Dark Matter Radio

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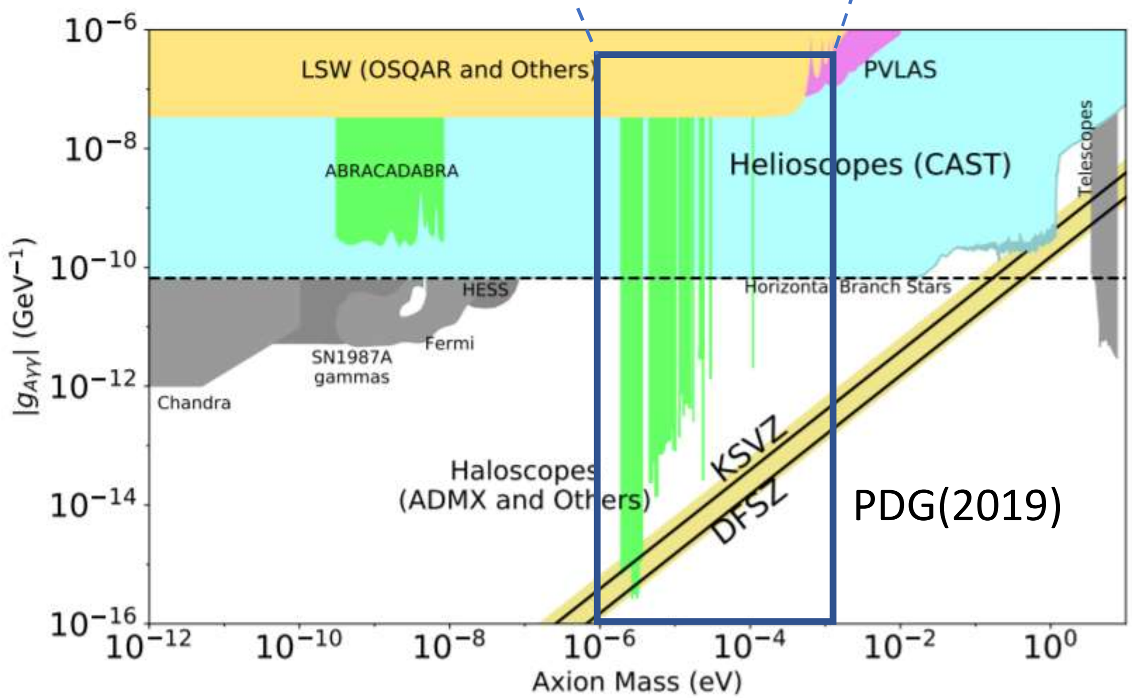
Cambridge High Energy Workshop

July 27, 2021

Axion Landscape

Post-Inflationary Scenario

- Masses 1 μeV-1 meV
- Microwave cavity detectors
- ADMX, HAYSTAC, CAPP…



PDG(2019)

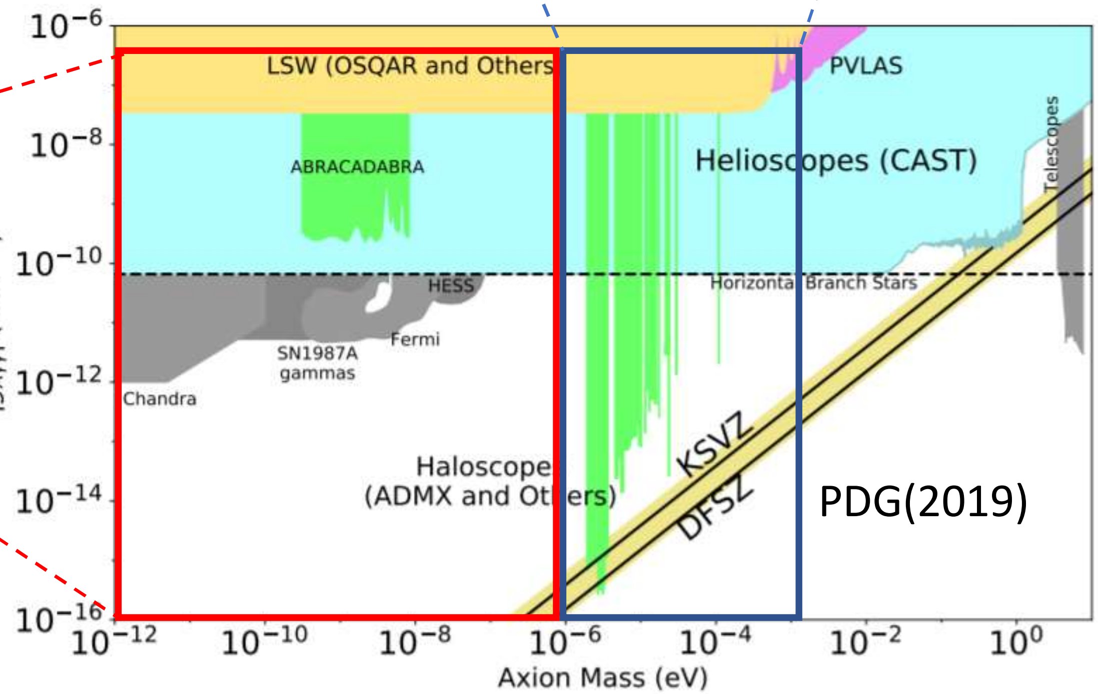
Axion Landscape

Post-Inflationary Scenario

- Masses 1 μeV-1 meV
- Microwave cavity detectors
- ADMX, HAYSTAC, CAPP…

Pre-Inflationary Scenario

- Masses 1 peV-1 ueV
- Compton wavelength much larger than apparatus
- Lumped element detectors
- DMRadio



PDG(2019)

Lumped Element Fundamentals

- Treat axion DM as classical field

$$a(t) = \frac{\sqrt{2\rho_{DM}}}{m_a}\cos(m_a t)$$

- Effect on Maxwell's equations in background DC magnetic field

$$\vec{\nabla} \times \vec{B} = \partial_t \vec{E} + g_{a\gamma\gamma}\vec{B}_{DC}\partial_t a$$

