Project 8

Using Radio Frequencies to Measure the Neutrino Mass

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MIT

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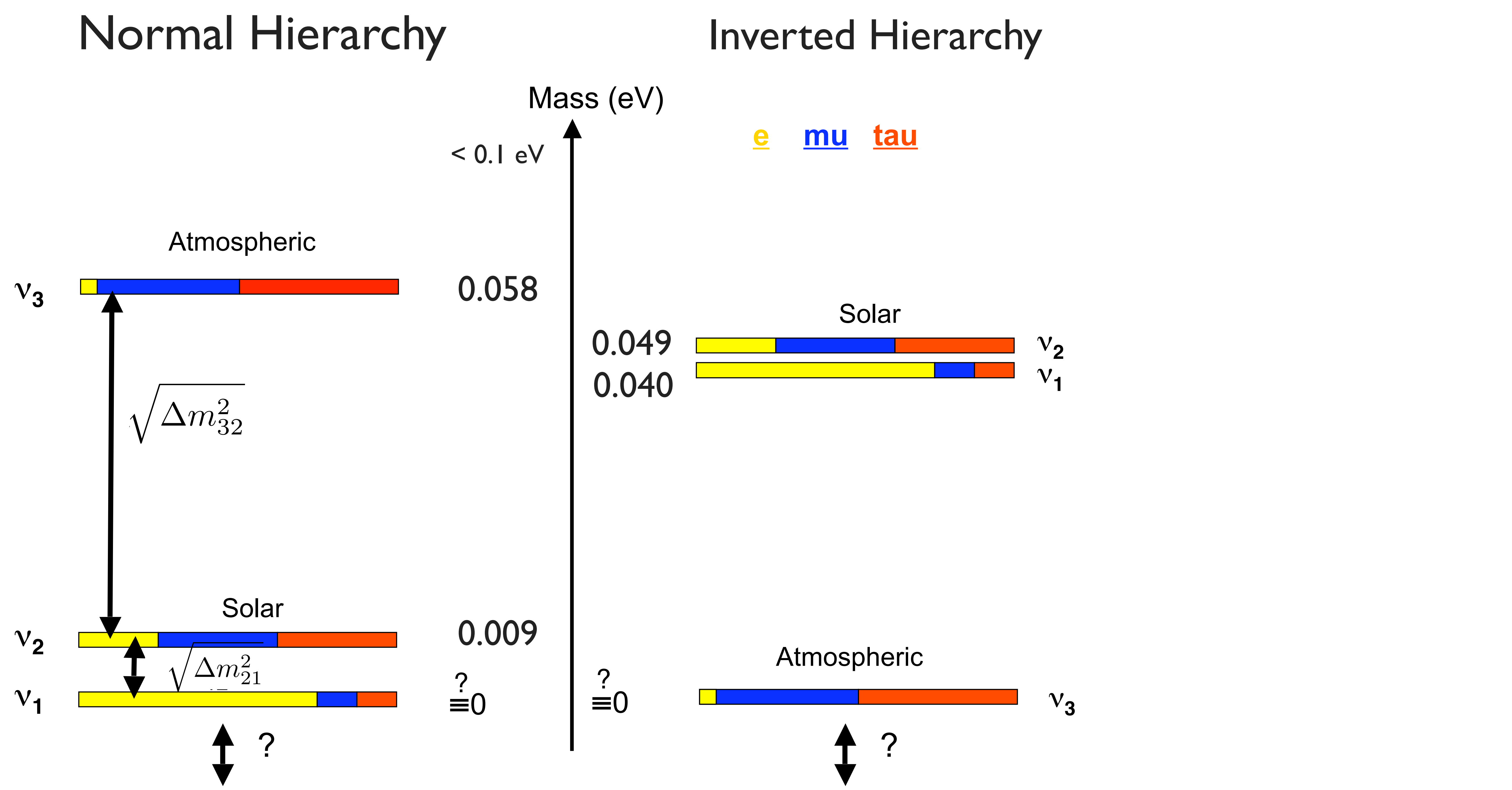
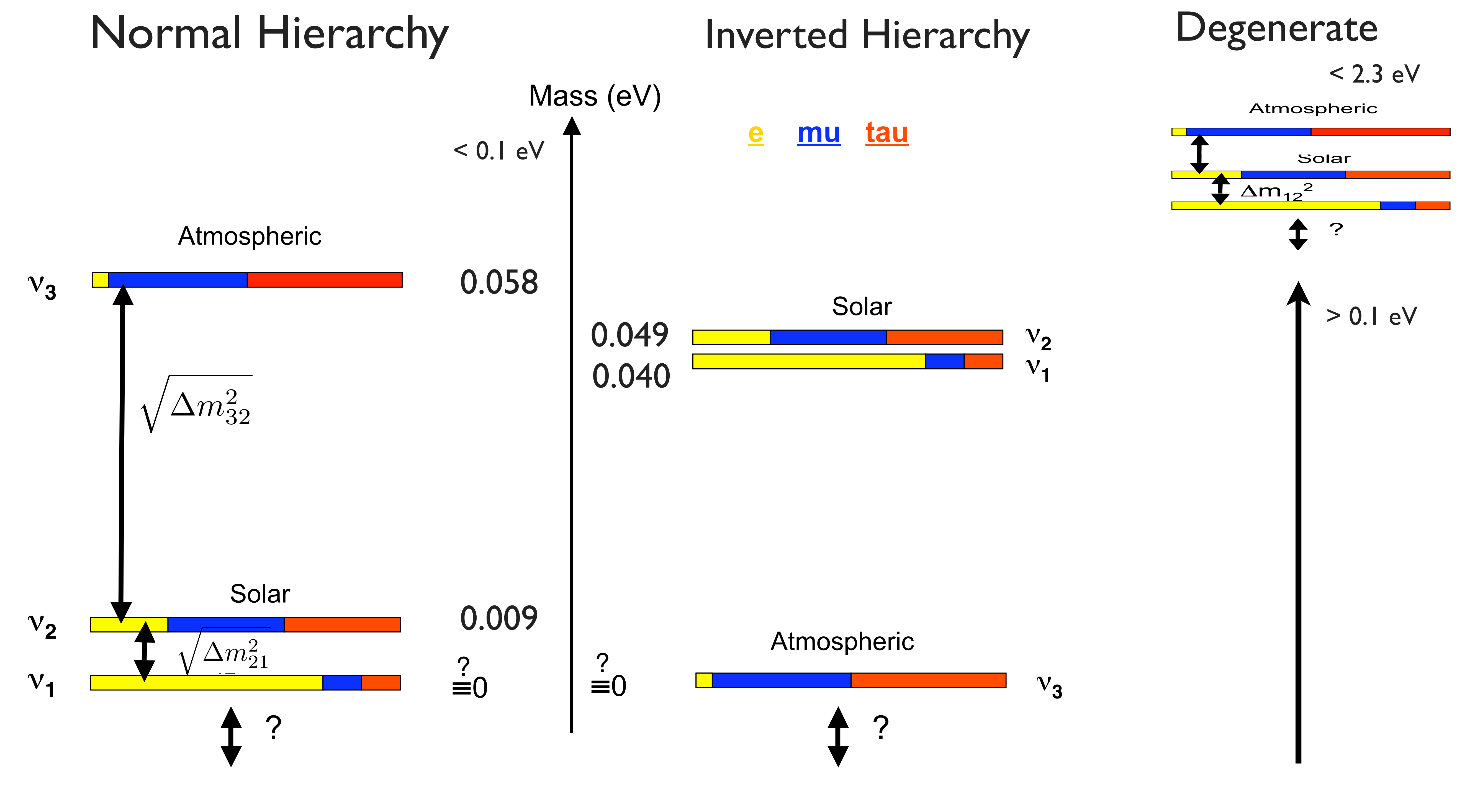
Laboratory for Nuclear Science

Neutrino Mass



Neutrino Mass



Tritium Beta Decay

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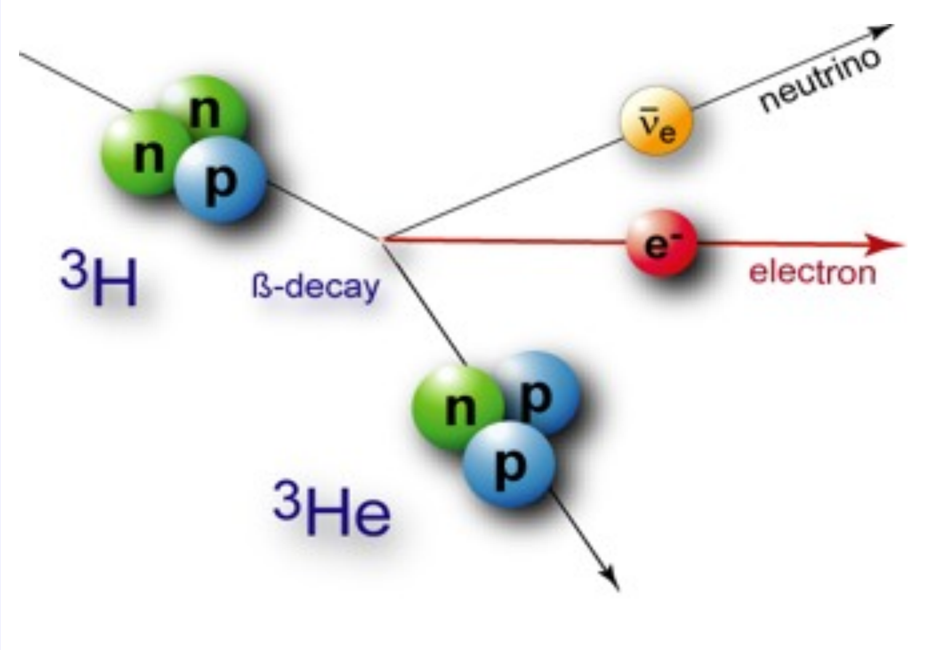
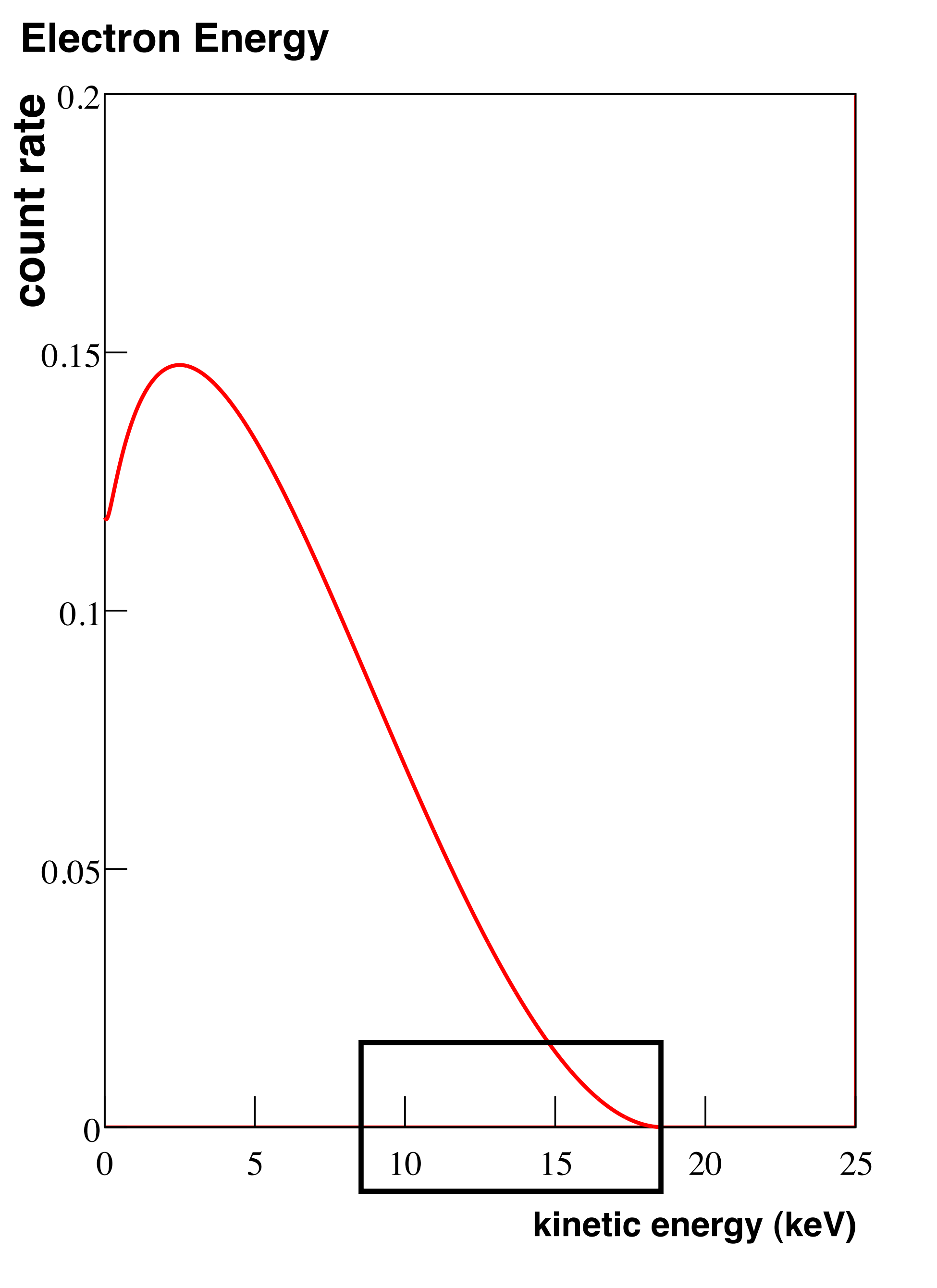


