Axion Dark Matter and High-Frequency Gravitational Wave Searches:

Calibrating DMRadio-50L and ABRACADABRA-10cm

Jessica Fry

Outline

Lumped Element Axion Haloscopes

ABRACADABRA-10 cm

DMRadio-50L

ABRACADABRA Gravitational wave search

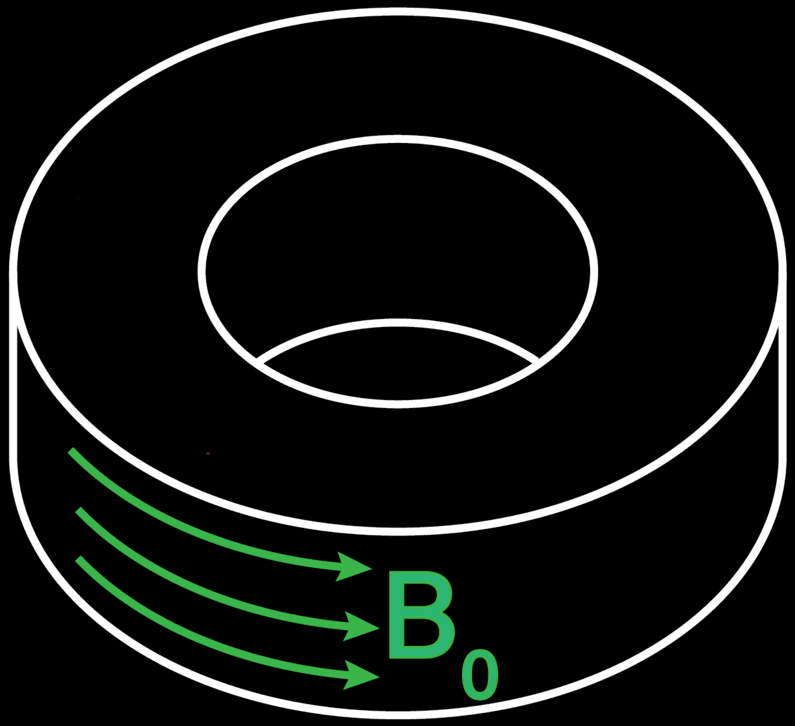
Axion Modified Maxwell's Equations

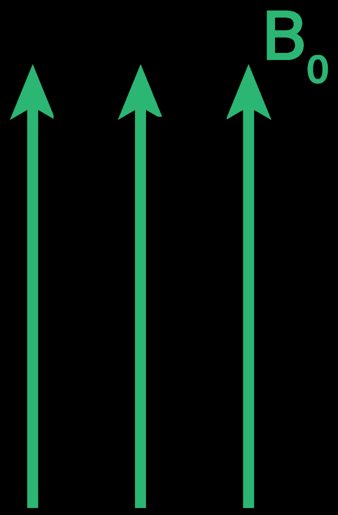
$$\nabla \times \mathbf{B} = \frac{\partial E}{\partial t} - g_{a\gamma\gamma}\left(\mathbf{E} \times \nabla a - \frac{\partial a}{\partial t}\mathbf{B}\right)$$

⇓

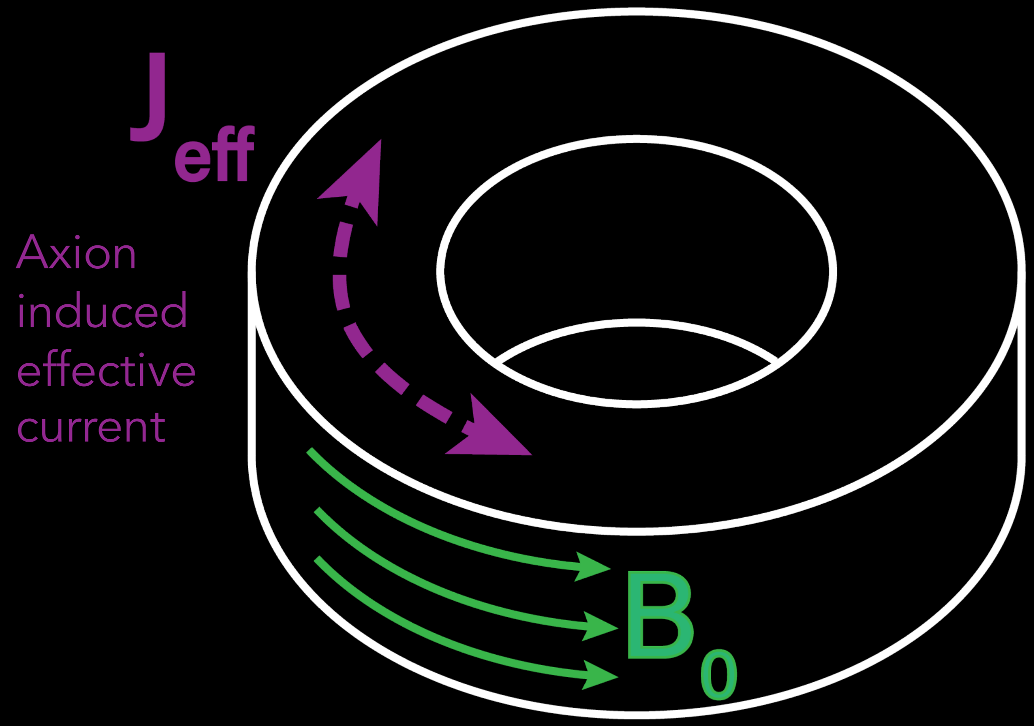
$$\mathrm{J}_{eff} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}cos(m_a t)\mathbf{B}$$

