The Beautiful City of

SEATTLE

Jonathan Ouellet

Massachusetts Institute of Technology

November 27, 2018

SEARCHING FOR SUB-μeV

AXION DARK MATTER

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Searching for Axion Dark Matter through EM Coupling

$$\mathcal{L}_{\mathrm{QED+a}} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}g_{a\gamma\gamma}aF^{\mu\nu}\tilde{F}_{\mu\nu}$$

Quantum Realm:

- Photons
- Axions

➡ Primakoff Effect

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ADM has very large occupation numbers ($>15\times10^6$ /L)!

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Quantum Realm:

- Photons
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Classical Realm

- E&B Fields
- Axion Field

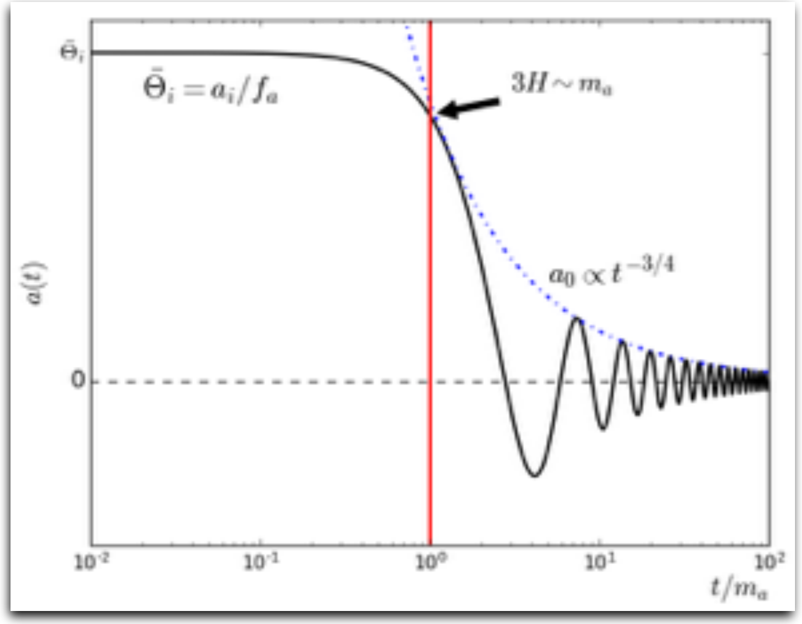
➡ Modified Maxwell's Equations

Axion modified Maxwell's equations

$$\nabla \cdot \mathbf{E} = \rho_e - g_{a\gamma\gamma}\mathbf{B}\cdot\nabla a\,,$$
$$\nabla \cdot \mathbf{B} = 0\,,$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}\,,$$
$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J}_e - g_{a\gamma\gamma}\left(\mathbf{E}\times\nabla a - \frac{\partial a}{\partial t}\mathbf{B}\right)$$

Searching for Axion Dark Matter through EM Coupling

ADM produced by the misalignment mechanism



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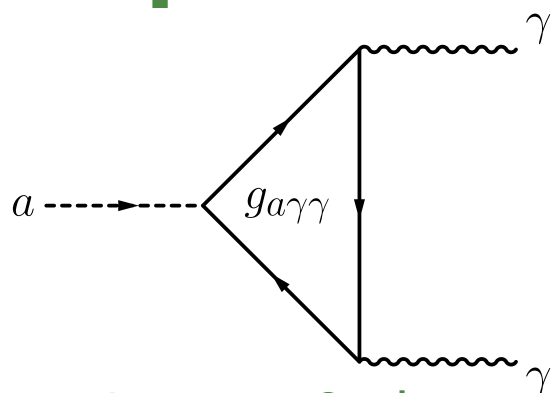

Axion to 2-photon coupling

Searching for Axion Dark Matter through EM Coupling

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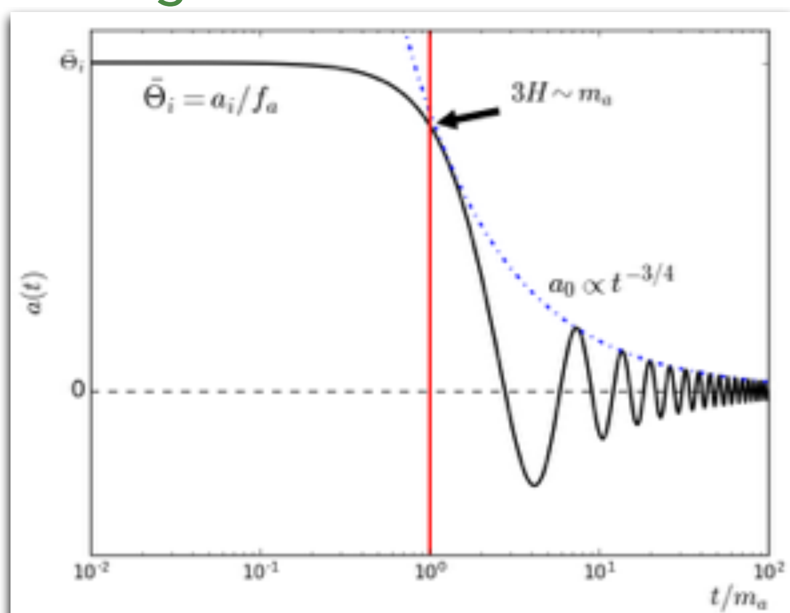

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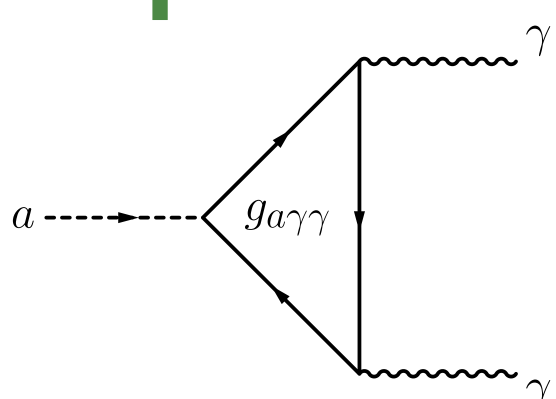


Axion to 2-photon coupling

Axion modified Maxwell's equations

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

$$\nabla \cdot \mathbf{B} = 0 \,,$$

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

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J}_e - g_{a\gamma\gamma} \left(\mathbf{E} \times \nabla a - \frac{\partial a}{\partial t} \mathbf{B} \right)$$

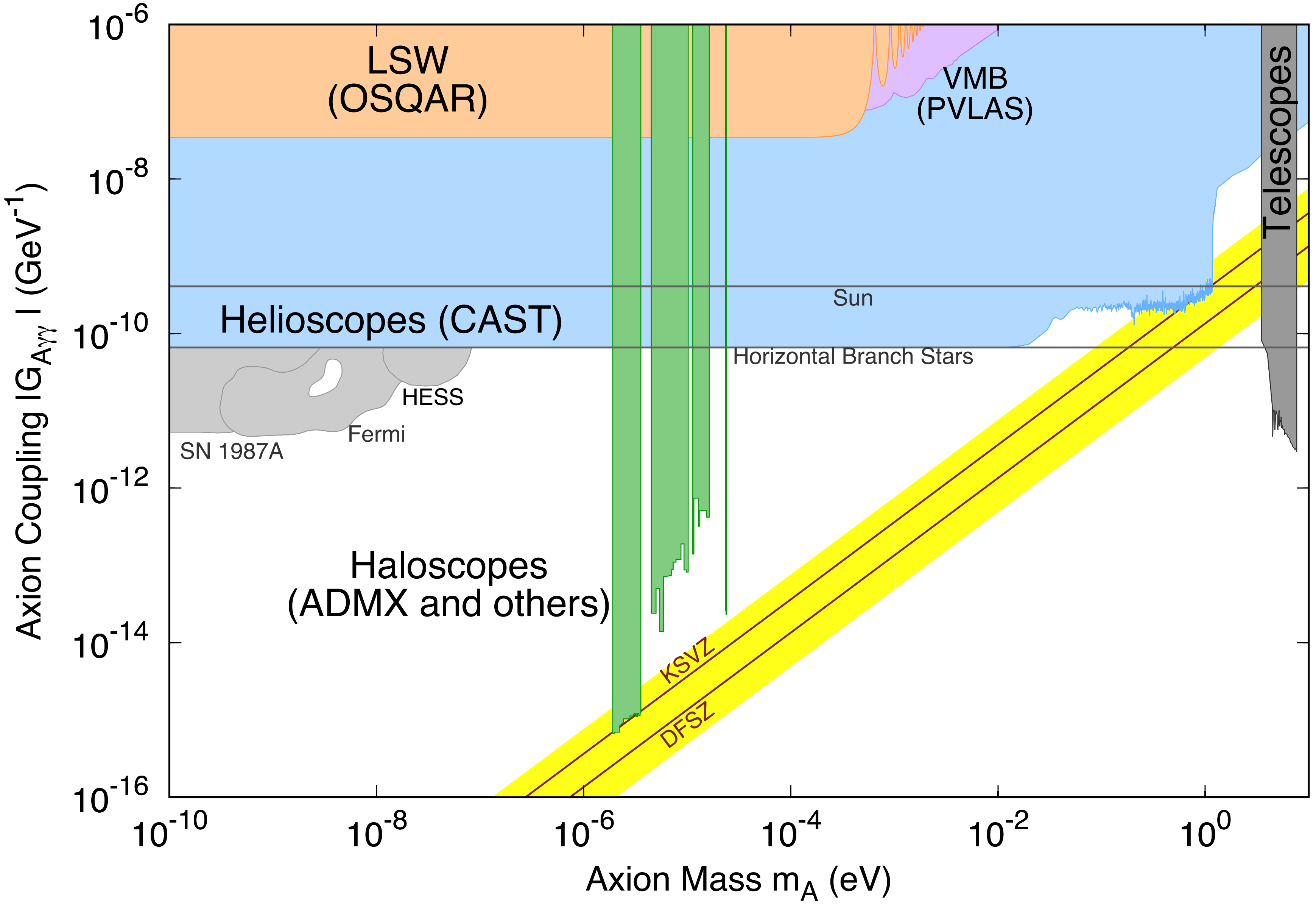
+

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

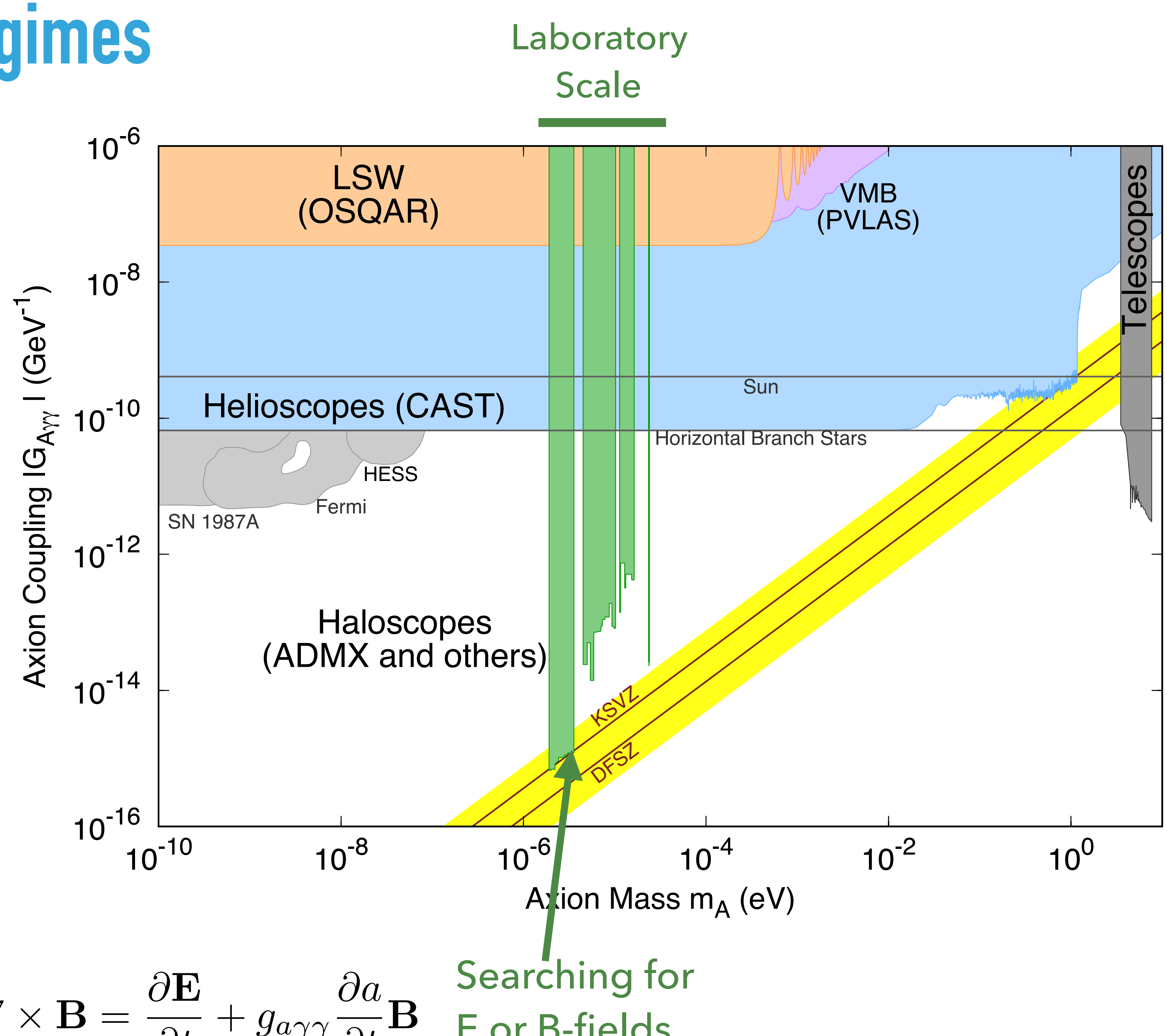
Throughout this talk, assume that spatial gradients are negligible $\nabla a \approx 0$.

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

Three Mass Regimes



Three Mass Regimes



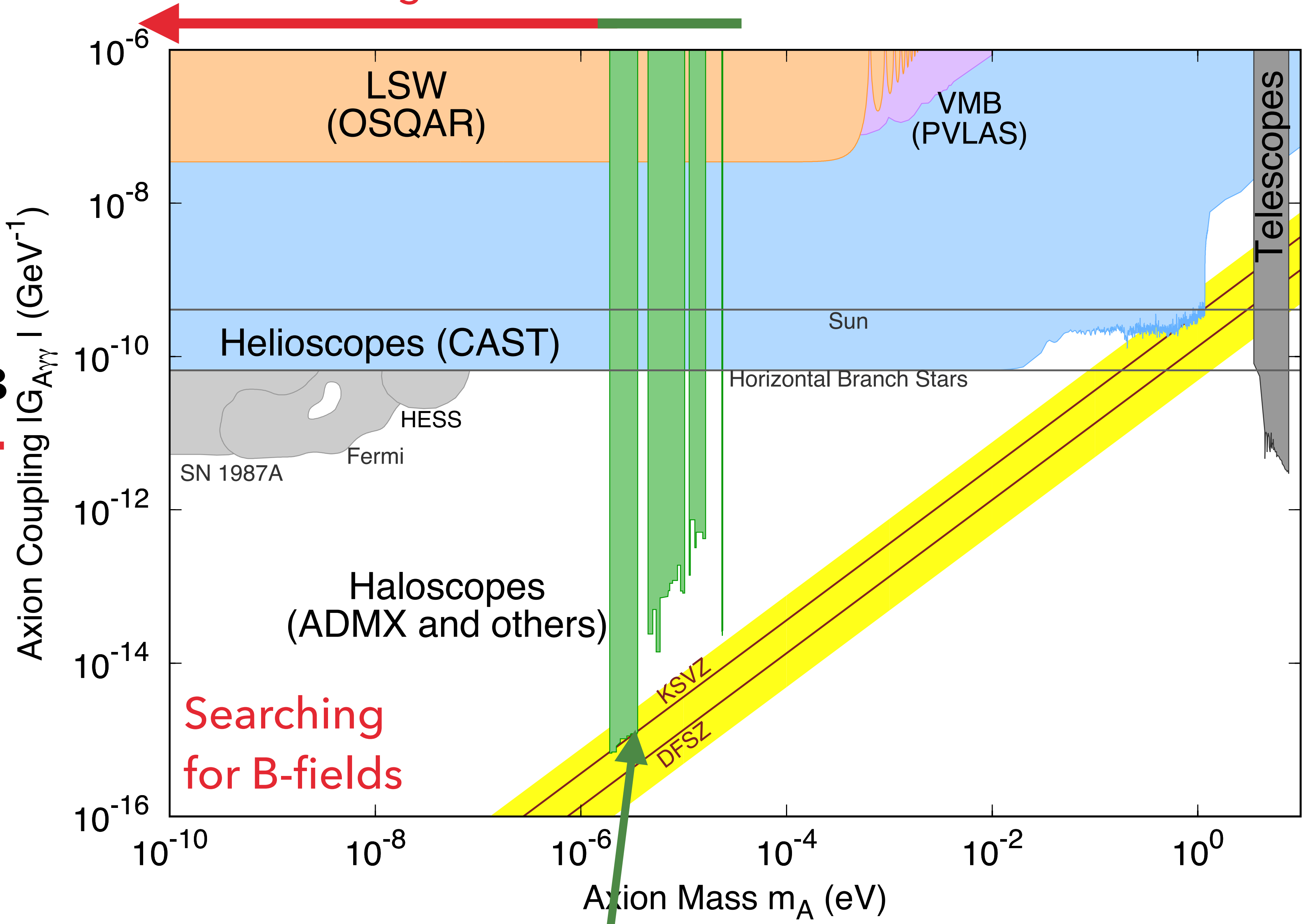
$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + g_{a\gamma\gamma} \frac{\partial a}{\partial t} \mathbf{B}$$

Three Mass Regimes

Long Compton Wavelength

Laboratory Scale

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



Searching for B-fields

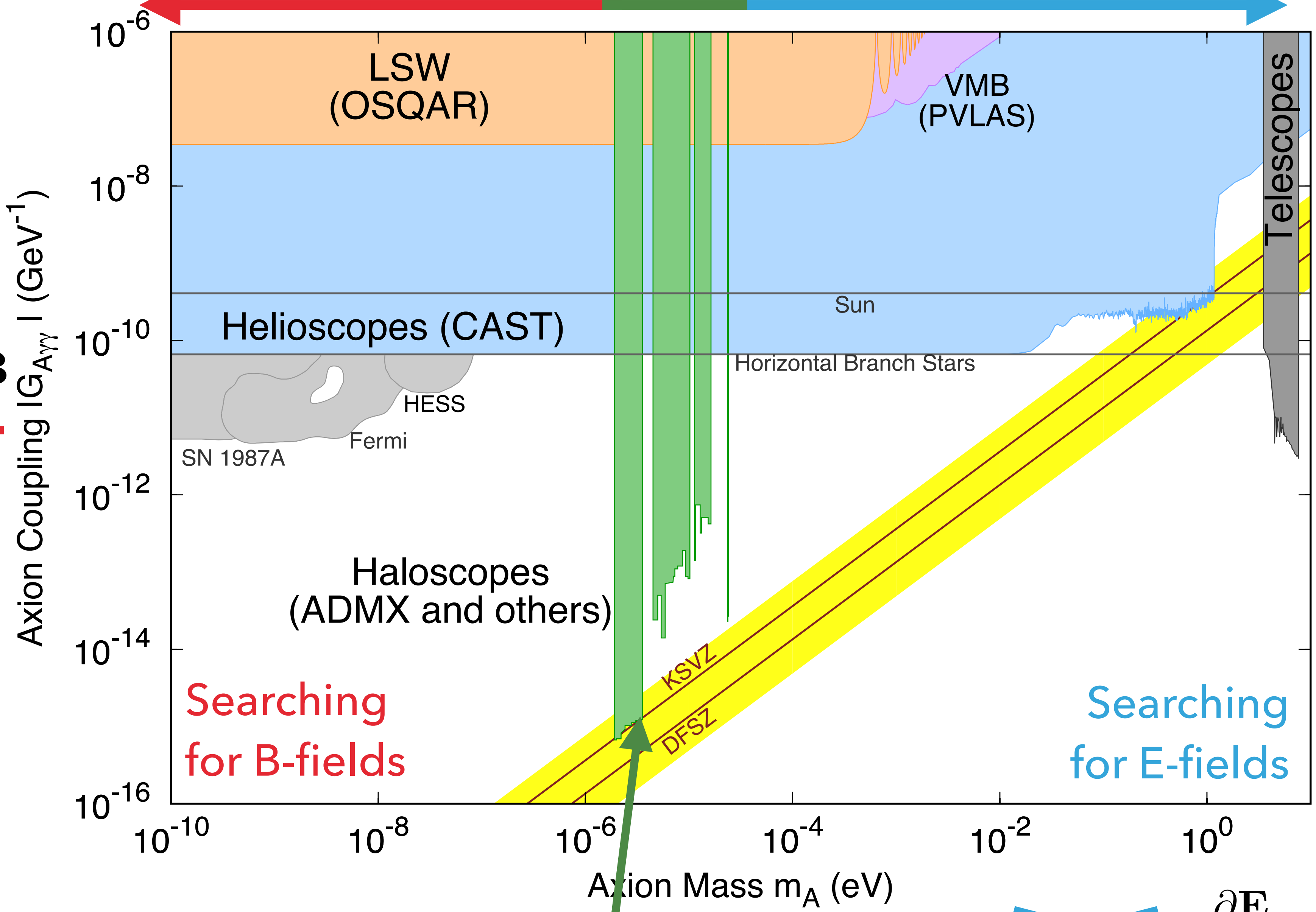
$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + g_{a\gamma\gamma}\frac{\partial a}{\partial t}\mathbf{B}$$

Searching for E or B-fields

Three Mass Regimes

Long Compton Wavelength | Laboratory Scale | Short Compton Wavelength

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



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Searching for E or B-fields

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Axion Dark Matter Energy Density

- According to current theory, we can write down the predicted energy density from axions

$$\Omega_a h^2 \sim 0.1 \left(\frac{10^{-5}\,\mathrm{eV}}{m_a} \right)^{7/6} \Theta_i^2$$

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- Experimentalist attitude:

If you find it, the theories will come.

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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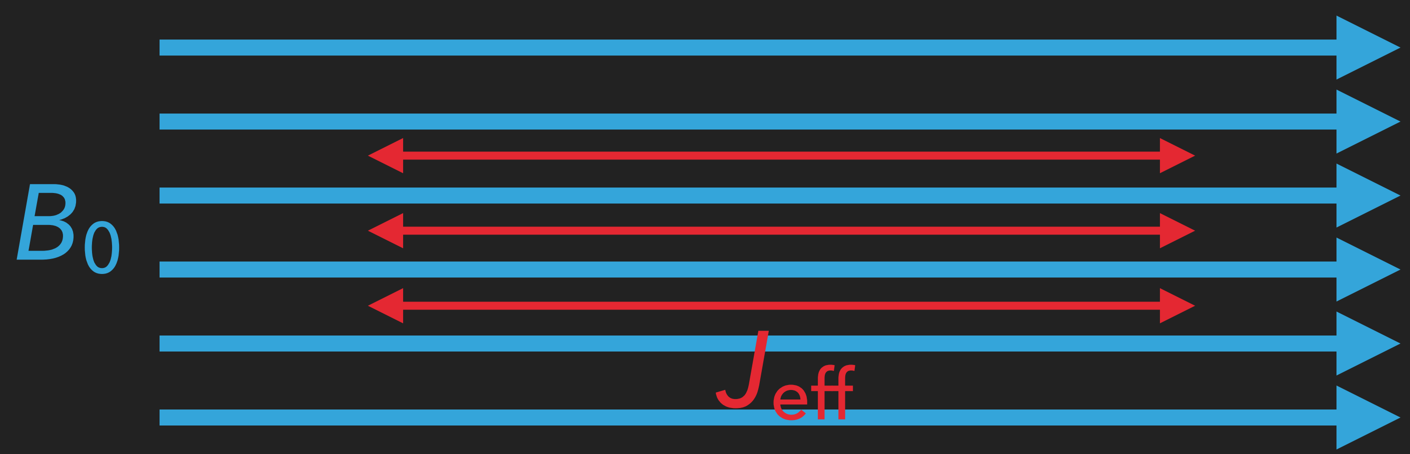

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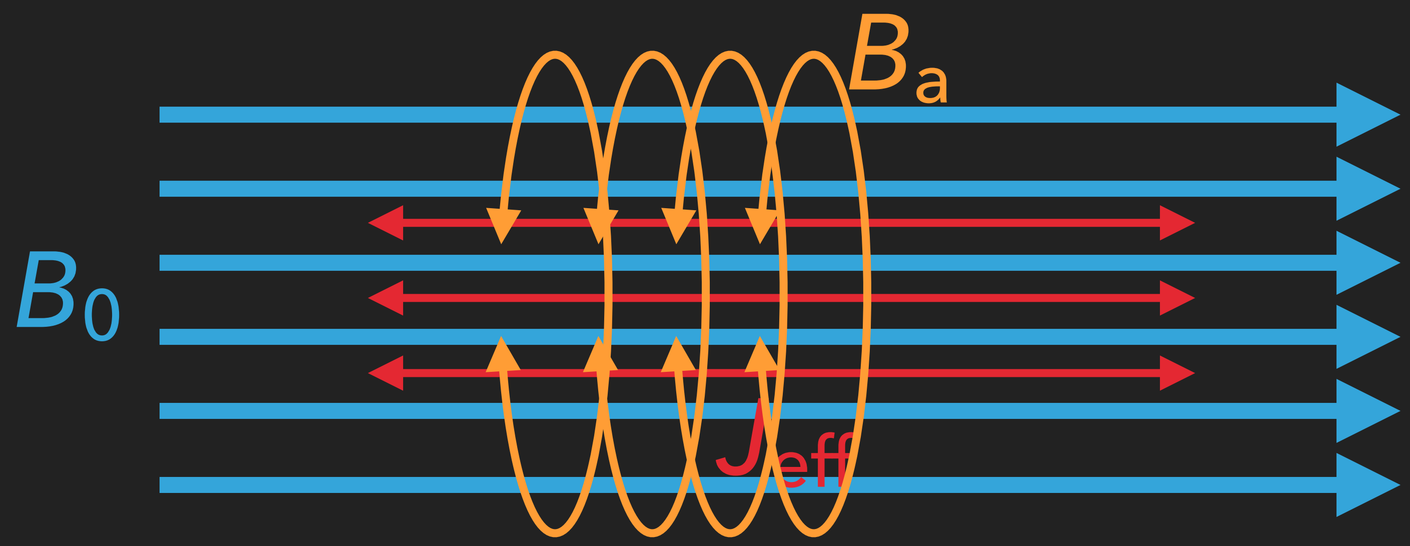
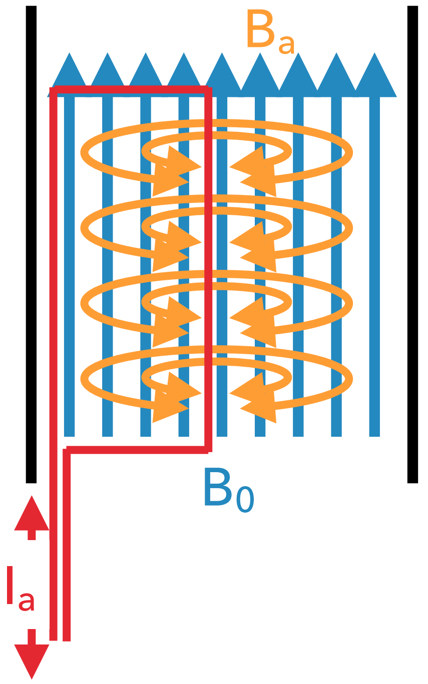


