Low Mass Axion Searches from ABRACADABRA Results to the DMRadio Program

UCLA Dark Matter in Los Angeles, CA
April 1, 2023

Maria Simanovskaia on behalf of the DMRadio Collaboration
Postdoc in the Irwin Group, Stanford University

Outline

- Axion parameter space
- Axion detection scheme
- ABRACADABRA-10 cm
- DMRadio program

Axion parameter space covers ~10^{10} mass range

- QCD axions solve the strong CP problem and are a leading dark matter candidate
- Wave-like dark matter: mass < 1 eV

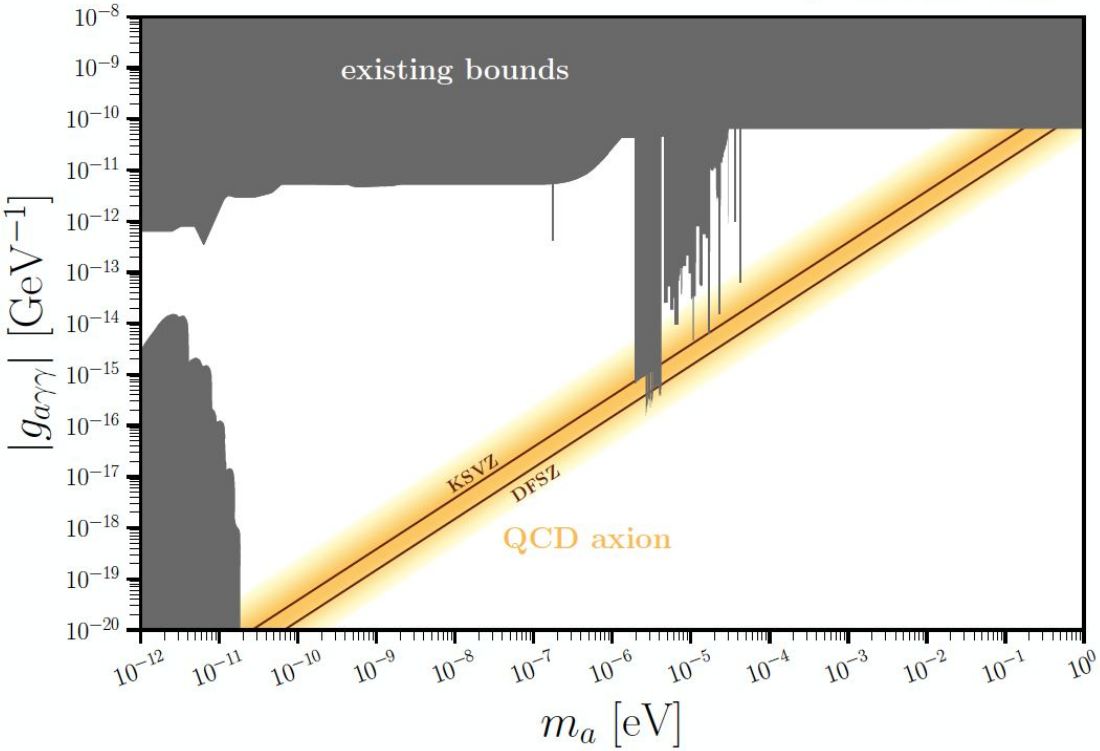


Figure by A. Berlin and others

Axion parameter space covers ~10^{10} mass range

- QCD axions solve the strong CP problem and are a leading dark matter candidate
- Wave-like dark matter: mass < 1 eV
- Pre-inflationary axions: mass < 1 μeV

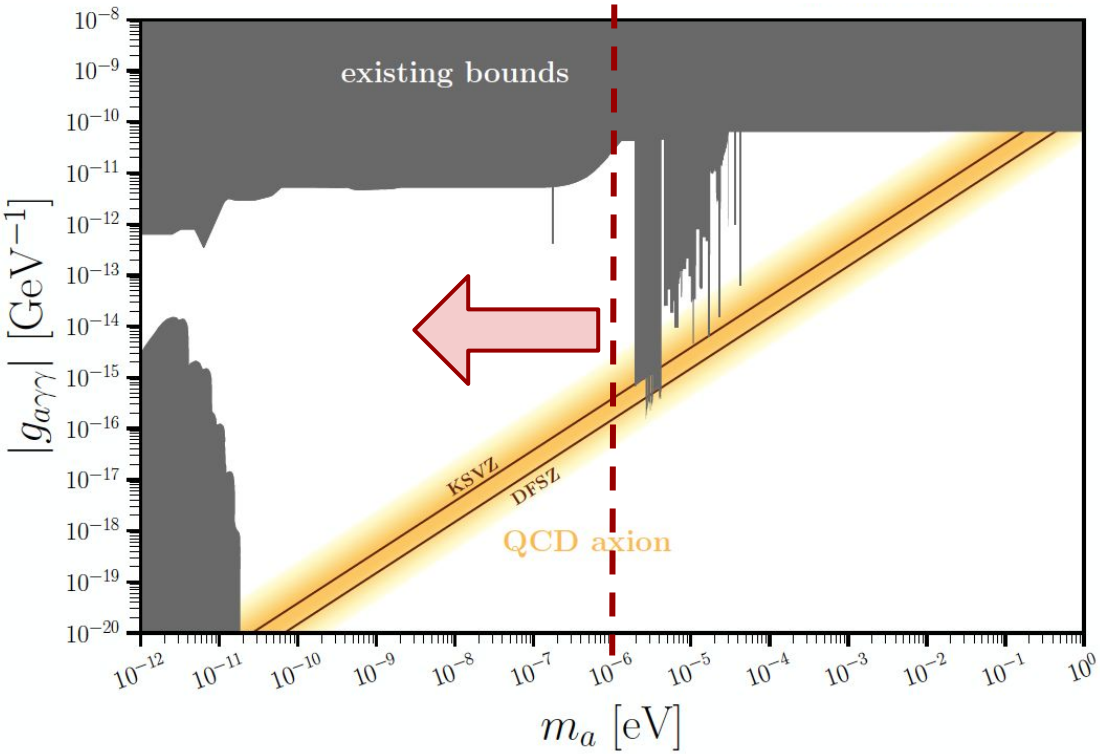
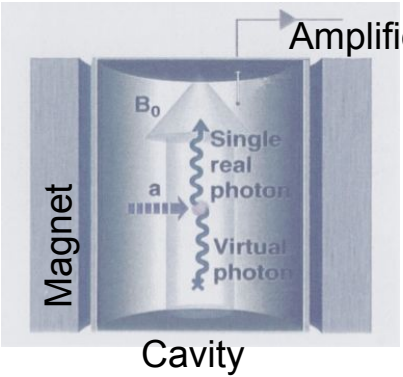


Figure by A. Berlin and others

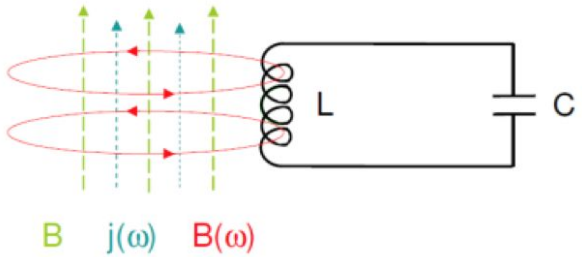
Probing QCD axions through electromagnetism

- Axion field converts to an oscillating electromagnetic signal in the presence of a magnetic field (Primakoff effect)
- Enhance signal with a tunable resonator

Proposal: Sikivie (1983)
v > 300 MHz
Cavity-based searches (ADMX, HAYSTAC,...)



Proposal: Cabrera, Thomas (2010)
v < 300 MHz
Lumped element searches (DMRadio,...)



