Dark Matter Radio - Cubic Meter

17th Patras Workshop on Axions, WIMPs, and WISPs in Mainz, Germany
August 11, 2022

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

DMRadio Collaboration

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SLAC National Accelerator Laboratory **- Location of DMRadio-m^3**

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Department of Physics
Stanford University **- Location of DMRadio-50L (see Poster #13 by Kent Irwin)**

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ABRACADABRA

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DMRadio-pathfinder

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Outline

- Axion parameter space and current experiments
- DMRadio program
- DMRadio - cubic meter
  - Science goals
  - Detector design
- Conclusion

QCD 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
- Two models of QCD axion
  - KSVZ
  - DFSZ
- DMRadio suite will cover ~10^6 mass range (neV-μeV)

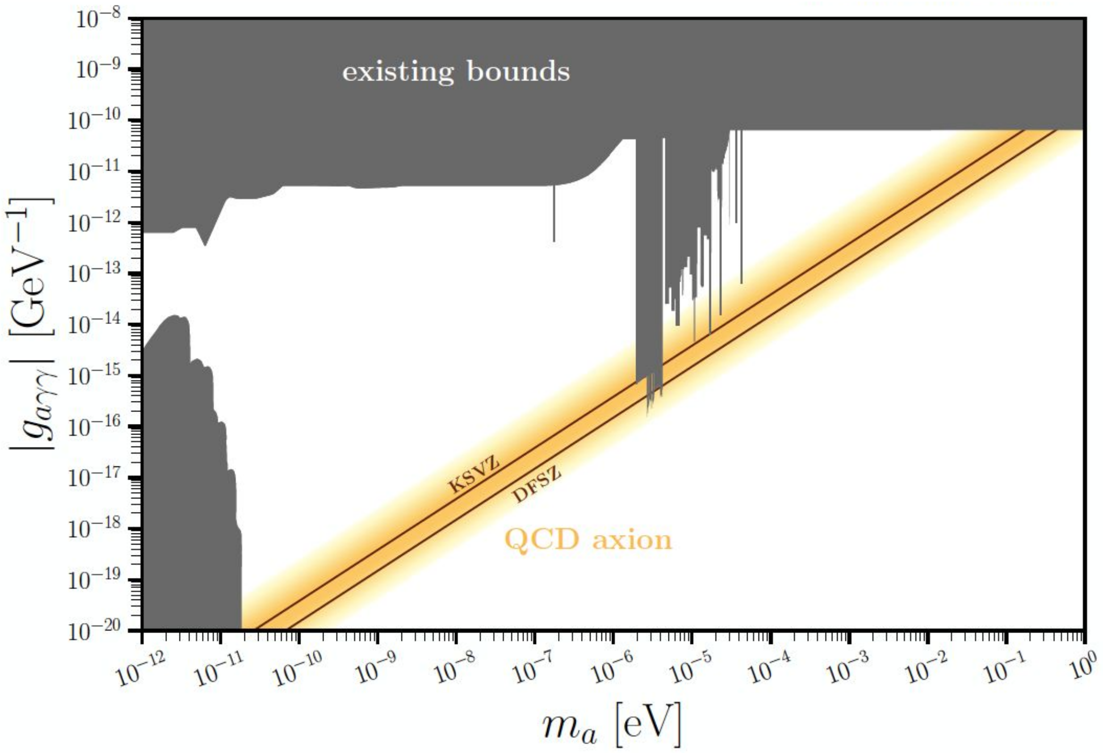
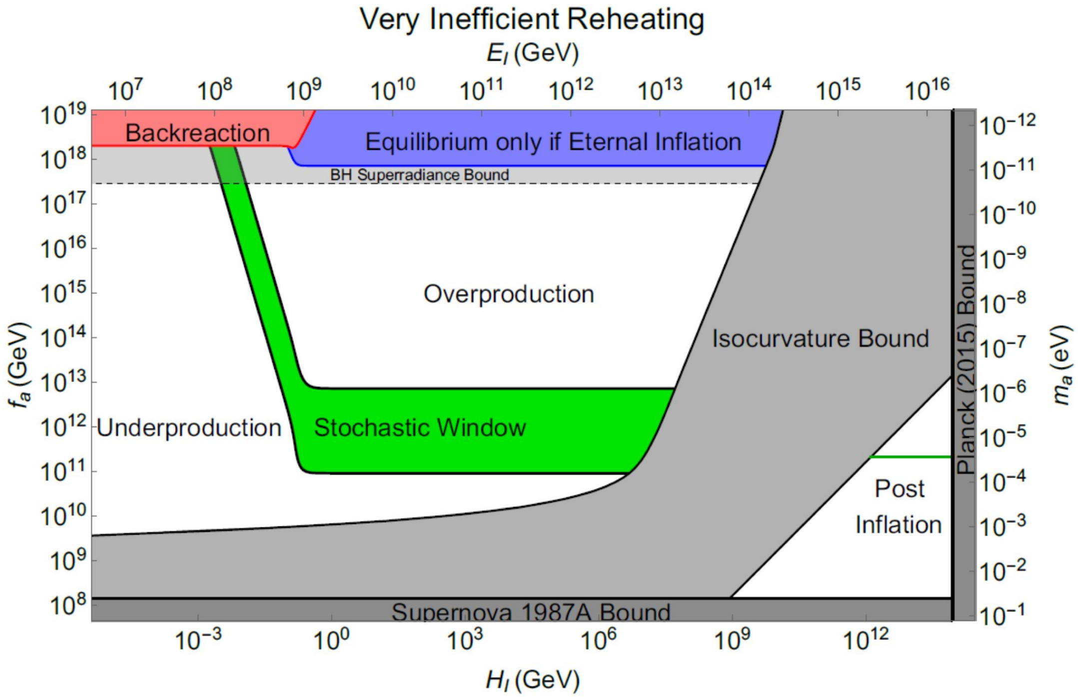


Figure by A. Berlin and others

Low-mass axions < 1 μeV are well-motivated

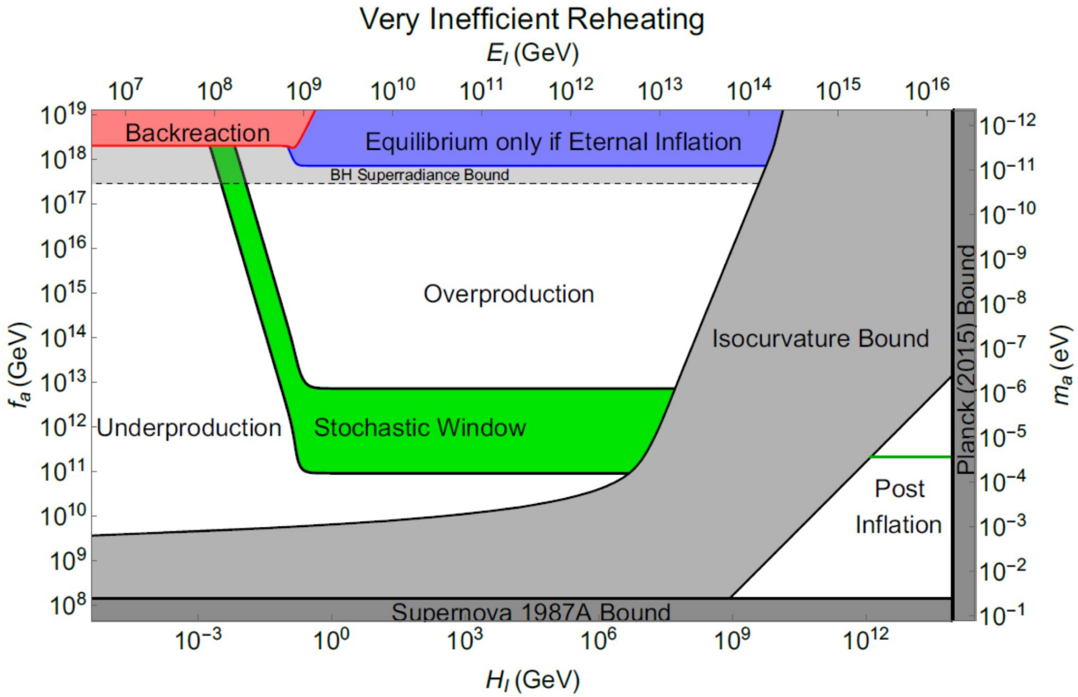


P.W. Graham and A. Scherlis, Phys. Rev. **D 98** (2018): 035017
F. Takahashi, W. Yin, A. H. Guth, Phys. Rev. **D 98** (2018): 015042

