Sensitivity analysis for the neutrino mass experiment Project 8

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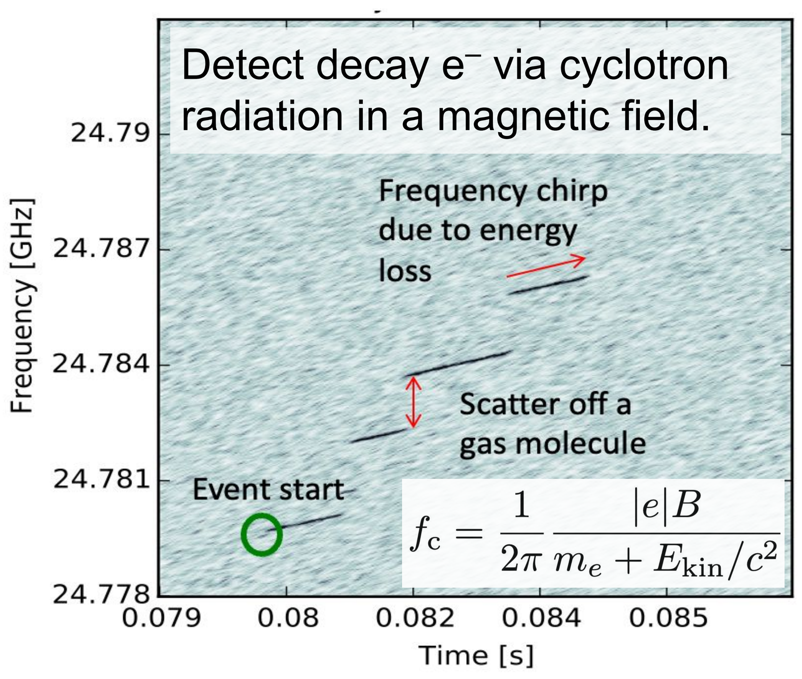
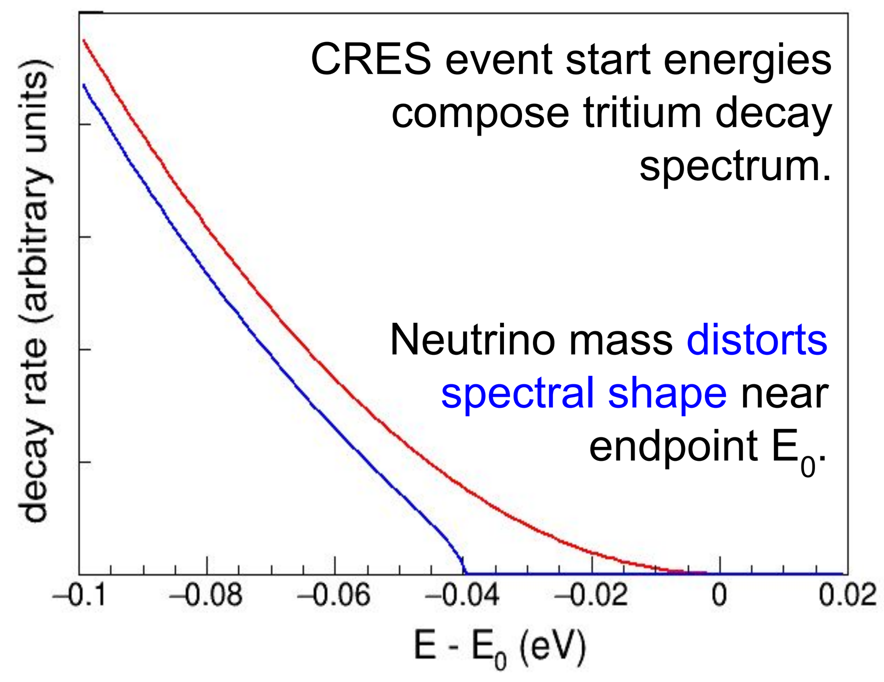
Neutrino mass sensitivity analysis in Project 8

Project 8 pursues a direct neutrino mass measurement with a target sensitivity of 40 meV/c^2 (90% C.L.) by recording a tritium spectrum using **Cyclotron Radiation Emission Spectroscopy (CRES)**.