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

A **B**roadband / **R**esonant **A**pproach to **C**osmic **A**xion **D**etection with an **A**mplifying **B**-field **R**ing **A**pparatus

ABRACADABRA-10cm for axion detection

- Broadband lumped-element axion detector

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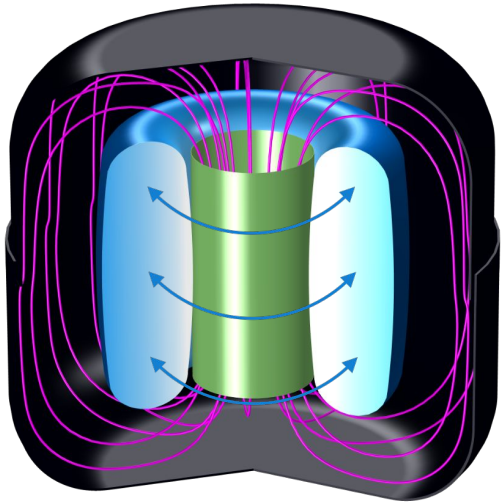
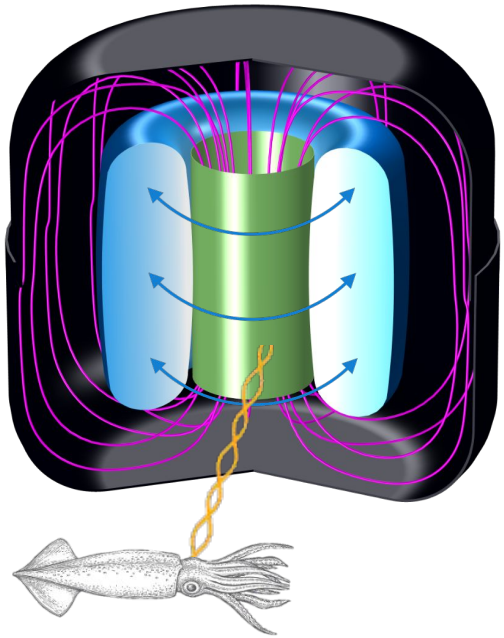
- The axion effective current creates an oscillating magnetic flux that induces screening currents on a pickup structure



ABRACADABRA-10cm for axion detection

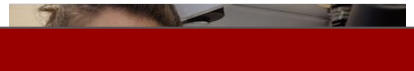
- Broadband lumped-element axion detector
- Axions interact with 1 T peak field toroidal magnet to create an effective current
- The axion effective current creates an oscillating magnetic flux that induces screening currents on a pickup structure
- Signal is read out from the pickup structure by a SQUID (Superconducting QUantum Interference Device)



ABRACADABRA-10cm for axion detection

C. Salemi with the ABRA-10cm at MIT

ABRACADABRA-10cm for axion detection



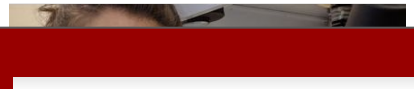
PHYSICAL REVIEW LETTERS **122,** 121802 (2019)

Discovery of $\sim 10^5$ axion-like-particles in the 1-10 neV range using the ABRACADABRA experiment

Jonathan L. Ouellet,[1] Chiara P. Salemi,[1] Joshua W. Foster,[2]

C. Salemi with the ABRA-10cm at MIT

ABRACADABRA-10cm for axion dete



PHYSICAL

Disco… …e 1-10 neV range using the …A experiment

…et,[1] Chiara P. Salemi,[1] Joshua W. Foster,[2]

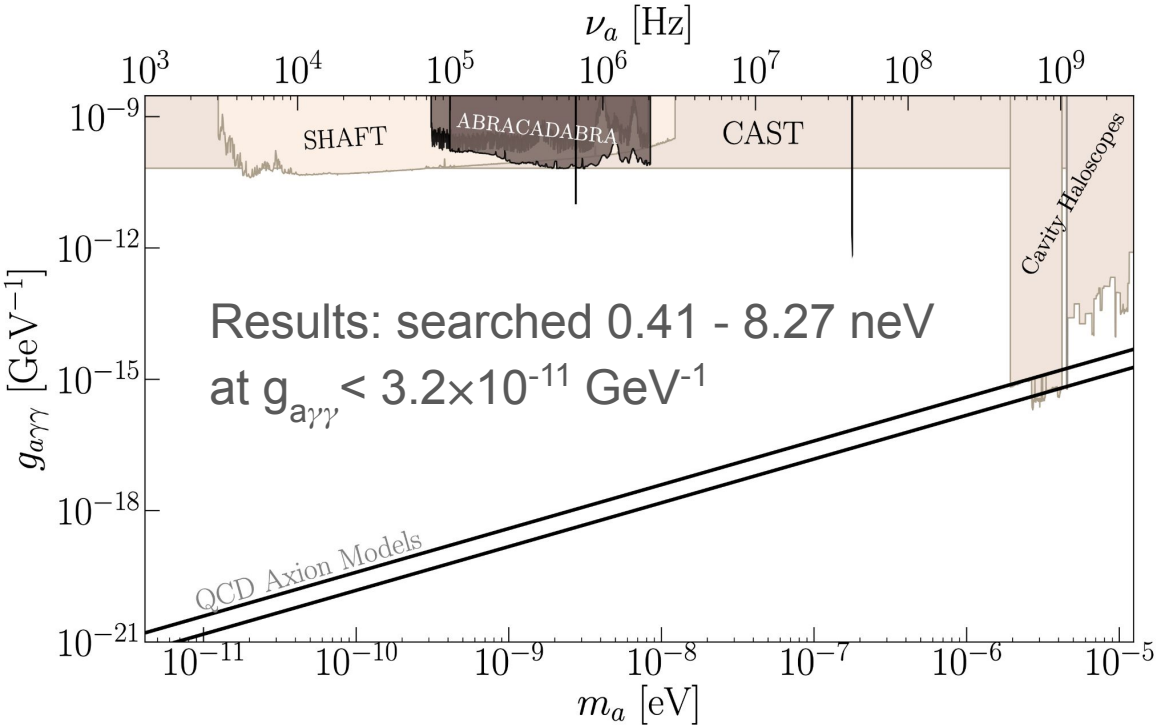
C. Salem… …BRA-10cm at MIT

Just kidding… 😜

ABRACADABRA-10cm results

C. Salemi with the ABRA-10cm at MIT

- PRL **122** (2019): 131802.
- PRL **127** (2021): 081801.



DMRadio Collaboration

ABRACADABRA-10cm

H.M. Cho, W. Craddock, D. Li, W. J. Wisniewski
SLAC National Accelerator Laboratory **- Location of DMRadio-m^3**

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DMRadio-pathfinder

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B. R. Safdi
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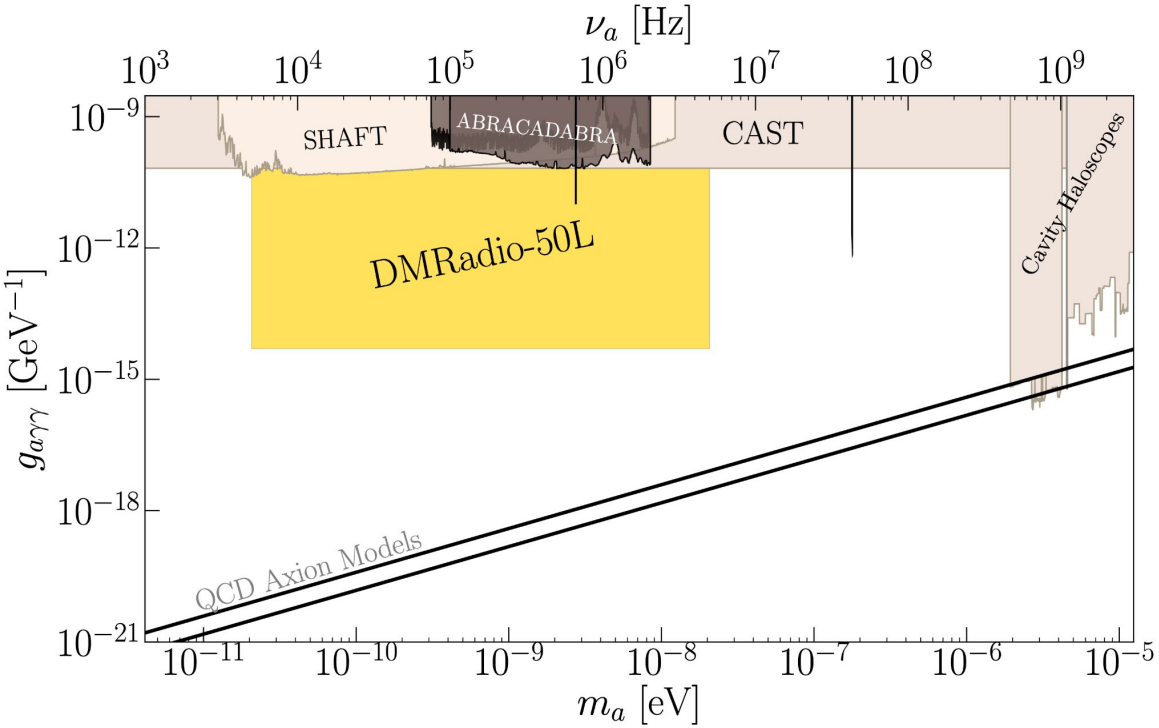
University of California Berkeley

