ABRACADABRA-10cm:

A Demonstrator for <1 micro-eV Axion Dark Matter Searches

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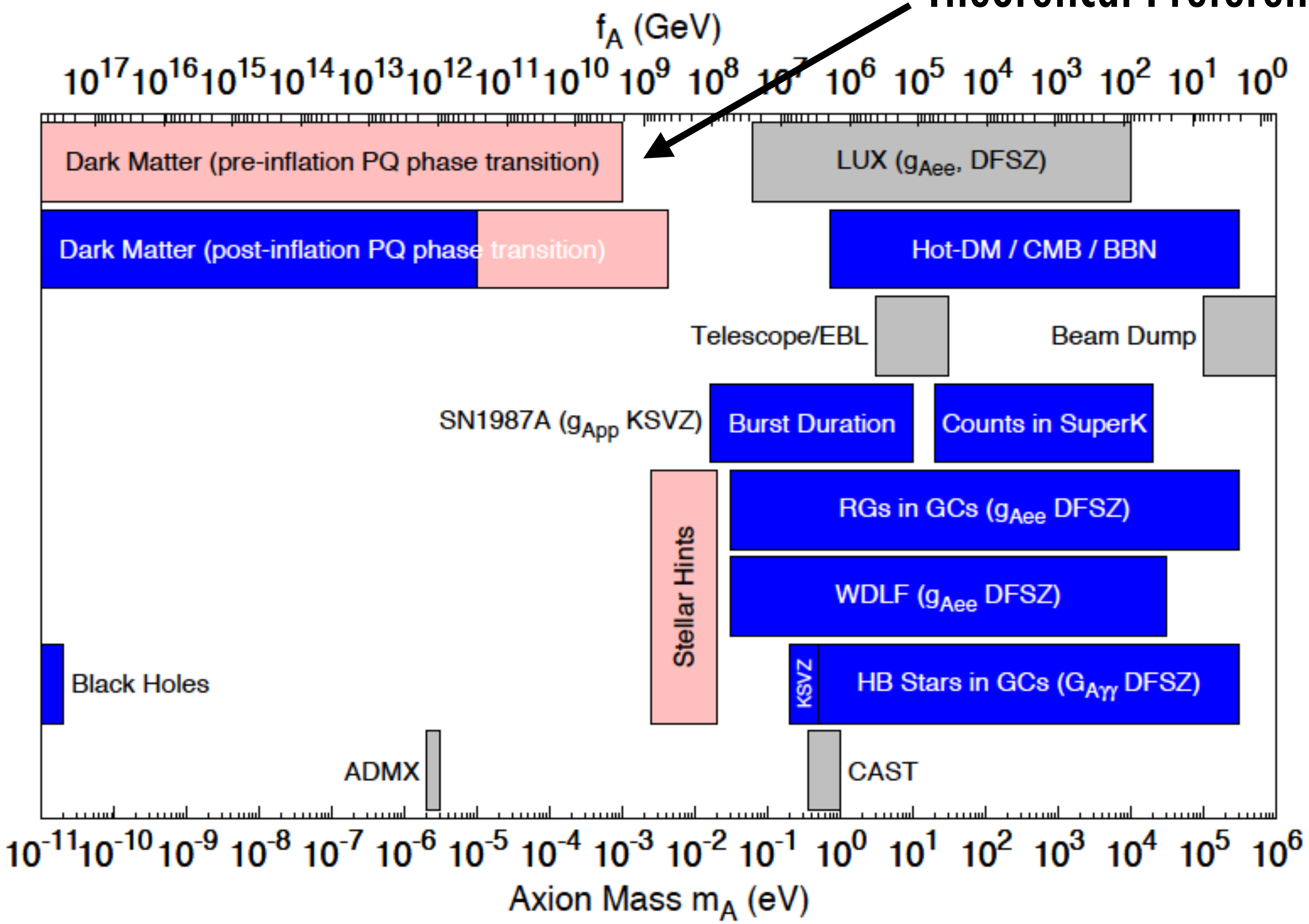
A **B**roadband / **R**esonant **A**pproach to **C**osmic **A**xion **D**etection with an **A**mplifying **B**-field **R**ing **A**pparatus

So we are looking for Axion Dark Matter

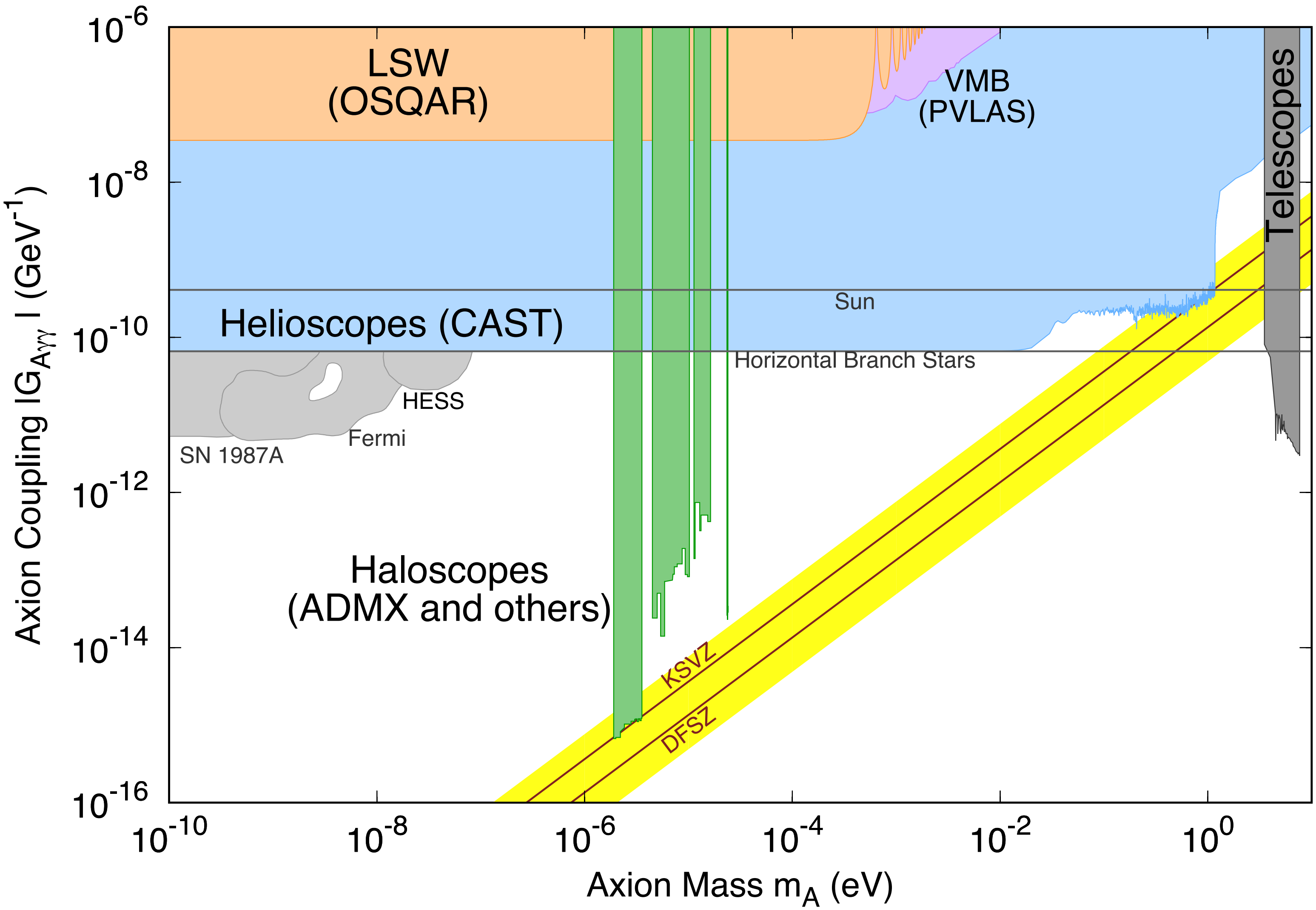
There is a lot of open axion parameter space!

Theoretical Preferences in Pink



PDG - Axion Review 2018

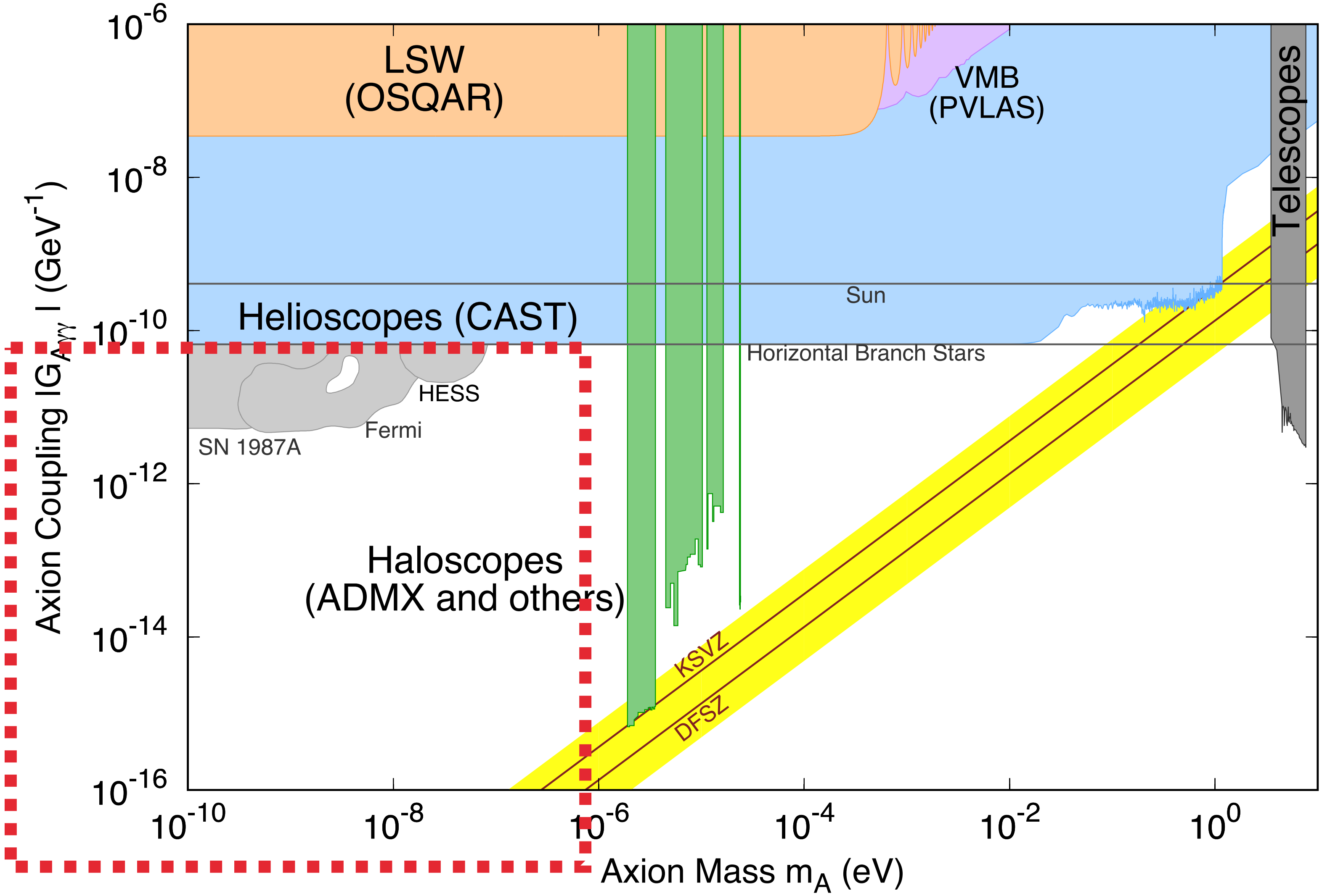
The Summary of the Axion Parameter Space



PDG - Axion Review 2018

The Lumped Element Parameter Space

$\lambda_{\mathrm{Comp}} \gg R_{\mathrm{exp}}$



Sensitive to m_A between 10^{-14} to 10^{-6} eV, ~Hz to~GHz

Axions couple to the electromagnetic force.

