DMRadio-50L Overview and Status Update

18th Patras Workshop on Axions, WIMPs, and WISPs
Rijeka, Croatia / Trieste, Italy
July 5, 2023

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

Outline

DMRadio motivation and context

DMRadio goals (see talk tomorrow by Dale Li at 10:15 am “The Dark Matter Radio Suite of Experiments”)

DMRadio-50L as an axion detector

Status of DMRadio-50L

Conclusion

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

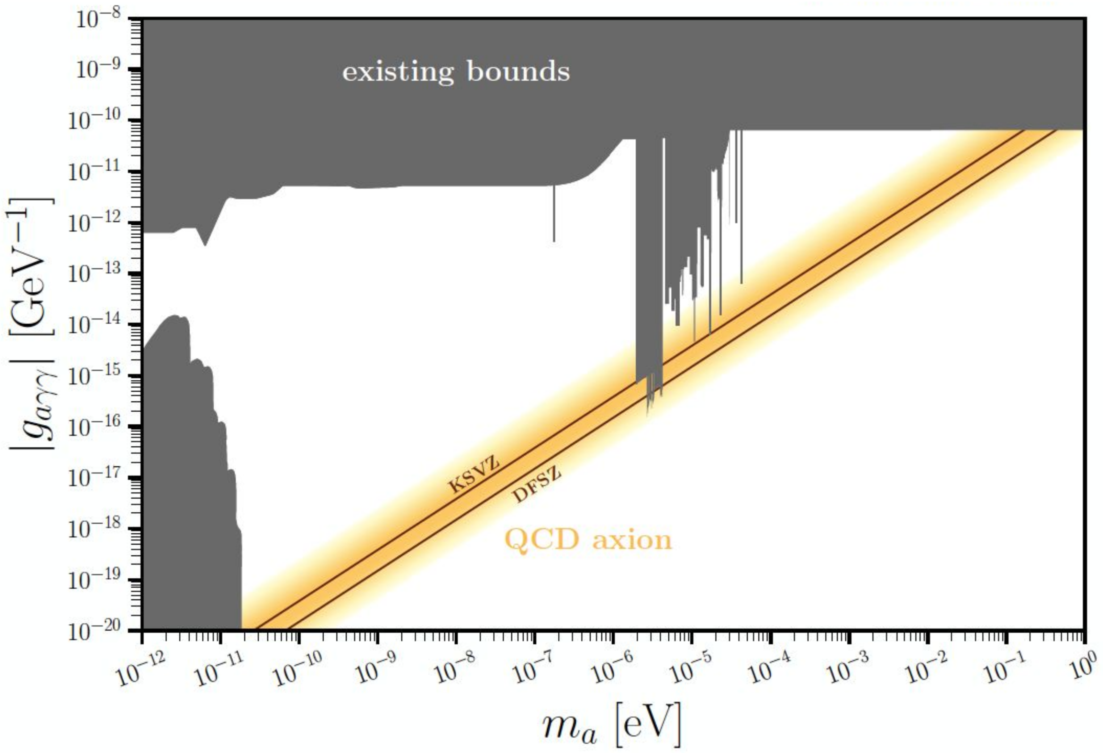


Figure by A. Berlin and others

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

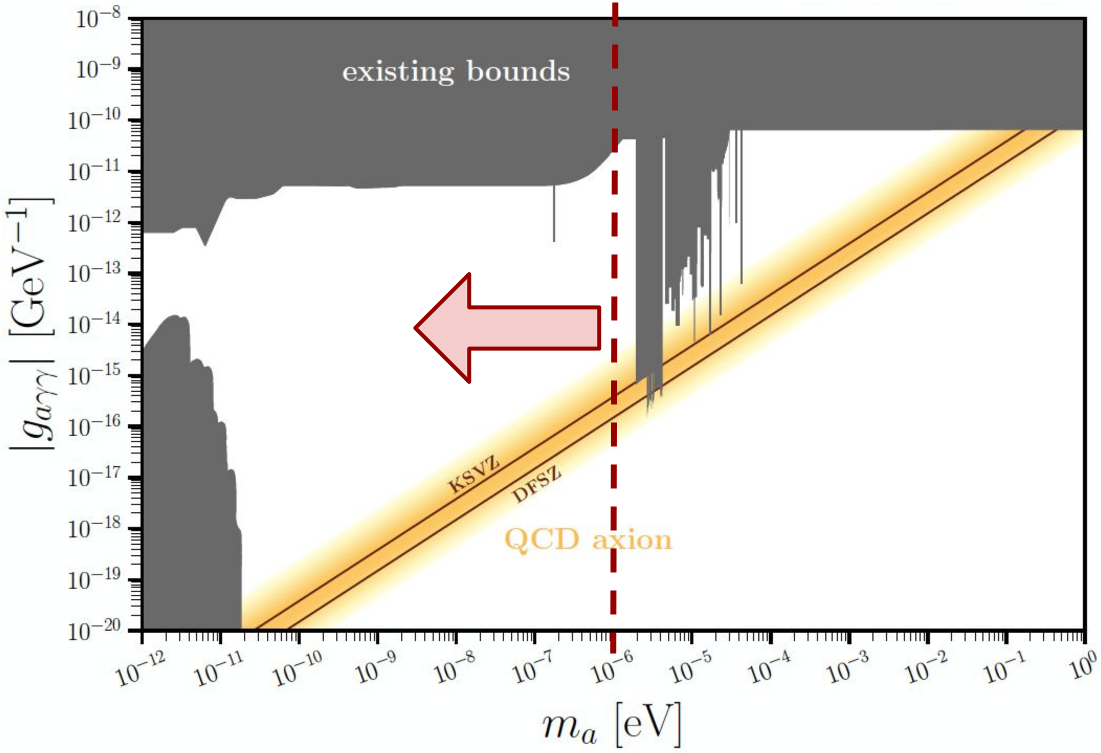
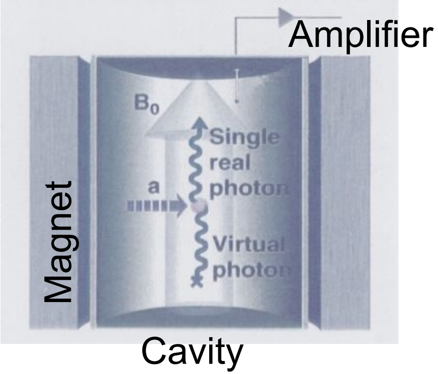


Figure by A. Berlin and others

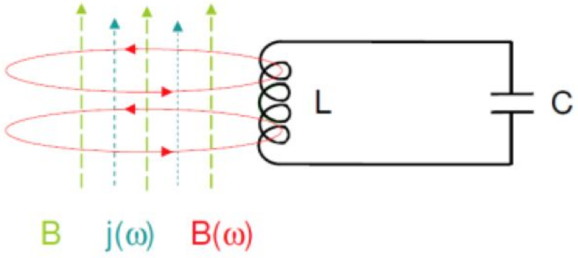
Probing QCD axions through electromagnetism

- 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,...)



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

DMRadio Collaboration

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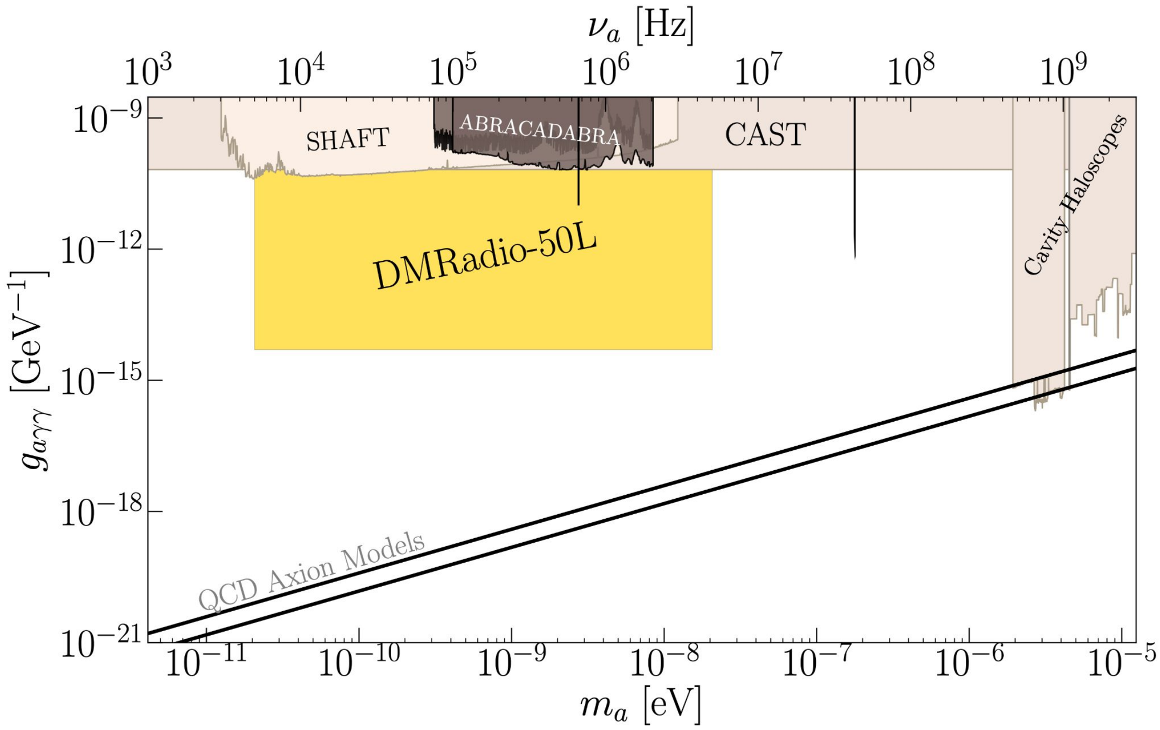
DMRadio program overview

