Active Resonators for ADMX

Ana Malagón

University of Washington, ADMX Collaboration

April 15, 2015 / April APS Meeting

Idea

- Axion microwave cavity haloscopes use microwave cavities.
- Expected signal power is proportional to Q:

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

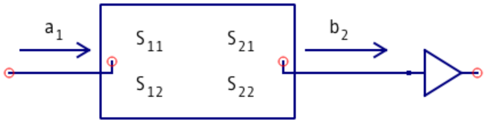
  axion quality factor: $Q_a \simeq 10^6$

- Theoretical Q goes as

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

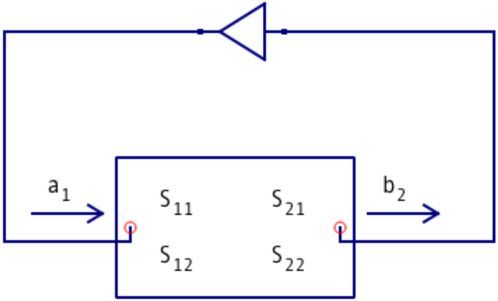
- anomalous skin depth (Cu): $\delta = 2.8 \times 10^{-5}\ \mathrm{cm}\left(\frac{\mathrm{GHz}}{f}\right)^{1/3}$
- $Q_L \approx 10^5$ for $f \approx 1$ GHz.
- Can we increase the loaded Q further?

Active Feedback

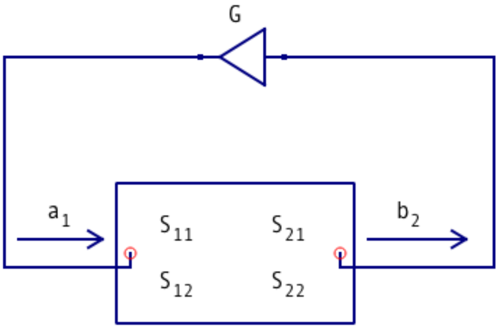


b = Sa

Active Feedback



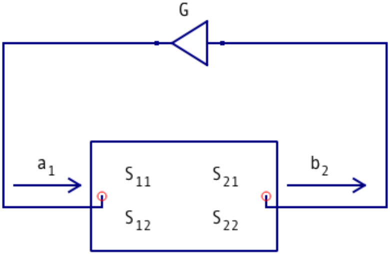
Active Feedback



$$b = Sa$$

$$a_1(t) = Gb_2(t-t_0) + s(t)$$

Active Feedback

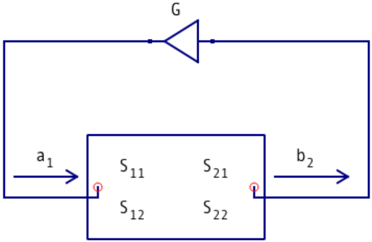


$b = Sa$

$$\frac{b_2(t)}{}$$

$$S_{21} a_1(t)$$
$$+ S_{21}^2 G a_1(t - t_0)$$
$$+ S_{21}^3 G^2 a_1(t - 2t_0)$$
$$+ \dots$$

Active Feedback



$$b = Sa$$

$$\frac{b_2(t)}{\;}$$

$$S_{21}a_1(t)$$

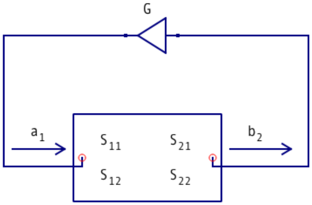
$$+\ S_{21}{}^2 G a_1(t-t_0)$$

$$+\ S_{21}{}^3\ G^2\ a_1(t\ -\ 2t_0)$$

$$+\ \ldots$$

$$b_2(t)\ =\ S_{21}a_1(t)(1-GS_{21})^{-1}$$

Active Feedback



$$b = Sa$$

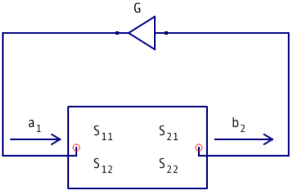
$$\boxed{\begin{array}{l} Q \propto (1 - GS_{21})^{-1} \\ P_{out} = \langle |b_2|^2 \rangle \propto (1 - GS_{21})^{-2} \end{array}}$$