. . . from which we detect the electron

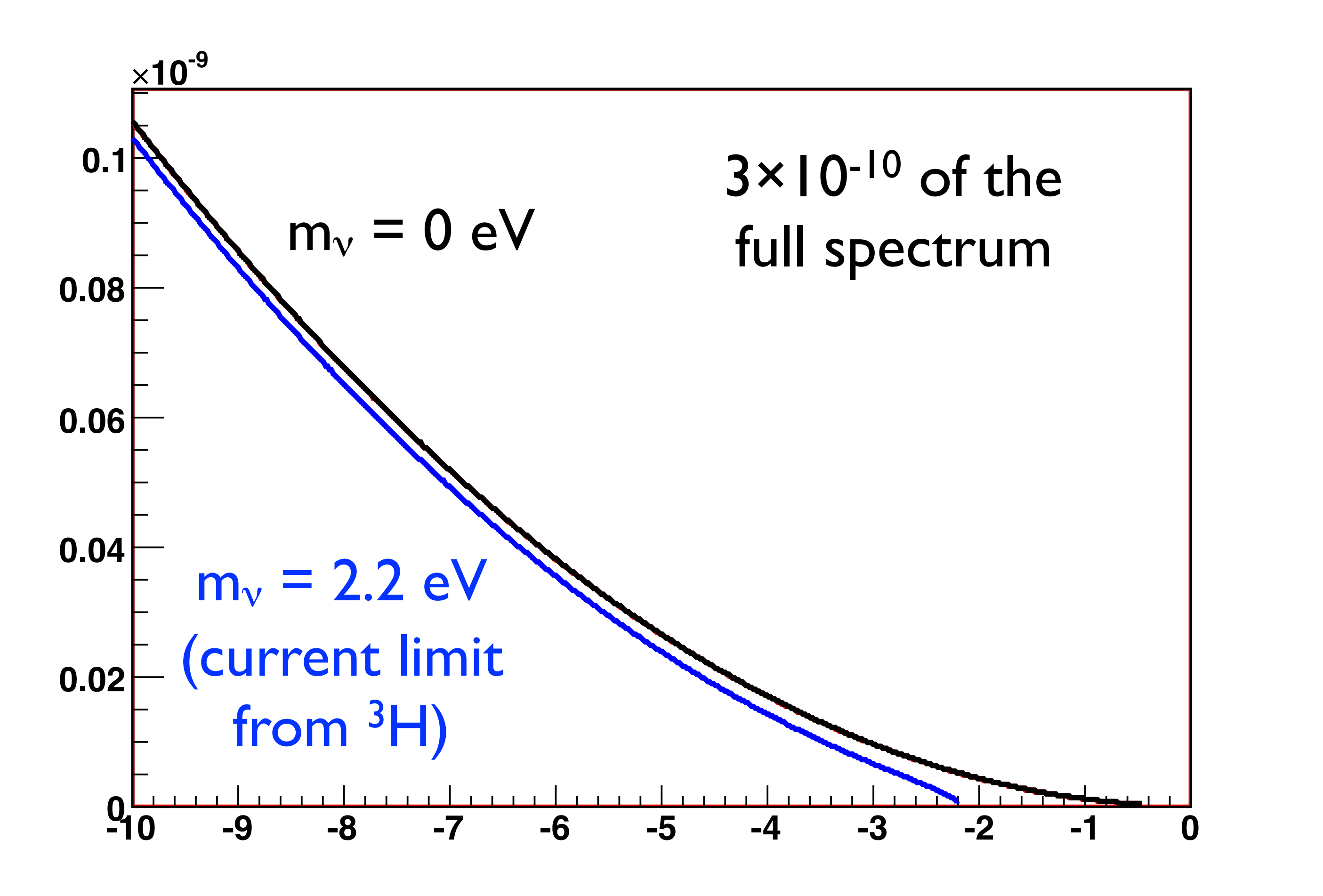
Beta decay allows a precise measurement of the absolute neutrino mass scale

Energy Spectrum



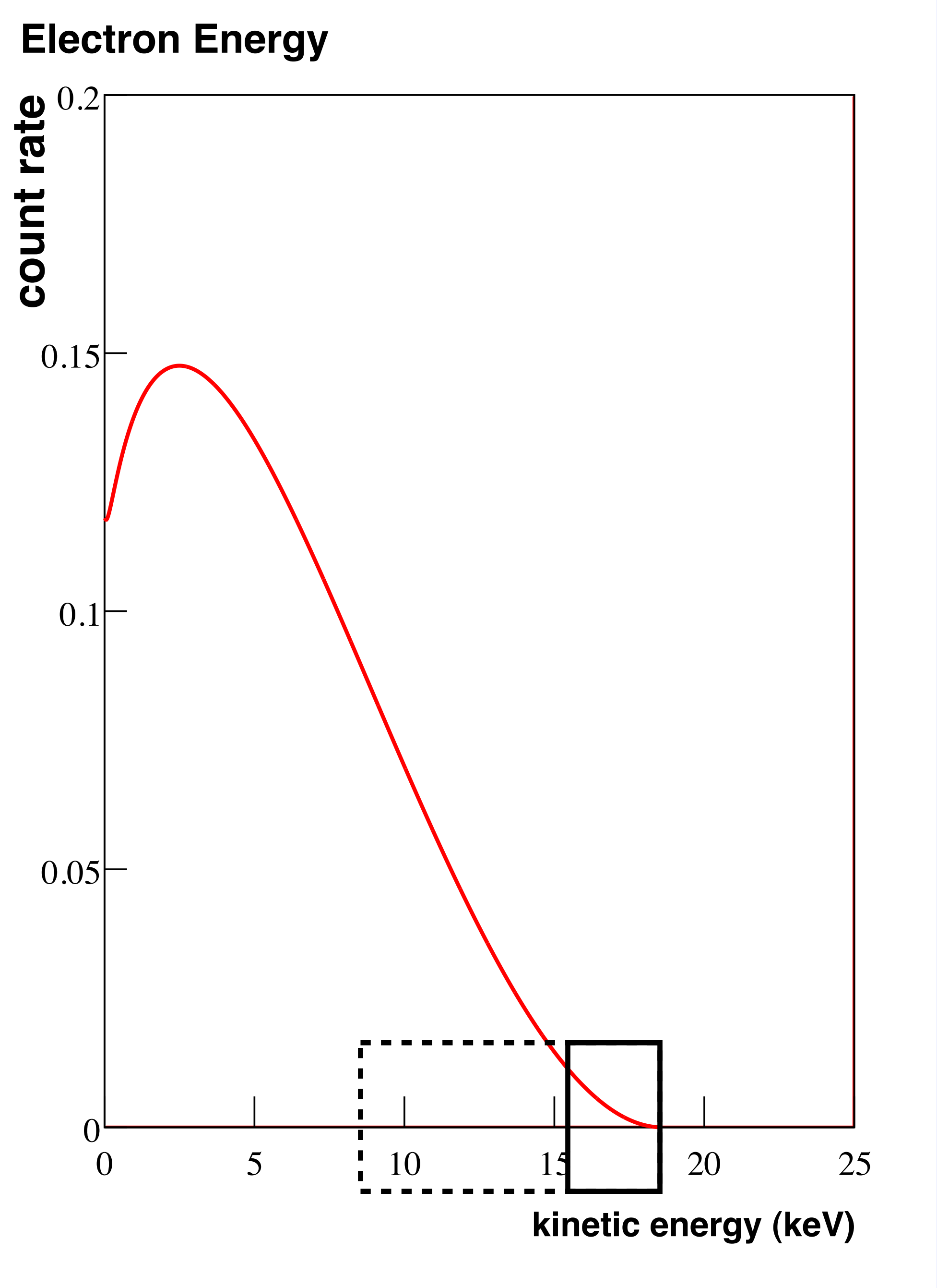
The shape is modified by the neutrino mass

Zoom in on the endpoint . . .