DMRadio program overview

DMRadio-50L

- 5 kHz - 5 MHz
- Quantum sensor testbed



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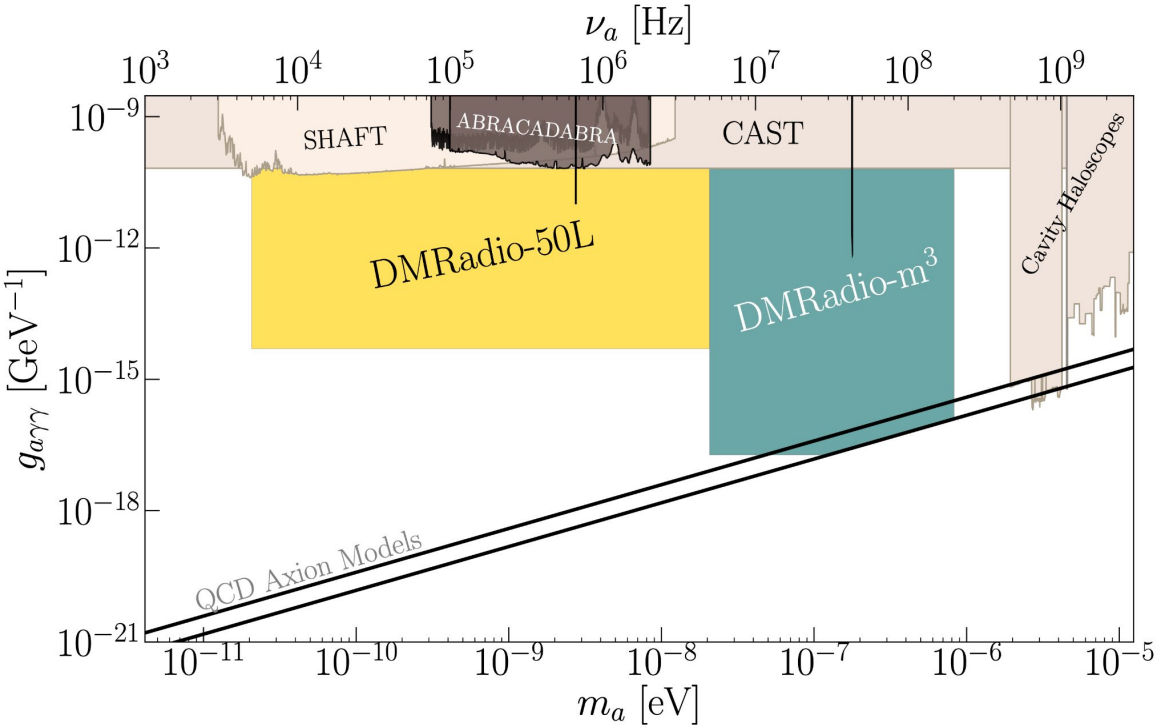
DMRadio-m^3 (PRD **106** (2022): 103008, arXiv:2302.14084)

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



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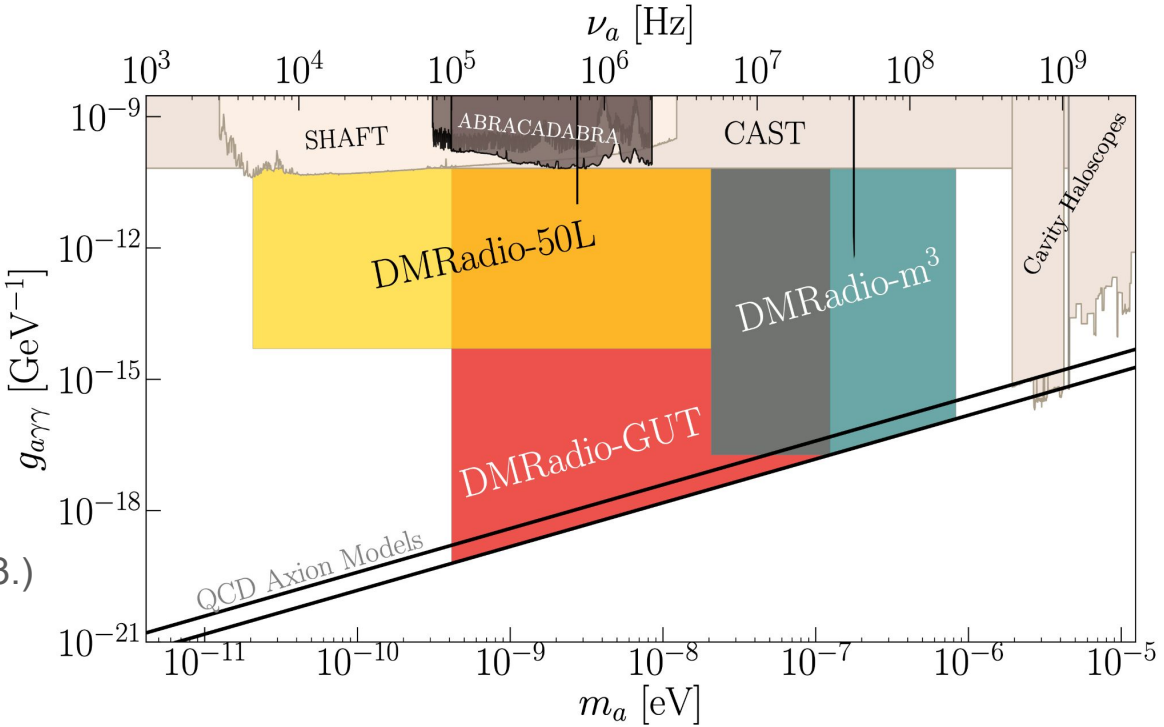
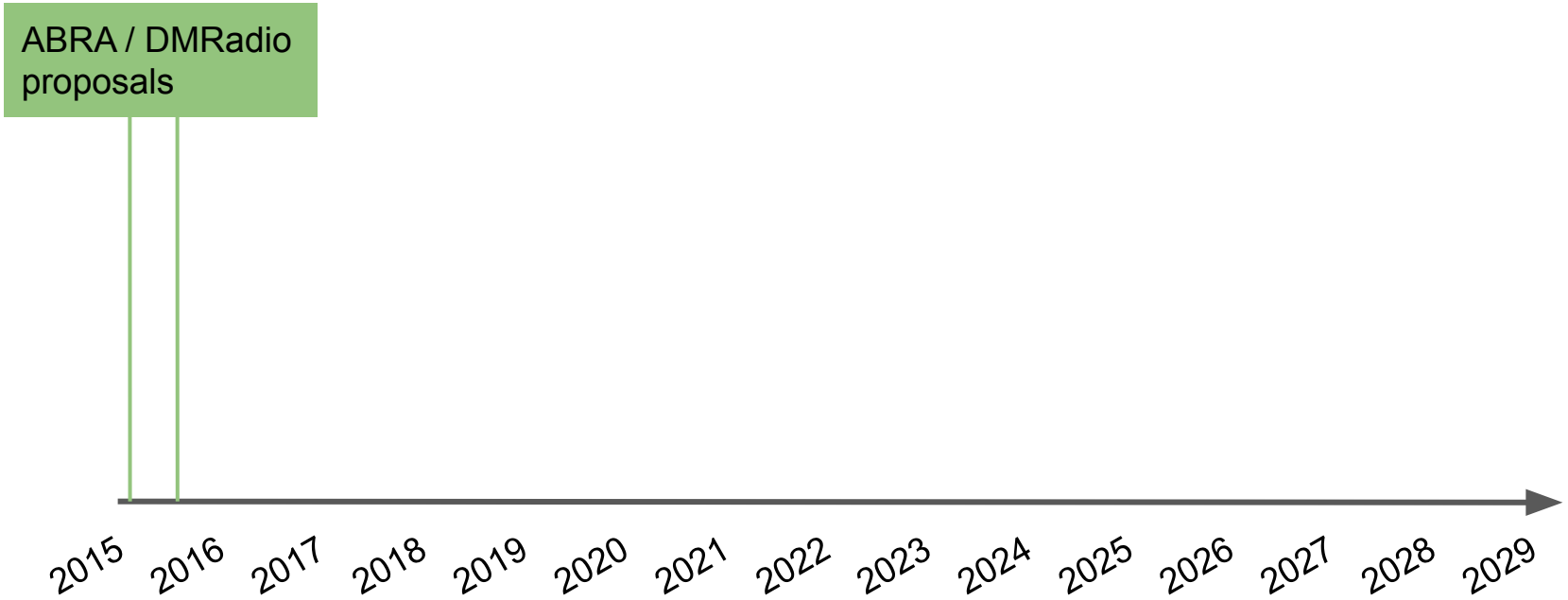
DMRadio-GUT (PRD **106** (2022): 112003.)

