Superconducting Non-Foster Networks for Axion Detection

Pam Stark, Ph.D. Candidate
Stanford University
Coordinating Panel on Advanced Detectors (CPAD), 2026

Elements of an axion experiment

Signal Source

How do you couple to the axion?

Readout

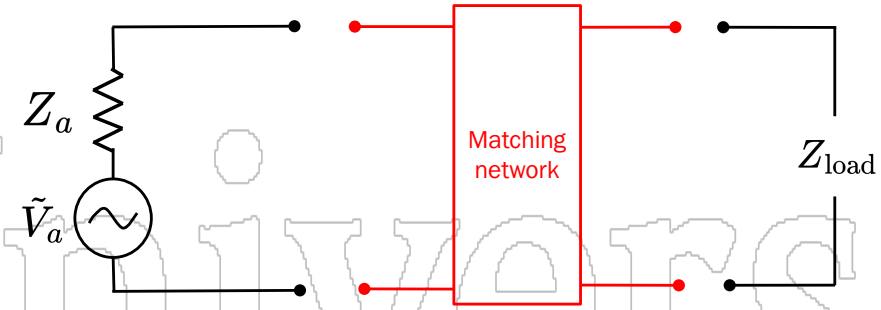
How do you amplify the signal?



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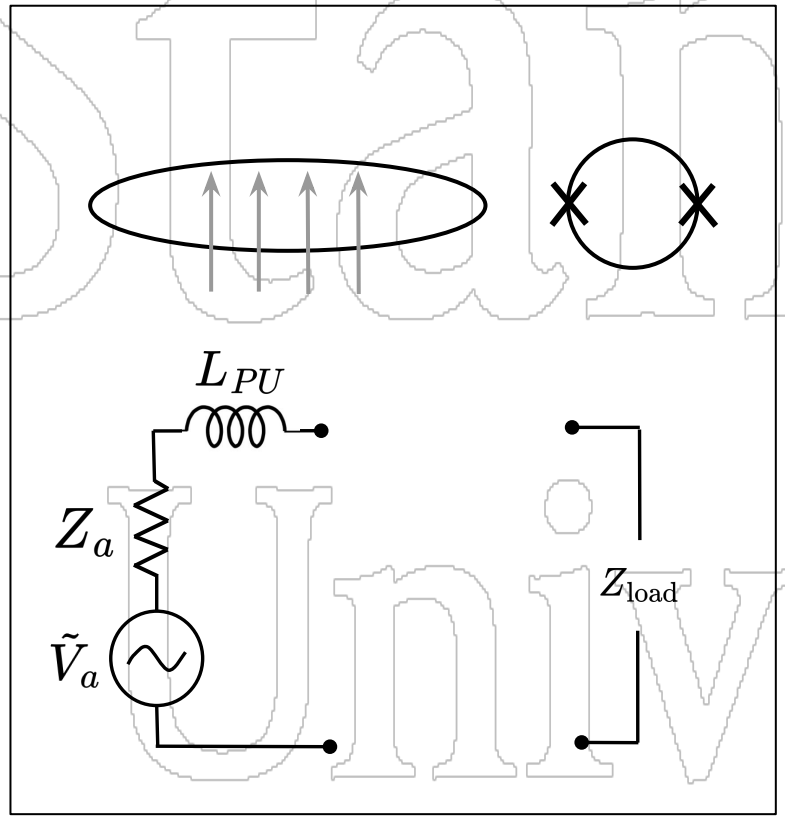
Elements of an axion experiment

Signal Source	Matching Network	Readout
How do you couple to the axion?	How do you match signal to readout?	How do you amplify the signal?



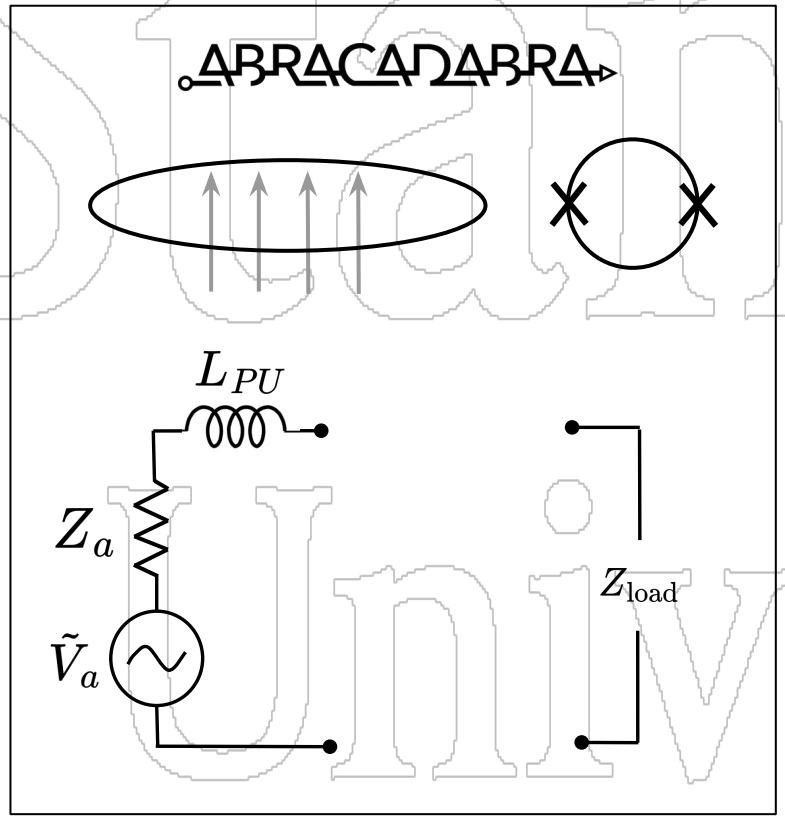
Your choice of matching network is a key factor to your sensitivity due to the impedance mismatch between the dark matter source impedance and the self impedance of your pickup.

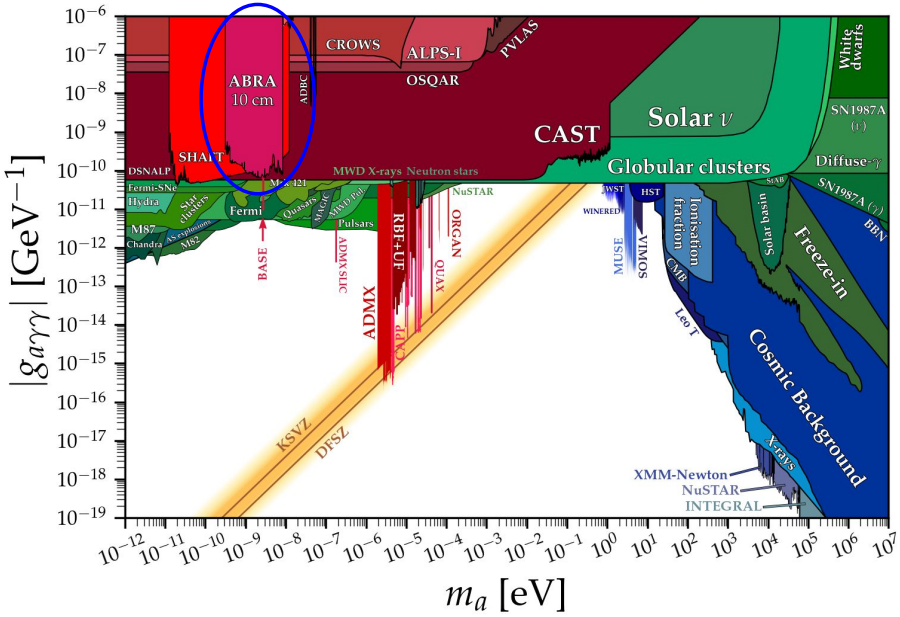
Let's consider some practical models of a lumped element axion experiment…



