A Broadband/Resonant Search for Axion Dark Matter

ABRACADABRA

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THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

MICHIGAN

Axion Dark Matter

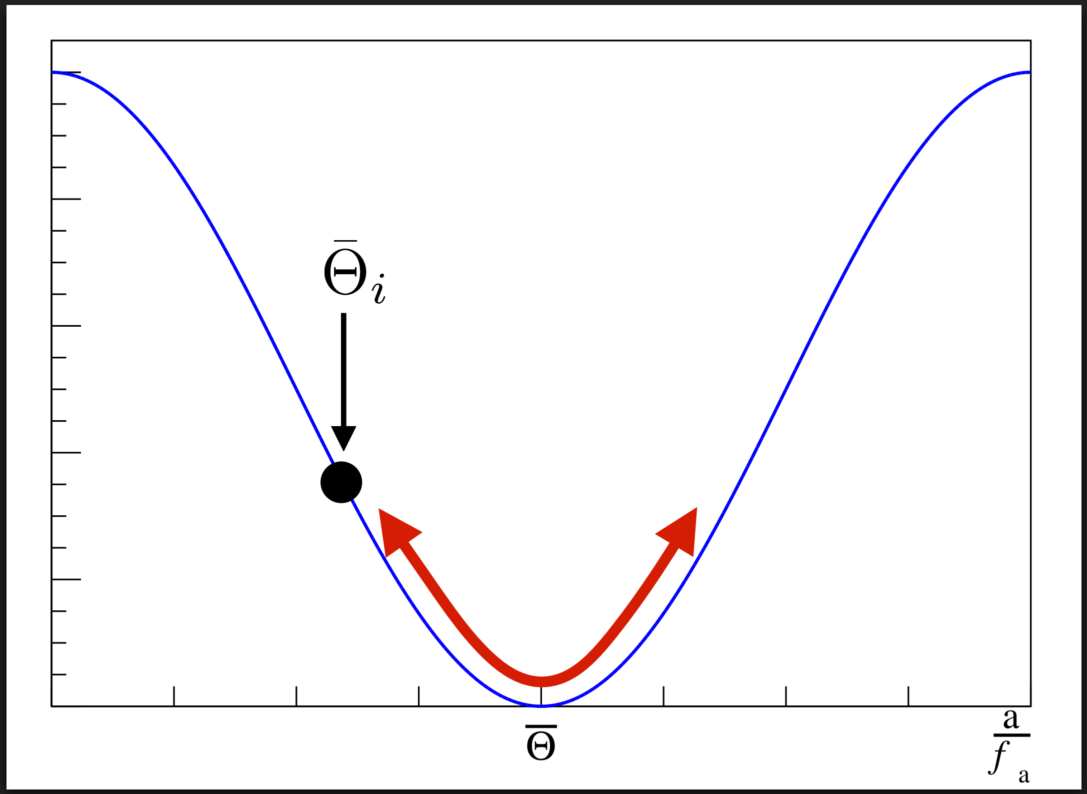
- Misalignment mechanism gives rise to an oscillating axion field:

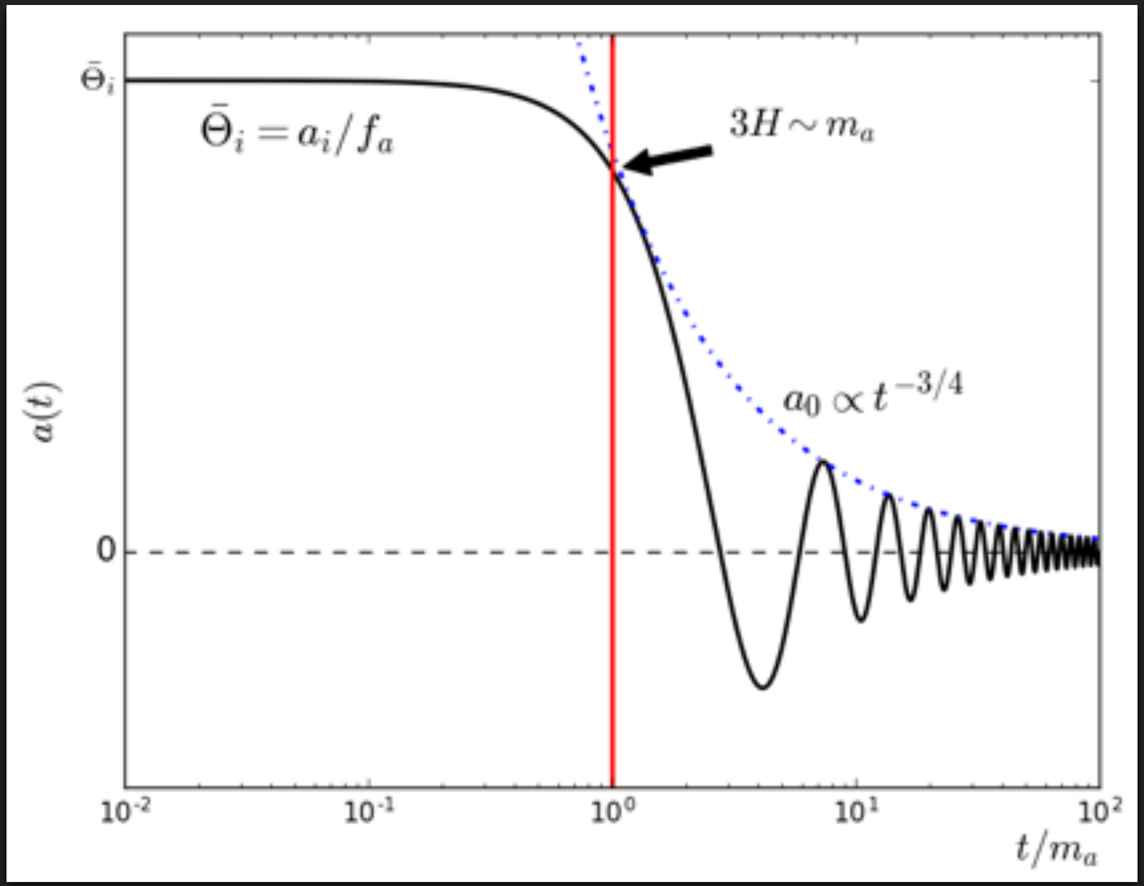
$$a(t) = a_0 \sin(m_a t)$$

- The combined field potential/kinetic energy behaves like DM

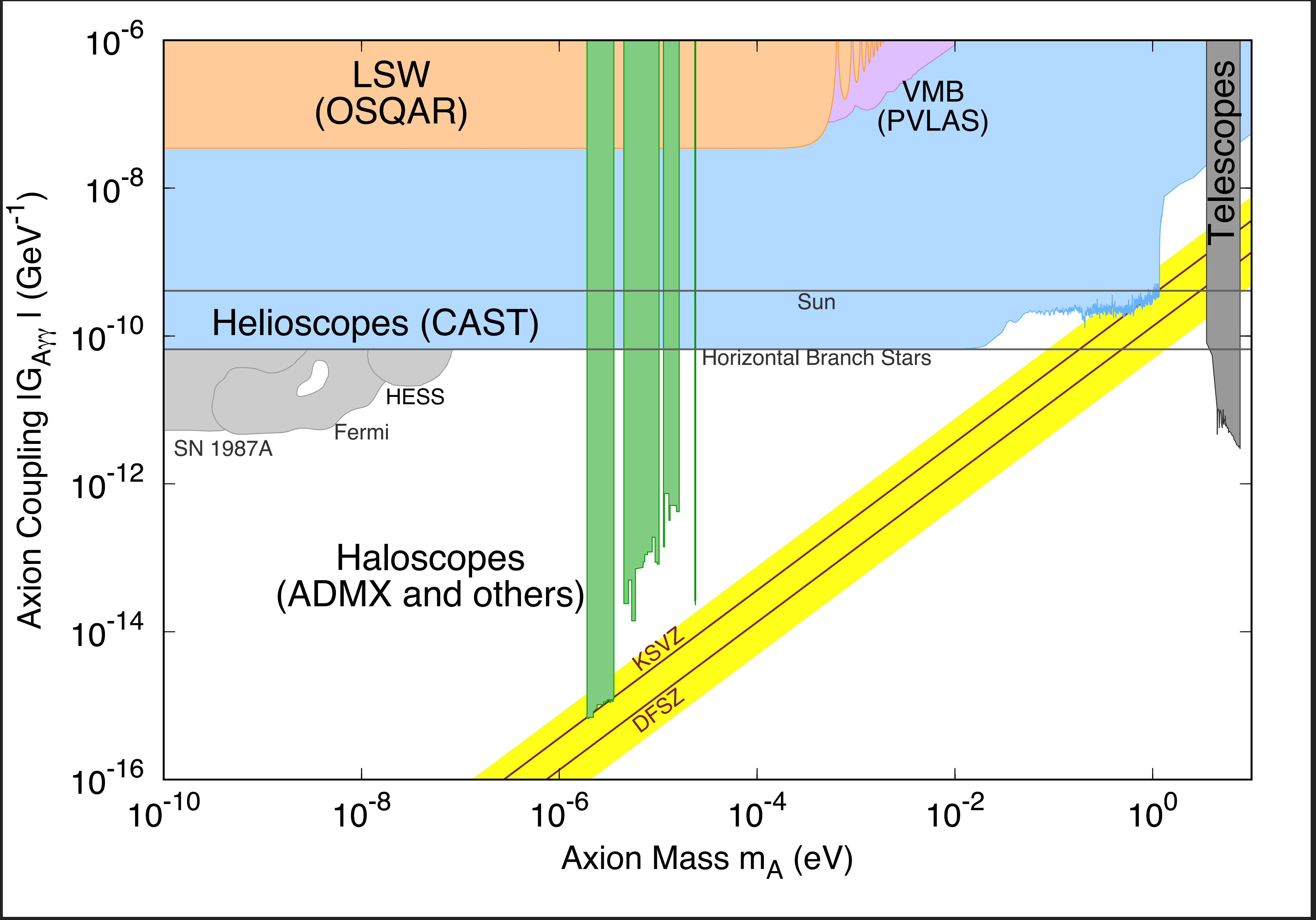
- Assuming the axion field accounts for the DM density, we can write:

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





Current State Of Axion Search



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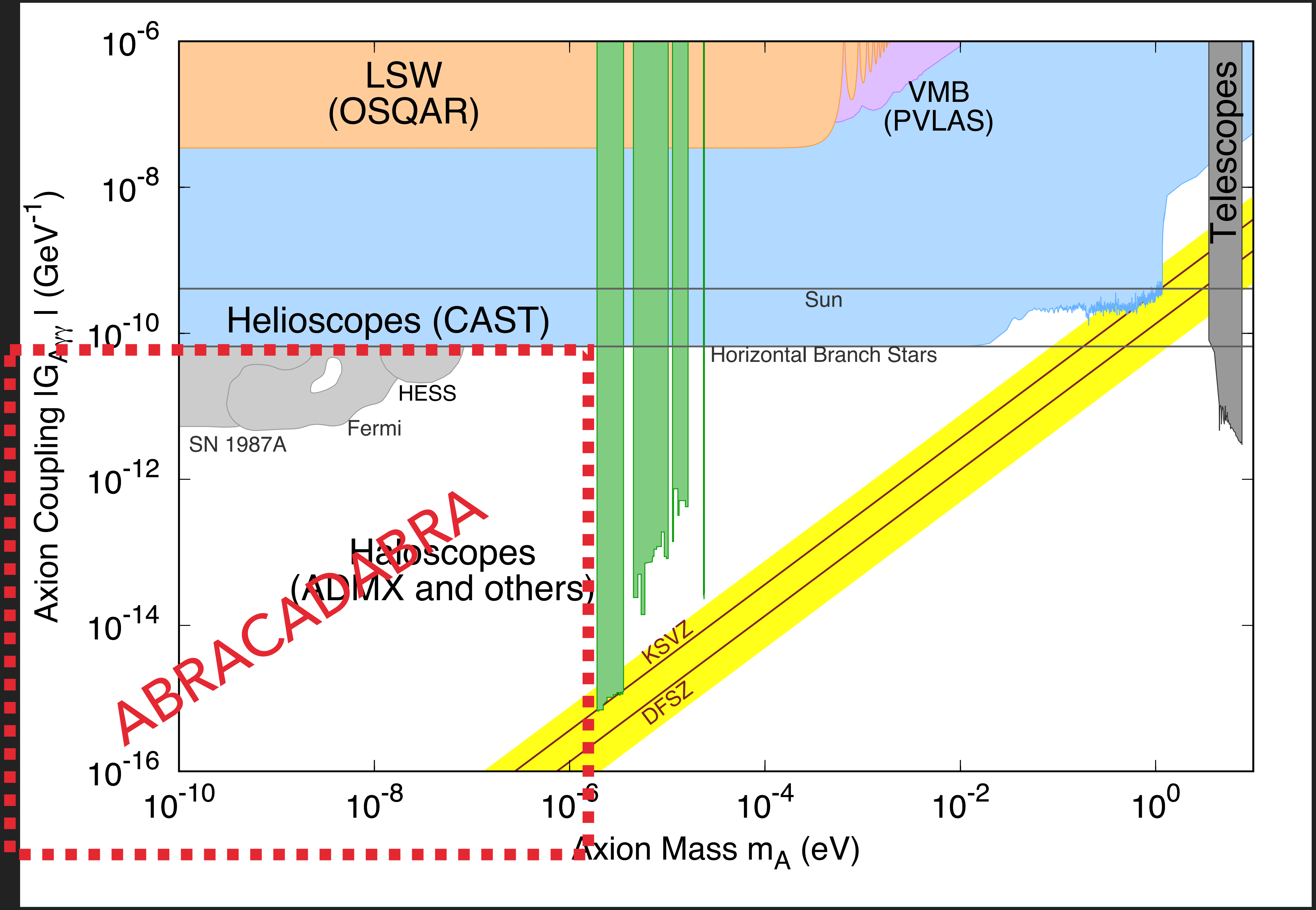
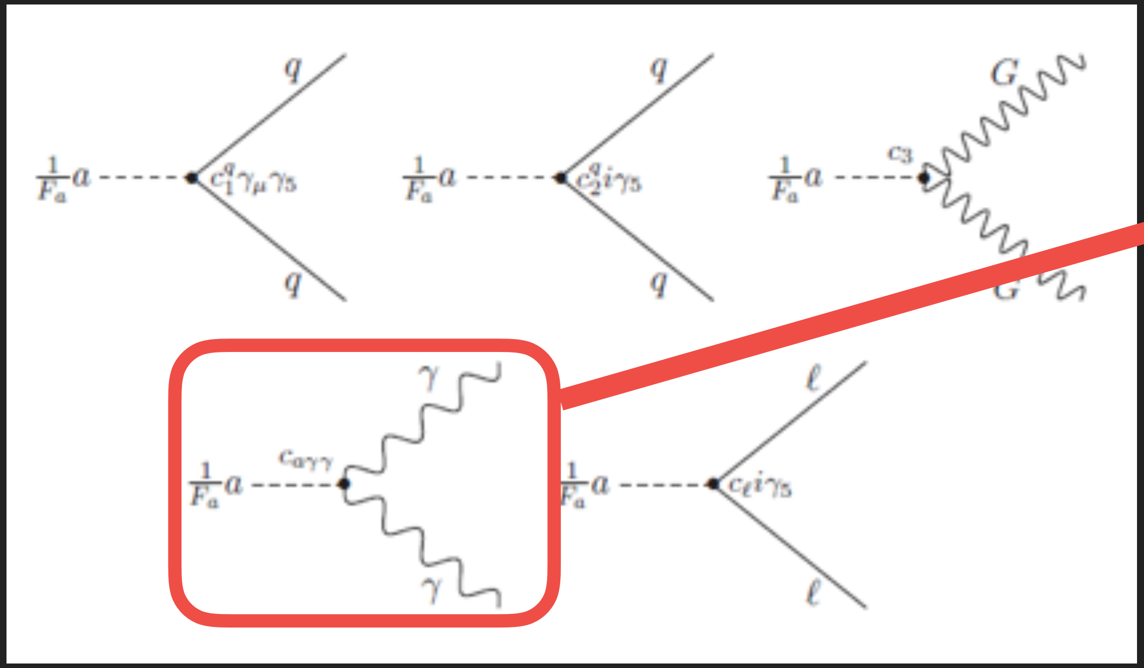


Axion Interactions with the Standard Model

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

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



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

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

Axion Interactions with the Standard Model

- New QED Lagrangian leads to new Maxwell's equations

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

Modified Source-Free Maxwell's Equations

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

An Axion In a Magnetic Field

- Modification to Ampere's law (MQS approximation)

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

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

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

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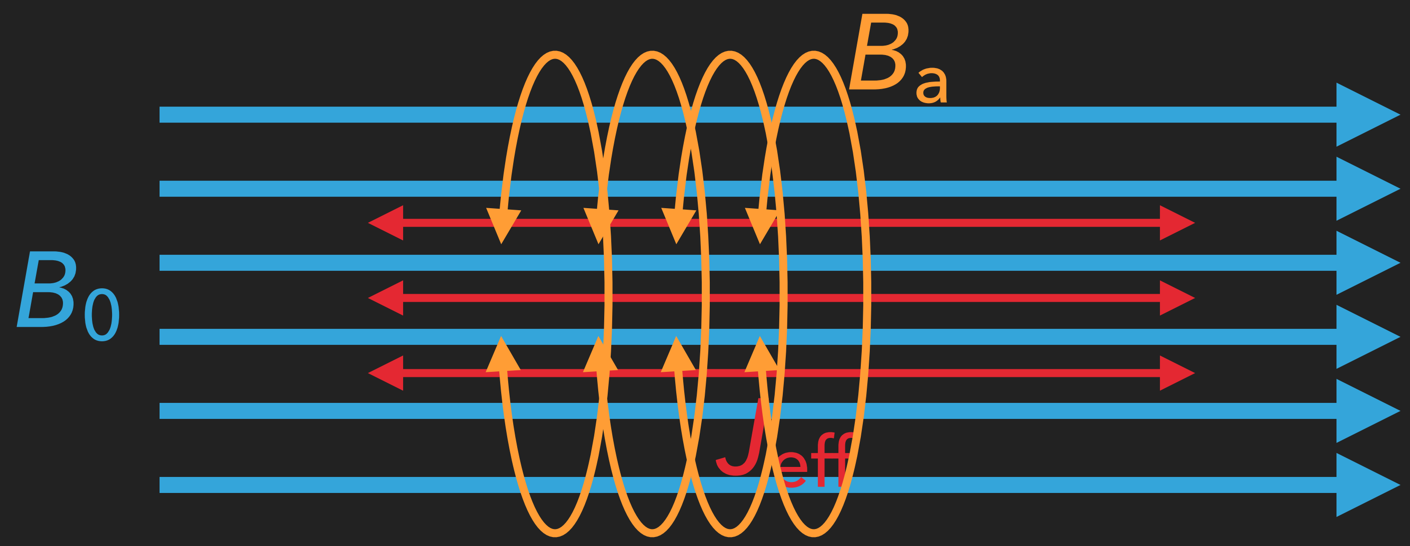