Energy Spectrum

PROJECT 8



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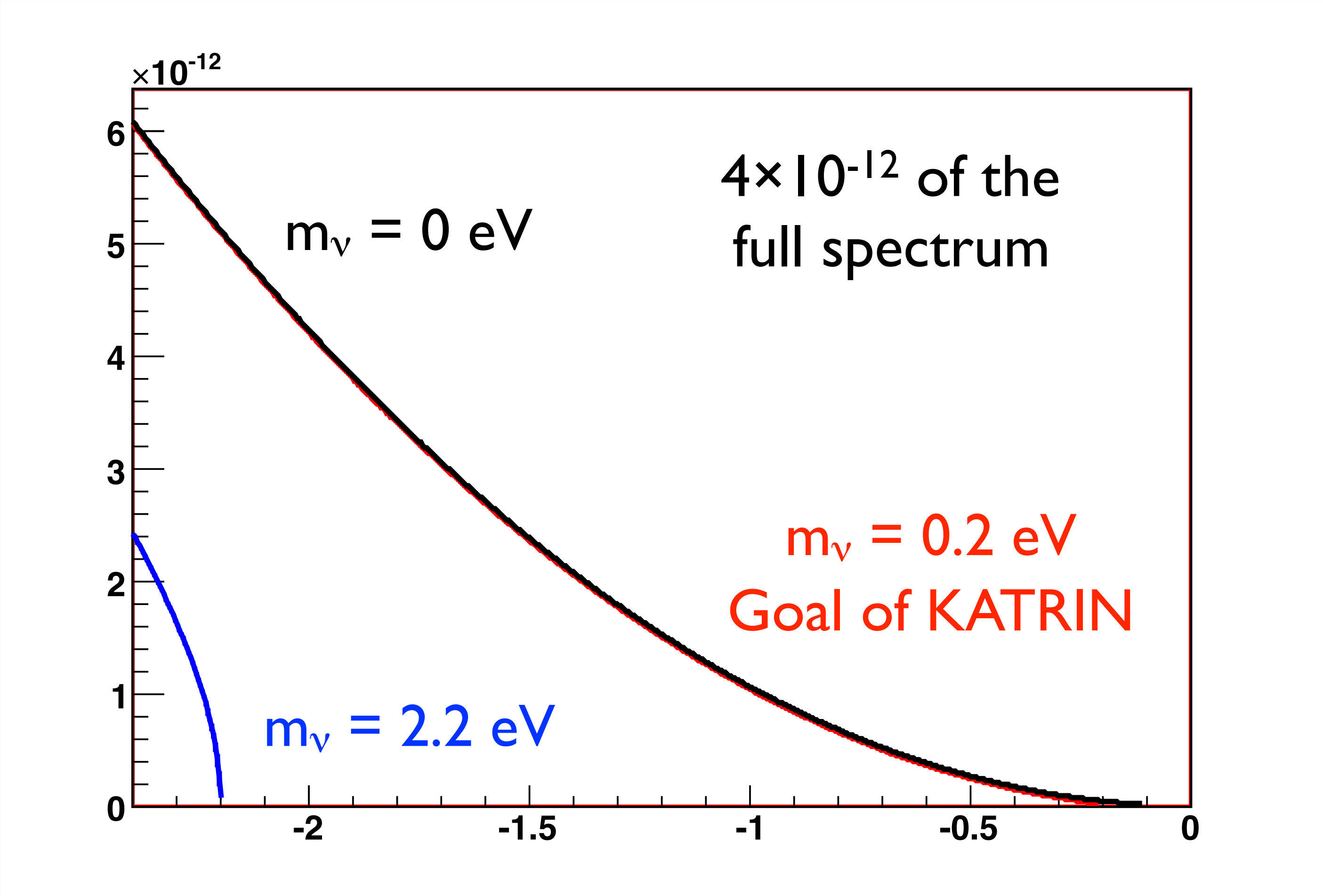

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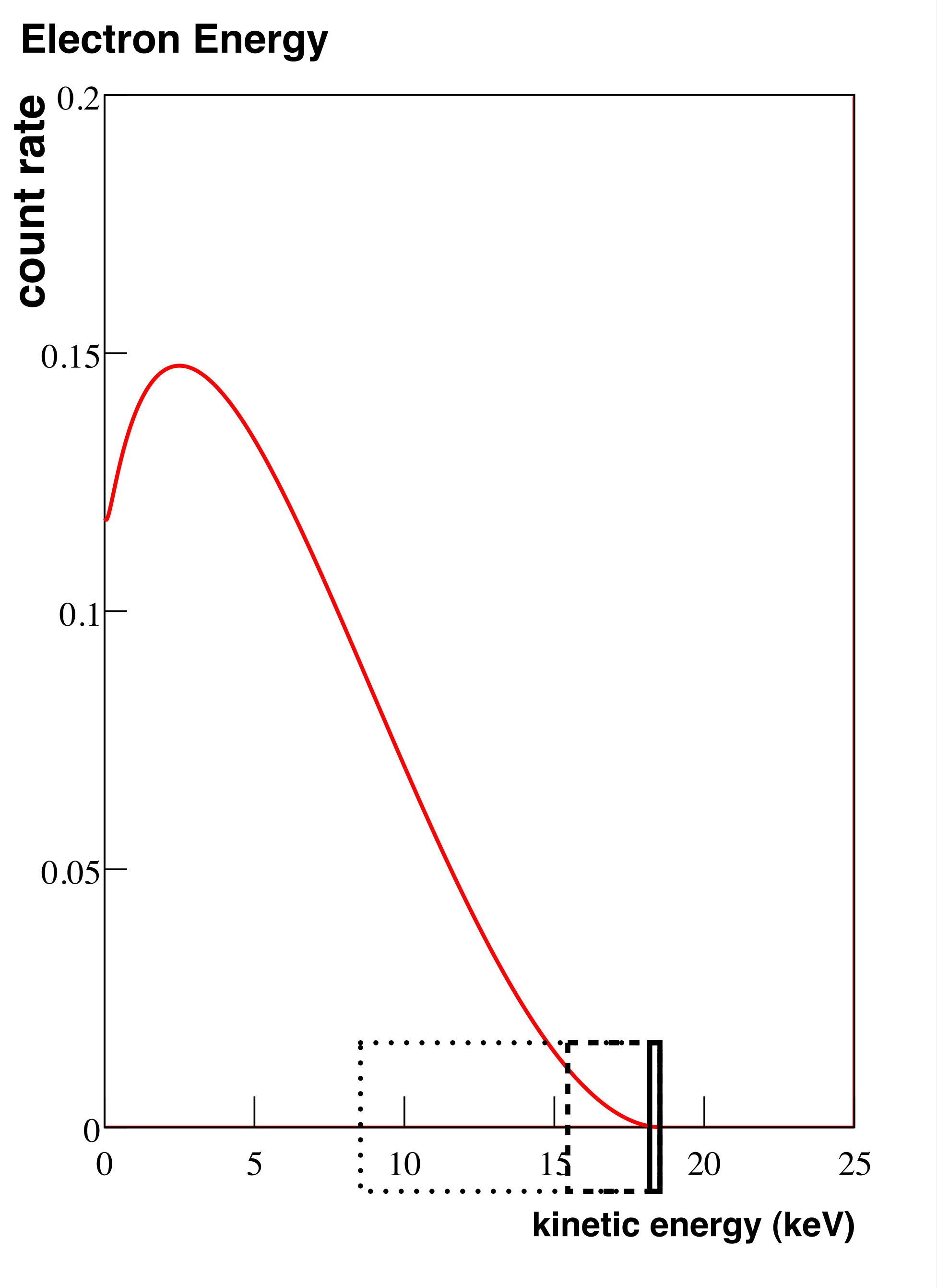

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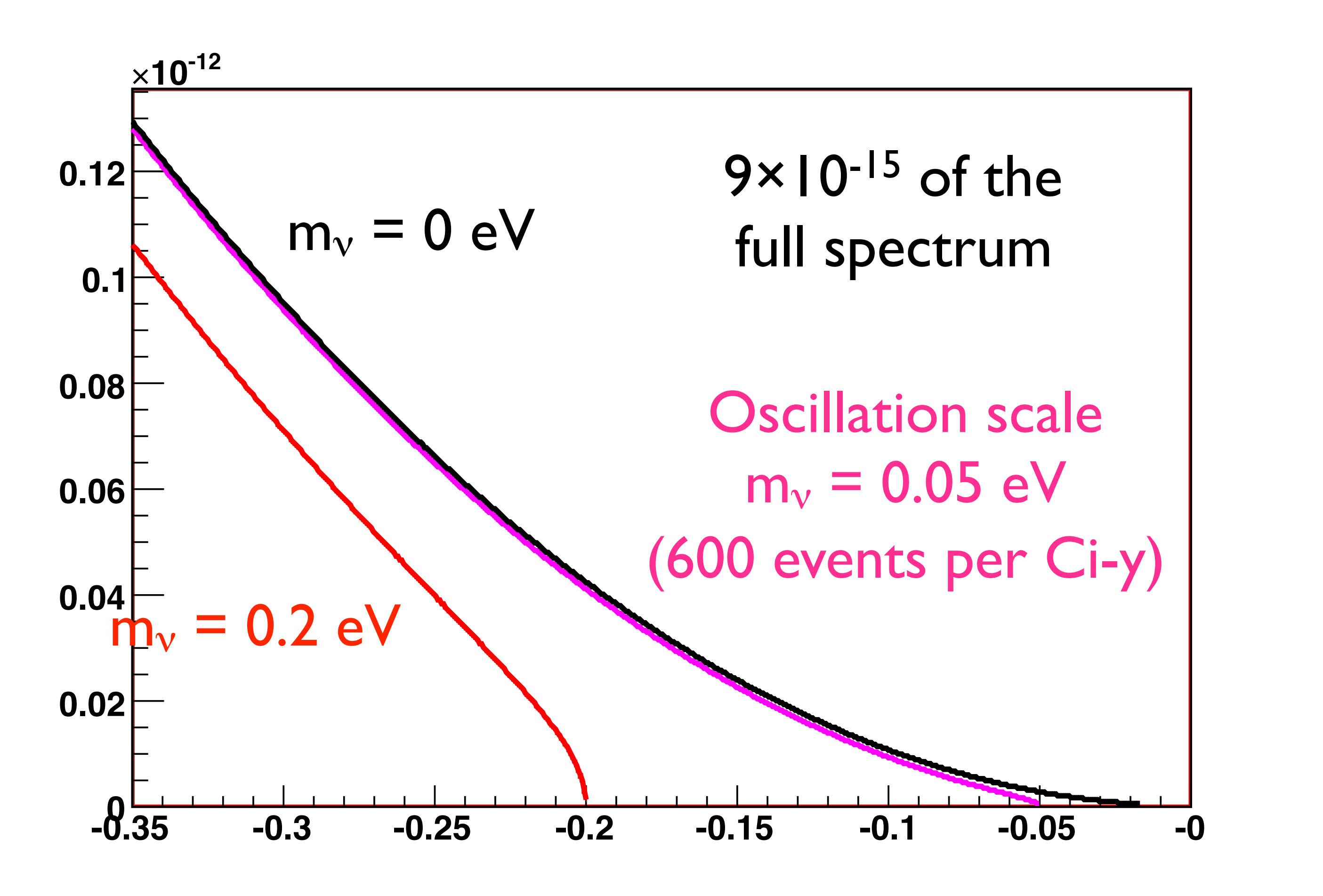