Axions modify Maxwell's Equations!

$$\nabla \cdot E = -g_{a\gamma\gamma} B \cdot \nabla a$$

$$\nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times B = \frac{\partial E}{\partial t} - g_{a\gamma\gamma}(E \times \nabla a - \frac{\partial a}{\partial t} B)$$

Modified Source-free Maxwell's Equations

Axions modify Maxwell's Equations!

$$\nabla \cdot E = -g_{a\gamma\gamma} B \cdot \cancel{\nabla a}$$

$$\nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times B = \frac{\partial E}{\partial t} - g_{a\gamma\gamma}(E \times \cancel{\nabla a} - \frac{\partial a}{\partial t} B)$$

These terms are assumed to be small.

From: Yoni Kahn

Axion-photon searches

$$\underbrace{\nabla \times \mathbf{B}_r = \frac{\partial \mathbf{E}_r}{\partial t}} + g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Cavity regime: $\lambda_{\mathrm{Comp}} \sim R_{\mathrm{exp}}$

ADMX

$$\nabla \times \mathbf{B}_r = \cancel{\frac{\partial \mathbf{E}_r}{\partial t}} + \underbrace{g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}_{\mathbf{J}_{\mathrm{eff}}}$$

Quasistatic regime: $\lambda_{\mathrm{Comp}} \gg R_{\mathrm{exp}}$

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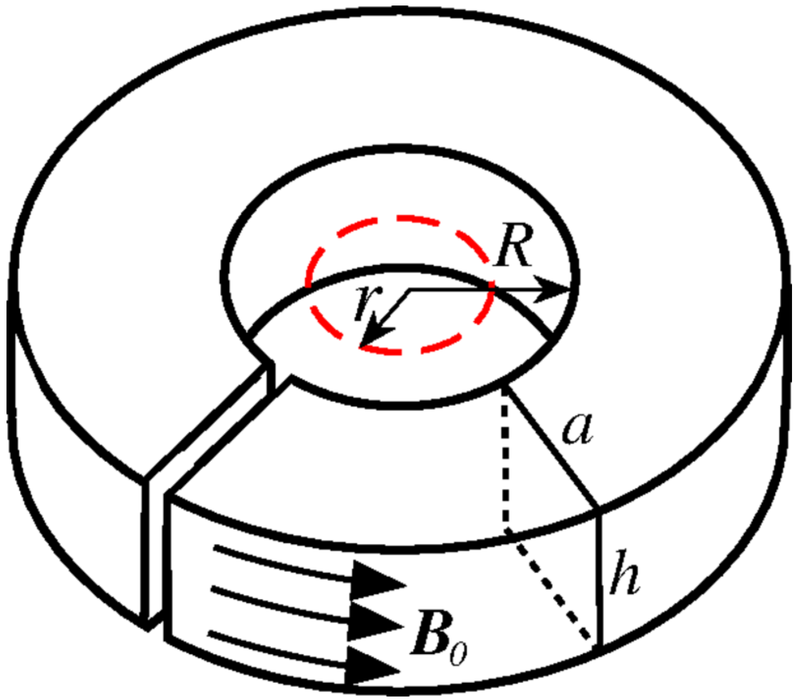
$$\cancel{\nabla \times \mathbf{B}_r} = \frac{\partial \mathbf{E}_r}{\partial t} + g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Radiation regime: $\lambda_{\mathrm{Comp}} \ll R_{\mathrm{exp}}$

MADMAX

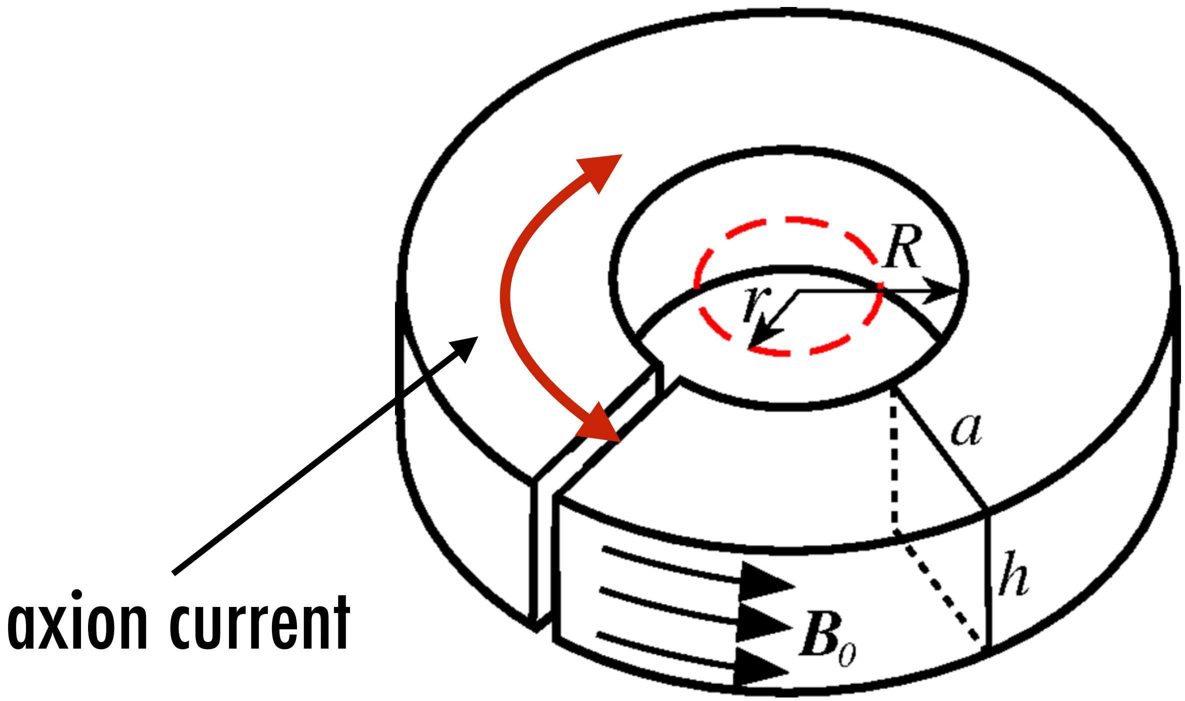
What is a B-field Ring Apparatus?