Geometric Configurations

P. Sikivie, N. Sullivan, and D. B. Tanner
Phys. Rev. Lett. 112, 131301 (2014)



- Pickup loop inside the magnetic field → strong coupling to induced field
- Less material near the pickup loop
- By measuring in high field region → large potential background

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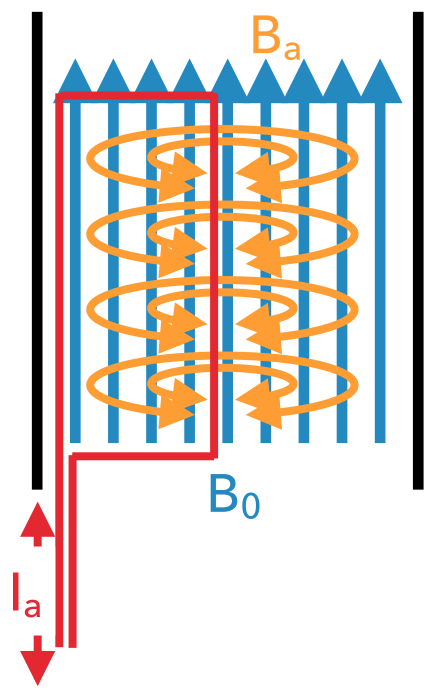

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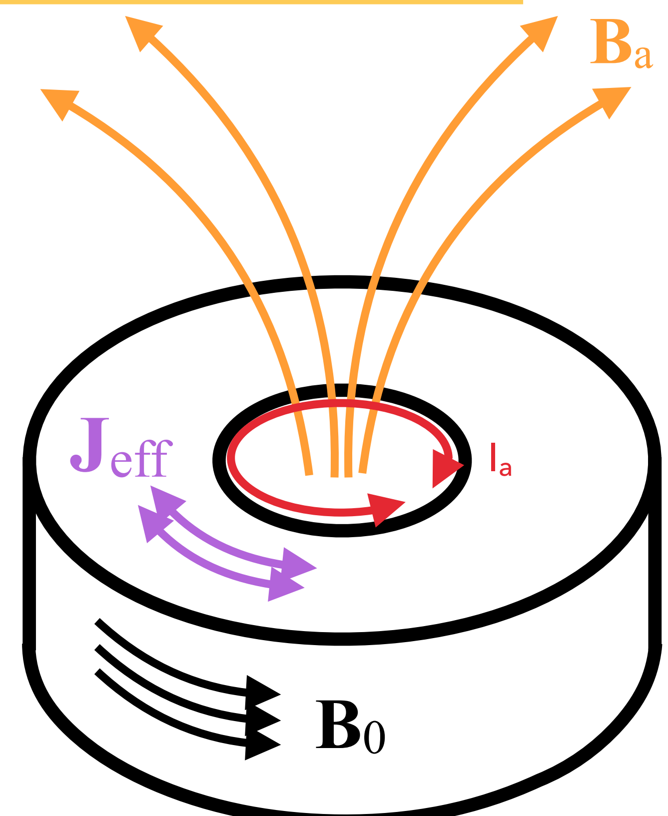
ABRACADABRA: Y. Kahn, B. R. Safdi and J. Thaler
Phys. Rev. Lett. 117, 141801 (2016)

DMRadio: Silva-Feaver et. al.
IEEE Trans. Appl. Supercond. 27(4) 1-4 (2017)

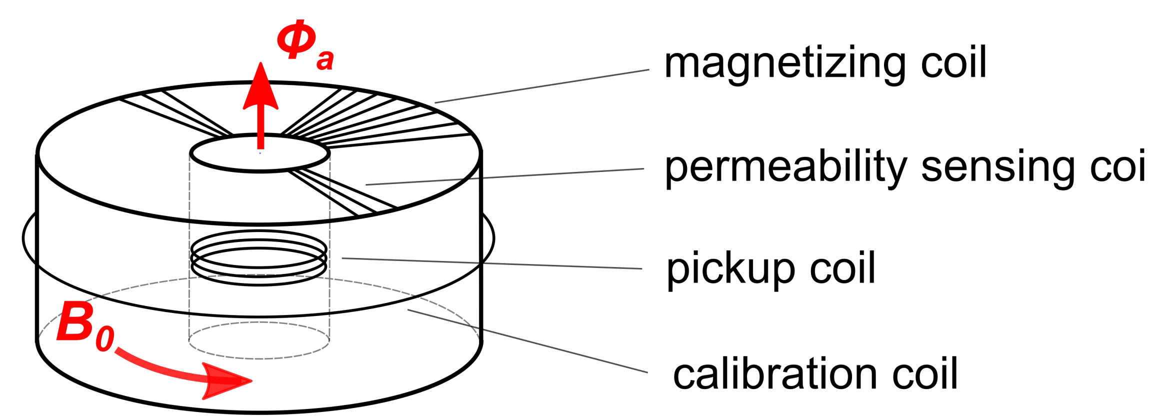


- Pickup loop outside the field → smaller coupling to induced field
- Magnet material near the pickup loop
- By measuring in zero field region → significantly suppressed background

USING ELECTROMAGNETS TO ENHANCE FIELDS

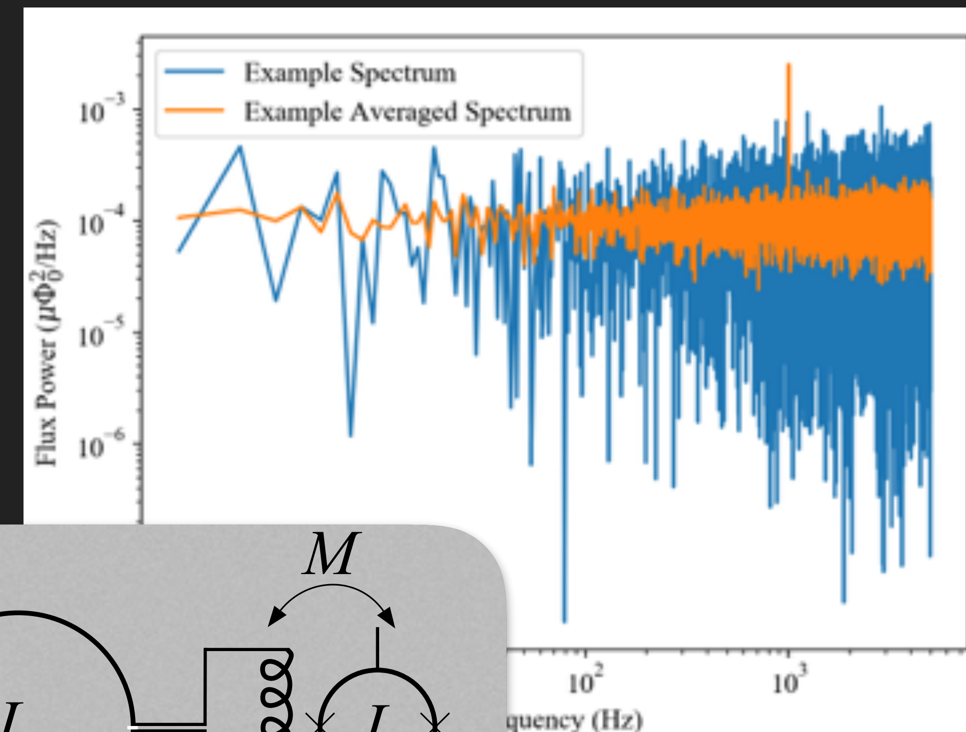
A. V. Gramolin, D. Aybas, D. Johnson, J. Adam, and A. O. Sushkov
arXiv: 1811.03231

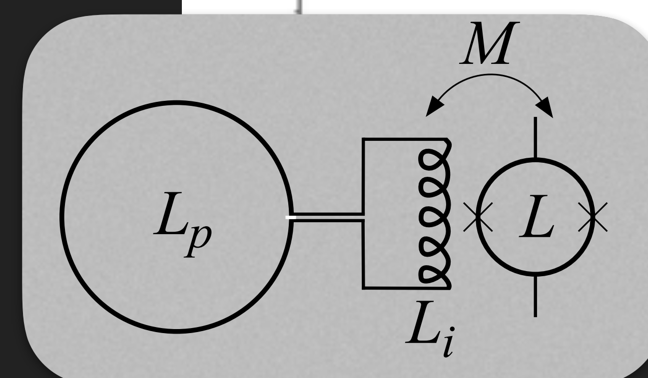
- One potential possibility is to use an electromagnet, to enhance your total B-field
  - Large permeabilities can enhance the B-field for the H-field that you buy
  - Possibly limits the eventual size
- Group working with 0.17 T from a 5 amp current
- Long term, magnetization noise may become an insurmountable problem



Two Readout Approaches

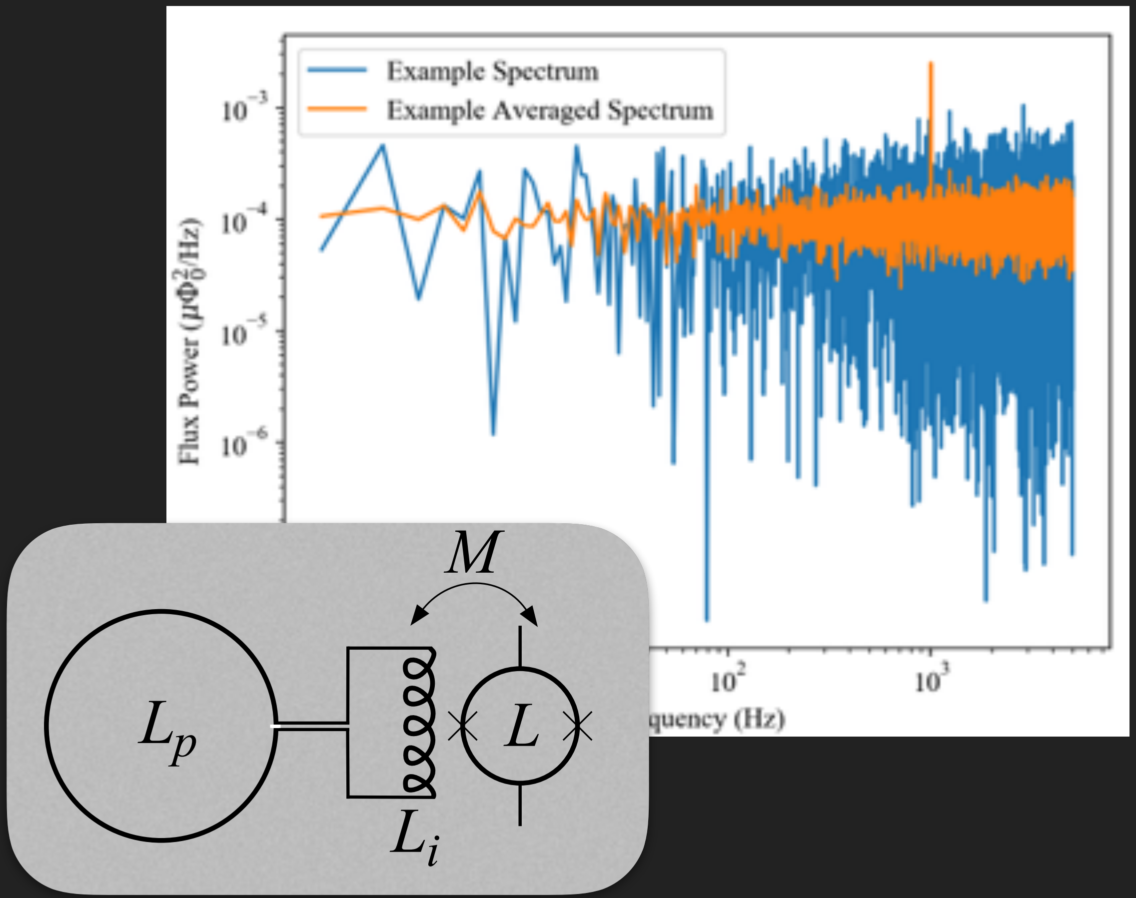
- Broadband Readout: Measure and average
  - Coupling pickup loop directly into a SQUID
  - Search all frequencies simultaneously
  - Averaging is *really* slow

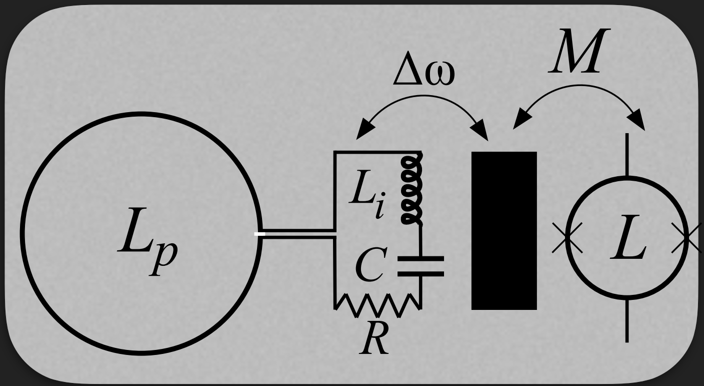


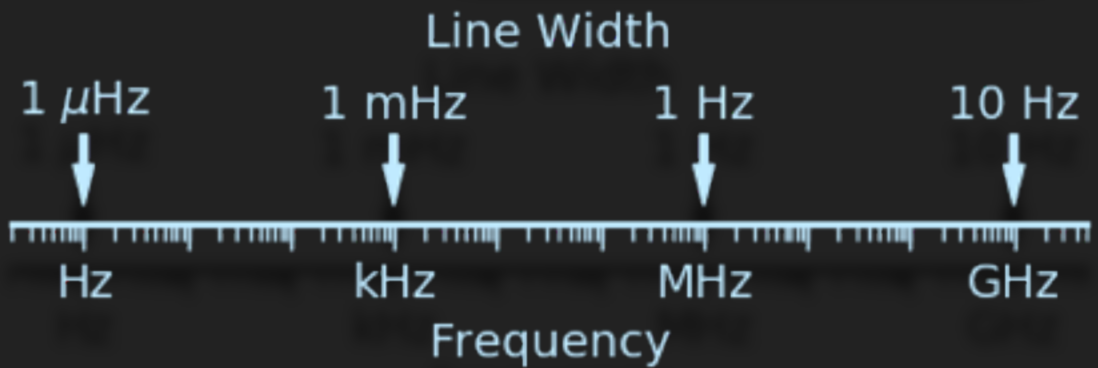


Two Readout Approaches

- Broadband Readout: Measure and average
  - Coupling pickup loop directly into a SQUID
  - Search all frequencies simultaneously
  - Averaging is *really* slow
- Resonant Readout: Lock in and amplify one frequency
  - Insert a resonator into the circuit before the SQUID readout
  - Can quickly pull signal from noise
  - Don't know what frequency to amplify, have to scan!

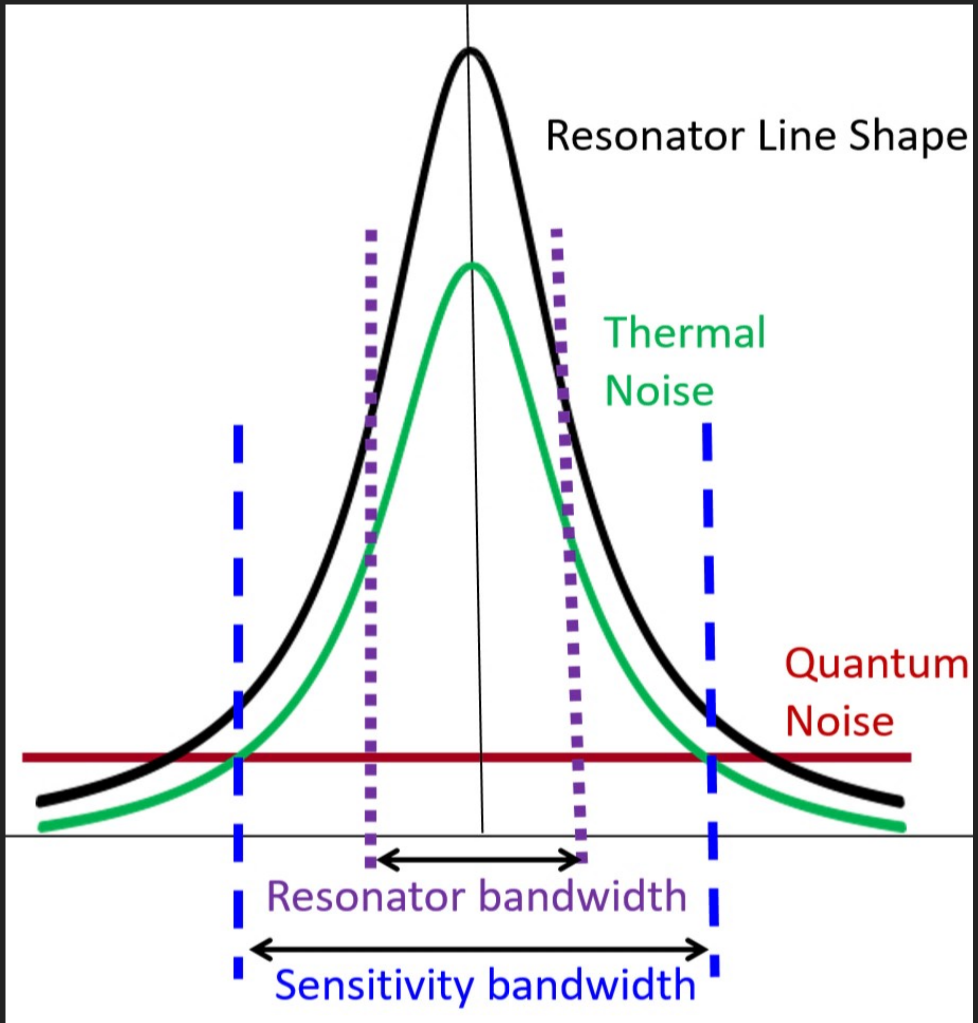






Enhanced Resonator Sensitivity (arXiv: 1803.01627)

- Constant SNR as long as noise floor set by thermal noise in pickup loop circuit
- Still want quantum limited amplifiers even in the high thermal occupancy regime
- Need to minimize back action from the amplifier
- Scan speed set by how low the noise floor can be pushed



Chaudhuri, Irwin, Graham, Mardon
arXiv: 1803.01627

Even at high thermal occupancy, you want to push beyond the SQL!

This is the Story of the (Dark Matter) Hurricane

- 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!

PHYSICAL REVIEW D **98,** 103006 (2018)

Featured in Physics

Dark matter hurricane: Measuring the S1 stream with dark matter detectors

Ciaran A. J. O'Hare,[1,*] Christopher McCabe,[2,†] N. Wyn Evans,[3,‡] GyuChul Myeong,[3] and Vasily Belokurov[3]

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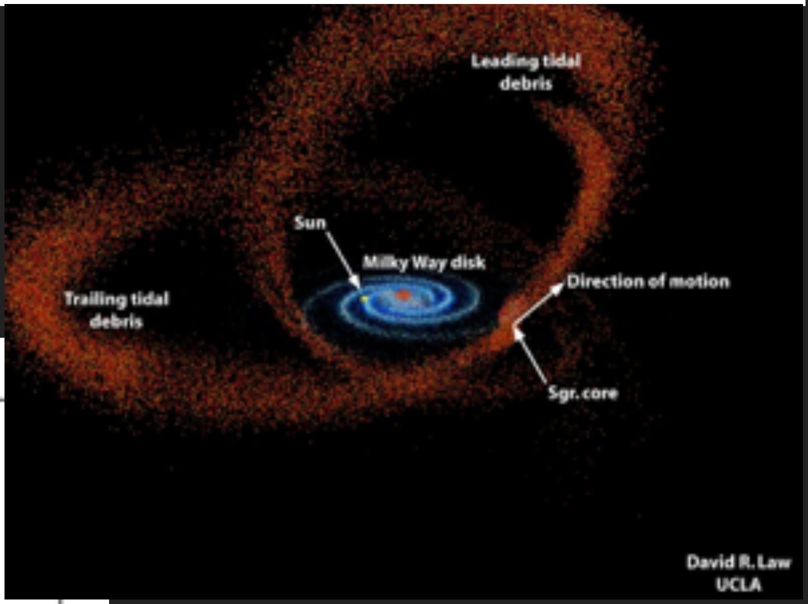
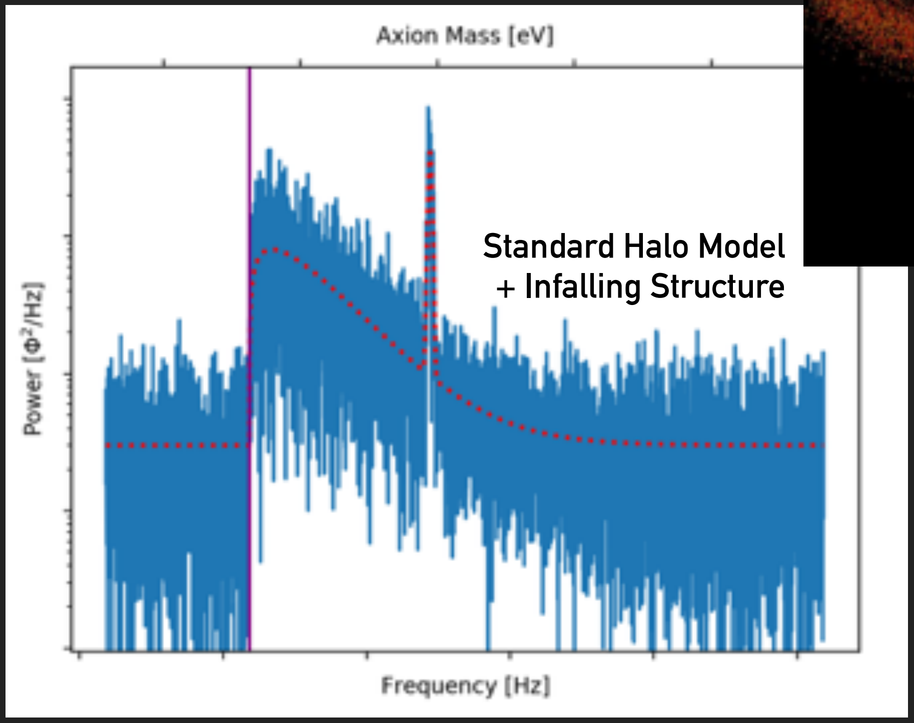
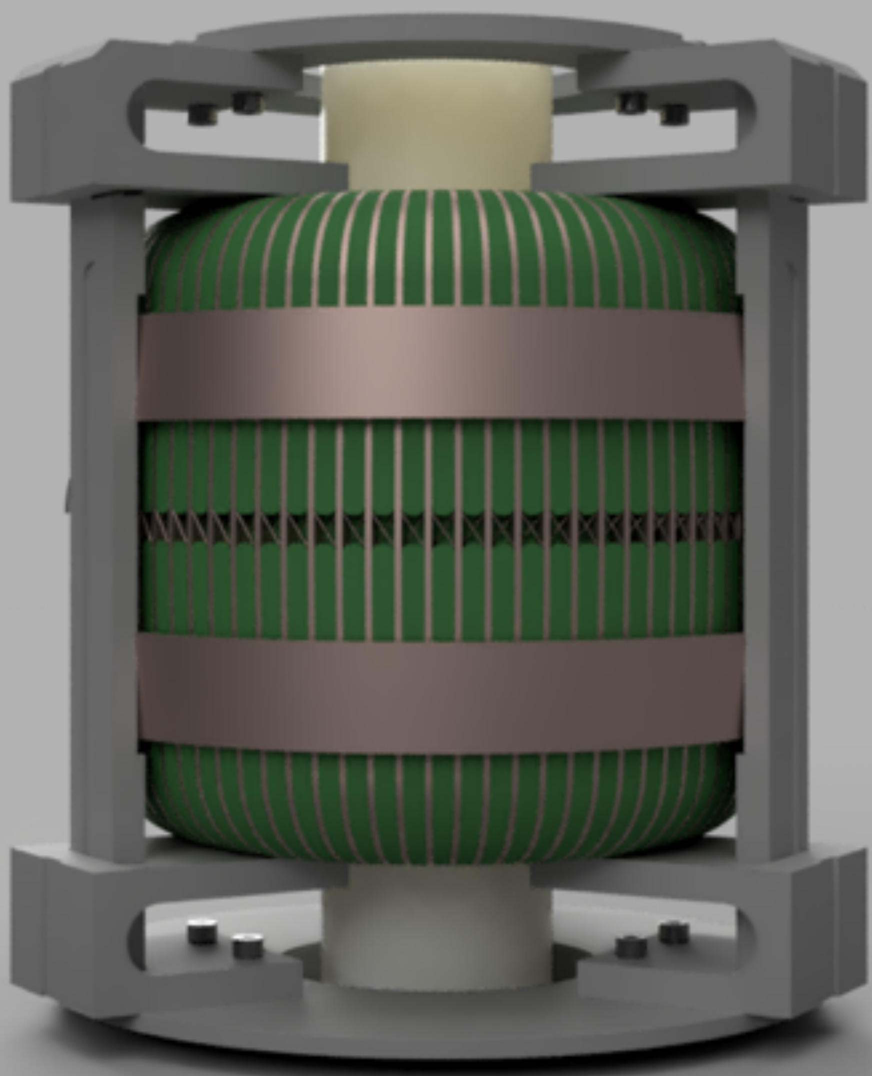
[2]*Department of Physics, King's College London, Strand, London, WC2R 2LS, United Kingdom*

[3]*Institute of Astronomy, Madingley Rd, Cambridge, CB3 0HA, United Kingdom*

(Received 13 August 2018; published 7 November 2018)



