

# Science reach and electromagnetic modeling of DMRadio-m<sup>3</sup>

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DMRadio Collaboration

TAUP 2023 – August 28 – Vienna, Austria

# Outline

1. DMRadio-m<sup>3</sup> introduction and geometry
2. Extracting the sensitivity
3. Science reach

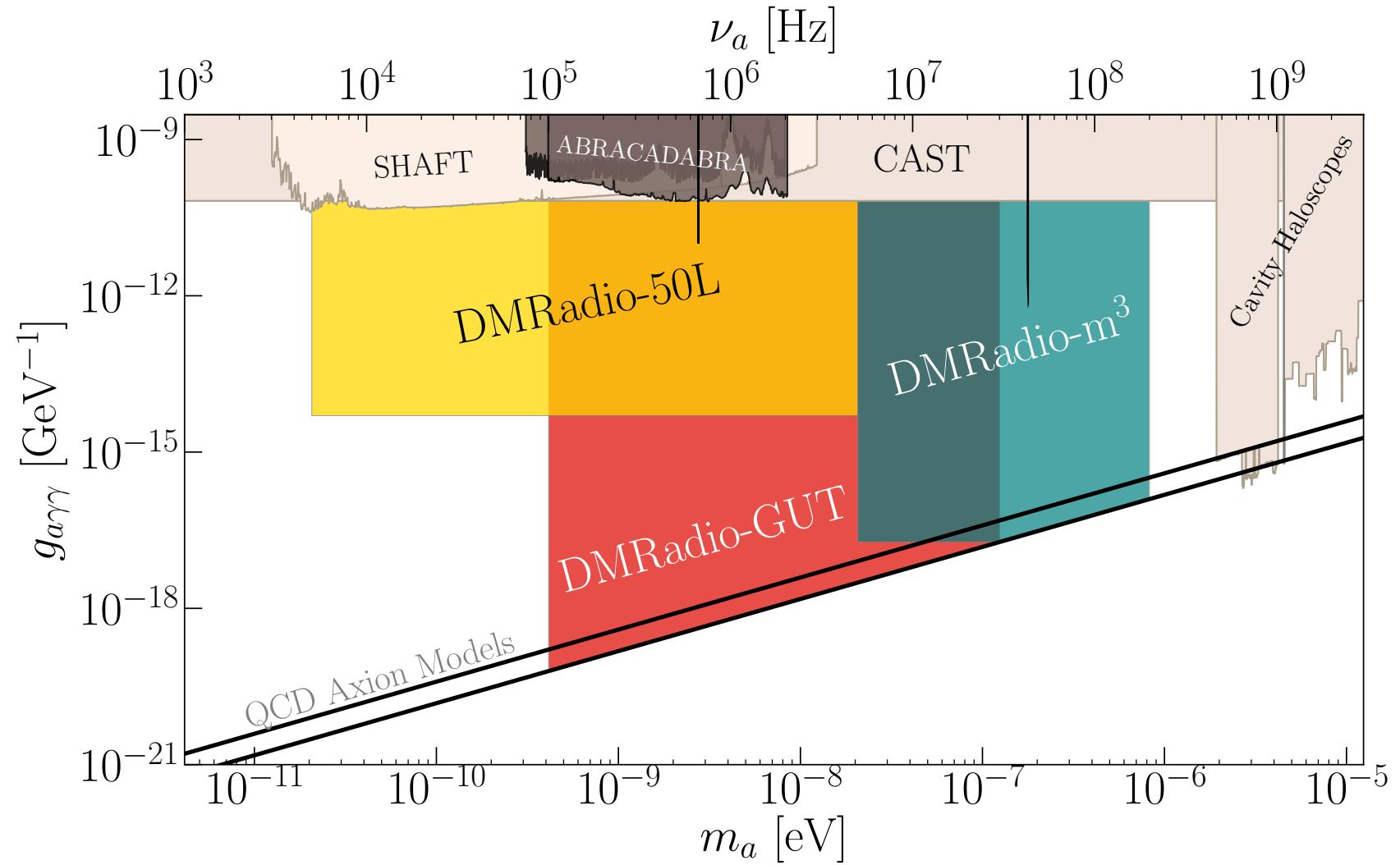
Based off of: arXiv:2302.14084

# Outline

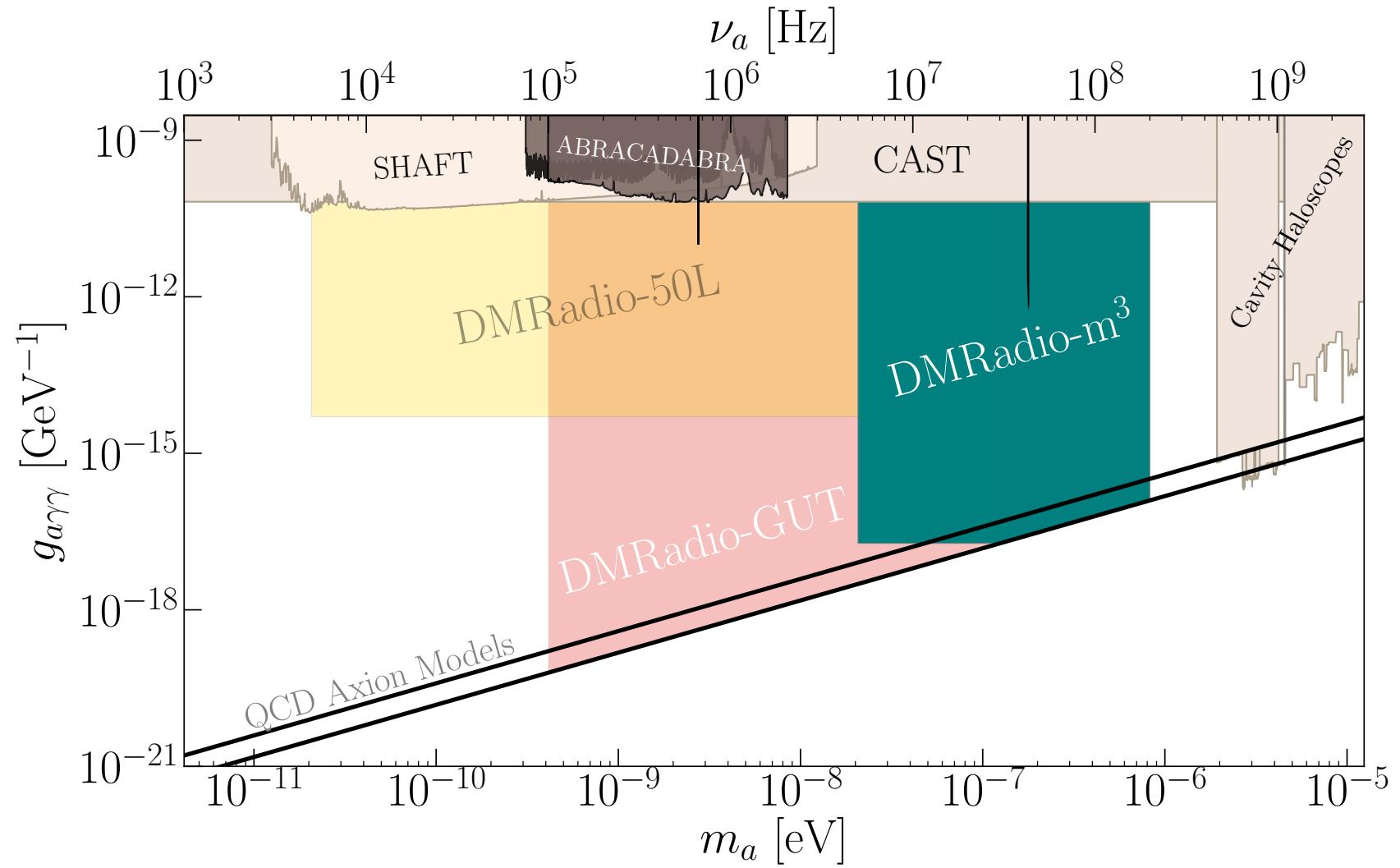
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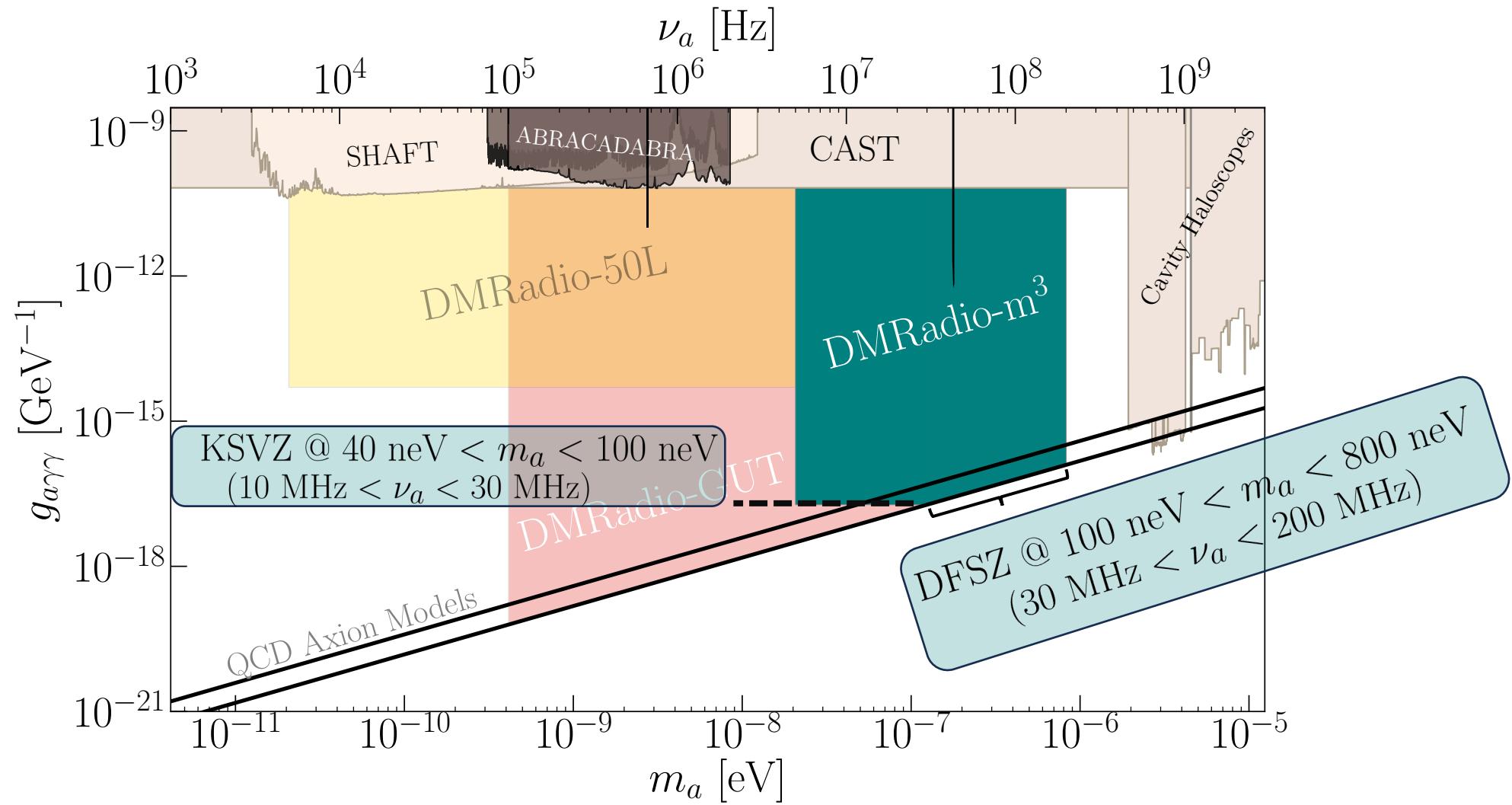
# DMRadio