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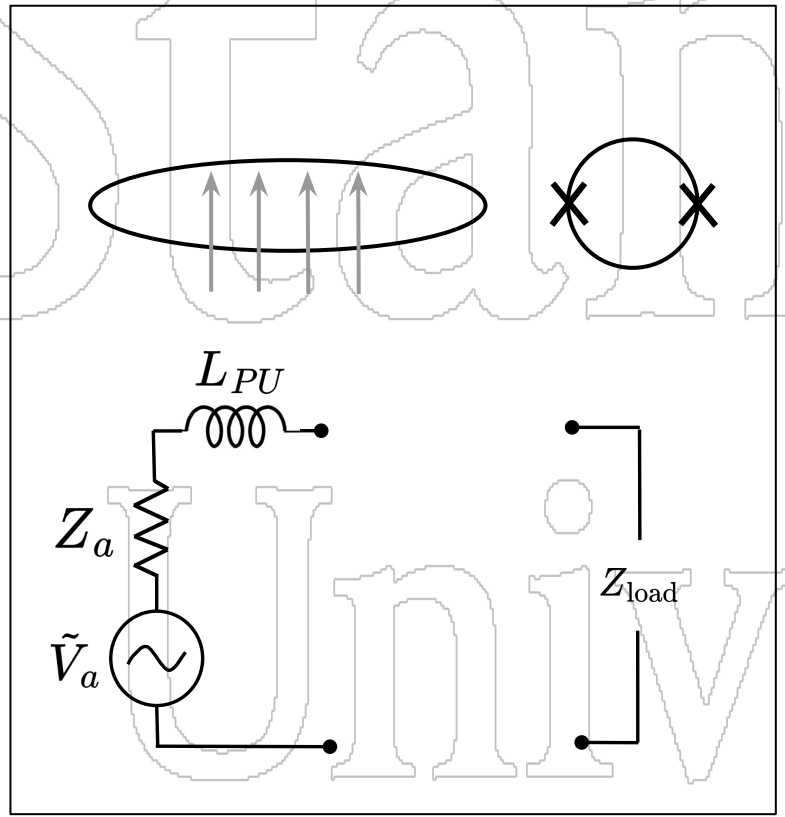
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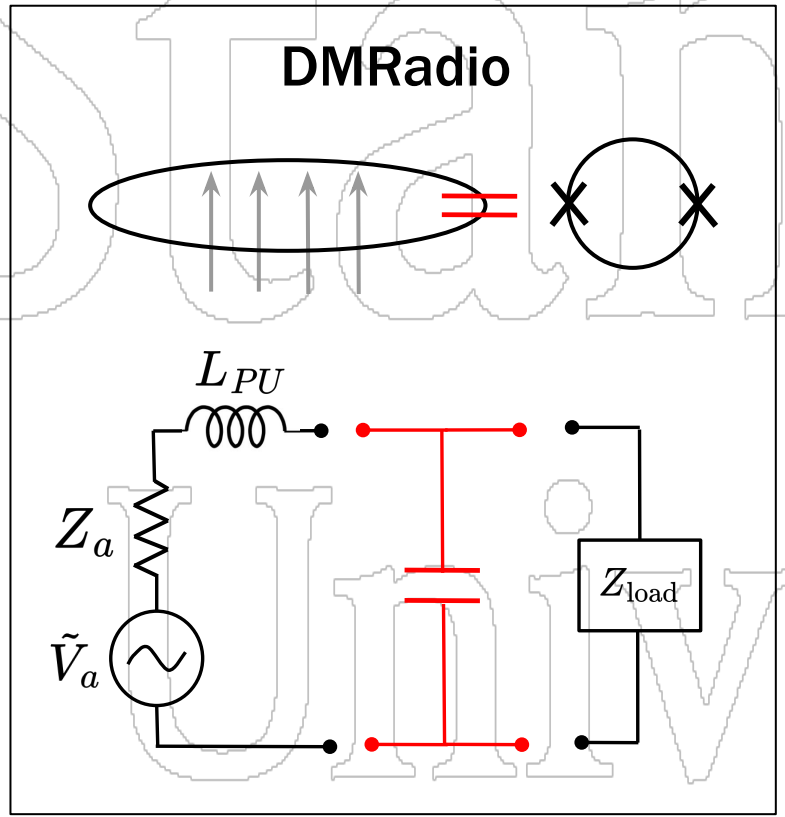
Courtesy of Ciaran O'Hare https://cajohare.github.io/AxionLimits/