$\underline{b_2(t)}$

$$\begin{aligned} & S_{21} a_1(t) \\ + \; & S_{21}{}^2 G a_1(t - t_0) \\ + \; & S_{21}{}^3 \, G^2 \, a_1(t - 2t_0) \\ + \; & \ldots \end{aligned}$$

$$b_2(t) = S_{21} a_1(t) (1 - GS_{21})^{-1}$$

Active Feedback



$b = Sa$

$$\boxed{\begin{aligned} &Q \propto (1-GS_{21})^{-1} \\ &P_{out} = \langle |b_2|\rangle^2 \propto (1-GS_{21})^{-2} \end{aligned}}$$

*assuming $\langle a_1(t) a_1(t-t_0)\rangle = a_1^2$

$b_2(t)$

$$\begin{aligned} &S_{21}a_1(t) \\ &+ S_{21}^2 G a_1(t-t_0) \\ &+ S_{21}^3 G^2 a_1(t-2t_0) \\ &+ \ldots \end{aligned}$$

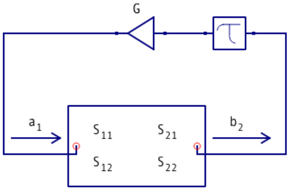
$b_2(t) = S_{21}a_1(t)(1-GS_{21})^{-1}$

- This idea is old; patented in 1914 and used for making higher gain amplifiers and more selective radio circuits.
- However, this amplifies noise and signal equally, so SNR should remain constant*.
- *Since axion signal goes with Q, SNR increases

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

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

Noise



$$b = Sa$$

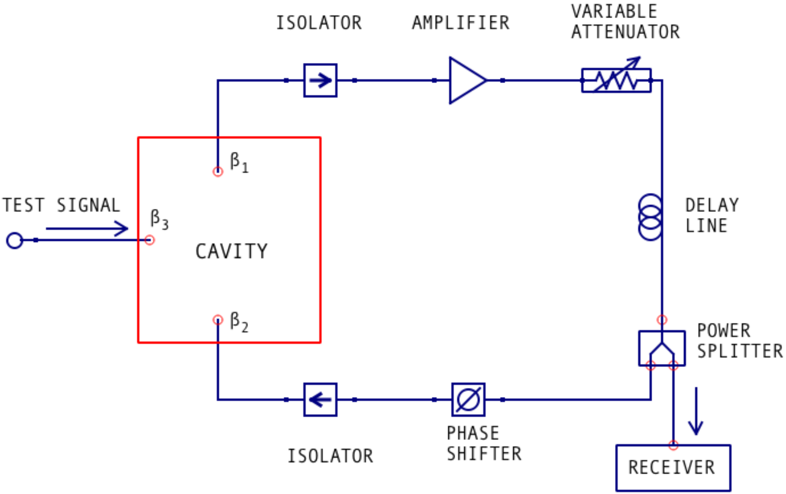
$$\boxed{\begin{aligned} &Q \propto (1-GS_{21})^{-1} \\ &P_{out} = \langle|b_2|\rangle^2 \propto \, ? \end{aligned}}$$

$$\begin{aligned}
&\underline{b_2(t)} \\
&\quad S_{21}a_1(t) \\
&+ S_{21}^2 G a_1(t-t_0) \\
&+ S_{21}^3 G^2 a_1(t - 2t_0) \\
&+ \ldots
\end{aligned}$$

$$b_2(t) = S_{21}a_1(t)(1-GS_{21})^{-1}$$

Active Feedback Resonator

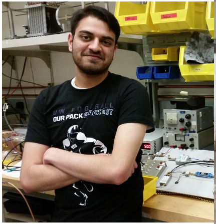
Ouroboros



Parameters

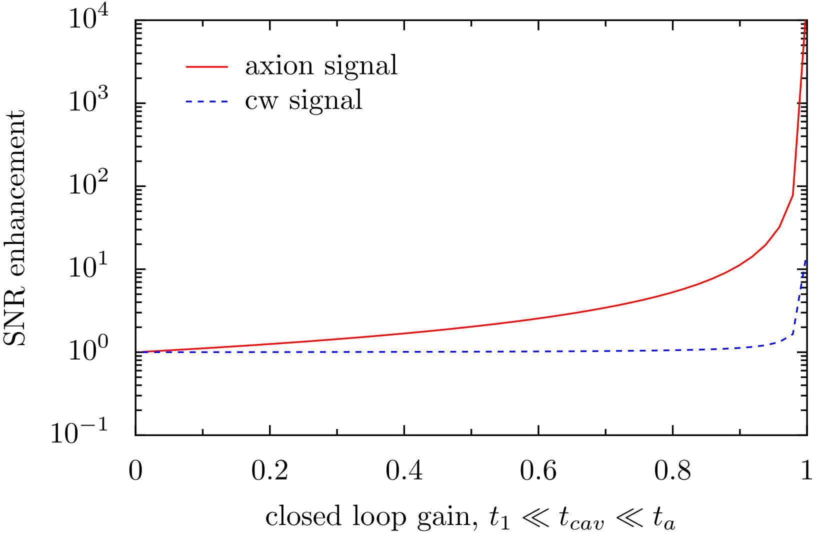
delay time: 2.4 μseconds
$Q \simeq 1200$
$f = 2.256$ GHz

