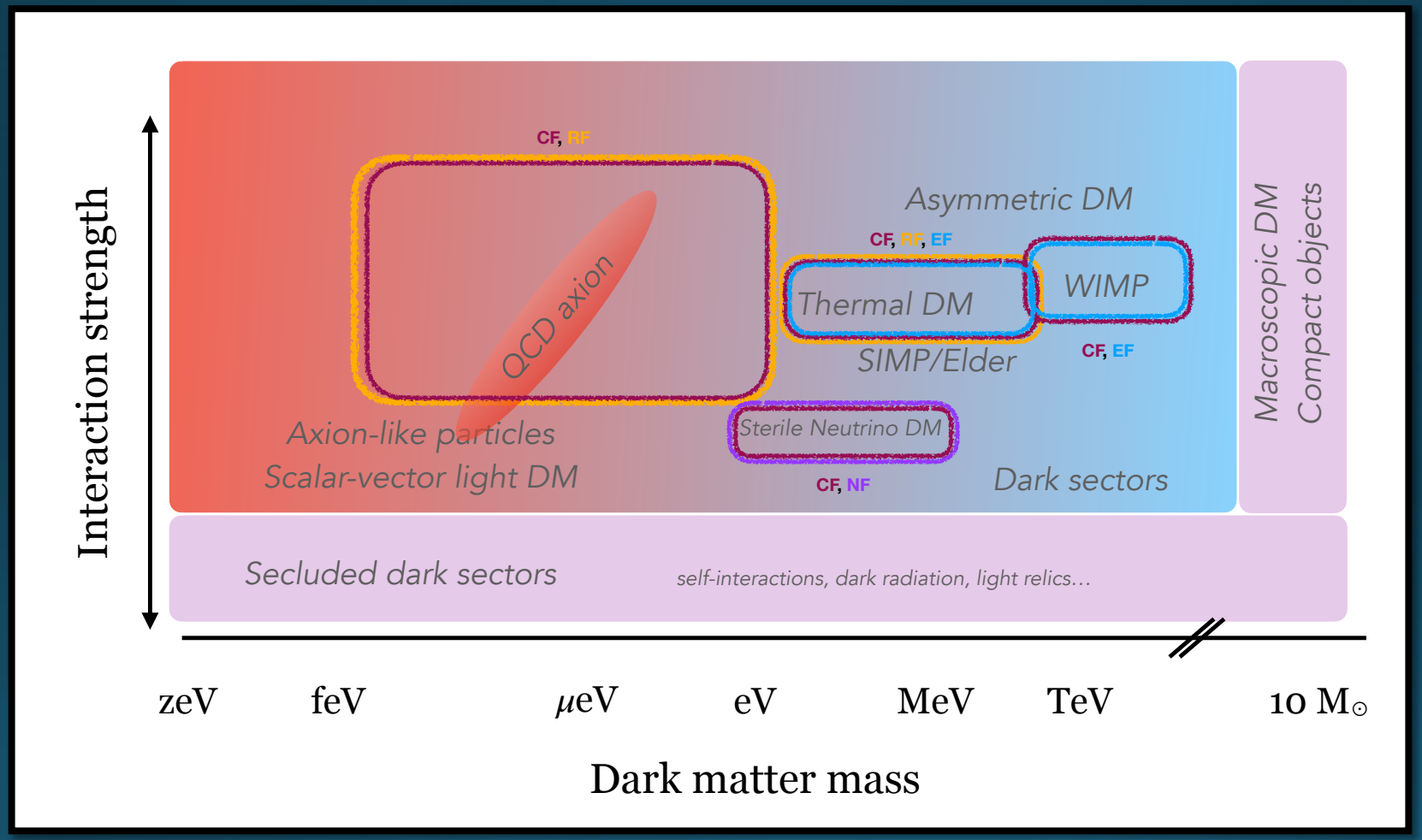
Seeing the Invisible: The Search for Low-Mass Axion Dark Matter

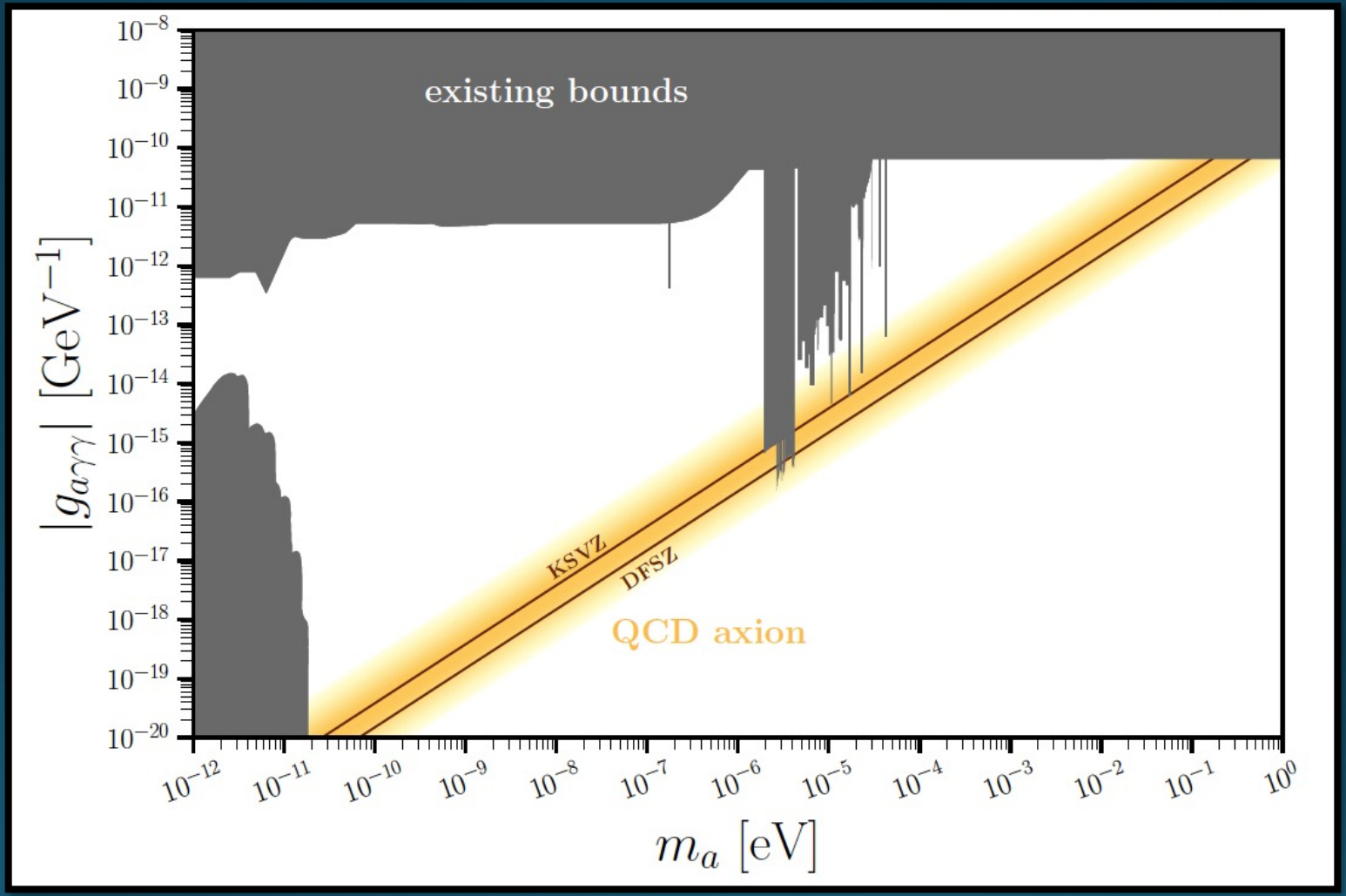
Chiara P. Salemi
Stanford University and SLAC
Prospecting for New Physics, March 2023

Invisible?



Snowmass 2021 Dark Matter Complementarity Report

Lots of highly motivated parameter space to cover!



A. Berlin and others

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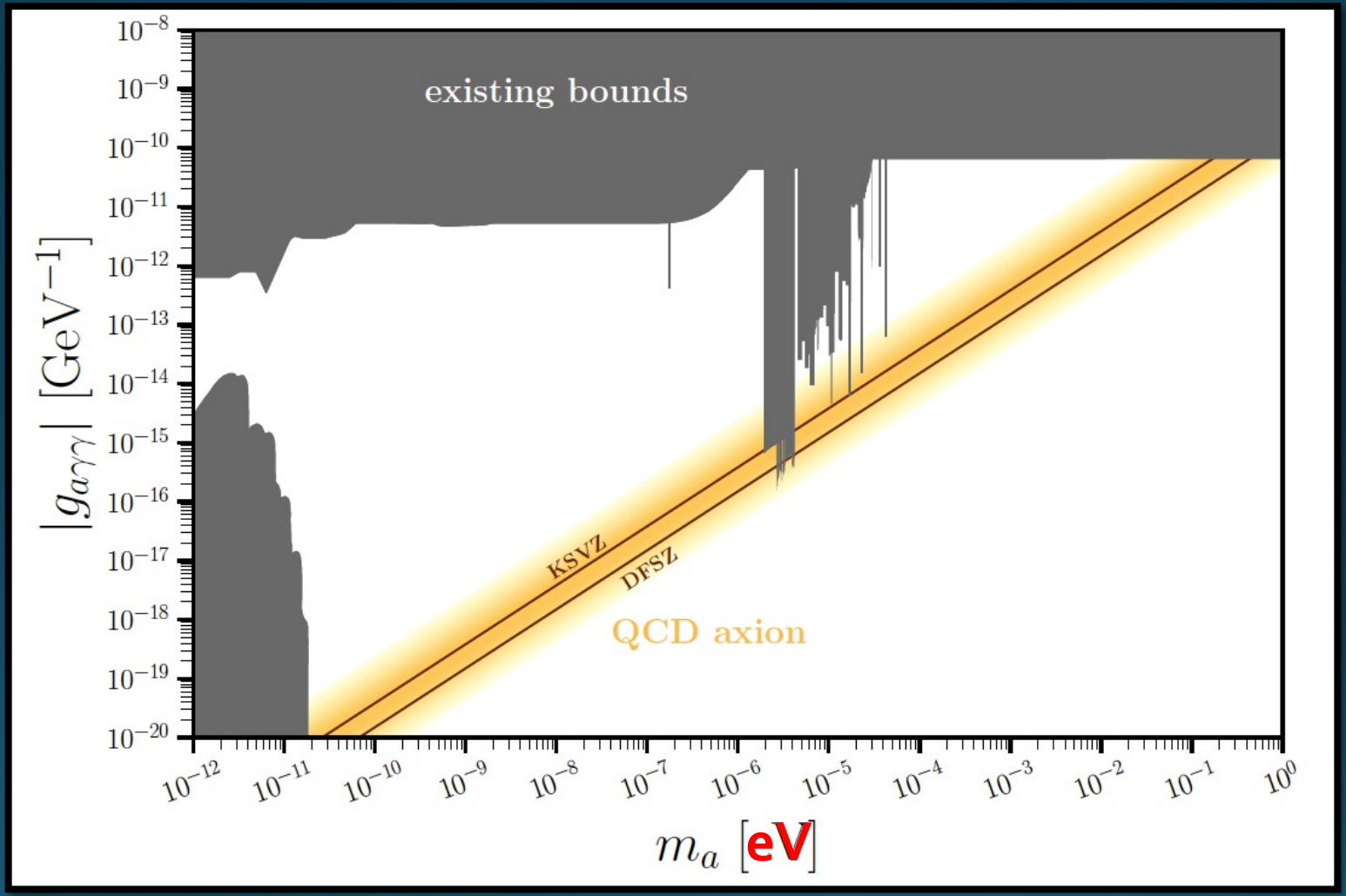

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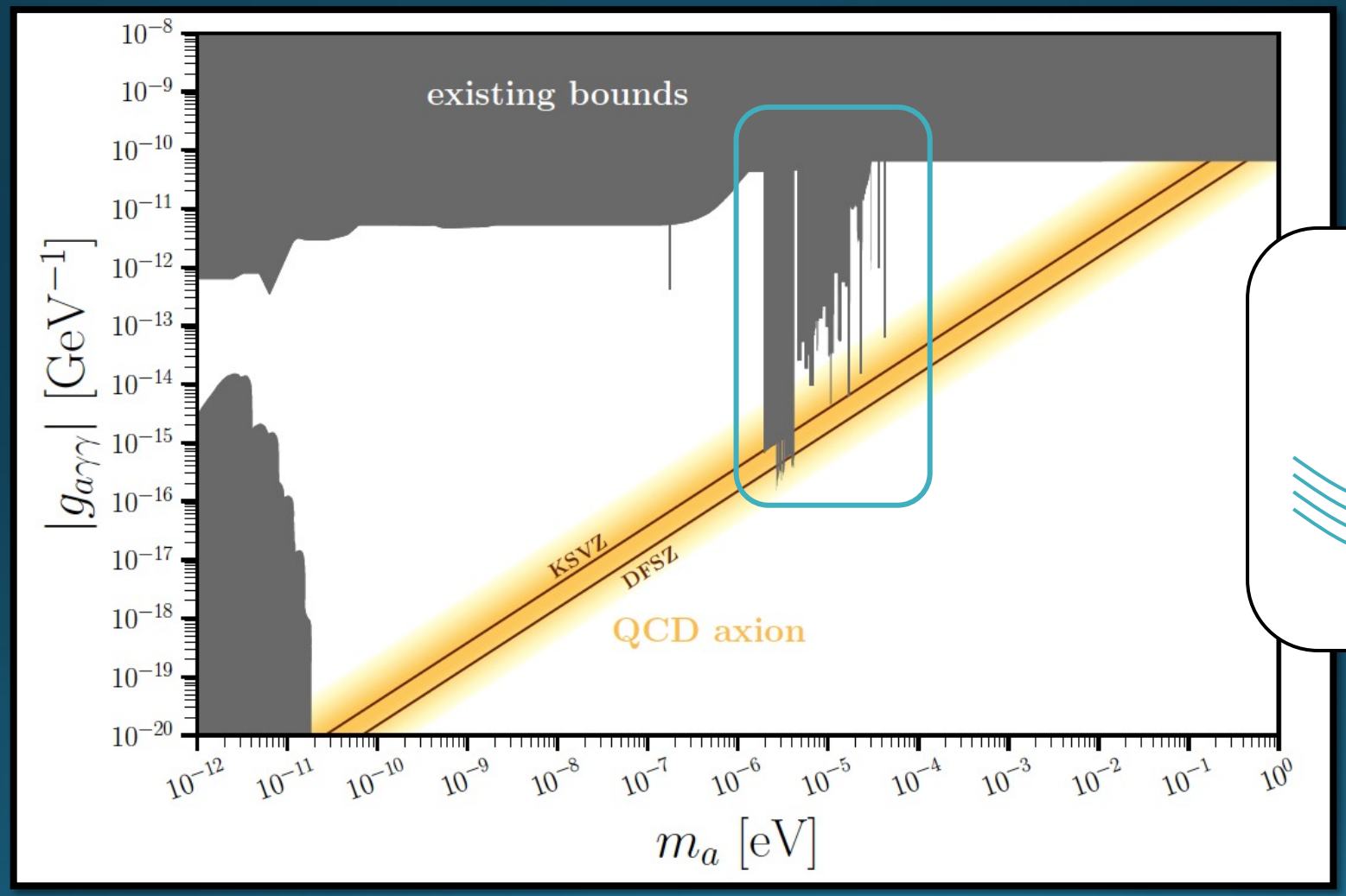
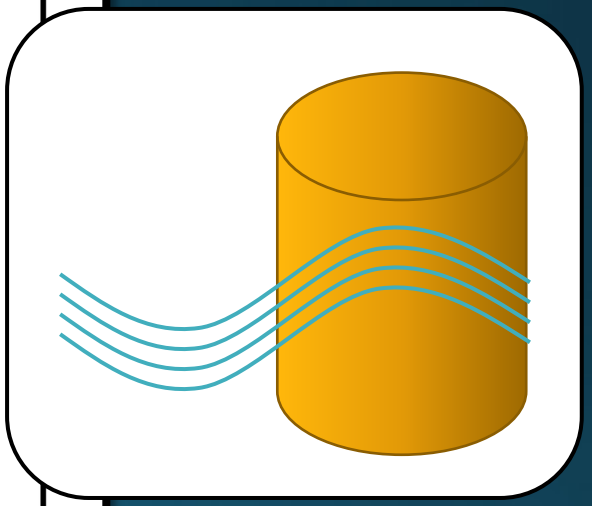