DMRadio-50L

- 5 kHz - 5 MHz
- Quantum sensor testbed



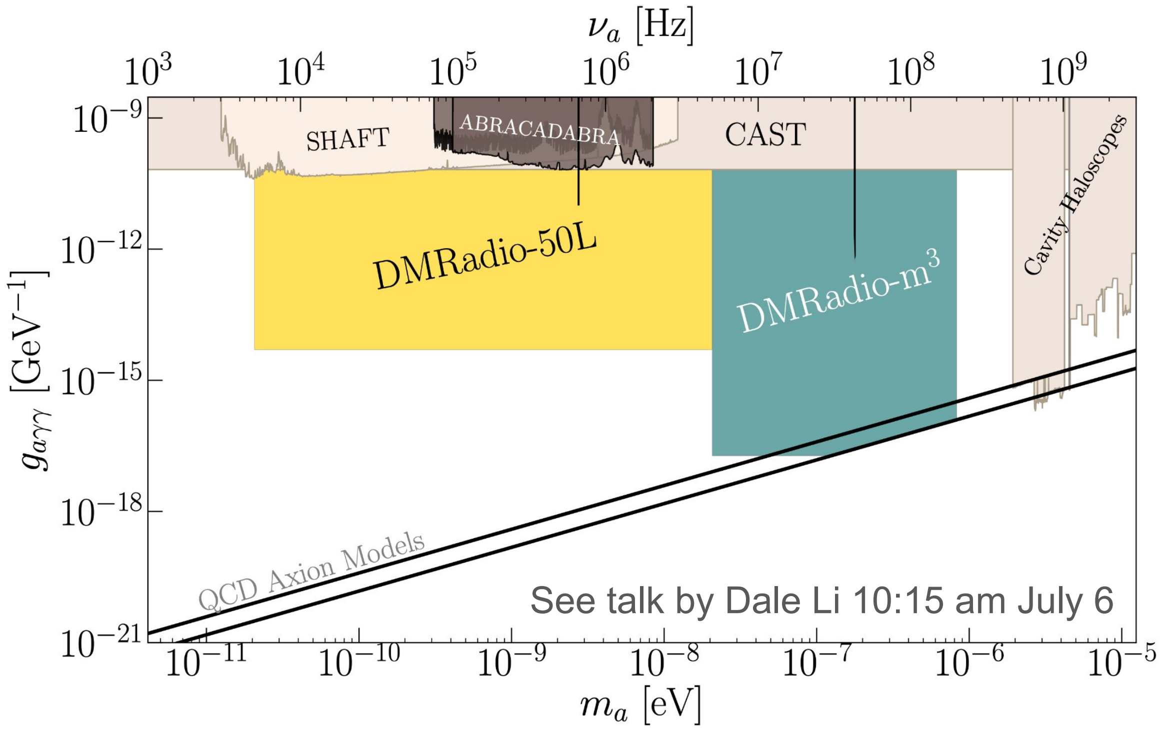
DMRadio program overview

DMRadio-50L

- 5 kHz - 5 MHz
- Quantum sensor testbed

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



DMRadio program overview

DMRadio-50L

- 5 kHz - 5 MHz
- Quantum sensor testbed

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

- Primary goal: DFSZ 30 MHz - 200 MHz
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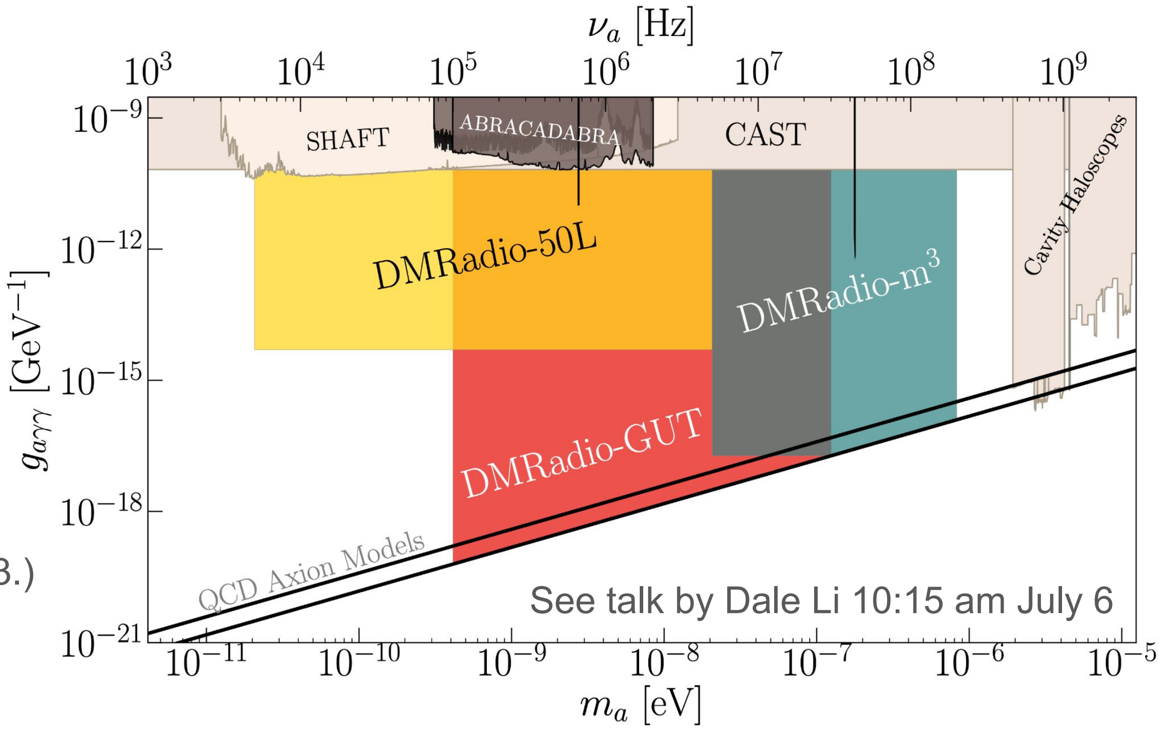
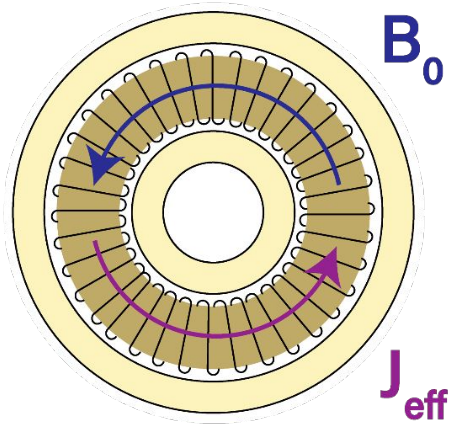
DMRadio-GUT (PRD **106** (2022): 112003.)

