Berkeley Axion Works™

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Searching for sub-μeV axions with DMRadio: Overview and Status

Alex Droster
July 10, 2024
IDM 2024, L'Aquila

Outline

1. The pre-inflationary axion
2. Lumped-element detection
3. DMRadio-50L
   a. Design
   b. Projected sensitivity
4. DMRadio-m^3
5. DMRadio-GUT
6. What’s happening now in DMRadio?
7. Summary

Axion parameter space

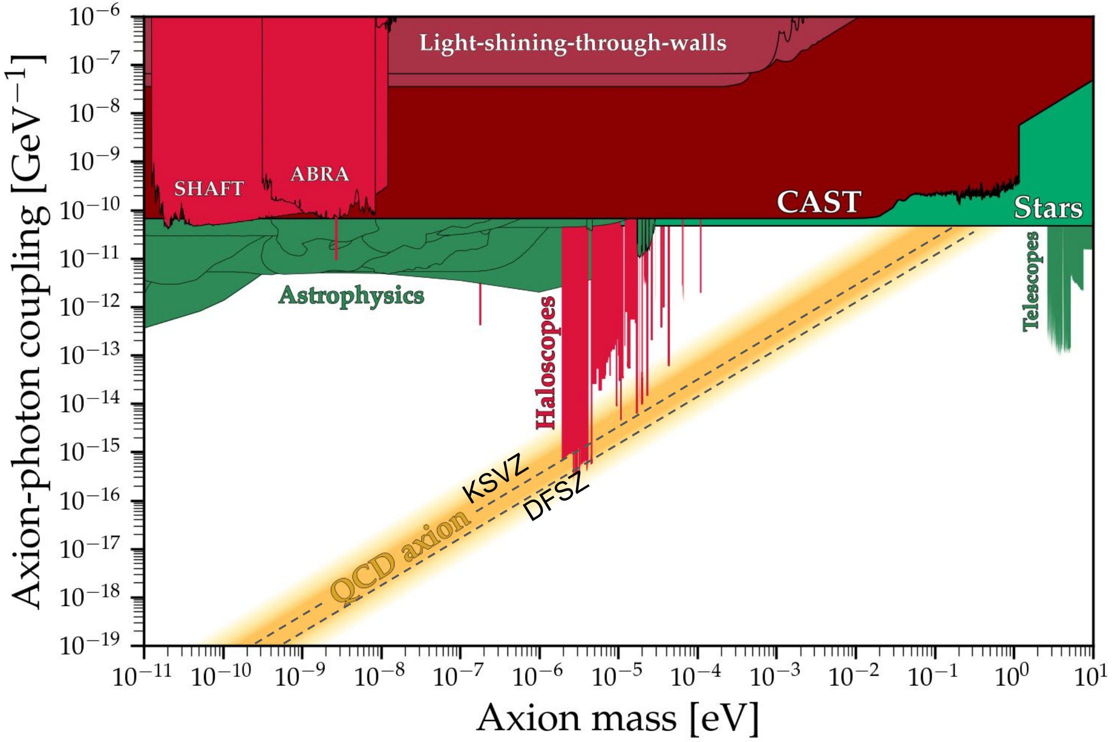
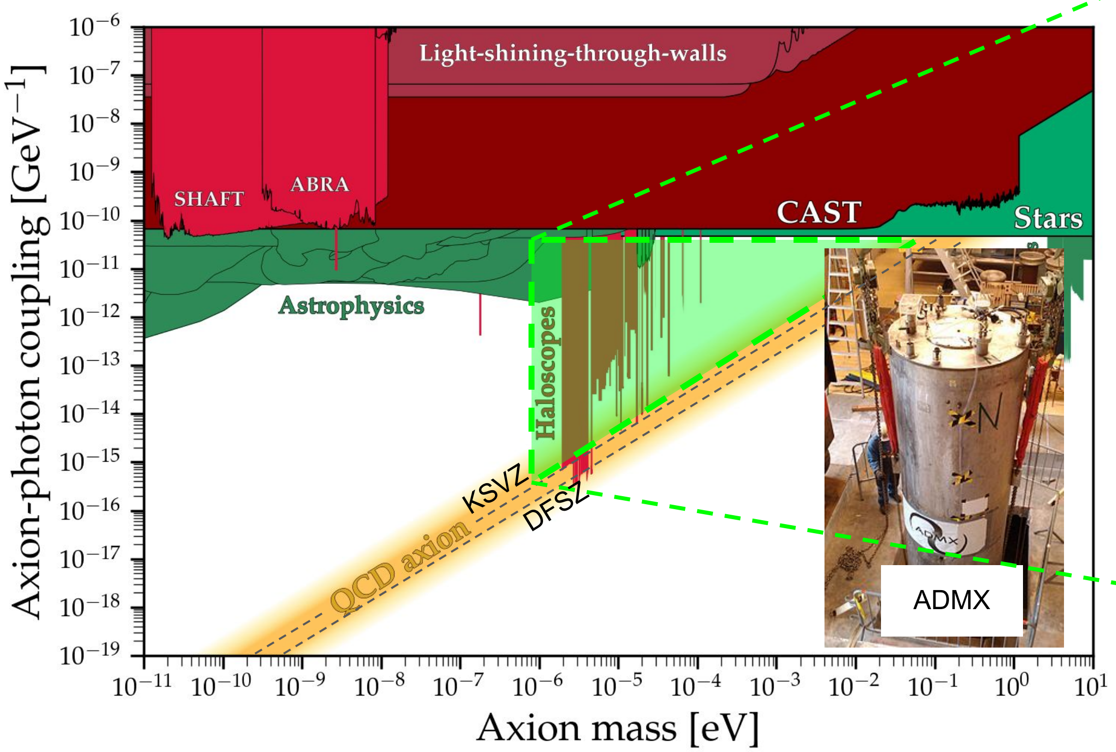


Image: Ciaran O'Hare

Axion parameter space



Wavelength $\lambda \leq 1$ m

Axion frequency matches cavity mode frequency

Many of us here today!

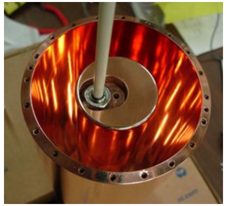
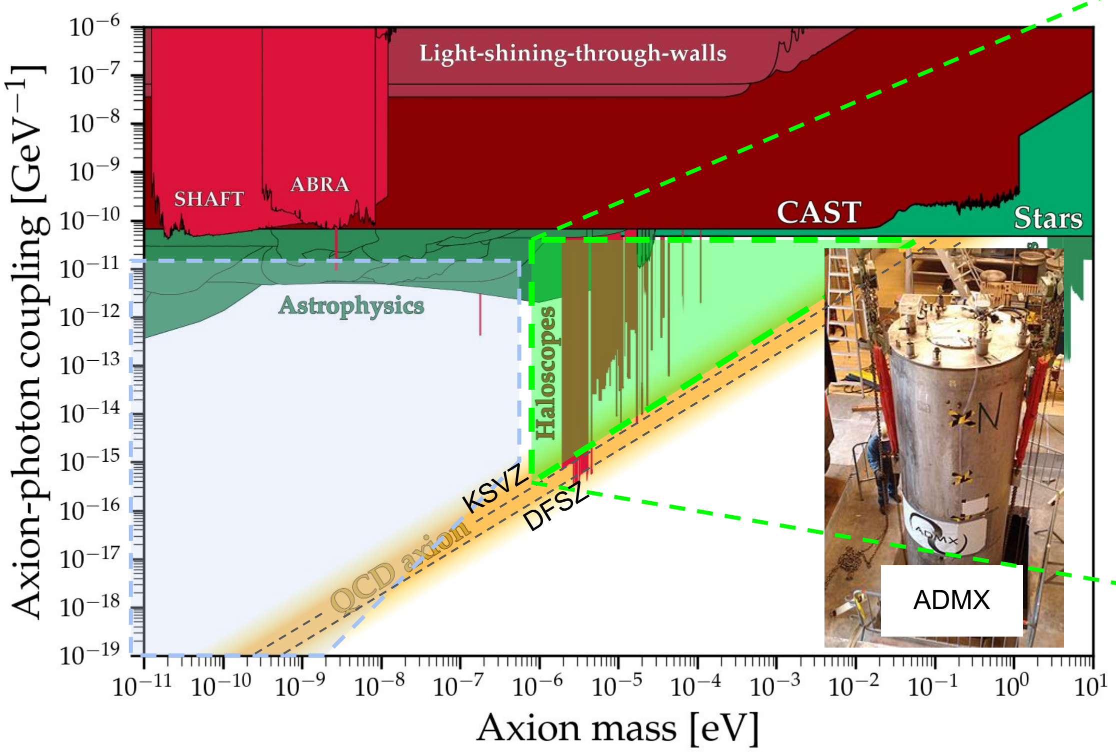


Image: Ciaran O'Hare

Axion parameter space



Wavelength $\lambda \leq 1$ m

Axion frequency matches cavity mode frequency

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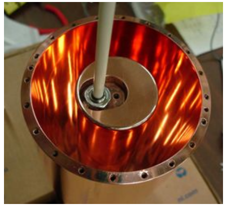


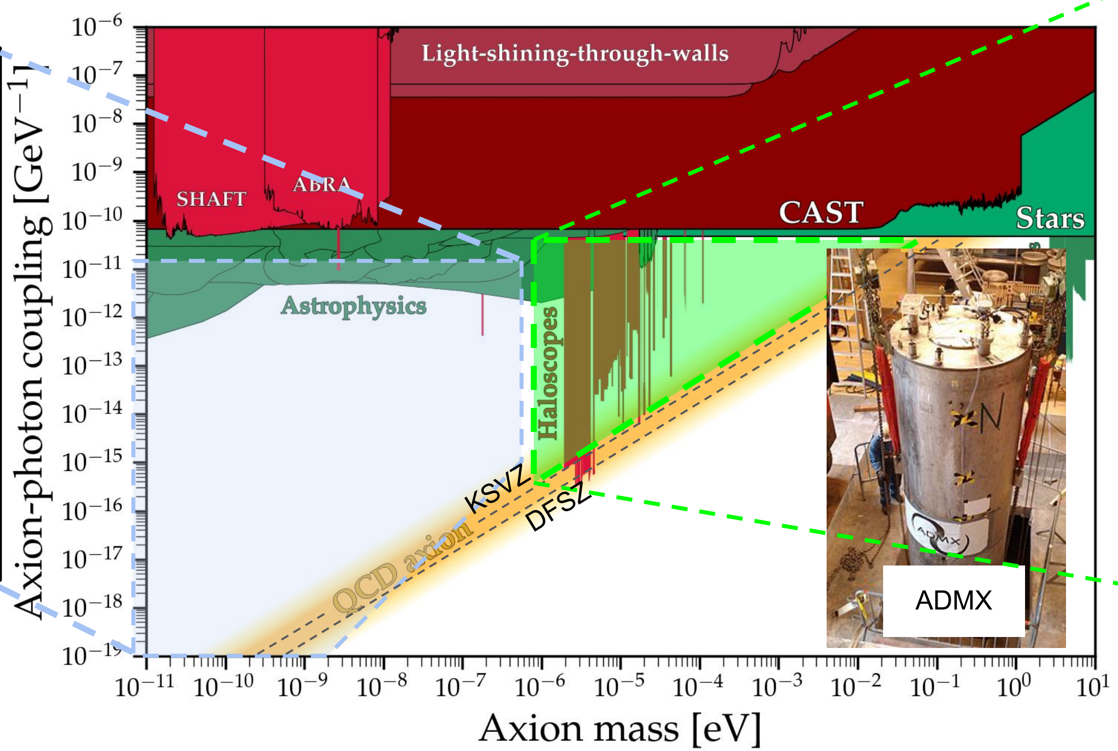
Image: Ciaran O'Hare

Much well-motivated parameter space left to explore!

Axion parameter space

Wavelength $\lambda \gg 1$ m

Axion frequency matches LC circuit resonance frequency



Wavelength $\lambda \leq 1$ m

Axion frequency matches cavity mode frequency

Many of us here today!

