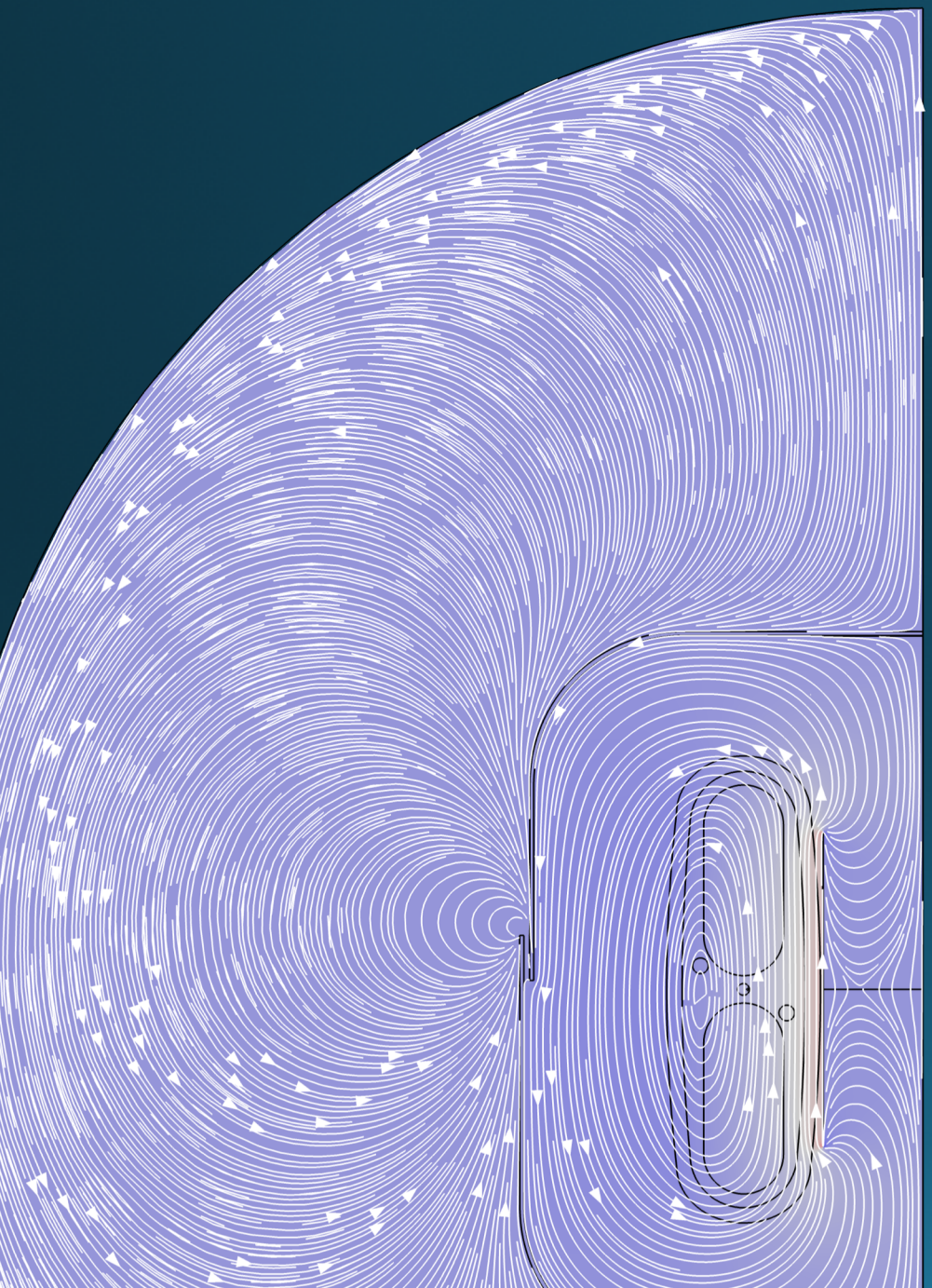


Lumped element searches for low-mass axion dark matter

Chiara Salemi, MIT

Axions Beyond Gen 2 Workshop, 2021

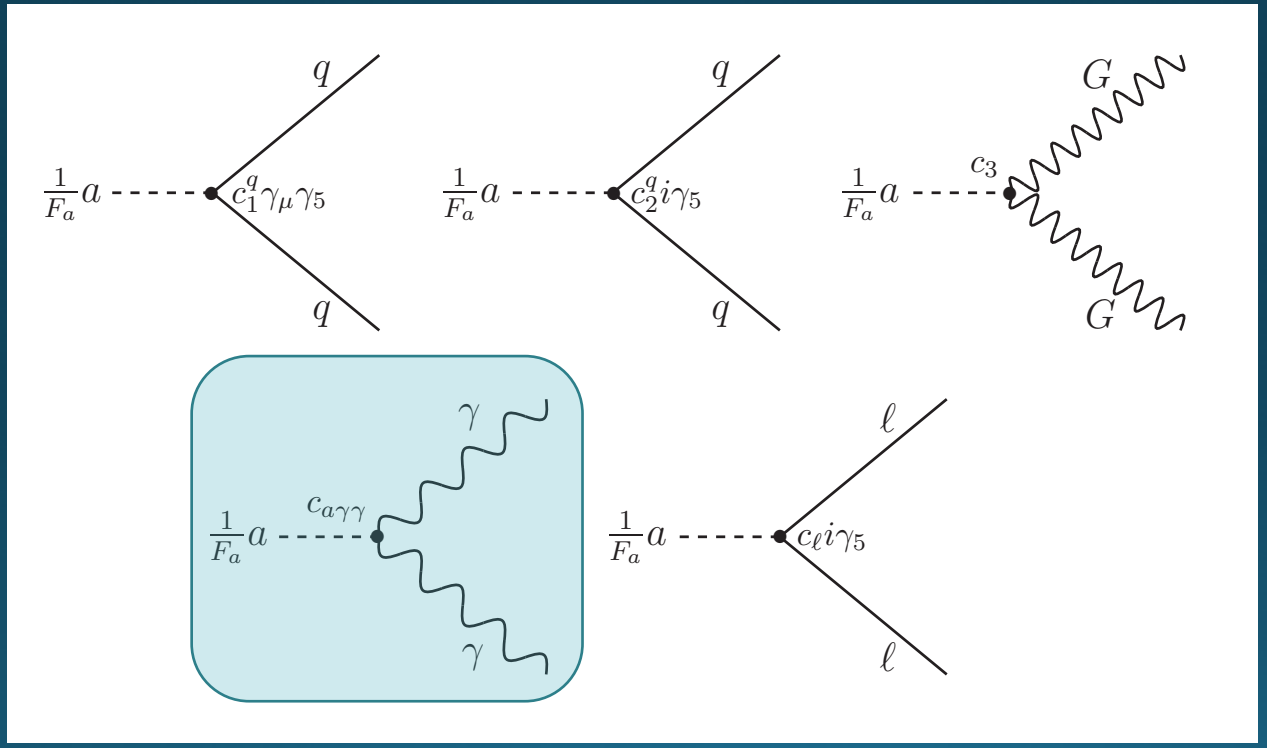
Agenda

- How to detect low-mass axions
- Experimental progress
- The future

Agenda

- How to detect long wavelength axions
- Experimental progress
- The future

How can we detect axions?



Axion E&M

Axion-photon interactions modify Ampere's Law:

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

Axion E&M

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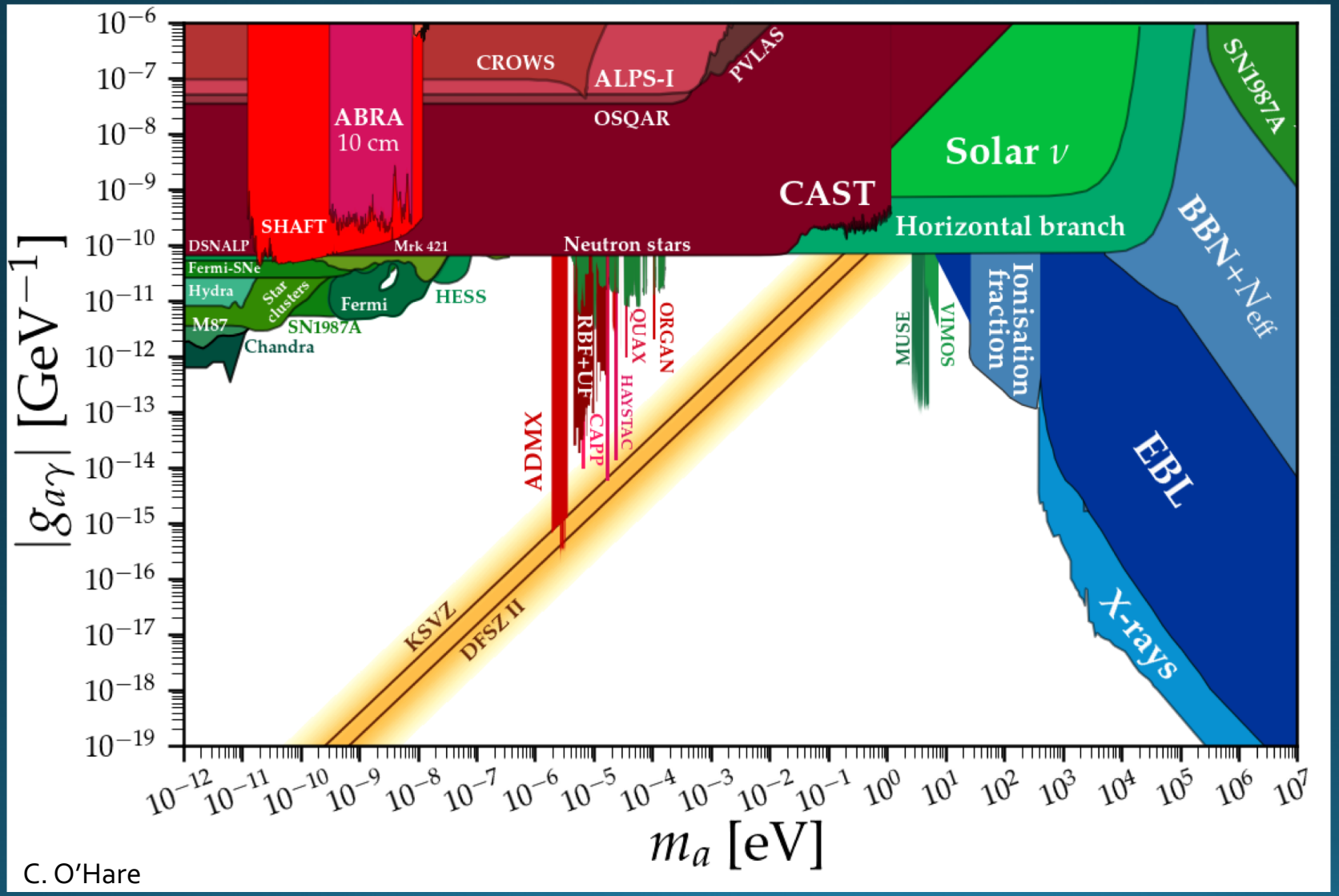
$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} - g_{a\gamma\gamma}(\mathbf{E} \times \cancel{\nabla a} - \frac{\partial a}{\partial t}\mathbf{B})$$

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

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

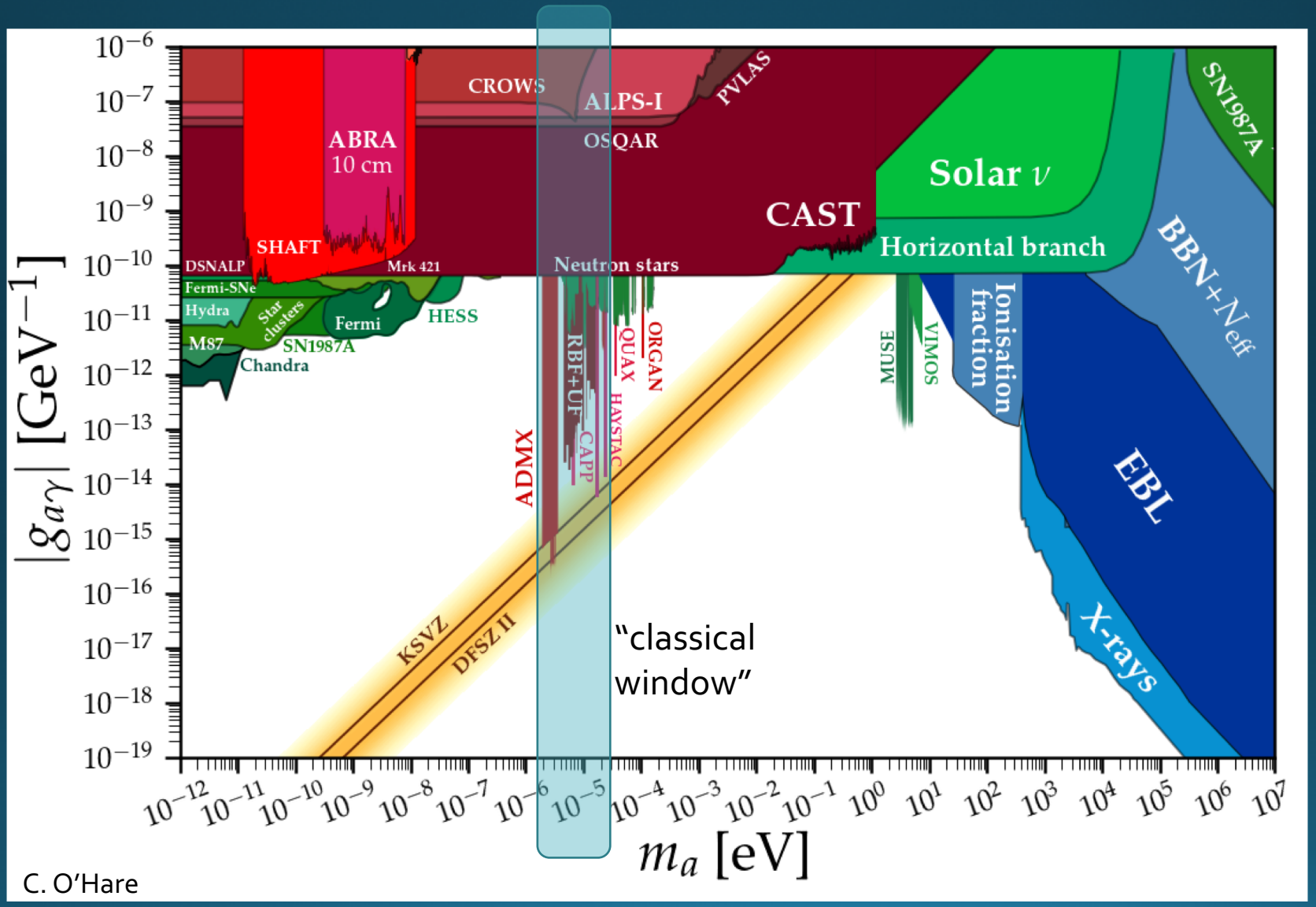
Where have we looked?



C. O'Hare

axion mass

Where have we looked?



axion mass

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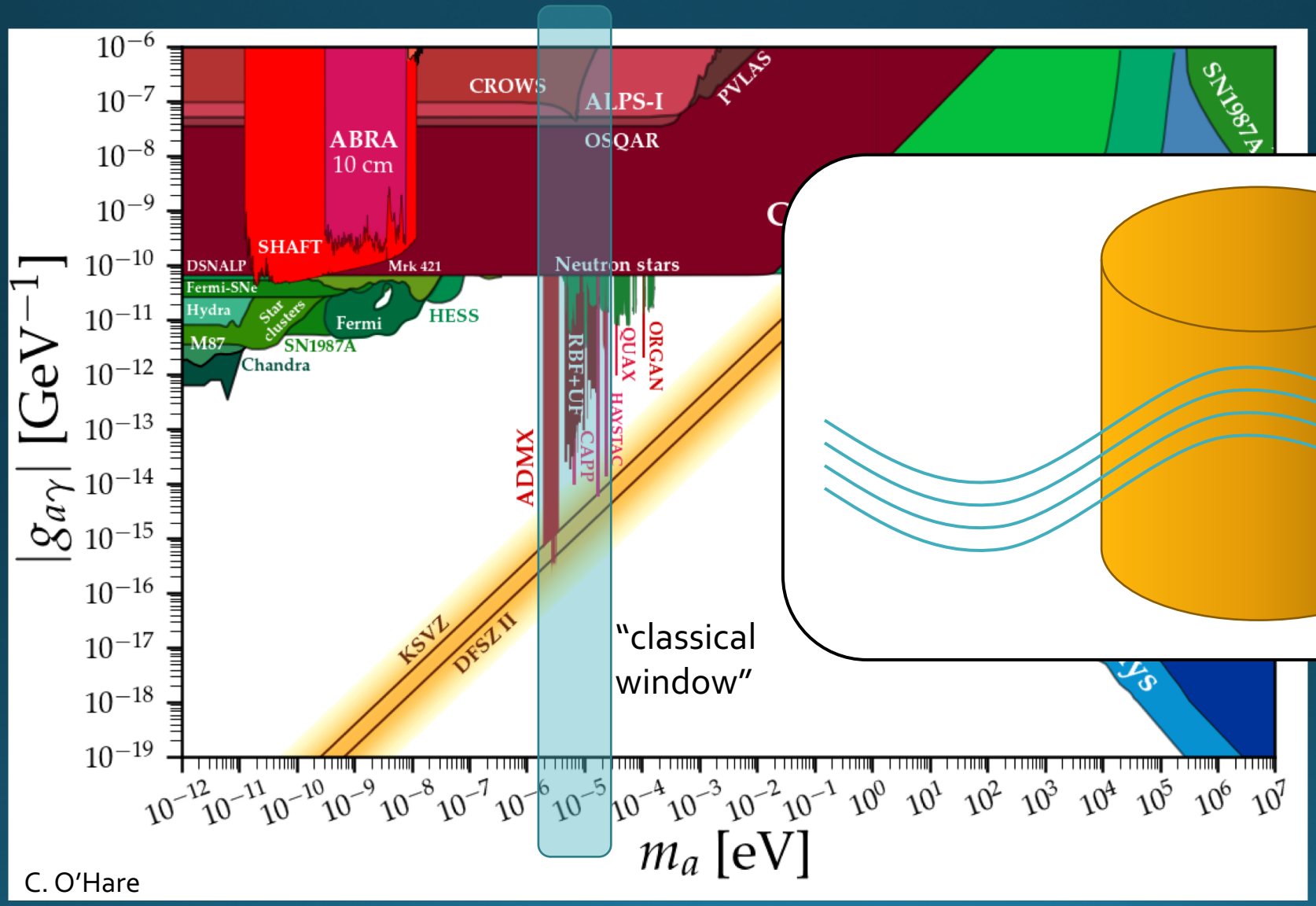

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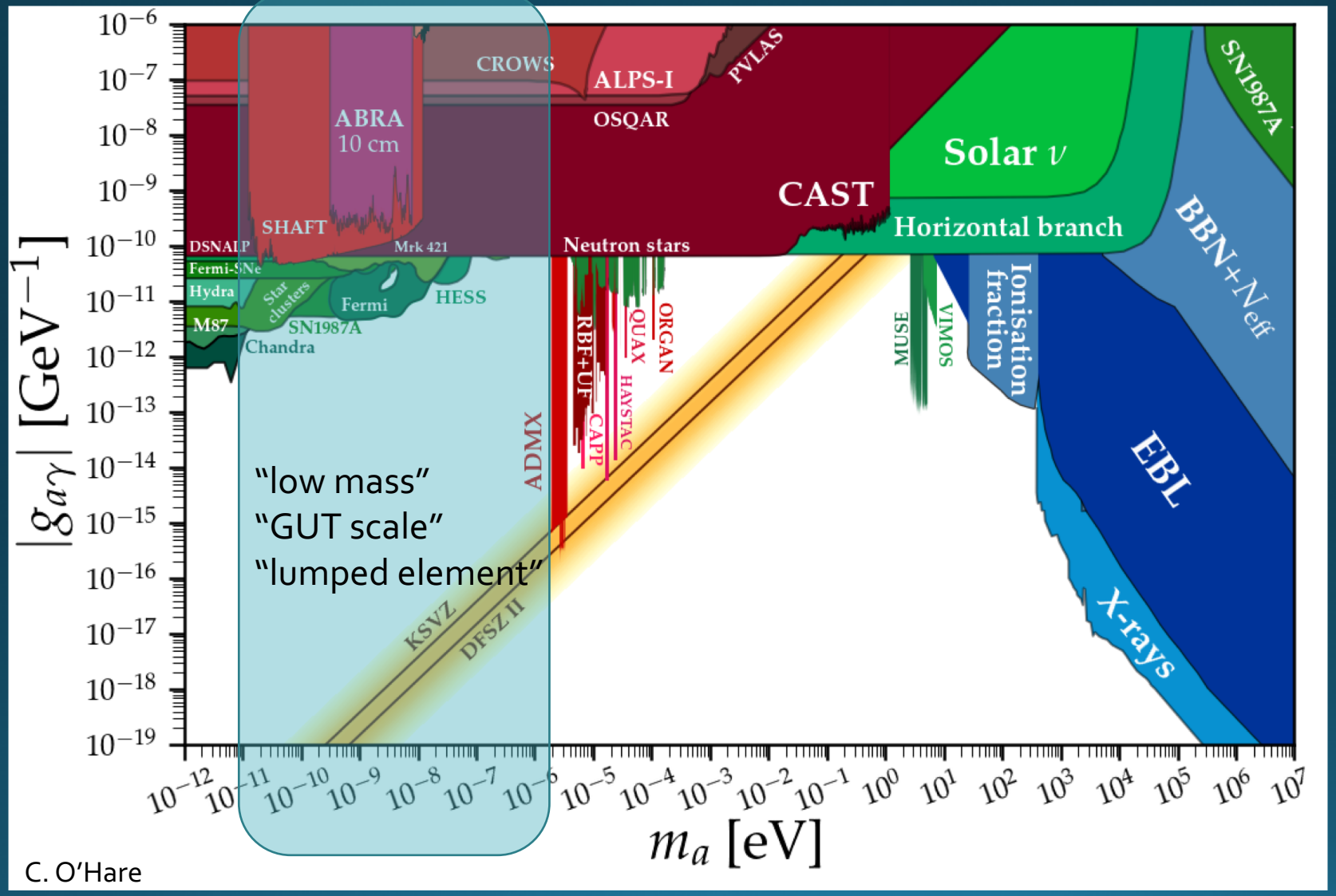

