A Broadband/Resonant Search for Axion Dark Matter

ABRACADABRA

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THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

MICHIGAN

NSF

Axion Dark Matter

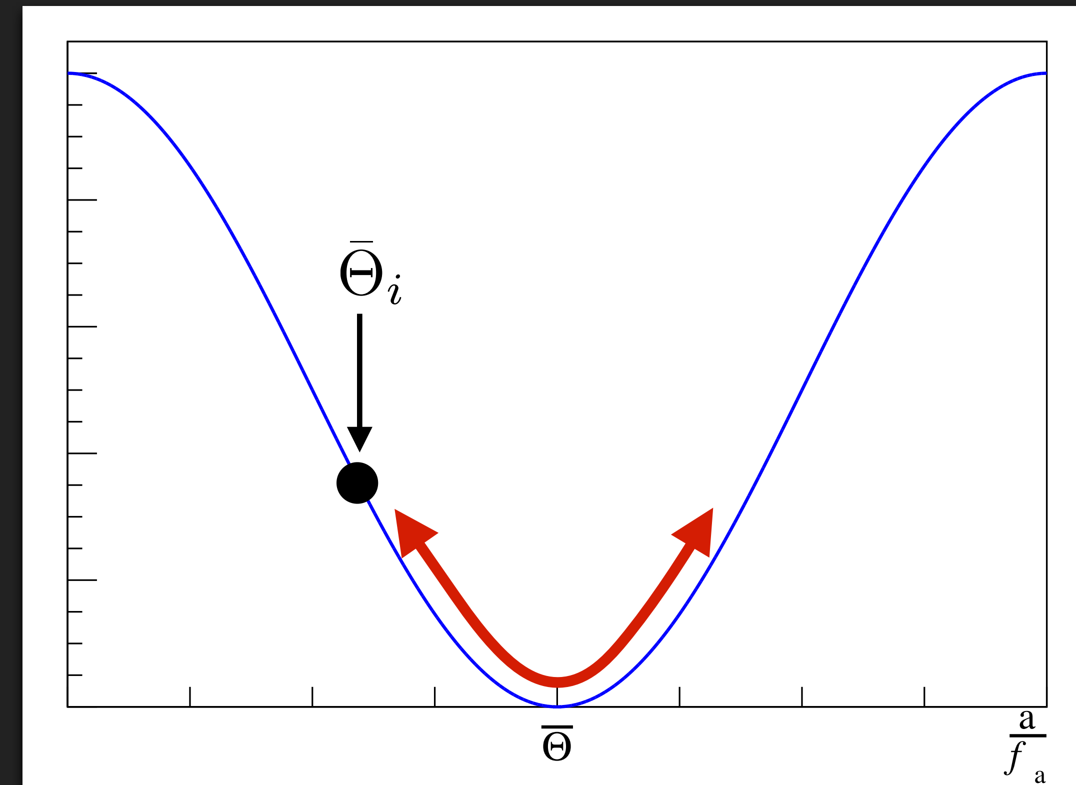
- Misalignment mechanism gives rise to an oscillating axion field:

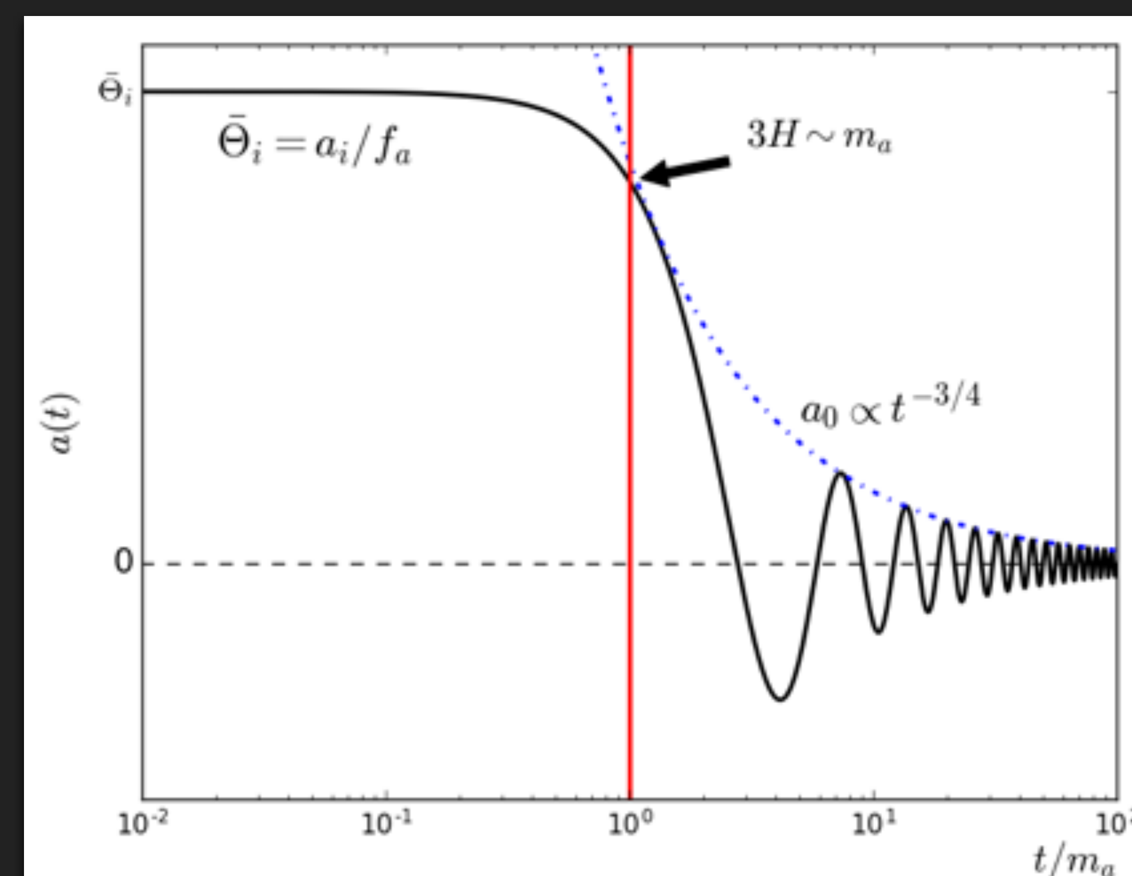
$$a(t) = a_0 \sin(m_a t)$$

- The combined field potential/kinetic energy behaves like DM

- Assuming the axion field accounts for the DM density, we can write:

$$a_0 = \frac{\sqrt{2\rho_{\rm DM}}}{m_a}$$

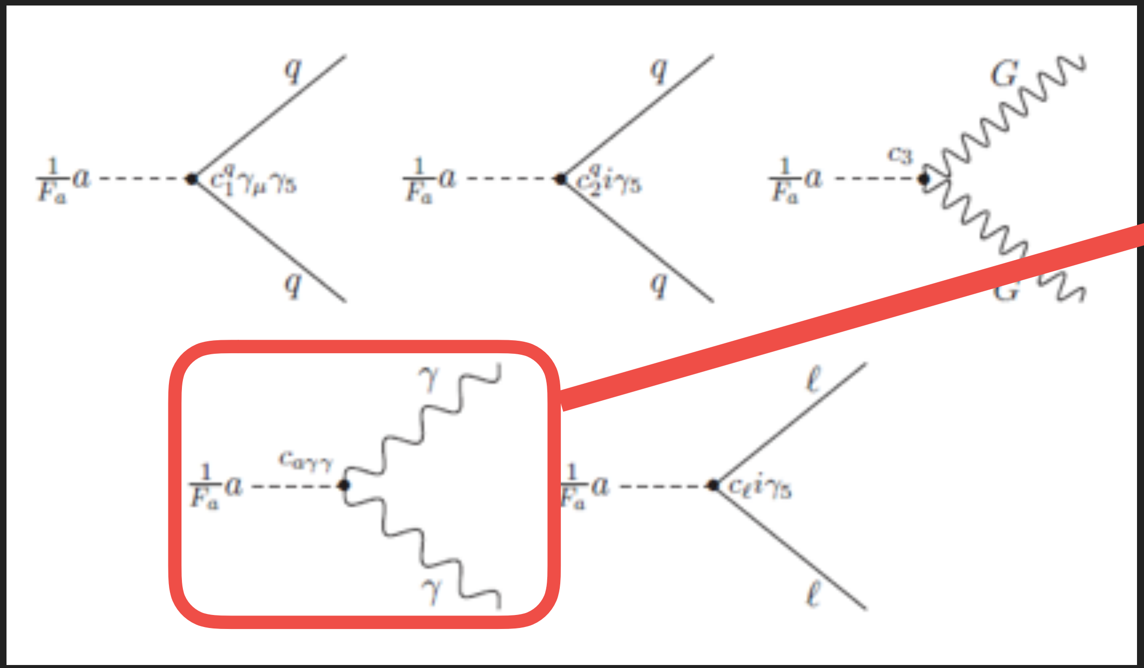




Axion Interactions with the Standard Model

- In addition to canceling the CP violating term, the axion also adds a lot of interactions with the SM!

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \left(\frac{a}{f_a} - \bar{\Theta}\right)\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$$
$$-\frac{1}{2}\partial_\mu a \partial^\mu a + \mathcal{L}_{\rm int}(a/f_a, \mathrm{SM})$$



$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\widetilde{F}^{\mu\nu}$$
$$= -g_{a\gamma\gamma}a\mathbf{E}\cdot\mathbf{B}$$
$$g_{a\gamma\gamma} \propto \frac{\alpha_{\rm EM}}{f_a}$$

Axion Interactions with the Standard Model

- New QED Lagrangian leads to new Maxwell's equations

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}g_{a\gamma\gamma}aF^{\mu\nu}\widetilde{F}^{\mu\nu}$$

Modified Source-Free Maxwell's Equations

$$\begin{aligned}
\nabla \cdot \mathbf{E} &= -g_{a\gamma\gamma}\mathbf{B} \cdot \nabla a \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
\nabla \times \mathbf{B} &= \frac{\partial \mathbf{E}}{\partial t} - g_{a\gamma\gamma}\left(\mathbf{E} \times \nabla a - \frac{\partial a}{\partial t}\mathbf{B}\right)
\end{aligned}$$

An Axion In a Magnetic Field

- Modification to Ampere's law (MQS approximation)

$$\nabla \times \mathbf{B} = g_{a\gamma\gamma} \frac{\partial a}{\partial t} \mathbf{B}$$

- An oscillating axion field creates an "effective current" in the presence of a magnetic field

$$\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma} \frac{\partial a}{\partial t} \mathbf{B}$$

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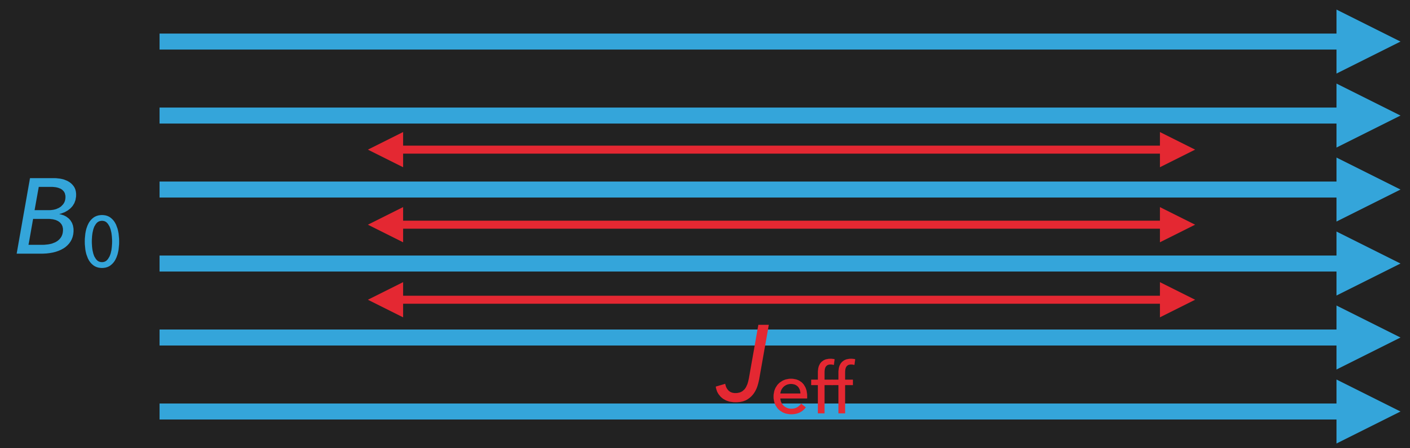

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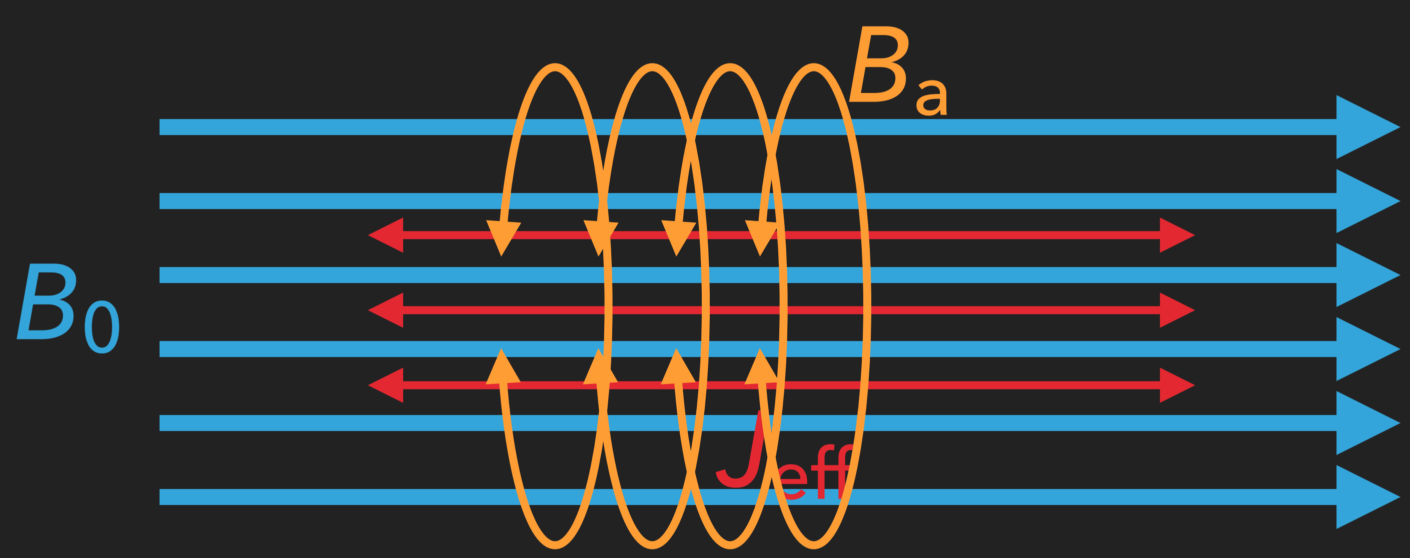

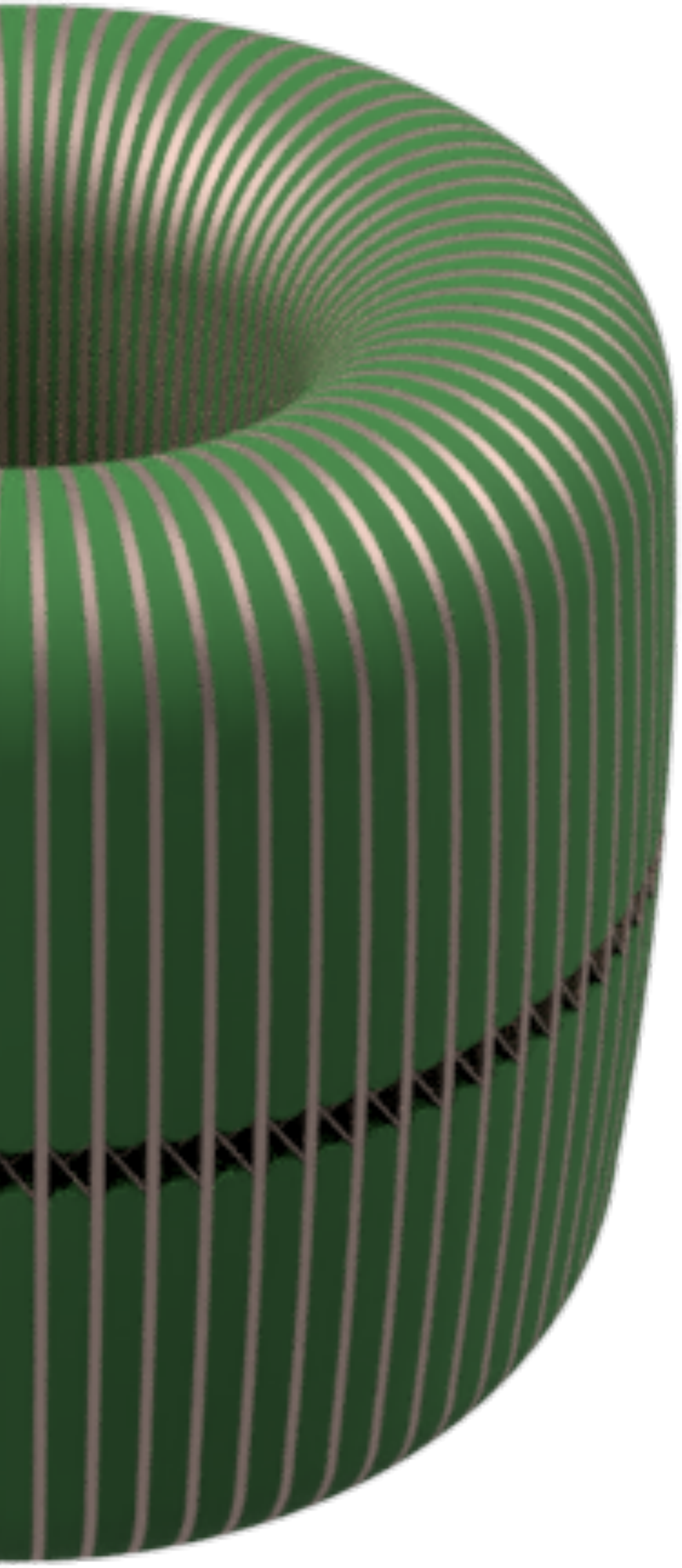

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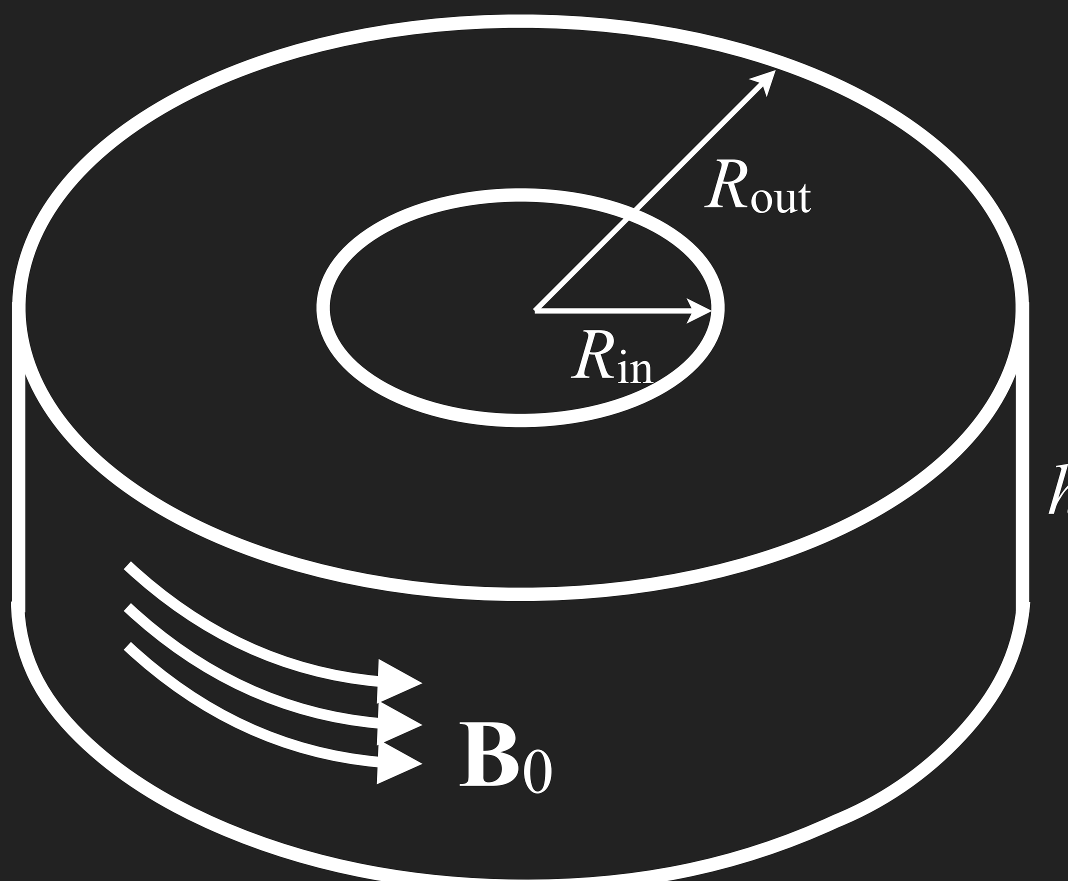
A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-Field Ring Apparatus

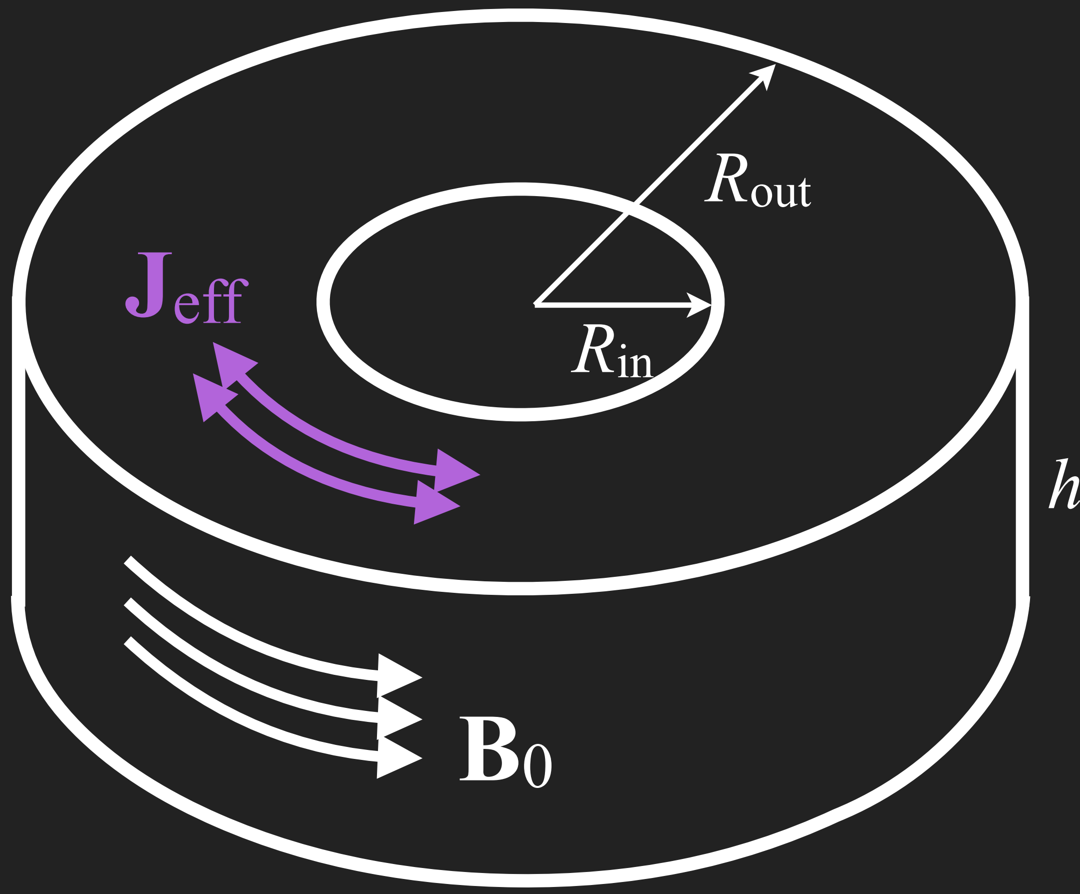
- Start with a toroidal magnet with a fixed magnetic field B_0



Phys. Rev. Lett. 117, 141801 (2016)

A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-Field Ring Apparatus

- Start with a toroidal magnet with a fixed magnetic field B_0
- ADM generates an oscillating effective current around the ring (MQS approx: $\lambda \gg R$)



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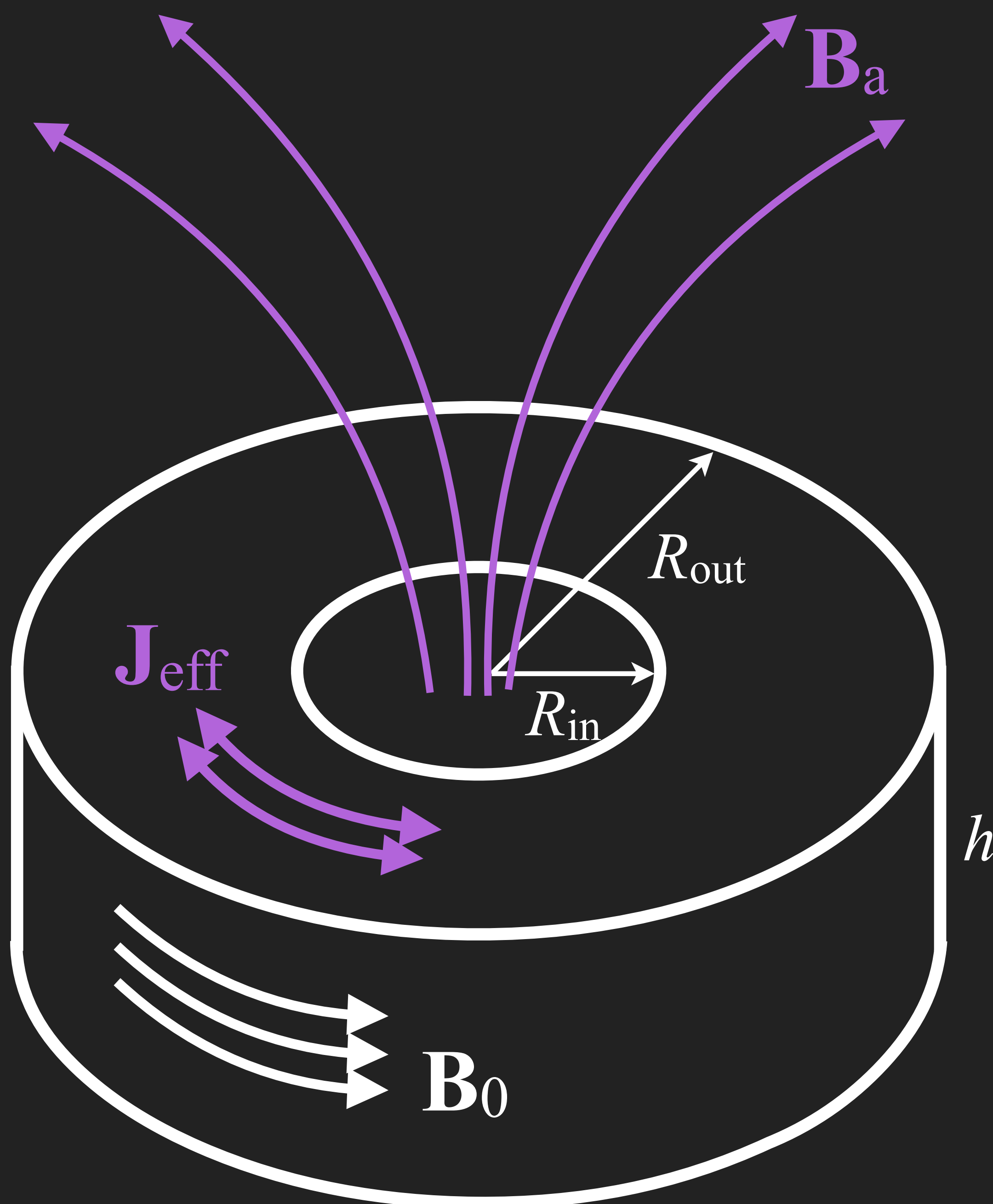