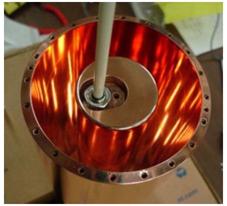


Image: Ciaran O'Hare

DMRadio: Probe low-mass axions by decoupling the detector's frequency its geometry

DMRadio collaboration

C. Bartram, H.M. Cho, W. Craddock, D. Li, W. J. Wisniewski, A. K. Yi
SLAC National Accelerator Laboratory

A. AlShirawi, J. Corbin, P. W. Graham, K. D. Irwin,, S. Kuenstner, A. Kunder, N. M. Rapidis, C. P. Salemi, M. Simanovskaia, J. Singh, E. C. van Assendelft, K. Wells
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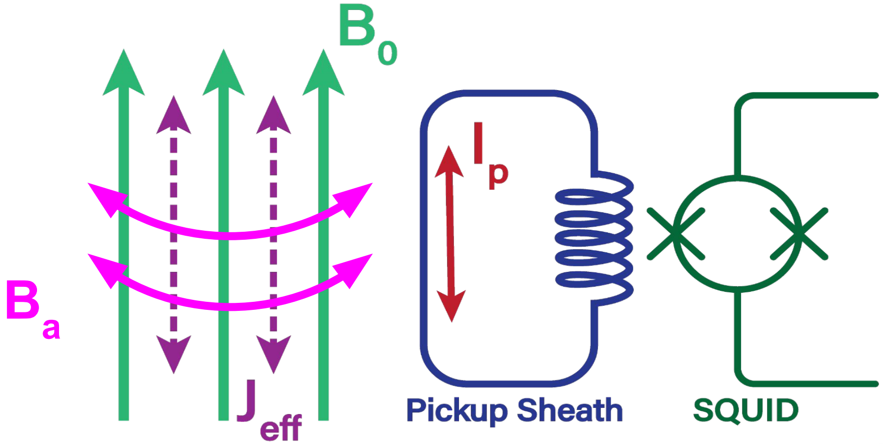
B. R. Safdi
Department of Physics
University of California Berkeley

Lumped-element detection

ABRACADABRA-10cm: **Broadband** search for neV axions!



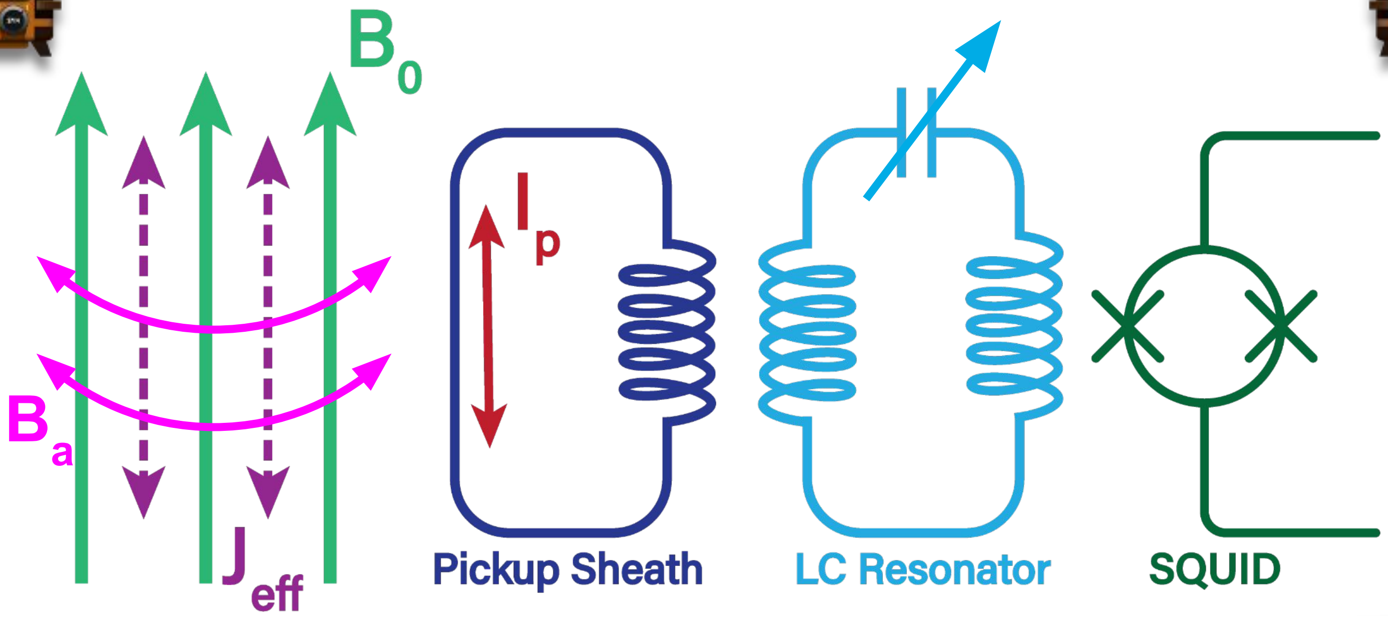
$$\vec{J}_{eff} = g_{a\gamma\gamma}\sqrt{2\rho_{\rm DM}}\cos{(m_a t)}\vec{\rm B}_0$$

Others: SHAFT, ADMX SLIC, DMR Pathfinder

C. Salemi et al., “The search for low-mass axion dark matter with ABRACADABRA-10cm,” Phys. Rev. Lett. 127, 2021

Lumped-element detection

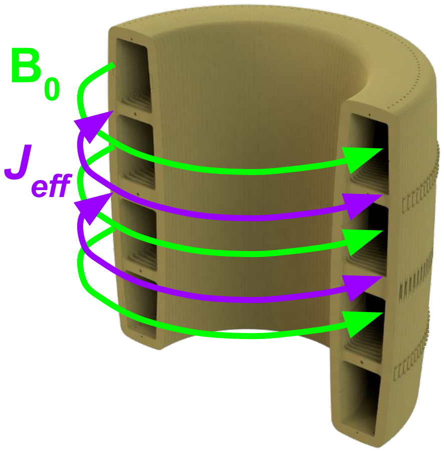
DMRadio: **Resonant** search for neV axions!



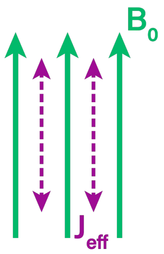
$$\vec{J}_{eff} = g_{a\gamma\gamma}\sqrt{2\rho_{\mathrm{DM}}}\cos\left(m_a t\right)\vec{\mathrm{B}}_0$$

The 50L detector

Magnet



Applied magnetic field B_0 induces effective axion current, J_{eff}



The 50L detector

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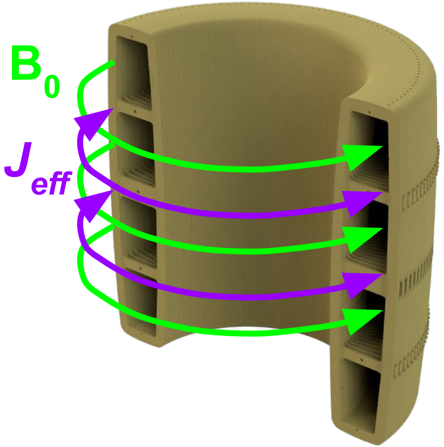

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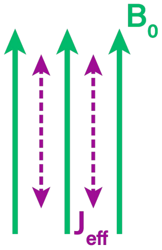
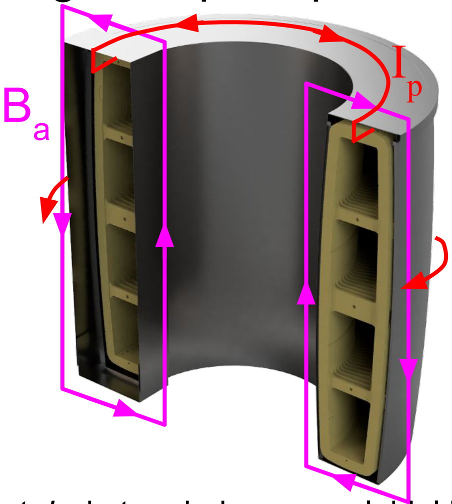
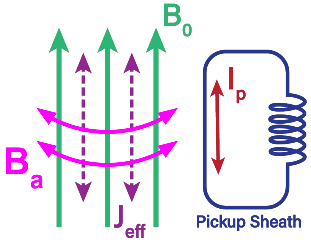


Magnet + pickup sheath

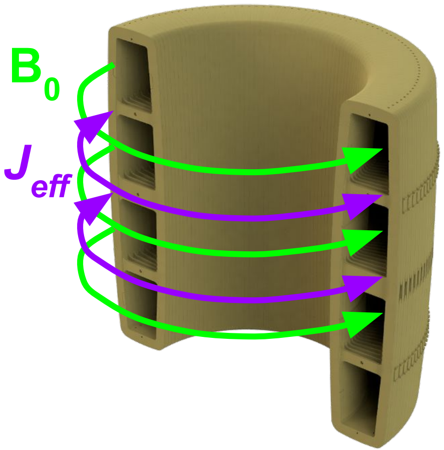


Axion current J_{eff} in turn induces a poloidal RF magnetic field, B_a, inducing currents I_p in a **superconducting sheath** which surrounds the toroidal magnet



The 50L detector

Magnet



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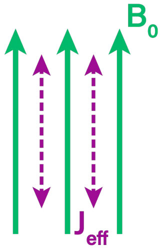

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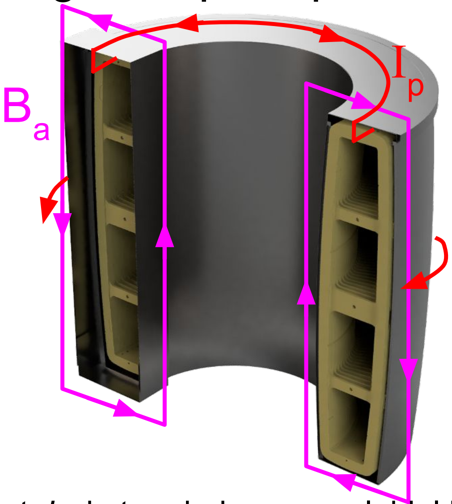

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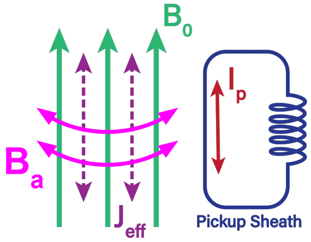
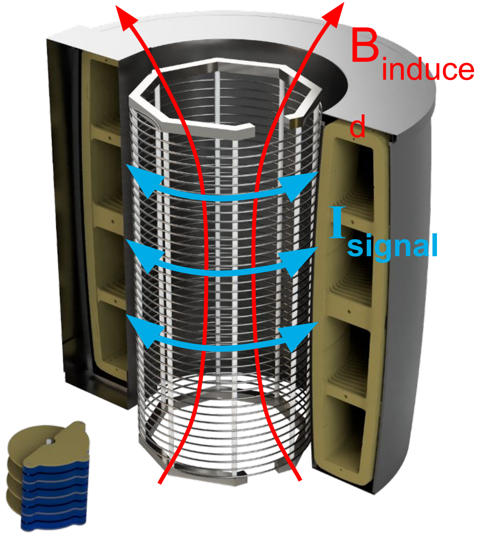
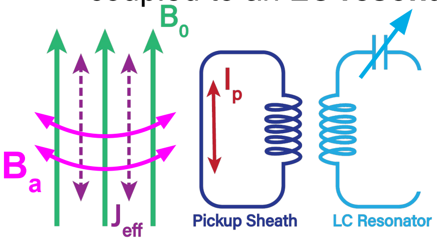


Magnet + pickup sheath +LC resonator



I_p may be sensed by a pickup loop coupled to an **LC resonator**



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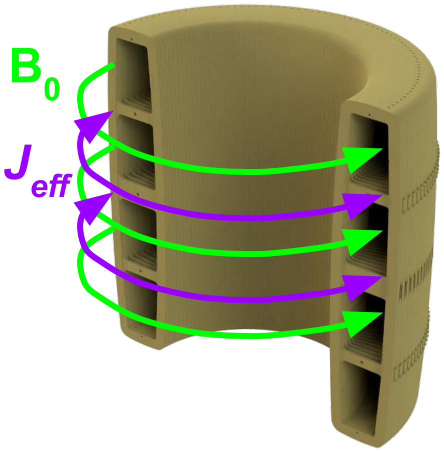
The 50L detector

