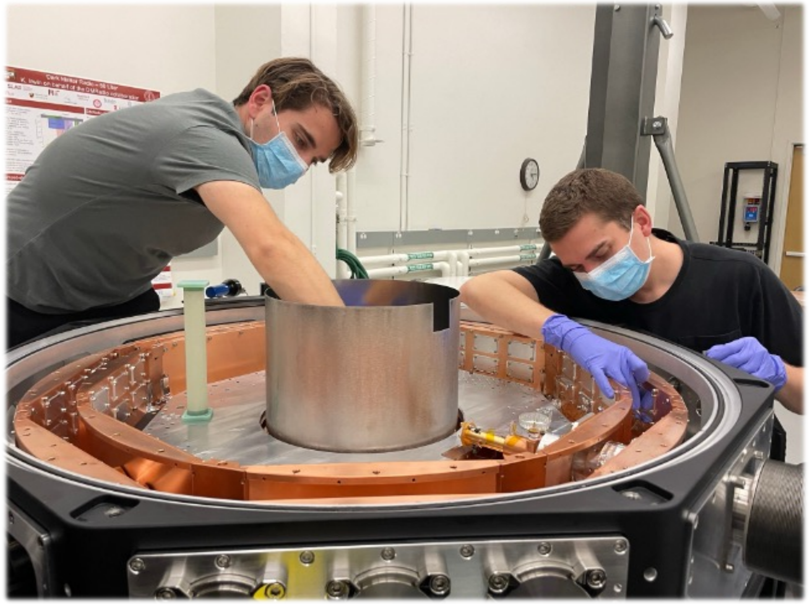
Commissioning DMRadio-50L

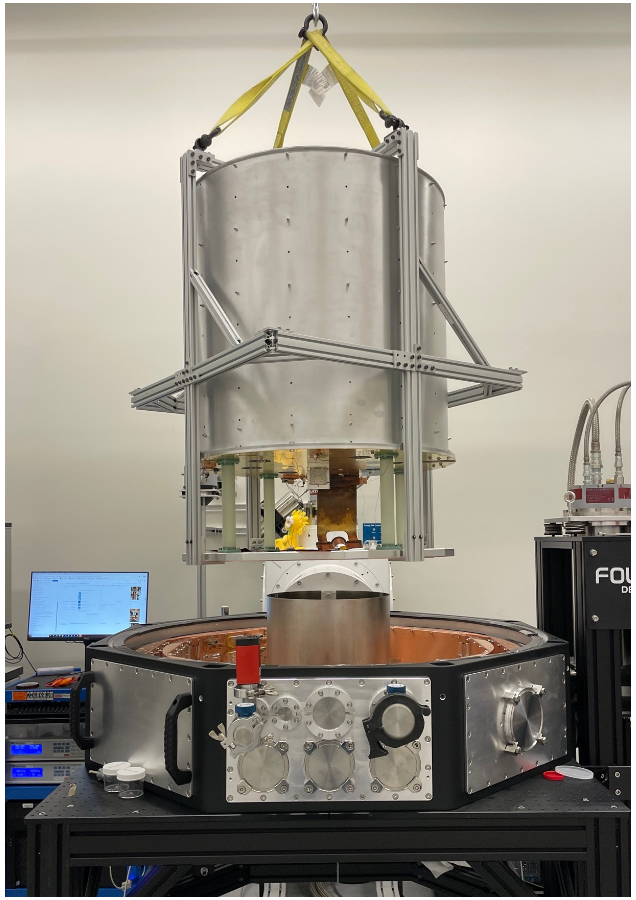


Tori Ankel

Stanford University-Irwin Group

DMRadio Collaboration

IDM Zaragoza 2026



Axion dark matter

Originally proposed to solve the strong CP problem

Produced athermally in early universe via misalignment mechanism

→

Compelling dark matter candidate

Axion dark matter

Originally proposed to solve the strong CP problem

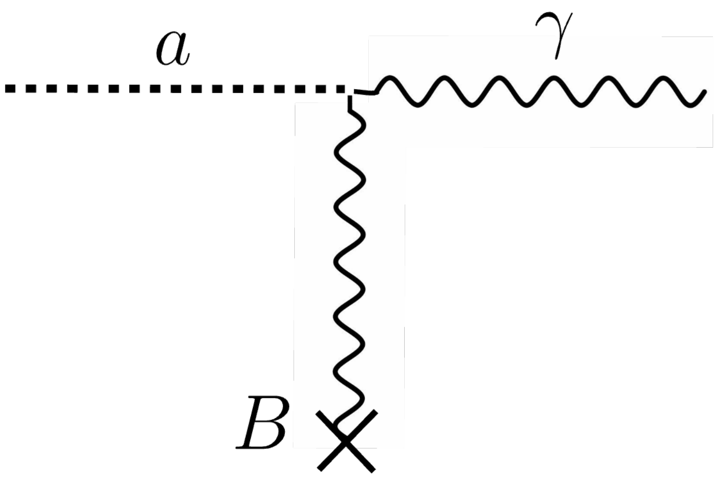
Produced athermally in early universe via misalignment mechanism

Compelling dark matter candidate

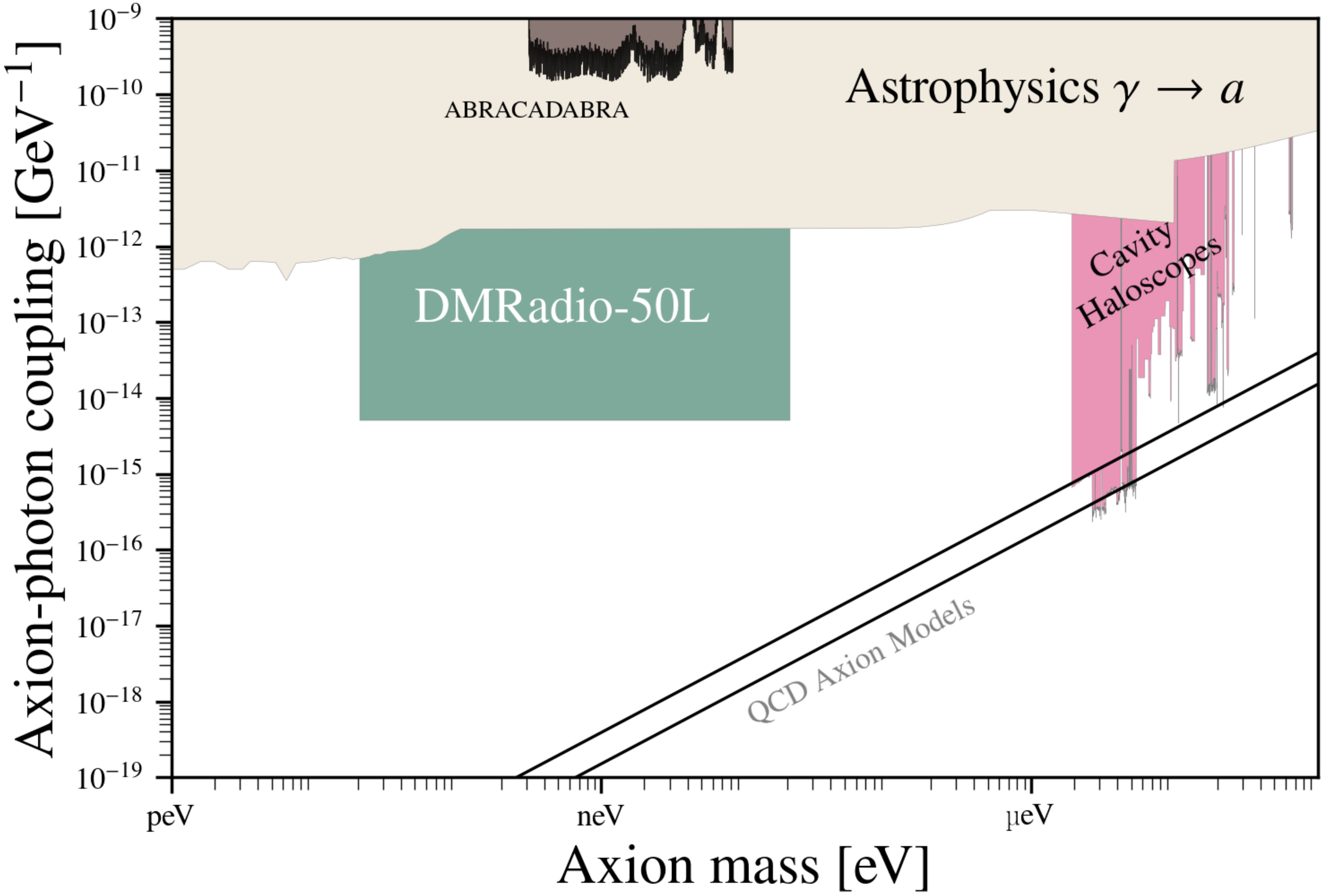
Axions couple to standard model photons via:

$$\mathcal{L}_{ax} \sim -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

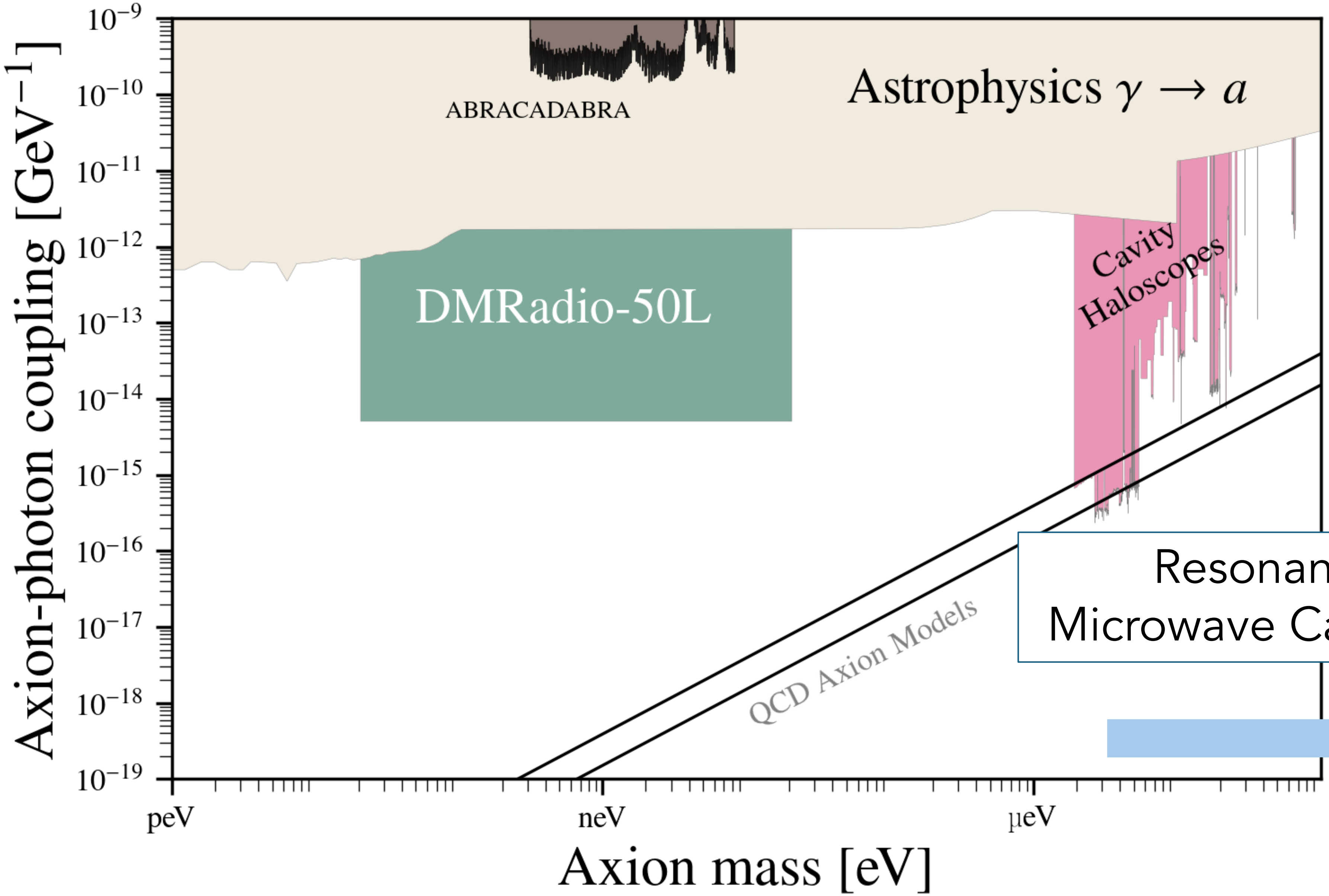
-> Look for axion-photon-photon interaction

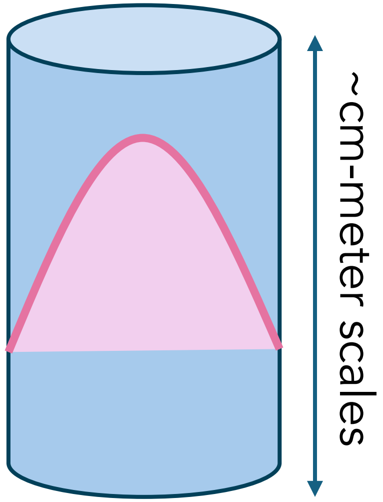


Axion dark matter

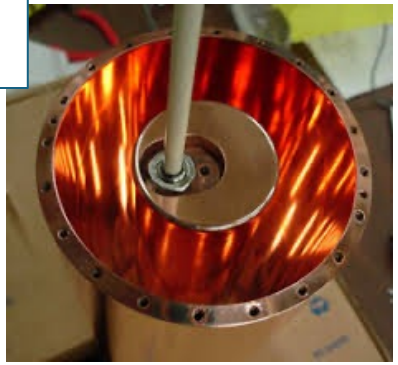


Axion dark matter



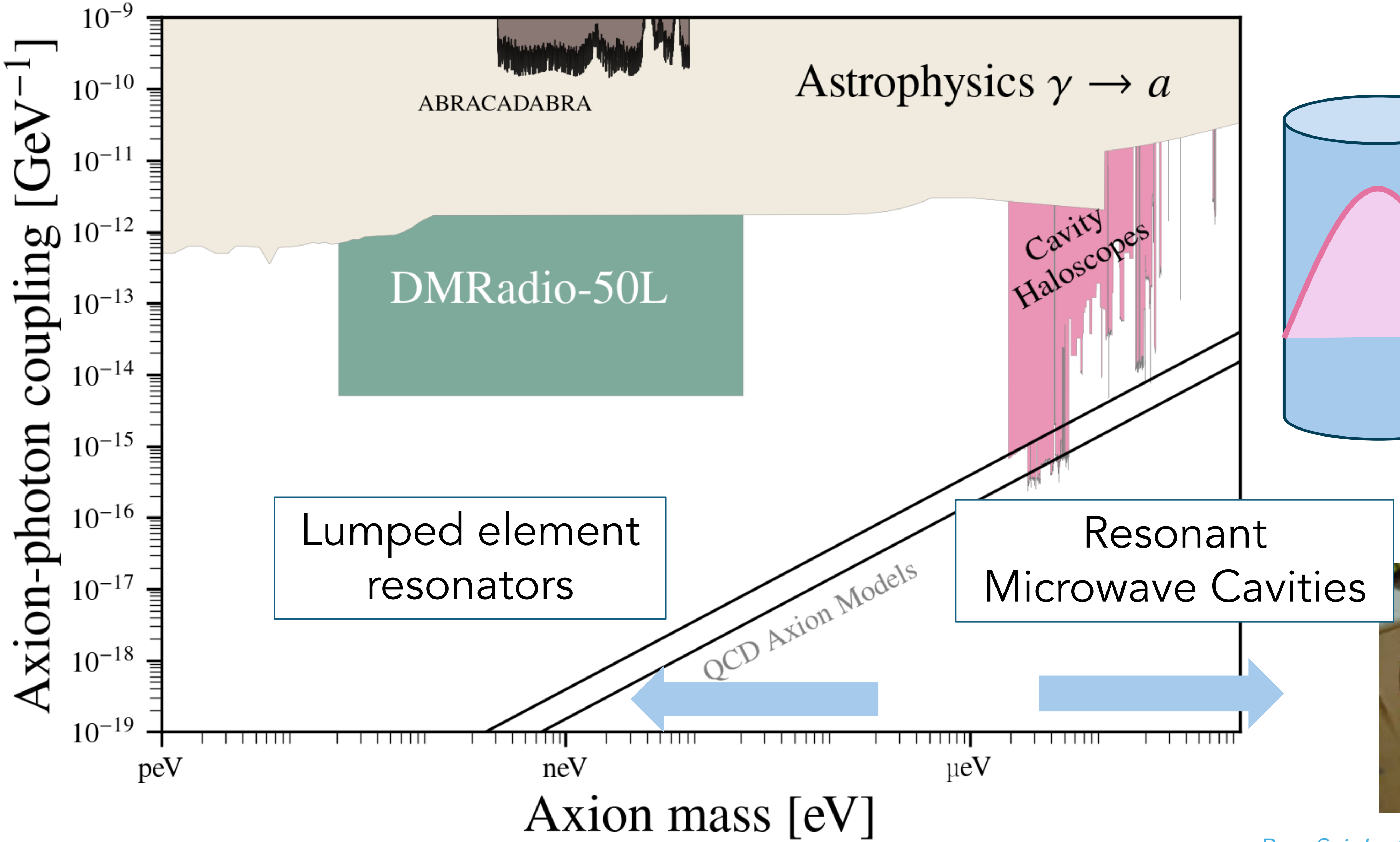


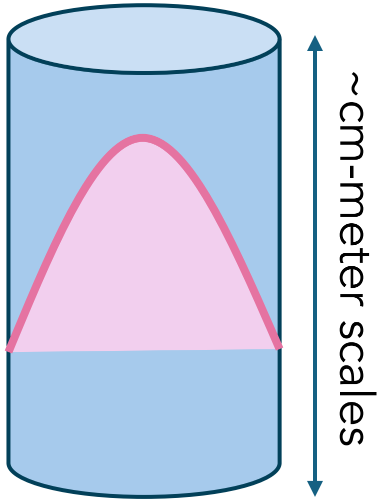
Resonant Microwave Cavities

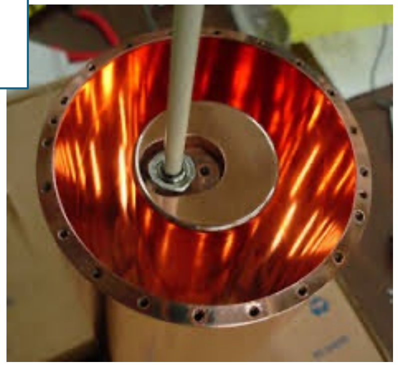


Rev. Sci. Instrum. 90, 024706 (2019)