People



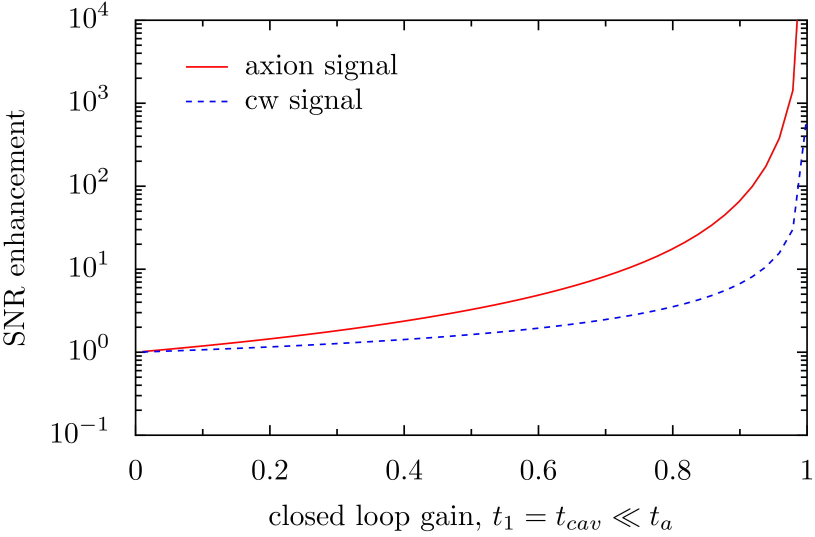
Axion and CW Signal

Scenario 1



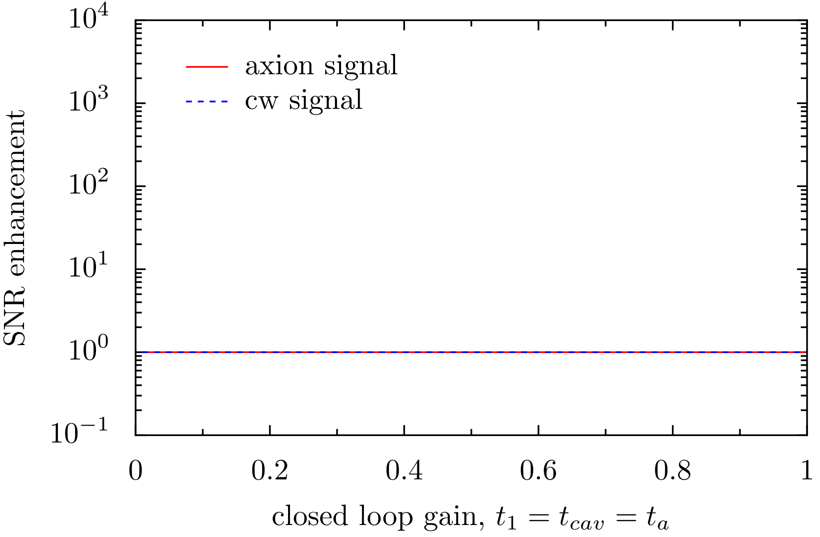
Axion and CW Signal

Scenario 2



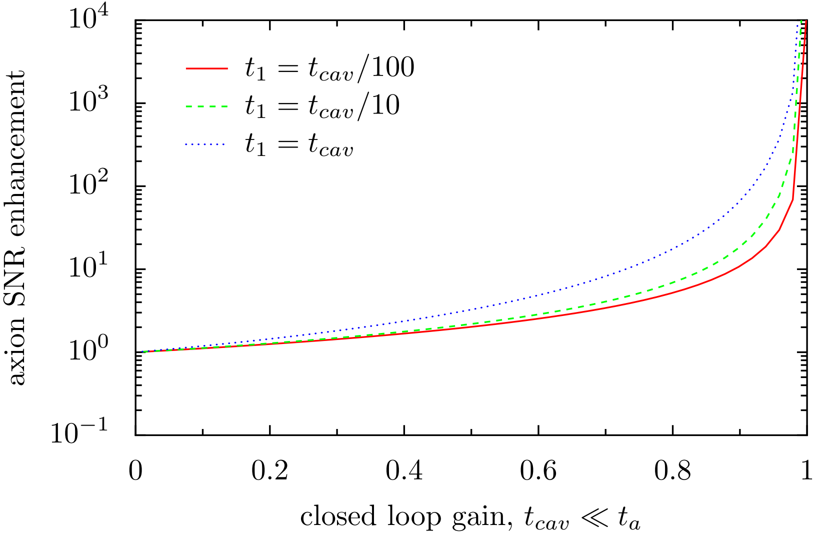
Axion and CW Signal

Scenario 3



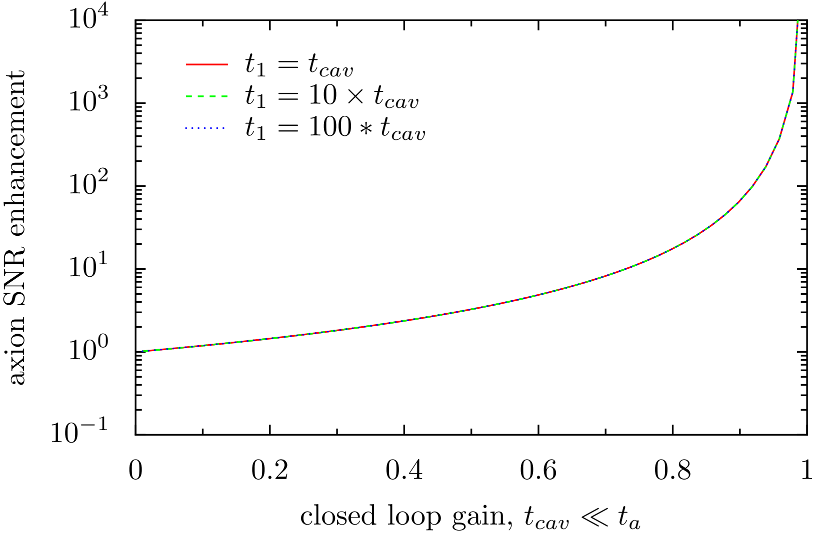
Exploring Second Limit

$t_1 \ll t_{cav}$



