Science reach and electromagnetic modeling of DMRadio-m^3

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Stanford University – Irwin Group
DMRadio Collaboration

APS April Meeting – April 5, 2024

DMRadio collaboration

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Outline

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

arXiv:2302.14084

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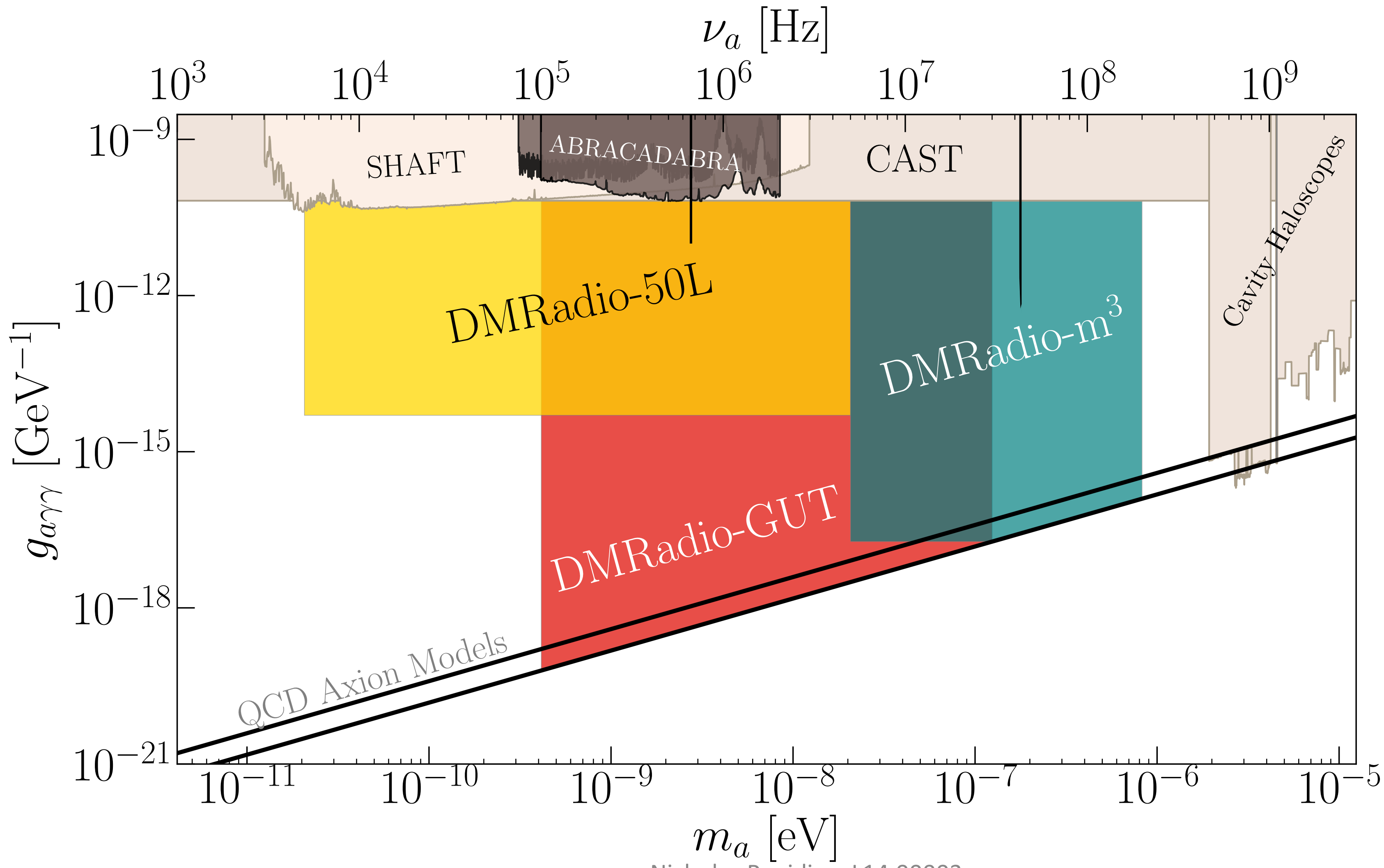
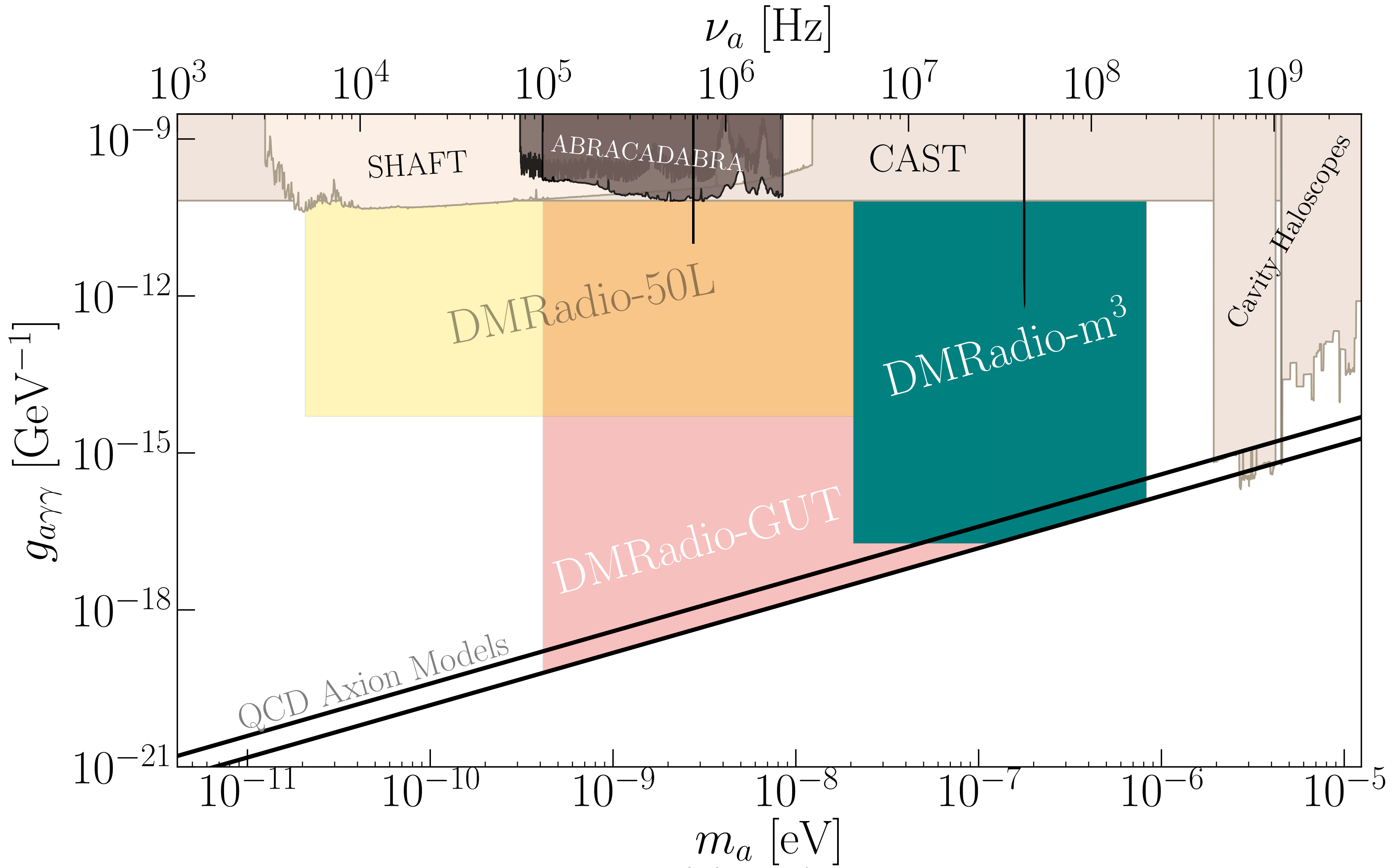
DMRadio



ν_a [Hz]
10^3 10^4 10^5 10^6 10^7 10^8 10^9
$g_{a\gamma\gamma}$ [GeV^{-1}]
10^{-9} 10^{-12} 10^{-15} 10^{-18} 10^{-21}
SHAFT
ABRACADABRA
CAST
Cavity Haloscopes
DMRadio-50L
DMRadio-m^3
DMRadio-GUT
QCD Axion Models
10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5}
m_a [eV]

DMRadio



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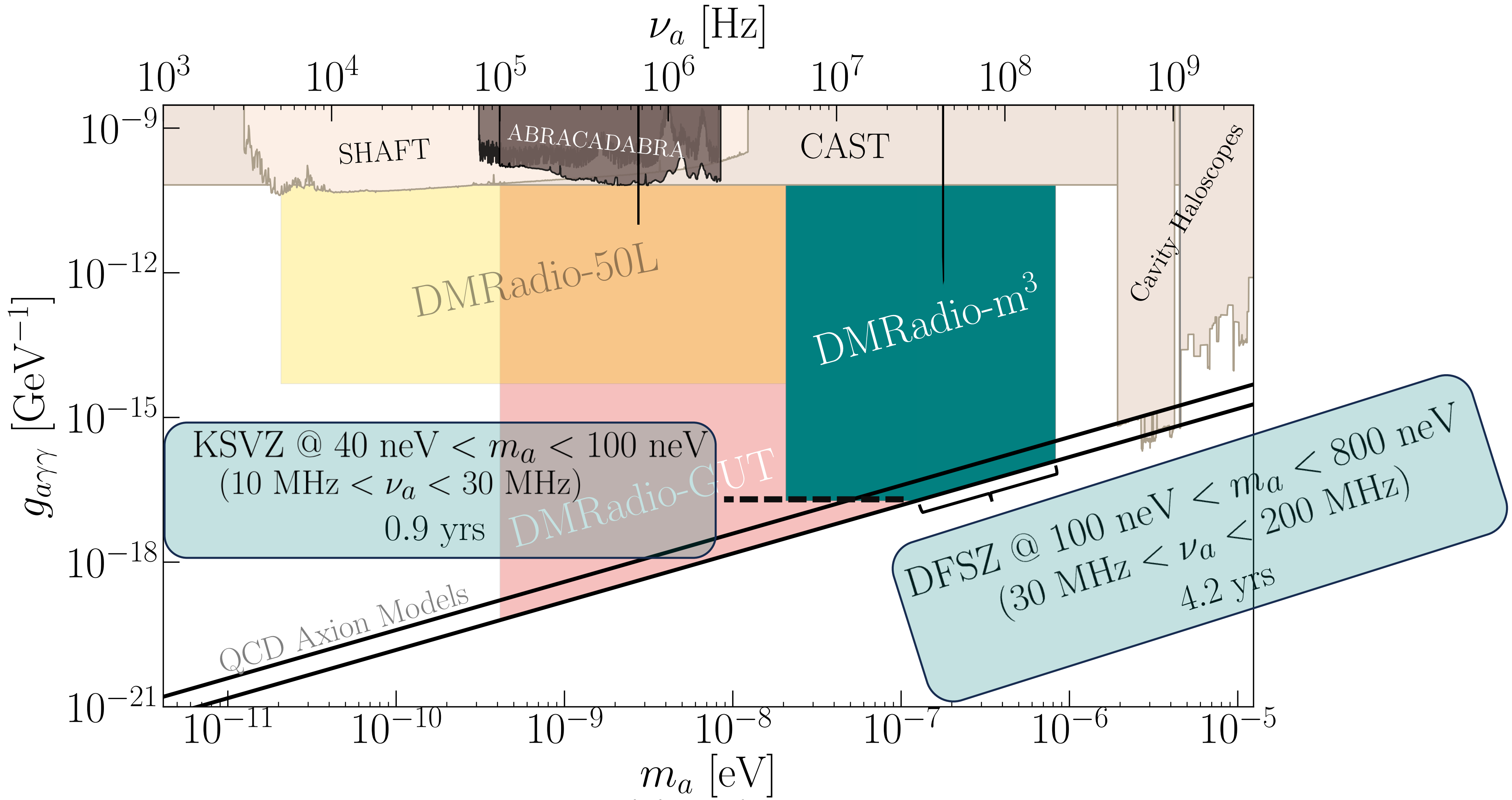
DMRadio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m_a [eV]
KSVZ @ 40 neV $< m_a <$ 100 neV
(10 MHz $< \nu_a <$ 30 MHz)
0.9 yrs
DFSZ @ 100 neV $< m_a <$ 800 neV
(30 MHz $< \nu_a <$ 200 MHz)
4.2 yrs

