The Dark Matter Radio Suite of Experiments

18th Patras Workshop on Axions, WIMPs, and WISPs in Rijeka, Croatia

July 6, 2023

Dale Li on behalf of the DMRadio Collaboration

SLAC NATIONAL ACCELERATOR LABORATORY
MIT
Stanford University
Berkeley UNIVERSITY OF CALIFORNIA
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
CAL STATE EAST BAY
PRINCETON UNIVERSITY
BERKELEY LAB
SANTA CLARA UNIVERSITY 1851
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN
TUNL TRIANGLE UNIVERSITIES NUCLEAR LABORATORY
GORDON AND BETTY MOORE FOUNDATION
NSF
U.S. DEPARTMENT OF ENERGY Office of Science
HEISING-SIMONS FOUNDATION

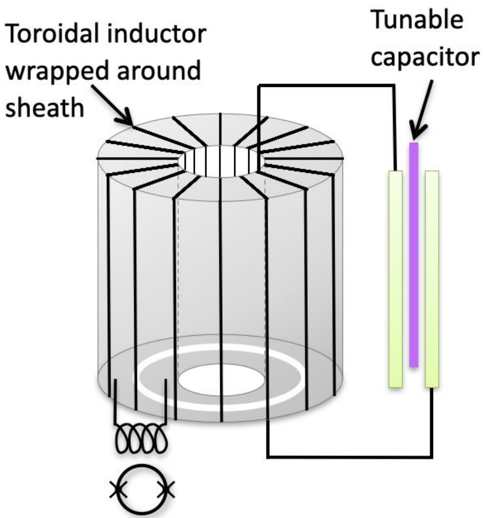
Outline

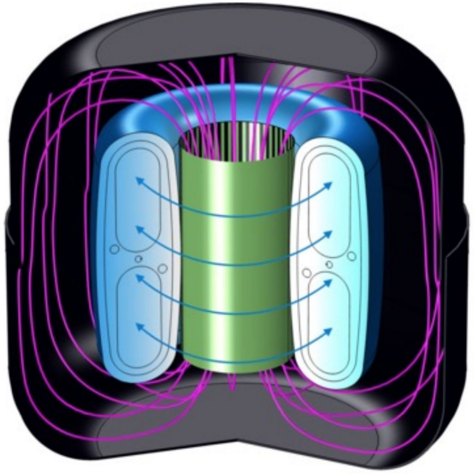
- History
- Collaboration
- DMRadio Science Reaches
- 50L and m^3 Design Concepts
- DMRadio-m^3 Design Details
- Summary and Expected Schedule

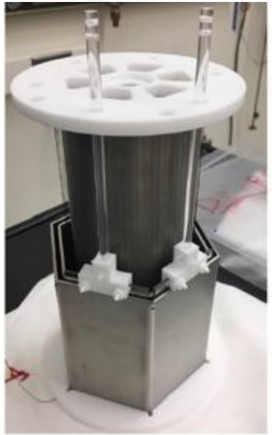
DMRadio Lineage

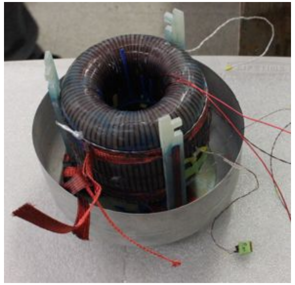
DMRadio-Pathfinder

ABRA-10cm









DMRadio Collaboration

H.M. Cho, W. Craddock, D. Li, W. J. Wisniewski
SLAC National Accelerator Laboratory

J. Corbin, C. S. Dawson, P. W. Graham, K. D. Irwin, F. Kadribasic, S. Kuenstner, N. M. Rapidis, M. Simanovskaia, J. Singh, E. C. van Assendelft, K. Wells
Department of Physics, Stanford University

A. Droster, A. Keller, A. F. Leder, K. van Bibber
Department of Nuclear Engineering, University of California Berkeley

S. Chaudhuri, R. Kolevatov
Department of Physics, Princeton University

L. Brouwer
Accelerator Technology and Applied Physics Division
Lawrence Berkeley National Lab

J. W. Foster, J. T. Fry, J. L. Ouellet, K. M. W. Pappas, C. P. Salemi, **L. Winslow**
Laboratory of Nuclear Science, Massachusetts Institute of Technology

R. Henning
Department of Physics, University of North Carolina Chapel Hill
Triangle Universities Nuclear Laboratory

Y. Kahn
Department of Physics, University of Illinois at Urbana-Champaign

A. Phipps
California State University, East Bay

B. R. Safdi
Department of Physics, University of California Berkeley

B. A. Young
Department of Physics, Santa Clara University

DMRadio Science Goals

DMRadio-50L (Maria's talk yesterday)

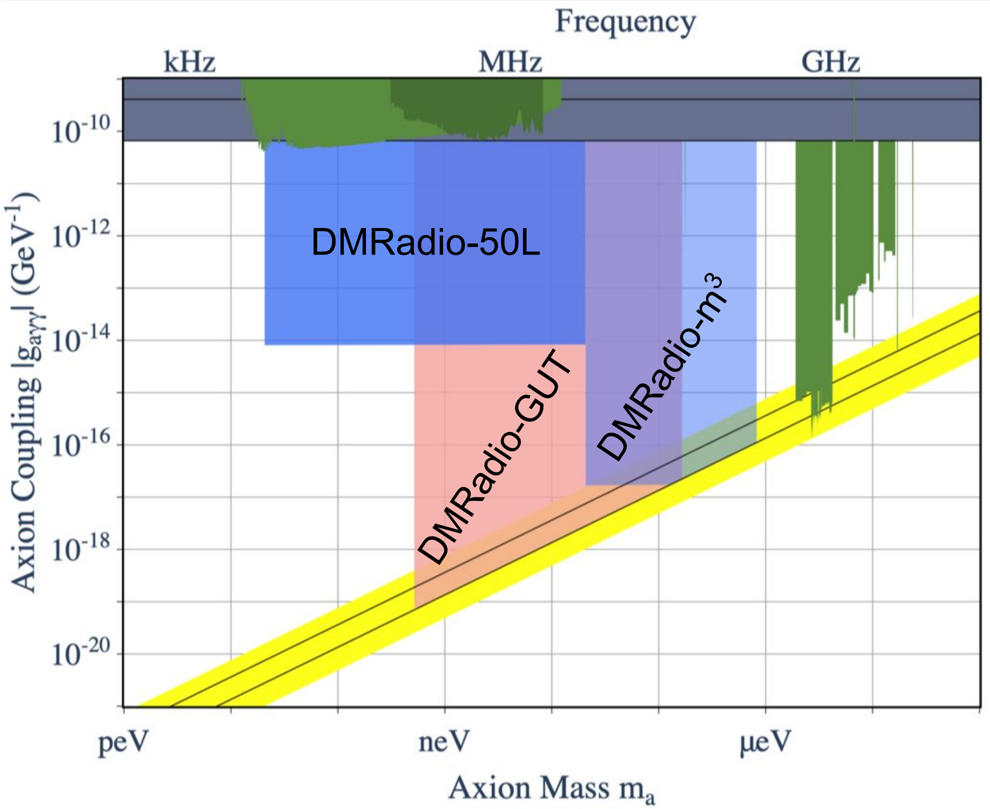
- 5 kHz - 5 MHz
- Quantum sensor testbed