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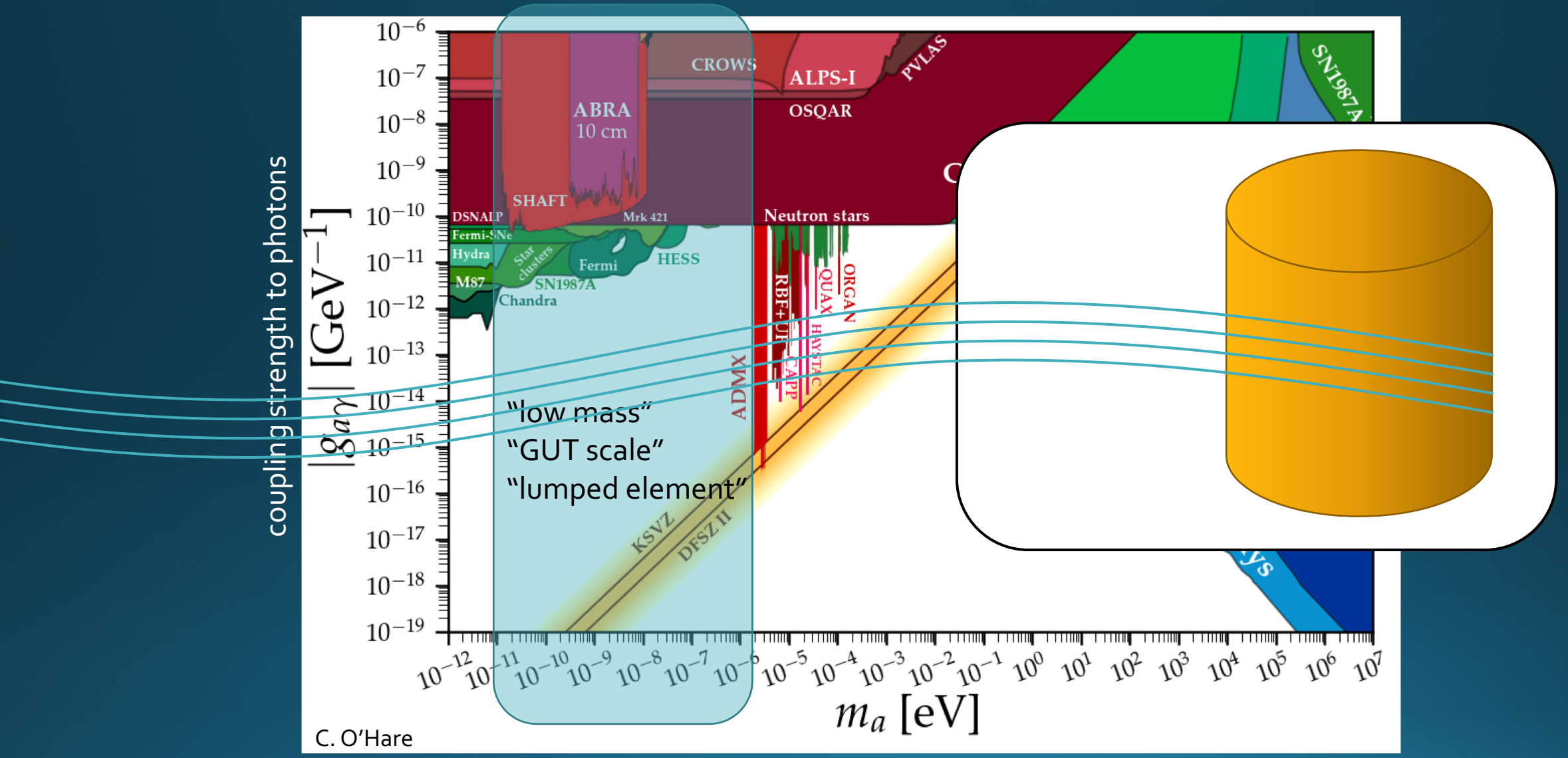
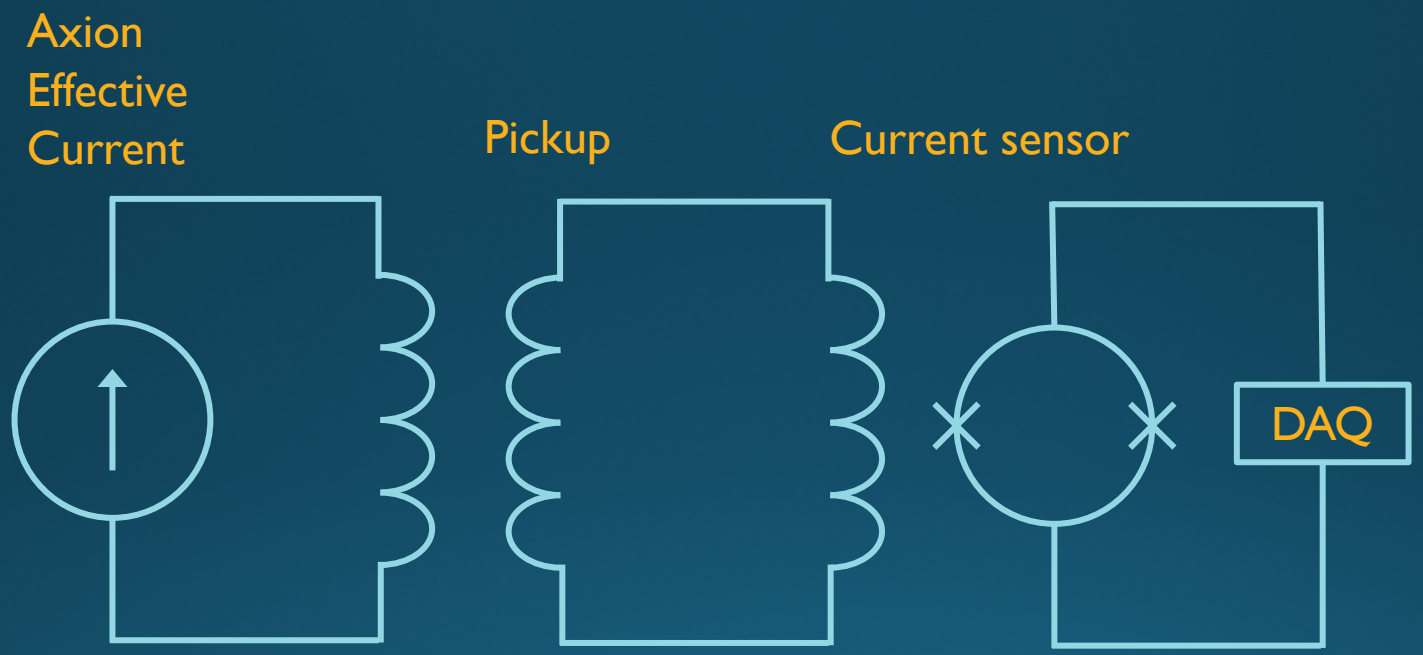
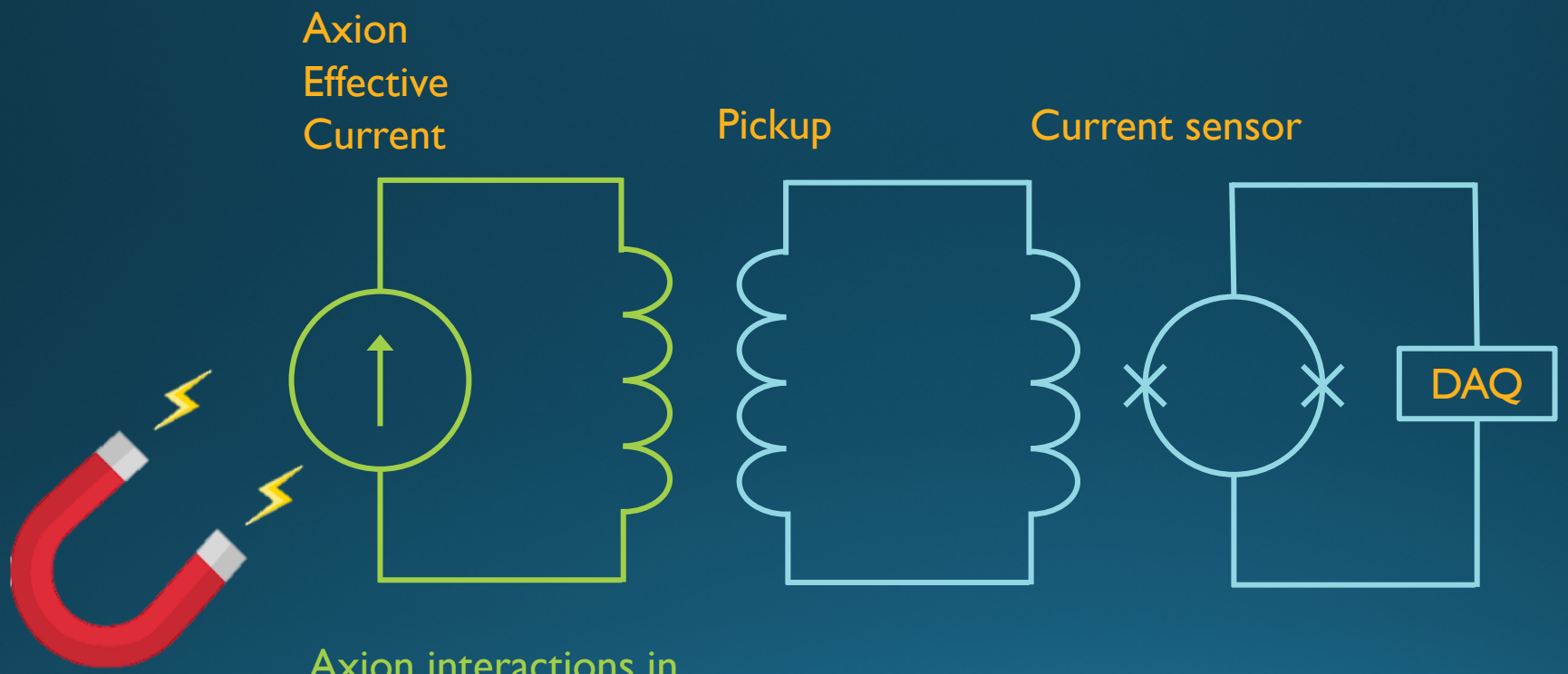


axion mass

Experiment schematic



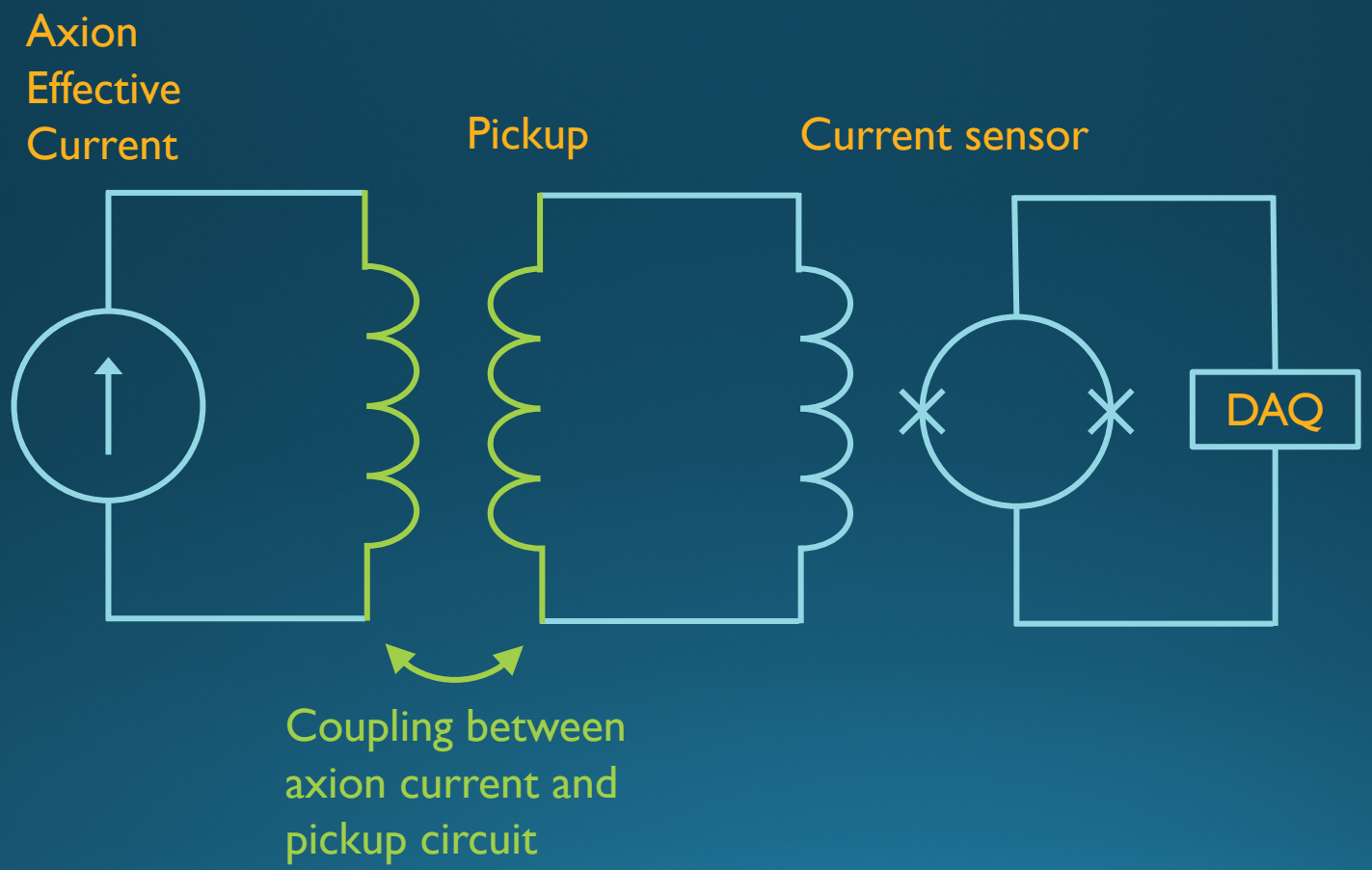
Experiment schematic



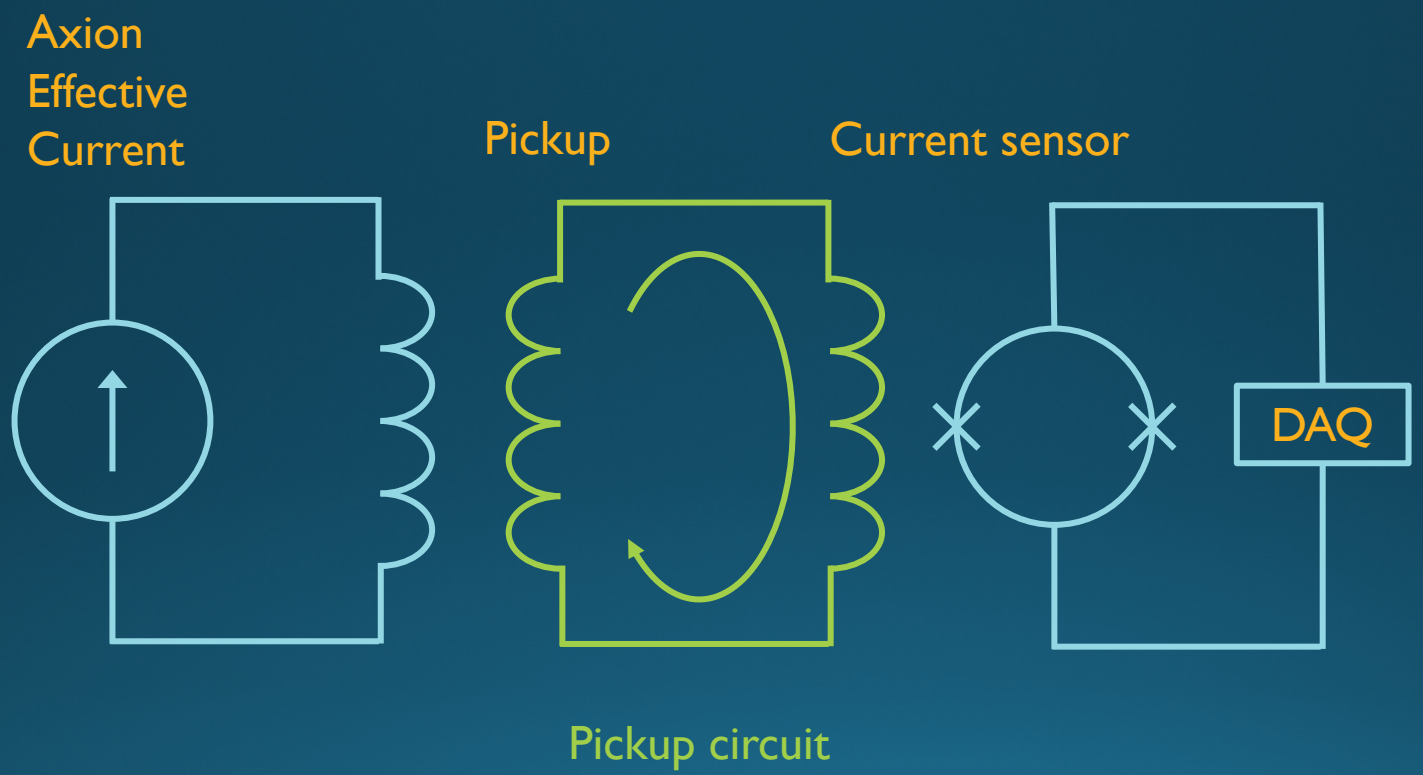
Axion interactions in magnetic field

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

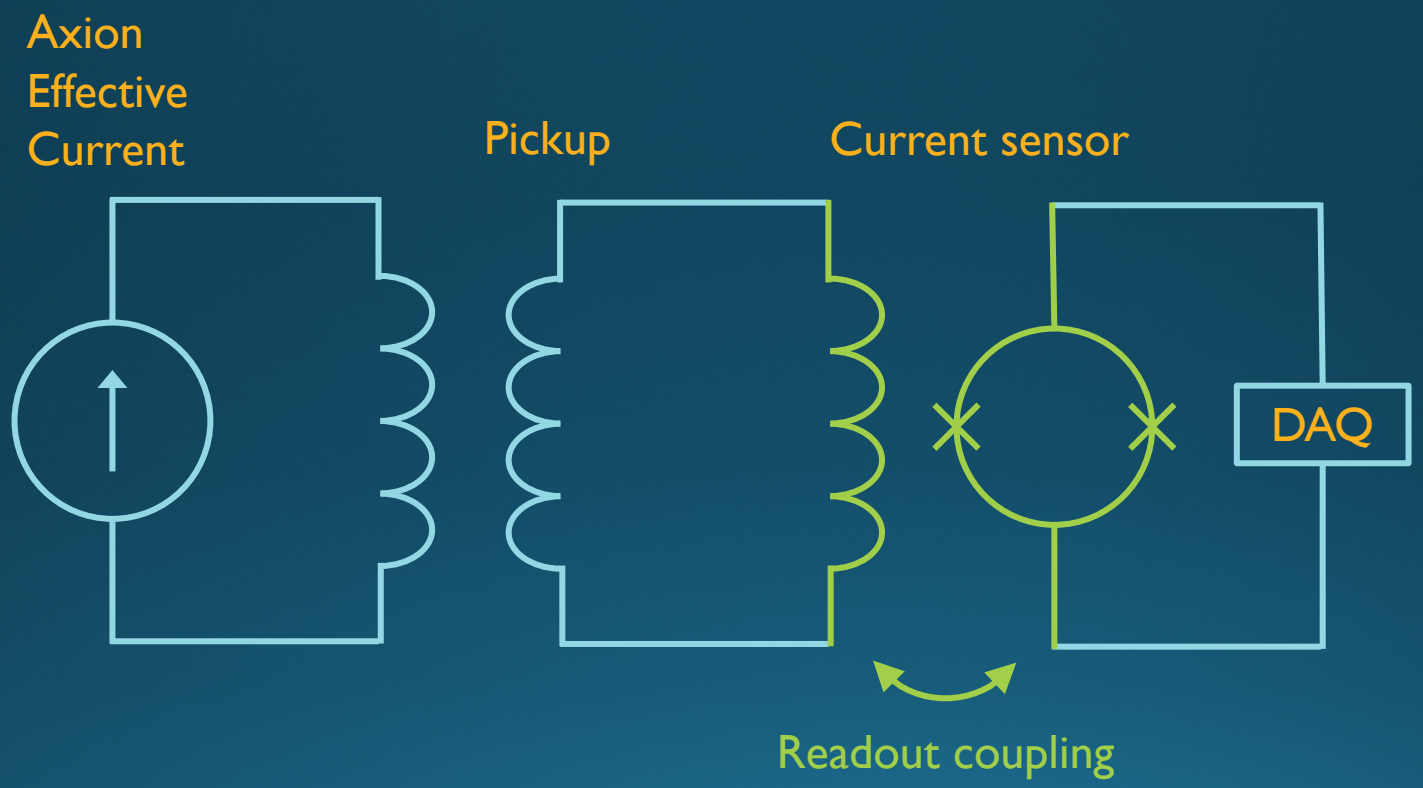
Experiment schematic



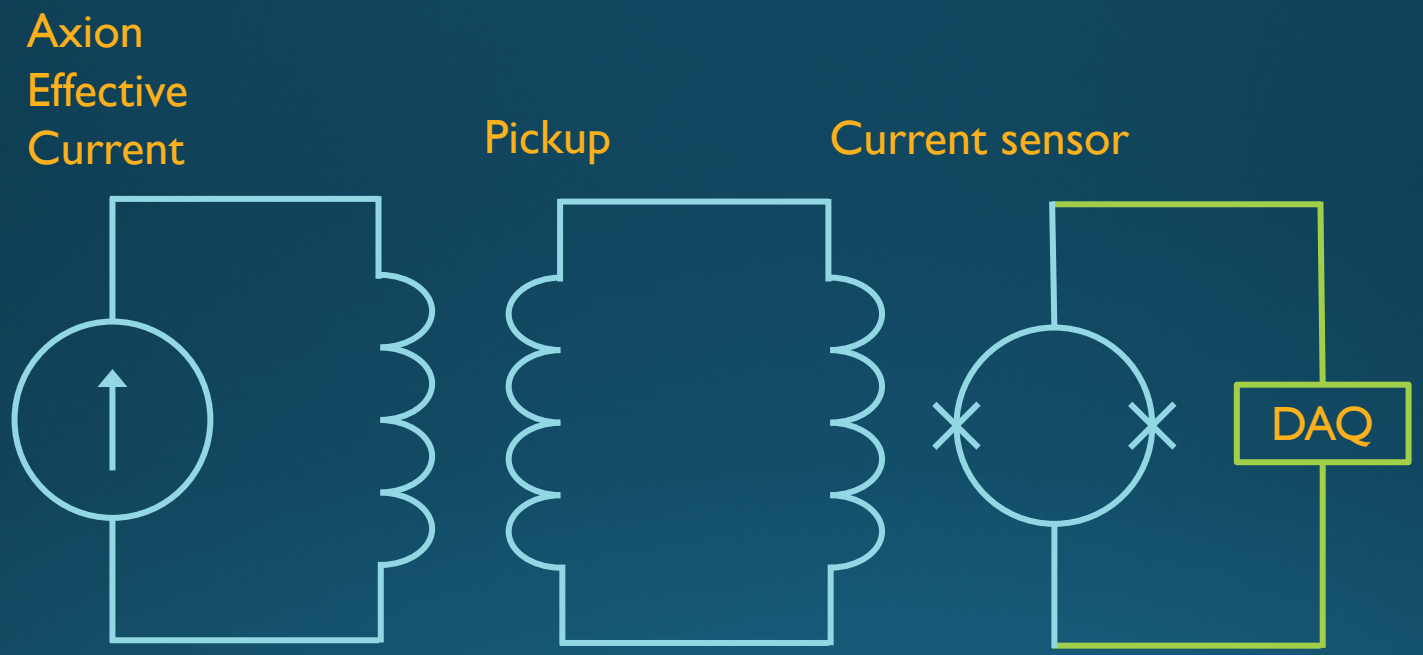
Experiment schematic



Experiment schematic



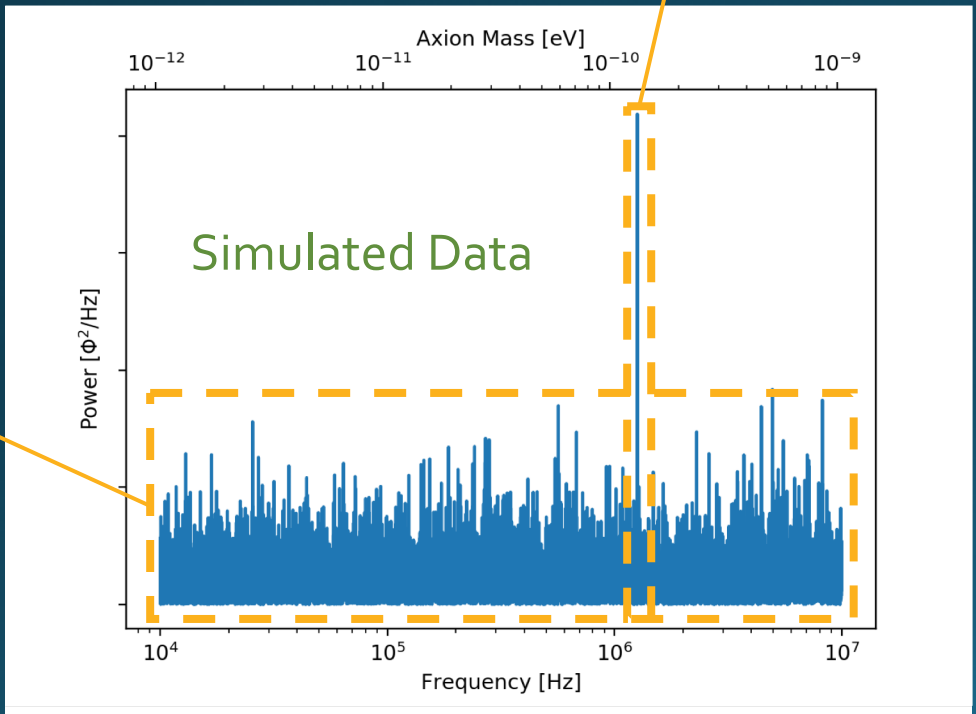
Experiment schematic

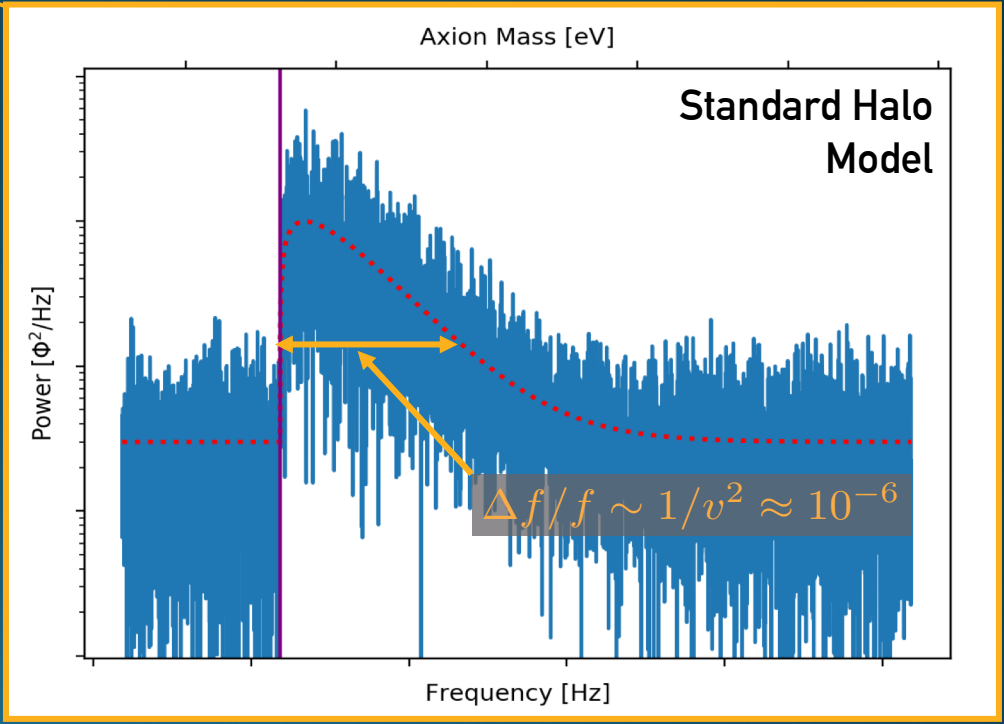


Axion Signal

Axion signal

Background noise





Lumped element detector ingredients

- Strong magnet (toroid or solenoid)
- Pickup structure
- Readout circuit (broadband or resonant)
- Quantum sensors
- Cryogenics
- Vibration isolation
- EM shielding