m^3 design

m^3 uses a solenoidal magnet + coaxial copper pickup

m^3 design

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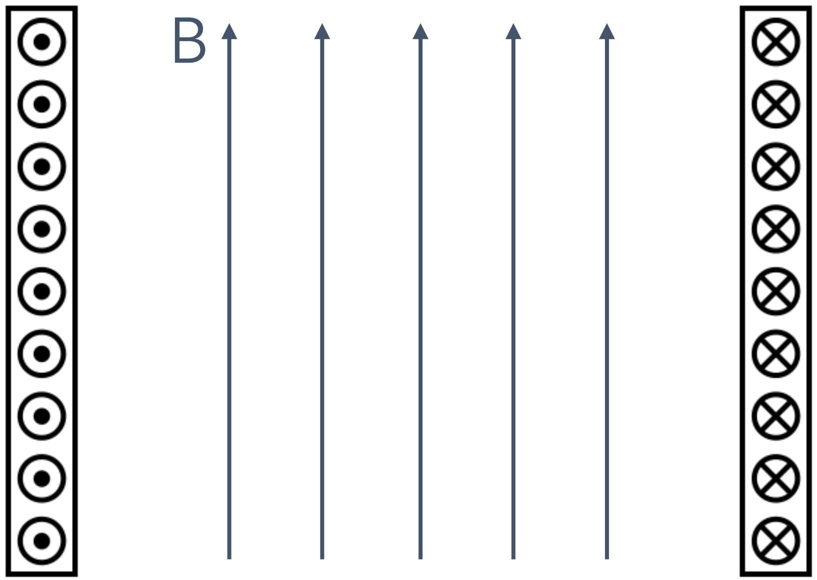
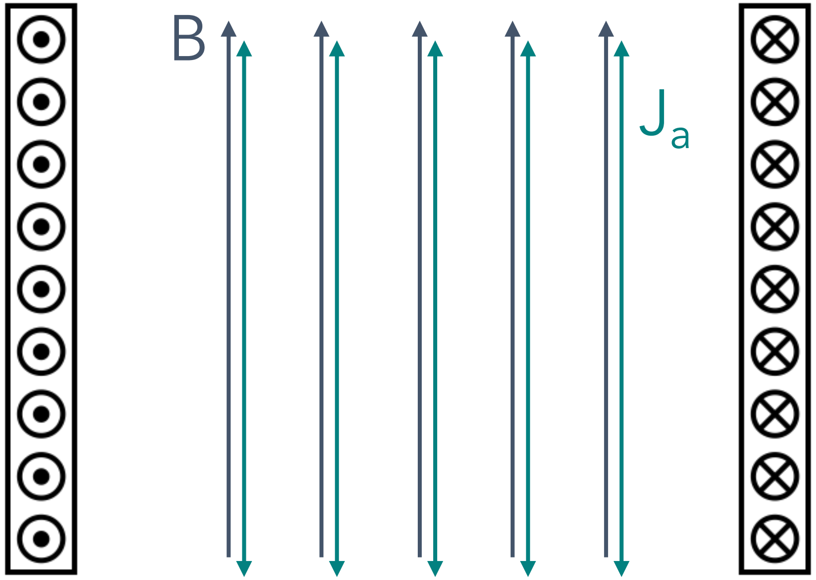


m^3 design

m^3 uses a solenoidal magnet + coaxial copper pickup

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



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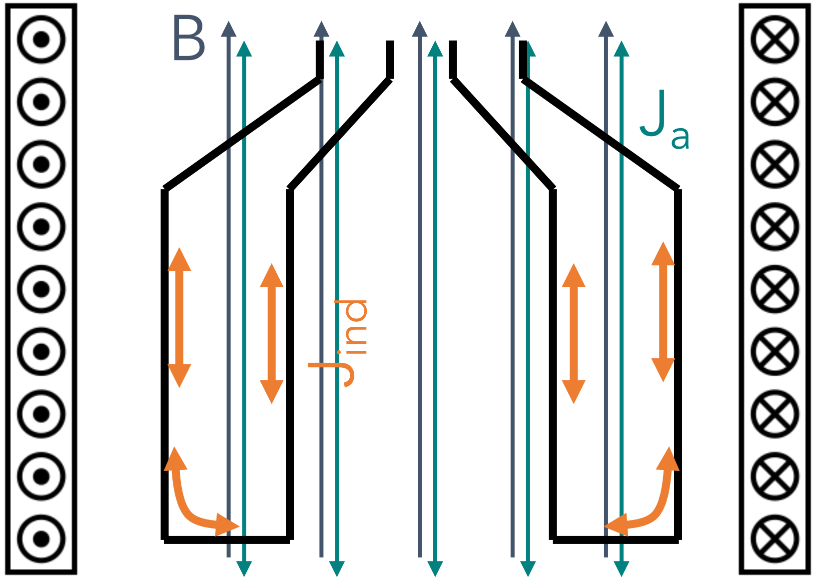

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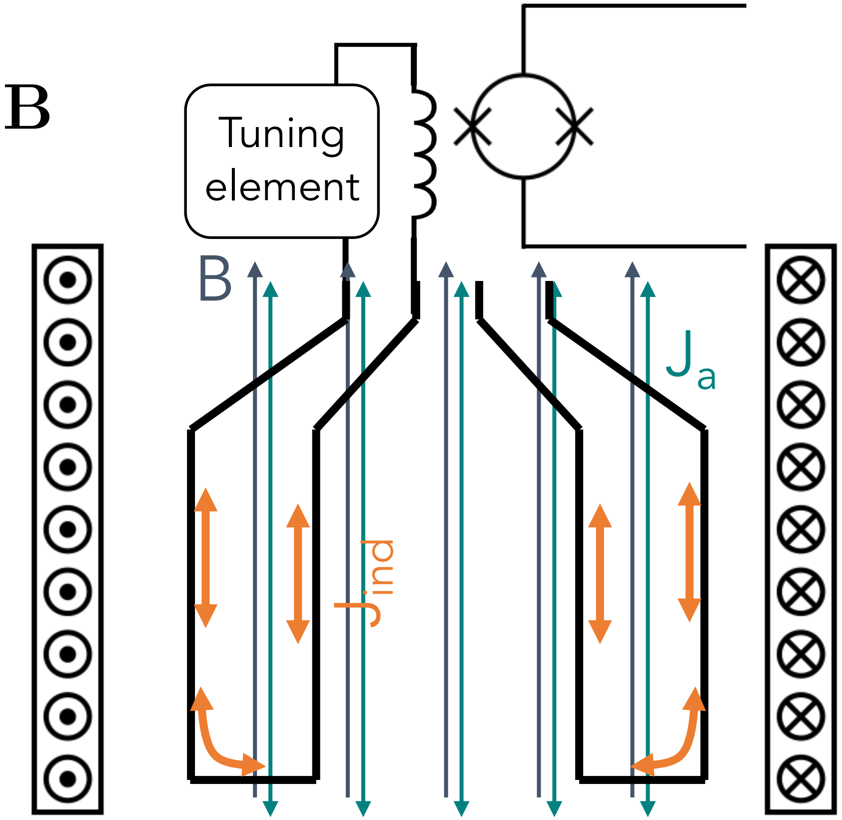
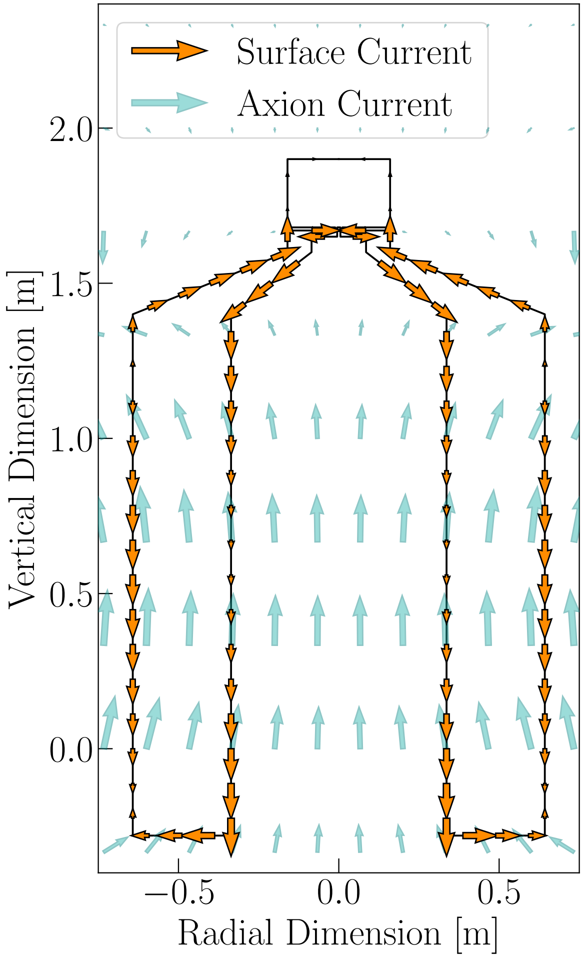
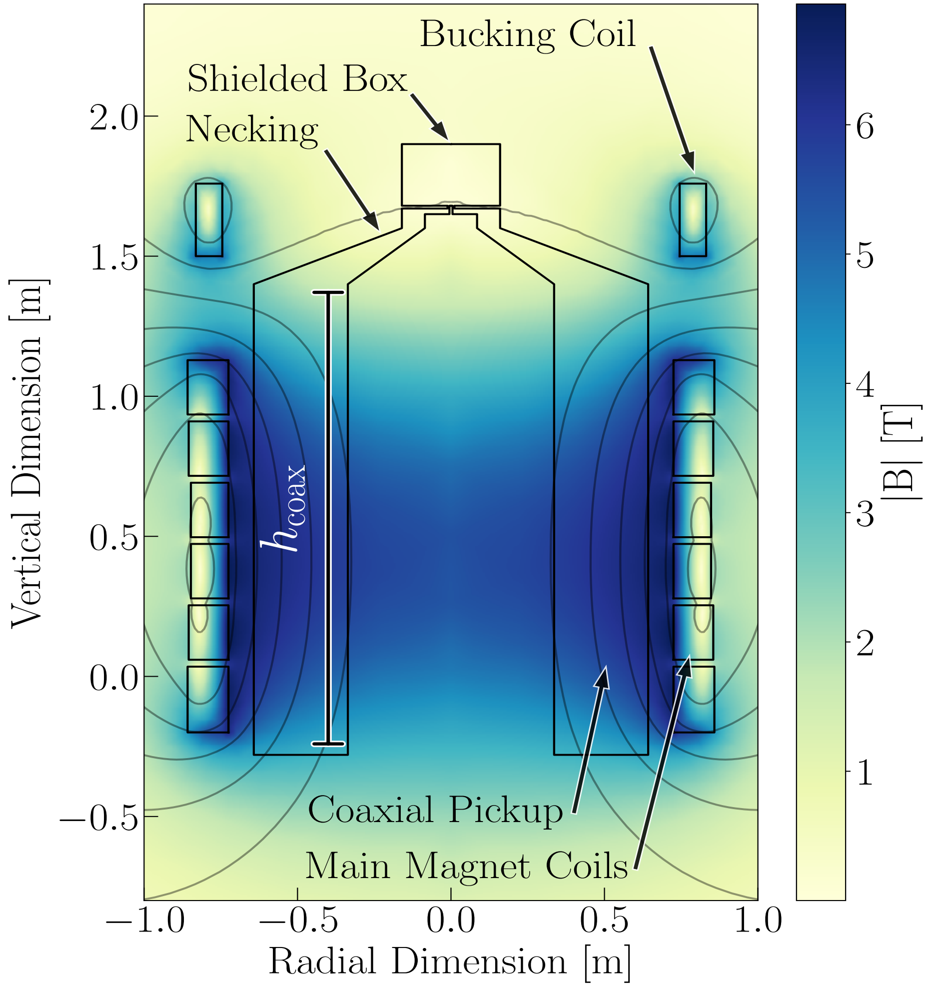