DMRadio-m^3 (arXiv:2204.13781)

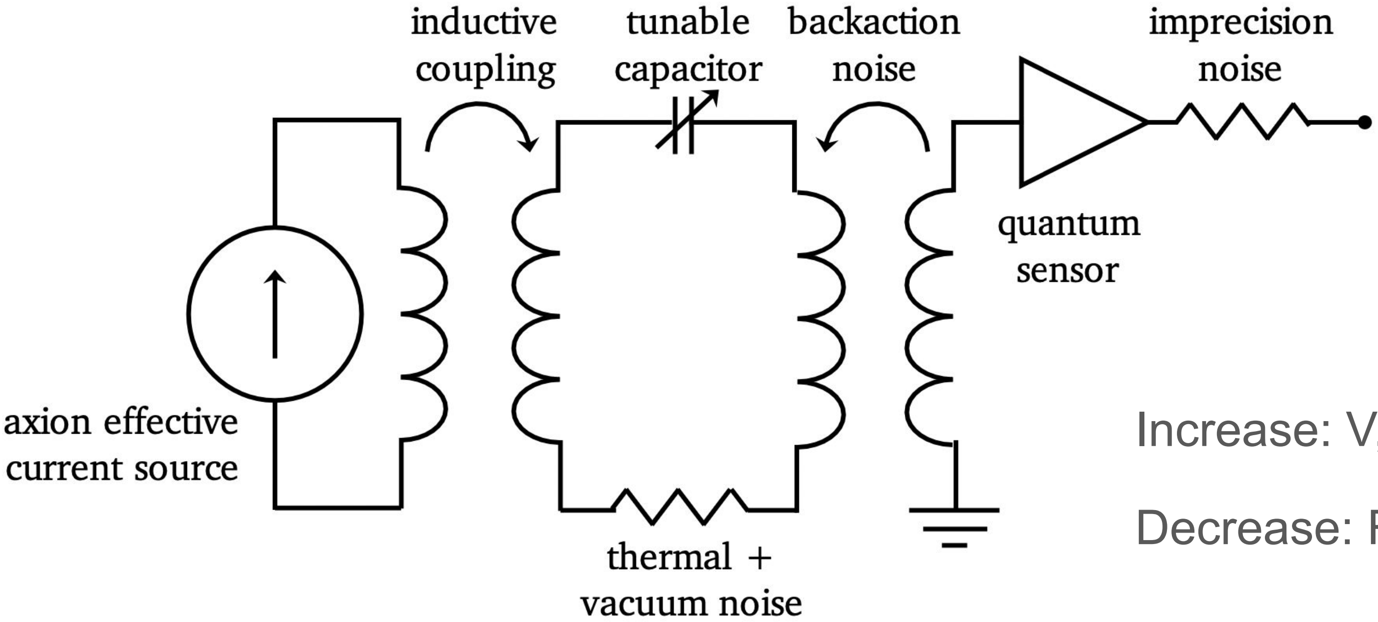
- Primary goal:
  - DFSZ 30 MHz - 200 MHz
- Secondary goals:
  - KSVZ down to 10 MHz
  - QCD axion band to 5 MHz
- Funding: DOE DMNI

DMRadio-GUT (arXiv:2203.11246)

