

Science reach and electromagnetic modeling of DMRadio-m³

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Stanford University – Irwin Group

DMRadio Collaboration

APS April Meeting – April 5, 2024

Outline

1. DMRadio-m³ introduction and geometry
2. Extracting the sensitivity
3. Science reach

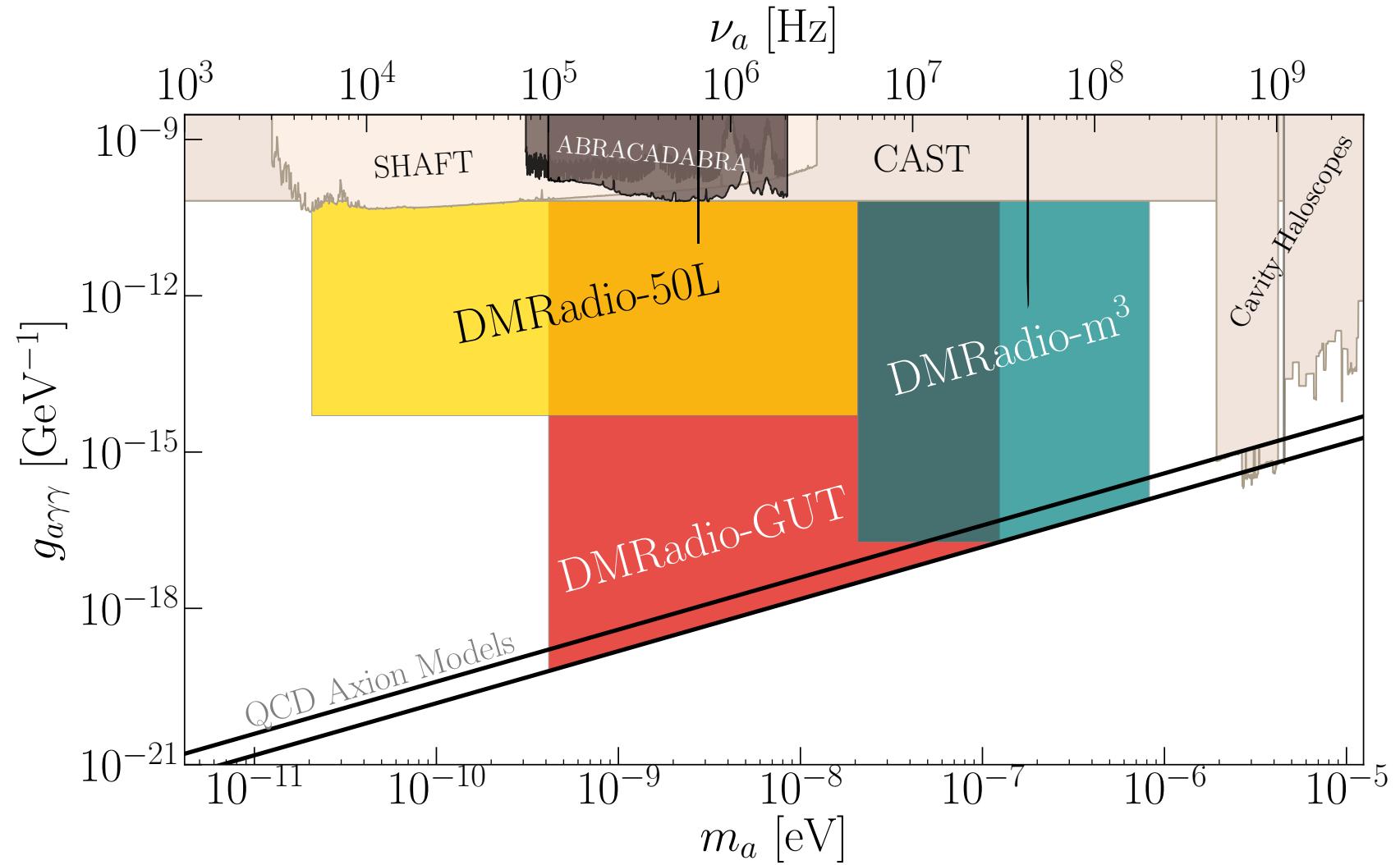
Based off of: arXiv:2302.14084

Outline

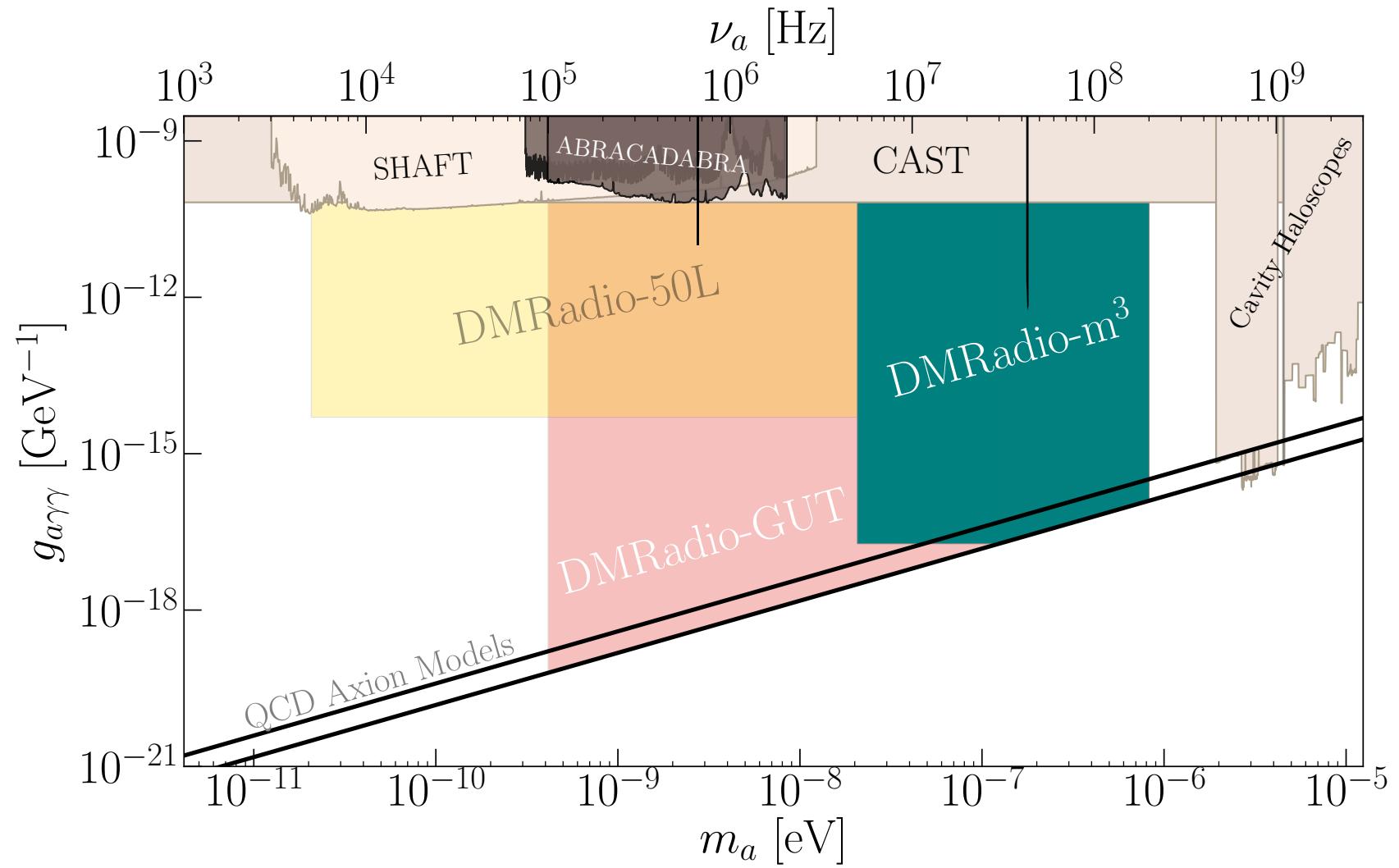
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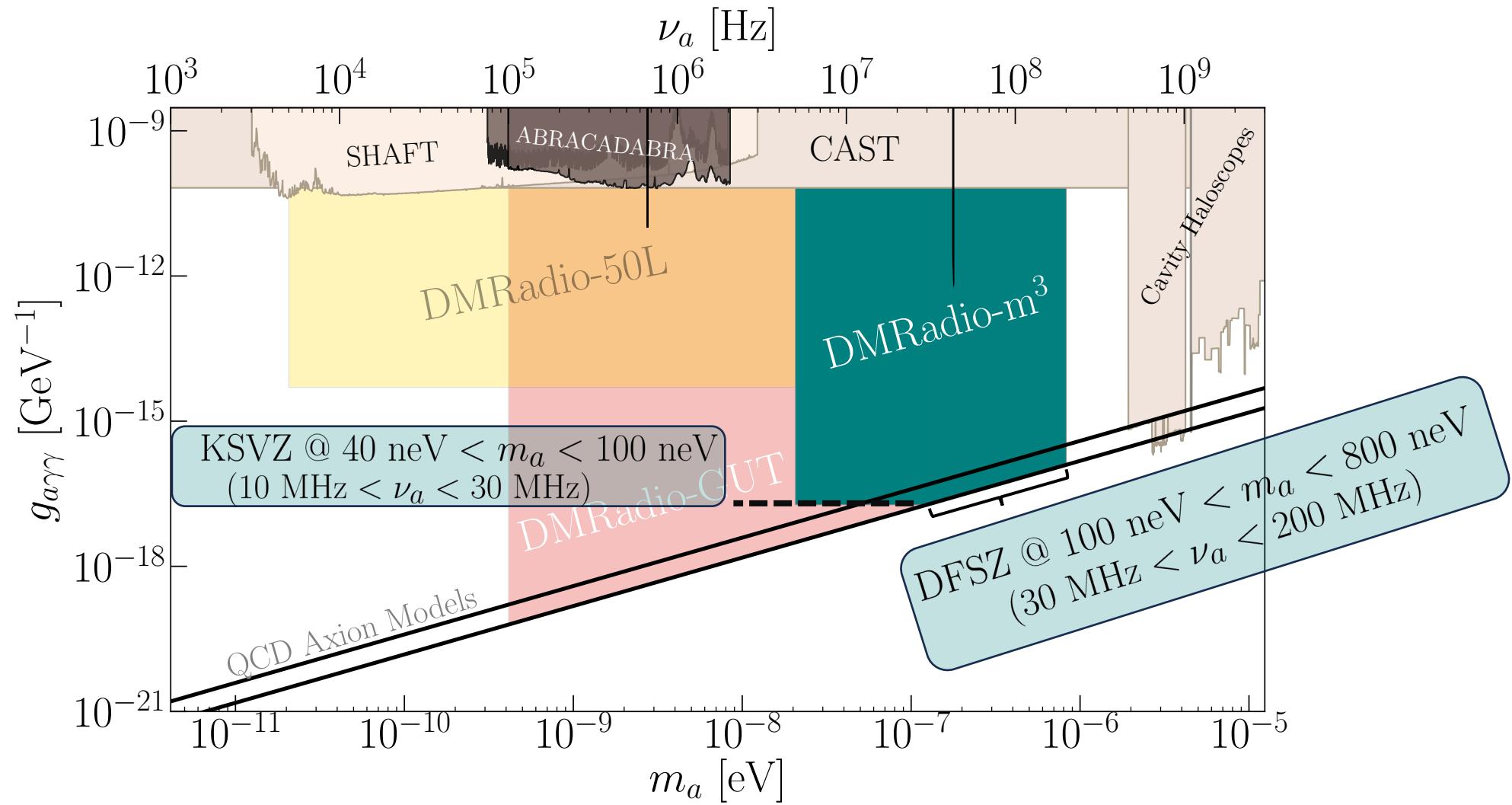
DMRadio