Axion dark matter





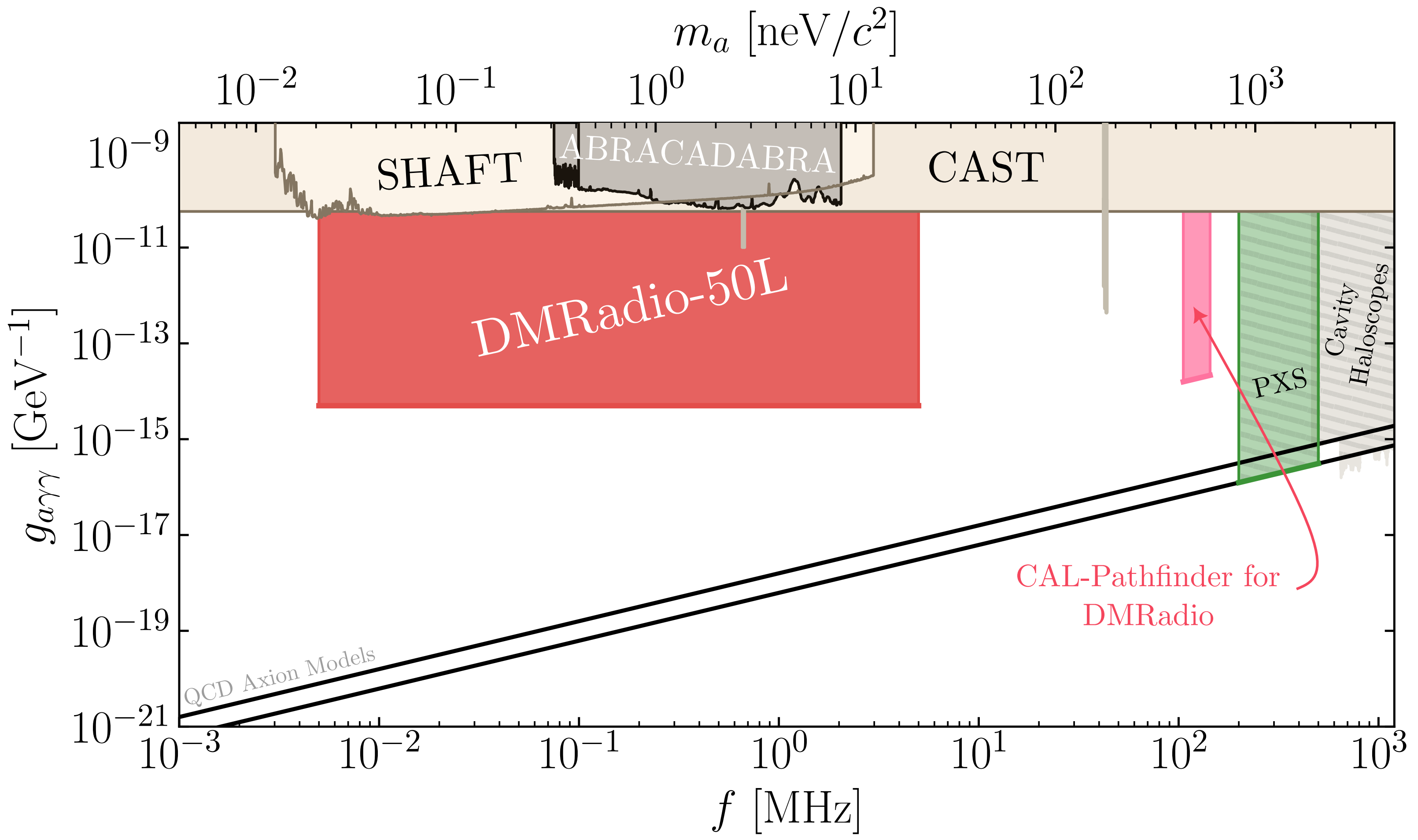


Rev. Sci. Instrum. 90, 024706 (2019)

50L-Goals

Search for pre-inflationary axions between $5\mathrm{KHz} - 5\mathrm{MHz}$

First axion search using a tunable LC resonator



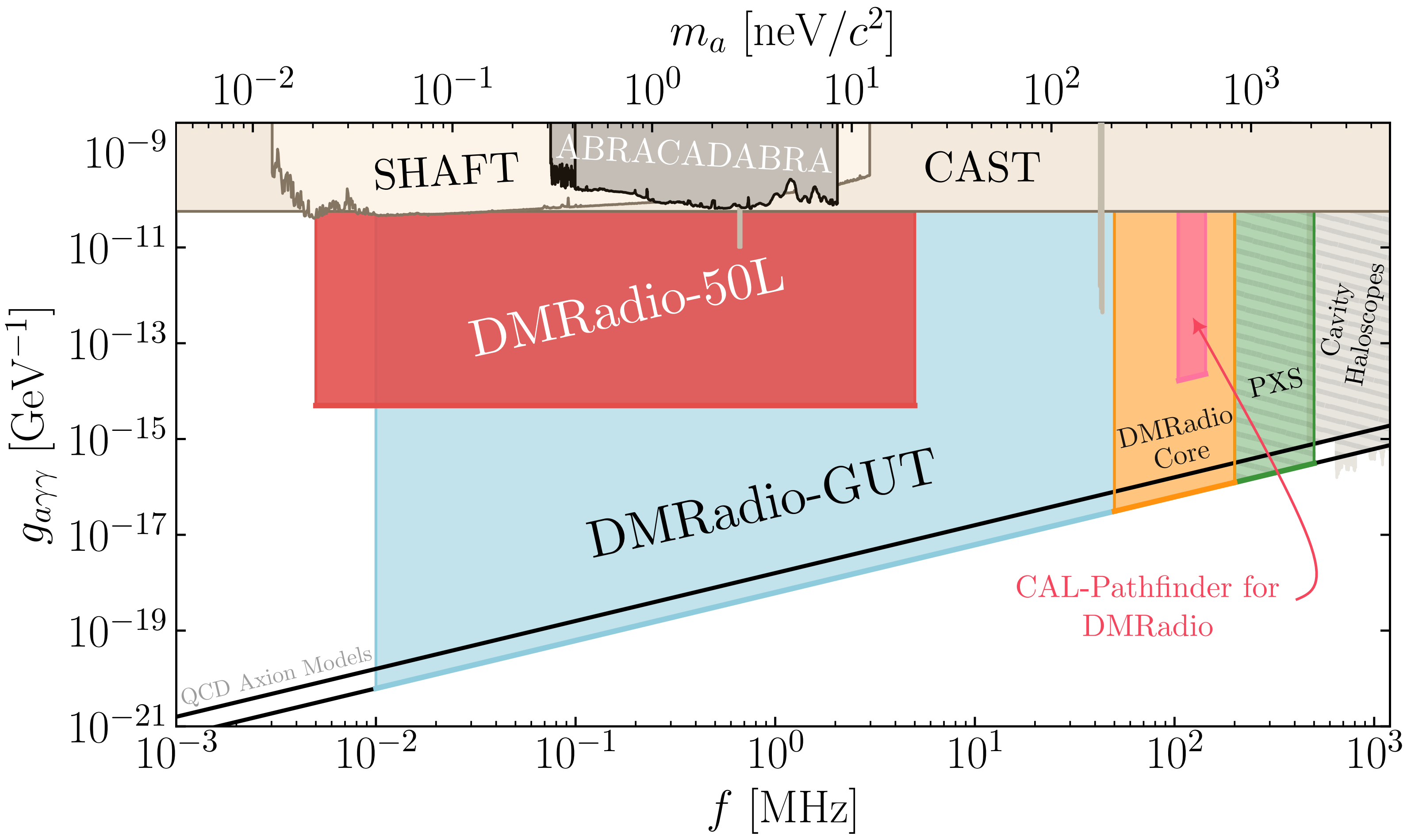
50L-Goals

Search for pre-inflationary axions between $5\text{KHz} - 5\text{MHz}$

First axion search using a tunable LC resonator

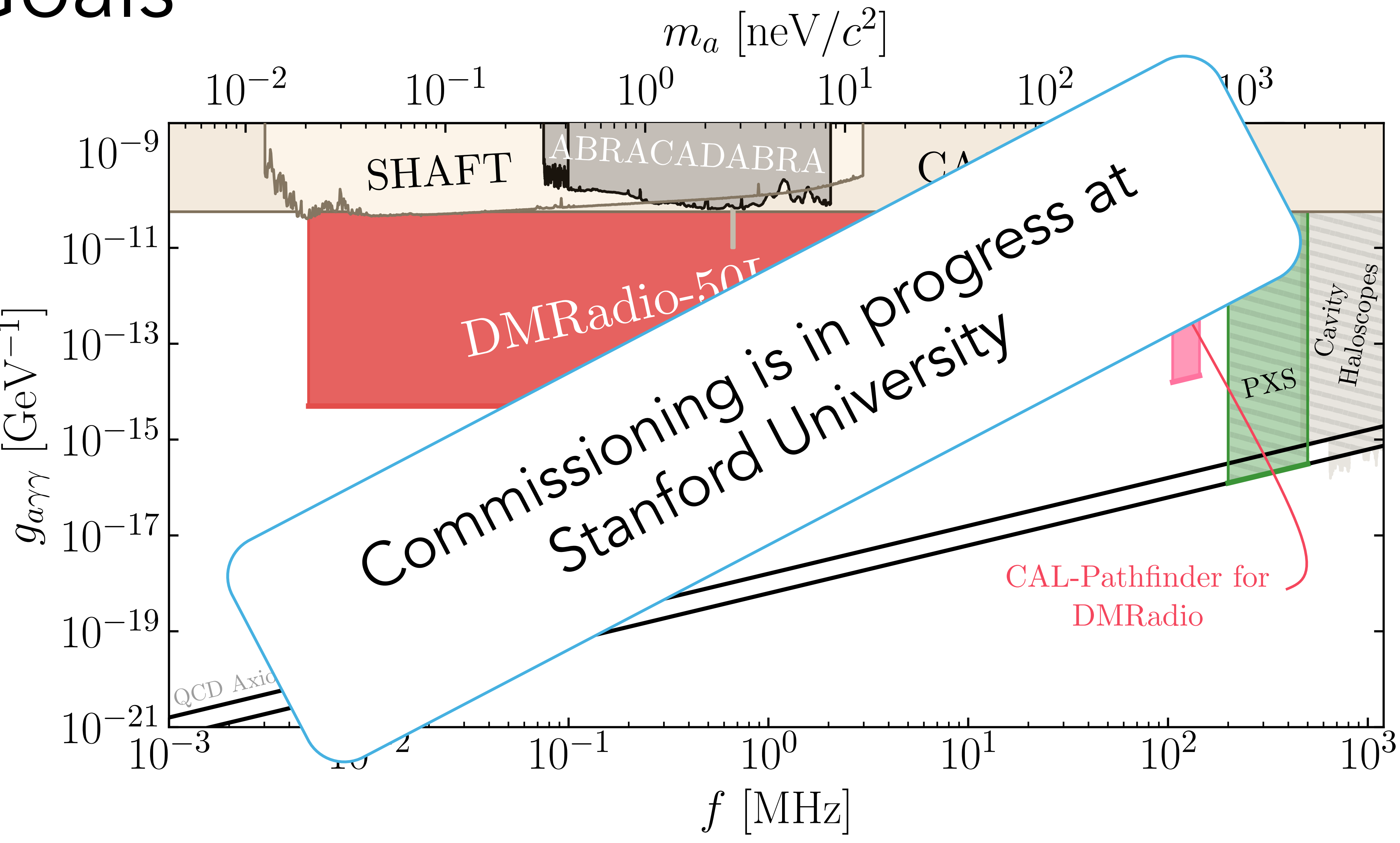
Testbed for SQL evading quantum devices

Like Radiofrequency Quantum Upconverters (RQUs)



arXiv:2203.11246

50L-Goals



Commissioning is in progress at Stanford University

DMRadio Collaboration

SLAC NATIONAL ACCELERATOR LABORATORY

KIPAC KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS & COSMOLOGY

Stanford University

MIT

PRINCETON UNIVERSITY

Berkeley UNIVERSITY OF CALIFORNIA

SANTA CLARA UNIVERSITY 1851

BERKELEY LAB

U.S. DEPARTMENT OF ENERGY Office of Science

GORDON AND BETTY MOORE FOUNDATION

HEISING-SIMONS FOUNDATION

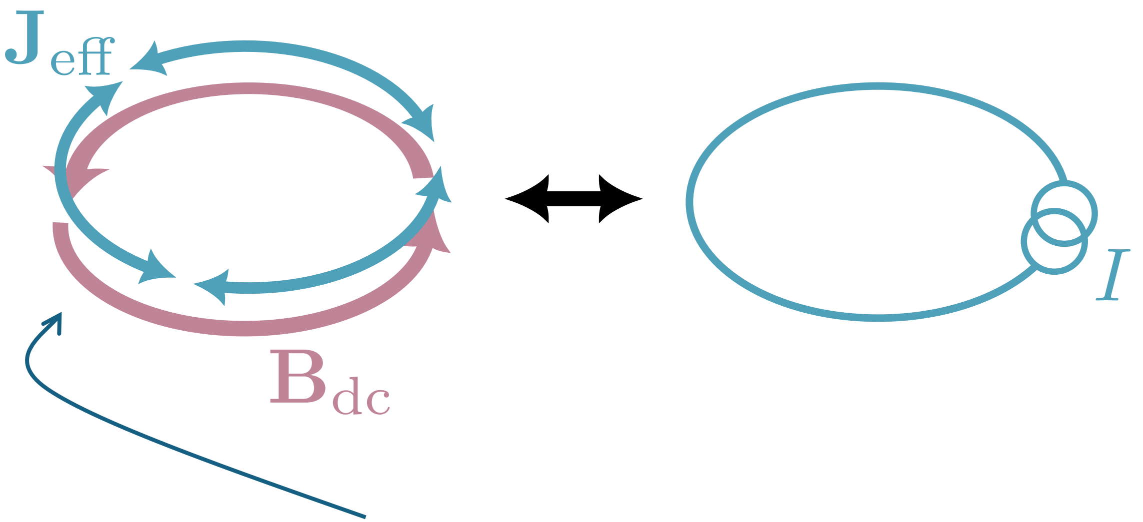
NSF

DMRadio principle

wavelength >> size of the detector → Lumped element regime

DMRadio principle

wavelength >> size of the detector



Consider a toroidal magnet geometry

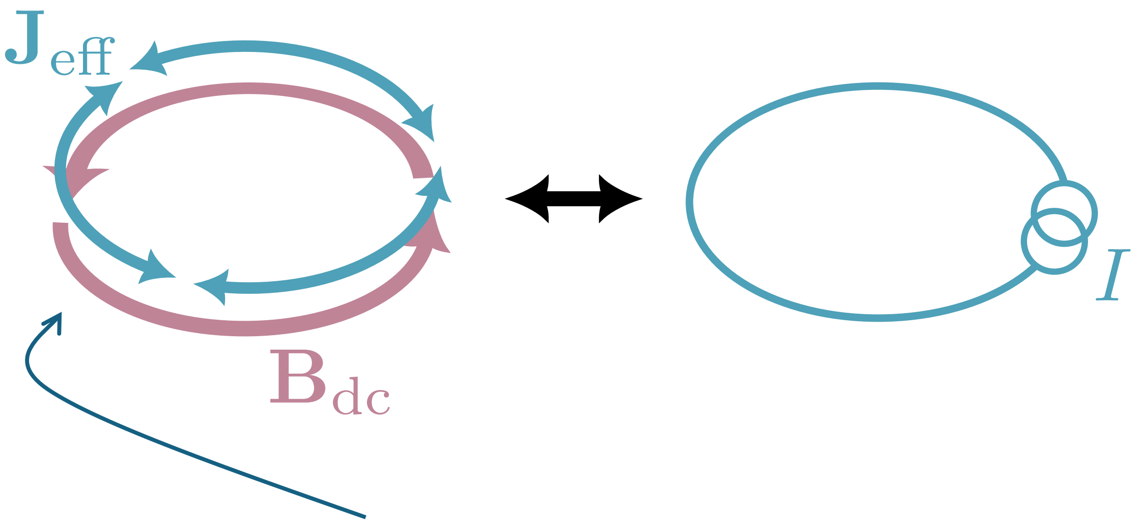
Start with a DC magnetic field →

axion effective current:

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

DMRadio principle

wavelength >> size of the detector



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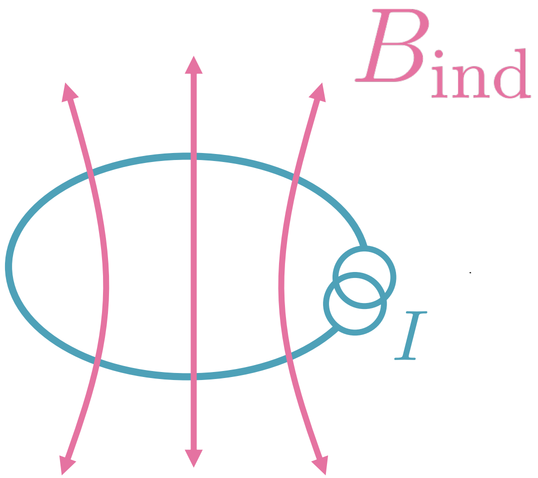
Start with a DC magnetic field ⟶

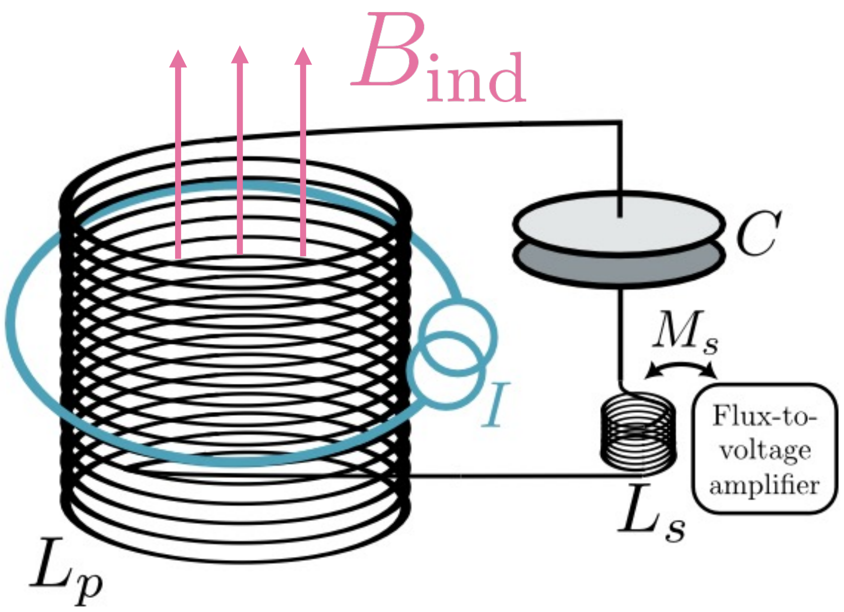
axion effective current:

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



Oscillating effective current produces an AC magnetic field

DMRadio principle



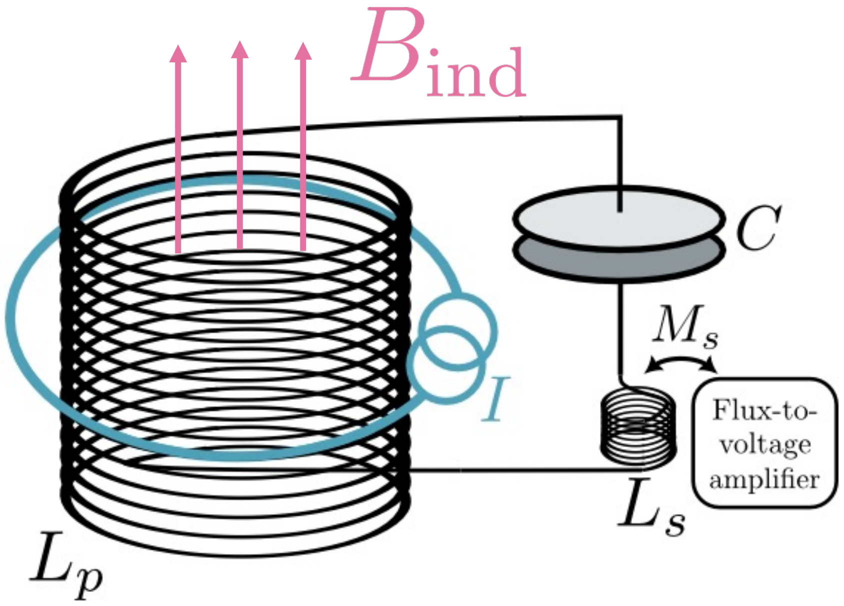
Pick-up the induced AC magnetic field using a tunable, LC resonant circuit

Read out the induced current in the circuit using a flux to voltage amplifier

DMRadio principle

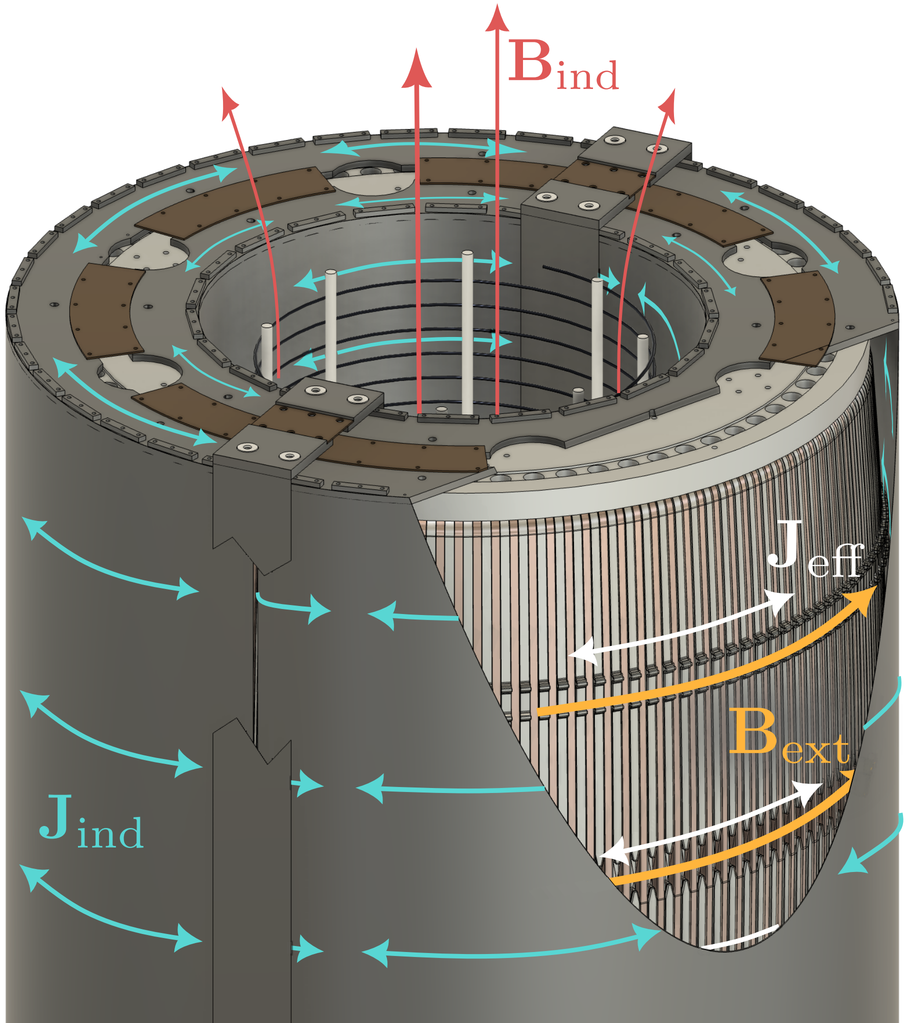
1T Toroidal magnet

Superconducting solenoidal inductor

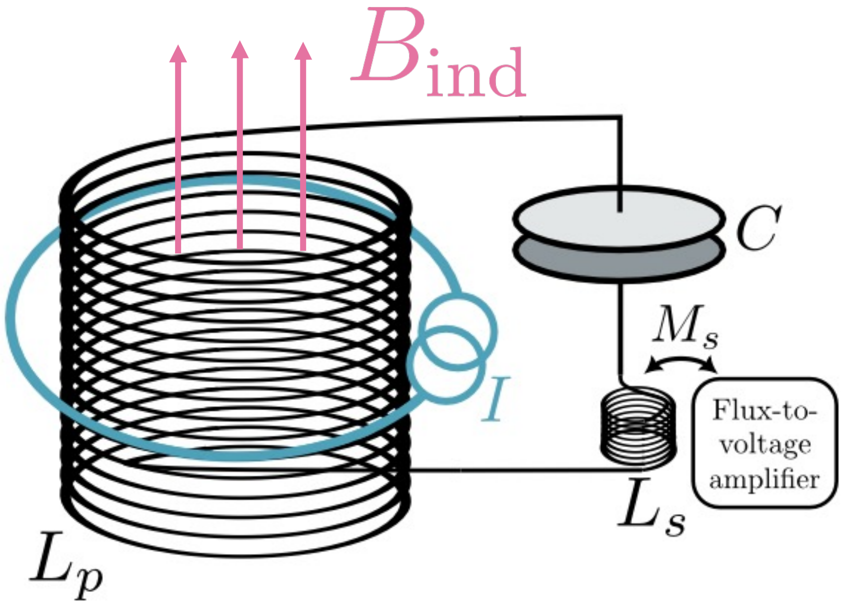


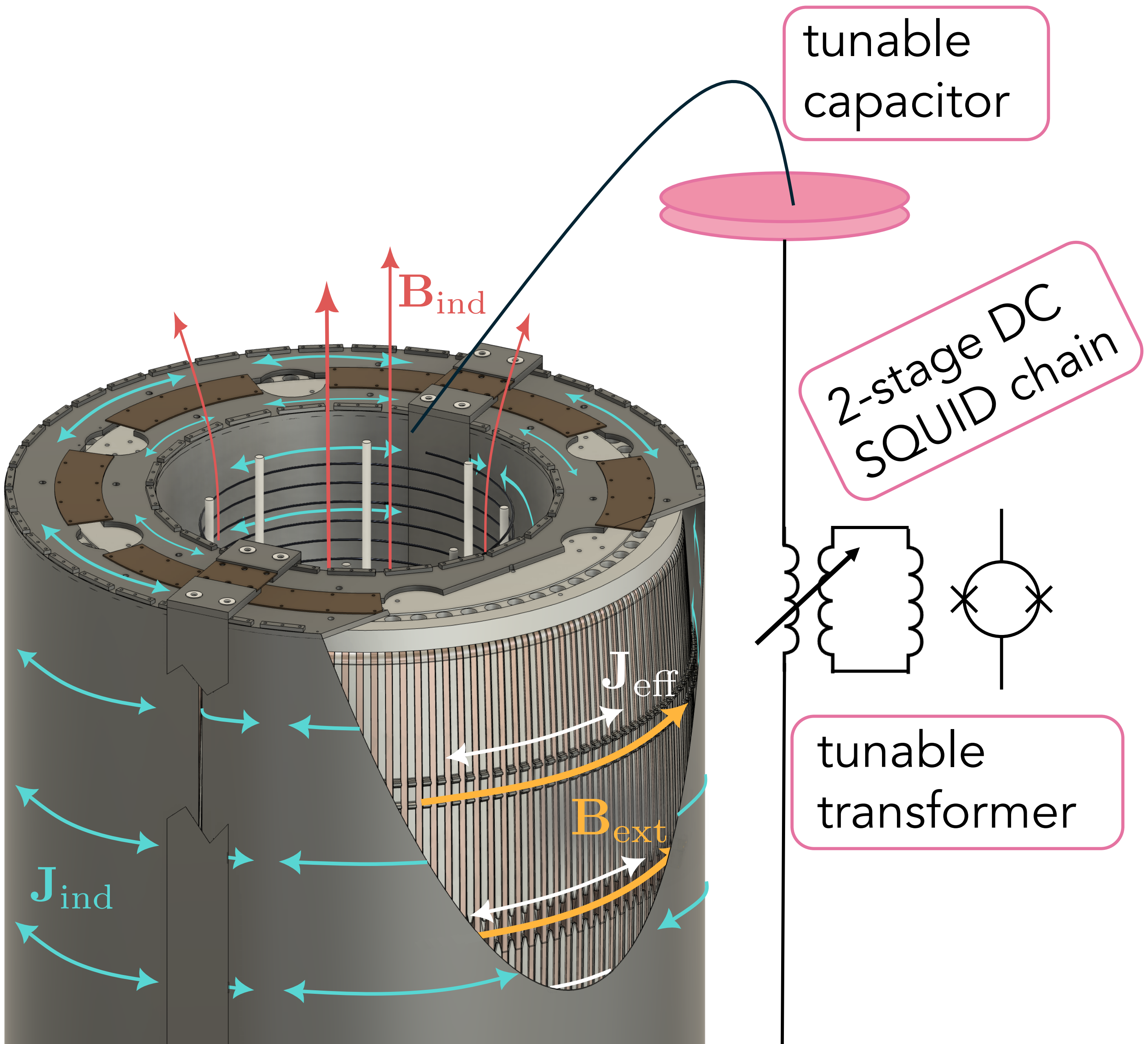
Pick-up the induced AC magnetic field using a tunable, LC resonant circuit