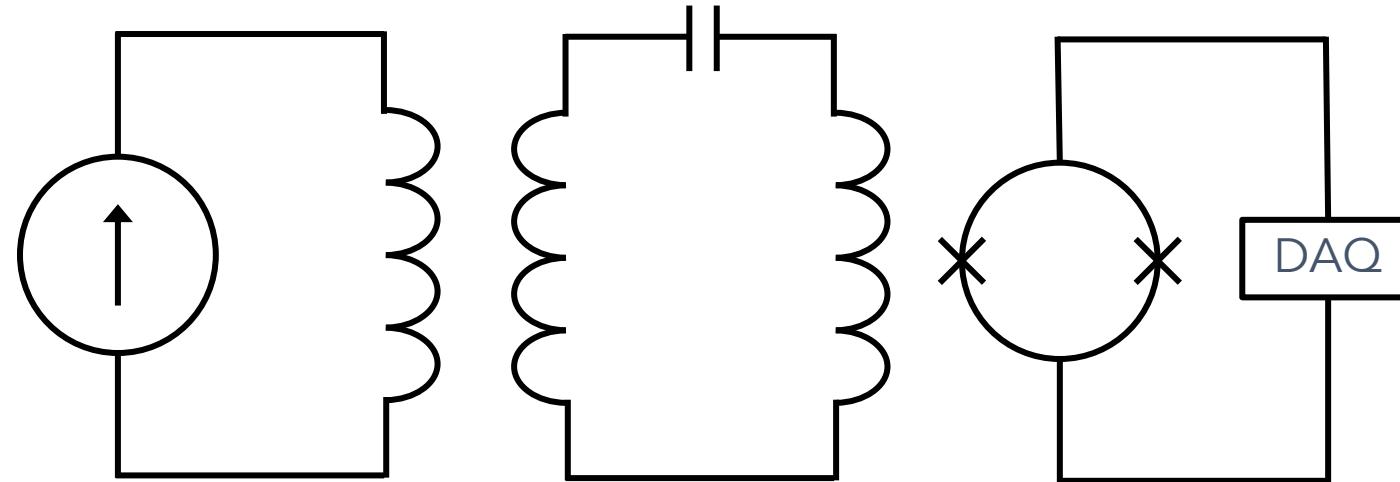
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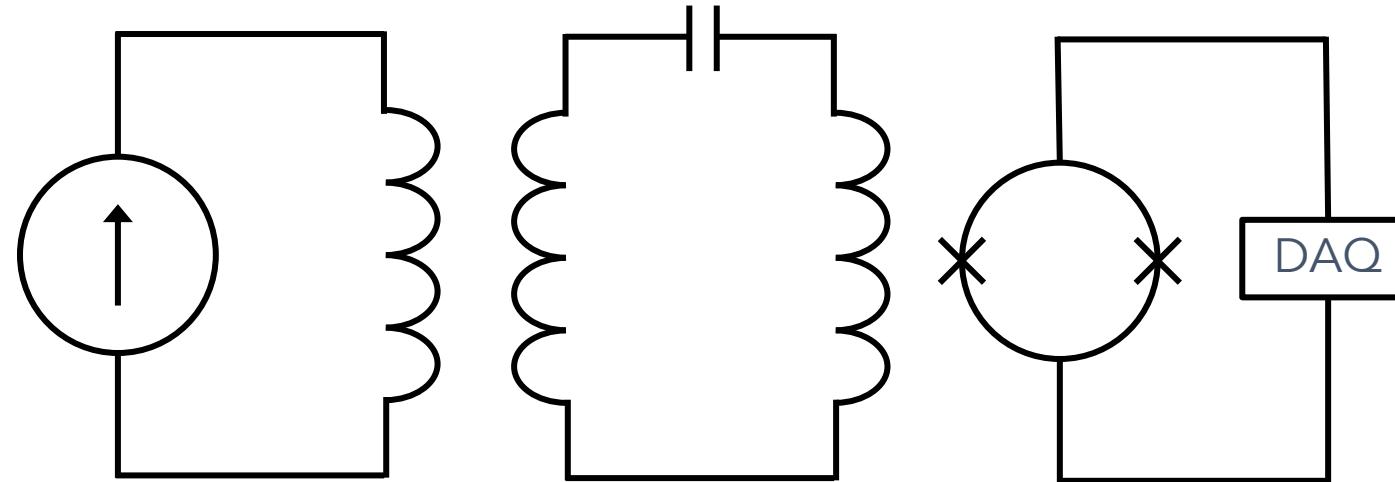


# Lumped element detectors



$$Z(\nu) = R(\nu) + iX(\nu)$$

# Lumped element detectors



$$Z(\nu) = R(\nu) + iX(\nu)$$

0

Resonance condition: Reactance goes to zero

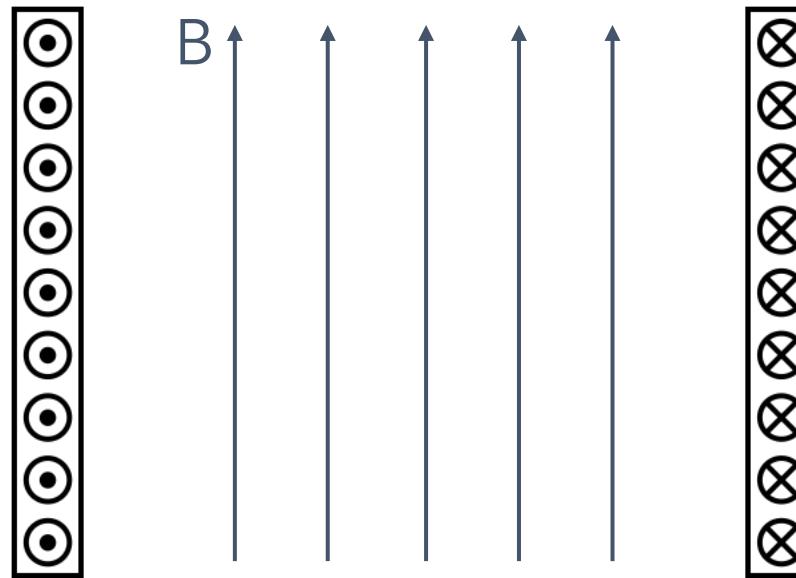
Enhancement of signal by Quality factor

# $m^3$ design

$m^3$  uses a solenoidal magnet + coaxial copper pickup

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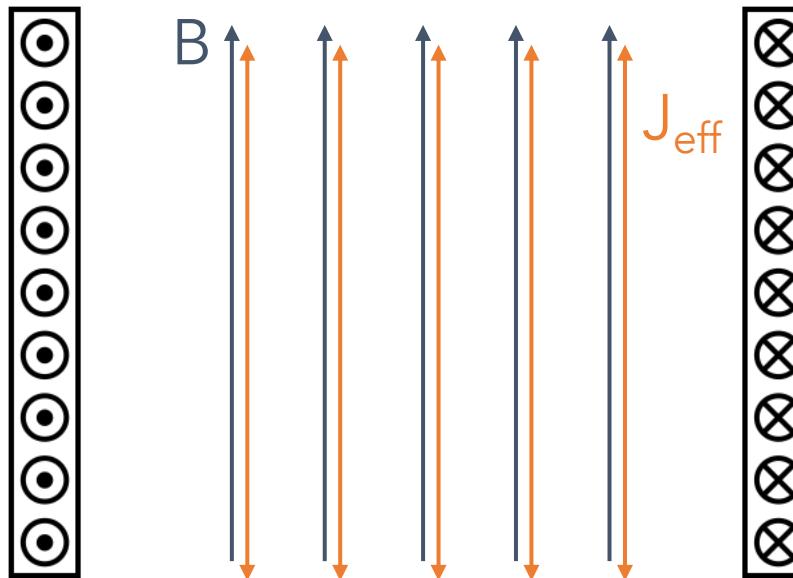
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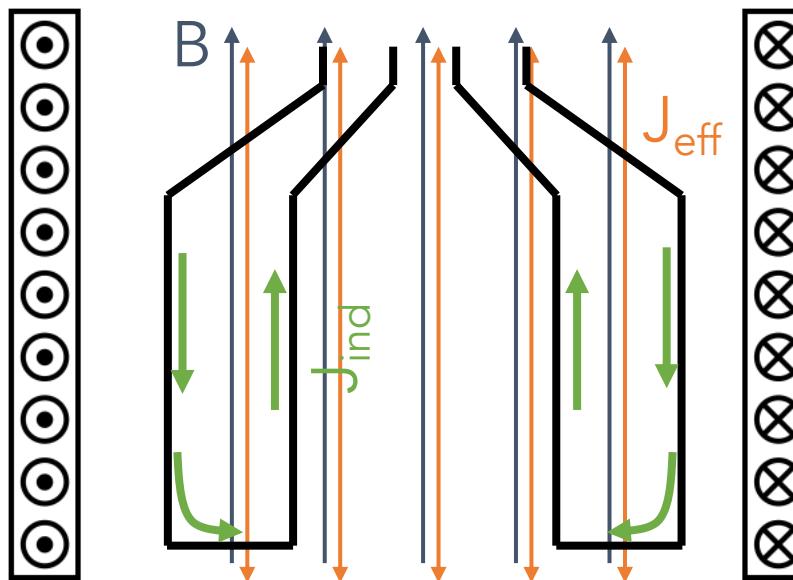
$$\mathbf{J}_{\text{eff}} \approx g_{a\gamma\gamma} \sqrt{2\rho_{\text{DM}}} \cos(m_a t) \mathbf{B}$$



