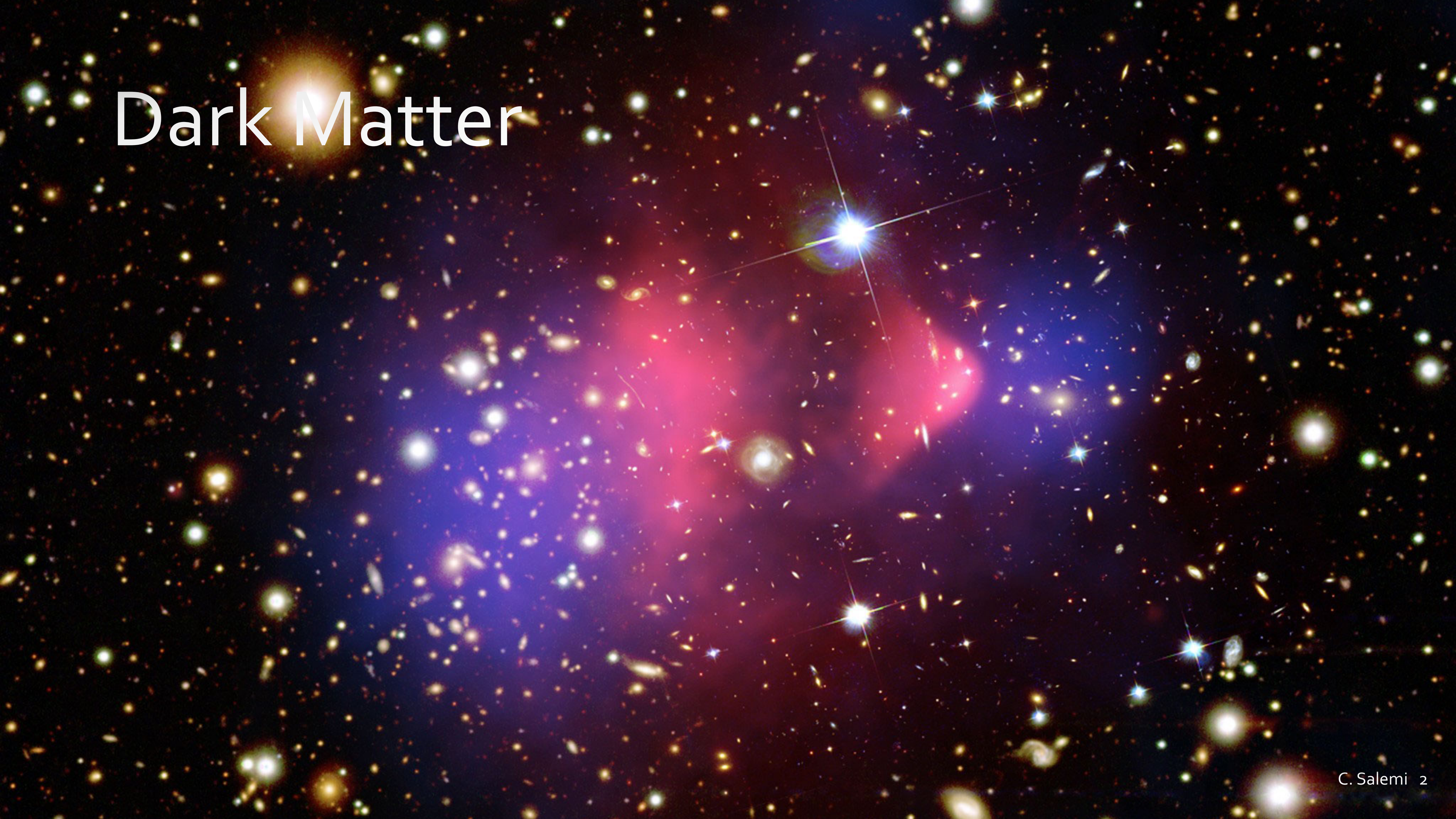
Seeing the Invisible:
The Search for Low-Mass Axion Dark Matter

Chiara P. Salemi
EPAP seminar, King's College London
Dec 6, 2022

Dark Matter



Dark Matter—so what is it?

- Particle
- Mass 10^{-22} eV – 5 $M_{\odot}$ (10^{-58} – 10^{30} kg)
- Feeble or nonexistent interactions with visible matter
- Feeble or nonexistent self-interactions
- Exists with energy density ~5x visible matter
- Cold

sterile neutrino

WIMPzilla

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QCD axion

MACHO

axion-like particle

extra dimensions

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asymmetric dark matter

little Higgs

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primordial black holes

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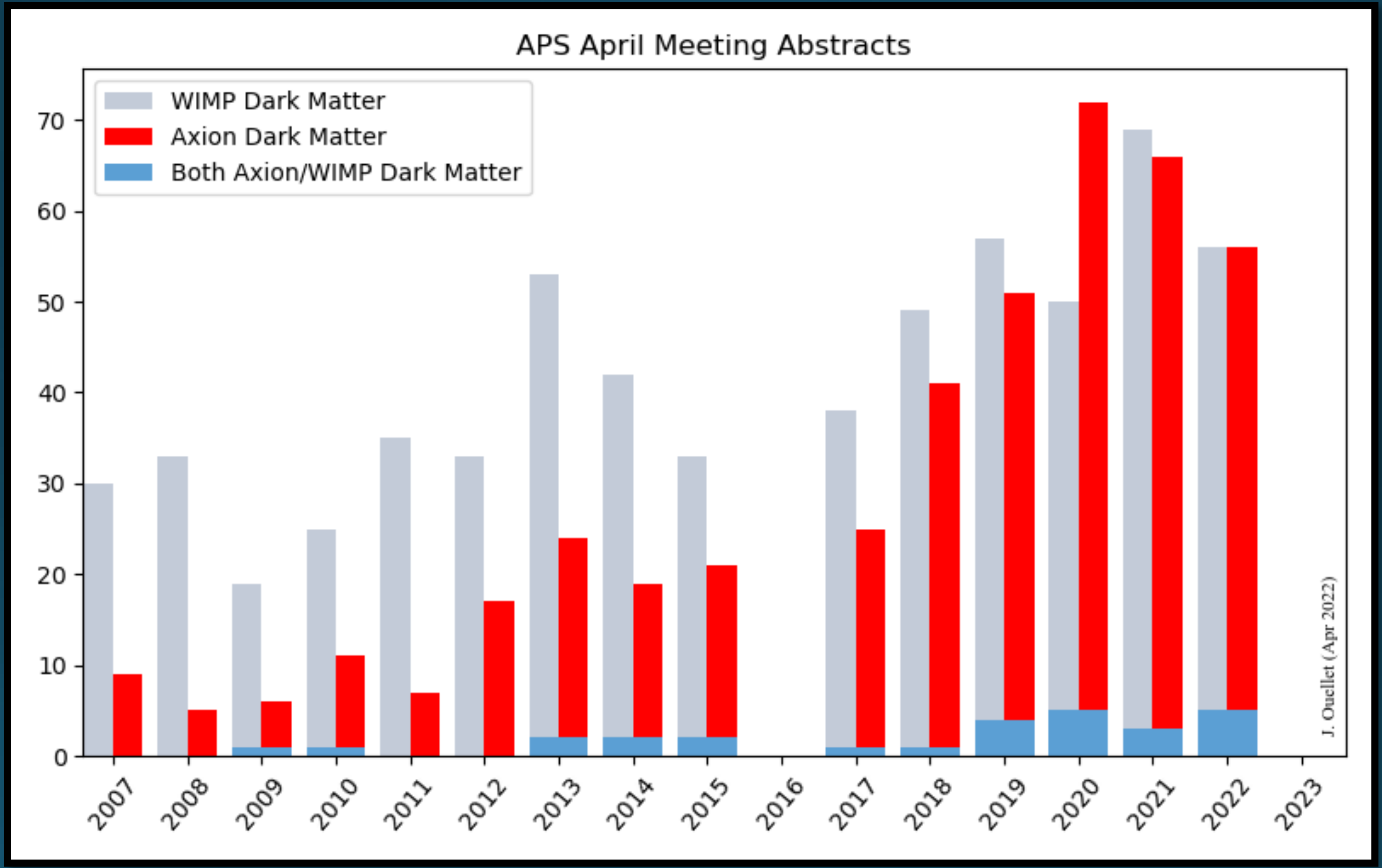
Axions are interesting (by popular consensus)



J. Ouellet

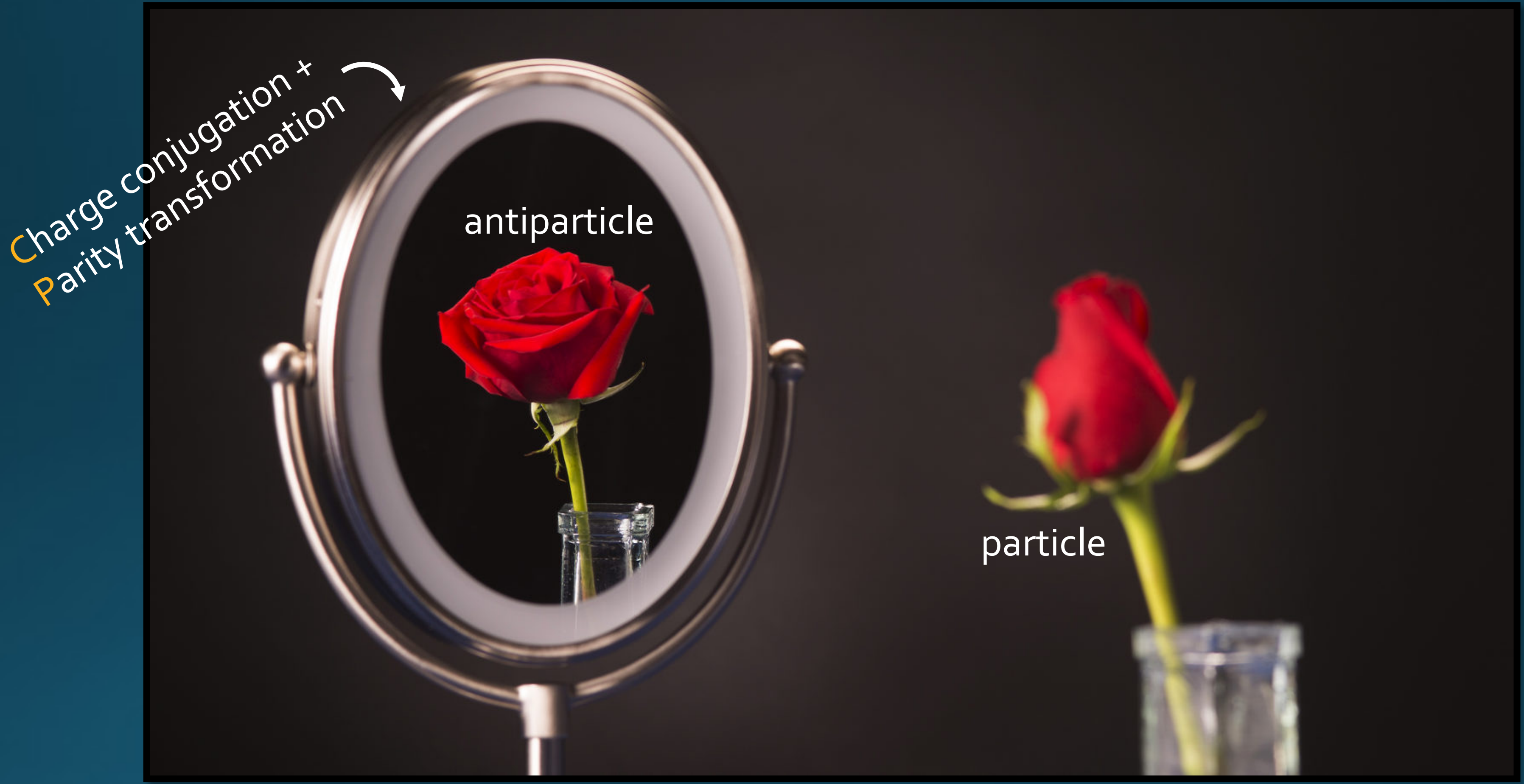
And they are also well motivated

Strong CP Problem –

The strong force should violate CP symmetry, but it does not*

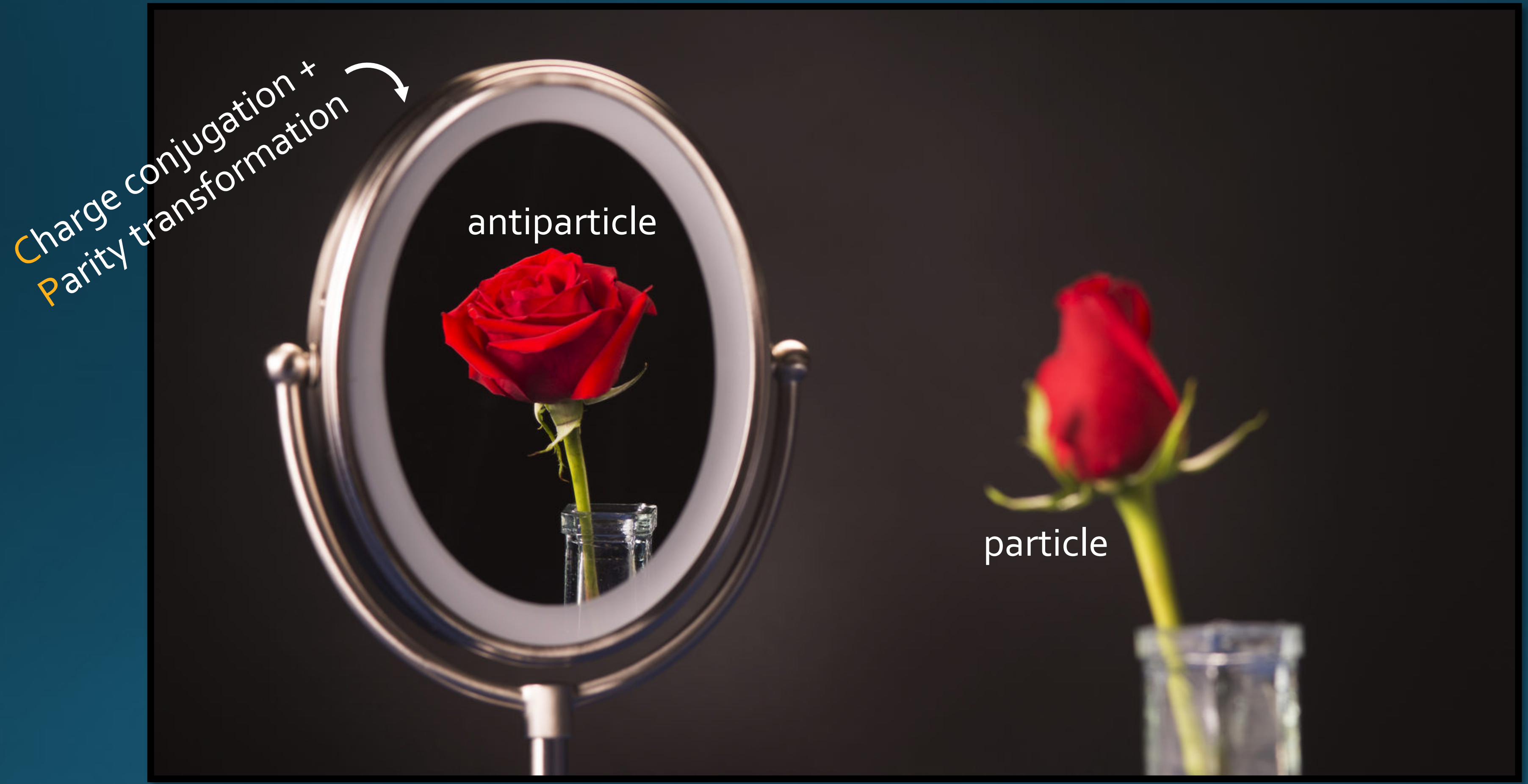
*to a very, very, very high precision

CP symmetry



R. Hahn, Symmetry Magazine

CP ~~symmetry~~ violation



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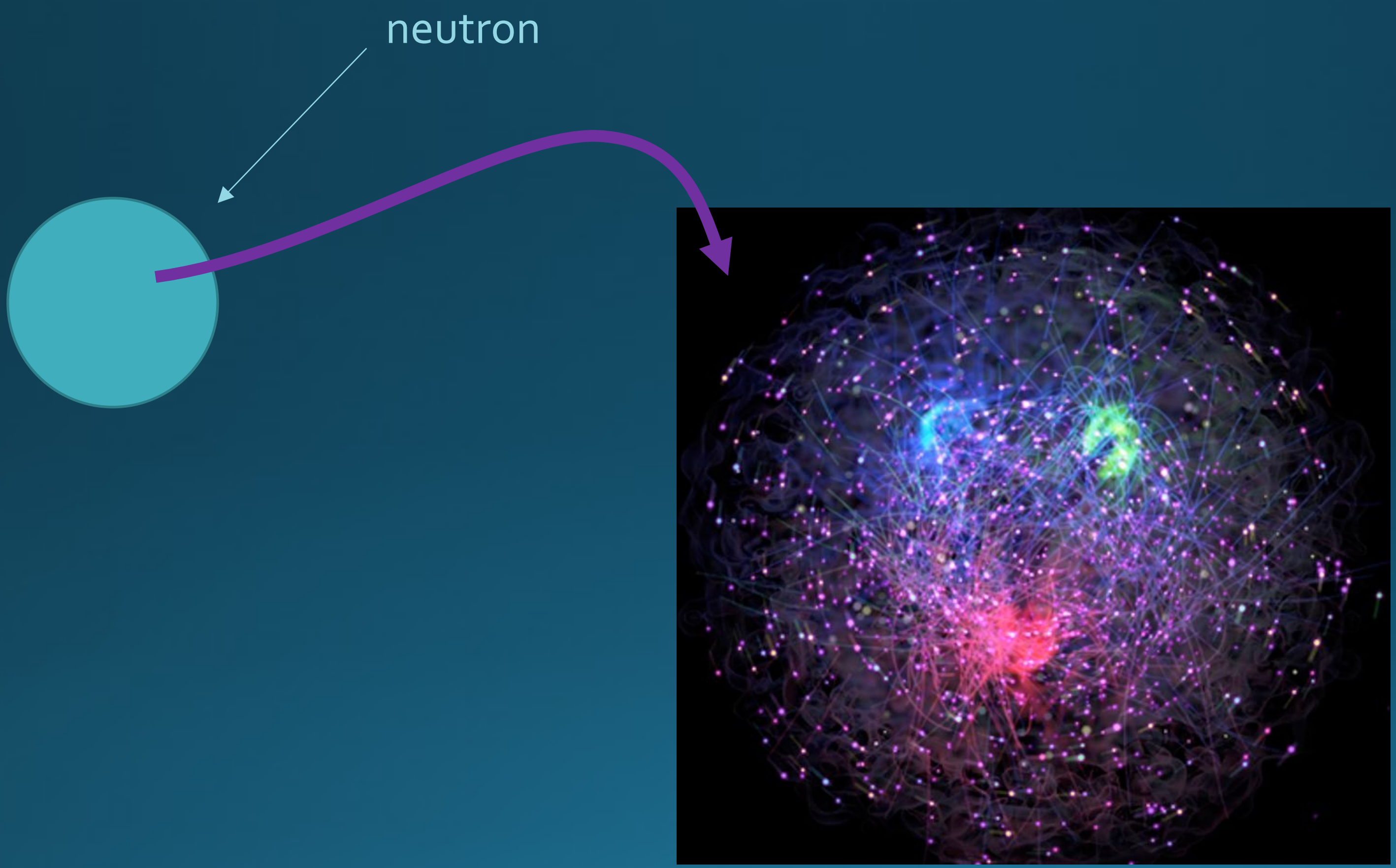
Why CP violation in QCD? (toy model)



MIT Center for Art, Science, and Technology;
Jefferson Lab

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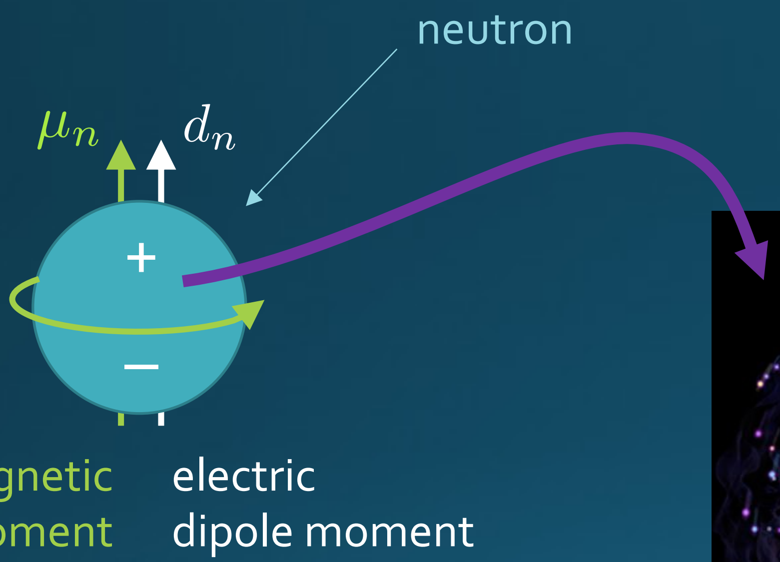

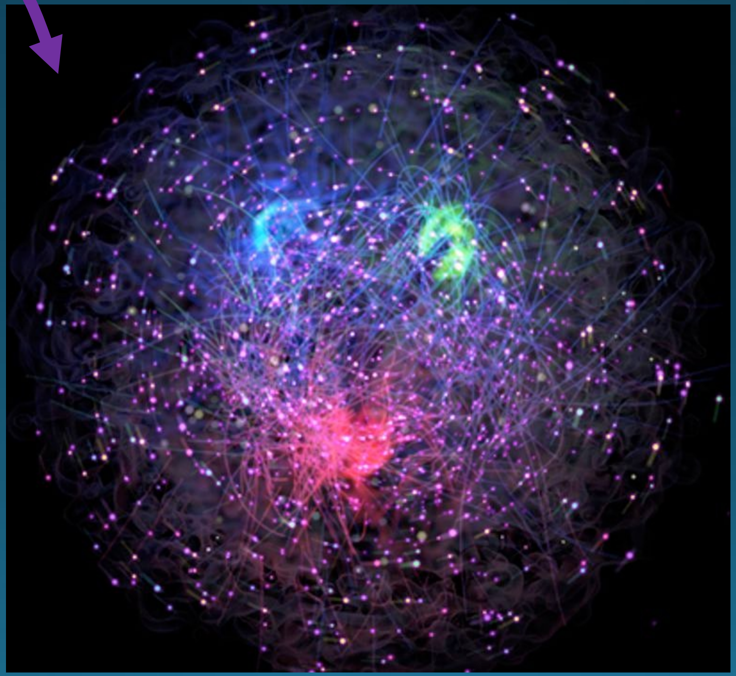

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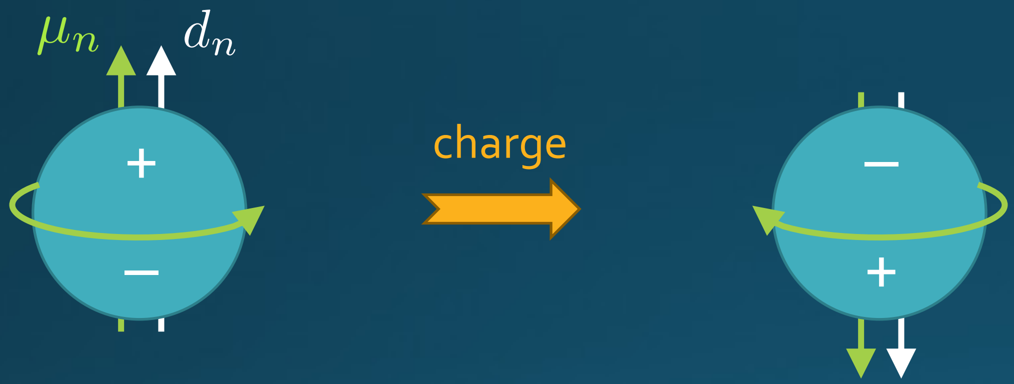

Why CP violation in QCD? (toy model)

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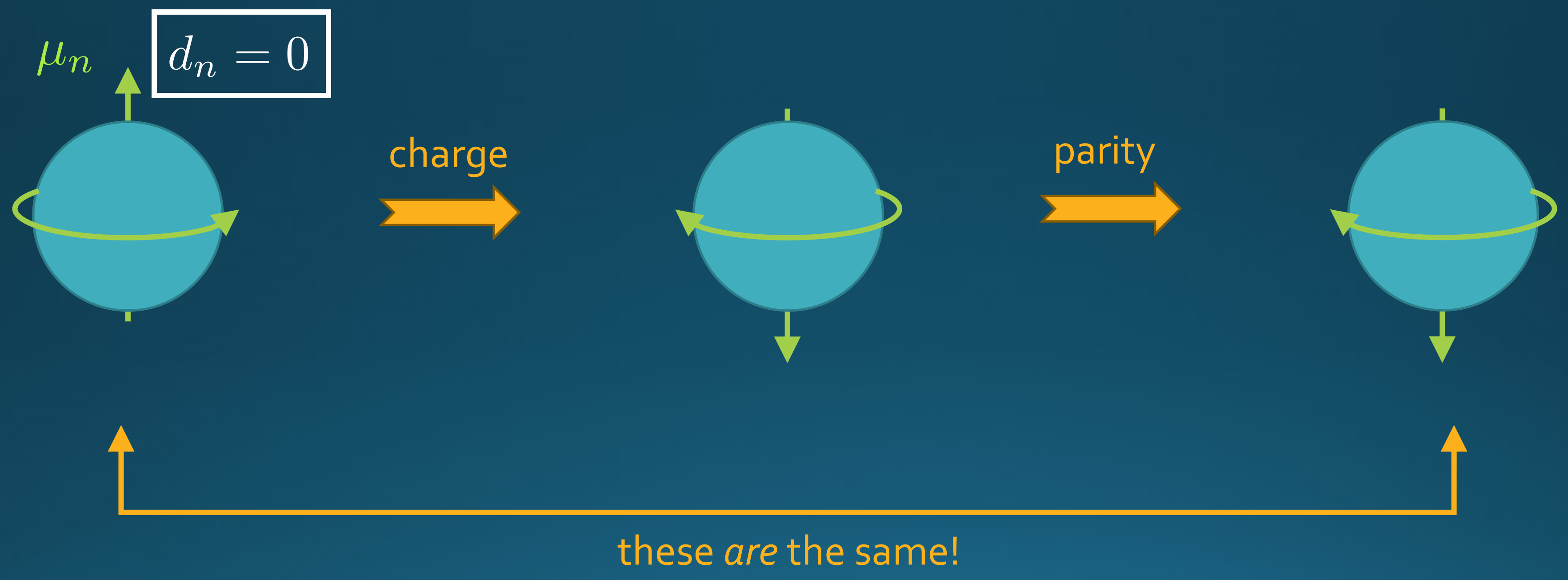
How to get CP *symmetry*



Why CP violation in QCD? (field theory)

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

$$\bar{\Theta} \equiv \Theta + \arg(\det M) \in [0, 2\pi]$$

from strong force
(multiple QCD vacua)

from Higgs coupling
(quark masses)

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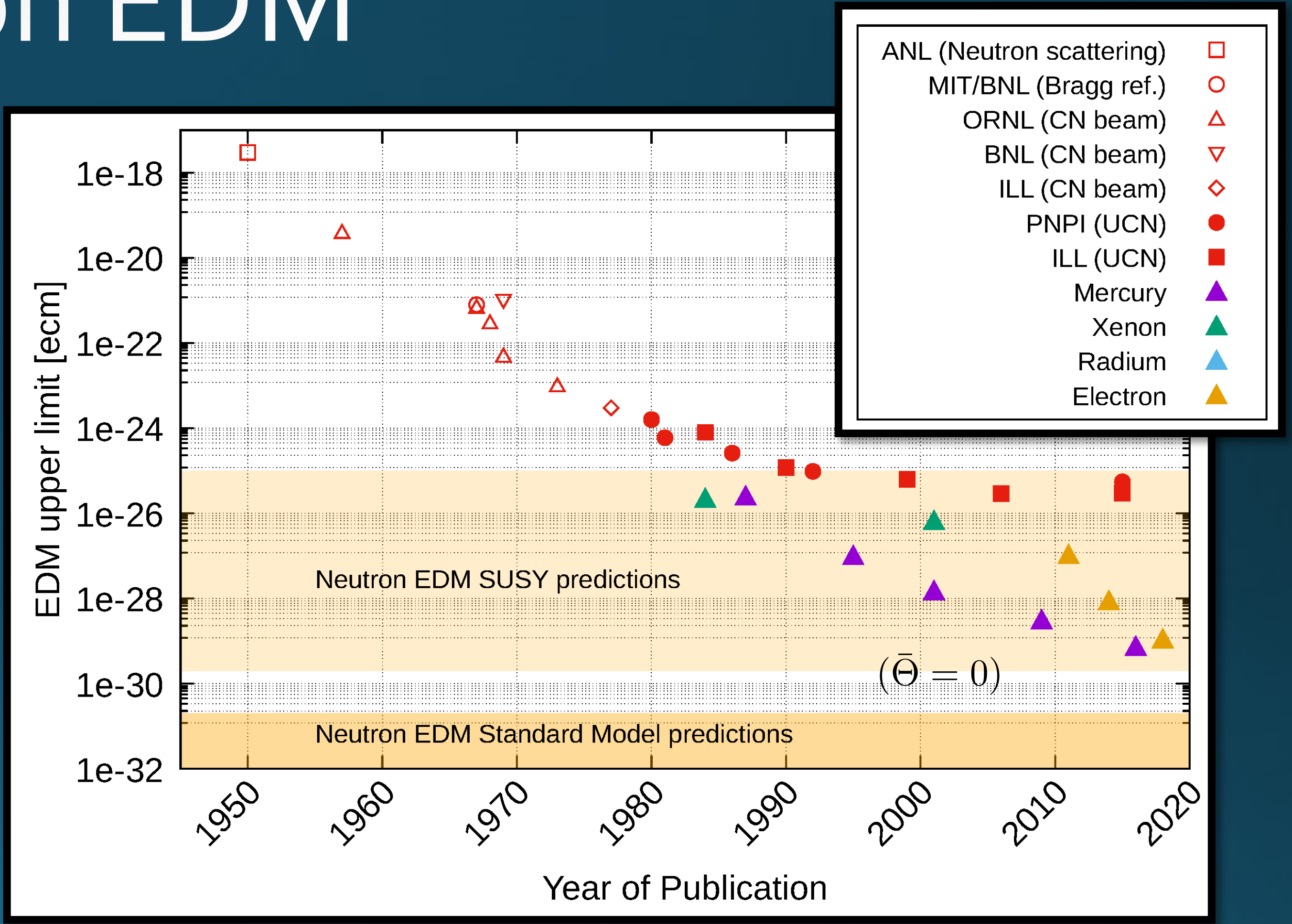
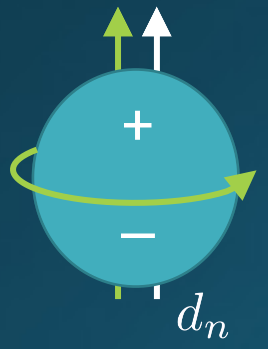
To get CP symmetry, $\bar{\Theta} = 0$

How much CP violation?
Measure $\bar{\Theta}$, neutron EDM

$$|d_n| \sim 3 \times 10^{-16} \bar{\Theta}\, e \cdot \mathrm{cm}$$
$$< 1.8 \times 10^{-26}\, e \cdot \mathrm{cm}$$



Kuchler 2019



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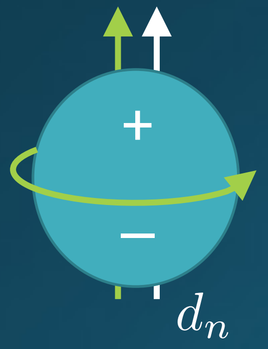
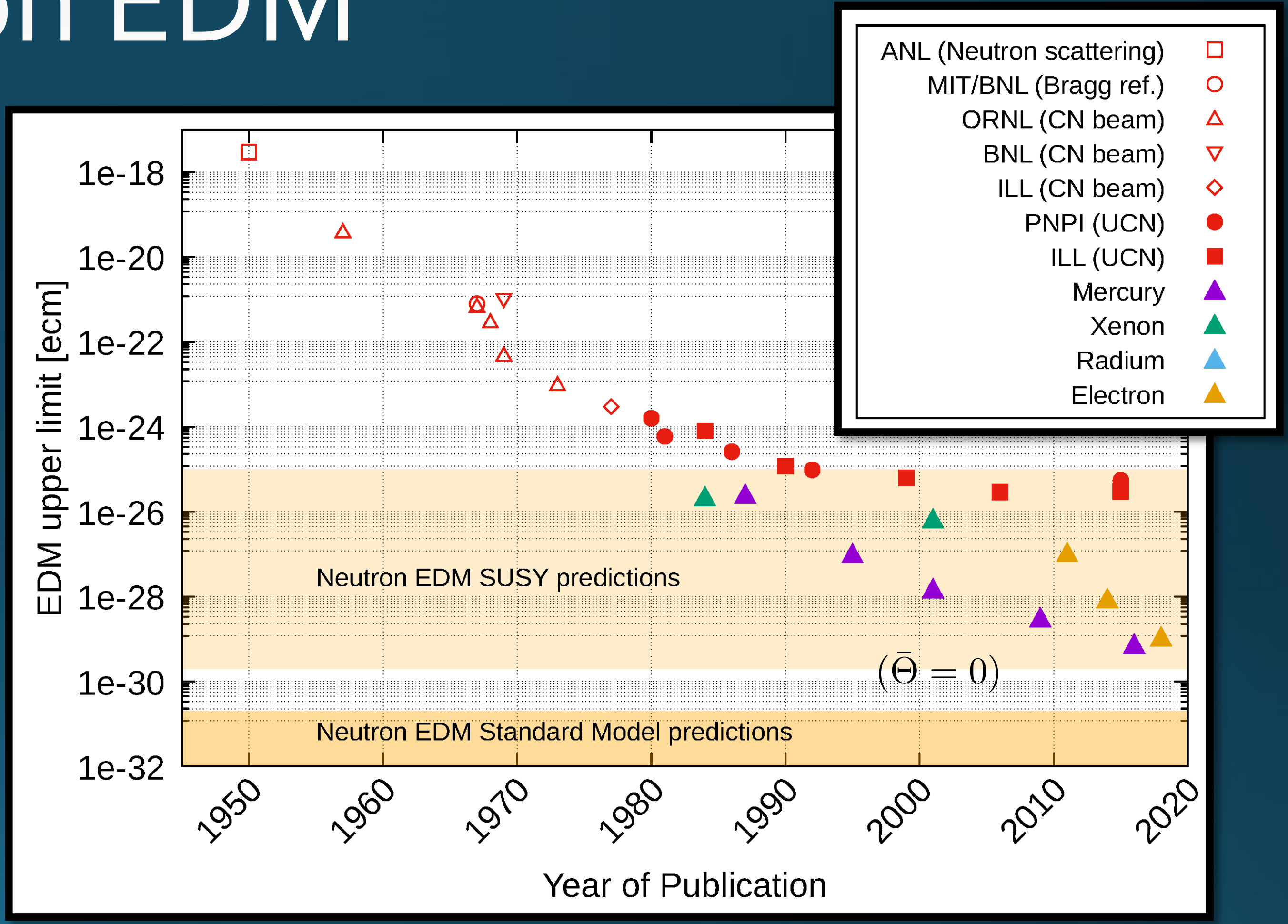
$$\Downarrow$$

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





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No CP violation is weird!