cavities



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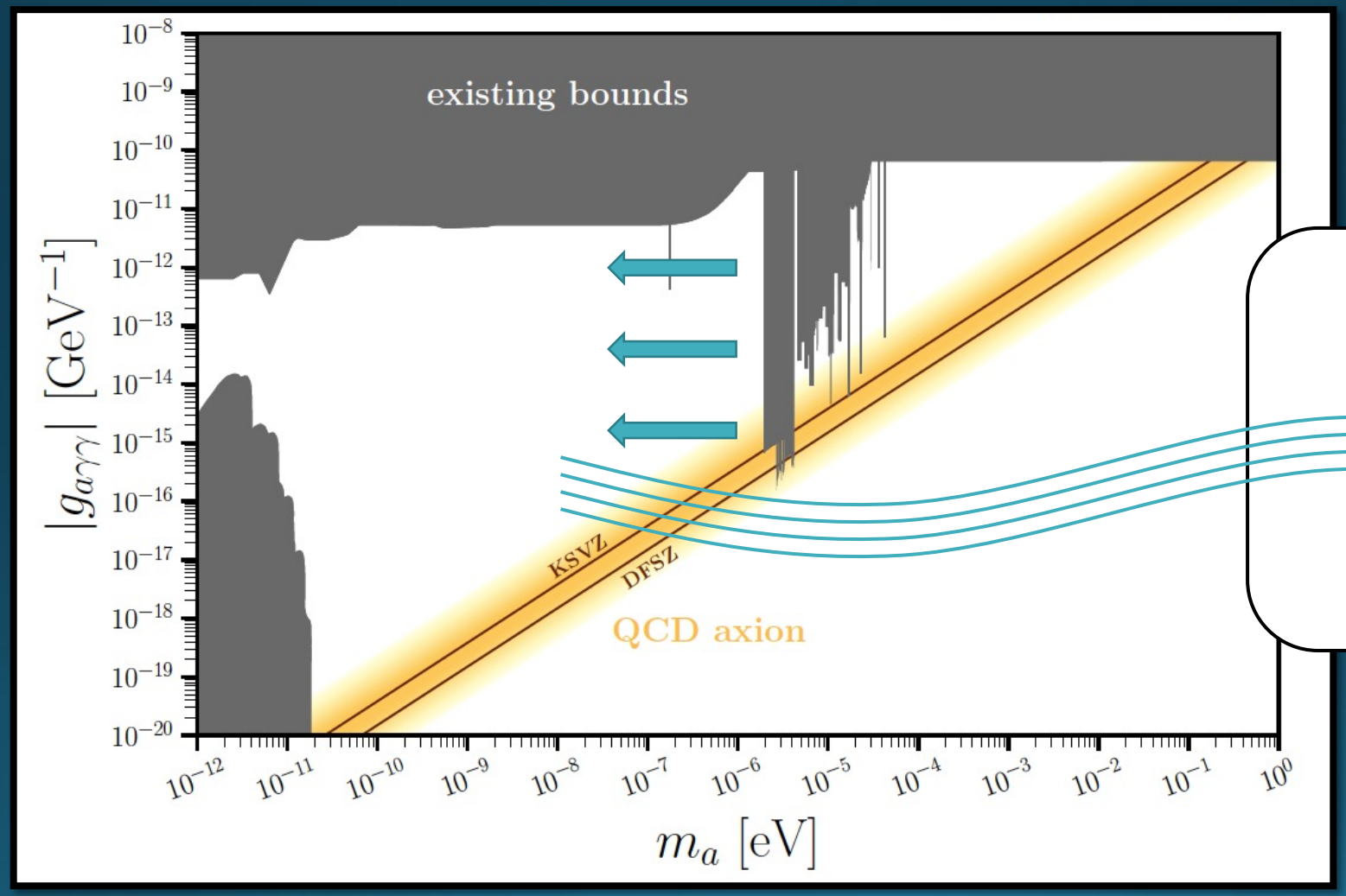
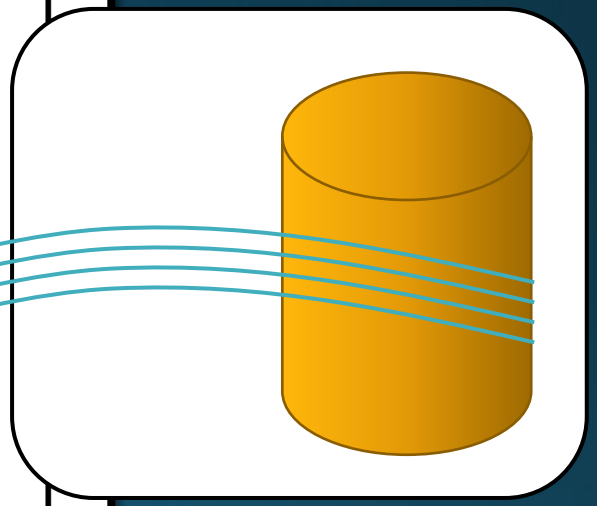


lumped elements



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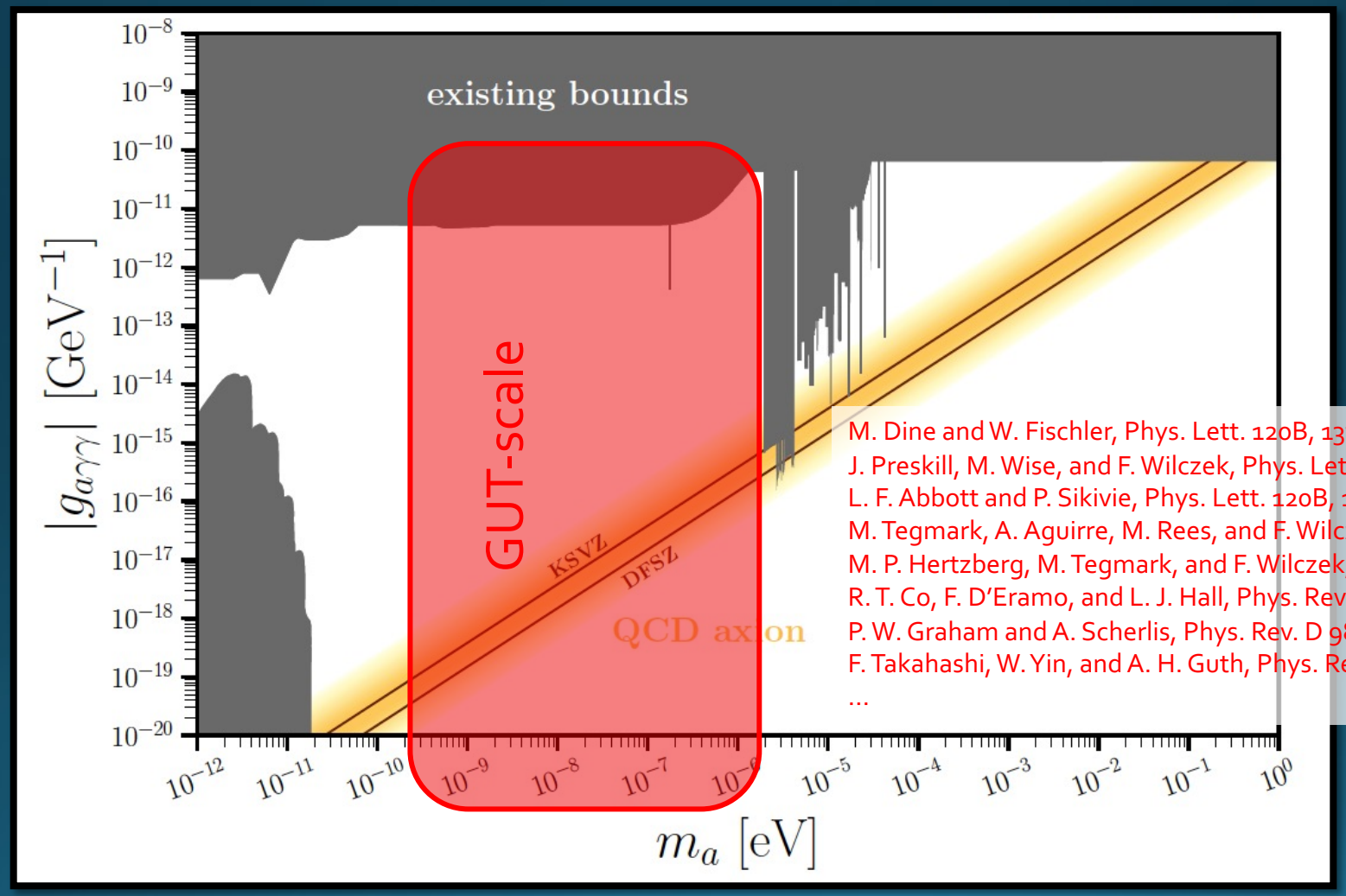

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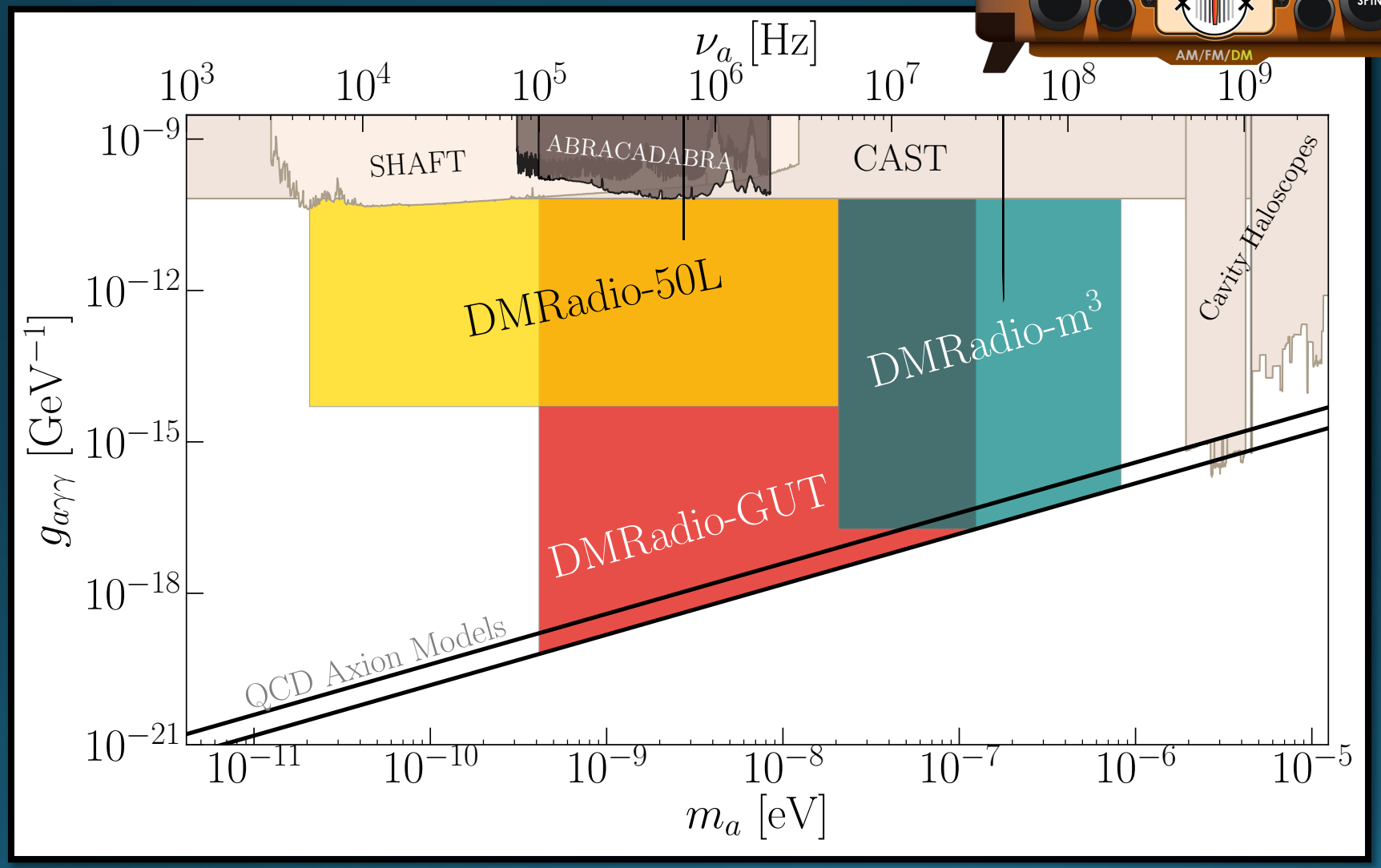
F. Takahashi, W. Yin, and A. H. Guth, Phys. Rev. D 98, 015042 (2018)
…

A. Berlin and others

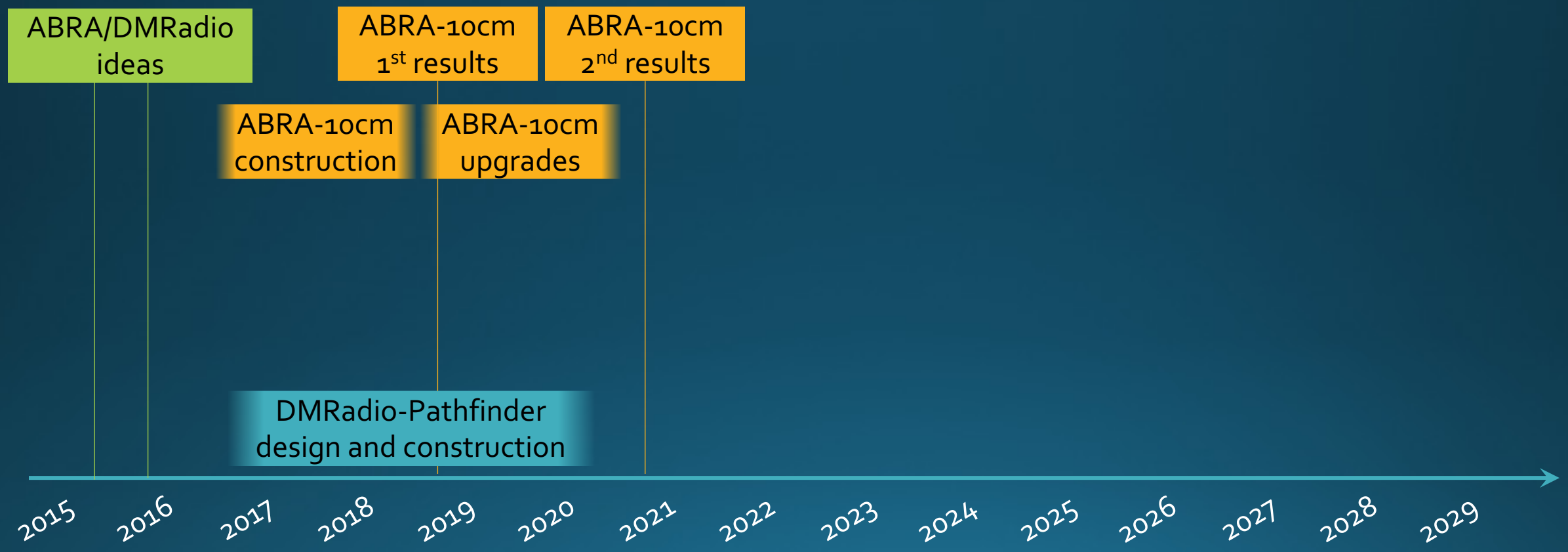
ABRACADABRA +



Timeline

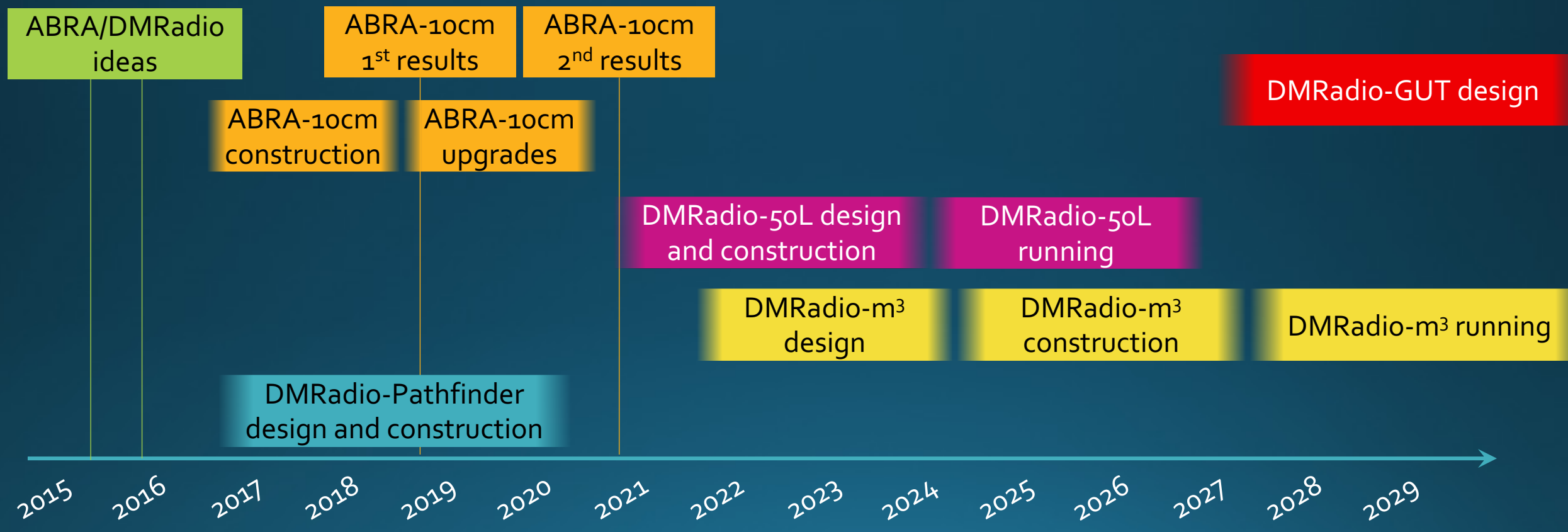
Chaudhuri et al. *Phys.Rev.D* 2015
Kahn, Safdi, Thaler *Phys.Rev.Lett.* 2016

