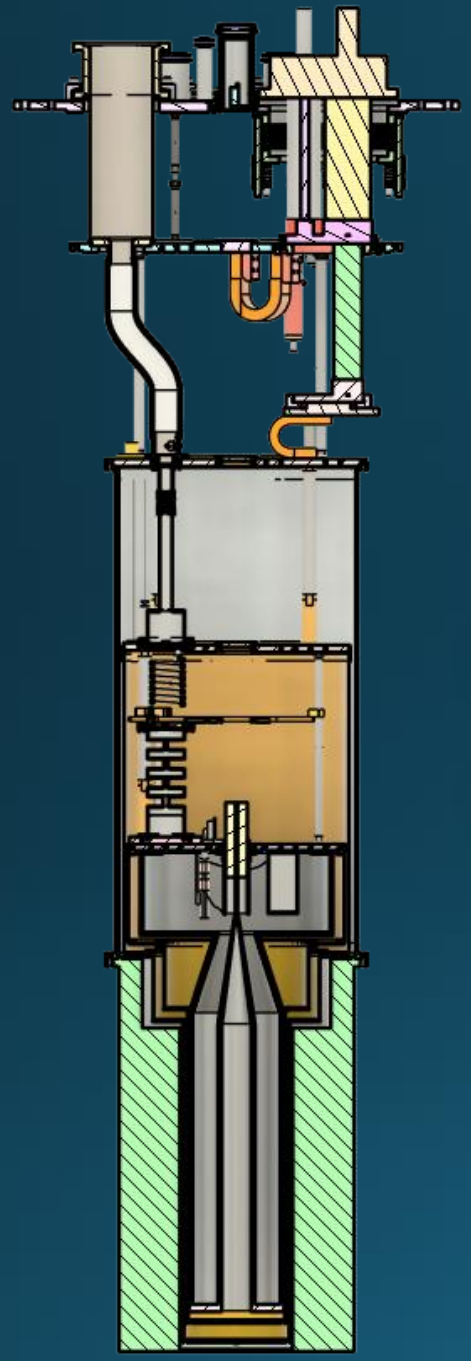

CAL-Pathfinder: a solenoidal DMRadio demonstrator

Chiara P. Salemi

DMRadio Collaboration Meeting

October 2025

*CAL = Cal Axion LC

Goals

1. Axion + GW science
   - Reach into new ALP and GW parameter space

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   - Solenoid magnet + coax pickup + coax tuner
   - Critical input for future large-scale experiments (GUT)

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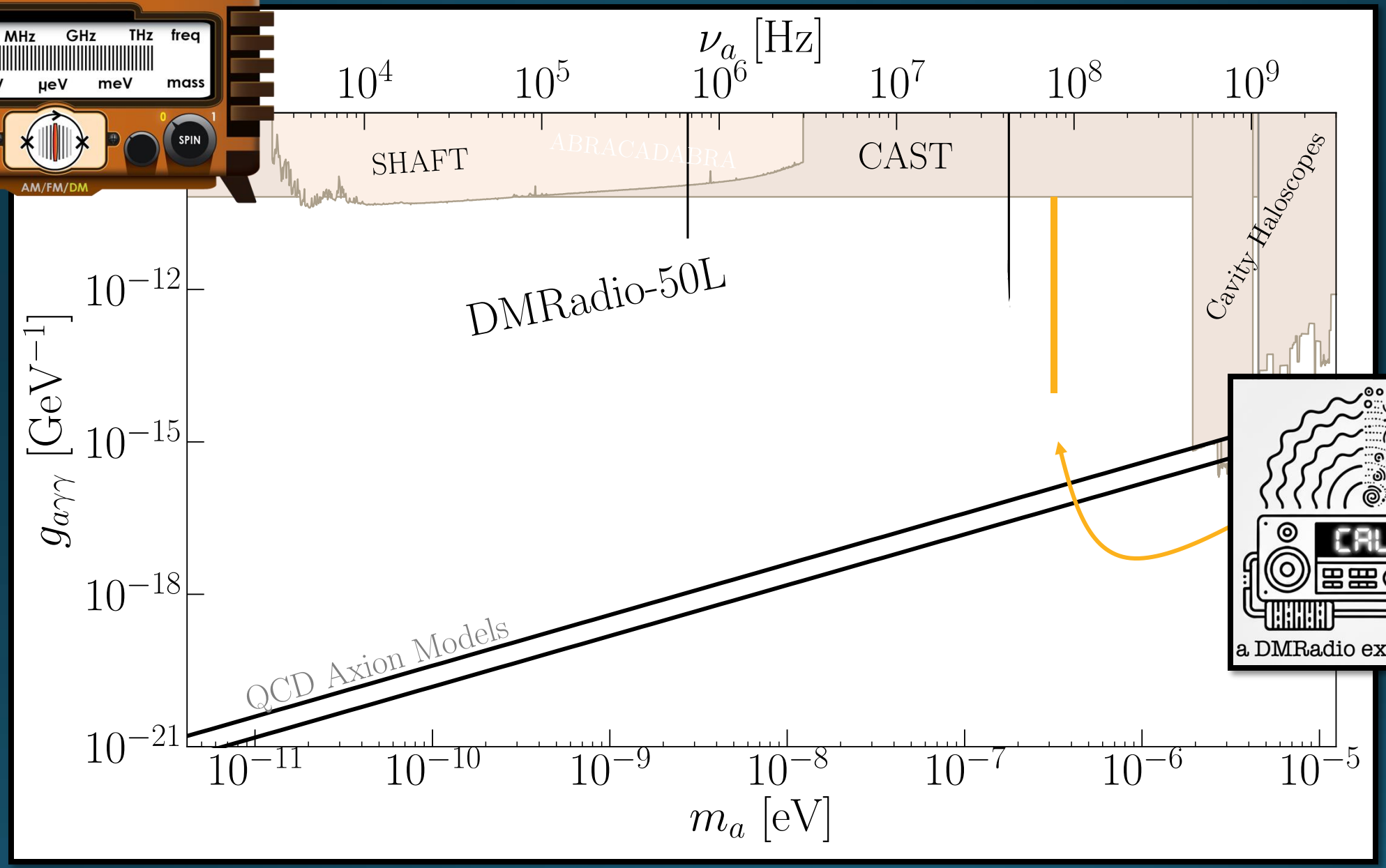
DARK MATTER RADIO
kHz
MHz
GHz
THz
freq
peV
neV
μeV
meV
mass
SPIN
AM/FM/DM


ν_a [Hz]
10^4
10^5
10^6
10^7
10^8
10^9
SHAFT
ABRACADABRA
CAST
Cavity Haloscopes
DMRadio-50L
10^{-12}
10^{-15}
10^{-18}
10^{-21}
$g_{a\gamma\gamma}$ [GeV^{-1}]
QCD Axion Models
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
m_a [eV]

CAL
a DMRadio experiment

ν_a [Hz]

10^4 10^5 10^6 10^7 10^8 10^9

SHAFT

ABRACADABRA

CAST

Cavity haloscopes

DMRadio-50L

frequency range subject to optimization!