Post-inflationary axions:

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

Low-mass axions < 1 μeV are well-motivated



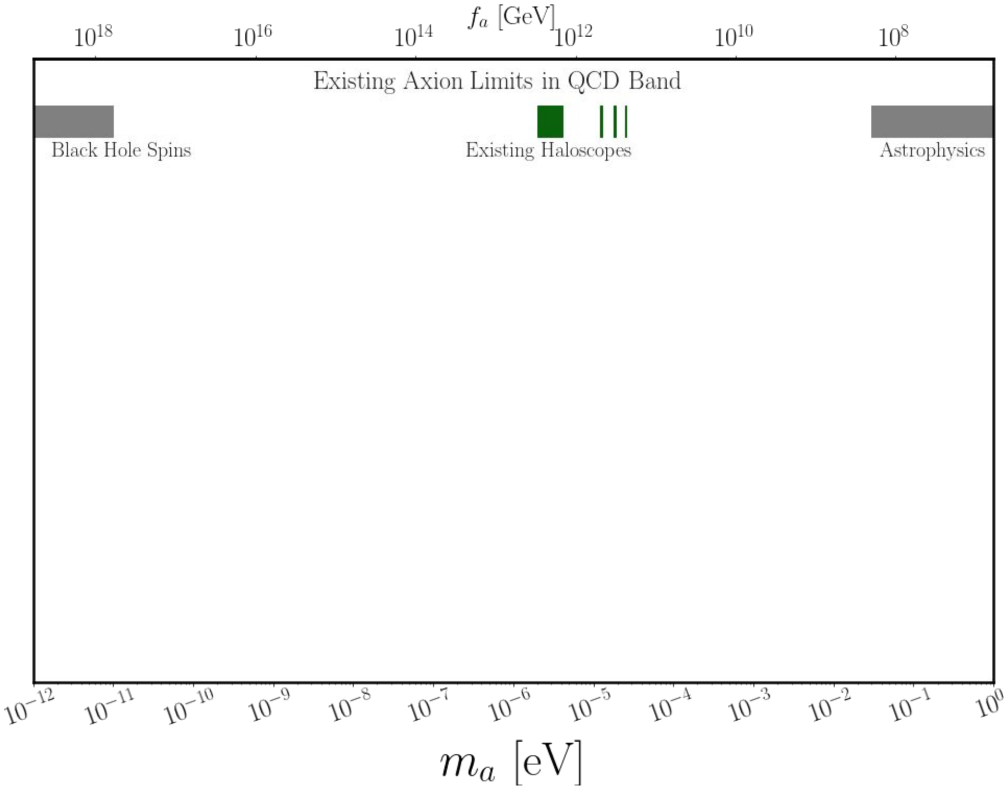
P.W. Graham and A. Scherlis, Phys. Rev. **D 98** (2018): 035017
F. Takahashi, W. Yin, A. H. Guth, Phys. Rev. **D 98** (2018): 015042

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)

The search for the QCD axion: current status

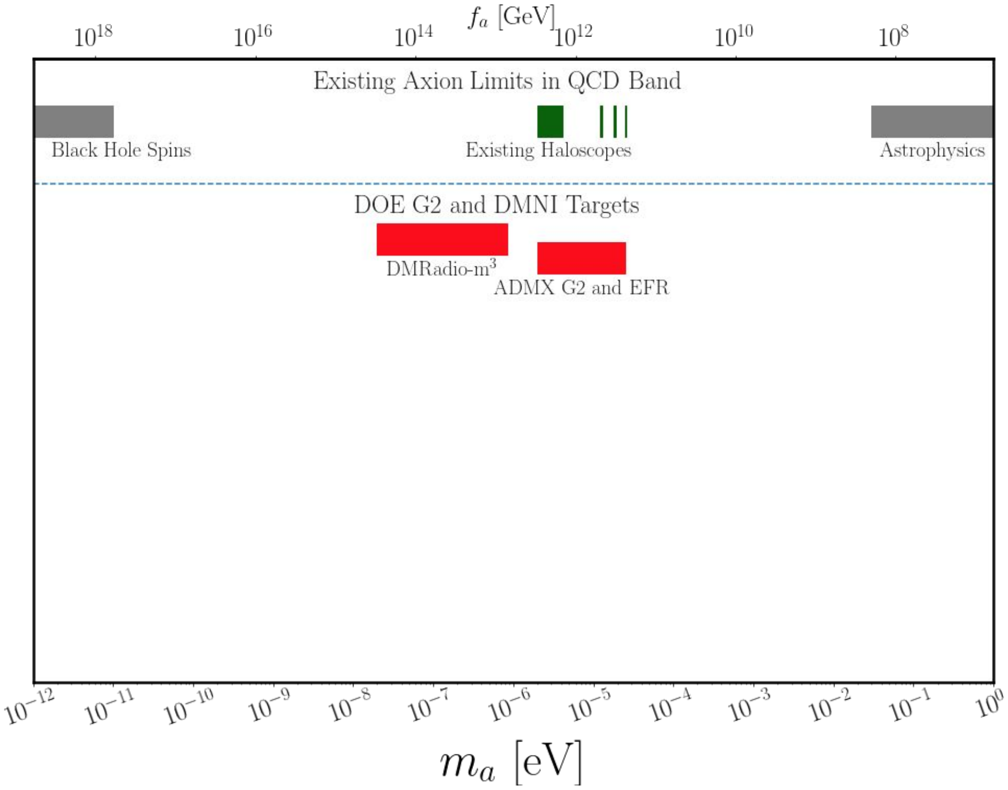
Existing haloscopes have started probing the QCD axion band in past few years