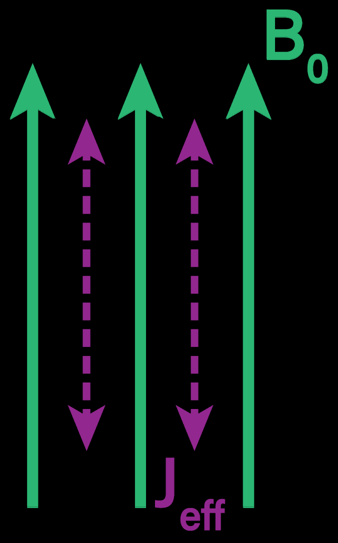
ABRA Cartoon



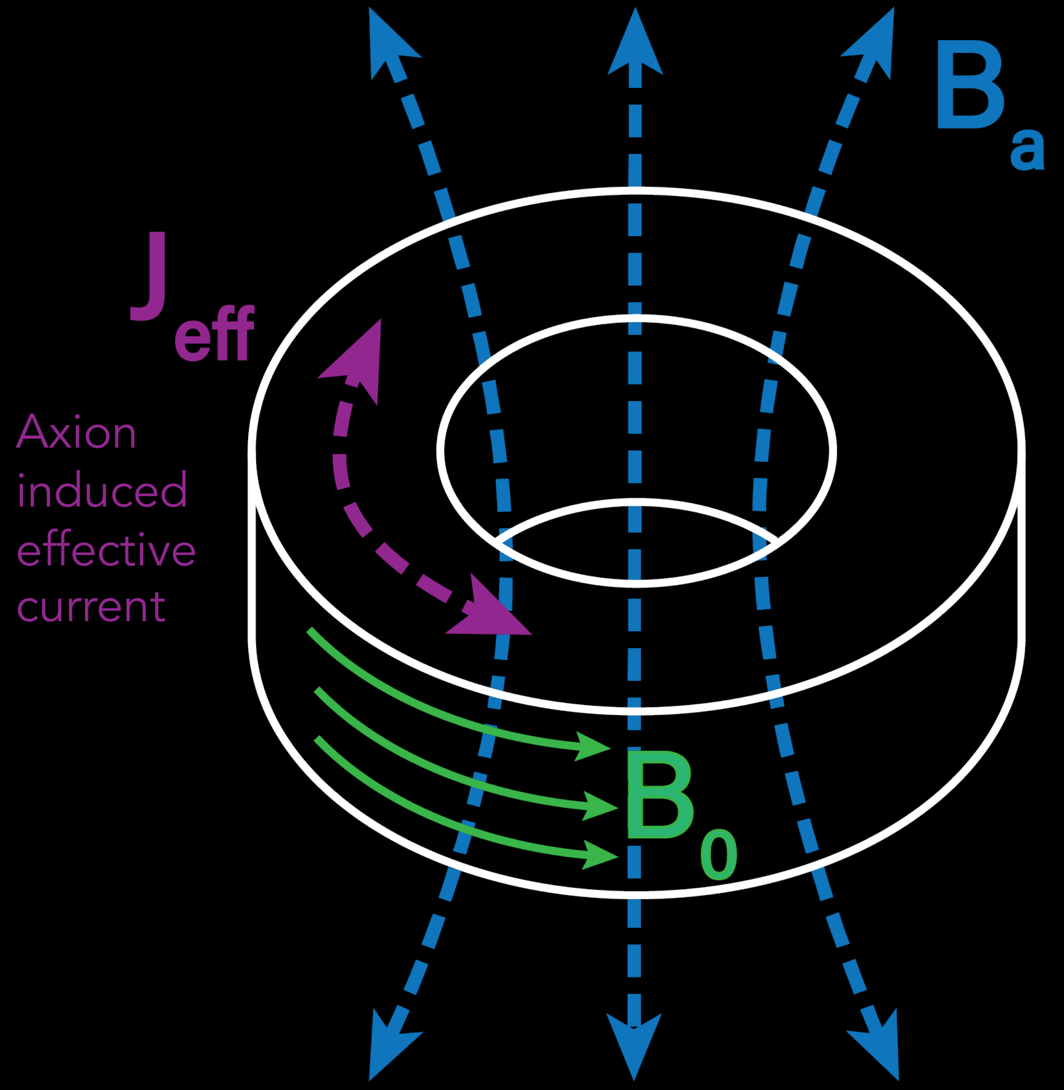


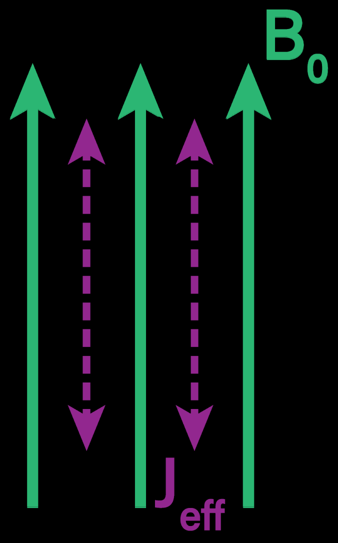
ABRA Cartoon



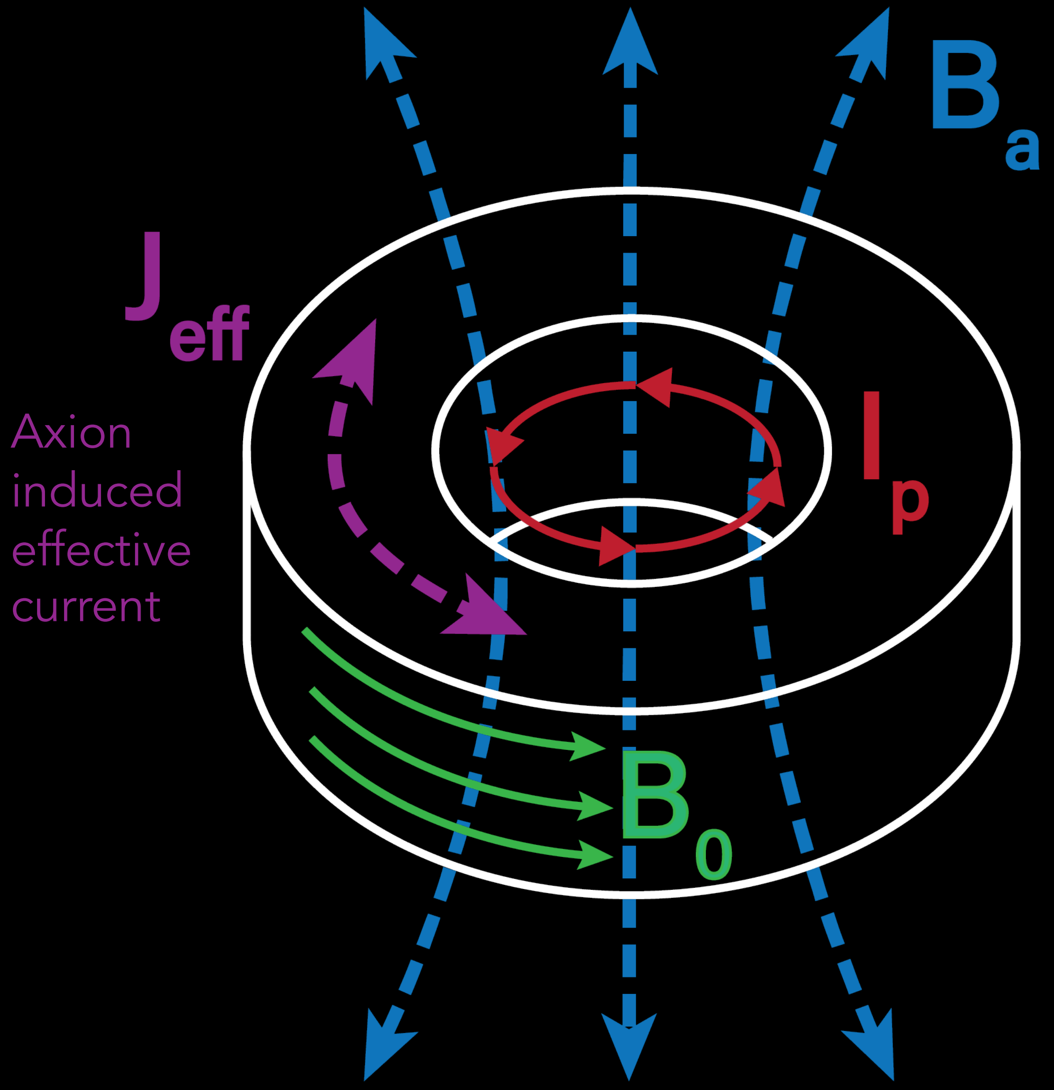


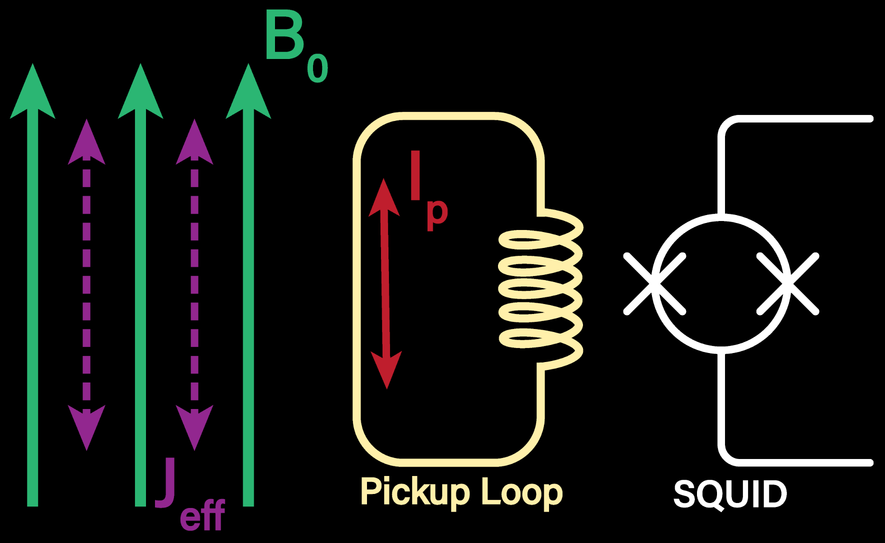
ABRA Cartoon



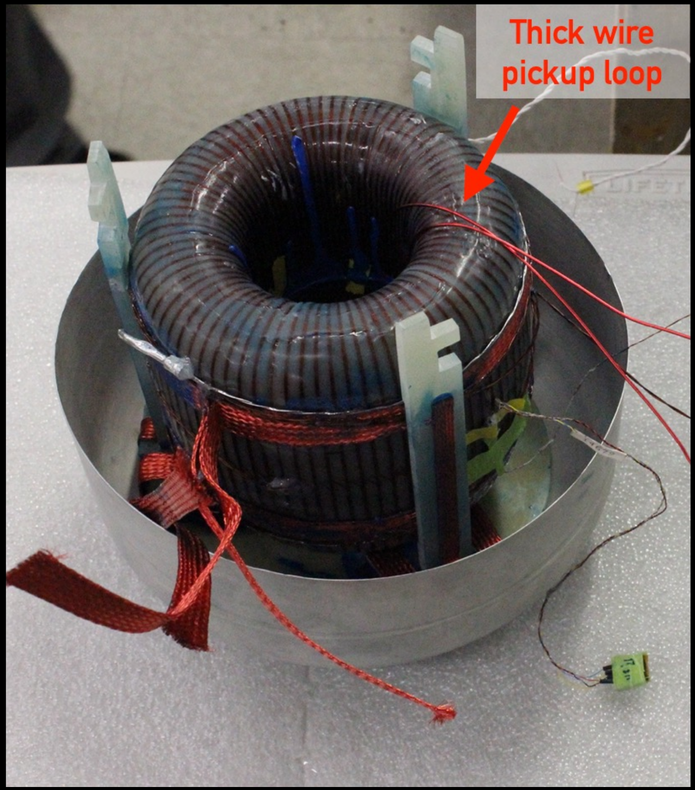


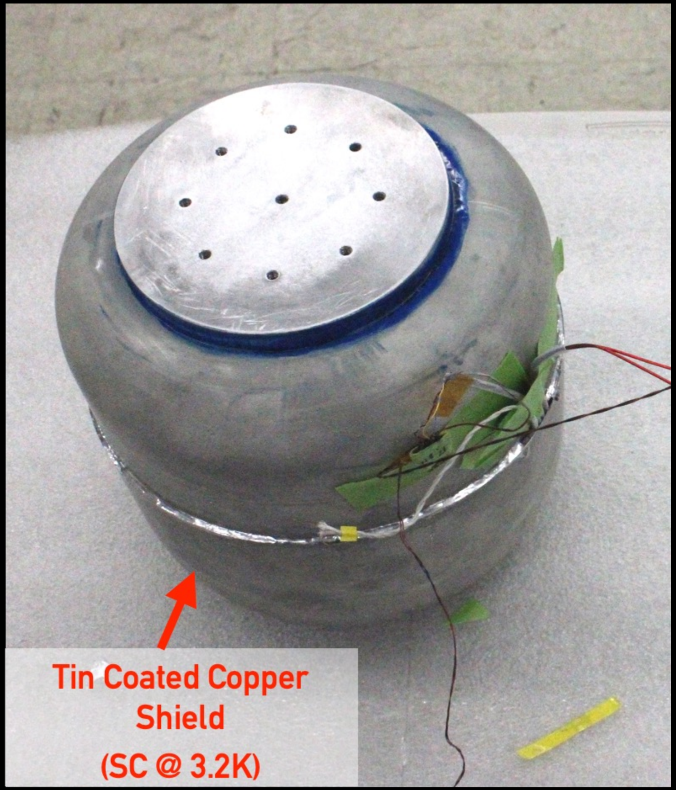
ABRA Cartoon





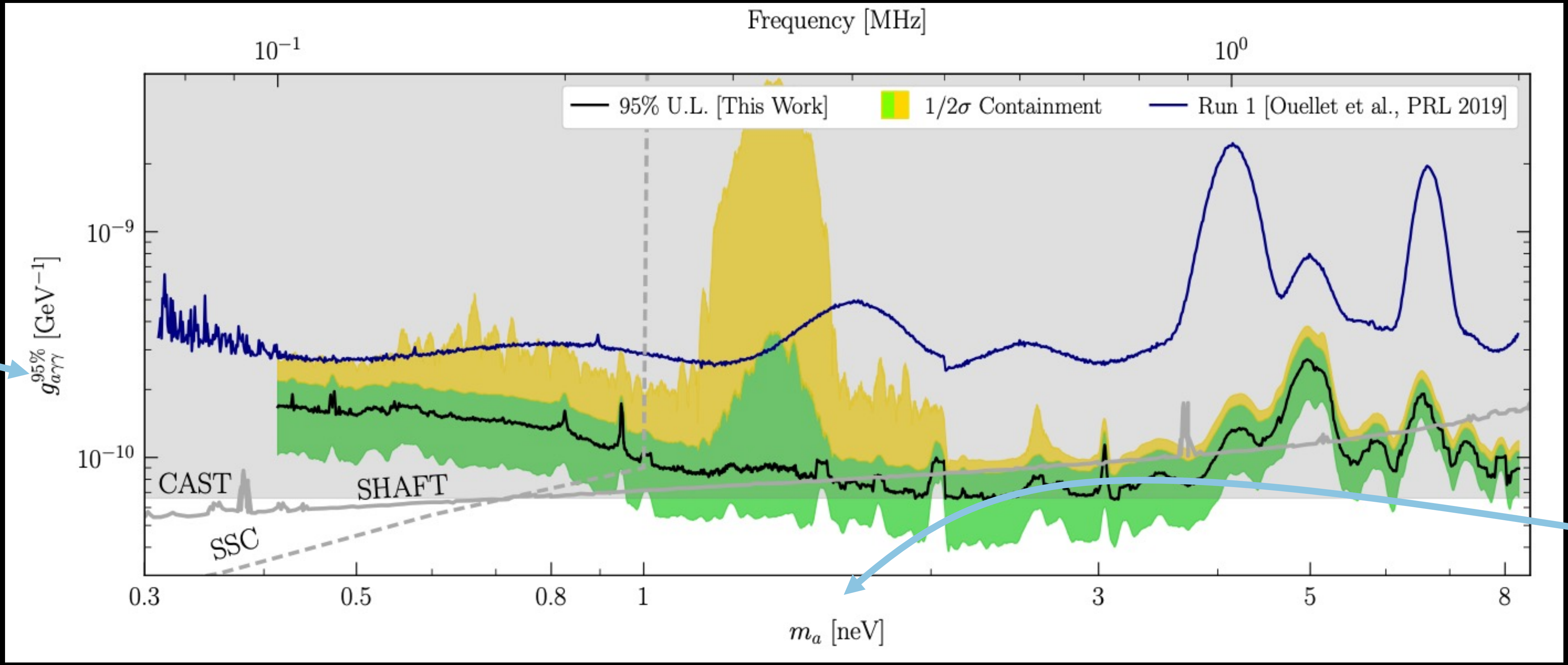
ABRA





ABRA Run 3

Axion to photon coupling, $g_{a\gamma\gamma}$, given by axion induced flux power



m_a given by frequency of oscillating field

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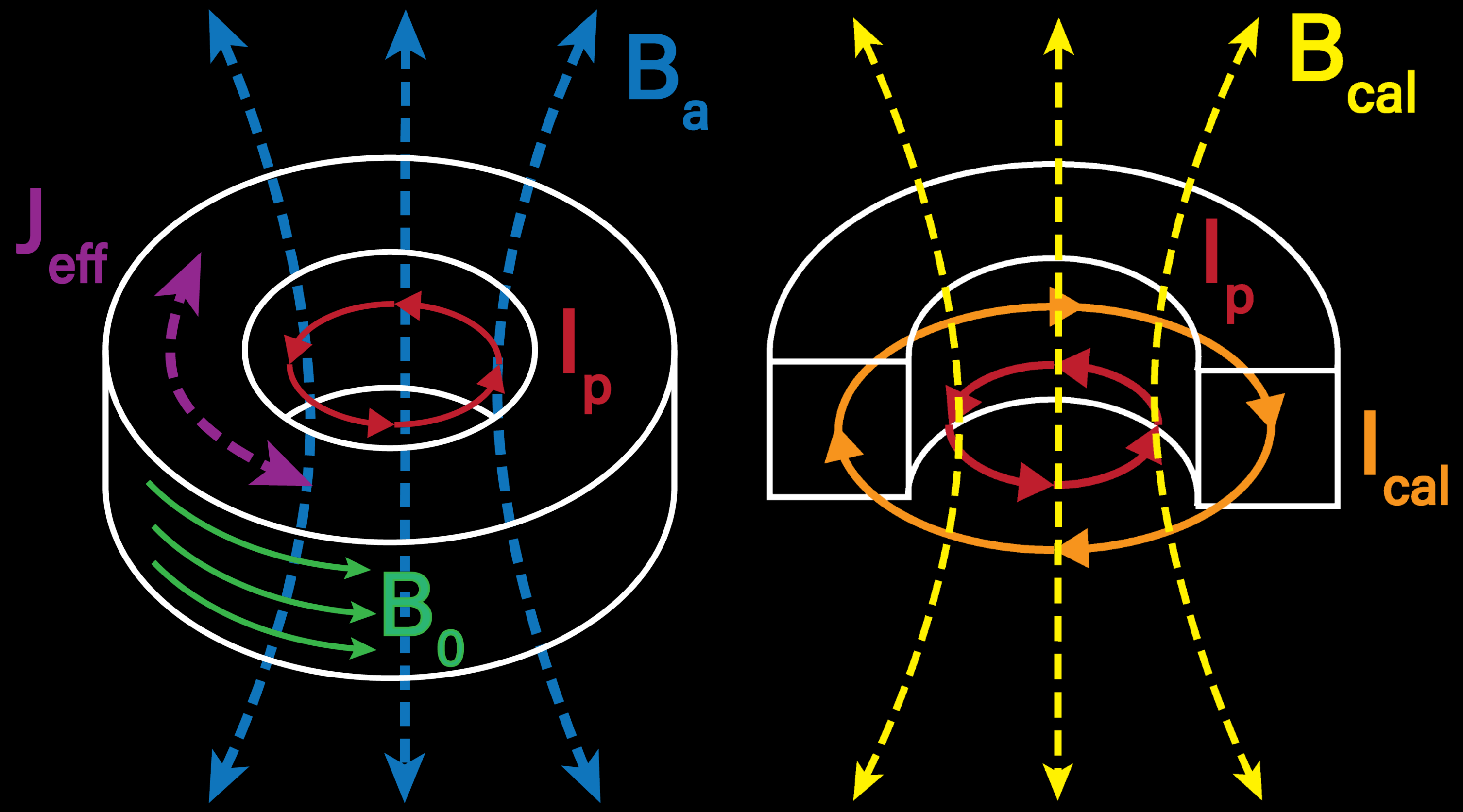
ABRA Calibration

Goal: Characterize end-to-end gain of the system
→ DAQ readout voltage to $g_{a\gamma\gamma}$ conversion

Method: Inject fake, axion mimetic signal through hardware

ABRA Calibration

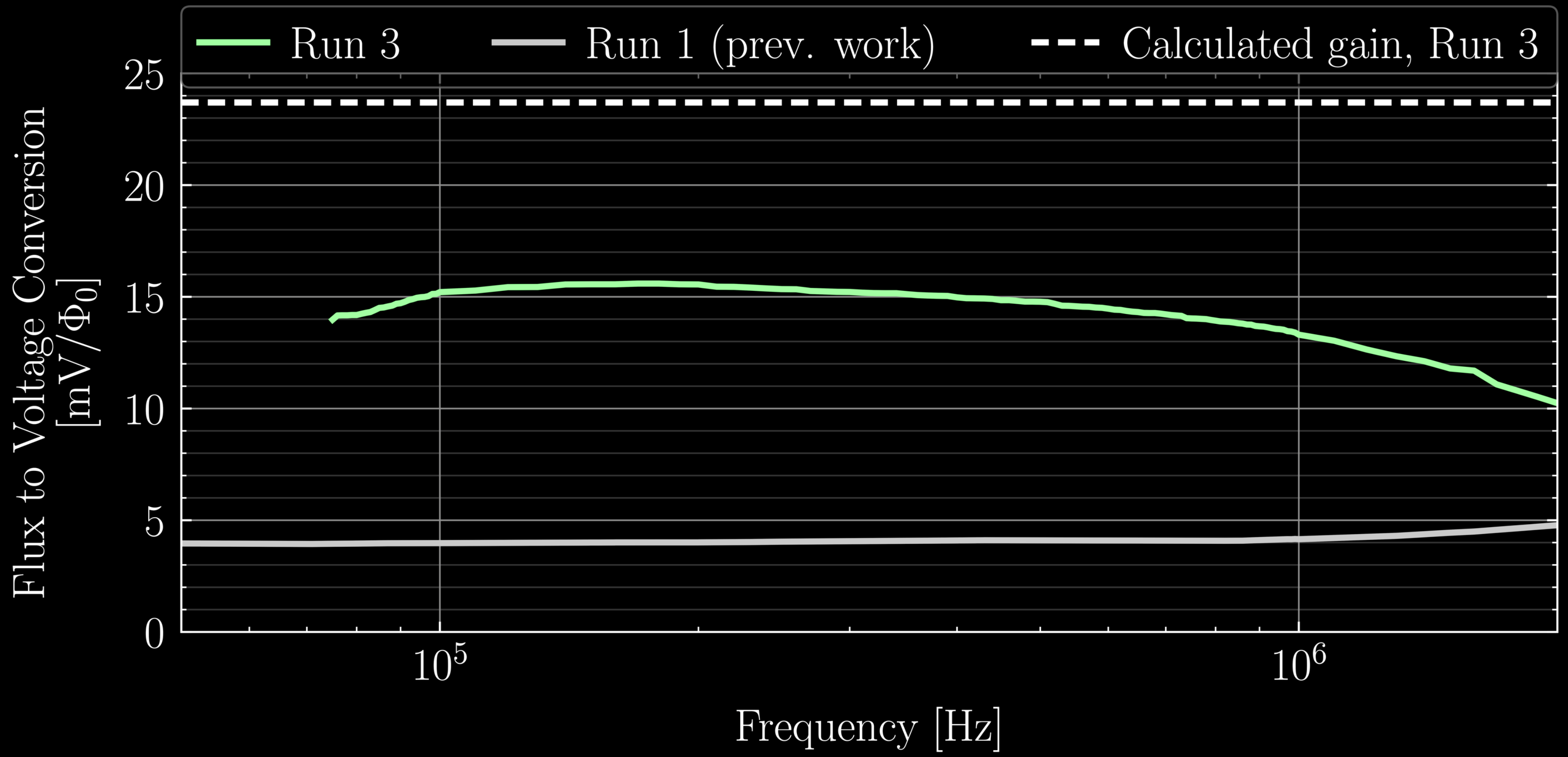


Axion excitation

Calibration scheme

Place a calibration loop in the magnet that produces an axion mimetic flux

ABRA Calibration



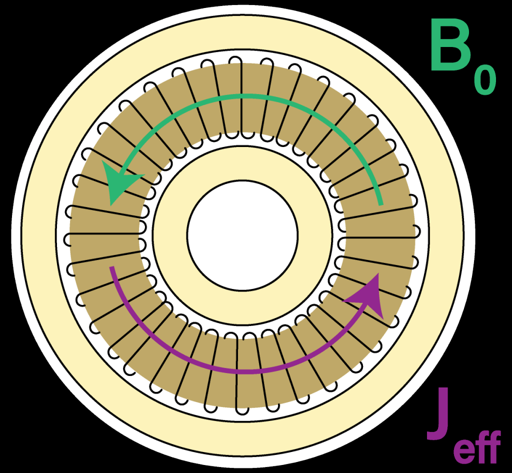
Compare expected gain to measured gain at various frequencies