Magnet



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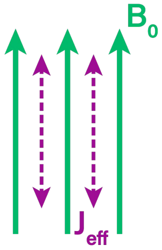
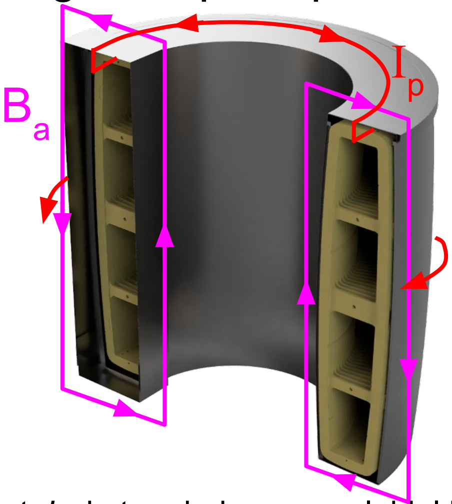


Magnet + pickup sheath



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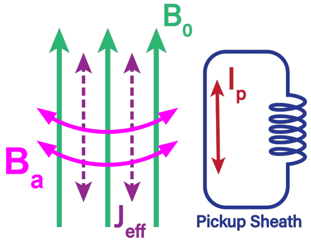
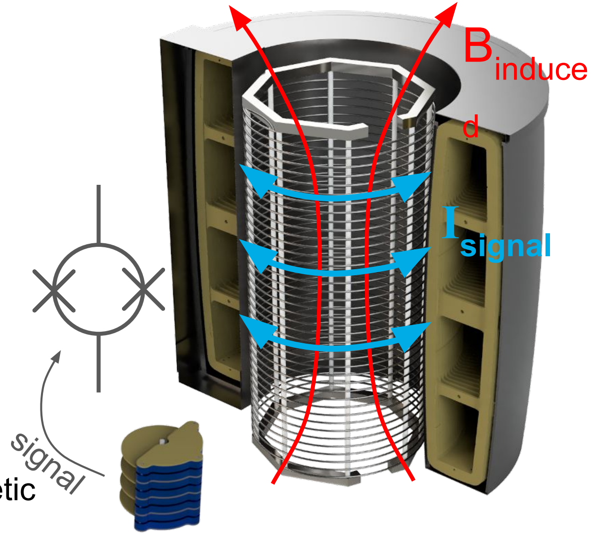


Magnet + pickup sheath +LC resonator



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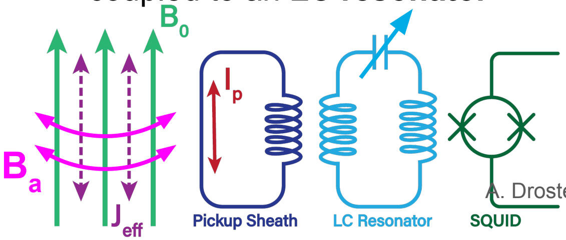
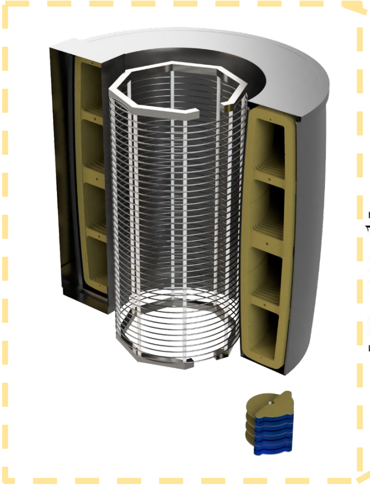
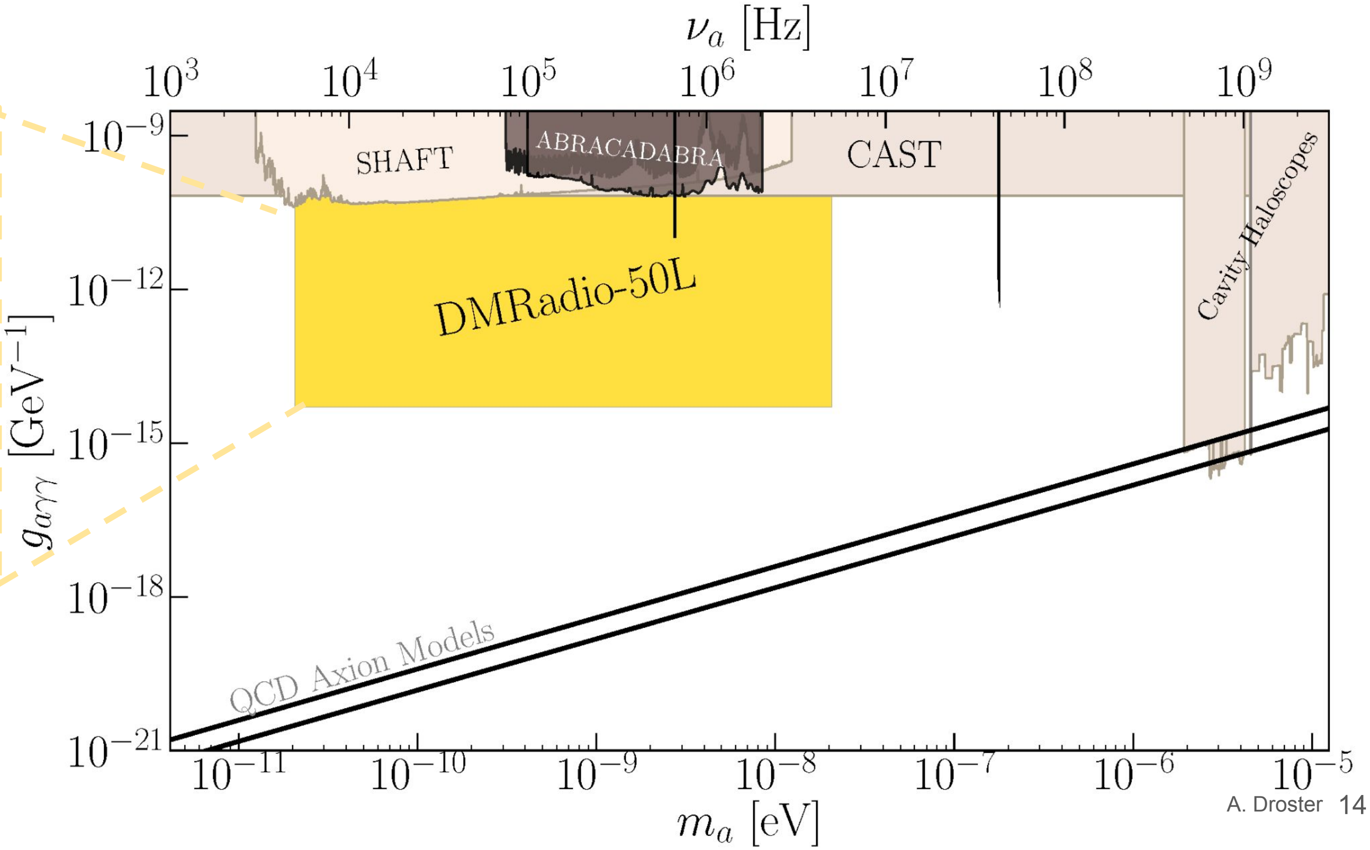


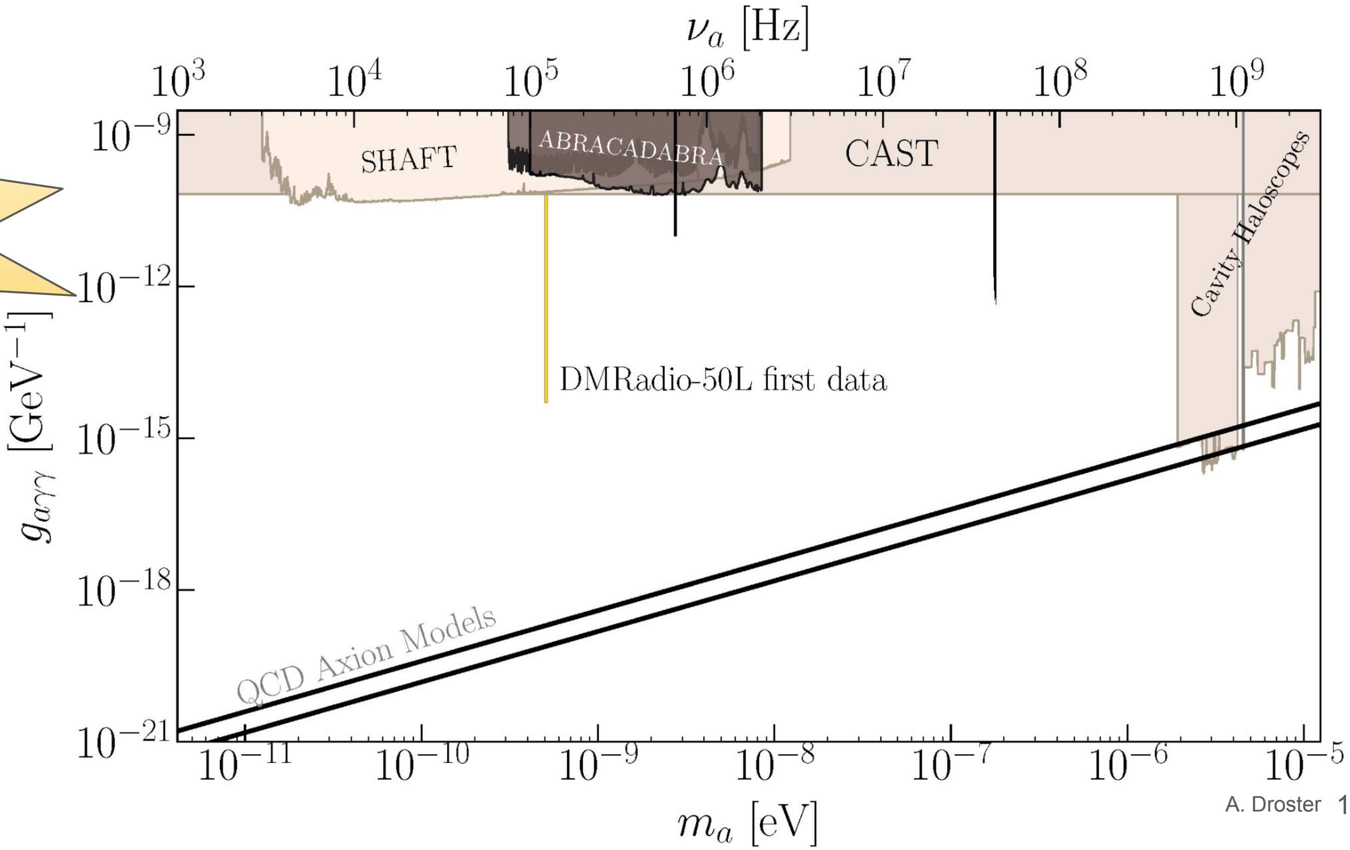
DMRadio-50L projected exclusion





DMRadio-50L first data projected exclusion

"Needle" in parameter space
Expected early 2025!