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



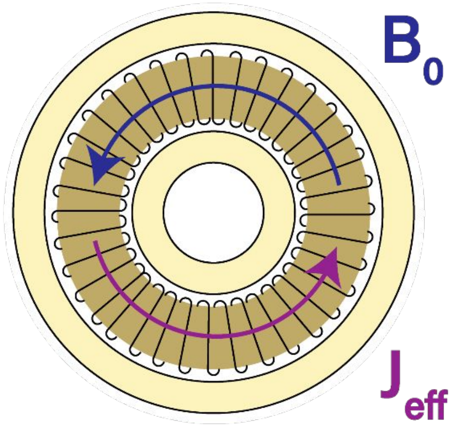
See talk by Dale Li 10:15 am July 6

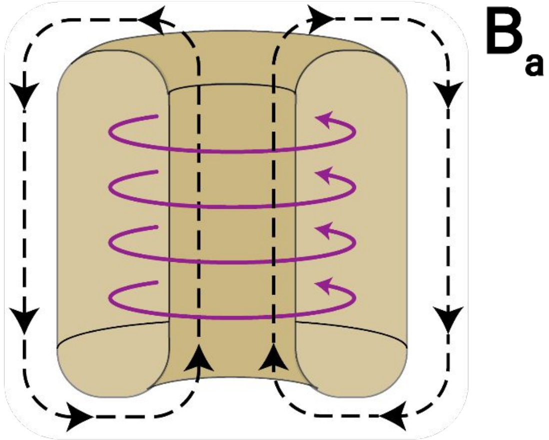
DMRadio-50L detection scheme



Toroidal magnet
with field B_0
creates current J_{eff}

DMRadio-50L detection scheme

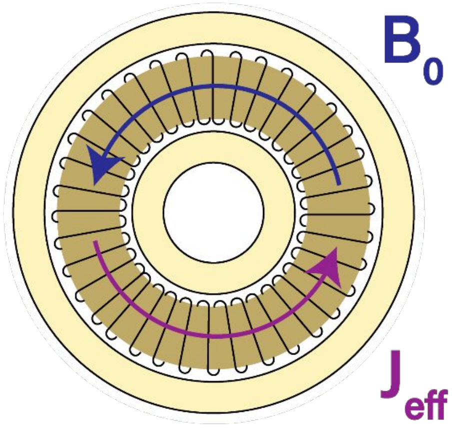


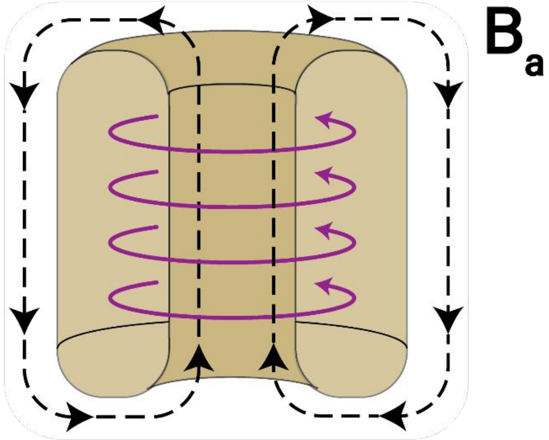


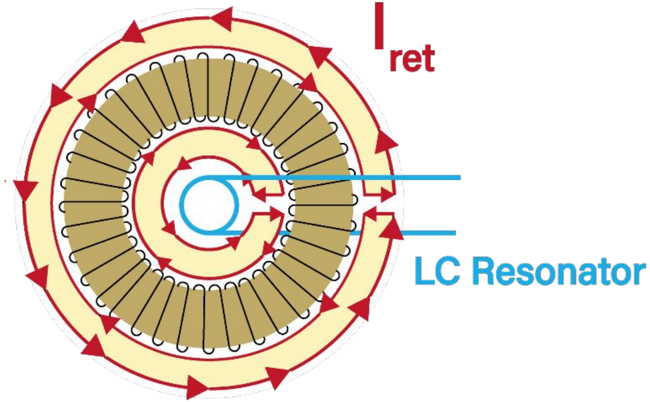
Toroidal magnet
with field B_0
creates current J_{eff}

J_{eff} creates
magnetic field B_a

DMRadio-50L detection scheme





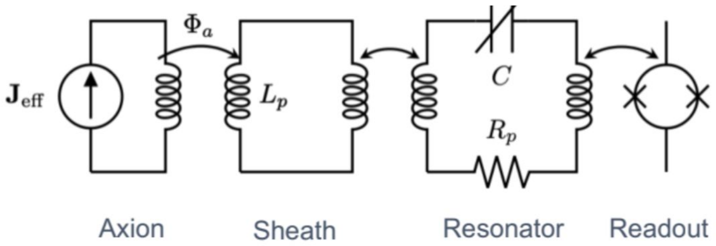


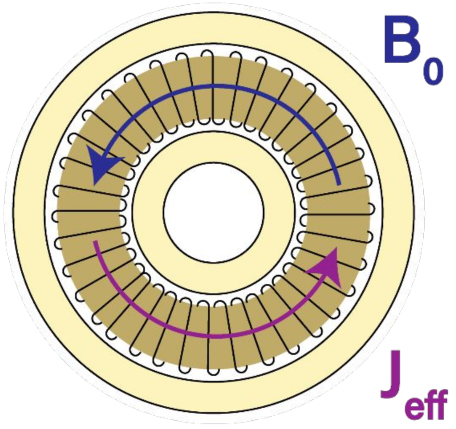
Toroidal magnet with field B_0 creates current J_{eff}

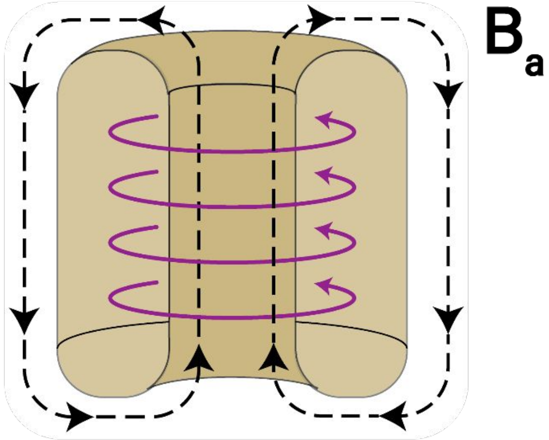
J_{eff} creates magnetic field B_a

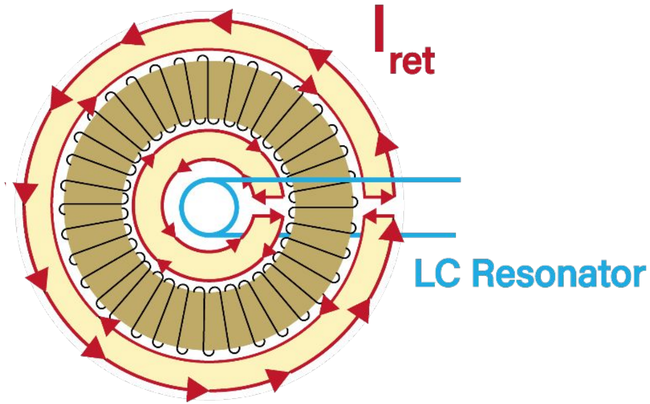
B_a induces I_{ret} which is enhanced by an LC resonator and picked up by a sensor

DMRadio-50L detection scheme









Toroidal magnet with field B_0 creates current J_{eff}

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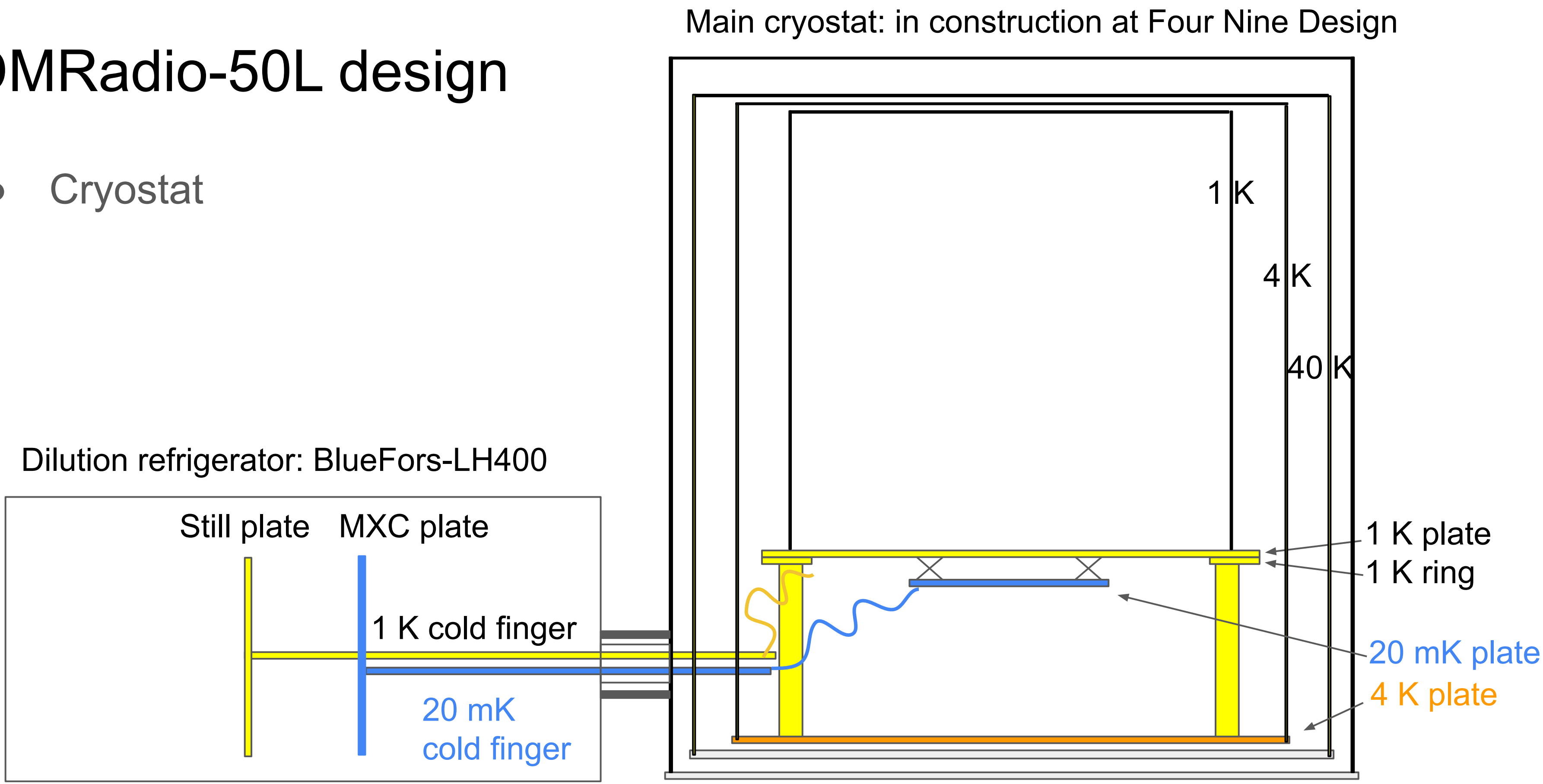
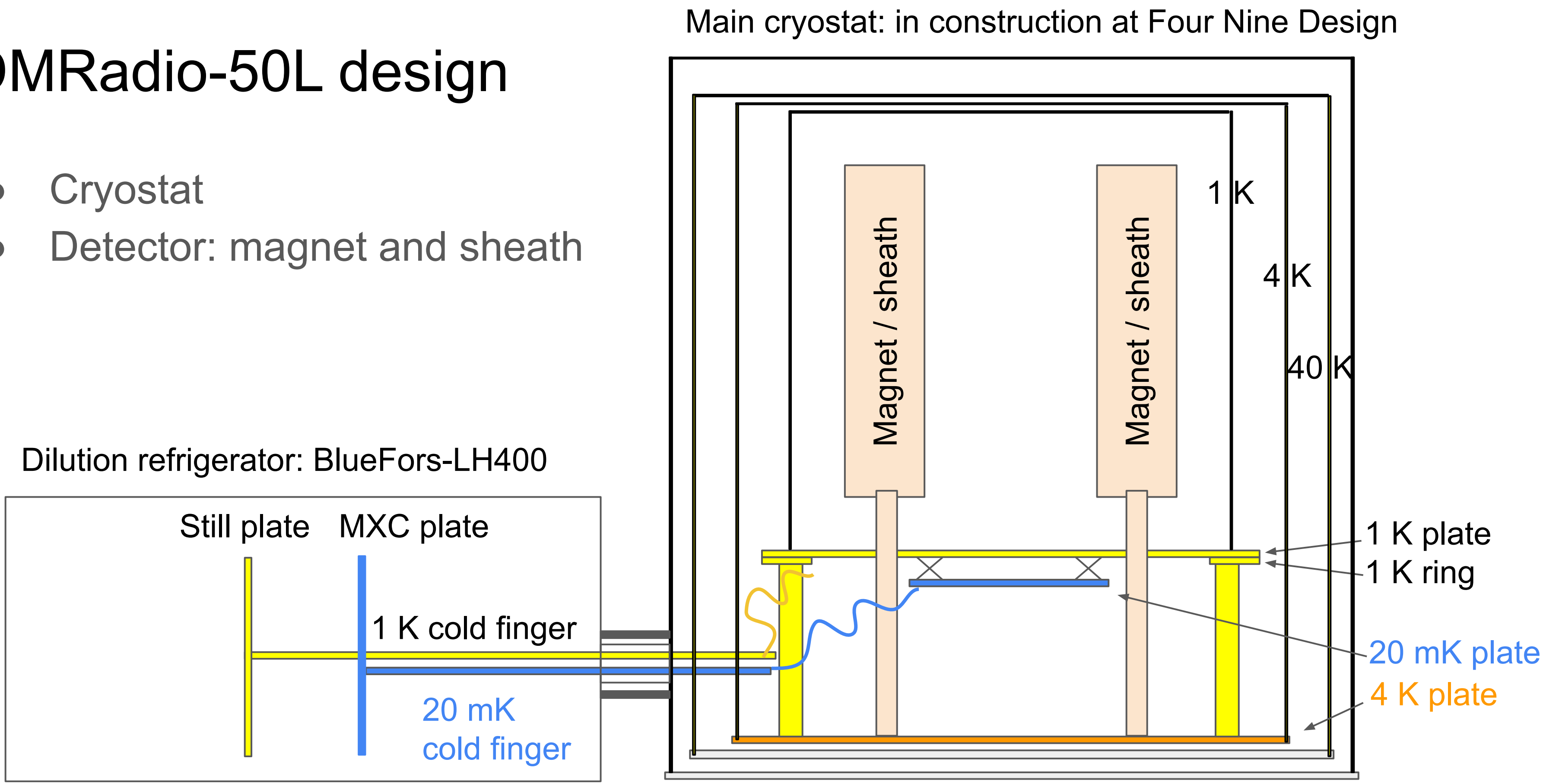
DMRadio-50L design