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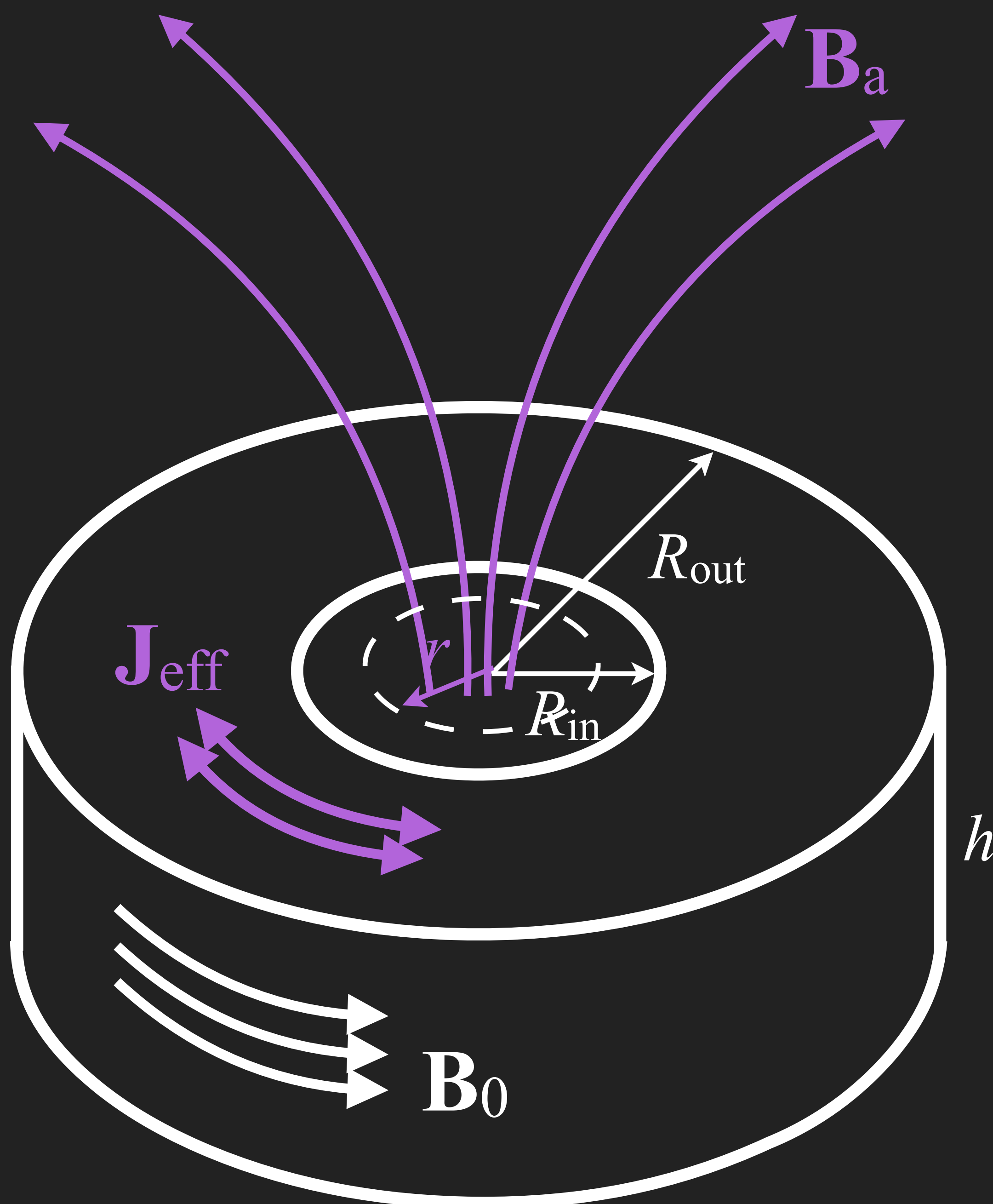
- Insert a pickup loop in the center and measure the induced current in the loop read out by a SQUID based readout

$$\Phi(t) = g_{a\gamma\gamma} B_{\max} \sqrt{2\rho_{\mathrm{DM}}} \cos(m_a t) \mathcal{G}_V V$$



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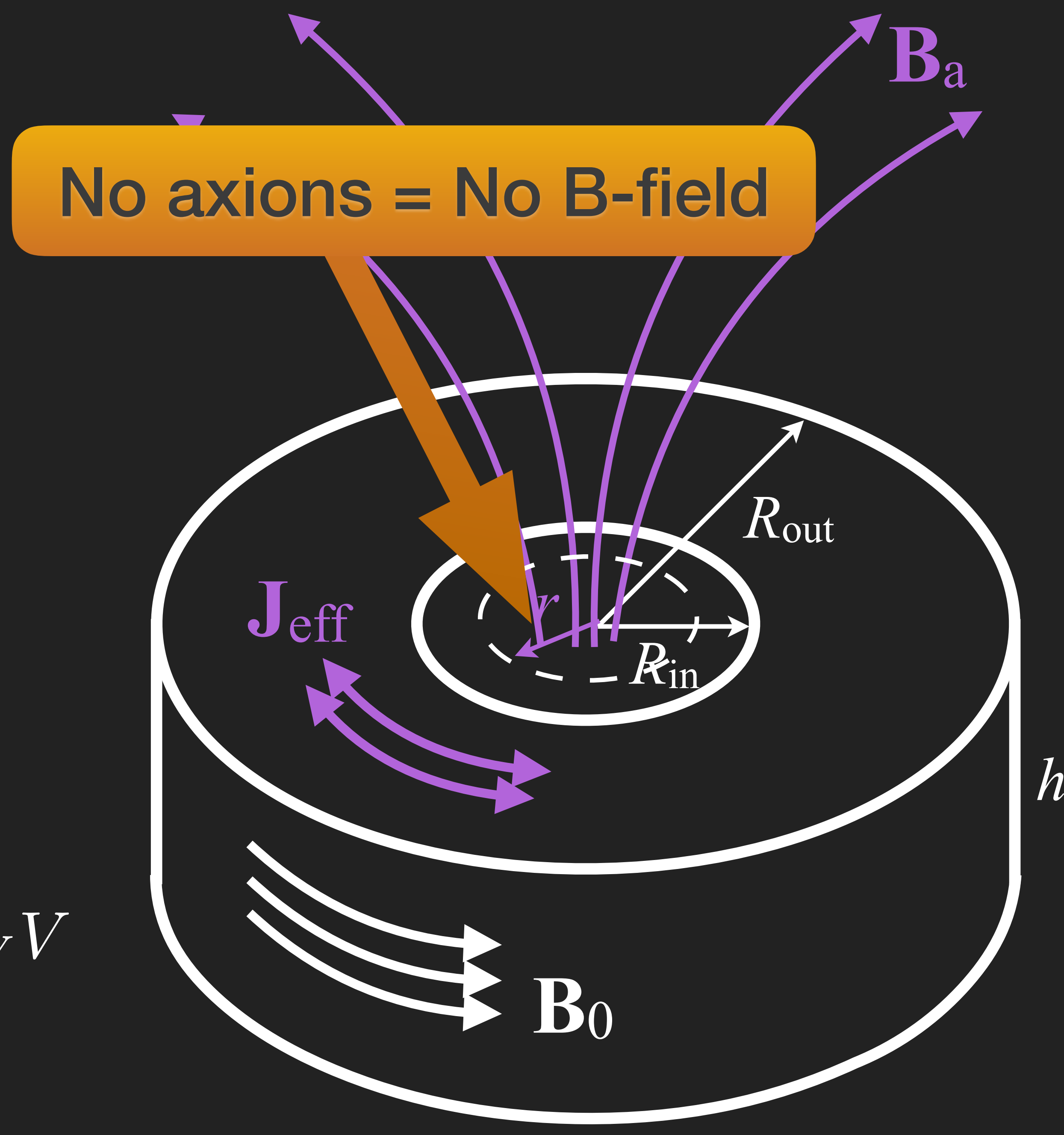
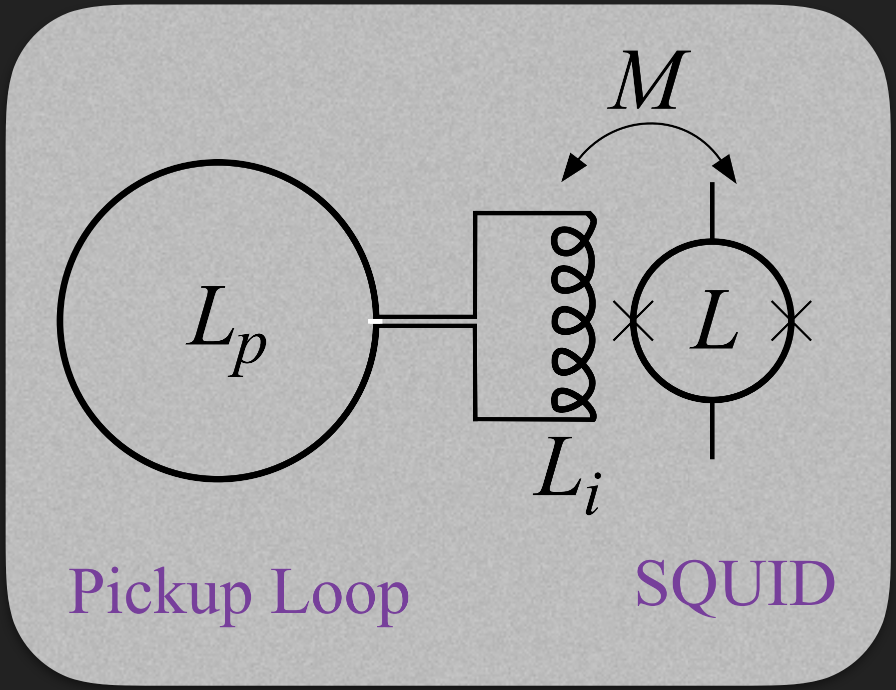
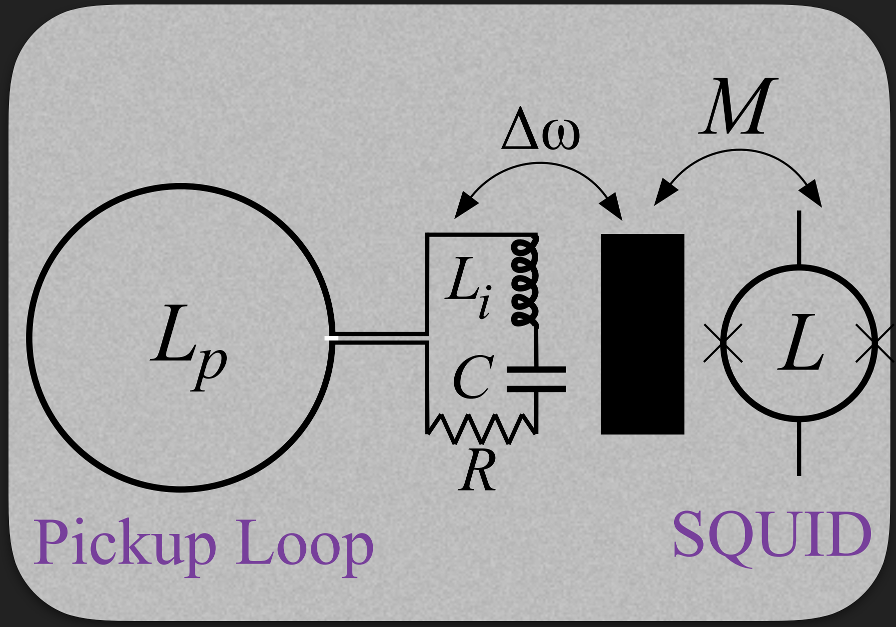


Phys. Rev. Lett. 117, 141801 (2016)

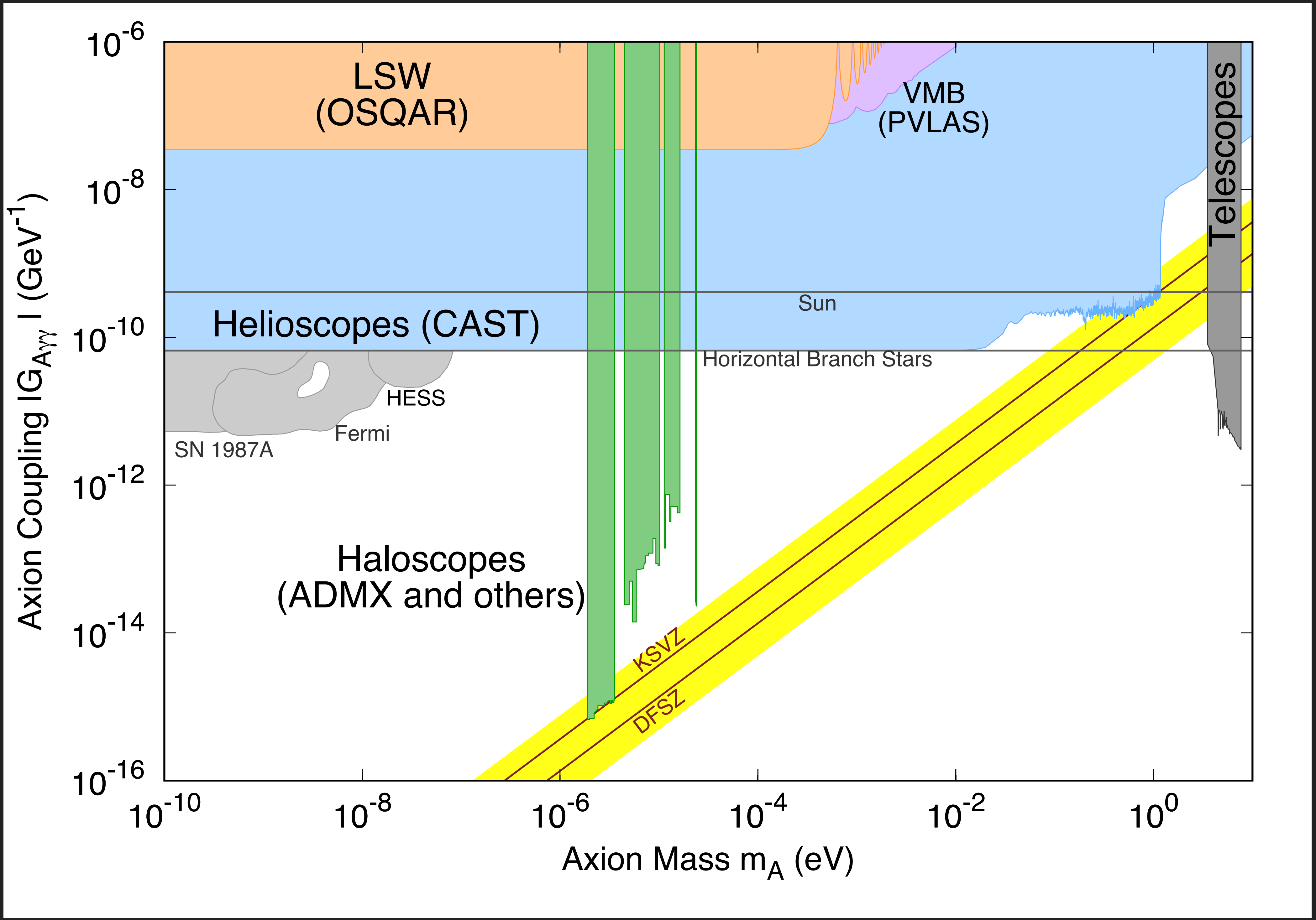
ABRACADABRA Readout

- ABRACADABRA will require very sensitive current detectors → SQUID current sensors
- Two limiting cases:
  - A broadband only readout, where the pickup loop is coupled directly to the SQUID
  - A resonant circuit readout, where the pickup loop is coupled through the SQUID through a resonator circuit.
- In practice, the optimal approach is a combination of the two
  - See talks from Arran and Kent





Current State Of Axion Search



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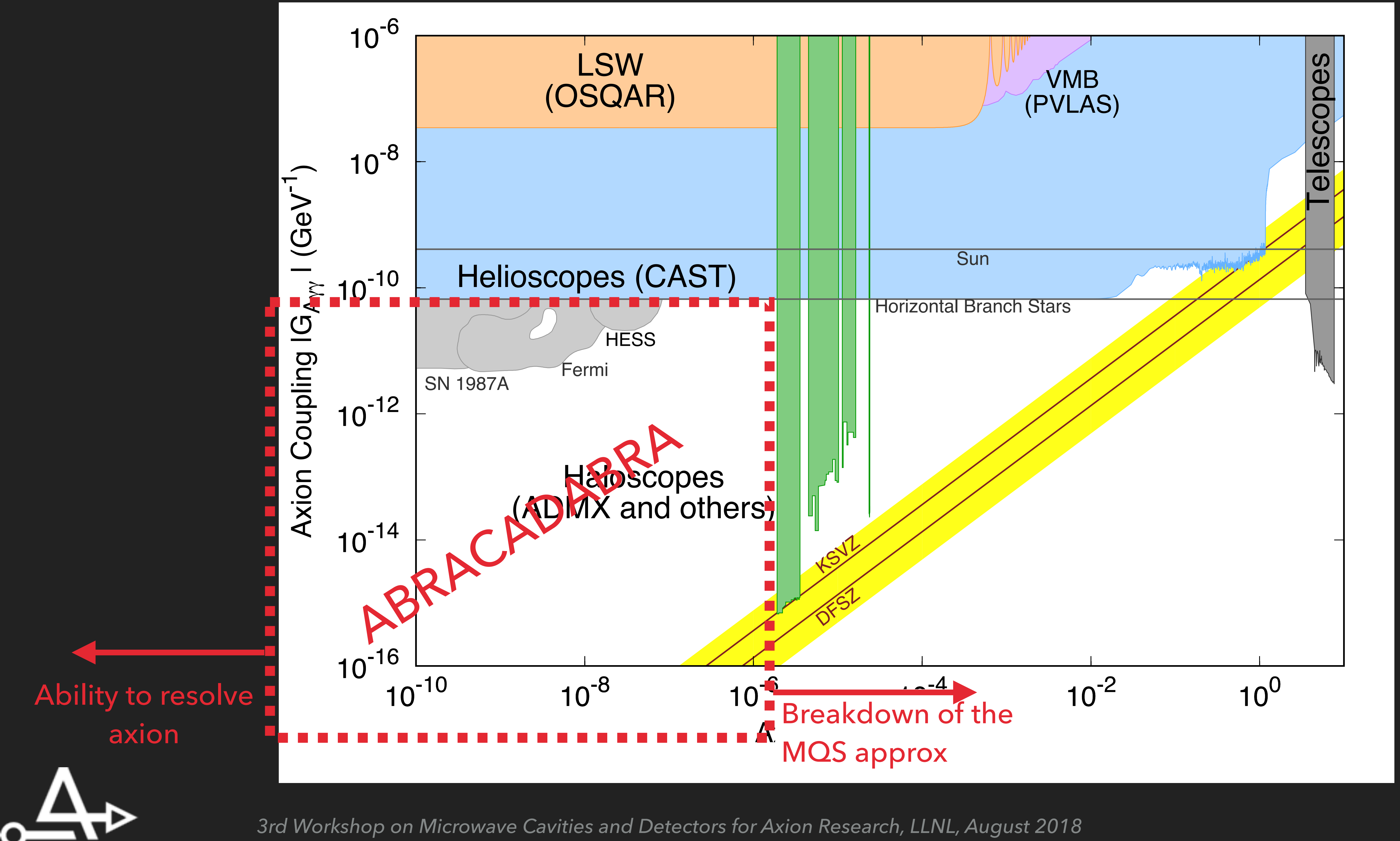
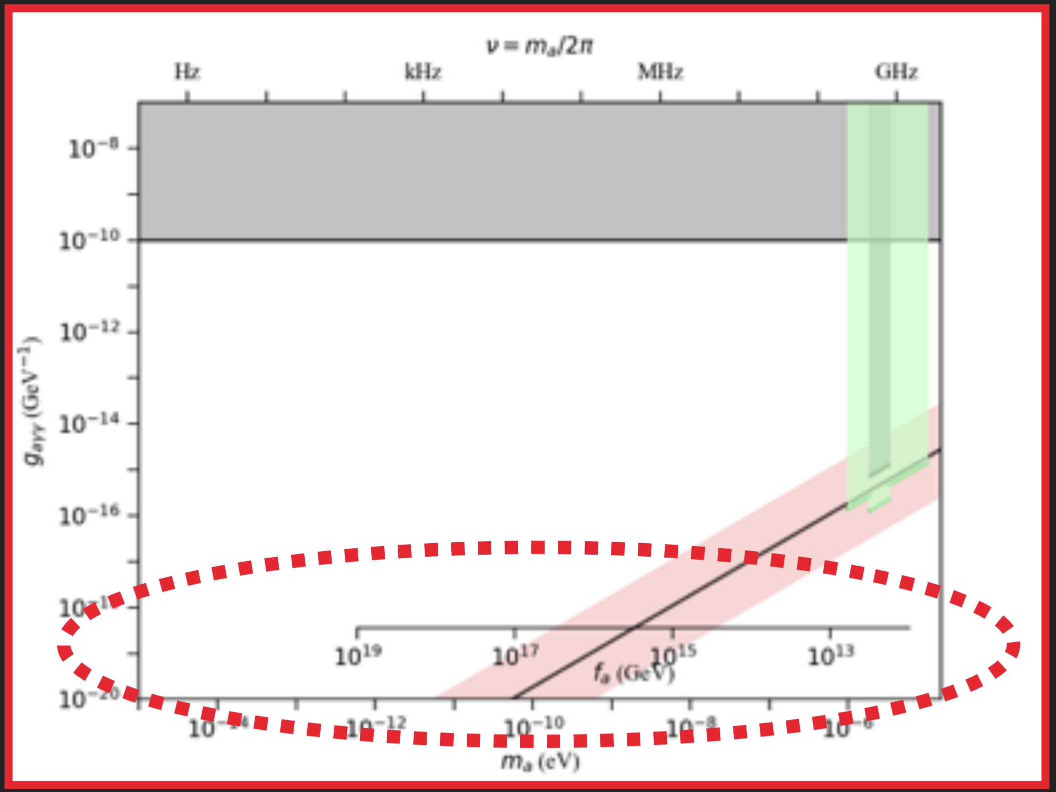
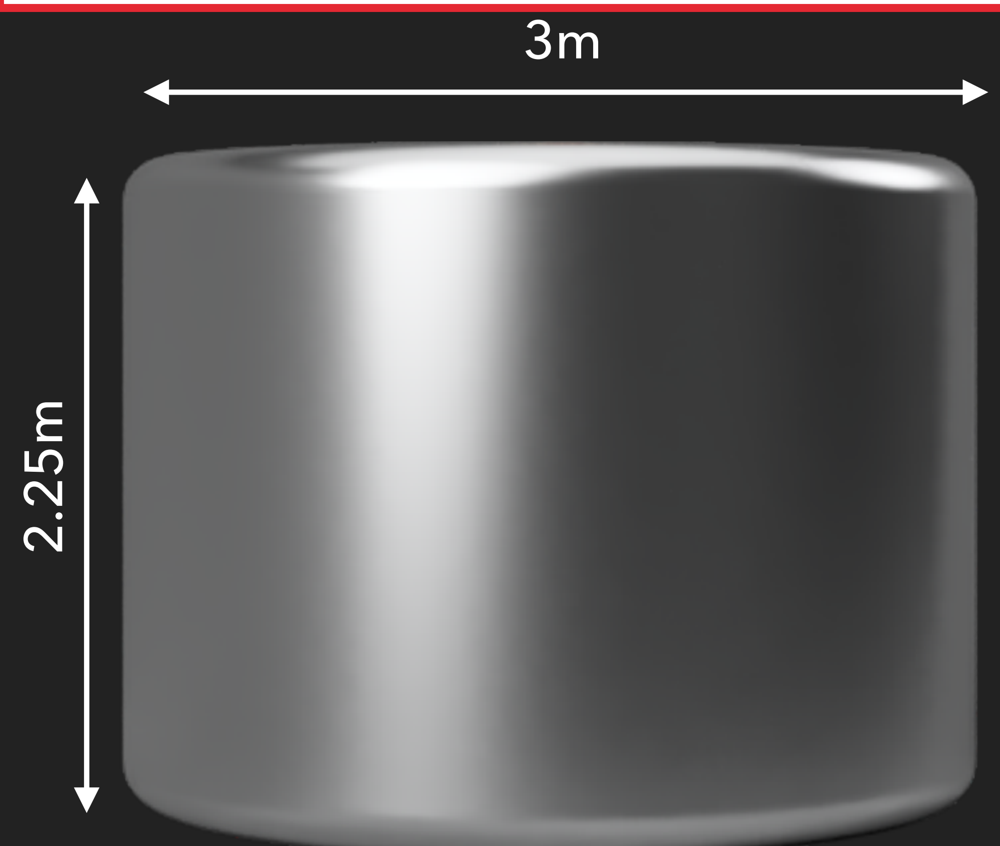


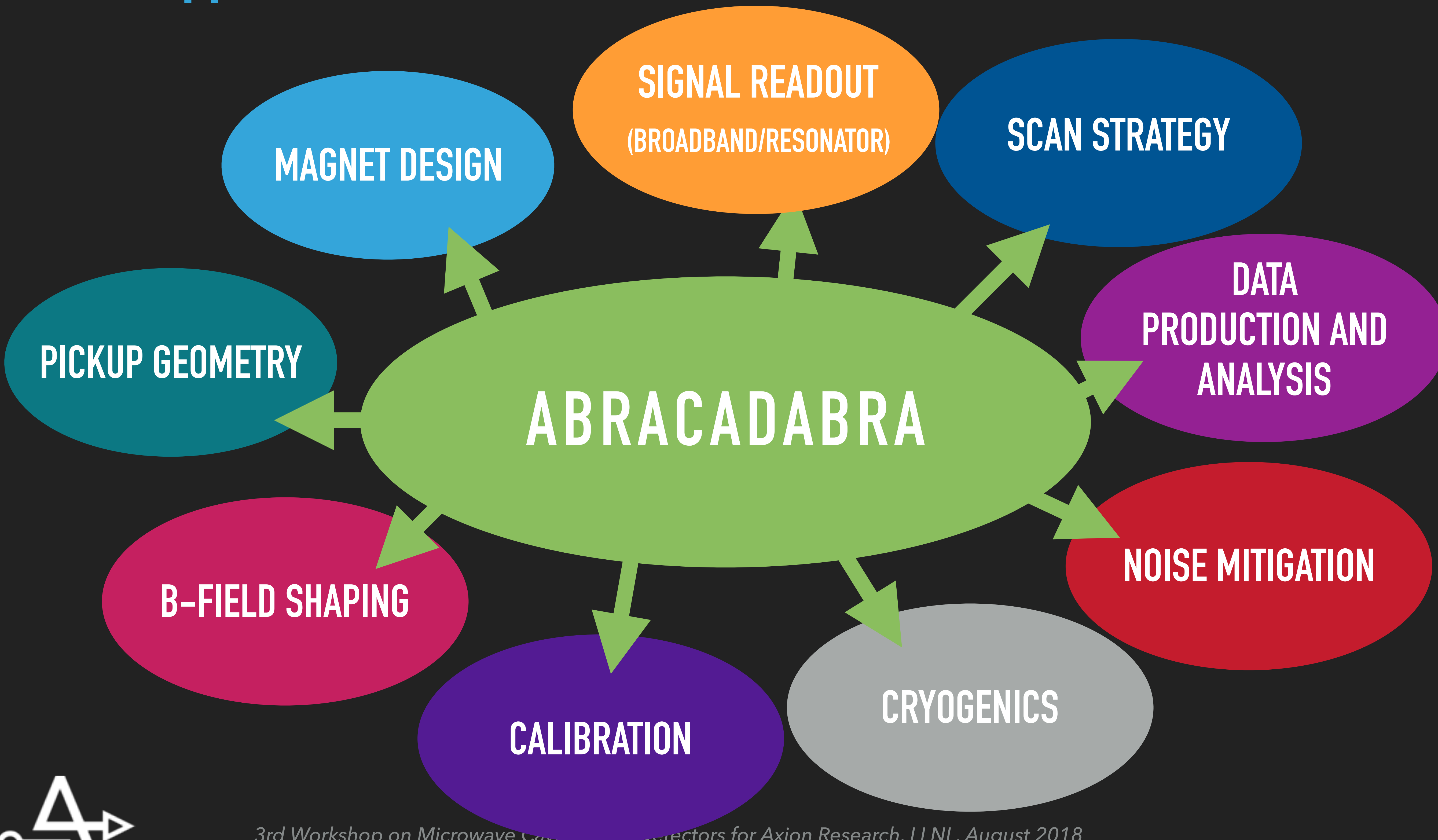
What Are We Aiming For?