DMRadio



DMRadio

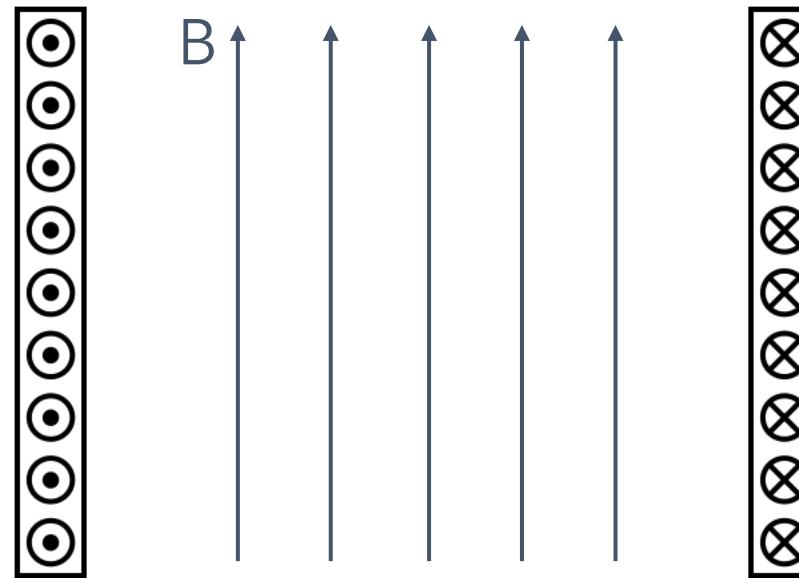


m^3 design

m^3 uses a solenoidal magnet + coaxial copper pickup

m^3 design

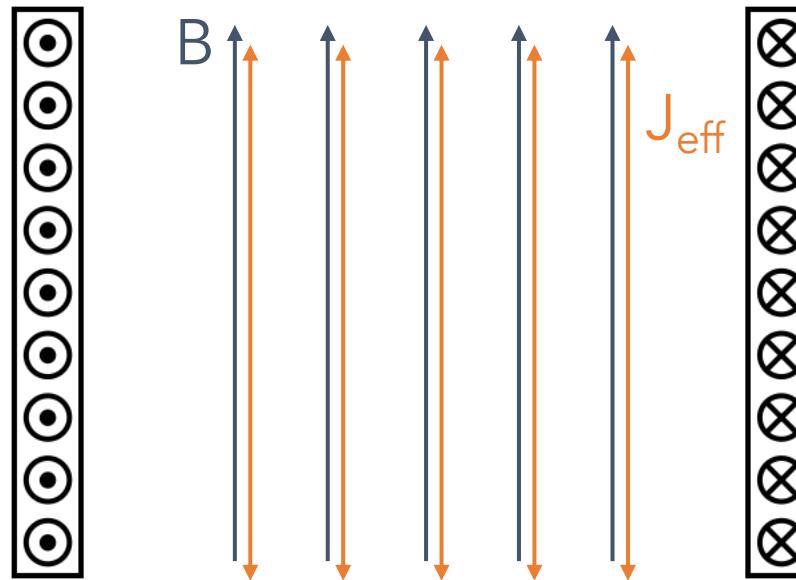
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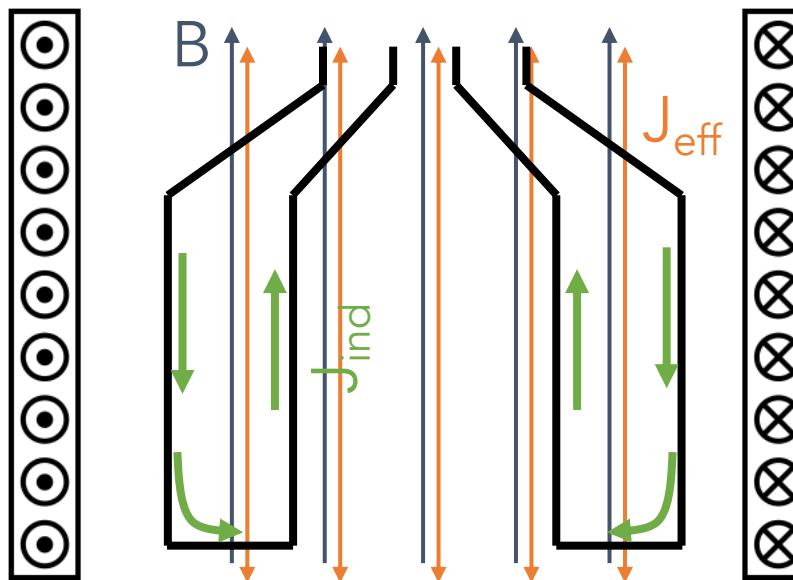
$$\mathbf{J}_{\text{eff}} \approx g_{a\gamma\gamma} \sqrt{2\rho_{\text{DM}}} \cos(m_a t) \mathbf{B}$$



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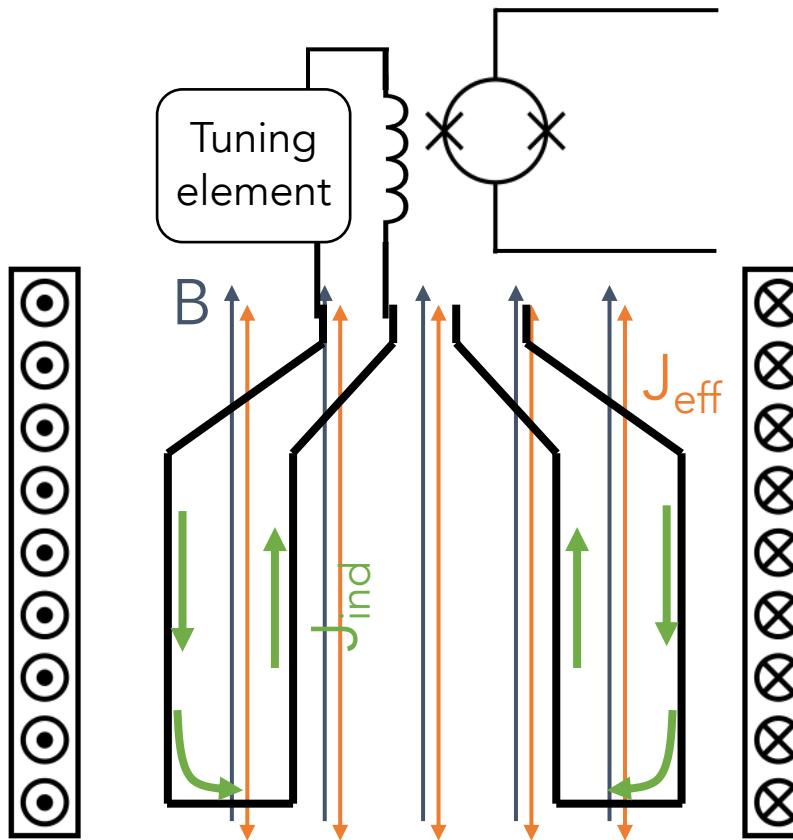
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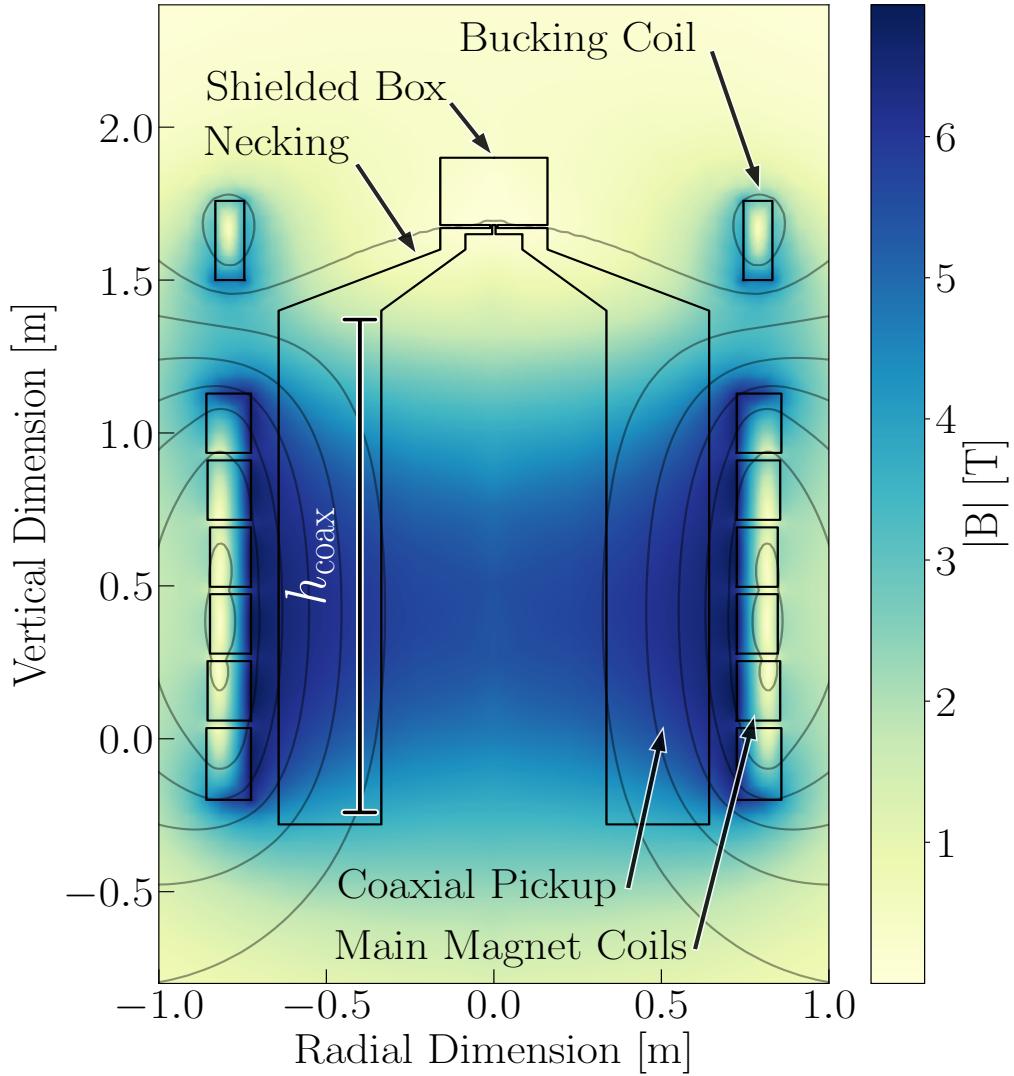
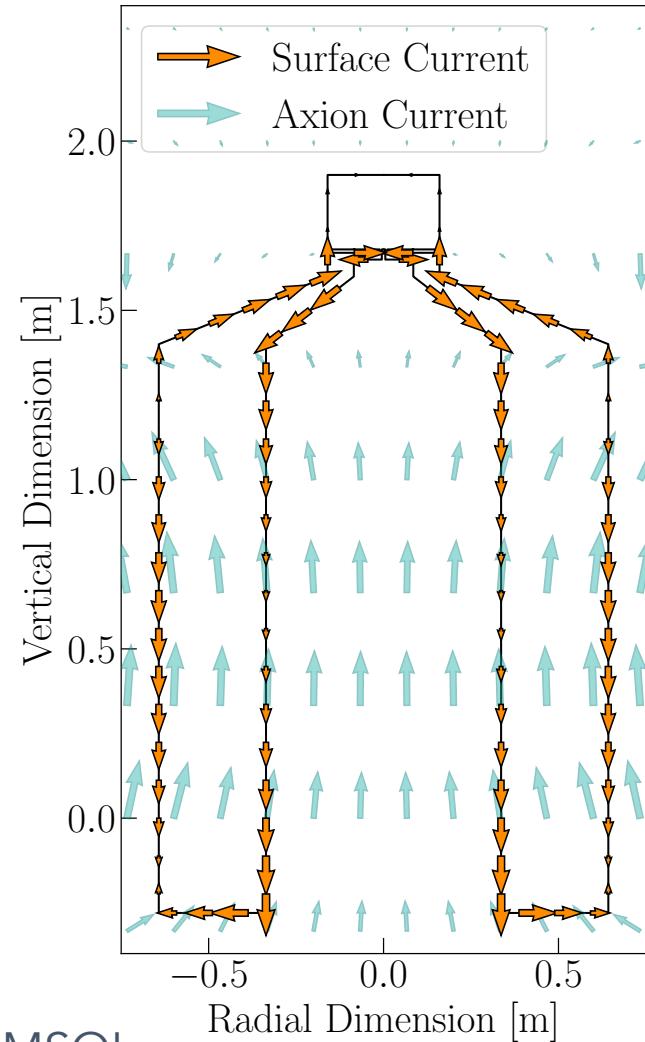
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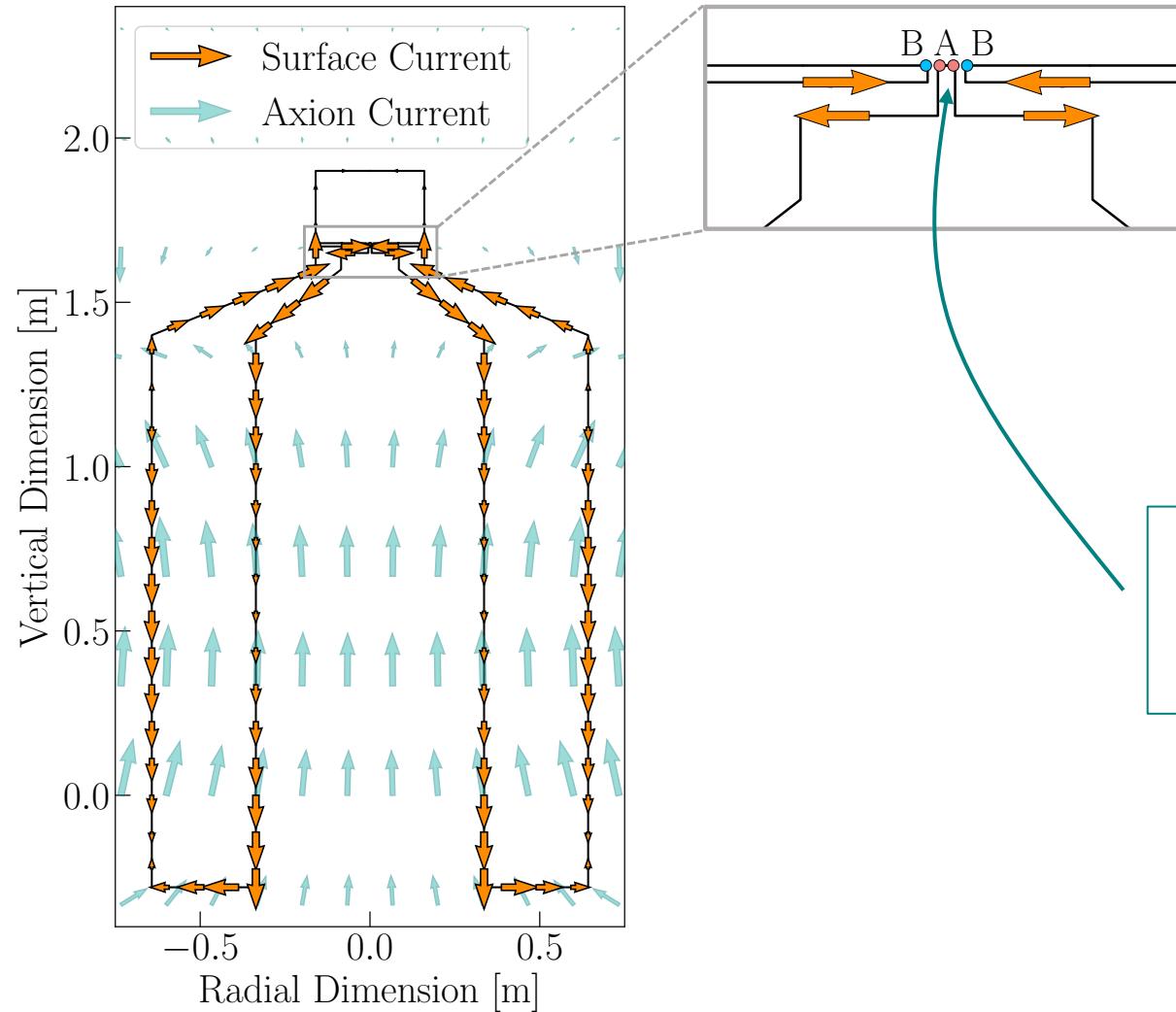