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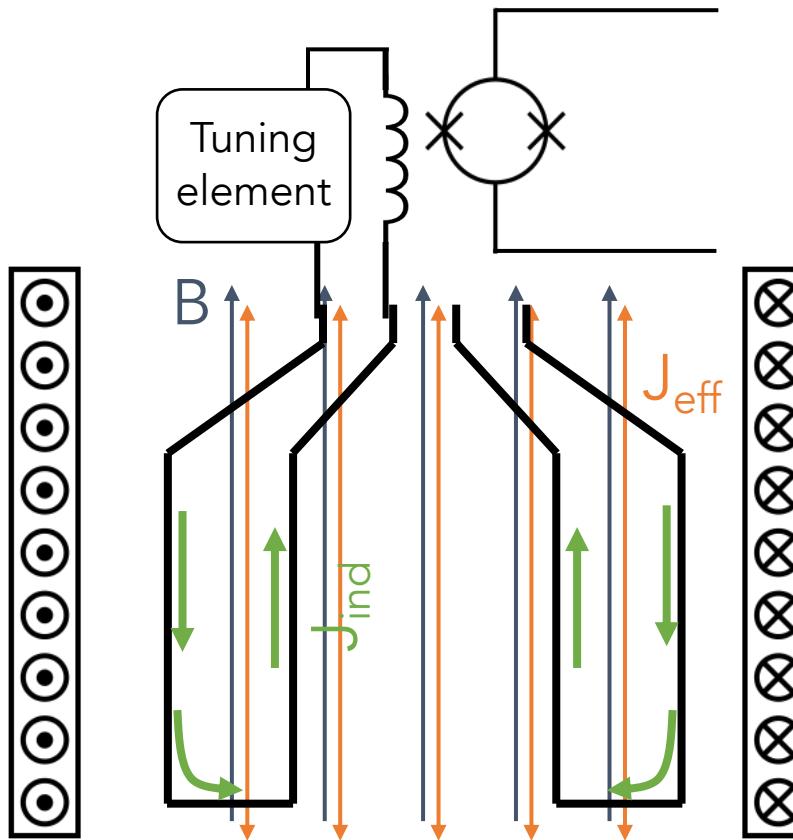
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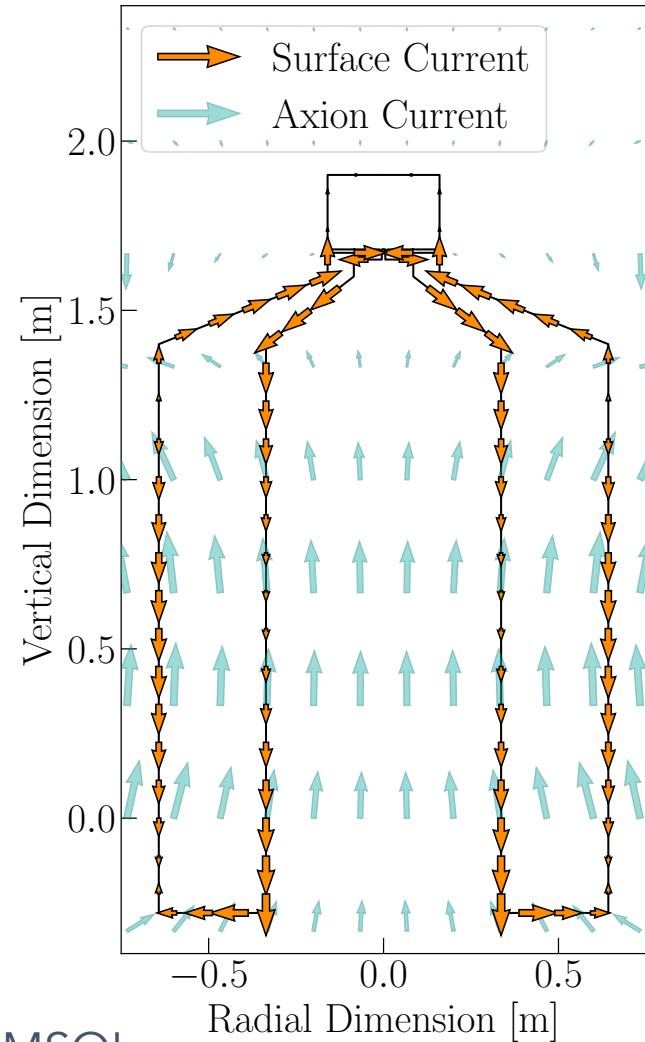
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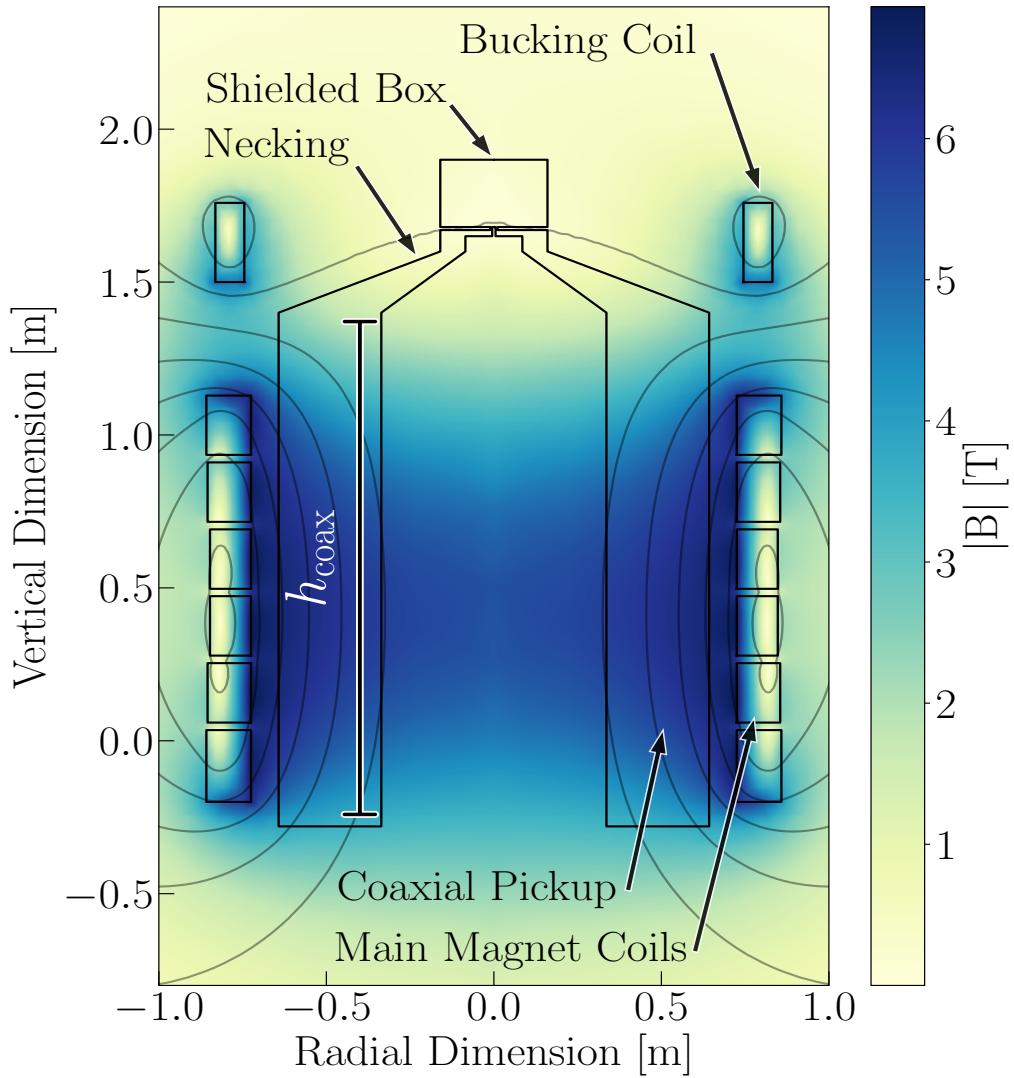
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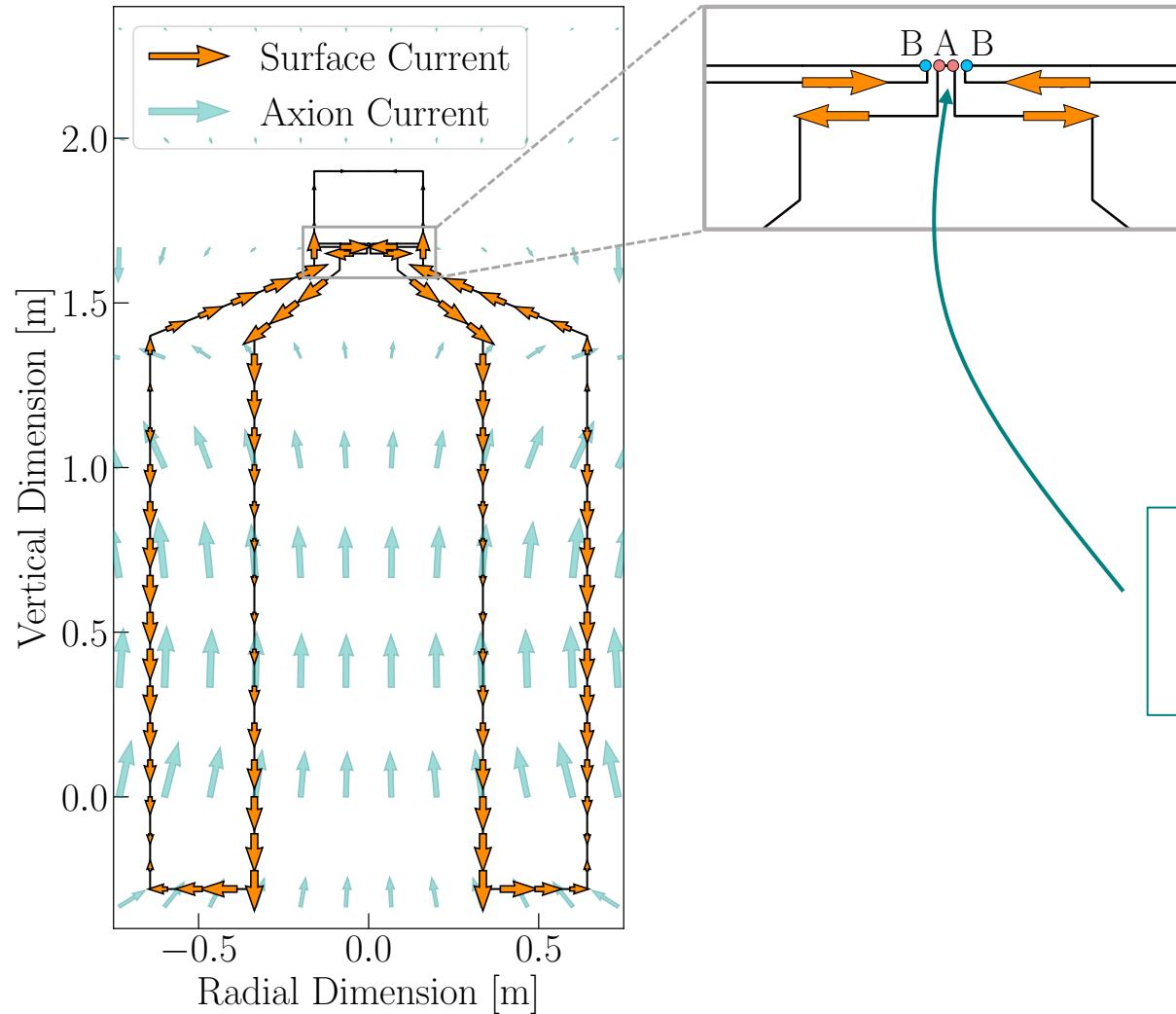
# $m^3$ design



Simulations on COMSOL



# $m^3$ design

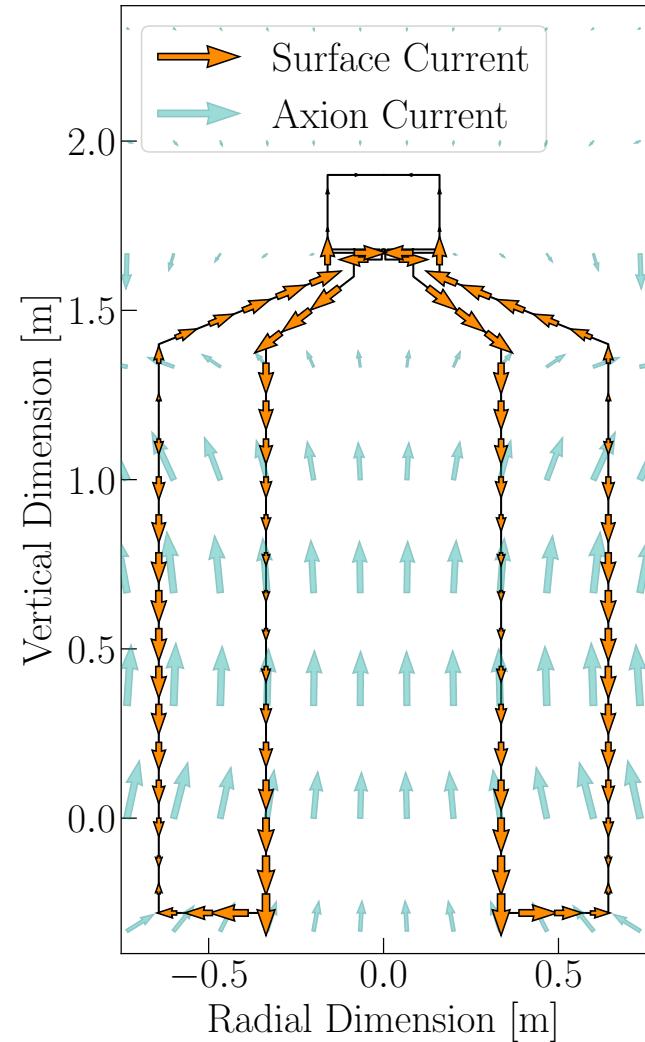


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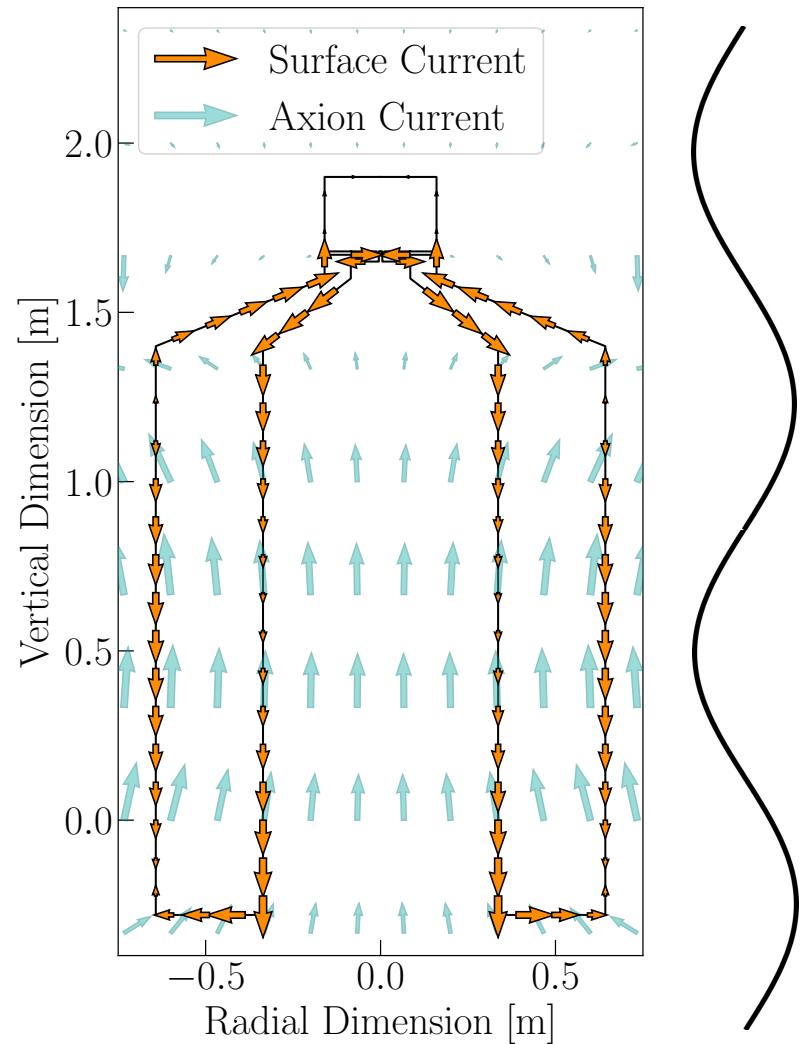
# Is this still lumped element?