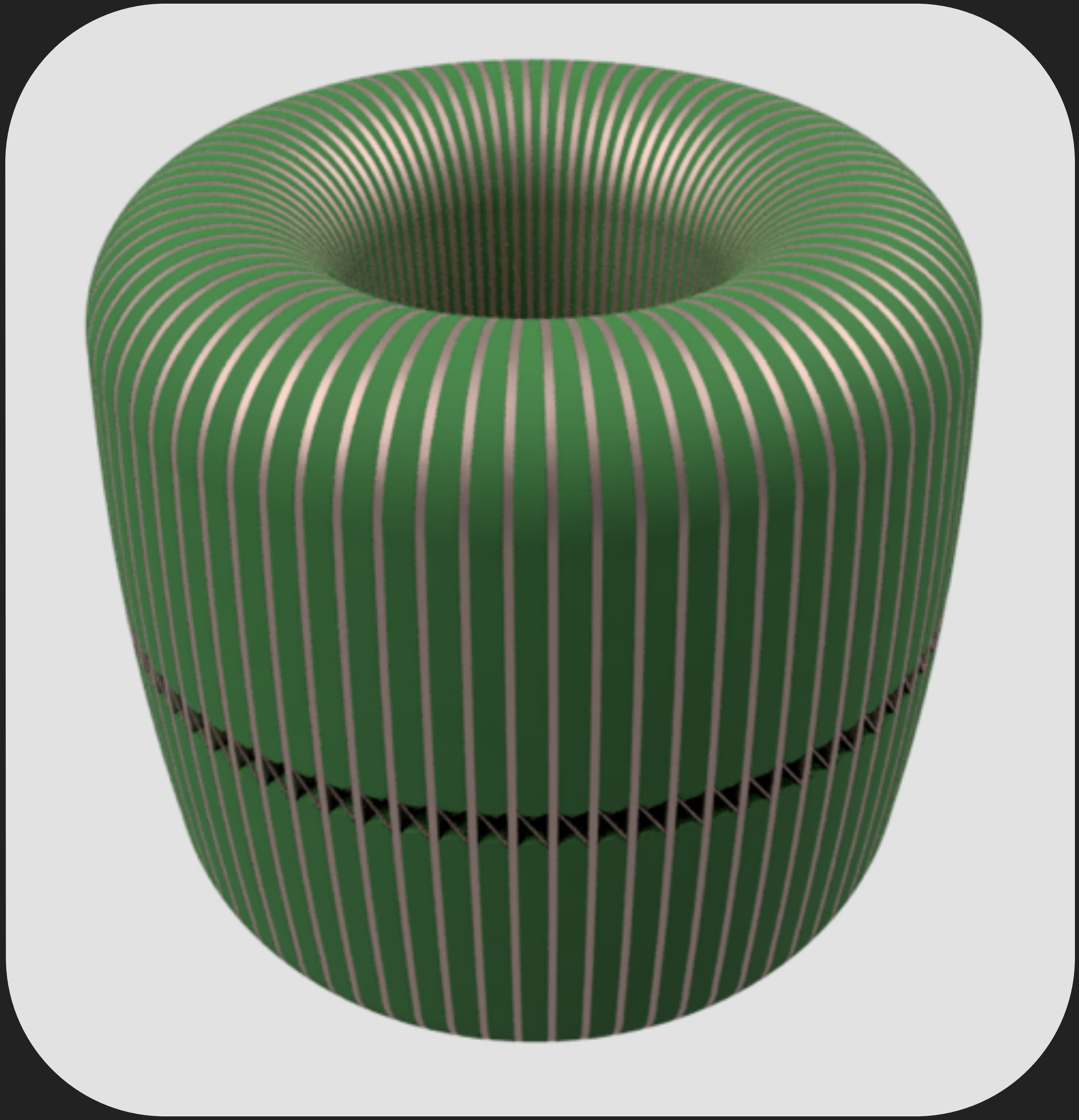




A PROTOTYPE DETECTOR

ABRACADABRA-10CM

Dissecting ABRACADABRA-10 cm



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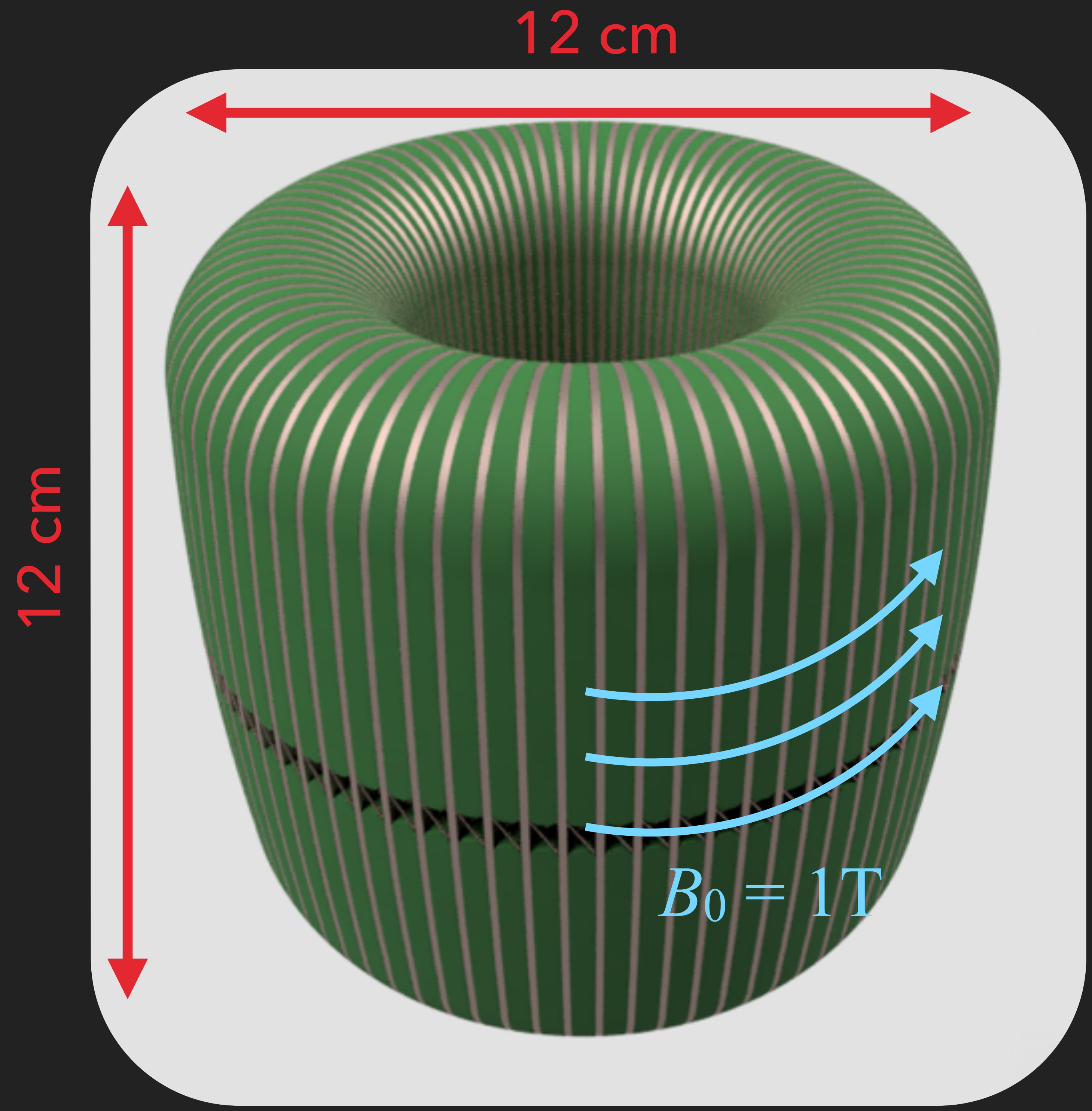

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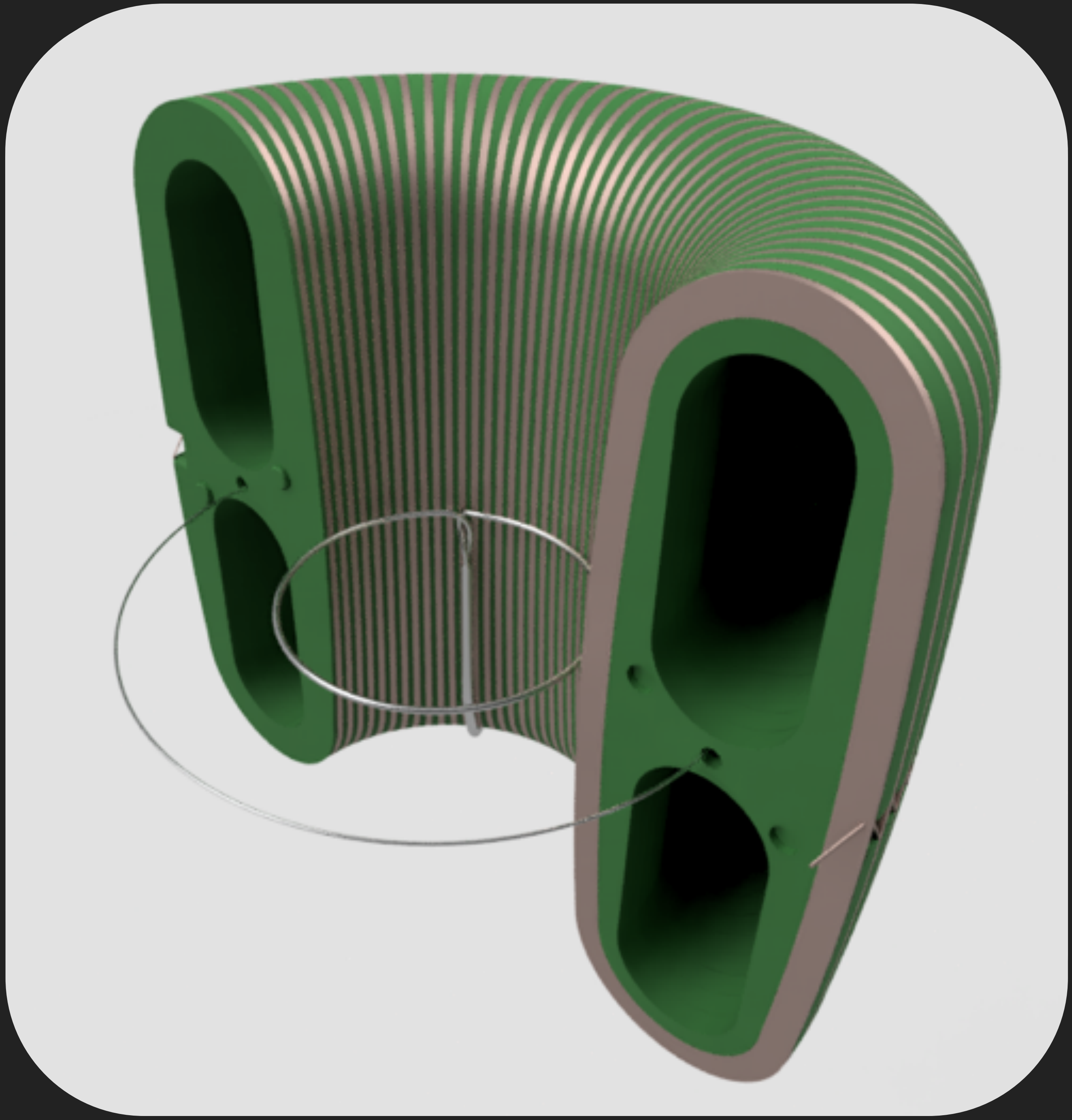
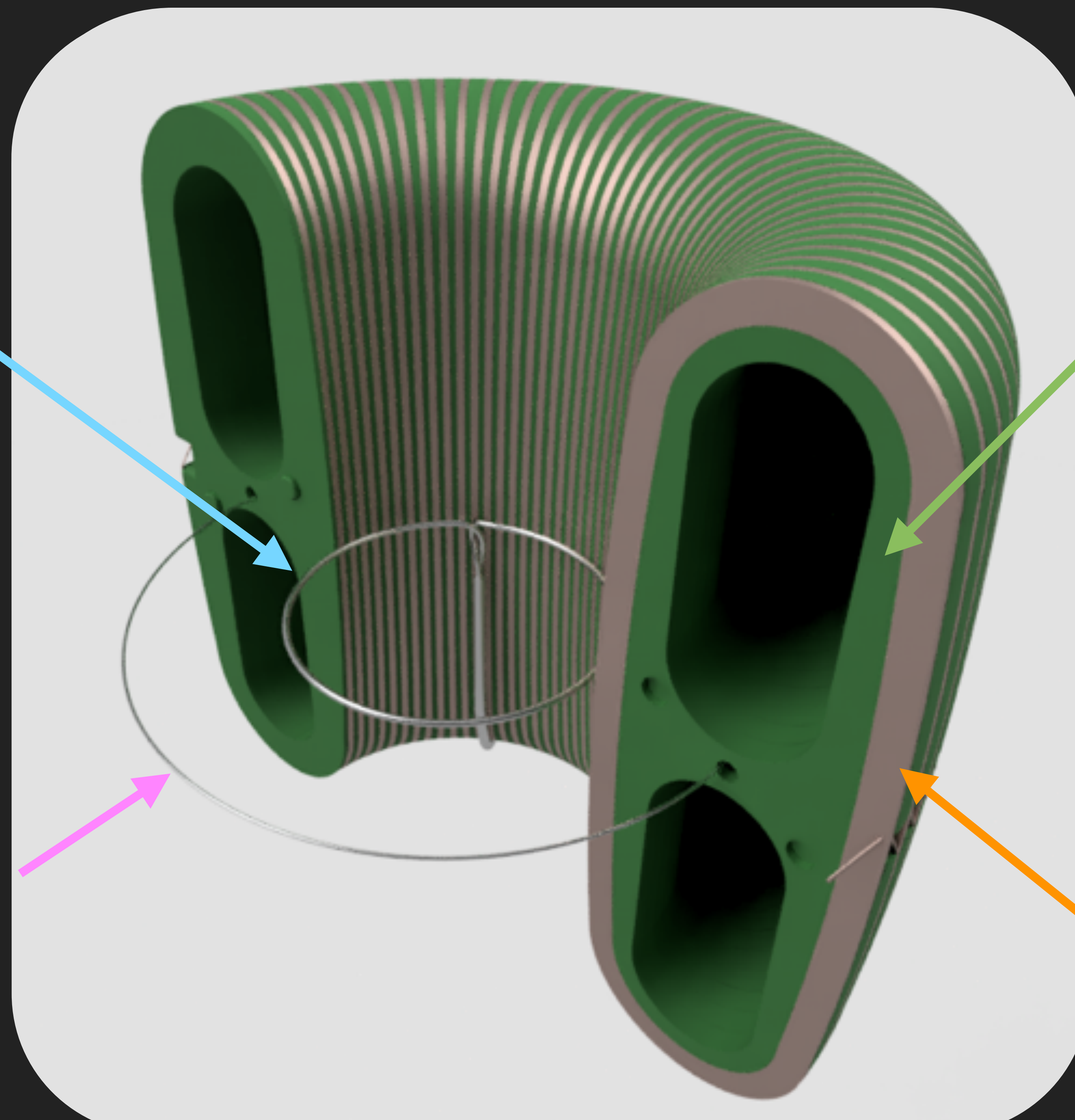


Dissecting ABRACADABRA-10 cm

Superconducting
Pickup Loop
$r_p = 2$ cm

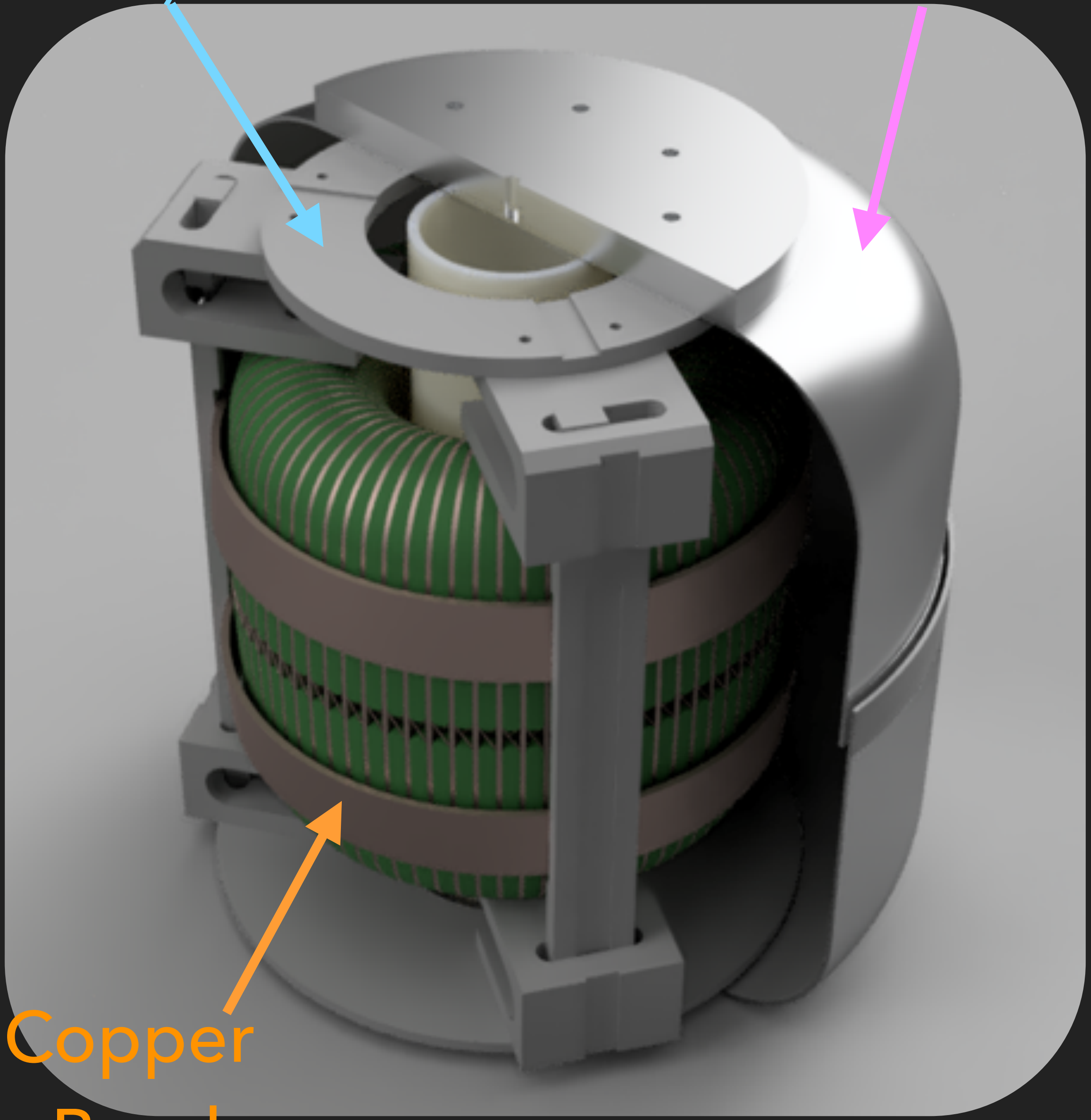
Superconducting
Calibration Loop
$r_c = 4.5$ cm



Delrin Toroid
Body

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

Dissecting ABRACADABRA-10 cm

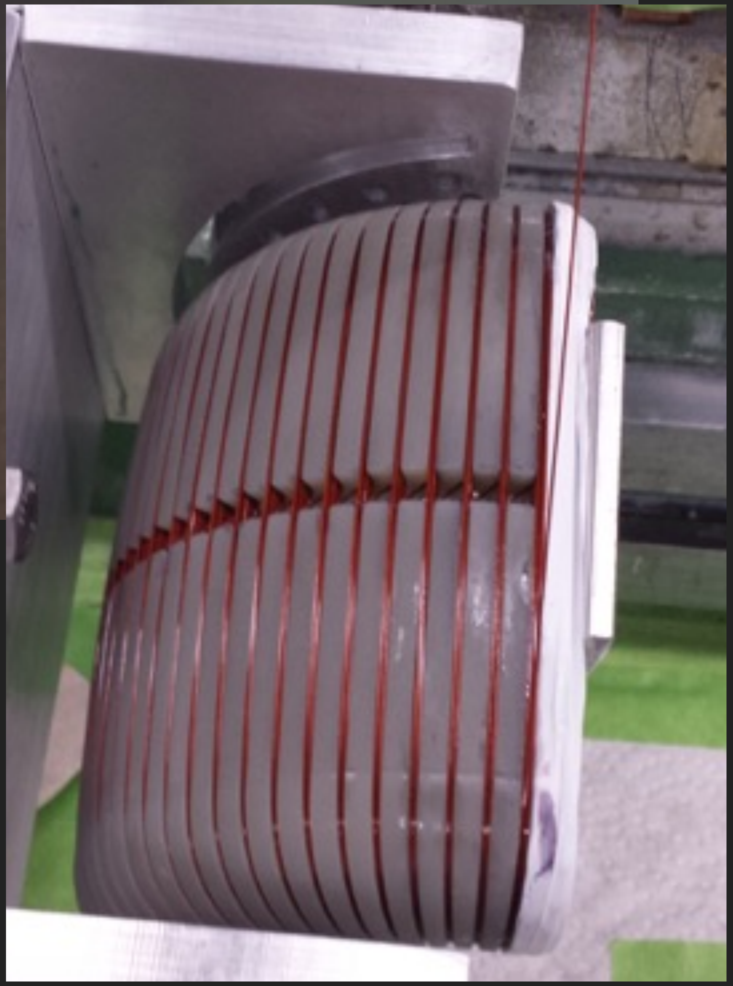


Assembling ABRACADABRA-10 cm

SUPERCONDUCTING SYSTEMS INC.

(Normally make MRI magnets!)

Assembling ABRACADABRA-10 cm



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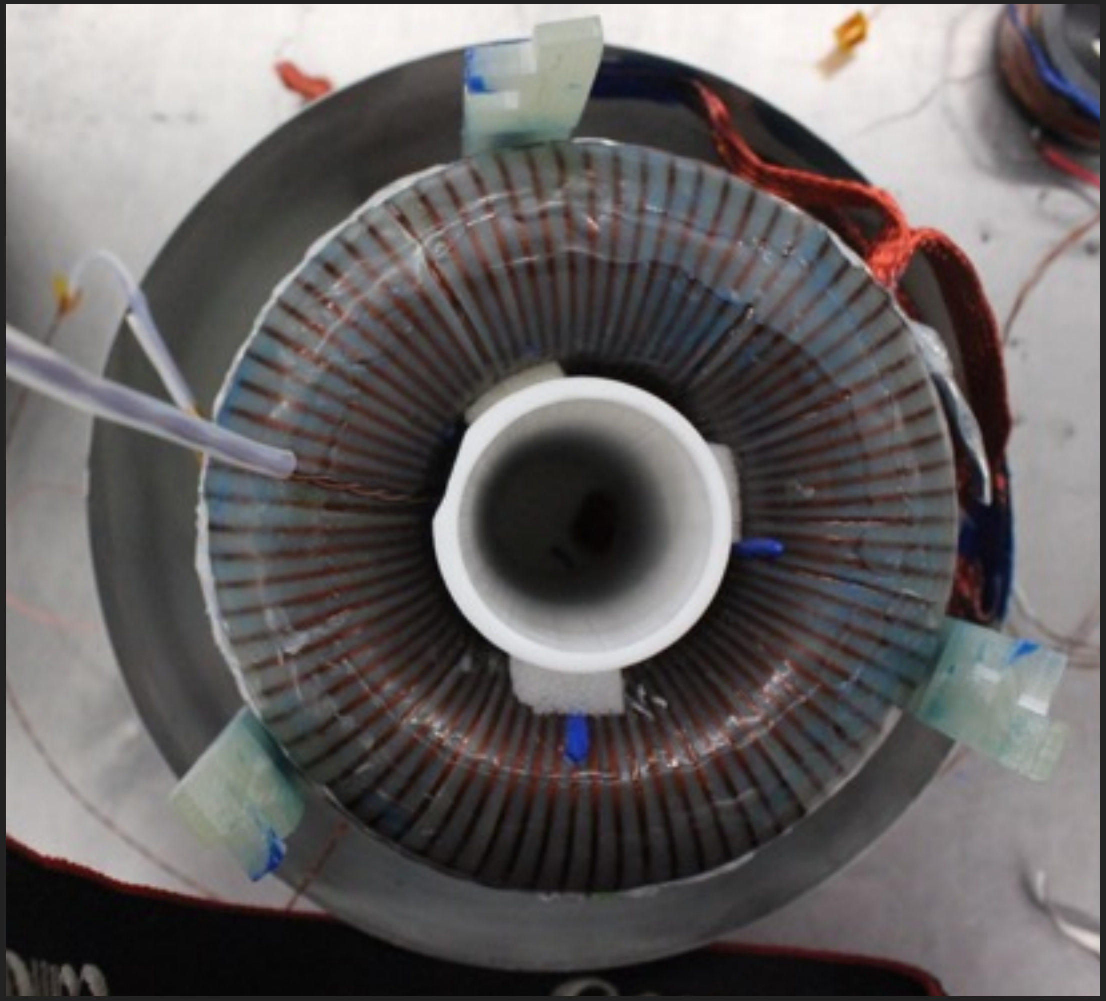
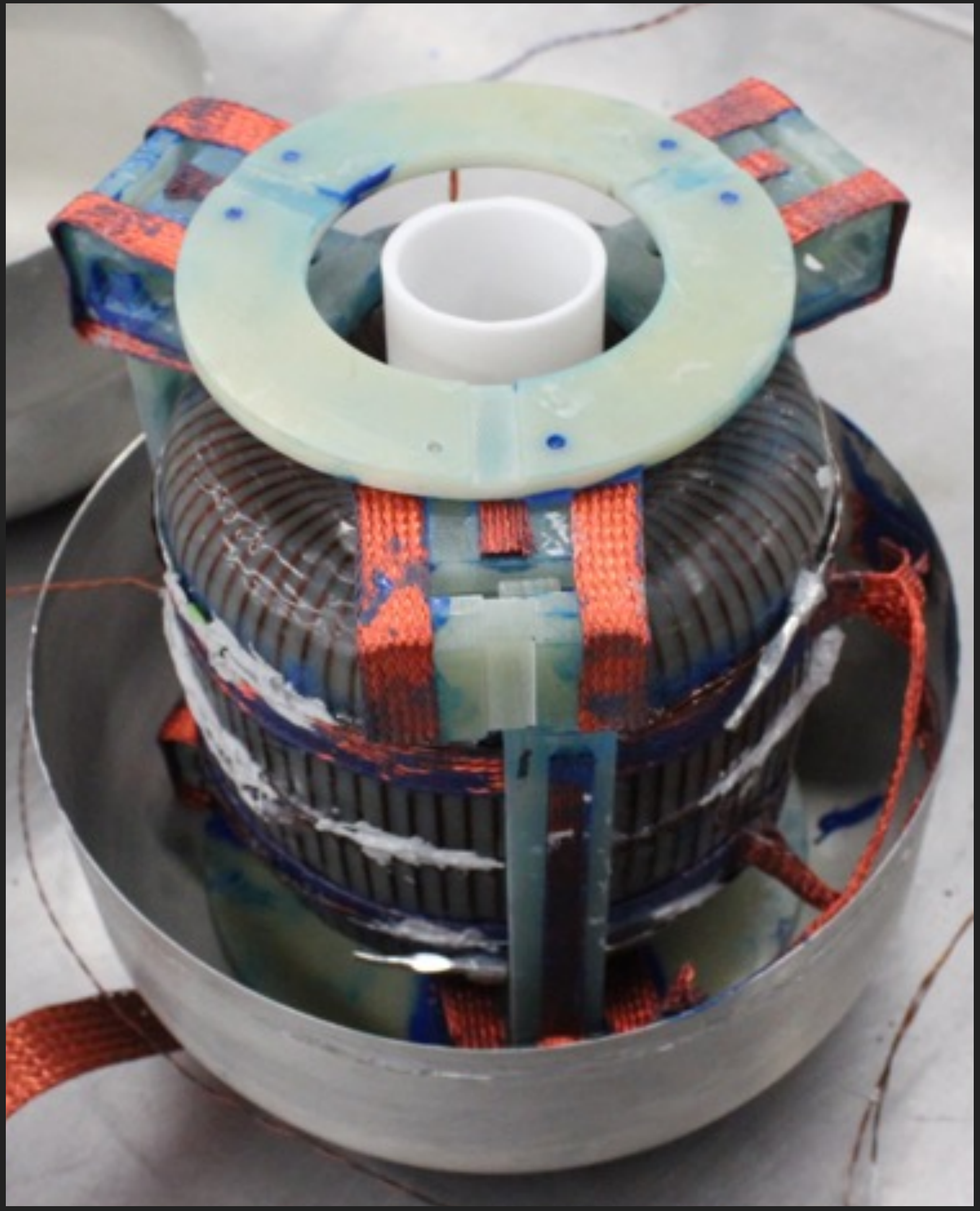
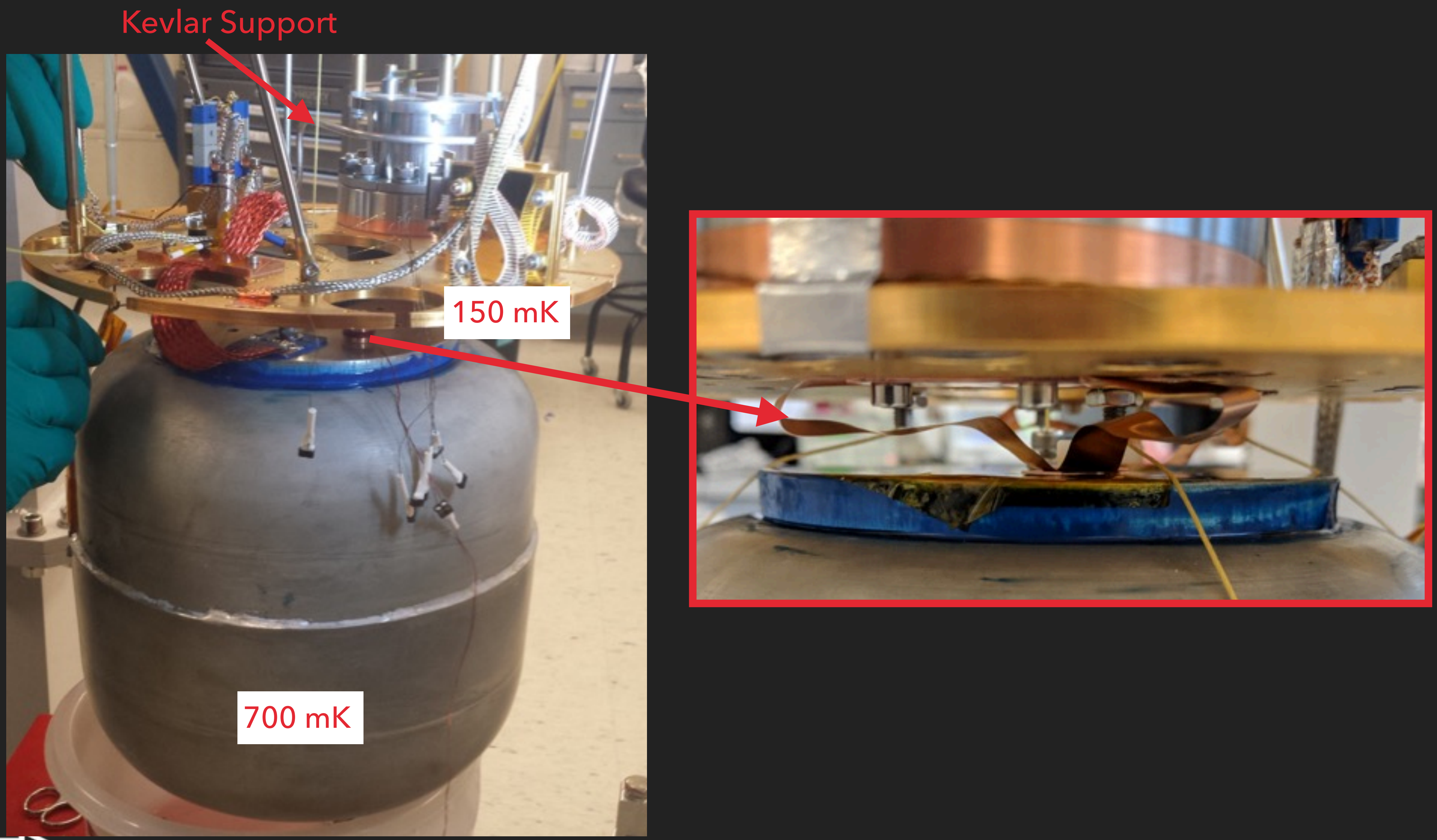
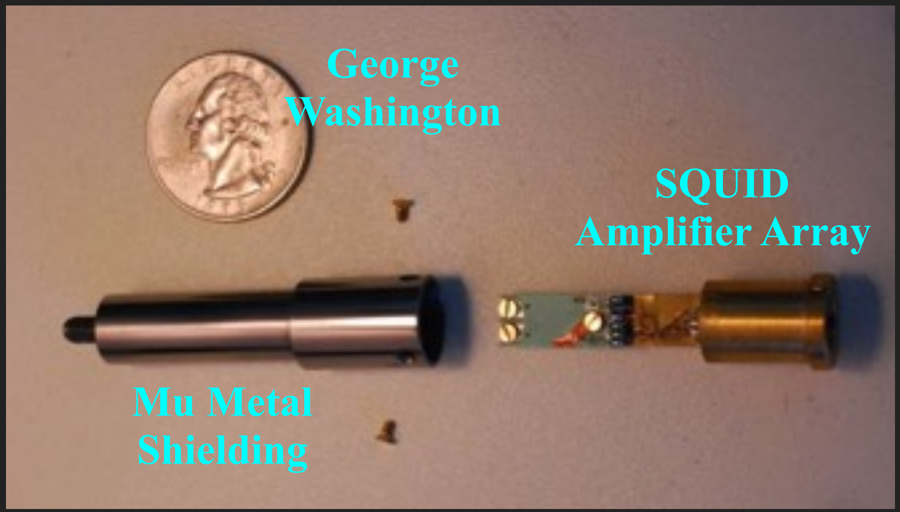