m^3 pickup simulations



Simulations on COMSOL

m^3 pickup simulations

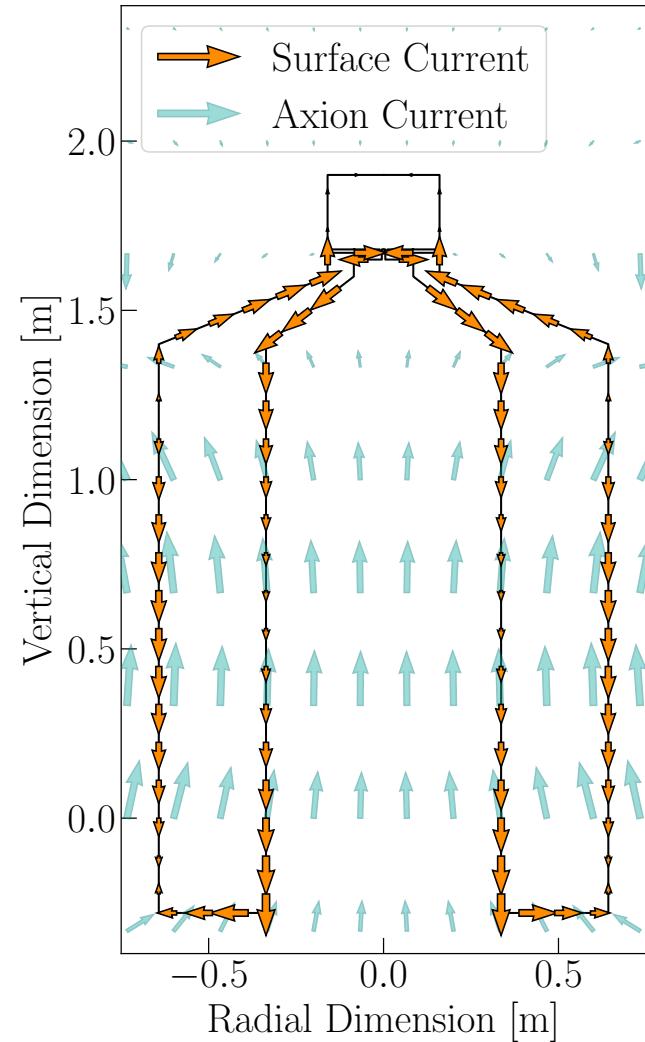


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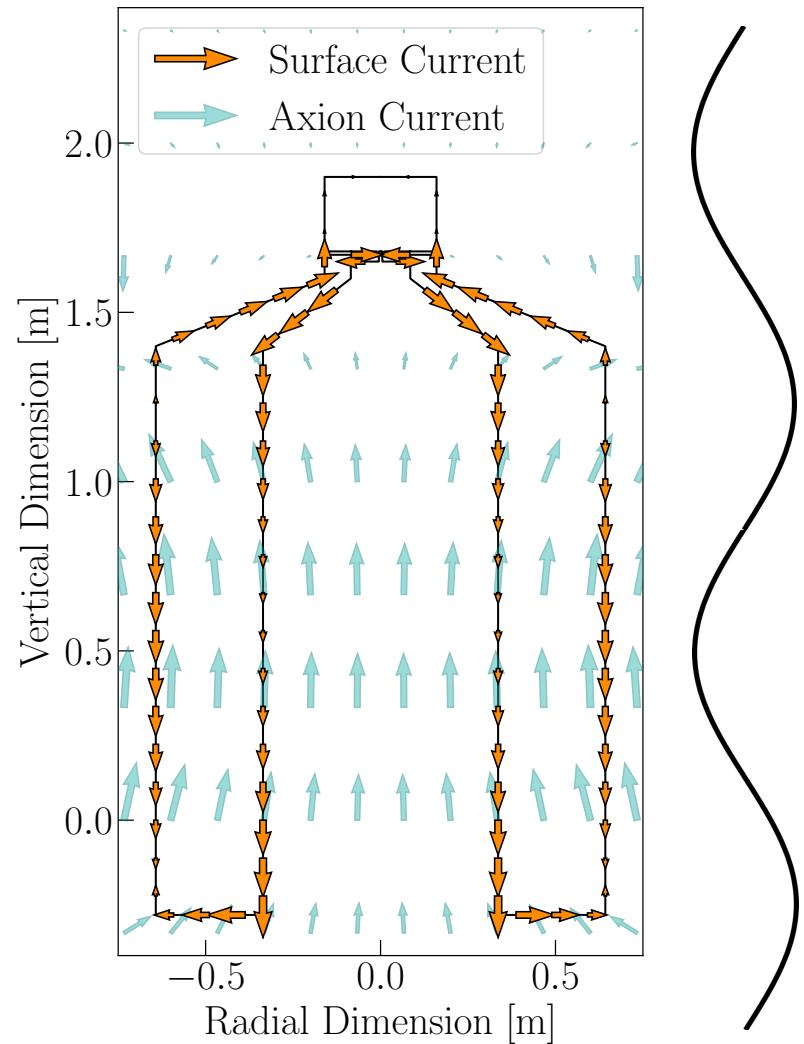
Is this still lumped element?



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

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

Is this still lumped element?



