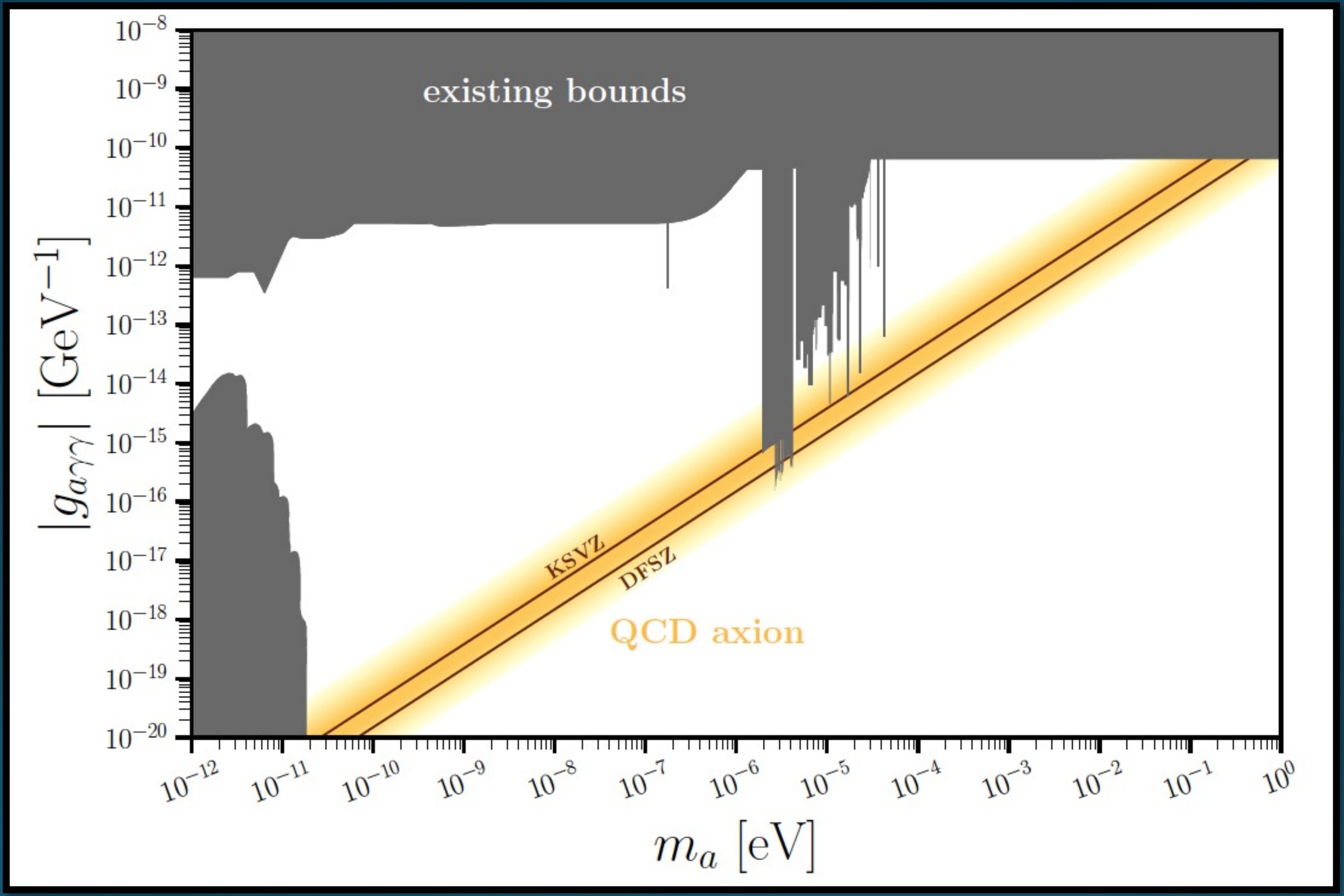
Searching for low-mass axion dark matter with DMRadio

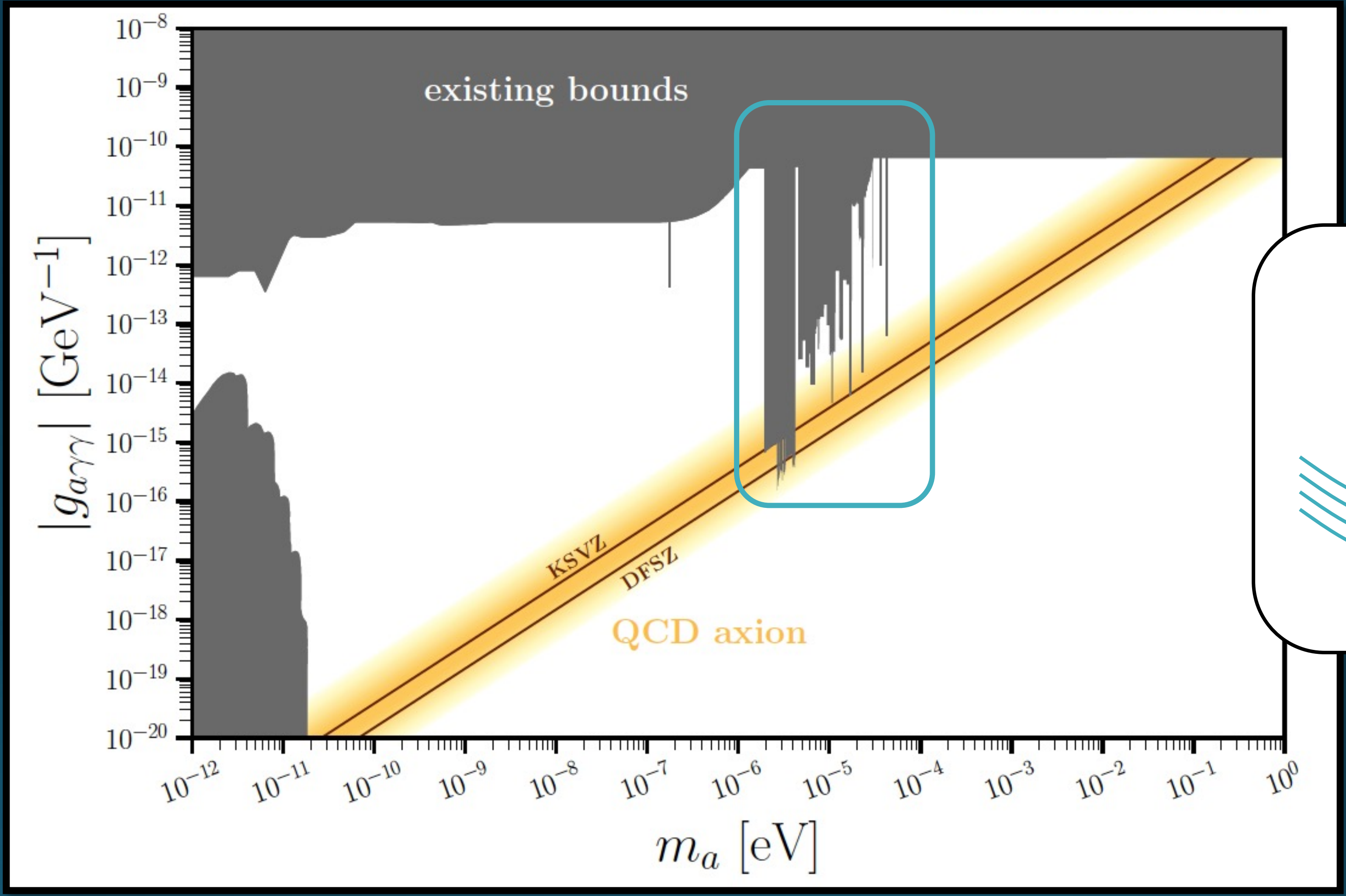
Chiara P. Salemi
Stanford University and SLAC
ALPS, April 2024

Lots of highly motivated parameter space to cover!



