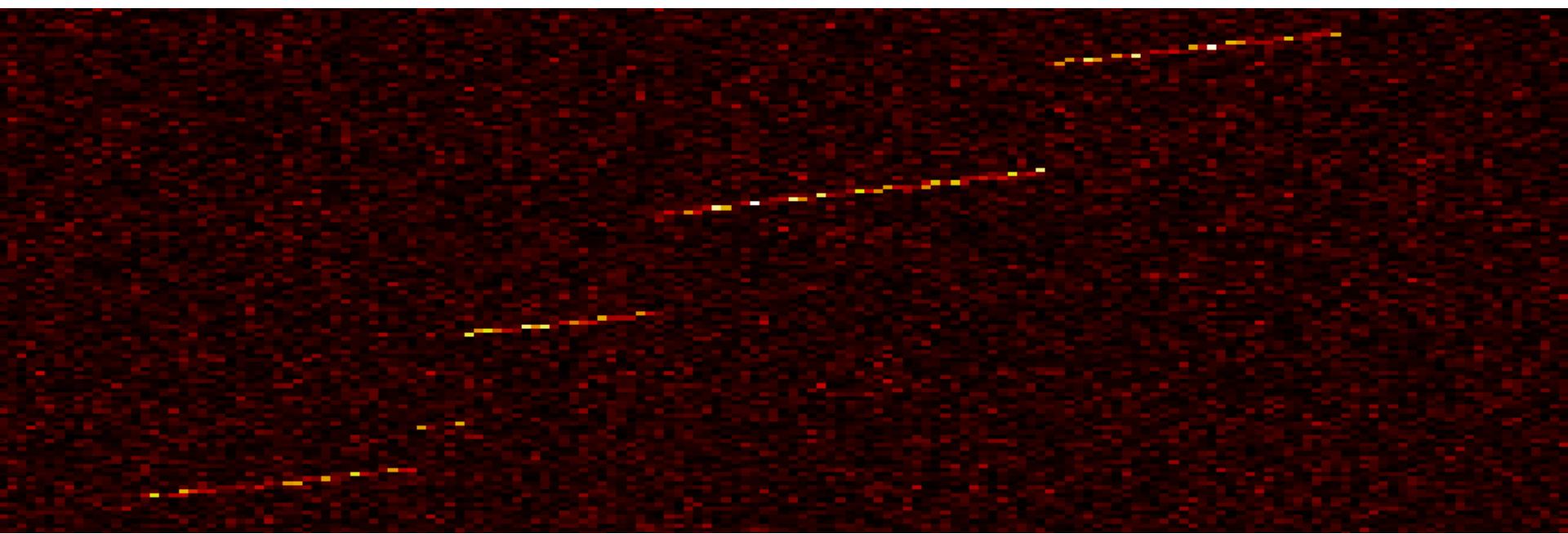


PROJECT 8



Massachusetts
Institute of
Technology

Going Big for Phase III of the Project 8 Neutrino Mass Experiment

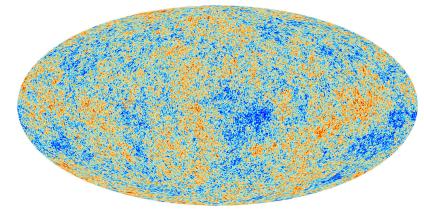


TAUP 2023, 29.08.2023

Juliana Stachurska

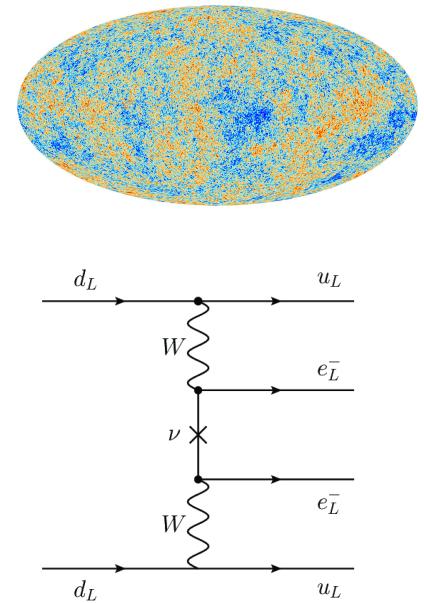
Neutrino Mass

- Cosmology: indirect, model-dependent, probing sum of masses
 - degeneracies between probed parameters



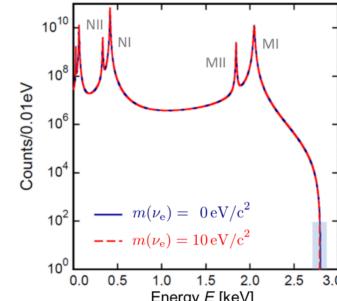
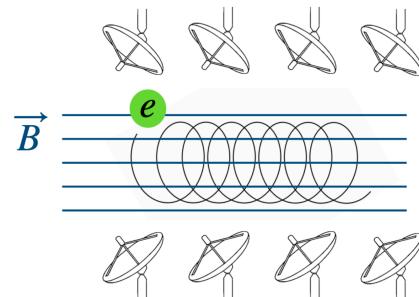
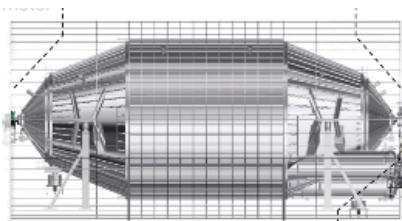
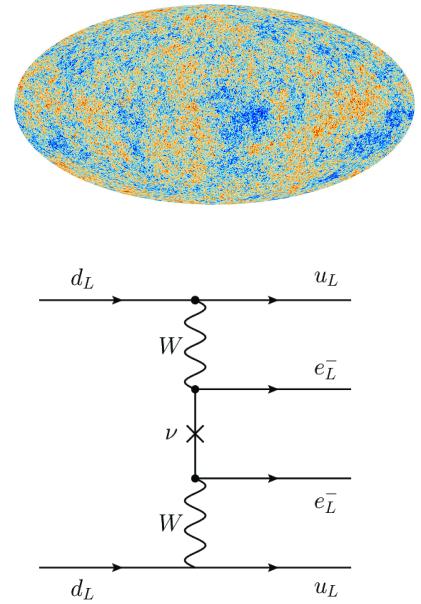
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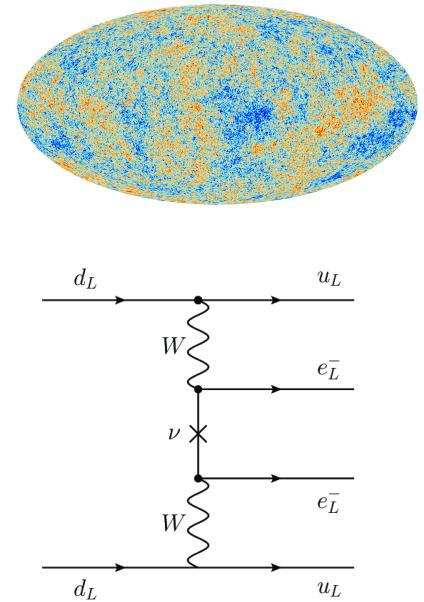
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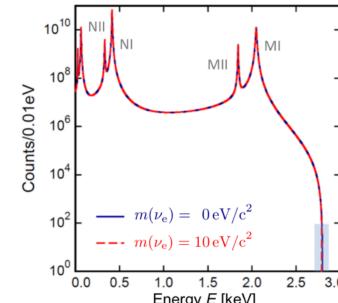
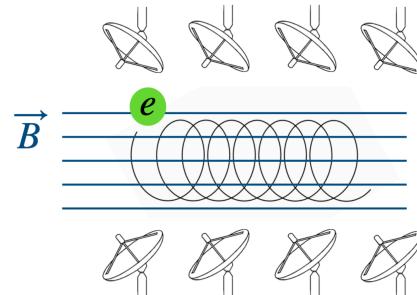
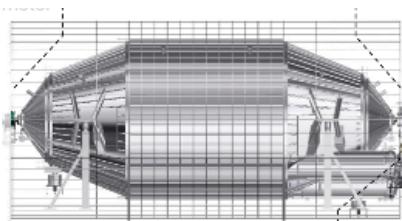


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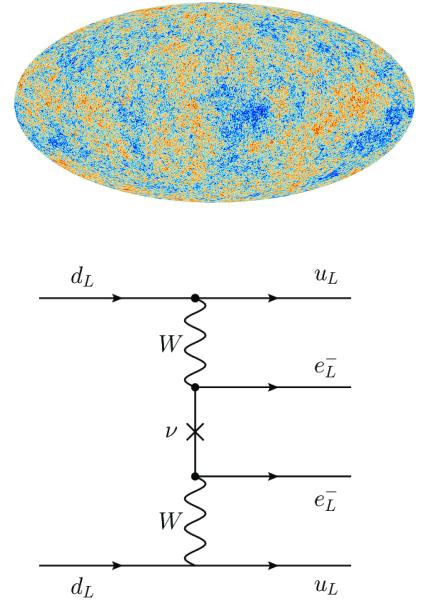


Phase II Results:
N. Oblath, 30.08.

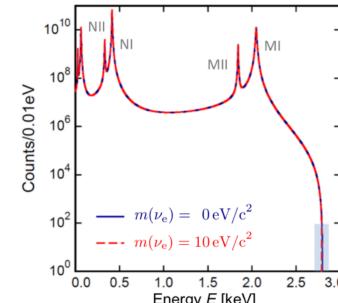
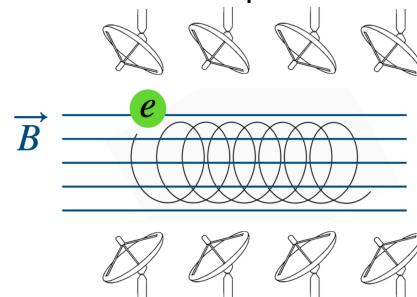
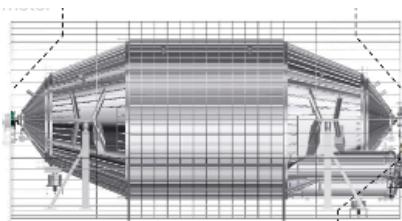