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:

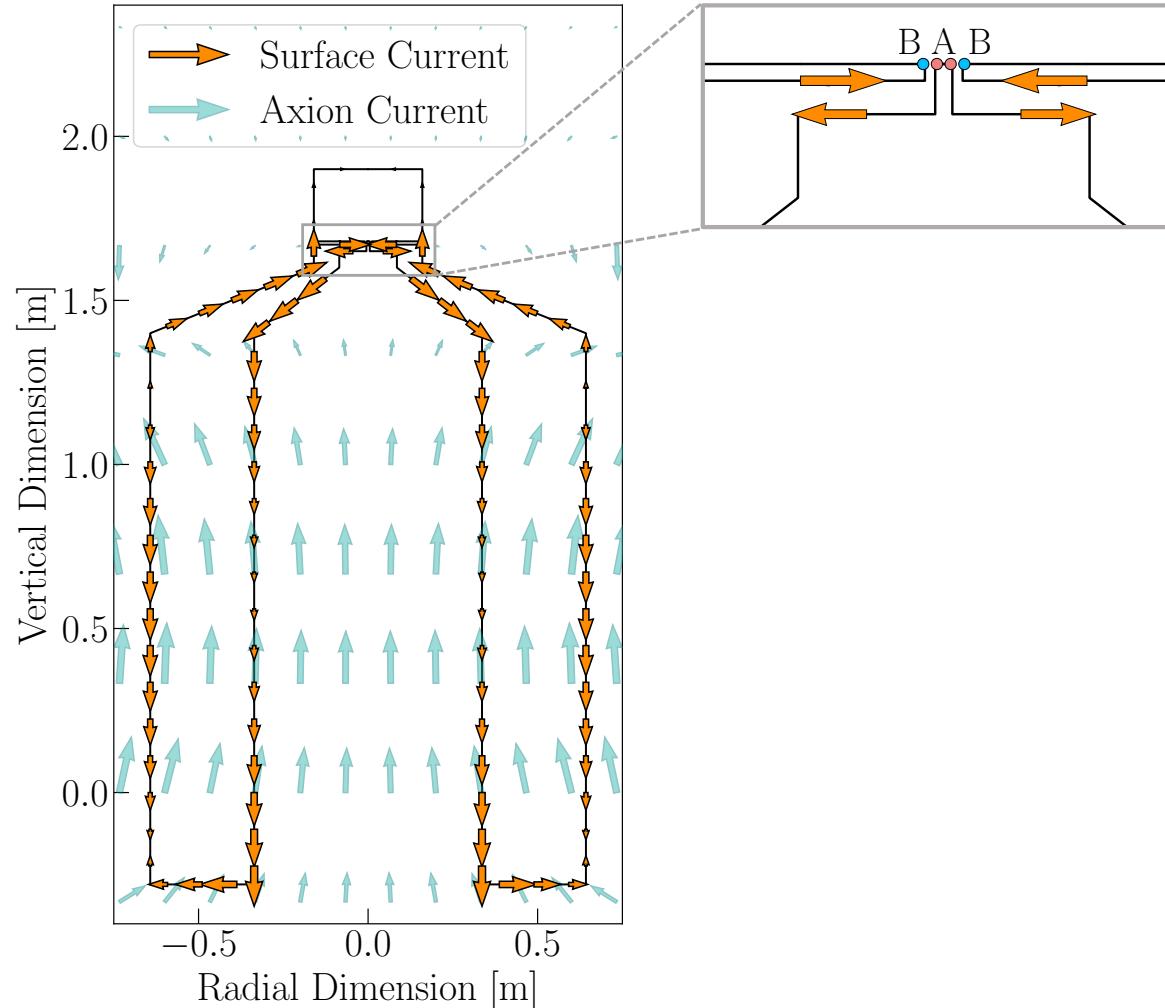
- DM halo physics**: $\pi (6.4 \times 10^5)$ (green dashed box)
- Axion induced voltage**: $[V(m_a, B, g_{a\gamma\gamma})]^4$ (orange dashed box)
- Quality Factor**: $Q(\nu_r)$ (blue dashed box)
- Noise physics**: $\bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)]$ (red dashed box)
- Effective inductance**: $L_{\text{eff}}(\nu_r)^2$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

How do we calculate these parameters in this limit?

Scan rate

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

DM halo physics Axion induced voltage Quality Factor
 Noise physics

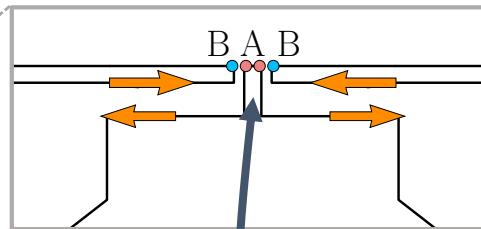
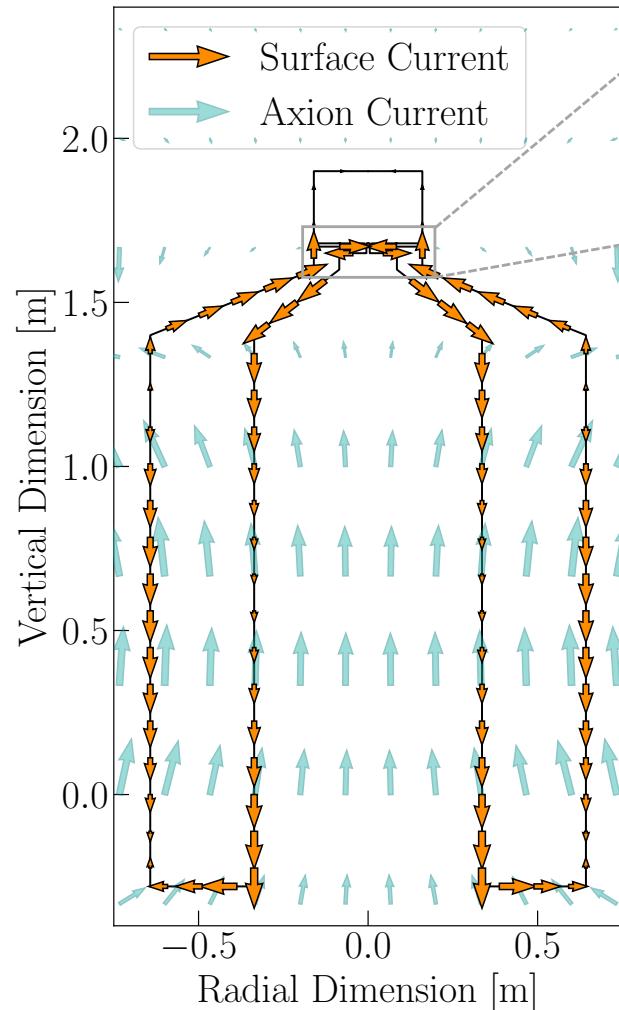


Effective inductance

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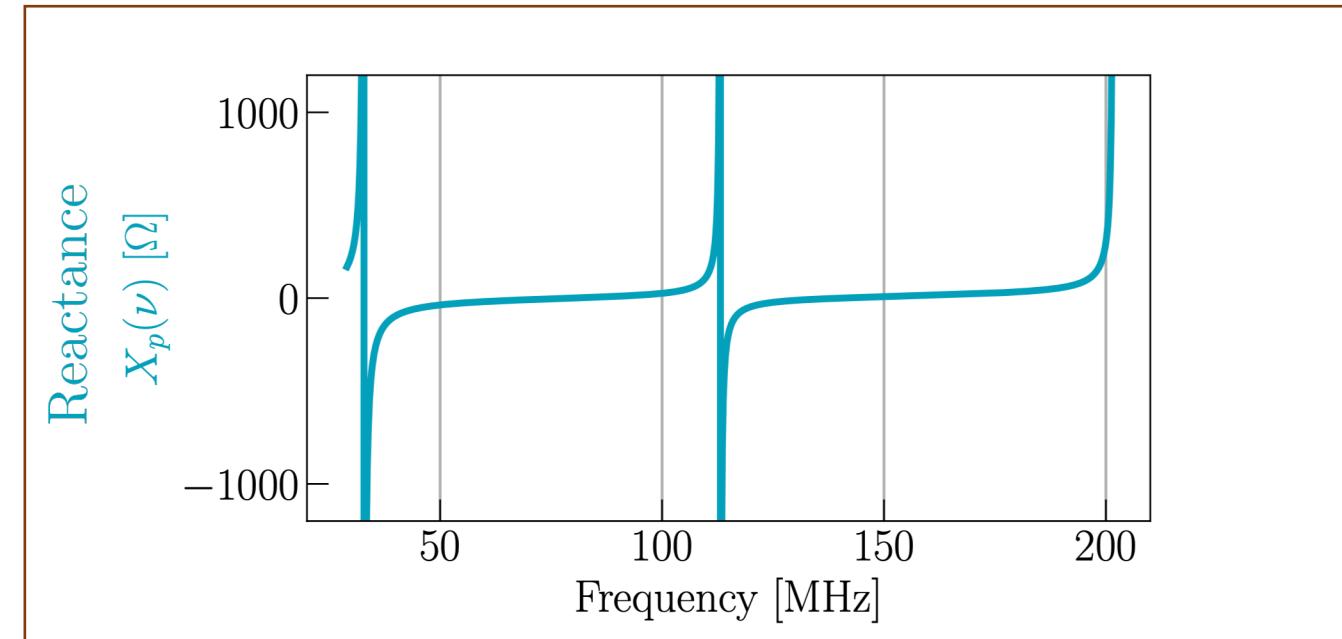
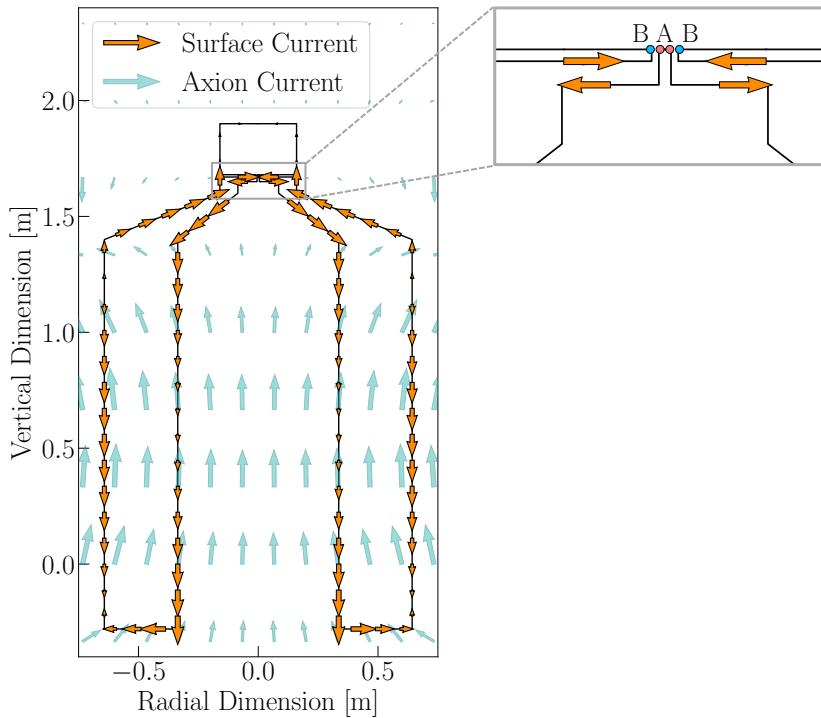
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Effective inductance