Beyond KATRIN

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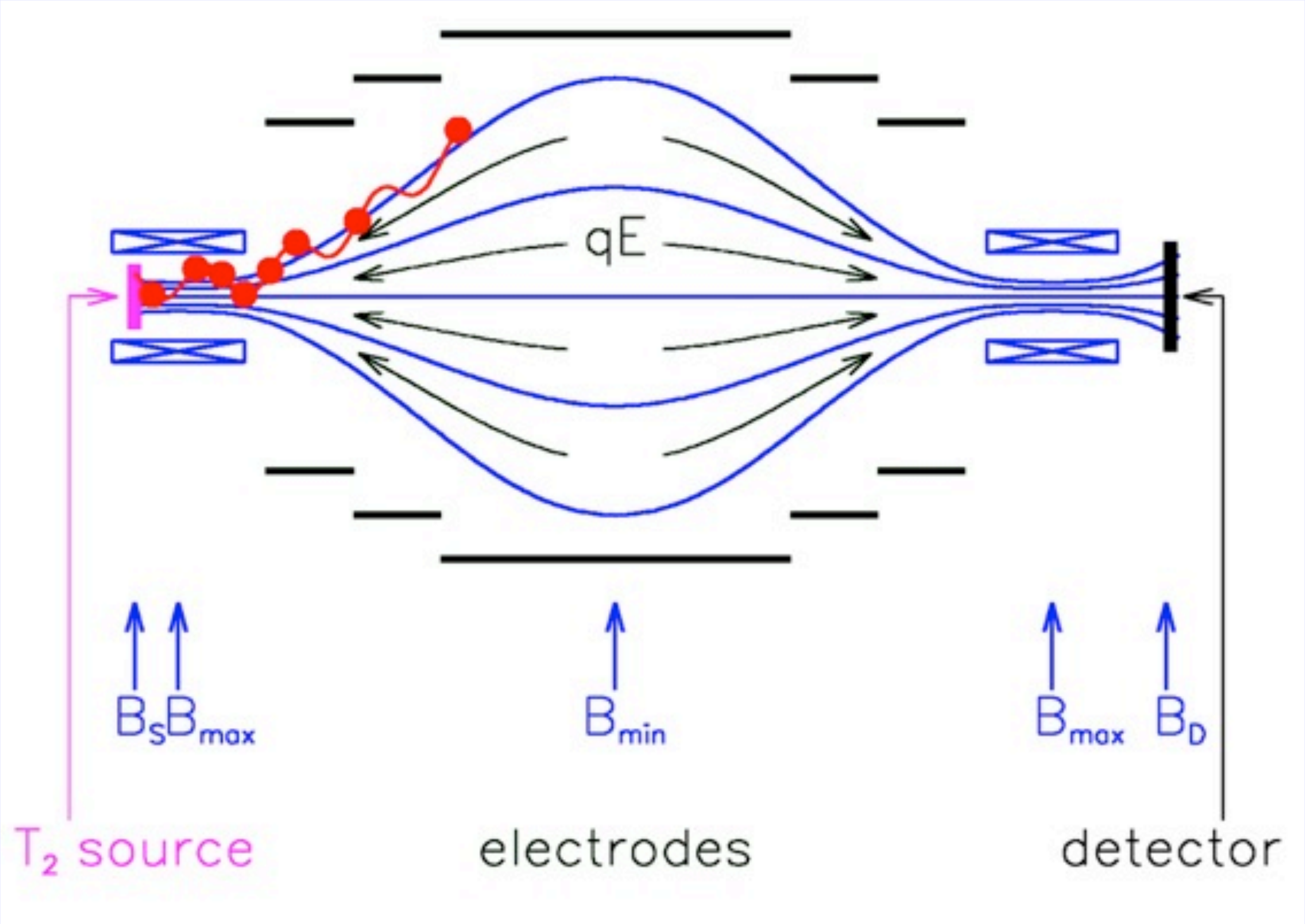
Limiting Factors

- Flux: Cannot increase source column density; can only scale up the area
- Resolution: Cannot reasonably scale up the size of the spectrometer

$$\Delta E = \frac{B_{\min} E}{B_{\max}}$$



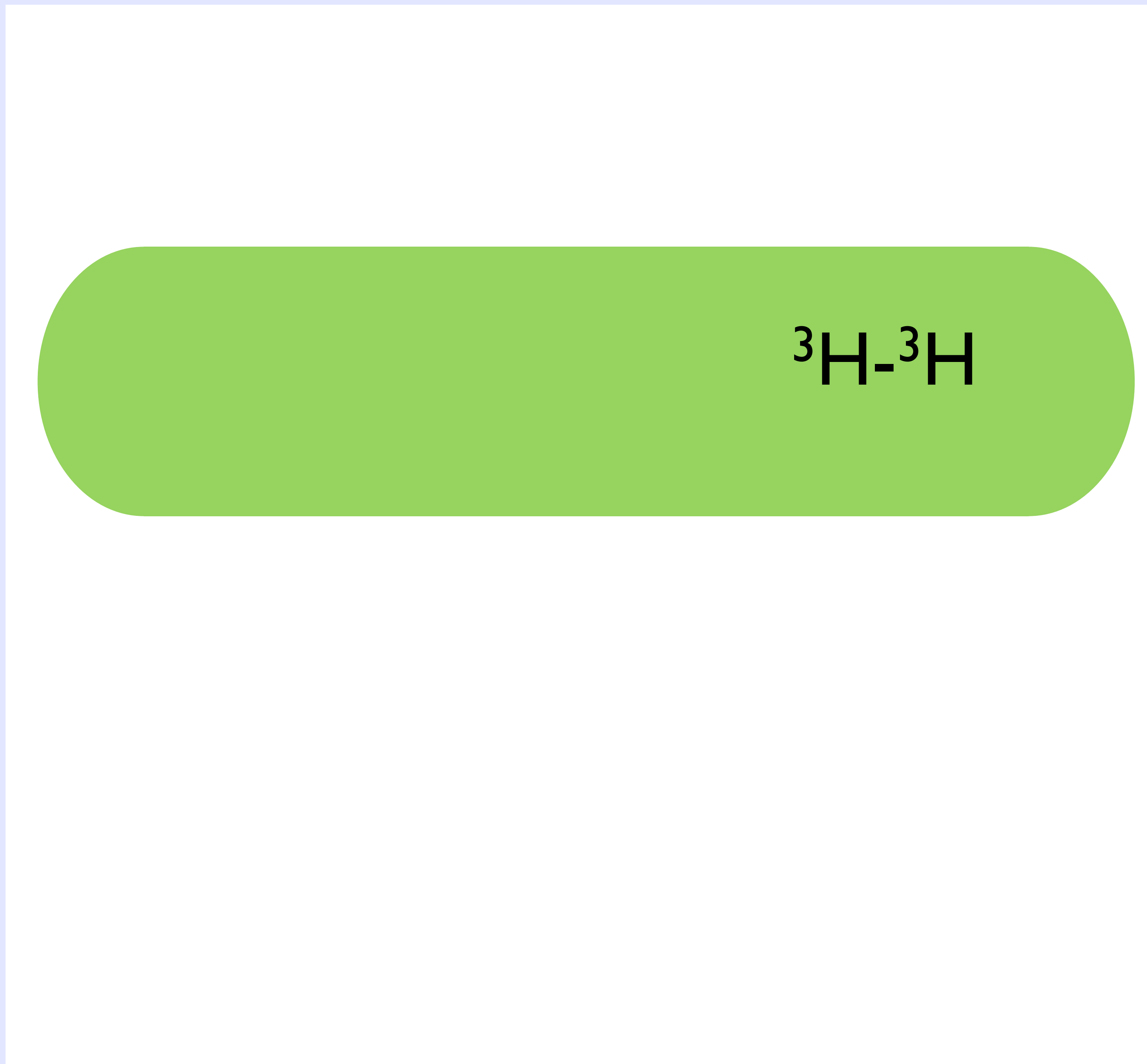
A new technique is necessary to achieve the desired target and resolution

