Cyclotron Radiation Signal Characterization and Noise Modeling in Resonant Cavities for Project 8

PROJECT 8

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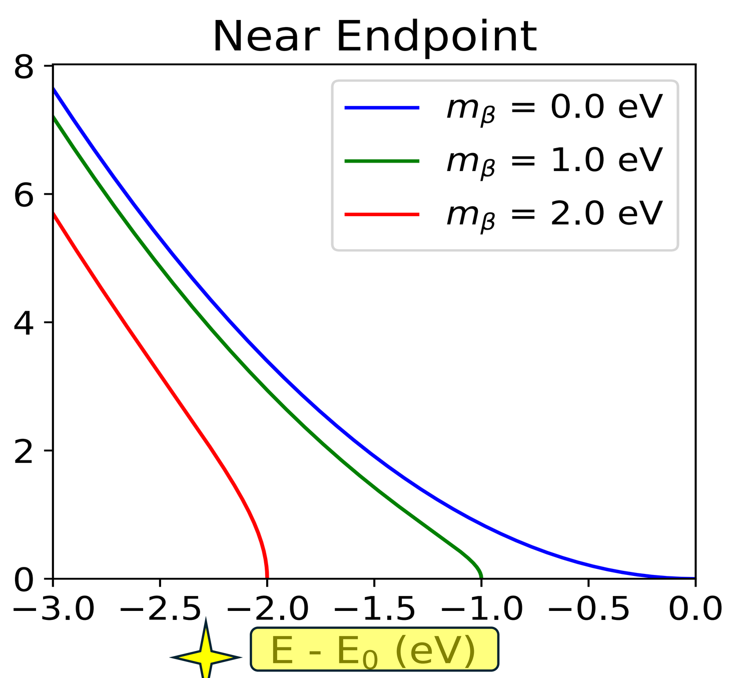
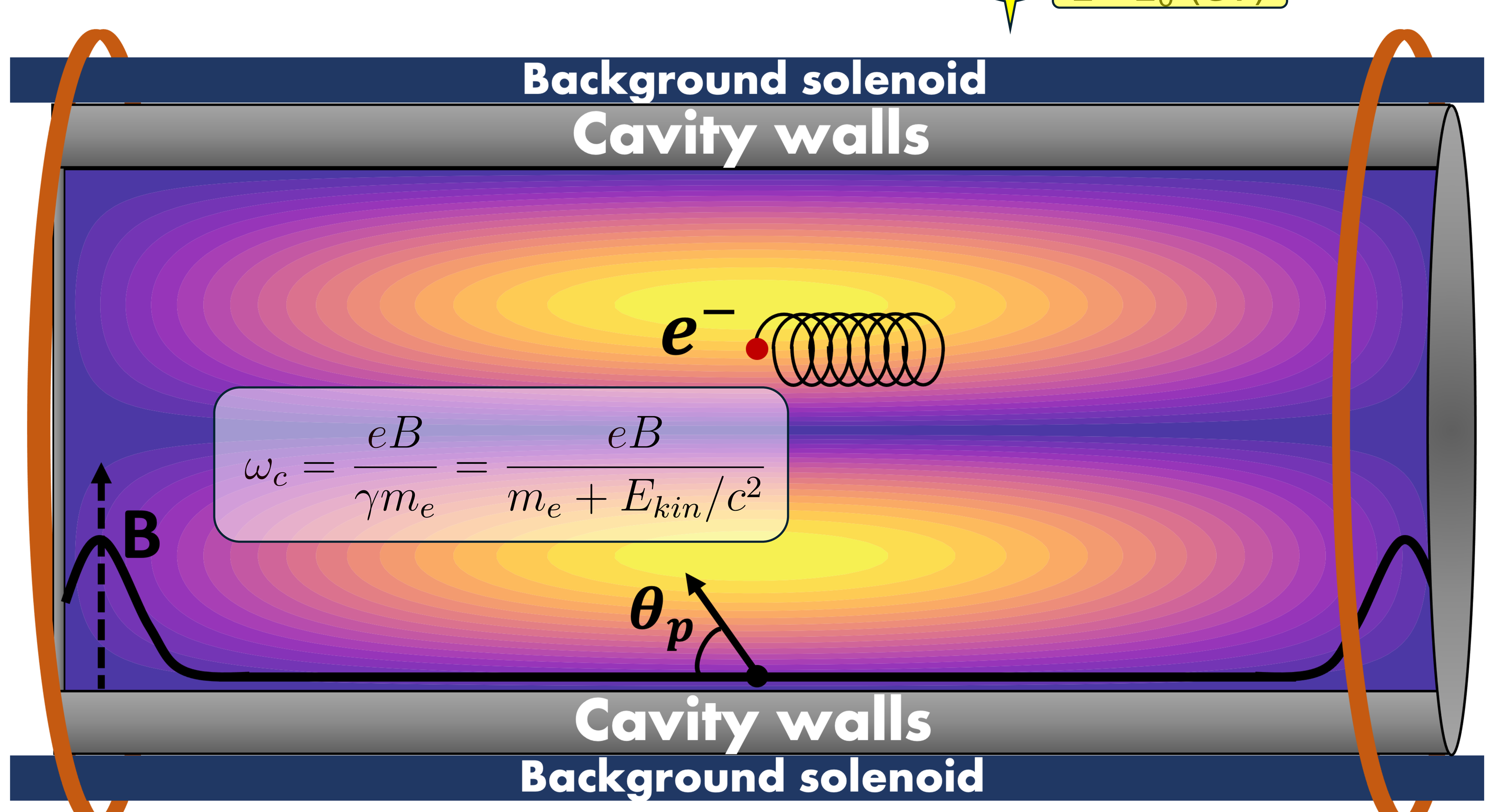
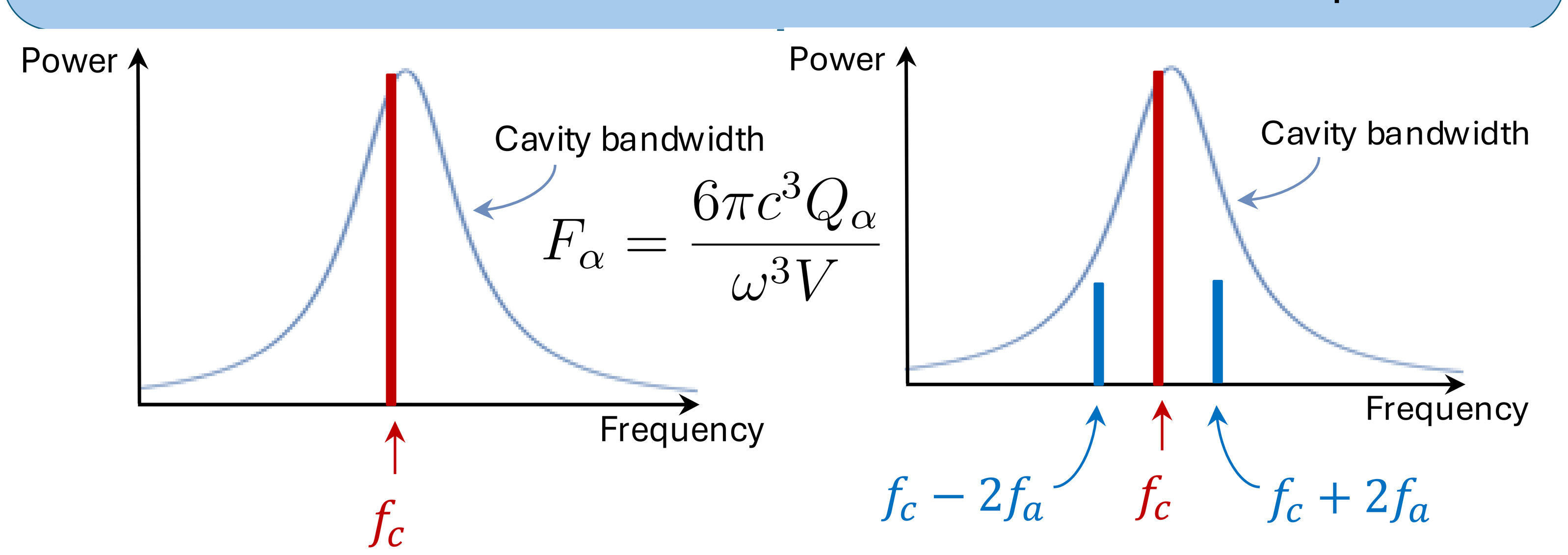
Project 8 and Cyclotron Radiation Emission Spectroscopy (CRES)

