A Broadband/Resonant Search for Axion Dark Matter

ABRACADABRA

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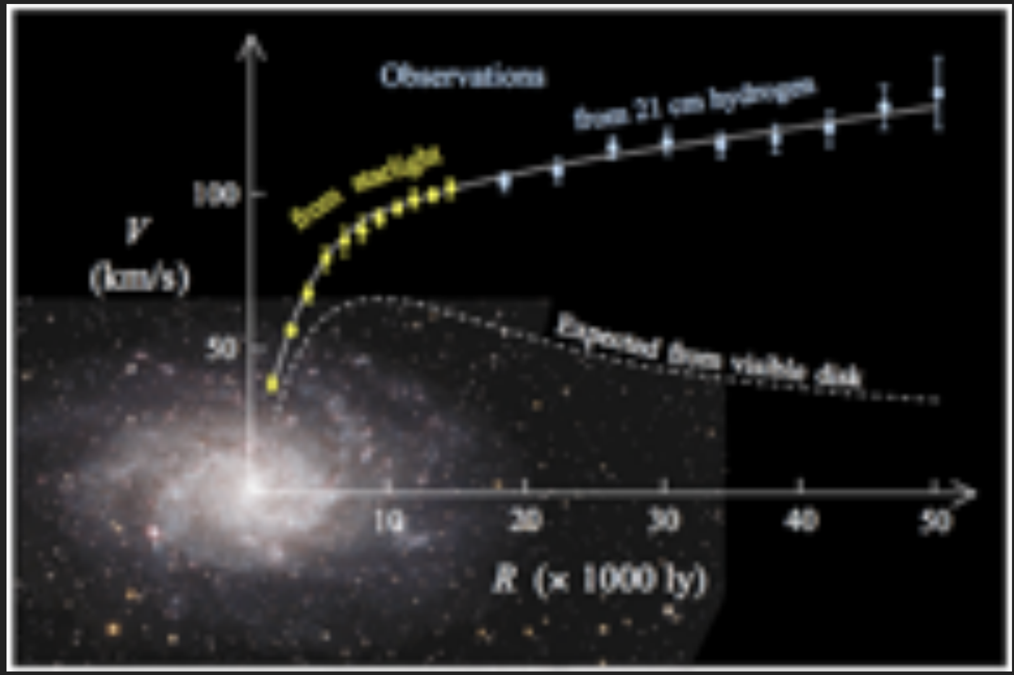
Massachusetts Institute of Technology

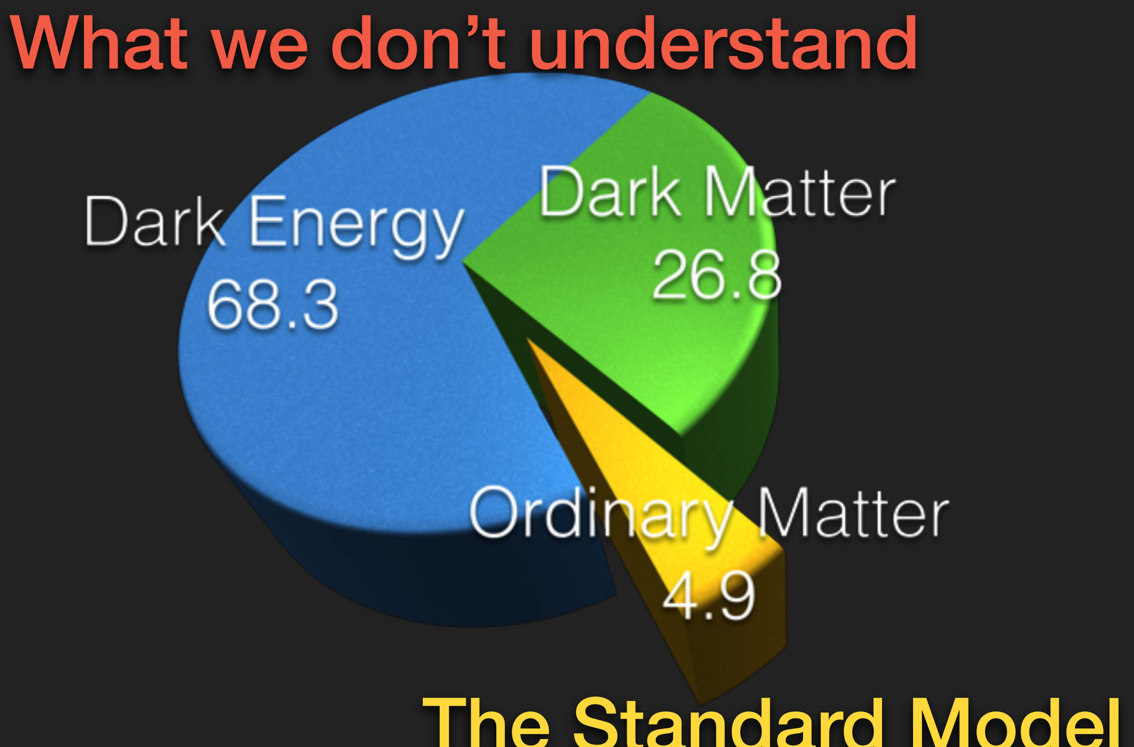
October 30, 2018

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)



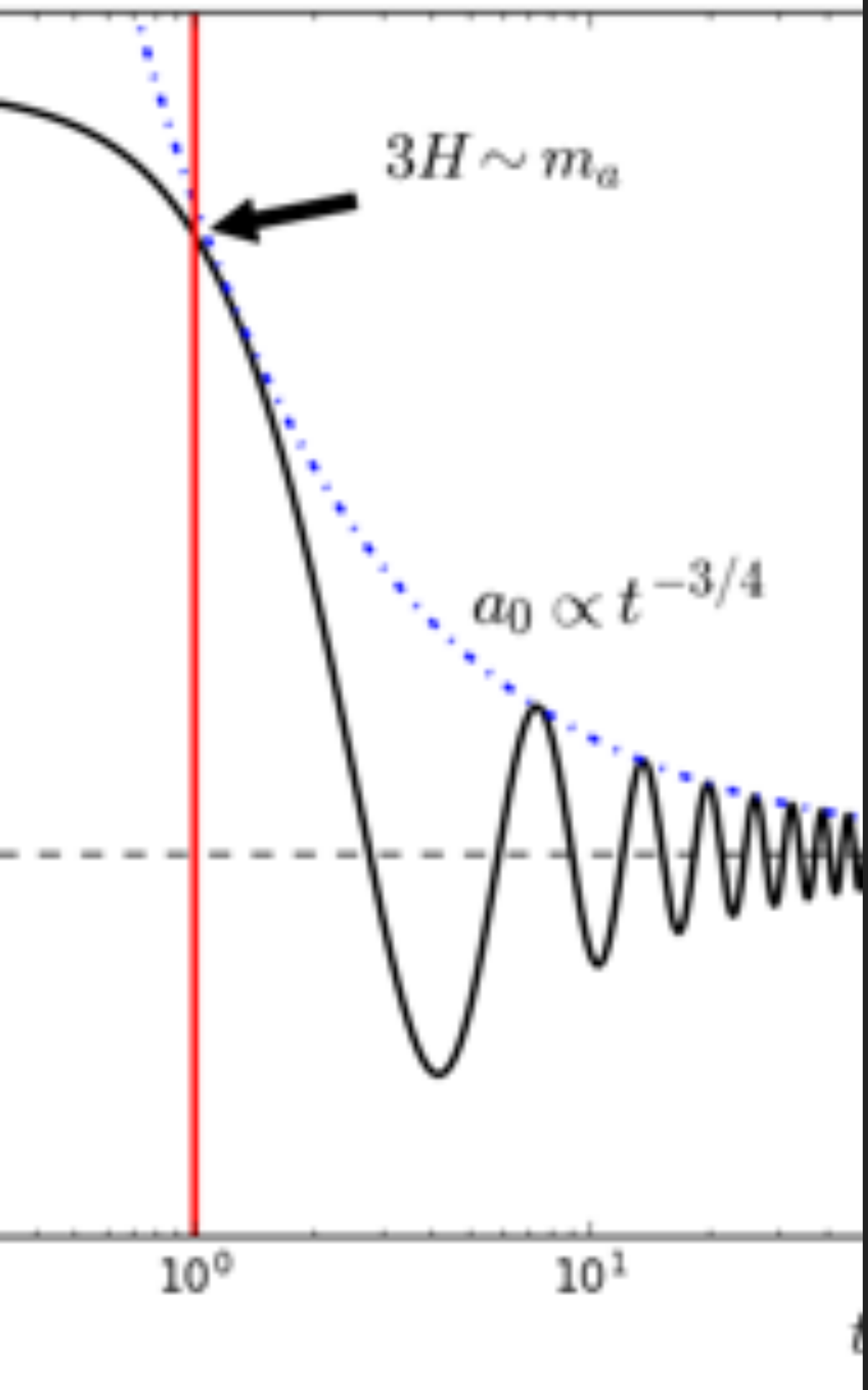


So What Is Dark Matter?

- We know that it requires physics beyond the Standard Model!
- Interacts gravitationally.
  - Does it interact Weakly? EM? New force mediator that mixes with the SM?
- 70 orders of magnitude in viable mass range

Figure from T. Tait

➡ Favor theories that solve more than one problem at once!



THE CASE FOR

AXION DARK MATTER

The Wonky Table of QCD Physics

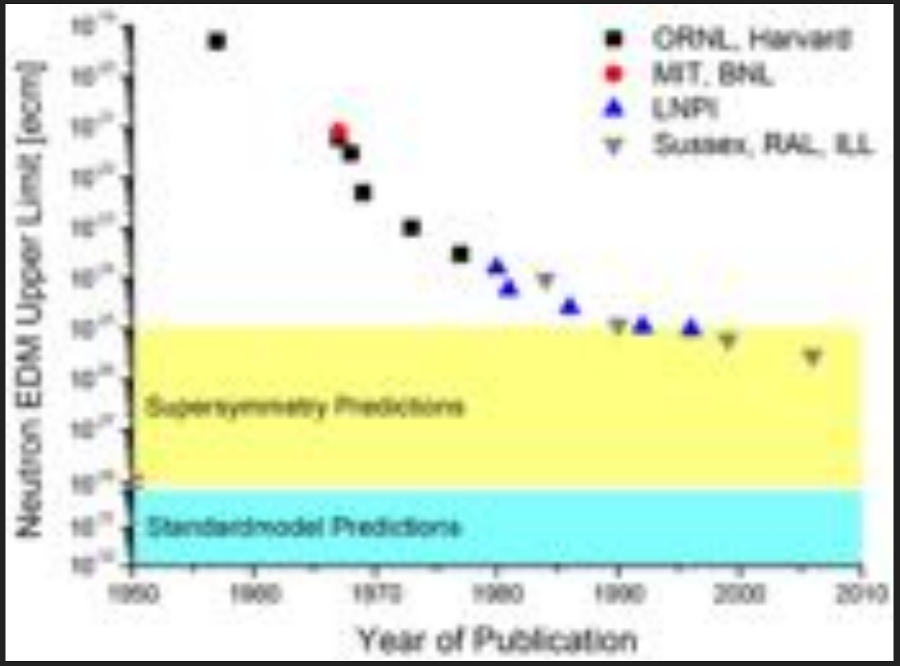
- The most general interaction that you can write down for the QCD interaction contains a CP-violating term

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi} G^a_{\mu\nu} G^{a\mu\nu} - \bar{\Theta}\frac{\alpha_s}{8\pi} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu} \qquad \bar{\Theta} \equiv \Theta + \arg\left(\det\left(M'\right)\right)$$

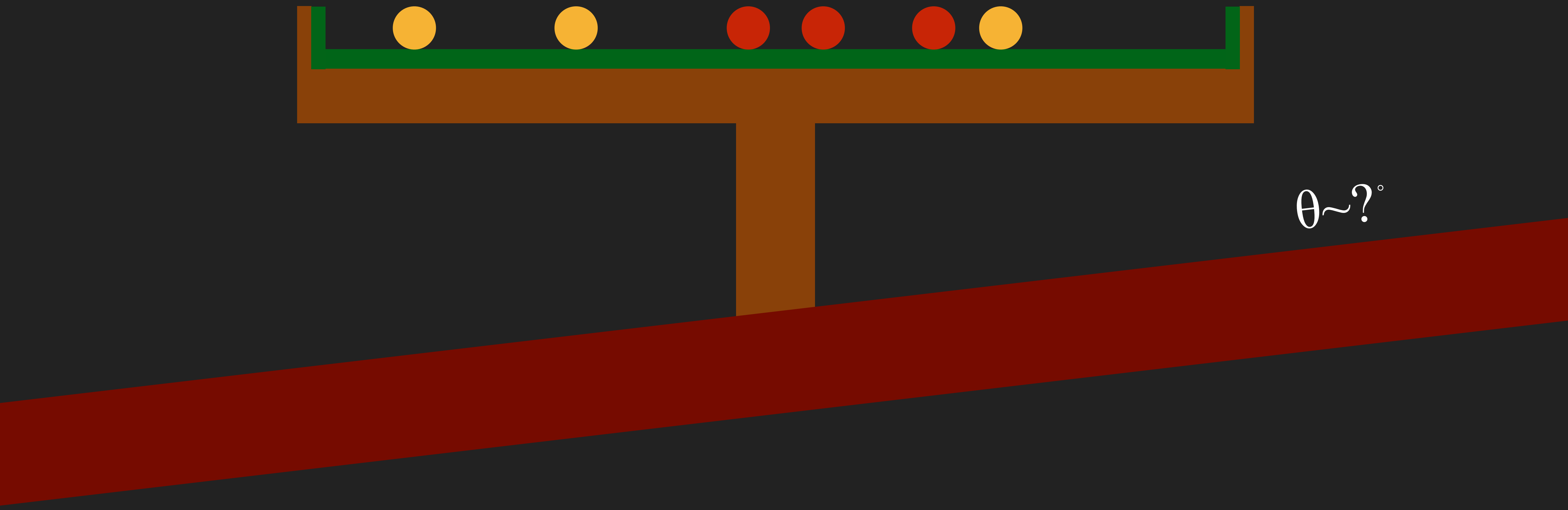
- Θ is arbitrary in the range: $0 \leq \Theta \leq 2\pi$
- The strong interaction should violate CP … a lot!
- Current limits on the neutron EDM place

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

➡ This is the Strong CP Problem!

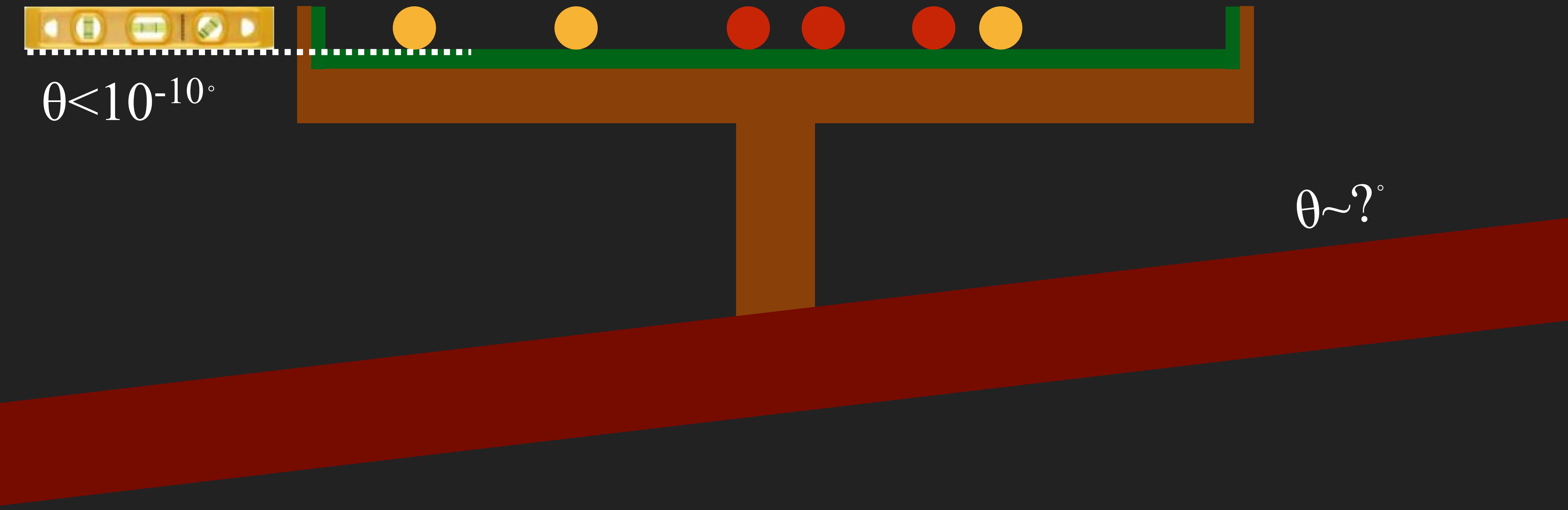


The Wonky Pool Table



Analogy from Pierre Sikivie

The Wonky Pool Table



Analogy from Pierre Sikivie

Peccei-Quinn Mechanism

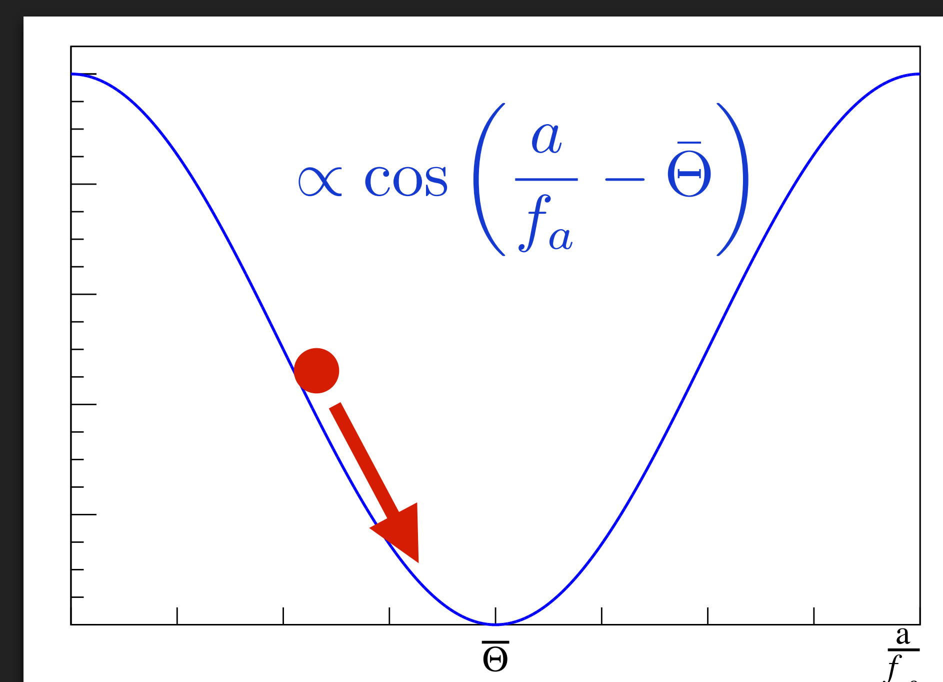
 

- Introduce a new field with the same CP violating term

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

- Interactions with SM (QCD) give the field a potential which cause it to:
  - dynamically cancel Θ!
  - gain a small but non-zero mass:

$$m_a \sim \frac{m_\pi f_\pi}{f_a} \sim 10^{-9}\,\mathrm{eV} \left(\frac{10^{16}\,\mathrm{GeV}}{f_a} \right)$$



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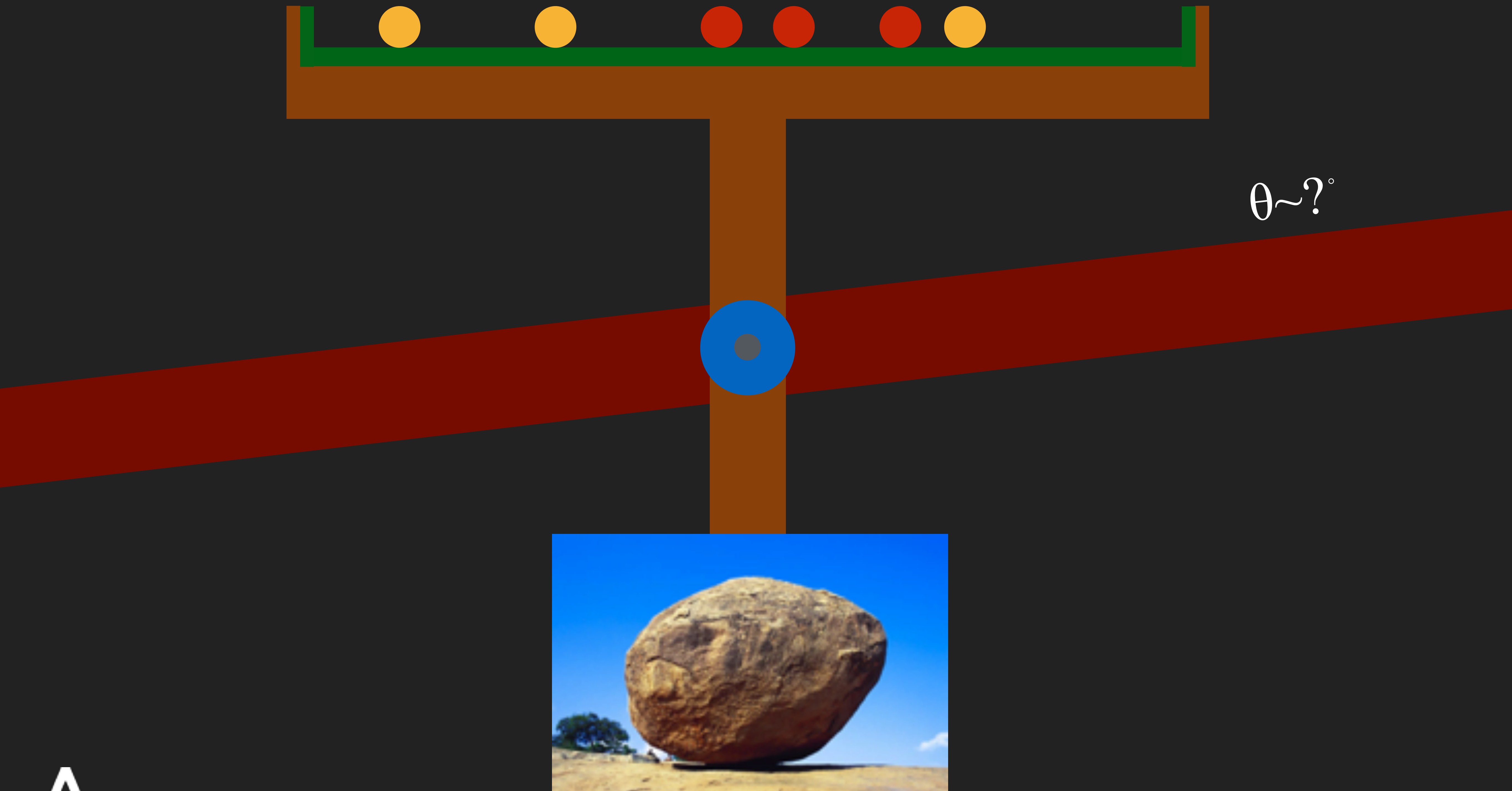


Analogy from Pierre Sikivie

Axion Dark Matter

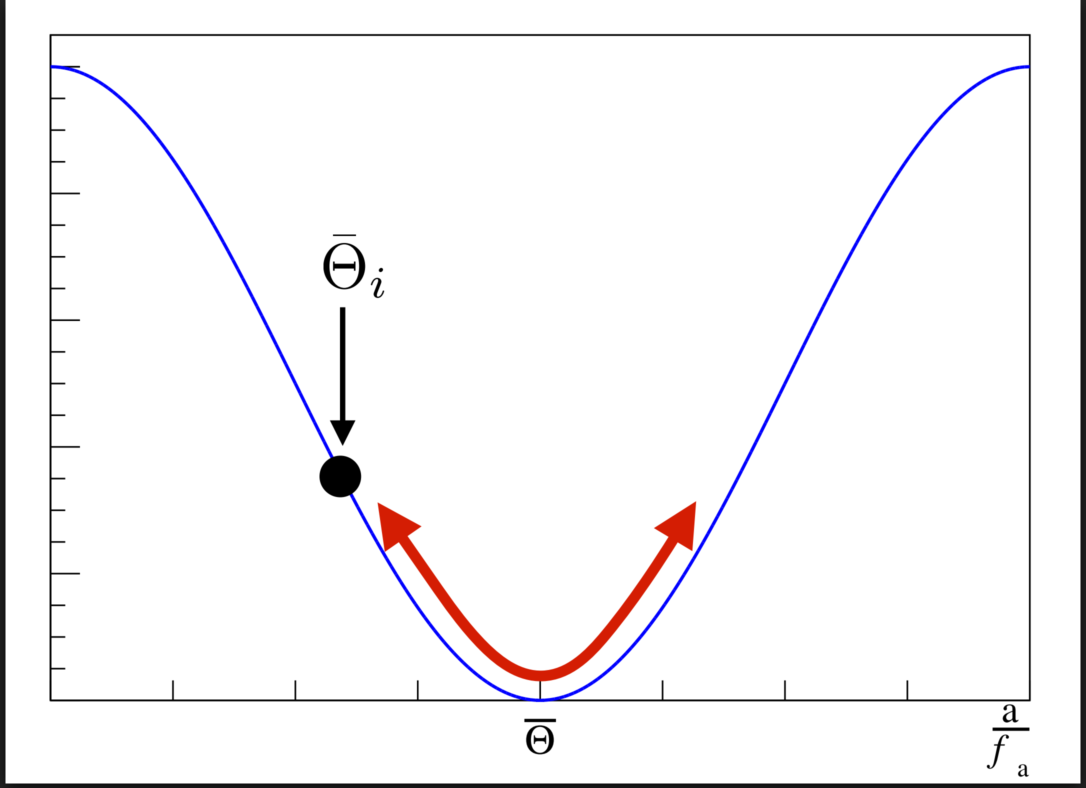
- Misalignment mechanism gives rise to an oscillating axion field:

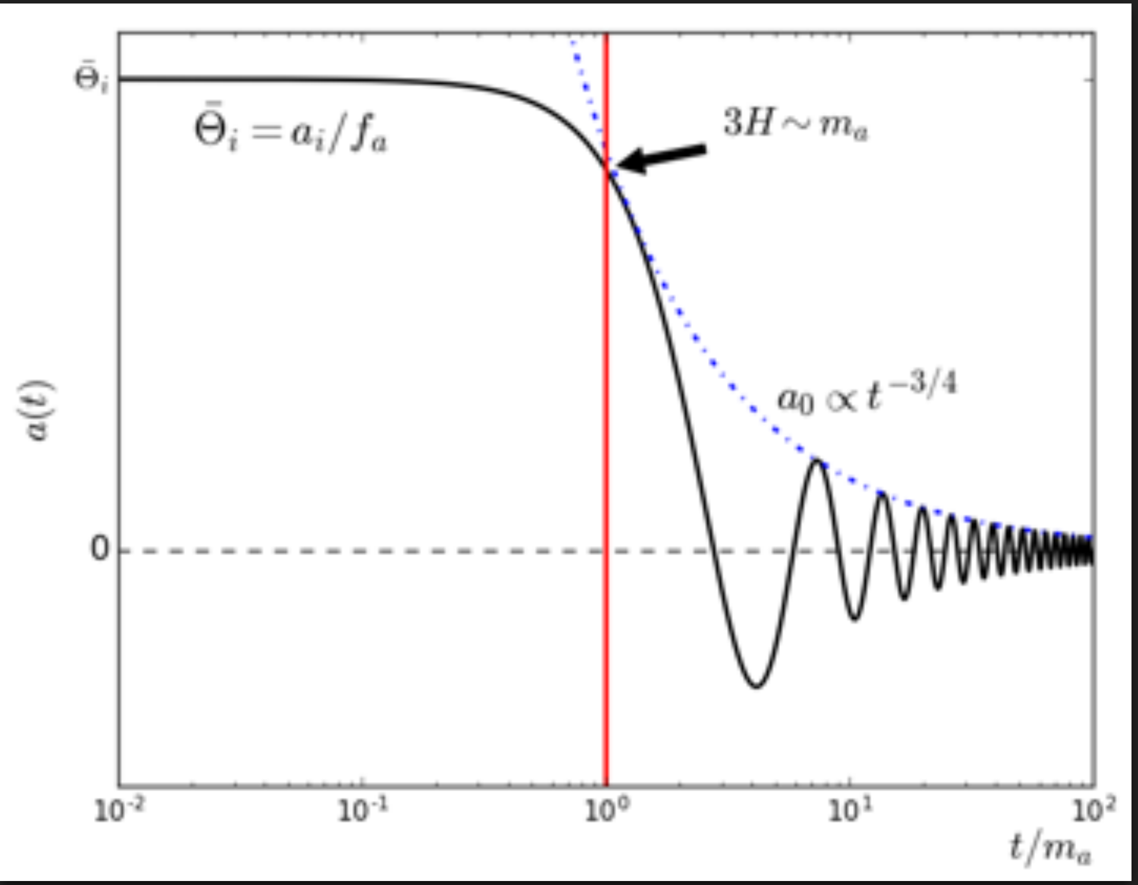
$$a(t) = a_0 \sin(m_a t)$$

- The combined field potential/kinetic energy behaves like DM!

- We can write the present day energy density in terms of the mass and initial alignment angle:

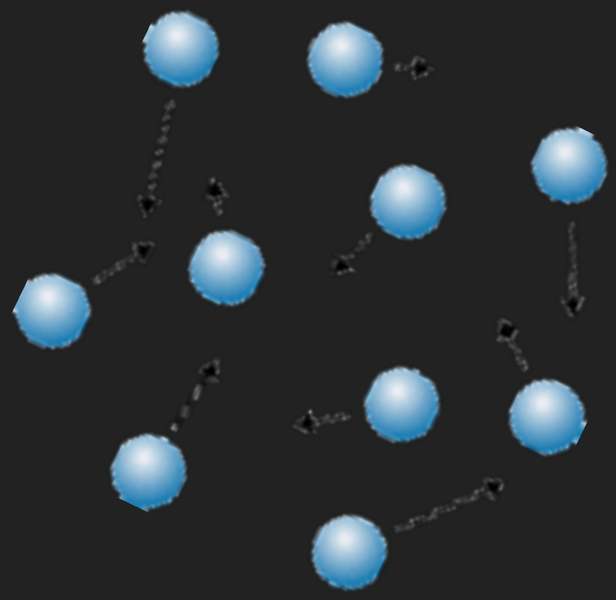
$$\Omega_a h^2 \sim 0.1 \left(\frac{10^{-5}\,\mathrm{eV}}{m_a} \right)^{7/6} \bar{\Theta}_i^2$$





DETECTING AXION DARK MATTER

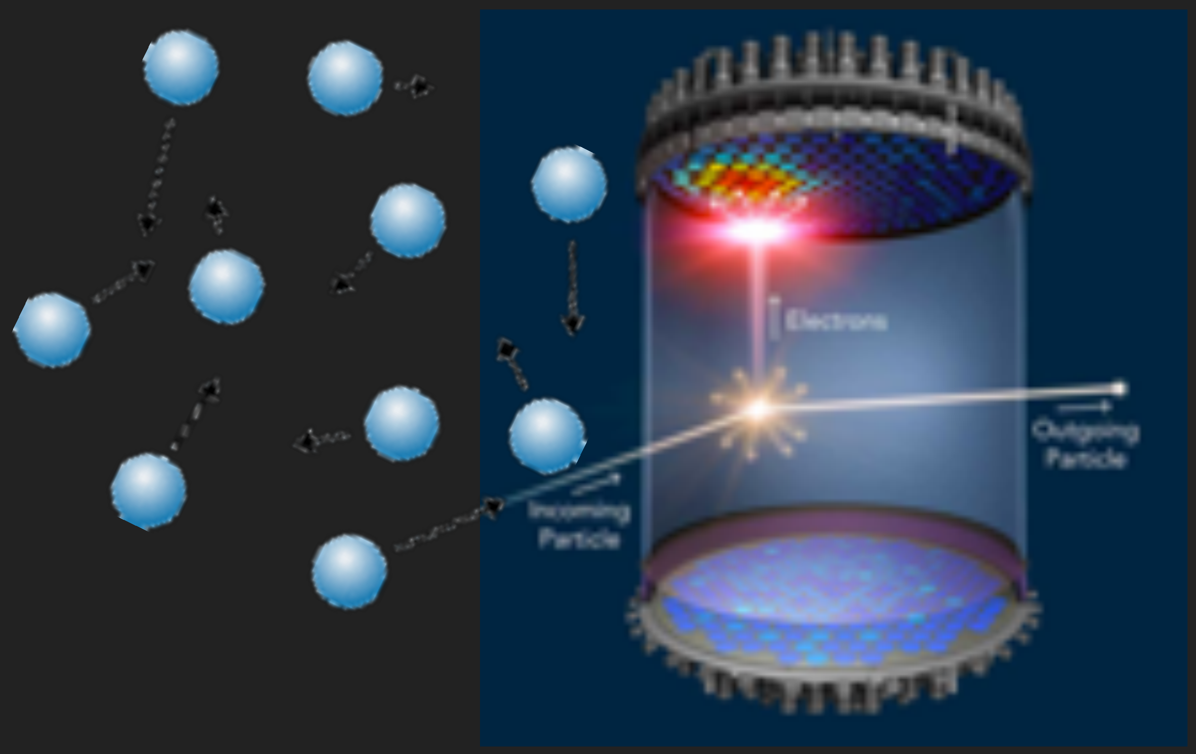
Particle vs Field



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

A few WIMPs per liter of space.