DFSZ @  $100 \text{ neV} < m_a < 800 \text{ neV}$

$30 \text{ MHz} < \nu_a < 200 \text{ MHz}$

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DFSZ @  $100 \text{ neV} < m_a < 800 \text{ neV}$

$30 \text{ MHz} < \nu_a < 200 \text{ MHz}$

$10 \text{ m} > \lambda_a > 1.5 \text{ m}$

Wavelength approaches the size of the experiment. This is not in the lumped element regime. How do we extract the sensitivity?

# Scan rate

$$\frac{d\nu}{dt} = \frac{\pi (6.4 \times 10^5)}{16 \text{ SNR}^2 m_a^4} \frac{|V(m_a, B, g_{a\gamma\gamma})|^4}{L_{\text{eff}}(\nu_r)^2} Q(\nu_r) \bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)]$$

DM halo physics   Axion induced voltage   Quality Factor   Noise physics  
Effective inductance

# Scan rate

$$\frac{d\nu}{dt} = \frac{\pi (6.4 \times 10^5)}{16 \text{ SNR}^2 m_a^4} [V(m_a, B, g_{a\gamma\gamma})]^4 Q(\nu_r) \bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)] L_{\text{eff}}(\nu_r)^2$$

Diagram illustrating the components of the scan rate equation:

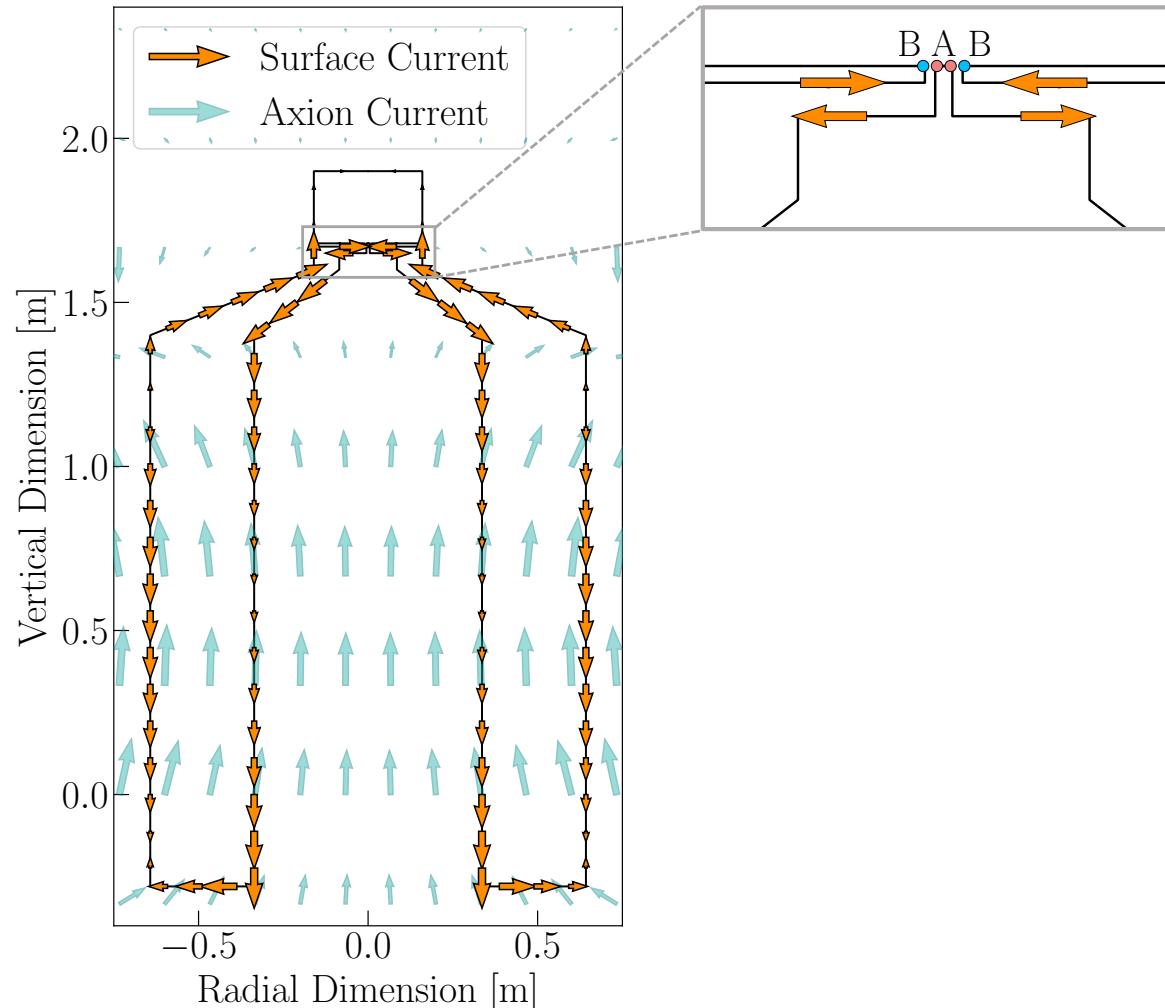
- DM halo physics**:  $\pi (6.4 \times 10^5)$  (green dashed box)
- Axion induced voltage**:  $[V(m_a, B, g_{a\gamma\gamma})]^4$  (orange dashed box)
- Quality Factor**:  $Q(\nu_r)$  (blue dashed box)
- Noise physics**:  $\bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)]$  (red dashed box)
- Effective inductance**:  $L_{\text{eff}}(\nu_r)^2$  (green solid box)

How do we calculate these parameters in this limit?

# Scan rate

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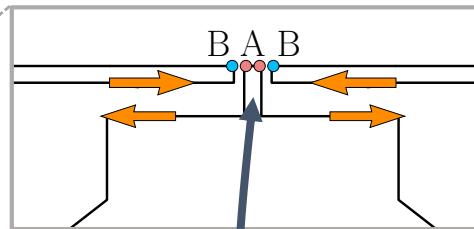
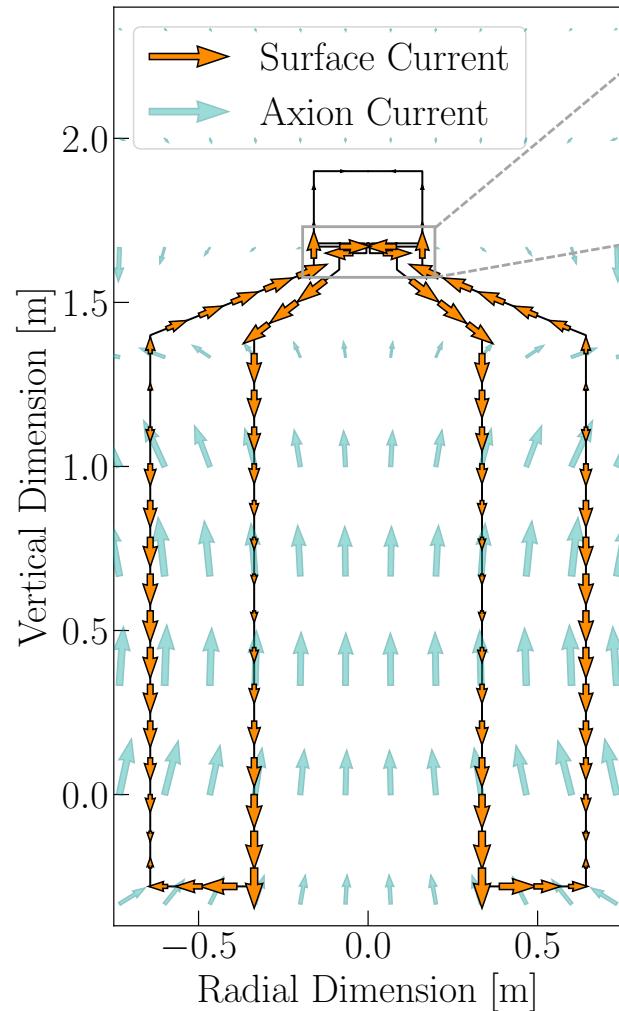
DM halo physics   Axion induced voltage   Quality Factor  
 Noise physics



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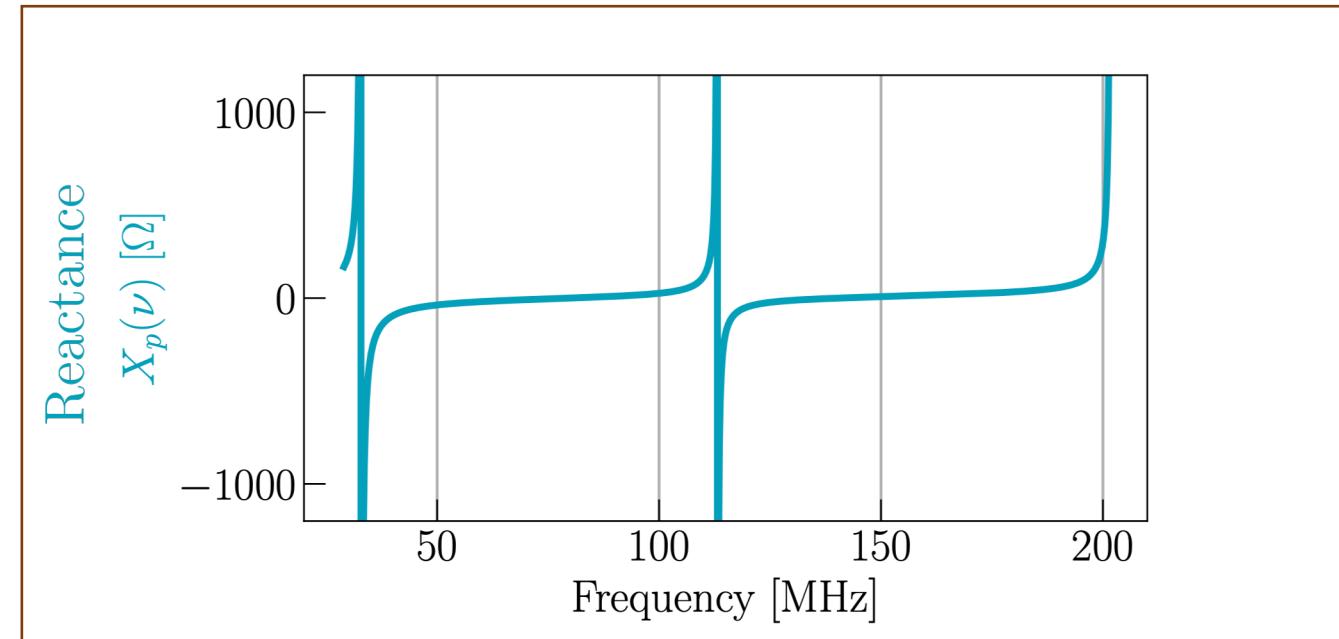
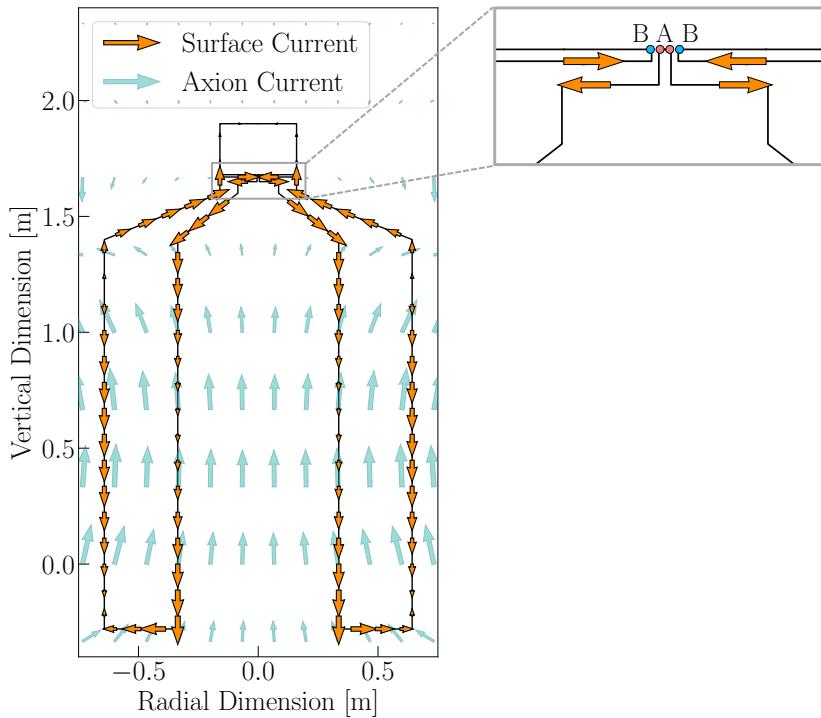
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Effective inductance

