

Active Resonators for ADMX

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University of Washington, ADMX Collaboration

April 15, 2015 / April APS Meeting

Idea

- ▶ Axion haloscopes experiments use high-Q microwave cavities.
- ▶ Expected signal power is proportional to Q:

$$P_{sig} \propto \min(Q_L, Q_a)$$

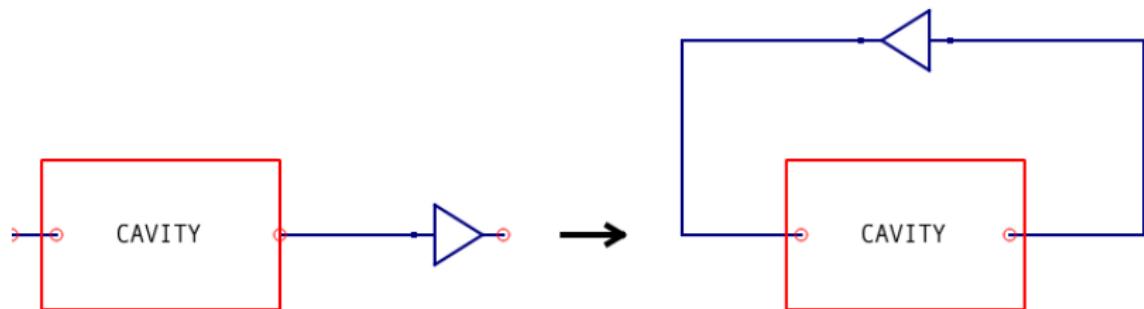
axion quality factor: $Q_a \simeq 10^6$

- ▶ Theoretical Q goes as

$$Q = \frac{L}{R+L} \frac{R}{\delta}$$

- ▶ anomalous skin depth (Cu): $\delta = 2.8 \times 10^{-5} \text{ cm} \left(\frac{\text{GHz}}{f} \right)^{1/3}$
- ▶ $Q_L \approx 10^5$ for $f \approx 1 \text{ GHz}$.
- ▶ Can we increase the loaded Q further?

Introduce Feedback



Proposal

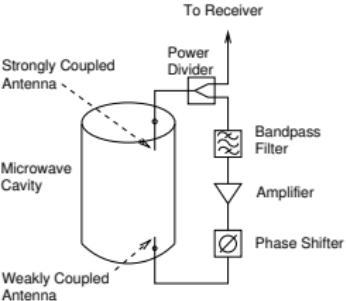
Improving Dark Matter Axion Searches with Active Resonators

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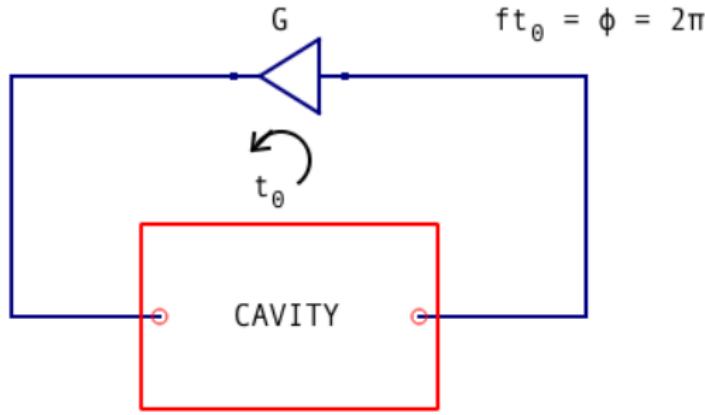
(Dated: March 27, 2014)

Axions are a well motivated candidate for dark matter. The most sensitive experiments searching for dark matter axions rely on the coupling of axions to the electromagnetic resonances of a microwave cavity immersed in a strong magnetic field. The sensitivity of the experiment is proportional to the Q of the resonance that is coupled to axions. To date, the resonators used in axion searches have all been passive, with Q s limited by power loss in the cavity walls. I propose the use of active feedback resonators to increase the Q of microwave cavity axion dark matter experiments by several orders of magnitude. This should allow experiments to significantly increase the rate at which they can test potential axion masses and couplings.



