

# Active Circuits for Resonant Axion Detectors

Second Workshop on Microwave Cavities and Detectors for Axion Research  
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The  
University  
Of  
Sheffield.

# Caveats!

- This talk is based on a clever ‘wild idea’ from Ed Daw.
- All credit for the concept and implementation of the electronics belongs to Ed.
- Any misconceptions are my own!

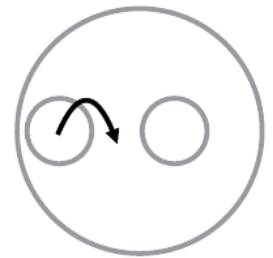
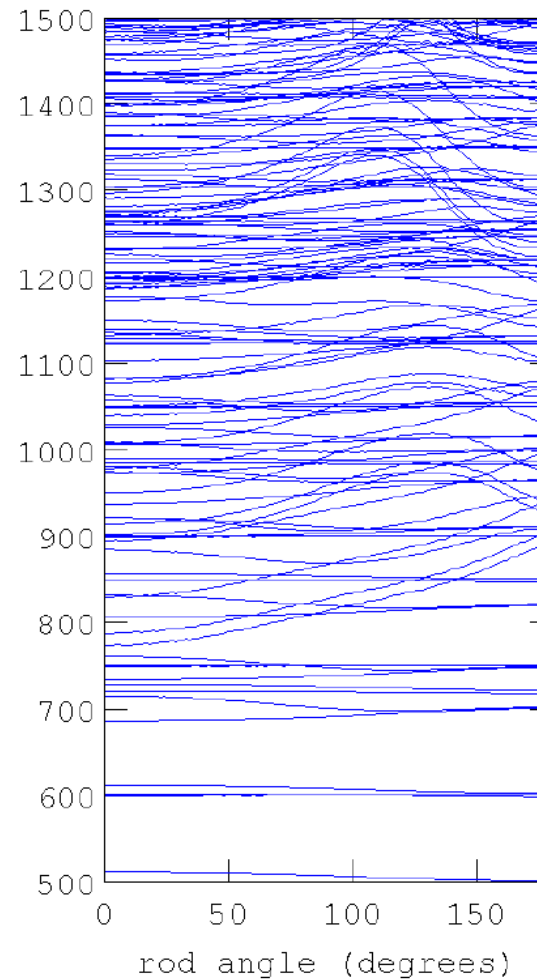
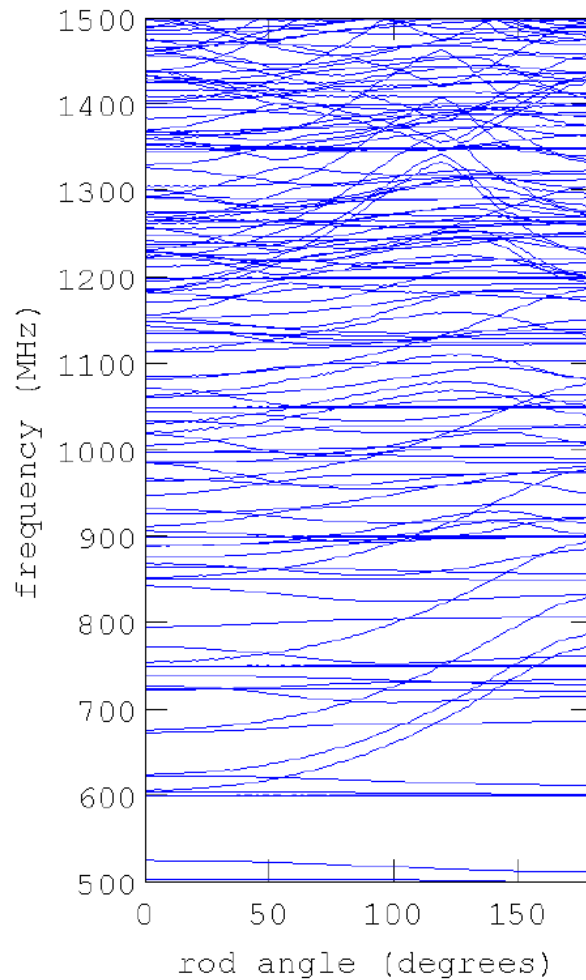
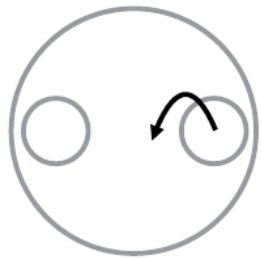
Active resonators....