Particle vs Field



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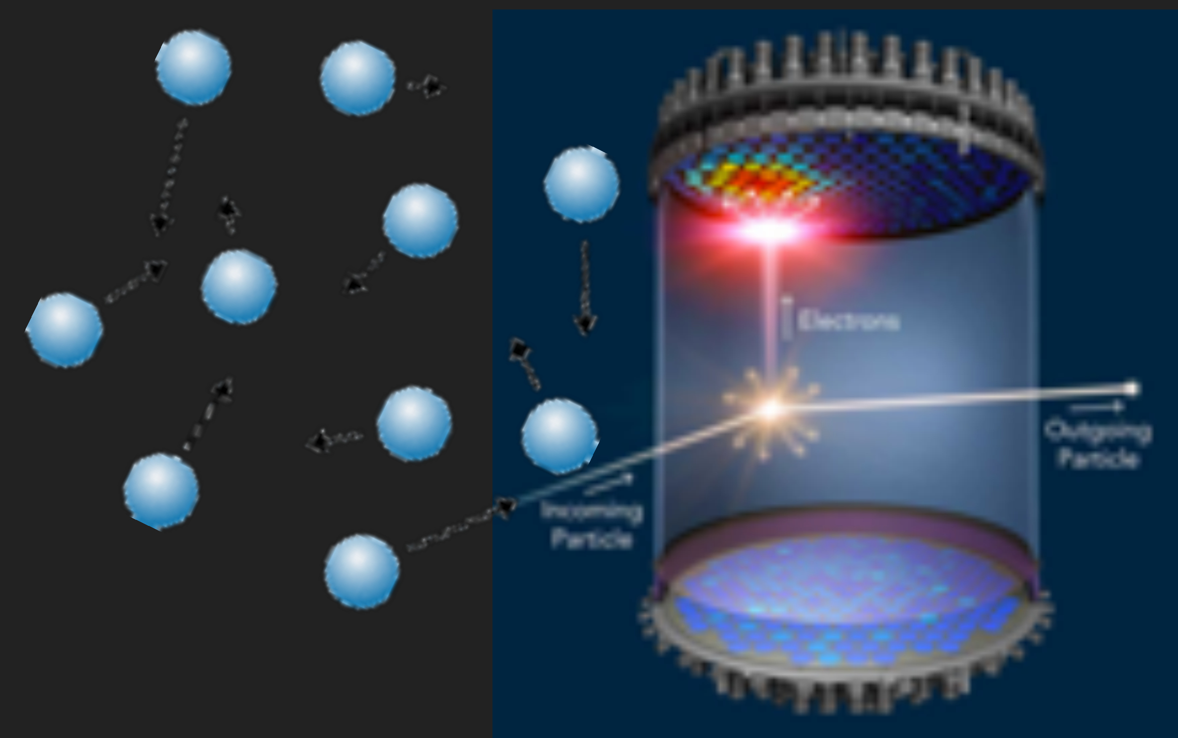

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Axions have a much higher number density and so behave like a classical field. Creating a very weak oscillating "wind" that we search for.

~10^{18} axions per liter of space

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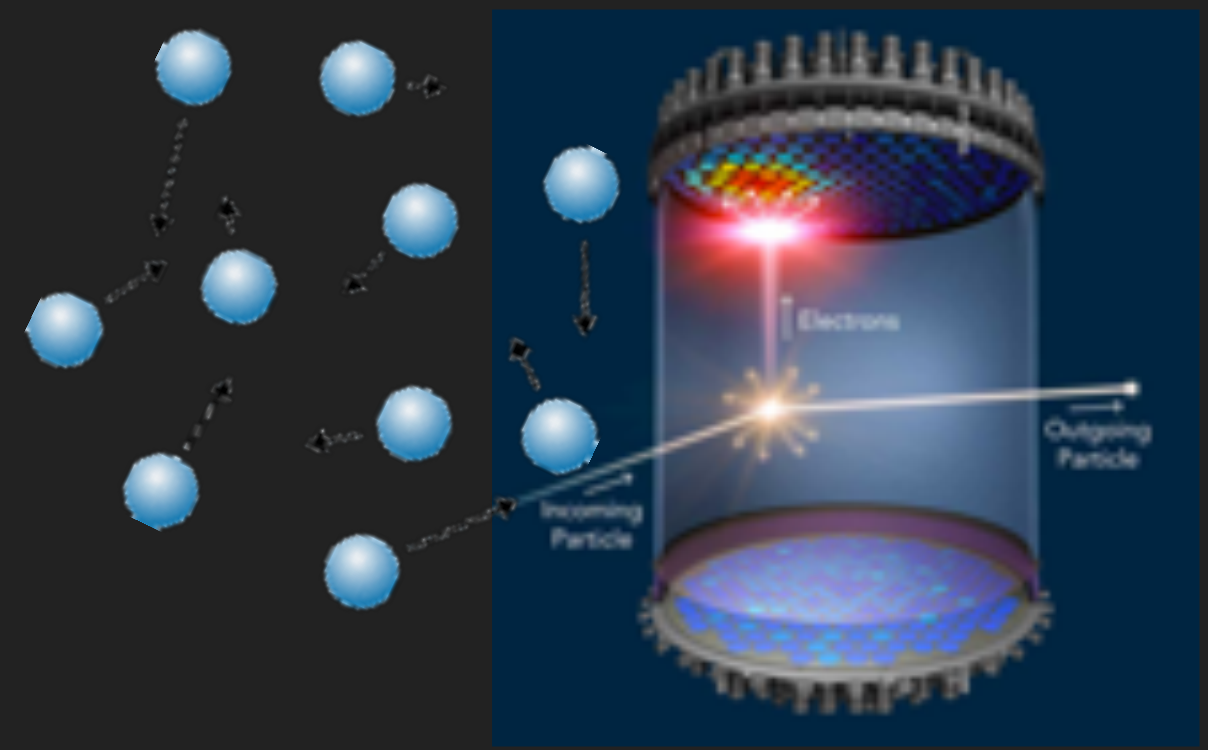

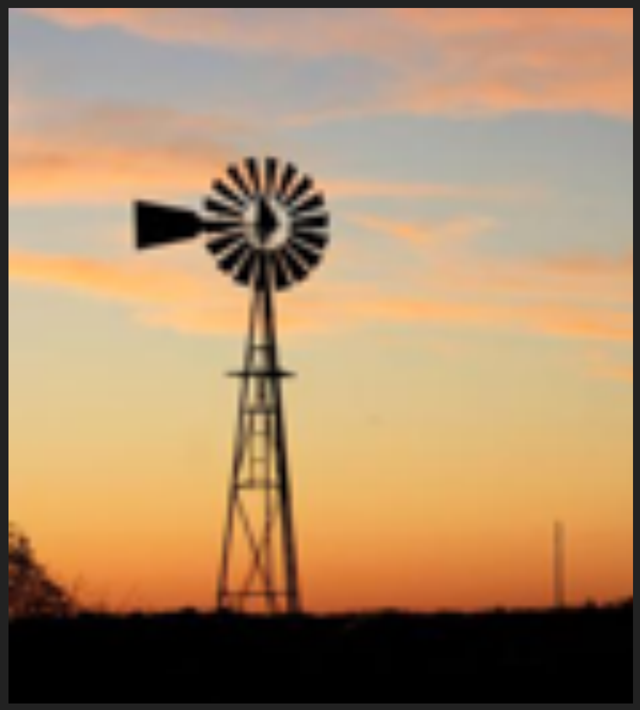

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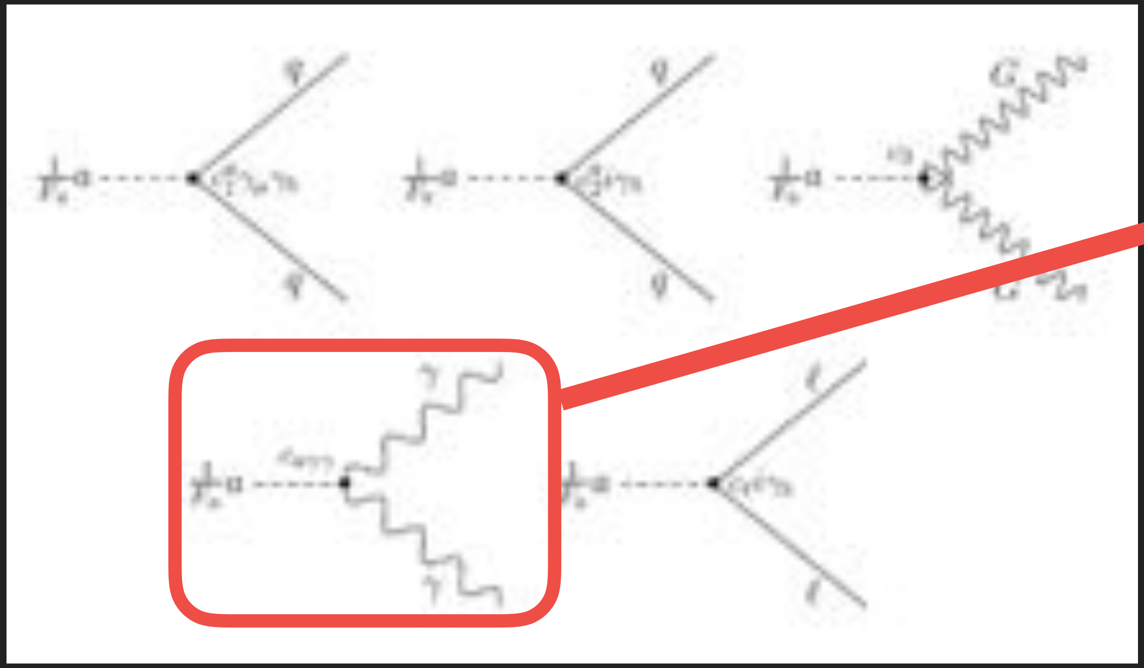
Axion Interactions with the Standard Model

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

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



$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\widetilde{F}^{\mu\nu} = -g_{a\gamma\gamma} a \mathbf{E}\cdot\mathbf{B}$$

$$g_{a\gamma\gamma} \propto \frac{\alpha_{\rm EM}}{f_a}$$

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

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

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\end{aligned}$$

Ouellet & Bogogad
(arXiv:1809.10709)

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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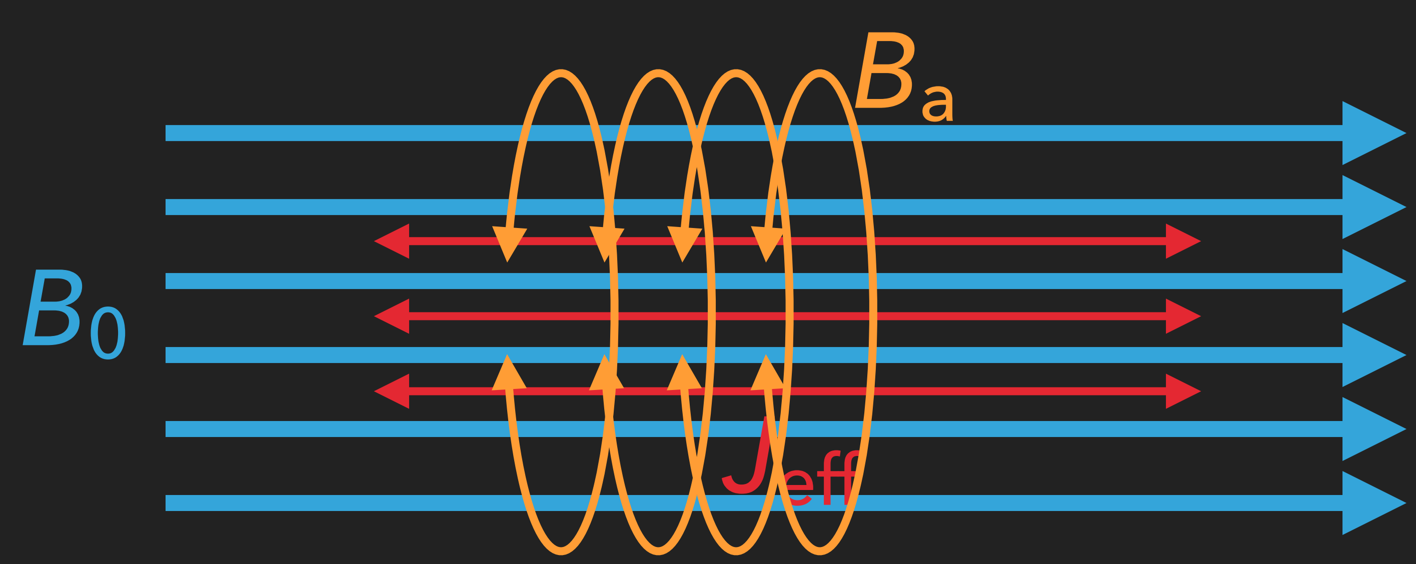

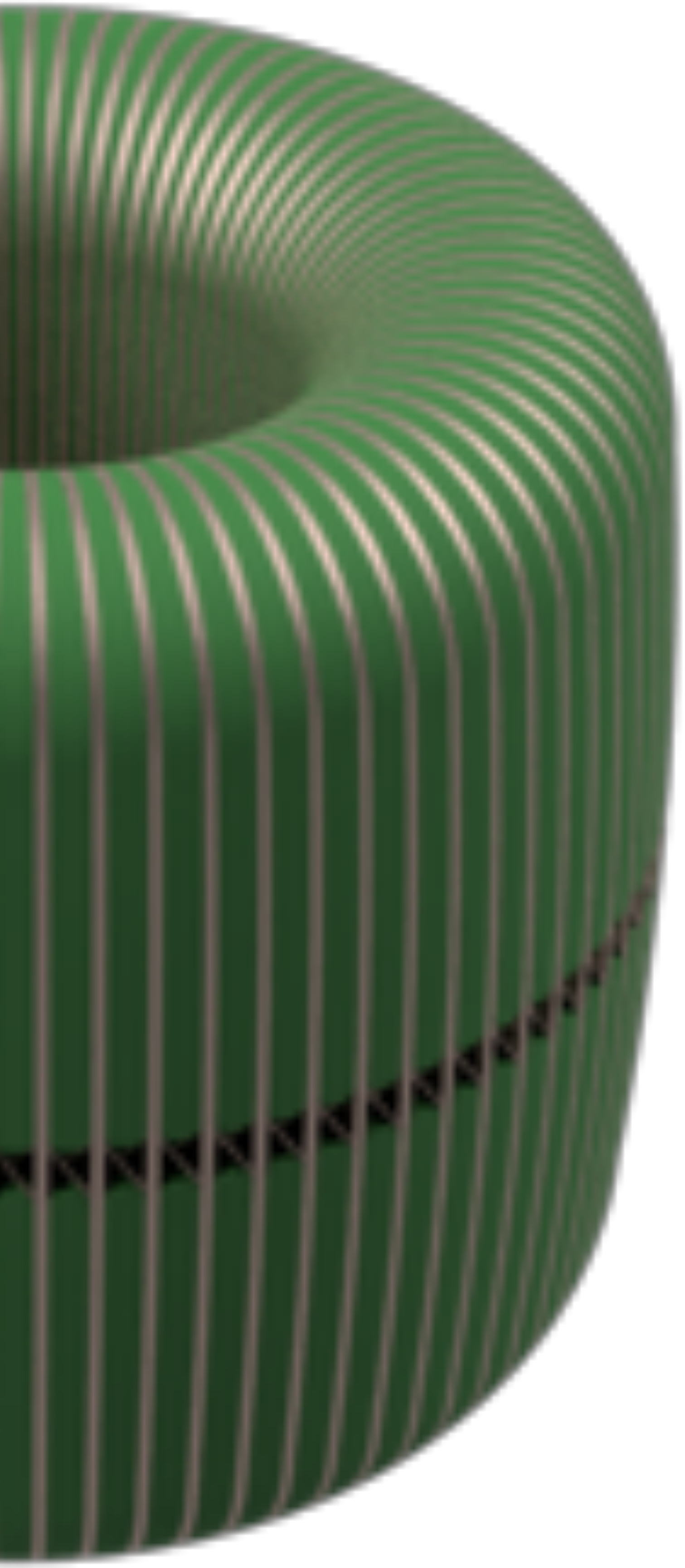

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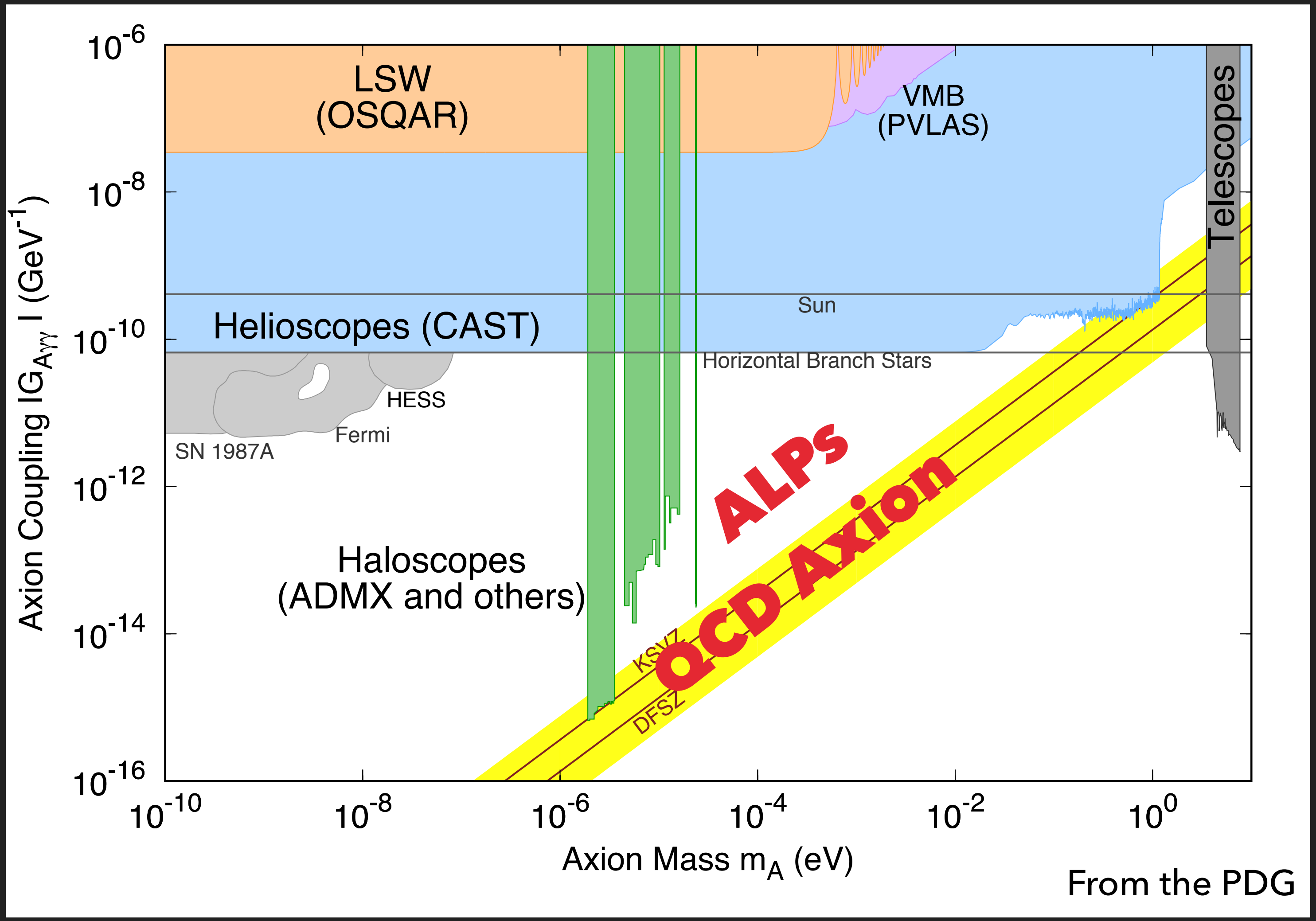
Current State Of Axion Search



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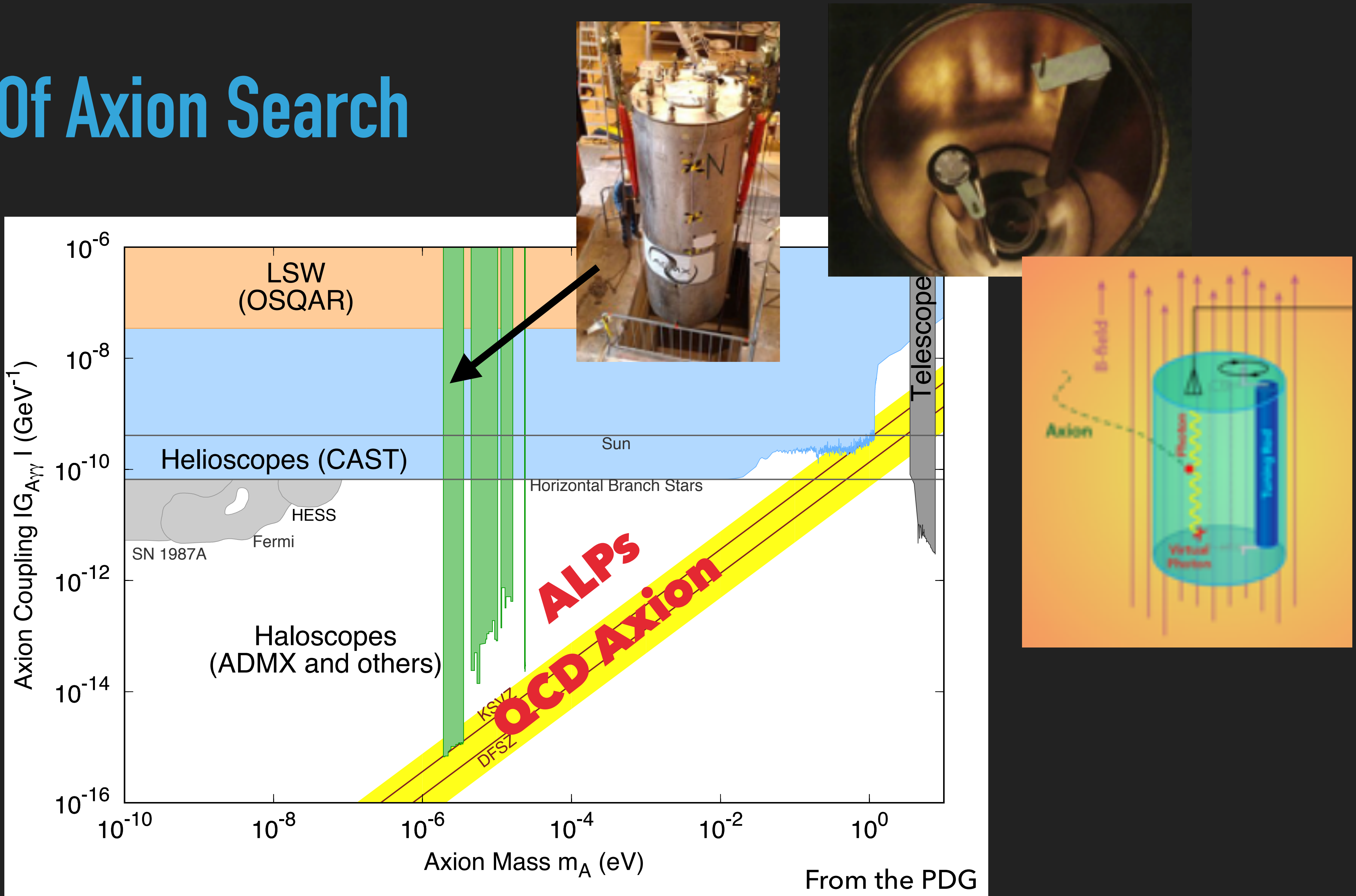
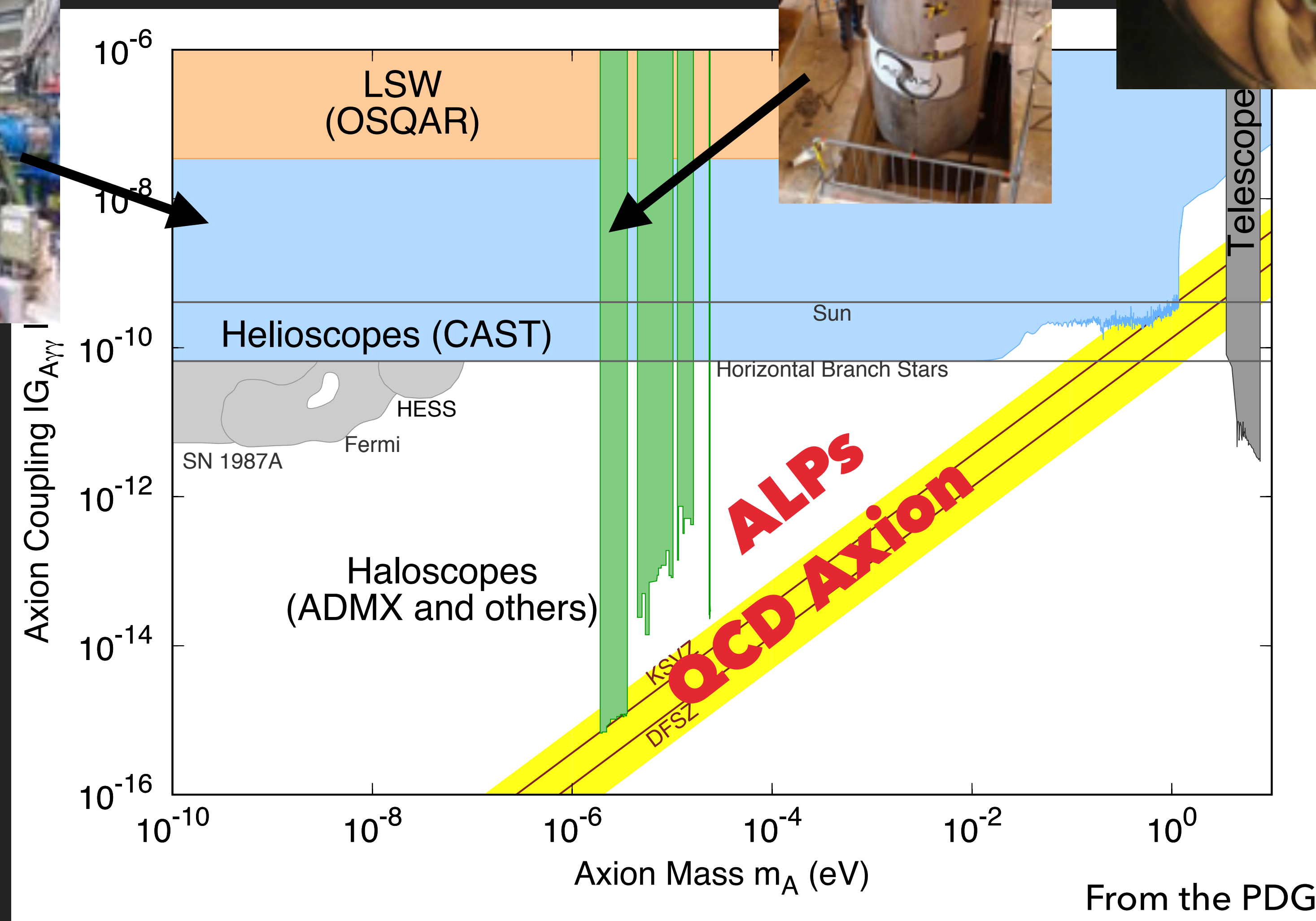
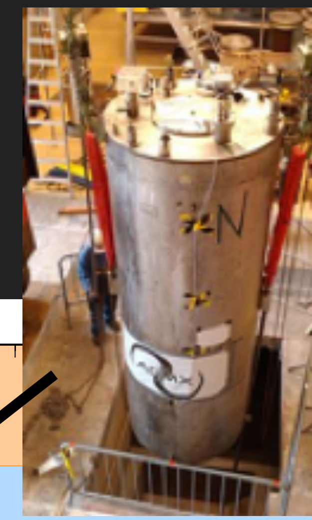
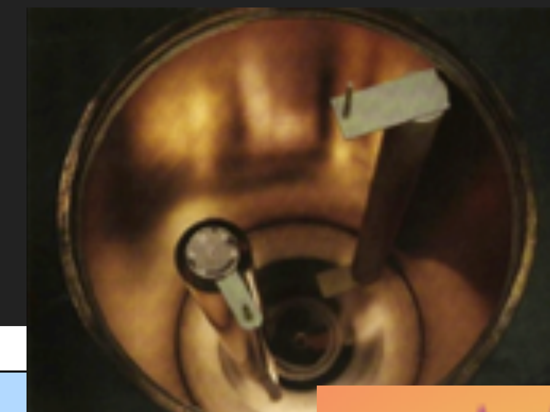


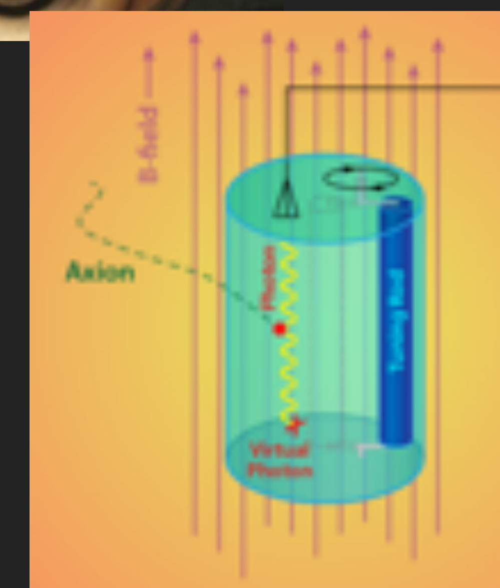
From the PDG

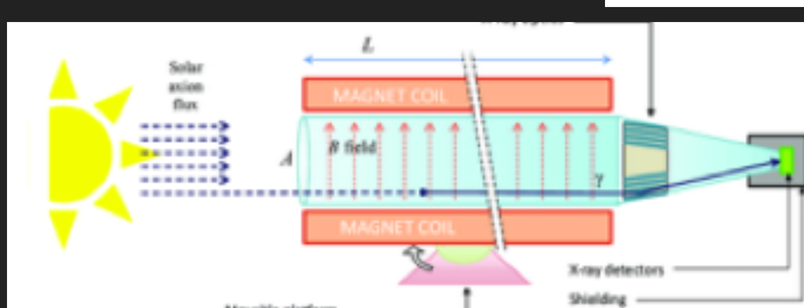
Current State Of Axion Search











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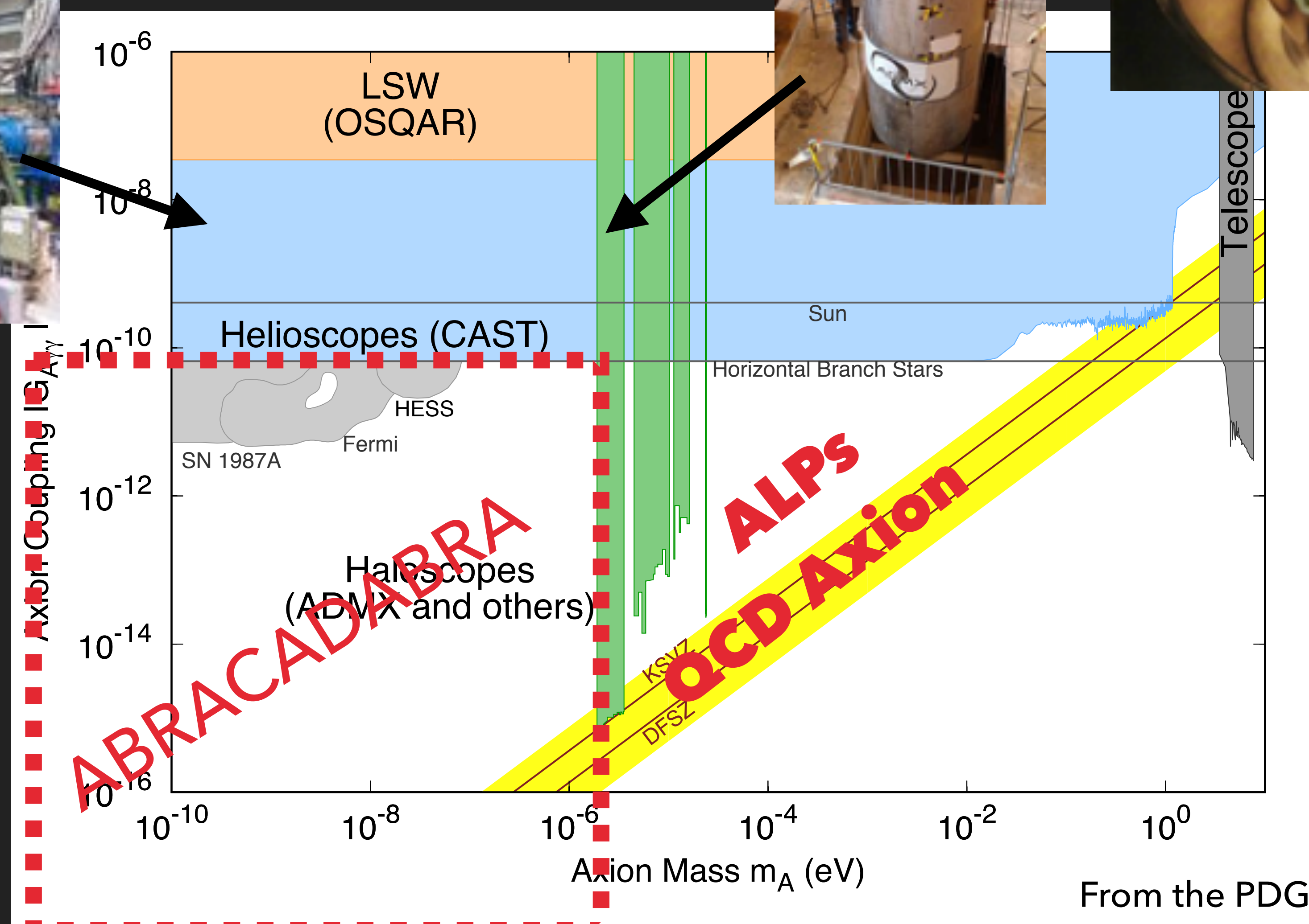
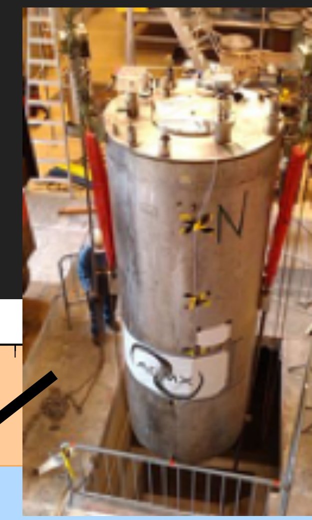
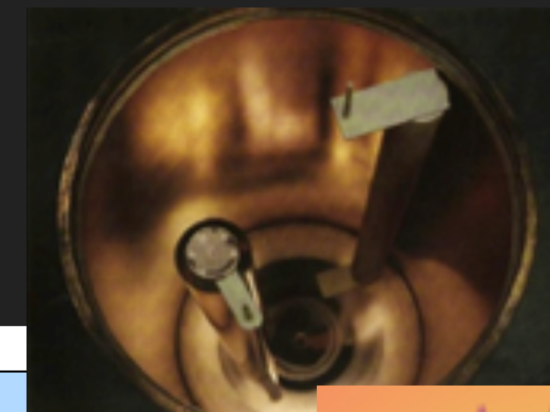
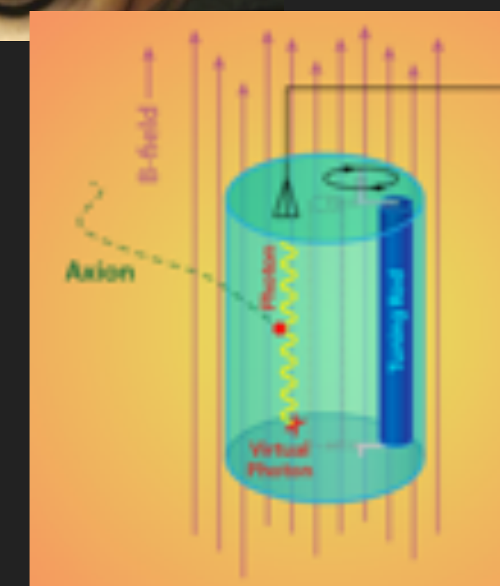
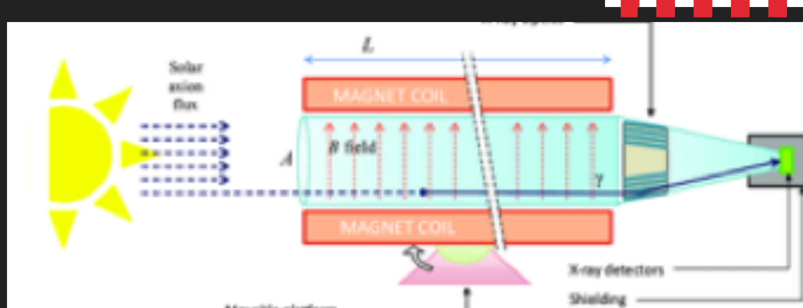