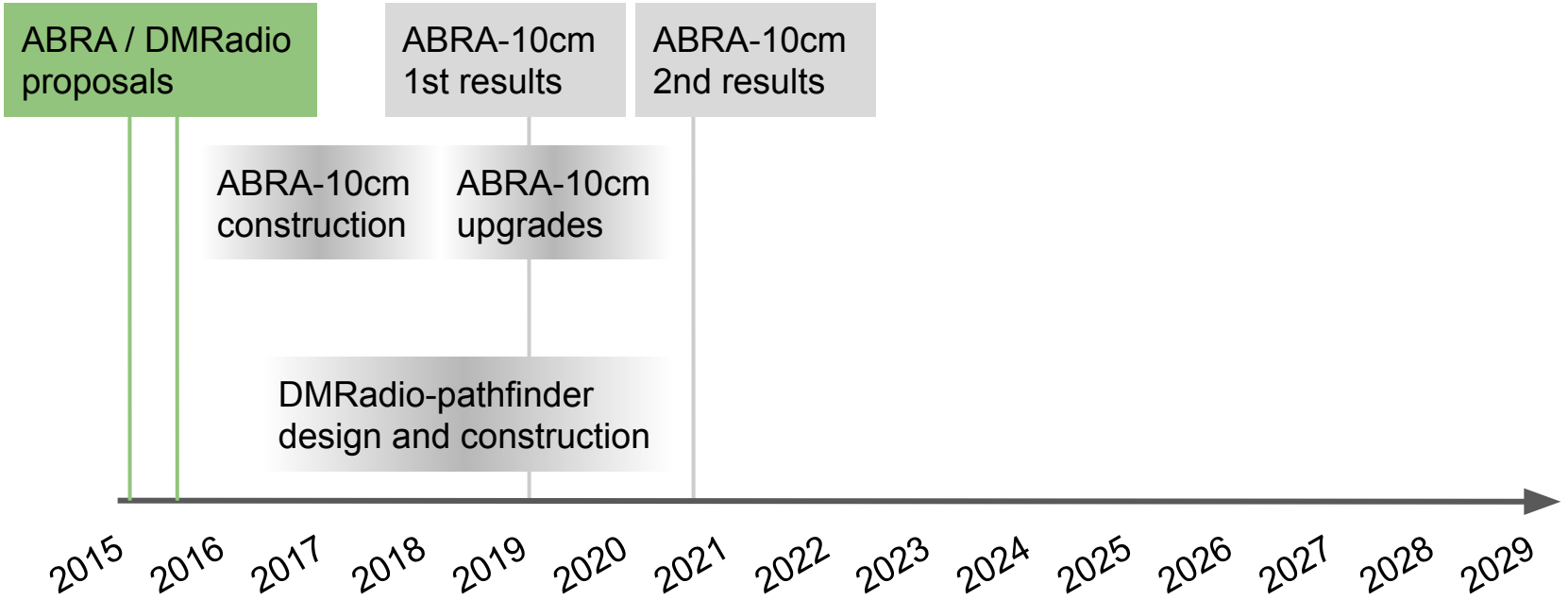
- DFSZ 100 kHz - 30 MHz
- Next-generation detector