- Probing the QCD scale axion around the GUT scale (m_a ~ neV)
- A ~meter scale detector with a max field of B_0~1-5 T
- Experimental challenge:
  - $B_a \sim 10^{-22}$ T
  - Frequency: kHz to a few 100 MHz
- Need a very sensitive, very low background detector!





New Approach, A Lot of Questions



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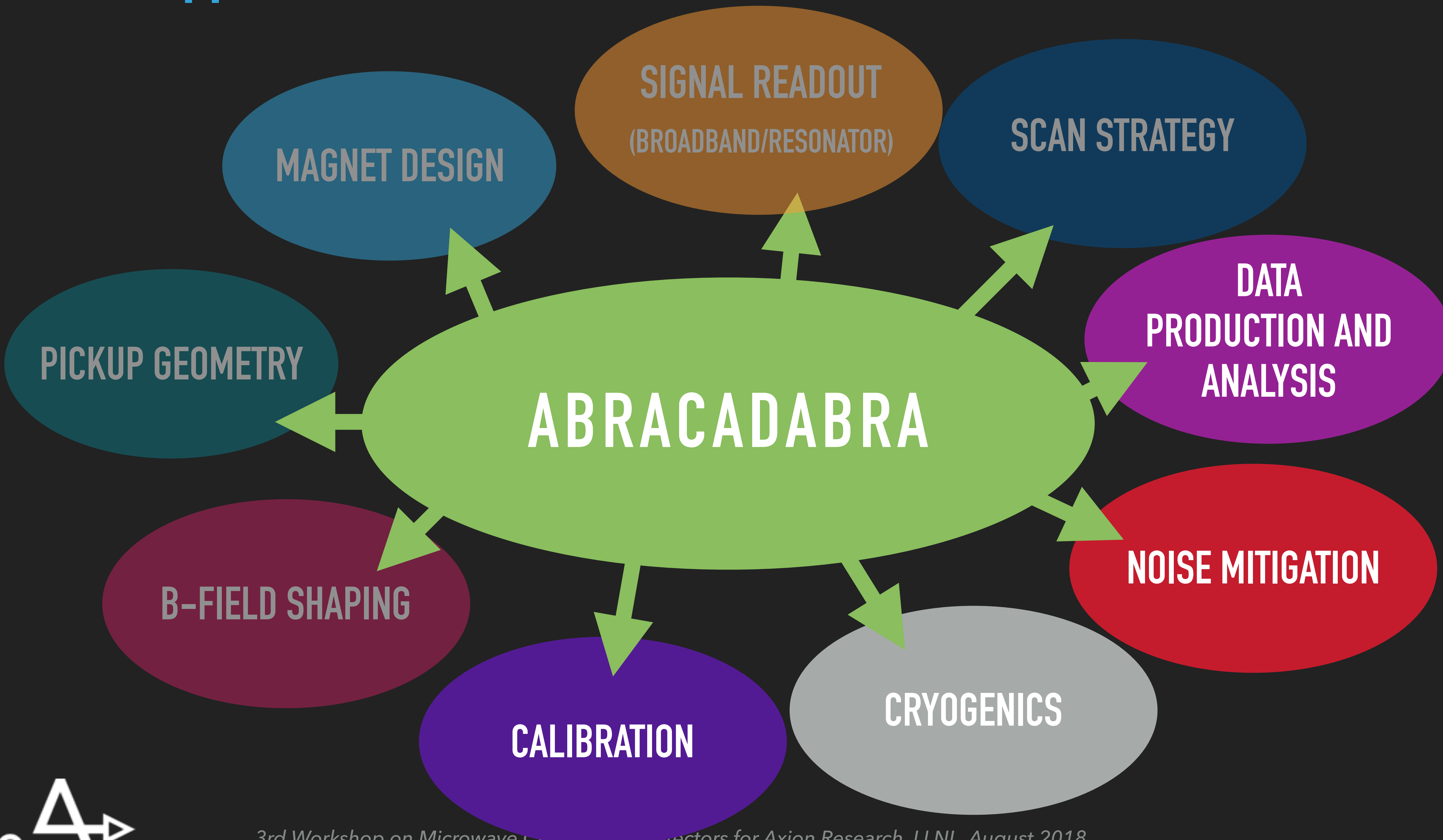
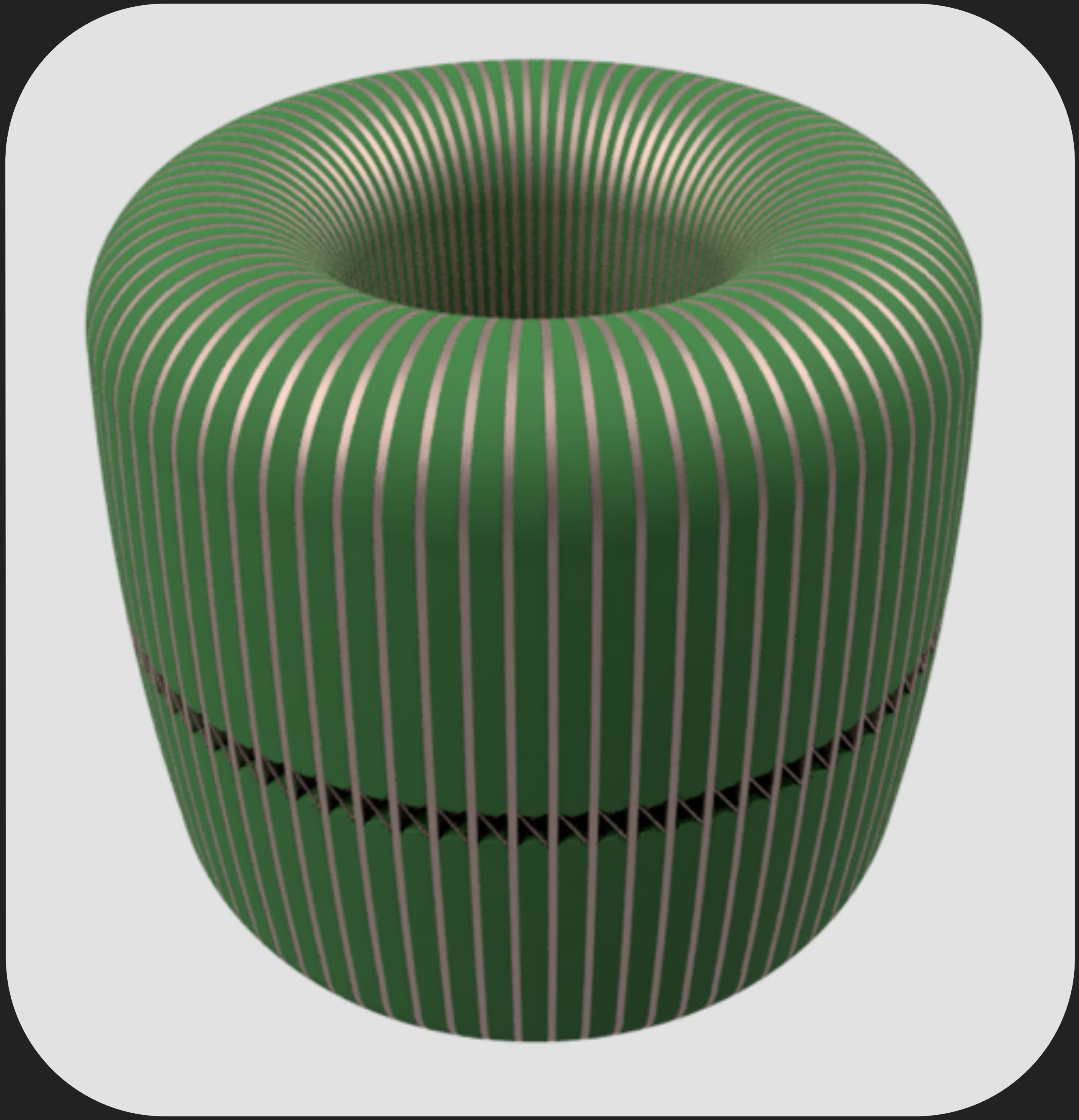


Dissecting ABRACADABRA-10 cm



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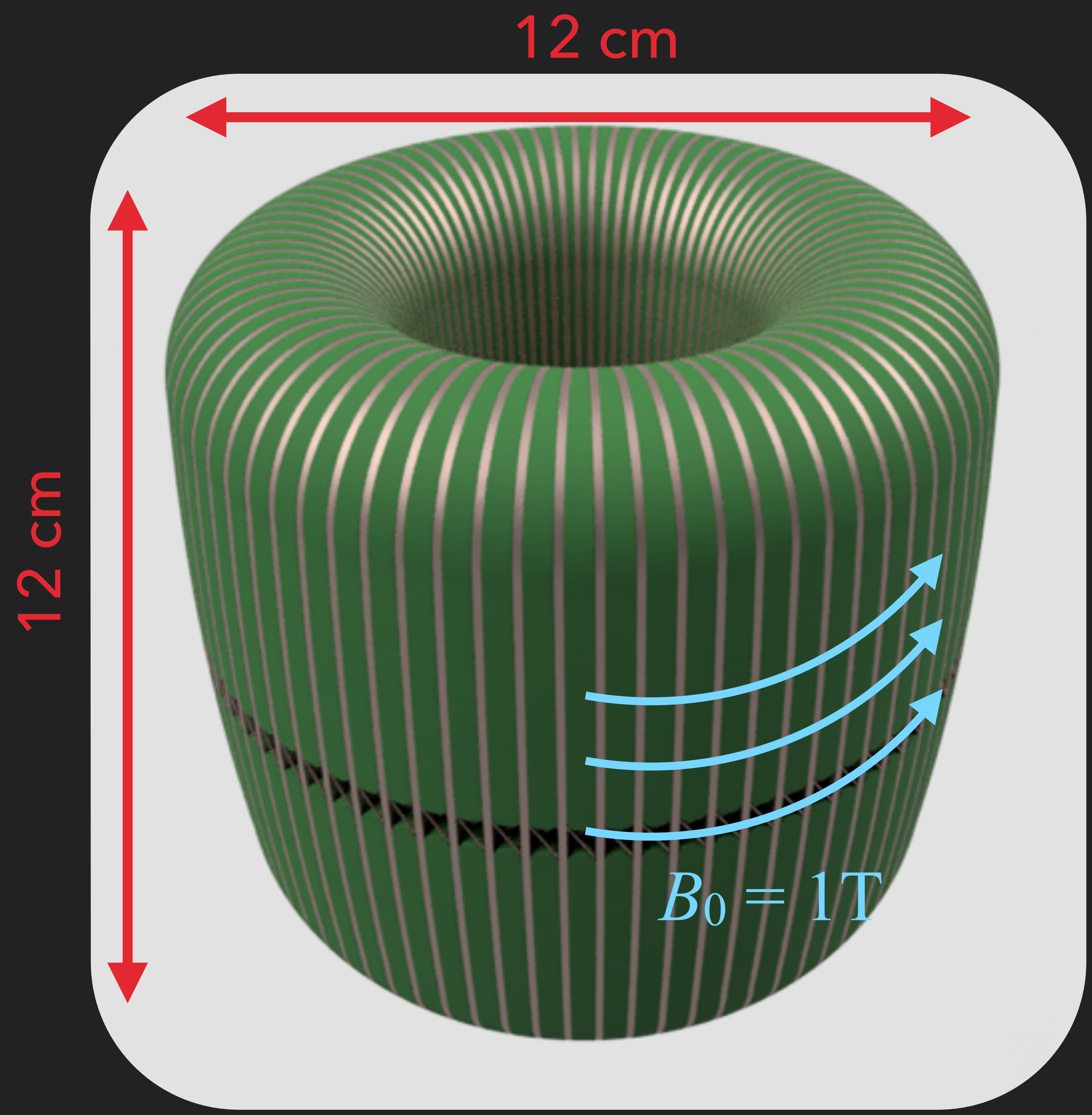

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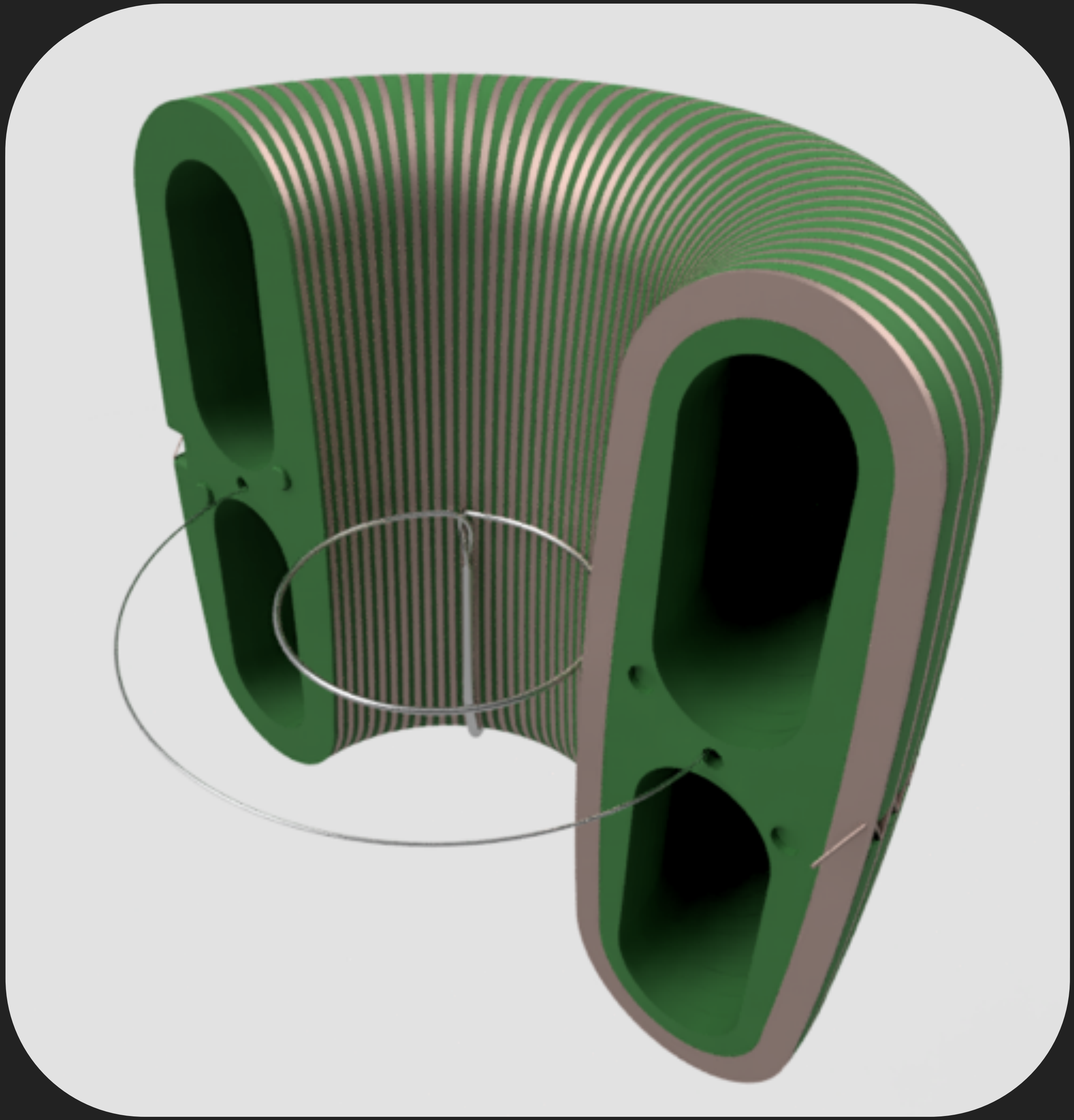
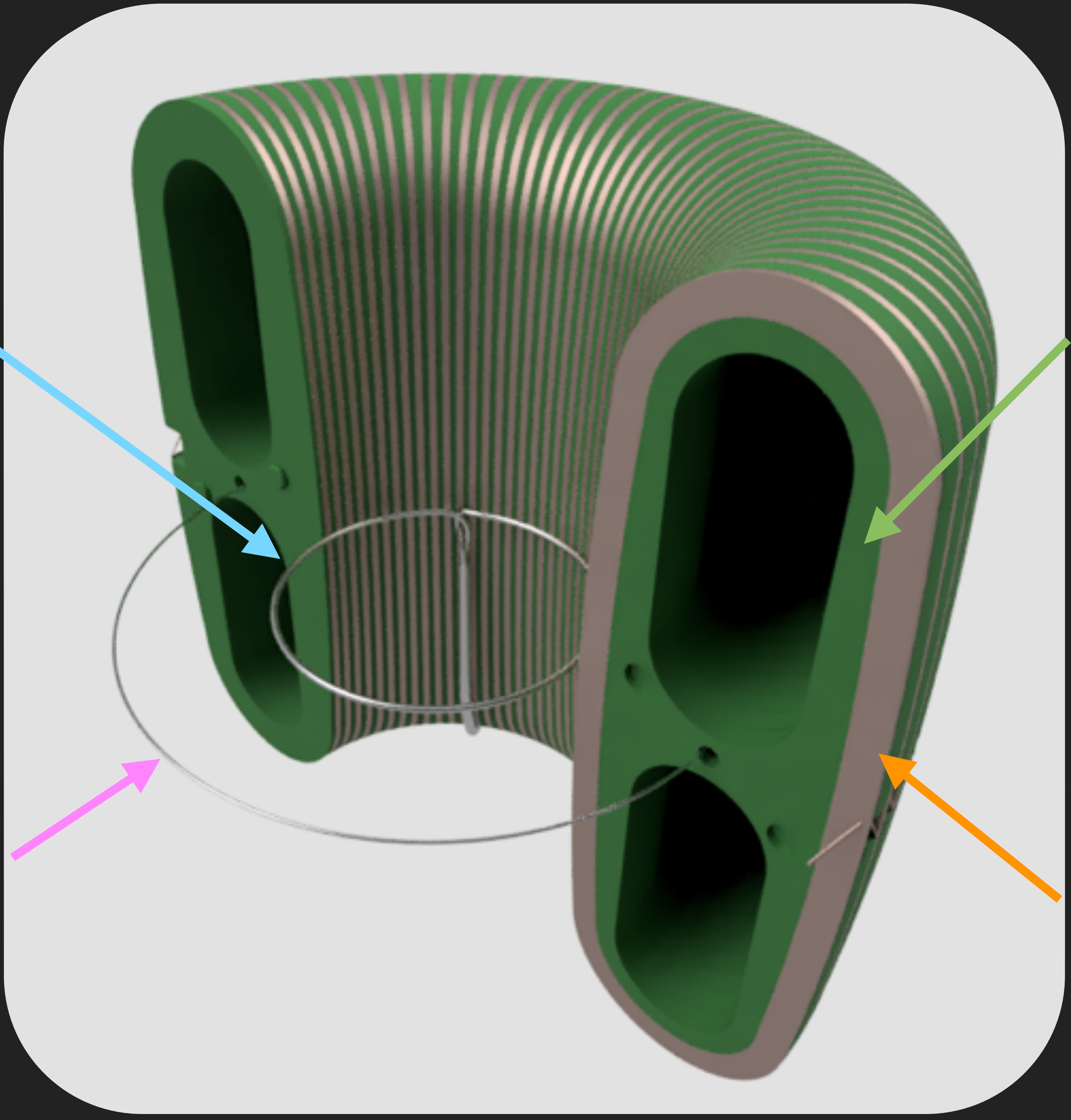


Dissecting ABRACADABRA-10 cm

Superconducting Pickup Loop
$r_p = 3$ cm

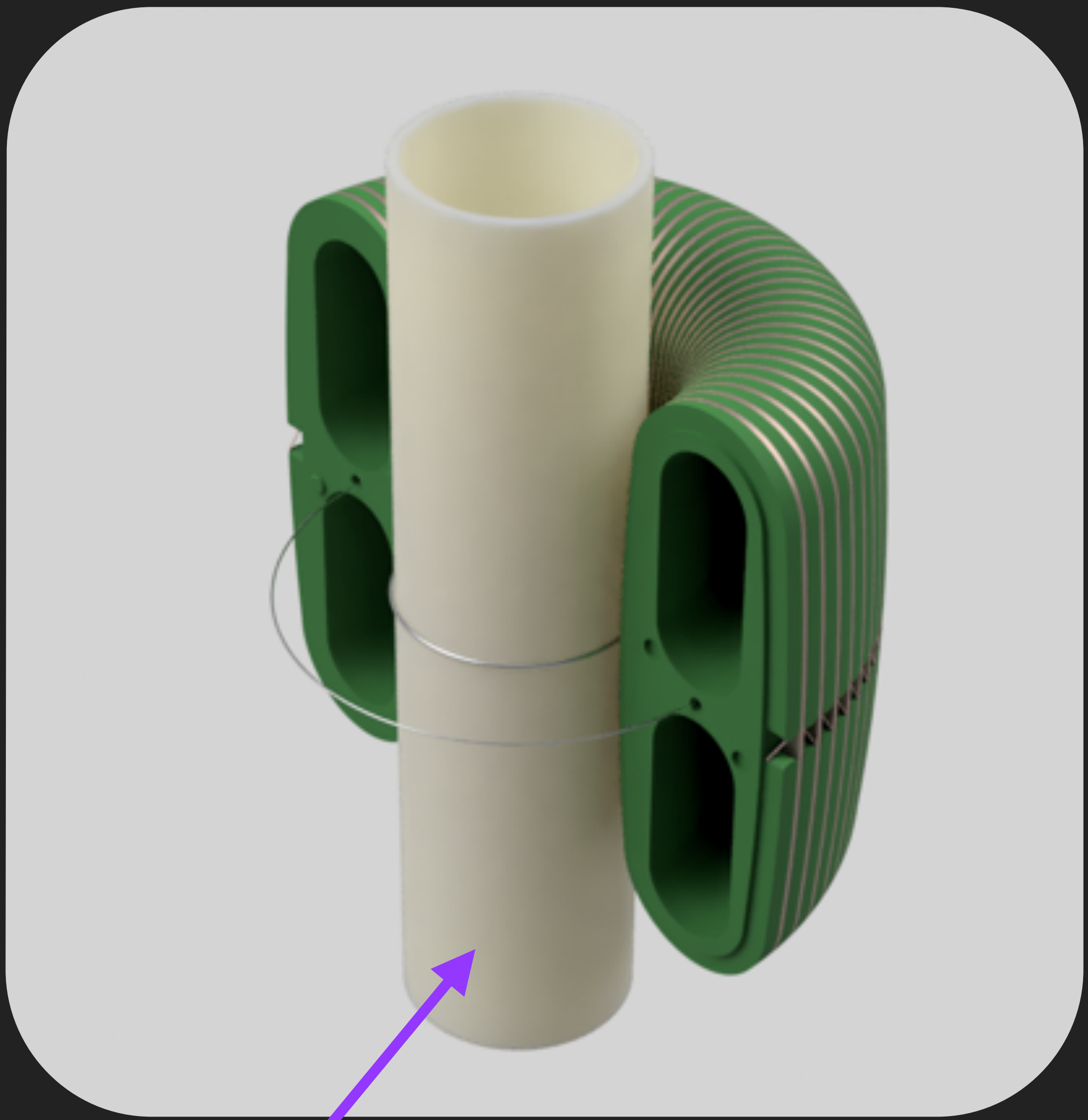


Delrin Toroid Body

Superconducting Calibration Loop
$r_c = 4.5$ cm

80×16 NbTi (CuNi) winds (counter-wound)

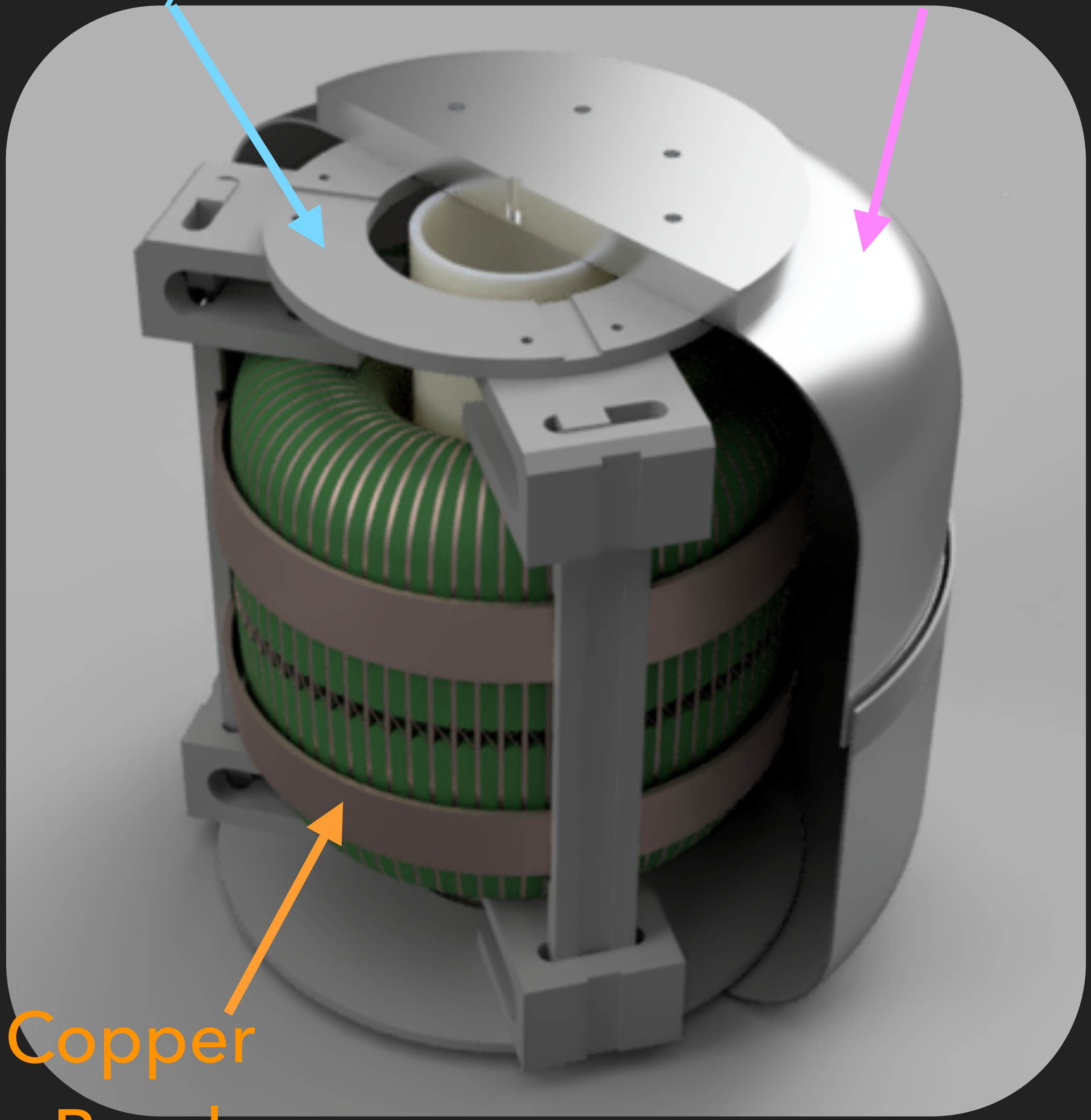
Dissecting ABRACADABRA-10 cm



Teflon Support Tube

G10 Support structure (nylon bolts)

Superconducting tin coated copper shield



Copper Thermalization Bands

Assembling ABRACADABRA-10 cm

SUPERCONDUCTING SYSTEMS INC.