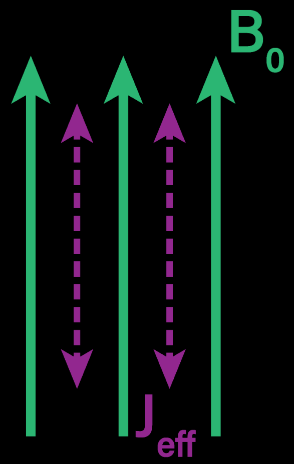
Outline

- Lumped Element Axion Haloscopes
- ABRACADABRA-10 cm
- DMRadio-50L
- ABRACADABRA Gravitational wave search

DMRadio-50L

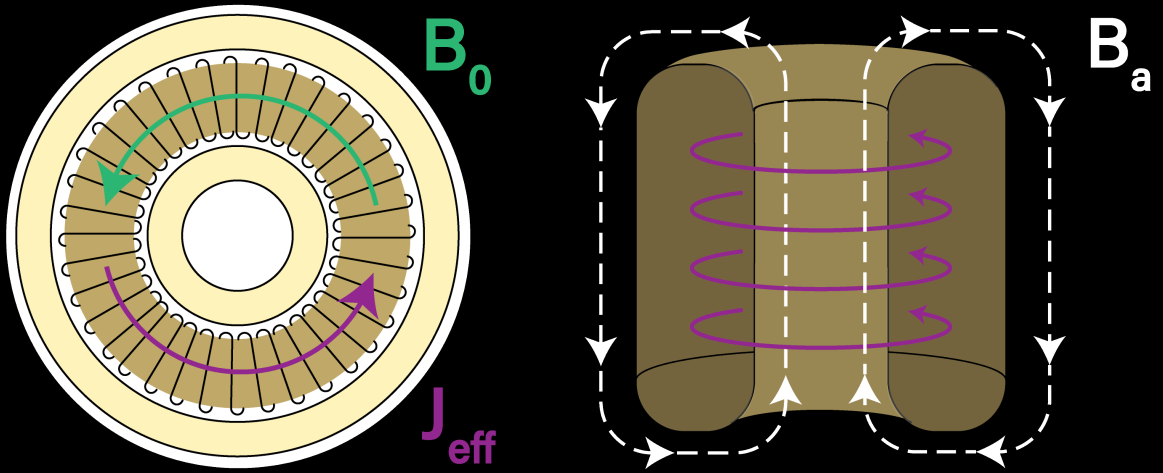
Resonant Lumped Element Haloscope

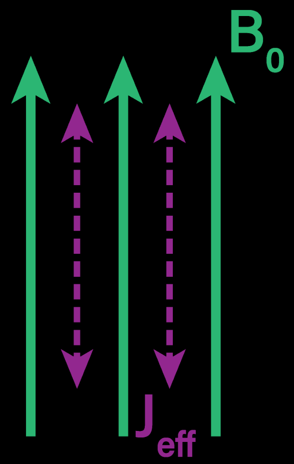




DMRadio-50L

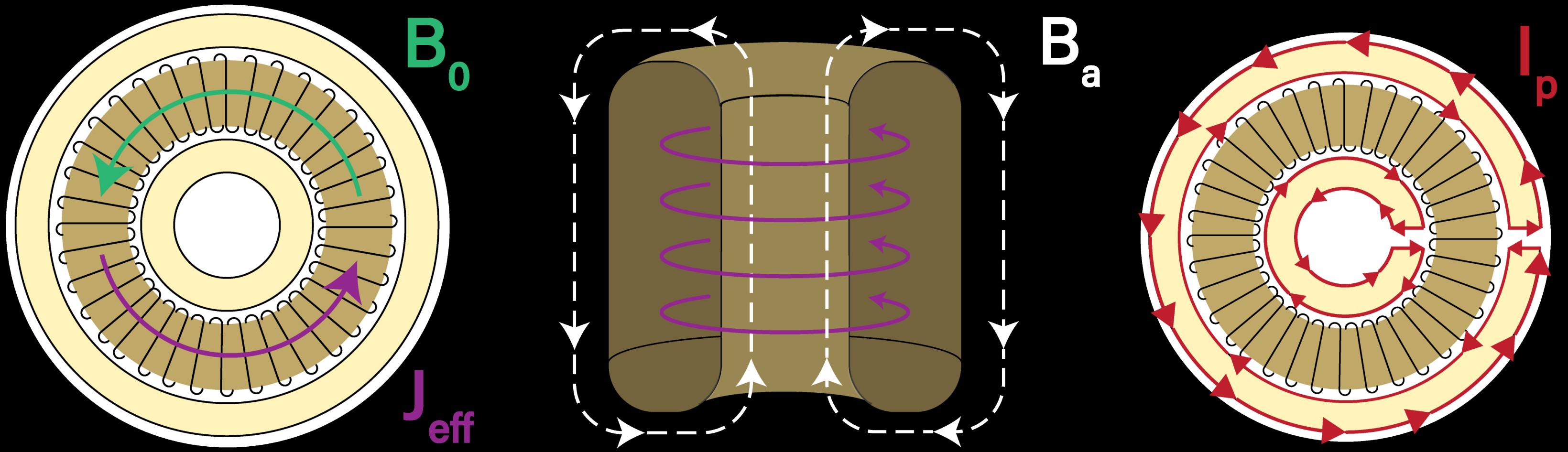
Resonant Lumped Element Haloscope

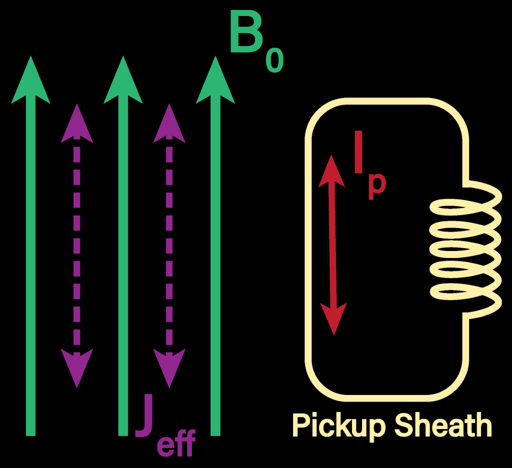




DMRadio-50L

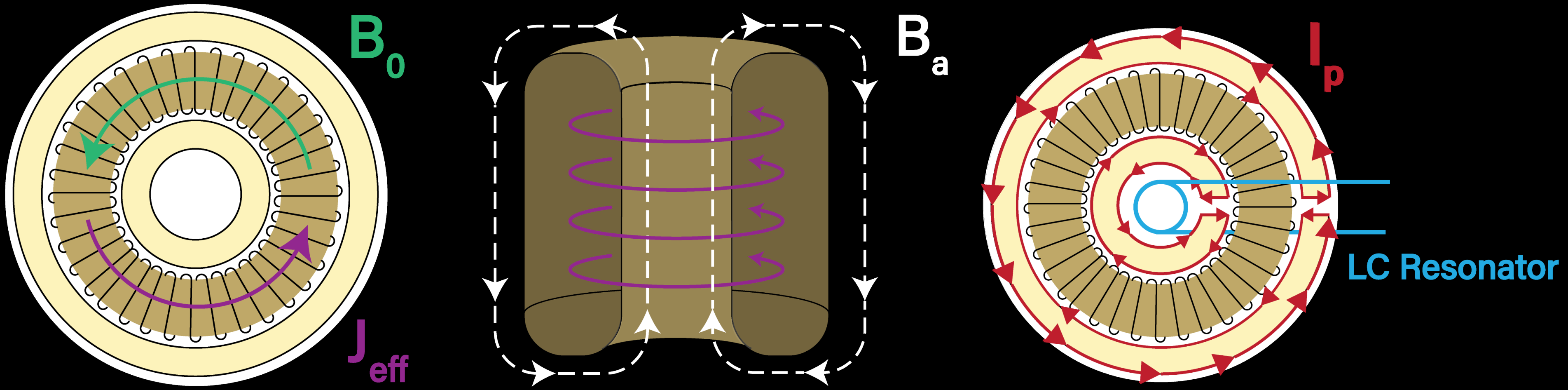
Resonant Lumped Element Haloscope

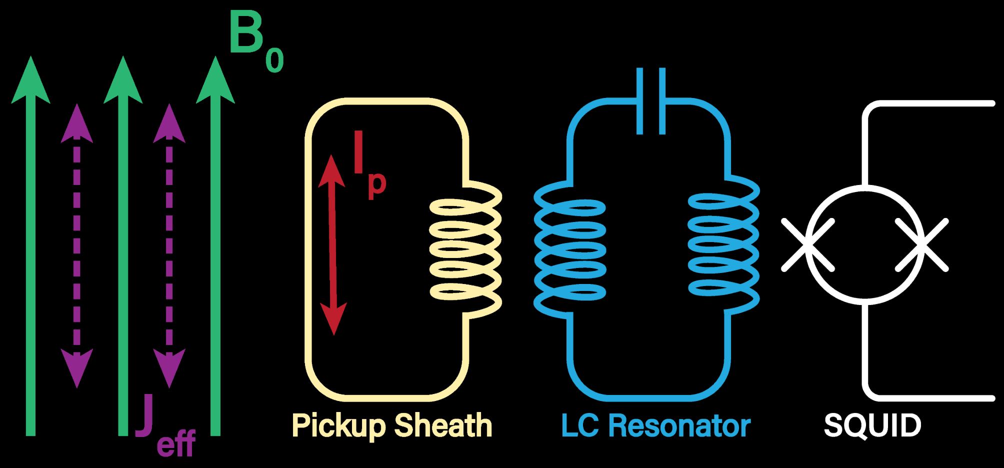




DMRadio-50L

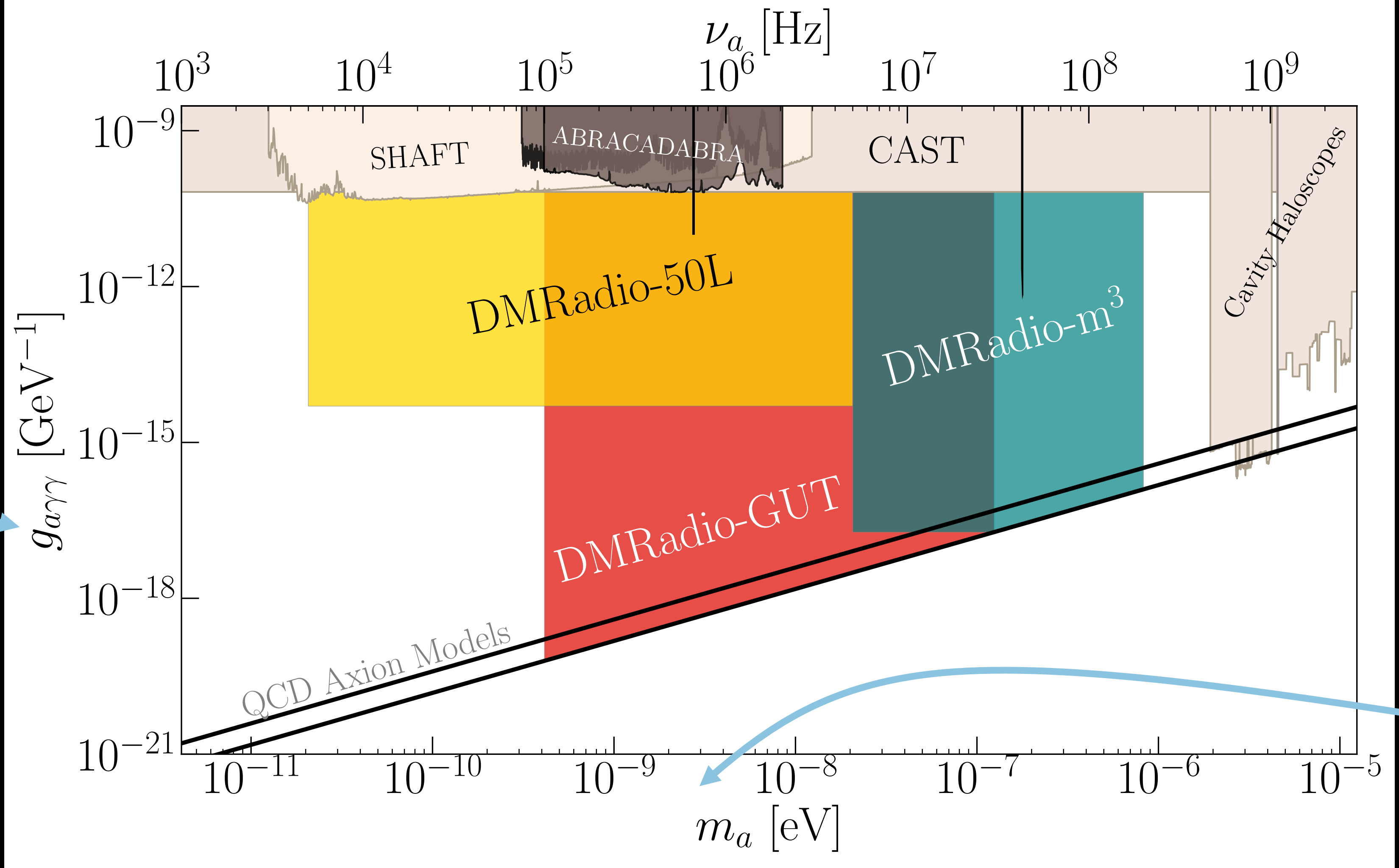
Resonant Lumped Element Haloscope





DMRadio-50L

Axion to photon coupling, $g_{a\gamma\gamma}$, given by axion induced flux power



m_a given by frequency of oscillating field

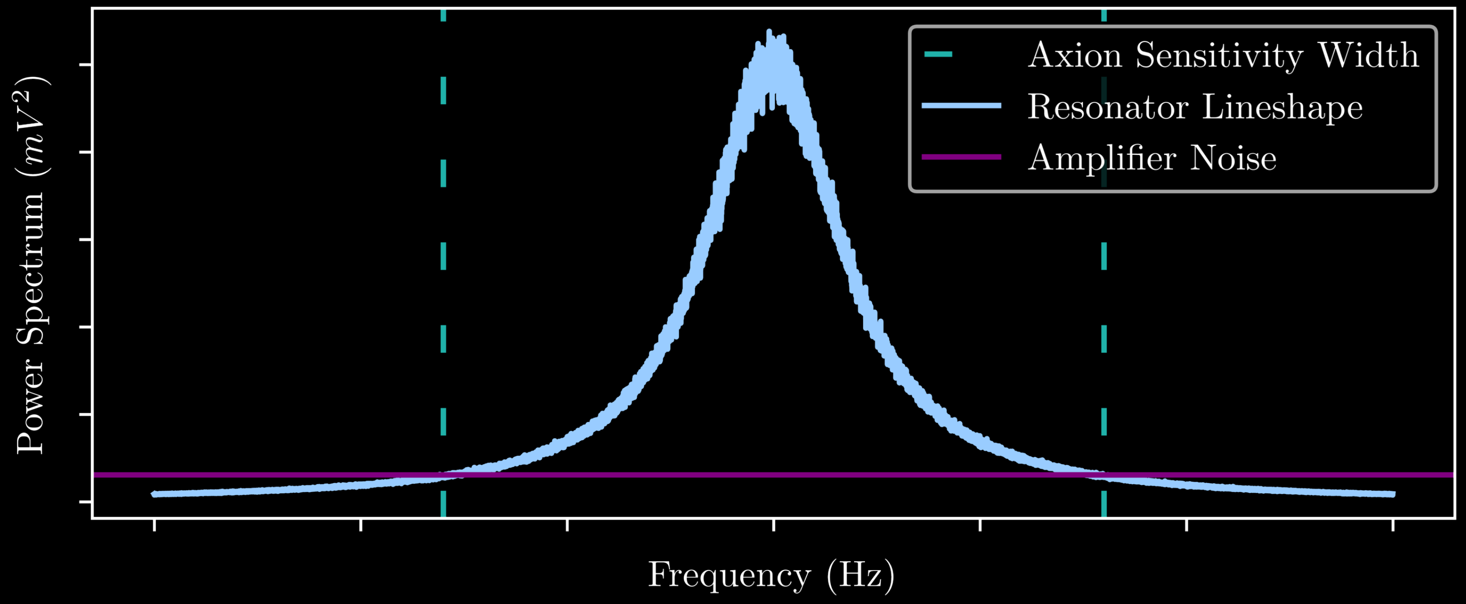
DMRadio-50L Calibration

Goal 1: Characterize end-to-end gain of the system for all tuning steps

DAQ readout voltage to $g_{a\gamma\gamma}$ conversion

Goal 2: Calibrate resonant frequency at each tuning step

ω_0 and Q of resonant components



DMRadio-50L Calibration

1. Excite pickup structure to perform end-to-end calibration
    - Axion mimetic injection
2. Measure individual components to get ω_0, amplification, and Q factor
    - Sideband injection
    - Ringdown measurement

