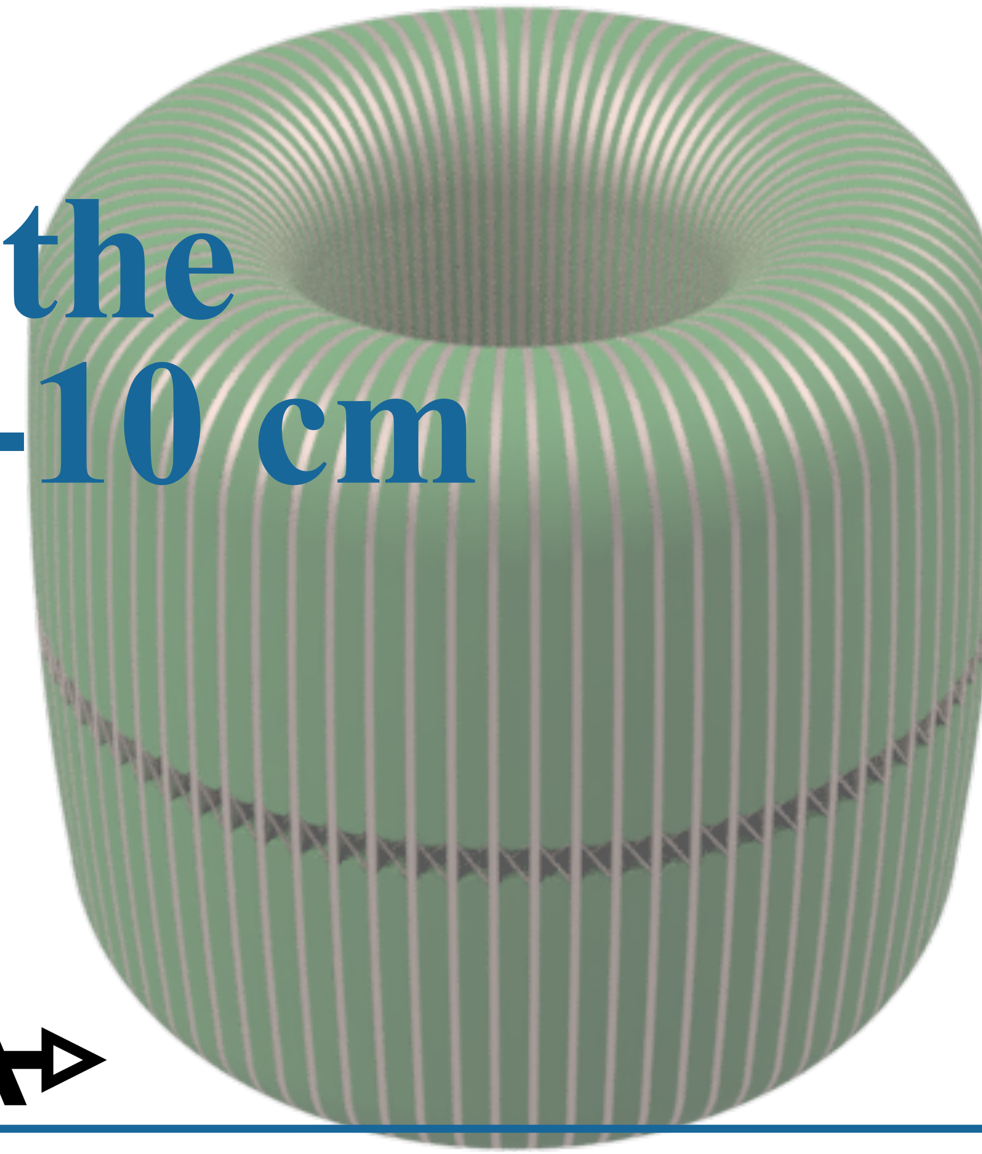
First Results from the ABRACADABRA-10 cm Prototype



ABRACADABRA

Jonathan Ouellet

Massachusetts Institute of Technology

June 5, 2019

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

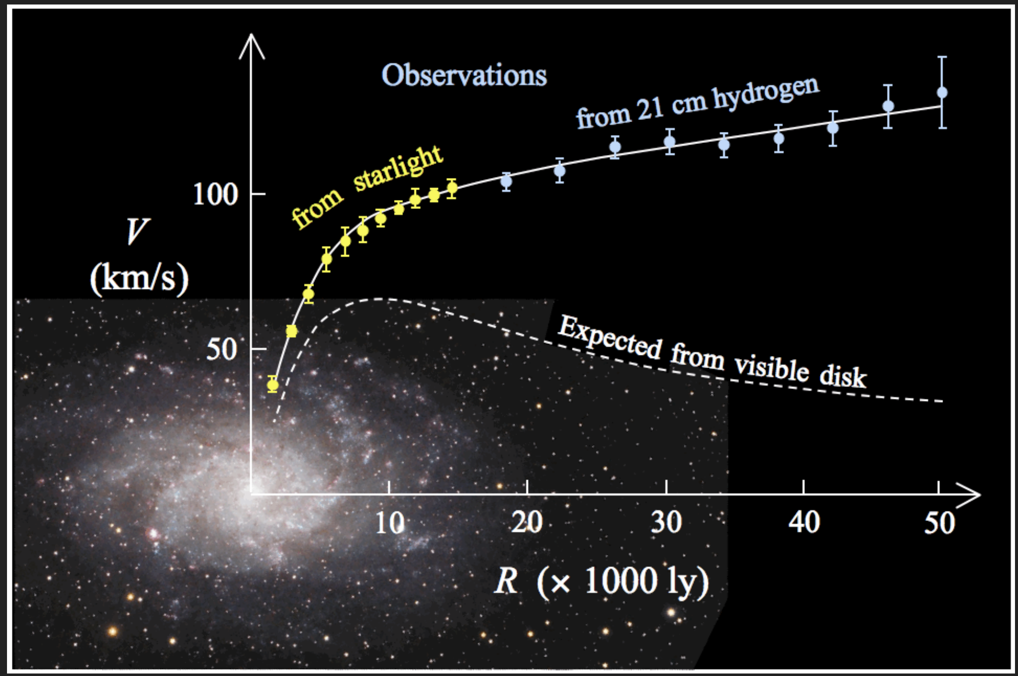
MICHIGAN

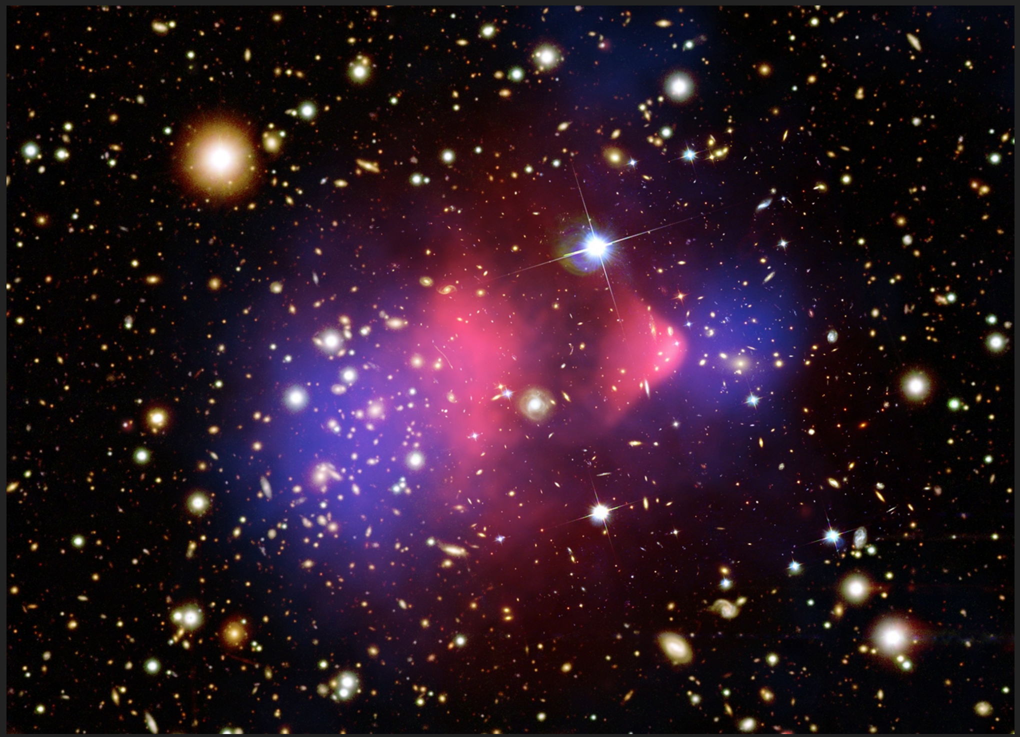
NSF

The Case for Dark Matter

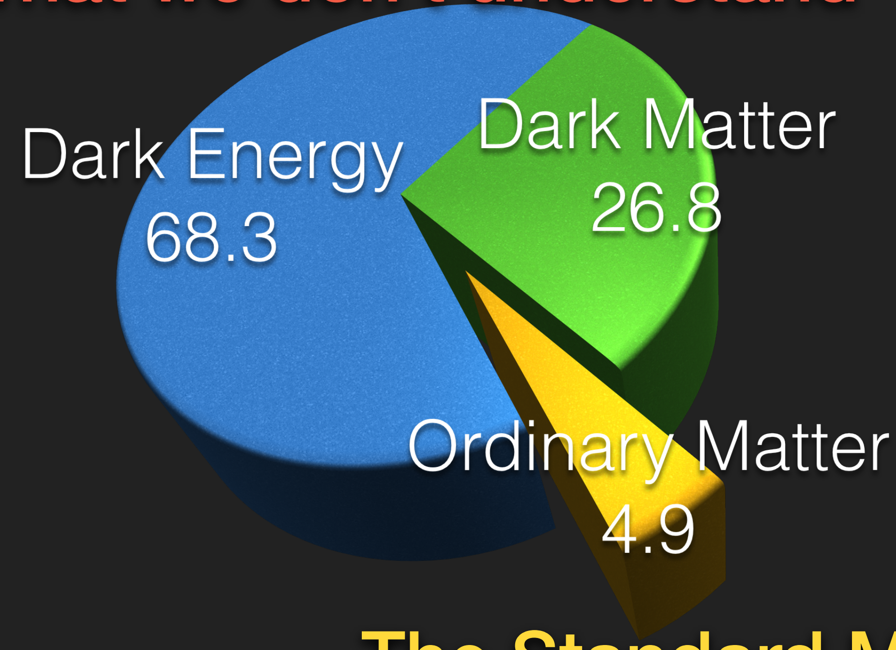
There is extensive evidence for the presence of Dark Matter in the Universe

- Galactic rotation curves
- Measurements of the CMB
- Weak Lensing, Clustering and Galactic dynamics (e.g. Bullet cluster)

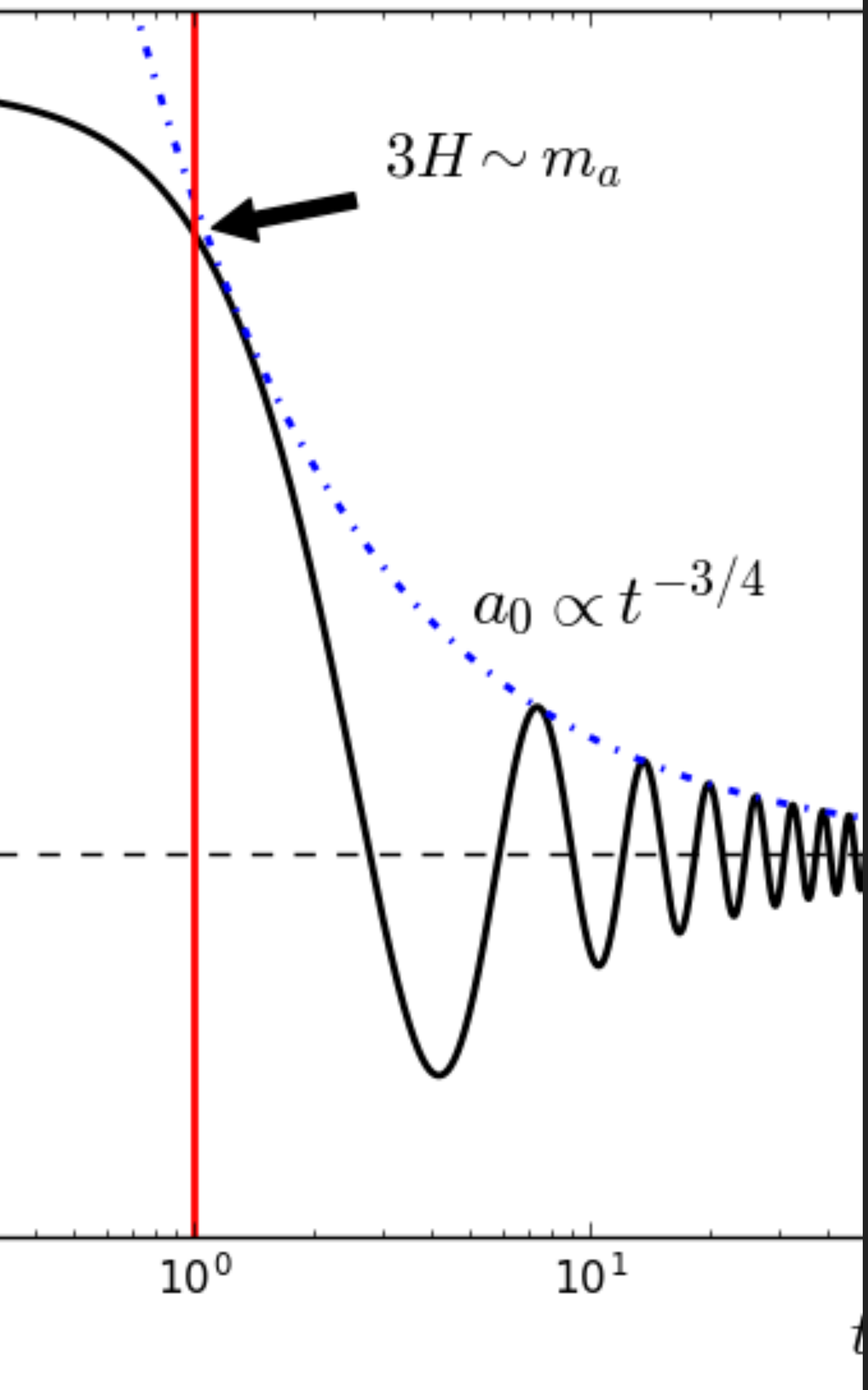




What we don't understand



The Standard Model



THE CASE FOR

AXION DARK MATTER

The Strong CP Problem

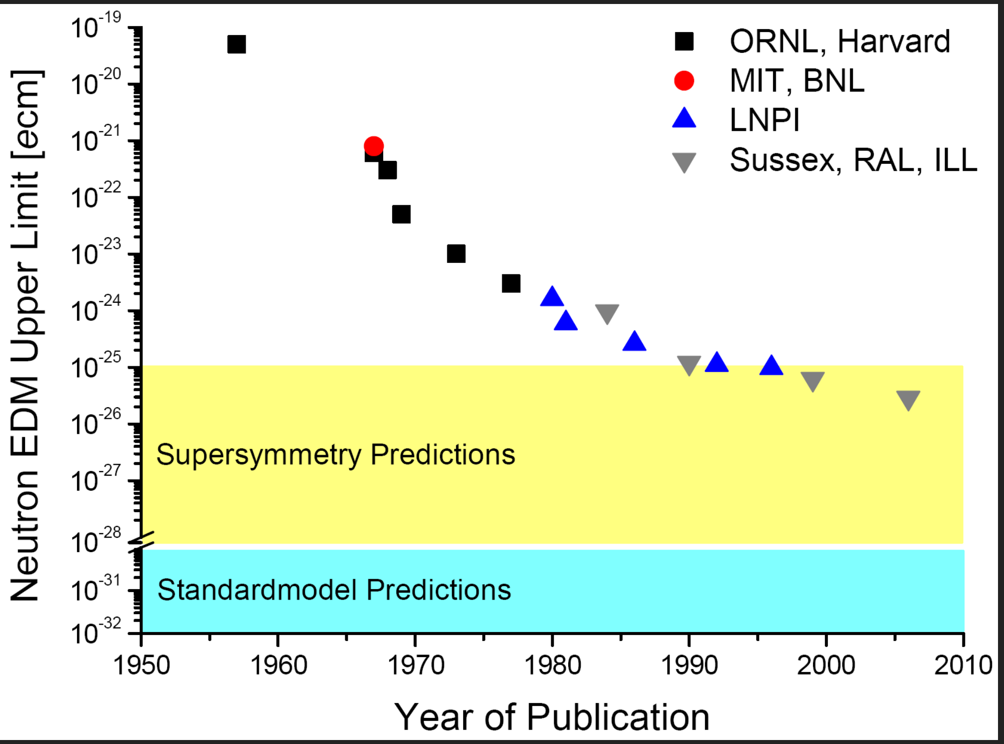
- QCD generically contains a CP violating term:

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi} G^a_{\mu\nu} G^{a\mu\nu} - \bar{\Theta} \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}$$

- Θ is arbitrary in the range: $0 \leq \Theta \leq 2\pi$
- Predicts a nEDM of the order of $d \sim 10^{-16}$ e·cm, however upper limits of $d < 10^{-26}$ e·cm.
- Places unnatural fine tuning of parameter:

$$|\bar{\Theta}| < 10^{-10}$$

➡ This is the Strong-CP Problem!

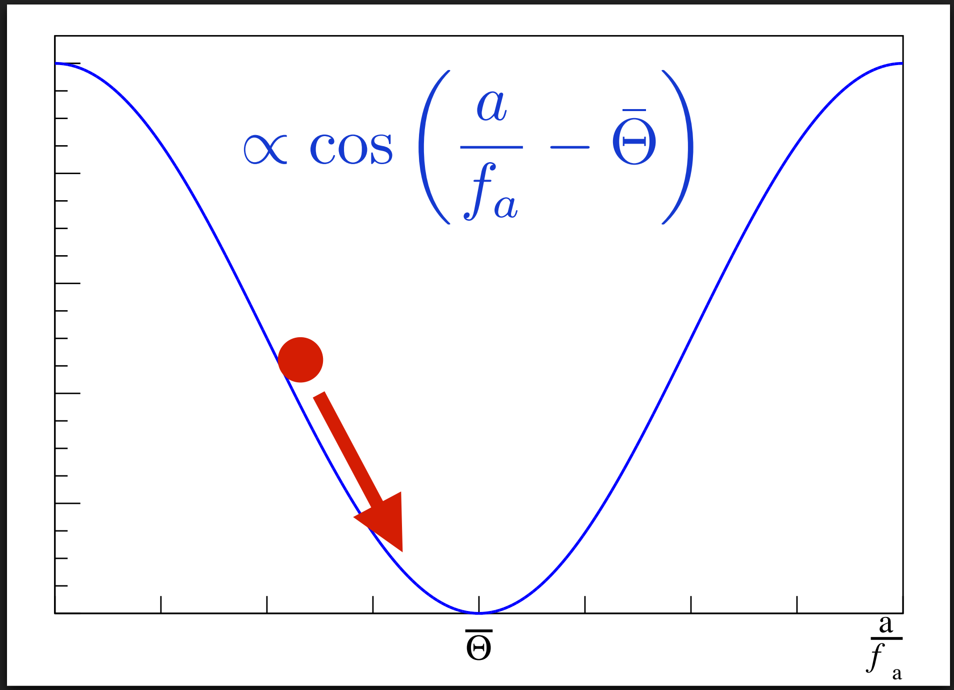


The Axion Solves the Strong-CP Problem and Creates Dark Matter!

- The Axion cancels the CP-violating term by rolling down a potential

$$\mathcal{L} \supset \left(\frac{a}{f_a} - \bar{\Theta}\right) \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

- Introduces a (light) massive spin-0 particle, with very weak couplings to the Standard Model



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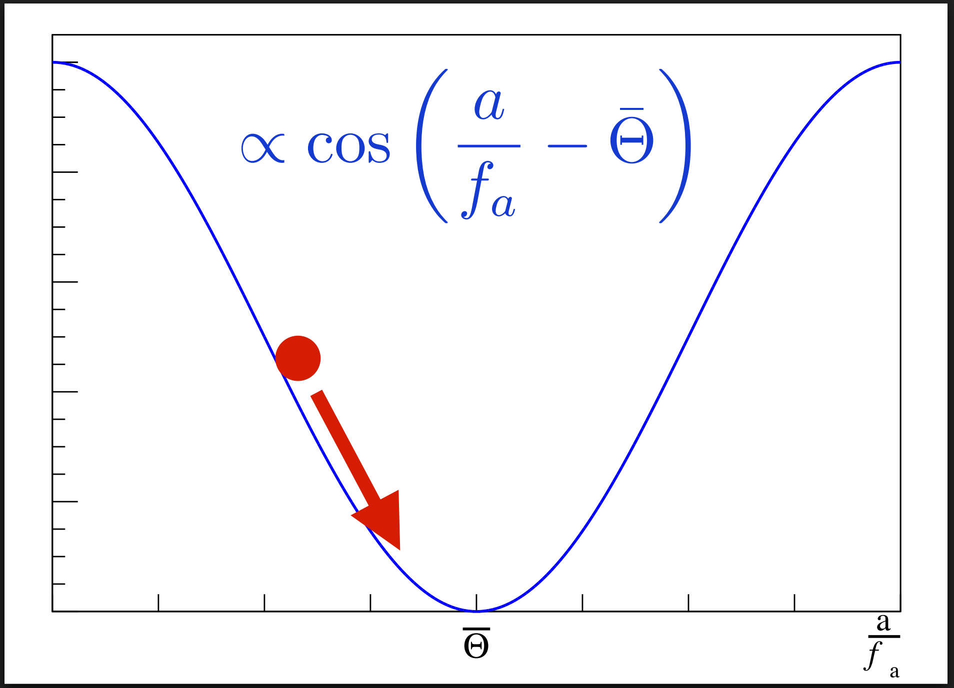
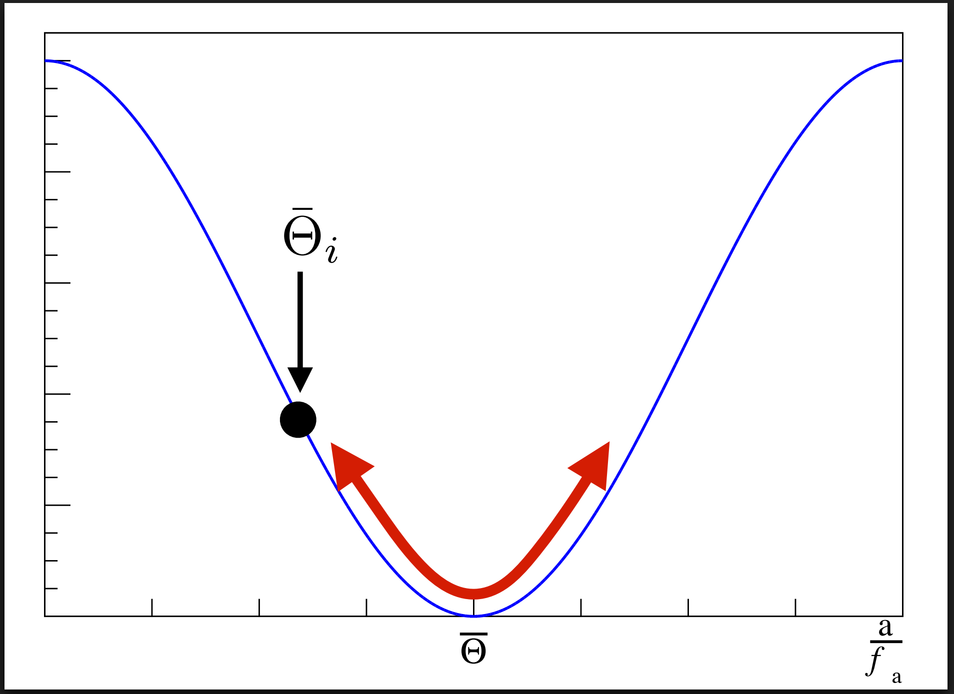
- Introduces a (light) massive spin-0 particle, with very weak couplings to the Standard Model

- Field starts with some initial potential energy
    - Field oscillating throughout the universe behaves *exactly like dark matter!*

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





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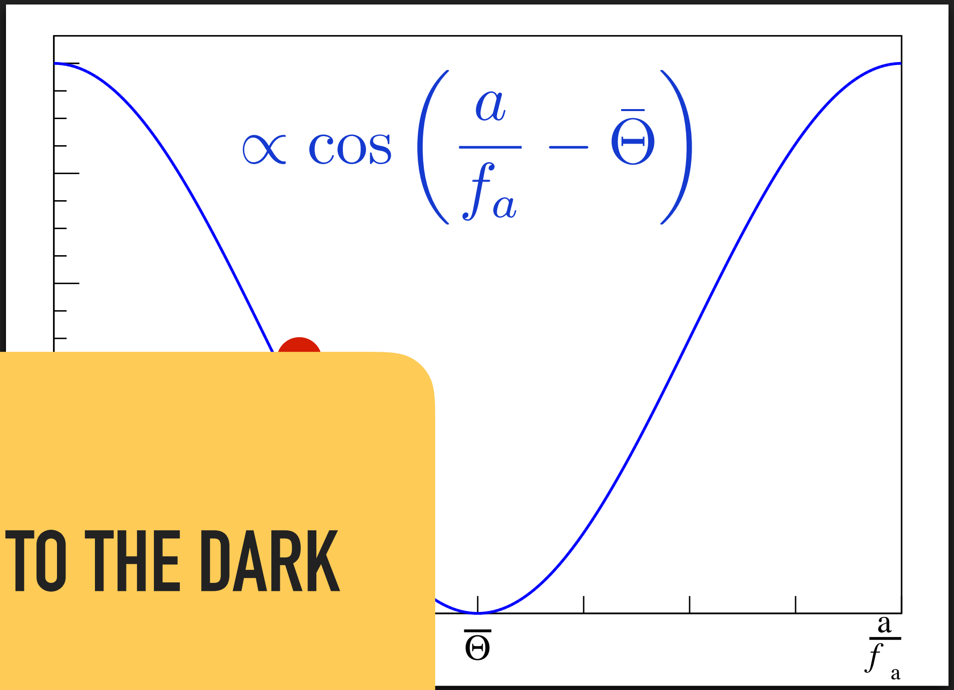

- The Axion cancels the CP-violating term by rolling down a potential

$\mathcal{L} \supset ($

THE AXION MIRACLE?

IF THE AXION EXISTS, IT CONTRIBUTES TO THE DARK MATTER DENSITY

- Introduces a (l
very weak cou

- Field starts with some initial potential energy
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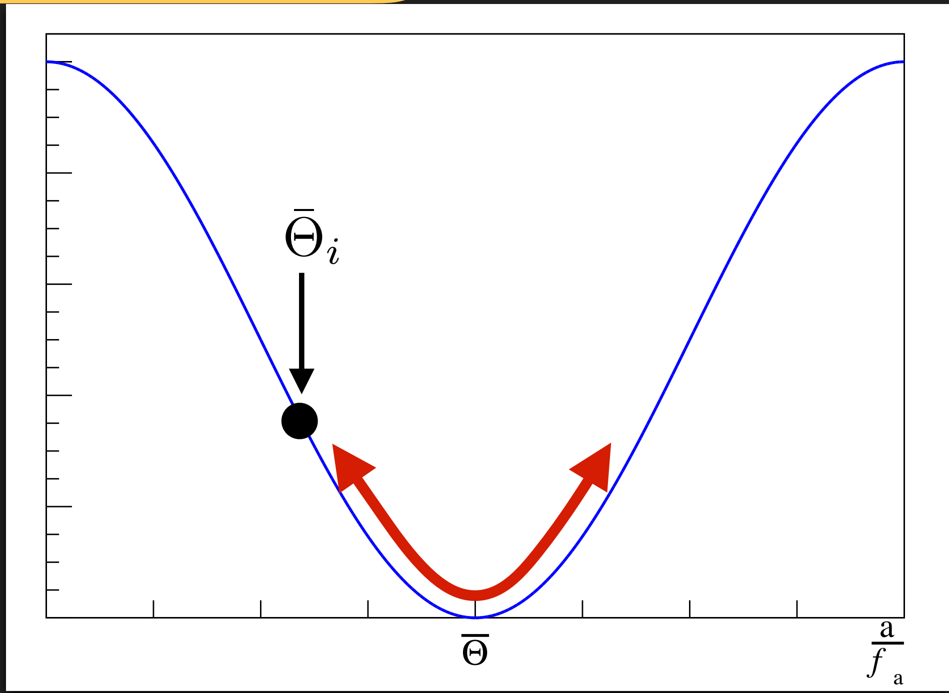
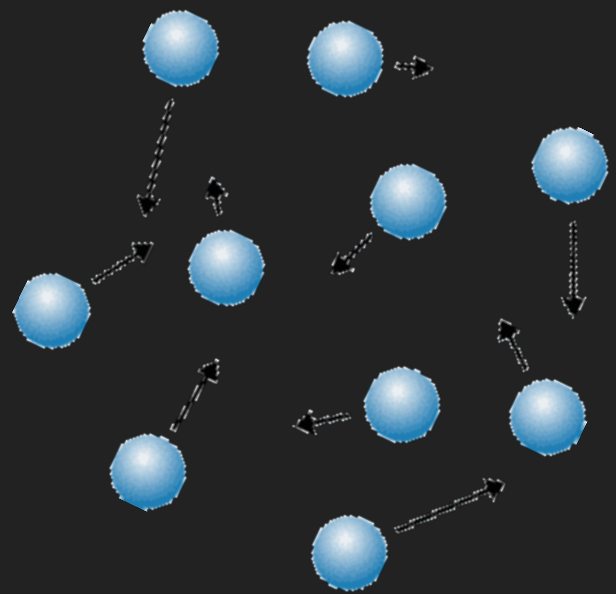


Particle vs Field

WIMPs behave like a dilute gas of particles zipping around. Occasionally one might bump into our detector.



A few WIMPs per liter of space.

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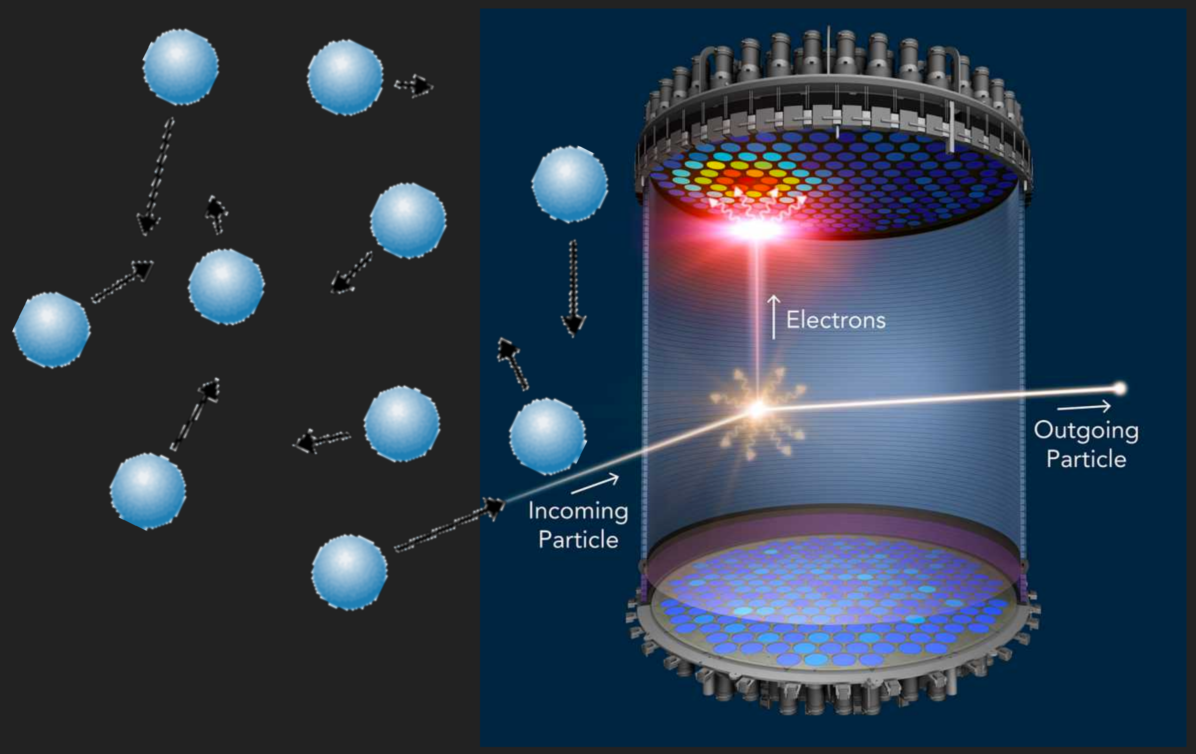

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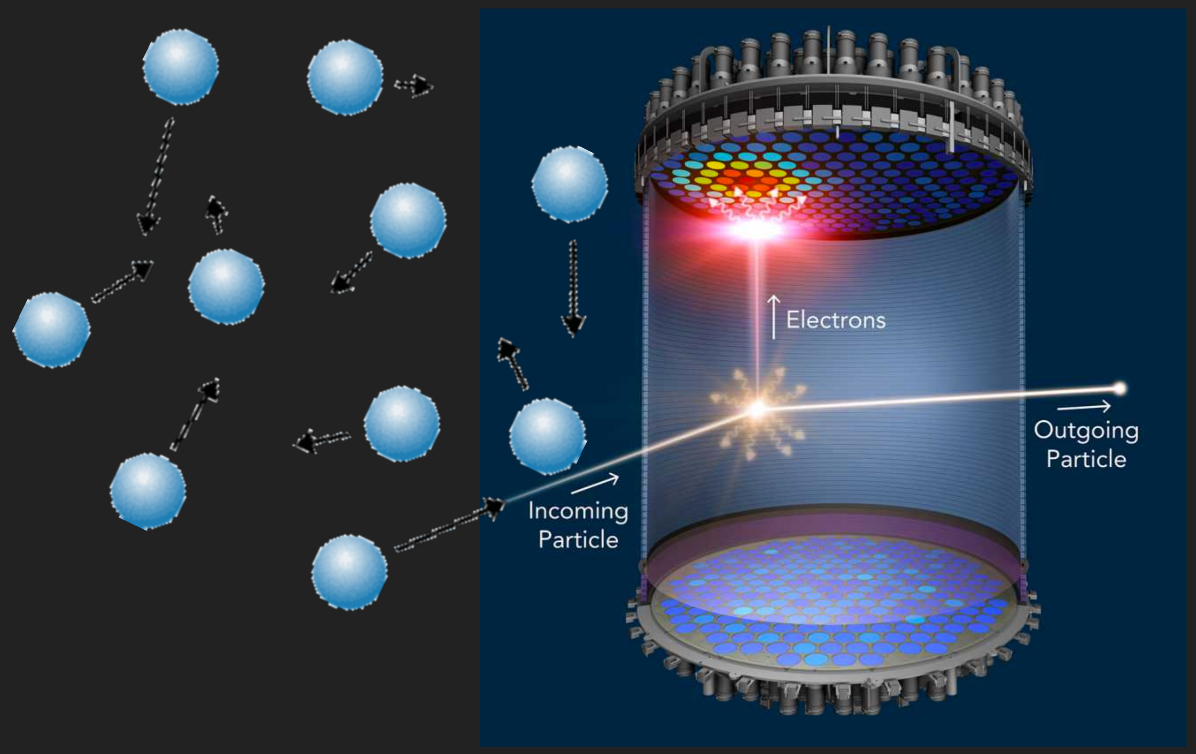

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Axions have a much higher number density and so behave like a classical field. Creating a very weak oscillating “wind” that we search for.