Read out the induced current in the circuit using a flux to voltage amplifier



DMRadio principle

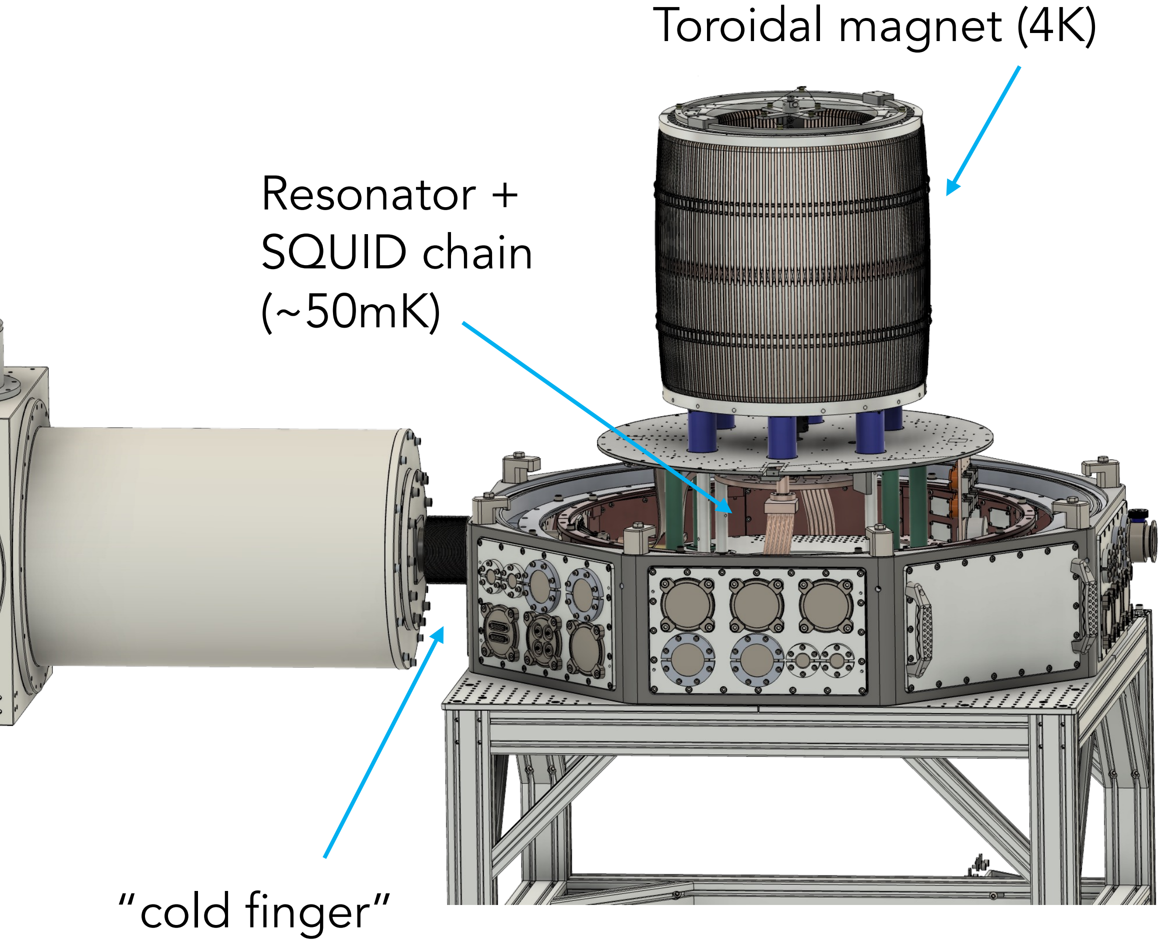


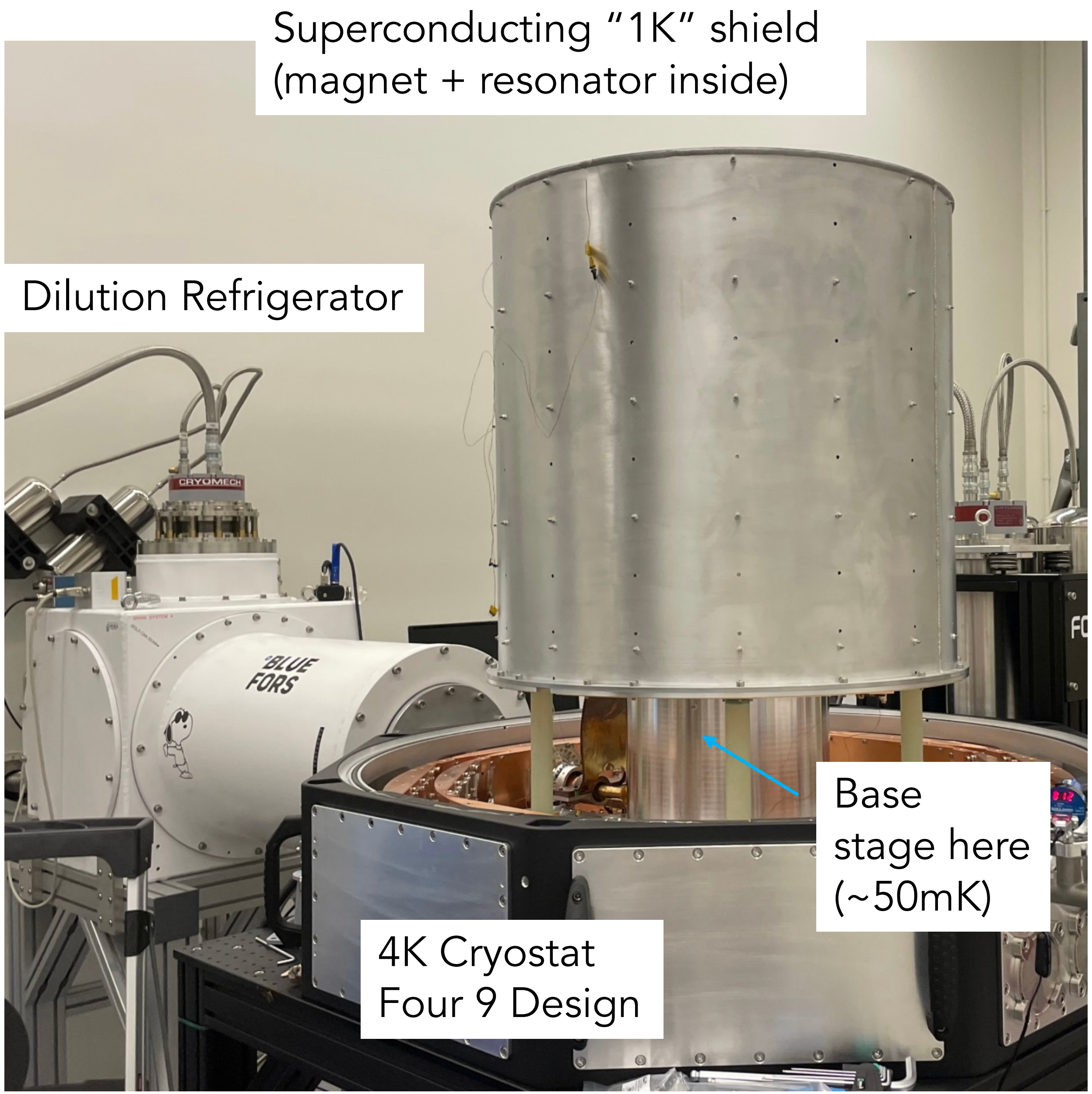


Pick-up the induced AC magnetic field using a tunable, LC resonant circuit

Read out the induced current in the circuit using a flux to voltage amplifier

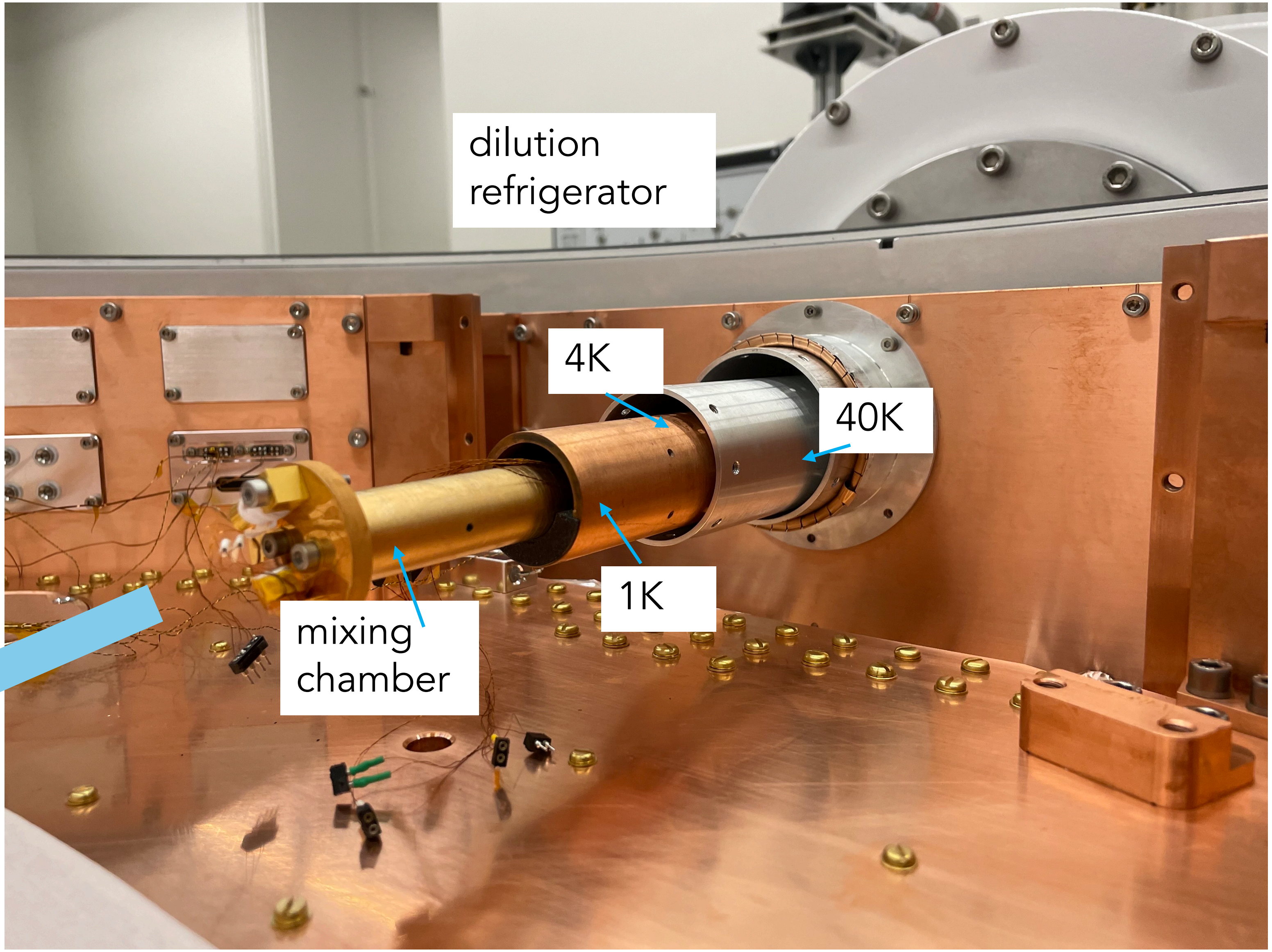
Cryogenics


Toroidal magnet (4K)
Resonator +
SQUID chain
(~50mK)
"cold finger"


Superconducting "1K" shield
(magnet + resonator inside)
Dilution Refrigerator
CRYOMECH
BLUE FORS
Base
stage here
(~50mK)
4K Cryostat
Four 9 Design

Cold Finger Connection

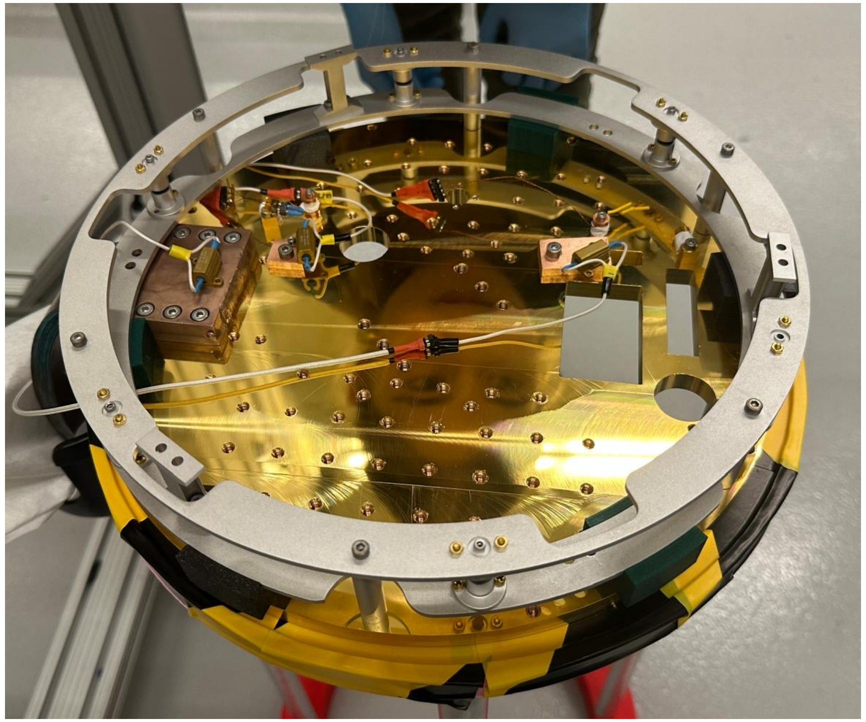
Thermal link between dilution fridge and 4K cryostat



50L here

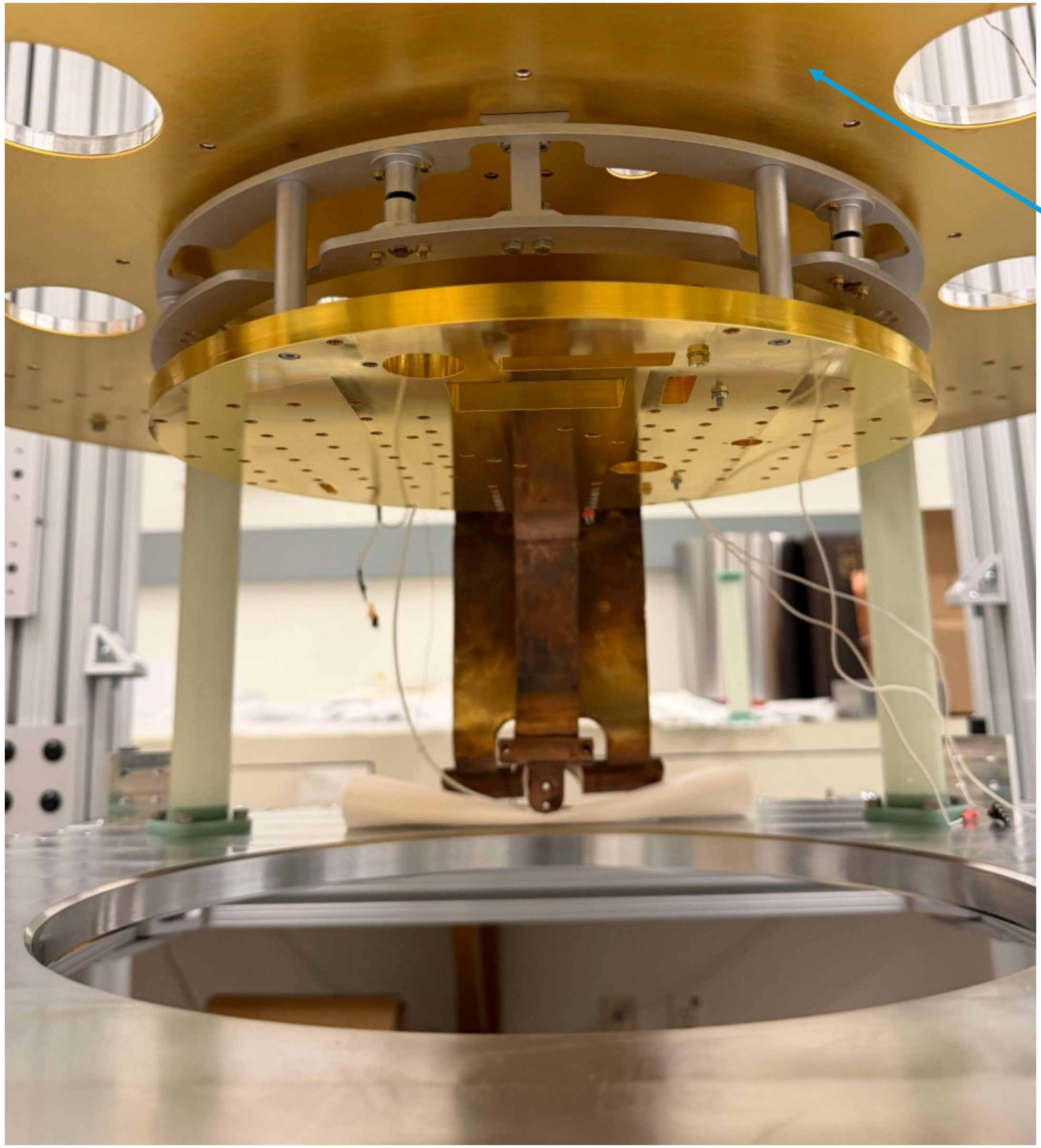
(other components not in cryostat)

Cold Stages



Houses inductor, tunable capacitor, tunable transformer & SQUID readout

Currently operating at 44 mK



"1K" stage supports base stage & shields the resonator

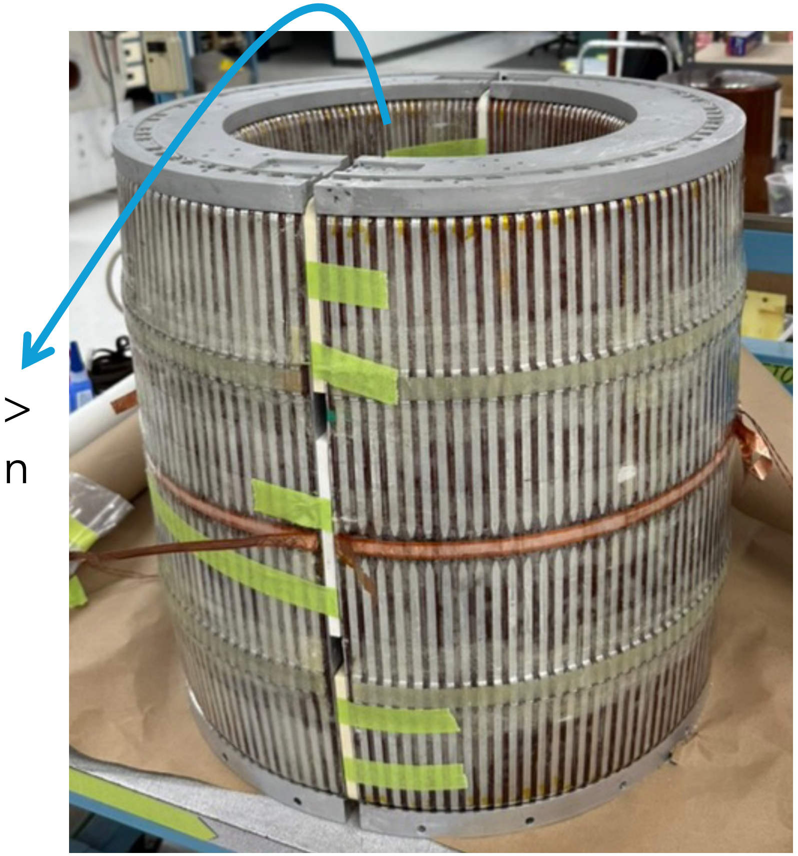
Currently operating at 700mK

Magnet

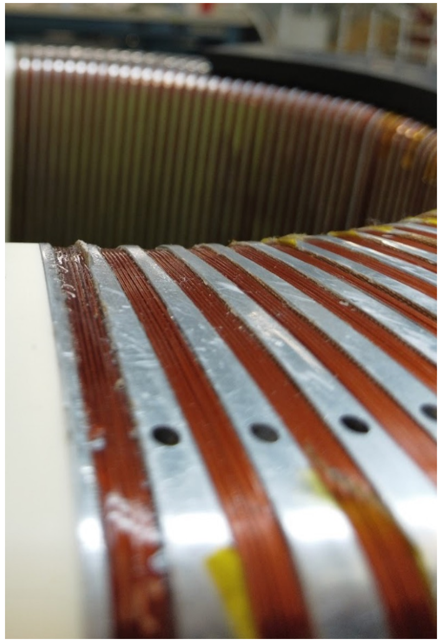
Final tests at SSI Inc.