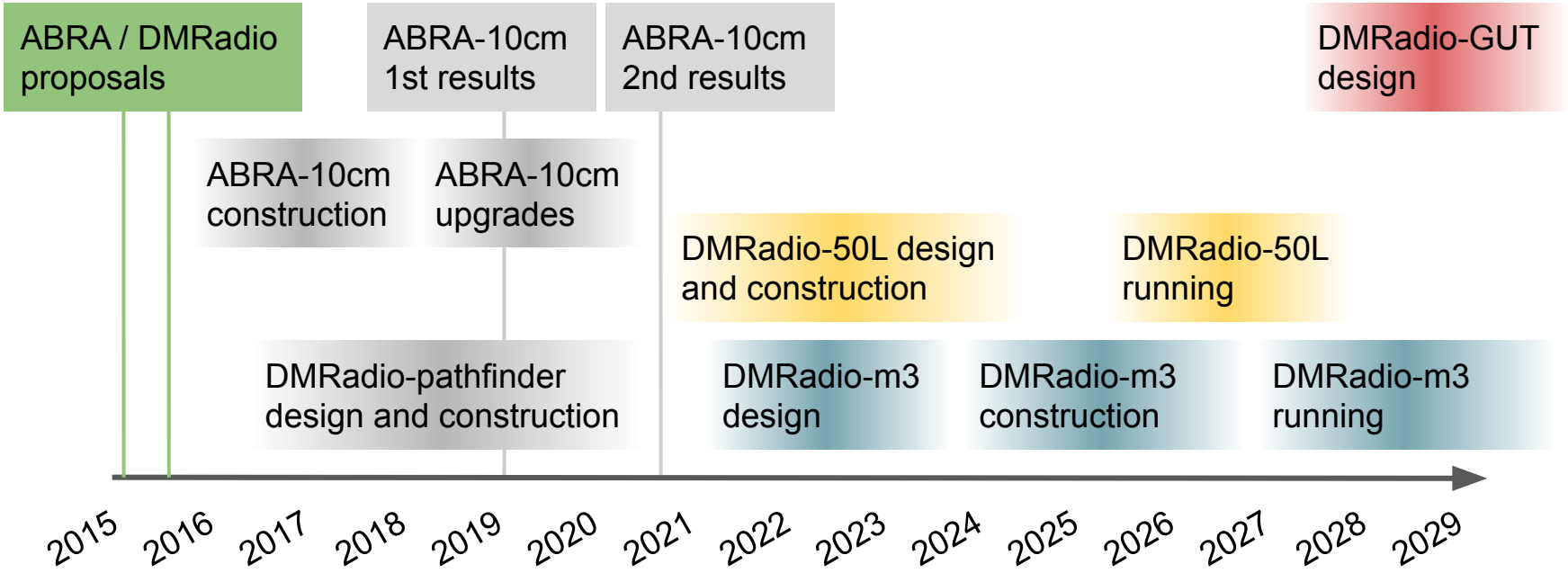
DMRadio program schedule



DMRadio program schedule

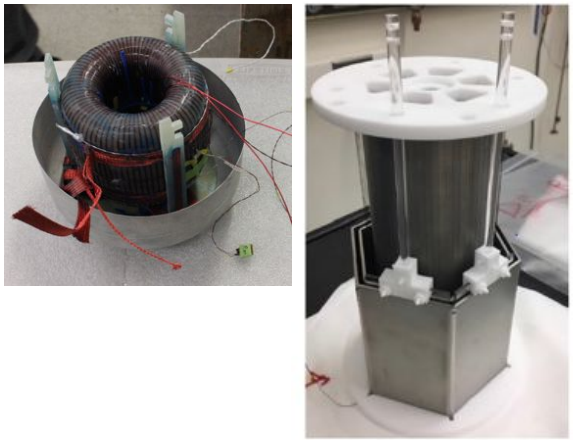


DMRadio program schedule



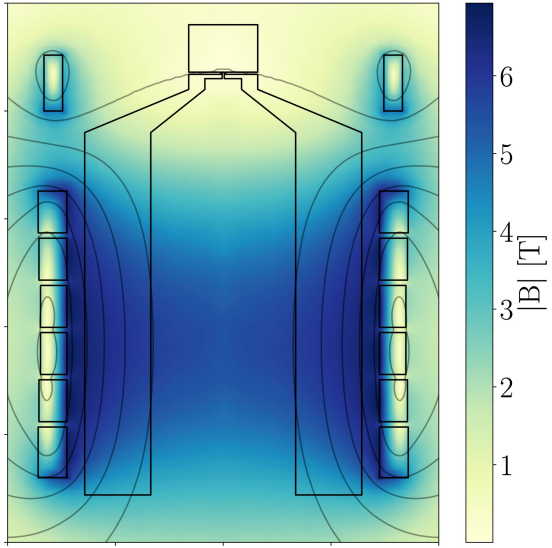
DMRadio program status

DMRadio-Pathfinder, ABRACADABRA-10cm: in operation

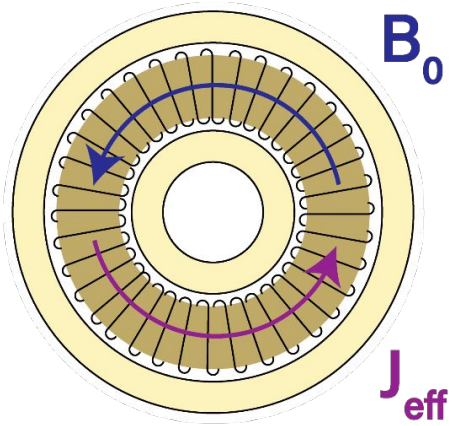


DMRadio-50L: under construction

DMRadio-m^3: design complete in 2024

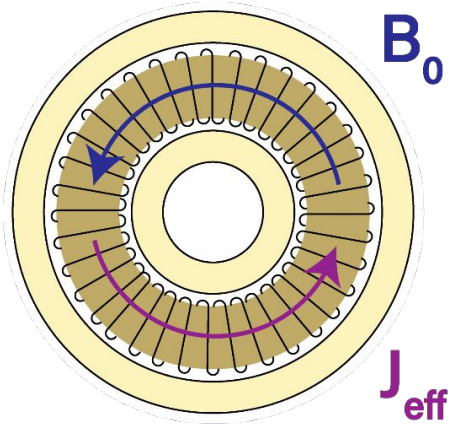


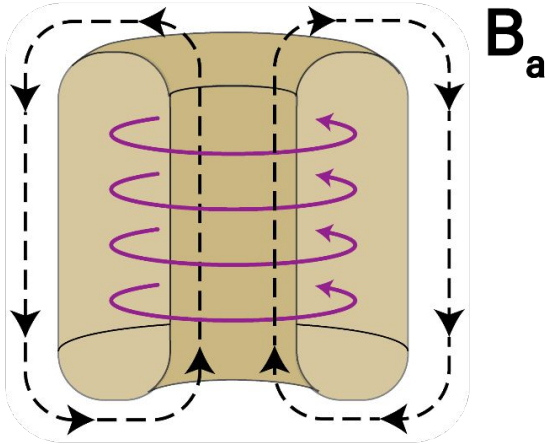
DMRadio-50L detection scheme



Toroidal magnet
with field B_0
creates current J_{eff}

DMRadio-50L detection scheme

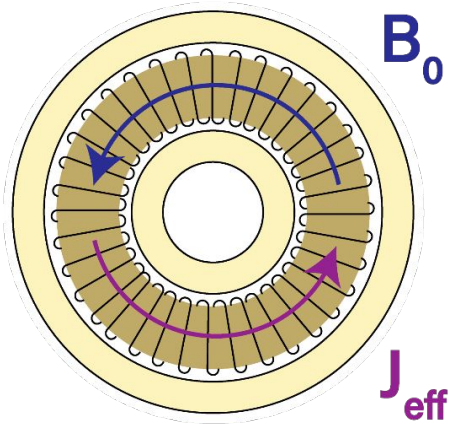


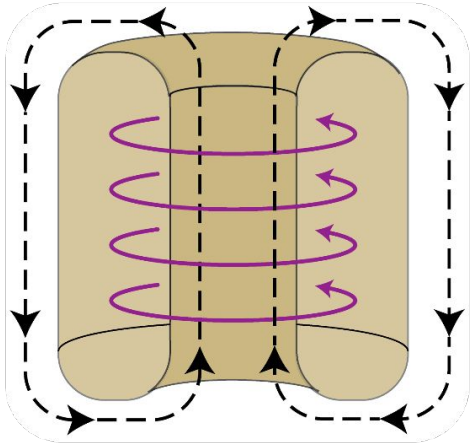


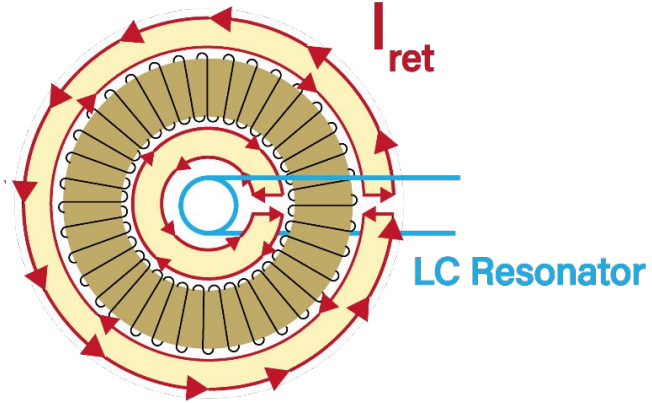
Toroidal magnet with field B_0 creates current J_{eff}

J_{eff} creates magnetic field B_a

DMRadio-50L detection scheme





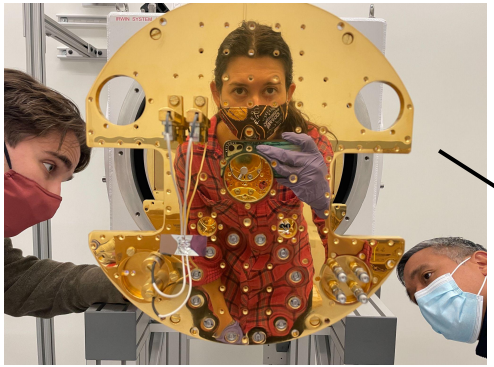


Toroidal magnet with field B_0 creates current J_{eff}

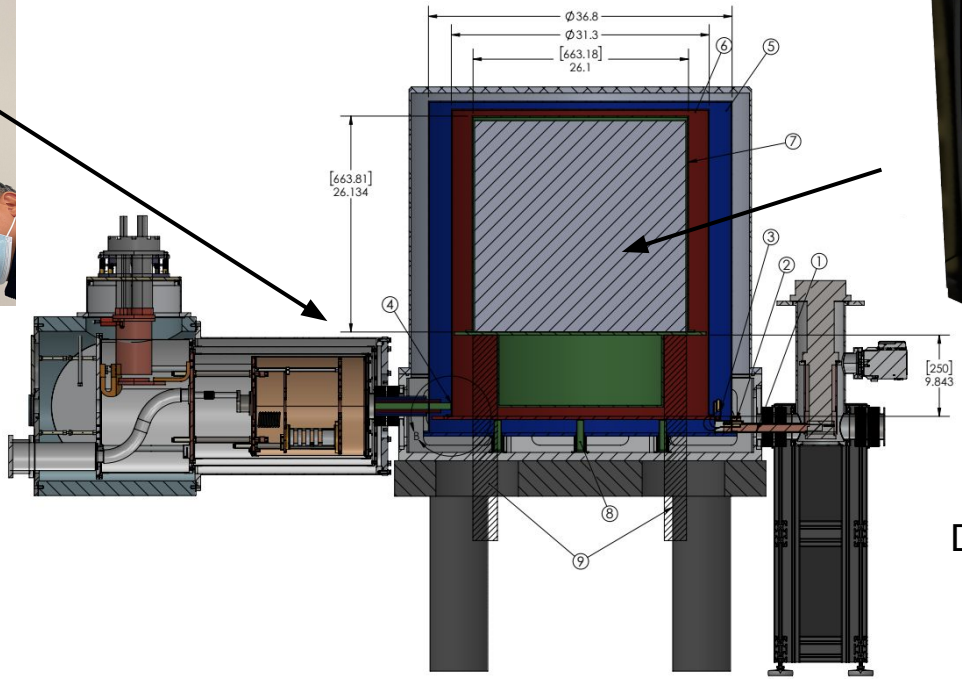
J_{eff} creates magnetic field B_a

B_a induces I_{ret} which is enhanced by an LC resonator and picked up by a sensor

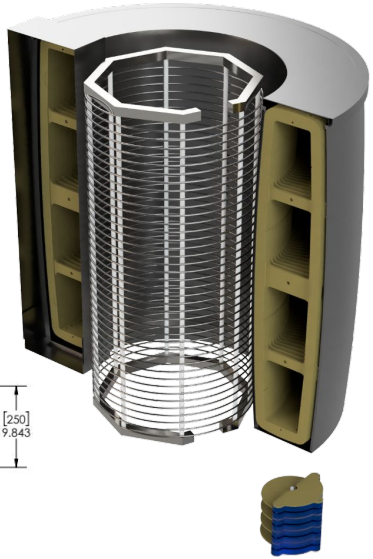
DMRadio-50L: under construction at Stanford



Working on the dilution refrigerator in the lab.