~10^{18} axions per liter of space

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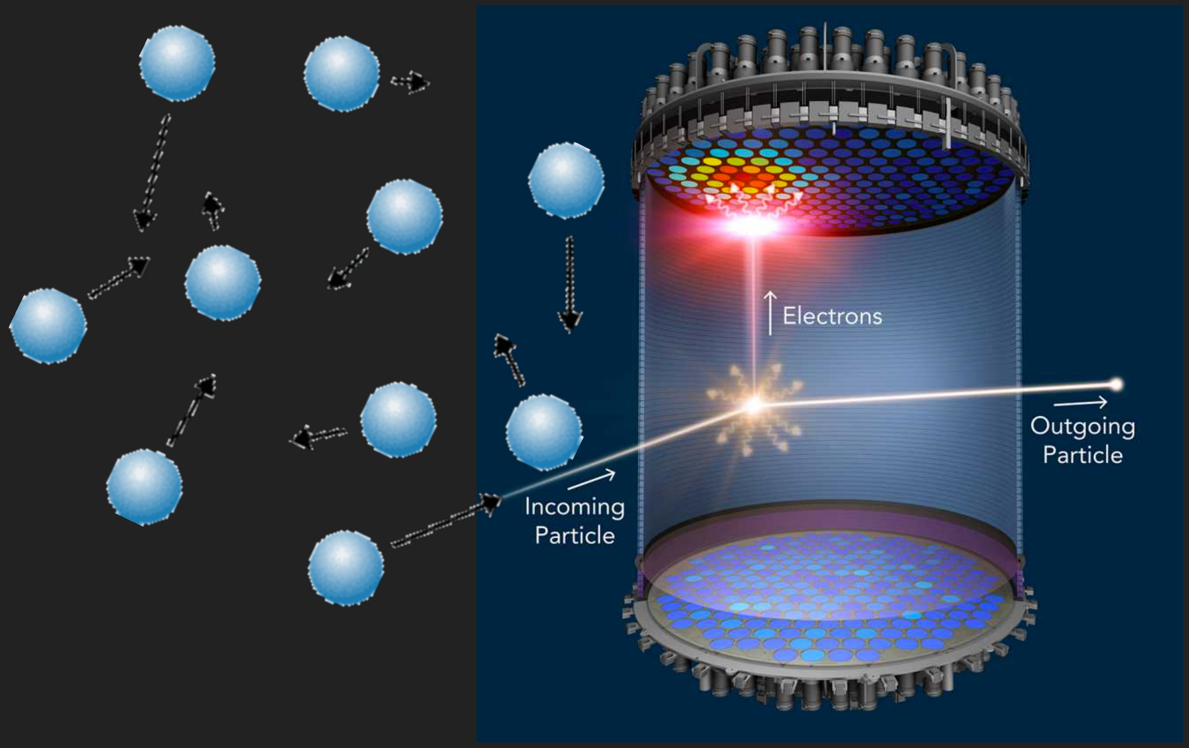

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Axion Electrodynamics

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

- Axion dark matter creates new terms in Maxwell's equations. Modifies Electromagnetism!
  - $g_{a\gamma\gamma}$ is the axion photon coupling (expected to be very small).

Axion Electrodynamics

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

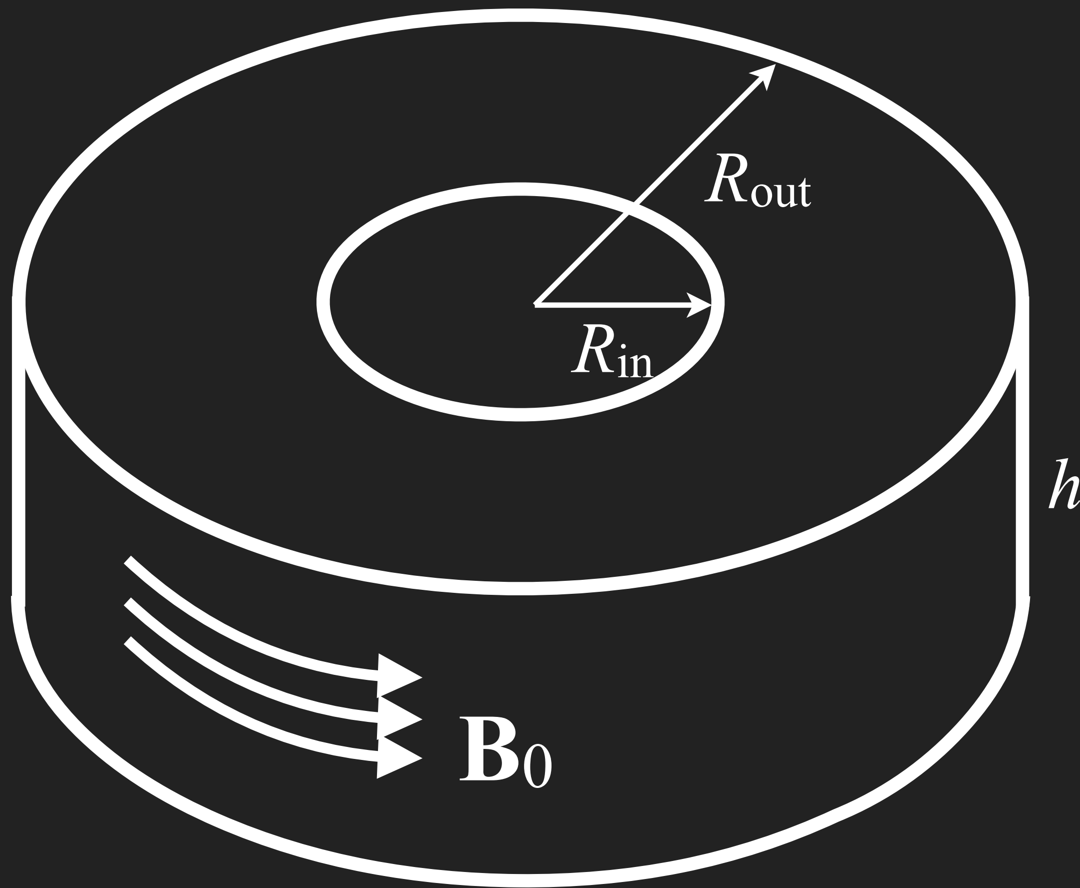
- Axion dark matter creates new terms in Maxwell's equations. Modifies Electromagnetism!
  - $g_{a\gamma\gamma}$ is the axion photon coupling (expected to be very small).
- In the presence of a large static magnetic field, ADM creates an "effective current" that generates oscillating magnetic fields in response

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

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

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

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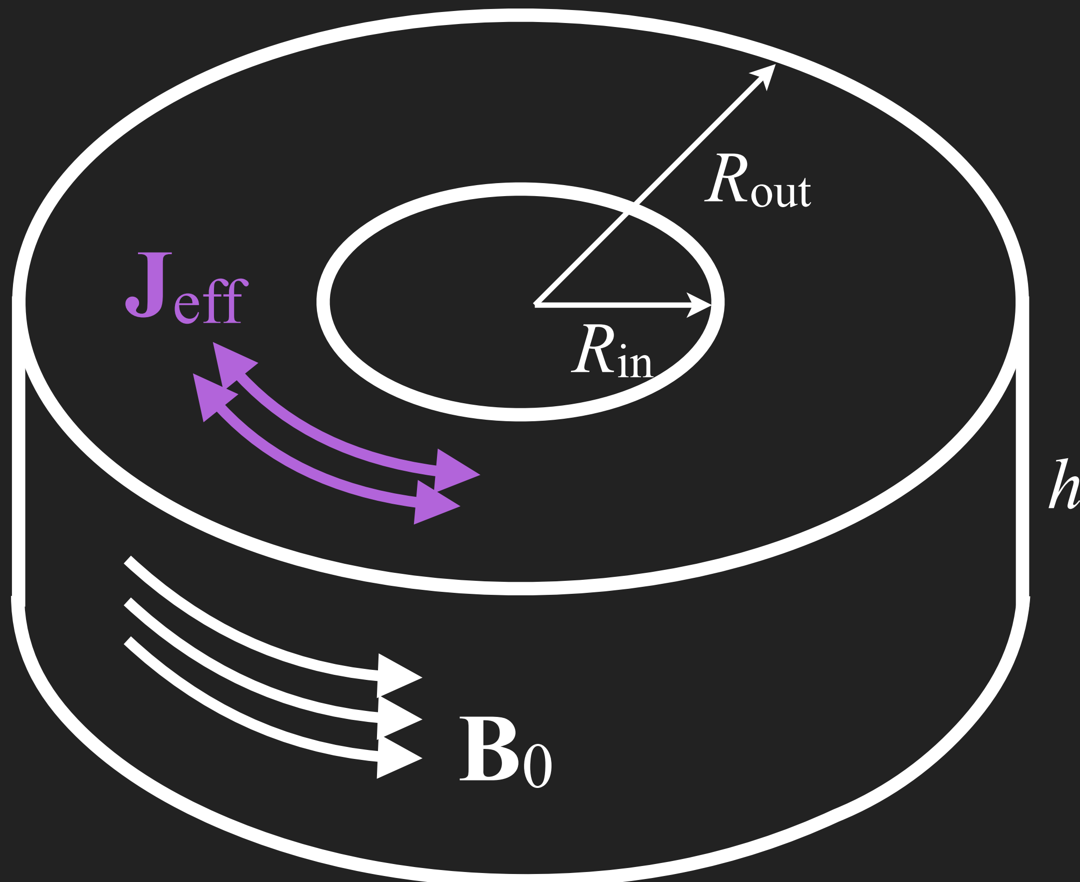
- ADM generates an oscillating effective current around the ring (MQS approx: $\lambda \gg R$)



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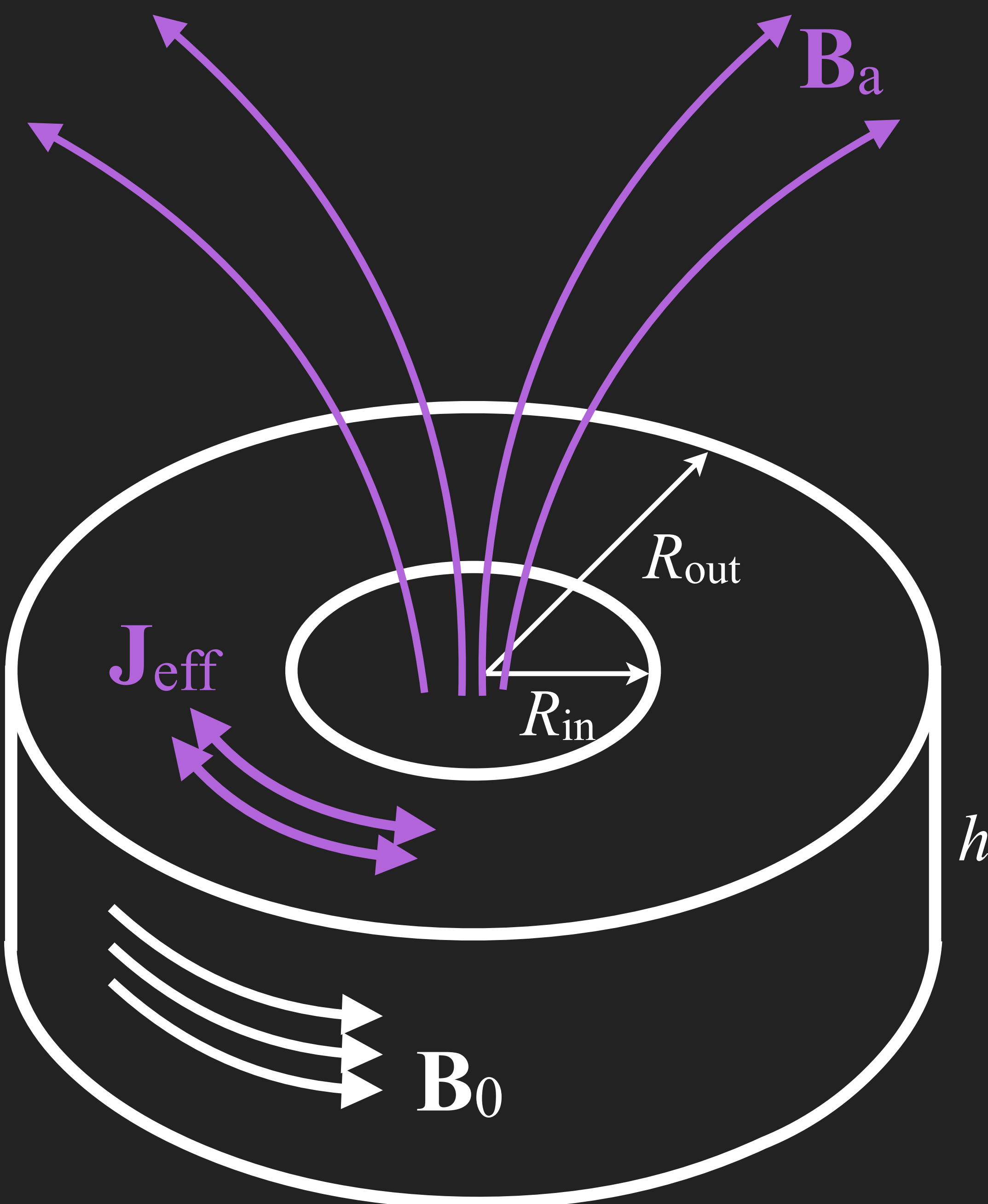

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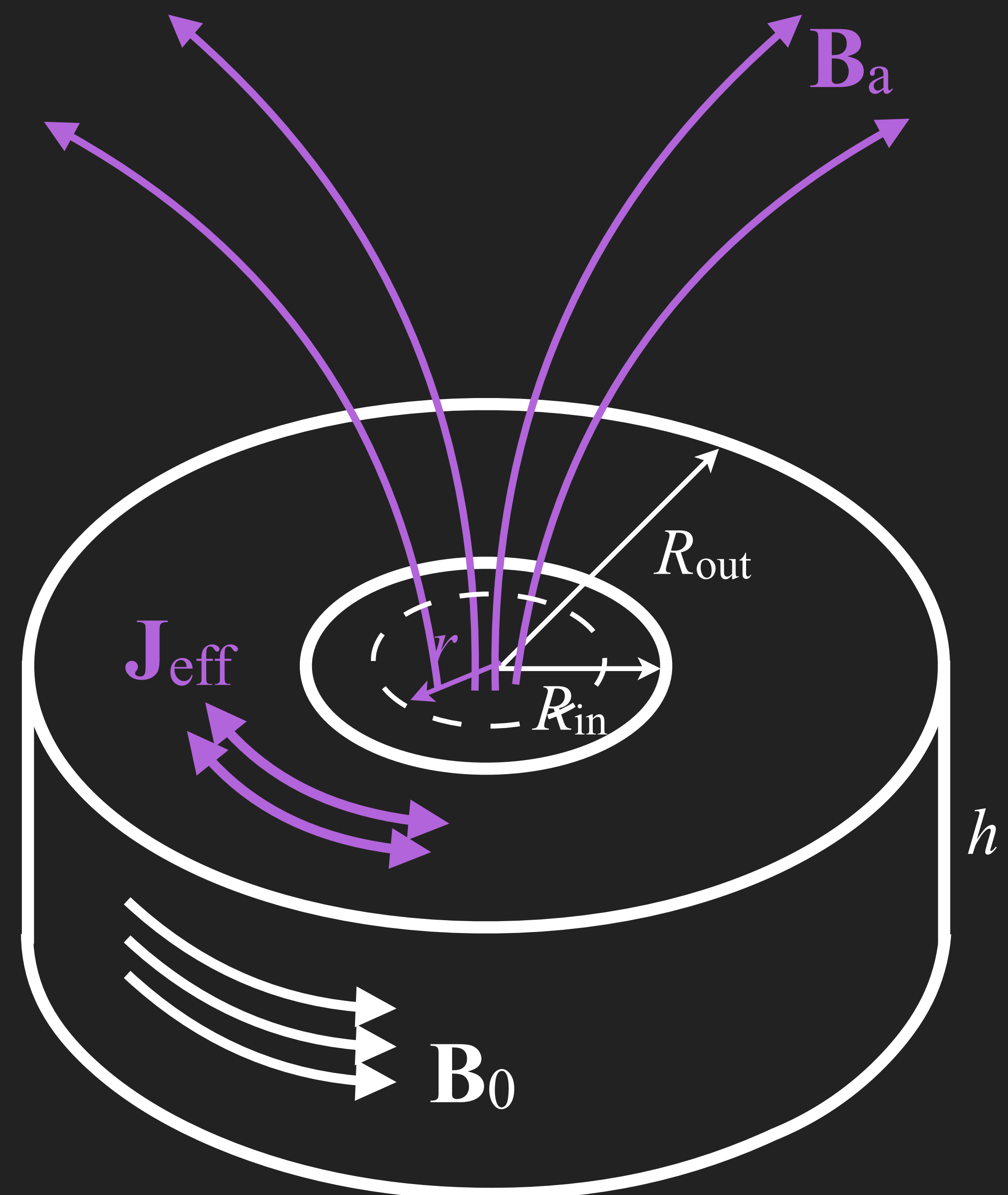
- Start with a toroidal magnet with a fixed magnetic field B_0
- ADM generates an oscillating effective current around the ring (MQS approx: $\lambda \gg R$)
- … this generates an oscillating magnetic field through the center of the toroid
- Insert a pickup loop in the center and measure the induced current in the loop read out by a SQUID based readout

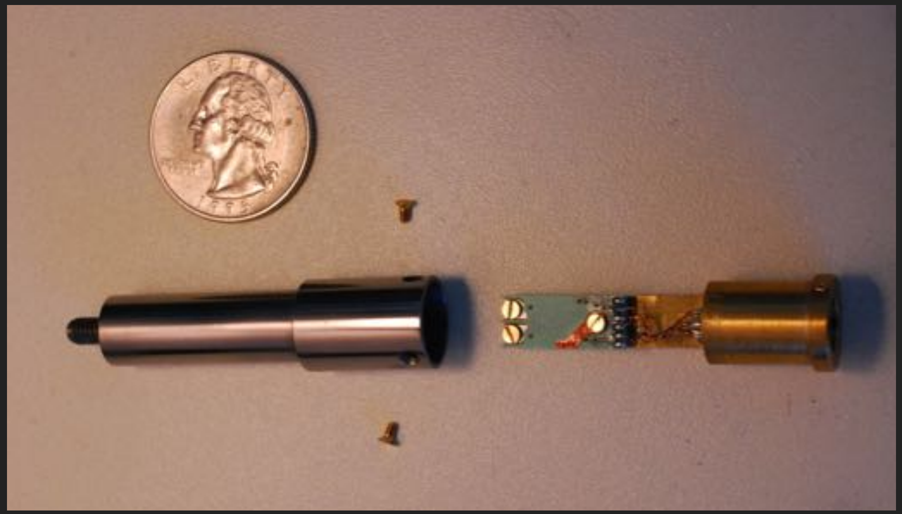
$$\Phi(t) = g_{a\gamma\gamma} B_{\max} \sqrt{2\rho_{\mathrm{DM}}} \cos(m_a t) \mathcal{G}_V V$$

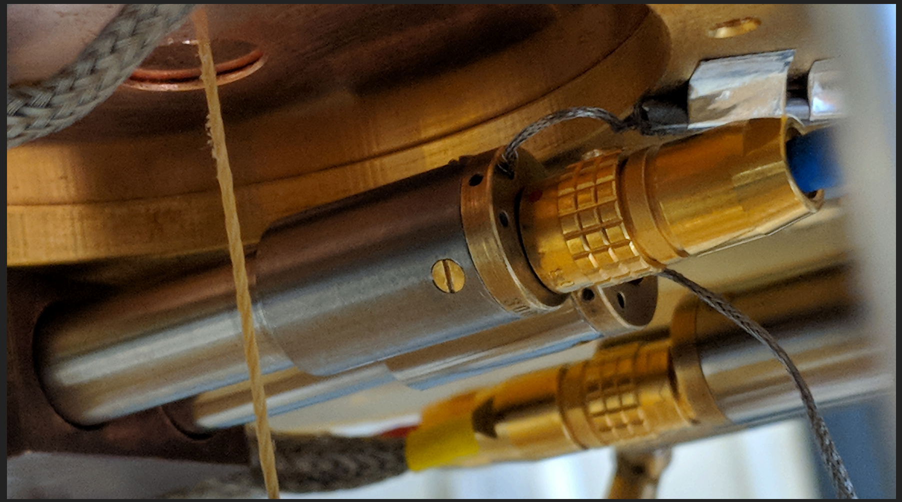


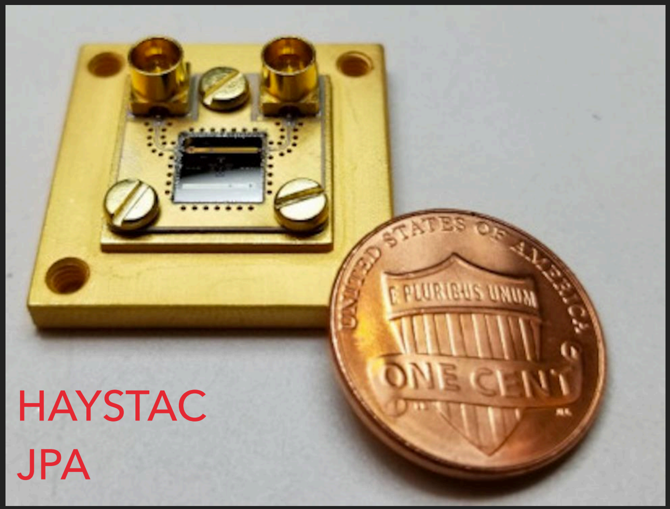
Phys. Rev. Lett. 117, 141801 (2016)

ABRACADABRA Readout Modes

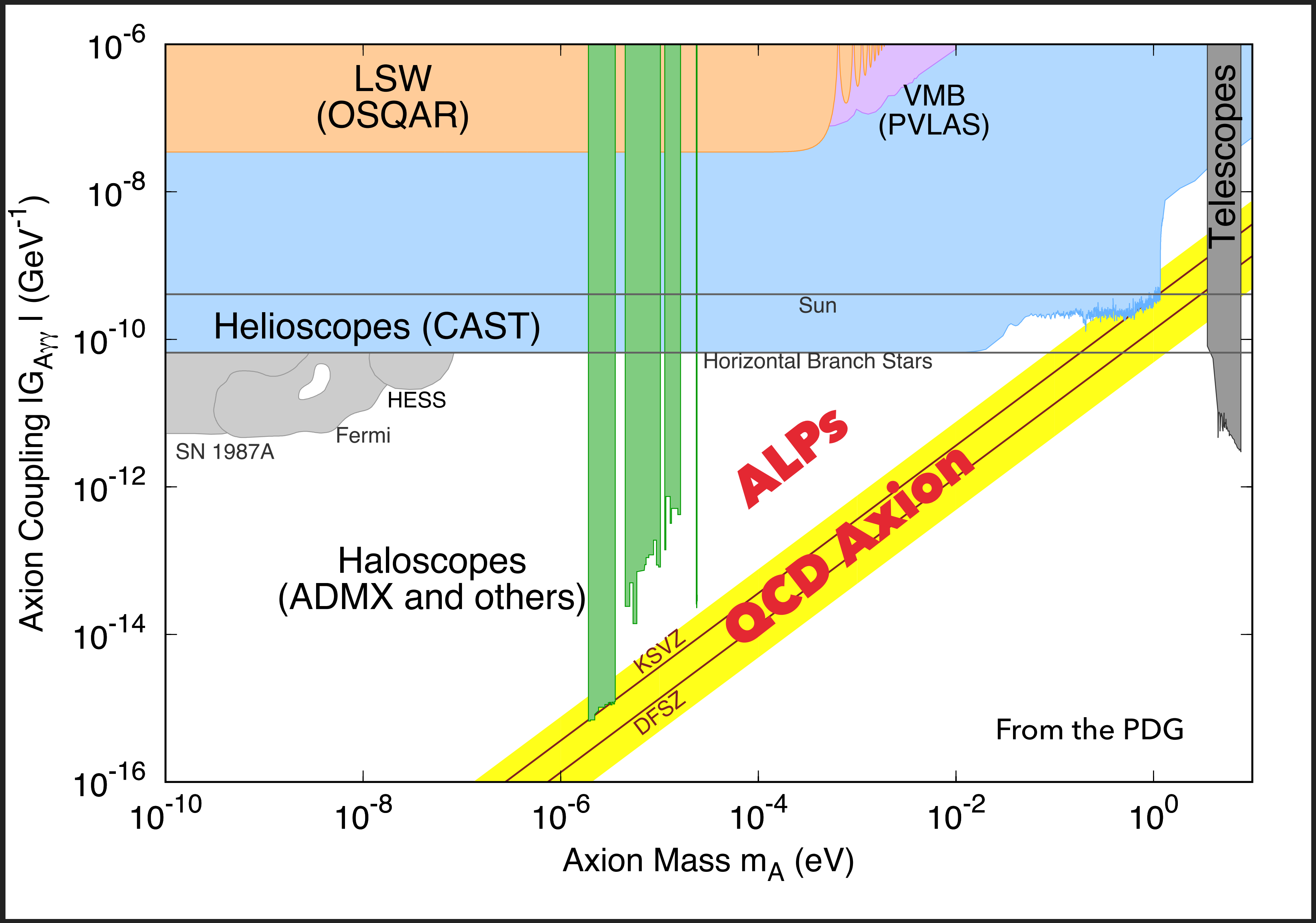
- ABRACADABRA will require very sensitive current detectors
  - ➡ SQUID current sensors
- Huge overlap with developments in Quantum Computing
  - ➡ Small signals, long coherence times
- Long term goal to push beyond the Standard Quantum Limit







Current State Of Axion Search



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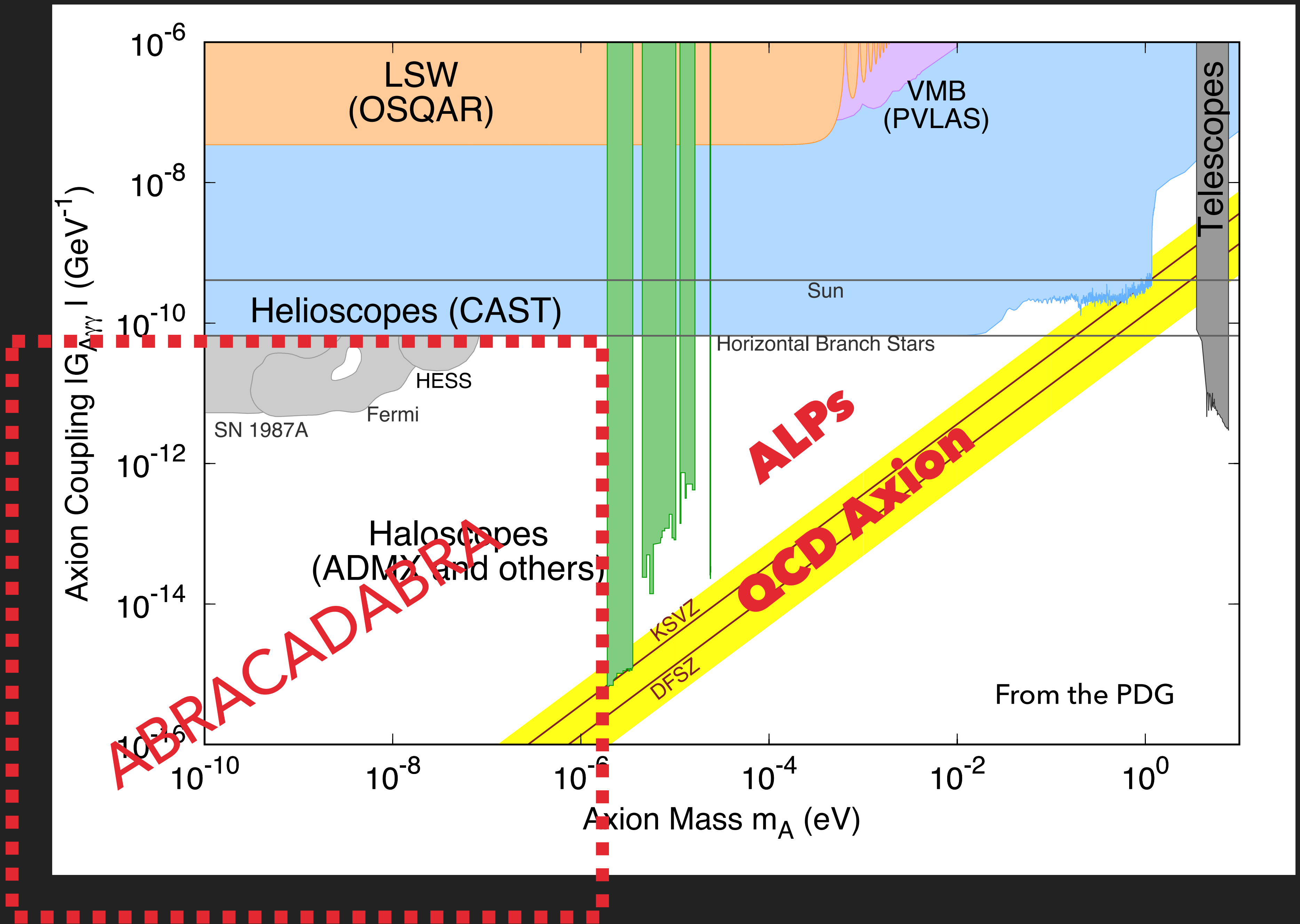
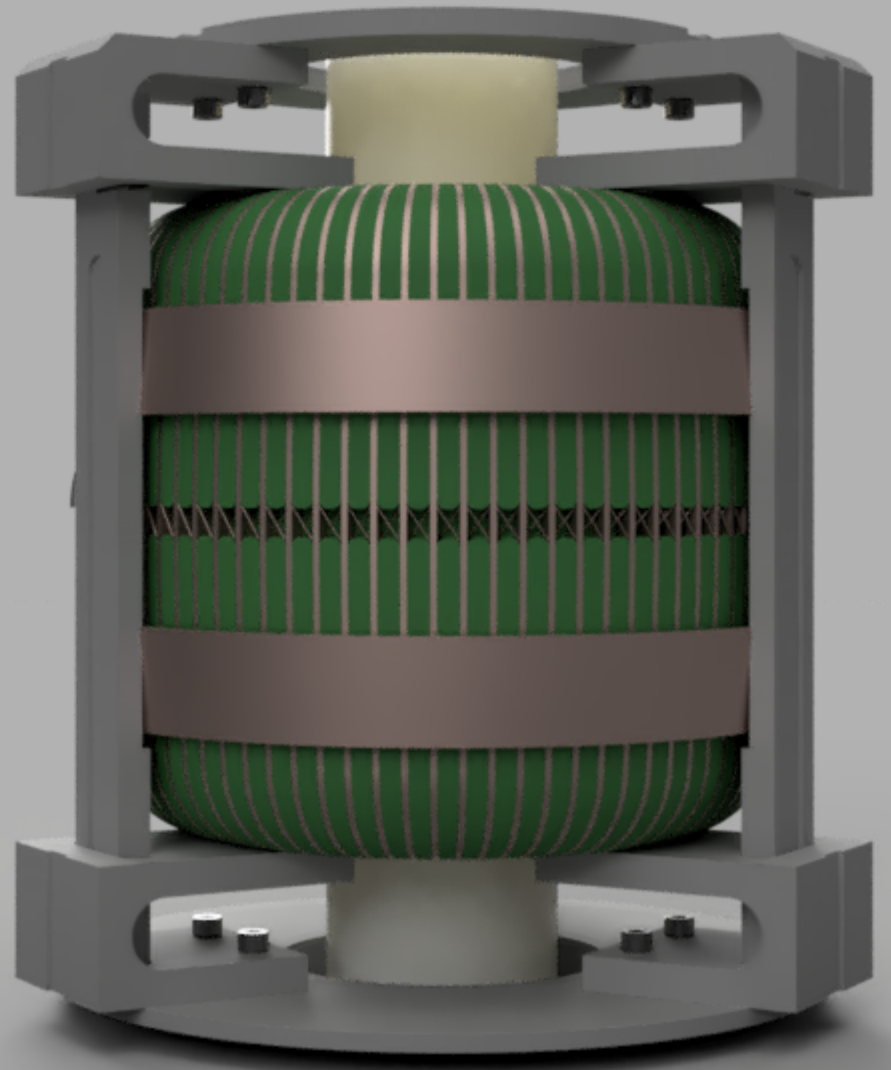
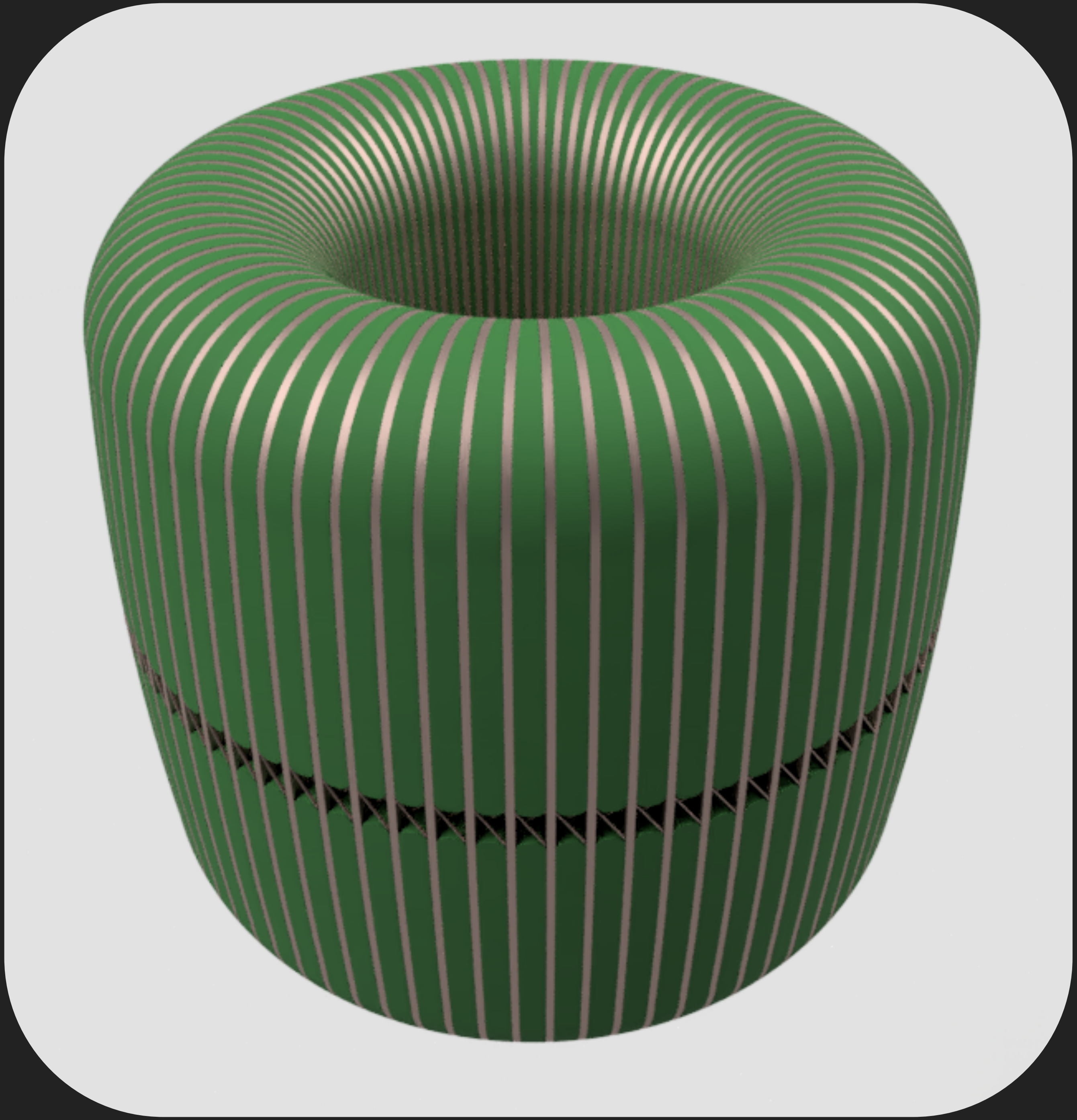