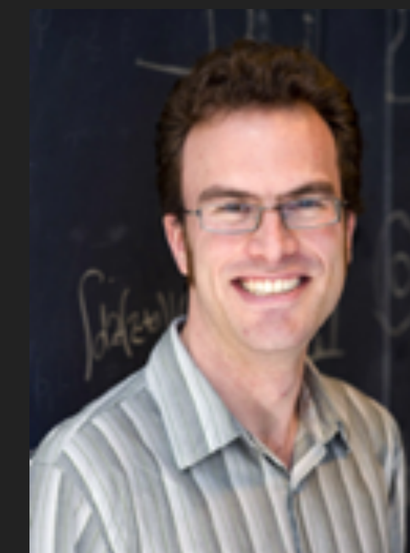








A New Way to Search for Axion Dark Matter



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

Broadband and Resonant Approaches to Axion Dark Matter Detection

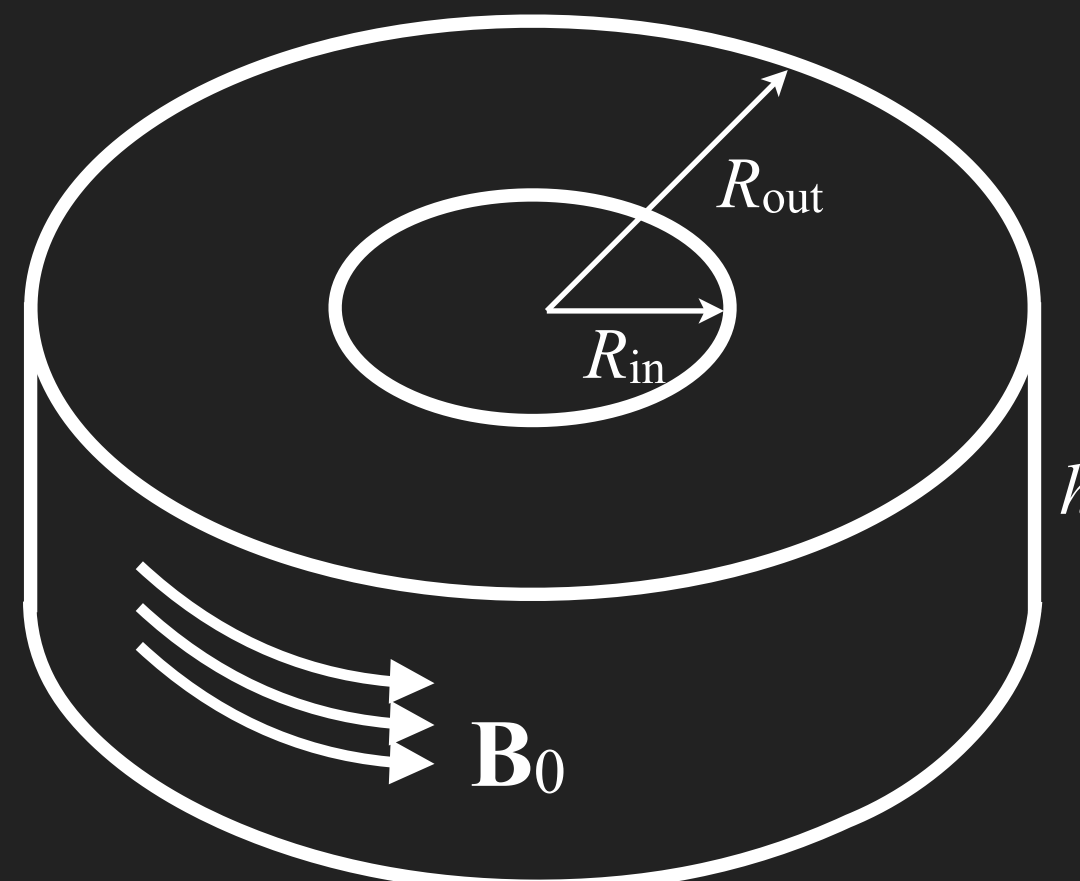
Yonatan Kahn,[1,*] Benjamin R. Safdi,[2,†] and Jesse Thaler[2,‡]
[1]*Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*
[2]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
(Received 3 March 2016; published 30 September 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

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)

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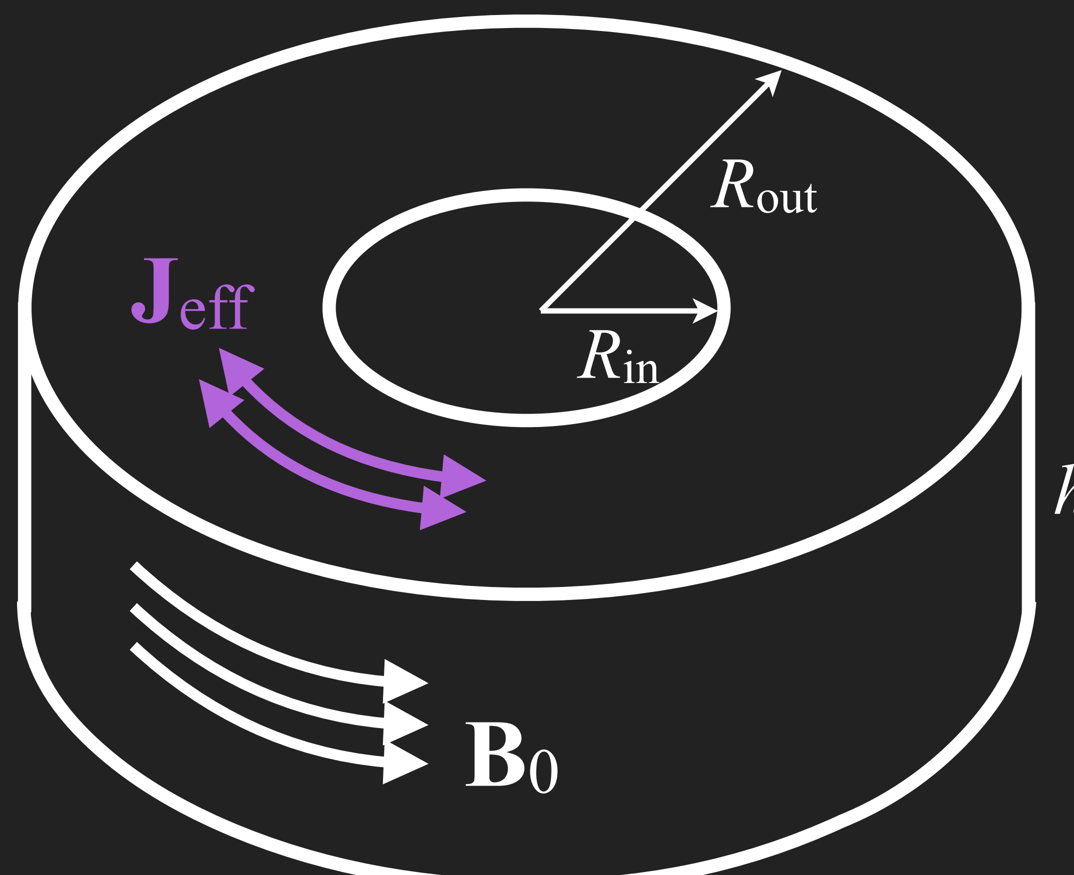
- ADM generates an oscillating effective current around the ring (MQS approx: $\lambda \gg R$)



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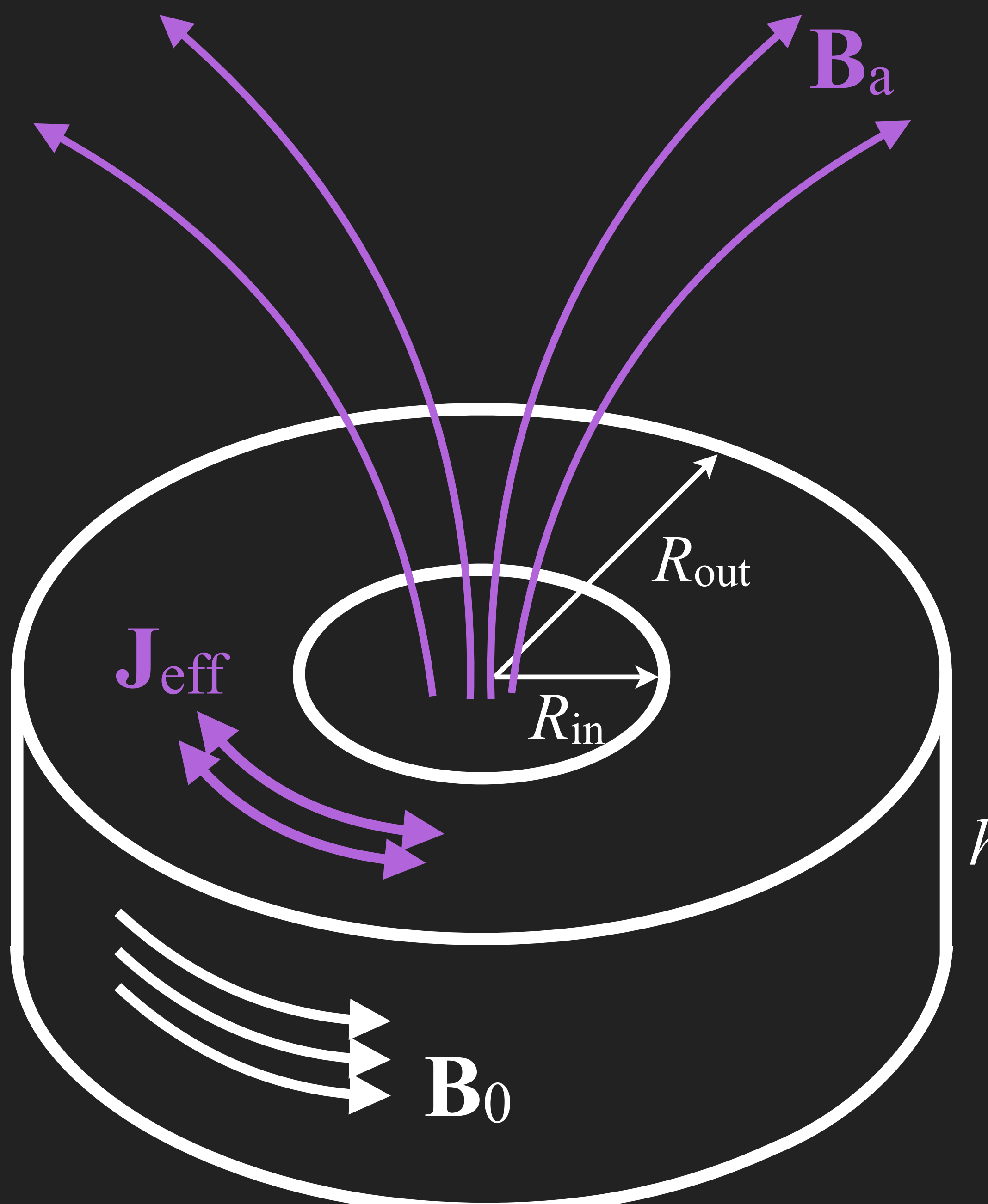
- … this generates an oscillating magnetic field through the center of the toroid



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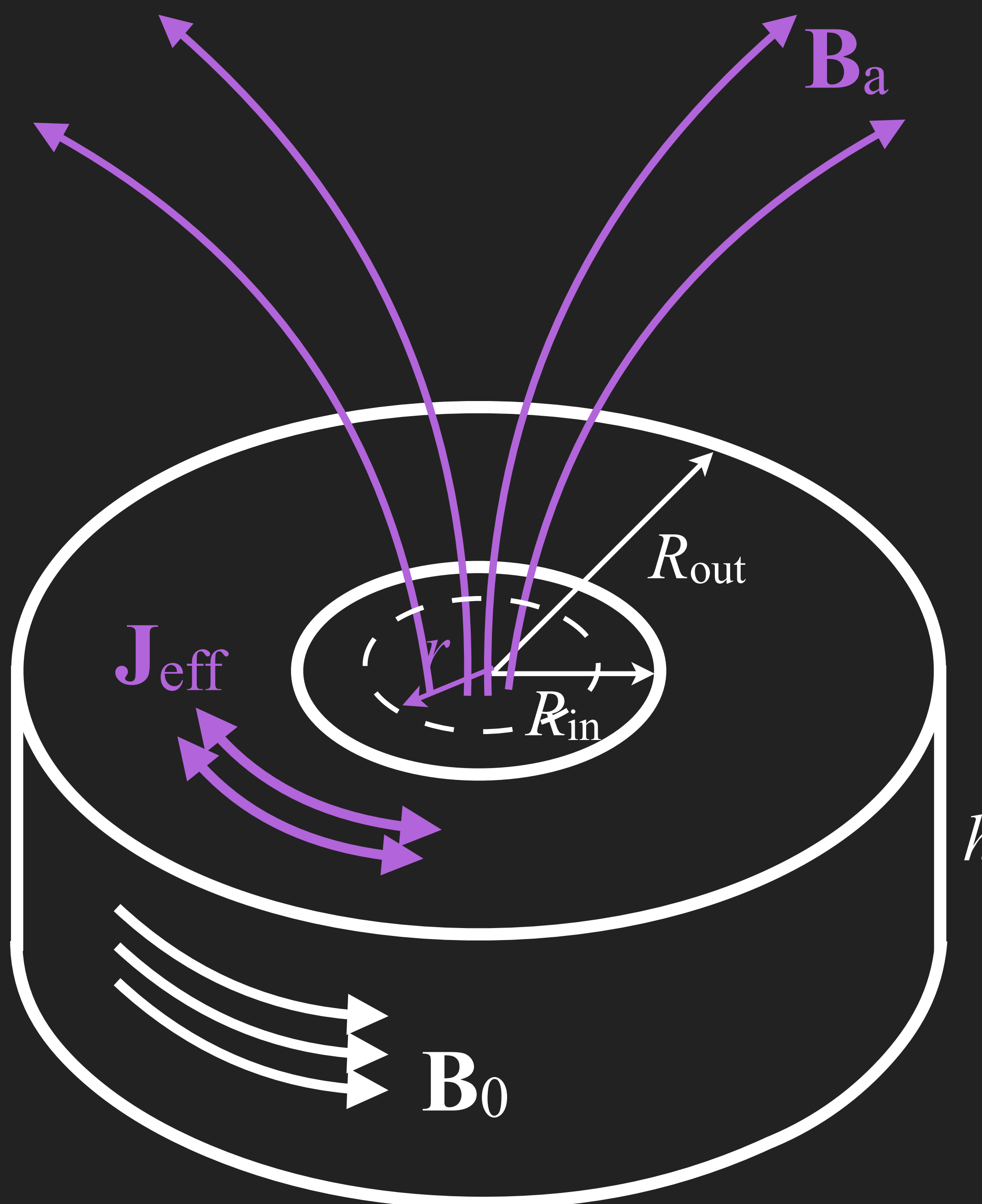
- Insert a pickup loop in the center and measure the induced current in the loop read out by a SQUID based readout

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



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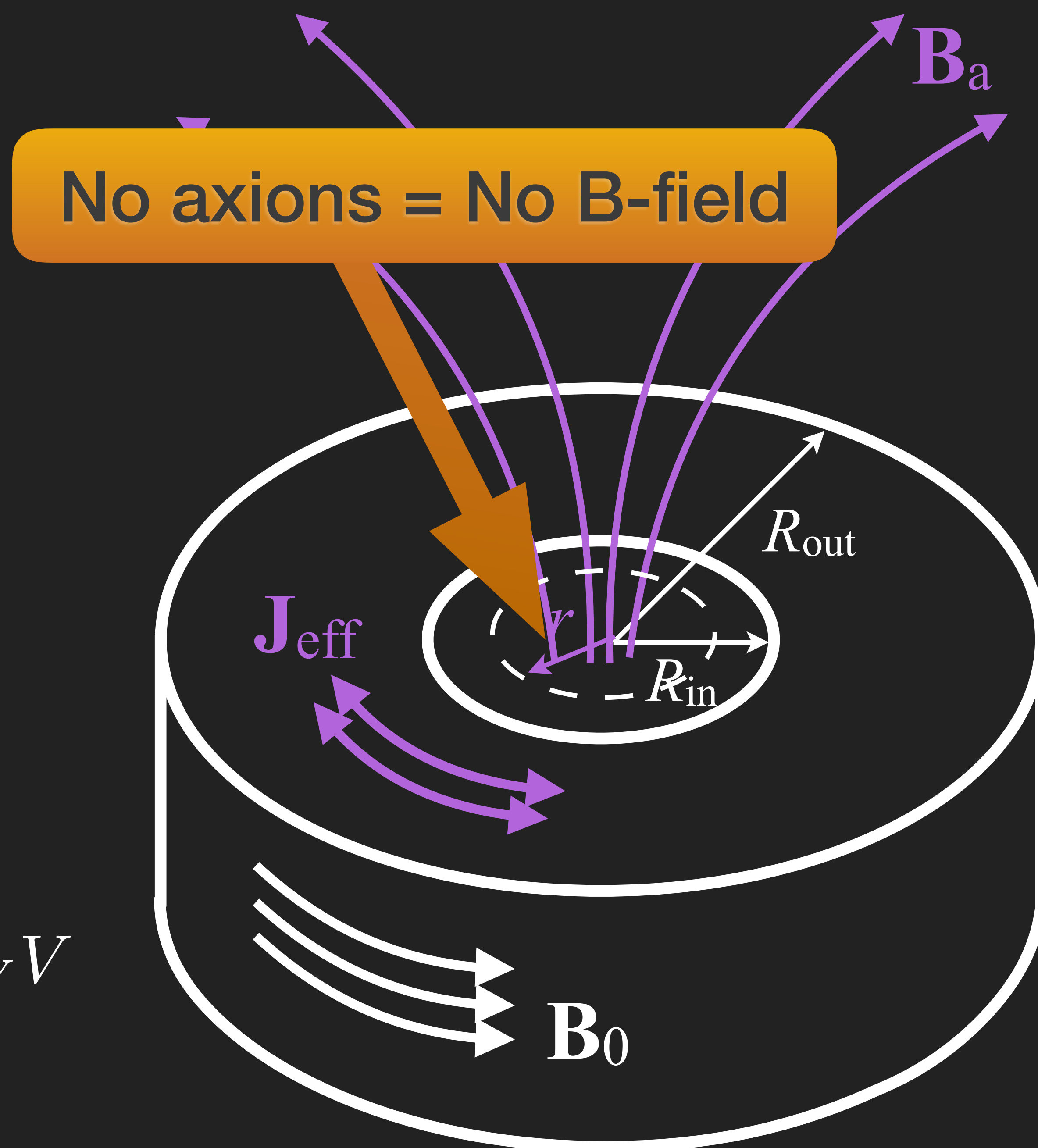
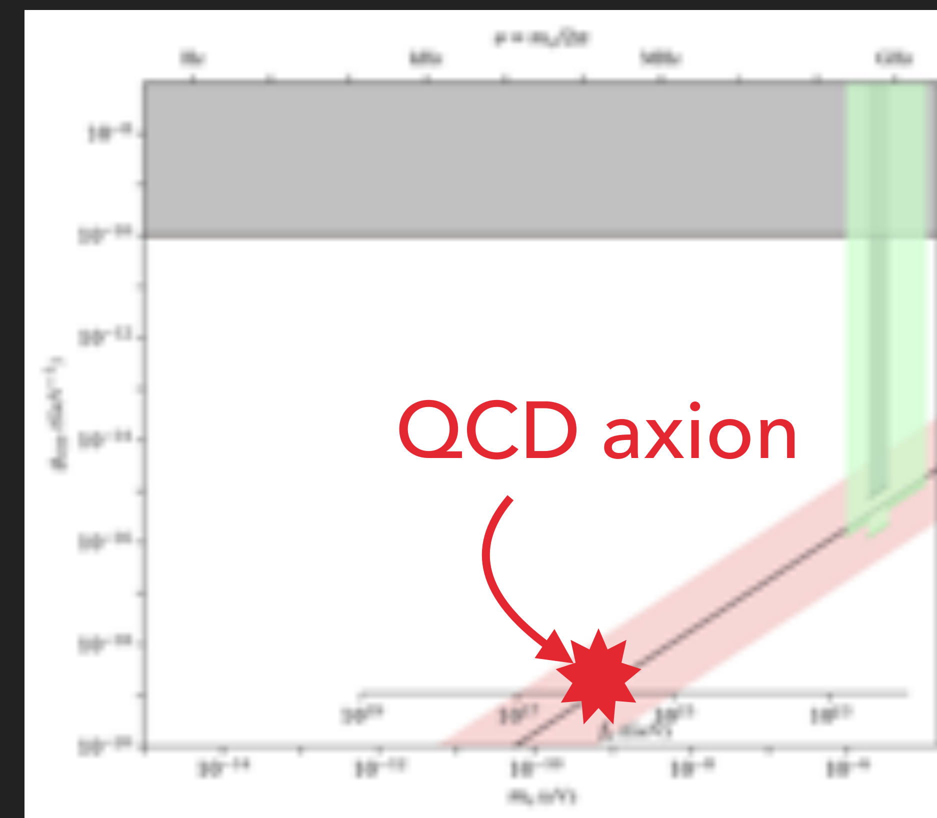
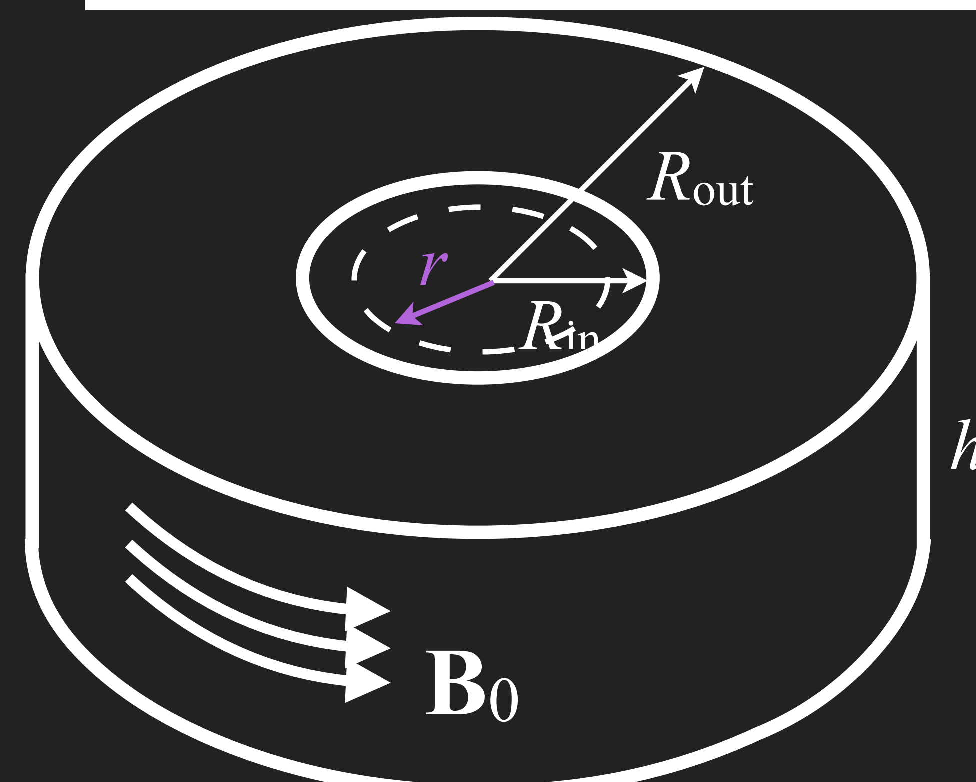


Phys. Rev. Lett. 117, 141801 (2016)

ABRACADABRA on the Back of the Envelope

- R_{in} = 1m, R_{out} = 2m, h=3m
- B_{max} = 5T
- m_a = 1 neV, KSVZ





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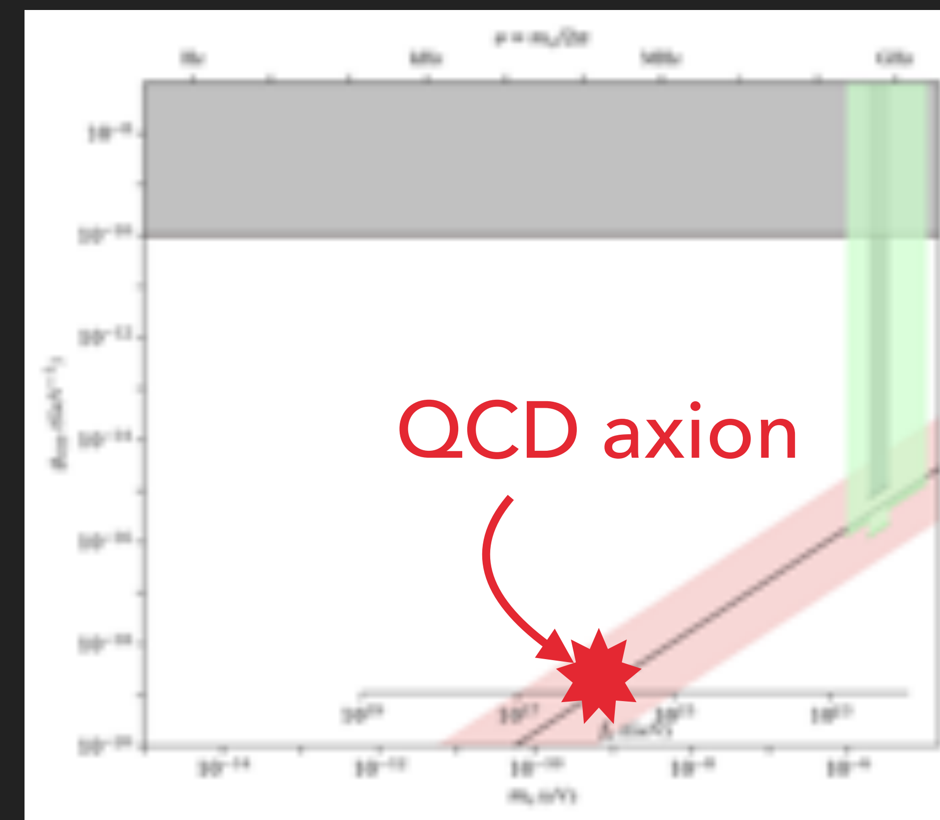
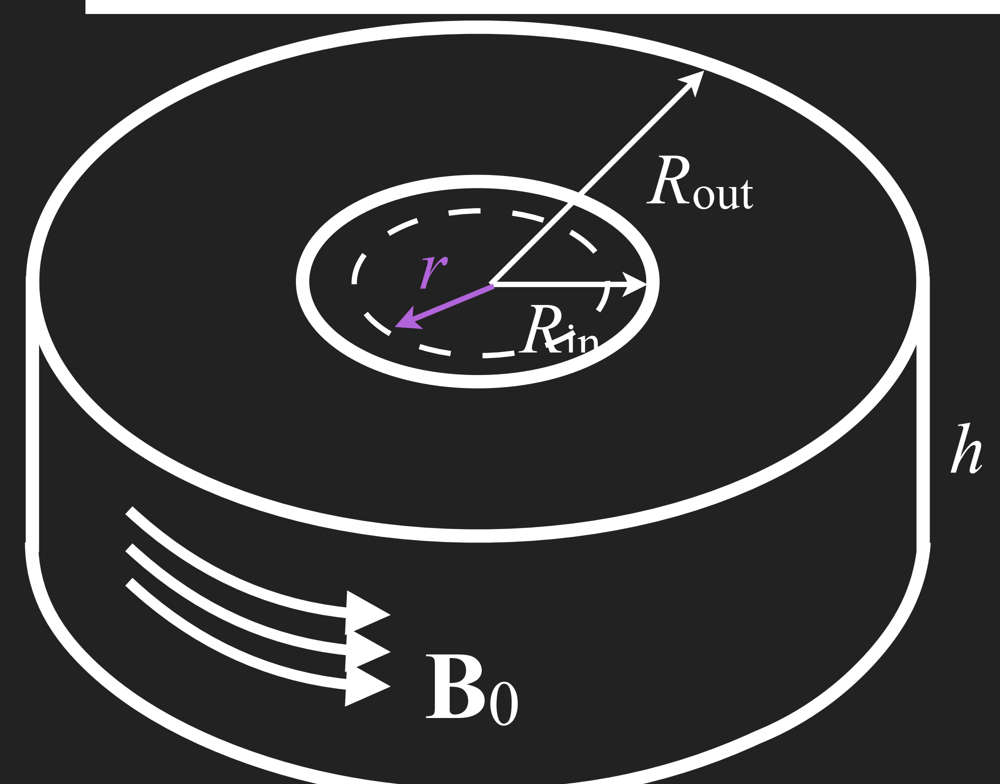
➡ $B_a \sim 5\times10^{-22}$ T





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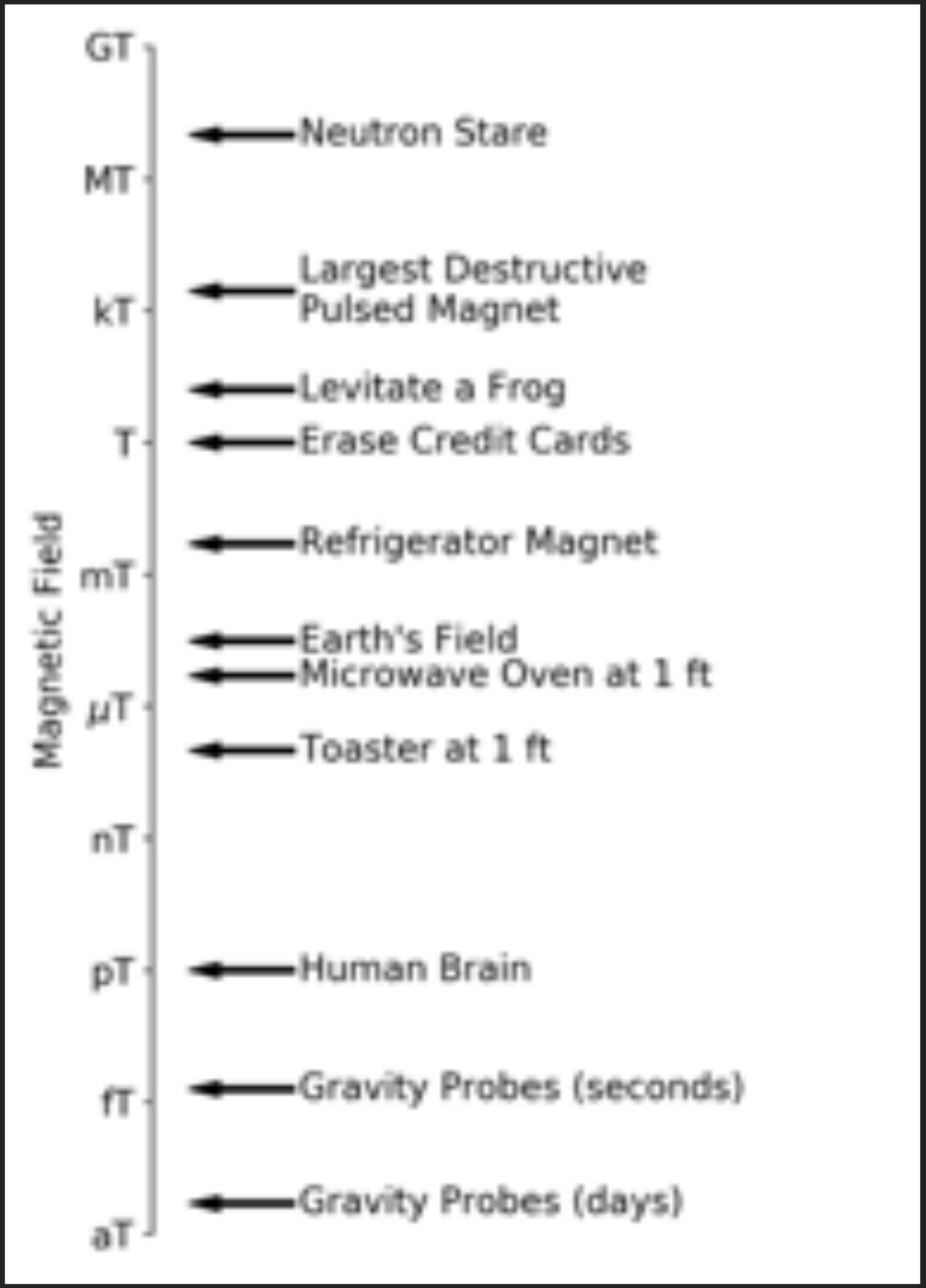