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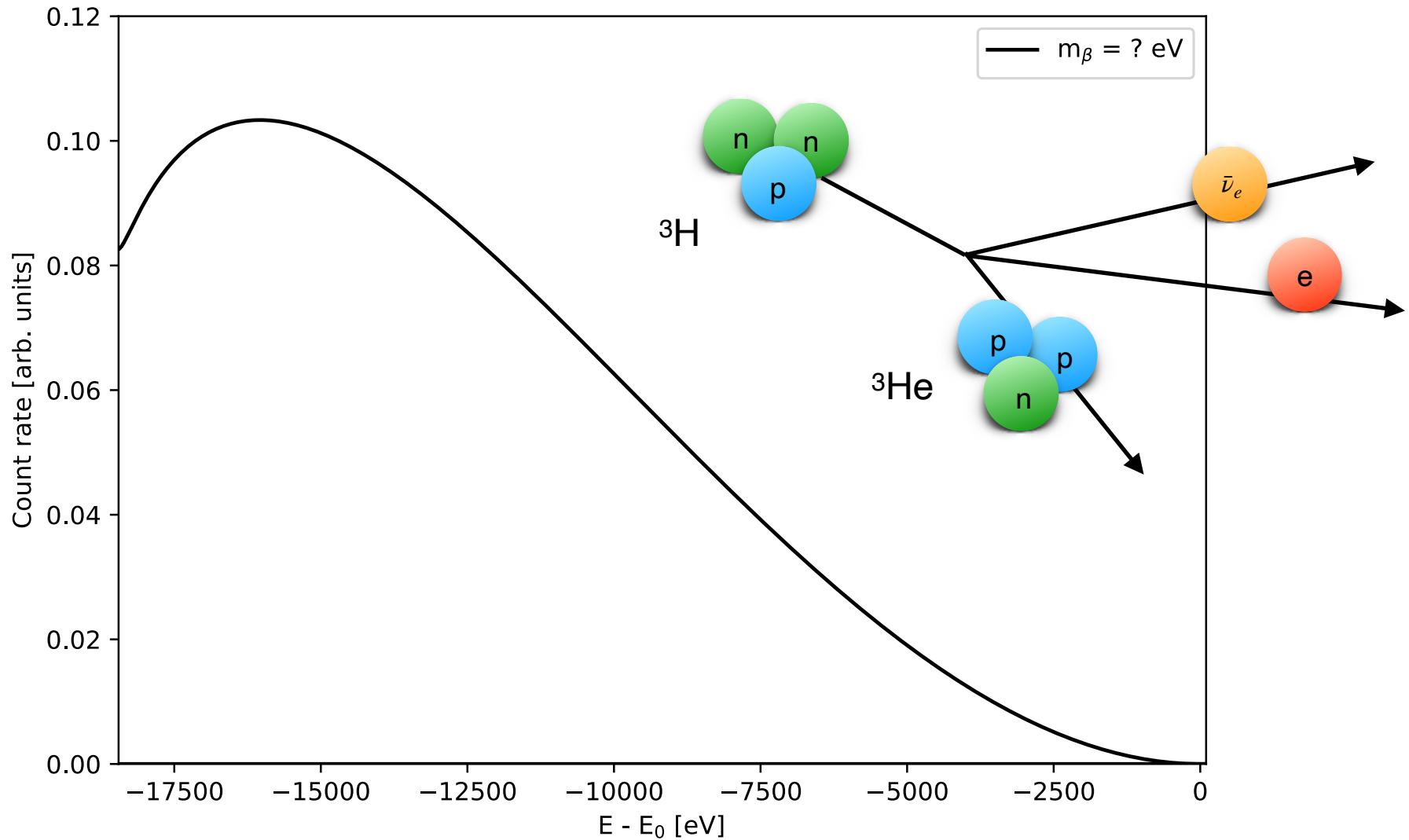
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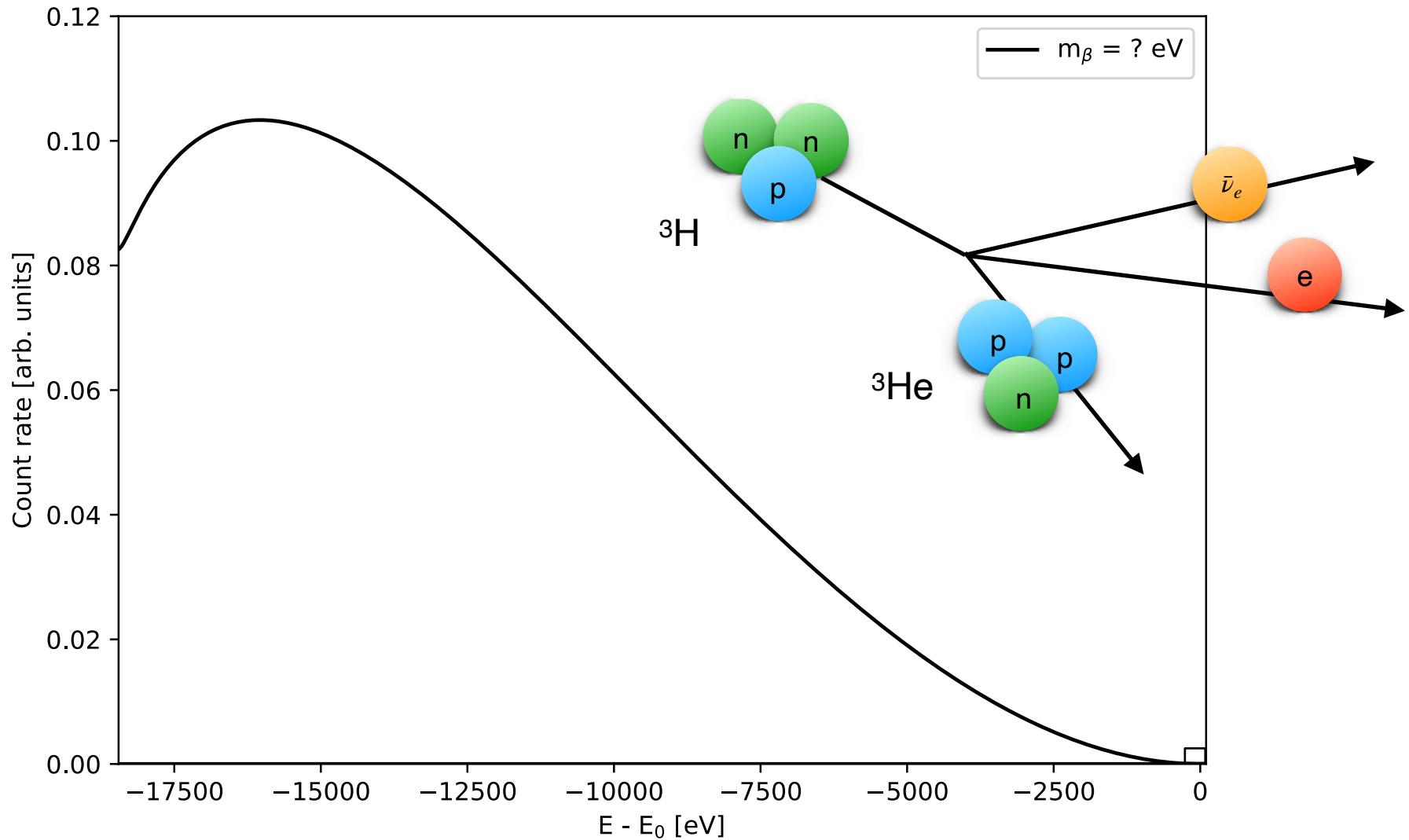
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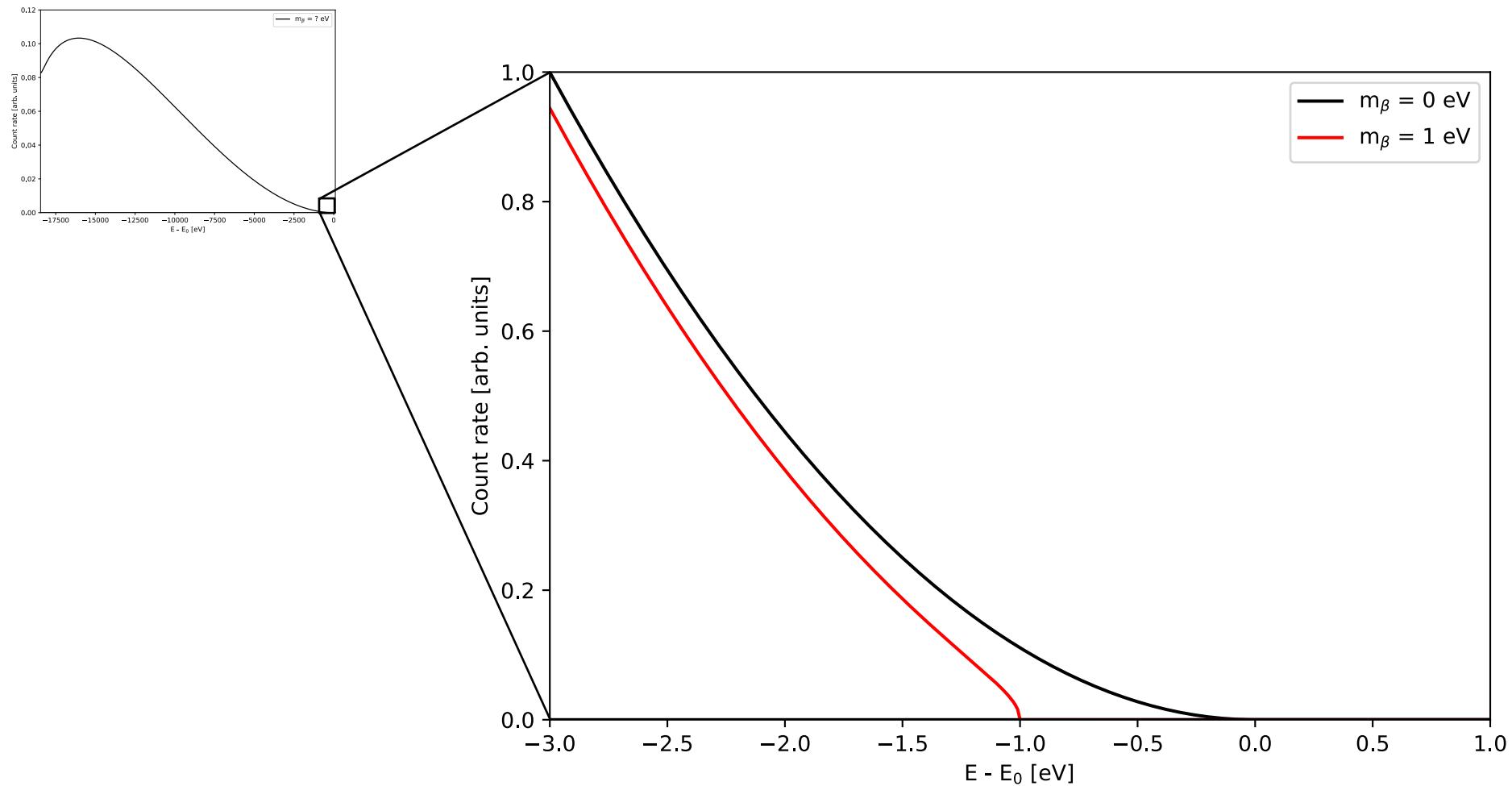
Beta Decay Spectrum