(Normally make MRI magnets!)

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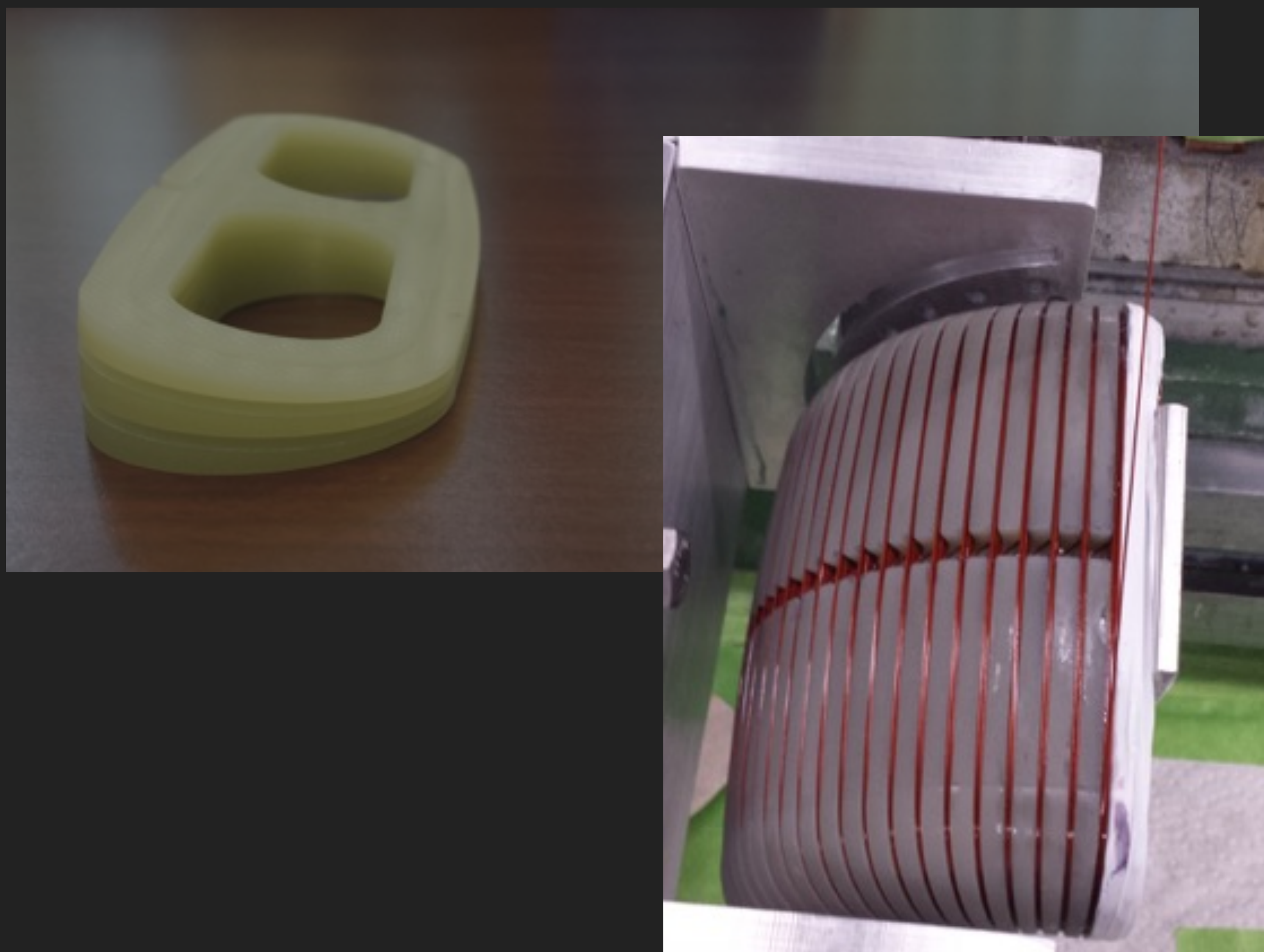

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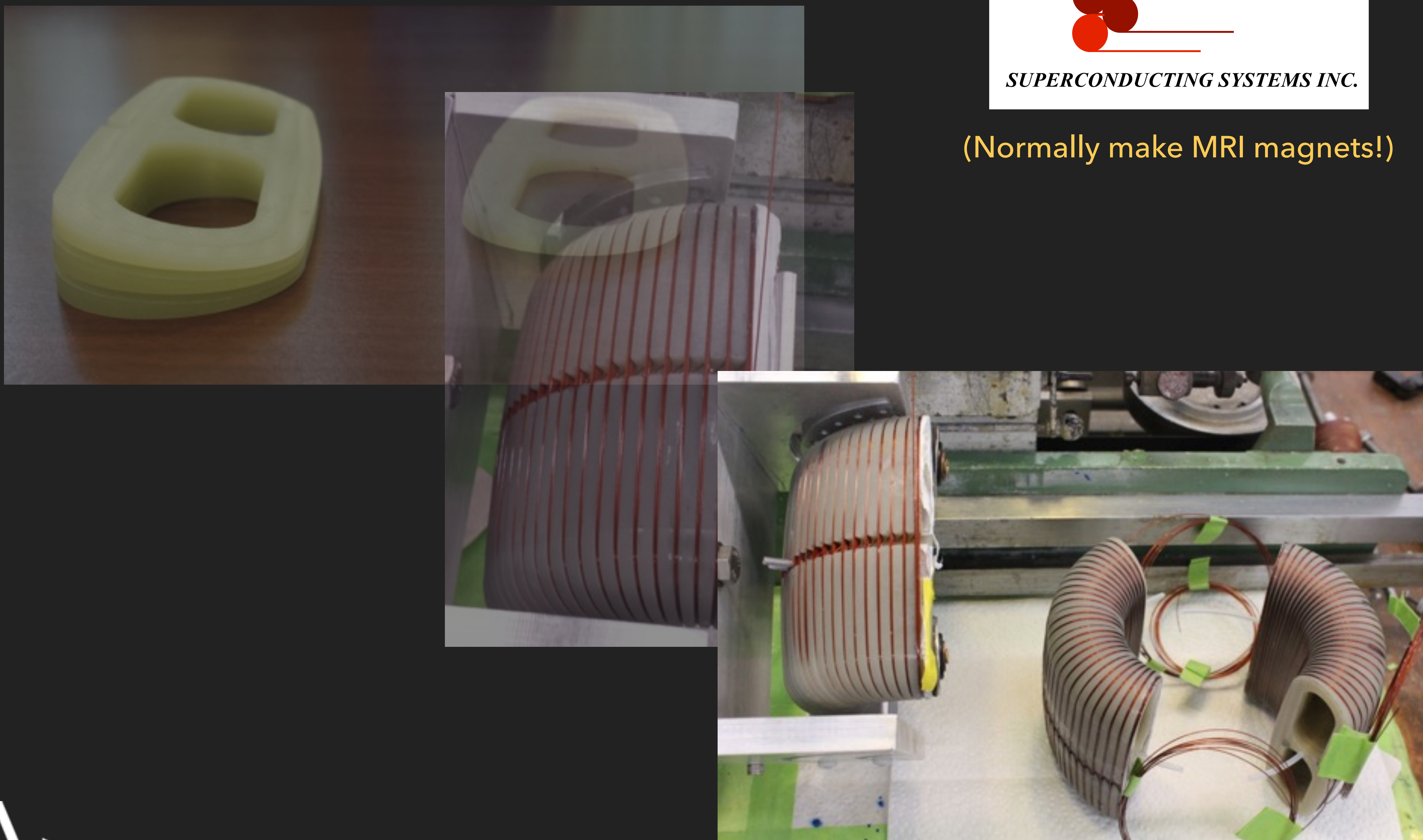

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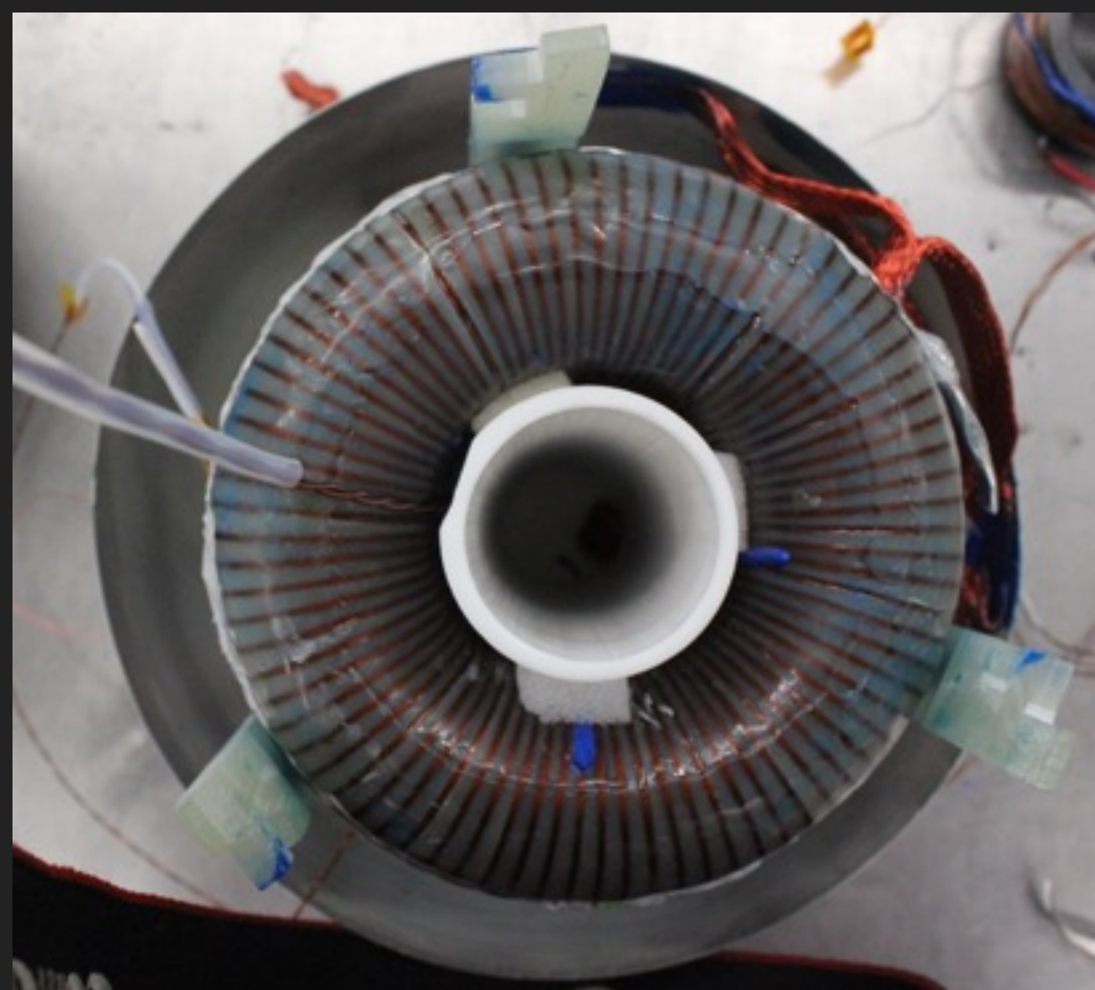
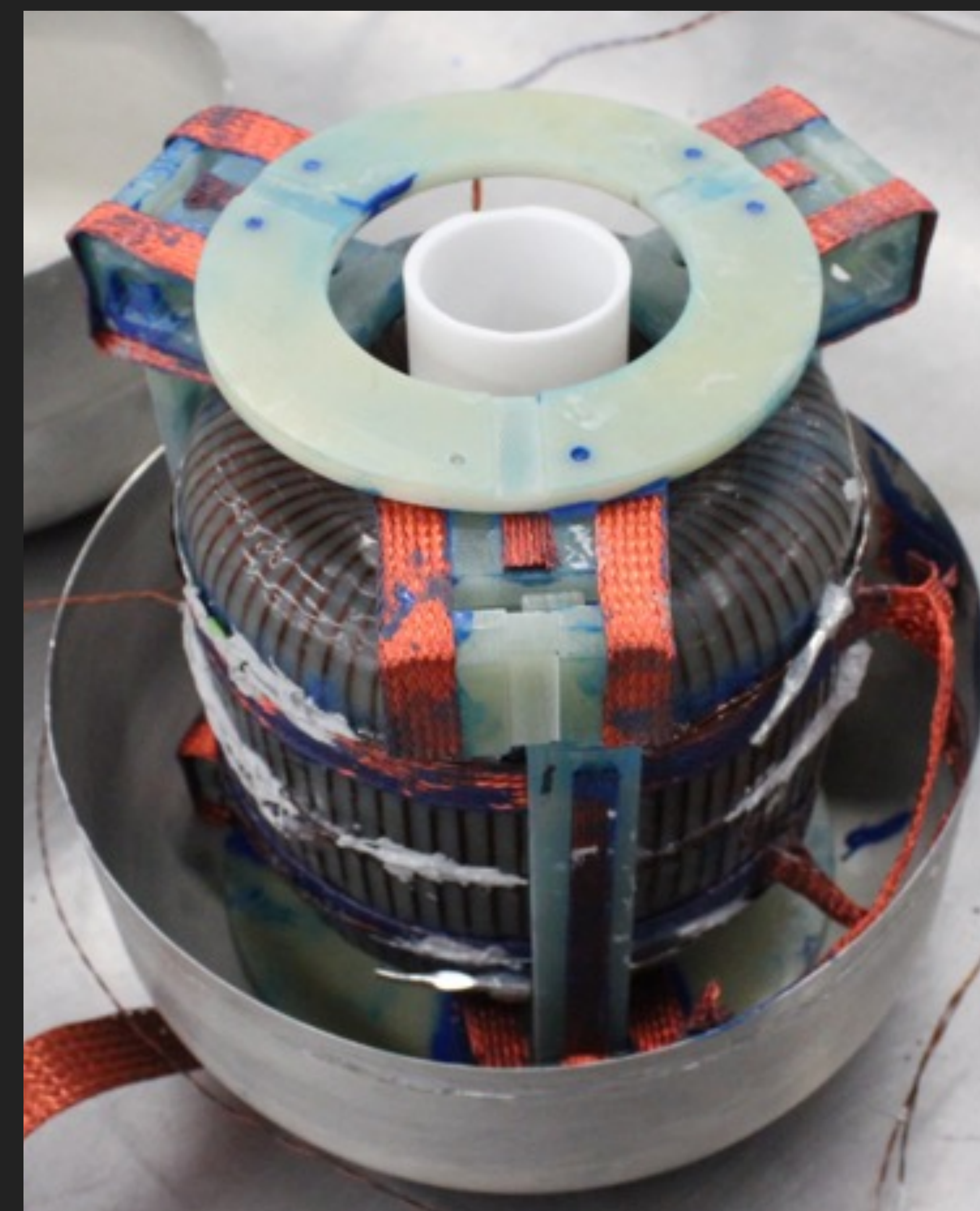
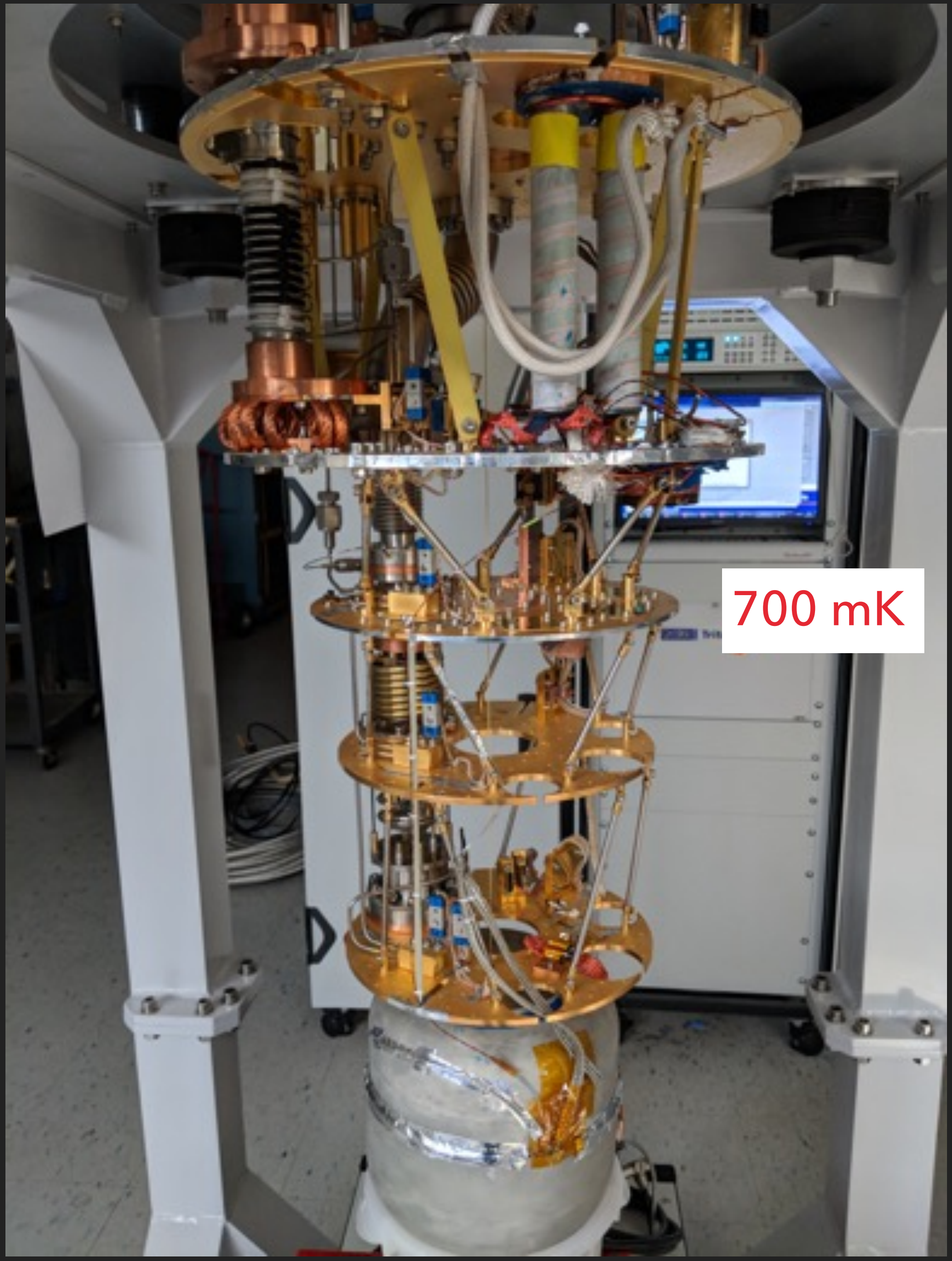
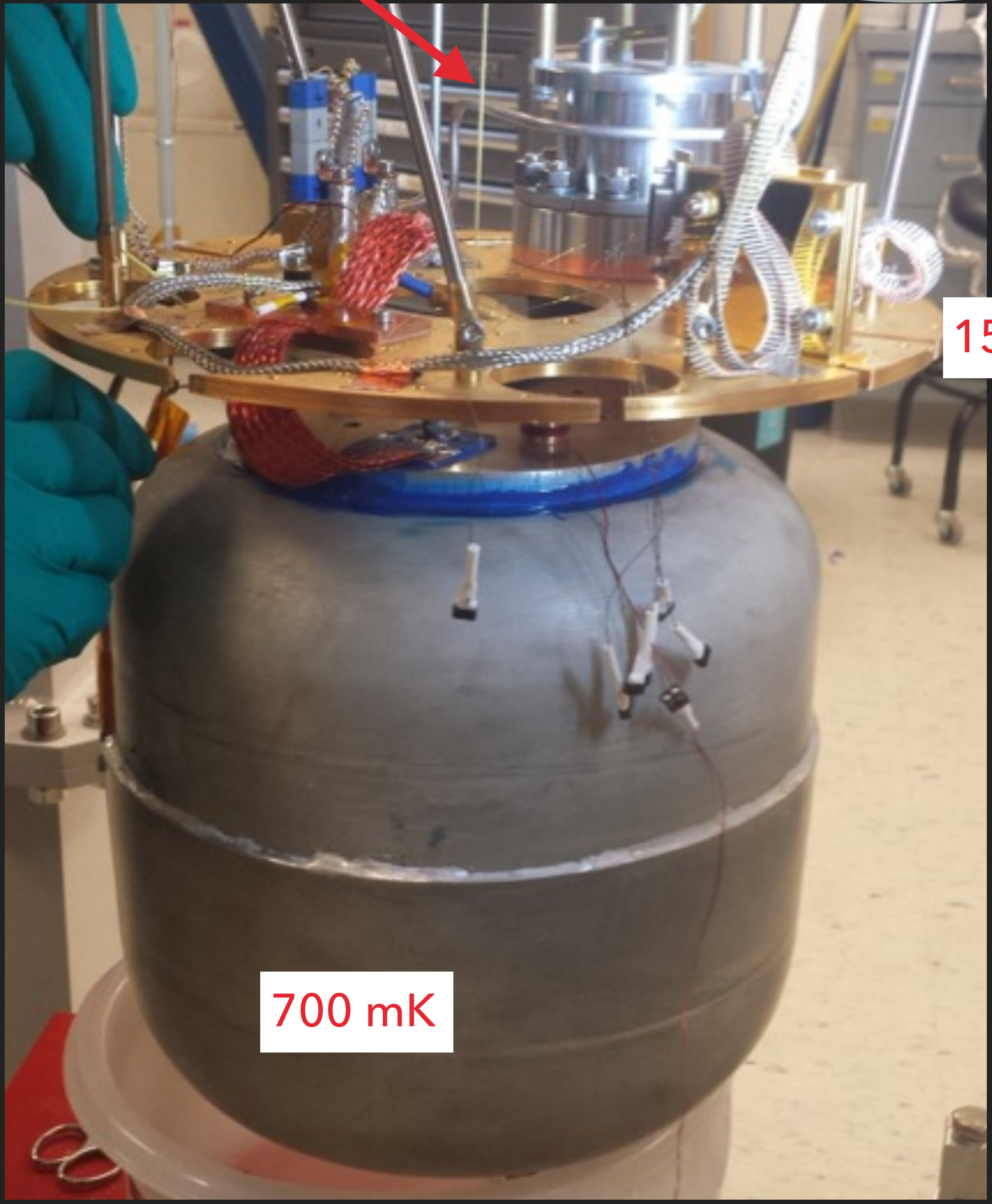




CRYOGENICS

Suspension System

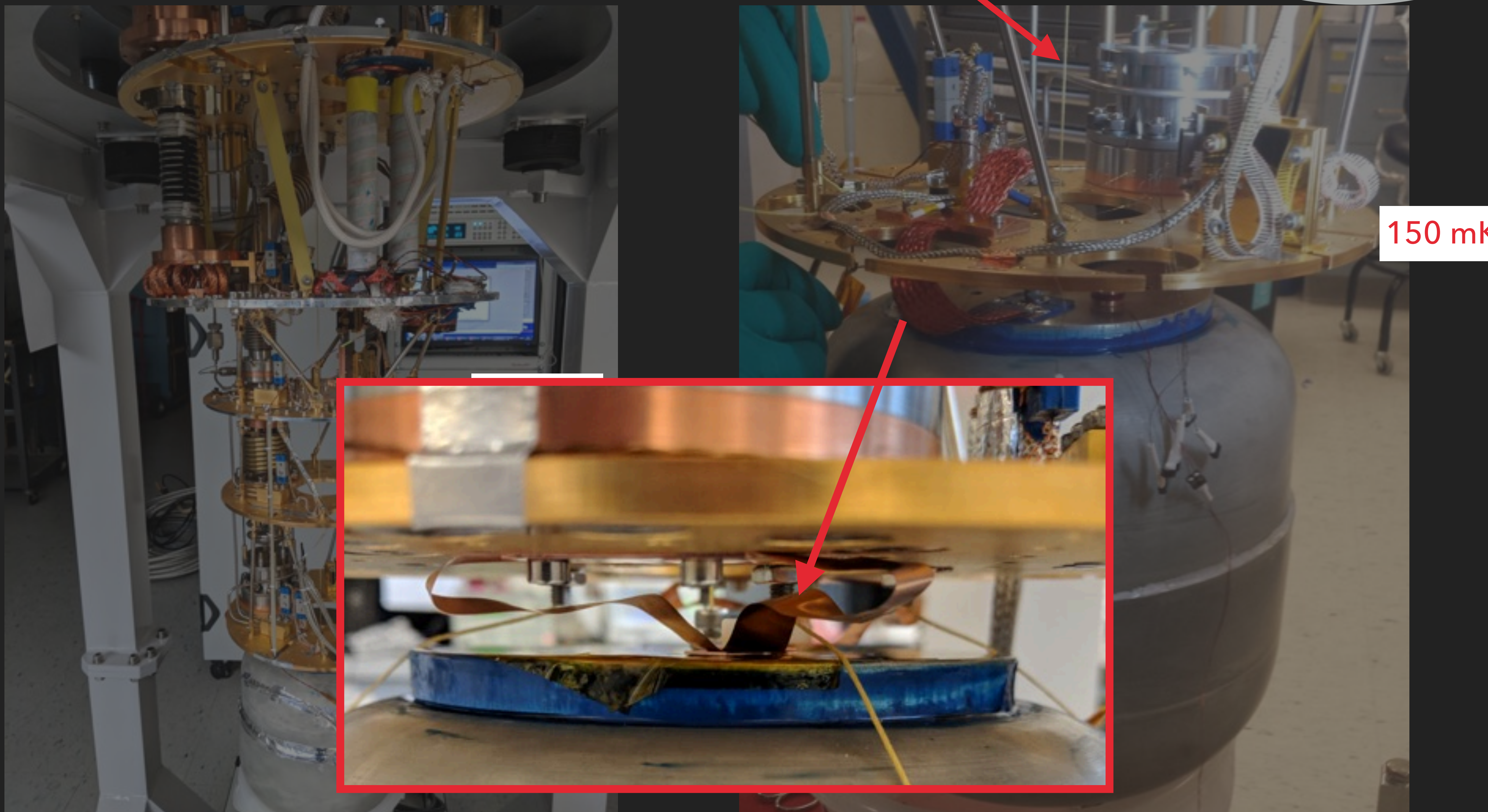




CRYOGENICS

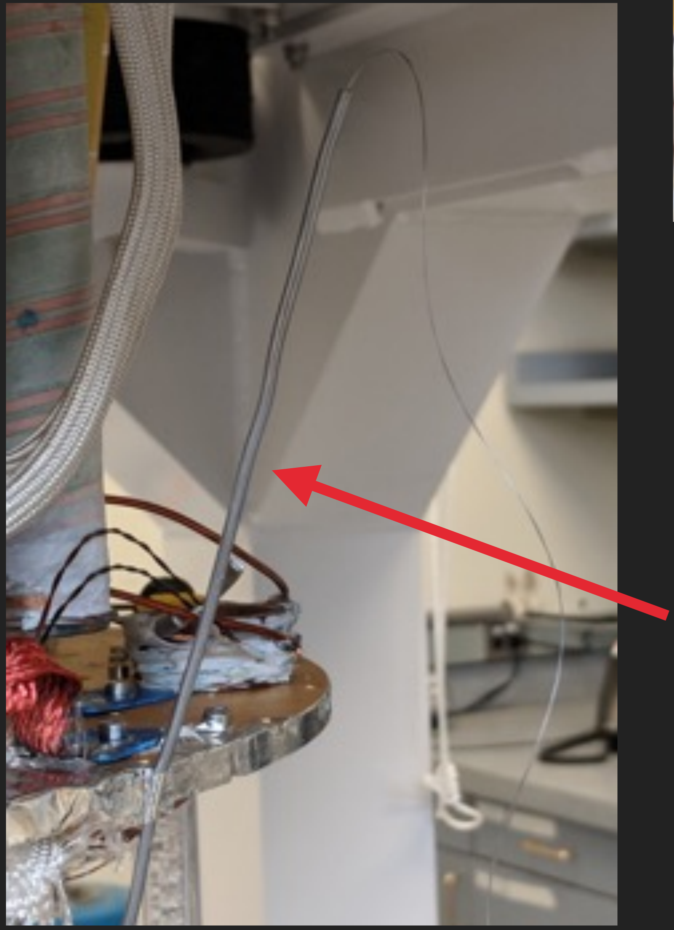
Suspension System

Kevlar Support



Superconducting Wiring

- Magnet wiring is NbTi(CuNi)
- All readout wiring and calibration loop is solid NbTi
- Readout wiring run inside single core solder wire that has had the flux removed