- Cryostat



DMRadio-50L design

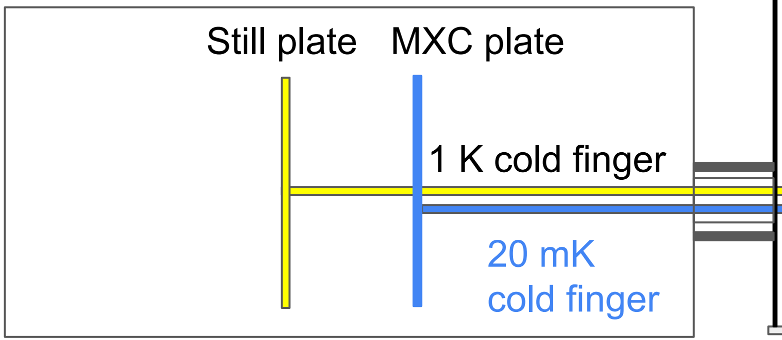
- Cryostat
- Detector: magnet and sheath



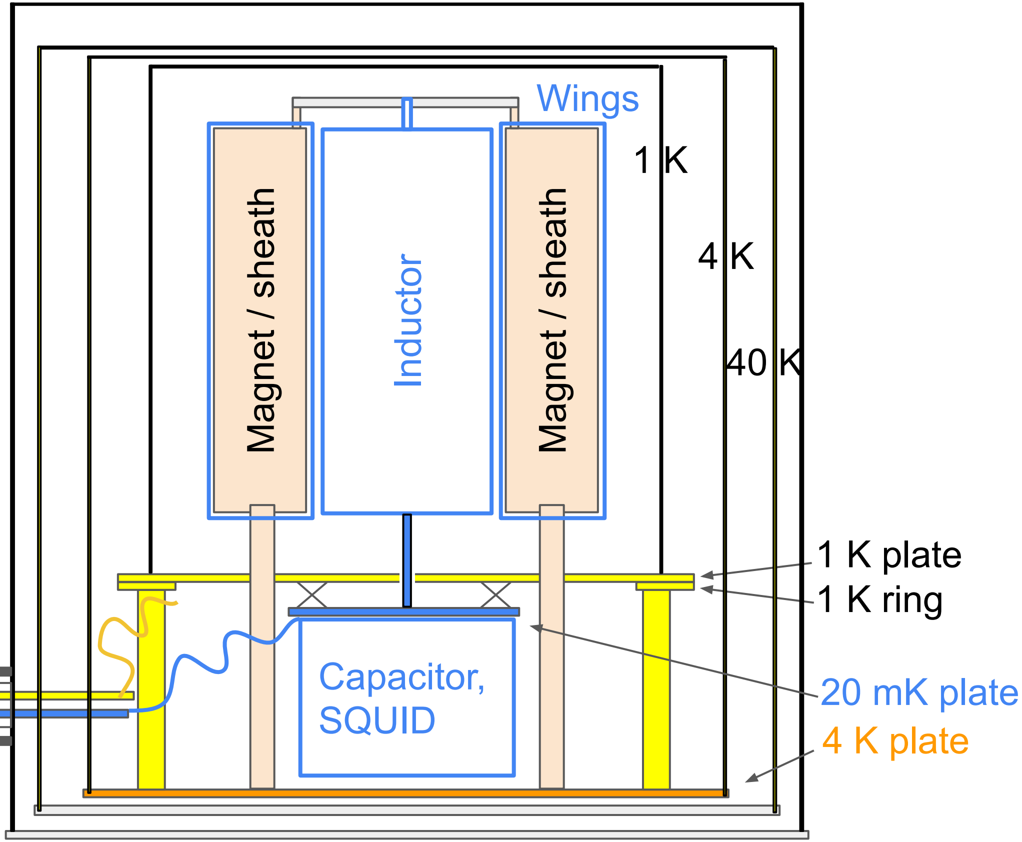
DMRadio-50L design

- Cryostat
- Detector: magnet and sheath
- Receiver: LC resonator and SQUID

Dilution refrigerator: BlueFors-LH400

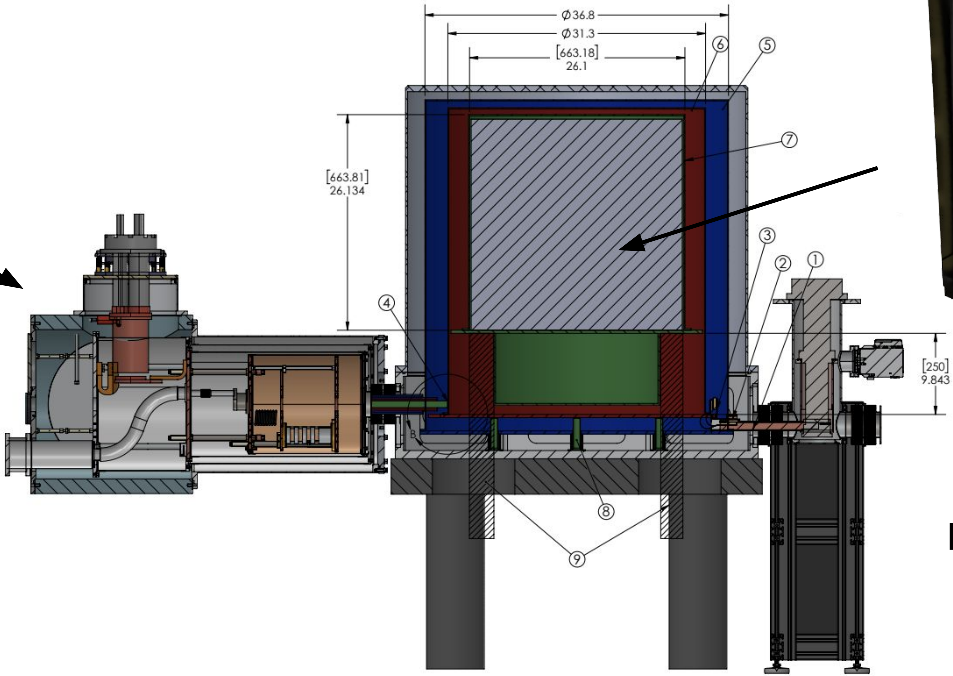


Main cryostat: in construction at Four Nine Design

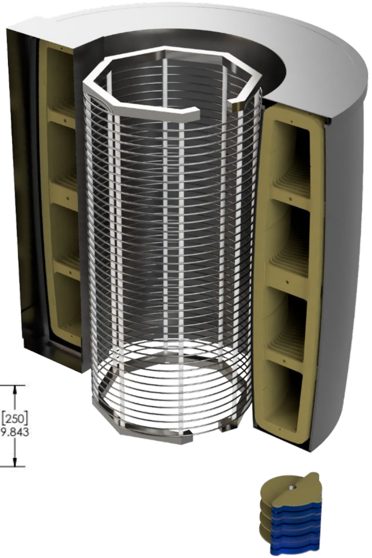


DMRadio-50L: under construction at Stanford

Dilution refrigerator in the lab.



