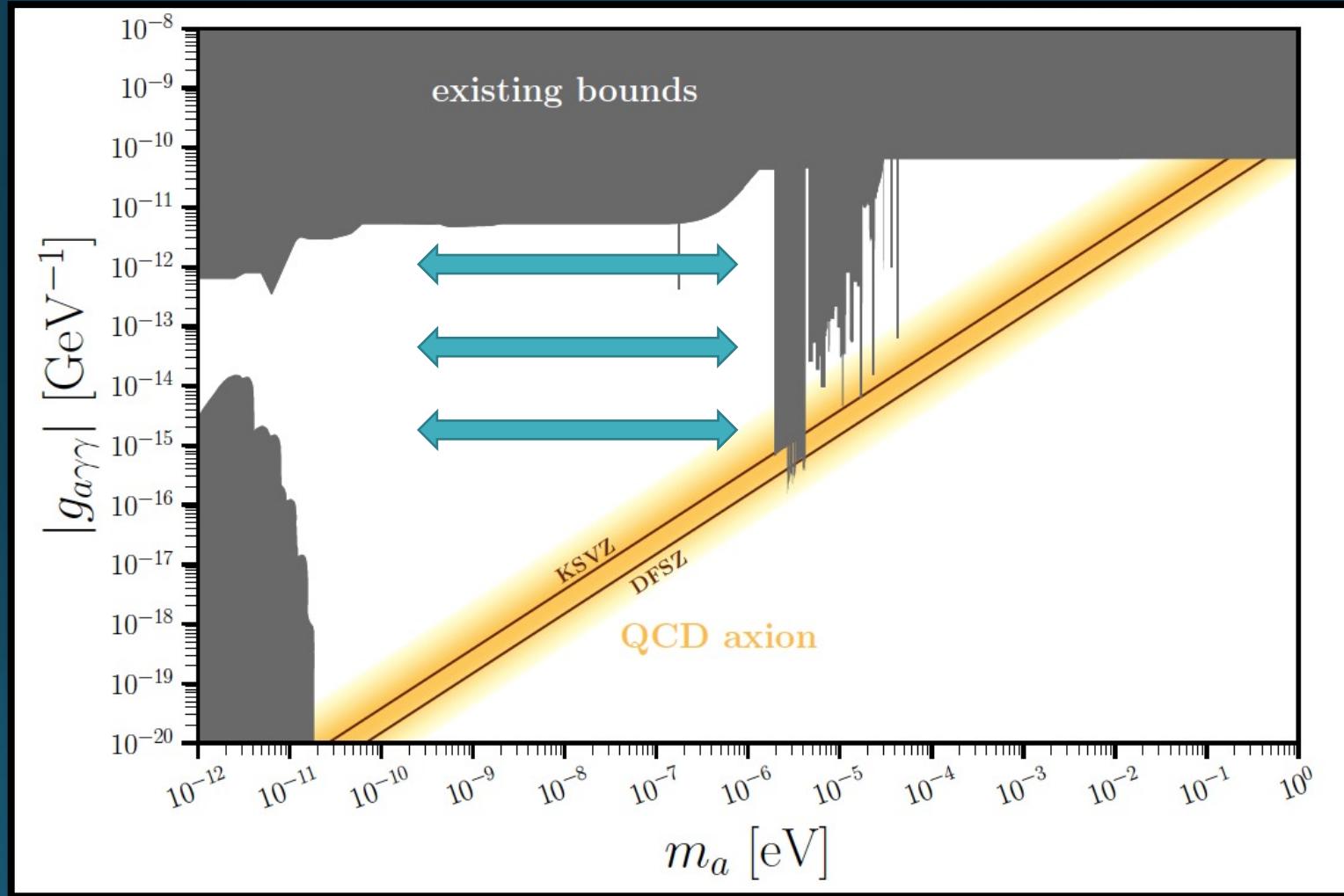


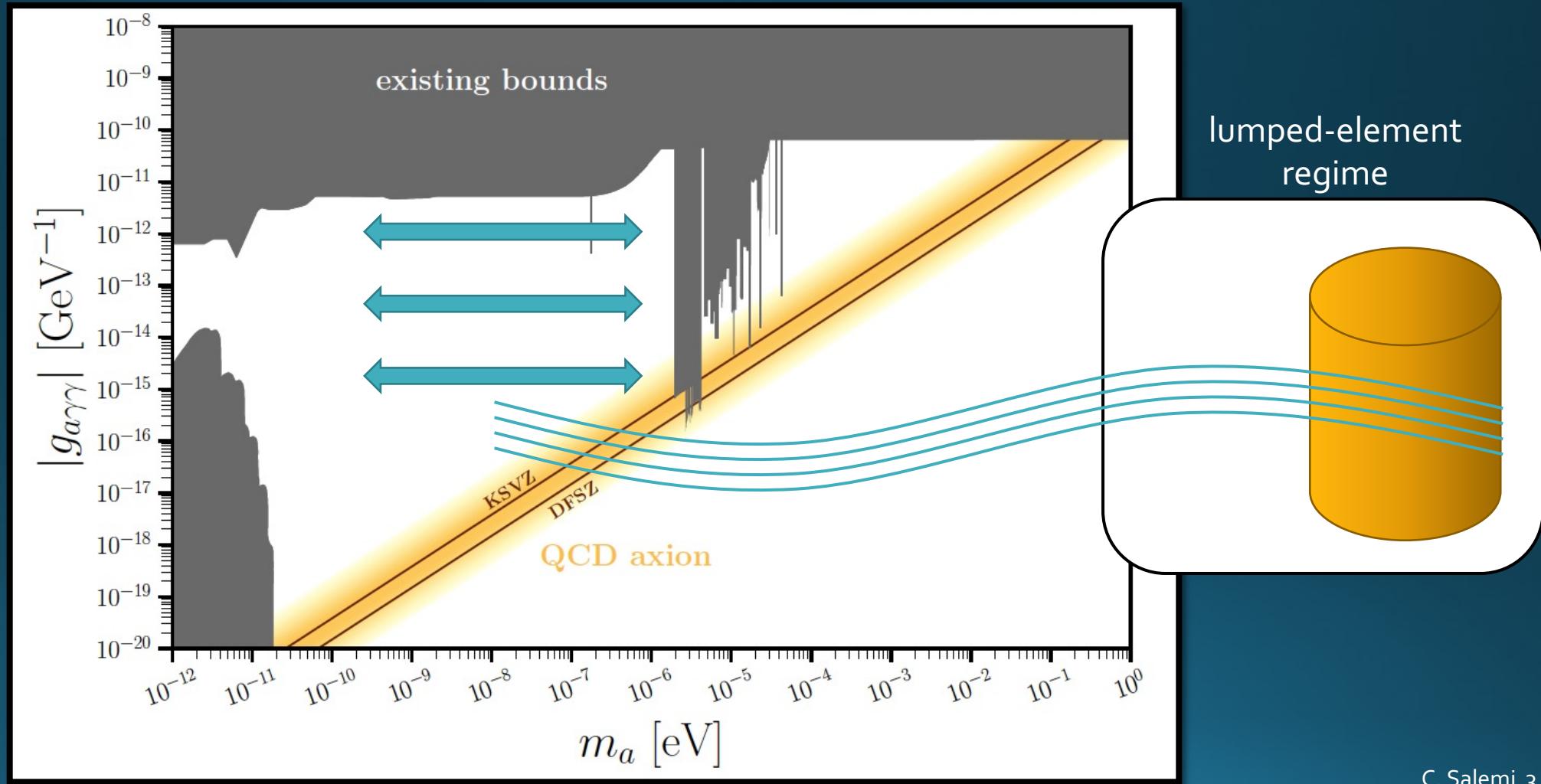
The Search for Low-Mass Axion Dark Matter with DMRadio

Chiara P. Salemi
Stanford University and SLAC
TAUP, August 2023

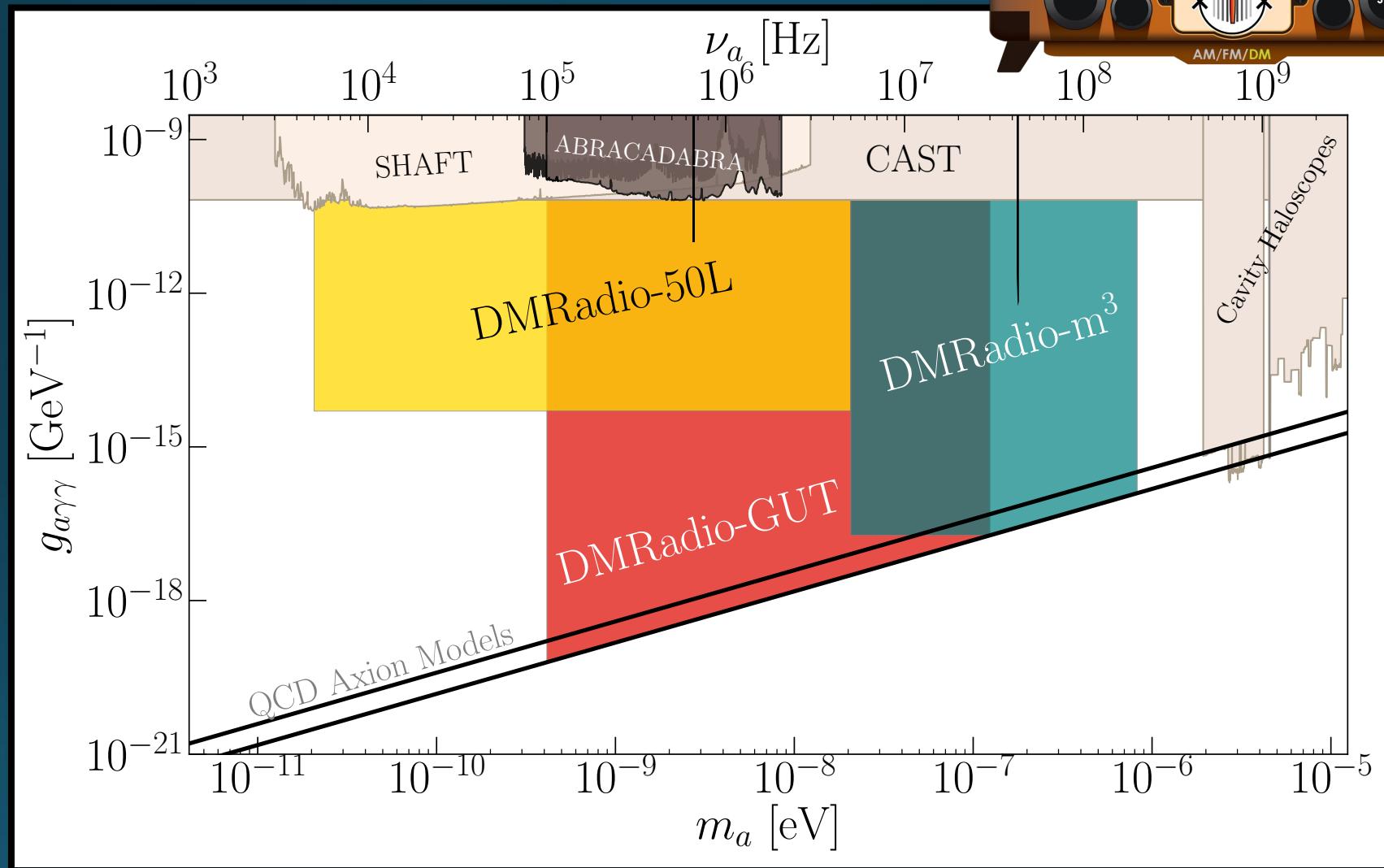
Lots of highly motivated parameter space to cover at low masses!



Lots of highly motivated parameter space to cover at low masses!



• ABRACADABRA → +



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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Axion E&M

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



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

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

Scan rate (our sensitivity FOM)

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

ν : resonator frequency

Q_a : axion quality factor

Q : resonator quality factor

c_{PU} : pickup coupling

B_0 : peak magnetic field

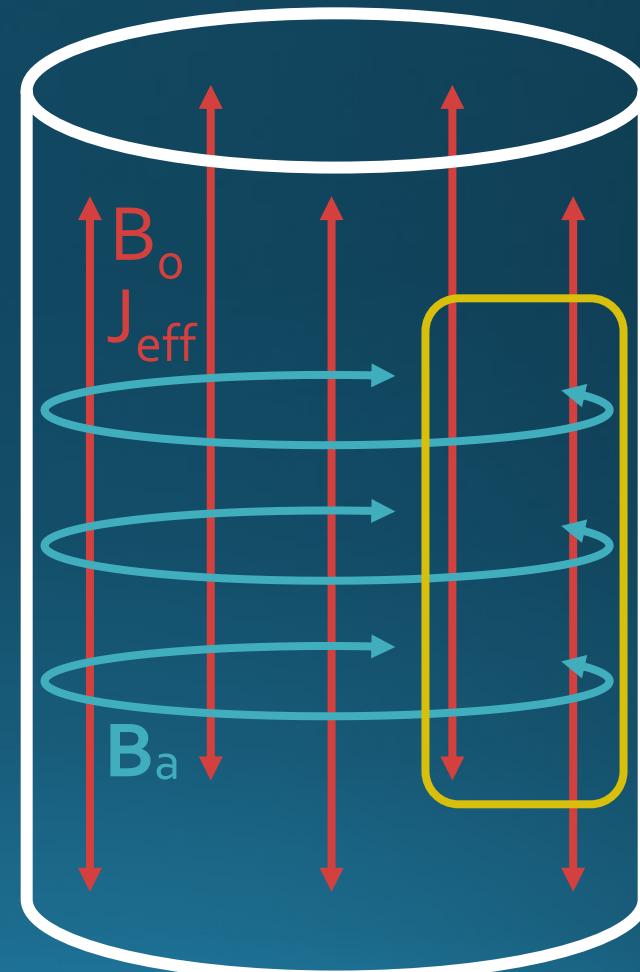
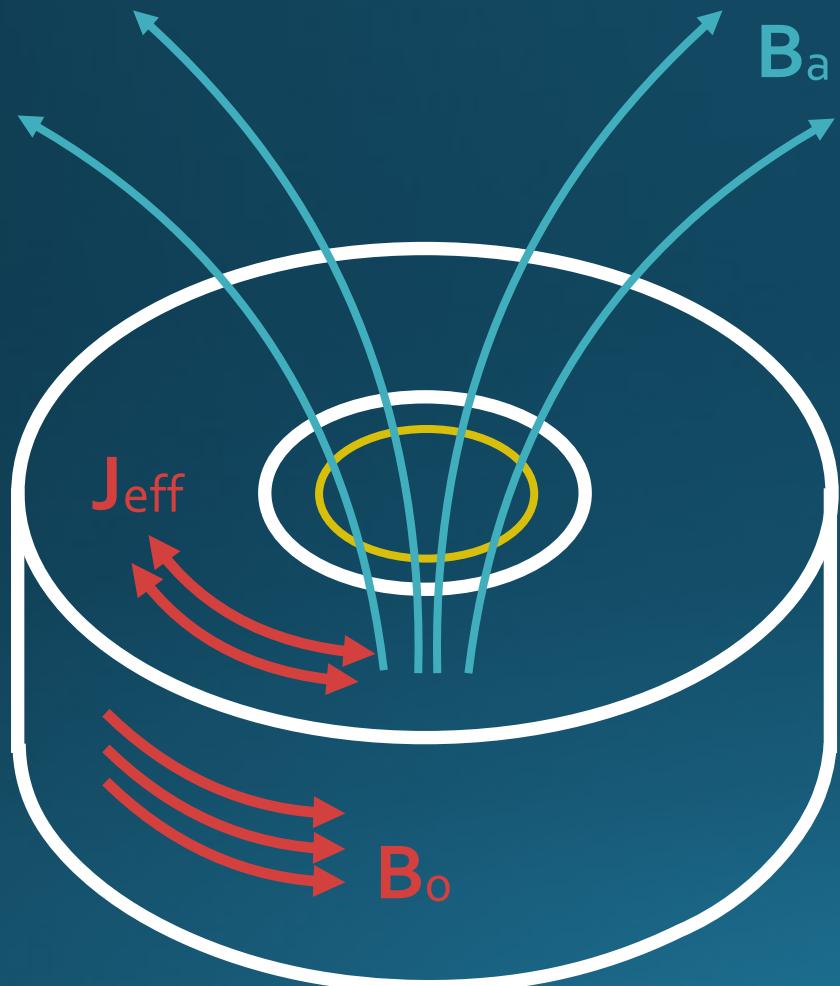
V : pickup volume

T : system effective temperature

η : amplifier noise

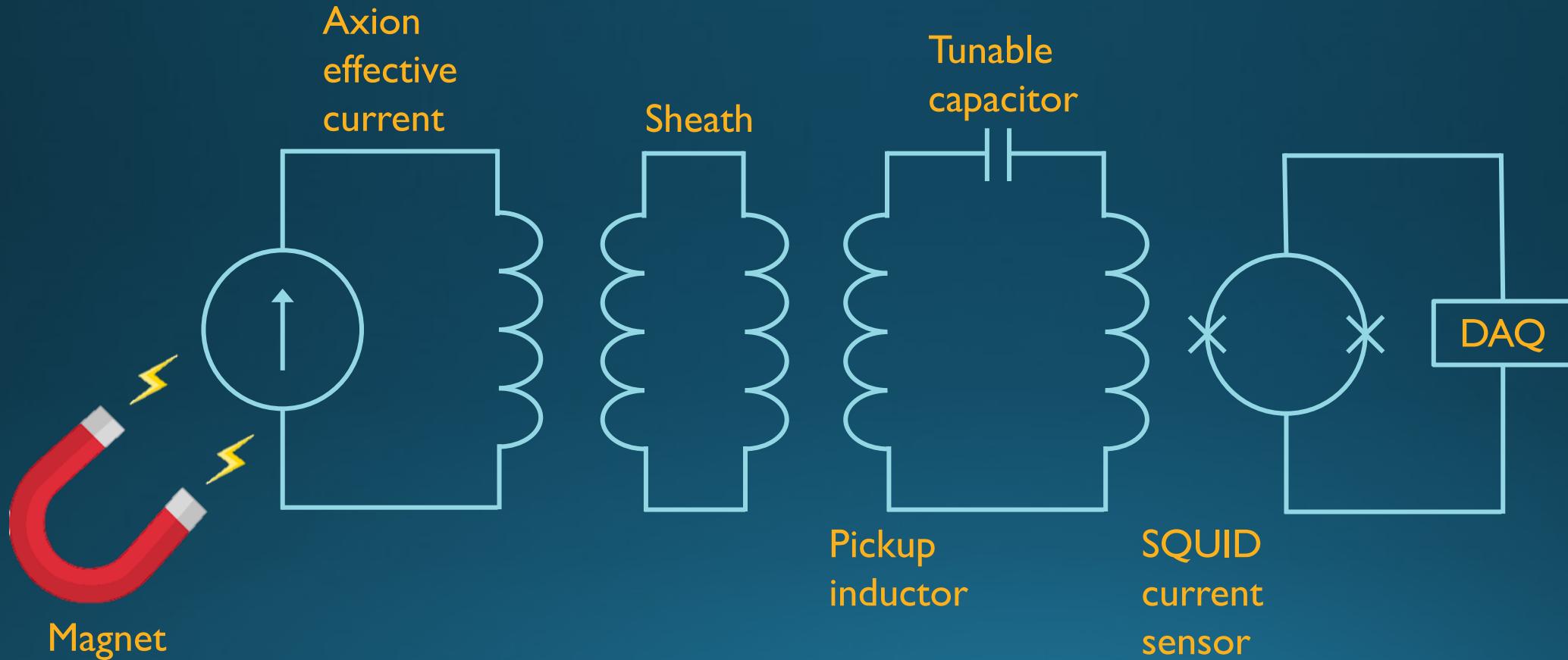
Detector geometry: toroid vs solenoid

ABRA-10cm
DMRadio-50L
(DMRadio-GUT)