Active Feedback

$$V_{out} = V_{in} S_{21} (1 + x + x^2 + \dots) = V_{in} S_{21} (1 - x)^{-1}$$



$$\begin{aligned}x &= GS_{21} \\Q &\propto (1 - x)^{-1}\end{aligned}$$

- ▶ Signal builds up through feedback
- ▶ Q increases by factor $(1 - x)^{-1}$
- ▶ Oscillation begins when $x = 1$

- ▶ This idea is old; patented in 1914 and used for making higher gain amplifiers and more selective radio circuits.¹
- ▶ However, this amplifies noise and signal equally, so SNR should remain the same for constant amplitude signal:

$$\text{SNR}_{\text{cw}} \propto \text{const.}$$

- ▶ Since axion signal is proportional to Q , SNR increases

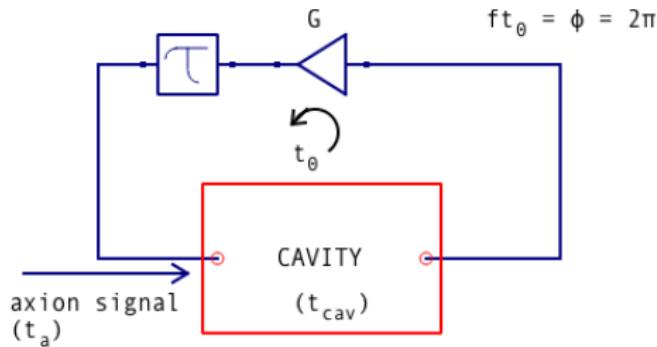
$$\text{SNR}_{\text{axion}} \propto (1 - x)^{-1}$$

- ▶ We can utilize the different coherence times of signal and noise to get more improvement.

¹Joe A. Rolf, "Q Multiplier Boosts Selectivity & Gain," Popular Electronics, April 1974

Time Delay

Introduce a time delay so t_0 greater than cavity coherence time



$$x = GS_{21}$$
$$Q \propto (1 - x)^{-1}$$

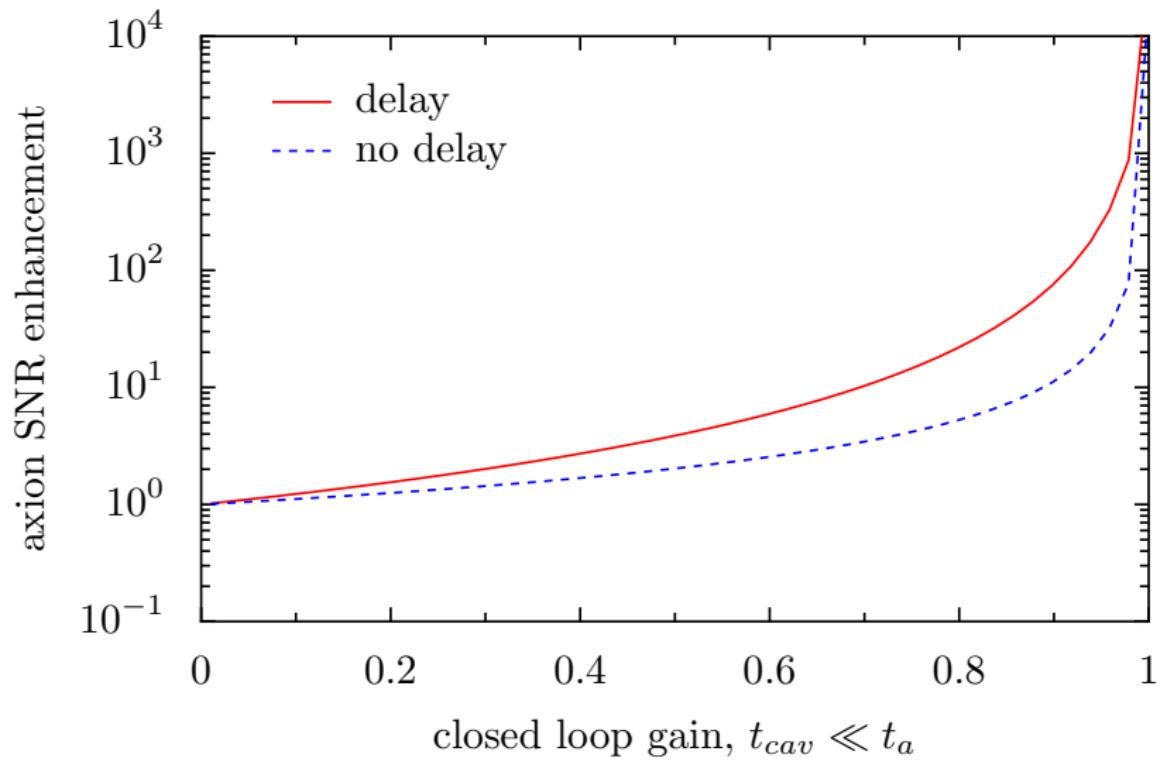
- ▶ Noise is only correlated over time t_{cav}
- ▶ Signal is coherent over longer time t_a
- ▶ If roundtrip time t_0 is greater than t_{cav} :