Toroidal detector

- Toroidal superconducting magnet with fixed field, $\mathbf{B_0}$

Toroidal detector

- Toroidal superconducting magnet with fixed field, $\mathbf{B_0}$
- Axion dark matter generates parallel oscillating effective current, $\mathbf{J_{eff}}$

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

Toroidal detector

- Toroidal superconducting magnet with fixed field, $\mathbf{B_0}$
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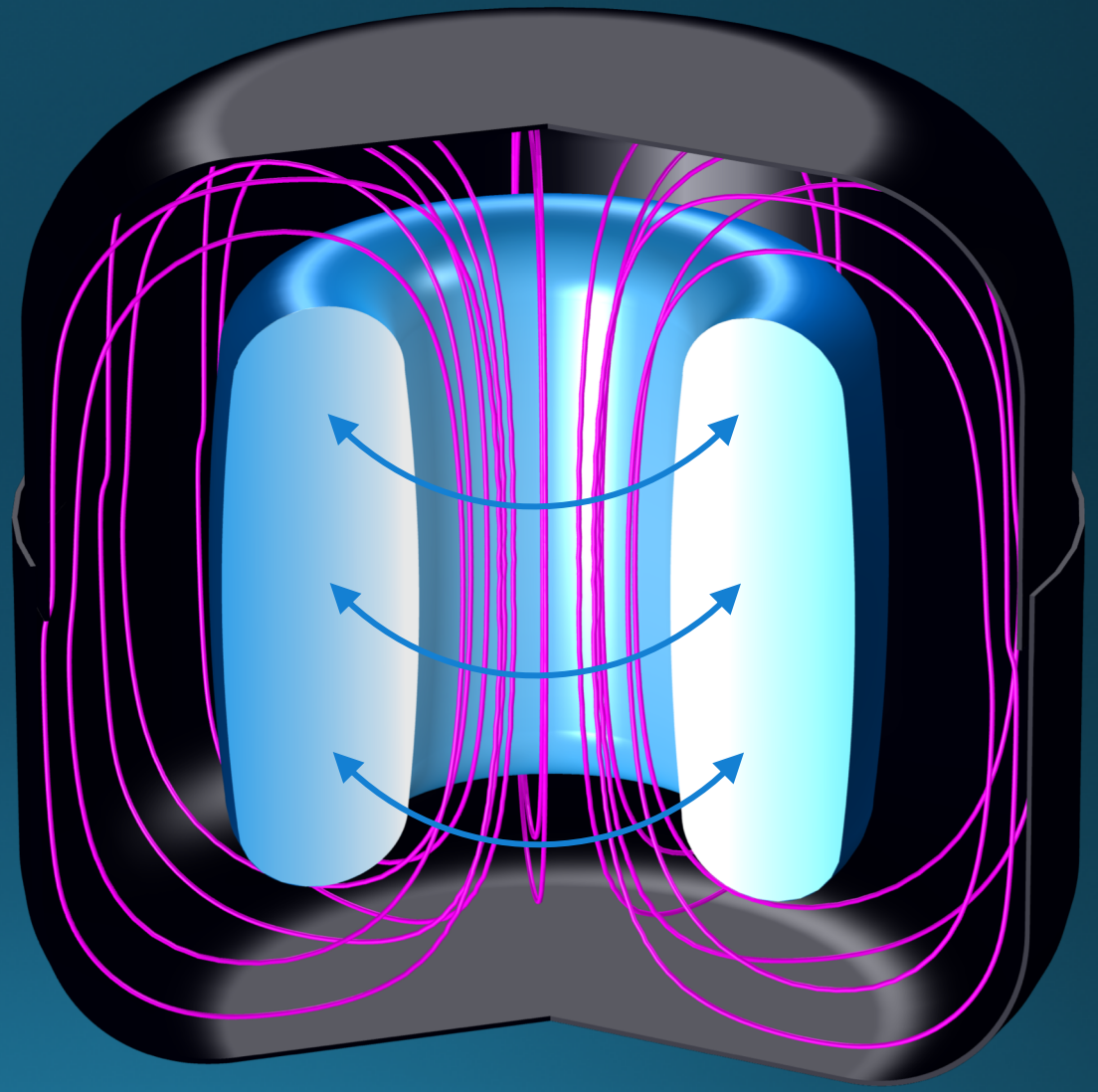
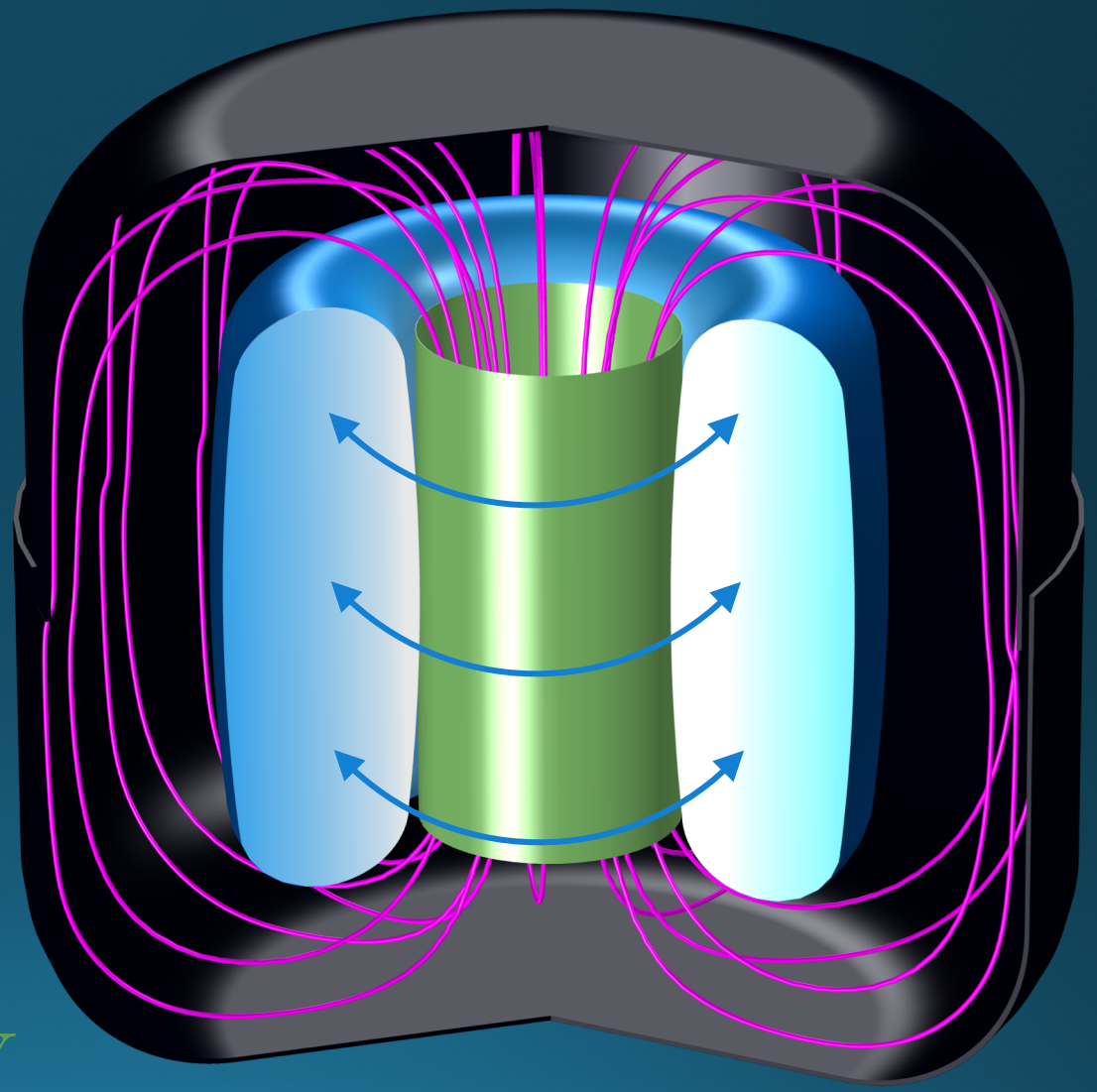
- …creating an oscillating magnetic flux through the center of the toroid



Toroidal detector

- Toroidal superconducting magnet with fixed field, B_0
- Axion dark matter generates parallel oscillating effective current, J_{eff}
- …creating an oscillating magnetic flux through the center of the toroid
- This flux is then read out from a pickup structure using quantum sensors

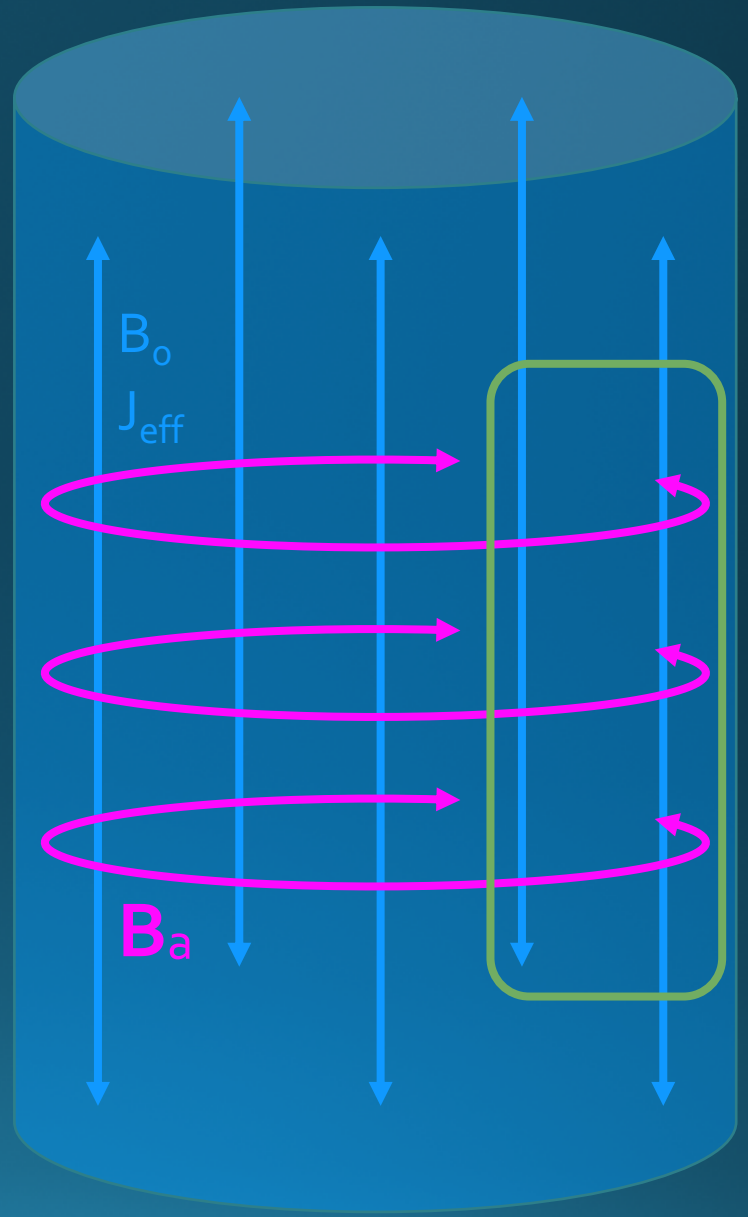
$$\Phi(t) = g_{a\gamma\gamma} B_0 \sqrt{2\rho_{DM}} \cos(m_a t) \mathcal{G} V$$



Kahn, Safdi, Thaler Phys. Rev. Lett. 2016

Solenoidal detector

- ***Solenoidal*** superconducting magnet with fixed field, $\mathbf{B_0}$
- Axion dark matter generates parallel oscillating effective current, J_{eff}
- …creating an oscillating ***azimuthal*** magnetic flux
- This flux is then read out from a pickup structure



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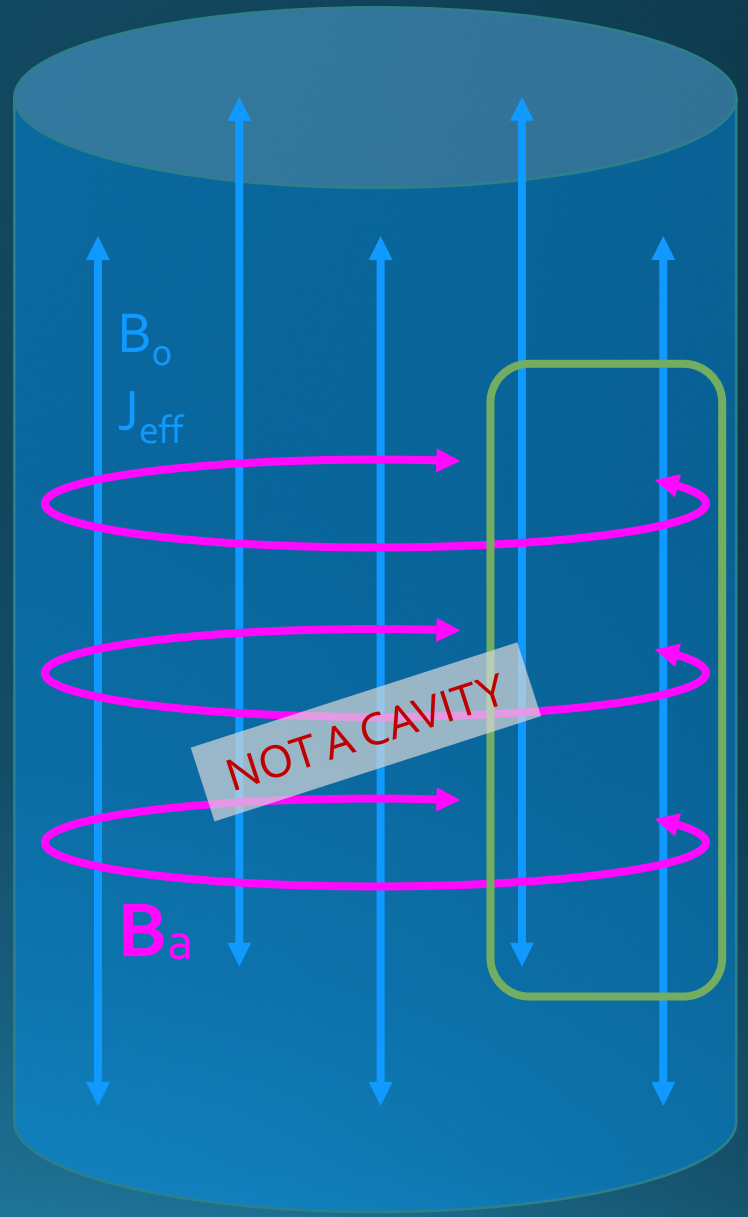
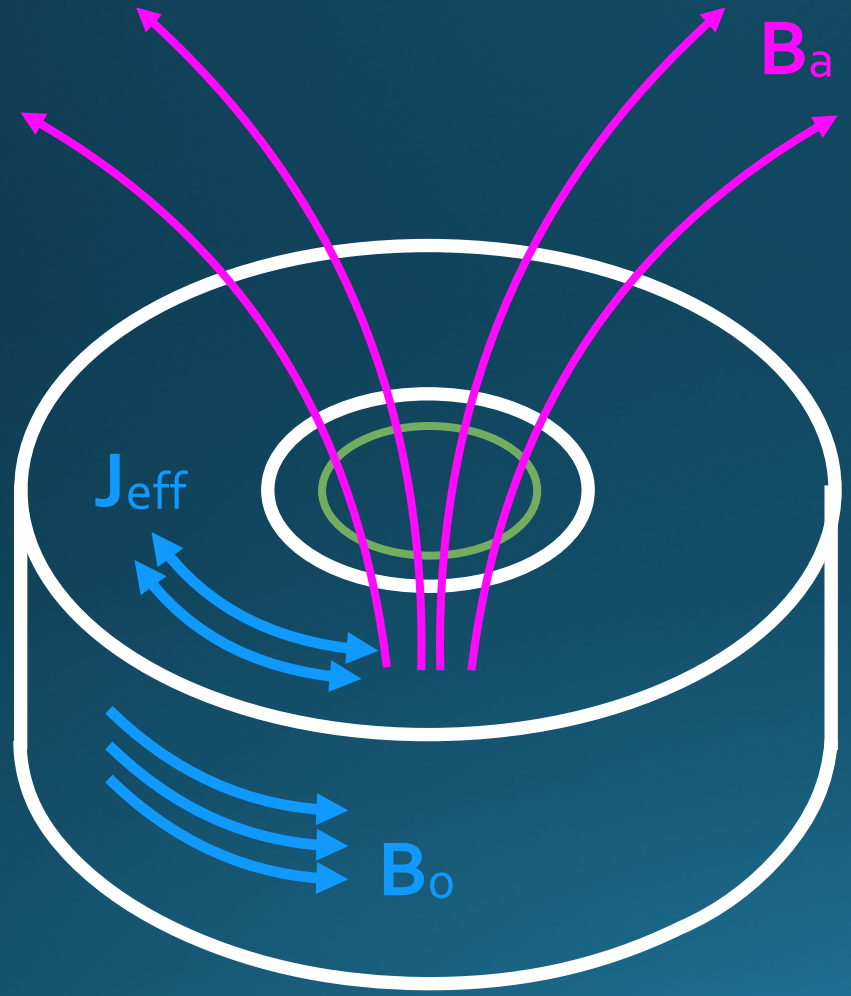
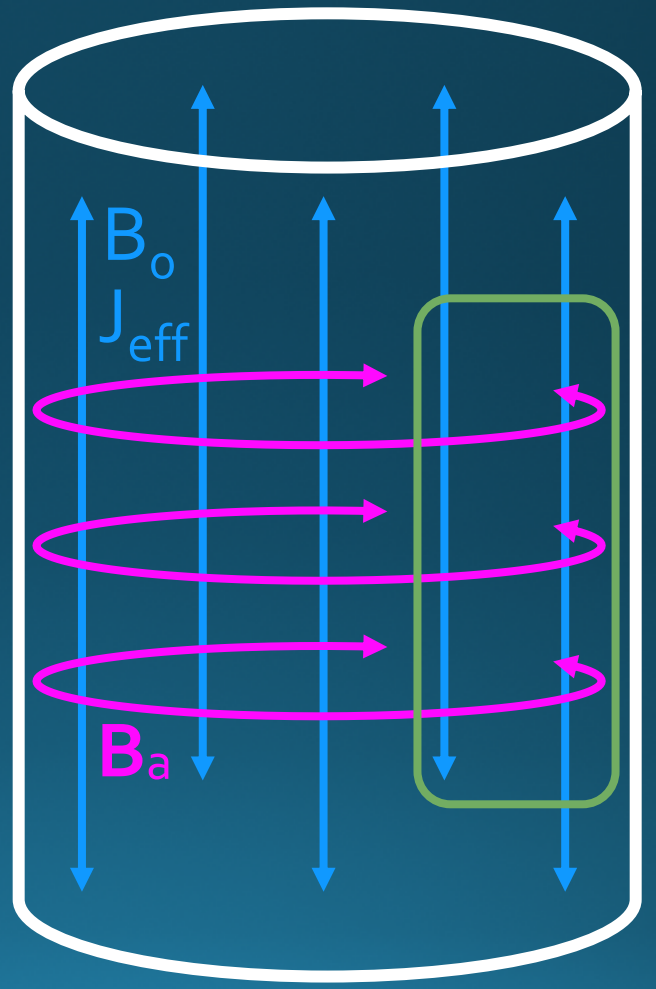
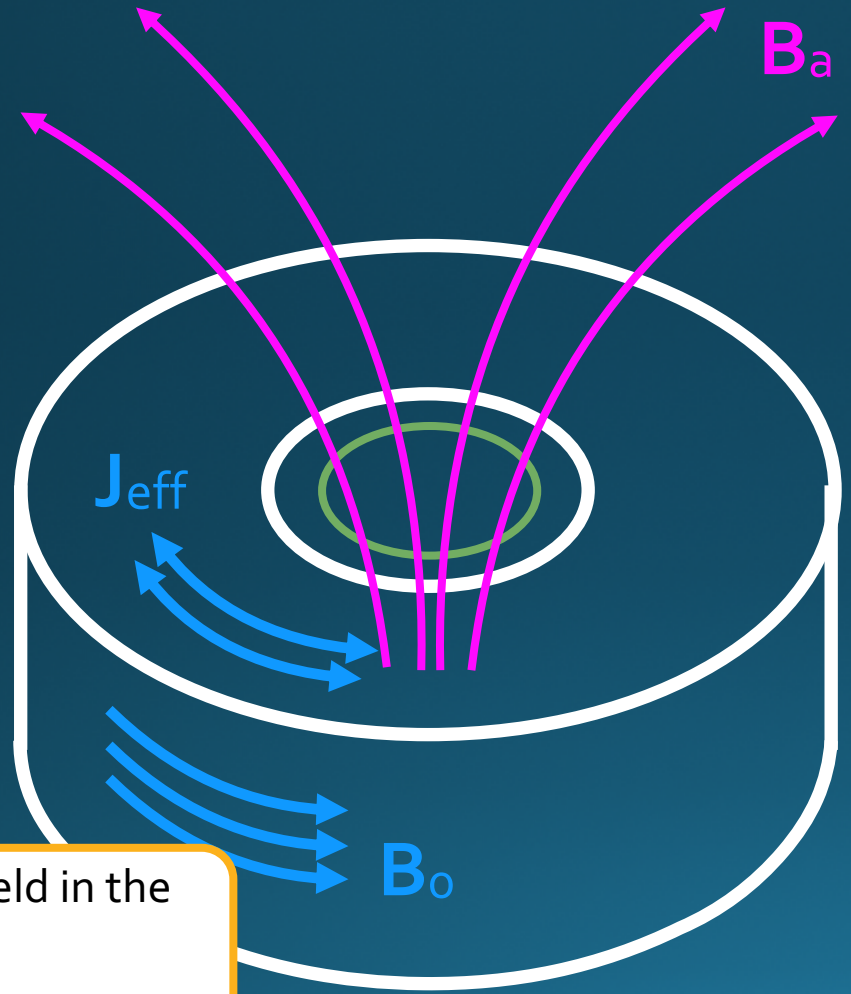