The search for the QCD axion: Dark Matter New Initiatives

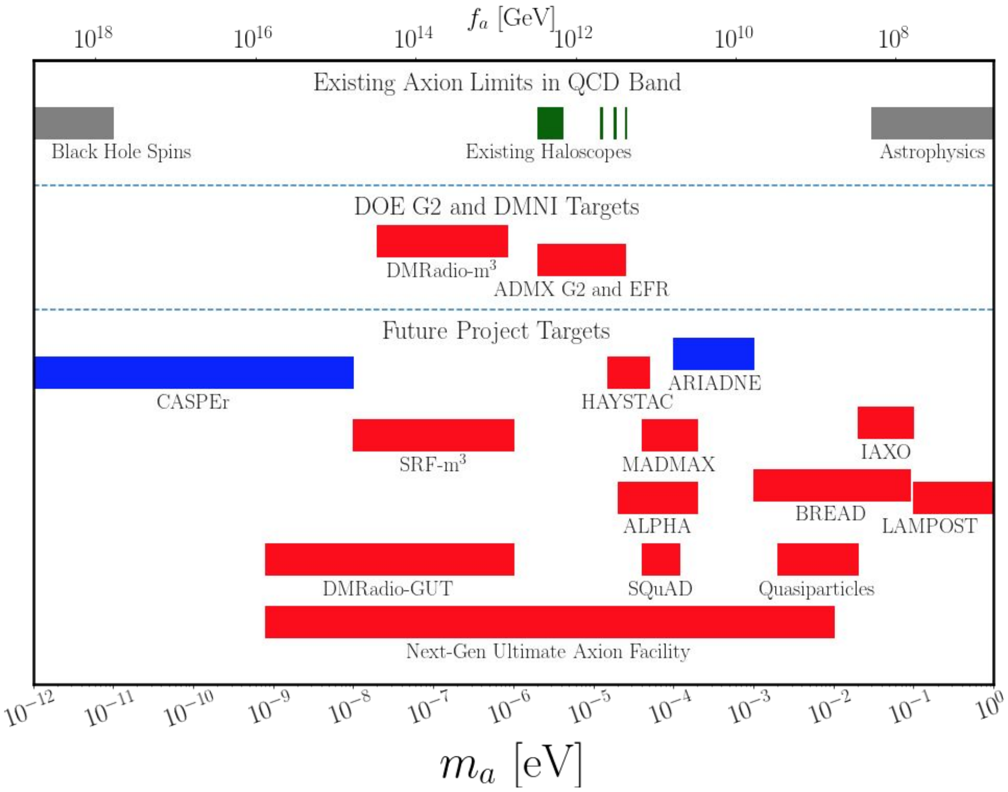
DMNI funded detailed design studies to be completed in June 2023

DMRadio-m^3 and ADMX are the two DOE DMNI projects poised to make significant inroads in QCD axion parameter space



The search for the QCD axion: future plans

Many detectors that vary from proof-of-principle to operating experiments will address the full QCD axion parameter space



DMRadio program overview

DMRadio-50L (see Poster #13)

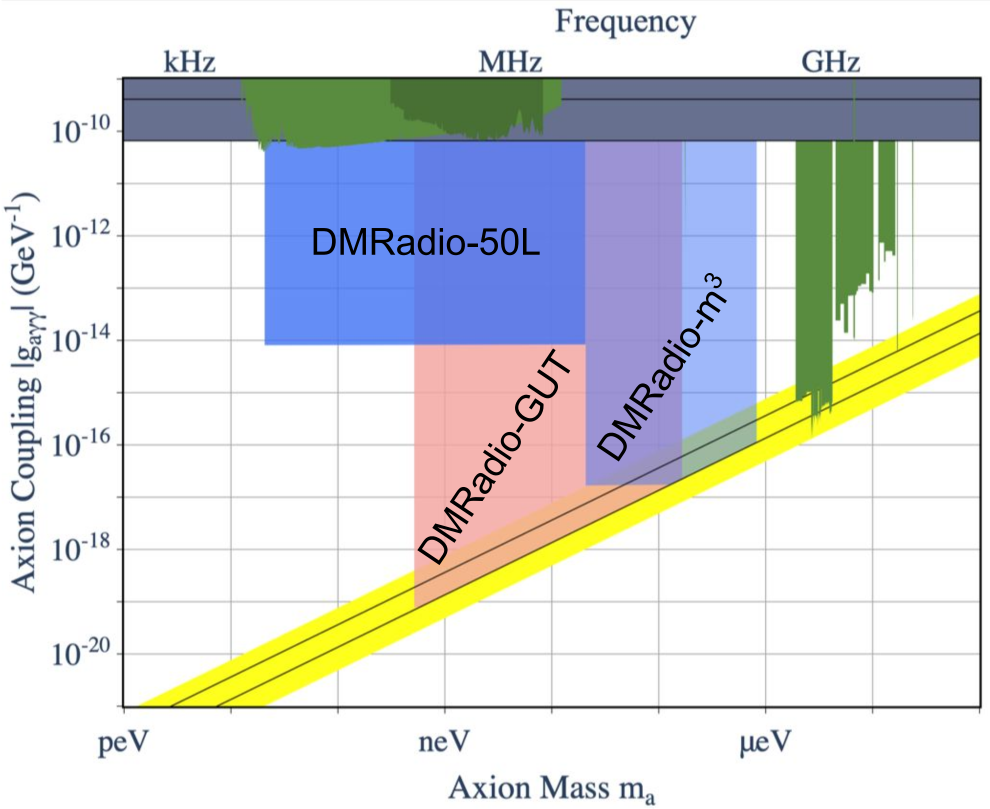
- 5 kHz - 5 MHz
- Quantum sensor testbed

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
- DOE DMNI

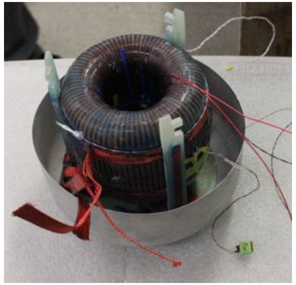
DMRadio-GUT (arXiv:2203.11246)

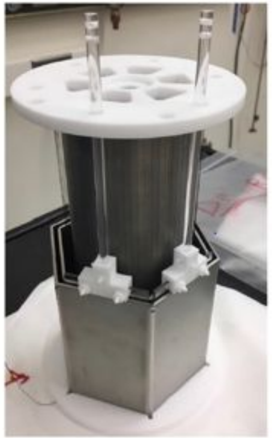
- DFSZ 100 kHz - 30 MHz
- Next-generation detector



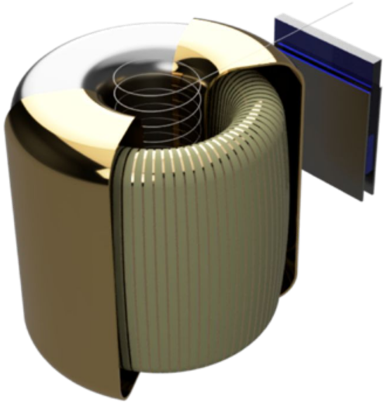
DMRadio program status

DMRadio-Pathfinder, ABRACADABRA: in operation

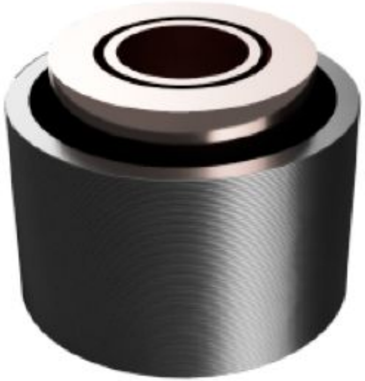




DMRadio-50L: under construction



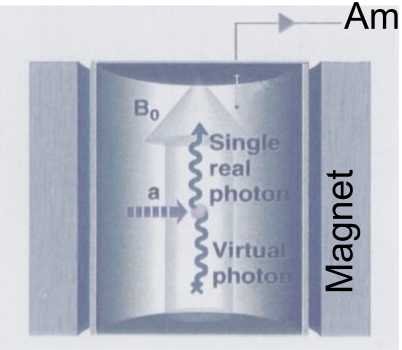
DMRadio-m^3: design complete in 2023



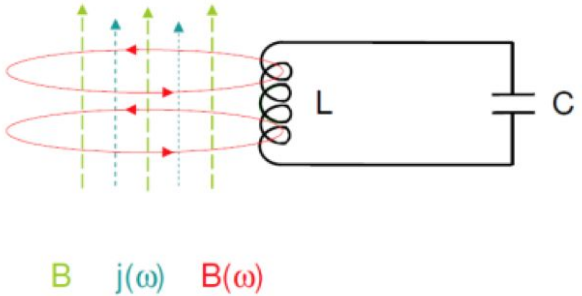
Probing QCD axions through electromagnetism

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

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

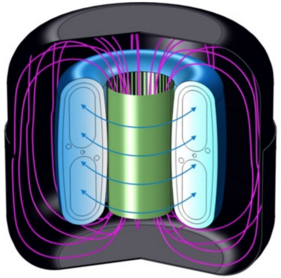


Proposal: Cabrera, Thomas (2010)
v < 300 MHz
Lumped element searches (DMRadio,...)