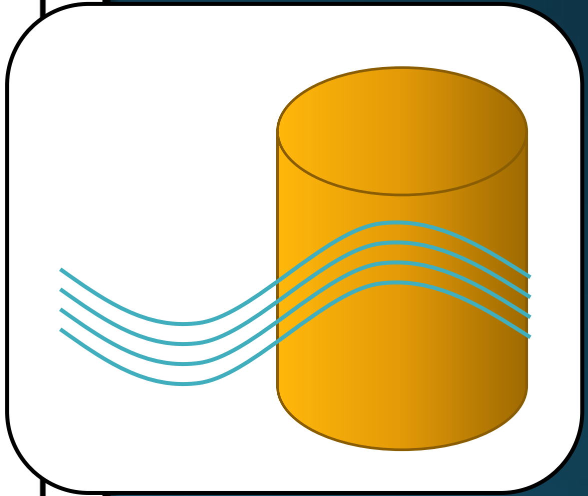
A. Berlin and others

Experimental methods

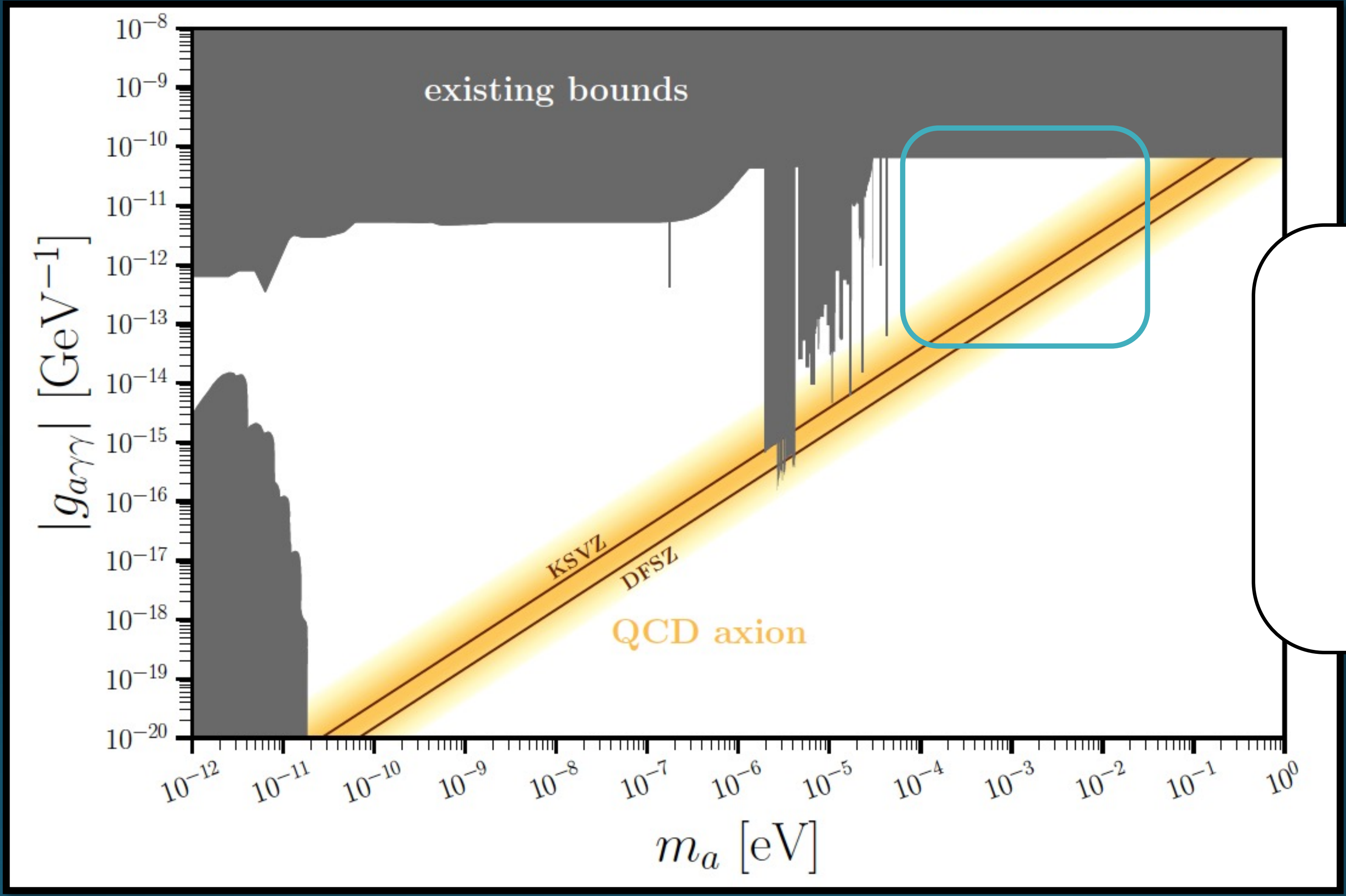


A. Berlin and others

cavities

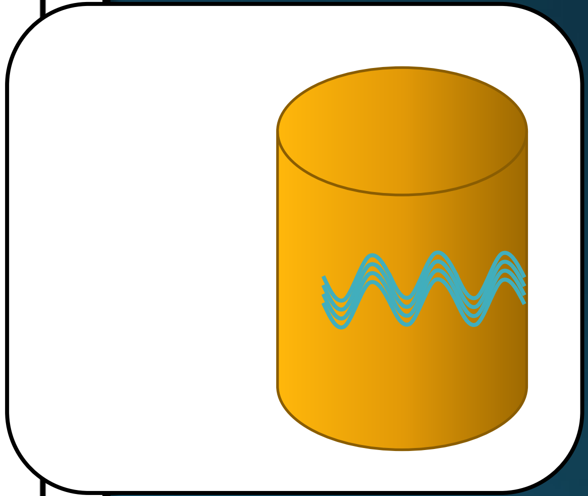


Experimental methods

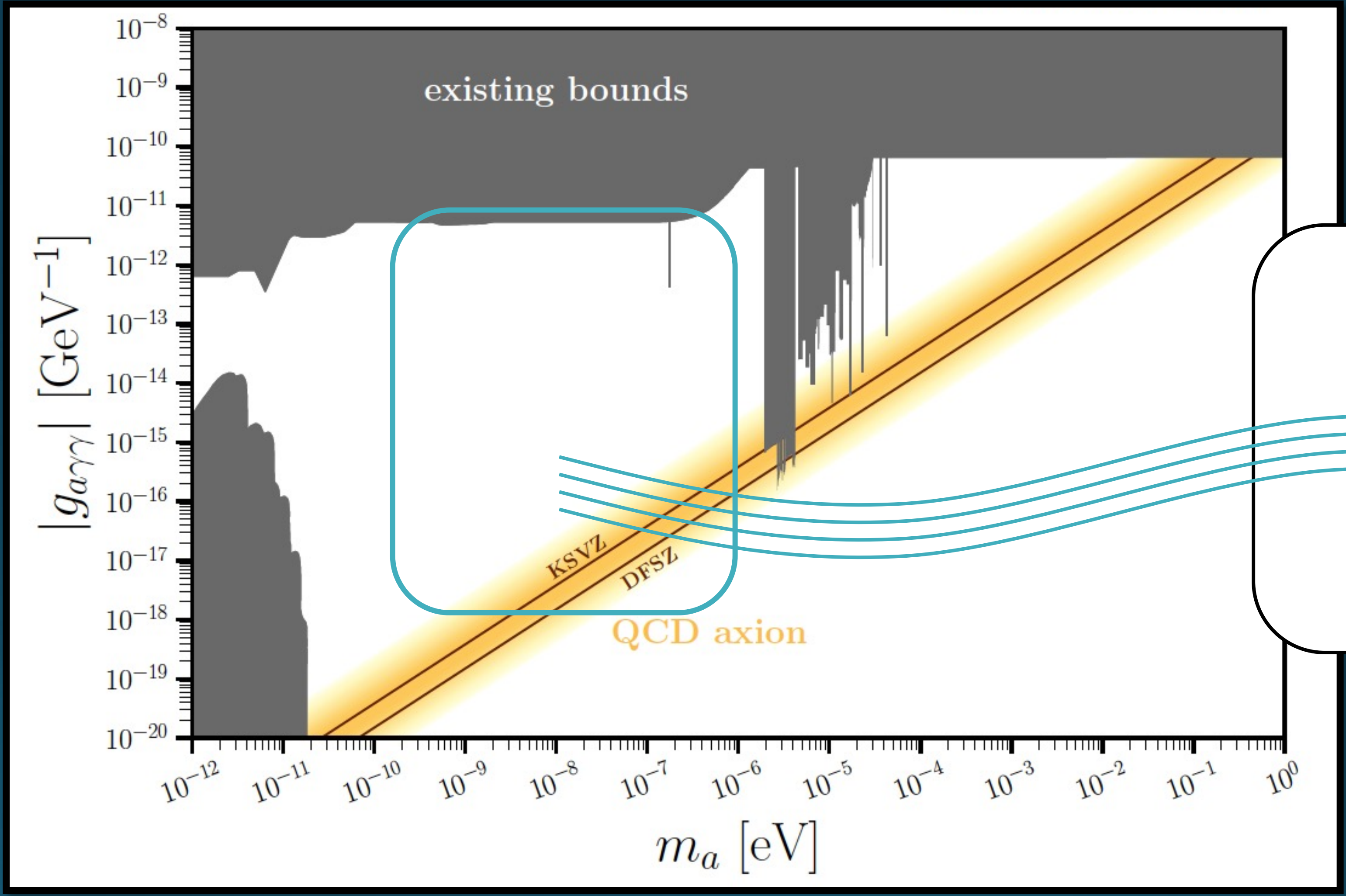


A. Berlin and others

reflectors

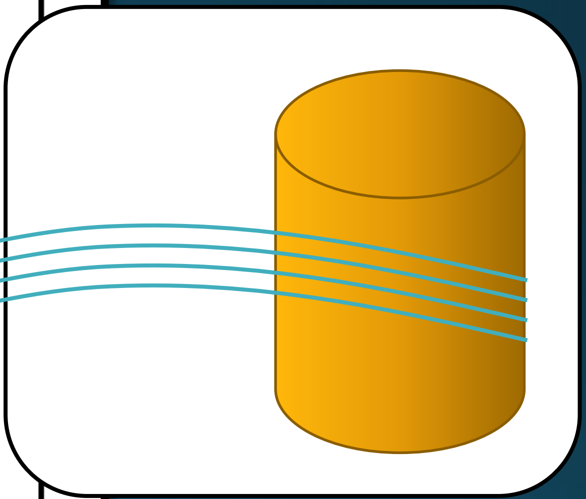


Experimental methods

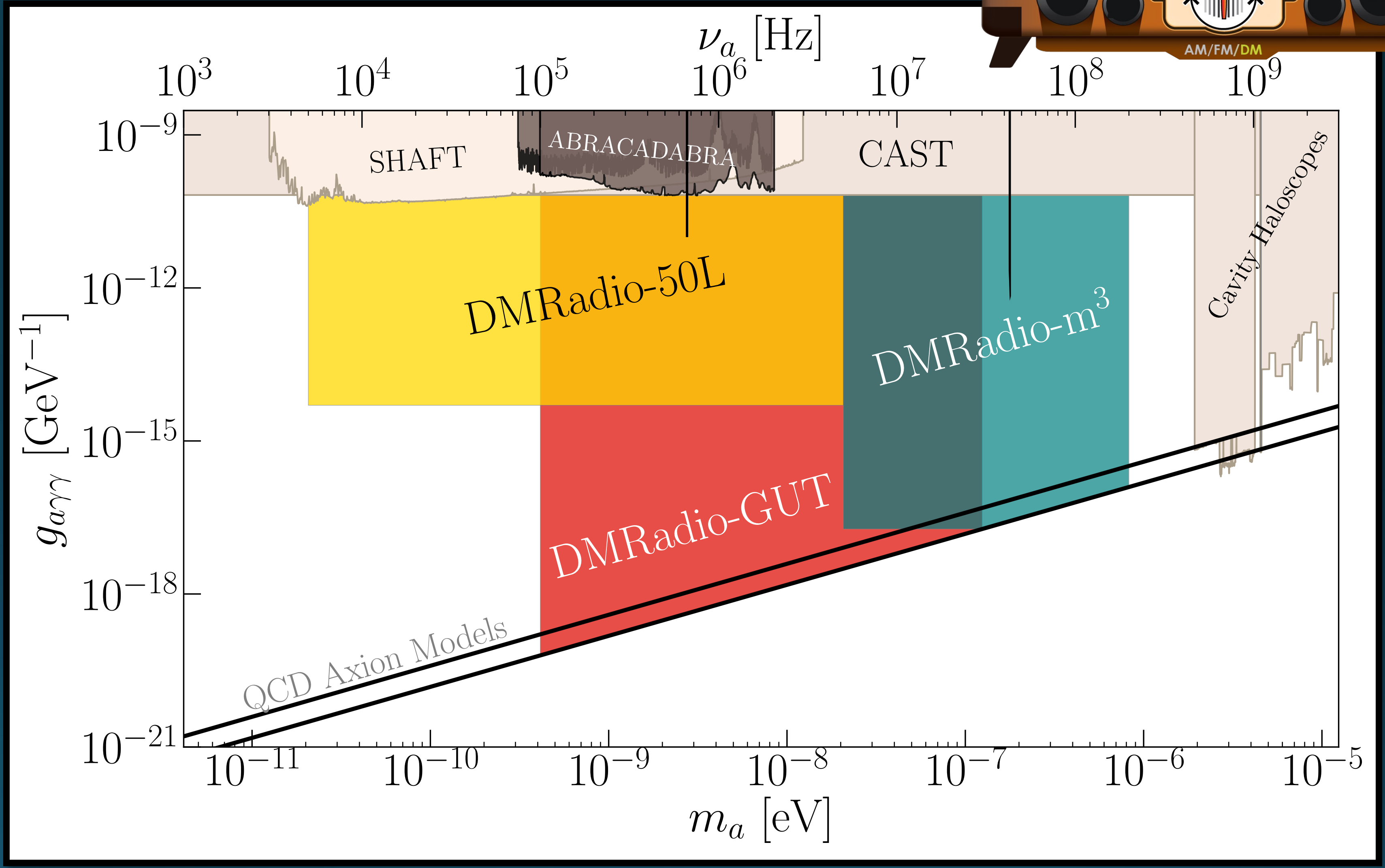


A. Berlin and others

lumped elements



ABRACADABRA +

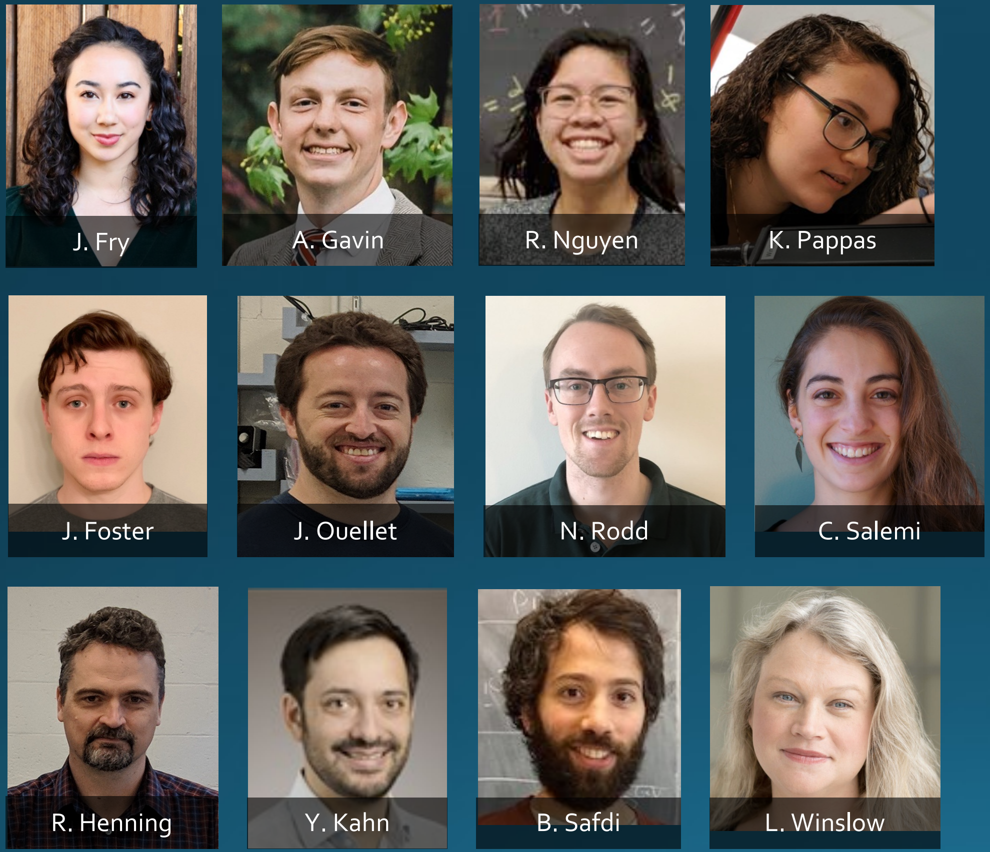


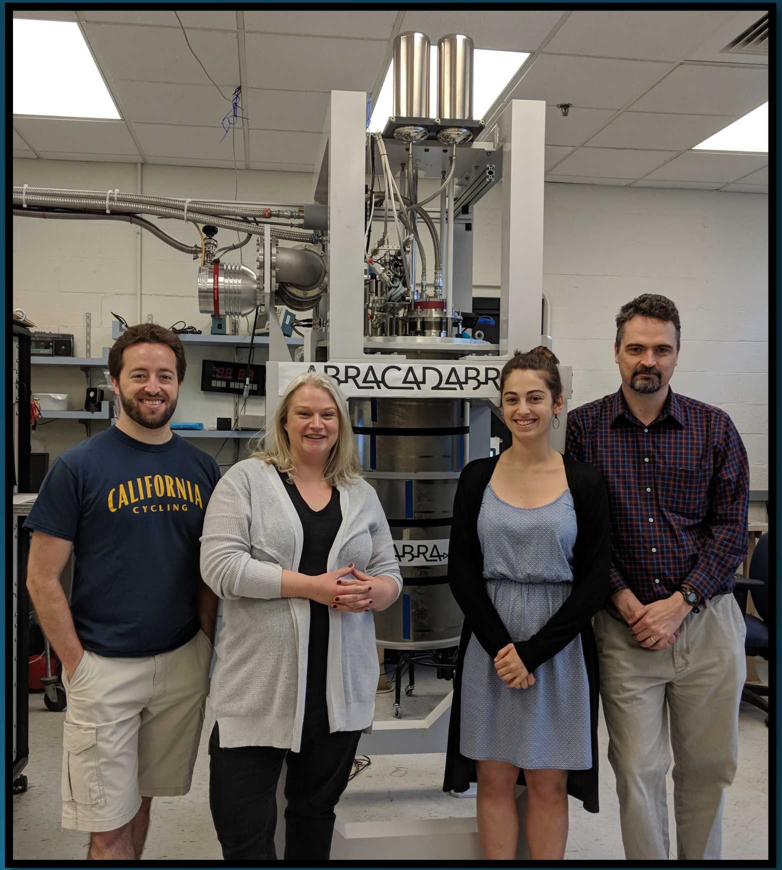
ABRACADABRA

Graduate students

Postdocs and research scientists

Principal investigators





DM RADIO

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SLAC National Accelerator Laboratory

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B. R. Safdi
Department of Physics
University of California Berkeley

Axion E&M

Axion-photon interactions modify Ampere's Law:

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

Axion E&M

Axion-photon interactions modify Ampere's Law:

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

Axion E&M

Axion-photon interactions modify Ampere's Law:

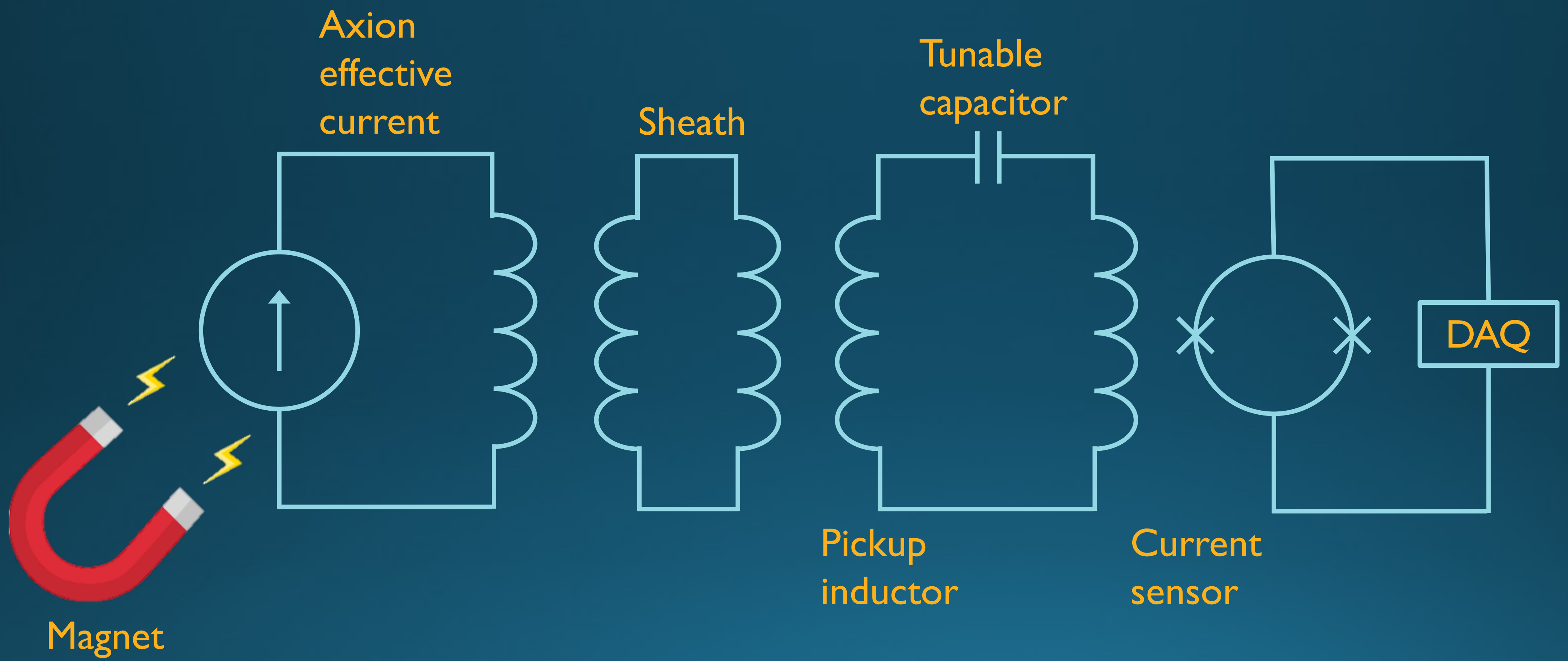
$$\nabla \times \mathbf{B} = \mathbf{J} + \frac{\partial \mathbf{E}}{\partial t} - g_{a\gamma\gamma}\left(\mathbf{E} \times \nabla a - \frac{\partial a}{\partial t}\mathbf{B}\right)$$

$$\Downarrow$$

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

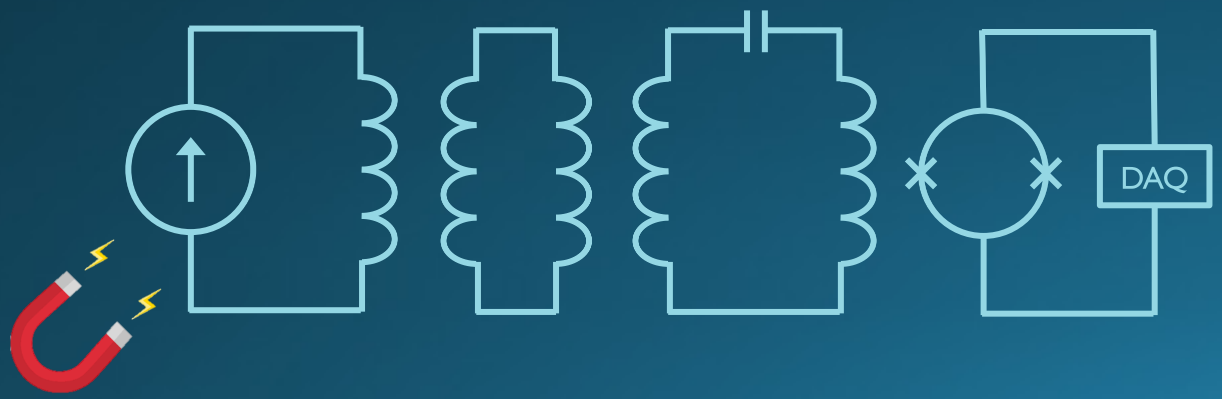
$$a(t) = \frac{\sqrt{2\rho_{DM}}}{m_a}\sin(m_a t)$$