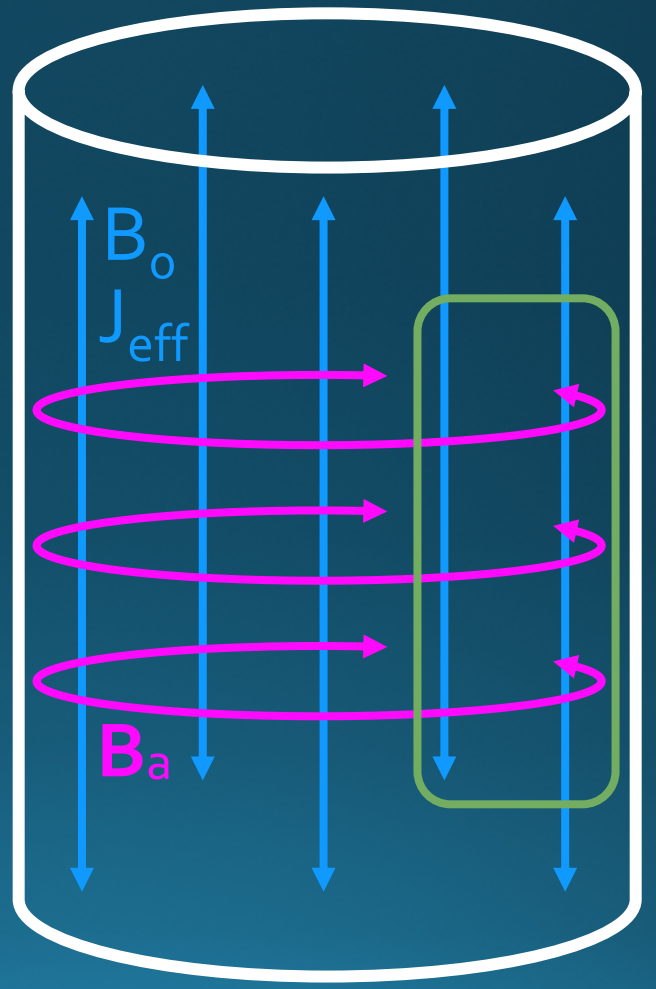
Toroid vs solenoid





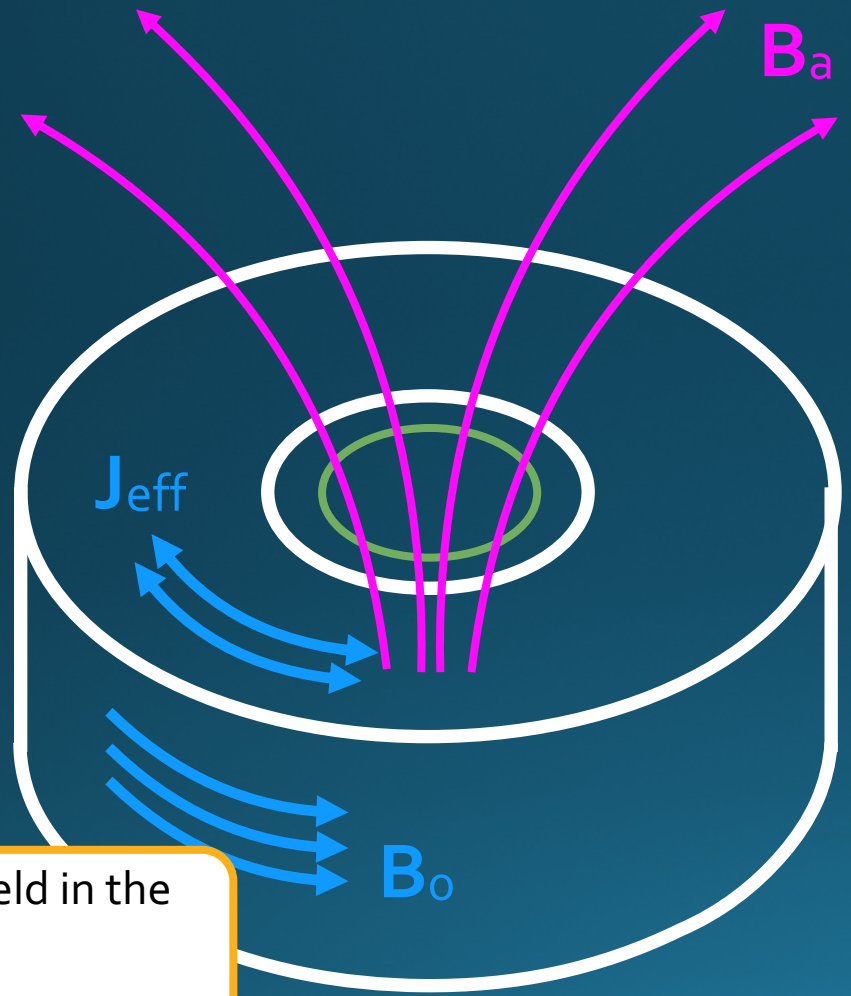
Toroid vs solenoid





- No axion ⟶ no field in the region of interest
- Few stray fields

Toroid vs solenoid



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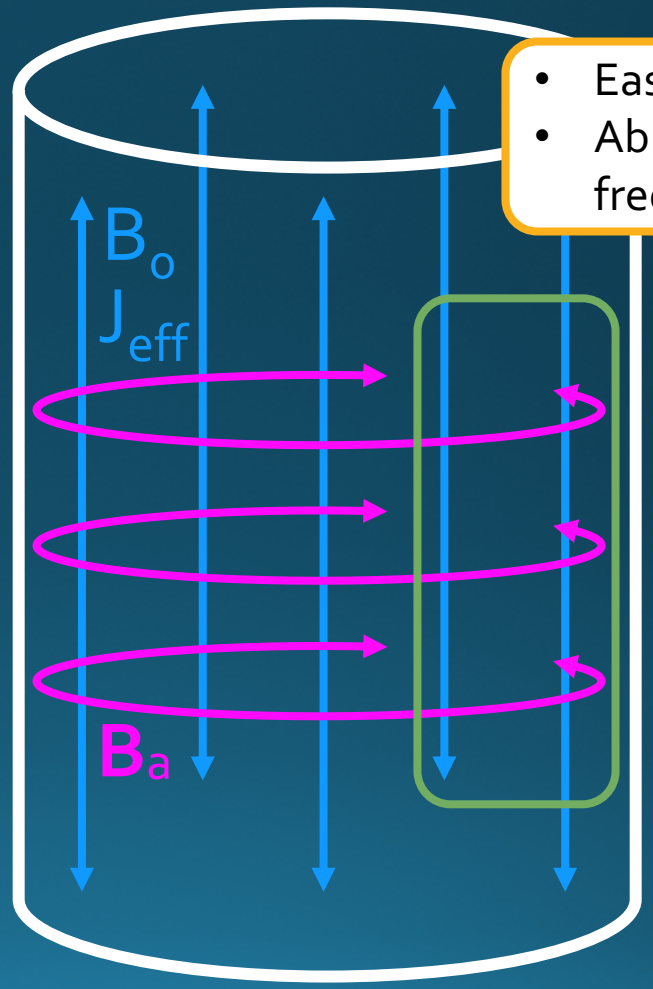
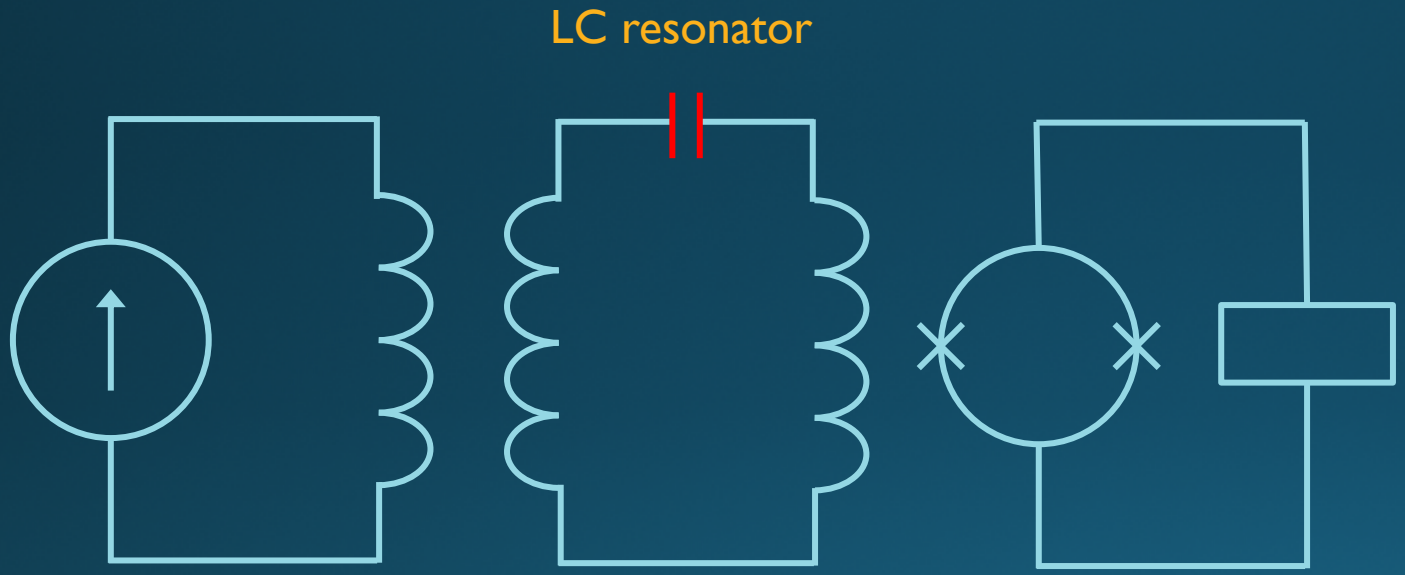
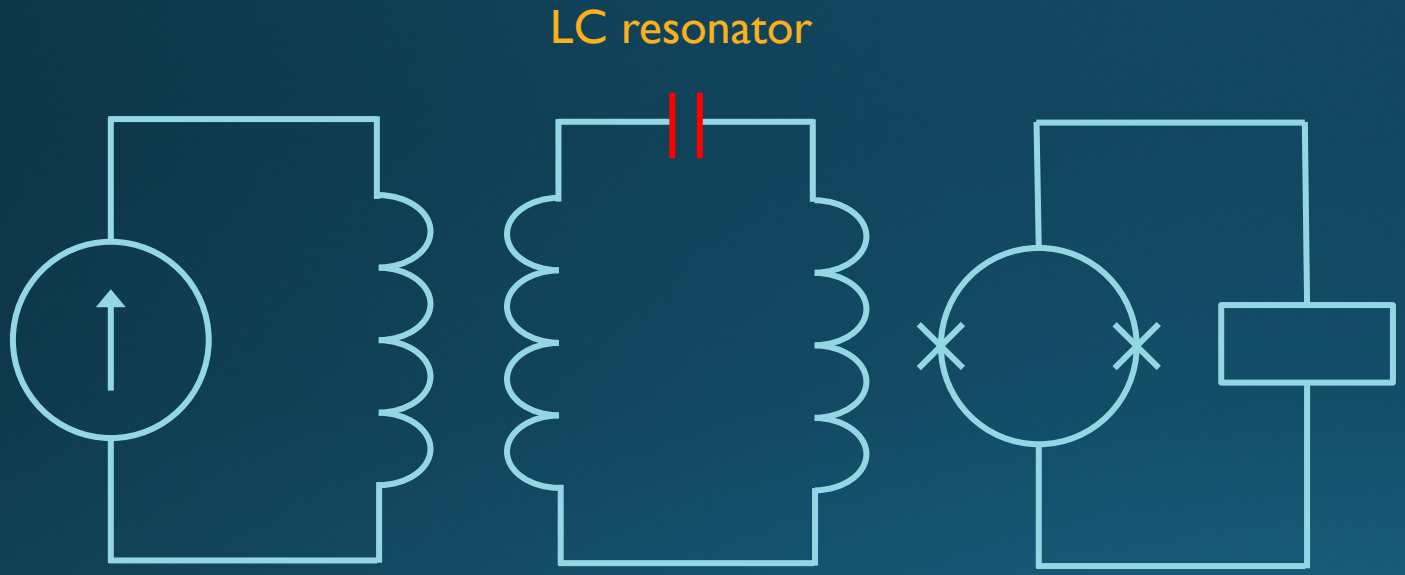


- Easier manufacturing
- Able to reach higher frequencies

Broadband vs. Resonant



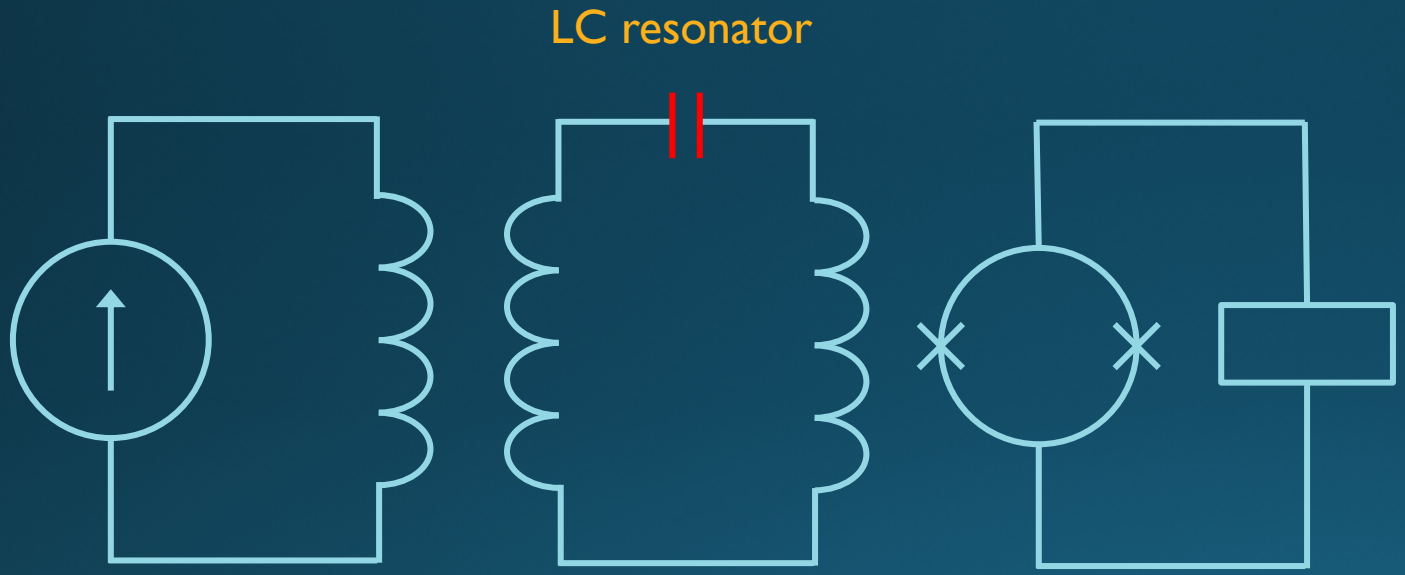
Broadband vs. Resonant



BROADBAND

- Easier to construct

Broadband vs. Resonant



BROADBAND

- Easier to construct

RESONANT

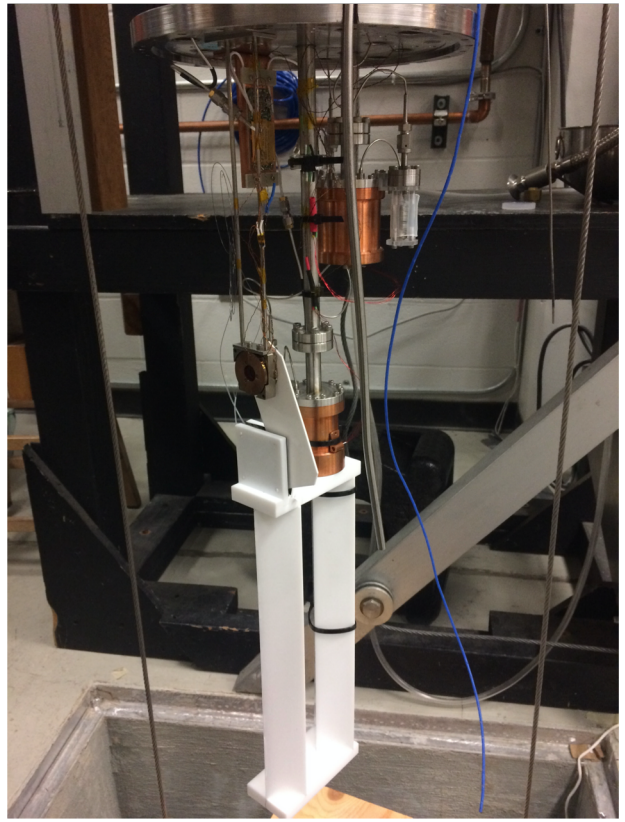
- More sensitive for any scan
  - Deeper in $g_{a\gamma\gamma}$
  - Wider frequency band at a given $g_{a\gamma\gamma}$

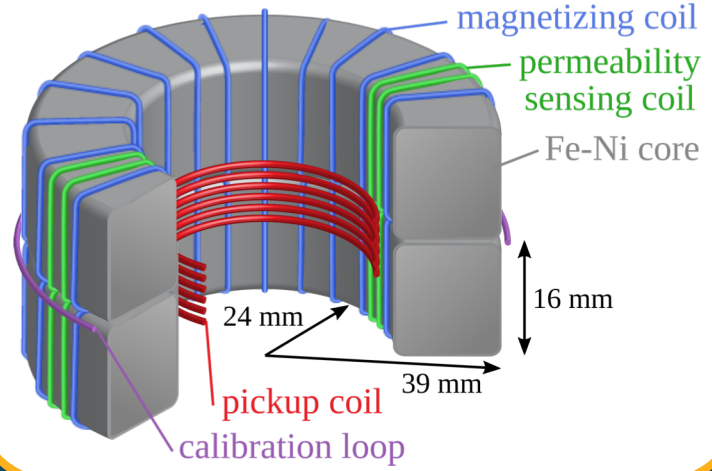
Chaudhuri et al. 1904.05806

Real experiments!

ABRACADABRA-10 cm

ADMX SLIC





SHAFT

A **B**roadband/**R**esonant **A**pproach to **C**osmic **A**xion **D**etection with an **A**mplifying **B**-field **R**ing **A**pparatus

ABRACADABRA-10cm

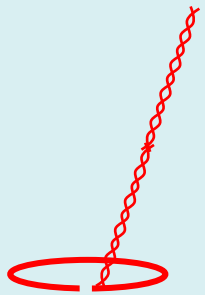
A **B**roadband/**R**esonant **A**pproach to **C**osmic **A**xion **D**etection with an **A**mplifying **B**-field **R**ing **A**pparatus

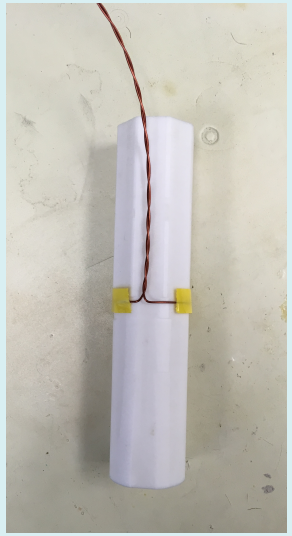
ABRA~~CADABRA~~-10cm

Experiment Details

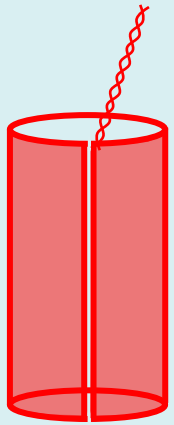
- Toroidal, broadband detector
- Pickup loop/cylinder