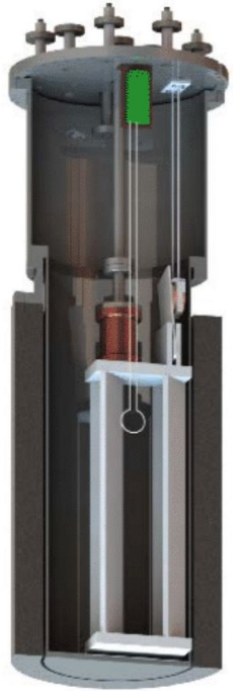


Partial history of sub-μeV searches

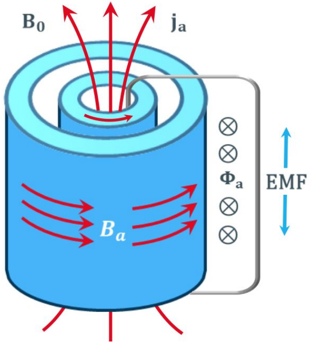
ABRACADABRA:
PRL 127 (2021) 081801.



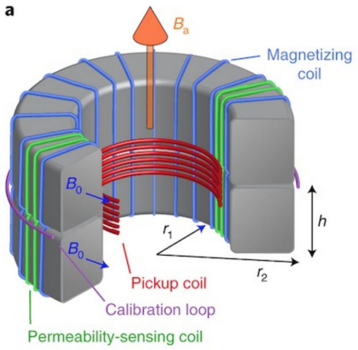
ADMX SLIC:
PRL 124 (2020) 241101.



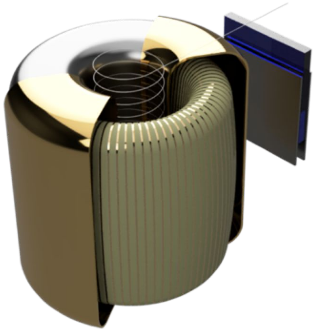
WISPLC:
PRD 106 (2022) 023003.



SHAFT:
Nature Physics 17 (2021) 79.

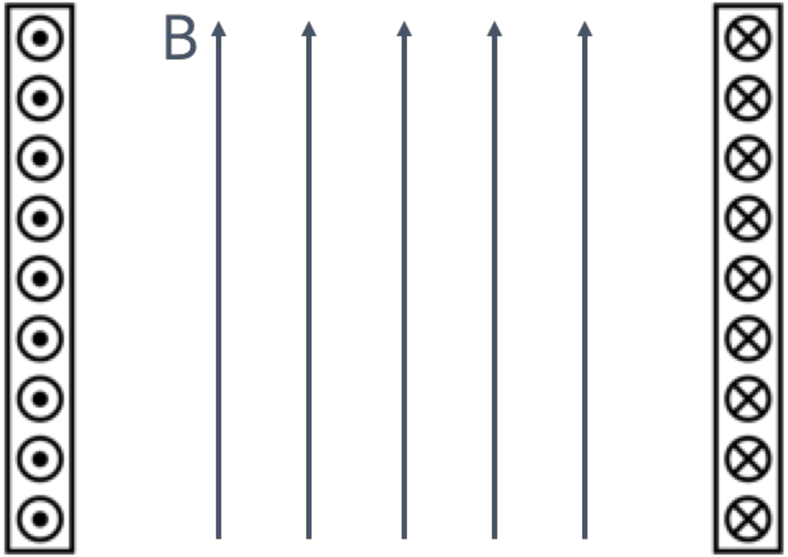


DMRadio:
PRD 92 (2015) 07512.



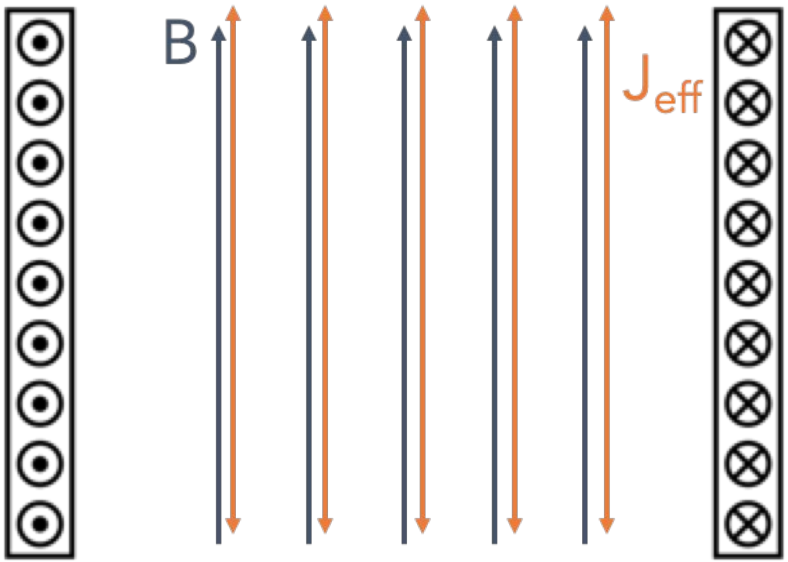
DMRadio-m^3 is an axion detector

- Solenoidal magnet provides a peak field of 7 T ($B_{z,avg}$ = 4.6 T)



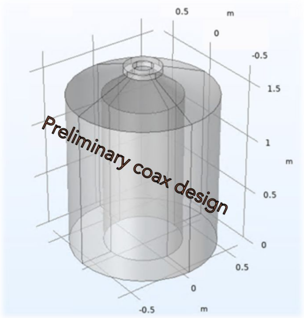
DMRadio-m^3 is an axion detector

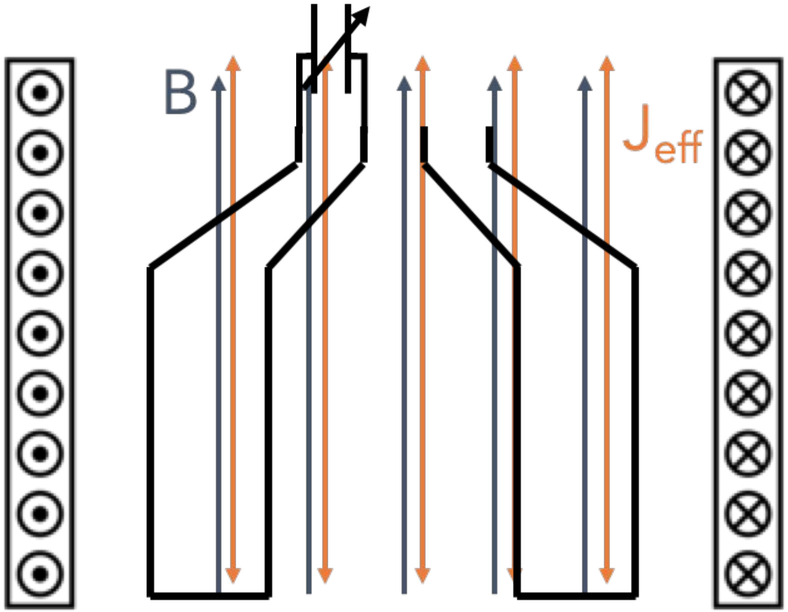
- Solenoidal magnet provides a peak field of 7 T ($B_{z,avg}$ = 4.6 T)
- Axions behave as an effective AC axion current