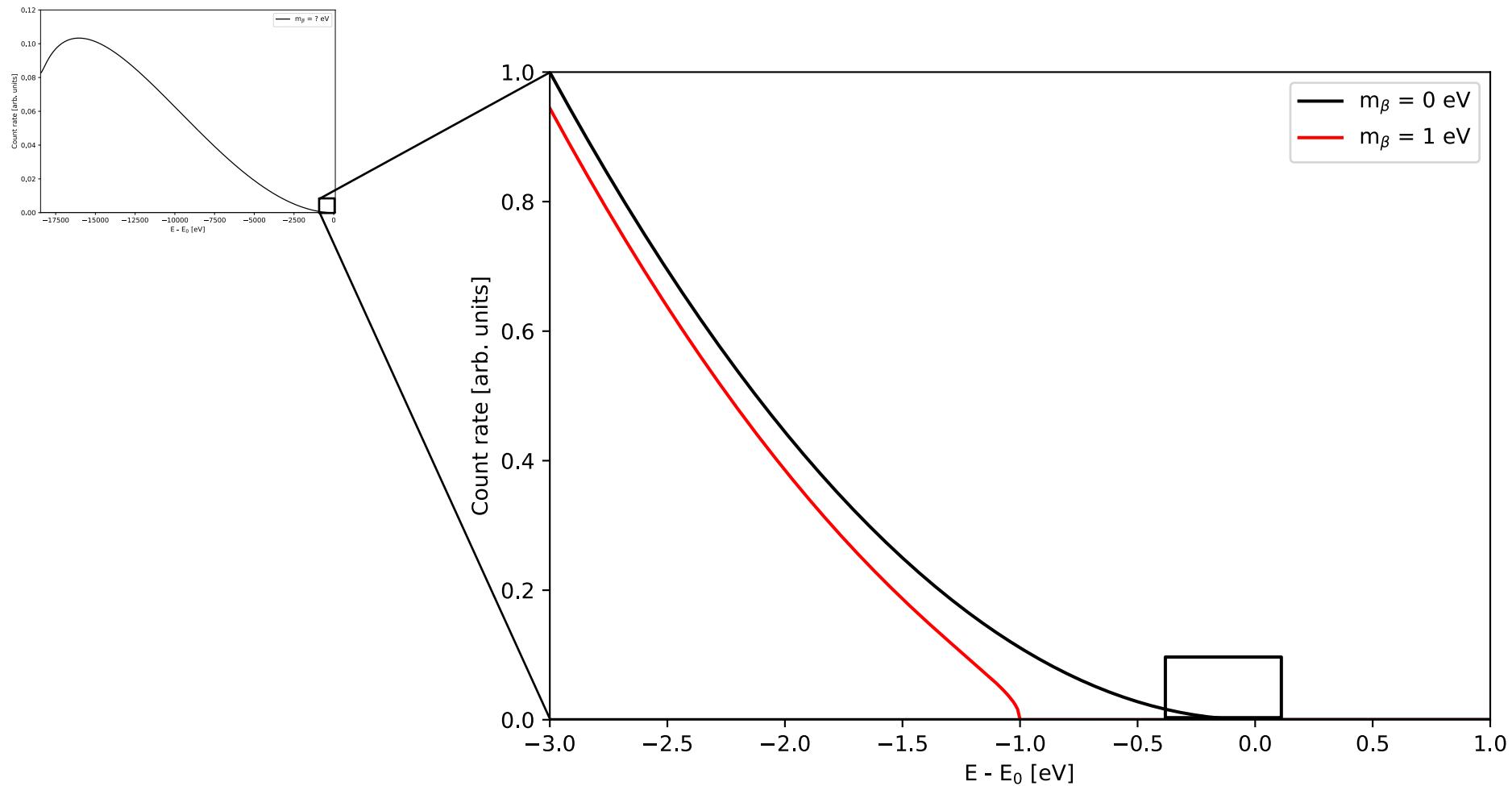
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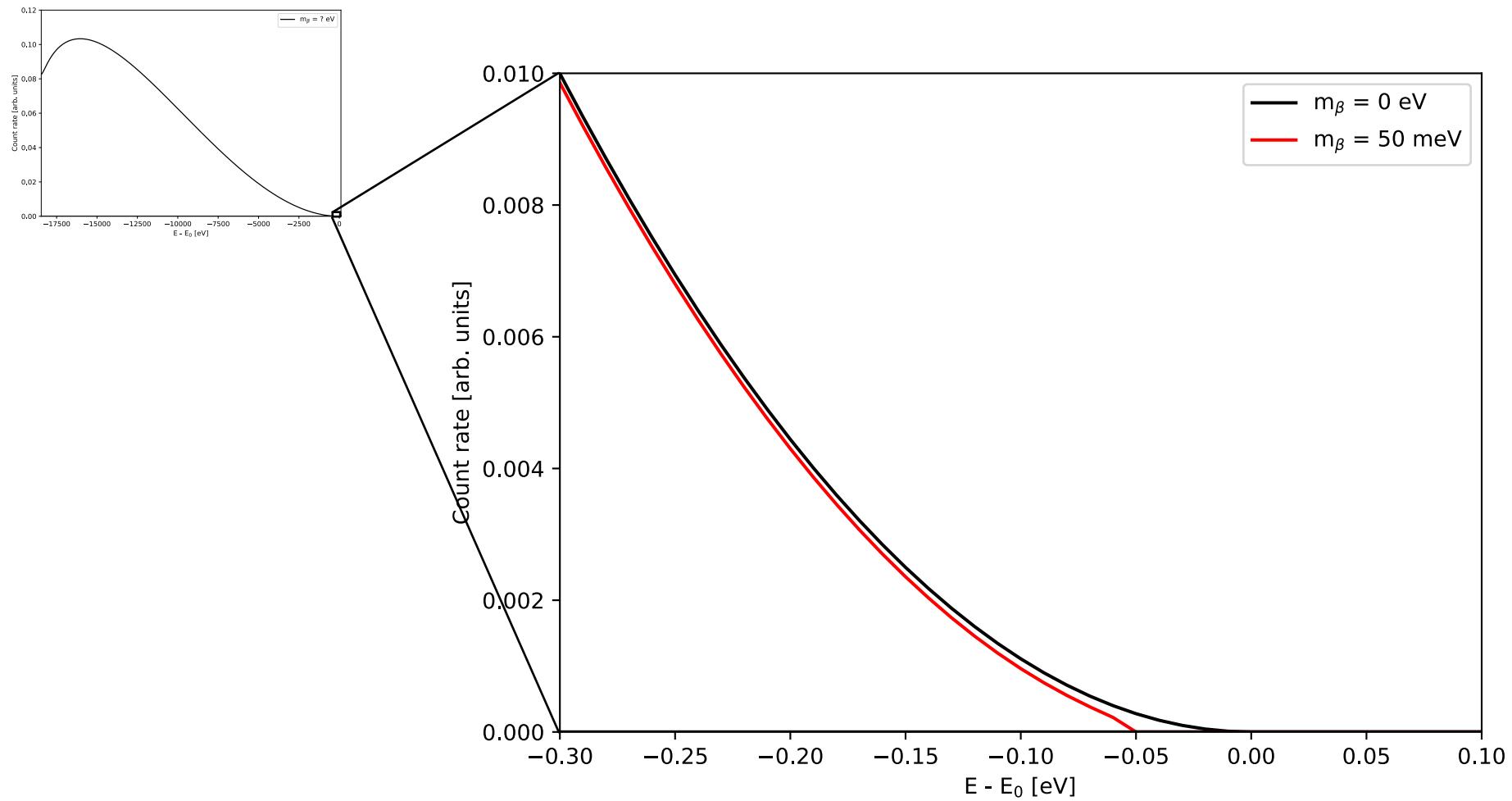
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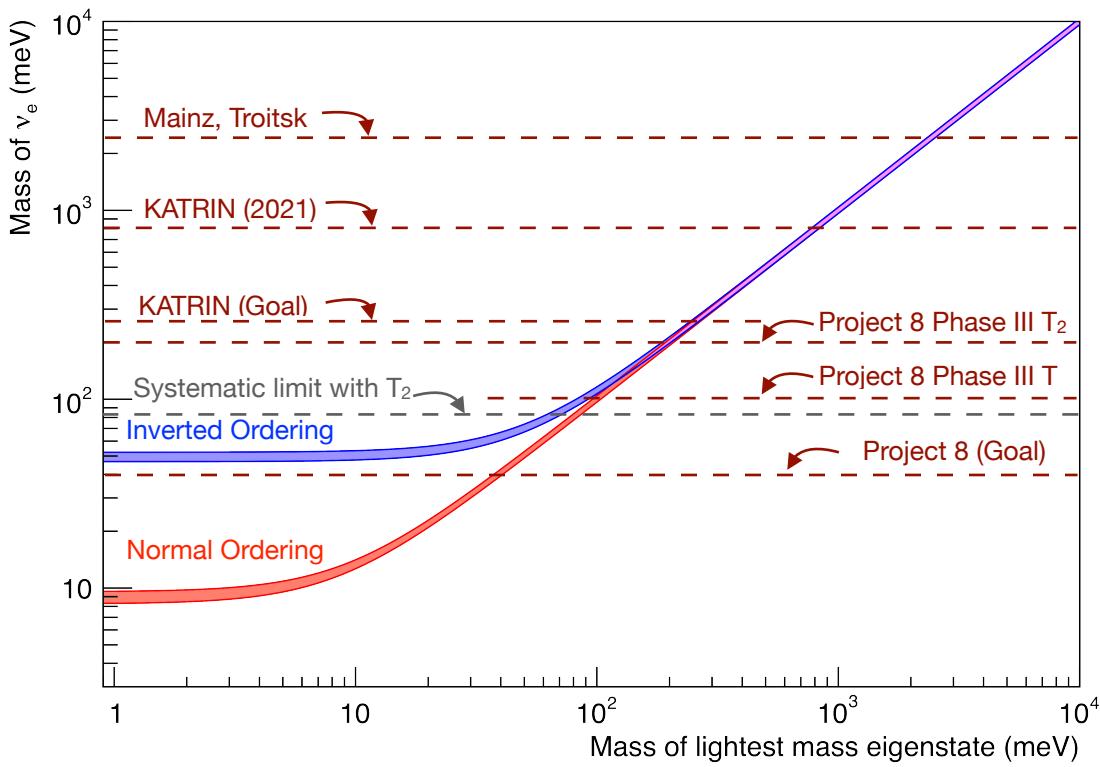
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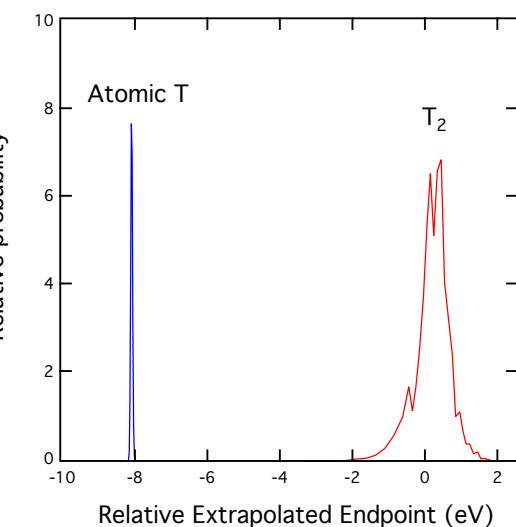
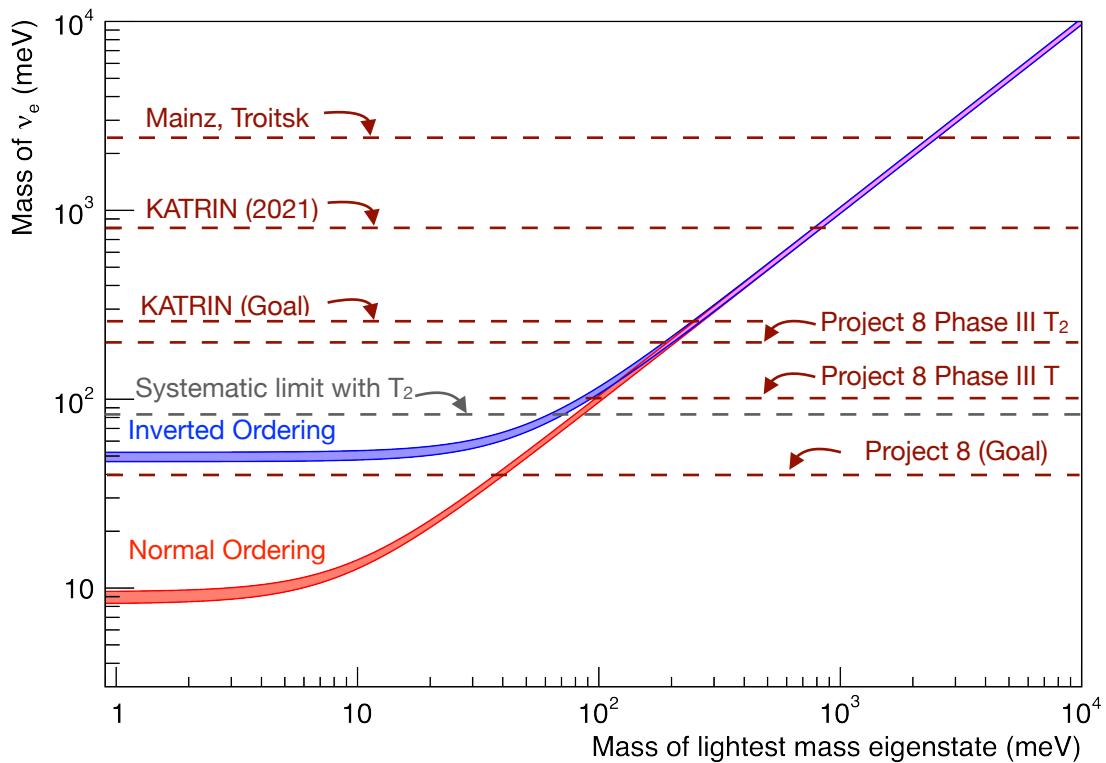
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Project 8 Goal

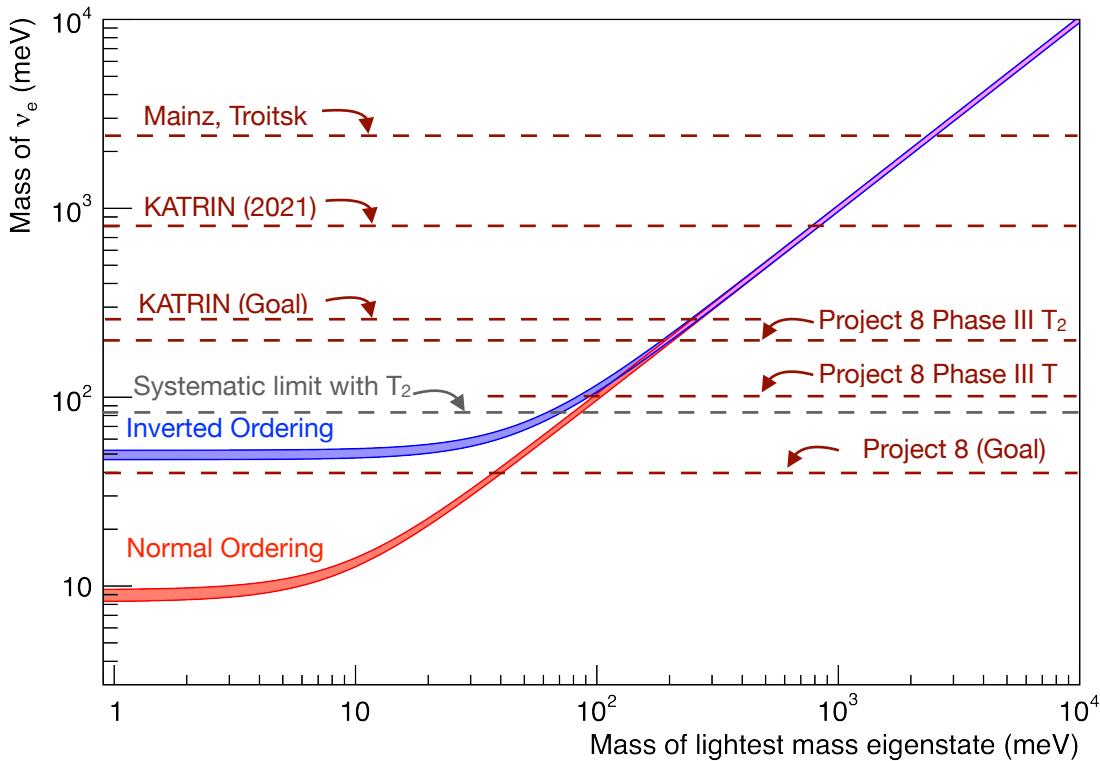


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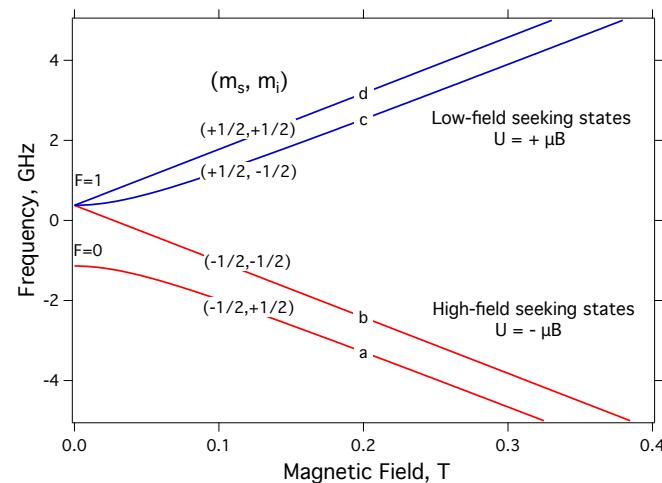
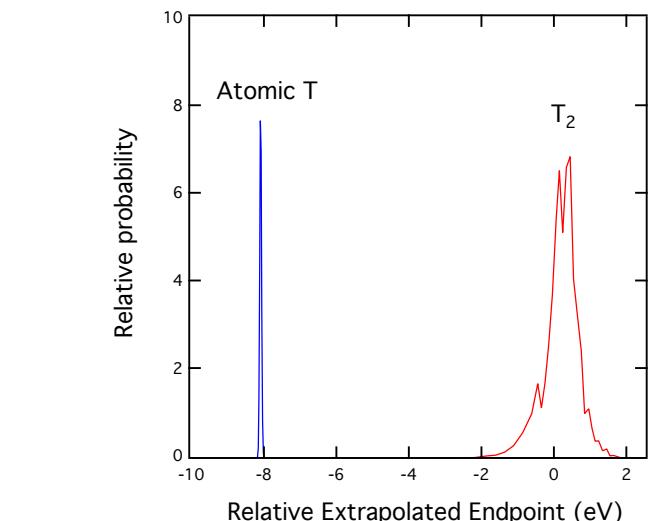