m^3 pickup simulations

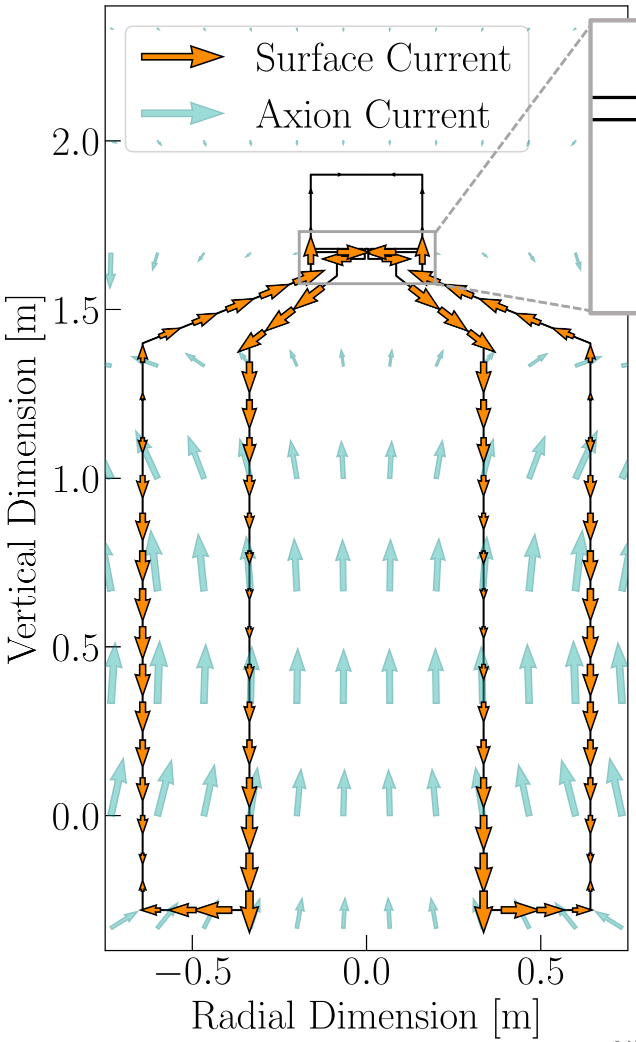


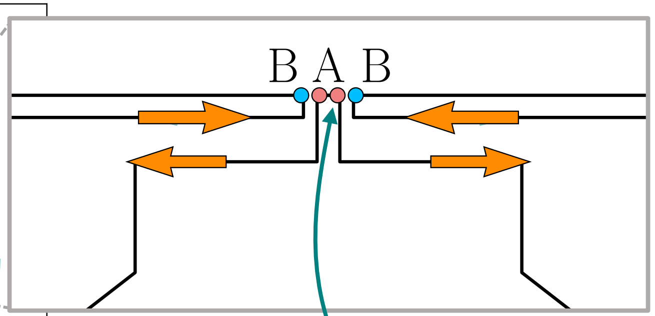
These simulations quantitatively determine science reach of DMRadio-m^3



Simulations on COMSOL

m^3 pickup simulations





Connect tuning elements + coupling to dc SQUID across points A and B

Outline

1. DMRadio-m^3 introduction and geometry
2. Extracting the sensitivity
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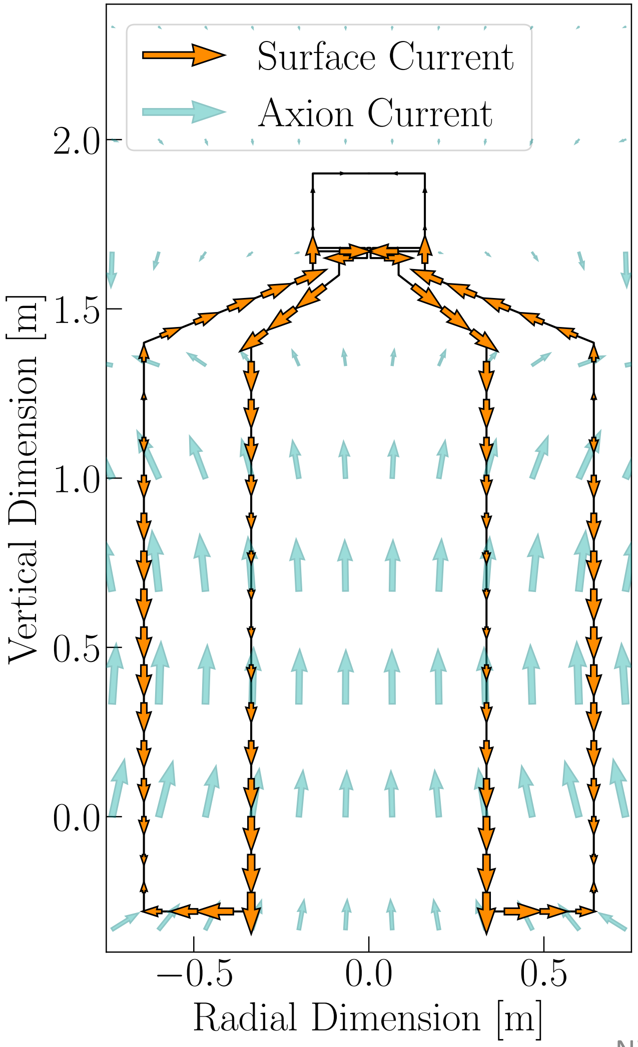
Is this still lumped element?



DFSZ @ 100 neV $< m_a <$ 800 neV

30 MHz $< \nu_a <$ 200 MHz

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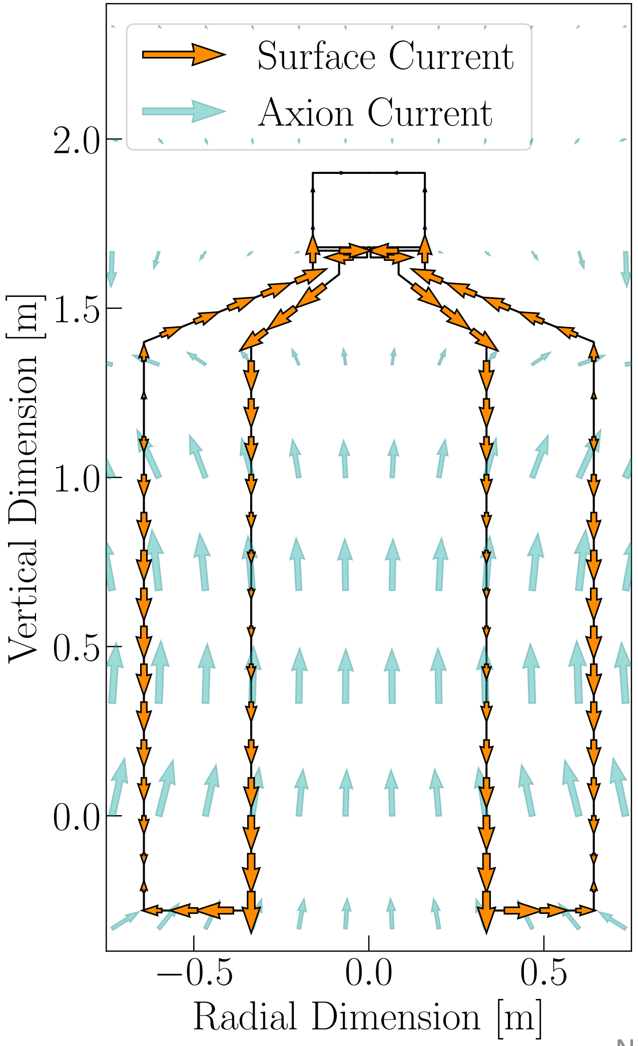


DFSZ @ 100 neV $< m_a <$ 800 neV

30 MHz $< \nu_a <$ 200 MHz

10 m $> \lambda_a >$ 1.5 m

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

Scan rate

$$\frac{d\nu}{dt} = \frac{\pi \overbrace{(6.4 \times 10^5)}^{\text{DM halo physics}}}{16\ \mathrm{SNR}^2 m_a^4} \frac{\overbrace{|V(m_a, B, g_{a\gamma\gamma})|^4}^{\text{Axion induced voltage}} \overbrace{Q(\nu_r)}^{\text{Quality Factor}} \overbrace{\bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)]}^{\text{Noise physics}}}{\underbrace{L_{\text{eff}}(\nu_r)^2}_{\text{Effective inductance}}}$$

Scan rate

DM halo physics

Axion induced voltage

Quality Factor

Noise physics

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

Effective inductance

How do we calculate these parameters in this limit?

Scan rate

$$\frac{d\nu}{dt} = \frac{\pi\,(6.4\times10^5)\,|V(m_a,B,g_{a\gamma\gamma})|^4\,Q(\nu_r)\,\bar{\mathcal{G}}[\nu_r,T,\eta(\nu_r)]}{16\ \mathrm{SNR}^2 m_a^4\,L_{\mathrm{eff}}(\nu_r)^2}$$