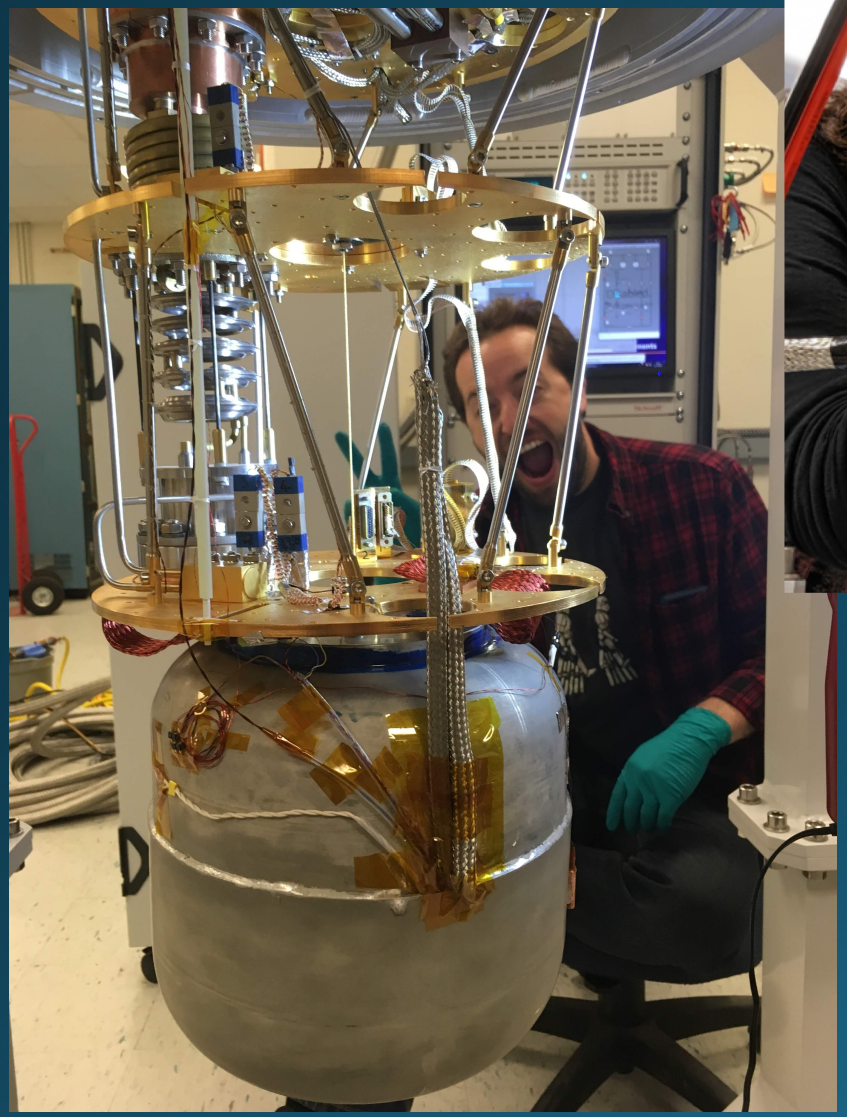
Run 1

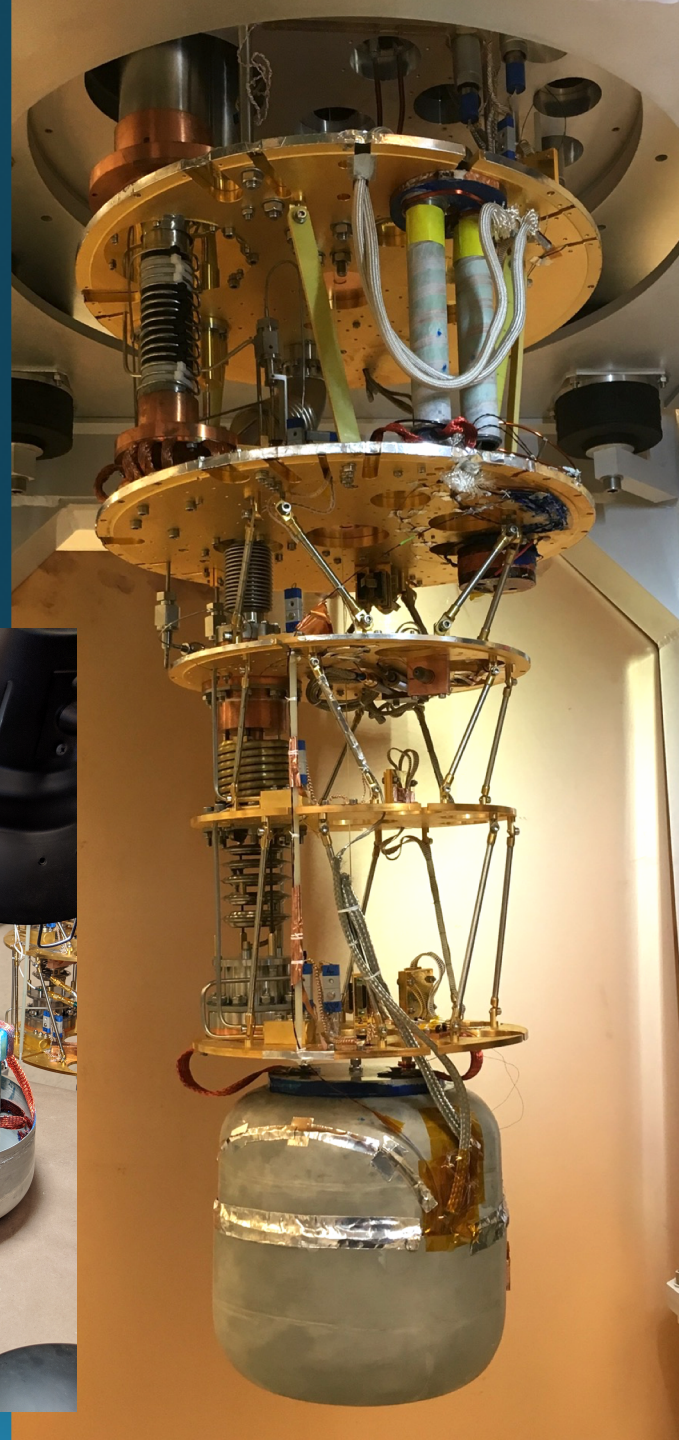




Runs 2+

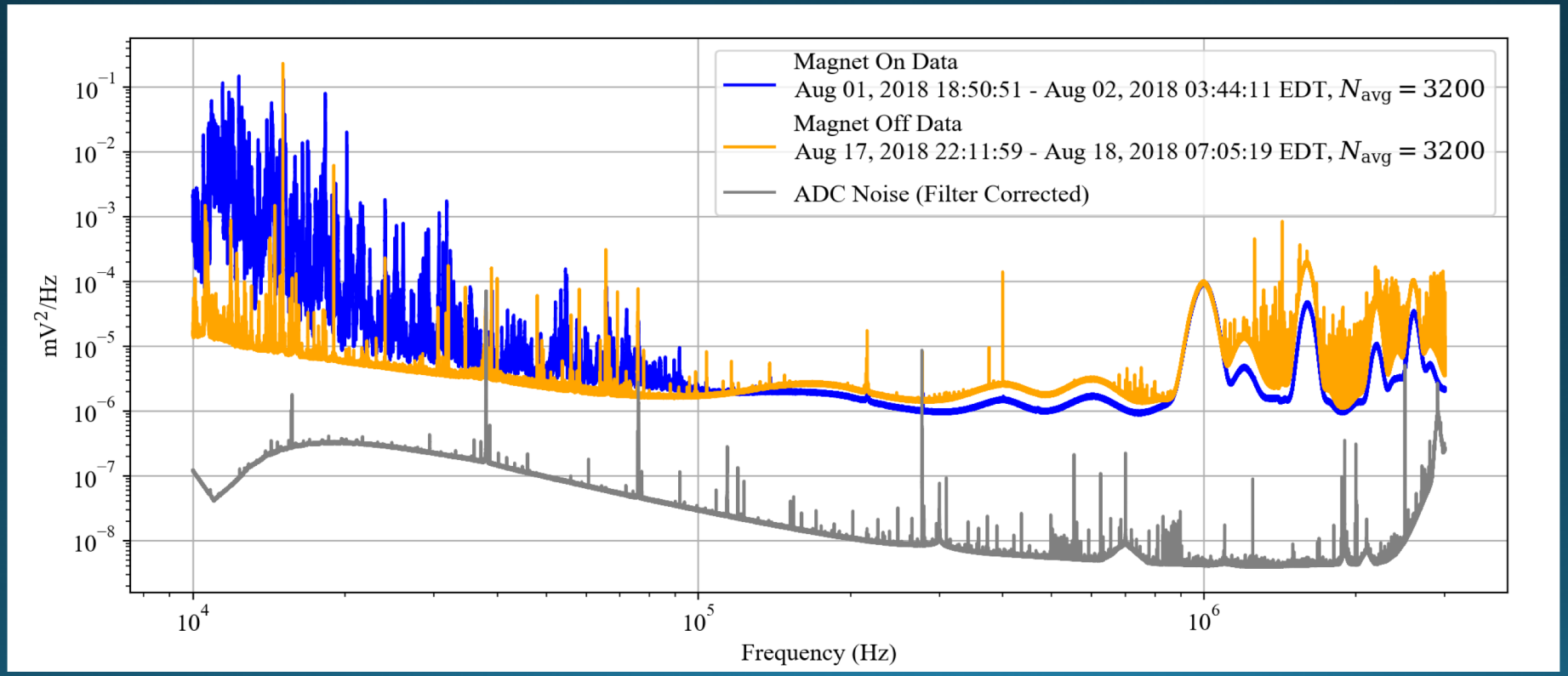




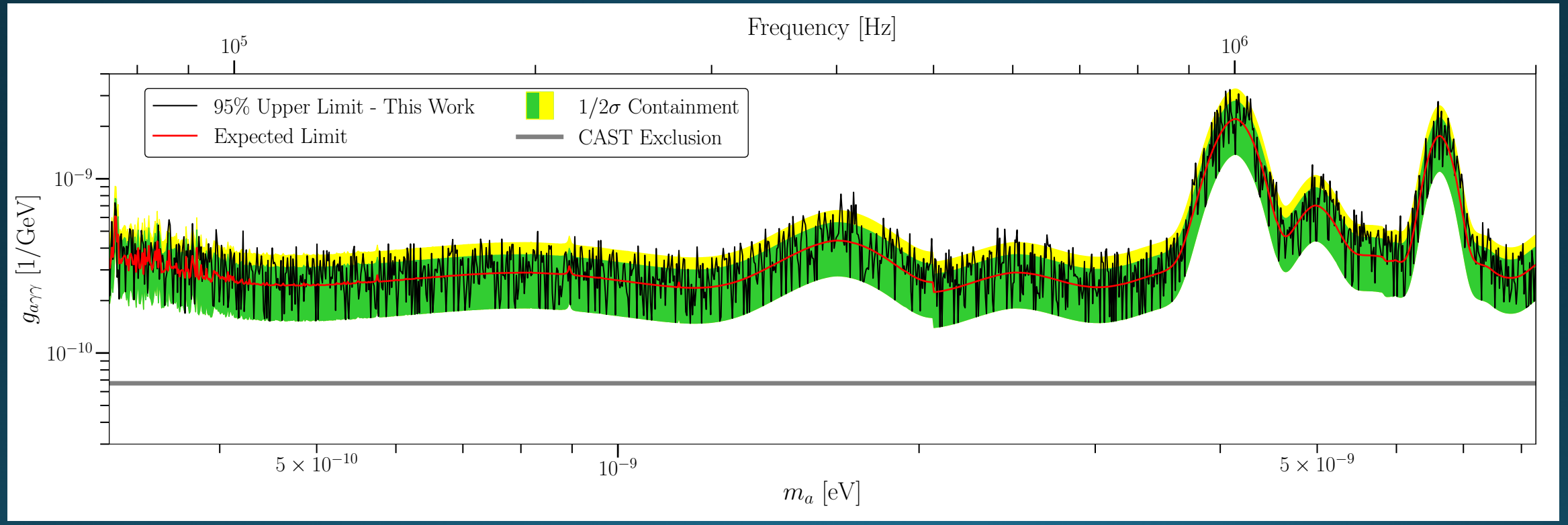


Data

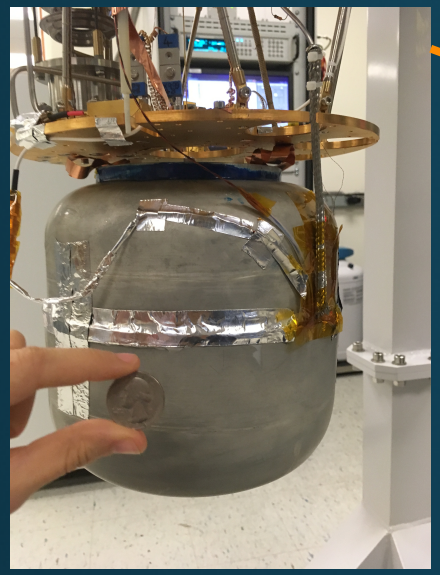
- Low frequencies limited by vibrations
- Sensitivity limited by circuit element inductances and noise

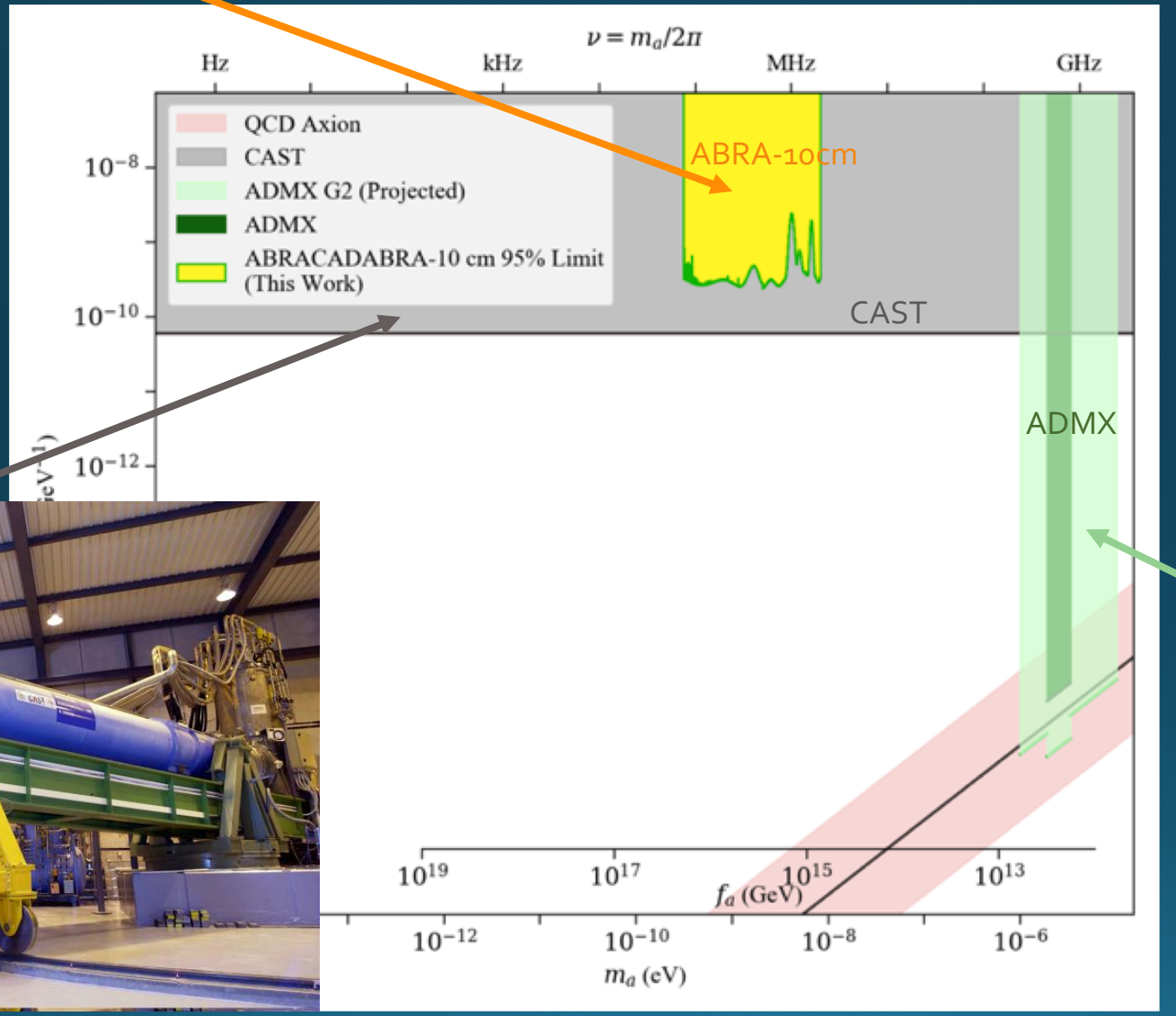


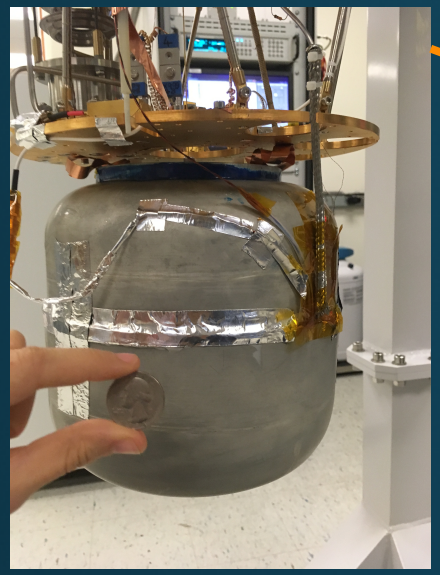
Limits on $g_{a\gamma\gamma}$ (Run 1)

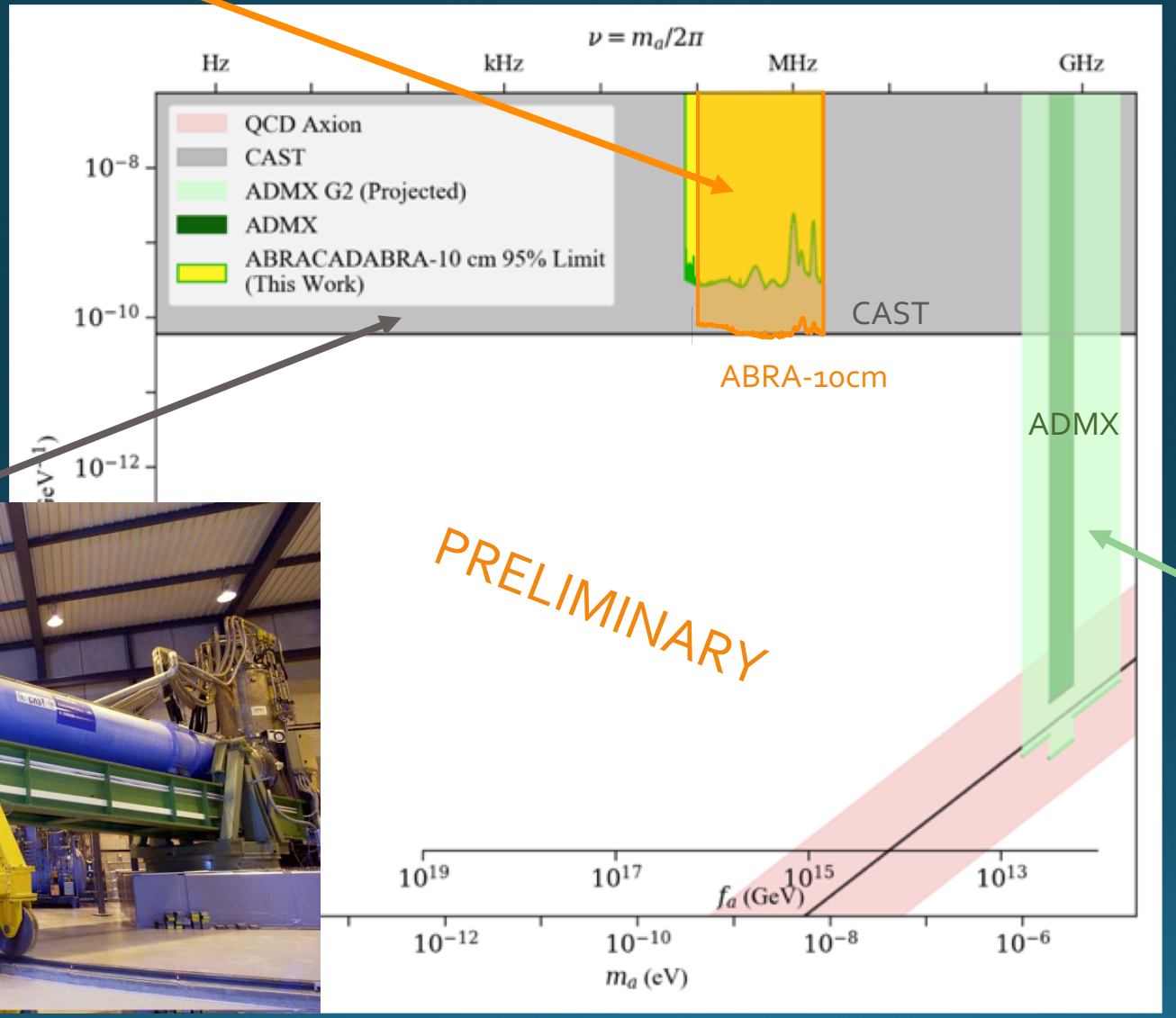


Ouellet, CPS et al. Phys. Rev. Lett. (2019)
Ouellet, CPS et al. Phys. Rev. D (2019)




$\nu = m_a/2\pi$
Hz
kHz
MHz
GHz
QCD Axion
CAST
ADMX G2 (Projected)
ADMX
ABRACADABRA-10 cm 95% Limit
(This Work)
ABRA-10cm
CAST
ADMX
10^{-8}
10^{-10}
10^{-12}
10^{19}
10^{17}
10^{15}
10^{13}
f_a (GeV)
10^{-12}
10^{-10}
10^{-8}
10^{-6}
m_a (eV)





CPS et al., in preparation

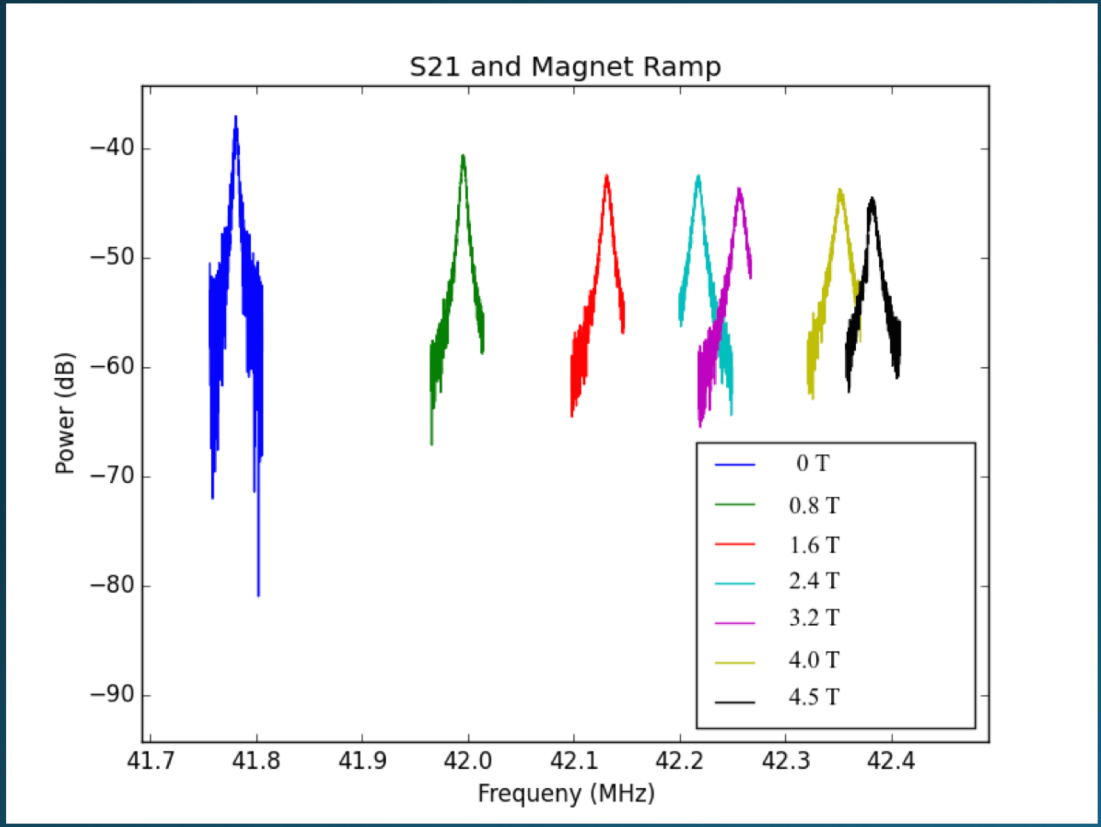
Axion **D**ark **M**atter e**X**periment

A **S**uperconducting **L**C Circuit **I**nvestigating **C**old Axions

ADMX SLIC

- Solenoid magnet
  - 7.5T average field
- Resonant search
  - NbTi pickup loop
  - Piezoelectric-tuned parallel plate capacitor

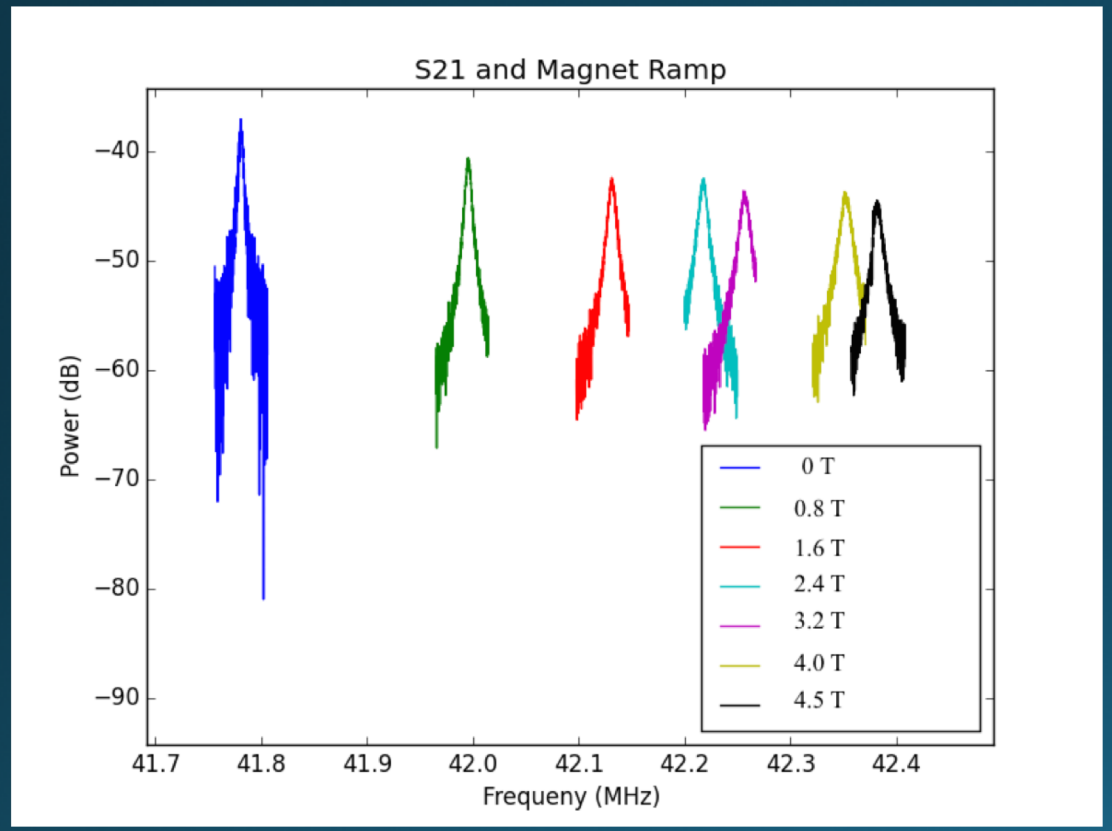
SLIC Results



Q reduction corresponding to magnetic field ramp

Crisosto et al. Phys. Rev. Lett. (2020)