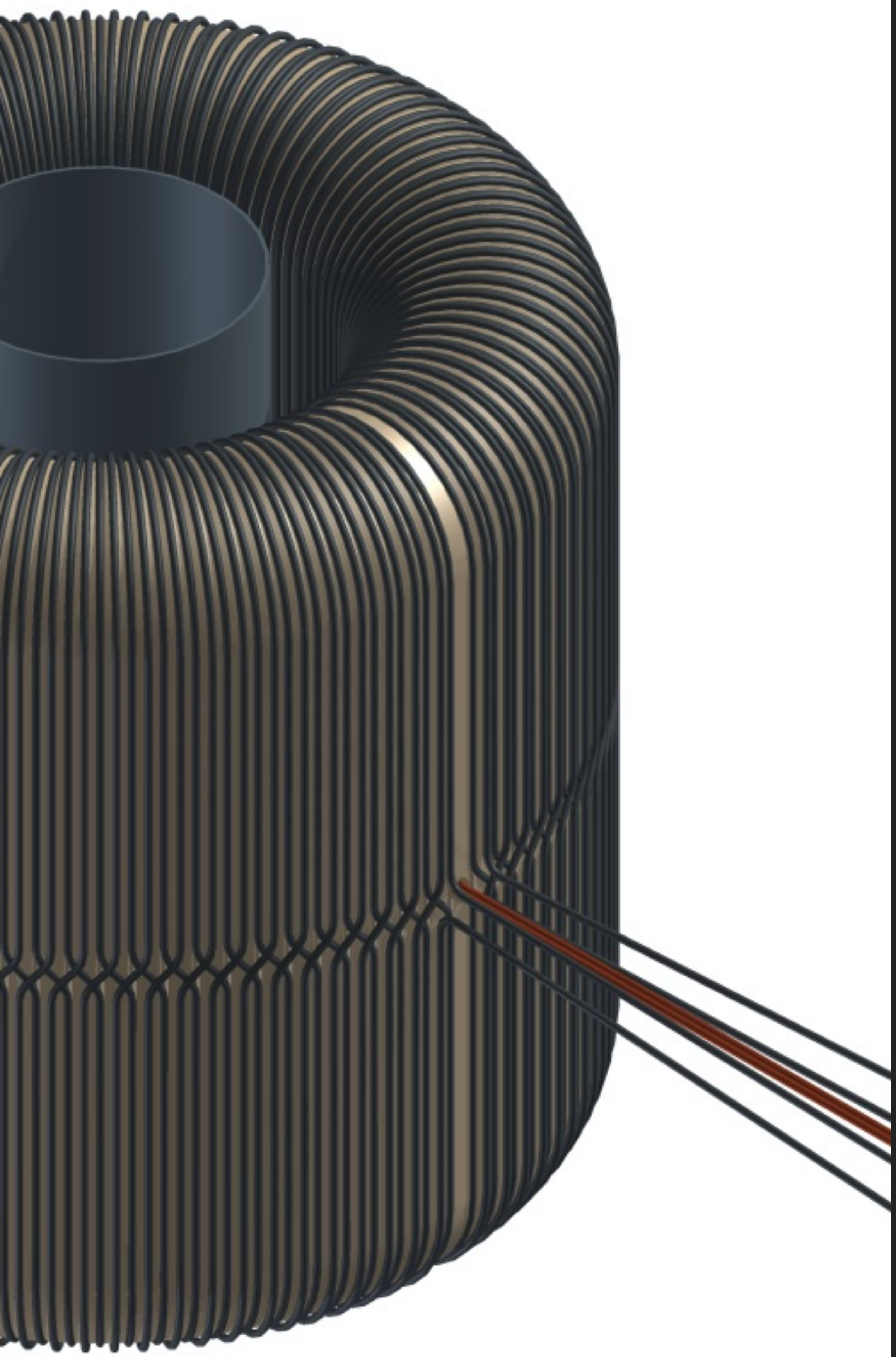

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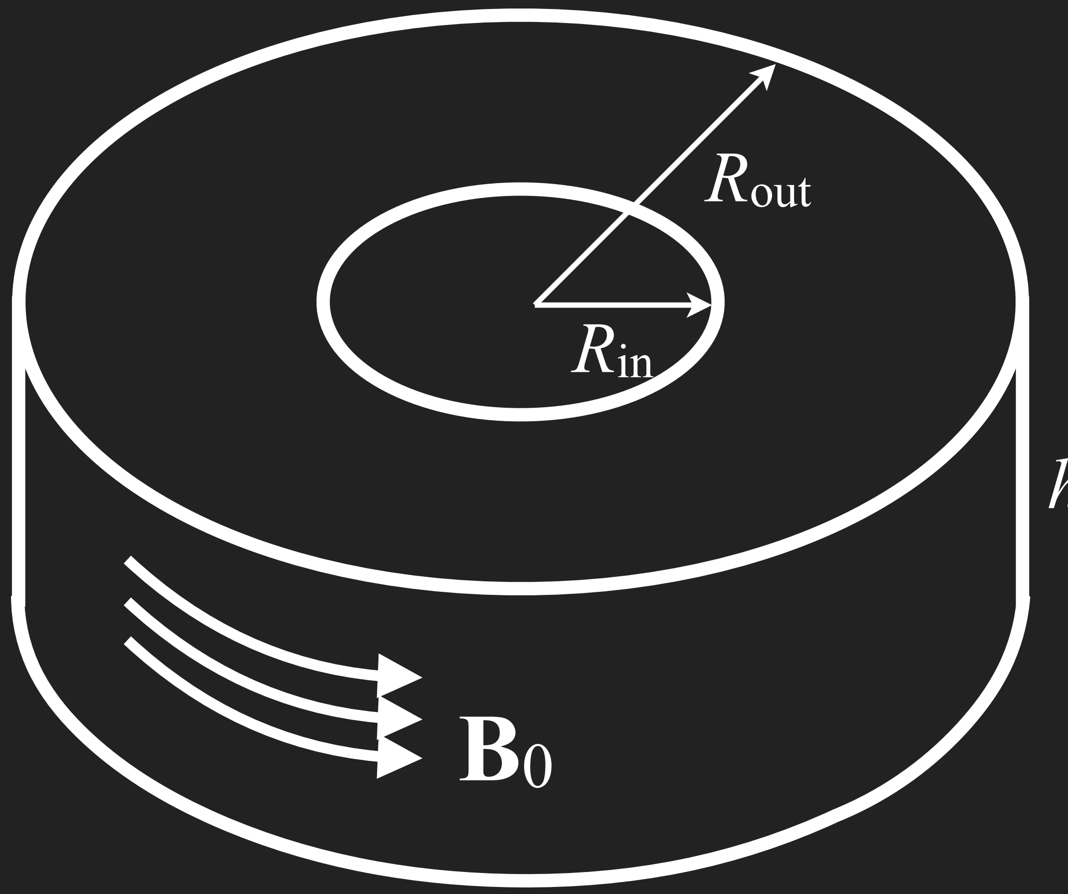
A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-Field Ring Apparatus

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



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

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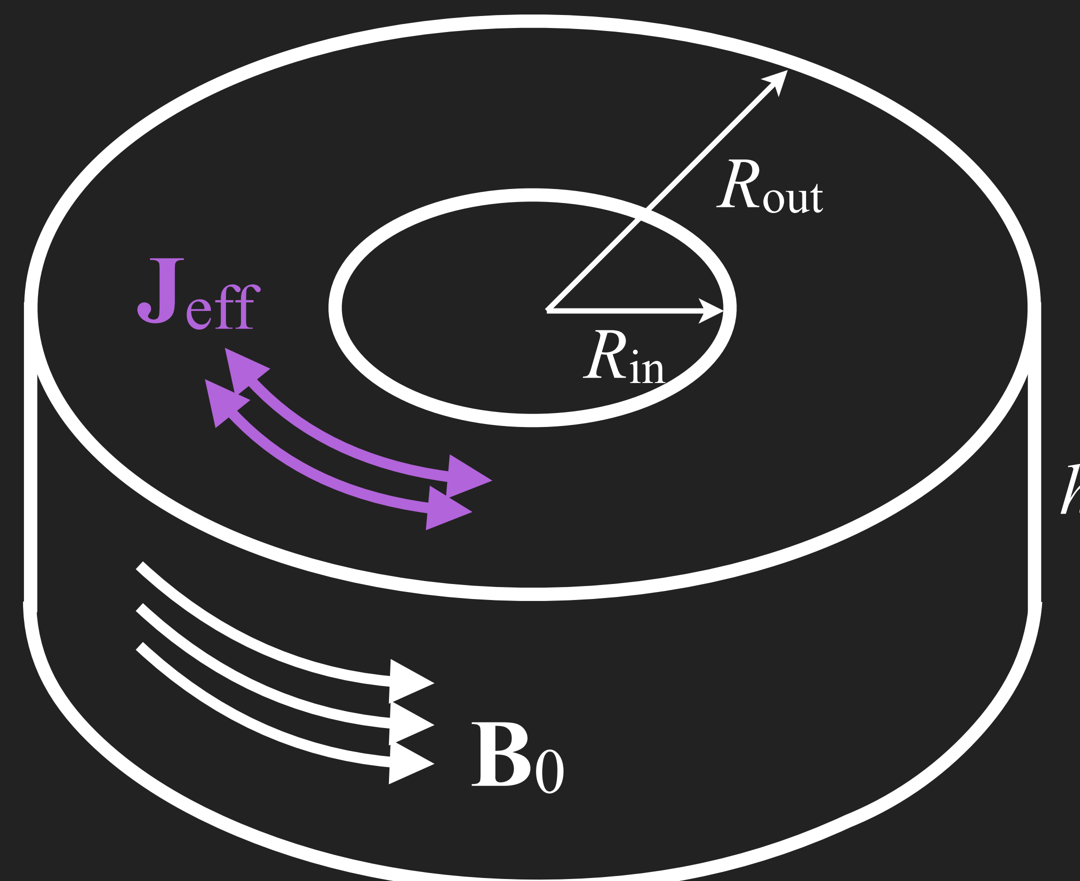

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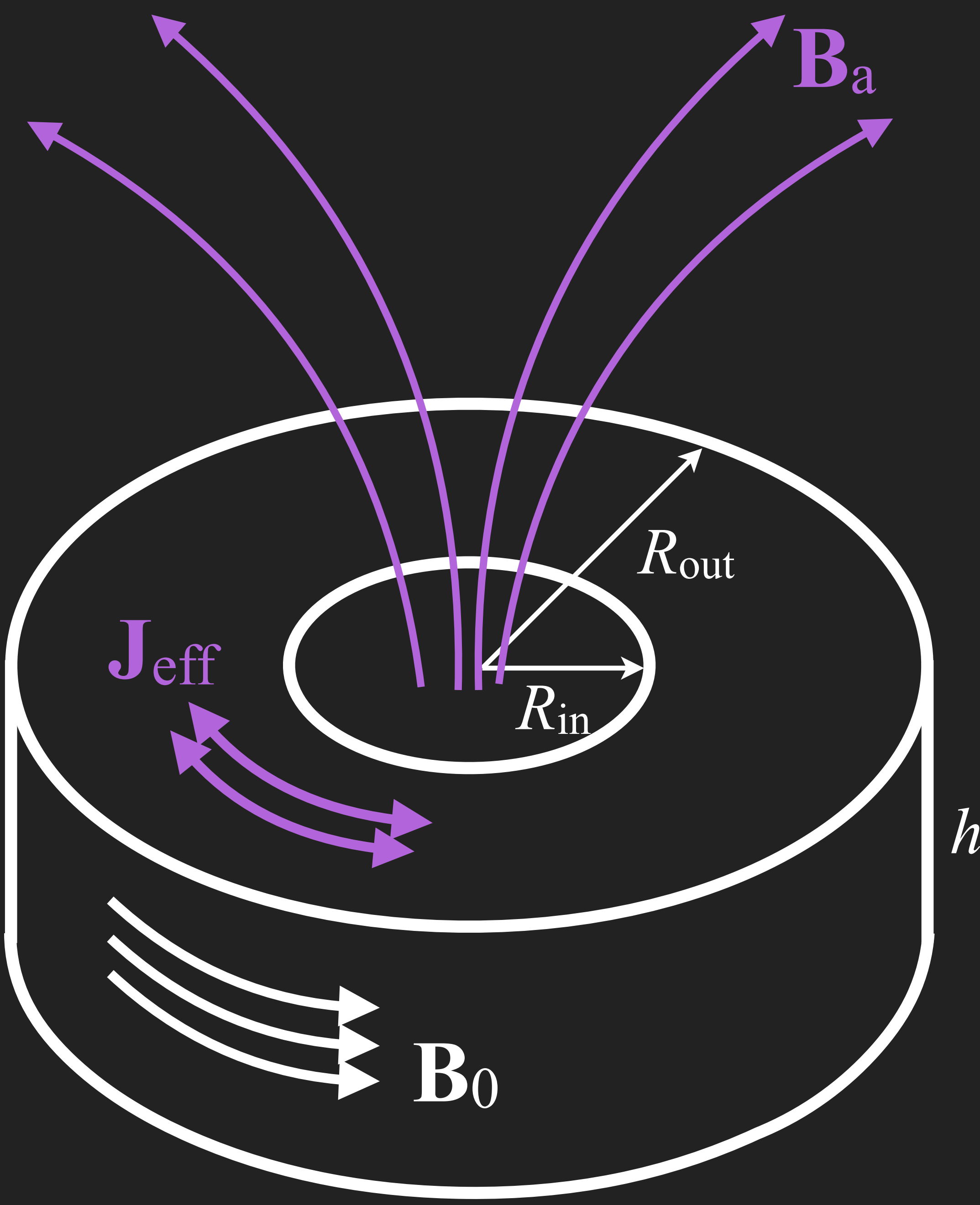

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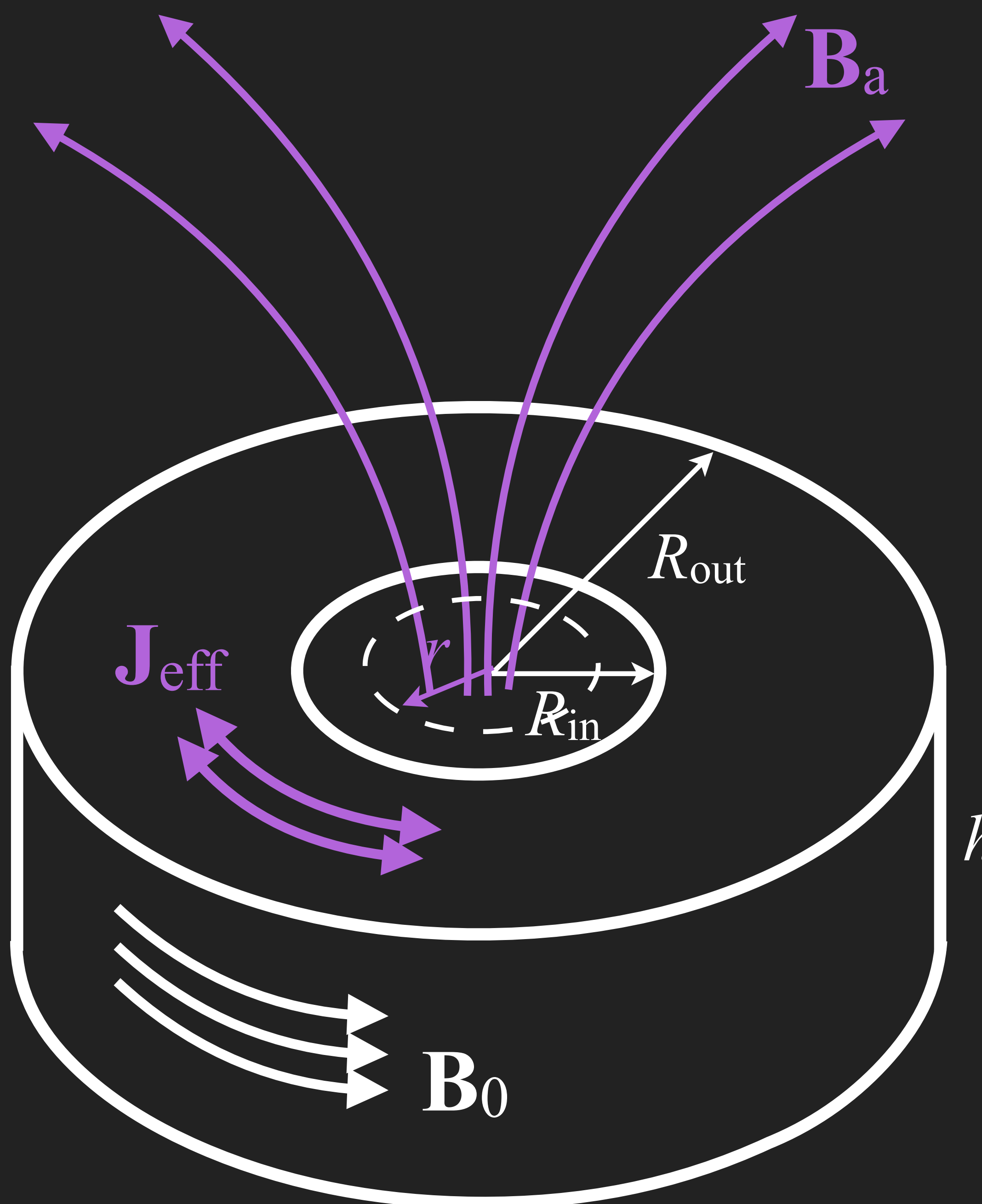
- Insert a pickup loop in the center and measure the induced current in the loop read out by a SQUID based readout

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



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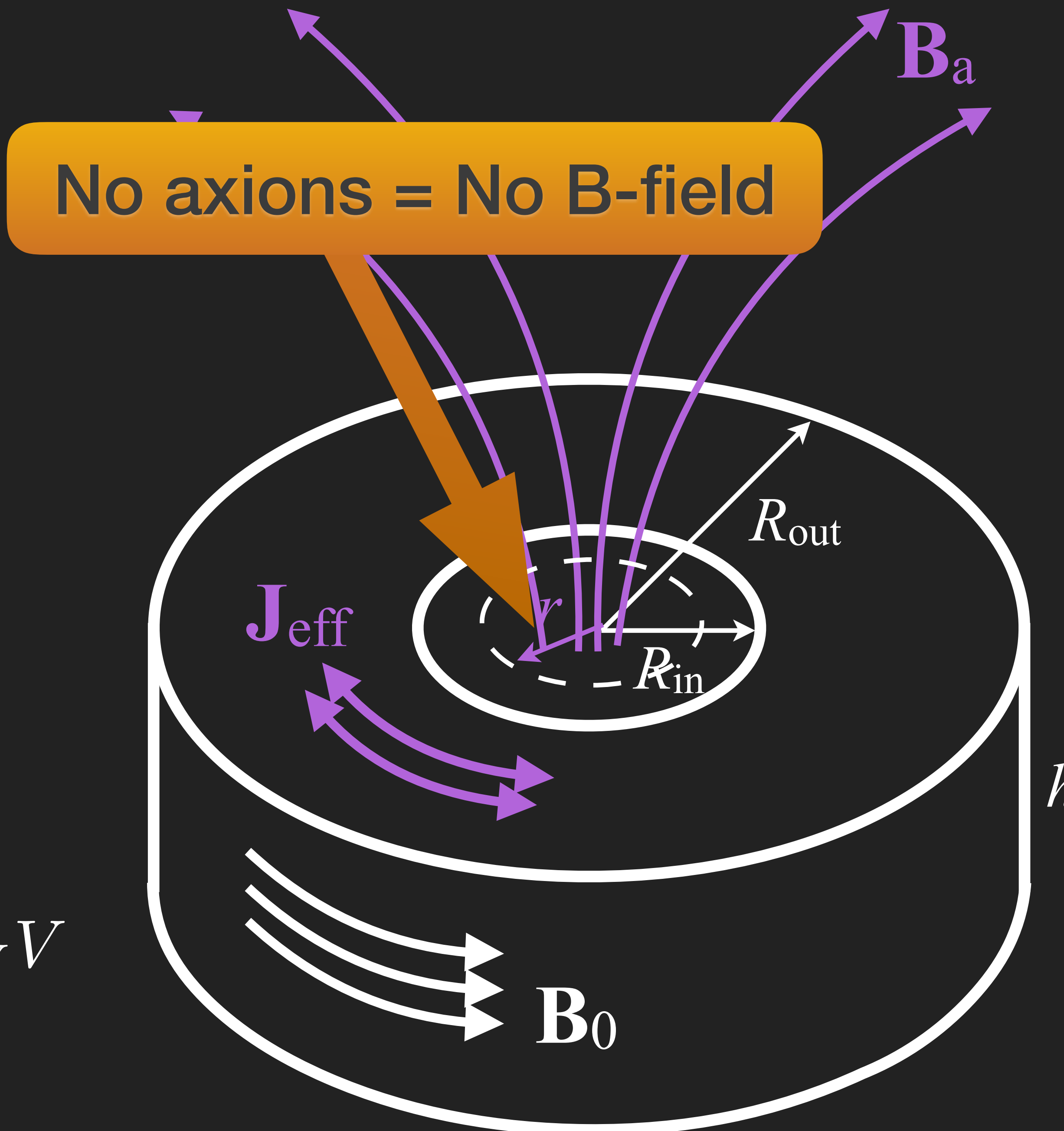