A PROTOTYPE DETECTOR

ABRACADABRA-10CM

Dissecting ABRACADABRA-10 cm



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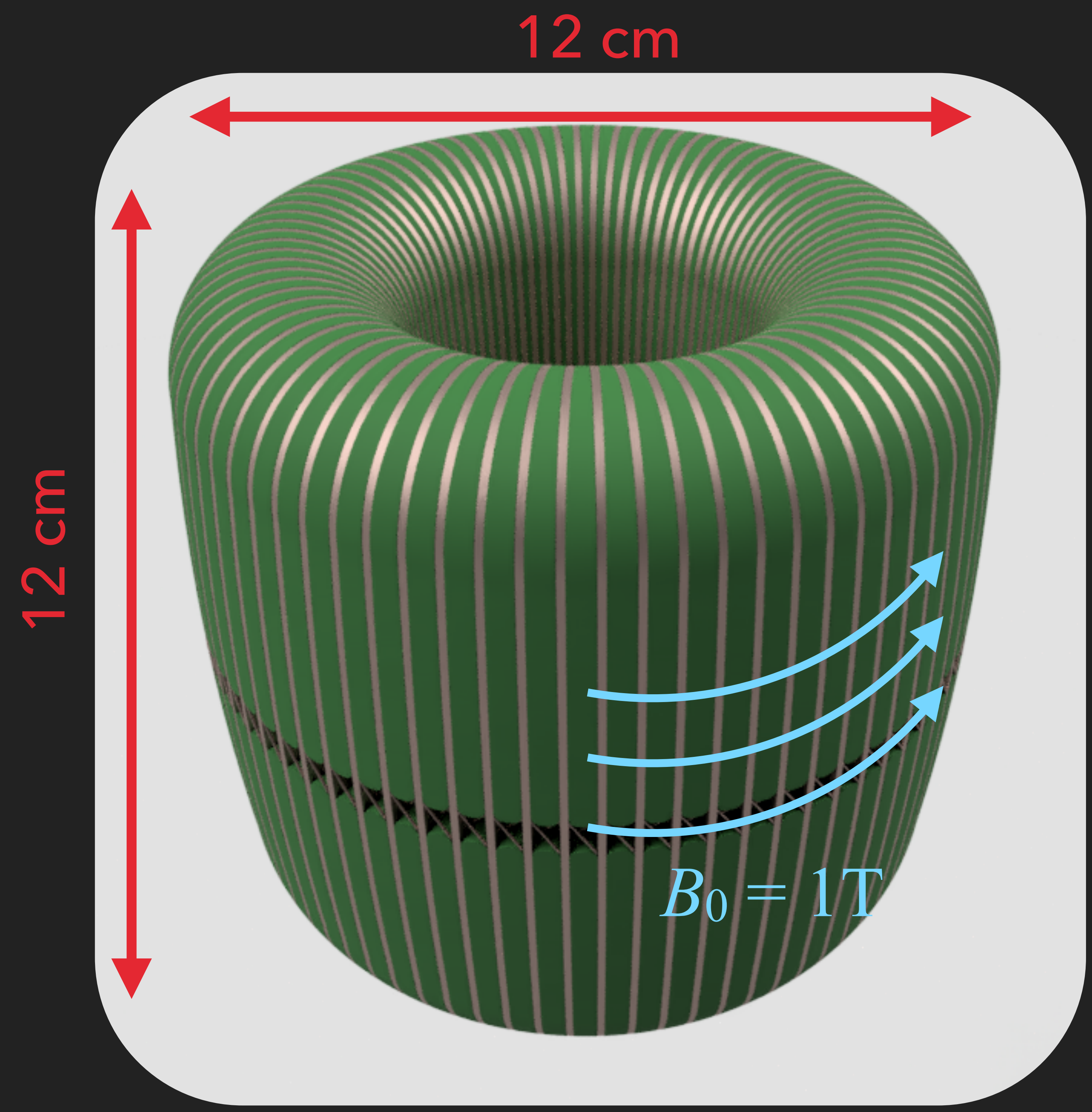

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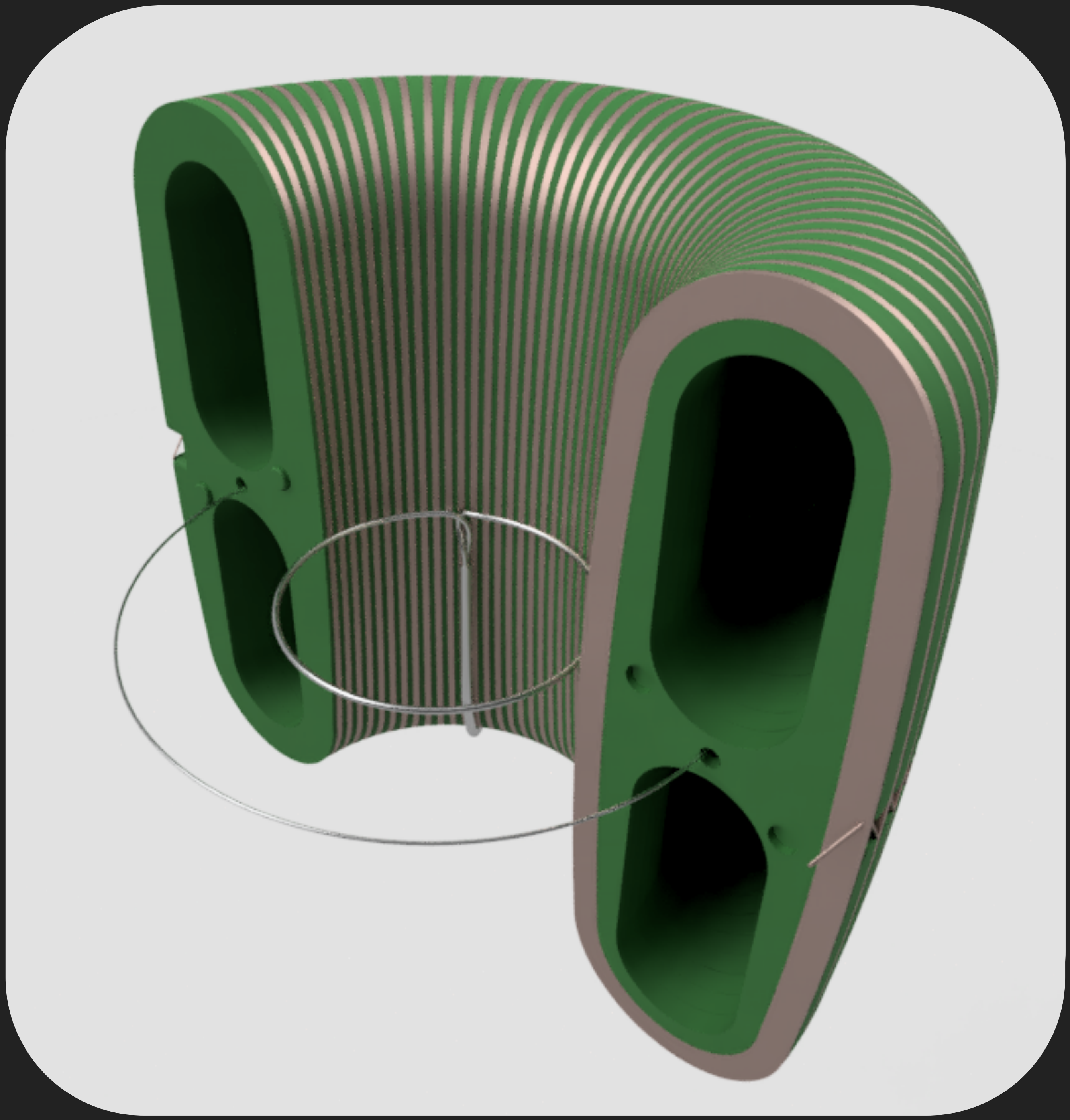
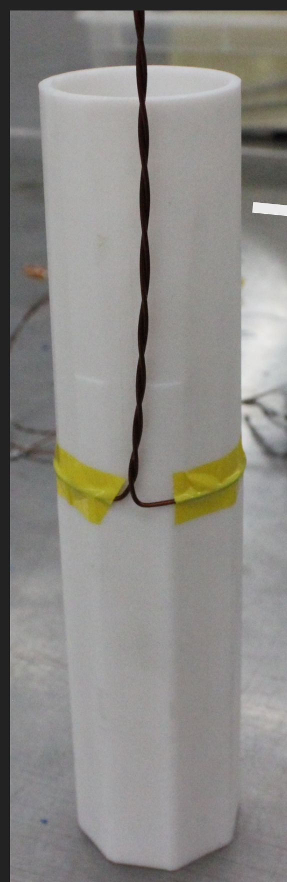
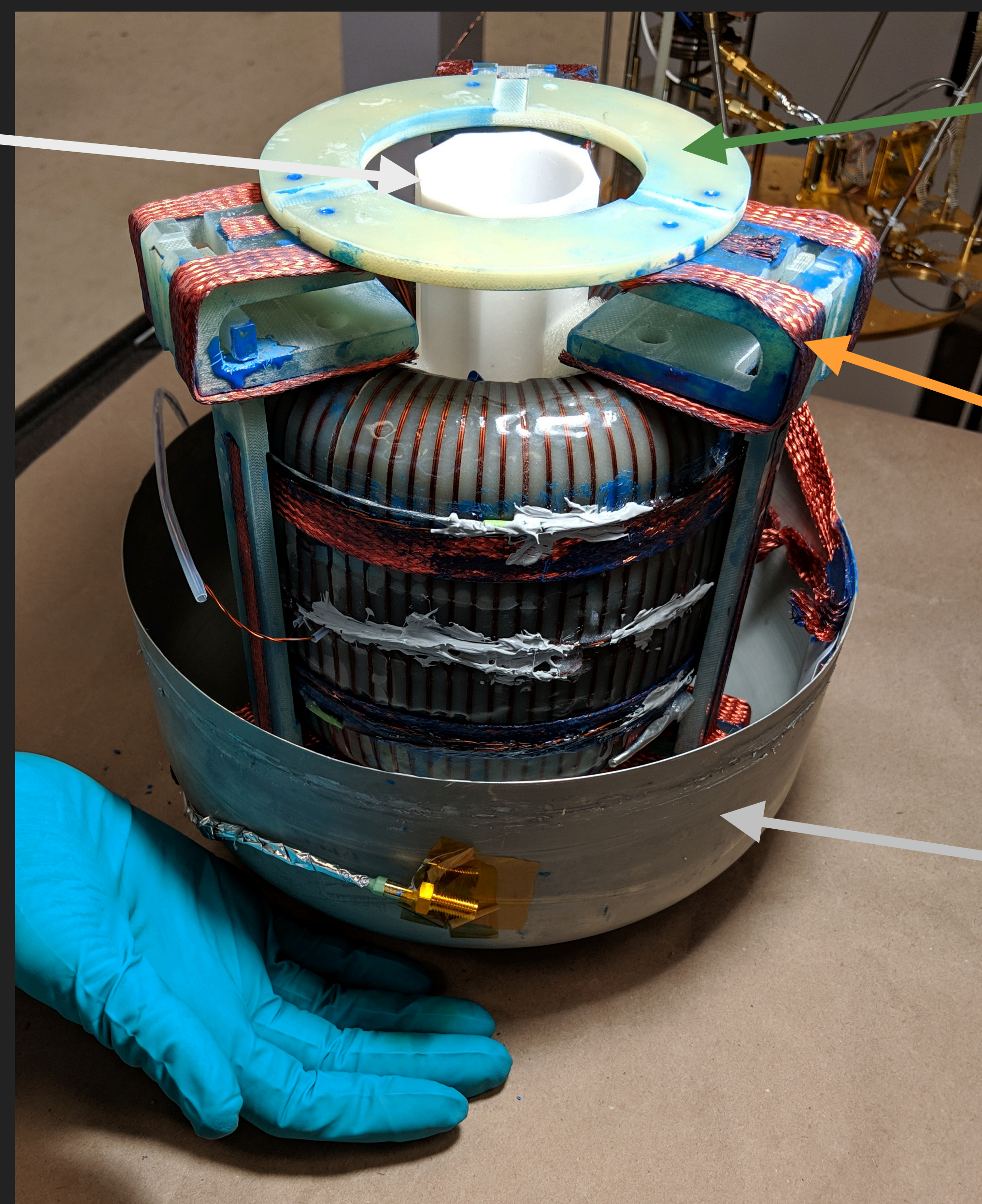


Assembling ABRACADABRA-10 cm



Superconducting pickup loop, mounted on teflon tube

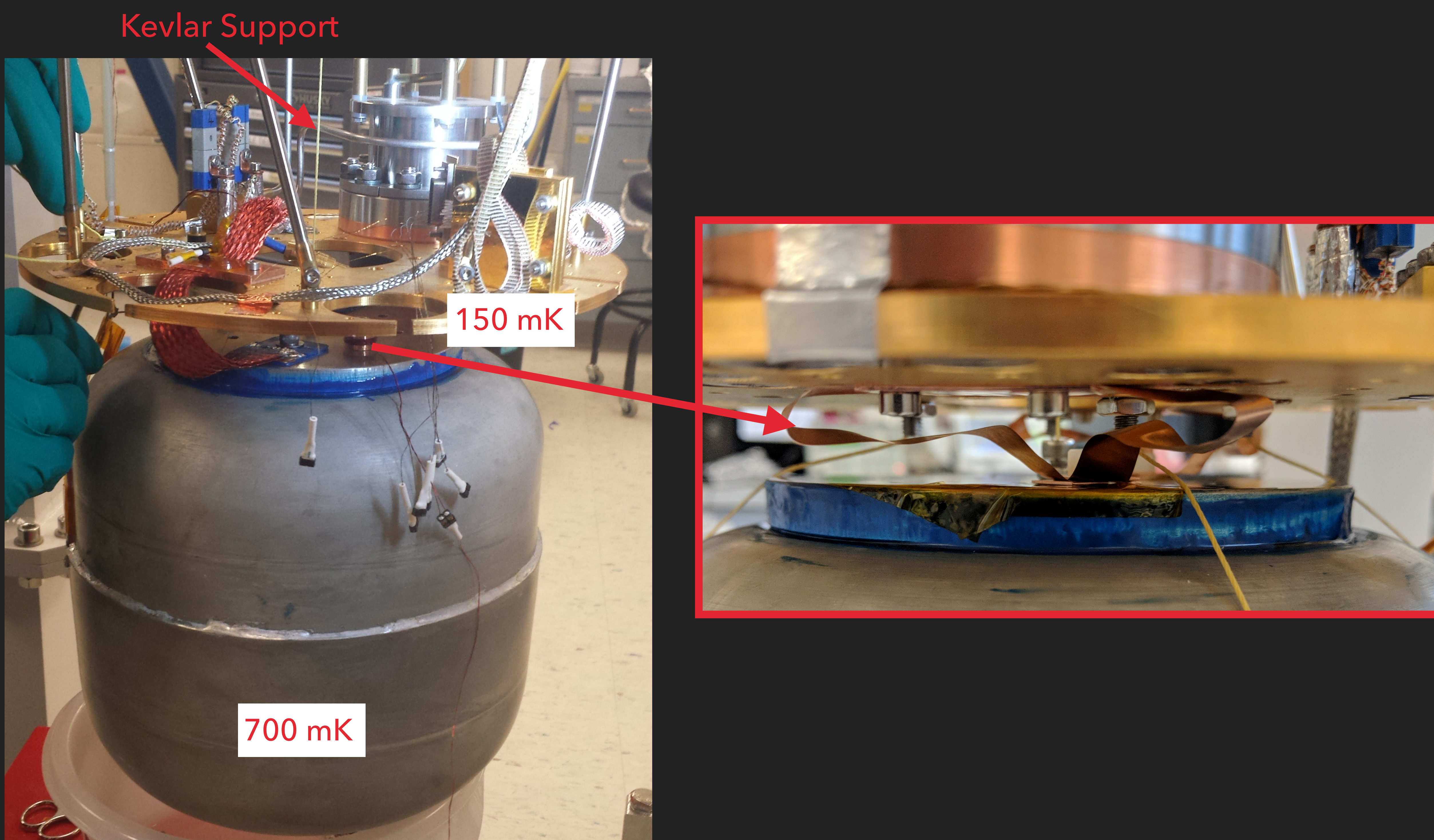


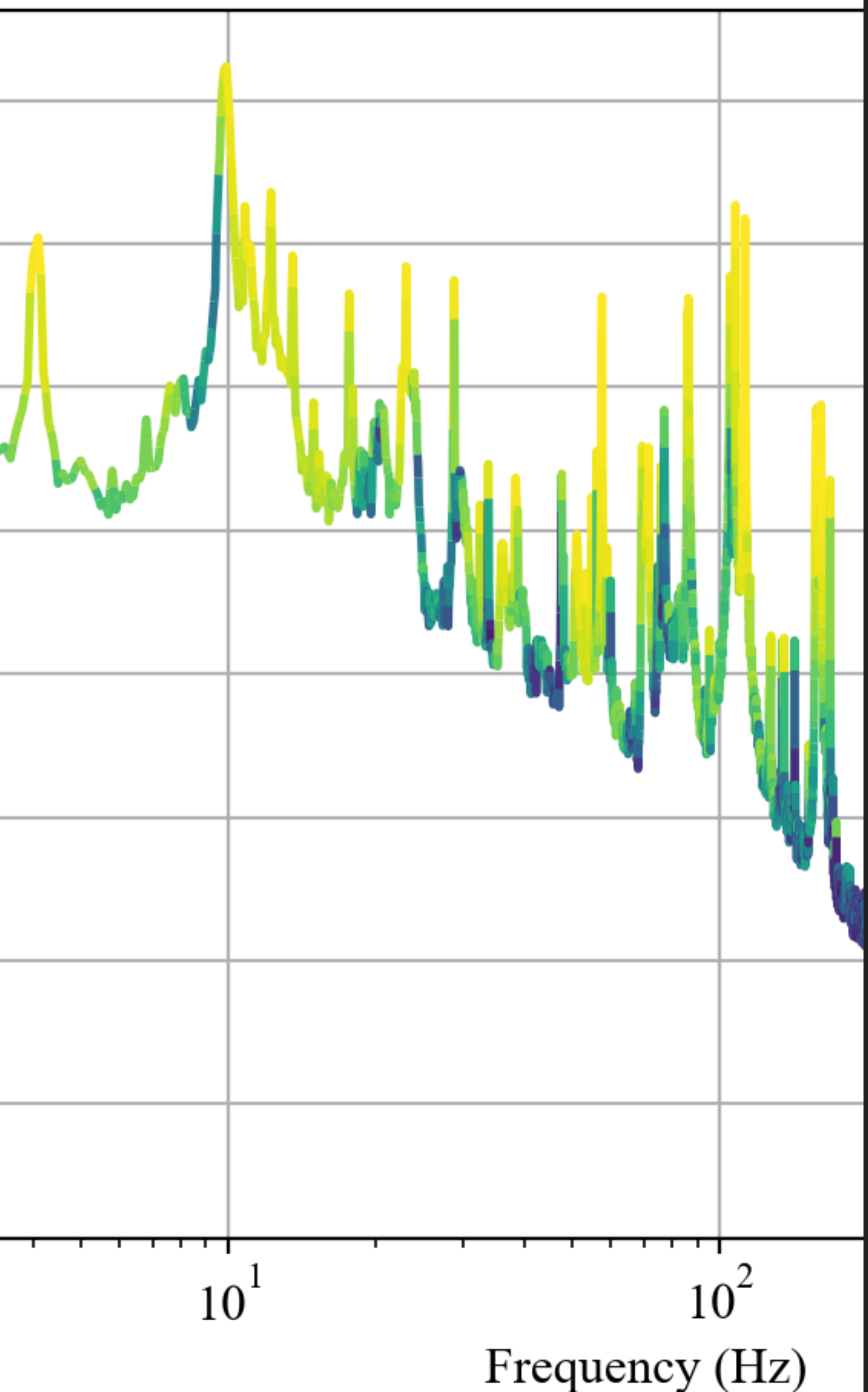
Non-magnetic support structure

Copper thermalization

Superconducting Shielding

ABRA Mounted In Dilution Refrigerator



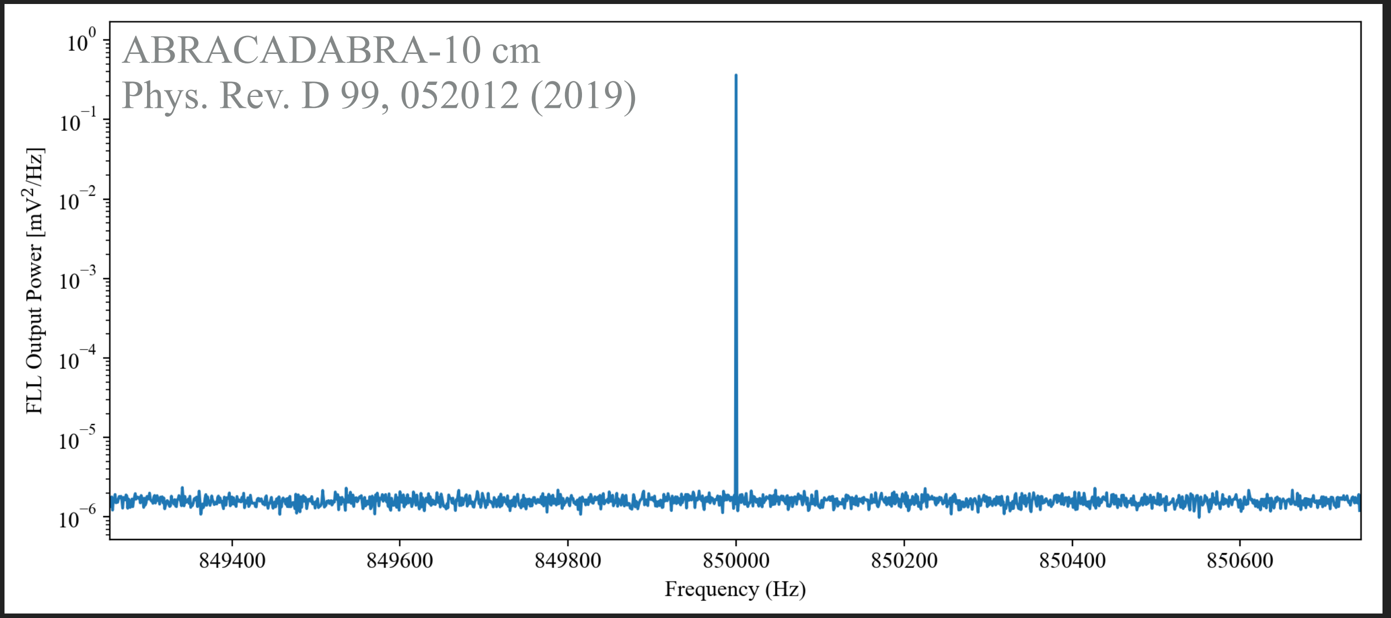


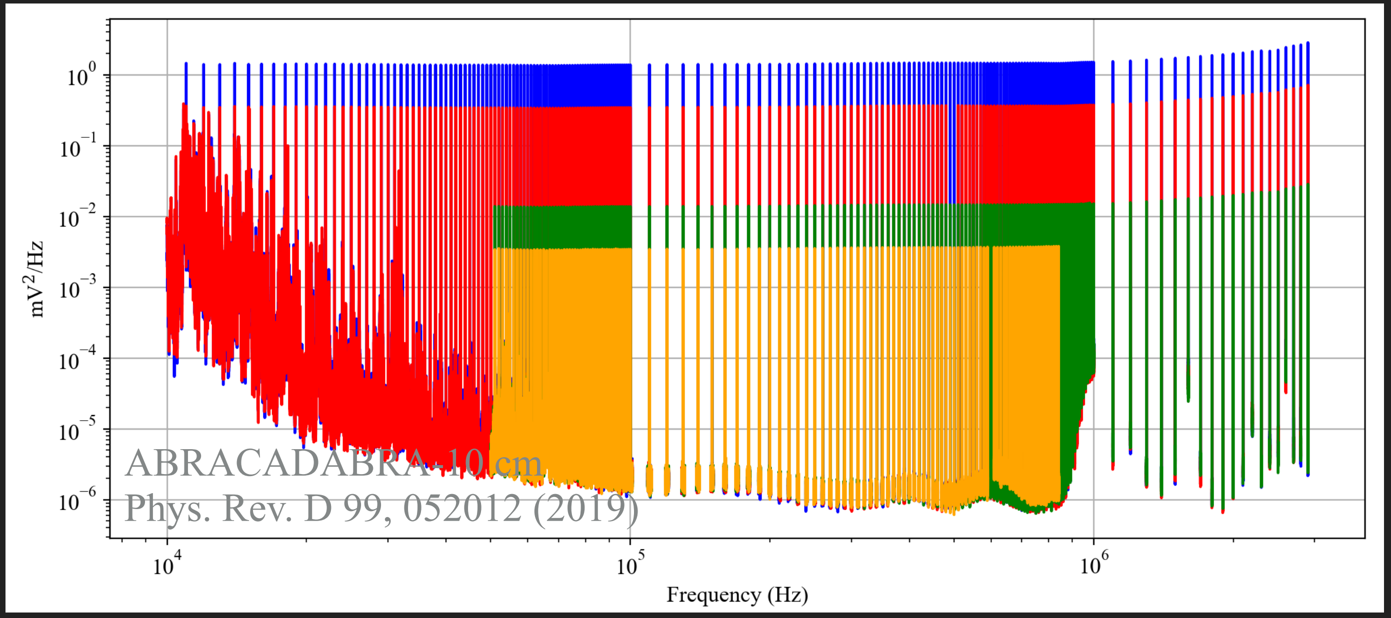
ABRACADABRA-10 CM

RUN I

Calibration Campaign

- 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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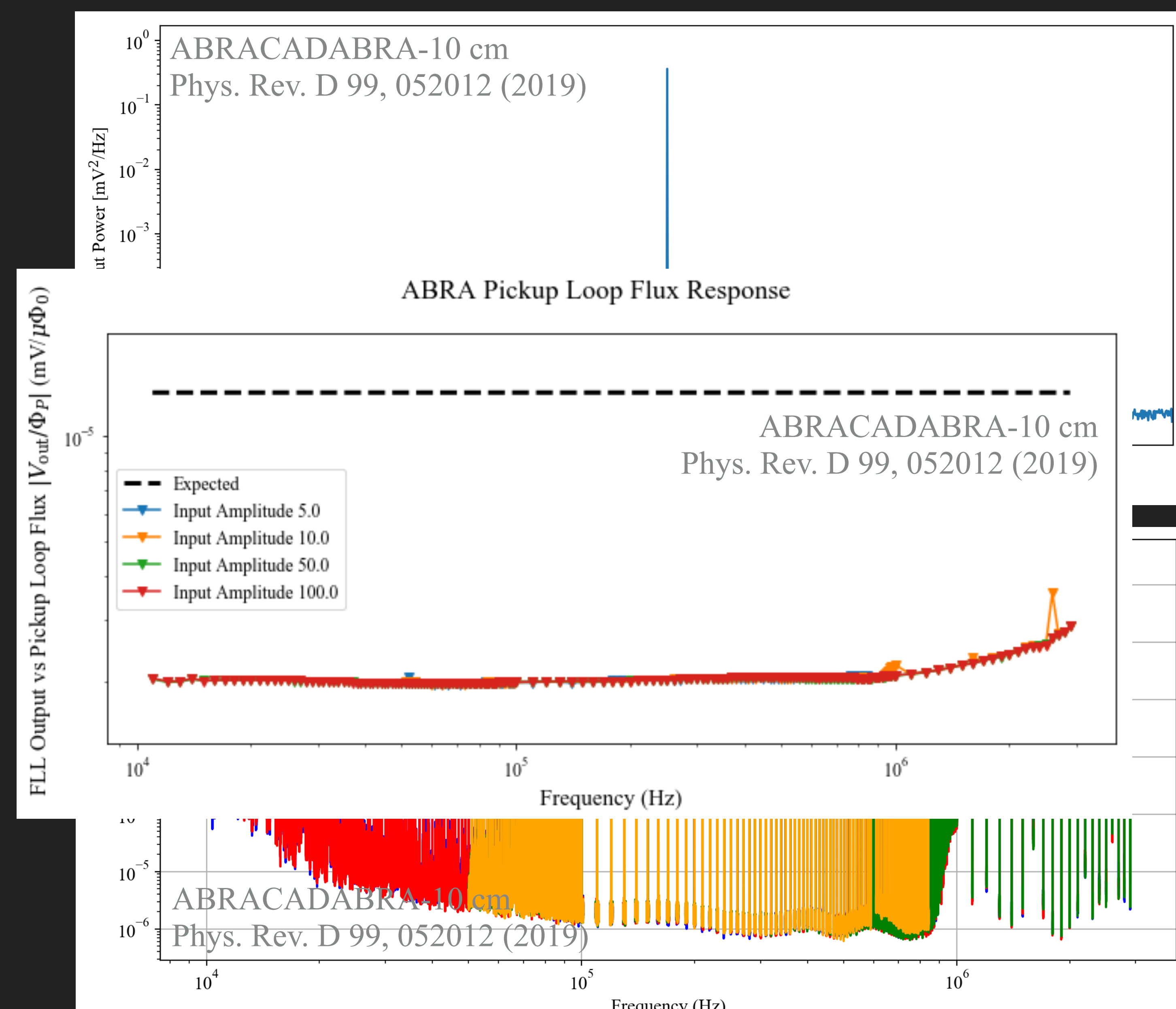
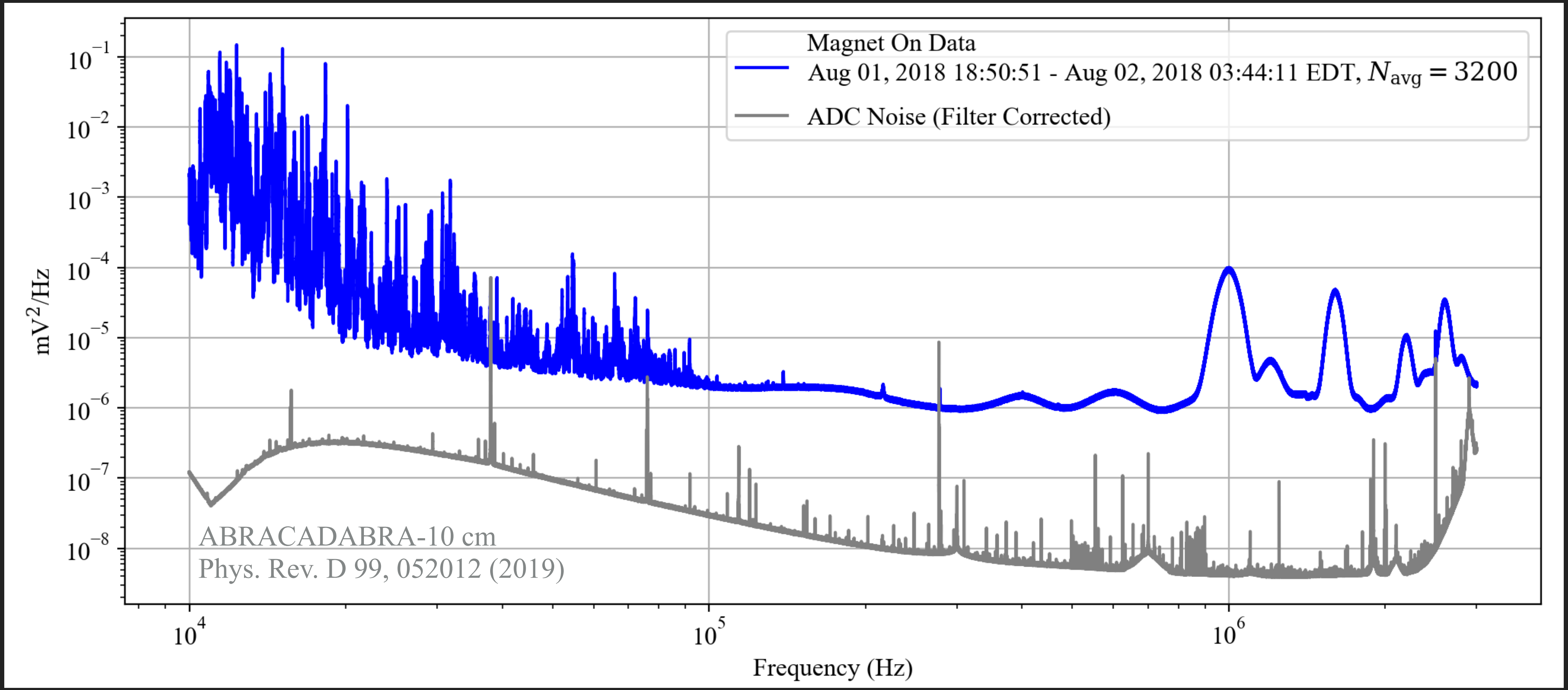


Run 1 Data Collection

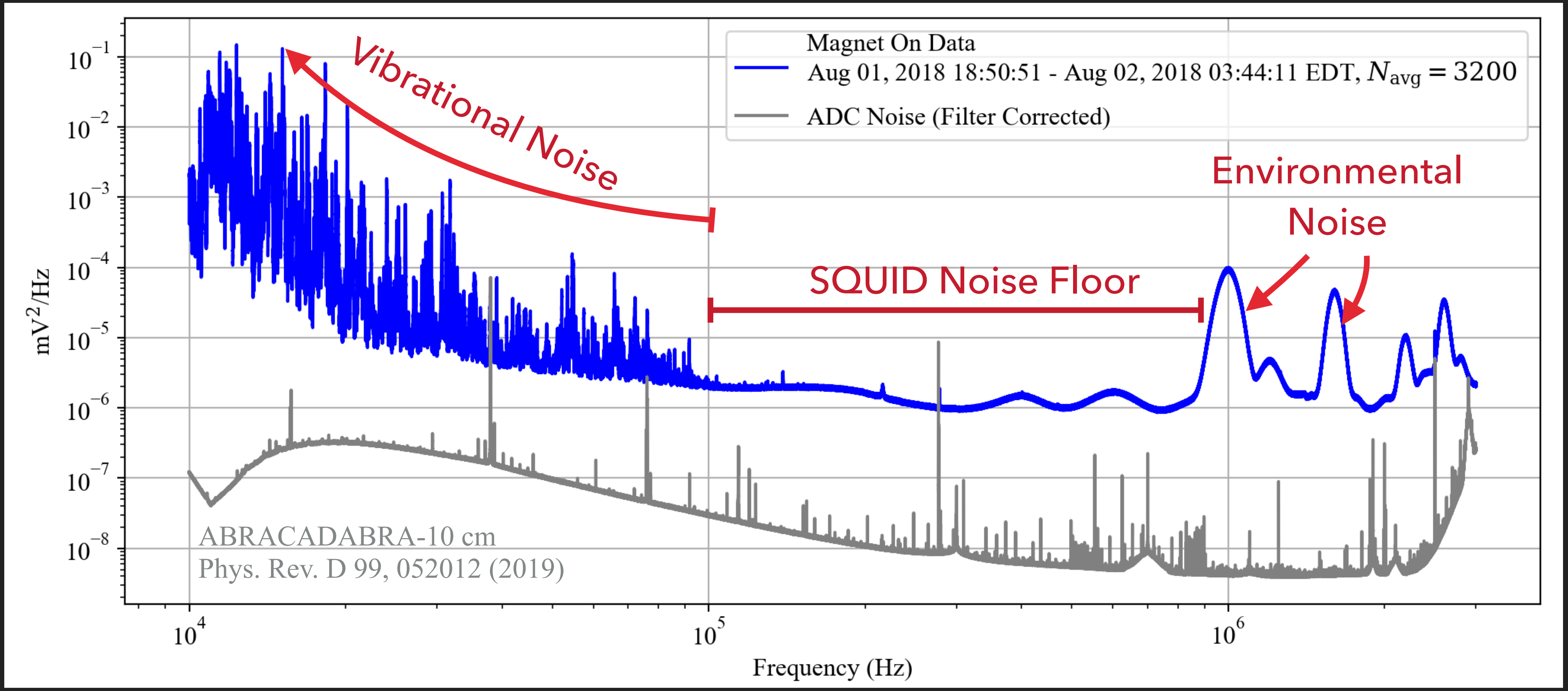
Example 9h Spectrum



- Collected a total of 1 month of Magnet On data from July - August of 2018.
- And an additional 2 weeks of Magnet Off (background) data.