SLIC Results



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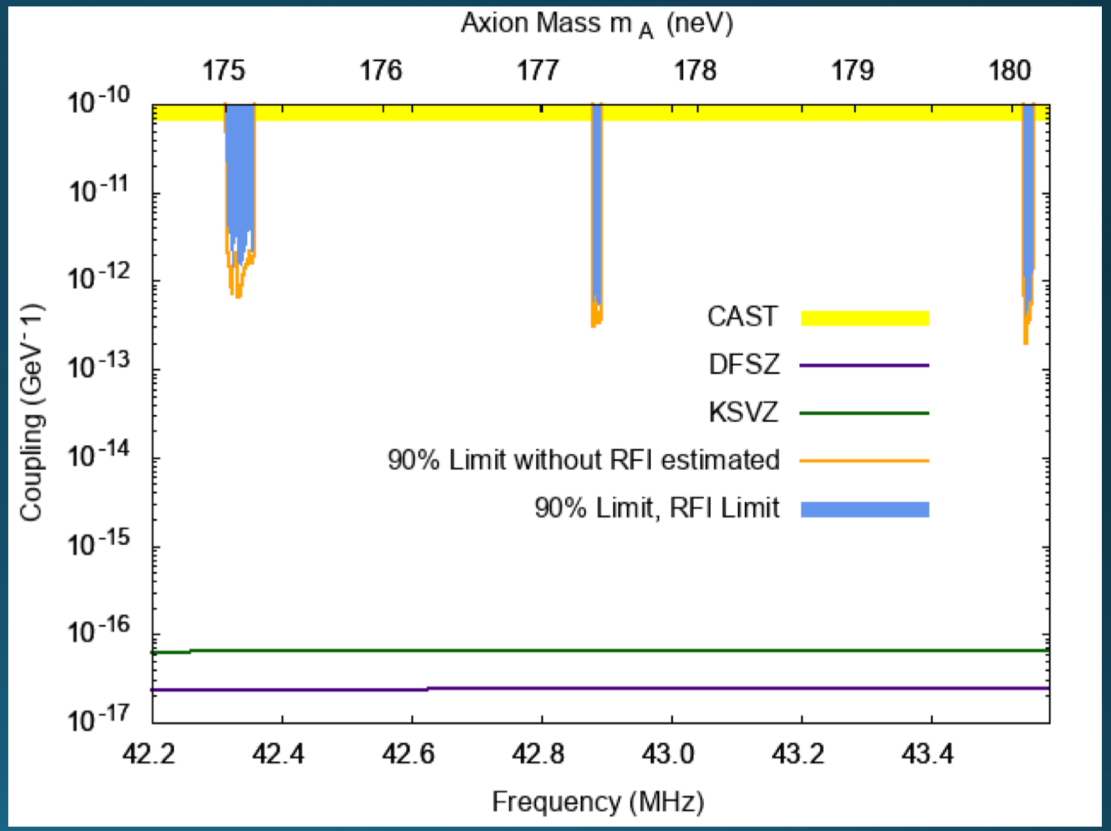
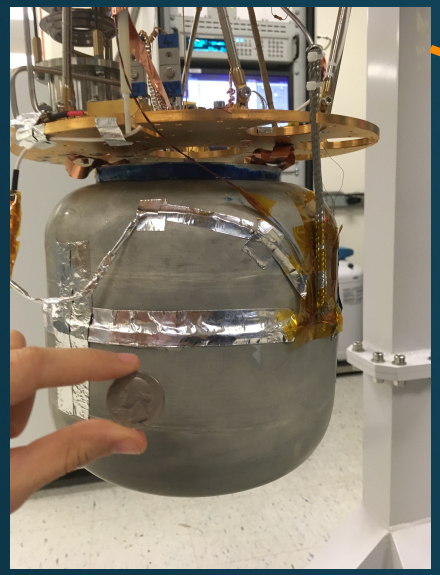
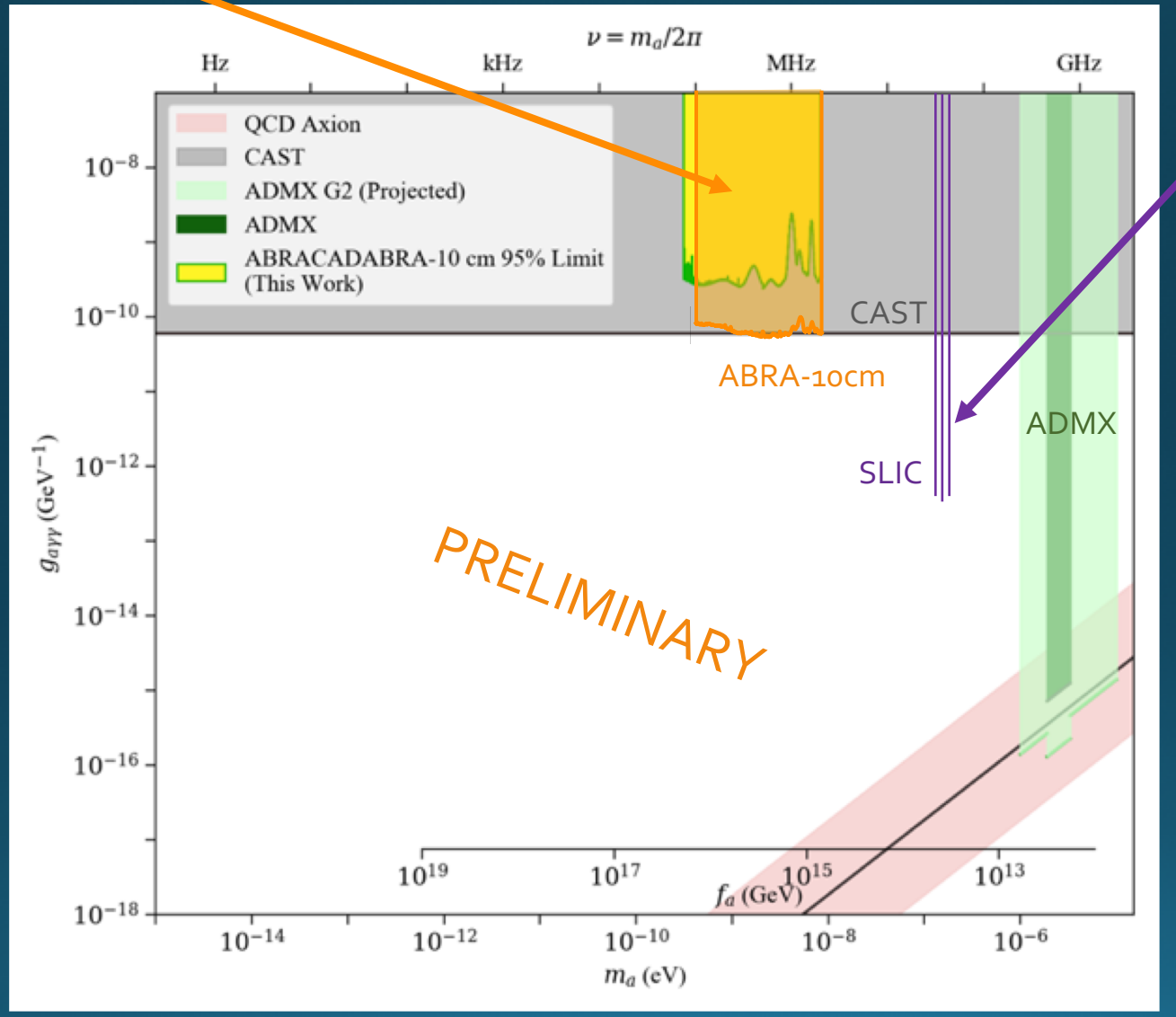


New limits around 40MHz

Crisosto et al. Phys. Rev. Lett. (2020)

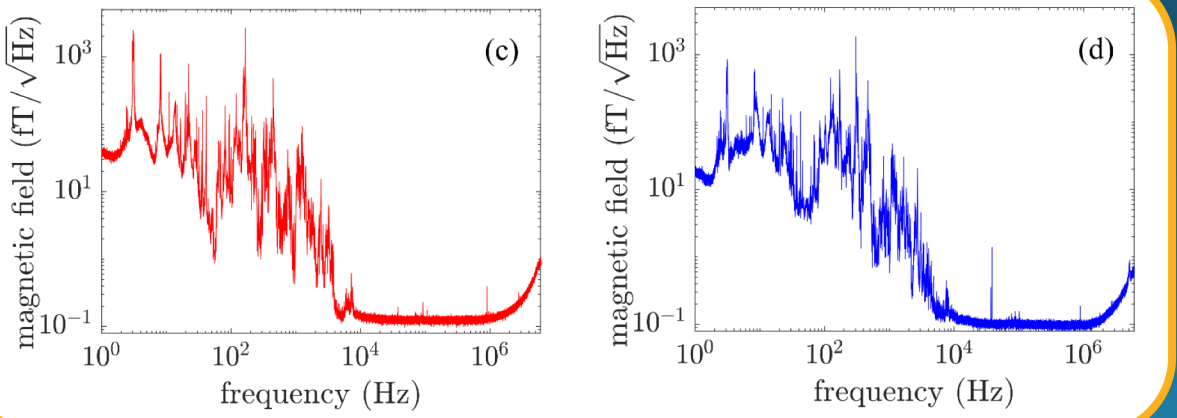


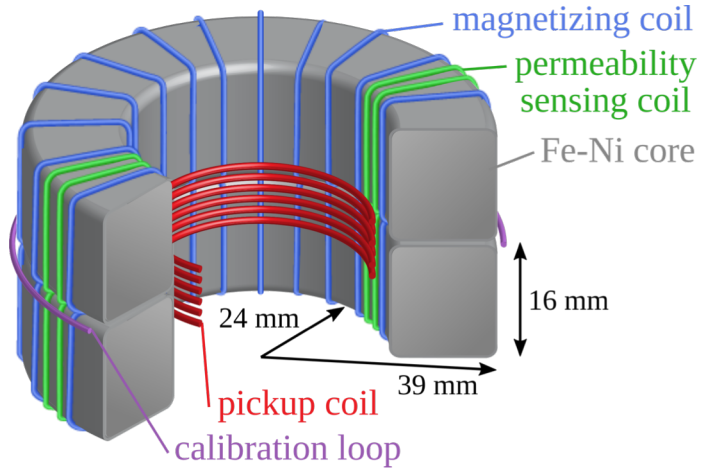

$\nu = m_a/2\pi$
Hz
kHz
MHz
GHz
QCD Axion
CAST
ADMX G2 (Projected)
ADMX
ABRACADABRA-10 cm 95% Limit
(This Work)
CAST
ABRA-10cm
ADMX
SLIC
PRELIMINARY
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{19}
10^{17}
10^{15}
10^{13}
f_a (GeV)
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
m_a (eV)

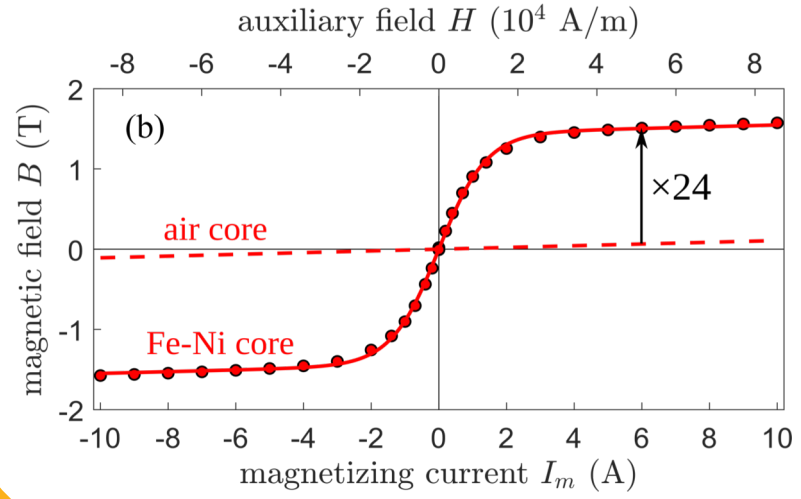
Search for Halo Axions with Ferromagnetic Toroids

SHAFT

- Fe-Ni toroid powder cores provide ×24 enhancement
- 1.5 T magnetic field at 6 A magnetizing current
- Two channels allow for rejection of systematics
- Magnetic field sensitivity 150 aT/√Hz using DC SQUIDs at 4.2 K

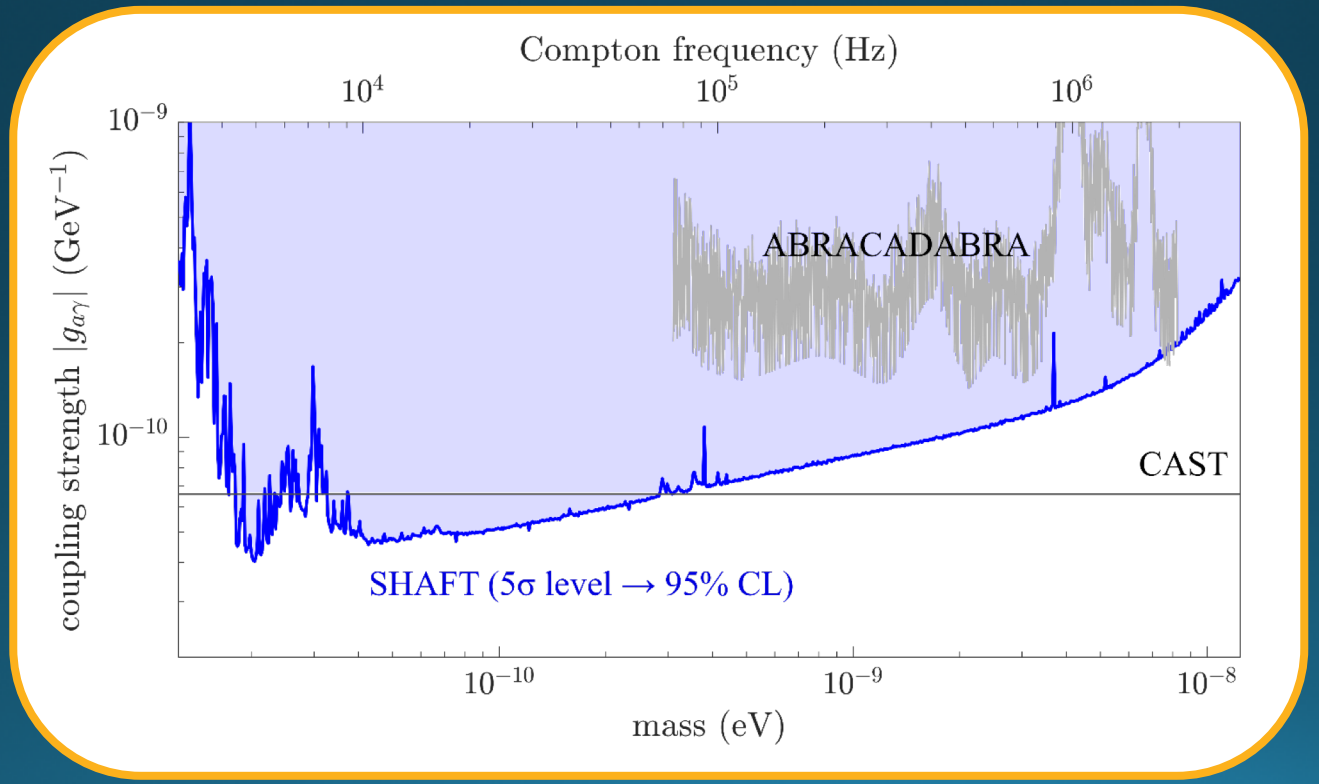




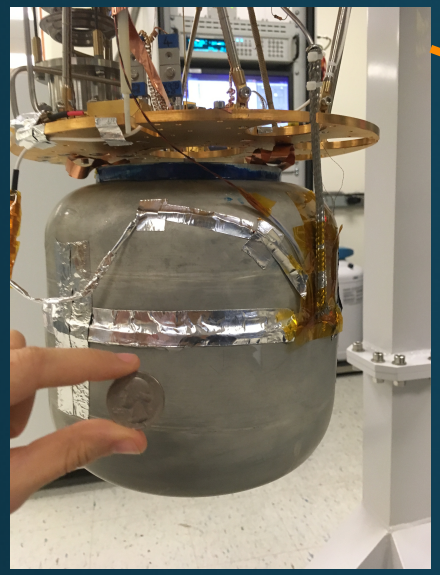


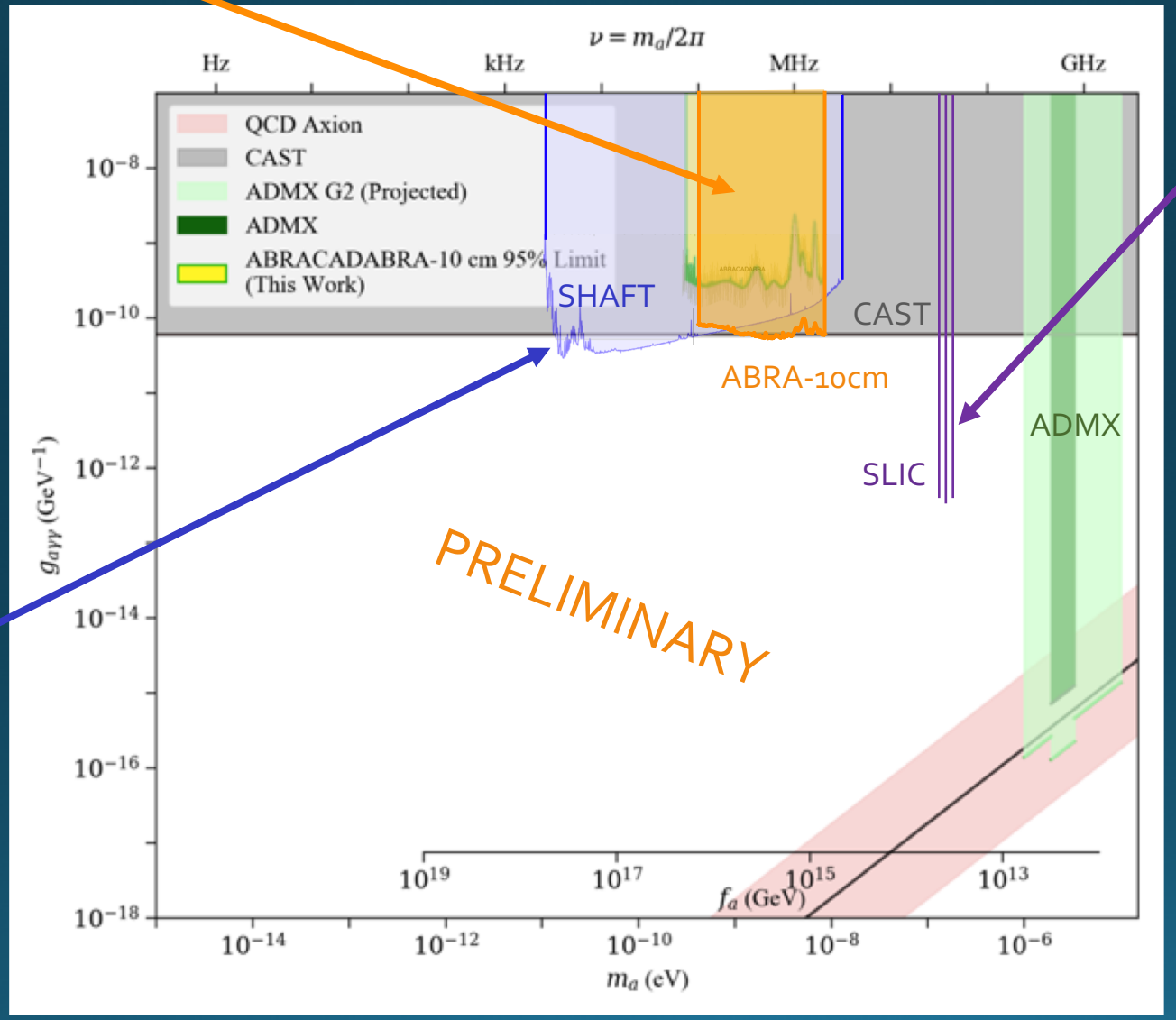
SHAFT Results

- 41 hours of ALP search data, 12 peV to 12 neV mass range
- Limits reach (at 5σ level): $|g_{a\gamma}| = 4.0 \times 10^{-11}\,\mathrm{GeV}^{-1}$



A. Gramolin et al., Nature Phys. (2021)

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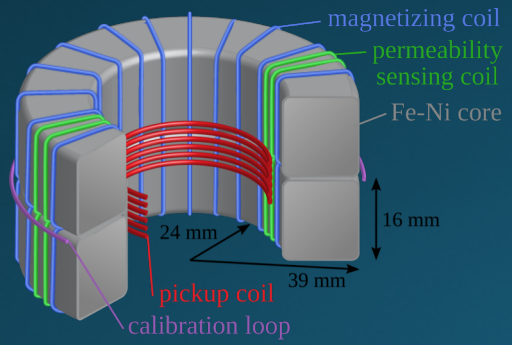

magnetizing coil
permeability
sensing coil
Fe-Ni core
16 mm
24 mm
39 mm
pickup coil
calibration loop

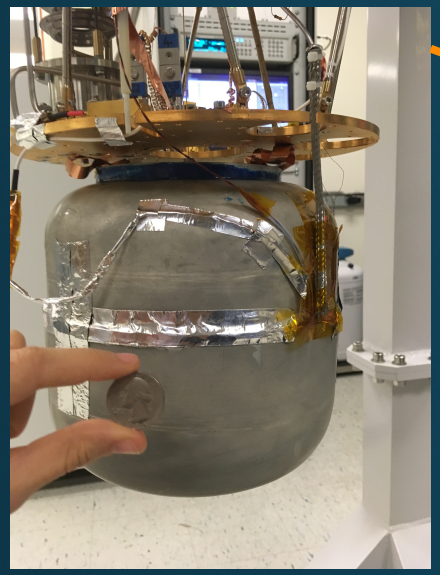
Gen 1 lumped element experiments

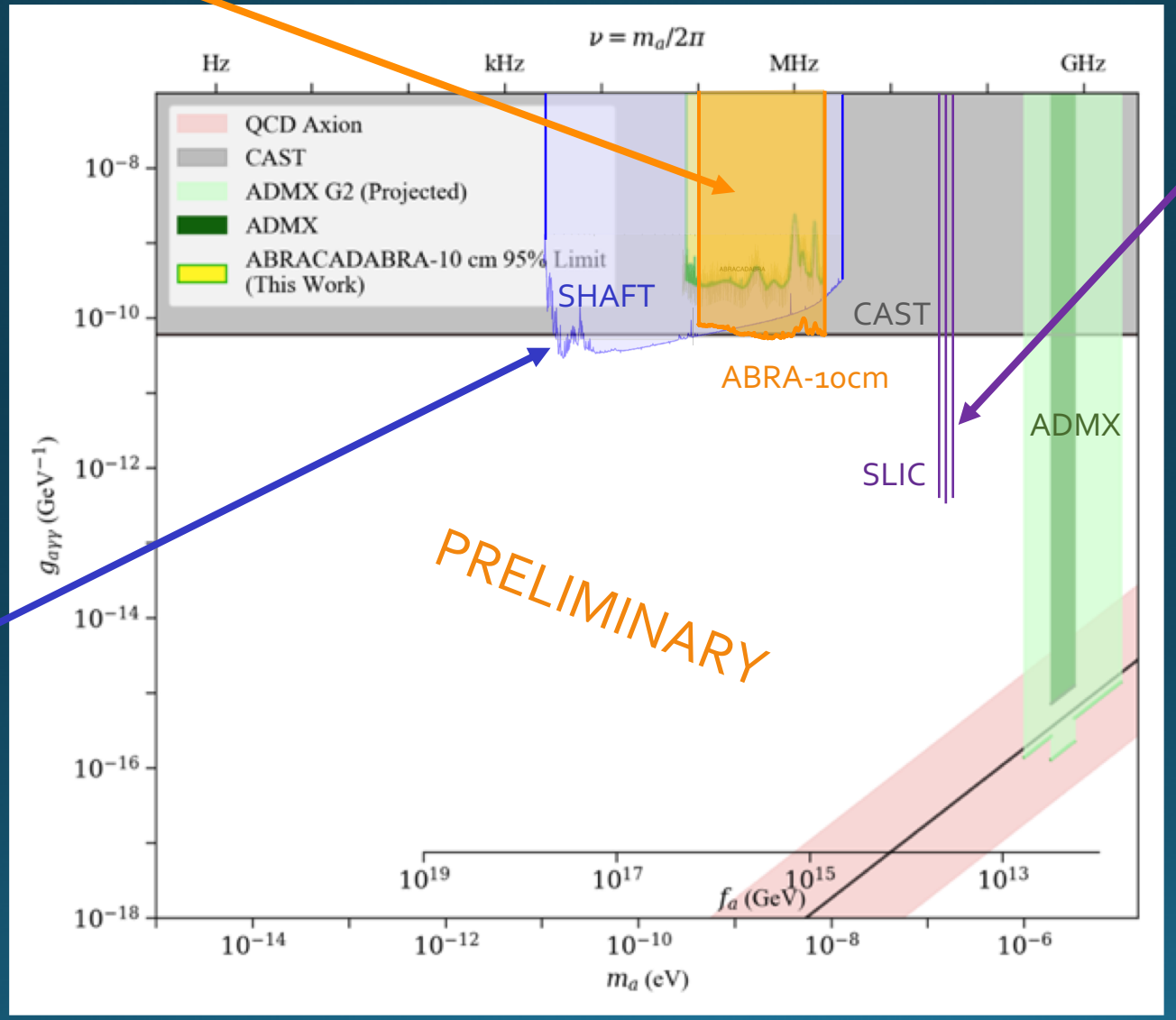
CHALLENGES

- Vibrations at low frequencies
- EMI
- Q reduction with magnetic field
- Parasitic inductances
- Limited tuning range