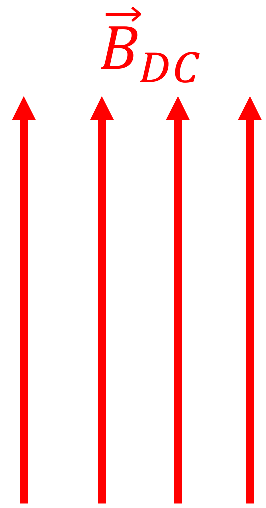
- Axion produces effective AC current density

$$\vec{J}_{eff} = g_{a\gamma\gamma}\vec{B}_{DC}\partial_t a$$

- Quasi-static limit: detect oscillating B-field

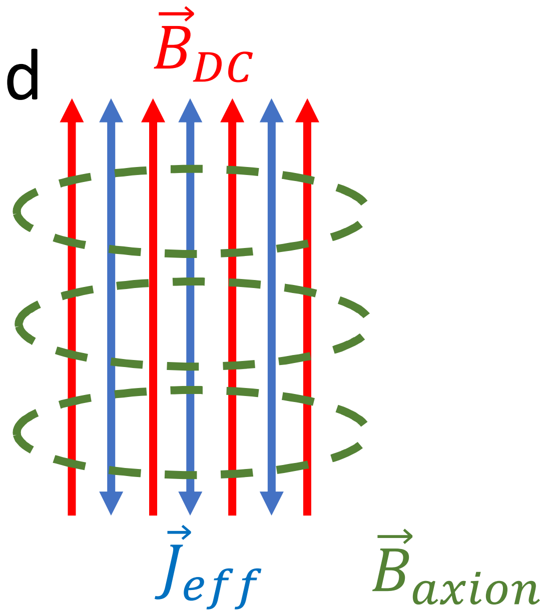
Lumped Element Detection

- Establish DC magnetic field



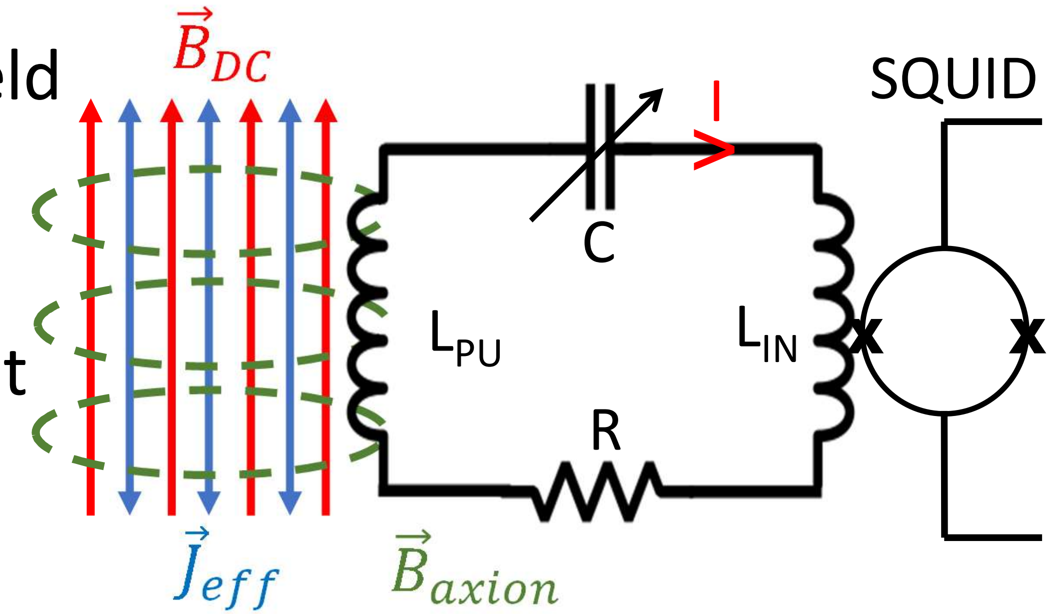
Lumped Element Detection

- Establish DC magnetic field
- Axion current produces oscillating B field



Lumped Element Detection

- Establish DC magnetic field
- Axion current produces oscillating B field
- Induces screening current in pickup inductor
- Use LC resonator for enhancement
- Read out with current sensor, e.g. SQUID



$$\omega_r = \frac{1}{\sqrt{(L_{PU}+L_{IN})C}}$$

tune using variable capacitor

Figure of Merit

- Optimize experimental design according to performance figure of merit (arXiv:1803.01627)

Geometry factor

$$FOM \propto \frac{1}{g_{a\gamma\gamma,min}} \propto \frac{c_{PU} B_0 V^{5/6} Q^{1/4} t_{int}^{1/4}}{T^{1/4} \eta^{1/4}}$$

Integration time

Amplifier noise

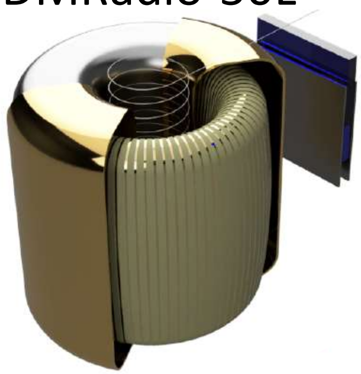
- Assumes:
  - Quasi-static limit
  - Optimized coupling to amplifier
  - Physical temperature greater than amplifier noise temperature