The cartoon experiment

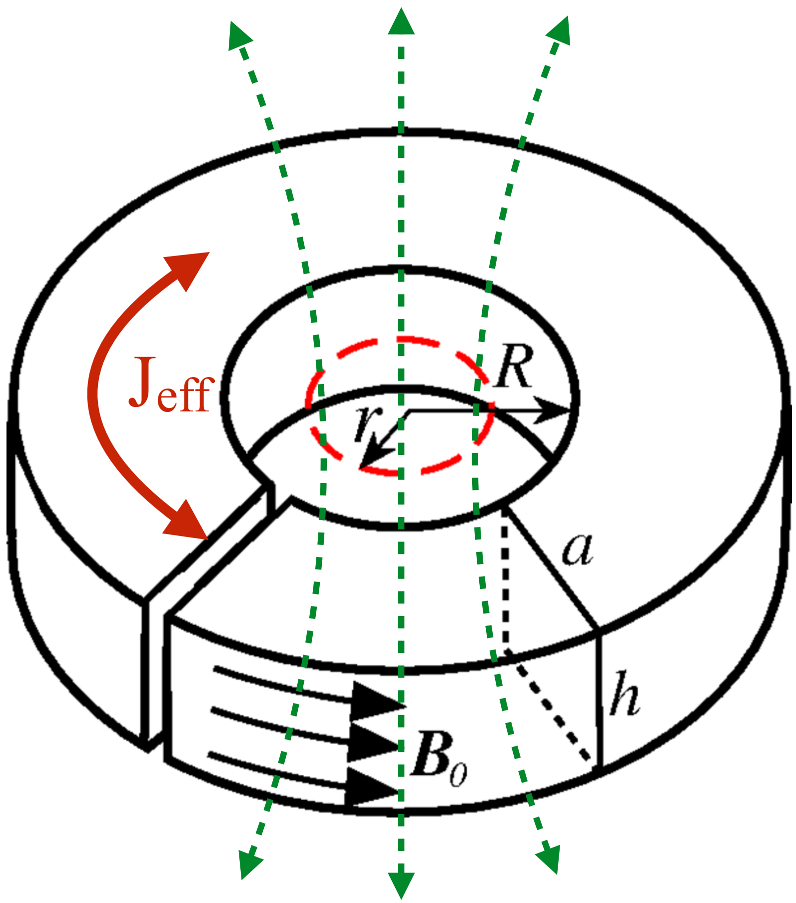


Based on Kahn, Safdi and Thaler, Phys.Rev.Lett. 117 (2016) no.14, 141801

The cartoon experiment

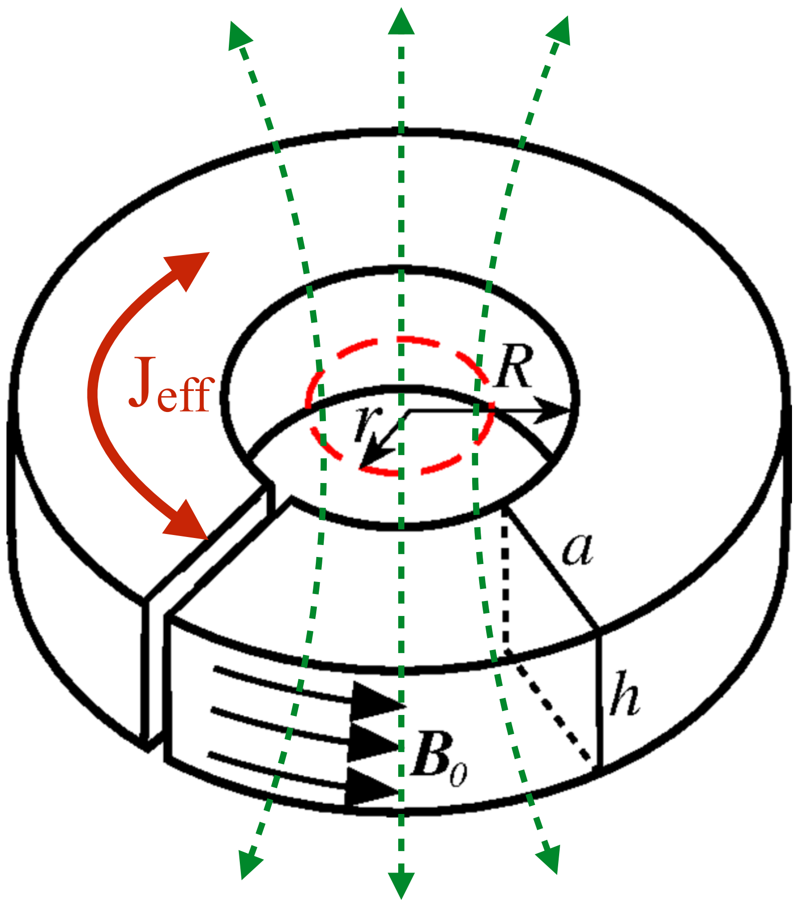


The cartoon experiment



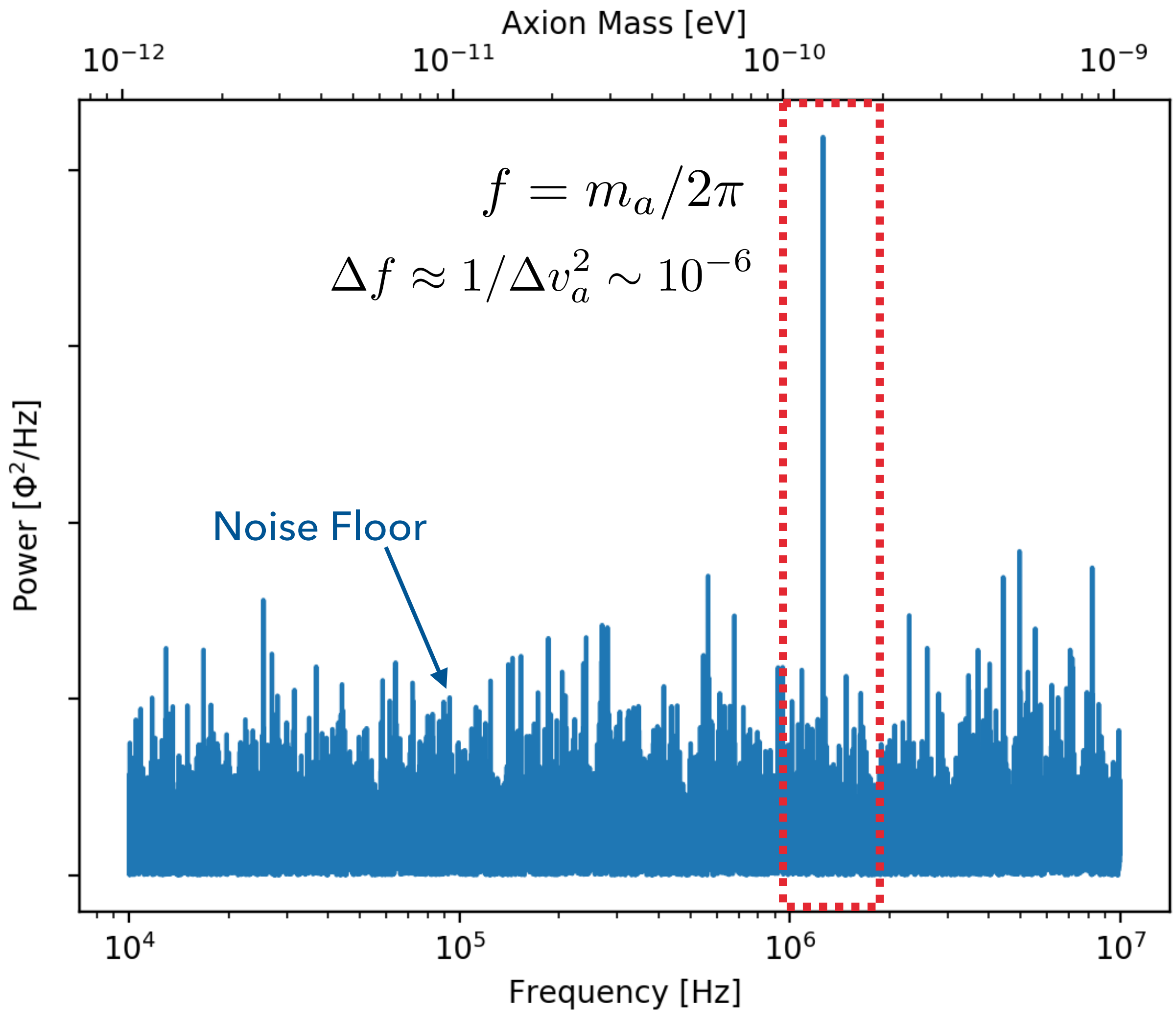
Real Magnetic Field!

The cartoon experiment



A real magnetic field induced in a zero field region.

An Example Signal



What we needed to get started:

Magnet - NSF EAGER Award

Dilution Refrigerator - Oxford Instruments Triton400

SQUID Current Sensor - Magnicon Inc.

Some Vibration Isolation

Some Warm and Cold Shielding

Does the experiment work?

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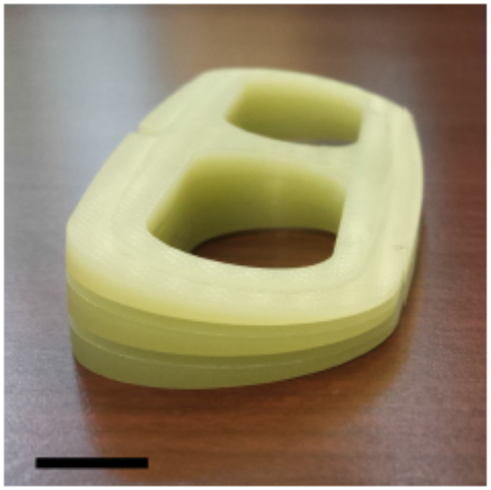
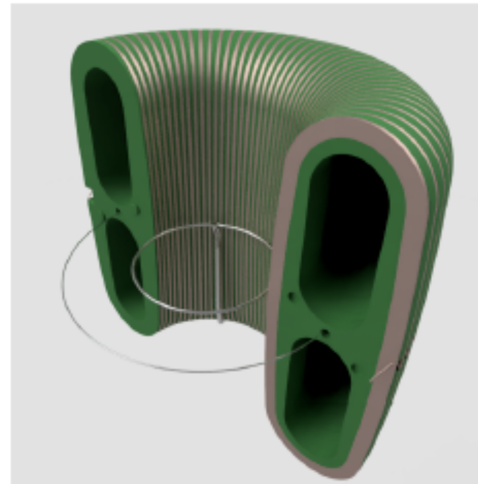
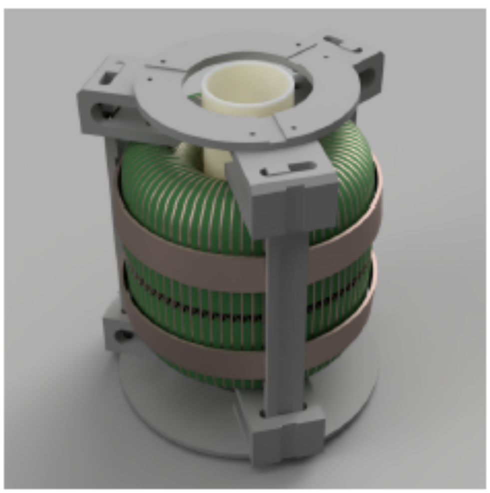
Delrin Supports