10^{-12}

10^{-15}

$g_{a\gamma\gamma}$ [GeV^{-1}]

Axion Models

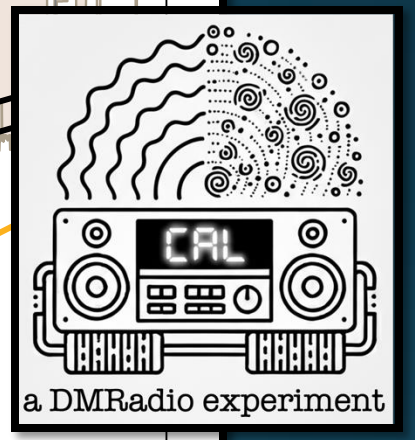
10^{-21}

10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5}

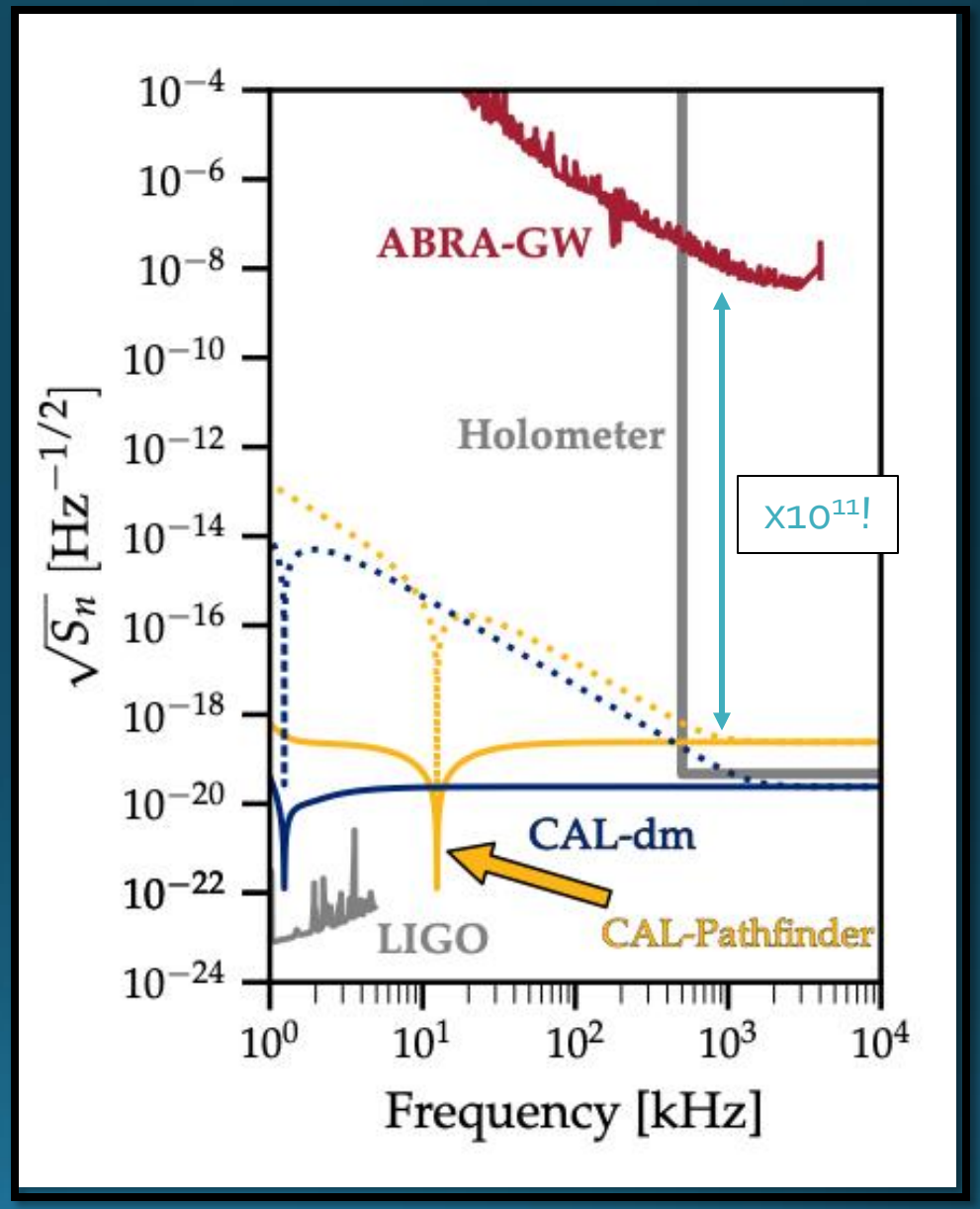
m_a [eV]

Baseline search range options:

1. f_0 ~ 80 MHz (1 MHz BW)
2. f_0 ~ 198 MHz (0.05 MHz BW)

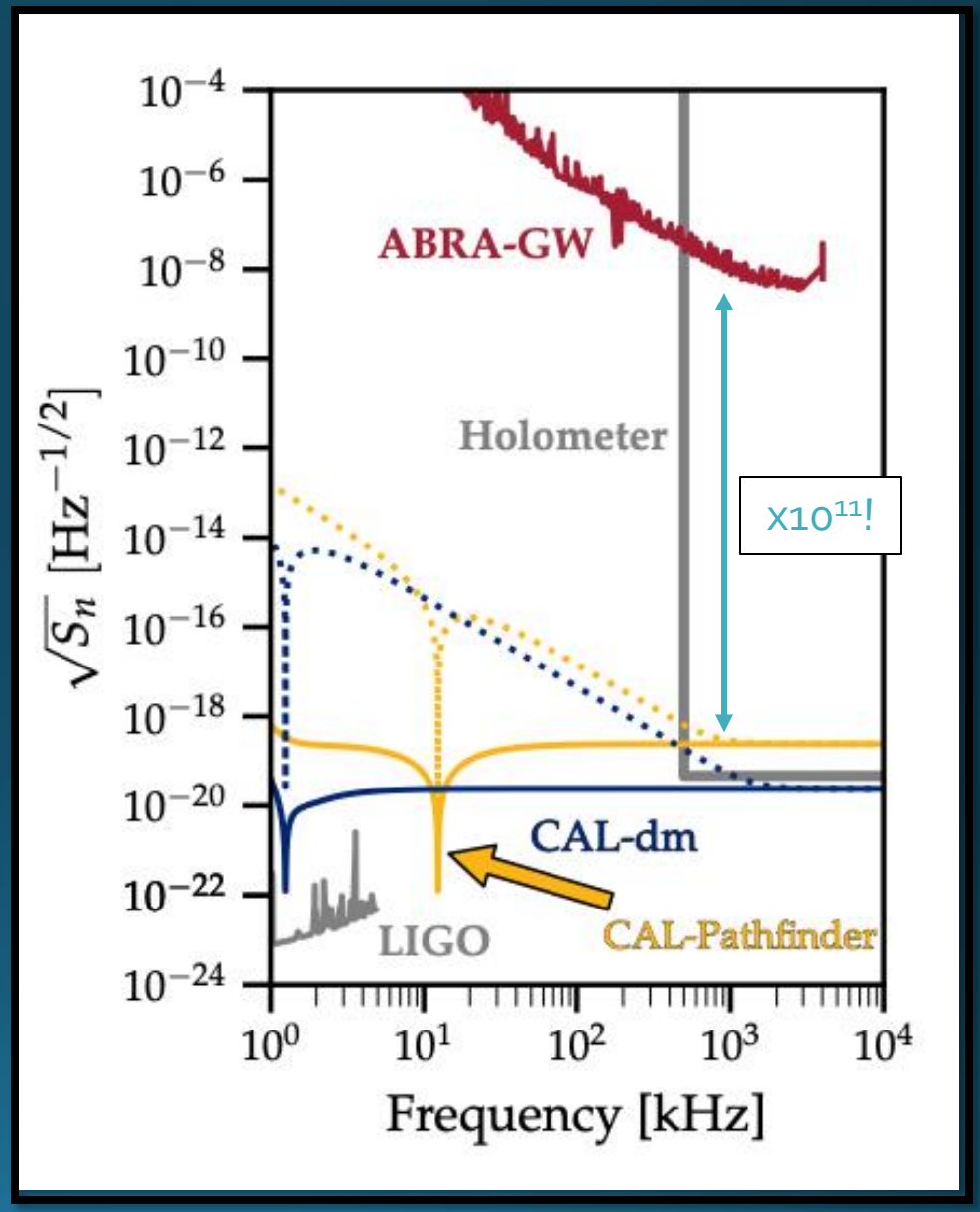


Solenoidal geometry provides huge improvement over toroid in gravitational wave sensitivity