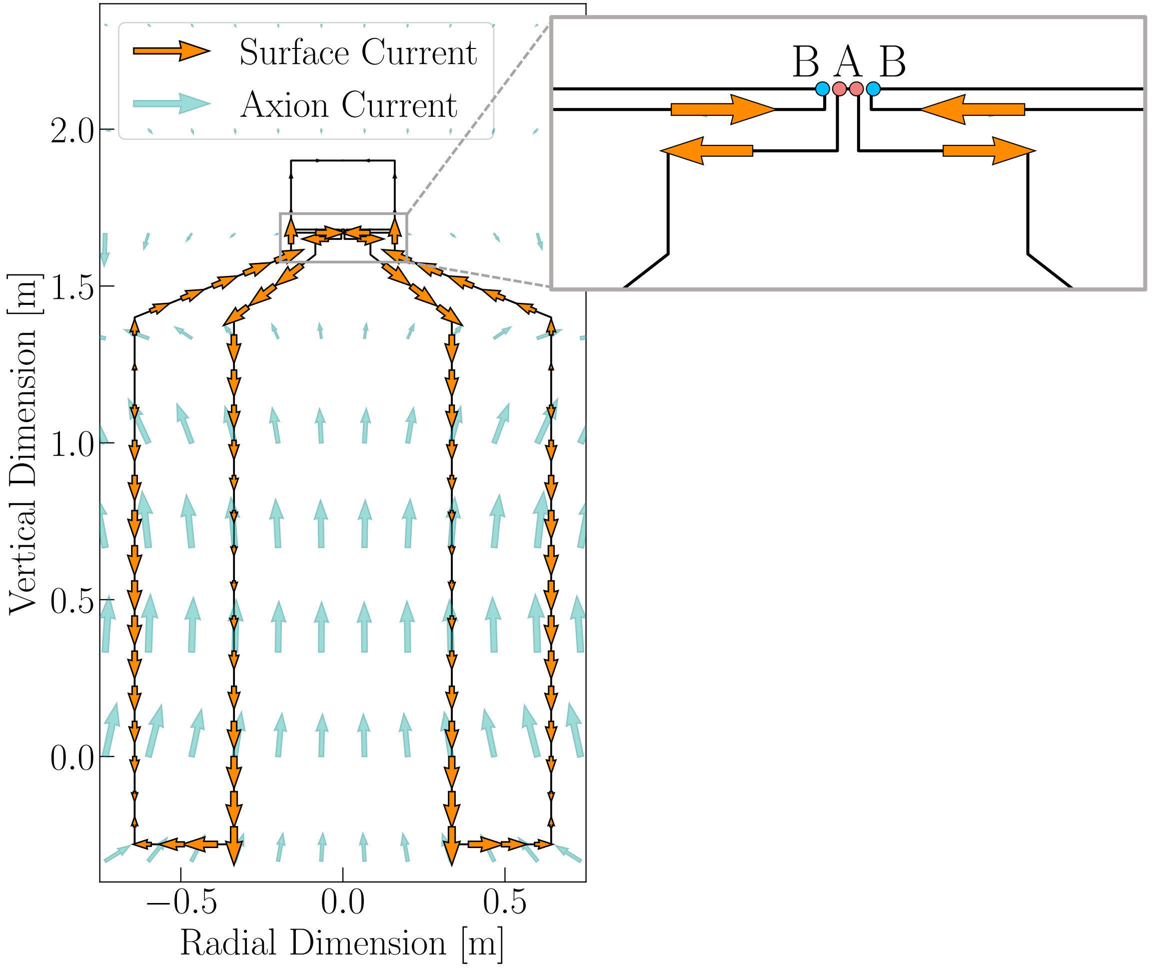
DM halo physics

Axion induced voltage

Quality Factor

Noise physics

Effective inductance

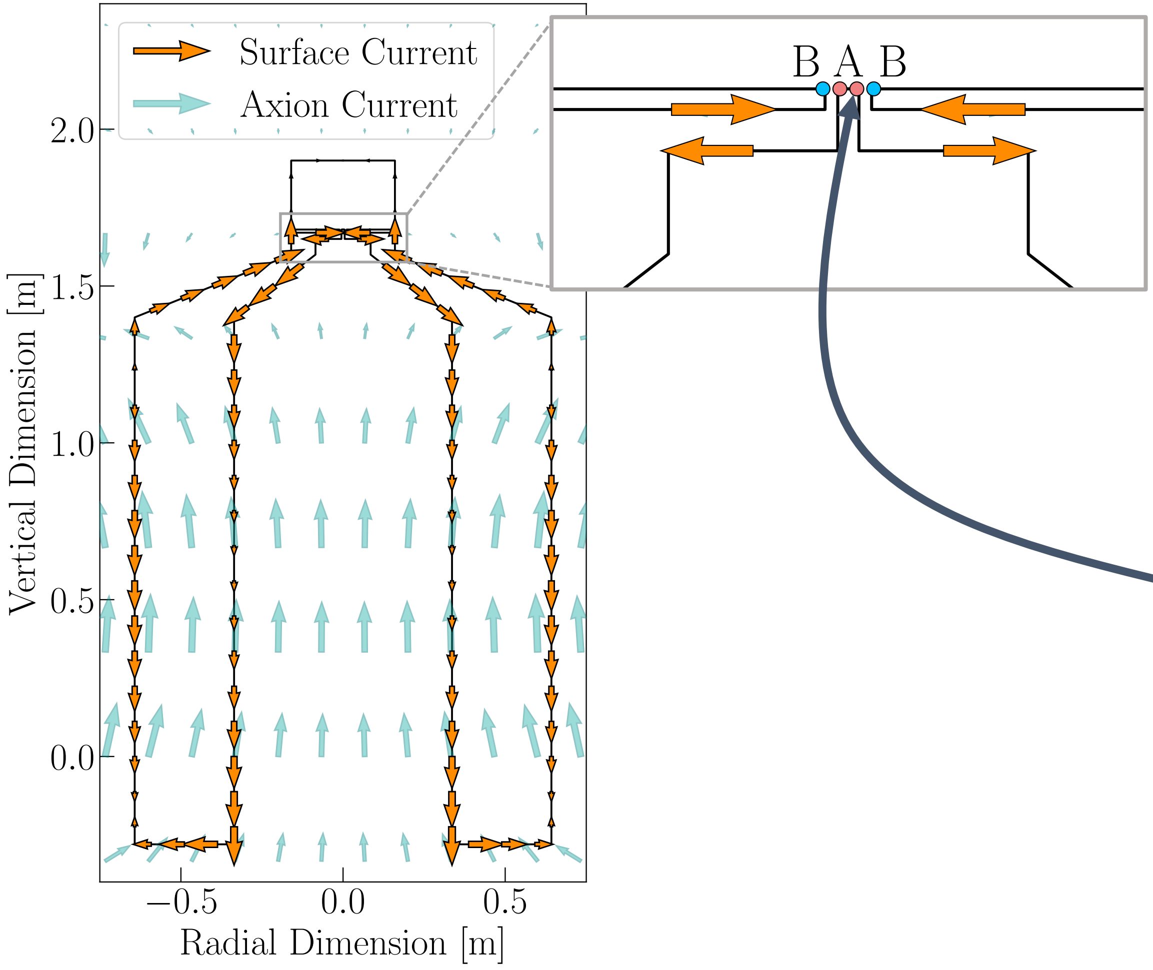


Scan rate

DM halo physics, Axion induced voltage, Quality Factor, Noise physics

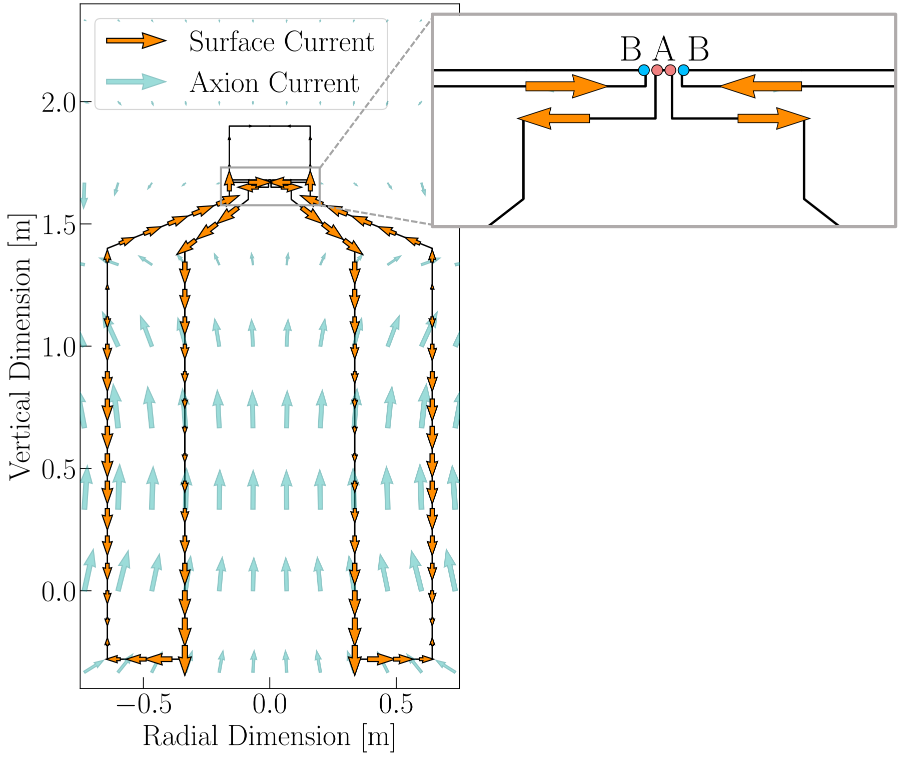
$$\frac{d\nu}{dt} = \frac{\pi\,(6.4\times 10^5)}{16\ \mathrm{SNR}^2 m_a^4}\frac{|V(m_a, B, g_{a\gamma\gamma})|^4\, Q(\nu_r)\,\bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)]}{L_{\rm eff}(\nu_r)^2}$$