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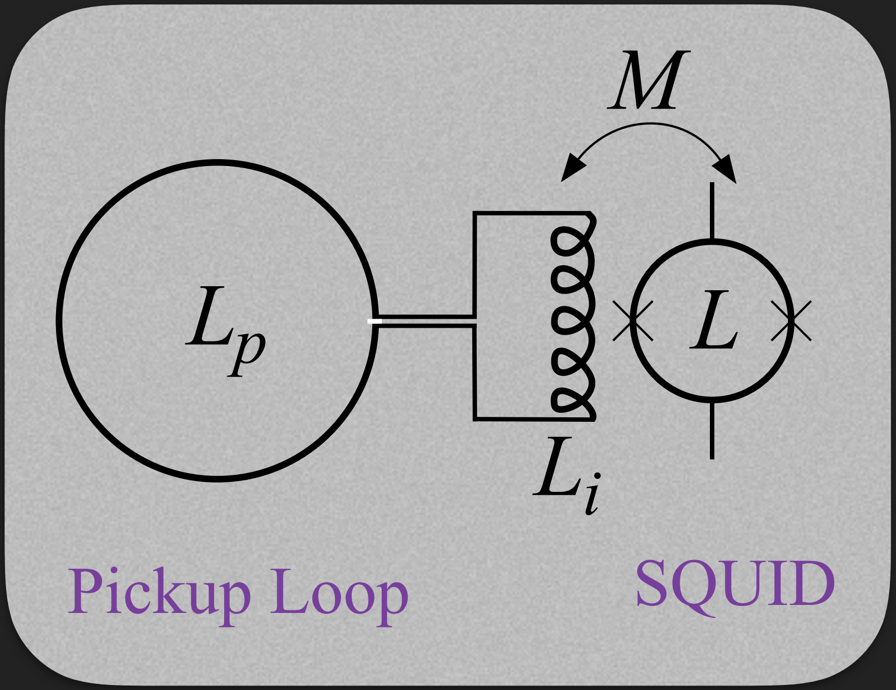
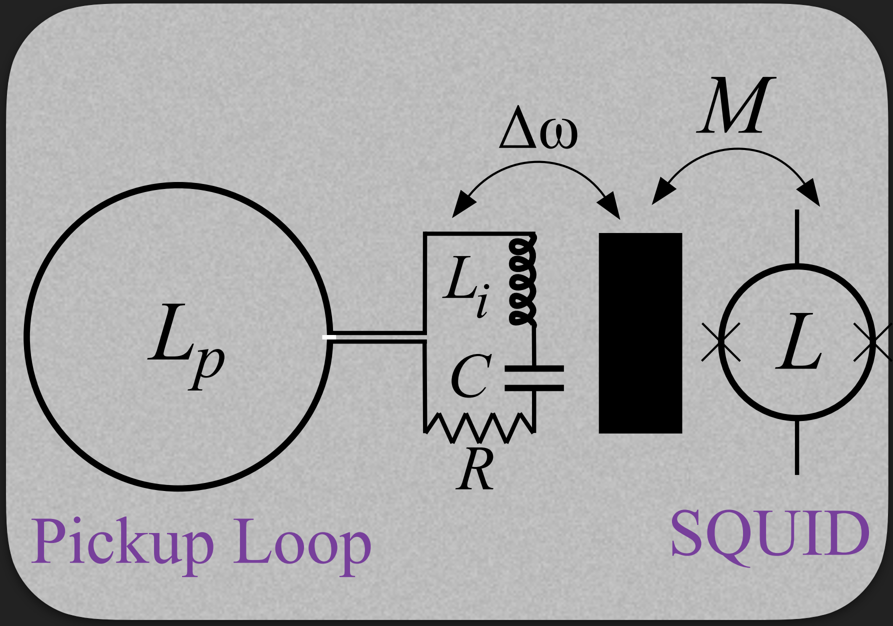
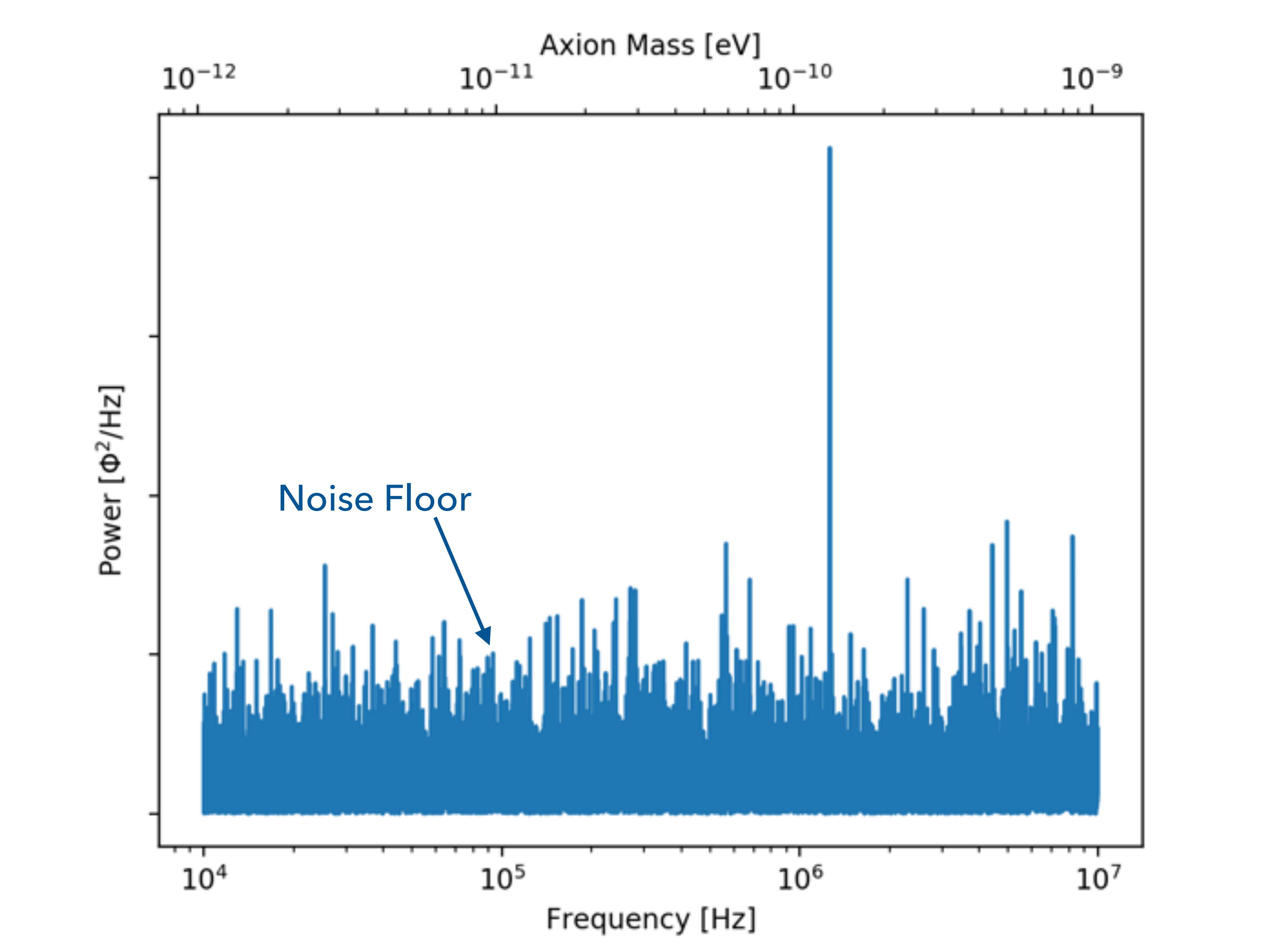
ABRACADABRA Readout

- 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, we plan to use a combination of the two
  - See talk from Saptarshi





An Example Axion Signal



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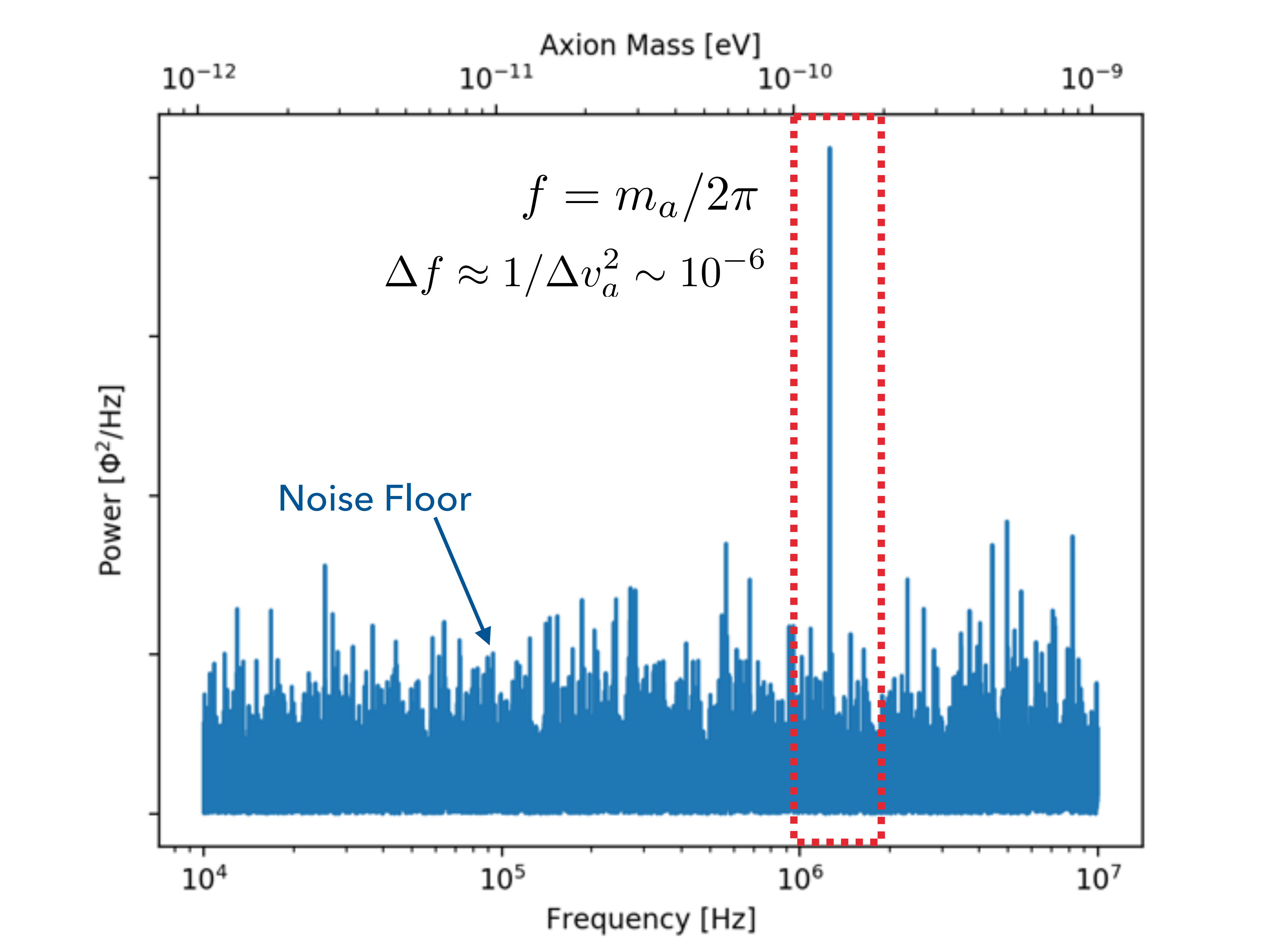
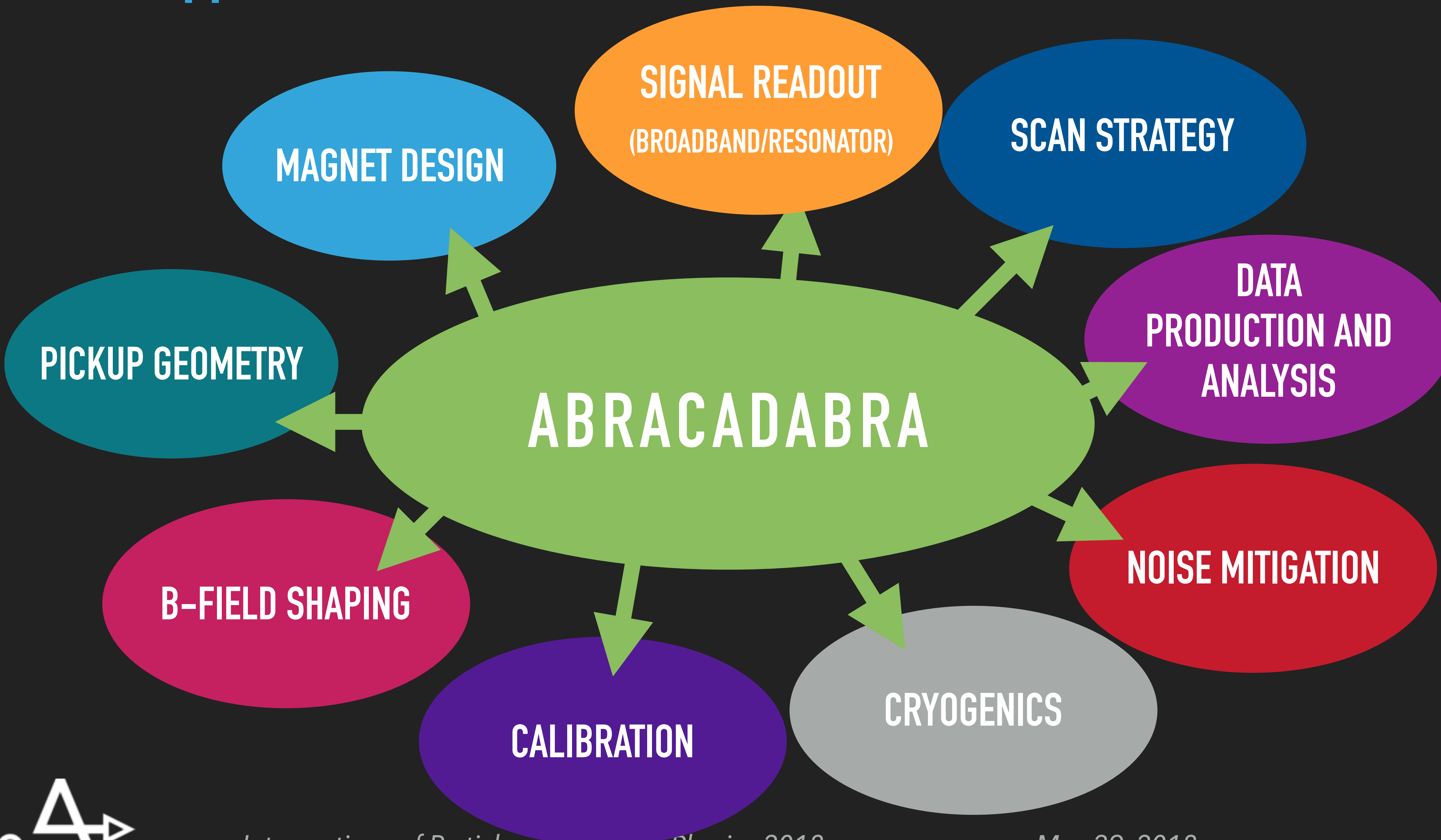