FUTURE IDEAS & PLANS

- Additional runs
- Vibration isolation
- Scaling up
- Reentrant cavities
- Improved couplings
- Improved tuning
- Precision magnetic fields

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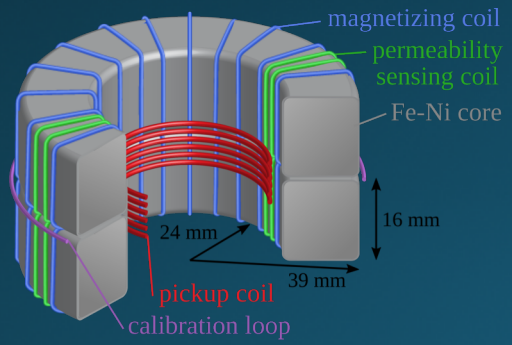
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permeability
sensing coil
Fe-Ni core
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24 mm
39 mm
pickup coil
calibration loop

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
- Lower parasitic impedance
- Lower noise (vibrations, environmental noise)
- Resonant readout
- Quantum acceleration
- Improved scan strategies

S. Silverstein

DARK MATTER RADIO
kHz
MHz
GHz
THz
freq
peV
neV
μeV
meV
mass
0
1
SPIN
AM/FM/DM

DMRadio

DARK MATTER RADIO
kHz
MHz
GHz
THz
freq
peV
neV
μeV
meV
mass
0
1
SPIN
AM/FM/DM

DMRadio

DM Radio Cubic Meter Consortium

Funded as part of DOE New Initiatives in Dark Matter program

R&D Phase Consortium Leadership:

Project manager for R&D phase: Dale Li

Name	Institution	Role / Team Lead
Kent Irwin	SLAC and Stanford	Consortium PI
Karl van Bibber	UC Berkeley	Magnet
Lindley Winslow	MIT	Magnetic shielding, vibration
Saptarshi Chaudhuri	Princeton	Control system, scan
Peter Graham	Stanford	Theory
Reyco Henning	UNC Chapel Hill	Calibration and DAQ
Dale Li	SLAC	Cryomechanical
Hsiao-Mei Cho	SLAC	SQUID
Wes Craddock	SLAC	Lead Engineer
Nadine Kurita	SLAC	Project Management Plan

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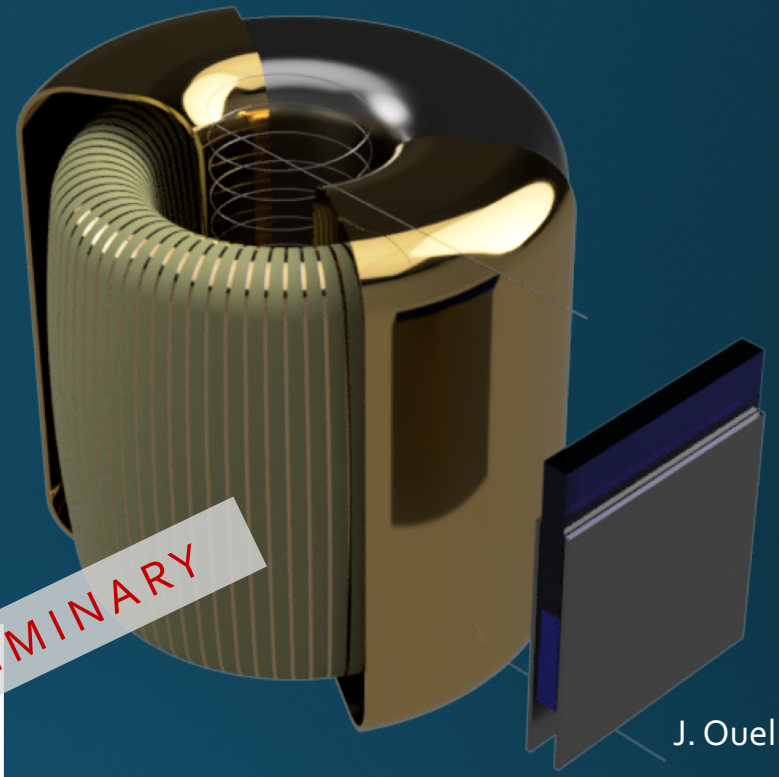
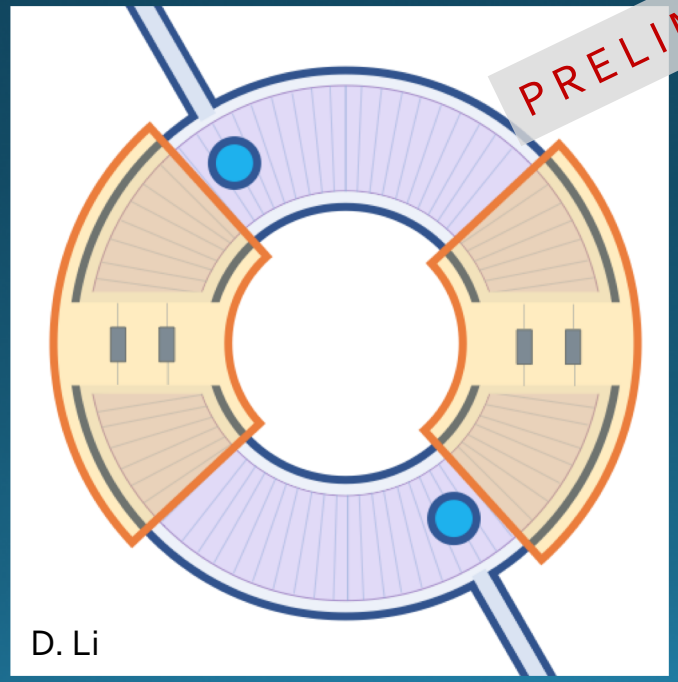
DMRadio-50L

- 50L volume @ 100mT - 1T
- Toroidal magnet
- Resonant readout
- Pickup sheath

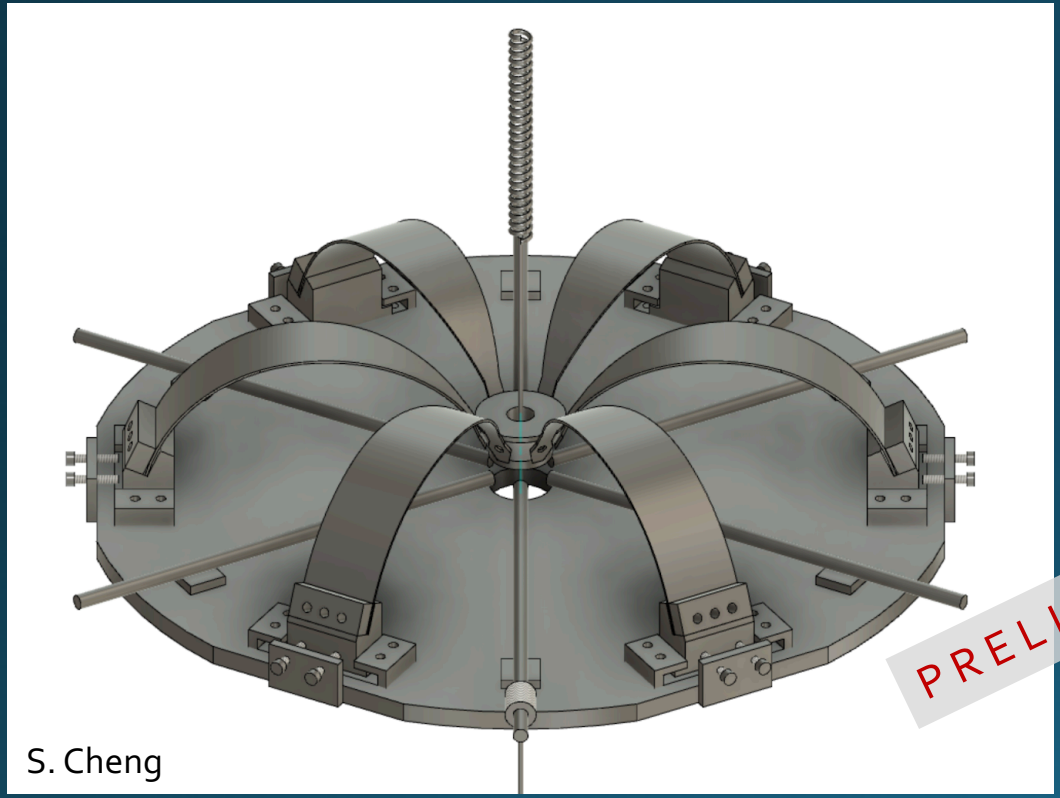


J. Ouellet



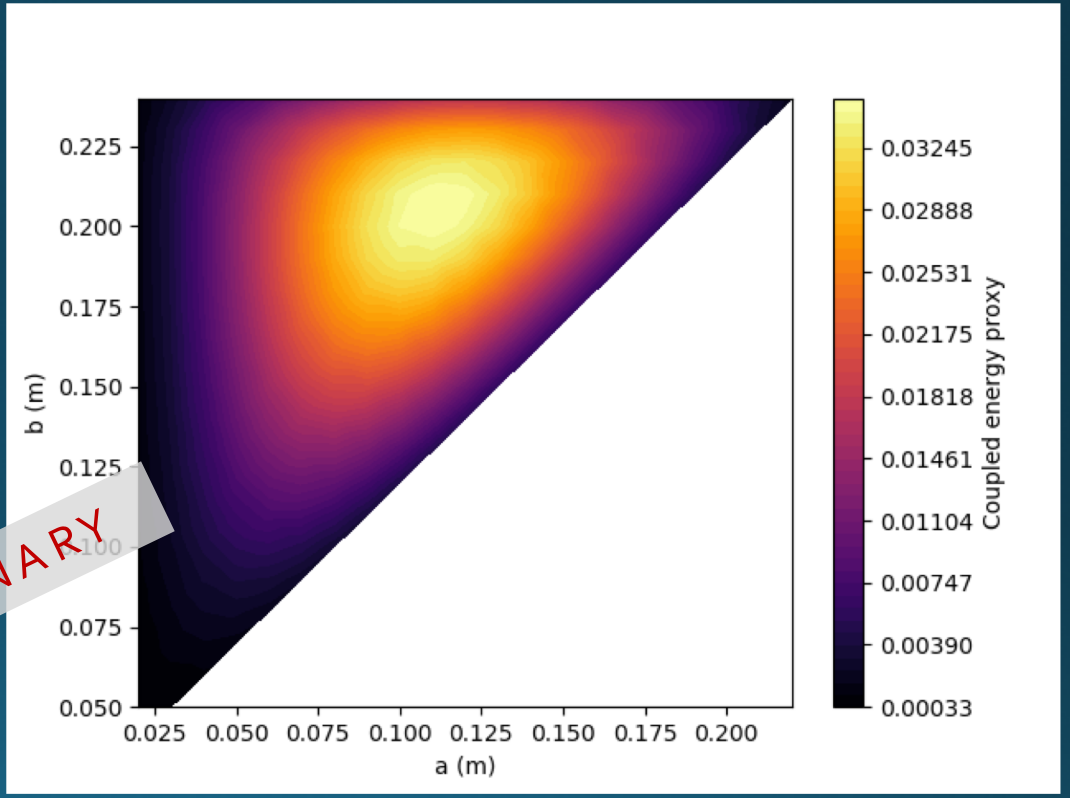
D. Li

Lower noise



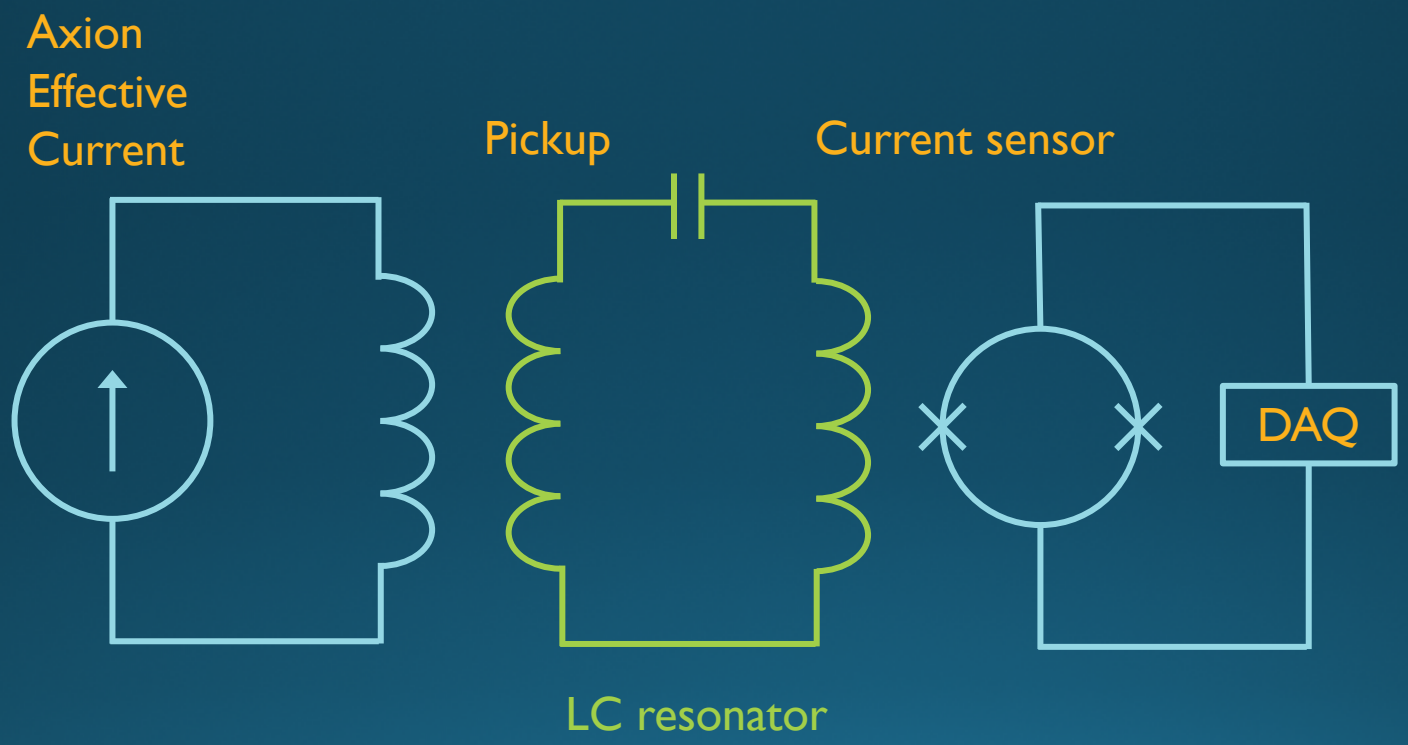
S. Cheng

Better coupling

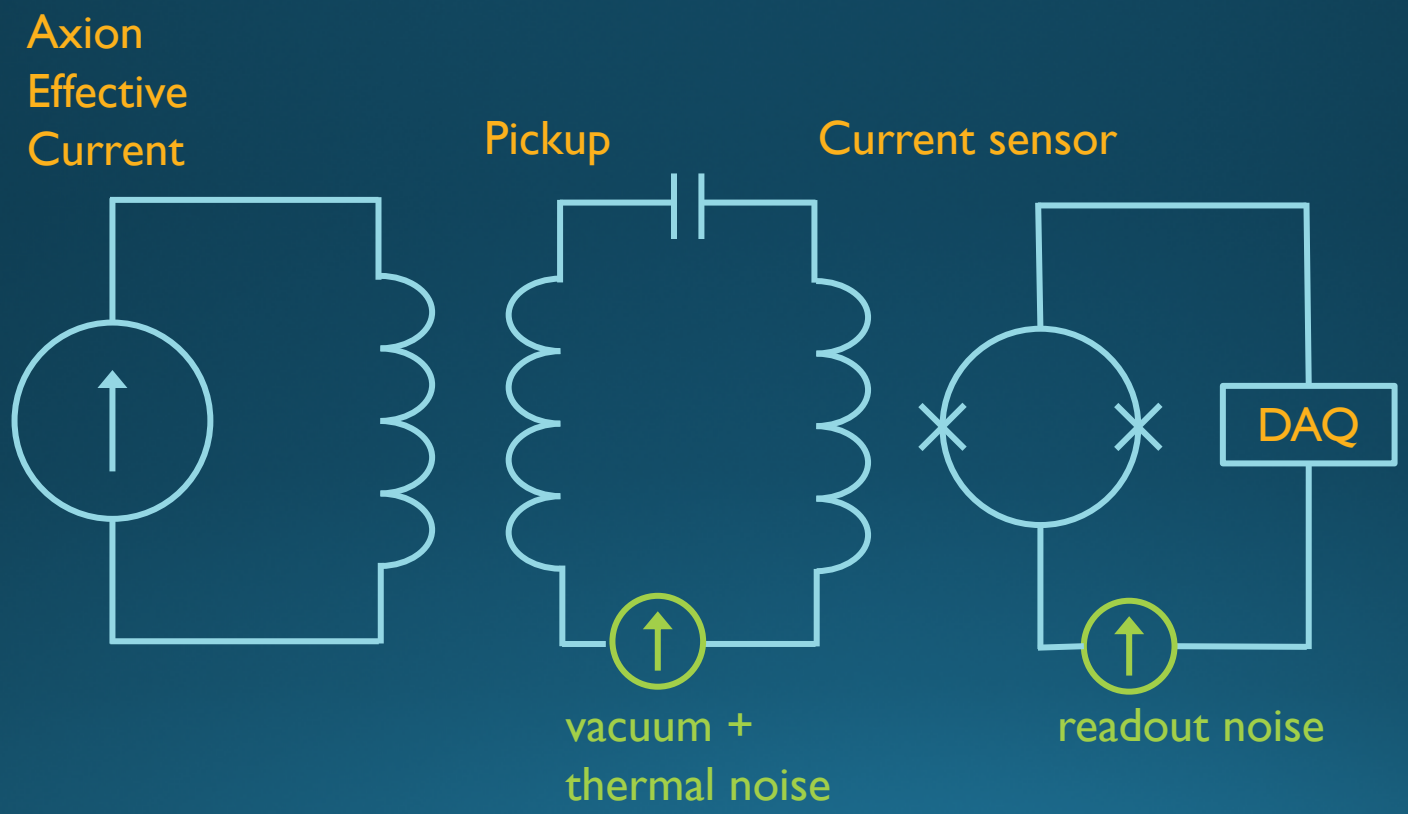


PRELIMINARY

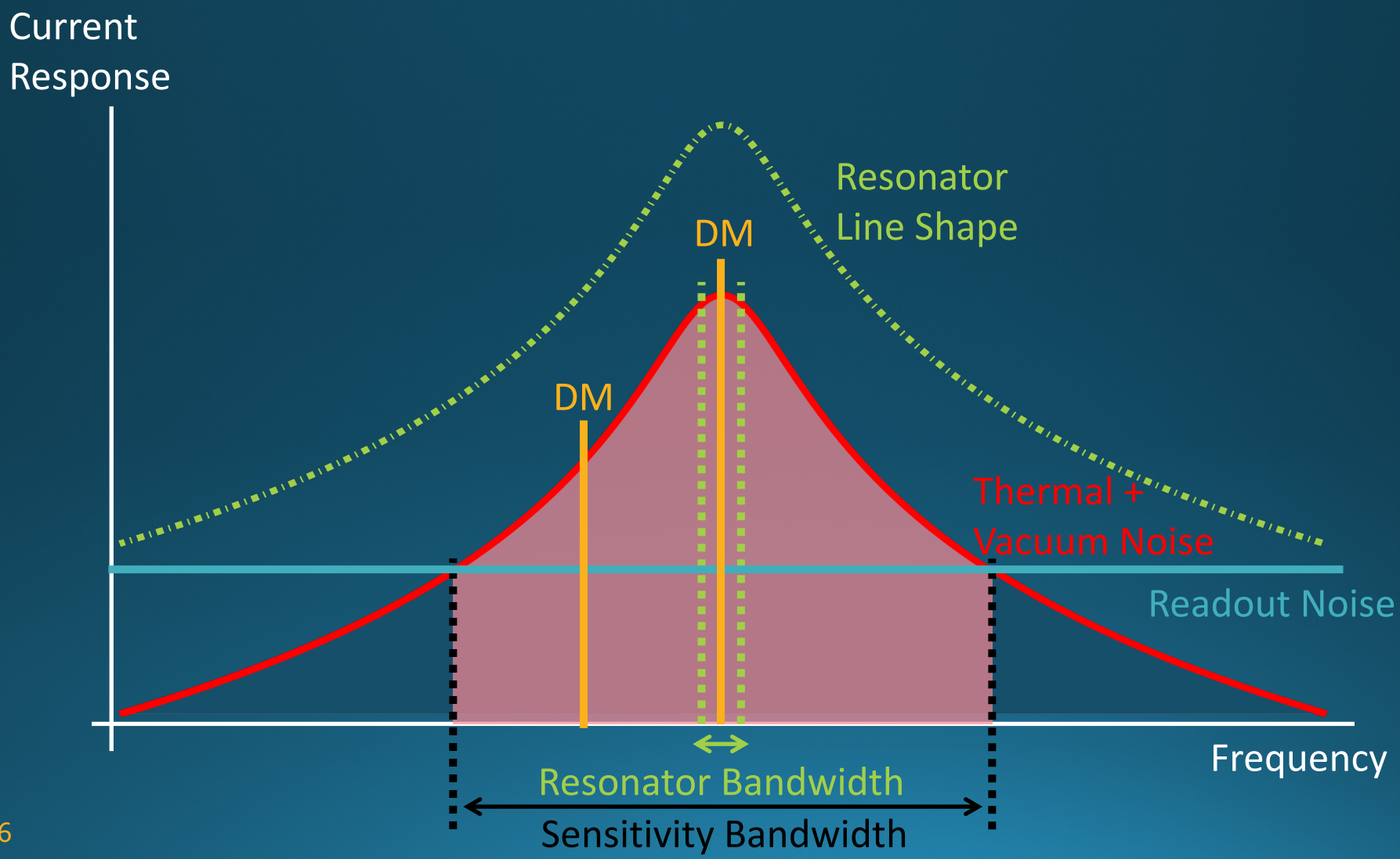
Resonant readout



Faster scanning

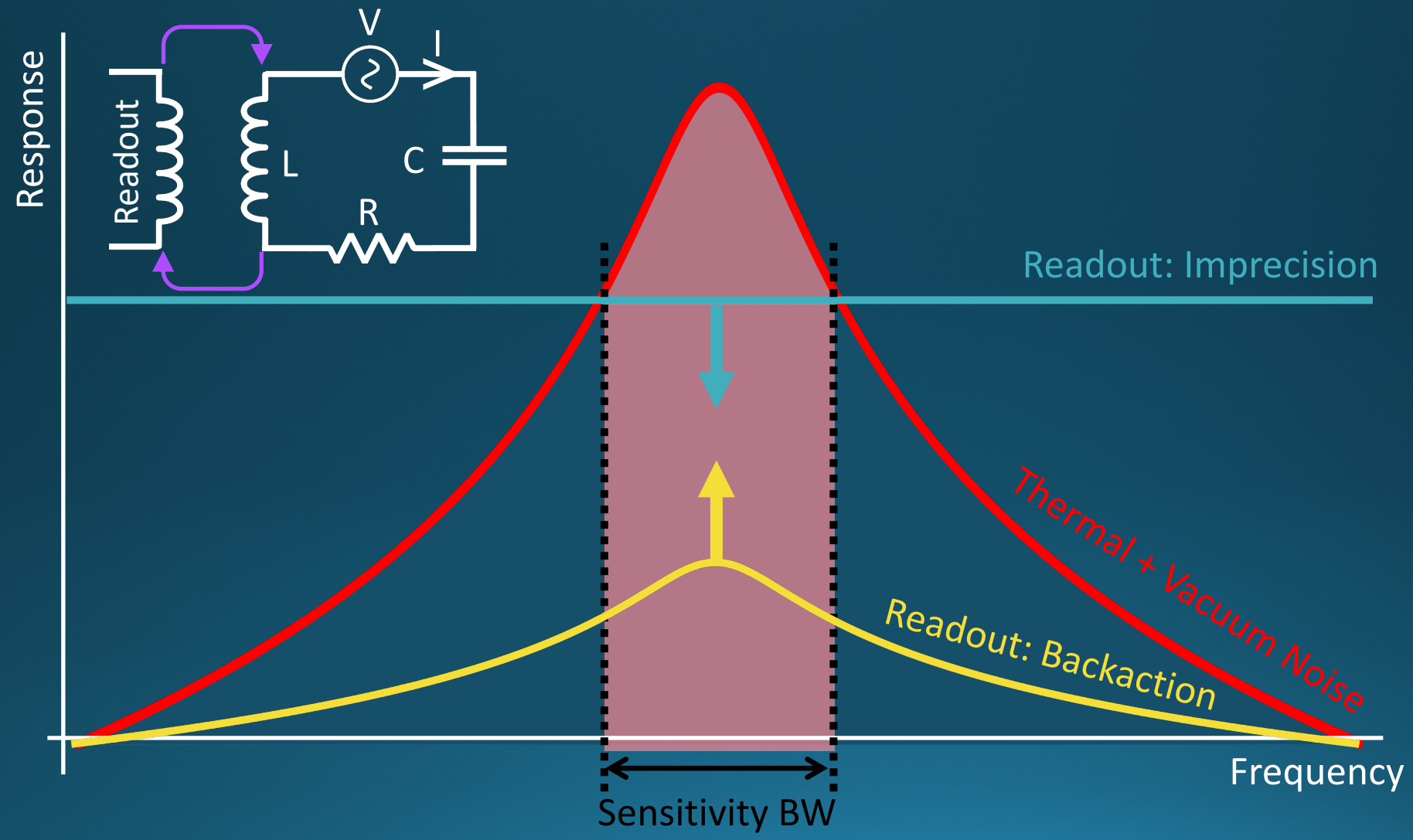


Scan rate enhancement; detuned SNR the same!