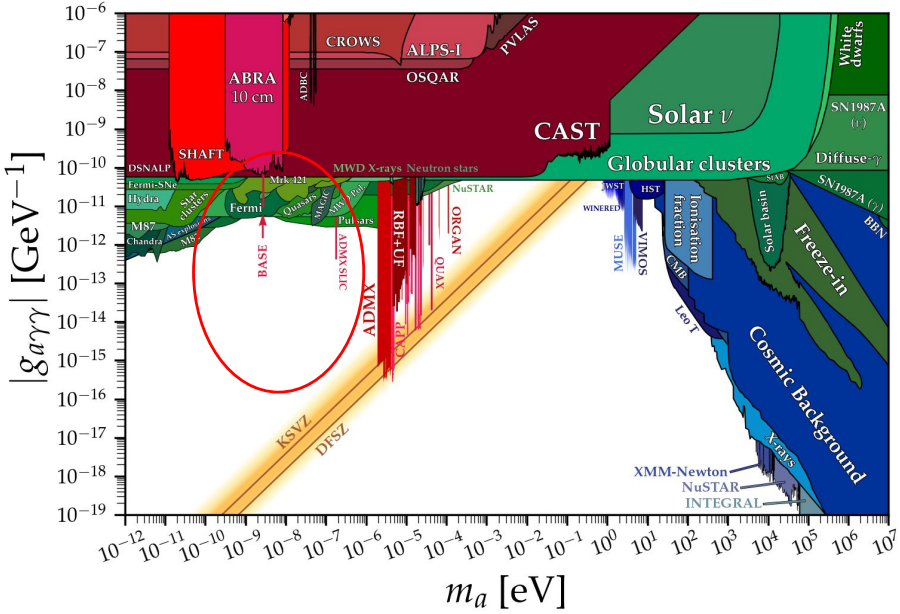
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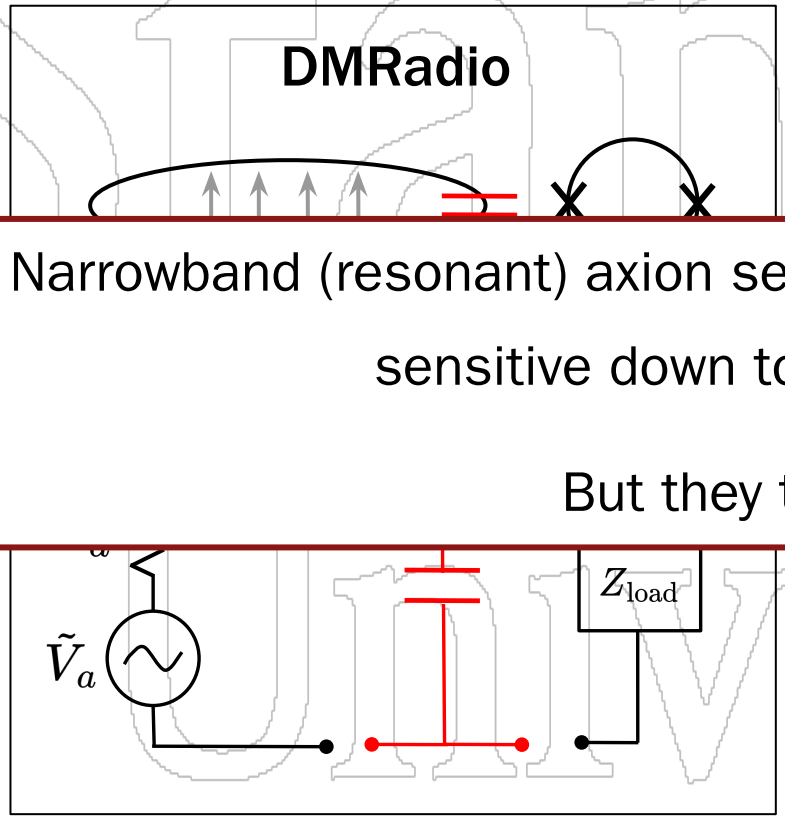
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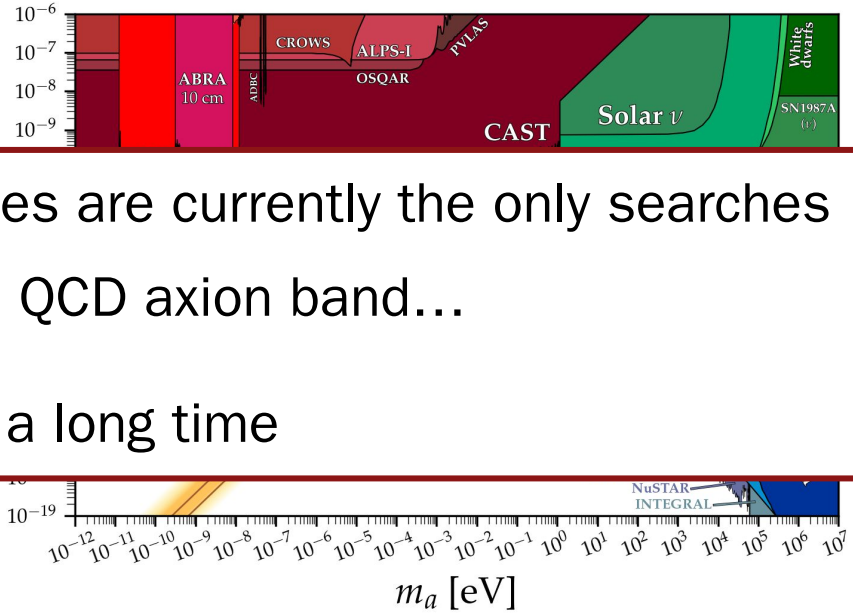




Courtesy of Ciaran O'Hare https://cajohare.github.io/AxionLimits/

Let's consider some practical models of existing axion experiments…



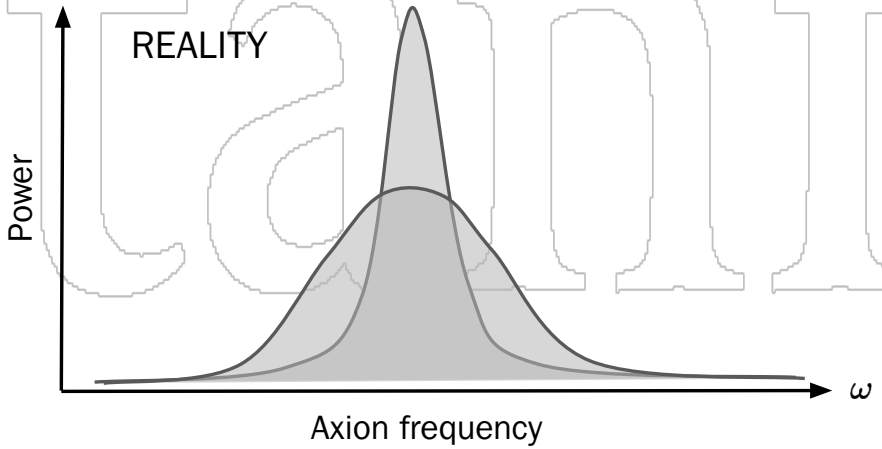


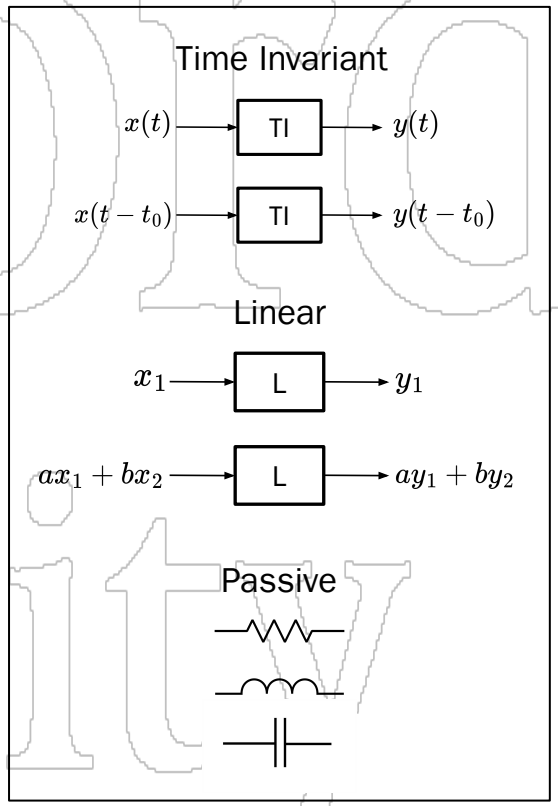
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Narrowband (resonant) axion searches are currently the only searches sensitive down to the QCD axion band…