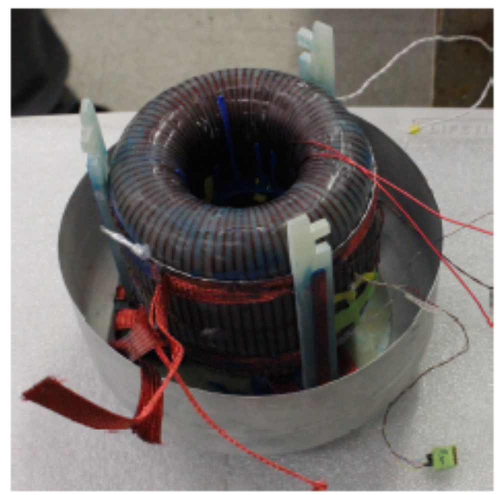


Pickup and Calibration Loops





Mechanical Design



Assembly in Progress

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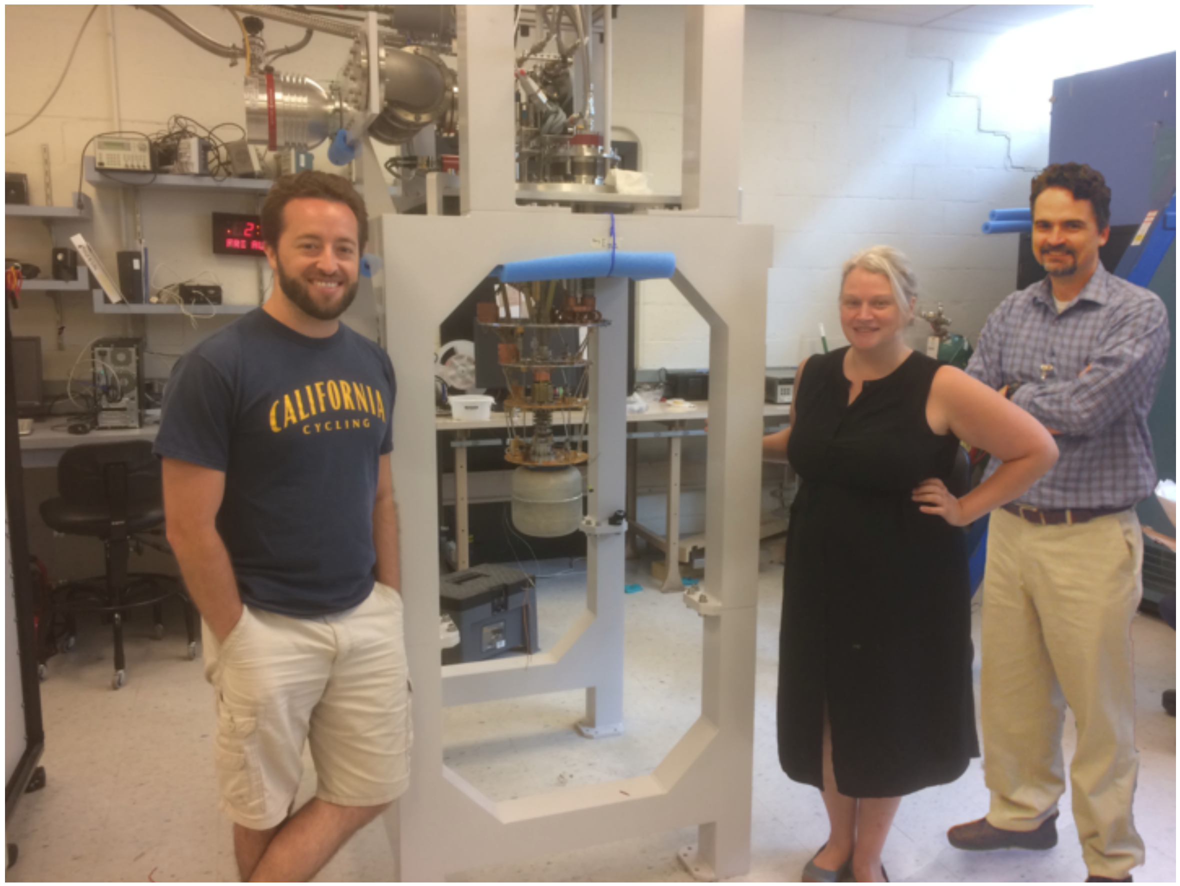
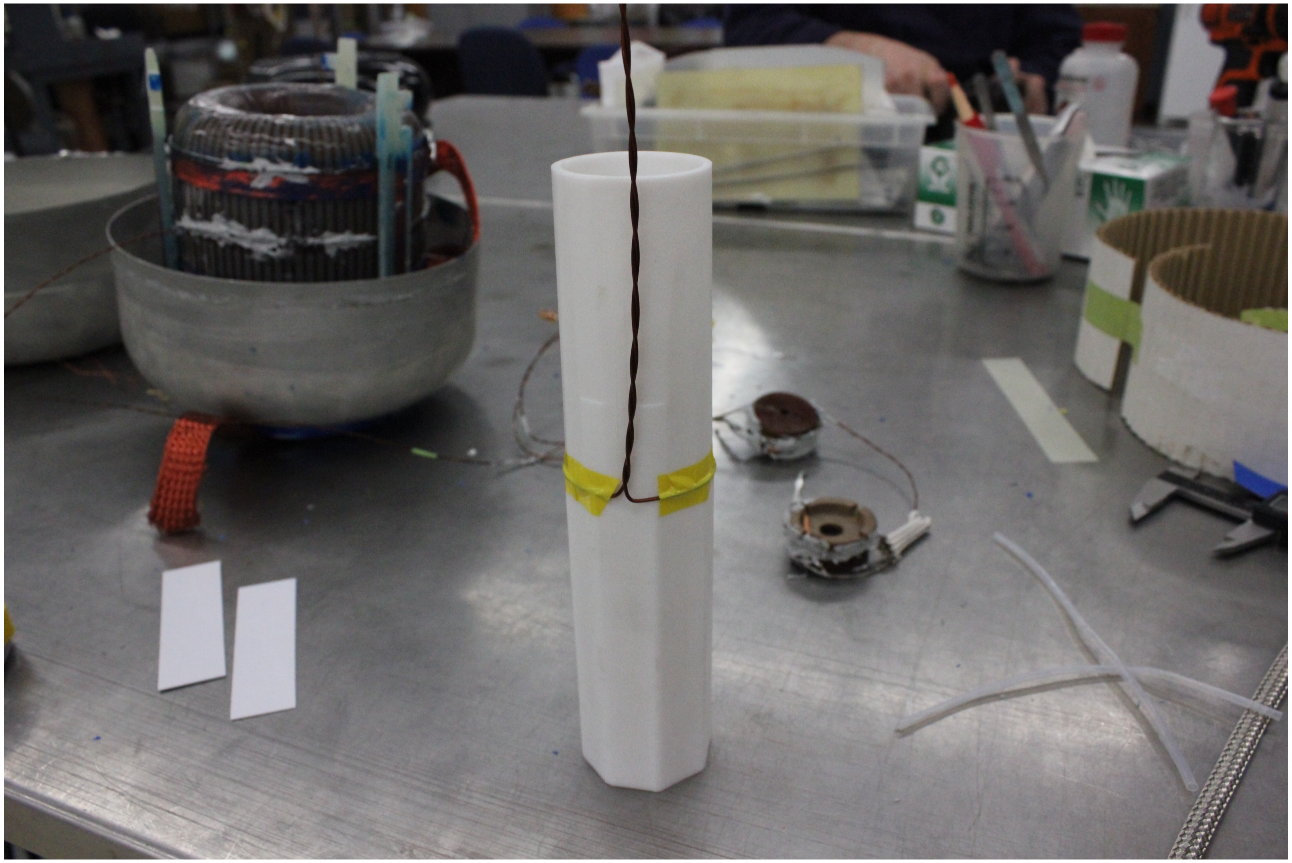


ABRACADABRA-10cm installed Fall 2017.



Some improvements to the geometry were completed in January 2018.

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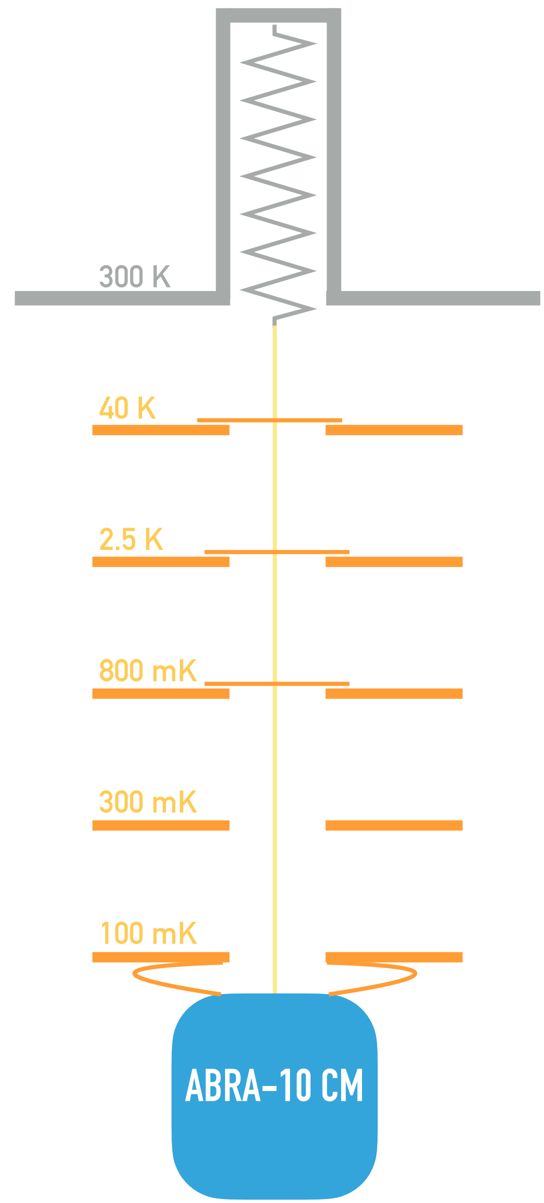
Suspension System

- Vibration isolation suspension system
  - 150 cm pendulum, with a resonance frequency of ~2 Hz
  - In the Z direction, a spring with a resonance frequency of ~8 Hz
- Supported by a thin Kevlar thread with very poor thermal conductivity
- Can be upgraded with minus-K isolation



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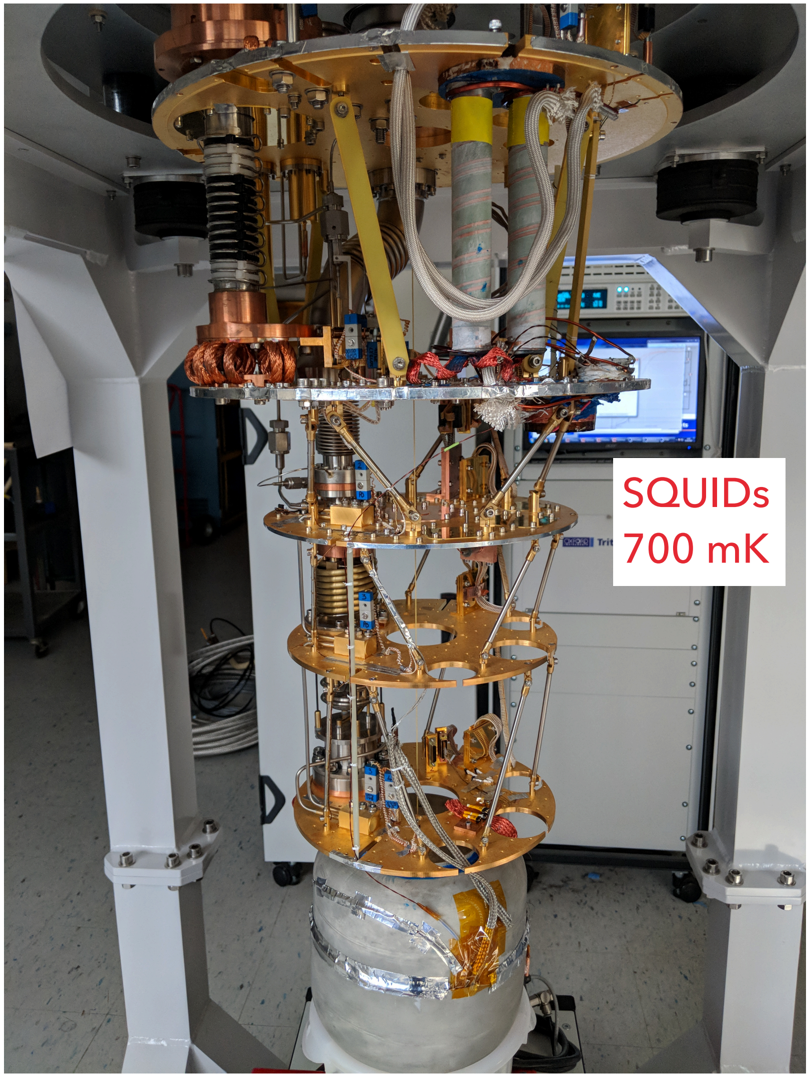