- Measuring the neutrino mass with the β-decay endpoint technique
- CRES: β-decay electrons in a magnetic trap undergo cyclotron motion, emitting EM waves at their relativistic cyclotron frequencies





- CRES with microwave cavities improves SNR and simplifies signal readout
- The electron's CRES signal is resonantly enhanced in the cavity while its motion leads to distinct features at various frequencies

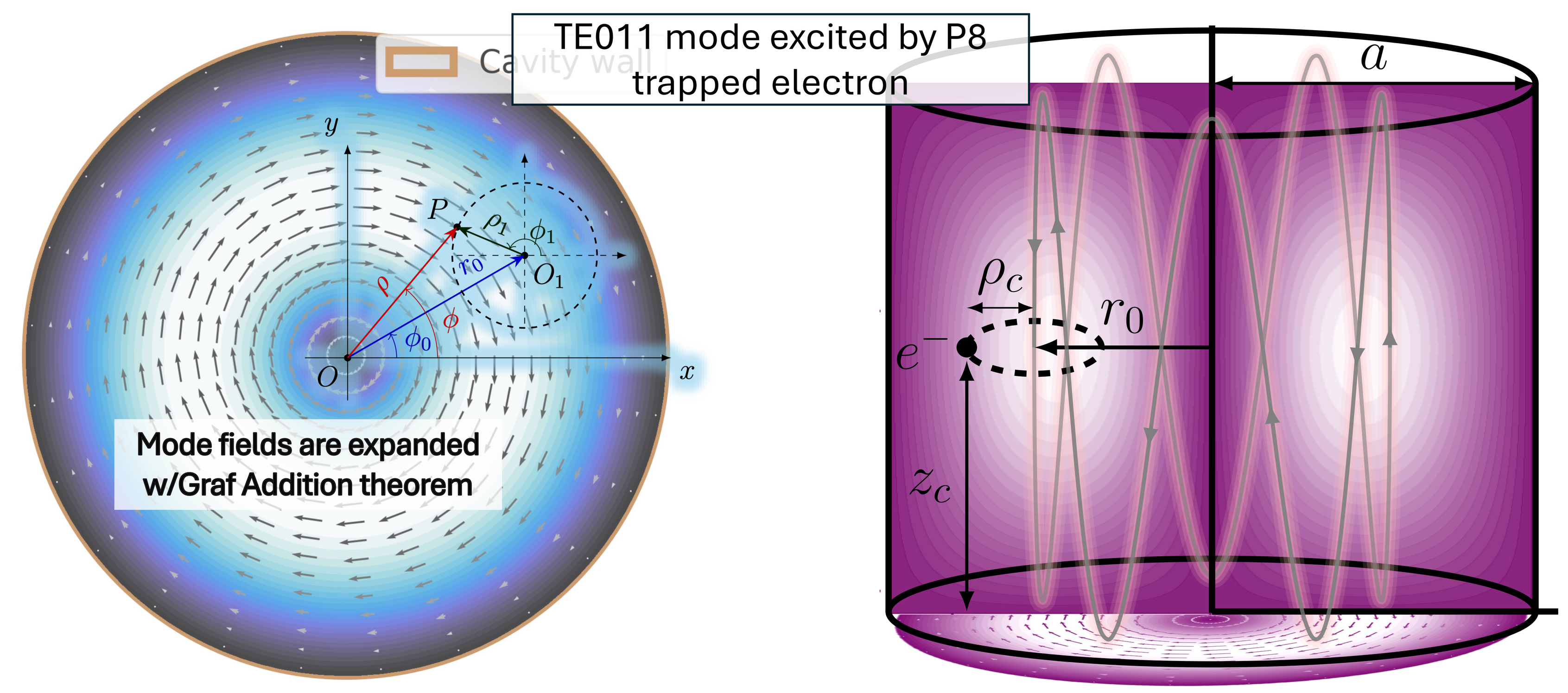


- We need predictions of the electron's radiation fingerprint in the cavity to reconstruct its energy in the β-decay endpoint