Credit: R. G. H. Robertson

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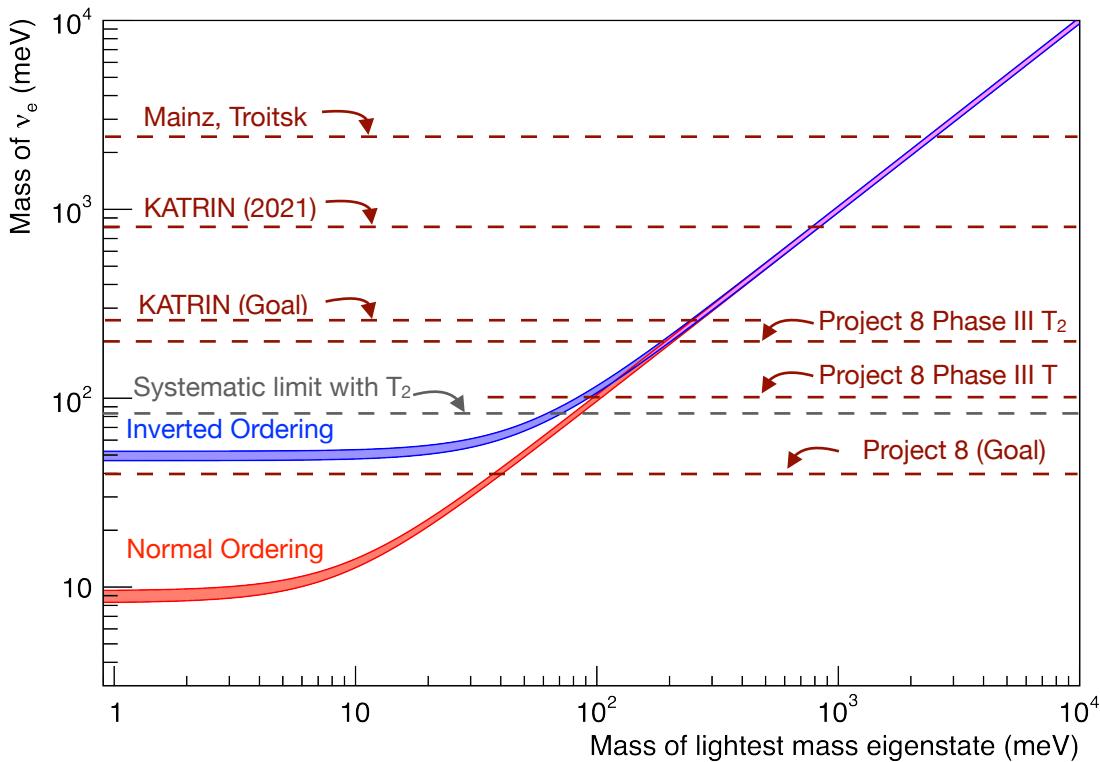


- Need atomic tritium for <100 meV sensitivity
- HFS: can trap atomic tritium magnetically



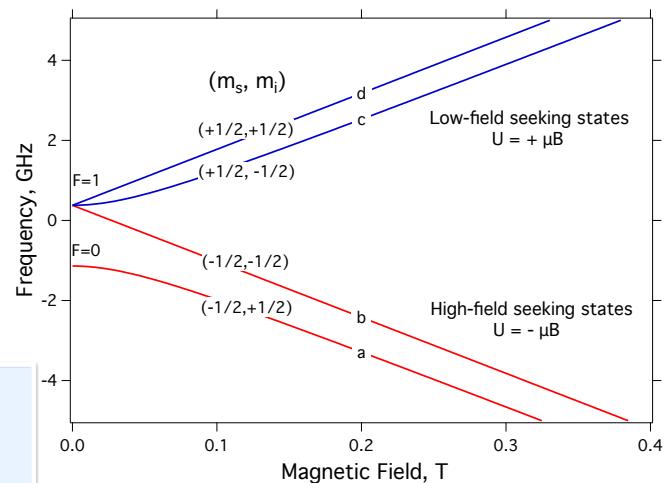
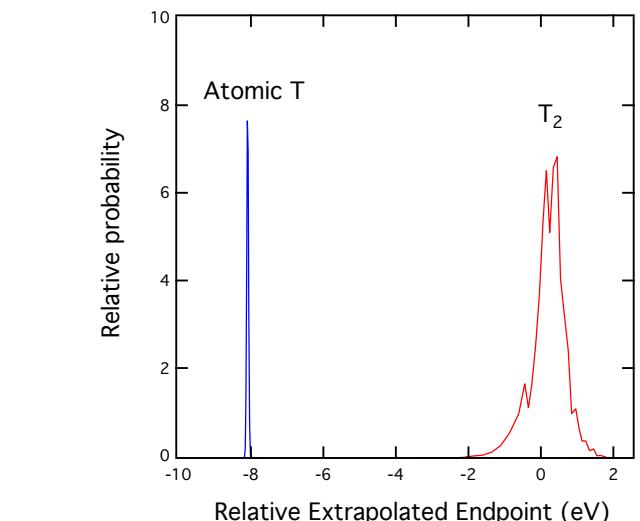
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Project 8 Goal



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Atomic Source Development:
L. Thorne, 30.08.



Credit: R. G. H. Robertson

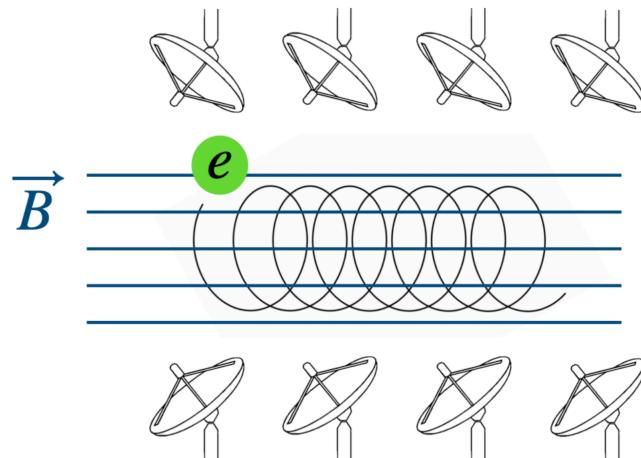
- Cyclotron Radiation Emission Spectroscopy
- Electron in B-field: cyclotron motion & radiation:

$$2\pi f = \frac{e\langle B \rangle}{m_e + K_e/c^2} = \frac{e\langle B \rangle}{\gamma m_e}$$

- Energy resolution:

$$\frac{\Delta E}{m_e} = \frac{\Delta f}{f}$$

“Never measure anything but frequency!” — A. L. Schawlow



Project 8: Phased Approach

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- Phase I:
 - First electron spectroscopy with CRES ¹

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- ✓ • Phase II:
 - First continuous spectrum measured with CRES ²
 - First m_β upper limit with CRES ² ← N. Oblath (tomorrow)

¹ Phys.Rev.Lett. 114 (2015) 162501

² Phys.Rev.Lett. (accepted, 2023)

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- Phase III:

- Atomic source development

- **Large-volume CRES**

← L. Thorne (tomorrow)

Sensitivity:
 $m_\beta < 100 \text{ meV}$ (90 % C. L.)



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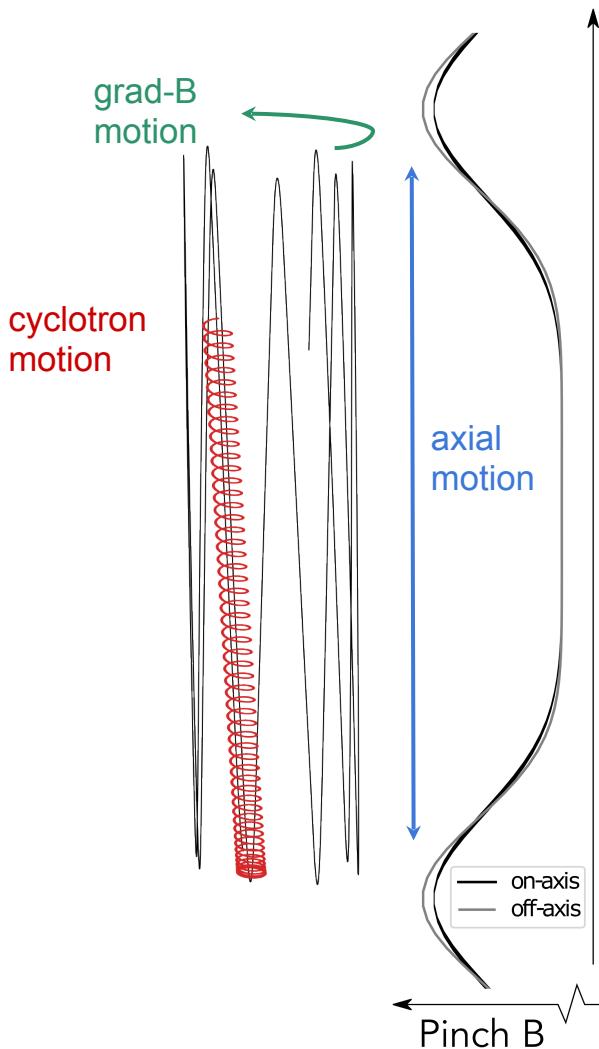
- Neutrino mass measurement if $m_\beta \geq 40 \text{ meV}$



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CRES Electron Motion



- Electron trapped in magnetic field
- Three superimposed motions:
 - Cyclotron motion with frequency

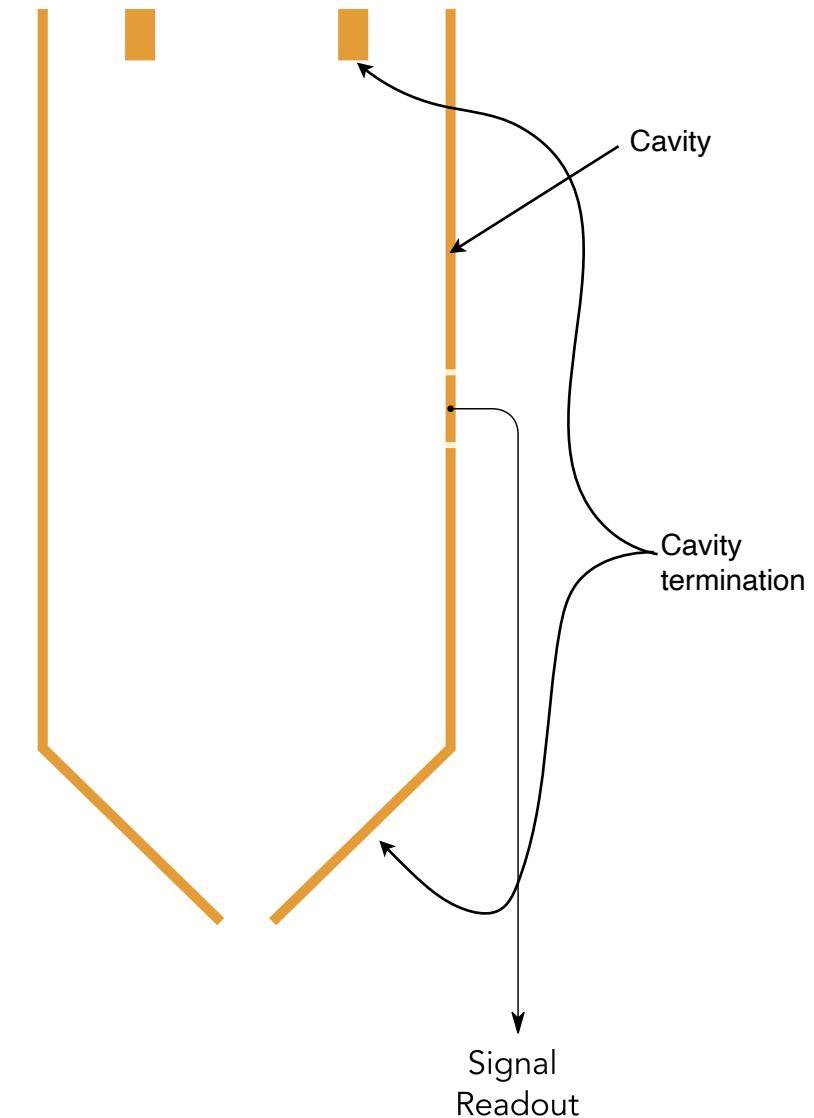
$$f_c = \frac{1}{2\pi} \frac{e\langle B \rangle}{m_e + E/c^2}$$

average magnetic field
along electron trajectory

- Axial motion with frequency f_a that depends on trap design and electron's pitch angle
- Grad-B motion $f_{\nabla B}$ from magnetic trapping field gradient

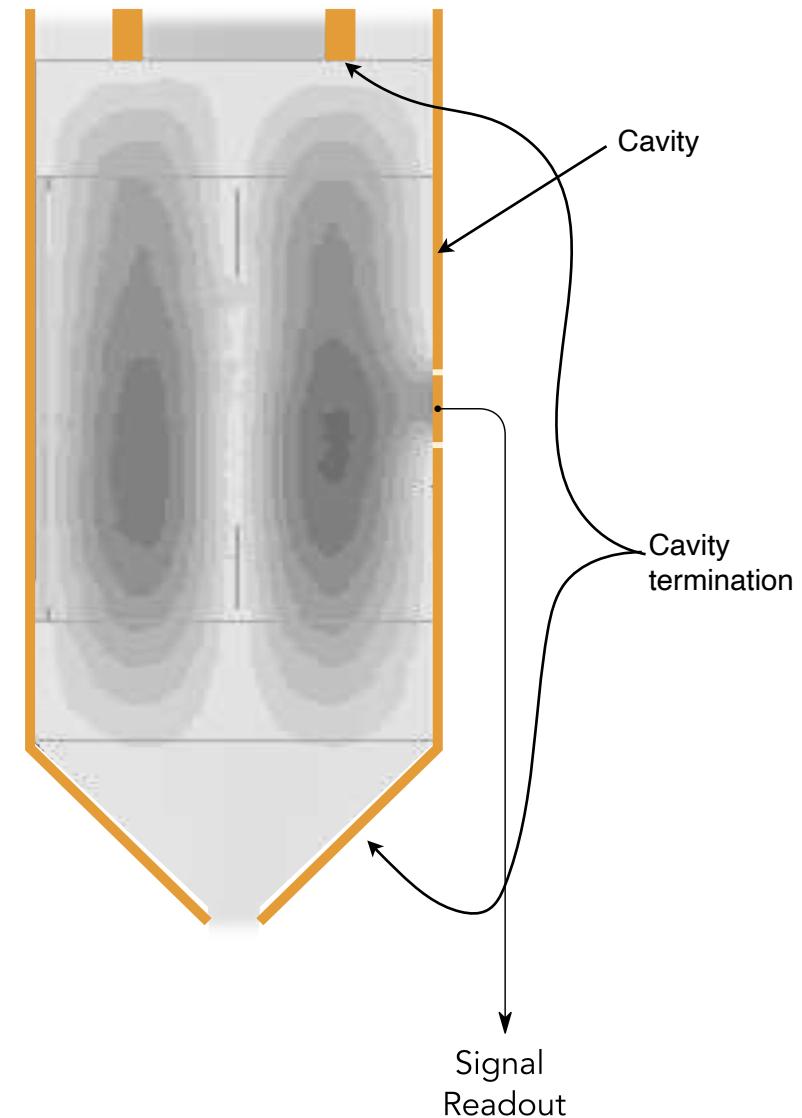
A Cavity-Based CRES Experiment

- Cavity: open-ended, specific mode structure
- Cavity coupling: appropriate loaded Q