DMRadio-50L Calibration

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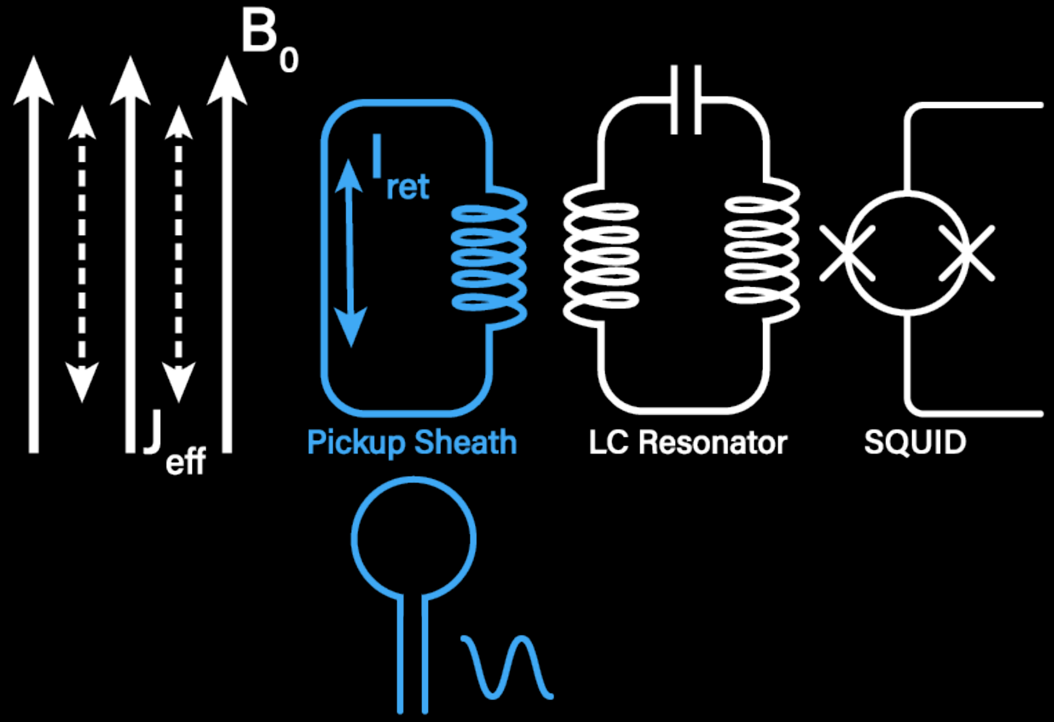
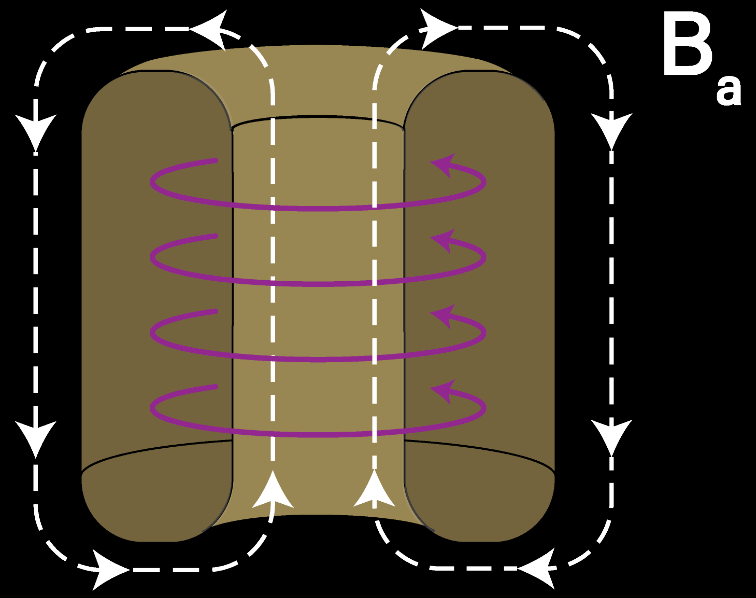
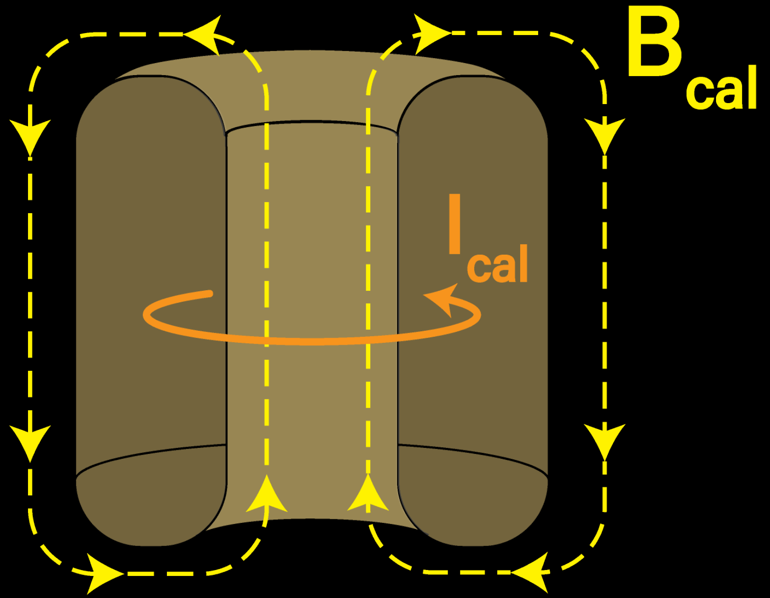


Axion Mimetic Injection



Axion excitation

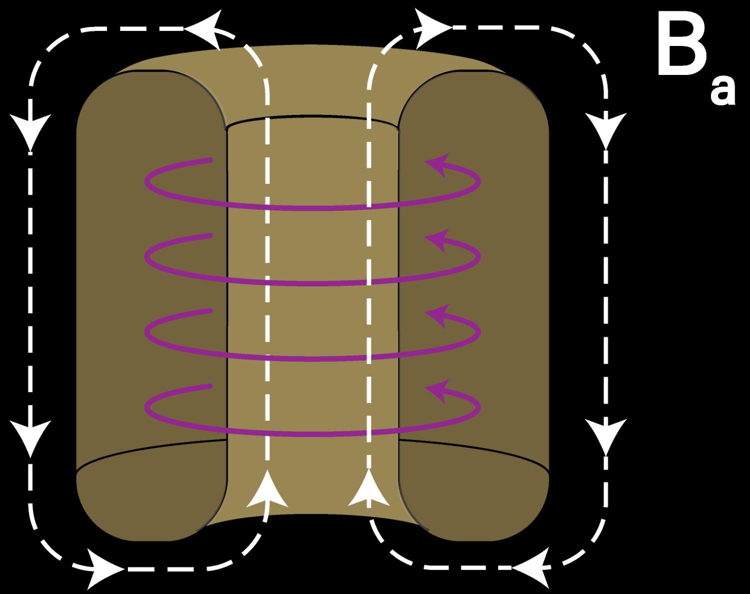


Calibration scheme

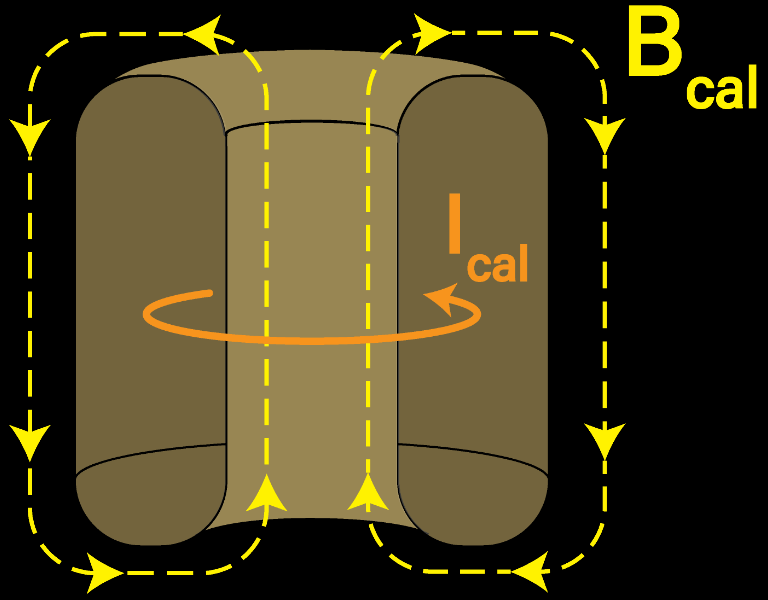
Place a calibration loop in the magnet that produces an axion mimetic flux