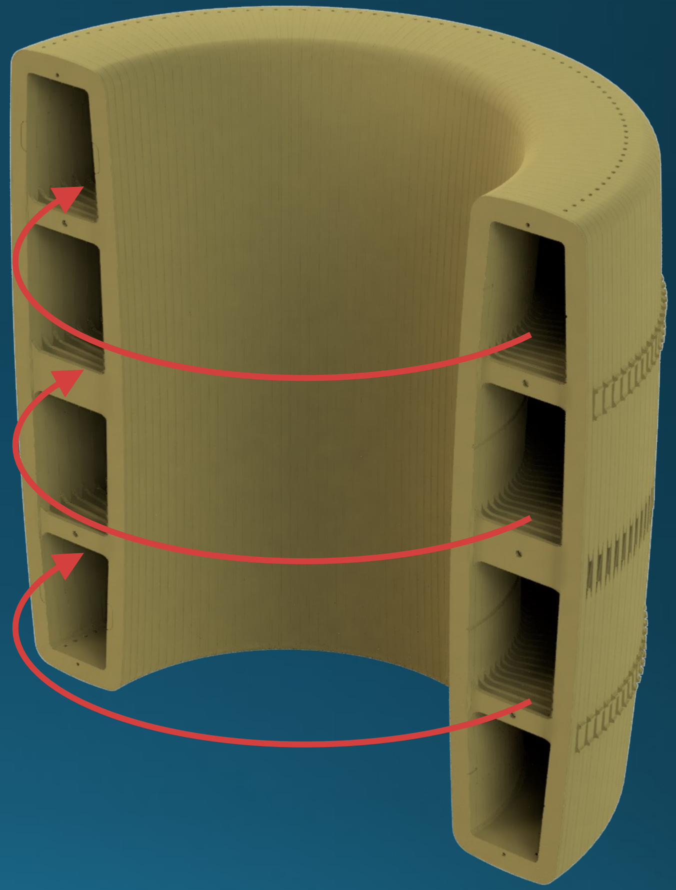
Schematic of lumped-element detection



The 50L detector

Toroidal superconducting magnet with fixed field, B_0

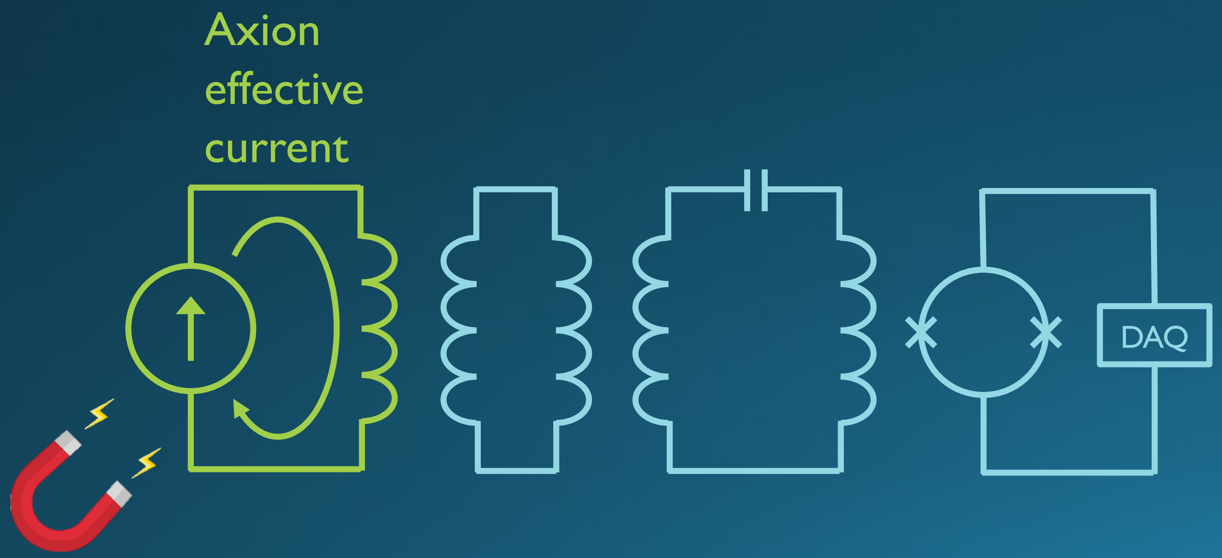


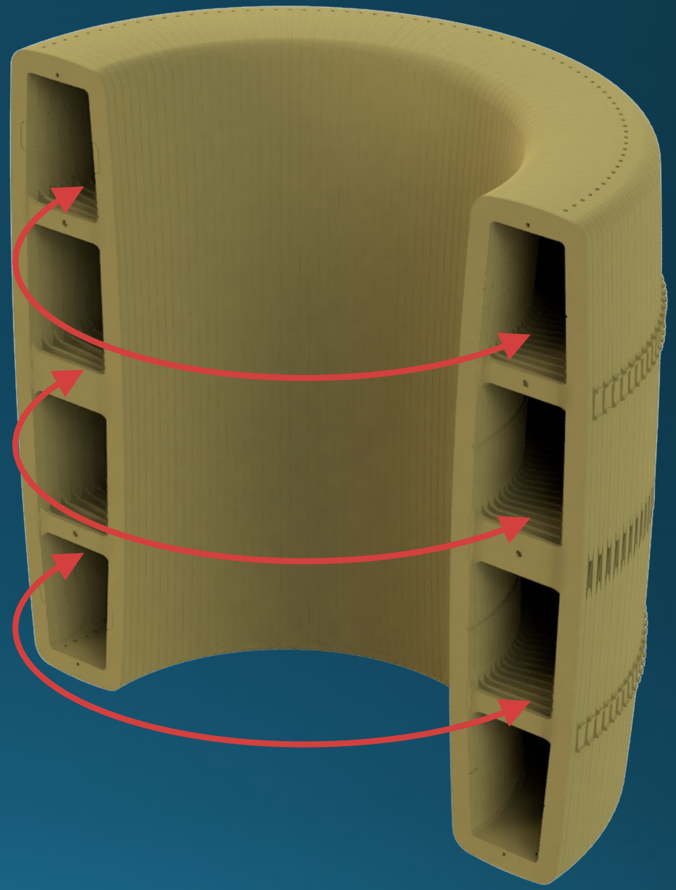


The 50L detector

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

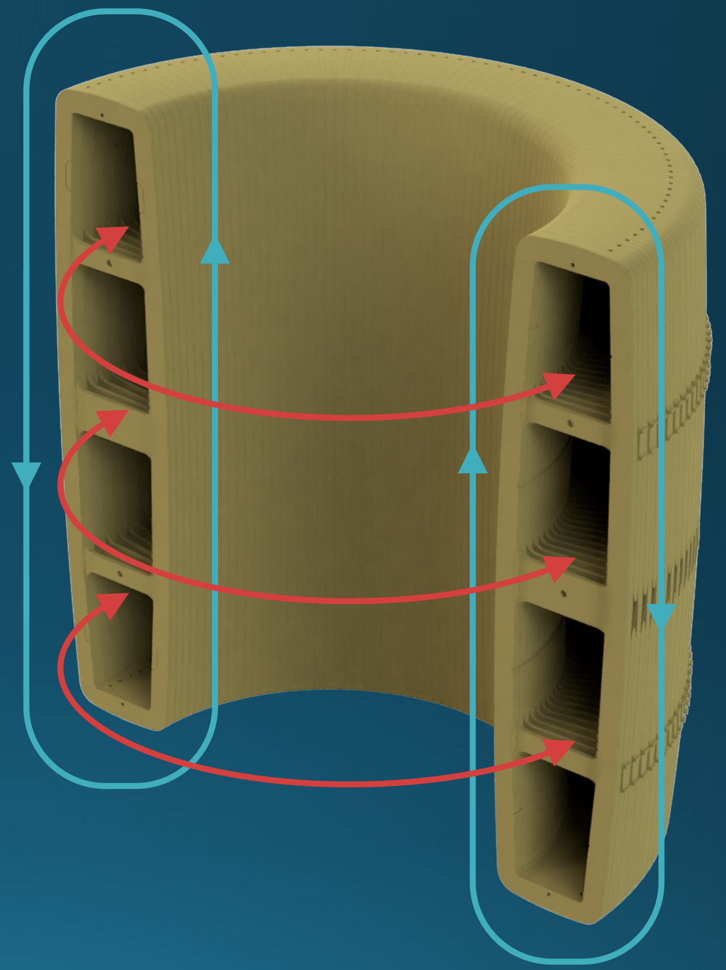
$$\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma}\sqrt{2\rho_{\text{DM}}}\cos(m_a t)\mathbf{B}_0$$

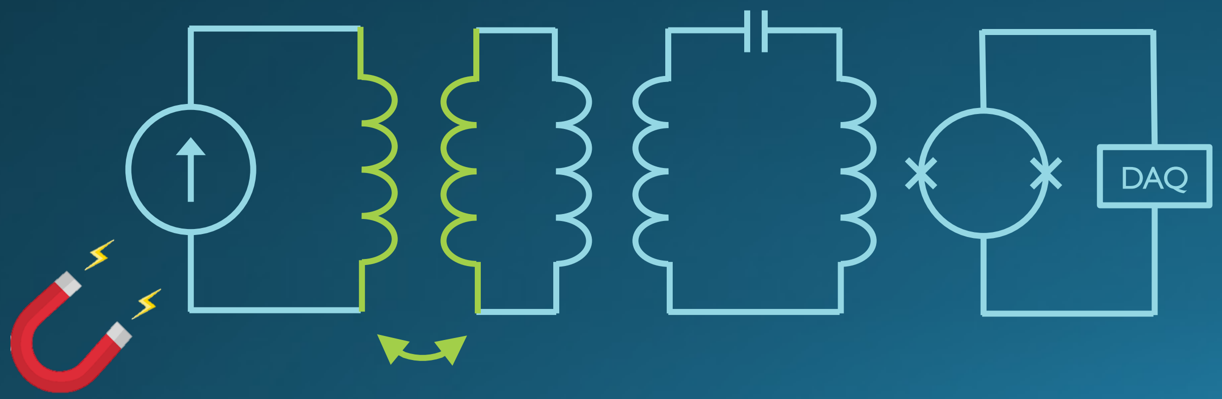




The 50L detector

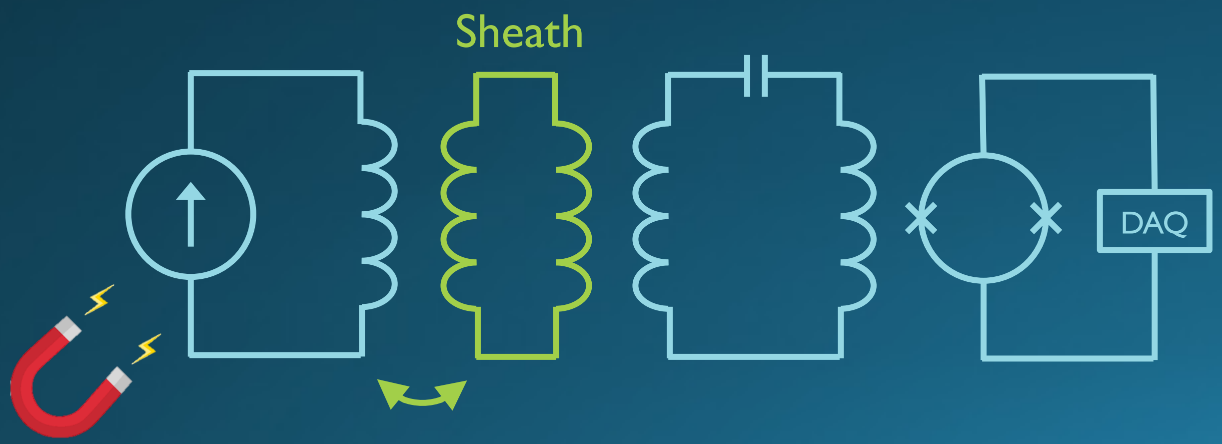
Axion dark matter generates parallel oscillating effective current, J_{eff}, which generates an oscillating magnetic field

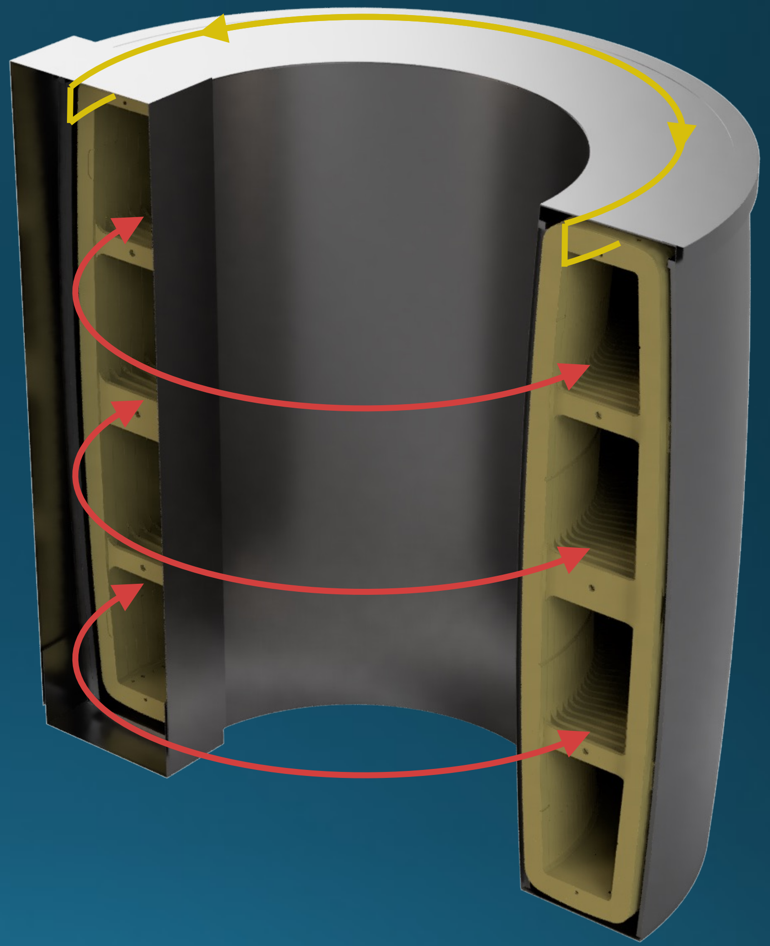




The 50L detector

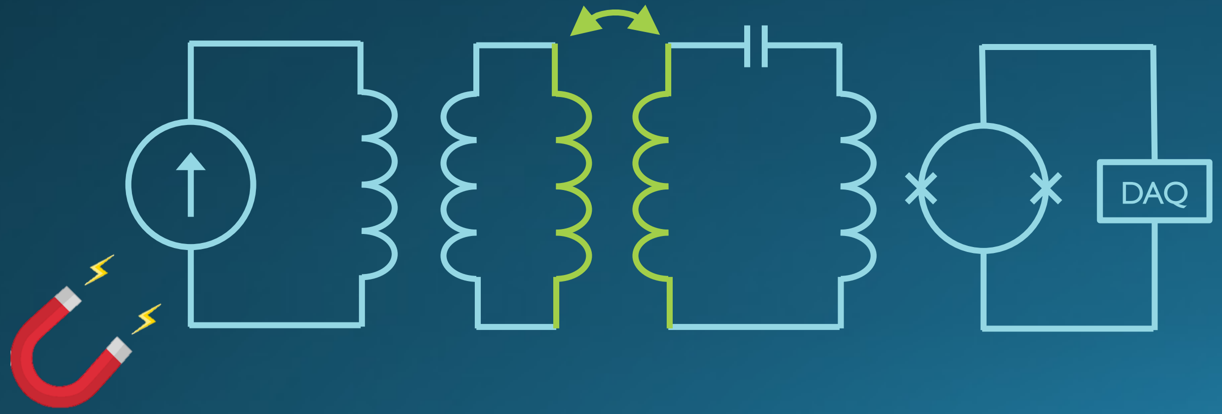
...inducing currents on the sheath

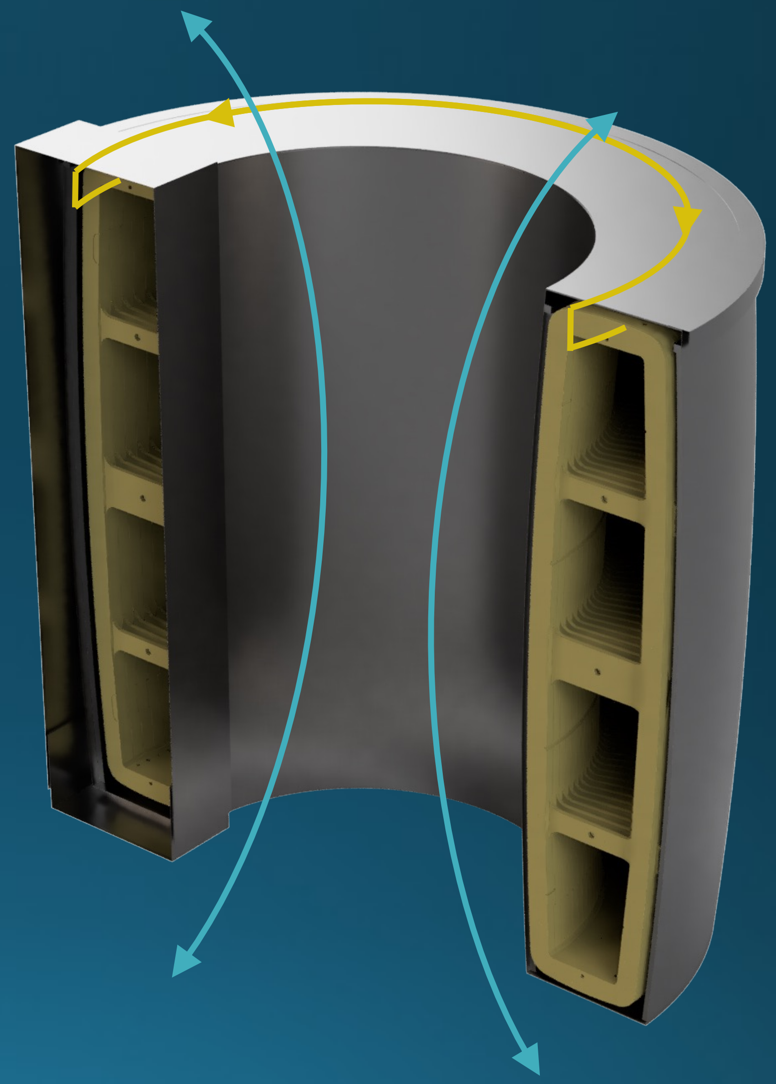




The 50L detector

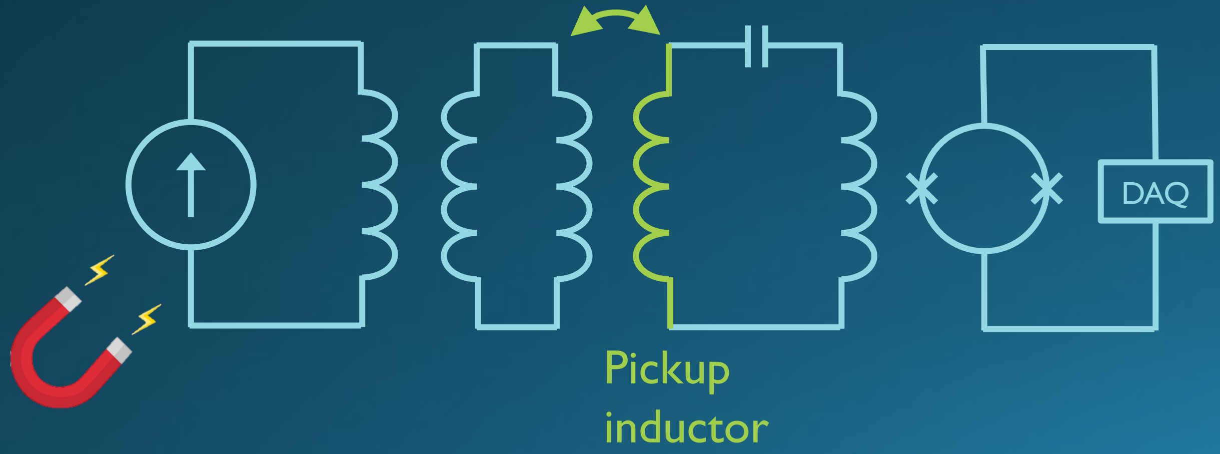
...inducing currents on the sheath, which in turn generates another oscillating magnetic field