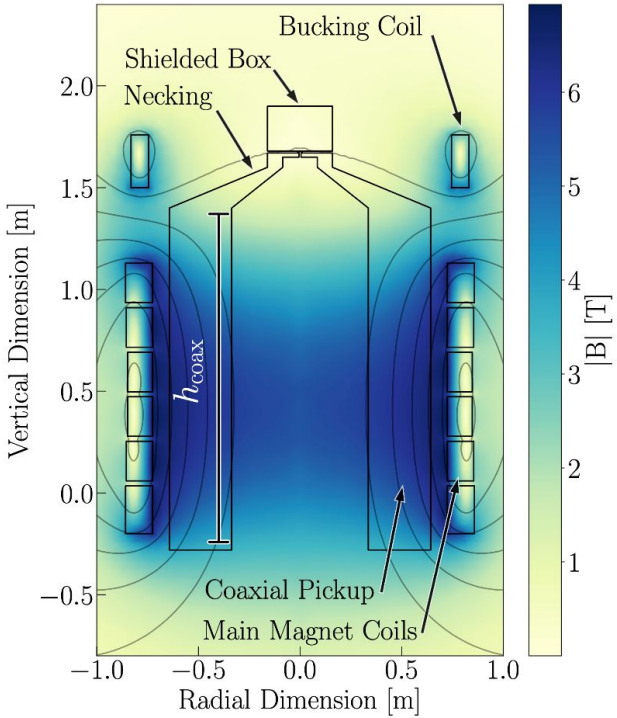


DMRadio-50L cryosystem CAD model.

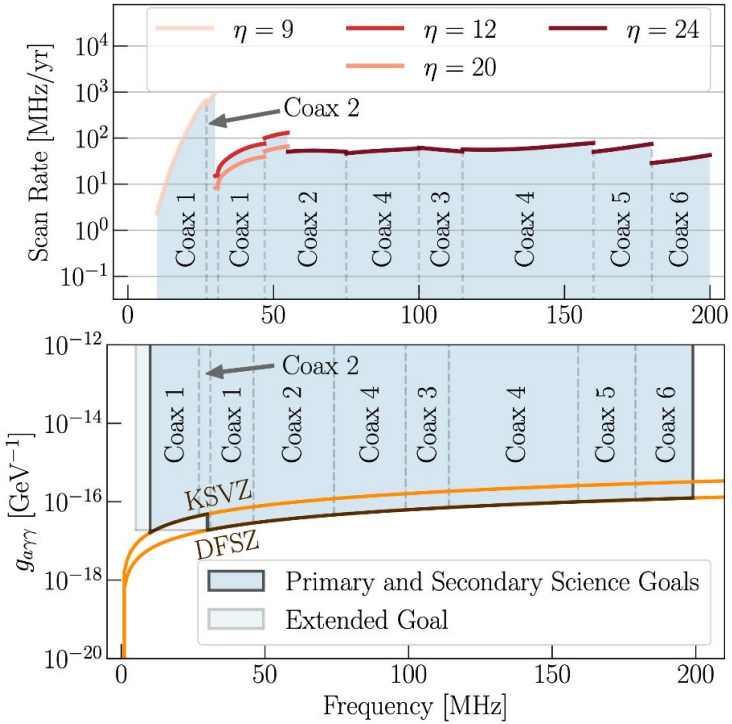


Detector and receiver CAD models.

DMRadio-m3: design to be completed in 2024



Coaxial cross section overlaid with simulation of the magnetic field.



Predicted scan rate and sensitivity across frequency range of interest.

arXiv:2302.14084

Summary and conclusions

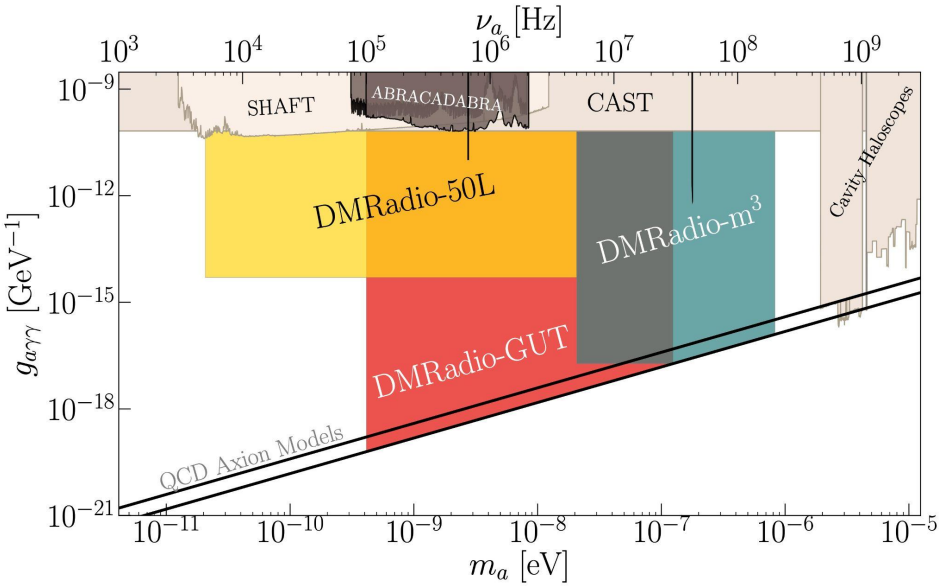
ABRACADABRA-10cm has excluded axions in 100 kHz - 2 MHz at $g_{a\gamma\gamma} < 3.2\times10^{-11}$ GeV^{-1}

DMRadio is a suite of lumped-element detectors for axions of masses < 1 μeV building on experience of ABRACADABRA and DMRadio-pathfinder

DMRadio-50L is an axion detector at 5 kHz - 5 MHz as well as an innovation platform for new amplifier technologies

DMRadio-m^3 is an axion detector with DFSZ sensitivity at 30-200 MHz, the design will be completed in 2024 as part of DOE's Dark Matter New Initiatives

DMRadio-GUT is a next-generation experiment that will require technology developments and experience from DMRadio-m^3 and DMRadio-50L