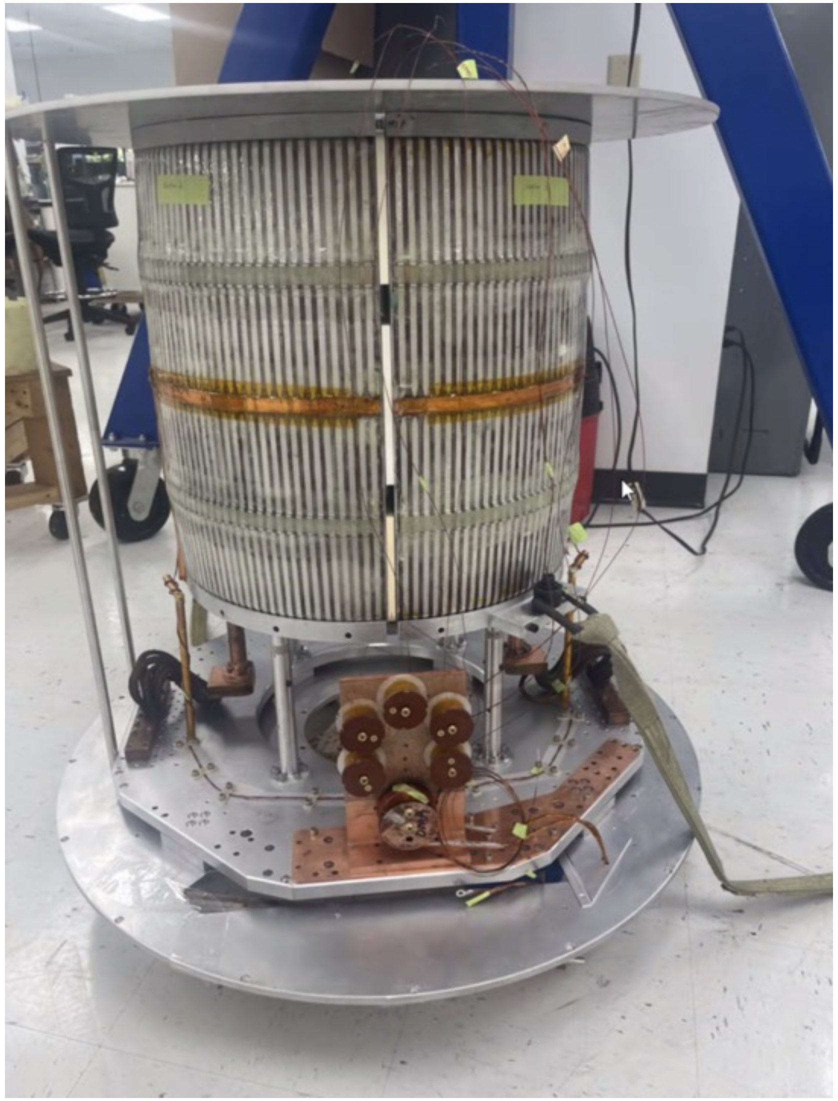
Magnet cooled to 4.5 K, hit 0.9T peak field–vendor working on final validation

Toroidal design -> low-field region in the center of the magnet



Magnet Windings

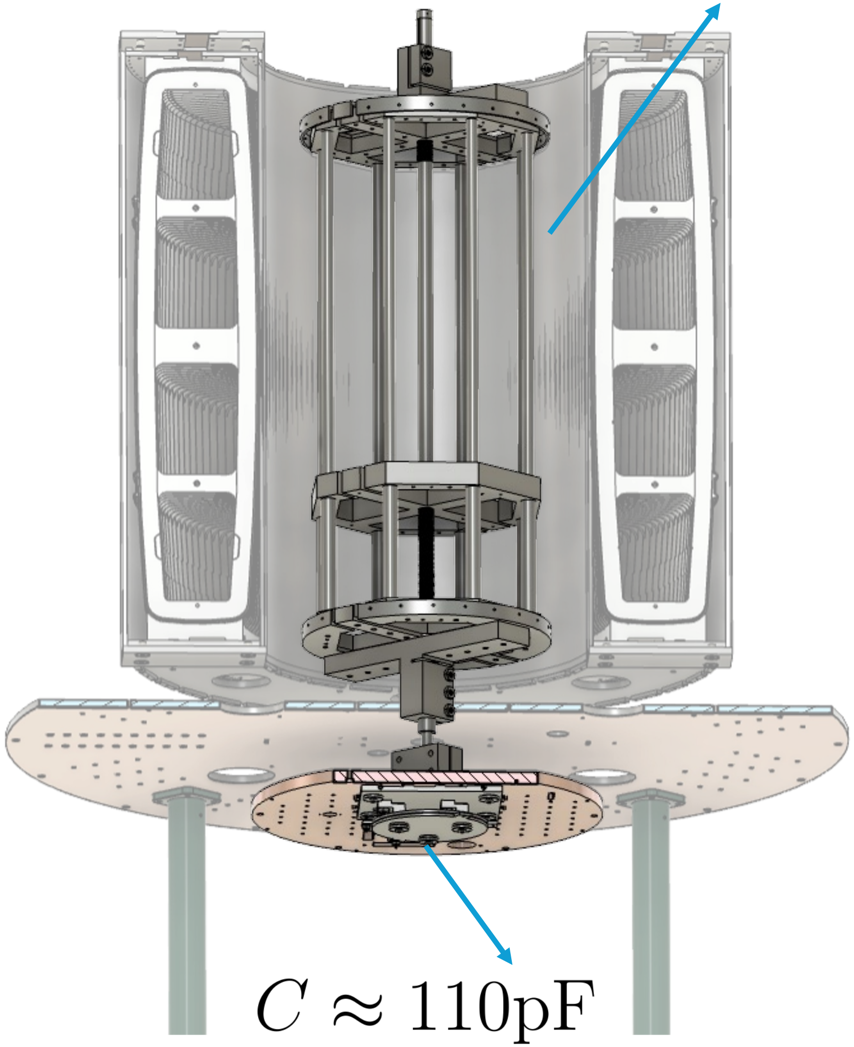




Resonator

Currently being tested at Princeton University

$L \approx 1 - 2\text{mH}$



$C \approx 110\text{pF}$

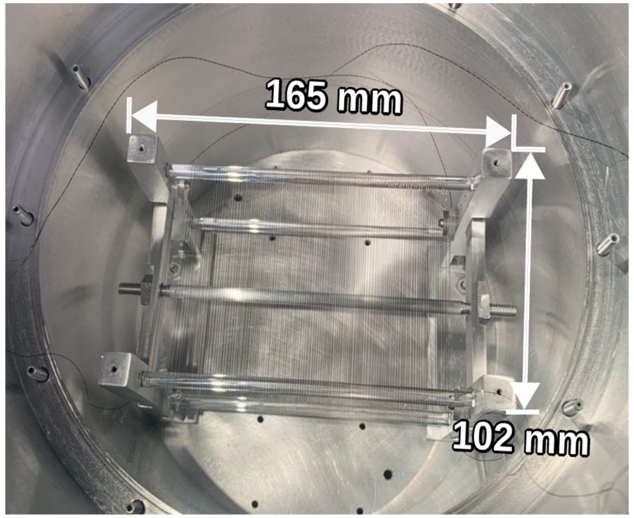
R&D LC resonator achieved:

$$Q = (2.06 \pm 0.02) \times 10^6$$

$$f_0 \approx 250\text{KHz}$$

Rev. Sci. Instrum. 97, 024503 (2026)

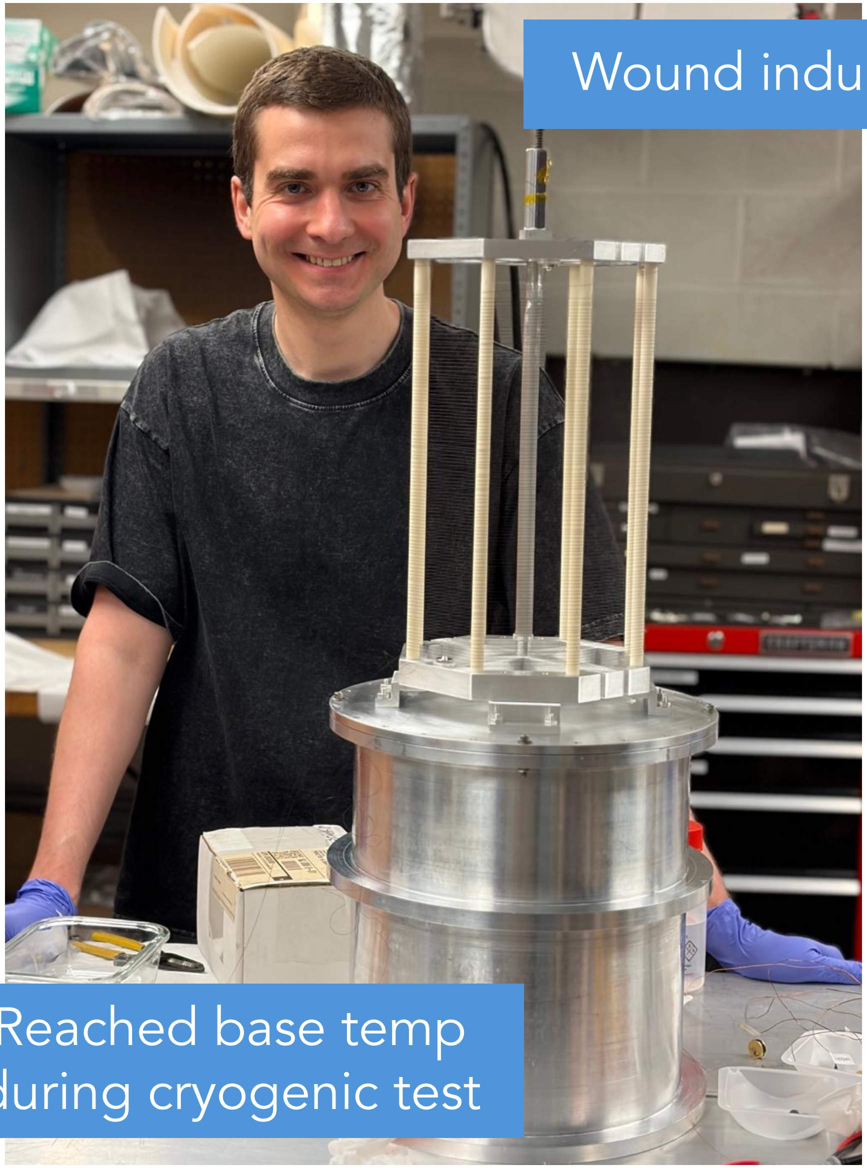
Fixed capacitor



Inductor coil

Resonator

Currently being tested at Princeton University



Wound inductor

Reached base temp during cryogenic test

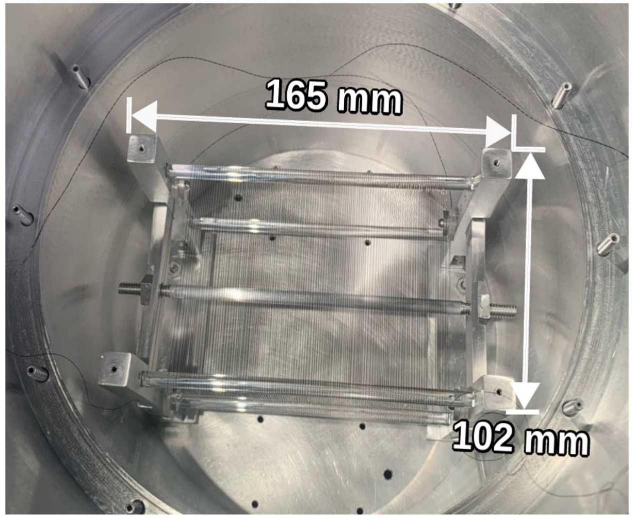
R&D LC resonator achieved:

$$Q = (2.06 \pm 0.02) \times 10^6$$

$$f_0 \approx 250\text{KHz}$$

Rev. Sci. Instrum. 97, 024503 (2026)

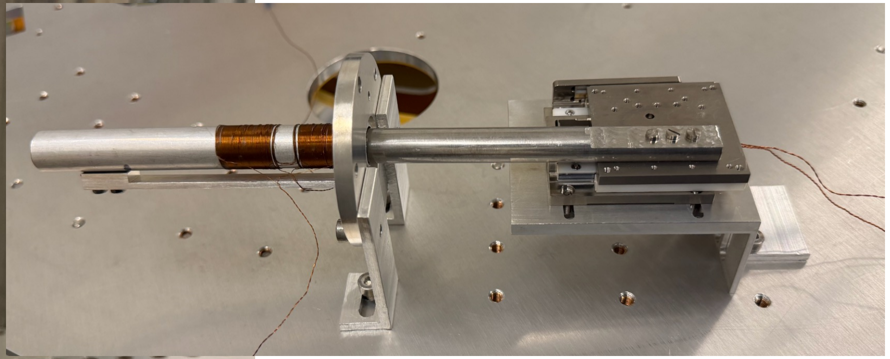
Fixed capacitor



Inductor coil

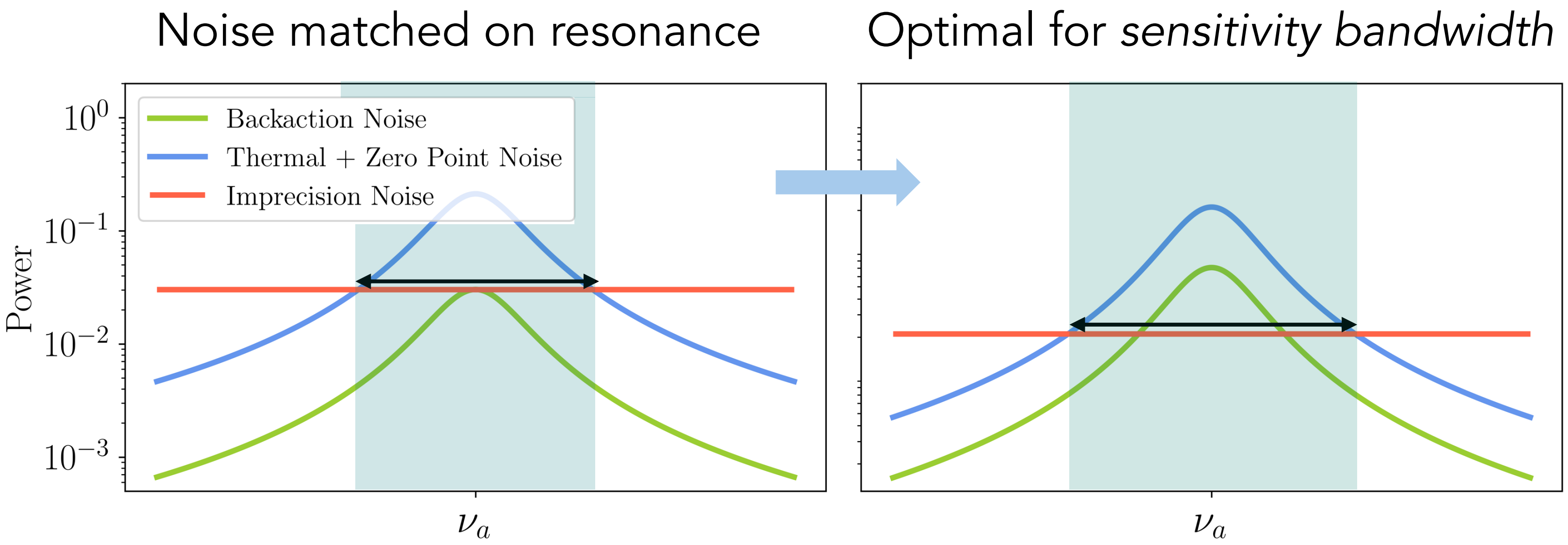
SQUID Readout Development

Using two independent SQUID chains to cross correlate noise



Calibrating a tunable transformer that optimizes scan speed of experiment -> Modulates coupling between resonator & readout chain

Sensitivity Bandwidth

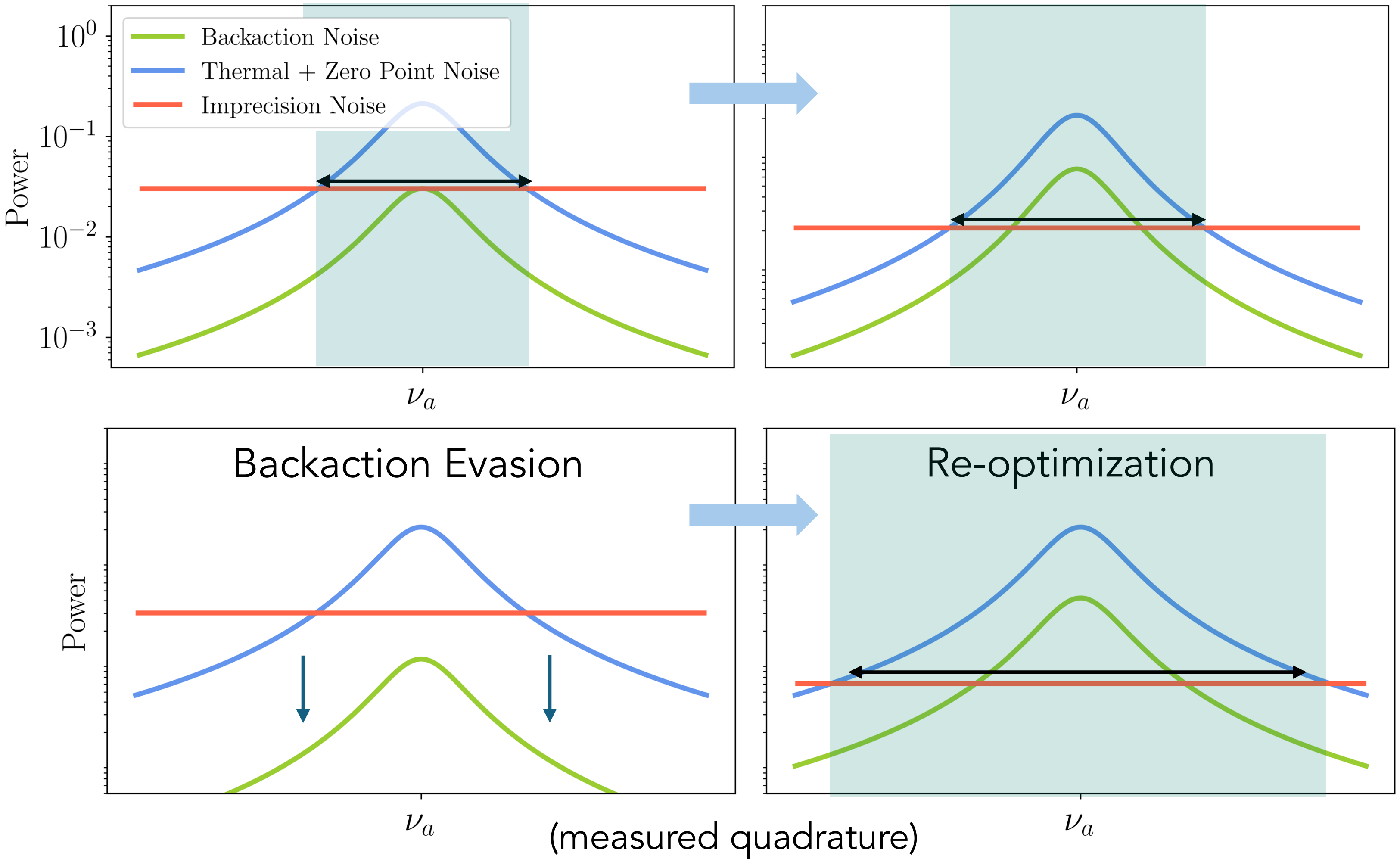


Imprecision noise- white
Backaction – resonator line shape

Relative strength dependent on how strongly the amplifier couples to the resonator