$$t_{cav} < t_0 < t_a$$

we expect noise to add incoherently and signal to add coherently

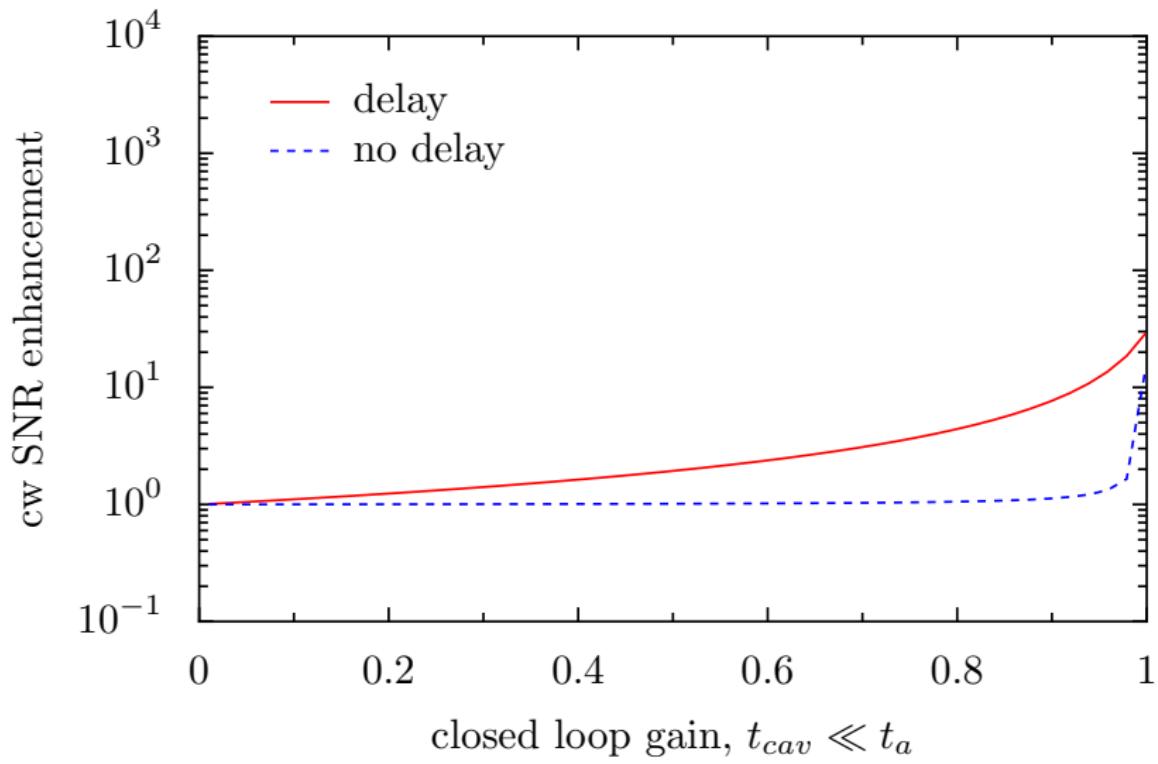
Expected Improvement in Axion SNR

axion snr improvement, $\text{SNR}(x)/\text{SNR}(x = 0)$, with and without delay line