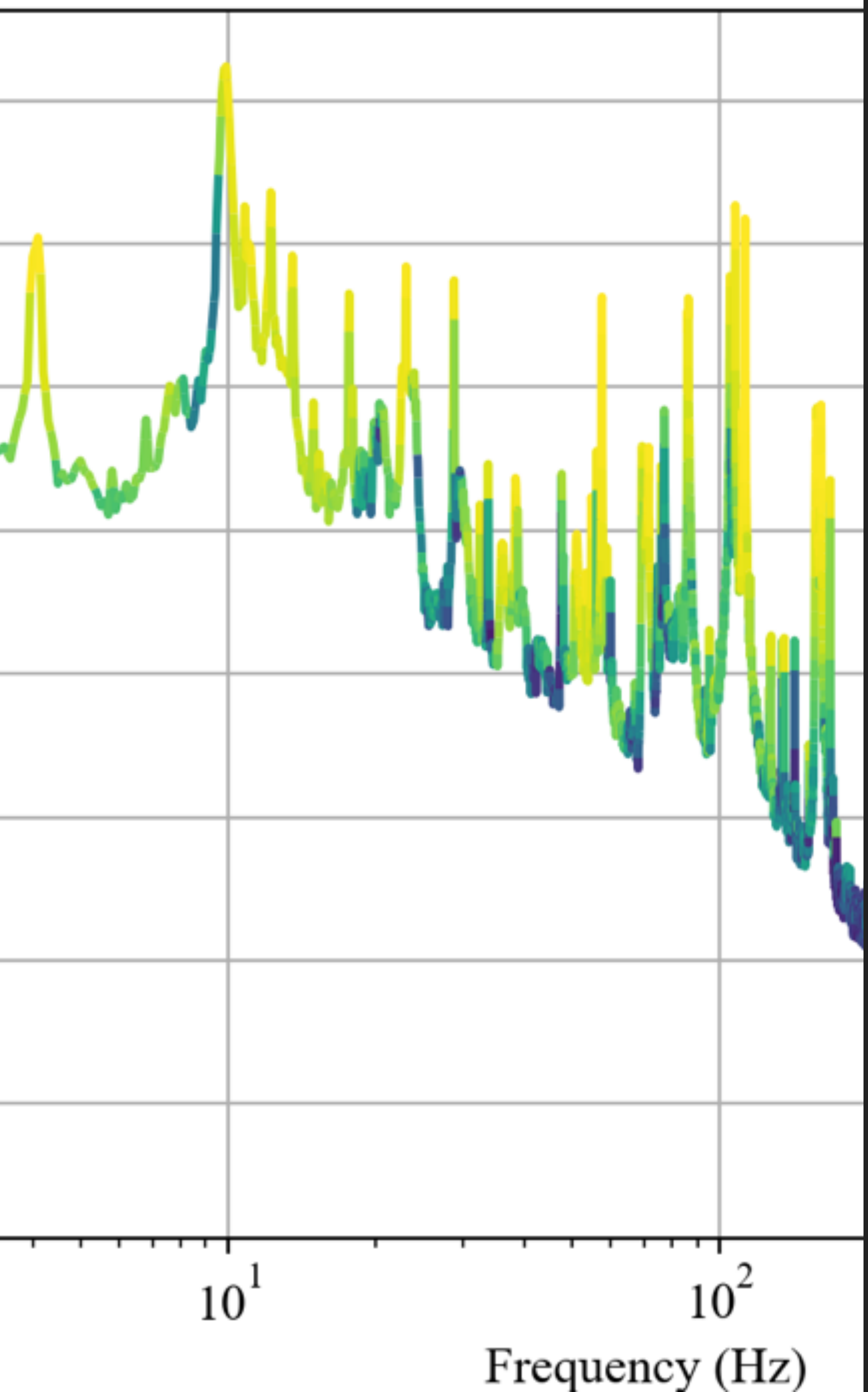


Superconducting solder capillary shield!

Magnetic Shielding

NOISE MITIGATION

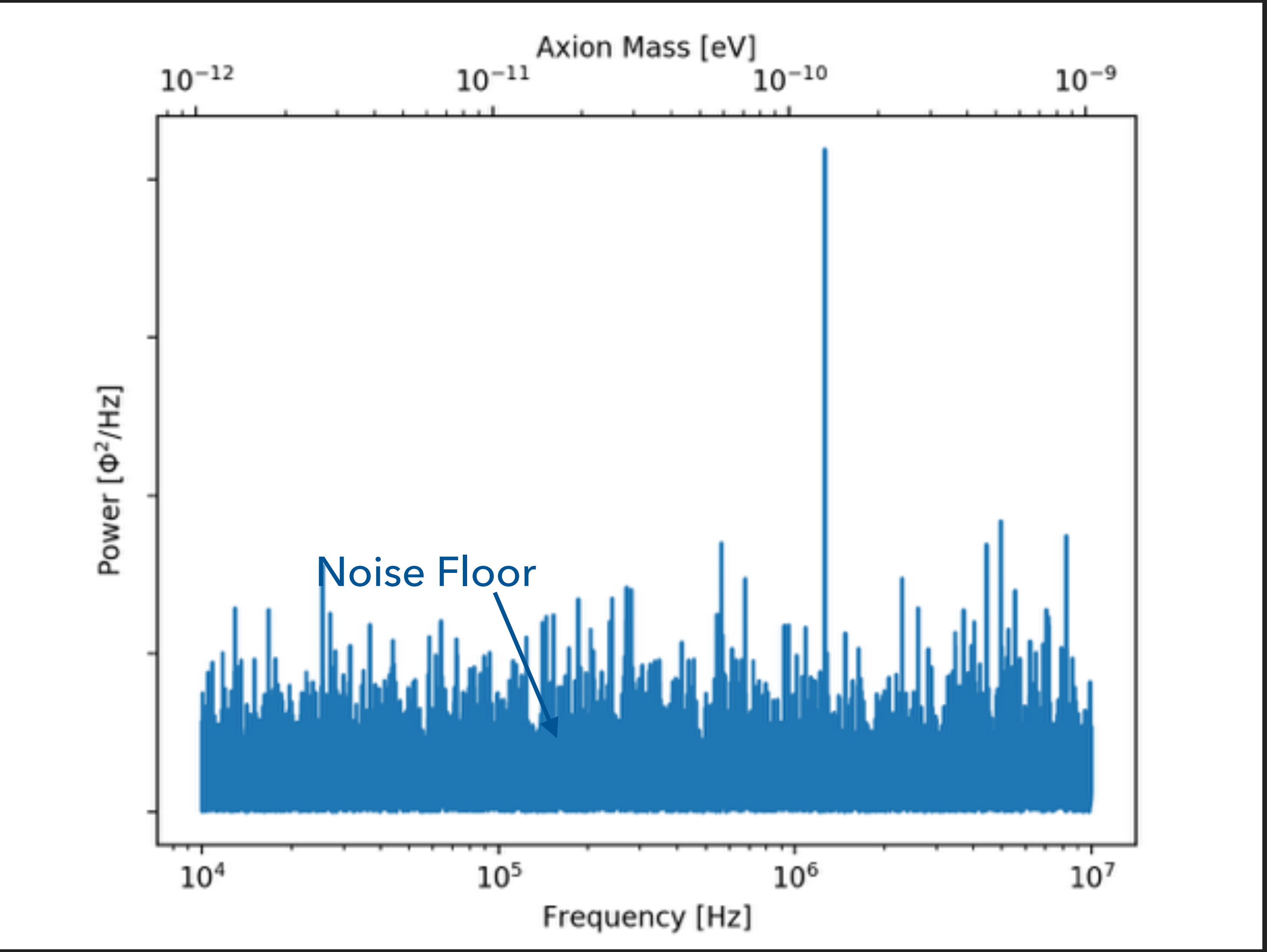
- Two layers of mu-metal shielding
- ~~Possibility of third layer later~~
- (Still need to measure the attenuation)



ABRACADABRA-10 CM

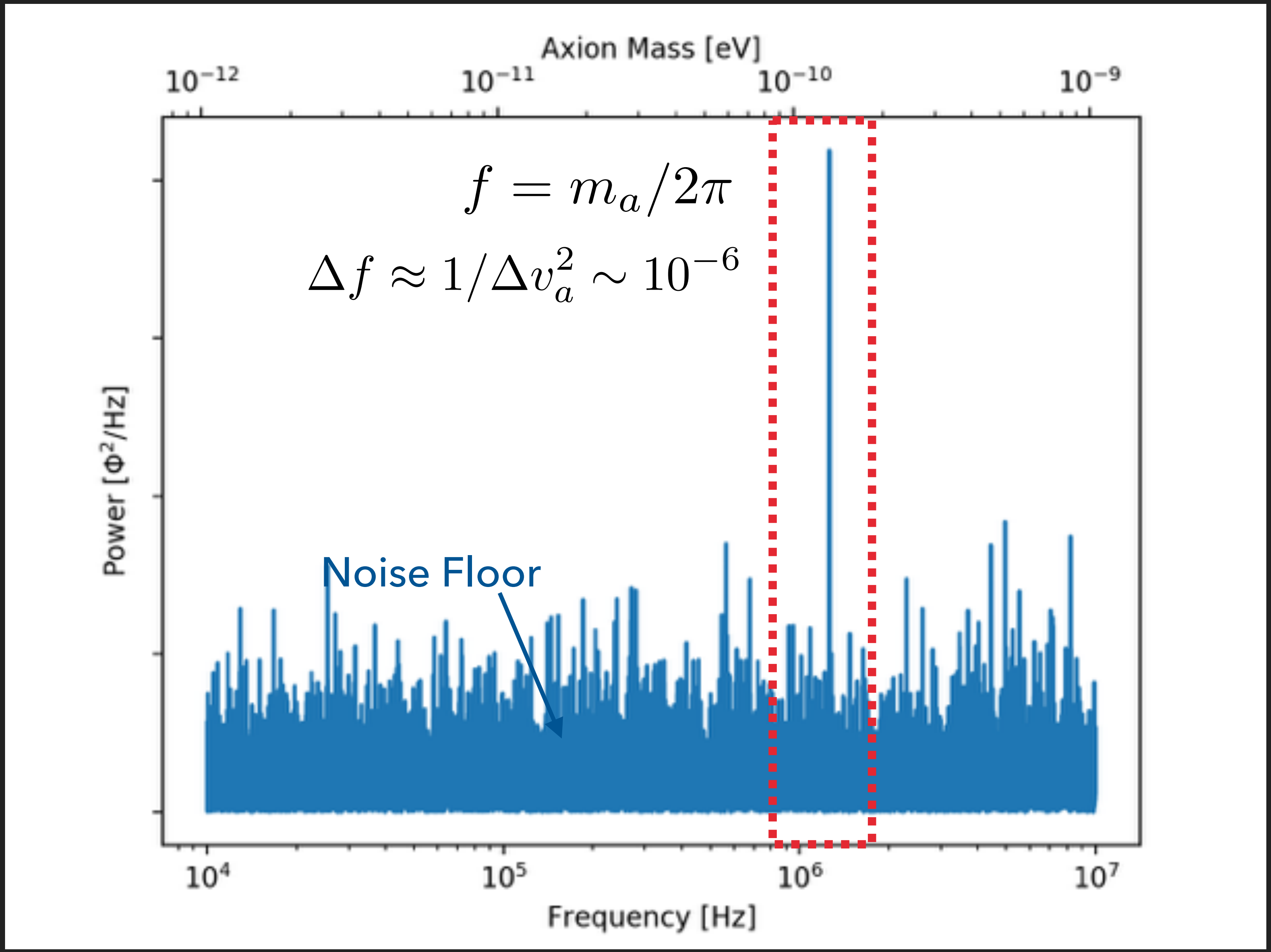
DATA TAKING AND PROCESSING

An Example Axion Signal



Broadband Readout

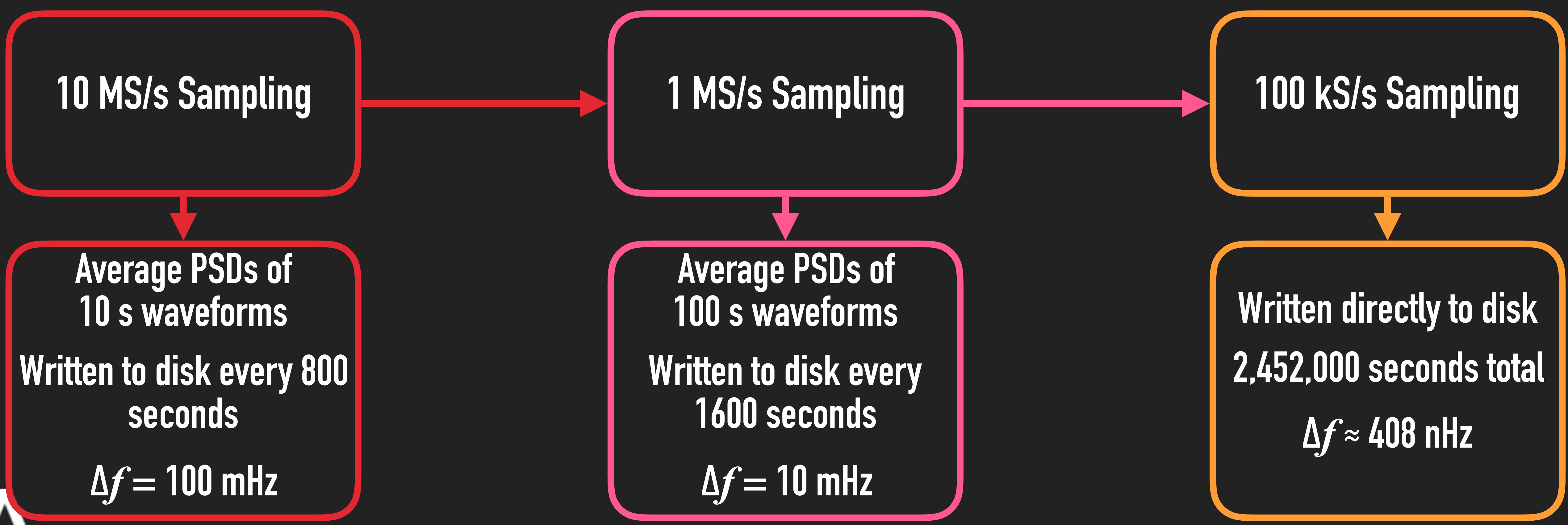
An Example Axion Signal



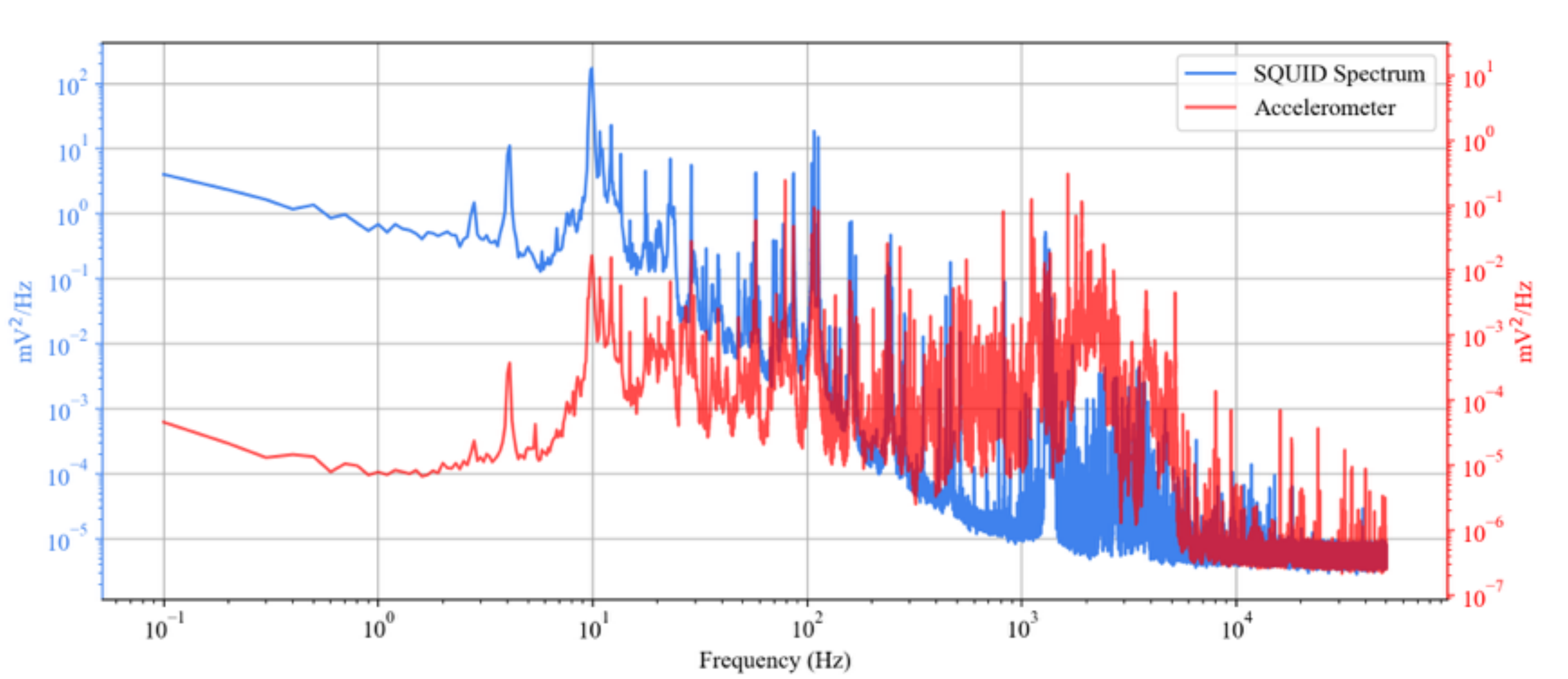
Broadband Readout

Broadband Data Collection Procedure

- Collected data continuous for 4 weeks from July - August
- Sampling at 10 MS/s continuously for 2.4×10^6 seconds (2.5T samples total)
- Digitizer locked to a Rb oscillator frequency standard
- Acquisition (currently) limited to 1 cpu and 8 TB max data size



Vibrational Noise (Magnet On)



*Accelerometer loses sensitivity above a few kHz

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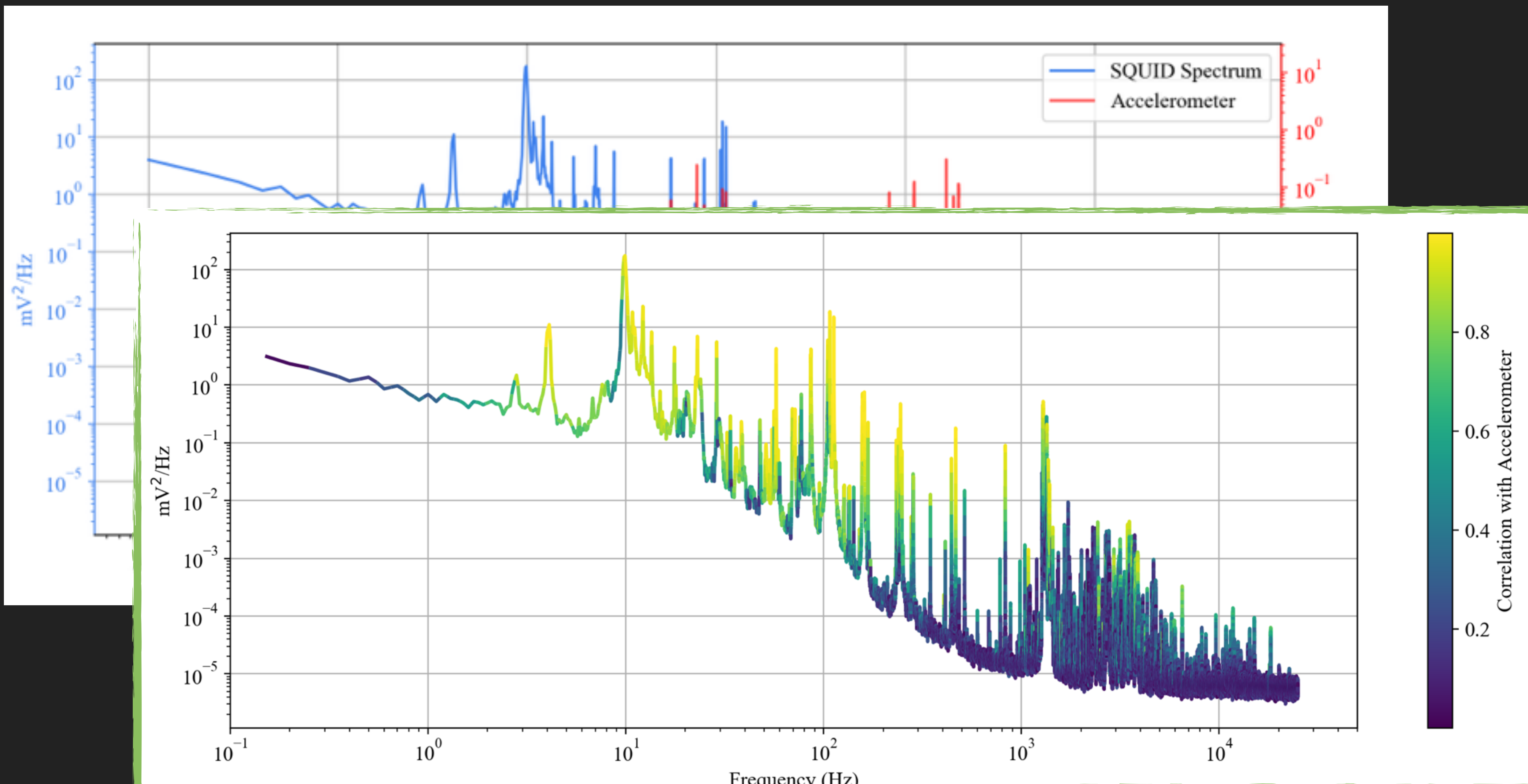

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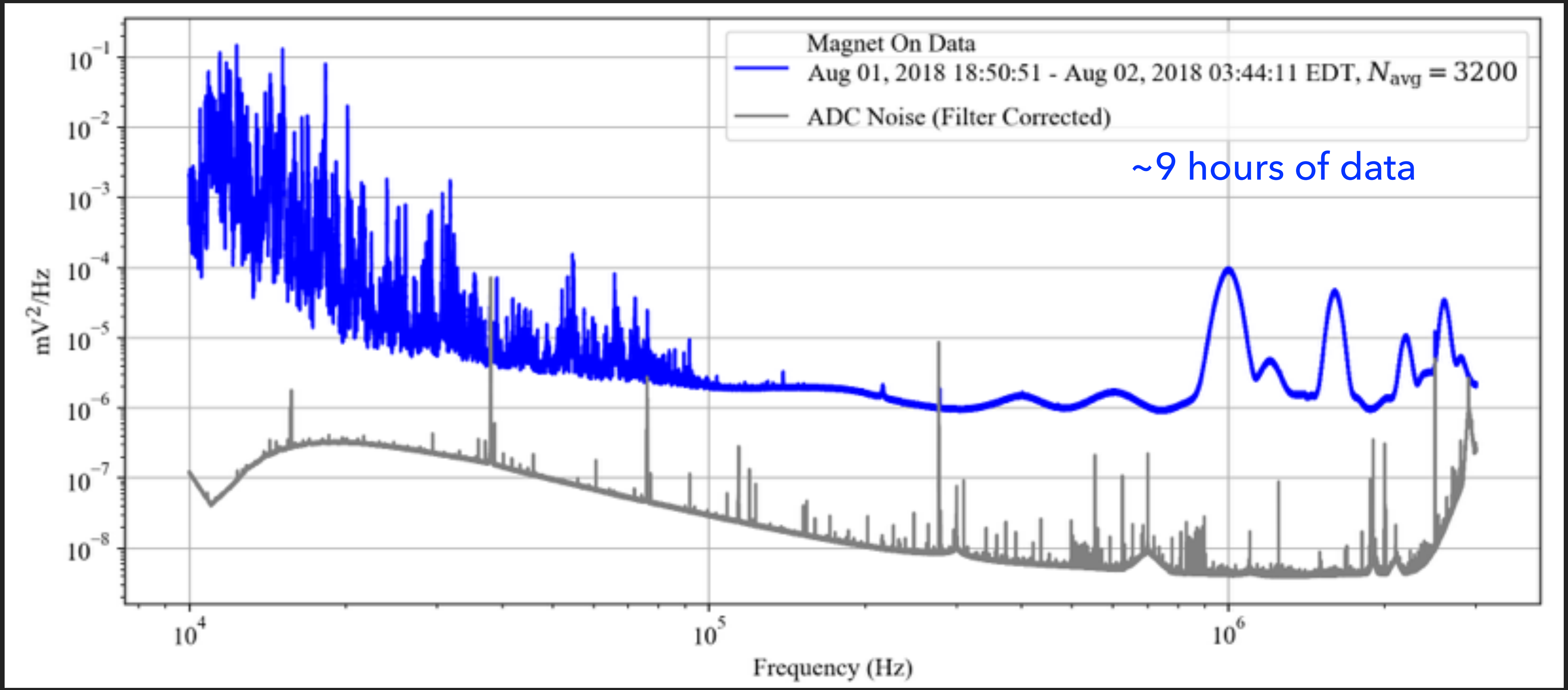
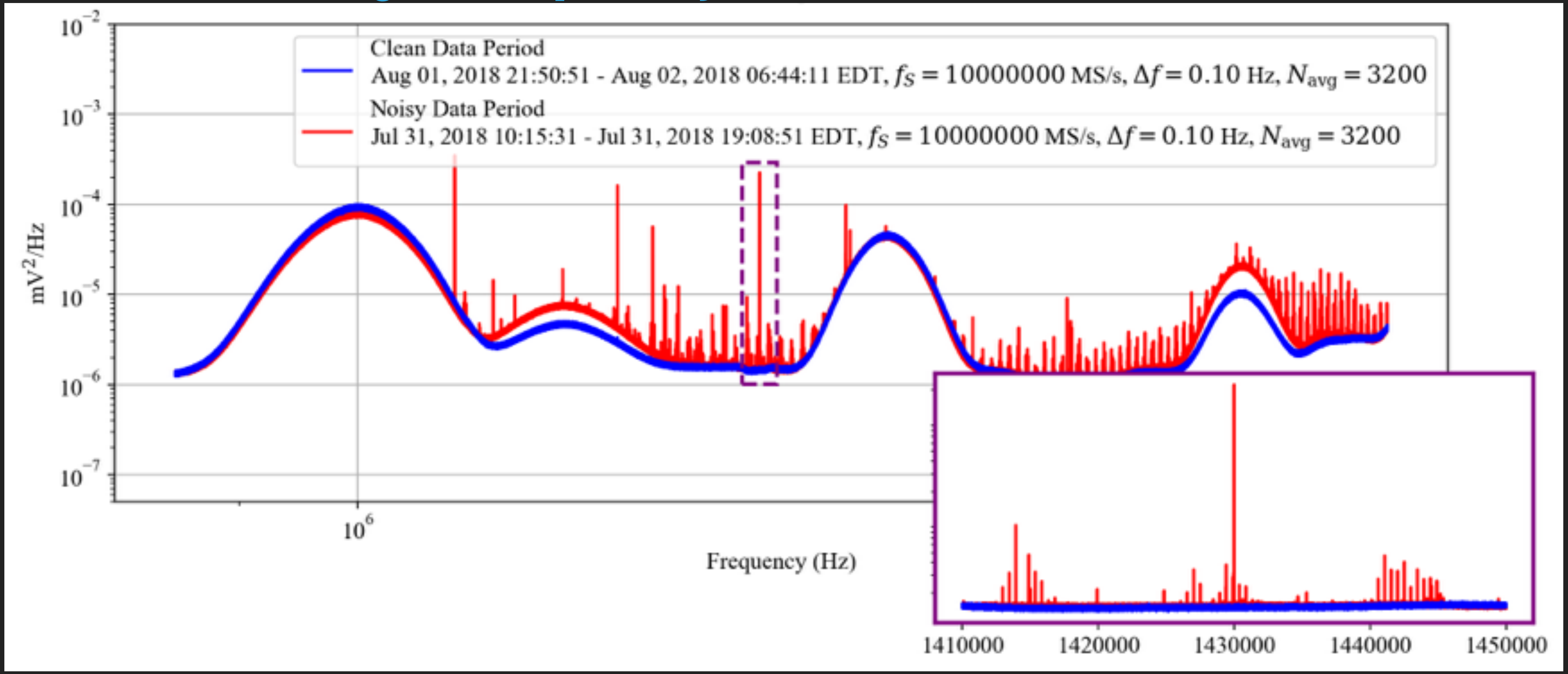
Example Spectrum