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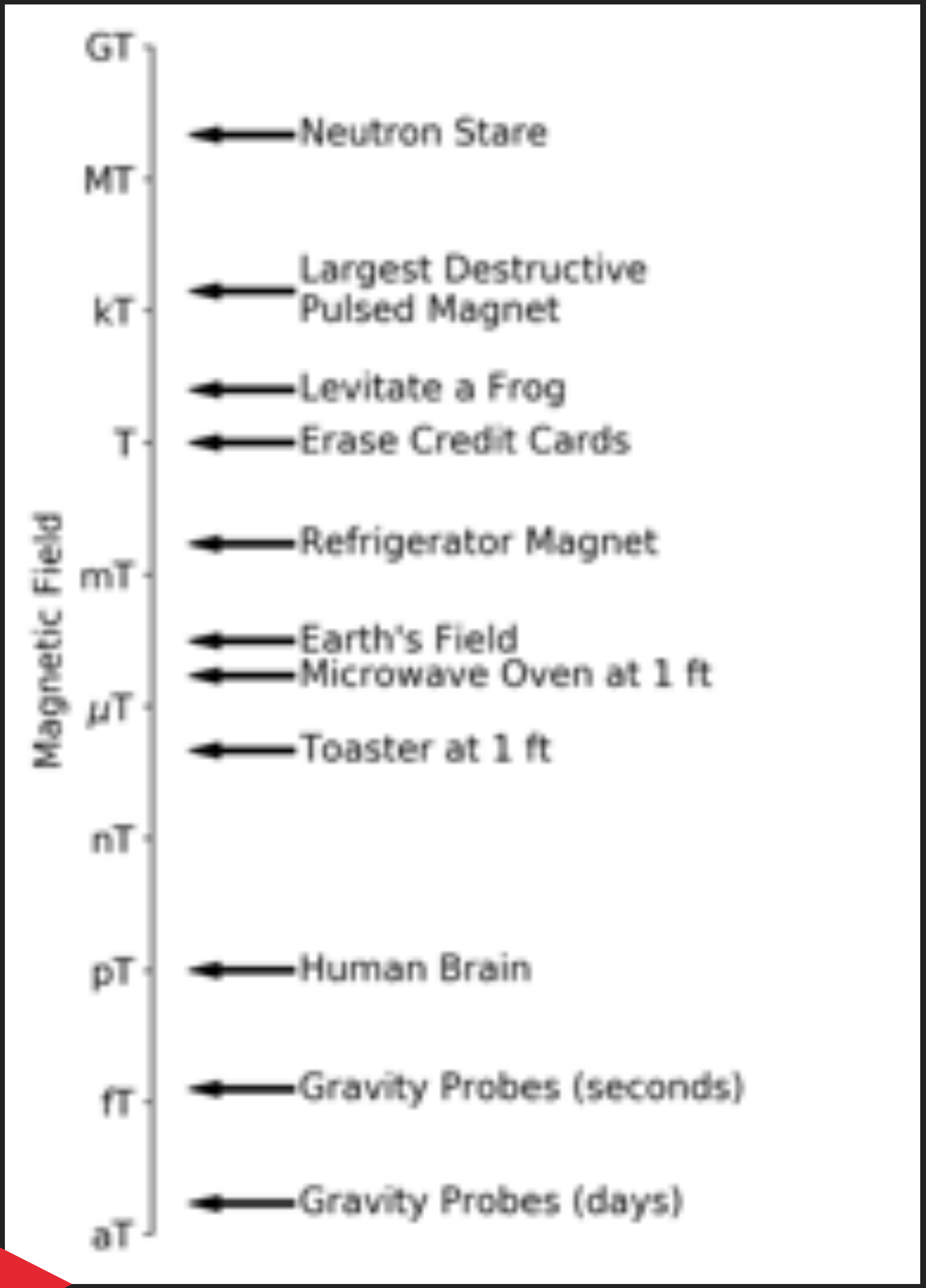

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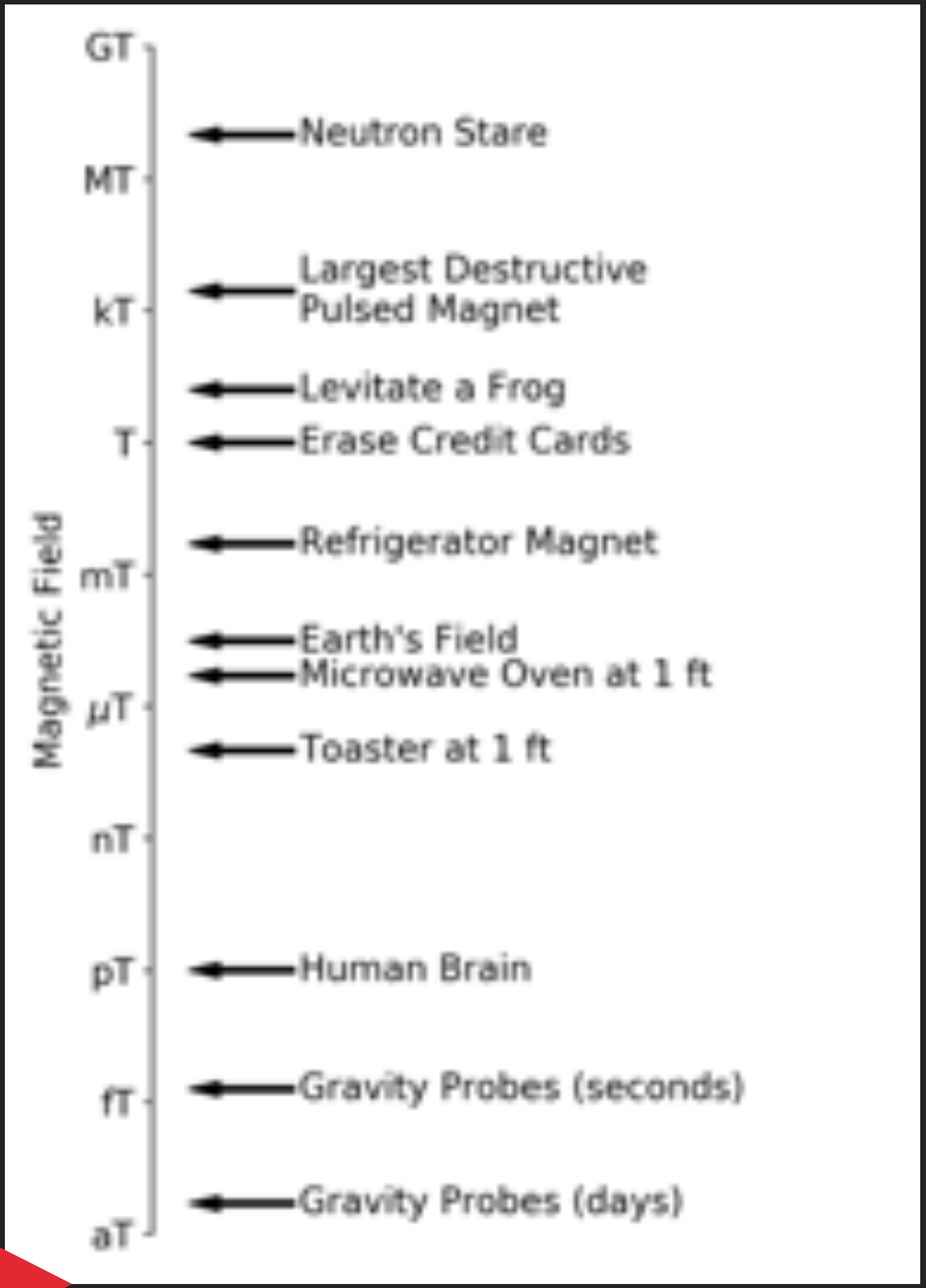
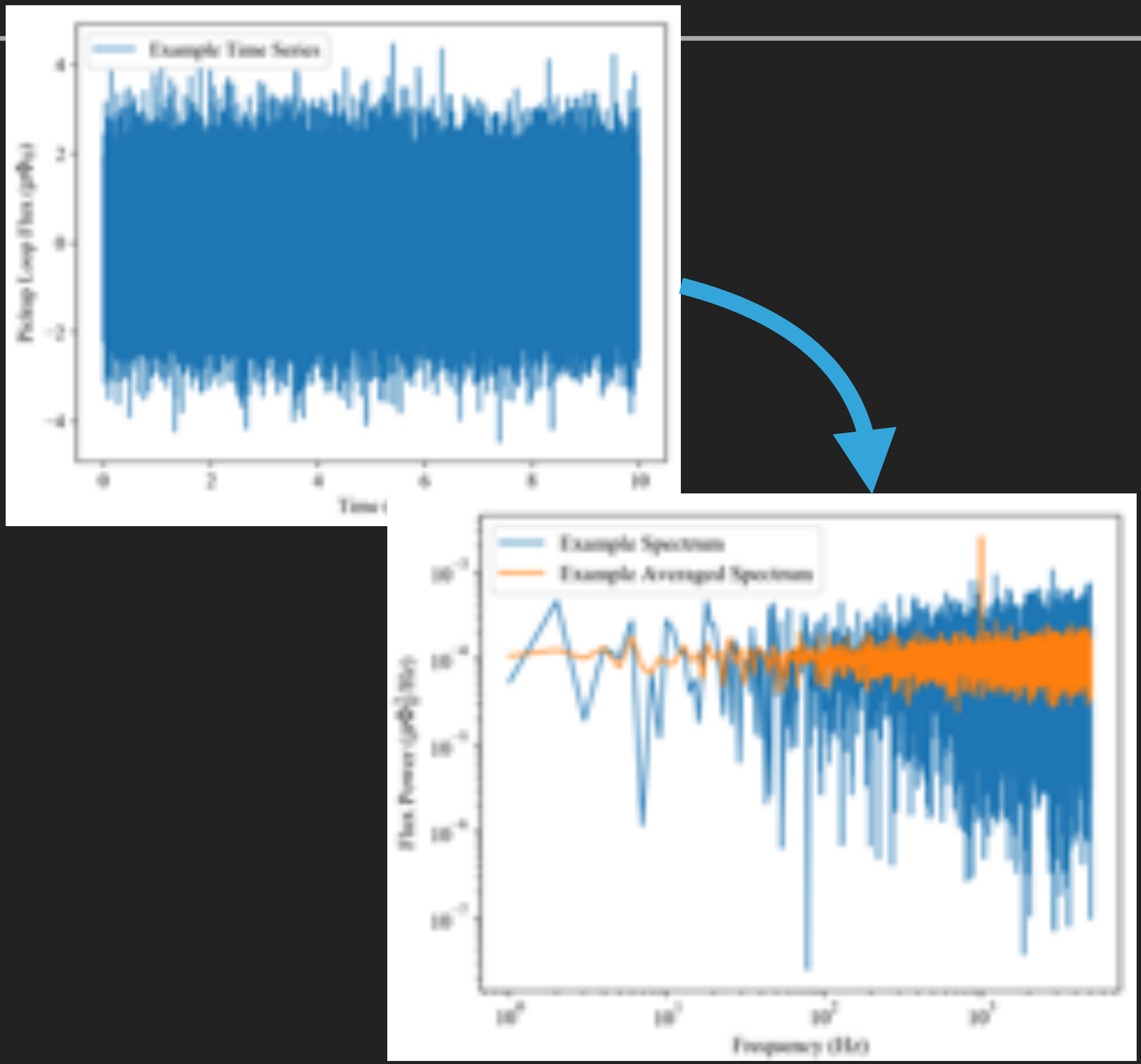
➡ $B_a \sim 5\times10^{-22}$ T

- Will require *extremely* sensitive *quantum limited* field sensors!



Axions in Power Spectra

- Collect continuous time series data and Fourier transform into frequency space
- Average over many time periods to beat down the noise

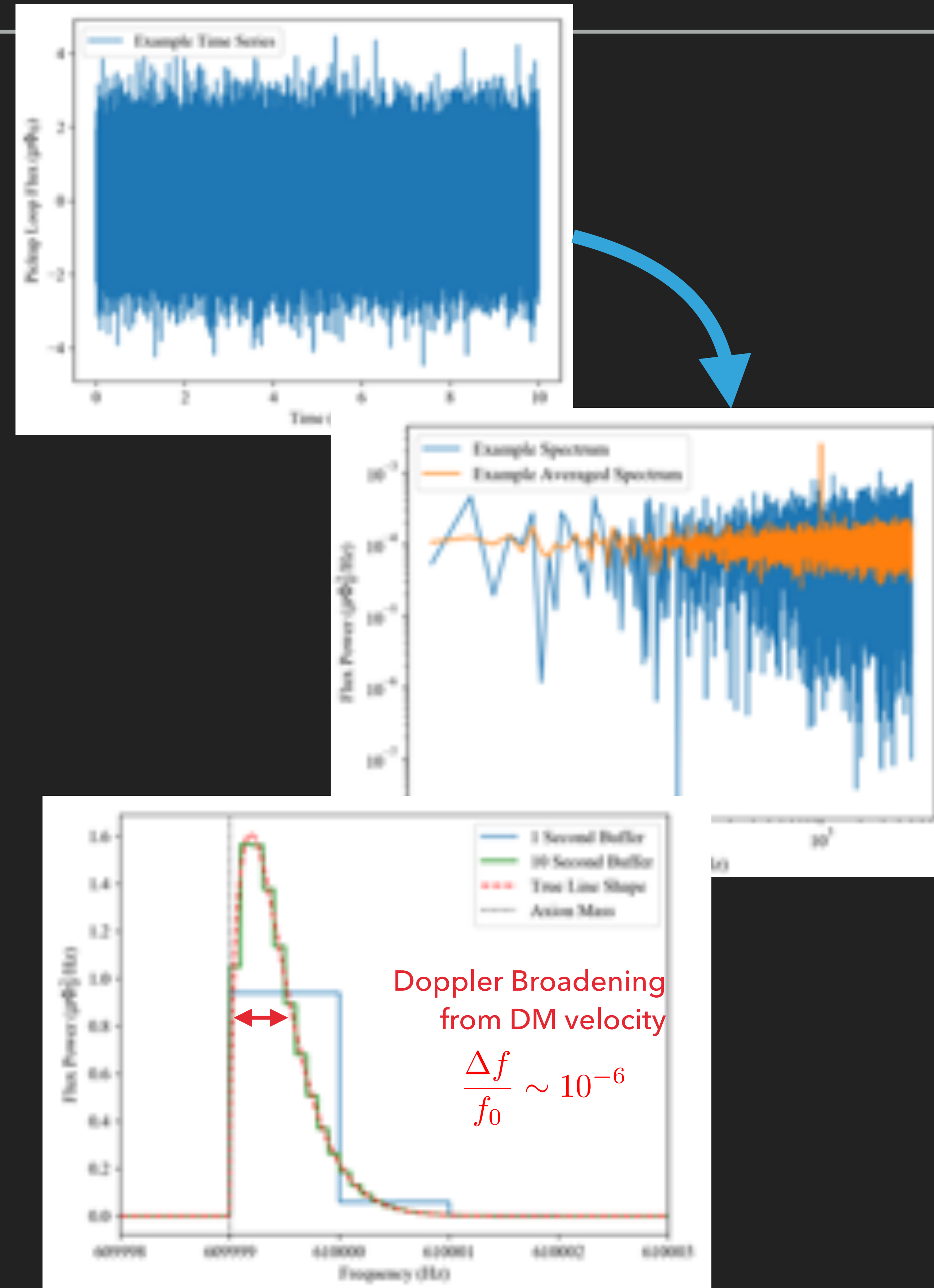


Doppler Broadening from DM velocity

$$\frac{\Delta f}{f_0} \sim 10^{-6}$$

Axions in Power Spectra

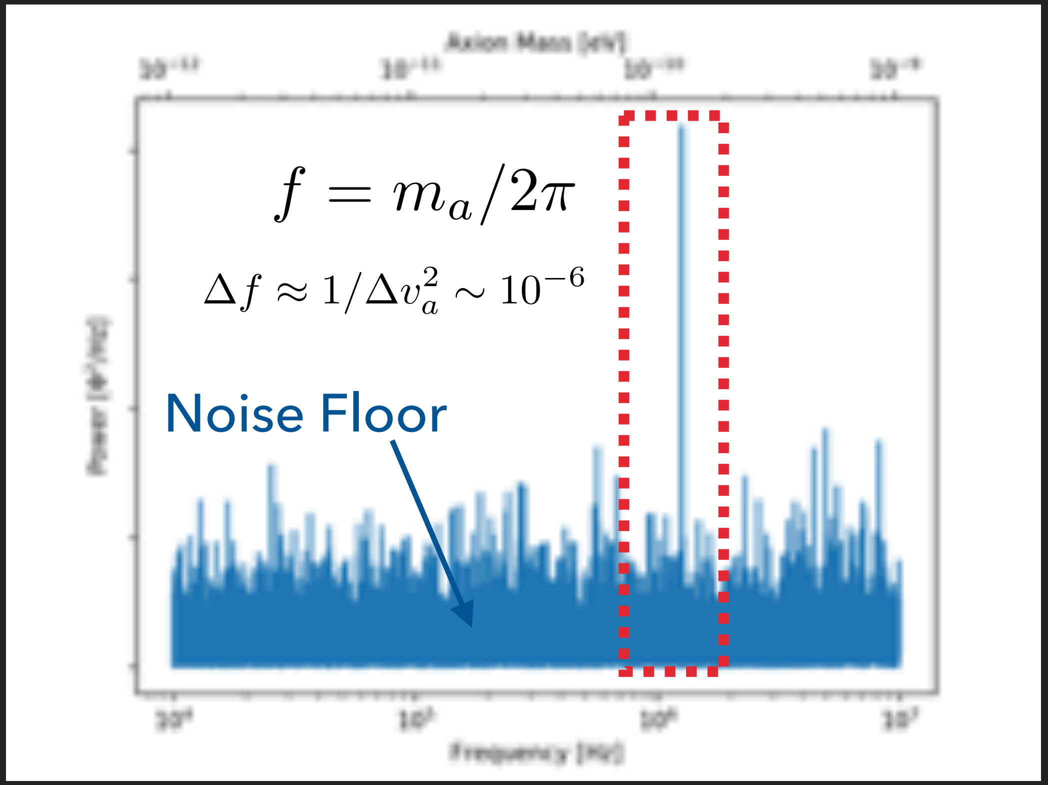
- Collect continuous time series data and Fourier transform into frequency space
- Average over many time periods to beat down the noise
- Highest useful frequency set by Nyquist frequency
- Lowest useful frequency set by ability to resolve the axion line (equal to 1/buffer time)



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

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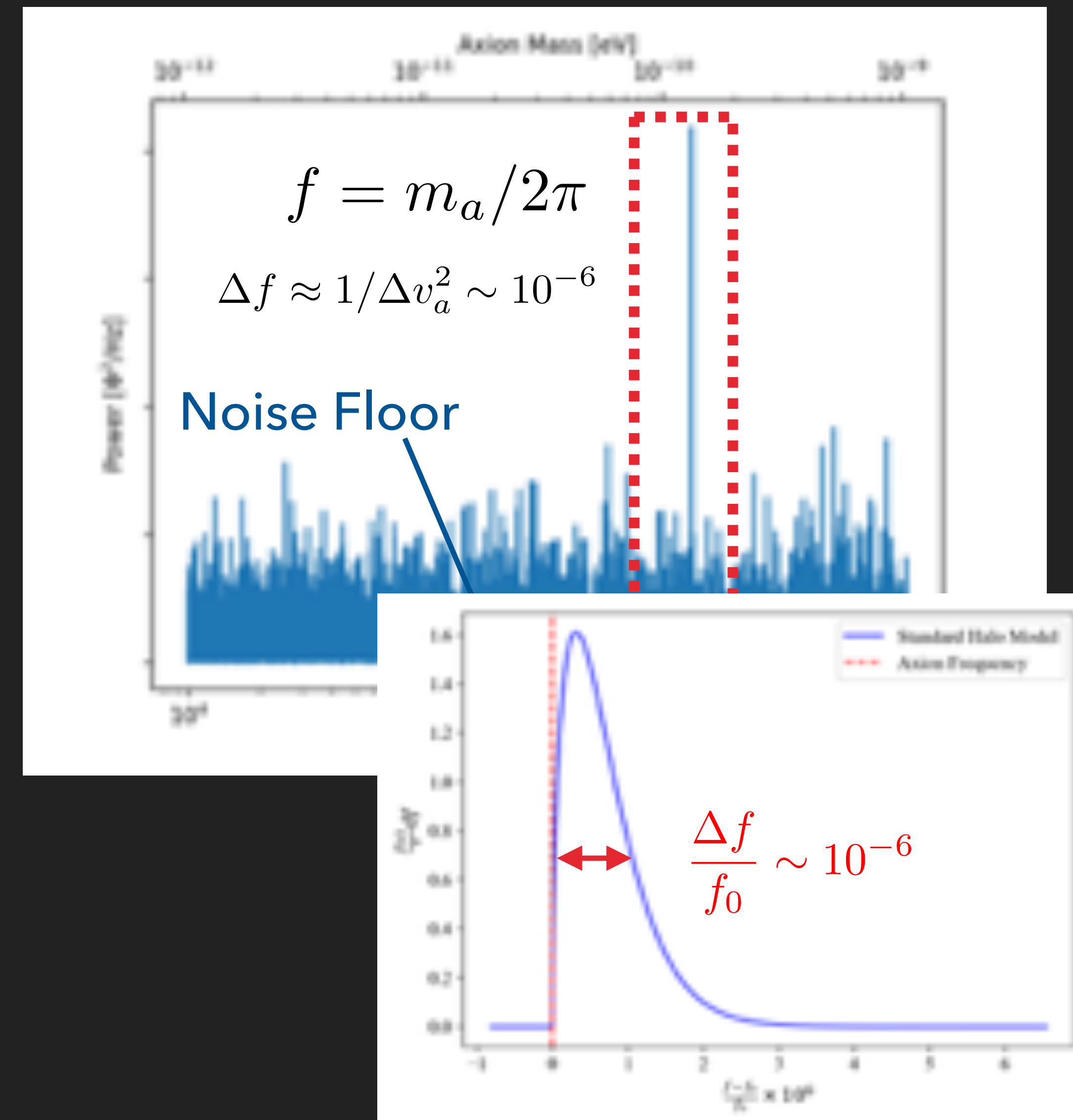
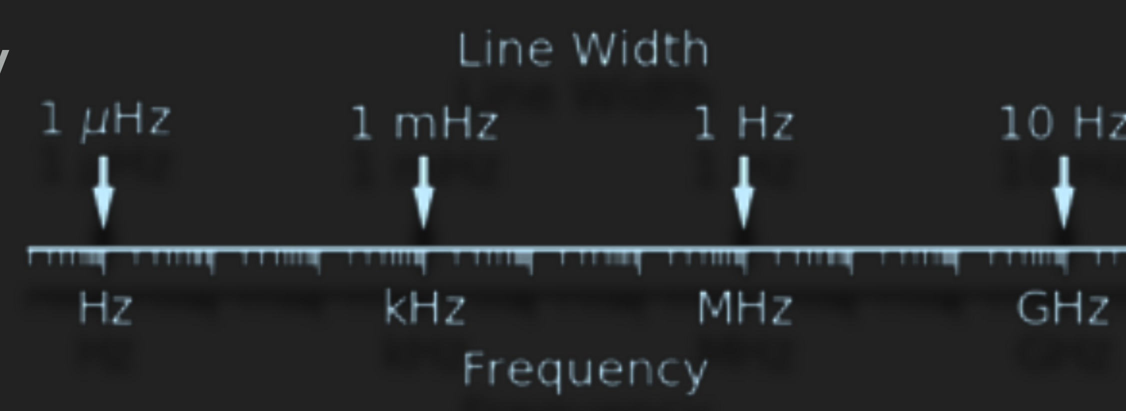
$$g_{a\gamma\gamma}\sqrt{2\rho_{\mathrm{DM}}}V\mathcal{G}_V B_{\max} \ll |n|$$

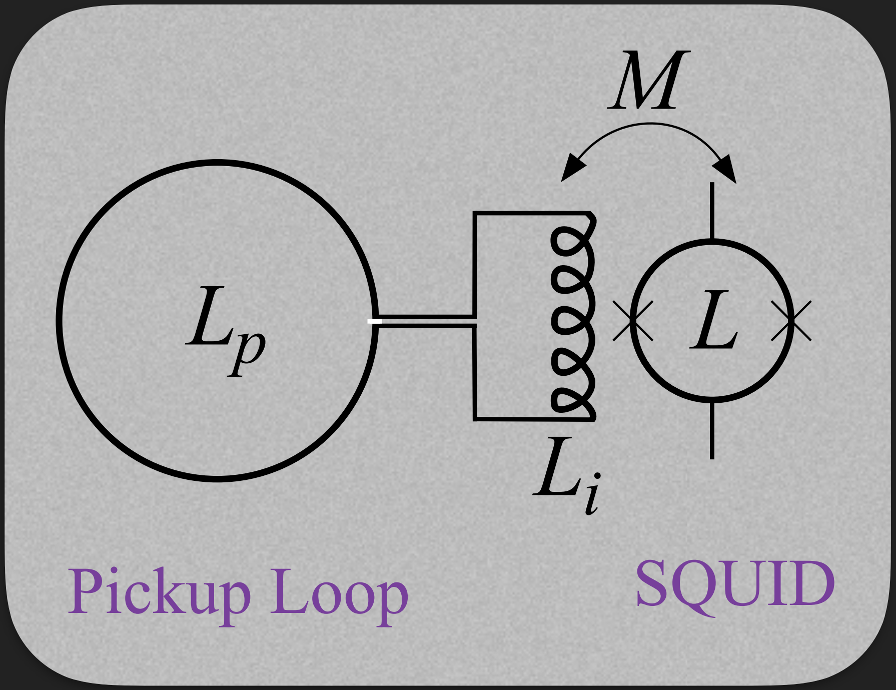


- Option A: Measure and Average
  - Can search all frequencies simultaneously
  - Averaging is *really* slow
- Option B: Lock in and amplify one frequency
  - Can quickly pull signal from noise
  - Don't know what frequency to amplify!



ABRACADABRA Broadband Readout

- ABRACADABRA will require very sensitive current detectors → SQUID current sensors
  - The pickup loop is coupled directly into the SQUID input and all frequencies are acquired equally
  - Able to search all frequencies simultaneously
  - The noise floor is set by the flux noise in the SQUID

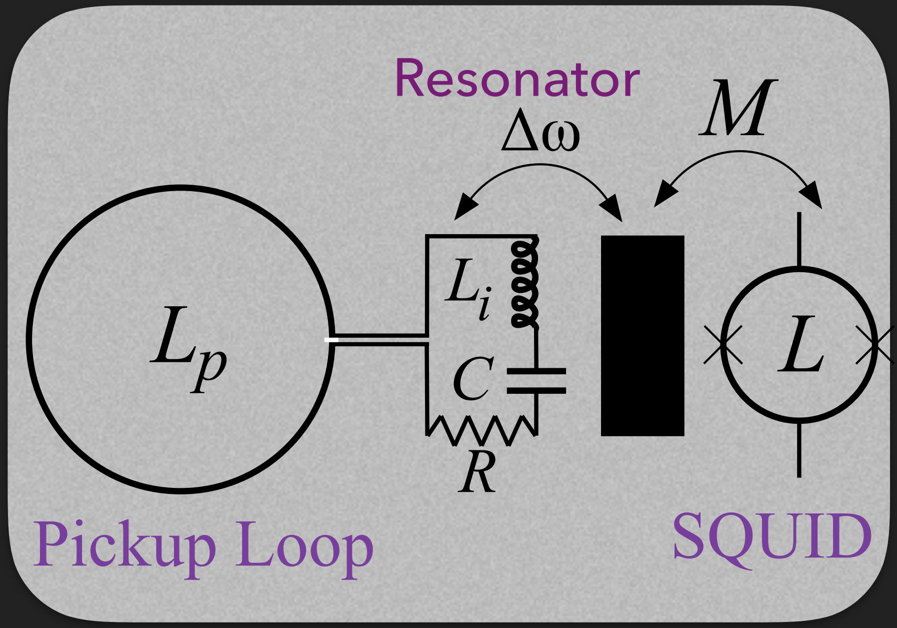


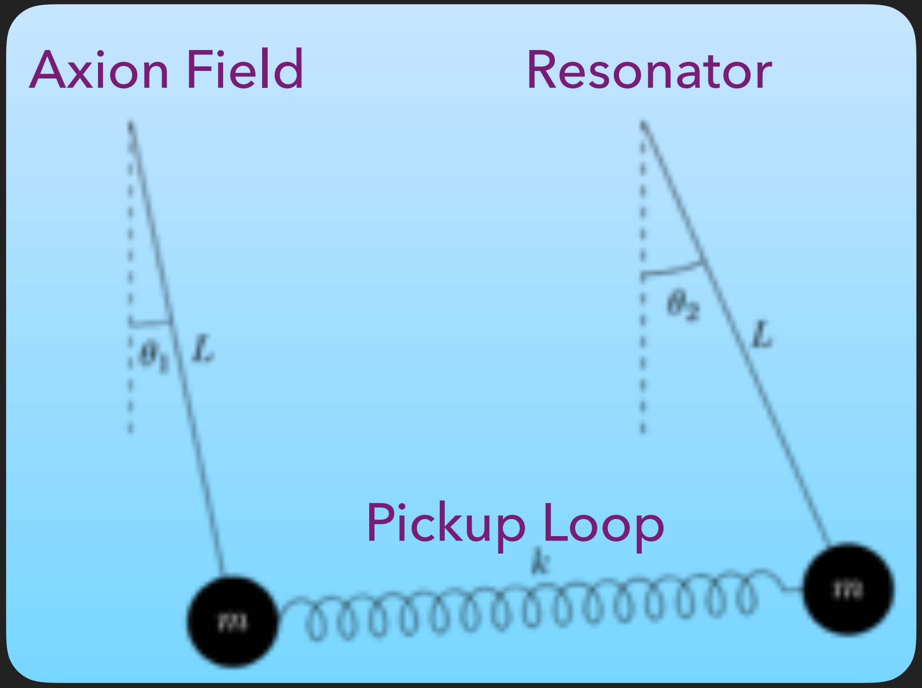
ABRACADABRA Resonant Readout

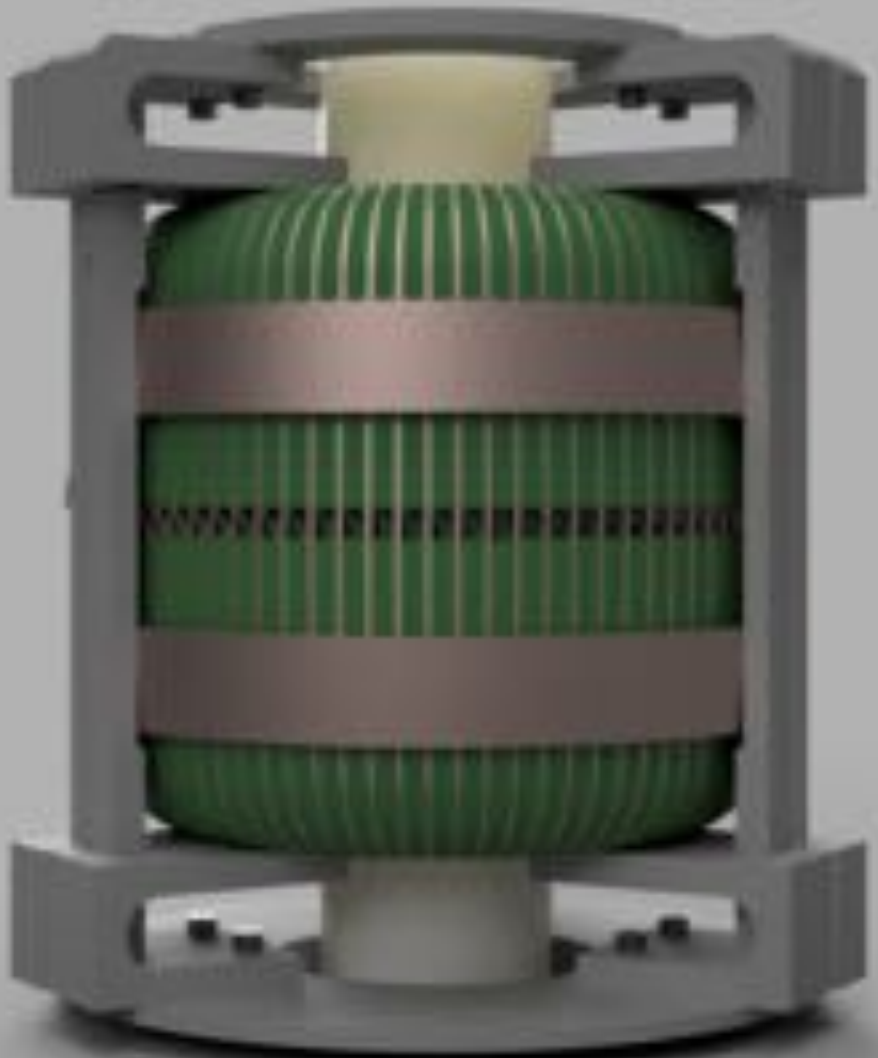
- Insert a resonator into the circuit that resonantly enhances the signal before the SQUID noise is introduced
  - Resonator is charged when driven on resonance by the axion field
  - Pickup loop acts as a weak coupling between axion field and resonator
  - Power flowing into our resonator is tiny, so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

➡ High Q resonator

➡ The need to scan (and scan quickly)