Run 1 Data Collection

Example 9h Spectrum



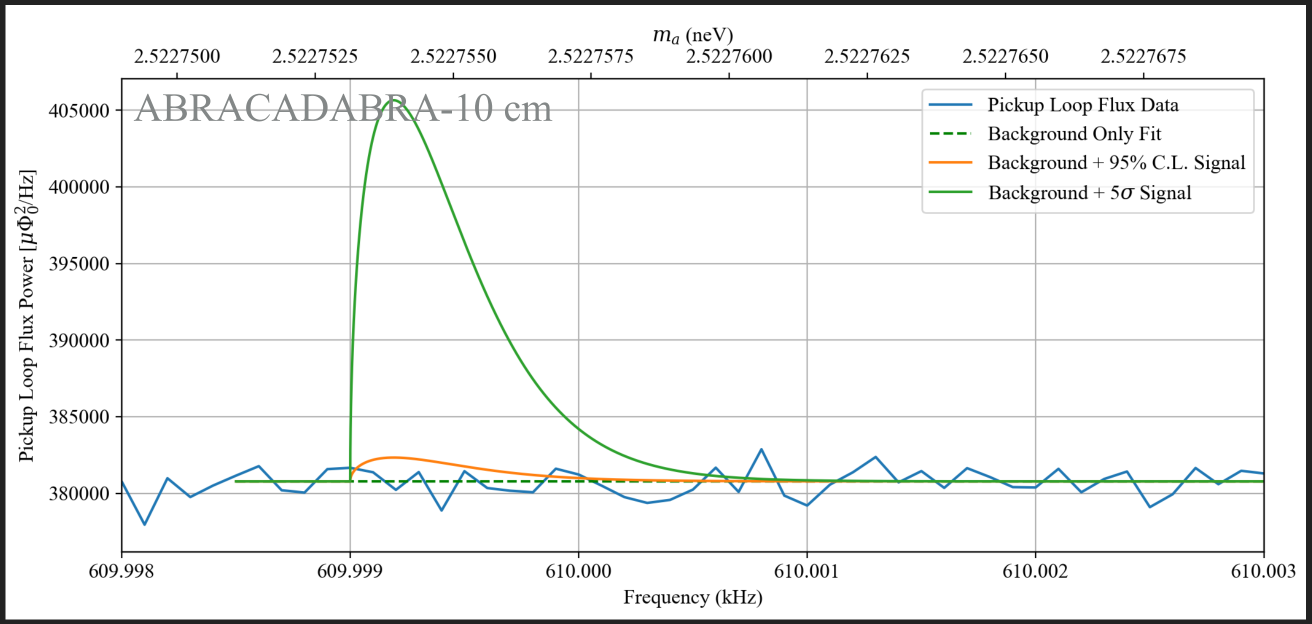
- Collected a total of 1 month of Magnet On data from July - August of 2018.
- And an additional 2 weeks of Magnet Off (background) data.

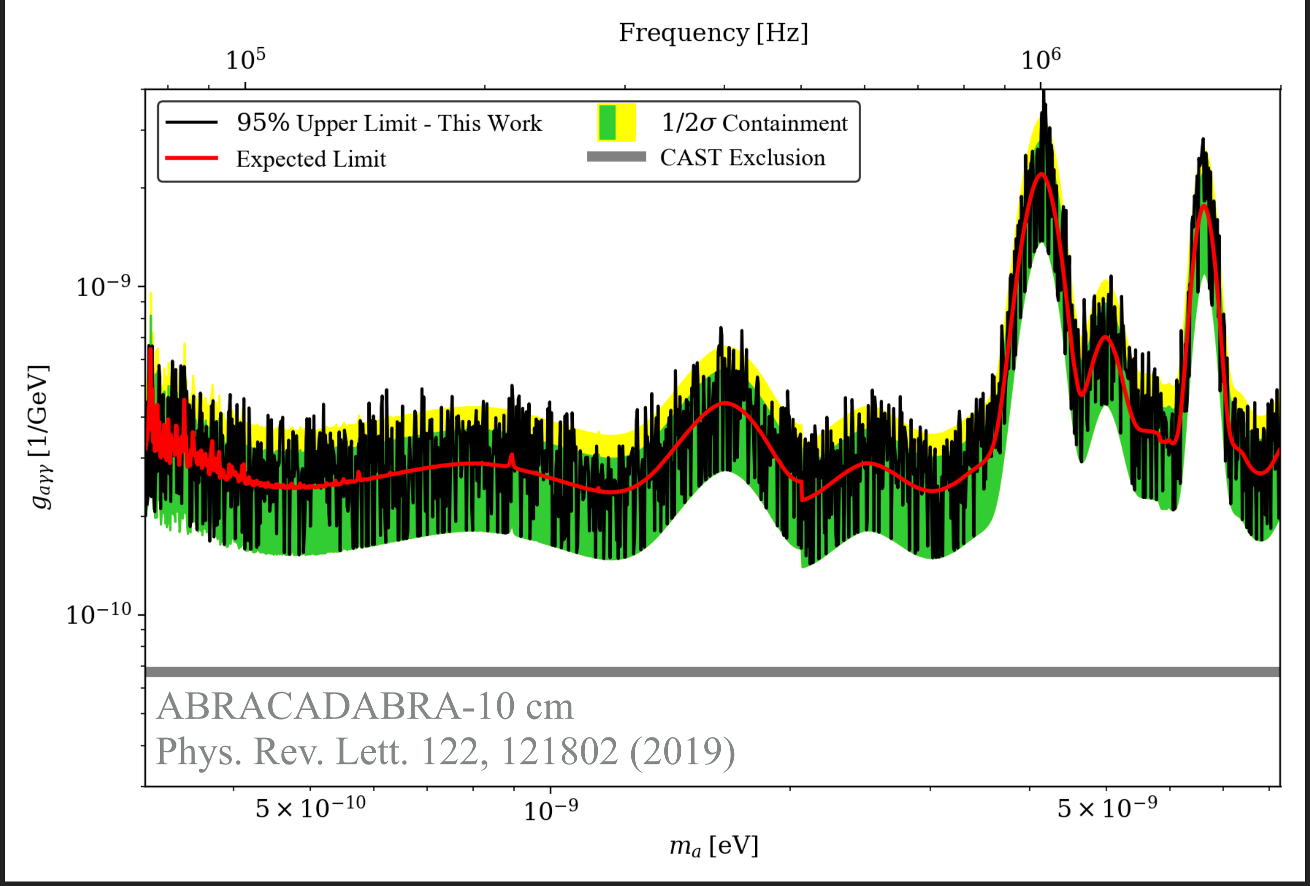
Axion Limits

- We saw no 5σ excesses that were not vetoed by Magnet off or digitizer data
  - 99.8% signal efficiency
- We place 95% C.L. upper limits using a similar log-likelihood ratio approach

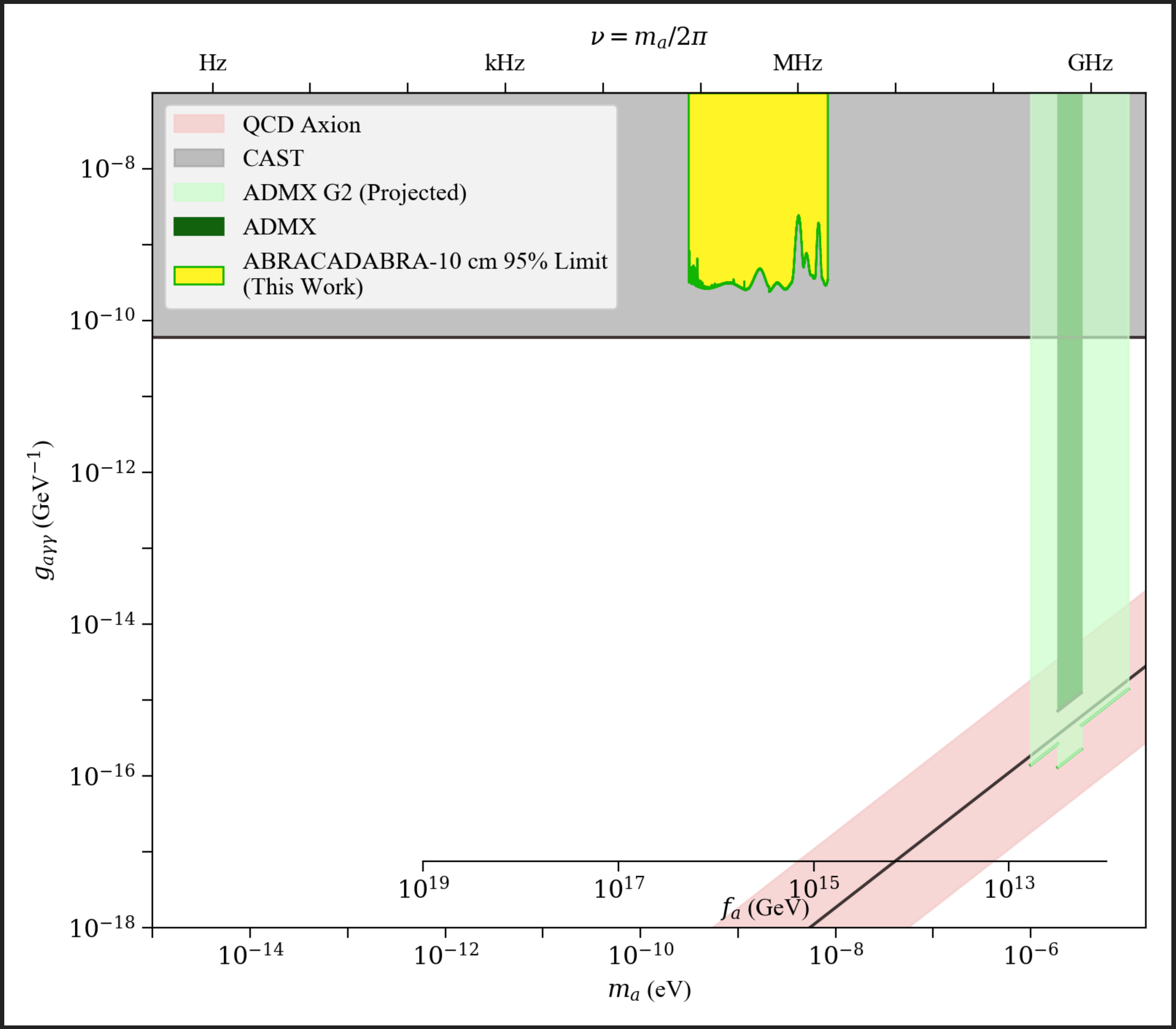
PHYS. REV. LETT. 122, 121802 (2019)

PHYS. REV. D 99, 052012 (2019)





ABRACADABRA-10 cm Run 1 Limits



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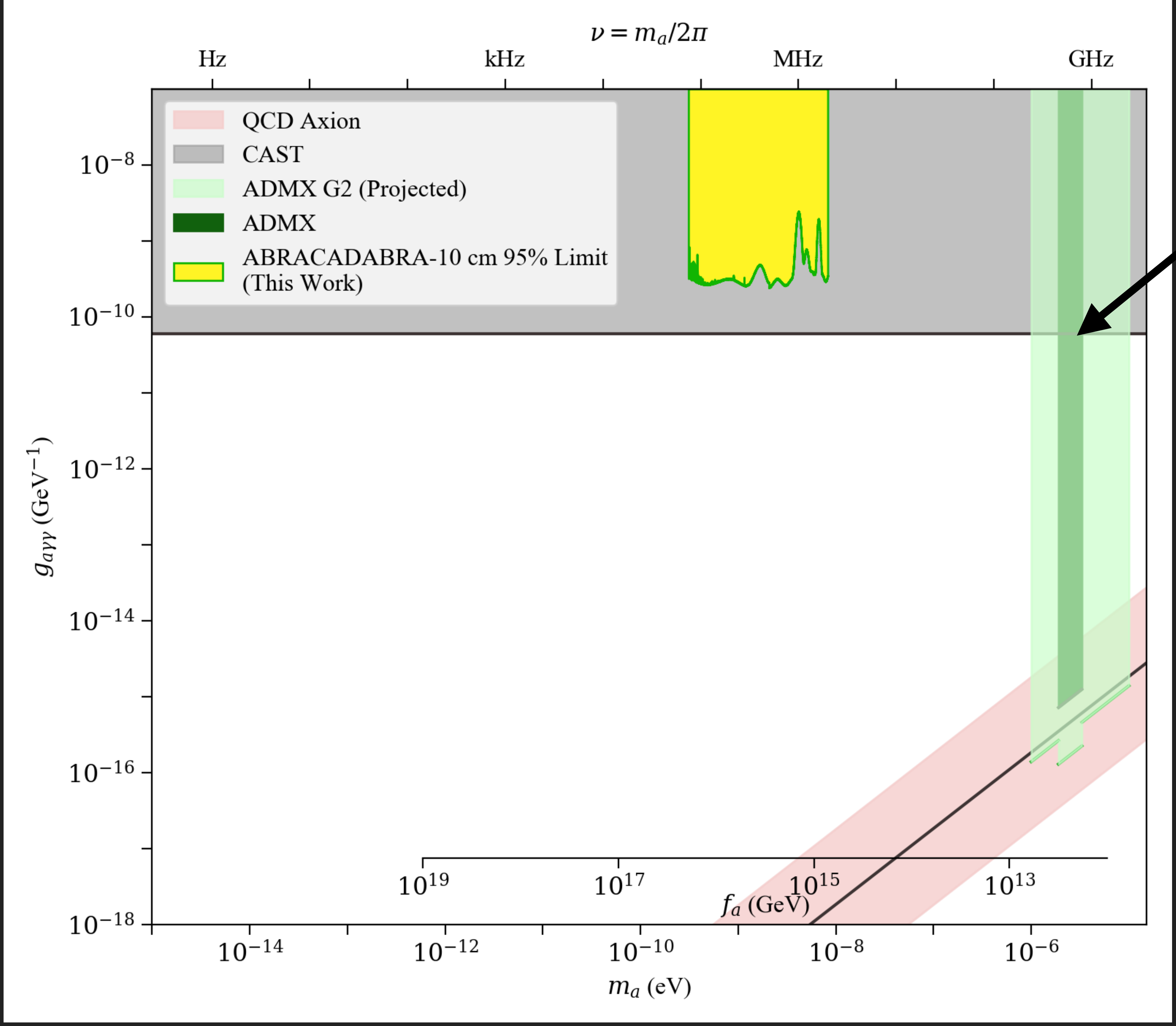

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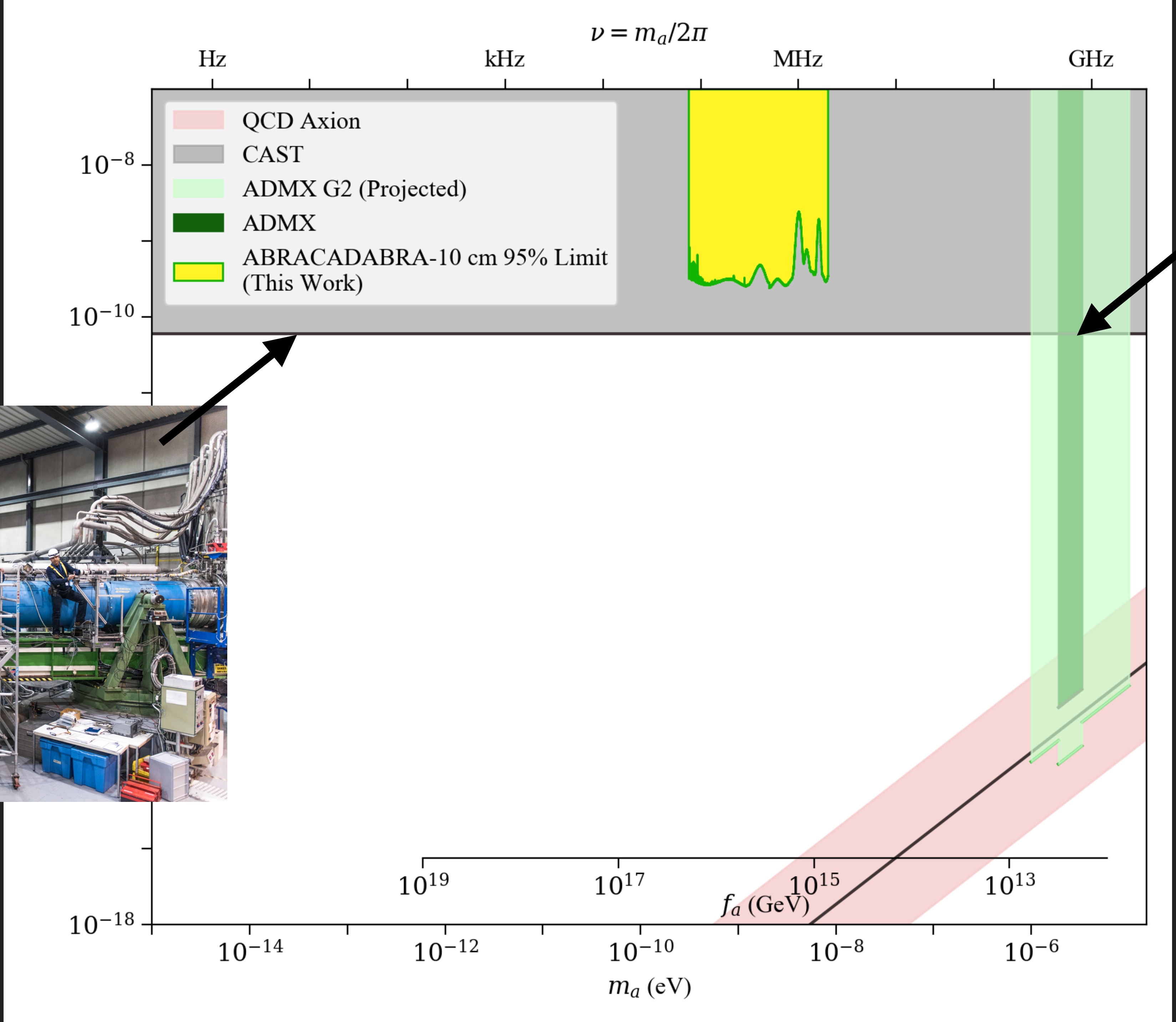

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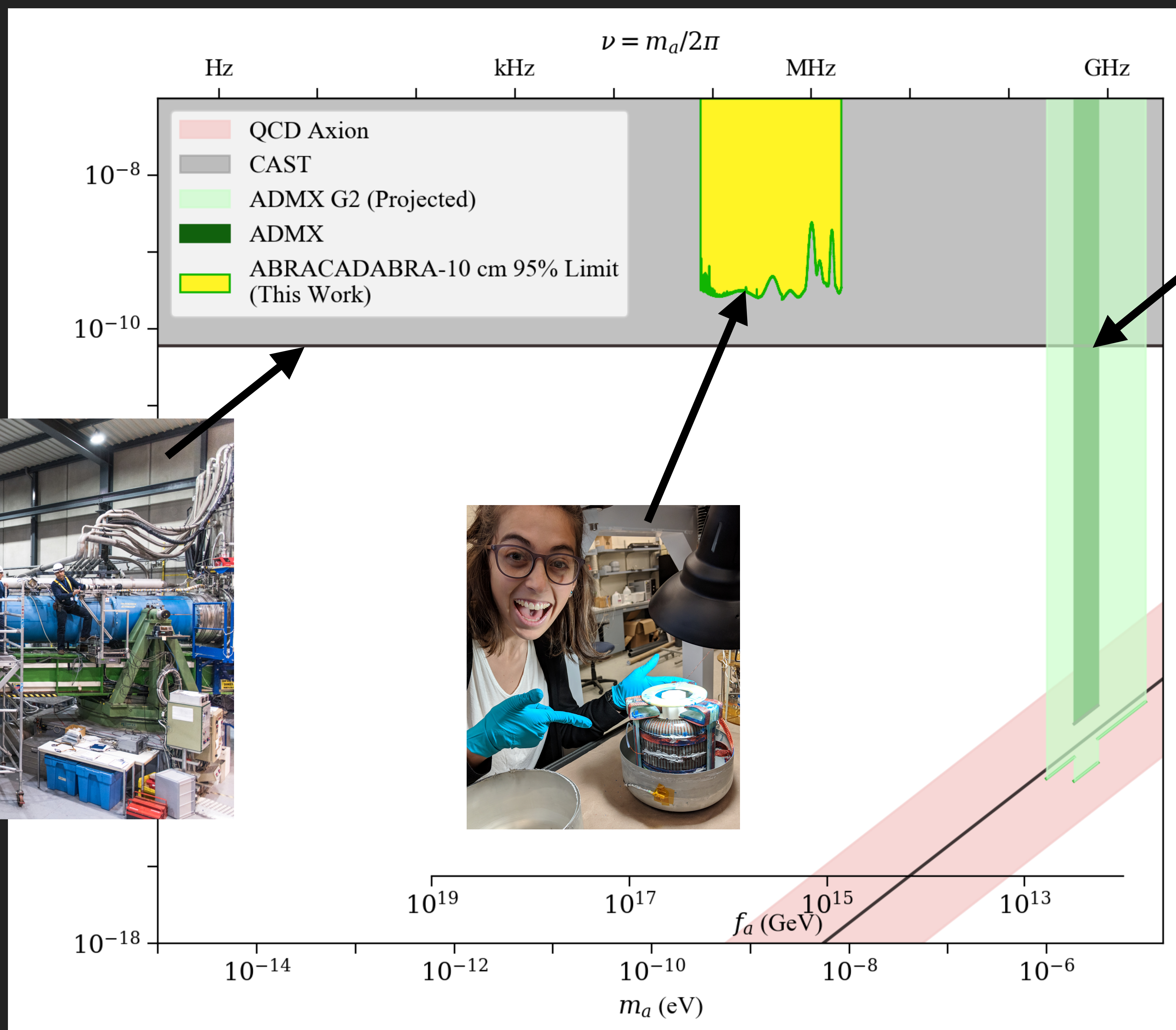
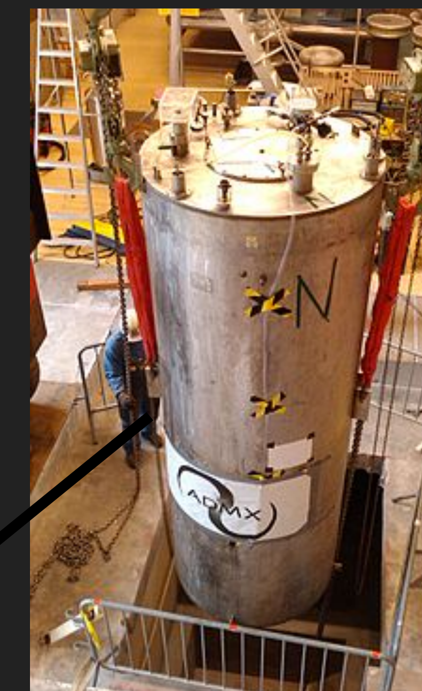
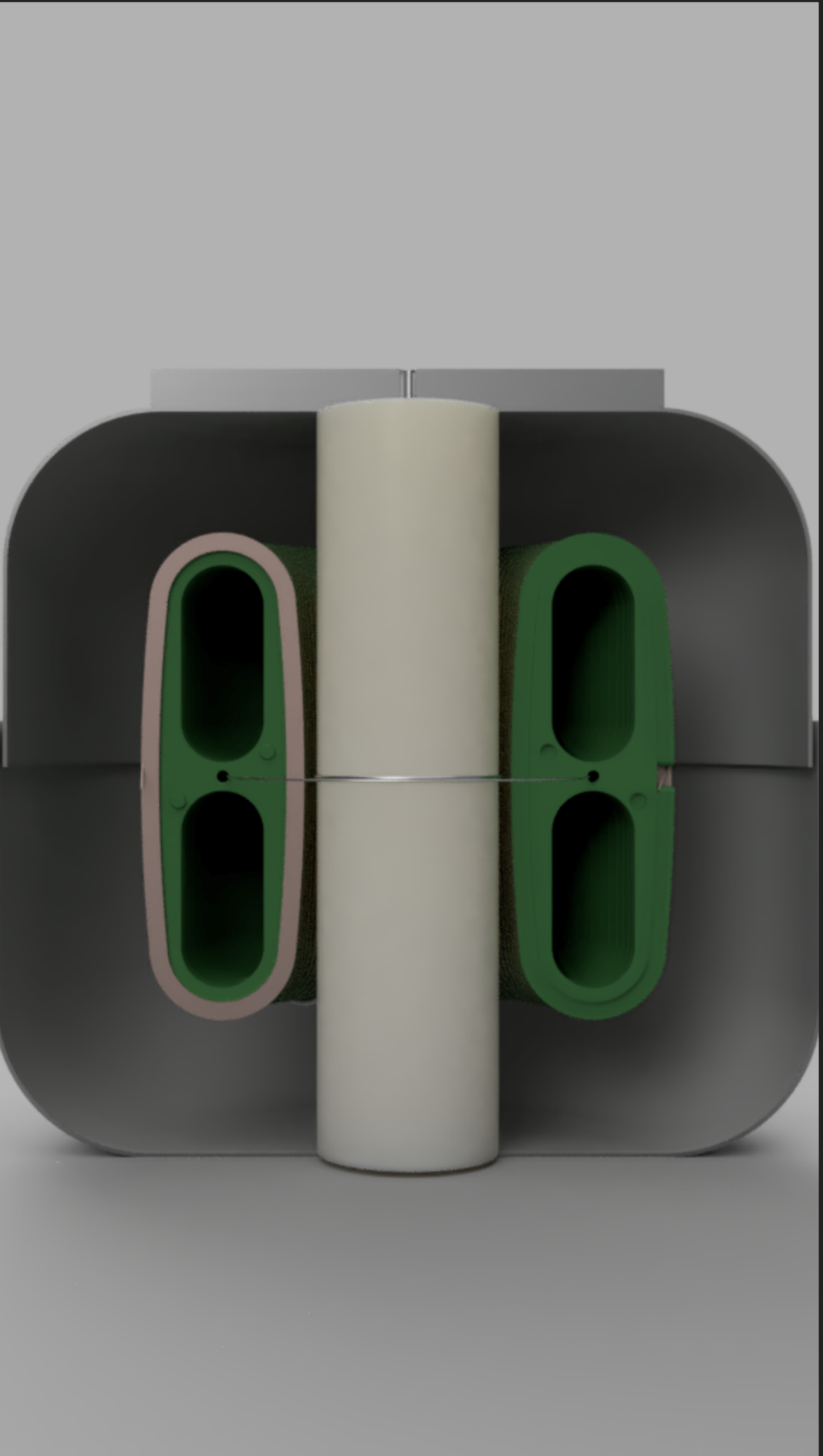


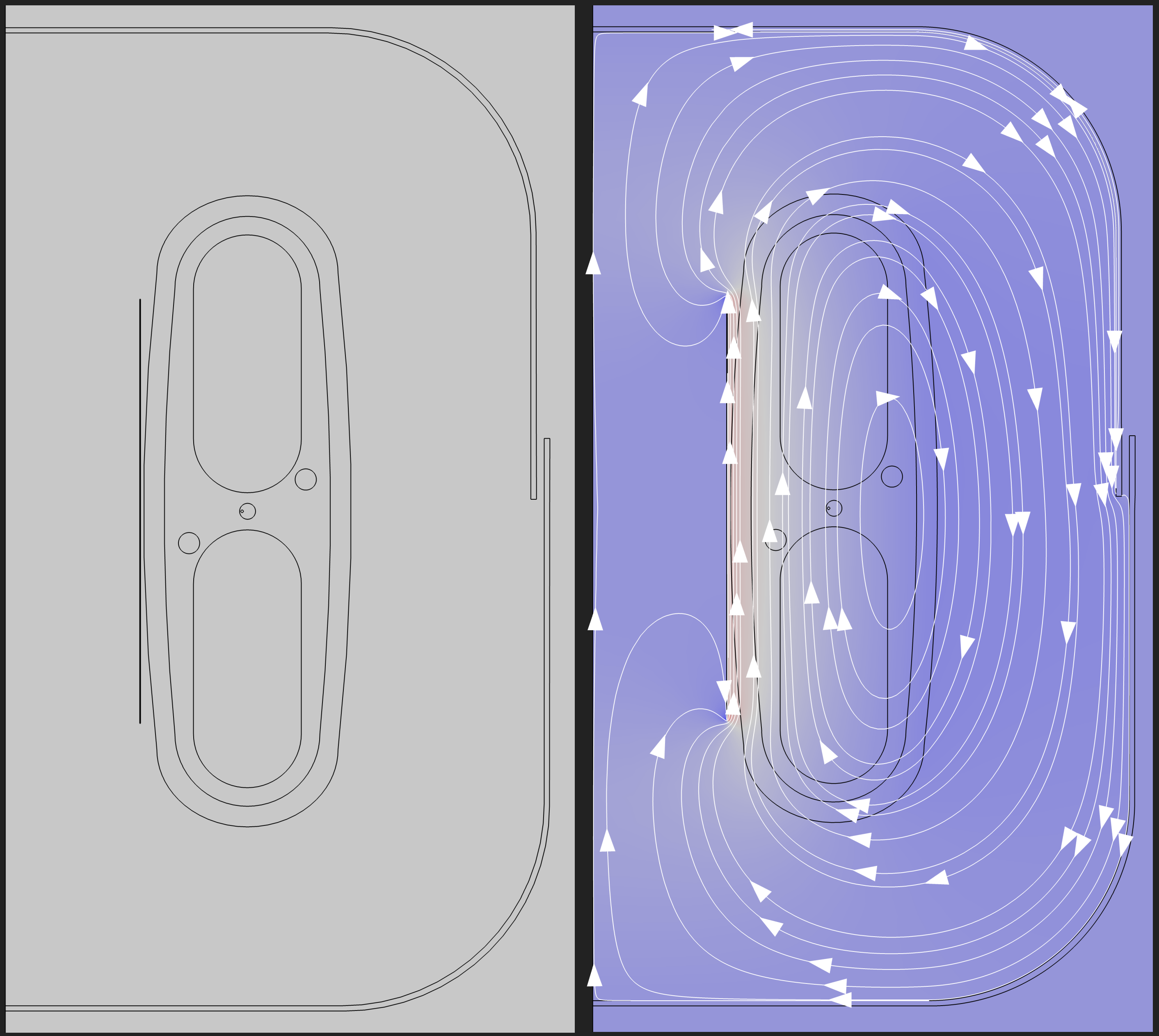




NEXT STEPS

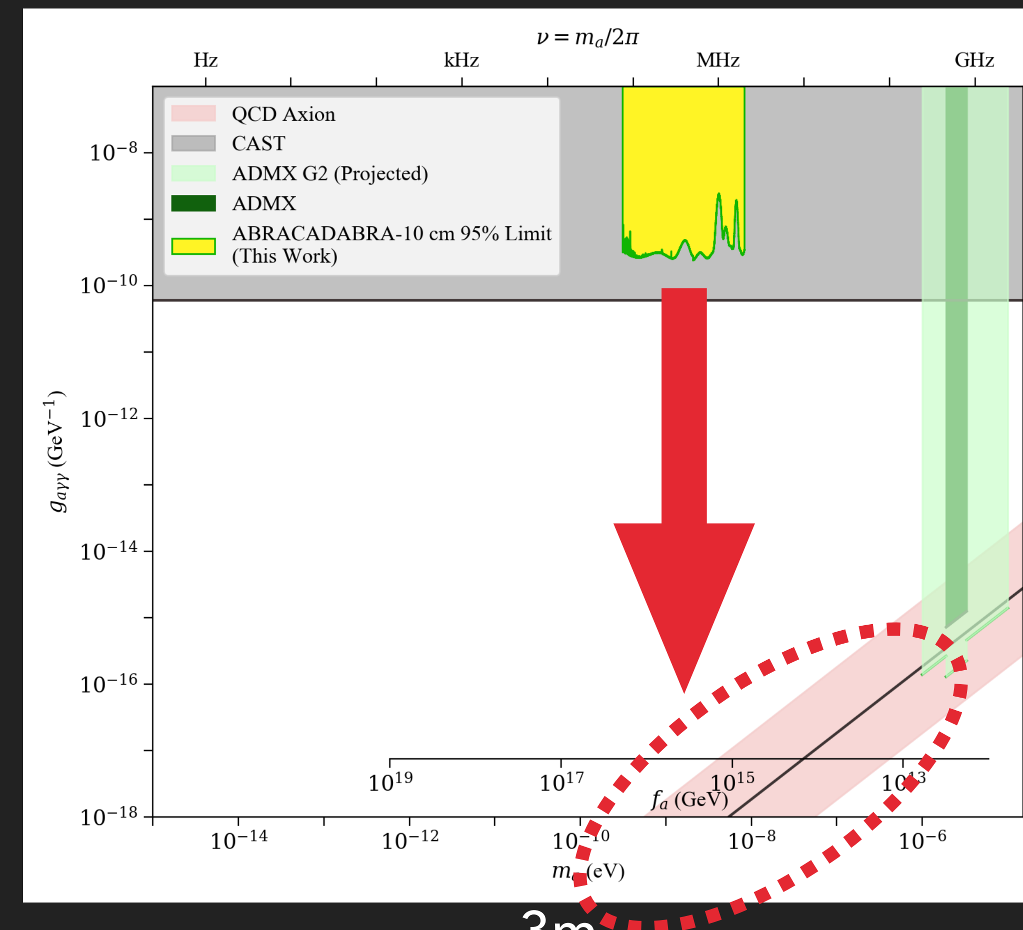
Second Run of ABRACADABRA-10 cm

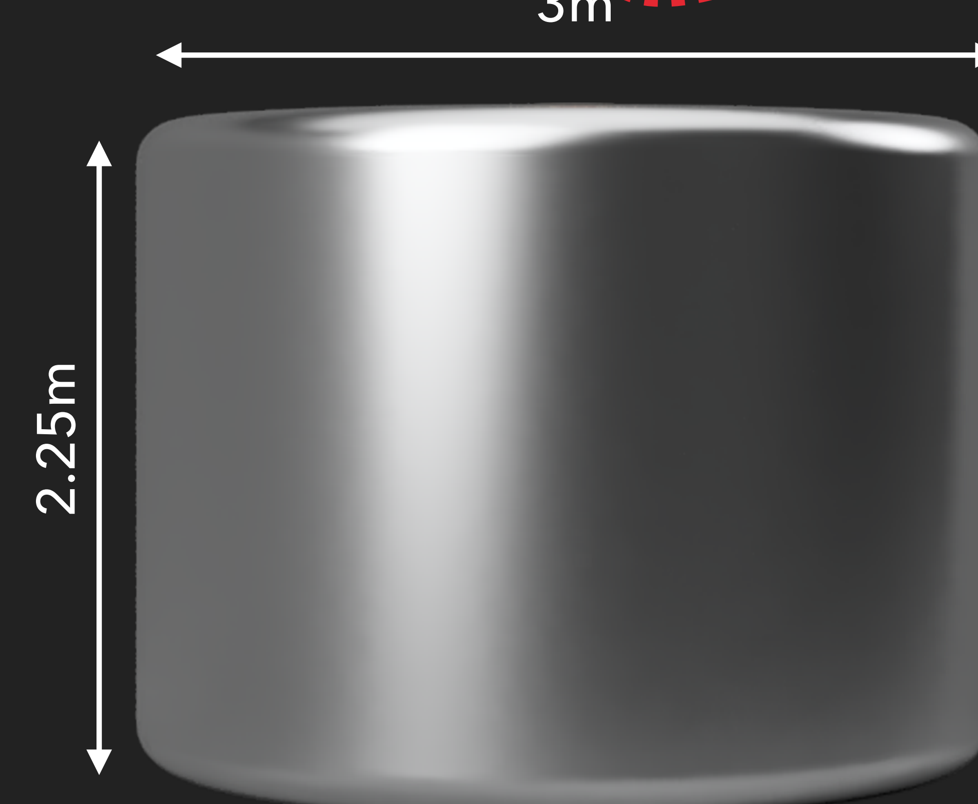
- Currently installing a new larger pickup cylinder
  - Improved coupling to axion induced field
  - Lower total inductance
- Expected to improve ADM sensitivity by about 1 order of magnitude
- Expecting to begin data taking later in the summer.