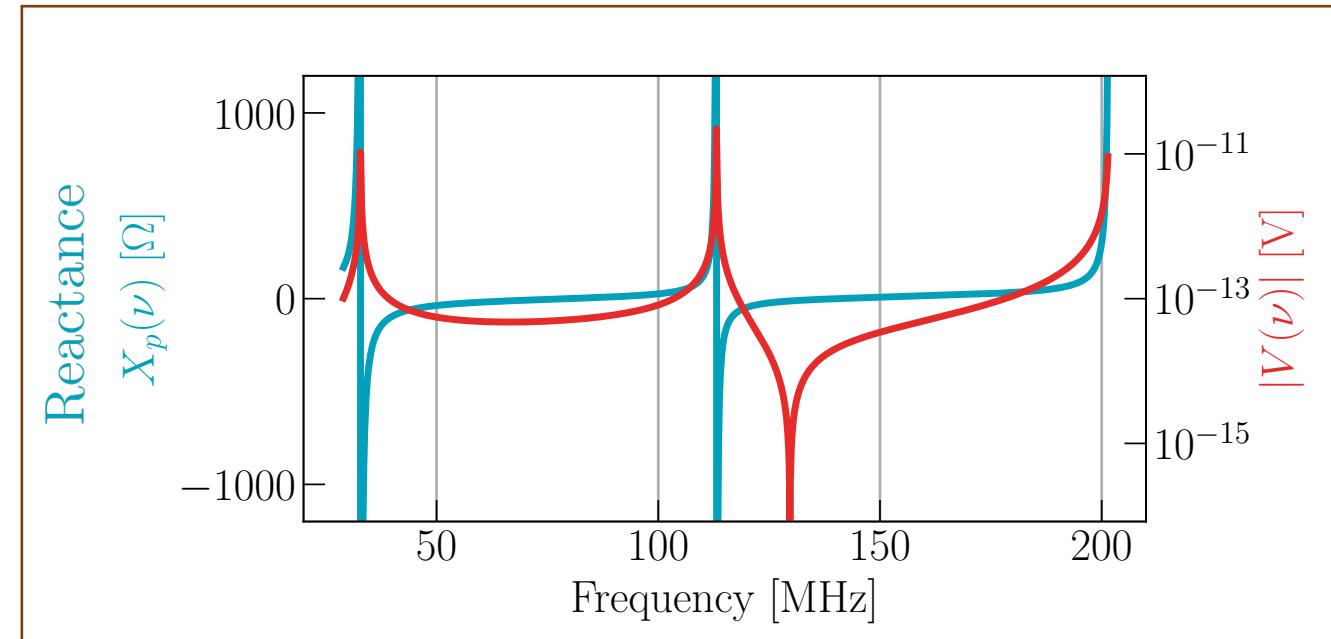
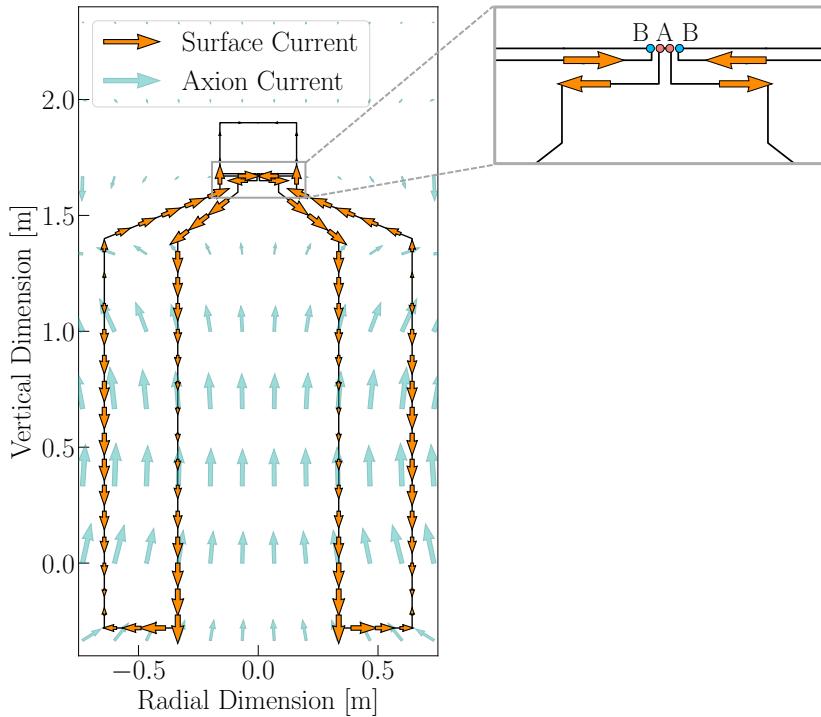
Calculate voltage  
and impedance  
across A - B  
numerically

# Impedance and voltage



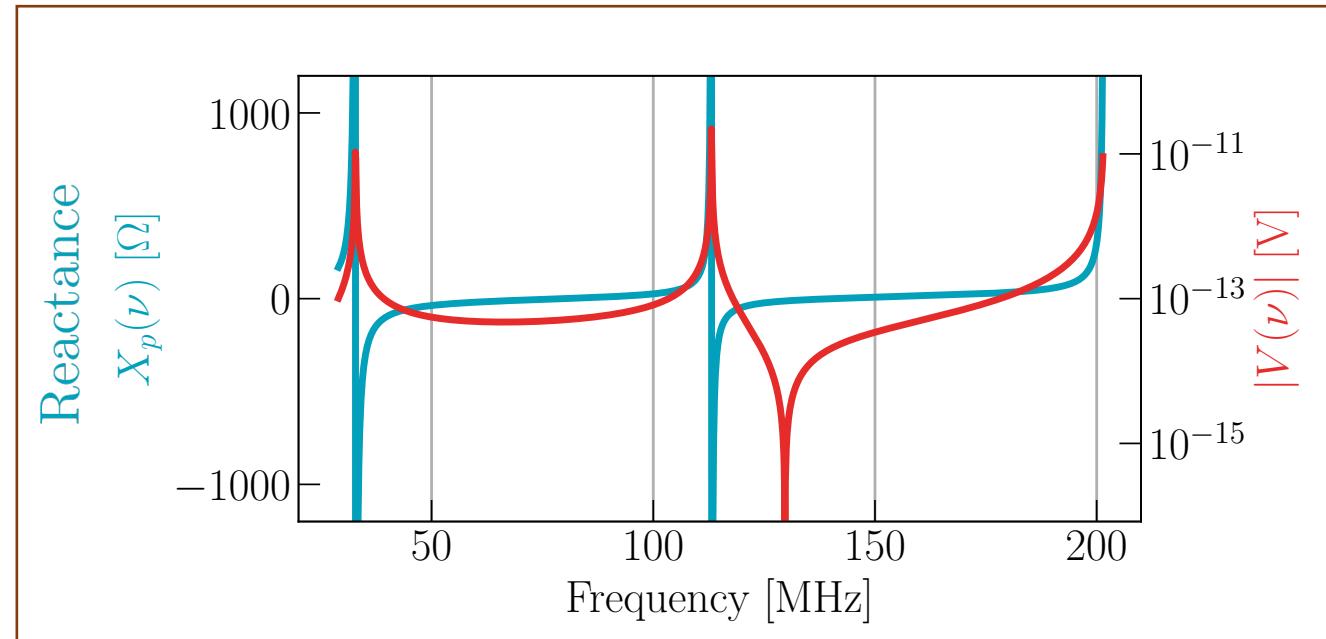
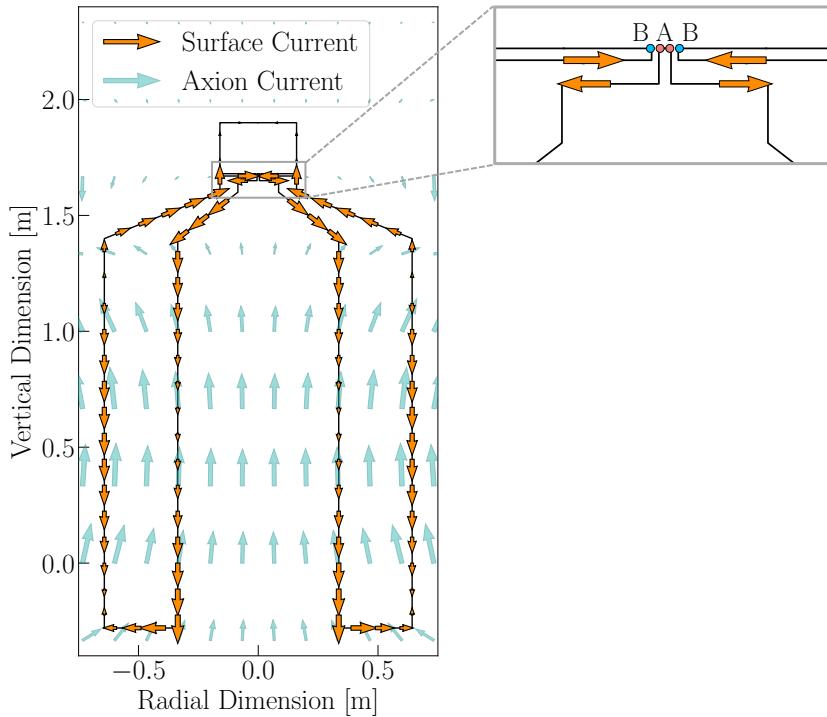
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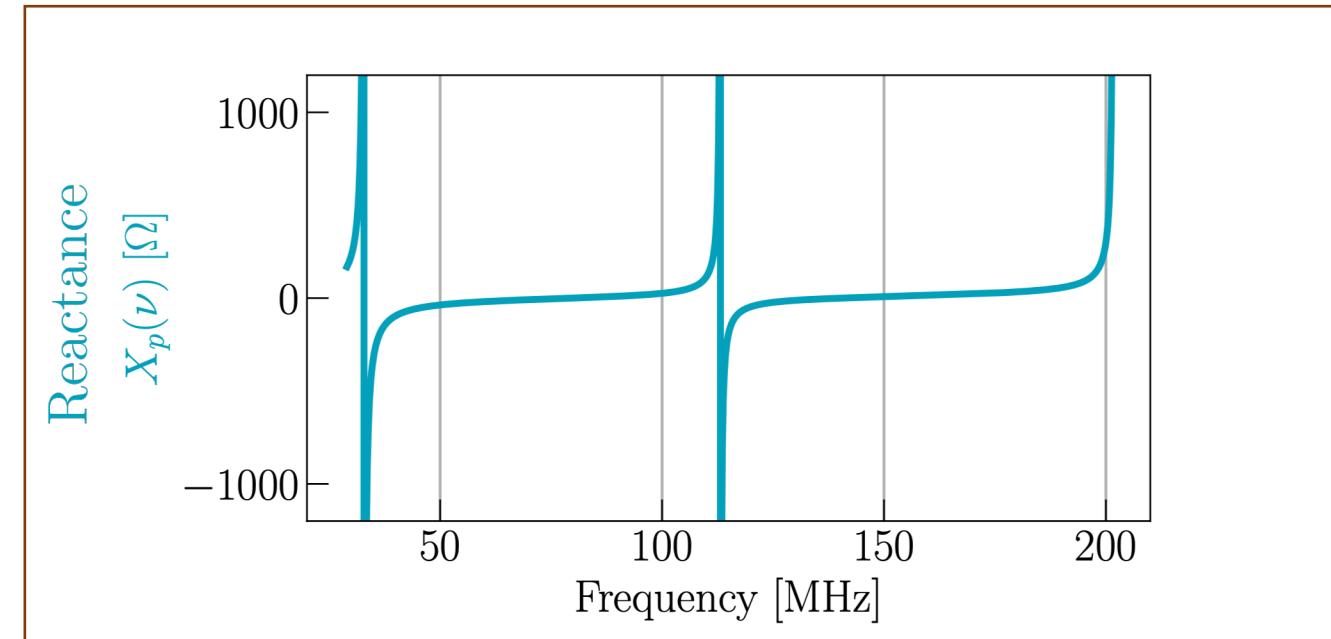
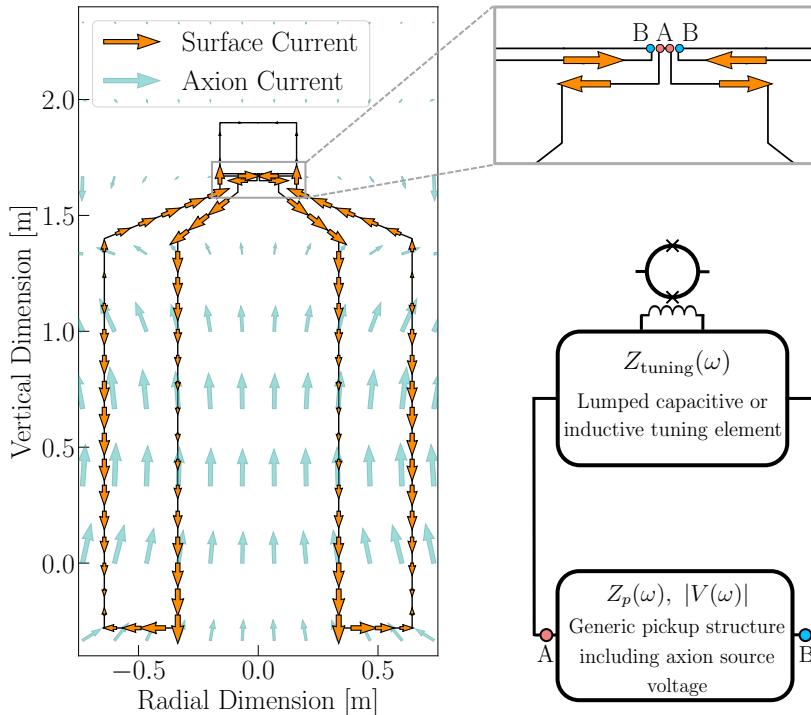
$$Z_p(\nu) = R_p(\nu) + iX_p(\nu)$$