Goals of sensitivity analysis:

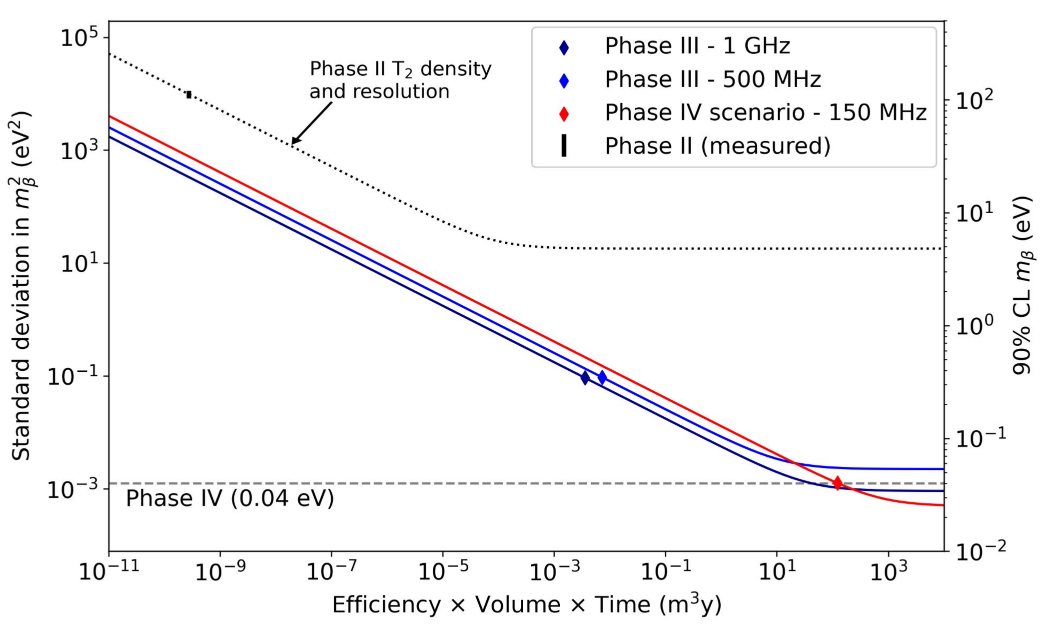
- **Study requirements** to achieve 40 meV/c^2 goal in Phase IV
- **Optimize design parameters** to minimize uncertainty on m_β
- **Predict sensitivity** of Project 8's future experiments

Analytic estimation of neutrino mass sensitivity for differential β-decay measurements

- **Statistical uncertainty:** Estimate m_β by counting the number of events in an energy window ΔE below the spectrum endpoint E_0
- **Systematic uncertainty:** Introduced from energy broadening σ_i and broadening uncertainty $\delta\sigma_i$
- **Total uncertainty on m_β^2:**

$$\sigma_{m_\beta^2} = 4\sqrt{\frac{1}{(6\, C_T\, V_{eff}\, n\, t)^2}\left[C_T\, V_{eff}\, n\, t\, \Delta E + \frac{b\, t}{\Delta E}\right] + \sum_i \sigma_i^2(n)\cdot \delta\sigma_i^2}$$

t : runtime n : gas density V_{eff} : effective volume b : background



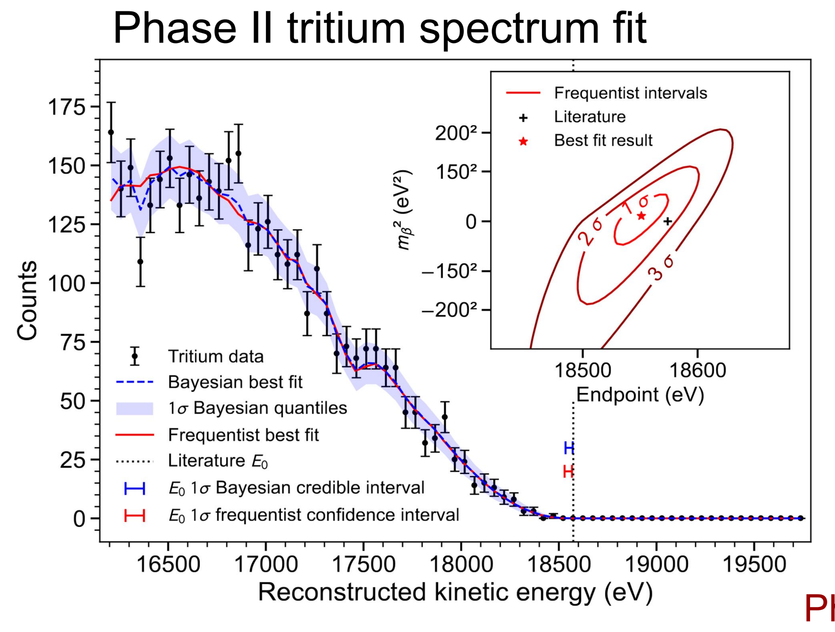
Sensitivity curves for 3 atomic T cavity experiments:

- dark blue: next phase, 1 GHz cavity
- bright blue: next phase, 500 MHz cavity
- red: final phase
- black: like Phase II T_2

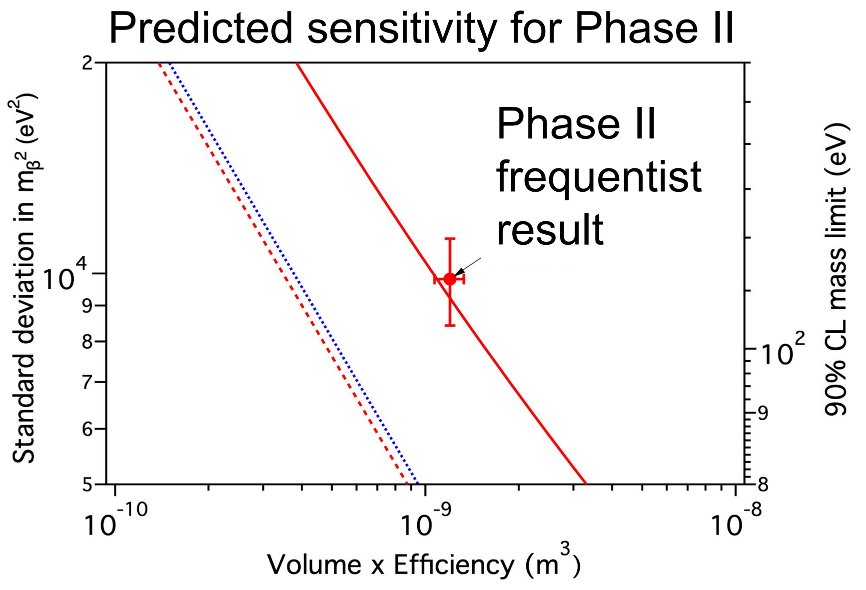
Phase II: A reality check for sensitivity estimation

- In Phase II, we recorded the **first tritium spectrum using CRES**.
- From this data, we placed a limit on m_β at 90% C.L.: Frequentist: **<152 eV/c²**; Bayesian: **<155 eV/c²**
- **Sensitivity predictions are in great agreement** with these results.

Phase II tritium spectrum fit



Predicted sensitivity for Phase II



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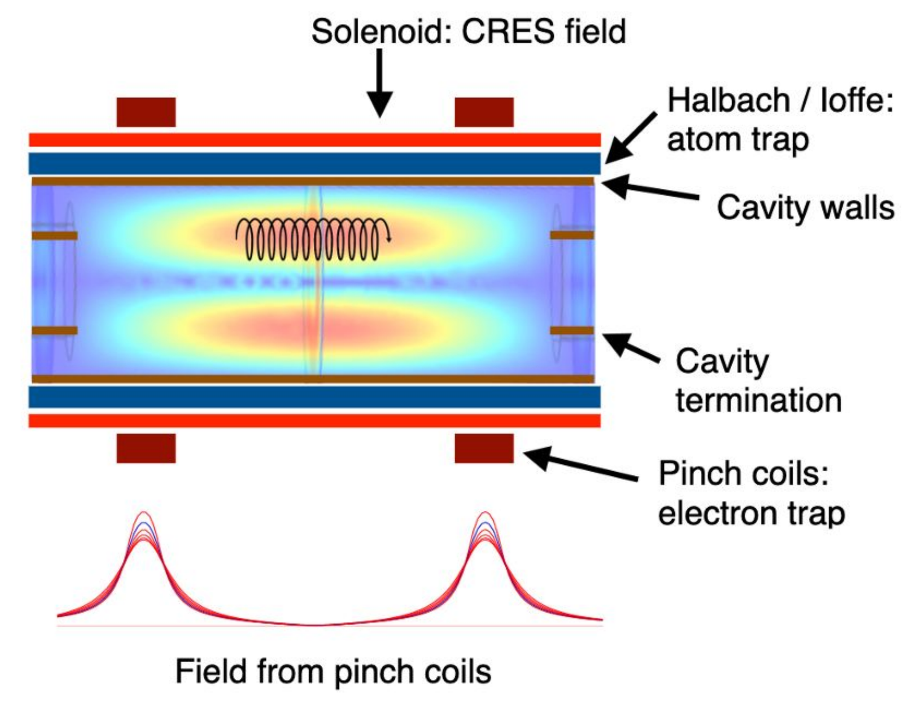
Including cavity-specific statistical and systematic effects

CRES in a cavity poses several advantages that improve sensitivity.