Scan rate

$$\frac{d\nu}{dt} \propto \frac{1}{\mathrm{SNR}^2}\underbrace{(g_{a\gamma\gamma}^4 \rho_{\mathrm{DM}}^2 Q_a)}_{\text{axion and dark matter physics}}\underbrace{\left(\frac{c_{\mathrm{PU}}^4 Q B_0^4 V_{\mathrm{PU}}^{10/3}\nu}{\eta T_{\mathrm{sys}}}\right)}_{\text{Experimental parameters}}$$

S. Chaudhuri et al., (2018), arXiv:1803.01627 [hep-ph].

Scan rate

$$\frac{d\nu}{dt} \propto \frac{1}{\mathrm{SNR}^2}\left(g_{a\gamma\gamma}^4 \rho_{\mathrm{DM}}^2 Q_a\right)\left(\frac{c_{\mathrm{PU}}^4 Q B_0^4 V_{\mathrm{PU}}^{10/3} \nu}{\eta T_{\mathrm{sys}}}\right)$$

Quality factor (Q)

Magnetic field (B_0^4)

volume ($V_{\mathrm{PU}}^{10/3}$)

Amplifier noise (η)

$\left(g_{a\gamma\gamma}^4 \rho_{\mathrm{DM}}^2 Q_a\right)$: axion and dark matter physics

$\left(\frac{c_{\mathrm{PU}}^4 Q B_0^4 V_{\mathrm{PU}}^{10/3} \nu}{\eta T_{\mathrm{sys}}}\right)$: Experimental parameters

S. Chaudhuri et al., (2018), arXiv:1803.01627 [hep-ph].

Scan rate

$$\frac{d\nu}{dt} \propto \frac{1}{\mathrm{SNR}^2}\left(g_{a\gamma\gamma}^4 \rho_{\mathrm{DM}}^2 Q_a\right)\left(\frac{c_{\mathrm{PU}}^4 Q B_0^4 V_{\mathrm{PU}}^{10/3} \nu}{\eta T_{\mathrm{sys}}}\right)$$

Quality factor (Q)

Magnetic field (B_0^4)

volume ($V_{\mathrm{PU}}^{10/3}$)

Amplifier noise (η)

axion and dark matter physics

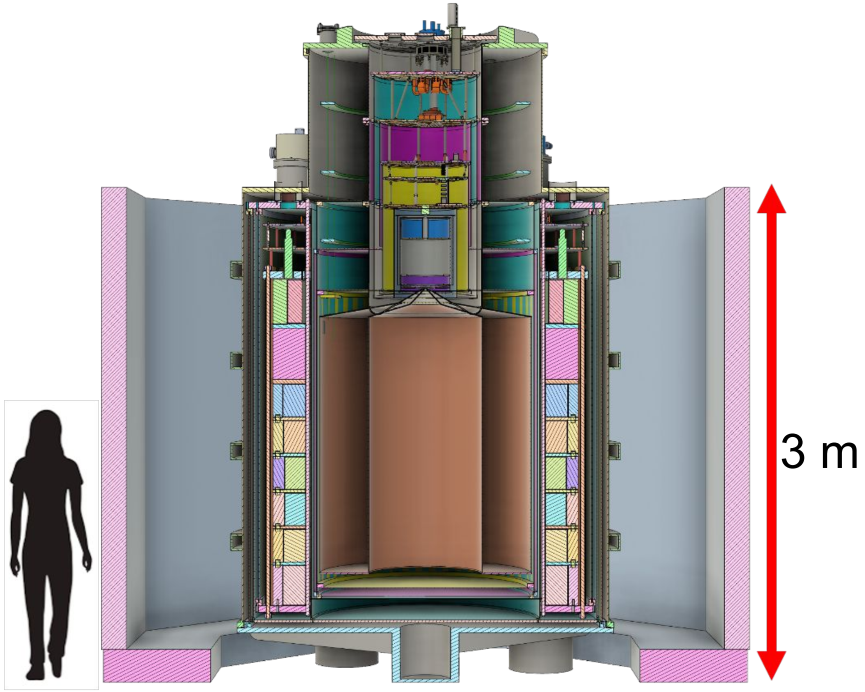
Experimental parameters

Motivates new experiments with improved designs!

S. Chaudhuri et al., (2018), arXiv:1803.01627 [hep-ph].

DMRadio-m^3

- DOE Dark Matter New Initiatives Program
- Q: Expected quality factor of $Q=10^6$ with copper "coax" - state of the art!
- V: Improved volume 1 m^3
- B: Improved magnetic field: B_{RMS} = 5 T
- η: SQUID readout, 100X SQL (50L) $\rightarrow$ ~20X SQL
- Probes QCD axion coupling 5-200 MHz
- First science in 2028



- Phys. Rev. D, 106 (2022)
- High frequency modeling, arXiv: 2302.1408
- Falferi 1998; Ulmer 2016

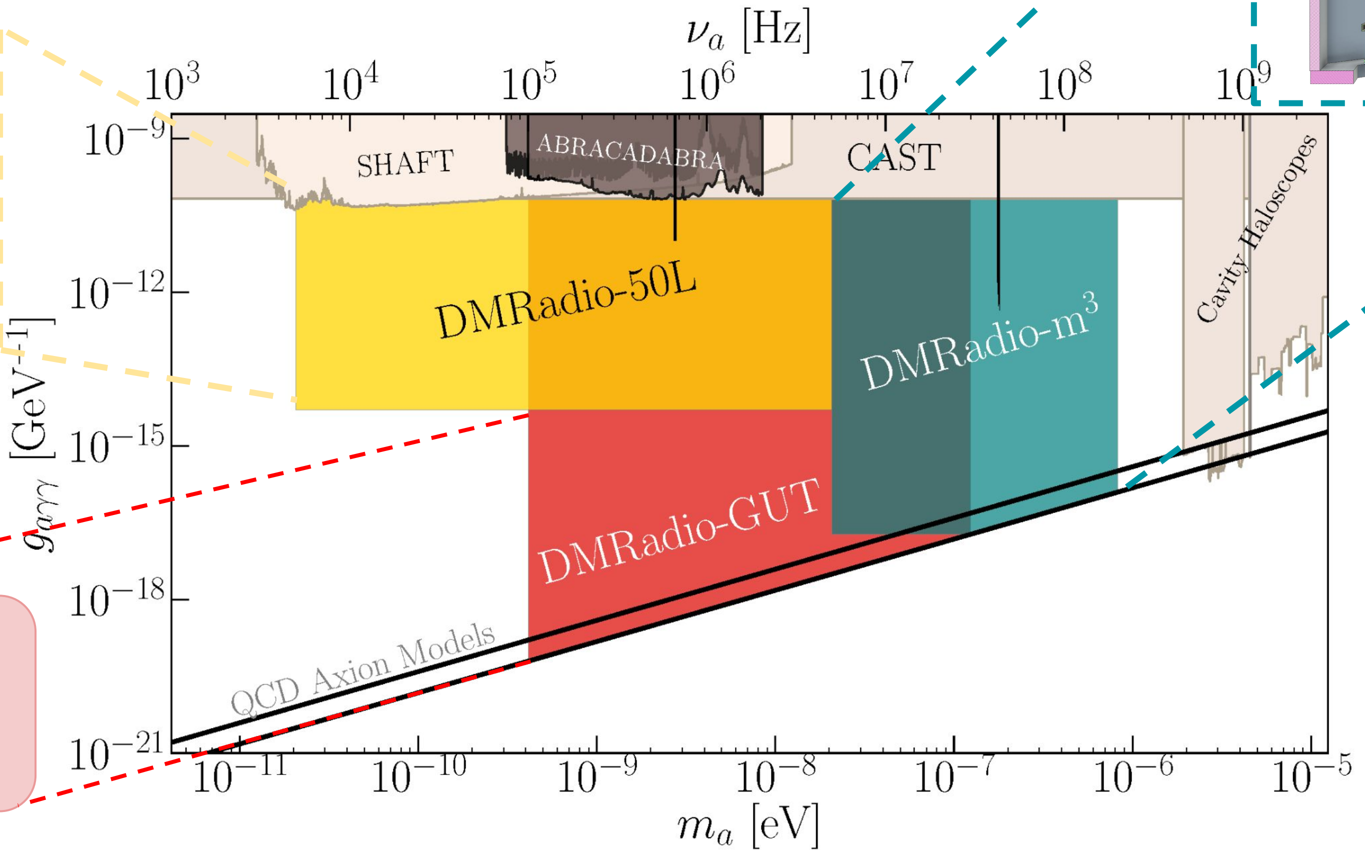
DMRadio-GUT

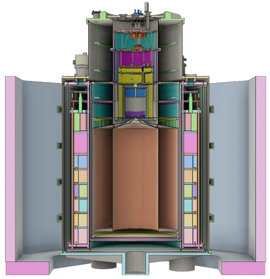
Ambitious long-term goal for GUT-scale QCD axion search
Requires **beyond SQL quantum sensing in 1 kHz-100 MHz range**

- Q: $10^6 \rightarrow 20\times10^6$
  - Resonator work ongoing
  - Active components
- V: 1 m^3 → 10 m^3
- B: 5 T → 16 T using REBCO tapes
- η: -20 dB backaction noise reduction via RF quantum upconverters (RQUs), currently in development
- Probes QCD axion coupling over wide frequency range (~100s peV - 100 neV)

L. Brouwer et al., "Introducing DMRadio-GUT, a search for GUT-scale QCD axions," PRD 106, 112003 (2022) (Arxiv:2203.11246)

DMRadio projected exclusion

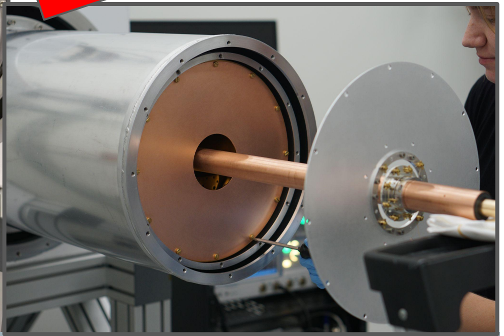




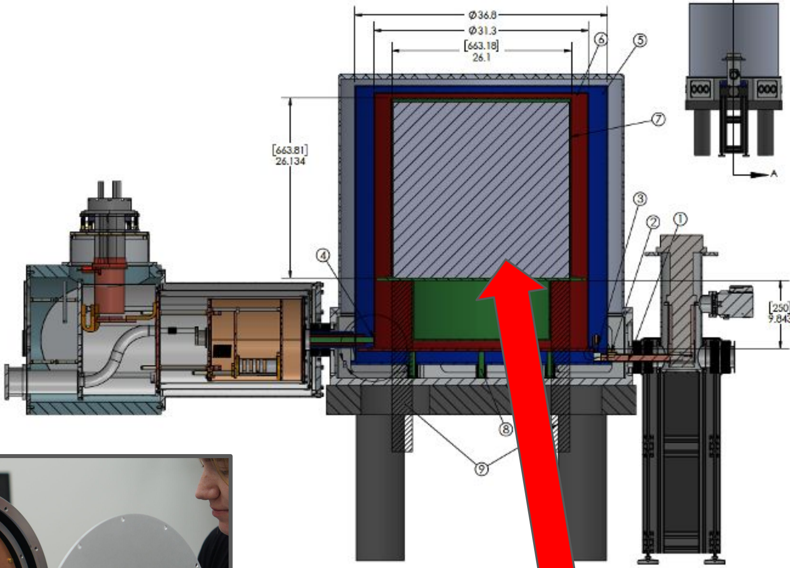
Next-gen experiment 😀

What’s happening now on DMRadio?

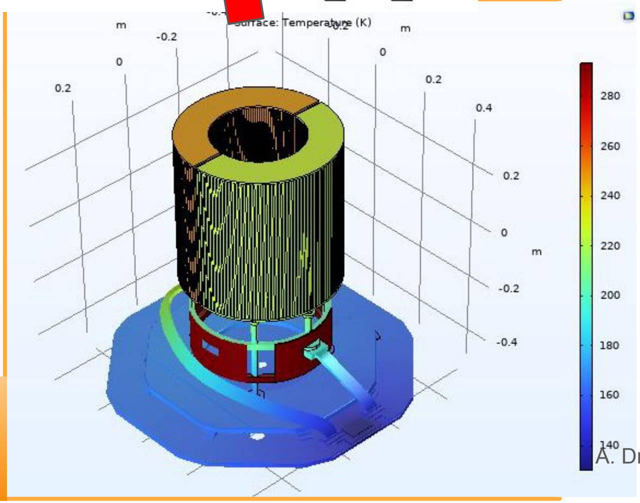
Cryogenics



Cold snout testing (Aya Keller, Maria Simanovskaia, Nicholas Rapidis, Elizabeth Berzin)



Dual cryogenic system (Four Nines Design, Maria Simanovskaia)



Thermalization modeling (Alex Droster, Jessica Fry)