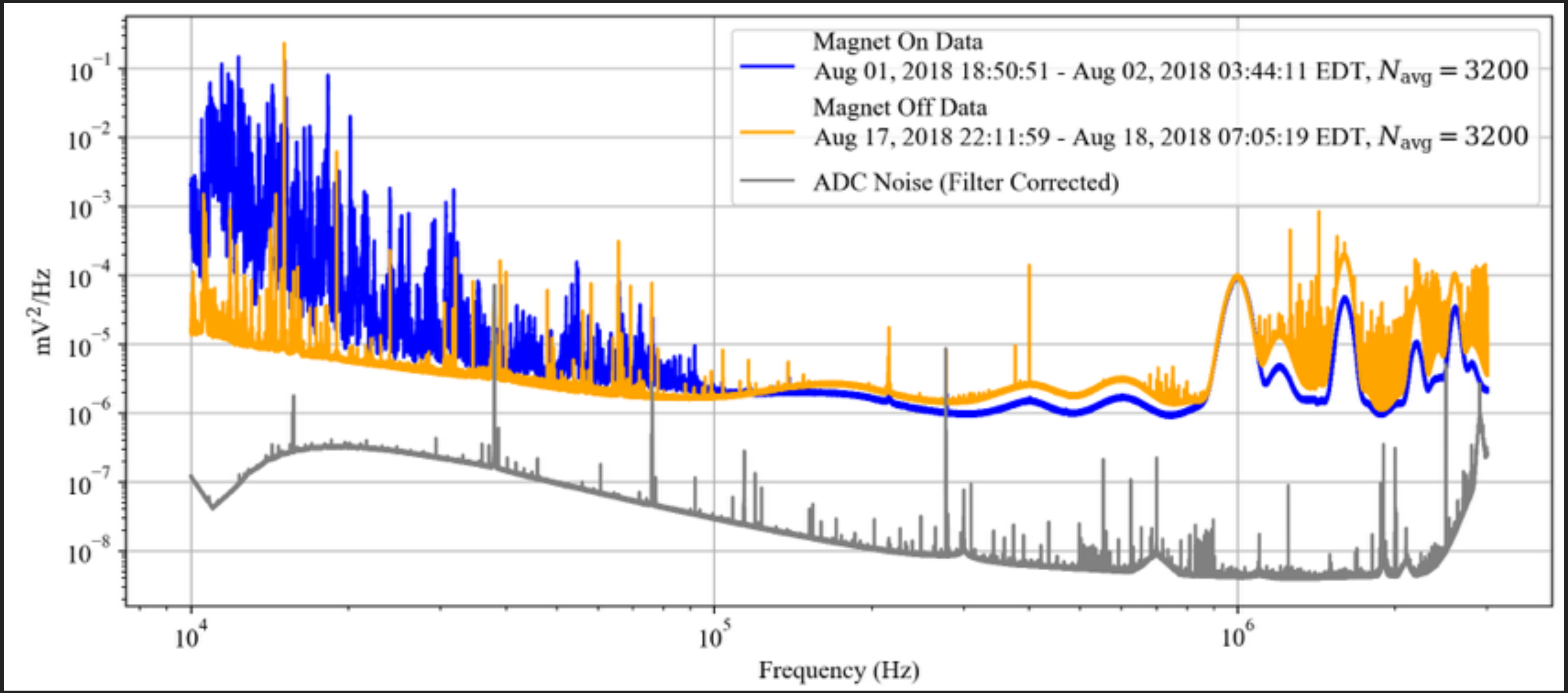
- Filter SQUID output through 10 kHz high-pass and 1.9MHz anti-aliasing filter
- Clean spectrum between 100 kHz - 850 kHz
- Spectrum from 850 kHz - 3 MHz has features of unknown origin, but can still be used for search

Transient Noise at High Frequency



- We see very narrow transient noise peaks
- Investigating the digitizer/DAQ computer as the source
- Plan is to veto a small fraction of the data

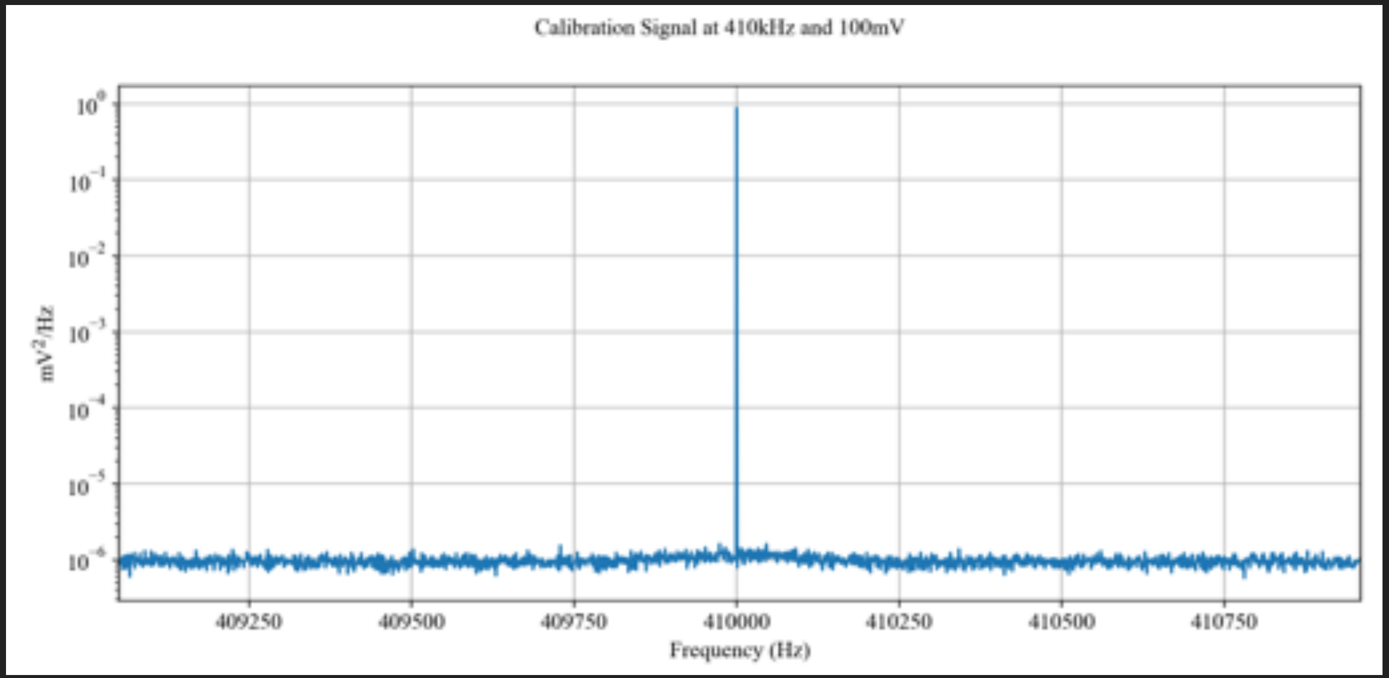
Magnet Off Data

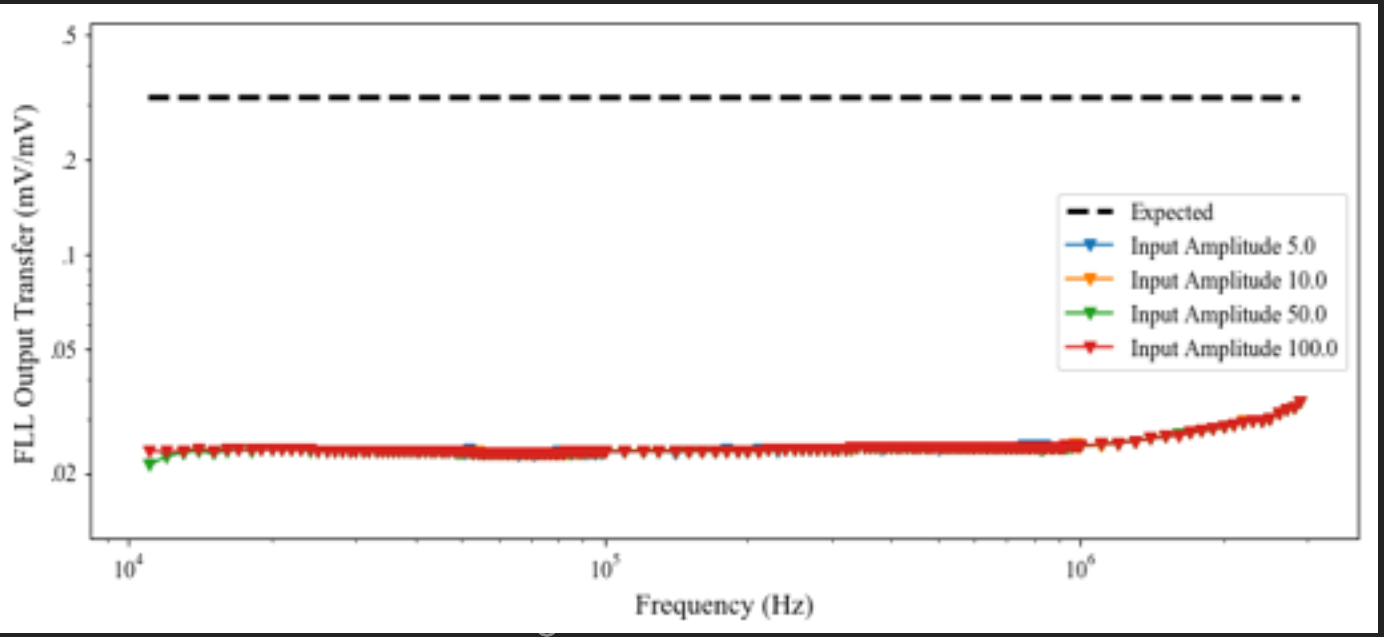


- MHz peaks present in the magnet off spectrum as well
- Transient noise also present
- Significantly lower noise background around 10kHz

Calibration

- Perform calibration by injecting current into the calibration loop measuring the spectrum
- Fine scan from 10 kHz - 3 MHz at multiple amplitudes
- Requires a total of ~90 dB of attenuation to get "reasonable" size signals
- Currently seeing a factor of ~15 disagreement between the data and expectation





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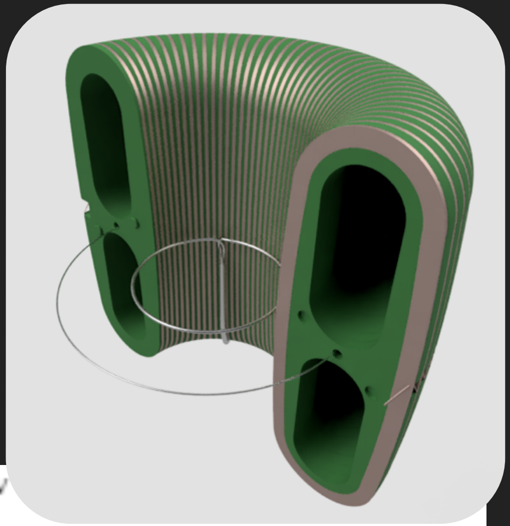

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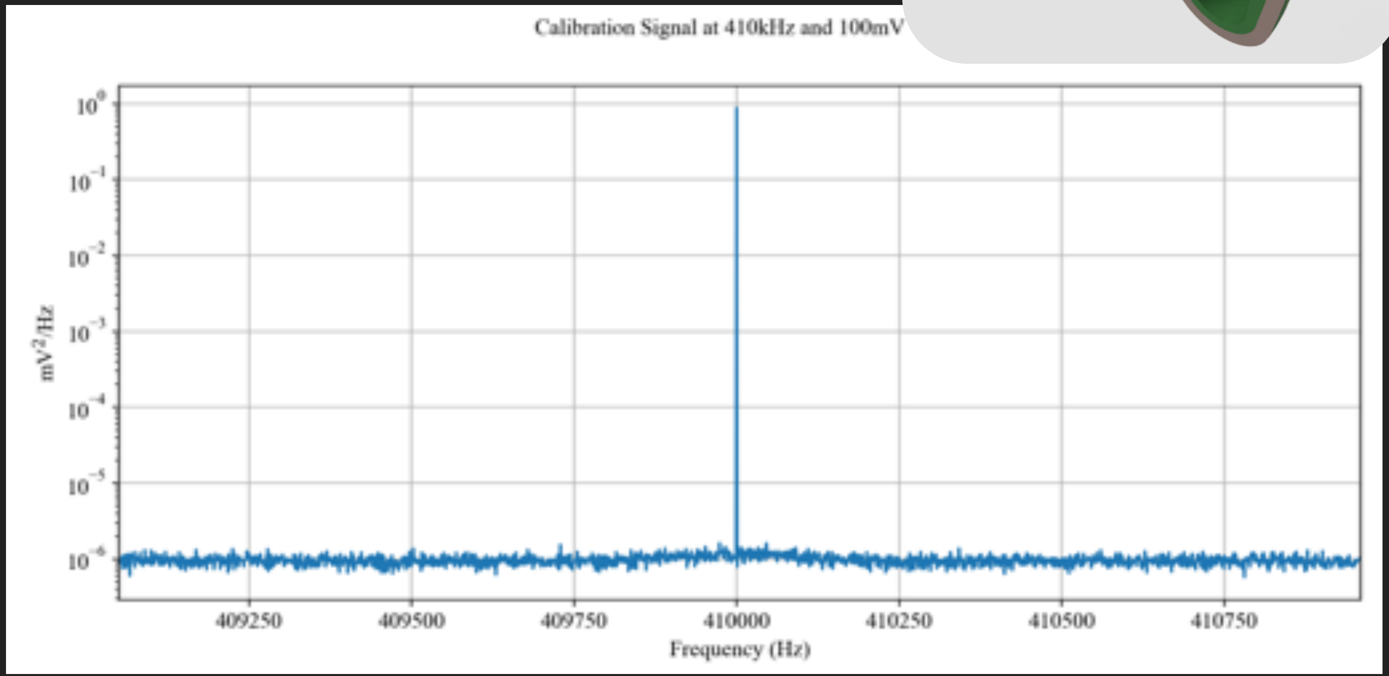
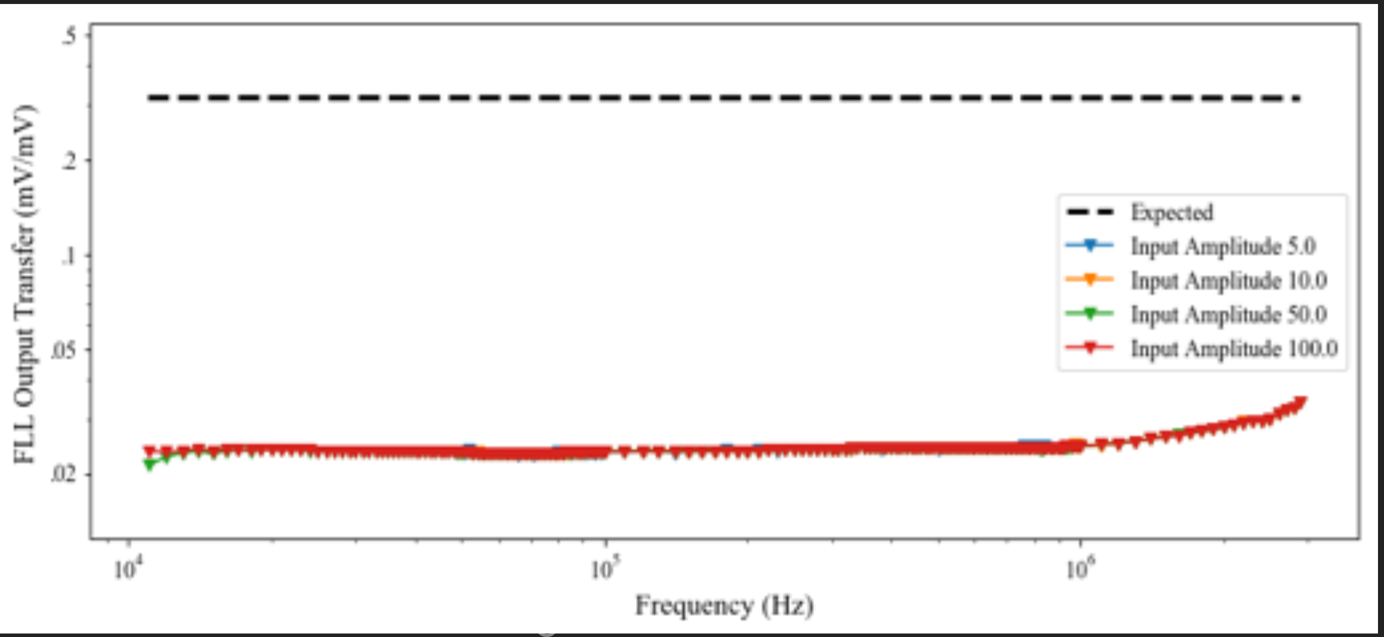
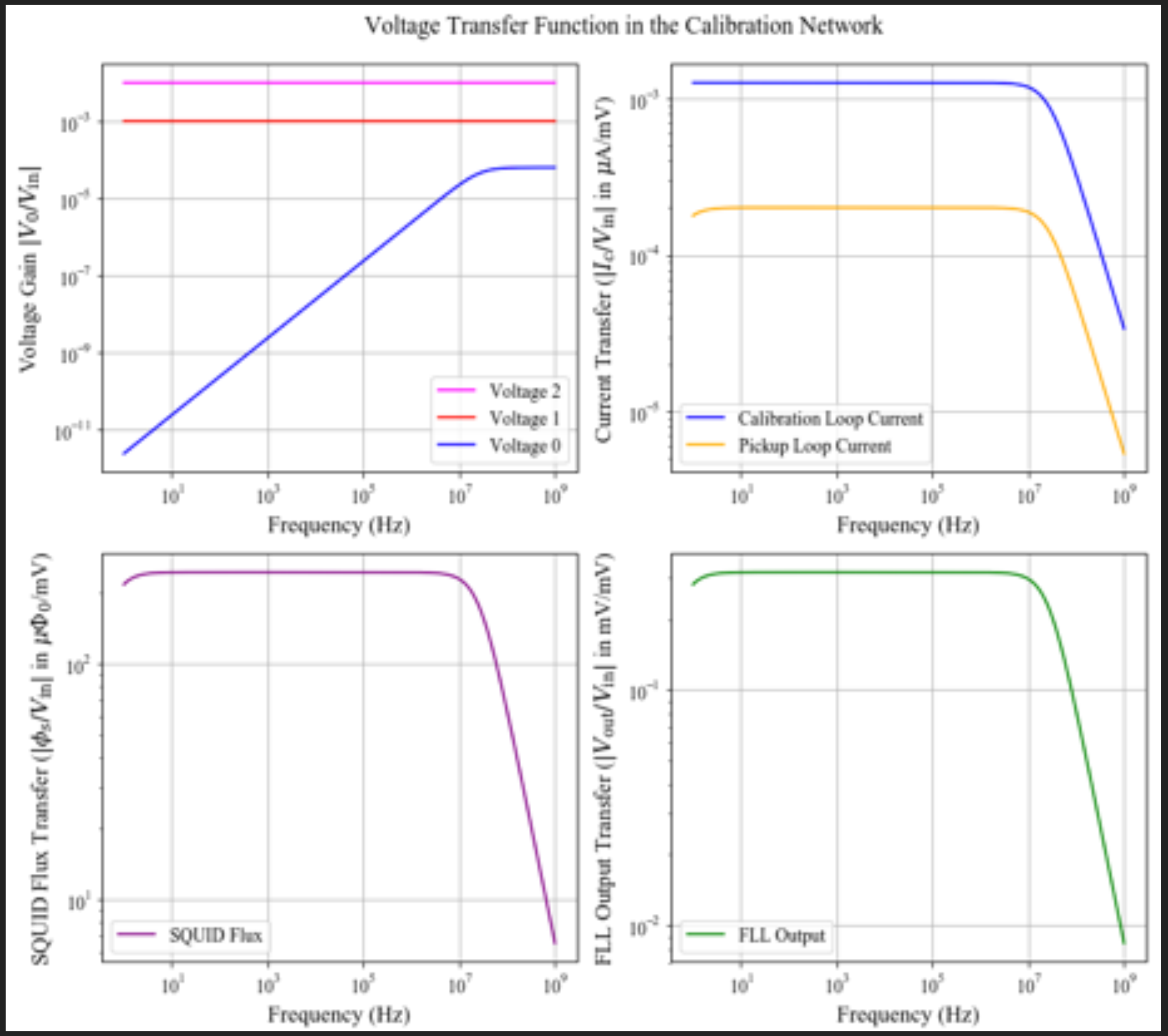
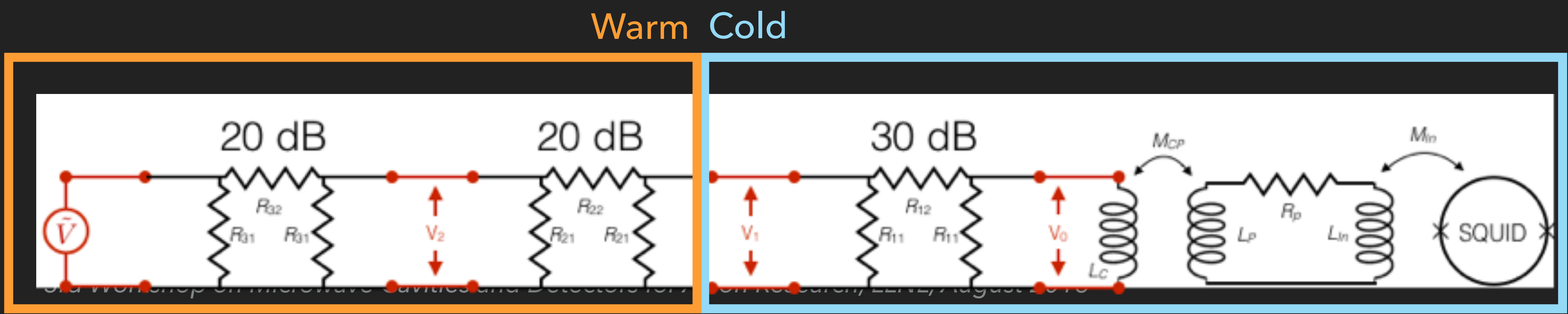