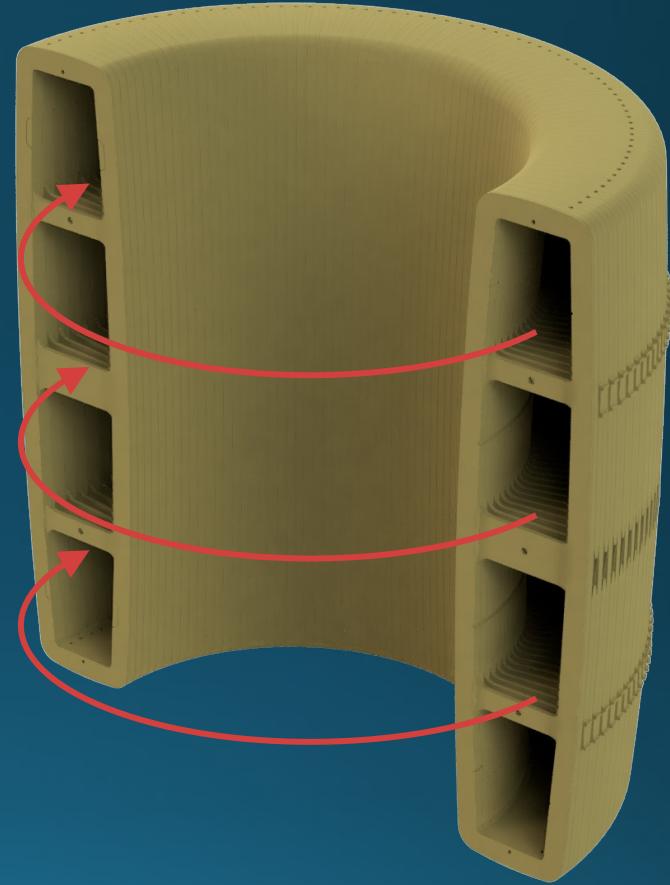
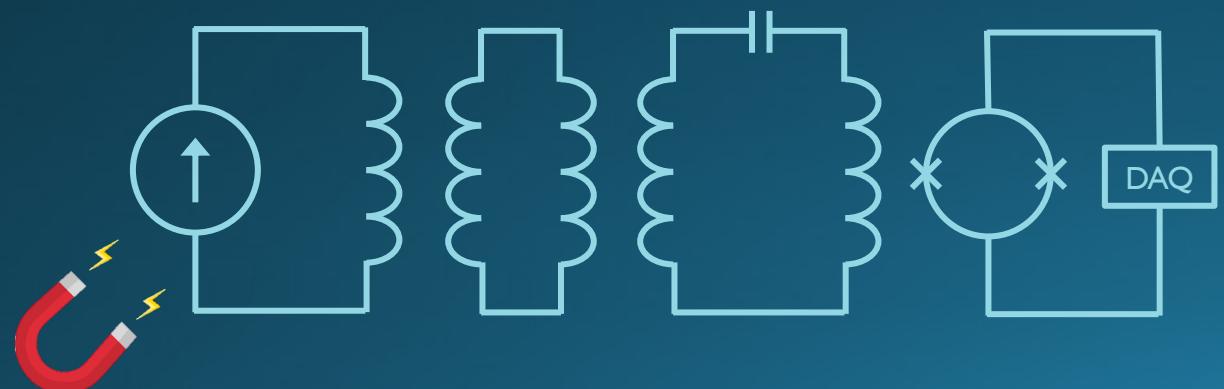
DMRadio-m³

Schematic of lumped-element detection



The 50L detector

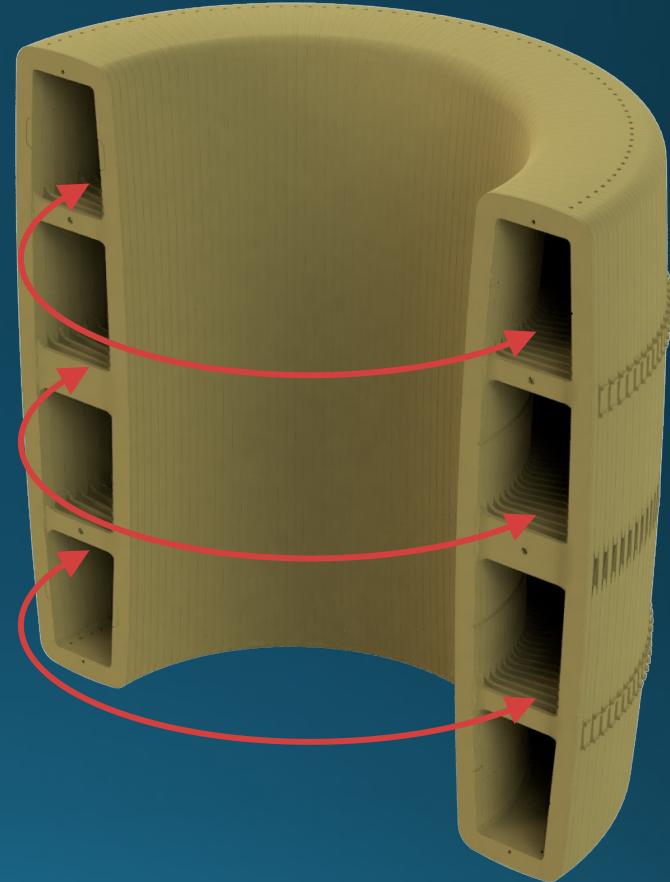
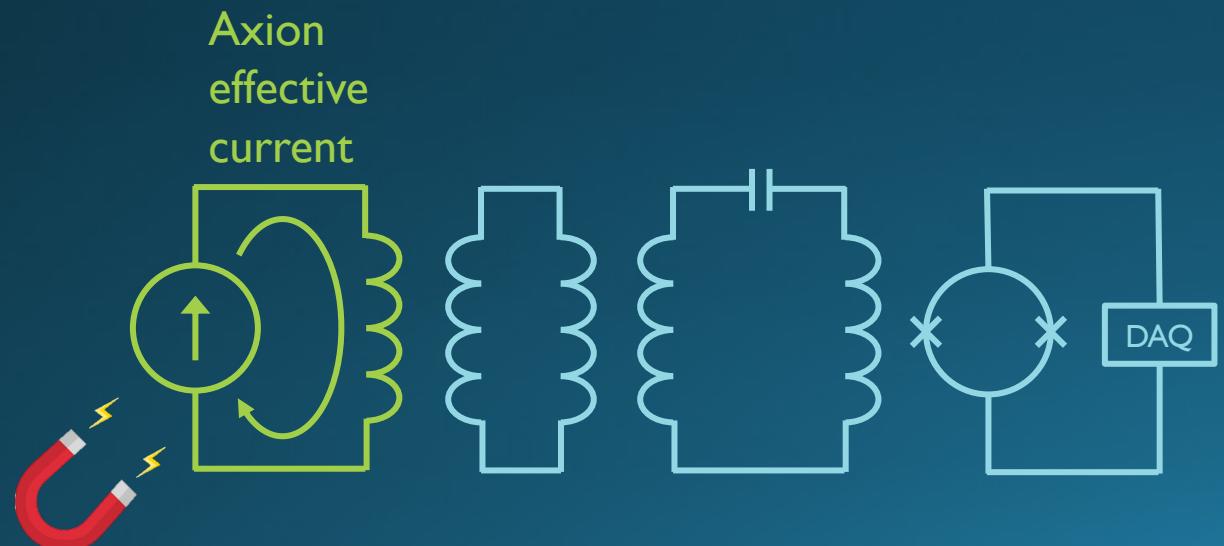
Toroidal superconducting magnet
with fixed field, B_0



The 50L detector

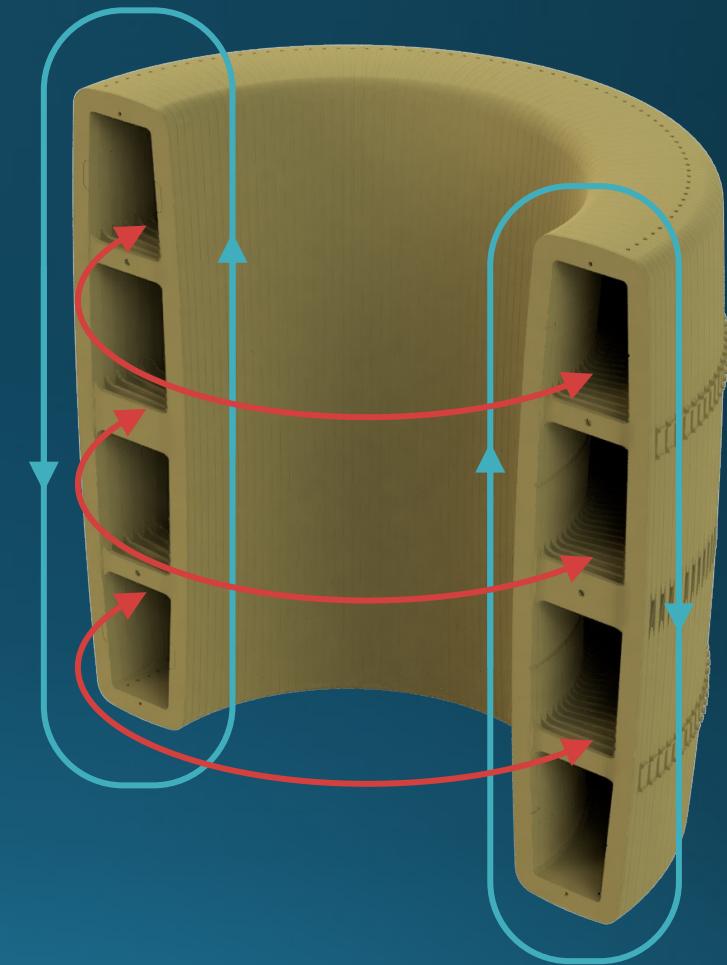
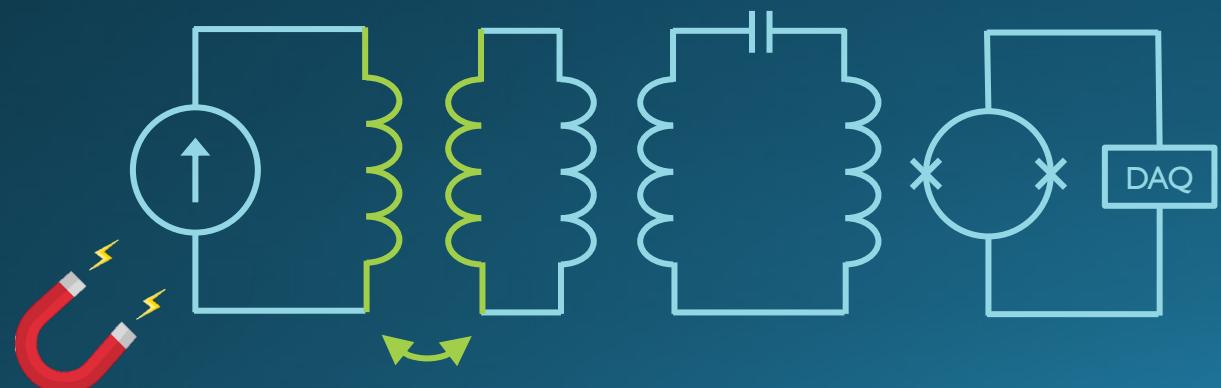
Axion dark matter generates parallel oscillating effective current, \mathbf{J}_{eff}

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



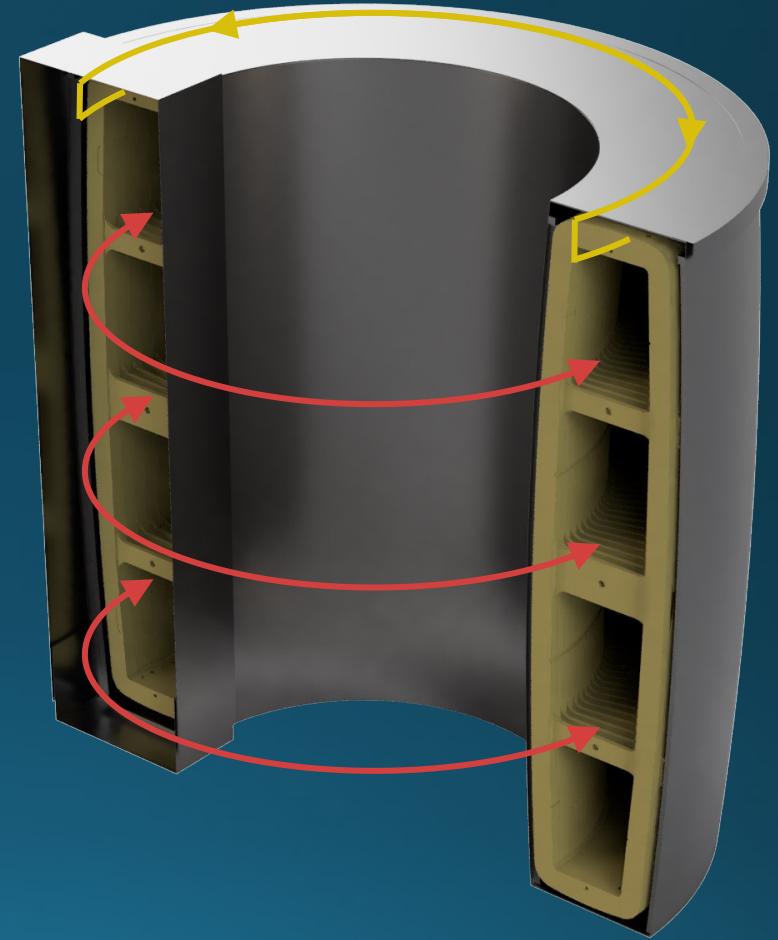
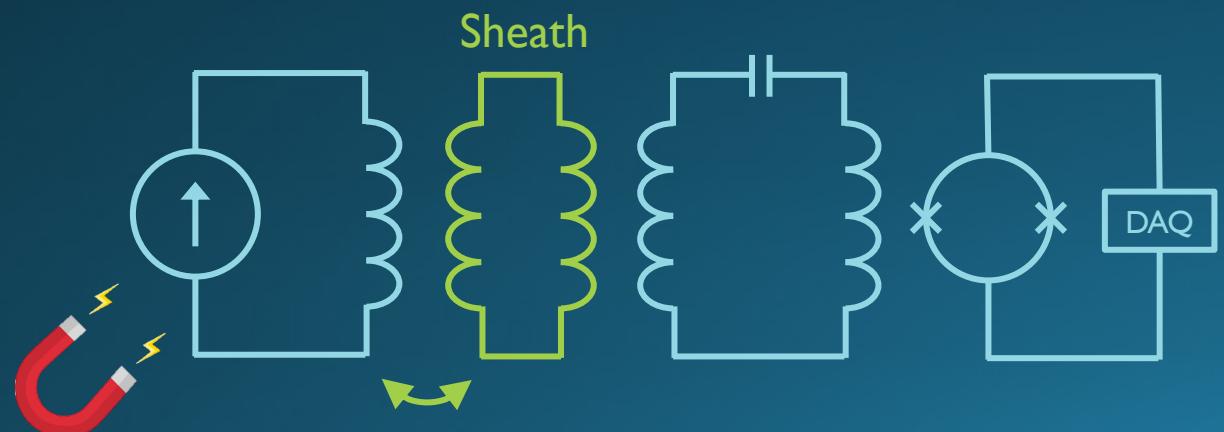
The 50L detector

Axion dark matter generates parallel oscillating effective current, \mathbf{J}_{eff} , which generates an oscillating magnetic field



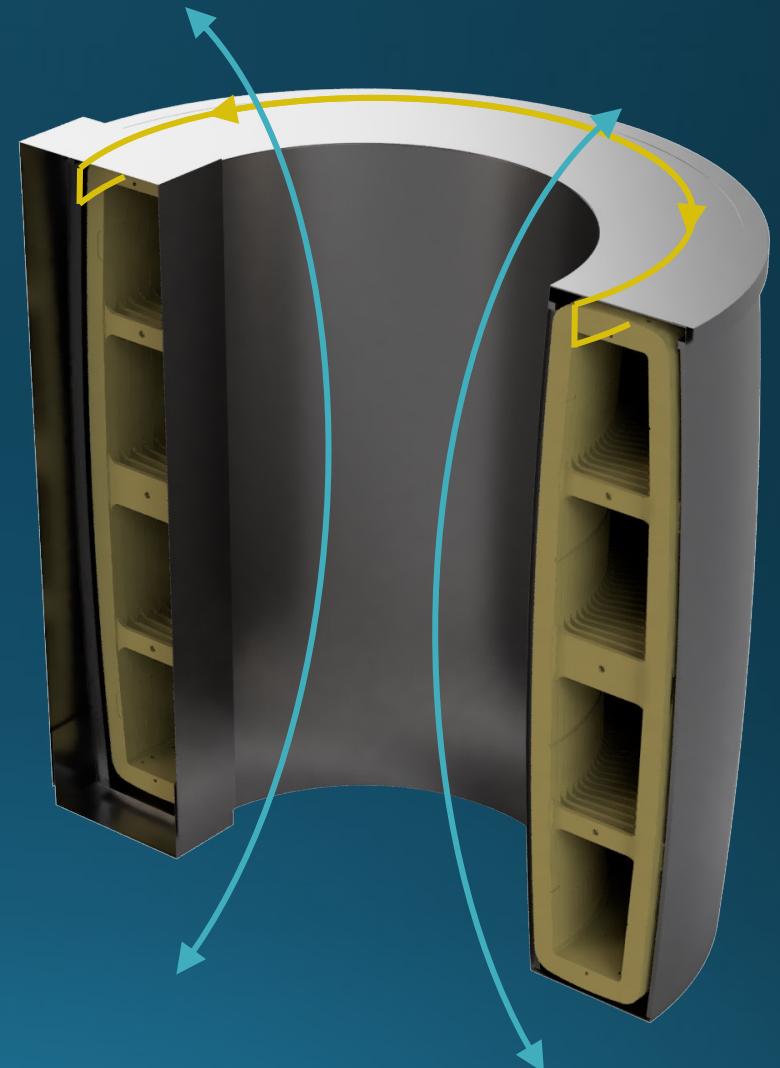
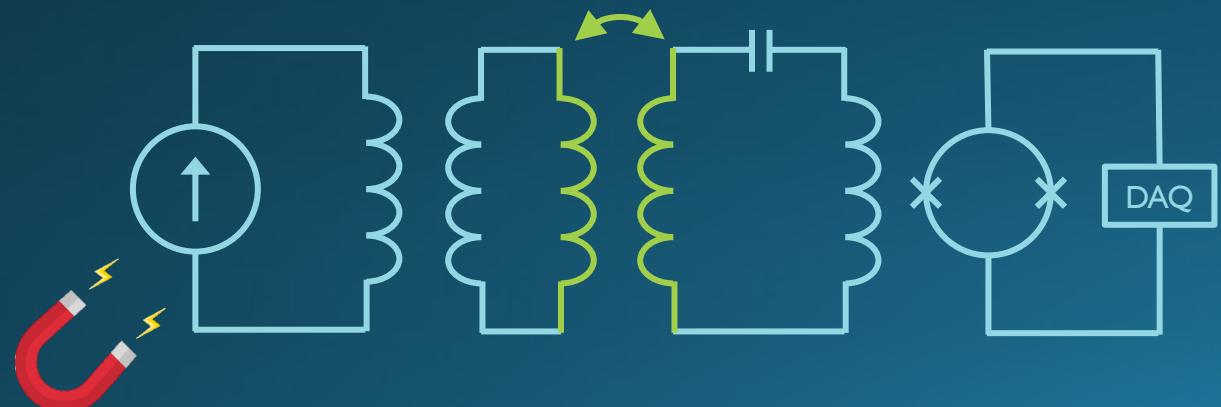
The 50L detector