Field theory

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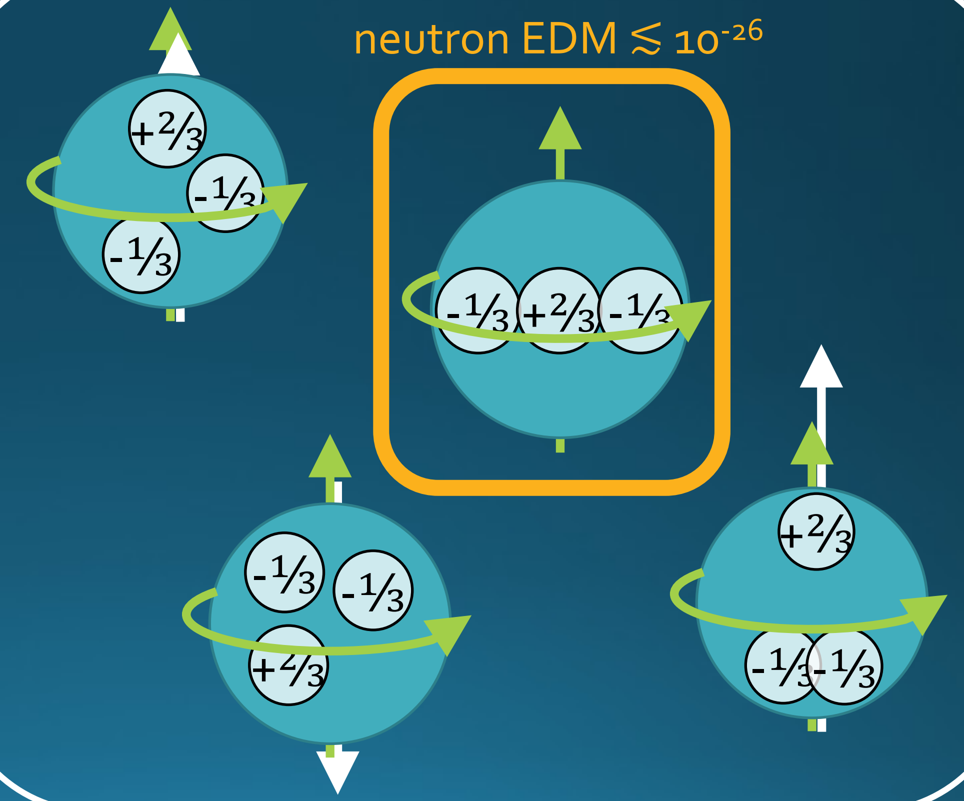
Toy model



A solution

Peccei and Quinn 1977, add an additional term:

$$\mathcal{L}_{\mathrm{QCD}} \supset \left(\frac{a}{f_a} - \bar{\Theta}\right)\frac{\alpha_S}{8\pi} G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$$

axion field

(large) symmetry
breaking energy scale

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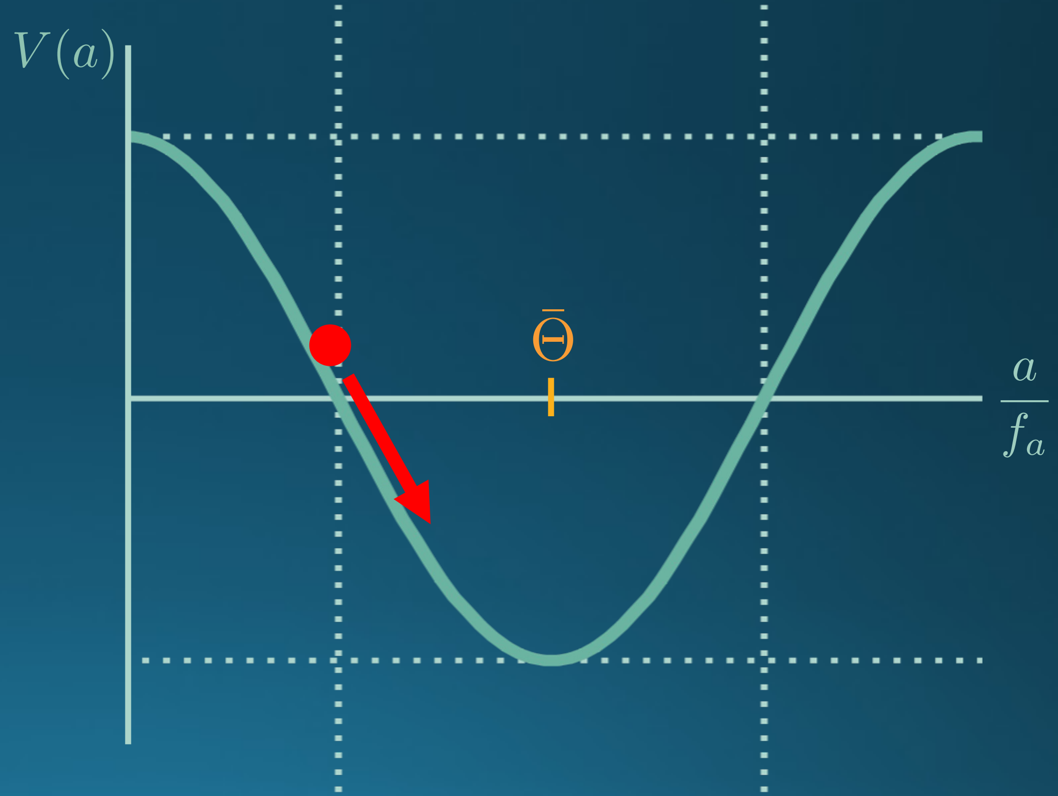

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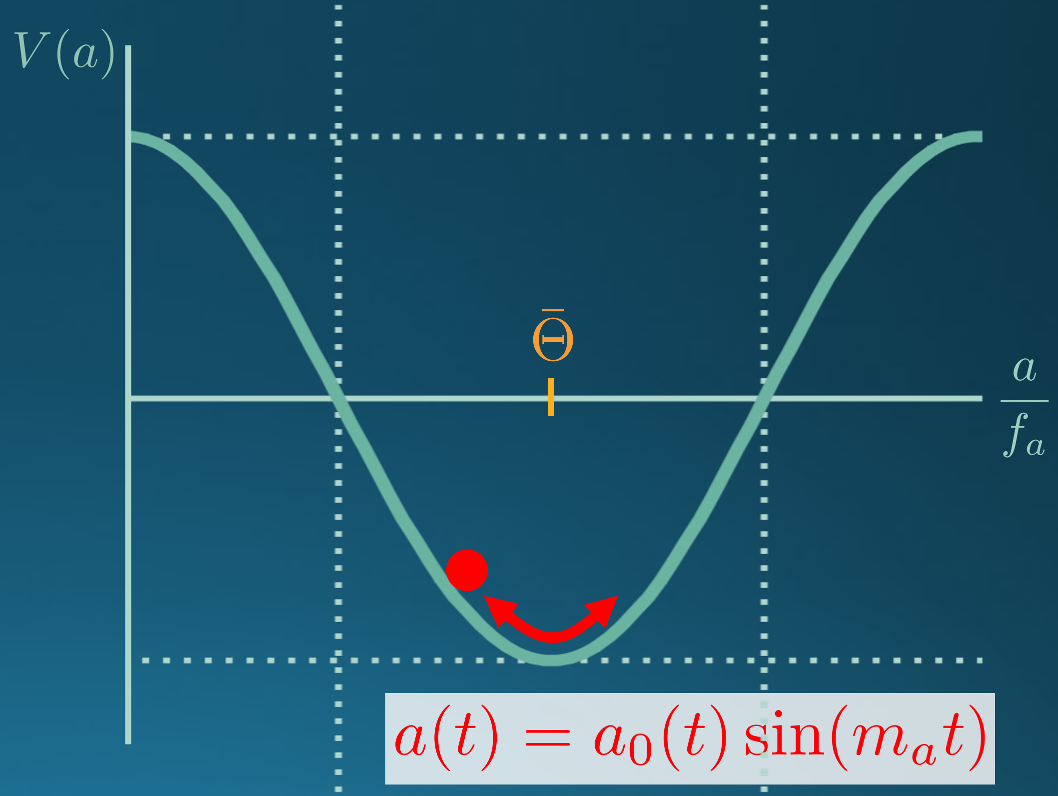

$$a(t) = a_0(t)\sin(m_a t)$$

Axions can be the dark matter

- Particle ✓
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- Feeble or nonexistent interactions with visible matter ✓
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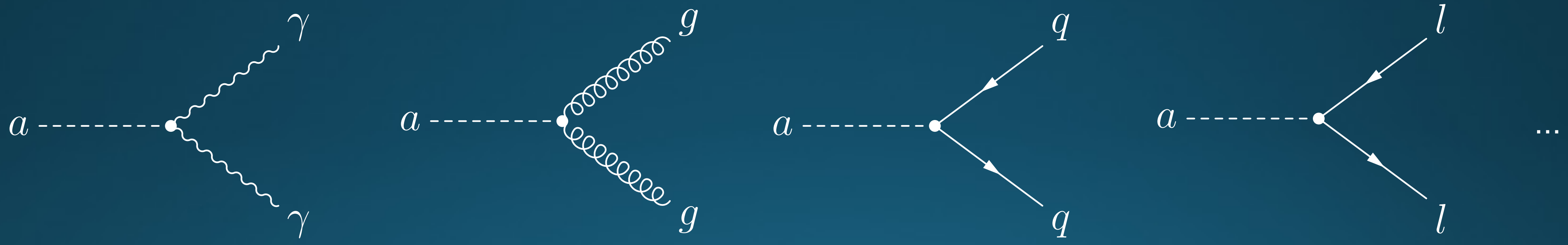
How do we detect them?

Many interactions to choose from, but all are feeble ($\propto 1/f_a$)



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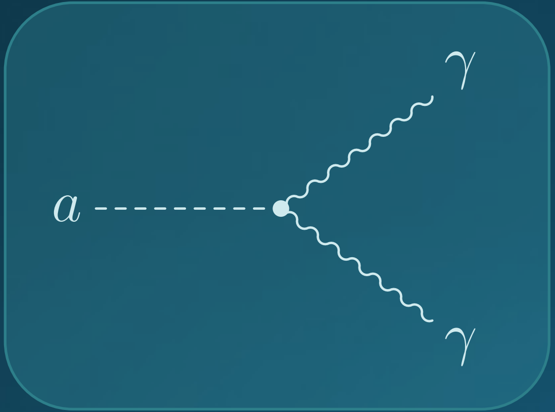

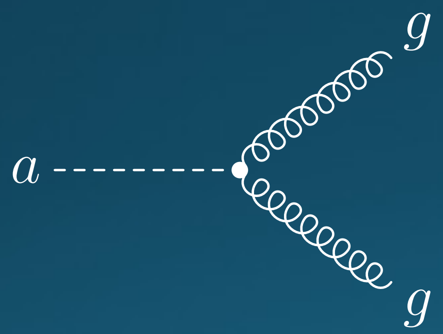

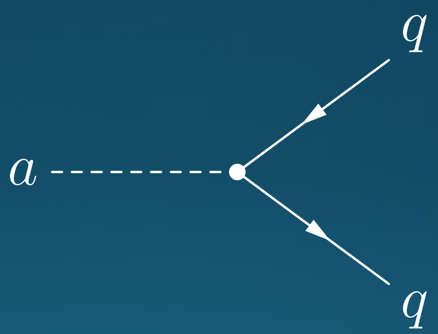

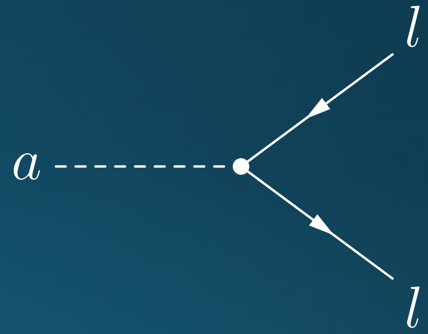

...

Not a normal scattering experiment

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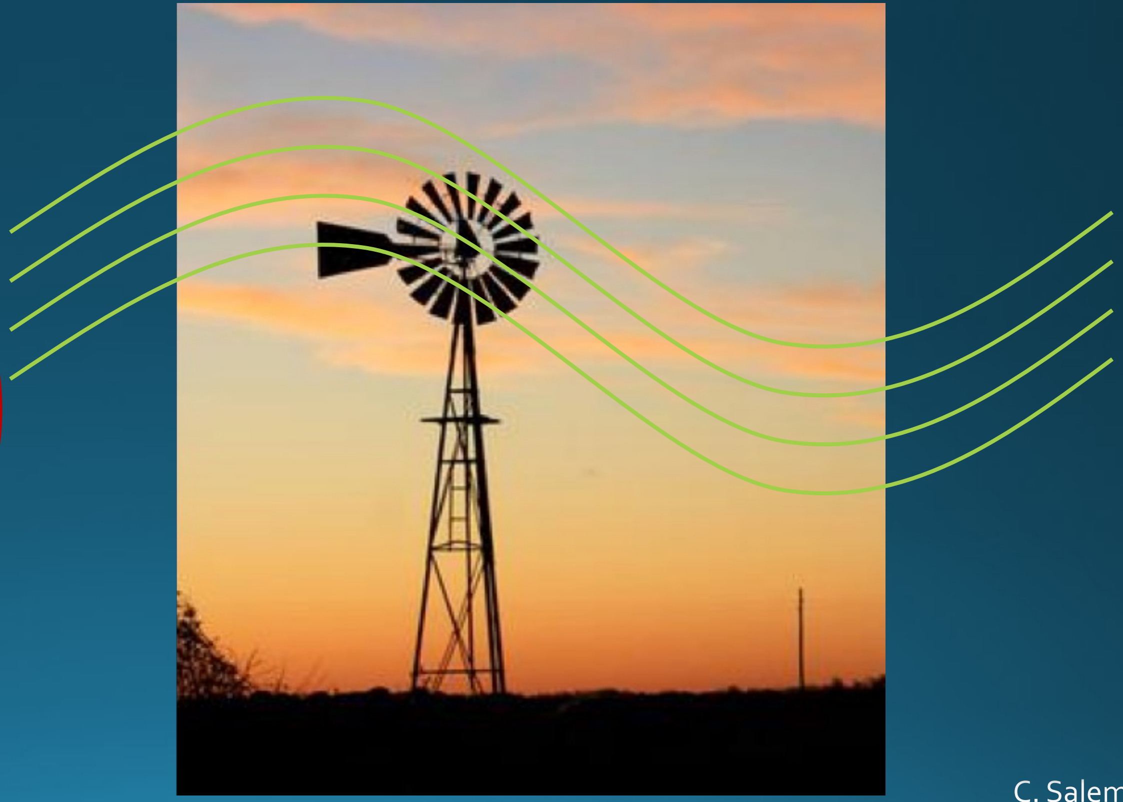
- Too light to use standard particle detectors

Not a normal scattering experiment

- Too light to use standard particle detectors
- But very numerous!



Axion E&M

Axion-photon interactions modify Ampere's Law:

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

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

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Search regimes

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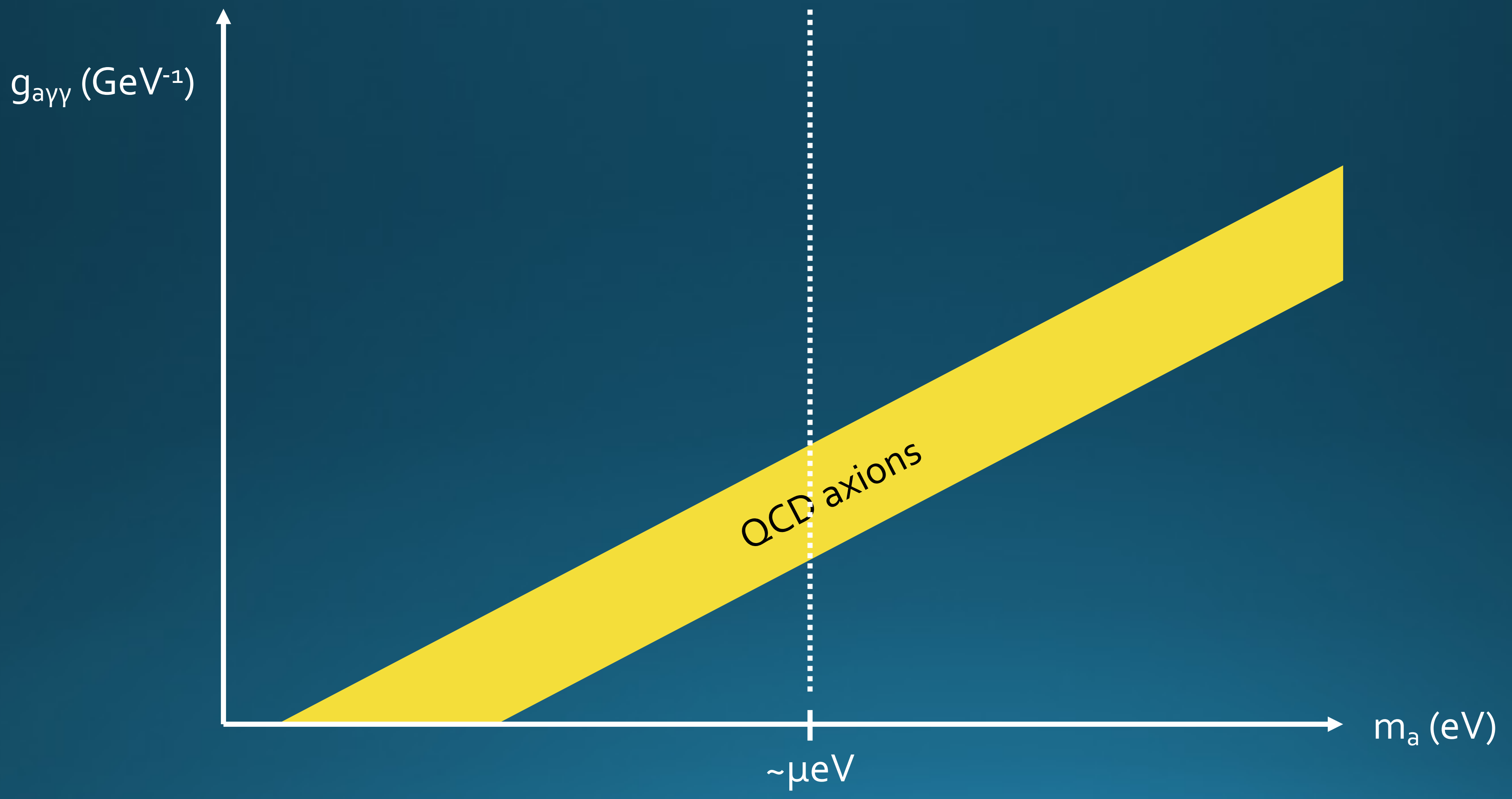

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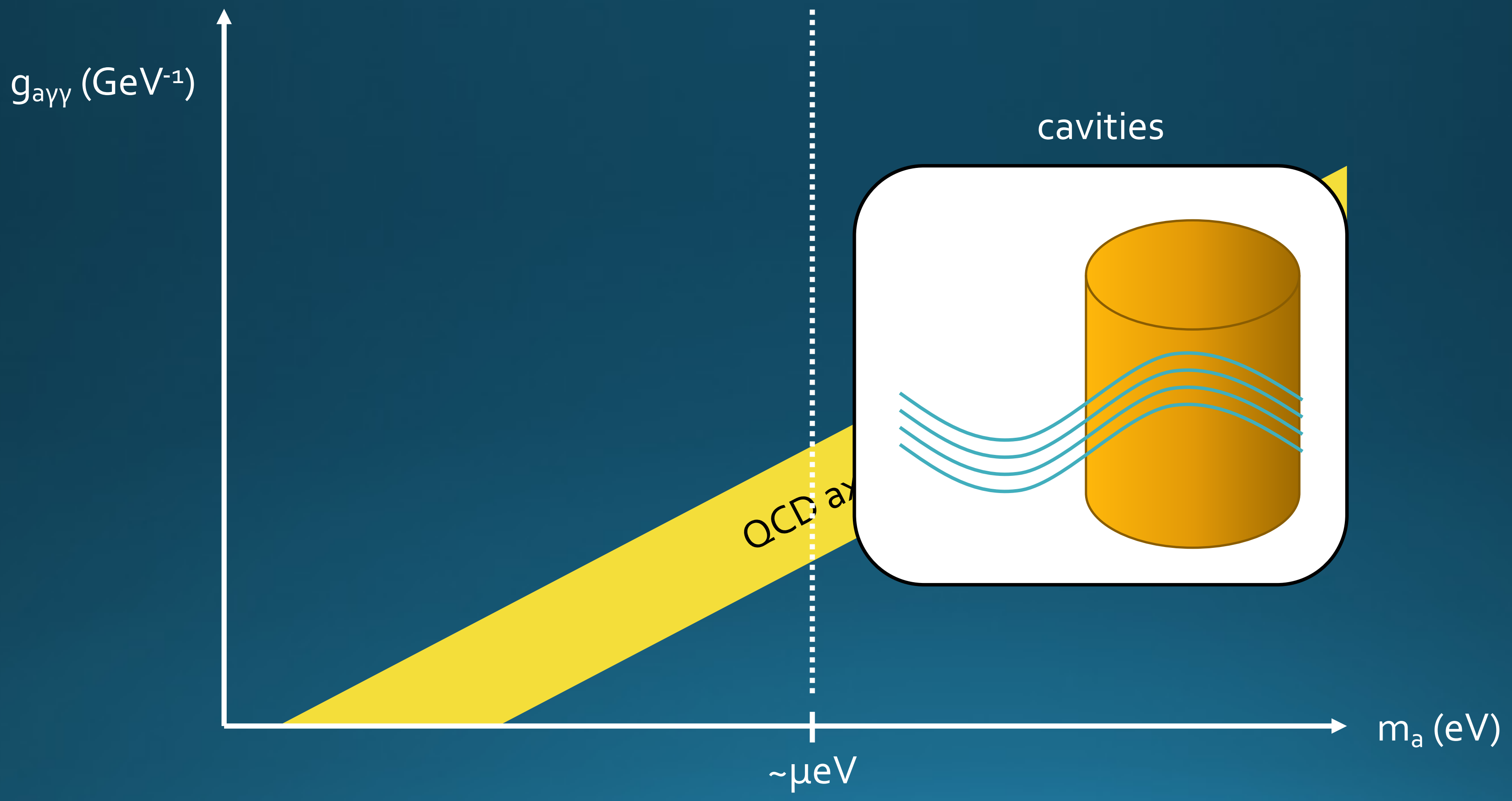

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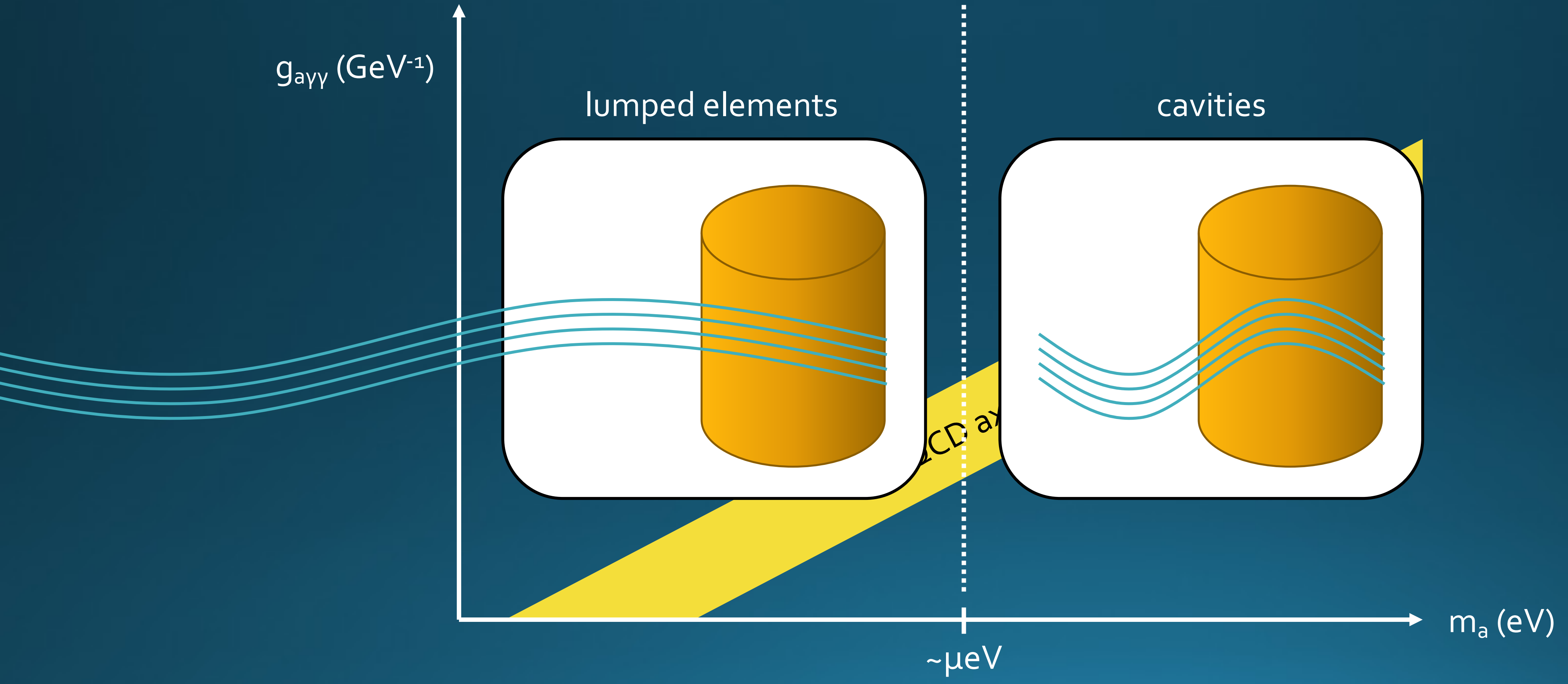
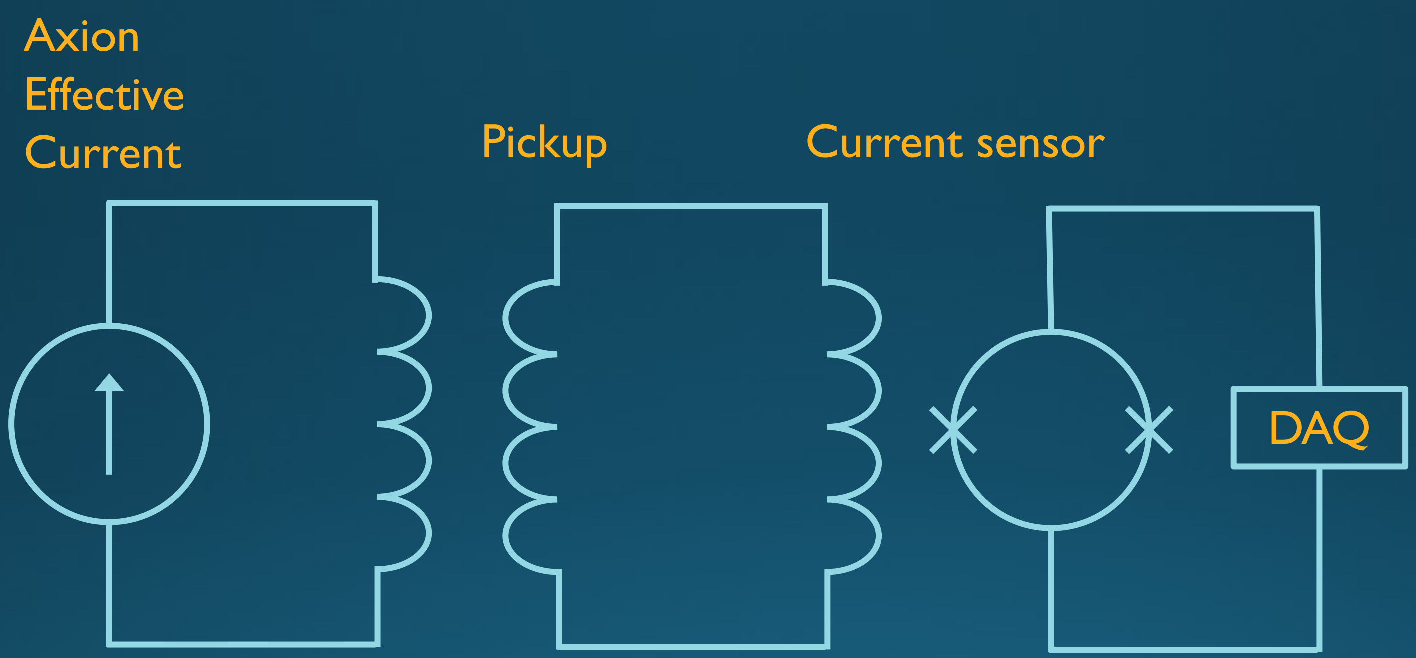


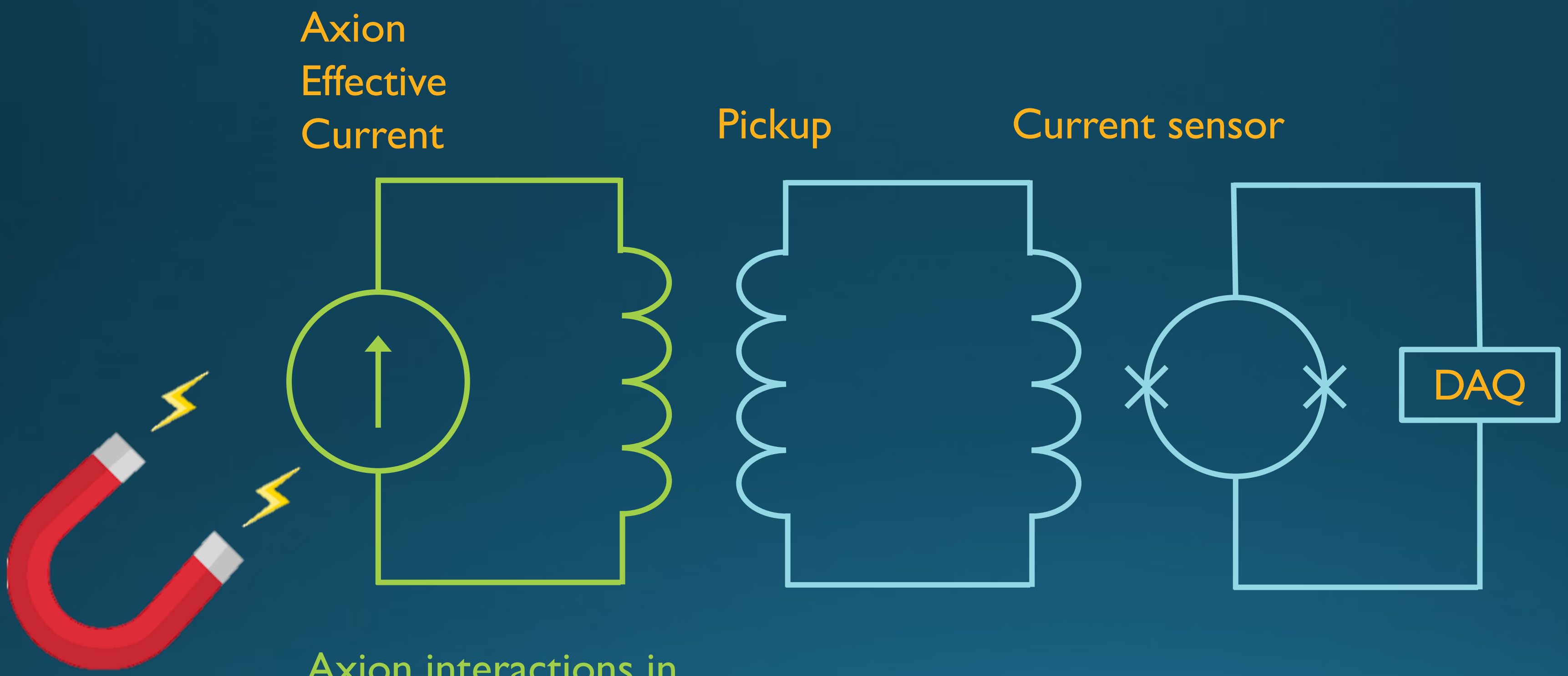
Kahn, Safdi, Thaler 2016

Schematic of lumped element detection



Lumped elements

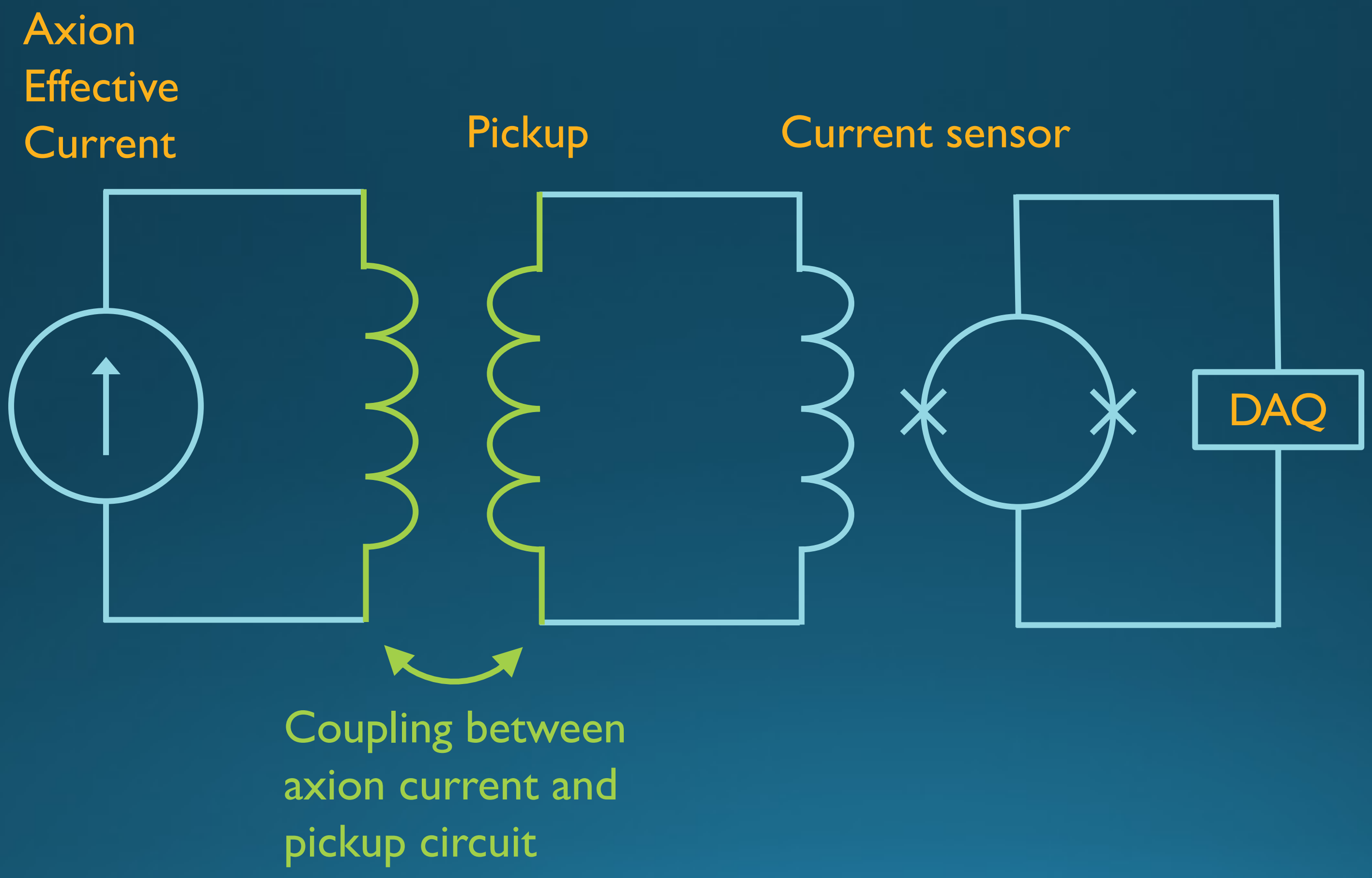
Schematic of lumped element detection



Axion interactions in magnetic field

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

Schematic of lumped element detection



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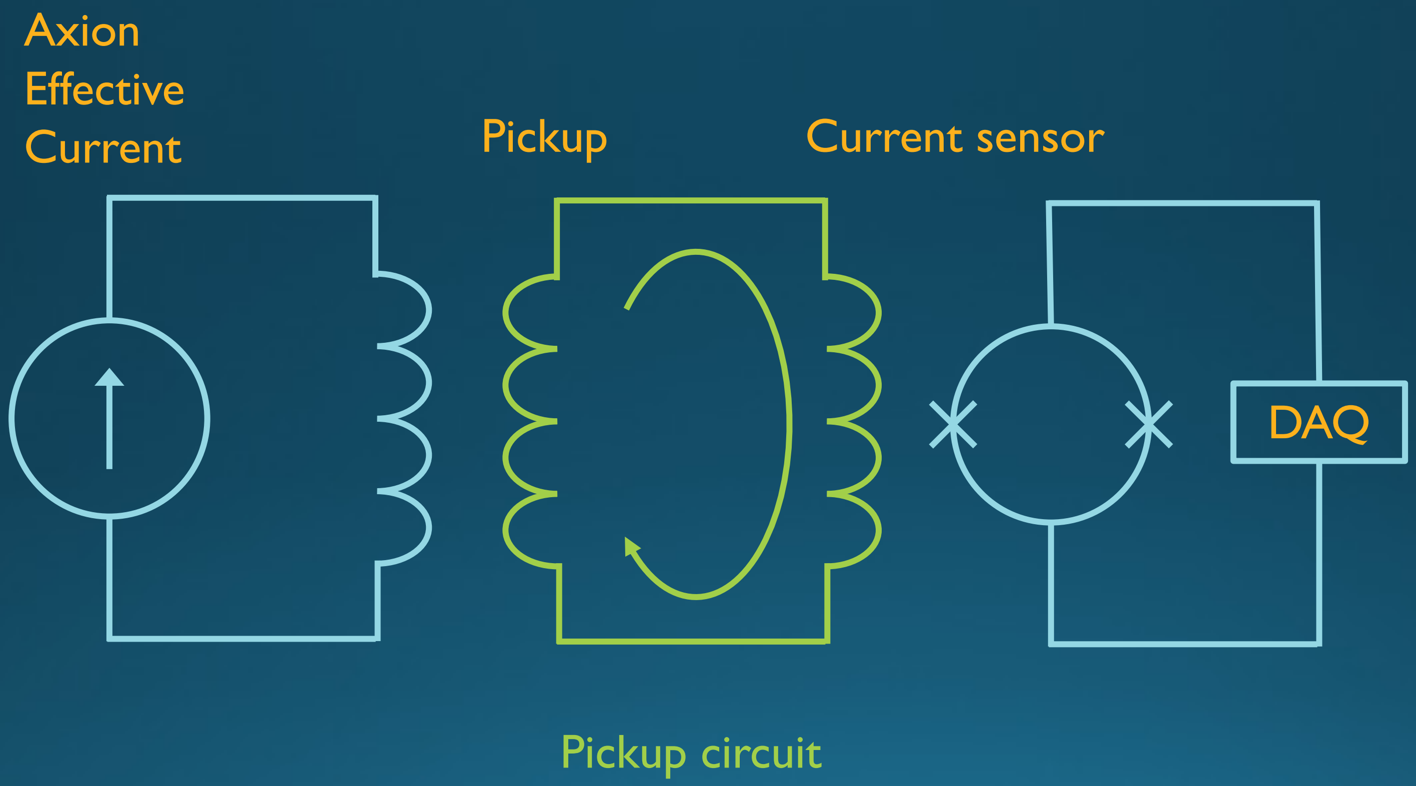