# The general problem

- You can only afford one fixed-bore magnet.
- You can put one or multiple cavities into the bore.
- A single cavity has a restricted tuning range in its lowest axion-coupling mode (e.g.  $TM_{010}$ )
- Higher-order modes typically have lower axion form factors and hence higher integration times.
- Combining outputs from multiple synchronously-tuned cavities is possible but challenging.

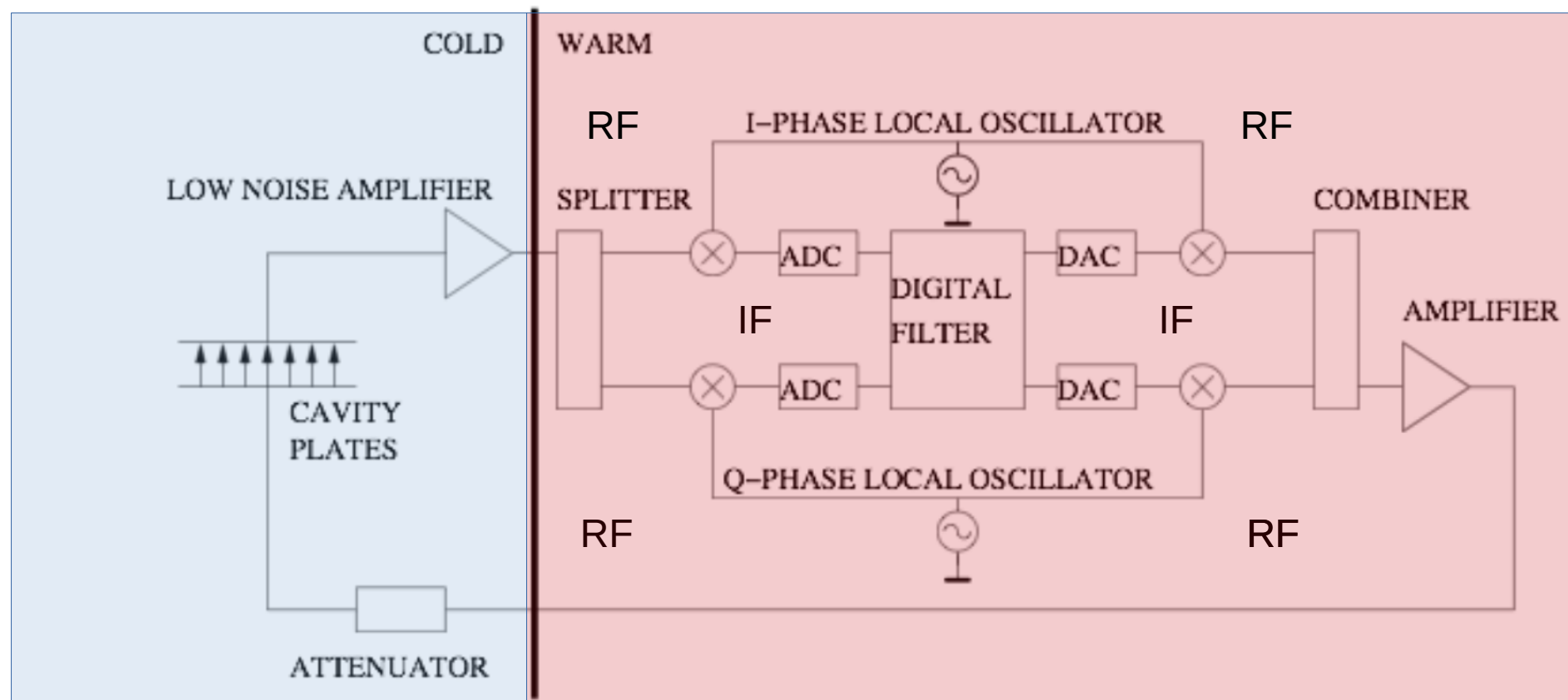
# Mode Crowding



‘Cavity crowding’ brings its own problems (both already much-discussed at this workshop)

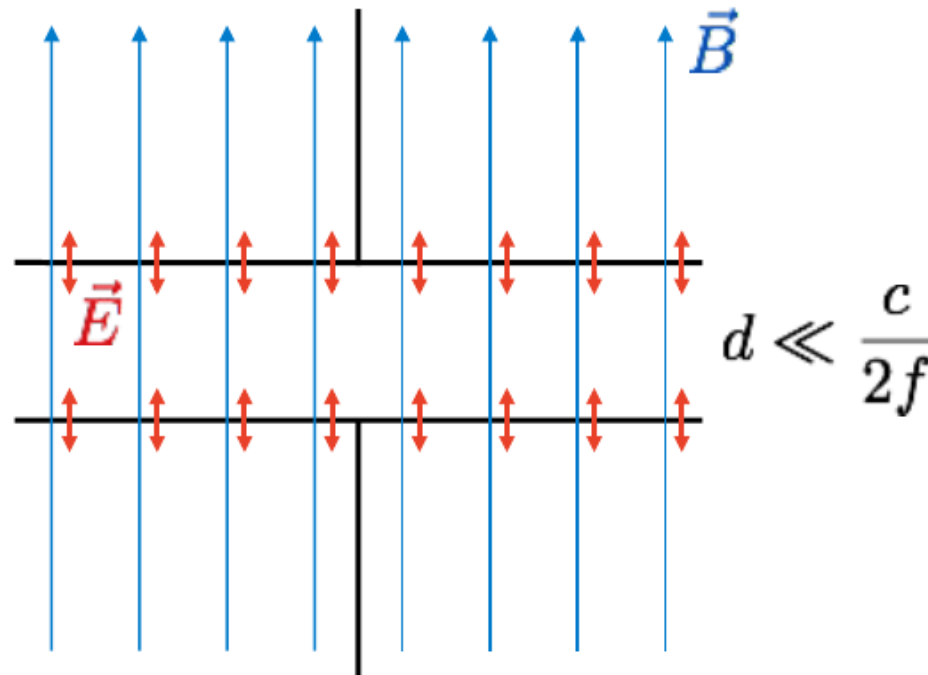
## Ed's “wild idea”!

- Let's throw away the cavity and create an artificial resonant mode using digital processing and feedback of the signal from a non-resonant structure.