...inducing currents on the sheath



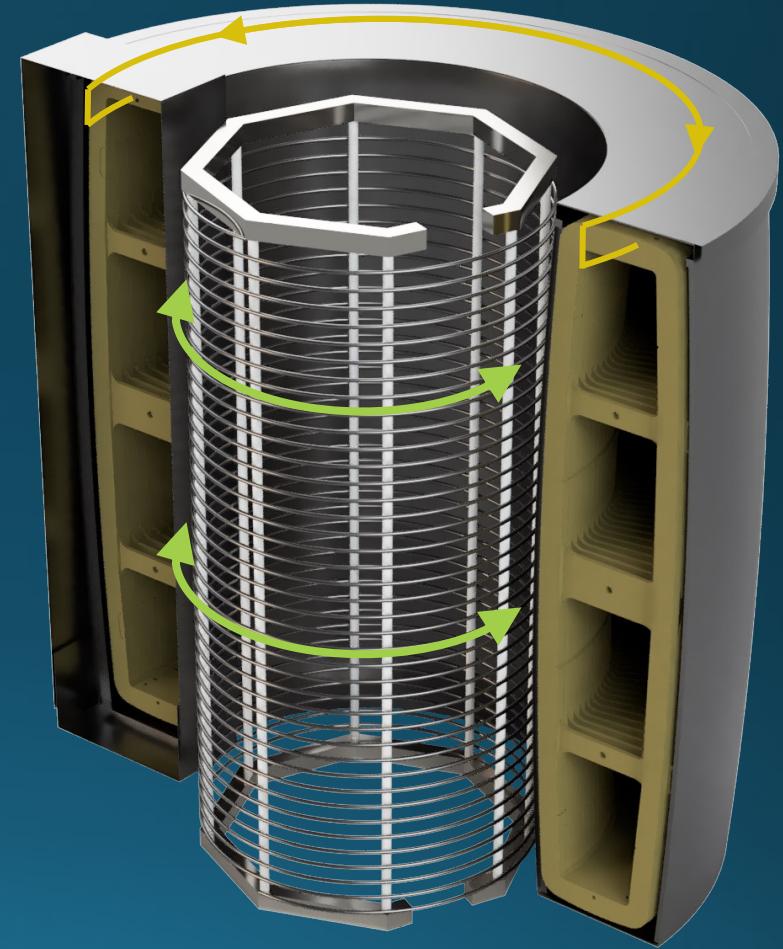
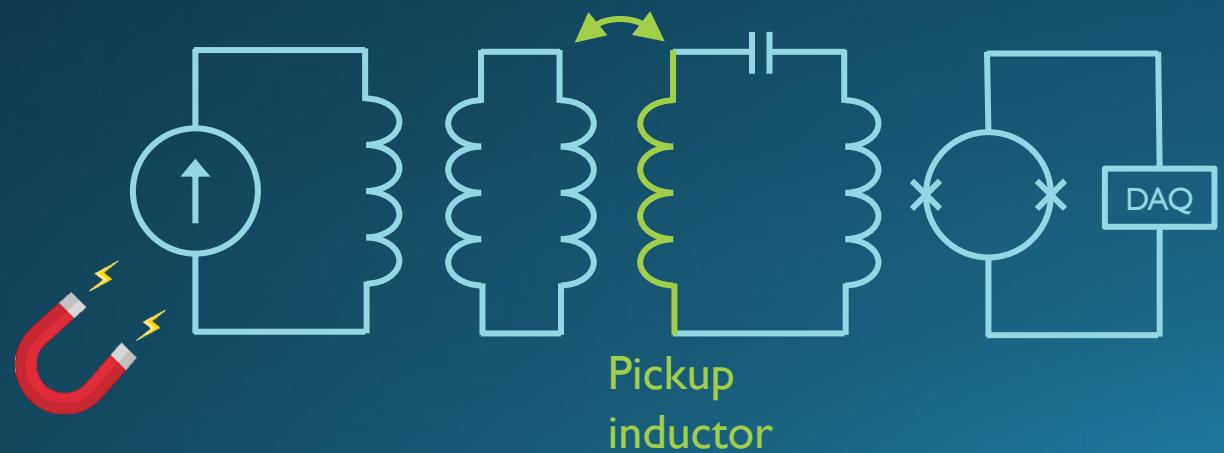
The 50L detector

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



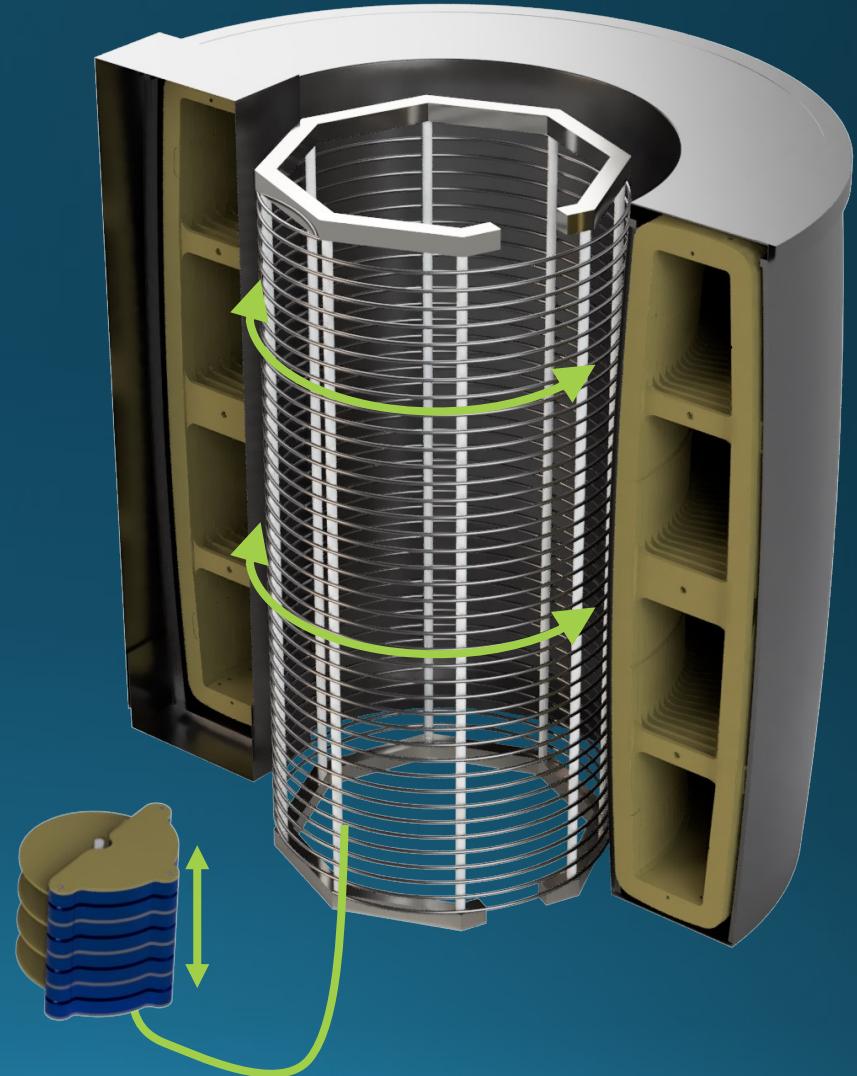
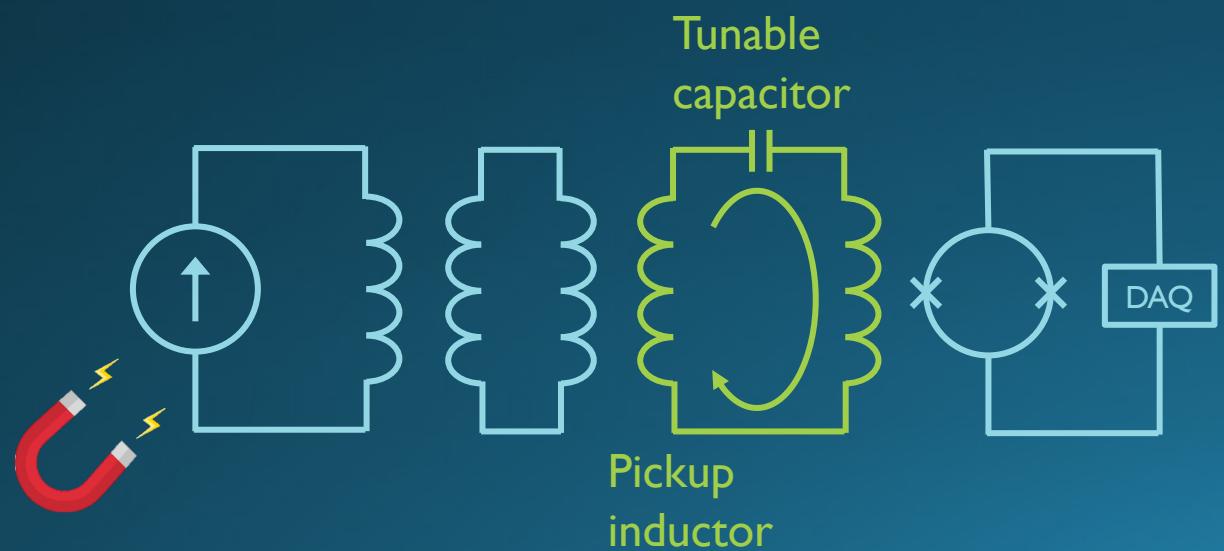
The 50L detector

...inducing currents on the pickup inductor



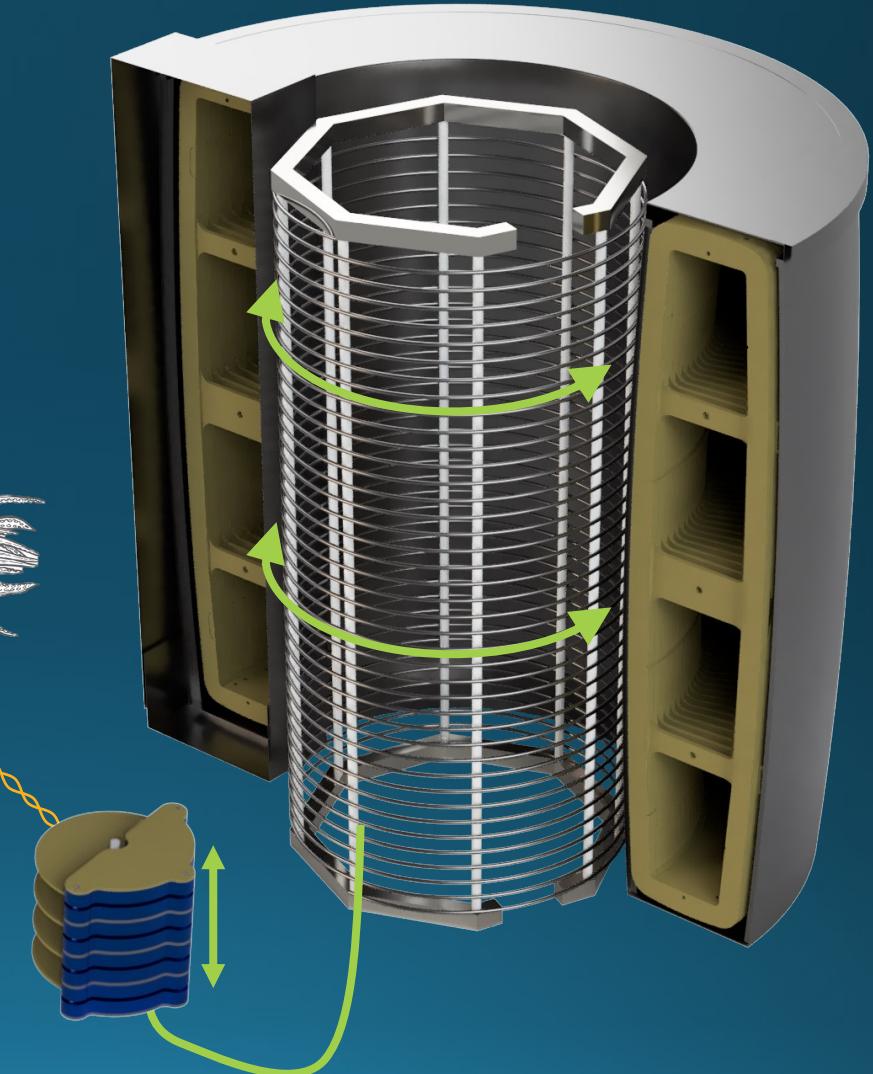
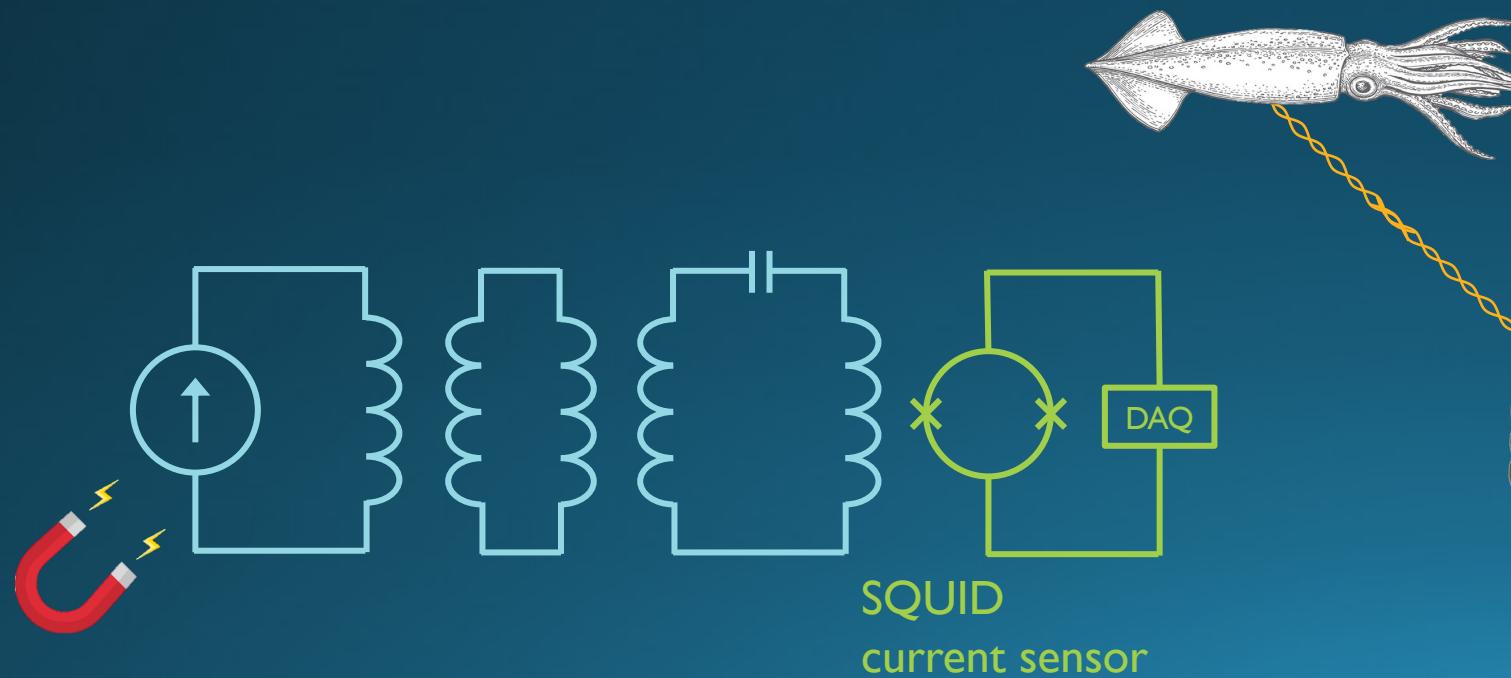
The 50L detector

...ringing up the LC resonator.

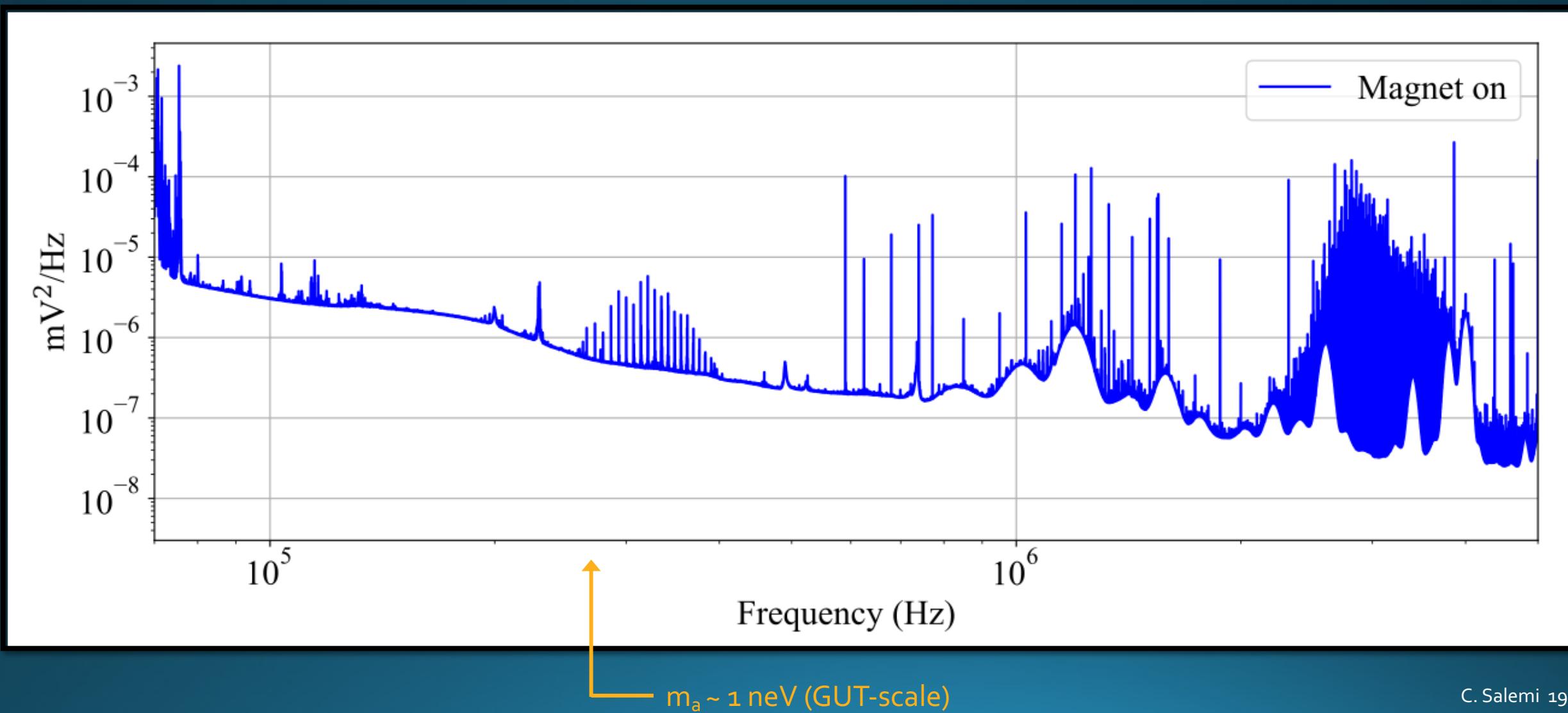


The 50L detector

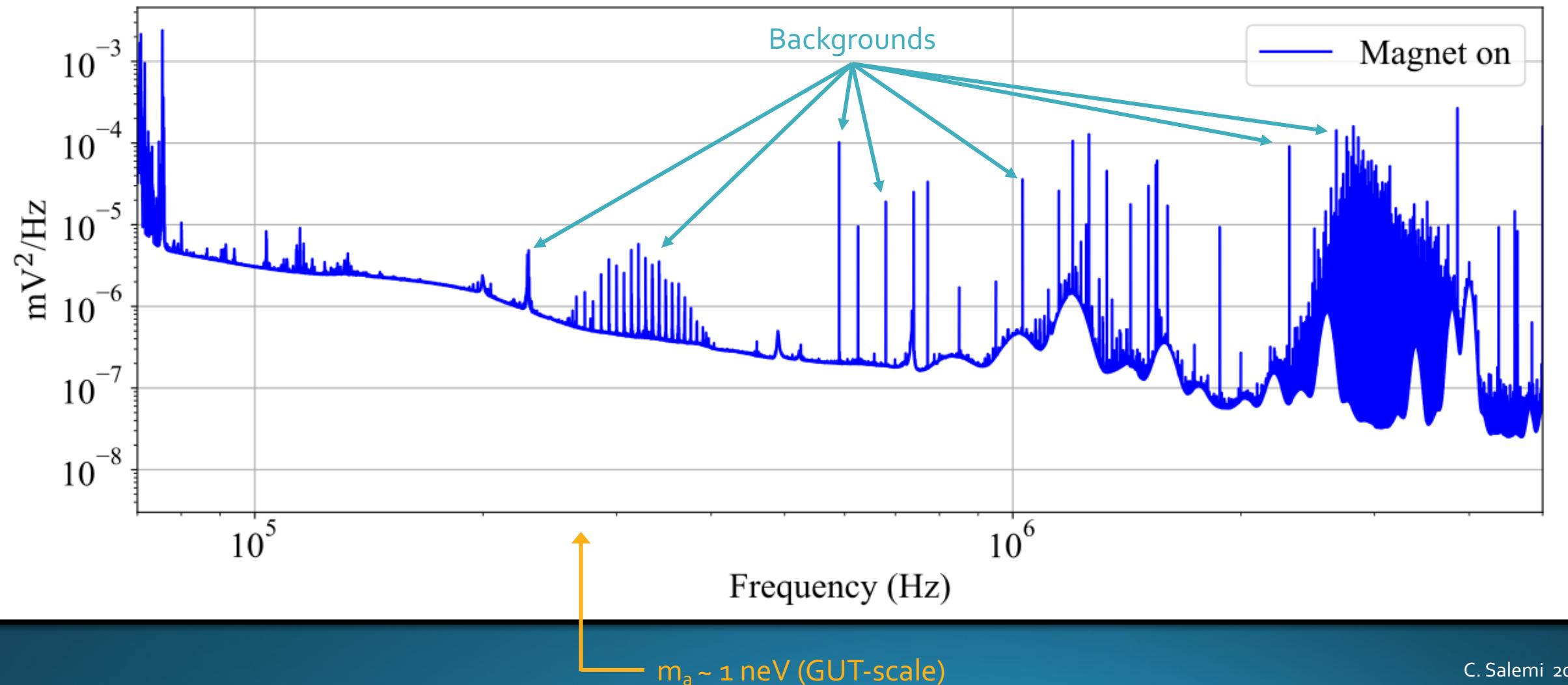
This signal is **read out** and amplified using a SQUID current sensor