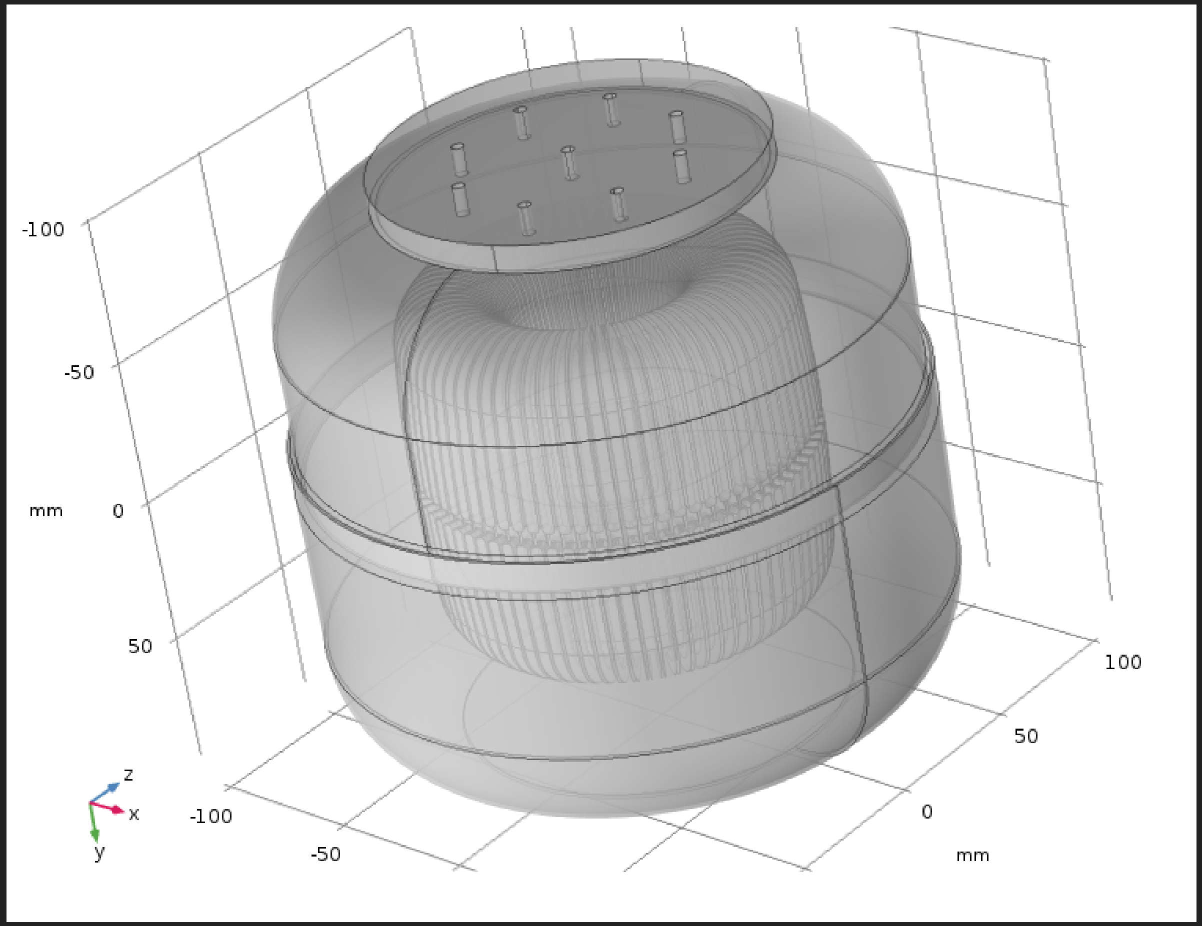
Calibration Network

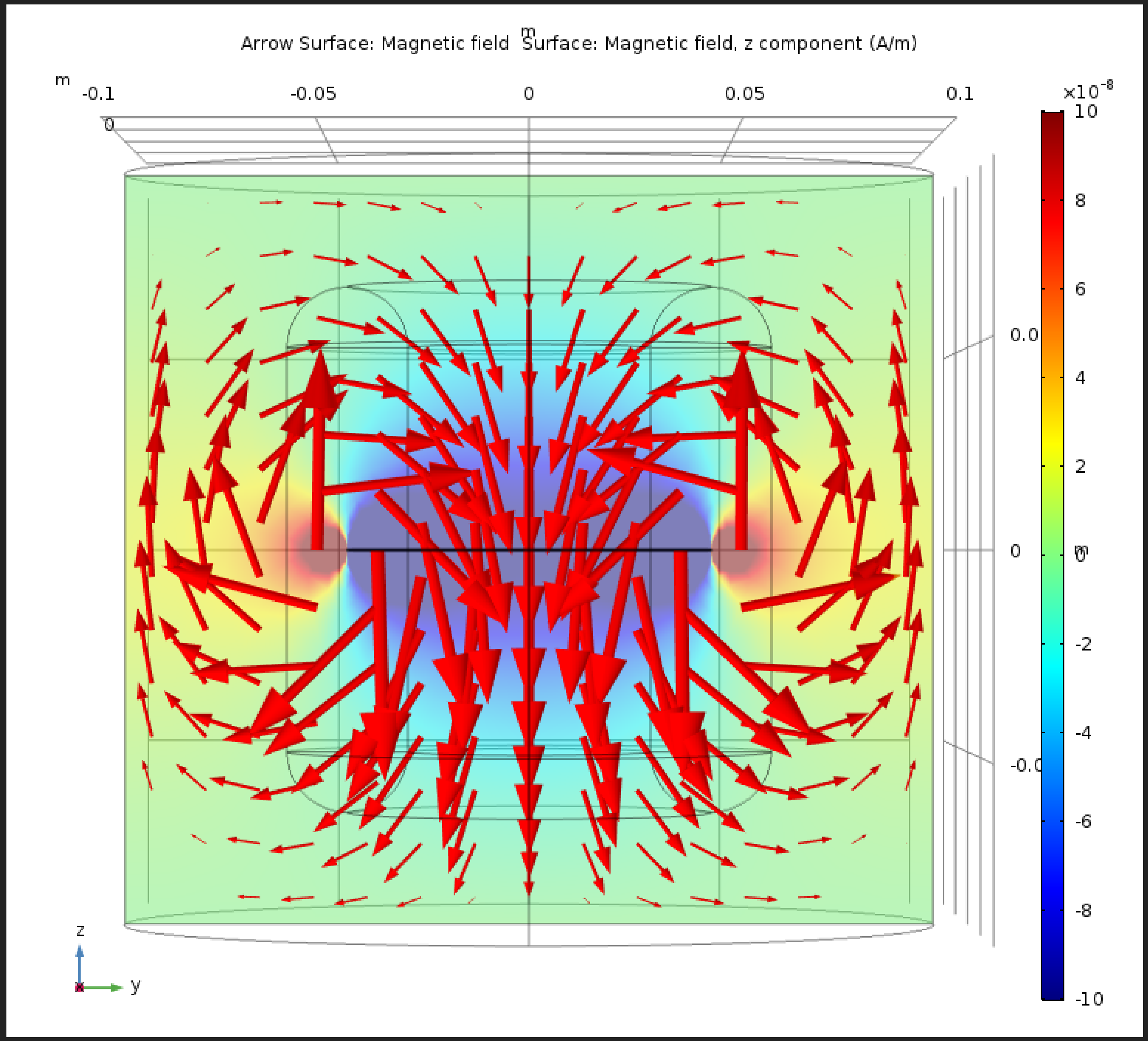
- ✓ 60 dB of warm attenuation
- ✓ Readout circuit
- ✓ SQUID noise is approximately as expected
- ✓ Parasitic resistance in the circuit
- ▸ Need to check cold attenuator (3 K)
- ▸ Flux coupling?





Building Simulations in COMSOL





Mutual Inductance (M_{CP})	
	SC Boundary
Cylinder	45.8 nH
Sphere	47.8 nH
ABRA	46.0 nH
Calculation	48.8 nH

*DC calculation. Shield + wire loops only.

Data Analysis Approach

- Write down a likelihood function for our averaged spectra, $\bar{S}^k_{\Phi\Phi}$

$$\mathcal{L}(x|\theta) = \prod_{k=1}^{N} \frac{N_{\rm Avg}}{(N_{\rm Avg}-1)!} \frac{(\bar{S}^k_{\Phi\Phi})^{N_{\rm Avg}-1}}{\lambda_k^{N_{\rm Avg}}} e^{N_{\rm Avg}\bar{S}^k_{\Phi\Phi}/\lambda_k}$$

- Calculate a test statistic comparing the likelihood ratio of the background + signal hypothesis (H_1) vs the background only hypothesis (H_0)

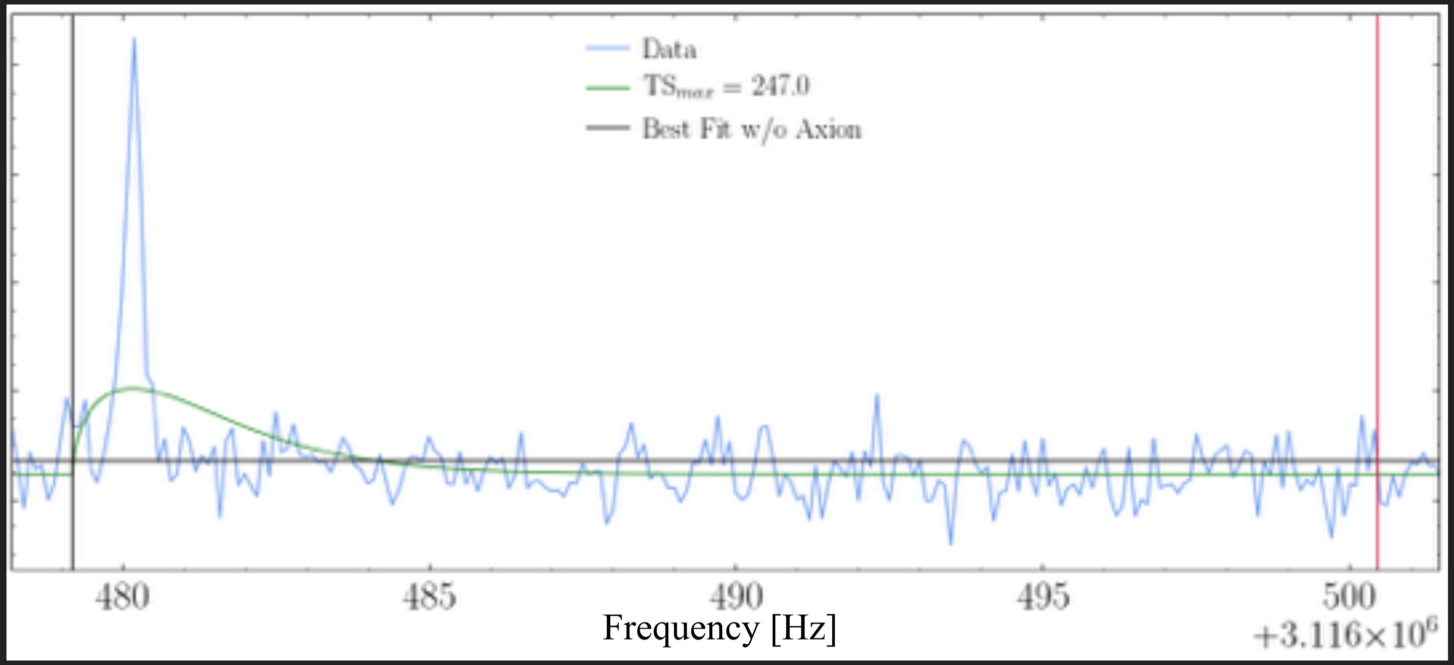
$$\Theta(m_a, g_{a\gamma\gamma}) = 2\left[\log\mathcal{L}(d|g_{a\gamma\gamma}, m_a, \hat{\theta}_B) - \log\mathcal{L}(d|g_{a\gamma\gamma}=0, m_a, \hat{\hat{\theta}}_B)\right]$$

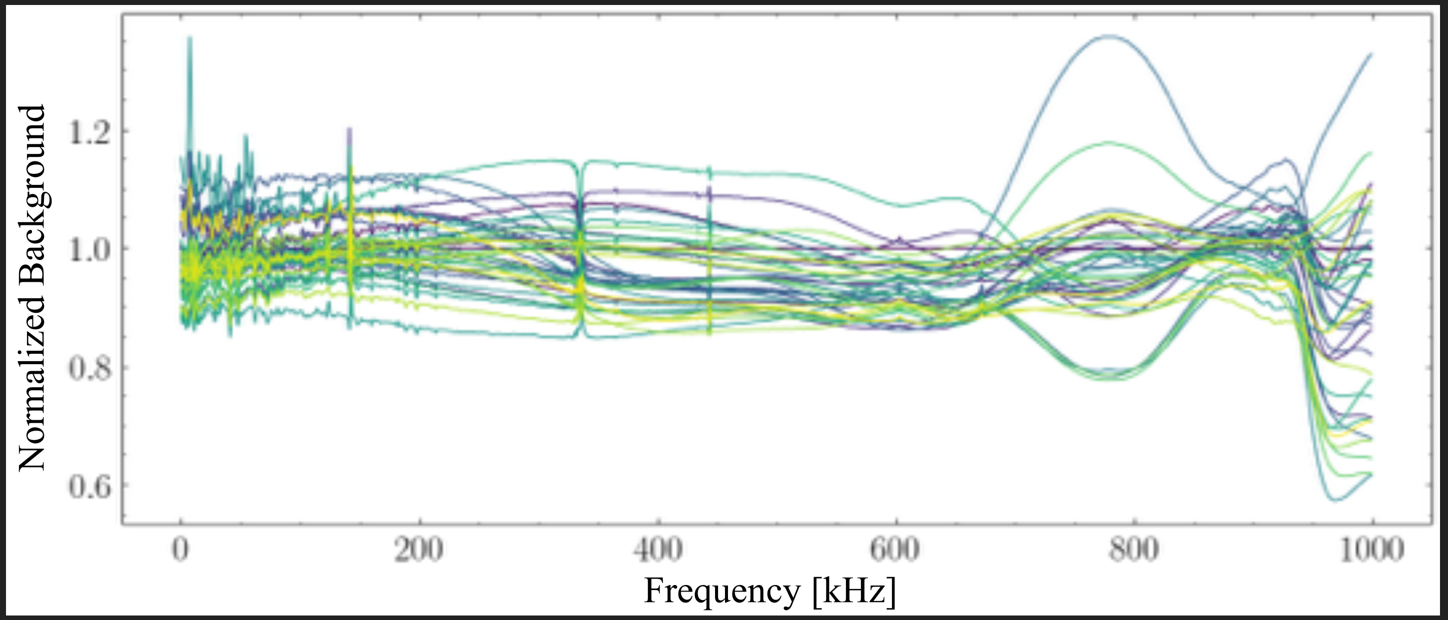
- 90% limit at where $\Theta < 2.71$ (frequentist limit)
- 5 sigma detection threshold set by size of search range to account for "look elsewhere effect"

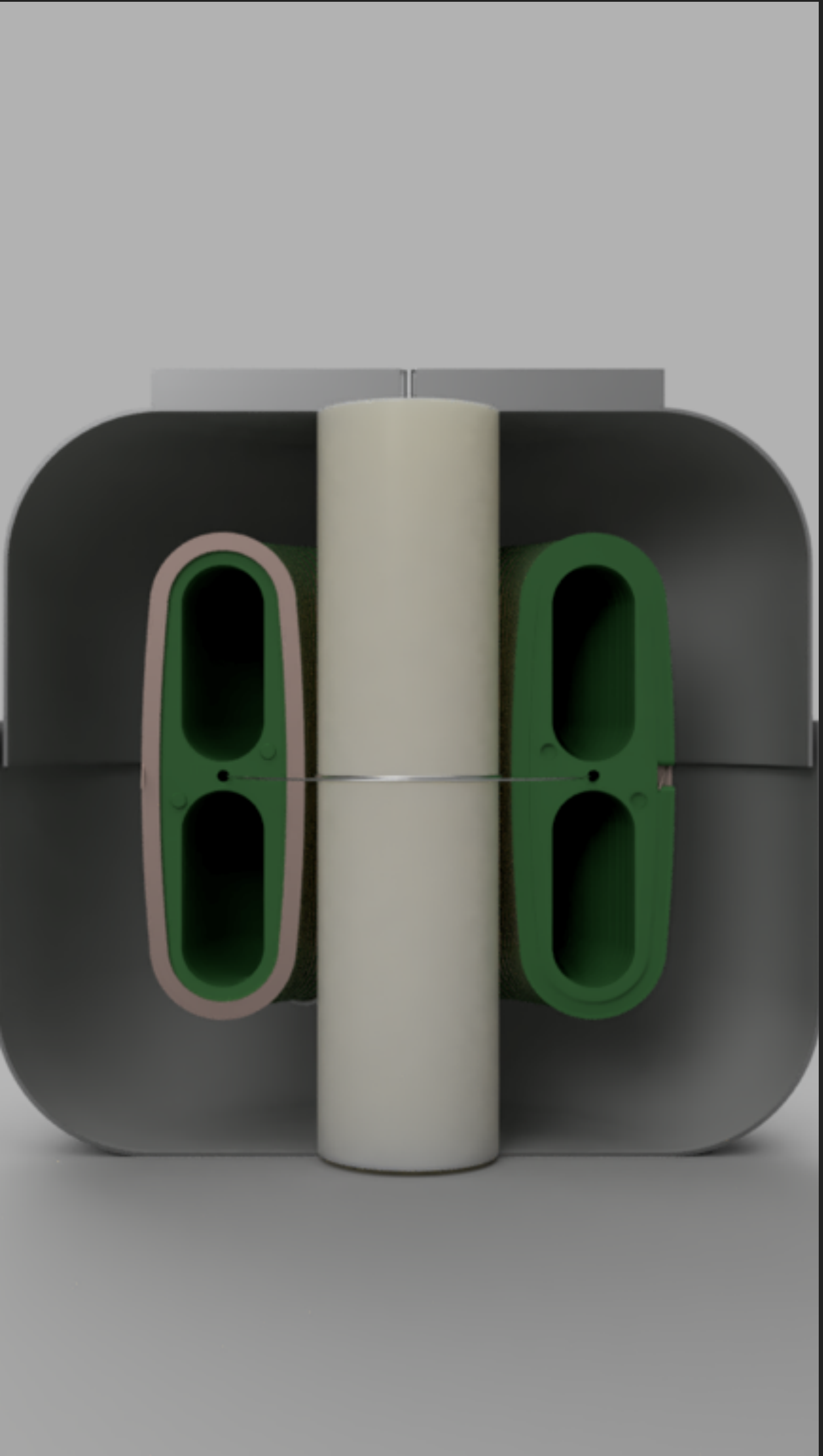
Based on Foster, Rodd, Safdi Phys. Rev. D 97, 123006 (2018)

Data Analysis Behavior

- Scan the range 100 kHz - 3 MHz
- Fit the 10 MS/s spectrum down to ~200 kHz and the 1 MS/s below
- Time resolution of 800s (10 MS/s) and 1600s (1 MS/s)
- ~50M frequency points across ~3000 spectra to search (can be parallelized)
- We see movement of the background by ~20% (40% in these peaks)



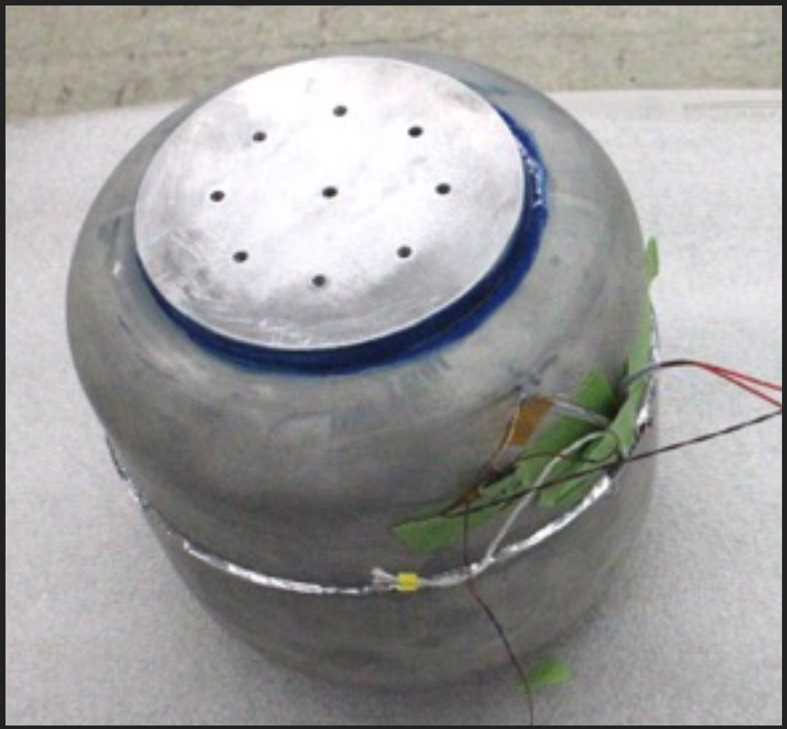




NEXT STEPS

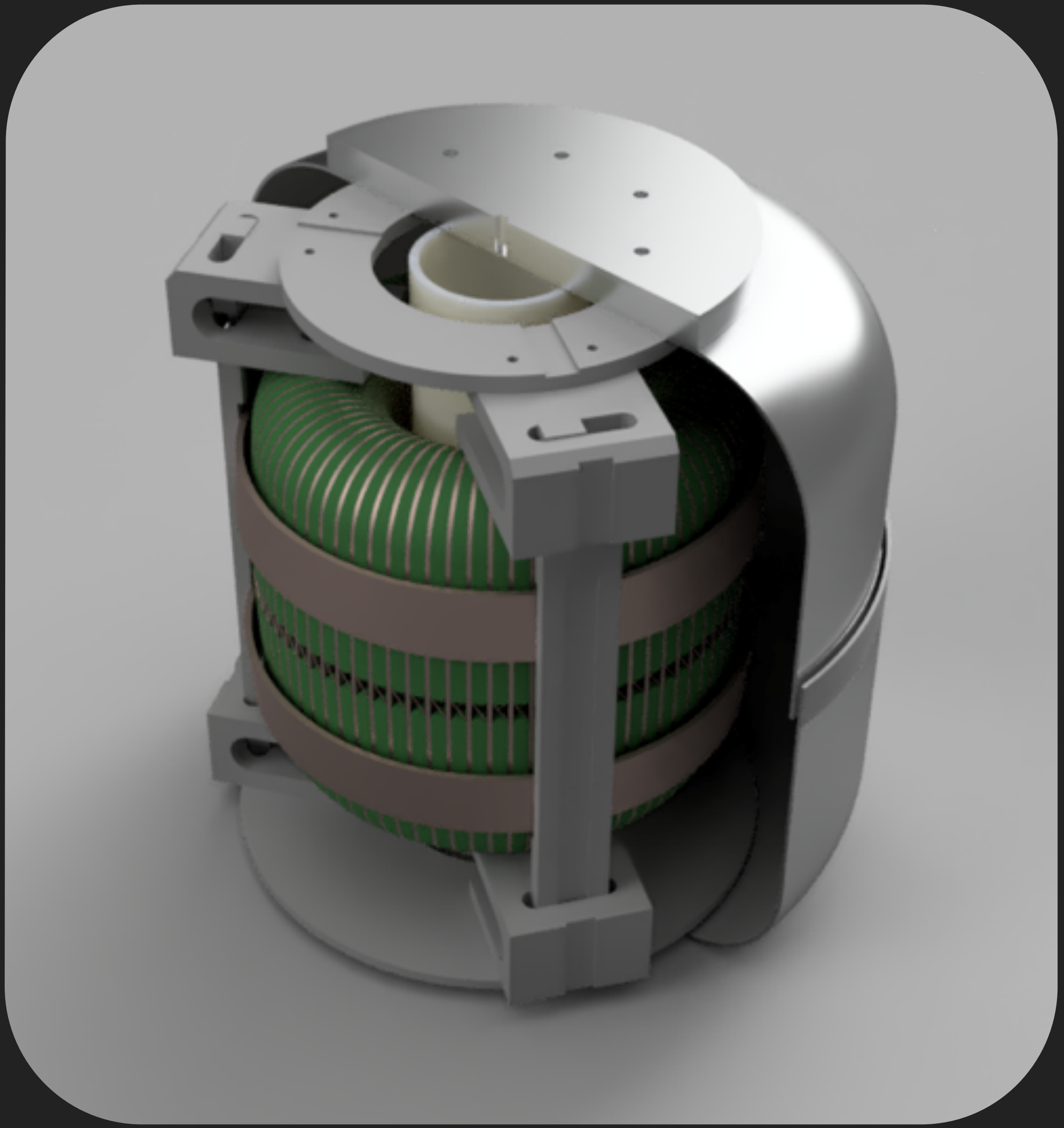
Additional Measurements to Take

- Tests with external antennae
- Backgrounds above and below transition temperature of the shield
- Parasitic resistance in the pickup loop
- Stray fields from the magnet
- Magnetless setup?
- Open to suggestions



Looking Towards Resonator Readout

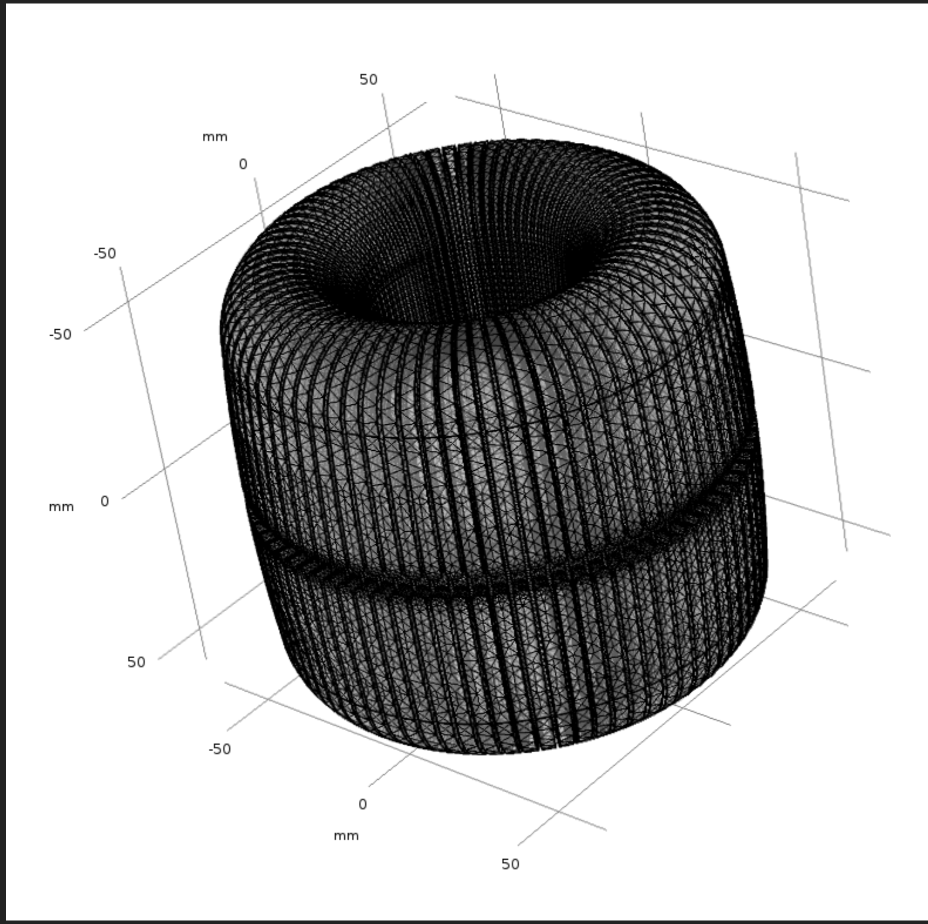
- There are a lot of materials inside the superconducting shields
  - Extra Johnson noise sources
  - Dielectric materials cause dissipation and limit Q factors
  - Stray fields from wiring
- Copper wiring is difficult to remove
- Alternatives to thermalizing magnet



Building Simulations in COMSOL

- Simulation of full ABRA-10 cm model
  - More computing power, better meshing, etc

- Move from DC to AC
  - Understanding magnetic susceptibility vs frequency
  - Dielectric loss vs frequency
  - Material Properties



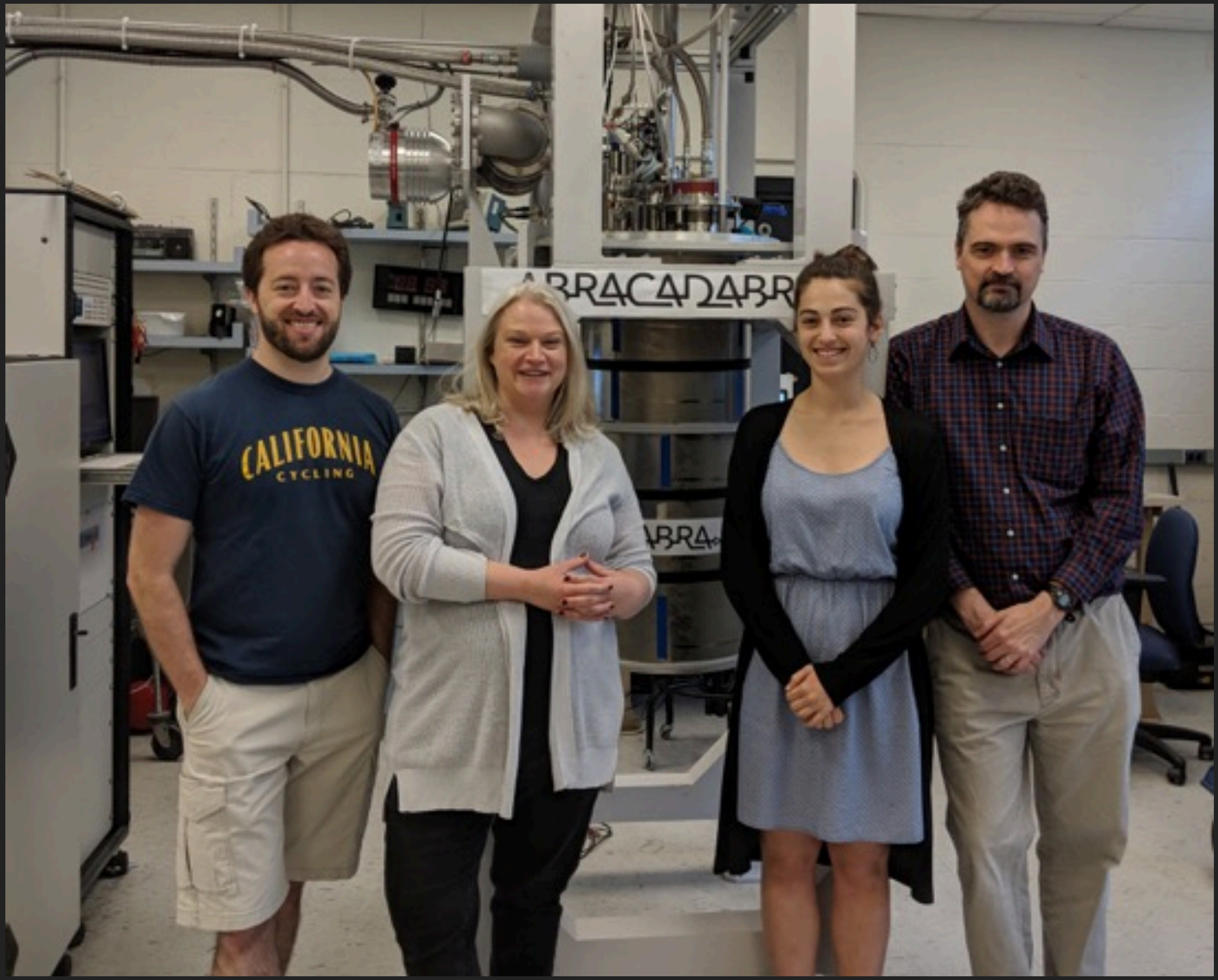
Summary

- We have built and operated a 10 cm scale ABRACADABRA prototype
- Demonstrated ability to do broadband readout and data analysis at frequencies < 5MHz
- Have a first measurement of the relevant background sources in the frequency range of interest
- Limits and paper forthcoming

- ABRA-10 cm will transition to a test bench for a future more sensitive detector
- Putting together a proposal for a ~1 m scale experiment (ABRACADABRA-75 cm)

Any additional suggestions for measurements welcome!