Solenoidal geometry provides huge improvement over toroid in gravitational wave sensitivity

GW search needs different pickup – planned for run 2

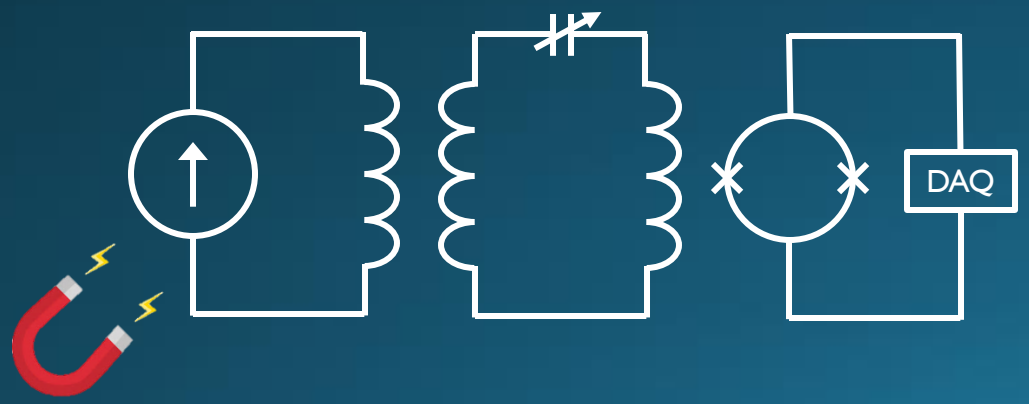


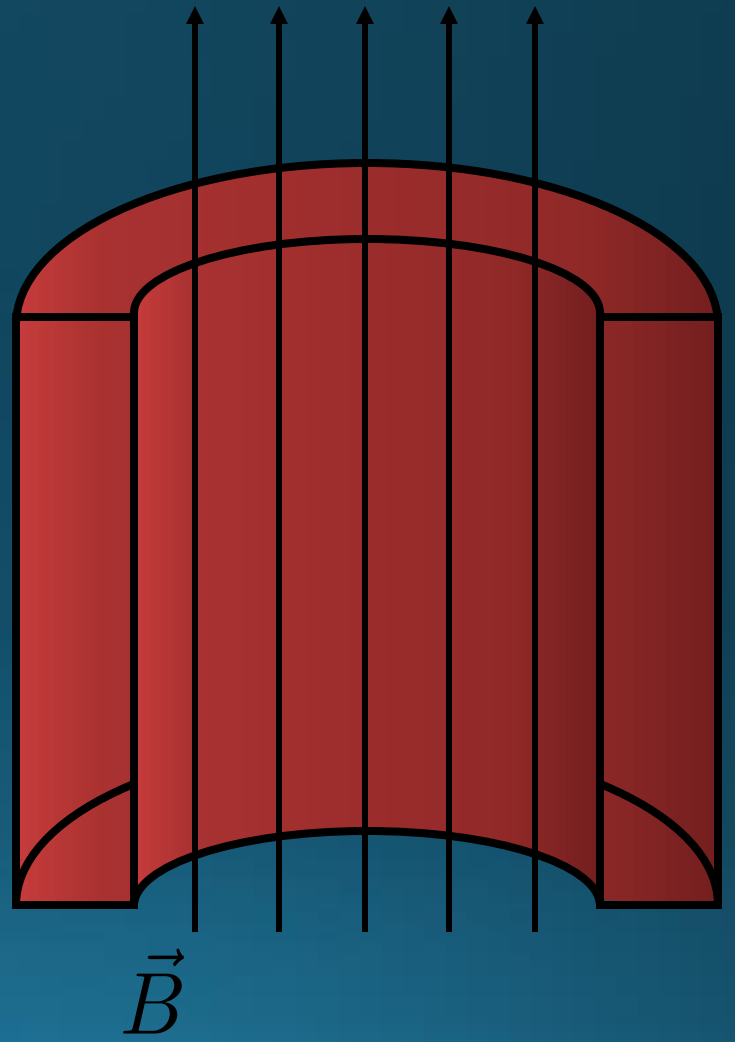
CAL concept

- Very similar to scaled-down DMRadio-m^3
- Builds on infrastructure from ABRA-10cm and DMRadio-50L
- Core components:
  - Solenoid magnet
  - Coaxial pickup
  - Coaxial tuner
  - Tunable transformer
  - High bandwidth SQUIDs*
  - DAQ with online PSD