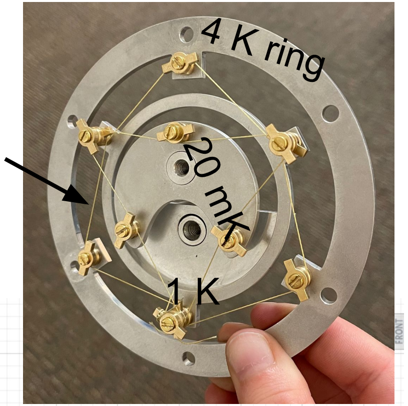
DMRadio-50L cryosystem CAD model.



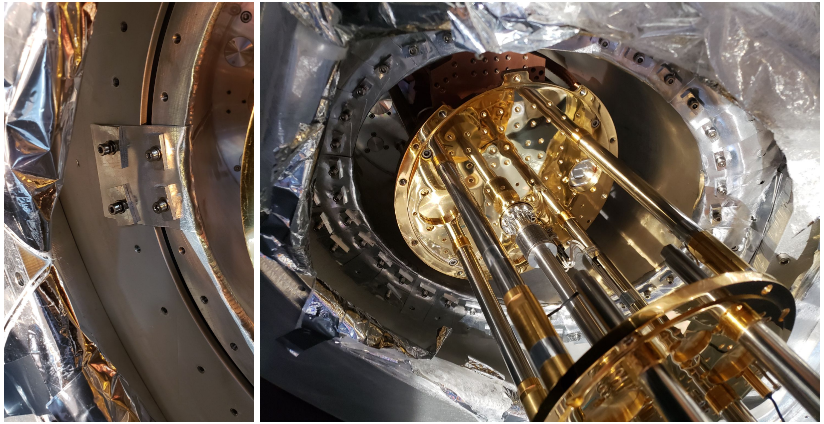
Detector and receiver CAD models.

DMRadio-50L cold snout needs to be flexible

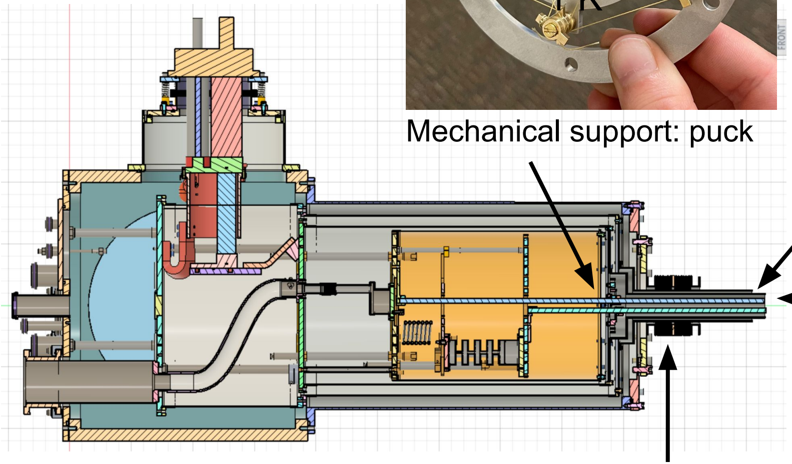
Kevlar string



Mechanical support: puck



Flexible 4 K, 40 K connections: aluminum strips



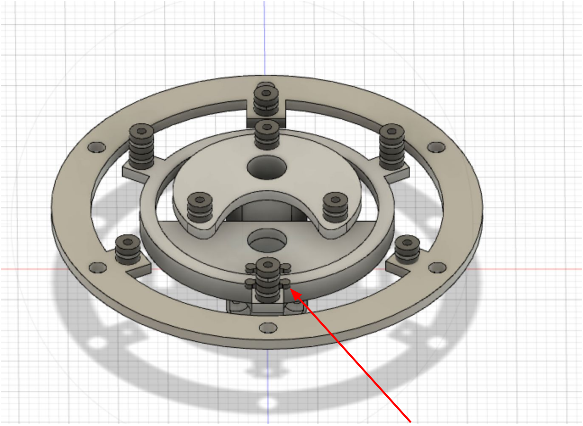
Flexible 1 K, 20 mK connections: copper braids

Dilution refrigerator

Bellows

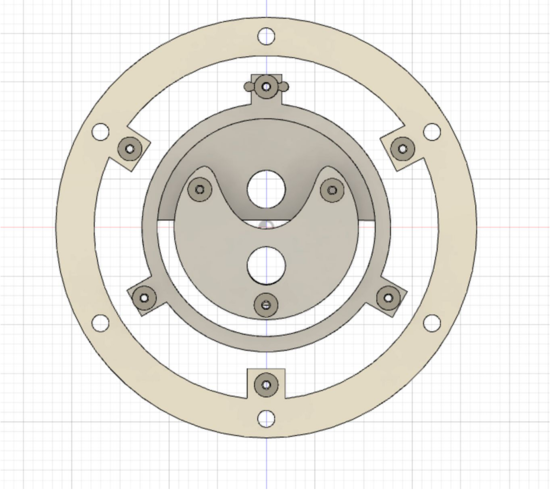
Puck design

Purpose: provide mechanical support for the 1 K and 20 mK cold fingers while keeping them thermally isolated

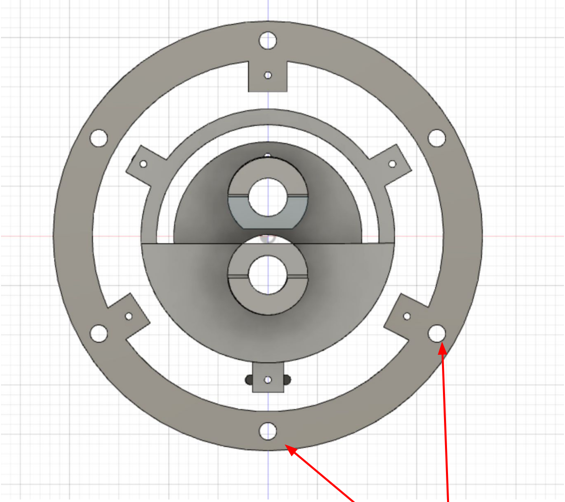


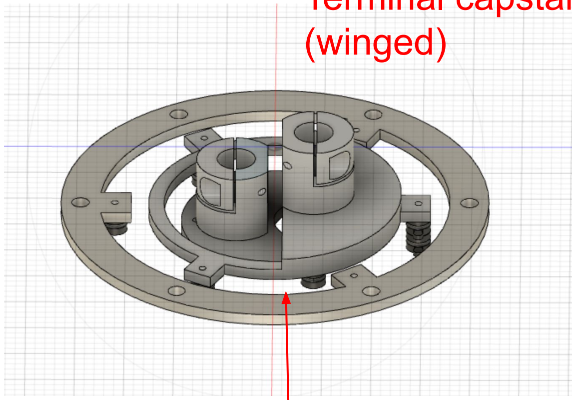
Terminal capstans (winged)

Capstan side



Clamp side





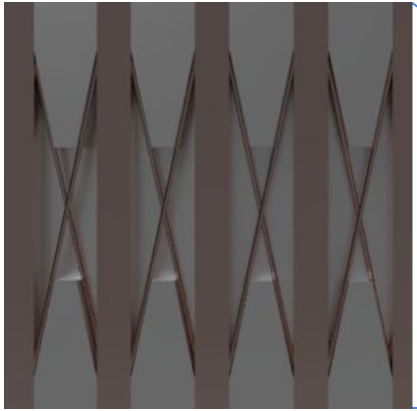
Cold finger diameter: 10 mm
Distance (edge-edge) between cold fingers: 10 mm

Mounting holes

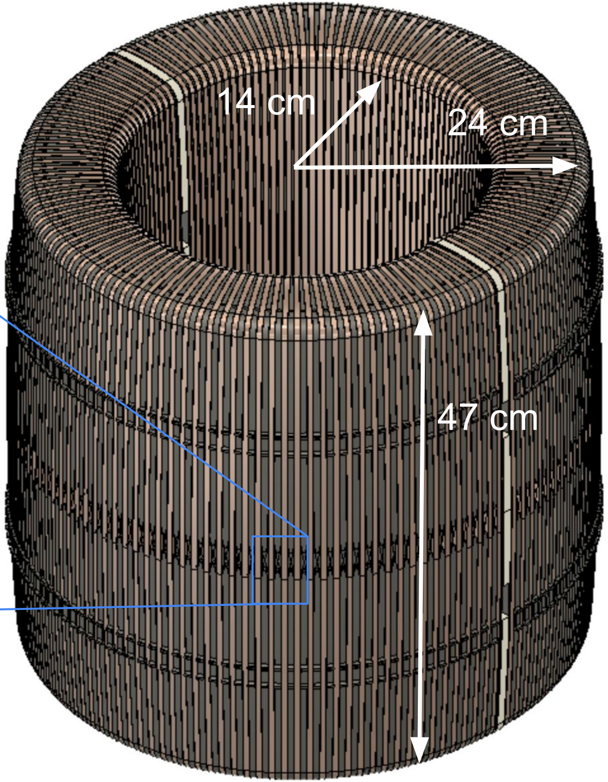
2-stage design

DMRadio-50L toroidal magnet

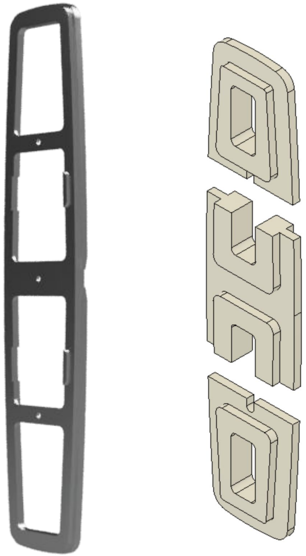
- 1 T peak field: ~140 A
- Superconducting Systems Inc