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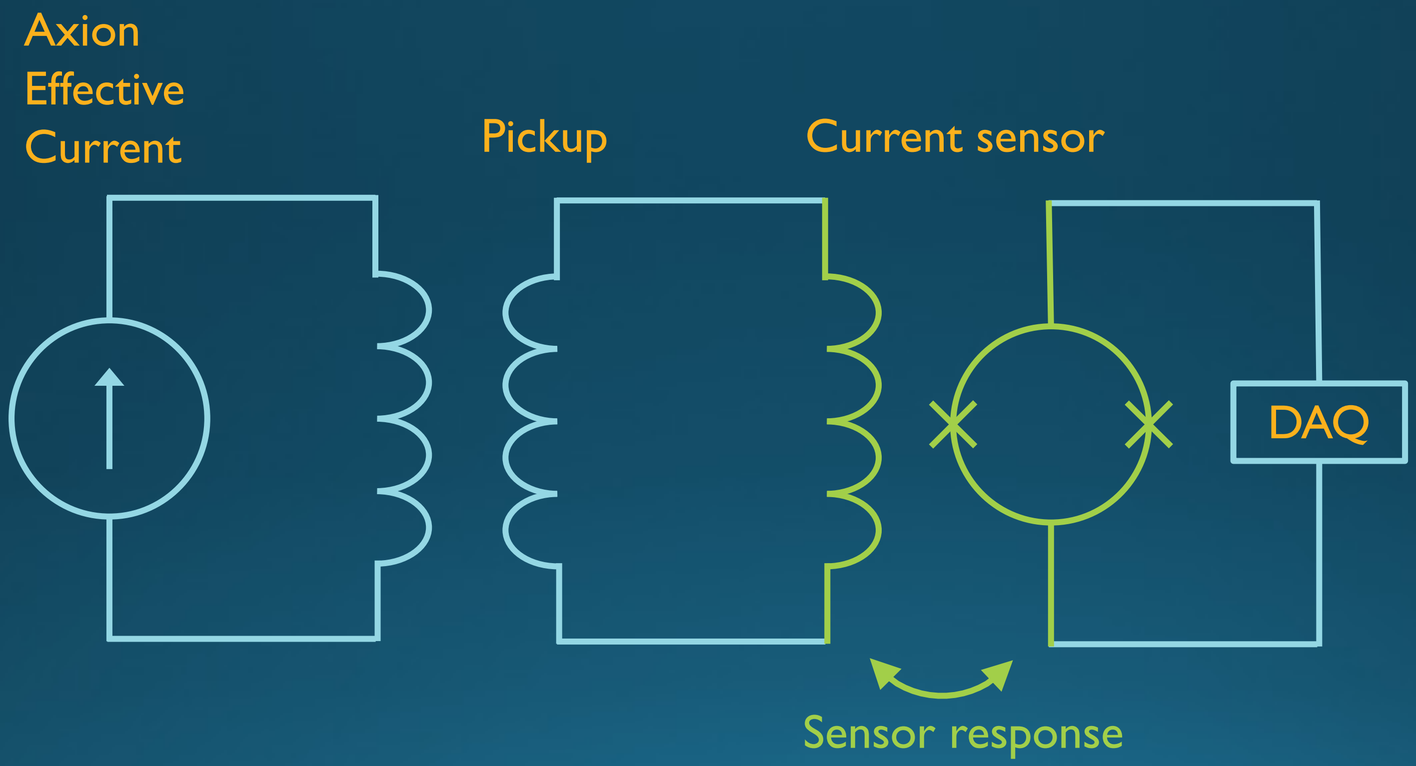

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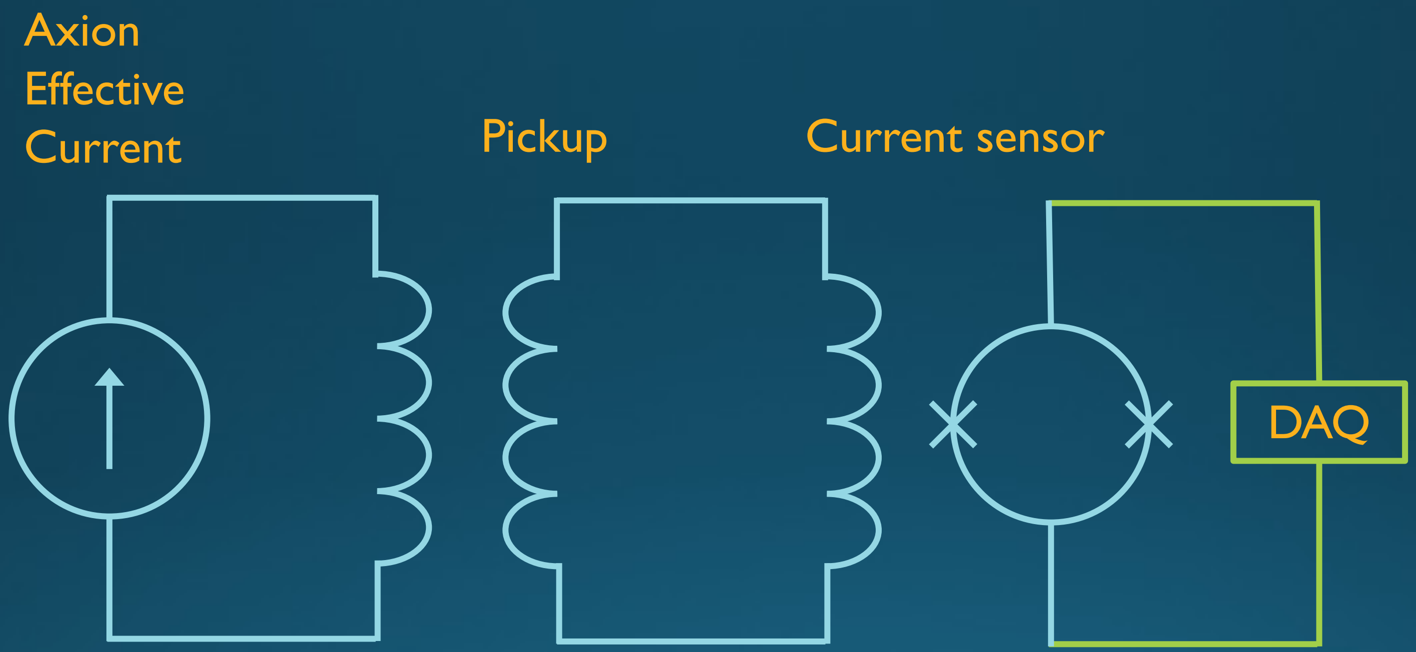

ABRACADABRA-10cm

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

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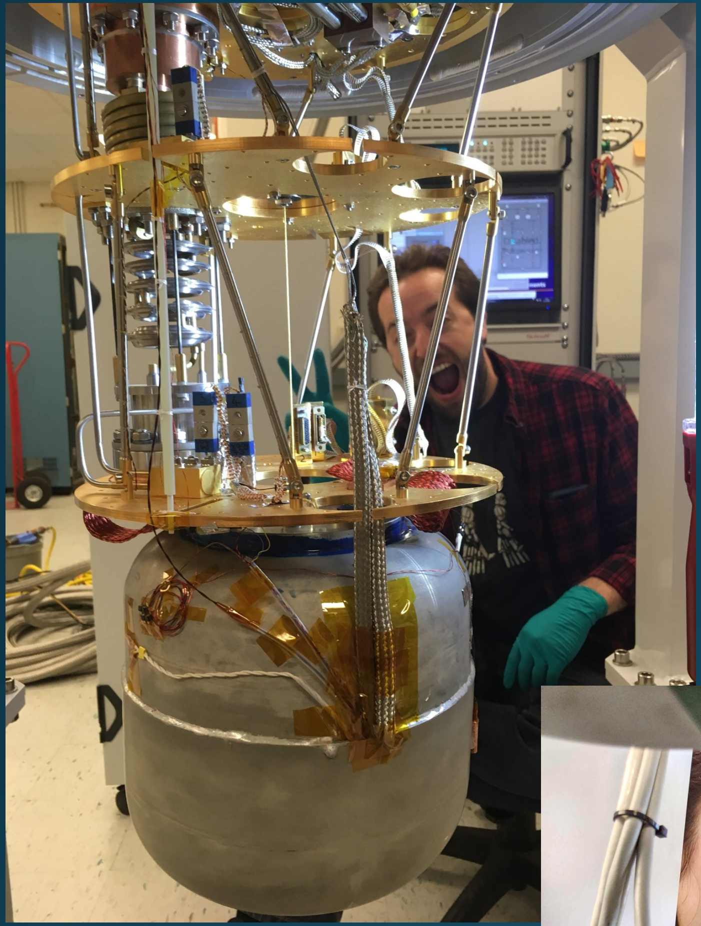
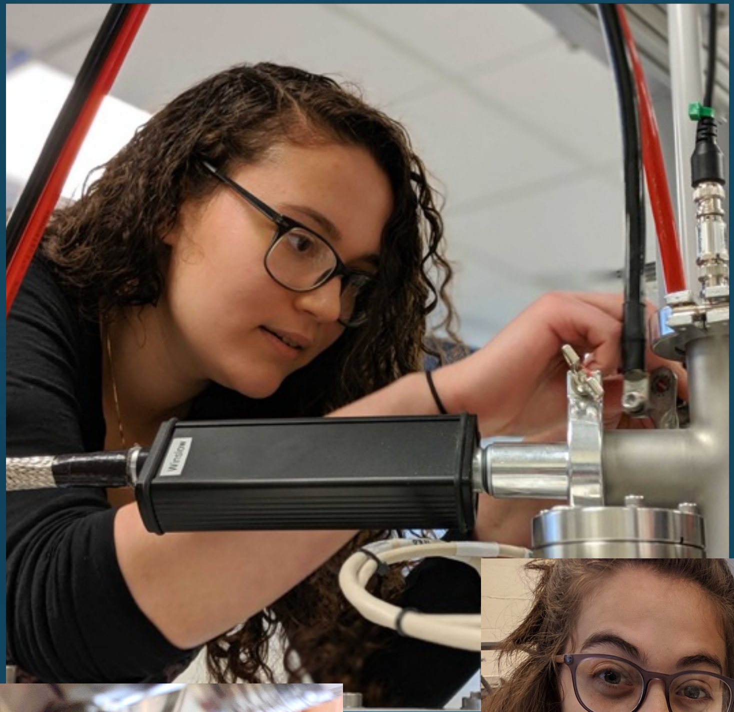
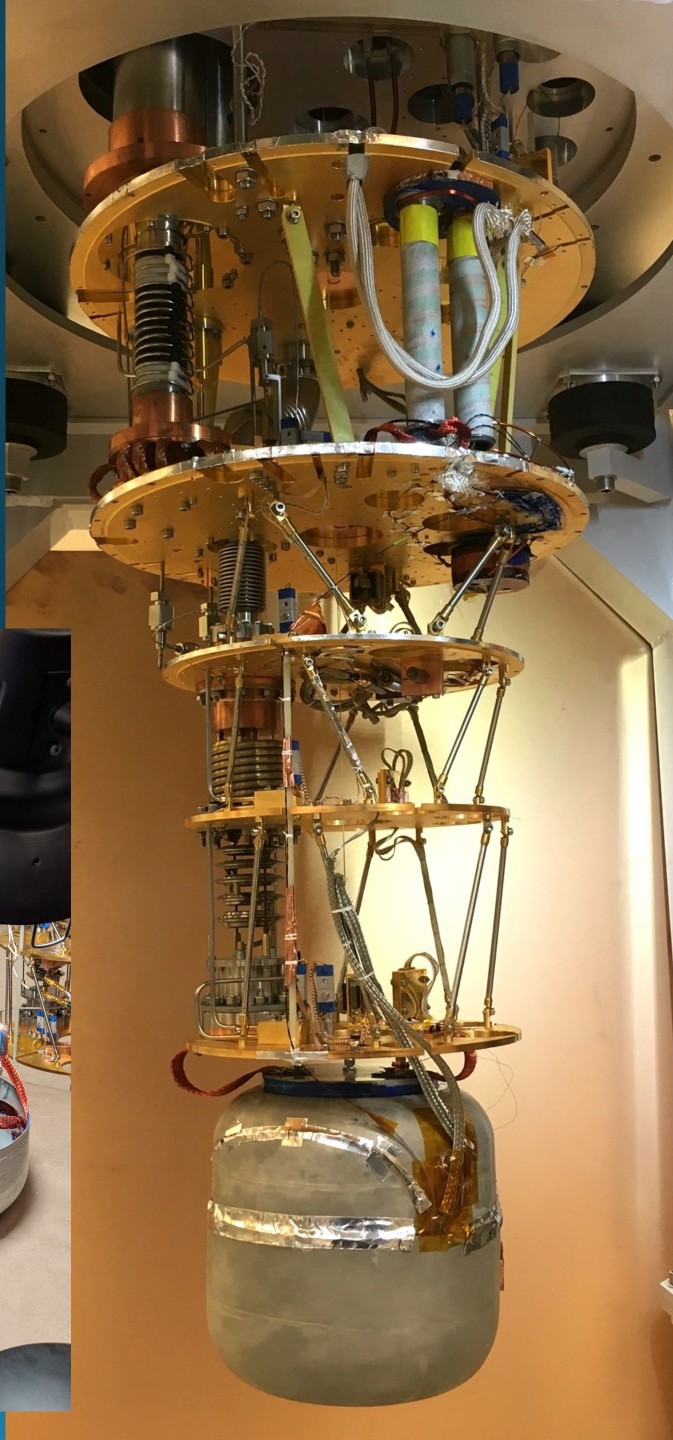
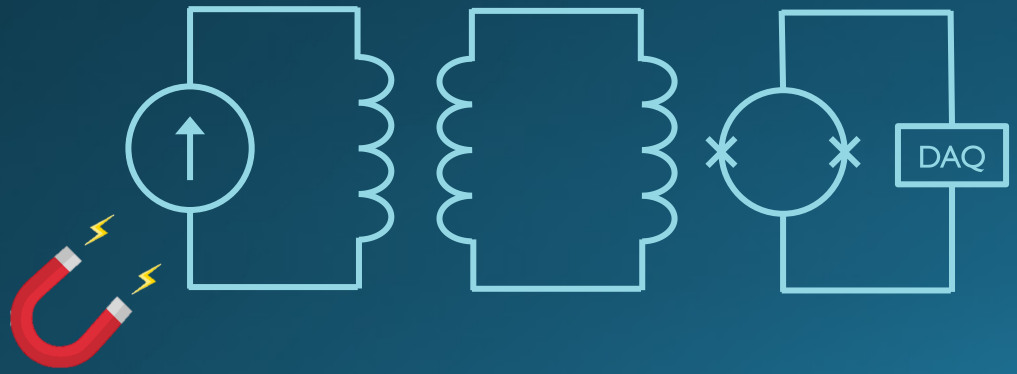






The detector

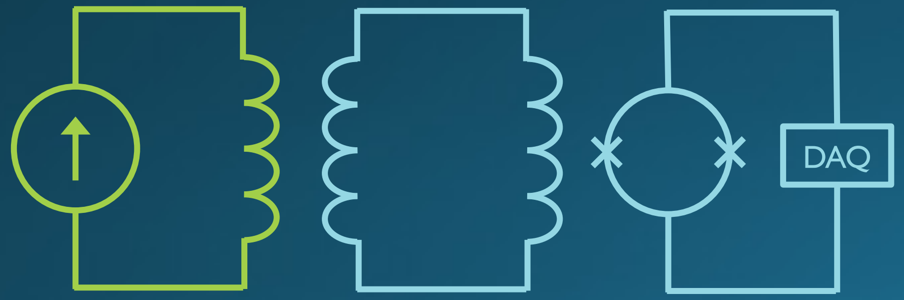
Toroidal superconducting magnet with fixed field, B_0



The detector

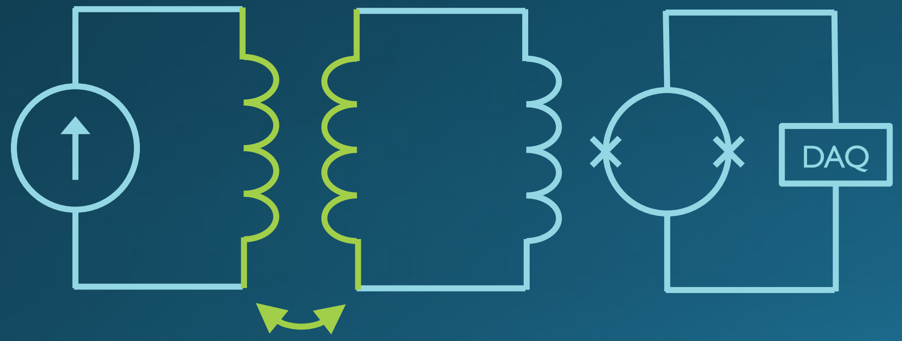
Axion dark matter generates parallel oscillating effective current, $\mathbf{J}_{\text{eff}}$

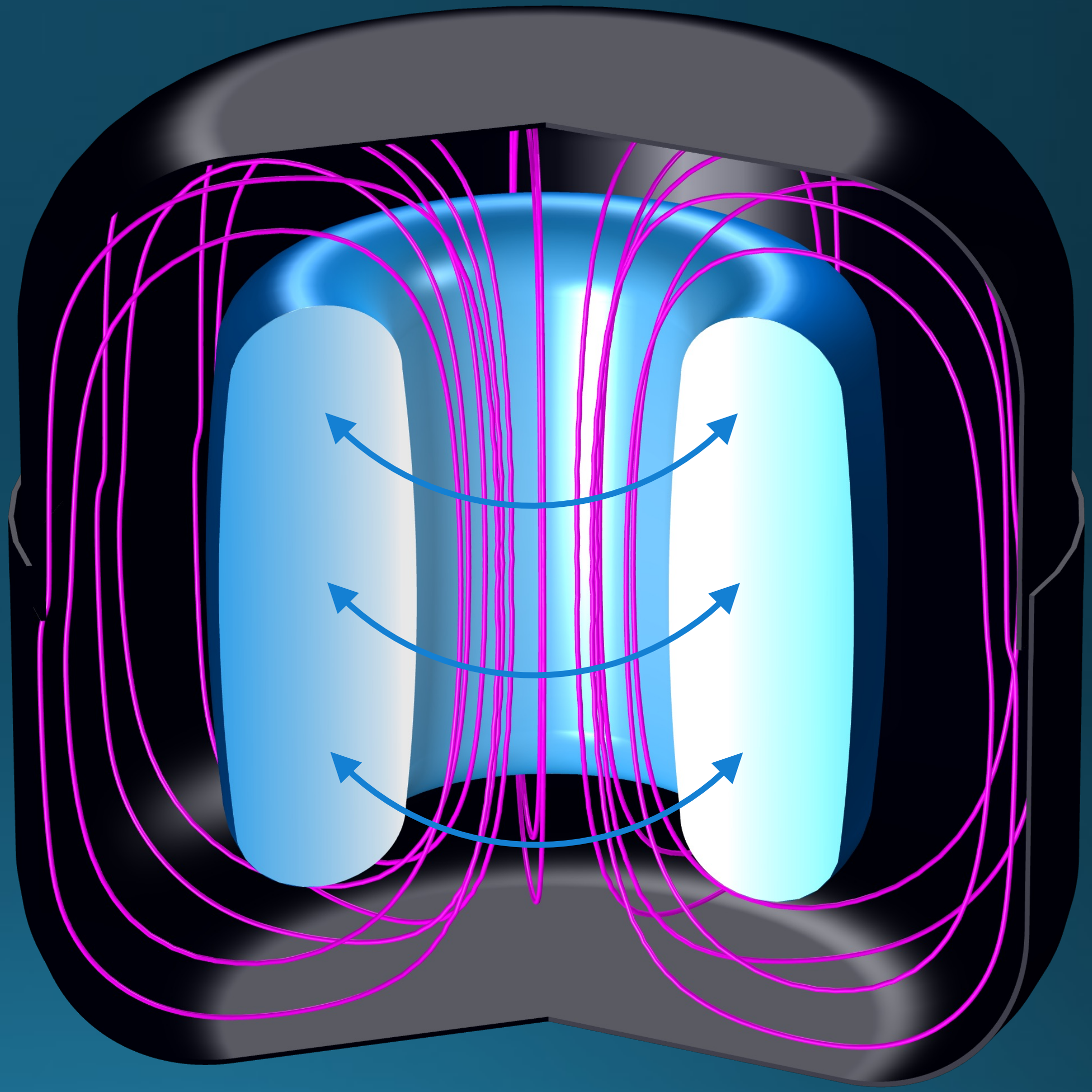
$$\mathbf{J}_{eff} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\cos(m_a t)\mathbf{B}_0$$



The detector

…creating an oscillating magnetic flux through the center of the toroid

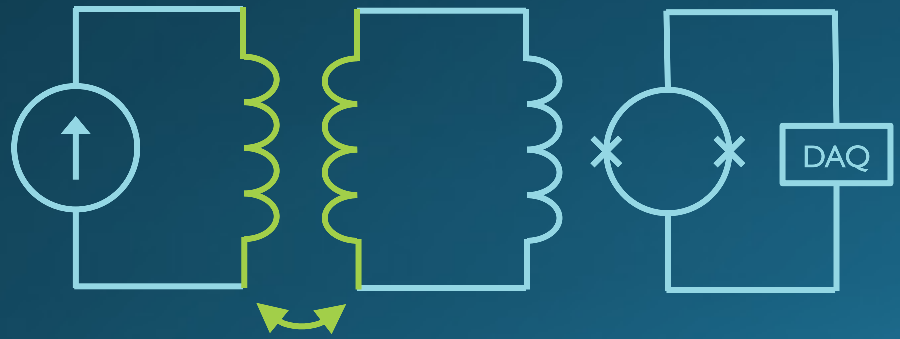


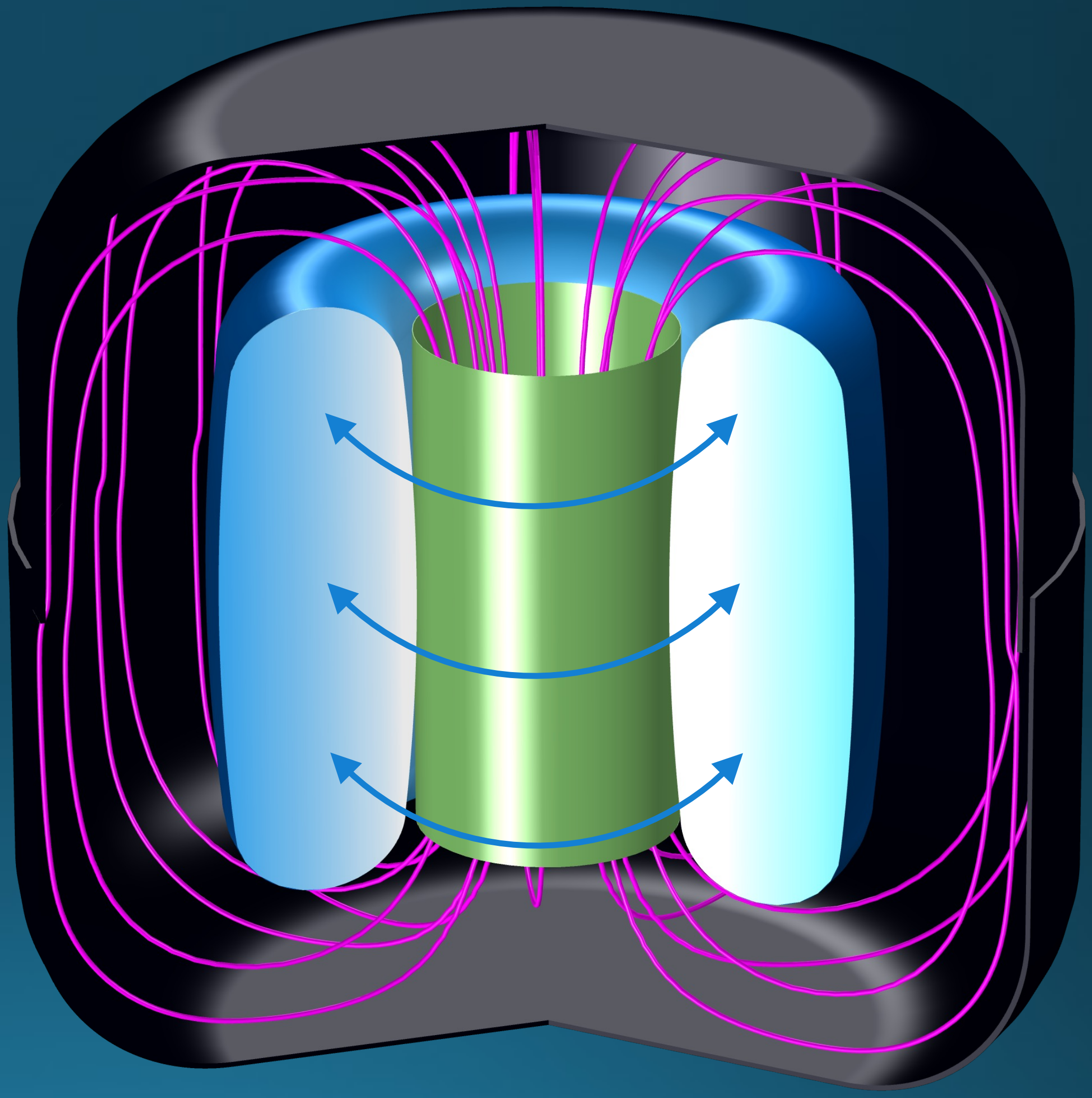


The detector

...and inducing currents on a pickup structure

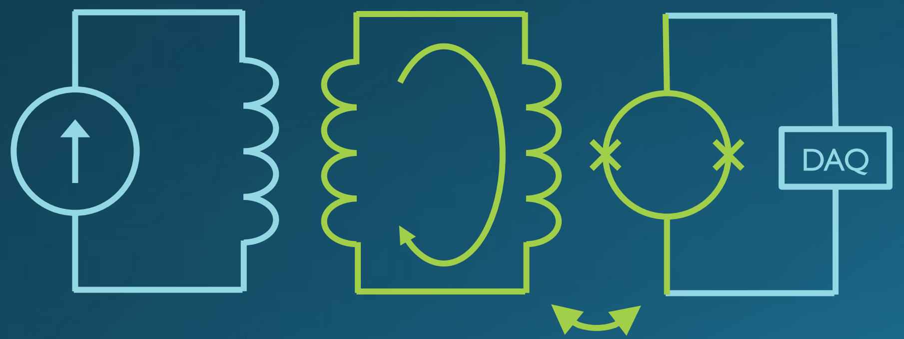
$$\langle \Phi \rangle = g_{a\gamma\gamma}\sqrt{\rho_{\mathrm{DM}}}B_0 V \mathcal{G}$$

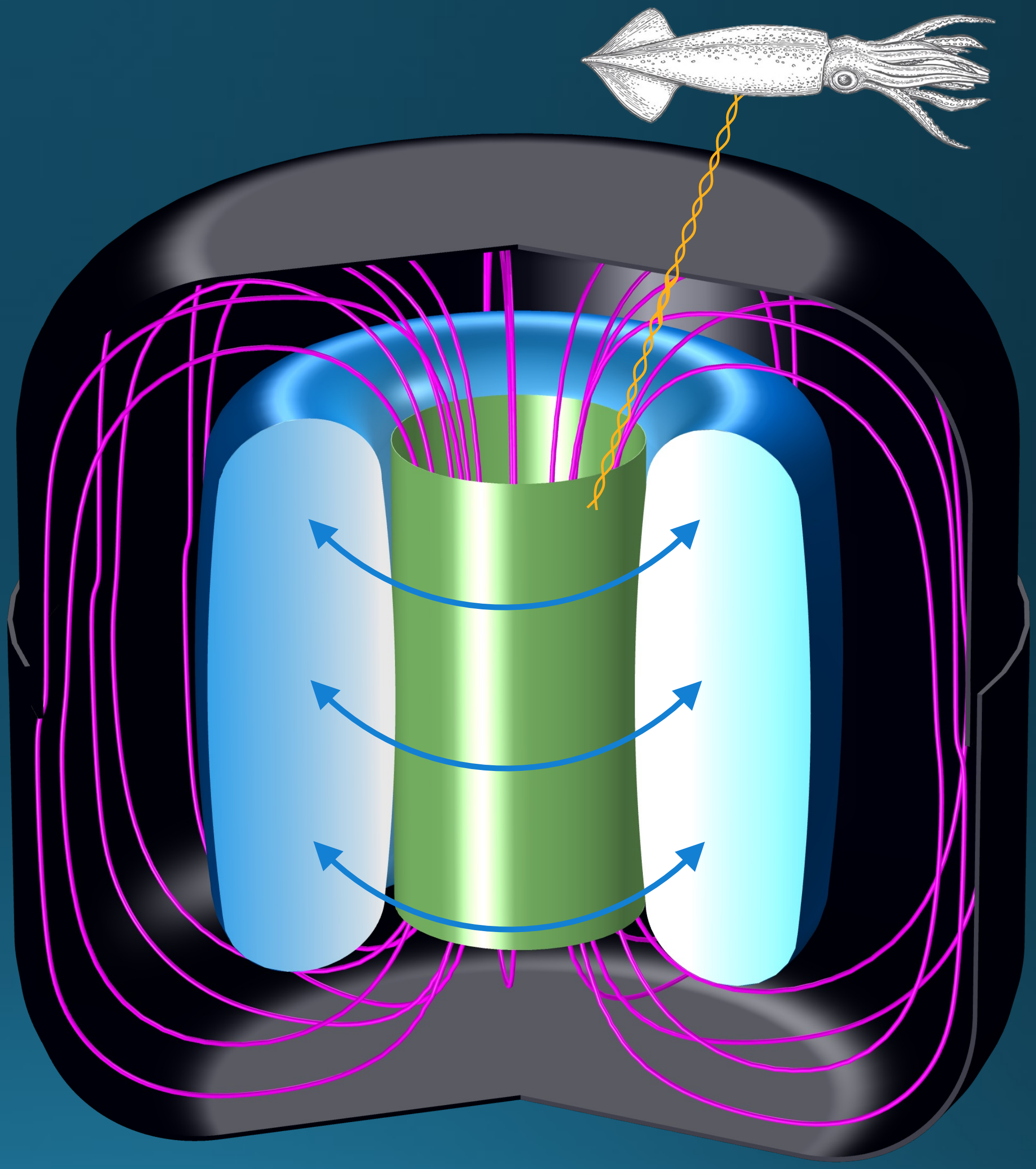




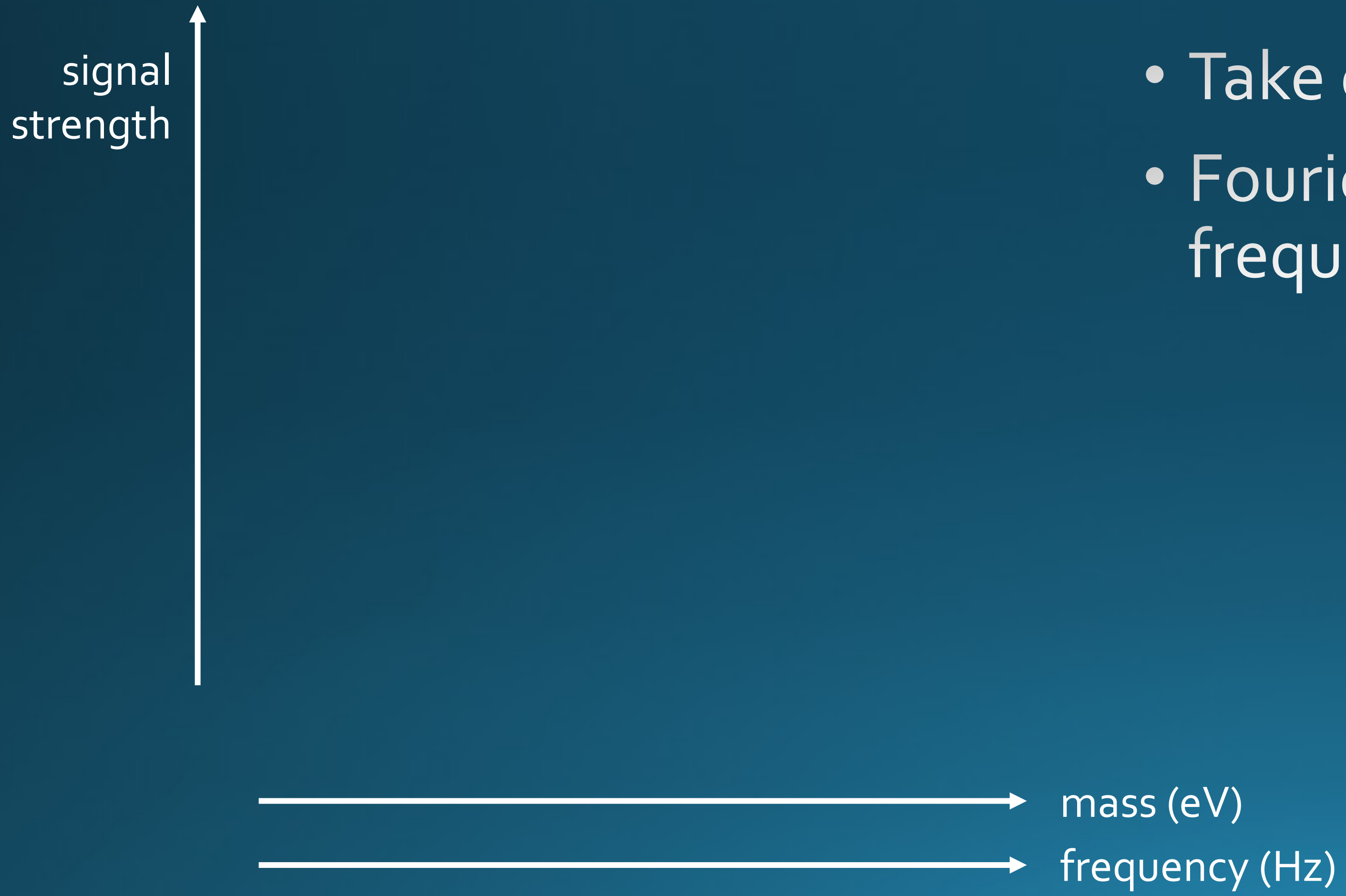
The detector

This signal is read out and amplified using a SQUID current sensor





What does a signal look like?