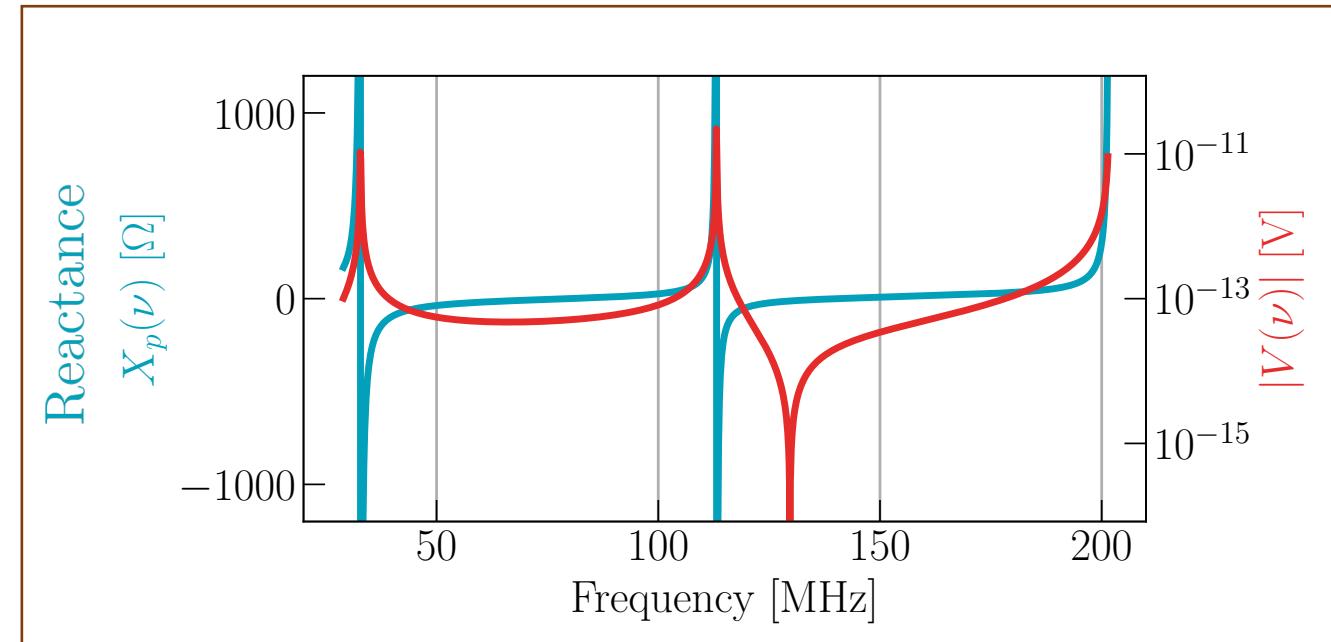
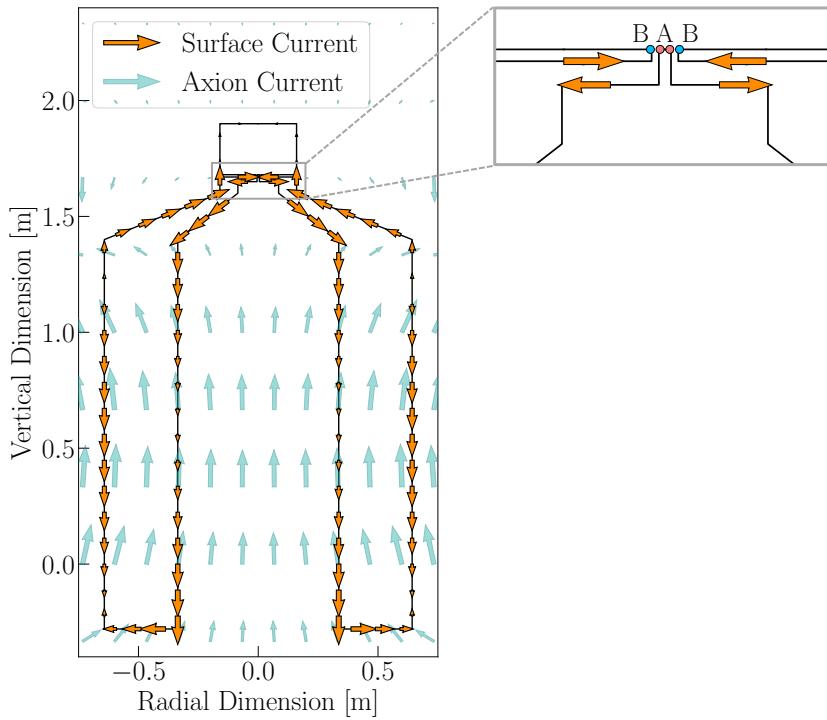
Calculate voltage
and impedance
across A - B
numerically

Impedance and voltage



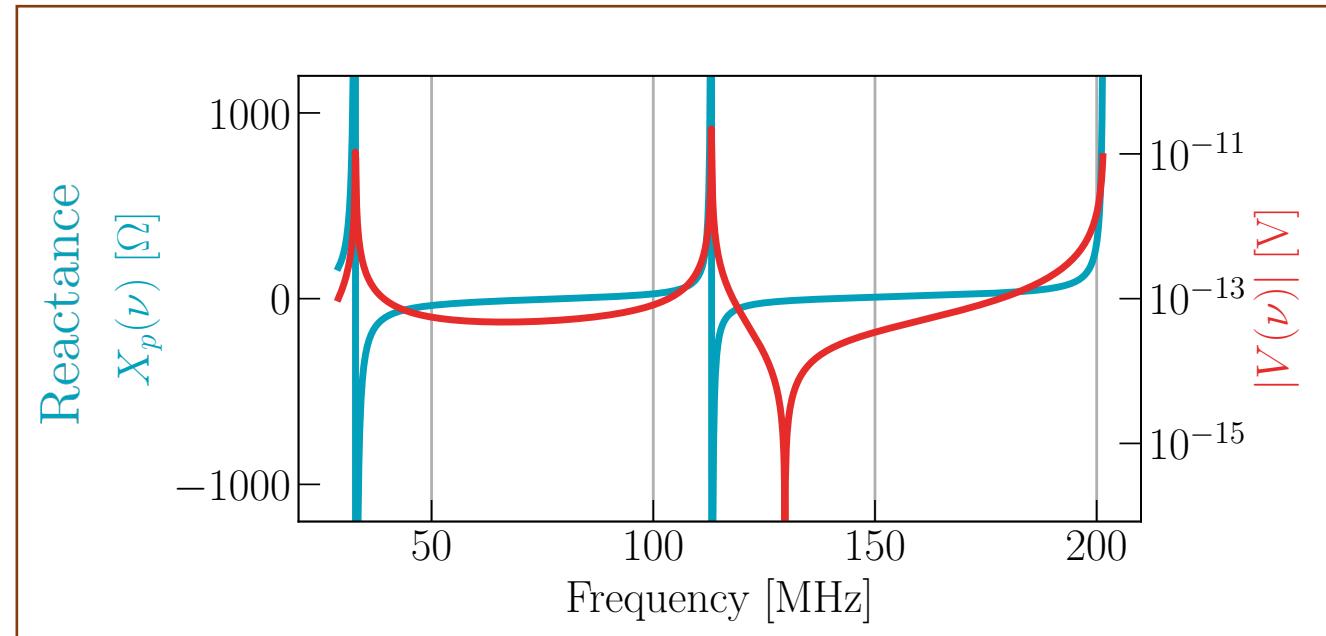
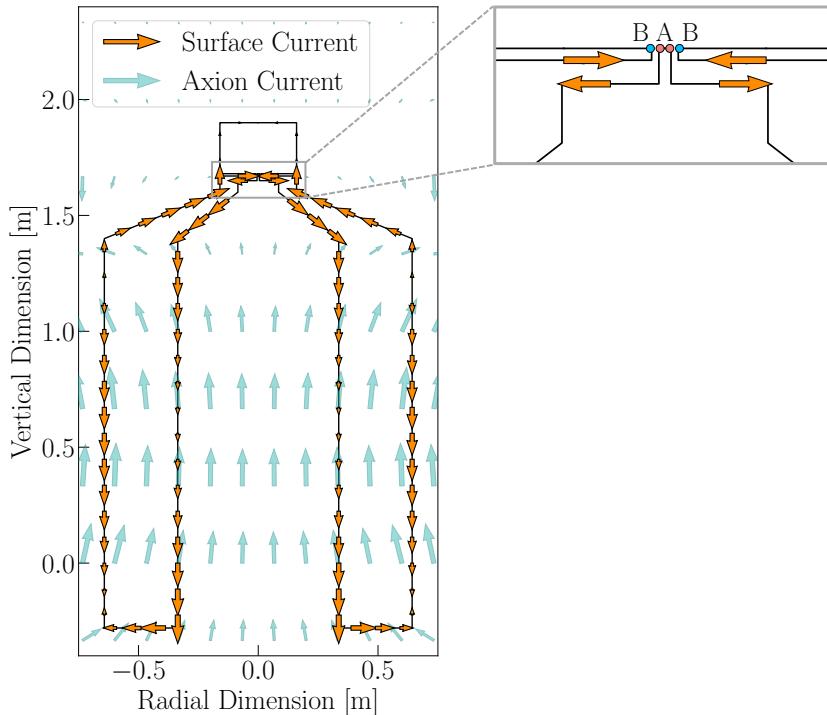
$$Z_p(\nu) = R_p(\nu) + iX_p(\nu)$$