The CAL detector

Solenoidal superconducting magnet with fixed field, B_0

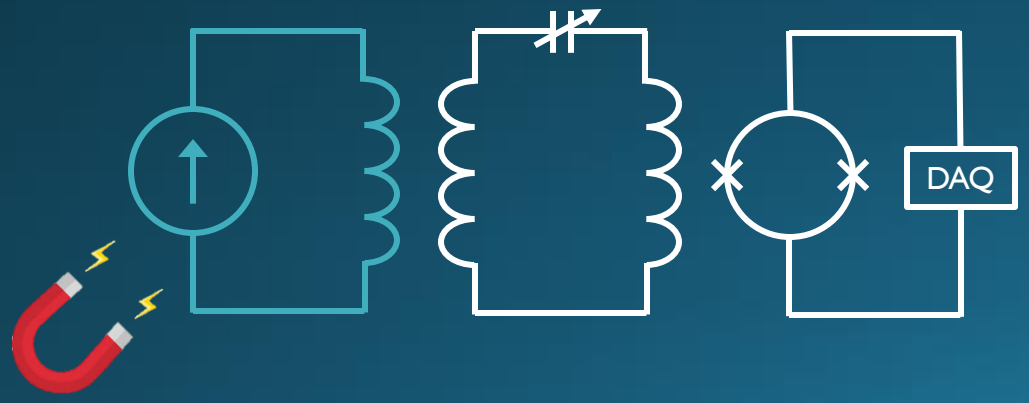


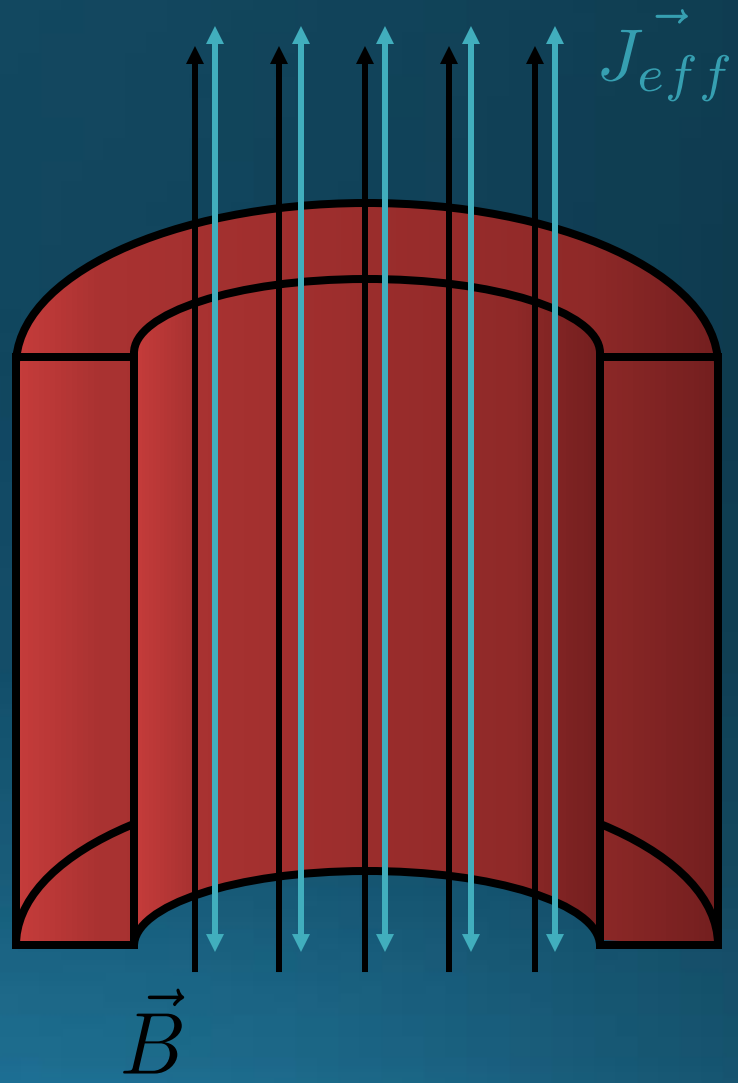


The CAL detector

Axion dark matter generates parallel oscillating effective current, J_{eff}

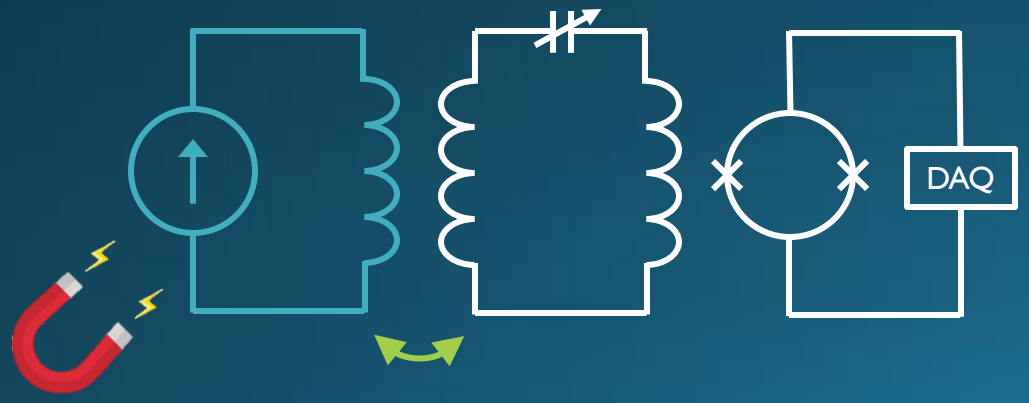
$$\vec{J}_{\text{eff}} = g_{a\gamma\gamma}\sqrt{2\rho_{\text{DM}}}\cos(m_a t)\vec{B}_0$$

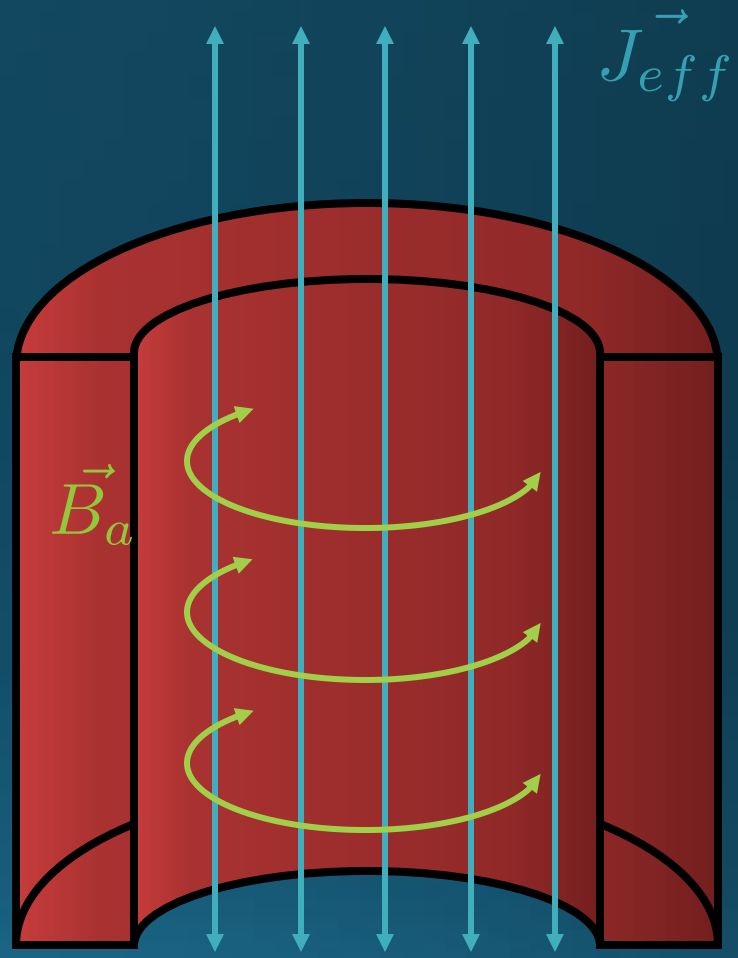




The CAL detector

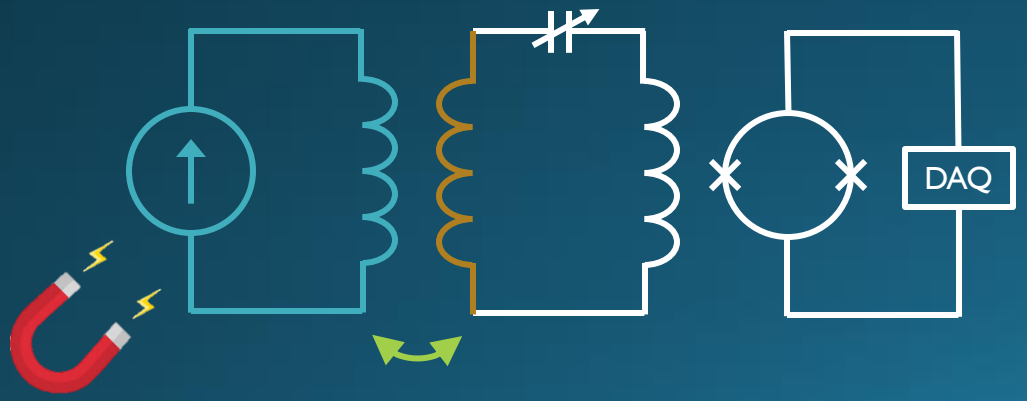
Axion dark matter generates parallel oscillating effective current, J_{eff}, which generates an oscillating magnetic field