Wire winding
- 140 grooves
- 36 winds in each groove
- Counter wound

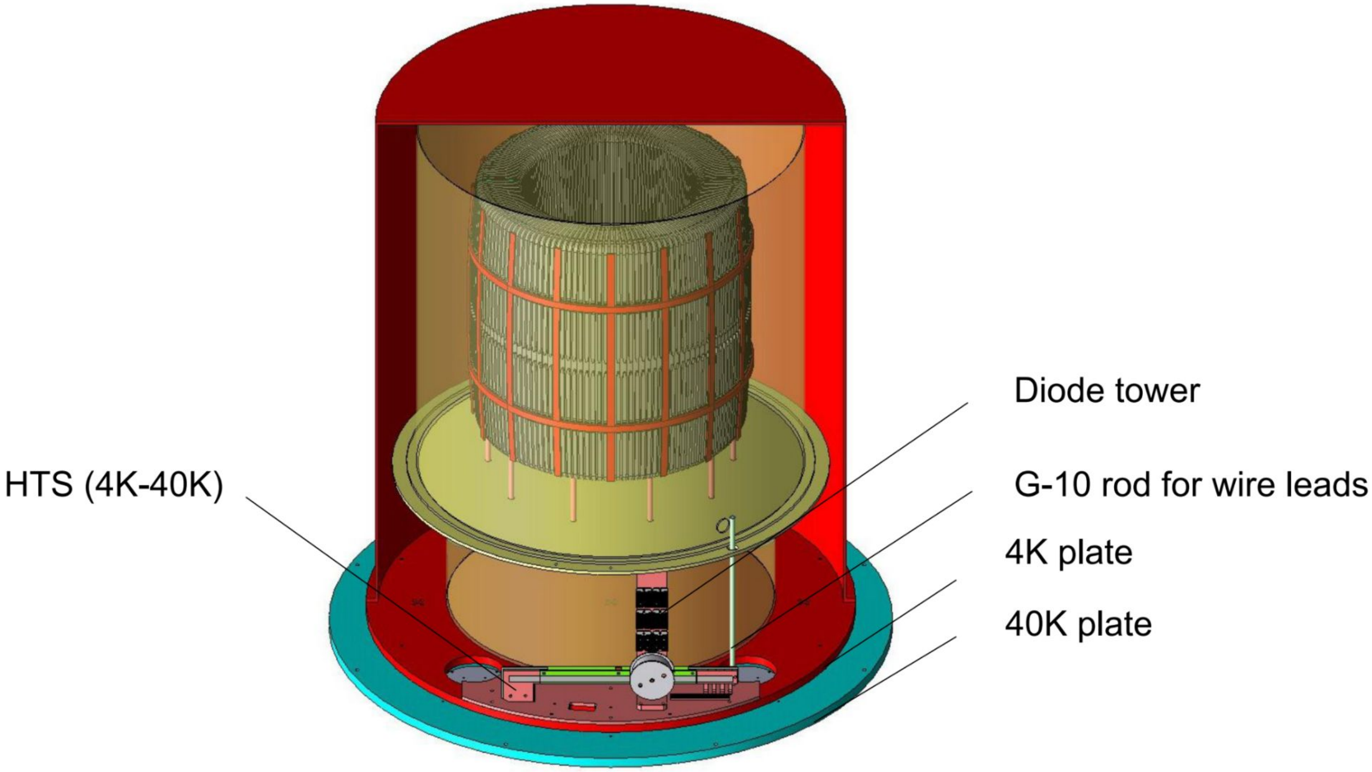


Aluminum mandrel



69 wedges per half, alumina spacers between two mandrel halves to decrease loss

DMRadio-50L toroidal magnet infrastructure



DMRadio-50L toroidal magnet

- ✓ Preliminary tests with sample wedges
  - ✓ Insulation on wedges
  - ✓ Glueing wedges
  - ✓ Winding of superconducting wire
  - ✓ Cryogenic tests

Practice wedge.

Practice winding on five wedges.

DMRadio-50L toroidal magnet

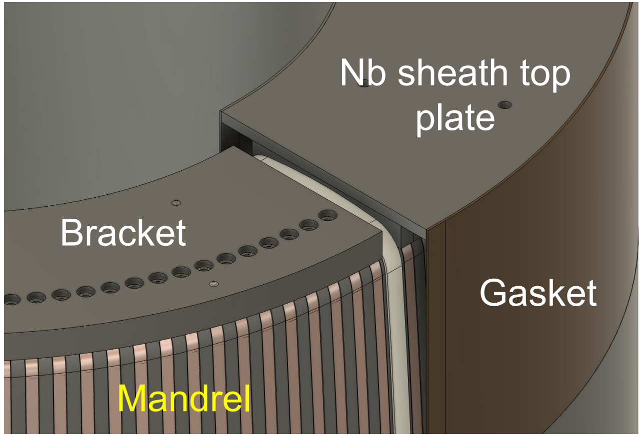
- ✓ Preliminary tests with sample wedges
  - ✓ Insulation on wedges
  - ✓ Glueing wedges
  - ✓ Winding of superconducting wire
  - ✓ Cryogenic tests
- ❏ Magnet production
  - ✓ 140 wedges are machined, arrived at SSI
  - ✓ First ten wedges are glued
  - ❏ First quarter of magnet wound
  - ❏ Full magnet wound
  - ❏ Magnet circuitry
  - ❏ Magnet testing

First 10 wedges.

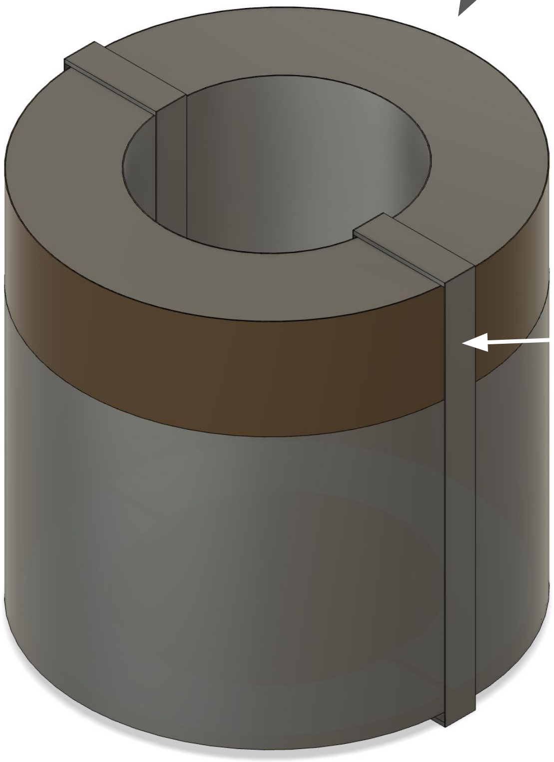
Wedge scale.

DMRadio-50L superconducting sheath

The sheath eliminates residual fringing field and isolates the magnet loss from the resonator for high Q



Magnet and sheath interface: connector bracket

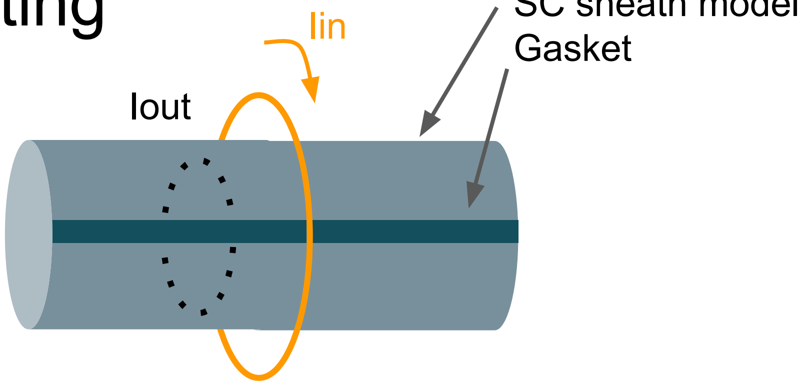


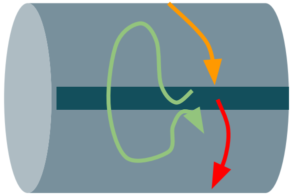
DMRadio-50L sheath: gasket testing

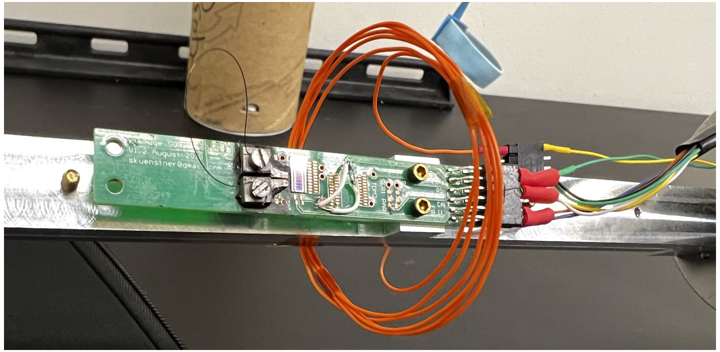
We do not want the gasket to allow coupling lossy materials inside the sheath to the inductor: how much of the poloidal current goes through the inside of the sheath vs across the gasket?