ABRA Mounted In Olaf



SQUID Readouts



- Off the shelf Magnicon DC SQUIDs
  - Typical noise floor ~1 $\mu\Phi_0/(\mathrm{Hz})^{1/2}$
  - Optimized for operation < 1 K
  - Typical gain of ~1.3 V/Φ_0^S (volts per SQUID flux quanta)
- No resonator (i.e. broadband readout)

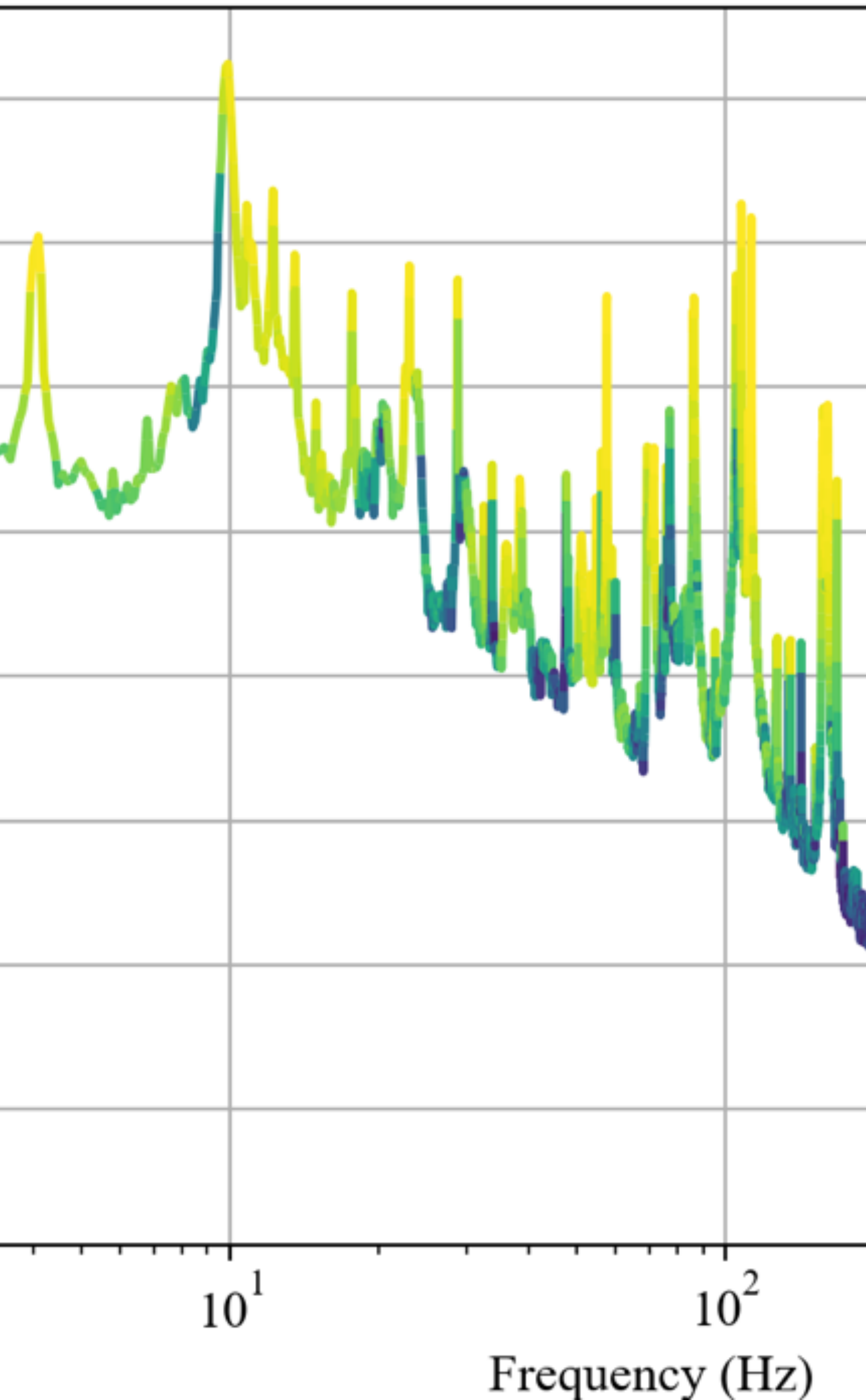
Quick note on units:

We measure magnetic flux in units of micro flux quanta ($\mu\Phi_0$)

$$\Phi_0 = 2 \times 10^{-15}\,\mathrm{Wb}$$

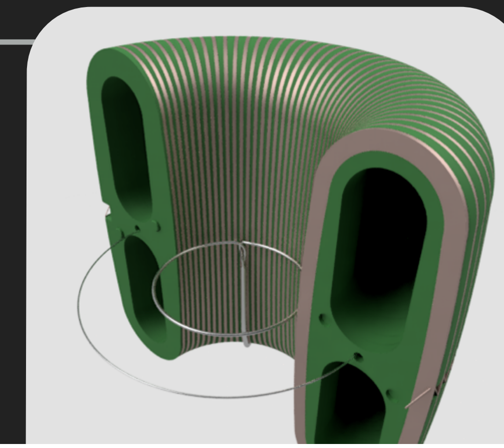
Magnetic Shielding

- Two layers of mu-metal shielding
- Recycled from the Bates Accelerator Pipe
- DC Attenuation ~ 10x



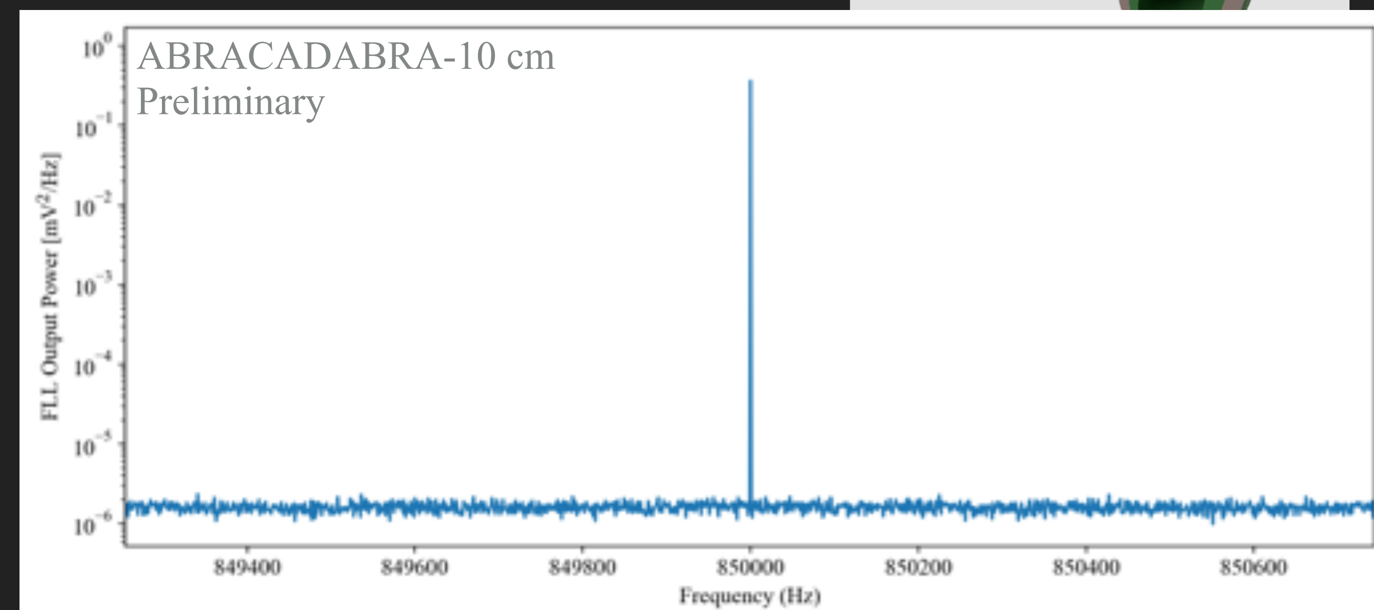
ABRACADABRA-10 CM

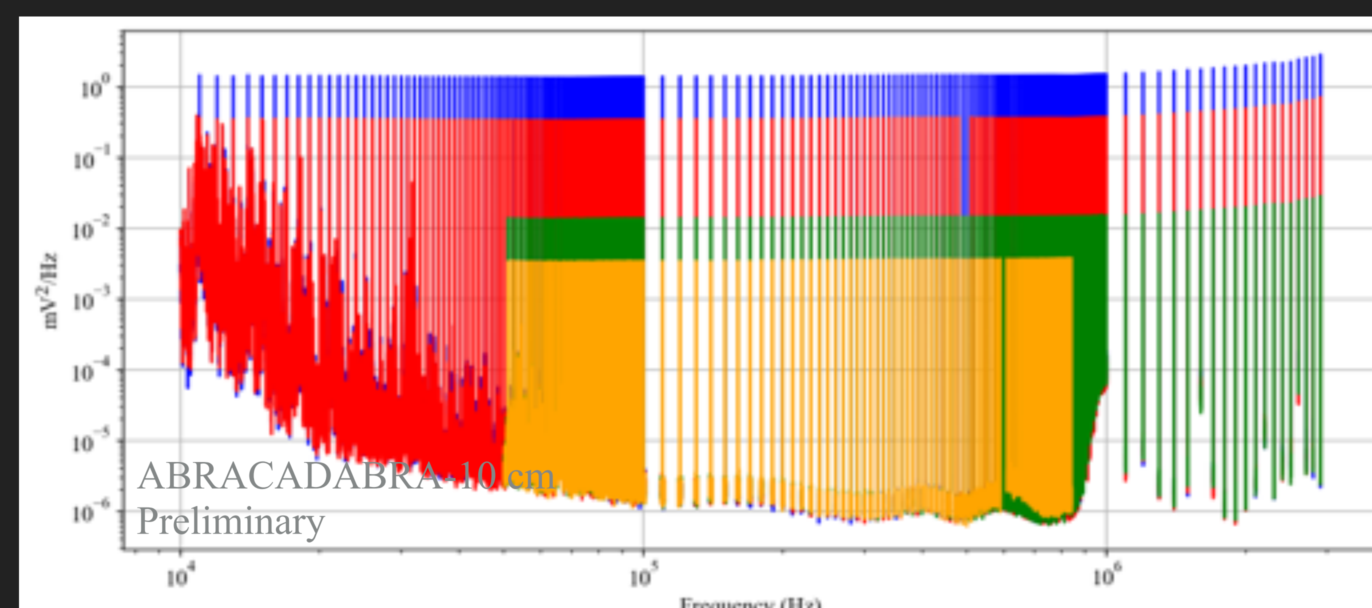
COMMISSIONING AND DATA TAKING



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
- Gain lower than expected by a factor of ~6.5 (suspect parasitic inductance)





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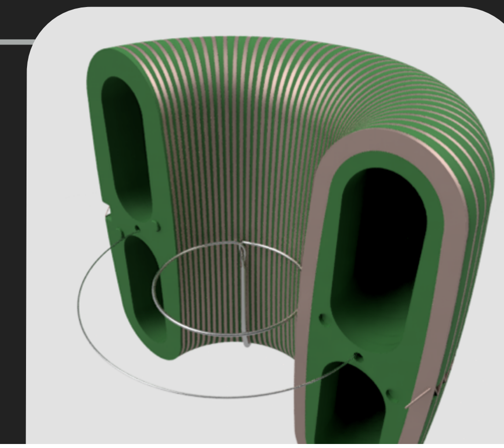

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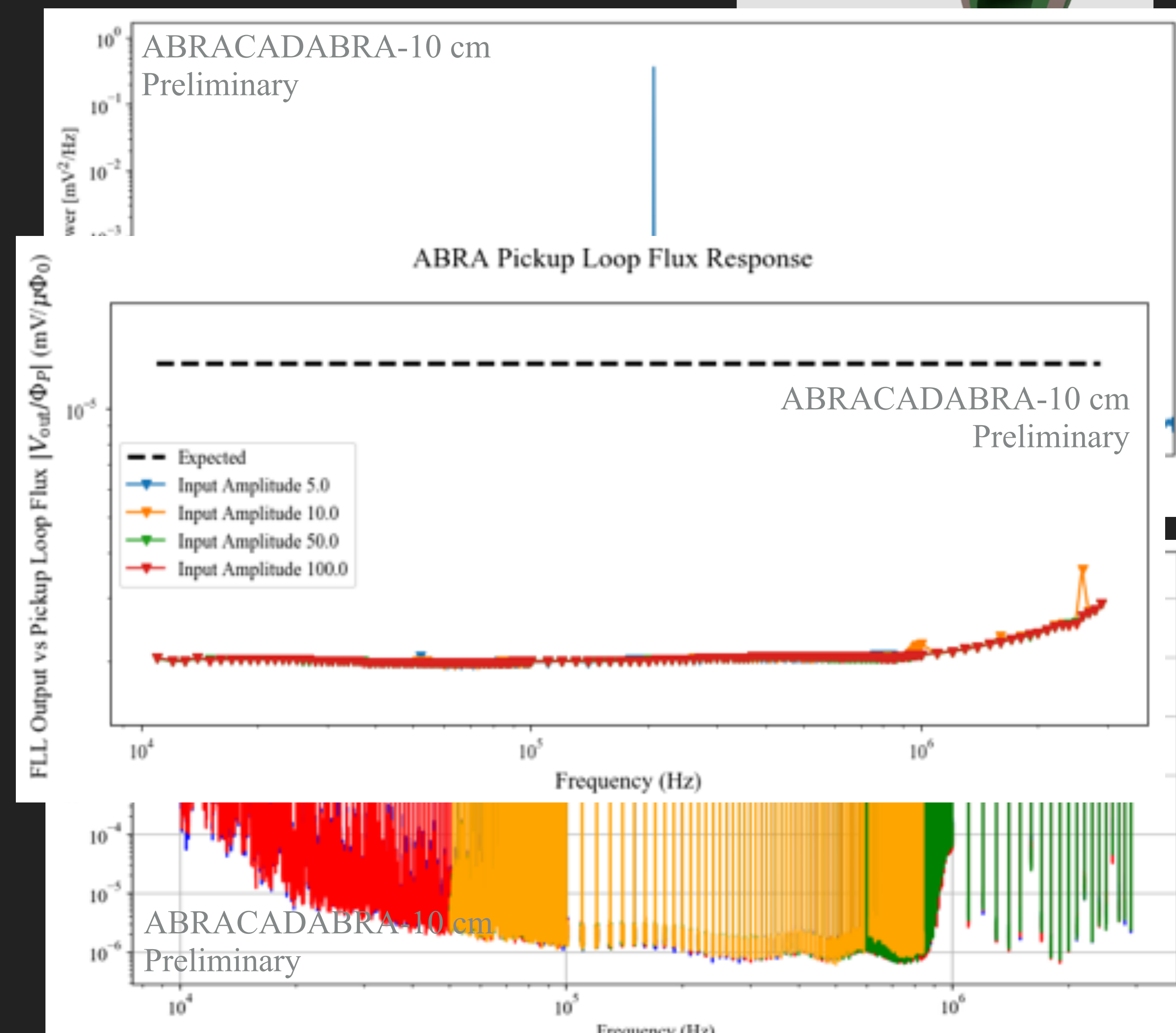
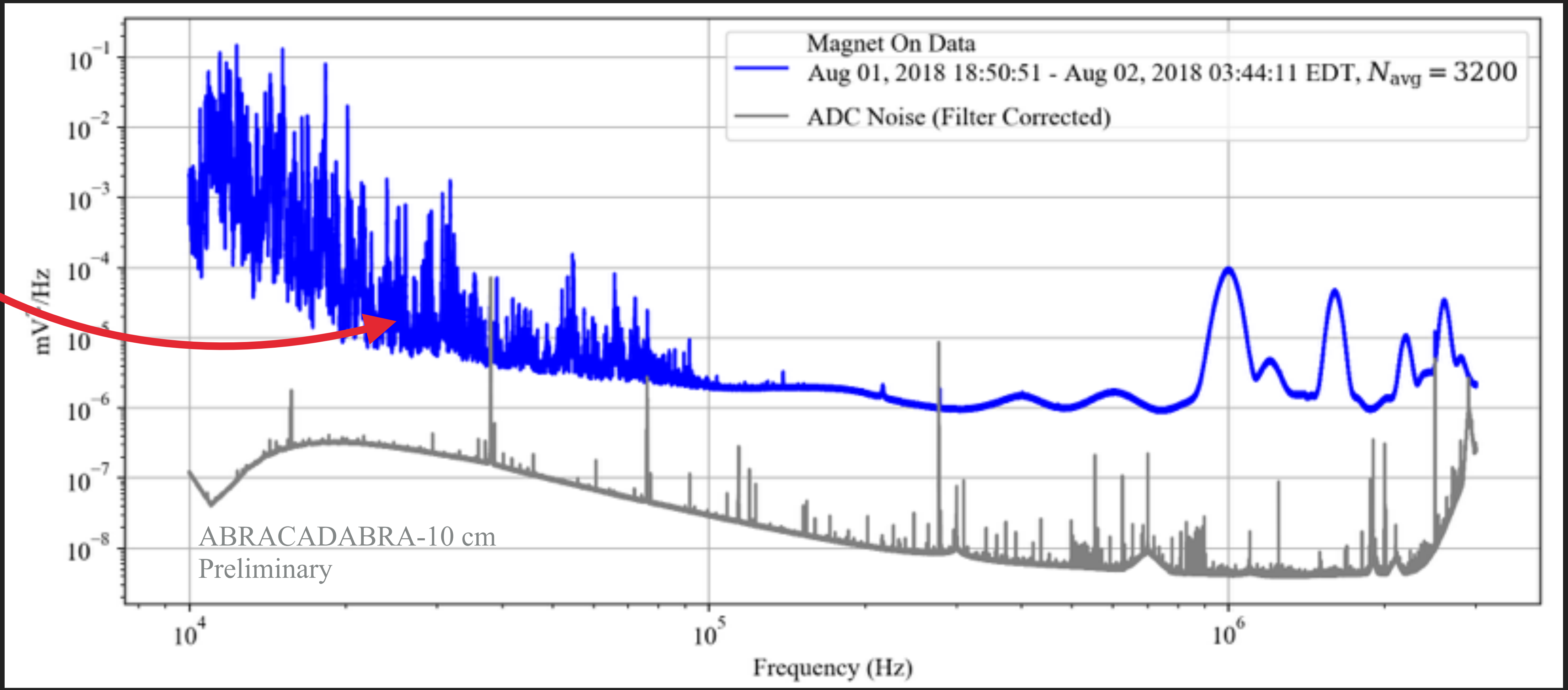


Example Spectrum

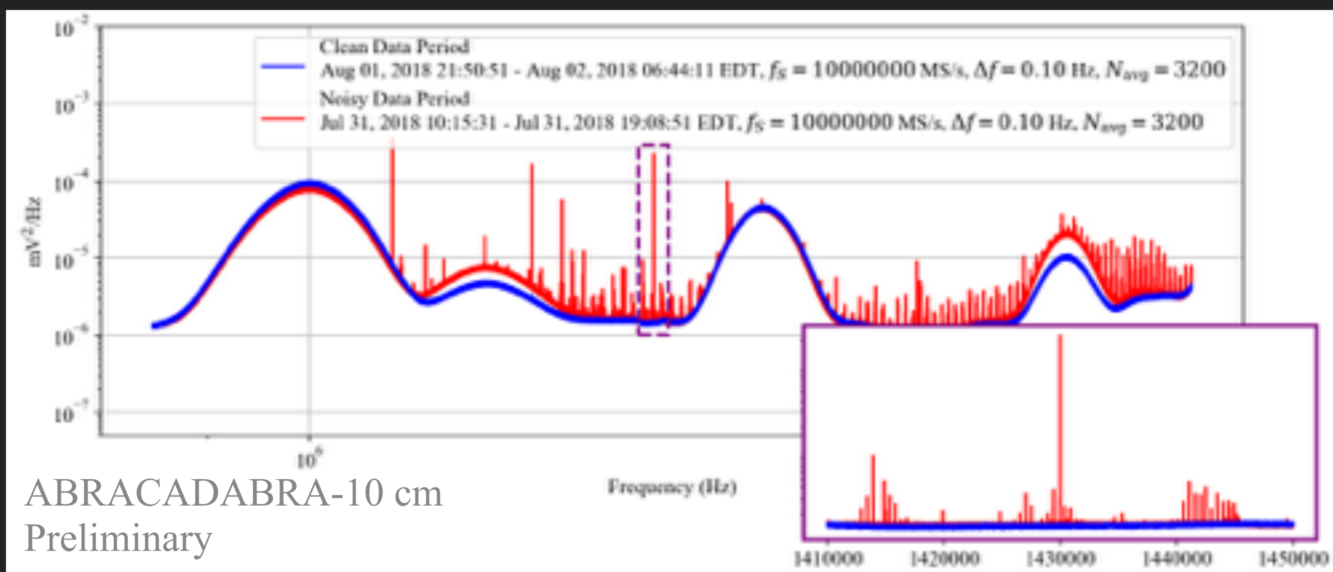
m_a ~ neV
(GUT scale PQ)

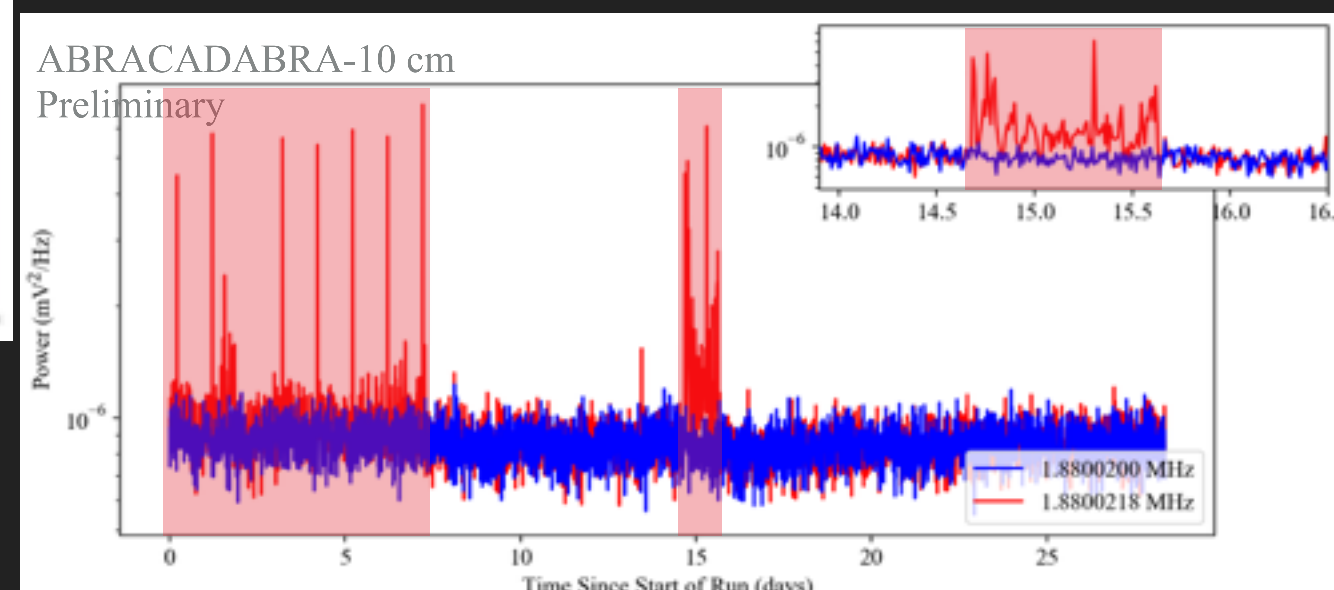
Tail of low frequency vibrational noise



- Filter SQUID output through 10 kHz high-pass and 1.9MHz anti-aliasing filter
- Digitizer noise (taken in dedicated run) shows spurious noise spikes that were vetoed.