DMRadio family of experiments

DMRadio-Pathfinder & ABRA-10cm

Running

DMRadio-50L



Under Construction

DMRadio-m^3

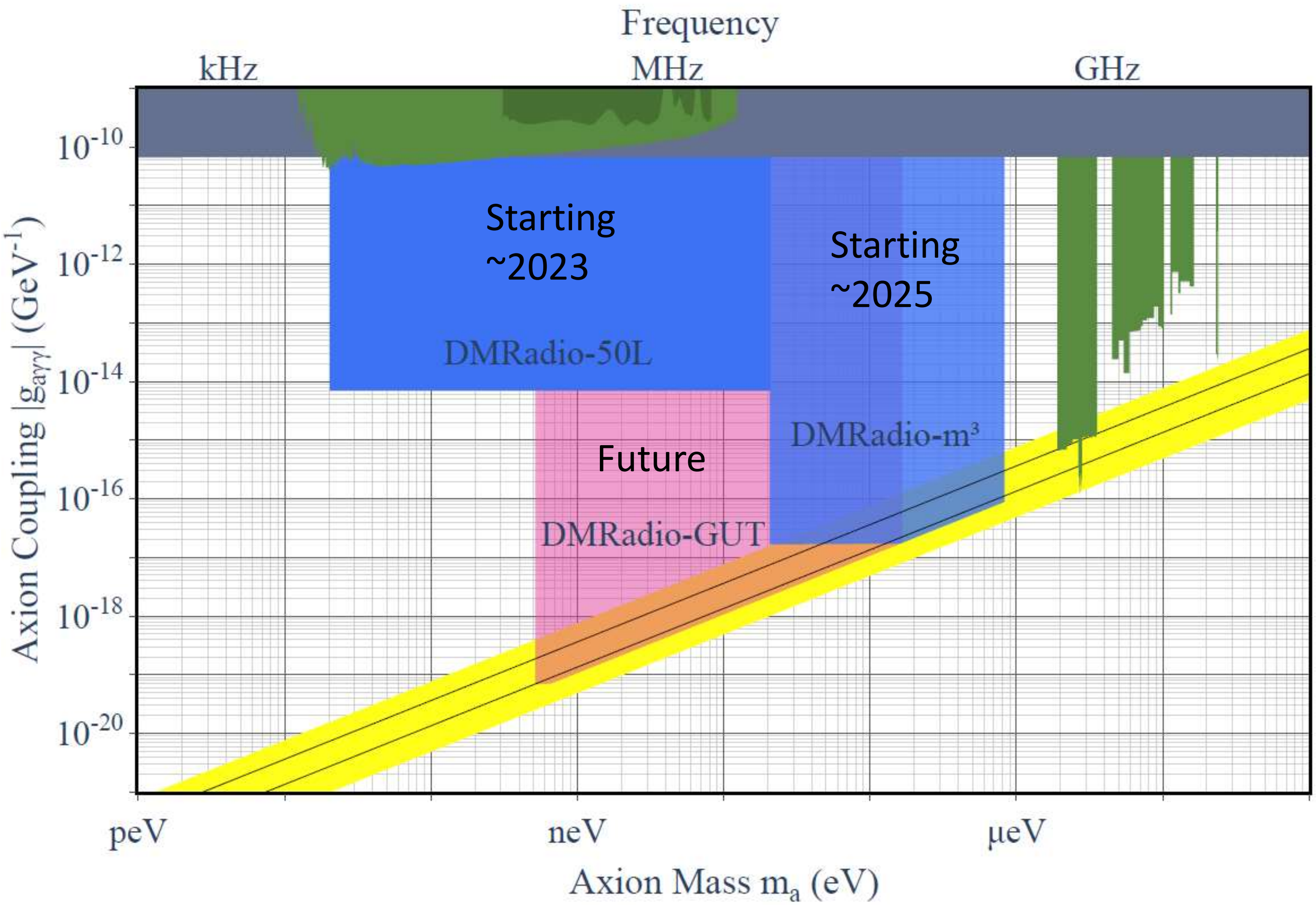
Design Phase

DMRadio-GUT

- Challenging, long-term experiment
- Turn everything up to 11!

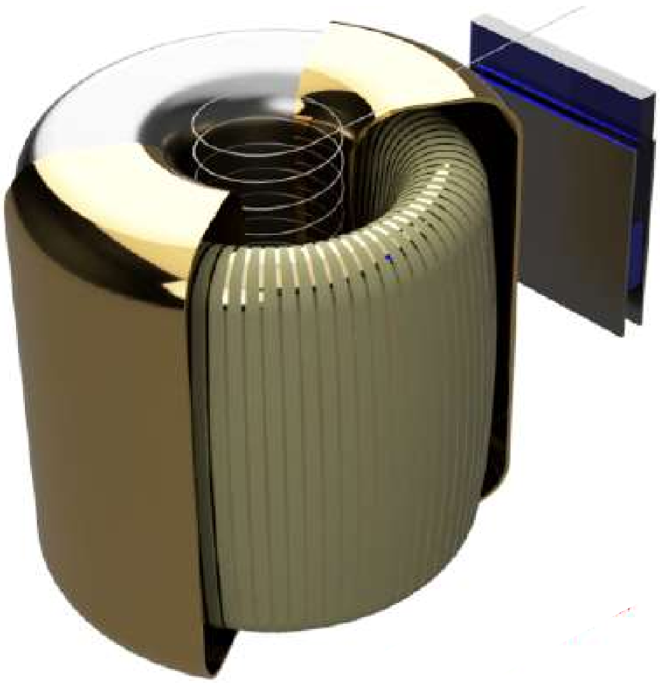
R&D Engine

DMRadio Science Reach

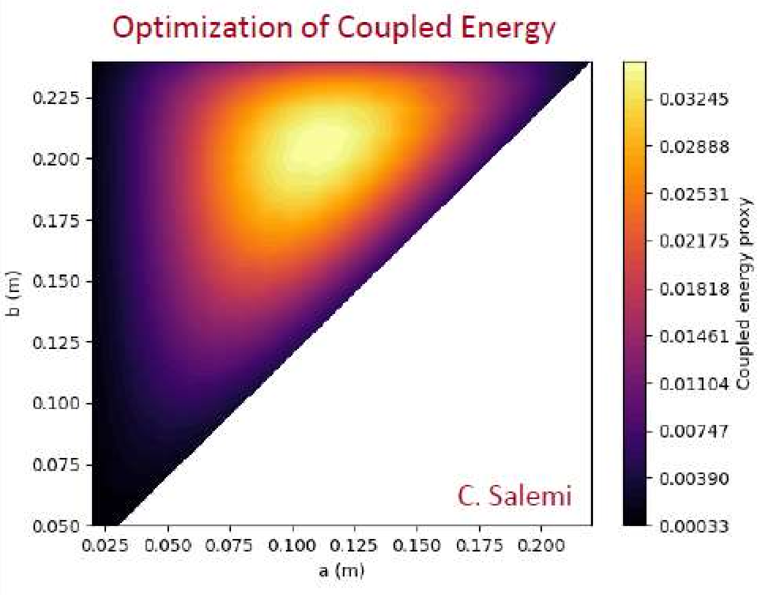


DMRadio-50L

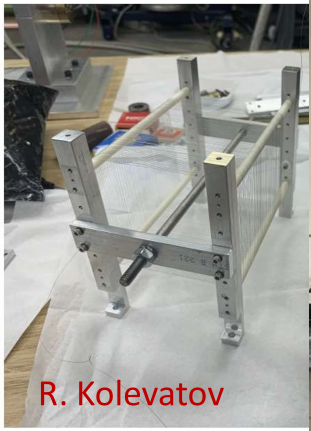
- Target $g_{a\gamma\gamma}$~$5x10^{-15}$ GeV^{-1} , 20 peV-20 neV
- 1T peak field in 50L volume
- Toroidal magnet, being constructed in conjunction with SSI
- Confined DC field enables use of high-Q superconducting pickup
- Aiming for Q~10^6, T~100 mK, η-100x quantum limit
- Testbed for quantum acceleration beyond SQL