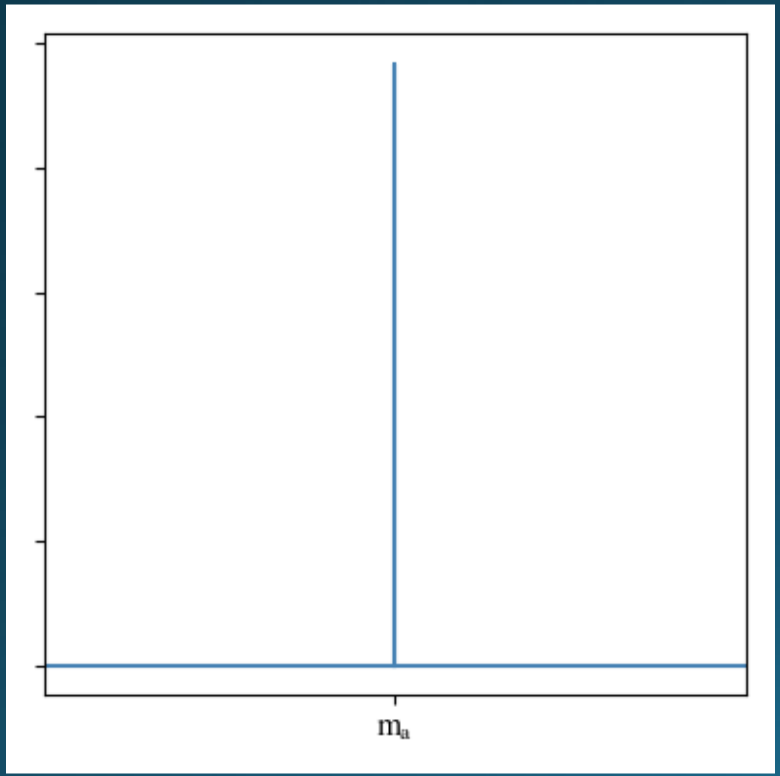


- Take continuous time series data
- Fourier transform to look for peaks in frequency space

What does a signal look like?

Sharp peak at axion mass

signal strength



mass (eV)

frequency (Hz)

- Take continuous time series data
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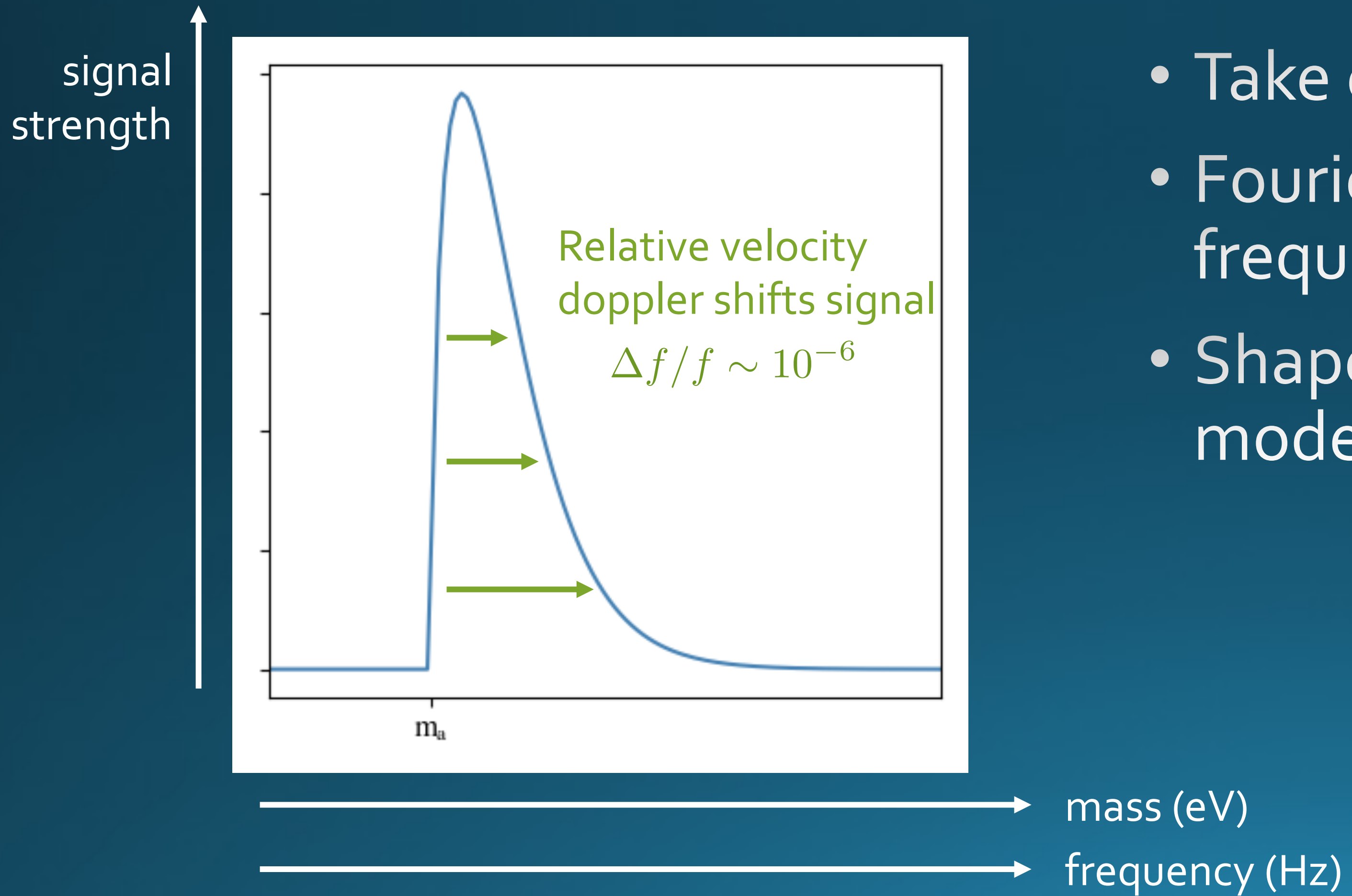
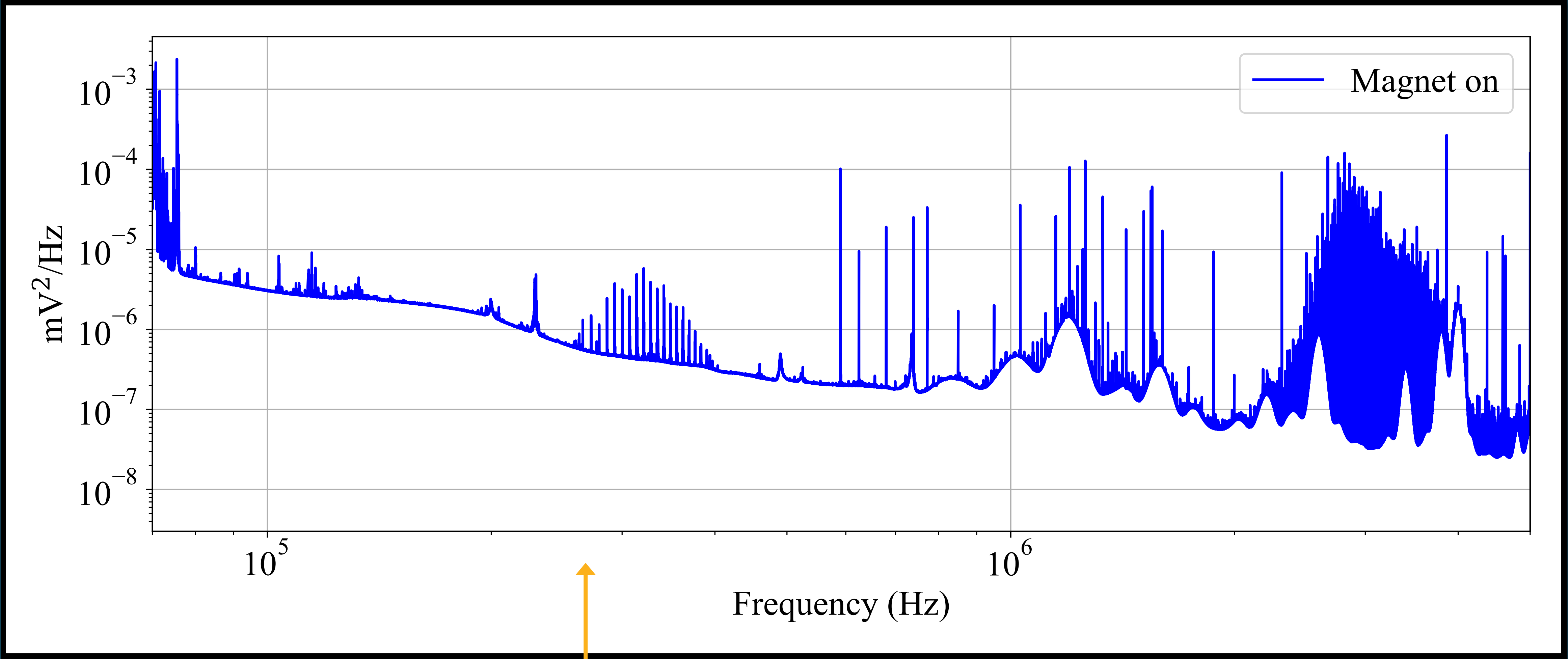
$$\mathbf{J}_{eff} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\cos(m_a t)\mathbf{B}$$

What does a signal look like?



- Take continuous time series data
- Fourier transform to look for peaks in frequency space
- Shape determined by standard halo model

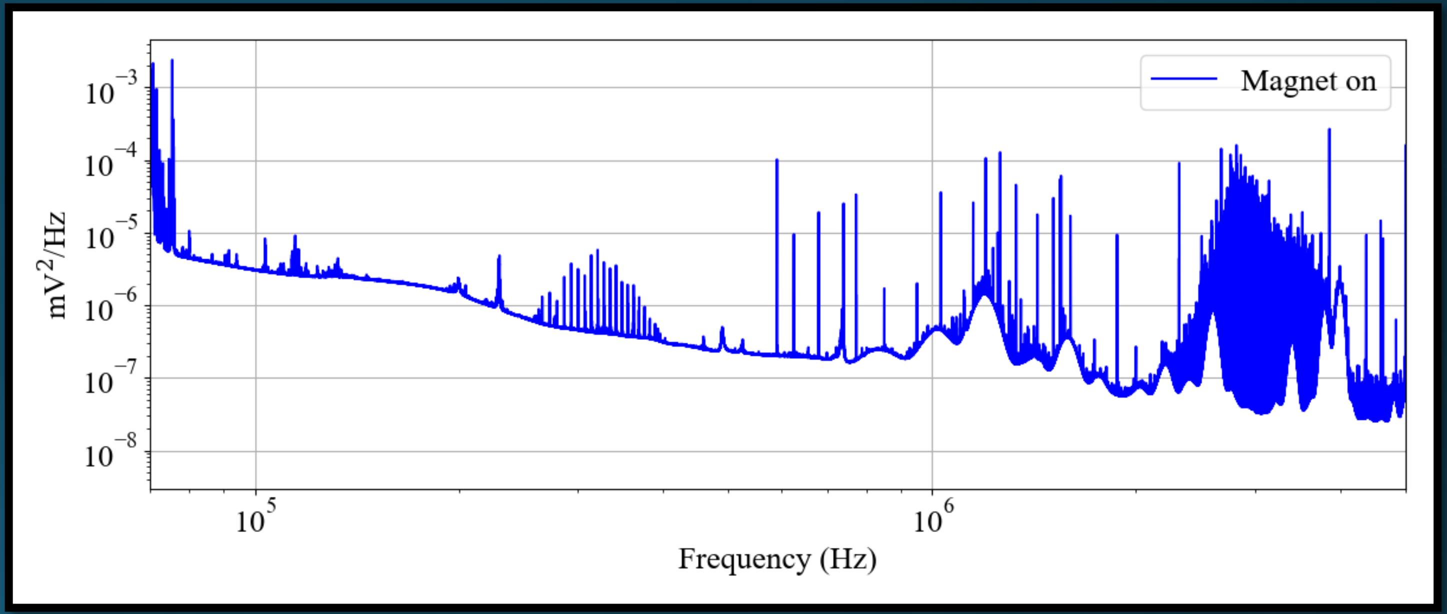
Run 3 averaged spectrum



m_a ~ 1 neV (GUT-scale)

From raw data to limit (or discovery)

1. Remove backgrounds
2. Calibrate
3. Fit axion signal



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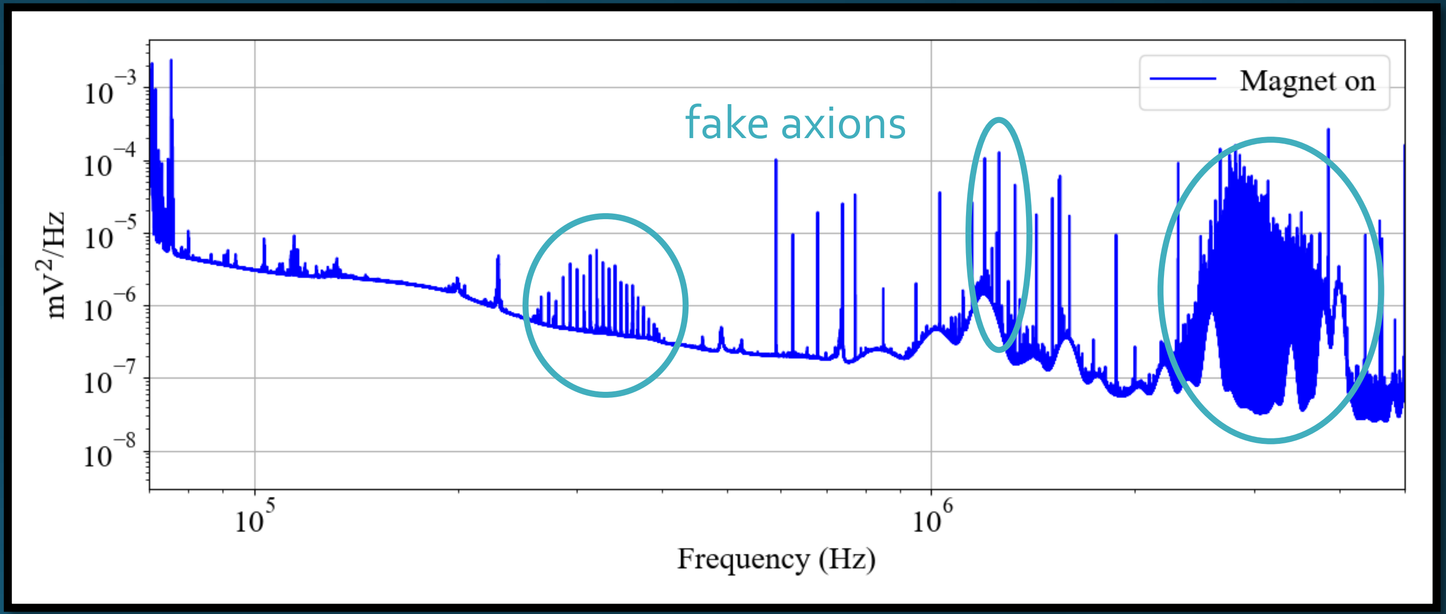
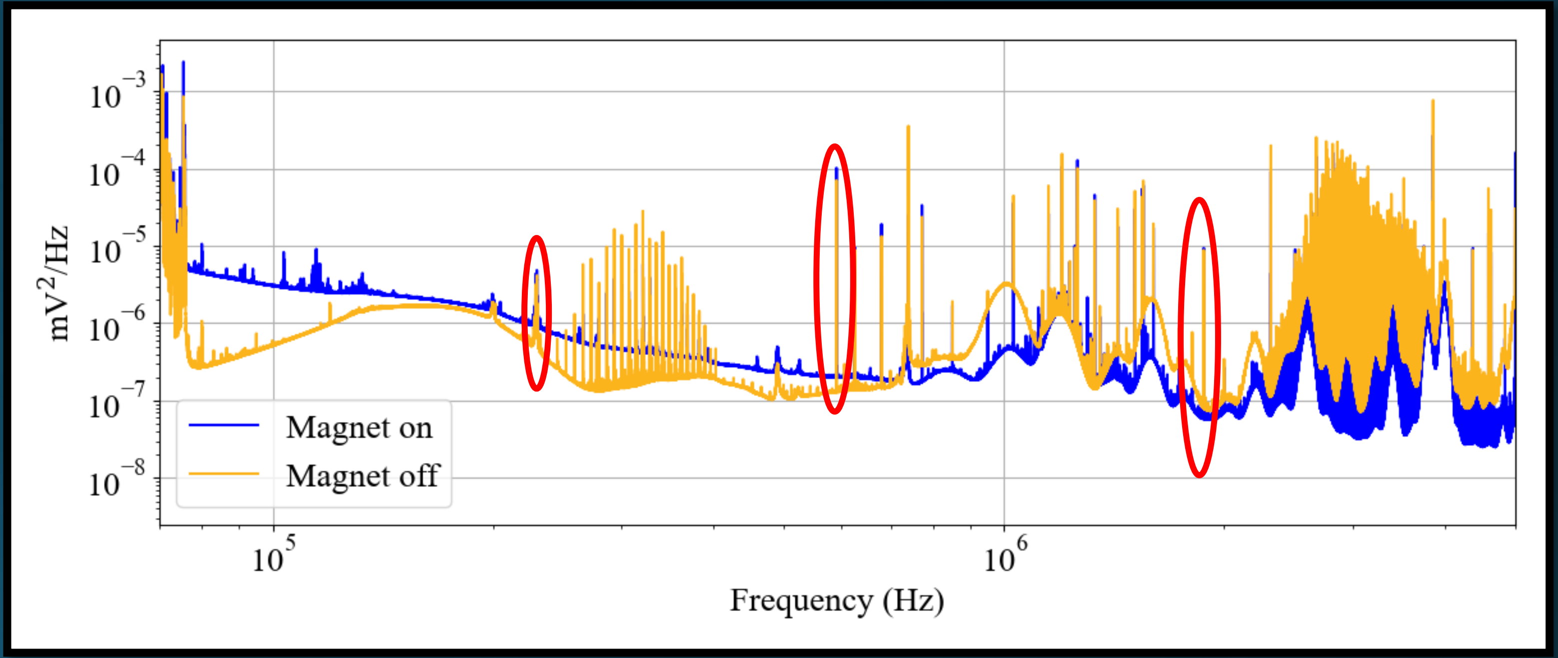


Remove backgrounds

- Magnet off spikes
- Transient excesses
- AM radio stations
- Single bin excesses
- Peaks that move



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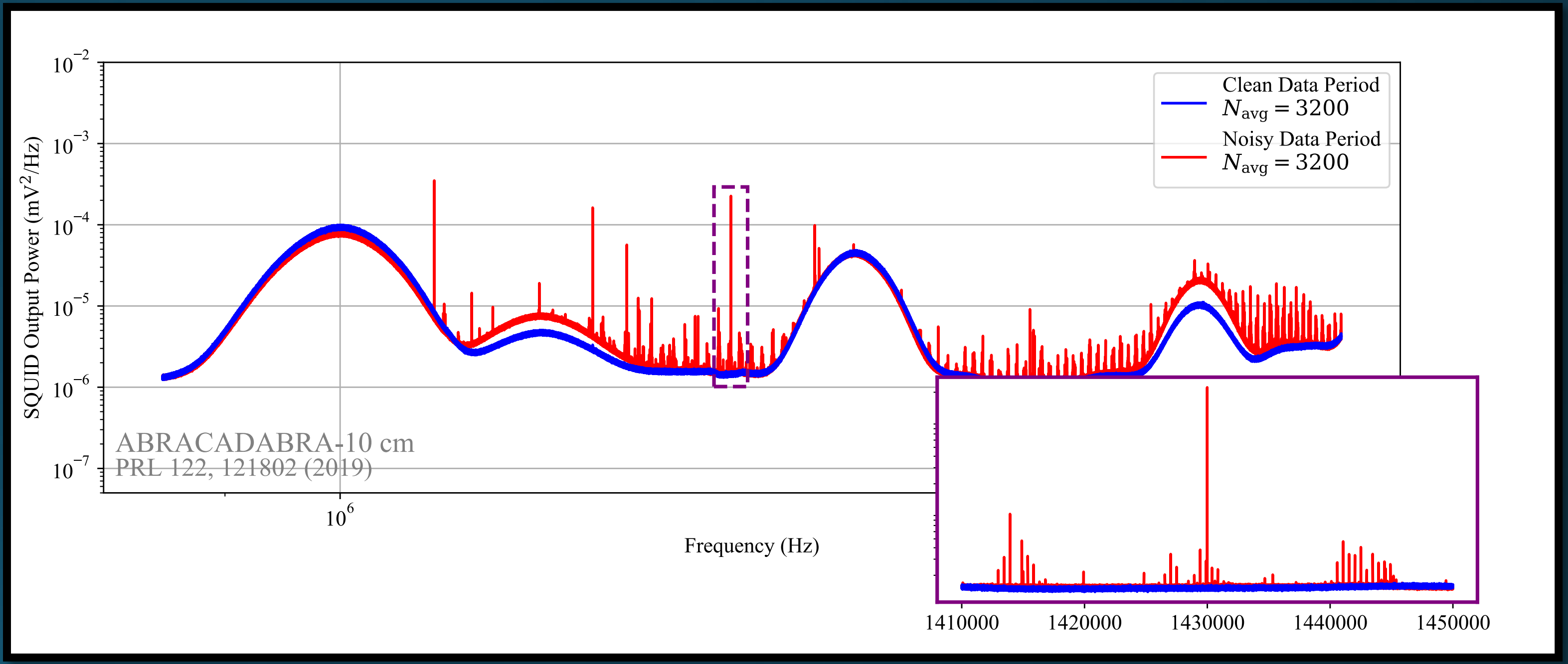

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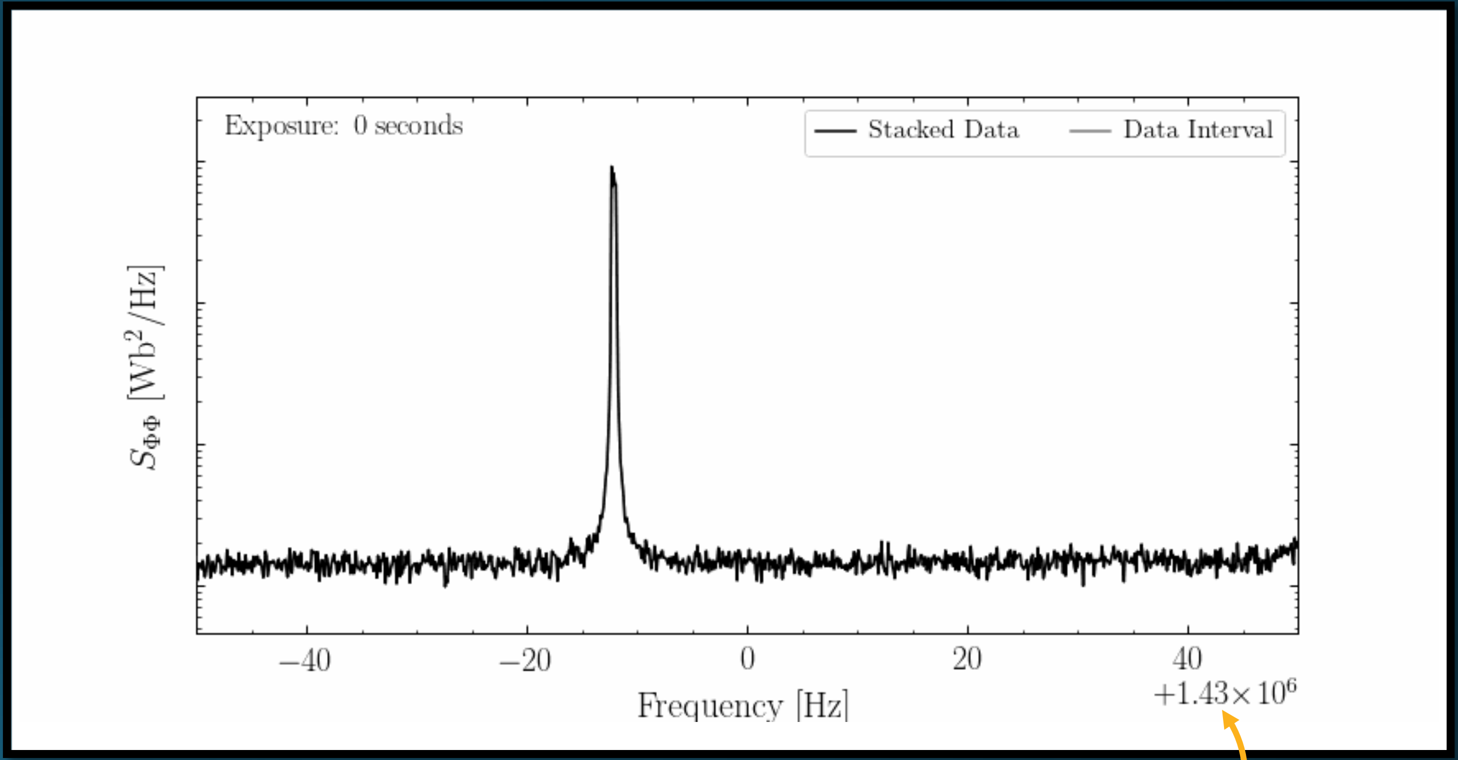
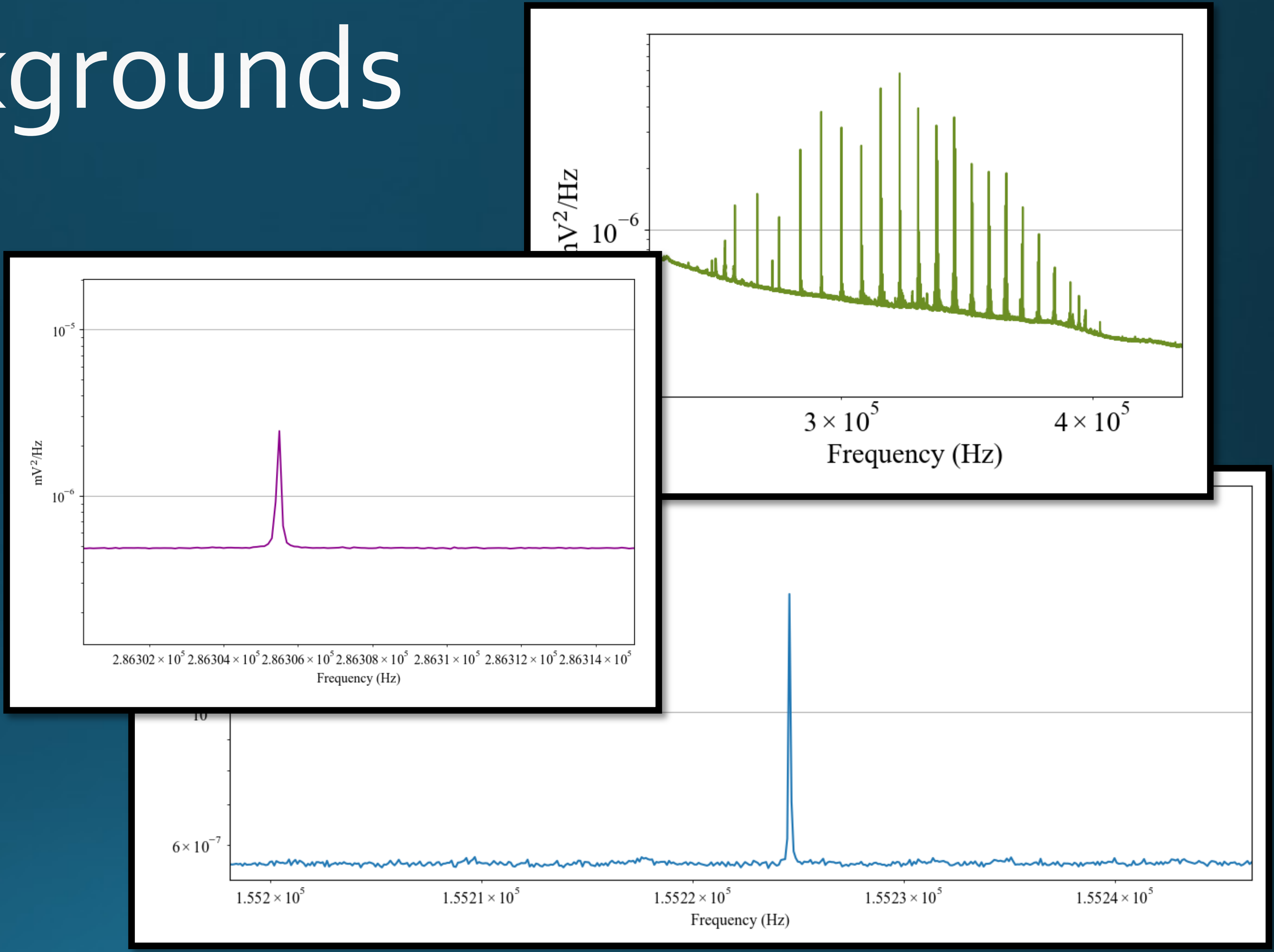
- Single bin excesses
- Peaks that move



J. Foster

Remove backgrounds

- Magnet off spikes
- Transient excesses
- AM radio stations
- Single bin excesses
- Peaks that move



Remove backgrounds

- Magnet off spikes
- Transient excesses
- AM radio stations
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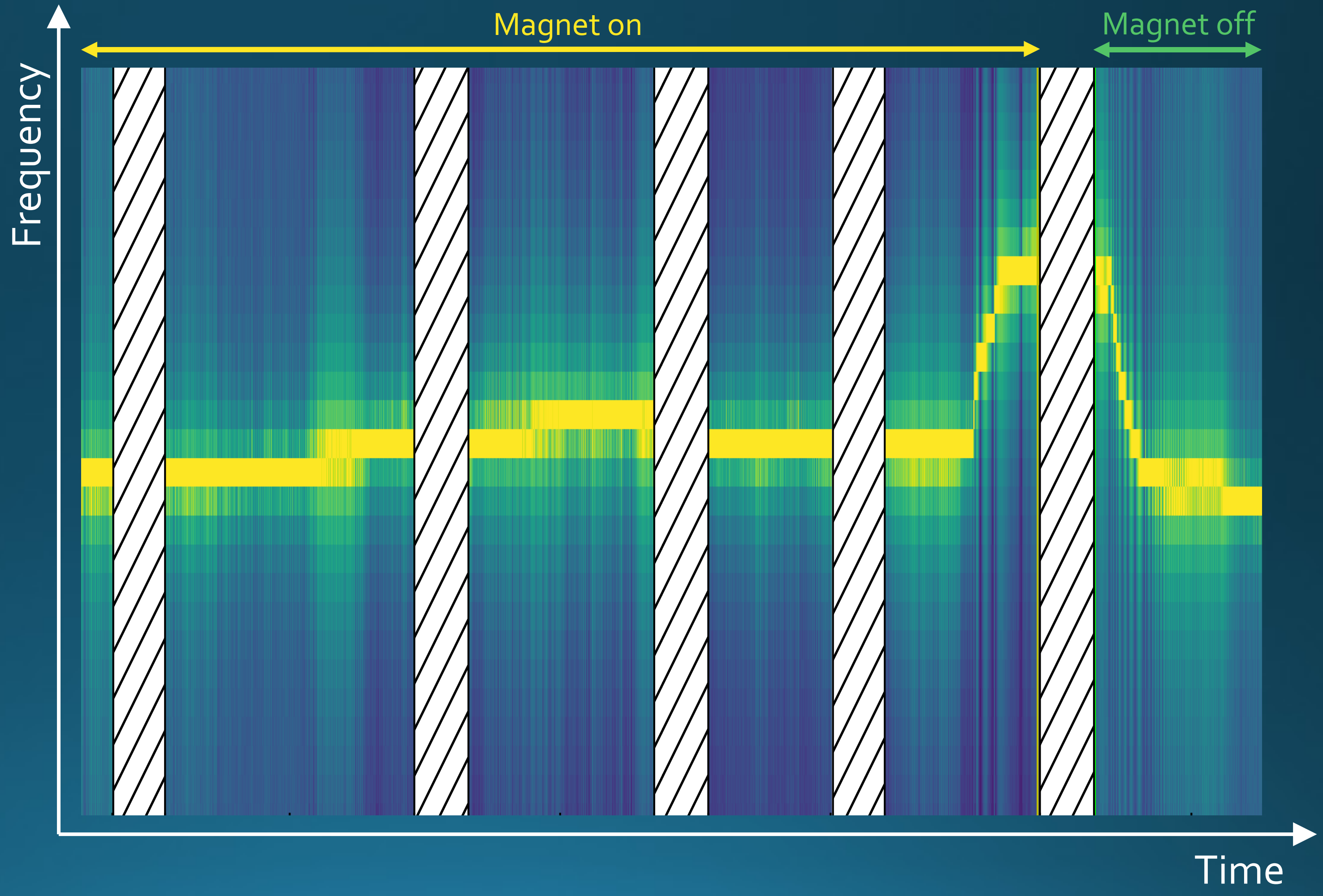
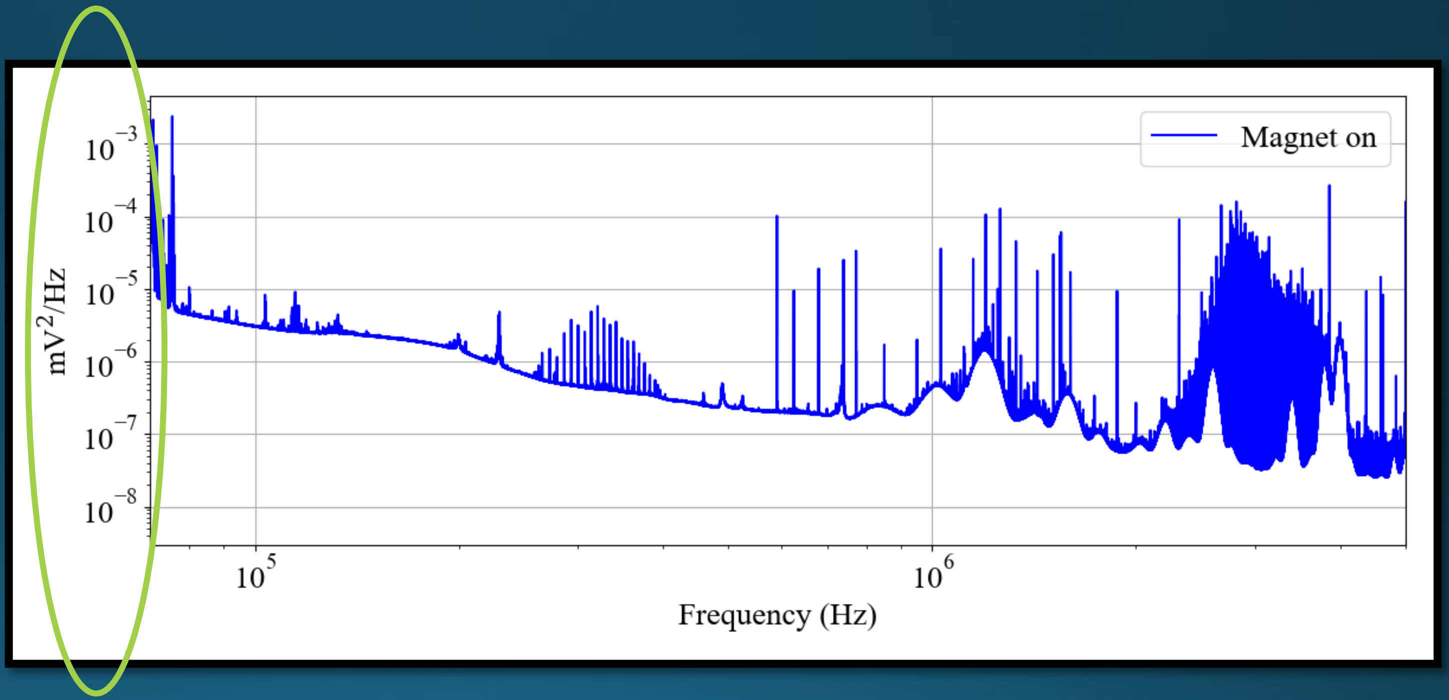
- Peaks that move