At every frequency, Taylor expand impedance to express impedance as frequency-specific series RLC:

$$Z_p(\nu_0) = \underbrace{R_p(\nu_0) + iX_p(\nu_0)}_{\text{Simulation}} = \boxed{R(\nu_0)} + i2\pi\nu_0 \boxed{L_{\text{eff}}(\nu_0)} - \frac{i}{2\pi\nu_0 \boxed{C_{\text{eff}}(\nu_0)}}$$

To be extracted

# How to tune resonance?

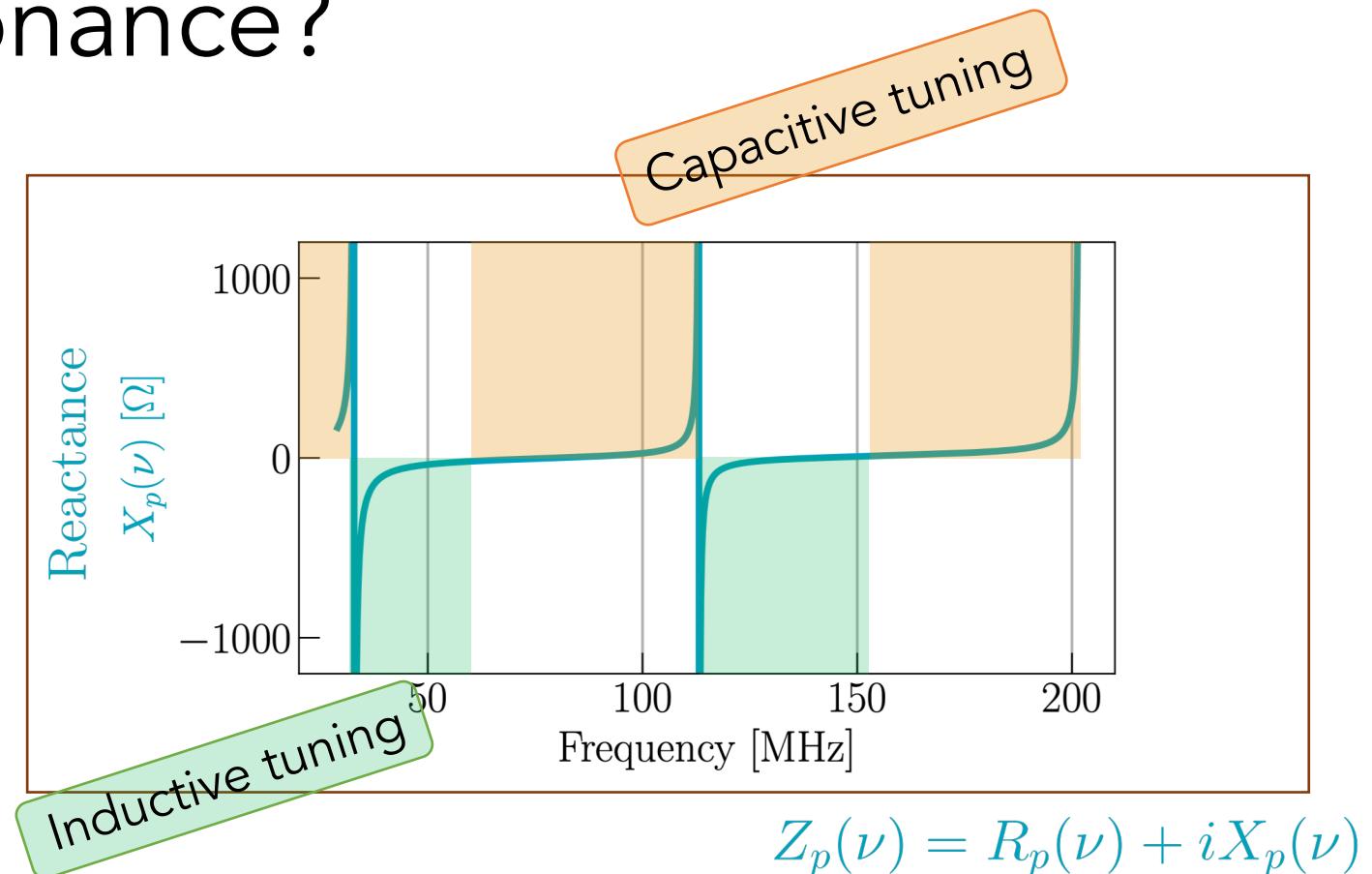
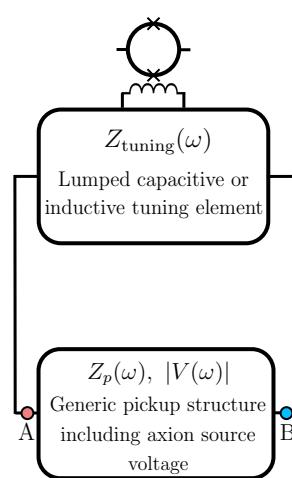
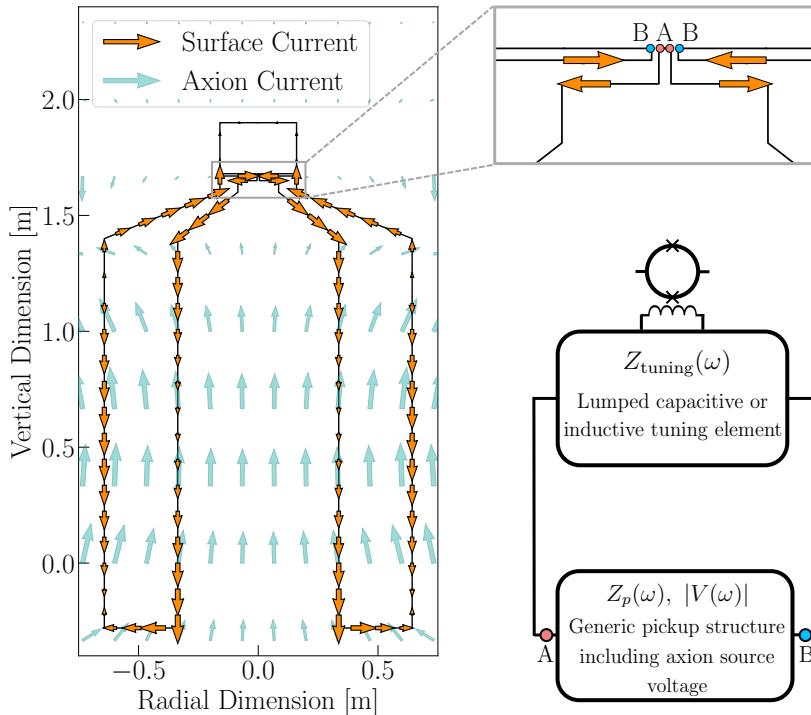


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To achieve resonance at any frequency, **reactance** must be tuned to zero using external capacitor or inductor:

$$X_{\text{tot}}(\nu_0) = X_{\text{tuning}}(\nu_0) + X_p(\nu_0) = 0$$

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- Use series RLC formulation to calculate  $R$ ,  $L_{\text{eff}}$ , and  $C_{\text{eff}}$

$$Z_p(\nu_0) = R_p(\nu_0) + iX_p(\nu_0) = R(\nu_0) + i2\pi\nu_0 L_{\text{eff}}(\nu_0) - \frac{i}{2\pi\nu_0 C_{\text{eff}}(\nu_0)}$$

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Axion induced voltage      Quality Factor  
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- Voltage simulations provide the axion induced voltage

$$\frac{d\nu}{dt} = \frac{\pi (6.4 \times 10^5)}{16 \text{ SNR}^2 m_a^4} \bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)] \frac{|V(m_a, B, g_{a\gamma\gamma})|^4 Q(\nu_r)}{L_{\text{eff}}(\nu_r)^2}$$

