_{atoms}	$\mathrm{lognorm}(44.07, 0.5677)$	1, 2	Design
m_β	$\gamma(1.135, 2.302\ \mathrm{eV}^{-1})$	1	Measured
Δm^2_{ee}	$\gamma(314.5, 122700\ \mathrm{eV}^{-2})$	2	Measured
m_L	$\gamma(2.186, 126.1\ \mathrm{eV}^{-1})$	2	N/A

- Sensitivity to the neutrino-mass scale
  - One neutrino mass model used
  - run time of 1 yr
  - 150 pseudo datasets generated

~0.04 eV -> 10x lower than Katrin's limit ~0.4 eV



Sensitivity to the mass ordering

- Methodology:
  - Similar procedure as the mass scale sensitivity
  - Pseudo data generated with 2 neutrino mass model (170 pseudo datasets)
  - Spectral model also generated with 2 neutrino mass model

	Claim N	Claim I
$\Delta t = 2\,\text{yrs}$, $m_L \lesssim 0.05$ eV		
Optimal κ	0.985	0.855
Truth: N	$86.8\% \pm 3.5\%$	$0.0\%\ (+1.3\%)$
Truth: I	$0.0\%\ (+1.5\%)$	$21.8\% \pm 4.7\%$
$\Delta t = 1\,\text{yr}$, $m_L \lesssim 0.05$ eV		
	Claim N	Claim I
Optimal κ	0.925	0.875
Truth: N	$45.6\% \pm 5.2\%$	$0.0\%\ (+1.3\%)$
Truth: I	$0.0\%\ (+1.2\%)$	$23.5\% \pm 4.3\%$