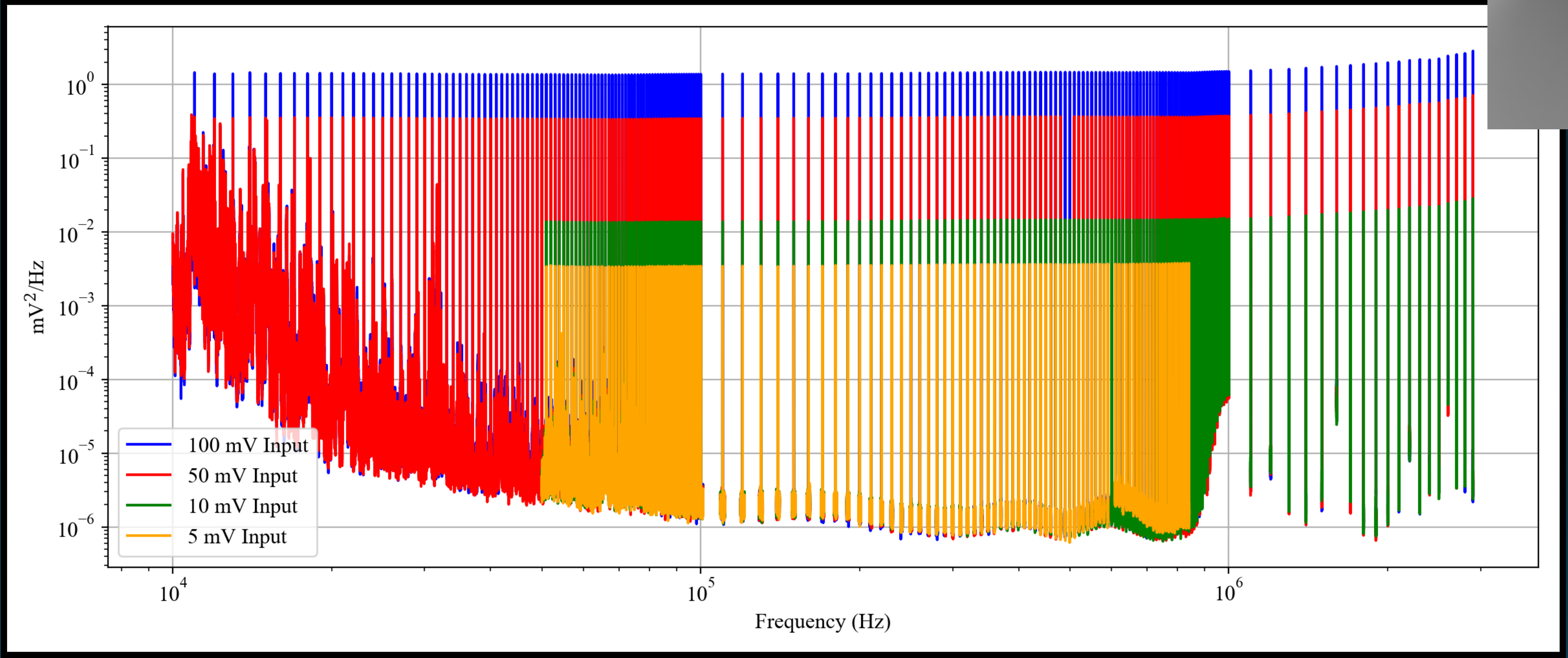
From raw data to limit (or discovery)

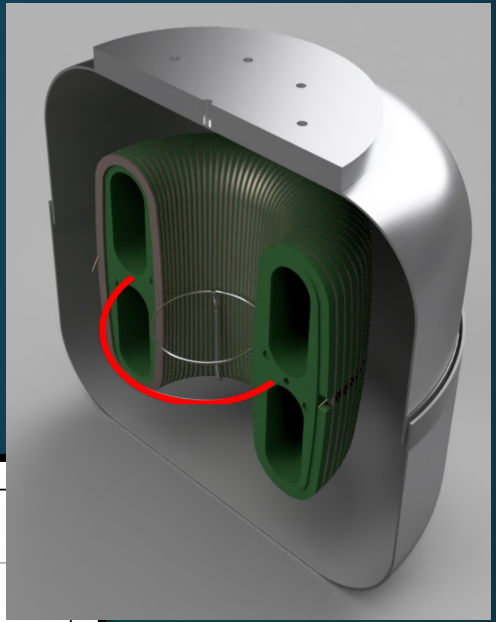
1. Remove backgrounds
2. Calibrate
3. Fit axion signal



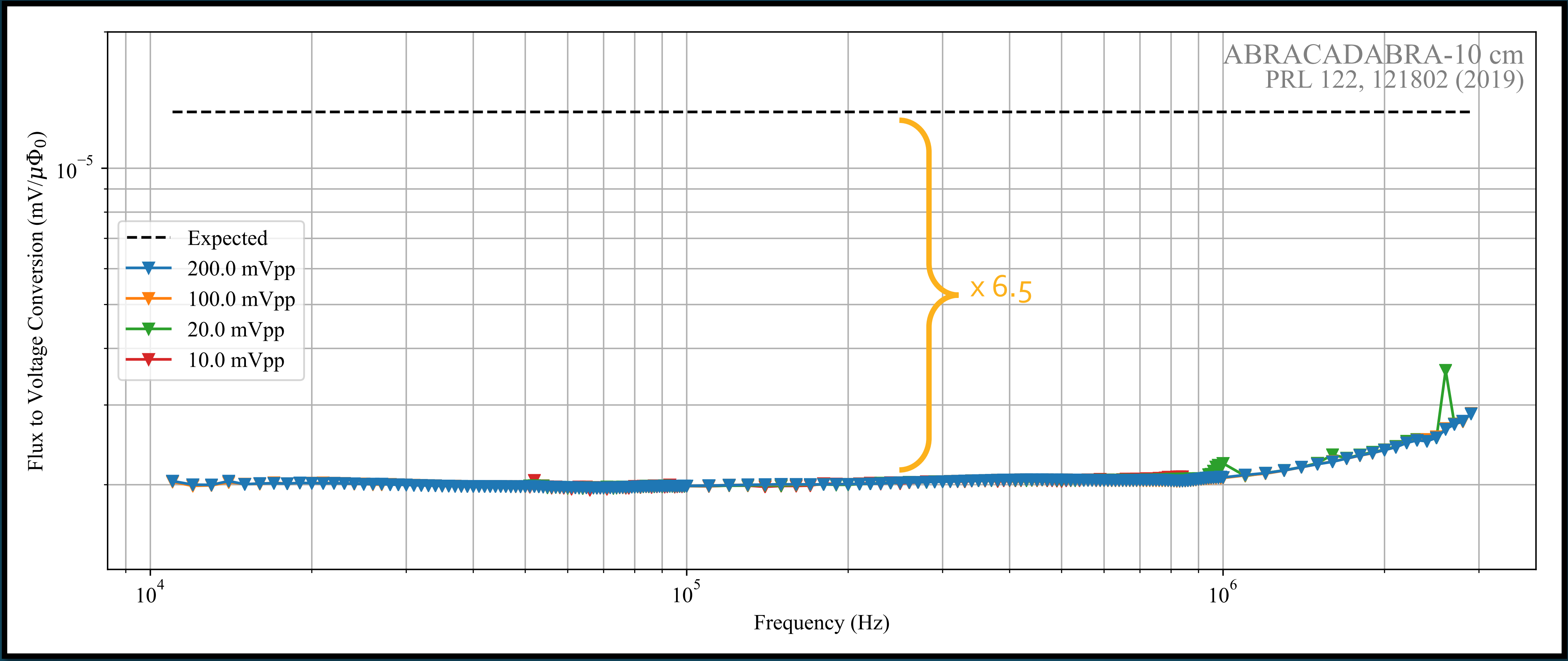
Digitizer voltage $\longrightarrow g_{a\gamma\gamma}$

End-to-end calibration

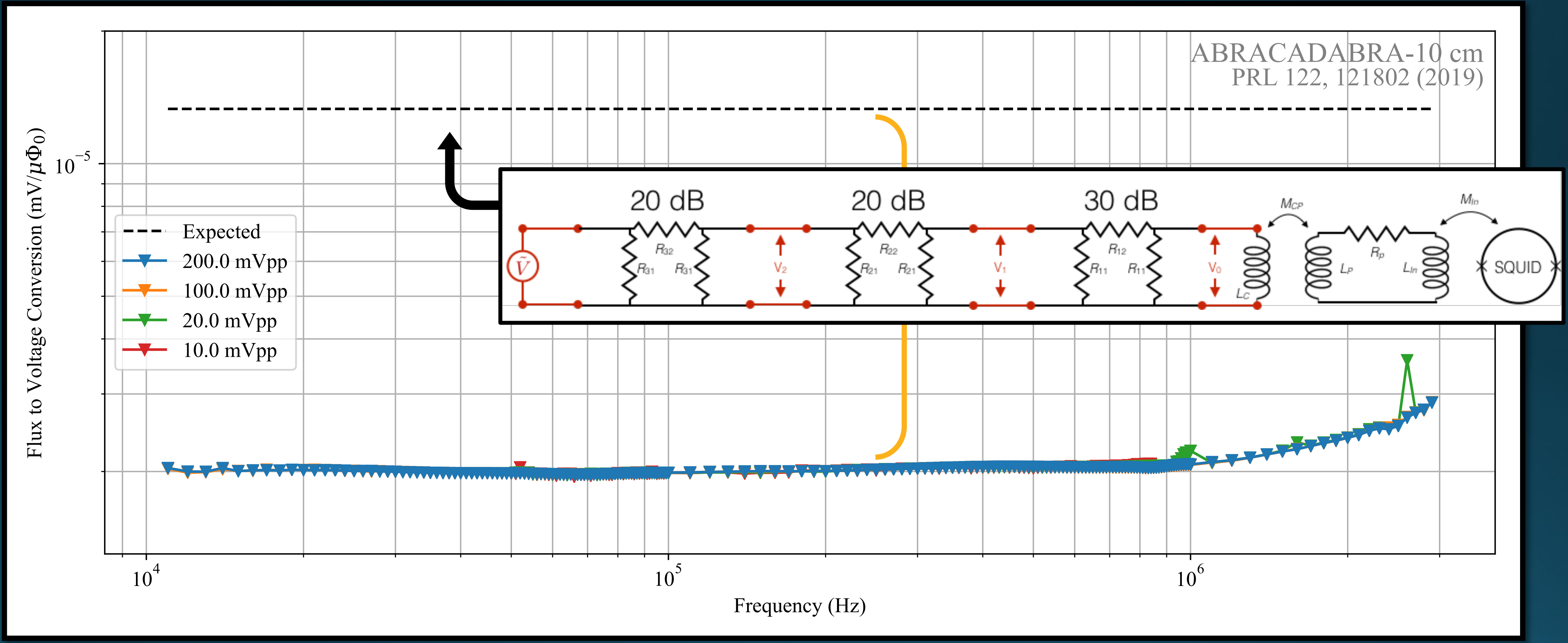




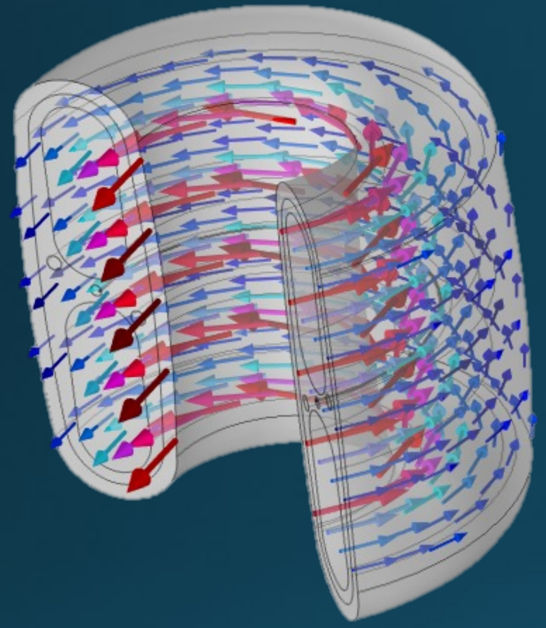
End-to-end calibration (run 1)



End-to-end calibration (run 1)

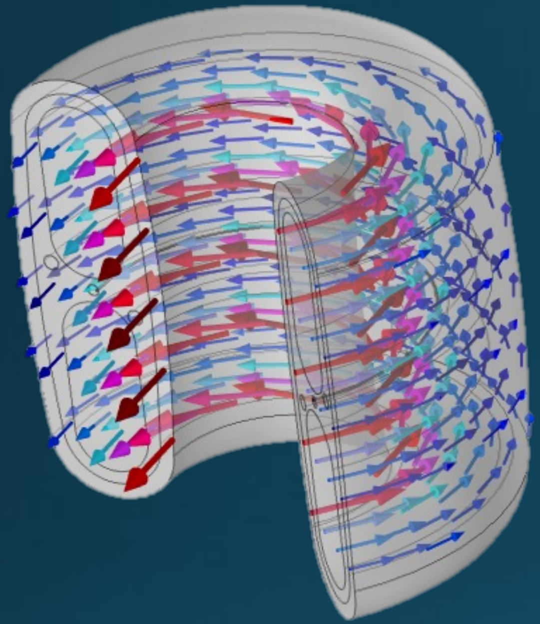


COMSOL simulations

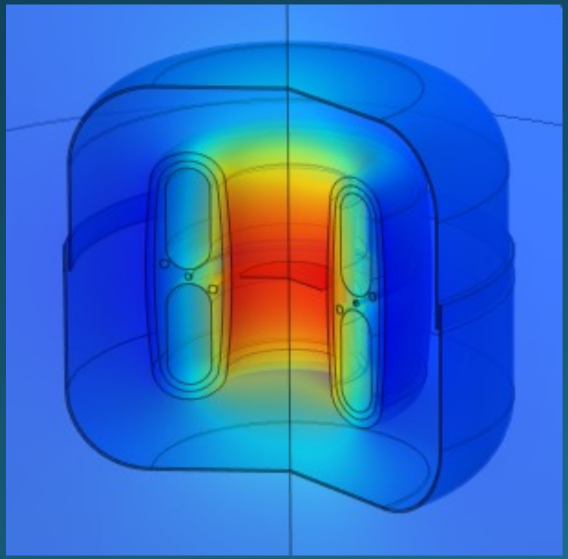


Axion effective current
distributed in magnetic field

COMSOL simulations

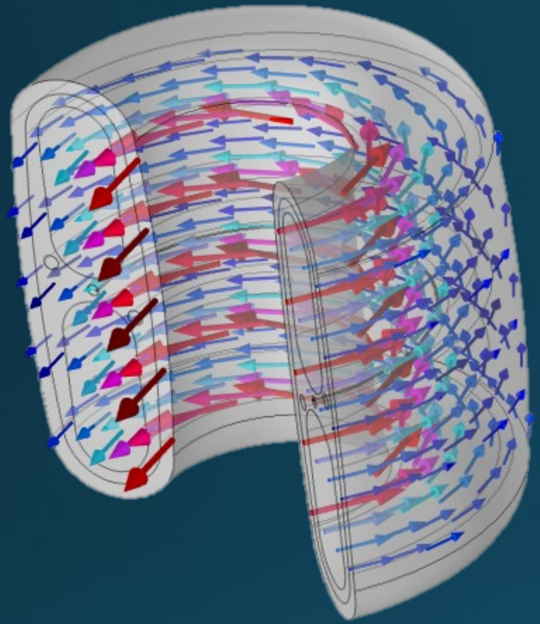


Axion effective current distributed in magnetic field

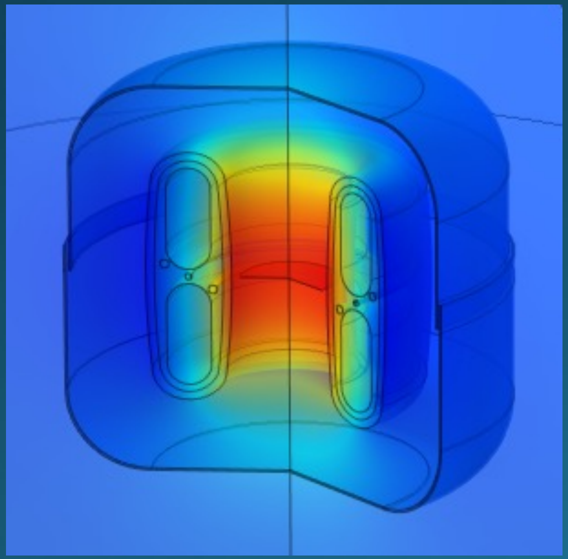


Axion magnetic field oscillates in toroid bore

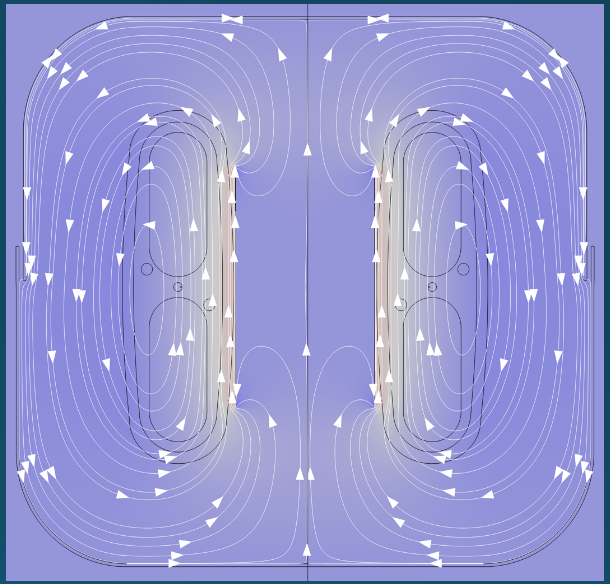
COMSOL simulations



Axion effective current distributed in magnetic field

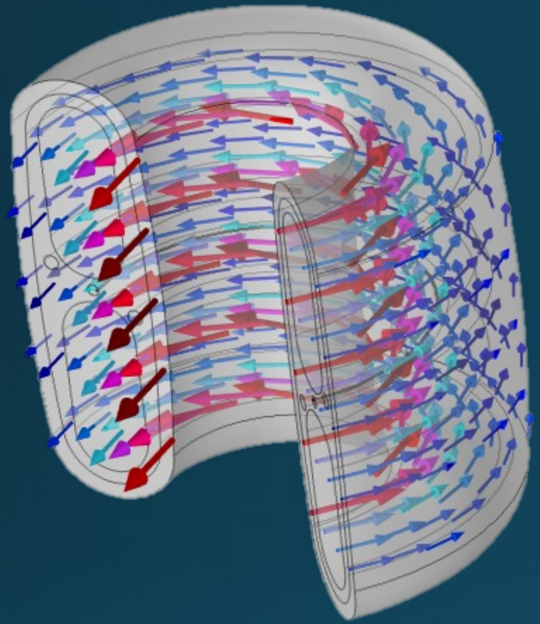


Axion magnetic field oscillates in toroid bore

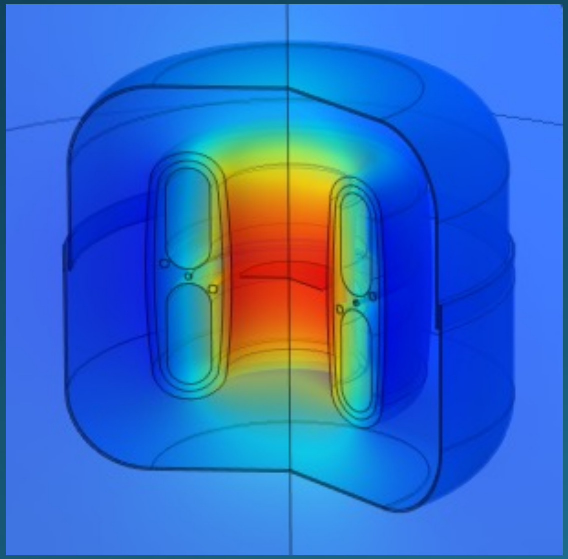


Current induced in pickup

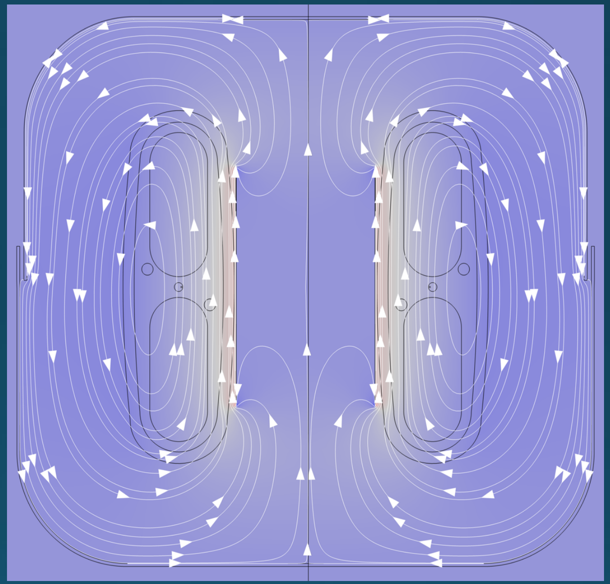
COMSOL simulations



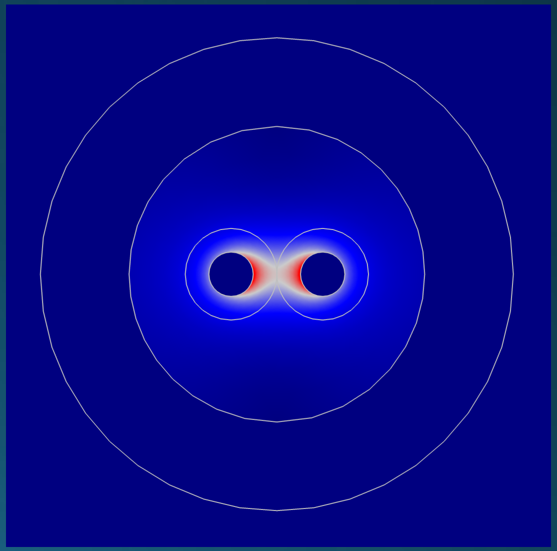
Axion effective current distributed in magnetic field



Axion magnetic field oscillates in toroid bore

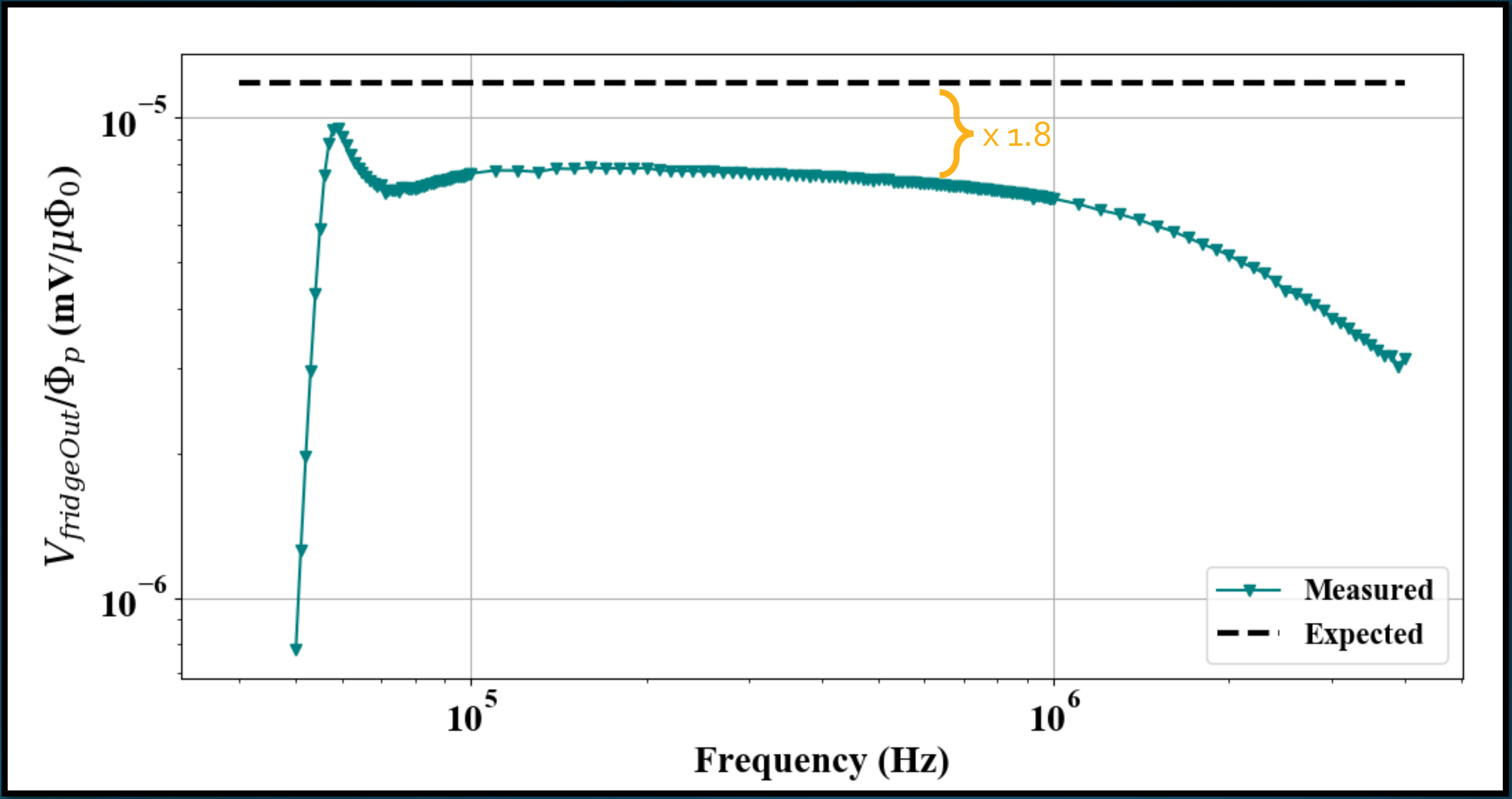


Current induced in pickup

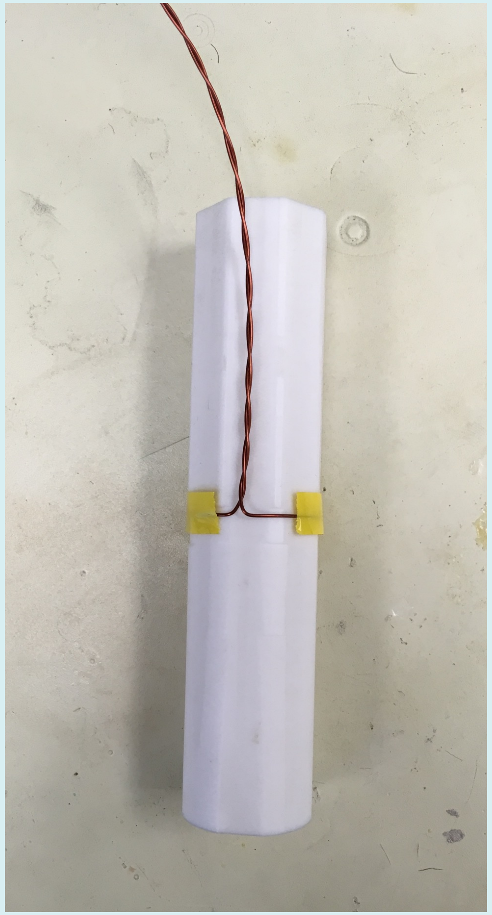


Current propagates through wiring

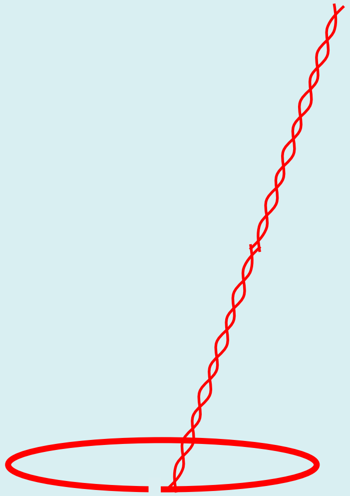
End-to-end calibration (run 3)



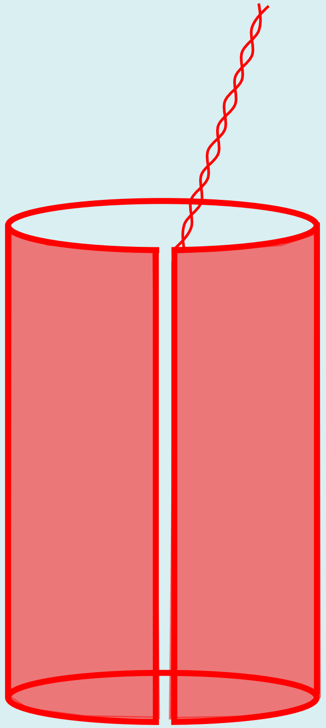
Replacing the pickup circuit



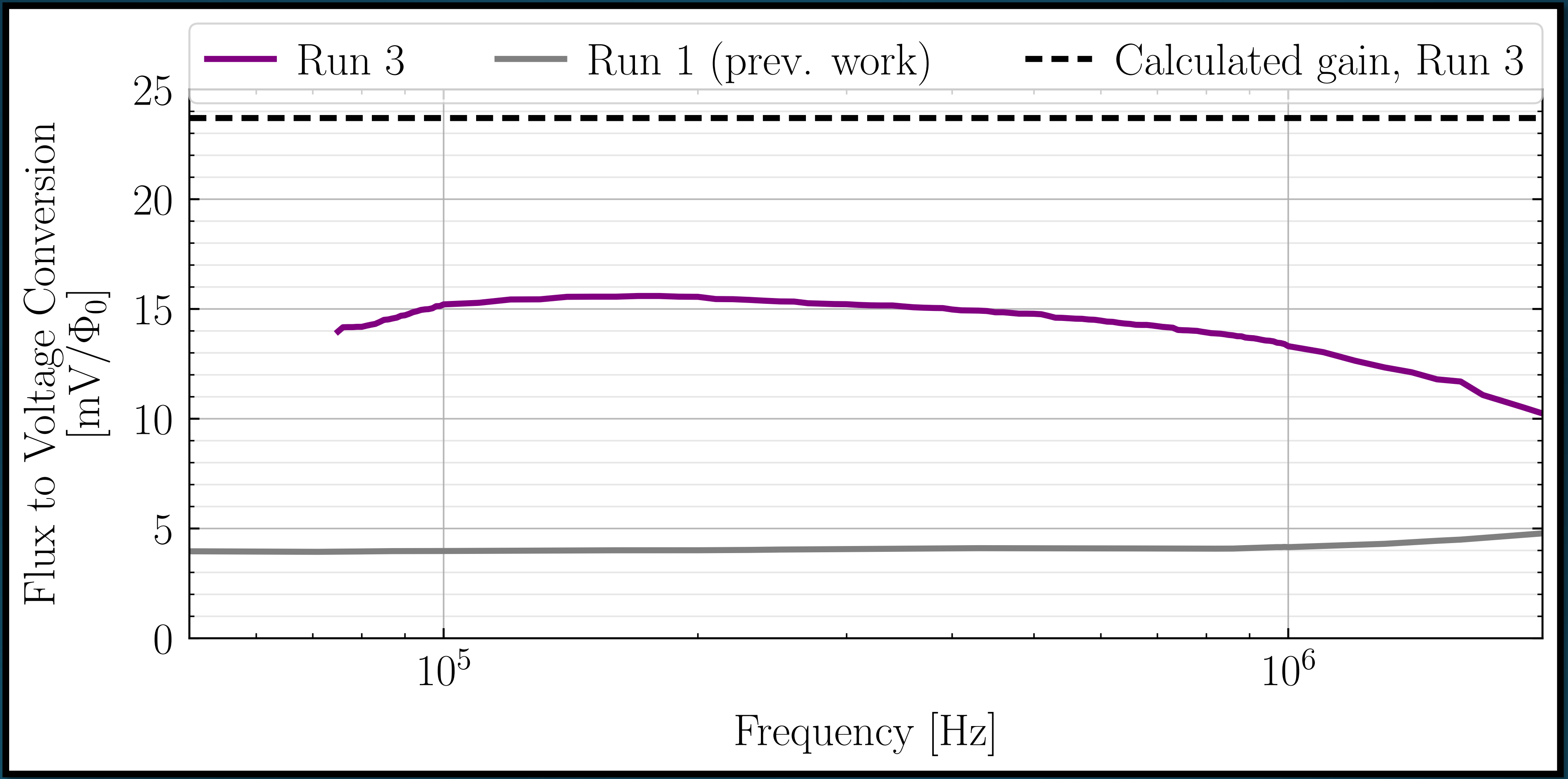
Run 1



Runs 2&3

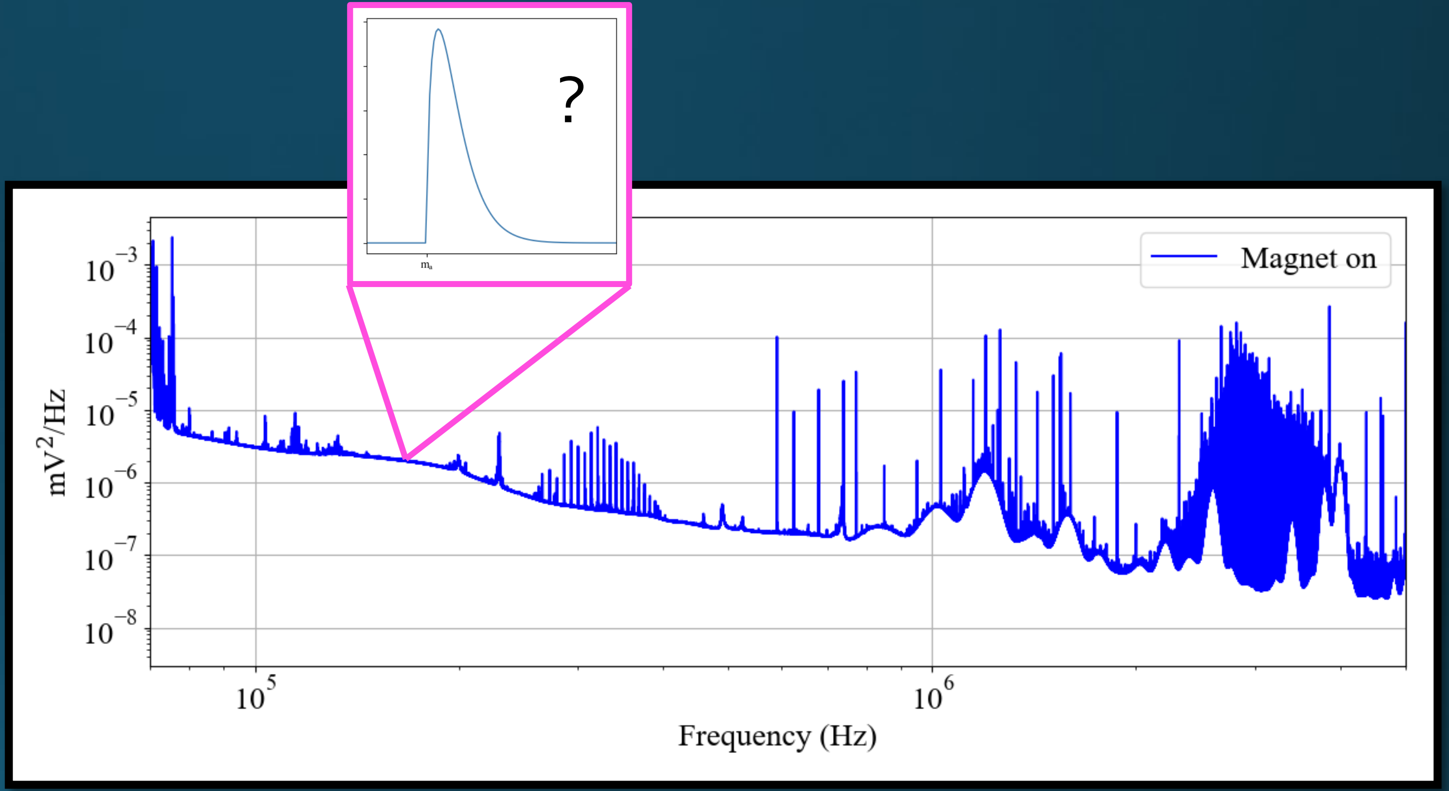


Improved sensitivity

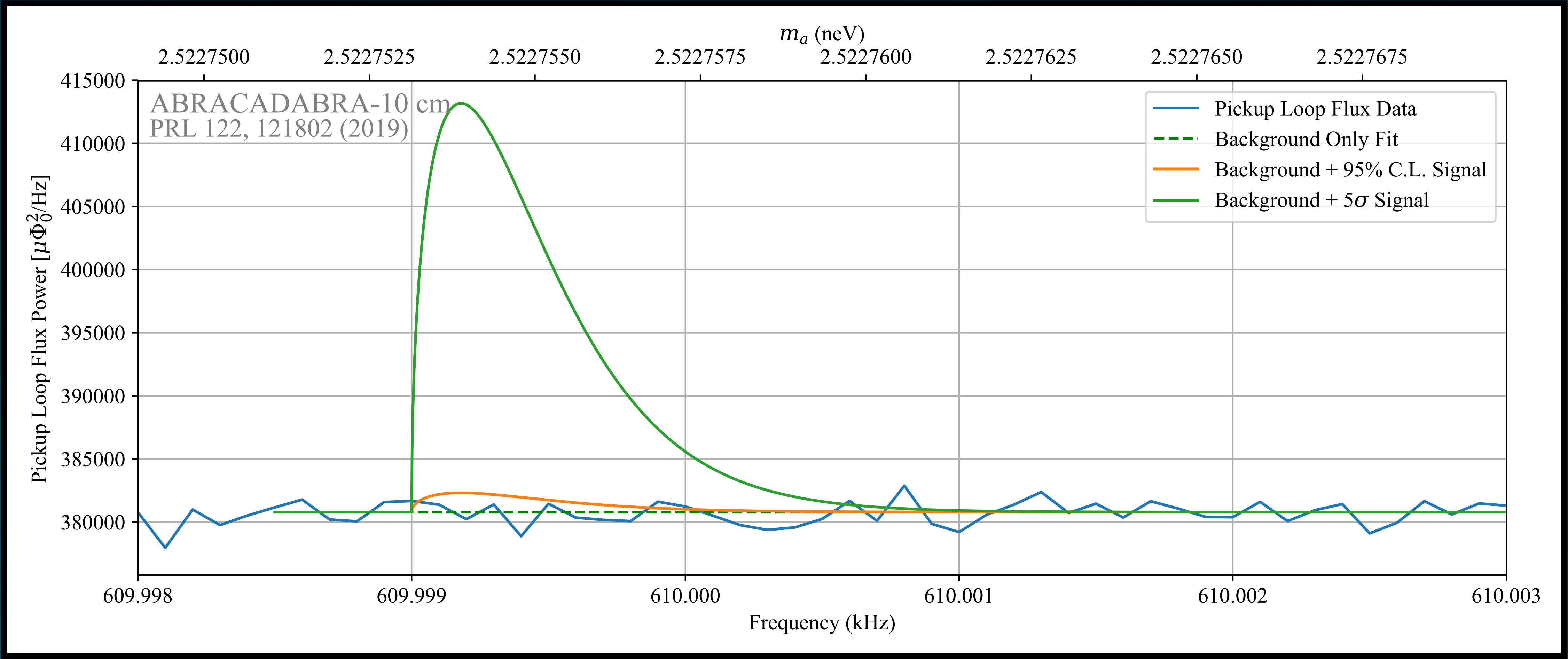


From raw data to limit (or discovery)