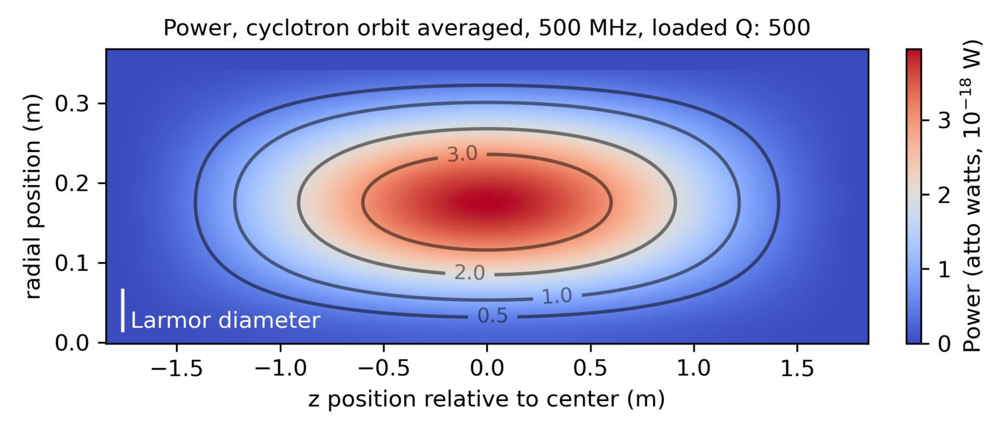
Large effective volume V_{eff}:

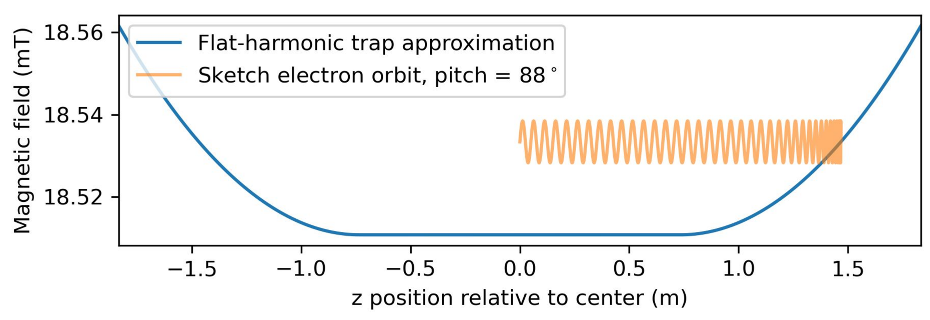
- V scales with $1/f^3$ → $1/B^3$
- Low-frequency cavity increases statistics
- Electron power couples to the TE_{011} mode
- Resonant mode enhances signal power → improves detection efficiency



Energy broadenings σ_i:

- Frequency resolution: Sinusoid's Cramér-Rao Lower Bound (vs. n) for given Signal-to-Noise Ratio (SNR)
- Calculate SNR from cavity and amplifier temperatures, cavity Q, and attenuations
- Magnetic field broadening:
  - Axial/pitch (θ): Analytic model of trap shape correction (vs. n)
  - r, ϕ, time: Calculated externally
- All σ_i must be calibrated to 1% precision ($\delta\sigma_i$)