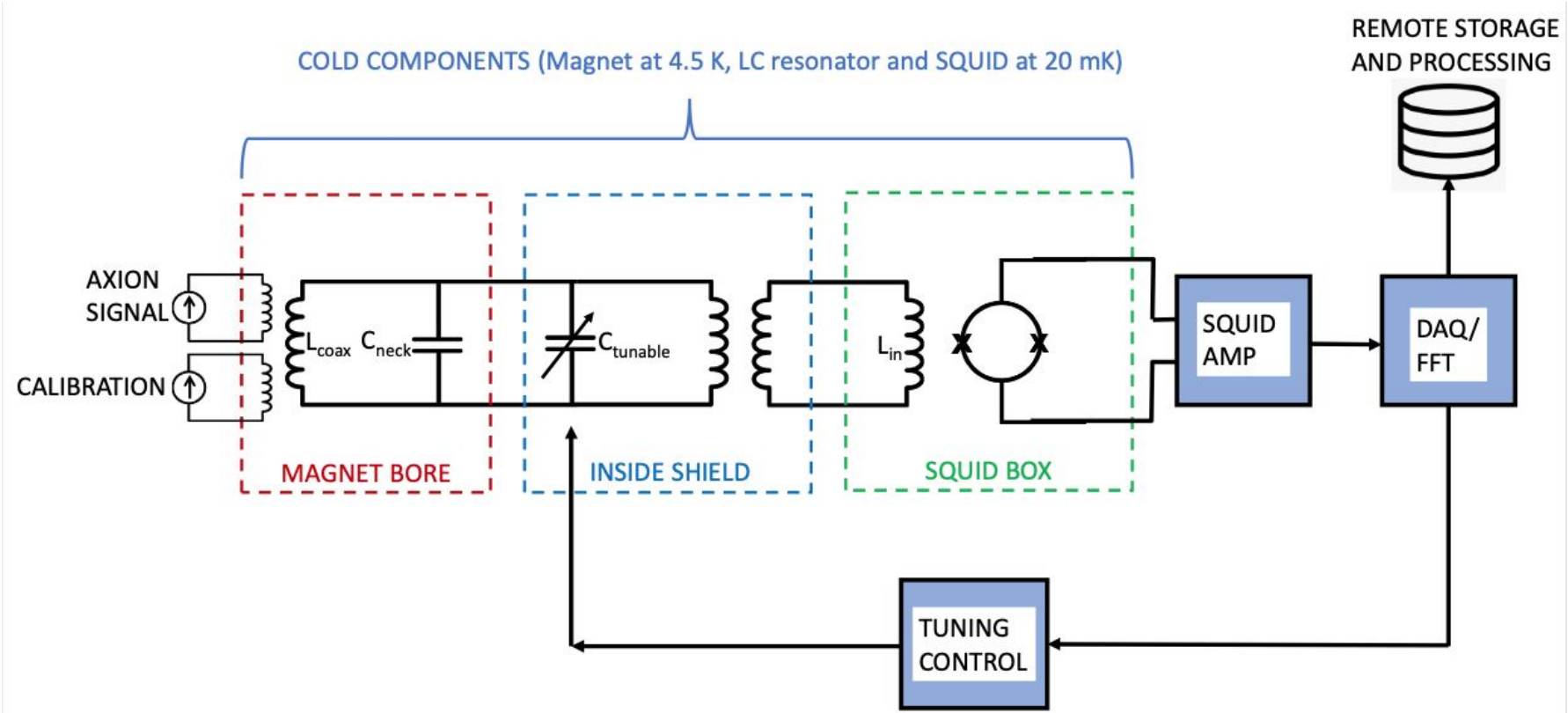


Thank you!

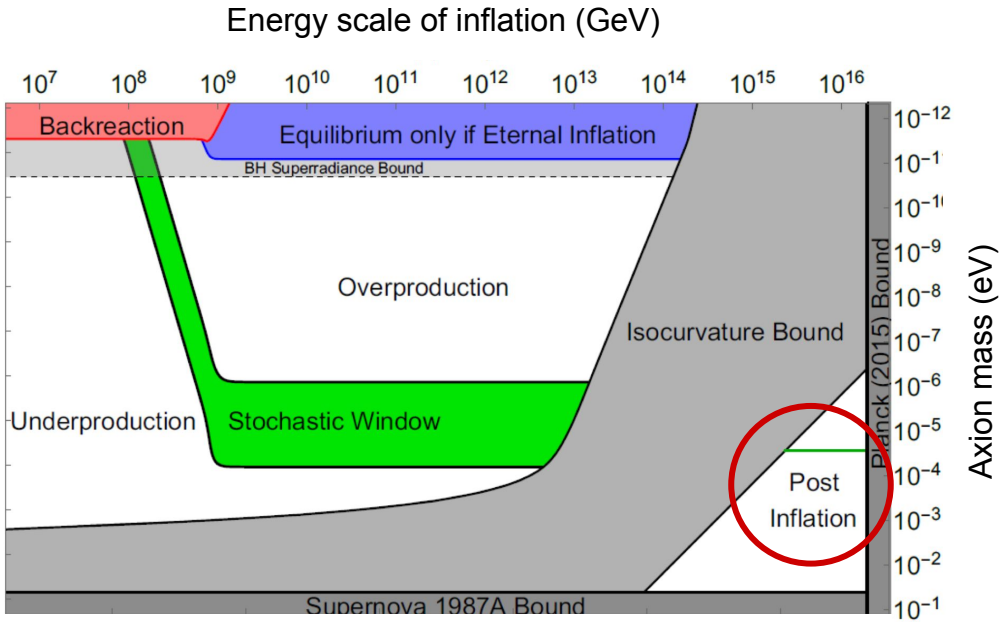
DMRadio posters at UCLA Dark Matter:

- “DMRadio-m3: An Overview” - Nicholas Rapidis
- “Calibrating the DMRadio-50L Detector” - Jessica Fry
- “DMRadio-50L Experiment Status and Overview” - Alex Leder
- “Searching for High-Frequency Gravitational Waves with ABRACADABRA-10cm” - Kaliroe Pappas

Signal flow and system overview



Low-mass axions < 1 μeV are well-motivated



Post-inflationary axions:

- Below 1 μeV, post-inflationary axions would over-produce
- “Classical axion window”
- Bounded to be > 1 μeV

P.W. Graham and A. Scherlis, Phys. Rev. D **98** (2018): 035017
F. Takahashi, W. Yin, A. H. Guth, Phys. Rev. D **98** (2018): 015042

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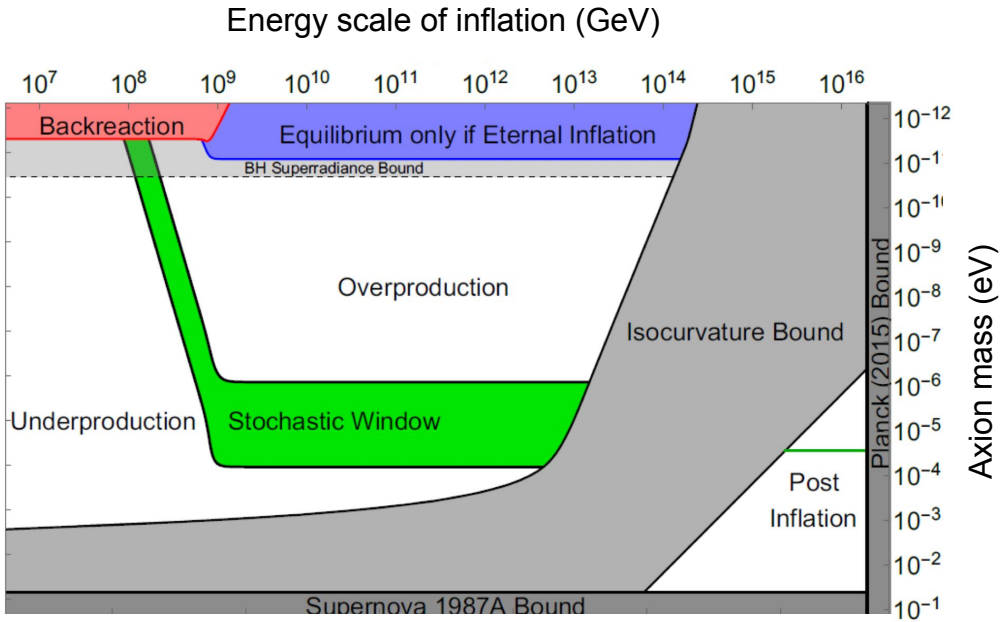


Pre-inflationary axions:

- QCD axions < 1 μeV
- QCD axions generated before inflation can naturally be produced in the observed abundance of dark matter over a large mass range (in green)

P.W. Graham and A. Scherlis, Phys. Rev. D **98** (2018): 035017.
F. Takahashi, W. Yin, A. H. Guth, Phys. Rev. D **98** (2018): 015042.

ABRACADABRA-10cm

PRL **127**, 081801 (2021).
PRL **122**, 131802 (2019).