But they take a long time

Bode-Fano Constraint: Any time-invariant, passive, linear network demonstrates a tradeoff between the bandwidth and the maximum power



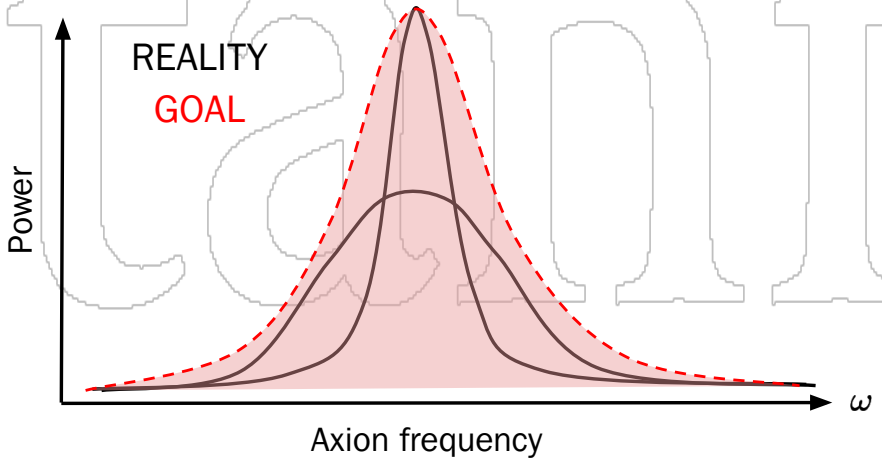


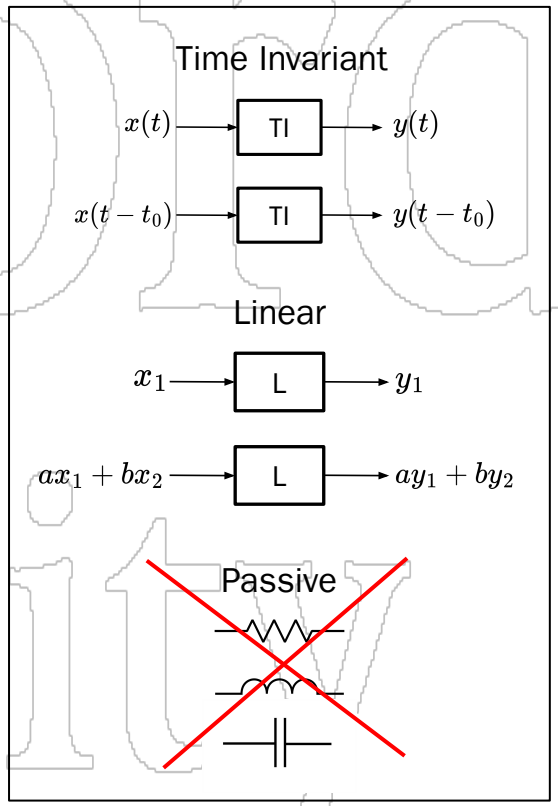
"Bode Fano integral"

$$\int_0^\infty \ln\frac{1}{|\rho|}d\omega = \text{ Some max. value}$$

Reflection coefficient $\rho = \dfrac{Z-1}{Z+1}$

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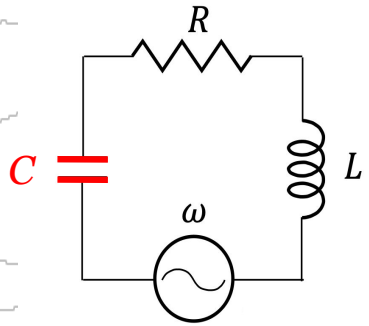
Some greater value!

Reflection coefficient $\rho = \dfrac{Z-1}{Z+1}$

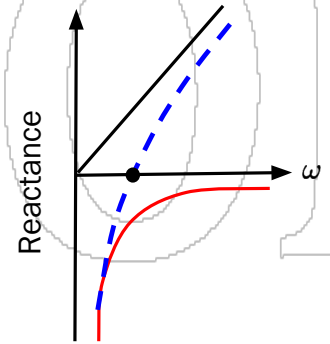
Non-Foster devices are active circuits that violate *Foster's reactance theorem* to build negative reactance devices

Power extracted from source:

$$P = \frac{V^2}{Z}$$



$$Z = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$



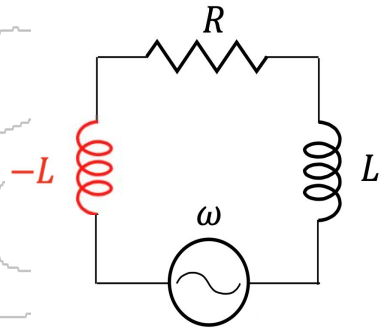
Z minimized, power maximized *on resonance*

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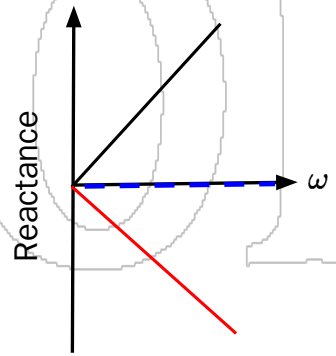
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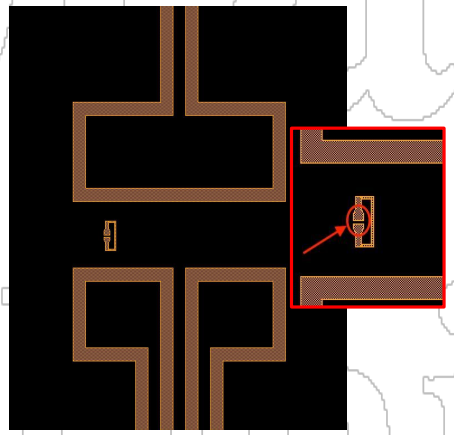
Power maximized at *all* frequencies

What properties would an idealized negative inductor need to have?