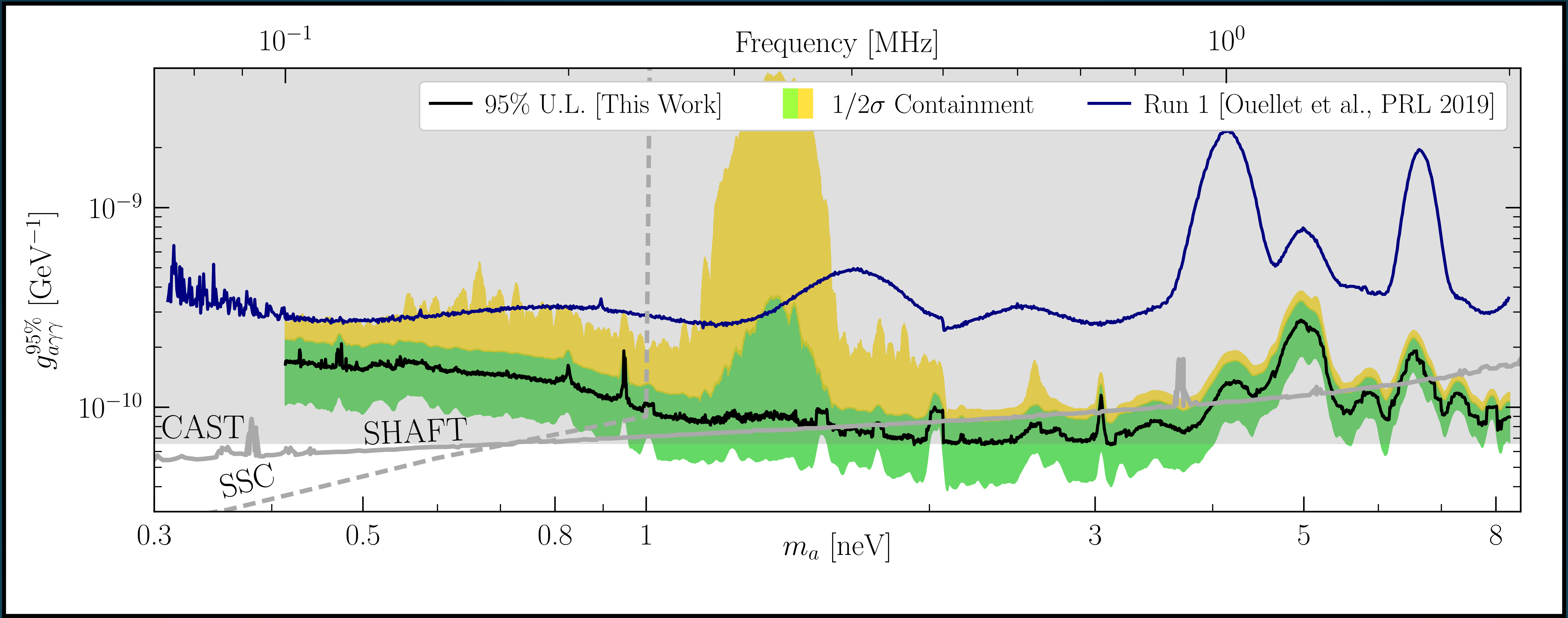
1. Remove backgrounds
2. Calibrate
3. Fit axion signal



Bump or background?

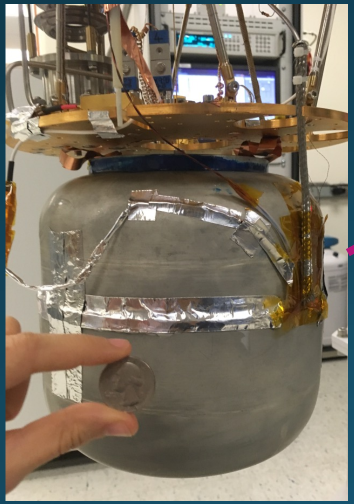


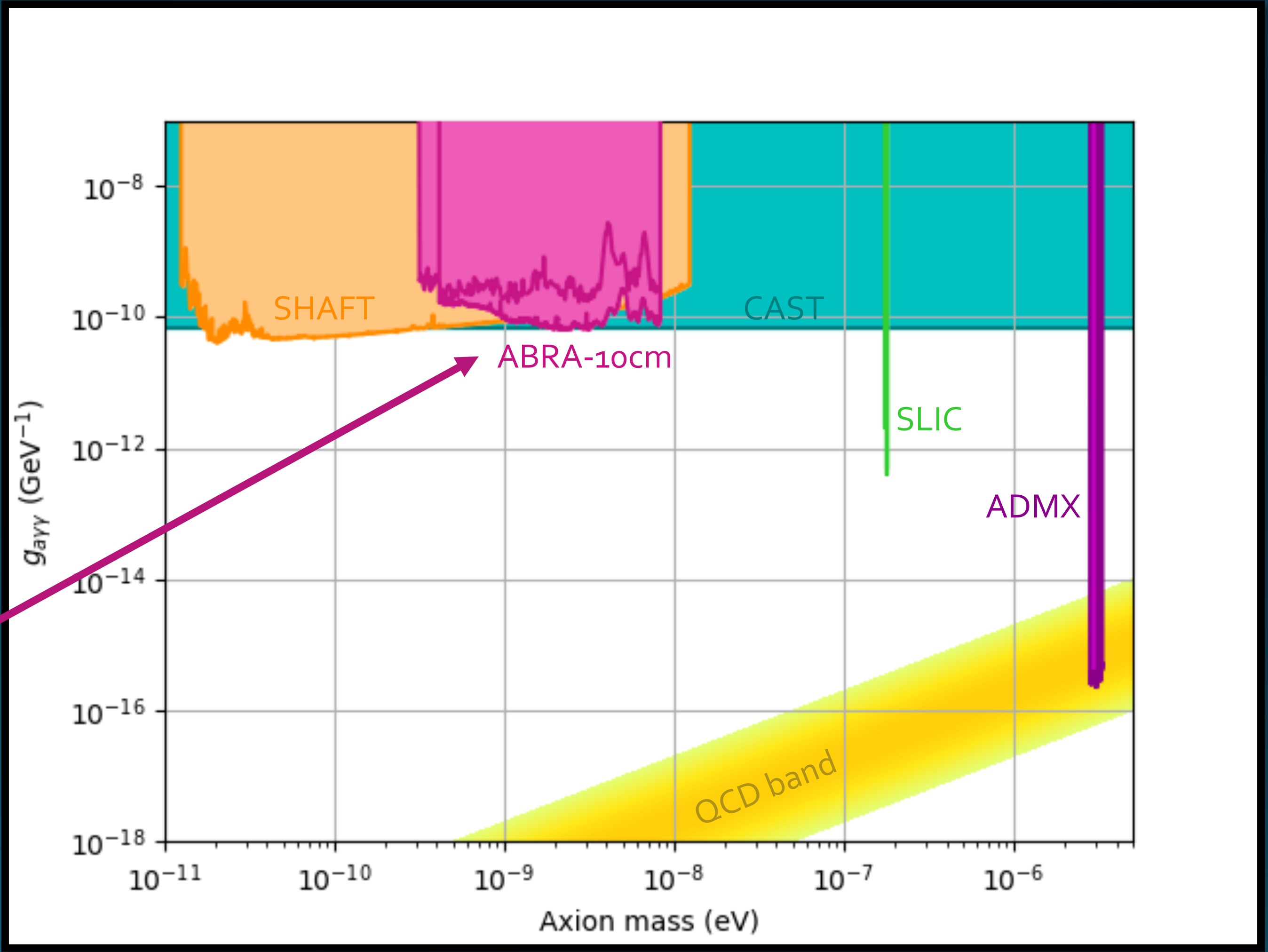
Limits on $g_{a\gamma\gamma}$



Ouellet, Salemi et al. *Phys.Rev.Lett.* 2019
Ouellet, Salemi et al. *Phys.Rev.D* 2019
Salemi et al. *Phys.Rev.Lett.* 2021

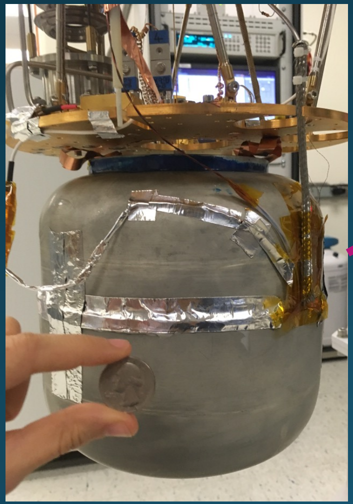
Our limits in context



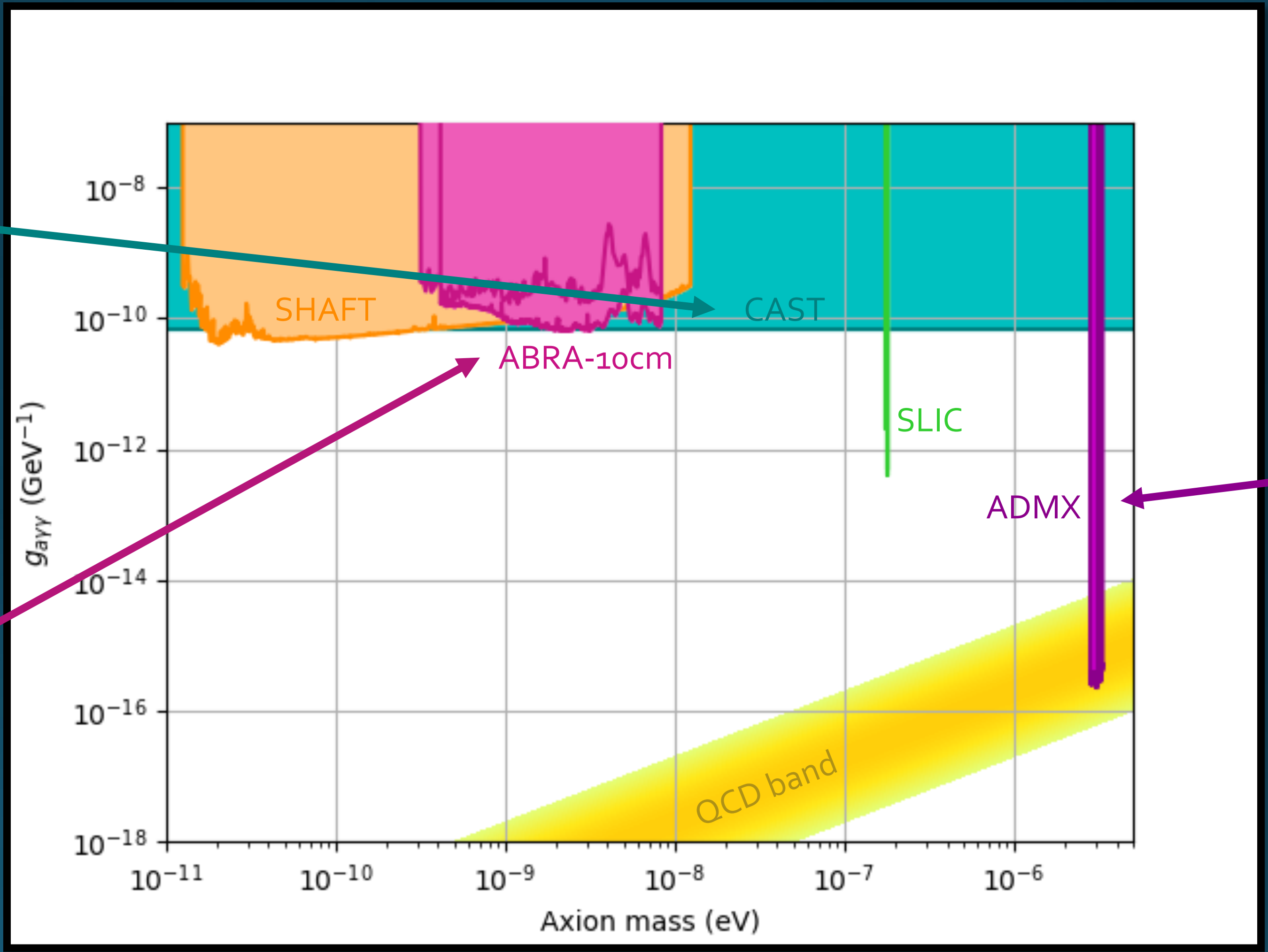


Salemi et al. *Phys.Rev.Lett.* 2021

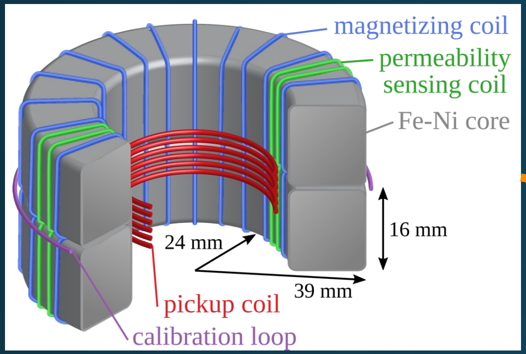
Our limits in context

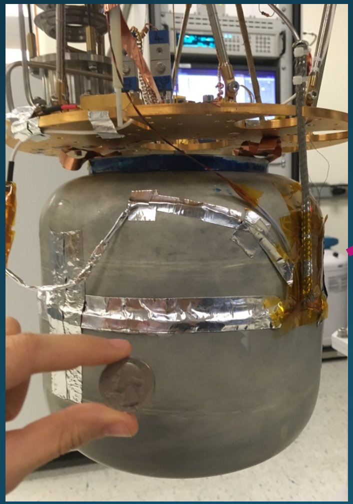


Salemi et al. *Phys.Rev.Lett.* 2021

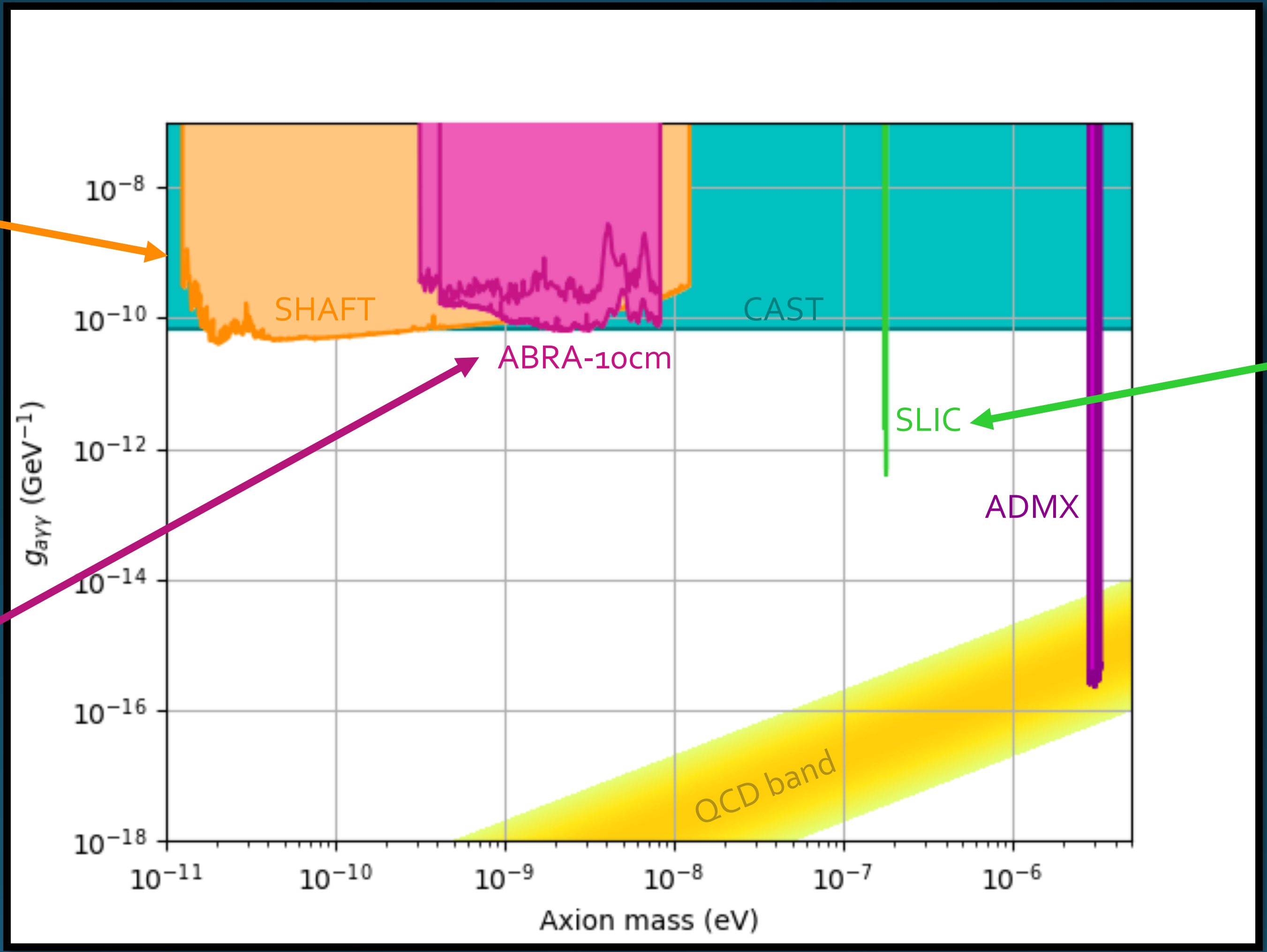


Our limits in context

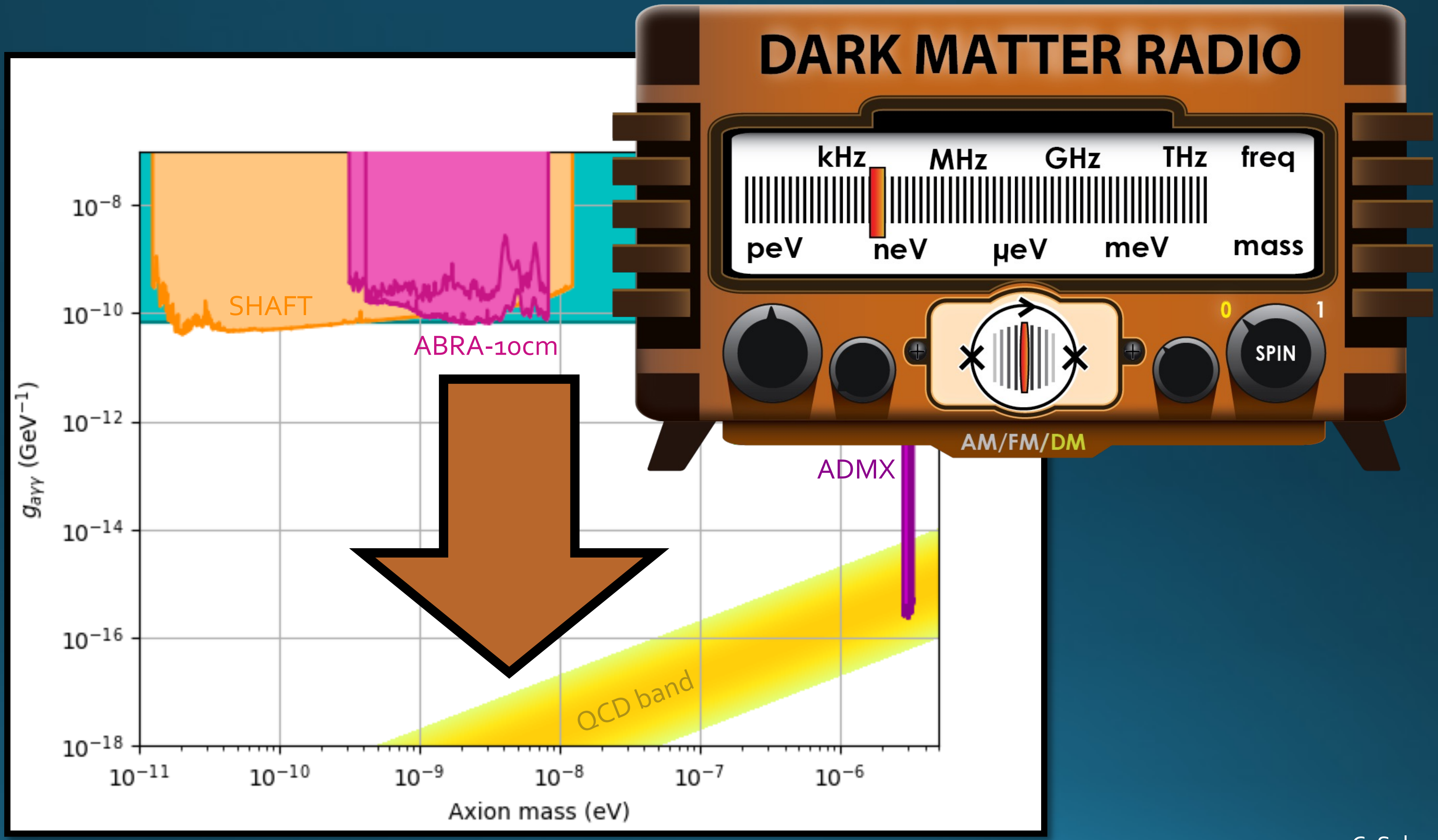




Salemi et al. *Phys.Rev.Lett.* 2021

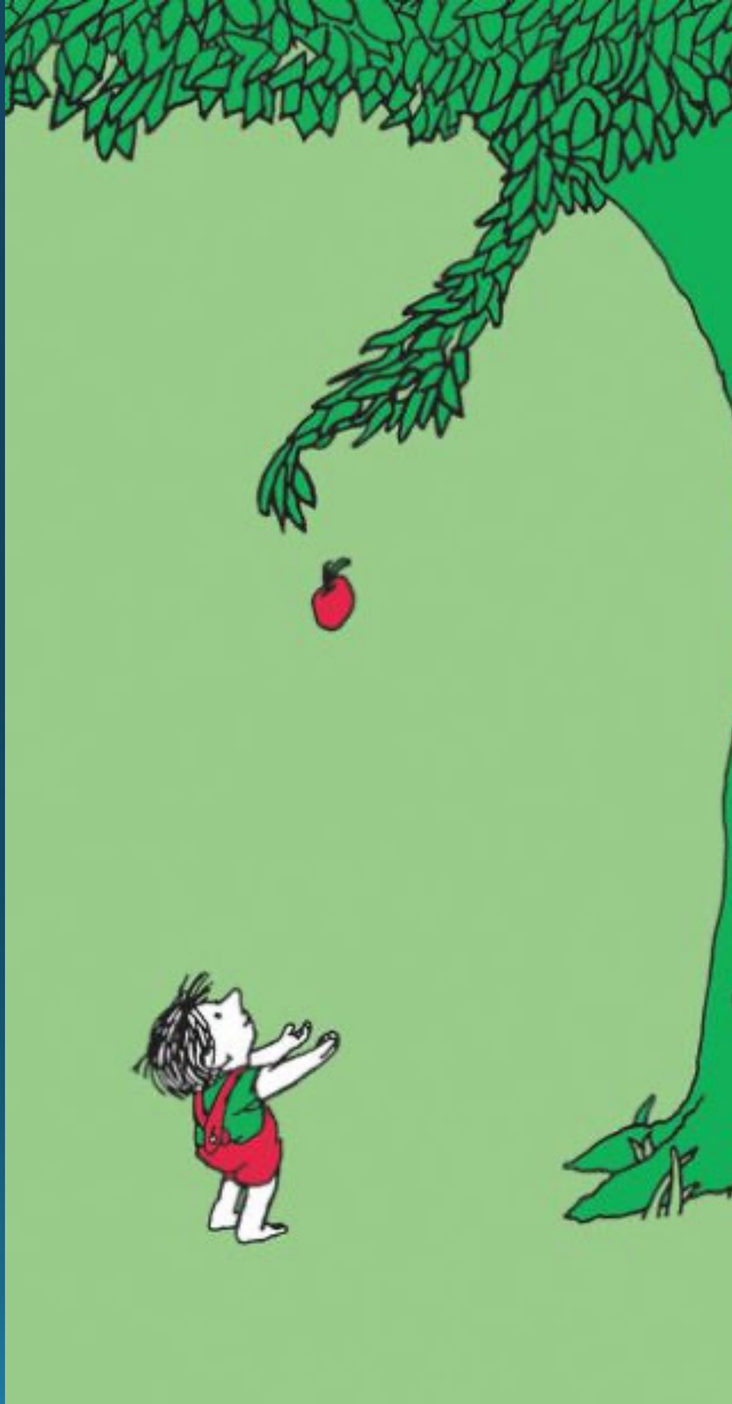


Our limits in context



How can we get more sensitive to axions?

- Bigger magnet
- Stronger magnetic field



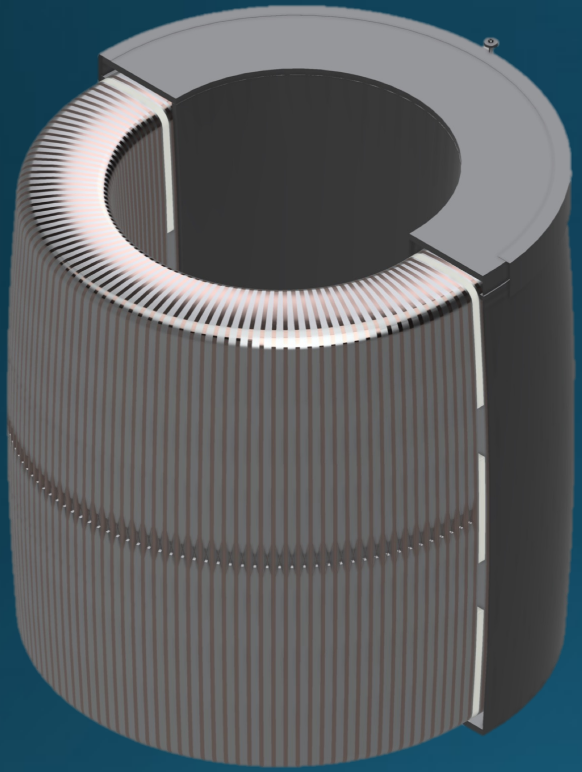
S. Silverstein

How can we get **much** more sensitive to axions?

- Bigger magnet
- Stronger magnetic field
- Better coupling between pickup and axion current
- Resonant readout
- Improved scan strategies
- Optimized circuit impedance
- Lower noise (vibrations, environmental noise)
- Quantum acceleration

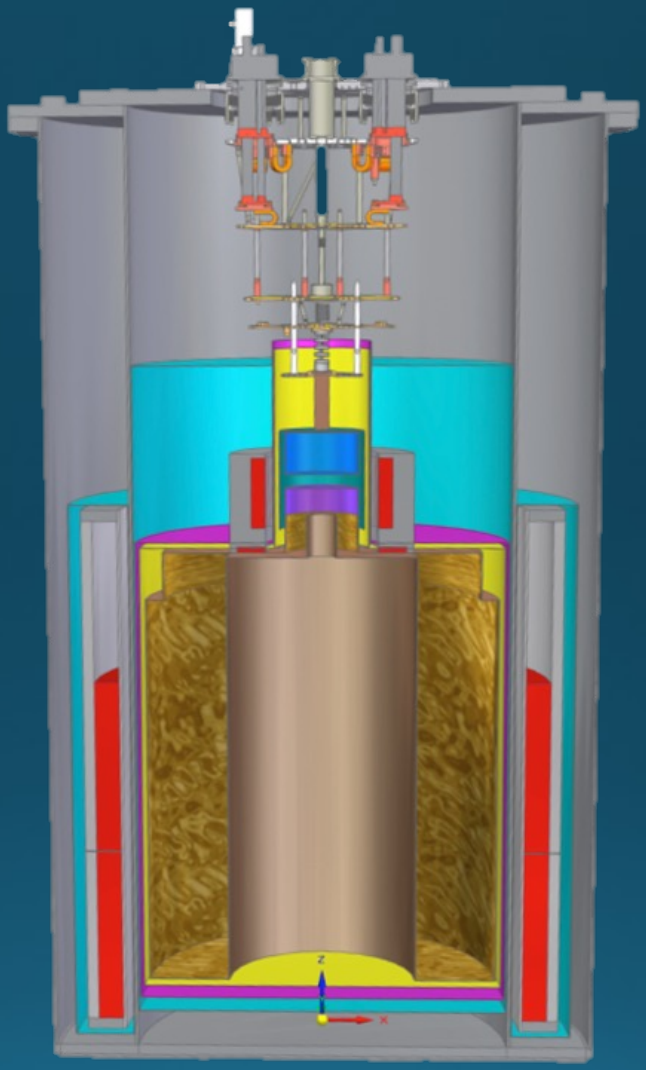
S. Silverstein

DMRadio



DMRadio-50L

under construction!