Impedance and voltage



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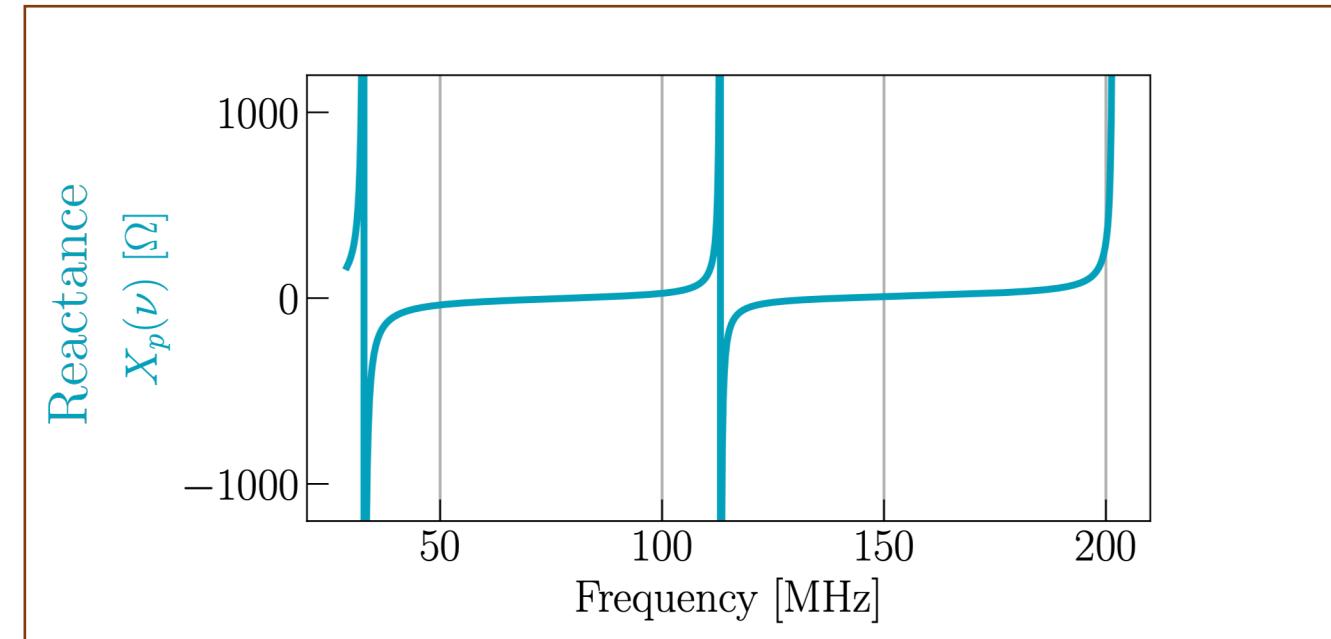
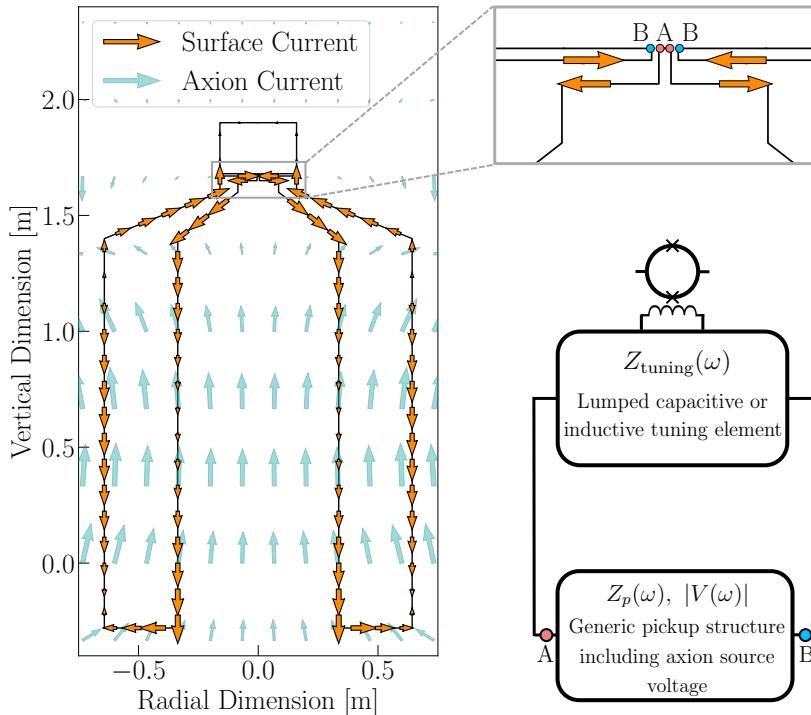
$$Z_p(\nu) = R_p(\nu) + iX_p(\nu)$$

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?

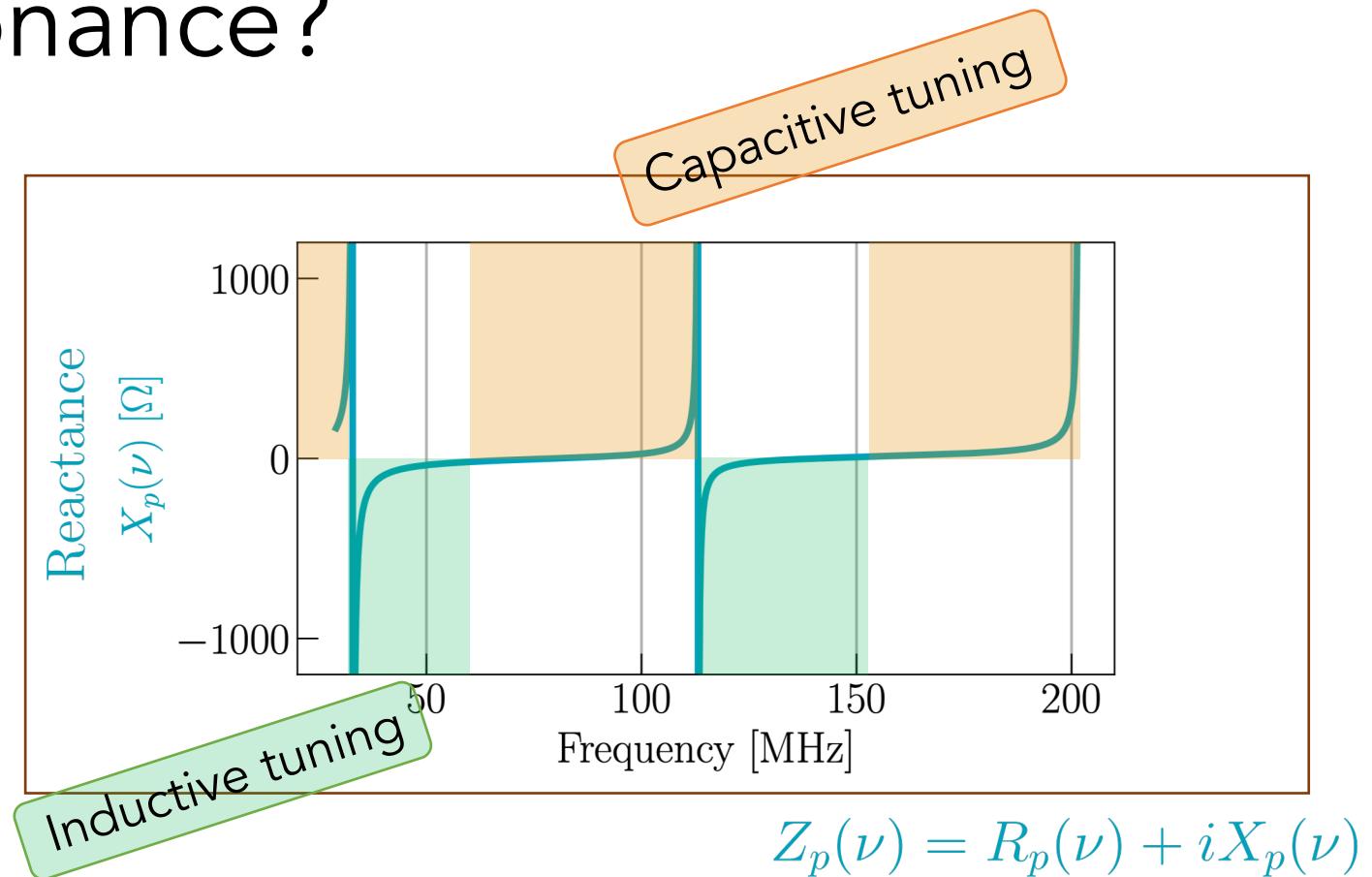
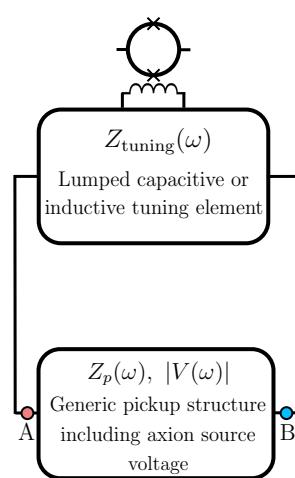
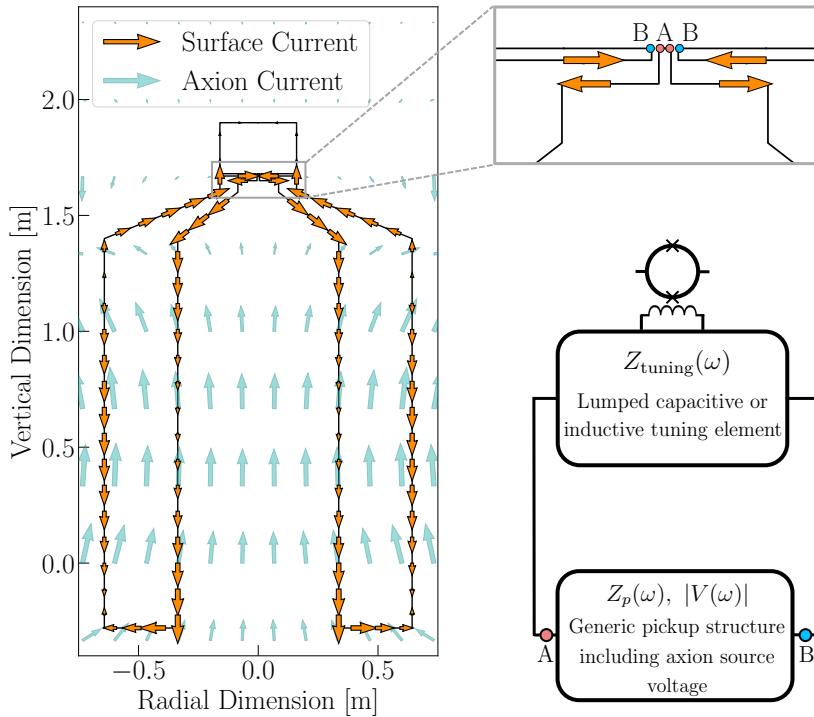


$$Z_p(\nu) = R_p(\nu) + iX_p(\nu)$$

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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Impedance and voltage

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

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

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

Axion induced voltage Quality Factor
Effective inductance

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→ Extract Quality Factor and Effective Inductance.

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- Voltage simulations provide the axion induced voltage