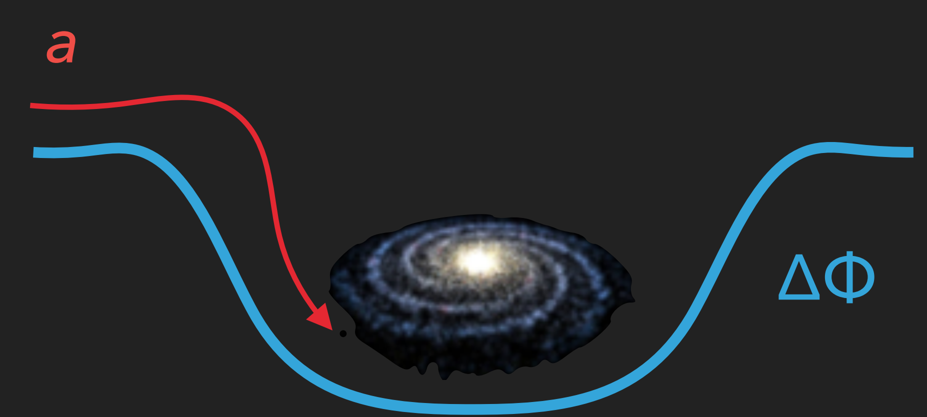
ABRACADABRA



Thank you for your attention!

Backup Slides

An Axion Signal

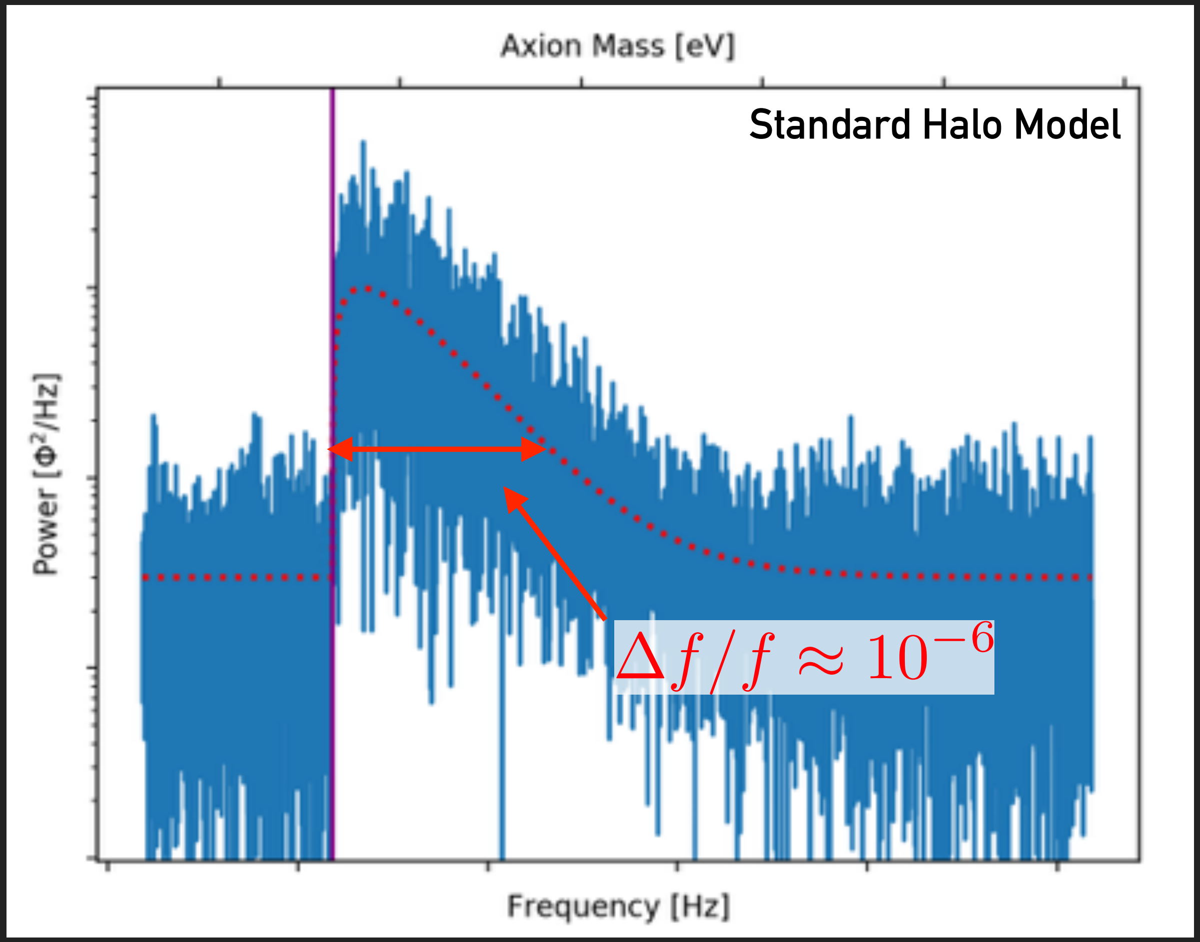


- The coherence time for an axion signal is given by

$$\tau_c \approx \frac{\lambda_D}{v} \approx \frac{1}{m_a v^2}$$

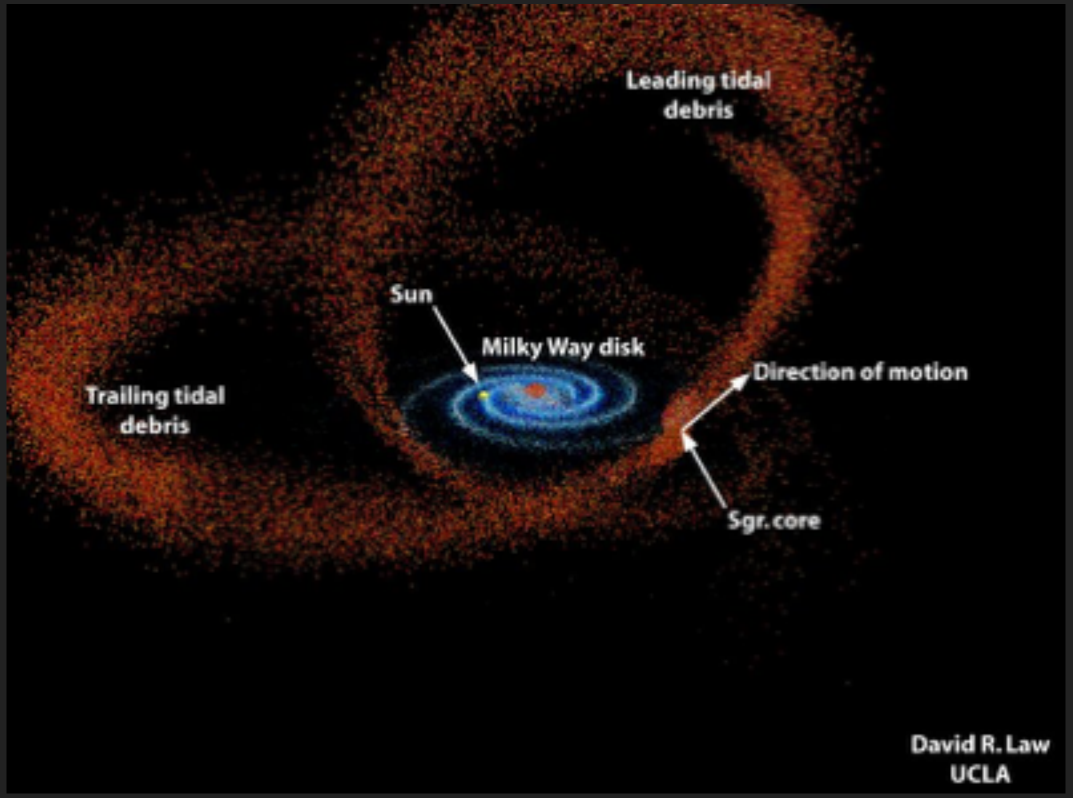
- And leads to a spread in the peak of

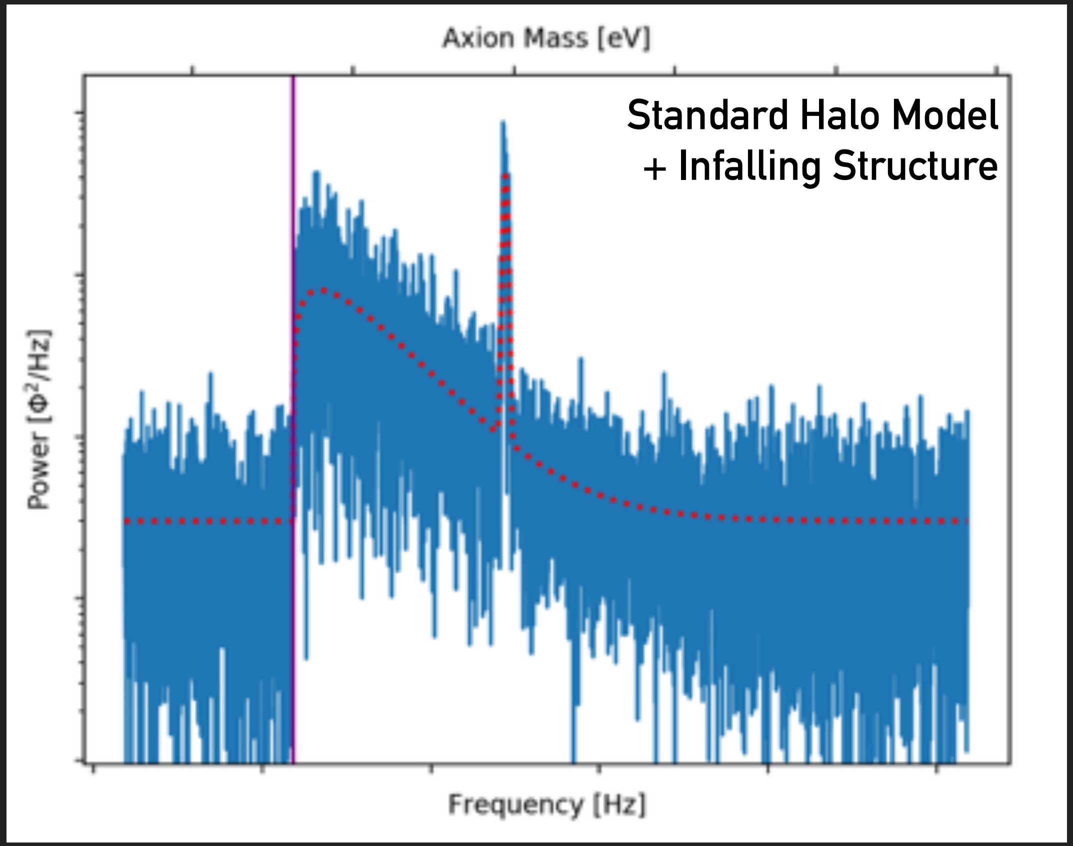
$$\Delta f/f \sim 1/v^2 \approx 10^{-6}$$



An Axion Signal

- Another (fun) possibility is the presence of substructure within the Dark Matter Halo
- If the velocity distribution of this substructure is much smaller, you can have coherence times much much larger.
- Opens the possibility of Axion astrophysics!
- See Foster, Rodd, Safdi 2017 (arXiv:1711.10489)

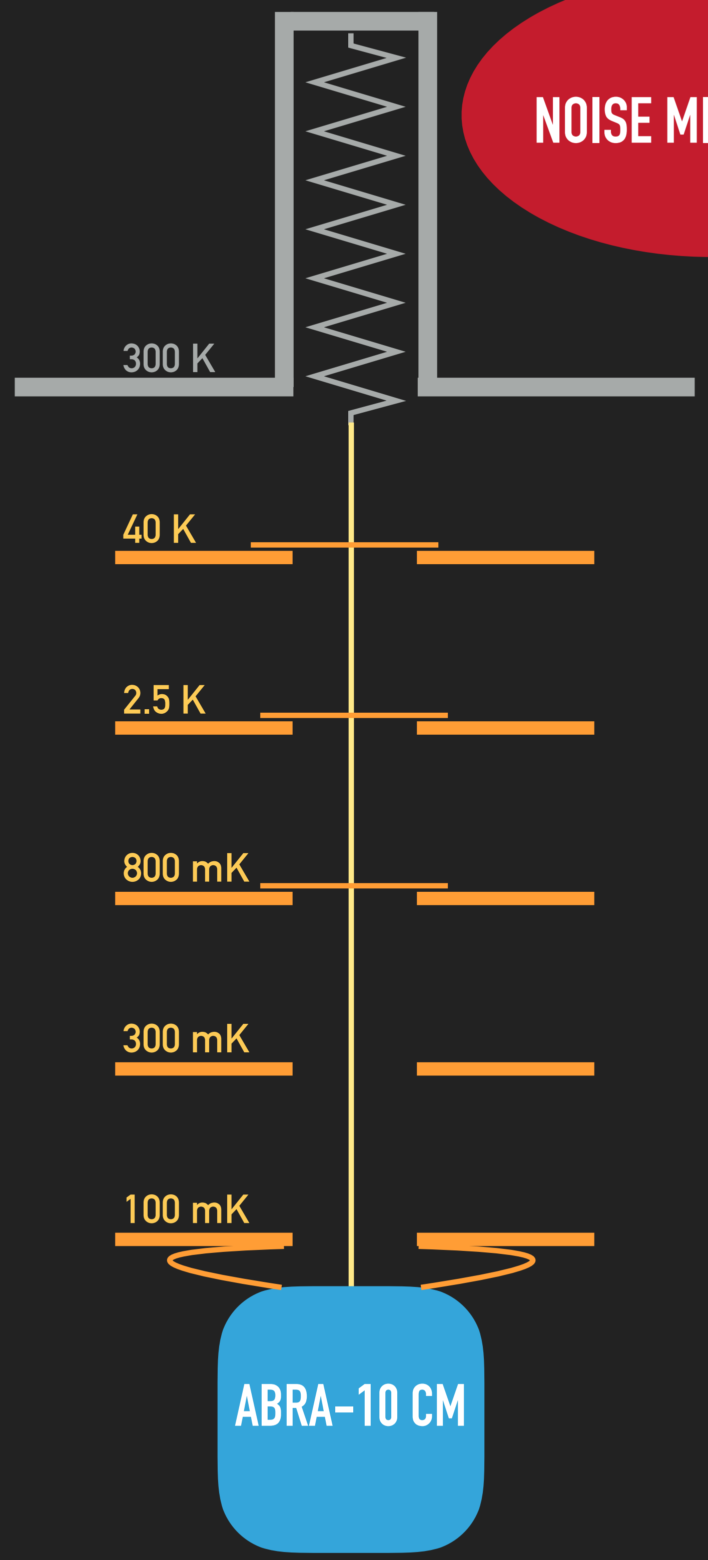




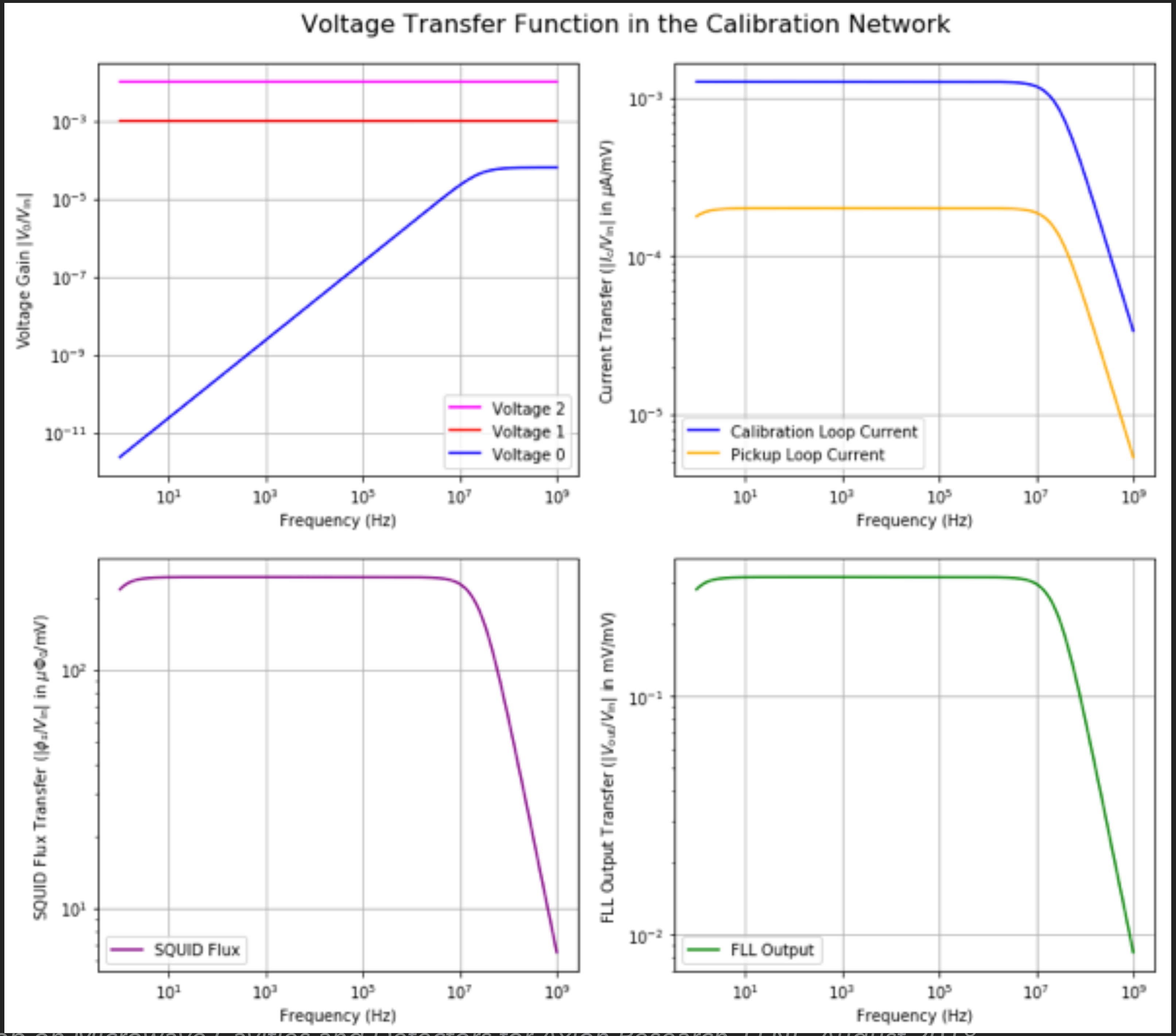
Suspension System

- 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

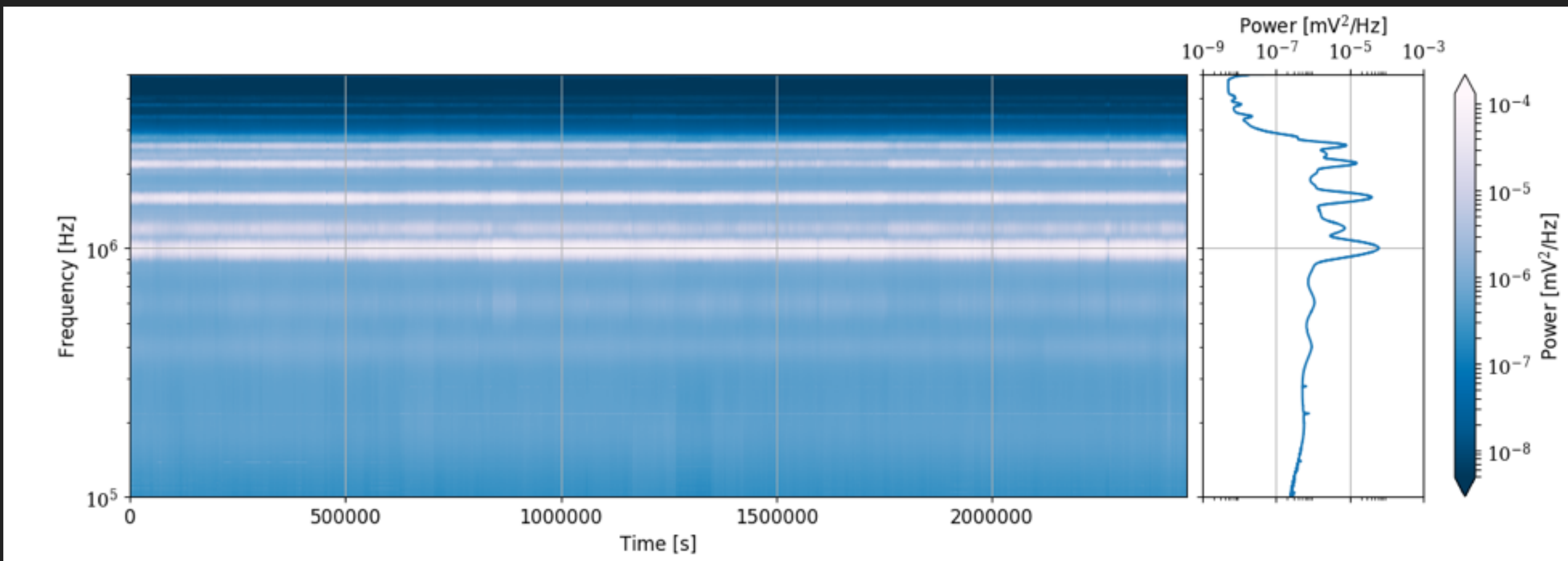
NOISE MITIGATION



Calibration Loop Transfer Functions

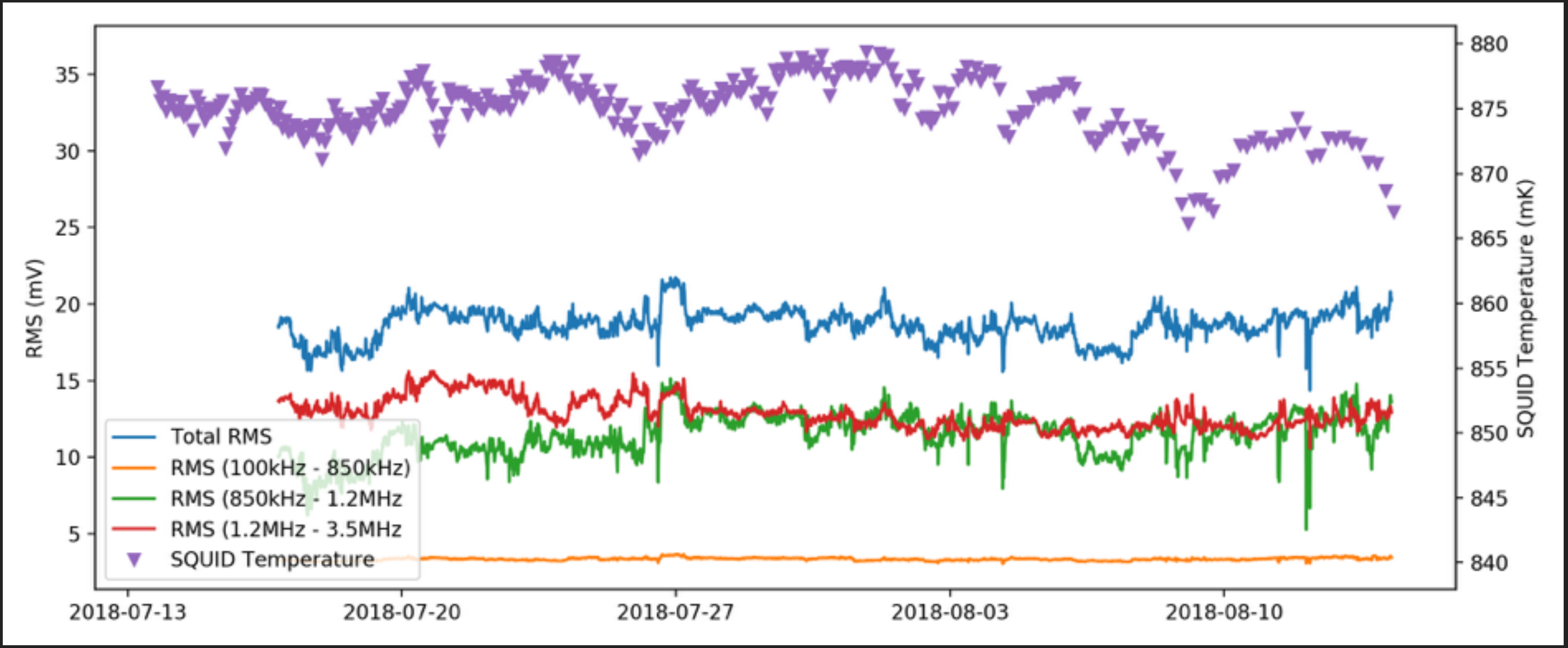


Stability



Power [mV²/Hz]
10⁻⁹
10⁻⁷
10⁻⁵
10⁻³
Frequency [Hz]
10⁶
10⁵
0
500000
1000000
1500000
2000000
Time [s]
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
Power [mV²/Hz]

Temperature Effects?



Nothing obvious..