DMRadio-m^3 is an axion detector

- Solenoidal magnet provides a peak field of 7 T ($B_{z,avg}$ = 4.6 T)
- Axions behave as an effective AC axion current
- Resonator is made of a copper coax in the high-B-field region and a superconducting tunable capacitor





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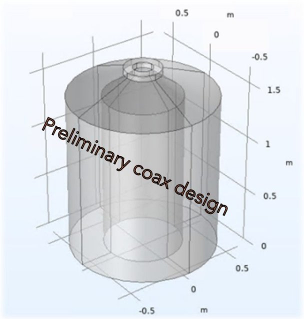

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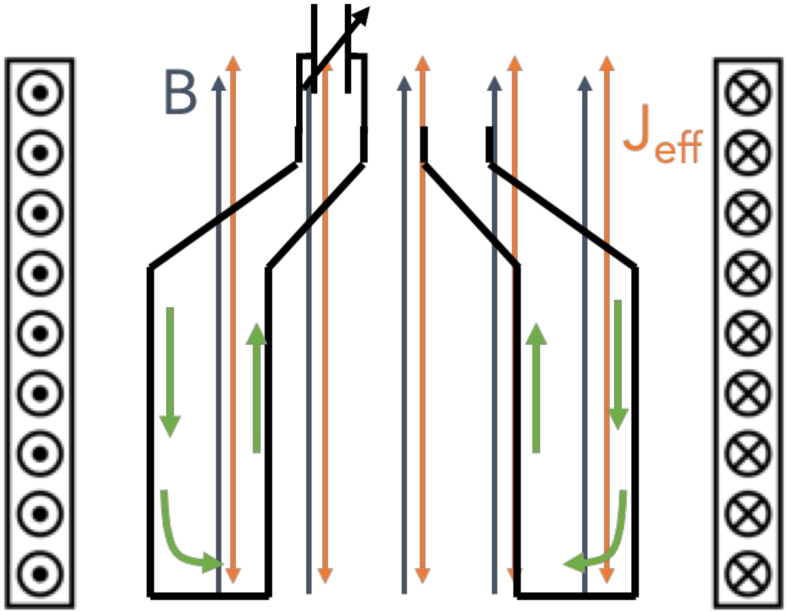
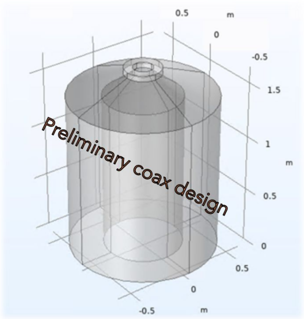
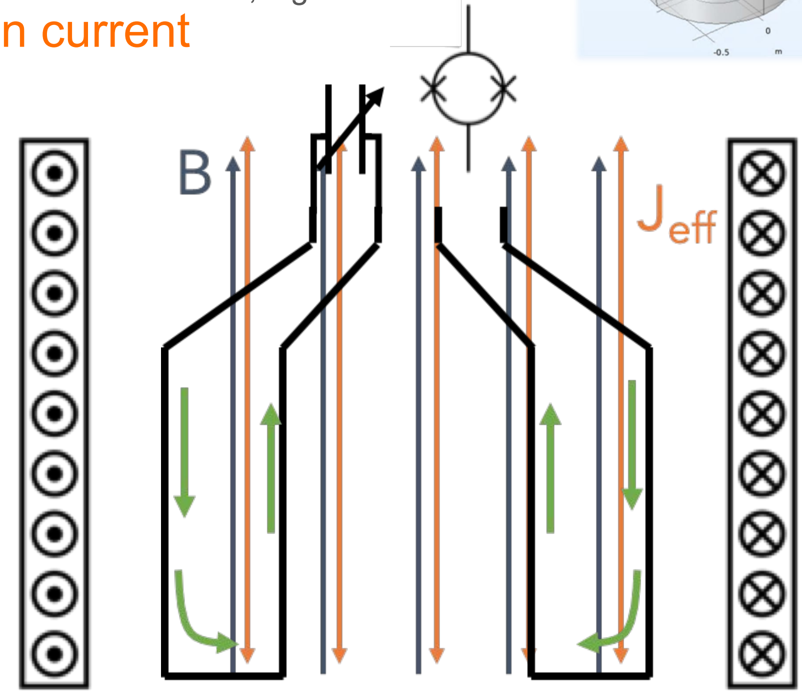
- Axions behave as an effective AC axion current
- Resonator is made of a copper coax in the high-B-field region and a superconducting tunable capacitor
- Effective AC axion current generates an oscillating magnetic field that induces screening currents to flow on the coax



DMRadio-m^3 is an axion detector

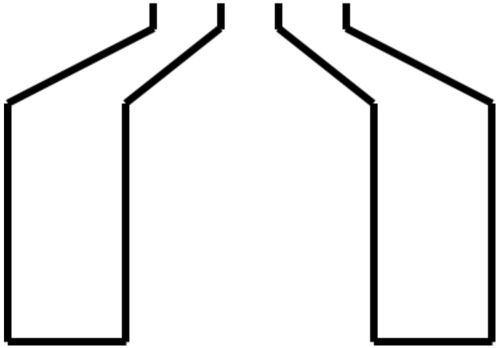
- Solenoidal magnet provides a peak field of 7 T ($B_{z,avg}$ = 4.6 T)
- Axions behave as an effective AC axion current
- Resonator is made of a copper coax in the high-B-field region and a superconducting tunable capacitor
- Effective AC axion current generates an oscillating magnetic field that induces screening currents to flow on the coax
- Signal readout by a dc SQUID



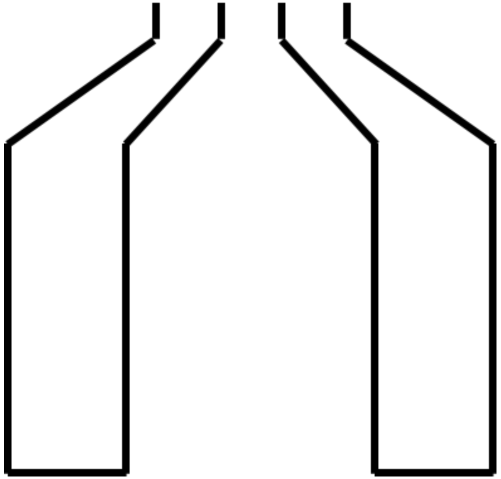


DMRadio-m^3 coaxial inductor

- Manufactured with OFHC copper with RRR > 100
- Resonator Q is limited by loss in the normal copper electrons (~150000 at 30 MHz)
- Coaxial inductor will be shorter at highest frequencies for optimal performance