New Approach, A Lot of Questions



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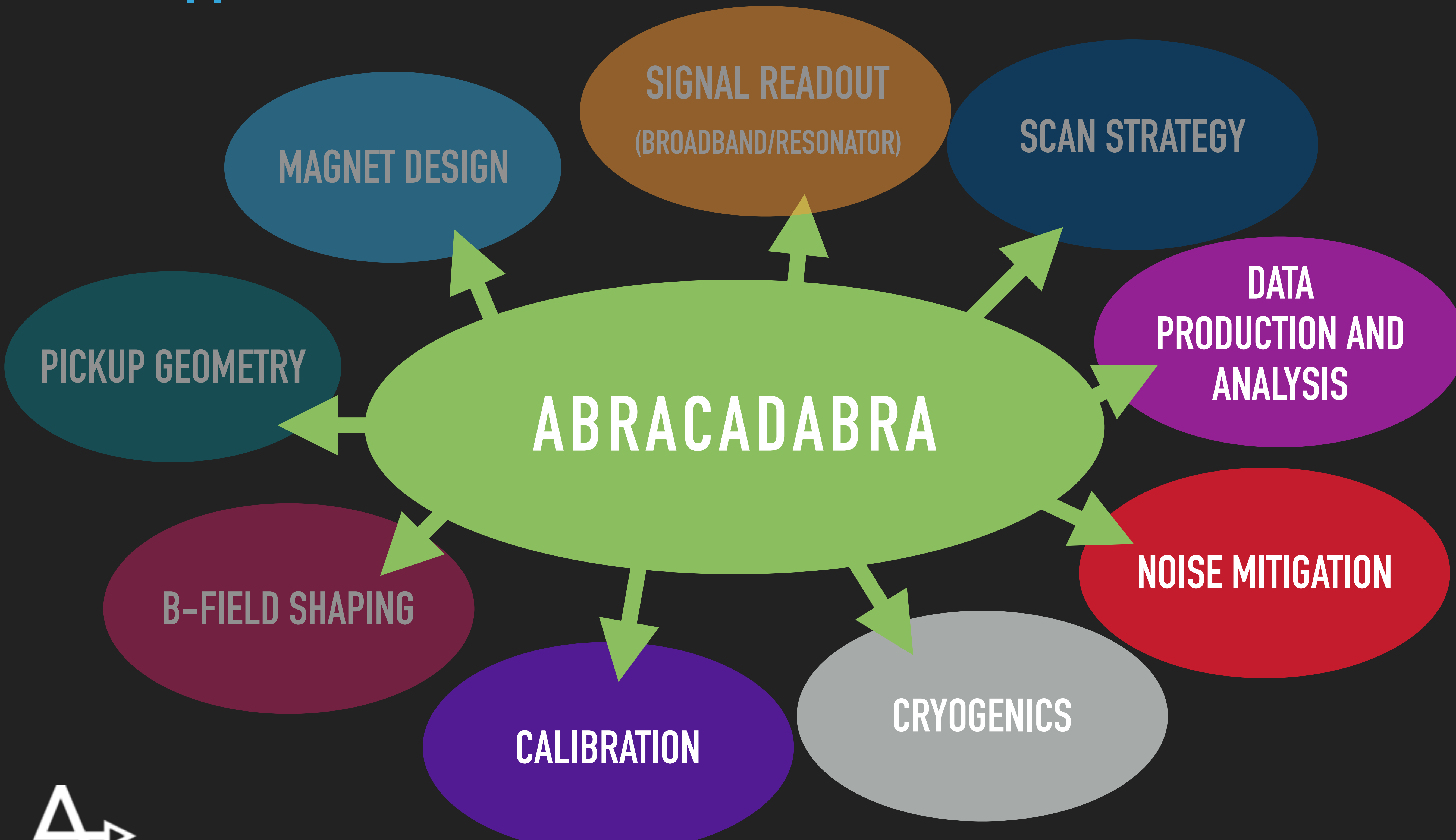
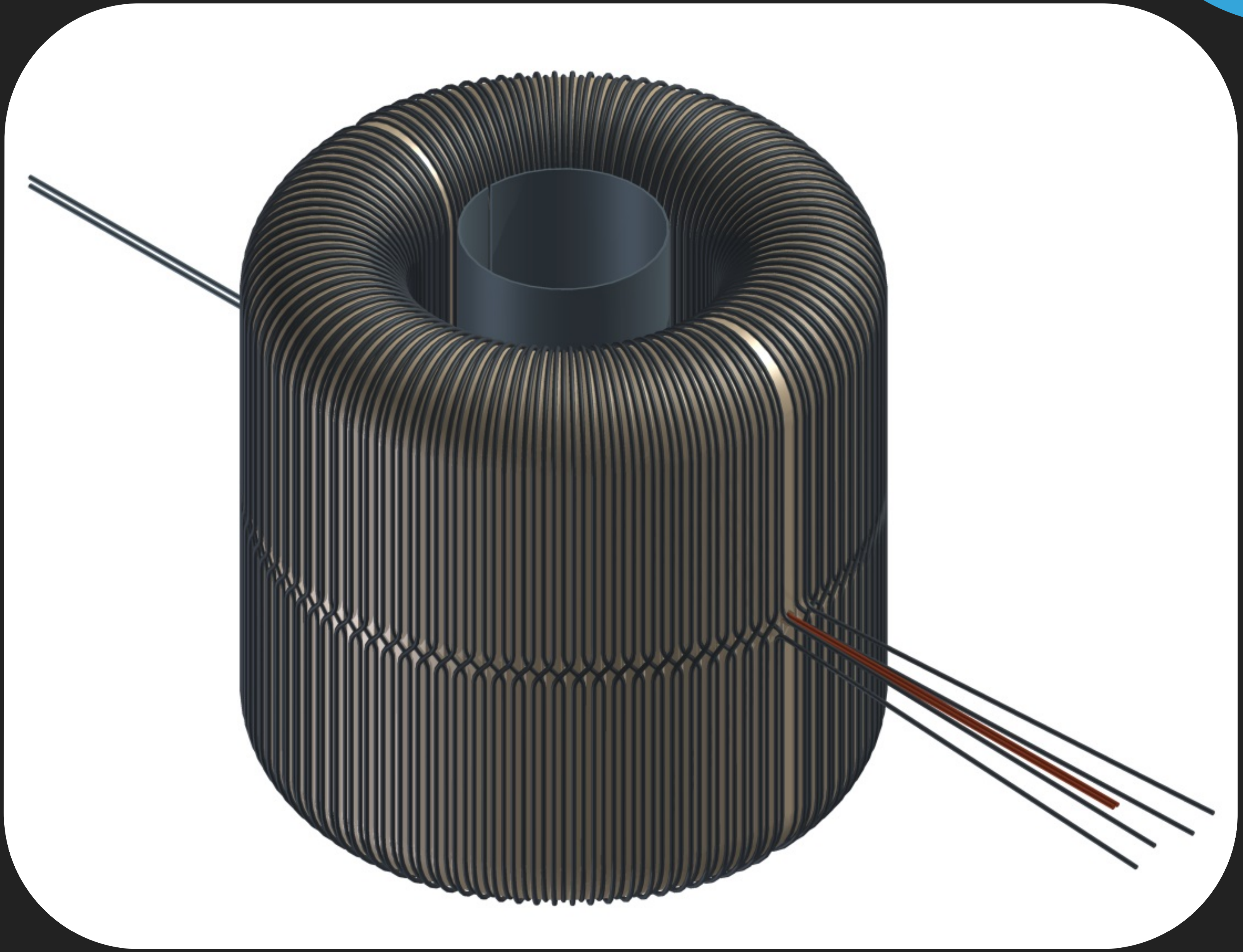


ABRACADABRA-10 cm

MAGNET DESIGN



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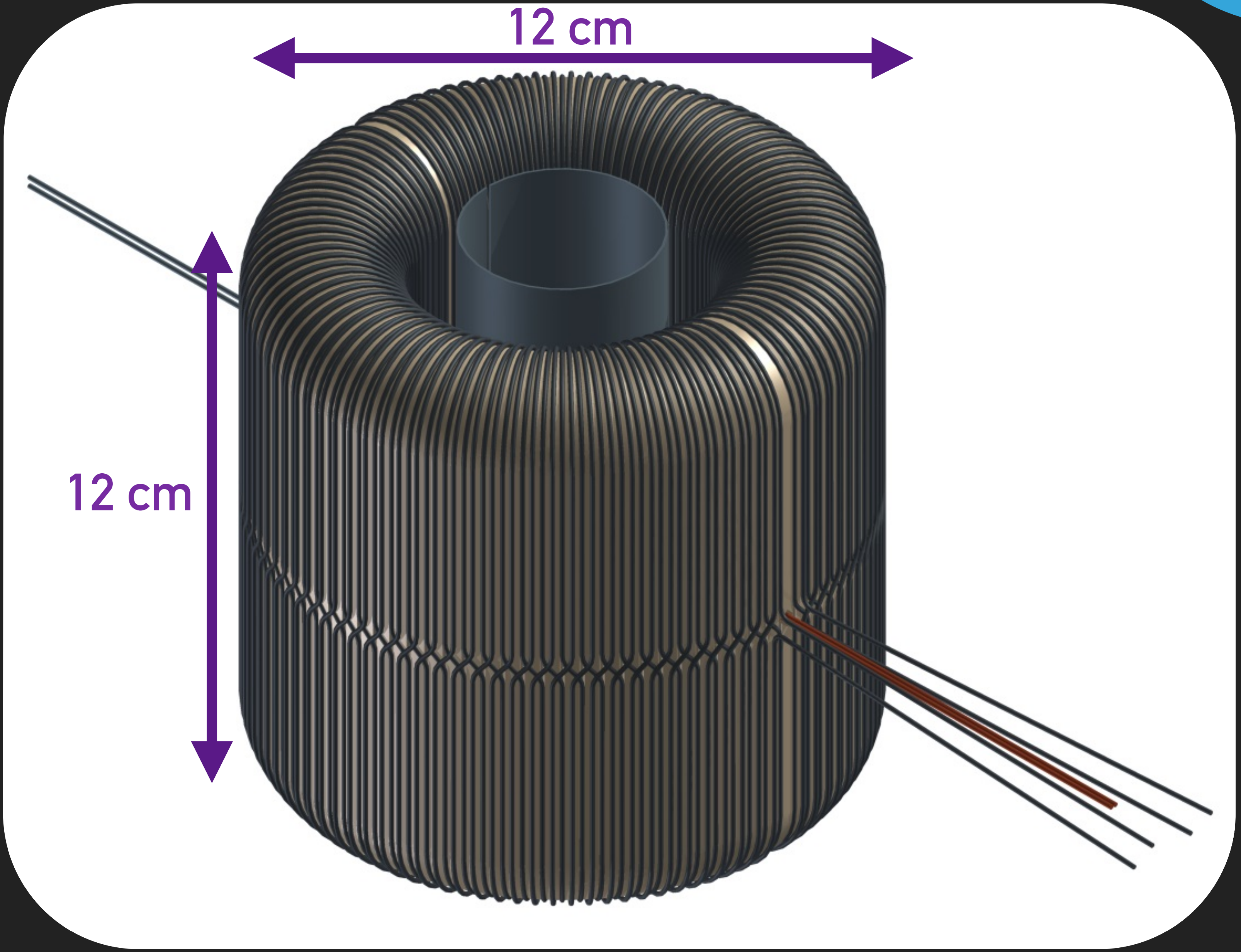

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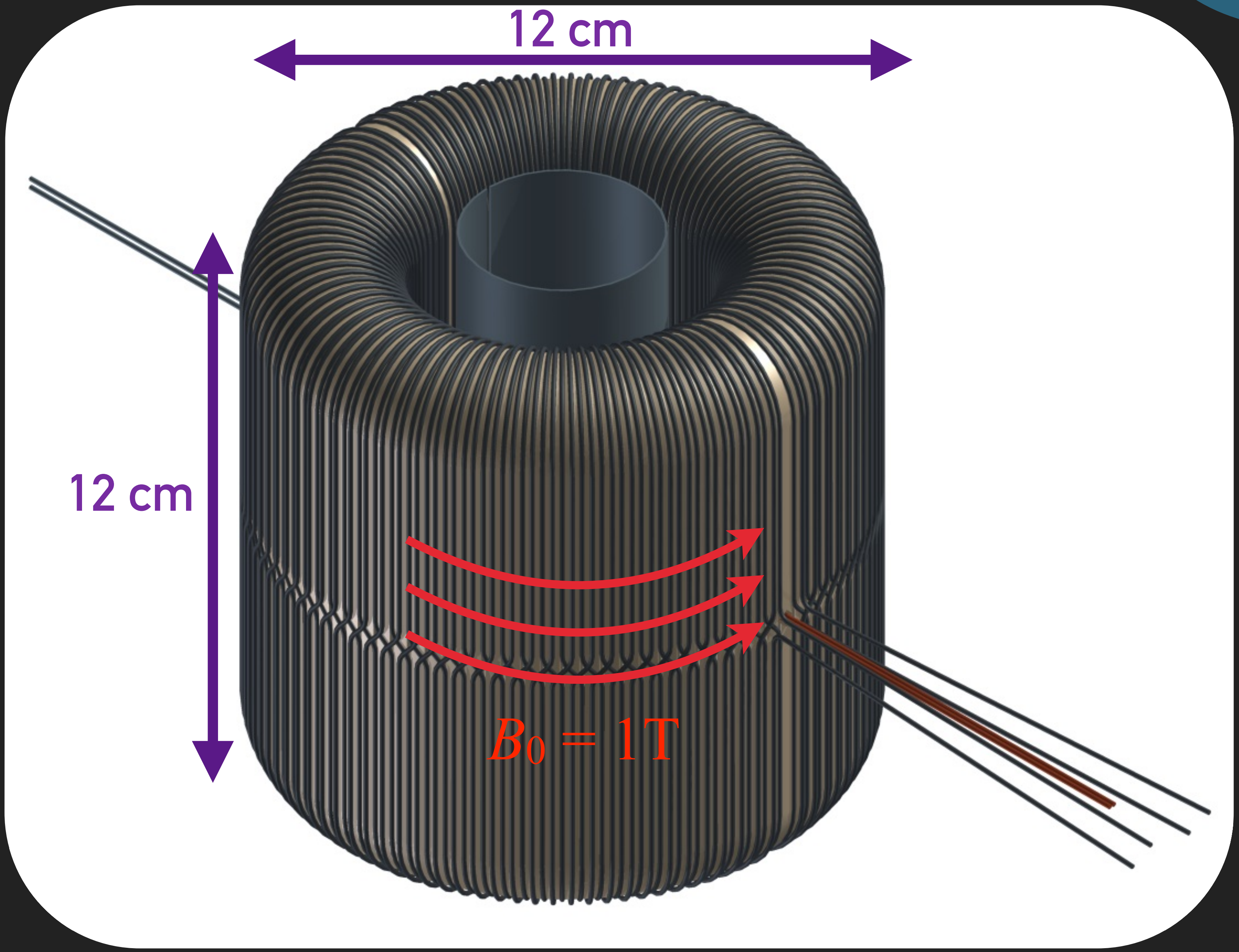
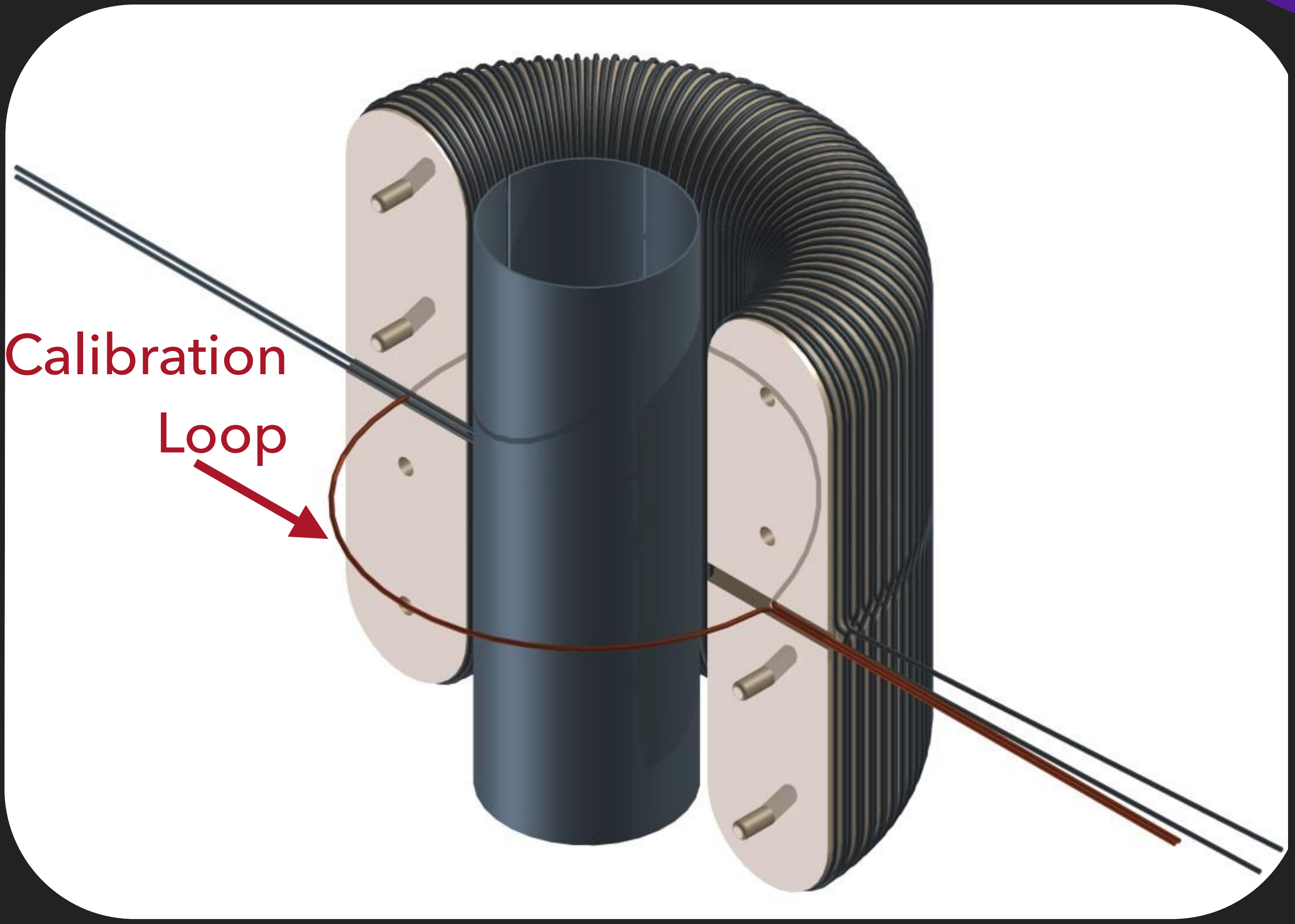


Calibration Loop

CALIBRATION



ABRACADABRA-10 cm

SUPERCONDUCTING SYSTEMS INC.

(Normally make MRI magnets!)

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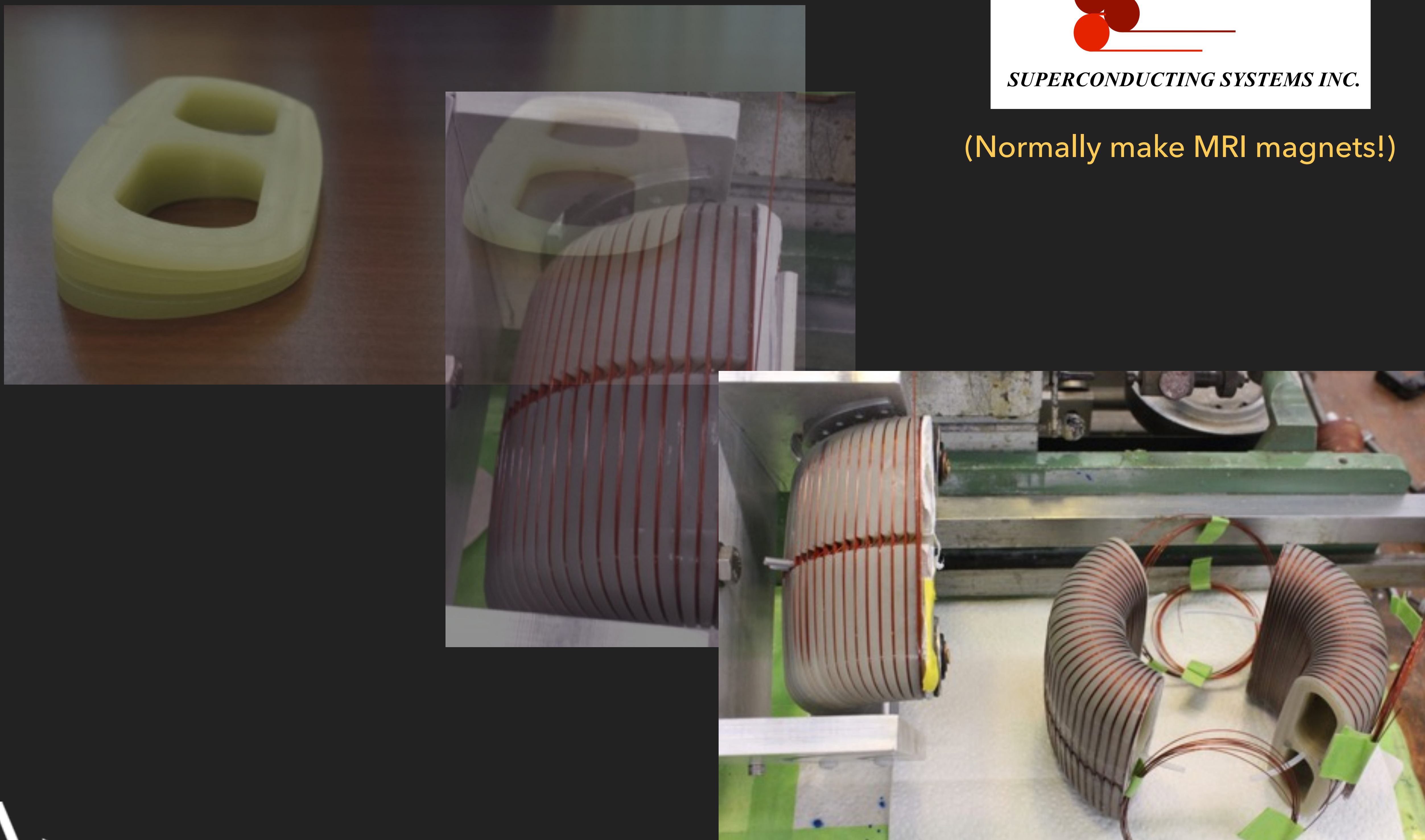