1 m Scale ABRACADABRA

- Goal: Probing the QCD scale axion from ~μeV down to ~neV (GUT scale axion)
- A ~ meter scale detector with a max field of B_0~1-5 T
  - Resonator readout with accelerated scan readout strategy
  - Quantum sensors able to push beyond the Standard Quantum Limit
  - Operating at or below 100 mK
- We have already begun putting together an interest group and a CDR to follow





1 m Sca

- Goal: ~μeV
- A ~ m field c
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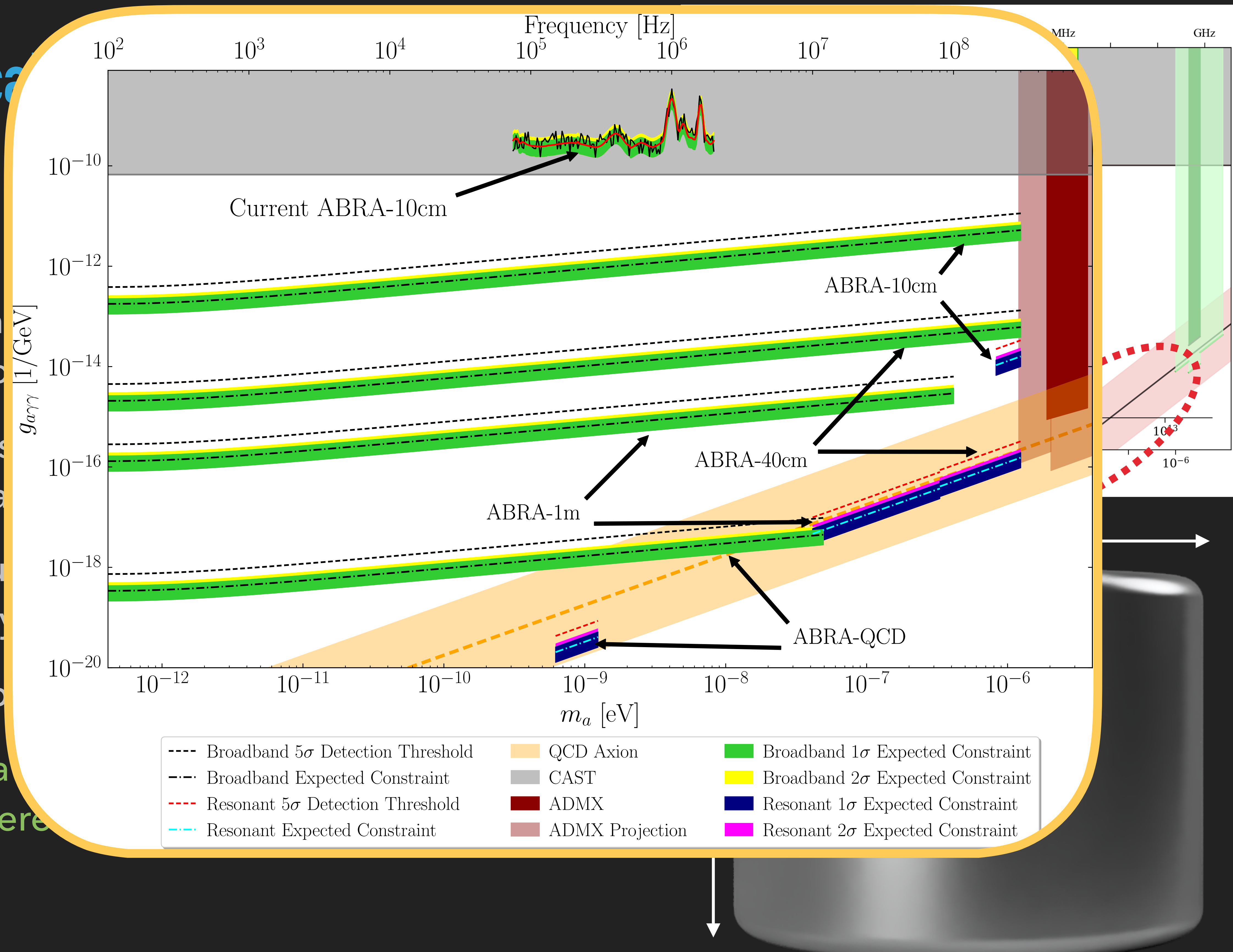
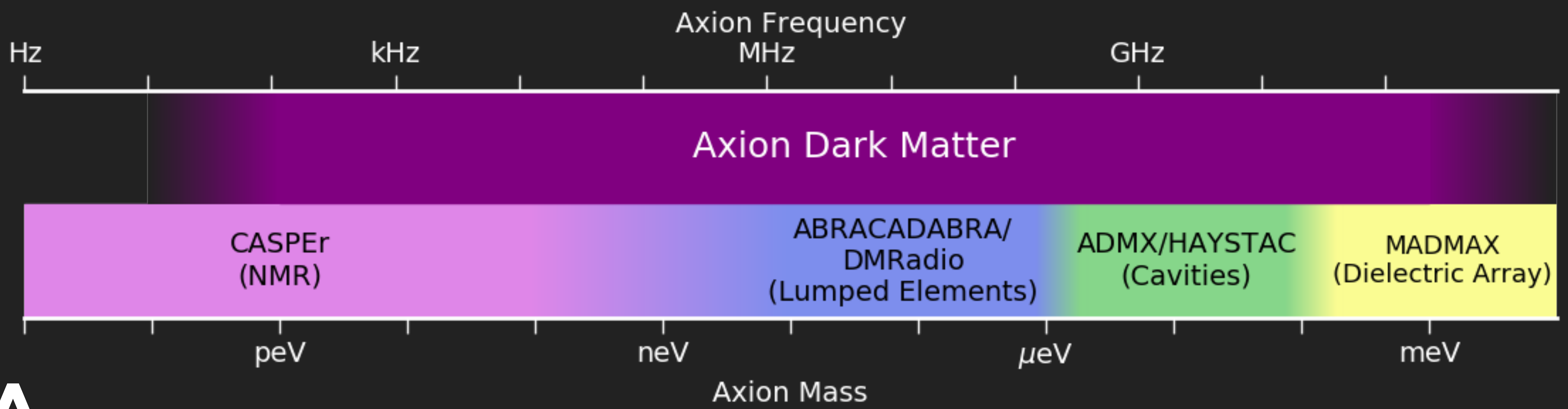
  - Qu bey
  - Op
- We ha an intere



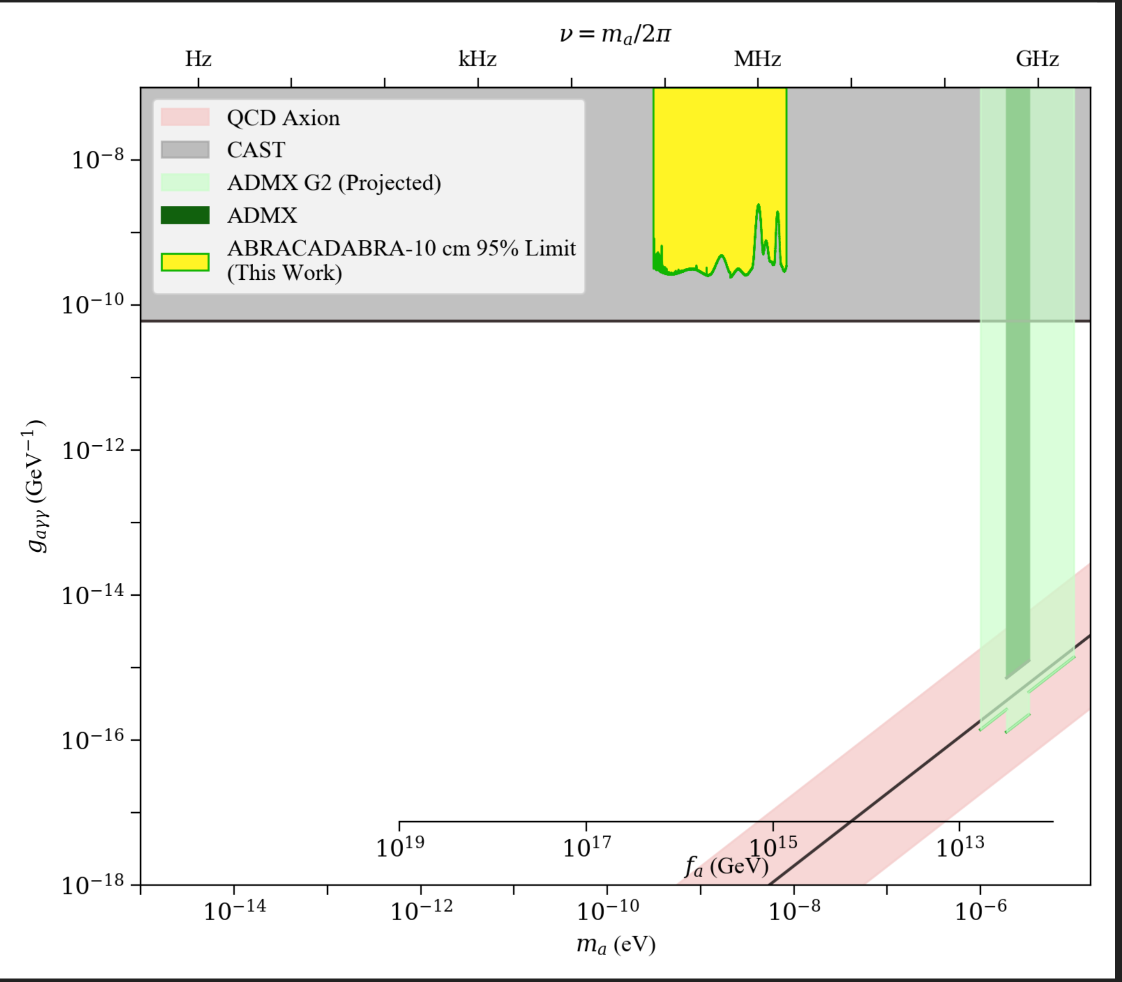
Axion Dark Matter Outlook

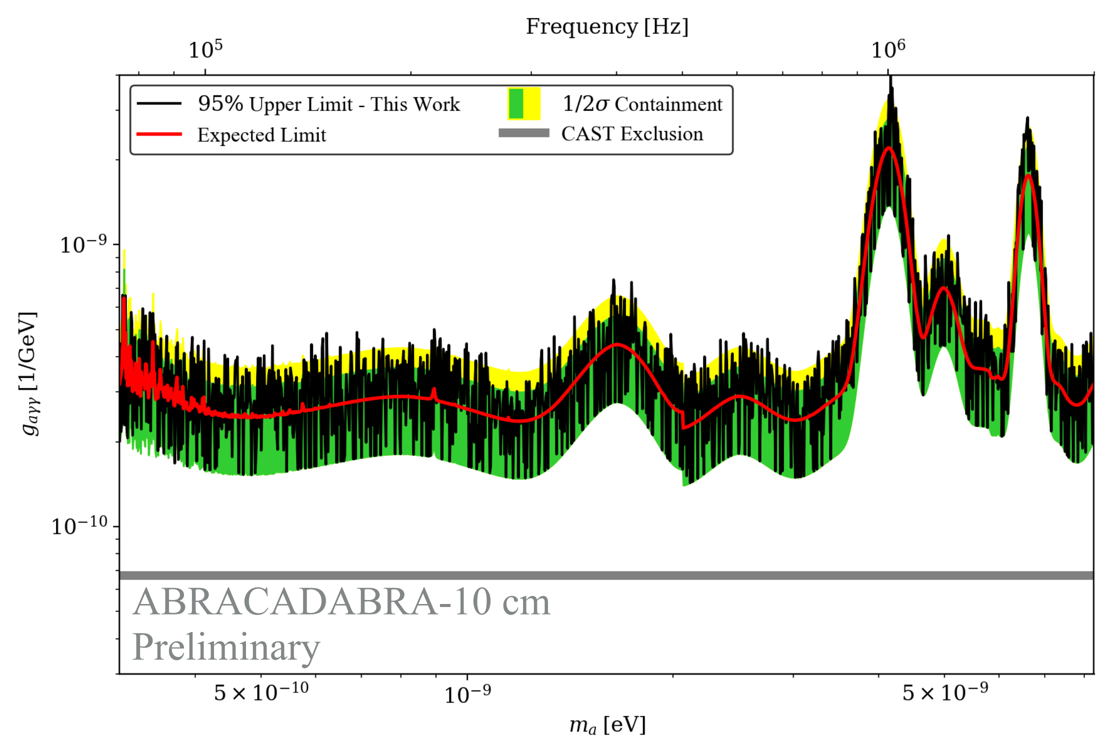
- The axion is the leading solution to the Strong-CP problem and is a compelling Dark Matter candidate
- Leveraging the recent advances in quantum measurement technology, the full axion Dark Matter parameter space could be probed in the next 10 ~ 15 years
- This would require a range of detector technologies all pushing beyond the Standard Quantum Limit



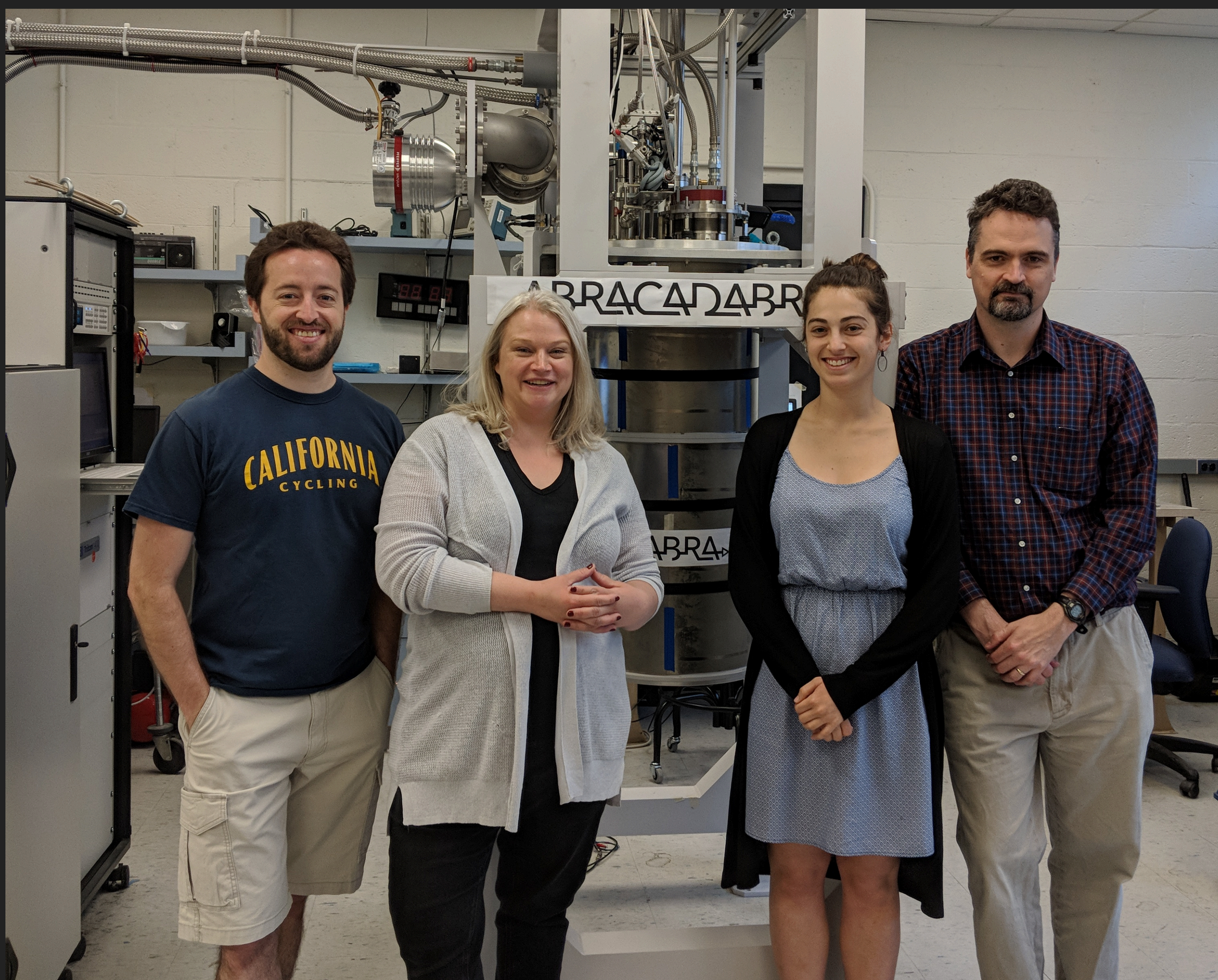
Summary

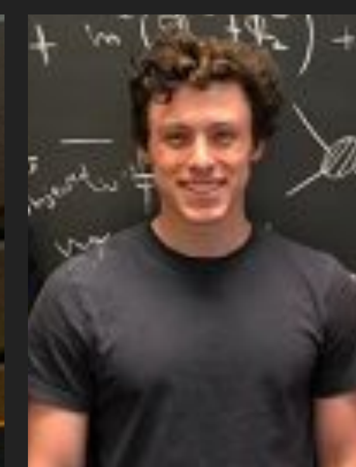
- We have built and operated the first broadband search for Axion Dark Matter in the sub μeV range.
- With a 10 cm scale detector and 1 month of exposure, we are competitive with the leading limits in the field!
- Currently preparing for a second run of ABRACADABRA-10 cm with ~ 1 order of magnitude improvement in sensitivity
- Putting together a proposal for a ~1 m scale experiment (ABRACADABRA-75 cm)





ABRACADABRA

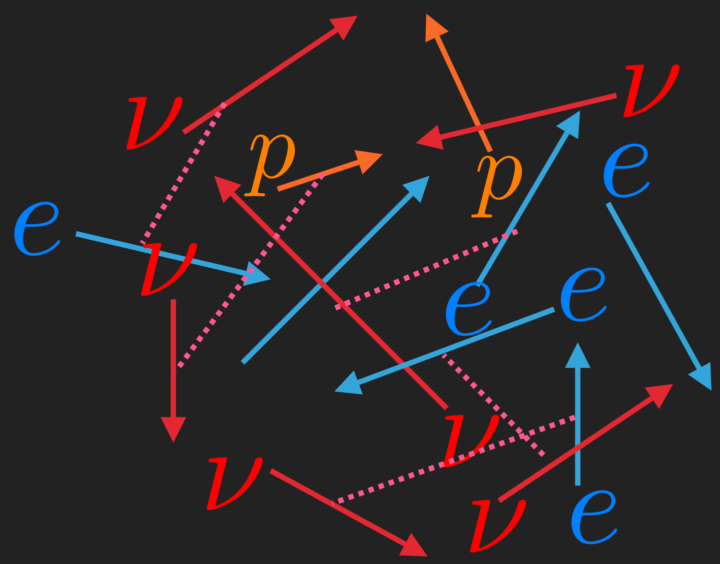




Thank you for your attention!

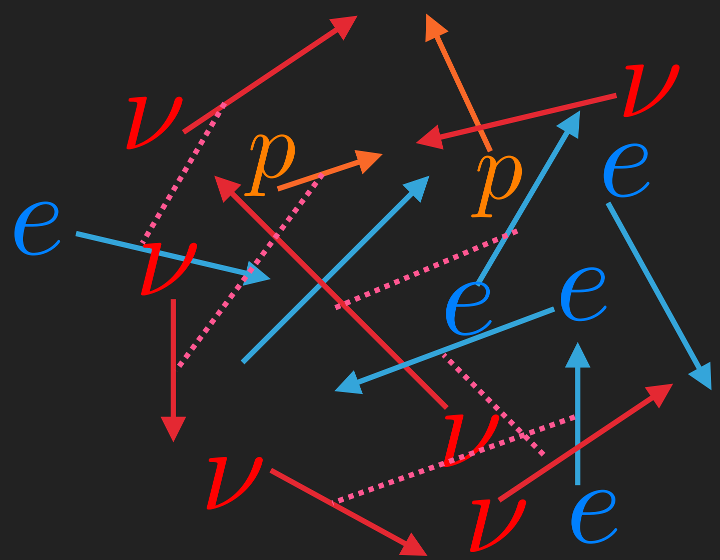
Backup Slides

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!

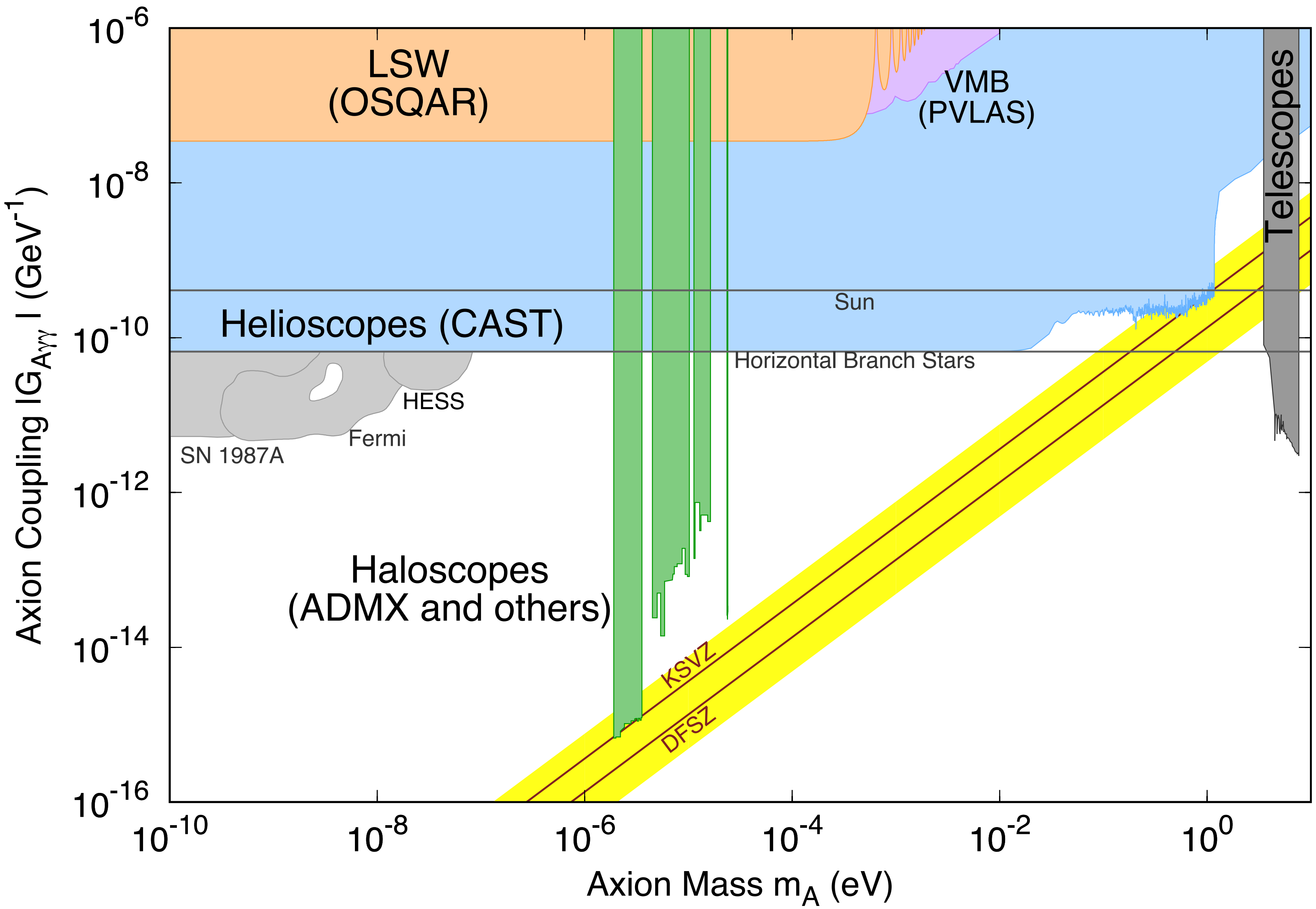
Cosmic Neutrinos vs Cosmic Axions



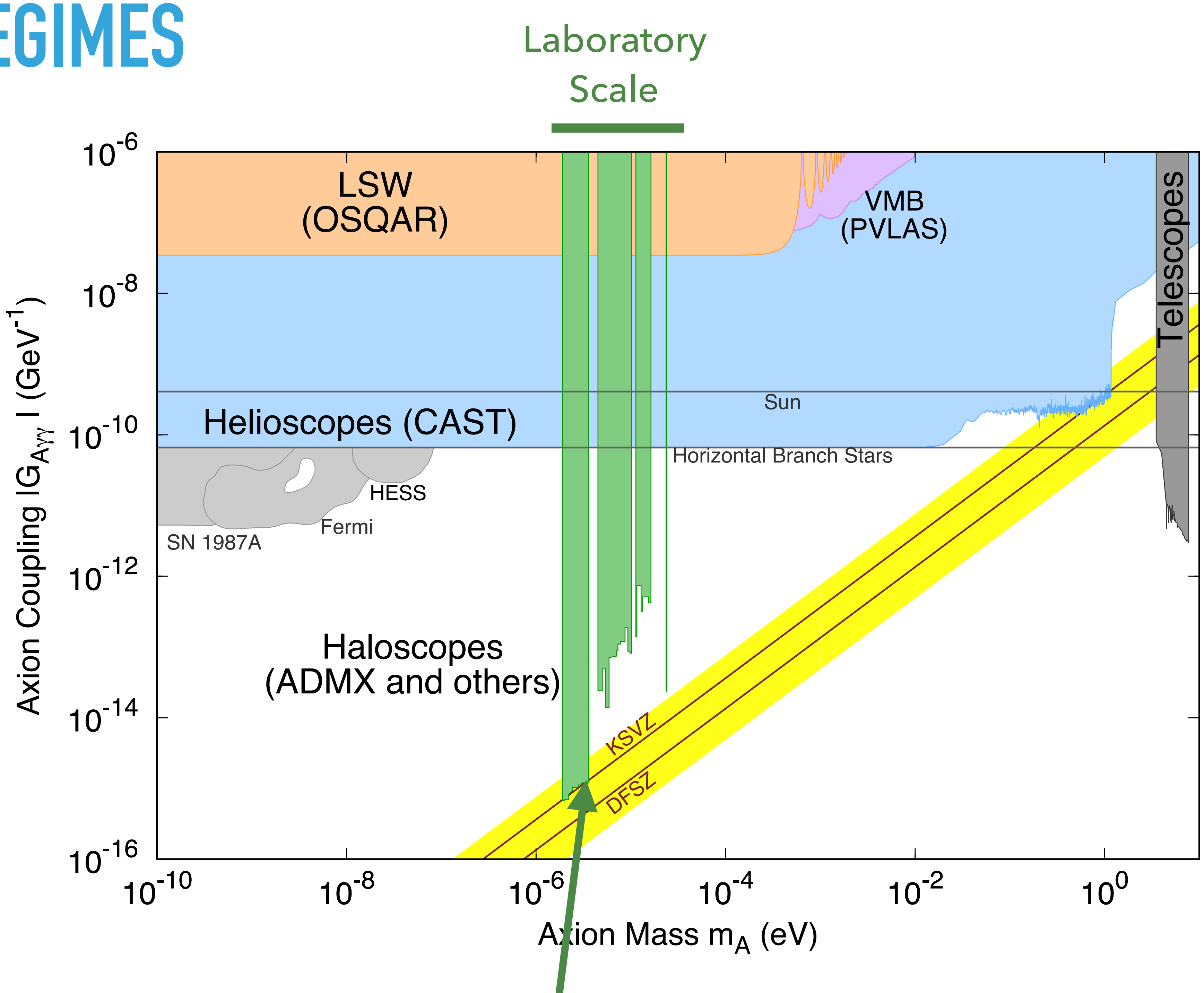
- In the early universe (t<1 s), the neutrinos are thermalized to the plasma
- After they decouple, they are hot and relativistic for most of cosmic history
- They are not COLD dark matter!