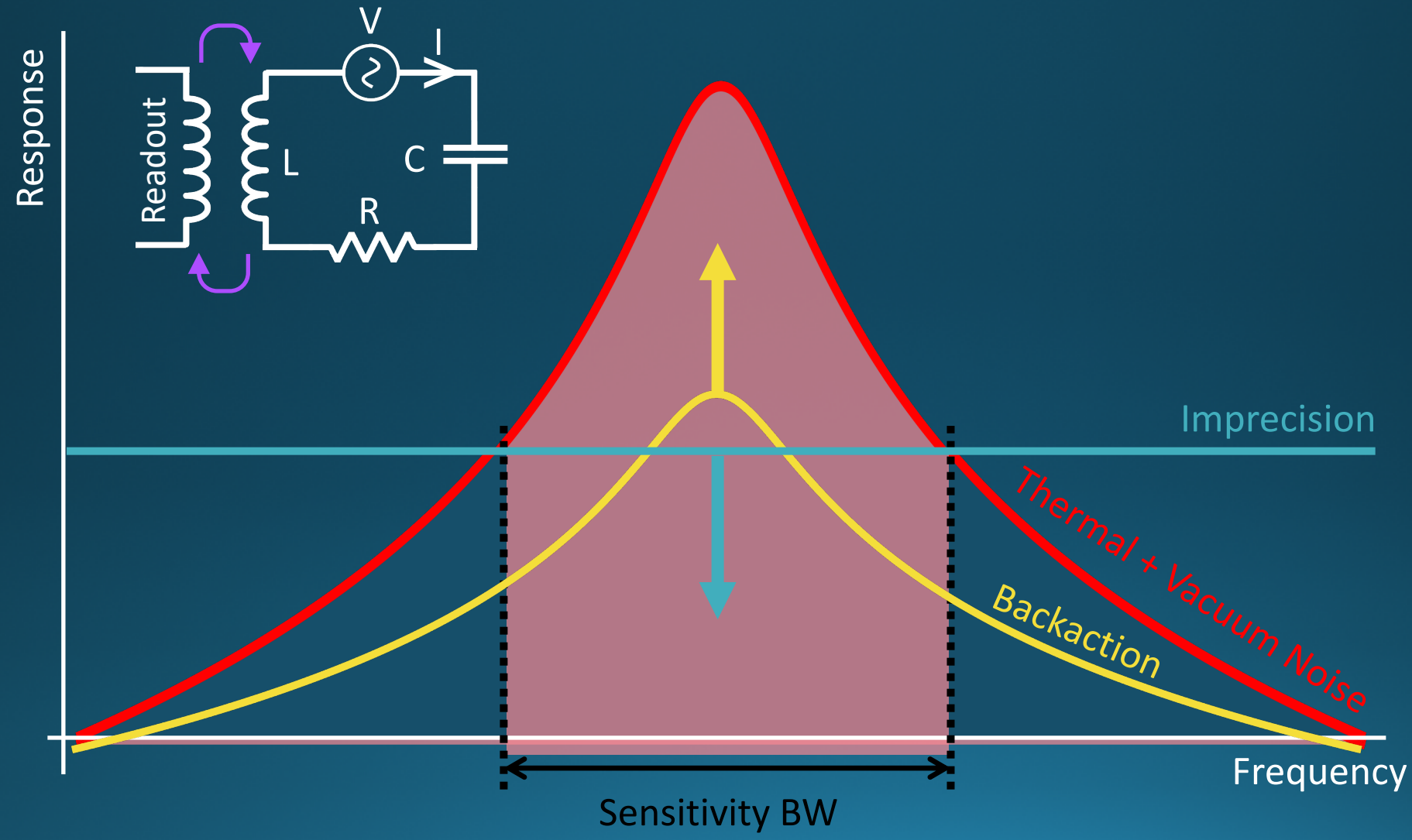
Chaudhuri et al. 1904.05806

Increase coupling to lower imprecision noise



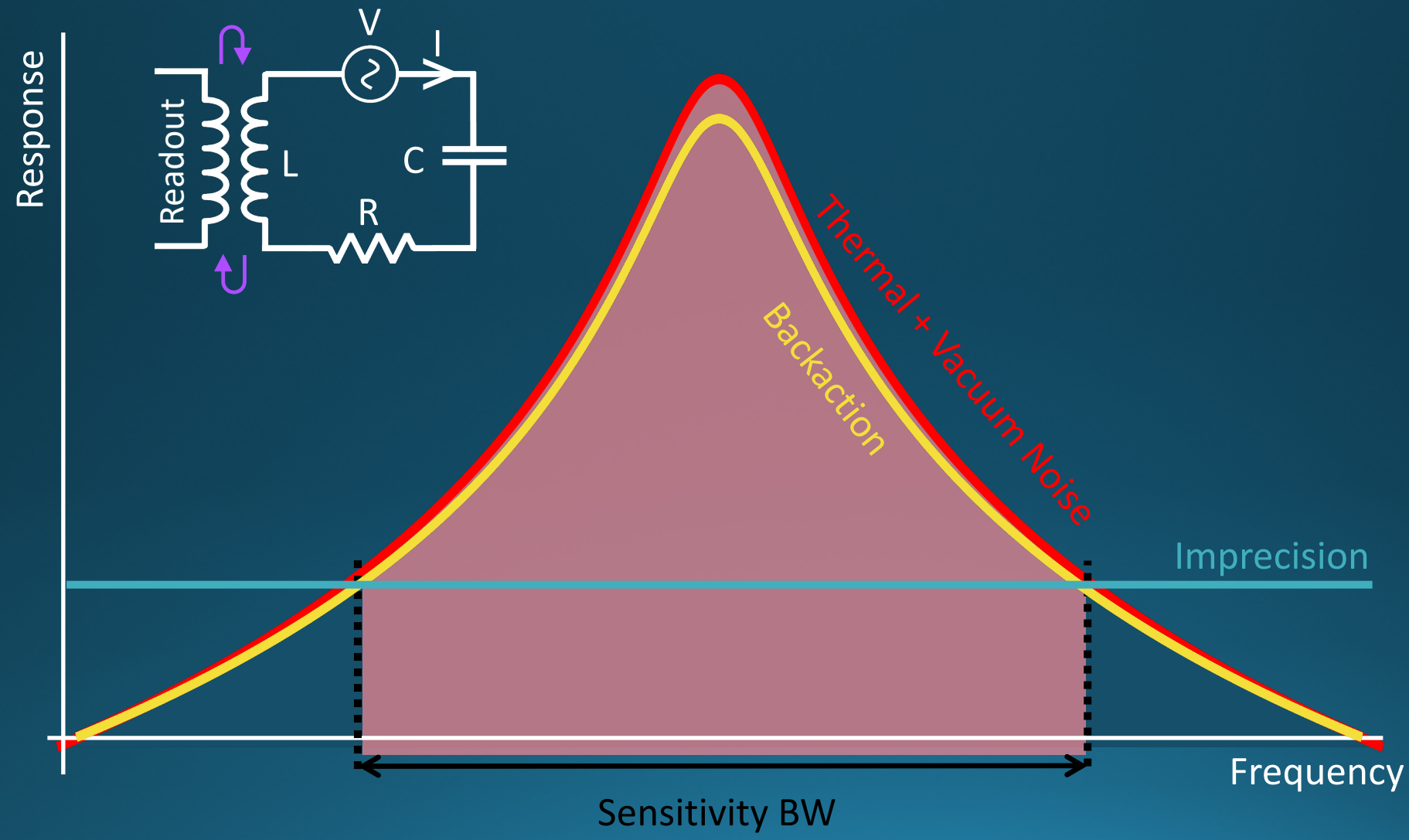
Chaudhuri et al. 1904.05806

Backaction is exchanged for imprecision



Chaudhuri et al. 1904.05806

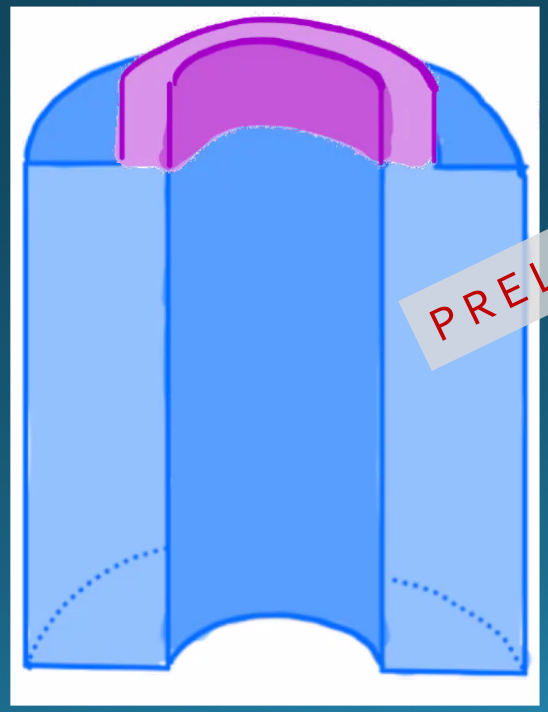
Optimize coupling to maximize sensitivity bandwidth



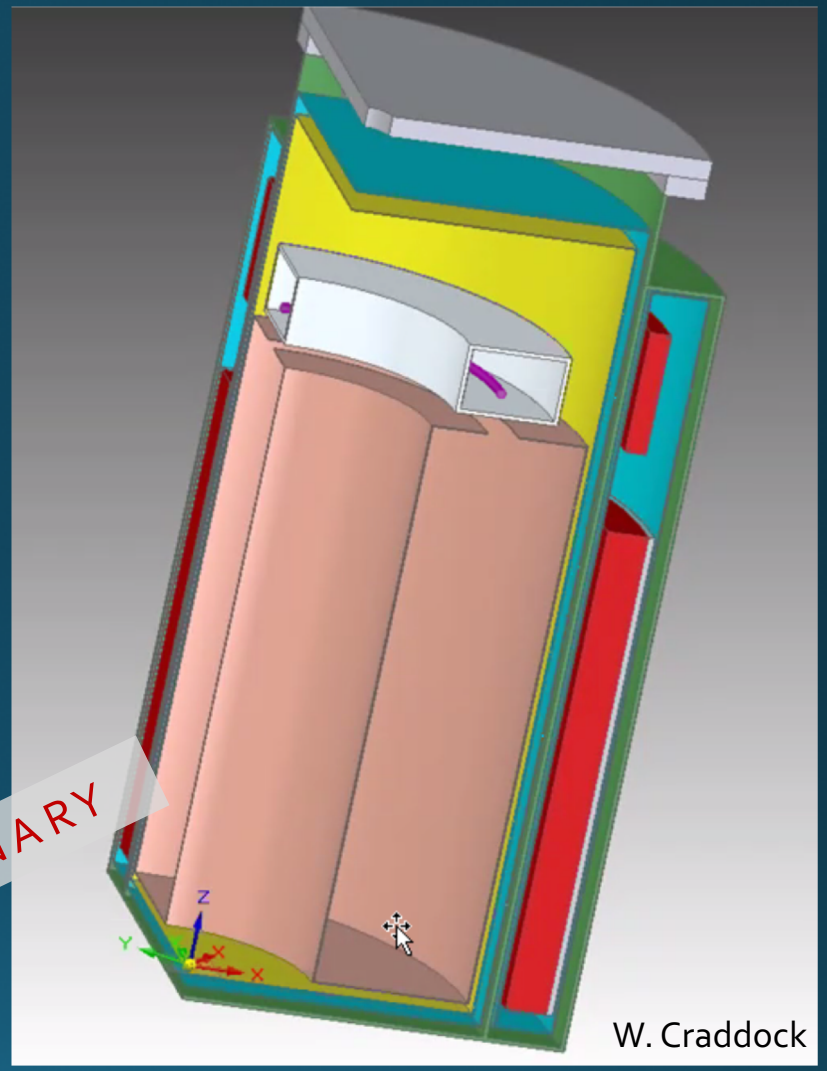
Chaudhuri et al. 1904.05806

DMRadio-m^3

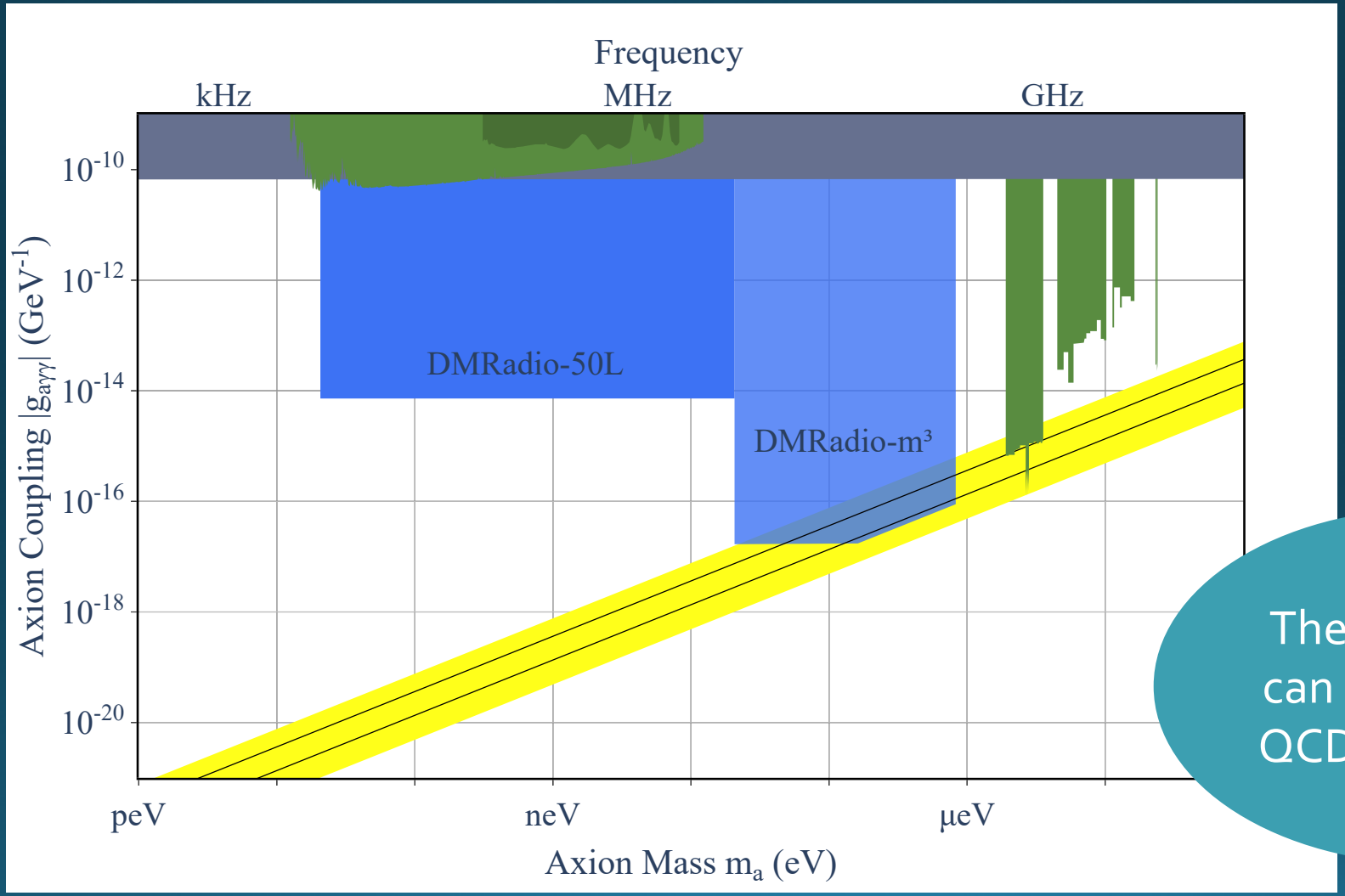
- m^3 volume @ 4T
- Solenoidal magnet
- Resonant readout
- Toroid pickup



C. van Assendelft



Better reach

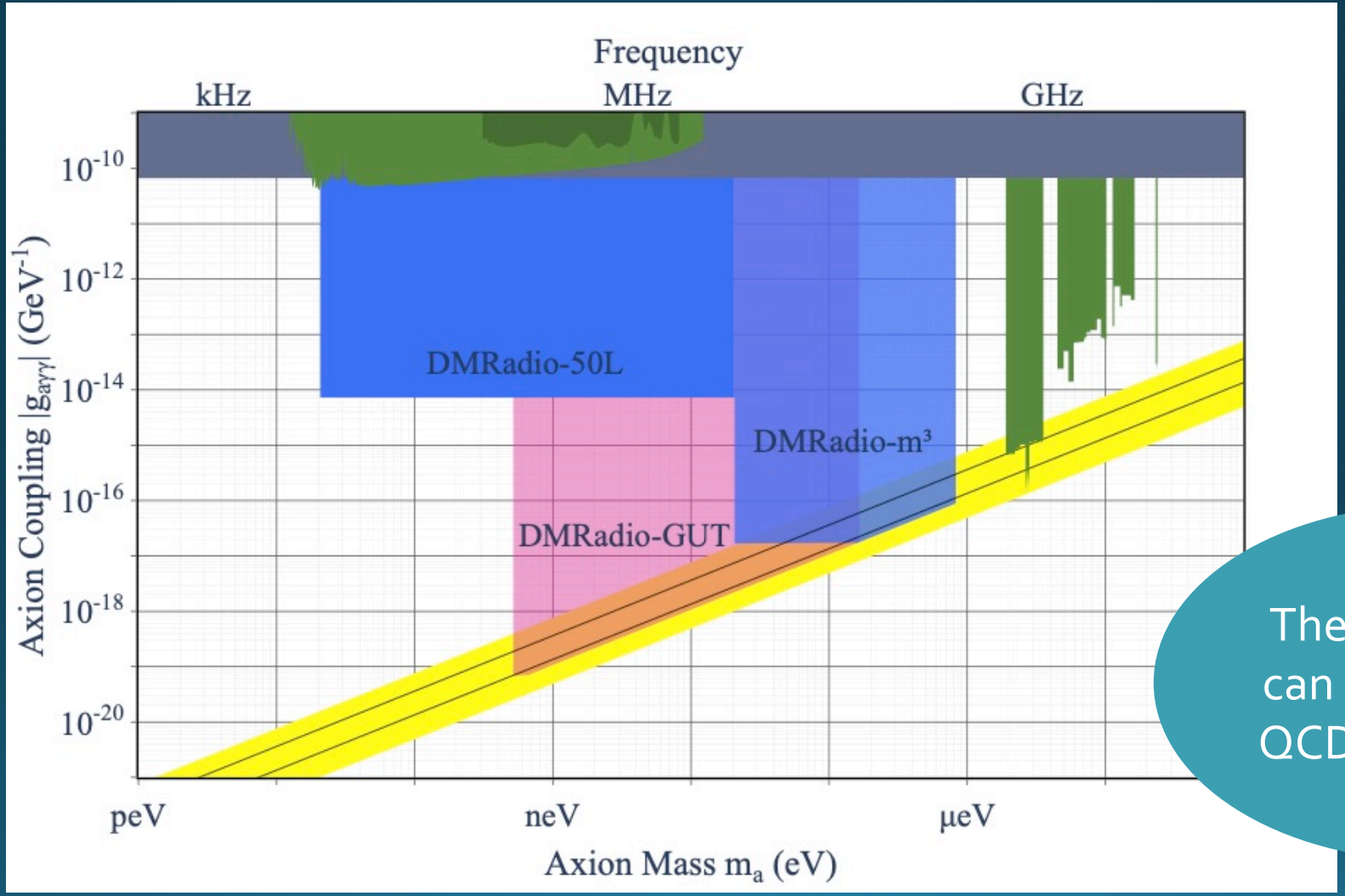


These upgrades can get us to the QCD axion band!

DMRadio-GUT

- Large volume with large field
- Beyond SQL amplifiers

Better reach



These upgrades can get us to the QCD axion band!

Summary

- Low-mass axions are well-suited to a lumped element method
- First generation experiments have results!
- Next generation experiments are underway
- Plans in place to probe the QCD axion band

DM Radio Cubic Meter Consortium

Funded as part of DOE New Initiatives in Dark Matter program

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Project manager for R&D phase: Dale Li

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Thanks!

ABRACADABRA

Sabrina Cheng
Joshua Foster
Andrew Gavin
Reyco Henning
Yonatan Kahn
Rachel Nguyen
Jonathan Ouellet
Kaliroë Pappas
Kate Richardson
Nicholas Rodd
Benjamin Safdi
Lindley Winslow

DMRadio

Lucas Brouwer
Saptarshi Chaudhuri
Sabrina Cheng
Sherry Cho
Carl Dawson
Alex Droster
Joshua Foster
Andrew Gavin
Peter Graham
Reyco Henning
Patty Ho
Kent Irwin
Fedja Kadribasic
Yonatan Kahn
Aya Keller
Stephen Kuenstner
Nadine Kurita
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Nicholas Rapidis
Kate Richardson
Nicholas Rodd
Benjamin Safdi
Maria Simanovskaia
Joe Singh
Cady van Assendelft
Karl van Bibber
Kevin Wells
Lindley Winslow
Betty Young

Others

Nicole Crisosto
Alex Sushkov
David Tanner

ABRACADABRA

C. Salemi