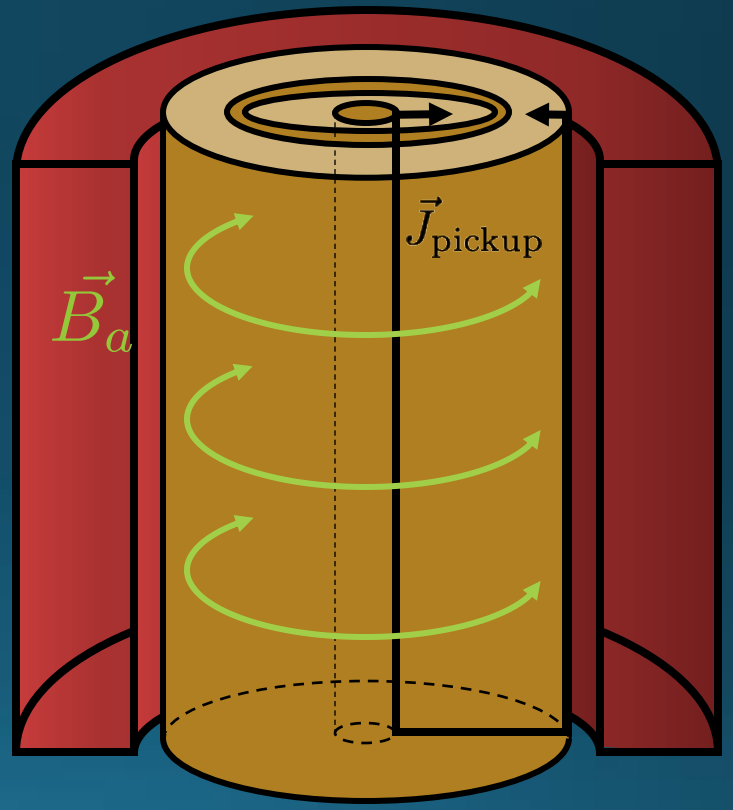




The CAL detector

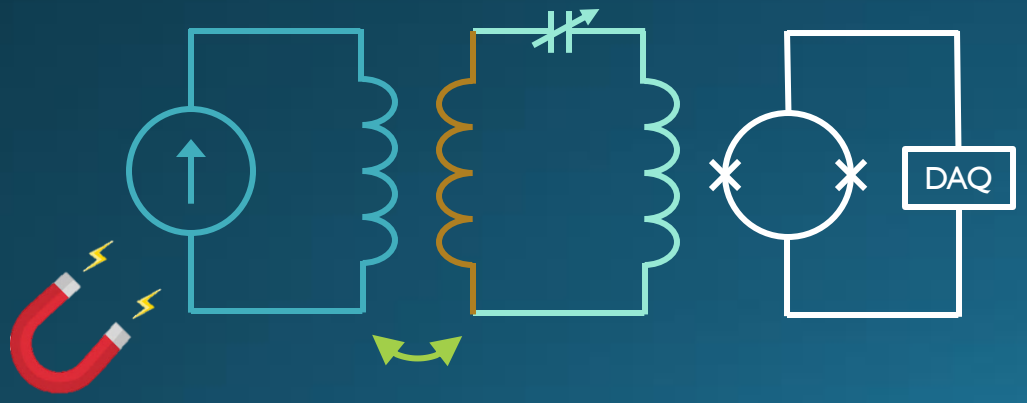
…inducing currents on the pickup coax

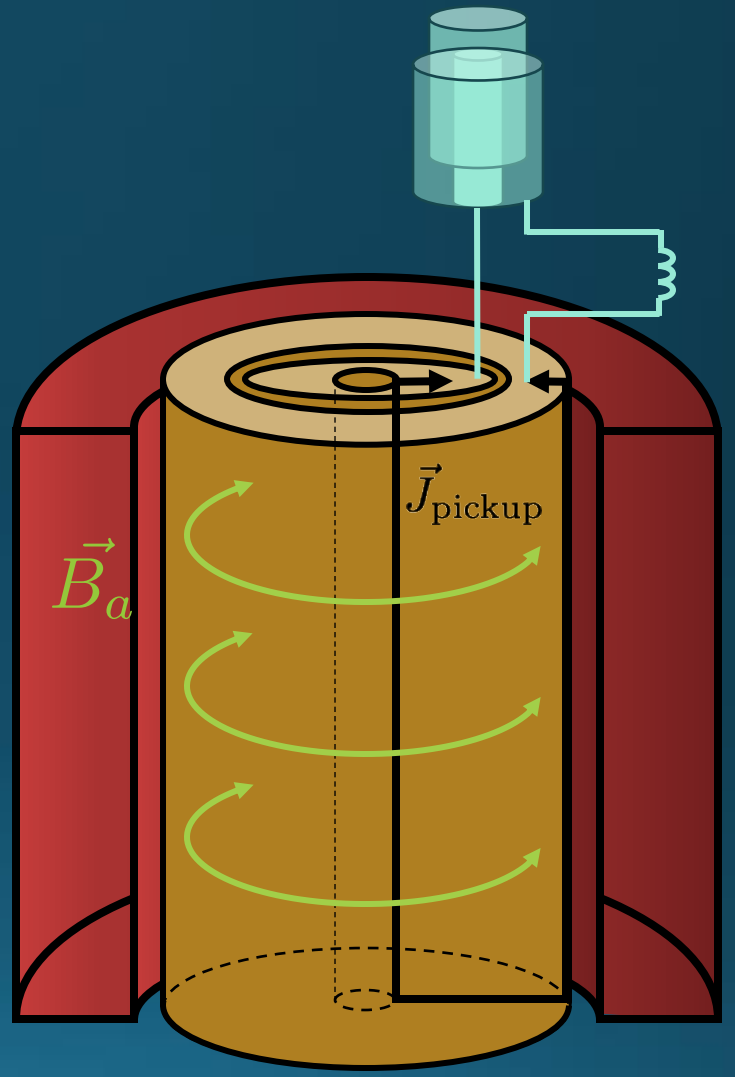




The CAL detector

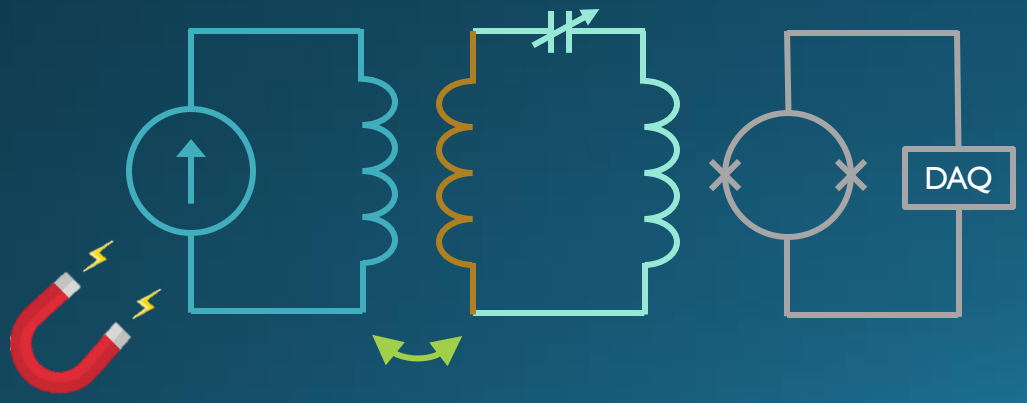
…inducing currents on the pickup coax and ringing up the tunable LC resonator