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

THREE MASS REGIMES



THREE MASS REGIMES



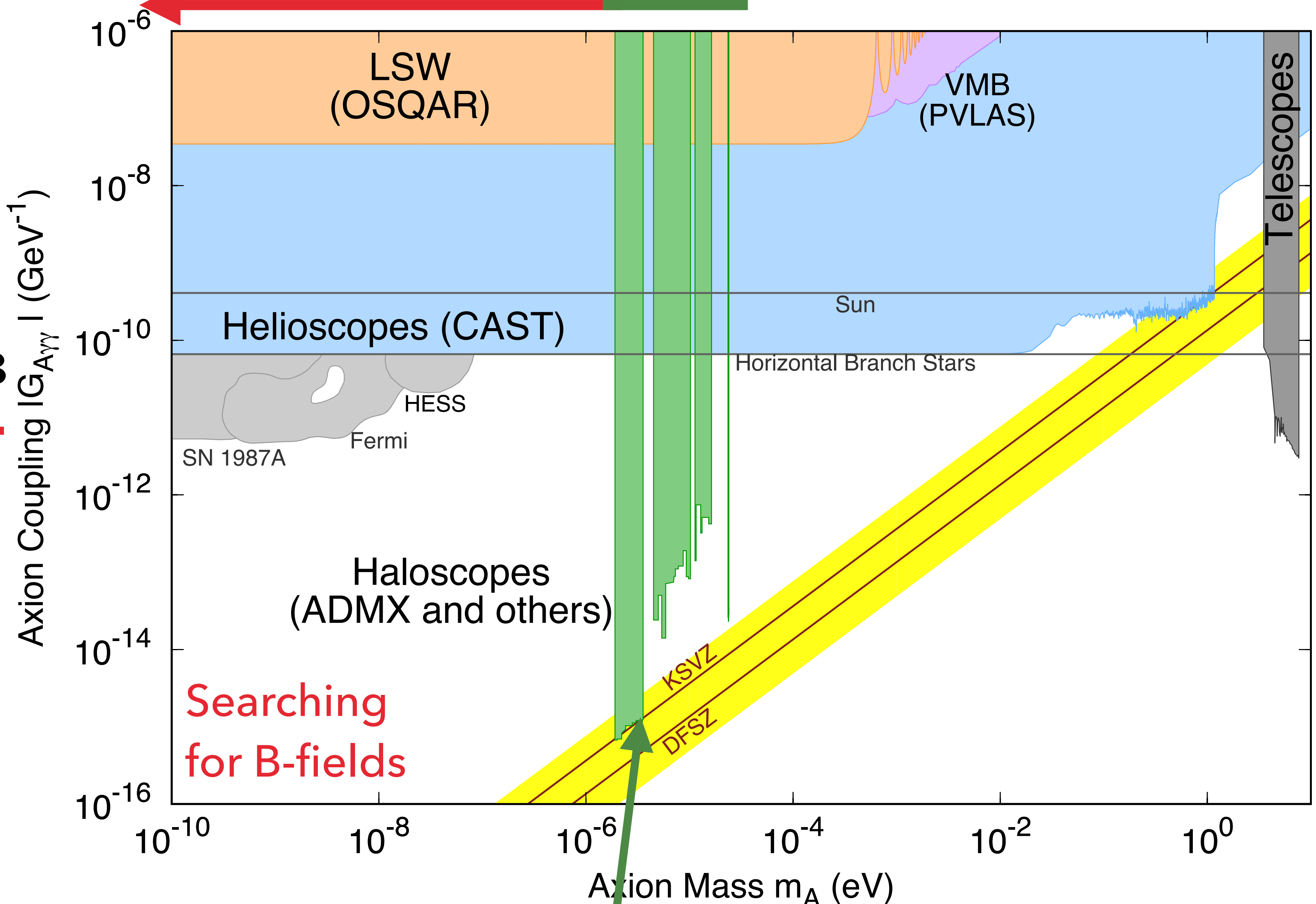
$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + g_{a\gamma\gamma} \frac{\partial a}{\partial t} \mathbf{B}$$

THREE MASS REGIMES

Long Compton Wavelength

Laboratory Scale

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



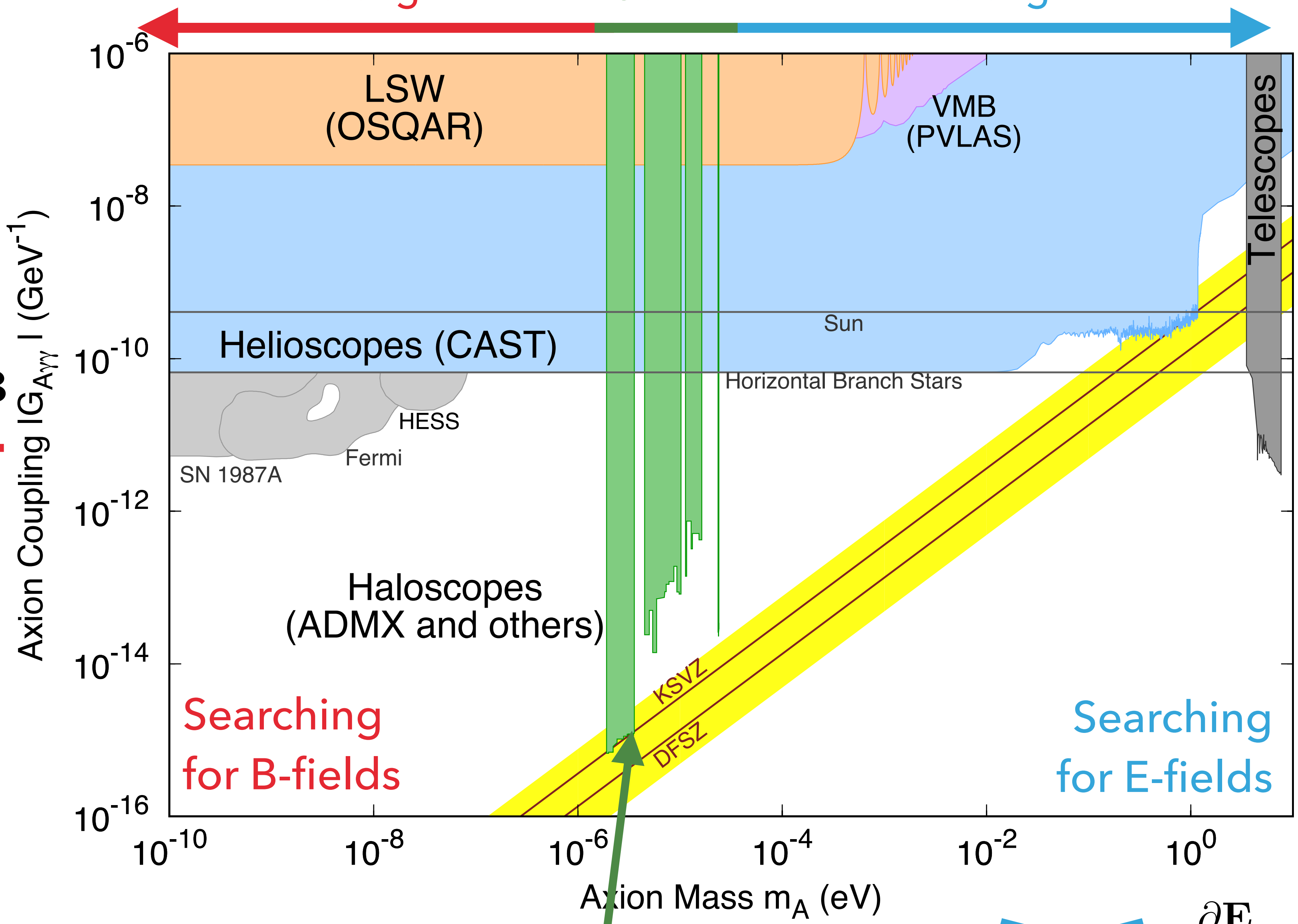
Searching for B-fields

Searching for E or B-fields

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

THREE MASS REGIMES

Long Compton Wavelength | Laboratory Scale | Short Compton Wavelength



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

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

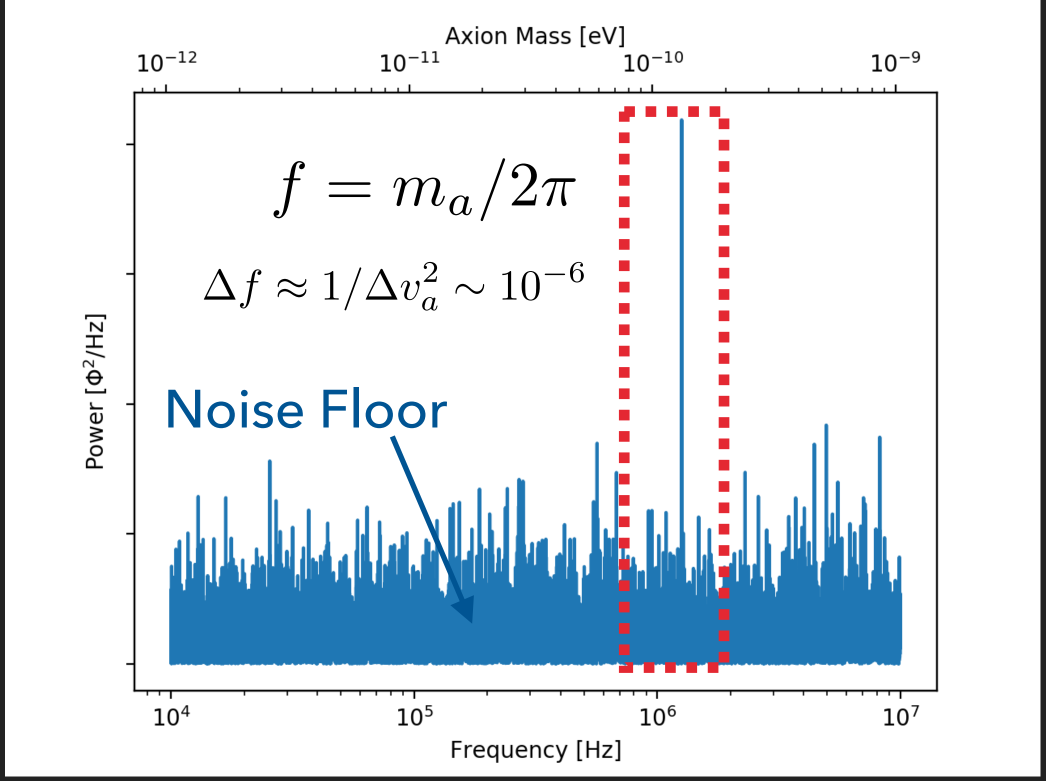
Searching for E or B-fields

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

Two Readout Approaches

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

$$g_{a\gamma\gamma}\sqrt{2\rho_{\rm DM}}V\mathcal{G}_V B_{\rm max} \ll |n|$$



- Option A: Measure and Average
  - Can search all frequencies simultaneously
  - Averaging is *really* slow

Two Readout Approaches

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

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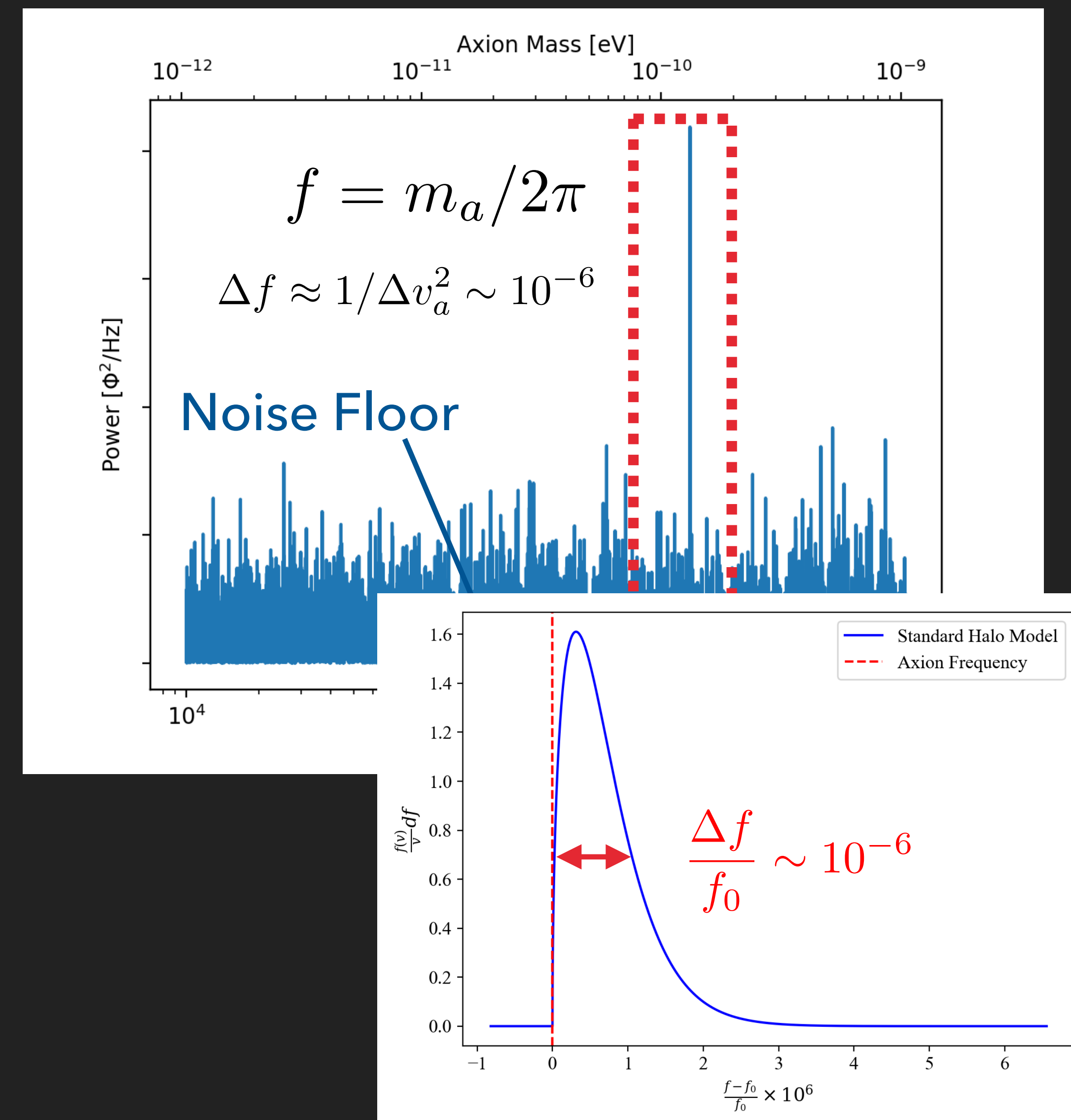
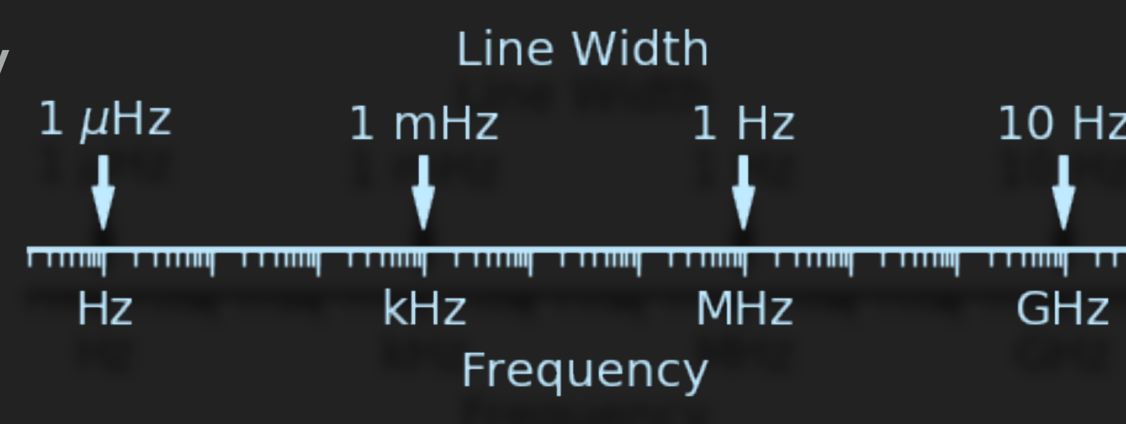
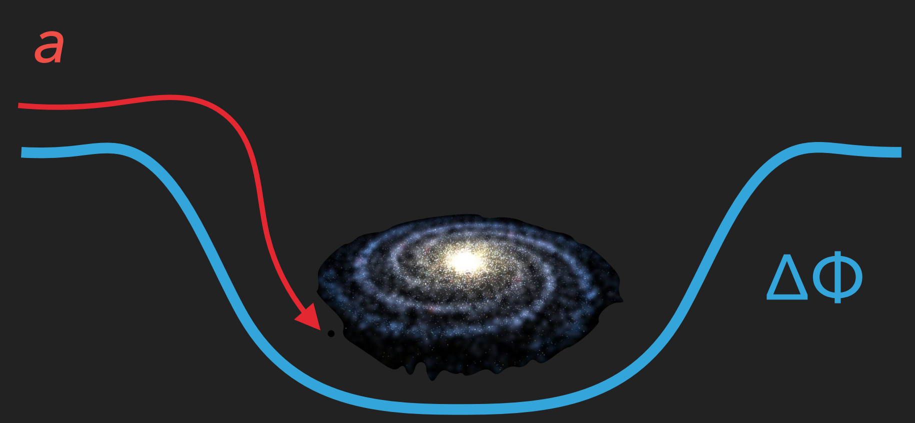


- Option A: Measure and Average
  - Can search all frequencies simultaneously
  - Averaging is *really* slow
- Option B: Lock in and amplify one frequency
  - Can quickly pull signal from noise
  - Don't know what frequency to amplify!



An Axion Signal

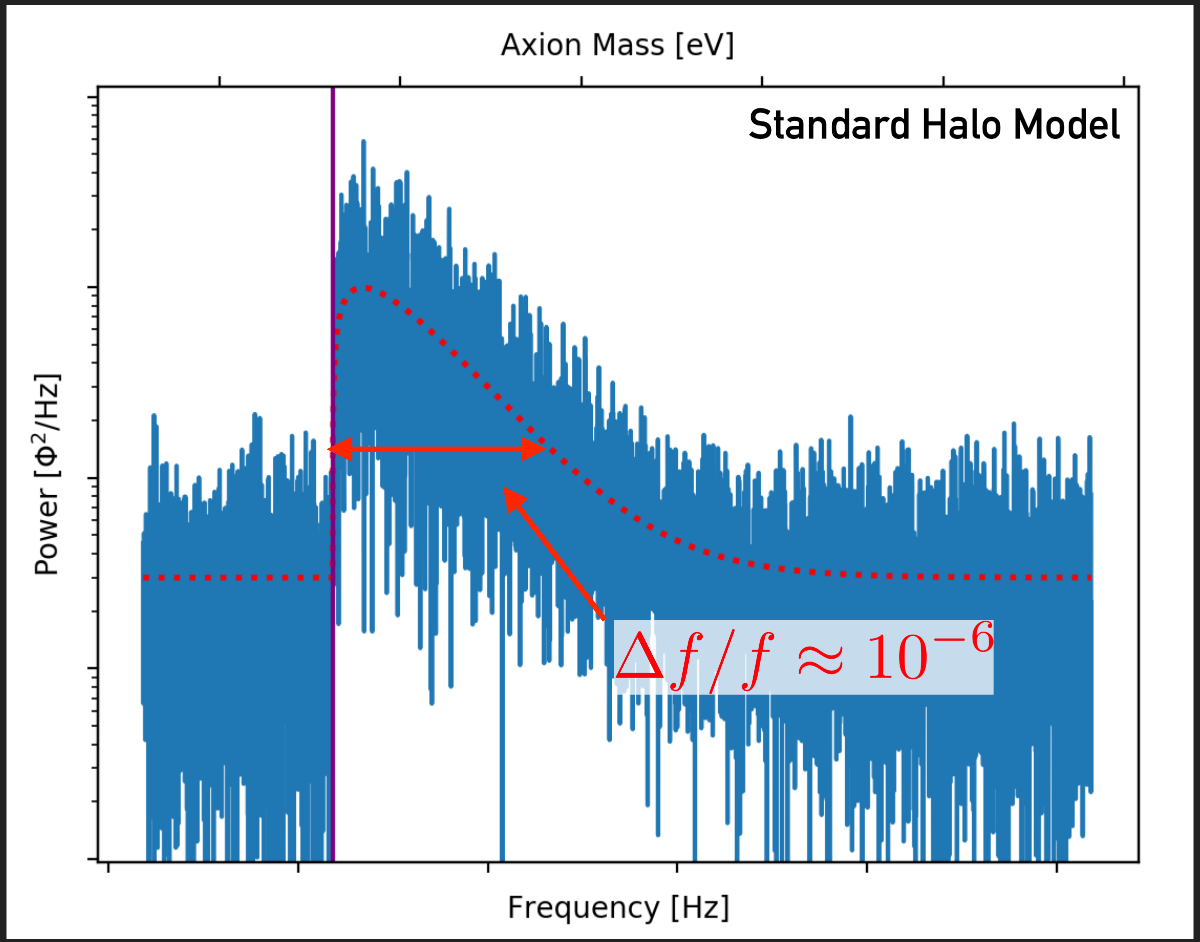


- The coherence time for an axion signal is given by

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

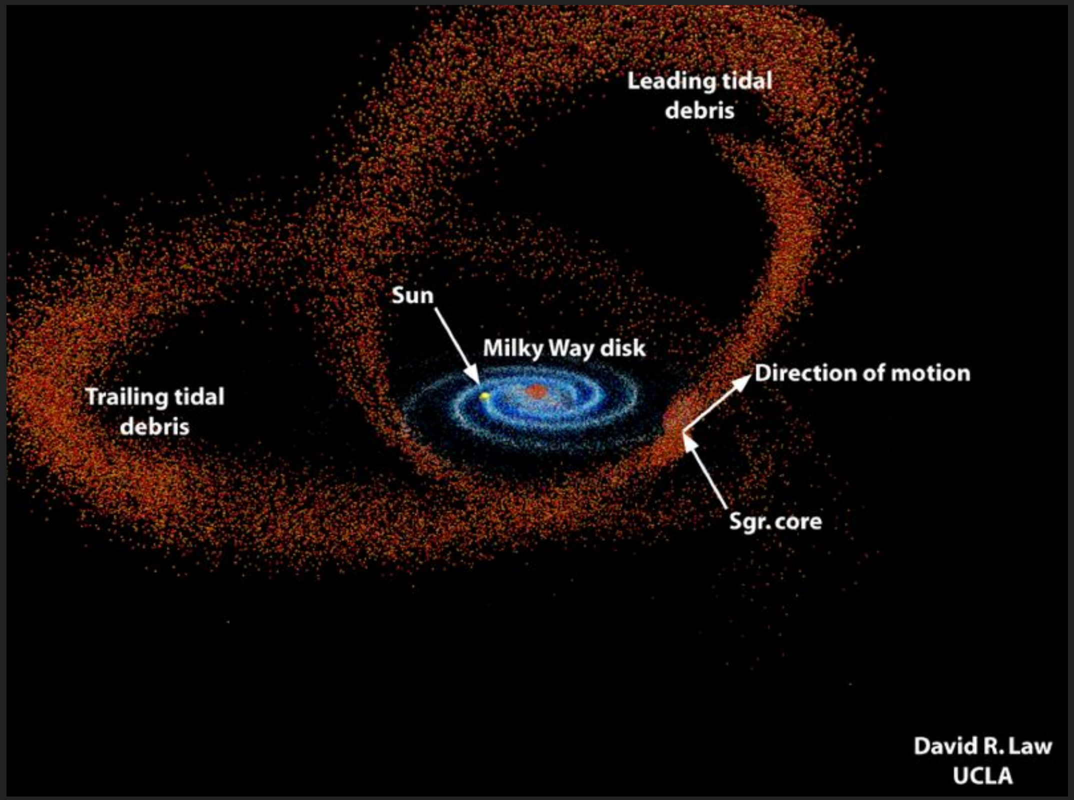
- And leads to a spread in the peak of

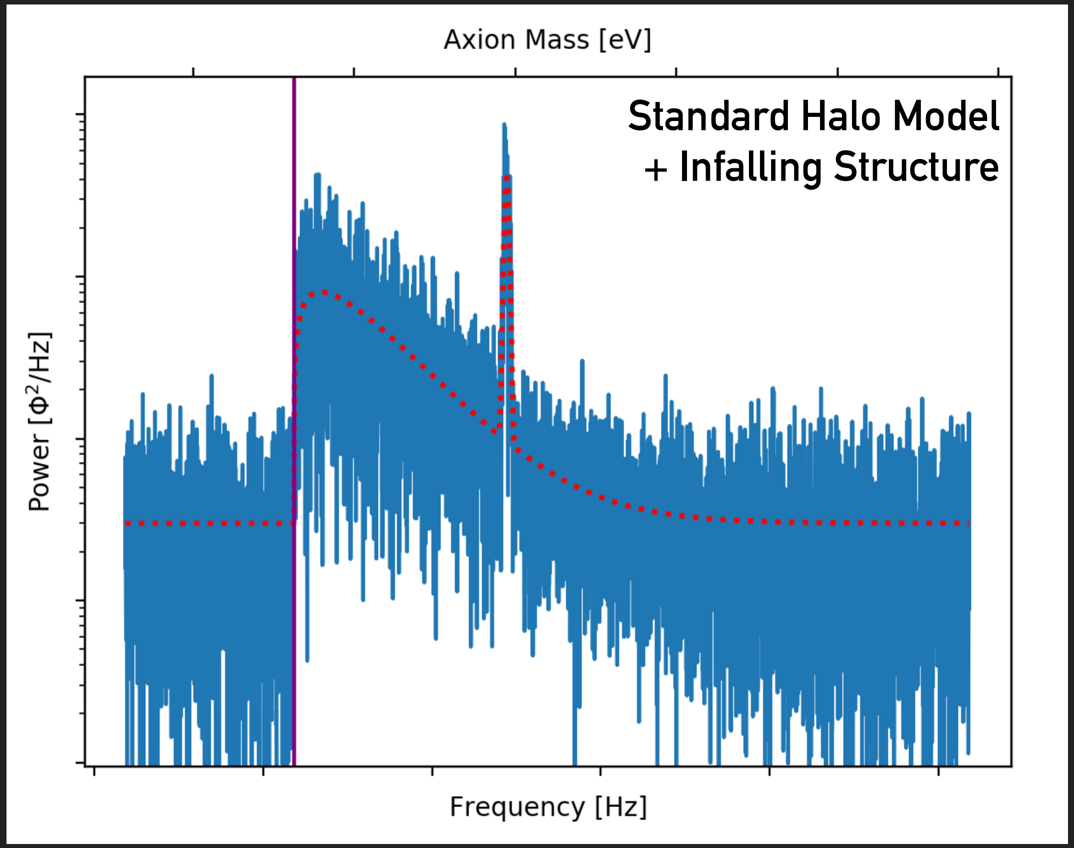
$$\Delta f / f \sim 1/v^2 \approx 10^{-6}$$



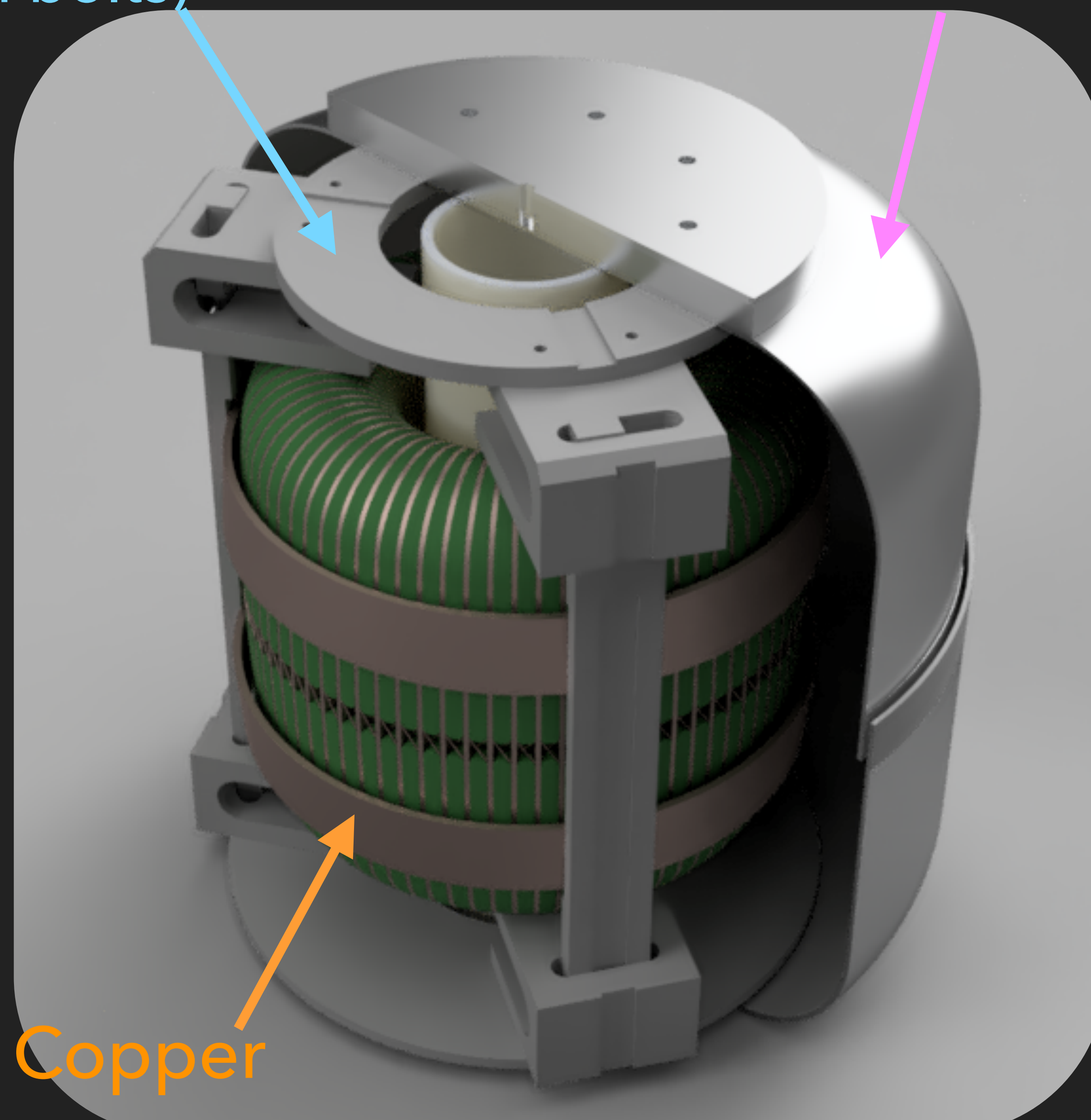
An Axion Signal

- 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)

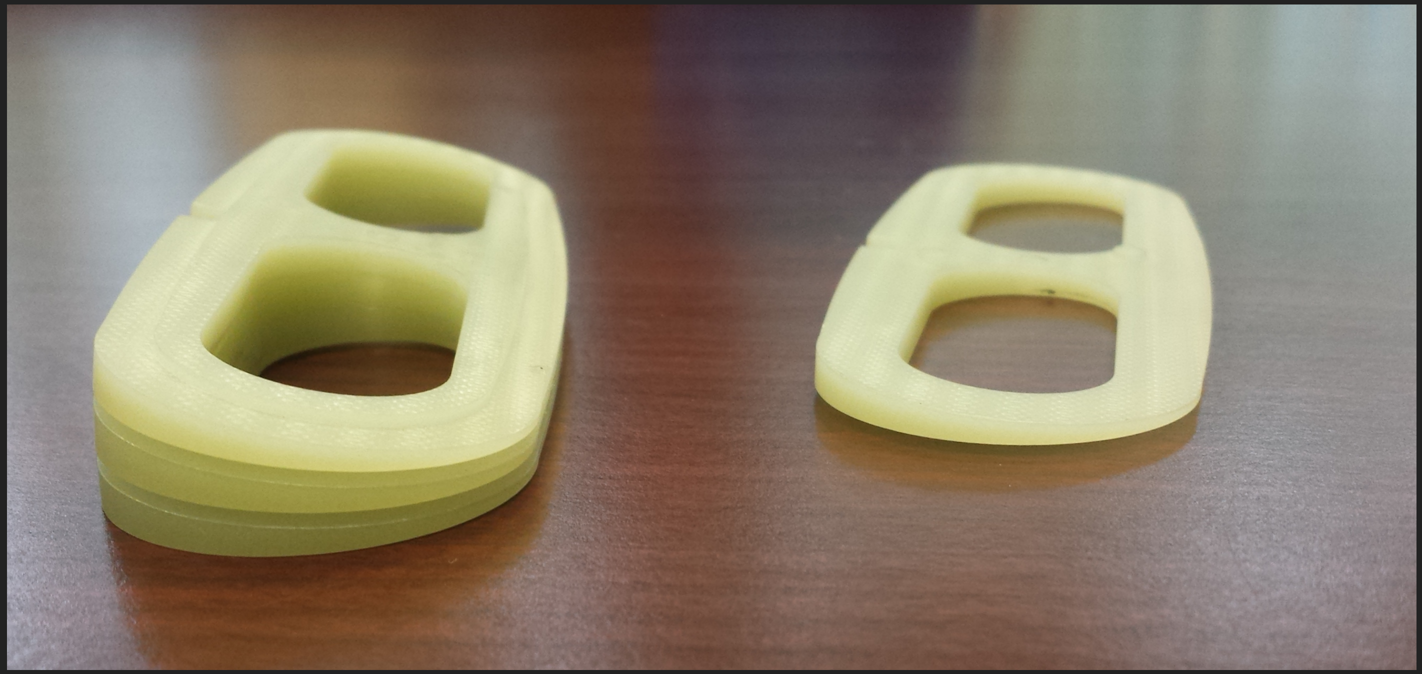




Dissecting ABRACADABRA-10 cm



Assembling ABRACADABRA-10 cm



SUPERCONDUCTING SYSTEMS INC.

(Normally make MRI magnets!)

Assembling ABRACADABRA-10 cm

SUPERCONDUCTING SYSTEMS INC.

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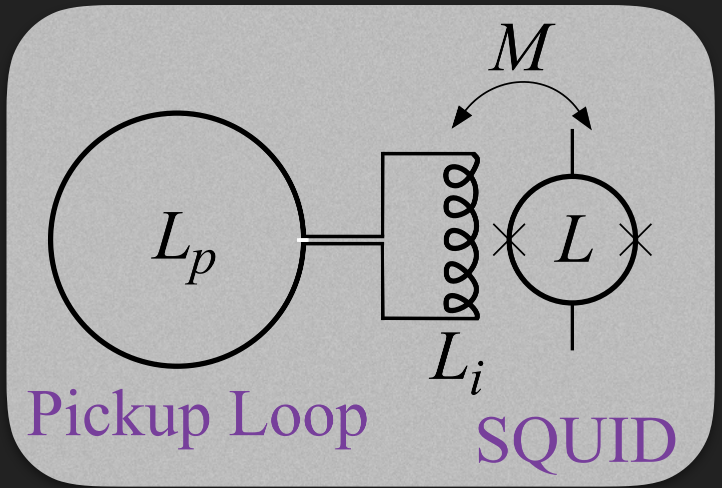
Assembling ABRACADABRA-10 cm

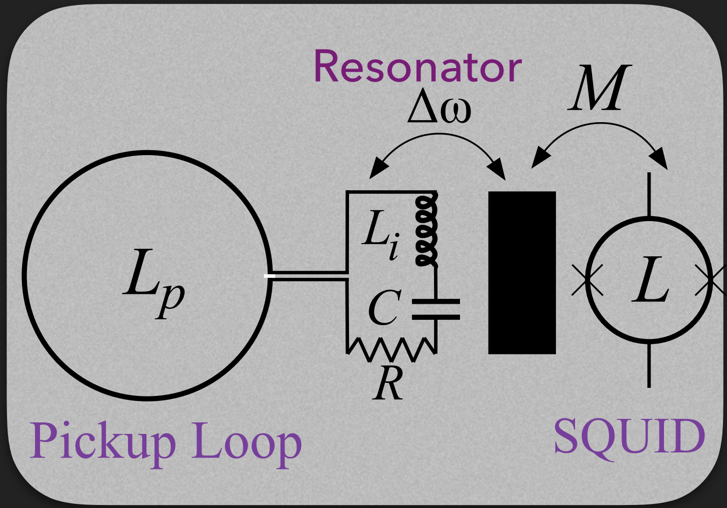
SUPERCONDUCTING SYSTEMS INC.

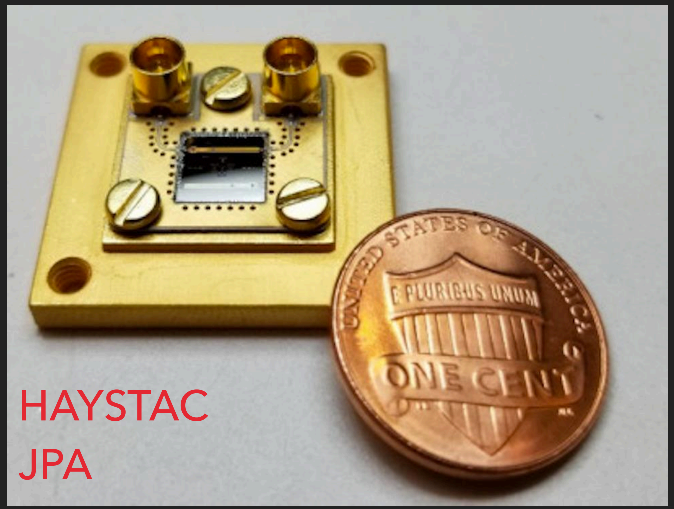
(Normally make MRI magnets!)