- DFSZ 100 kHz - 30 MHz
- Next-generation detector



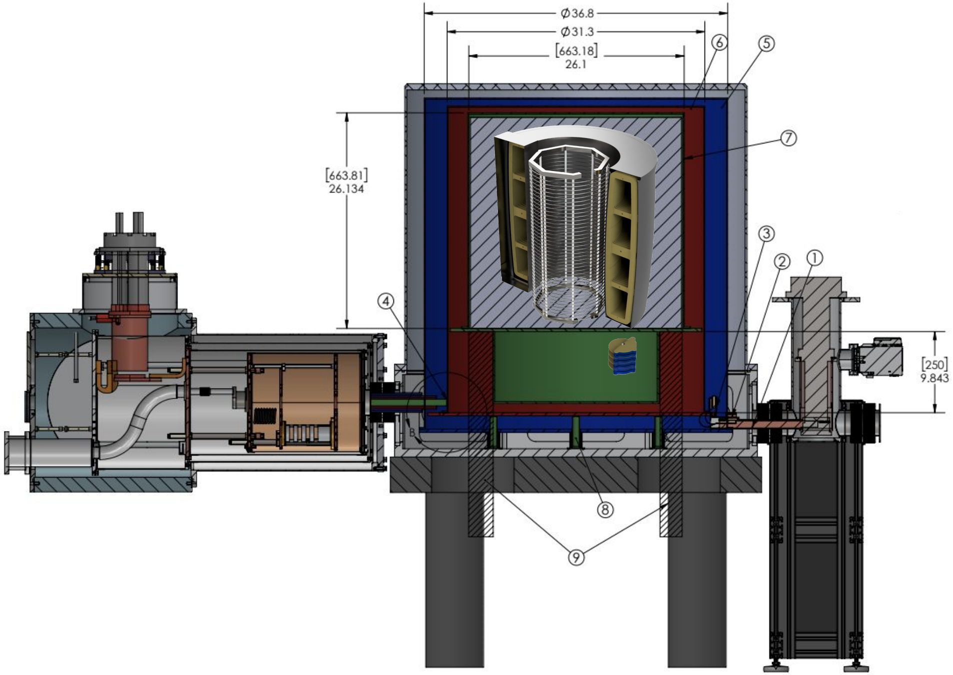
DMRadio is a Resonant Search

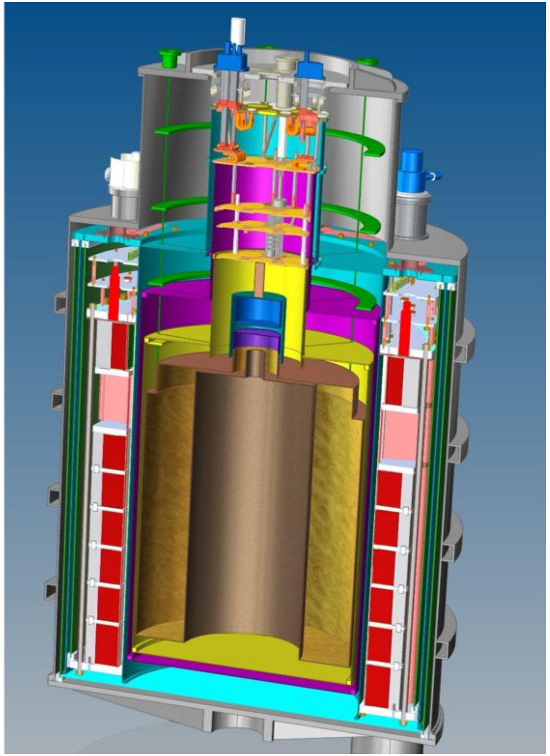


Increase: V, B, Q

Decrease: R, T, Imp, BA

Current Experiments DMRadio-50L and DMRadio-m^3

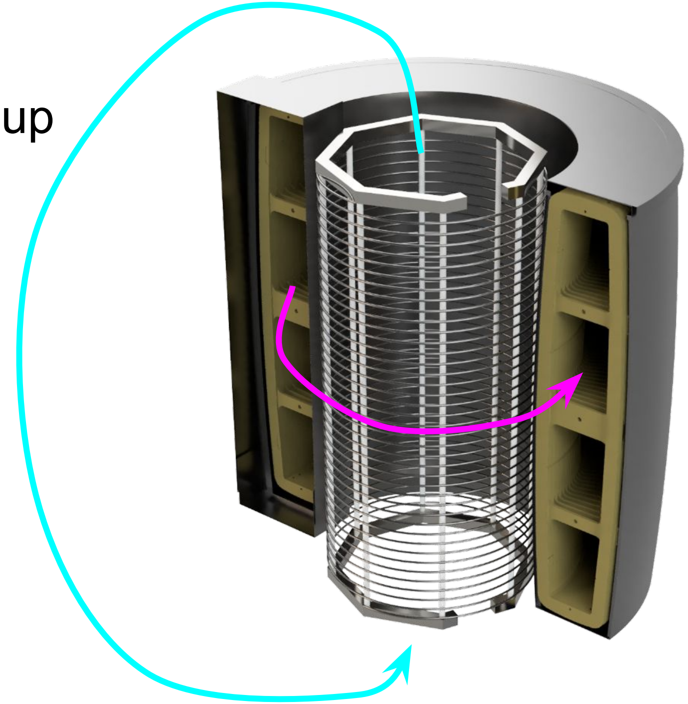




DMRadio-50L Converts a Cylindrical J_{eff} to Toroidal Flux

Toroidal magnet sets up J_{eff} direction

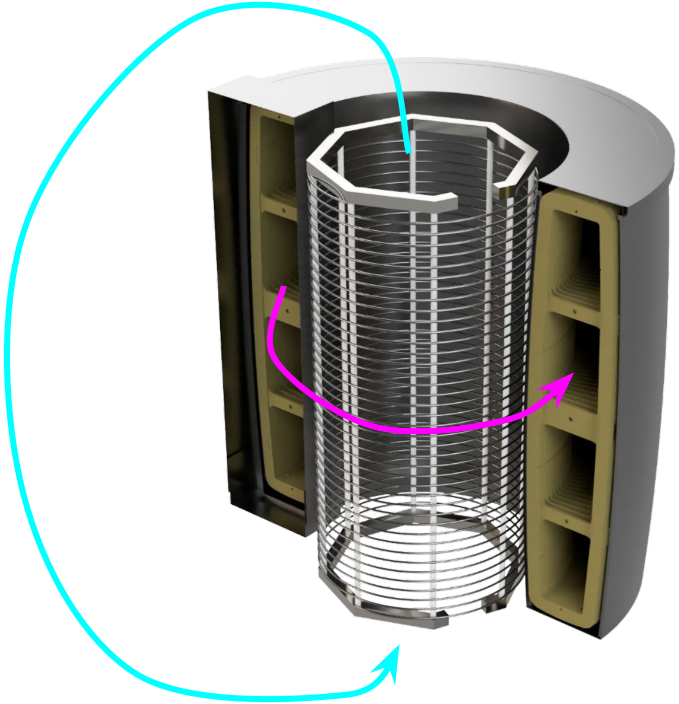
Sheath converts J_{eff} to flux

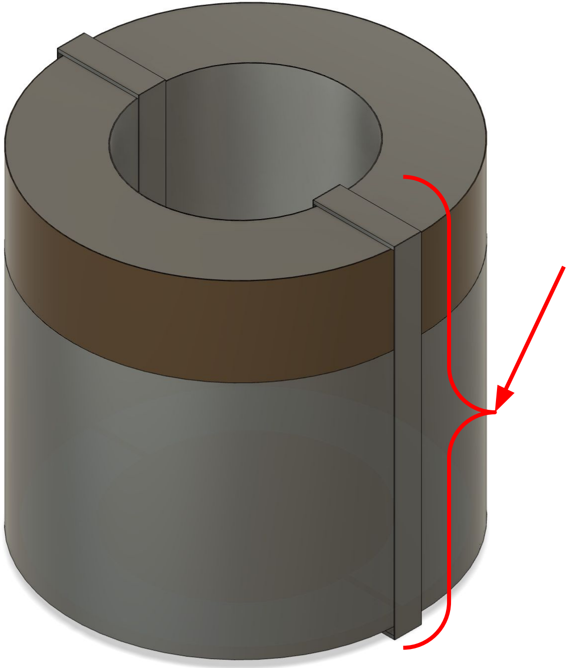


Flux is picked up by LC resonator

Resonator is read out by a SQUID amplifier

DMRadio-m^3 Needs a Different Geometry





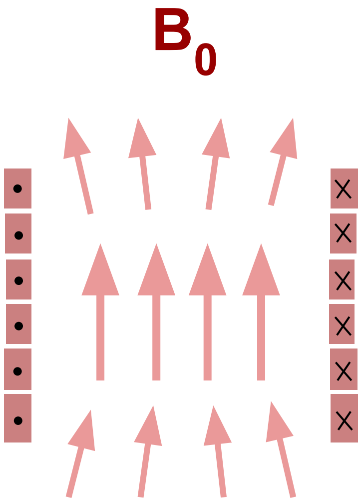
Long vertical Slit creates a parasitic capacitance