Axion Mimetic Injection

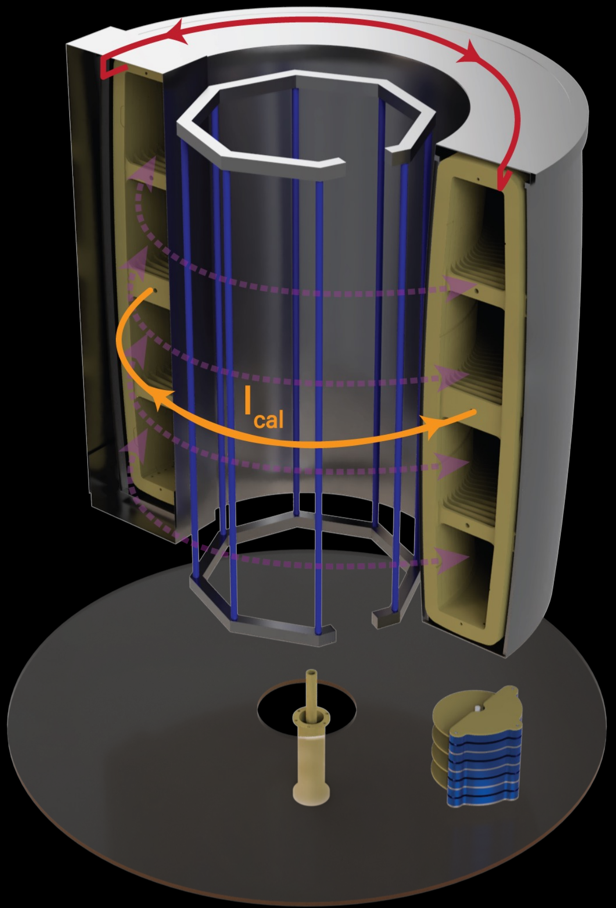
- Magnet enclosed in high Q sheath



Axion excitation

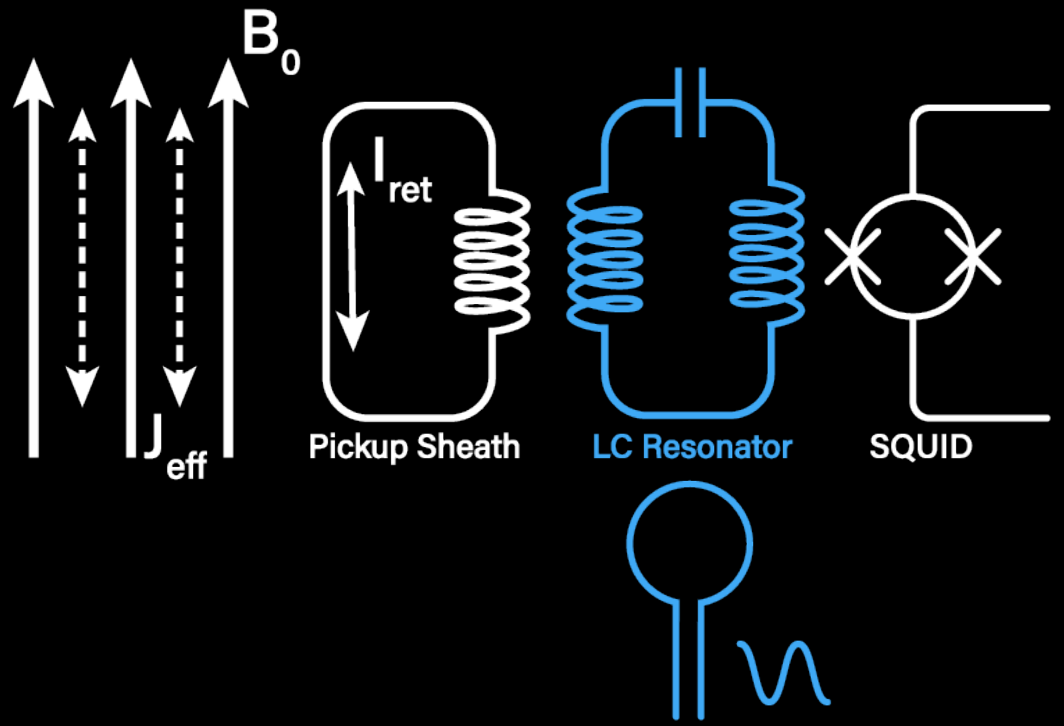


Calibration scheme



DMRadio-50L Calibration

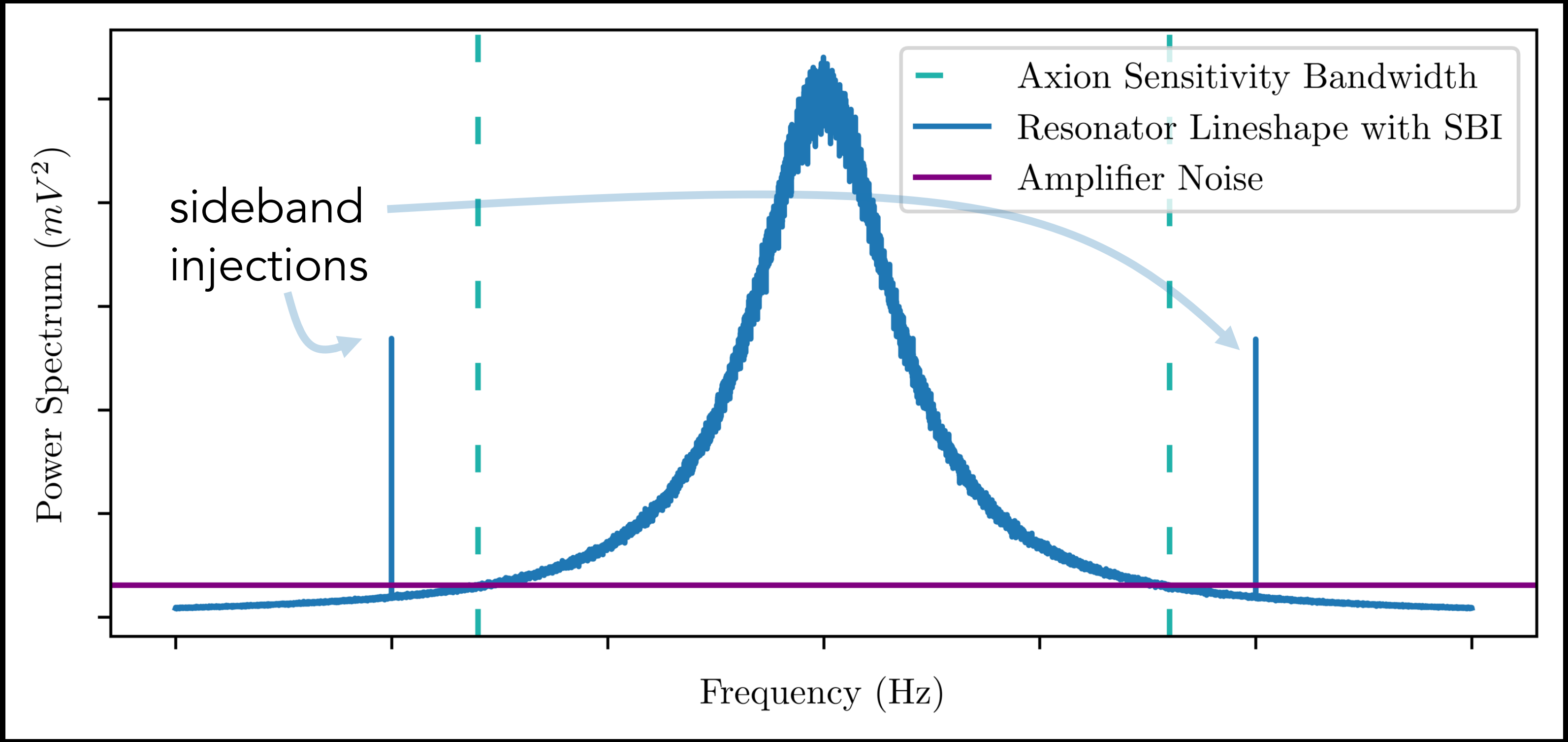
1. Excite pickup structure to perform end-to-end calibration
   - Axion mimetic injection
2. Measure individual components to get ω_0, amplification, and Q factor
   - Sideband injection
   - Ringdown measurement



Sideband Injection

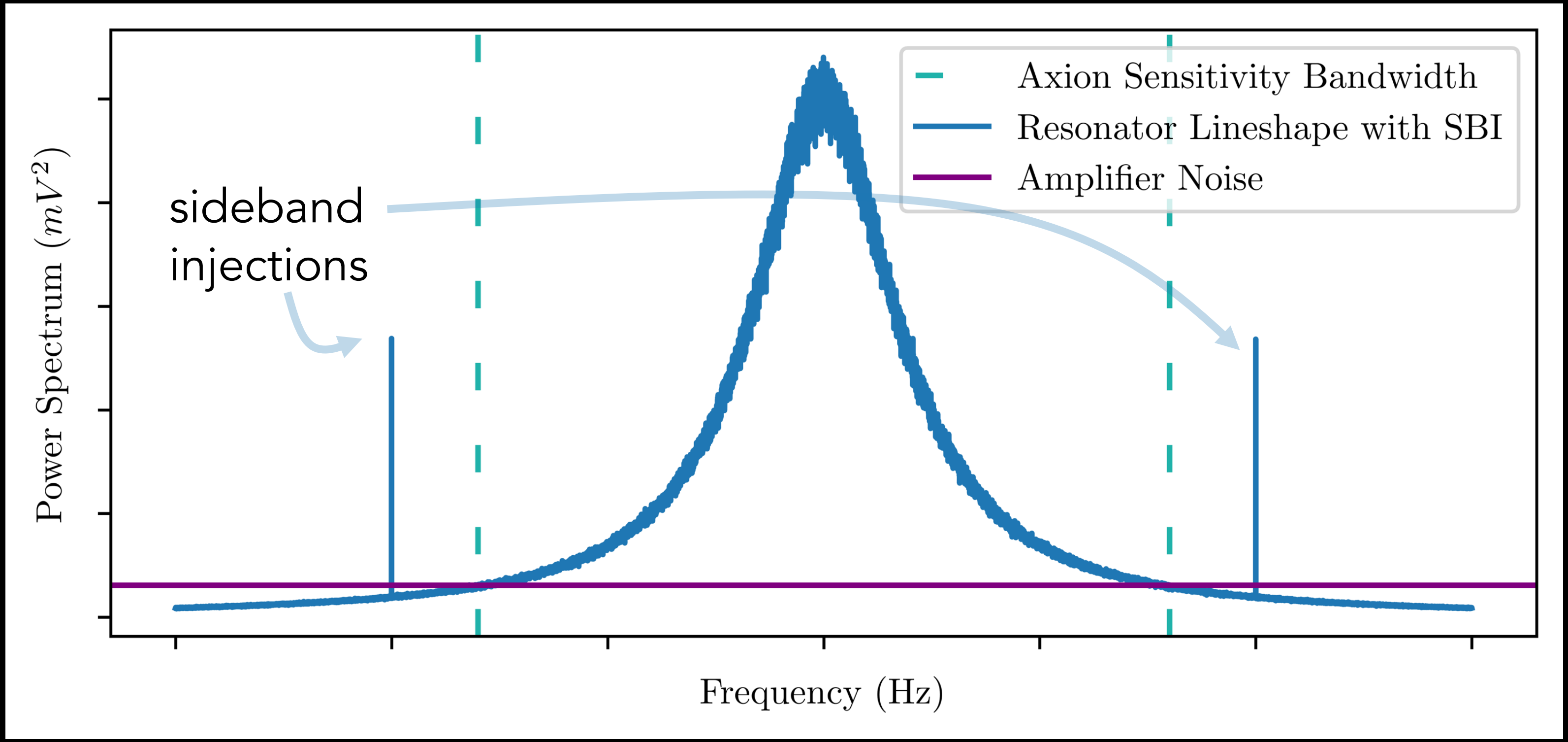
- Inject two monotonic tones outside of axion signal band

$$\left(\frac{\Delta\omega}{\omega}\right)_{AS} = \frac{8}{Q} \qquad \left(\frac{\Delta\omega}{\omega}\right)_{SBI} = \left(\frac{\Delta\omega}{\omega}\right)_{AS} \times \mathrm{frac}_{SBI} = \frac{10}{Q}$$



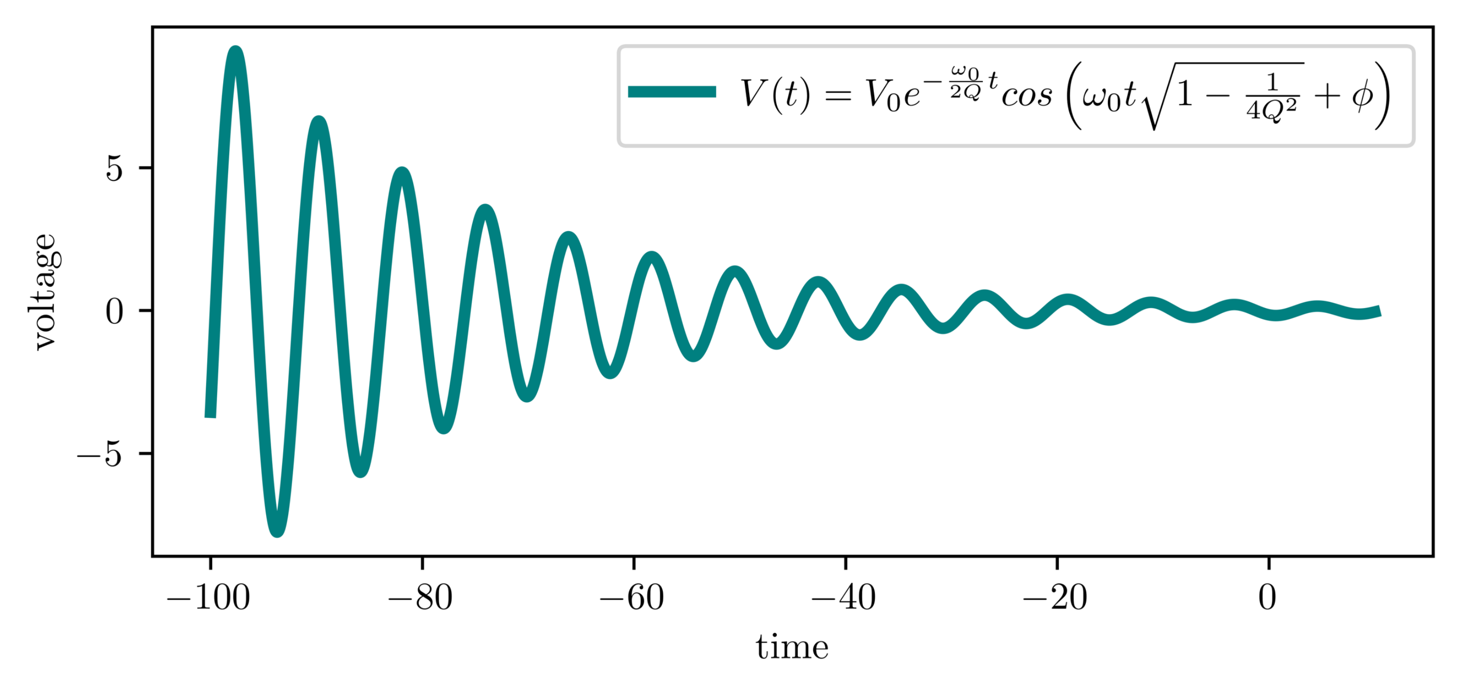
Sideband Injection

- Compare V_{in}/V_{out} of SBI frequency to get SQUID amplification
- Measure SQUID amplification at each tuning step
- Calibration simultaneous with data taking



Ringdown Measurement

- Inject on-resonance signal directly onto resonator
- Record free decay
- N_{cycles} to half amplitude gives Q factor and ω_0
- Demonstrated with DMRadio Pathfinder



Outline

Lumped Element Axion Haloscopes

ABRACADABRA-10 cm

DMRadio-50L

ABRACADABRA Gravitational wave search

ABRACADABRA Gravitational Wave Search

axions and high frequency gravitational waves

$$\nabla \times \mathbf{B} = \frac{\partial E}{\partial t} + \nabla \times \mathbf{M} + \frac{\partial \mathbf{P}}{\partial t}$$

$$\Downarrow$$

$$\mathrm{j}^{\mu}_{eff} = \partial_{\nu} \left(-\tfrac{1}{2} h F^{\mu\nu} + F^{\mu} h^{\nu}_{\alpha} - F^{\nu\alpha} h^{\mu}_{\alpha}\right)$$

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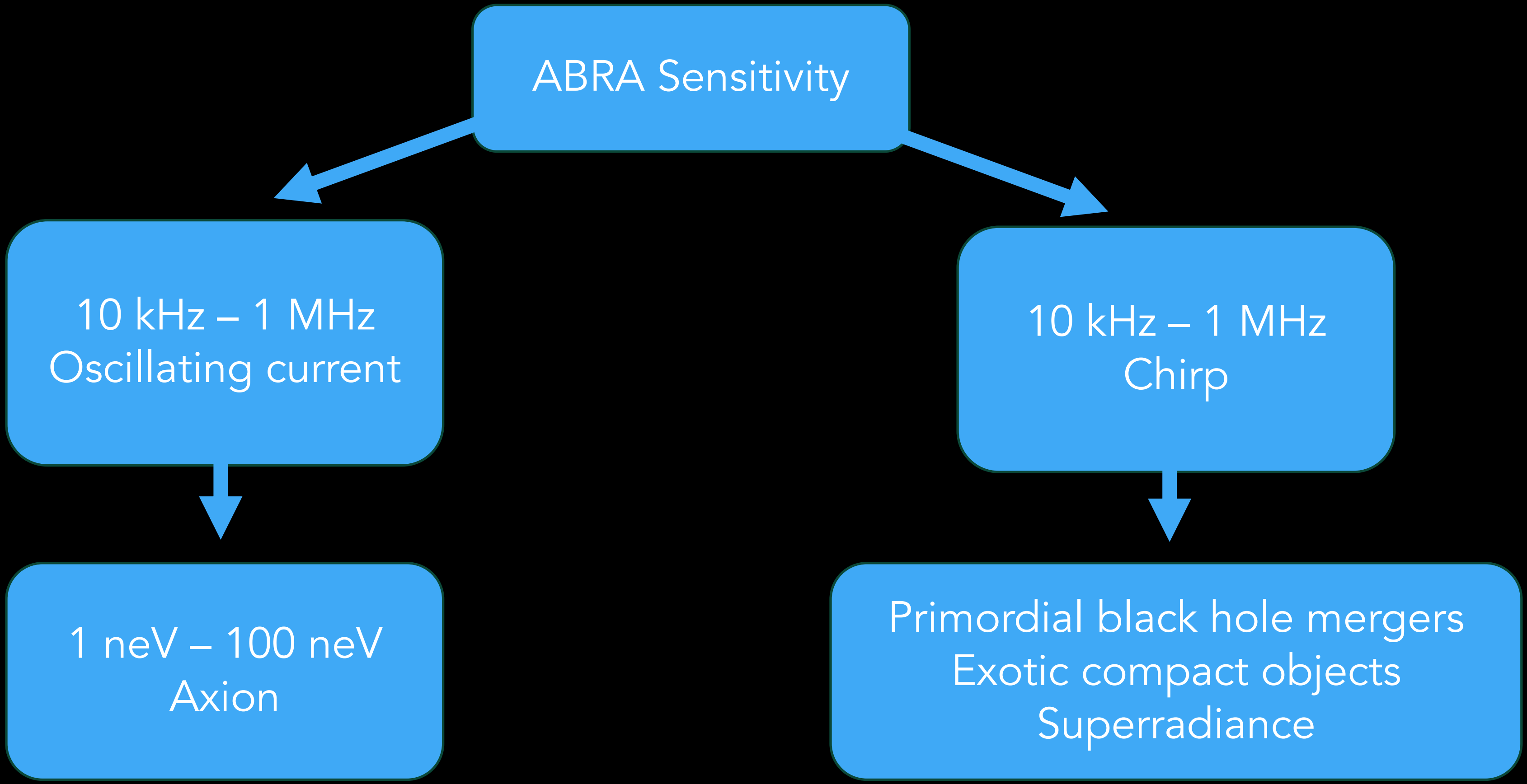
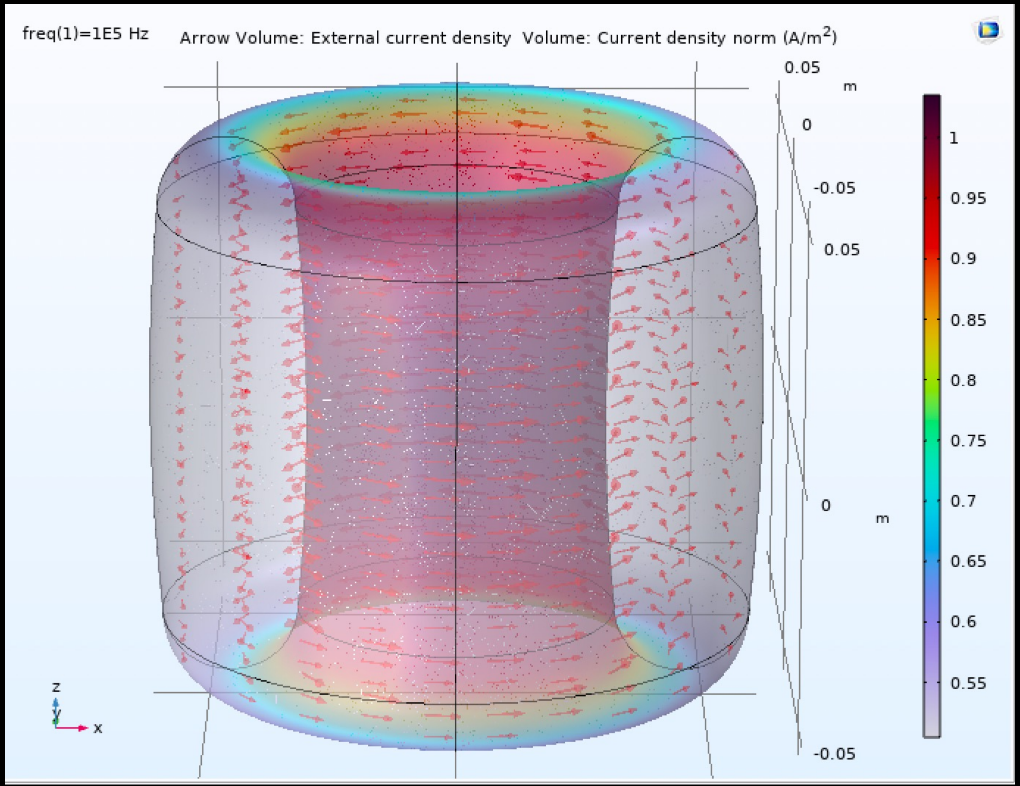
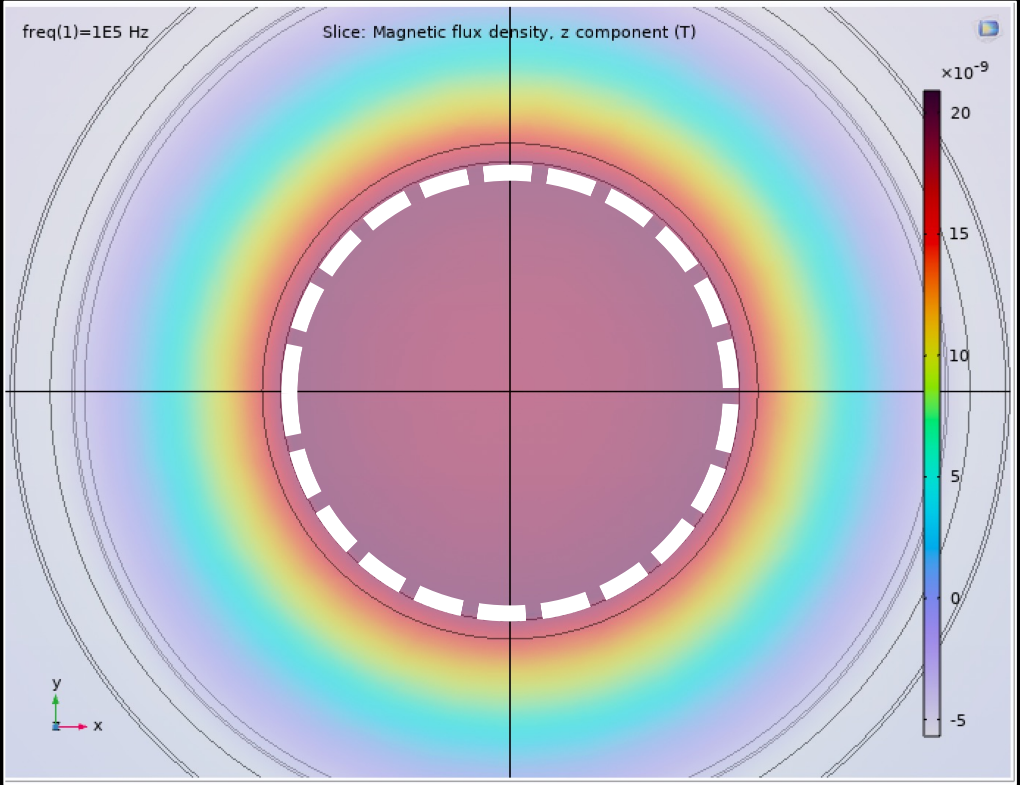
Gravitational Wave Sources