ABRACADABRA Readout Modes

- ABRACADABRA will require very sensitive current detectors → SQUID current sensors
  - Broadband mode sensitive to all frequencies or resonant mode that amplifies one frequency and requires scanning
  - Thermal noise limits require cooling the detector to 10 - 100 mK
- Huge overlap with developments in Quantum Computing, and aim to push beyond the Standard Quantum Limit





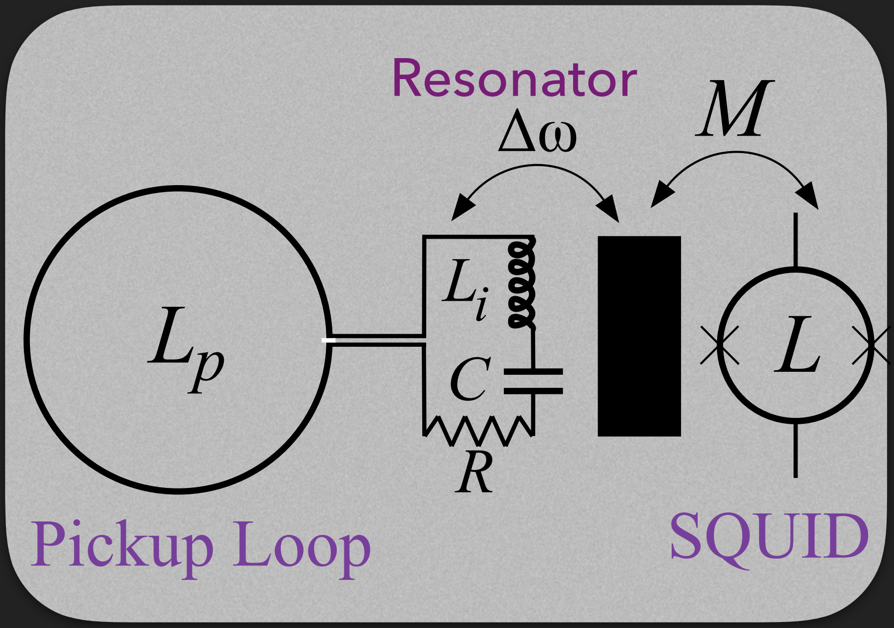


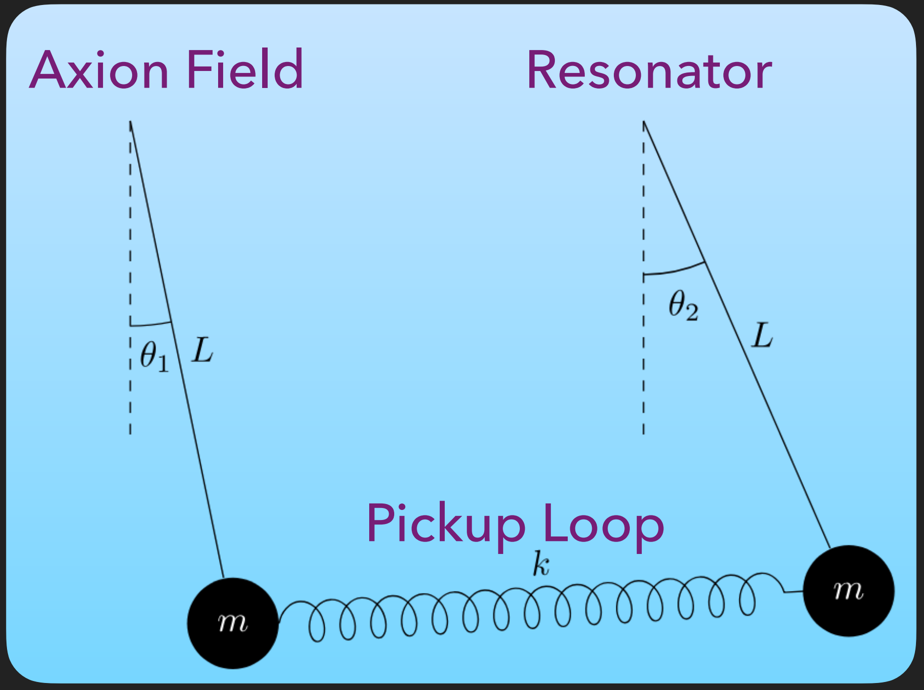
ABRACADABRA Resonant Readout

- Insert a resonator into the circuit that resonantly enhances the signal before the SQUID noise is introduced
  - Resonator is charged when driven on resonance by the axion field
  - Pickup loop acts as a weak coupling between axion field and resonator
  - Power flowing into our resonator is tiny, so power flowing out should be comparably small

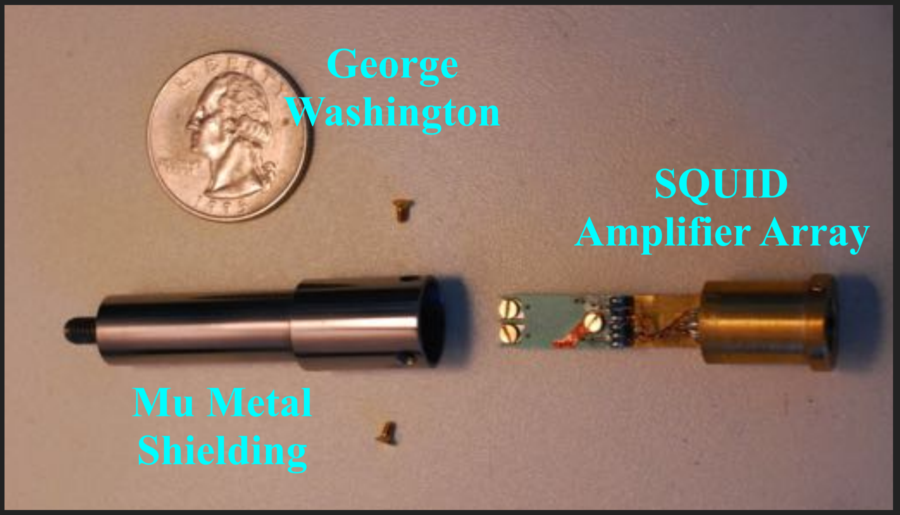
➡ High Q resonator

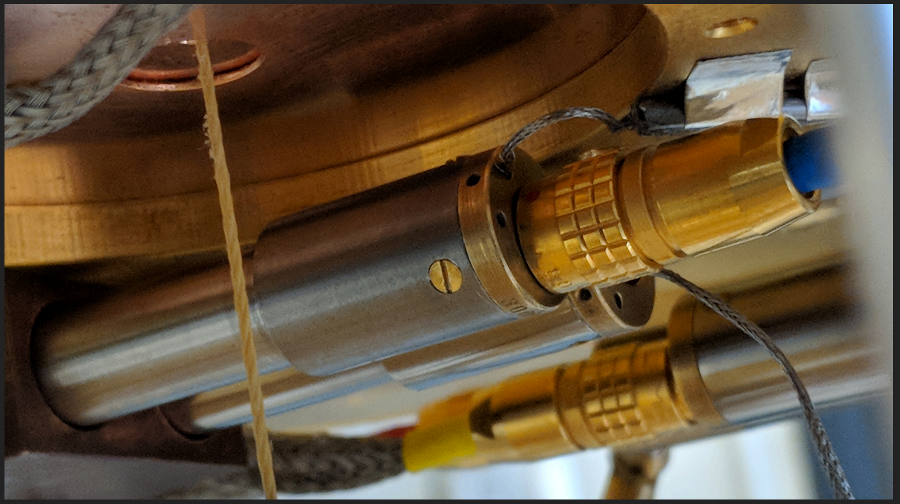
➡ The need to scan (and scan quickly)





First Readout Configuration





- 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)

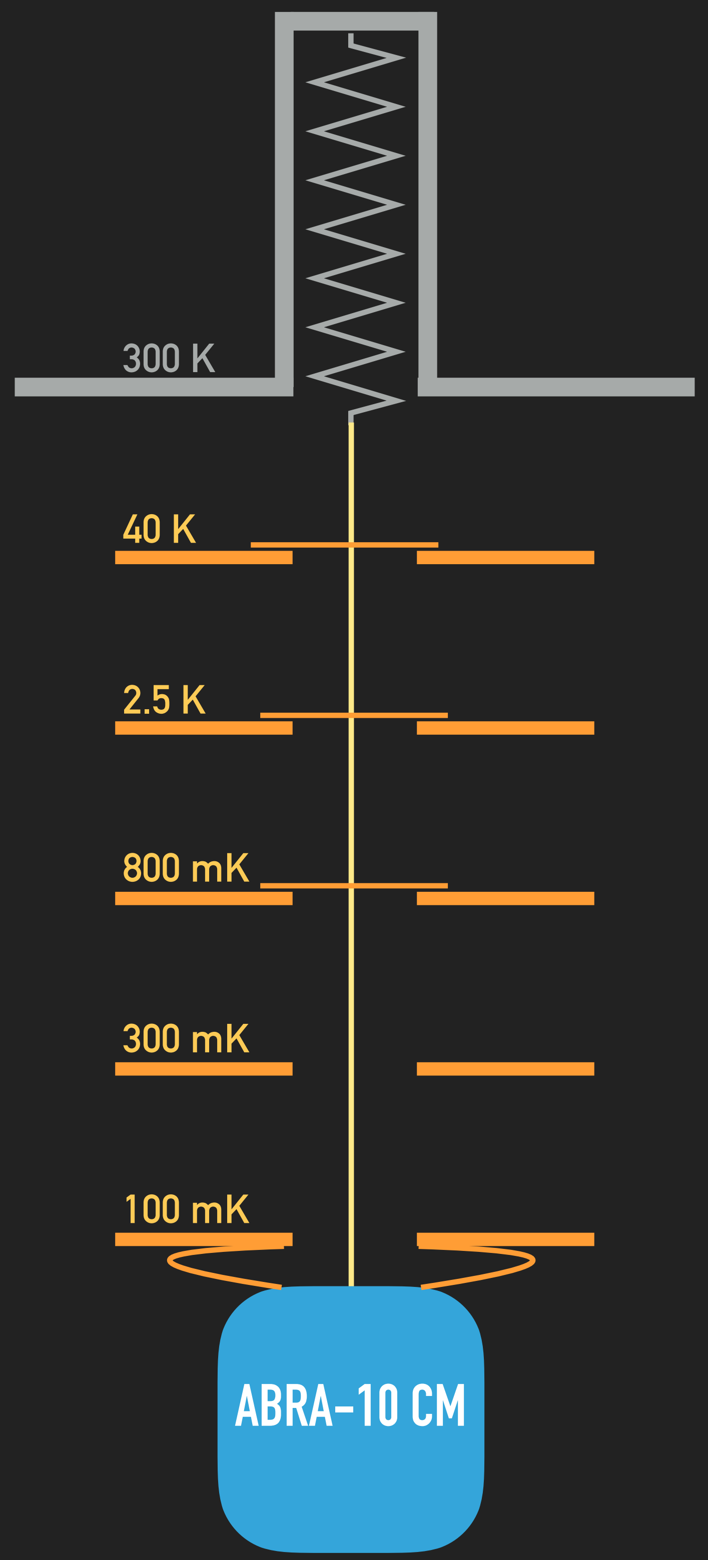
Quick note on units:

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

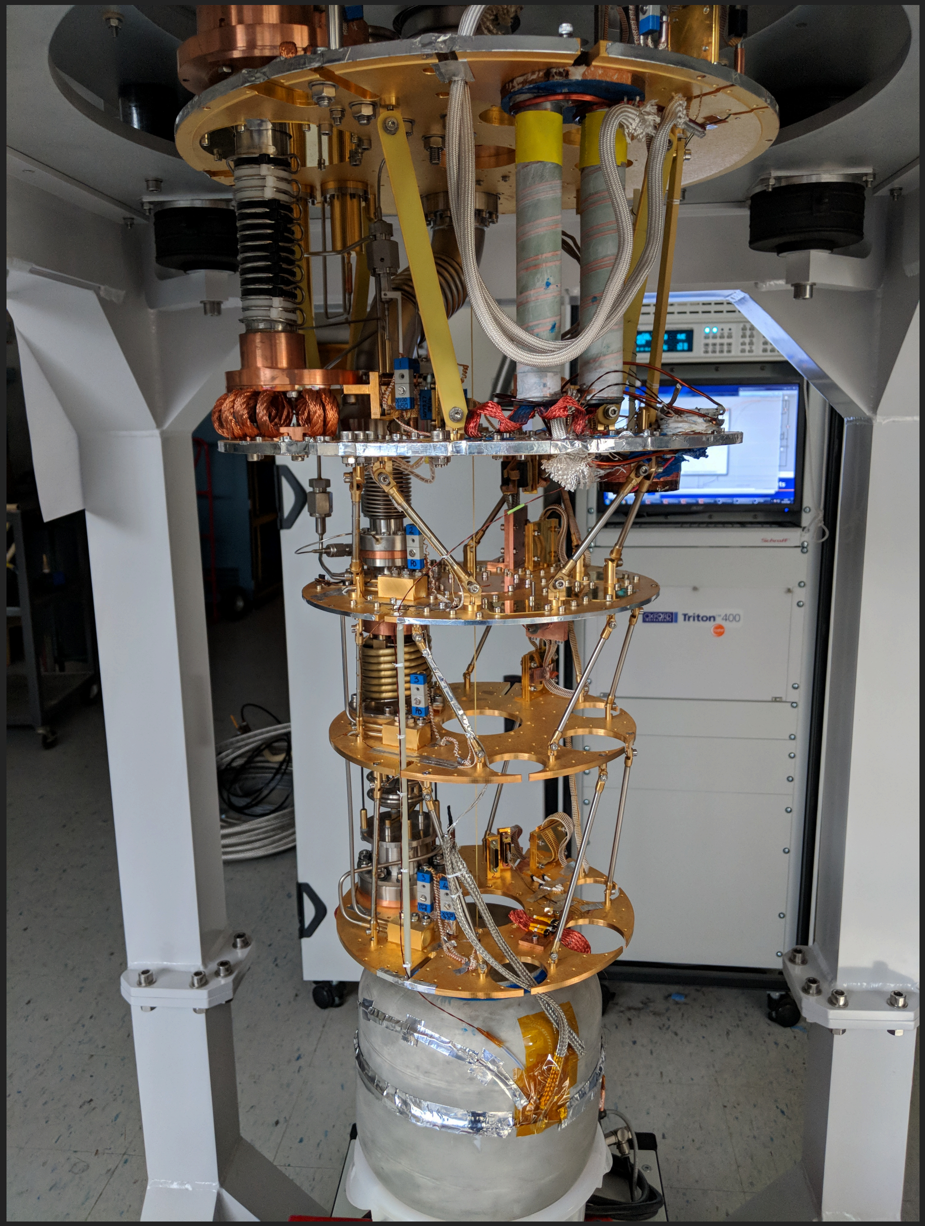
$$\Phi_0 = 2 \times 10^{-15}\,\mathrm{Wb}$$

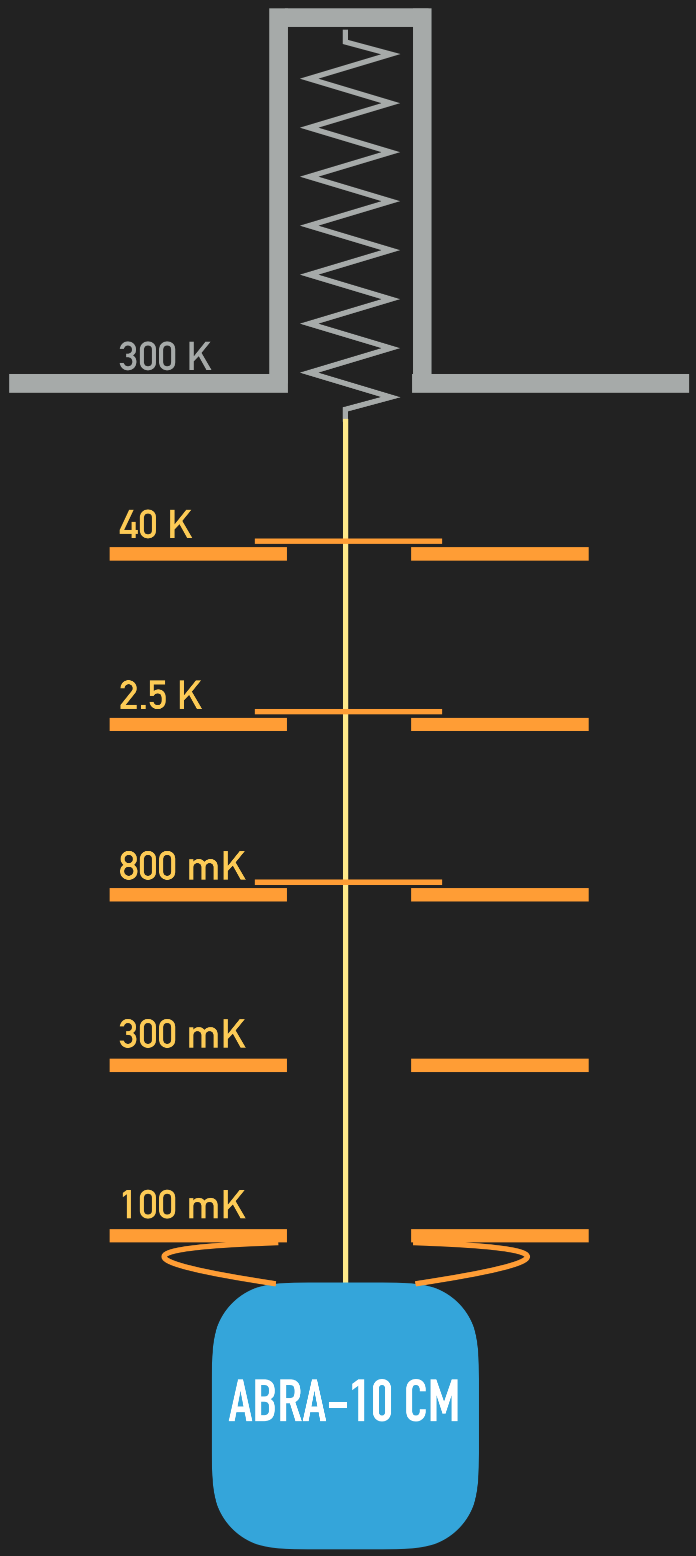
Suspension System

- 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

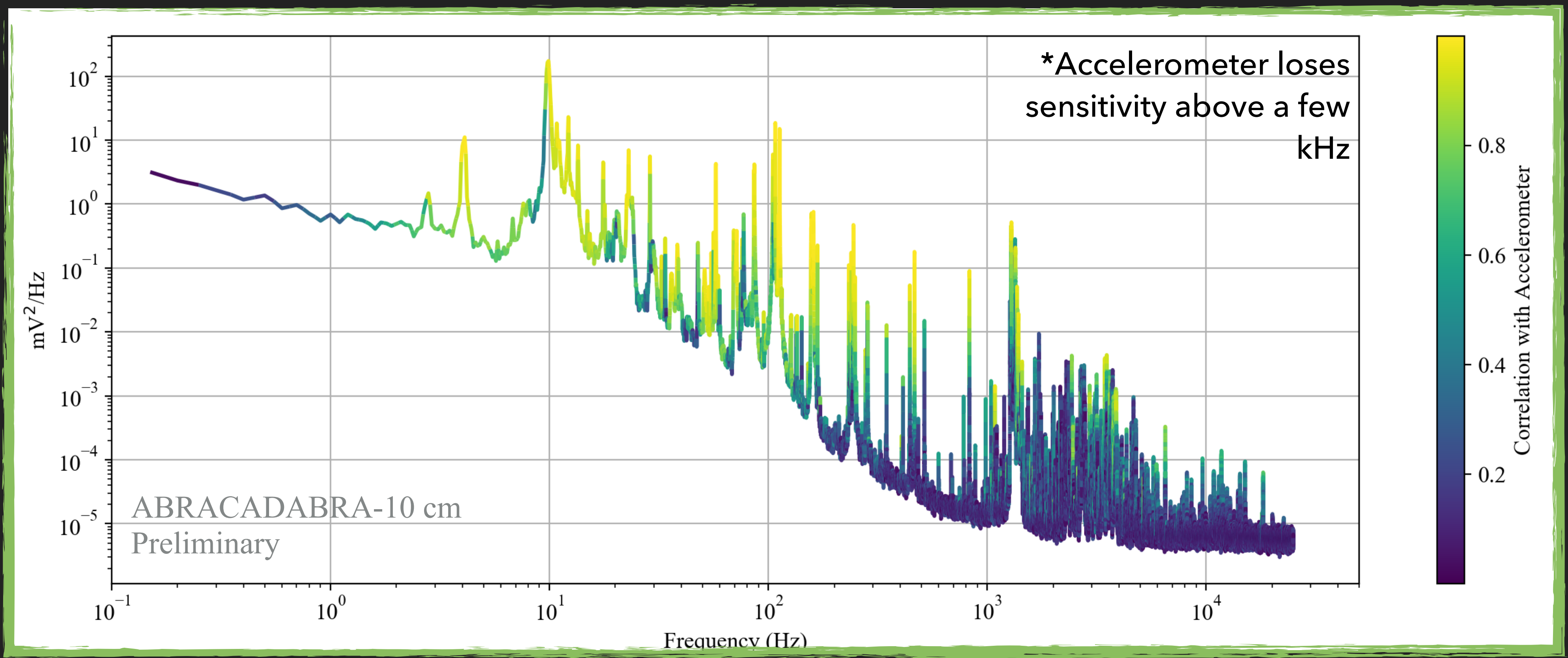


Suspension System





Vibrational Noise (Magnet On)

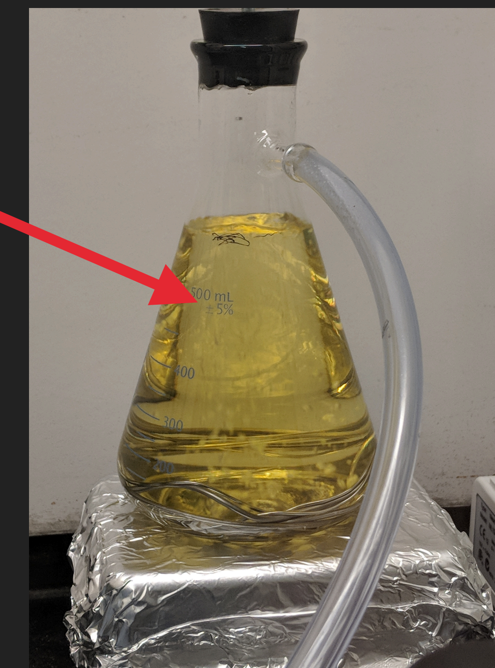


- Huge amount of noise below ~10 kHz, strongly correlated with vibration on the 300K plate
- Had to use a 10kHz high pass filter to get the data to fit in the digitizer window
- Hard limit on the low end search window

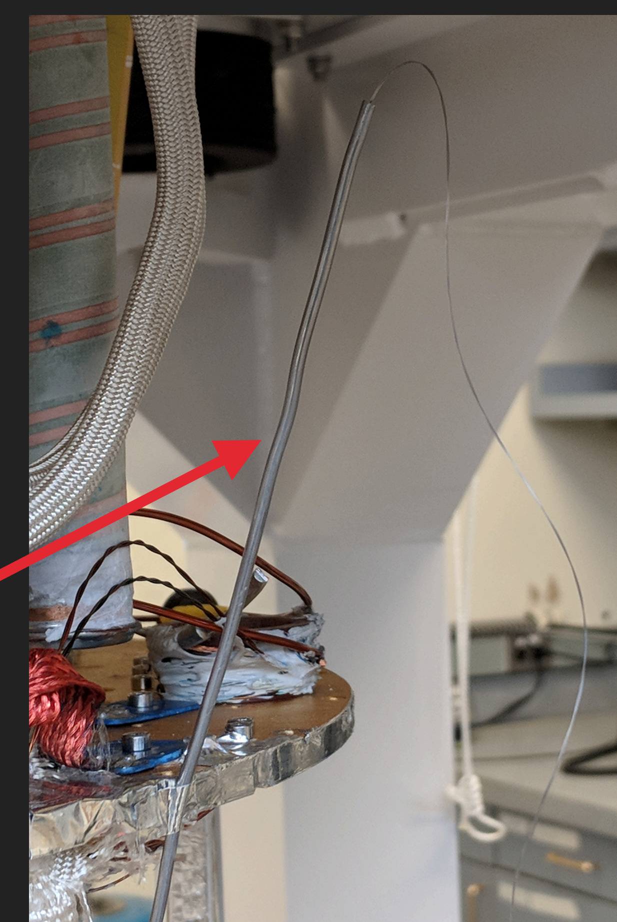
Superconducting Wiring

- 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

Boiling turpentine



Superconducting solder capillary shield!

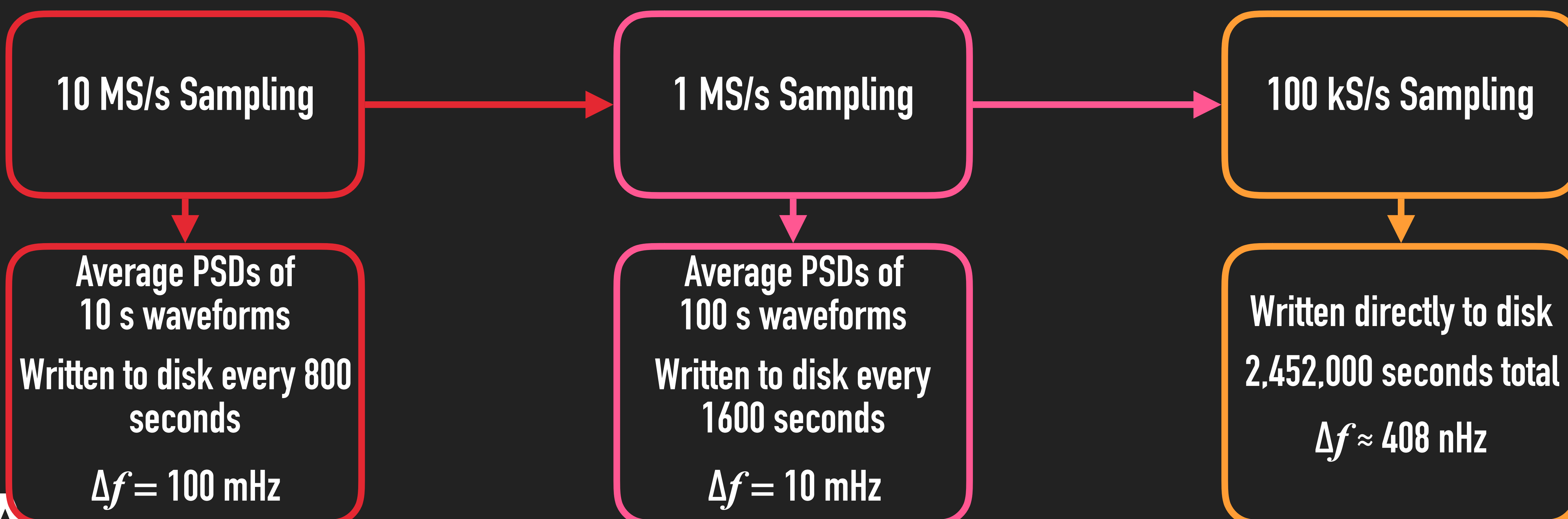


Magnetic Shielding

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

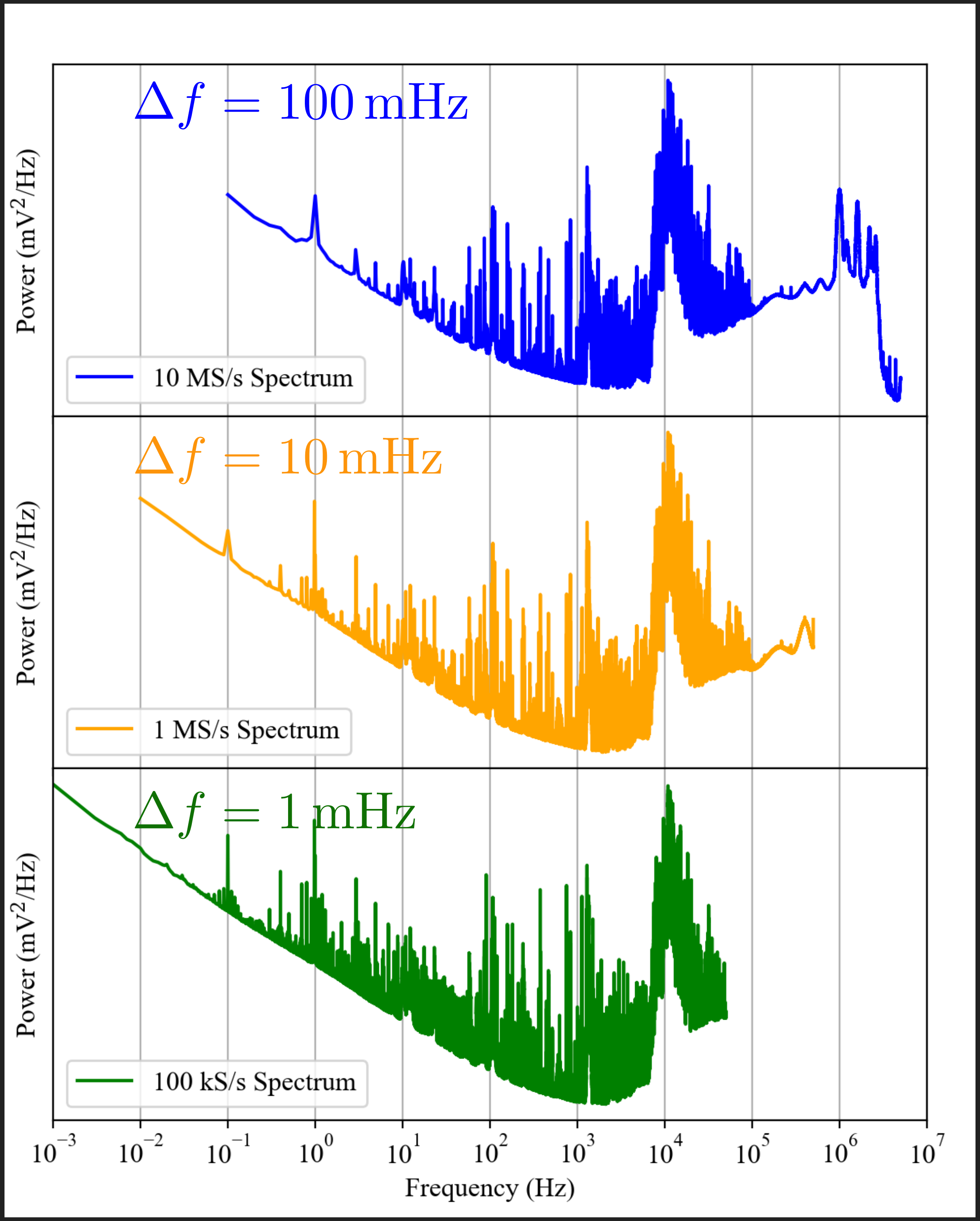
Broadband Data Collection Procedure

- 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
- Acquisition (currently) limited to 1 cpu and 8 TB max data size