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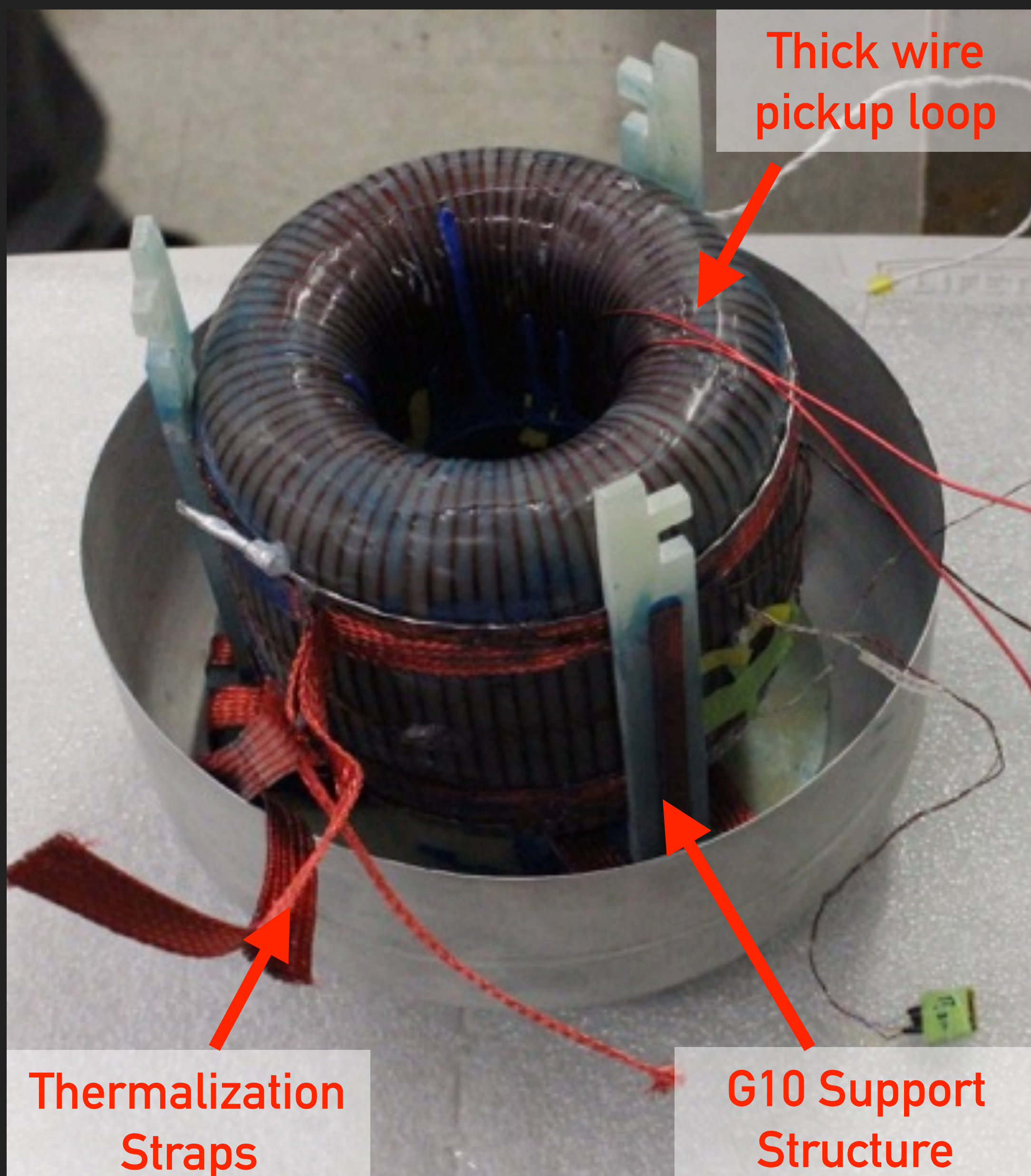
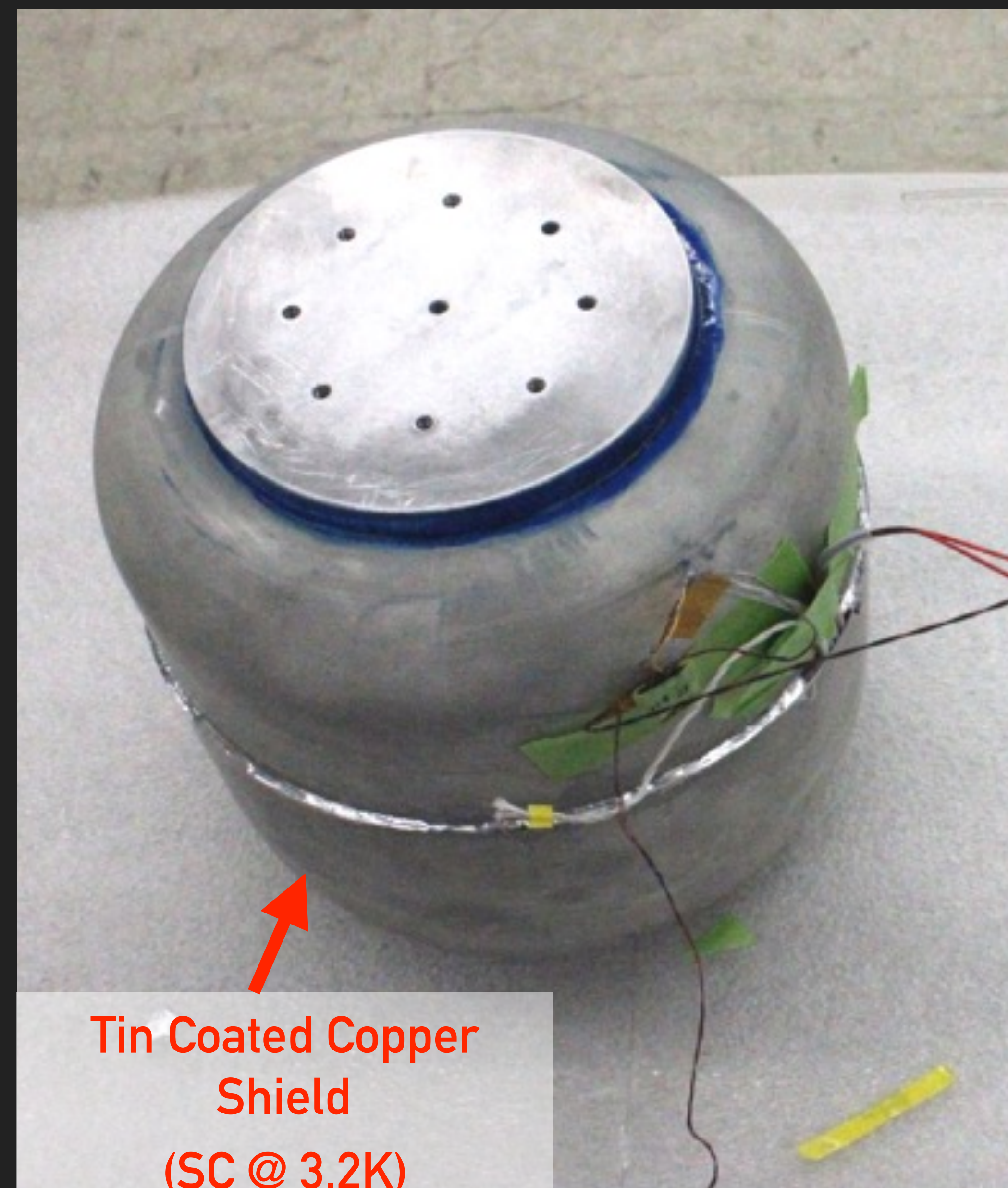
CRYOGENICS

NOISE MITIGATION

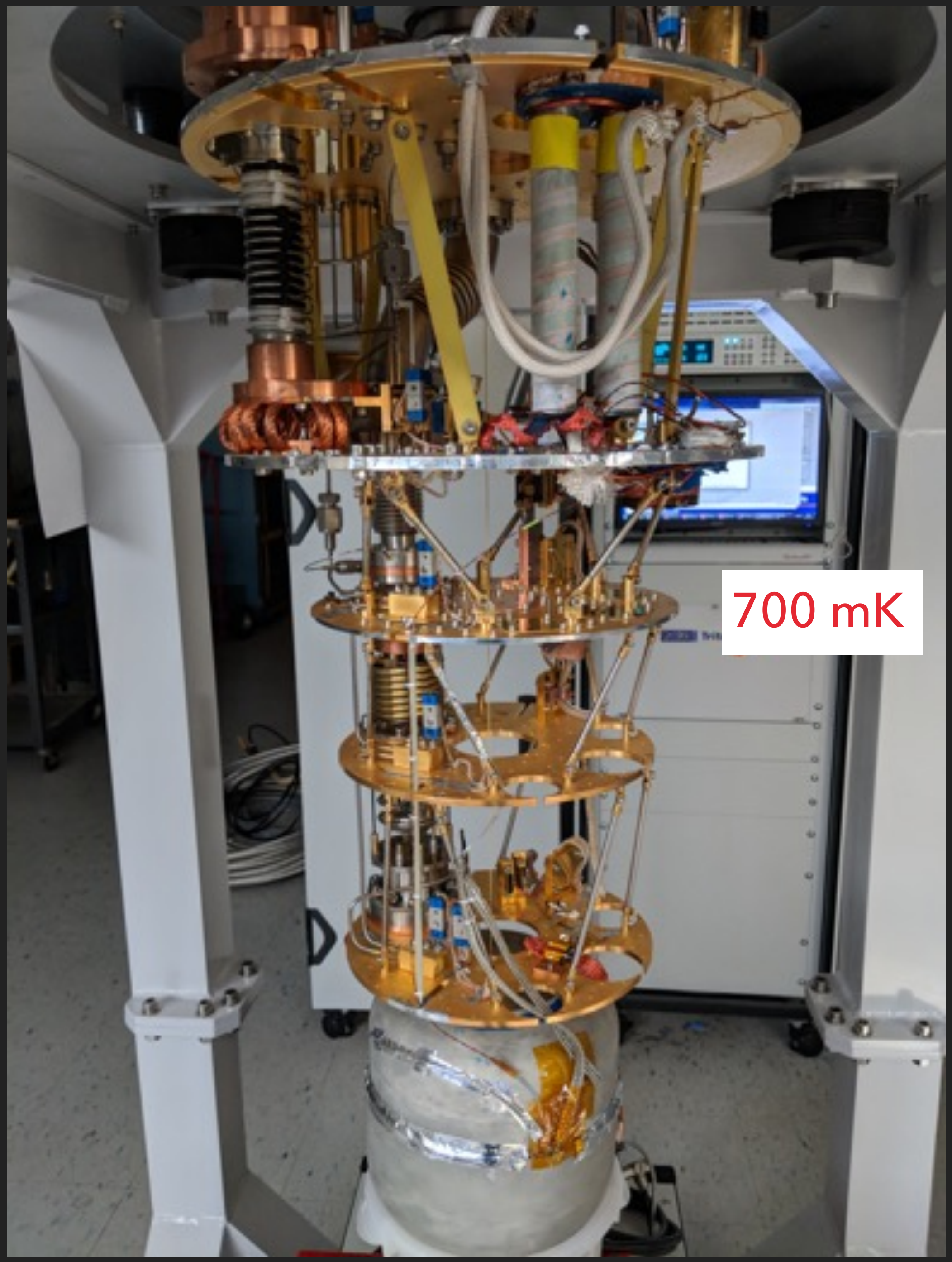
ABRACADABRA-10 cm

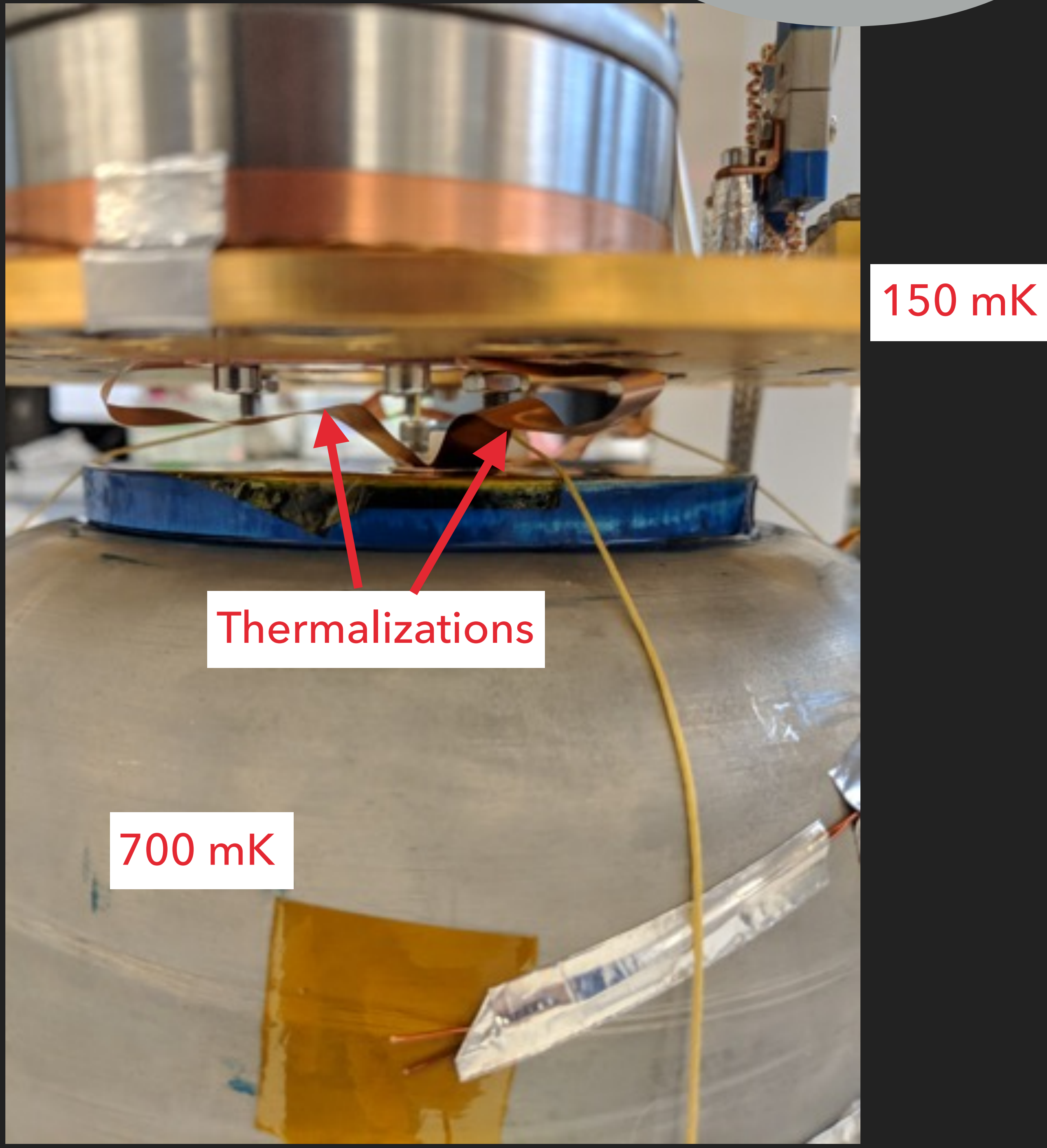




CRYOGENICS

Suspension System

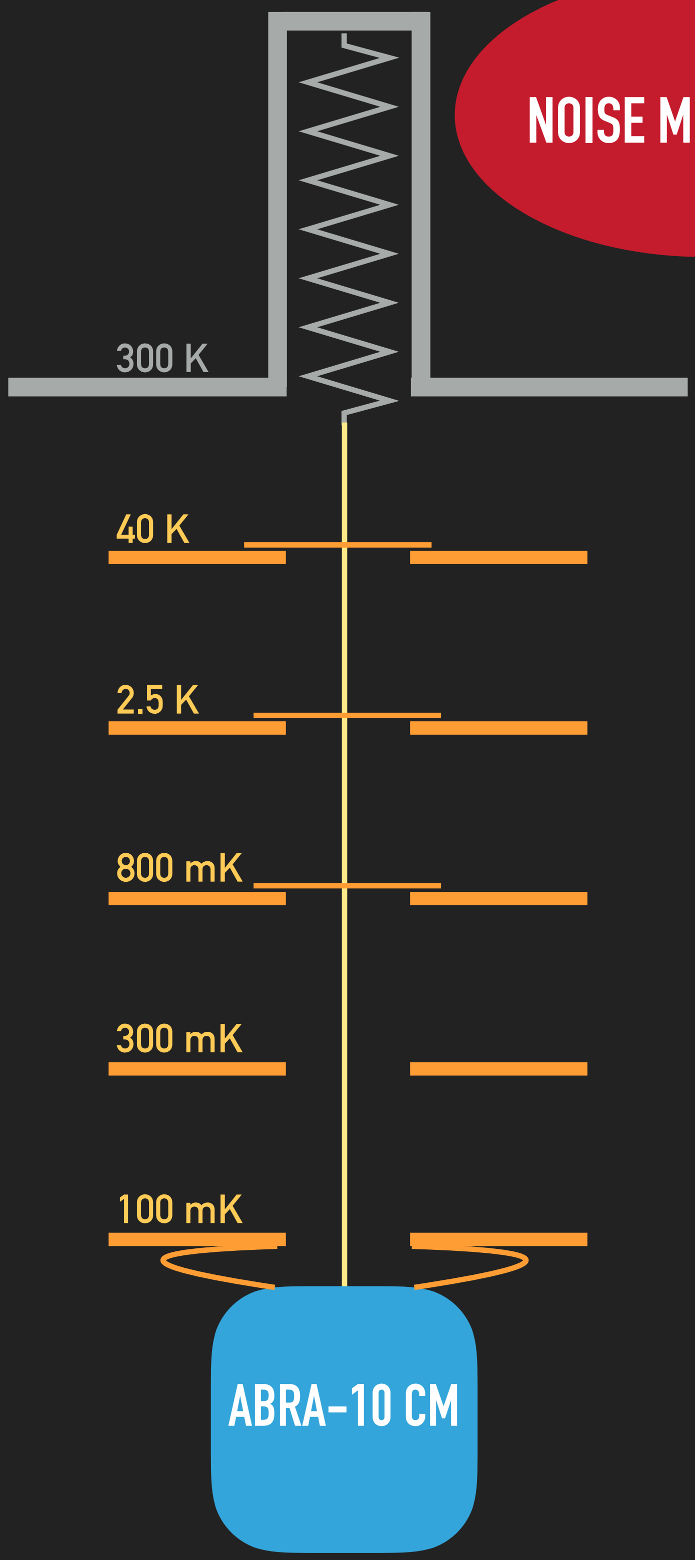




Suspension System

NOISE MITIGATION

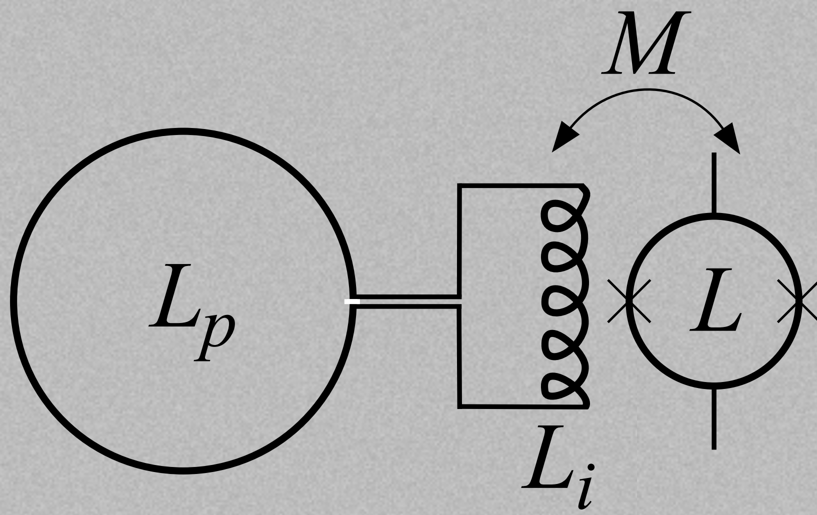
- Vibration isolation suspension system
  - 150 cm pendulum, with a resonance frequency of ~ 2 Hz
  - In the Z direction, a spring with a resonance frequency of ~8 Hz
- Supported by a thin Kevlar thread with very poor thermal conductivity
- Can be upgraded with minus-K isolation