# What non-resonant structure?

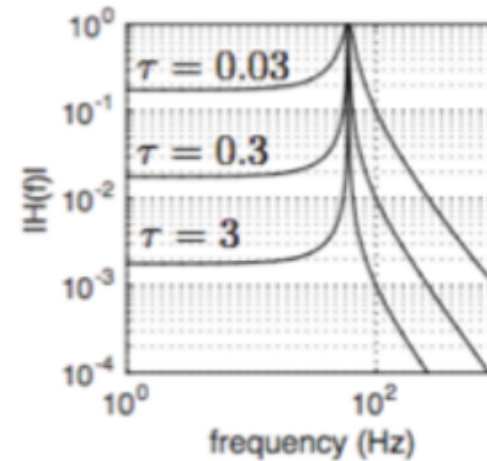
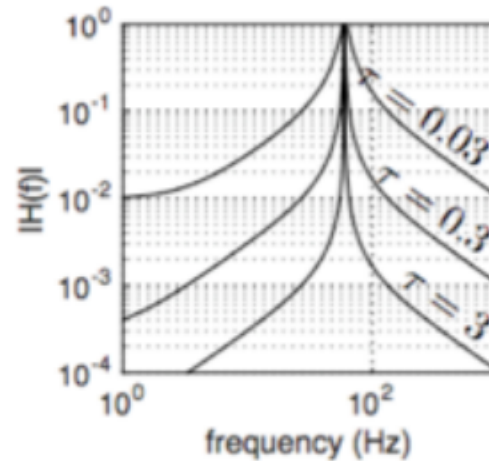
- Simplest concept is to just have a parallel-plate capacitor operating below cut-off in a uniform B field.



- What does the field look like when we start implementing multiple structures, etc?  
Not yet simulated.

# Digital Transfer Function

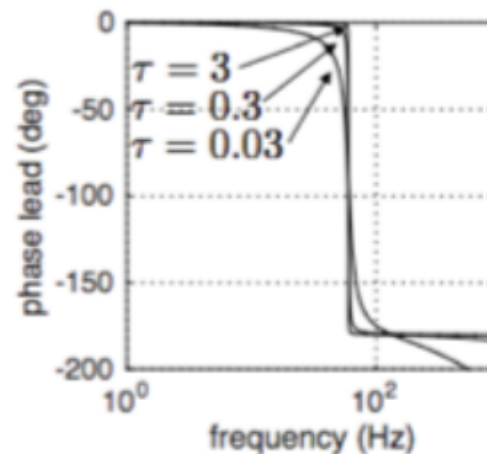
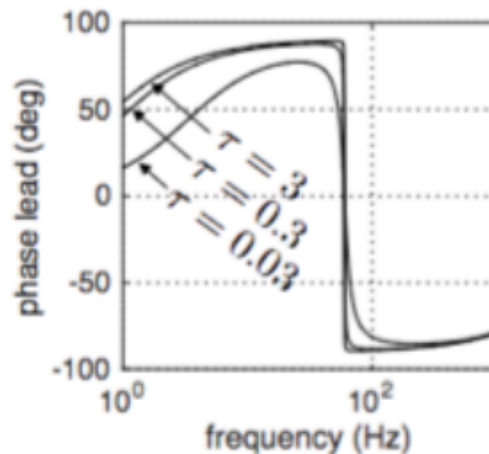
Amplitude



It's possible to implement a function that looks just like a tunable damped harmonic oscillator.

The ringing-down time will be determined by the sampling frequency scaled by one of the two free parameters in the digital transfer function.

Phase lead



In phase

Quadrature

# Benefits

- No more tuning rods. The resonant frequency is determined by the parameters of the digital filter.
- Tuning frequency is not limited by the position of the cavity walls.
- Many external filters can operate in parallel on the same structure.
- Many rf structures can be run in parallel coupled to the same filter. E.g. fill the magnet bore with a stack of capacitors.
- Having the capacitor plates normal to the B field should give close to optimal coupling to the axions field.