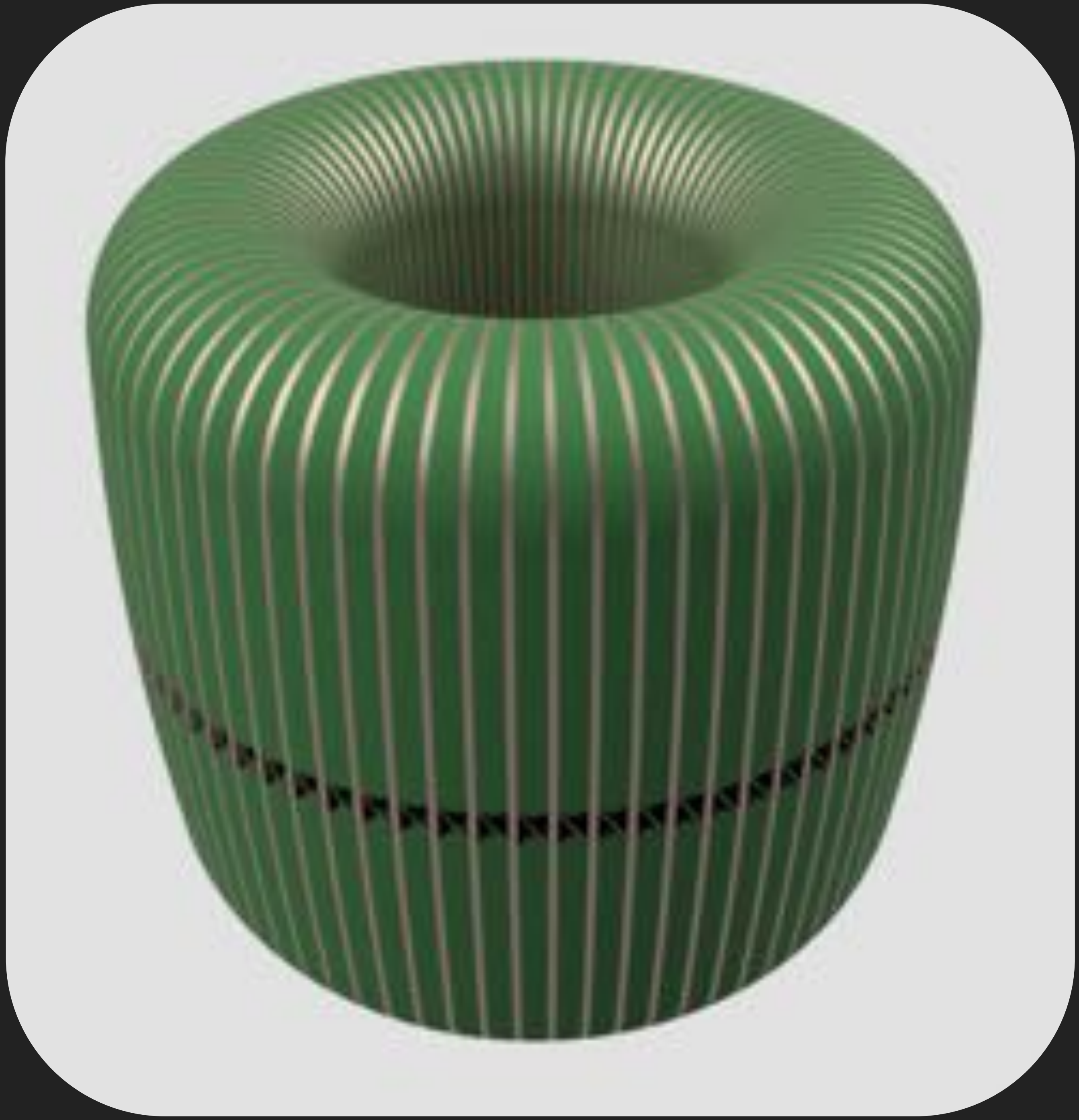




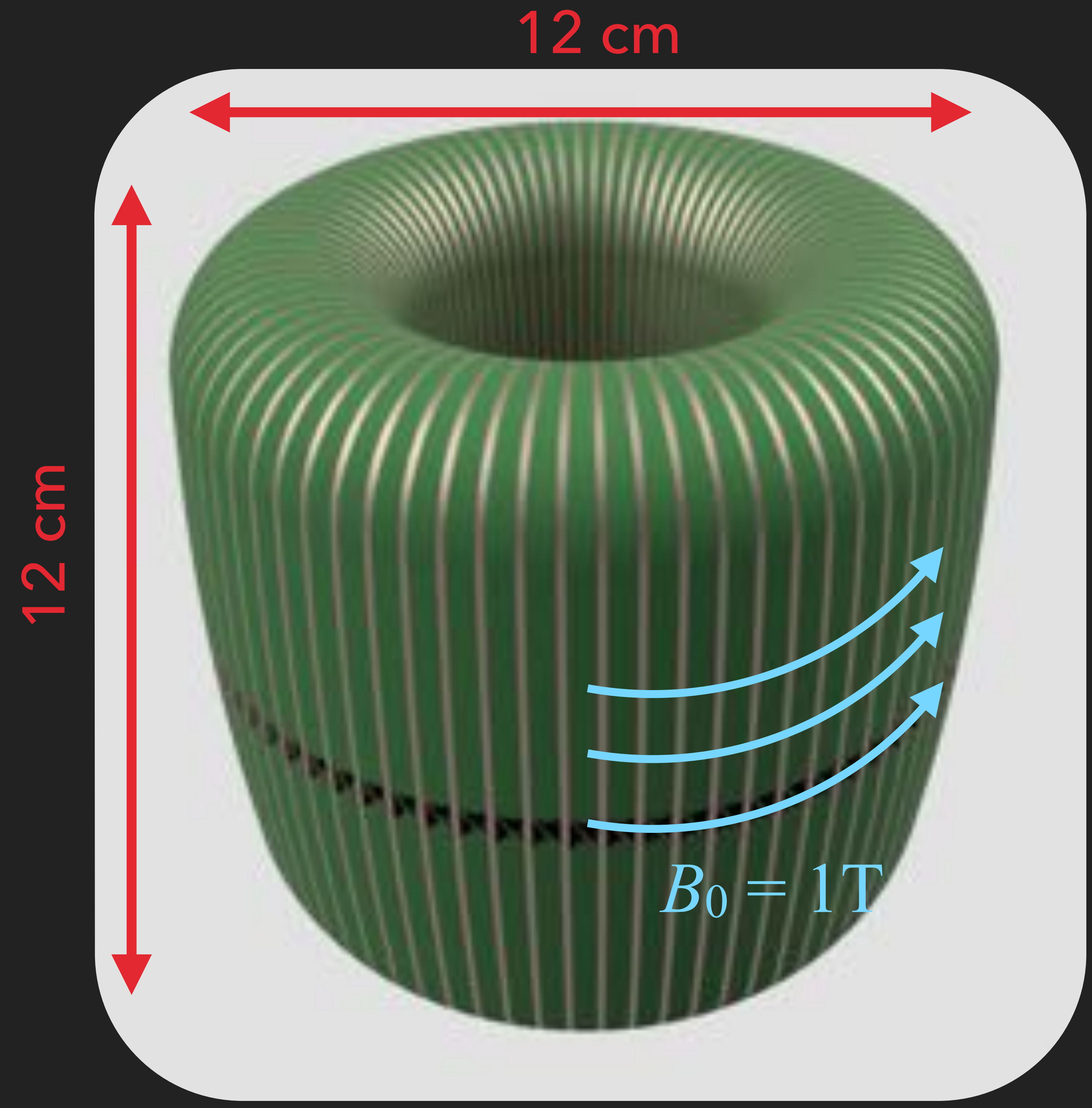
A PROTOTYPE DETECTOR

ABRACADABRA-10CM

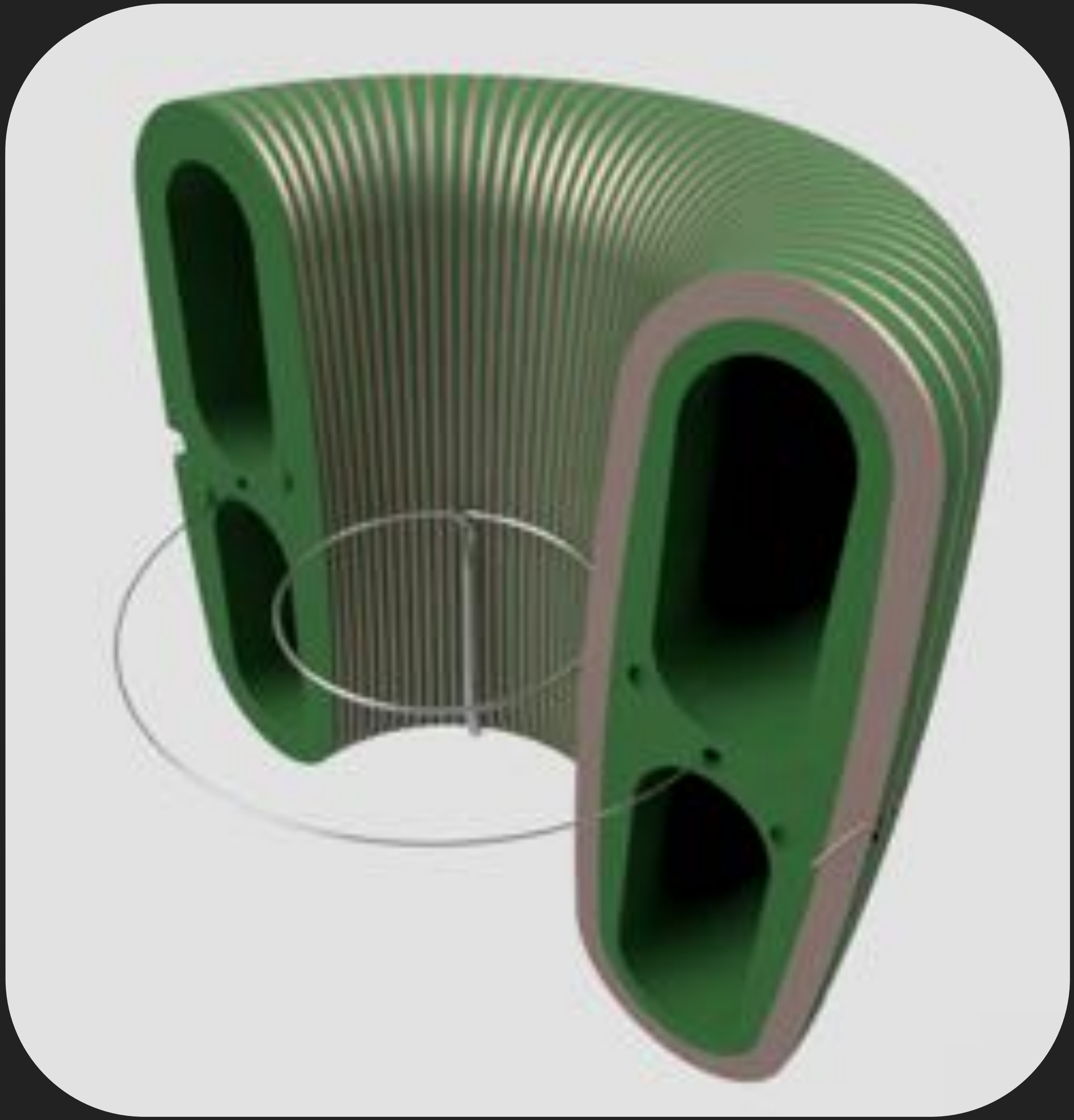
Dissecting ABRACADABRA-10 cm



Dissecting ABRACADABRA-10 cm

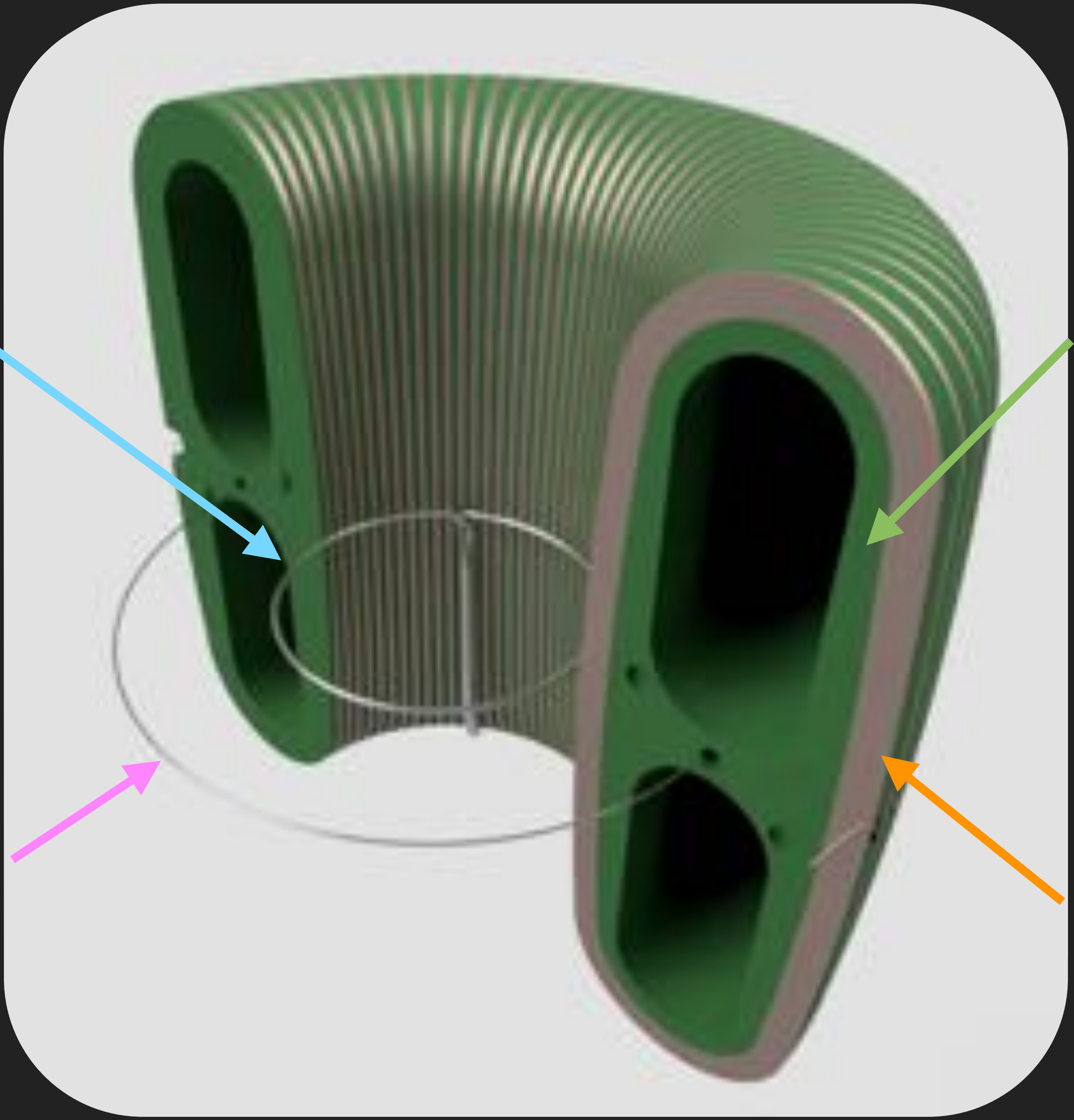


Dissecting ABRACADABRA-10 cm



Dissecting ABRACADABRA-10 cm

Superconducting Pickup Loop
$r_p = 2$ cm

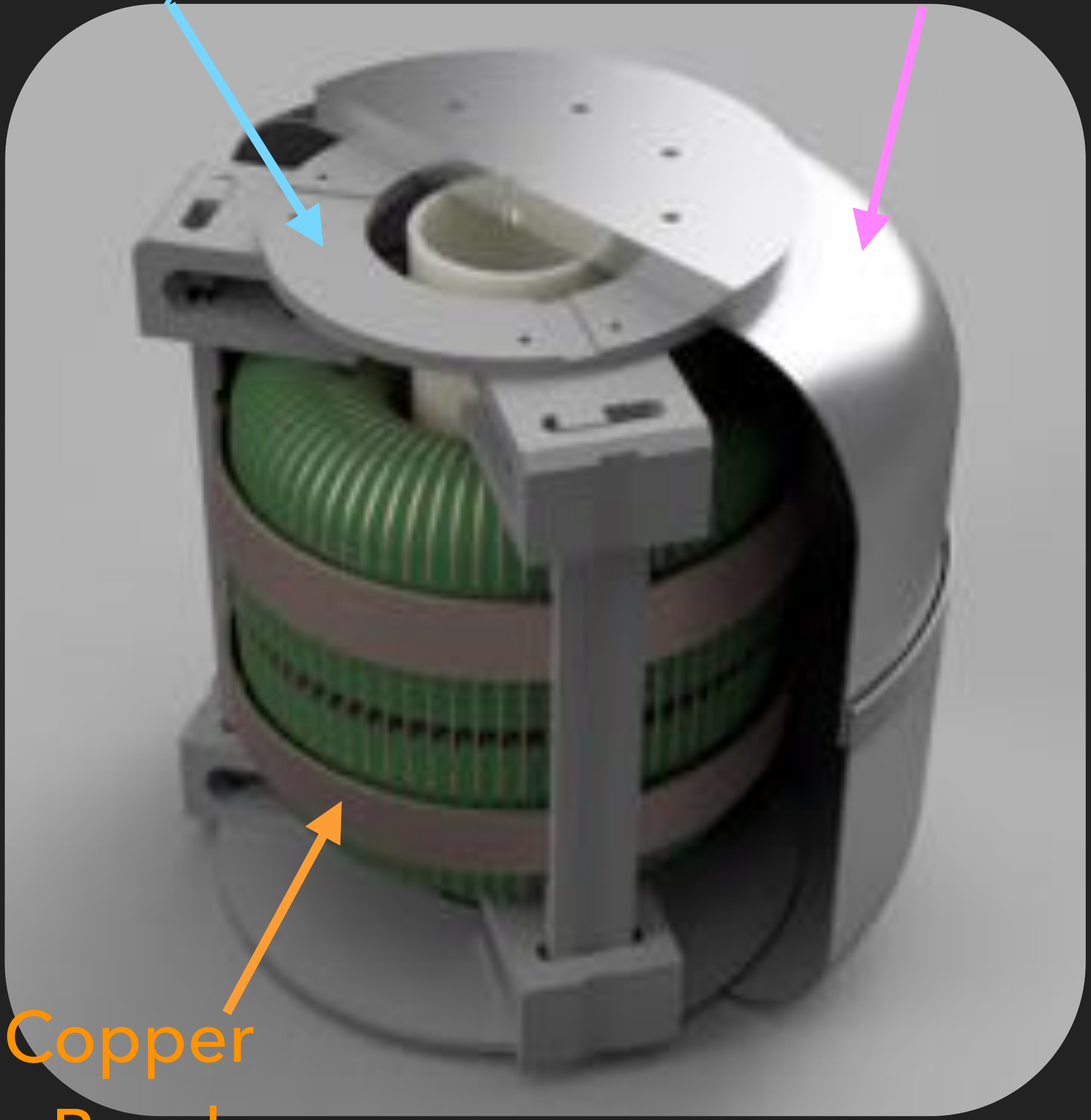


Delrin Toroid Body

Superconducting Calibration Loop
$r_c = 4.5$ cm

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

Dissecting ABRACADABRA-10 cm

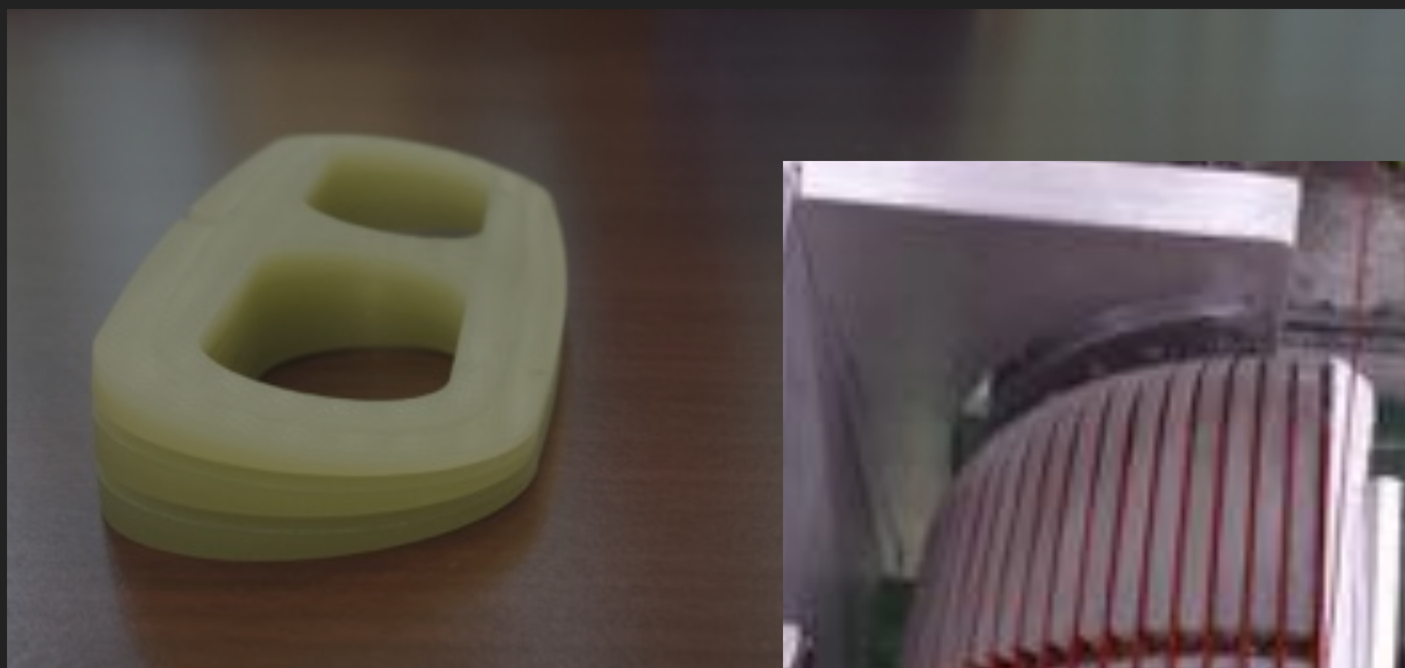


Assembling ABRACADABRA-10 cm

SUPERCONDUCTING SYSTEMS INC.

(Normally make MRI magnets!)

Assembling ABRACADABRA-10 cm



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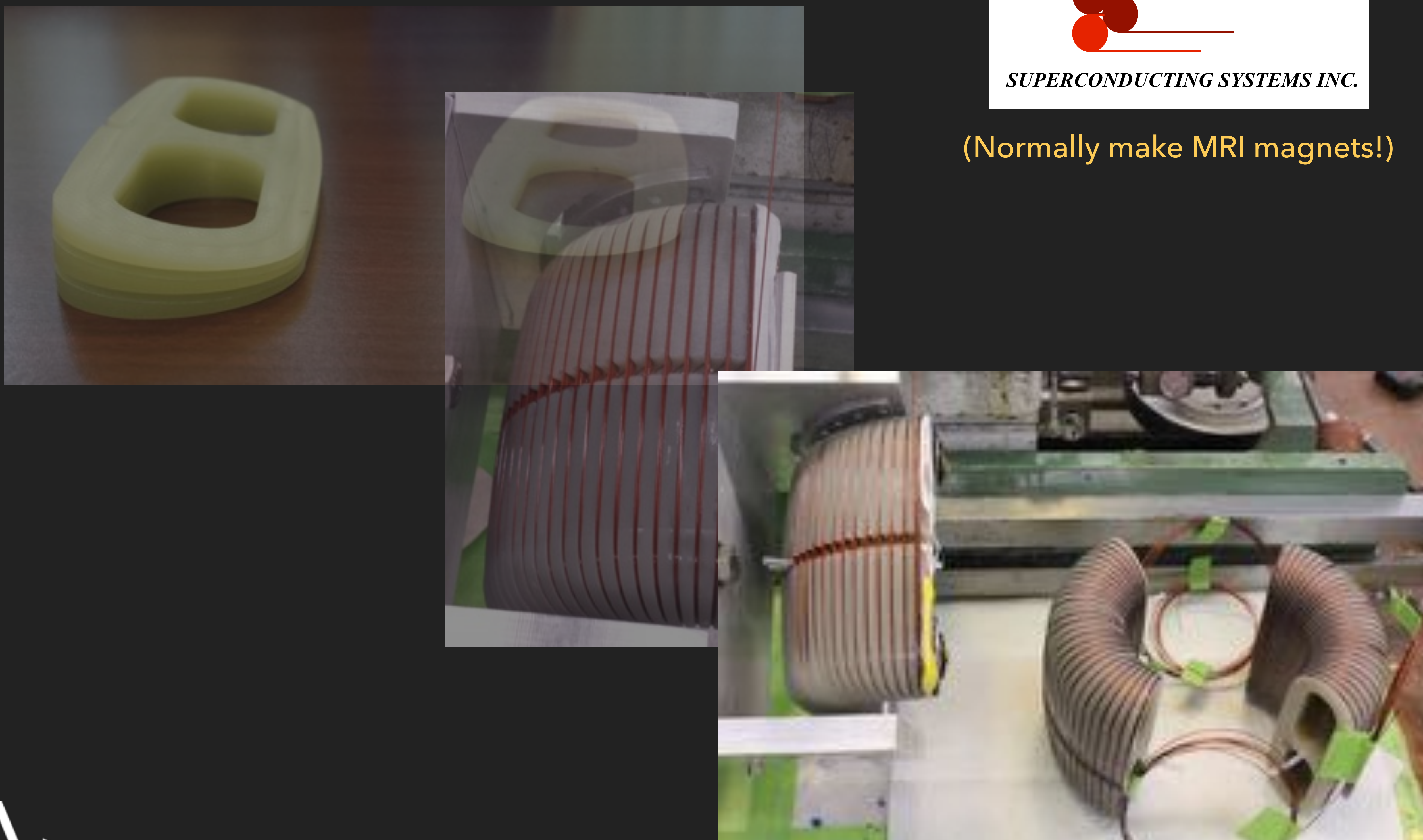

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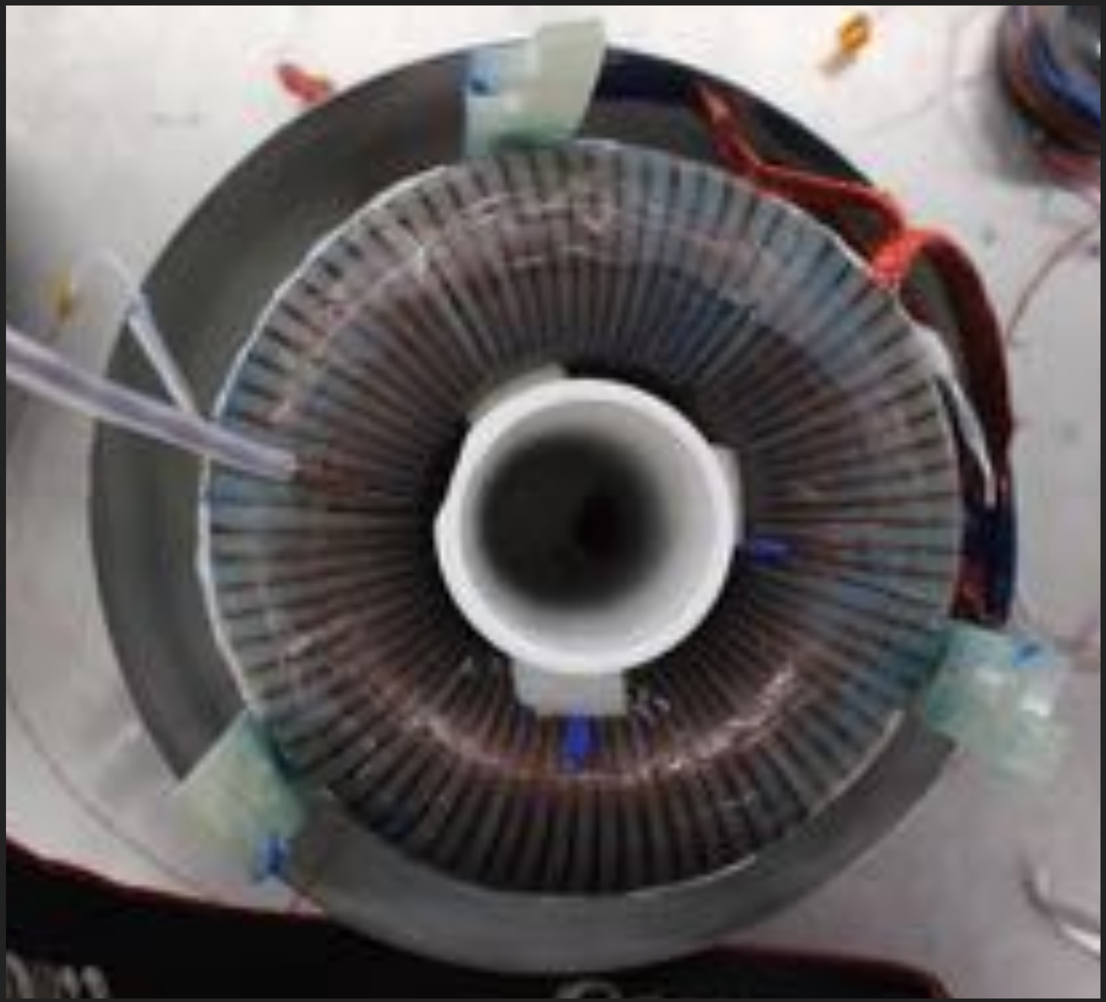
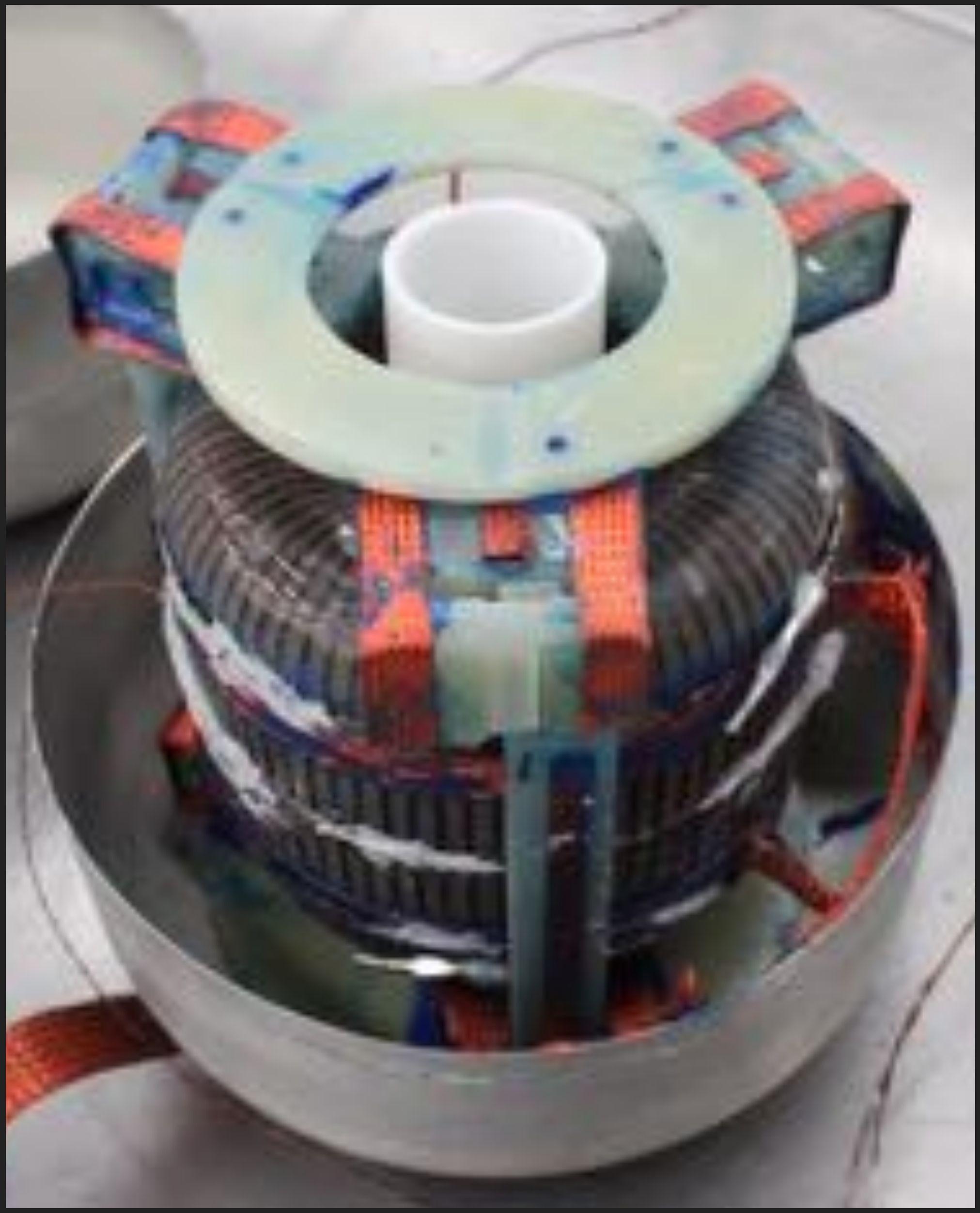
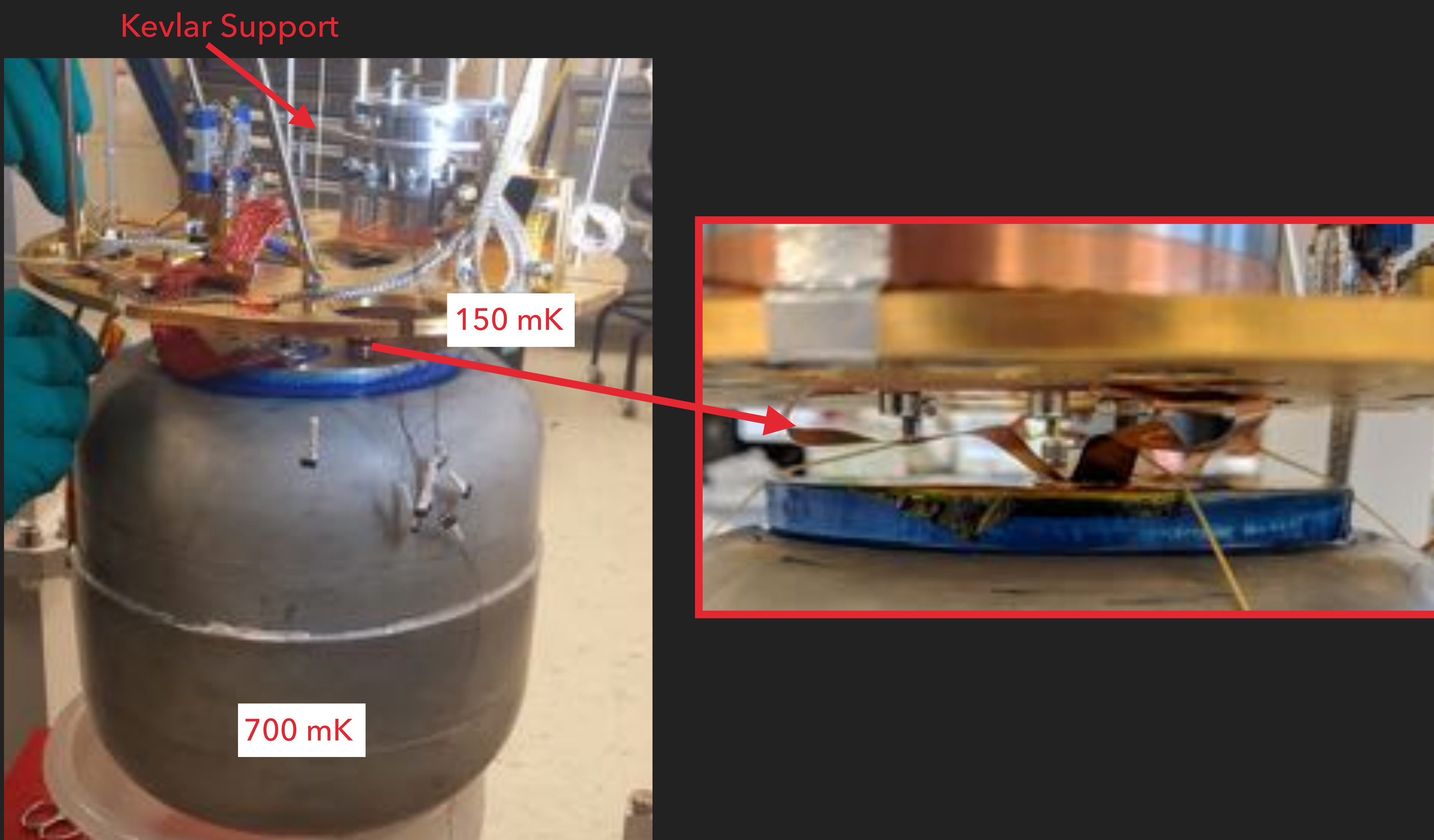




