The search for low-mass axion dark matter with ABRACADABRA-10 cm

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(Dated: February 16, 2021)

ABRACADABRA

Kaliroë Pappas

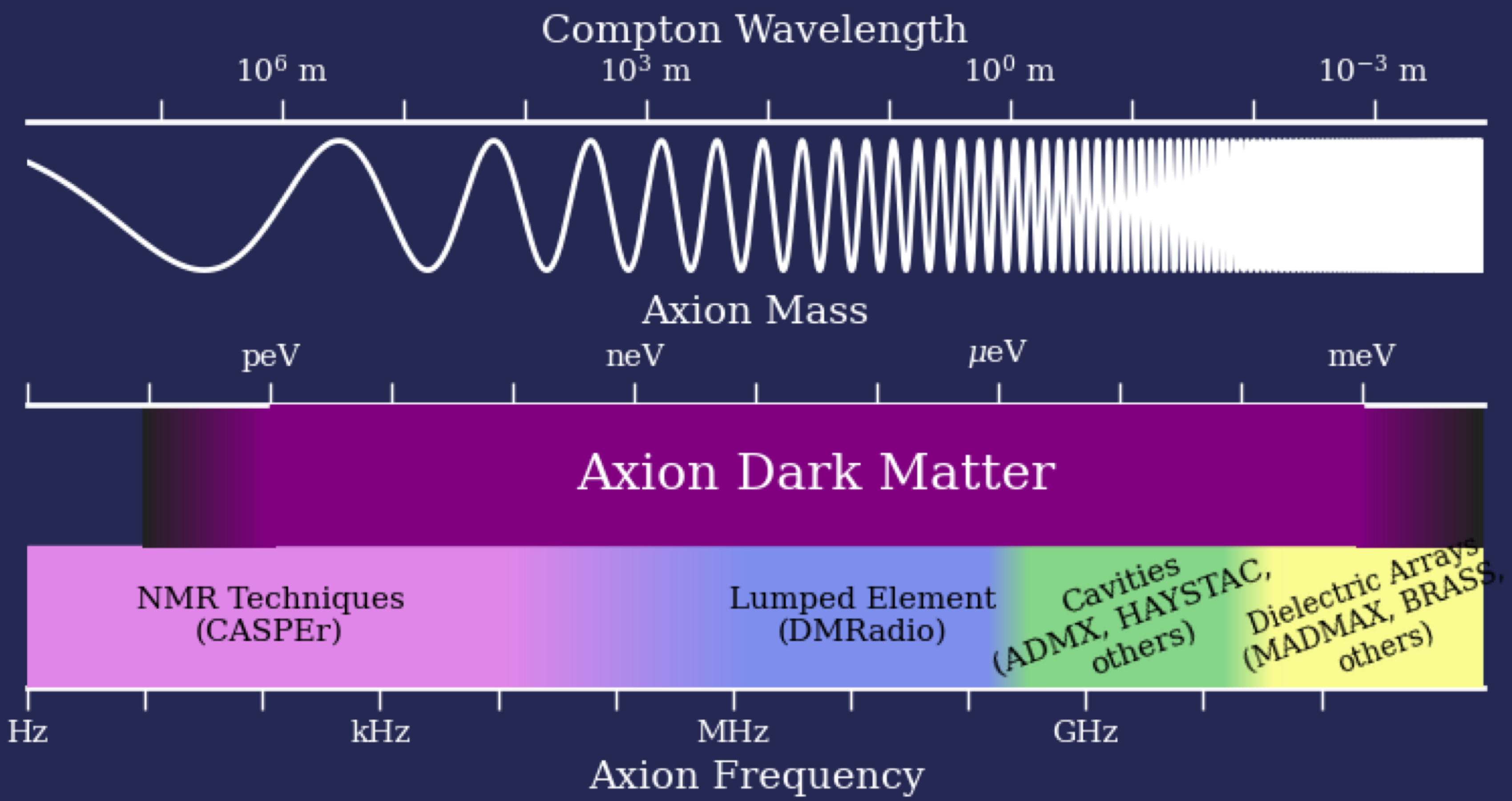
MIT

Cambridge High Energy Workshop 2021 - Axion Physics

Outline

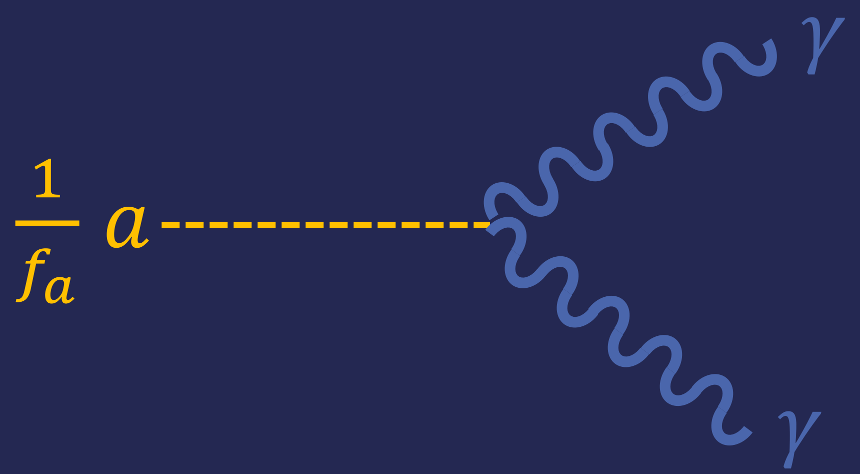
- Low-mass/Long-wavelength axions
- How to detect them
- Experimental setup and results for ABRACADABRA

Axion Mass and Frequency



How do we detect axions?

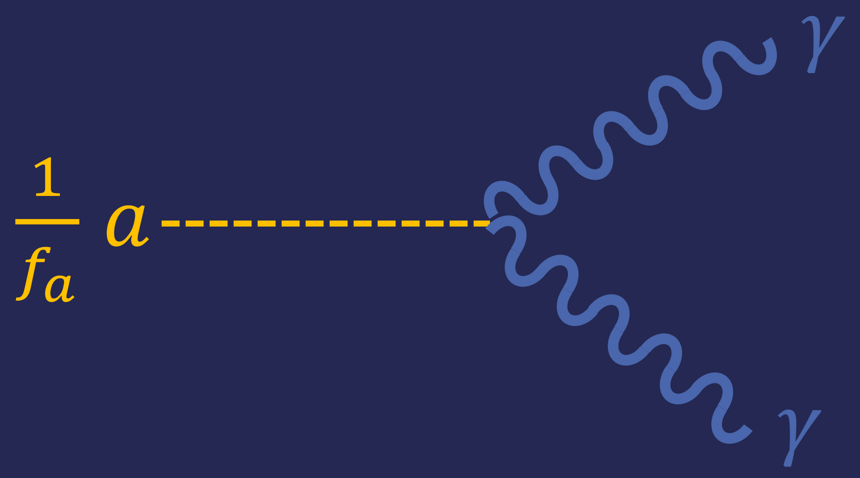
Axion interactions with photons



Modifications to Maxwell's Equations

Ampere's Law

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



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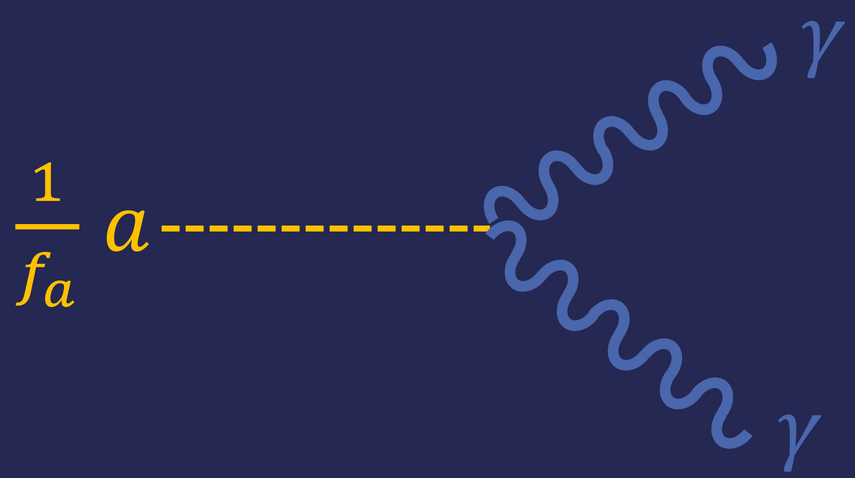
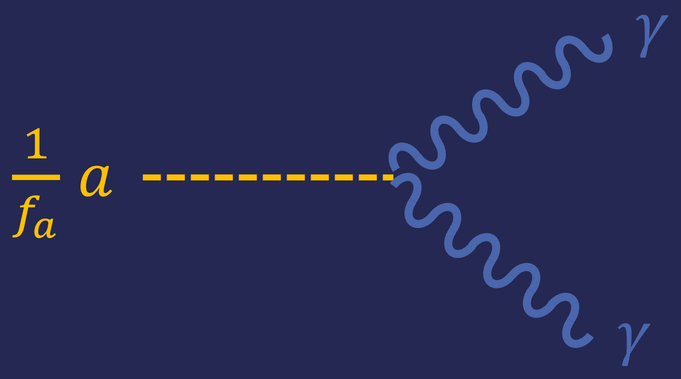


Modifications to Maxwell's Equations



Ampere's Law

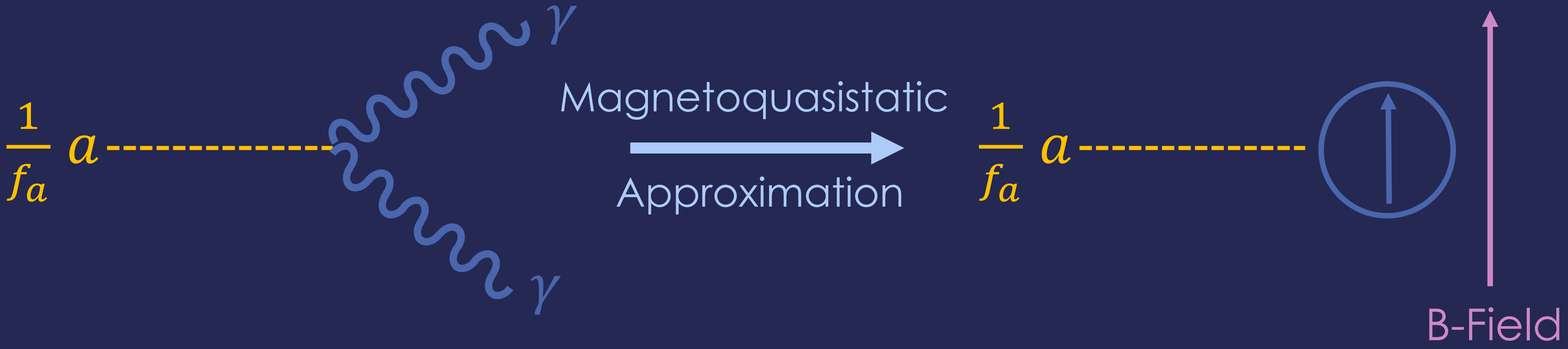
$$\nabla \times B = \frac{\partial E}{\partial t} + g_{a\gamma\gamma}\left(\frac{\partial a}{\partial t} B\right)$$

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

$$\boxed{\rho_a = \rho_{DM}}$$

Magnetoquasistatic Approximation

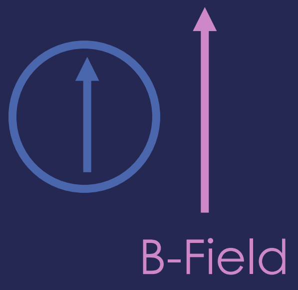
In the long wavelength regime, we can think of the axion interaction with photons as a current