- Same **frequency-dependence** as a positive inductor
- Same **IV relation** as a capacitor (180 phase shift from positive inductor)

Josephson junctions offer a potential path towards building cryogenic non-Foster elements

- JJs are a fundamental **non-linear, active circuit** component with a phase-dependent kinetic inductance that can be tuned by biasing the device



Josephson Junction mask design
Credit to Jason Corbin

"Magic bias point"

$$\phi = \pi$$

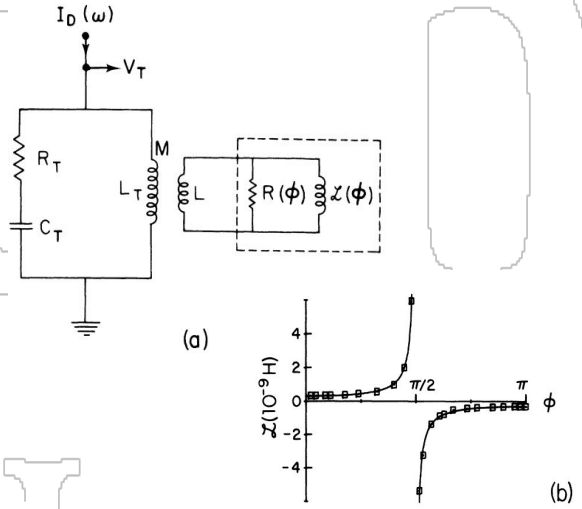
Josephson Equations:

$$I(t) = I_c \sin(\phi(t))$$

$$\frac{\partial \phi}{\partial t} = \frac{2eV(t)}{\hbar}$$

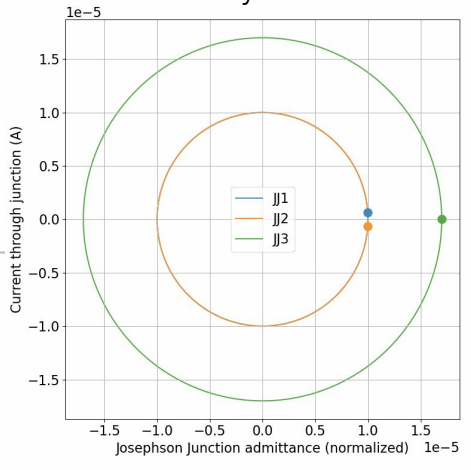
$$L = \frac{\Phi_0}{2\pi} \frac{1}{I_c \cos\phi}$$

Negative inductance as part of larger junction networks has already been observed



Rifkin & Deaver[2] negative junction circuit

Created by Andrew Yi

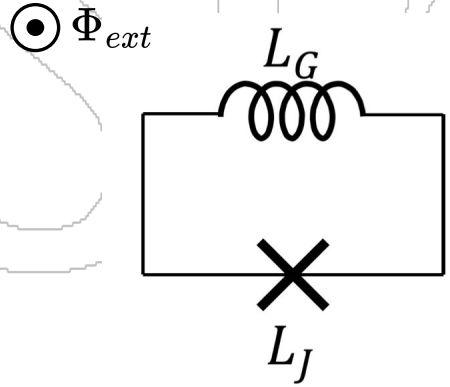


Demonstration of stable negative inductance states in quantum devices by the Irwin group

...but not all negative inductance configurations are Bode-Fano evading

[2] R. Rifkin and B.S. Deaver, Jr., Phys. Rev. B 13, 3894 (1976)

We start by considering the flux quantization equation for a simple superconducting loop, then generalize to a larger network

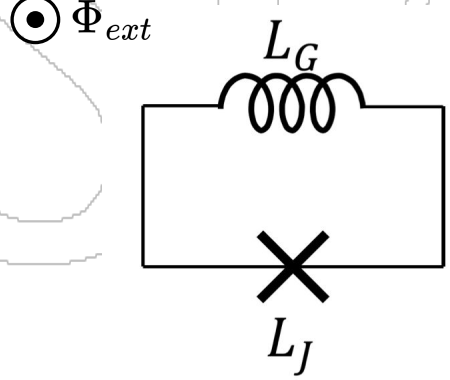


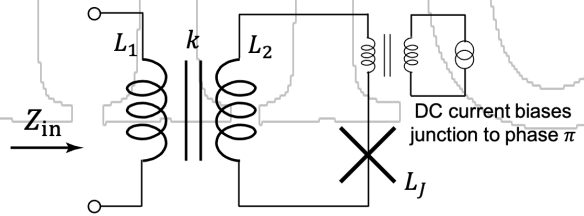
$$\frac{\Phi_0}{2\pi}\left[\phi - \phi_0 + \underbrace{\frac{L_G}{L_{J,0}}}_{\beta_L}\sin\phi\right] = n\Phi_0,$$

$\beta_L < 1$, non-hysteretic
$\beta_L > 1$, hysteretic

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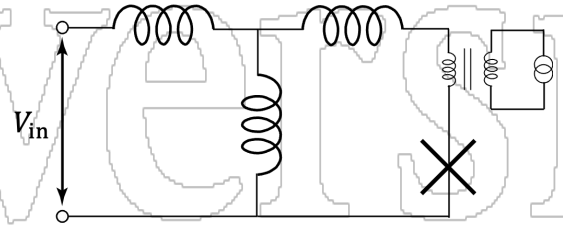




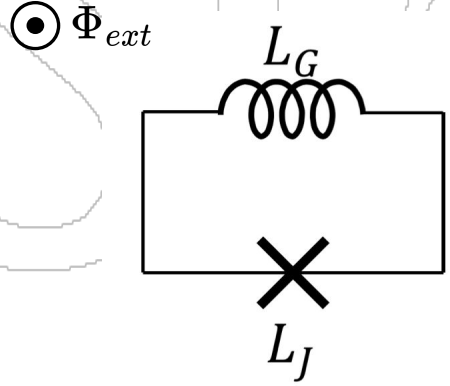
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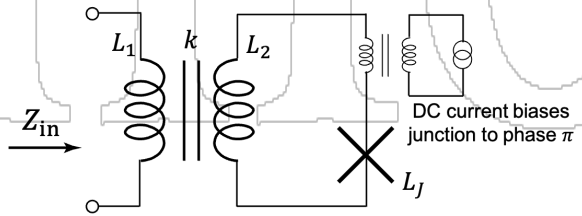


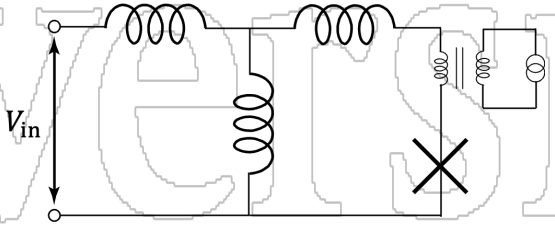
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When the junction loop part of a larger network, the inductance it sees is now the total network inductance