ABRA Mounted In Olaf



SQUID Readouts

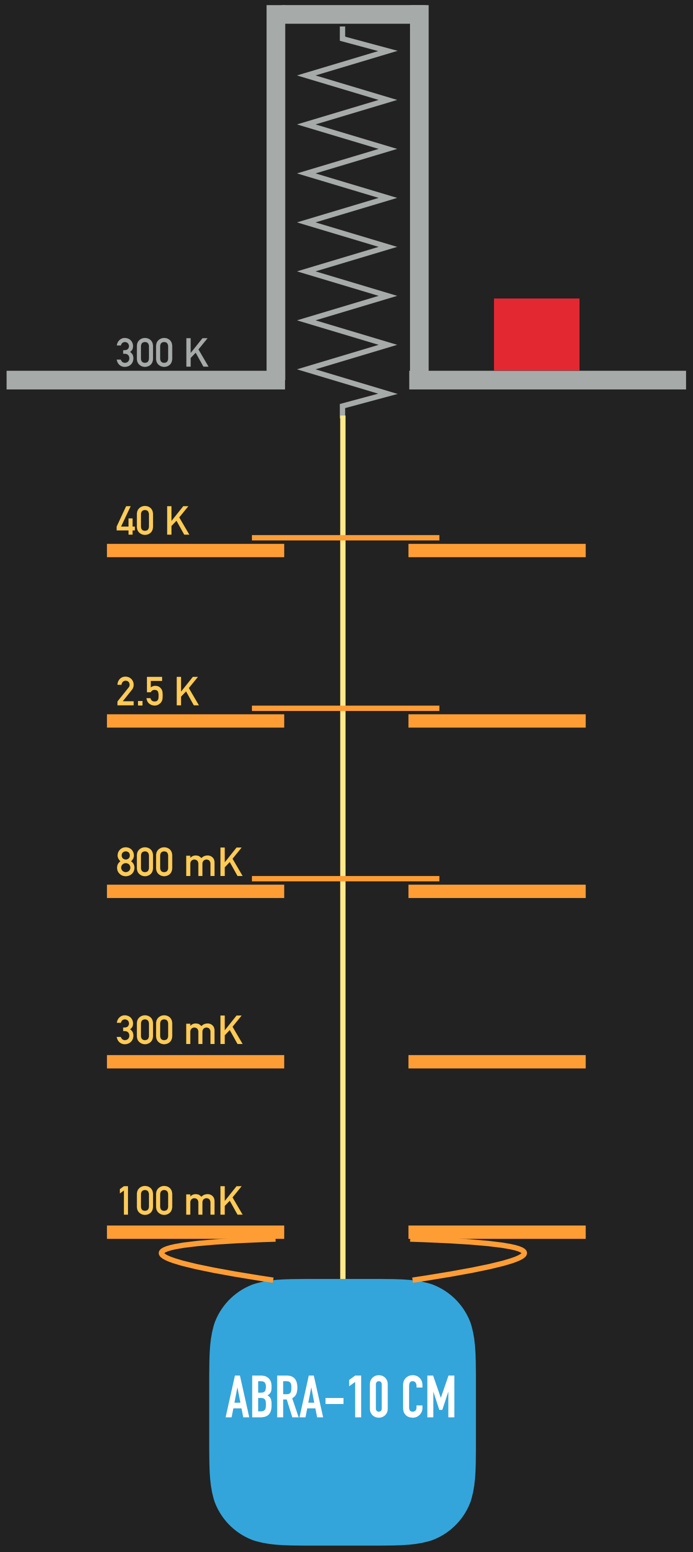
- Off the shelf Magnicon DC SQUIDs
  - Typical noise floor ~1 $\mu\Phi_0/(\mathrm{Hz})^{1/2}$
  - Optimized for operation < 1 K
  - Typical gain of ~1.3 V/Φ_0^S (volts per SQUID flux quanta)
- No resonator (i.e. broadband readout)

Quick note on units:

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

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

Suspension System



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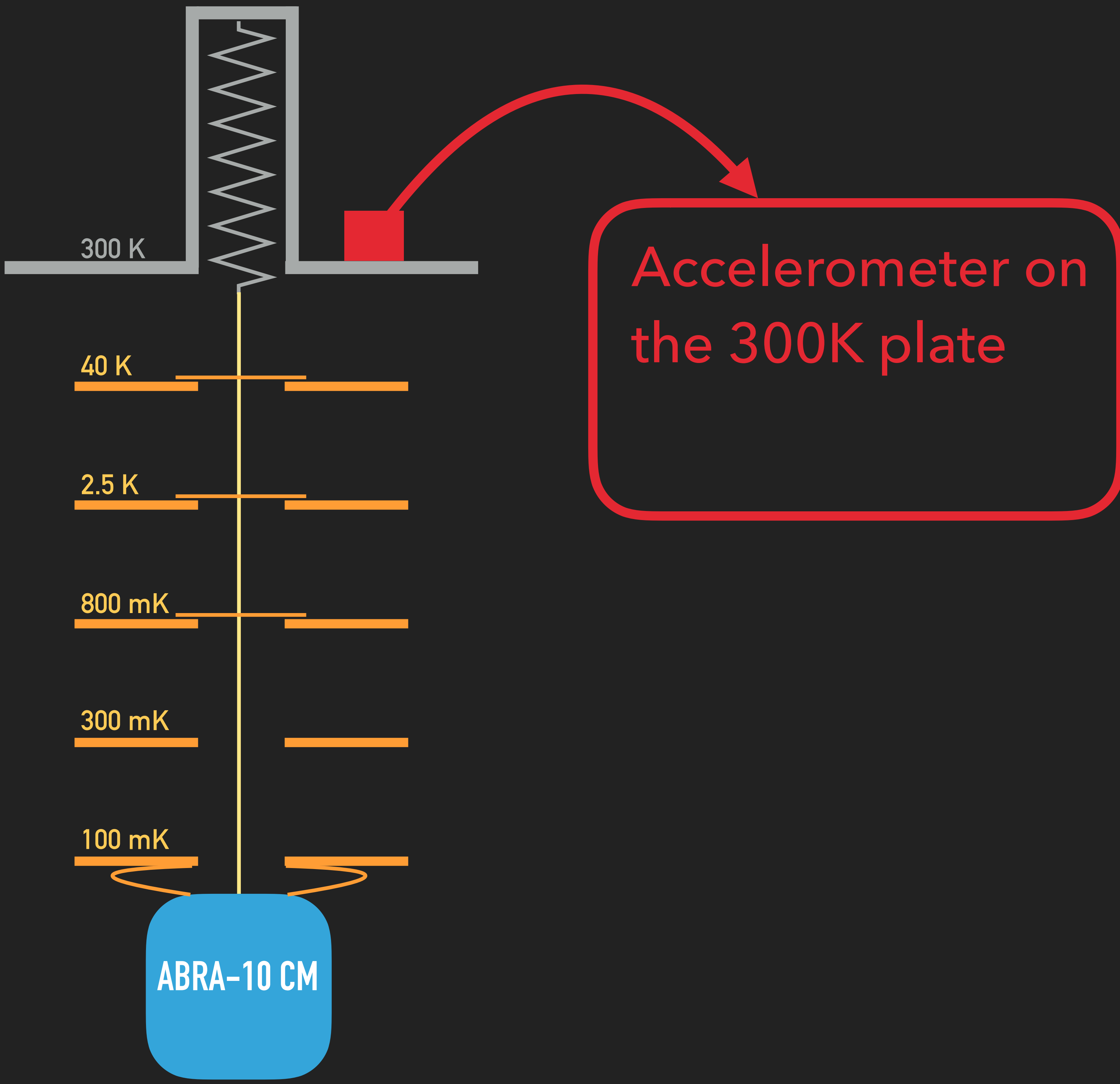

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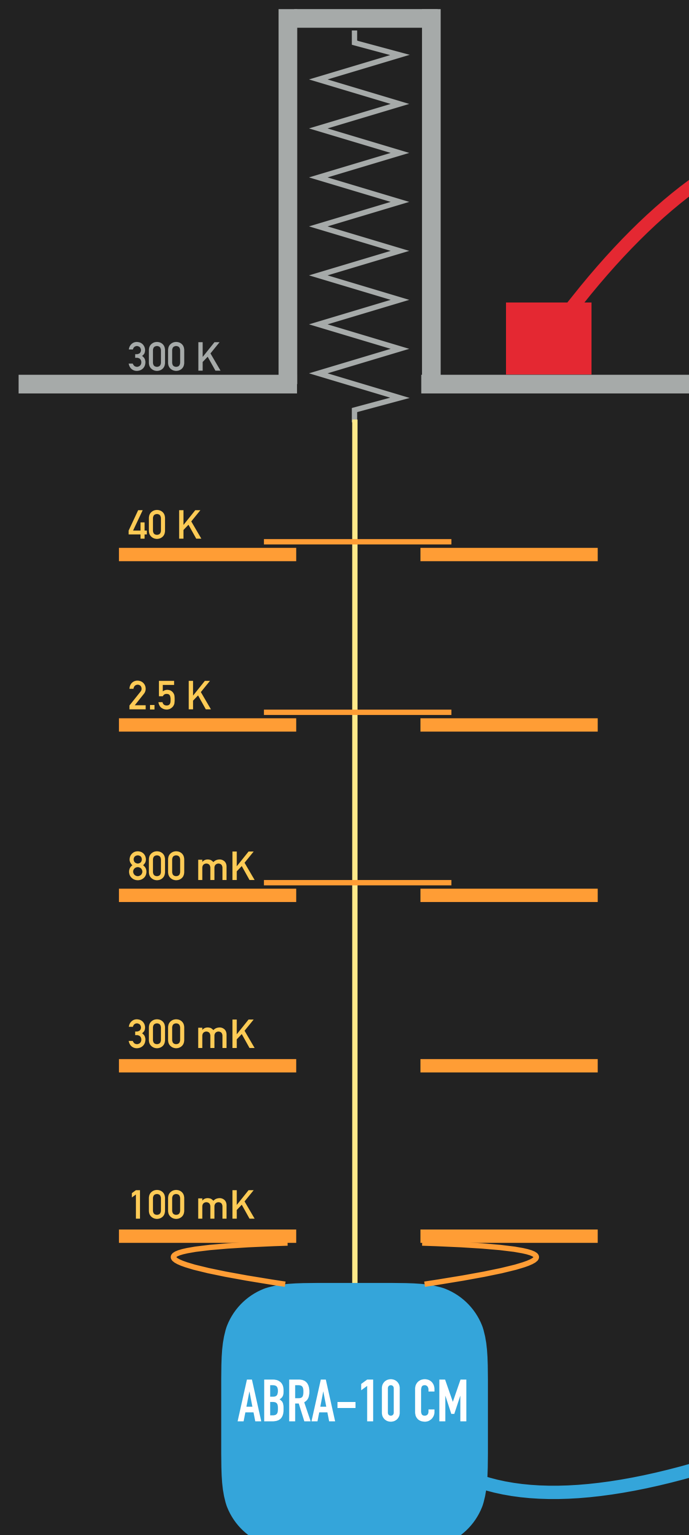
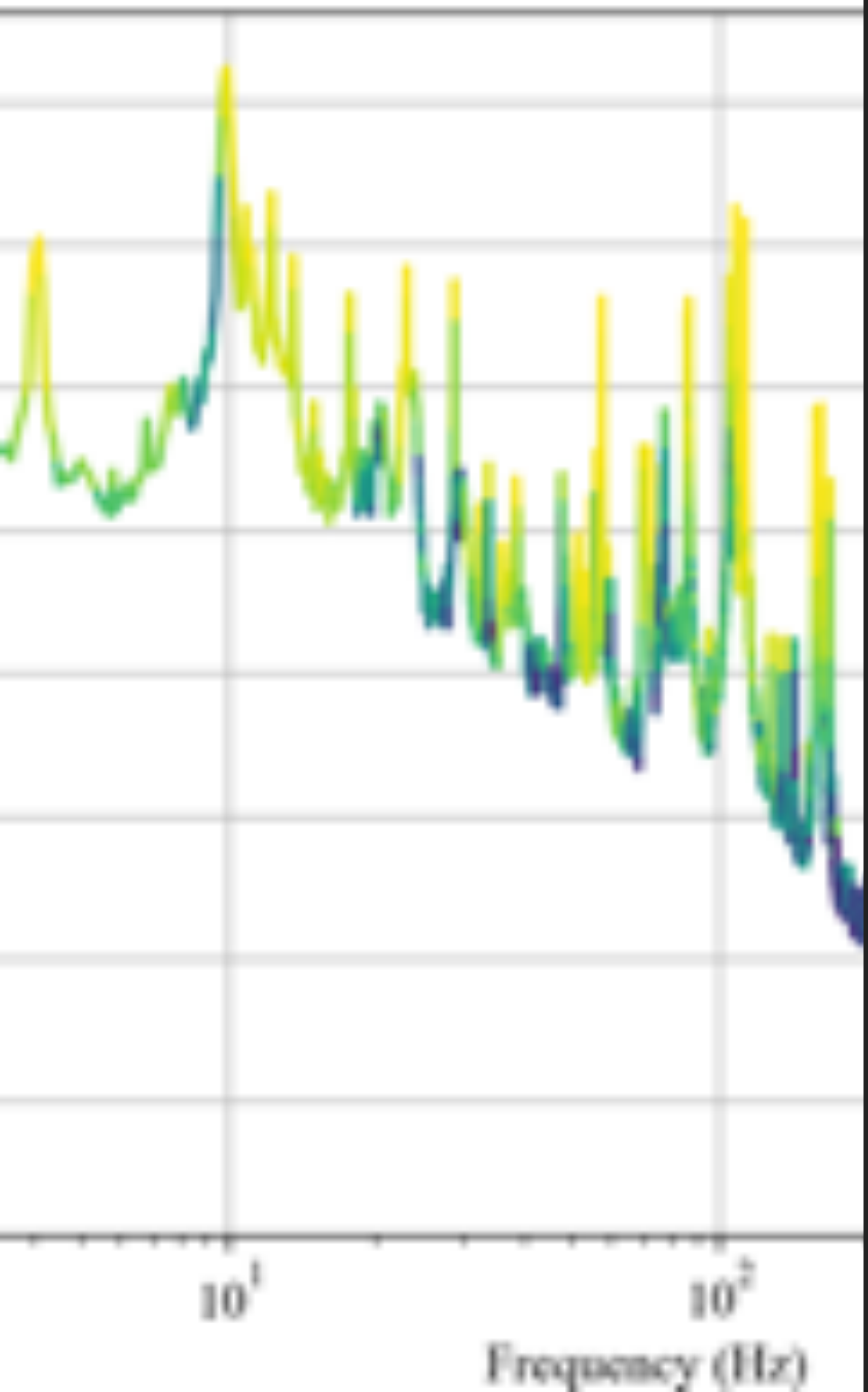


Accelerometer on the 300K plate

Flux through the ABRA pickup loop

Magnetic Shielding

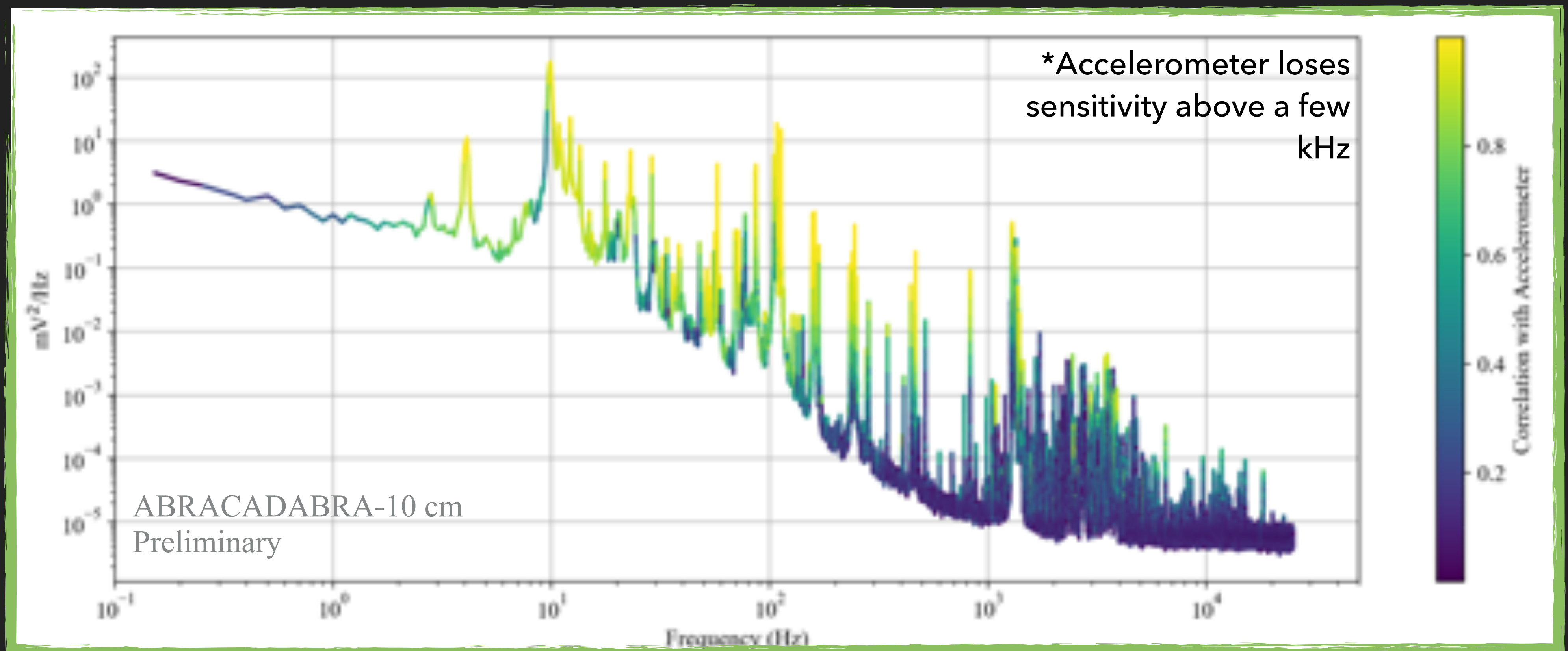
- Two layers of mu-metal shielding
- Recycled from the Bates Accelerator Pipe
- DC Attenuation ~ 10x



ABRACADABRA-10 CM

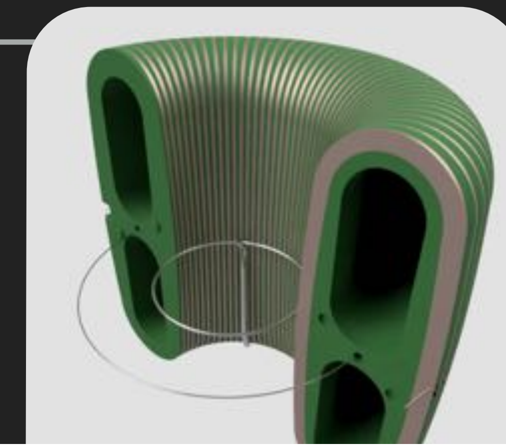
COMMISSIONING AND DATA TAKING

Vibrational Noise (Magnet On)

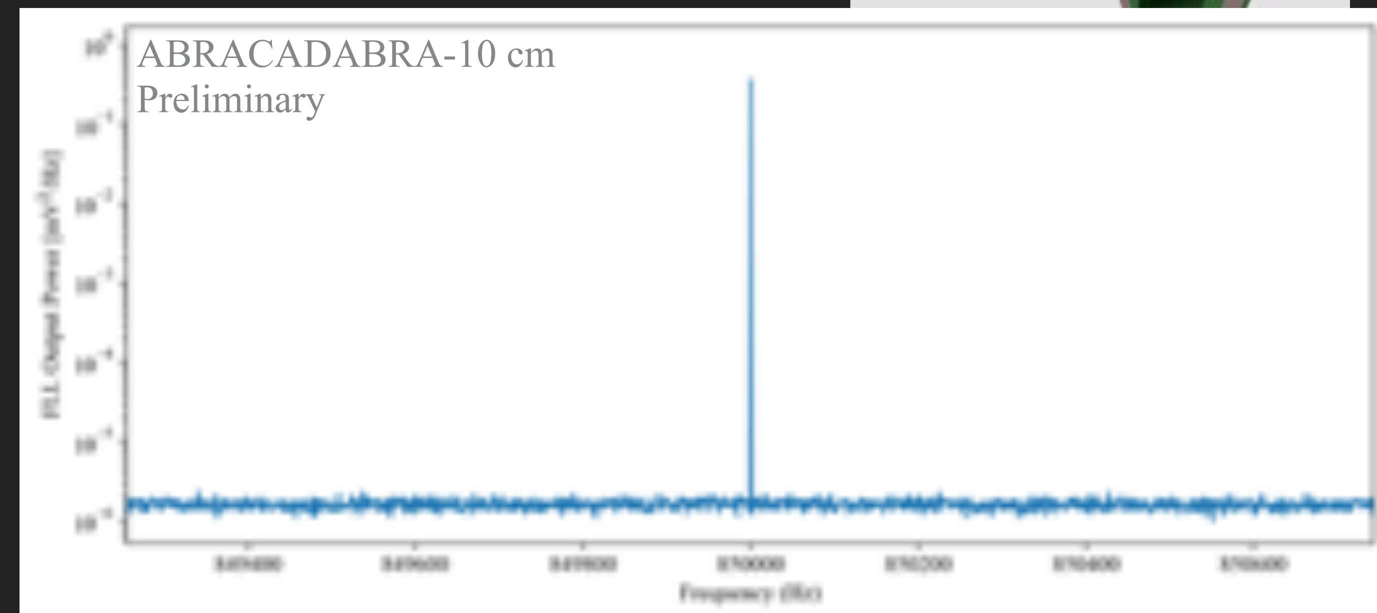


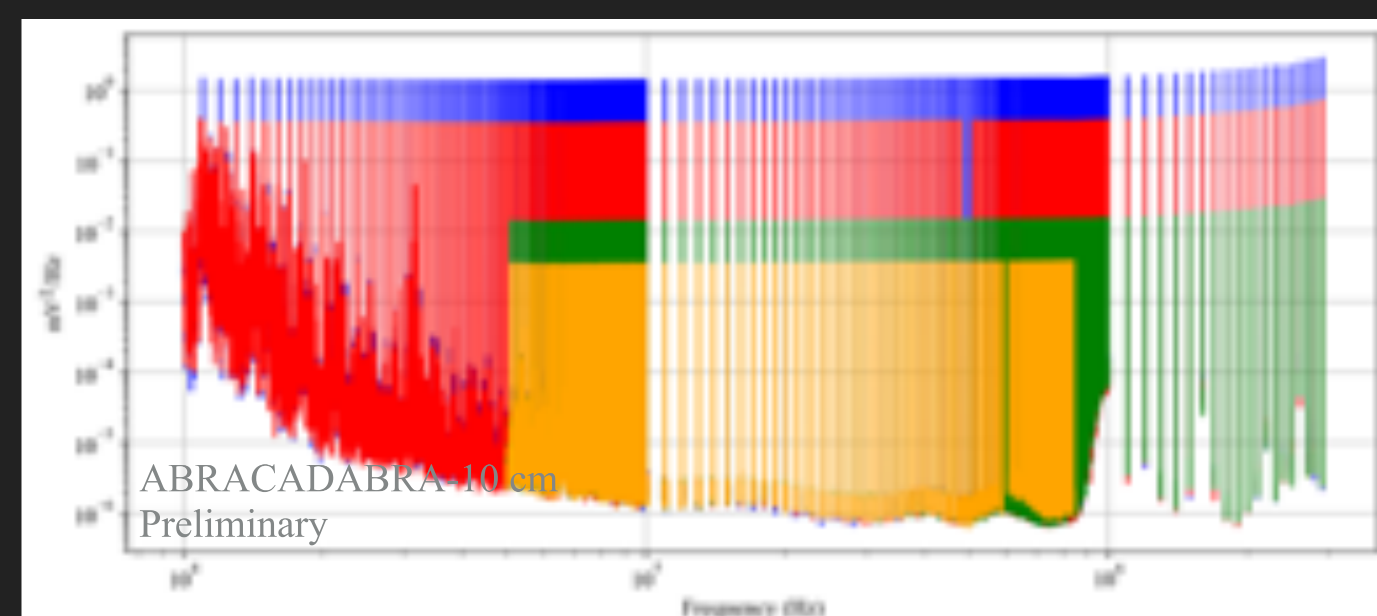
- Huge amount of noise below ~10 kHz, strongly correlated with vibration on the 300K plate
- Had to use a 10kHz high pass filter to get the data to fit in the digitizer window
- Hard limit on the low end search window

Calibration

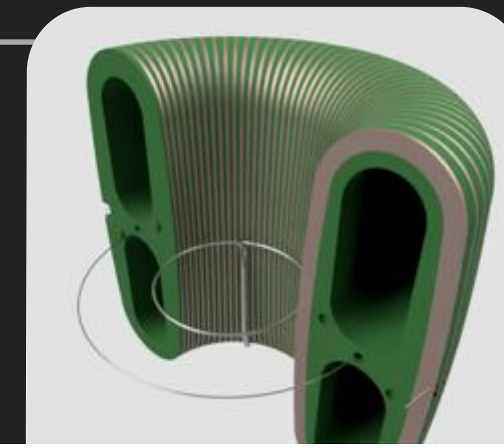


- Perform calibration by injecting current into the calibration loop measuring the spectrum
- Fine scan from 10 kHz - 3 MHz at multiple amplitudes
- Requires a total of ~90 dB of attenuation to get "reasonable" size signals
- Gain lower than expected by a factor of ~6.5 (suspect parasitic inductance)





Calibration



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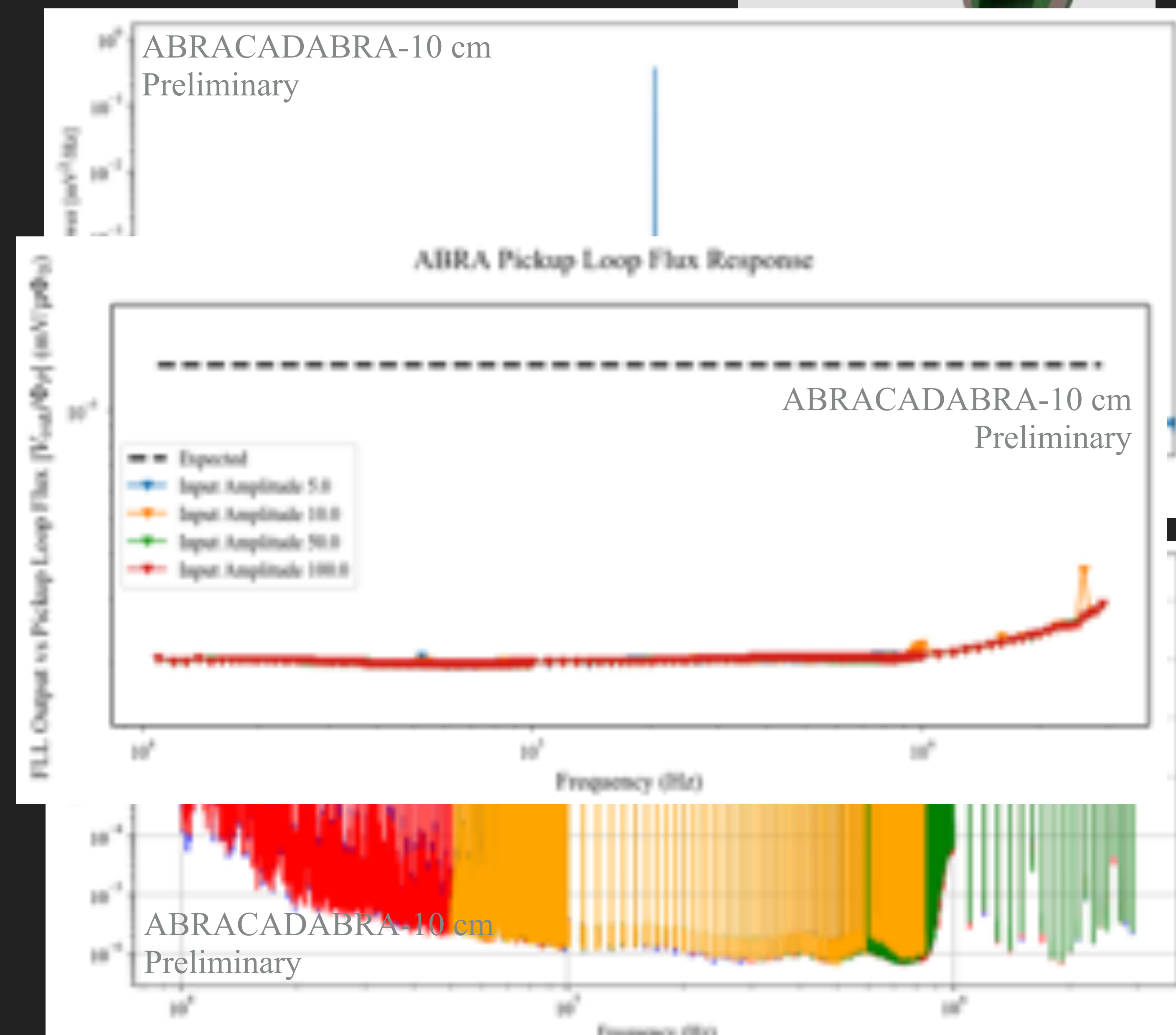
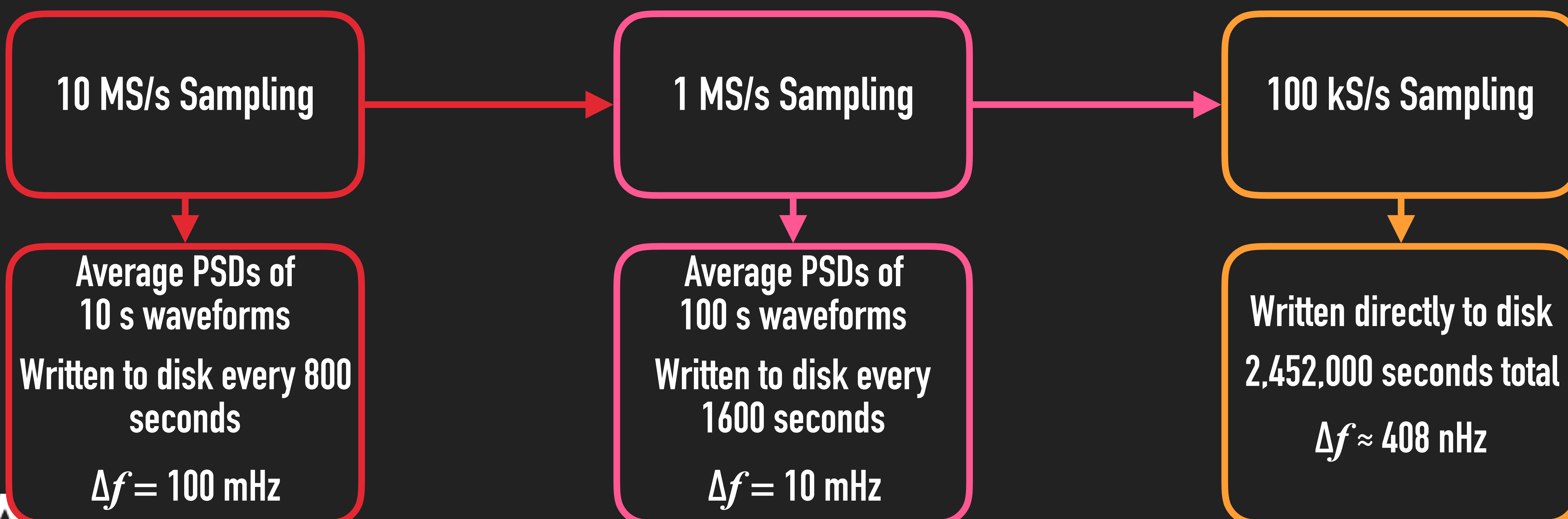