Work towards DMRadio-50L

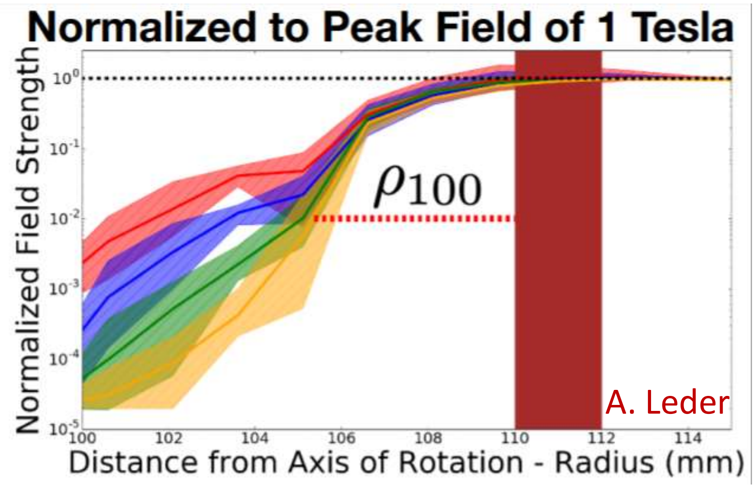


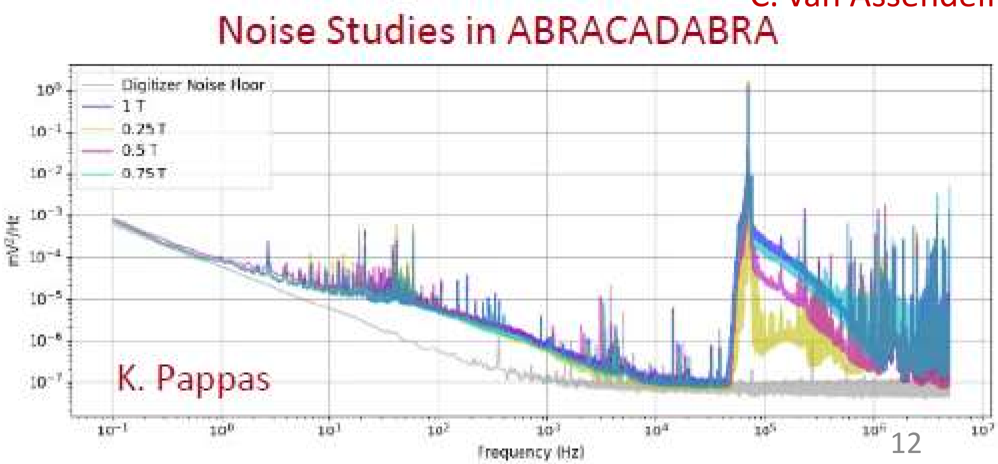
Resonator probes



SQUID characterization

C. van Assendelft

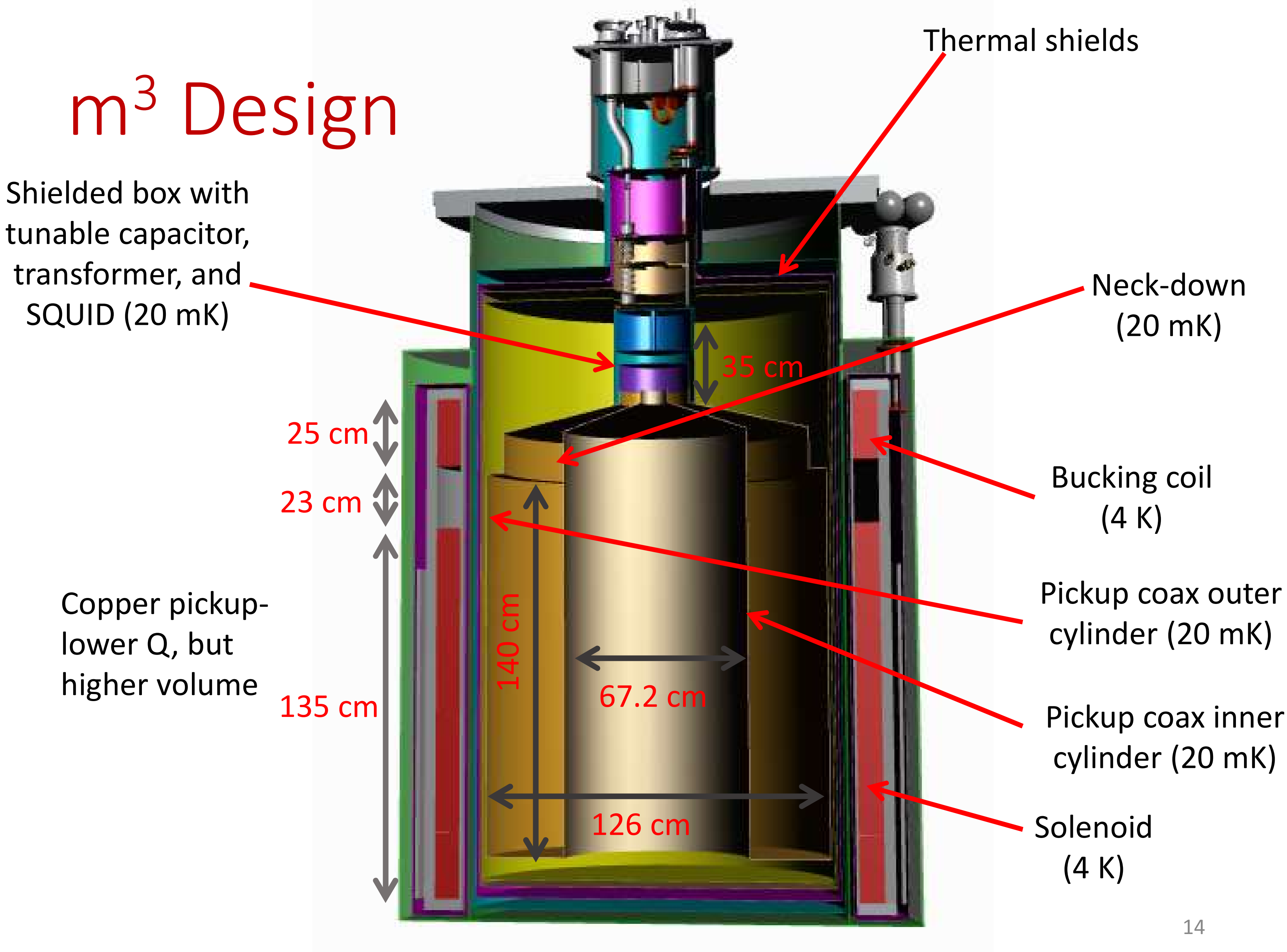




DMRadio-m^3

- Design study as part of DOE Dark Matter New Initiatives
- Aiming for sensitivity to QCD axions 20 neV-800 neV, DFSZ 120 neV-800 neV
- Parasitics make toroid design difficult at large volumes, high frequencies
- Developing ~4 T, 2000L detector with solenoid magnet

m^3 Design



Shielded box with tunable capacitor, transformer, and SQUID (20 mK)
Thermal shields
Neck-down (20 mK)
35 cm
25 cm
23 cm
Bucking coil (4 K)
Copper pickup- lower Q, but higher volume
140 cm
135 cm
67.2 cm
Pickup coax outer cylinder (20 mK)
Pickup coax inner cylinder (20 mK)
126 cm
Solenoid (4 K)