Axion Signal

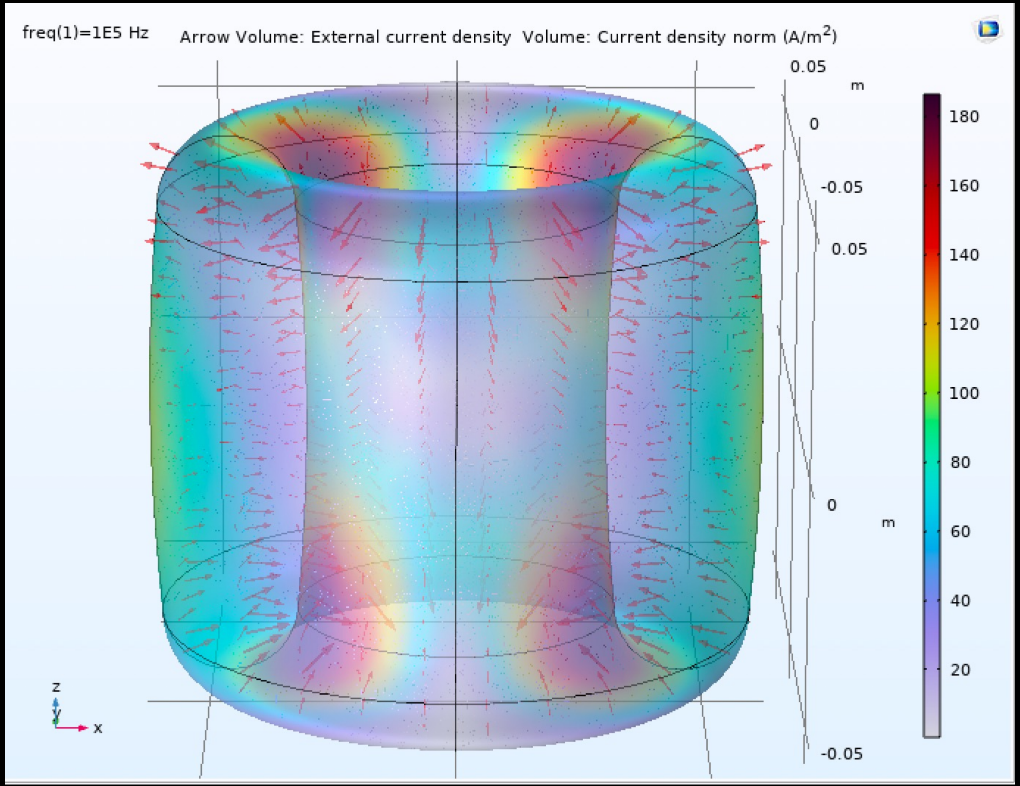


Axion current in the ABRACADABRA toroidal magnet

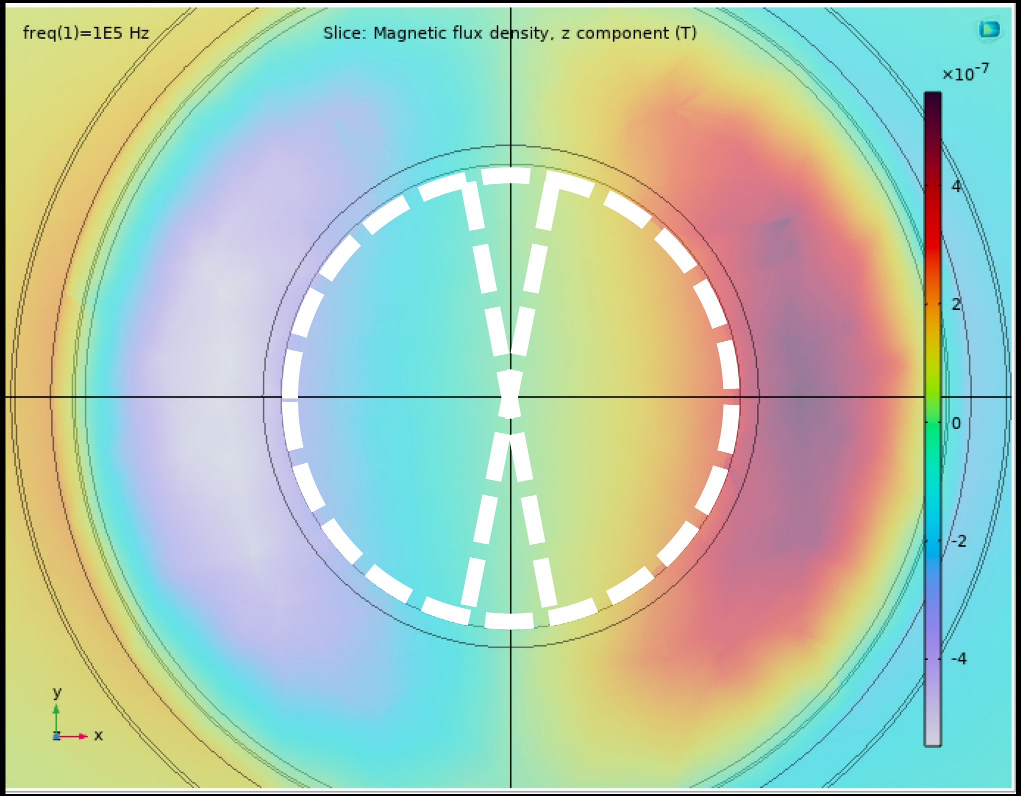


The z-component of the magnetic field resulting from an axion effective current

Gravitational Wave Signal

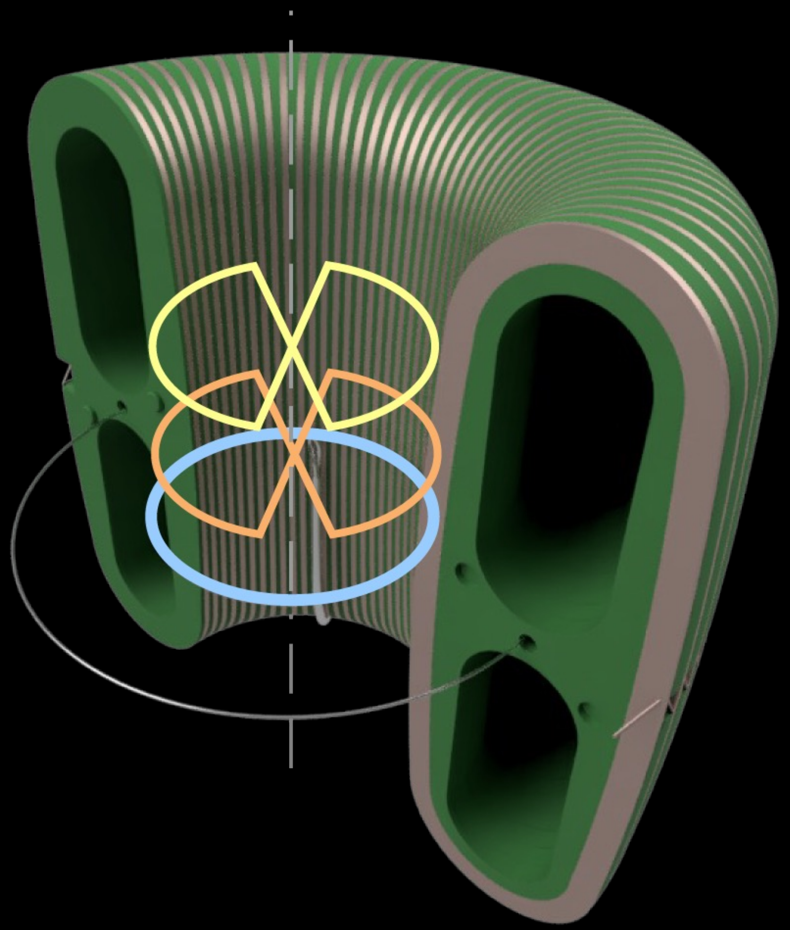


Gravitational wave current in the ABRACADABRA toroidal magnet



The z-component of the magnetic field resulting from a gravitational wave effective current

Gravitational Wave Detector Geometry



Gravitational wave calibration loop
Gravitational wave pickup loop
Axion pickup loop
Axion calibration loop

ABRA Grav Calibration

Goal 1: Characterize gain of the system

DAQ readout voltage to gravitational wave induced flux conversion

Goal 2: Prove simultaneity of axion and gravitational wave

Does a gravitational wave signal excite the axion pickup loop (and vice versa)?

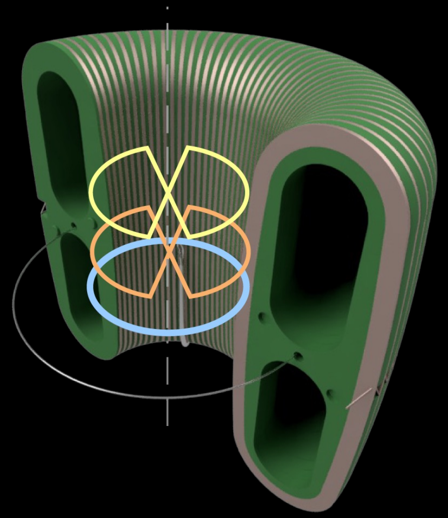
ABRA Grav Calibration

Inject axion mimetic signal through calibration loop

1. Read out axion pickup → Measure axion end-to-end gain
2. Read out grav pickup → Measure cross talk

Inject gravitational wave signal through calibration loop

3. Read out axion pickup → Measure cross talk
4. Read out grav pickup → Measure grav end-to-end gain



ABRA Grav Calibration

Inject axion mimetic signal through calibration loop

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Inject gravitational wave signal through calibration loop