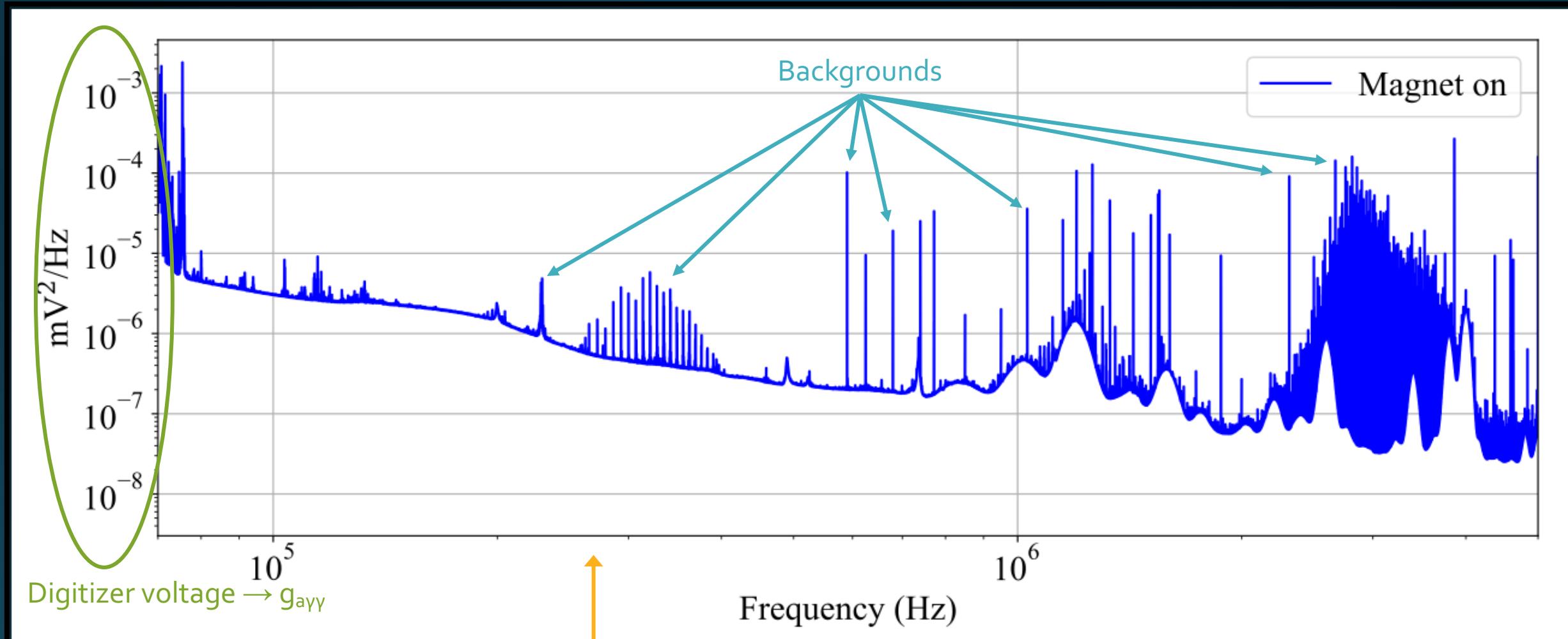
ABRA-10cm averaged spectrum



ABRA-10cm averaged spectrum



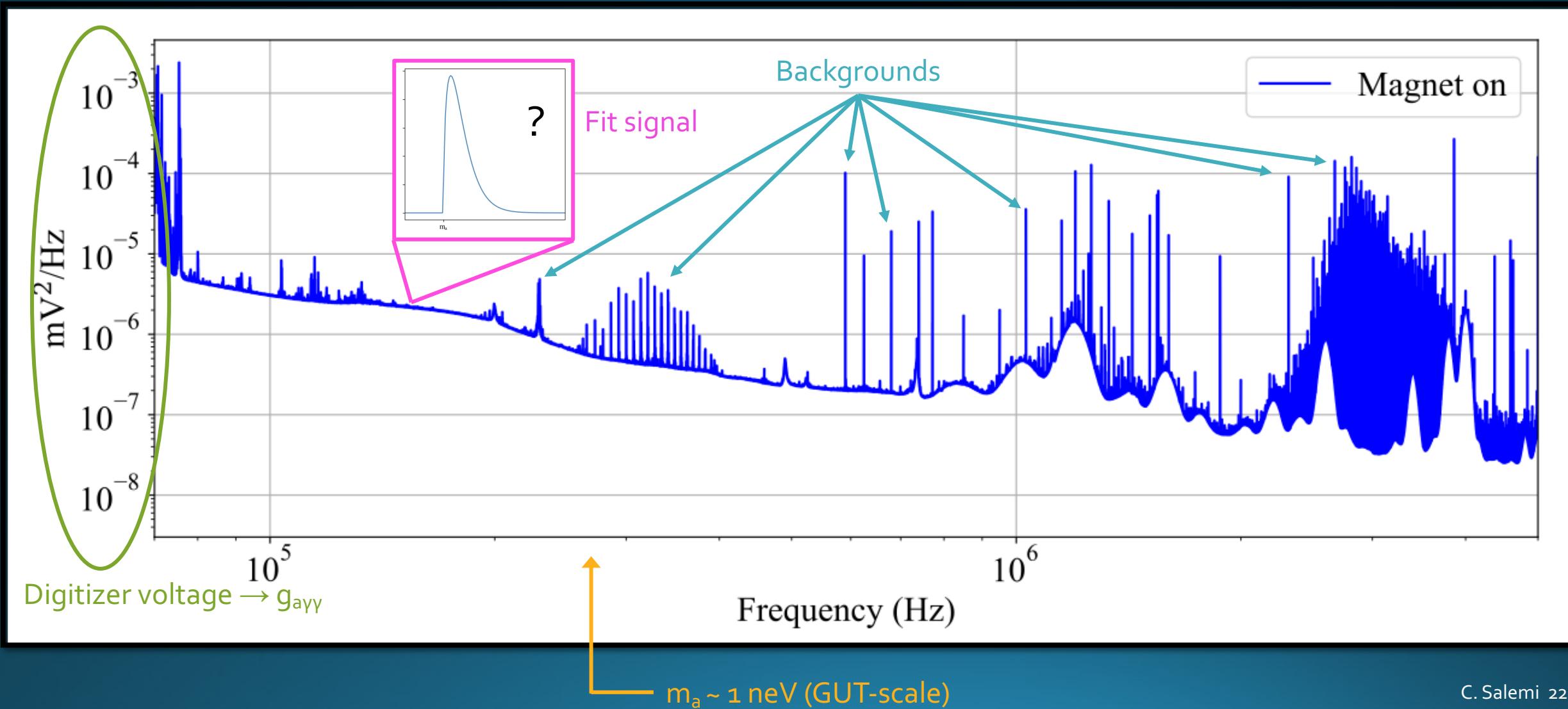
ABRA-10cm averaged spectrum



See talk by Jessica Fry

C. Salemi 21

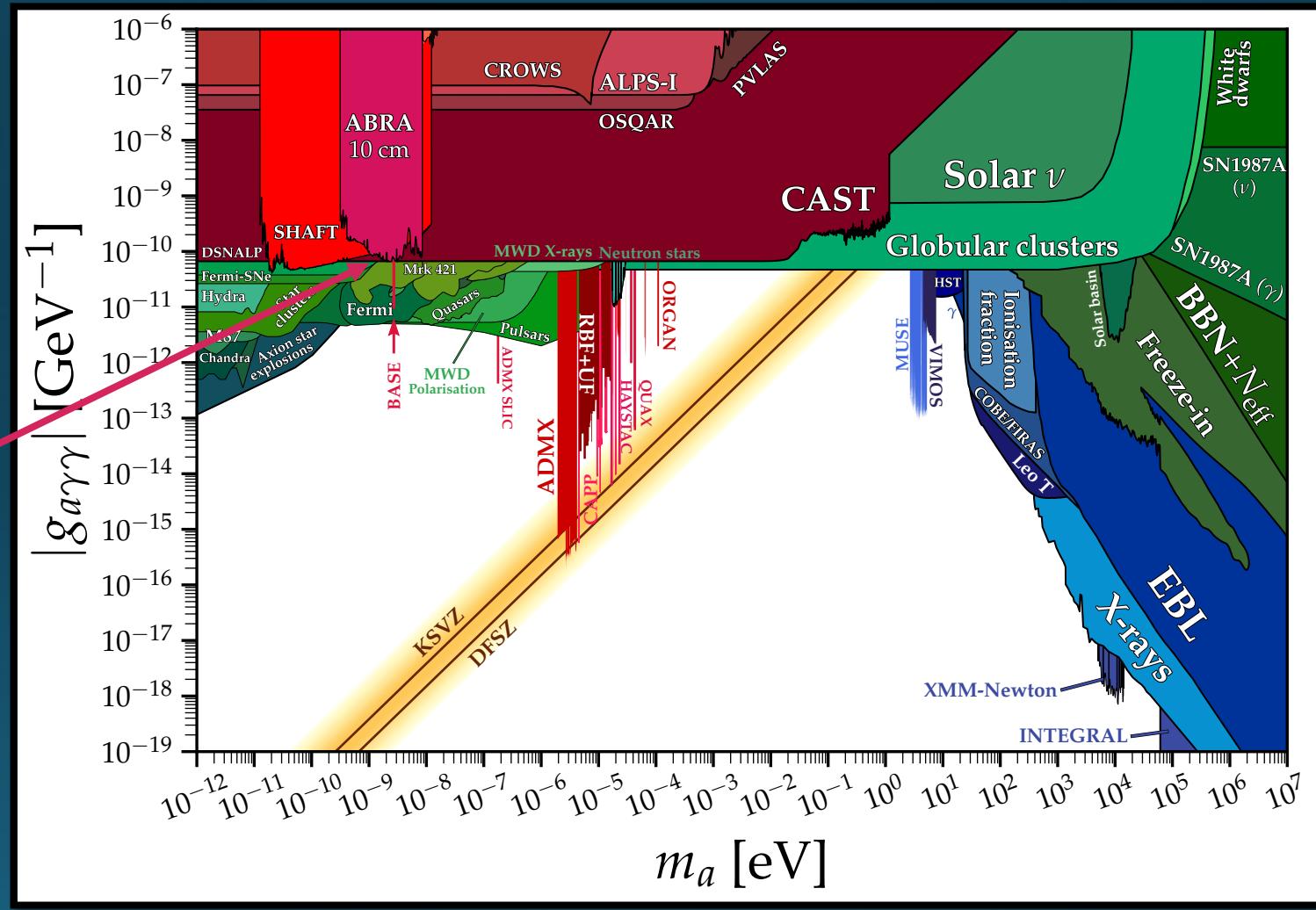
ABRA-10cm averaged spectrum



No axions found yet!



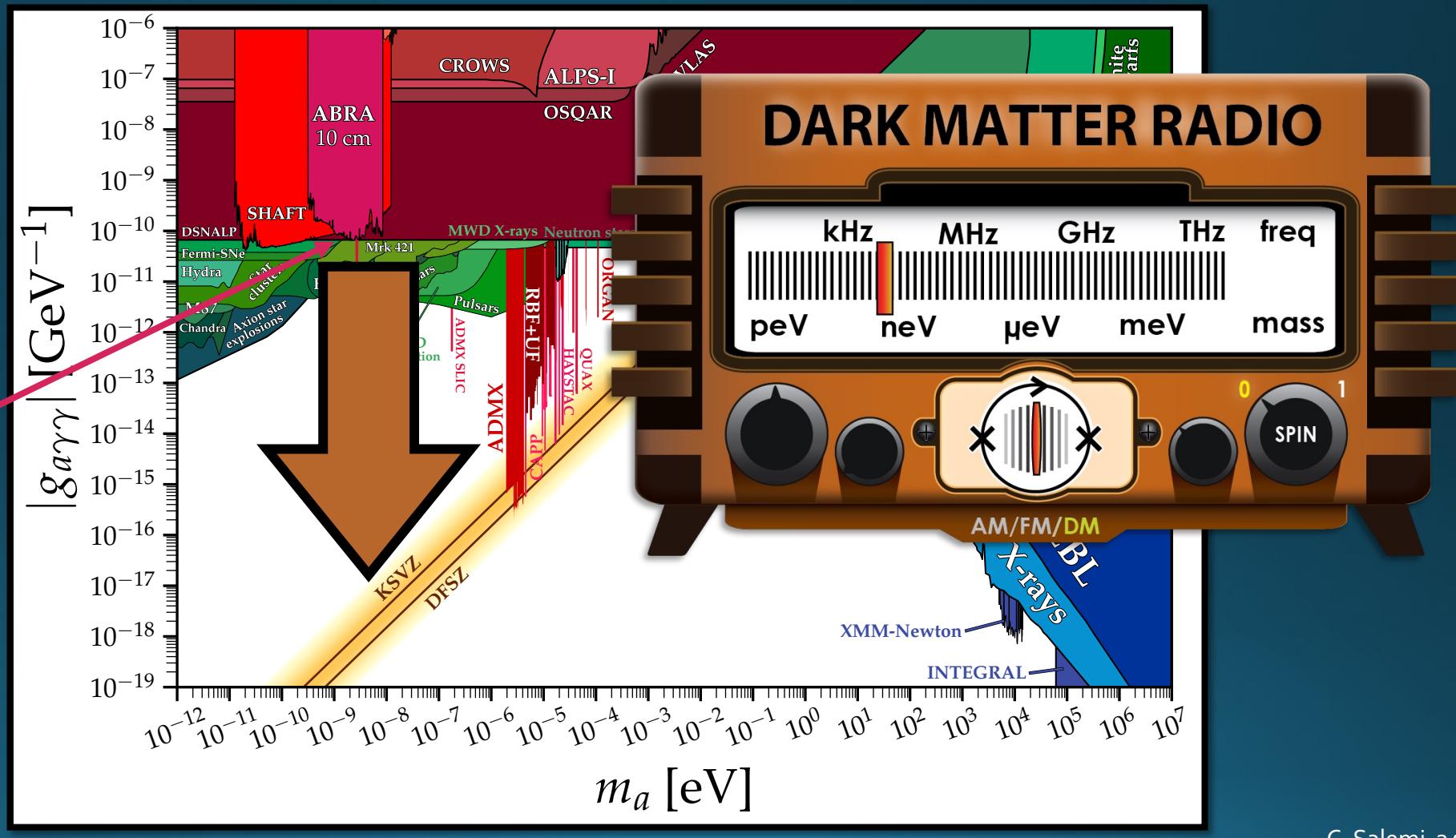
Salemi et al. *Phys.Rev.Lett.* 2021
Ouellet, Salemi et al. *Phys.Rev.Lett.* 2019
Ouellet, Salemi et al. *Phys.Rev.D* 2019



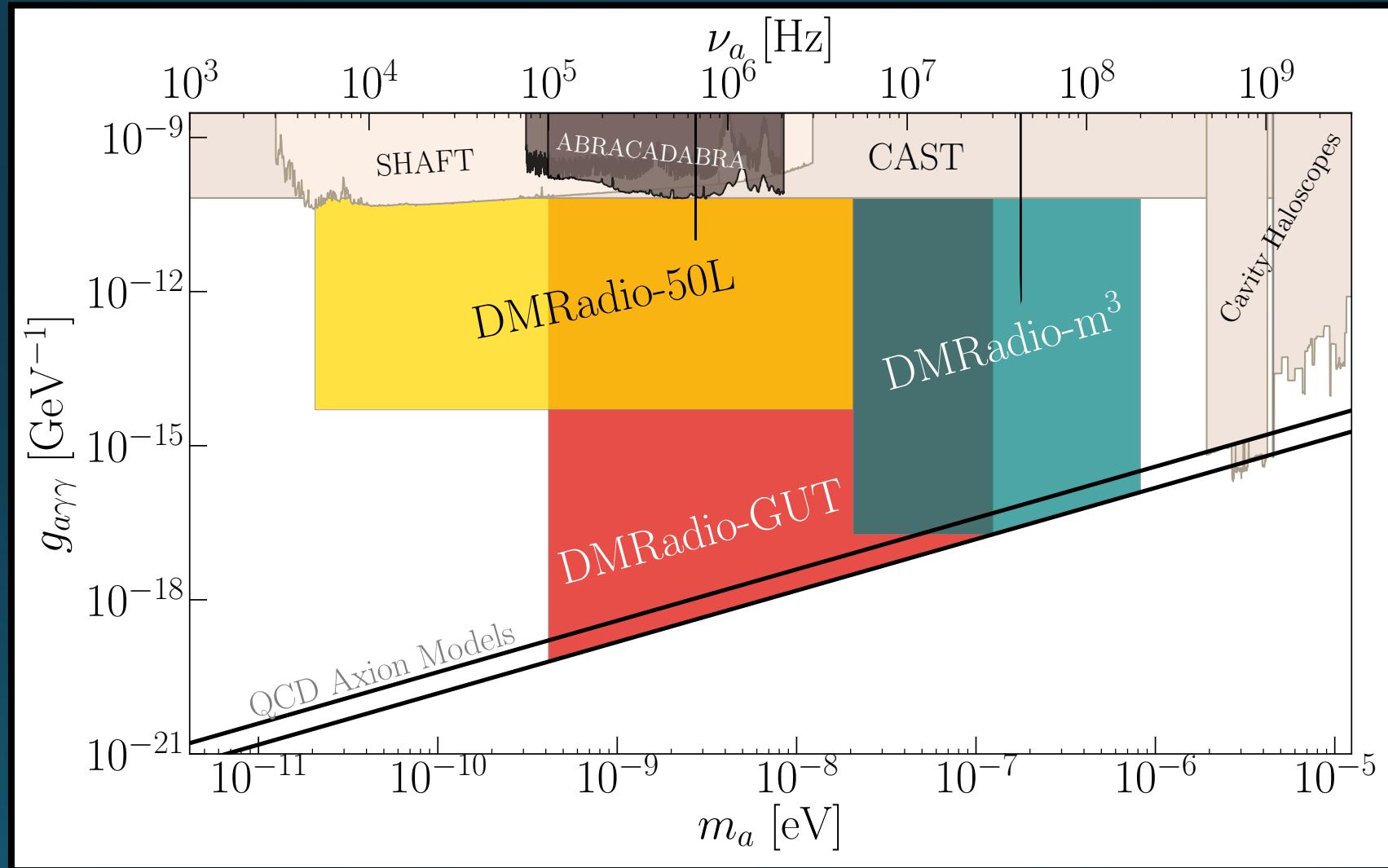
No axions found yet!