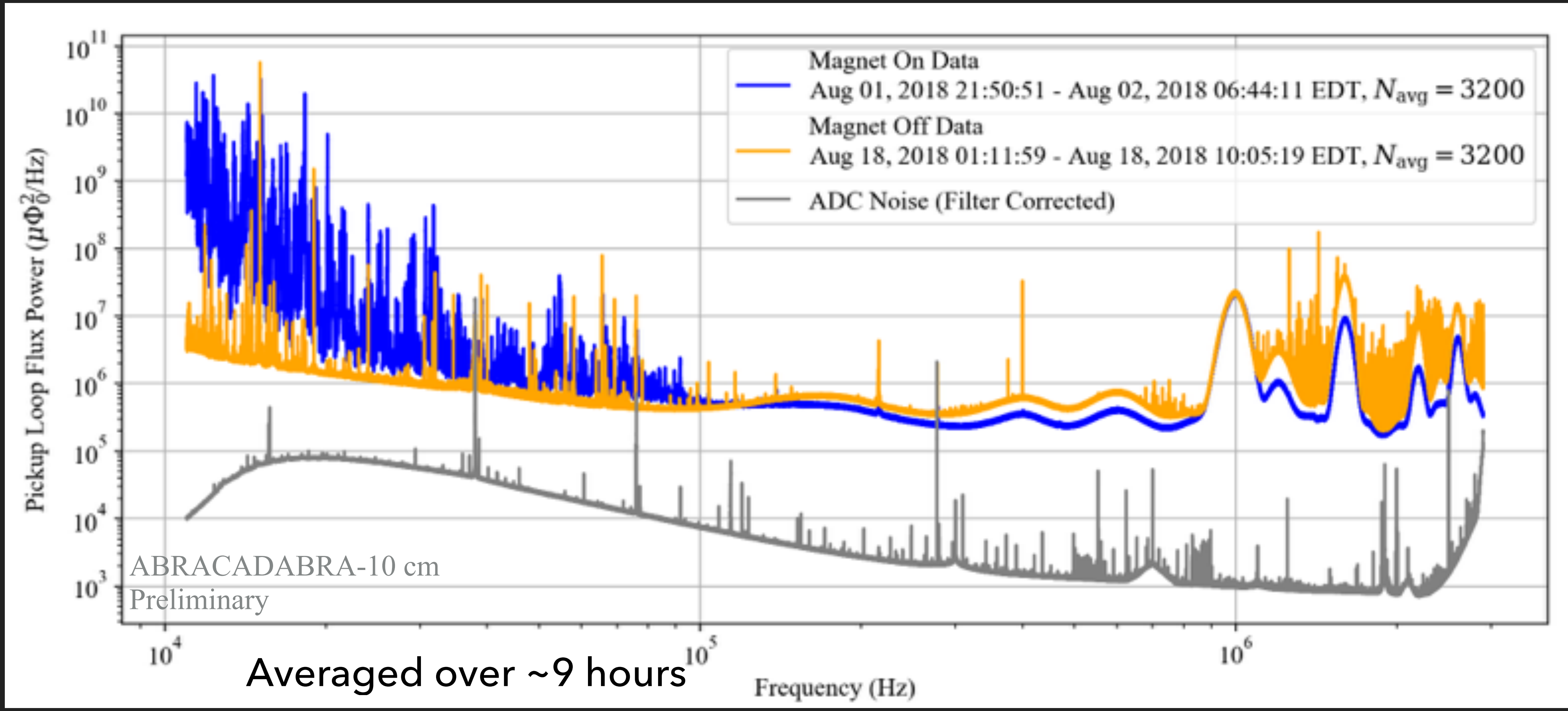
Transient Noise at High Frequency





- Appeared after we were in the lab
- Seemed to be correlated with working hours?
- Investigating the digitizer/DAQ computer, grounding schemes, shielding, etc…
- In the present analysis, we had to discard ~30% of the data

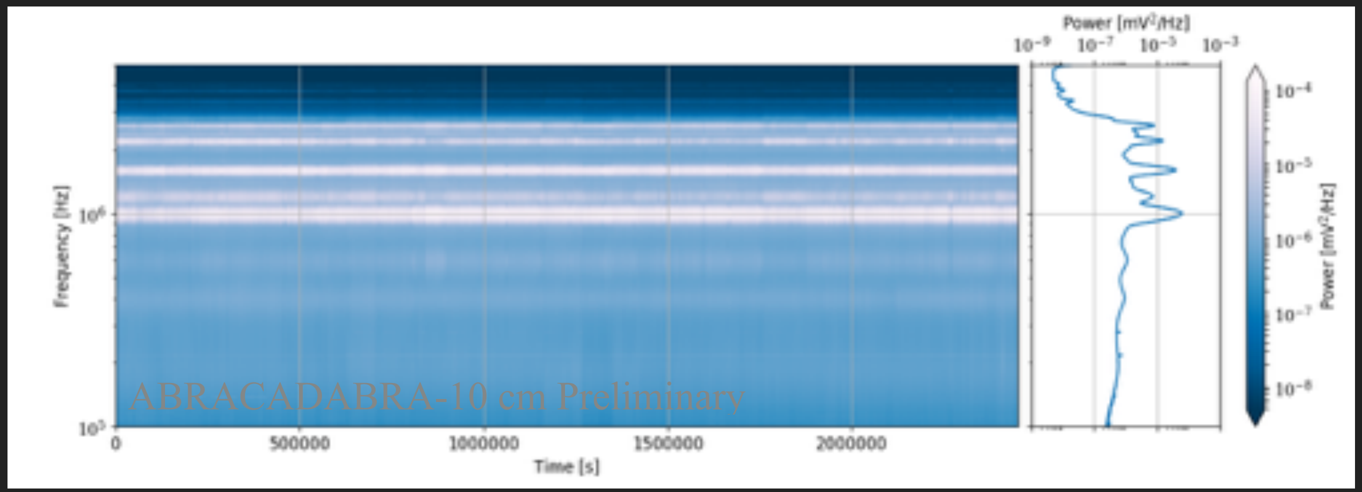
Magnet Off Data



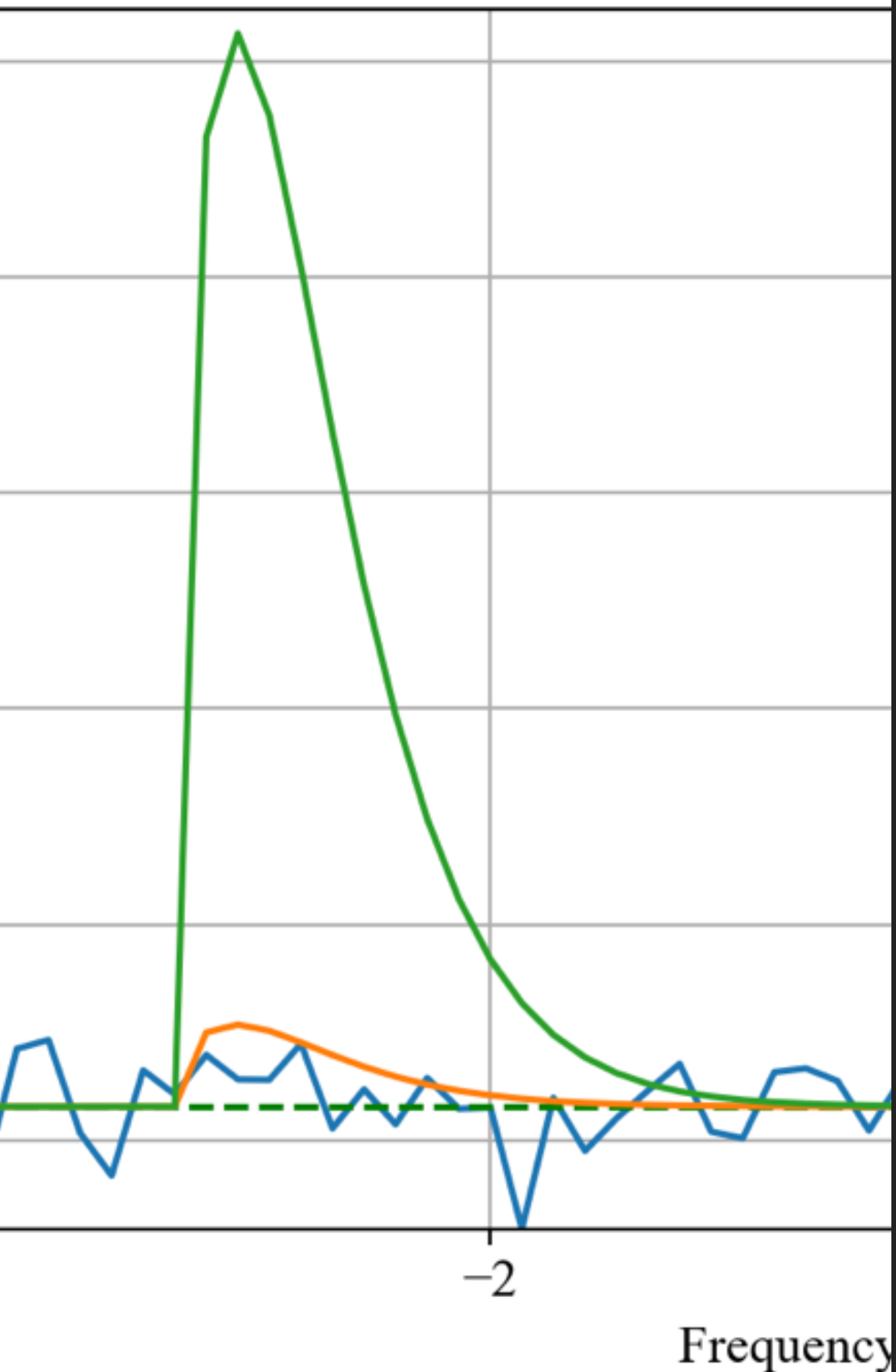
- Collected 2 weeks of magnet off data with the same configuration
- High frequency transient noise also present
- Significantly lower noise background around 10kHz (vibration of stray fields)
- Used for spurious signal veto

ABRACADABRA-10 cm First Dataset

- Collected data with magnet on continuously for 4 weeks from July - August
- Sampling at 10 MS/s for 2.4×10^6 seconds (25T samples total)
- Digitizer locked to a Rb oscillator frequency standard



	10 MS/s Dataset	1 MS/s Dataset
Integrated Time	471 h	427h
Individual Spectra	2120	960
Frequency Range	500 kHz - 3 MHz	75 kHz - 500 kHz



ABRACADABRA-10 CM

AXION SEARCH

AXION FIELD STATISTICS

J. W. Foster, N. L. Rodd, B. R. Safdi
Phys. Rev. D 97, 123006 (2018)

- The axion field is going to be a sum over a huge number of axion components, each with their own phase, φ_i

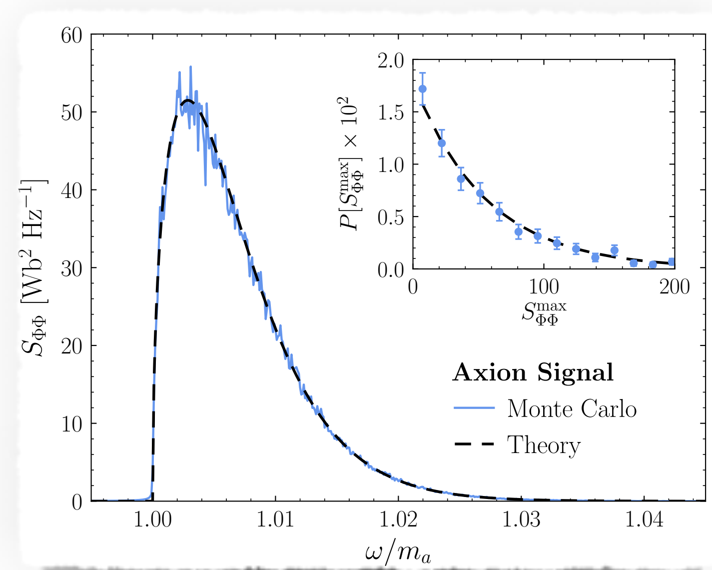
$$a_j(t) = \sum_{i \in \Omega_j} \frac{\sqrt{2\rho_{\rm DM}}}{m_a \sqrt{N_a}} \cos\left[m_a\left(1+\frac{v_j^2}{2}\right)t + \phi_i\right]$$

- This is similar to a random walk in phase space and results in a signal power which is exponentially distributed

$$P\left[S_{\Phi\Phi}(\omega)\right] = \frac{1}{\lambda(\omega)} e^{-S_{\Phi\Phi}(\omega)/\lambda(\omega)},$$

$$\lambda(\omega) \equiv \langle S_{\Phi\Phi}(\omega)\rangle = A\, \frac{\pi f(v)}{m_a v}\bigg|_{v=\sqrt{2\omega/m_a - 2}}$$

Detector power coupling



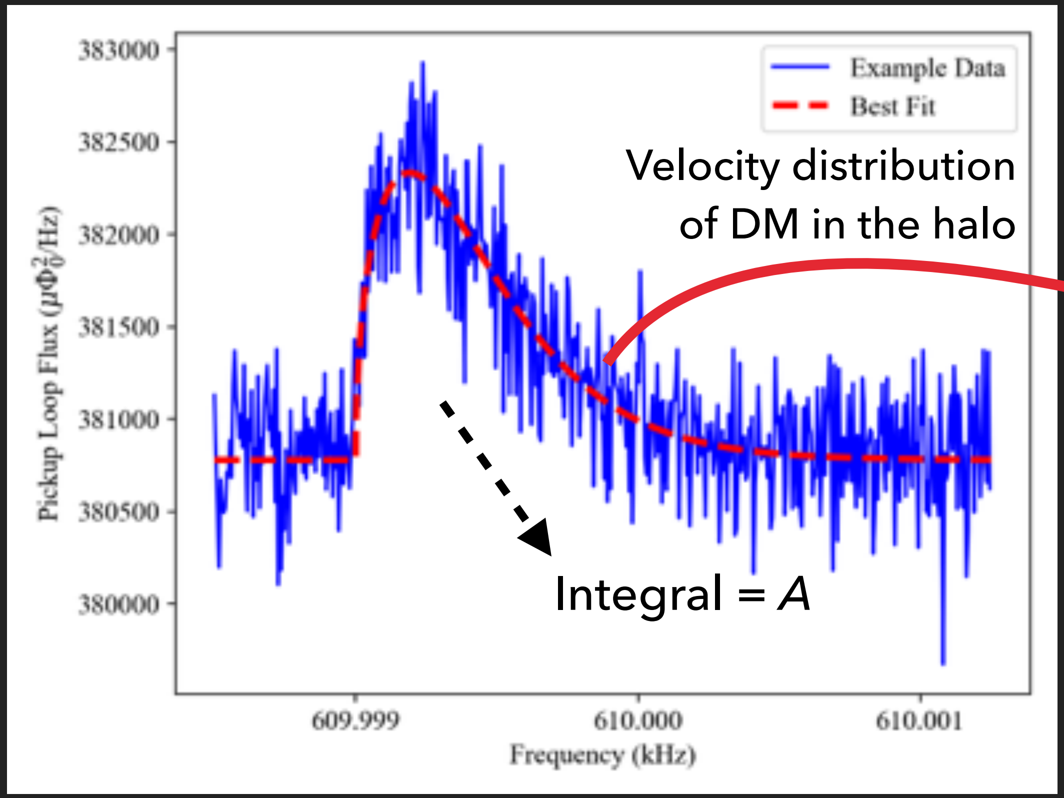
- The correct statistics are needed when analyzing our 8.1M mass points (a broadband experiment cannot "rescan" excesses).

Axion Signal

- Time averaged flux through the pickup loop:

$$\langle \Phi^2_{\text{Pickup}} \rangle = g^2_{a\gamma\gamma} \rho_{\text{DM}} V^2 \mathcal{G}^2 B^2_{\text{max}} \equiv A \qquad (\text{Units: } \mu\Phi_0^2/\text{Hz})$$

- Signal shape given by the standard halo model



$$f(v|v_0, v_{\text{obs}}) = \frac{v}{\sqrt{\pi} v_0 v_{\text{obs}}} e^{-(v+v_{\text{obs}})^2/v_0^2} \times \left(e^{4vv_{\text{obs}}/v_0^2} - 1 \right)$$

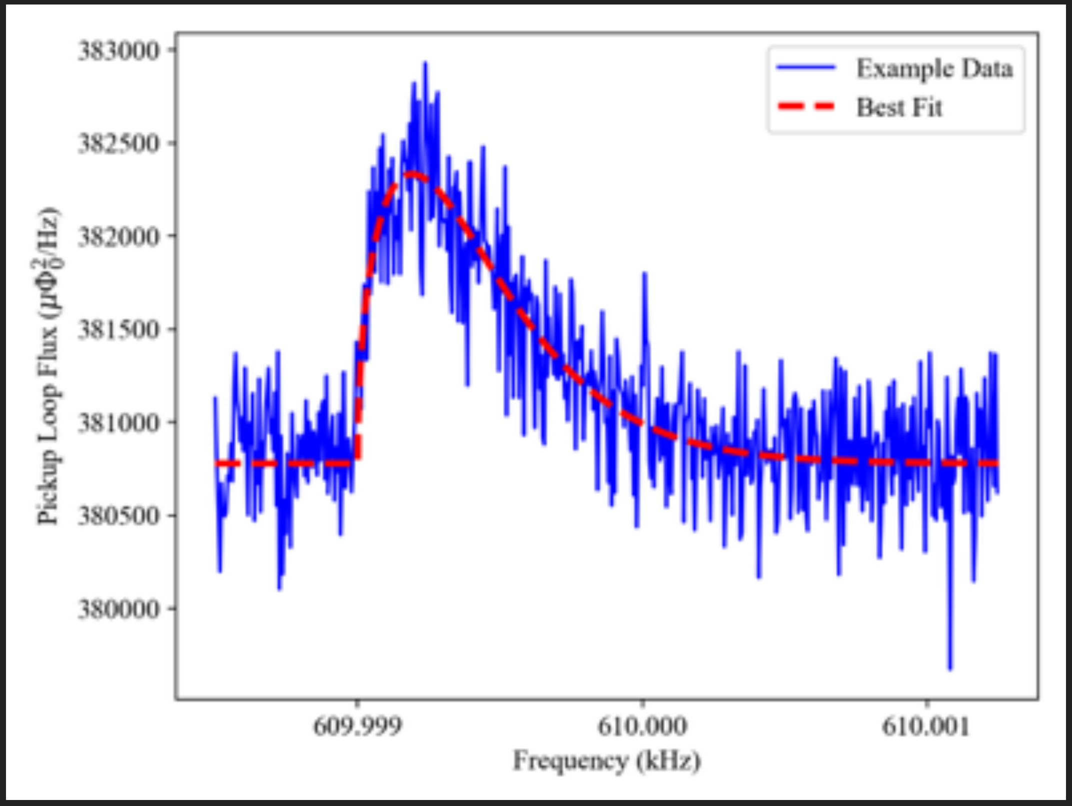
Axion Search Approach

- Rebin the data into 53 (24) of our 10 MS/s (1 MS/s) spectra that span the data taking period
- Limit search range to 75 kHz - 2 MHz (m_a in 0.31 – 8.1 neV) for a total of 8.1M mass points
- For each mass point, we calculate a likelihood function

$$\mathcal{L} = \prod_i^{N_{\text{Spectra}}} \prod_j^{N_{\text{Freq}}} \text{Erlang}(N_{\text{Avg}}, s_{i,k} + b_i)$$

$N_{\text{Avg}} = 3200\ (640)$

- Power bins are Erlang distributed with shape parameter N_{avg} (average over N_{avg} exponential distributions) and mean $s_{i,k}+b_i$
- Depends only on $g_{a\gamma\gamma}$ and nuisance parameters, b_i, which are assumed to be constant across the axion signal, but can vary slowly in time

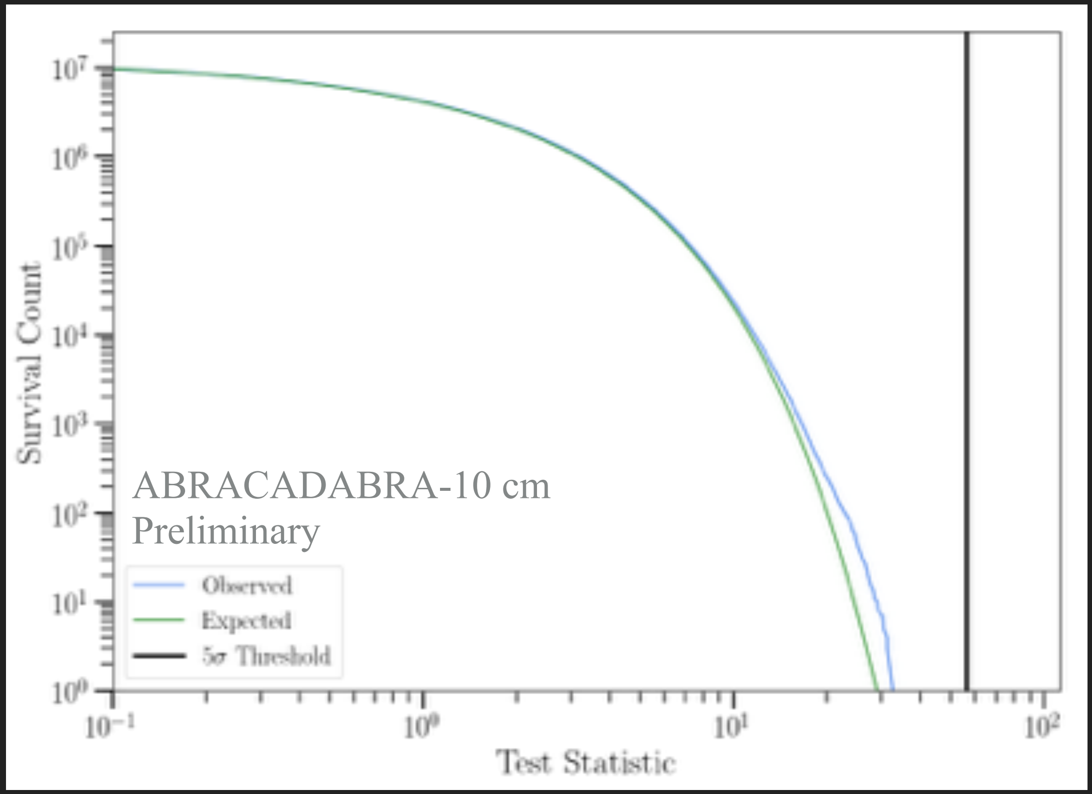


Axion Search Approach

- We then perform our axion discovery search based on a log-likelihood ratio test, between the best fit and the null hypothesis

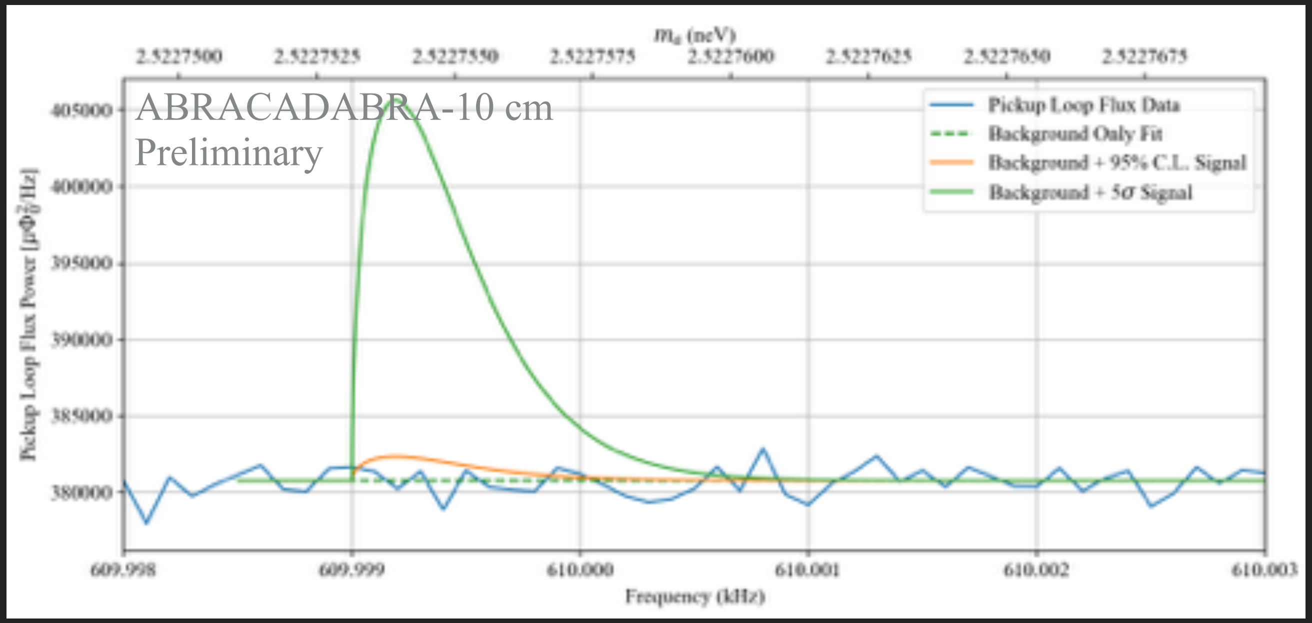
$$TS = 2\left[\log\mathcal{L}\left(\hat{g}_{a\gamma\gamma}, m_a, \hat{\hat{\mathbf{b}}}\right) - \log\mathcal{L}\left(g_{a\gamma\gamma} = 0, m_a, \hat{\mathbf{b}}\right)\right]$$