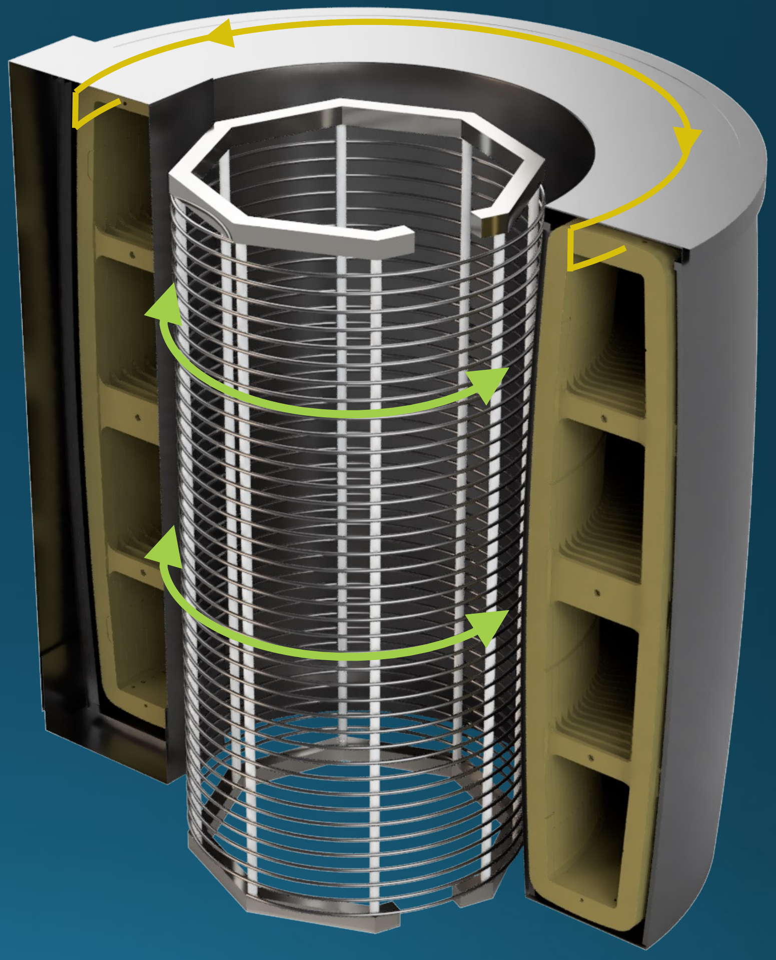




The 50L detector

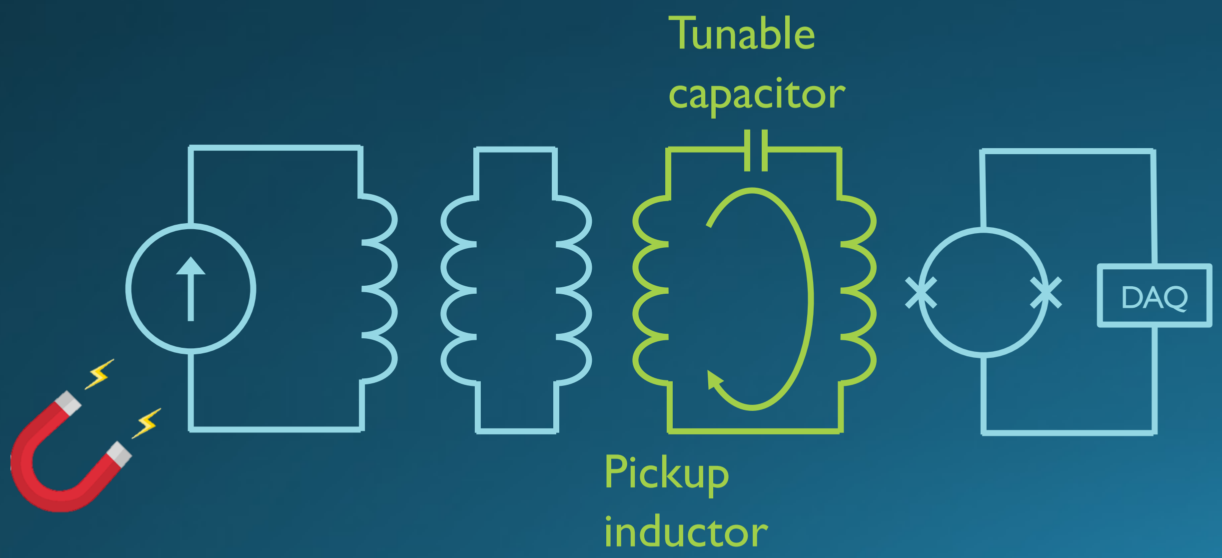
...inducing currents on the pickup inductor

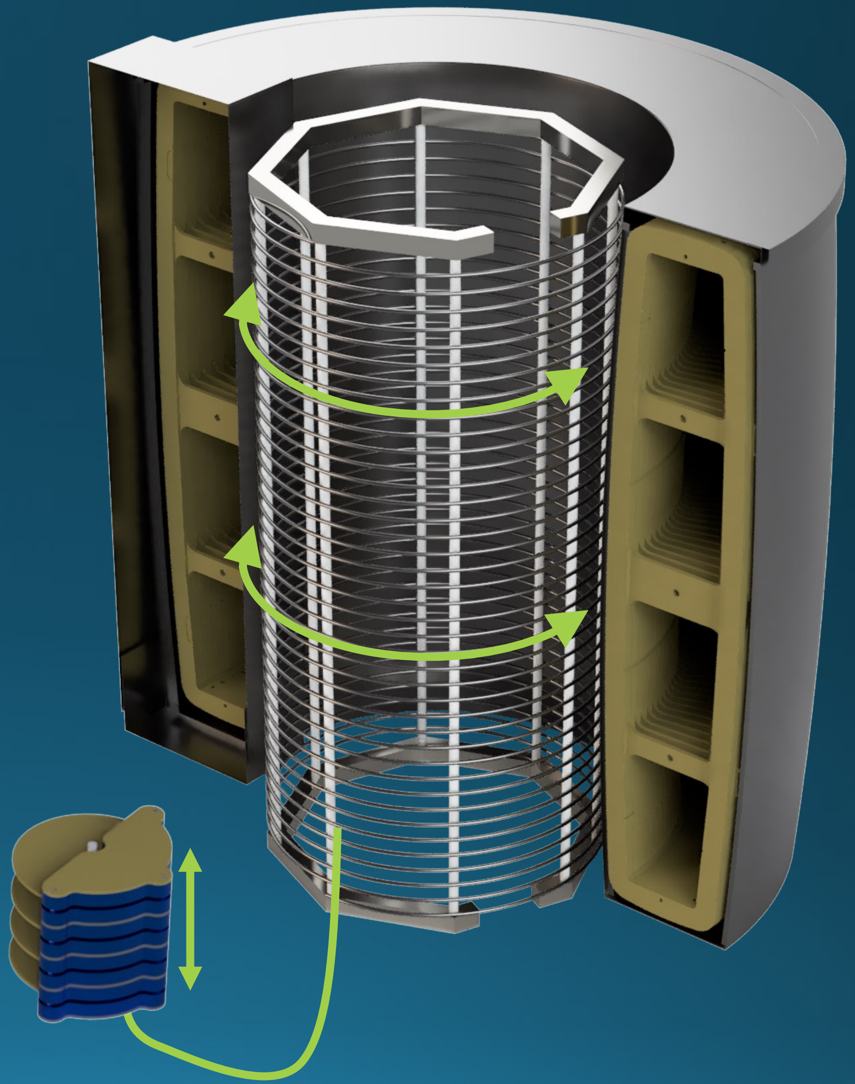




The 50L detector

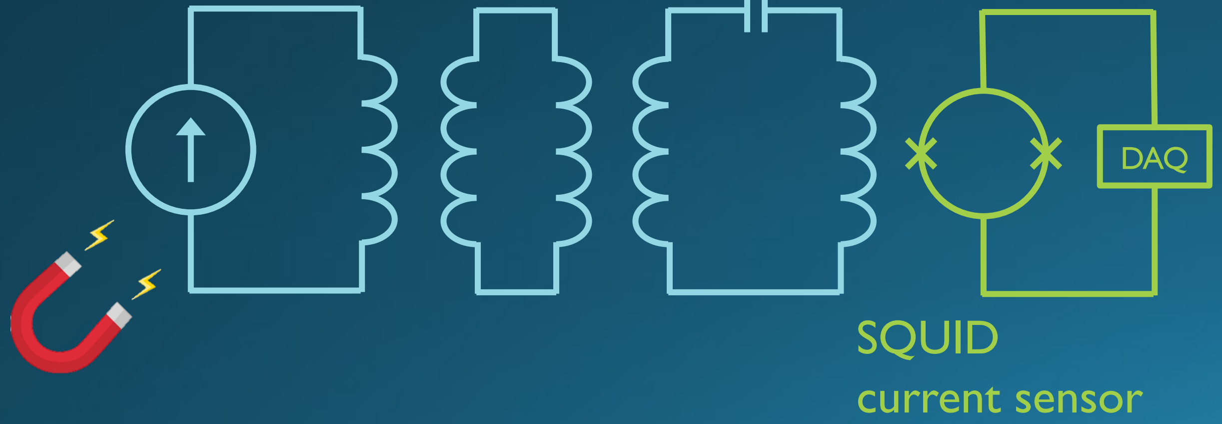
...ringing up the LC resonator.