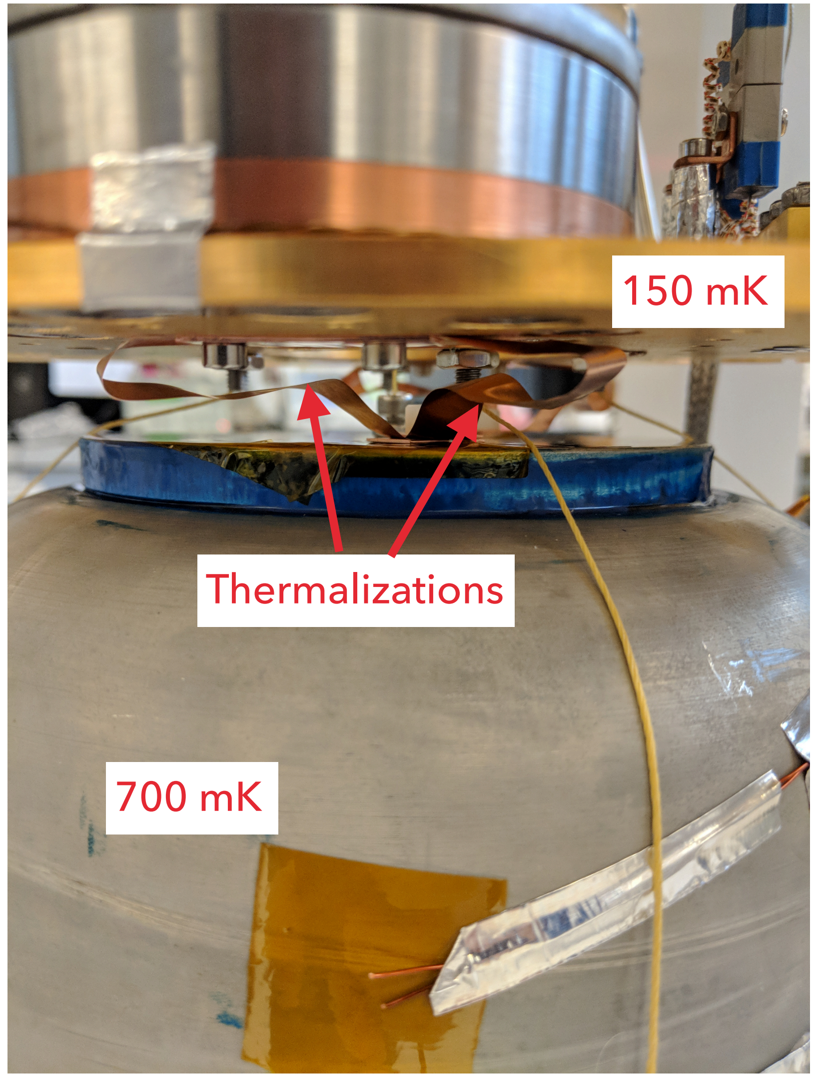

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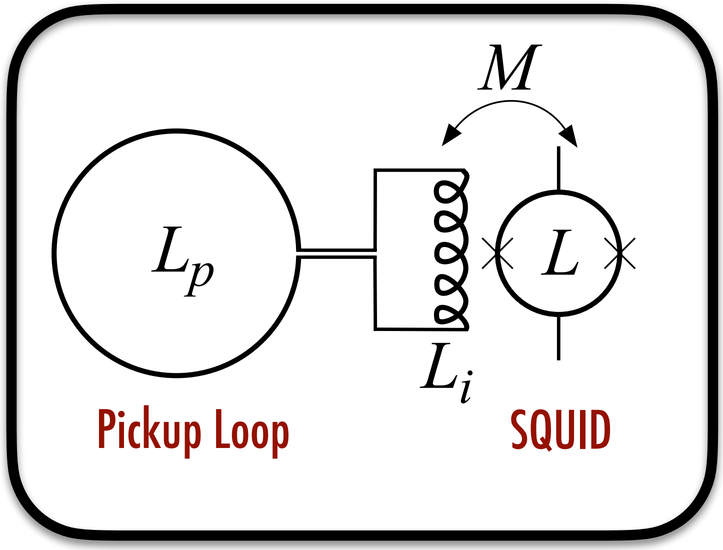
ABRA Readout Options:

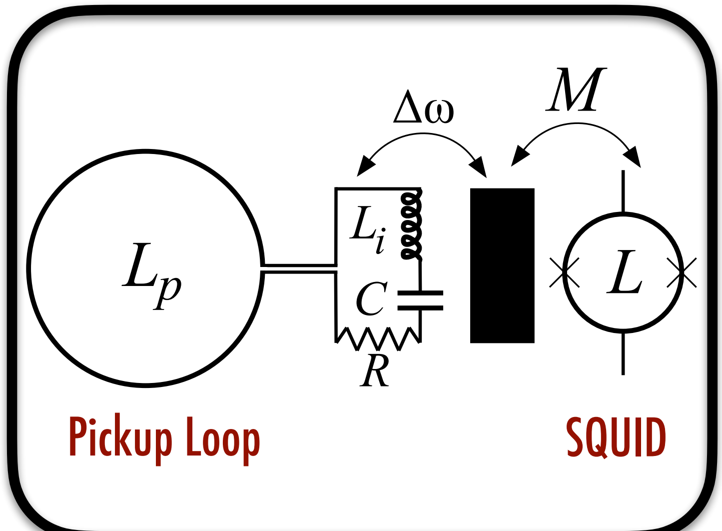
Option #1 - Broadband Readout

- pickup loop directly coupled to the SQUID
- simultaneous scan of all frequencies
- simple and fast



Option #2 - Resonant Readout

- pickup loop coupled to the SQUID through a resonant circuit
- scan across all frequencies
- signal enhancement by $Q_{value} \sim 10^6$ on resonance but significant enhancement of sidebands as well
- better ultimate sensitivity



For a review of this issue see Chaudhuri, Irwin et al. arXiv:1803.01627

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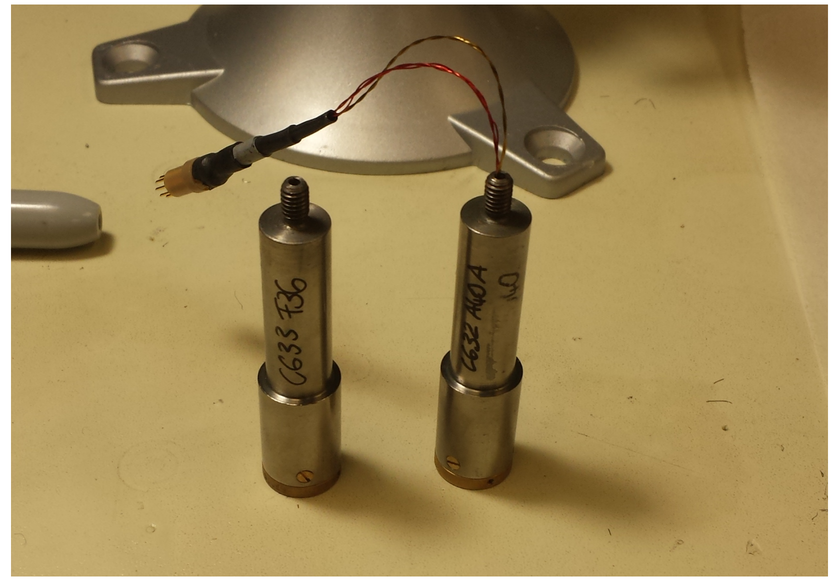
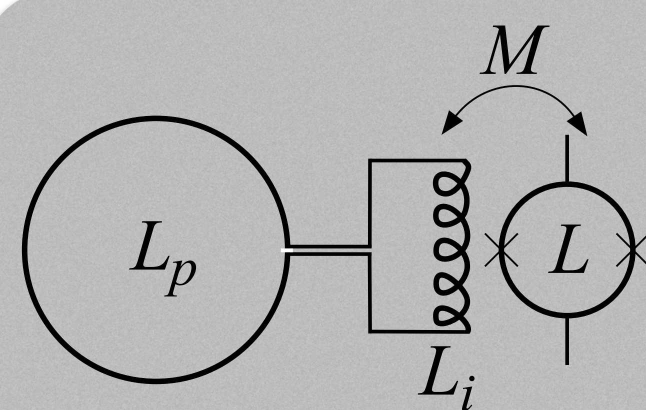
Broadband Readout:

- Off the shelf SQUIDs from Magnicon
  - Two stage current sensor + series array amplifier
  - Optimal temperature: ~700 mK
  - Input inductance: 150 nH
  - Noise floor: ~1.2 $\mu\Phi_0/\mathrm{Hz}^{1/2}$
  - 1/f corner: ~50 Hz
  - Bandwidth Limit: ~6MHz
- Additional filters limit bandwidth to 2kHz-2MHz





Broadband Configuration

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Magnetic Shielding

- Two layers of mu-metal shielding

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First Results October 2018!

Ouellet et al., Phys.Rev.Lett. 122 (2019) no.12, 121802

arXiv:1810.12257

Long Technical Paper

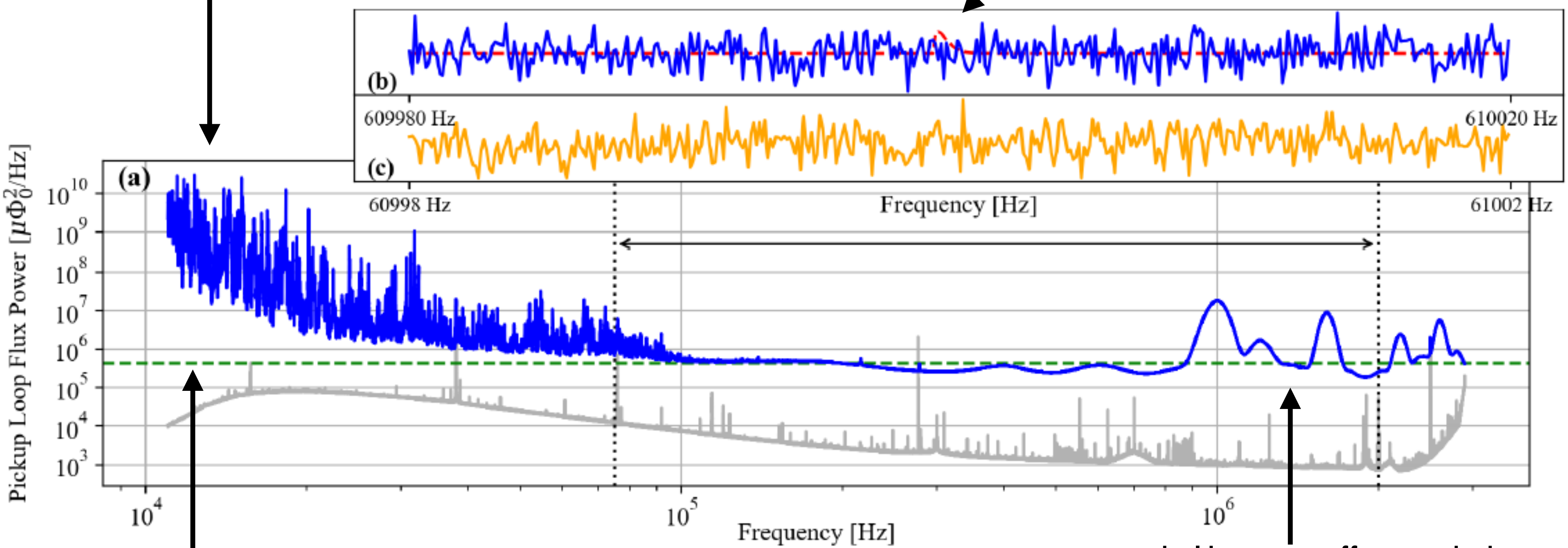
Ouellet et al., Phys.Rev. D99 (2019) no.5, 052012

arXiv:1901.10652

Physics Data

Mechanically cooled fridge so vibration dominate at low frequency.