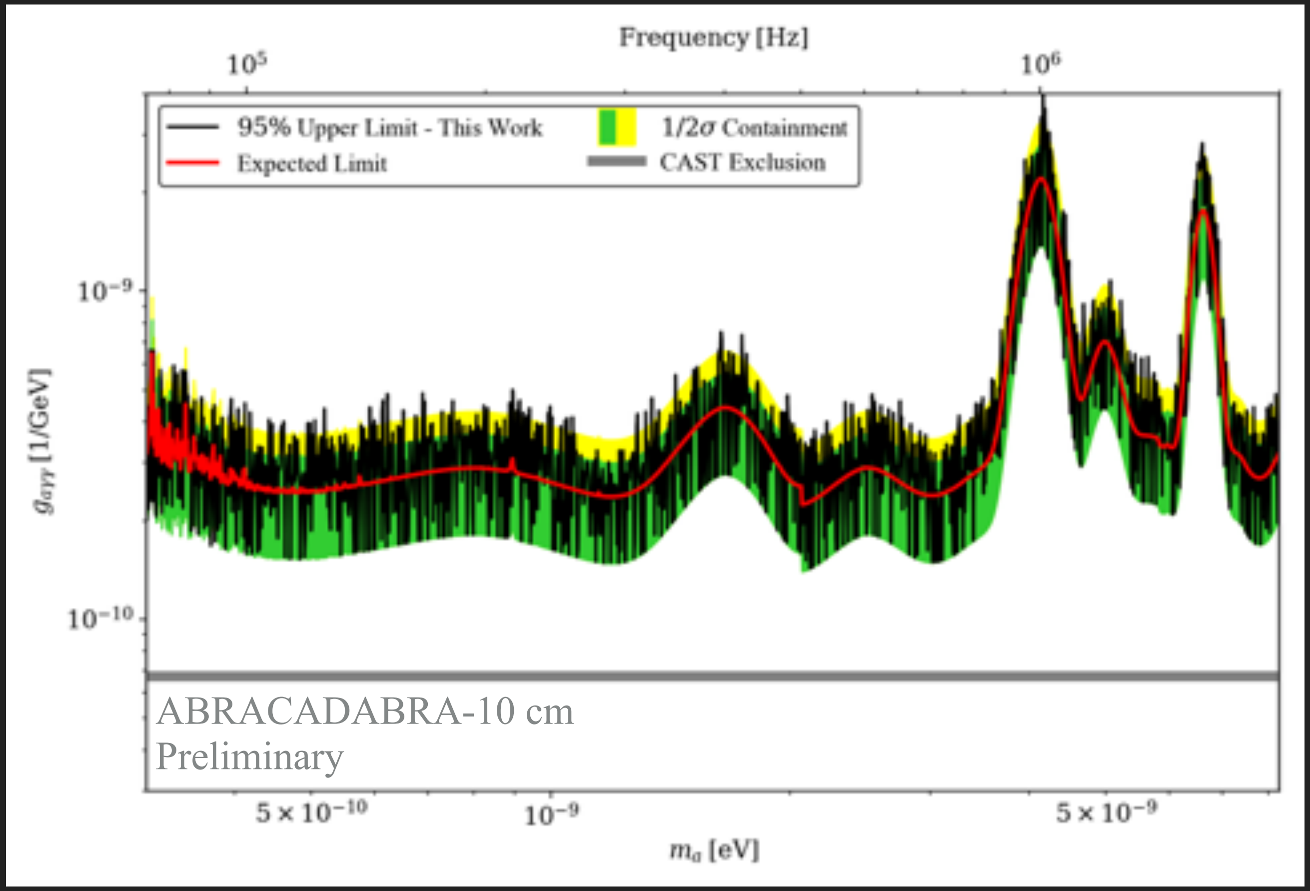
- Profiling over all nuisance parameters, b_i
- We set the 5σ discovery threshold as TS>56.1 (accounting for the Look Elsewhere Effect for our 8M mass points)



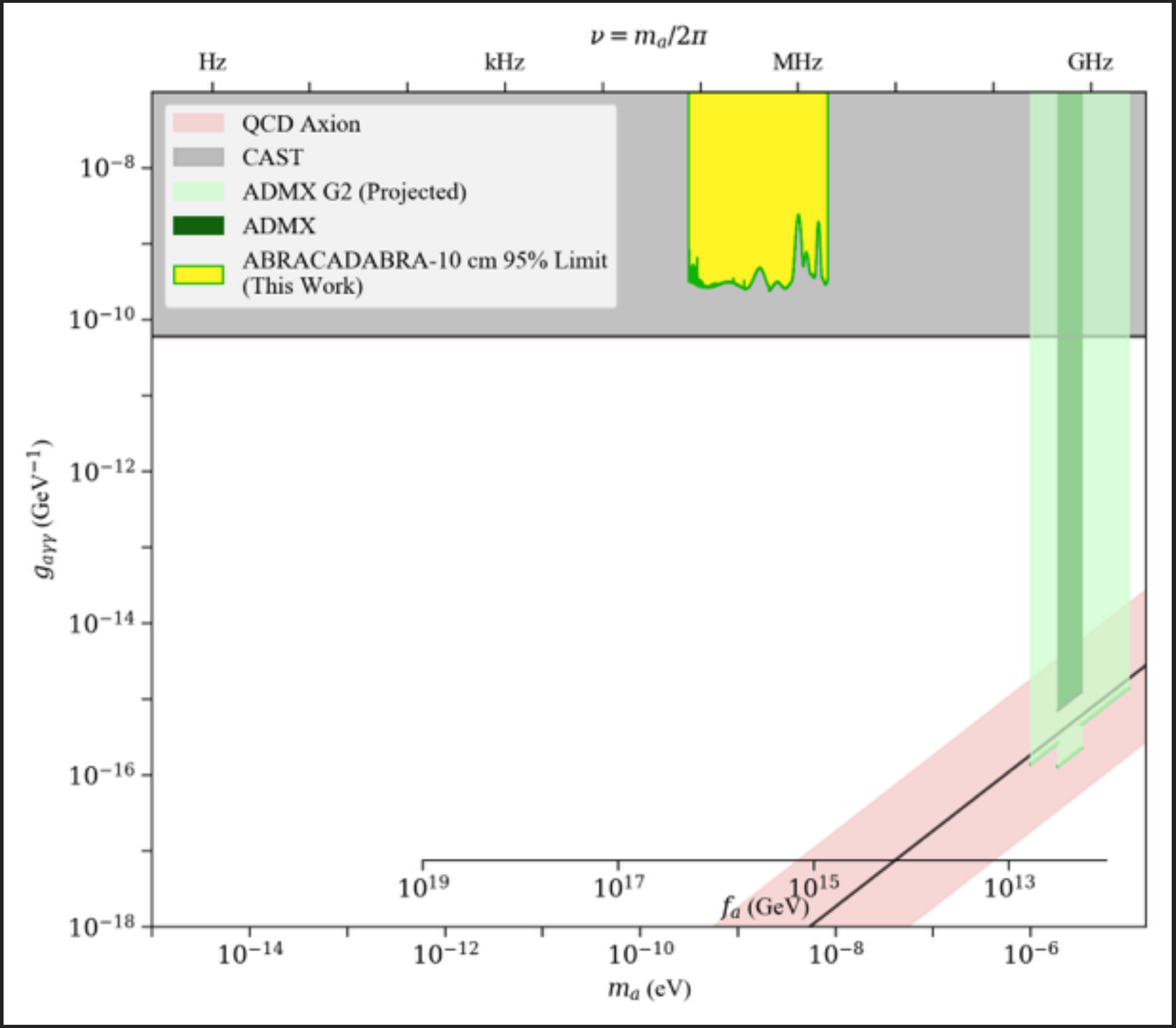
Axion Limits

- 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

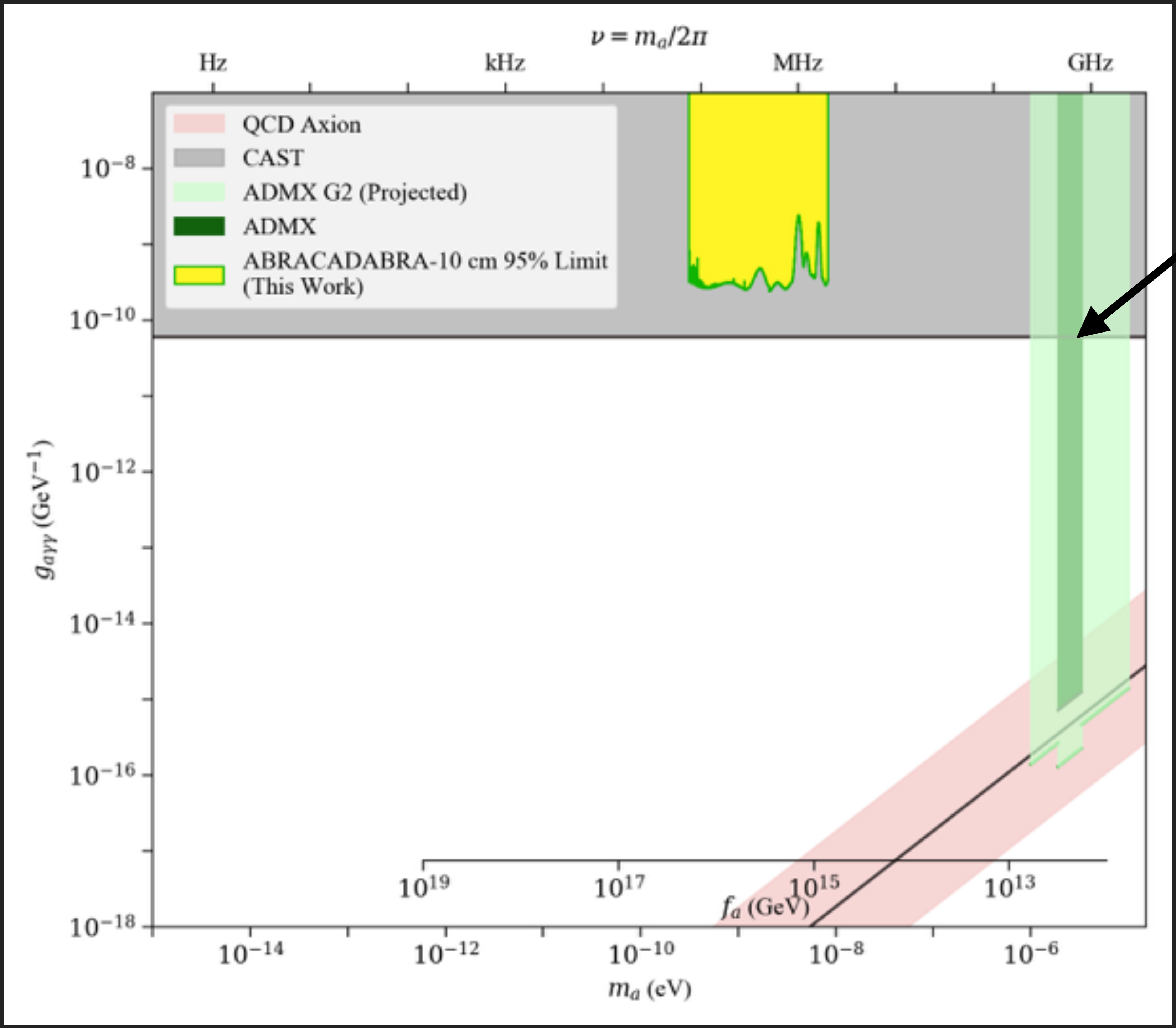




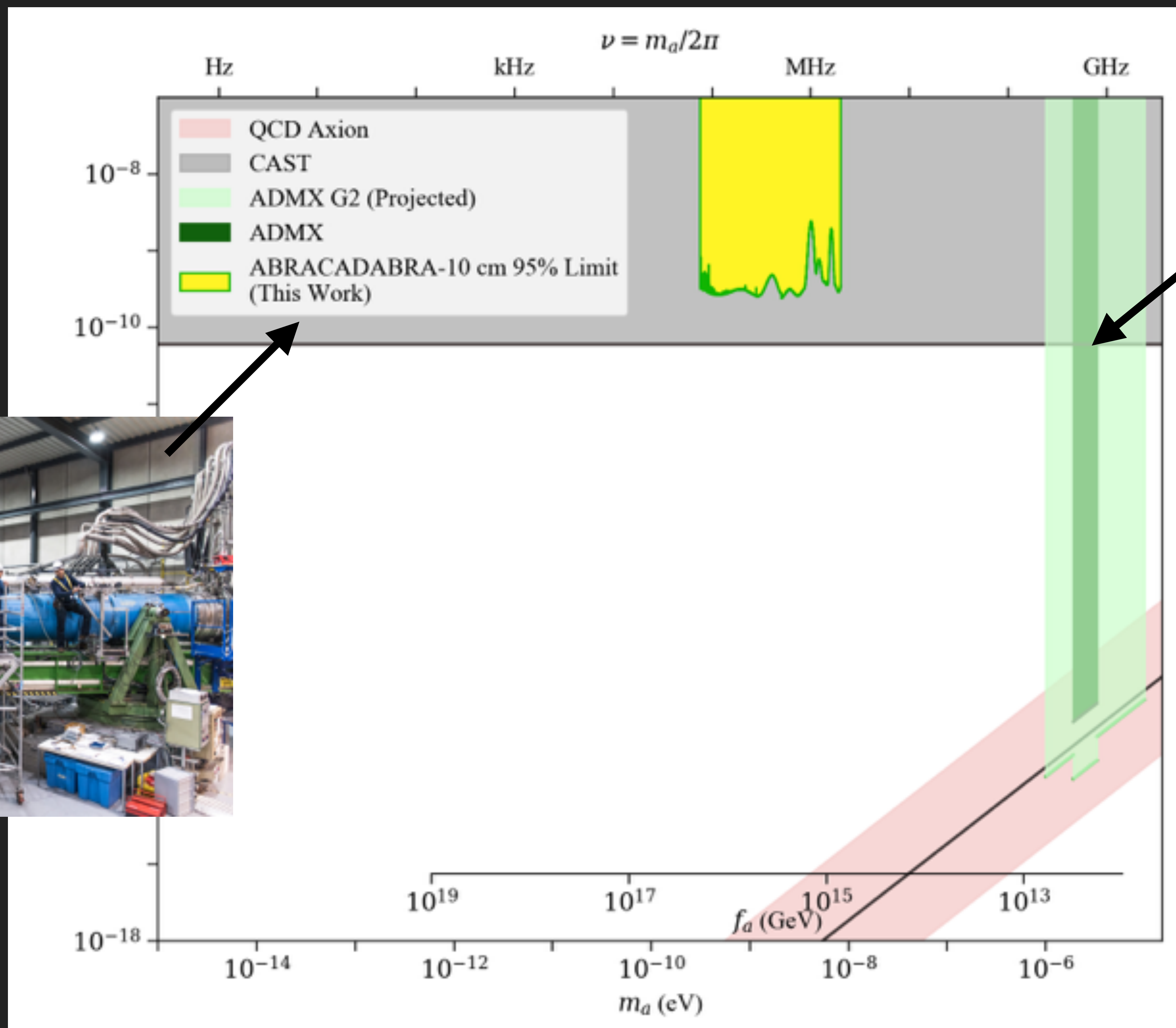
ABRACADABRA-10 cm Run 1 Limits

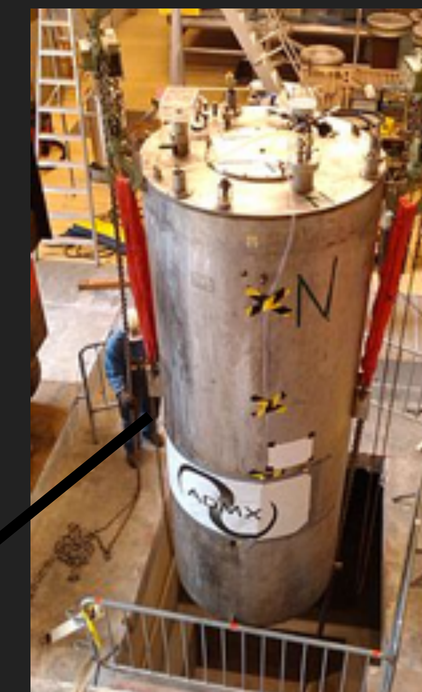


ABRACADABRA-10 cm Run 1 Limits



ABRACADABRA-10 cm Run 1 Limits





ABRACADABRA-10 cm First Results

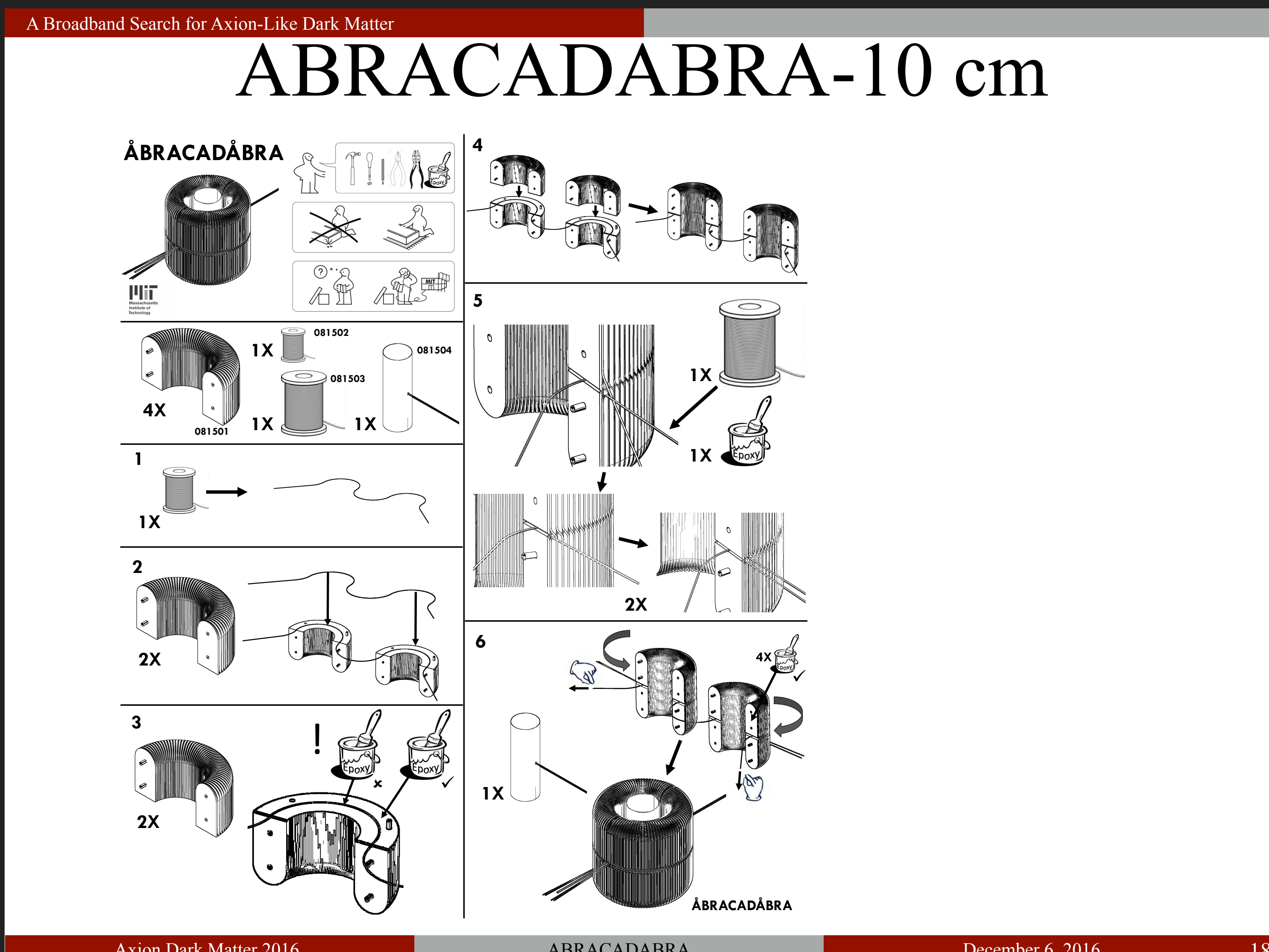
First Results from ABRACADABRA-10 cm: A Search for Sub-μeV Axion Dark Matter

Jonathan L. Ouellet,[1,*] Chiara P. Salemi,[1] Joshua W. Foster,[2] Reyco Henning,[3,4] Zachary Bogorad,[1] Janet M. Conrad,[1] Joseph A. Formaggio,[1] Yonatan Kahn,[5,6] Joe Minervini,[7] Alexey Radovinsky,[7] Nicholas L. Rodd,[8,9] Benjamin R. Safdi,[2] Jesse Thaler,[10] Daniel Winklehner,[1] and Lindley Winslow[1,†]

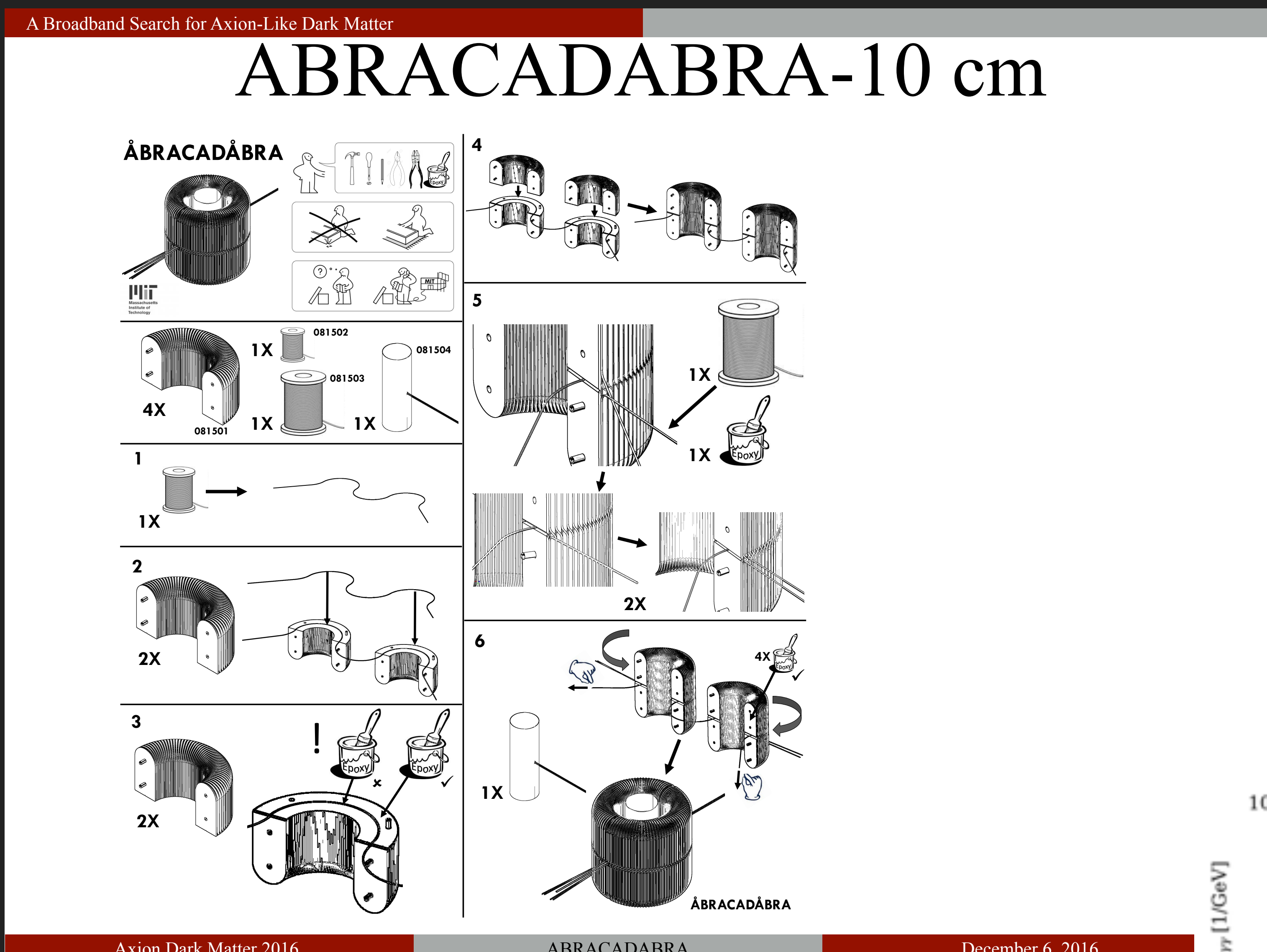
arXiv:1810.12257

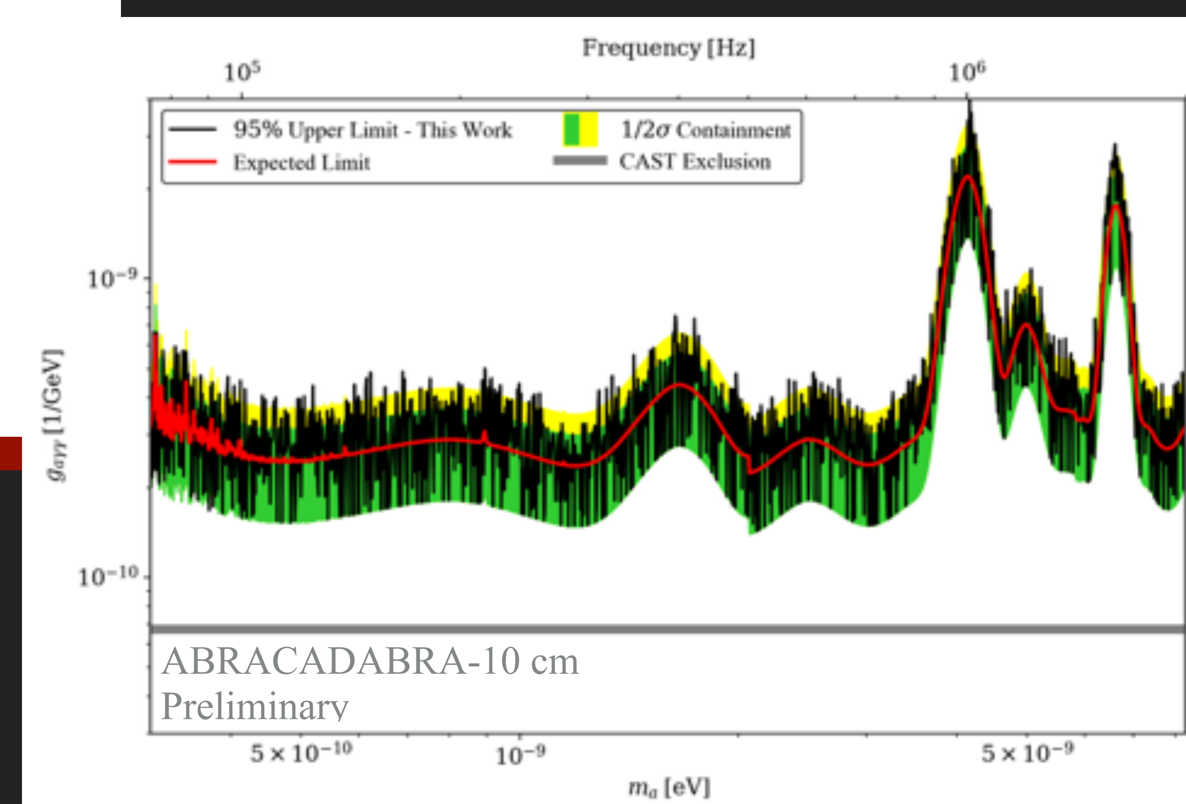
ABRACADABRA-10cm Technical Paper
(Coming Soon)