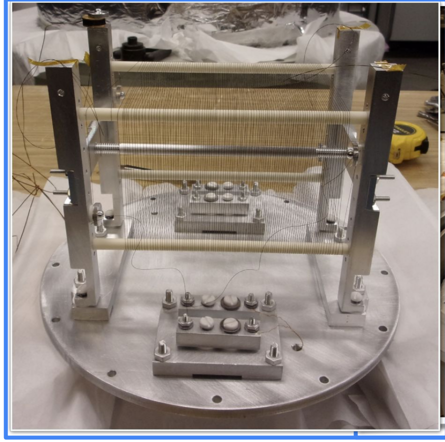
Magnet

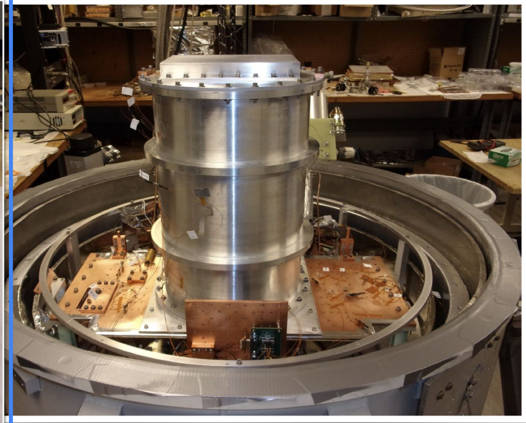
Magnet winding & testing at Superconducting Systems, Inc (SSI)

Structural support construction at Stanford (Alex Droster, Johny Echevers)

Resonator

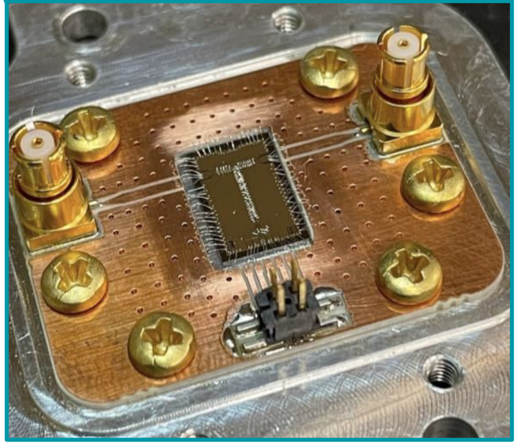
Prototype inductor & Q testing (Roman Kolevatov & Saptarshi Chaudhuri



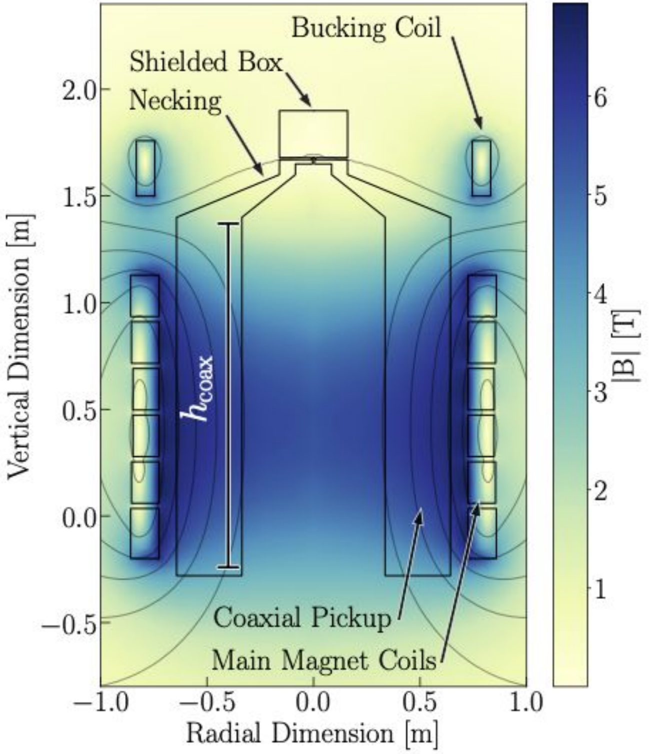


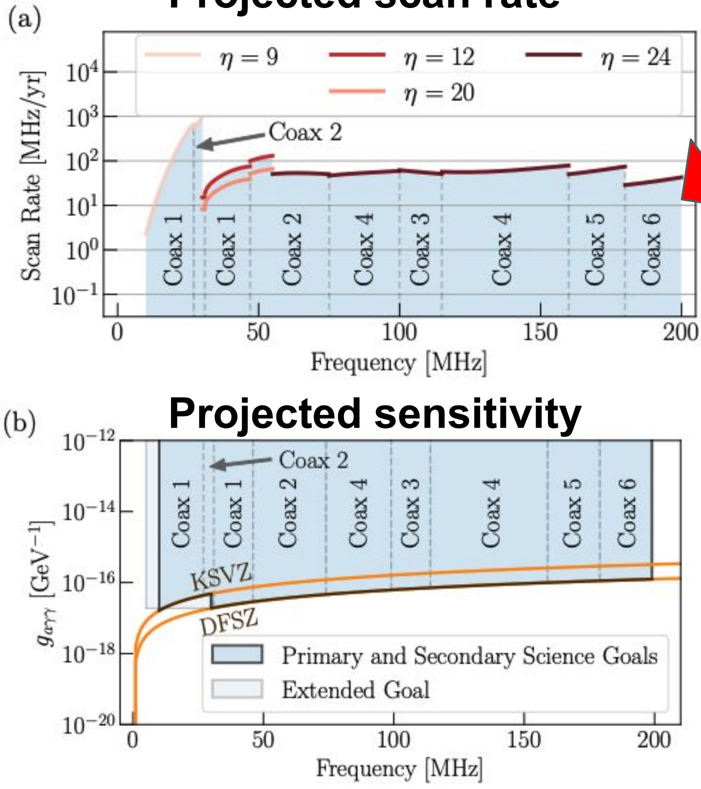
Dip probe for SQUID testing (Joe Singh, Chiara Salemi)

RF quantum upconverters (RQUs) (Andrew Yi, Chelsea Bartram)



DMRadio-m^3 sensitivity simulations in COMSOL





Projected scan rate

Projected sensitivity

Multiple "coaxes" required due to TEM modes

(Nicholas Rapidis, Joshua Foster, Alex Droster)

A. AlShirawi, et a. "Electromagnetic Modeling and Science Reach of DMRadio-m^3," https://arxiv.org/pdf/2302.14084

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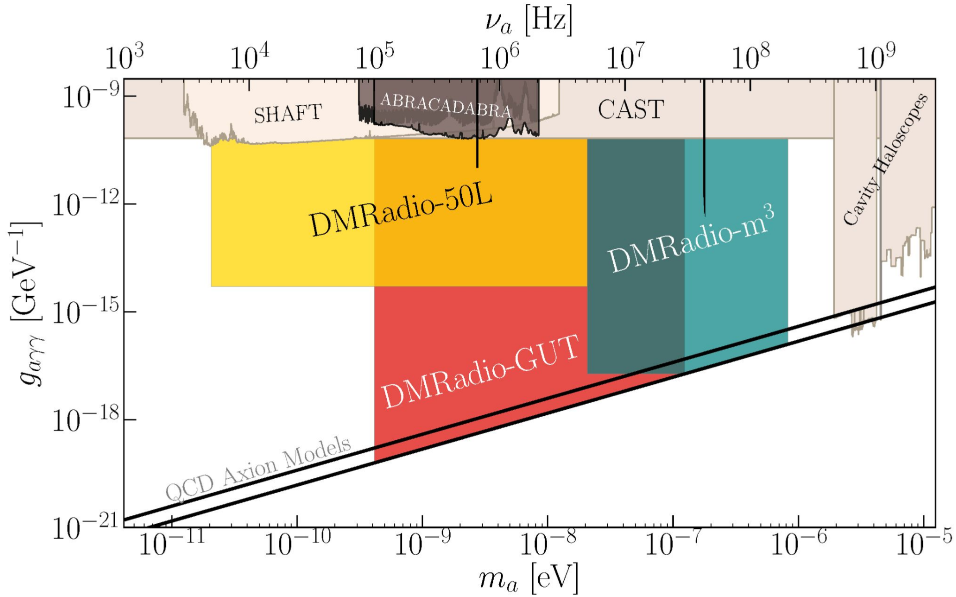
Outlook + conclusions

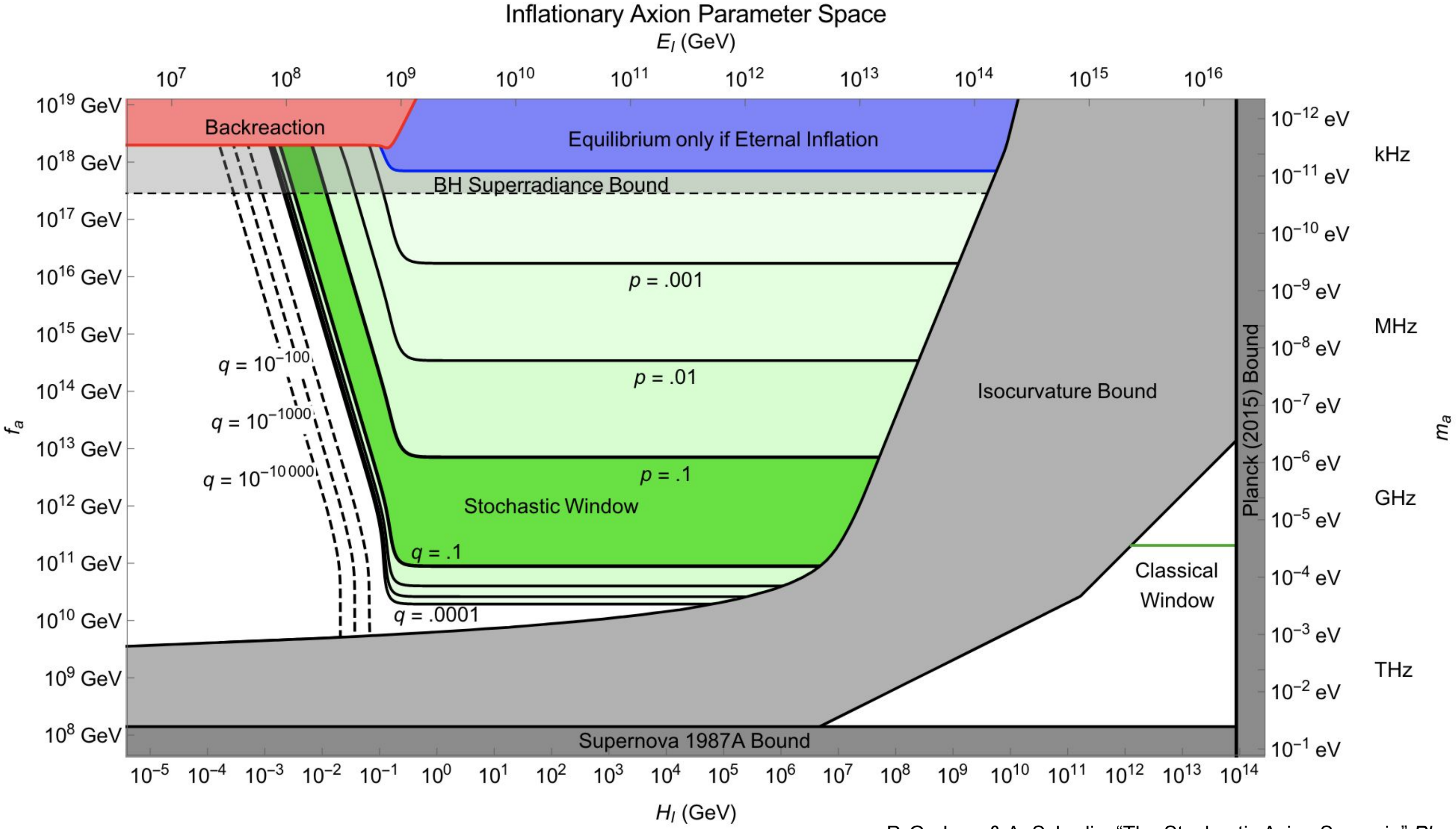
Grazie mille!