A New Technique

- Enclosed volume

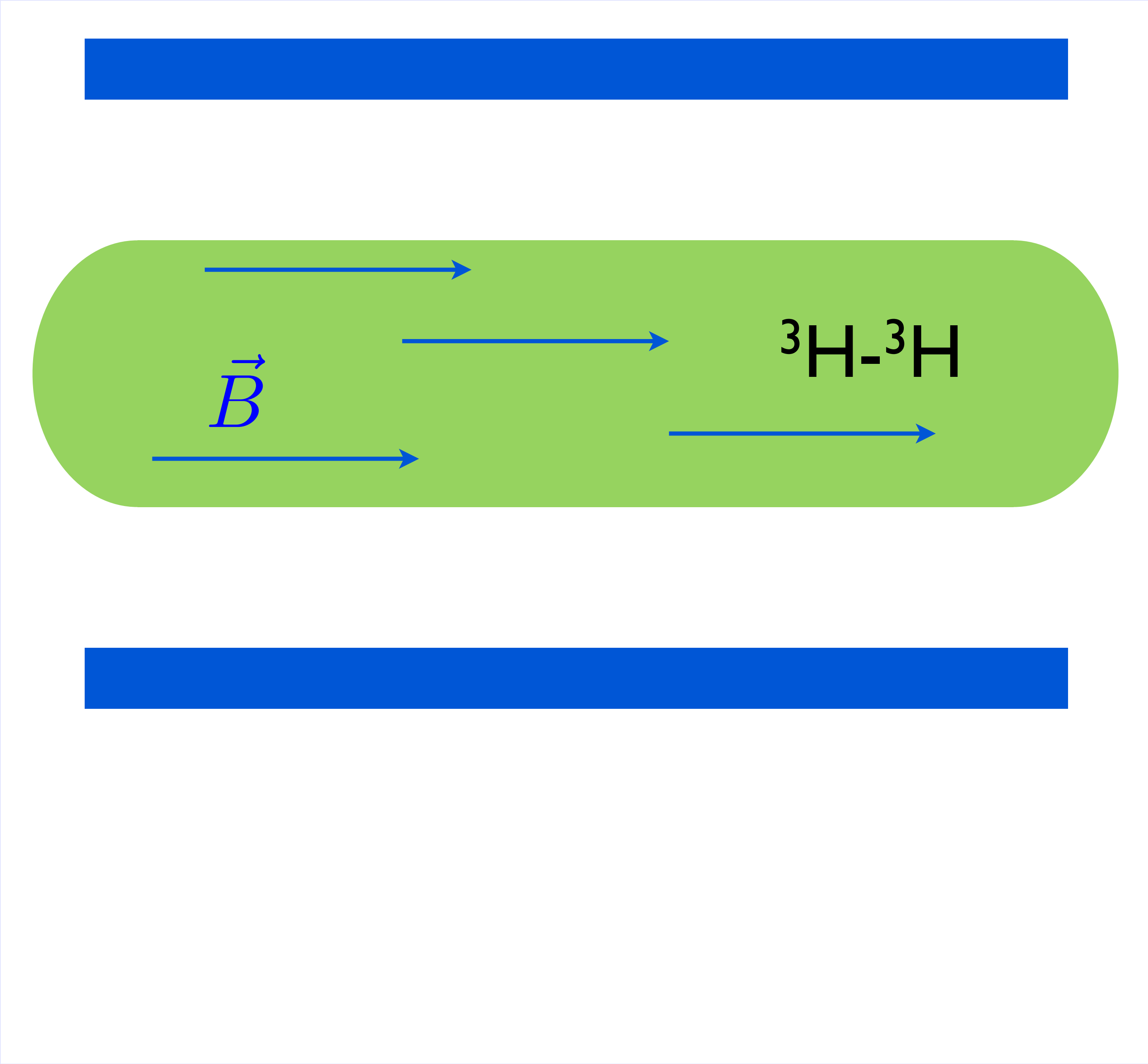
A New Technique

- Enclosed volume
- Fill with tritium gas



A New Technique

- Enclosed volume
- Fill with tritium gas
- Add a magnetic field



A New Technique

PROJECT 8

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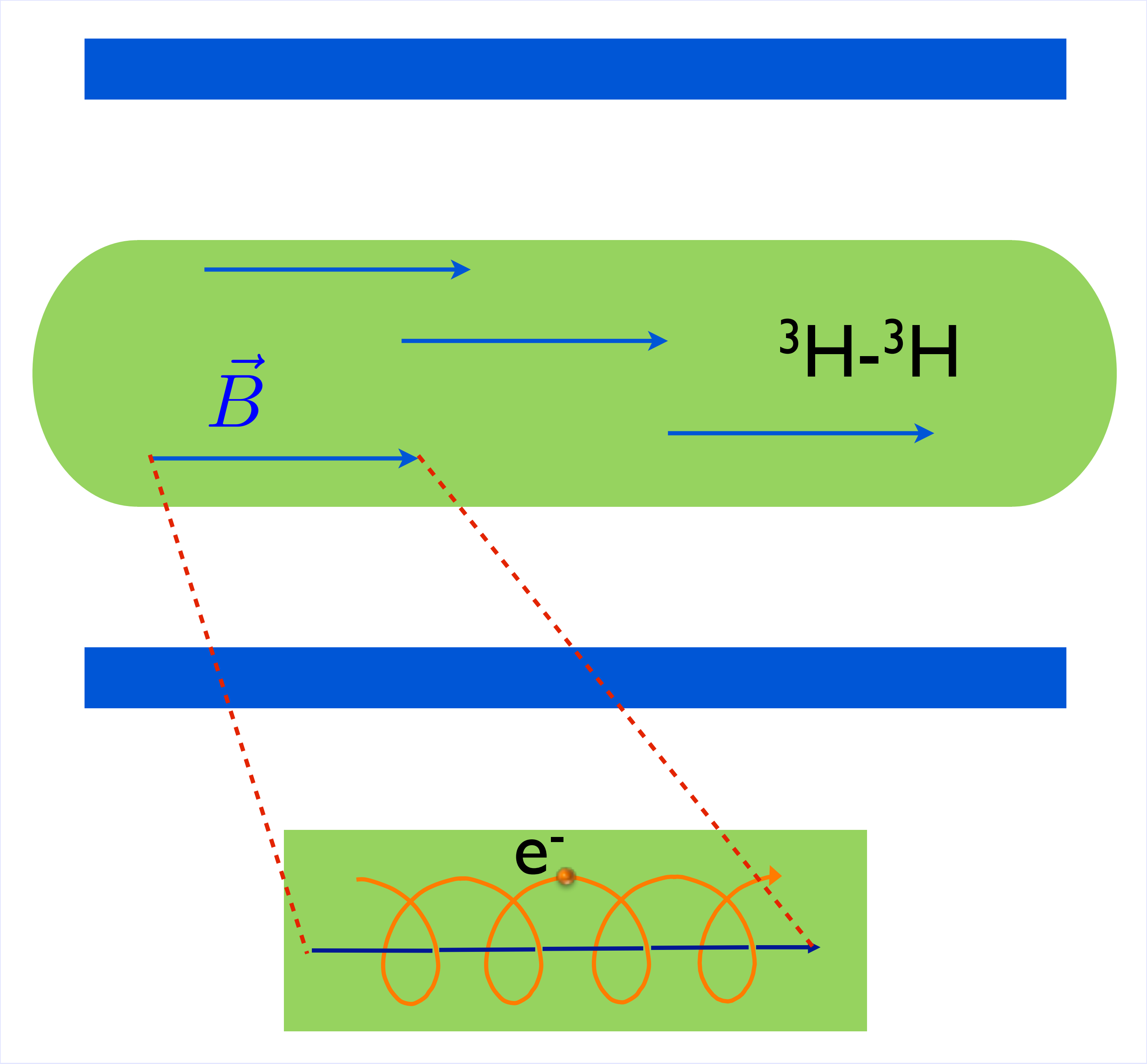

- Decay electrons spiral around field lines

A New Technique

- Enclosed volume
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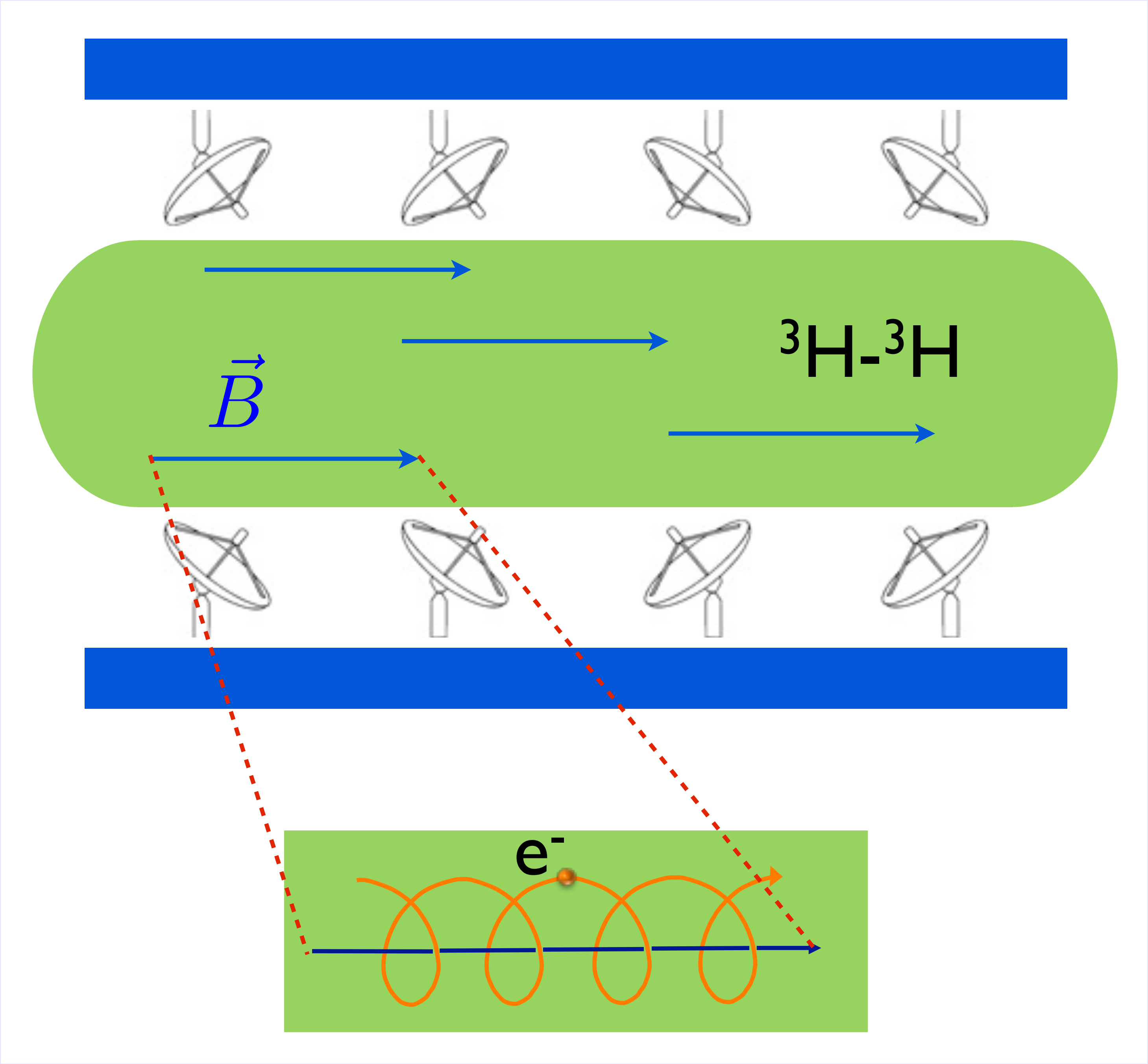
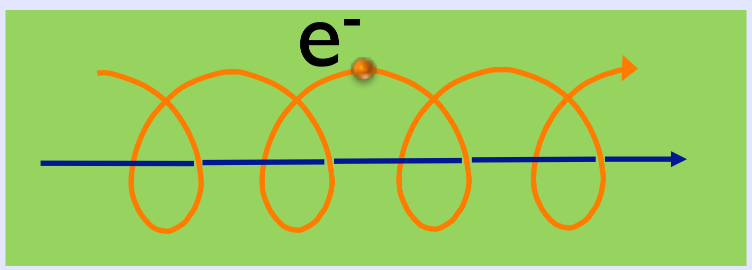
- Add a magnetic field

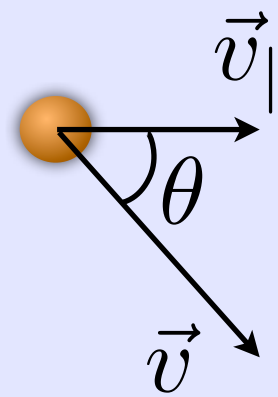


- Decay electrons spiral around field lines
- Add antennas to detect the cyclotron radiation

Cyclotron Radiation

- The frequency of the emitted radiation (ω) depends on the relativistic boost (γ and β dependence), and is independent of the pitch angle of the electron (θ)