Sheath inductance and C_{par} has a resonant feature in the science band for 1 m^3

DMRadio-m^3 with a Solenoidal Magnet

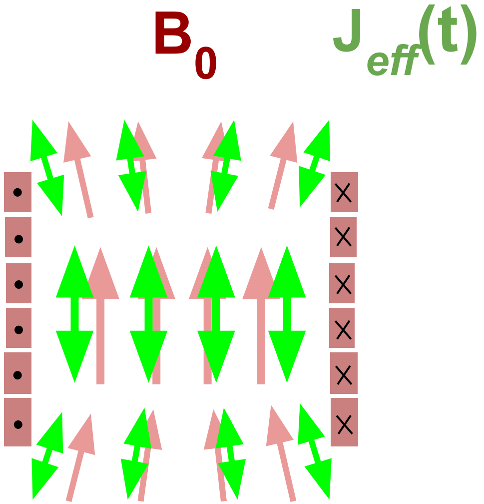
DMRadio-m^3 with a Solenoidal Magnet

- Solenoidal Magnet gives B in z-direction (lots of stray fields)



DMRadio-m^3 with a Solenoidal Magnet

- Solenoidal Magnet gives B in z-direction (lots of stray fields)
- Axions and B_0 couples to time-varying J_{eff}



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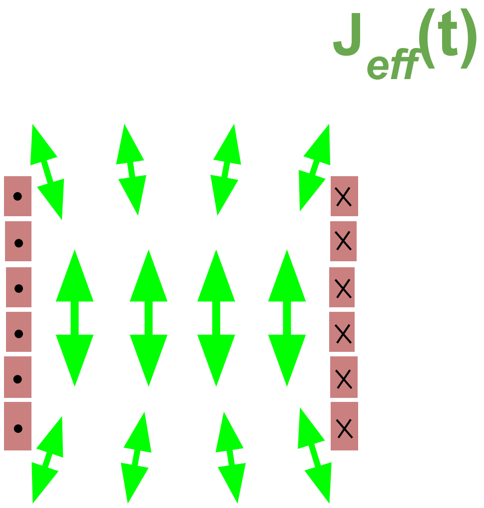

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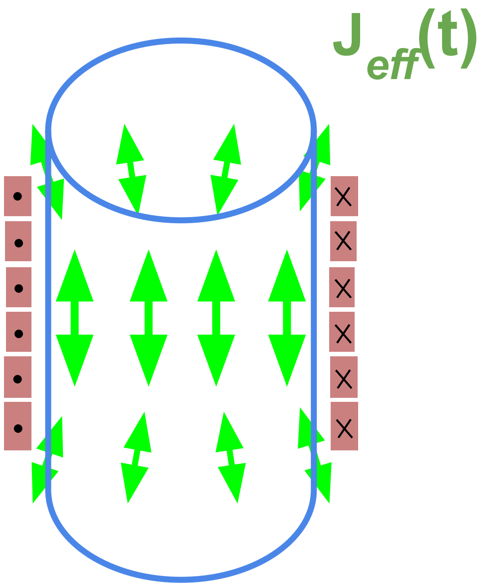
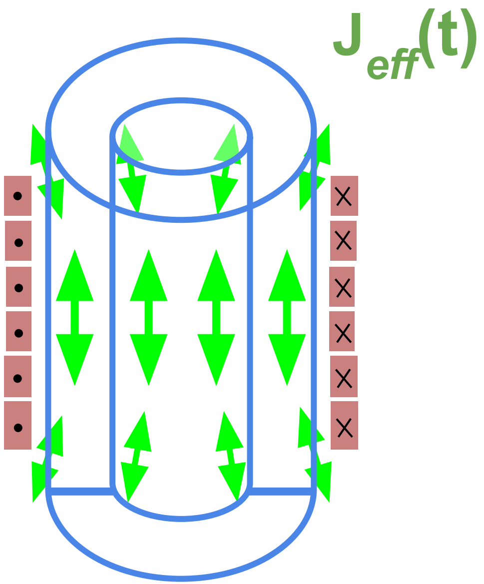


- Hard to build a cavity at these frequencies (Compton wavelength)

DMRadio-m³ with a Solenoidal Magnet

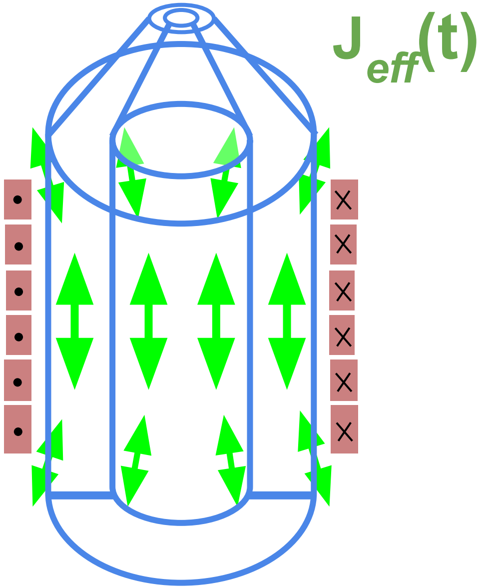
- Solenoidal Magnet gives B in z-direction (lots of stray fields)
- Axions and B_0 couples to time-varying J_{eff}



- Hard to build a cavity at these frequencies (Compton wavelength)
- Use a coaxial cylinder to inductively pickup flux induced by J_{eff}

DMRadio-m^3 with a Solenoidal Magnet

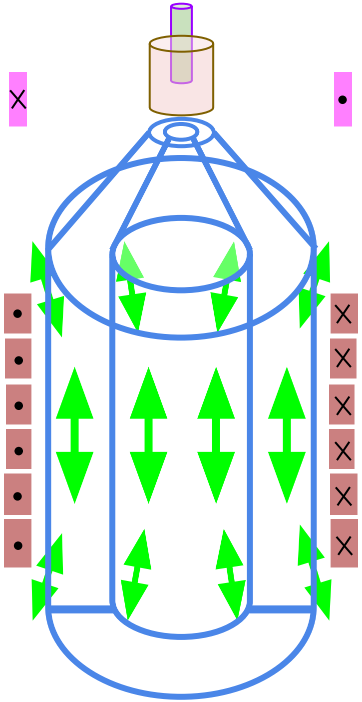
- Solenoidal Magnet gives B in z-direction (lots of stray fields)
- Axions and B_0 couples to time-varying J_{eff}