- Lumped-element detection enables searching for the pre-inflationary axion
- The DMRadio suite of experiments will search for axion dark matter from 5 kHz-200 MHz (m_a=0.02-800 neV)
- DMRadio-50L is under construction– we hope for “first dark” in early 2025 🤯 🤞
- DMRadio-m^3 is in the design and development stages
- DMRadio-m^3 and DMRadio-GUT will be sensitive to the QCD axion



Extras

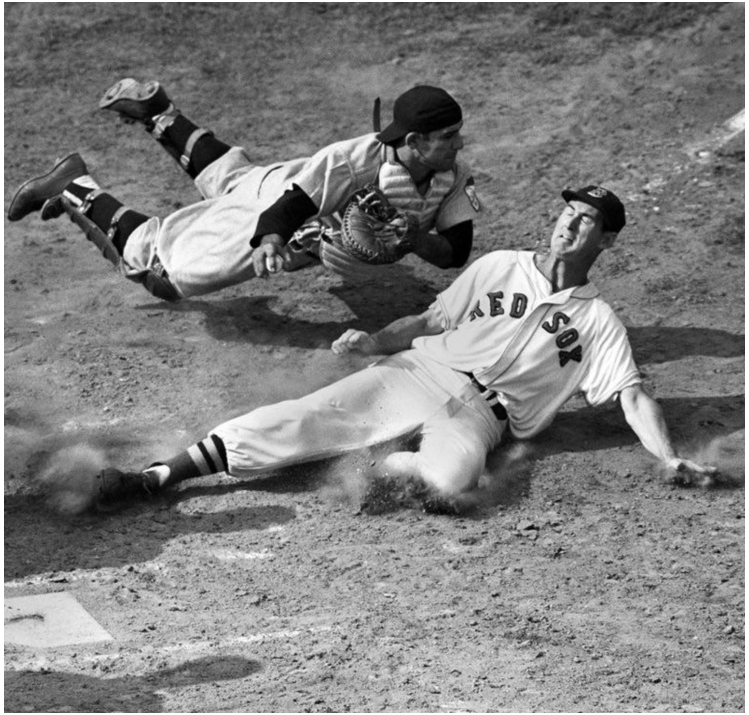
Pre-inflationary axion



P. Graham & A. Scherlis, “The Stochastic Axion Scenario” *Phys. Rev. D* 98, 2018

Design philosophy

"You can observe a lot by watching"
- Yogi Berra
(1925-2015)



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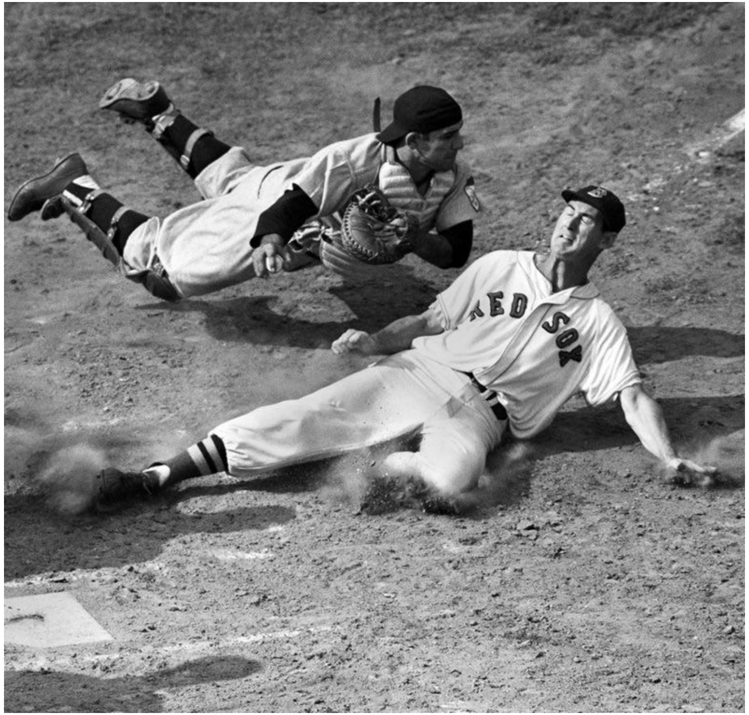
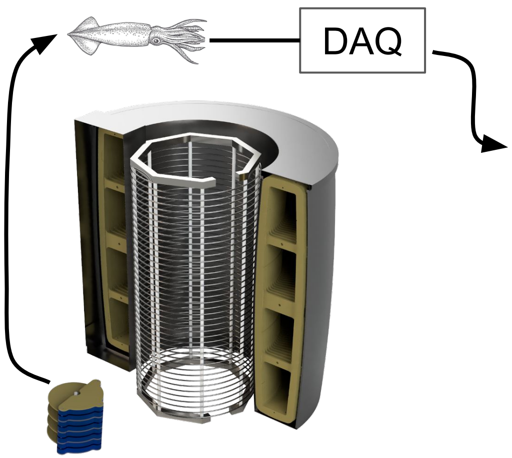
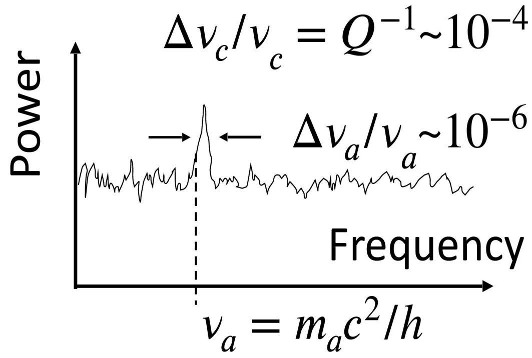


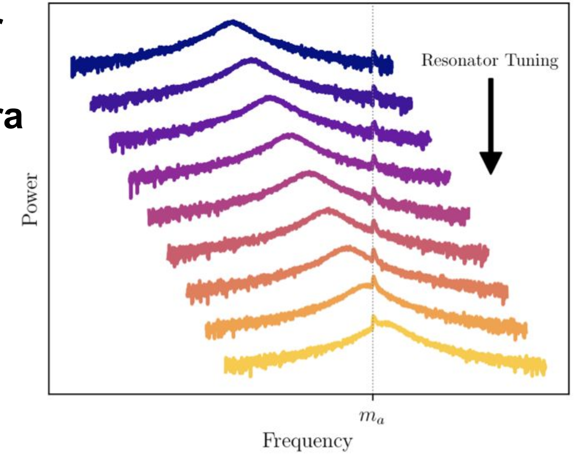
DMRadio: a lumped-element search for low-mass QCD axions

Axion signal





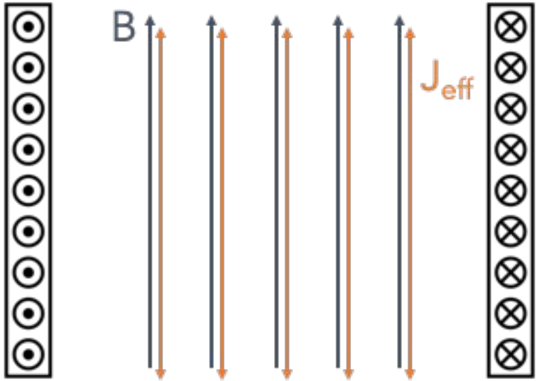
Tune detector and stack multiple spectra



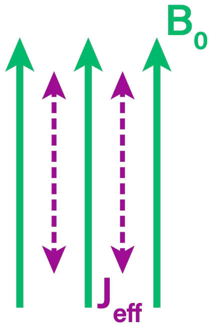
Scan rate in a different form

$$\frac{d\nu}{dt} = \frac{\pi 6 \times 10^5}{16\mathrm{SNR}^2 m_a^4} \frac{\overbrace{|V(B_0, m_a, g_{a\gamma\gamma})|^4}^{\text{Axion induced voltage}} \overbrace{Q(\nu)}^{\text{Resonator quality factor}} \overbrace{\bar{\mathcal{G}}(\nu, T, \eta)}^{\text{Noise parameter}}}{\underbrace{L_{eff}(\nu)^2}_{\text{Resonator inductance}}}$$

Detection principle for DMRadio-m^3



Applied magnetic field B_0 induces effective axion current, J_{eff}



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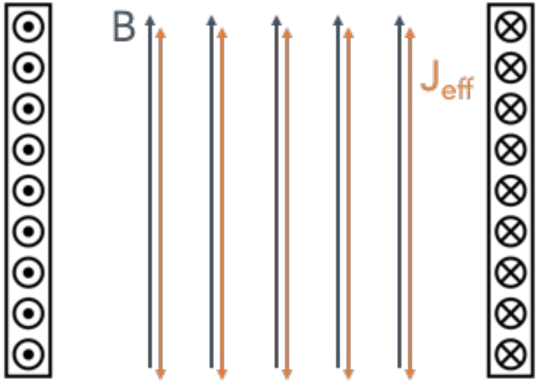

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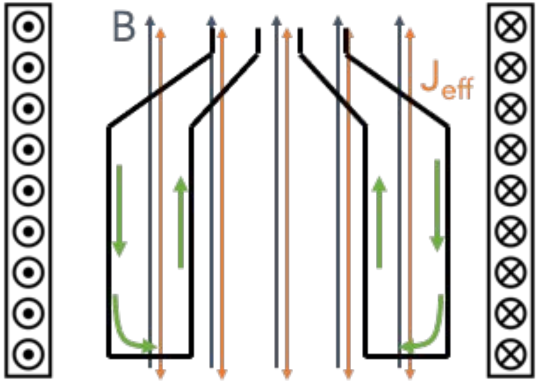
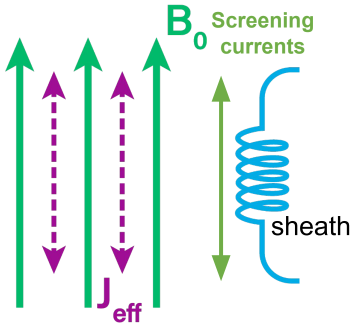


Axion current J_{eff} induces an RF magnetic field (not shown), which in turn induces screening currents on the surface of a **coaxial copper sheath**



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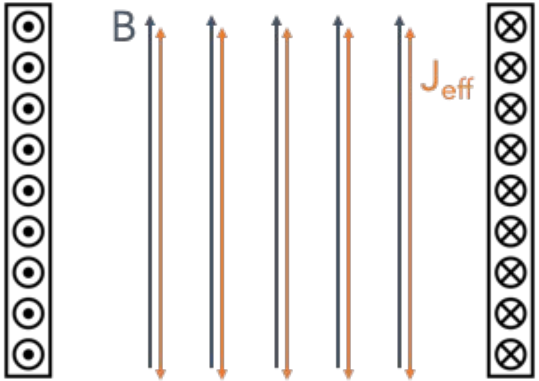

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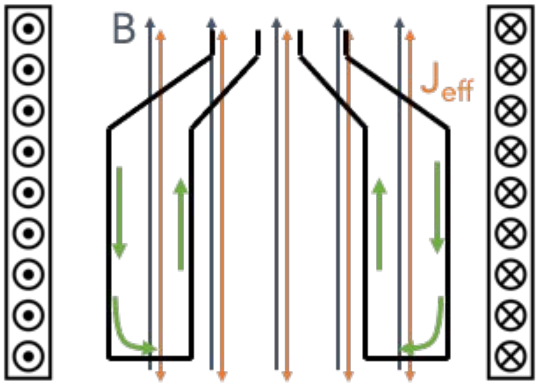

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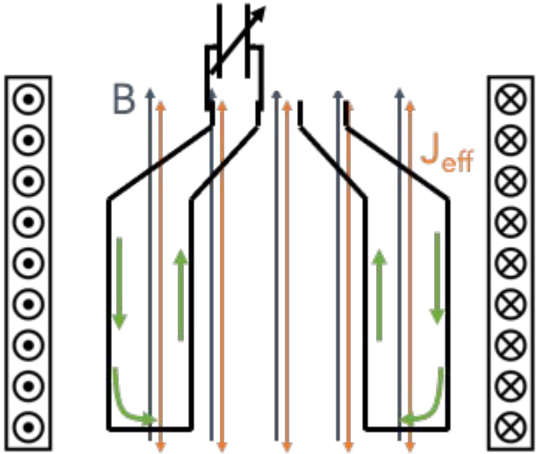
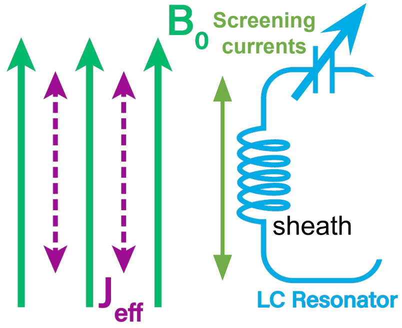


The screening currents may be sensed by a DC SQUID coupled to a tunable LC circuit