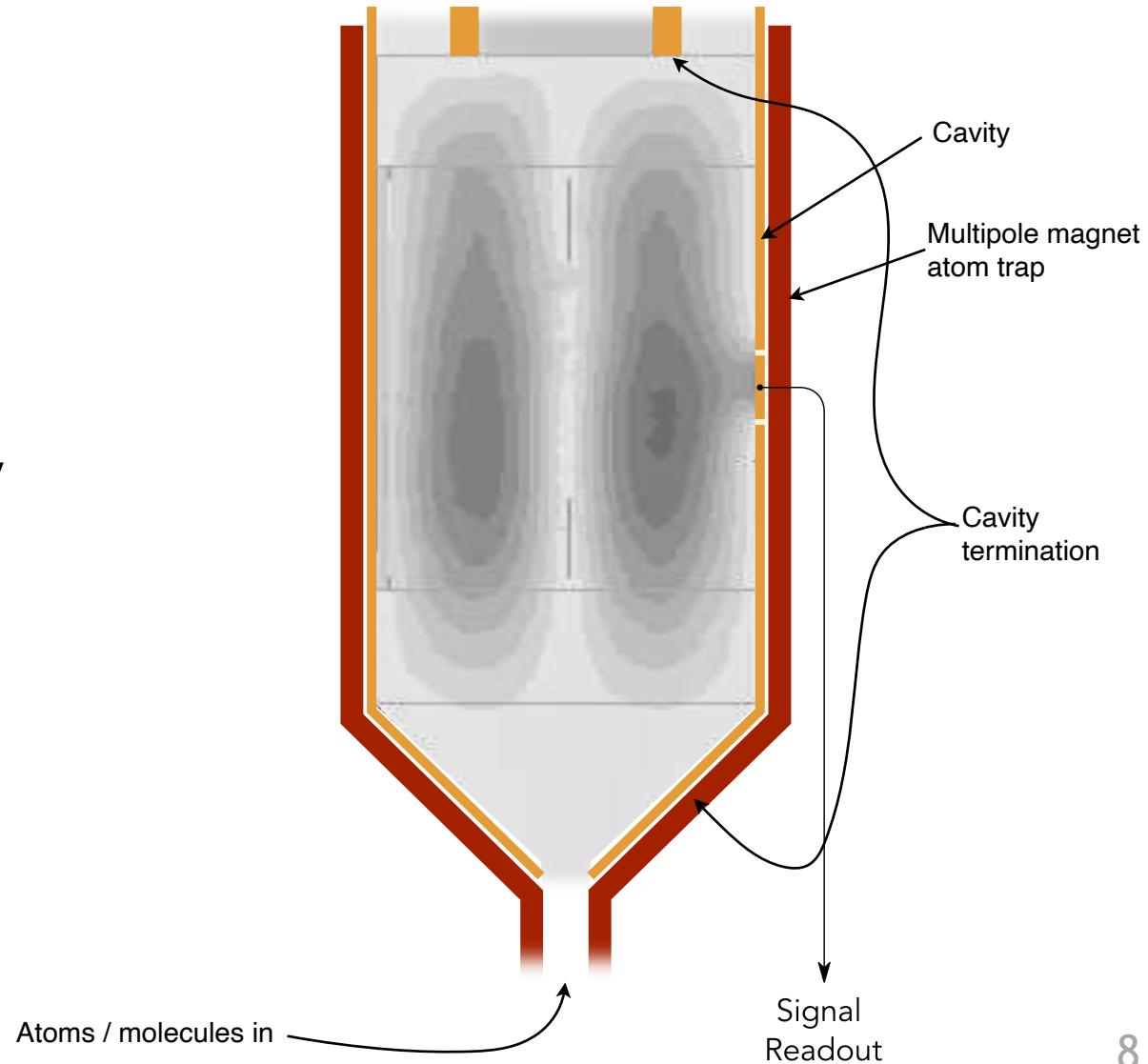
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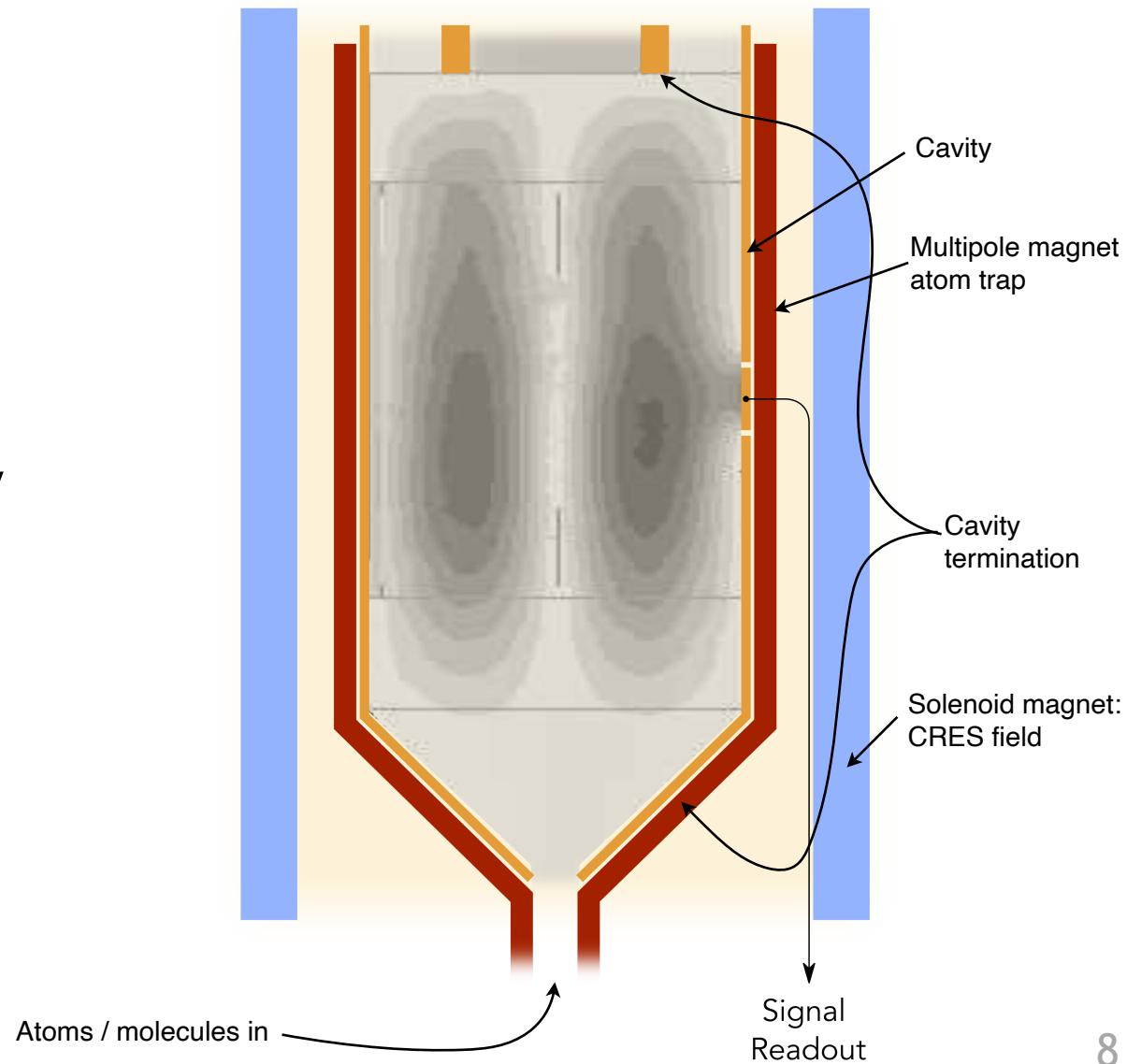
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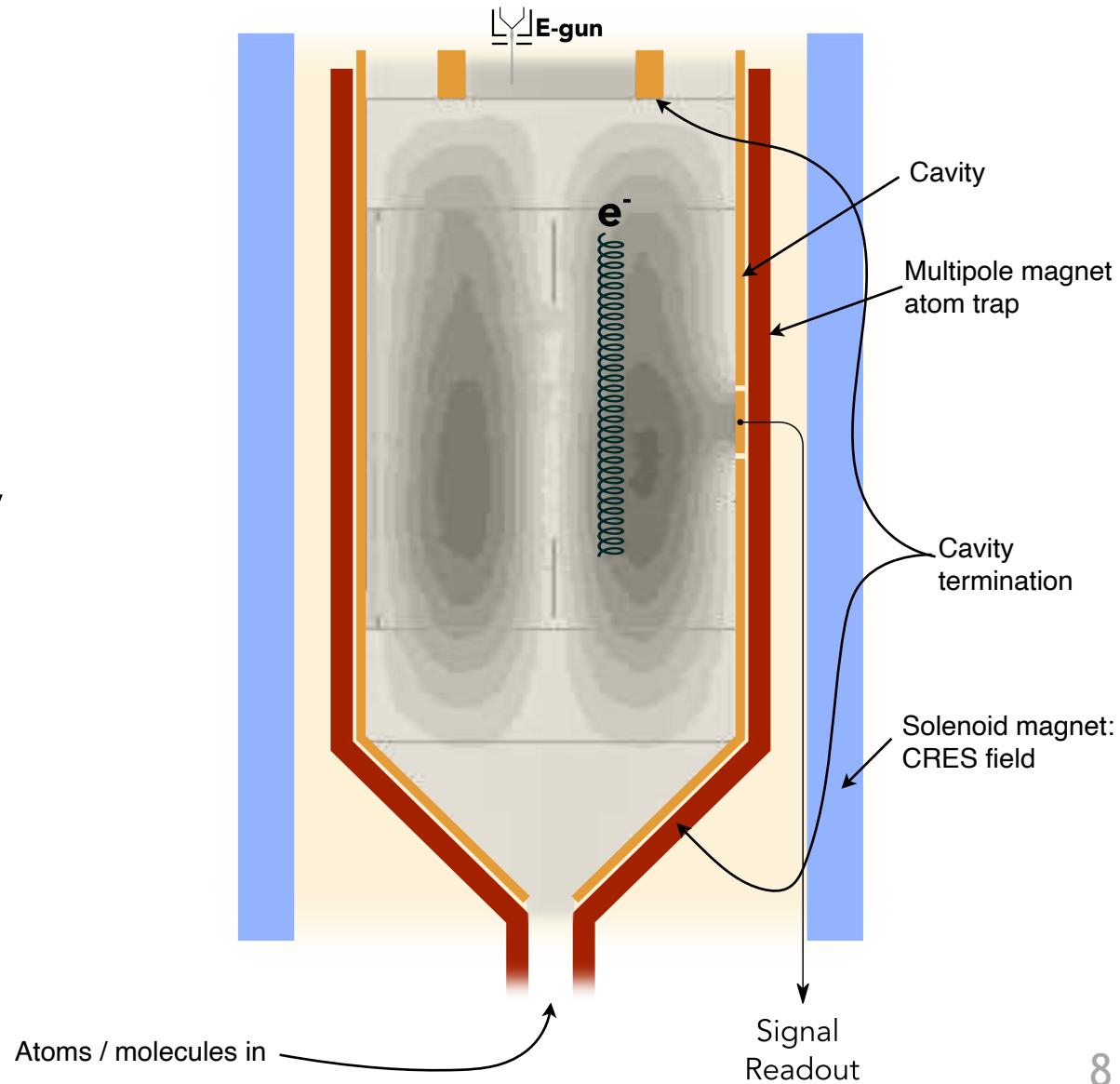
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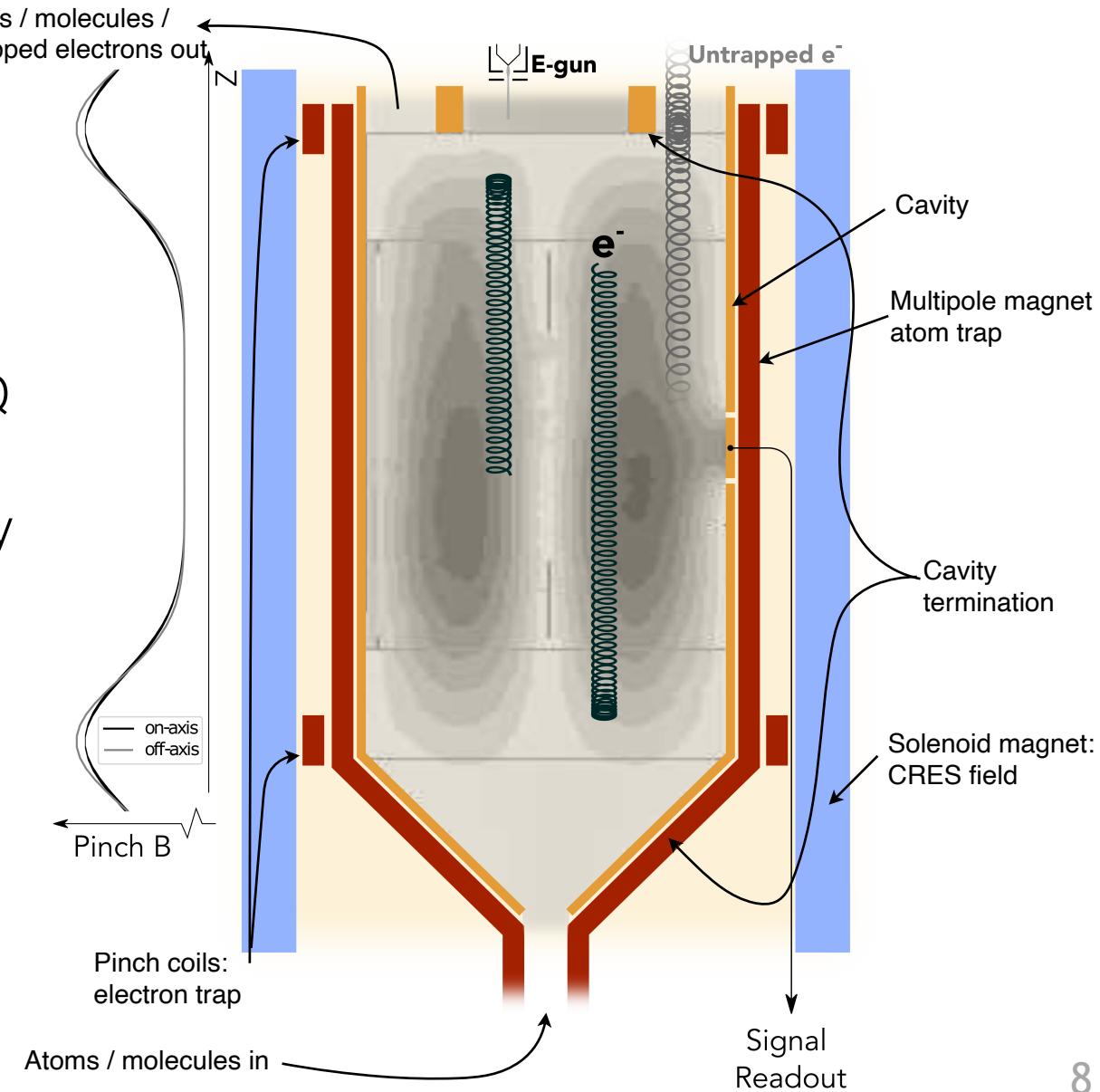
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- Solenoid to provide CRES field
- Pinch coils provide electron trapping