ABRACADABRA-10 cm At Axion Dark Matter 2016



ABRACADABRA-10 cm At Axion Dark Matter 2016



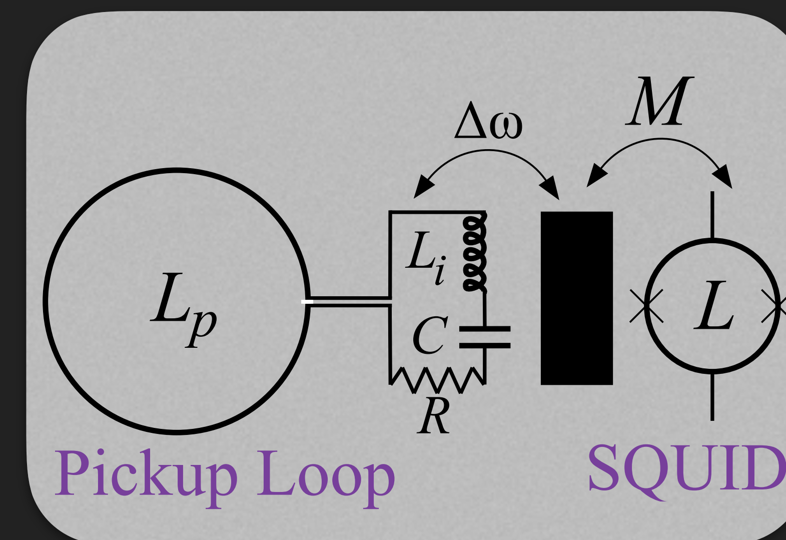


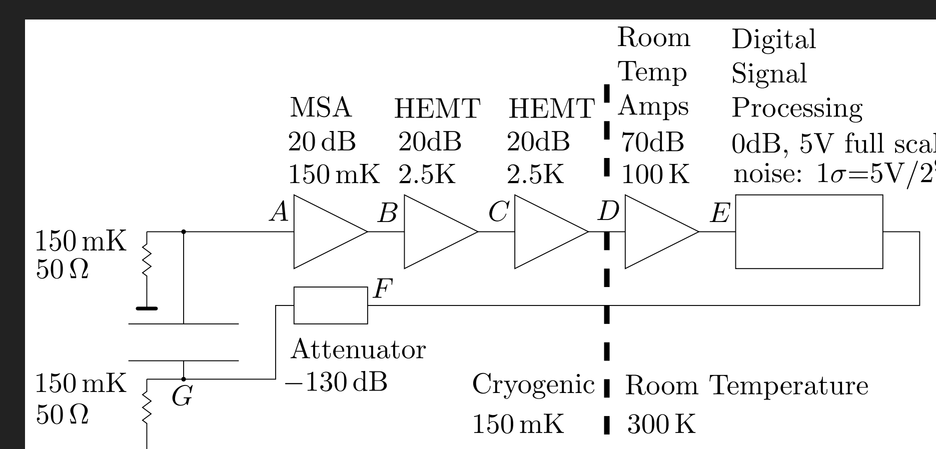
REACHING THE QCD SCALE WITH

ABRACADABRA 1m

Resonant Approach

- Feed signal back in on itself to amplify narrow frequency band by large factors (Q~10^6)
- Can use a physical resonator (capacitor), but requires very high Q with very large capacitance
    - Physical tuning, swapping out resonators
- Alternate approach with "digital" resonator
    - Much faster scanning
    - Broadband cold amplification, SNR set by first amplifier





E. Daw (arXiv:1805.11523)

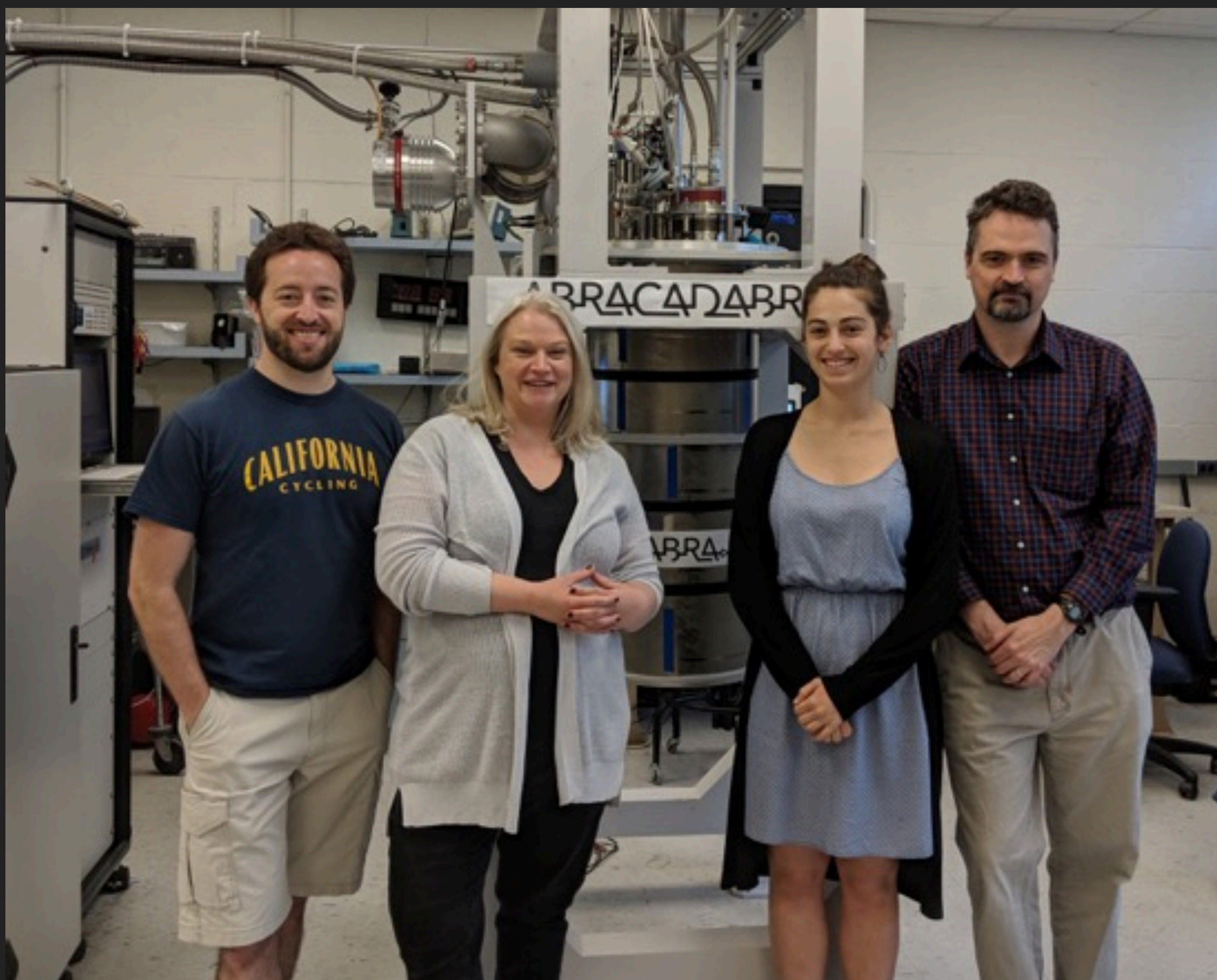
Resonant Approach

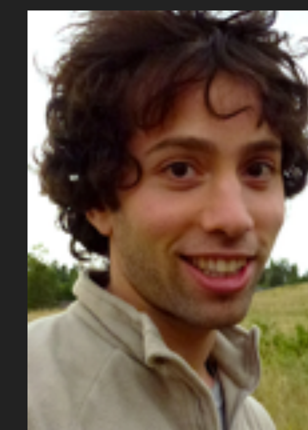
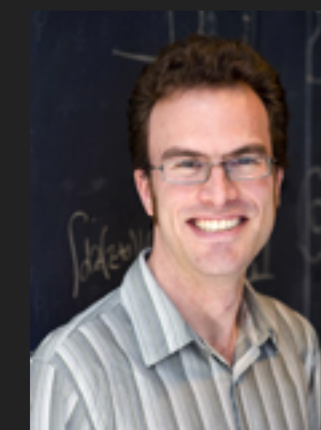
$$\mathrm{SNR} = \frac{P_{\mathrm{sig}}}{P_{\mathrm{noise}}}\sqrt{\Delta f_{\mathrm{Exp}} t}$$

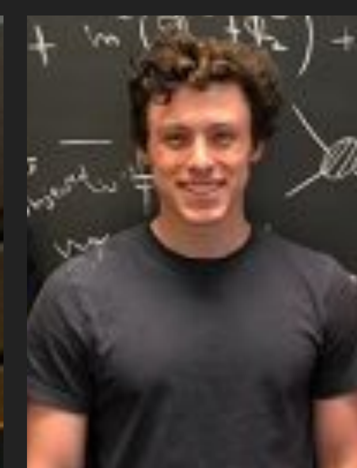
$$P_{\mathrm{Sig}} \sim \frac{g_{a\gamma\gamma}^2 B_{\mathrm{max}}^2 \mathcal{G}_V^2 V^2 Q^2 \rho_{\mathrm{DM}}}{L_T}$$

$$P_{\mathrm{Noise}} \sim kT_{\mathrm{Eff}} \Delta f_{\mathrm{Exp}}$$

ABRACADABRA



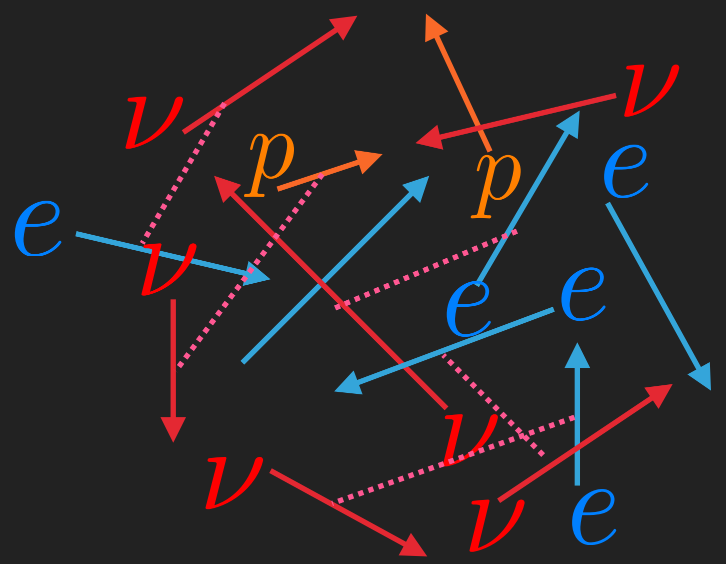






Thank you for your attention!

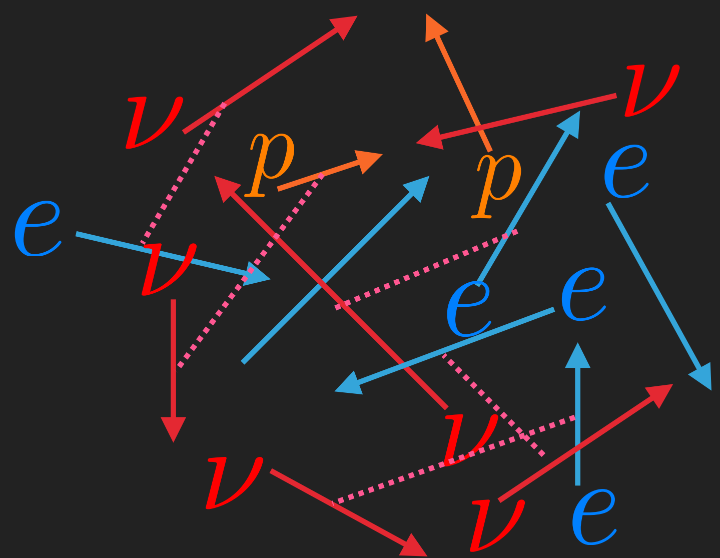
Backup

Cosmic Neutrinos vs Cosmic Axions



- In the early universe (t<1 s), the neutrinos are thermalized to the plasma
- After they decouple, they are hot and relativistic for most of cosmic history
- They are not COLD dark matter!

Cosmic Neutrinos vs Cosmic Axions



- In the early universe (t<1 s), the neutrinos are thermalized to the plasma
- After they decouple, they are hot and relativistic for most of cosmic history
- They are not COLD dark matter!

- All axions start at the same alignment
  - Very very cold!
- Energy density comes from field potential and kinetic energy

A New Way to Search for Axion Dark Matter

PRL **117,** 141801 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

Broadband and Resonant Approaches to Axion Dark Matter Detection

Yonatan Kahn,[1,*] Benjamin R. Safdi,[2,†] and Jesse Thaler[2,‡]
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[2]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

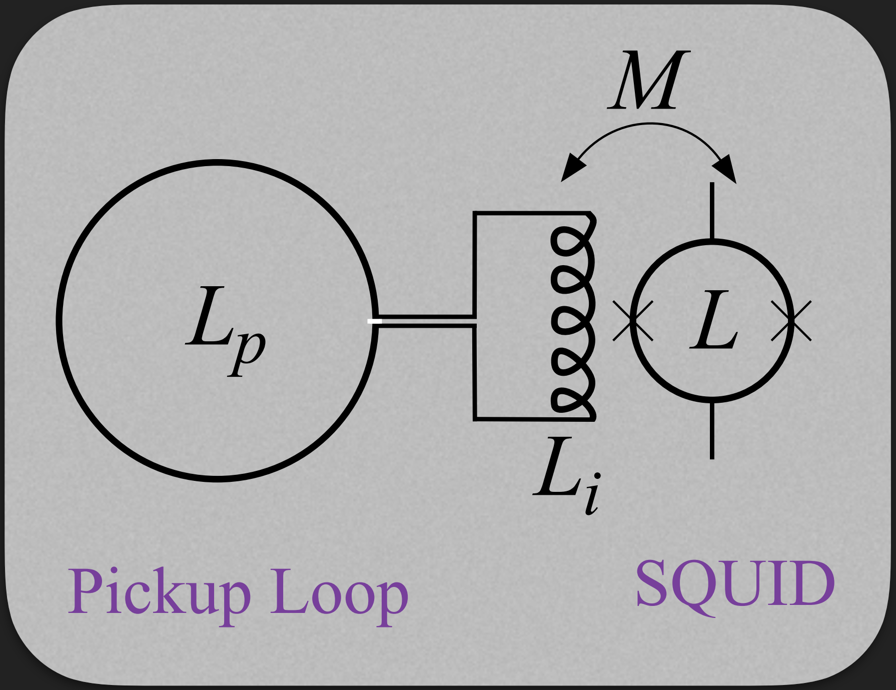
(Received 3 March 2016; published 30 September 2016)

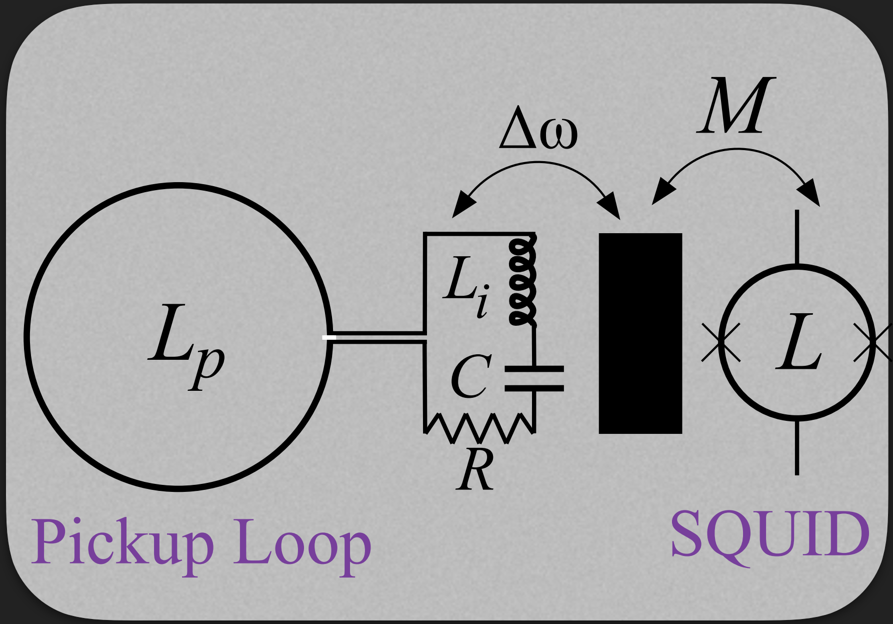
When ultralight axion dark matter encounters a static magnetic field, it sources an effective electric current that follows the magnetic field lines and oscillates at the axion Compton frequency. We propose a new experiment to detect this axion effective current. In the presence of axion dark matter, a large toroidal magnet will act like an oscillating current ring, whose induced magnetic flux can be measured by an external pickup loop inductively coupled to a SQUID magnetometer. We consider both resonant and broadband readout circuits and show that a broadband approach has advantages at small axion masses. We estimate the reach of this design, taking into account the irreducible sources of noise, and demonstrate potential sensitivity to axionlike dark matter with masses in the range of 10^{-14}-10^{-6} eV. In particular, both the broadband and resonant strategies can probe the QCD axion with a GUT-scale decay constant.

DOI: 10.1103/PhysRevLett.117.141801

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



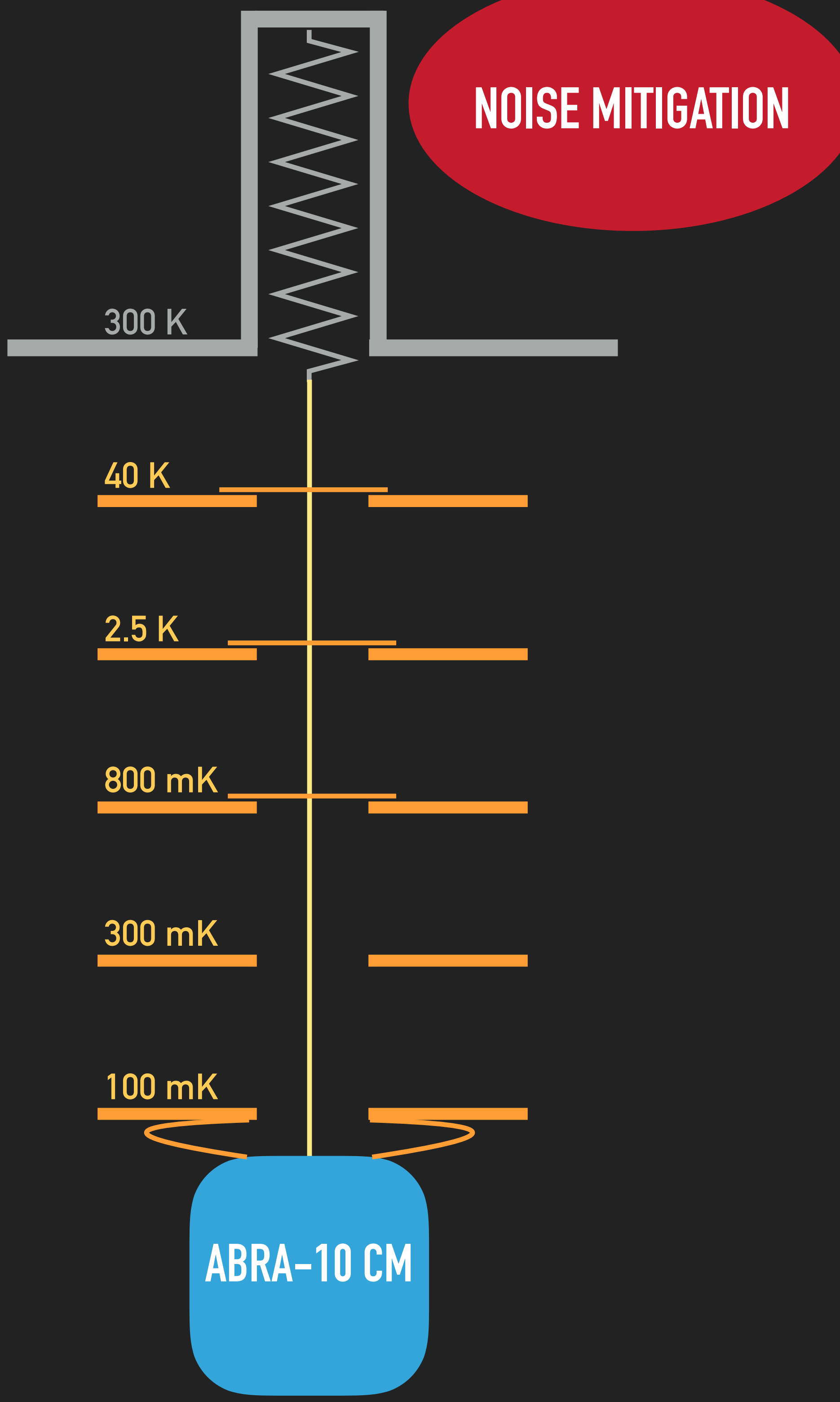


ABRACADABRA-10 cm Tour

ABRACADABRA-10 cm Tour

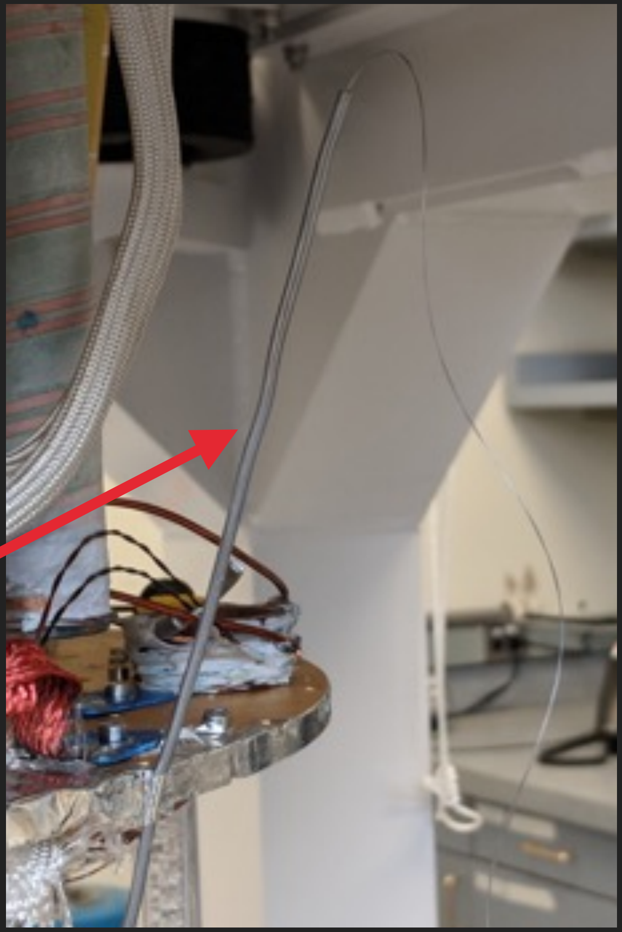
Suspension System

- 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



Superconducting Wiring

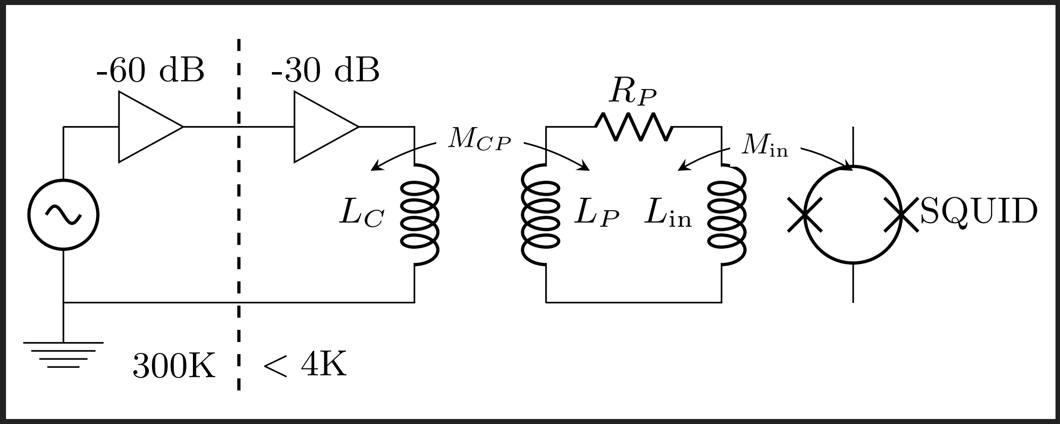
- Magnet wiring is NbTi(CuNi)
- All readout wiring and calibration loop is solid NbTi
- Readout wiring run inside single core solder wire that has had the flux removed