SQL Evading Readout

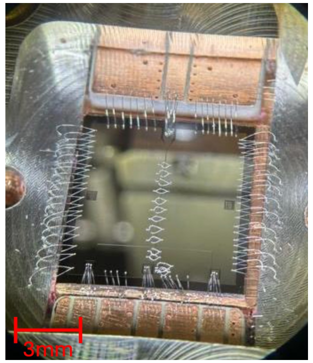
Noise matched on resonance | Optimal for *sensitivity bandwidth*



Imprecision noise- white
Backaction – resonator line shape

Relative strength dependent on how strongly the amplifier couples to the resonator

RQUs enable phase-sensitive amplification that allows us to perform SQL evading techniques

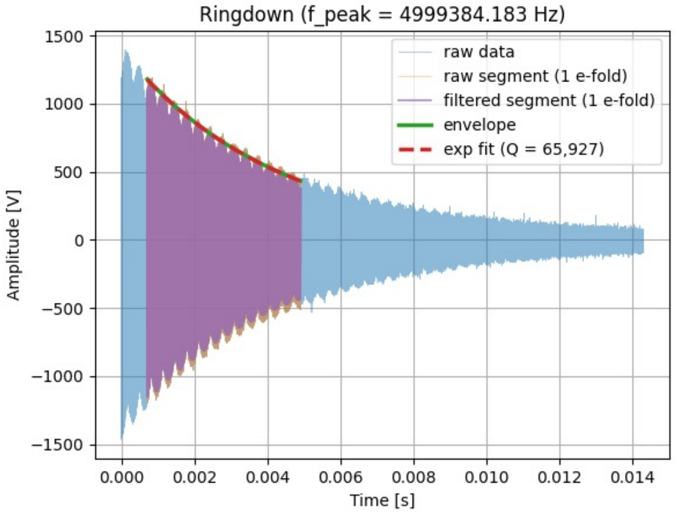


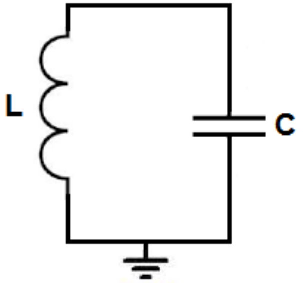
Phys. Rev. Research **7**, 013281

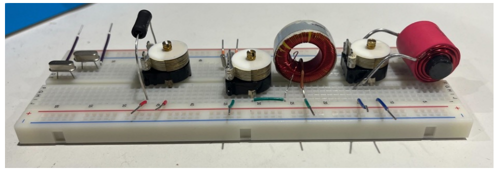
DAQ System

DAQ prepared to preform calibration and science measurements required for a needle search

Ringdown Measurement

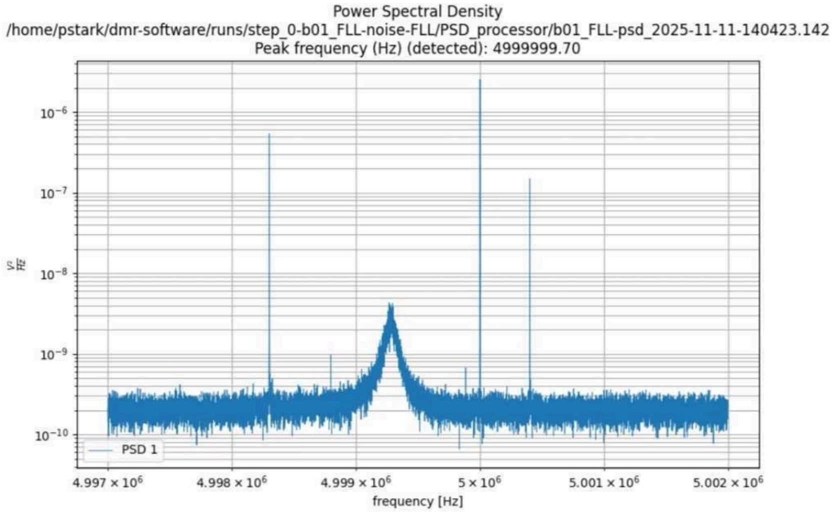




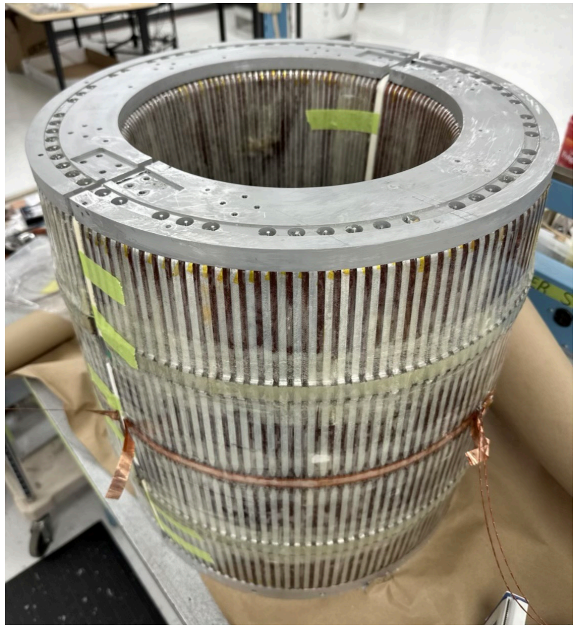


Room temperature testing of a crystal oscillator confirmed DAQ pipeline functionality

Sideband Injection



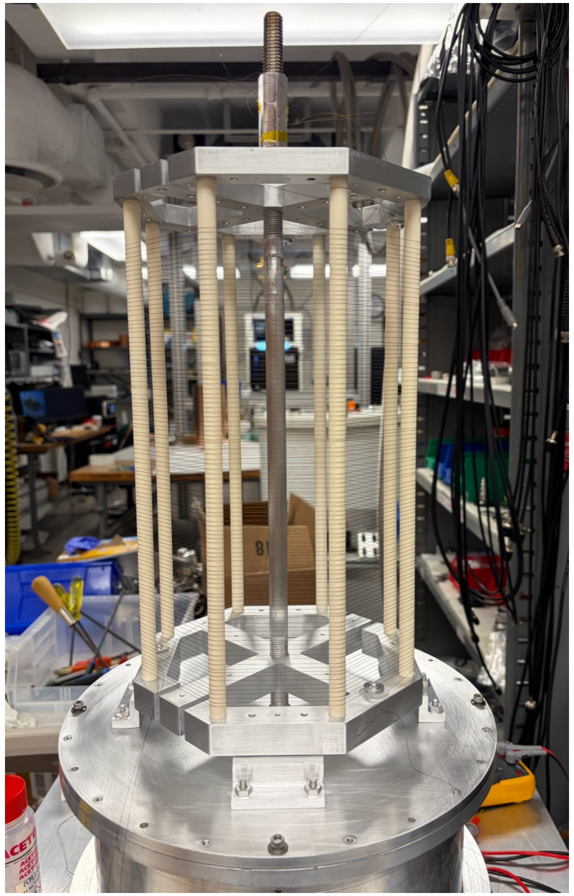
Next Steps



Magnet integration

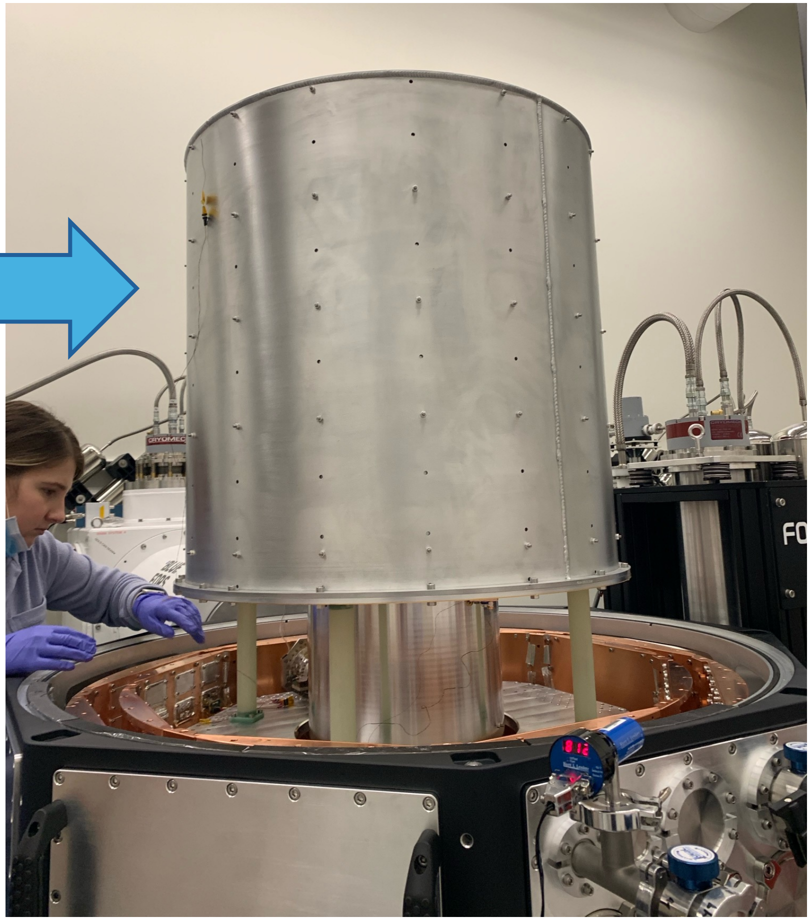
Shipping in ~month

Resonator integration



Preparing for final Princeton cooldown before shipment

First Science Data

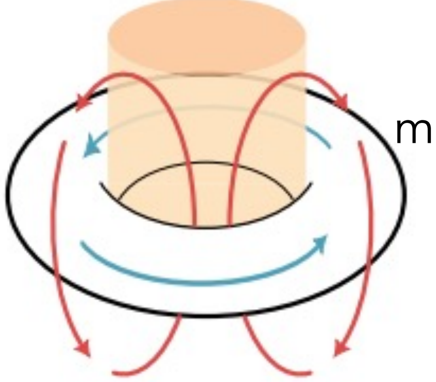


Future Directions

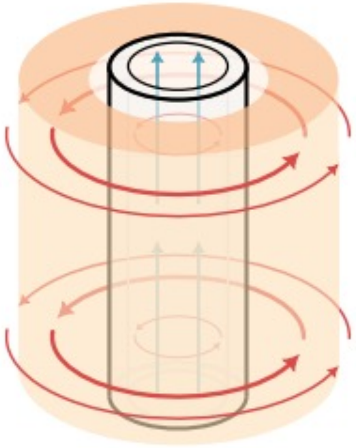
arXiv:2604.16602

Core Geometry

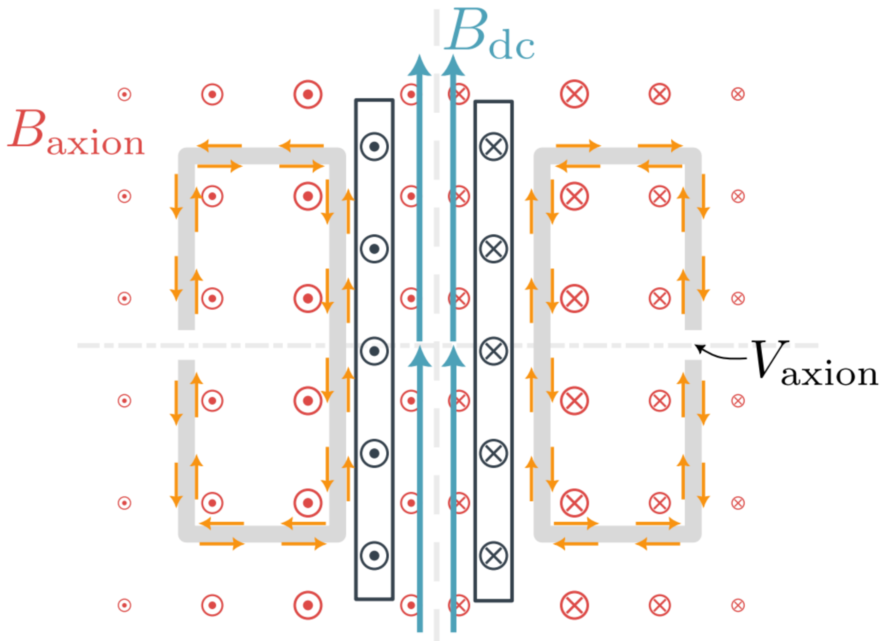
Solenoidal magnet + Superconducting pickup located outside the magnet bore



Toroidal geometry (DMRadio-50L)