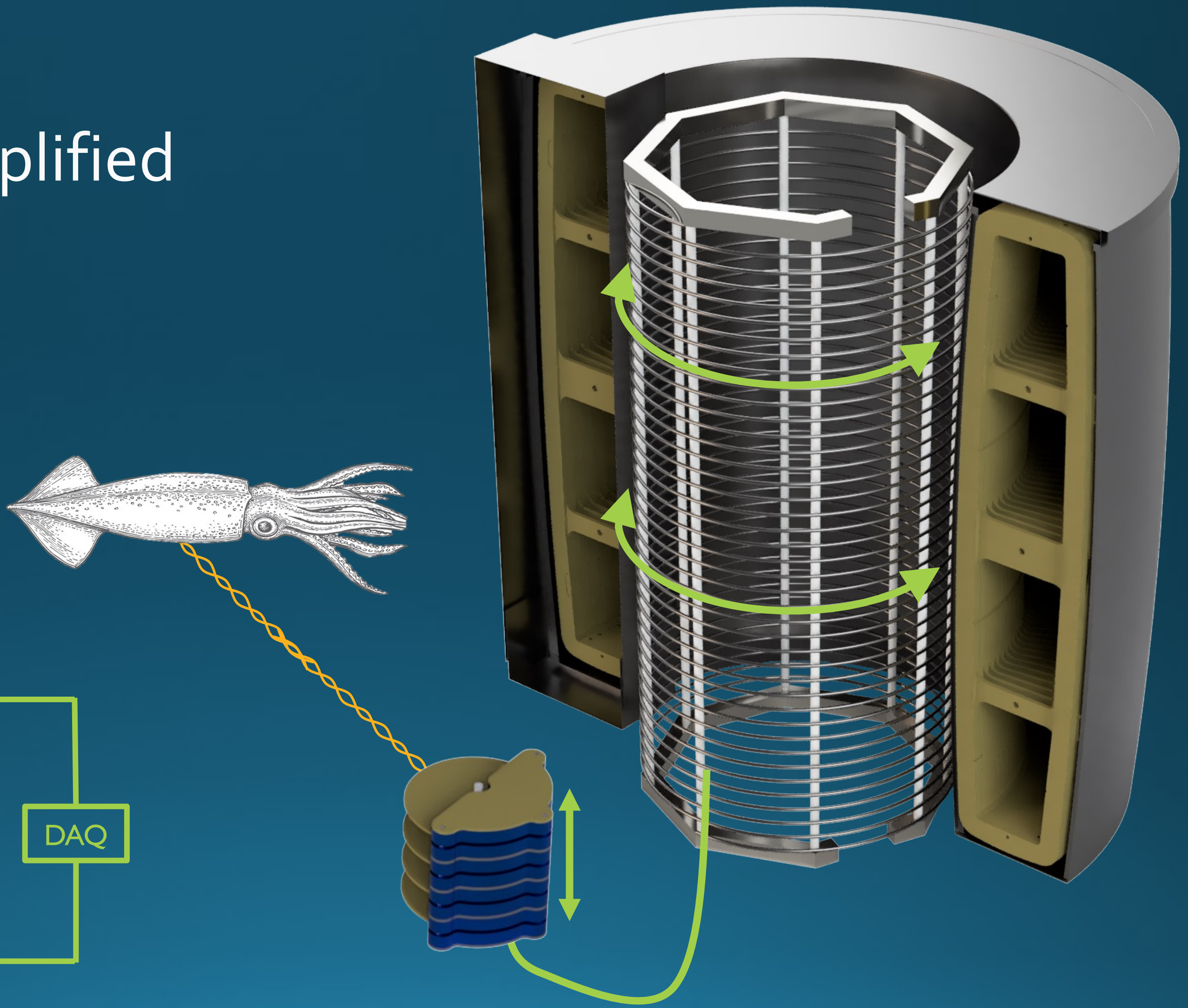




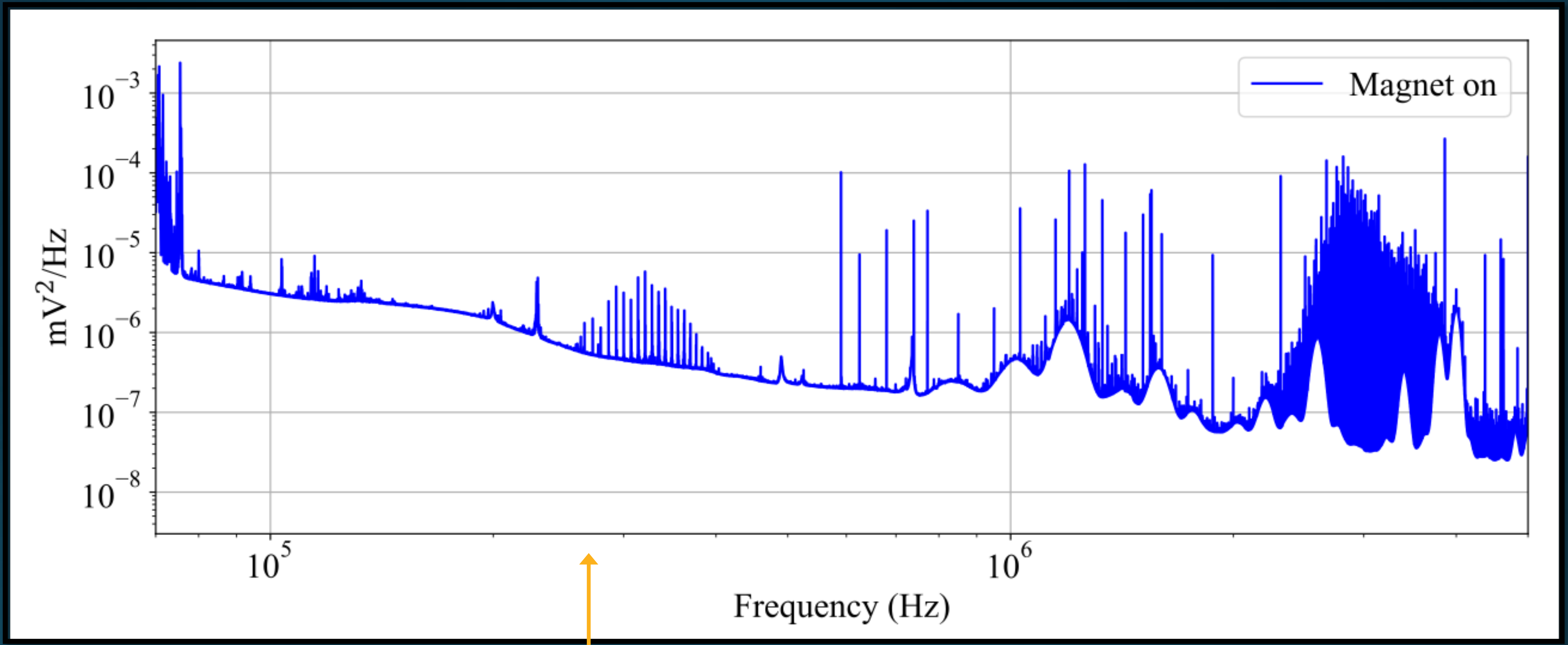
The 50L detector

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



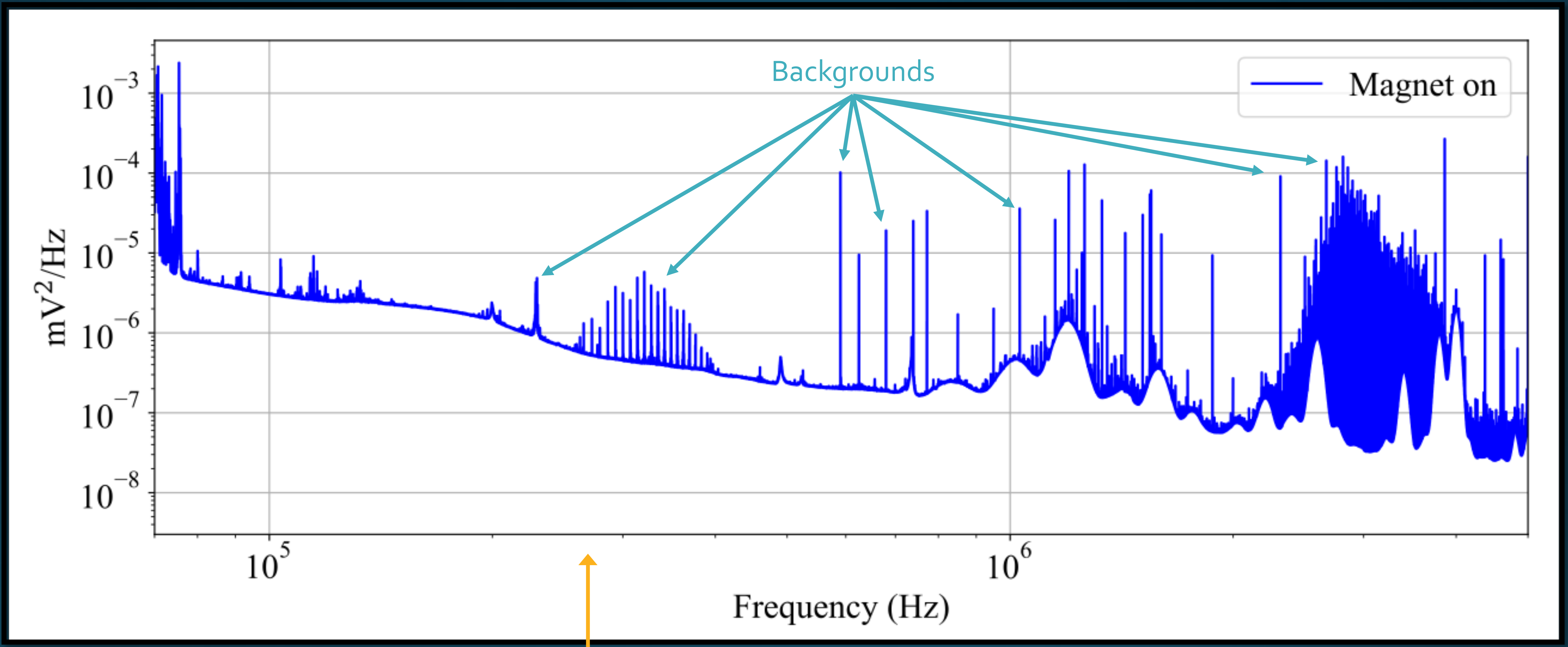


ABRA-10cm averaged spectrum



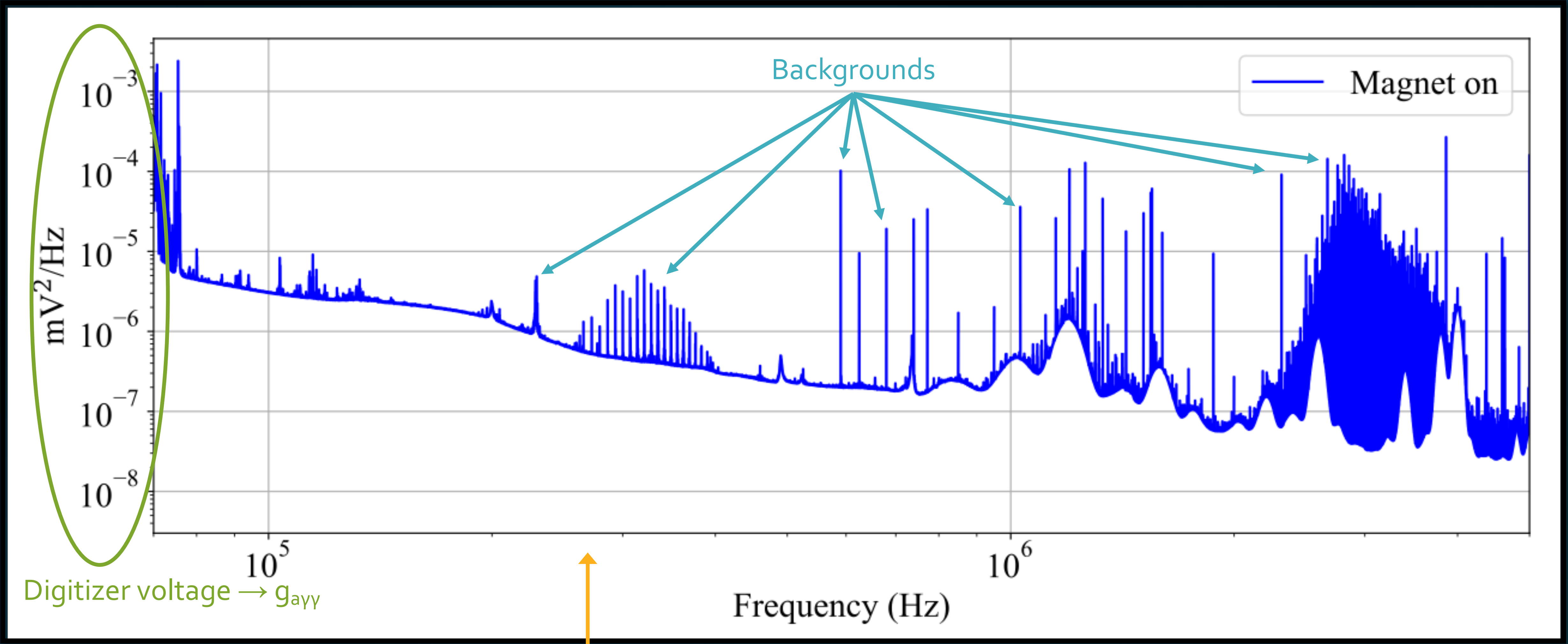
$m_a \sim 1$ neV (GUT-scale)

ABRA-10cm averaged spectrum



m_a ~ 1 neV (GUT-scale)

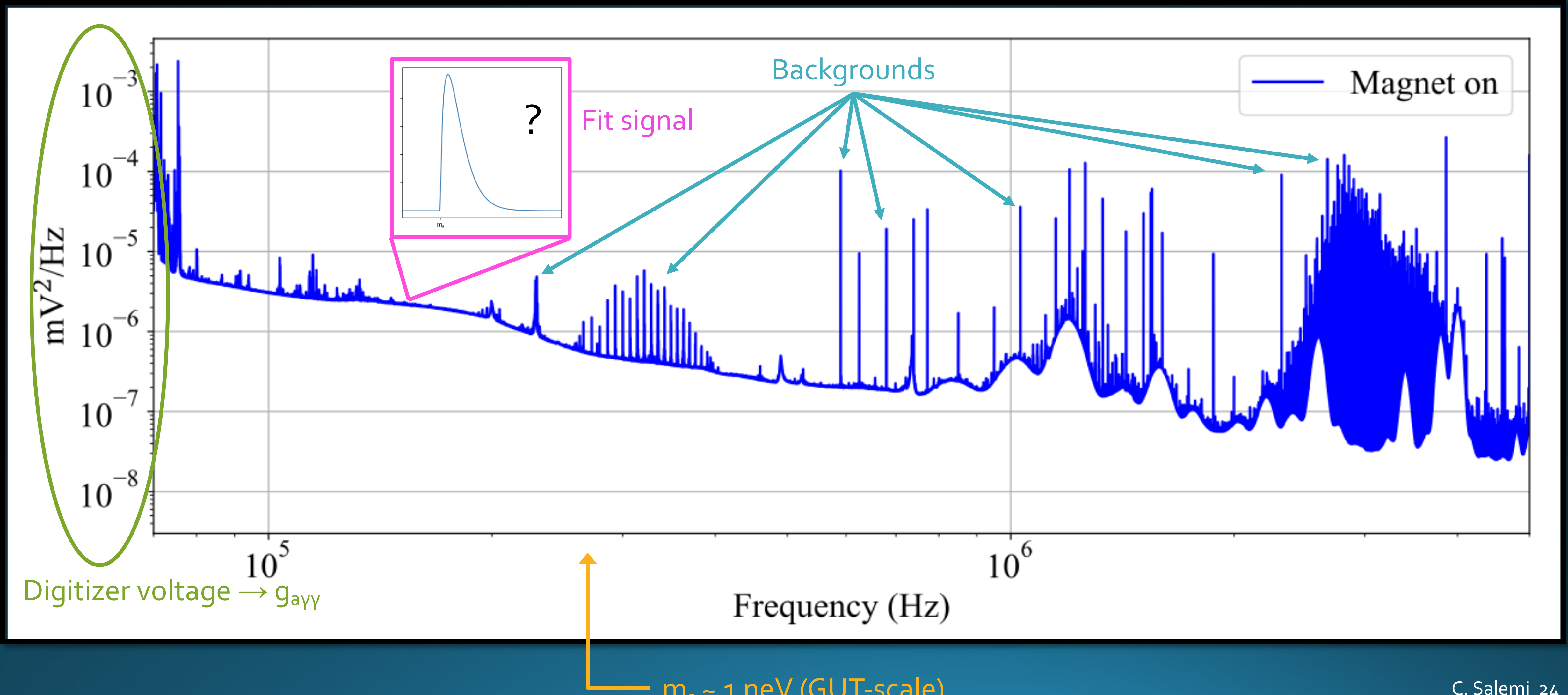
ABRA-10cm averaged spectrum



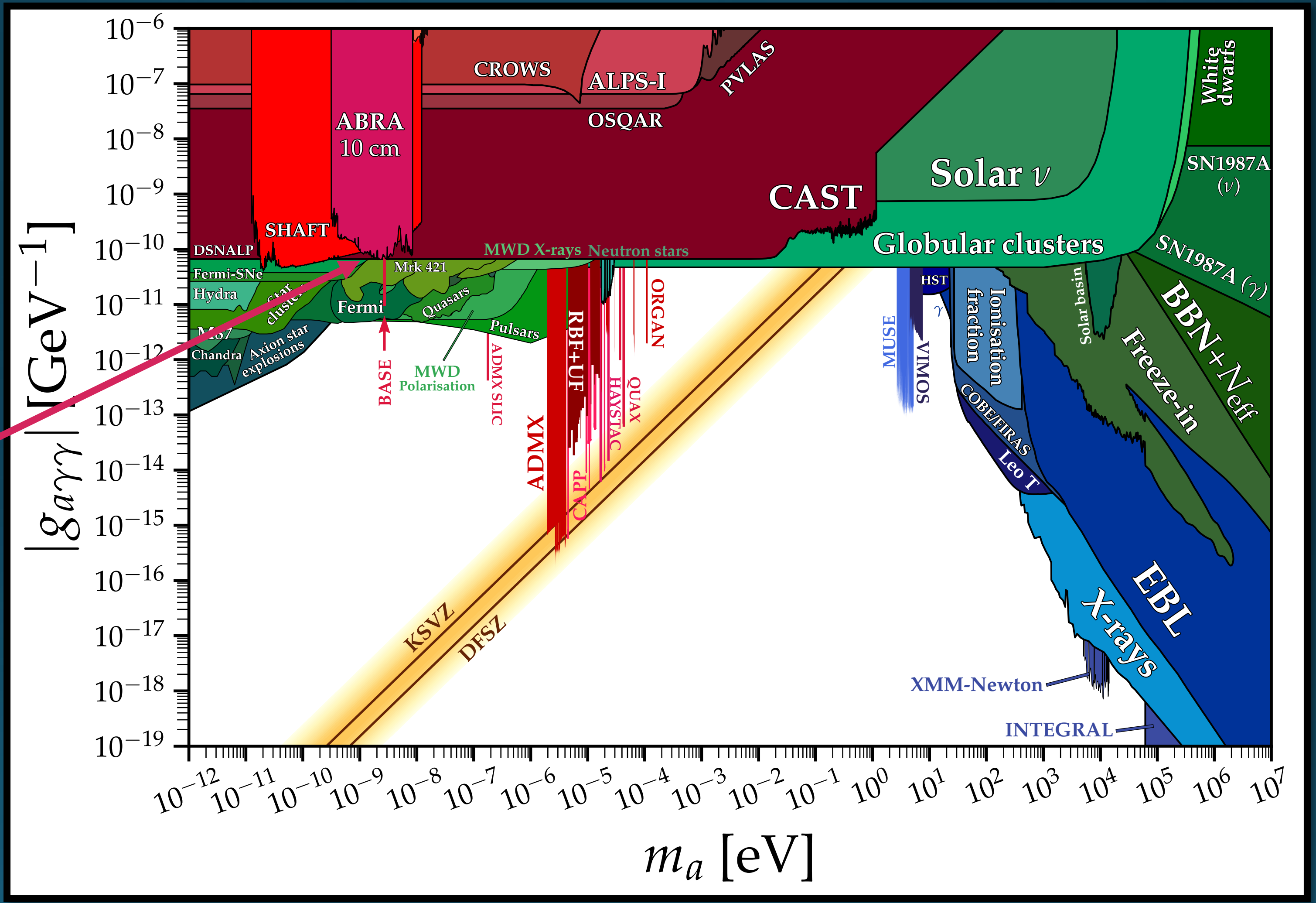
Digitizer voltage ⟶ $g_{a\gamma\gamma}$

m_a ~ 1 neV (GUT-scale)

ABRA-10cm averaged spectrum



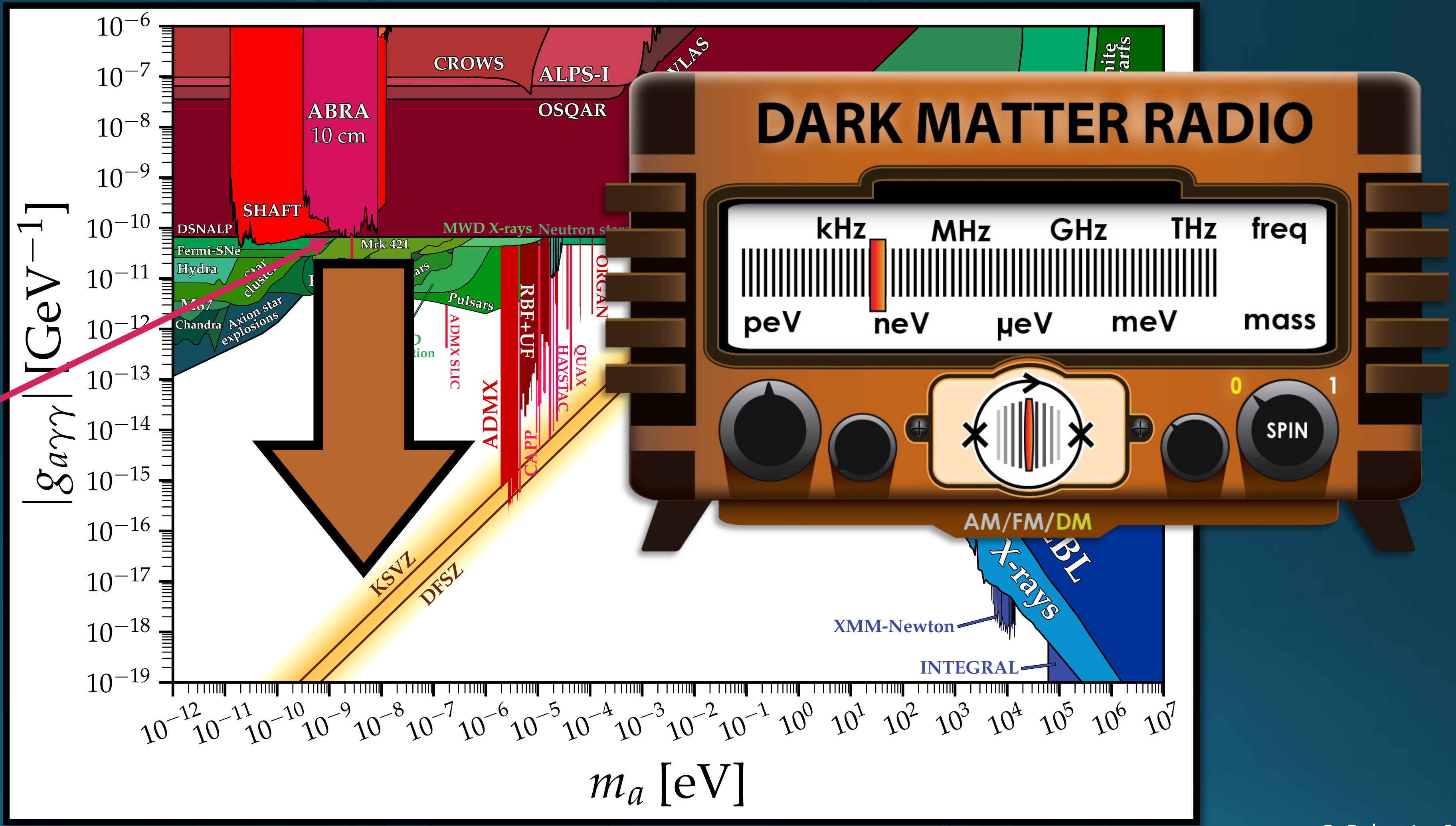
No axions found yet!