Cylindrical Cavities

- Transverse electric (TE) & transverse magnetic (TM) modes, TE_{mnp} and TM_{mnp} with frequencies

$$f_{\text{TE},mnp} = \frac{c}{2\pi} \sqrt{\left(\frac{X'_{mn}}{R}\right)^2 + \left(\frac{p\pi}{L}\right)^2}, \quad \begin{matrix} \text{Cavity length } L \\ \text{Cavity radius } R \end{matrix}$$

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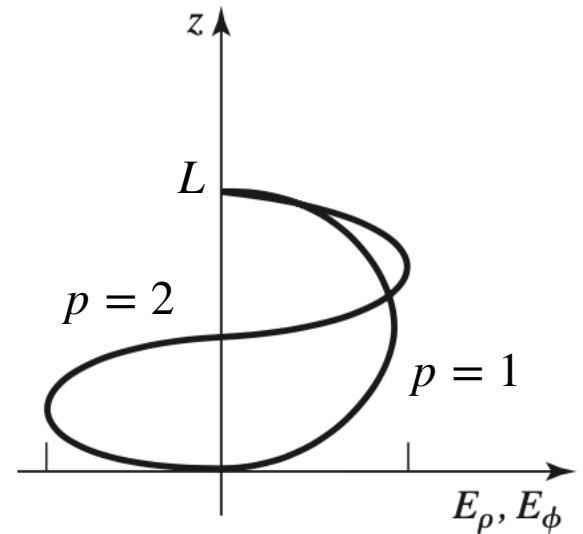
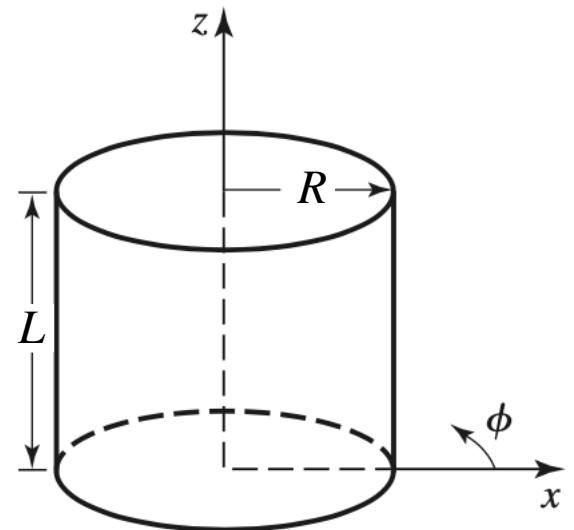
X_{mn} : n -th zero of m -th Bessel function

X'_{nm} : n -th zero of derivative of m -th Bessel function

m = # of antinodes in ϕ direction

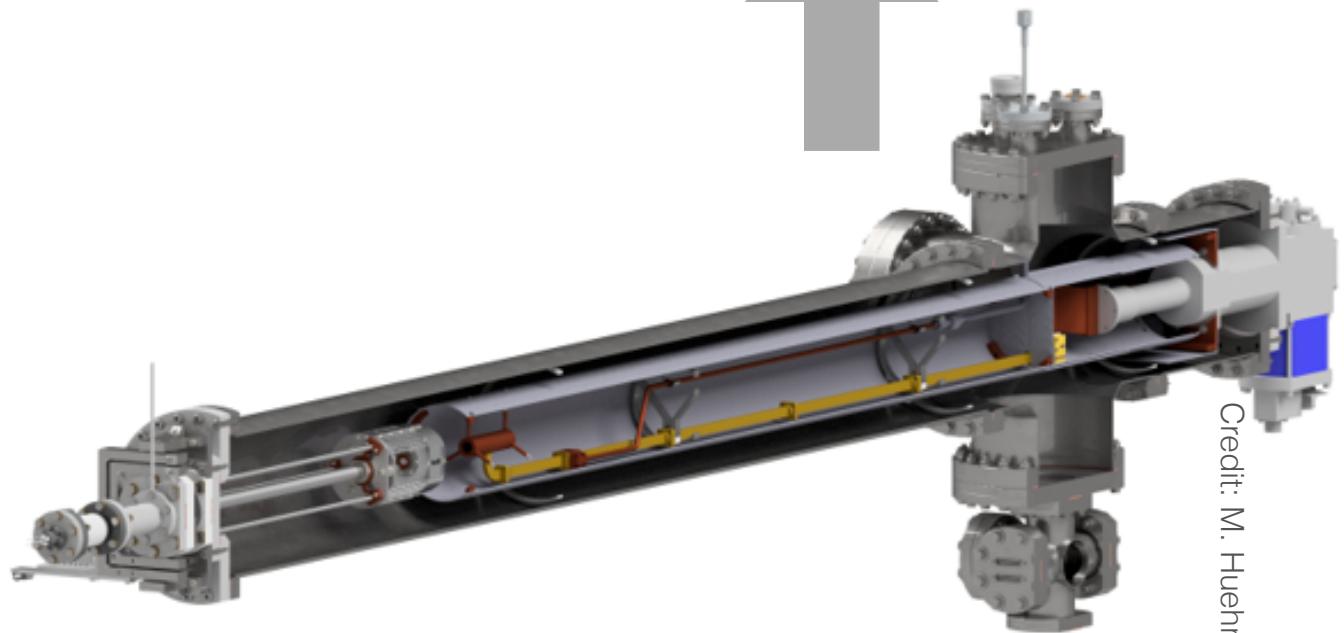
n = # of antinodes in ρ directions

p = # of antinodes in z direction



Cavity CRES Apparatus

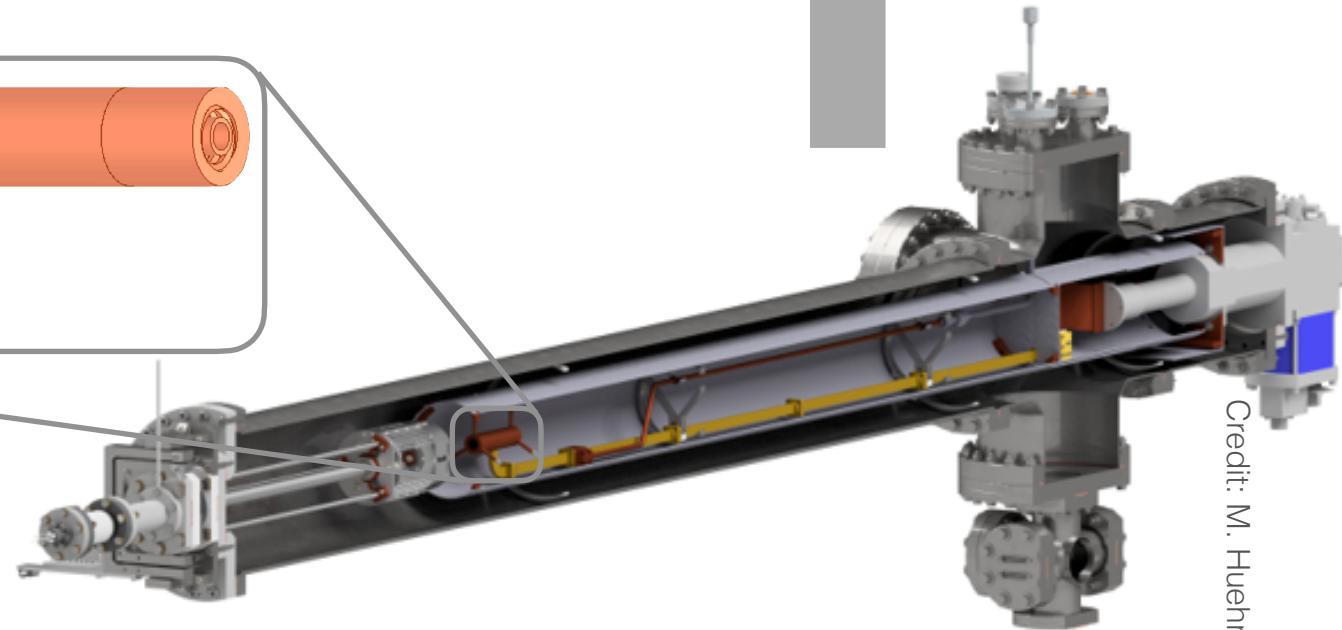
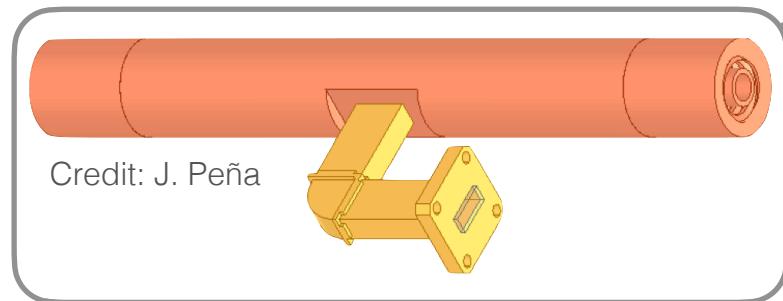
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 $L = 14 \text{ cm}$, $R = 0.7 \text{ cm}$, $V \sim 20 \text{ cm}^3$
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 - Same frequency as Phase II: can reuse RF setup, waveguide



Credit: M. Huehn

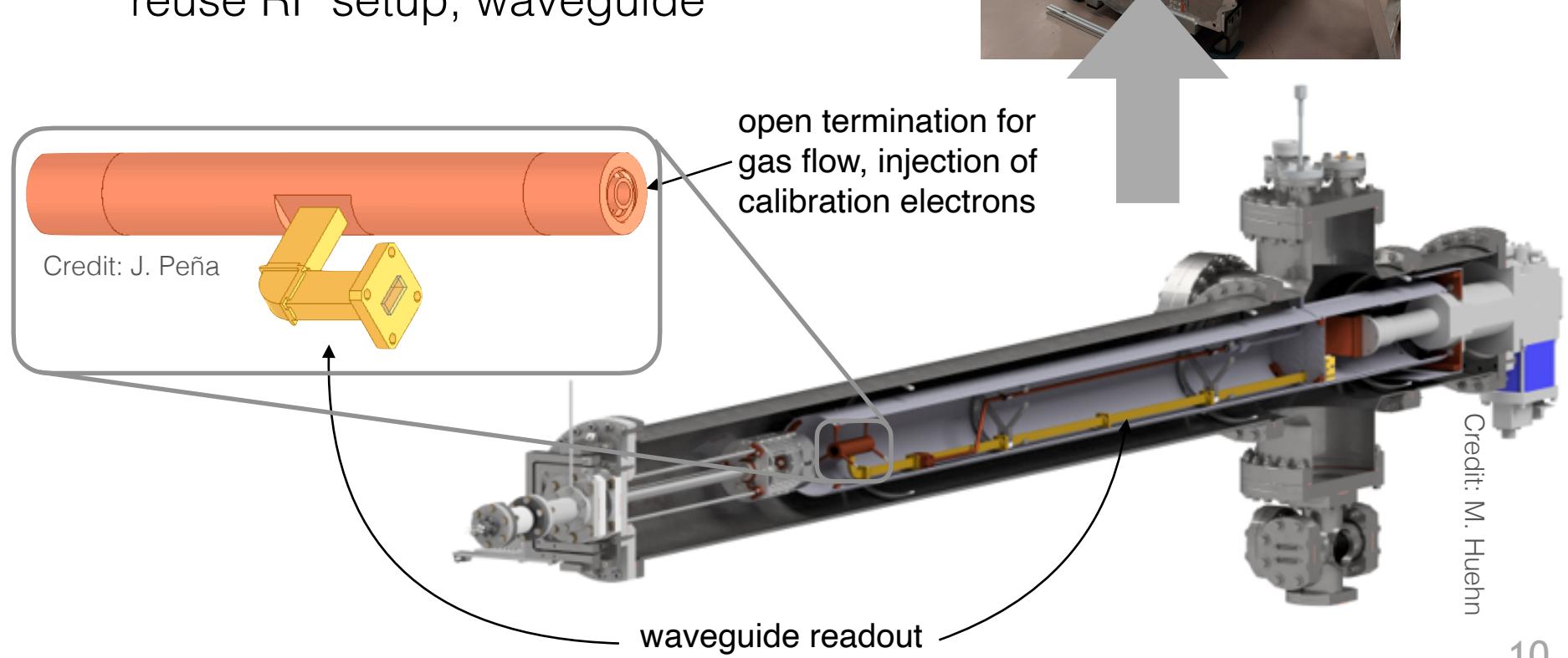
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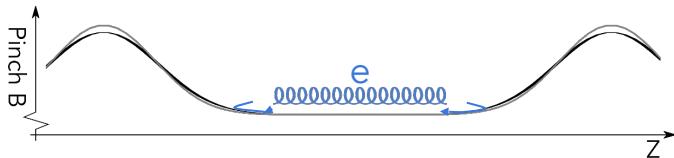
CCA Goals