# Equivalent Circuit (axion signal in a cavity)

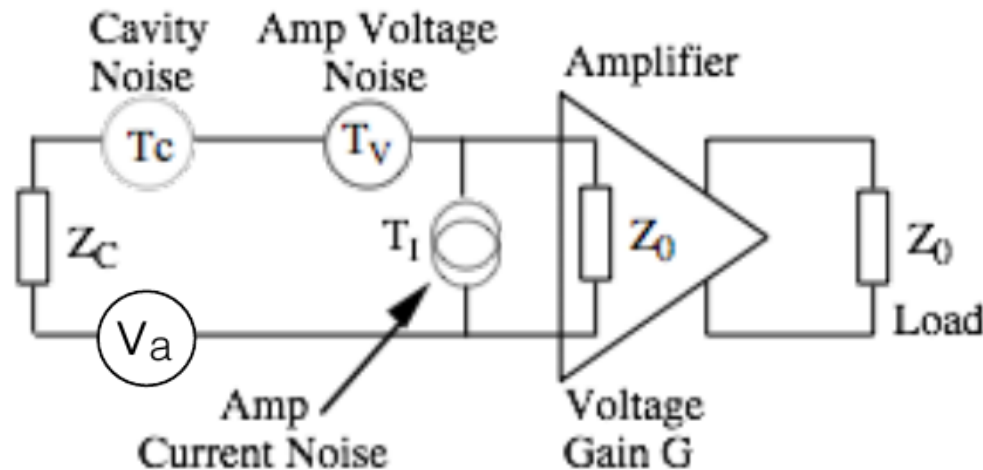


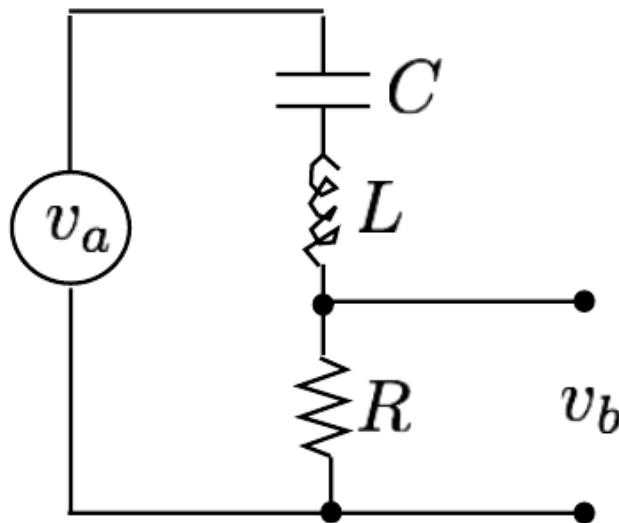
Figure A3.5 Equivalent circuit of cavity and amplifier input  
assuming a short connecting cable

From Daw Ph.D. Thesis (1998!)

Axion signal represented by a voltage source in series with a cavity load (Thevenin equivalent circuit).

We want to reproduce the real cavity response with the digital transfer function.