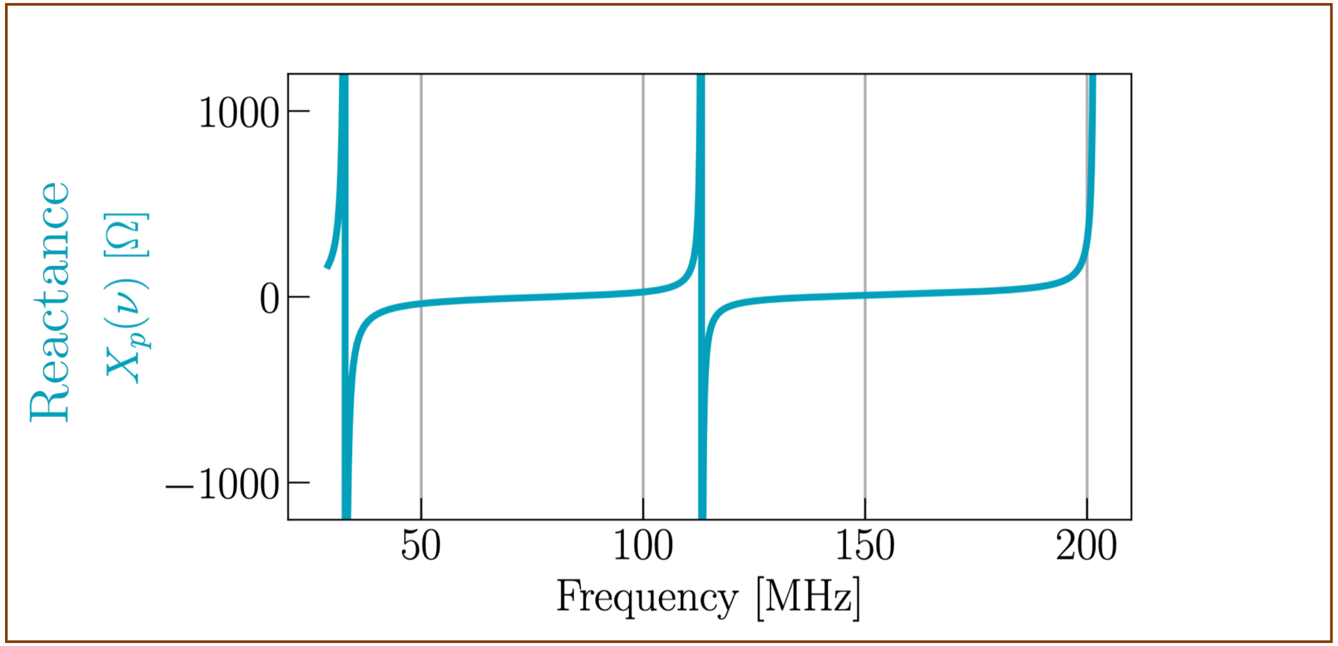
Effective inductance



Calculate voltage and impedance across points A and B numerically

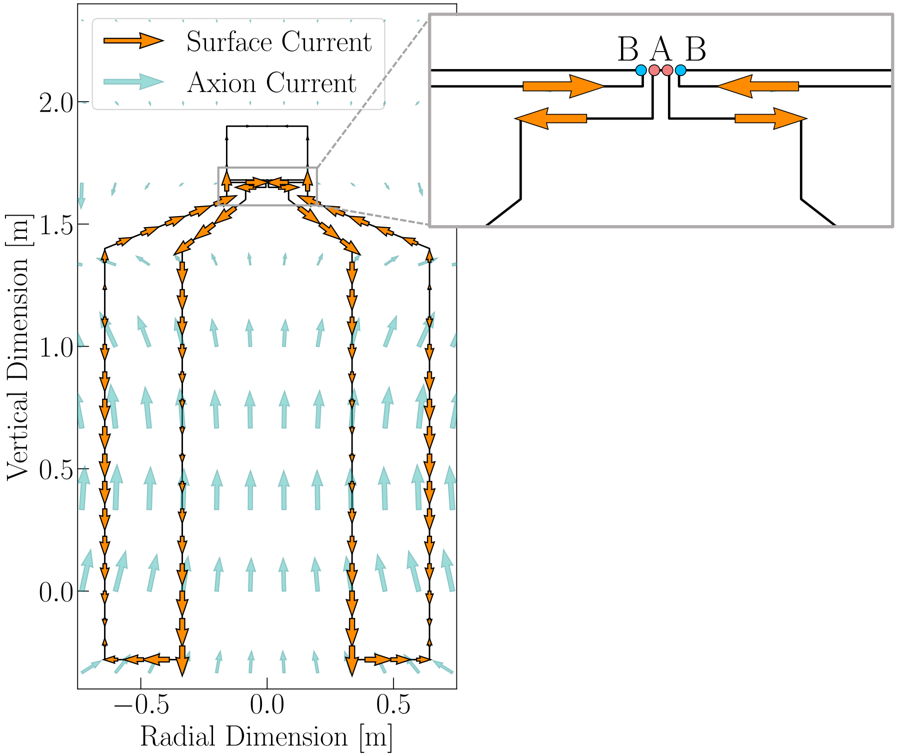
Impedance and voltage

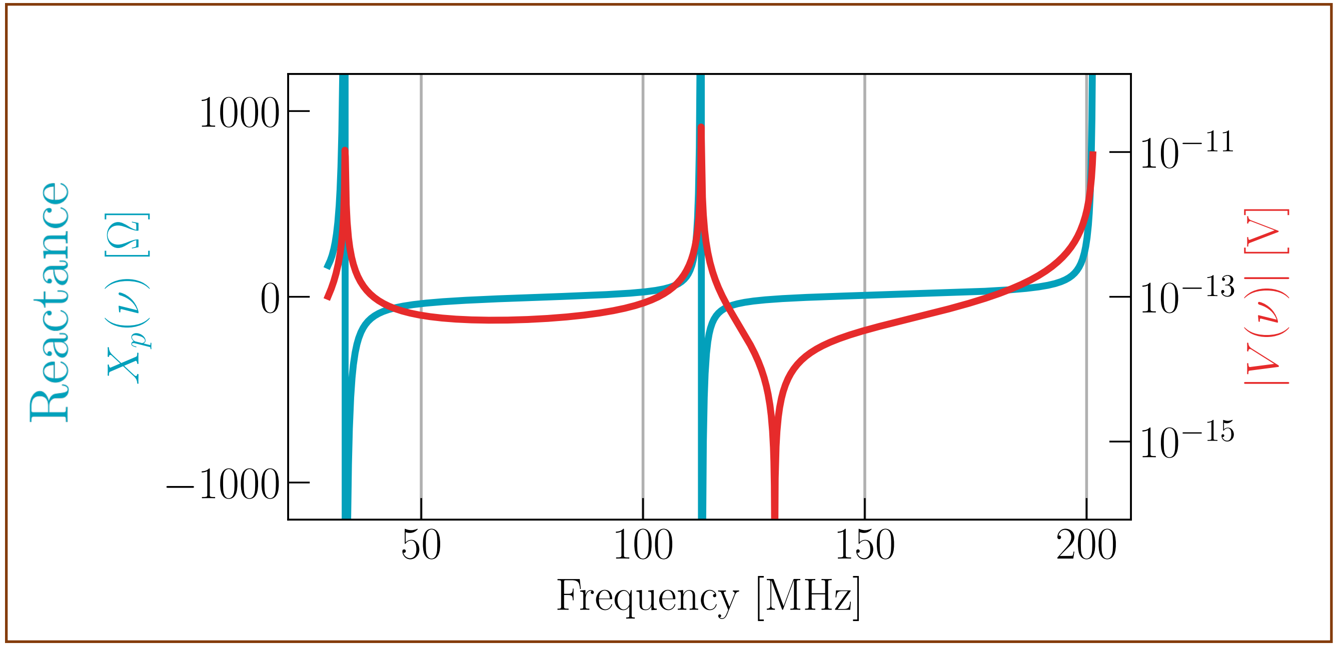




$$Z_p(\nu) = R_p(\nu) + iX_p(\nu)$$

Impedance and voltage





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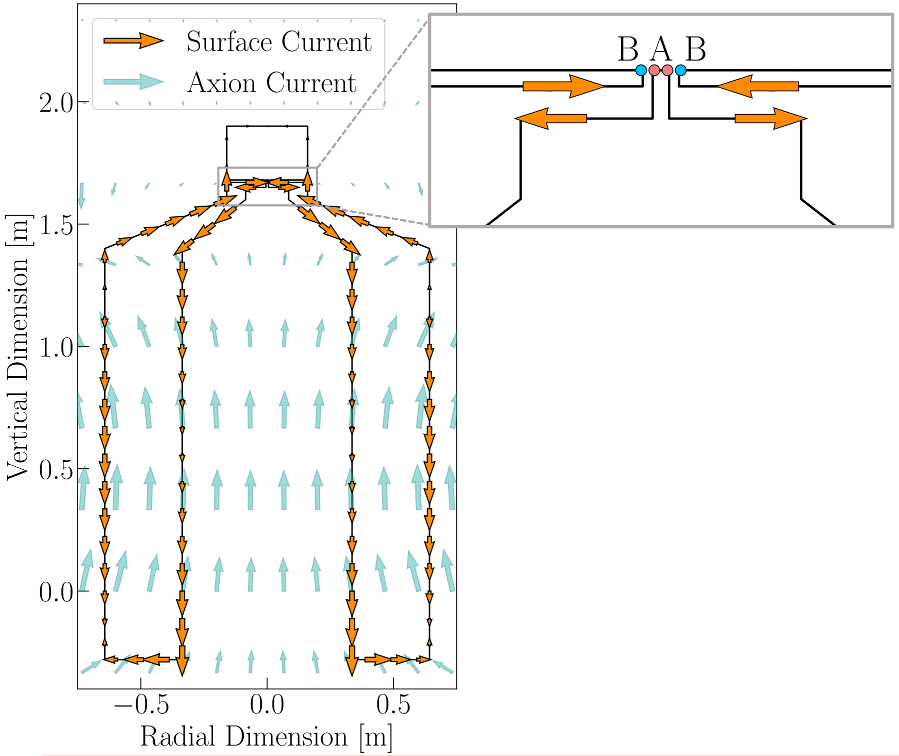
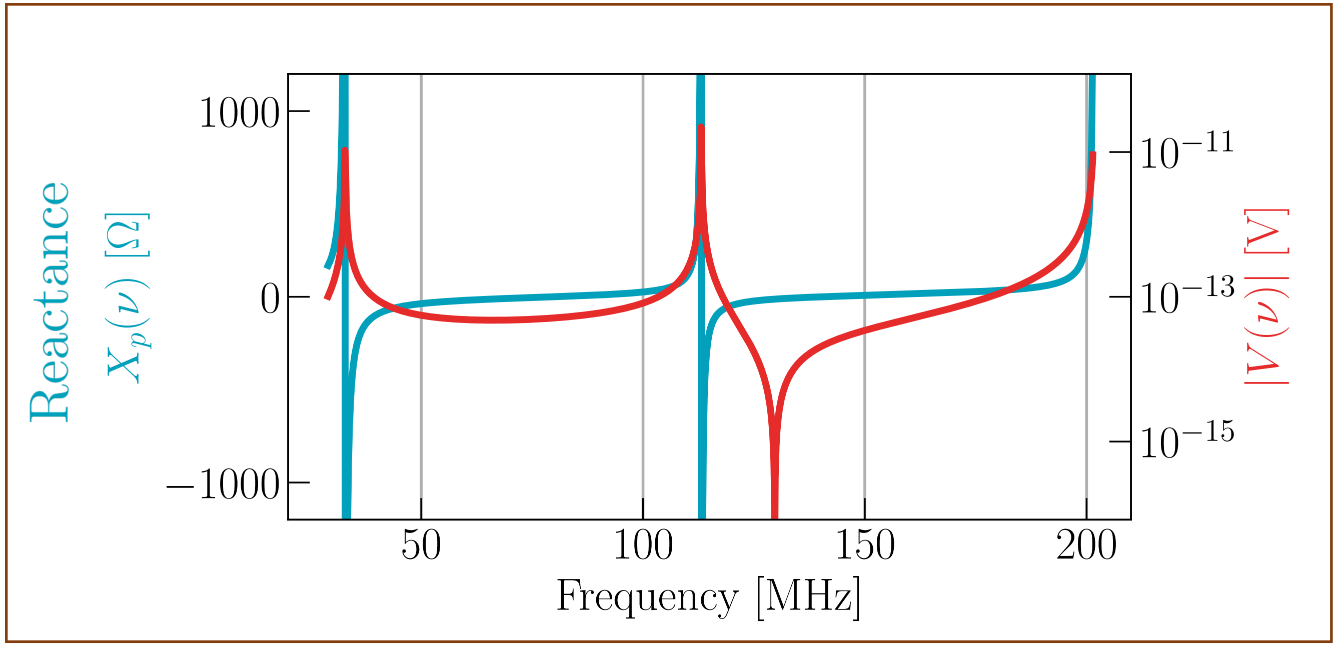