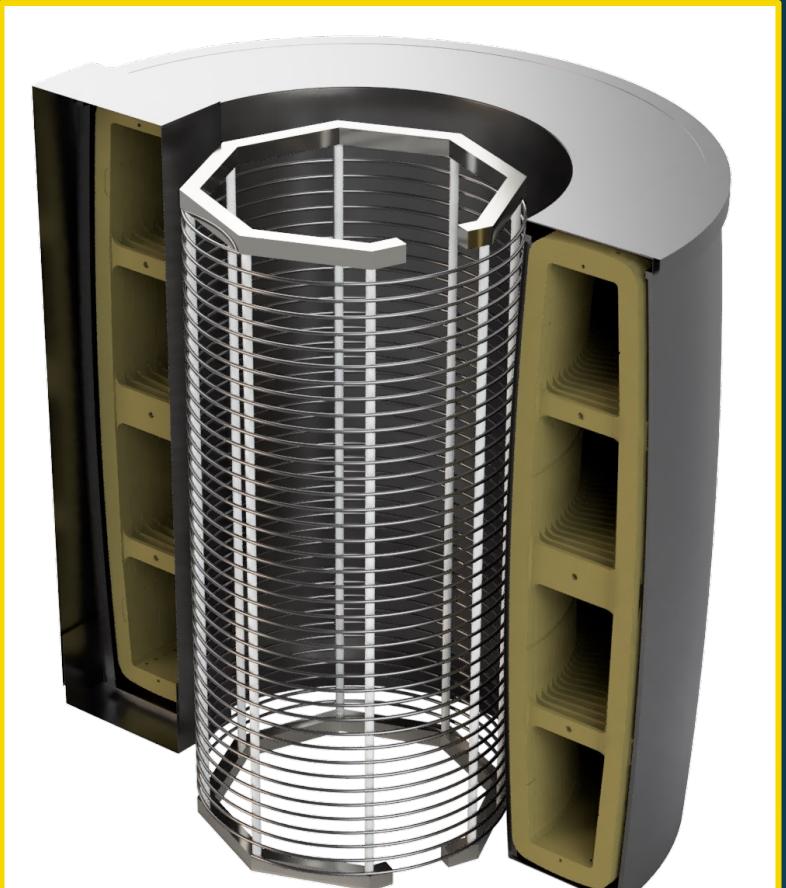
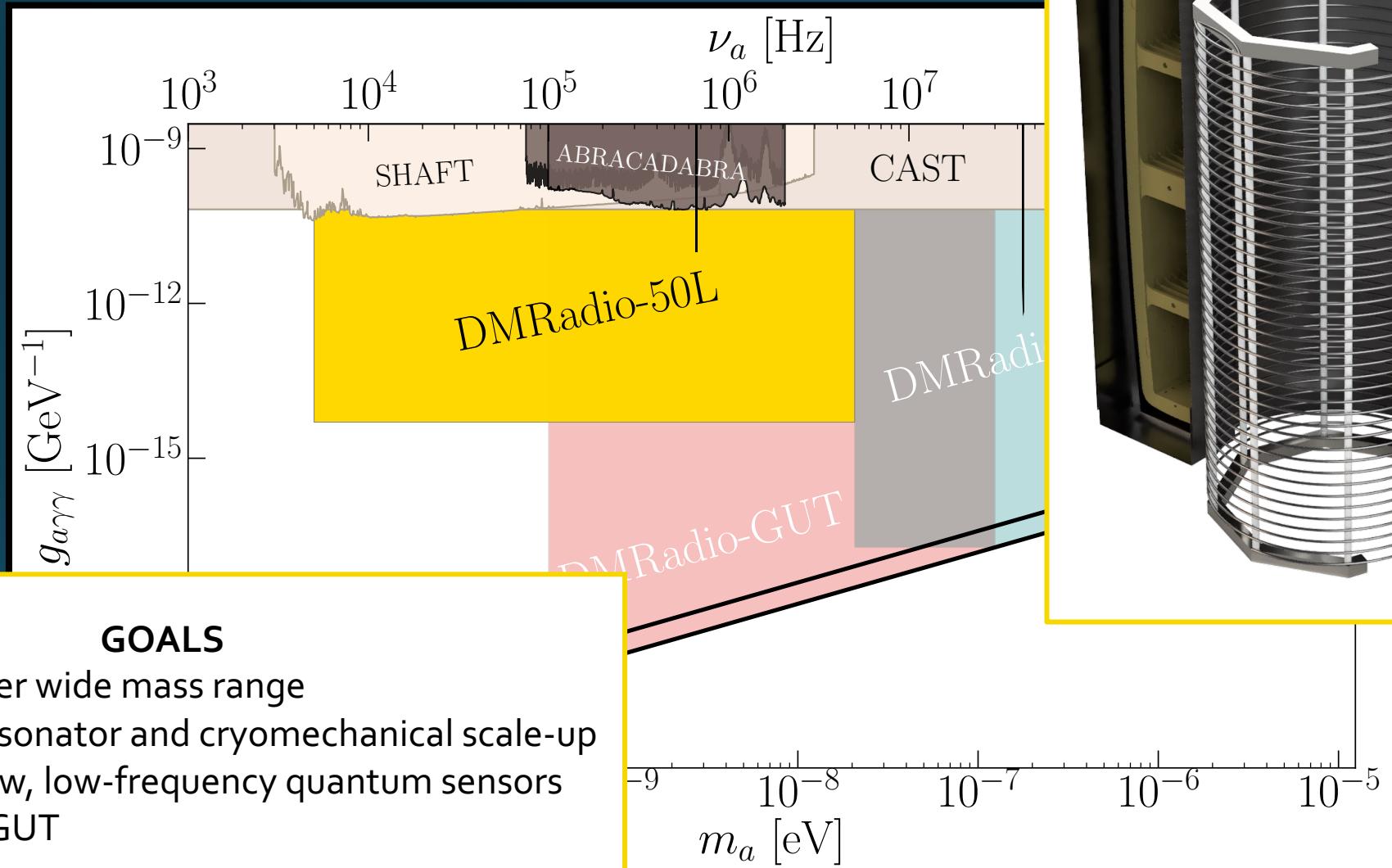
Salemi et al. *Phys.Rev.Lett.* 2021
Ouellet, Salemi et al. *Phys.Rev.Lett.* 2019
Ouellet, Salemi et al. *Phys.Rev.D* 2019



DMRadio program

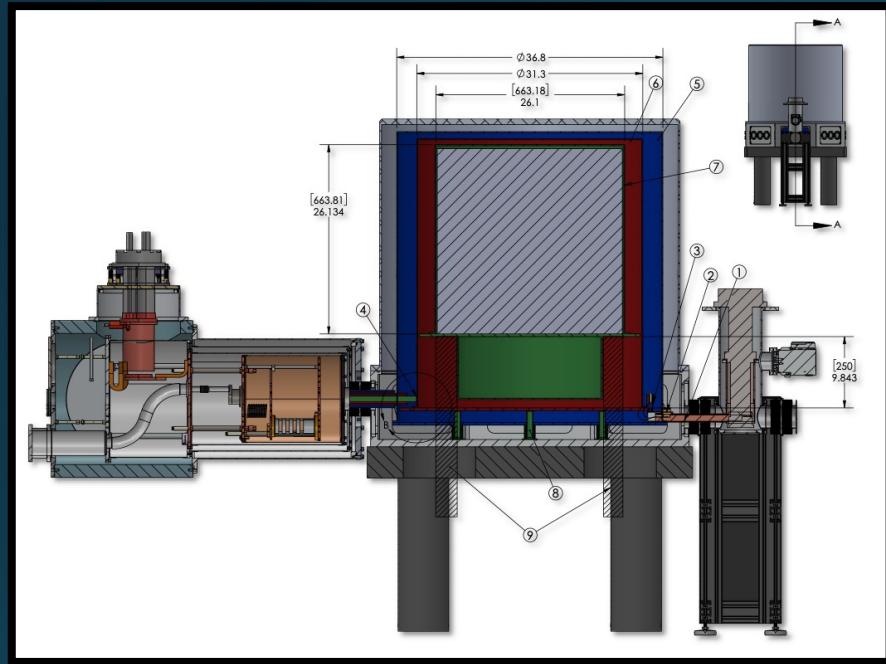


DMRadio program—50L



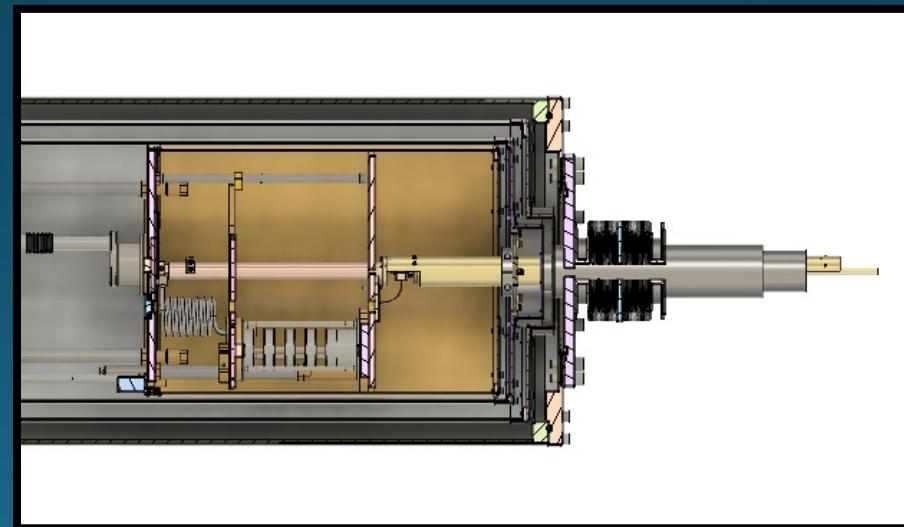
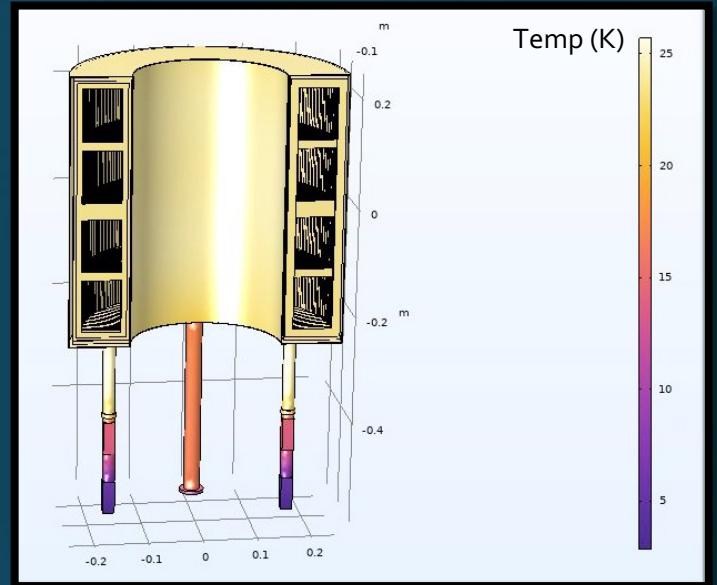
Recent 5oL progress highlights

Cryogenic systems



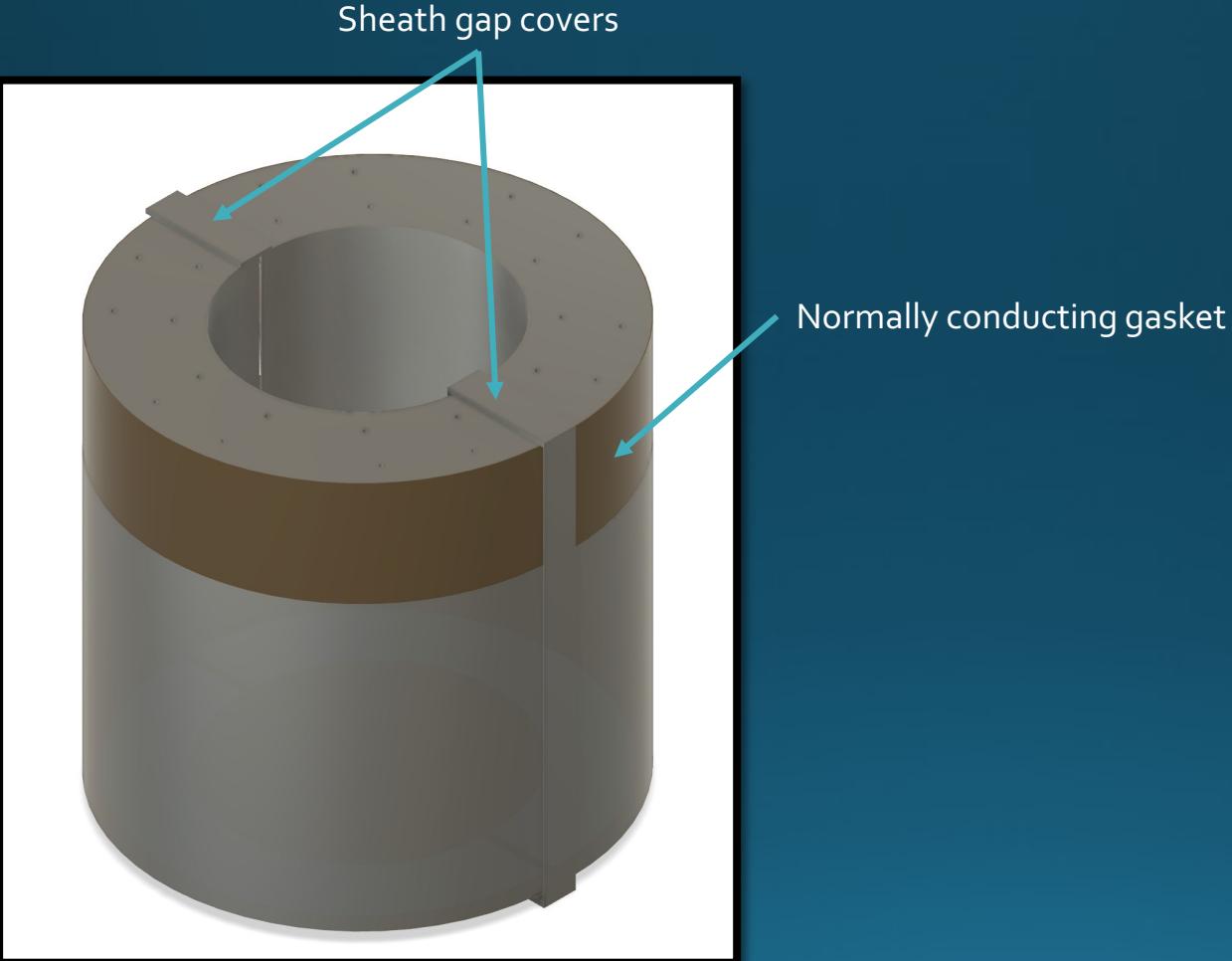
Dual cryogenic system
(Four Nine Design and Maria Simanovskaya)

Magnet cooling time
(Alex Droster)

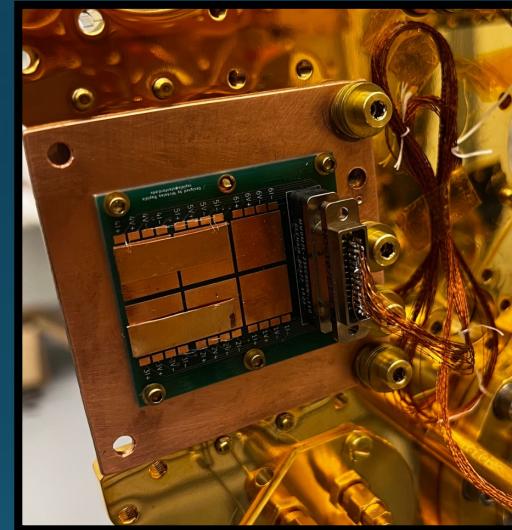


"Cold snout" fridge interface
(Aya Keller)

Sheath



Sheath design
(Nicholas Rapidis)

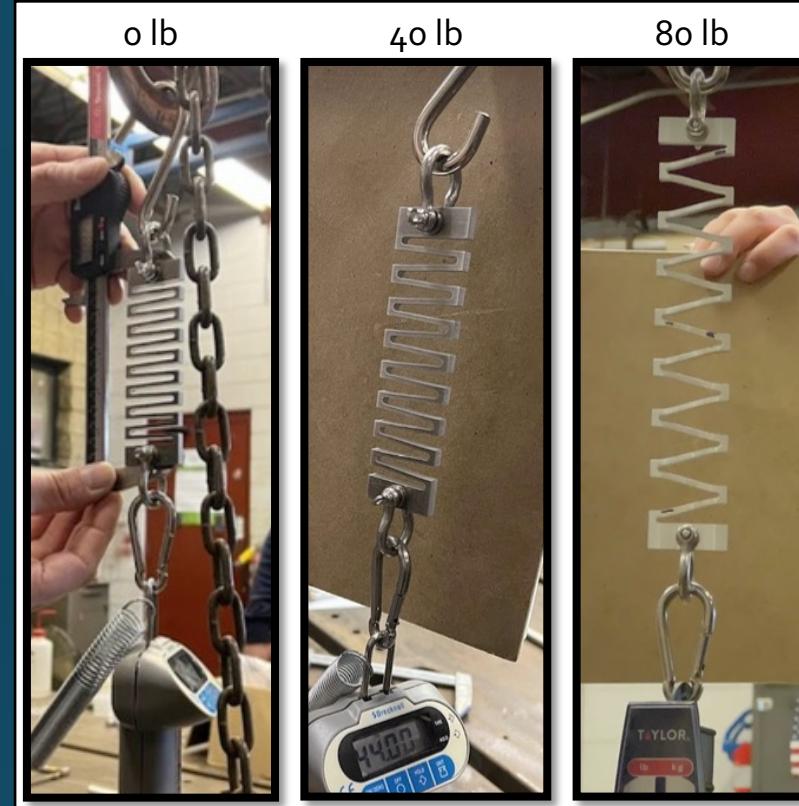


Materials testing for gasket
(Nicholas Rapidis)

Magnet



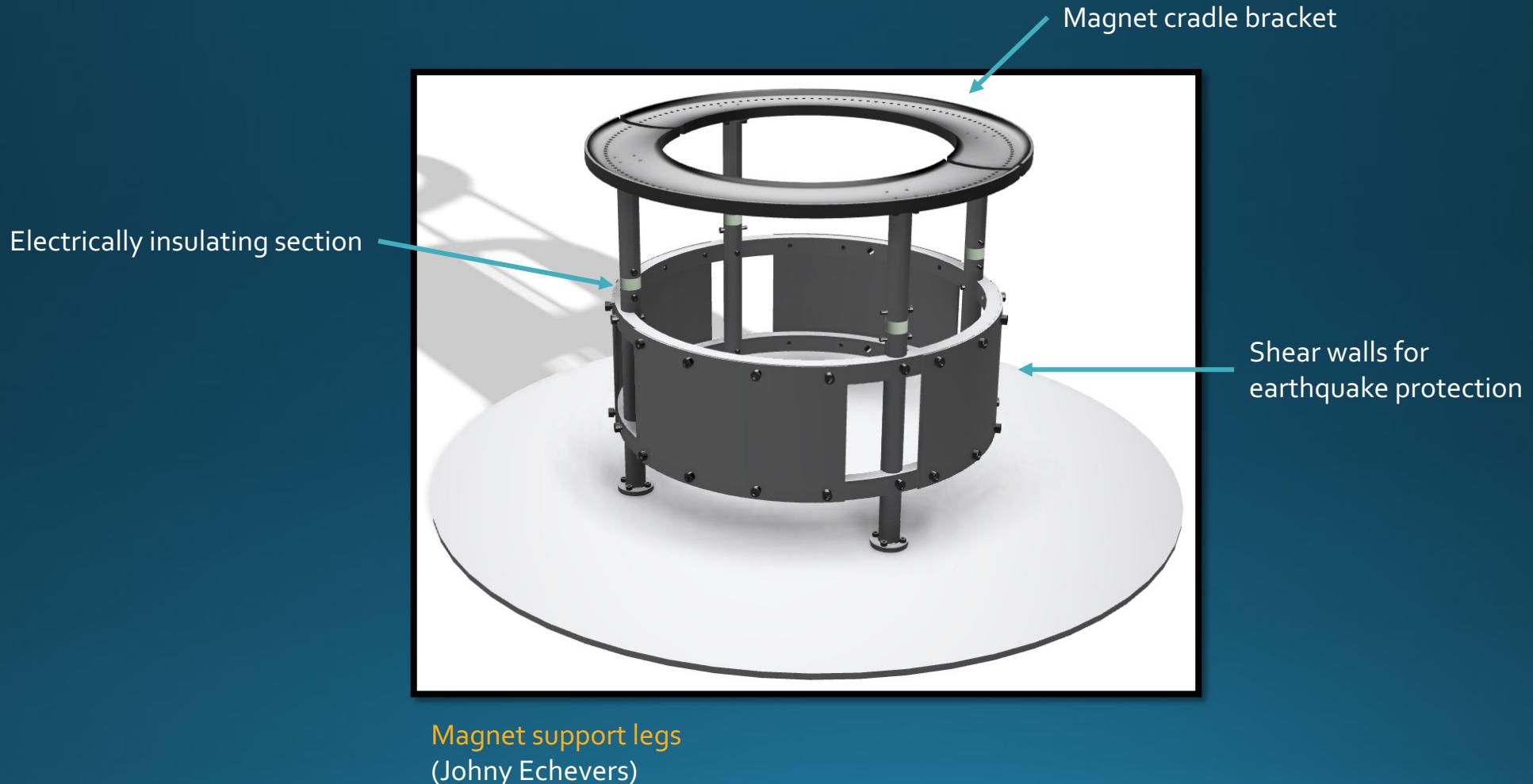
Magnet winding
(Superconducting Systems, Inc.)