C. O'Hare

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

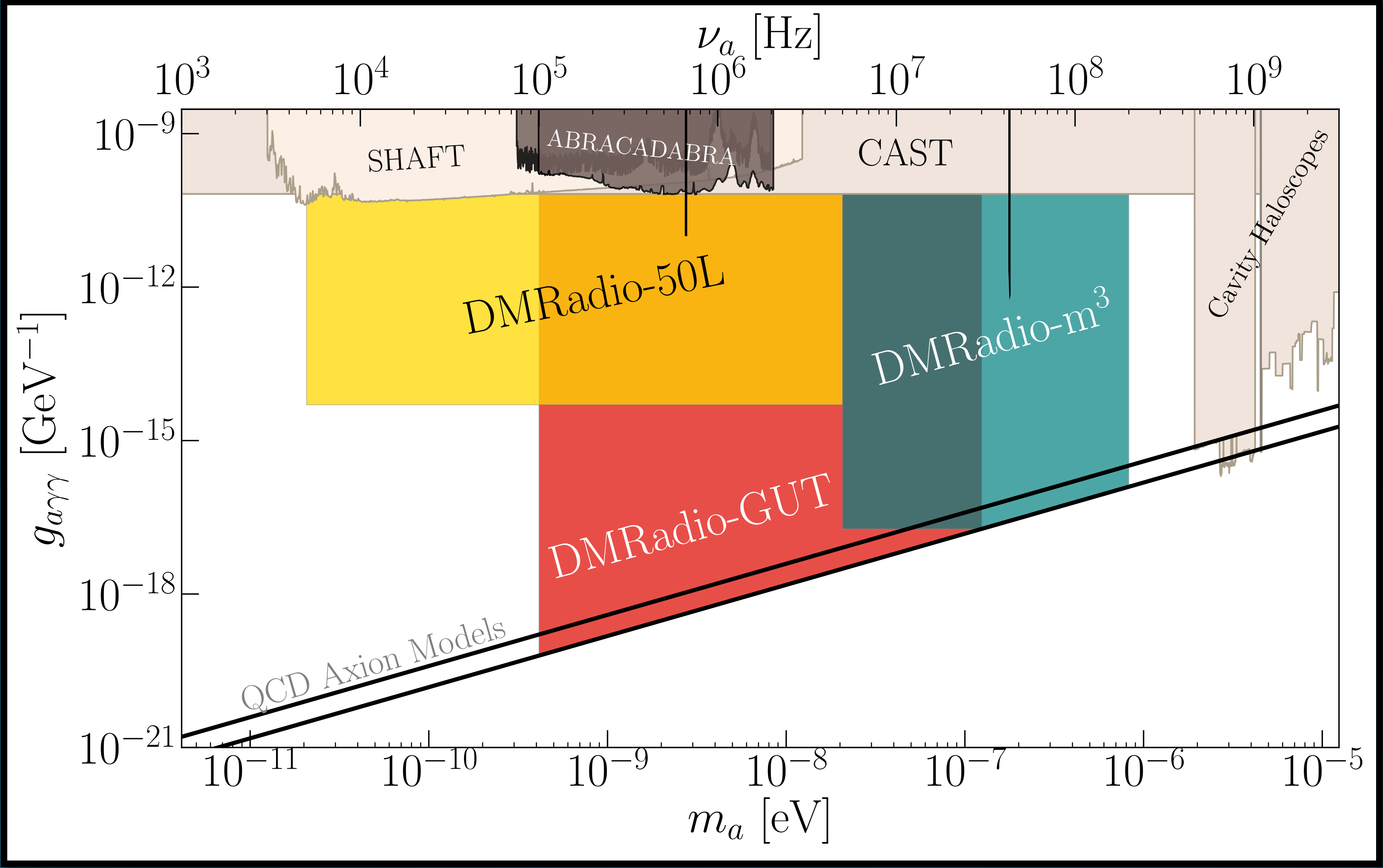
No axions found yet!



C. O'Hare

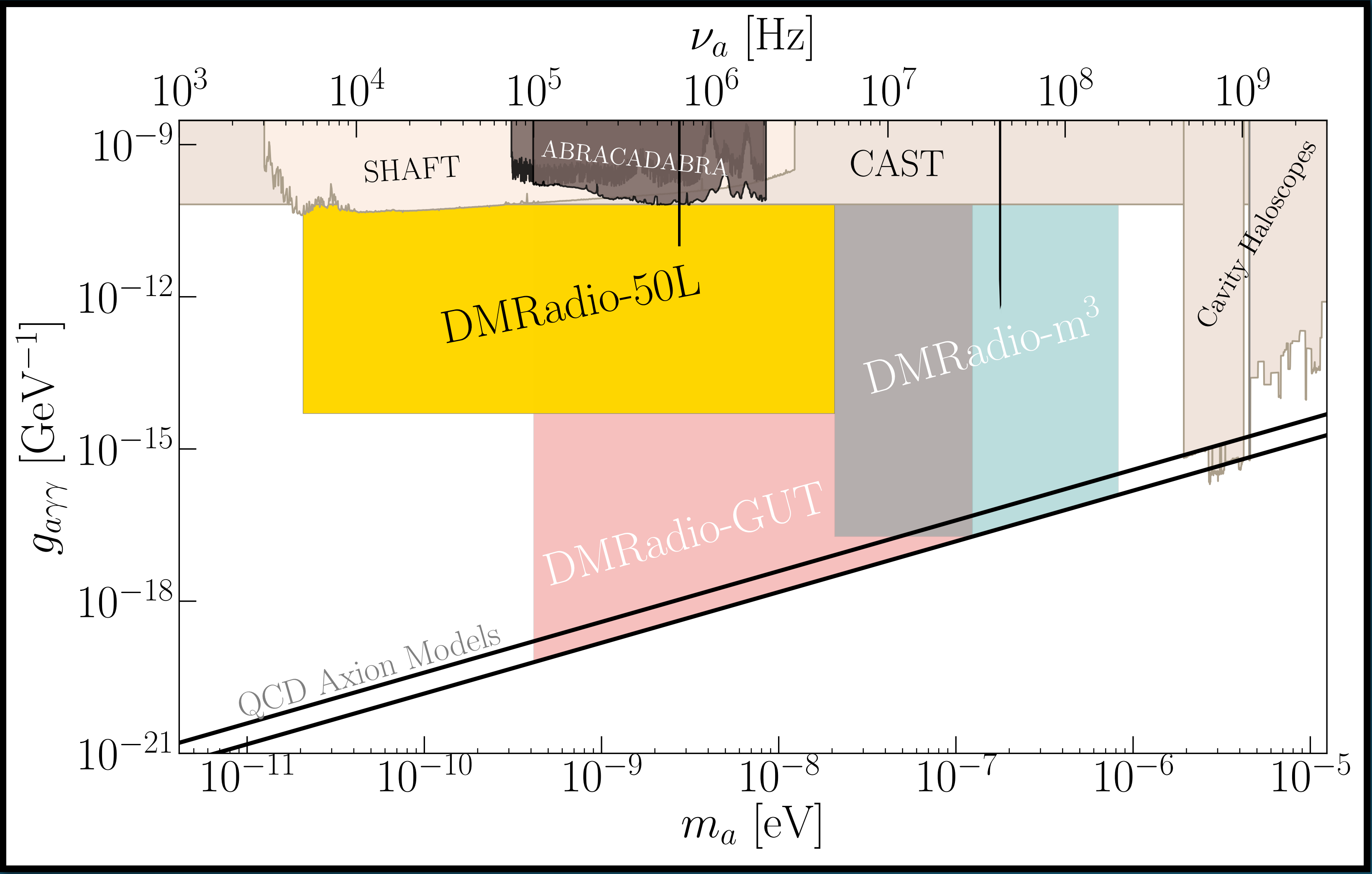
Salemi et al. *Phys.Rev.Lett.* 2021
Ouellet, Salemi et al. *Phys.Rev.Lett.* 2019
Ouellet, Salemi et al. *Phys.Rev.D* 2019

DMRadio program



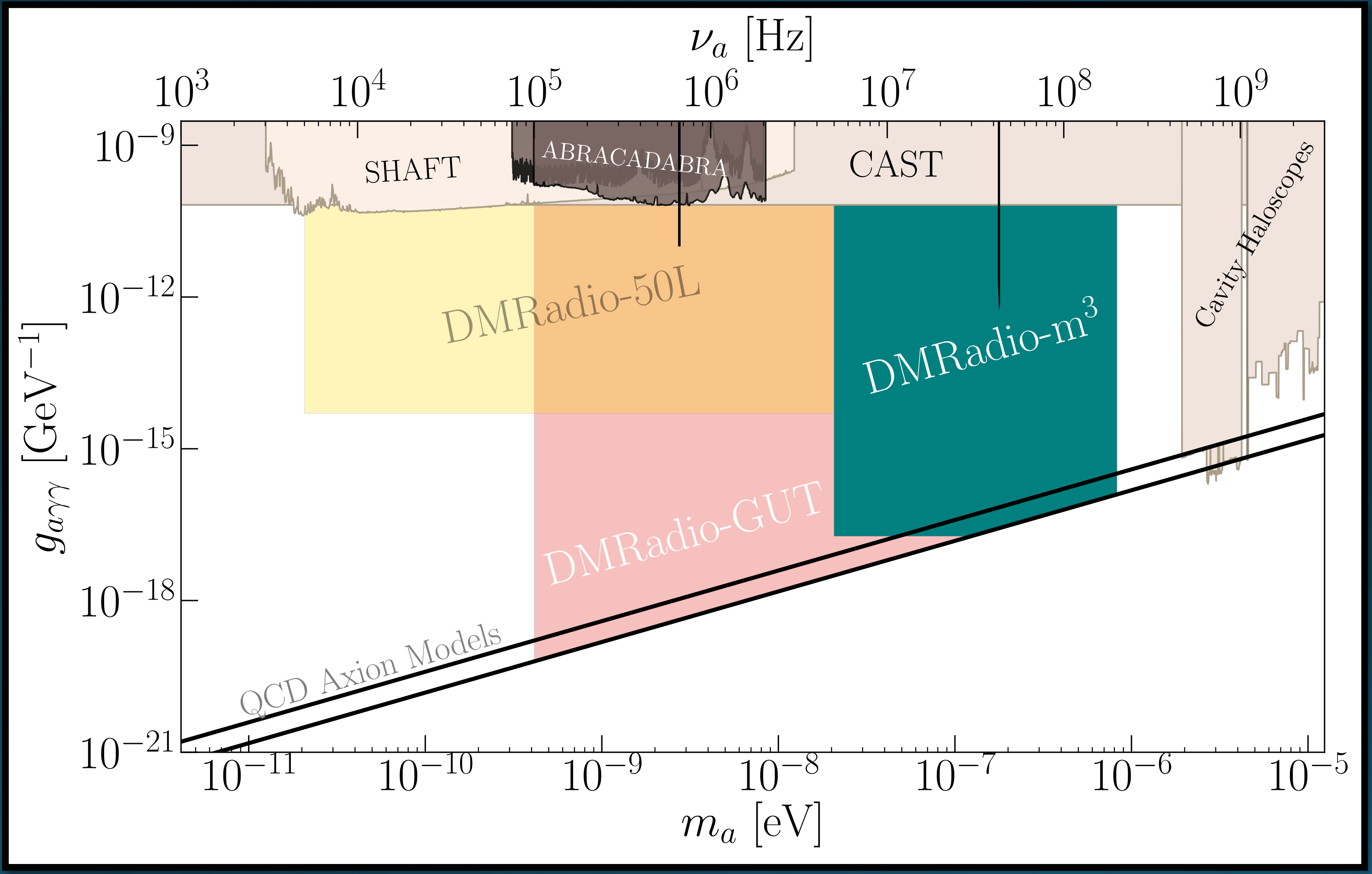
DMRadio-50L

Under construction



- ALP search kHz – MHz
- Demonstration of scaling up of lumped element method
- Testbed for new quantum sensors

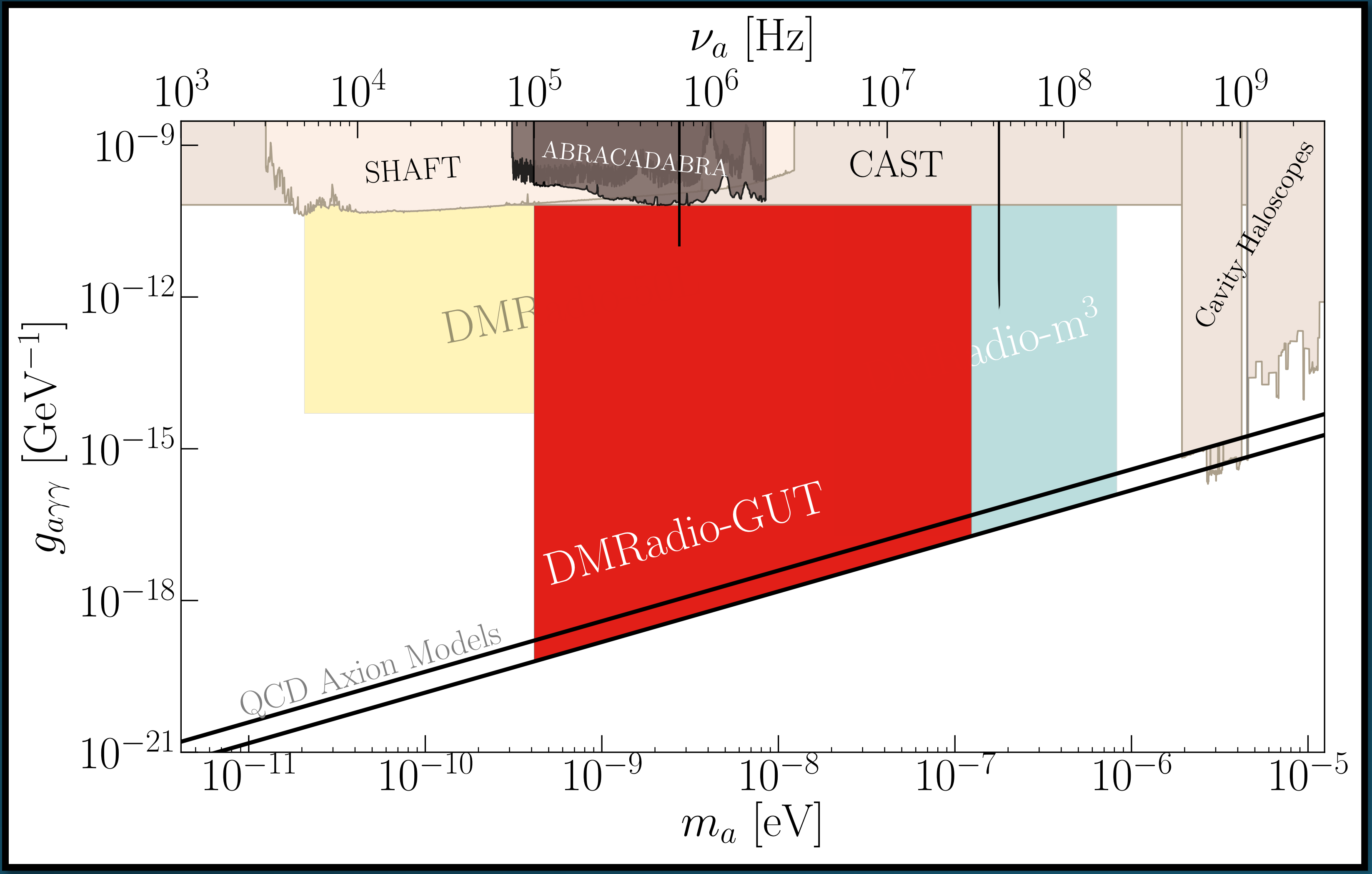
DMRadio-m³



- QCD axion search MHz – 100's MHz
- Based on robust technologies

Brouwer et al. *Phys.Rev.D*, 2022a
Benabou et al. *Phys.Rev.D*, 2023
AlShirawi et al. arxiv:2302.14084, 2023