# Equivalent Circuit Analysis (Open Loop Case)



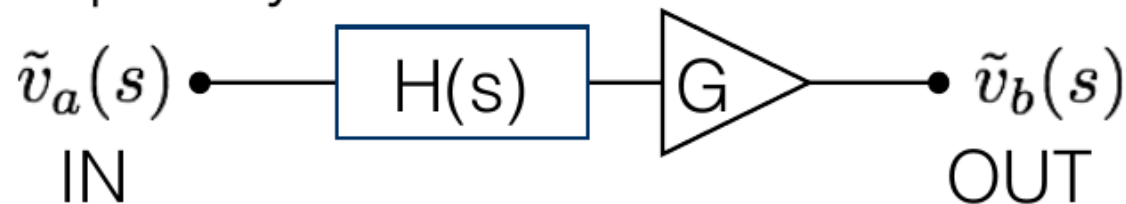
$$s = i\omega$$

$$H(s) = \frac{\tilde{v}_b}{\tilde{v}_a} = \frac{R}{\frac{1}{sC} + R + sL}$$

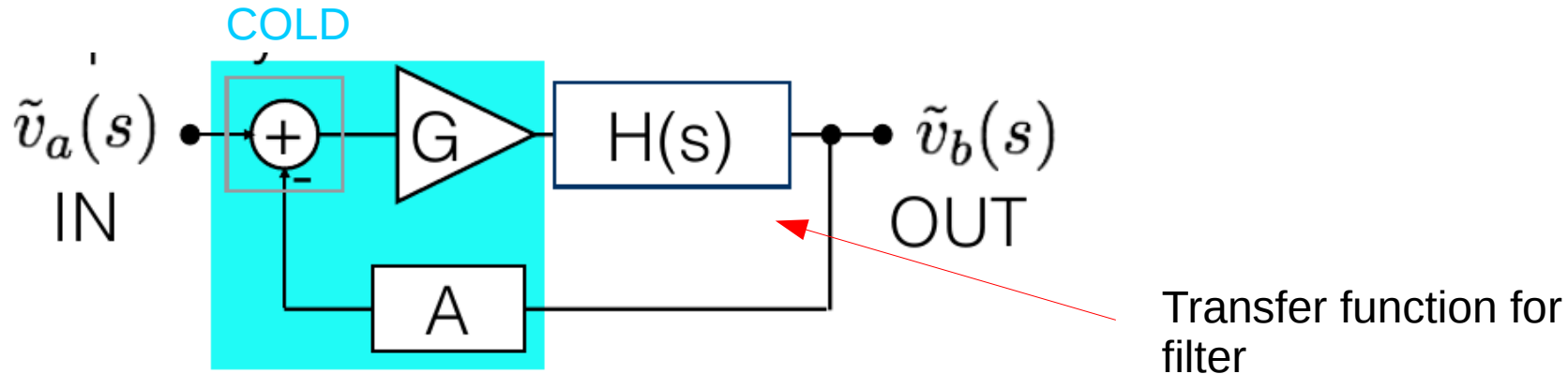
$$\omega_0 = \frac{1}{\sqrt{LC}} \quad \frac{\Gamma}{\omega_0^2} = RC$$

$$H(s) = \frac{\frac{s\Gamma}{\omega_0^2}}{1 + \frac{s\Gamma}{\omega_0^2} + \frac{s^2}{\omega_0^2}}$$

Frequency domain model:



# Equivalent Circuit Analysis (Closed Loop Case)



$$\tilde{v}_b(s) = GH(s)\tilde{v}_a(s) - AGH(s)\tilde{v}_b(s)$$

$$H_C(s) = \frac{\tilde{v}_b(s)}{\tilde{v}_a(s)} = \frac{GH(s)}{1 + AGH(s)} = \frac{\frac{Gs\Gamma}{\omega_0^2}}{1 + \frac{(1+AG)s\Gamma}{\omega_0^2} + \frac{s^2}{\omega_0^2}}$$

FWHM =  $(1+AG)\Gamma$  which for stable operation must be less than  $2\Gamma$  (see next slide)

# Does it Oscillate?

The Nyquist criteria for oscillation are that, at the frequency  $\omega_0$  where resonance might occur, the OPEN LOOP gain of the circuit is 1 or greater, and the phase shift is  $2n\pi$ . Here we have:

$$H_O(s) = AGH(s) = \frac{\frac{AGs\Gamma}{\omega_0^2}}{1 + \frac{s\Gamma}{\omega_0^2} + \frac{s^2}{\omega_0^2}}$$

So that when  $s = i\omega_0$  we get  $H_O(i\omega_0) = AG$

In other words, as long as the attenuator has greater attenuation than the amplifier gain, the feedback loop will not oscillate.

# Practical Issues

- The amplifier needs to have a low-noise first stage and the attenuator must be cold.
- Both gain and attenuation must be high enough to make noise of r.t. electronics negligible.
- Gain \* attenuation must be stabilised to be less than 1 for all structures.
  - Sharing common electronics so leave some open circuit to monitor the gain and use this to control the gain in the room-temperature filter electronics.

# Further Work

- Test in lab with r.t. capacitor. Measure Q and test ability to tune resonant frequency.
  - Filter can be made using something like AD9361 ‘agile transceiver’ controlled by FPGA.
  - Alternatively a ADC/DAC board and dedicated components could be used to make a simpler testbed.
- Modelling of rf coupling to plate structures needed (CST).
- Could use these ‘artificial modes’ even in a resonant cavity structure.