- Hard to build a cavity at these frequencies (Compton wavelength)
- Use a coaxial cylinder to inductively pickup flux induced by J_{eff}
- Taper down out of high field region

DMRadio-m^3 with a Solenoidal Magnet

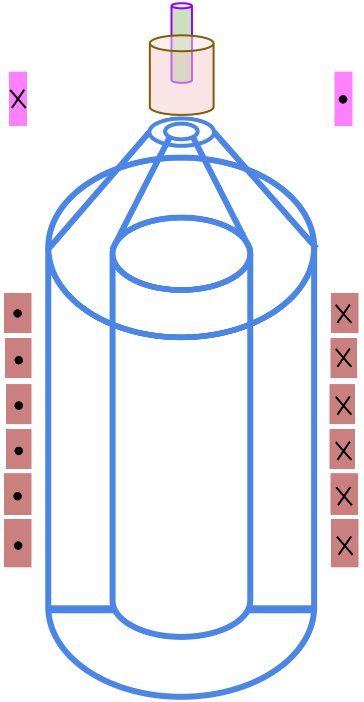
- Solenoidal Magnet gives B in z-direction (lots of stray fields)
- Axions and B_0 couples to time-varying J_{eff}



- Hard to build a cavity at these frequencies (Compton wavelength)
- Use a coaxial cylinder to inductively pickup flux induced by J_{eff}
- Taper down out of high field region
- Add tuning element and SQUID Readout
- Add Bucking coils

DMRadio-m^3 with a Solenoidal Magnet

- Solenoidal Magnet gives B in z-direction (lots of stray fields)
- Axions and B_0 couples to time-varying J_{eff}



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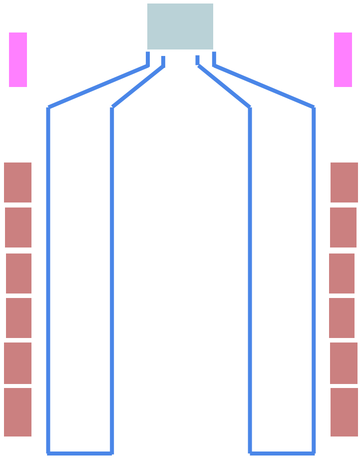
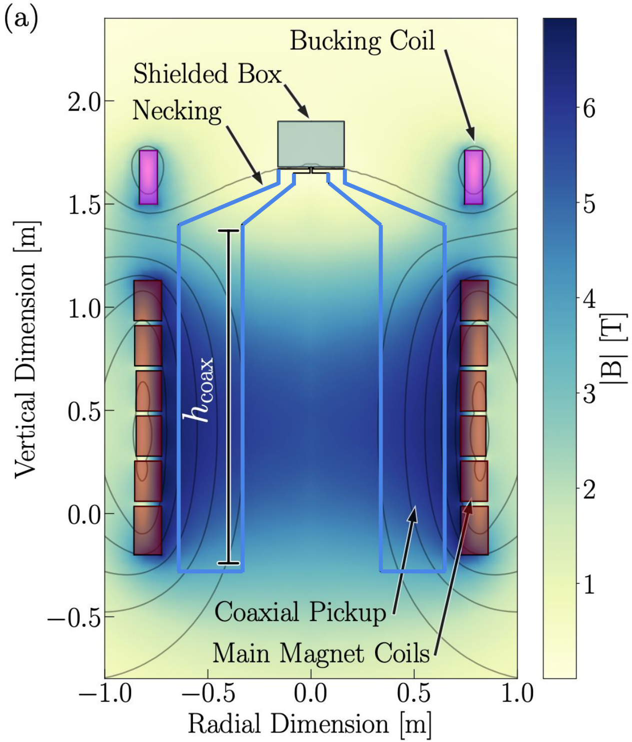
- Use a coaxial cylinder to inductively pickup flux induced by J_{eff}
- Taper down out of high field region
- Add tuning element and SQUID Readout
- Add Bucking coils

Higher Frequencies Need Modeling!

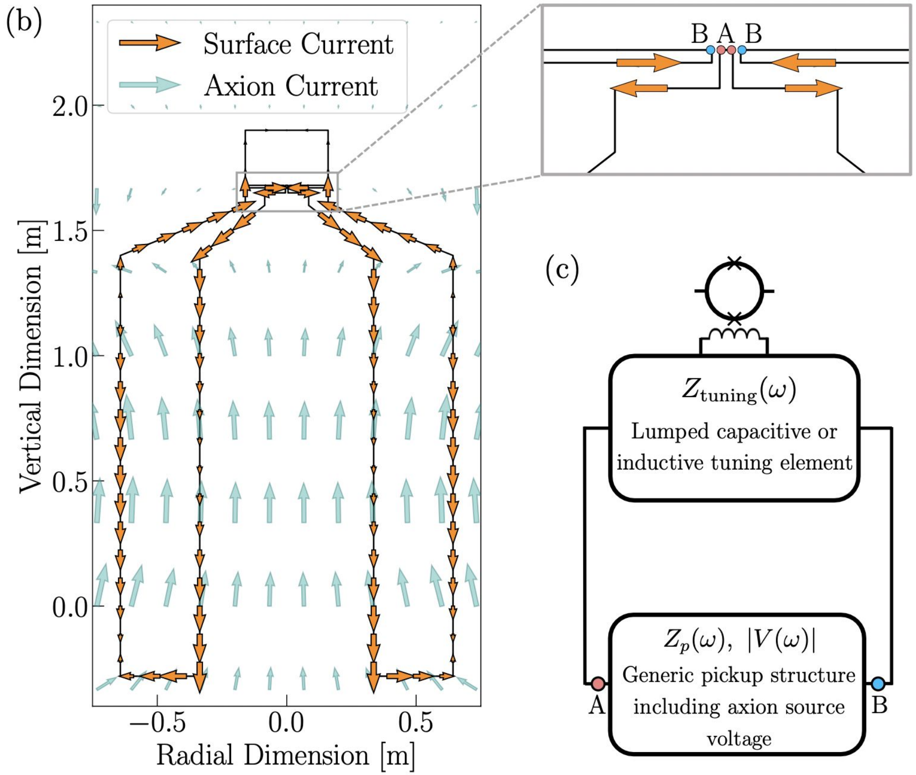
Modeling with Coaxial Geometry



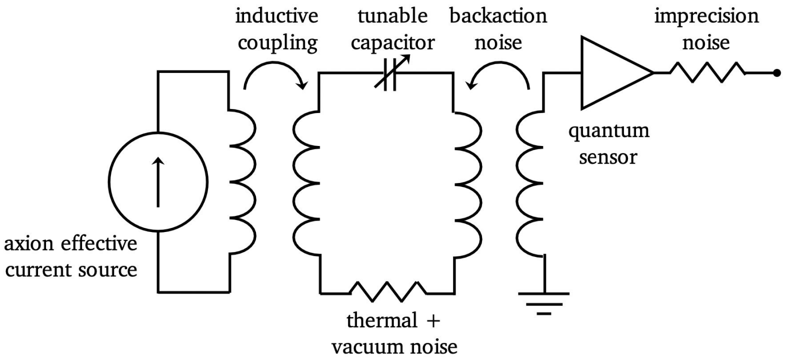
Magnetic Field Profile Design with Low-Field Region