DMRadio-GUT

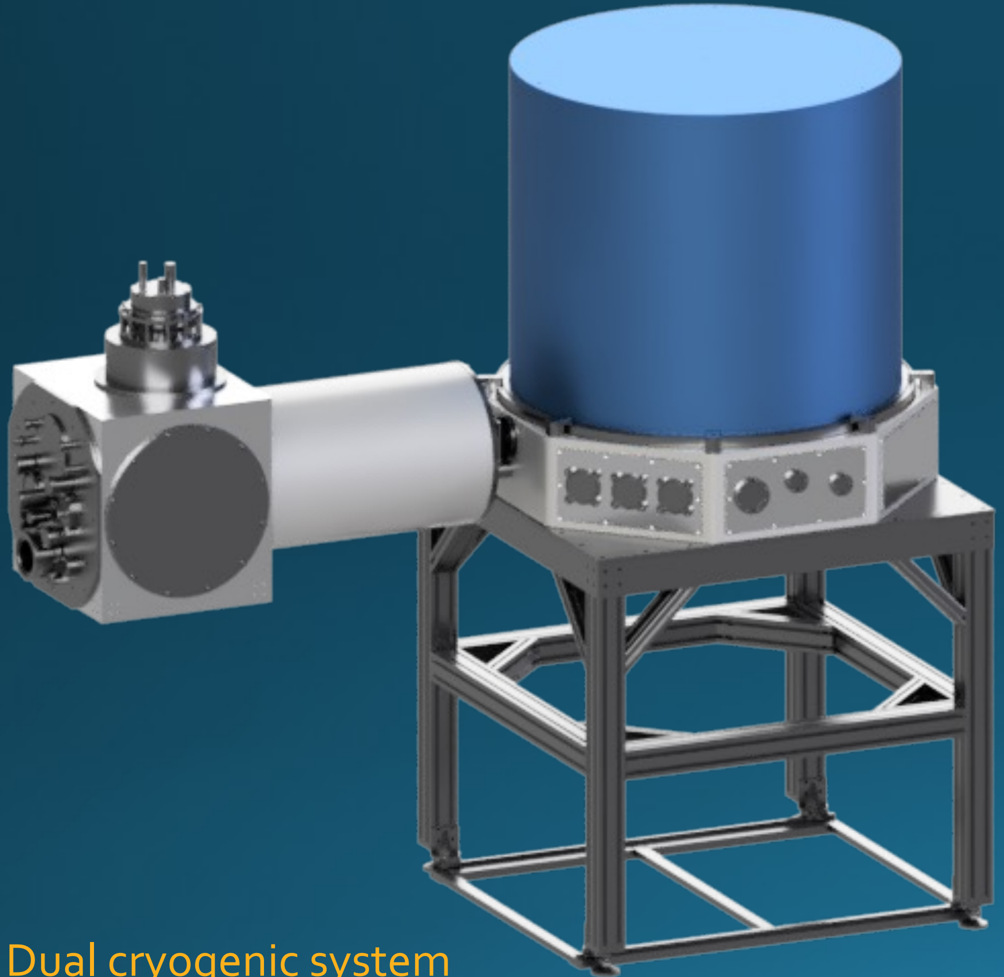


- QCD axion search kHz – MHz
- Probe of most motivated parameter space
- Platform for new technologies and techniques

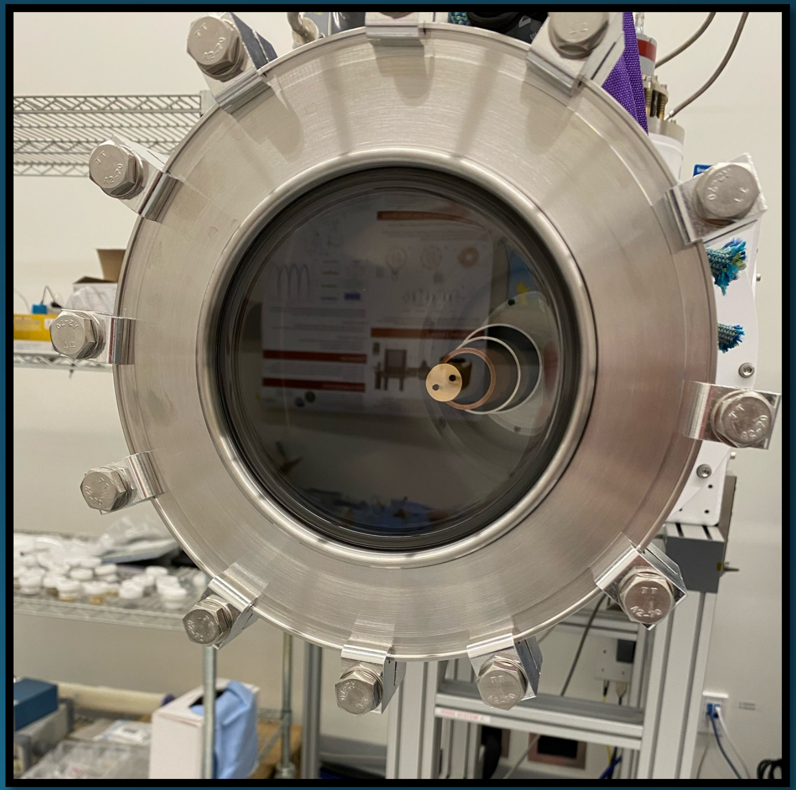
Brouwer et al. *Phys.Rev.D*, 2022b

What's happening now on DMRadio-50L

Cryostat under construction



Dual cryogenic system
(Four Nine Design, Maria Simanovskaia)

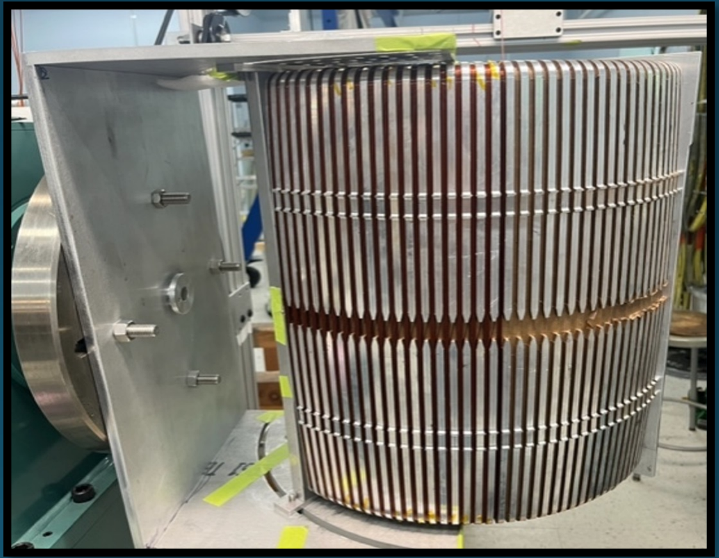


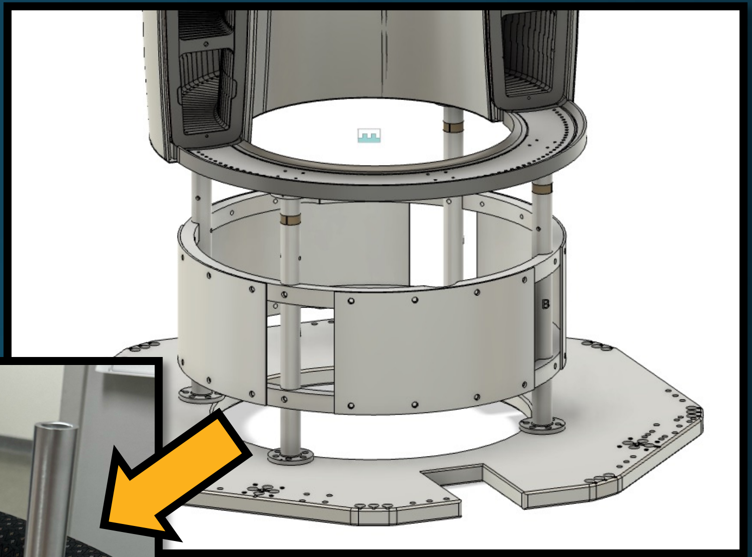
Cold snout testing
(Elizabeth Berzin, Aya Keller, Maria Simanovskaia, Nicholas Rapidis)

What’s happening now on DMRadio-50L

Magnet under construction

Magnet mandrel and winding
(Superconducting Systems, Inc.)



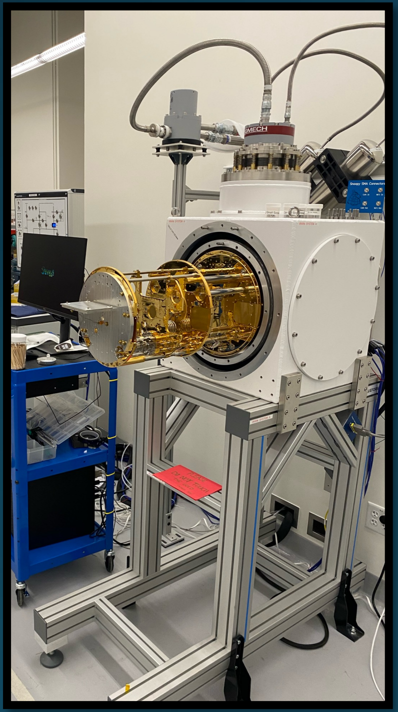


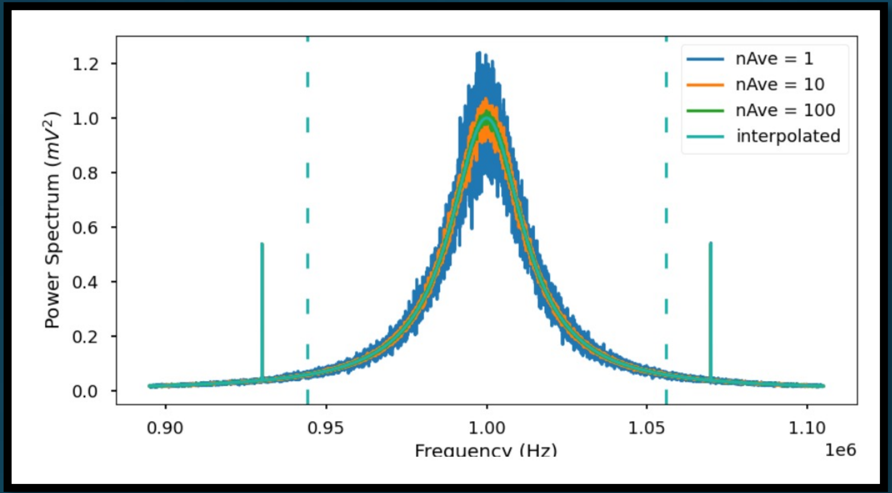
Magnet support legs
(Alex Droster, Johny Echevers)

What's happening now on DMRadio-50L

Many other systems in development/testing

Dilution fridge testing of prototype capacitor
(Joe Singh)

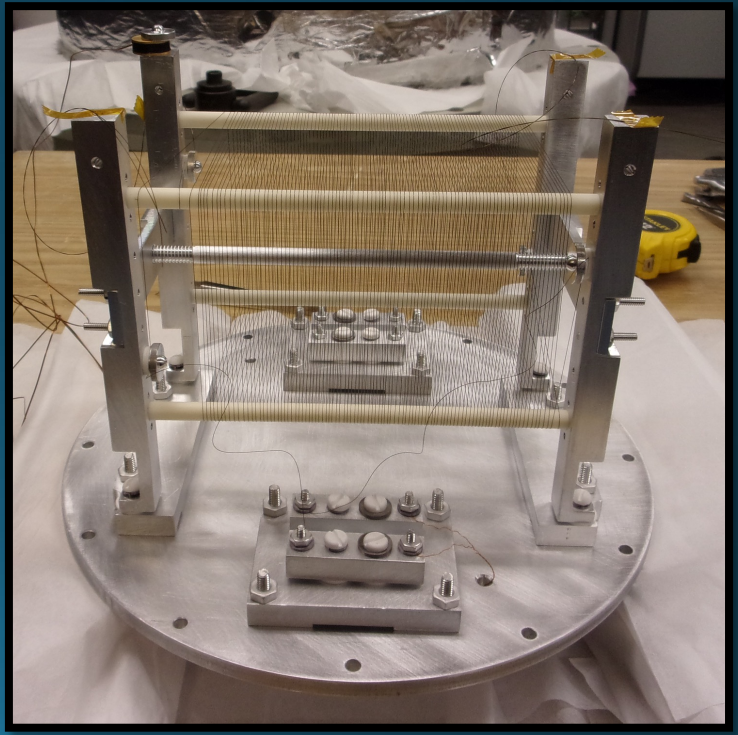




Sideband injection simulation
(Jessica Fry, CS)

Dip probe with resonator and SQUID readout for calibration testing
(Joe Singh, CS)

Prototype resonator: Q ~ 720,000
(Roman Kolevatov, Saptarshi Chaudhuri)



How do we get more sensitive?

Scan rate:

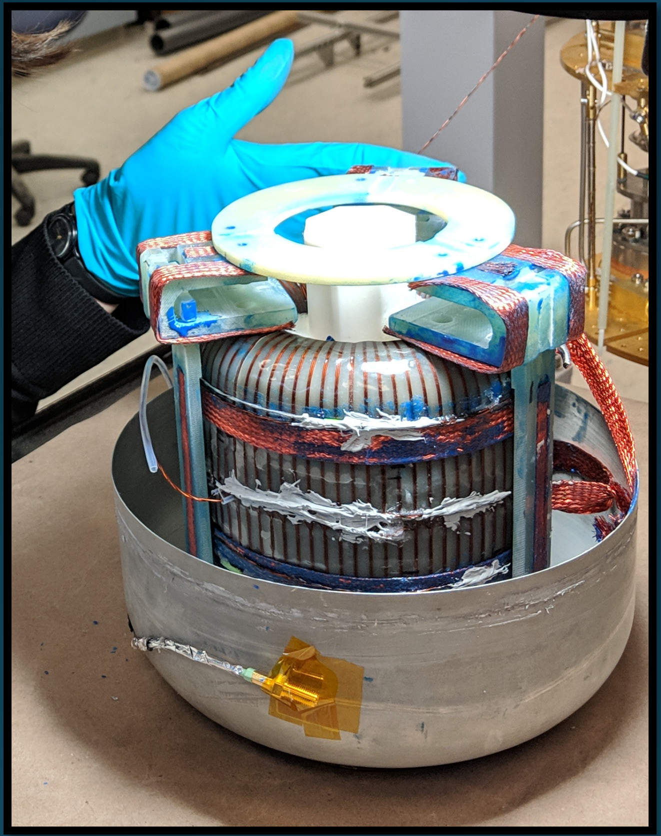
$$\frac{d\nu}{dt} \approx \frac{1}{\mathrm{SNR}^2} \underbrace{\left(g_{a\gamma\gamma}^4 \rho_{\mathrm{DM}}^2 Q_a \nu\right)}_{\text{axion physics}} \underbrace{\left(c_{\mathrm{PU}}^4 \frac{Q B_0^4 V^{10/3}}{k_B T \eta}\right)}_{\text{detector}}$$

Critical development paths

- Magnet
- Resonator
- Sensors

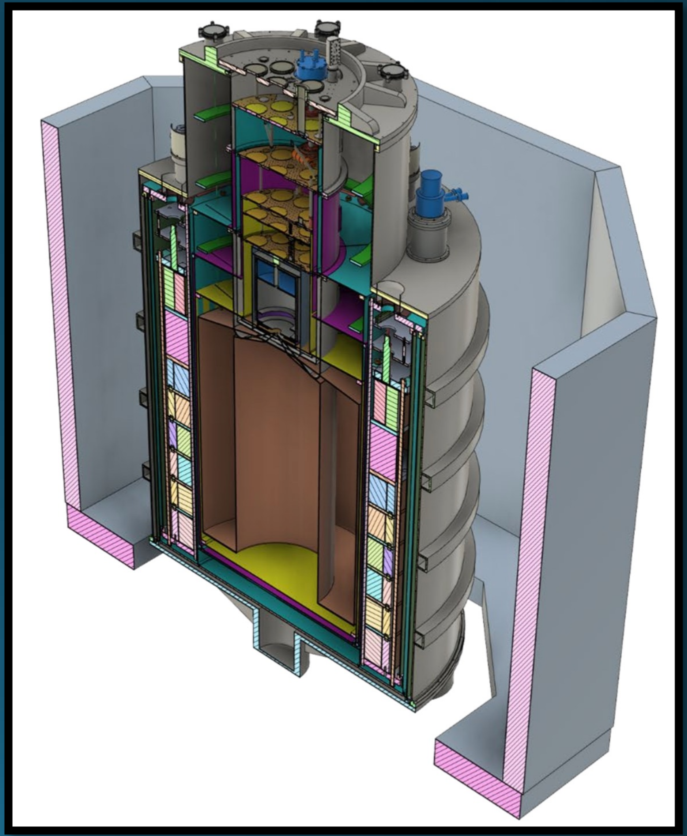
$$\frac{d\nu}{dt} \approx \frac{1}{\mathrm{SNR}^2}\left(g_{a\gamma\gamma}^4 \rho_{\mathrm{DM}}^2 Q_a \nu\right)\left(c_{\mathrm{PU}}^4 \frac{\boxed{Q}\,\boxed{B_0^4 V^{10/3}}}{k_B T \boxed{\eta}}\right)$$