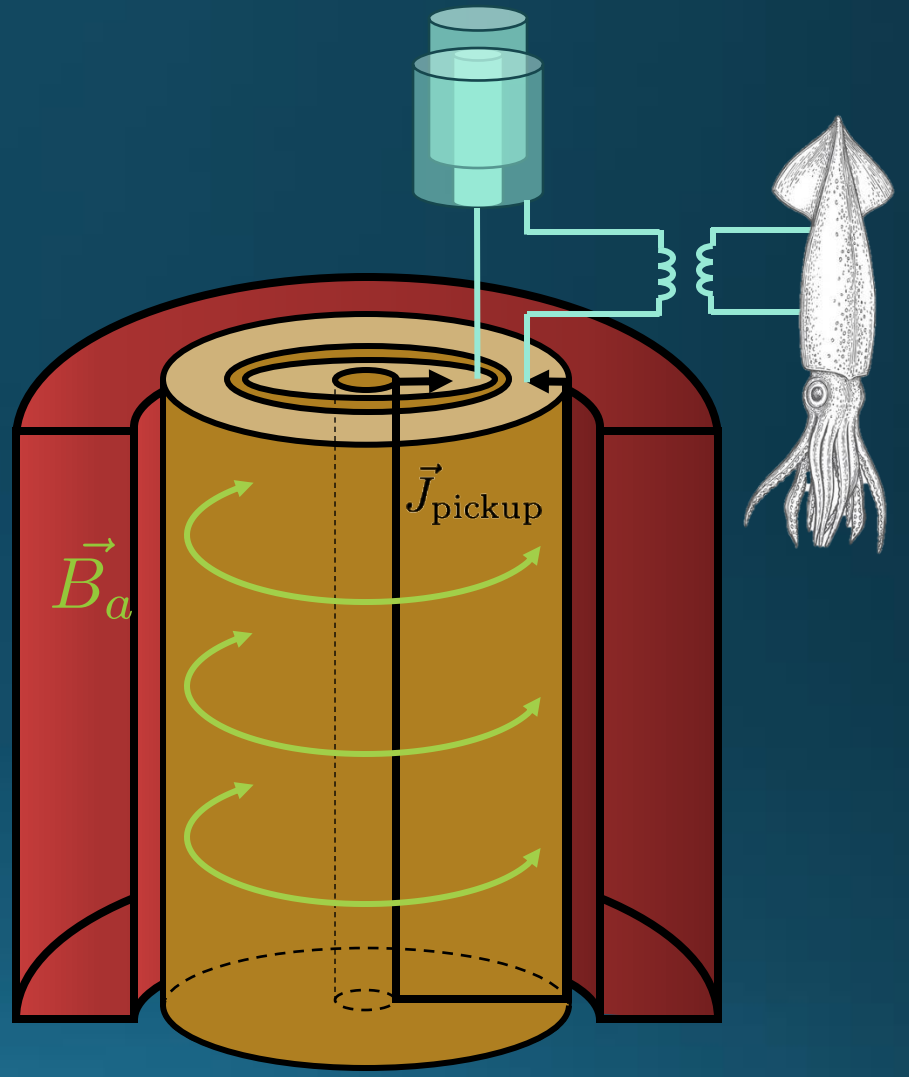




The CAL detector

This signal is read out and amplified using a SQUID current sensor



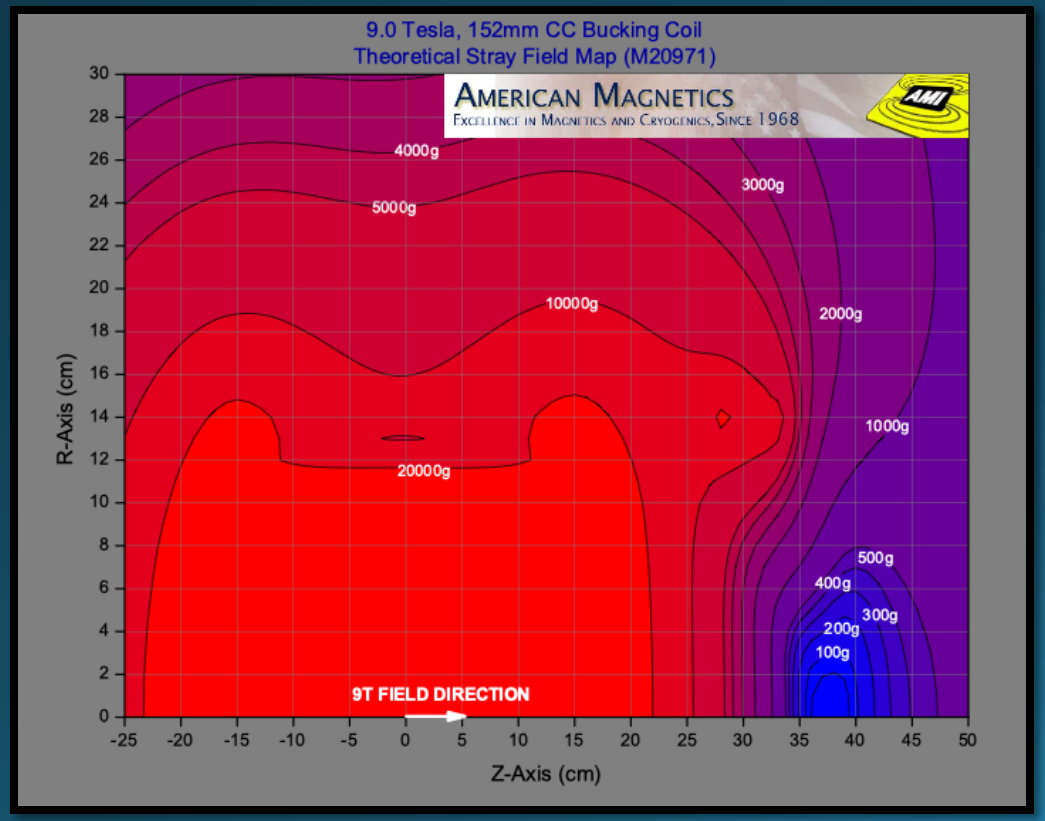


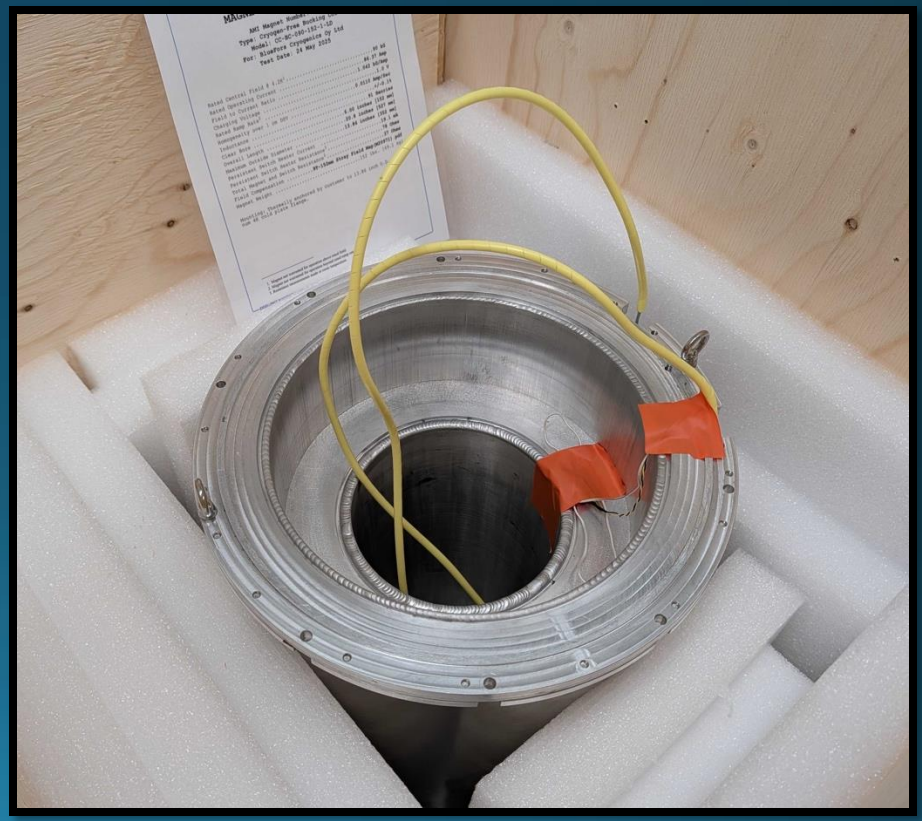
Next: key detector components

- Detector subsystems will build off of considerable collaboration work in preparation for DMRadio-m^3
- Maturing their design for CAL will be a many-person, multi-institution effort!
- Successful demonstration in CAL will set us up well for next-stage experiments