Timeline



Ouellet, Salemi et al. *Phys.Rev.Lett.* 2019
Salemi et al. *Phys.Rev.Lett.* 2021
Phipps et al. *Axion Cavity Workshop Proceedings* 2020

Timeline


ABRA/DMRadio ideas
ABRA-10cm 1st results
ABRA-10cm 2nd results
DMRadio-GUT design
ABRA-10cm construction
ABRA-10cm upgrades
DMRadio-50L design and construction
DMRadio-50L running
DMRadio-m3 design
DMRadio-m3 construction
DMRadio-m3 running
DMRadio-Pathfinder design and construction
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029

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

Axion-photon interactions modify Ampere's Law:

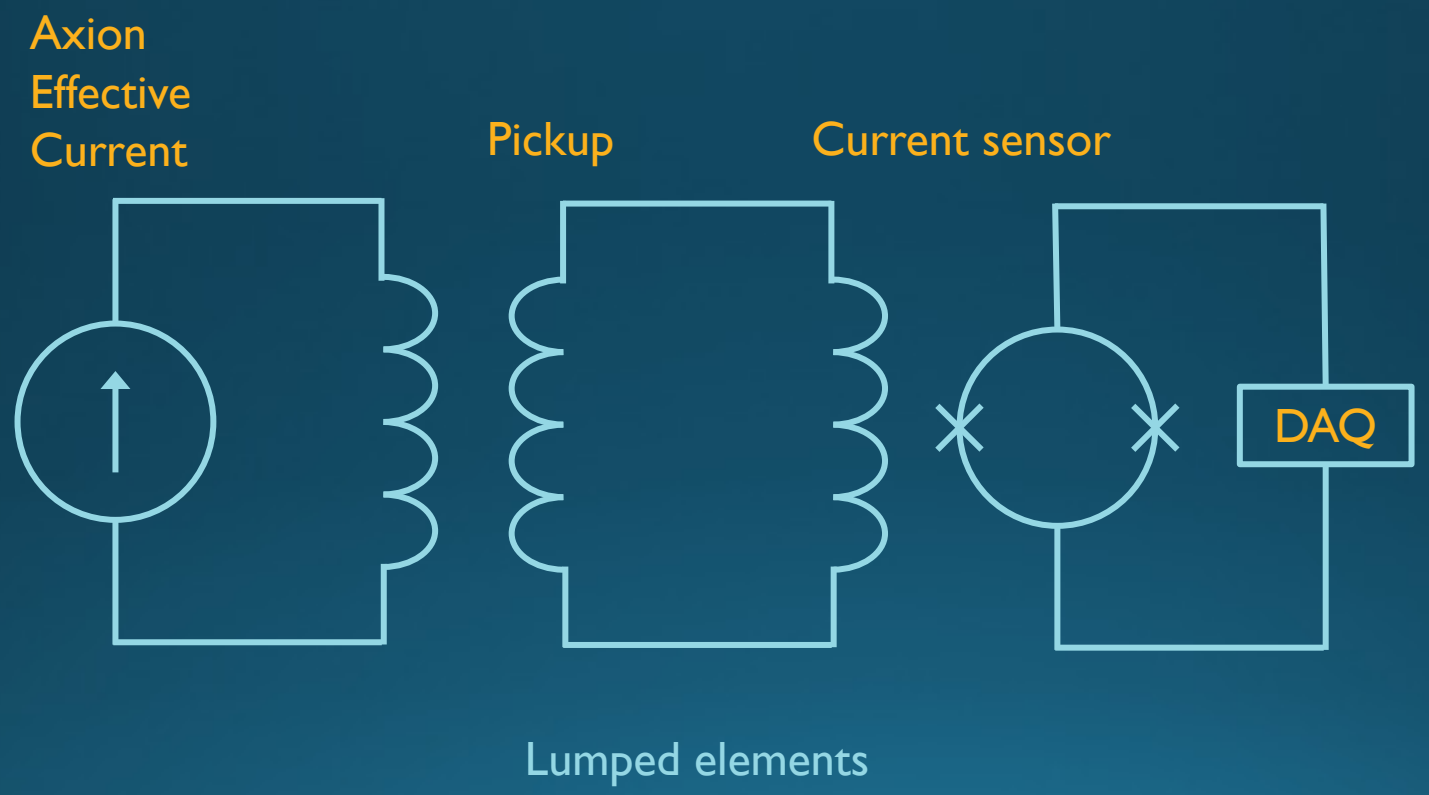
$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} - g_{a\gamma\gamma}(\cancel{\mathbf{E} \times \nabla a} - \frac{\partial a}{\partial t}\mathbf{B})$$

$$\Downarrow$$

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

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

Schematic of lumped-element detection



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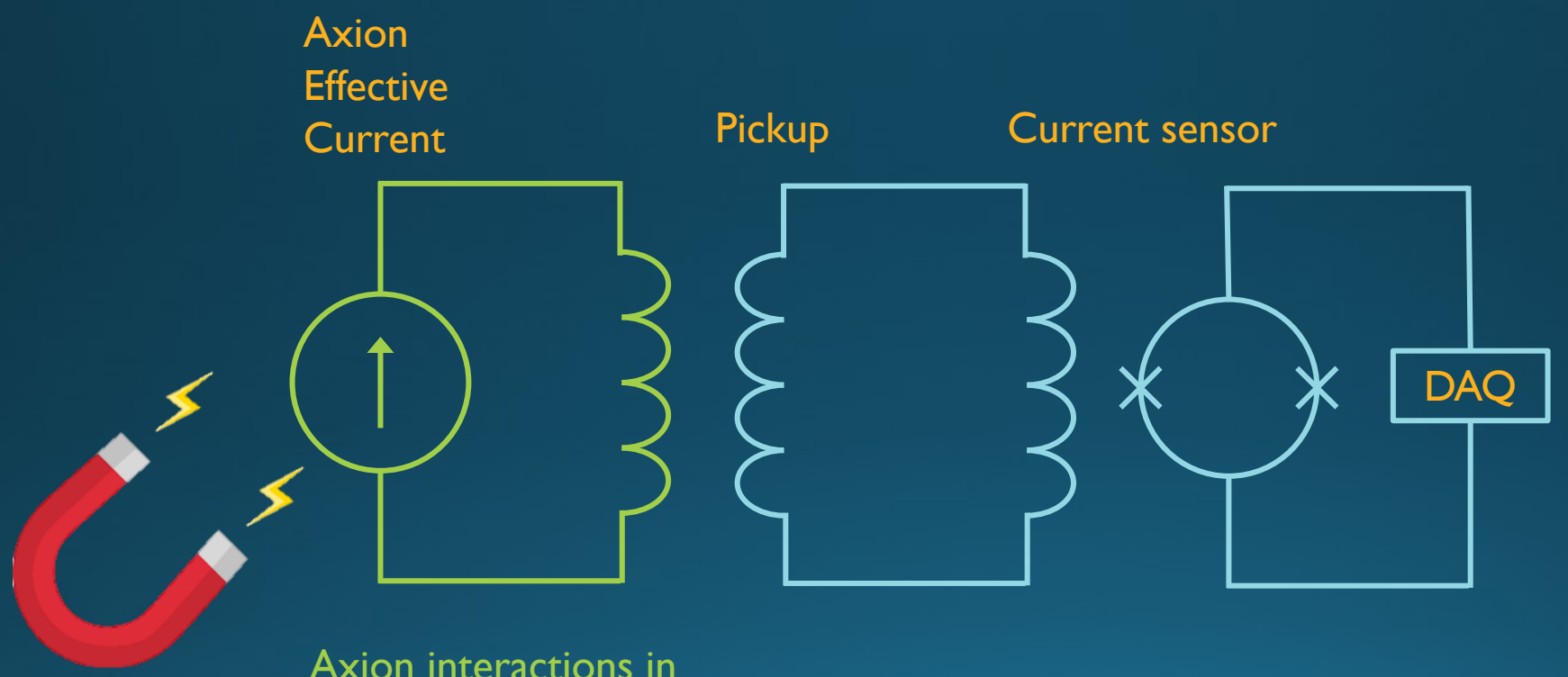
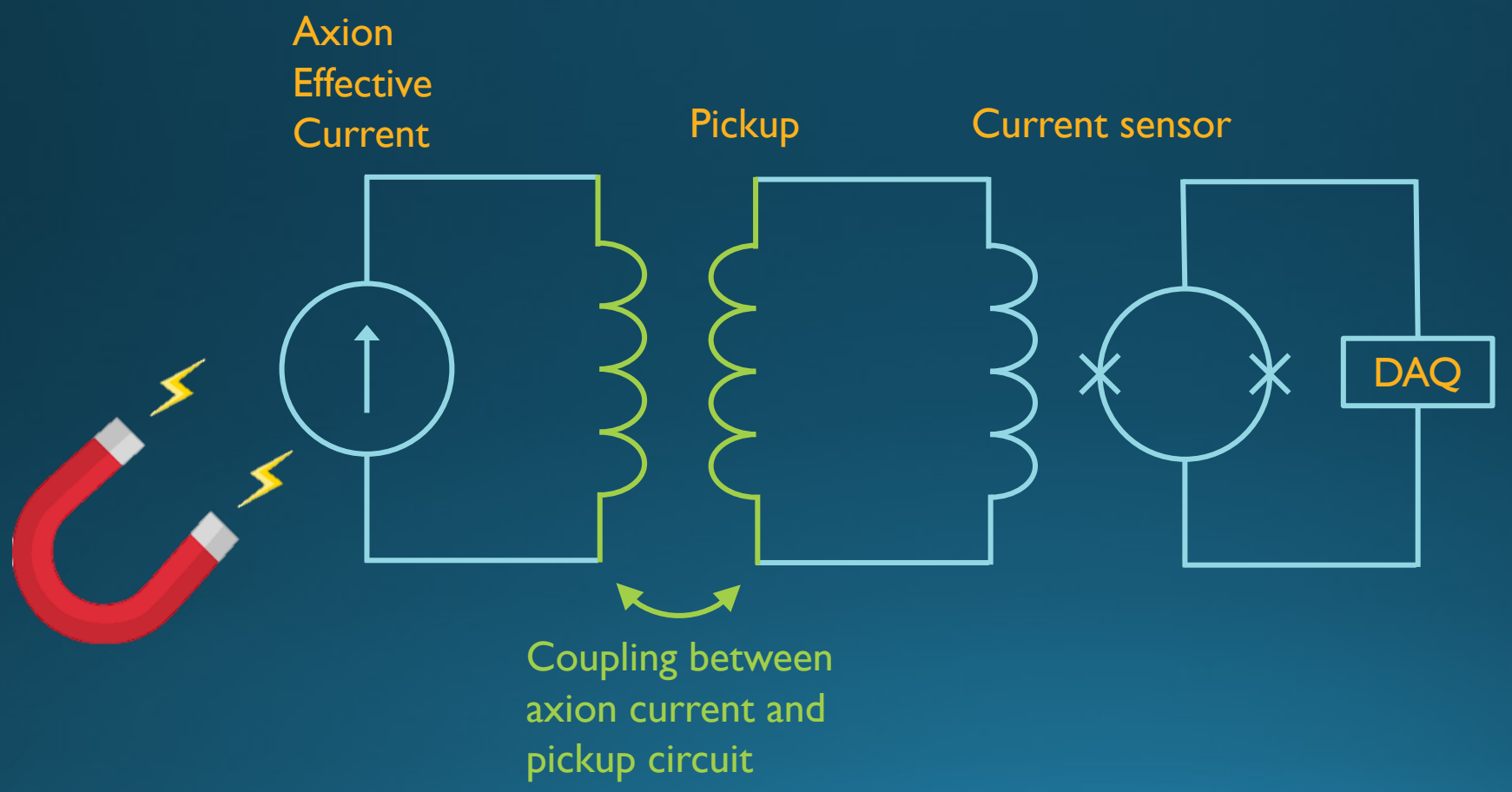