DMRadio-GUT

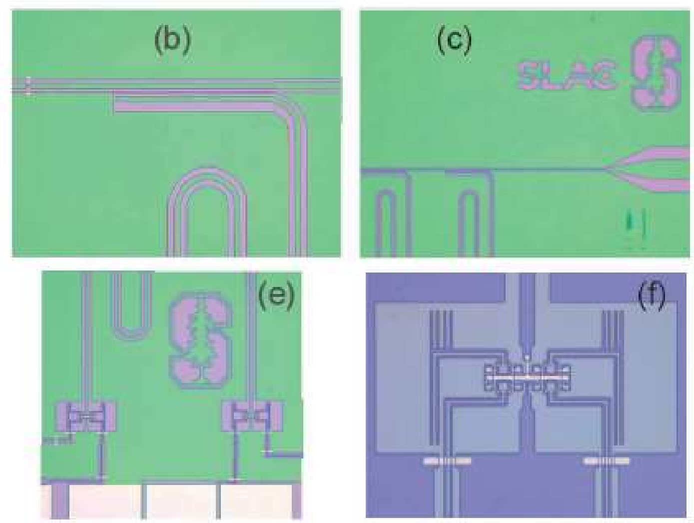
- Ambitious, long-term experiment to probe GUT-scale QCD axions near 1 neV
- Push on all parts of FOM
- 12T, 10m^3 magnet
- Q of 20 million resonator
- 20 dB of backaction noise reduction below SQL
- 7 years of run time

Emerging and future R&D

LIGO Livingston

T. Henderson- MIT PSFC

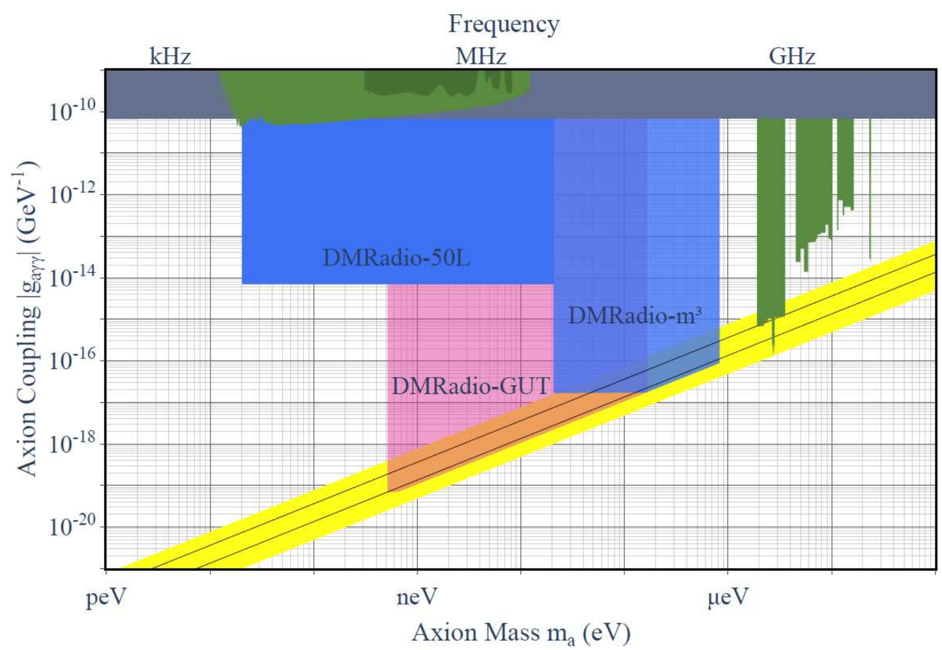
Large-scale toroidal magnets for plasma physics (SPARC), IAXO



LIGO-inspired quantum sensing

Summary

- DMRadio: a lumped-element resonant search for sub-μeV axions
- DMRadio-50L: ALPS search, testbed for quantum acceleration, starting data-taking ~2023
- DMRadio-m^3: QCD axions 20 neV-800 neV, starting data-taking ~2025
- DMRadio-GUT: ambitious, long-term search for GUT-scale QCD axions near 1 neV



DMRadio Scientific Collaboration

DM RADIO

Sponsors:

U.S. DEPARTMENT OF ENERGY Office of Science

NSF

HEISING-SIMONS FOUNDATION

GORDON AND BETTY MOORE FOUNDATION

Members:

SLAC NATIONAL ACCELERATOR LABORATORY

Berkeley UNIVERSITY OF CALIFORNIA

MIT

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Stanford University

CAL STATE EAST BAY

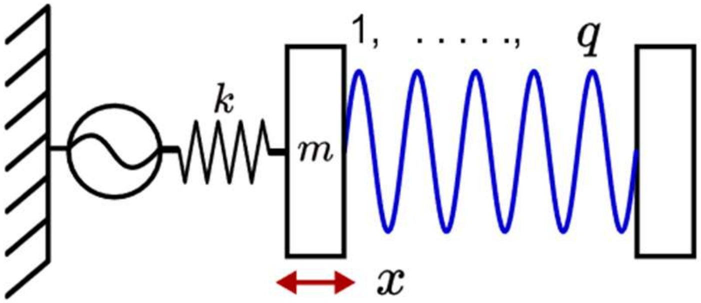
PRINCETON UNIVERSITY

BERKELEY LAB

Extras

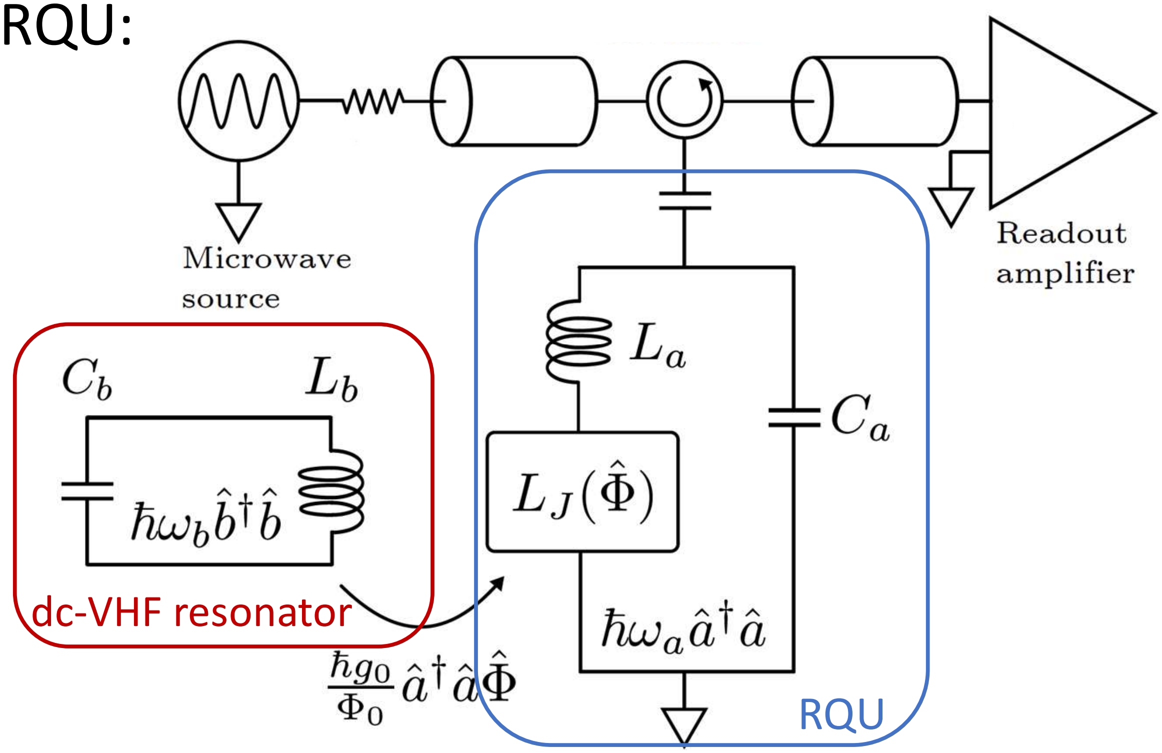
Quantum metrology with RF Quantum Upconverters

LIGO:



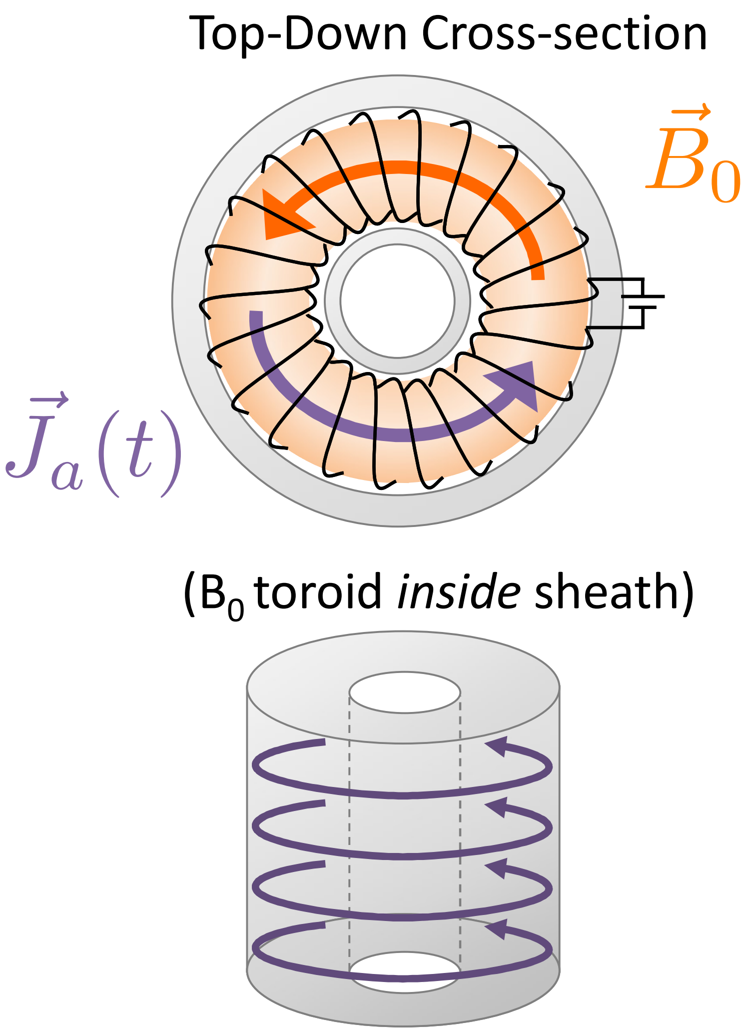
$$\omega_B = \sqrt{\frac{k}{m}} \qquad \omega_A = \frac{2\pi q c}{l(x)}$$

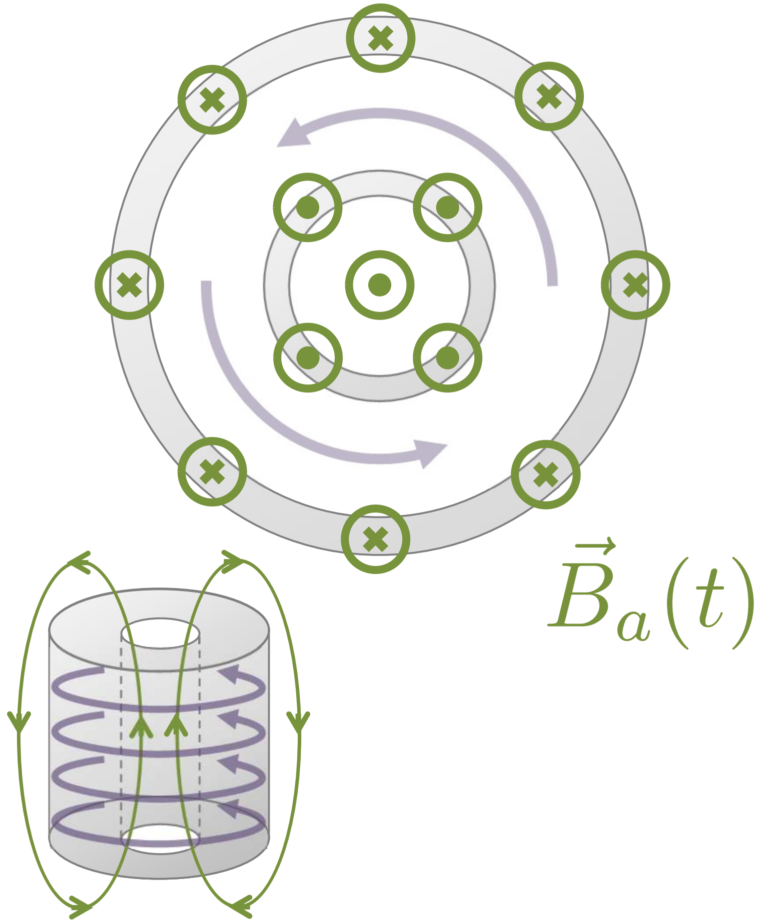
RQU:



- Identical Hamiltonians enable leveraging of existing quantum metrology protocols

Axion detection

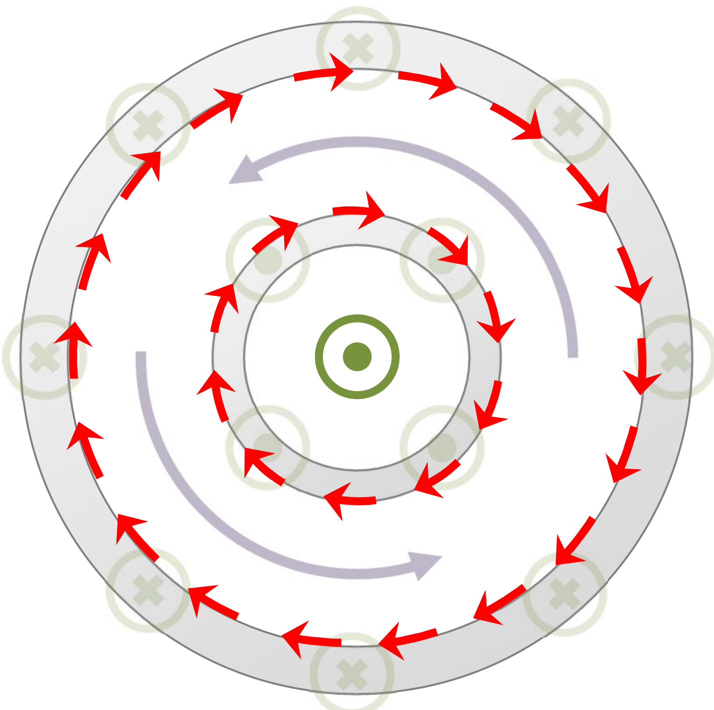


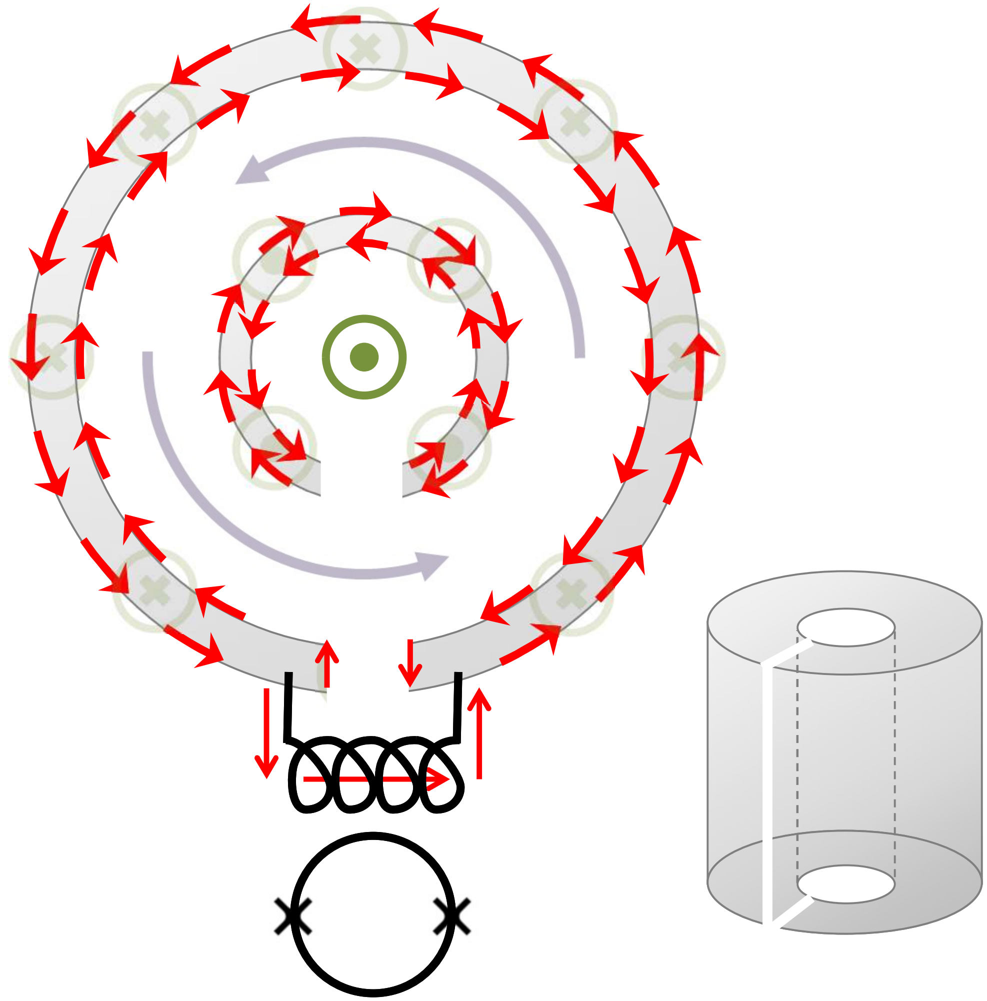


1. Toroidal coil produces DC magnetic field inside sheath. Axions behave as AC current.

2. Current generates oscillating, quasi-static B-field.