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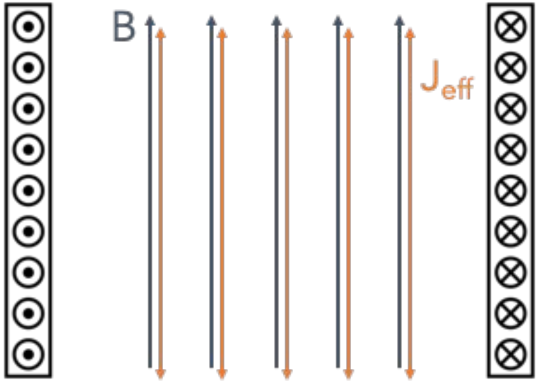

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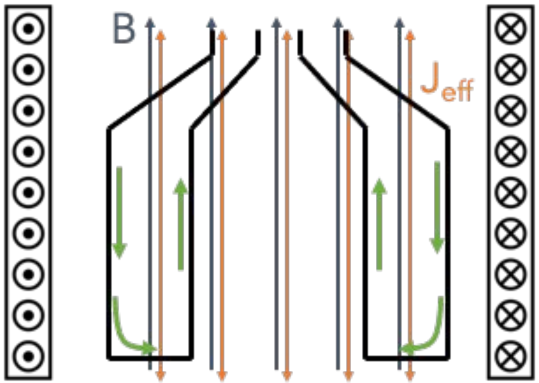

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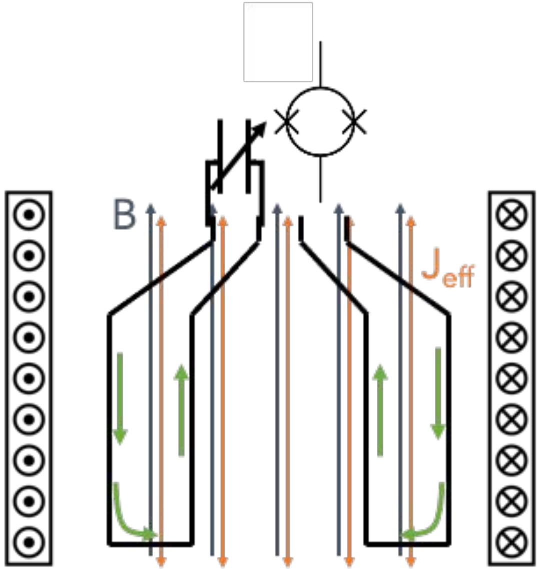

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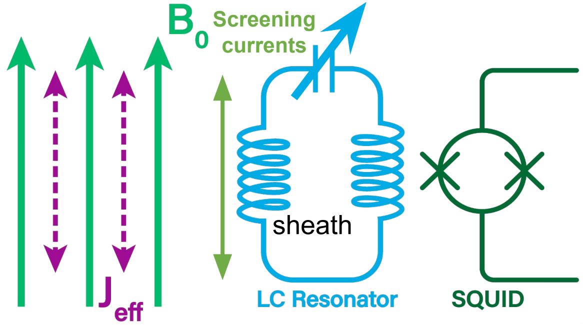

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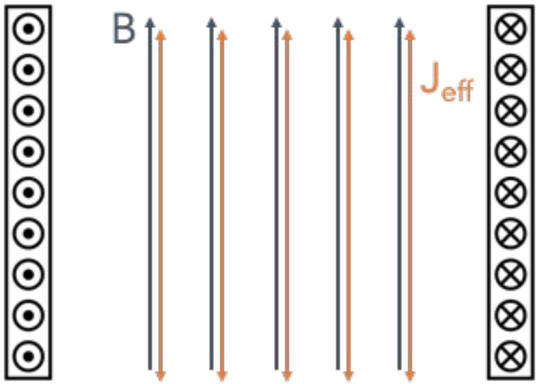

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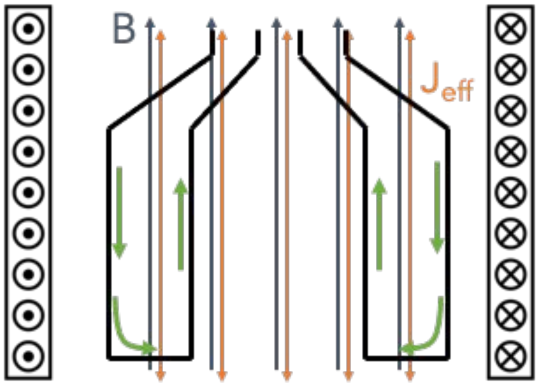

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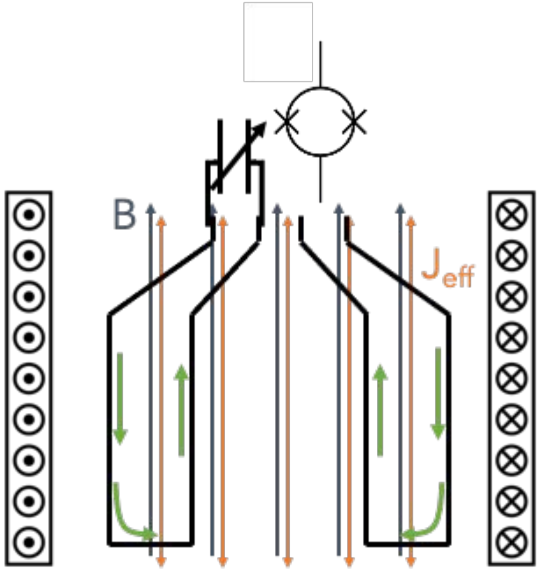

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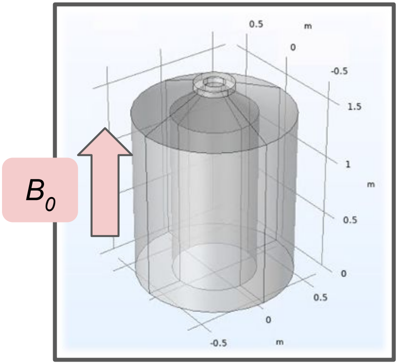
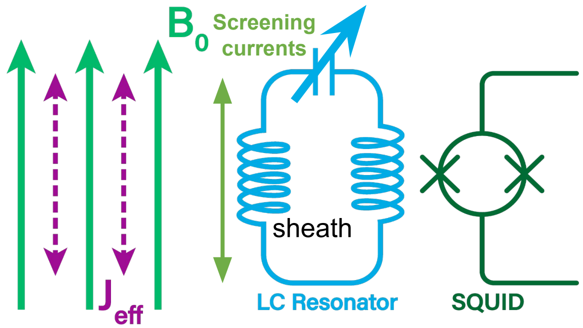
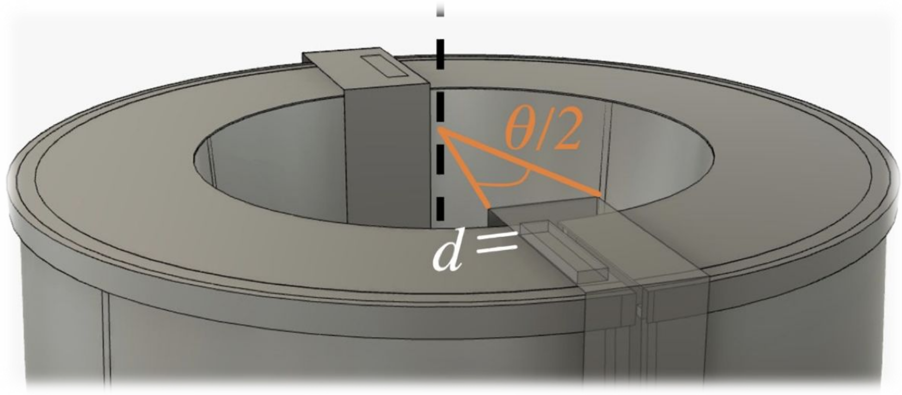




Solenoidal geometry is preferred at higher frequencies (>50 MHz)

DMRadio-m^3 design



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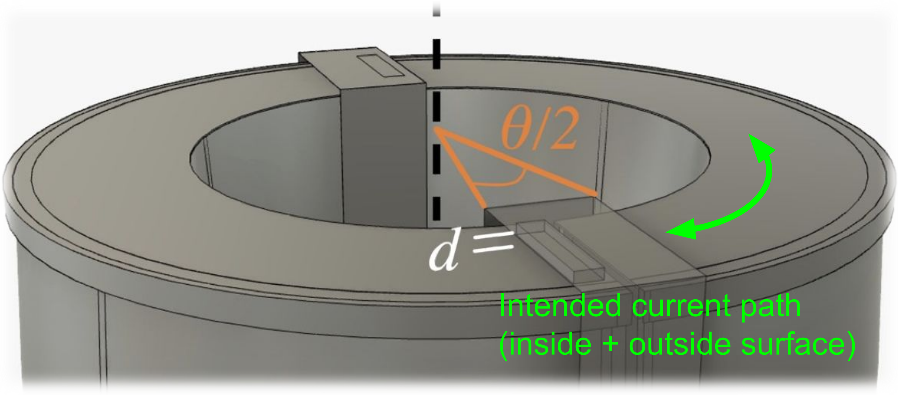
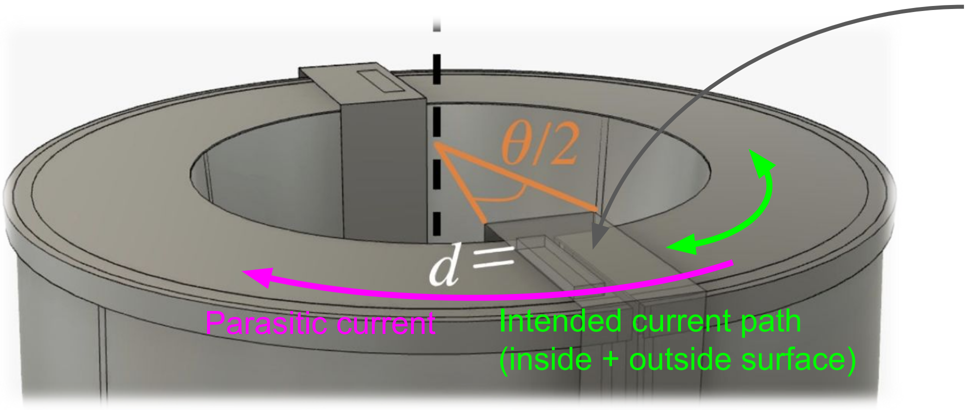


DMRadio-m^3 design



Parasitic capacitance, C_p, shorts out signal!

Parasitic capacitance also defines a resonance frequency:

$$C_p \propto \frac{\epsilon_0 \theta}{d}$$

$$f_p = \frac{1}{2\pi\sqrt{L_{sheath} C_p}} \approx 50 \text{ MHz}$$

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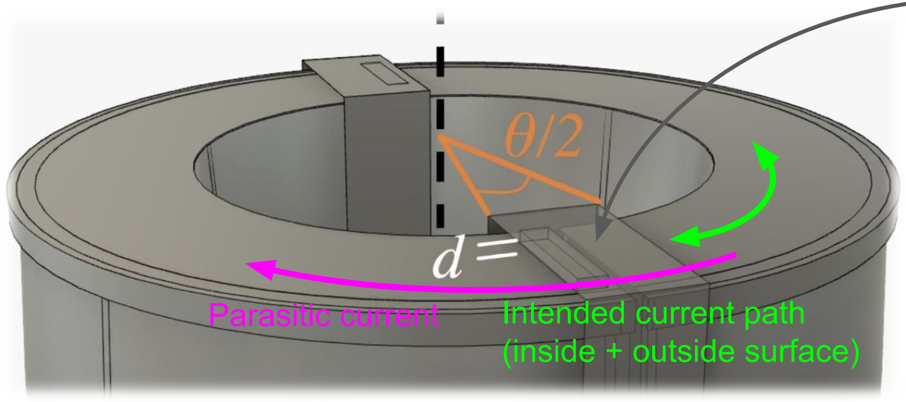

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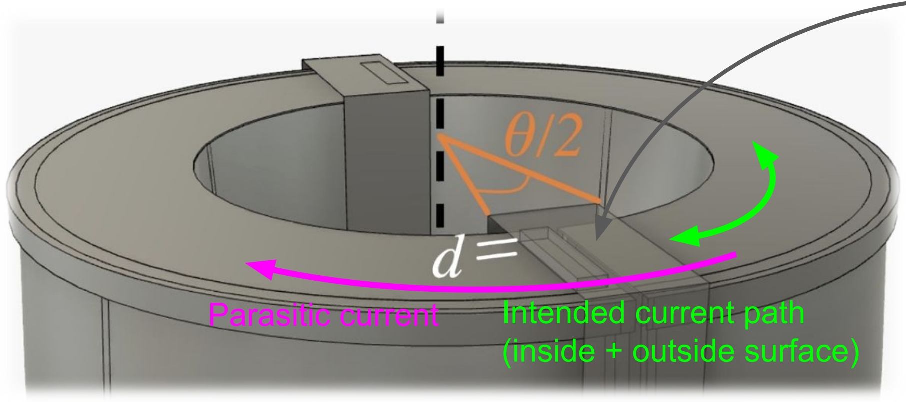
Scaling up to 1 m^3 volume requires $d/\theta \geq 50$ m to ensure f_p>200 MHz!