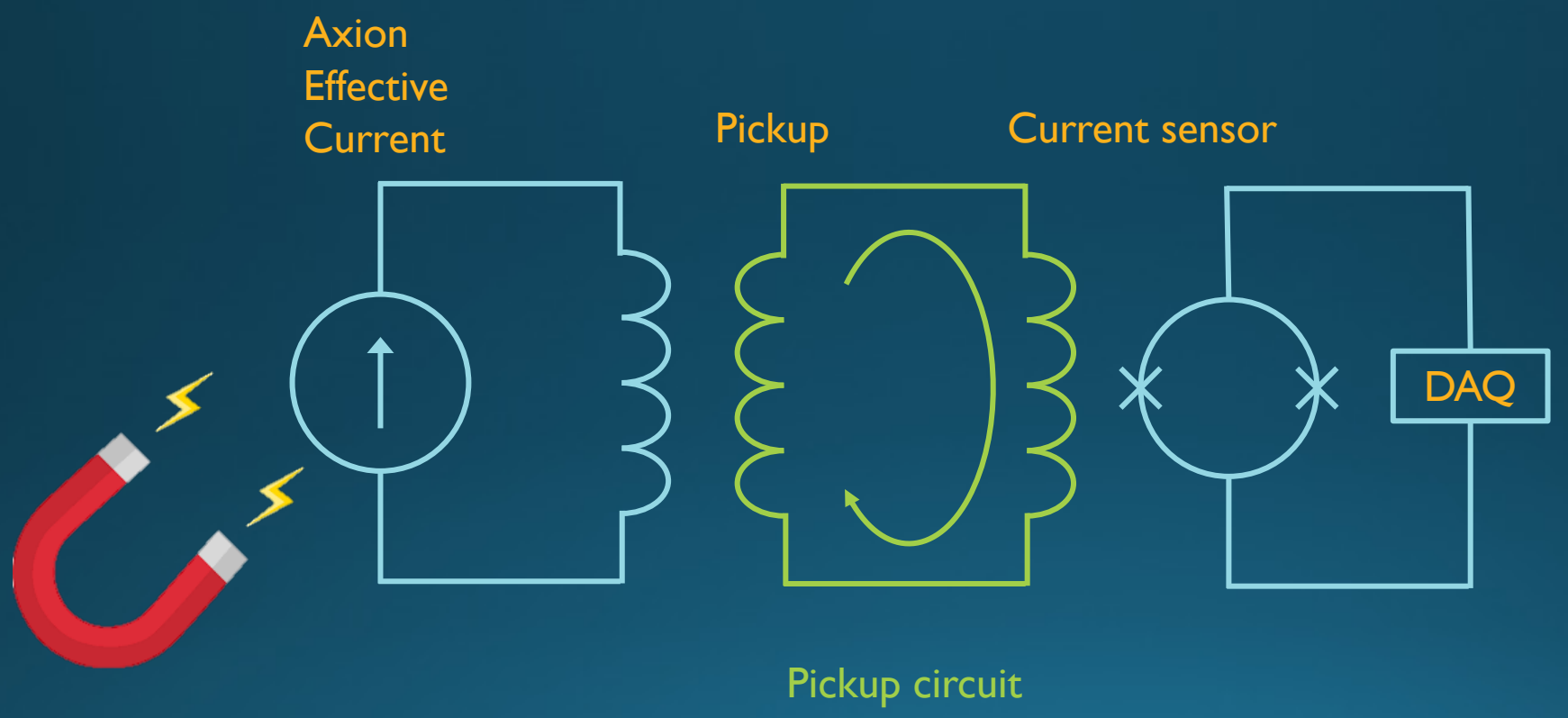
Axion interactions in magnetic field

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

Schematic of lumped-element detection



Schematic of lumped-element detection



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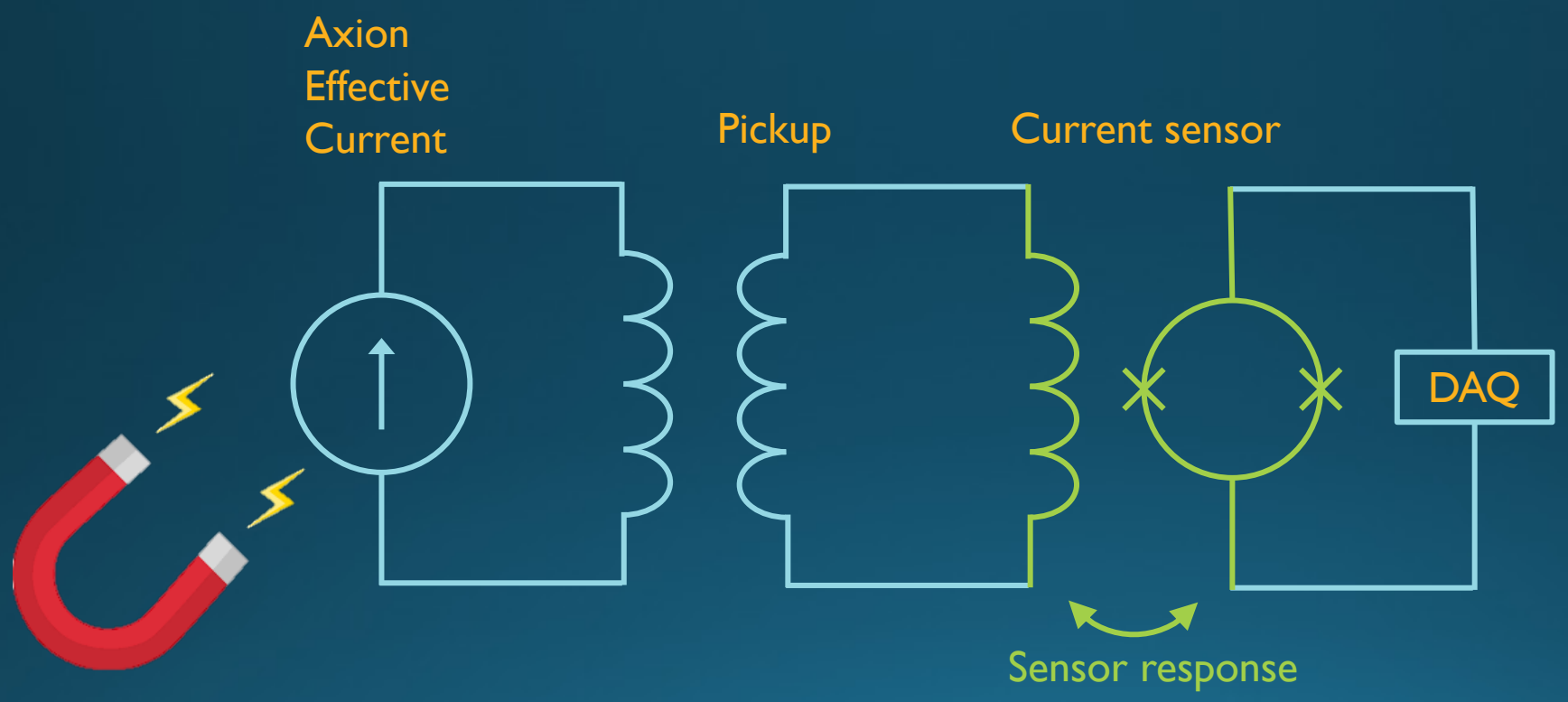
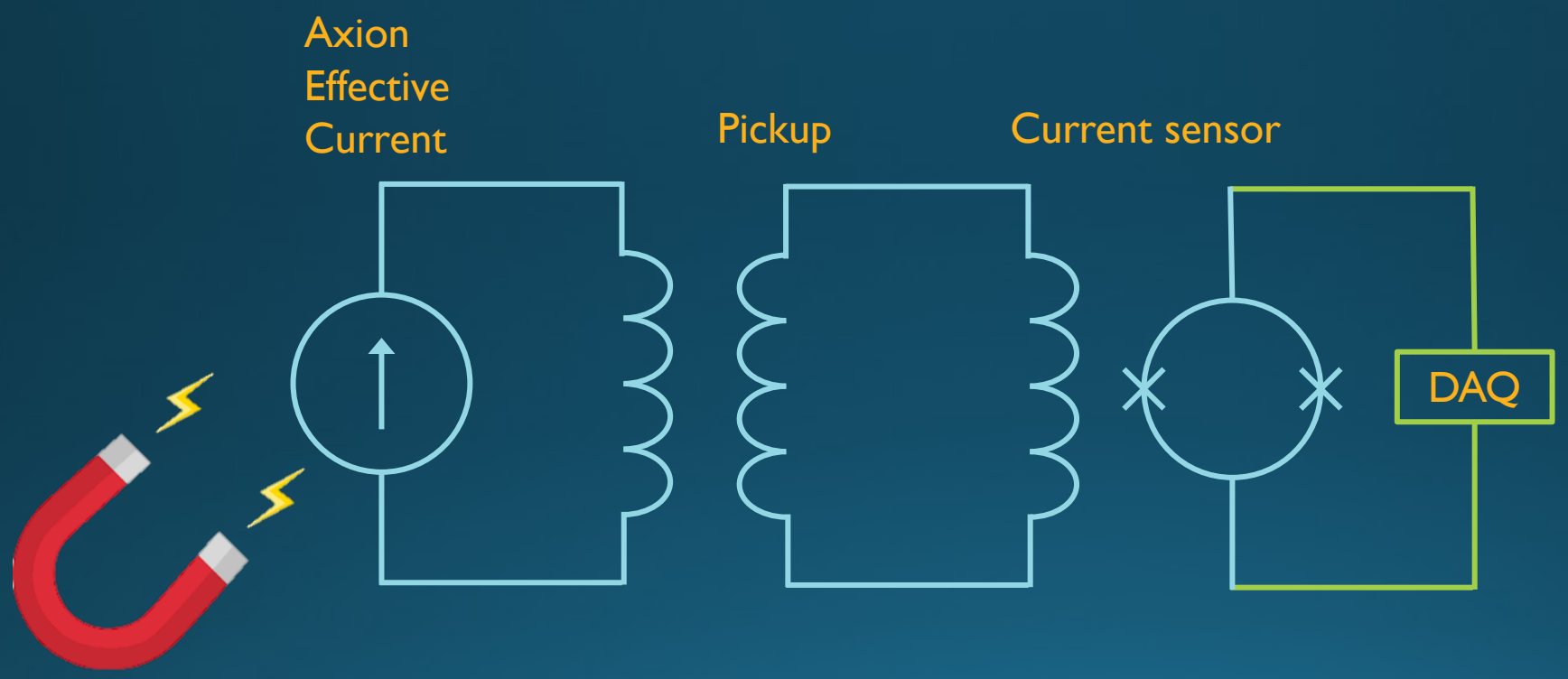
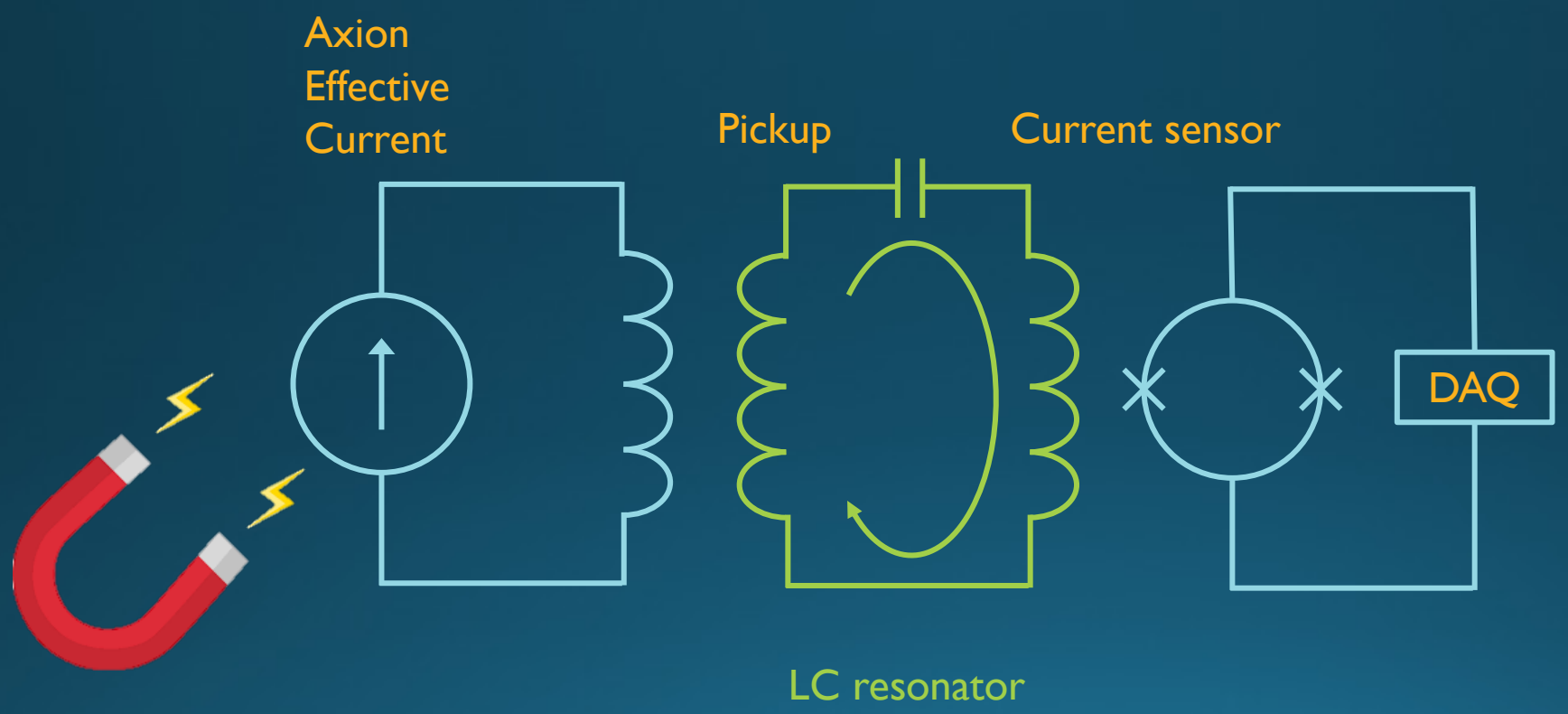


Schematic of lumped-element detection



Schematic of lumped-element detection

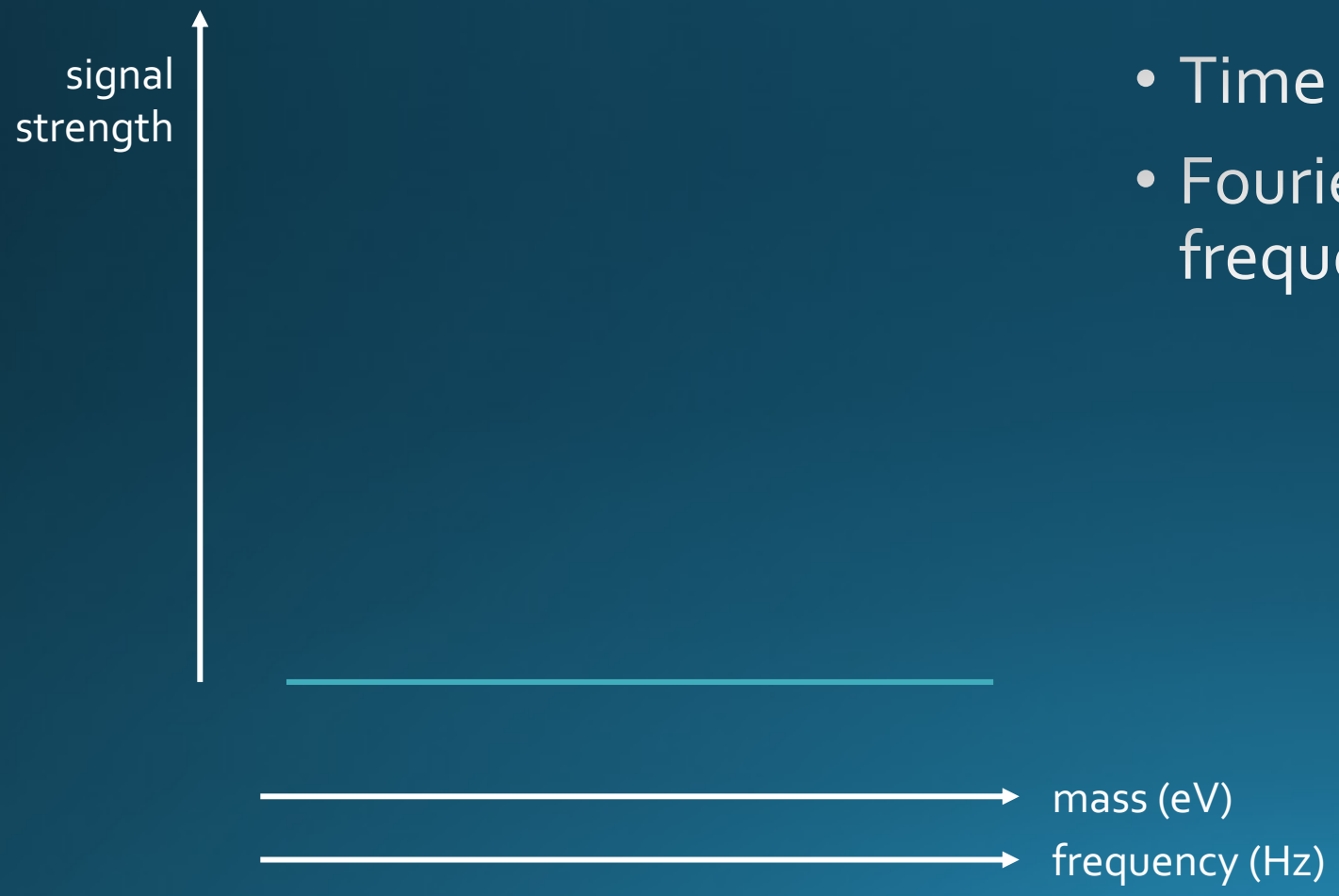
Resonant readout



What does a signal look like?

- Time series data collection
- Fourier transform to look for peaks in frequency space

What does a signal look like?