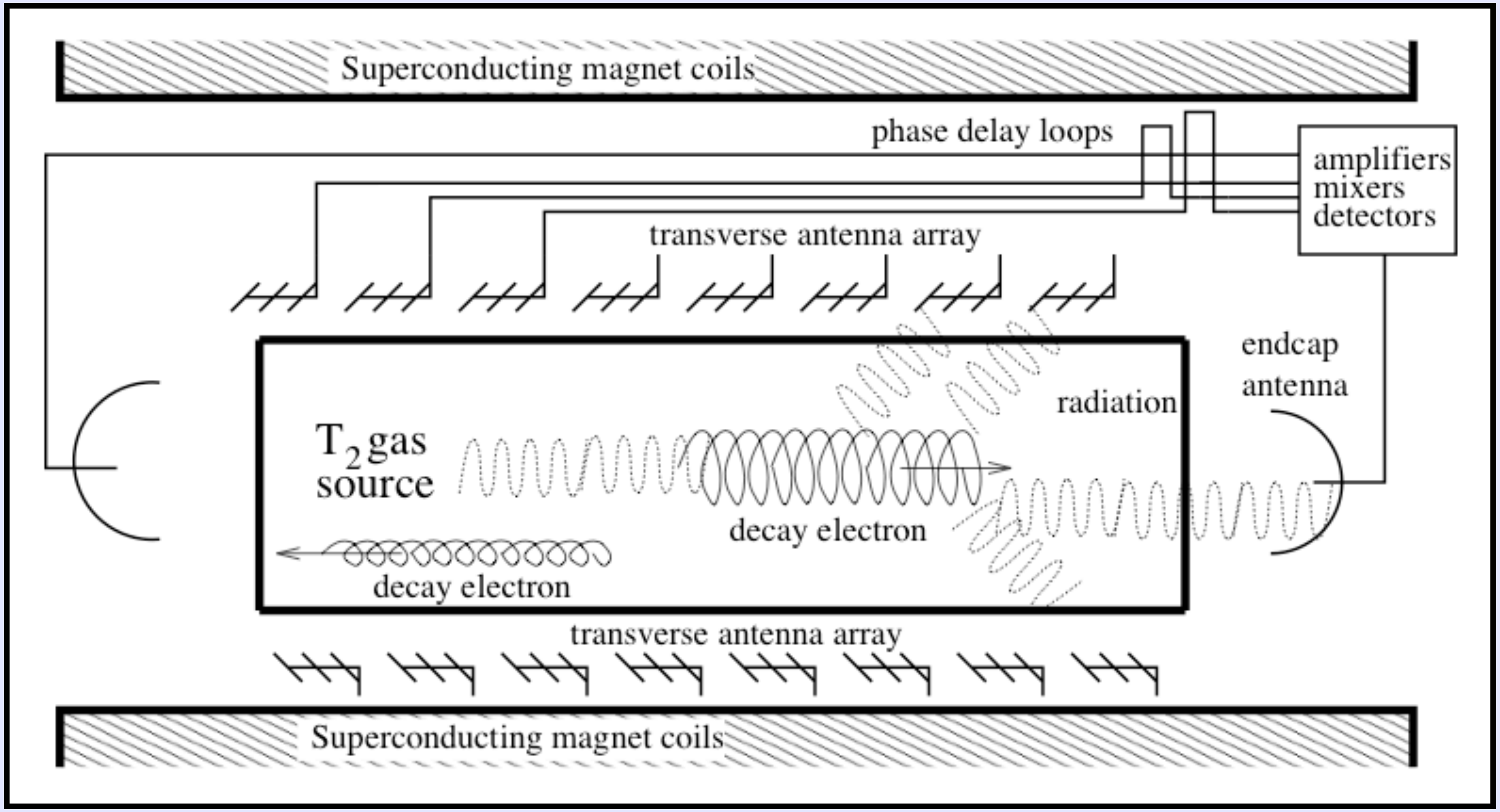


$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

$$P_{\mathrm{tot}} = \frac{1}{4\pi\epsilon_0}\frac{2q^2\omega_c^2}{3c}\frac{\beta_\perp^2}{1-\beta^2}$$

- The radiation emitted can be collected to measure the electron energy in a non-destructive manner

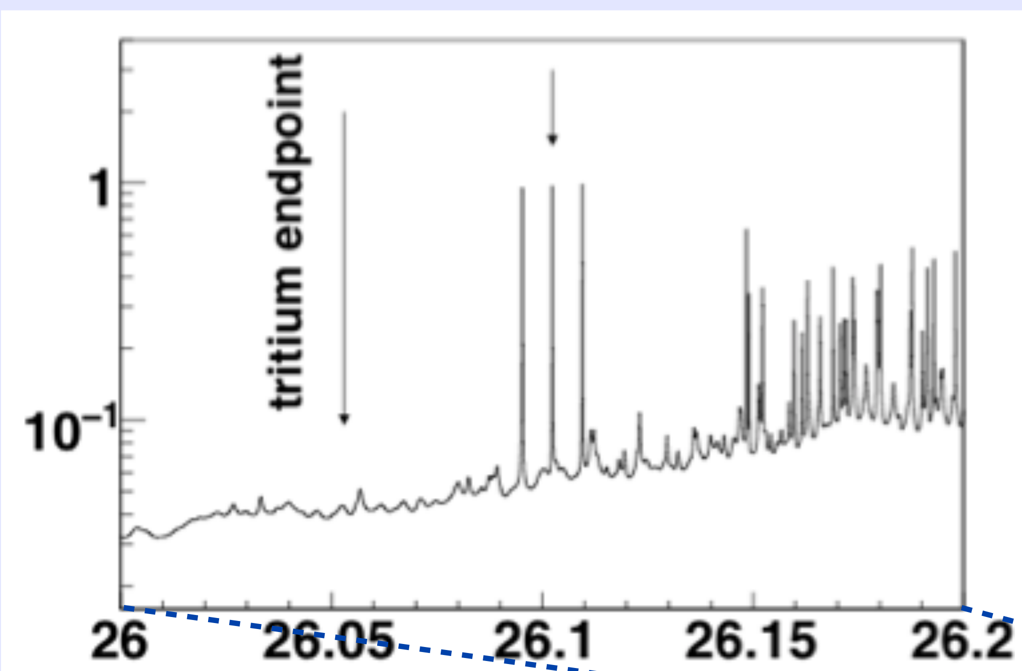
Initial Simulation

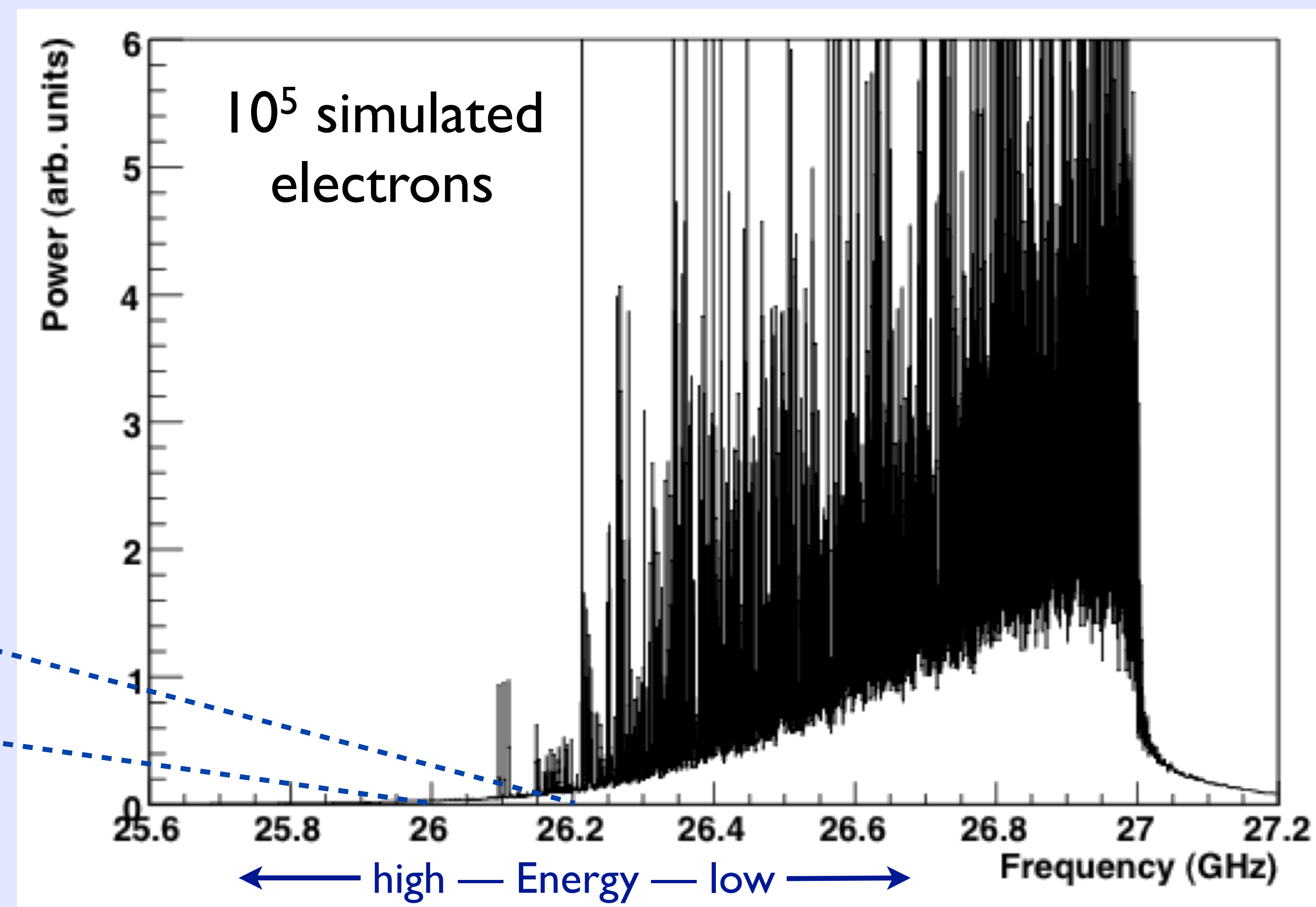


From B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2008)

Frequency Spectrum

- Low energy electrons dominate at higher frequencies
- Rare, high energy electrons give a clean signature at the endpoint