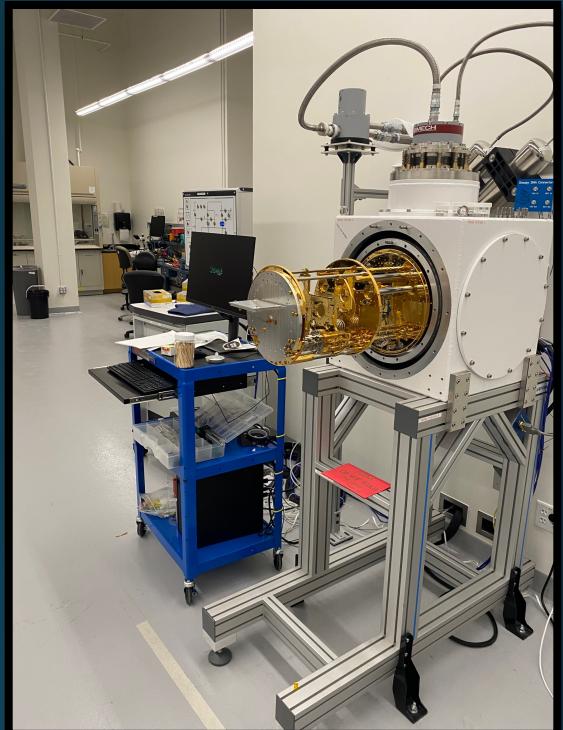
Magnet strap design and
spring testing
(Jessica Fry)



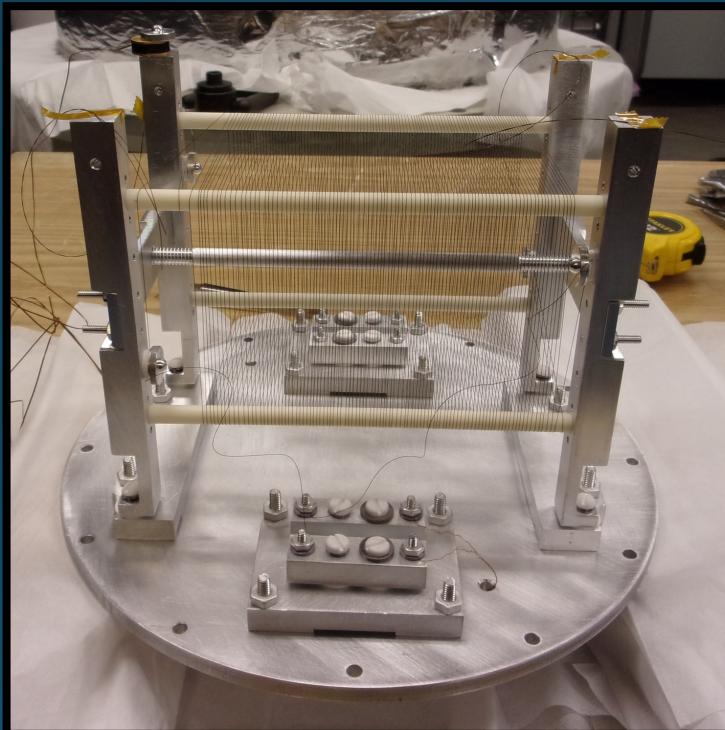
Structural supports for magnet



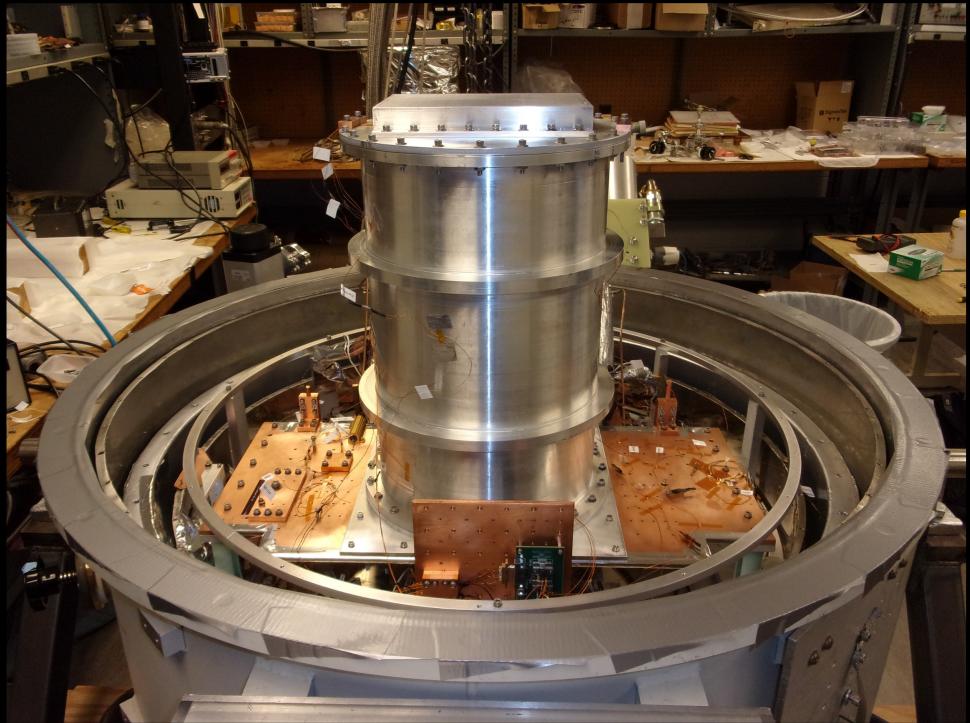
Resonator



Dilution fridge testing of
prototype capacitor
(Joe Singh)



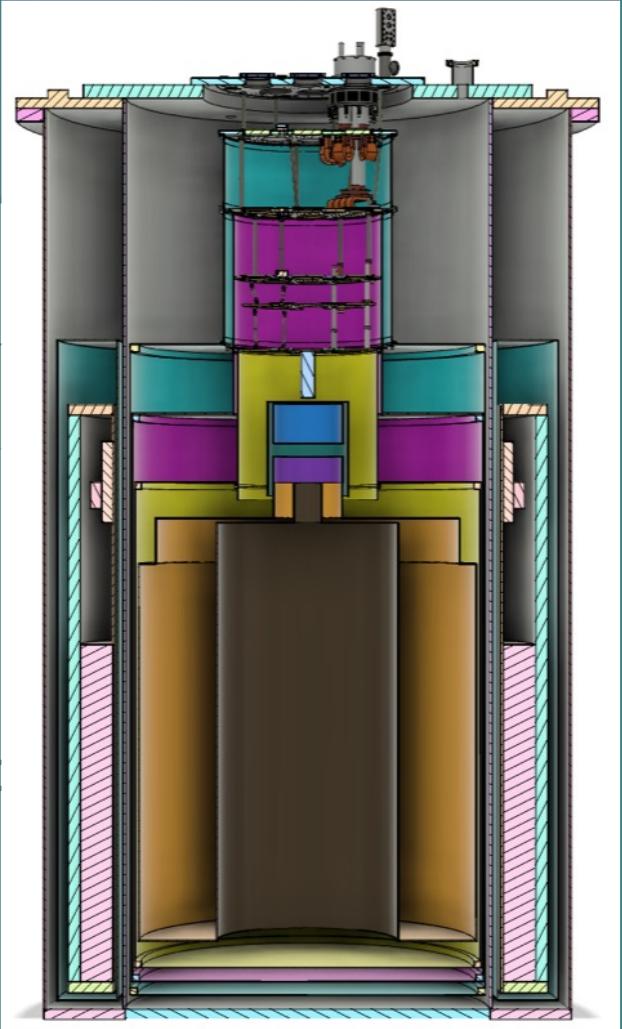
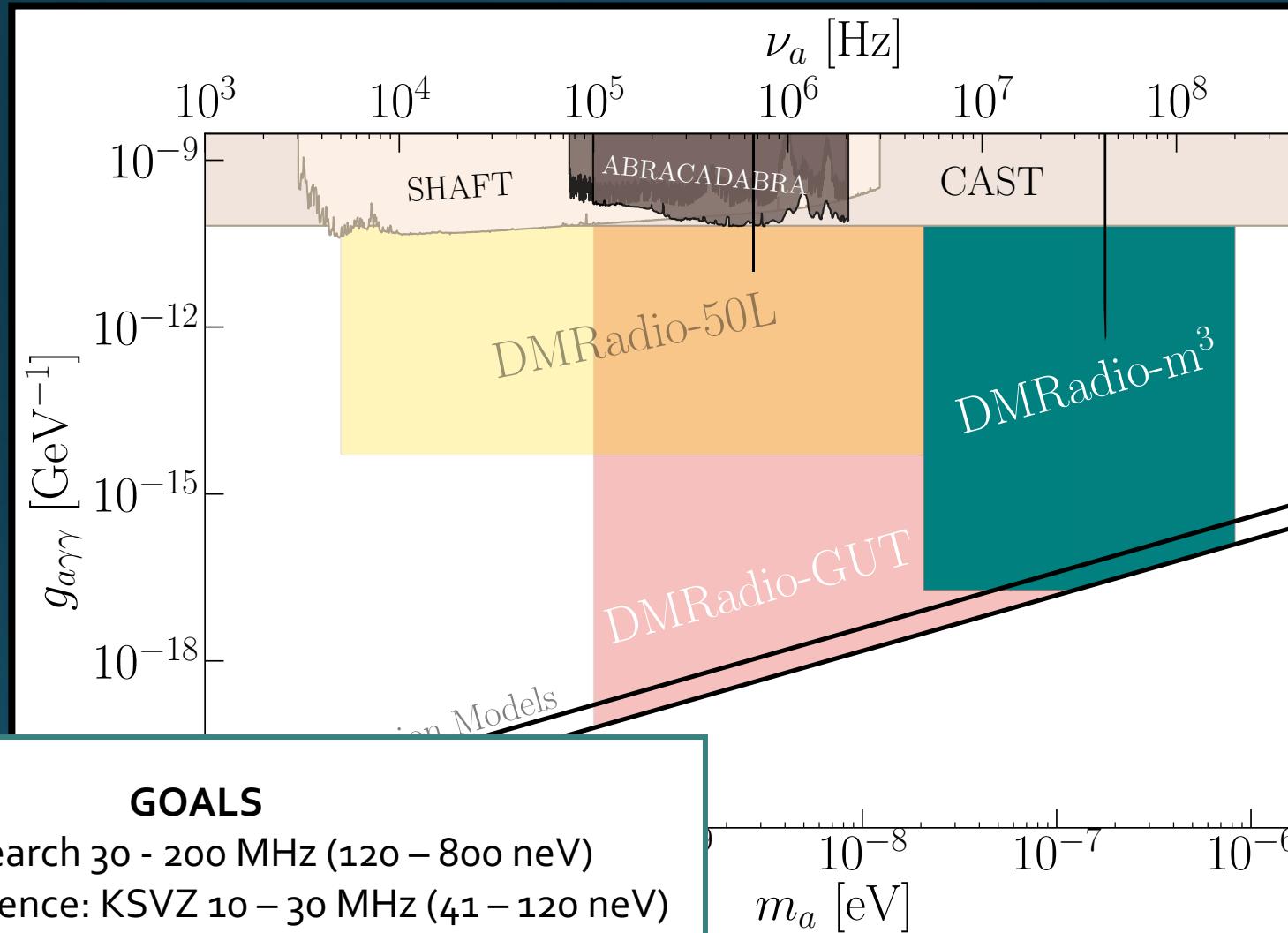
Prototype inductor
(Roman Kolevatov and
Saptarshi Chaudhuri)



Resonator Q testing
(Roman Kolevatov and
Saptarshi Chaudhuri)

Prototype Q = 374,000 @ 300kHz!

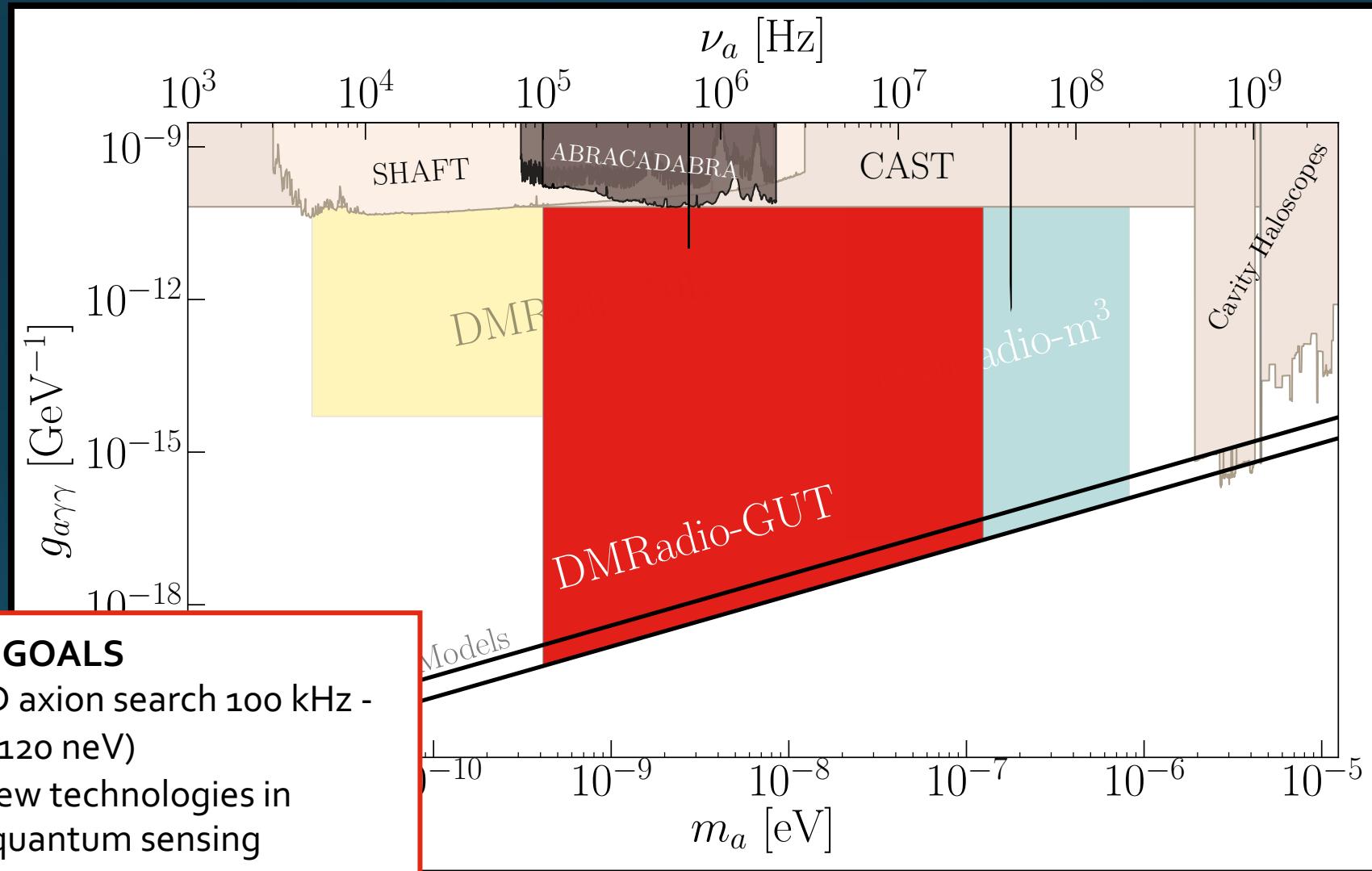
DMRadio program—m³



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

DMRadio program—GUT

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



ABRACADABRA



Undergraduate researchers



A. Colon Cesani



I. Vital

Graduate students



J. Fry



A. Gavin



R. Nguyen



K. Pappas

Postdocs and research scientists



J. Foster



J. Ouellet



N. Rodd



C. Salemi

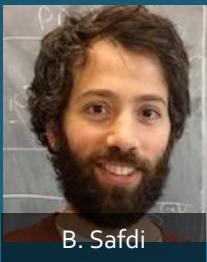
Principal investigators



R. Henning



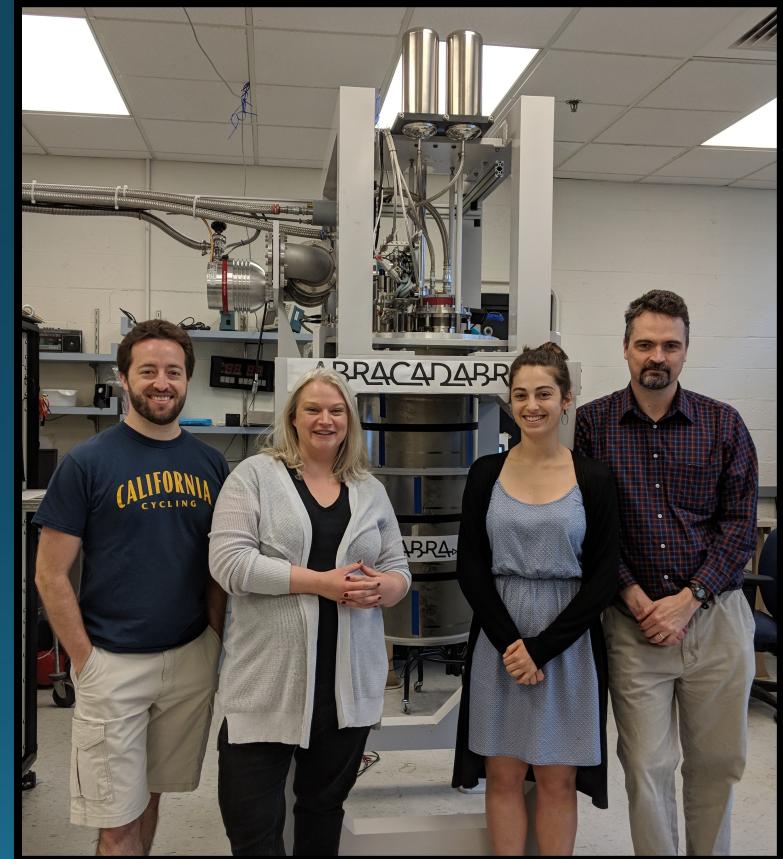
Y. Kahn



B. Safdi



L. Winslow





C. Bartram, H. –M. Cho, W. Craddock, N. Kurita, D. Li, W. J. Wisniewski

SLAC National Accelerator Laboratory

A. AlShirawi, H. –M. Cho, J. Corbin, P. W. Graham, K. D. Irwin, F. Kadribasic, S. Kuenstner,

N. M. Rapidis, C. P. Salemi, M. Simanovskiaia, J. Singh, E. C. van Assendelft, K. Wells

*Department of Physics,
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K. M. W. Pappas, L. Winslow

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Y. Kahn

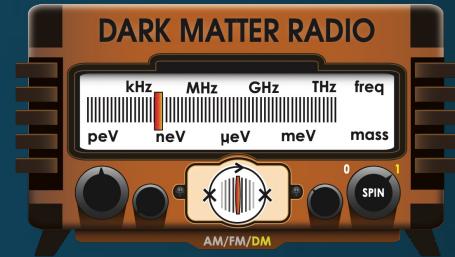
*Department of Physics,
University of Illinois at Urbana-Champaign*