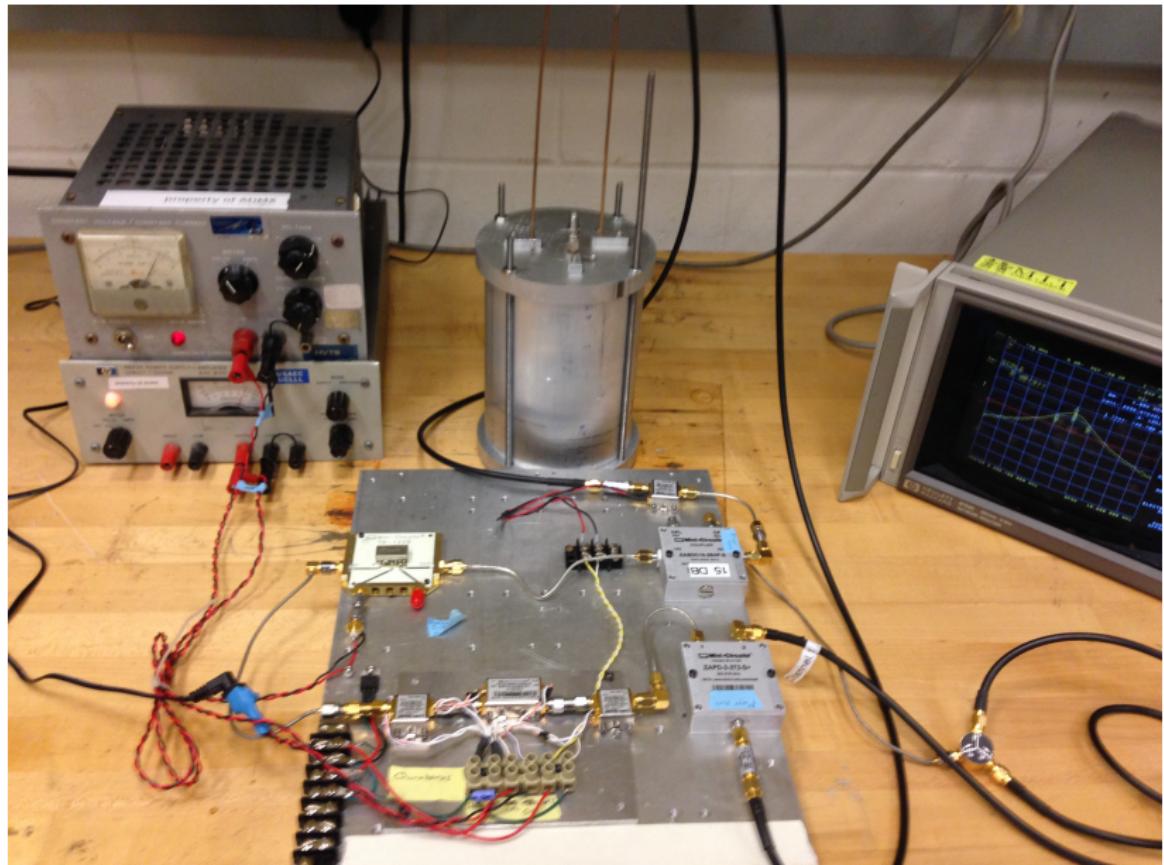
Expected Improvement in Constant Signal

cw snr improvement, $\text{SNR}(x)/\text{SNR}(x = 0)$, with and without delay line