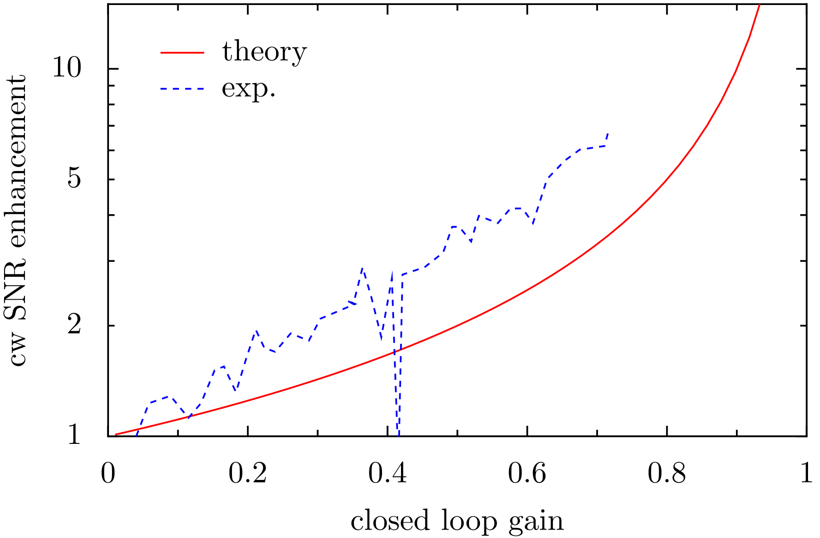
Exploring Second Limit

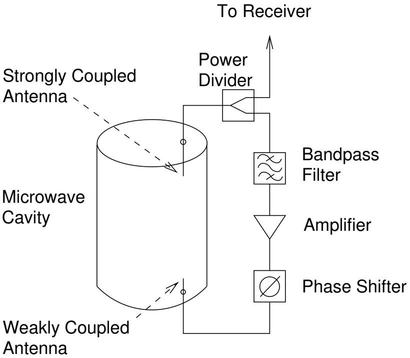
$t_1 > t_{cav}$



Theory and Experiment

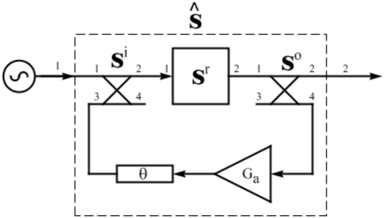
Comparison





- t: time around loop
- τ: coherence time of cavity
- Intuition: signal feeds back coherently; when $t > \tau$, noise adds incoherently