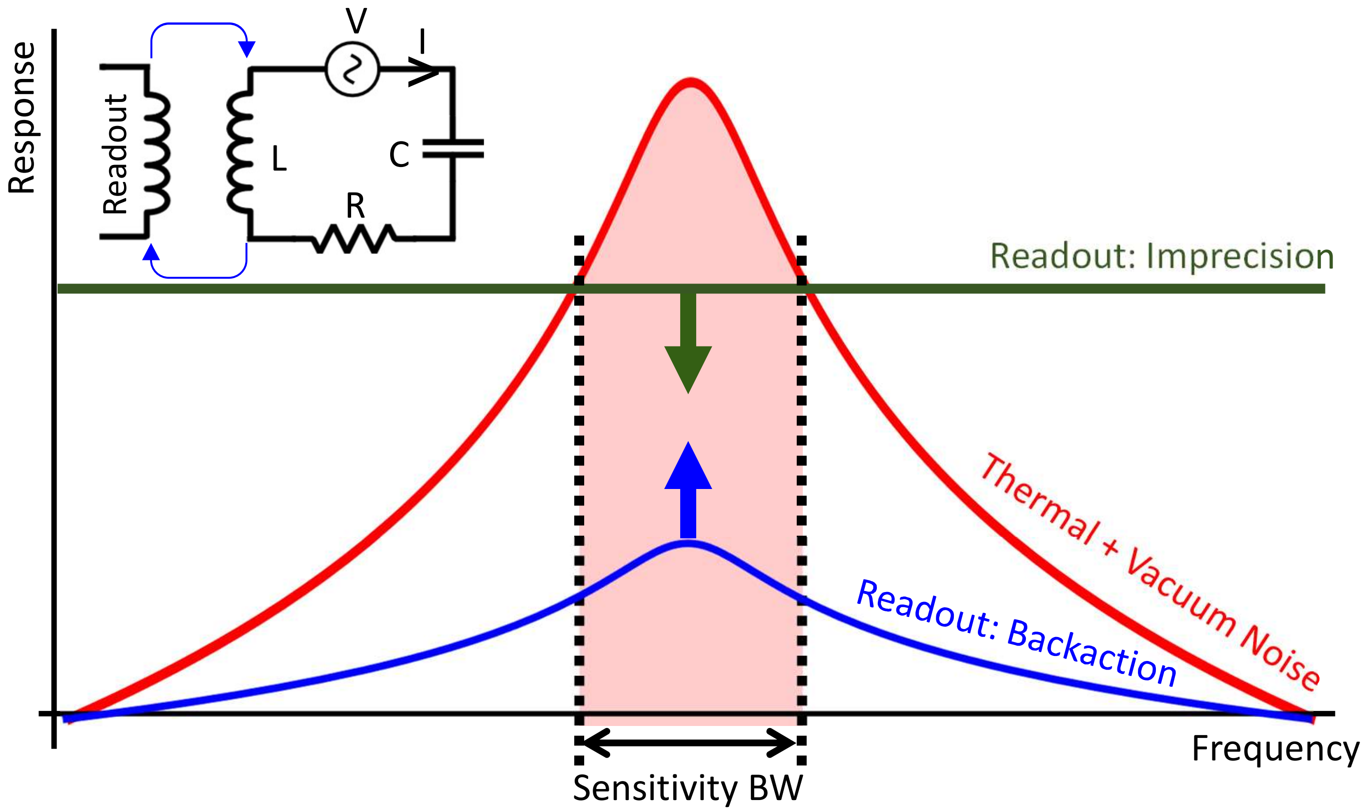
Axion detection



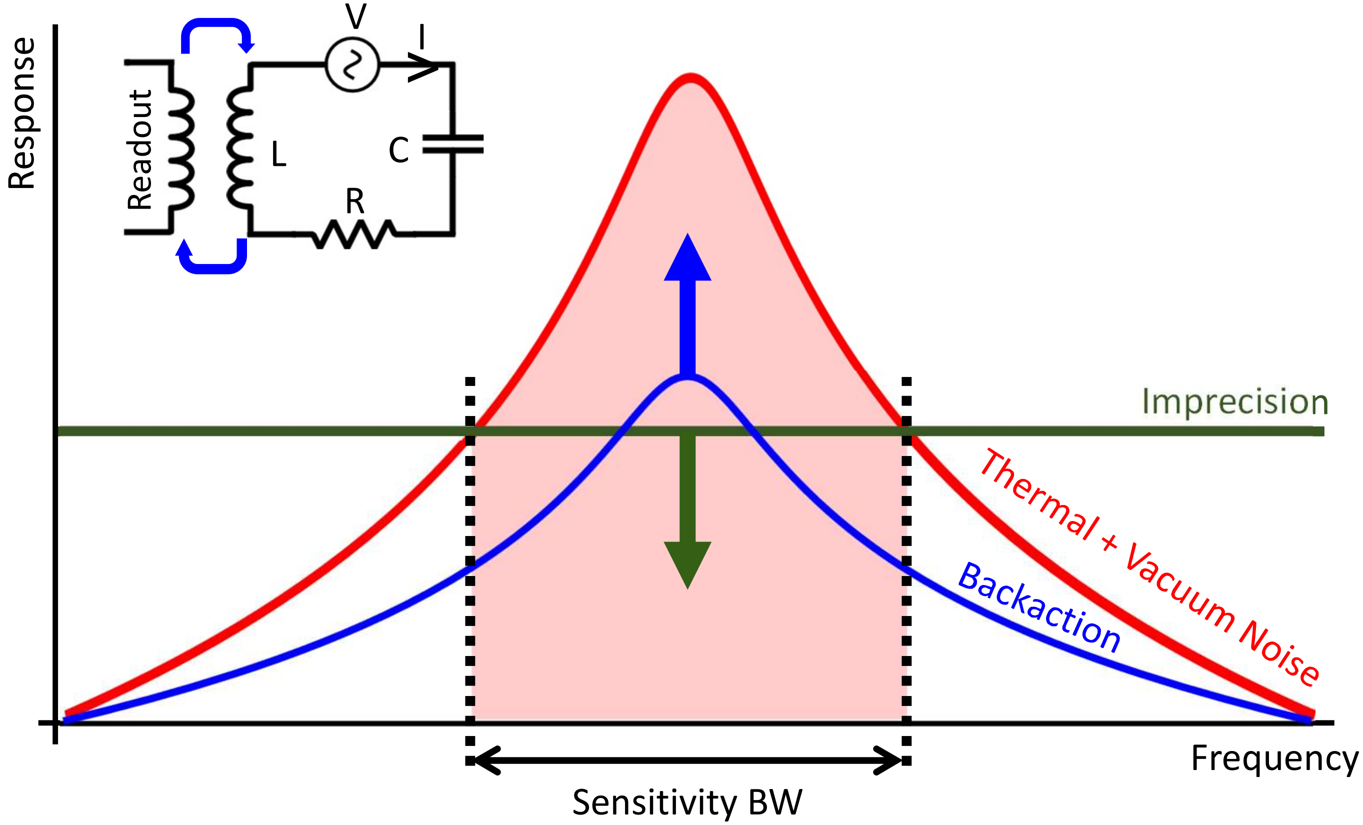


3. Screening currents (red) flow to cancel field in bulk.
4. Cut side slit in sheath, detect currents with SQUID.

Increase coupling to lower imprecision noise



Backaction is exchanged for imprecision



Optimize coupling to maximize sensitivity BW