Initial Setup

feedback using amplifiers, variable attenuator, and phase shifter

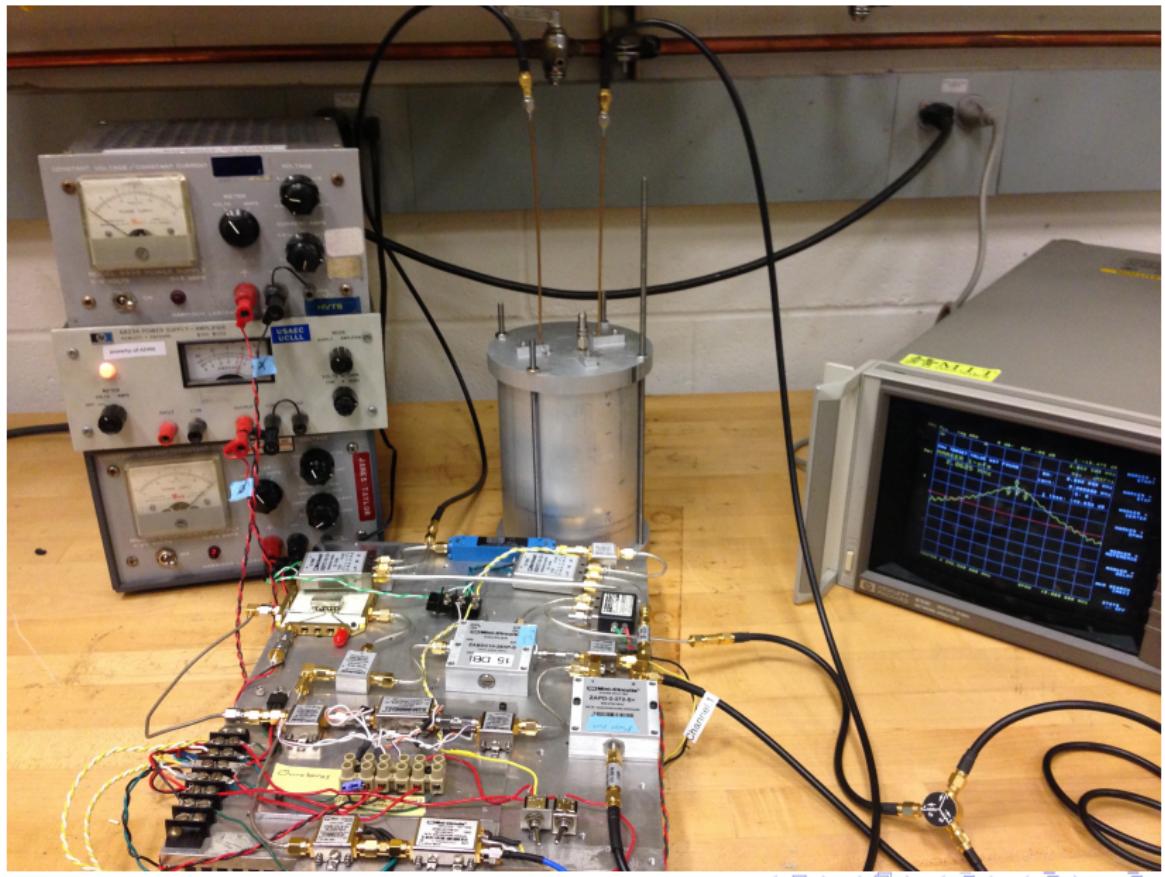


Q Enhancement

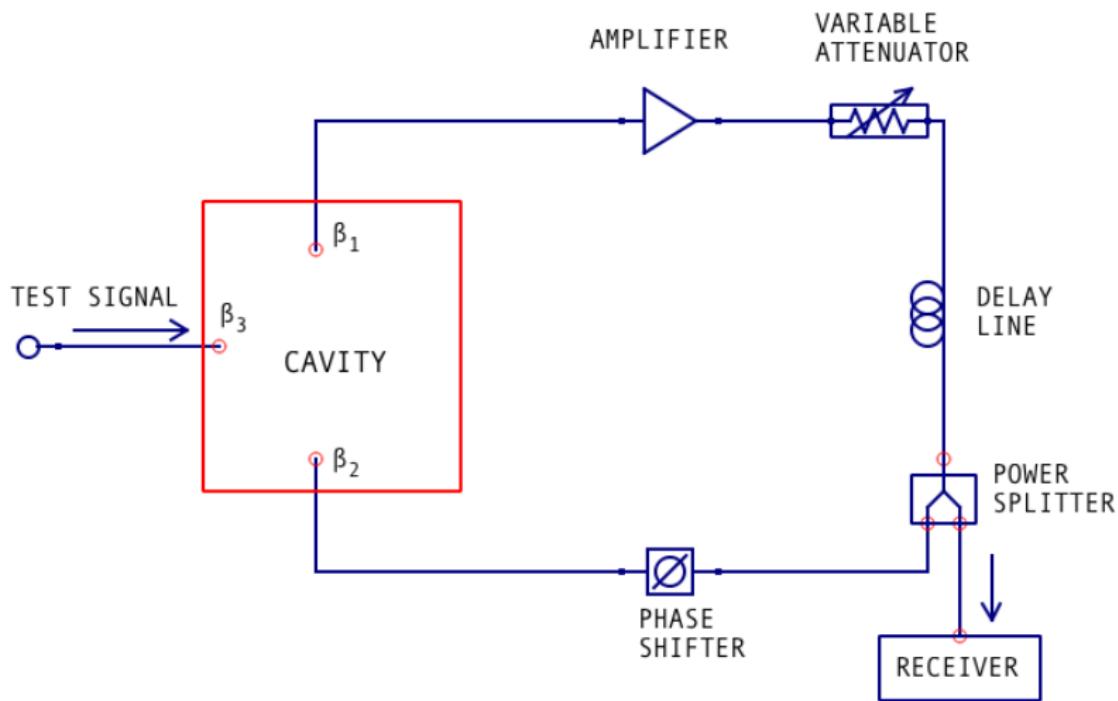
adjusting variable attenuator allows Q to range from 1000 to 9000 before oscillations begin