Equivalent Circuit

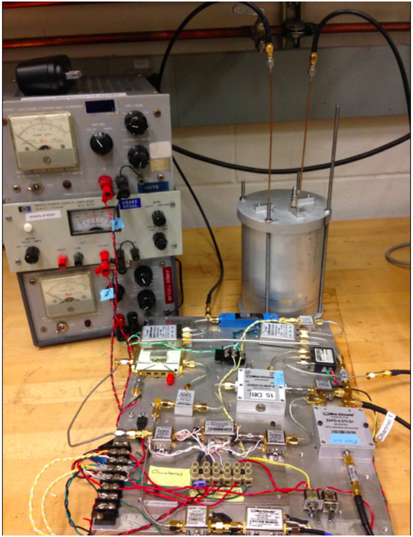


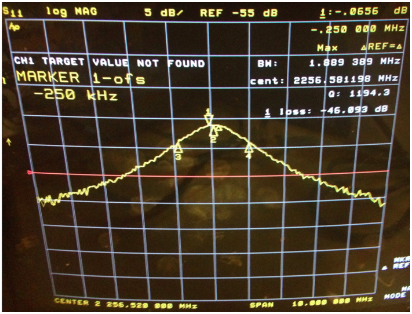
G_l the loop gain
Q_0 the active quality factor
T_a the amplifier noise temperature

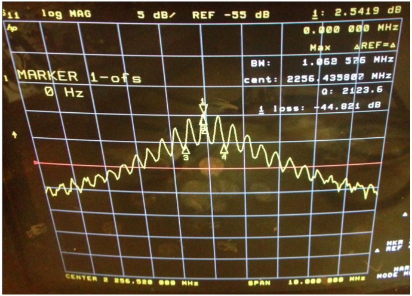
$$Q_0 = Q_L(1 - \sqrt{G_l})^{-1}$$
$$|\hat{S}_{21}|^2 \propto (1 - \sqrt{G_l})^{-2}$$

$$T_{noise} = \frac{T_{cav} + G_l T_a}{1 + G_l - 2\sqrt{G_l} e^{-t/\tau - i\theta}}$$

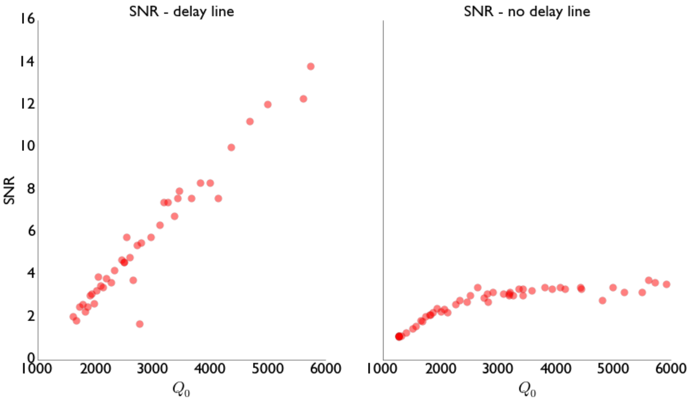
Prototype




S11 log MAG 5 dB/ REF -55 dB 1:-.0656 dB
-.250 000 MHz
Max ΔREF=Δ
CH1 TARGET VALUE NOT FOUND
MARKER 1-ofs
-250 kHz
BW: 1.889 389 MHz
cent: 2256.581198 MHz
Q: 1194.3
1 loss: -46.093 dB
CENTER 2 256.520 000 MHz
SPAN 10.000 000 MHz


S11 log MAG 5 dB/ REF -55 dB 1: 2.5419 dB
0.000 000 MHz
Max ΔREF=Δ
BW: 1.062 576 MHz
MARKER 1-ofs
0 Hz
cent: 2256.435807 MHz
Q: 2123.6
1 loss: -44.821 dB
CENTER 2 256.520 000 MHz
SPAN 10.000 000 MHz

Results


SNR - delay line
SNR - no delay line
SNR
16
14
12
10
8
6
4
2
0
1000
2000
3000
4000
5000
6000
Q_0
1000
2000
3000
4000
5000
6000
Q_0

Acknowledgments

DOE HEP