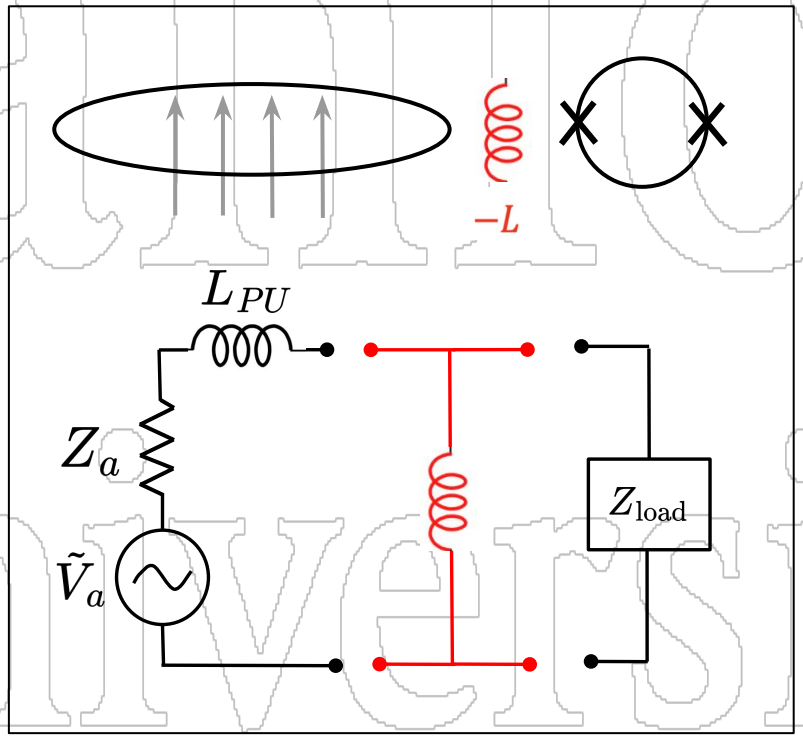




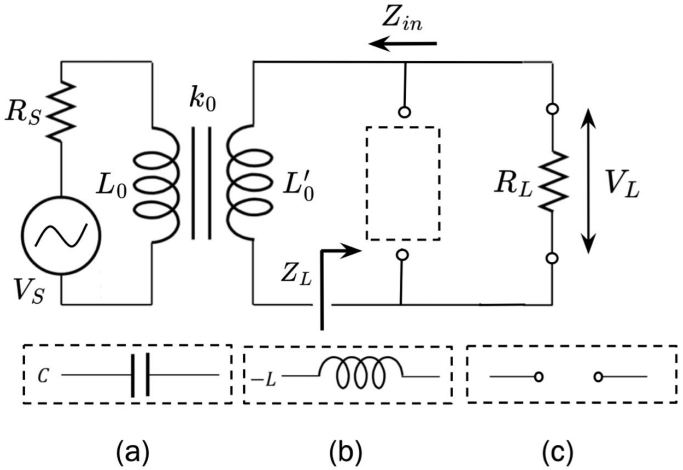
$$L_G = L_2\left(1 - \frac{k^2 L_1}{L_1 + L_0}\right)$$

L0: upstream network inductance; assumed to be dominant compared to sources of capacitive or resistive impedance

Returning to our model of the axion… what if we can replace the capacitor with our proposed negative inductance device?

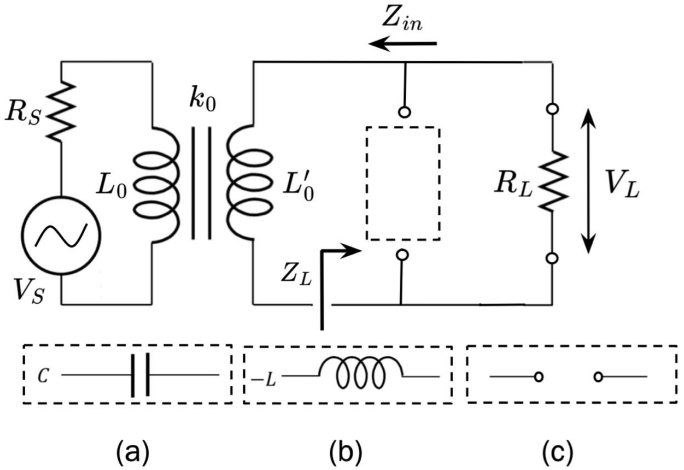


We incorporate the device as part of a larger axion-like receiver chain and evaluate it in WRSpice against two common matching networks