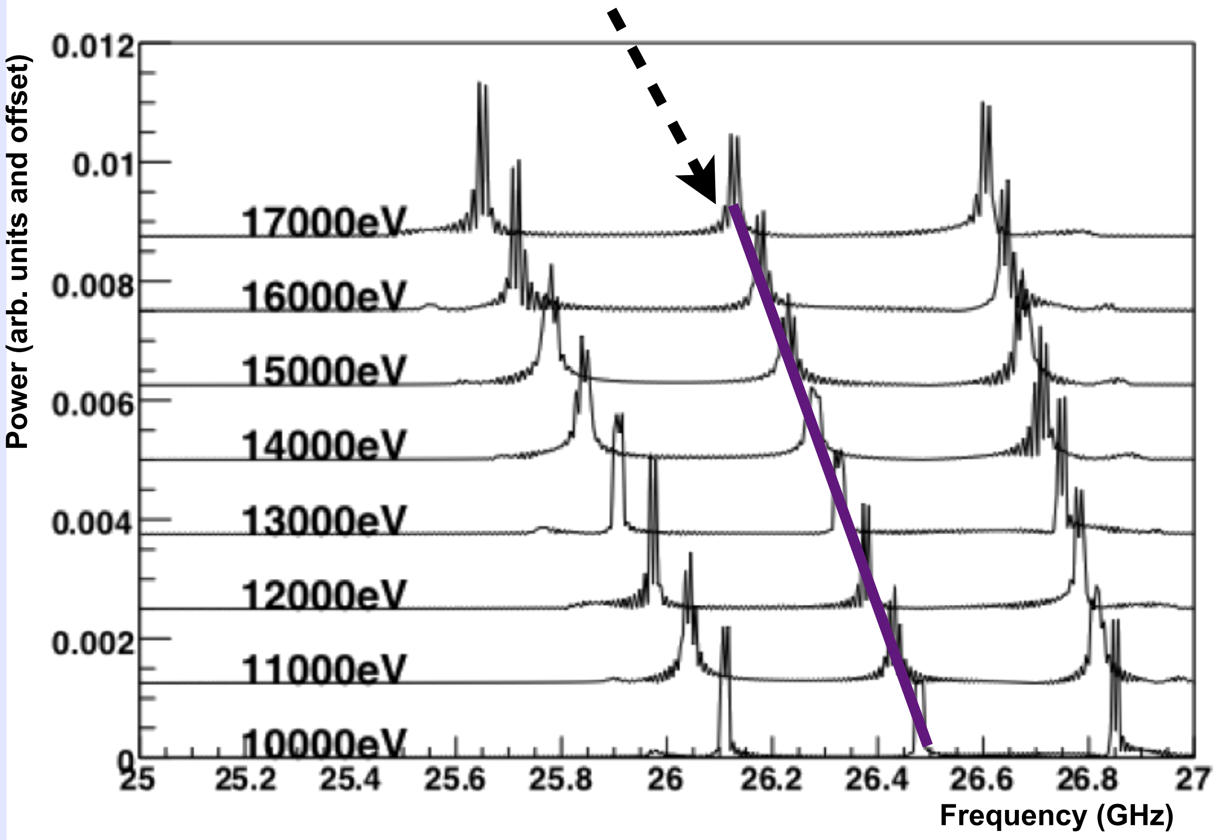




Observed Frequencies

Central frequency

Dependent on the electron energy



This effect is highly dependent on the antenna configuration

Observed Frequencies

PROJECT 8

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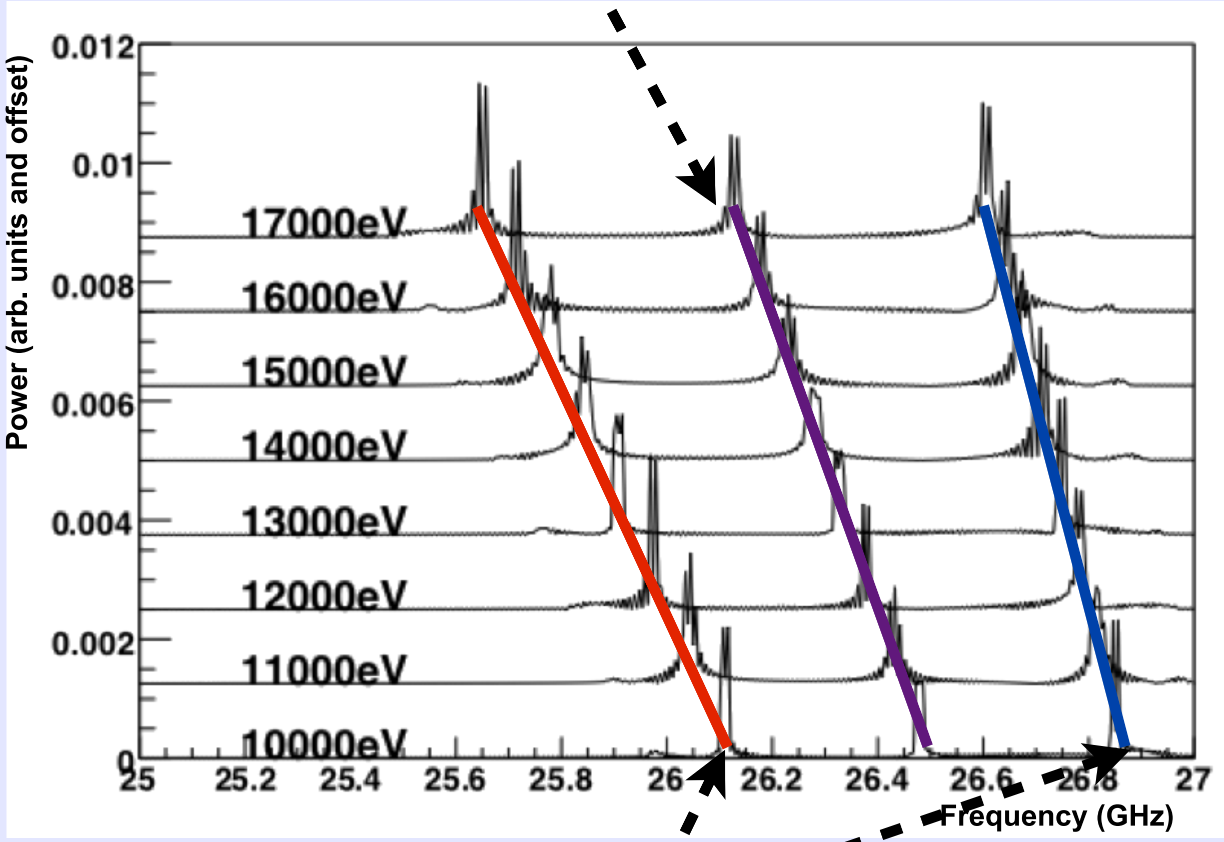
Dependent on the electron energy

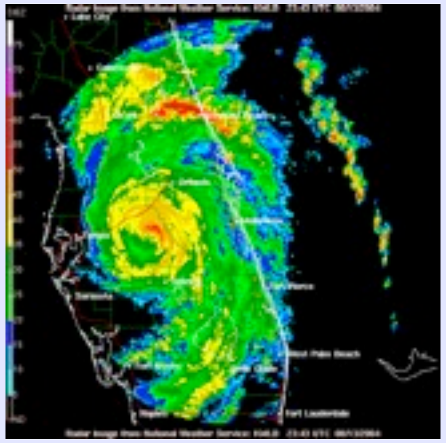


Sidebands
Dependent on the momentum parallel
to the magnetic field

This effect is highly dependent on the antenna configuration

Magnetic Field

- Frequency ~ magnetic field strength
- At 1 T, the tritium endpoint falls around 27 GHz



- Power radiated: 10^{-15} W
  - ❖ 18.6 keV = 3×10^{-15} J
  - ❖ Measurement time: $\sim 10^{-5}$ s

Is this even Possible?

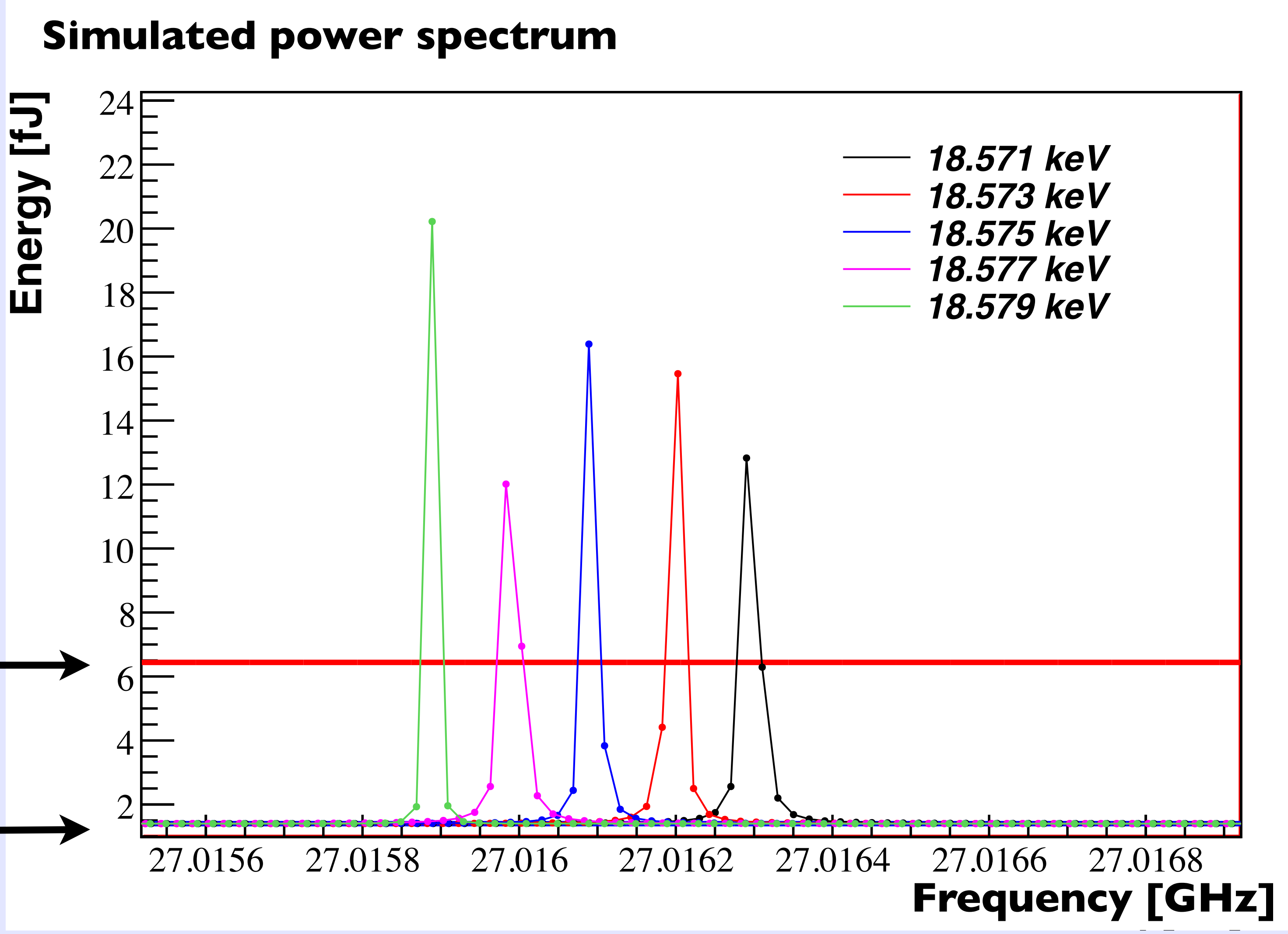
PROJECT 8

- With $B = 1$ T
- Power radiated $P_{\mathrm{signal}} = 10^{-15}$ W
- Thermal noise power @ 60 K $P_{k\mathrm{T}} = 5\mathrm{x}10^{-17}$ W

- Energy resolution $\Delta E = 1$ eV
  - ❖ $\Delta E/E \sim \Delta f/f \sim 10^{-6}$
  - ❖ $\Delta f \approx 50$ kHz