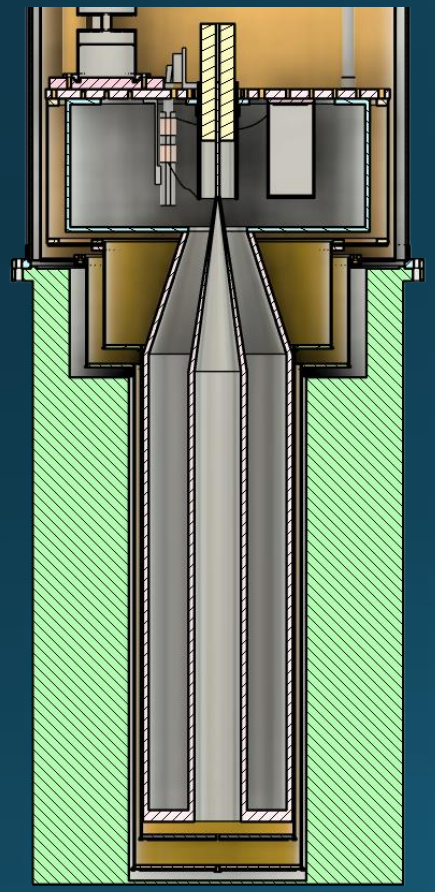
Magnet

- 9 T, 152mm-bore solenoid with field cancellation at MXC from AMI
- Commissioning next week with Bluefors engineer



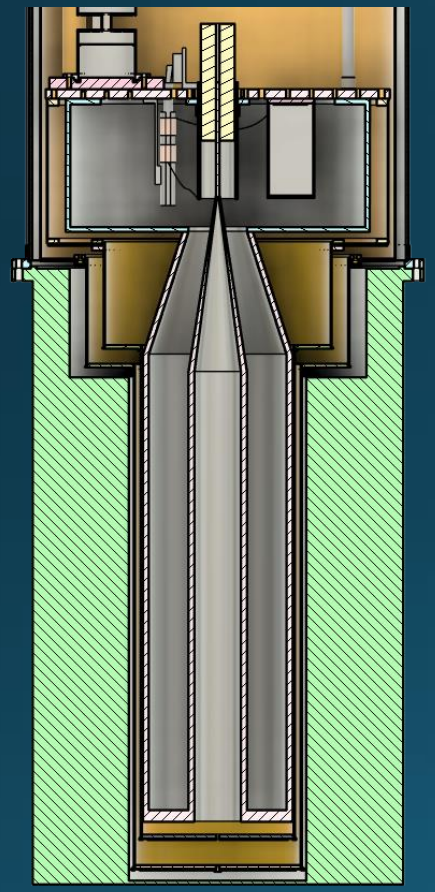


Magnet



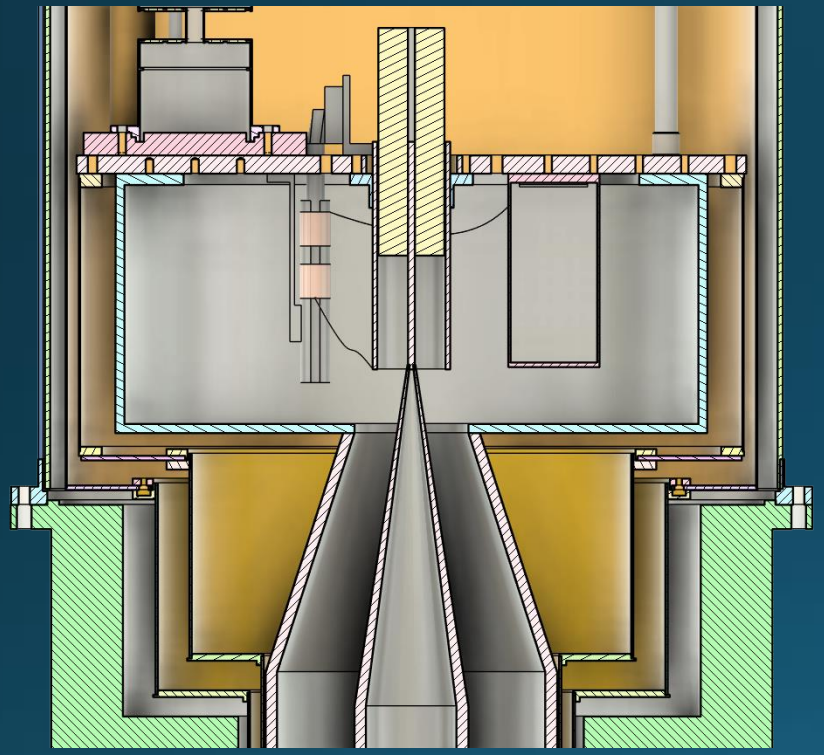
- Magnet thermalized to 4K
- 1K and MXC radiation shields available in bore
- TO DO:
  - Commission
  - Understand quench forces on materials in bore (pickup!)
  - Understand vibration damping effect

Coaxial pickup



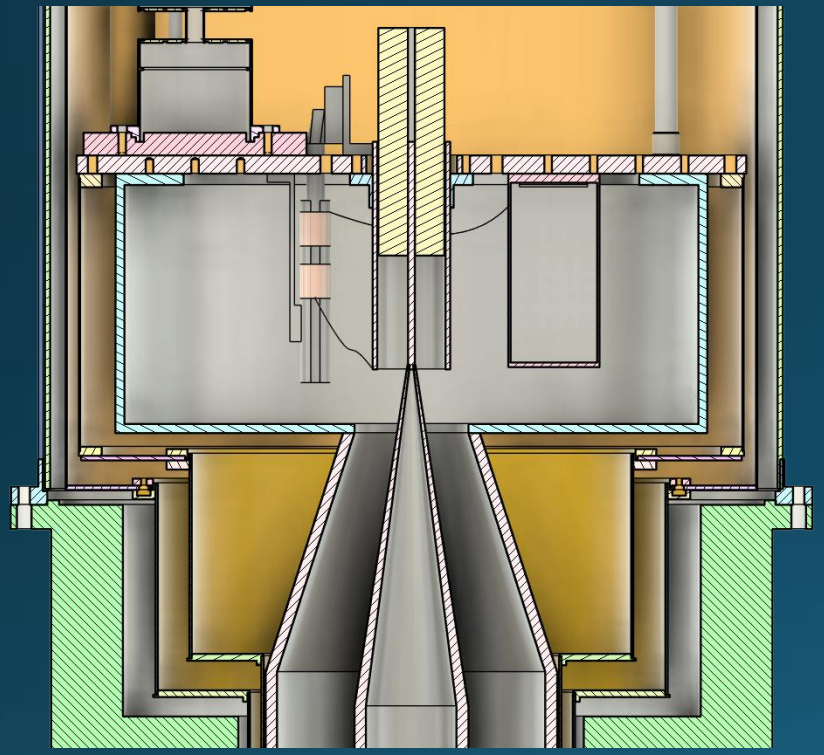
- Baseline material (as in m3): copper with Nb-coated neck-down
  - Possible upgrade path: MgB_2 coating
- Manufacture with knife-edge joints
- TO DO:
  - Design for optimized reach with realistic manufacture, including interfaces with low-field box, tuner, tunable transformer
  - Determine neckdown and its coating
  - Quench protection scheme
  - Thermalization