Hope: all goes across the gasket

Measure Iout/Iin







Testing setup without SC shield

Resonator tests at Stanford: cooling and SQUID backaction

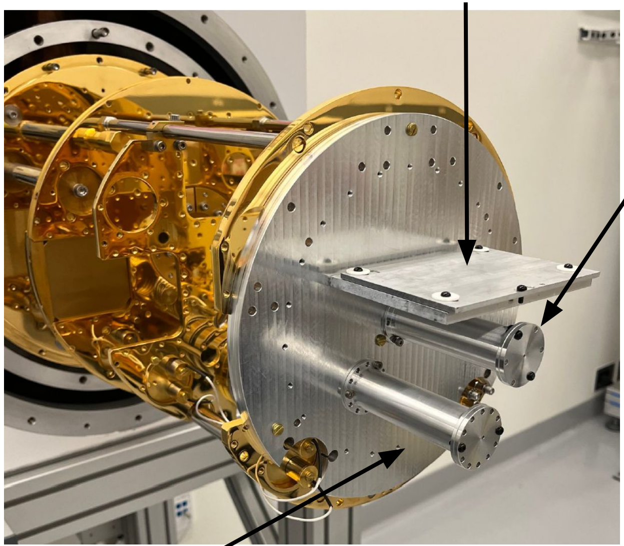
Cooling tests to mK DR temperatures ongoing

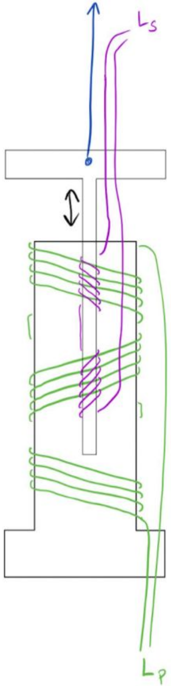
Attocube for tunable transformer acquired

Will begin SQUID testing in August

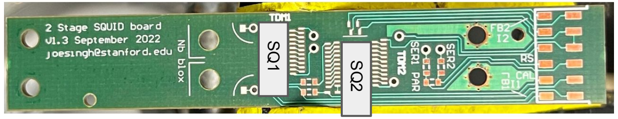
Capacitor

Tunable transformer



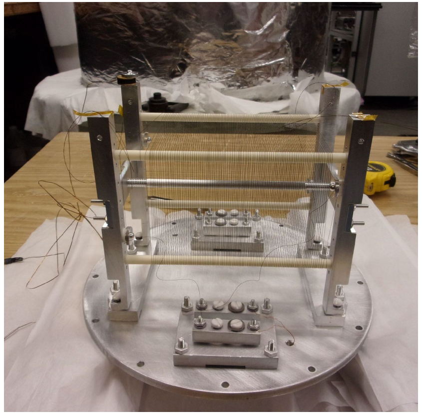


SQUID

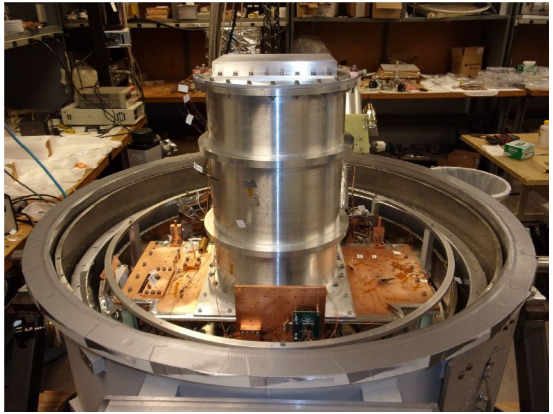


Resonator tests at Princeton: high Q goal

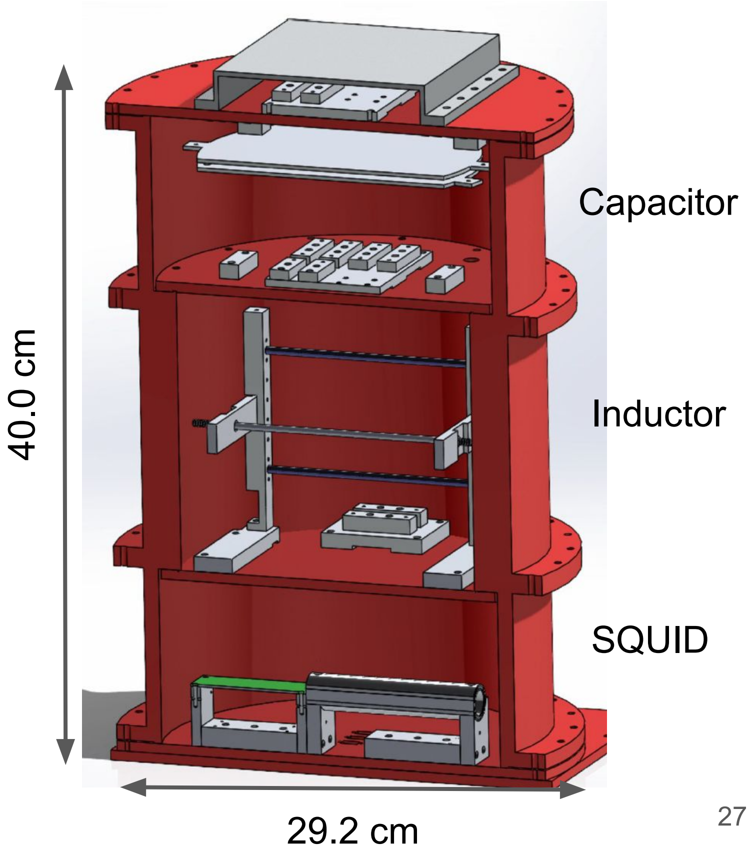
Optimizing Q of superconducting resonator by studying fundamental loss mechanisms (materials, joints, etc)



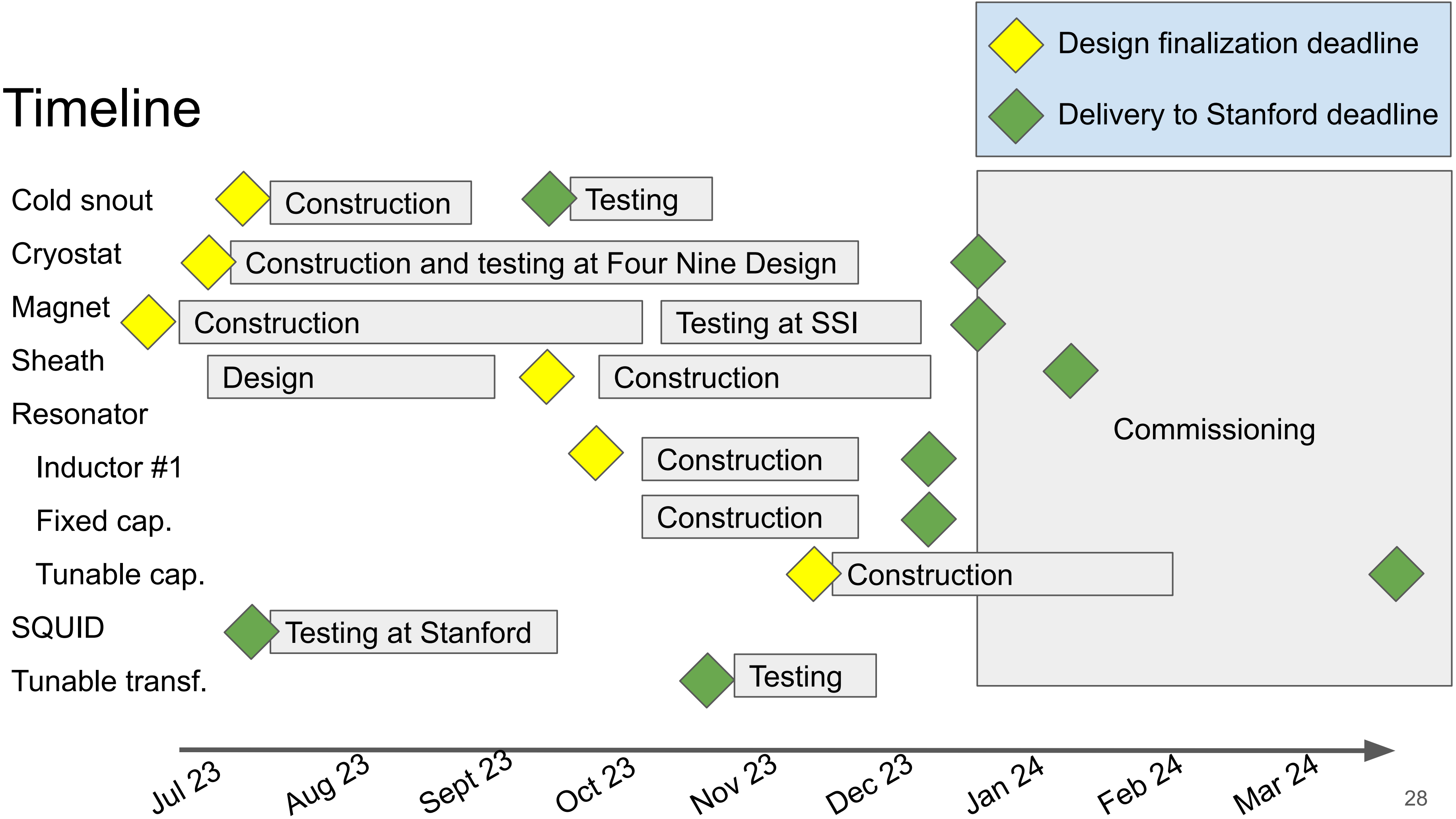
Inductor: NbTi wire, alumina rods,



5N Al shield mounted inside the cryostat. Cold stage is 750 mK.