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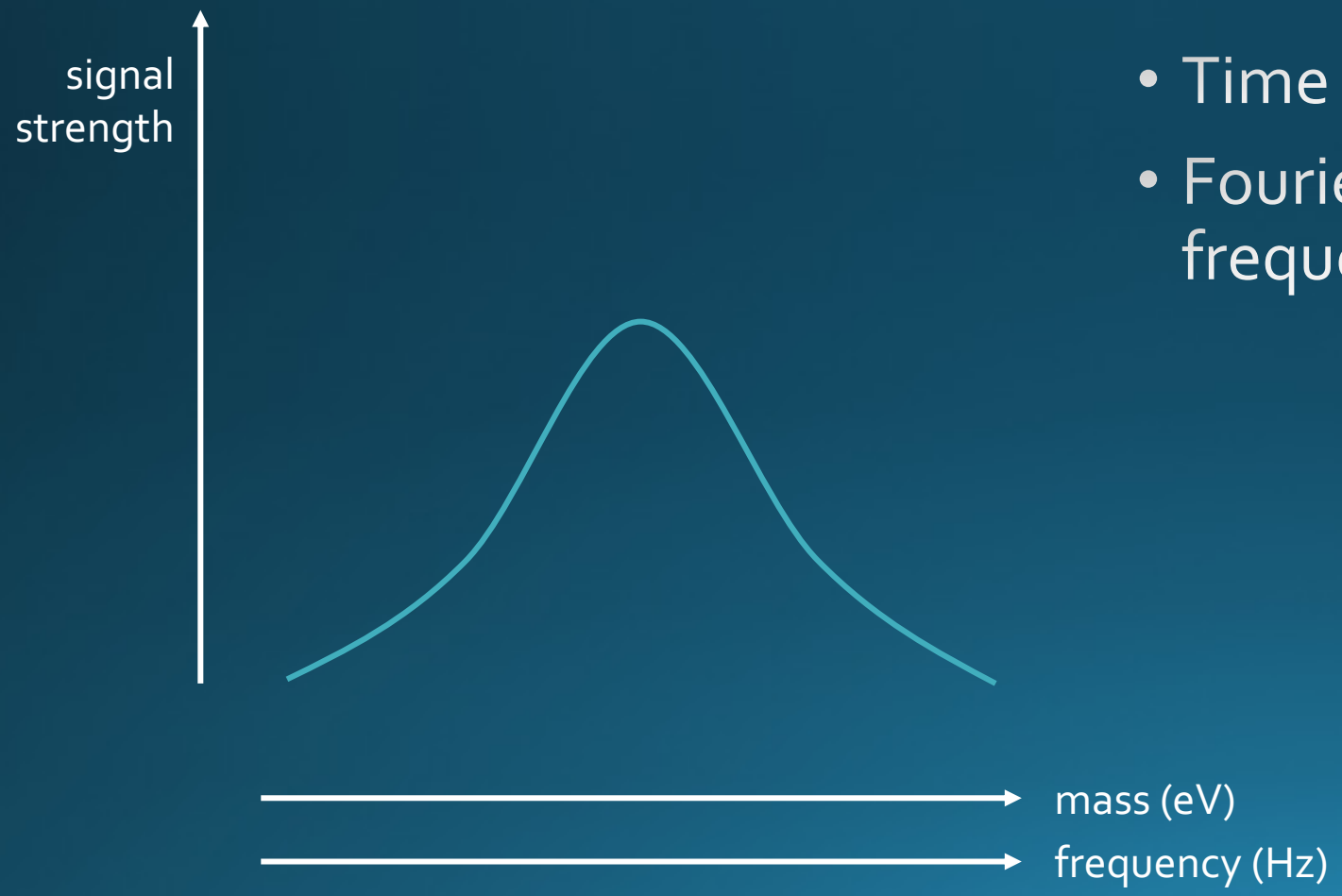

- Time series data collection
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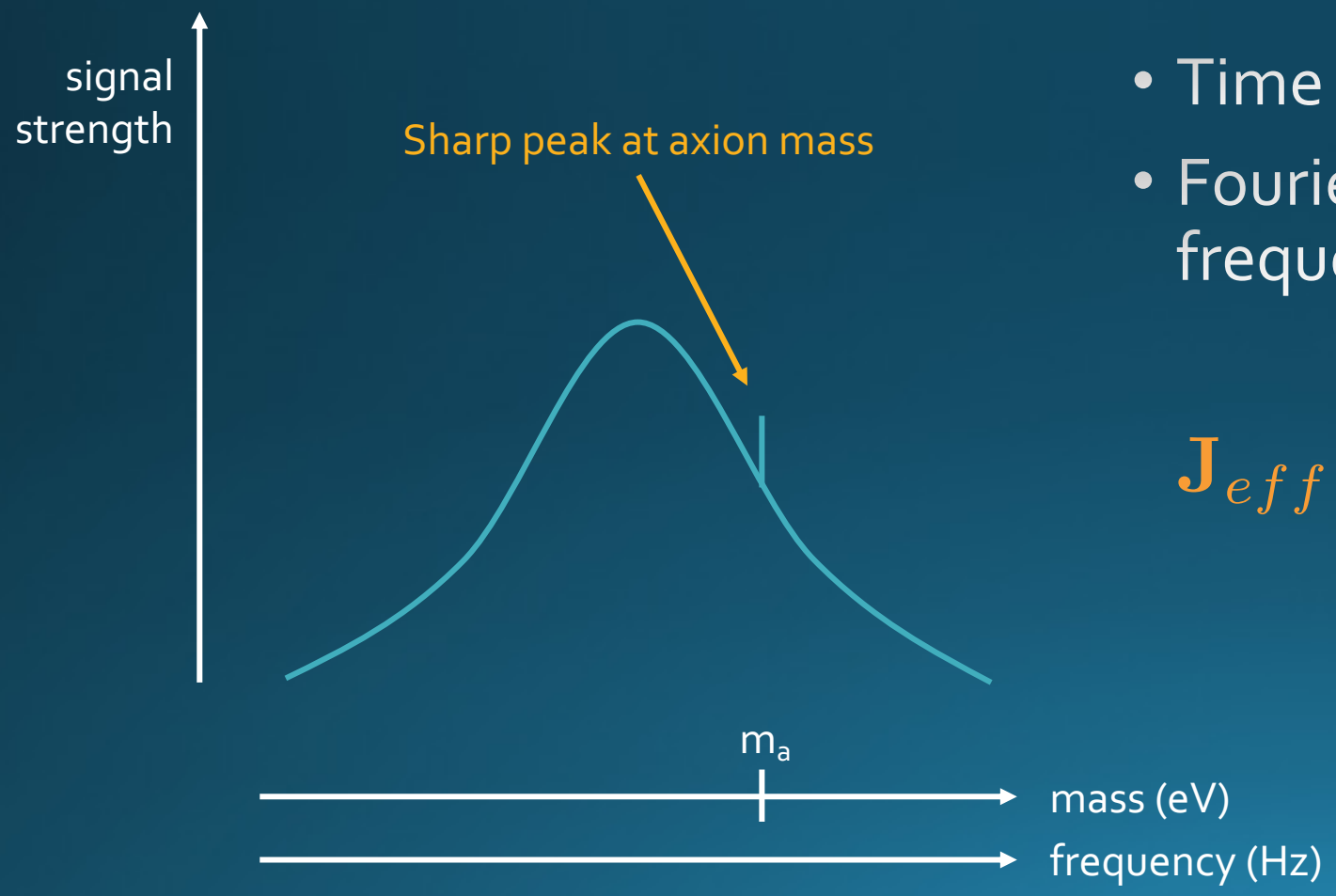
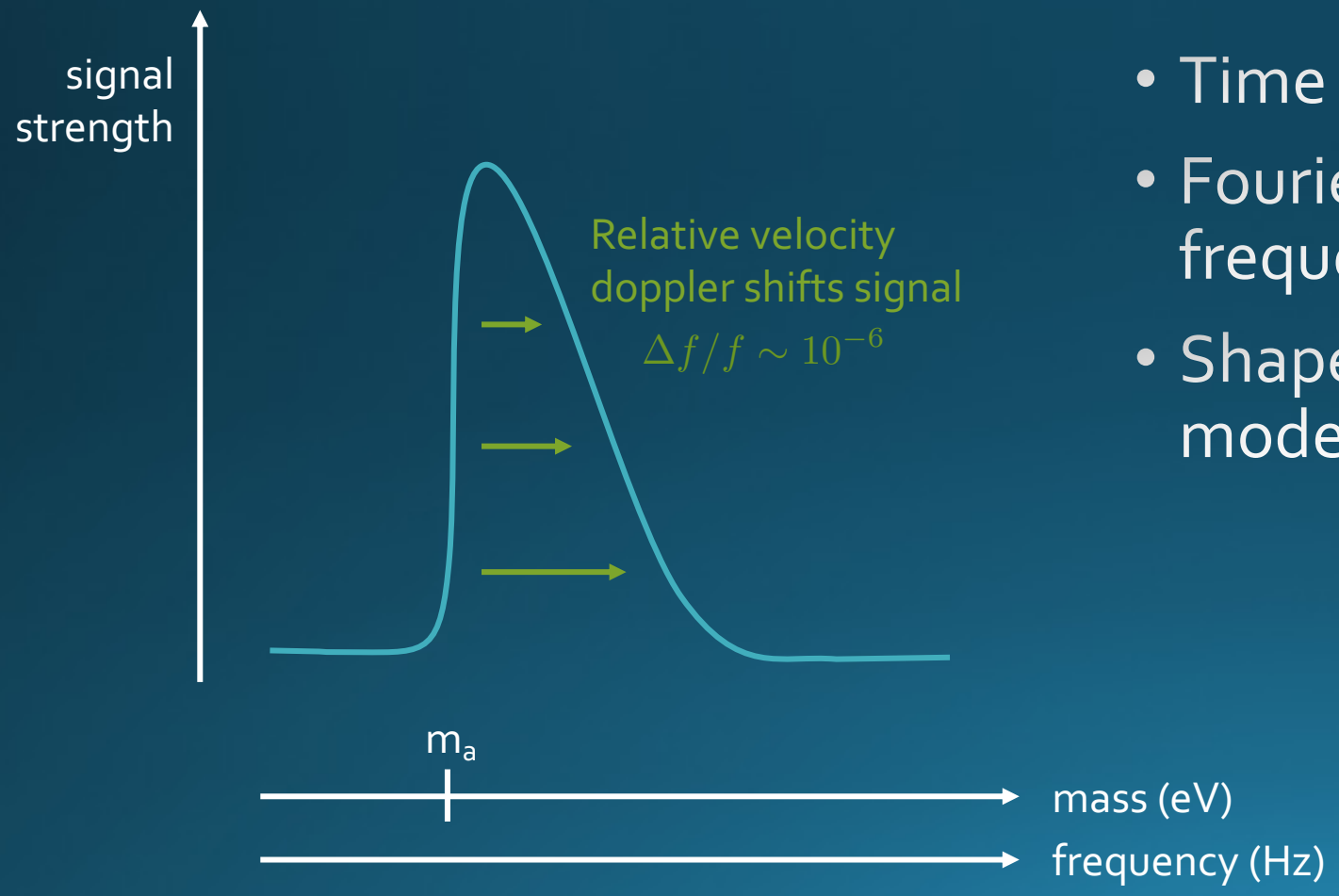


- Time series data collection
- Fourier transform to look for peaks in frequency space

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

What does a signal look like?



- Time series data collection
- Fourier transform to look for peaks in frequency space
- Shape determined by standard halo model

Scan rate (our sensitivity FOM)