Modifications to Maxwell's Equations

Ampere's Law

$$\frac{1}{f_a}a$$



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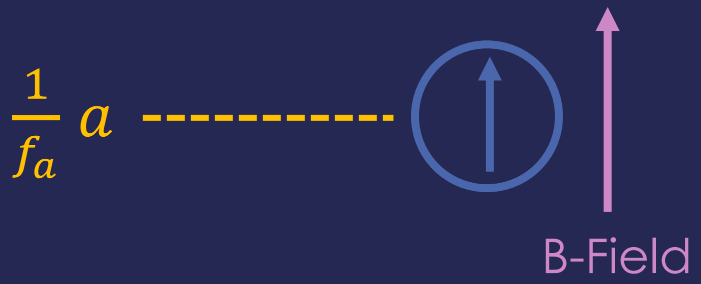
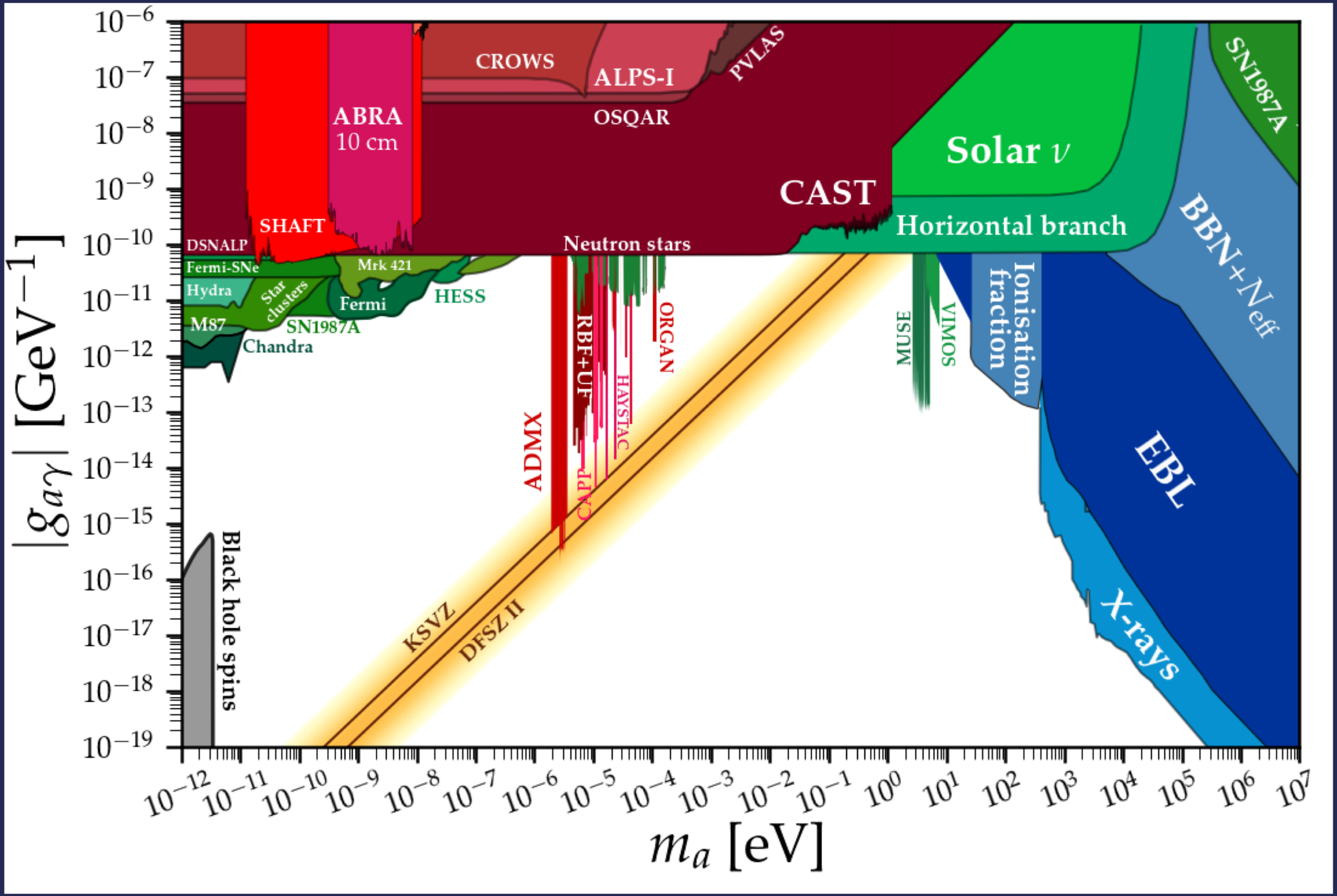


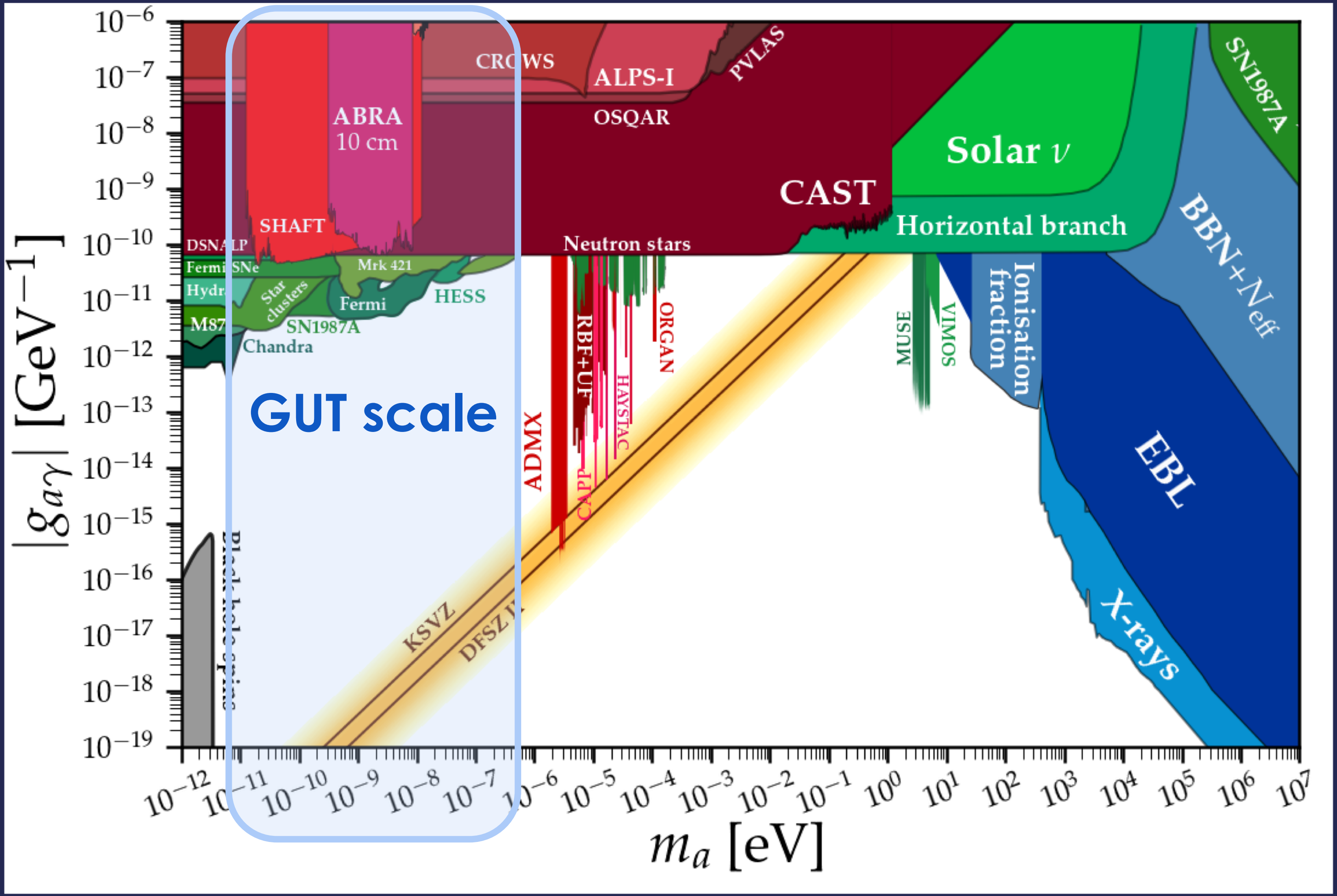
$$a(t) = \frac{\sqrt{2\rho_{DM}}}{m_a}\sin(m_a t)$$