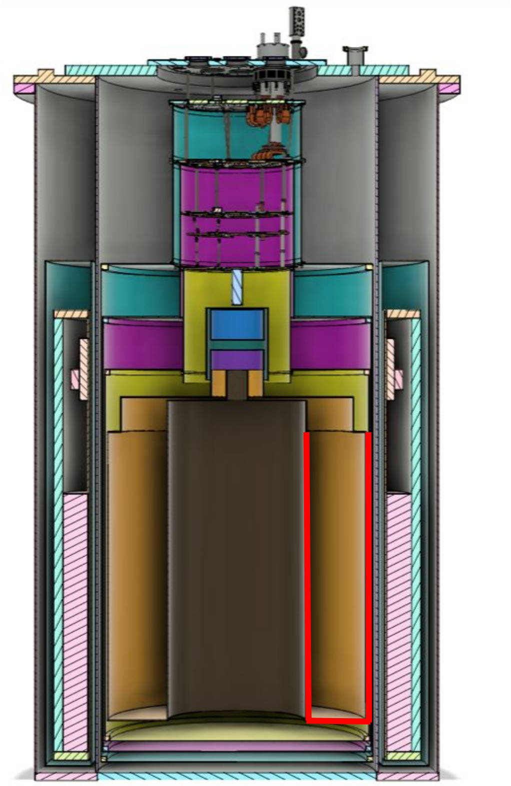


Coax for higher frequencies

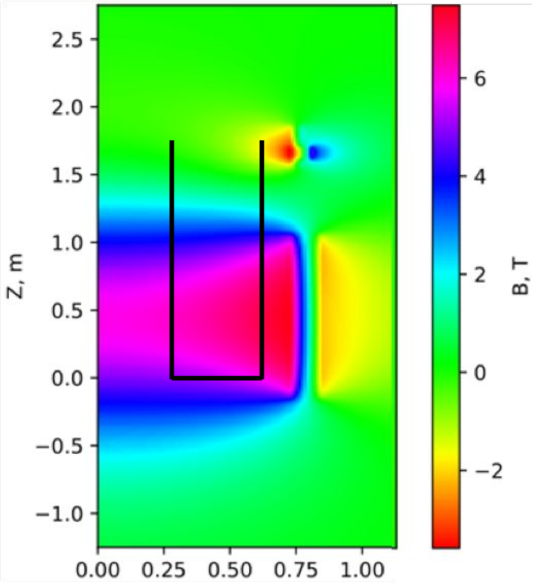


Coax for lower frequencies

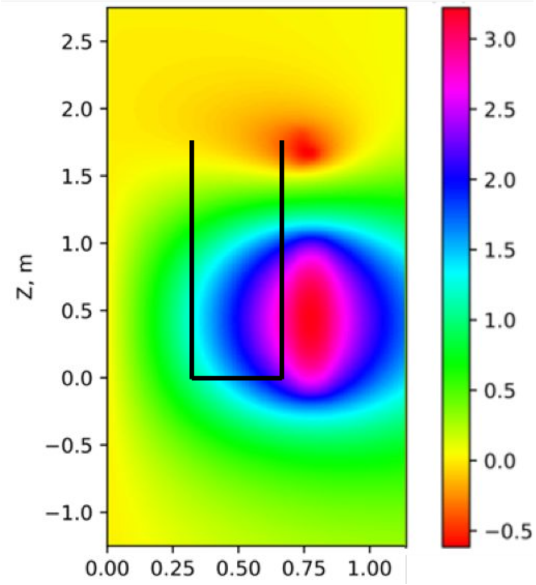
Coaxial coupled energy simulations



Axial
DC magnetic field



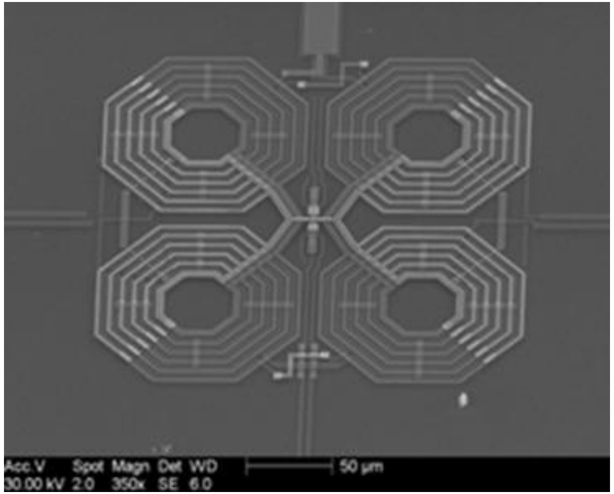
Circumferential
AC axion signal



Axis of rotational symmetry

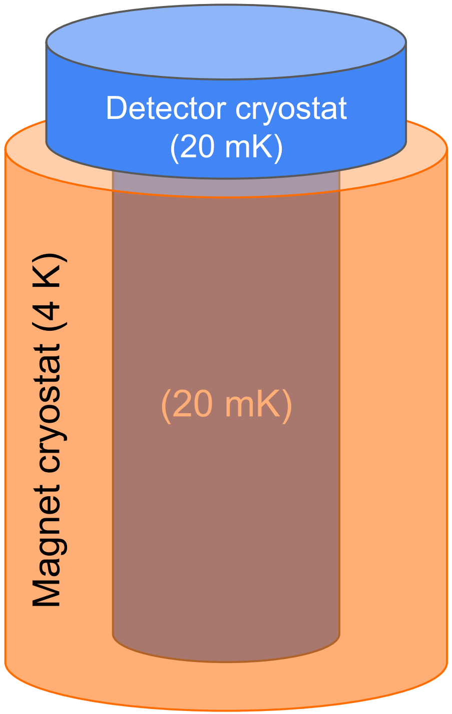
DC SQUIDs as a readout for DMRadio-m^3

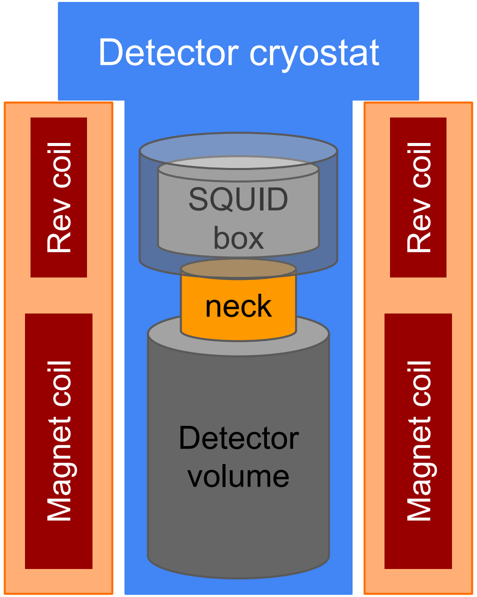
- Two dc SQUID channels: science channel and calibration channel
- We are evaluating SQUIDs from NIST, Magnicon, Quantum Design, Star Cryo, SeeQC, VTT. The selected SQUIDs may be based on our own design (fabricated by NIST), or fully commercial.