Magnets so far



ABRA-10cm: 1T, 0.9L, NbTi

DMRadio-50L: 1T, 50L, NbTi

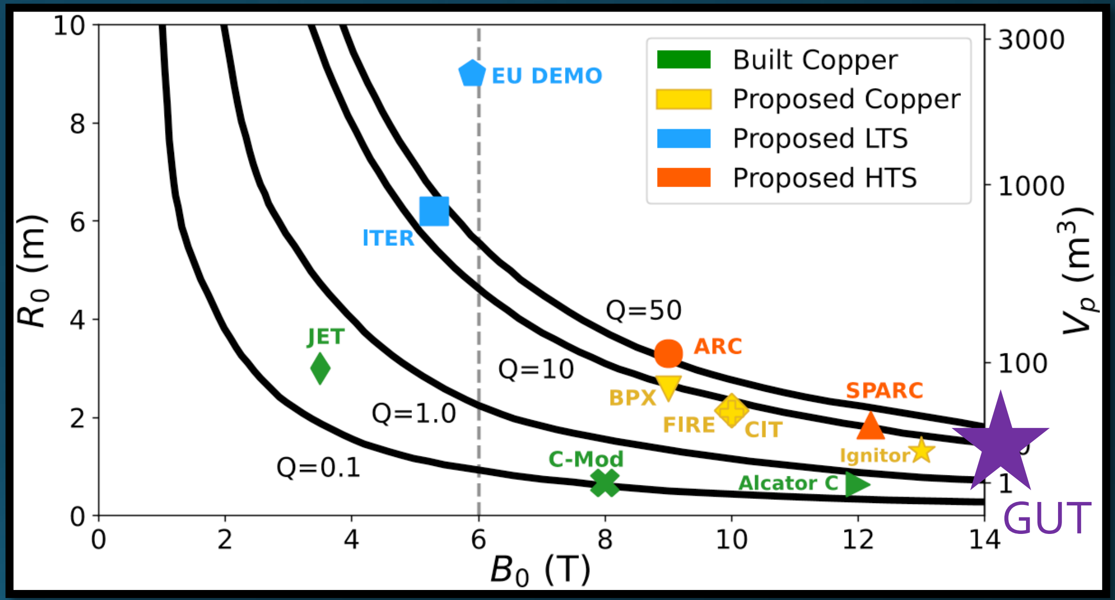


DMRadio-m^3: ~5T, 1000L, NbTi

Magnet for GUT

Need advanced magnet materials and engineering

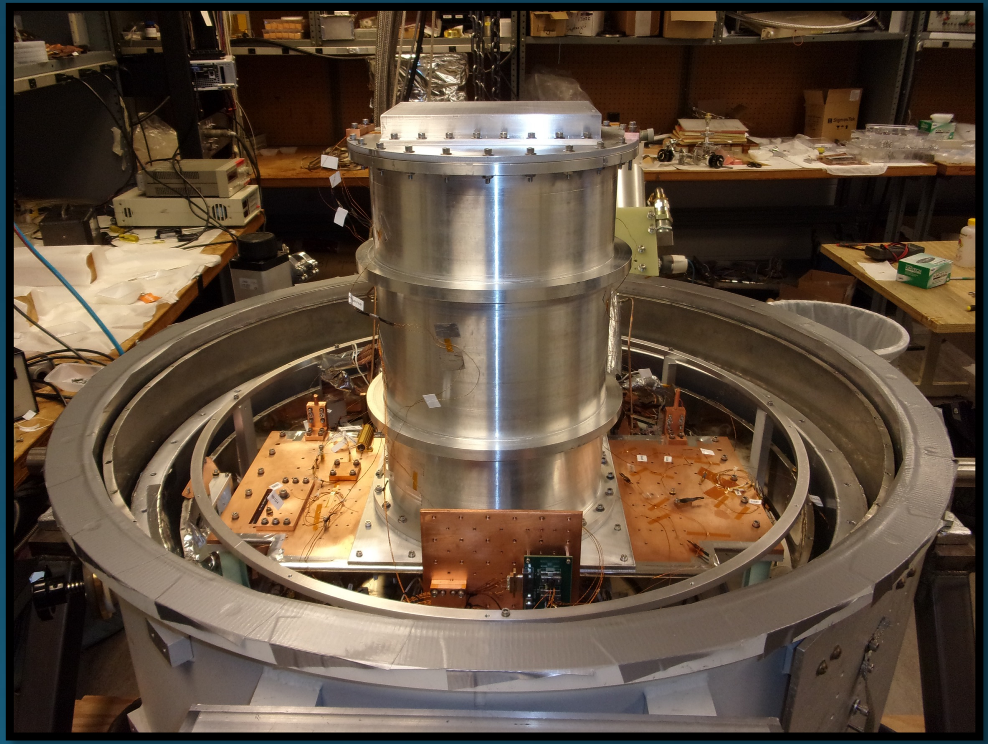
- Nb_3Sn
- High temperature superconductors (HTS)



Comparison to fusion magnets
Creely et al. (SPARC)

Resonator for GUT

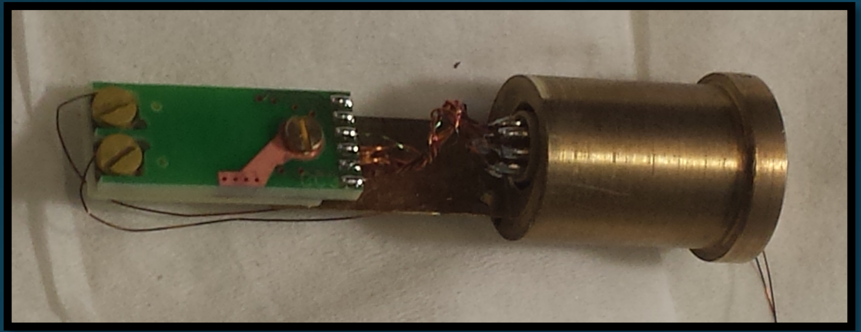
- Goal Q ~ $10^6 - 10^7$
- Achieve with
  - Passive resonator
  - Active components?



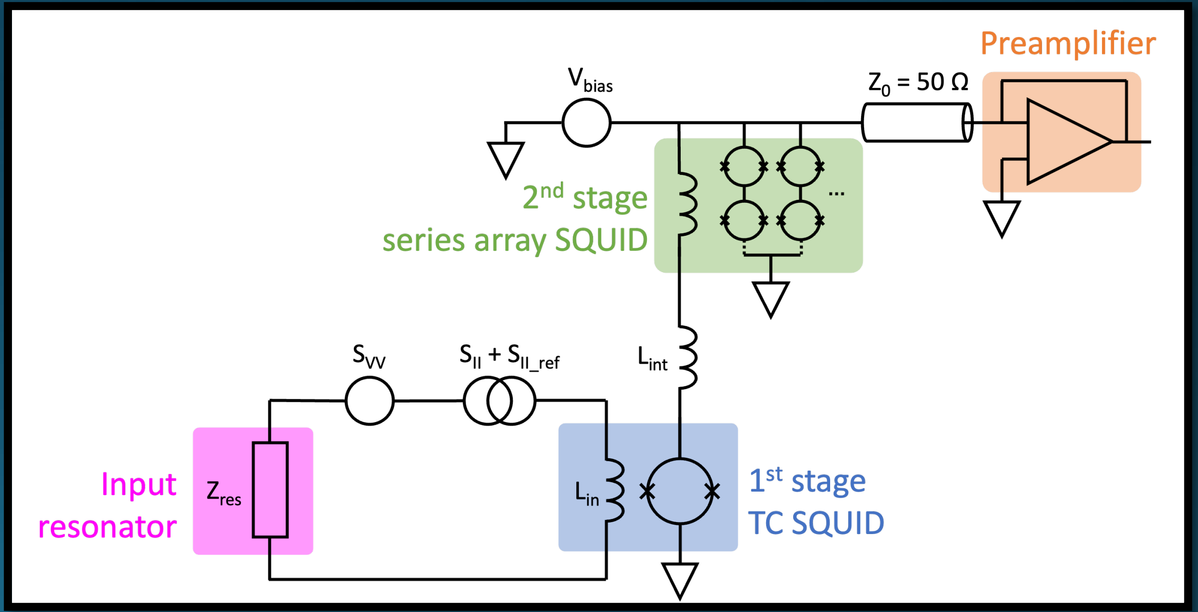
Princeton resonator test setup

Sensors so far: SQUIDs

- Above Standard Quantum Limit (SQL)
  - Add > half photon of noise



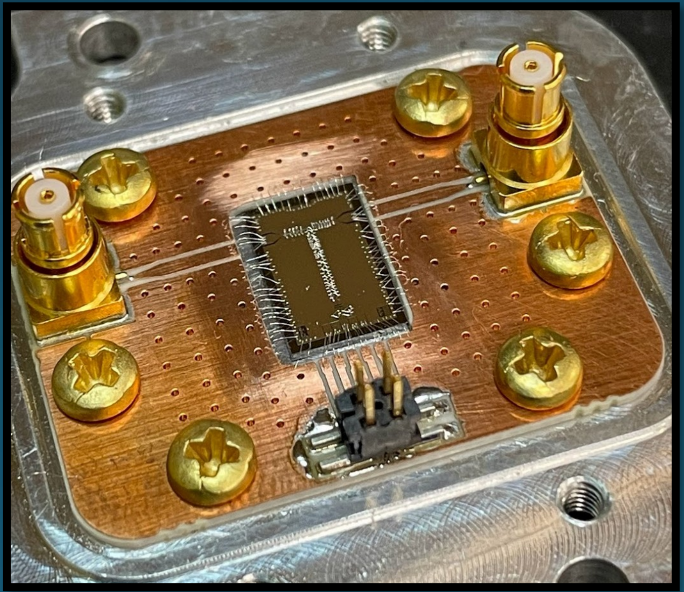
ABRA-10cm Magnicon 2-stage SQUID
(Similar system for DMRadio-50L)



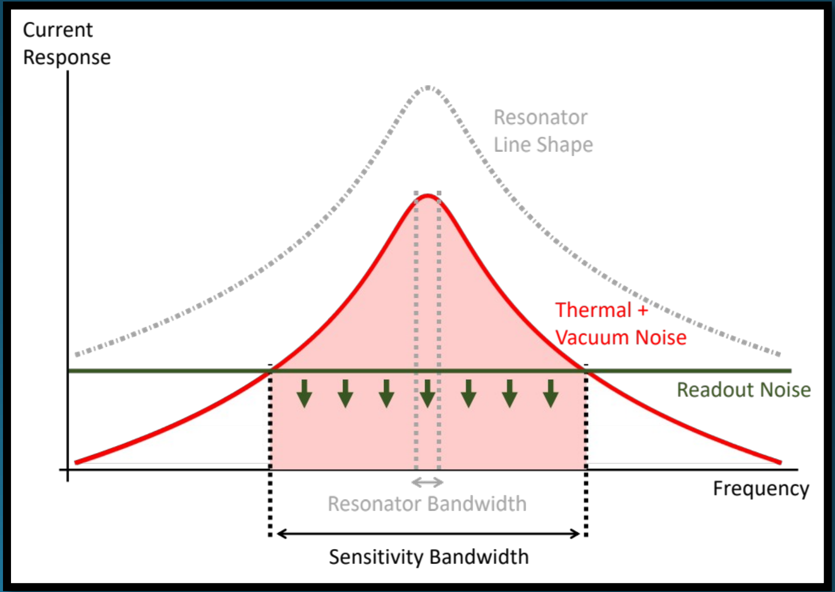
DMRadio-m³ planned SQUID chain
(CS, Kent Irwin)

Sensors for GUT: RQUs

- RF Quantum Upconverters (RQUs)
  - Capable of phase sensitive amplification → beyond-SQL performance
  - "Backaction evasion"
- Improve sensitivity bandwidth for faster scanning



RQU chip
(Cady van Assendelft)



Sensitivity bandwidth

GUT scenarios

Scenario	B_0	V	c_{PU}	Q	η_A	T	*Scan time*
Baseline	16 T*	10 m^3	0.1	20×10^6	−20 dB	10 mK	6.2 years
Stronger magnet + higher noise	29 T	10 m^3	0.1	20×10^6	−5 dB	10 mK	3.2 years
Lower noise + lower volume	16 T	8 m^3	0.1	20×10^6	−25 dB	10 mK	7.3 years
Higher volume + lower Q	16 T	17 m^3	0.1	2×10^6	−20 dB	10 mK	10.6 years
Stronger magnet + lower Q	26 T	10 m^3	0.1	2×10^6	−20 dB	10 mK	8.9 years

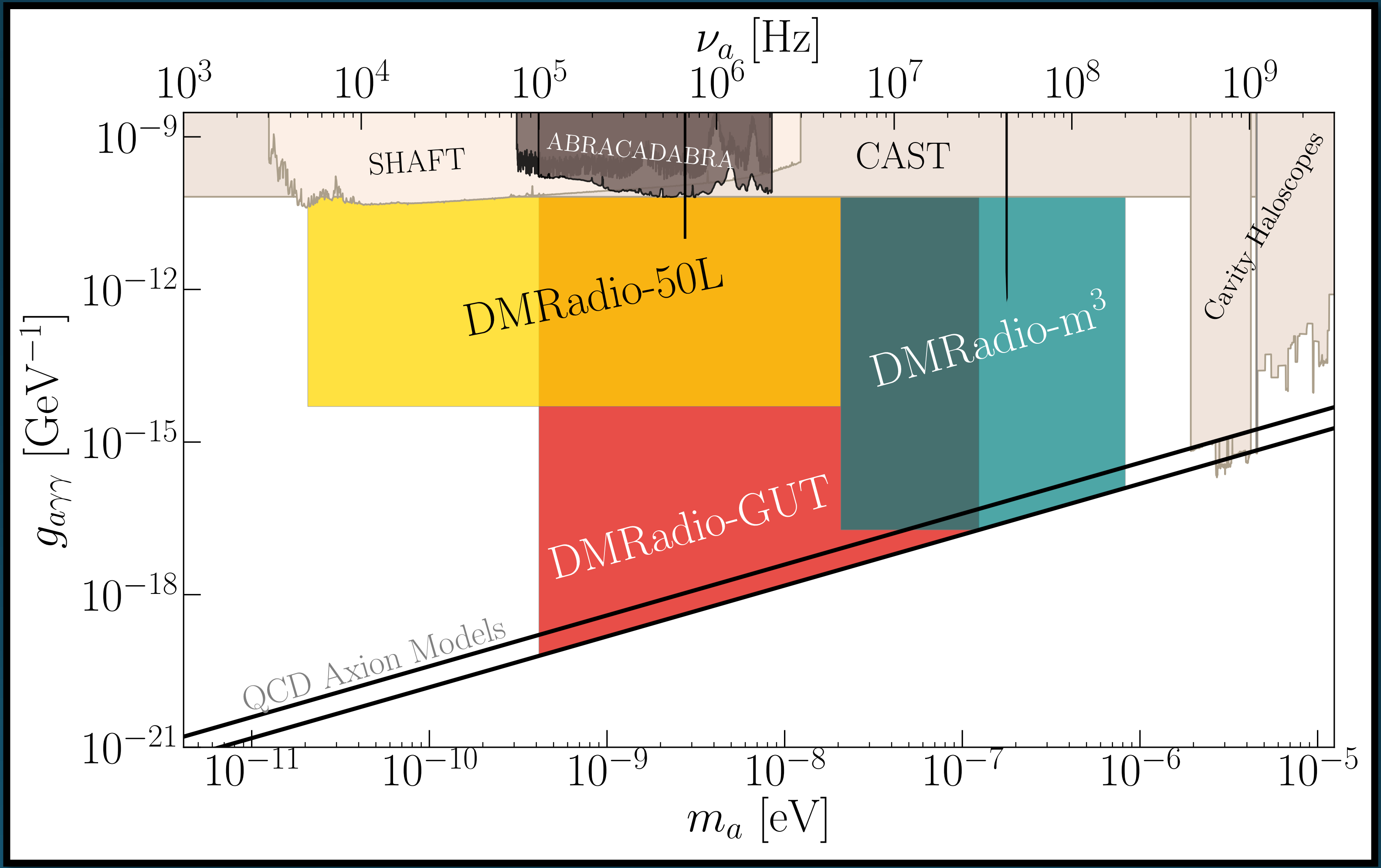
Brouwer et al. *Phys.Rev.D*, 2022b

*16 T peak/12 T RMS

Summary

- The lumped element method enables direct searches for low-mass axion dark matter
- DMRadio-50L is under construction now—stay tuned!
- DMRadio-m^3 and DMRadio-GUT will reach QCD axion sensitivities
- R&D is under way to prepare for GUT

Thank you!



ν_a [Hz]
10^3 10^4 10^5 10^6 10^7 10^8 10^9
10^{-9}
10^{-12}
10^{-15}
10^{-18}
10^{-21}
$g_{a\gamma\gamma}$ [GeV^{-1}]
SHAFT
ABRACADABRA
CAST
Cavity Haloscopes
DMRadio-50L
DMRadio-m^3
DMRadio-GUT
QCD Axion Models
10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5}
m_a [eV]