CORE geometry

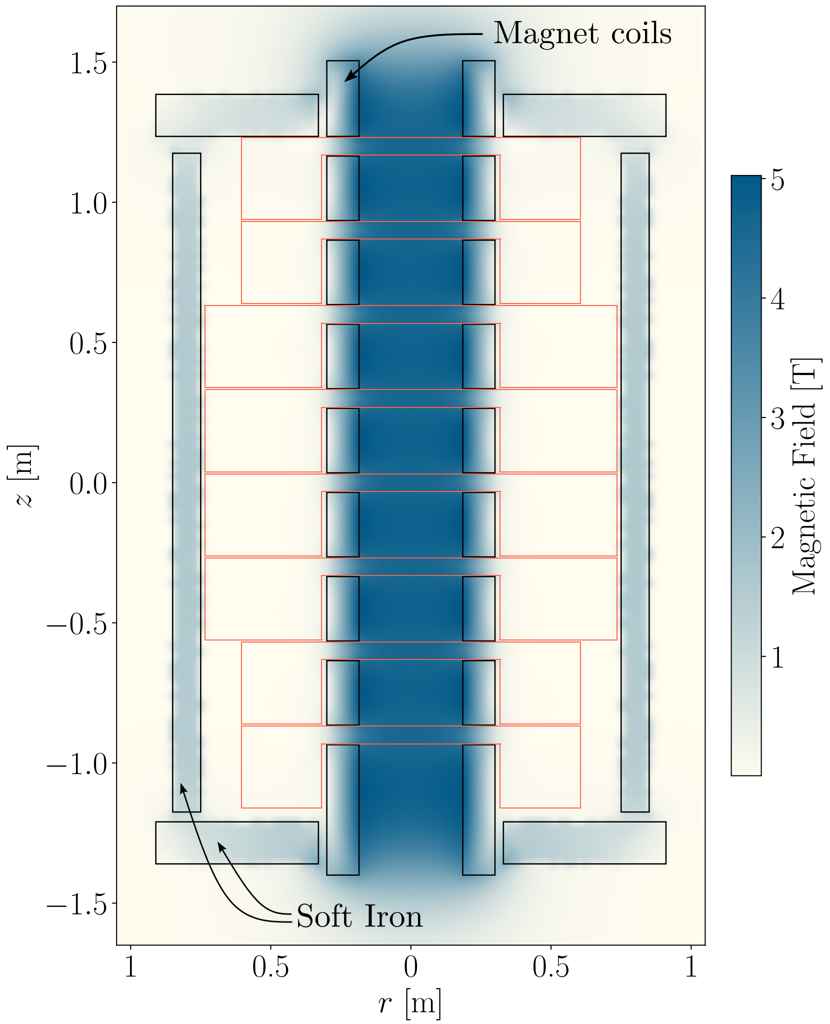


Axion induced magnetic field extends outside the magnet bore

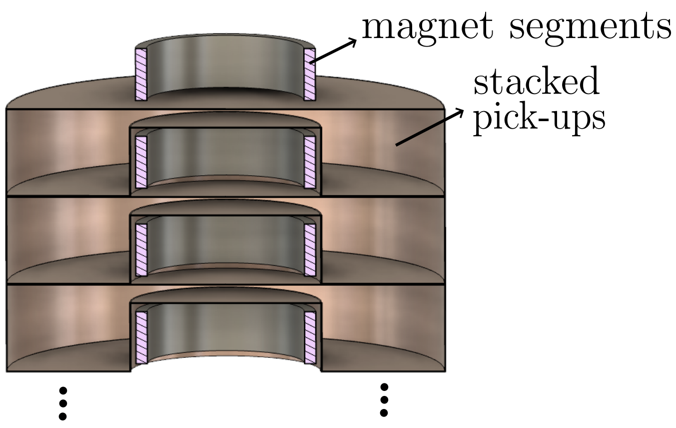
Currently planning DMRadio-Core

Future Directions

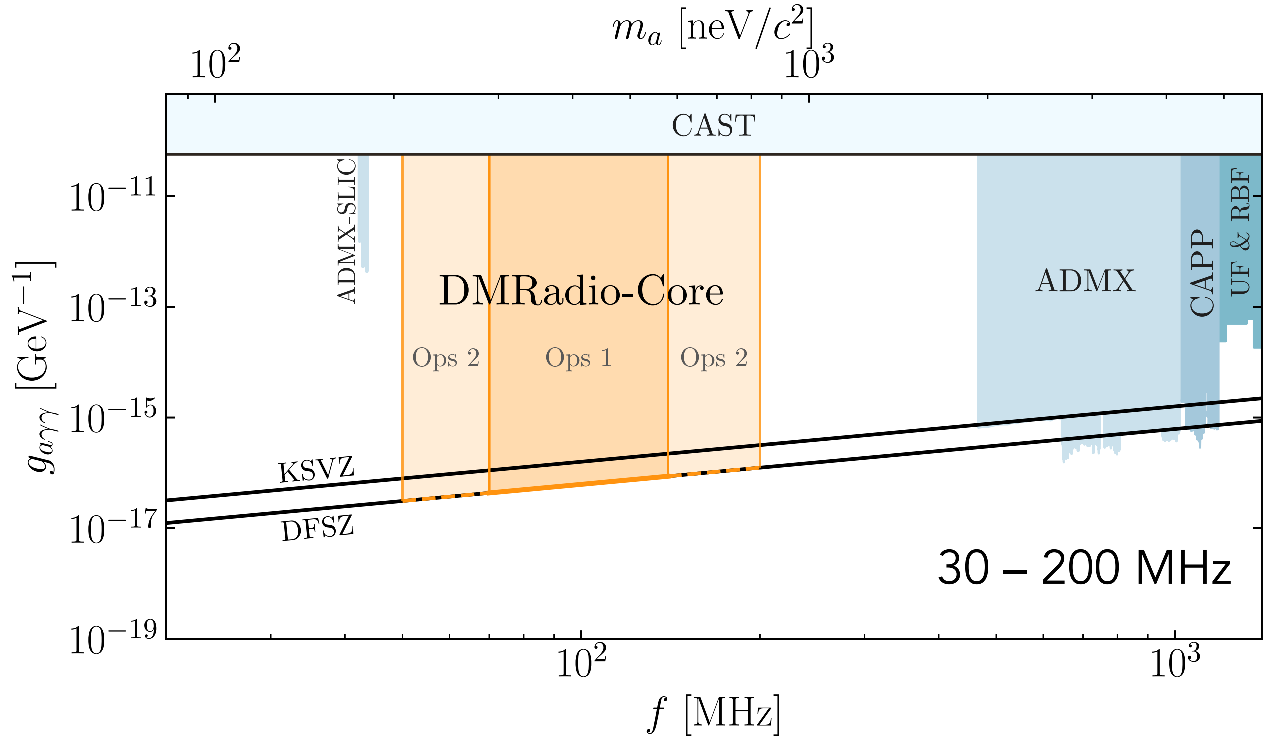
arXiv:2604.16602



5T peak field magnet



Segmented design



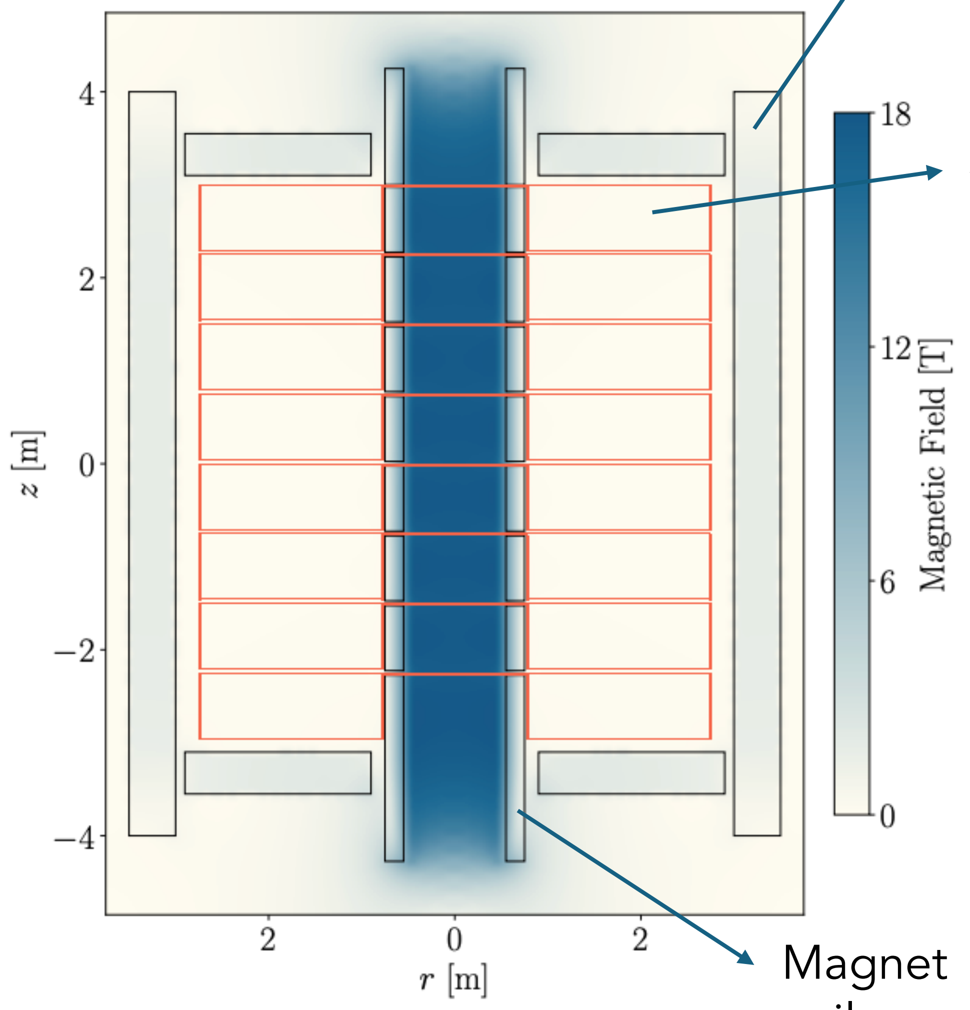
Currently planning DMRadio-Core

Thank you!

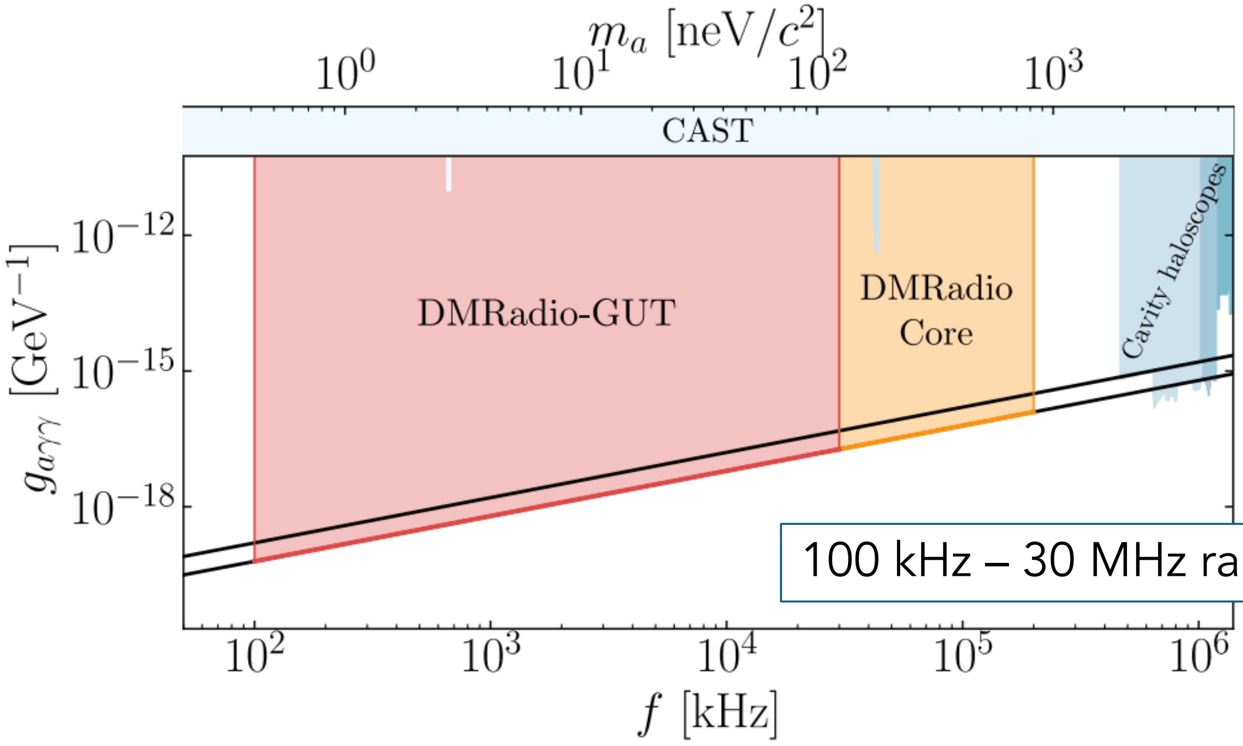
Backup slides

DMRadio-GUT

Core Geometry

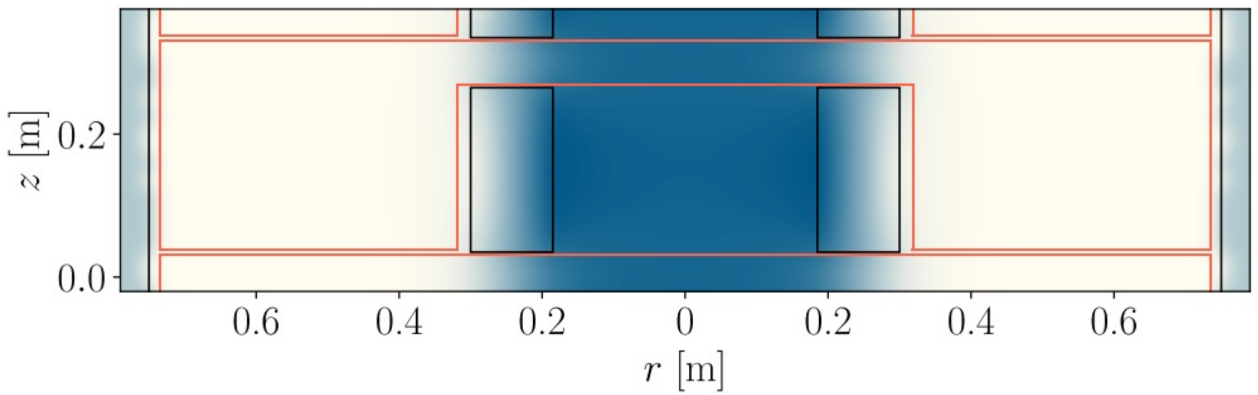


18T magnets, sub-SQL sensors, high Q LC resonators



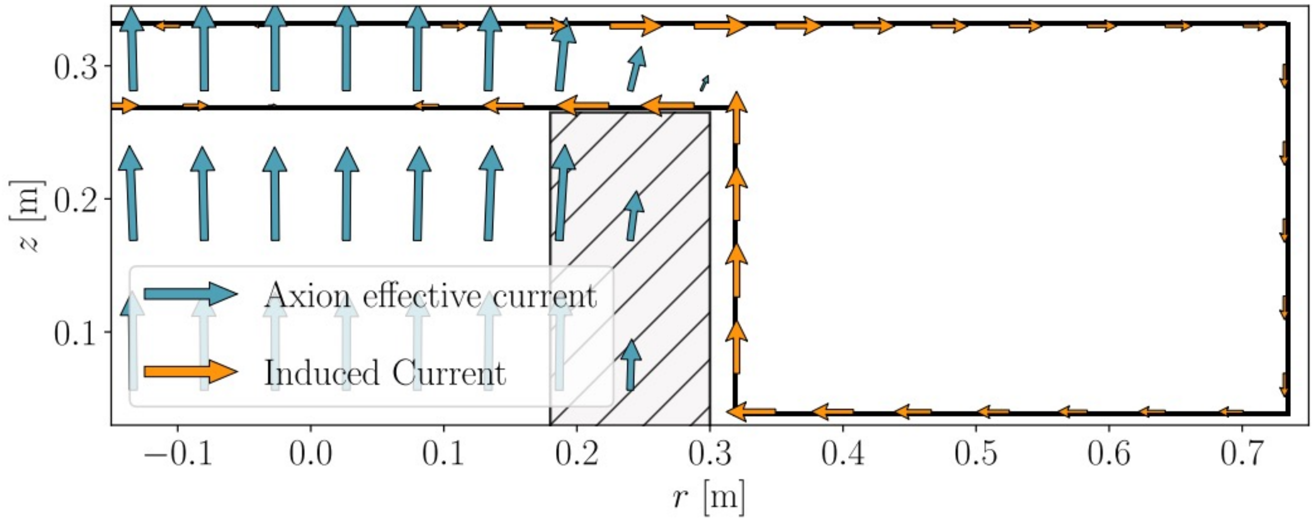
100 kHz – 30 MHz range

arXiv:2604.16602 arXiv:2203.11246



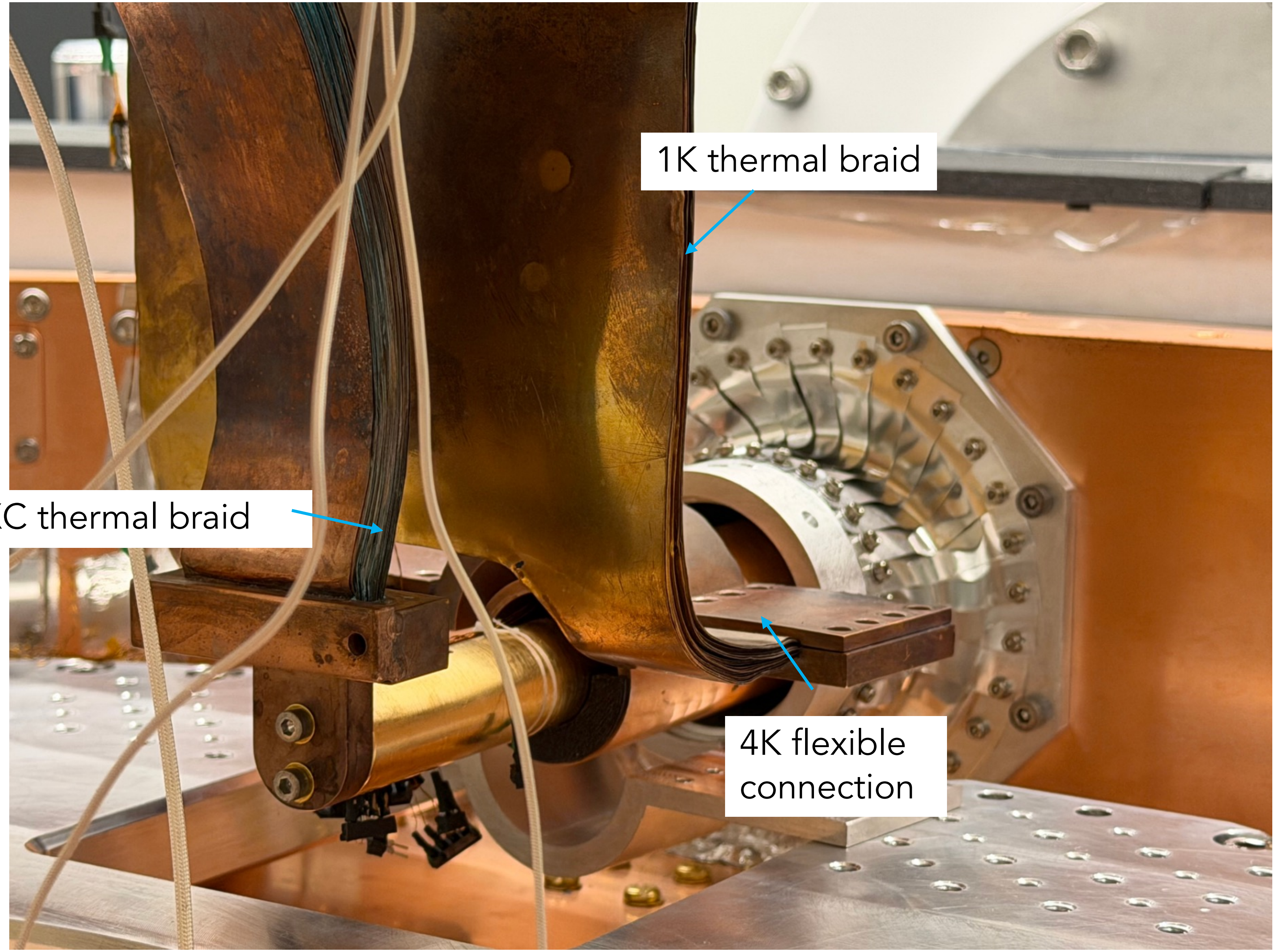
z [m]
0.2
0.0
0.6
0.4
0.2
0
0.2
0.4
0.6
r [m]