Example signal



EM Shielding not as effective at high frequency or large sources.

SQUID Noise Floor!

Data taken from July 16, 2018 to August 14, 2018, continuous digitization and data transfer was a major accomplishment in itself!

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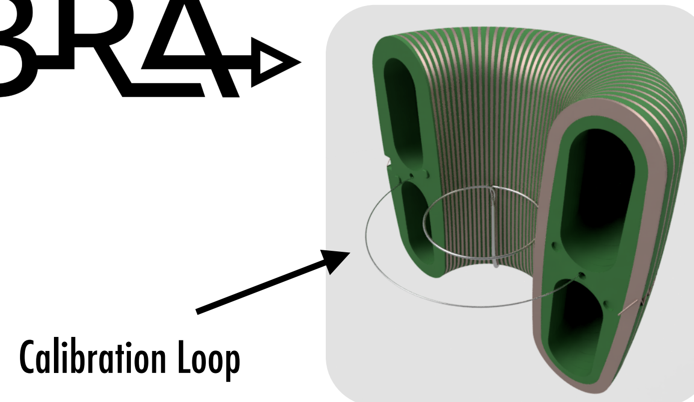
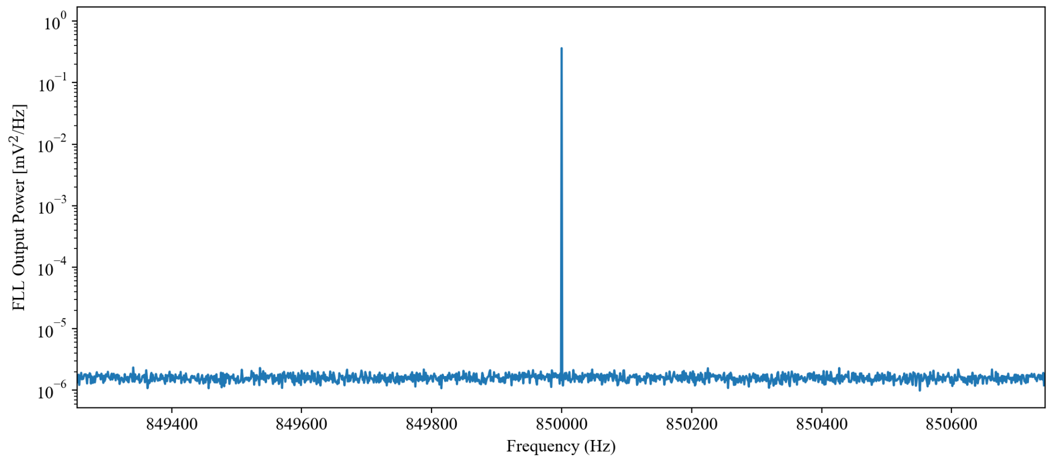
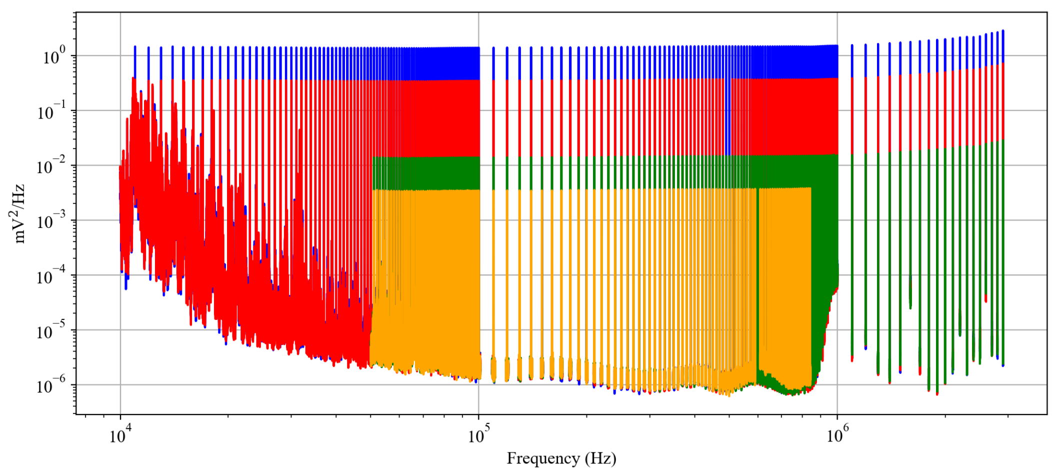
Calibration



One of the key experimental details is how you calibrate the system.

We performed detailed scans to determine that our efficiency was flat over a broadband of frequencies. Unfortunately, the gain was low by a factor of 6.5 low relative to the theoretical gain, most likely due to parasitic inductances.





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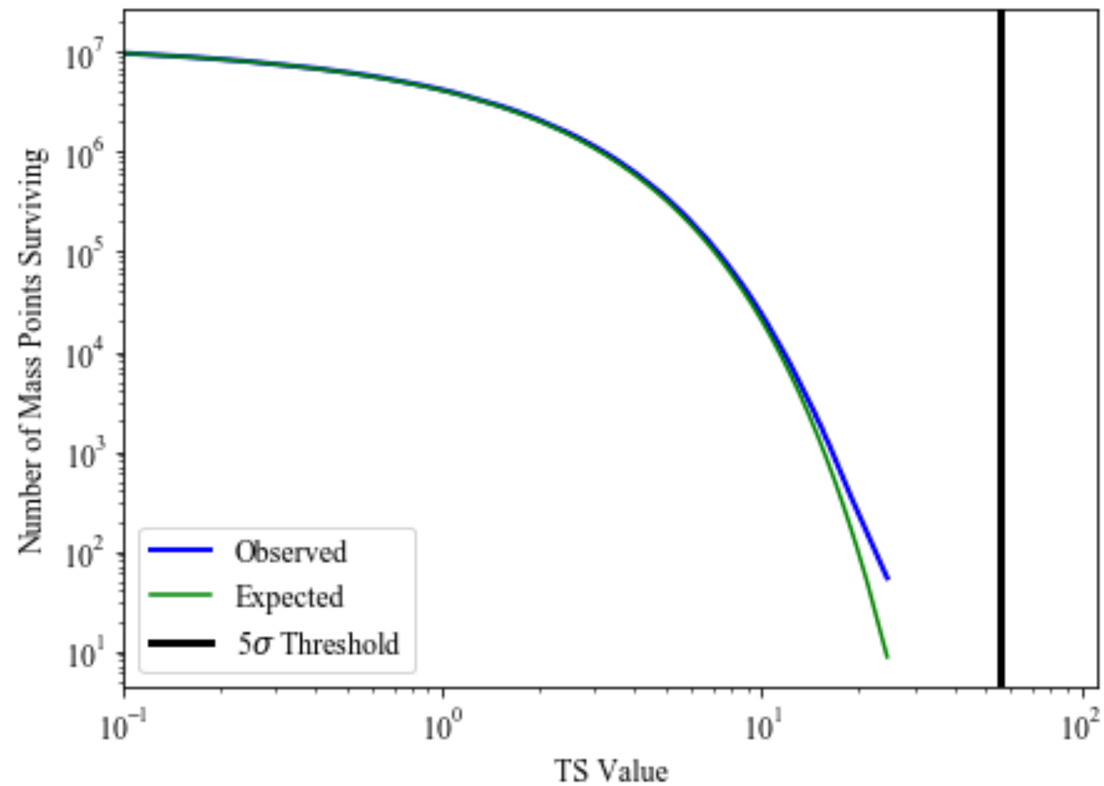
The Search

- Limit our search range to 75 kHz - 2 MHz (m_a in 0.31 – 8.1 neV). 8 million mass points
- For each mass point, we calculate a likelihood function
- Axion discovery search based on a log-likelihood ratio test, between the best fit and the null hypothesis
- We set the 5σ discovery threshold as TS>56.1 (accounting for the Look Elsewhere Effect)



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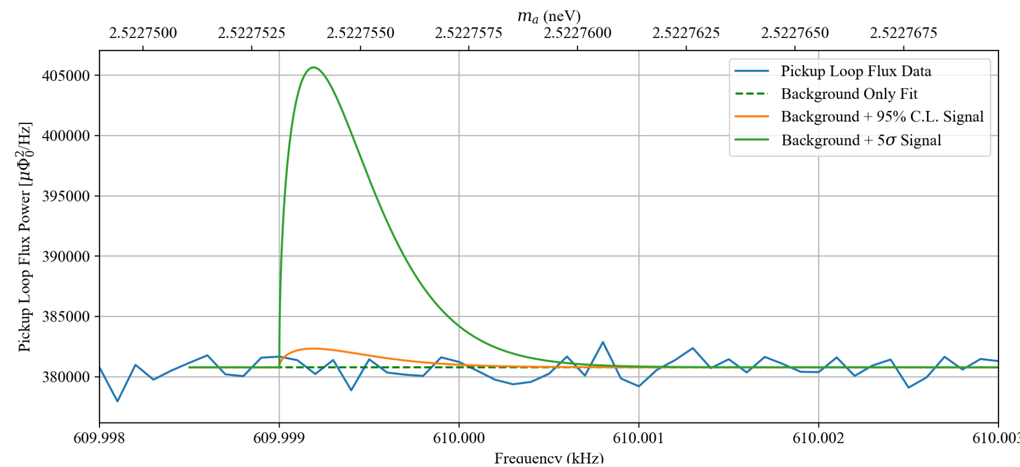
The Search