$$\boxed{J_{eff} = g_{a\gamma\gamma}\sqrt{\rho_{DM}}\cos(m_a t) B}$$

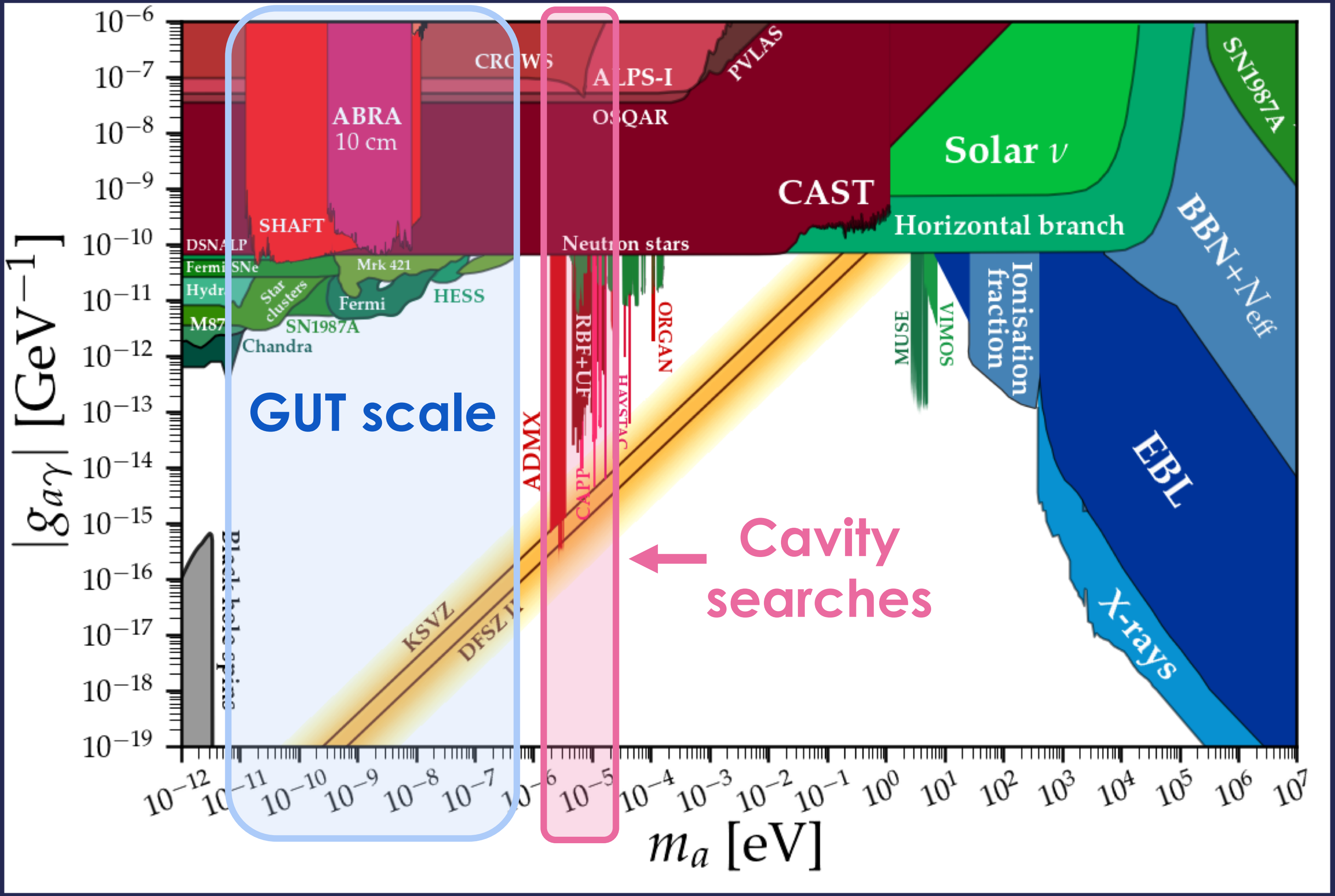
Axions parameter space



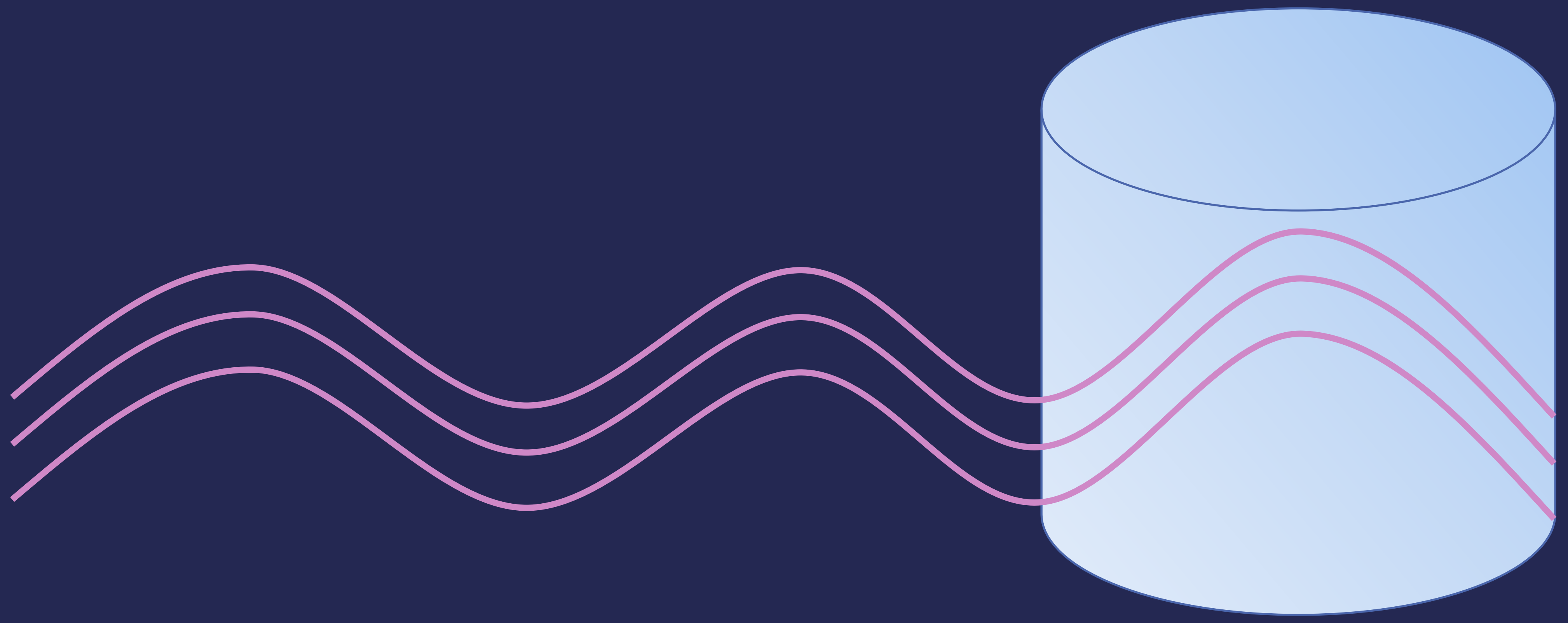
Low-mass axions



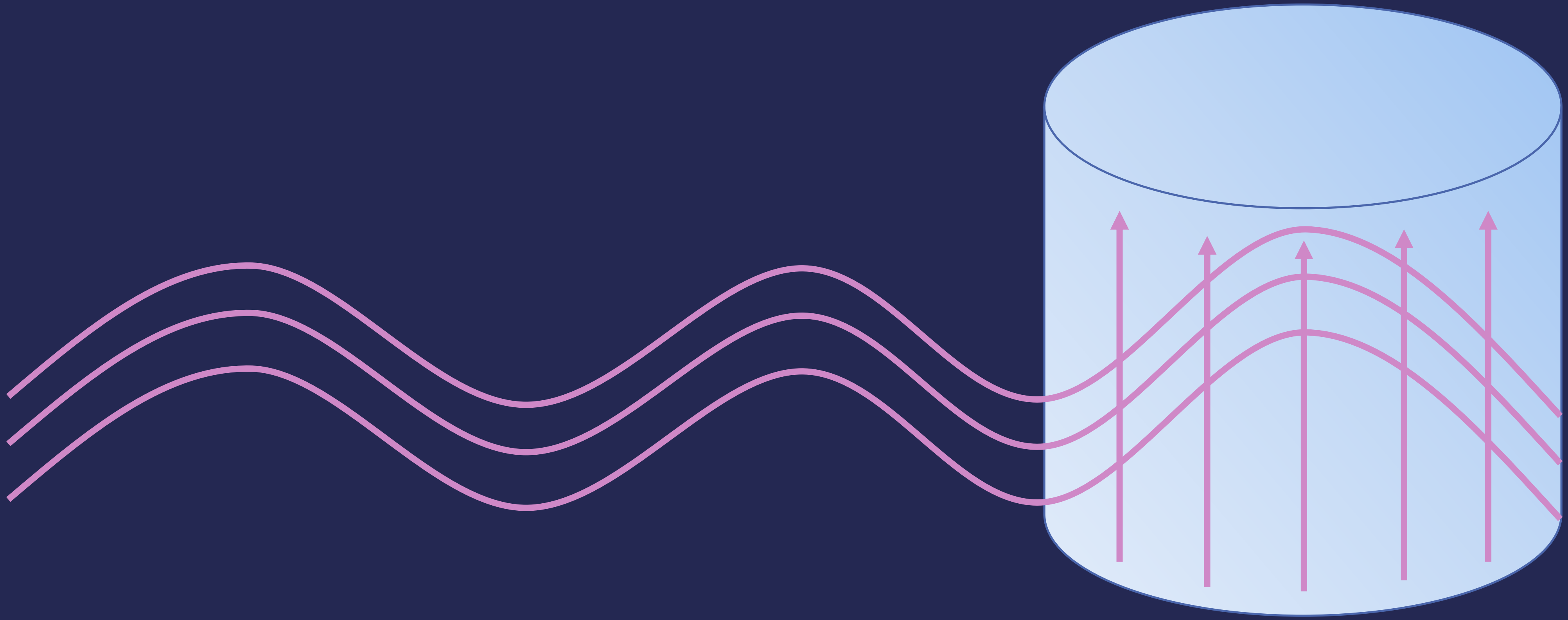
"Classical" axions



Cavity axion searches



Cavity axion searches

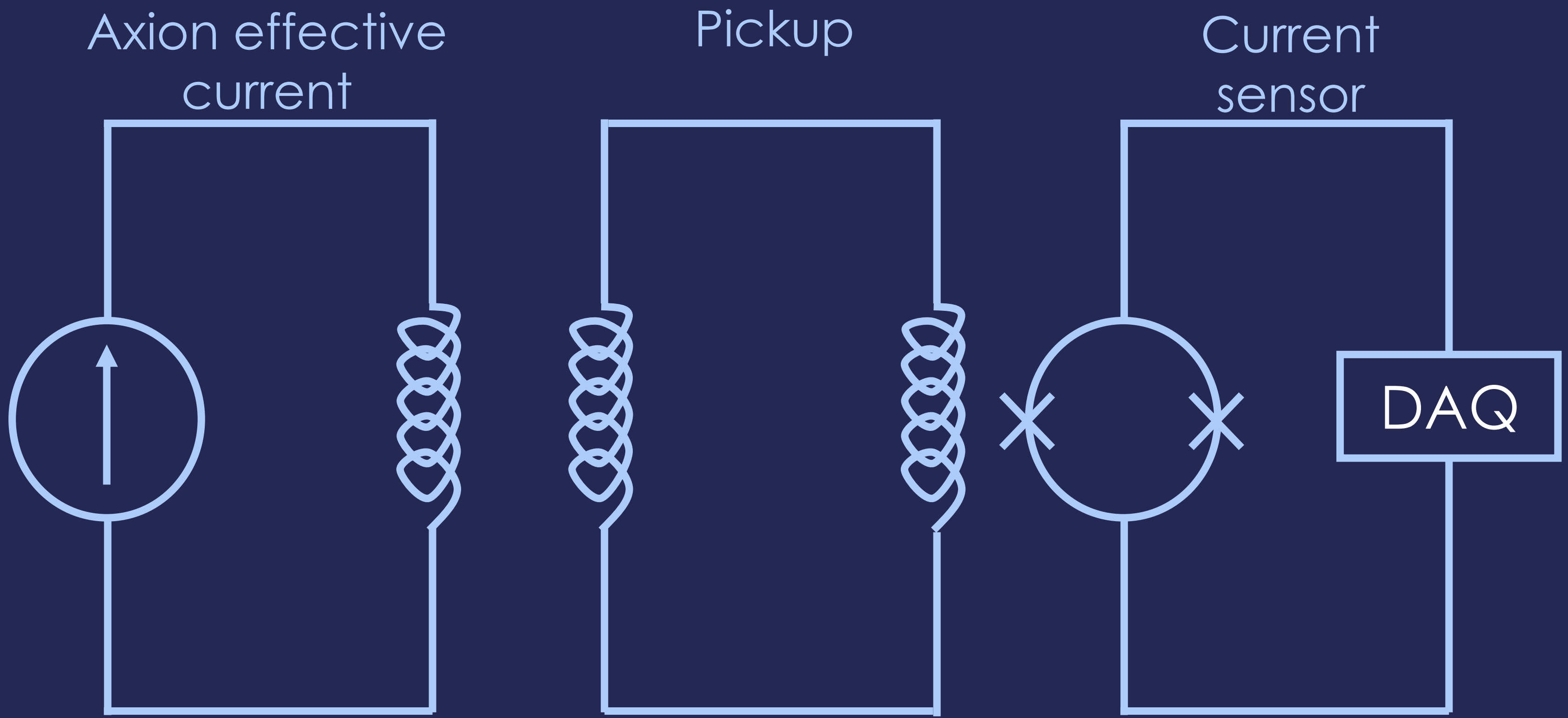


Low-mass/long-wavelength

Low-mass/long-wavelength

Lumped-element search

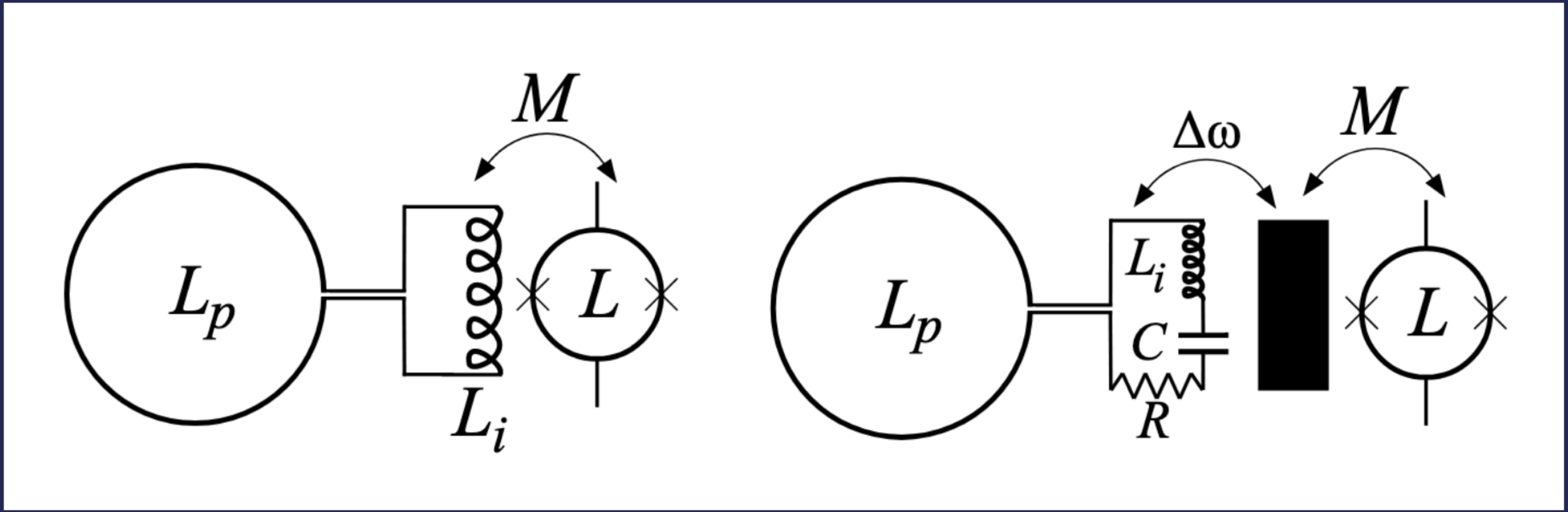
Lumped element searches



Lumped element searches

Broadband

Resonant



Kahn, Safdi, Thaler
10.1103/PhysRevLett.117.141801

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A Broadband/Resonance Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus