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

ν : resonator frequency

Q : resonator quality factor

B_0 : peak magnetic field

T : system effective temperature

Q_a : axion quality factor

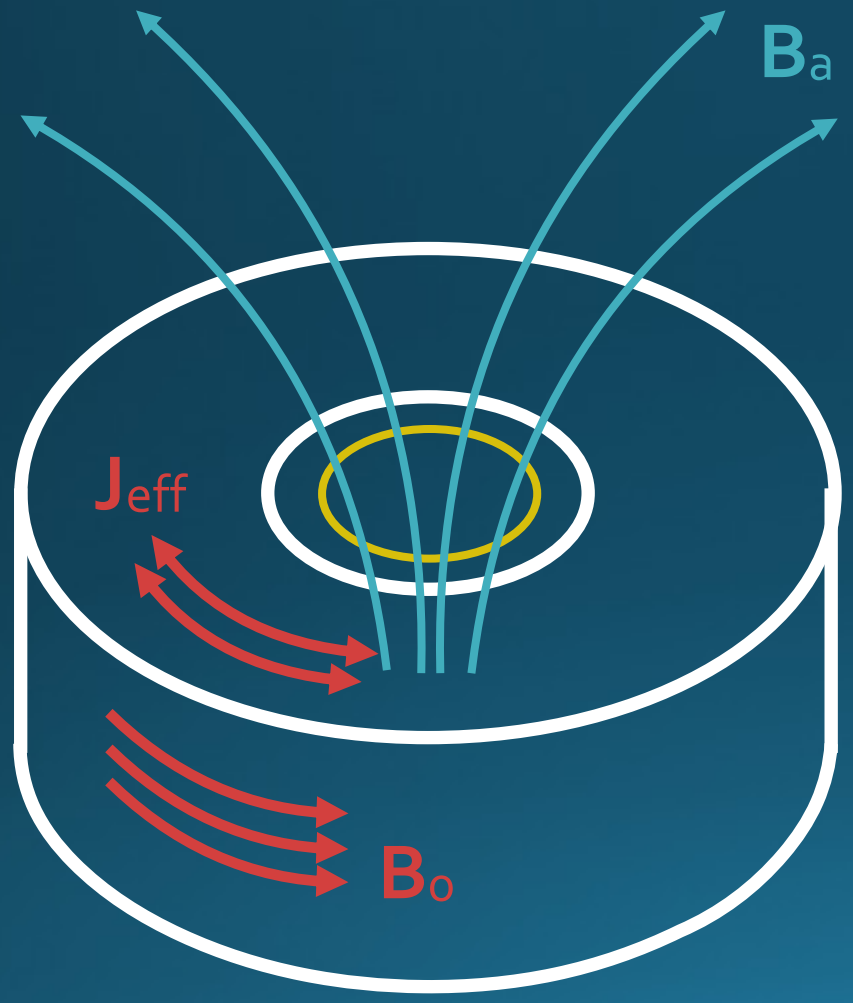
c_{PU} : pickup coupling

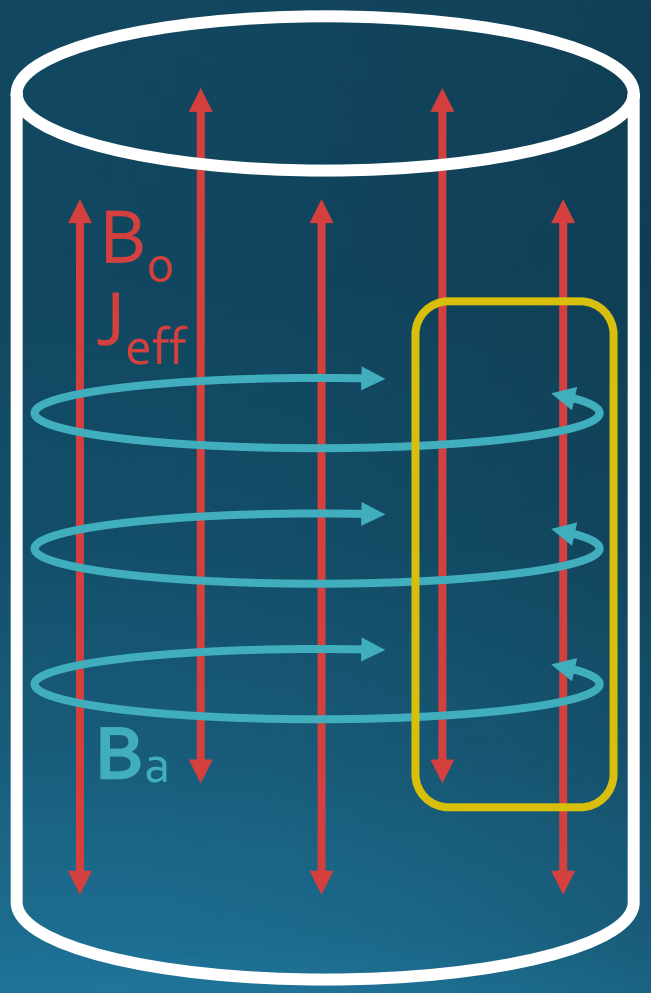
V : pickup volume

η : amplifier noise

Detector geometry: toroid vs solenoid

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

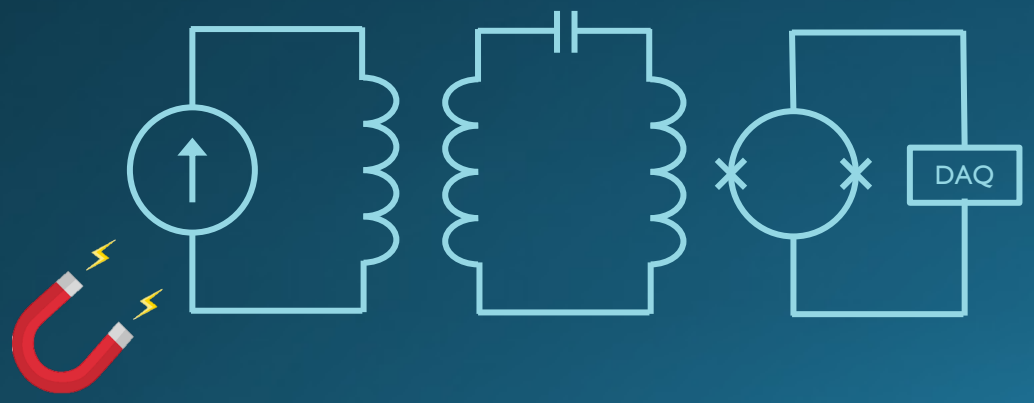


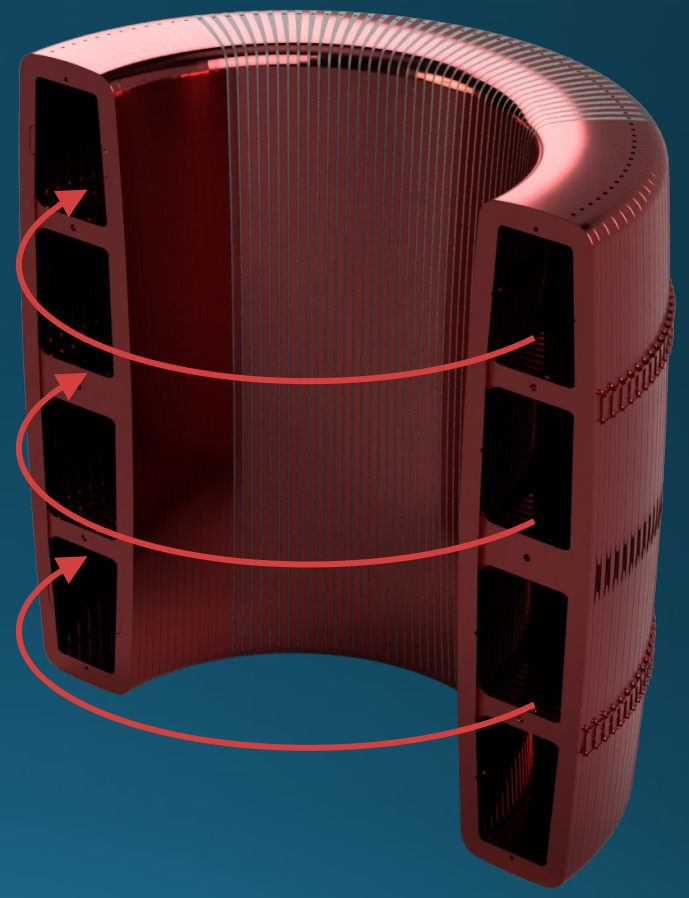


DMRadio-m^3

The 50L detector

Toroidal superconducting magnet with fixed field, B_0

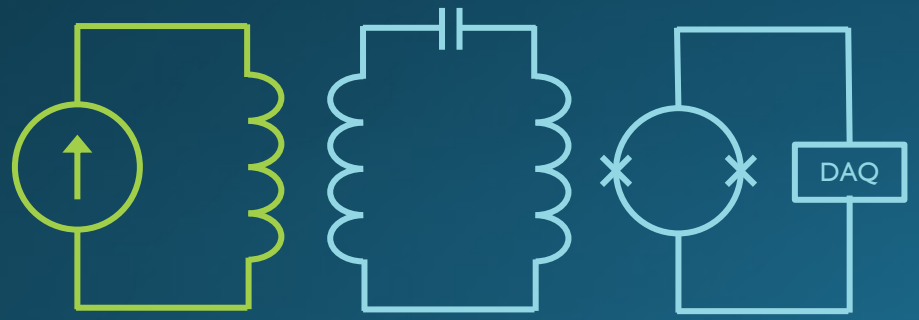


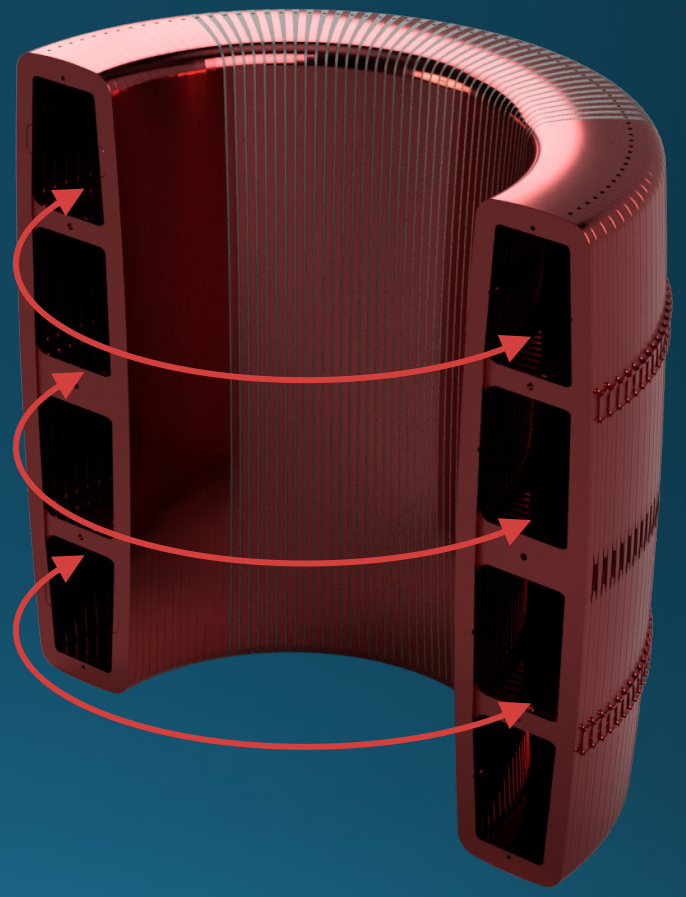


The 50L detector

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

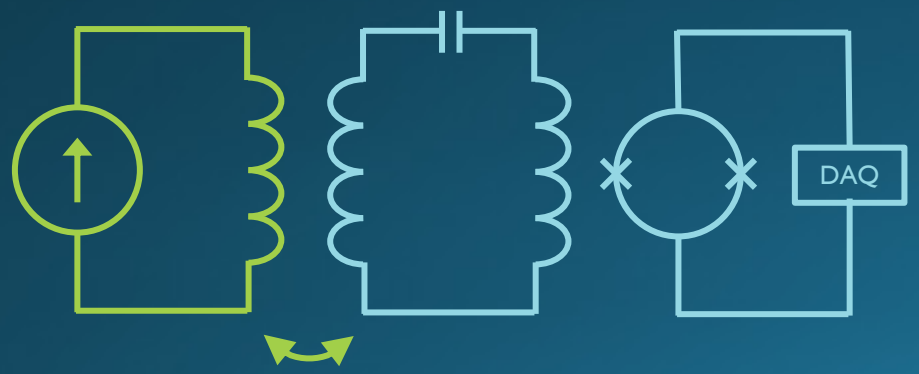
$$\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma}\sqrt{2\rho_{\text{DM}}}\cos(m_a t)\mathbf{B}_0$$

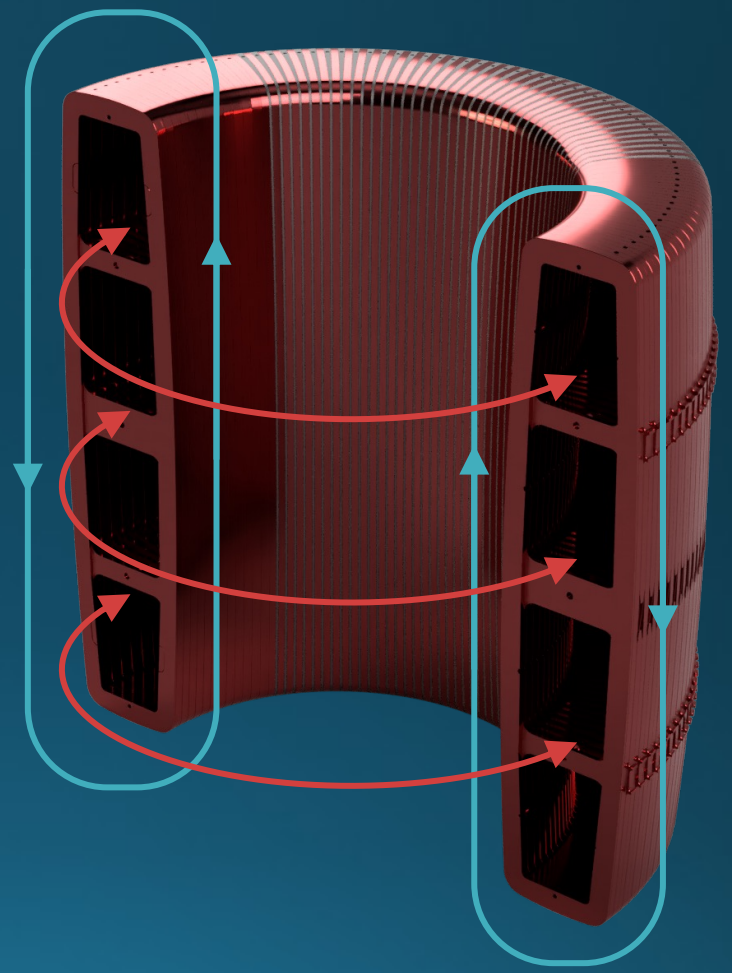




The 50L detector

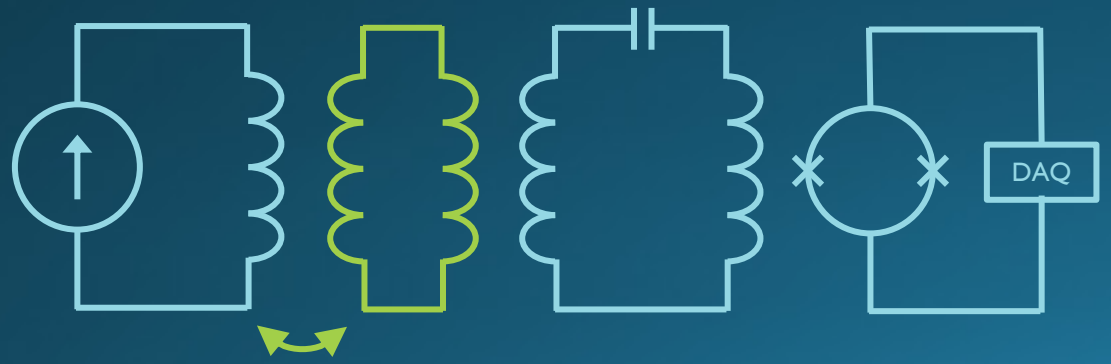
Axion dark matter generates parallel oscillating effective current, J_{eff}, which generates an oscillating magnetic field