TEM Mode Modeling with Coaxial Geometry

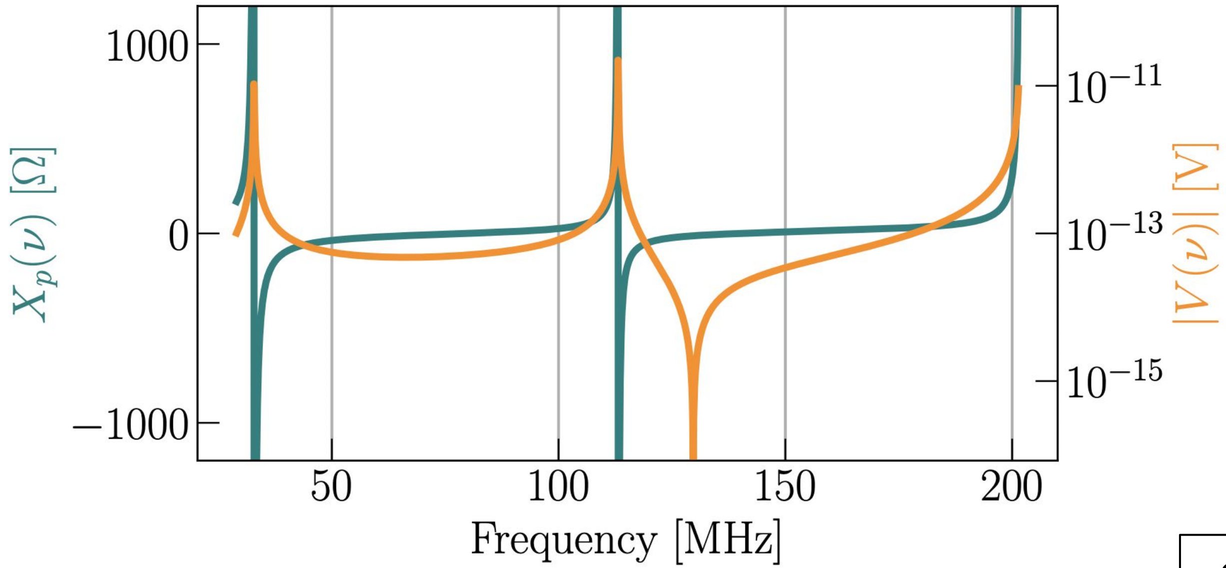


- Modeling gives reactance and voltage values vs frequency



- Use resonance circuit analysis from modeled values of impedance and voltage.

DMRadio-m^3 Modeling Different Coax Lengths



For $h_{\text{coax}} = 1.4\,\text{m}$

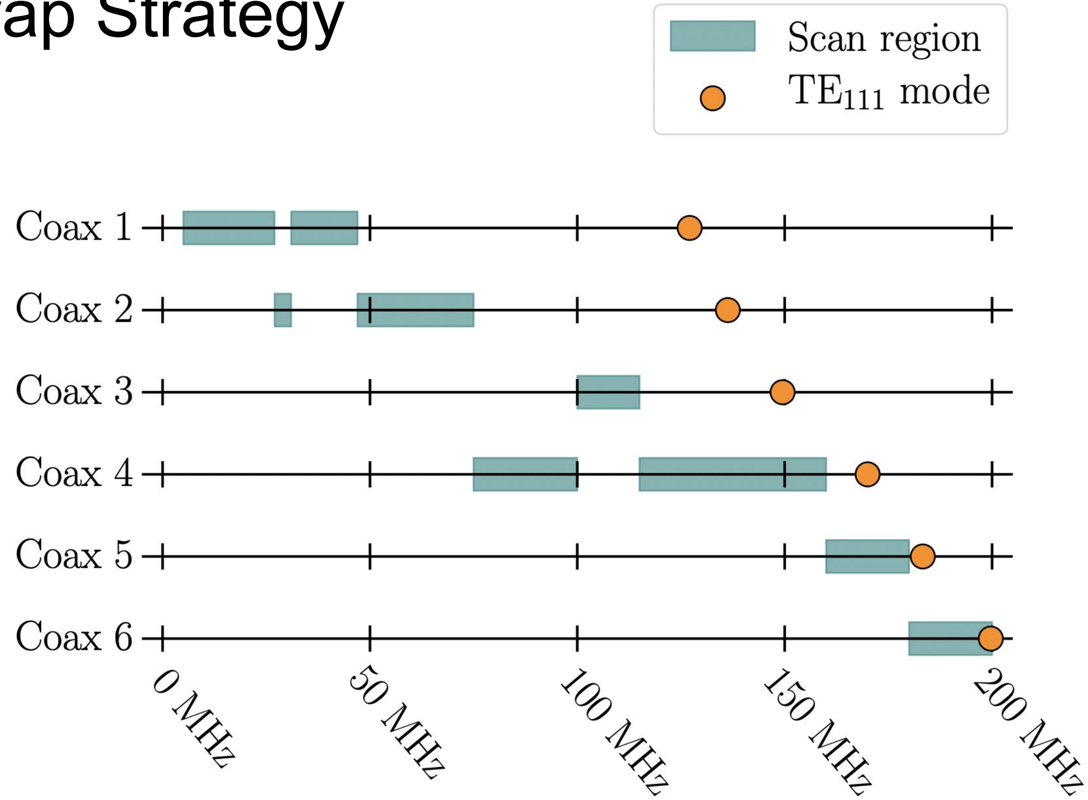
$$r_o = 0.628\,\text{m}$$
$$r_i = 0.336\,\text{m}$$

- Plot Reactance and Impedance for each coax
- Identify and avoid resonant modes at poles and zeros!
- Add C or L to zero reactance