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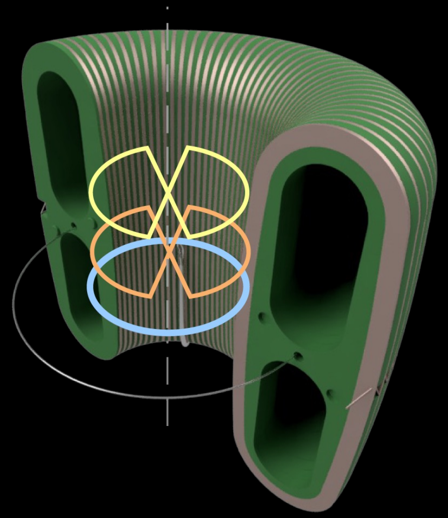
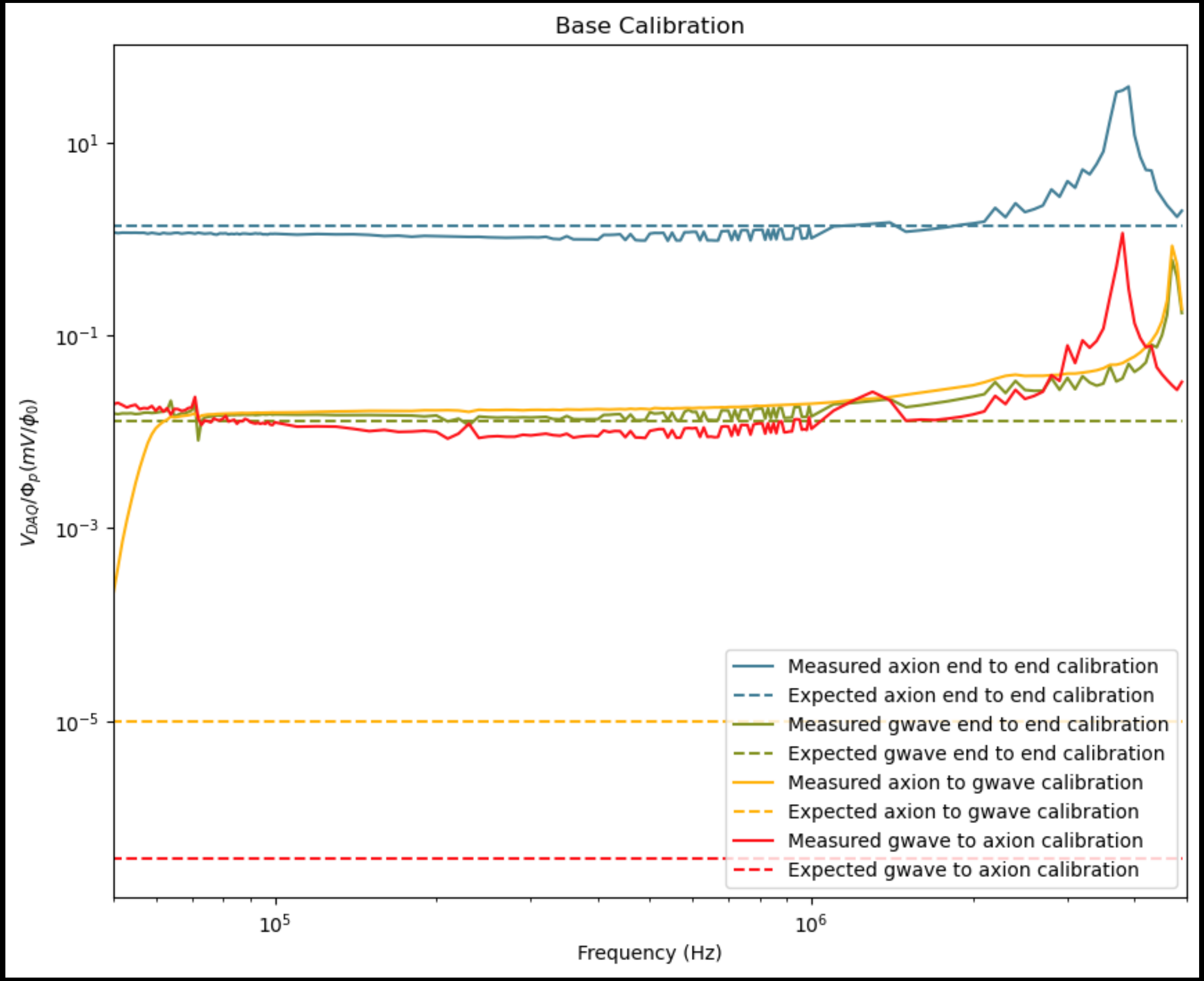
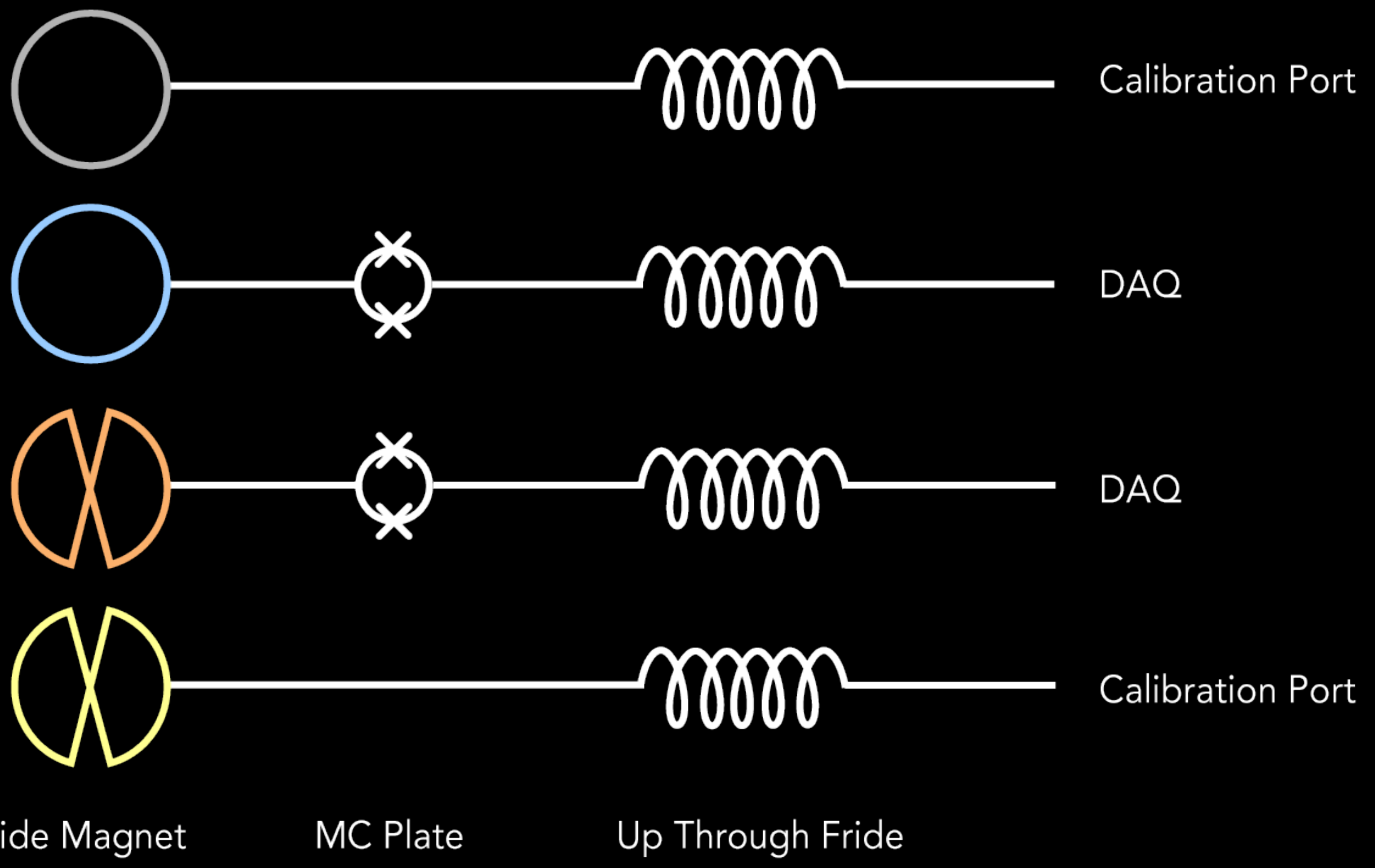


ABRA Grav Cross Talk

Gain of off-diagonal components (cross talk measurements) larger than expected

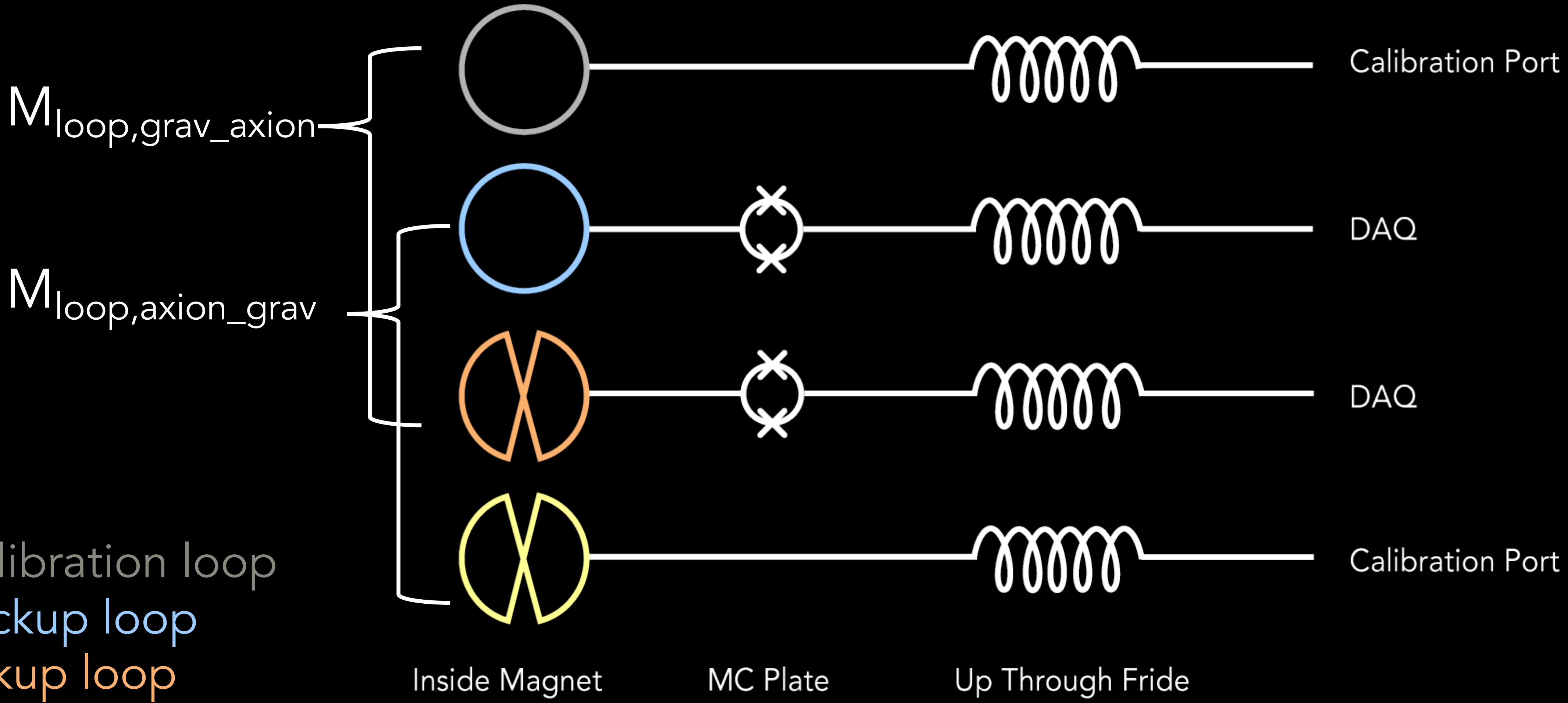


ABRA Grav Calibration



Axion calibration loop
Axion pickup loop
Grav pickup loop
Grav calibration loop

ABRA Grav Calibration



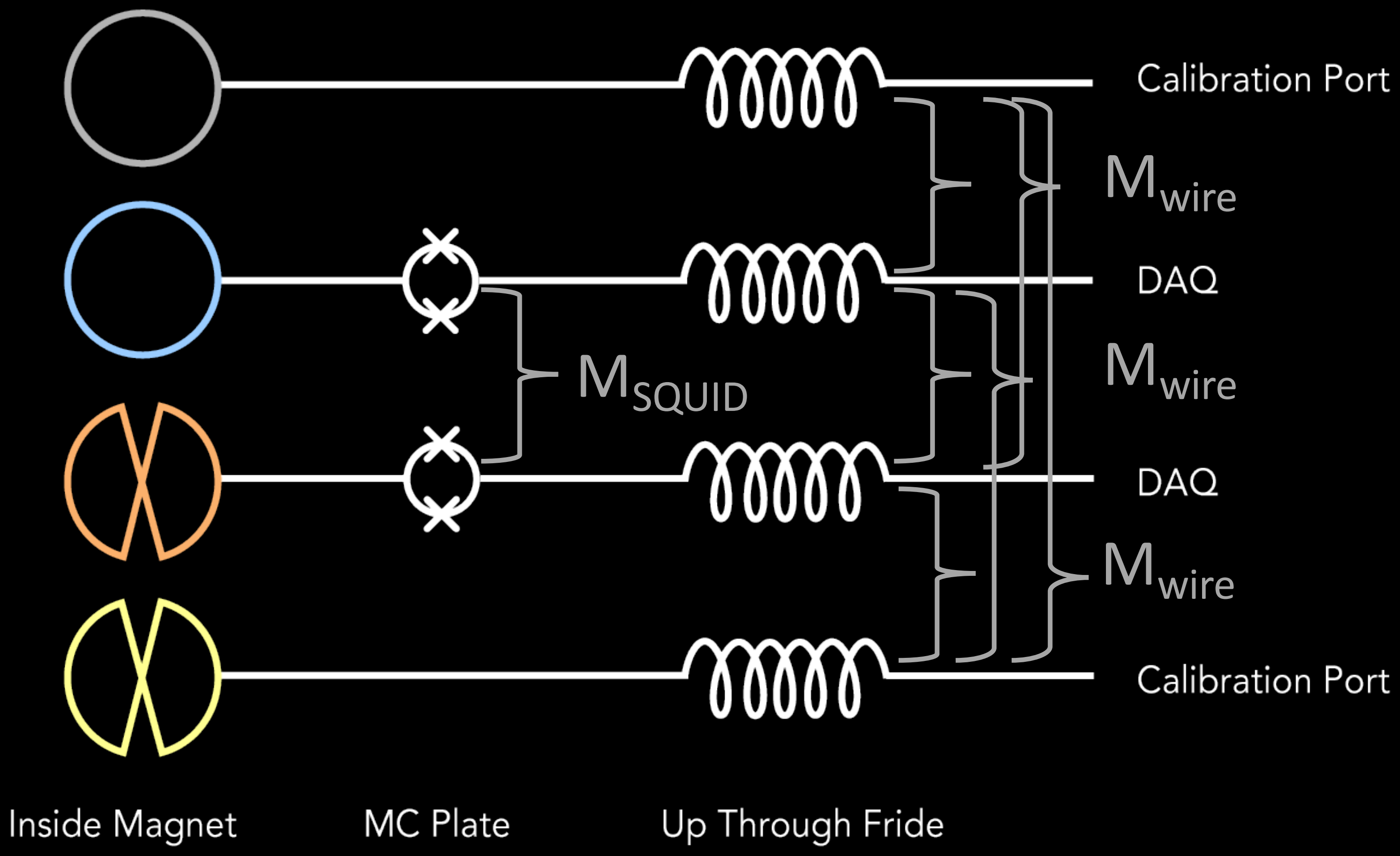
Axion calibration loop
Axion pickup loop
Grav pickup loop
Grav calibration loop

ABRA Grav Calibration

Could also be caused by SQUID and wire cross talk.

Tests underway to disentangle cross talk source.