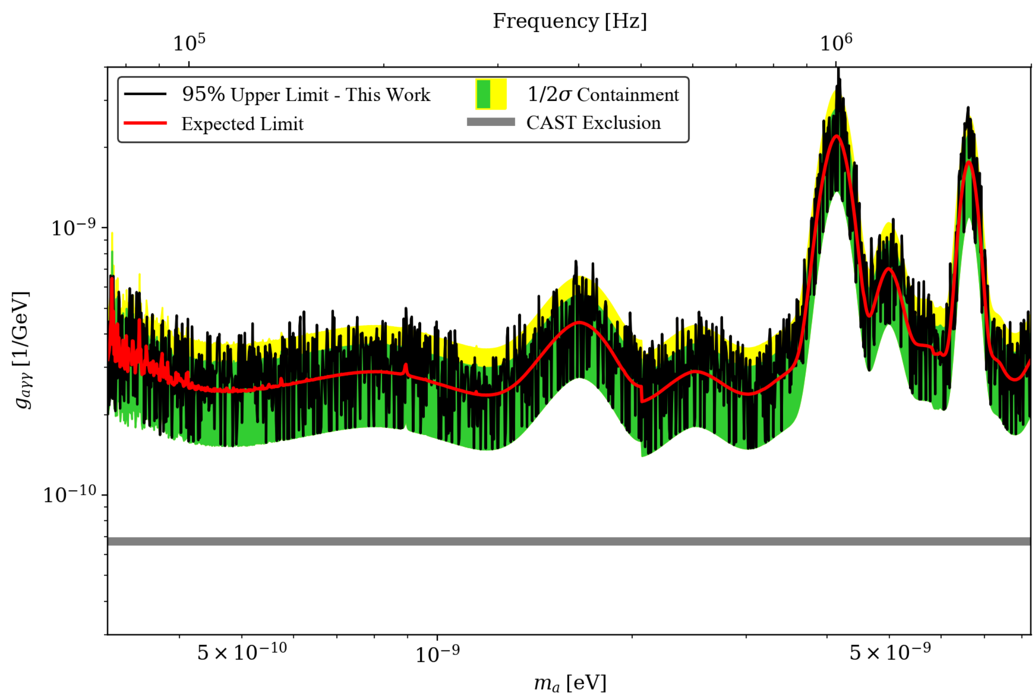
- We saw no 5σ excesses that were not vetoed by Magnet off or digitizer data

  87 (0) mass points were vetoed in the 10MS/s (1MS/s) data

- We place 95% C.L. upper limits using a similar log-likelihood ratio approach

- Our limits are approaching the limits set by CAST





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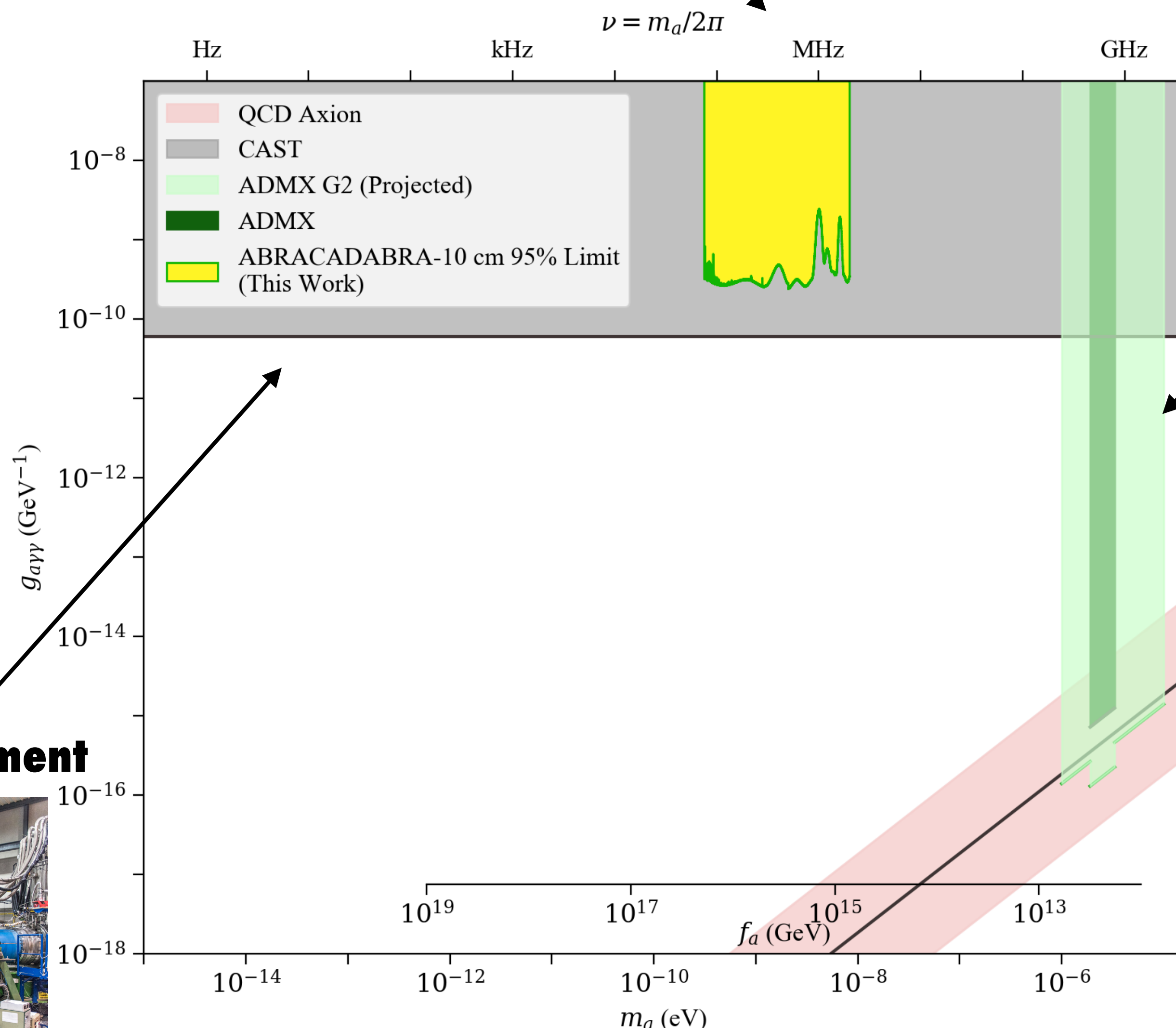
First direct search for axion dark matter below 1μeV, and we are just beginning!



ADMX

CAST
Solar Axion Experiment

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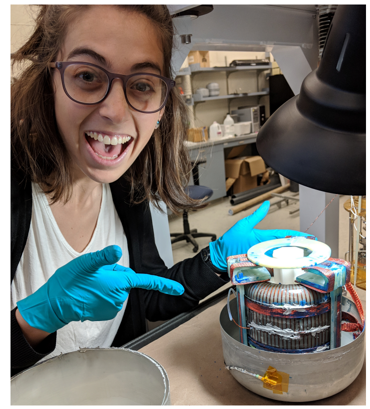
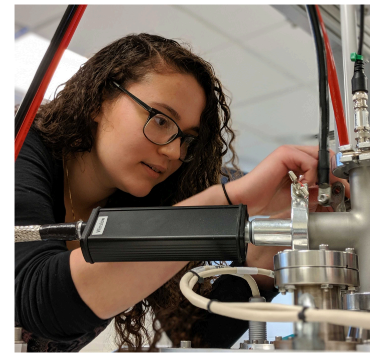
ABRACADABRA-10 cm Run 3 (2020)

(Pictures taken pre-pandemic)

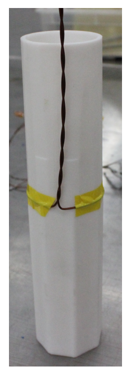
Chiara Salemi

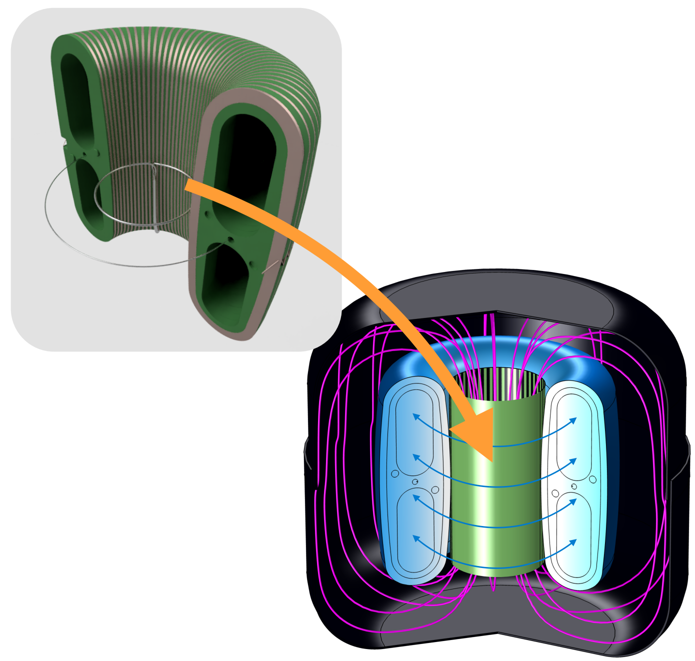


Kaliroë Pappas



- Detector pickup upgraded from simple wire loop to cylinder
  - Stronger mutual coupling to the axion J_{eff}
  - Lower inductance increases coupled energy
  - Cleaner wiring
- Lower SQUID temperatures dropped flux noise floor
  - Seeing a lot more environmental noise, vibrational noise
- Run 3 Data: 2 weeks of data taking in June 2020