Timeline

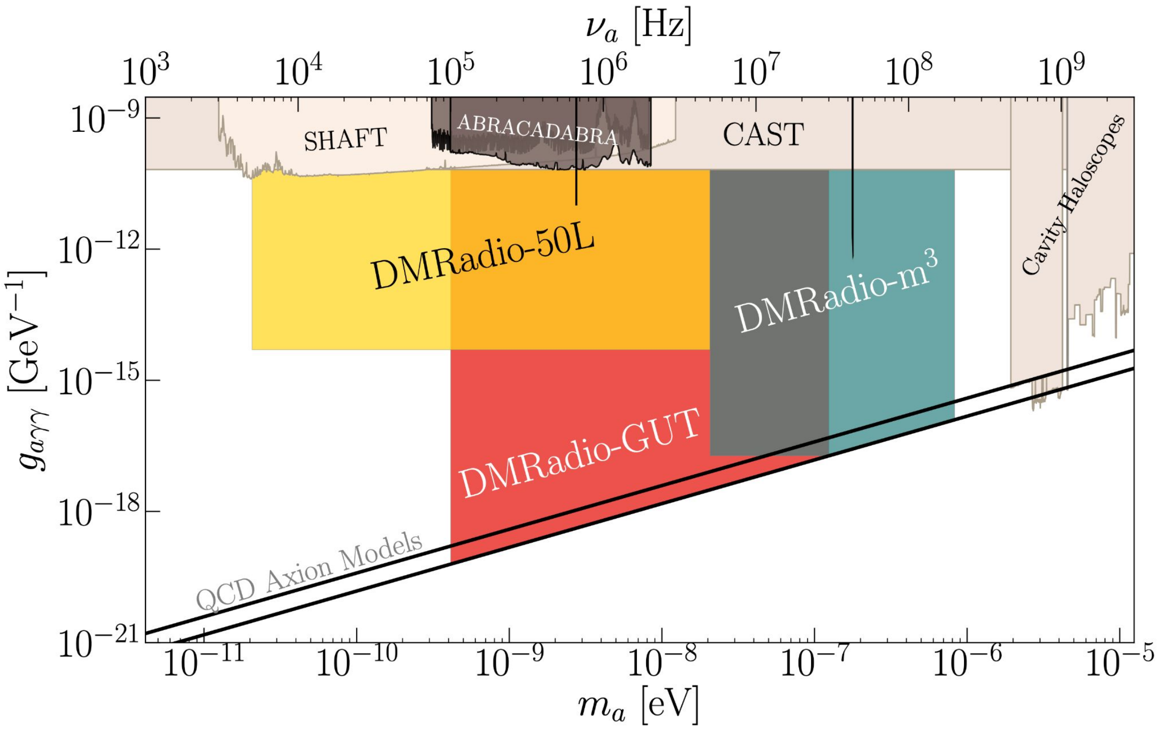

Design finalization deadline
Delivery to Stanford deadline
Cold snout
Construction
Testing
Cryostat
Construction and testing at Four Nine Design
Magnet
Construction
Testing at SSI
Sheath
Design
Construction
Resonator
Inductor #1
Construction
Fixed cap.
Construction
Tunable cap.
Construction
SQUID
Testing at Stanford
Tunable transf.
Testing
Commissioning
Jul 23
Aug 23
Sept 23
Oct 23
Nov 23
Dec 23
Jan 24
Feb 24
Mar 24

DMRadio-50L is an R&D platform for amplifier technology

Radio-frequency quantum upconverters (RQUs) upconvert signals from ~MHz to microwave frequencies

RQUs take advantage of mature microwave technologies

More info: arXiv:2210.05576



Conclusions: DMRadio-50L

- Axion search in 20 peV - 20 neV with target sensitivity $g_{a\gamma\gamma} < 5\times10^{-15}$ GeV^{-1}
- Comprised of a toroidal 1 T magnet surrounded by a superconducting sheath, and read out by tunable LC oscillator
- Technology test bed and innovation platform for amplifiers to inform future experiments
- Expect to receive cryostat and magnet by the end of 2023, commissioning in 2024

Upcoming DMRadio collaboration talk:

- "The Dark Matter Radio Suite of Experiments" - Dr. Dale Li at 10:15 am on Thursday, July 6th

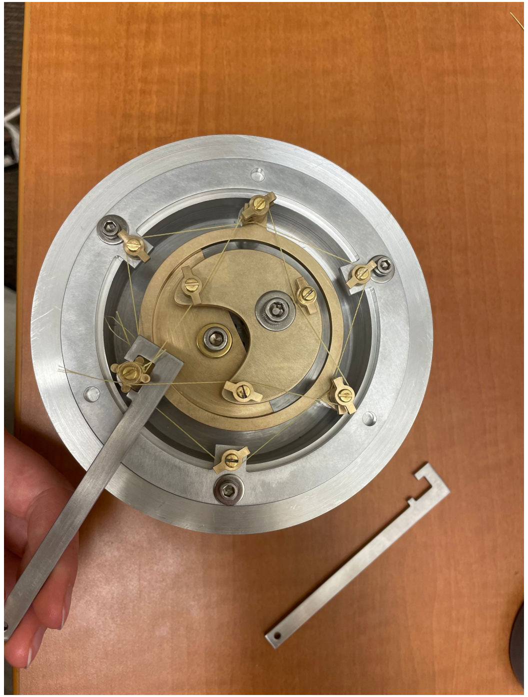
Thank you!

Puck Test Assemblies

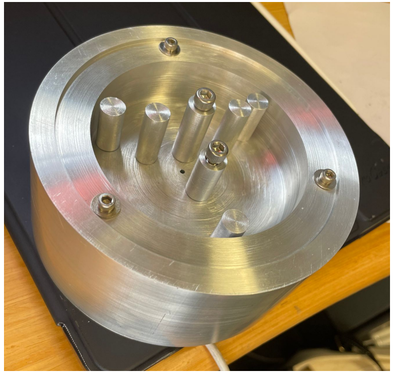
All Aluminum

Kevlar string

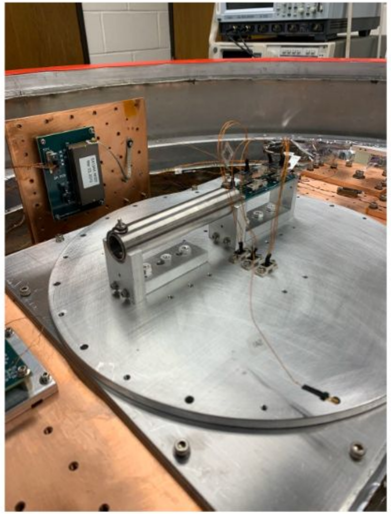
Brass / Aluminum Hybrid



Assembly Jig

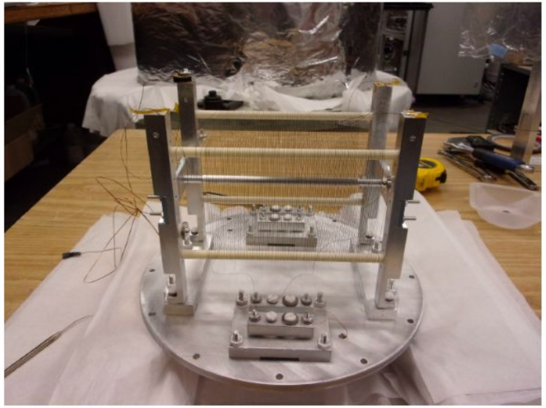


Resonator testing apparatus components at Princeton



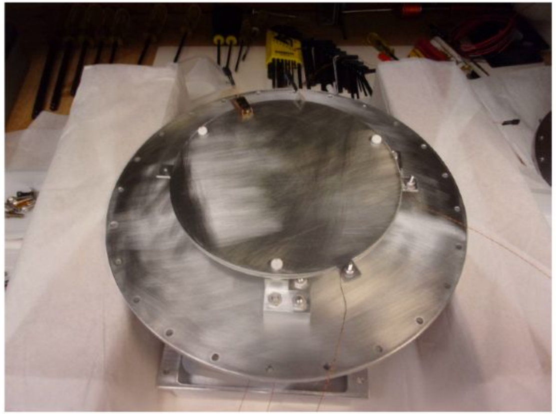
SQUID chamber:

- 2-stage SQUID system
- SQUID1 + SA
- Cylindrical shield around PCB
- Shells: Nb+Cryoperm+Nb
- Al trace PCB is out from fabrication



Inductor coil:

- NbTi wire
- Alumina horizontal rods
- Al 1100 frame
- Al 1100 threaded rod
- Teflon screw
- Tantalum washers
- Transformer and injection loops winded on Alumina rods



Circular-plate capacitor:

- Separated by vacuum
- Alumina washers to separate the plates
- Al 1100
- Teflon screw
- Tantalum washers

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	