SIGNAL READOUT
(BROADBAND/RESONATOR)

SQUID Current Sensors

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



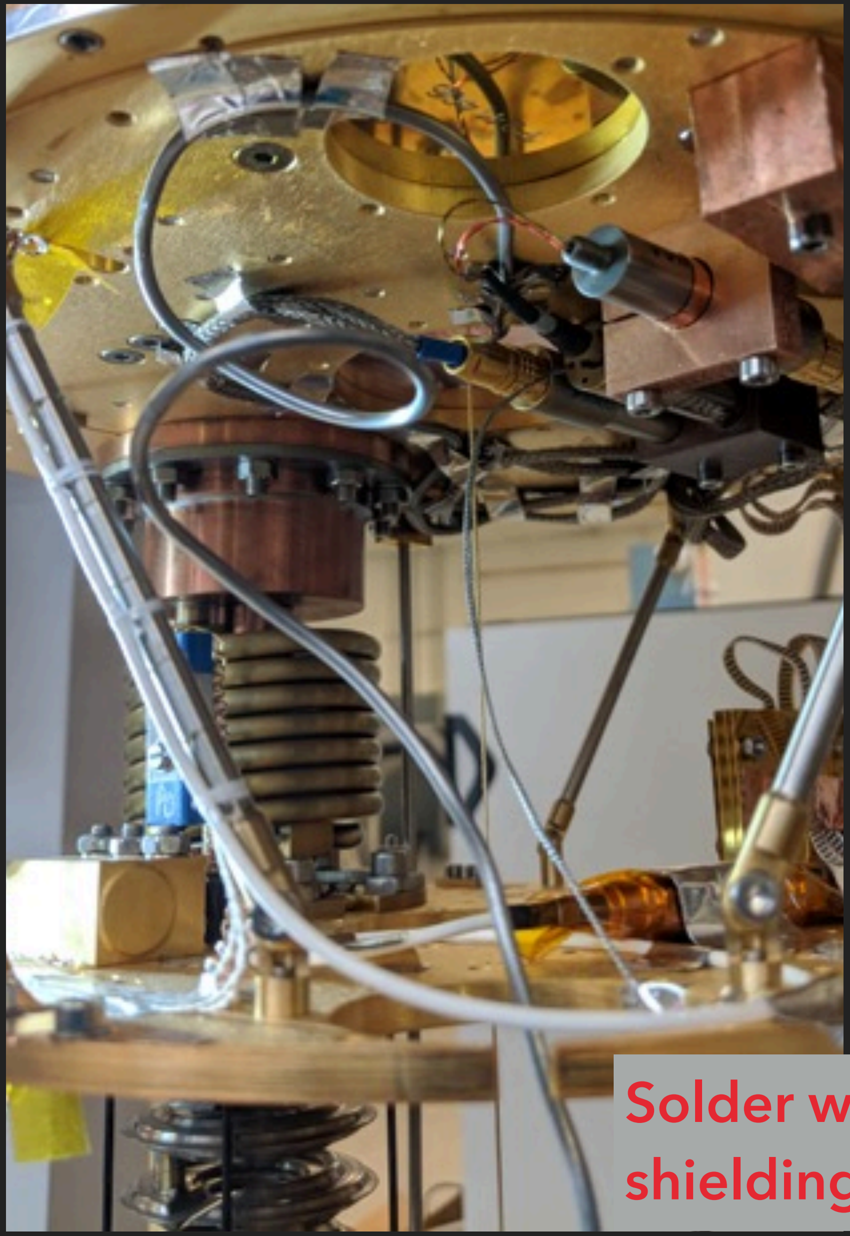
Broadband Configuration

Magnetic Shielding

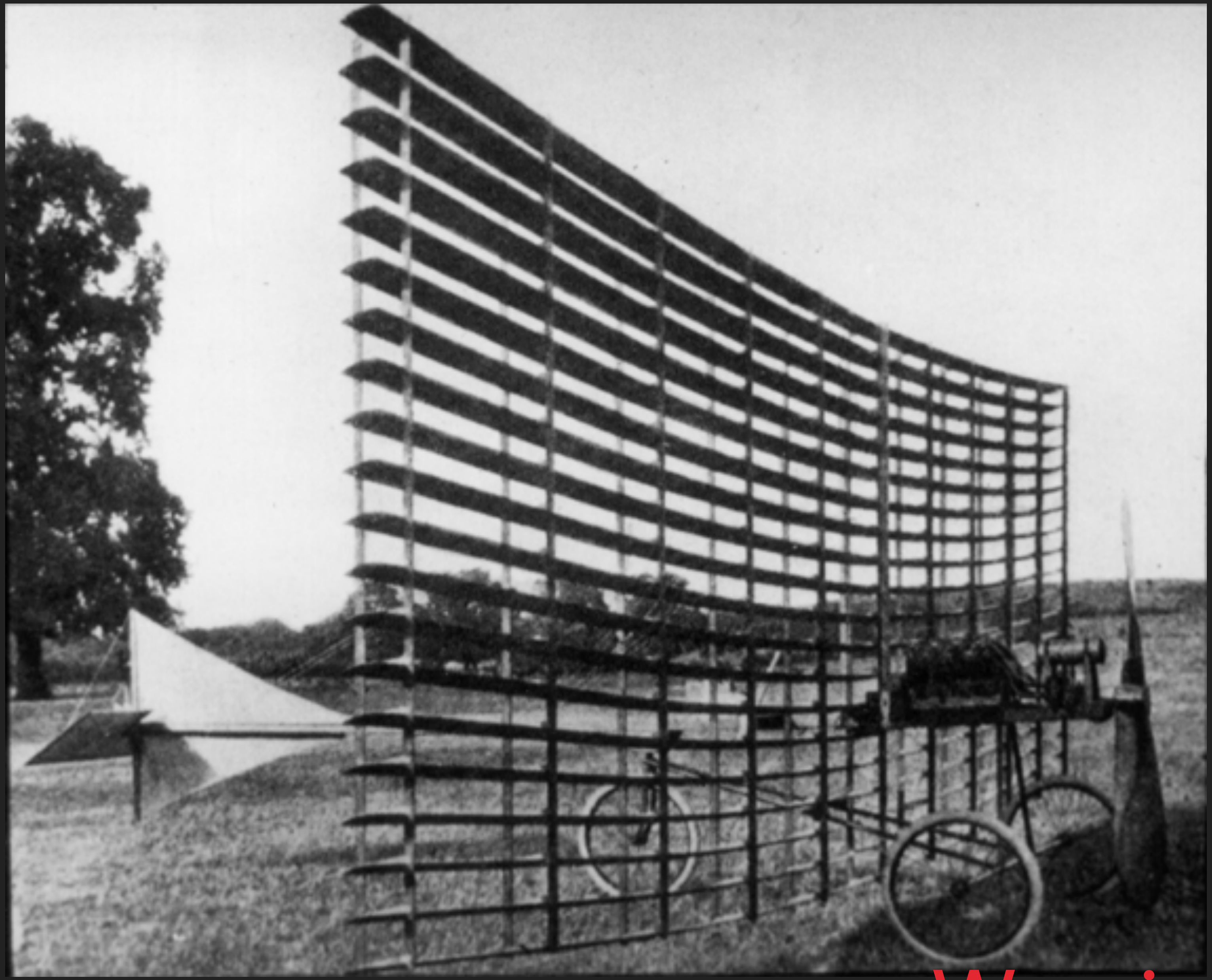
NOISE MITIGATION

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

Wiring and Shielding



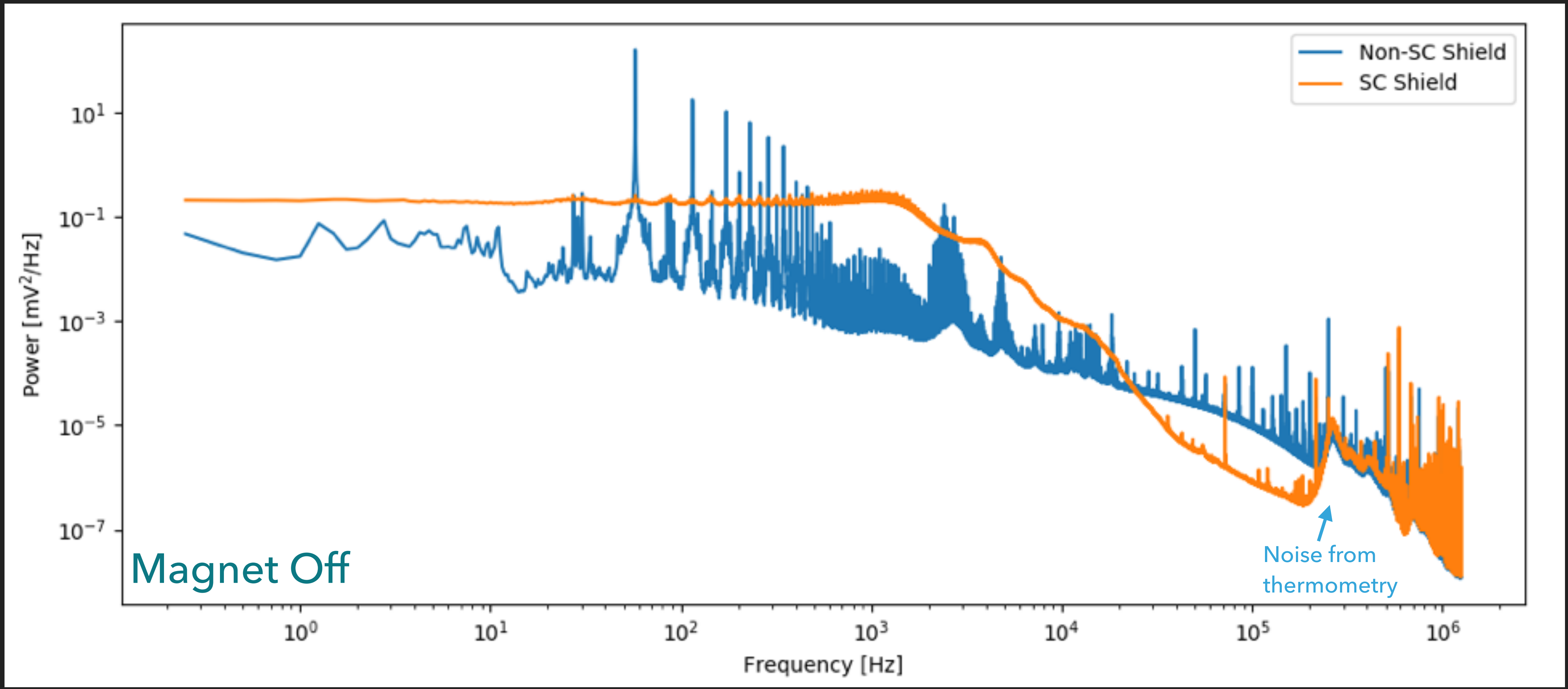
Early Data



Warning: Very Preliminary

Proceed with caution!

Early Data



Note: Do not trust the normalizations of this plot, look at the overall shape.

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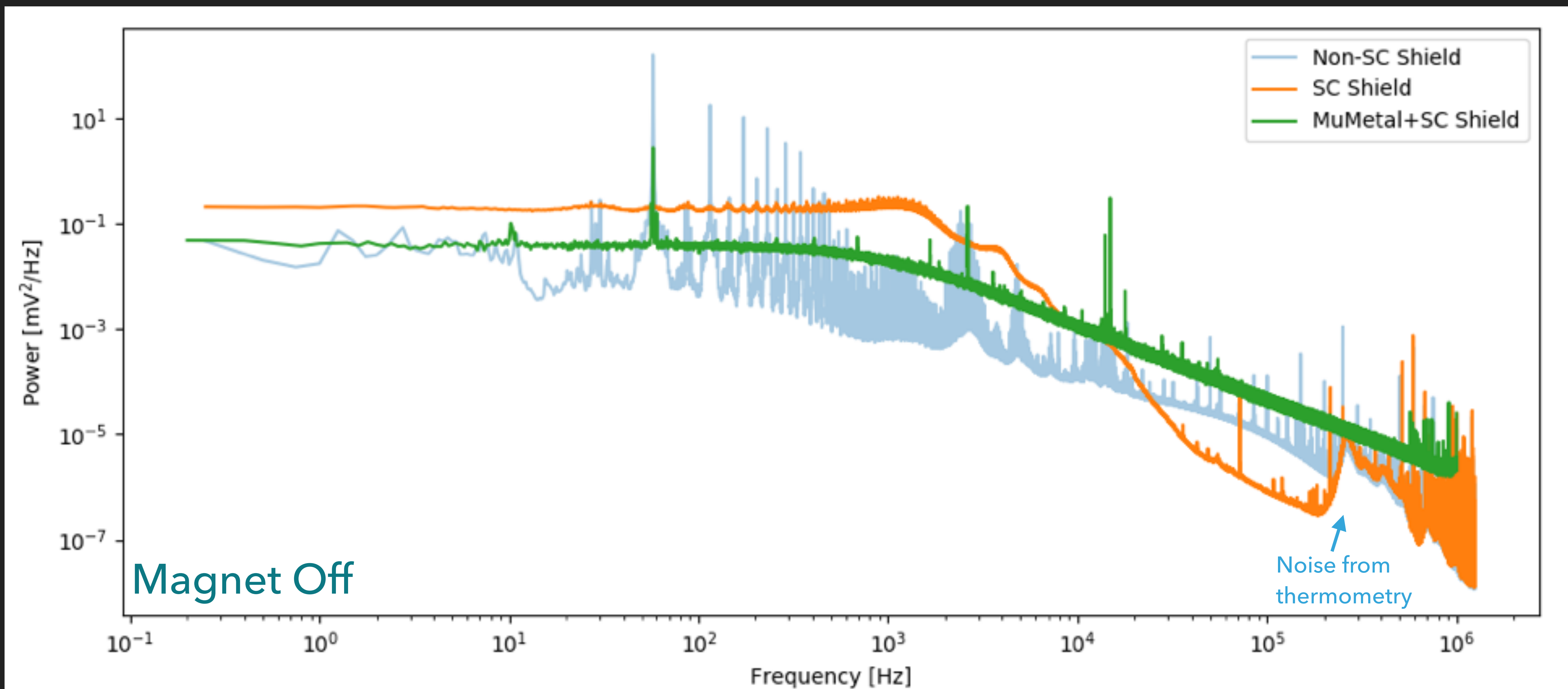

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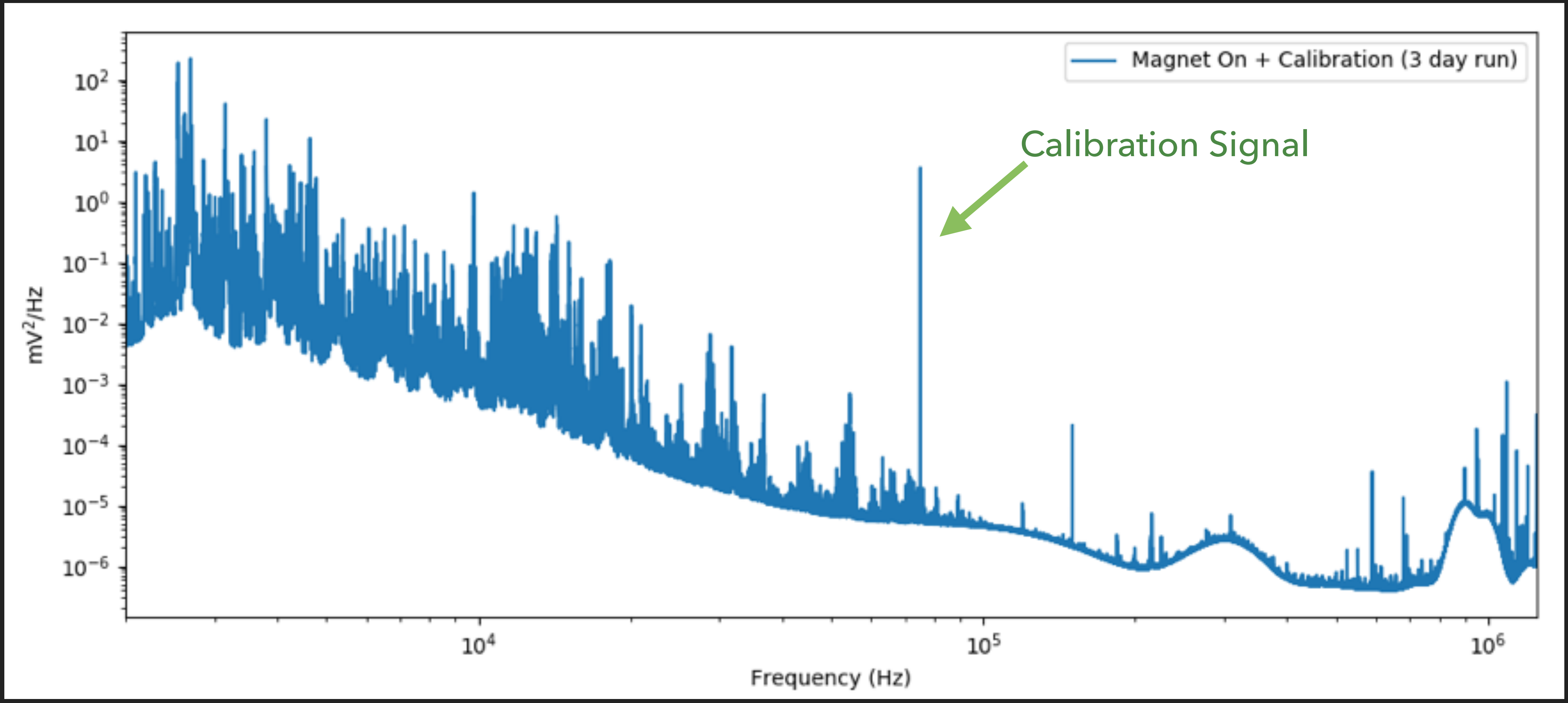