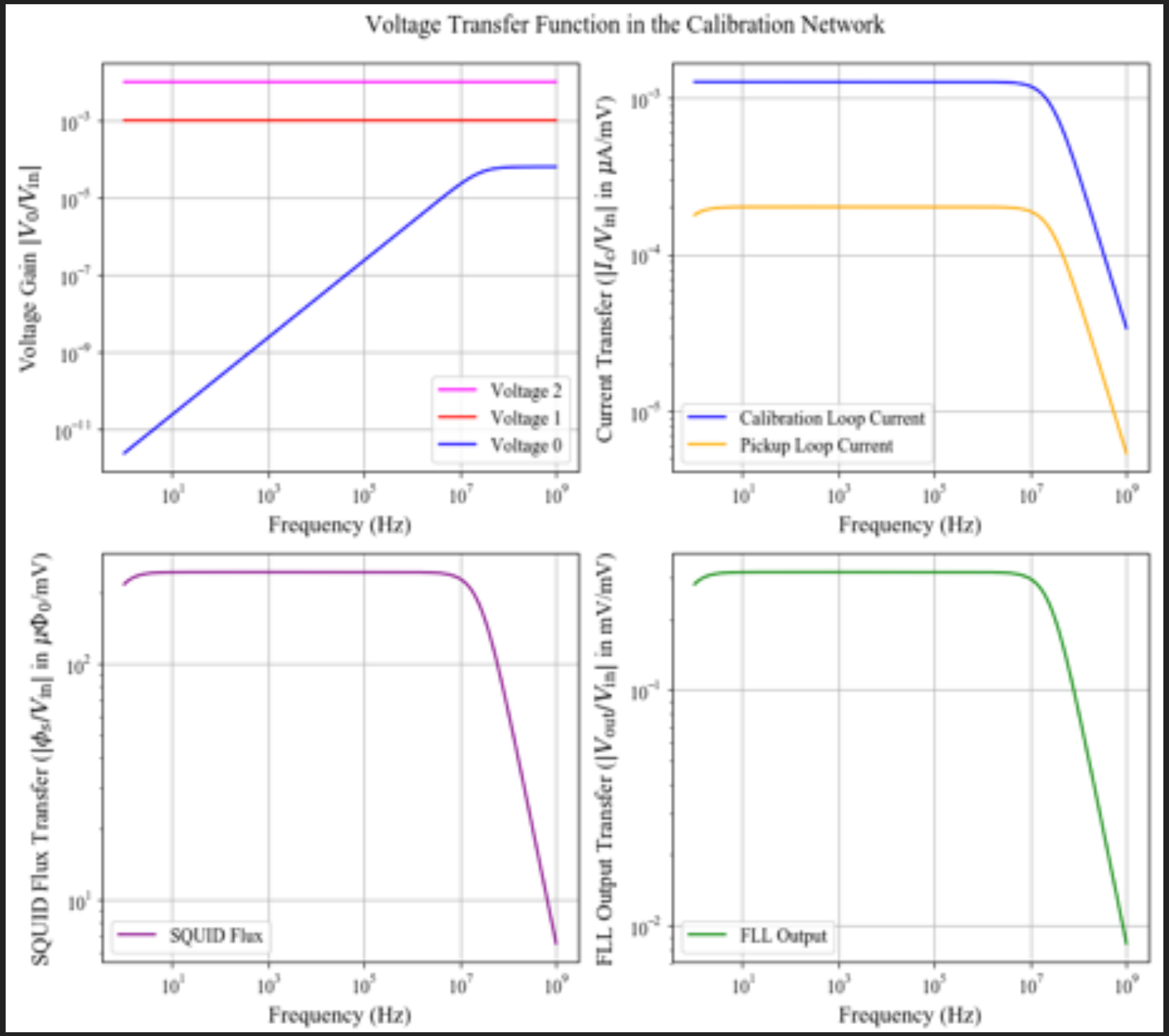


Calibration Network

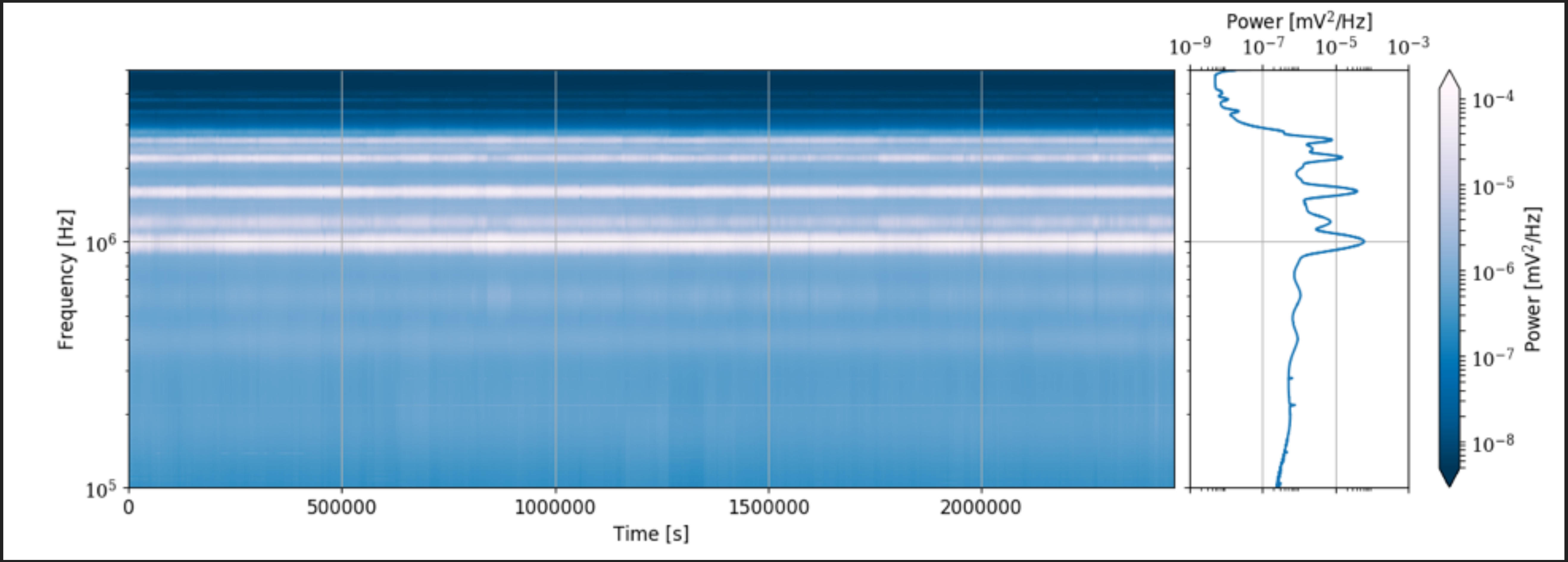
- ✓ 60 dB of warm attenuation
- ✓ Readout circuit
- ✓ SQUID noise is approximately as expected
- ✓ Parasitic resistance in the circuit
- x ~~Need to check cold attenuator (3 K)~~
- x ~~Flux coupling?~~

➡ Parasitic Inductance from the wires

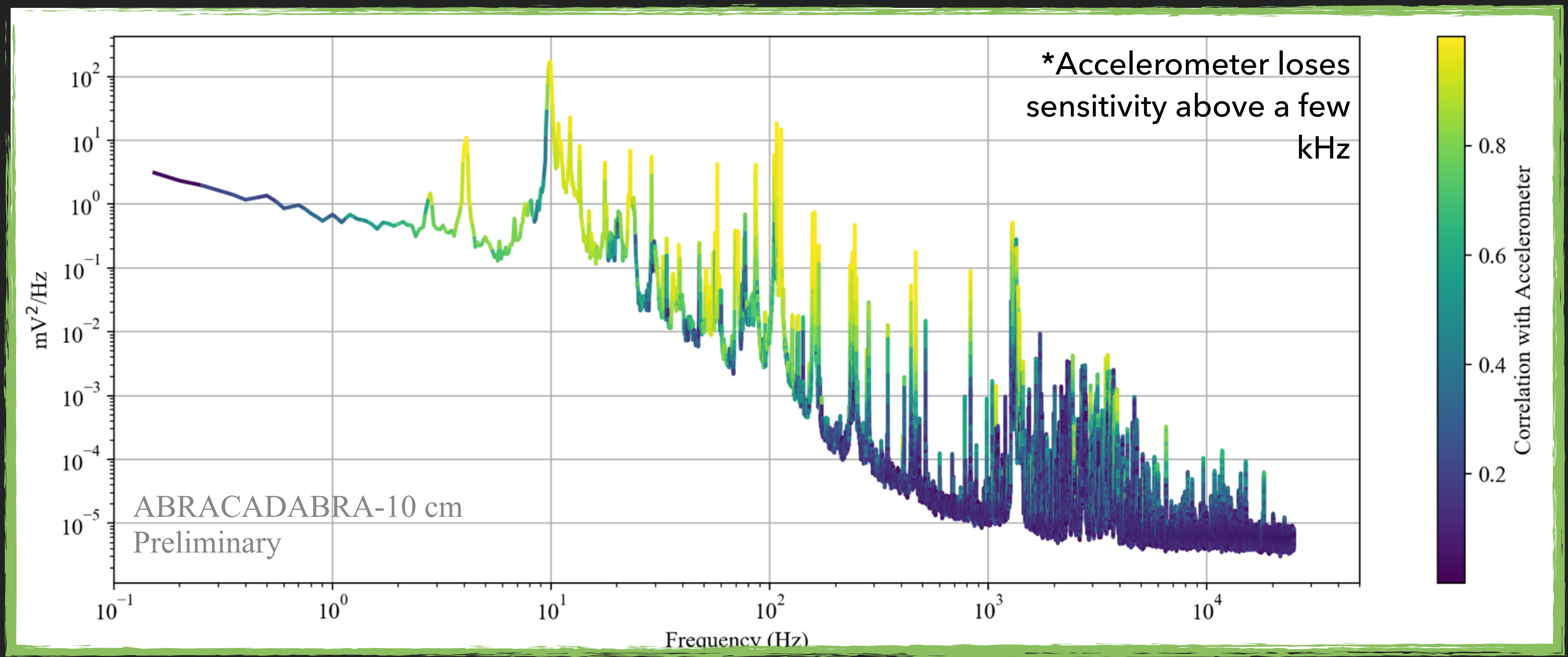




Stability


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]

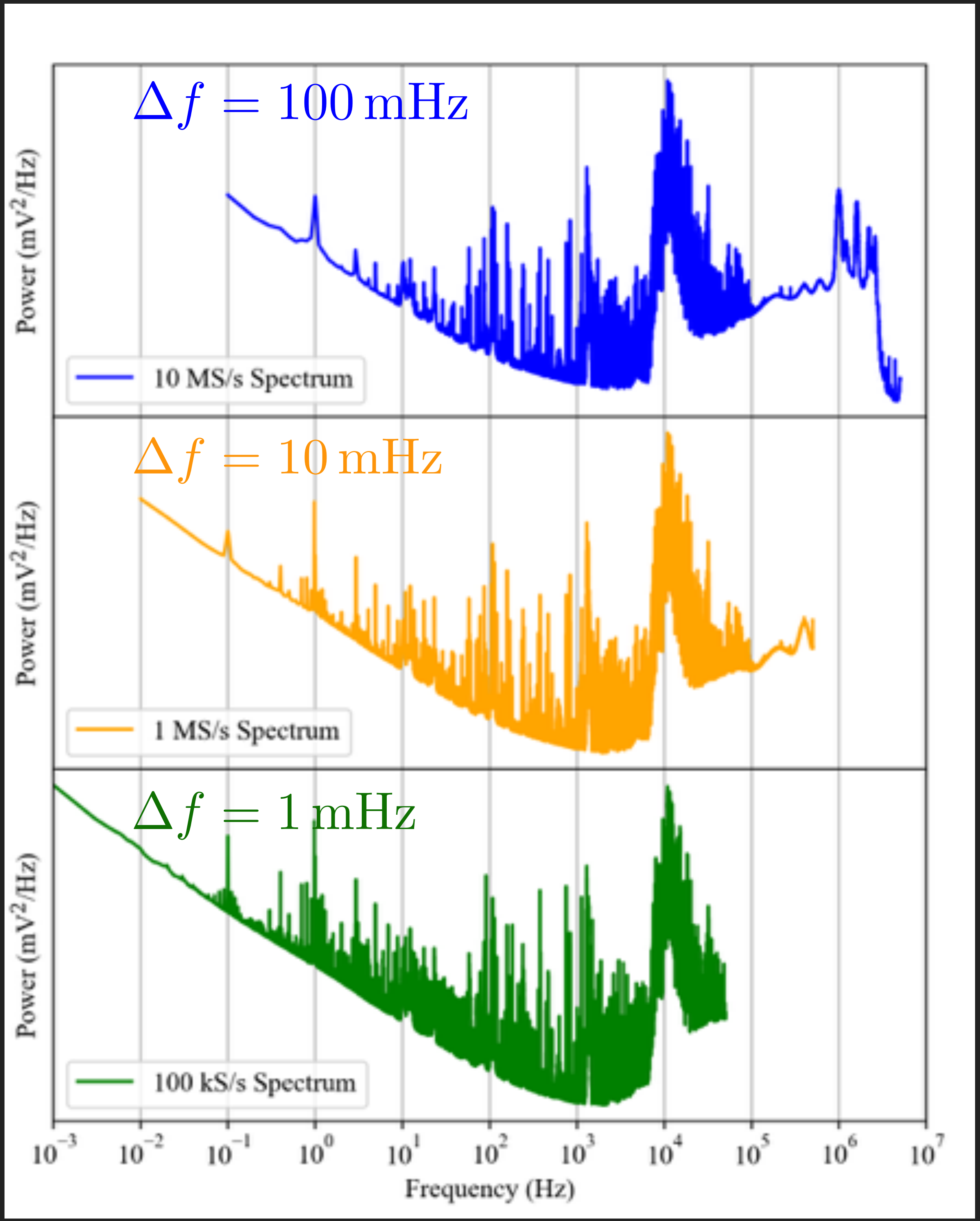
Vibrational Noise (Magnet On)



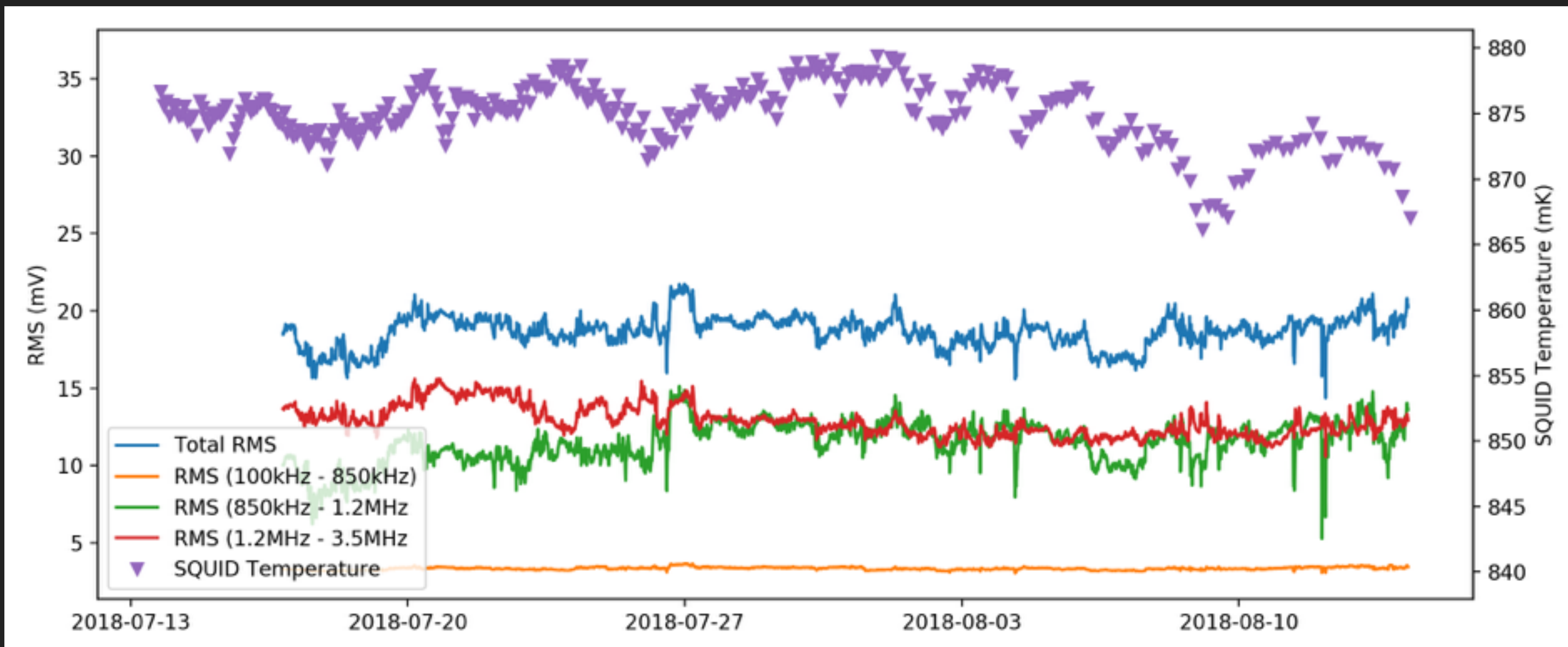
- Huge amount of noise below ~10 kHz, strongly correlated with vibration on the 300K plate
- Had to use a 10kHz high pass filter to get the data to fit in the digitizer window
- Hard limit on the low end search window

Broadband Data Collection Procedure

- Collected data with magnet on continuously for 4 weeks from July - August
- Sampling at 10 MS/s for 2.4×10^6 seconds (25T samples total)
- Digitizer locked to a Rb oscillator frequency standard
- Continuously transforming and downsampling → simultaneously produced a 10MS/s, 1MS/s and 100kS/s spectrum



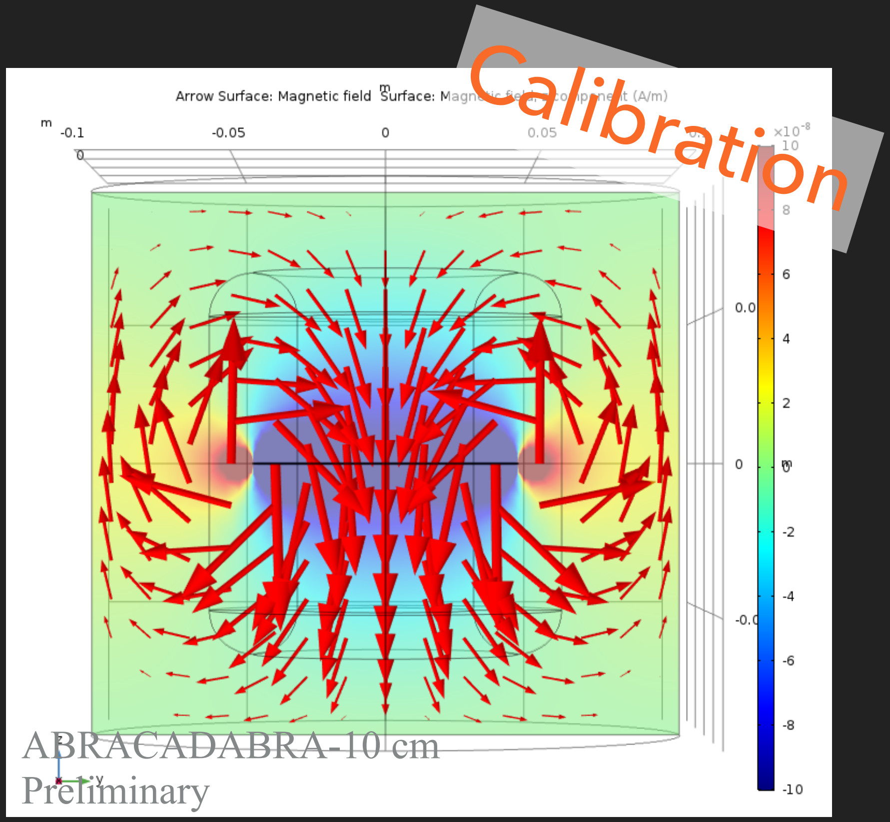
Temperature Effects?

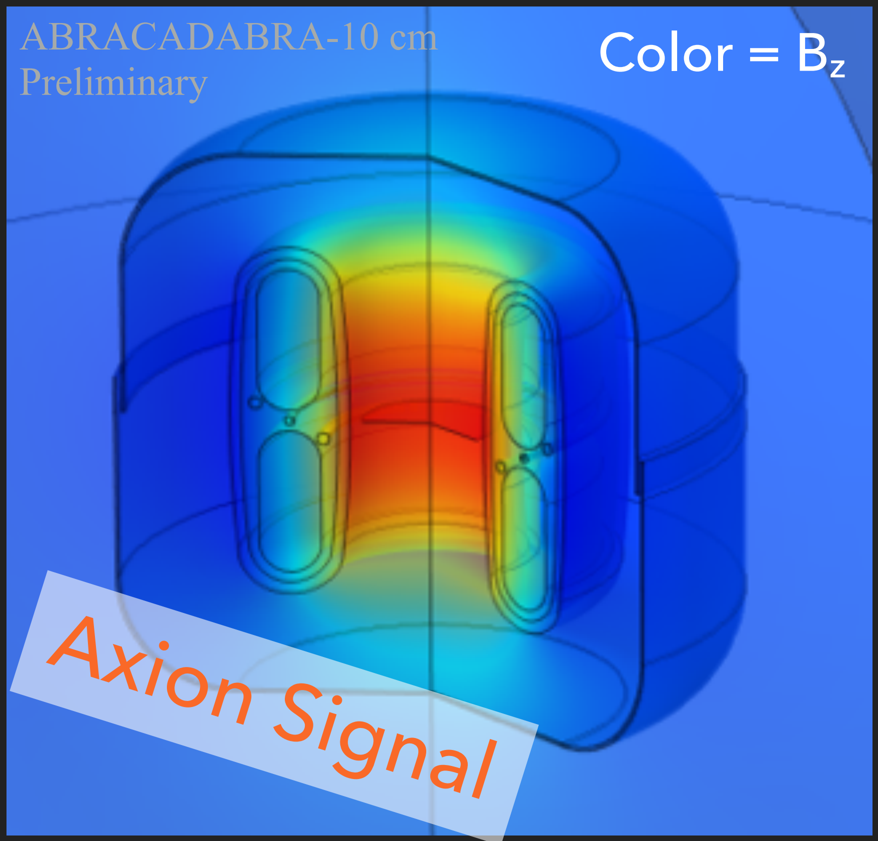


Nothing obvious..

Building Simulations in COMSOL

- Geometric factor encodes the flux through the pickup loop due to the integrated effective current
- Use COMSOL simulations to calculate the coupling to the axion field (and confirm calibration coupling)
  - Simulation of ABRACADABRA-10 cm geometry
  - Material properties need to be measured in the future





Data Analysis Approach

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

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

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

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

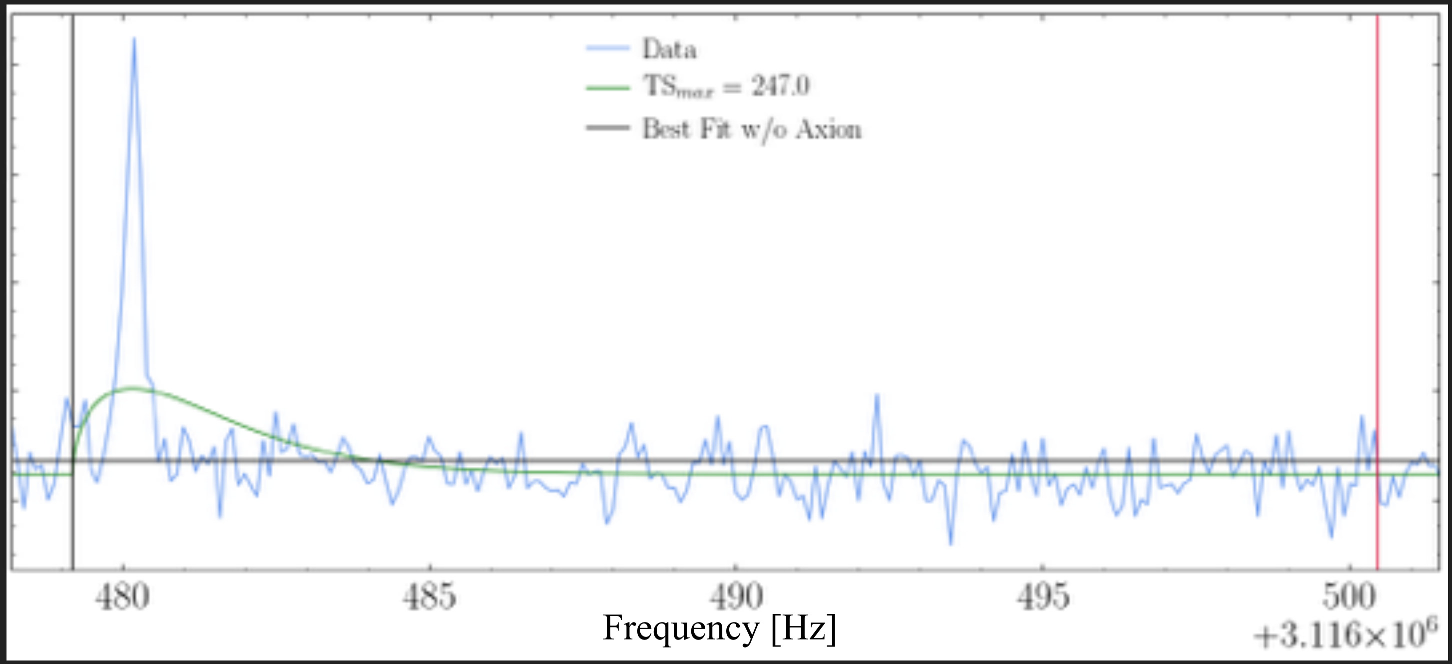
- 90% limit at where $\Theta < 2.71$ (frequentist limit)

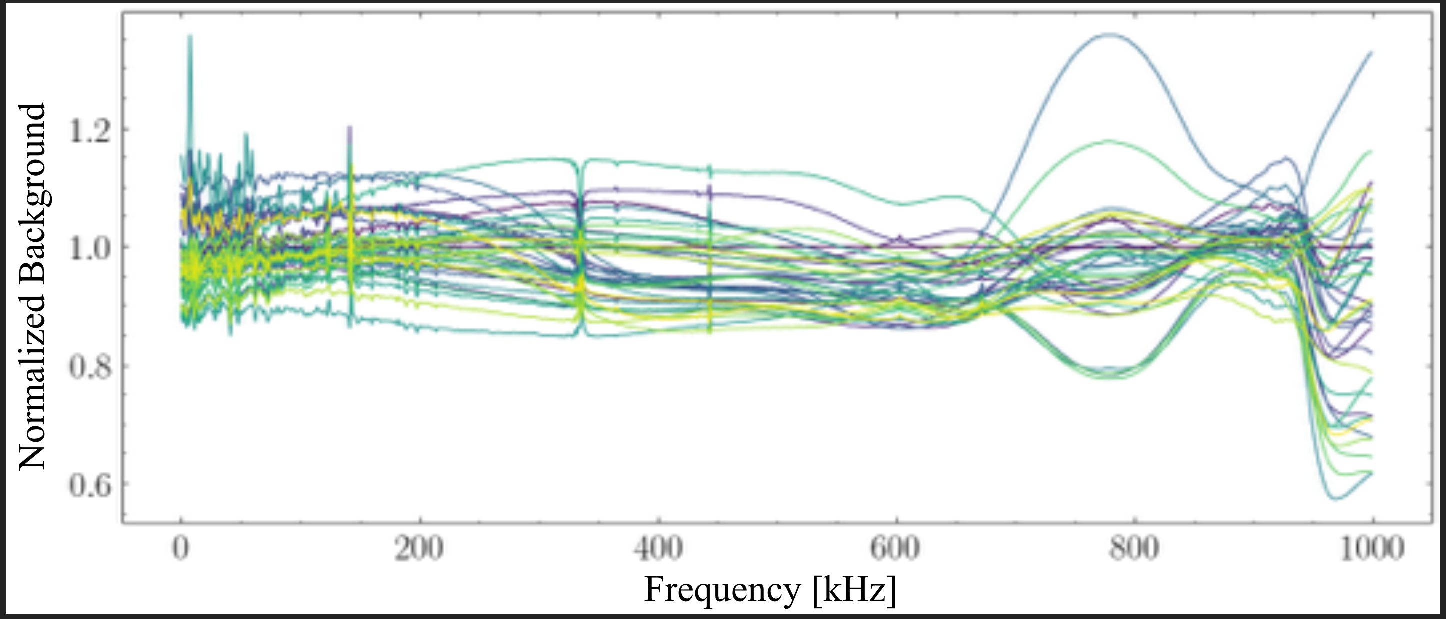
- 5 sigma detection threshold set by size of search range to account for “look elsewhere effect”

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)





Resonator Sensitivity

- At a single frequency, the signal flux can be given by

$$\Phi^S \propto \frac{g_{a\gamma\gamma} B_{\max} \mathcal{G}_V V Q \sqrt{\rho_{DM}}}{\sqrt{L_T}}$$

- Constant SNR as long as noise floor set by thermal noise in pickup loop circuit

- Scan speed set by how low the noise floor can be pushed

  ➡ Pushing beyond the SQL