A. Phipps

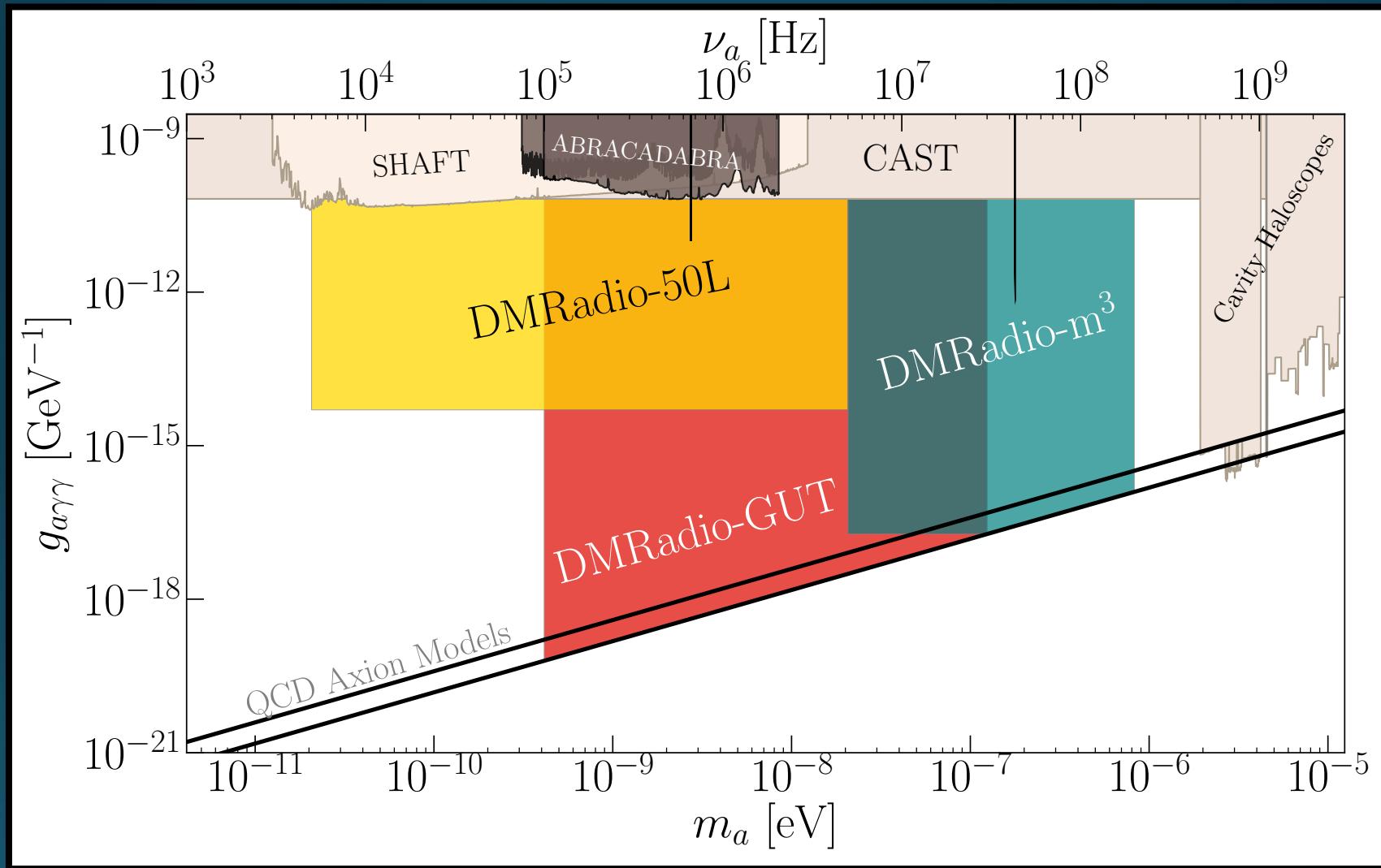
California State University, East Bay

J. N. Benabou, B. R. Safdi

*Department of Physics
University of California Berkeley*

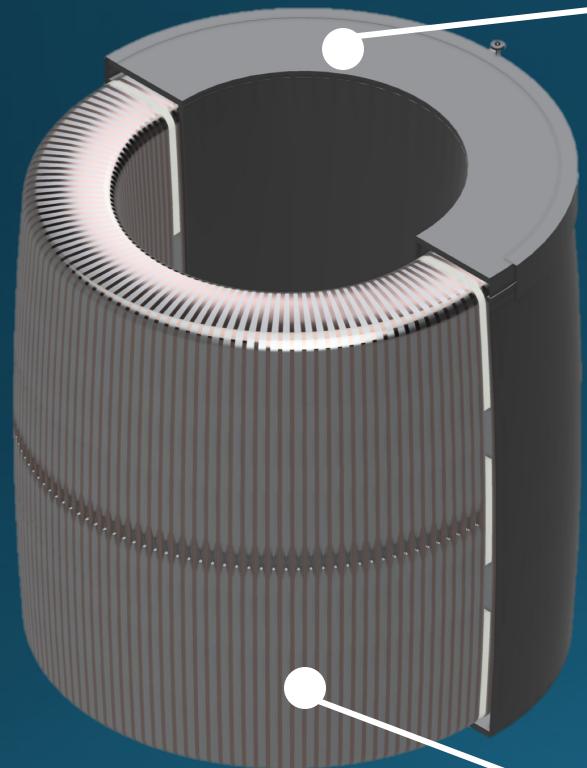


Thank you!

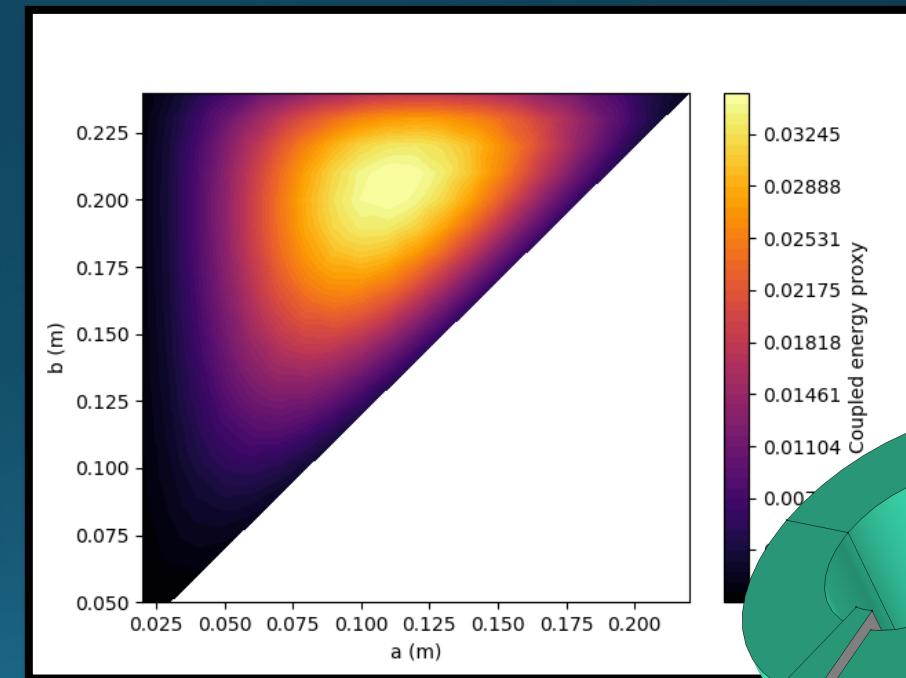


Backup slides

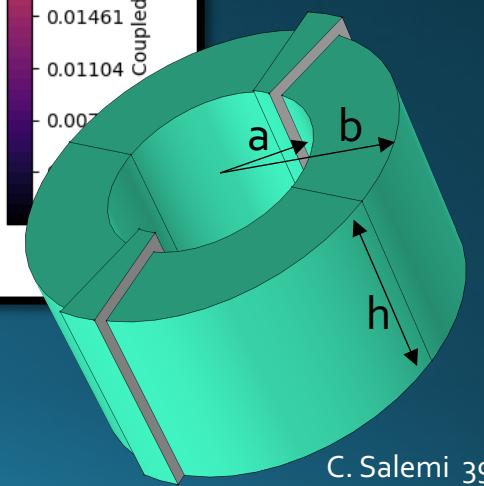
DMRadio-50 L



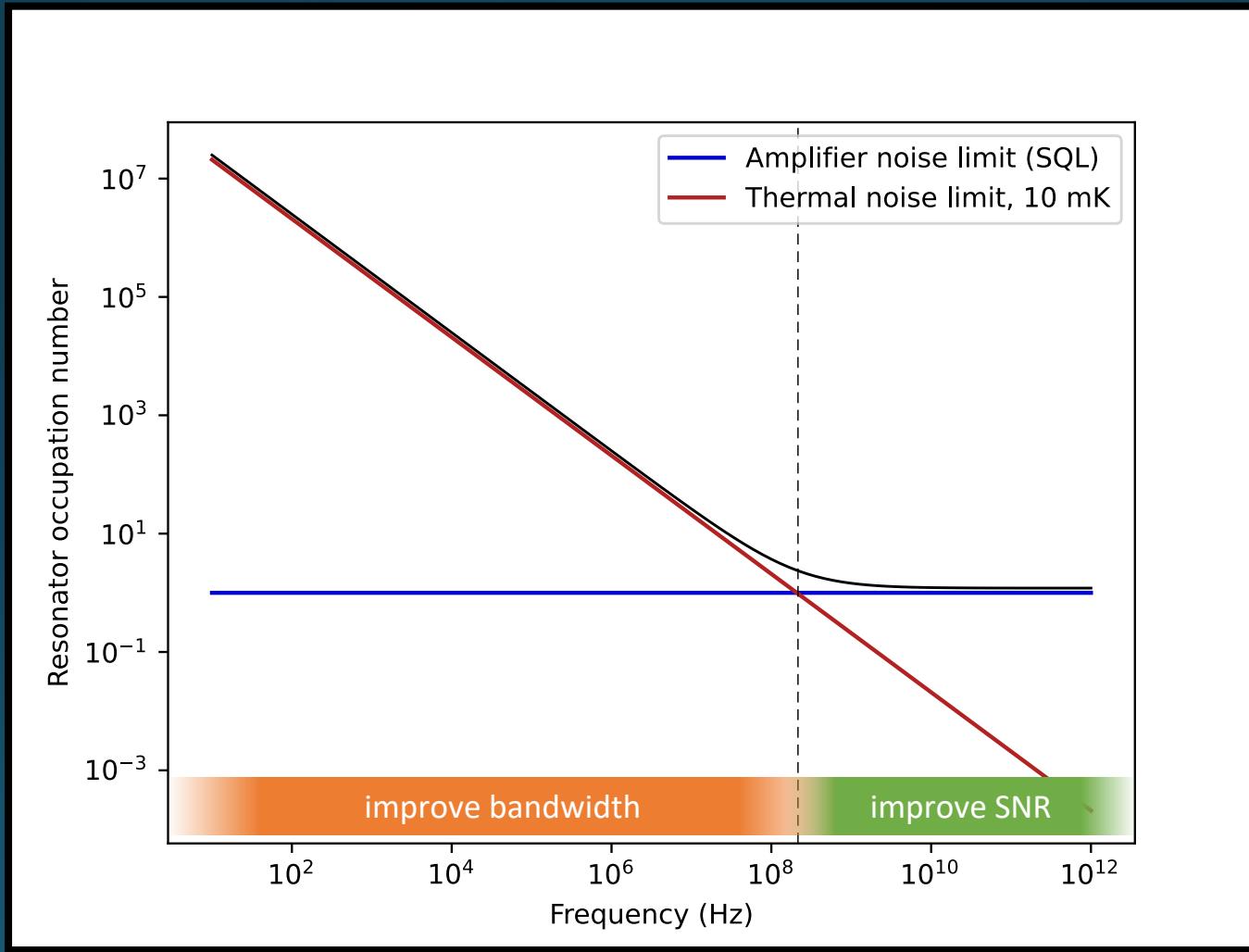
optimized axion-detector coupling
with pickup sheath



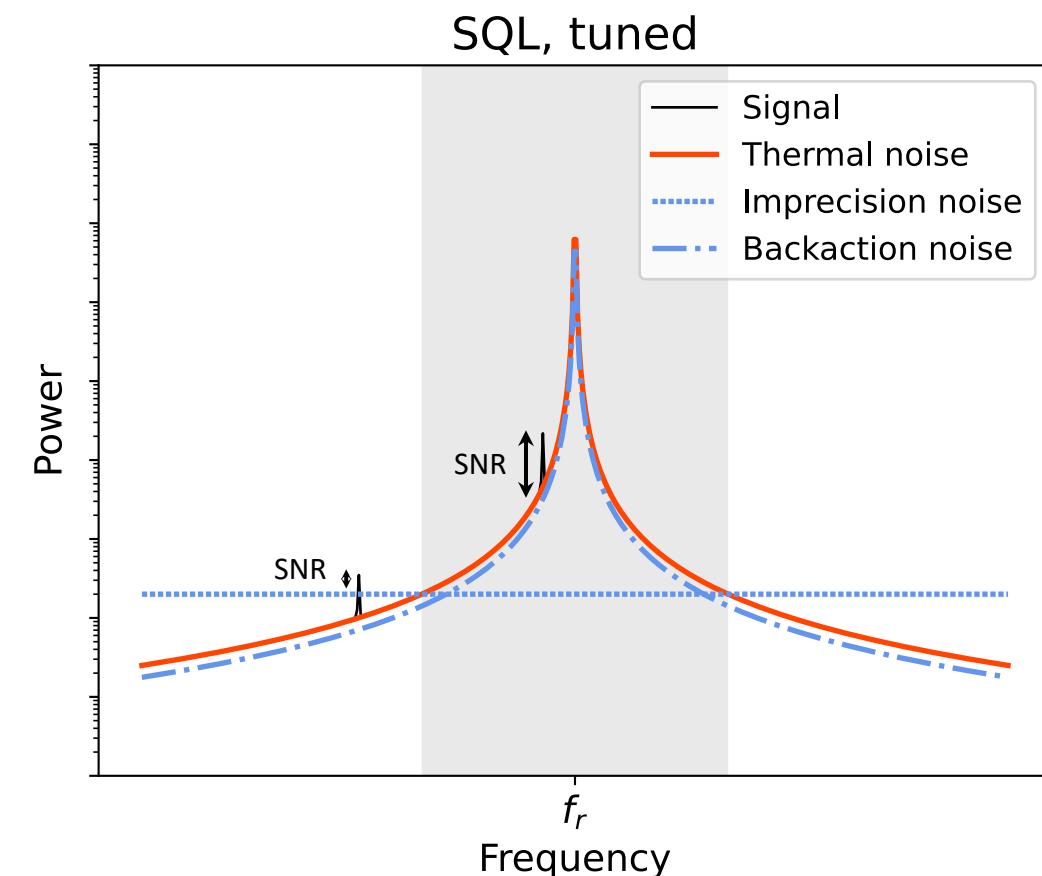
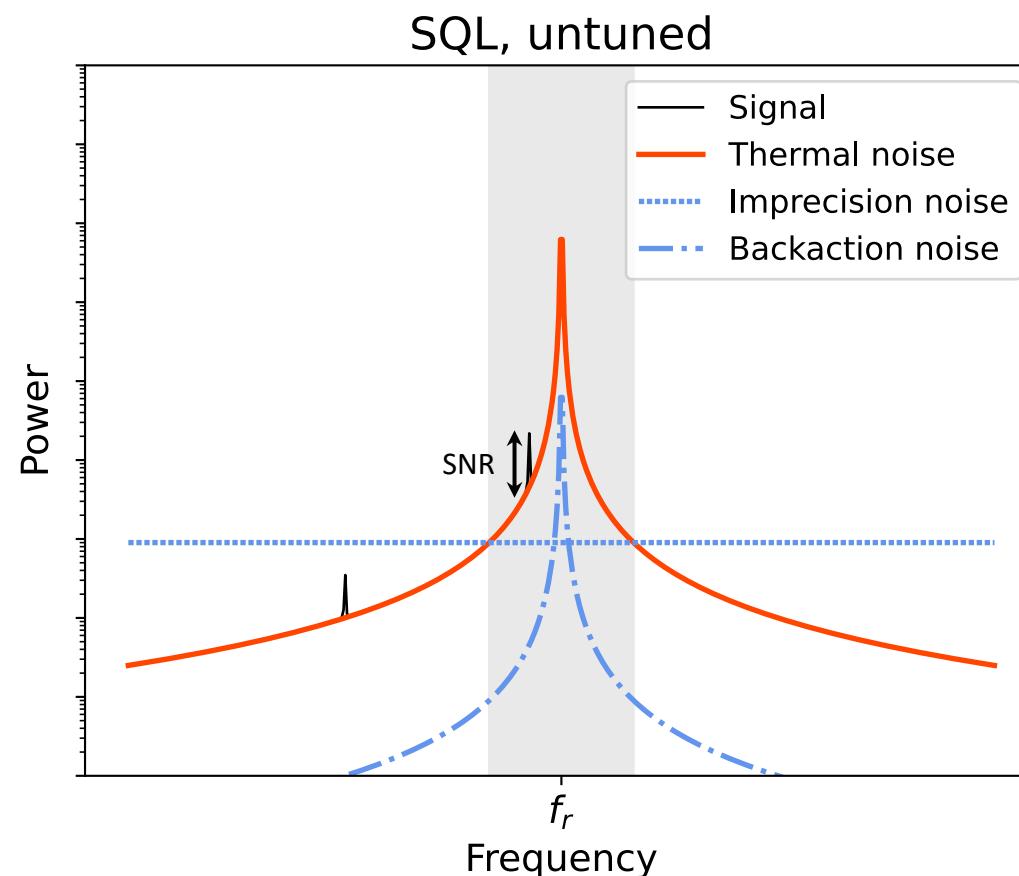
50 L volume, 1T field



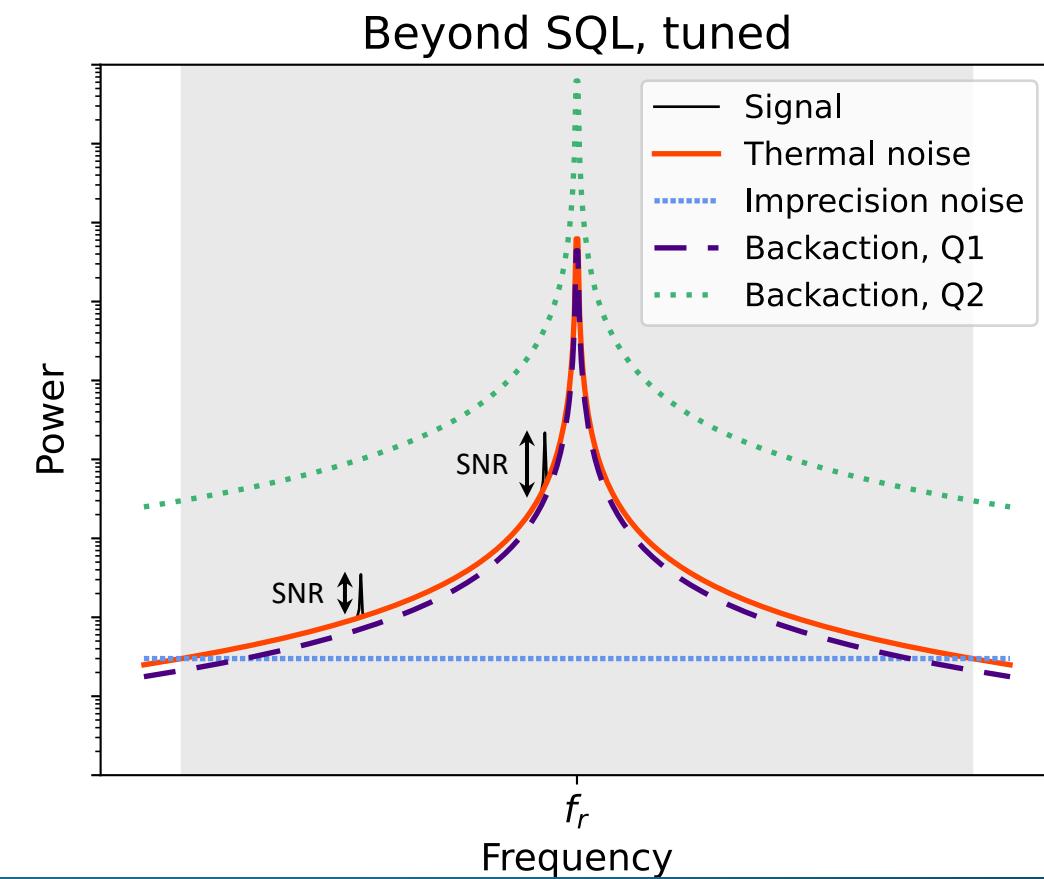
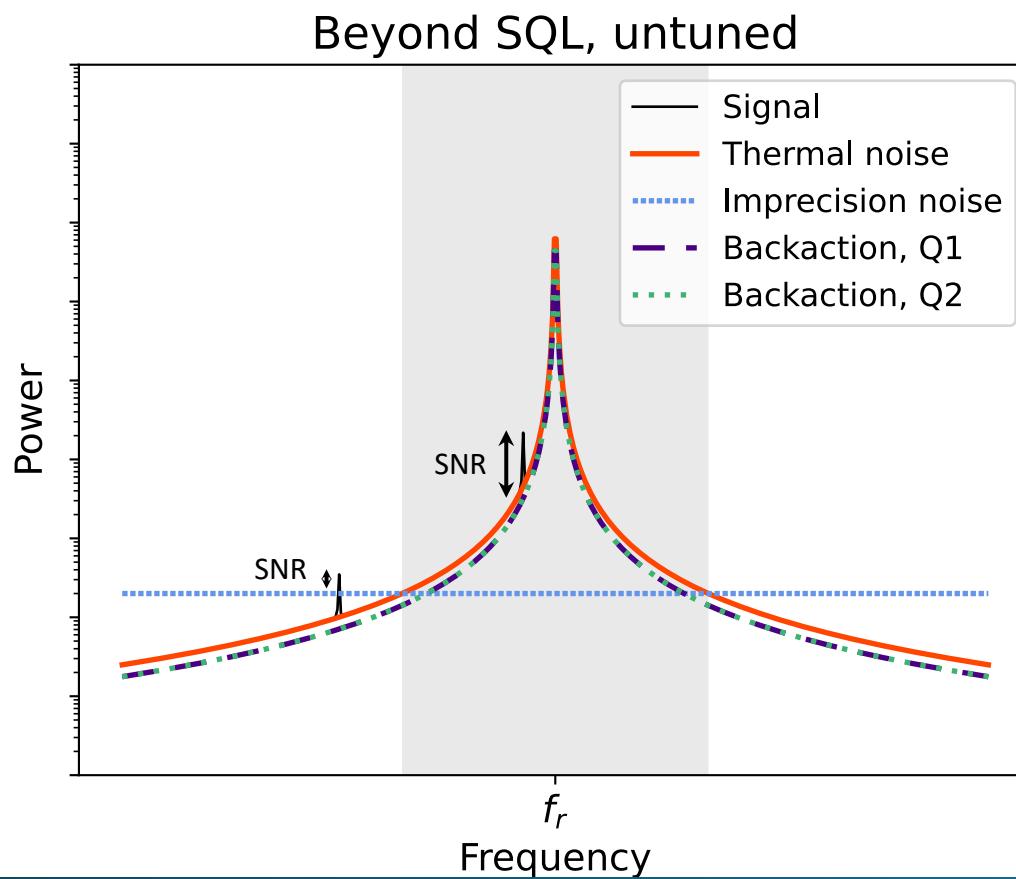
Noise regimes