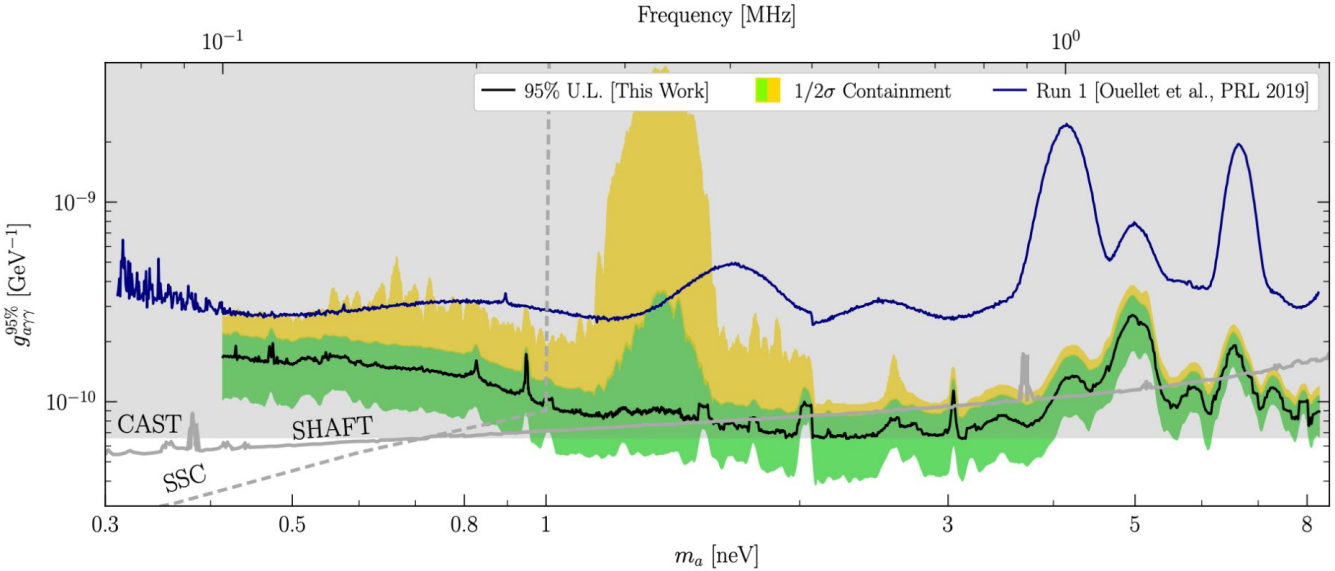
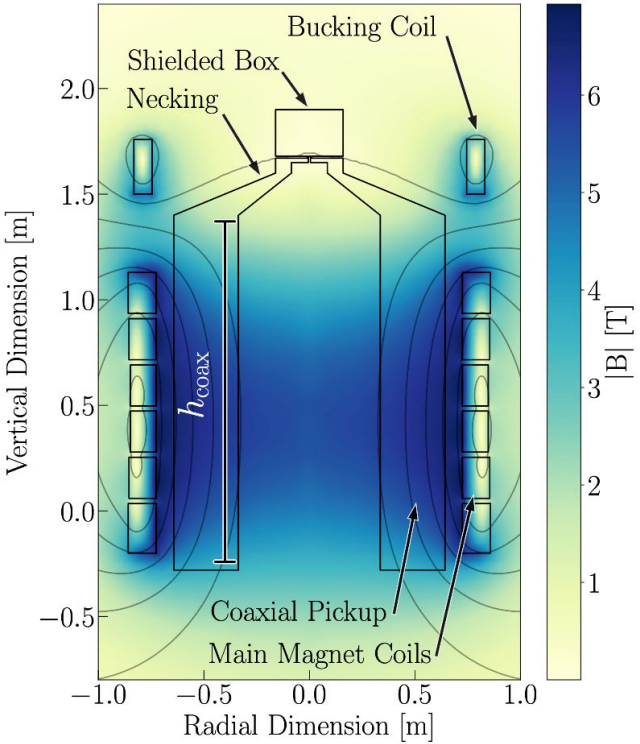
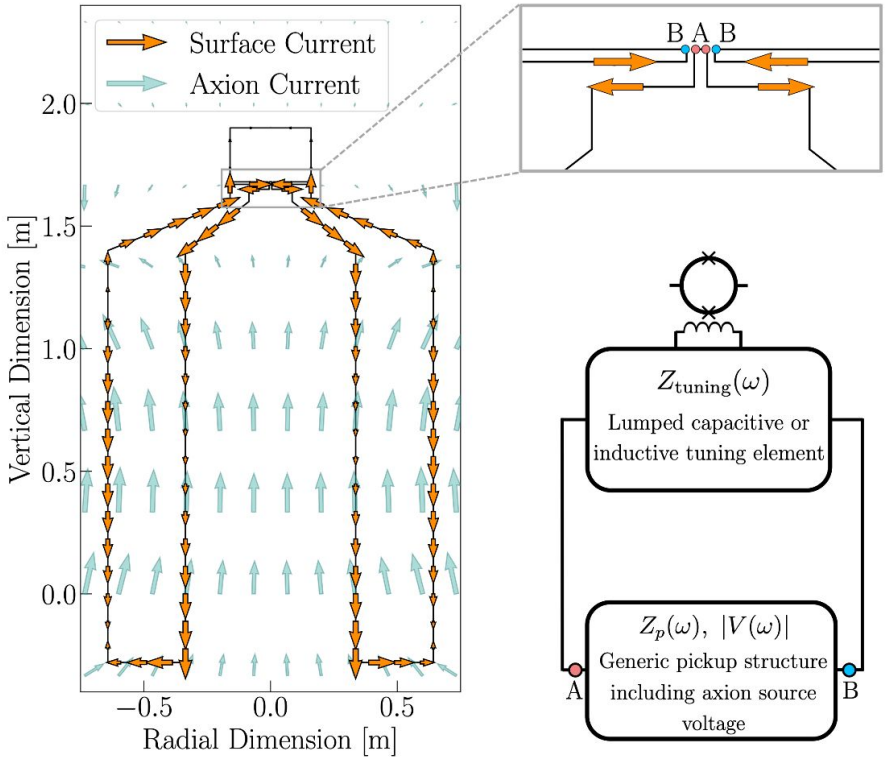


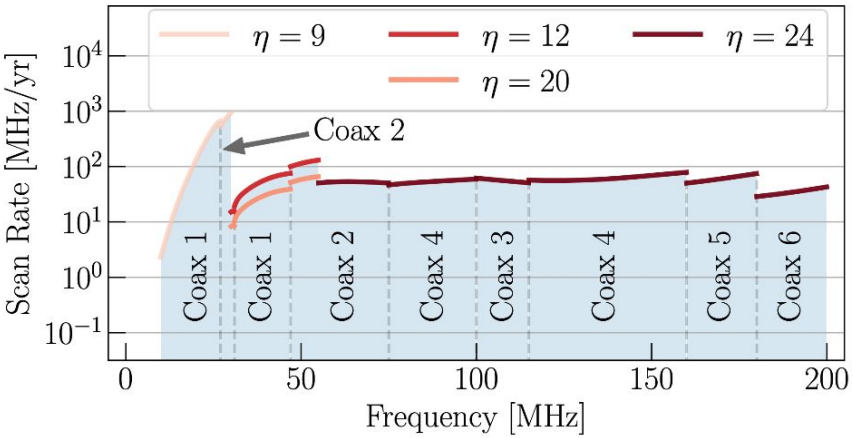
Figure 4. The one-sided 95% upper limit (U.L.) on $g_{a\gamma\gamma}$ from this work excludes previously unexplored regions of ADM parameter space. The 1σ and 2σ containment regions are constructed by taking the appropriate percentiles of the distributions of the limits over narrow mass ranges; note that this means that ∼16% of the upper limits lie at the bottom of the green band. While ∼11.1 million mass points are analyzed, the data in the figure are smoothed for clarity. Before smoothing, the strongest limit obtained is $g_{a\gamma\gamma} \lesssim 3.2 \times 10^{-11}$ GeV^{-1} at $m_a \sim 2.99$ neV. Our limits surpass those from a number of indicated astrophysical and laboratory searches in this mass range (see text for details).

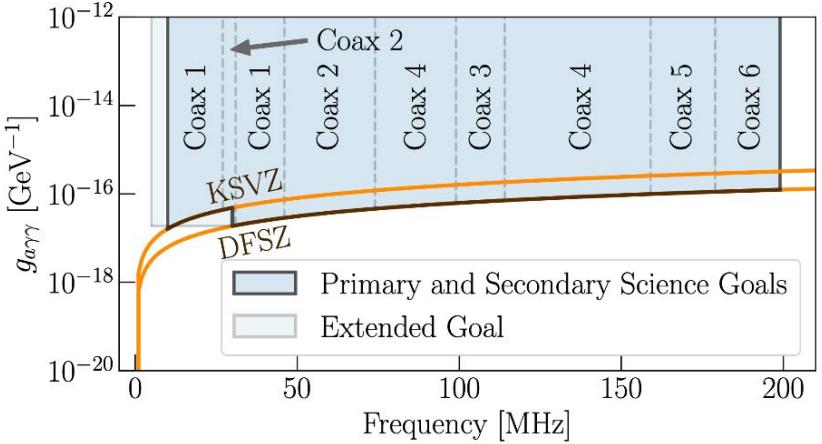
DMRadio-m3 coax design





DMRadio-m3 set of coaxes to cover frequency range





DMRadio - GUT

Parameter	**Target Value**	**State of the Art**
Magnetic field	16 T	~8 T (ADMX-G2)
Volume	$10\ m^3$	$\sim 0.1\ m^3$ (ADMX-G2)
Quality Factor	2×10^7	$\sim 10^6$ (Falferi, 1998; Ulmer, 2016)
Temperature	10 mK	7 mK (commercial DRs)
Amplifier Noise	-20 dB of backaction noise reduction below SQL	Few times SQL (dc SQUIDs, JPAs)
Integration time	6.2 years	