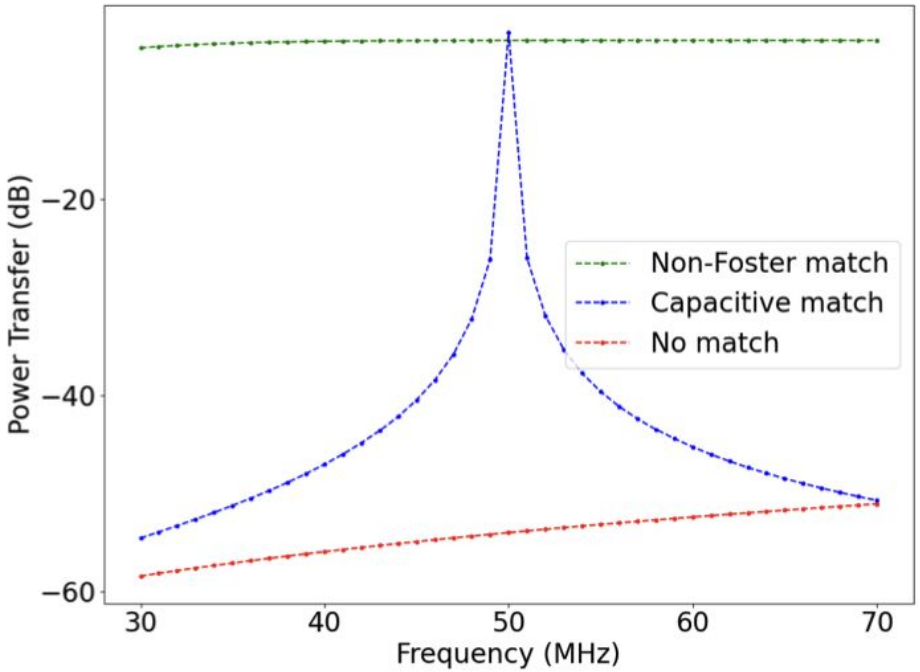


(a) Standard capacitive match
(b) Negative inductor match
(c) Open – no match

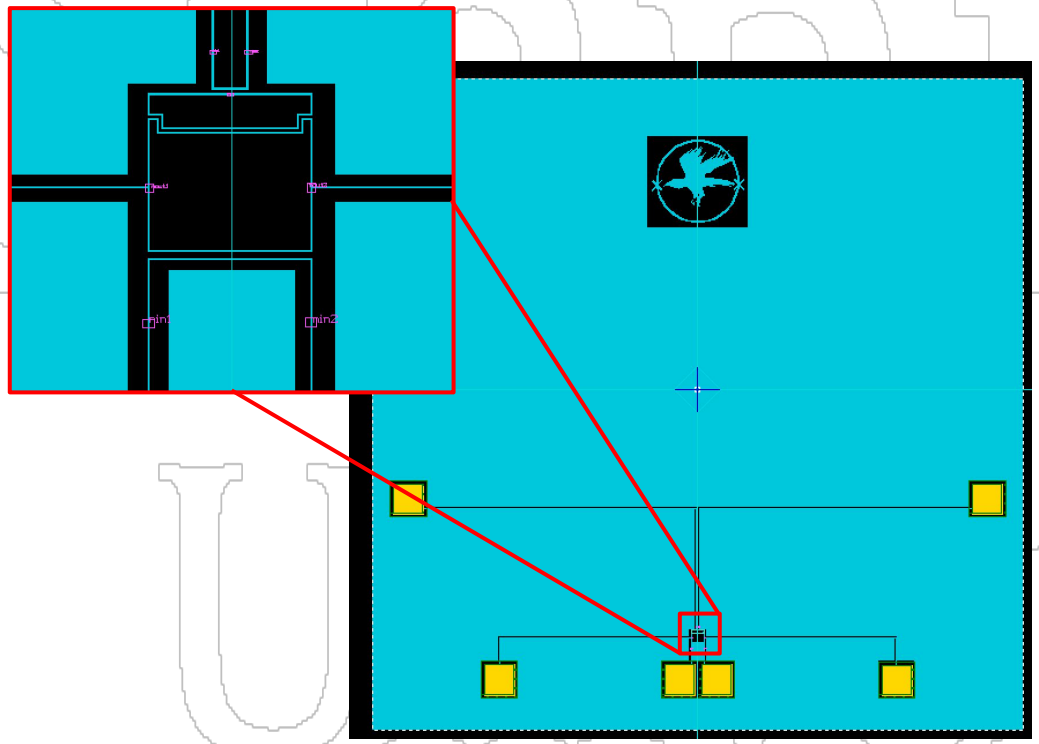
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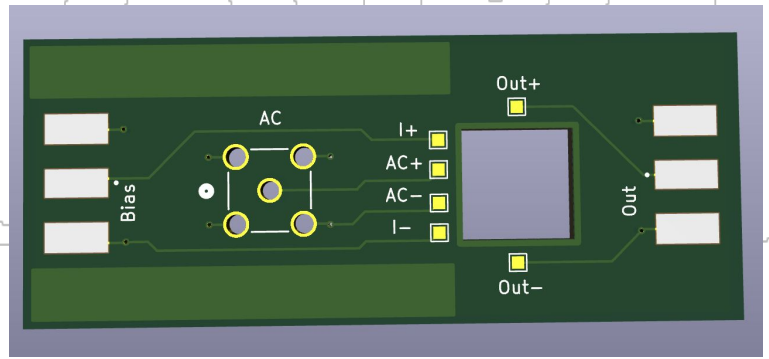


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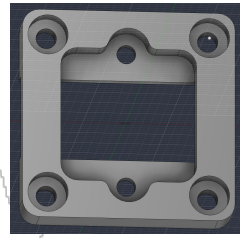


First on-chip design to be fabricated at the Stanford Nanofabrication Facility









Can this actually be realized as a stable device?

Stability considerations:

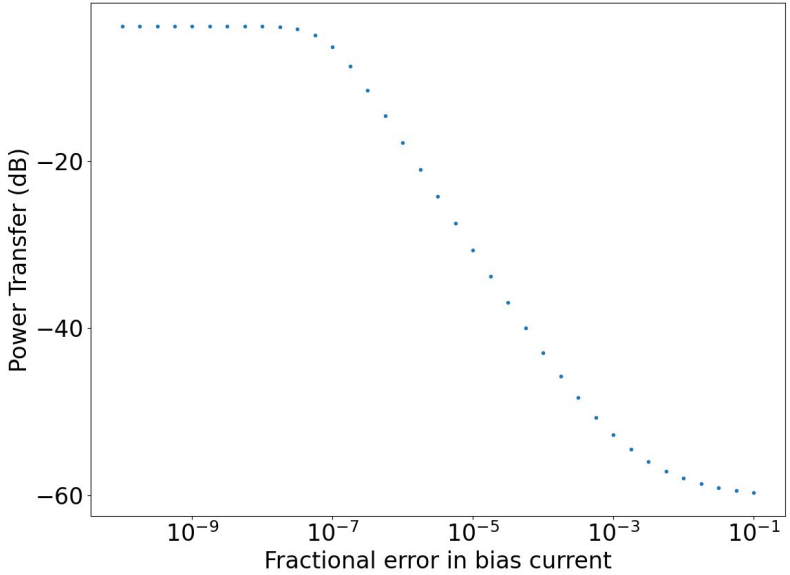
1) Tolerances needed for critical parameters to achieve to intended negative inductance
2) Stability over time

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Natural variations in fabrication parameters and noise on bias sources could lead to sub-optimal device performance

Stability considerations:

1) Tolerances needed for critical parameters to achieve to intended negative inductance
2) Stability over time



Configuration	L_1	L_2	k	A	B	C
$L_{\text{eff}} = -L_0$	3.297	3.449	0.3	-3.844	-12.061	-30.625
$L_{\text{eff}} = -1.005L_0$	3.747	3.459	0.3	-8.035	-10.451	-30.154
$L_{\text{eff}} = -1.01L_0$	3.498	3.453	0.3	-13.331	-13.797	-29.615

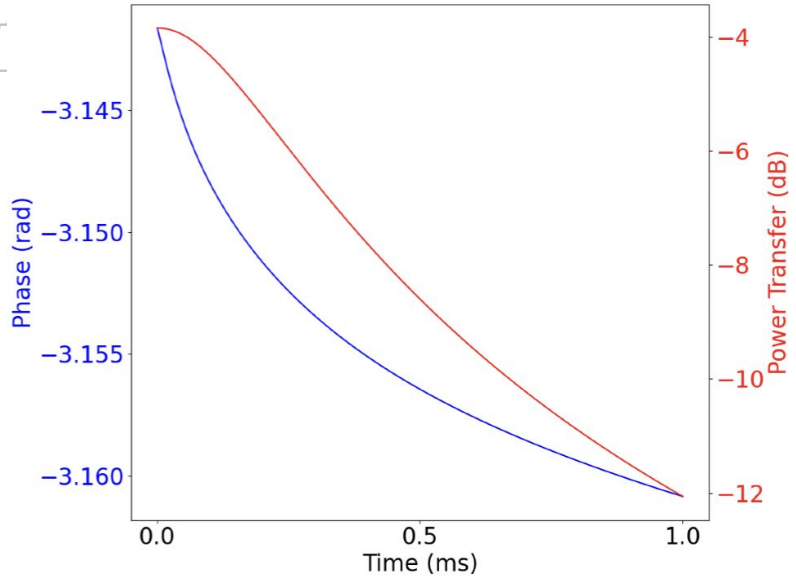
Comparison of transfer values at A: 1us,

B: 1ms, and C: 1ms with current error

Device is coherent on time scales of ~0.1 milliseconds before prepared state begins to drift

Stability considerations:

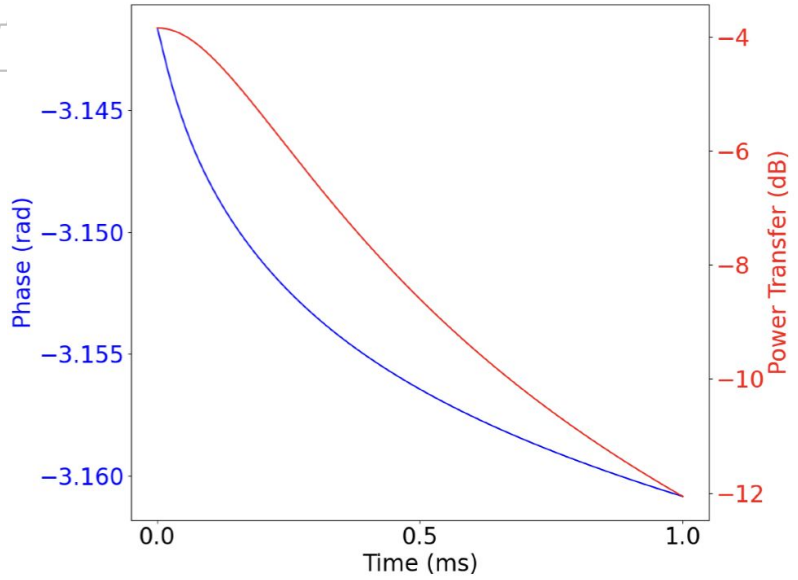
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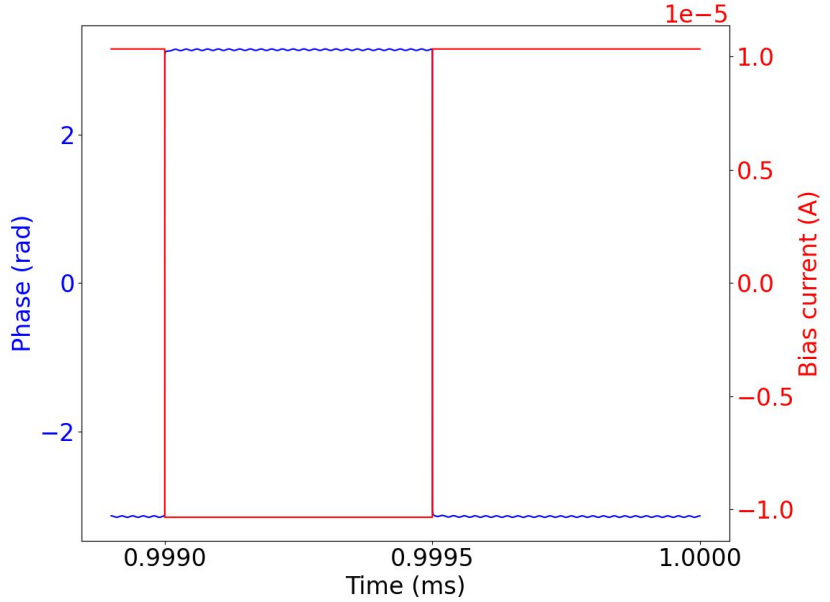


Pulsed operation may allow us to maintain coherence for longer, but introduces more complexity into data acquisition

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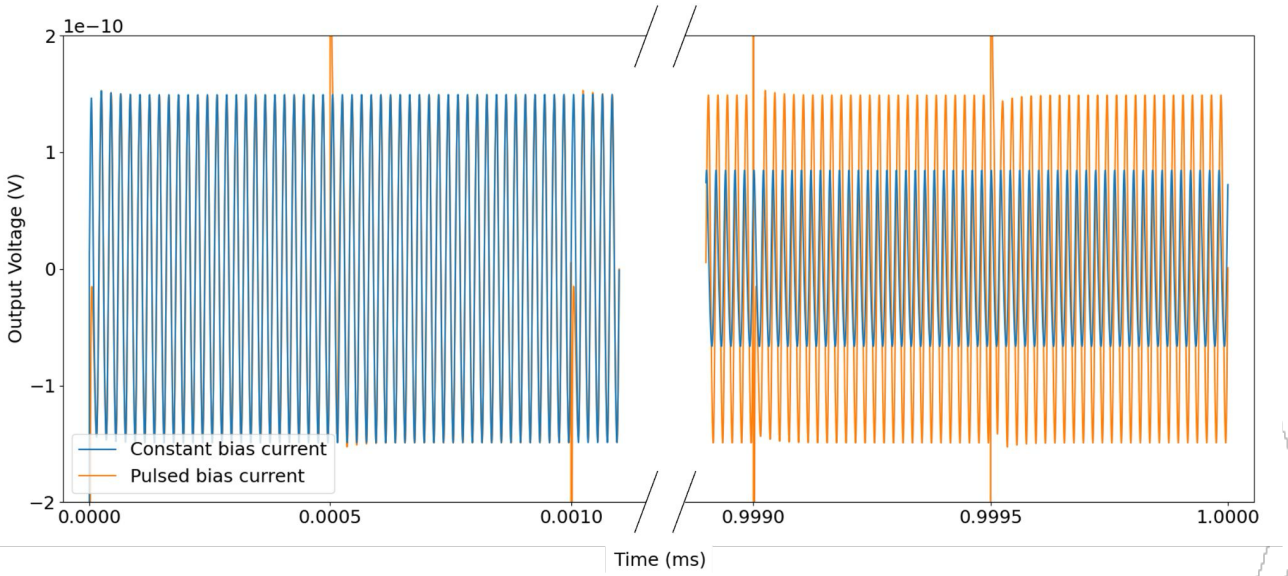




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Stability considerations:

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Conclusion: By framing the sensitivity of axion detectors as an *impedance matching problem*, we propose a device that may enable broadband detector operation

Josephson junctions as building blocks for non-Foster broadband networks are an under-explored area

Current priorities:

- Fabricating first prototype and establishing infrastructure in our dilution refrigerator
- Developing a data acquisition system that can support pulsed operation
- Incorporating realistic sources of noise into simulation and modeling

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Acknowledgments



Chelsea Bartram



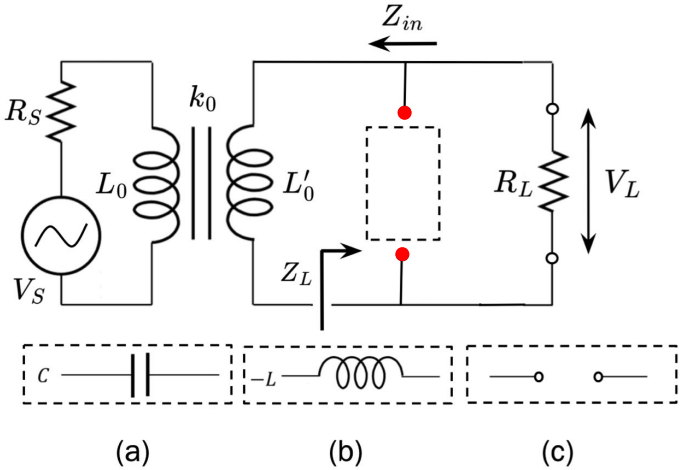
Andrew Yi



Pam Stark

Andrew Yi and materials for this research were supported by the Department of Energy, Laboratory Directed Research and Development program at SLAC National Accelerator Laboratory, under contract DE-AC02-76SF00515 and as part of the Panofsky Fellowship awarded to Chelsea Bartram. Pamela Stark is supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-2146755.

We incorporate the device as part of a larger axion-like receiver chain and evaluate it in WRSpice against two common matching networks



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More current is flowing through the network!