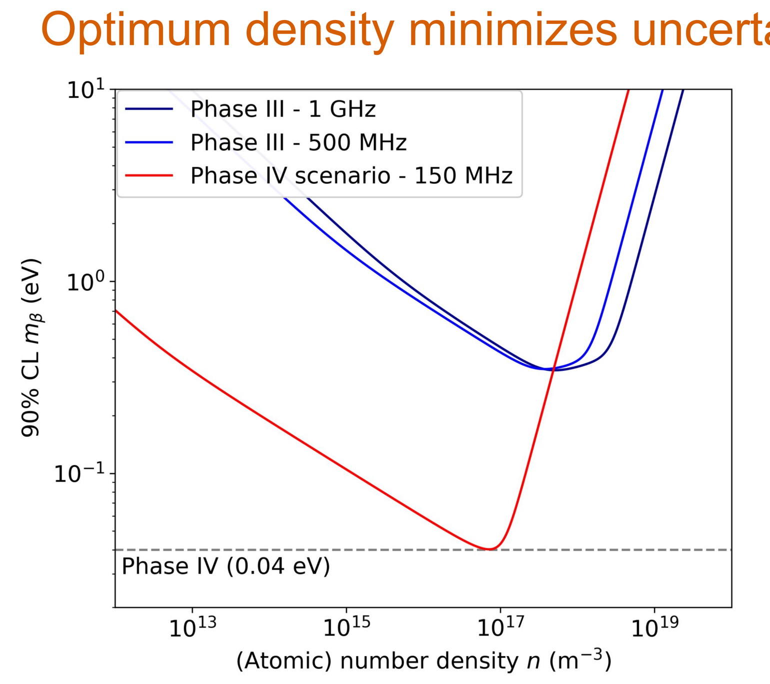


Sensitivity in future Project 8 experiments

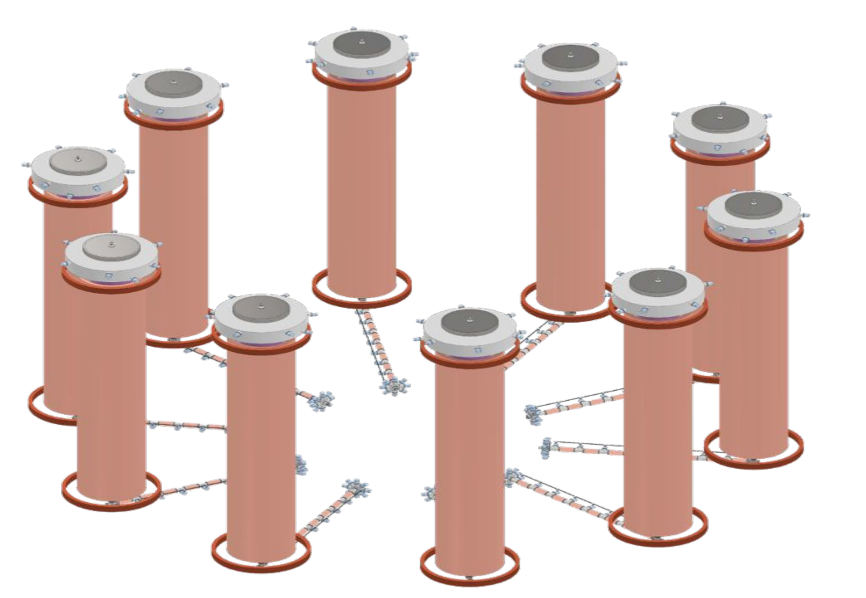
A Phase IV scenario that reaches 40 meV sensitivity:

- **Statistics target:**
  - 10 cavities with 2.5 m diameter running for 6 years
  - ~5% trapping efficiency, ~60% detection efficiency
- **Systematic broadening σ_i target:** 0.13 eV (total)
  - Frequency resolution: 0.05 eV
  - Resolution from spatial and temporal field variation: 0.09 eV each

Optimum density minimizes uncertainty

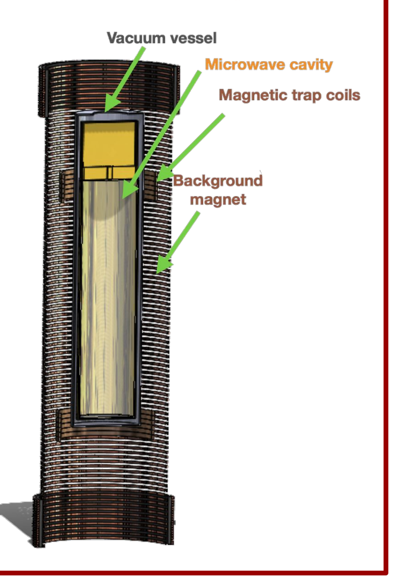


Phase IV with 10 cavities



Next: **Intermediate size** experiment (e.g. 2 m^3) with **sub-eV** sensitivity

- Demonstrate technology requirements for Phase IV
- 0.2 eV total energy broadening at ~20 mT field
- Achieve excellent SNR with 20 mK amplifier temperature and 4 K cavity temperature
- Compatibility of magnet design with atomic tritium: Magnetic atom and electron traps, and homogenous background field



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