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A Broadband/Resonance Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus

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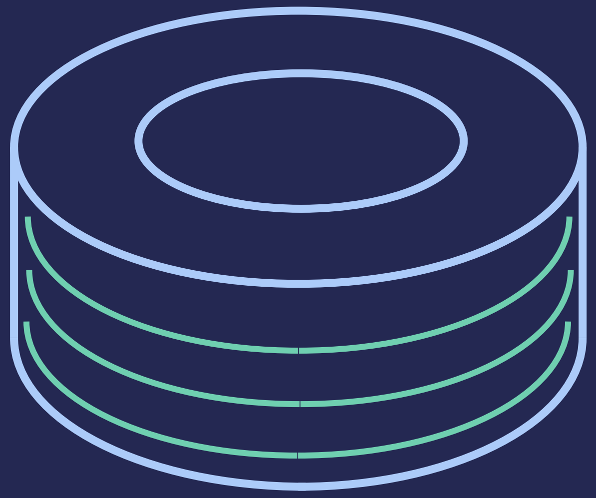
Toroidal magnet



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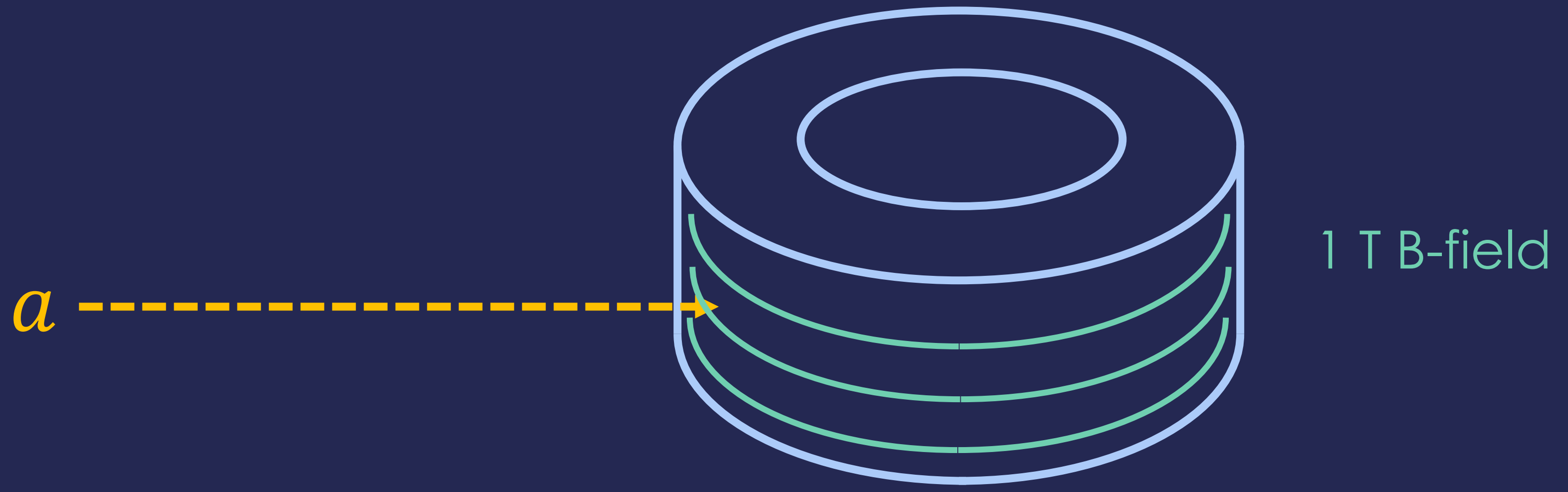
Axion comes in



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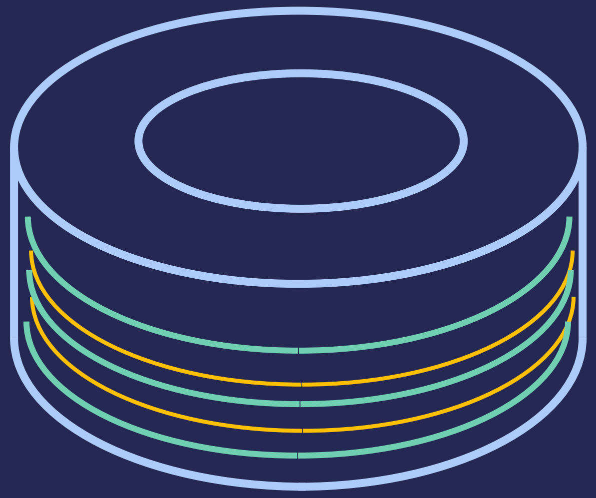
Converts to a current



$$J_{eff} = g_{a\gamma\gamma}\sqrt{\rho_{DM}}\cos(m_a t)B$$

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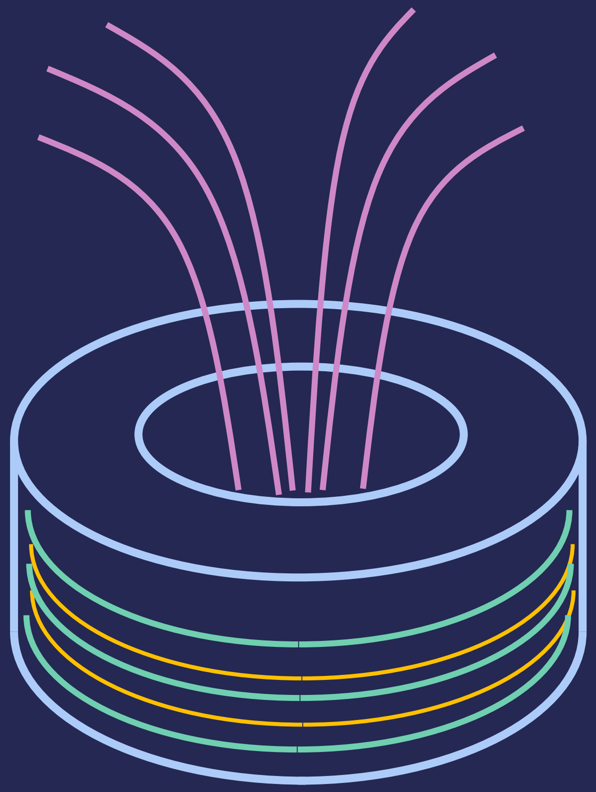
Induces a magnetic field



$$J_{eff} = g_{a\gamma\gamma}\sqrt{\rho_{DM}}\cos(m_a t)B$$

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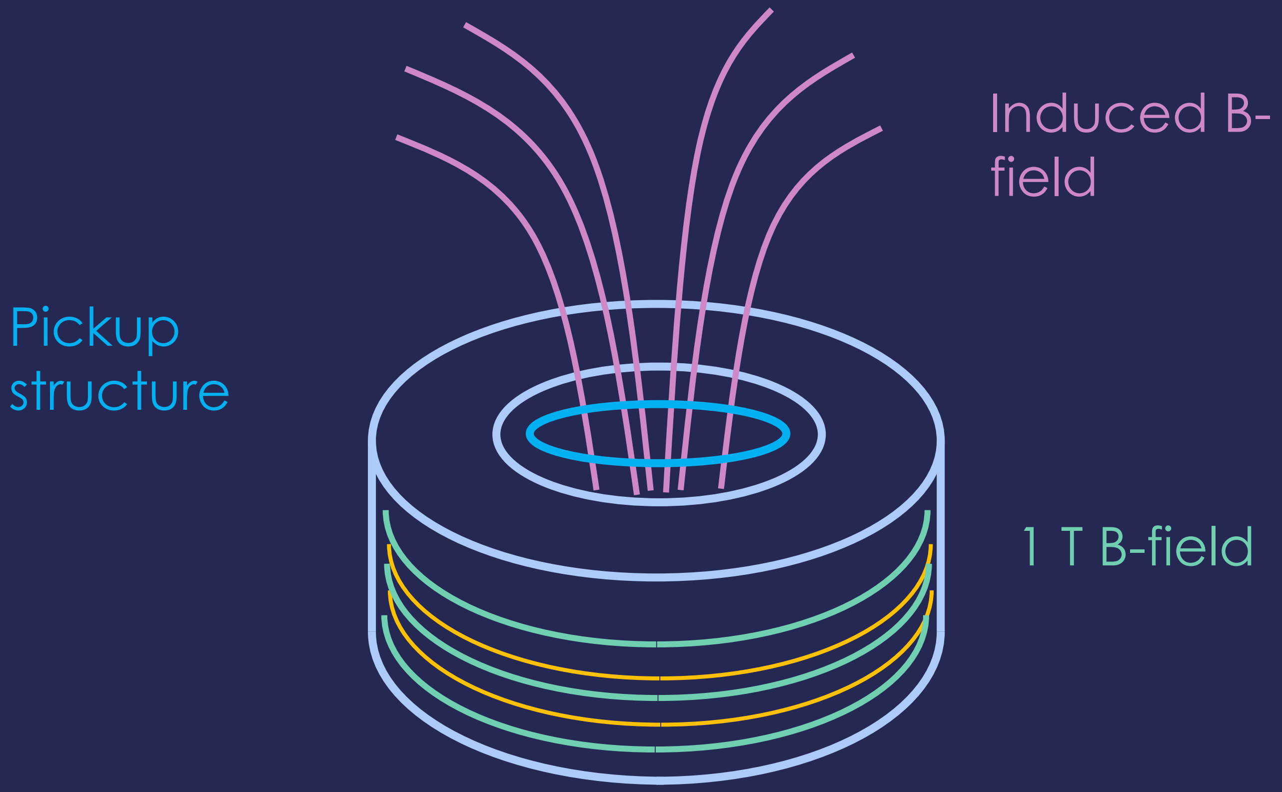
We measure it!