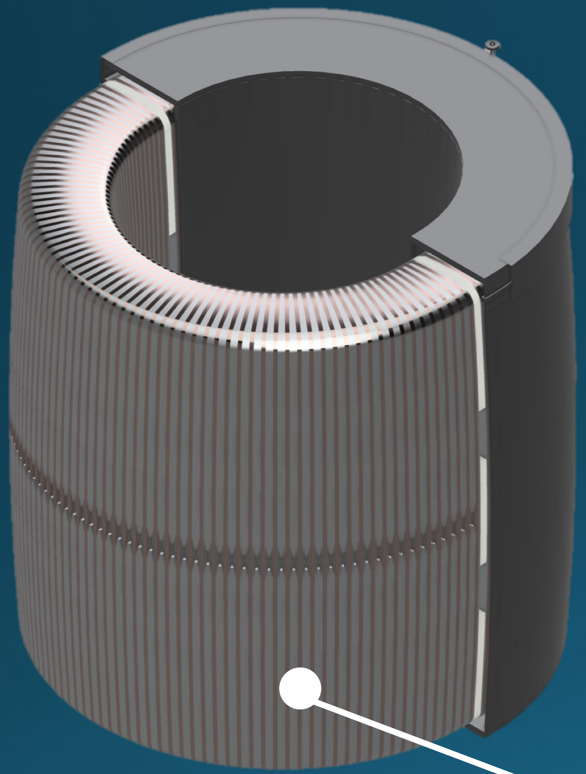
DMRadio-m3

in design

+ DMRadio-GUT

the future:
DFSZ sensitivity
to neV axions

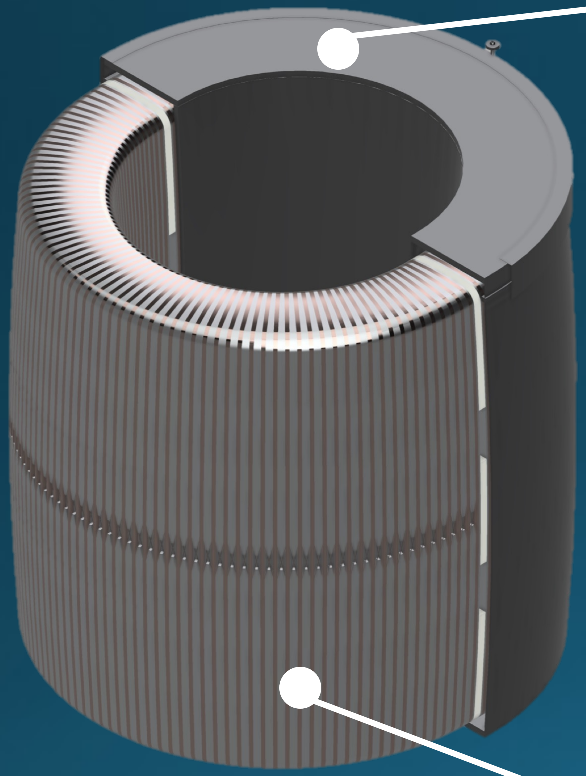
DMRadio-50 L



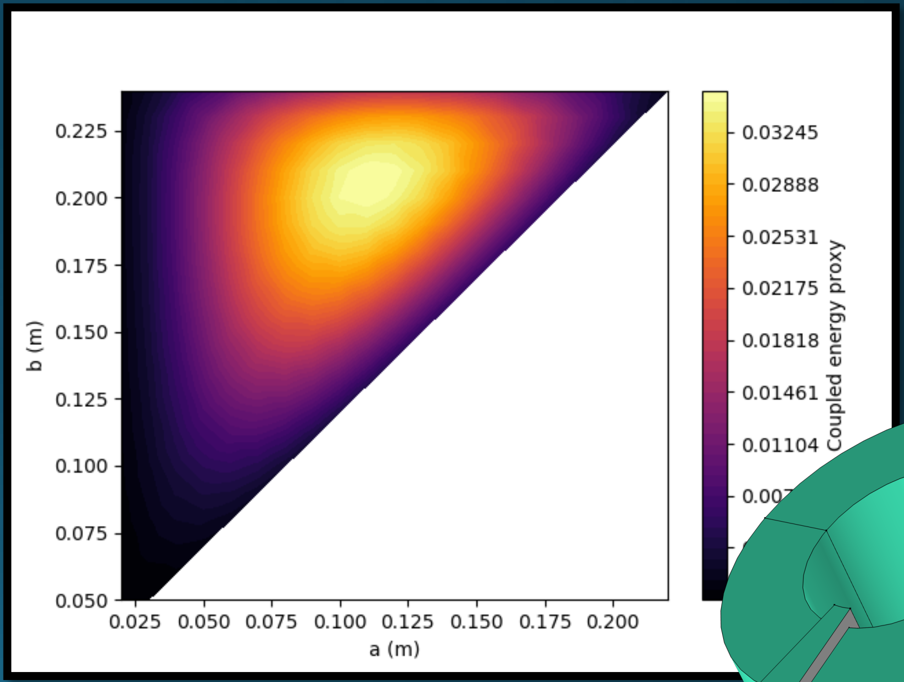
50 L volume, 1T field

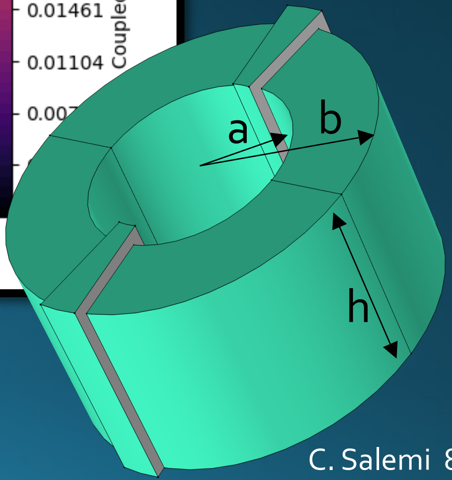
*ABRA-10cm ~ 0.9 L

DMRadio-50 L



optimized axion-detector coupling
with pickup sheath

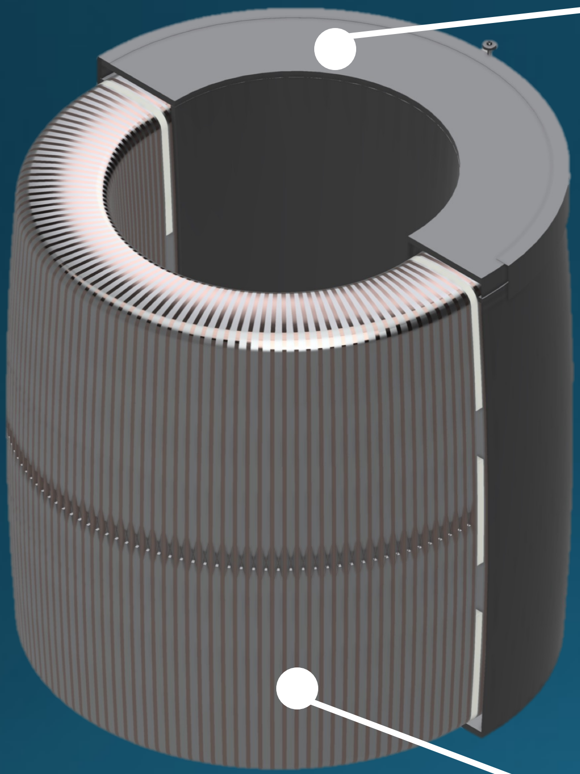


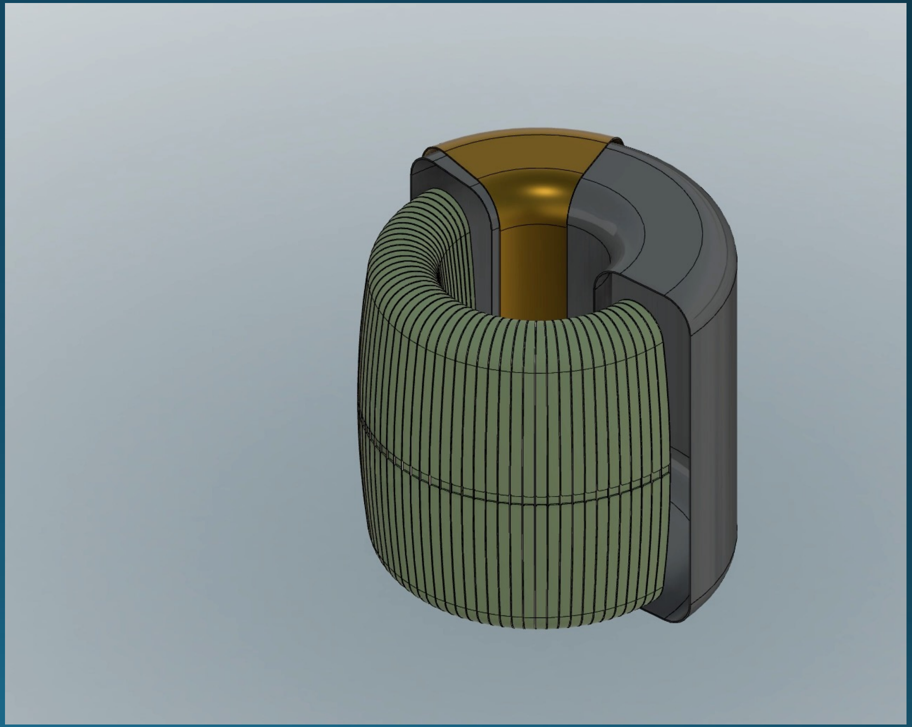


50 L volume, 1T field

DMRadio-50 L

optimized axion-detector coupling
with pickup sheath

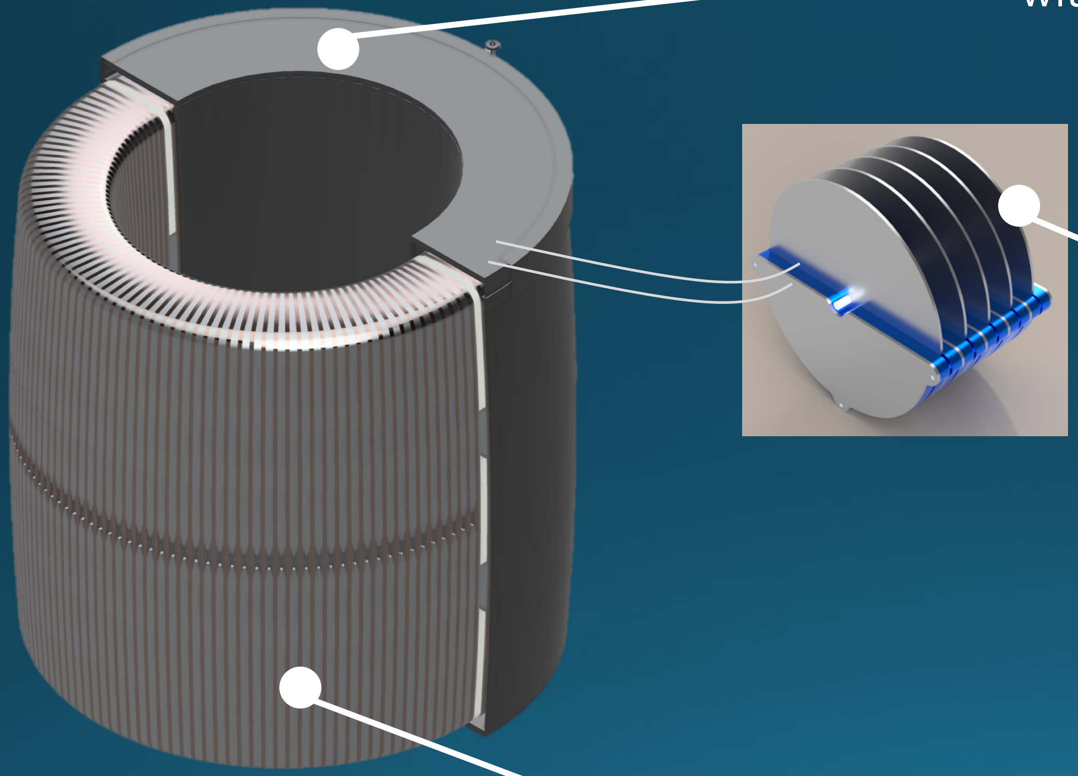




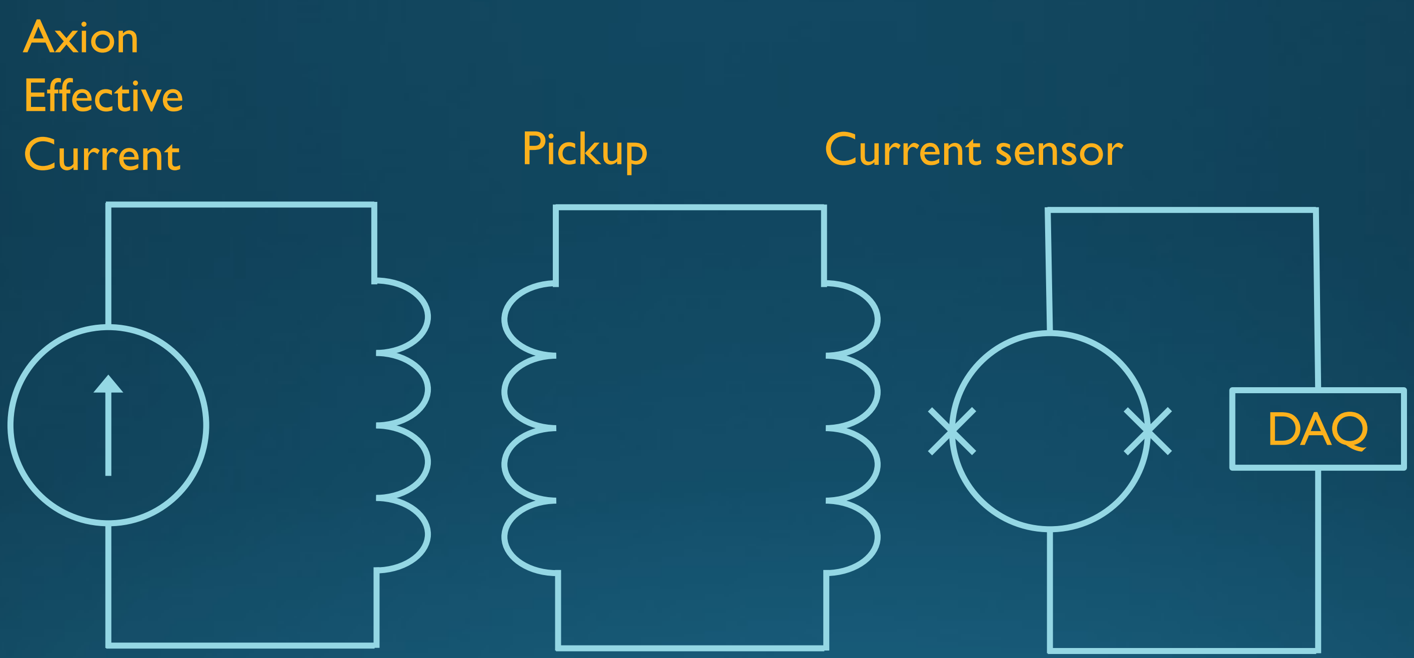
J. Ouellet

50 L volume, 1T field

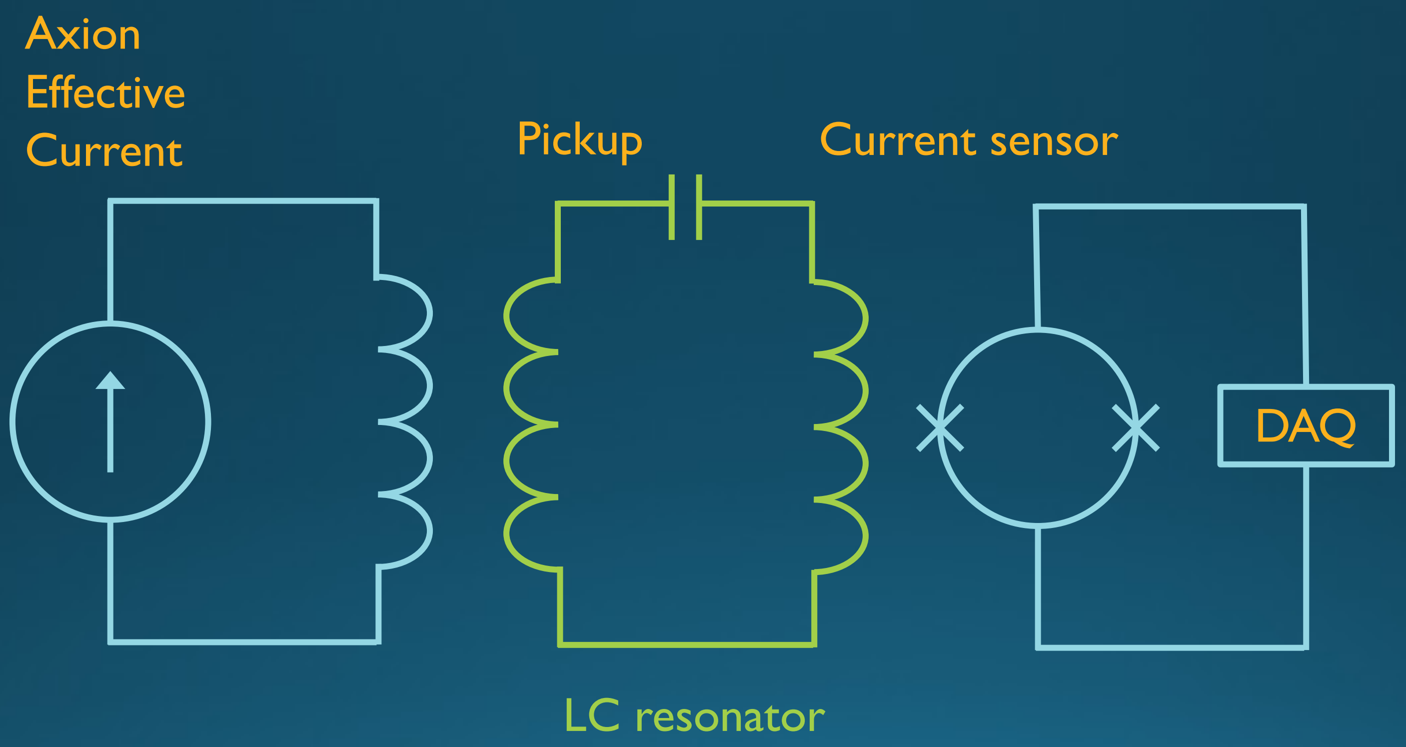
DMRadio-50 L


optimized axion-detector coupling
with pickup sheath
resonant readout
50 L volume, 1T field

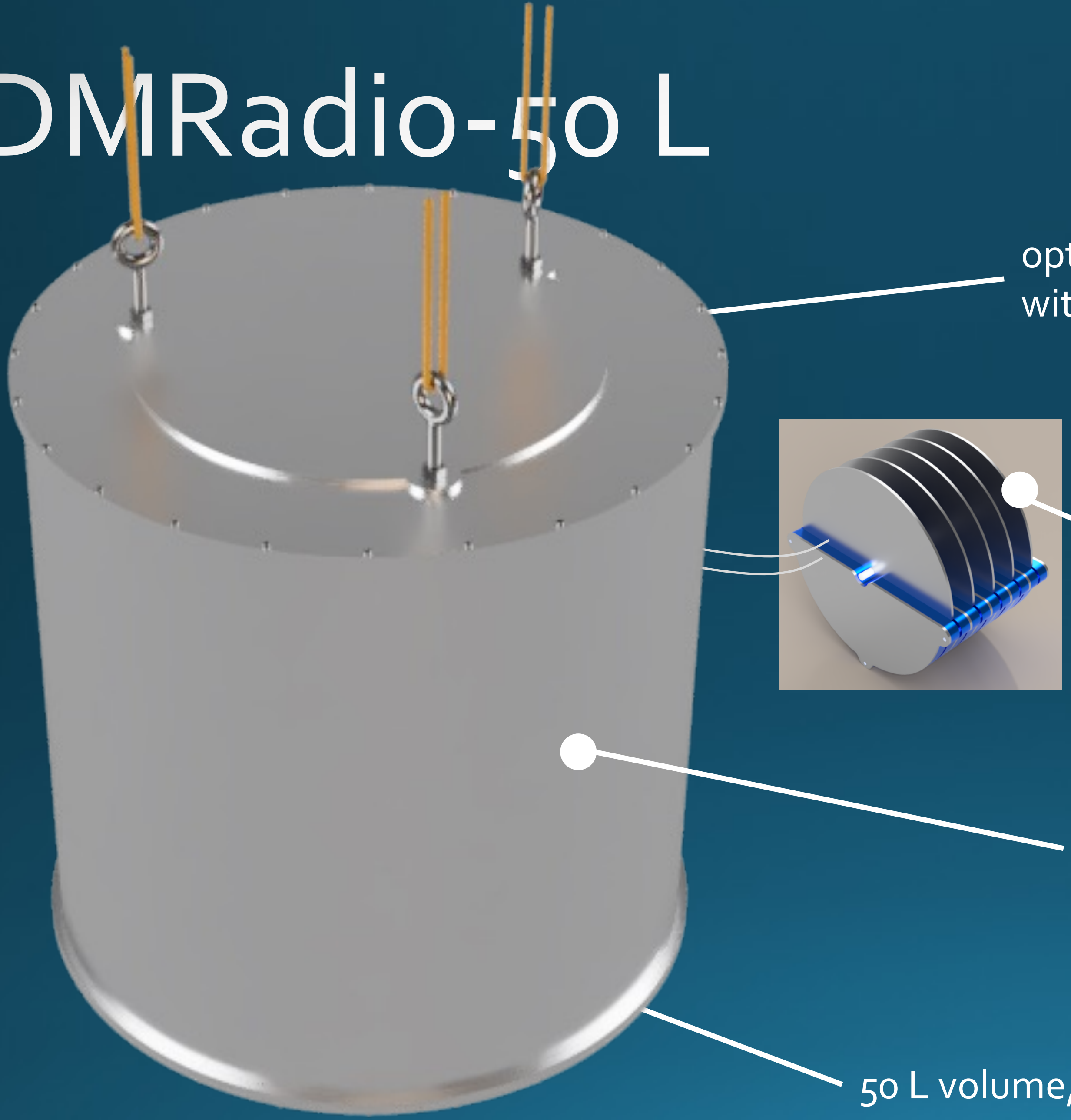
Broadband readout



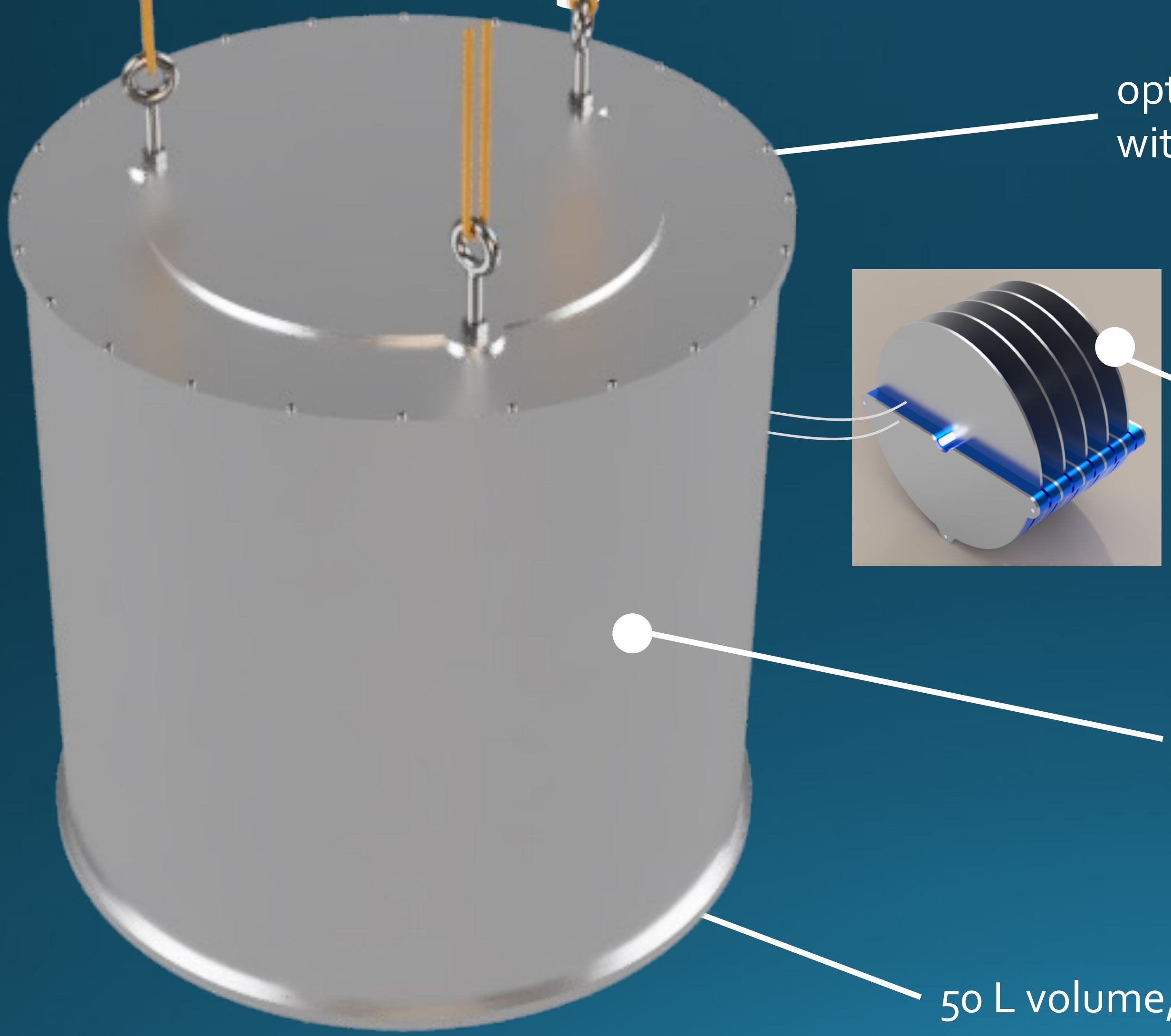
Resonant readout



DMRadio-50 L


optimized axion-detector coupling with pickup sheath
resonant readout
noise reduction
50 L volume, 1T field

DMRadio-50 L



optimized axion-detector coupling
with pickup sheath

resonant readout

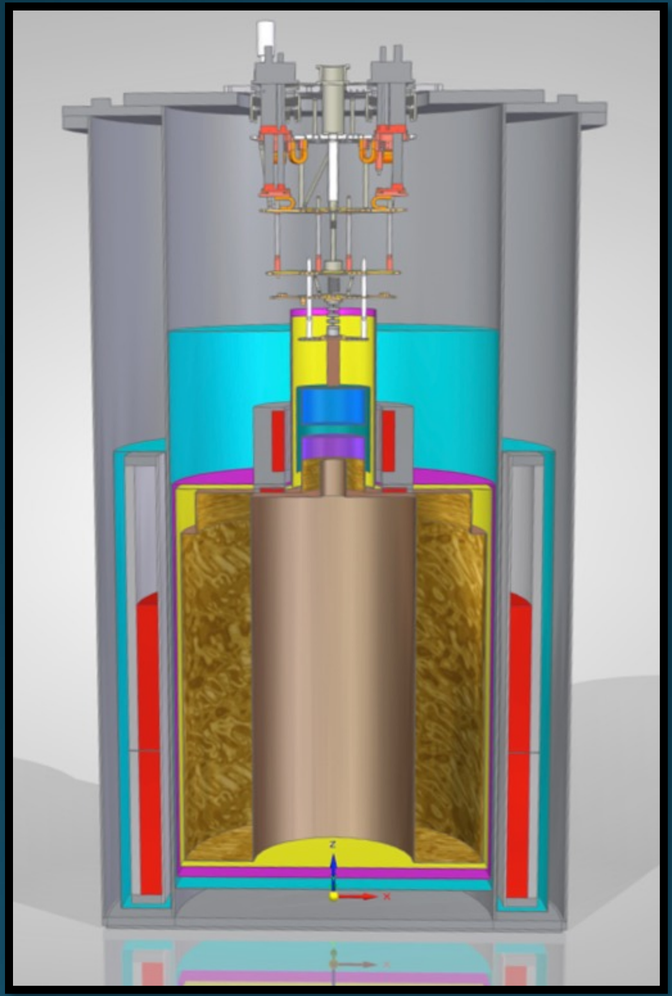
noise reduction

50 L volume, 1T field

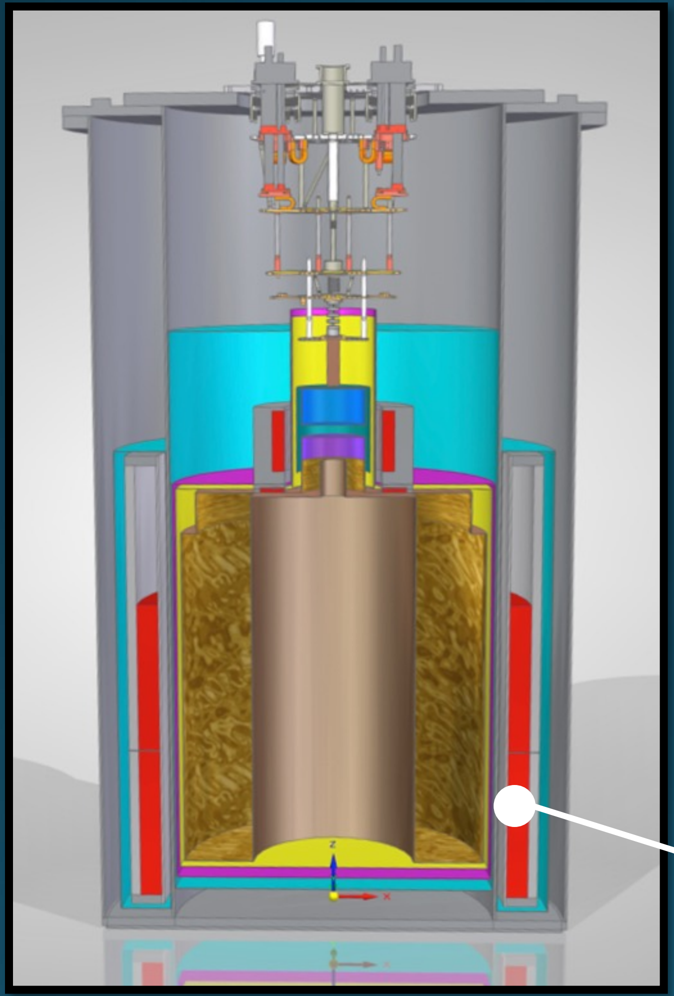
+ test bed for new
quantum sensors

Kuenstner et al. arxiv 2210.05576

DMRadio-m^3



DMRadio-m^3

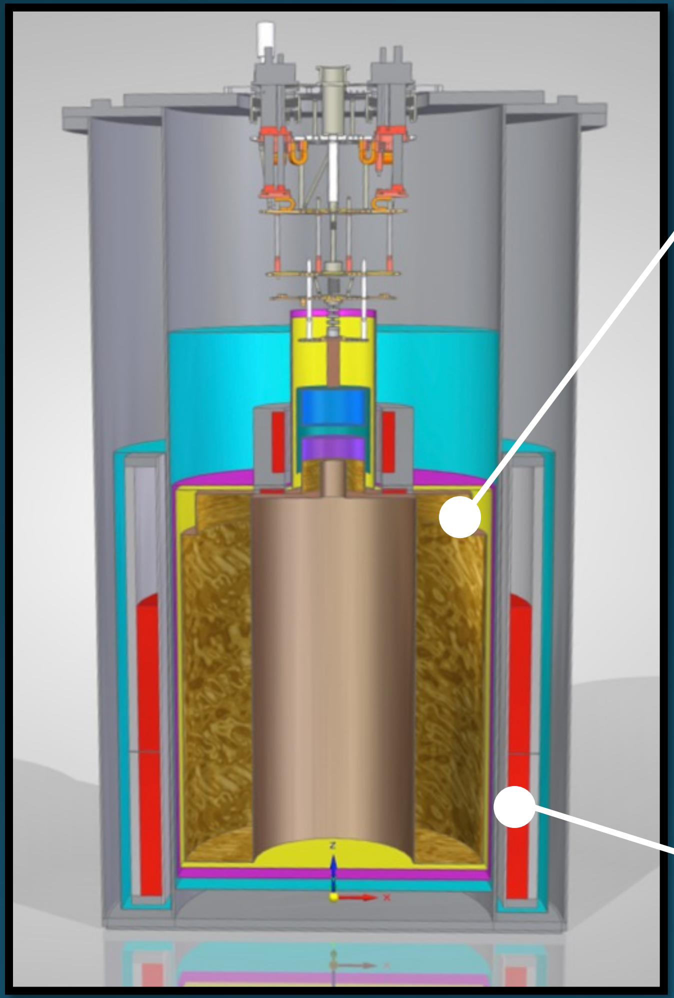


solenoidal magnet,
1 m^3 volume, 4-5T field

*ABRA-10cm ~ 0.9 L

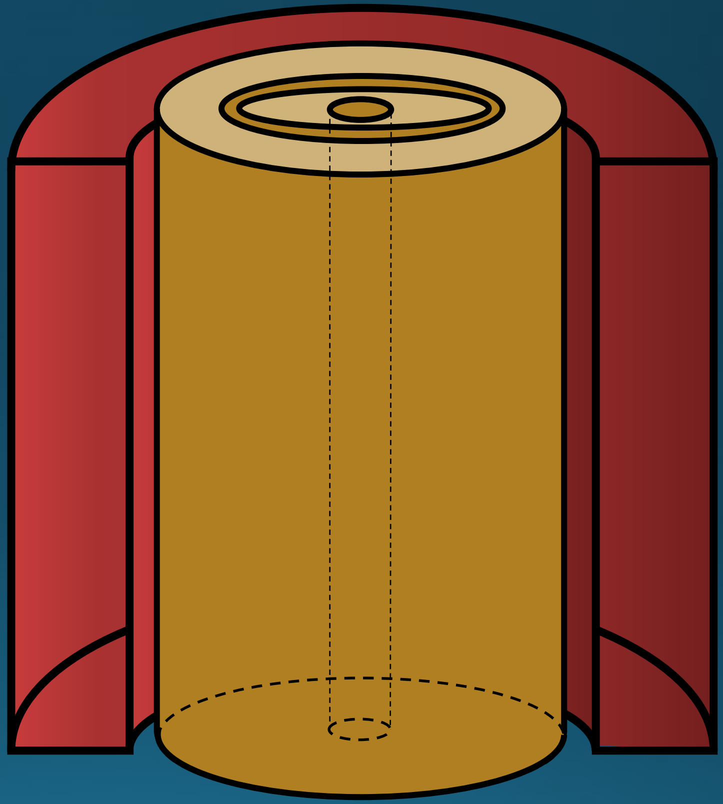
*1 m^3 = 1000 L

DMRadio-m^3



coaxial pickup sheath

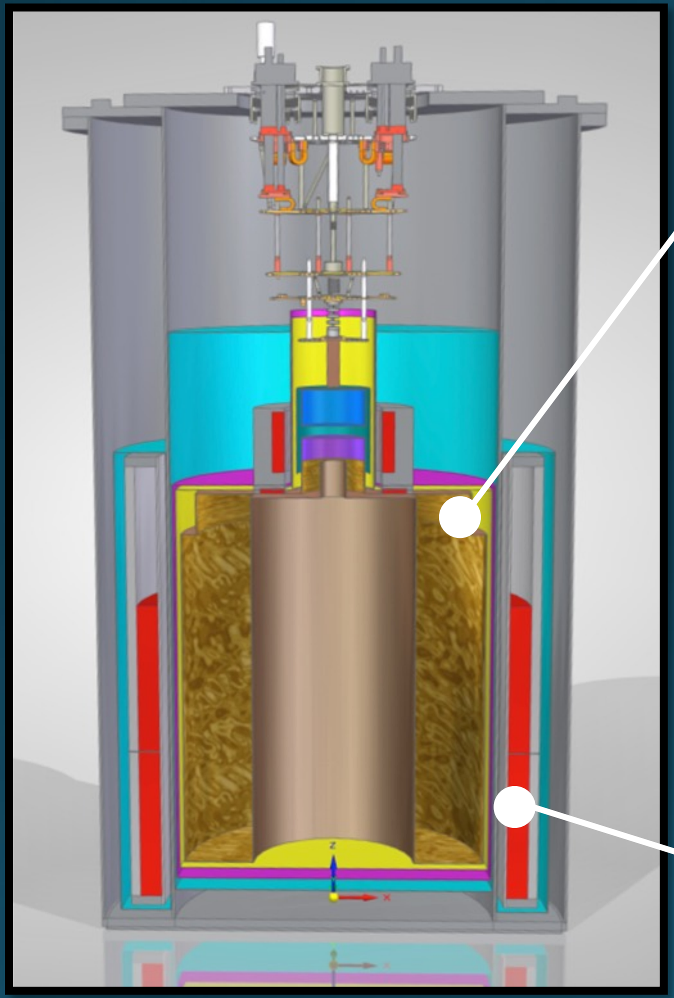
solenoidal magnet, 1 m^3 volume, 4T field



solenoidal magnet

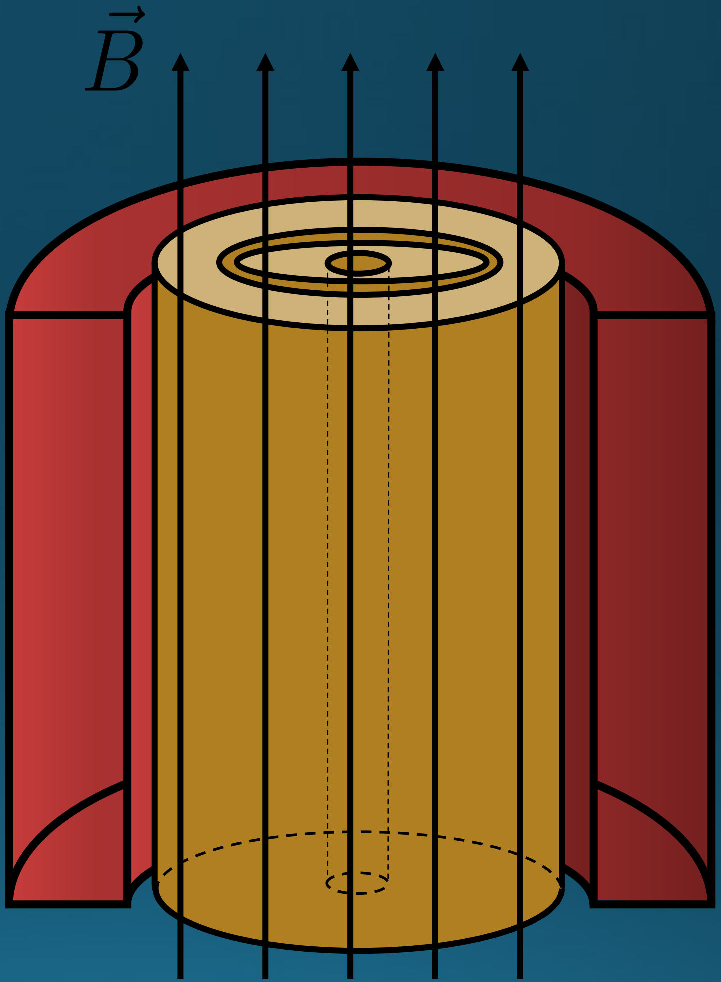
coaxial sheath

DMRadio-m^3



coaxial pickup sheath

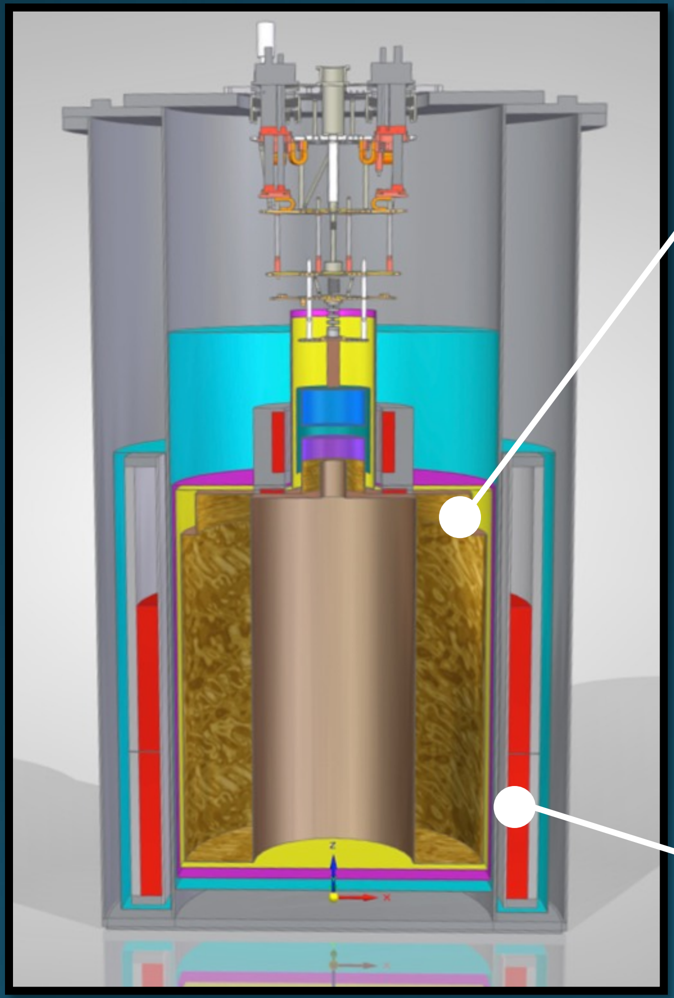
solenoidal magnet, 1 m^3 volume, 4T field