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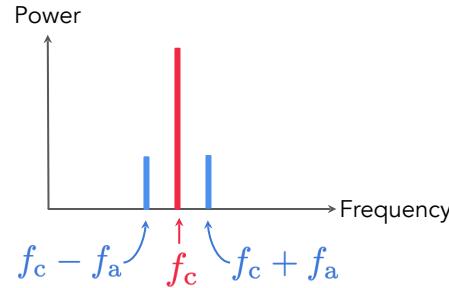
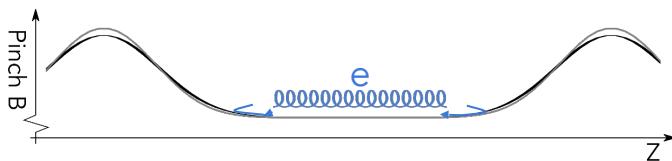
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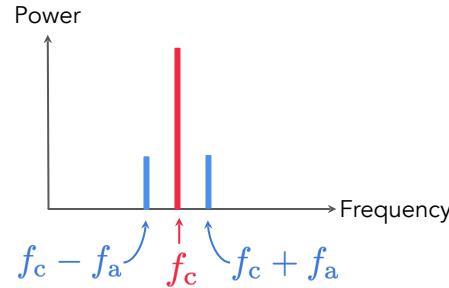
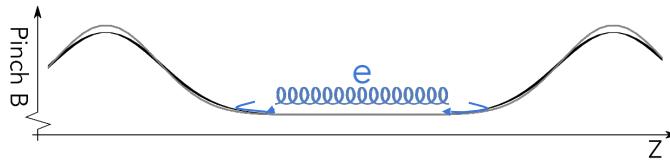
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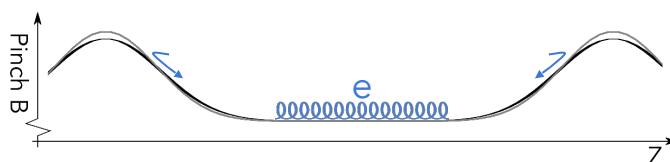
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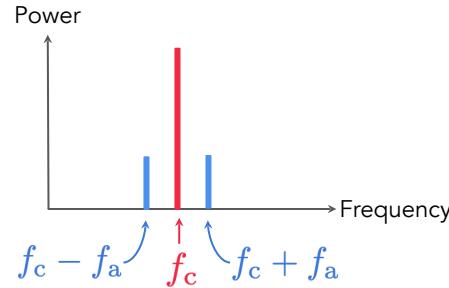
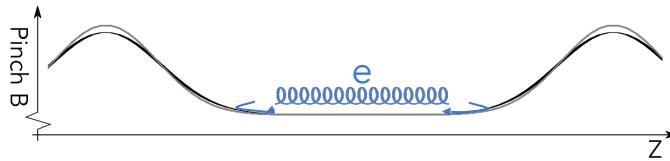
"Small" pitch angle, $\theta \rightarrow \theta_{\min}$:



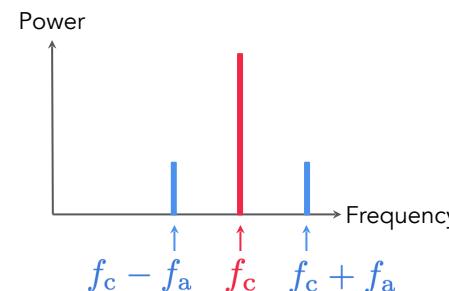
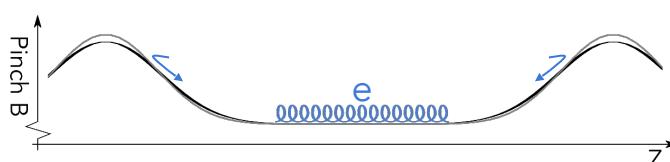
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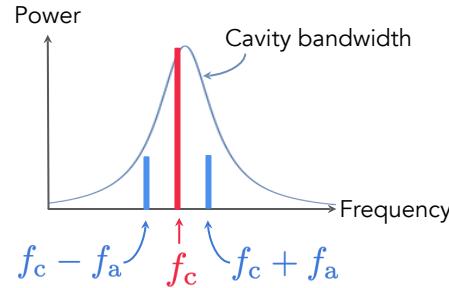
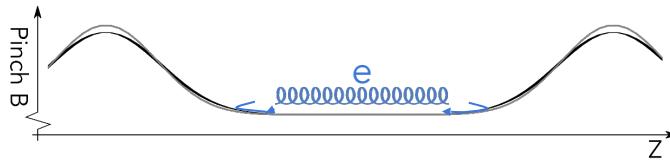
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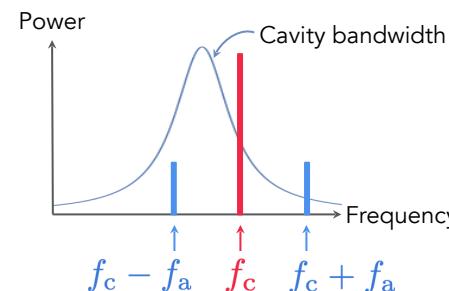
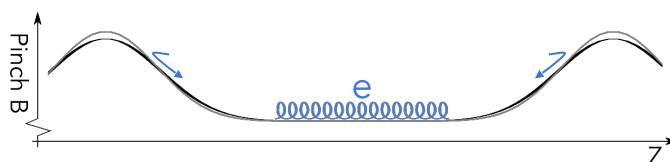
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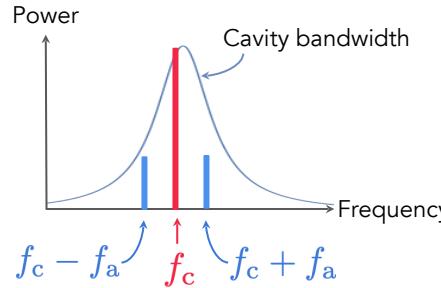
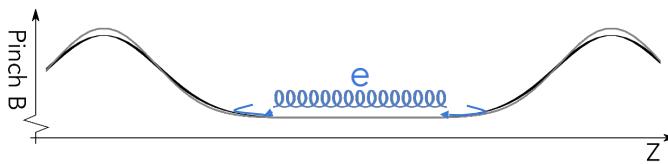
"Small" pitch angle, $\theta \rightarrow \theta_{\min}$:



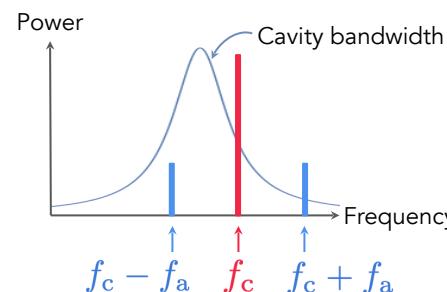
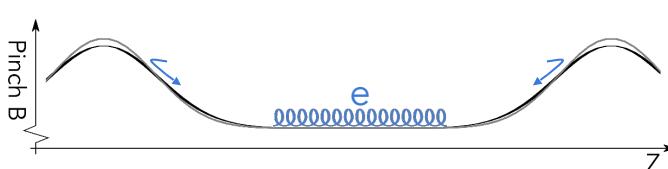
CCA Goals

- Verify CRES phenomenology in resonant cavity with high SNR
 - Simulation verification
 - Reconstruction with event-by-event magnetic field corrections
 - Verify higher volume & pitch angle efficiency
- Calibration development: electron gun
 - Main calibration device going forward
- High resolution of 0.3 eV in small volume
- Krypton line energy measurements

Large pitch angle, $\theta \approx 90^\circ$:



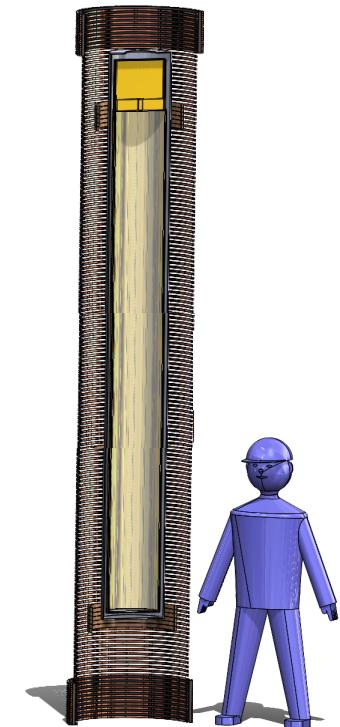
"Small" pitch angle, $\theta \rightarrow \theta_{\min}$:



- Sidebands due to axial motion
- Axial motion leads to variation in magnetic field along electron track
- Larger average magnetic field and higher carrier frequency
- Sideband detection for magnetic field correction

Low Frequency Apparatus

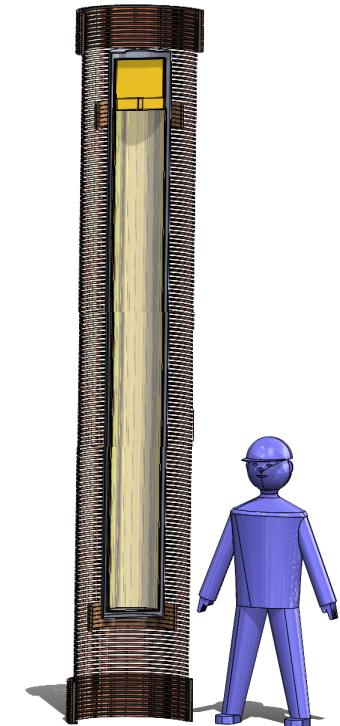
- Goal: Prove feasibility of CRES in large volumes $V \approx 0.3 \text{ m}^3$, low fields $B \approx 0.035 \text{ T}$, and frequencies $f_c \approx 1 \text{ GHz}$
 - $P \propto V^{-1} f^{-1} \propto f^2$ for cavities
 - Collected power is $\mathcal{O}(\text{aW})$ ($1 \text{ aW} = 10^{-18} \text{ W}$)



Credit: A. Telles

Low Frequency Apparatus

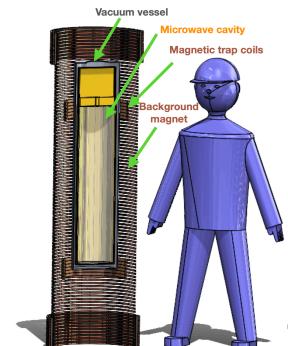
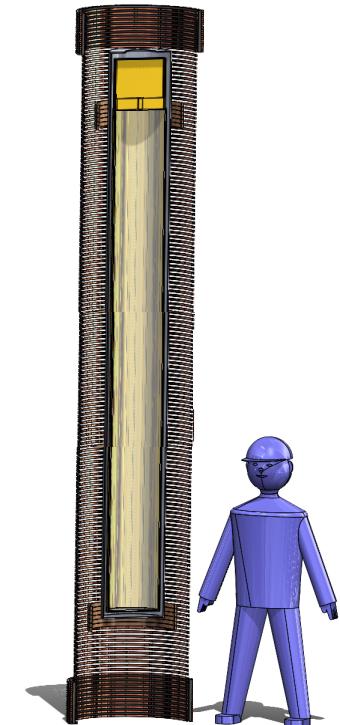
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- Custom-designed high-uniformity magnet