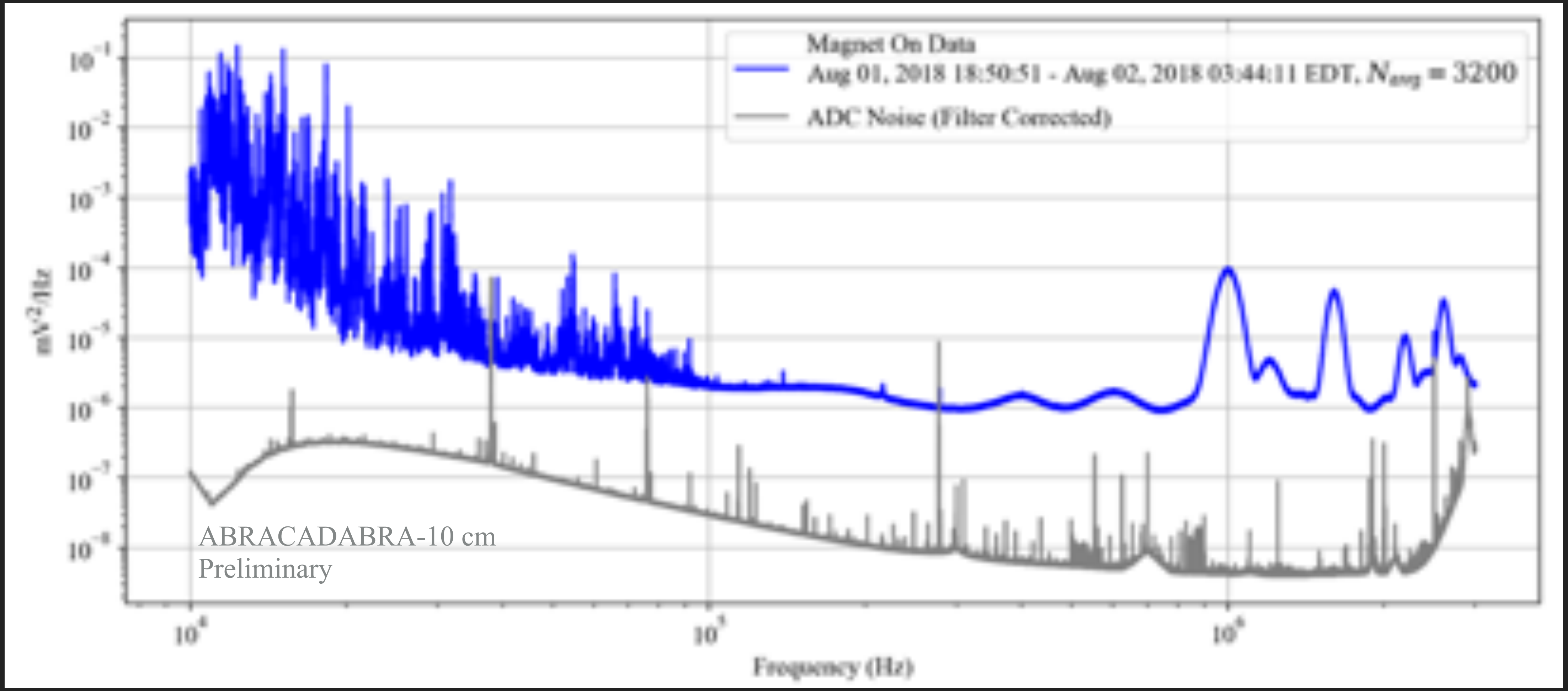
Broadband Data Collection Procedure

- 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



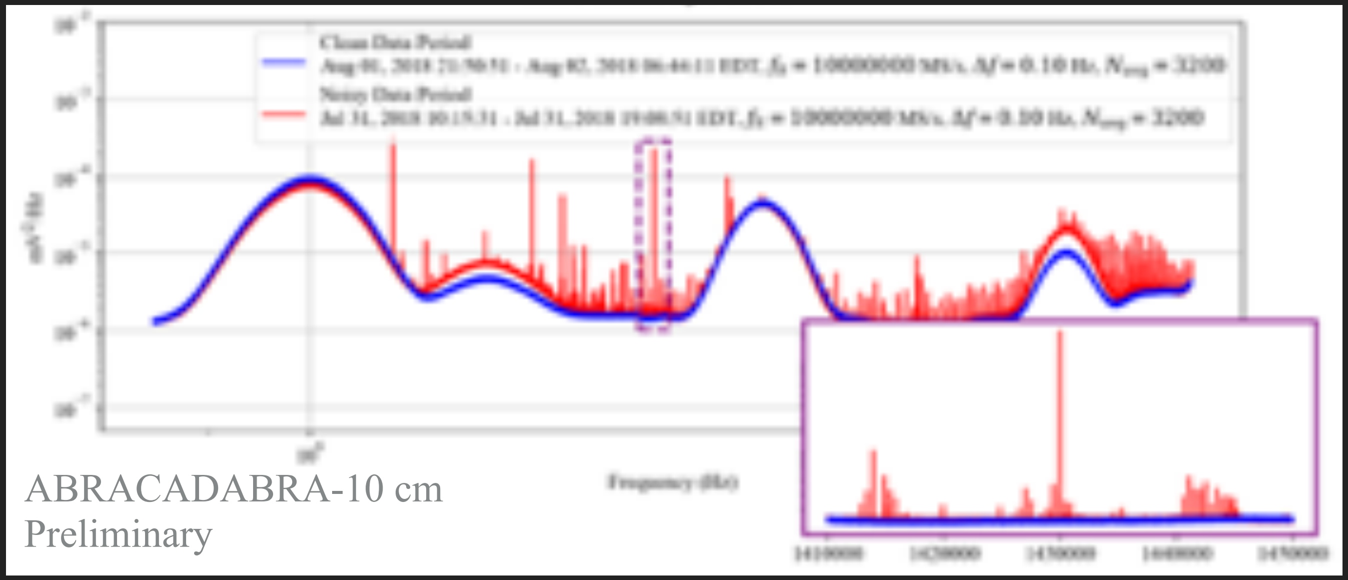
Example Spectrum

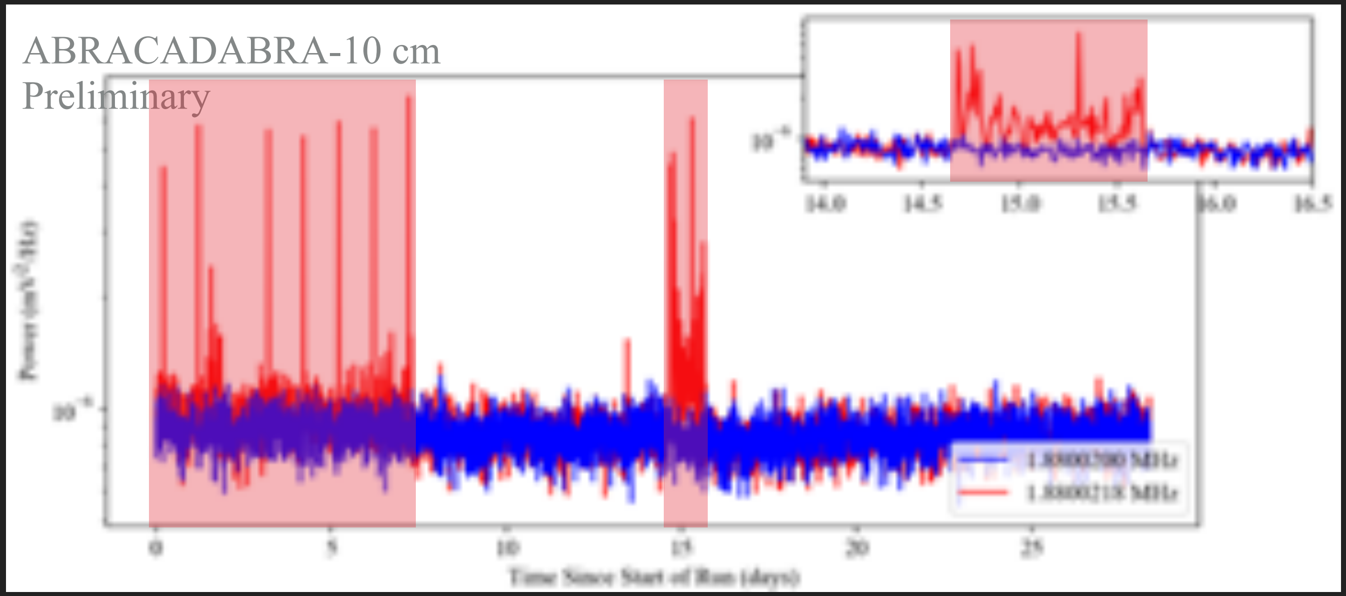
m_a ~ neV
(GUT scale PQ)



- 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.

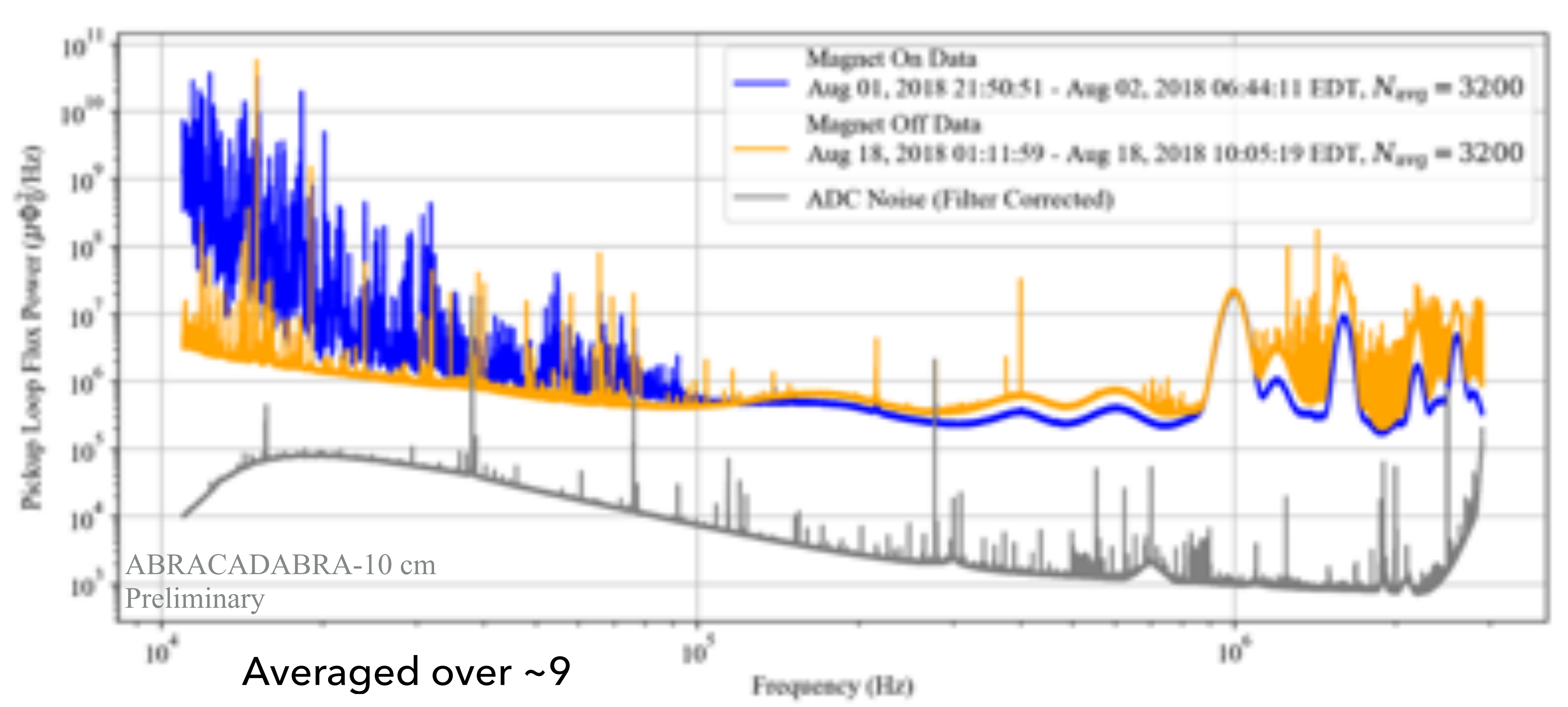
Transient Noise at High Frequency





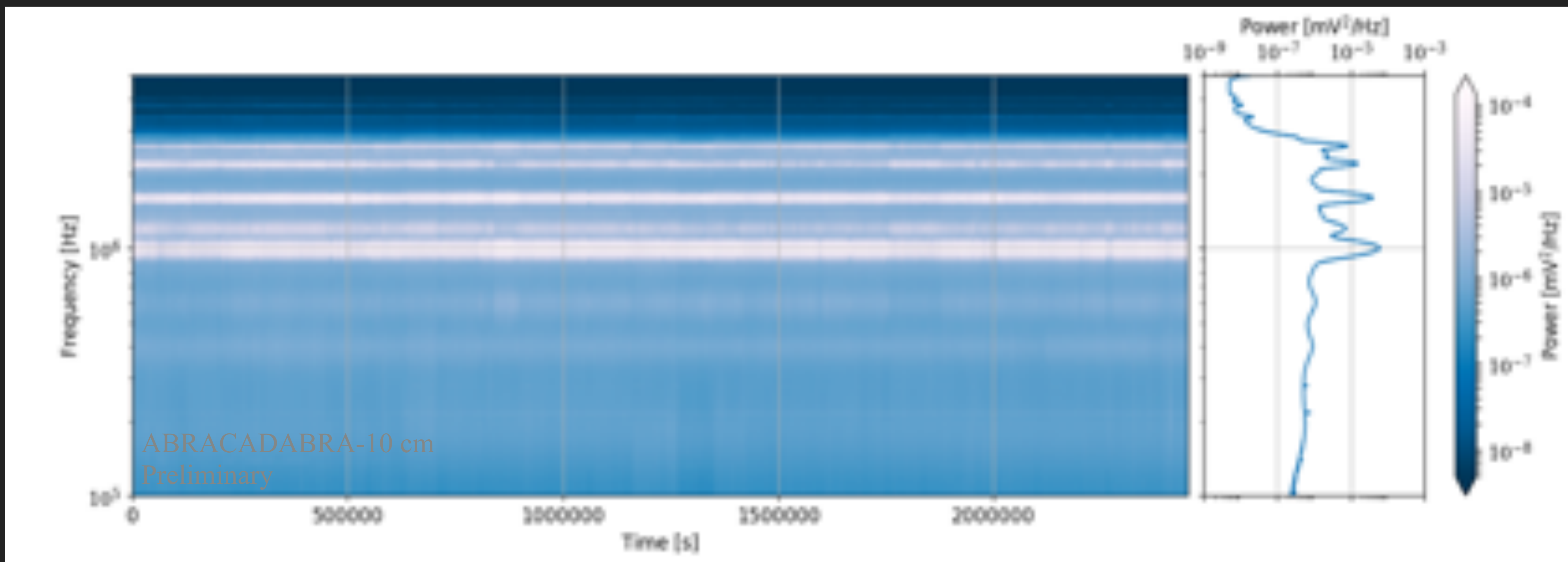
- Appeared after we were in the lab
- Seemed to be correlated with working hours?
- Investigating the digitizer/DAQ computer, grounding schemes, shielding, etc…
- In the present analysis, we had to discard ~30% of the data

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



	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

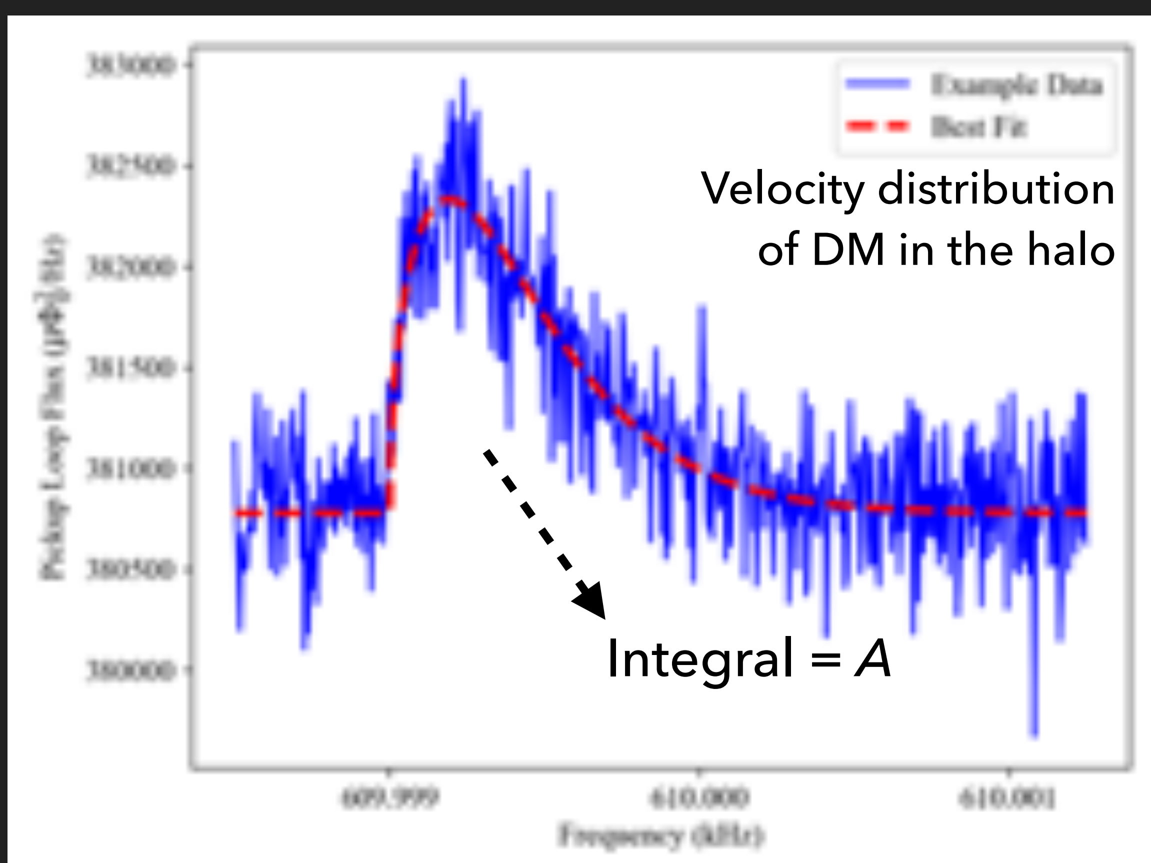
AXION SEARCH

Axion Signal

- Time averaged flux through the pickup loop:

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

- Signal shape given by the standard halo model

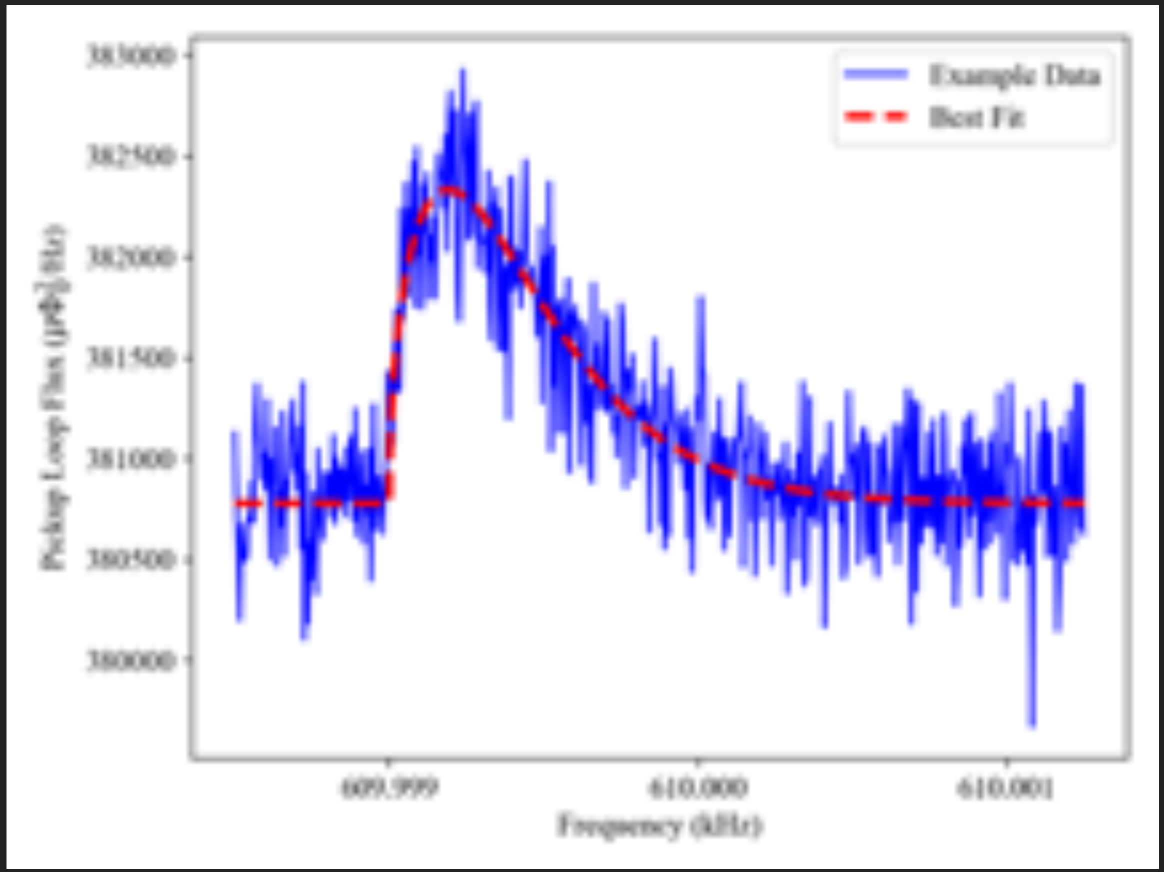


Axion Search Approach

- 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

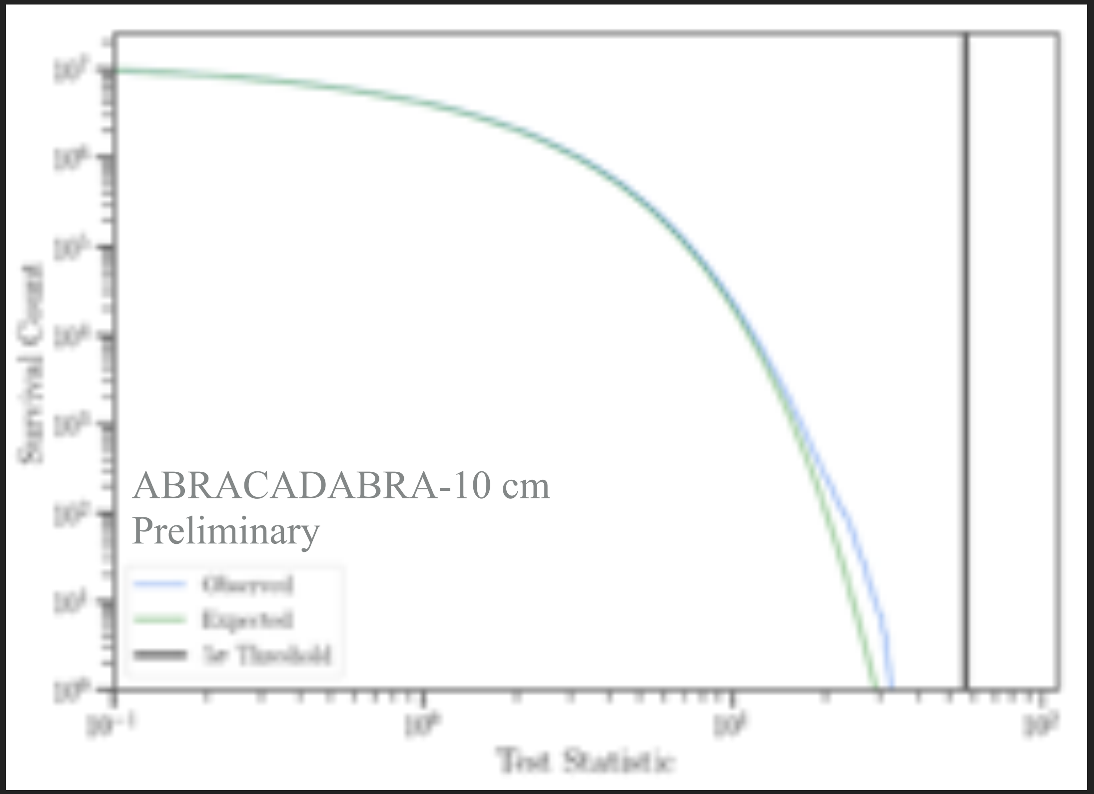


Axion Search Approach

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

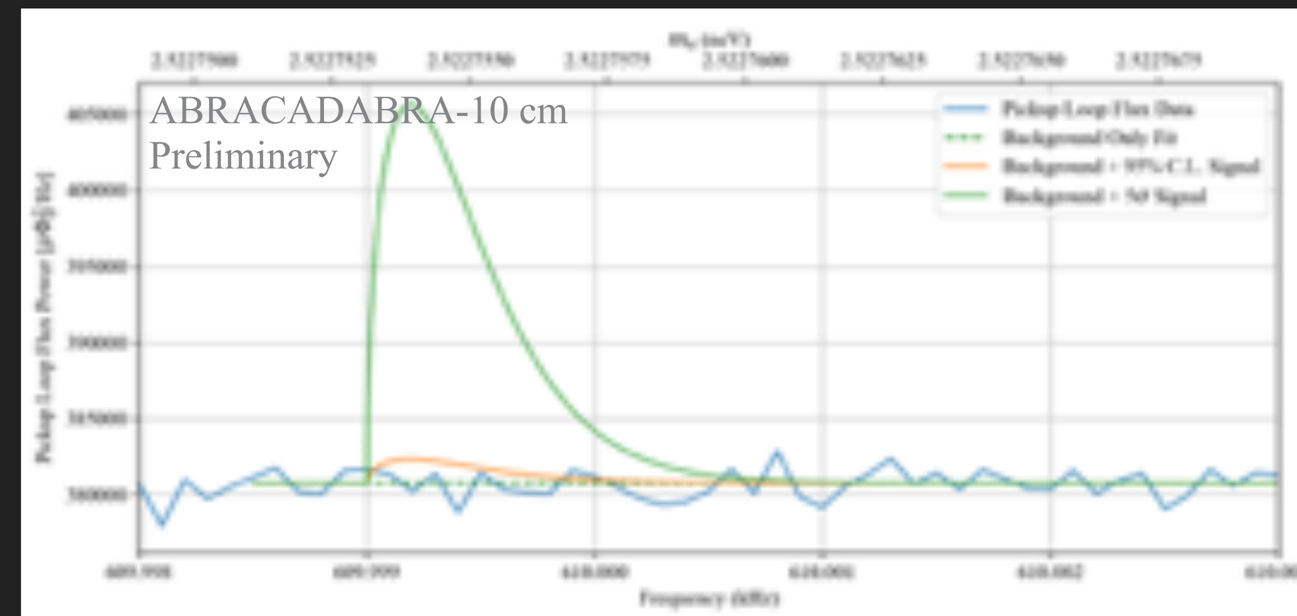
$$\mathrm{TS} = 2\left[\log \mathcal{L}\left(\hat{g}_{a\gamma\gamma}, m_a, \hat{\mathbf{b}}\right) - \log \mathcal{L}\left(g_{a\gamma\gamma} = 0, m_a, \hat{\hat{\mathbf{b}}}\right)\right]$$

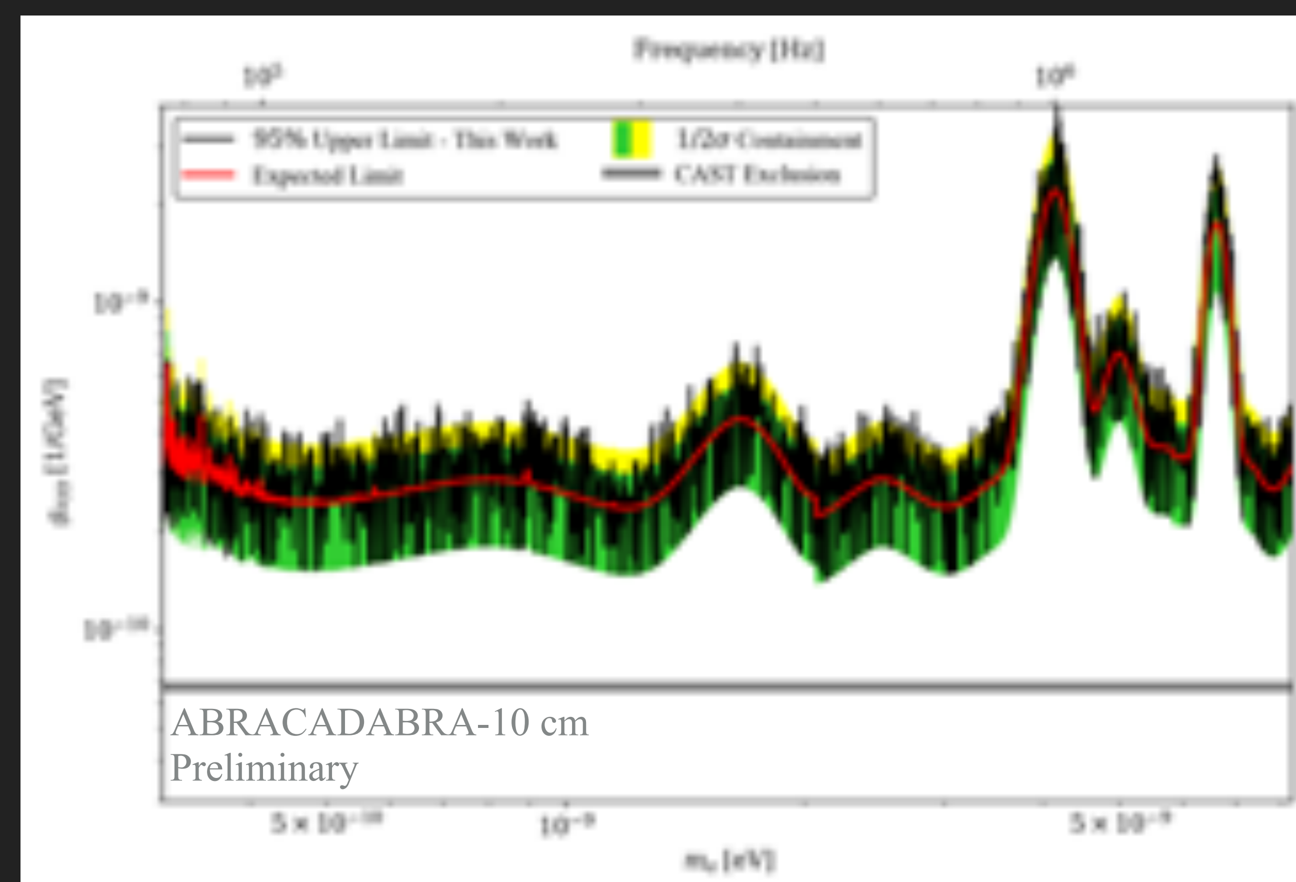
- Profiling over all nuisance parameters, b_i
- We set the 5σ discovery threshold as TS>56.1 (accounting for the Look Elsewhere Effect for our 8M mass points)