Setup



Schematic



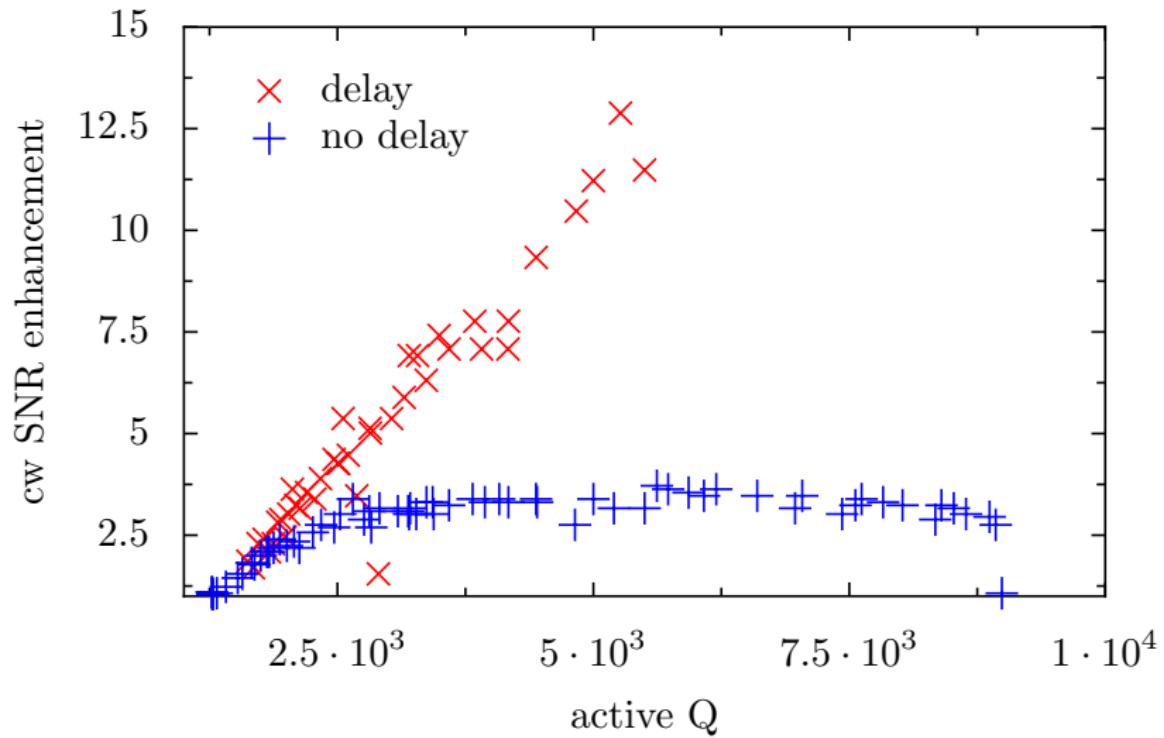
Parameters

Parameter	Values
f_{cav}	2.256 GHz
t_{delay}	2.4 μ s
t_{cav}	70 ns
t_{axion}	70 μ s

Experiment

- ▶ Set attenuation of variable attenuator
- ▶ Adjust phase so Q is maximal
- ▶ Measure Q, f_{cav}
- ▶ Inject constant amplitude signal at f_{cav}
- ▶ Measure height of signal relative to noise floor in detected spectrum

Results



Considerations

- ▶ move to digital delay lines
- ▶ major design considerations would center around gain instability; to get 10x increase in Q, need $x \simeq 0.9$.