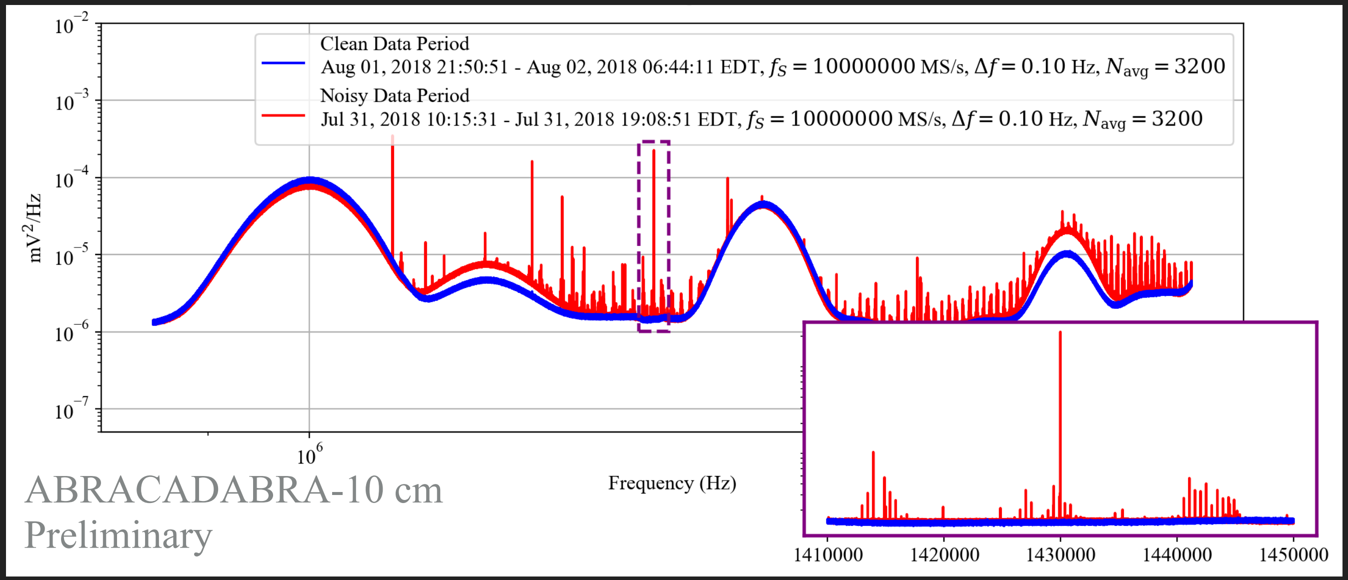


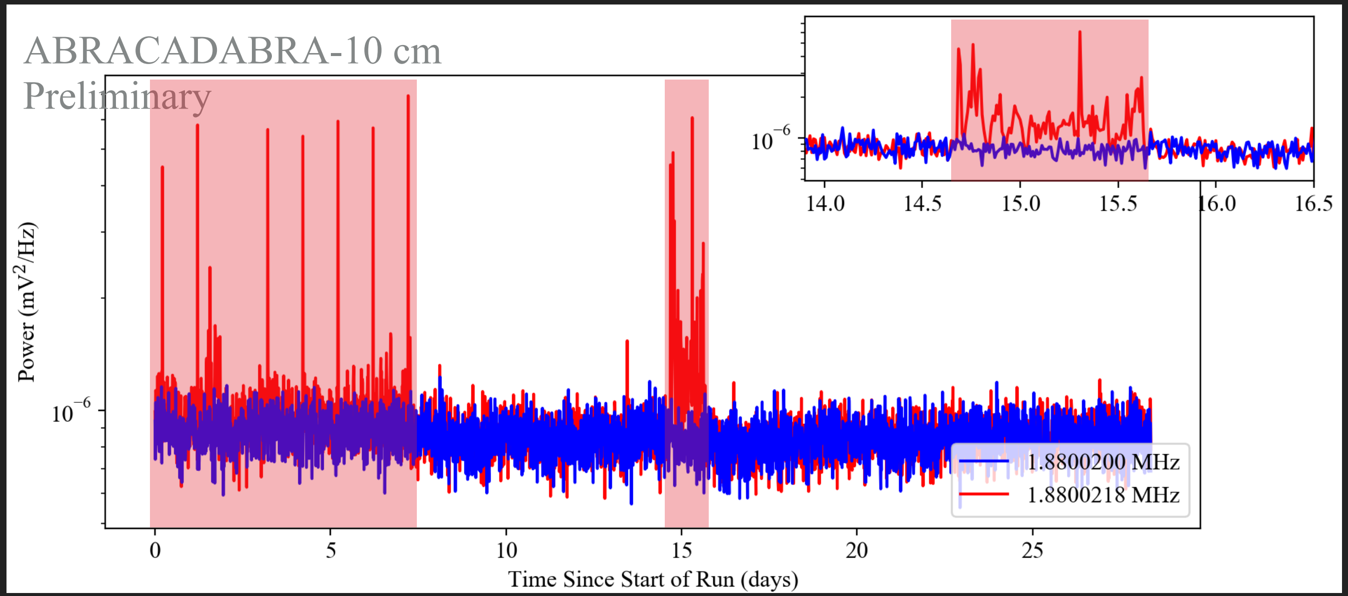
Broadband Data Collection Procedure

- 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



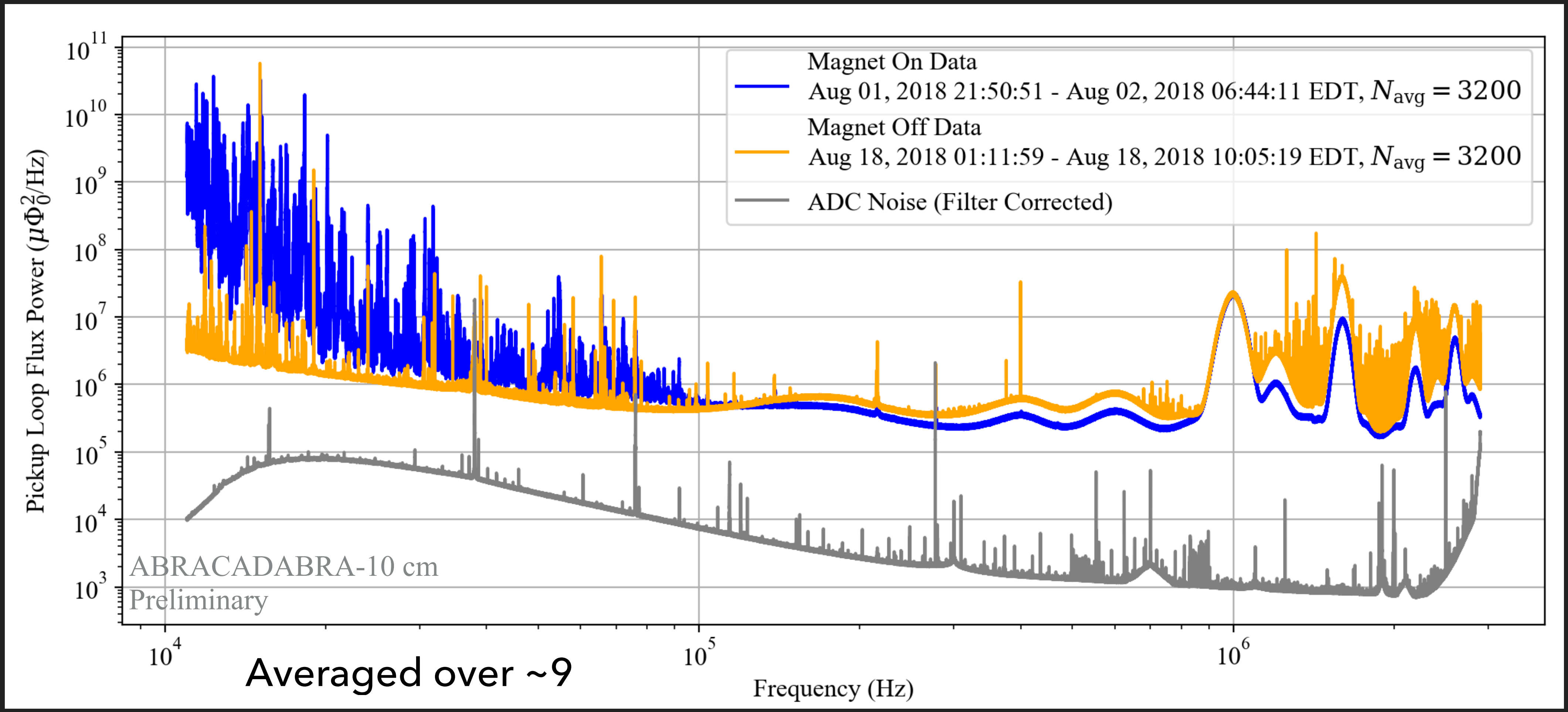
Transient Noise at High Frequency





- 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

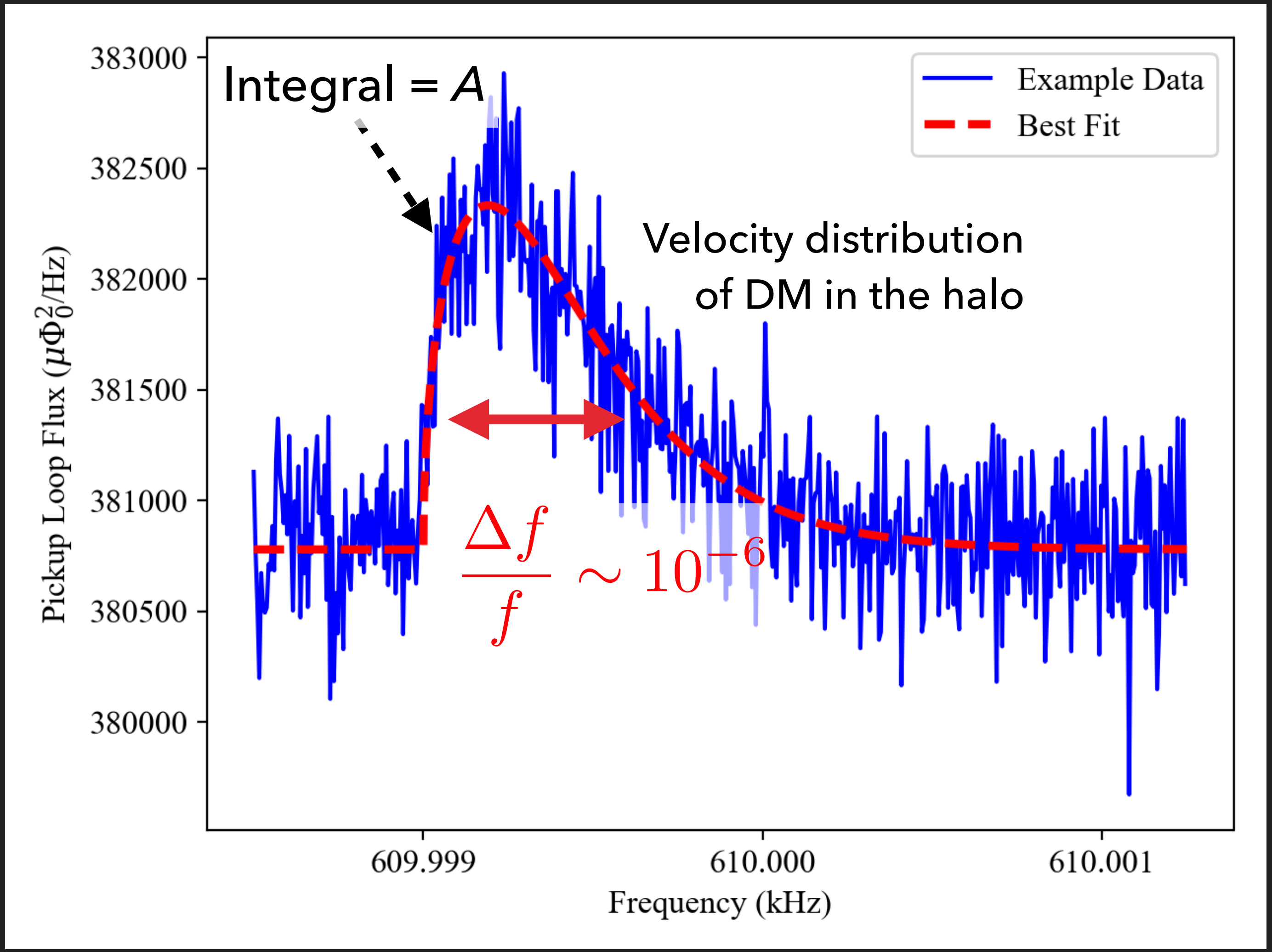


- Collected 2 weeks of magnet off data with the same configuration
- High frequency transient noise also present
- Significantly lower noise background around 10kHz (vibration of stray fields)
- Used for spurious signal veto

Axion Signal

- Time averaged flux through the pickup loop:

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

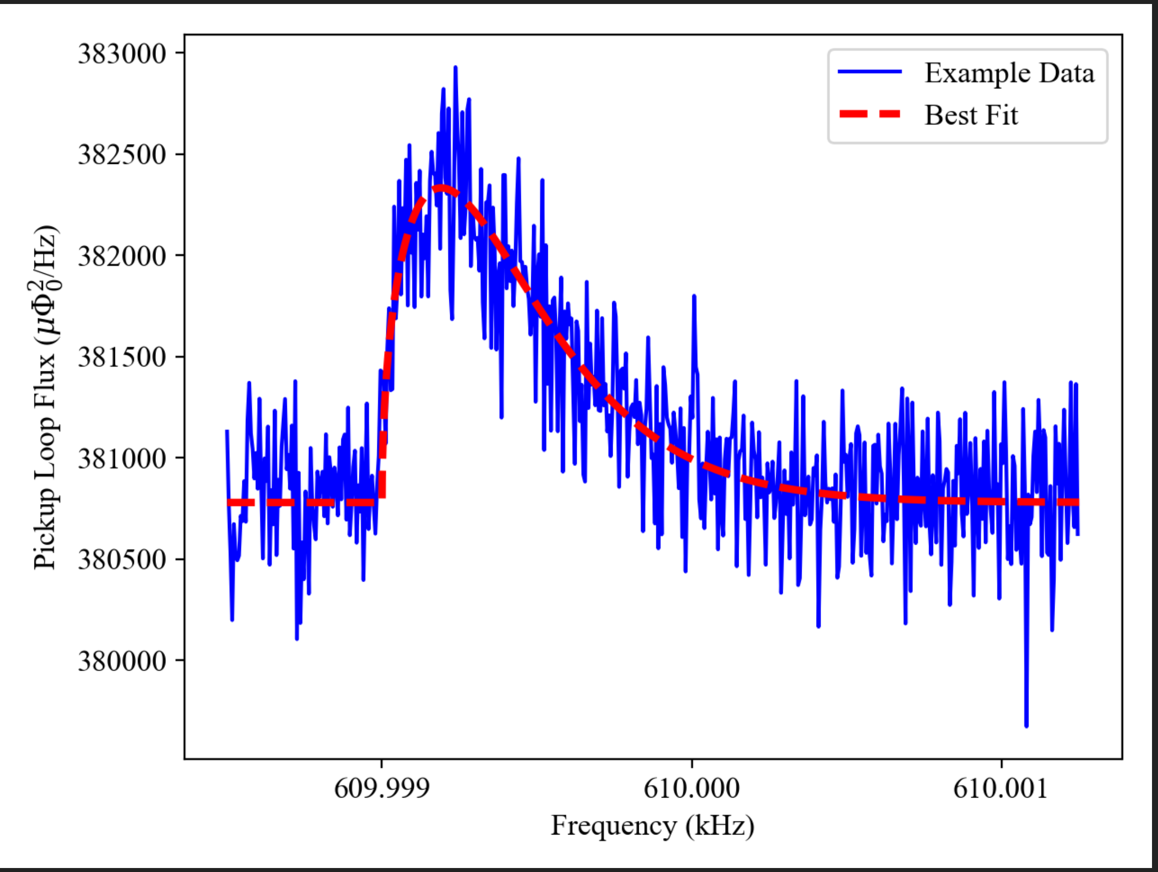


Axion Search Approach

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

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

- 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

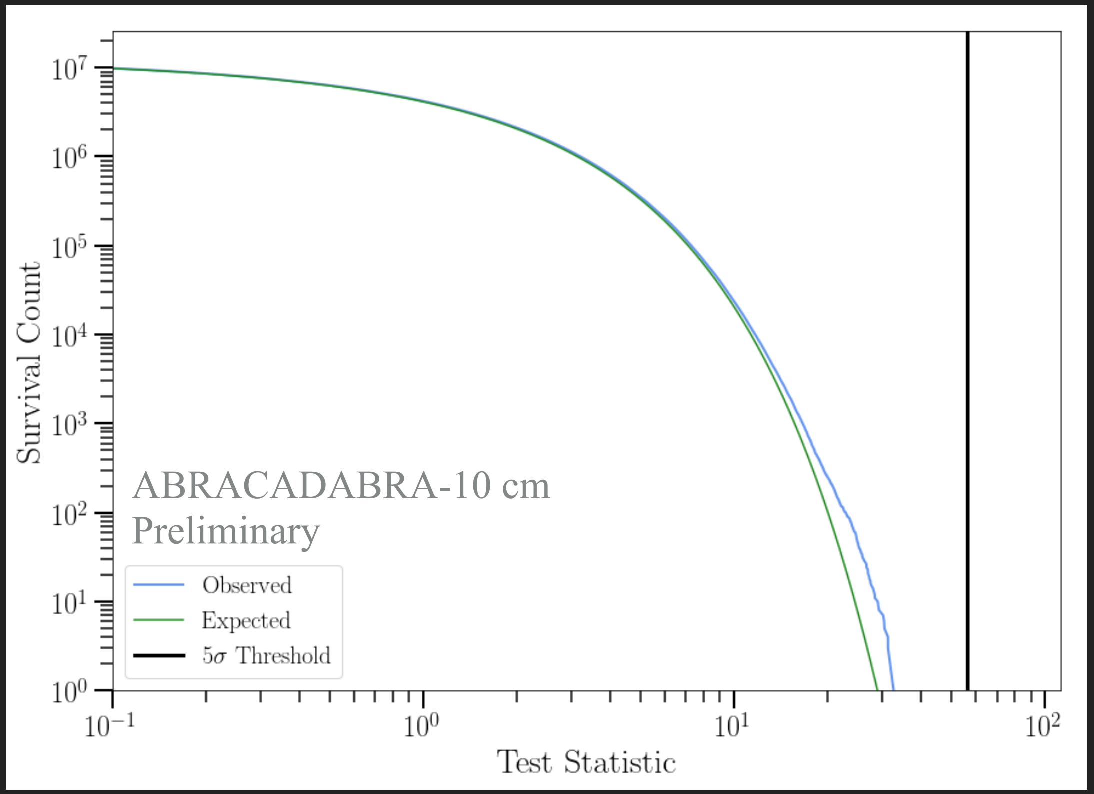


Axion Search Approach

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

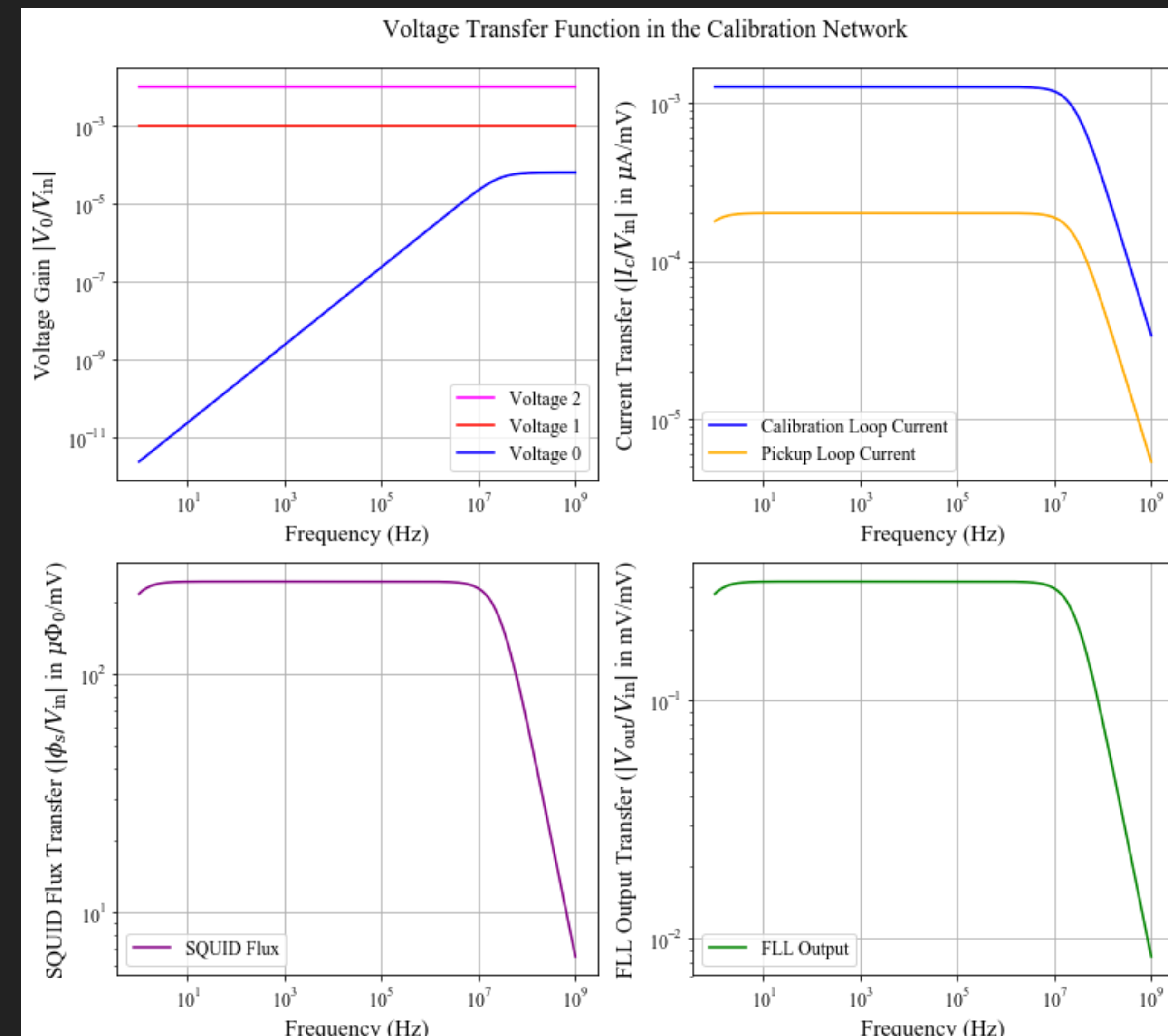
$$\mathrm{TS} = 2\left[\log\mathcal{L}\left(\hat{g}_{a\gamma\gamma}, m_a, \hat{\mathbf{b}}\right) - \log\mathcal{L}\left(g_{a\gamma\gamma} = 0, m_a, \hat{\hat{\mathbf{b}}}\right)\right]$$

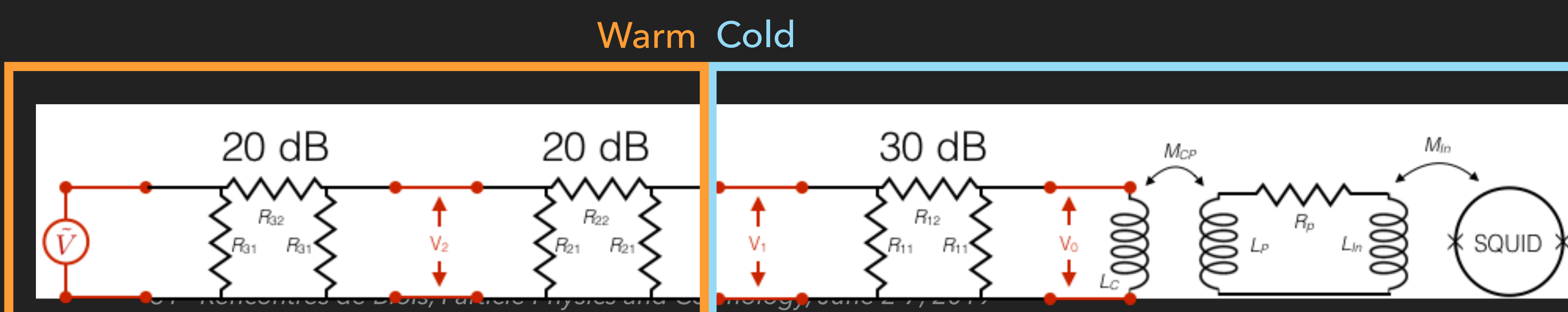
- Profiling over all nuisance parameters, b_i
- We set the 5σ discovery threshold as TS>56.1 (accounting for the Look Elsewhere Effect for our 8M mass points)



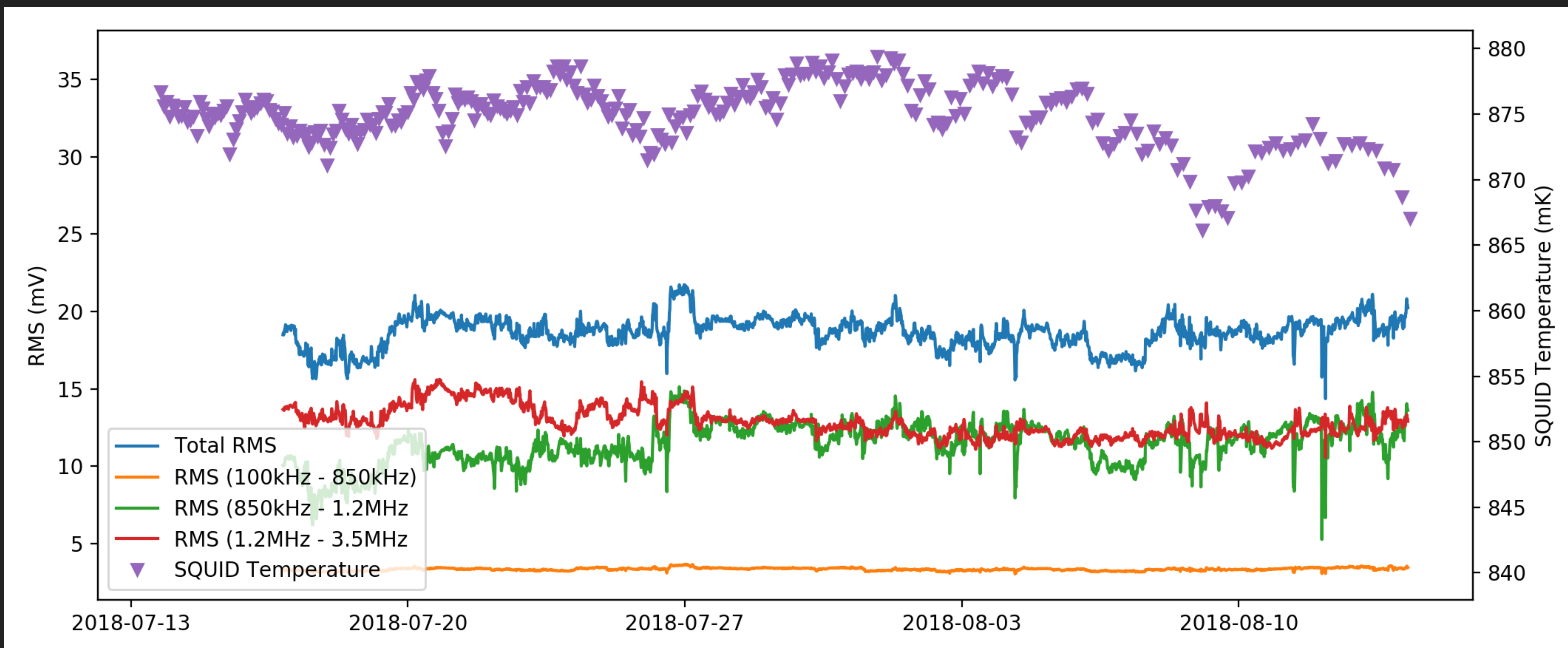
Calibration Network

- ✓ 60 dB of warm attenuation
- ✓ Readout circuit
- ✓ Cold attenuator performance
- ✓ SQUID noise is approximately as expected
- ✓ Parasitic resistance in the circuit
- ▸ Flux coupling?





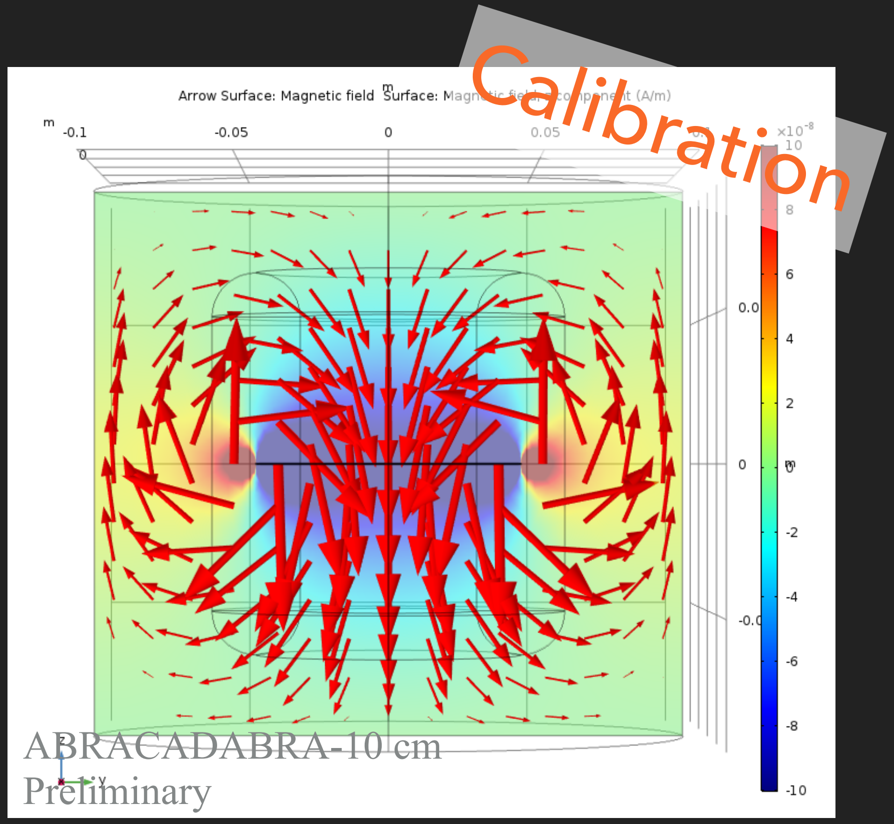
Temperature Effects?

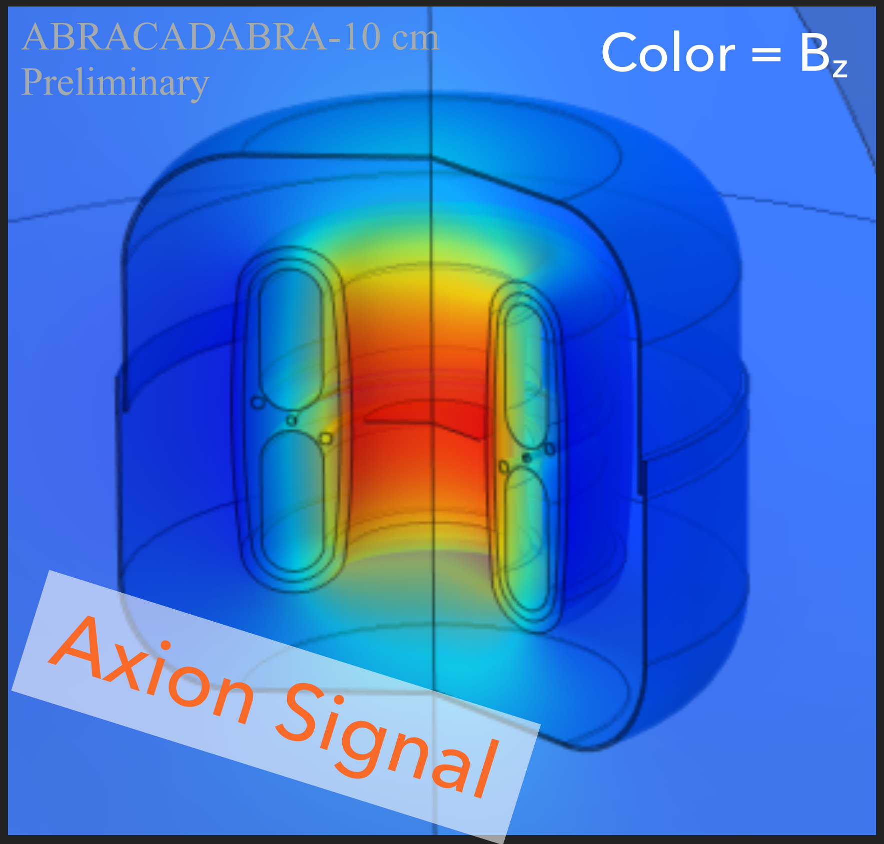


Nothing obvious..

Building Simulations in COMSOL

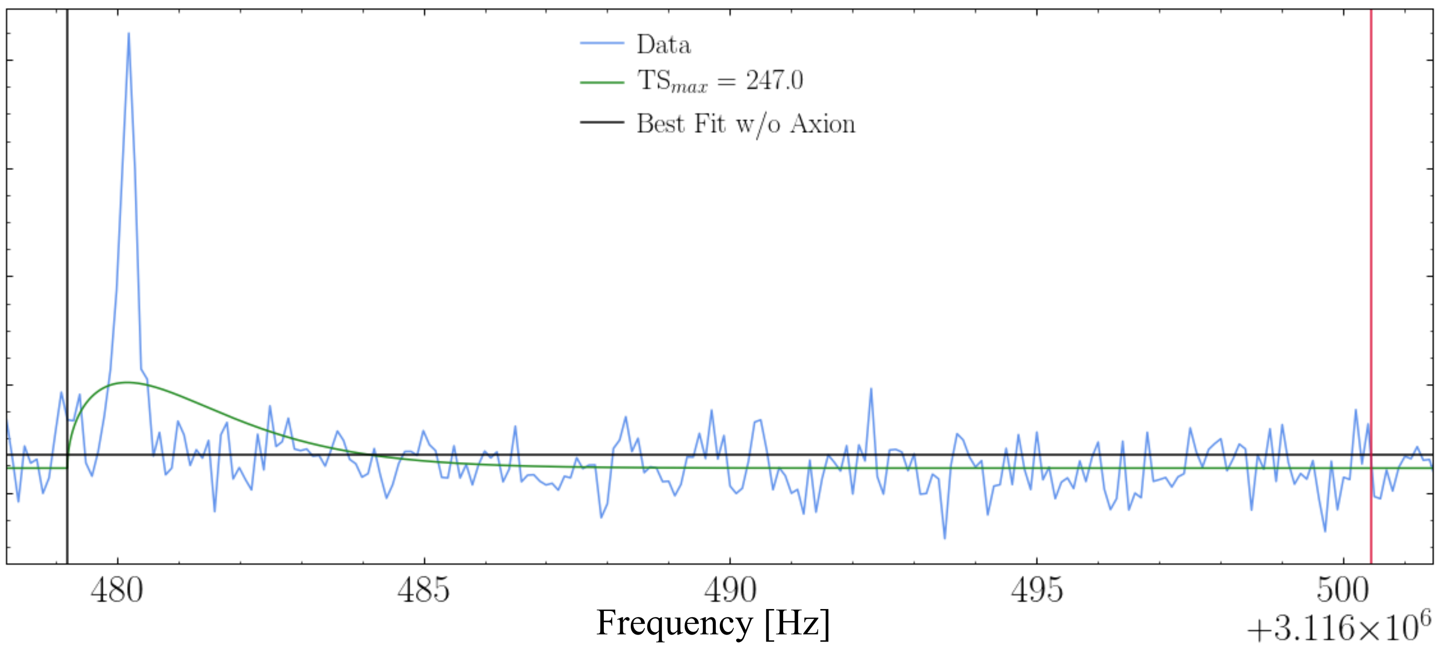
- Geometric factor encodes the flux through the pickup loop due to the integrated effective current
- Use COMSOL simulations to calculate the coupling to the axion field (and confirm calibration coupling)
    - Simulation of ABRACADABRA-10 cm geometry
    - Material properties need to be measured in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

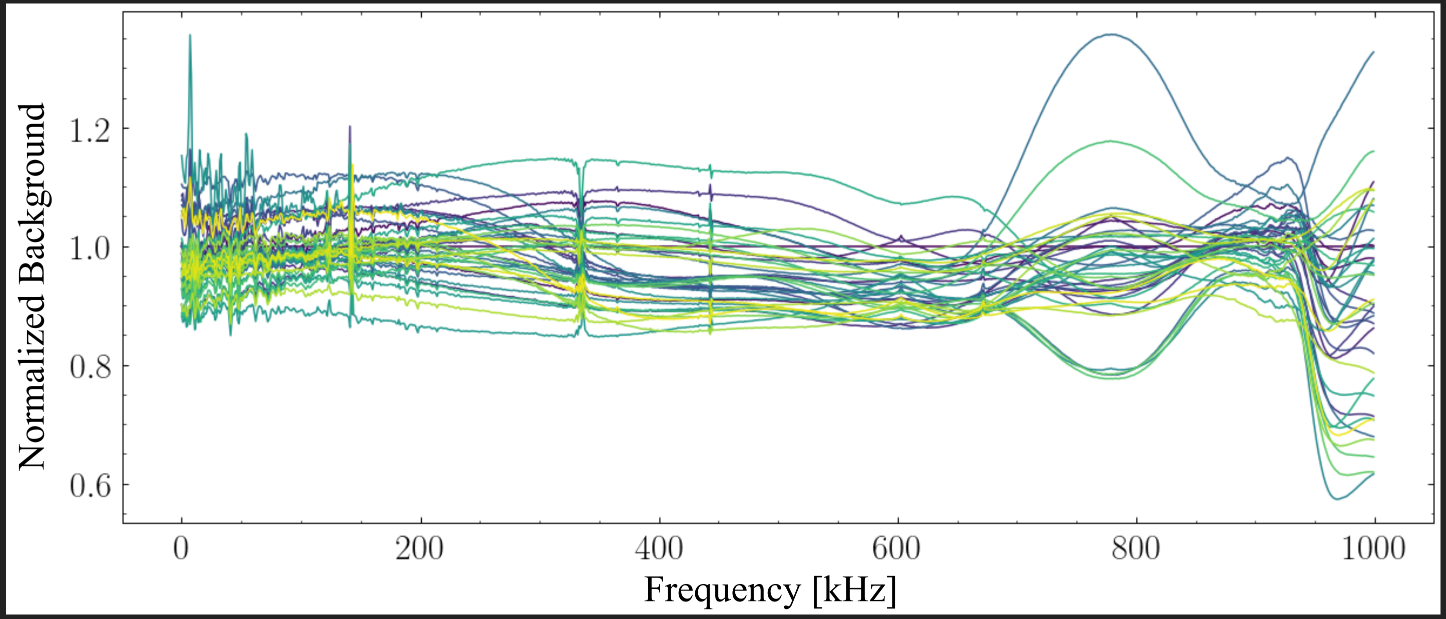




Data Analysis Behavior

- 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)





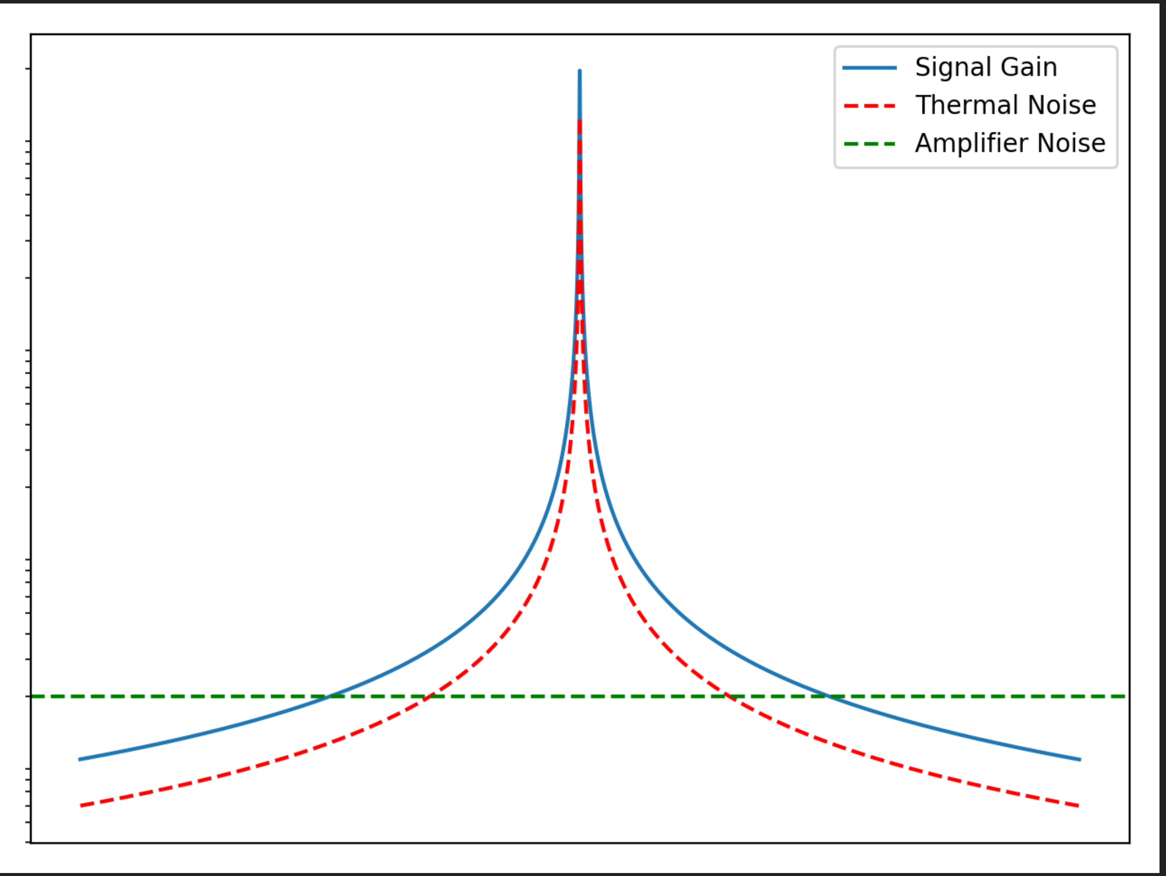
Resonator Sensitivity

- 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




WIMP SEARCHES
DARK PHOTON SEARCHES
AXION / ALP SEARCHES
Direct Dark Matter Searches