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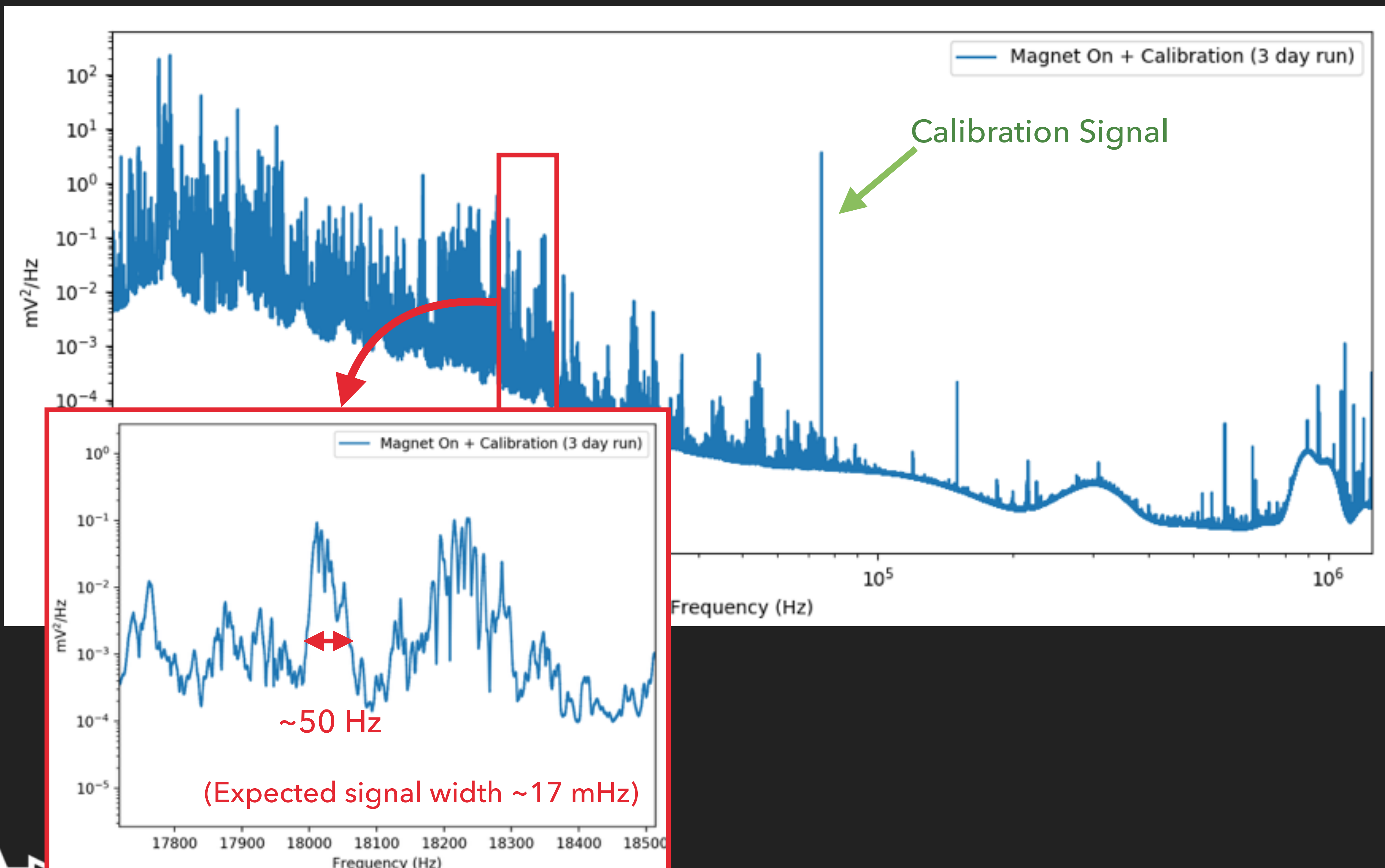

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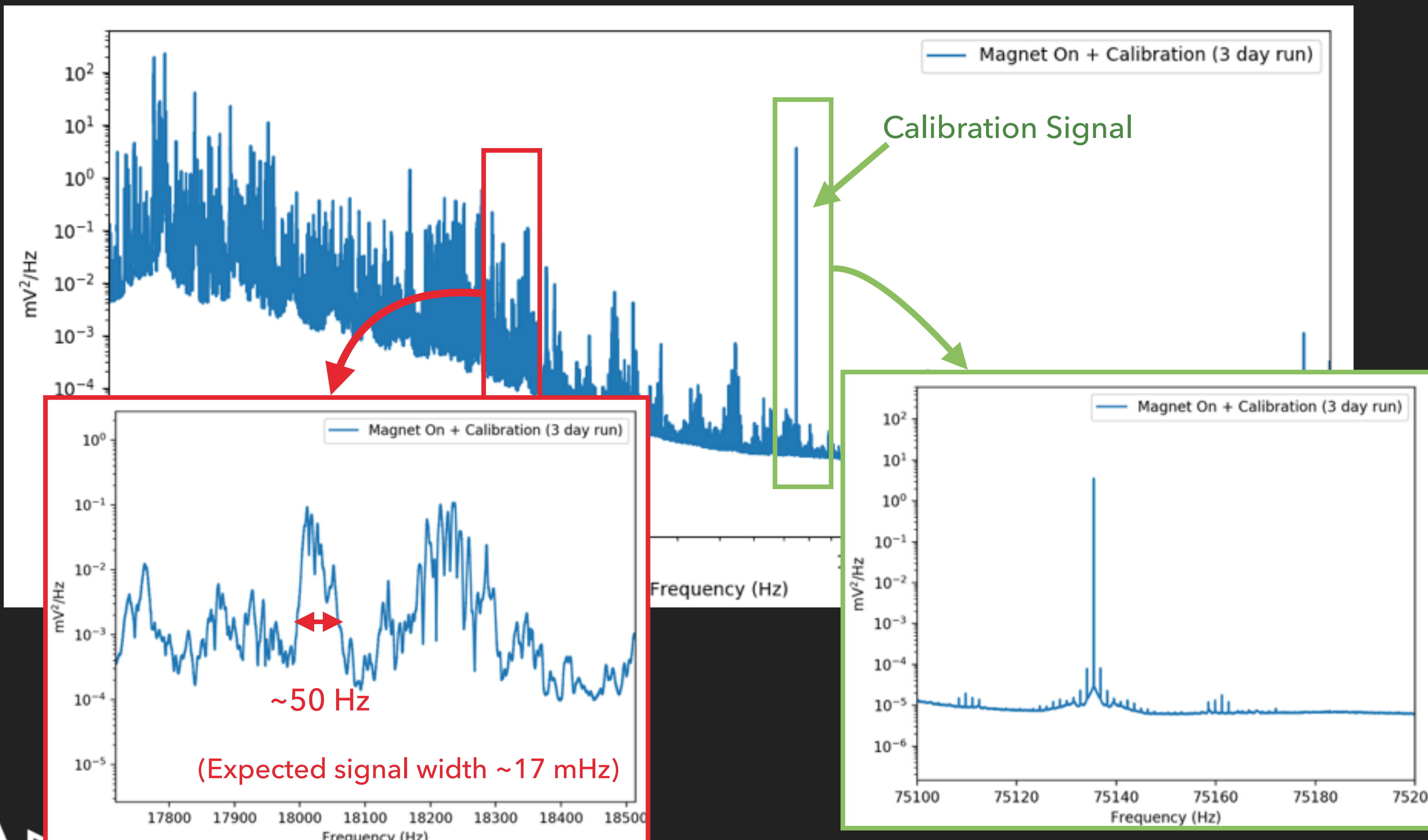
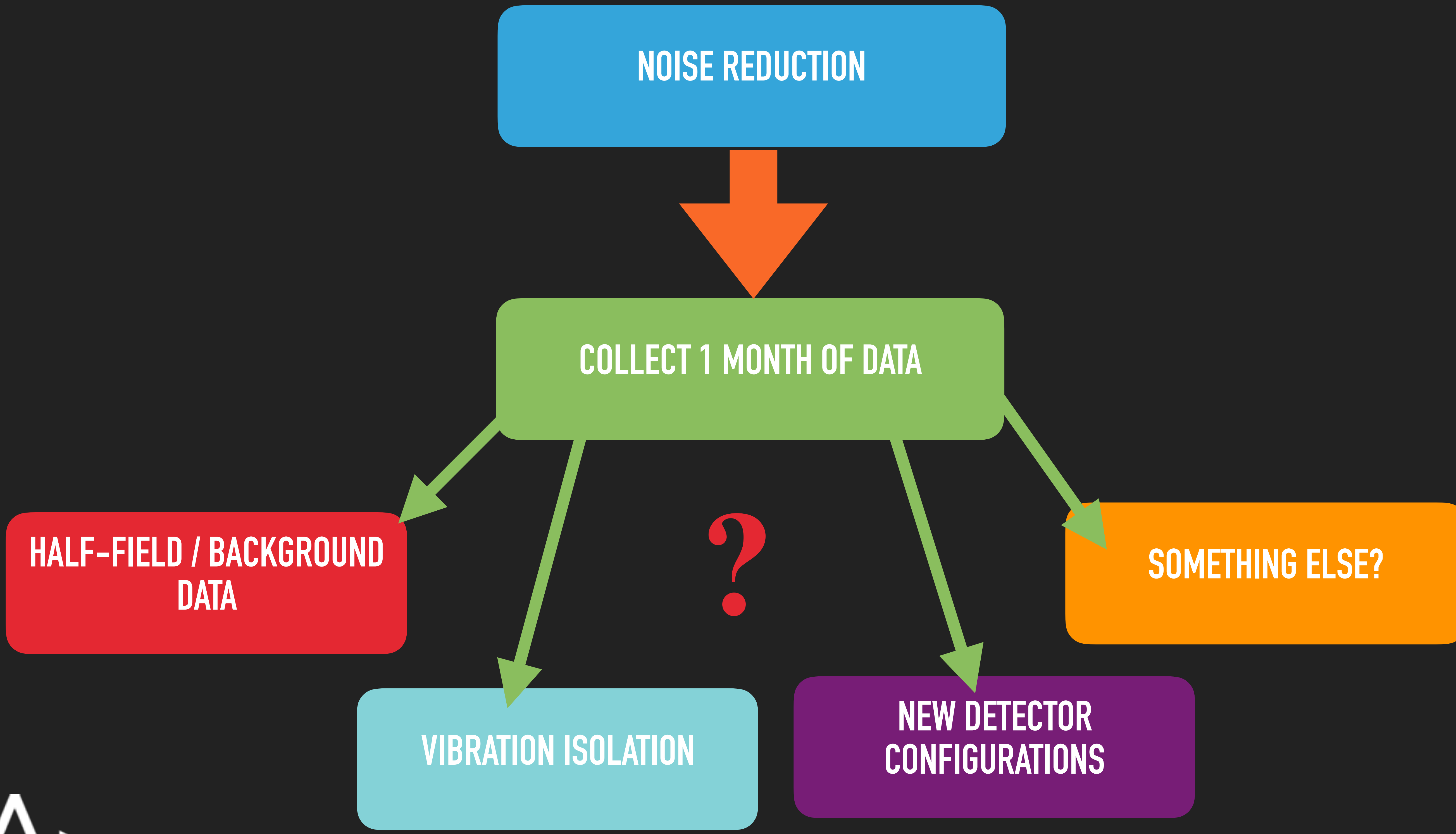


Next Steps


NOISE REDUCTION
COLLECT 1 MONTH OF DATA
HALF-FIELD / BACKGROUND DATA
VIBRATION ISOLATION
?
NEW DETECTOR CONFIGURATIONS
SOMETHING ELSE?

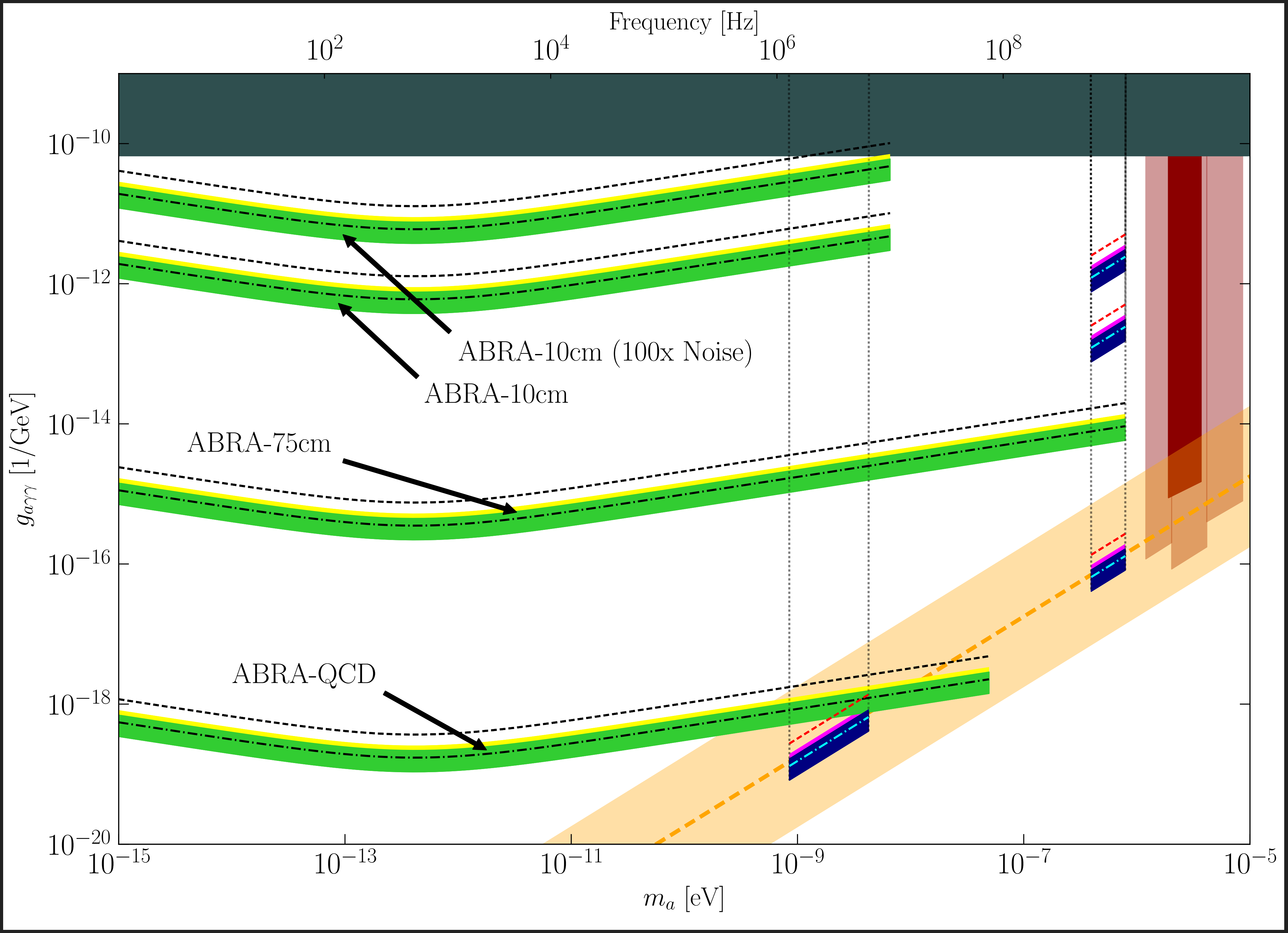
NEXT GENERATION:

ABRACADABRA-75 CM

ABRACADABRA-75 cm

- $R_{\text{in}} = R_{\text{out}}/2 = h/3 = 75$ cm
- $B_0 = 1 - 5$ T
- Resonant Goals:
  - Quality factor of 10^6
  - Thermal noise limited at 100 mK
- ABRACADABRA Magnet
  - Approx. 2 - 50 MJ stored energy
  - Cost around \$500k ~ 10M
- Capable of reaching the QCD axion regime

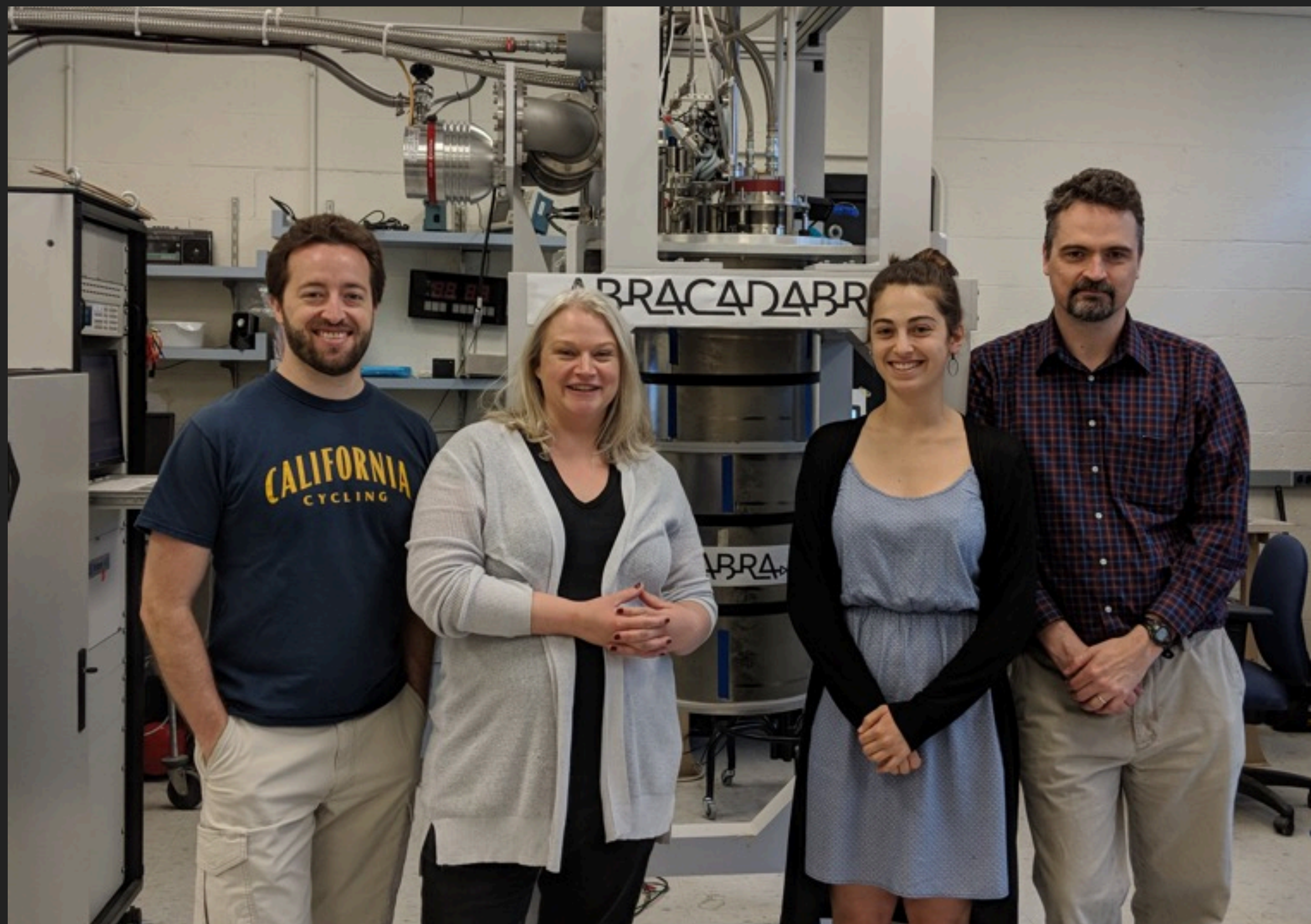
ABRACADABRA Sensitivity



Summary

- ABRACADABRA-10 cm is currently commissioning
  - Have a magnet and have charged it!
  - Reducing Noise Sources
  - Developing data acquisition and analysis infrastructure
  - Pushing to have first results later this year
- Working towards a larger m^3 version of the detector capable of probing QCD scale
  - Using the ABRA-10 cm to investigate noise sources, shielding configurations, etc
  - Investigate optimal data taking configurations

Thanks for your attention!