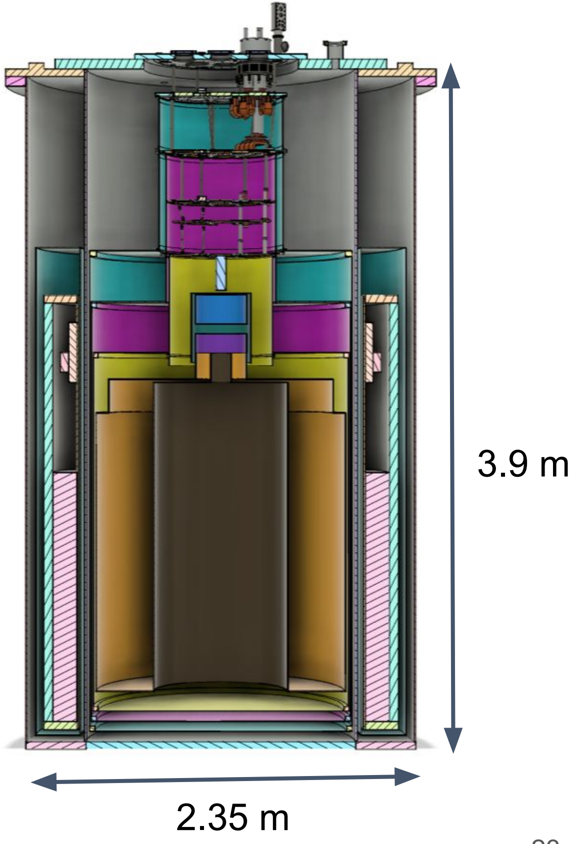


100 µm

DMRadio-m^3 cryogenic system







DMRadio-m^3 design

Inconel 718 support rods and anti-sway rings

G-10 magnet support tubes

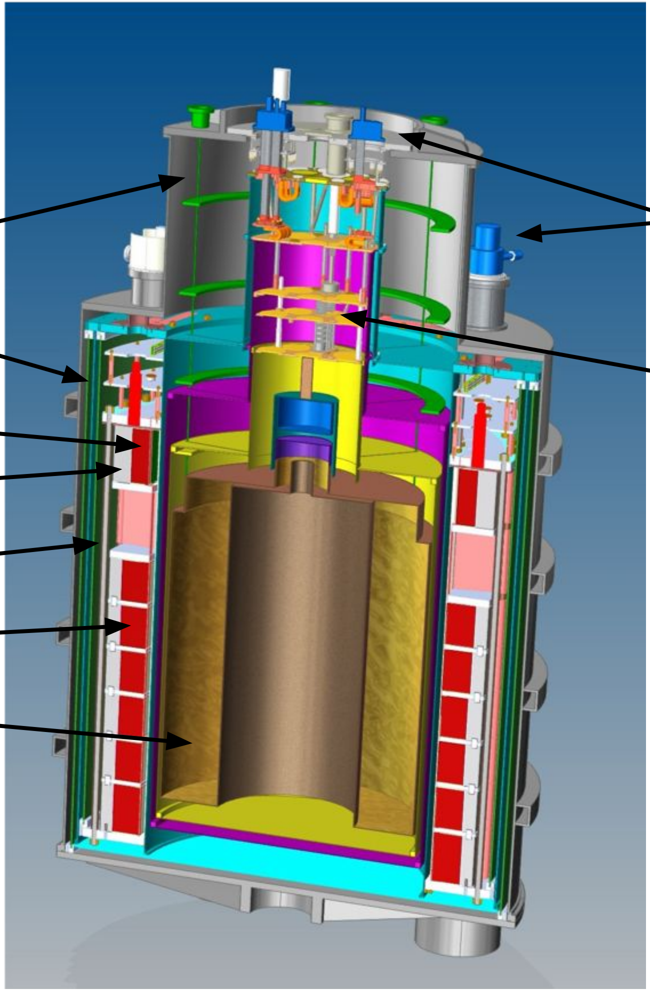
Bucking coil

Outer 6063 Al support ring

OD Inconel 718 magnet rods

Six main solenoid coils

Copper coax (at 20 mK)



Cryocoolers: Cryomech PT425

- 4 for magnet
- 2 for dilution refrigerator

Dilution refrigerator: Bluefors XLD 1000

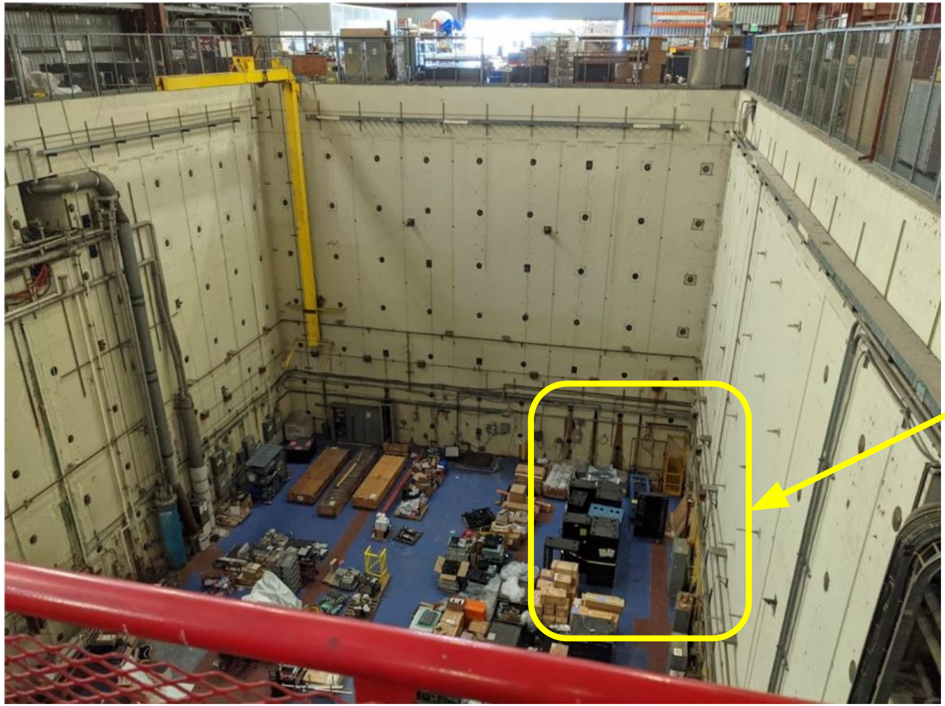
Vacuum shell

55 K thermal shield

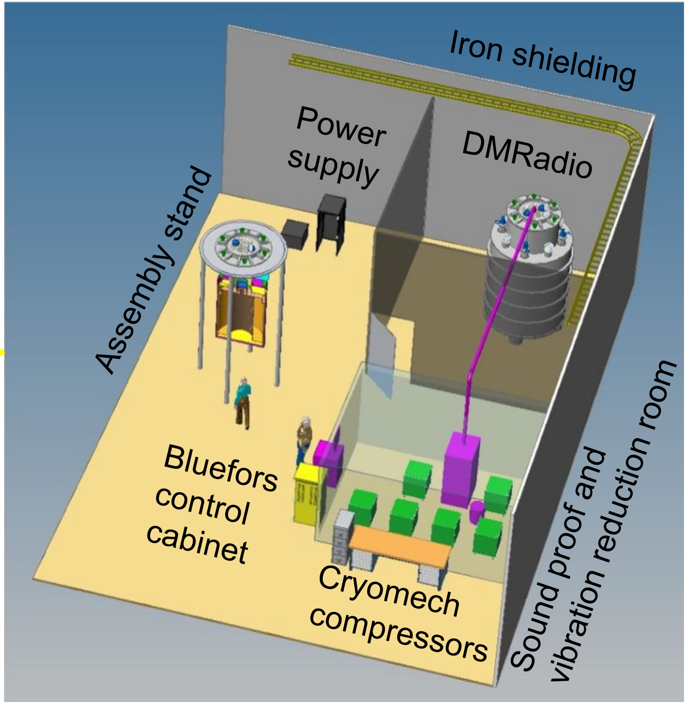
4 K thermal shield

1 K thermal shield

Installation site at SLAC



SLAC Building 750 - DMRadio-m^3 to be located in the NW corner. Utilities run along the bottom at head height.