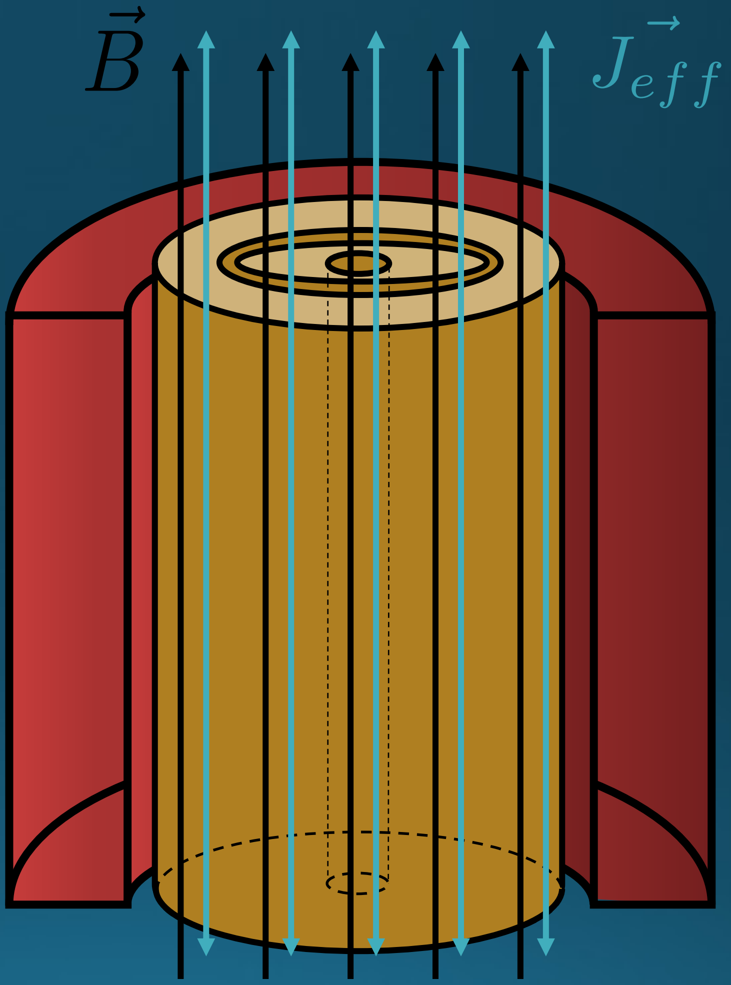
solenoidal magnet

coaxial sheath

DMRadio-m³

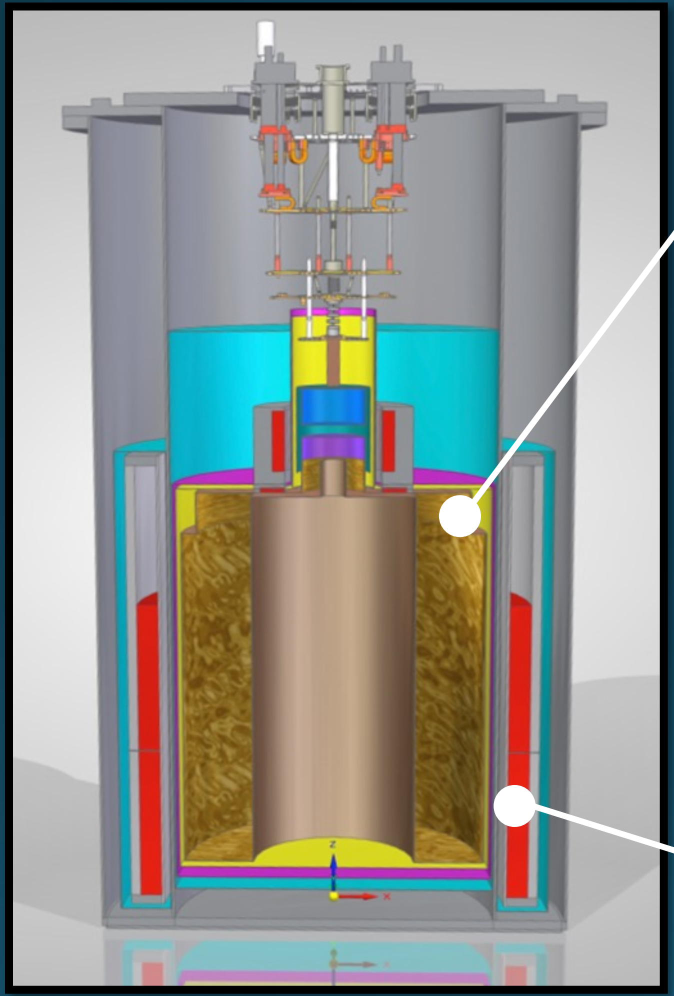


coaxial pickup sheath
solenoidal magnet, 1 m³ volume, 4T field



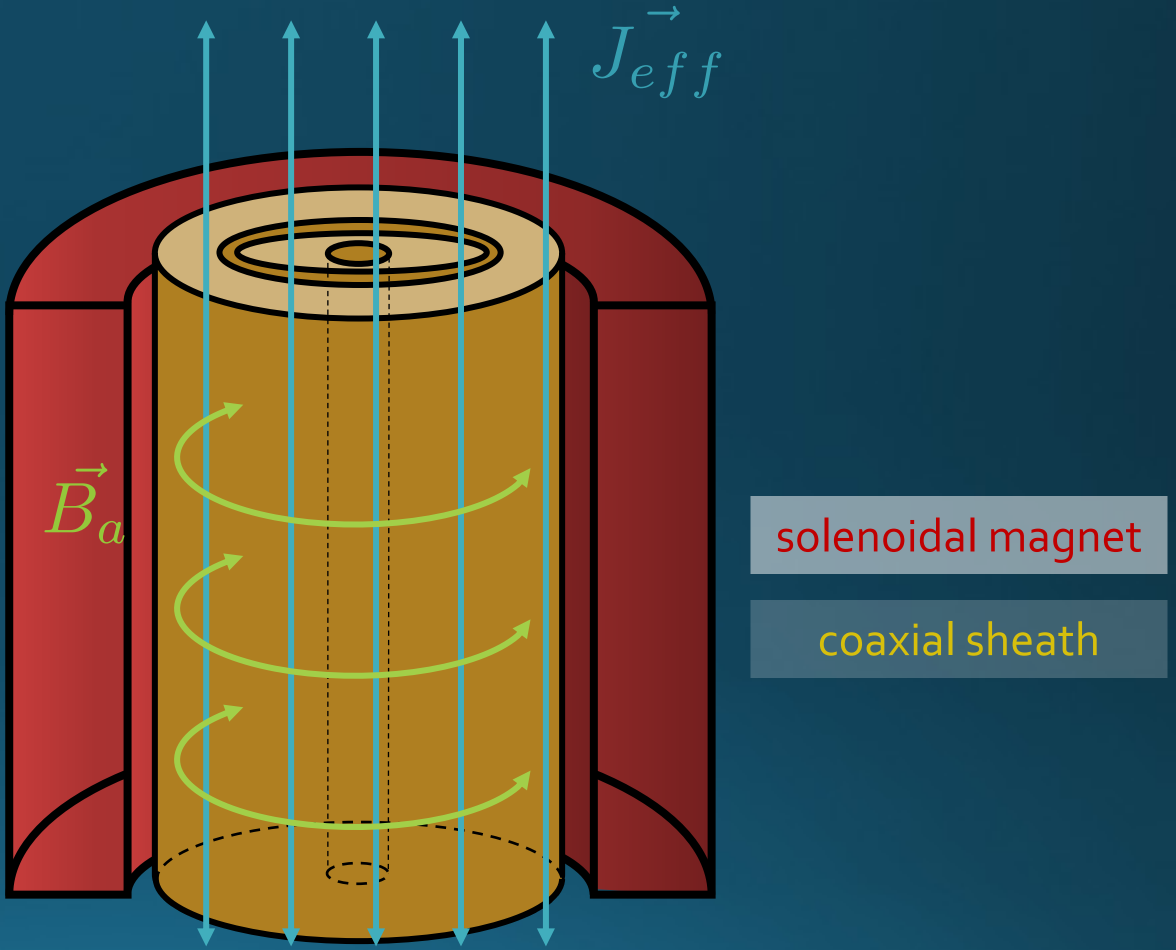
$\vec{B}$
$\vec{J}_{eff}$
solenoidal magnet
coaxial sheath

DMRadio-m^3

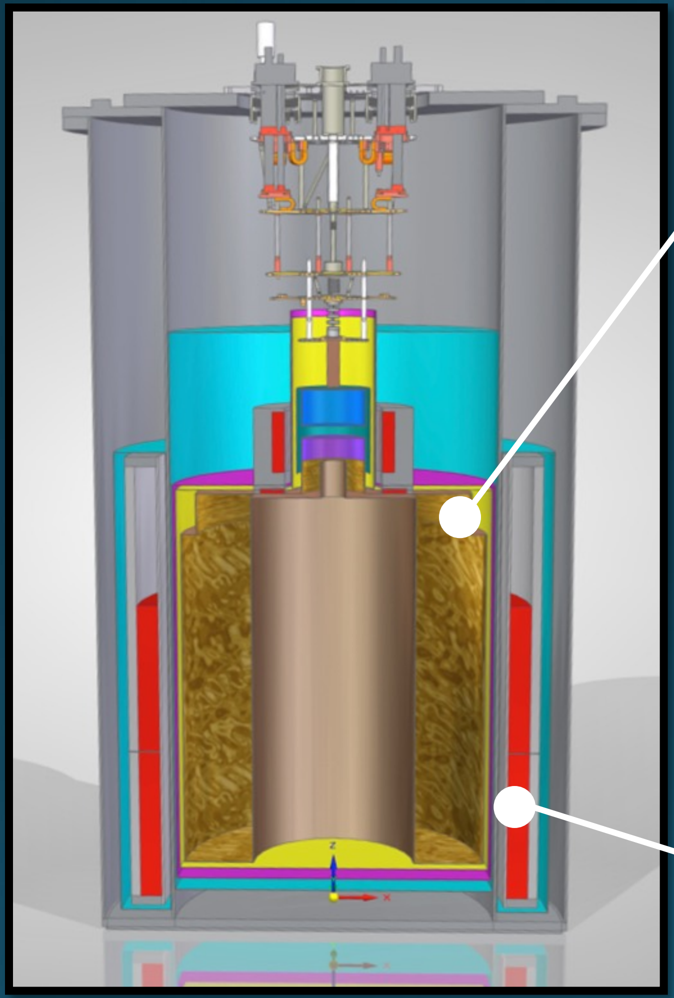


coaxial pickup sheath

solenoidal magnet,
1 m^3 volume, 4T field

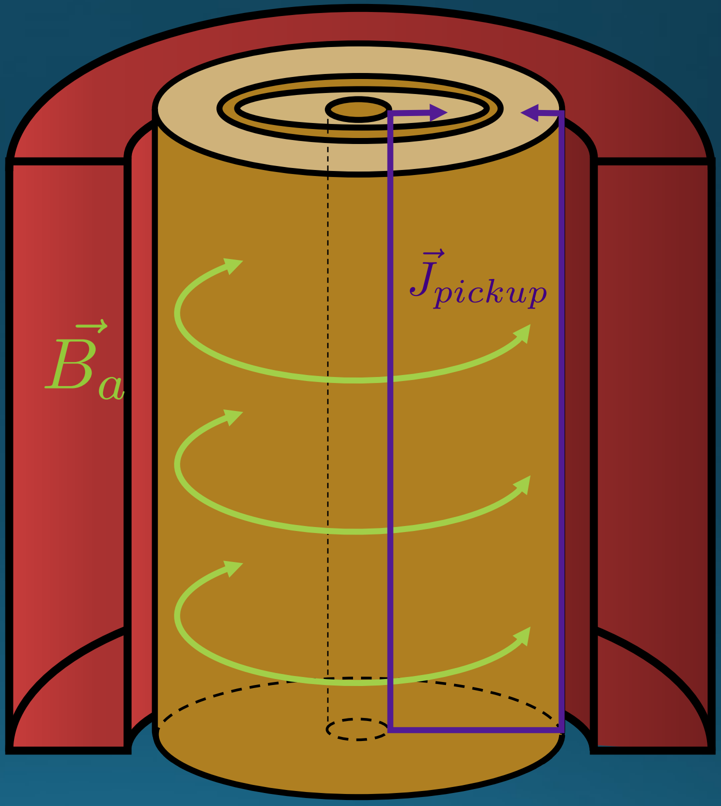


DMRadio-m^3



coaxial pickup sheath

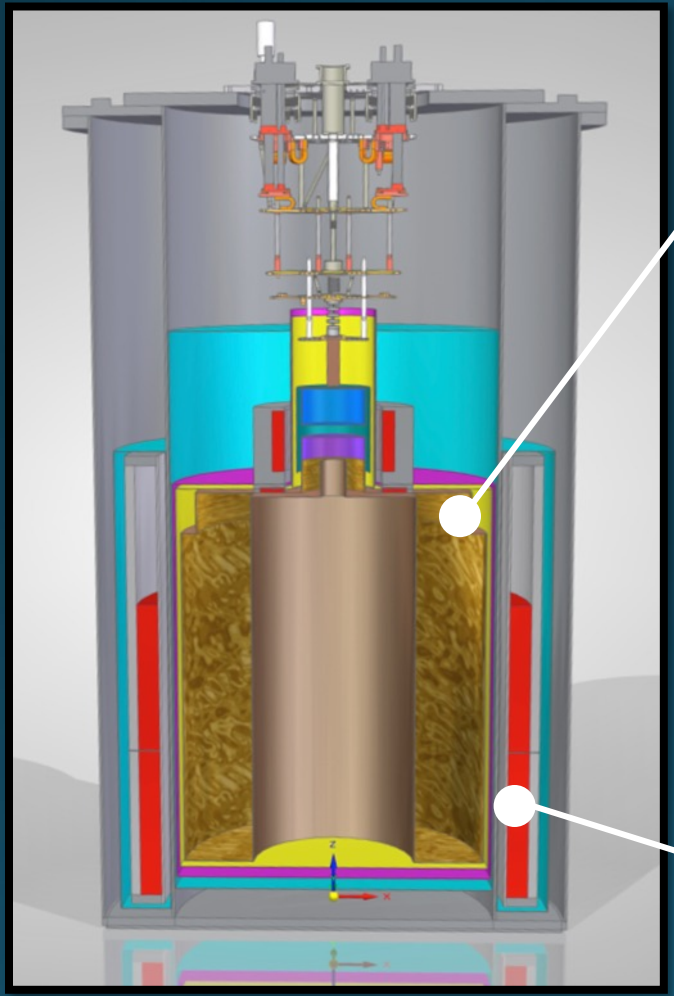
solenoidal magnet, 1 m^3 volume, 4T field



solenoidal magnet

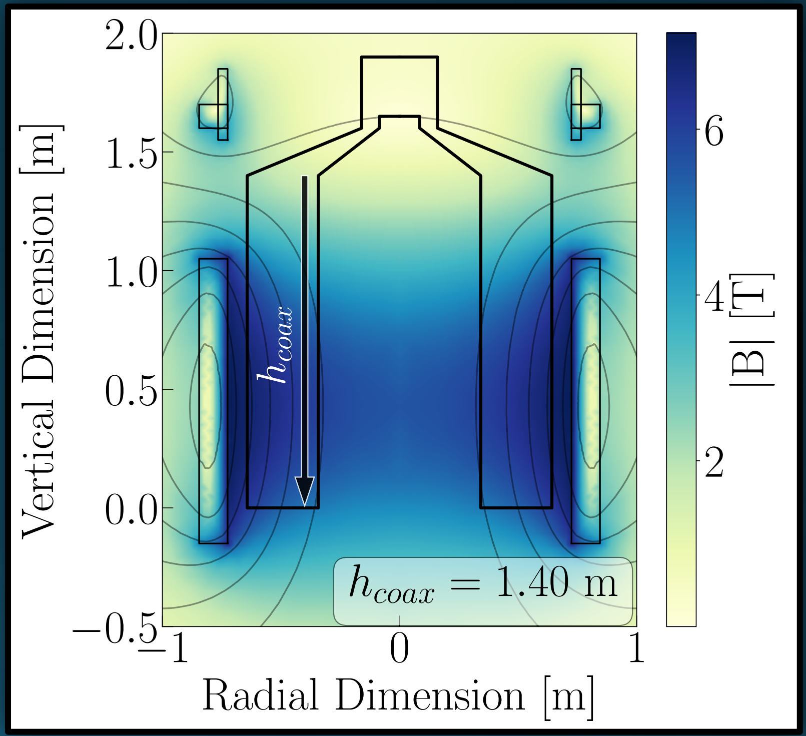
coaxial sheath

DMRadio-m^3



coaxial pickup sheath

solenoidal magnet,
1 m^3 volume, 4T field

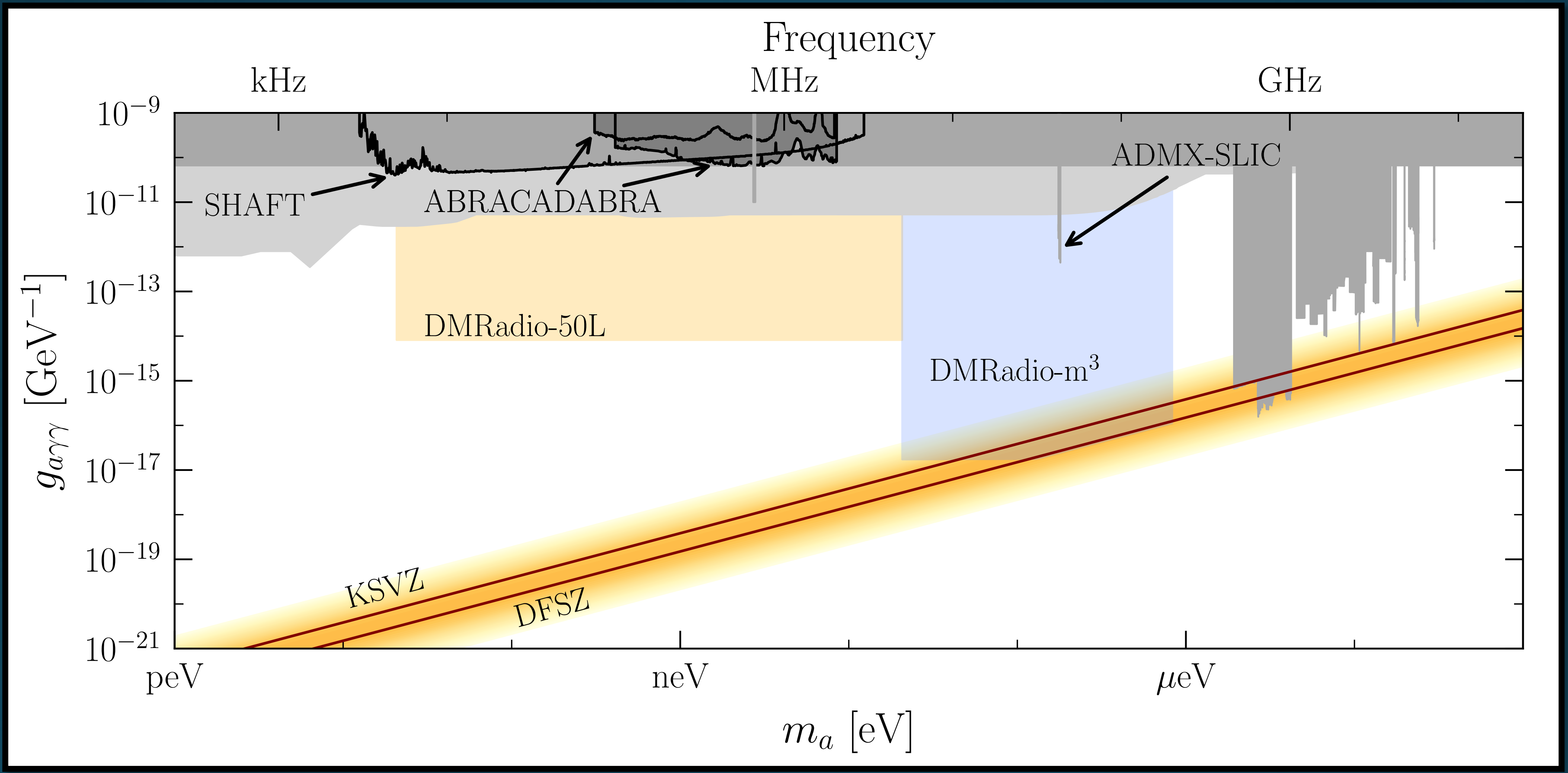


PRELIMINARY

Next-generation reach

Brouwer, Salemi et al. *Phys.Rev.D* 2022

See also:
Benabou, Salemi et al. arxiv 2211.00008
Brouwer, Salemi et al. in prep



DMRadio-GUT

DMRadio-GUT

- 10 m^3 volume, 16 T peak field (12 T RMS field)

*ABRA-10cm ~ 0.9 L

*1 m^3 = 1000 L

*10 m^3 = 10,000 L

DMRadio-GUT

- 10 m^3 volume, 16 T peak field (12 T RMS field)
- Q ~ 20 million
- Backaction-evading amplifiers, η ~ -20 dB
- Low temperature, T ~ 10 mK

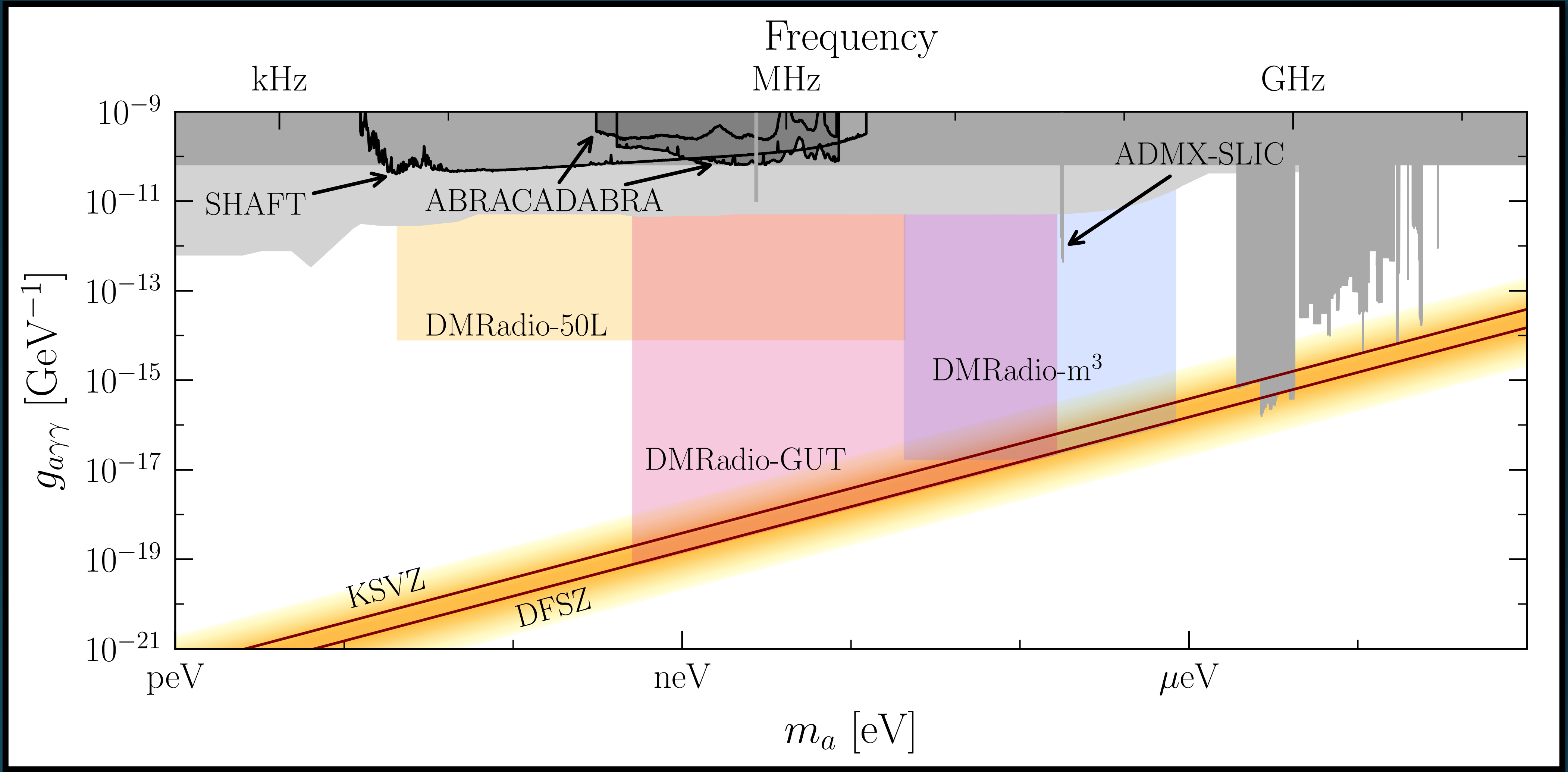
*ABRA-10cm ~ 0.9 L

*1 m^3 = 1000 L

*10 m^3 = 10,000 L

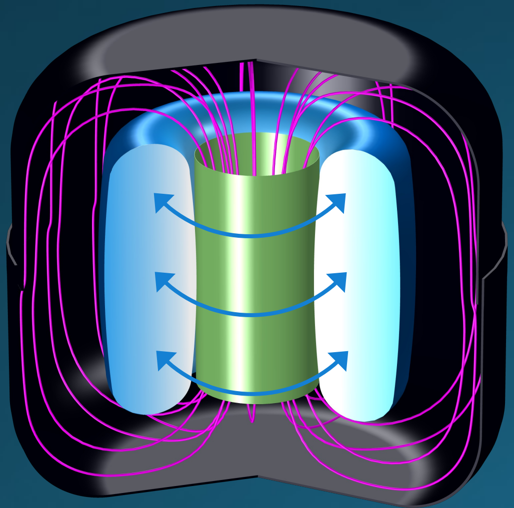
Brouwer, Salemi et al. accepted *Phys.Rev.D* 2022

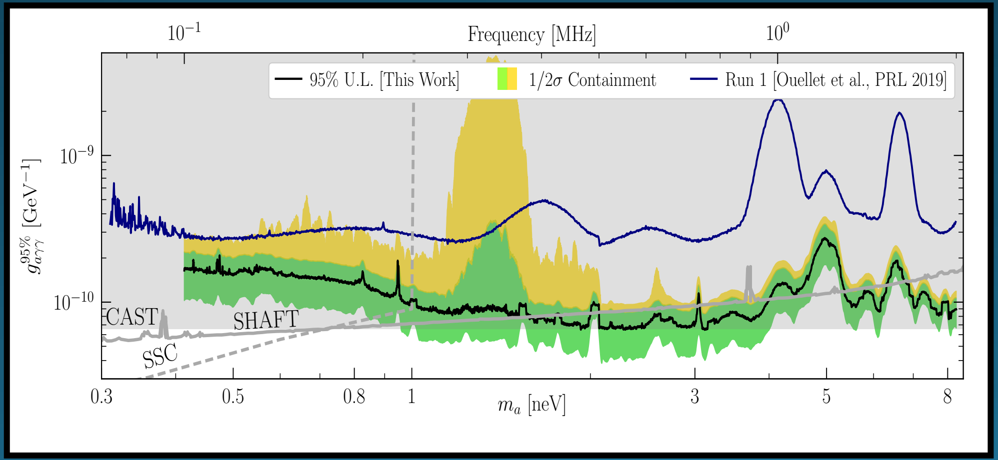
DMRadio program reach

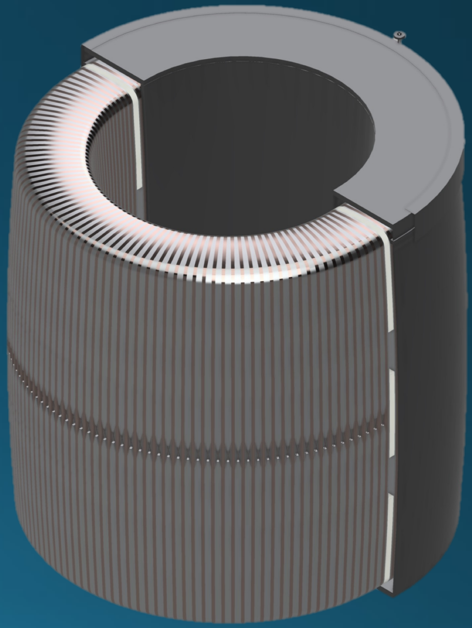


Summary

- Axions are a highly motivated dark matter candidate
- The new lumped-element method enables us to detect low-mass axions
- The ABRACADABRA-10 cm prototype detector set world-leading limits and opened new dark matter parameter space
- It's now time to scale up with the DMRadio program

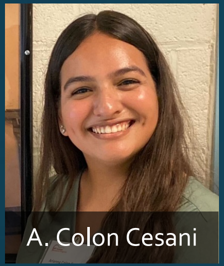




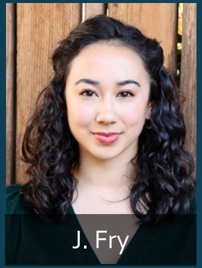


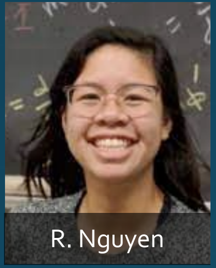
ABRACADABRA

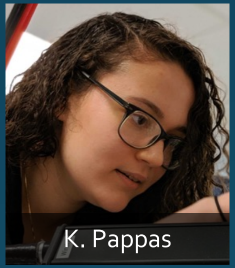
Undergraduate researchers



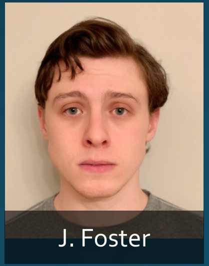
Graduate students



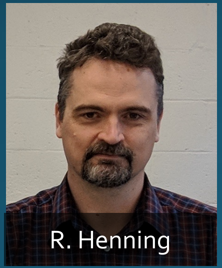


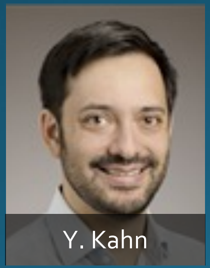


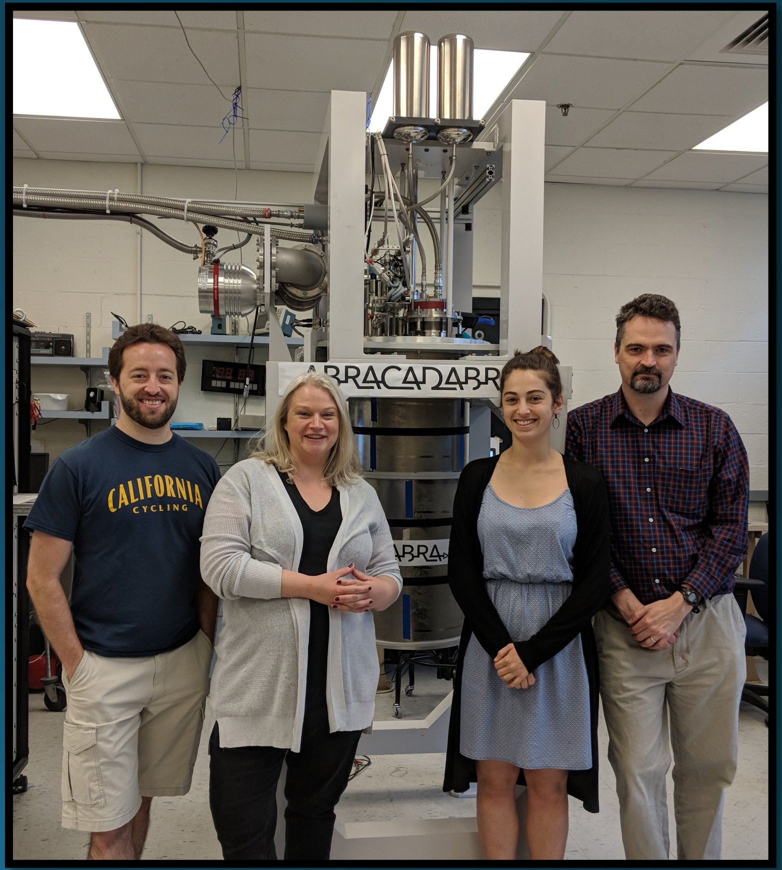
Postdocs and research scientists



Principle investigators







DM RADIO

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Thank you!