Improving the bandwidth

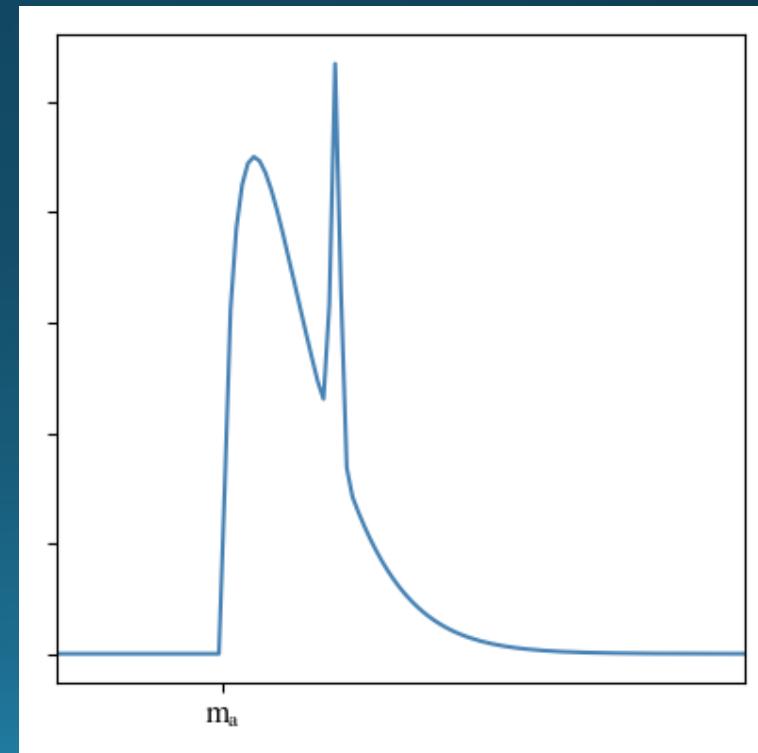
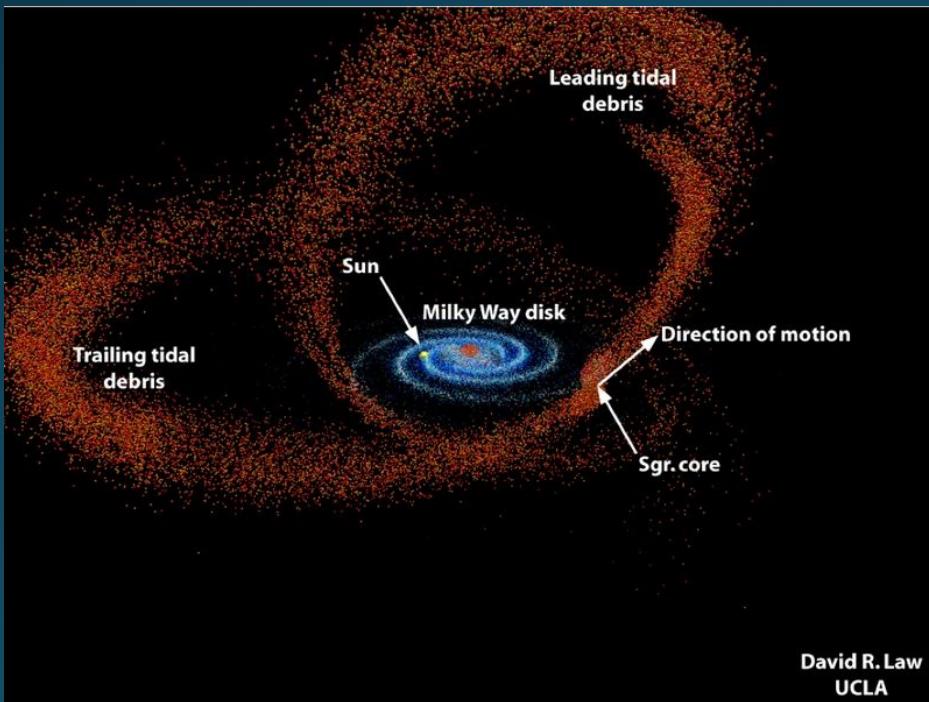


Backaction evasion



Axion astrophysics?

- Could see substructure within dark matter halo
- Low velocity distribution: sharp, narrow peak

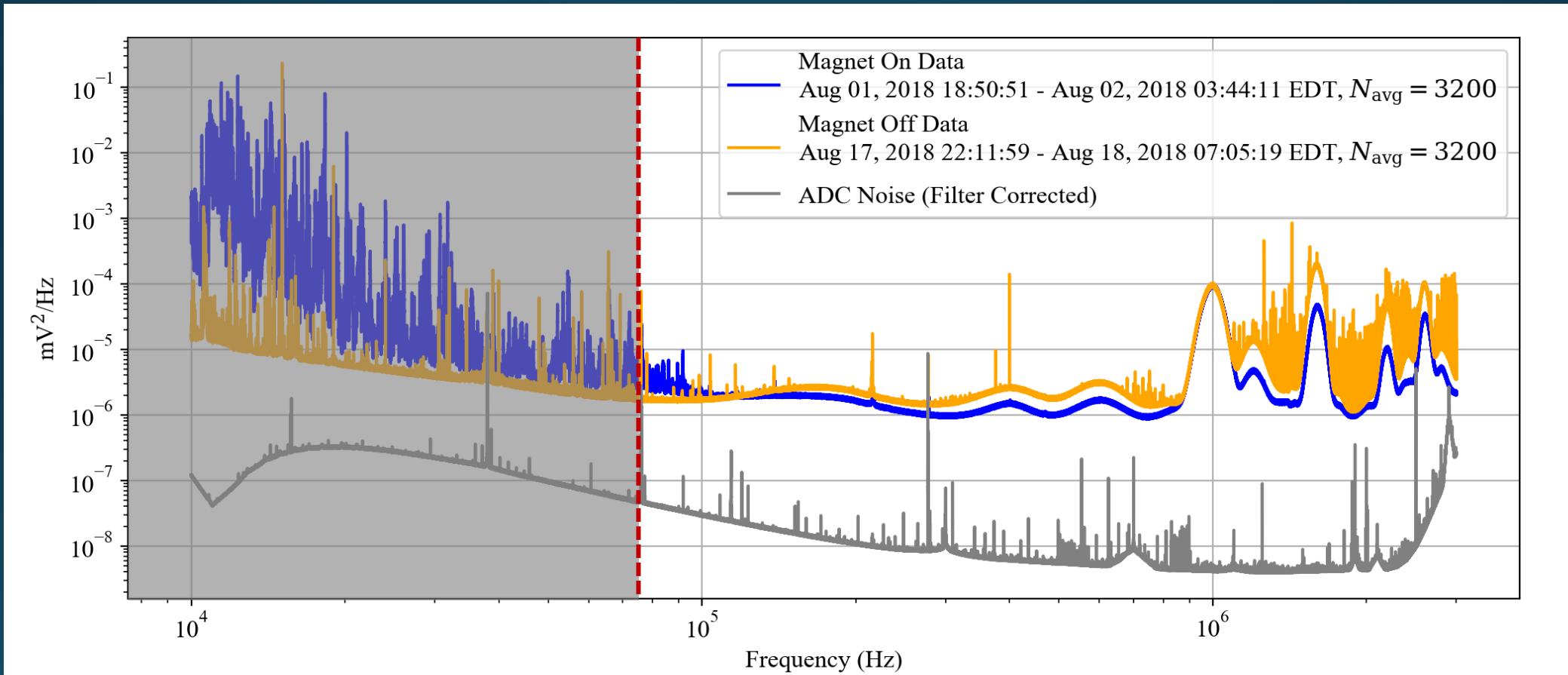


ABRA run 3 analysis procedure

1. Data cleaning
 - Single bin excesses
 - Radio signals
 - Moving peaks
 - Frequency combs e.g. every 50 Hz
 - Transient excesses
 - Magnet off excesses
2. Nuisance parameter modification of likelihood
 - Tuned with ensemble of observed significance values in clean dataset

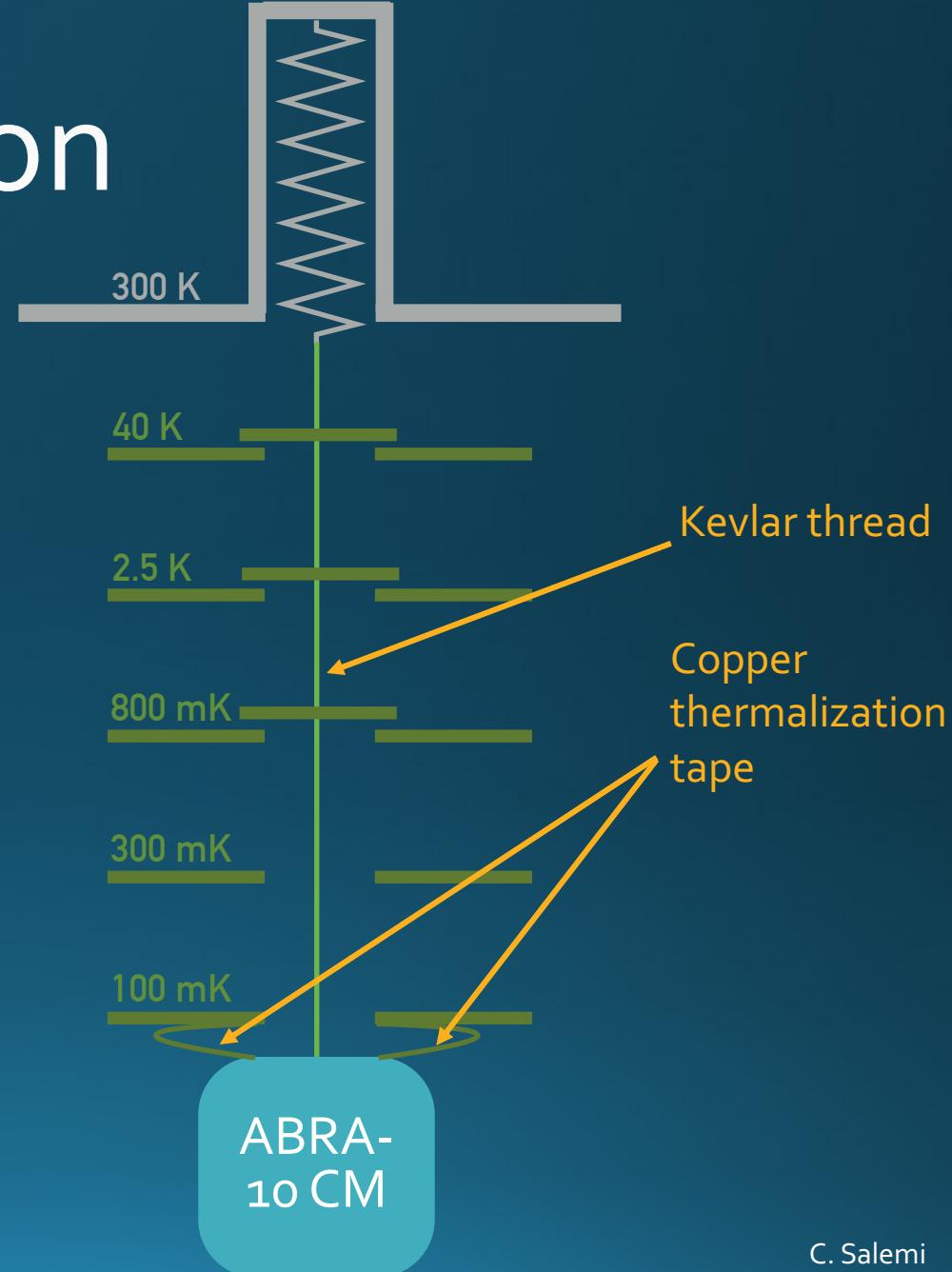
ABRA run 1

$m_a \sim \text{neV}$, "GUT-scale"

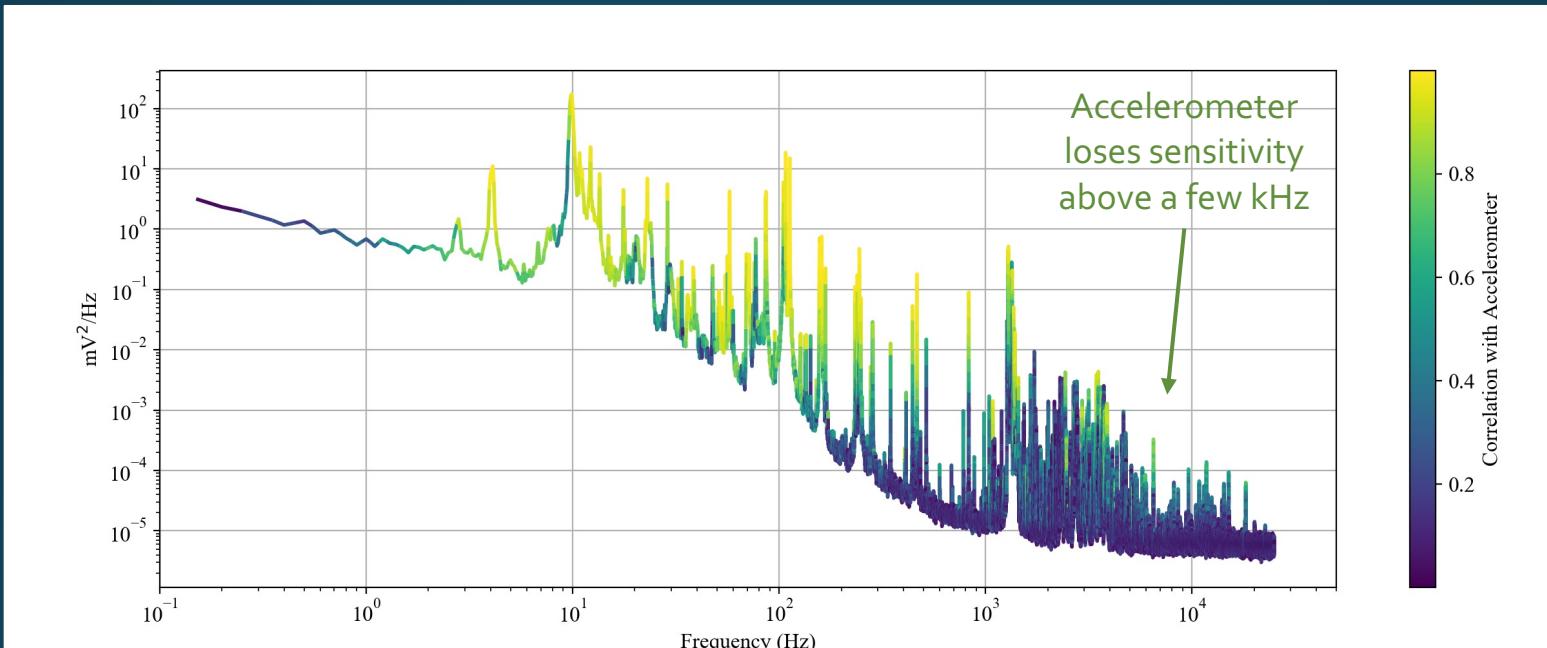


ABRA Vibration Isolation

- Suspension system added to reduce vibrations
 - x,y damping with 1.5 m pendulum (~2 Hz resonance frequency)
 - z damping with spring (~2 Hz resonance frequency)

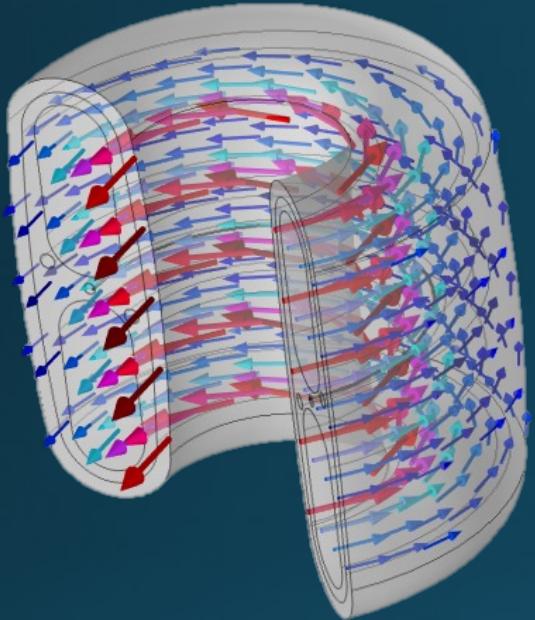


ABRA Vibrational Noise

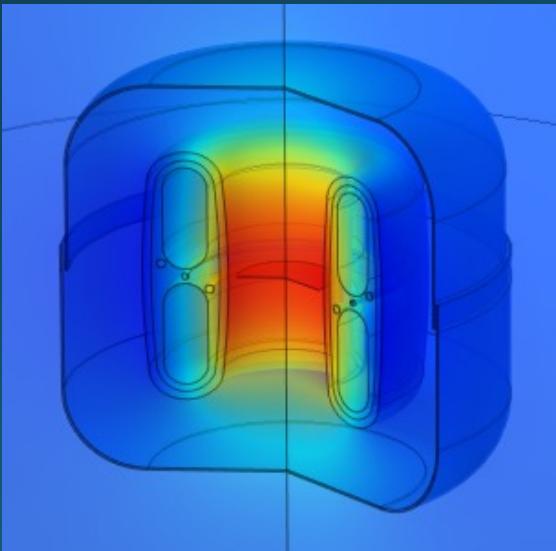


- Huge amount of noise below ~ 10 kHz, strongly correlated with vibration on the 300K plate
- Had to use a 10kHz high pass filter to get the data to fit in the digitizer window
- Hard limit on the low end of the search window

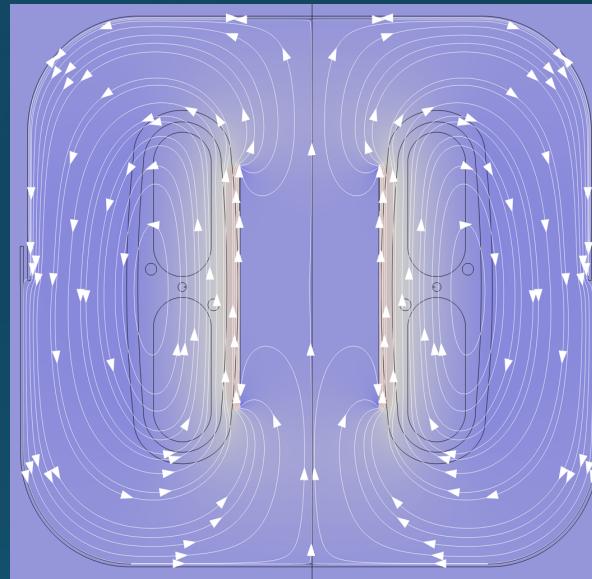
COMSOL simulations



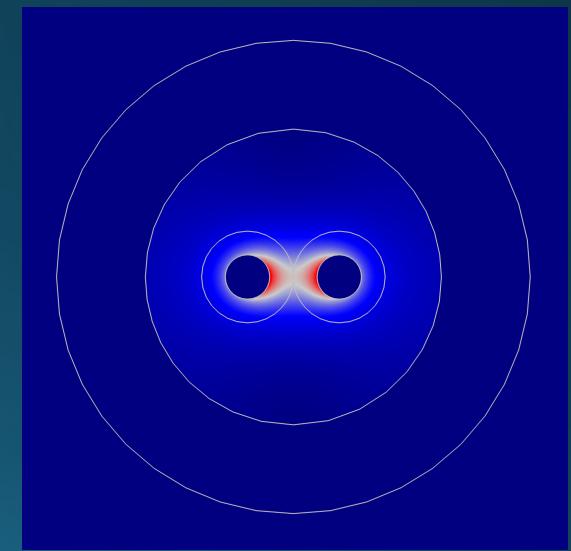
Axion effective current
distributed in magnetic field



Axion magnetic field
oscillates in toroid bore



Current induced in pickup



Current propagates
through wiring