- Axial motion within the trap siphons off the cyclotron radiation into sidebands

Detector Signal Characterization: Spontaneous enhancement and inhibition of cyclotron radiation

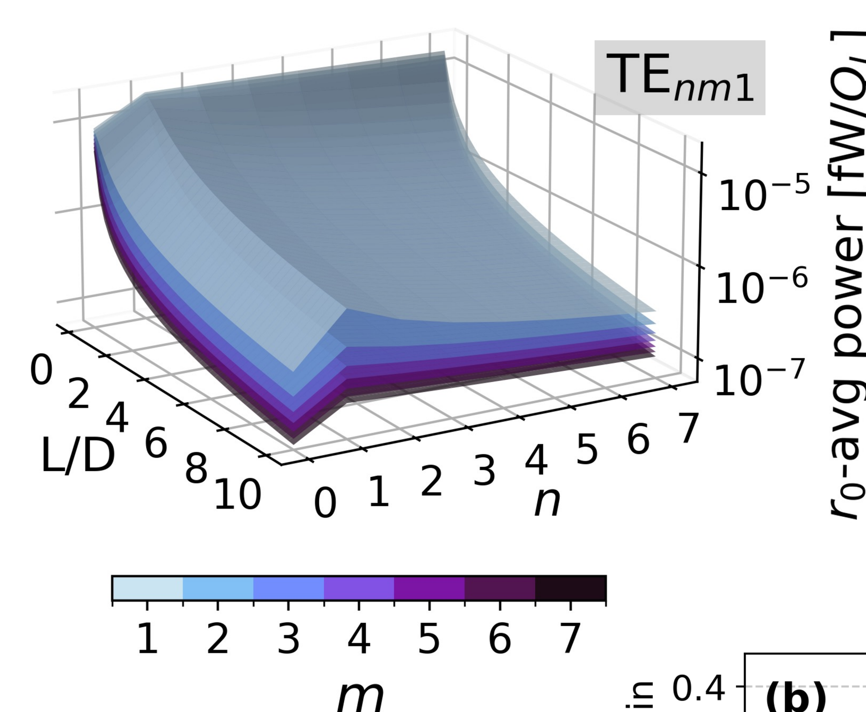
- The electron's cyclotron and axial motion within the cavity can be decomposed in Fourier space as well as the cavity modes:

$$j_\alpha^M(\omega) = -e\mathcal{F}\left\{\int_V \delta(\mathbf{r} - \mathbf{r}_c(t))\,\mathbf{v}_c(t)\cdot\mathbf{E}_\alpha^M(\mathbf{r})dV\right\}$$