Axion calibration loop
Axion pickup loop
Grav pickup loop
Grav calibration loop



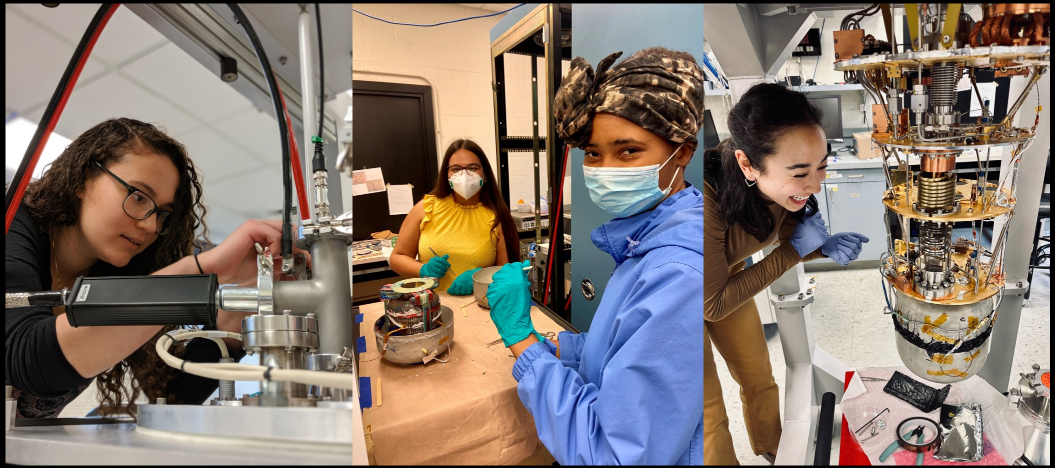
Summary

Lumped Element Axion Haloscopes

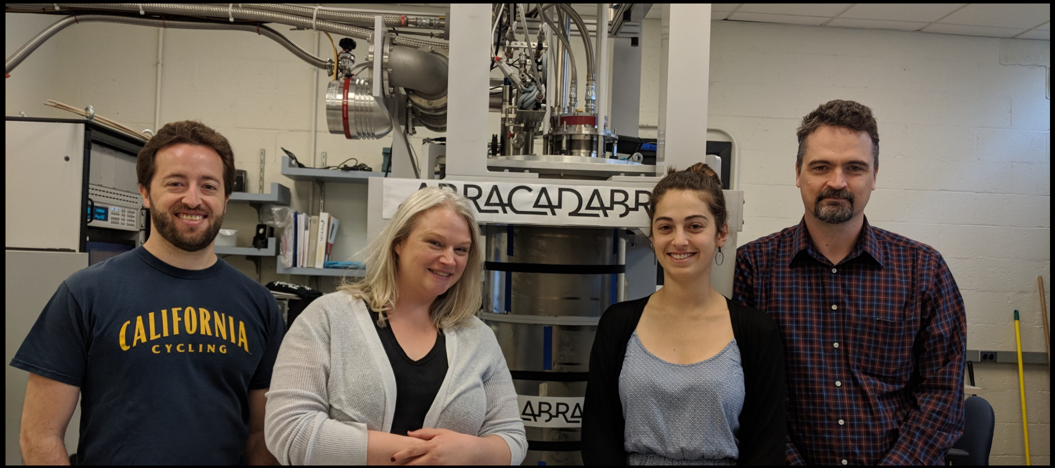
ABRACADABRA-10 cm

DMRadio-50L

ABRACADABRA Gravitational wave search



ABRACADABRA



DARK MATTER RADIO

kHz MHz GHz THz freq

peV neV μeV meV mass

SPIN

AM/FM/DM

Stanford University

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

MIT

CAL STATE EAST BAY

TUNL

Triangle Universities Nuclear Laboratory

Berkeley UNIVERSITY OF CALIFORNIA

BERKELEY LAB

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

DMRadio Collaboration Apple Picking

PRINCETON UNIVERSITY

SLAC NATIONAL ACCELERATOR LABORATORY

SANTA CLARA UNIVERSITY 1851

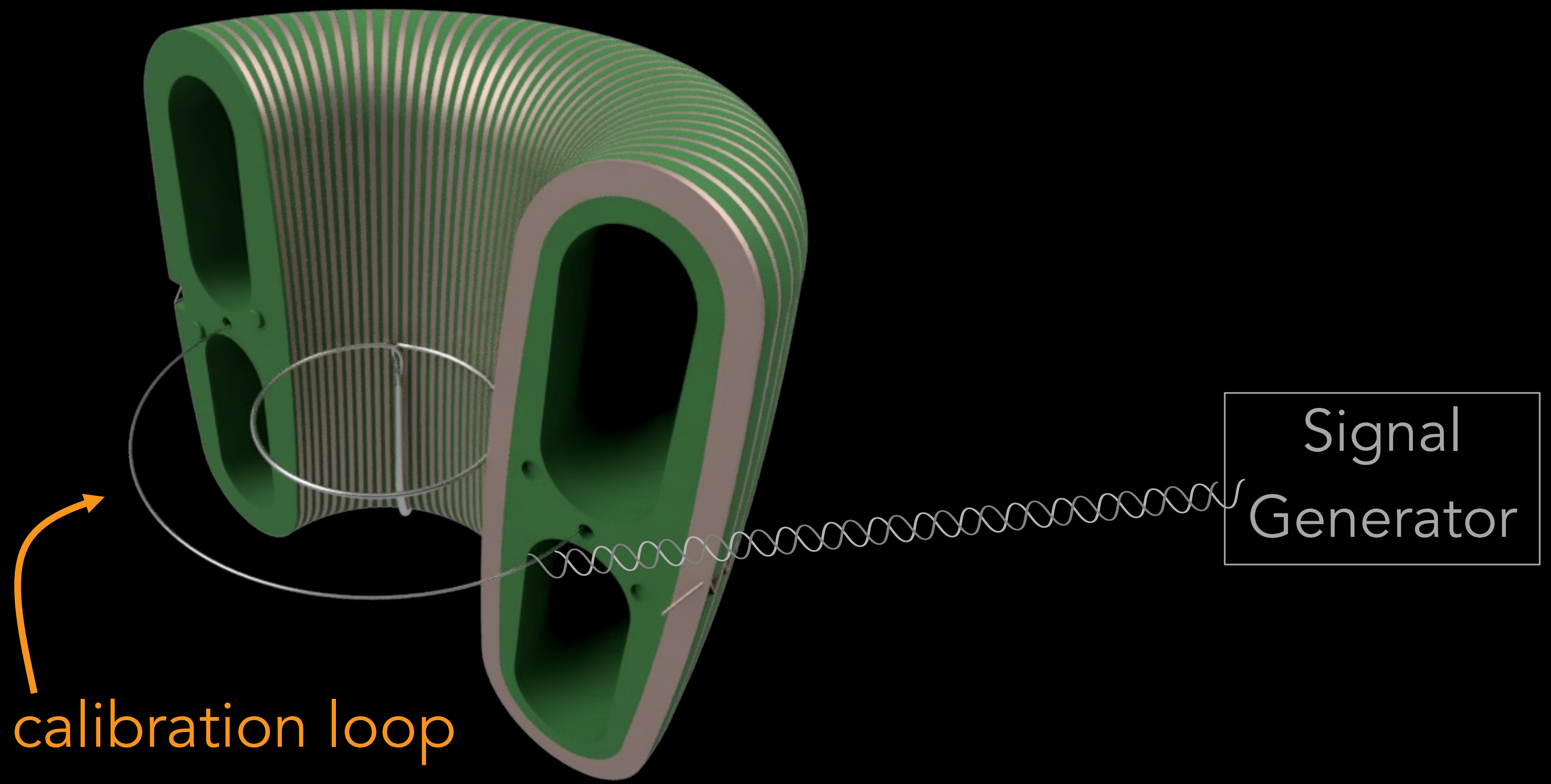
DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

HEISING-SIMONS FOUNDATION

NSF

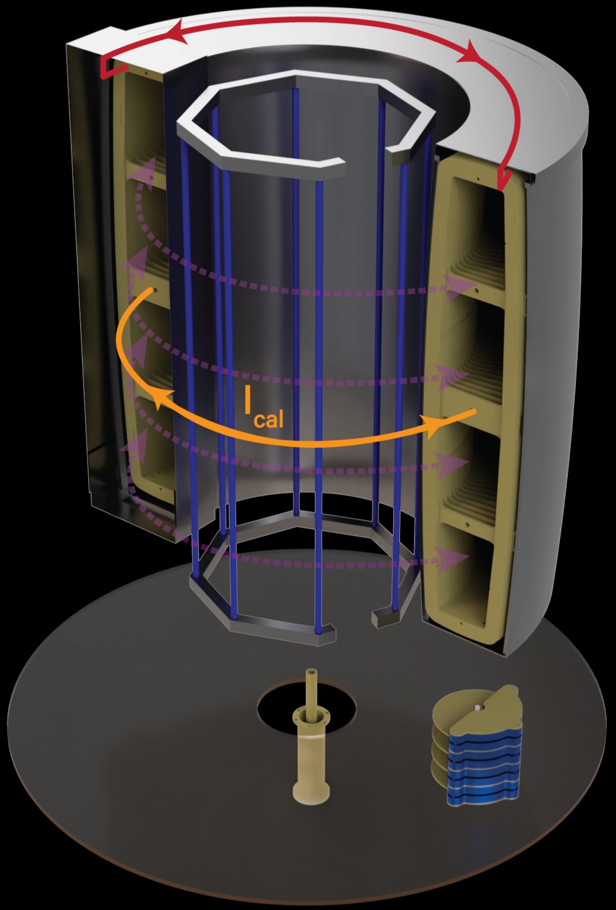
GORDON AND BETTY MOORE FOUNDATION

ABRA Calibration



Axion Mimetic Injection

- Magnet enclosed in high Q sheath
- To keep high Q factor, need to minimize conductive toroidal elements
- Cannot take data with axion mimetic loop in detector

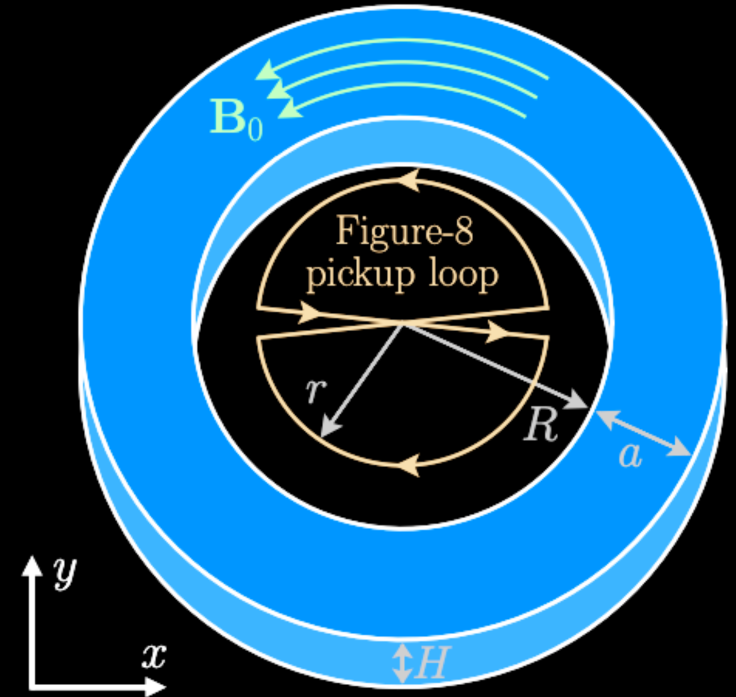


Gravitational Wave Sources

- Primordial black holes (1 kHz – 1e11 GHz)
- Exotic compact objects (1 kHz – 1e11 GHz)
- Superradiance (1 kHz – 300 kHz)

Gravitational Wave Figure of Merit

$$\Phi_8 = \frac{e^{-\mathrm{i}\omega t}}{3\sqrt{2}}\,\omega^2 B_{\mathrm{max}} r^3 R \ln\left(1 + a/R\right) s_{\theta_h} \times \left(h^{\times} s_{\phi_h} - h^{+} c_{\theta_h} c_{\phi_h}\right).$$



Gravitational Wave Strain Limits

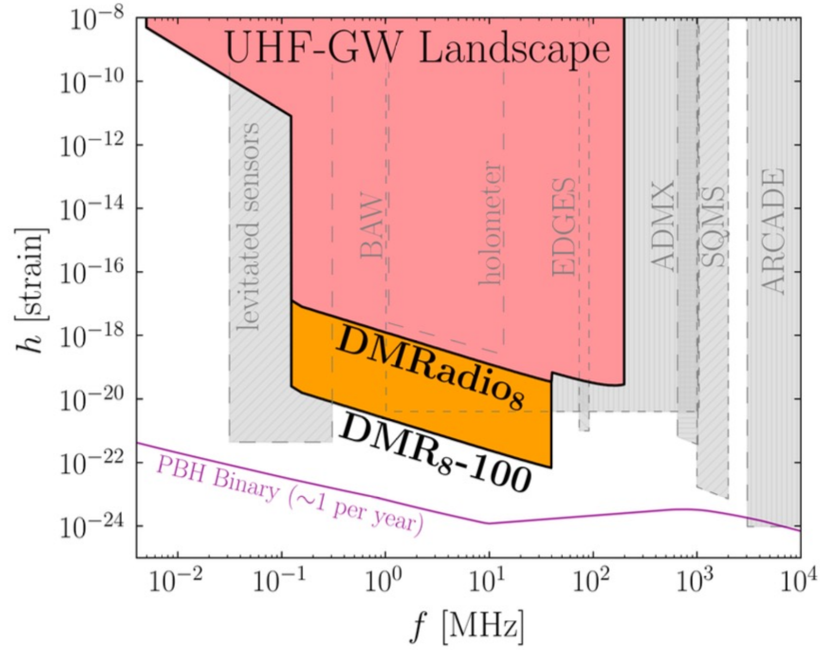


FIG. 1. The UHF-GW experimental landscape, with the approach introduced in this work shown in color. DMRadio$_8$ shows the projected reach of the full suite of DMRadio instruments (50L, m^3, and GUT) adopting our advocated figure-8 pickup loop geometry. Looking to the far future, we also show the reach of an upscaled DMRadio with a magnetic field volume of 100 m^3, labelled DMR$_8$-100. A subset of existing proposals in this frequency range are shown in grey, taken from Refs. [1, 2], as well as an estimate for the required sensitivity to see one signal from primordial black hole (PBH) binaries per year. Additional specifics are provided in the text.

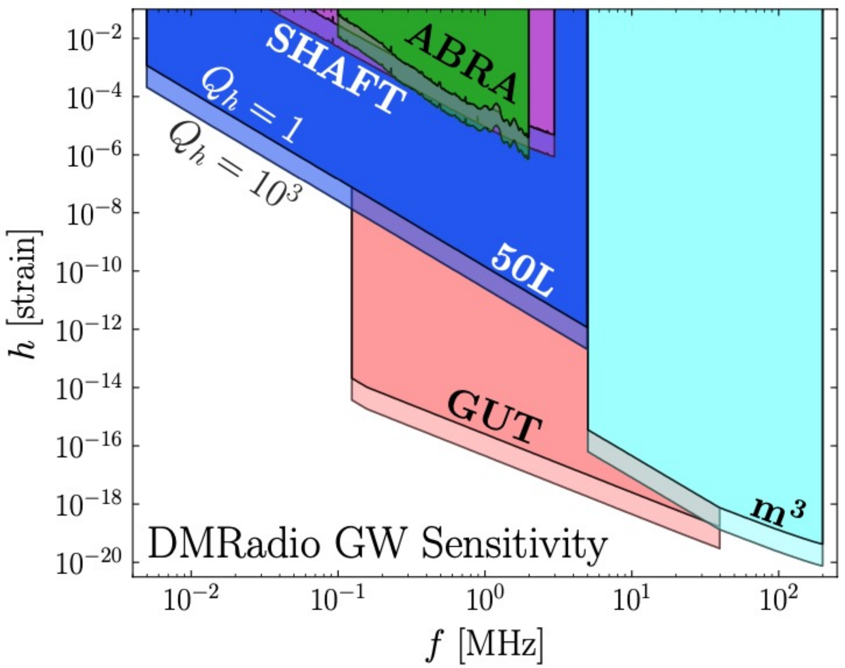


FIG. 3. The GW strain sensitivity of low-mass axion haloscopes. We recast the existing limits obtained by ABRA [6] (green) and SHAFT [7] (purple). For DMRadio we use the projected future sensitivity of the three instruments that will make up that program: 50L (blue), m^3 (cyan), and GUT (pink) [10, 11]. In each case, results are shown for two choices of the GW signal coherence, $Q_h = 1$ (opaque) and $Q_h = 10^3$ (transparent). All results assume a circular pickup loop, for results using the optimal figure-8, see Fig. 1.

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