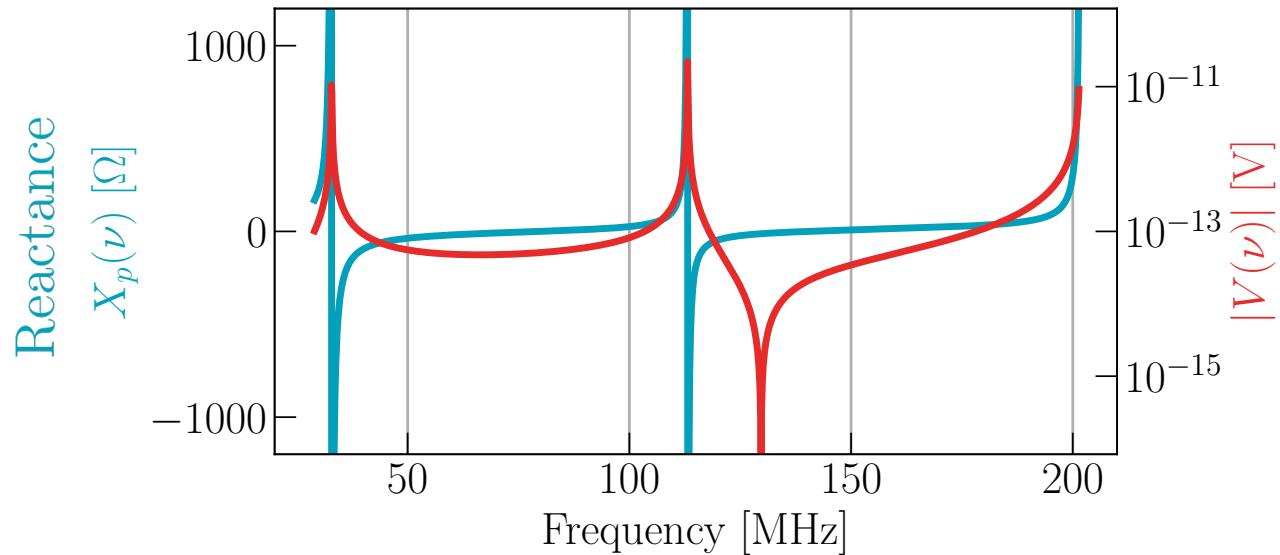
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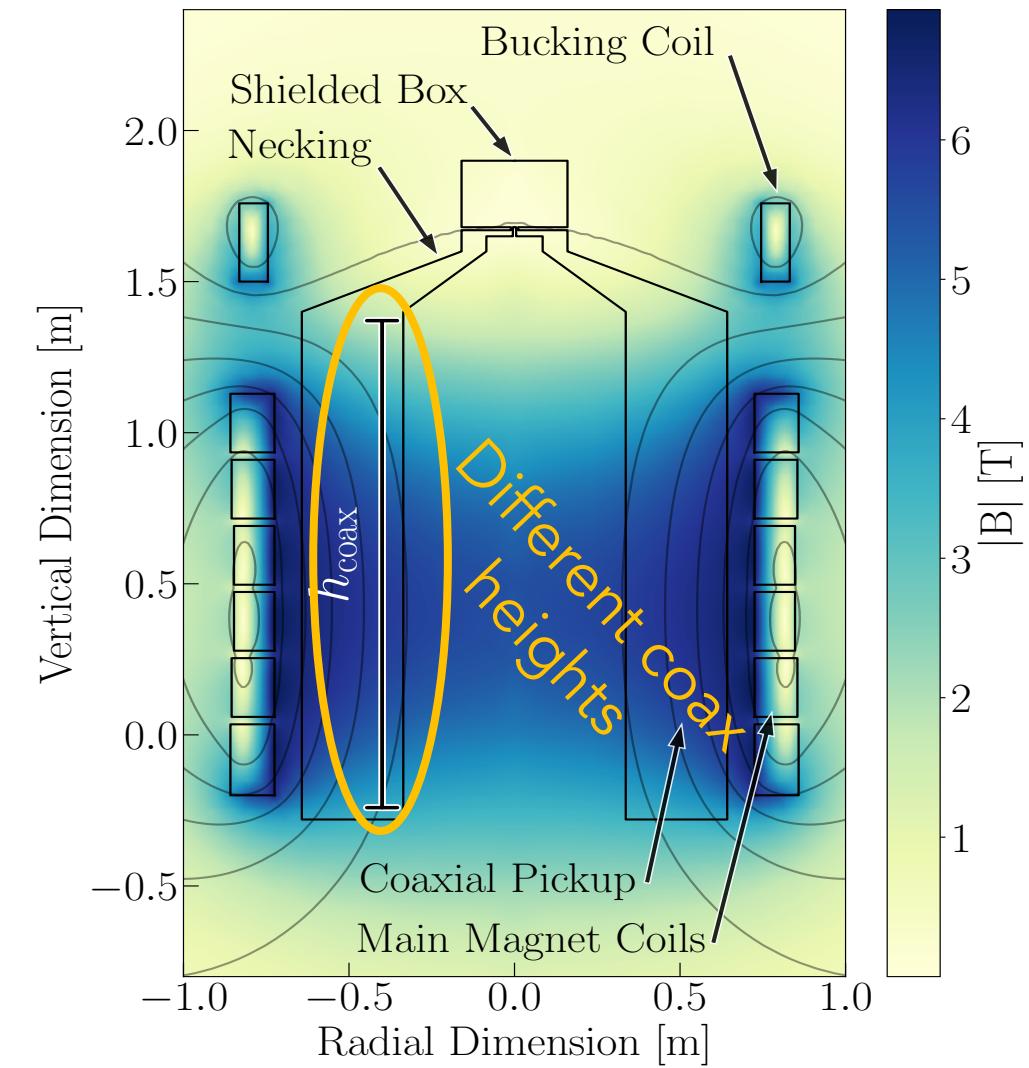
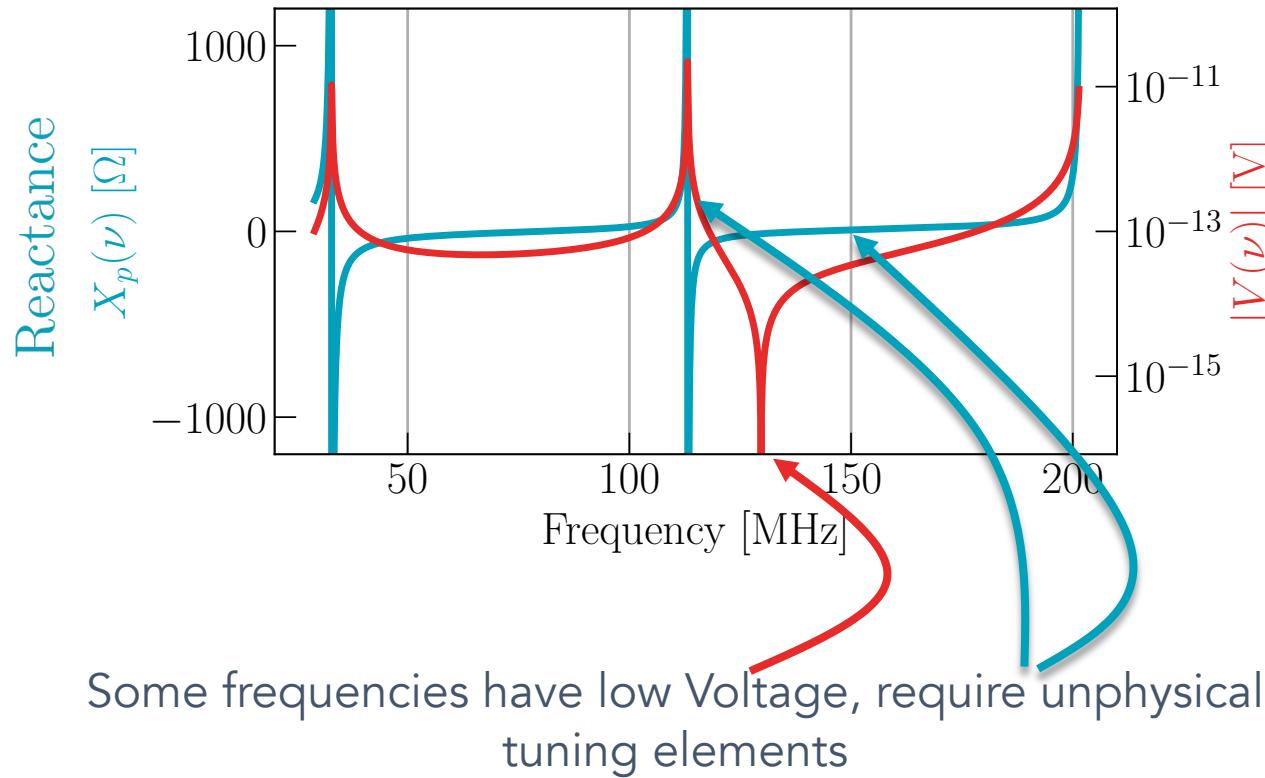
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# Challenges of a single coax

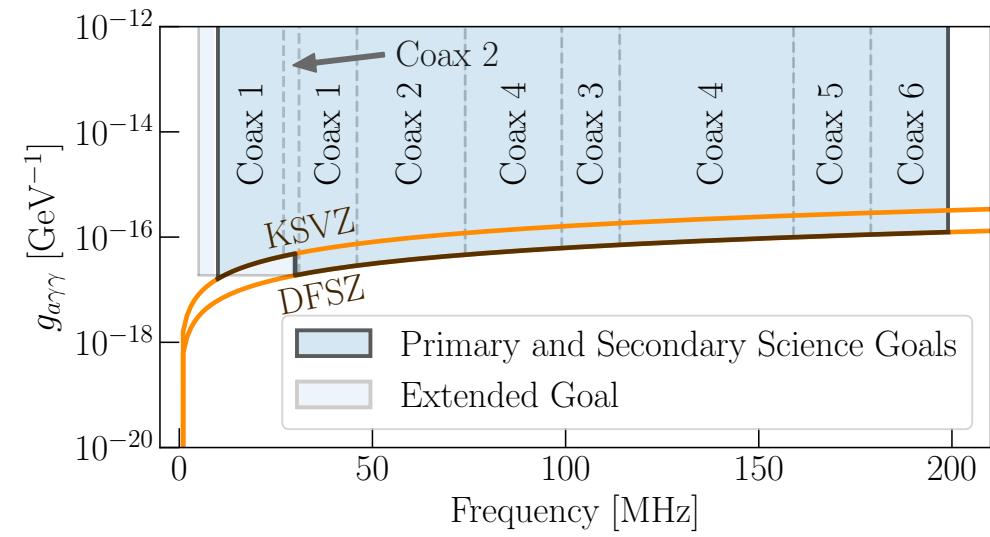
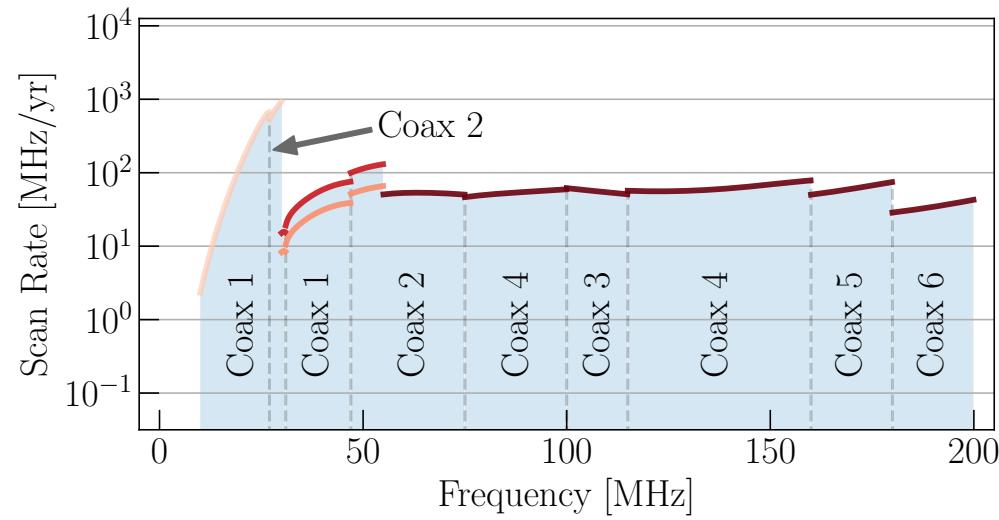


Some frequencies have low Voltage, require unphysical tuning elements

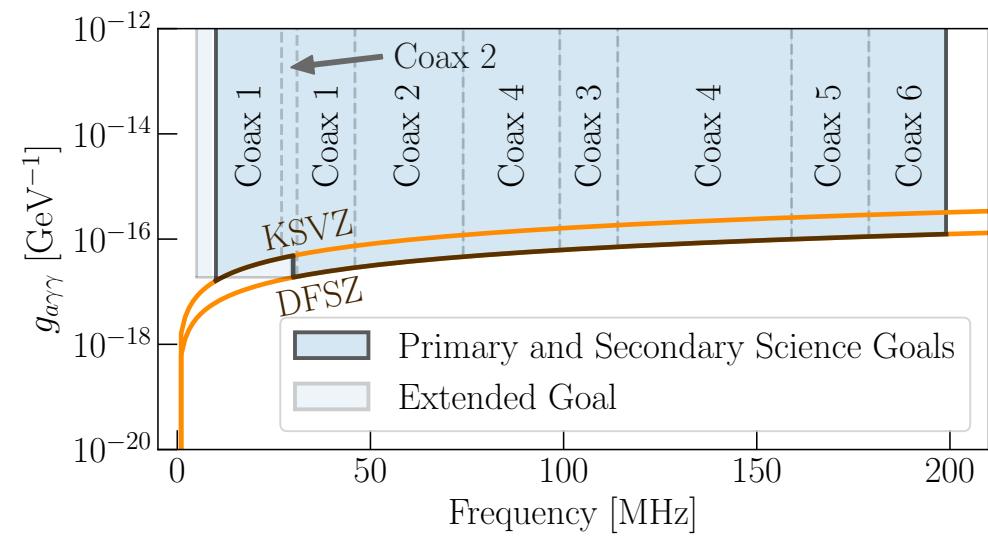
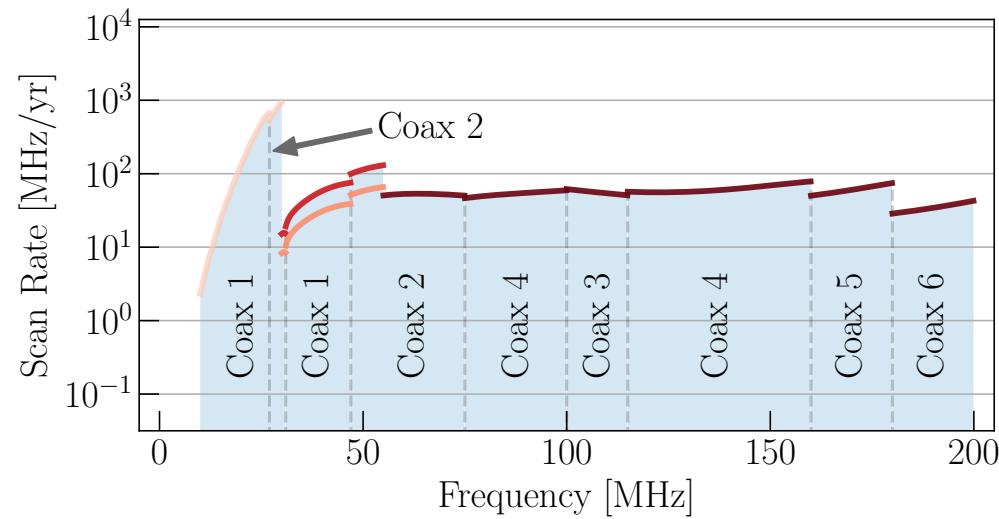
# Multiple coaxes