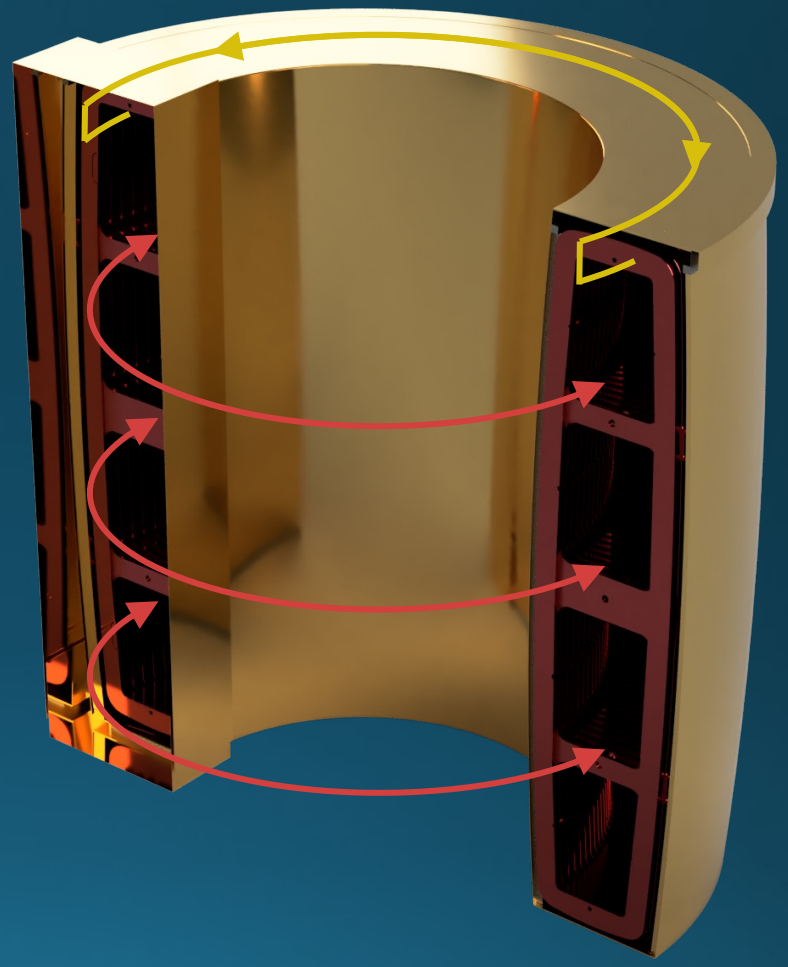




The 50L detector

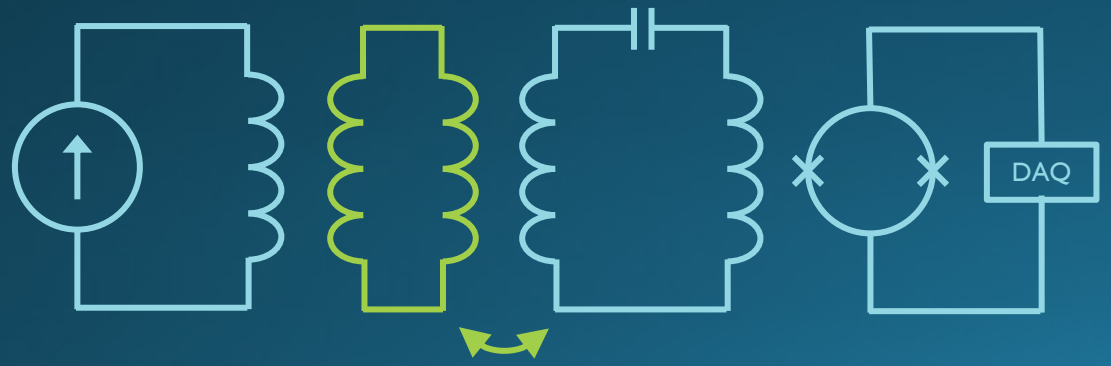
...inducing currents on the sheath

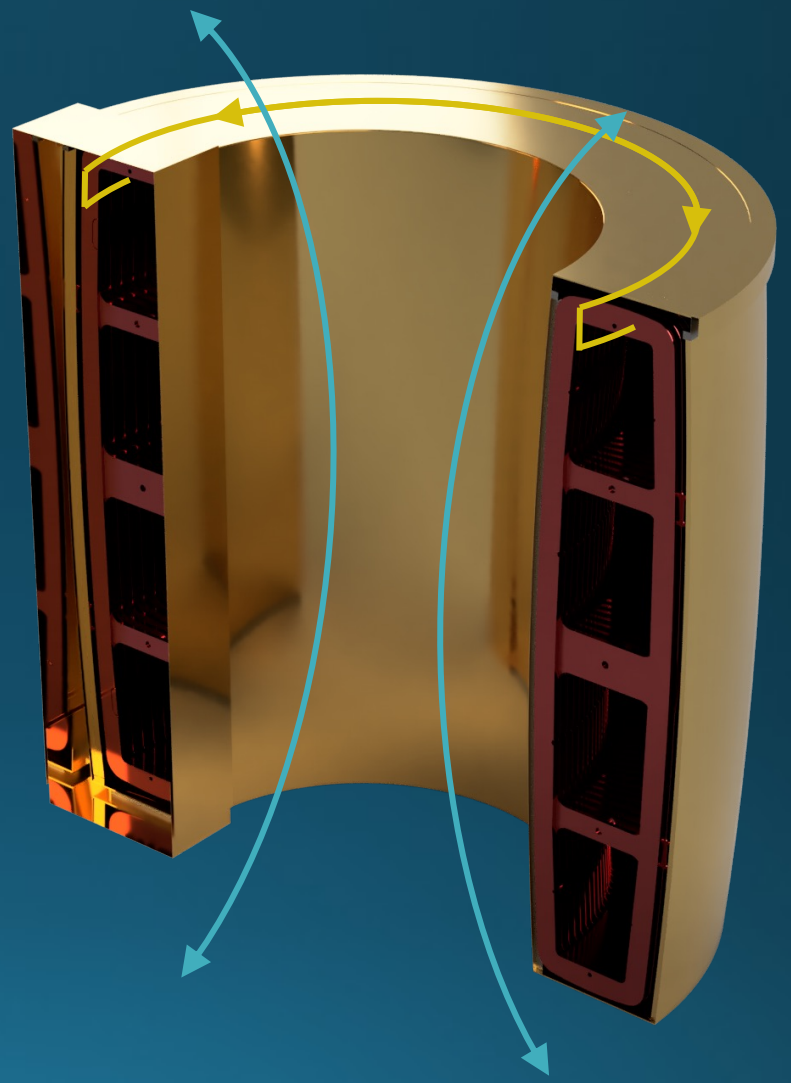




The 50L detector

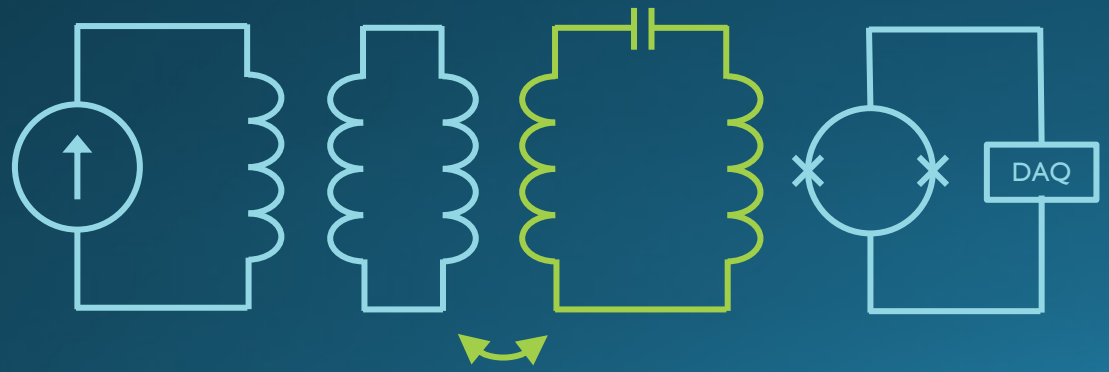
…inducing currents on the sheath, which in turn generates another oscillating magnetic field

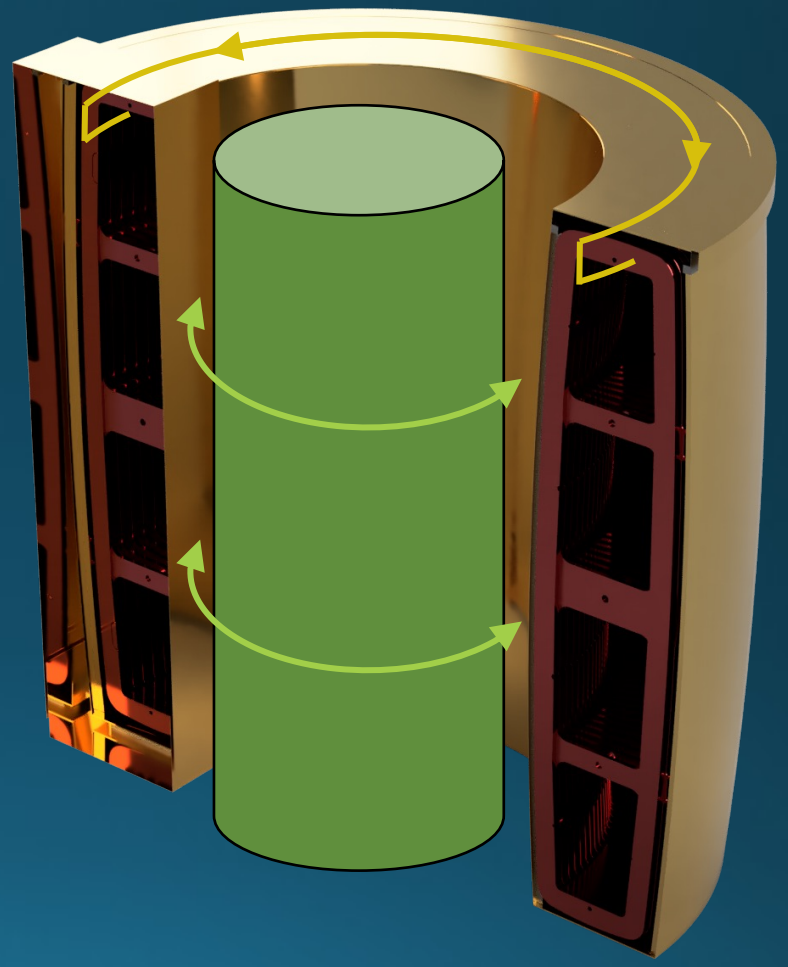




The 50L detector

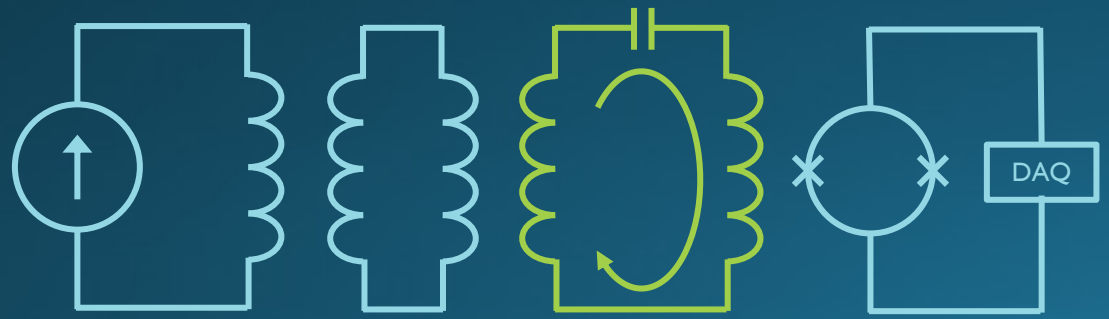
…inducing currents on the pickup inductor

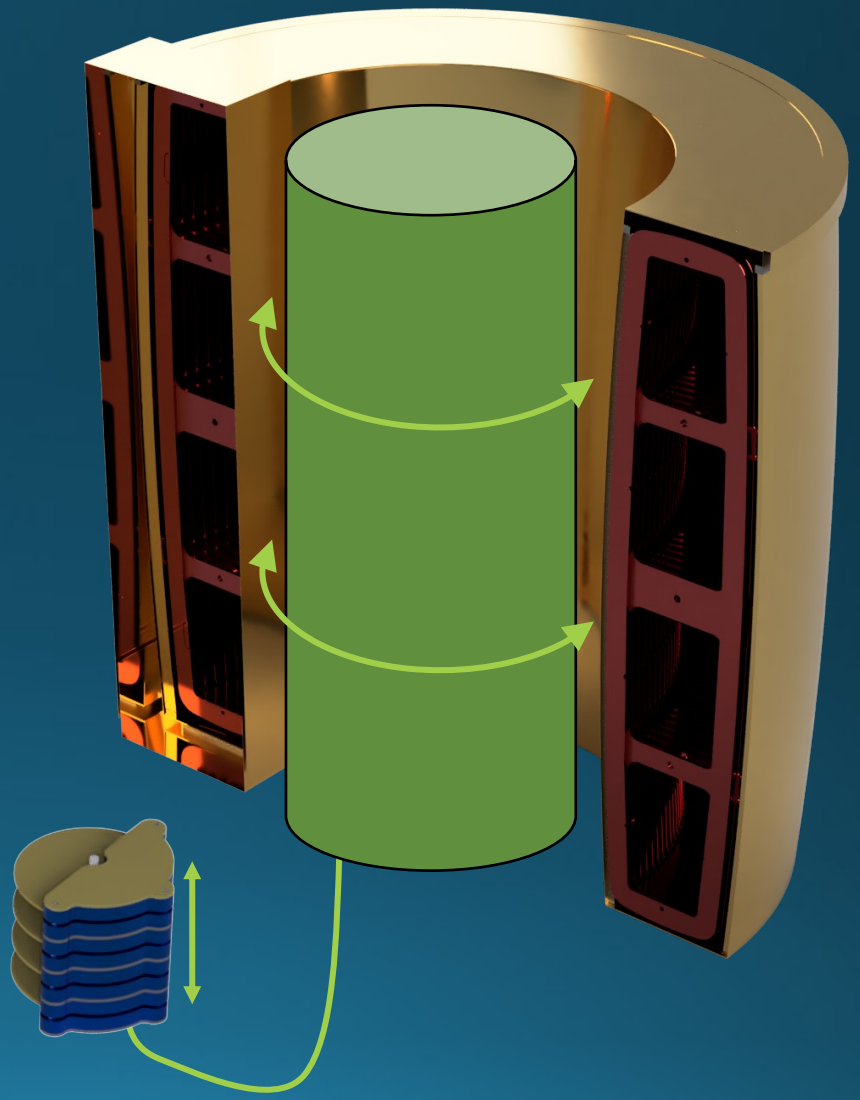




The 50L detector

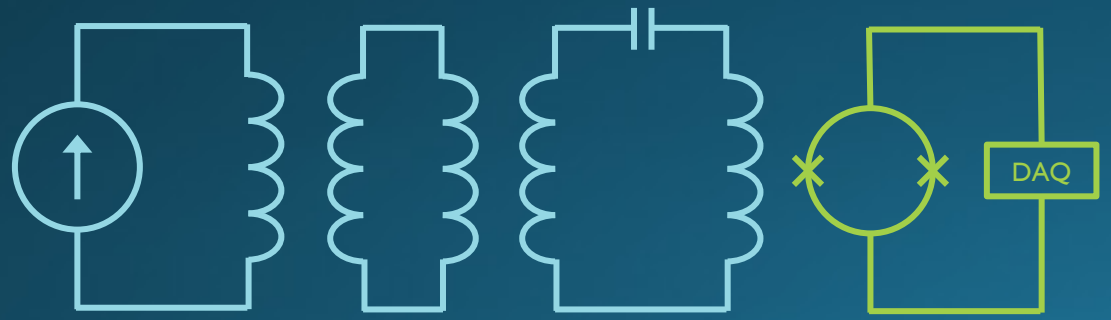
...ringing up the LC resonator.