See arXiv:2302.14084
DMRadio Collaboration

DMRadio-m^3 Coax Swap Strategy

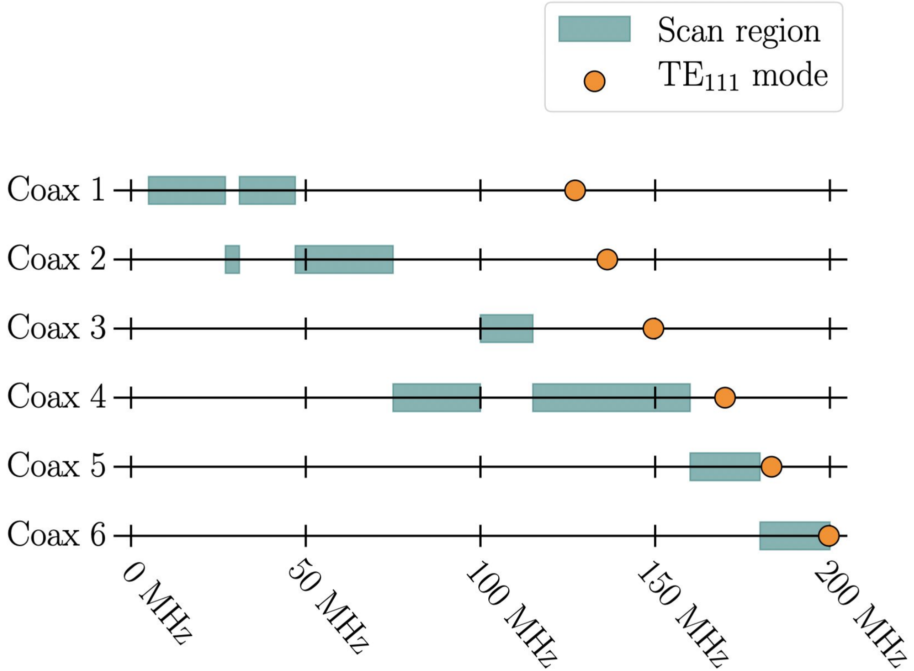
- Keep Coax single-moded (TEM-like)
- Stay below TE11
- Exchange Coax when scan rate drops or when at tuning limit of slide



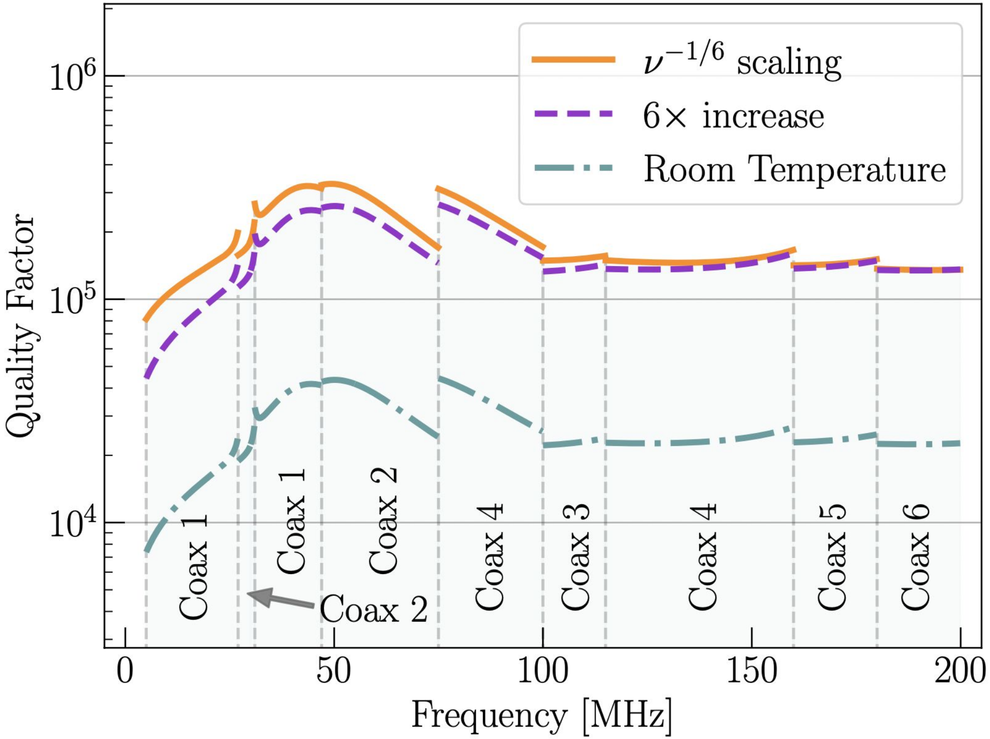
DMRadio-m³ Coax Swap Strategy

$$r_o = 0.628\,\mathrm{m}$$
$$r_i = 0.336\,\mathrm{m}$$

Coax Number	h_{coax}	Frequency Range(s) (MHz)
1	1.68 m	5–27 MHz 31–47 MHz
2	1.40 m	27–31 MHz 47–75 MHz
3	1.12 m	100–115 MHz
4	0.84 m	75–100 MHz 115–160 MHz
5	0.70 m	160–180 MHz
6	0.56 m	180–200 MHz