Conclusions

- ▶ active feedback is a simple technique to increase Q
- ▶ delay line provides additional increase in SNR
- ▶ independent of other parts of the experiment
- ▶ does not need to be operated cryogenically

People

Lisa McBride, Kunal Patel, Gray Rybka

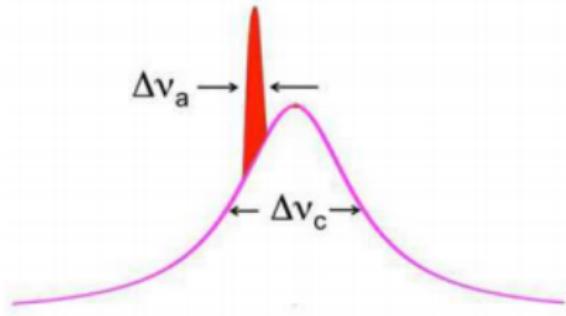
This work was supported by the Dept. of Energy, Division of High Energy Physics.



Backup

Backup Slides

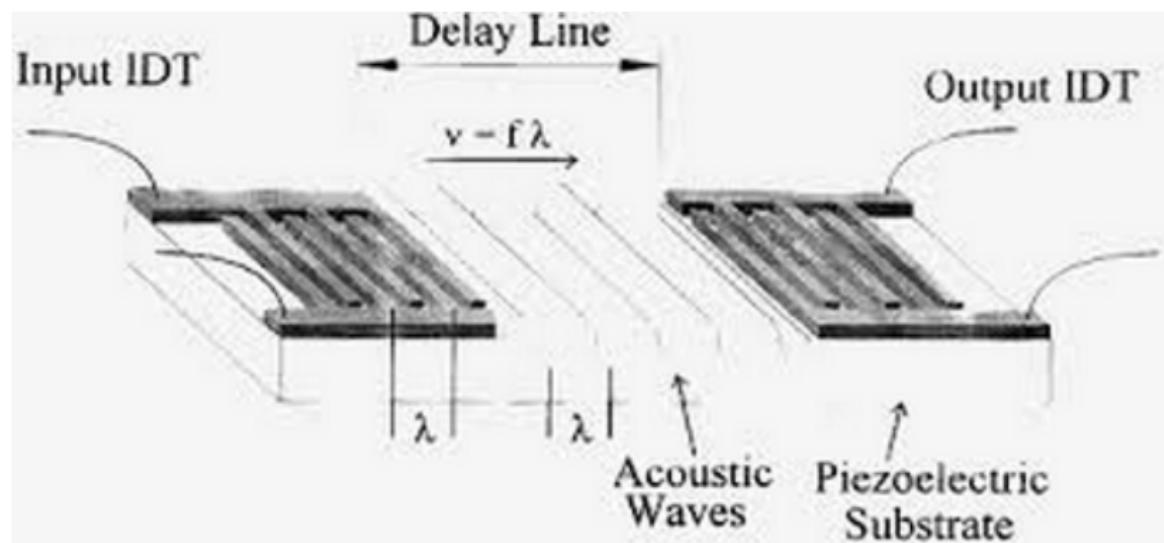
If $Q_L > Q_a$



If cavity Q is larger than axion Q (or $t_{cav} > t_a$), we no longer detect the full axion power within the cavity bandwidth.