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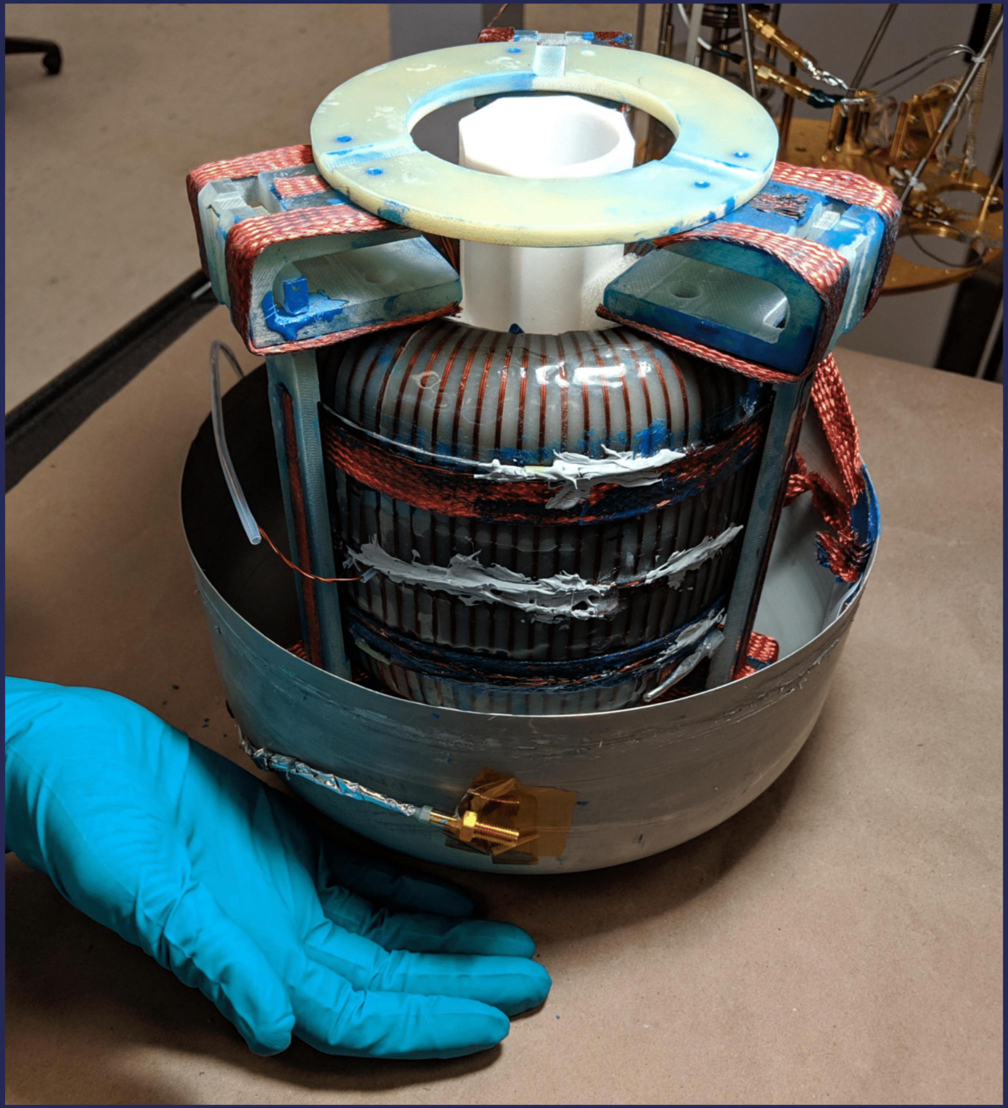
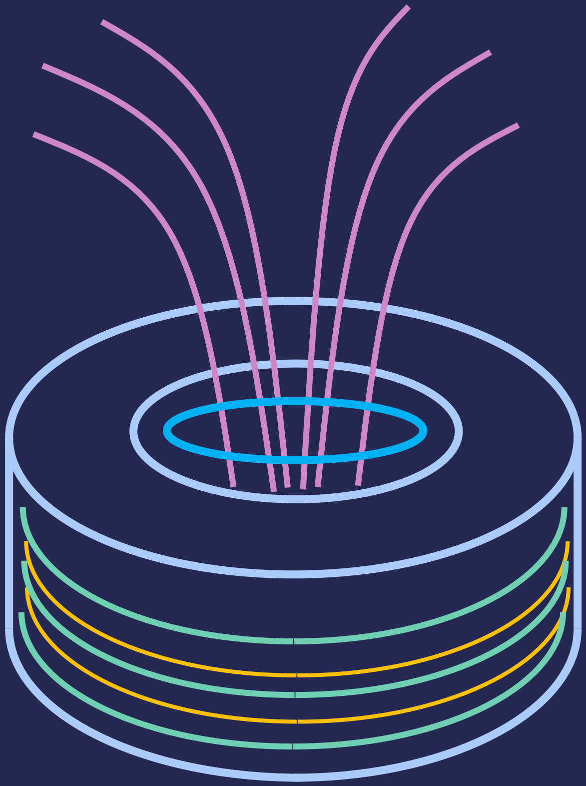




$$J_{eff} = g_{a\gamma\gamma}\sqrt{\rho_{DM}}\cos(m_a t)B$$

Signal to noise ratio

$$SNR = g_{a\gamma\gamma}\sqrt{\rho_{DM}}\mathcal{G}V B_{max}\left(\frac{M_{in}}{L_T}\right)\frac{(\tau t)^{1/4}}{S_{\Phi\Phi}{}^{1/2}}$$

Signal to noise ratio

$$SNR = \boxed{g_{a\gamma\gamma}}\boxed{\sqrt{\rho_{DM}}}\,\mathcal{G}VB_{max}\left(\frac{M_{in}}{L_T}\right)\frac{(\tau t)^{1/4}}{{S_{\Phi\Phi}}^{1/2}}$$

Axion to photon coupling constant

Local dark matter density

Signal to noise ratio

$$SNR = g_{a\gamma\gamma}\sqrt{\rho_{DM}}\boxed{\mathcal{G}}V B_{max}\left(\frac{M_{in}}{L_T}\right)\frac{(\tau t)^{1/4}}{S_{\Phi\Phi}{}^{1/2}}$$

Geometric factor

Signal to noise ratio

$$SNR = g_{a\gamma\gamma}\sqrt{\rho_{DM}}\mathcal{G}\boxed{V}\,\boxed{B_{max}}\left(\frac{M_{in}}{L_T}\right)\frac{(\tau t)^{1/4}}{{S_{\Phi\Phi}}^{1/2}}$$

Magnetic field volume

Maximum value of the magnetic field

Signal to noise ratio

$$SNR = g_{a\gamma\gamma}\sqrt{\rho_{DM}}\mathcal{G}VB_{max}\left(\boxed{M_{in}}\over L_T\right)\frac{(\tau t)^{1/4}}{S_{\Phi\Phi}{}^{1/2}}$$

Inductive coupling of the SQUIDs

Signal to noise ratio

$$SNR = g_{a\gamma\gamma}\sqrt{\rho_{DM}}\mathcal{G}V B_{max}\left(\frac{M_{in}}{\boxed{L_T}}\right)\frac{(\tau t)^{1/4}}{{S_{\Phi\Phi}}^{1/2}}$$

Inductive coupling to the readout circuit

Signal to noise ratio

$$SNR = g_{a\gamma\gamma}\sqrt{\rho_{DM}}\mathcal{G}V B_{max}\left(\frac{M_{in}}{L_T}\right)\frac{\boxed{(\tau t)}^{1/4}}{S_{\Phi\Phi}{}^{1/2}}$$

Axion coherence time and the integration time

Signal to noise ratio

$$SNR = \; g_{a\gamma\gamma}\sqrt{\rho_{DM}}\mathcal{G}VB_{max}\left(\frac{M_{in}}{L_T}\right)\frac{(\tau t)^{1/4}}{\boxed{S_{\Phi\Phi}}^{1/2}}$$

Flux noise level/
noise on our SQUIDs

Signal to noise ratio

$$SNR = g_{a\gamma\gamma}\sqrt{\rho_{DM}}\mathcal{G}VB_{max}\boxed{\left(\frac{M_{in}}{L_T}\right)}\frac{(\tau t)^{1/4}}{S_{\Phi\Phi}{}^{1/2}}$$