ABRA Backup Slides

Sensitivity (Roughly)

- Broadband mode is independent of temperature

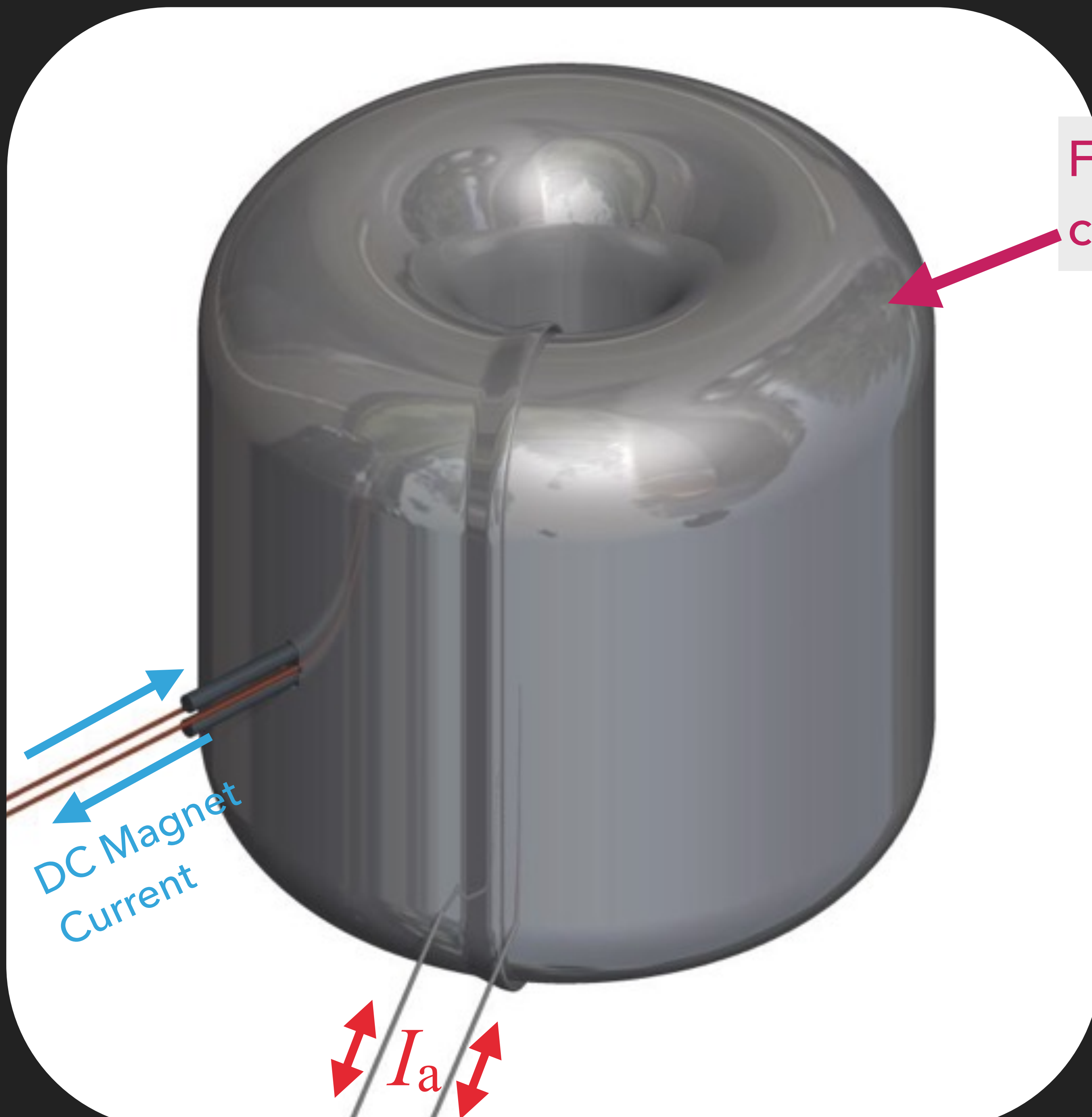
$$g_{a\gamma\gamma} \propto \left(\frac{m_a}{t}\right)^{1/4} \frac{1}{B_{\max}} \frac{1}{\mathcal{G}_V V} \frac{1}{\sqrt{\rho_{\mathrm{DM}}}} S_{\Phi,0}^{1/2}$$

- Resonant mode limited by thermal noise

$$g_{a\gamma\gamma} \propto \sqrt{L_T} \left(\frac{1}{m_a t_{\mathrm{scan}}}\right)^{1/4} \frac{1}{B_{\max}} \frac{1}{\mathcal{G}_V V} \sqrt{\frac{1}{\rho_{\mathrm{DM}}} \frac{k_B T}{Q_0}}$$

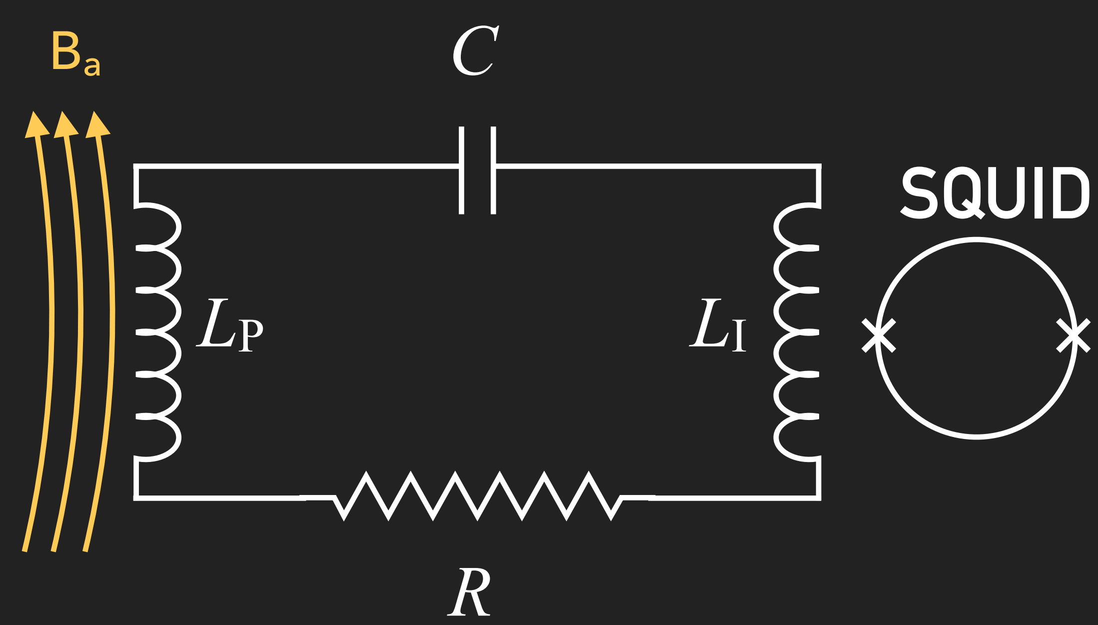
- Caveat: Neither of these are quite correct or ideal

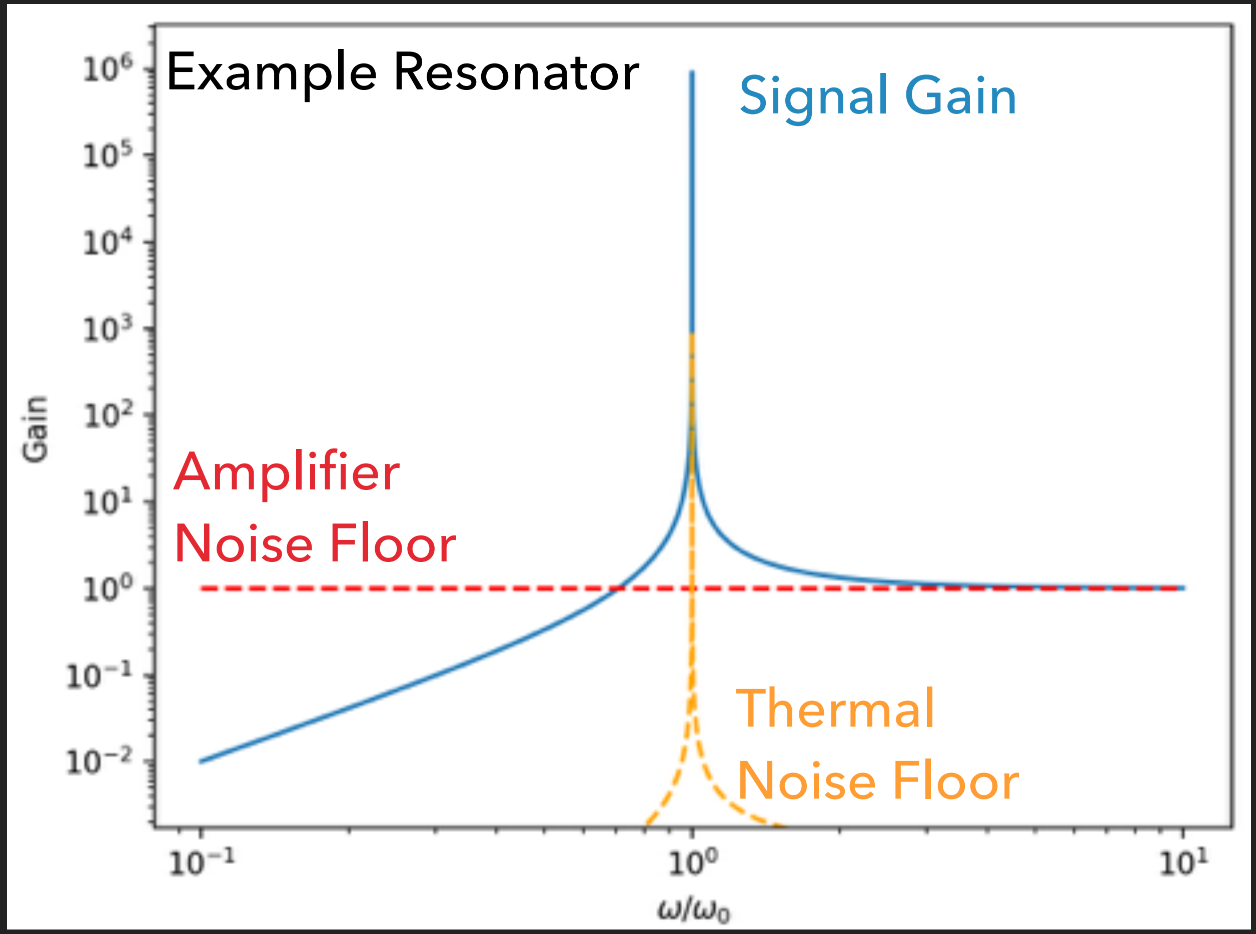
Pickup Loop Geometry



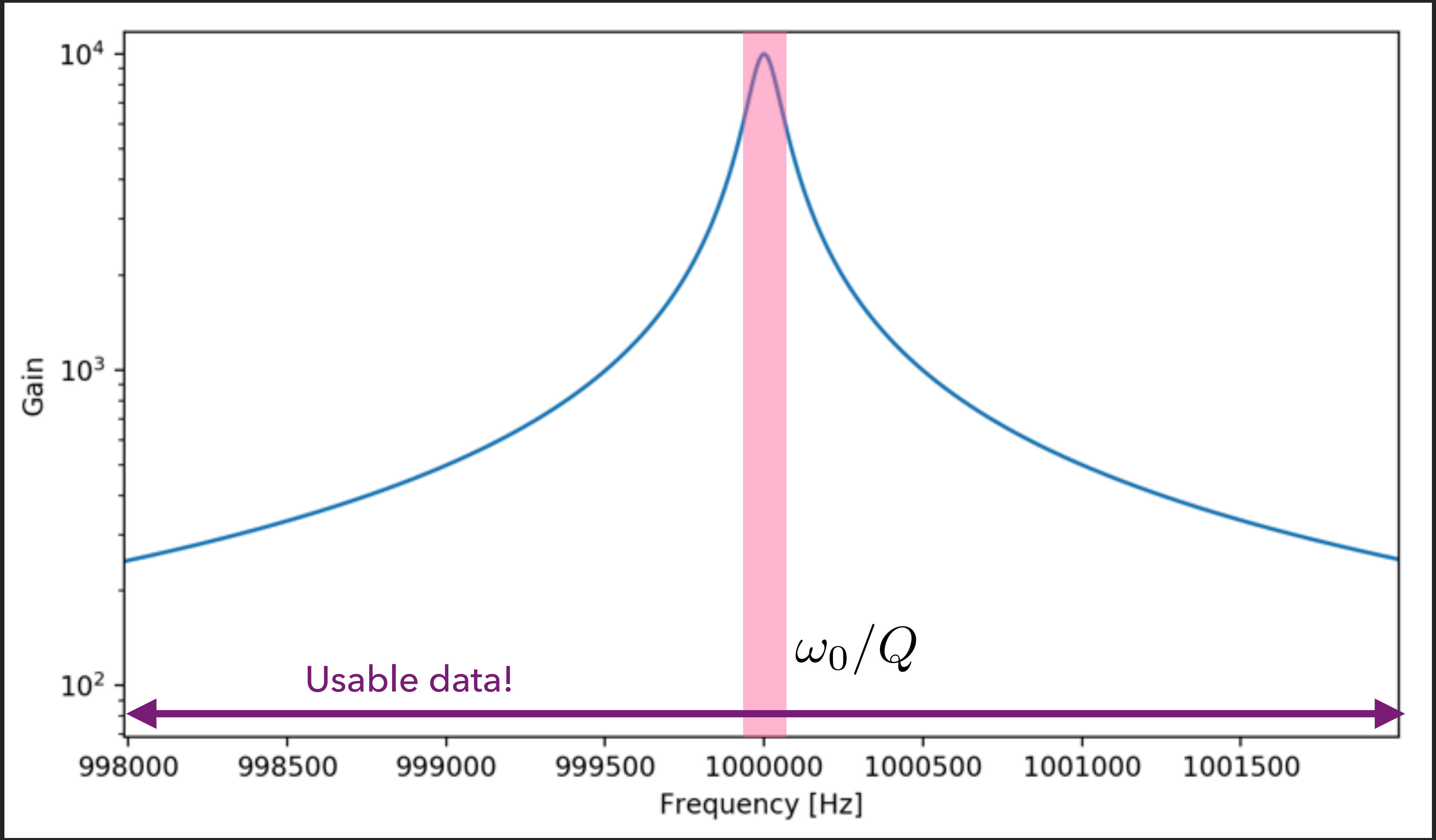
Resonator Circuit

- Resonator in electronics rather than in cavity!
- Similar to a cavity, can amplify by ~6 orders of magnitude in a narrow band
  - Can reach the thermal noise floor!
  - Need to scan
- Unlike a cavity, the search should not be limited to a narrow band!
  - Amplification over a wide band
  - Broadband search above resonance frequency



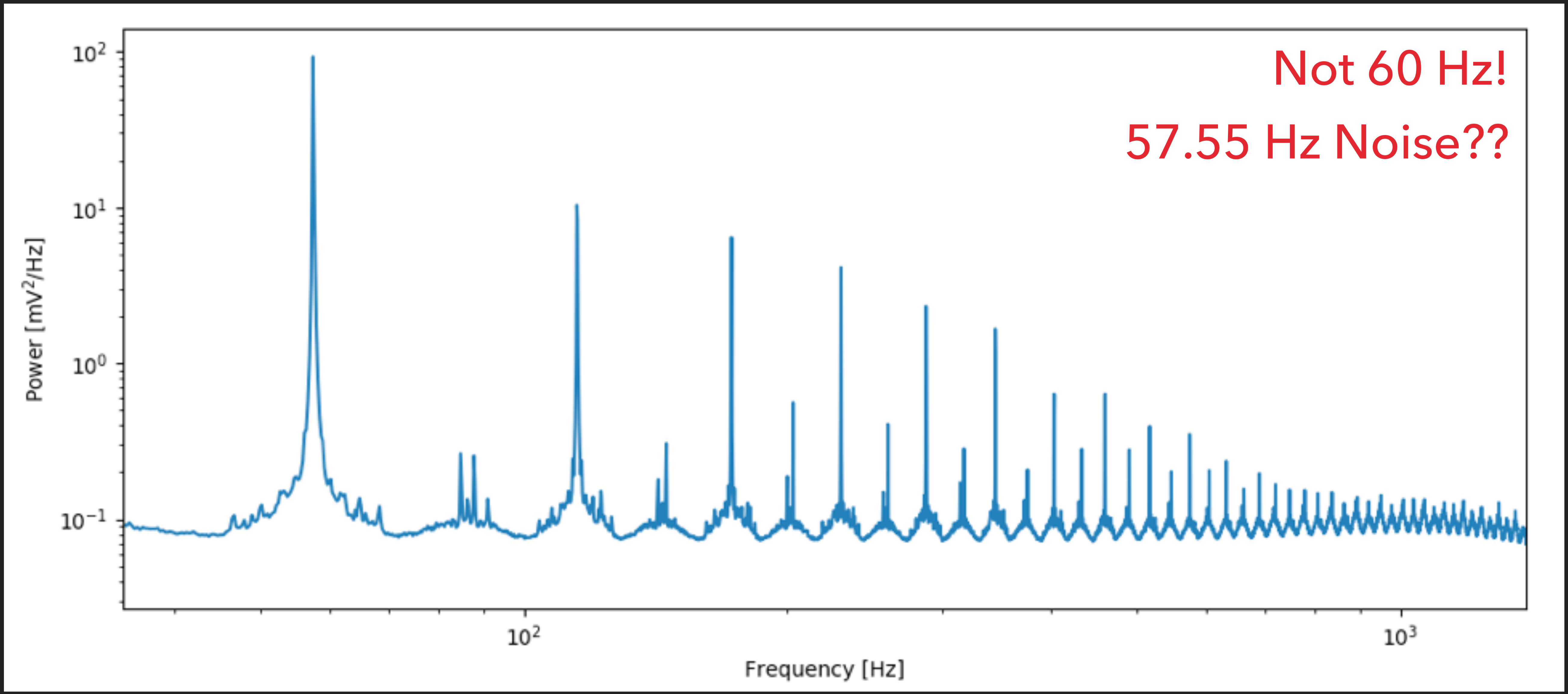


Improving Resonant Sensitivity



See talks by DM Radio

Early Data


Not 60 Hz!
57.55 Hz Noise??
Power [mV^2/Hz]
10^2
10^1
10^0
10^{-1}
10^2
10^3
Frequency [Hz]

Black Hole Superradiance

- A wave incident on a rotating black hole can scatter with a higher outgoing energy than it came in with ⇛ Superradiance
- A massive bosons can become bound around the black hole like a gravitational "atom"
- When the compton wavelength of the boson, matches the size of the spinning black hole, you can have exponential growth in the occupation number and efficiently remove angular momentum from the system through emission of gravitational waves (faster than accretion can replenish it)
- Black holes are natural tests for ultra low mass axions
- LIGO may eventually be able to see axions near the GUT scale!