Delay Lines

Surface Acoustic Wave (SAW) Resonator



Expected SNR Improvement

analysis of signal correlation

Scenario 1: $t_0 \ll t_{cav}$:

$$\langle V_{in}(t)V_{in}(t-t_0) \rangle = \bar{V}_{in}^2$$

$$\langle |V_{out}|^2 \rangle = |\bar{V}_{in}S_{21}|^2(1+x+x^2+\dots)^2 = \bar{V}_{in}^2|S_{21}|^2(1-x)^{-2}$$

Scenario 2: $t_0 \sim \mathcal{O}(t_{cav})$:

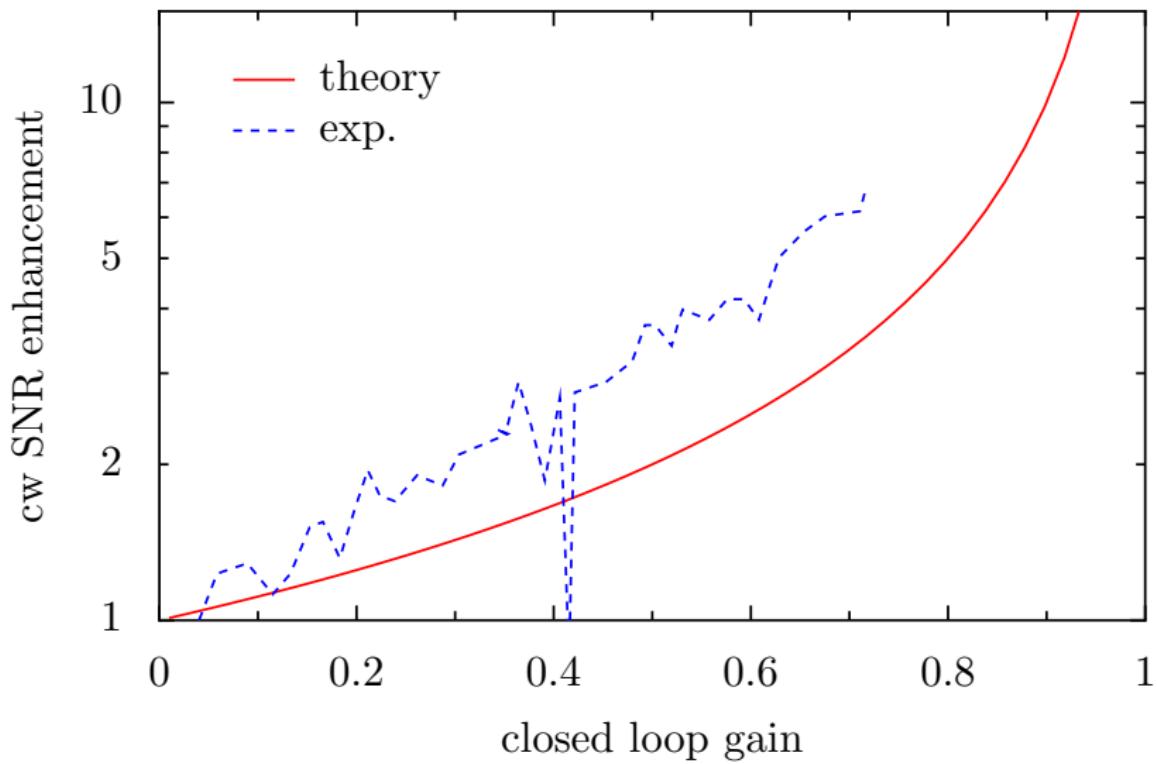
$$\langle V_{in}(t)V_{in}(t-t_0) \rangle = \bar{V}_{in}^2 e^{-t_0/t_{cav}}$$

$$\begin{aligned}\langle |V_{out}|^2 \rangle &= |\bar{V}_{in}S_{21}|^2(1+xe^{-t_0/t_{cav}}+x^2e^{-2t_0/t_{cav}}+\dots)^2 \\ &= \bar{V}_{in}^2|S_{21}|^2(1-xe^{-t_0/t_{cav}})^{-2}\end{aligned}$$

this analysis is not completely correct - it predicts a turnover at $x=0.5$. One needs to treat the nonlinearity properly to get the correct result:

$$\langle |V_{out}|^2 \rangle = \frac{\bar{V}_{in}^2|S_{21}|^2}{(1-x)^2} \frac{1+xe^{-t_0/t_{cav}}}{1-xe^{-t_0/t_{cav}}}$$

Comparison (preliminary)



Interference Fringes

When $\Delta f t_0 > \pi$, one sees interference fringes, due to off resonant signals acquire an extra phase shift of $\pi/2$ relative to the phase acquired by the resonant frequency.