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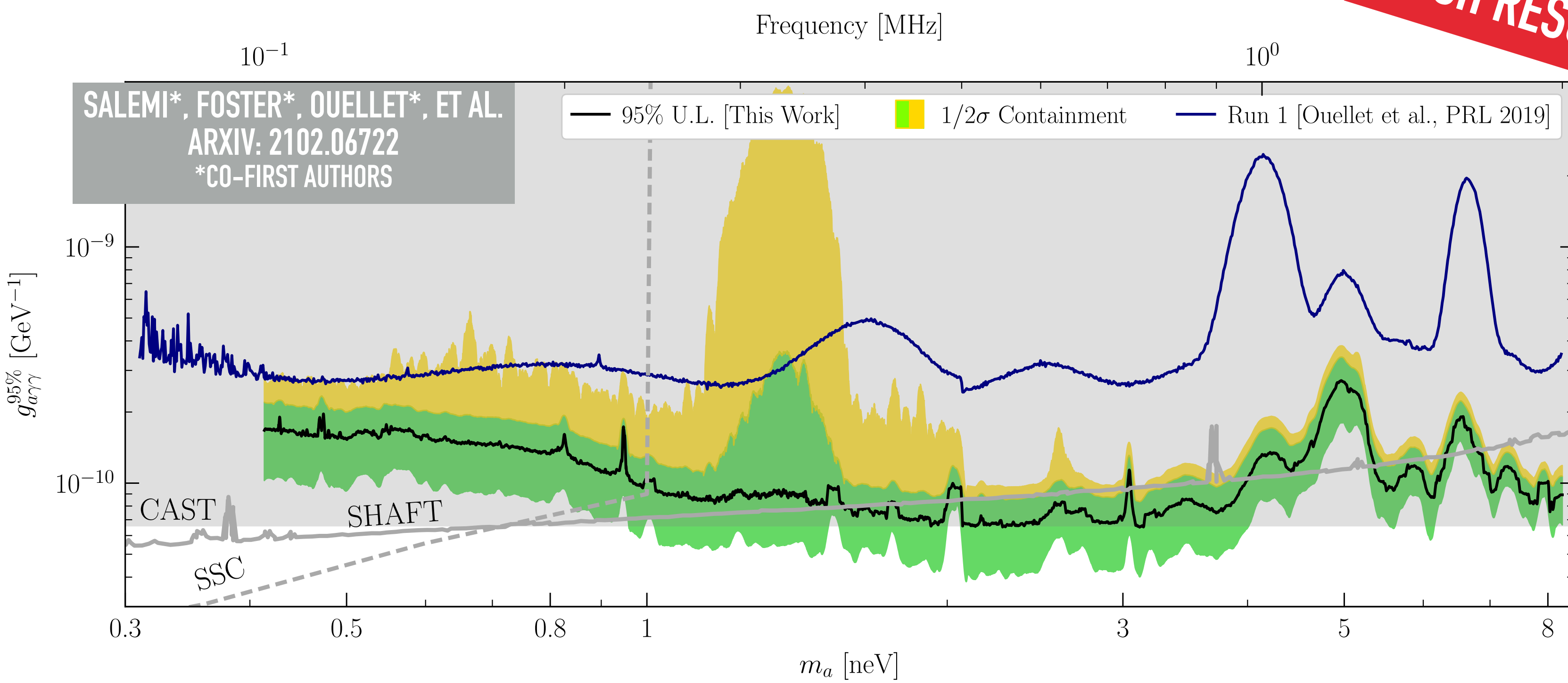
ABRACADABRA-10 cm Run 3 (2020)

FRESH RESULTS!



- Improved limits by a factor of 4-10
- Surpassed CAST limits over a wide range of masses, setting some of the strongest limits in this mass range
- No longer limited by SQUID Flux Noise
- Environmental noise sources are now driving limitation

On to the Next Experiment: DMRadio

What we need now:

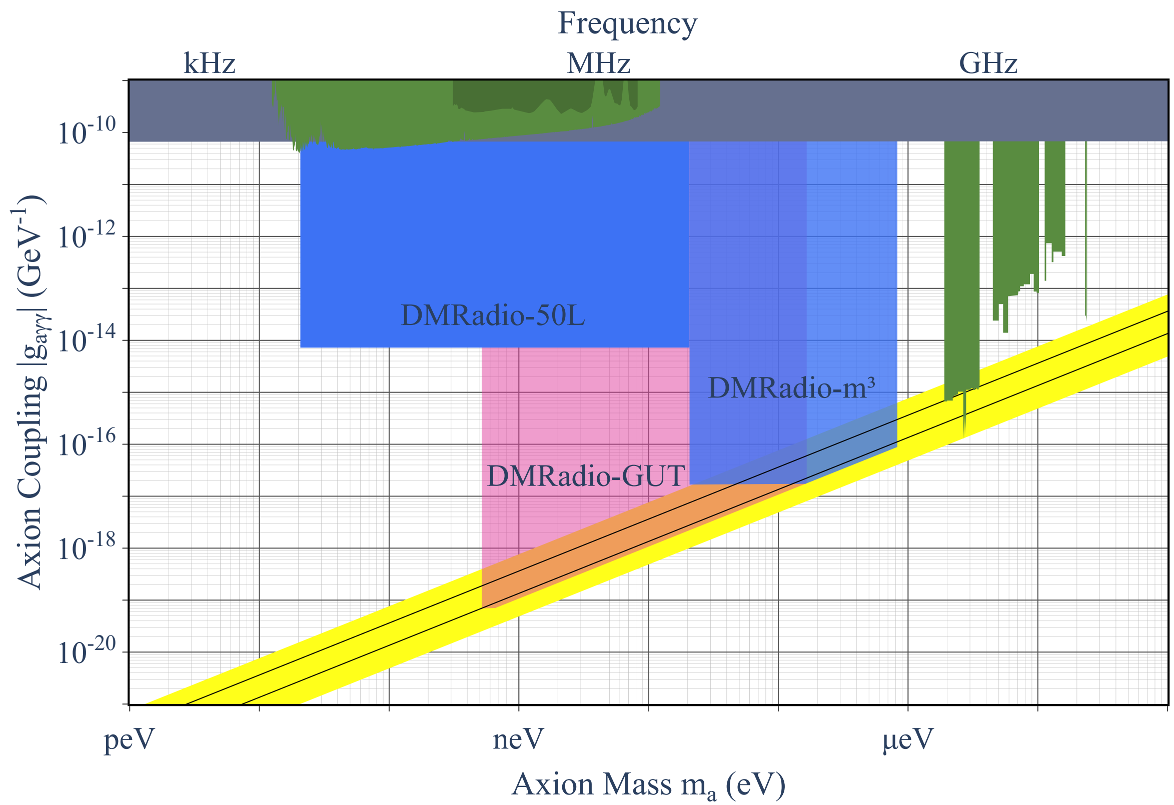
Bigger Magnet

Dilution Refrigerator

Resonant Readout

Some Vibration Isolation

Some Warm and Cold Shielding



"Stay Tuned" for more exciting results!

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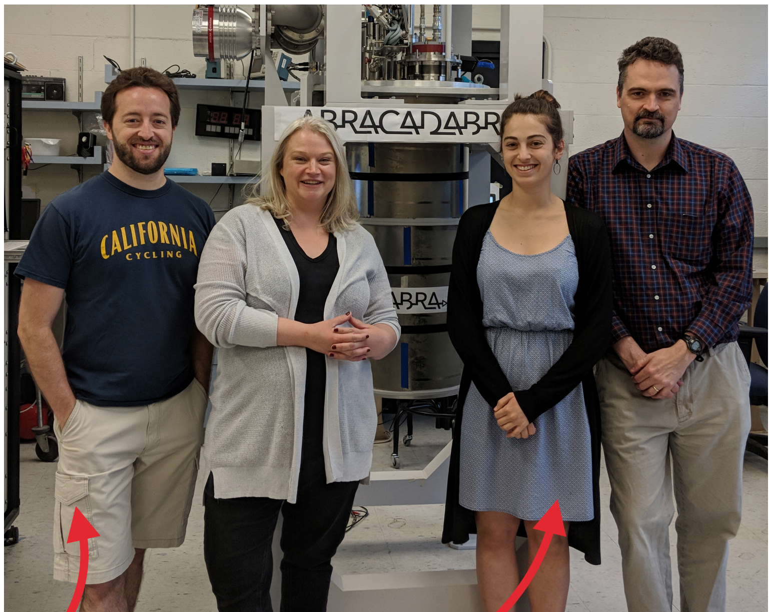

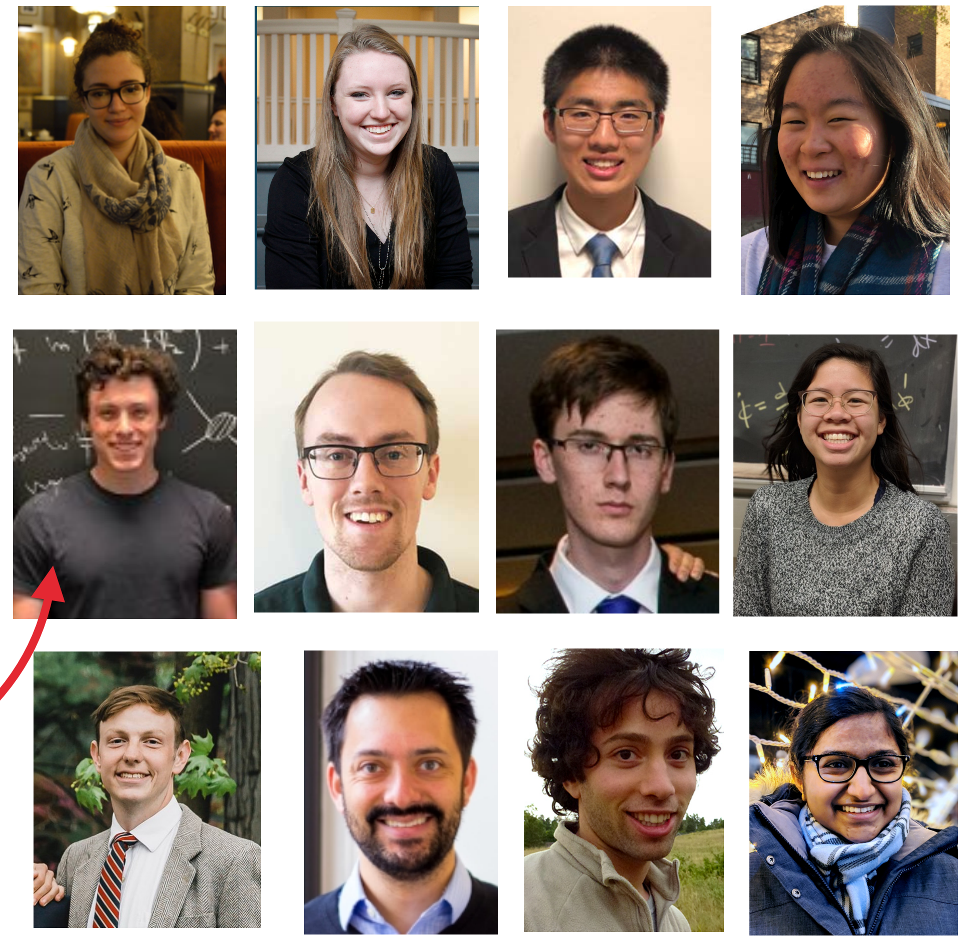

Dr. Jon Ouellet Chiara Salemi Josh Foster

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Berkeley UNIVERSITY OF CALIFORNIA

BERKELEY LAB

KICP

TUNL Triangle Universities Nuclear Laboratory

M UNIVERSITY OF MICHIGAN

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NSF

DM Radio Cubic Meter Consortium

Funded as part of DOE New Initiatives in Dark Matter program

R&D Phase Consortium Leadership:

Project manager for R&D phase: Dale Li

Name	Institution	Role / Team Lead
Kent Irwin	SLAC and Stanford	Consortium PI
Karl van Bibber	UC Berkeley	Magnet
Lindley Winslow	MIT	Magnetic shielding, vibration
Saptarshi Chaudhuri	Princeton	Control system, scan
Peter Graham	Stanford	Theory
Reyco Henning	UNC Chapel Hill	Calibration and DAQ
Dale Li	SLAC	Cryomechanical
Hsiao-Mei Cho	SLAC	SQUID
Wes Craddock	SLAC	Lead Engineer
Nadine Kurita	SLAC	Project Management Plan

Thank you!