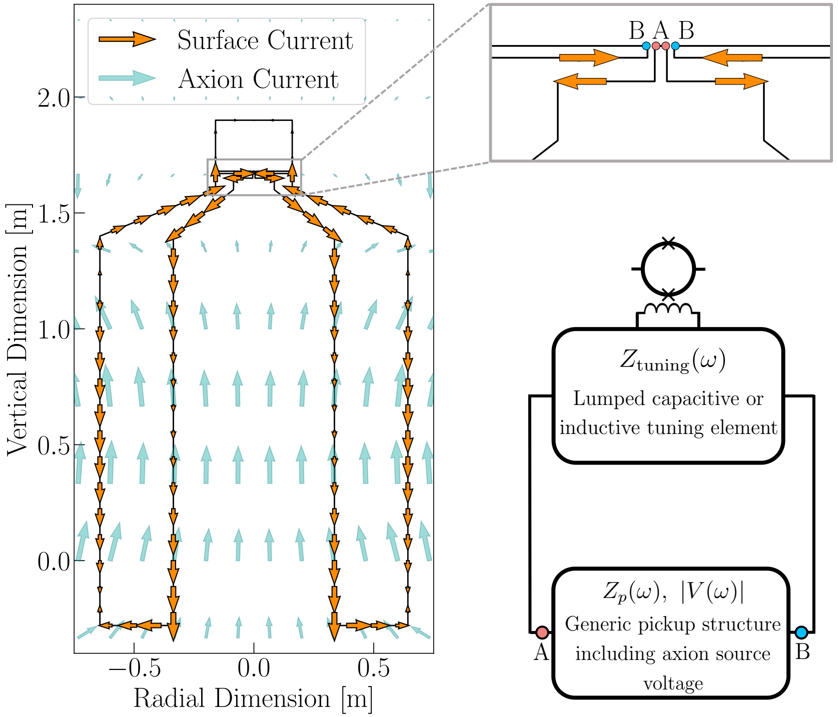
$$Z_p(\nu) = R_p(\nu) + iX_p(\nu)$$

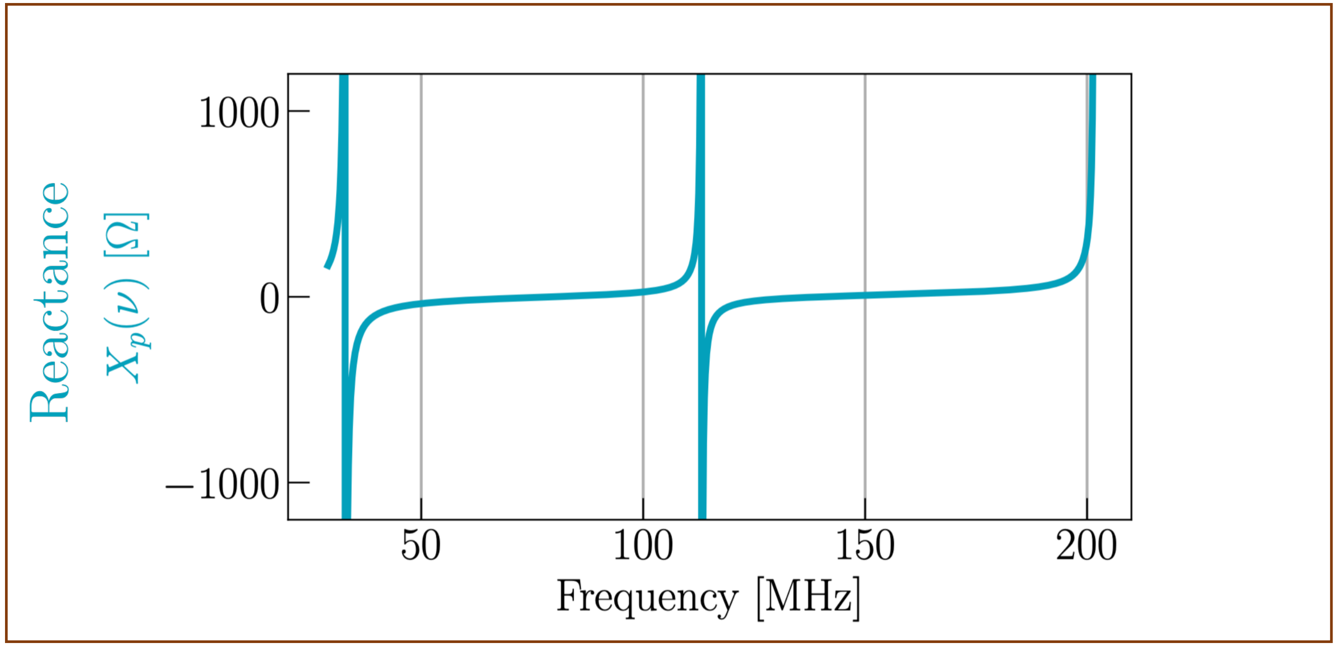
At every frequency, Taylor expand impedance to express impedance as frequency-specific series RLC:

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

To be extracted

How to tune resonance?

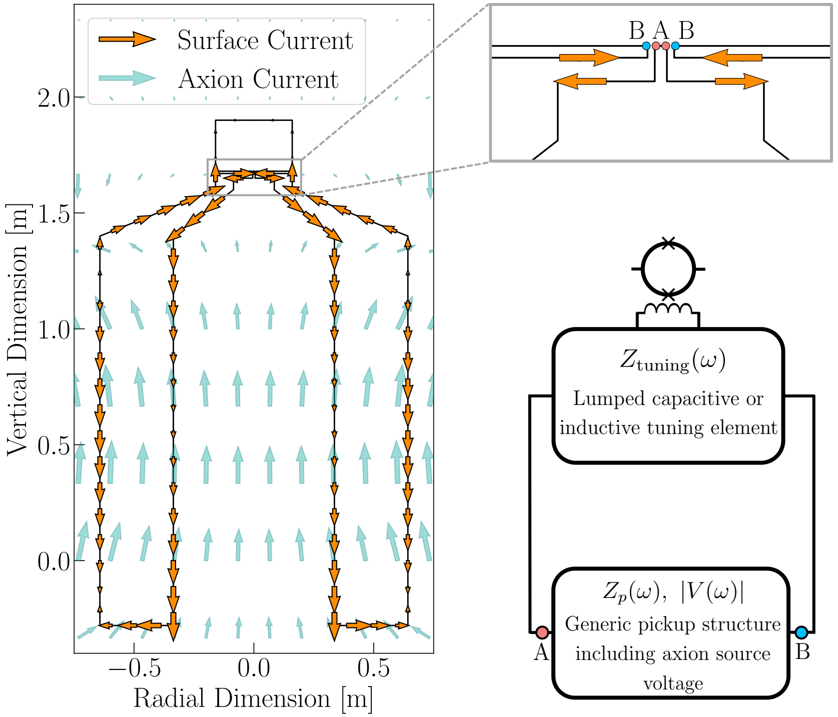


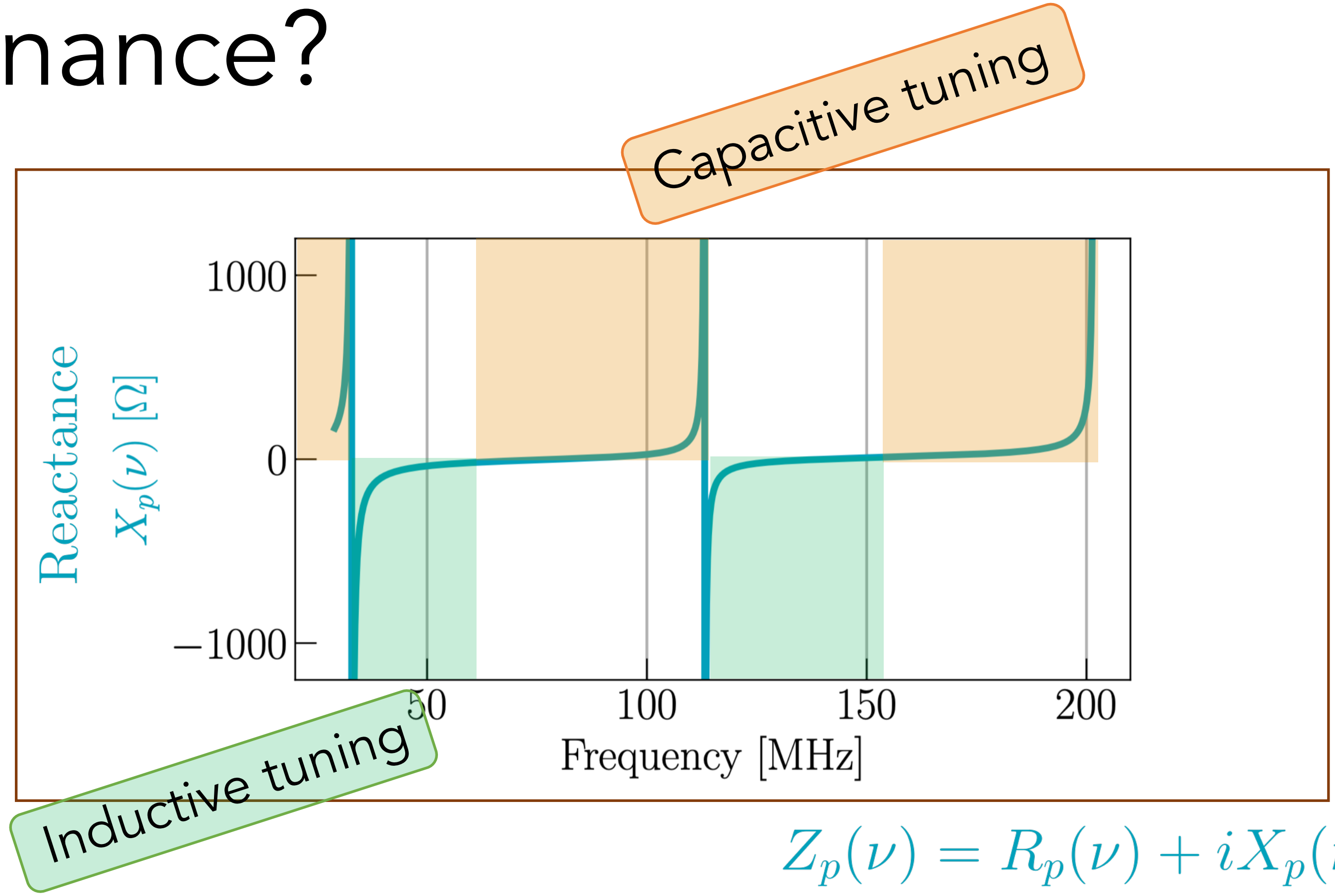


$$Z_p(\nu) = R_p(\nu) + iX_p(\nu)$$

To achieve resonance at any frequency, reactance must be tuned to zero using external capacitor or inductor: $X_{\text{tot}}(\nu_0) = X_{\text{tuning}}(\nu_0) + X_p(\nu_0) = 0$

How to tune resonance?





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Impedance and voltage

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

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

$$\frac{d\nu}{dt} = \frac{\pi\left(6.4\times10^5\right)}{16\ \mathrm{SNR}^2 m_a^4}\bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)]\frac{\overbrace{\boxed{|V(m_a, B, g_{a\gamma\gamma})|^4}}^{\text{Axion induced voltage}}\overbrace{\boxed{Q(\nu_r)}}^{\text{Quality Factor}}}{\underbrace{\boxed{L_{\text{eff}}(\nu_r)^2}}_{\text{Effective inductance}}}$$

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→ Extract Quality Factor end Effective Inductance.

Axion induced voltage

Quality Factor

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Effective inductance

Impedance and voltage

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→ Extract Quality Factor end Effective Inductance.