# Sensitivity



# Sensitivity



	Sensitivity & Range	$3\sigma$ Live Scan Time
Primary Science Goal	DFSZ; 30–200 MHz	3.7 yr
Secondary Science Goal	KSVZ; 10–30 MHz	0.9 yr
Extended Goal	$1.87 \times 10^{-17}$ GeV $^{-1}$ ; 5–30 MHz	2.6 yr

# DMRadio Collaboration

H.M. Cho, W. Craddock, D. Li, C. P. Salemi, W. J. Wisniewski  
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J. Corbin, P. W. Graham, K. D. Irwin, F. Kadribasic, S. Kuenstner, N. M. Rapidis, M. Simanovskiaia, J. Singh, E. C. van Assendelft, K. Wells  
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*Santa Clara University*



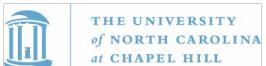
J. W. Foster, J. T. Fry, J. L. Ouellet, K. M. W. Pappas, L. Winslow  
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R. Henning  
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*Triangle Universities Nuclear Laboratory*

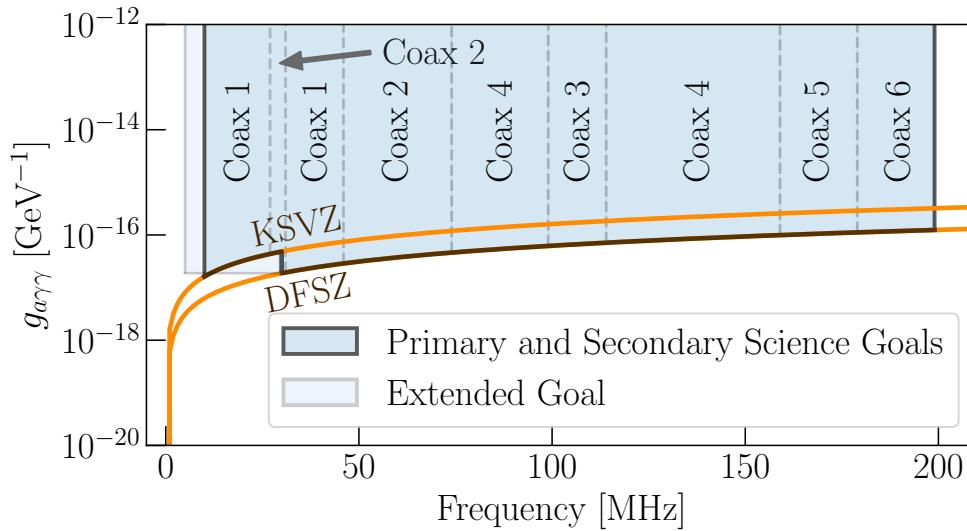
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A. Phipps  
*California State University, East Bay*

B. R. Safdi  
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*University of California Berkeley*



# Thank you!

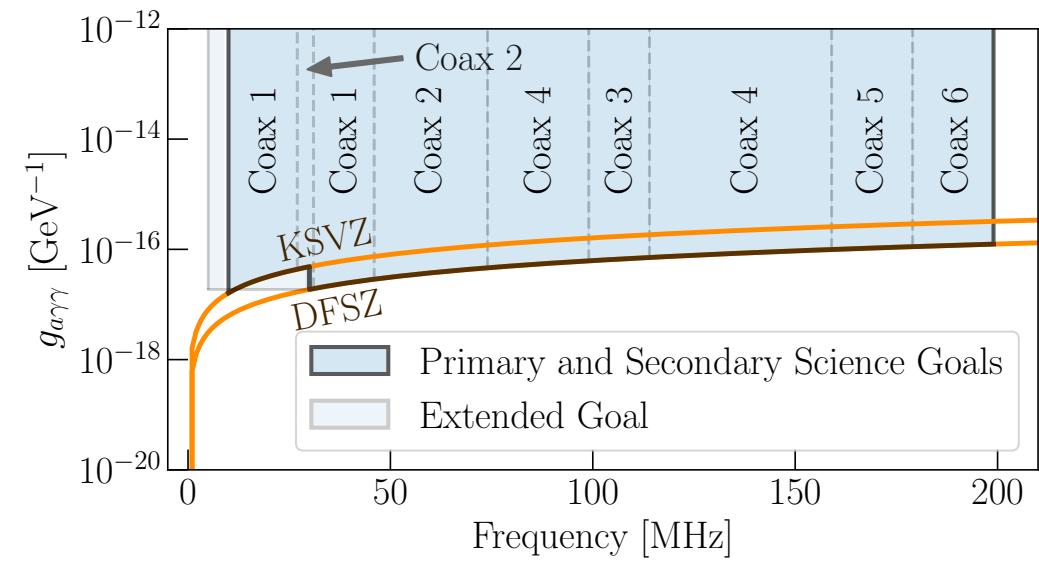
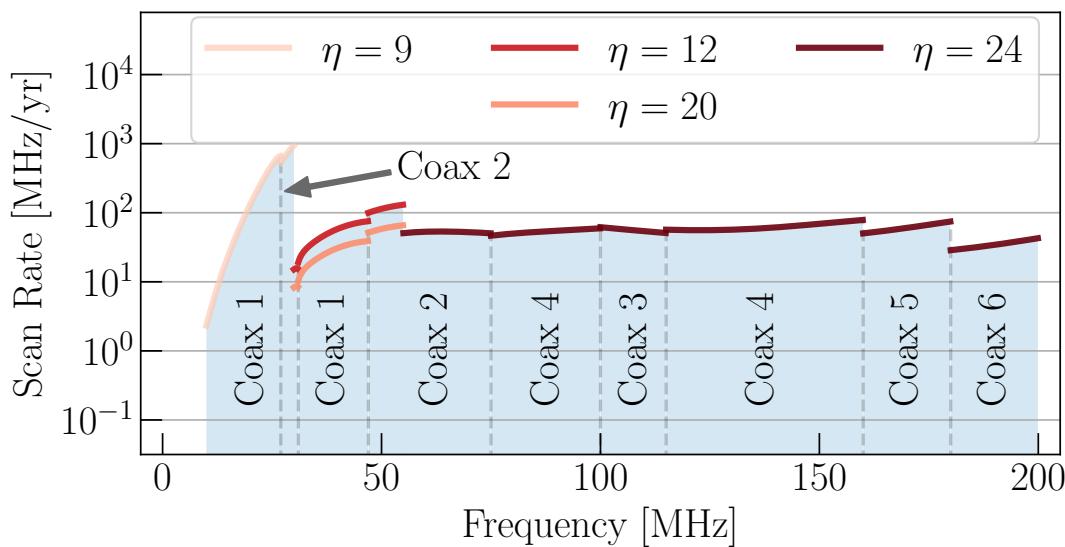


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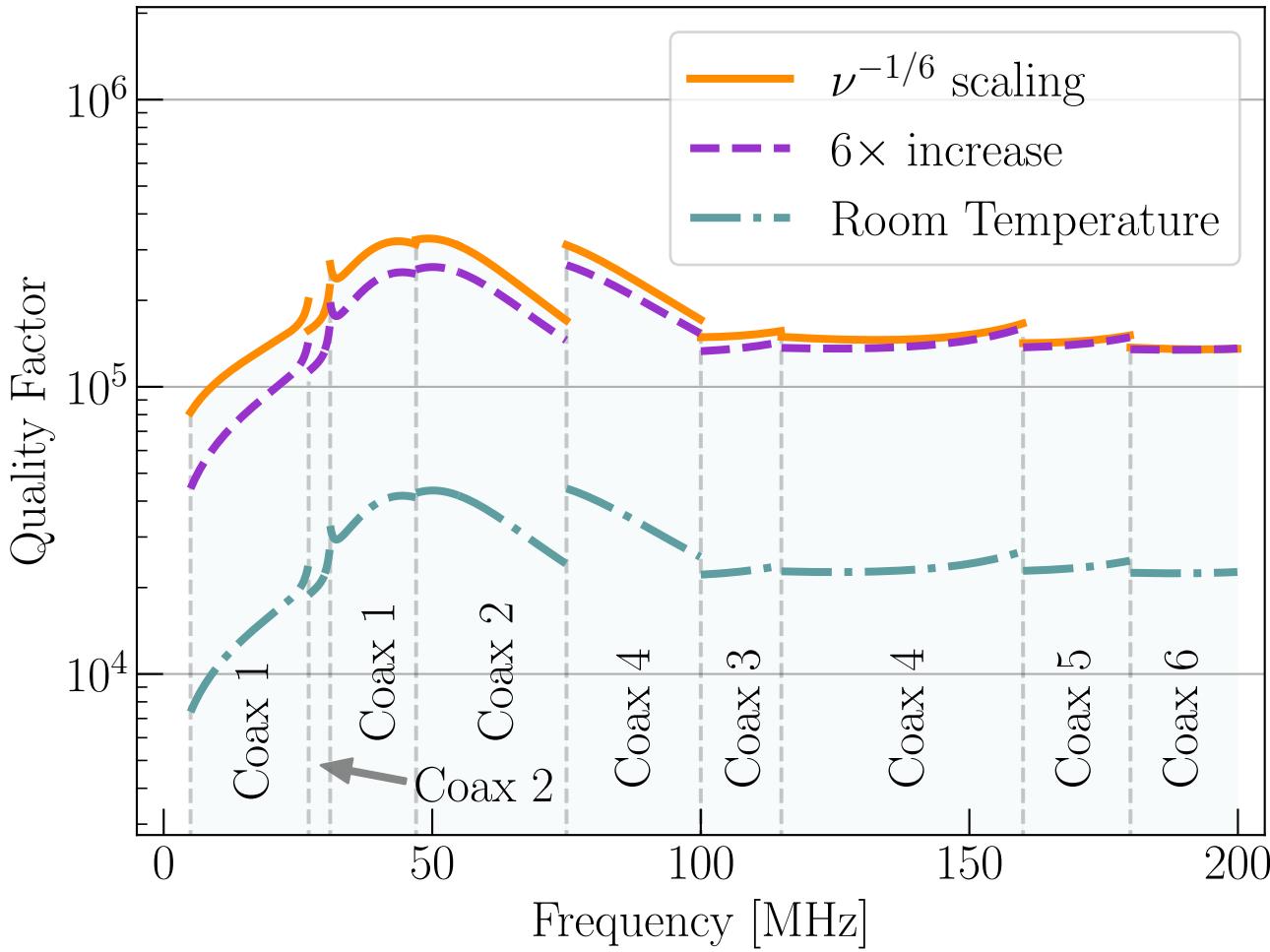
# Backup Slides

# SQUID parameter



$$\eta(\nu_r) \equiv \frac{k_B T_N^{\min}(\nu_r)}{h\nu_r/2} \geq 1$$

# Quality factor



$$Re \{Z_{\text{RT}}\} = \sqrt{\frac{\omega \mu_0}{2\sigma_{\text{RT}}}}$$

$$Re \{Z_{\text{cold}}\} = \frac{8}{9} \left( \frac{\sqrt{3} \lambda_{\text{mfp}} \omega^2 \mu_0^2}{16\pi \sigma_{\text{cold}}} \right)^{1/3}$$

# Shielded Box