Coupling of SQUIDS to axion signal through the pickup structure

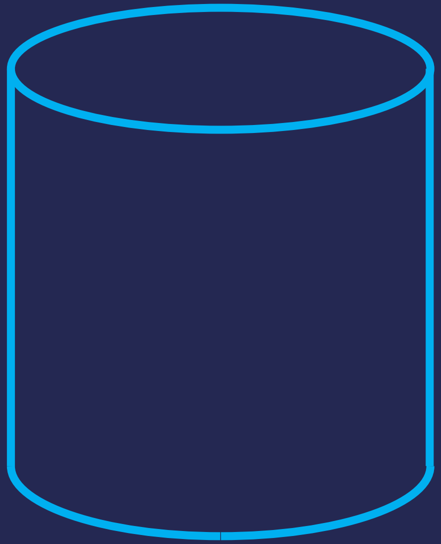
ABRACADABRA pickup update

Run 1

ABRACADABRA pickup update

Run 1

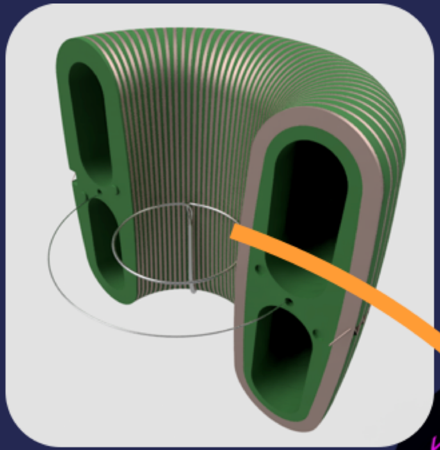
Run 2+

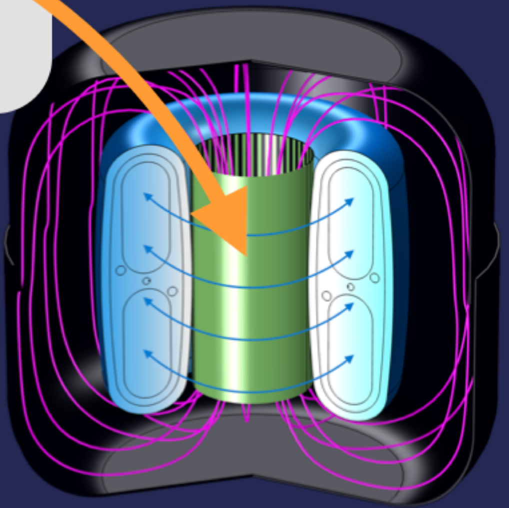


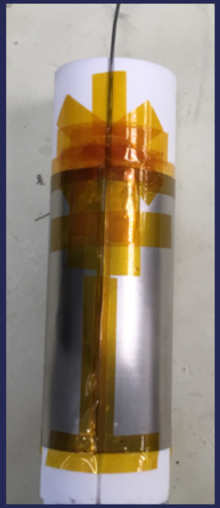
ABRACADABRA pickup update

Run 1

Run 2+







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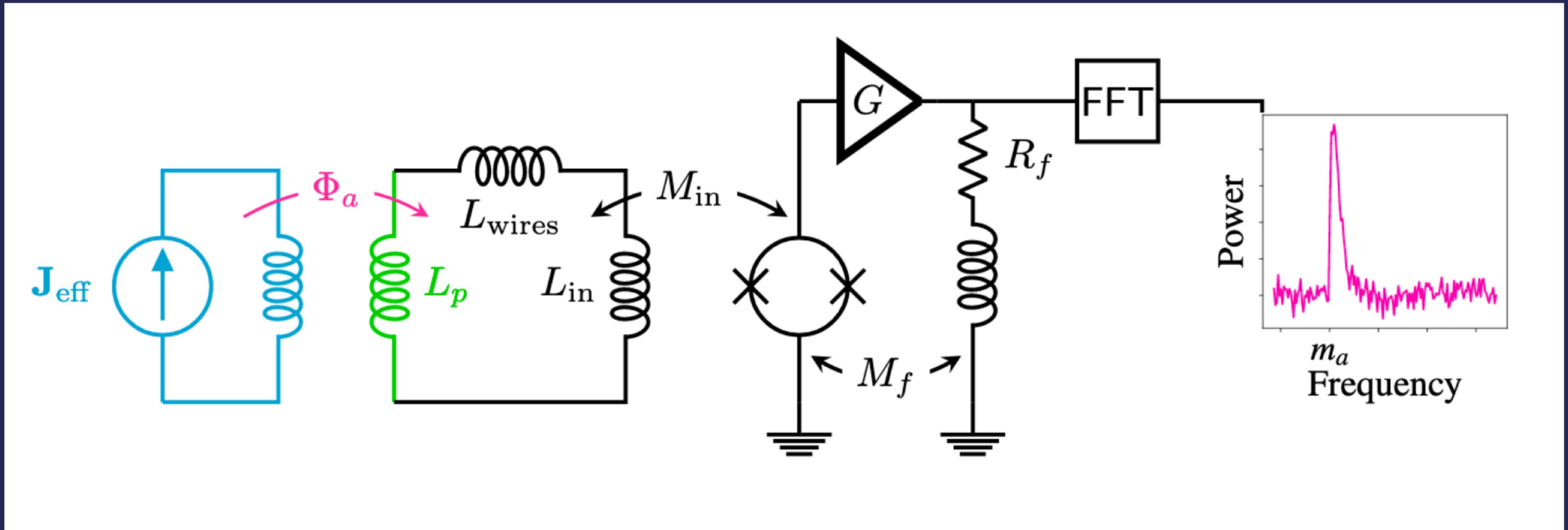
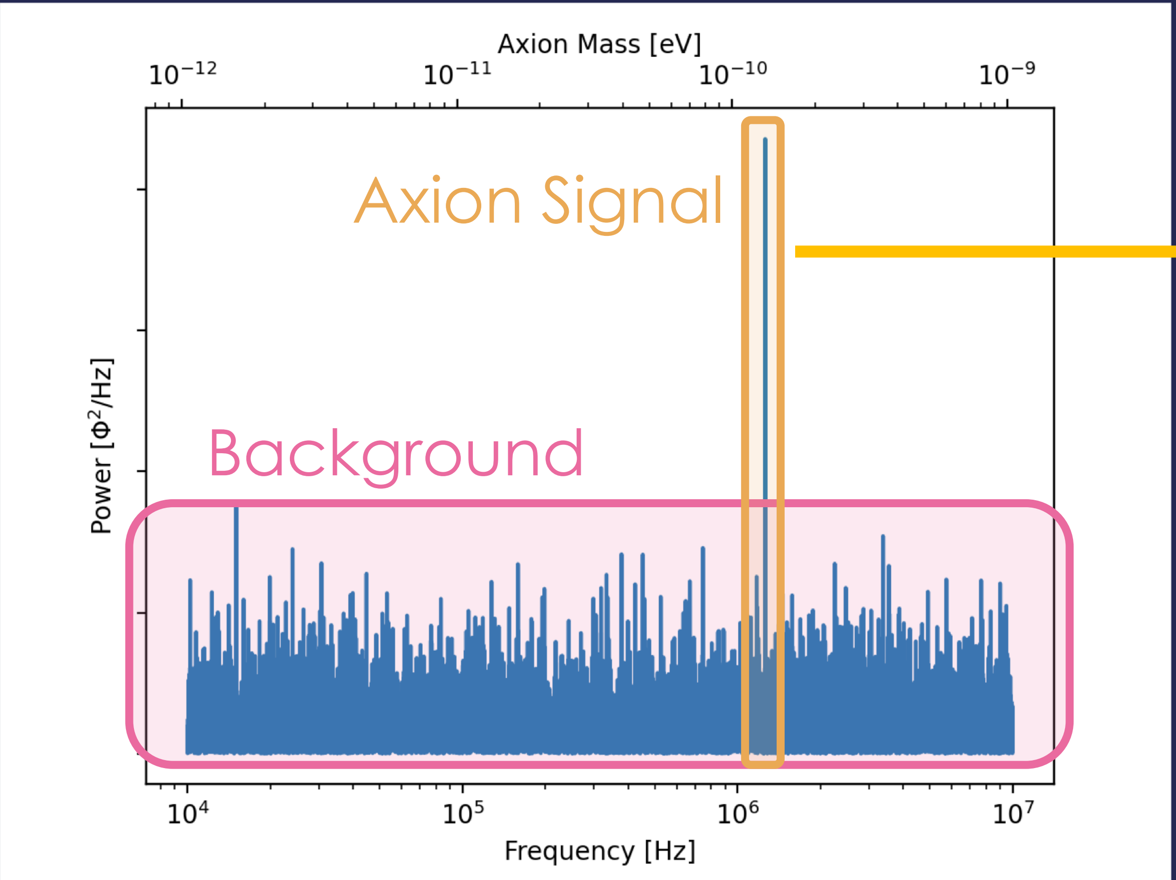
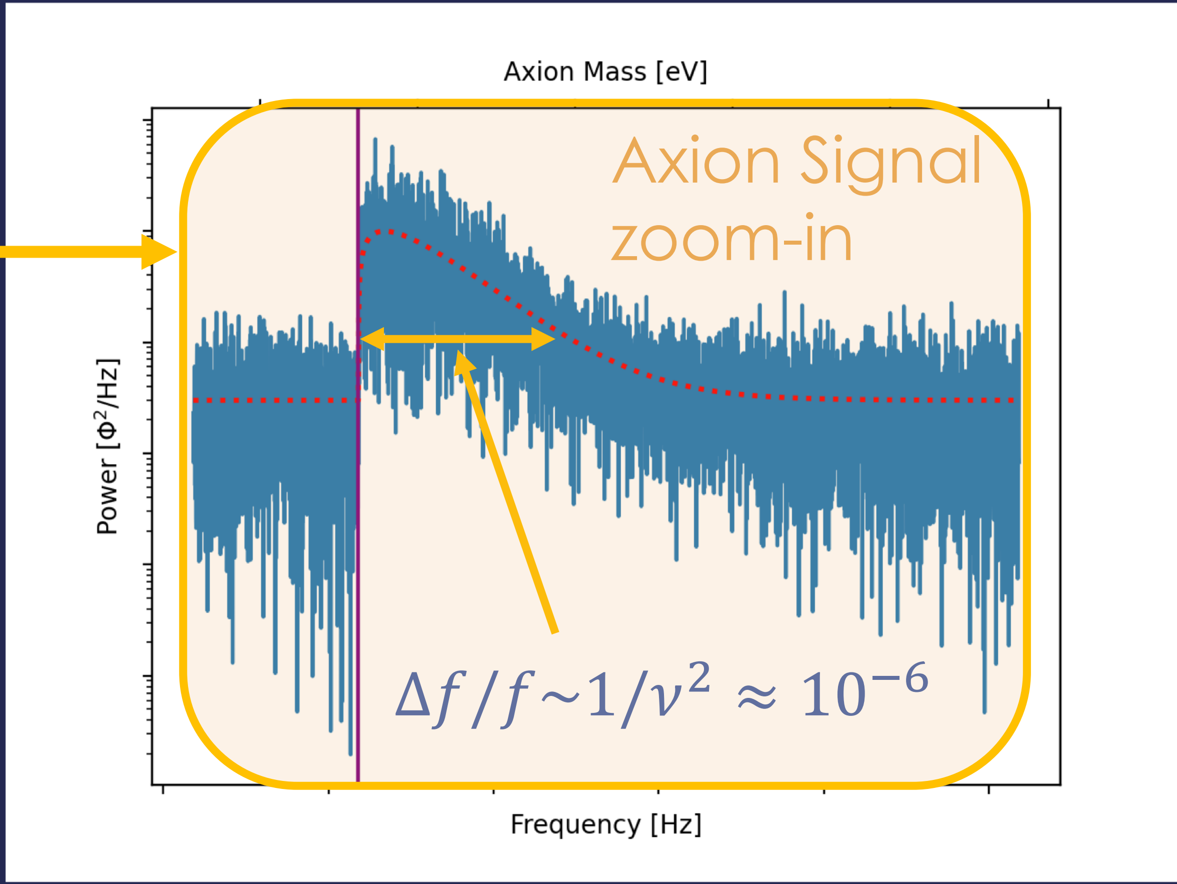