-Voltage simulations provide the axion induced voltage

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2. Extracting the sensitivity
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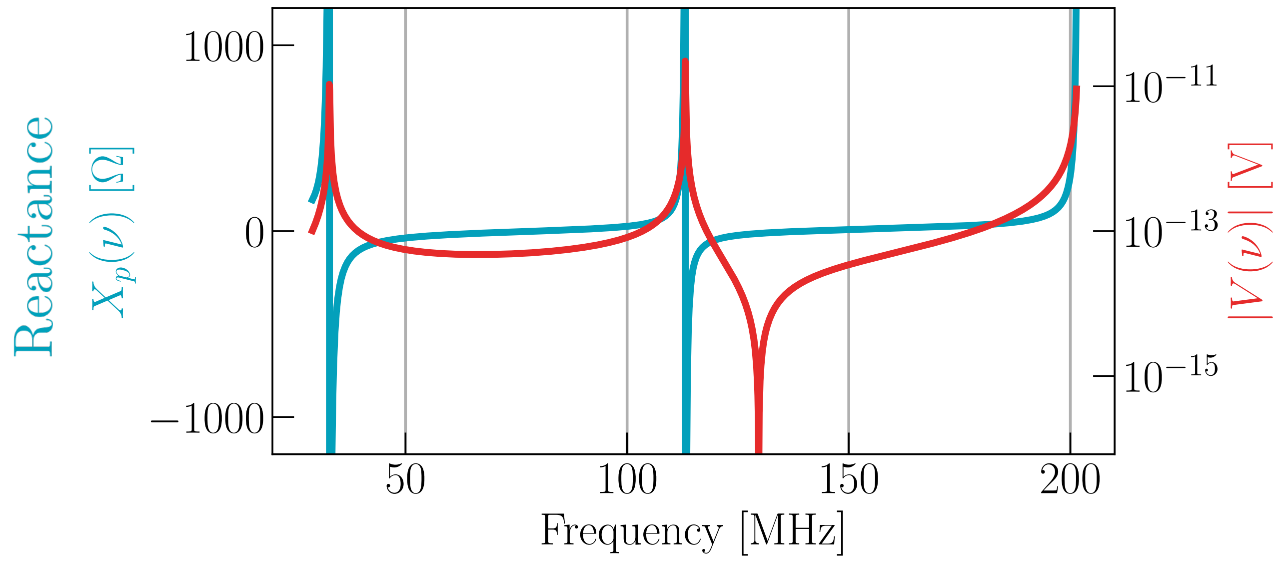
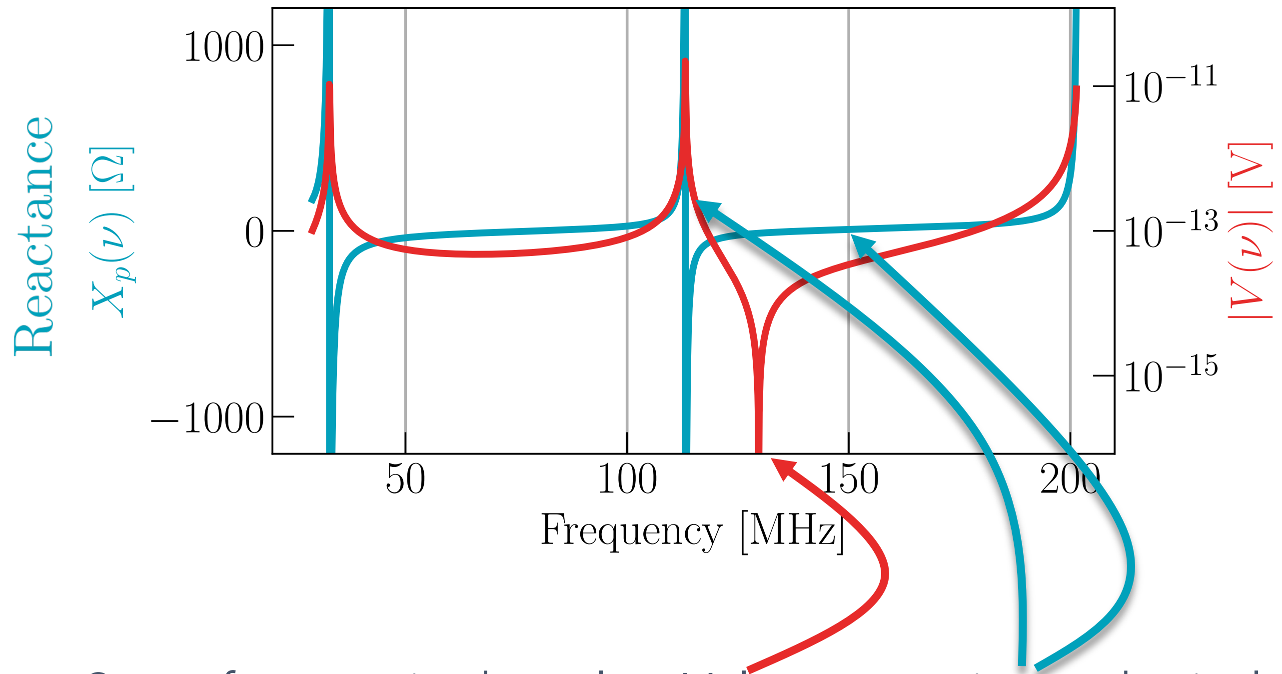
Challenges of a single coax



Some frequencies have low Voltage, require unphysical tuning elements

Multiple coaxes



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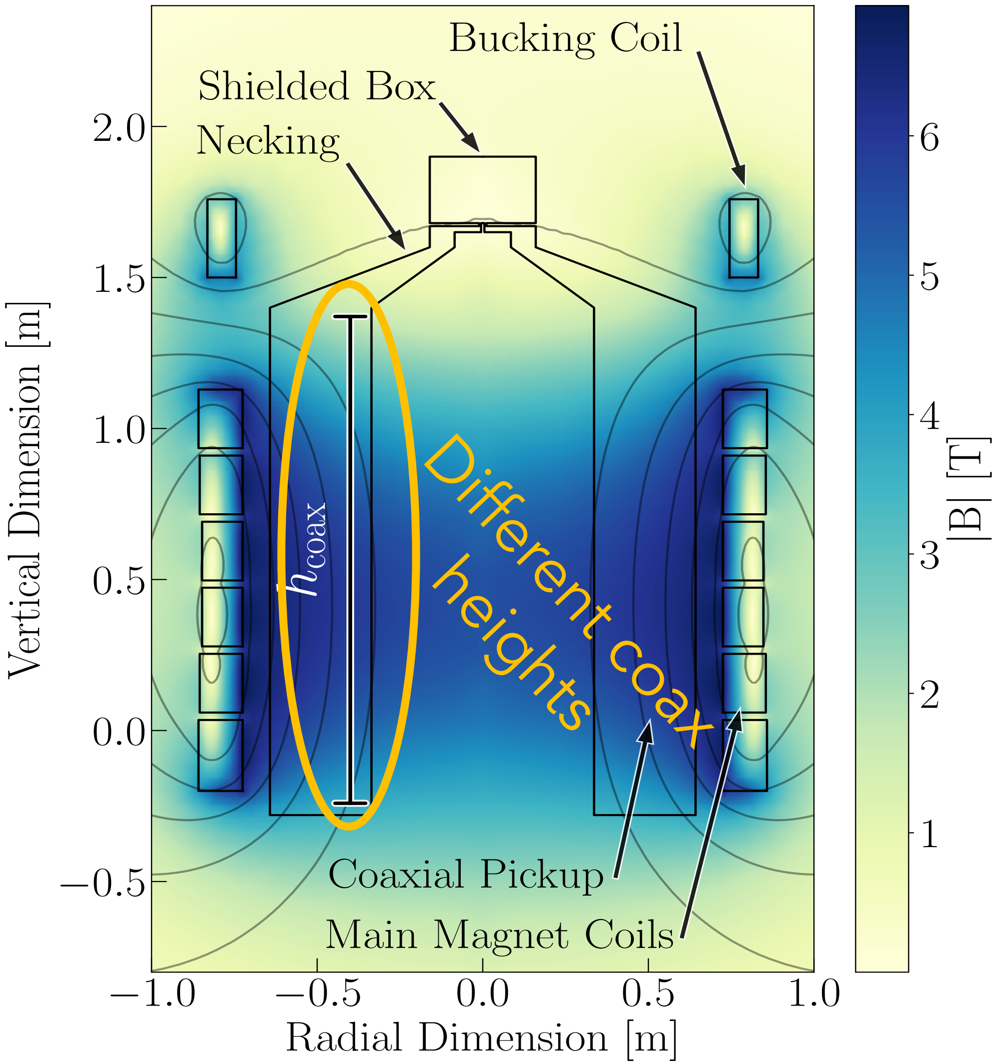
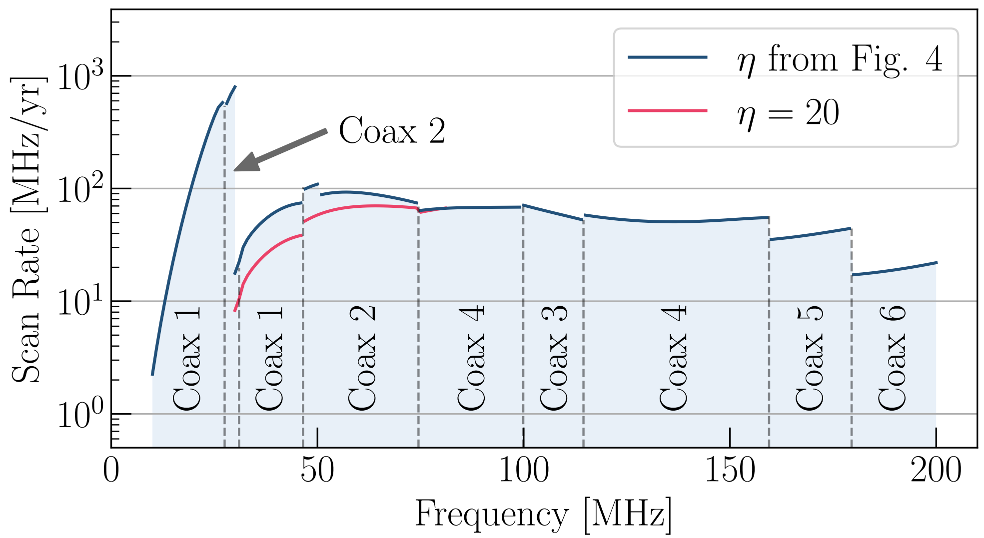
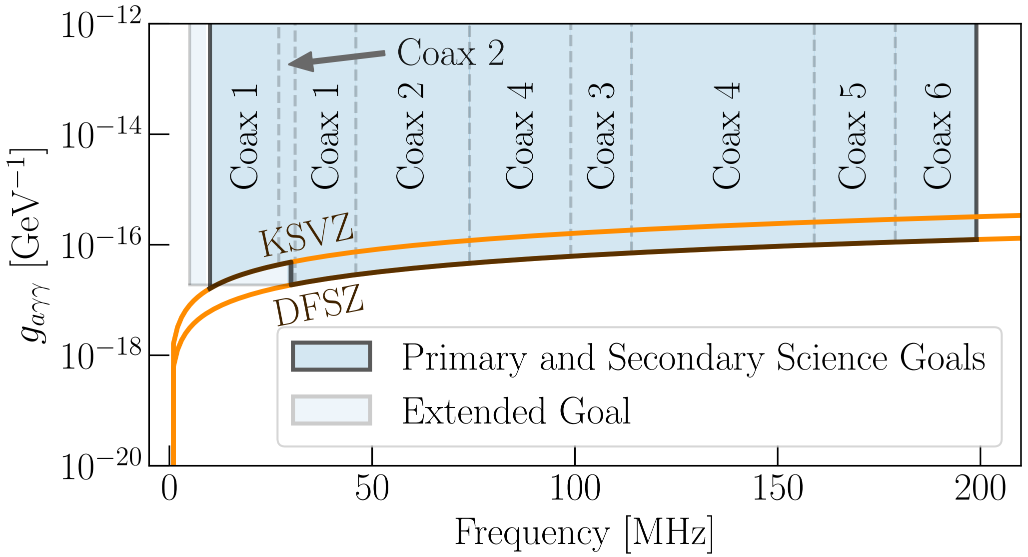