Tuner



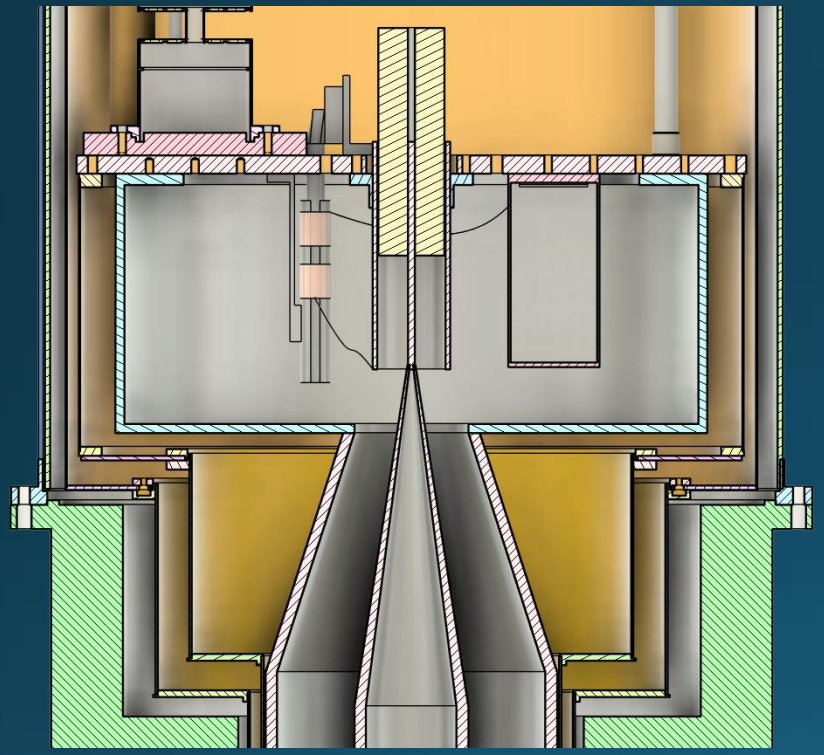
- Coaxial design to minimize parasitic impedance
- Motion with higher temperature actuation via central line-of-sight ports
- TO DO:
  - Full design, including motion and friction reduction as well as interfaces to rest of resonator
  - Cover on top to prevent TEM mode leakage
  - Thermalization

Tunable transformer



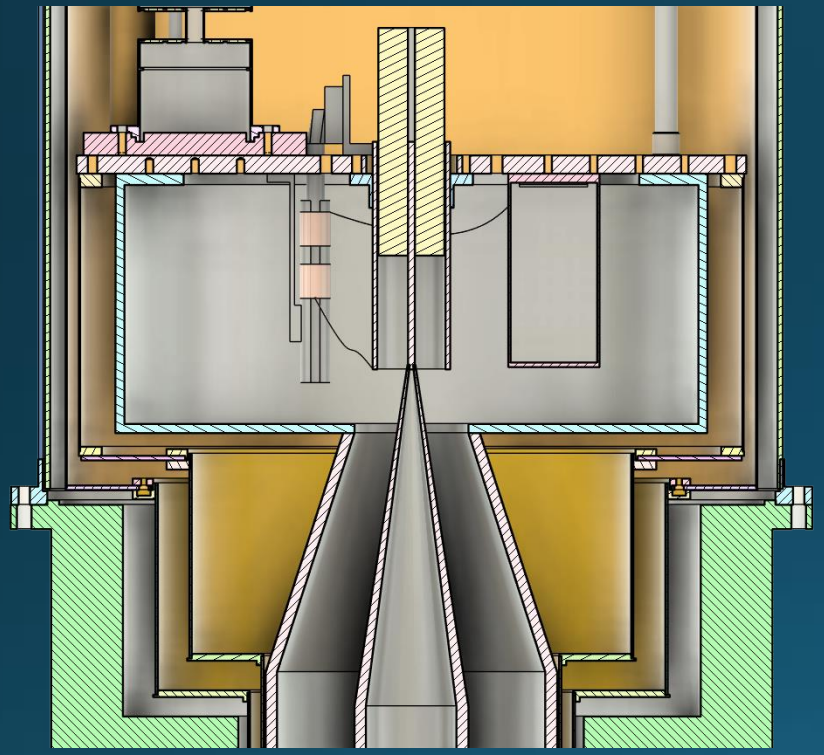
- Baseline design is same as for 50L
- Actuation is likely to be with attocube because of space constraints
- TO DO:
  - Optimize location in low-field region
  - Adjust design based on 50L testing
  - Design interfaces

SQUIDs



- Baseline is m^3 SQUIDs a la SQUID paper
  - DMNI funds got rescinded! Working on this option
- Second option: existing Stanford SQUIDs at lower bandwidth
- TO DO:
  - Determine existing SQUID bandwidth (Kent calculation)
  - Design, fabrication, and "vertical slice test" of optimized SQUID chain

Low-field box



- Need to further reduce B field for superconducting electronics
- TO DO:
  - Calculate layers of shielding needed
  - Design interfaces and thermalization

DAQ

- Plan to copy as much of 50L DAQ infrastructure as possible
  - Also will provide a second site for tests relevant for 50L
- Need new, faster digitizer card
- Will need to update software for digitizer, higher frequencies
- Also need to update for broadband GW search

Design/construction/run plan

- Planning for aggressive schedule ~ 2 years to first data run
- This year:
  - Finalize major design decisions
- Next year:
  - Subsystem prototyping
  - Integration of resonator
- Following year:
  - Full experiment integration and engineering runs
  - Science run 1: "normal" resolution data taking
- After:
  - Fine resolution data taking for alternative halo analyses
  - Switch configuration to GW mode

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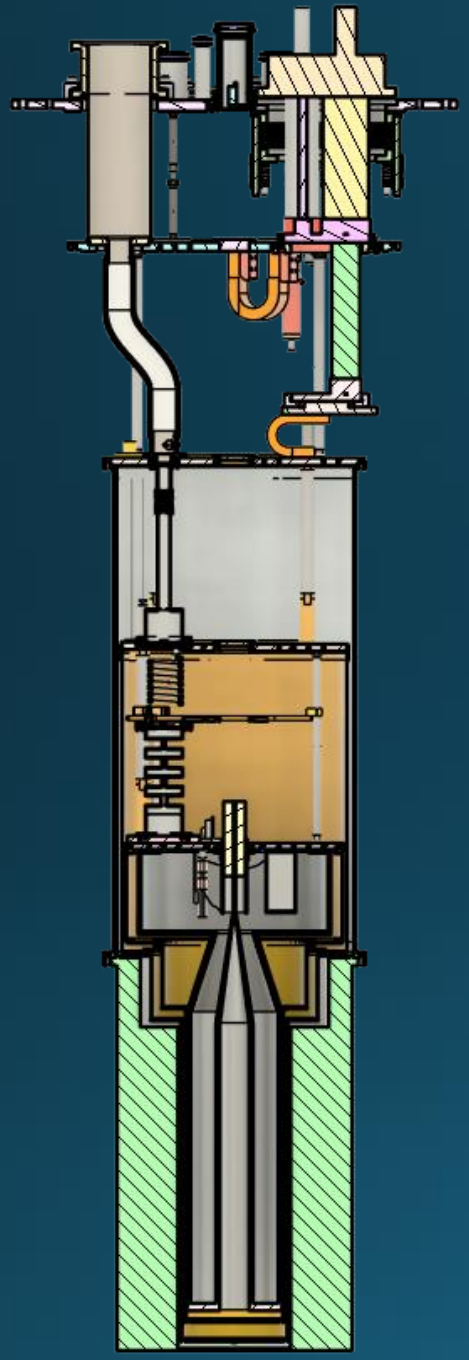
Schedule under construction!



CAL-Pathfinder

- CAL is part of the larger DMRadio program exploring low-mass axions with the lumped-element technique
- It will be beginning data-taking as 50L transitions into quantum test-bench mode
- In conjunction with other low-mass efforts (e.g. Core, ABRA), it will demonstrate new ideas to solidify our technical readiness for a large-scale experiment: DMRadio-GUT