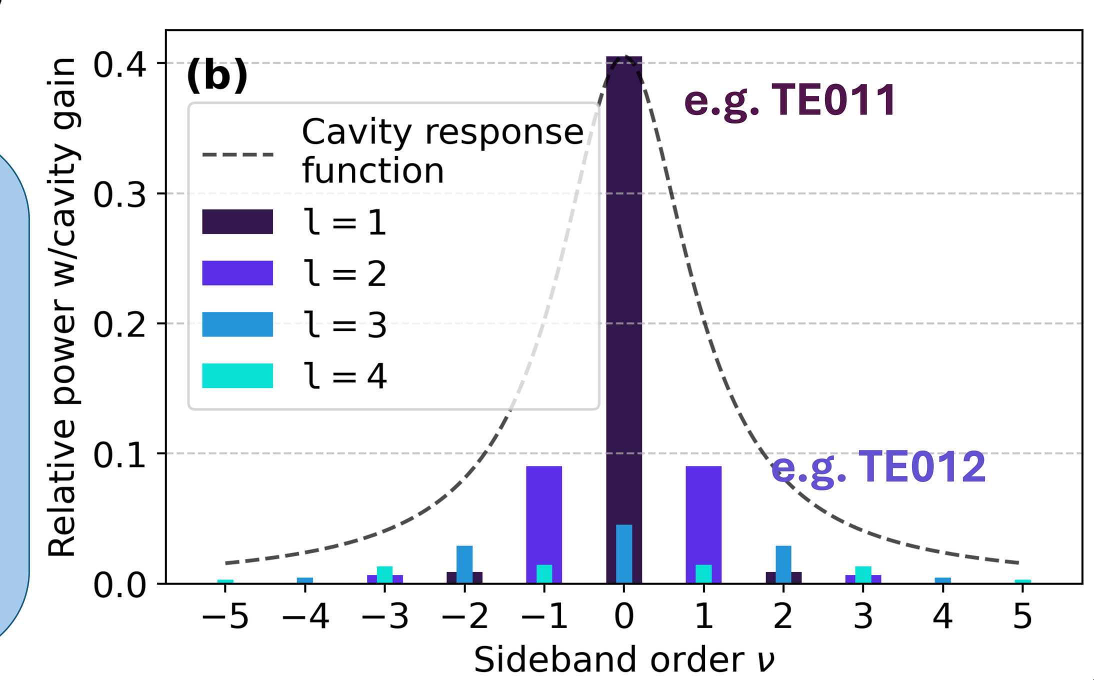
- If the j_α decomposition can be found analytically, it immediately yields the signal power P_α

$$P_\alpha(\omega) = \frac{1}{2\pi^2\epsilon}\left[\frac{Q_\alpha \frac{\omega}{\Omega_\alpha^2}\left|j_\alpha(\omega)\right|^2}{1 + \frac{Q_\alpha^2}{\Omega_\alpha^4}\left(\Omega_\alpha^2 - \omega^2 - \frac{\Omega_\alpha^2}{(2Q_\alpha)^2}\right)^2}\right]$$



- The choice of length-to-diameter ratio (L/D) and operating mode is found to greatly influence the average expected signal power