Calculated science reach





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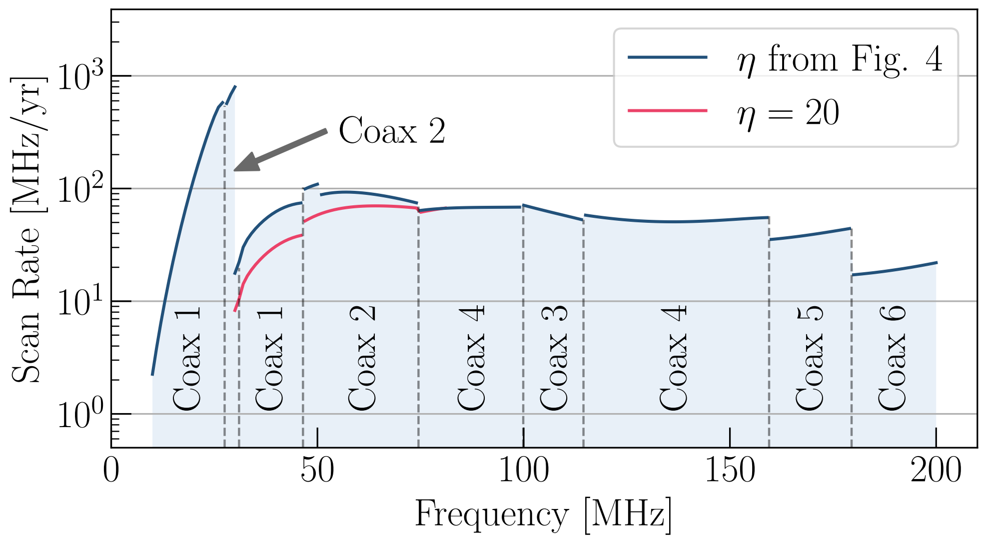
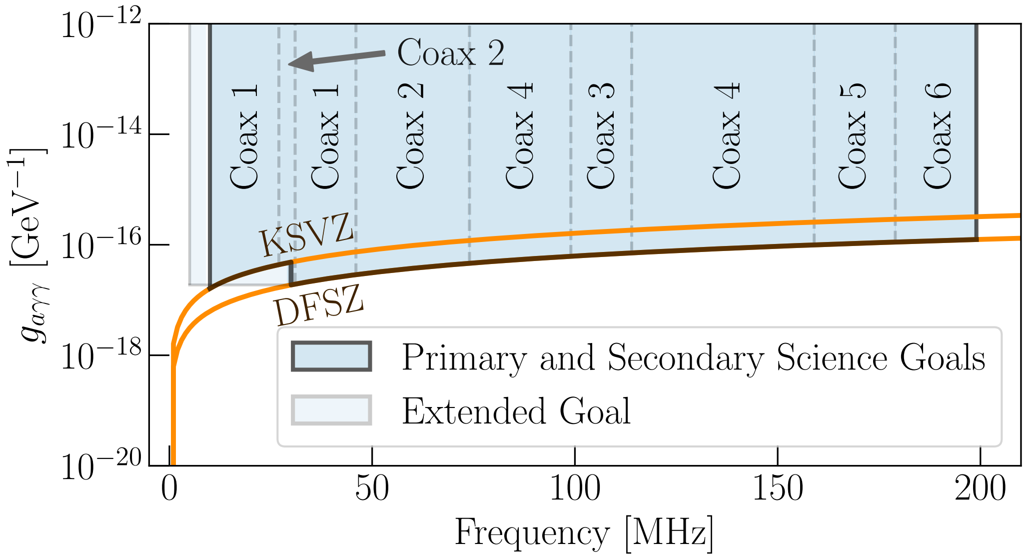


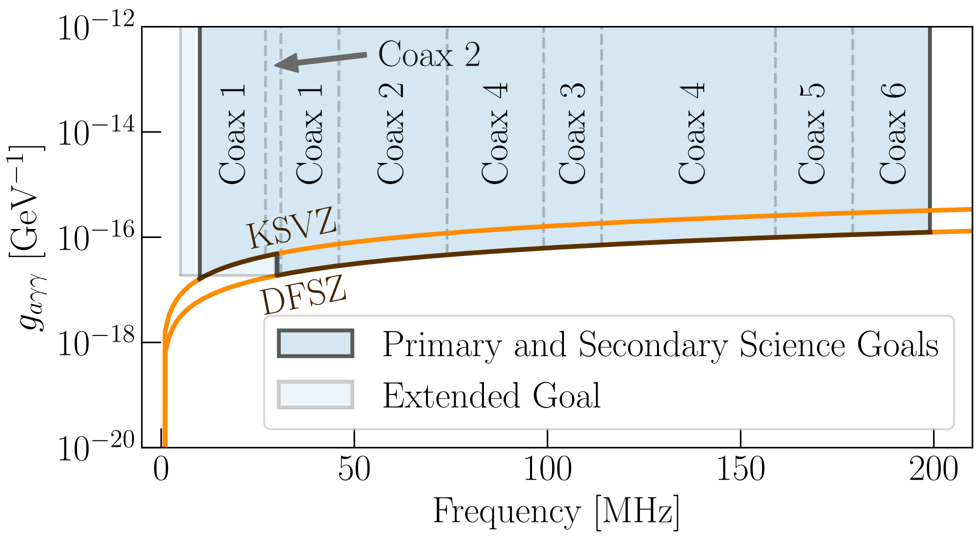


	Sensitivity & Range	3σ Live Scan Time
Primary Science Goal	DFSZ; 30–200 MHz	4.2 yr
Secondary Science Goal	KSVZ; 10–30 MHz	0.9 yr
Extended Goal	1.87×10^{-17} GeV^{-1}; 5–30 MHz	3.2 yr

Part of DOE Dark Matter New Initiatives program, now part of the ASTAE program recommended in P5 report

To be built at SLAC National Lab

Thank you!



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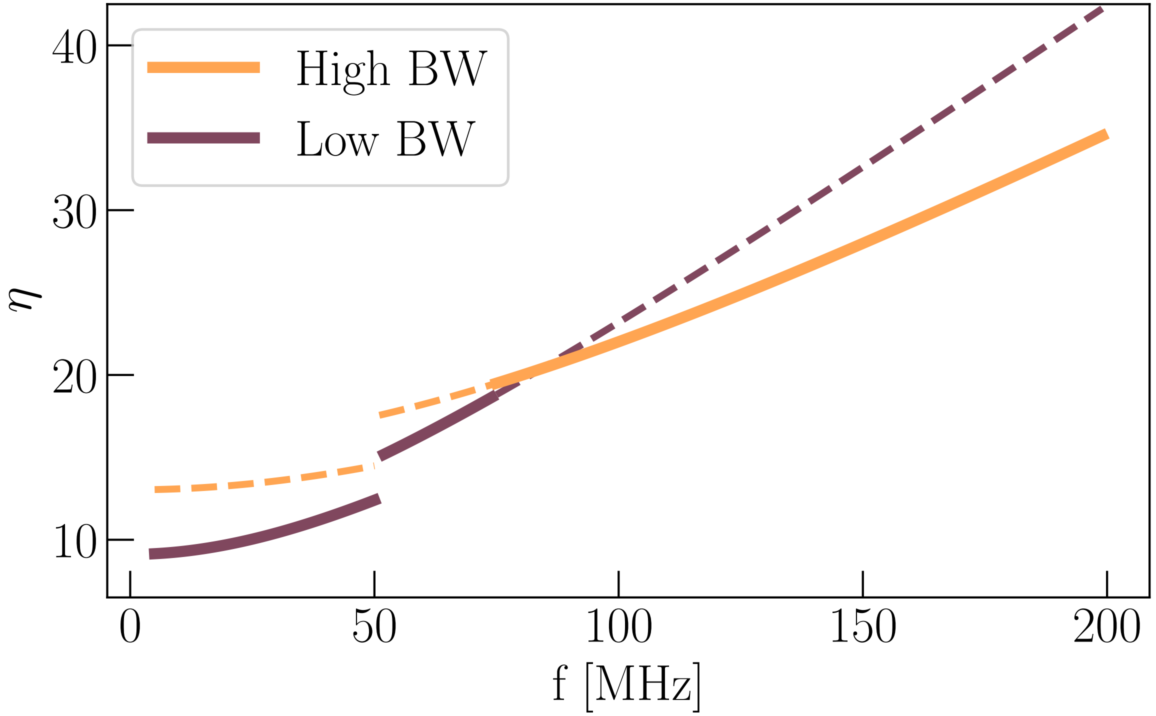
These slides

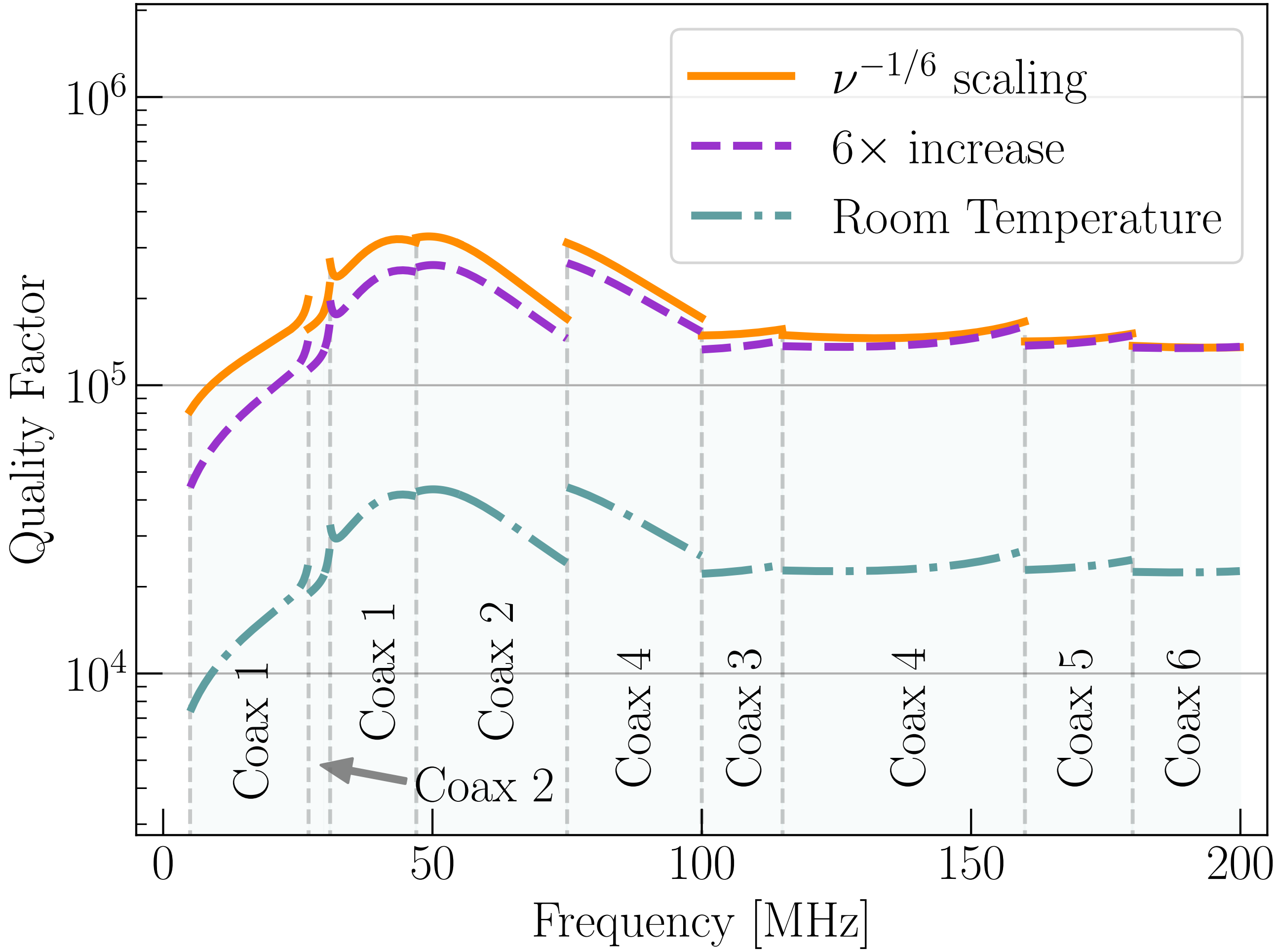
Backup Slides

SQUID parameter



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

Quality factor



$$Re\left\{Z_{\mathrm{RT}}\right\} = \sqrt{\frac{\omega\mu_0}{2\sigma_{\mathrm{RT}}}}$$

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

Shielded Box