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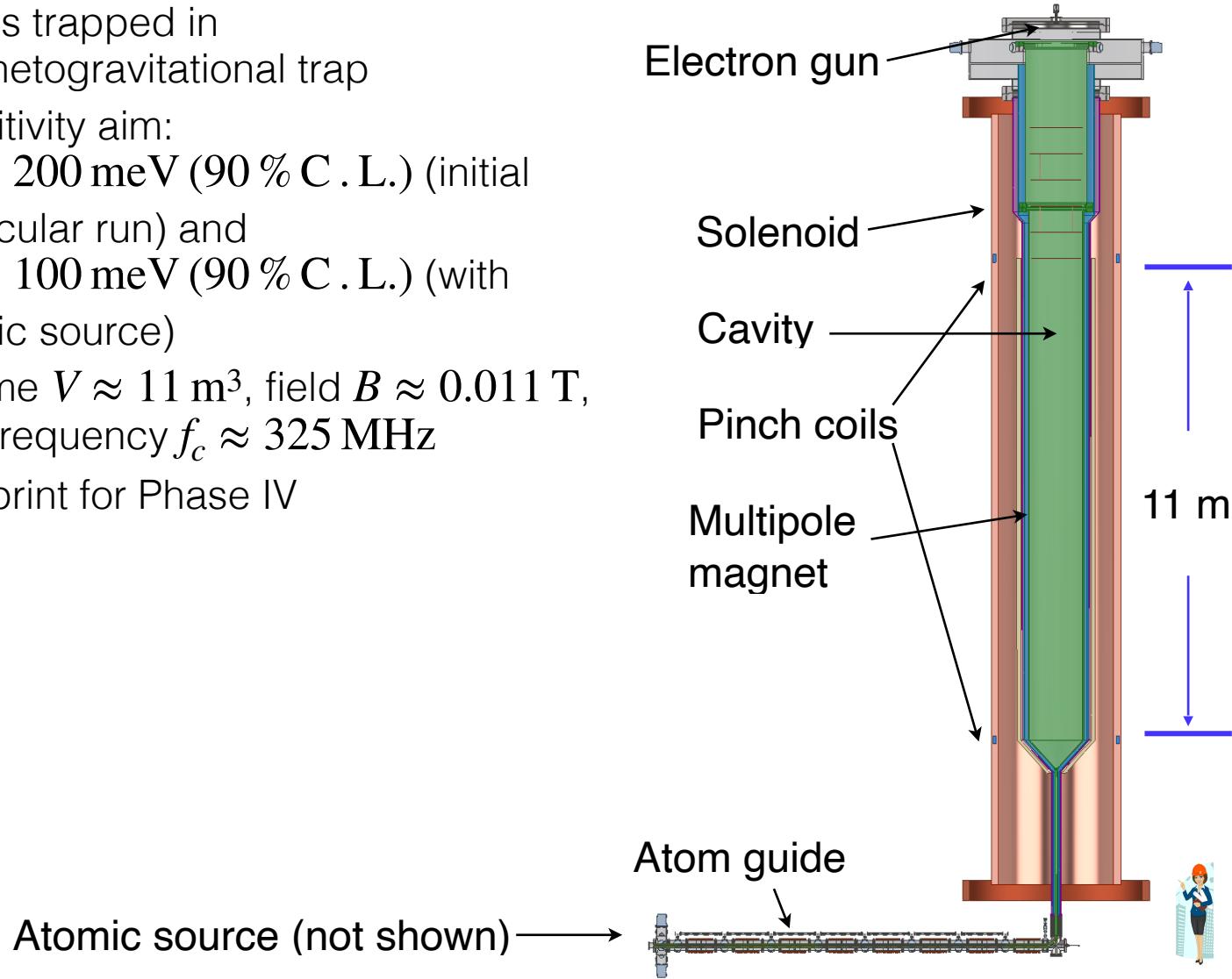
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 - Collected power is $\mathcal{O}(\text{aW})$ ($1 \text{ aW} = 10^{-18} \text{ W}$)
- Custom-designed high-uniformity magnet
- First low-field prototype LUCKEY at 1.5 GHz , optimized for maximum power (lower volume $V \approx 0.025 \text{ m}^3$)
 - Low field CRES detection
 - First work on custom magnet design



Cavity-based Phase III

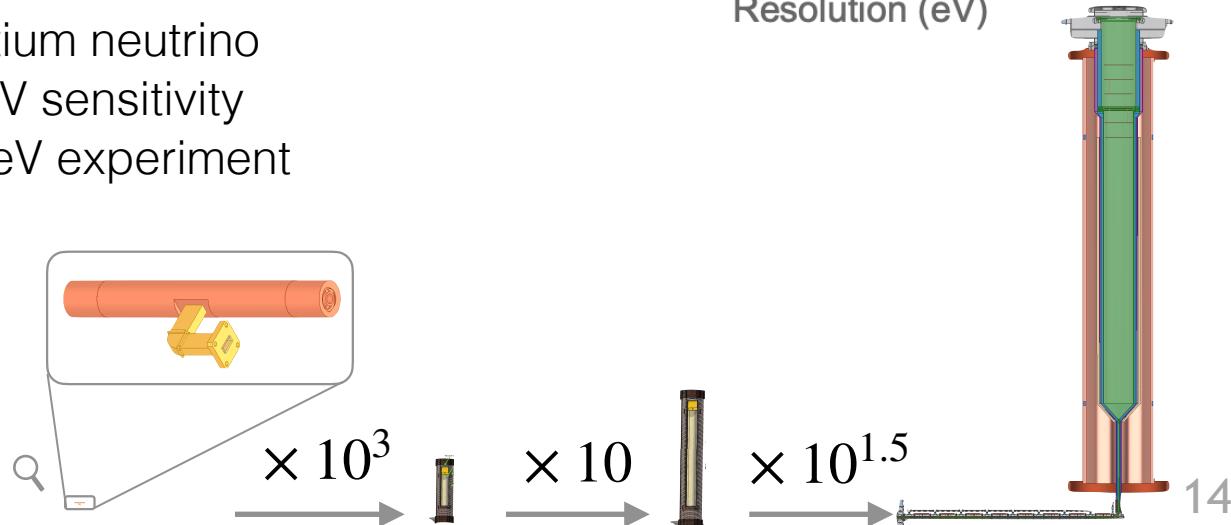
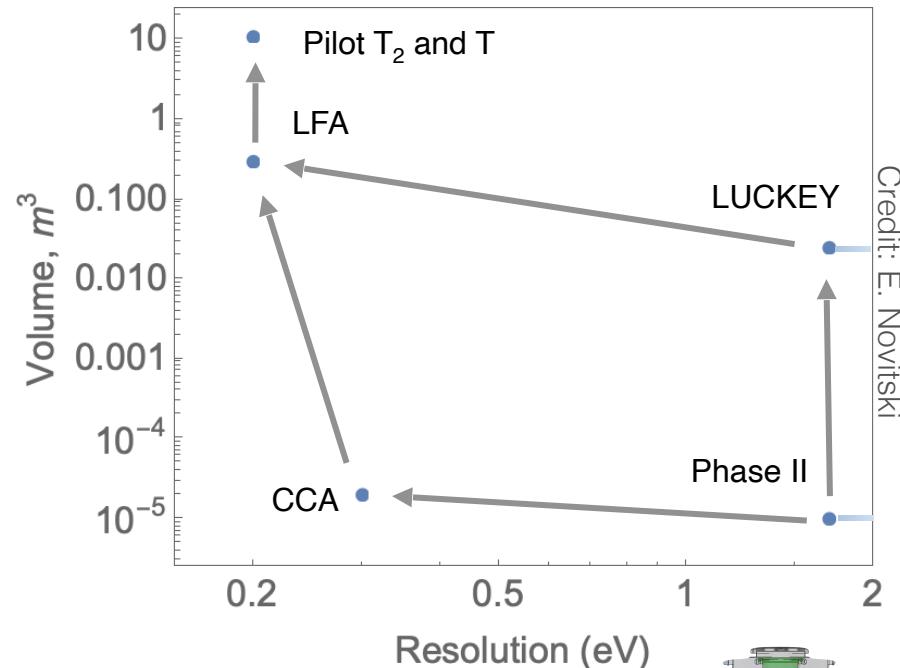
- Atoms trapped in magnetogravitational trap
- Sensitivity aim:
 $m_\beta < 200 \text{ meV}$ (90 % C . L.) (initial molecular run) and
 $m_\beta < 100 \text{ meV}$ (90 % C . L.) (with atomic source)
- Volume $V \approx 11 \text{ m}^3$, field $B \approx 0.011 \text{ T}$, and frequency $f_c \approx 325 \text{ MHz}$
- Blueprint for Phase IV



Credit: R. G. H. Robertson

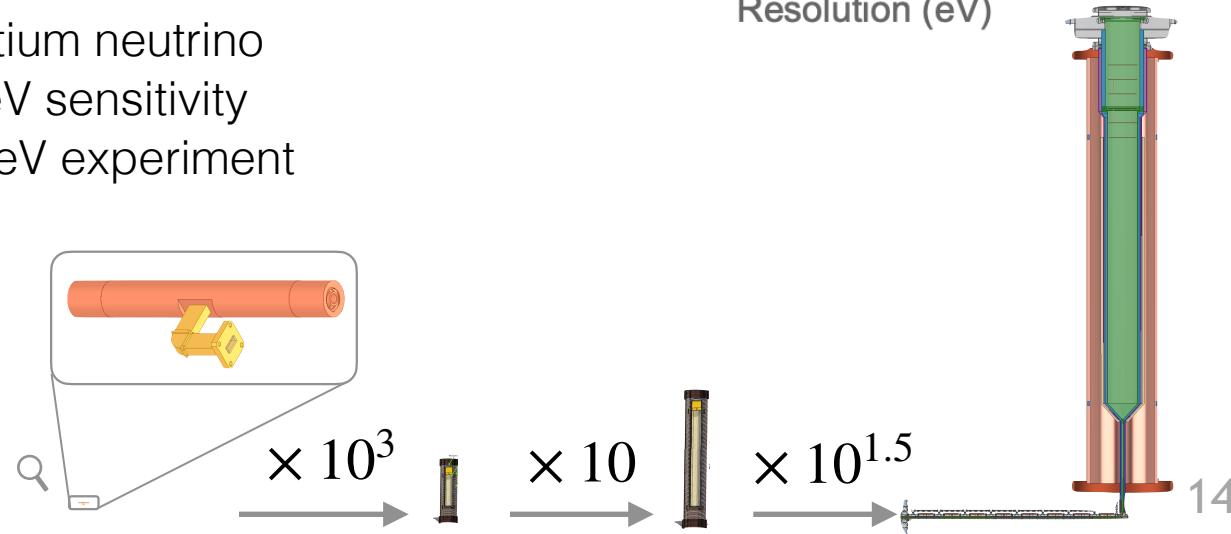
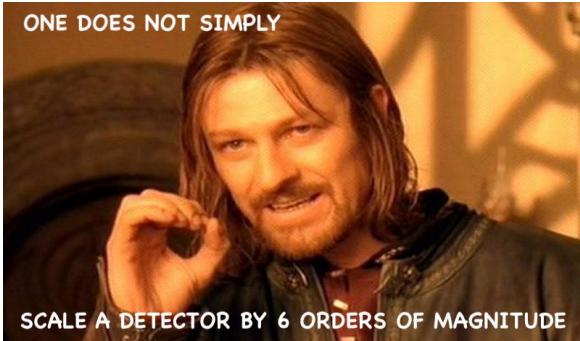
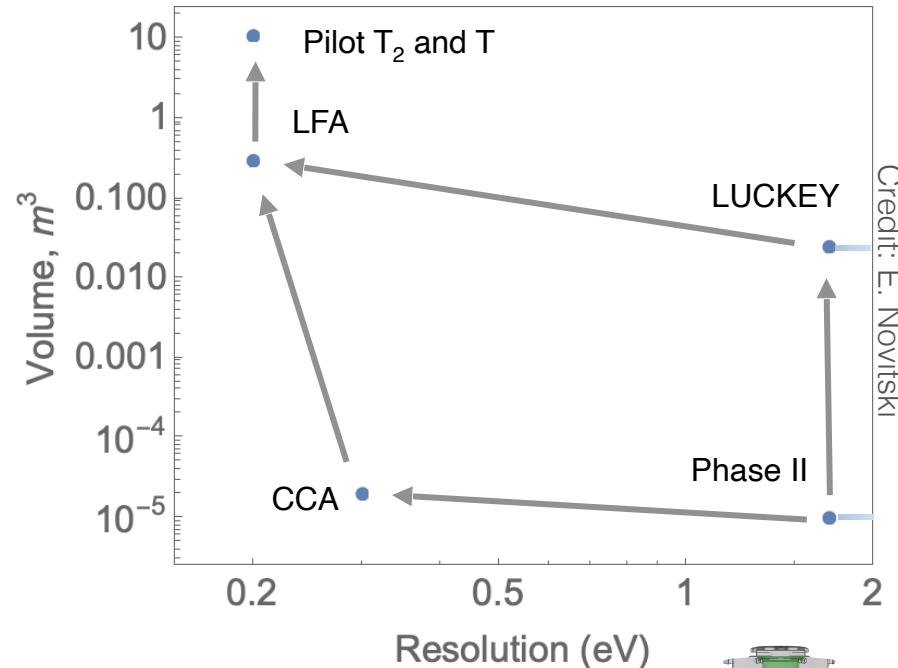
Project 8 CRES Development

- Resonant cavities provide an attractive way of scaling Project 8 to large volumes
 - High volume efficiency
 - High pitch angle efficiency
- Set of demonstrators:
 - High resolution (CCA)
 - Large volume (LUCKEY)
 - High resolution and large volume (LFA)
- Phase III: First atomic tritium neutrino mass extraction: 100 meV sensitivity
→ blueprint for full 40 meV experiment



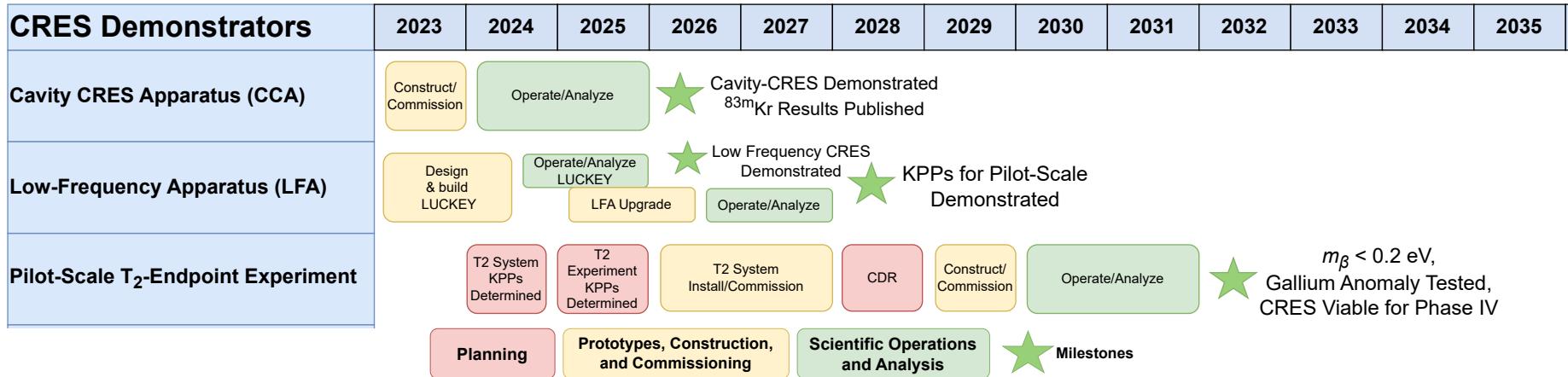
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Timeline



- CRES characterization in cavity and Krypton line measurements
- Characterization of electron gun as calibration tool
- Low-frequency CRES demonstration
- Neutrino mass measurement with 0.2 eV sensitivity using molecular tritium