Salemi et al
arXiv:2102.06722

Axion Signal



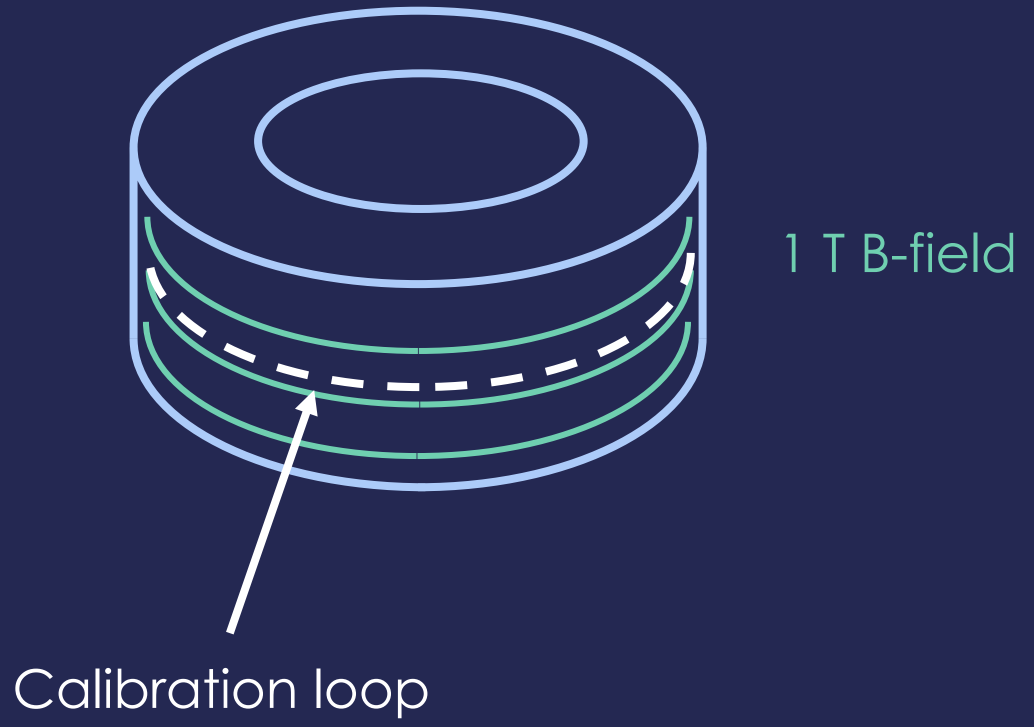


Simulated Data

Standard Halo Model

Calibration and data taking

We inject a fake axion signal to calibrate our system

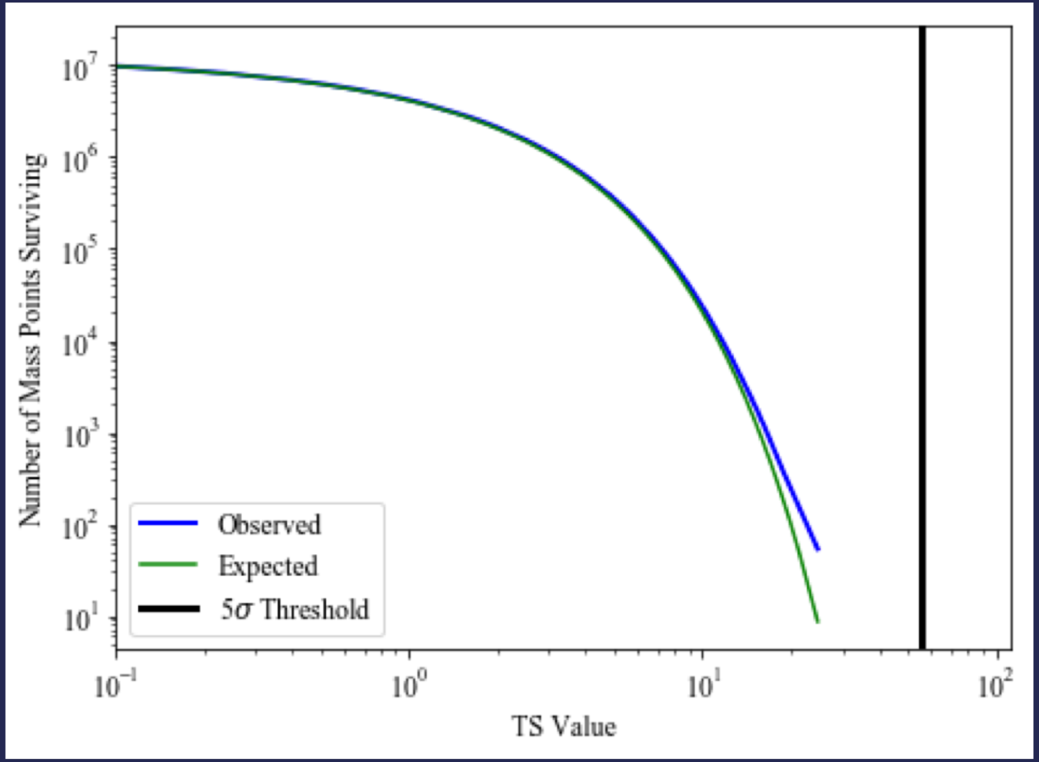


Calibration and data taking

We take data in the magnet off and on configurations to veto false signals

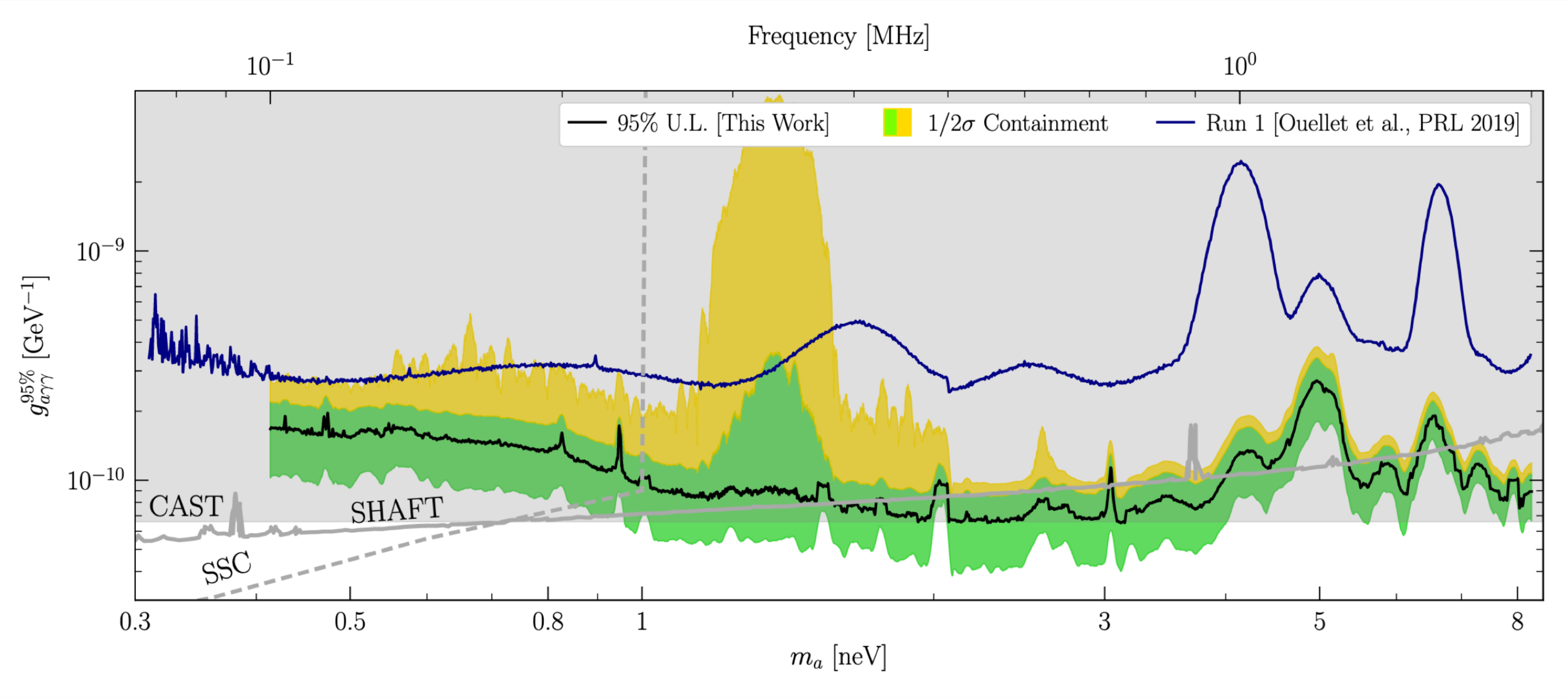
Data taking and processing

- We limit our search range to 75 kHz – 2 MHZ (m_a in 0.31 – 8.1 neV). With 11.1 million mass points
- For each mass point, a likelihood function is calculated
- Axion discovery search is based on a log-likelihood ratio test, between the best fit and the null hypothesis
- We set the 5σ discovery threshold as TS > 56.1 (accounting for the Look Elsewhere Effect)



ABRACADABRA 2021 Result

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



Backgrounds

Two categories of backgrounds:

Backgrounds

Two categories of backgrounds:

1. Electromagnetic
   - Most annoying at higher frequencies (1 kHz – 5 MHz)

Backgrounds

Two categories of backgrounds:

1. Electromagnetic
   - Most annoying at higher frequencies (1 kHz – 5 MHz)
2. Vibrations
   - Most annoying at low Frequencies (1 Hz – 100 Hz)

Backgrounds mitigation

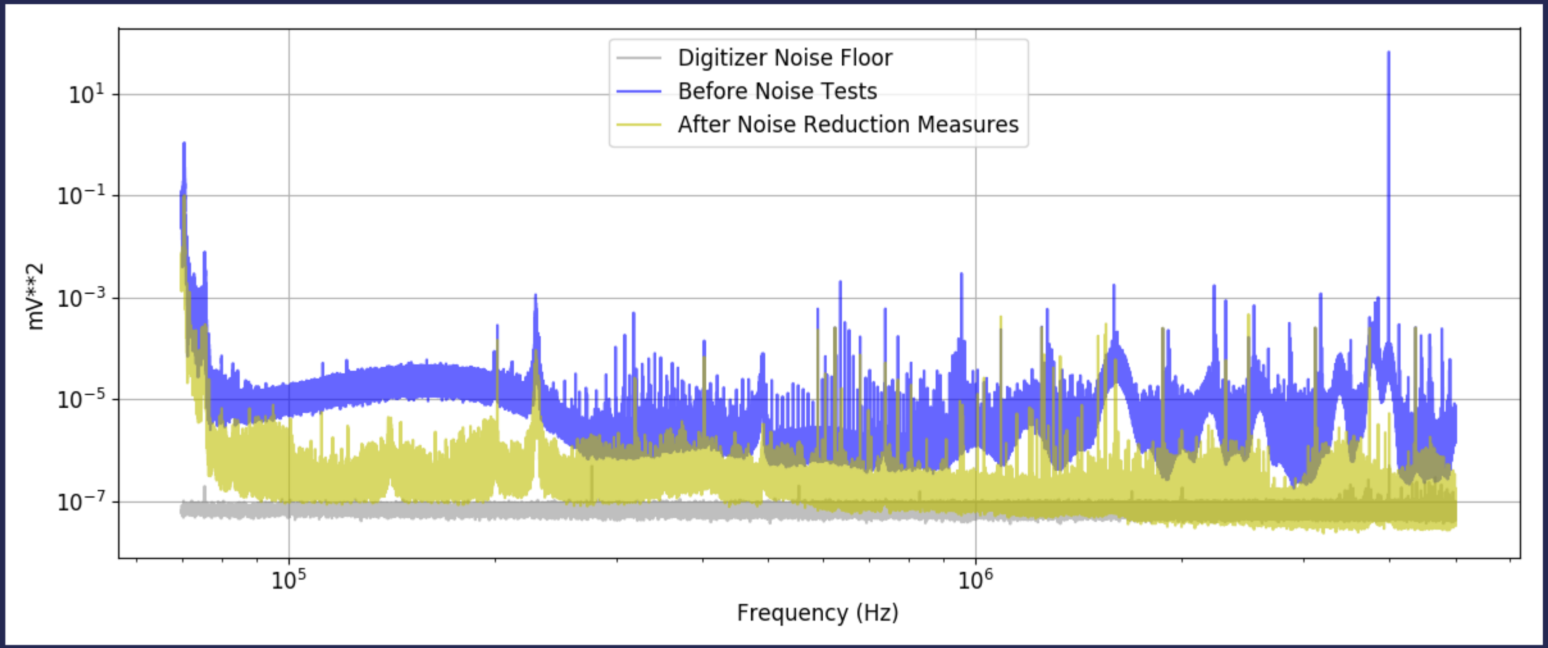
1. Electromagnetic
   - Most annoying at higher frequencies (1 kHz – 5 MHz)