Experimental layout located within concrete walls and iron shielding walls.

DMRadio-GUT: next-generation experiment

Scan rate for quasi-static search in thermal limit: $d\nu/dt \sim B^4 V^{10/3} Q / T \eta$

- Strong magnetic field B: 16 Tesla peak field
- Large volume V: ~ 10 m^3
- High quality factor Q: ~ 10^7
- Low temperature T: 10 mK with dilution refrigerator
- Minimal readout noise η: quantum sensors

References on arXiv: 2203.11246, 1803.01627

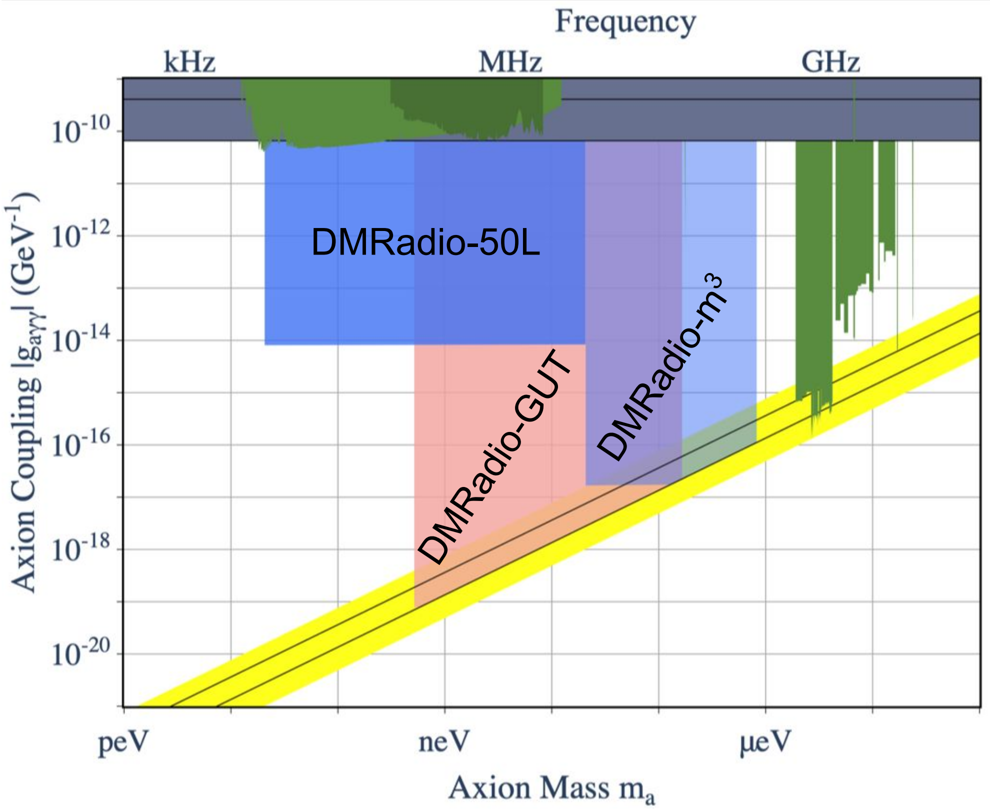
Summary and conclusions

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

DMRadio-m^3 is an axion detector with DFSZ sensitivity 30-200 MHz

DMRadio-m^3 design will be completed in 2023 as part of DOE's Dark Matter New Initiatives

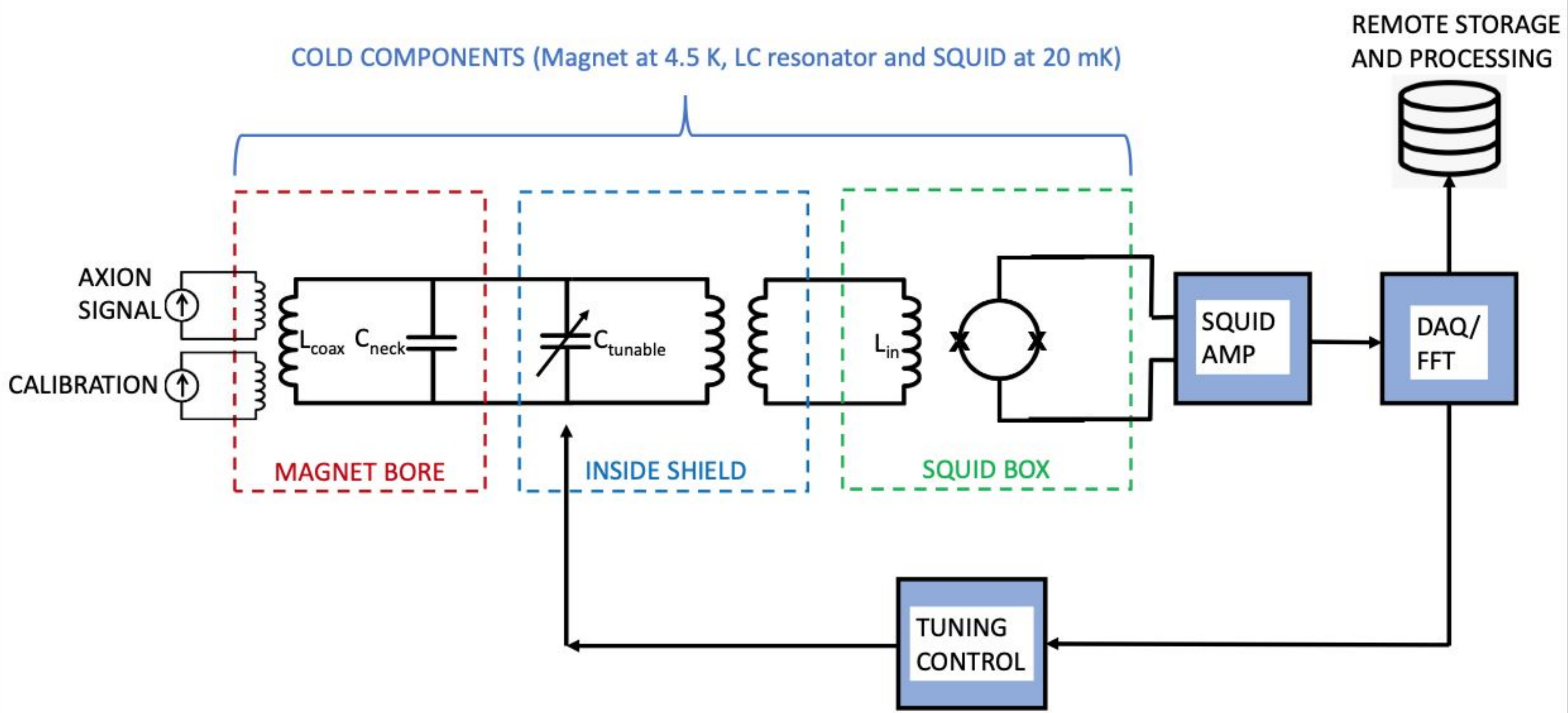
DMRadio-GUT is a next-generation experiment that will require technology developments and experience from DMRadio-m^3 and DMRadio-50L



Check out Kent Irwin’s poster #13 on Dark Matter Radio - 50 Liter

Thank you for listening!
- DMRadio collaboration

Signal flow and system overview



DMRadio - GUT

Parameter	Target Value	State of the Art
Magnetic field	16 T	~8 T (ADMX-G2)
Volume	10 m^3	~0.1 m^3 (ADMX-G2)
Quality Factor	2 x 10^7	~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	