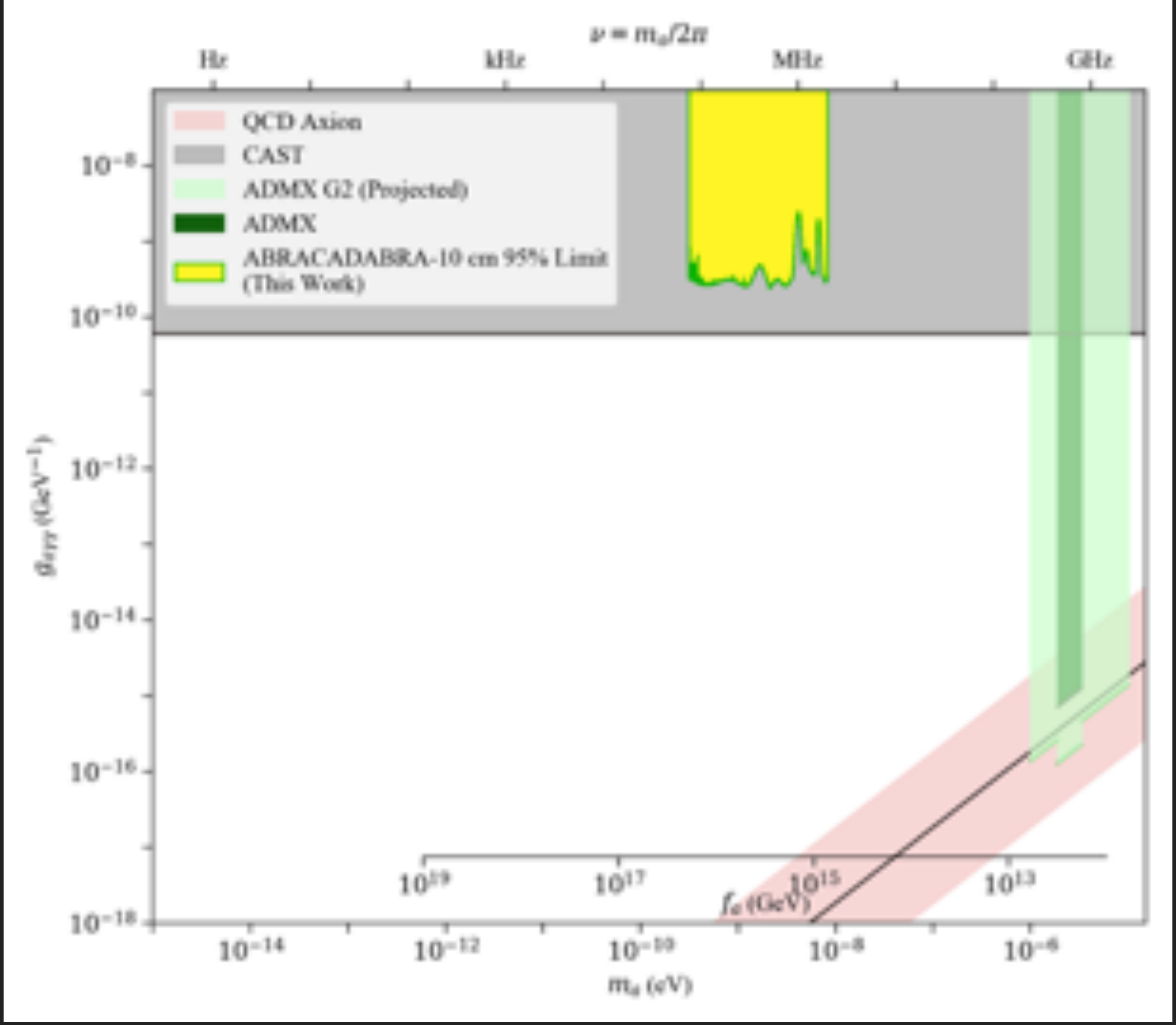
Axion Limits

- 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

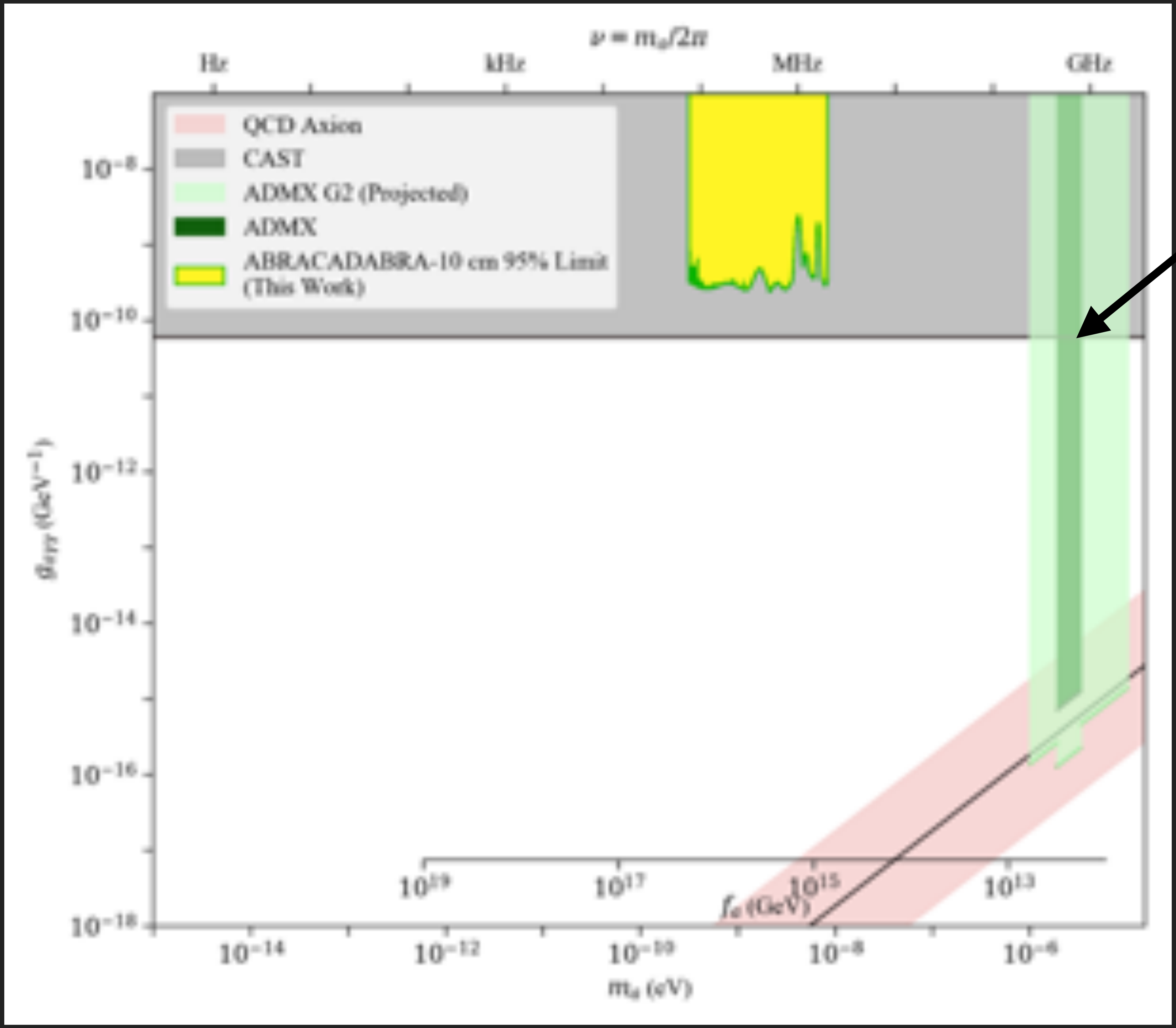




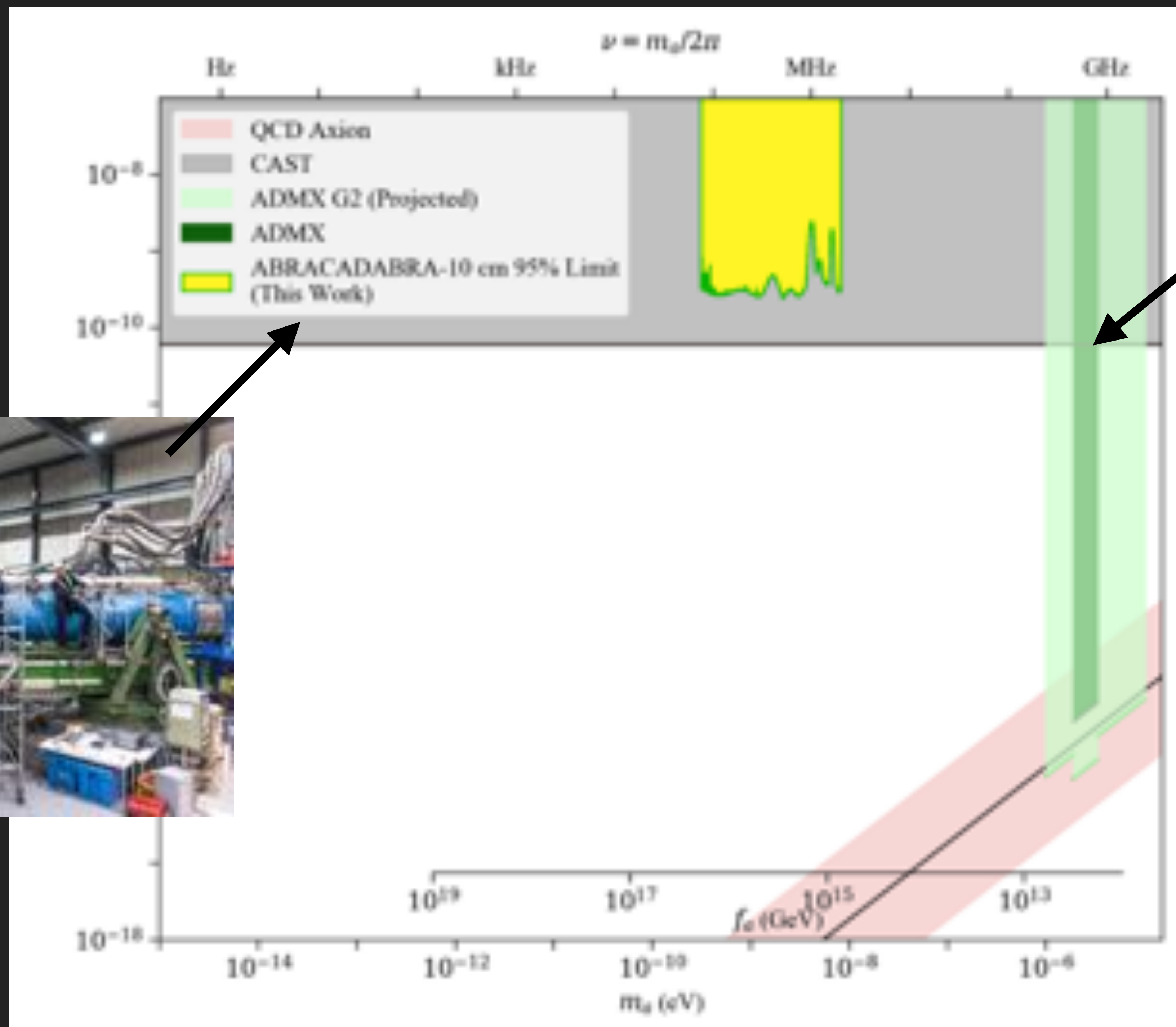
ABRACADABRA-10 cm Run 1 Limits

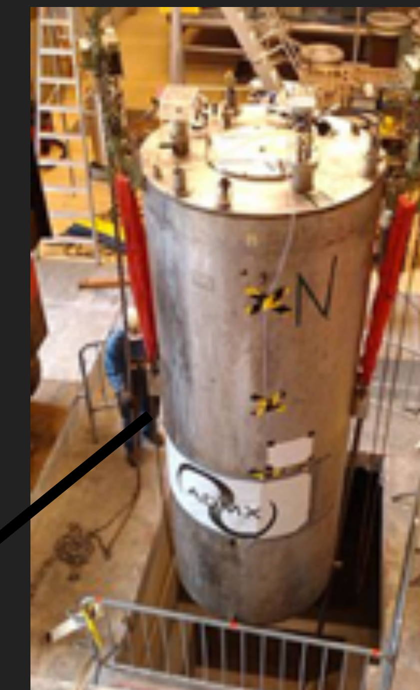


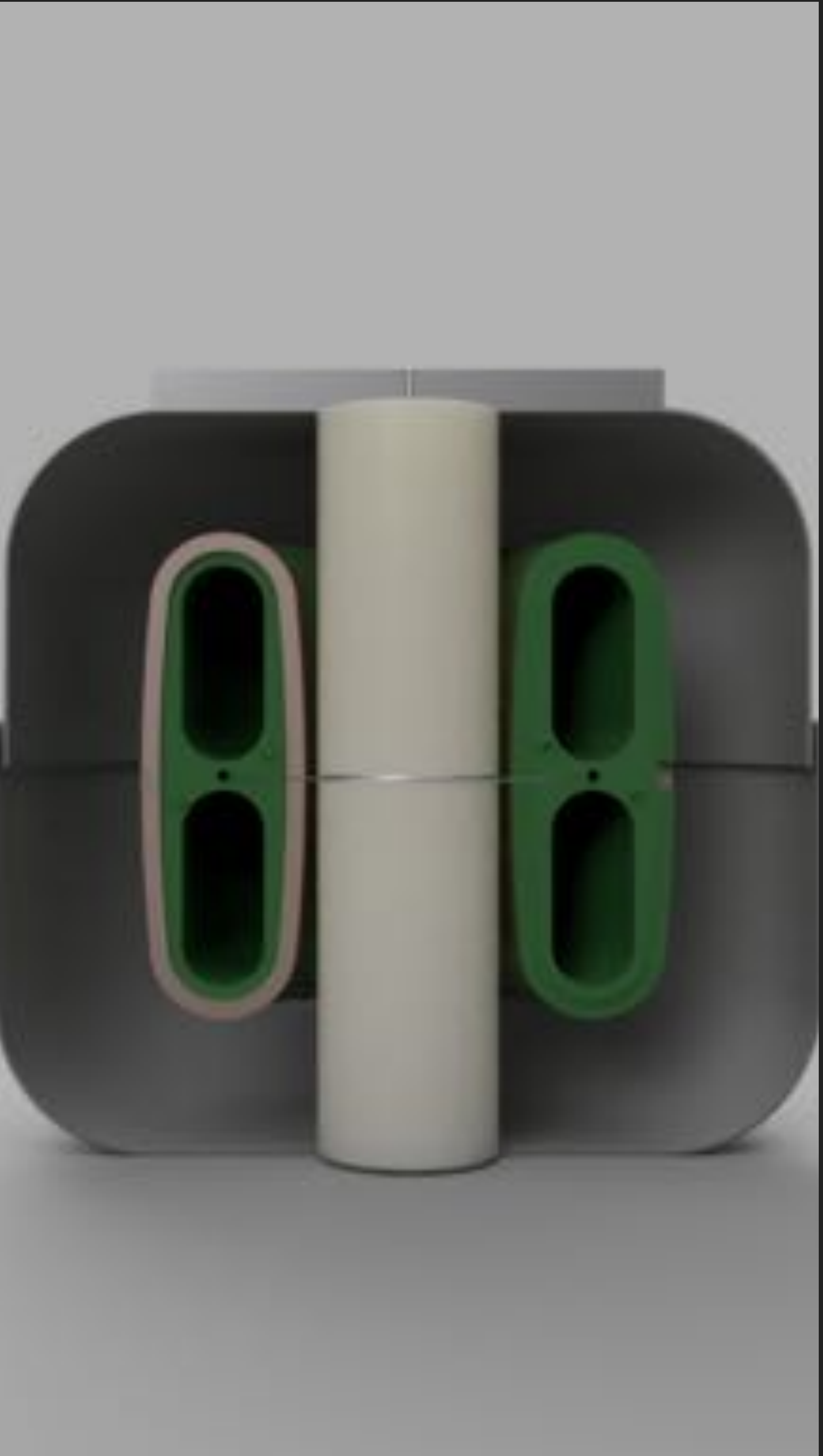
ABRACADABRA-10 cm Run 1 Limits



ABRACADABRA-10 cm Run 1 Limits



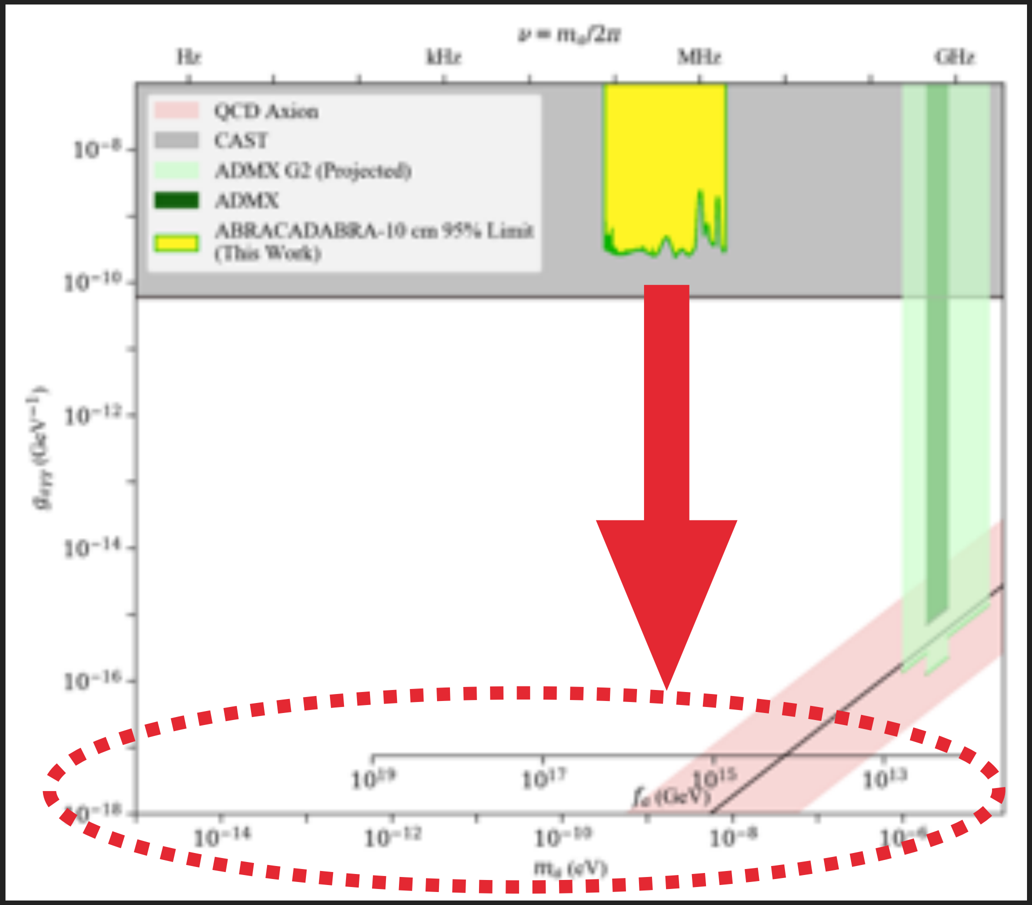


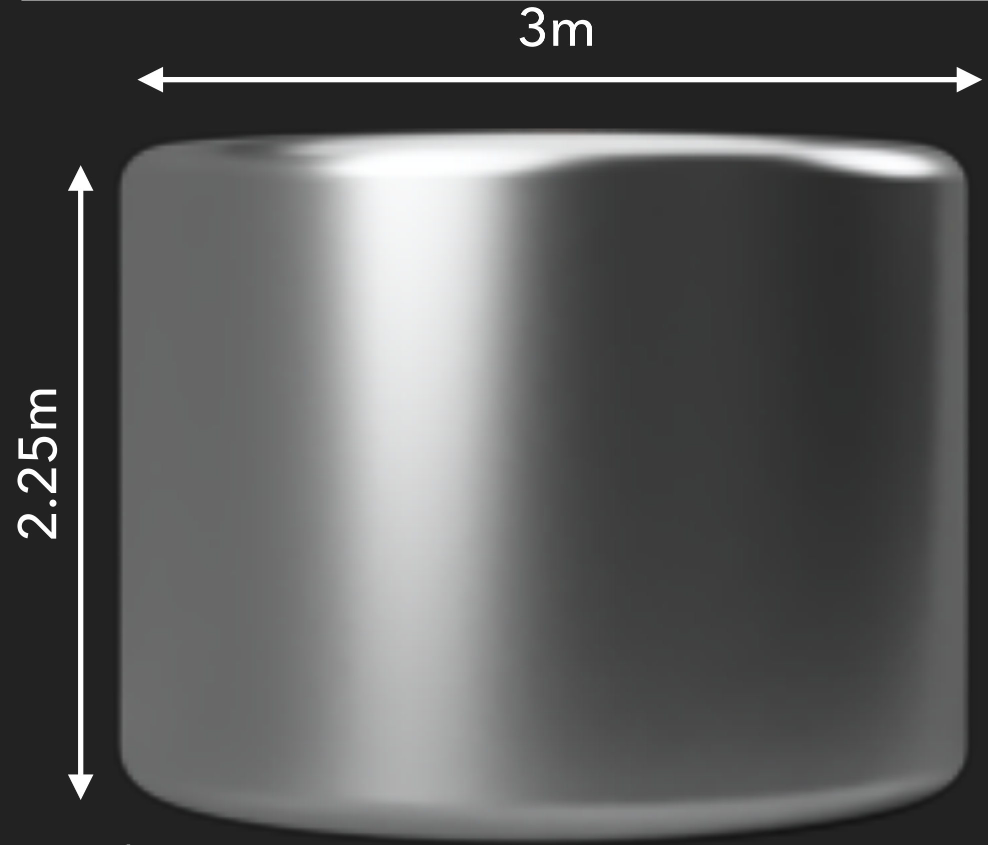


NEXT STEPS

ABRACADABRA-75 cm

- Goal: 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
  - Resonator readout with accelerated* scan readout strategy
  - Quantum limited 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 TDR to follow



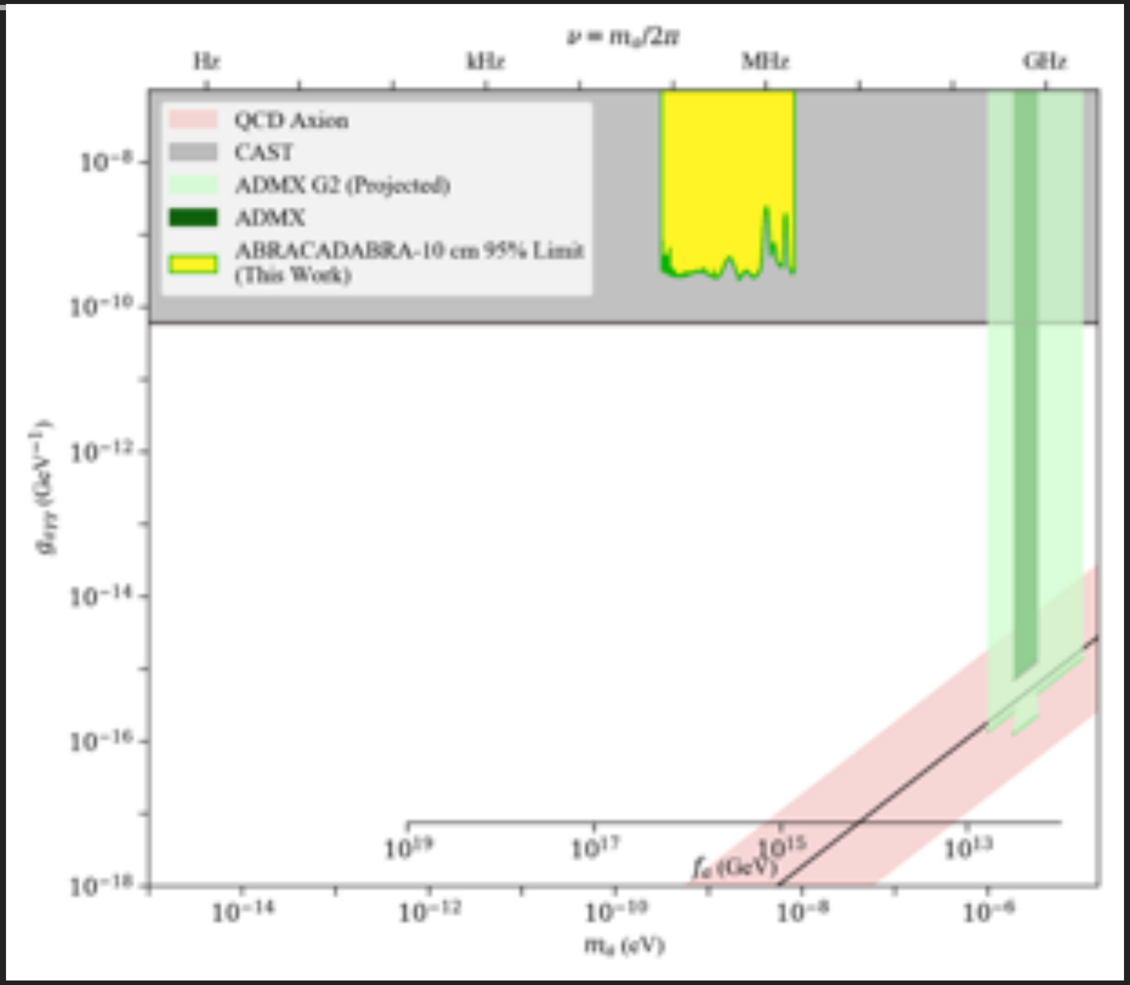


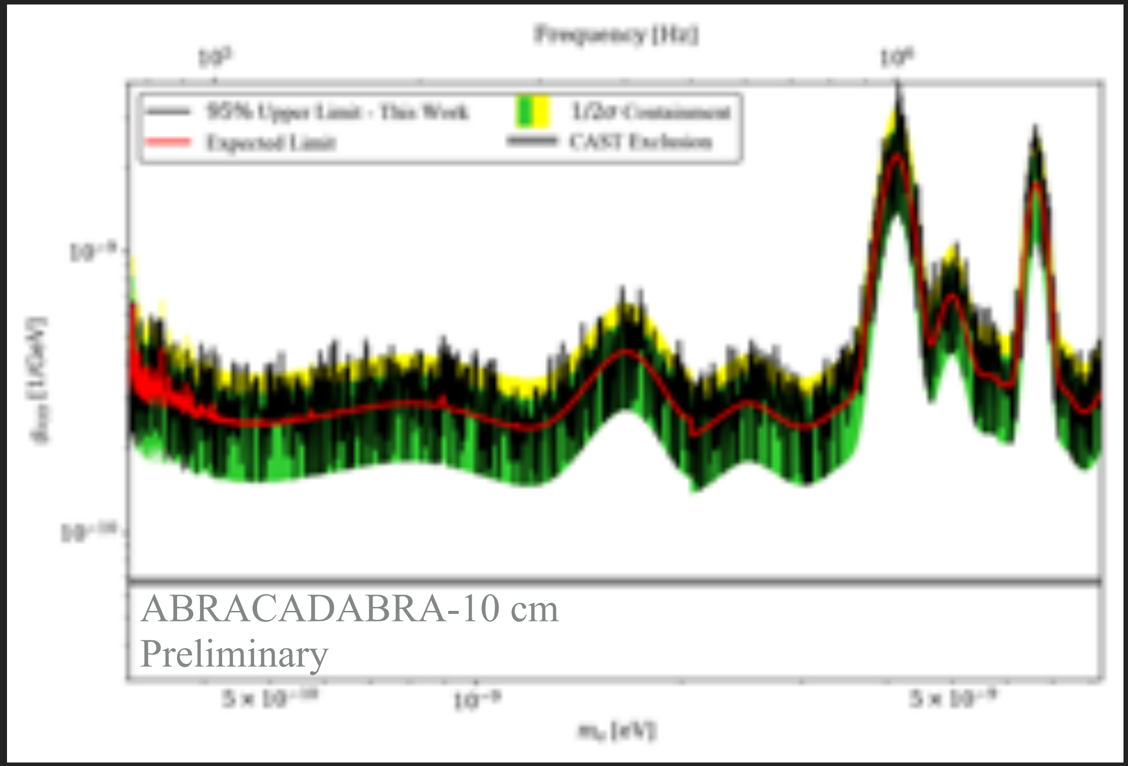
*Ask more about this!

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!

- 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)





On the arXiv!

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

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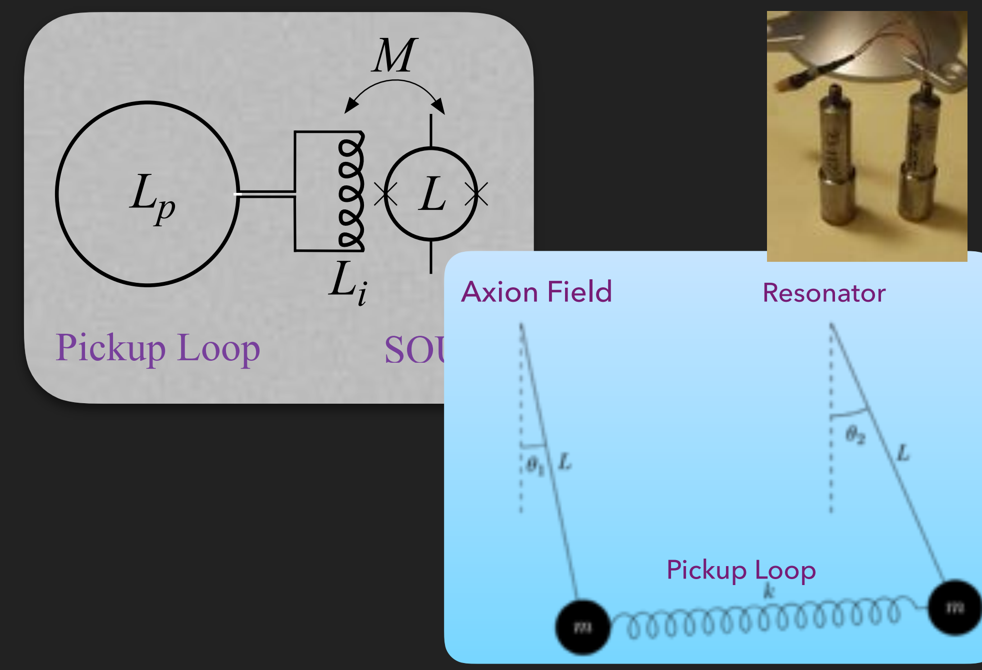
(Dated: October 29, 2018)

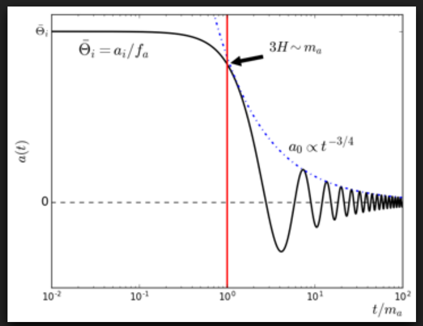
ARXIV:1810.12257

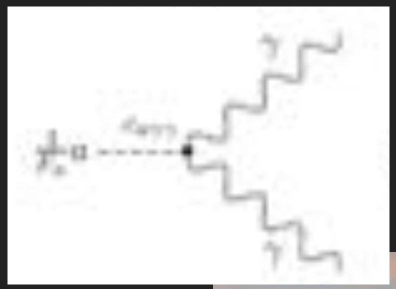
We've Explained the Acronym!

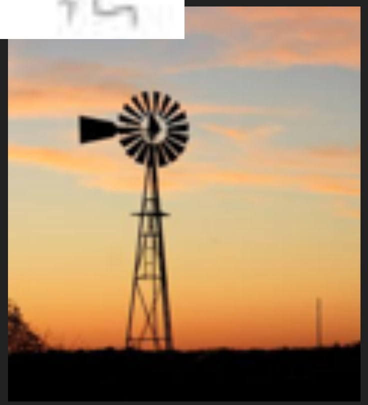
A Broadband/Resonant Approach



Cosmic Axion Detection



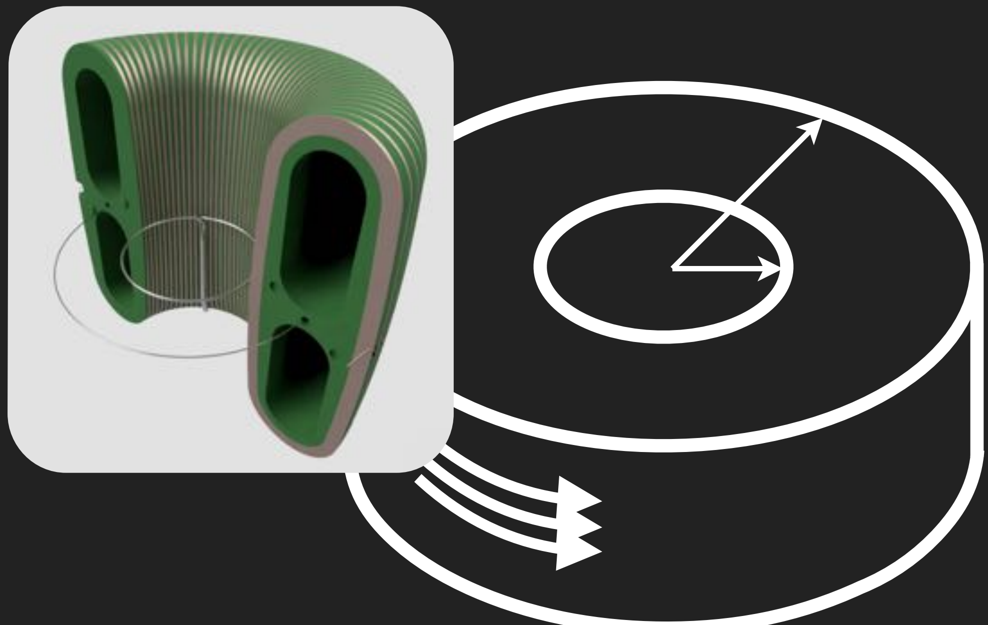




$$\mathbf{J}_{\mathrm{eff}} = g_{a\gamma\gamma}\frac{\partial a}{\partial t}\mathbf{B}$$

A
B
R
A
C
A
D
A
B
R
A

Amplifying B-Field Ring Apparatus



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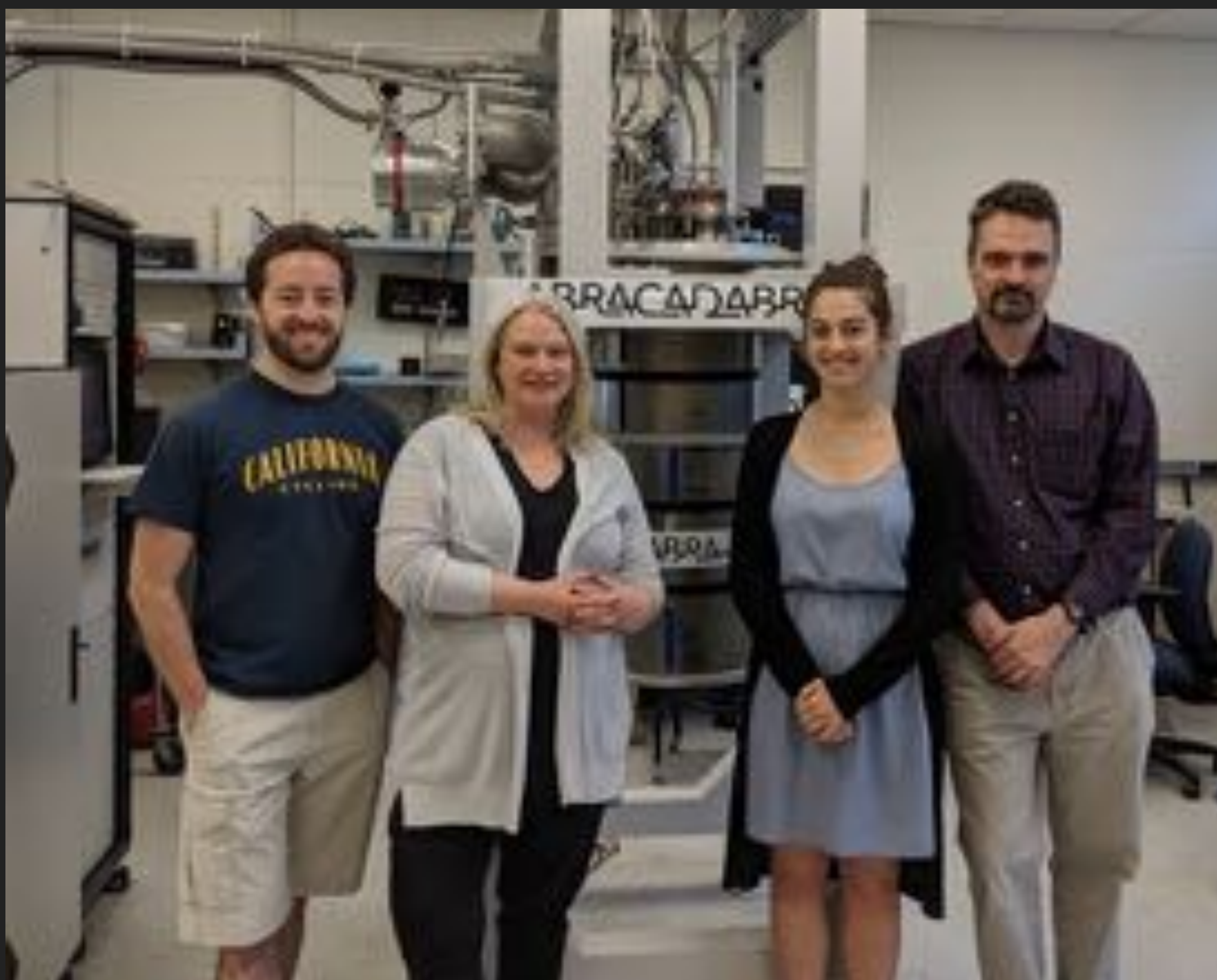

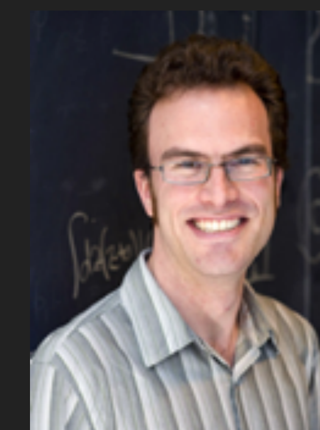

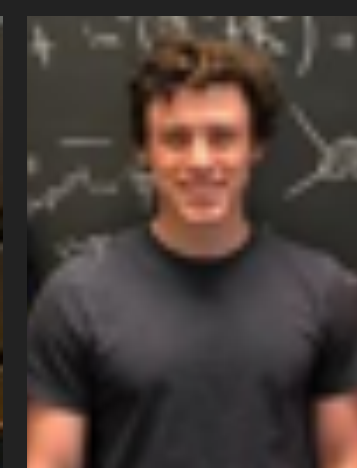

Thank you for your attention!