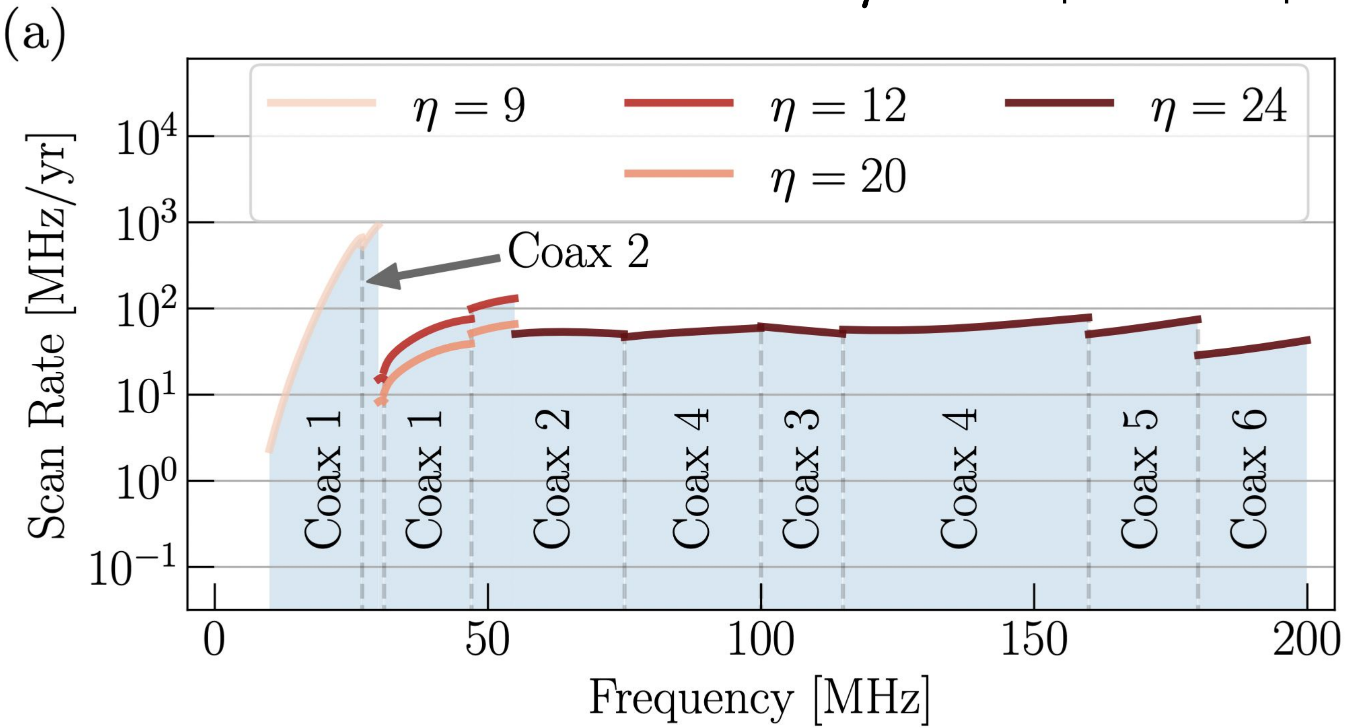
DMRadio-m^3 Anticipated Cu Coax Q



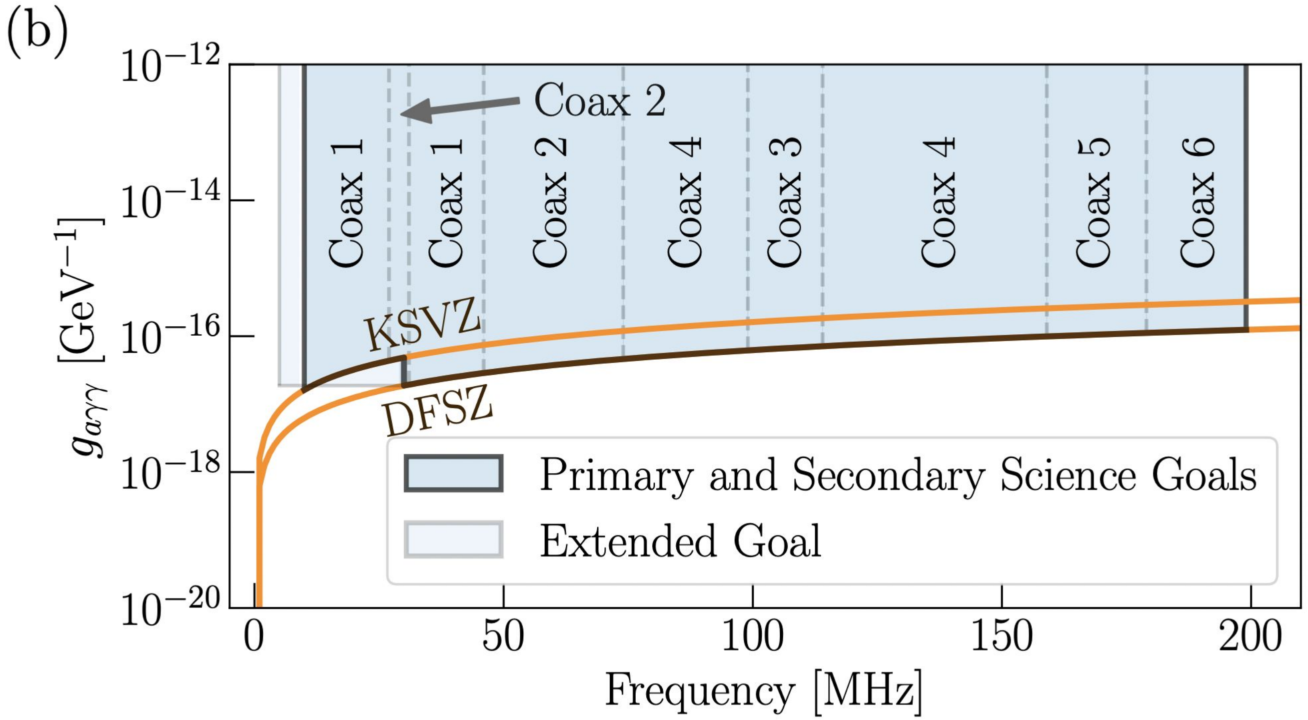
- Room Temperature Comsol simulations Q ~ 10^4
- Q improves at low temperatures, but are limited by anomalous skin-depth effects, magnetoresistance, imperfections
- Roughly 6x increase in Q at these frequencies

DMRadio-m^3 Extrapolated Scan Rate

η: ratio of squid noise to quantum limit



DMRadio-m^3 Sensitivity Reach with Coax Designs



DMRadio-m^3 Scan Time to Reach Target Sensitivity

	Sensitivity & Range	3σ Live Scan Time: Baseline (Scaled)
Primary Science Goal	DFSZ; 30–200 MHz	3.7 yr (3.0 yr)
Secondary Science Goal	KSVZ; 10–30 MHz	0.9 yr (0.6 yr)
Extended Goal	1.87×10^{-17} GeV^{-1}; 5–30 MHz	2.6 yr (1.6 yr)

DMRadio-m^3 Additional Challenges

Complete field engineering of shielded region

Cryogenic:

- Maximize volume with shared vacuum.
- Minimize thermal gradients in coax length

Vibration mitigation elements to be deployed

Readout noise with dc SQUIDs is sufficient (Full analysis in preparation)

Summary

DMRadio-50L
- Commissioning in early 2024!
- Quantum Sensing in 2025

DMRadio-m^3
- Engineering Complete Spring 2024
- Construction Ready 2025

DMRadio-GUT (arXiv:2203.11246)
- DFSZ 100 kHz - 30 MHz
- Technological improvements in
  - Magnets 16 Tesla
  - Quantum sensing (from 50L)
  - Active Feedback