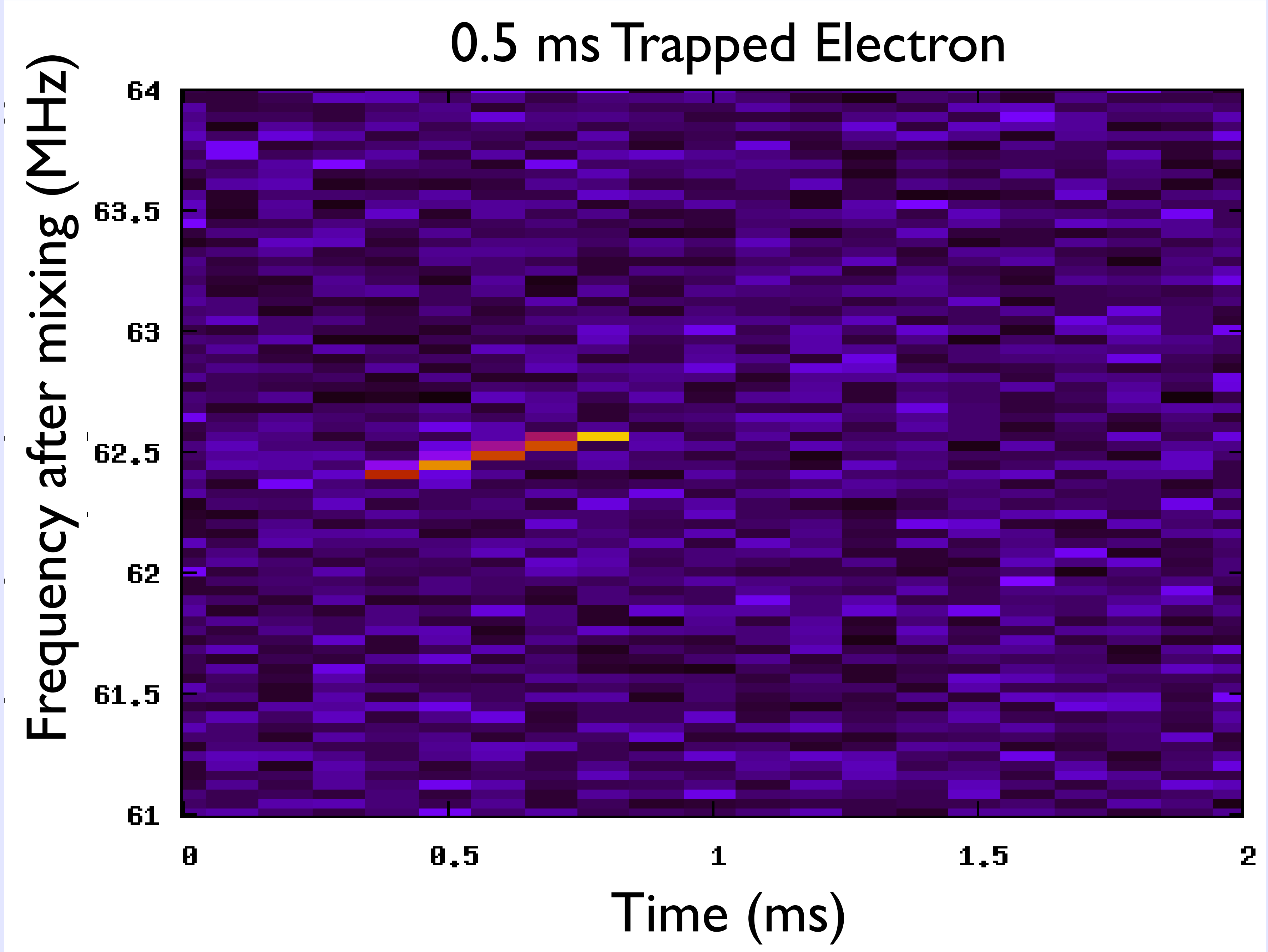
1% thermal fluctuation →

mean thermal noise →



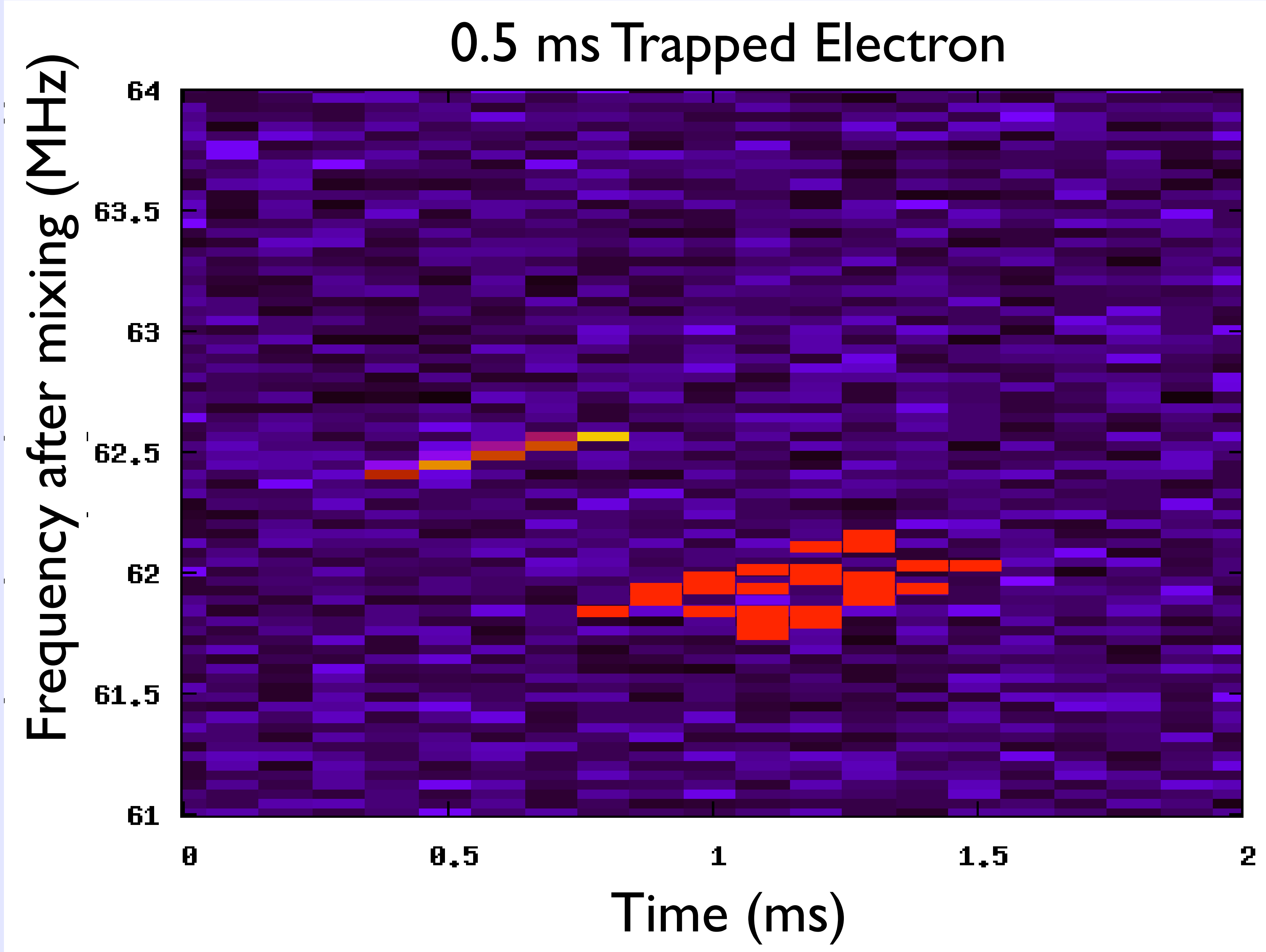
Complexities

- Electron energy is not constant



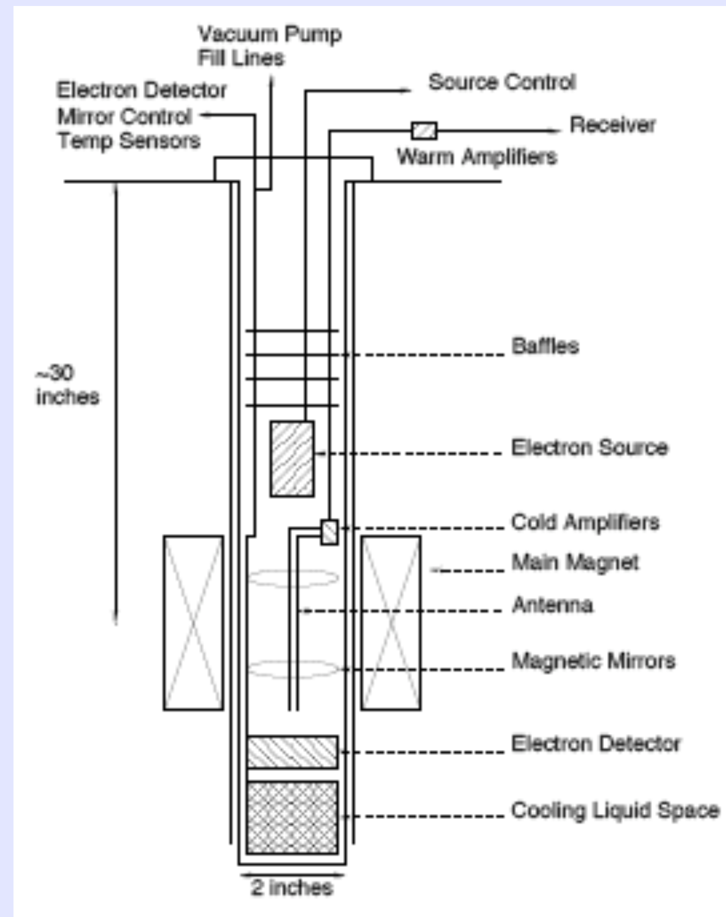
Complexities

- Electron energy is not constant
- B field may not be uniform

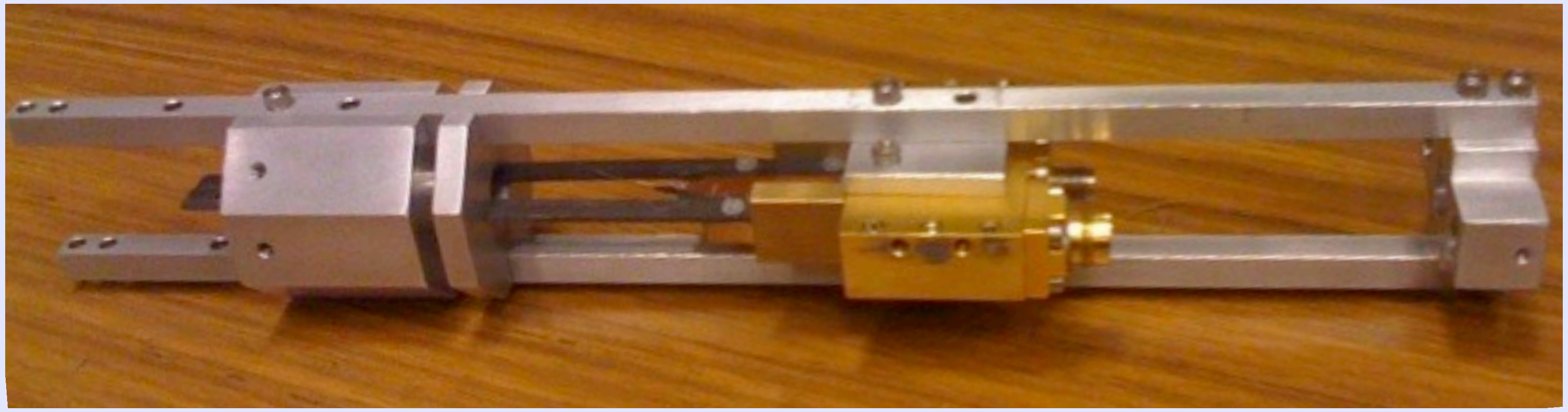


Prototype Experiment

- A prototype is being built at UW
- There are several questions to answer
  1. Can we detect the signal?
  2. What is the resolution of the technique?
  3. Can we measure the ^{83m}Kr spectrum?



Antenna Options



Parallel-strip waveguide

Rectangular waveguide

Prototype Status

- Almost ready to test parallel-strip antenna
- ^{83m}Kr source plumbing is being put together
- Magnet, antenna, receiver chain, etc., are ready
- Rectangular waveguide is partially complete

Summary

- Project 8 is the first realistic prospect for a post-KATRIN neutrino mass experiment
- We will soon make the first attempts at single-electron detection with a ^{83m}Kr source
- We will also investigate antenna design and potential energy resolution
- We are currently working on scalable designs for making neutrino mass measurements