(c)



Axion effective current
Induced Current
z [m]
0.3
0.2
0.1
−0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
r [m]

Thermal Braids



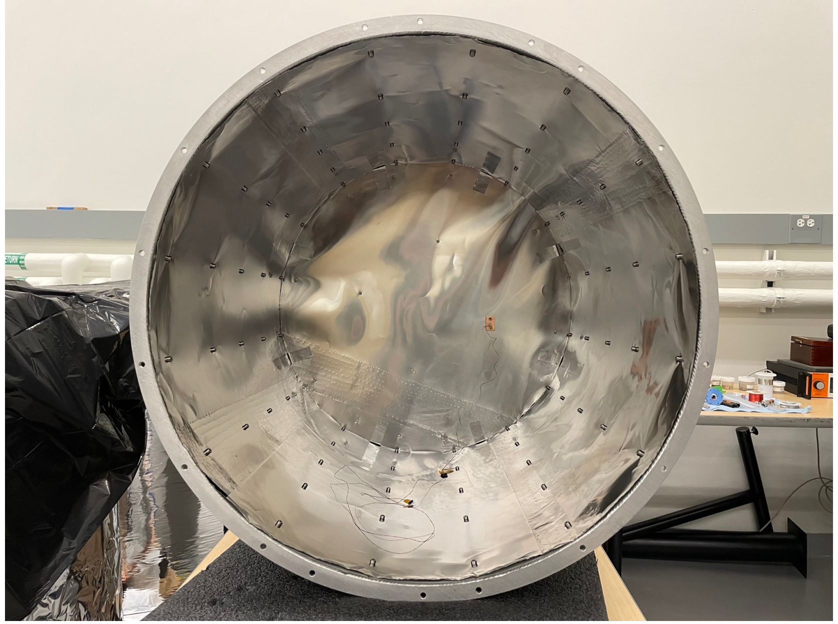
1K Space

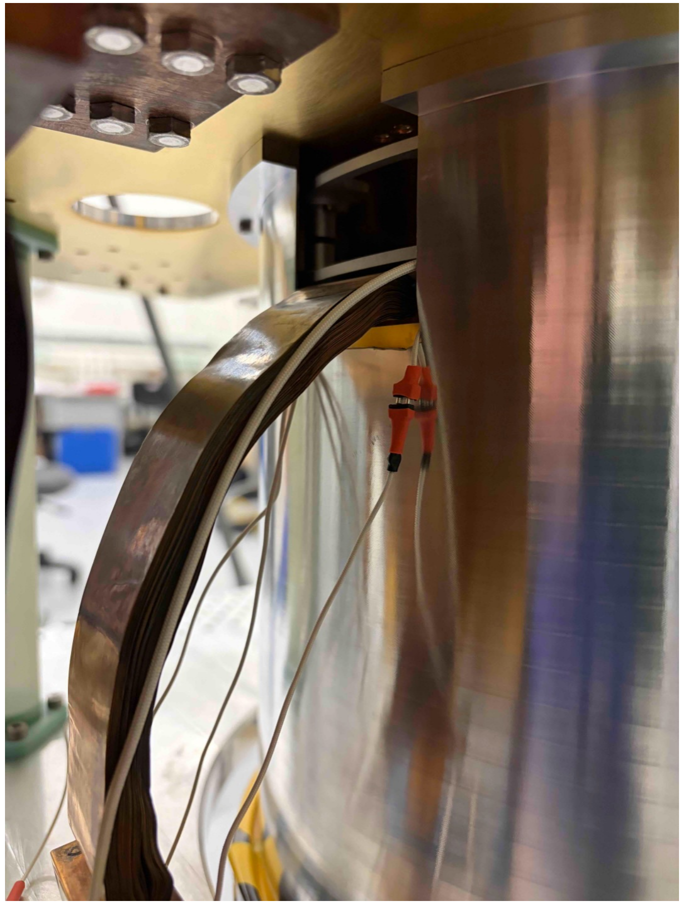
Currently operating at 700mK

Superconducting 1K shield surrounds the resonator to protect Q

Supported from 4K by 4x G10 standoffs

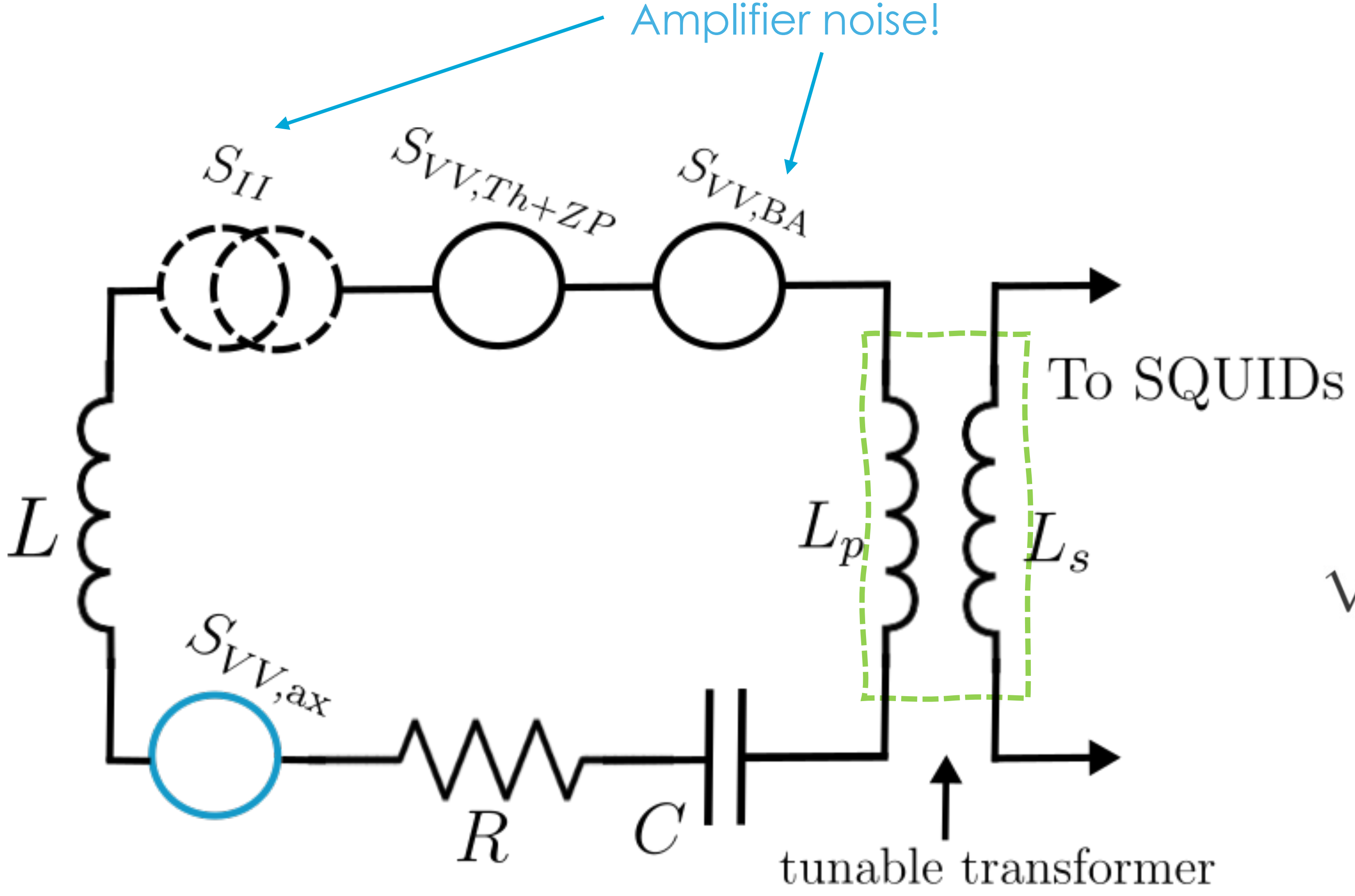
Inside of the shield lined with spotwelded Nb foil





Tunable Transformer

Imprecision noise- white
Backaction – resonator line shape



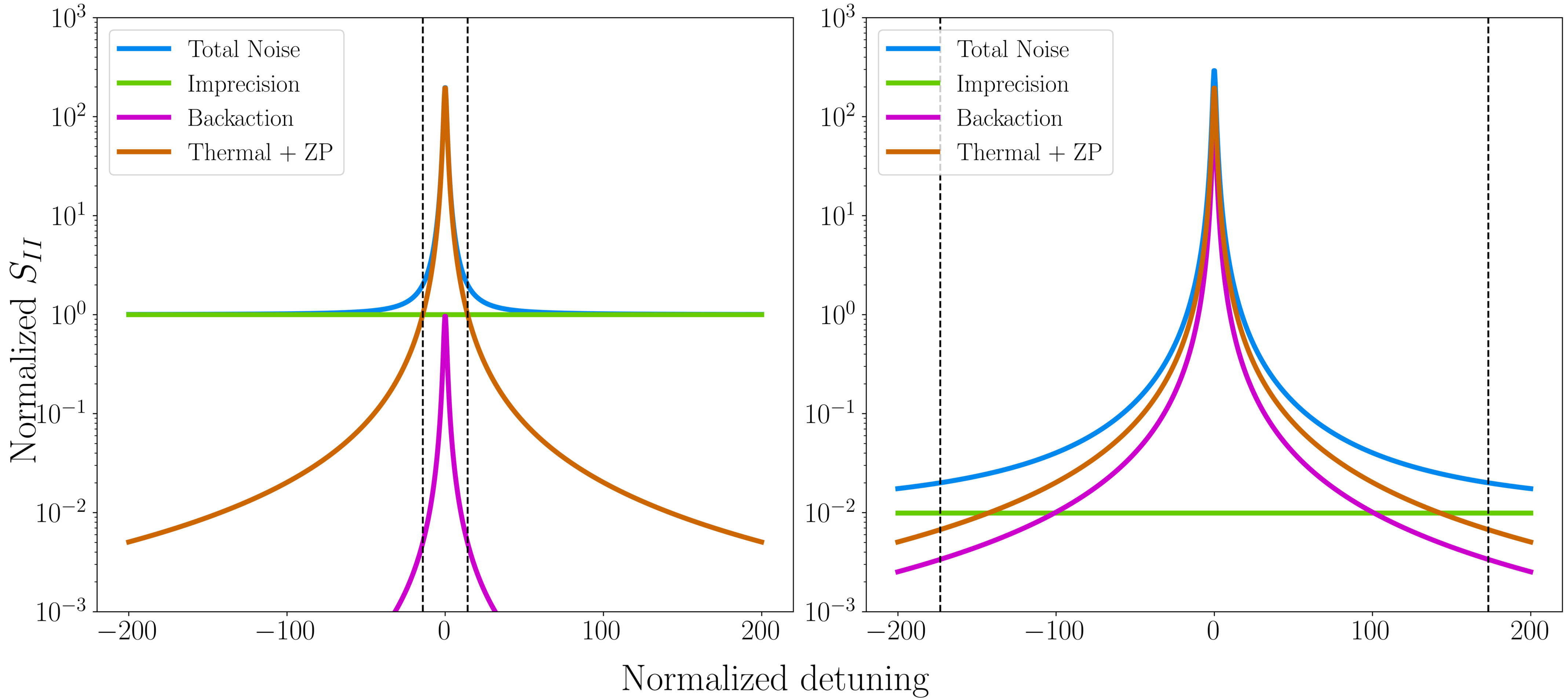
Noise sources are inversely proportional

$$\sqrt{S_{VV,\mathrm{BA}} S_{II,\mathrm{Imp}}} \geq \hbar\omega/2$$

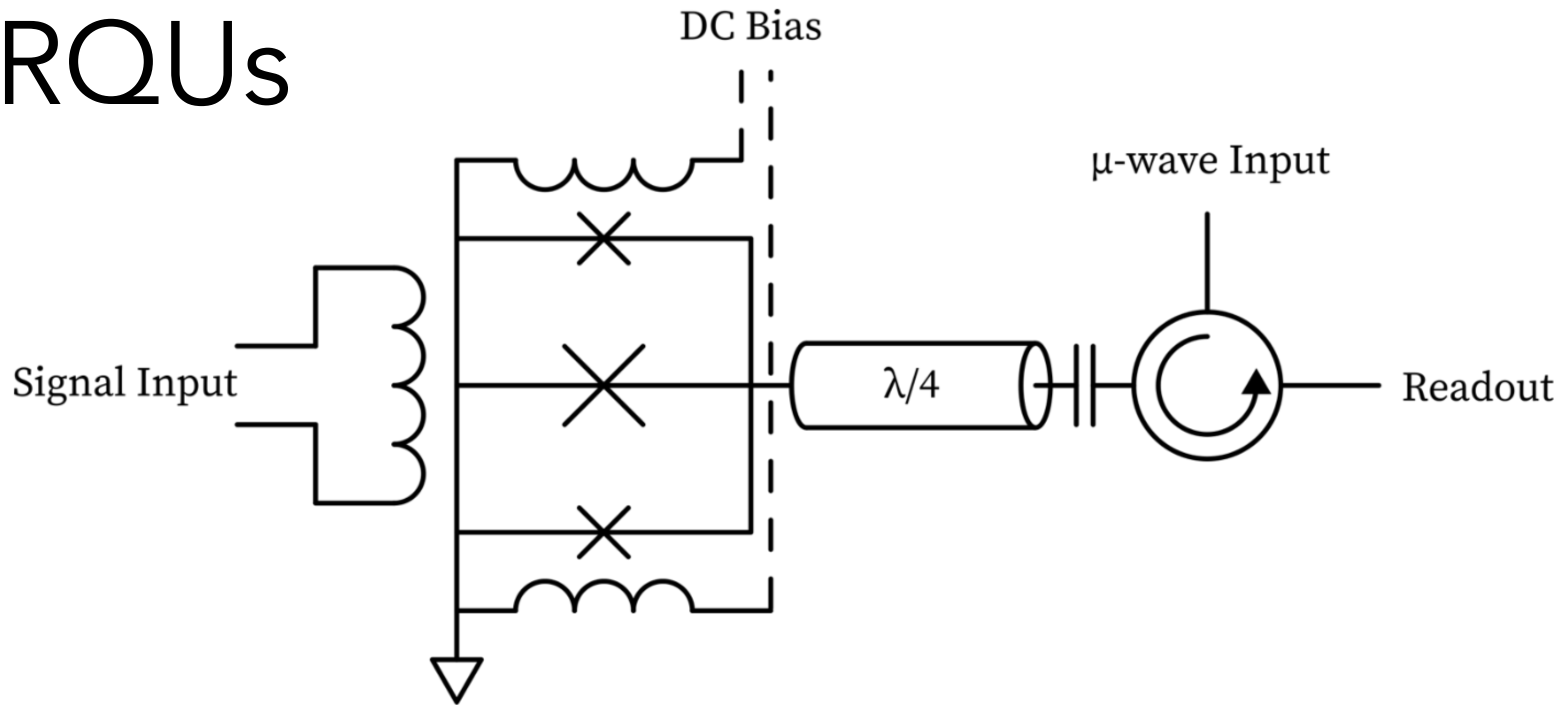
Optimizing scan rate

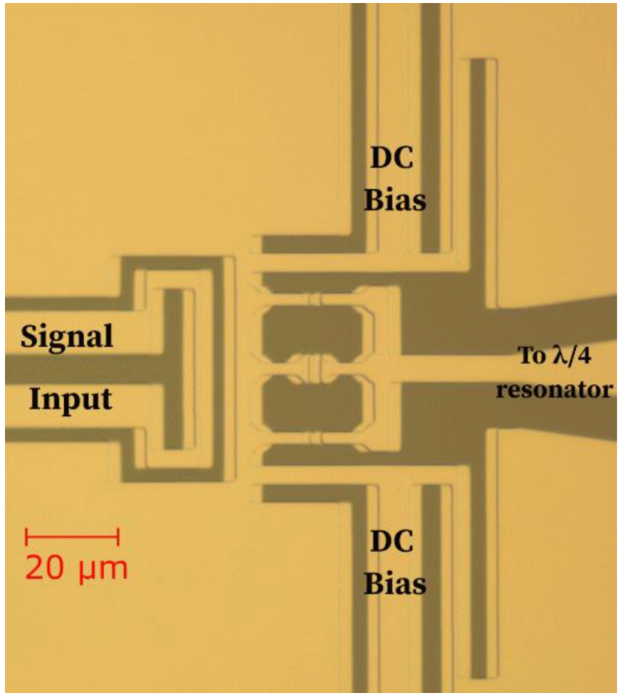
Integrated sensitivity over a wide range of axion masses

Sensitivity bandwidth is the frequency range over which SNR is approximately undegraded



RQUs





- Flux from the signal input tunes the inductance of the josephson junction interferometer -> modulates the electrical length of microwave resonator

- Low frequency input signal is upconverted and rides as sidebands on microwave tone