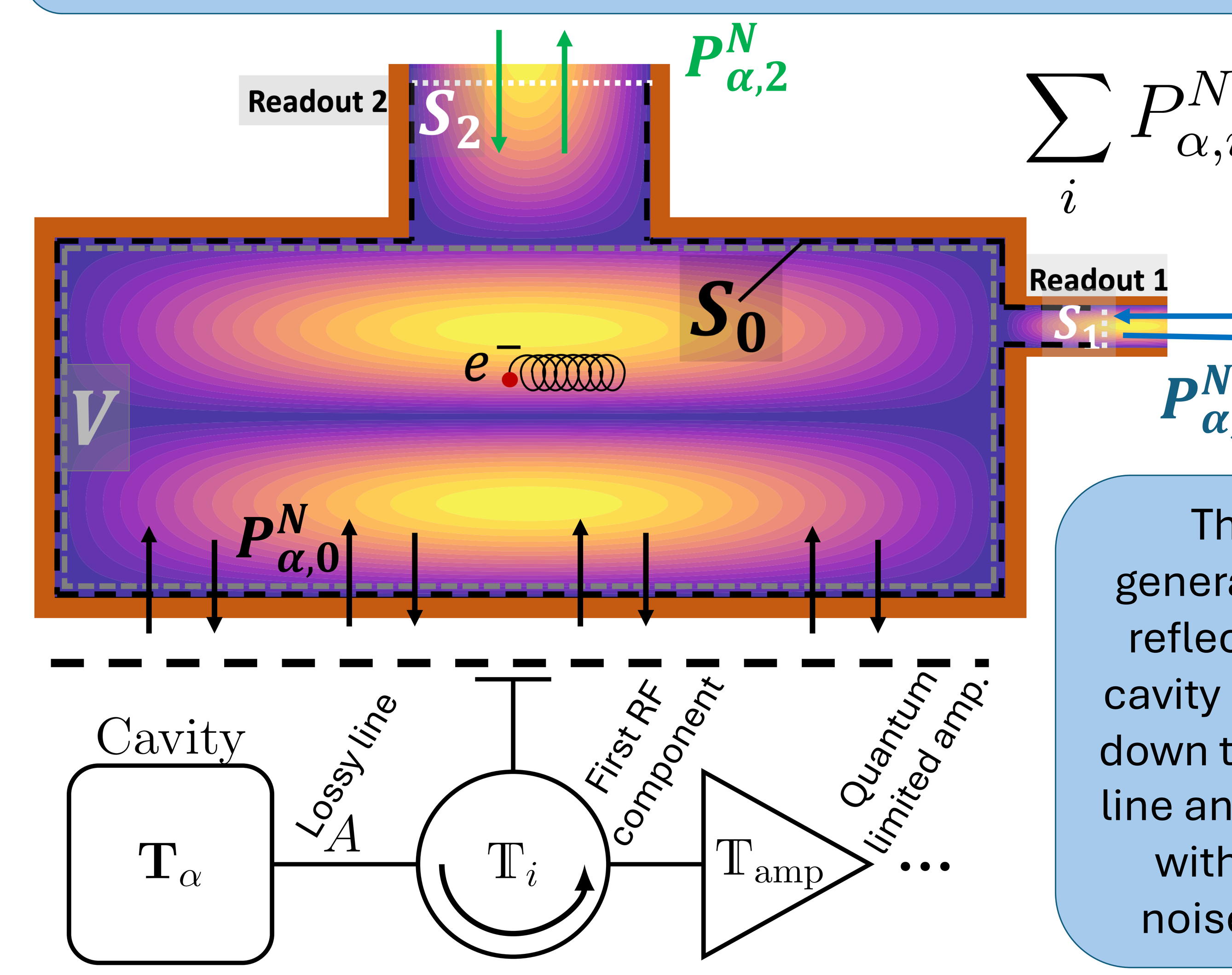
- Dominant signal sidebands are created by the axial motion relative to the cavity mode's gain: odd modes (TE011) have even sidebands



Noise Model: Steady state blackbody radiation through a common cavity channel

- If the system has reached a thermal steady state, the cavity has a constant thermal noise temperature
- The cavity does not contain thermal sources:

$$\sum_i P_{\alpha,i}^N(\omega) = 0$$

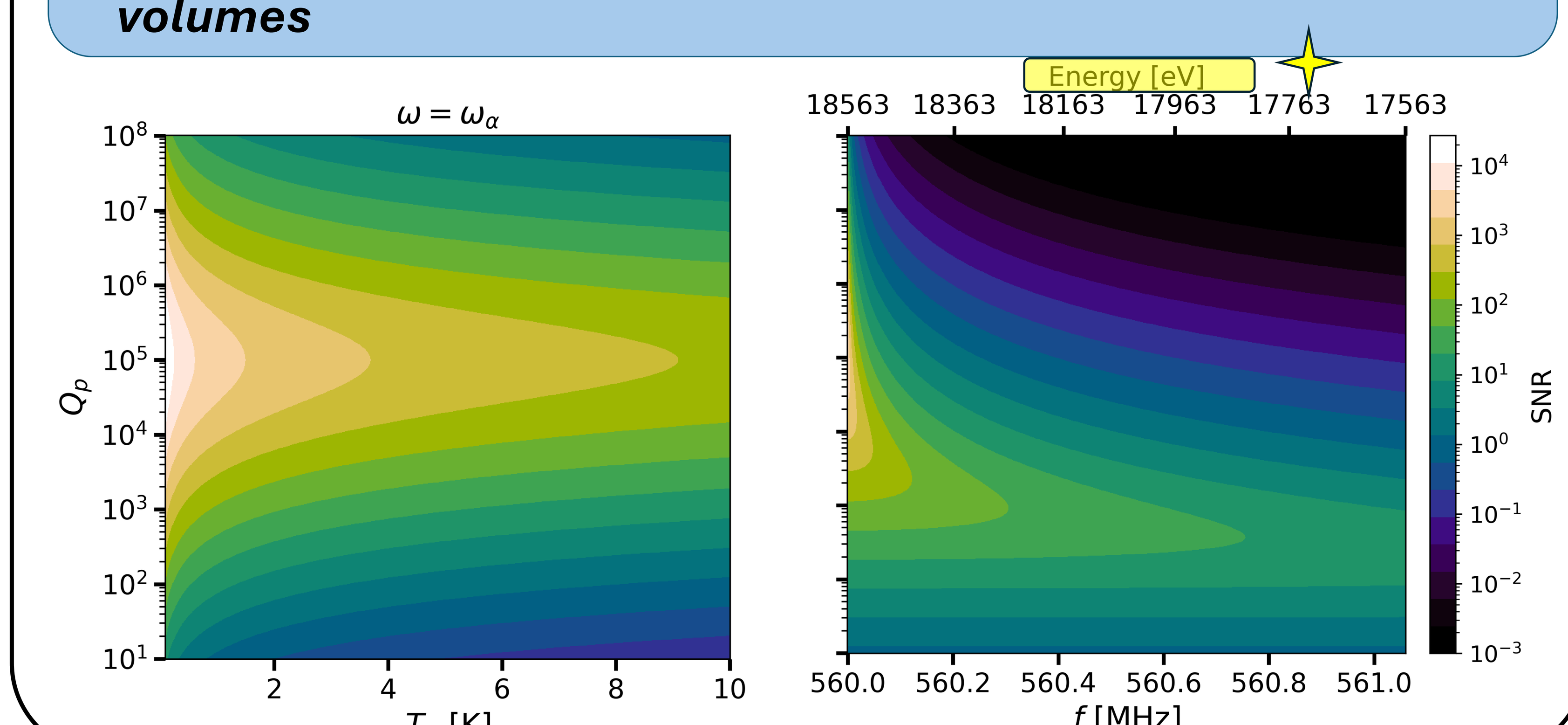


The noise generated by and reflected off the cavity is cascaded down the RF signal line and combined with other RF noise sources.

Application of the Fluctuation-Dissipation theorem for the cavity's Green dyadic yields the cavity noise contribution from all ports

$$P_{\alpha,p}^N = \frac{4k_B\frac{\omega}{\Omega_\alpha}\left(\mathbb{T}_0 - \mathbb{T}_p\right)\frac{Q_\alpha^2}{Q_{\alpha,0}Q_{\alpha,p}}}{1 + \frac{Q_\alpha^2}{\Omega_\alpha^4}\left(\Omega_\alpha^2 - \omega^2 - \frac{\Omega_\alpha^2}{(2Q_\alpha)^2}\right)^2}$$

- High-Q cavities greatly enhance SNR—but only on resonance !
- Low-Q cavities optimize the SNR of the β-decay endpoint region
- ***Low-frequency cavities are viable for scaling CRES to large volumes***



Cavity CRES Apparatus (CCA) 26 GHz // 560 MHz Low Frequency Apparatus (LFA) // 150 MHz Pilot ~150 MHz Phase IV

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