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

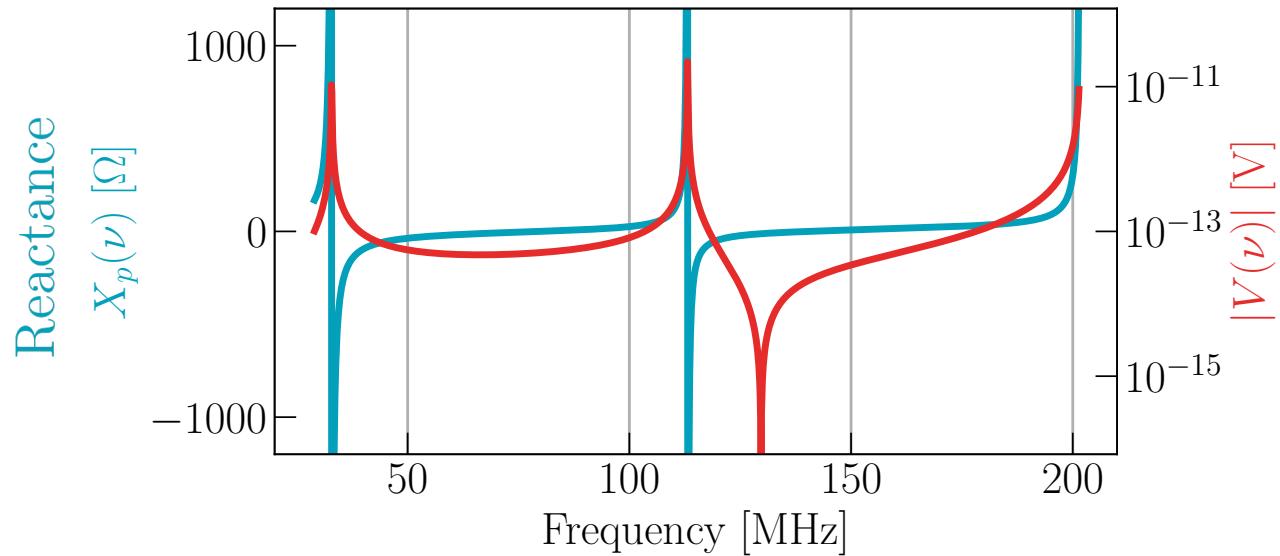
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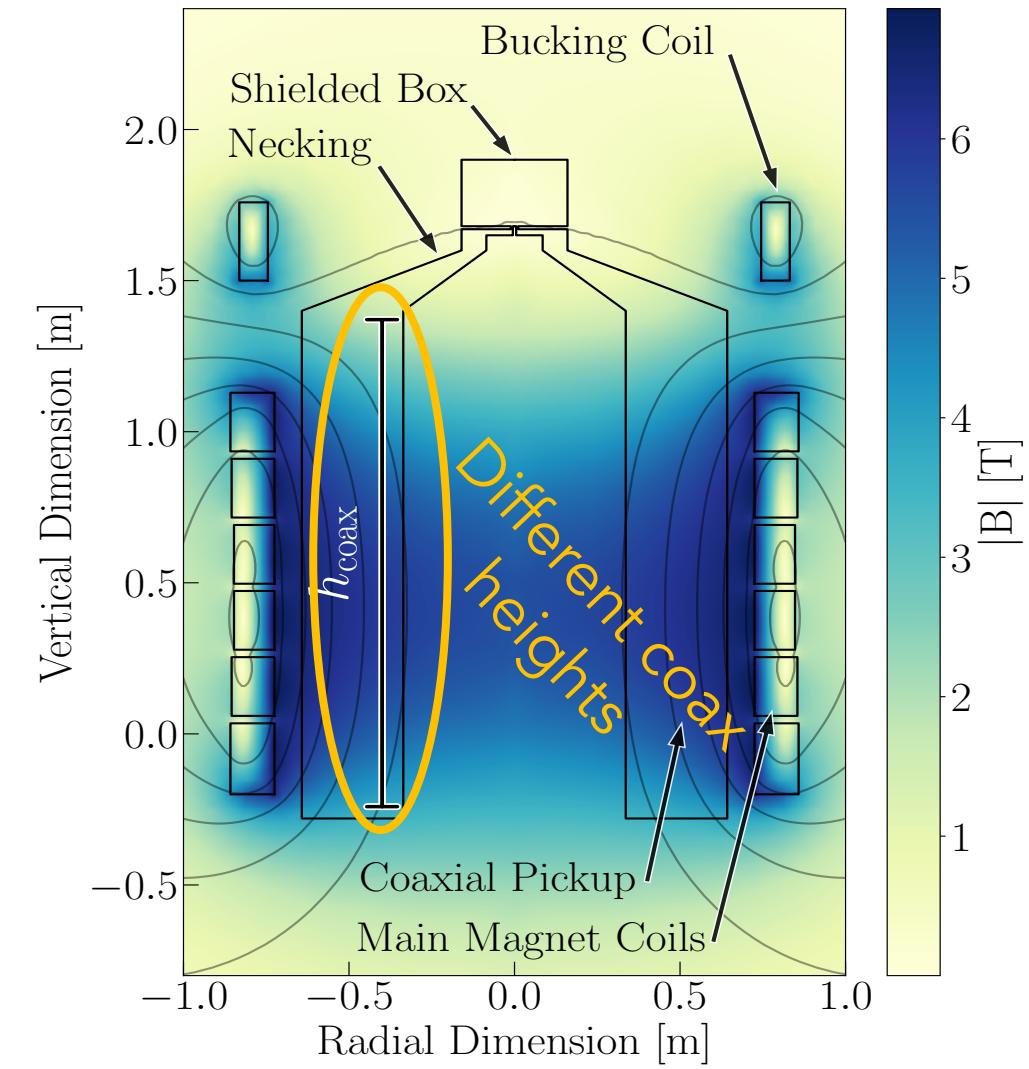
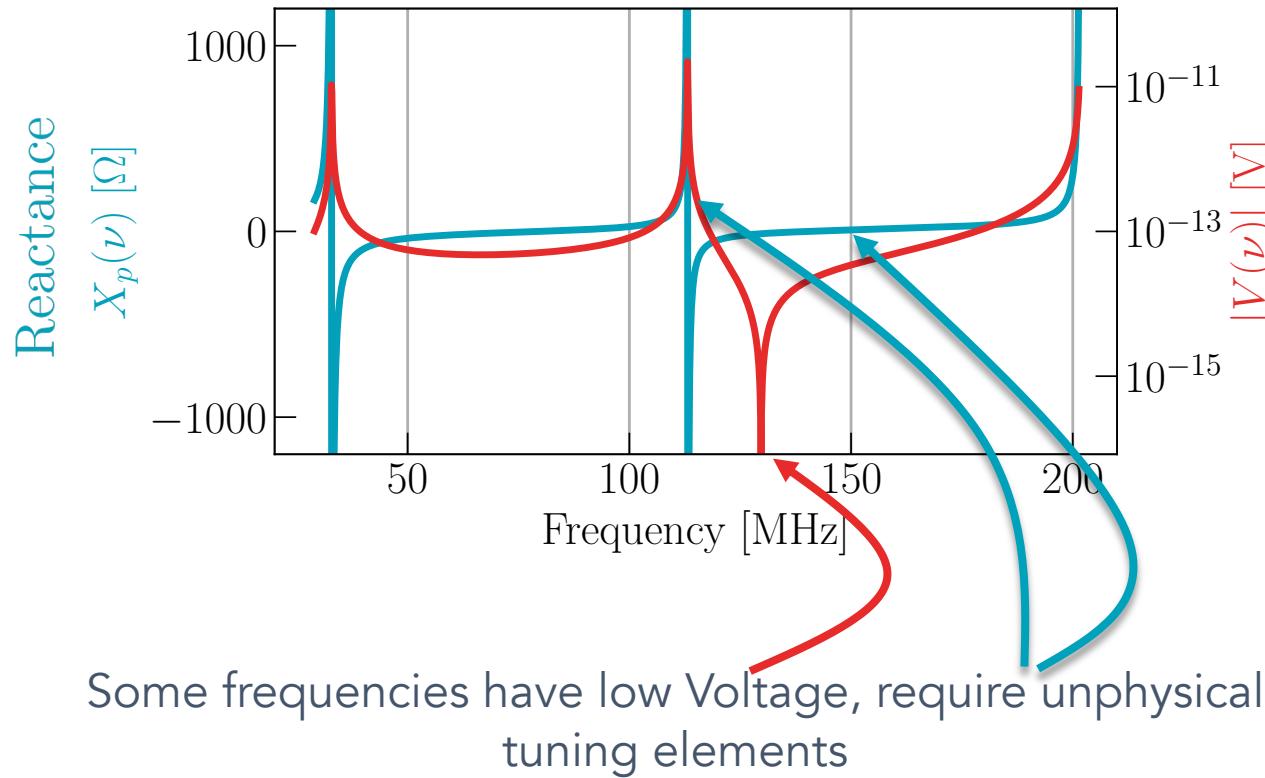
Based off of: arXiv:2302.14084

Challenges of a single coax

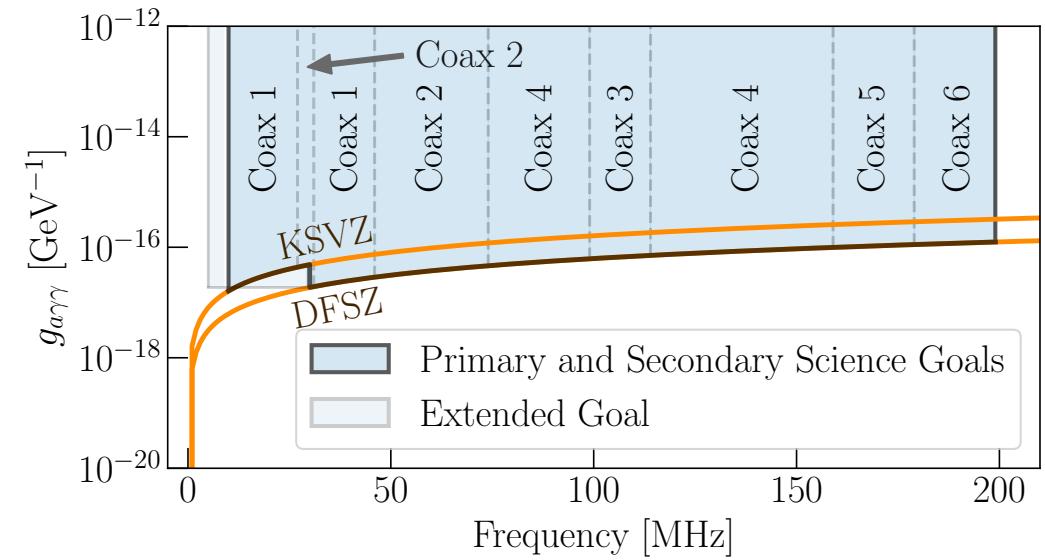
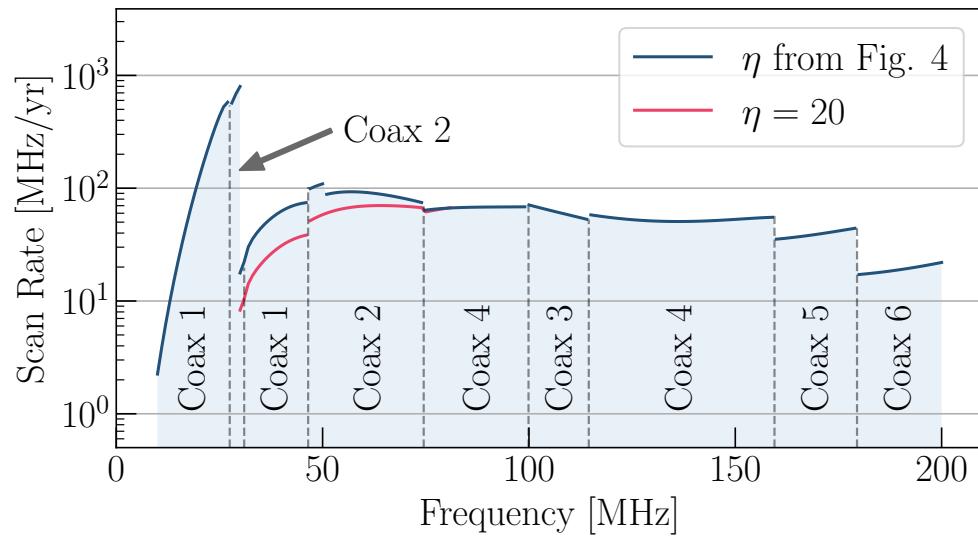