A toroidal design cannot be used for DMRadio-m^3 due to problems at high frequency

DMRadio-m^3 design



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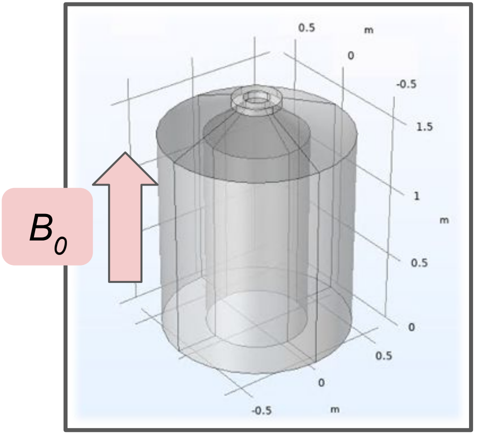

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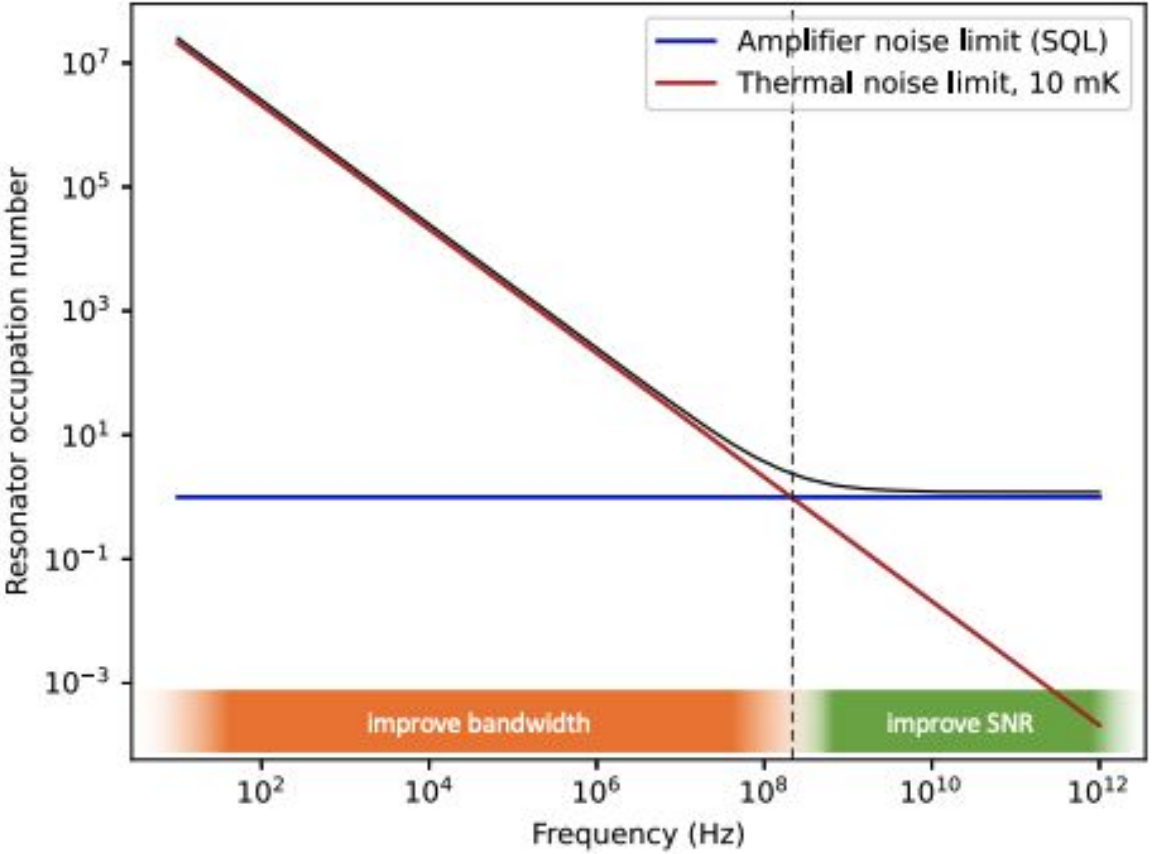
Therefore, DMRadio-m^3 will use a 5 T solenoidal magnet and a coaxial copper pickup

Noise in DMRadio



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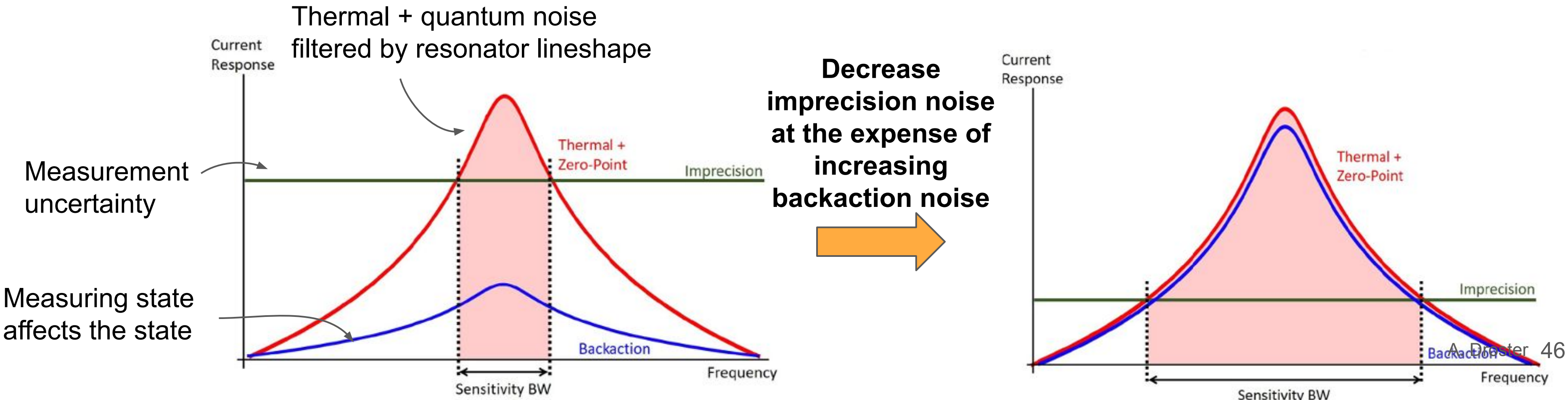
Proposed solution: DMRadio

Two design principles give DMRadio an advantage in searching for low mass axions:

- Decouple detector geometry from resonant frequency by using a tunable LC circuit
- Overcoupling enables an increase in scan rate



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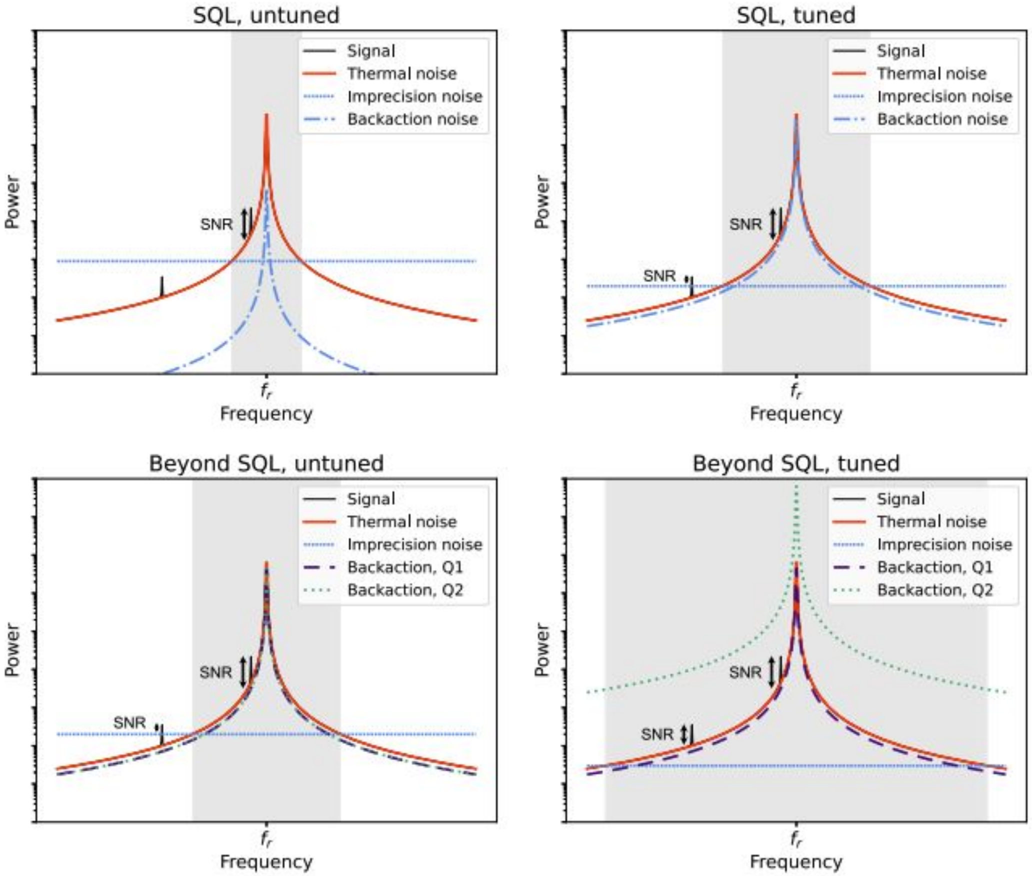
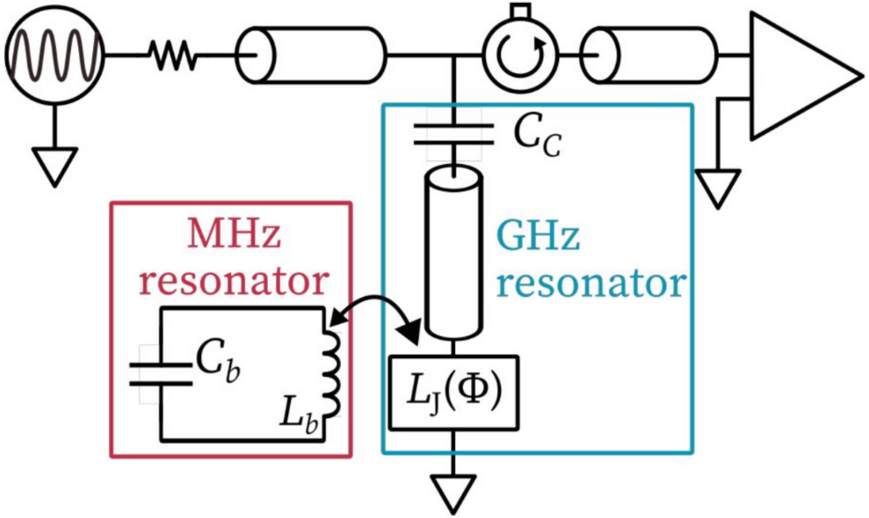


Radiofrequency Quantum Upconverter (RQU)

- Coherently upconvert MHz signal frequencies to GHz frequencies where superconducting quantum metrology techniques are more mature
- Implemented by embedding a Josephson-junction based flux-tunable inductor in a microwave resonator
- Low frequency signal modulates the microwave resonant frequency



More on RQUs:
Stephen E. Kuenstner, et al.
arXiv: 2210.05576 (2022)

Slide courtesy of A. K. Yi