Shielding

Backgrounds mitigation

1. Electromagnetic
   - Most annoying at higher frequencies (1 kHz – 5 MHz)

Power spectra over frequency



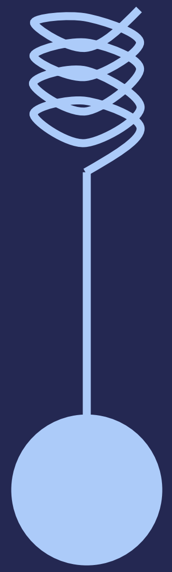
Backgrounds mitigation

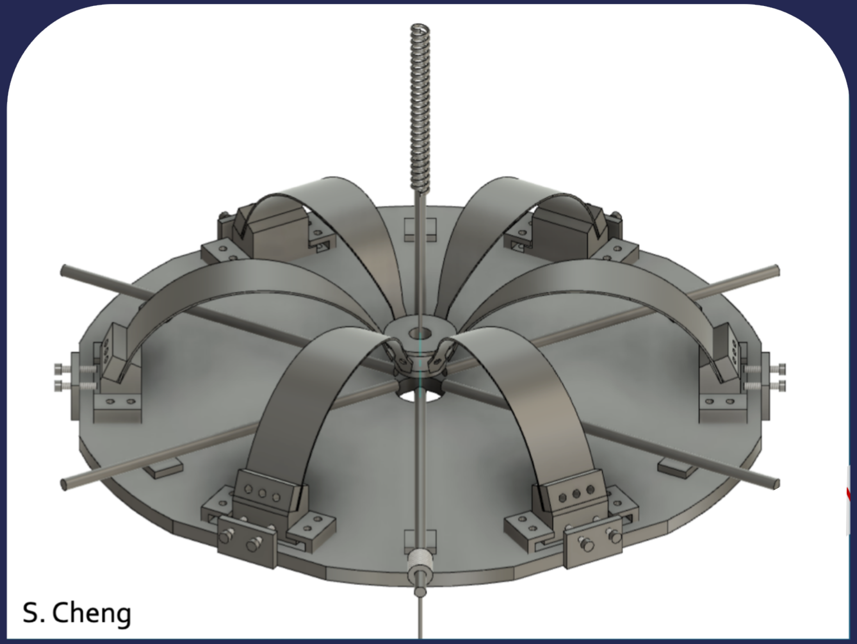
2. Vibrations
   - Most annoying at low frequencies (1 Hz – 100 Hz)

Isolation

Backgrounds mitigation

2. Vibrations
   - Most annoying at low frequencies (1 Hz – 100 Hz)

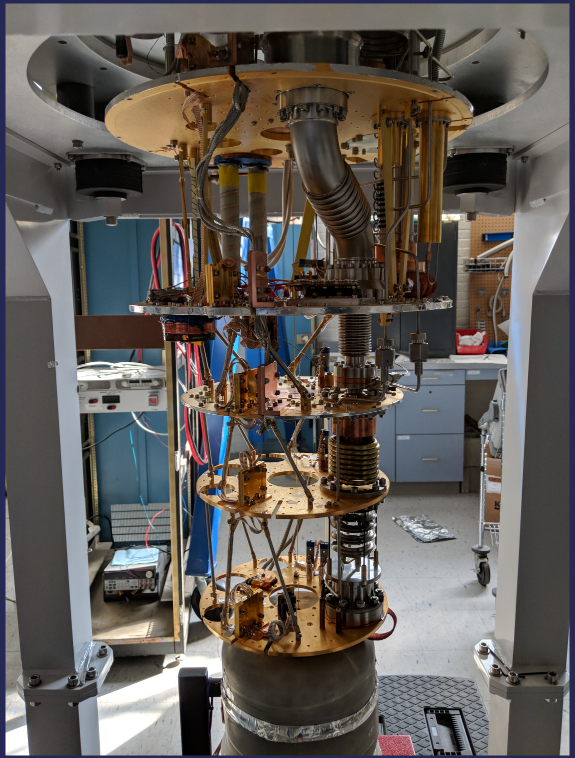


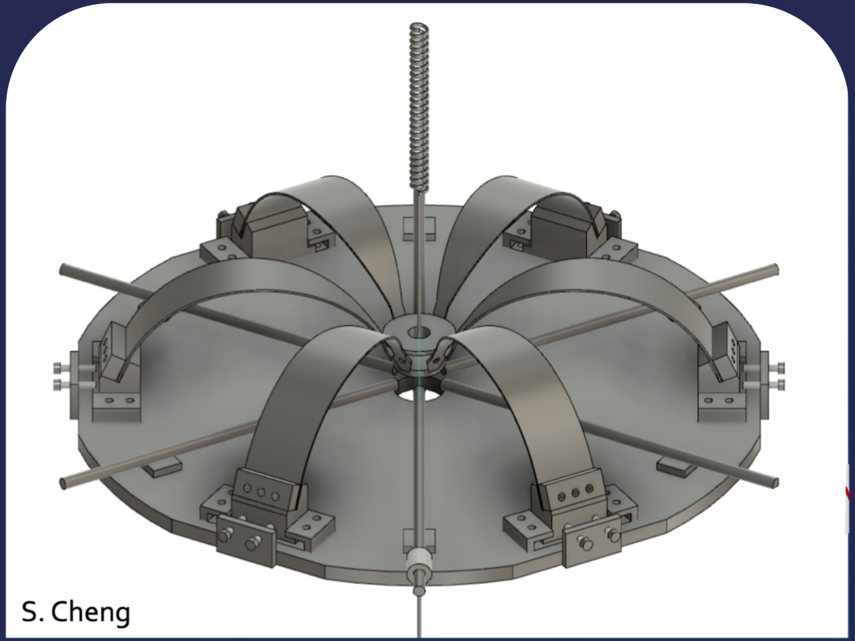


Geometric anti-spring filter

Backgrounds mitigation

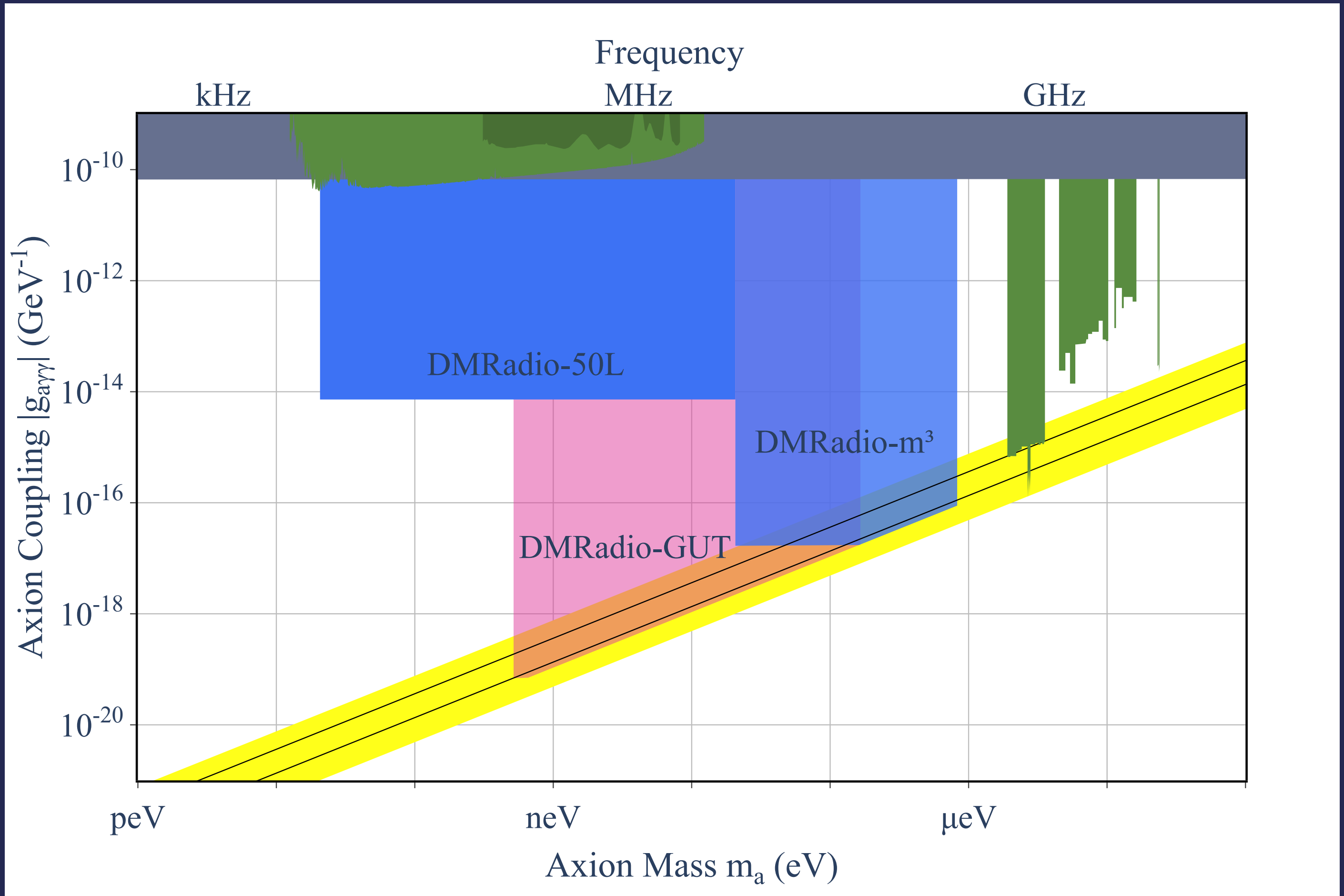
2. Vibrations
   - Most annoying at low frequencies (1 Hz – 100 Hz)

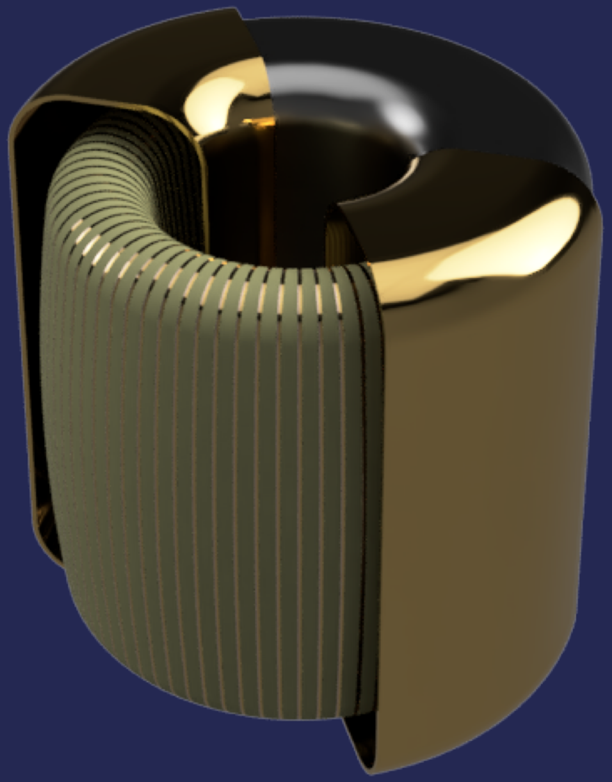




Geometric anti-spring filter

DMRadio


Frequency
kHz
MHz
GHz
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
Axion Coupling $|g_{a\gamma\gamma}|$ (GeV^{-1})
DMRadio-50L
DMRadio-m³
DMRadio-GUT
peV
neV
μeV
Axion Mass m_a (eV)



Summary

- Long-wavelength/Low-mass/GUT-scale axions can be found using lumped element searches
- With ABRA we were able to probe the 0.31 – 8.1 neV mass range and place world-leading limits
- DMRadio will expand the lumped element search for axions down to the QCD axion band

ABRACADABRA Collaboration

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Chiara Salemi
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