Some frequencies have low Voltage, require unphysical tuning elements

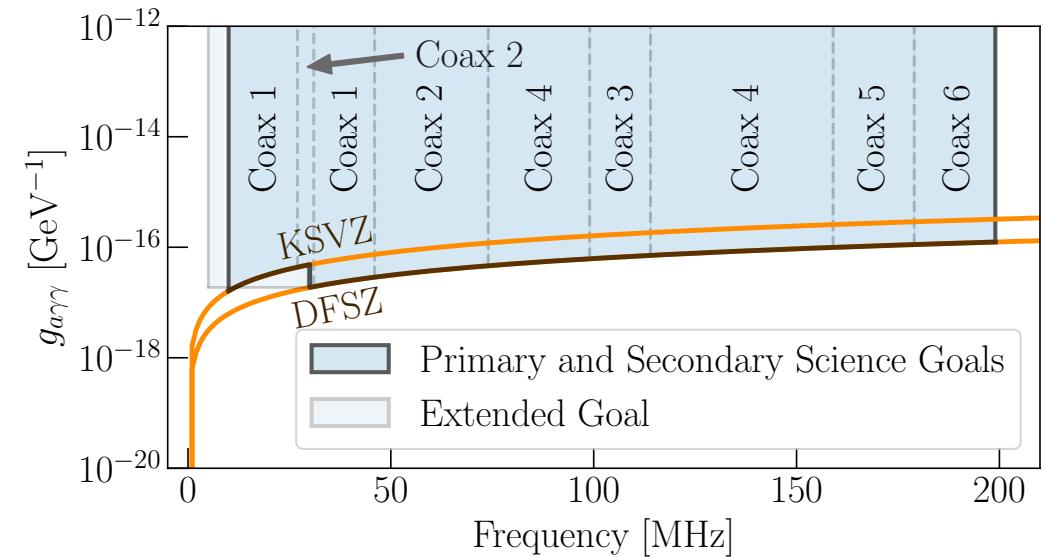
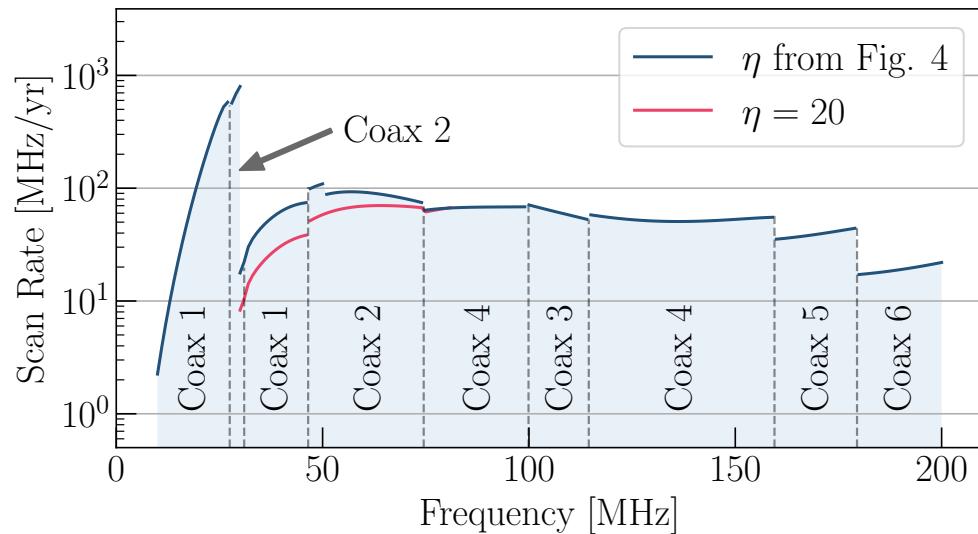
Multiple coaxes



Calculated science reach

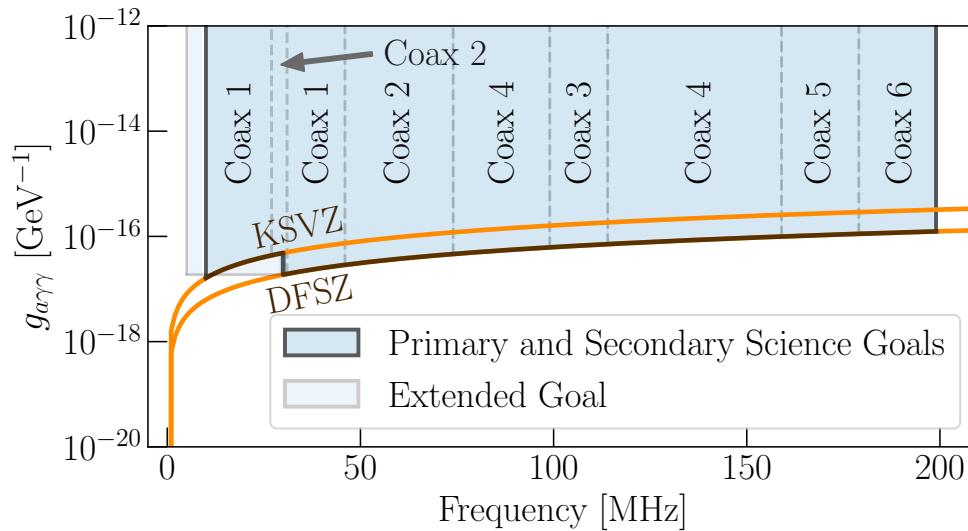


Calculated science reach



	Sensitivity & Range	3σ Live Scan Time
Primary Science Goal	DFSZ; 30–200 MHz	3.8 yr
Secondary Science Goal	KSVZ; 10–30 MHz	0.9 yr
Extended Goal	$1.87 \times 10^{-17} \text{ GeV}^{-1}$; 5–30 MHz	1.7 yr

Thank you!



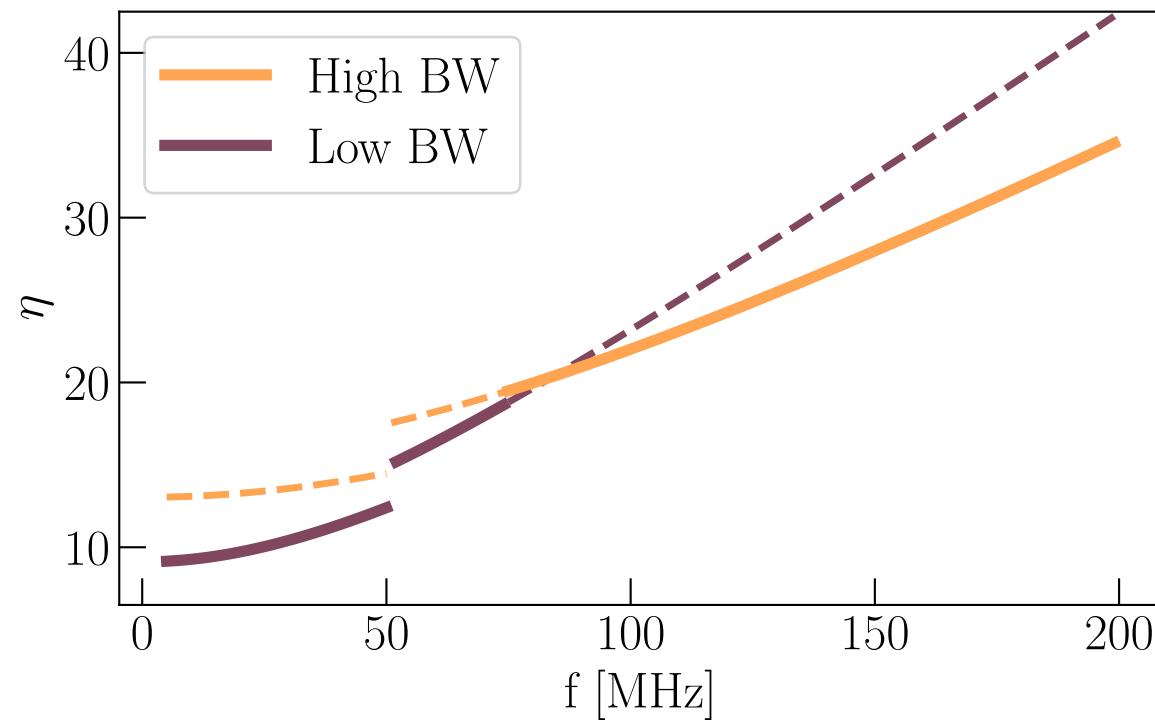
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These slides

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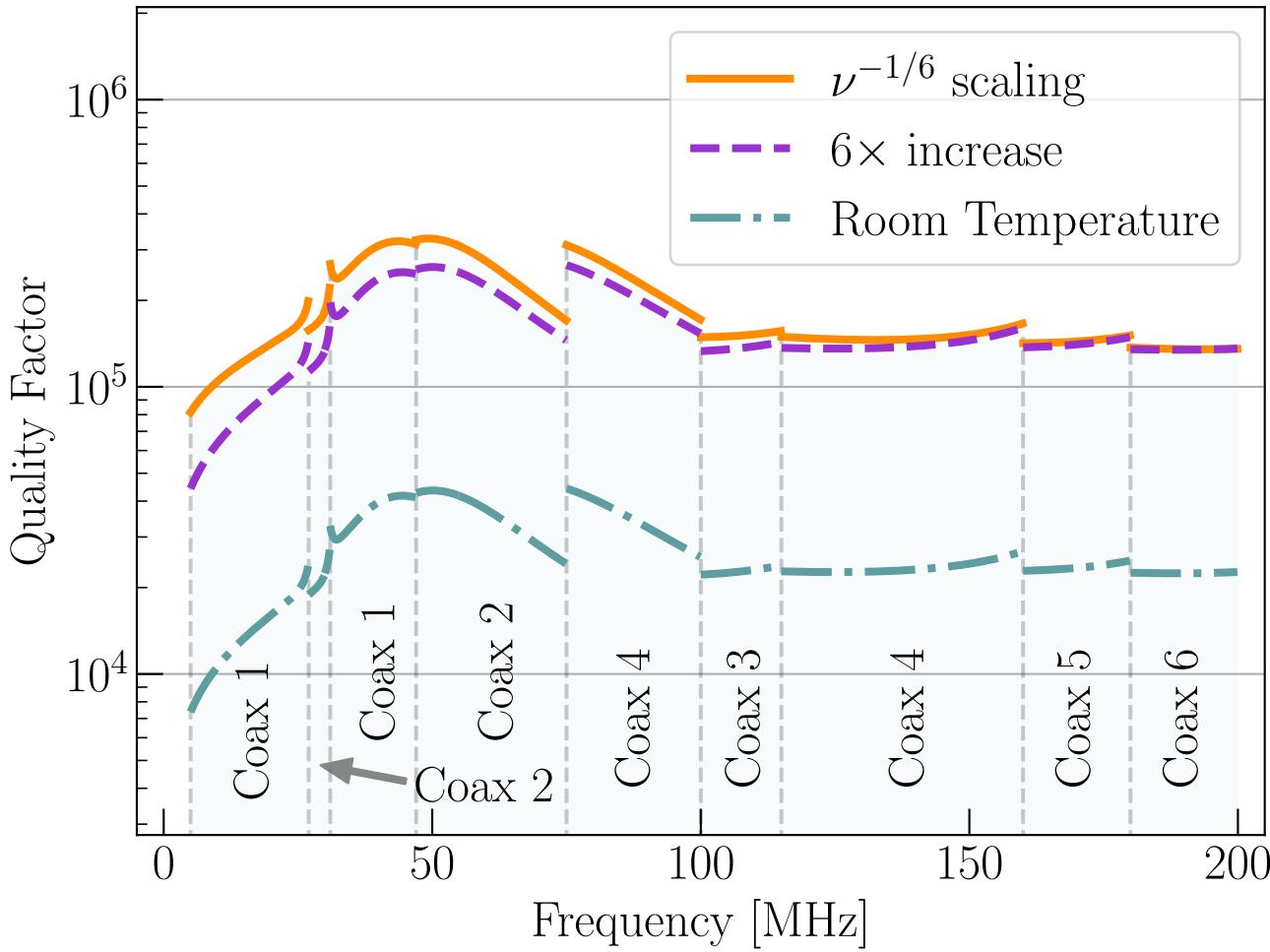
Backup Slides

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