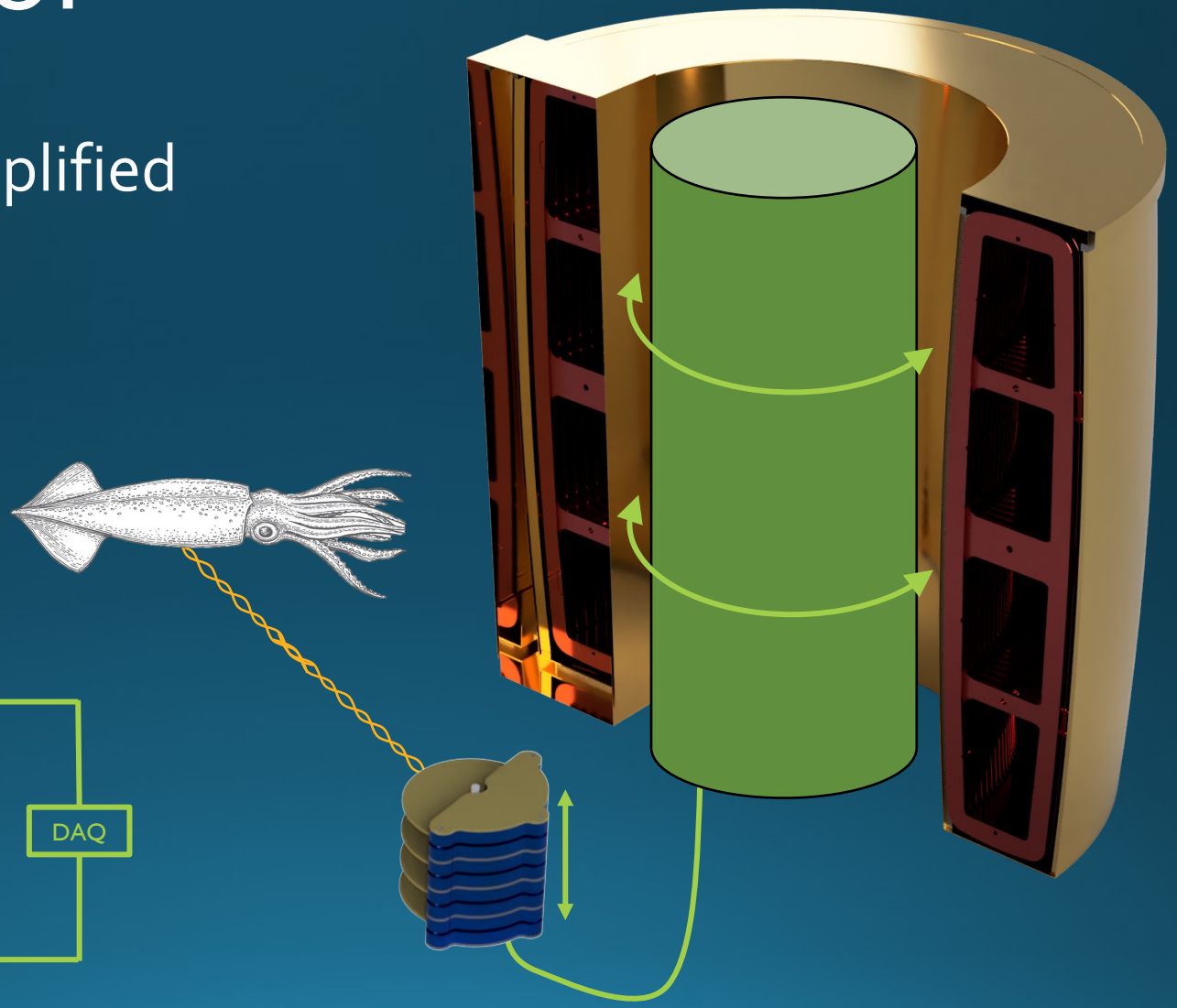




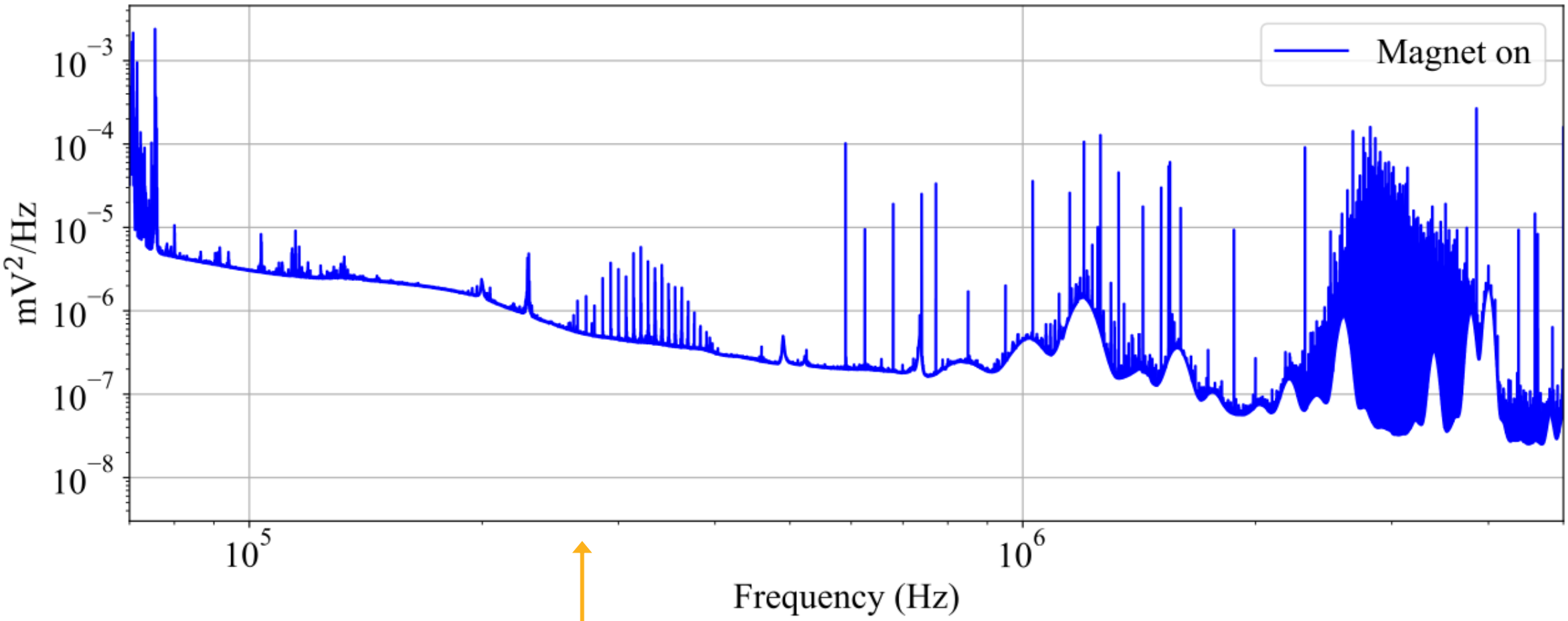
The 50L detector

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



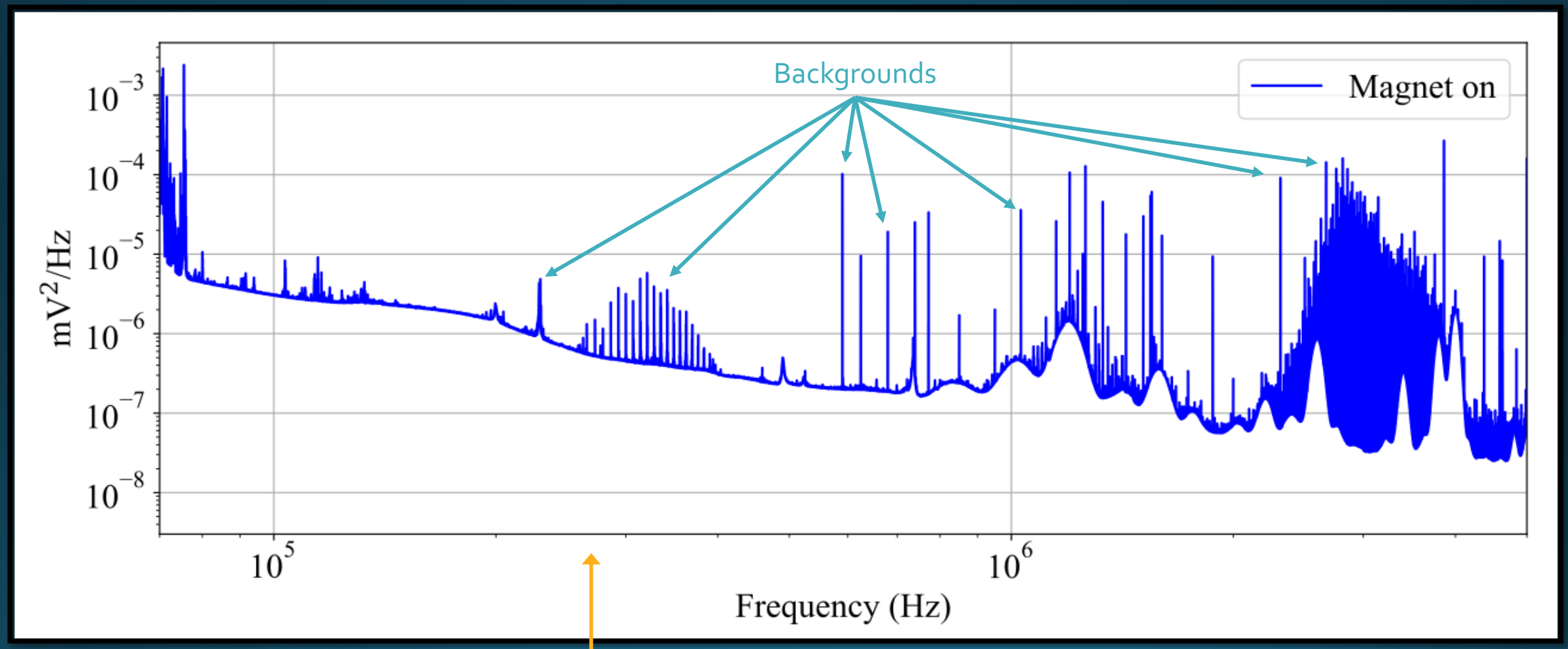


ABRA-10cm averaged spectrum



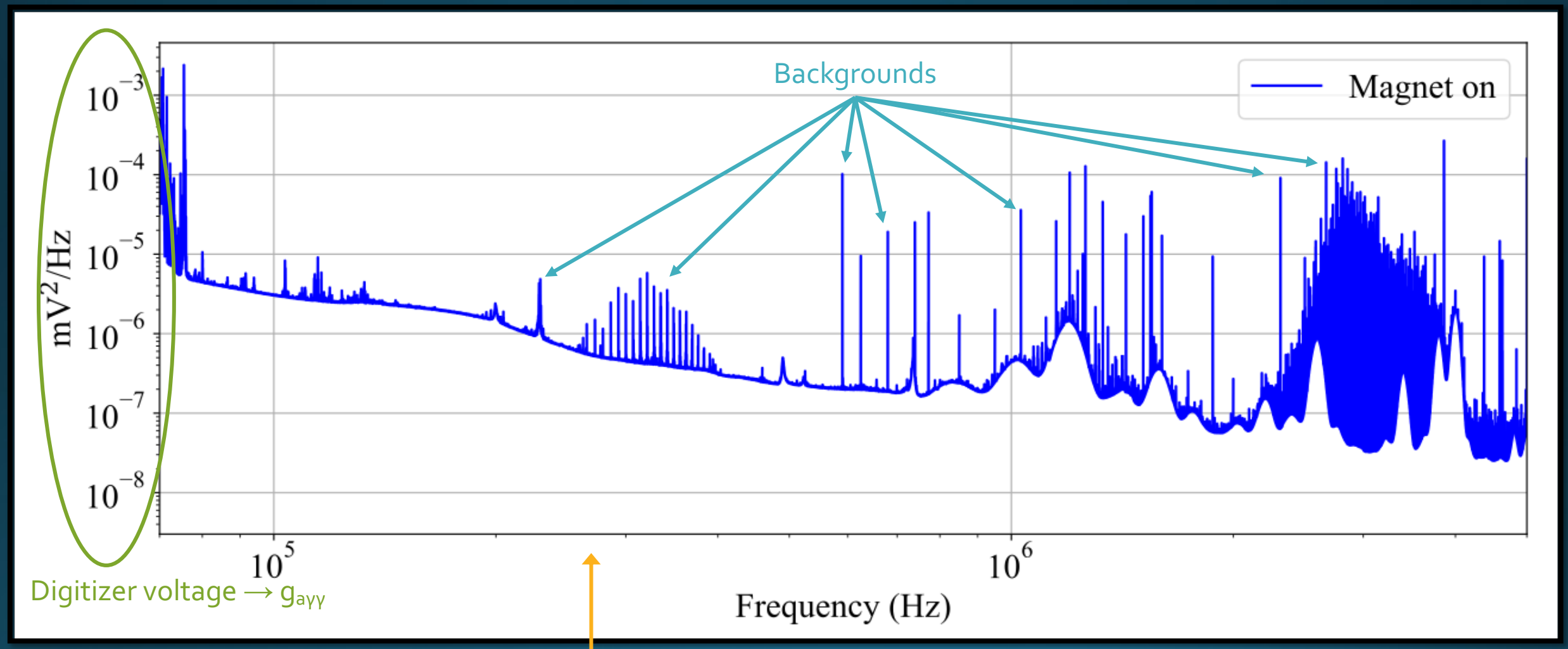
$m_a \sim 1$ neV (GUT-scale)

ABRA-10cm averaged spectrum



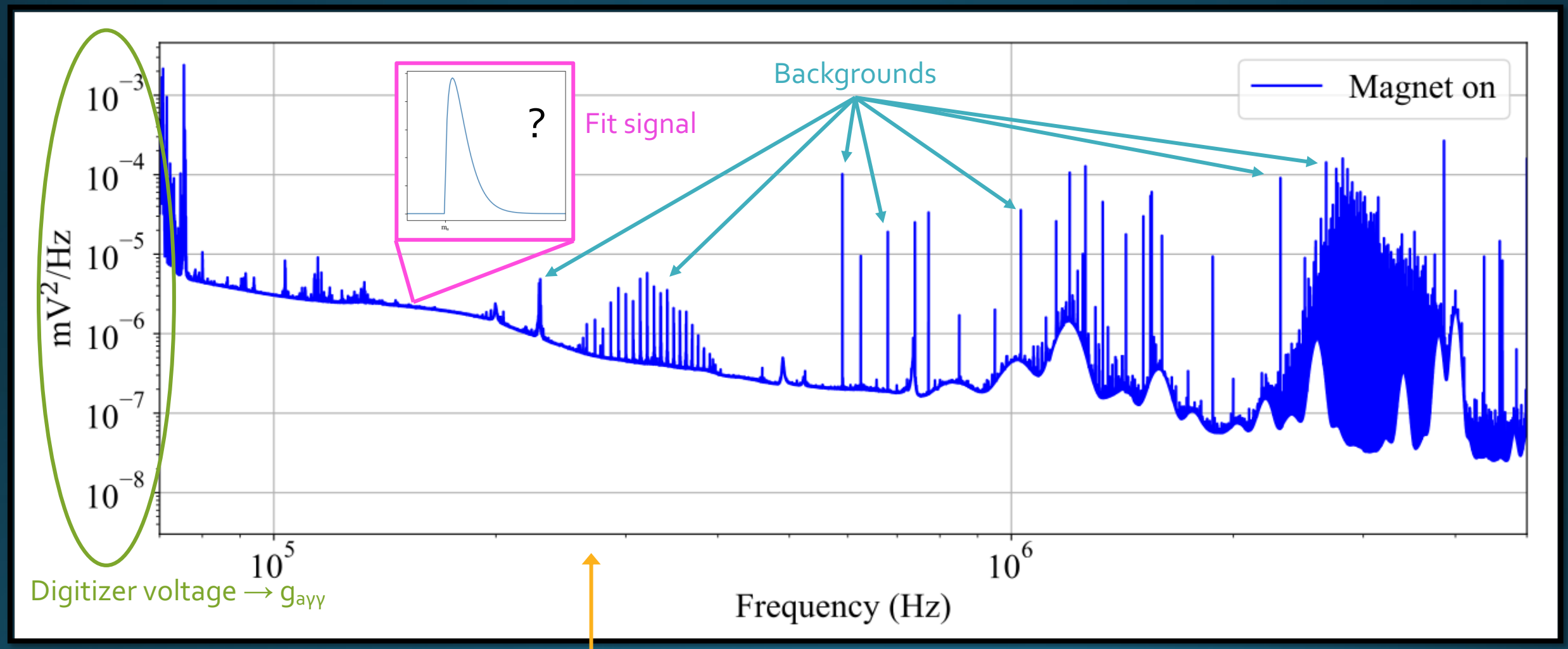
$m_a \sim 1$ neV (GUT-scale)

ABRA-10cm averaged spectrum



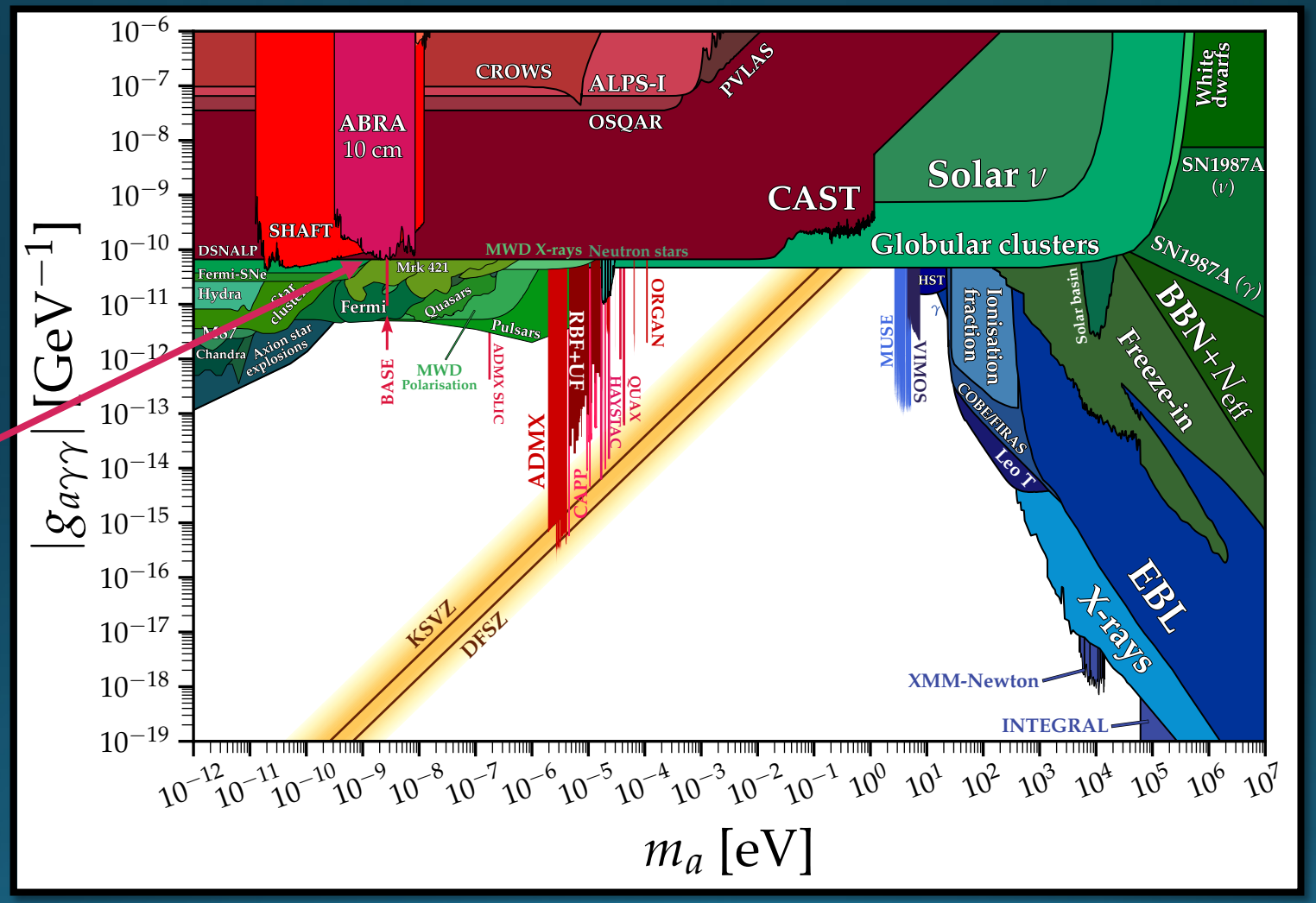
$m_a \sim 1$ neV (GUT-scale)

ABRA-10cm averaged spectrum



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

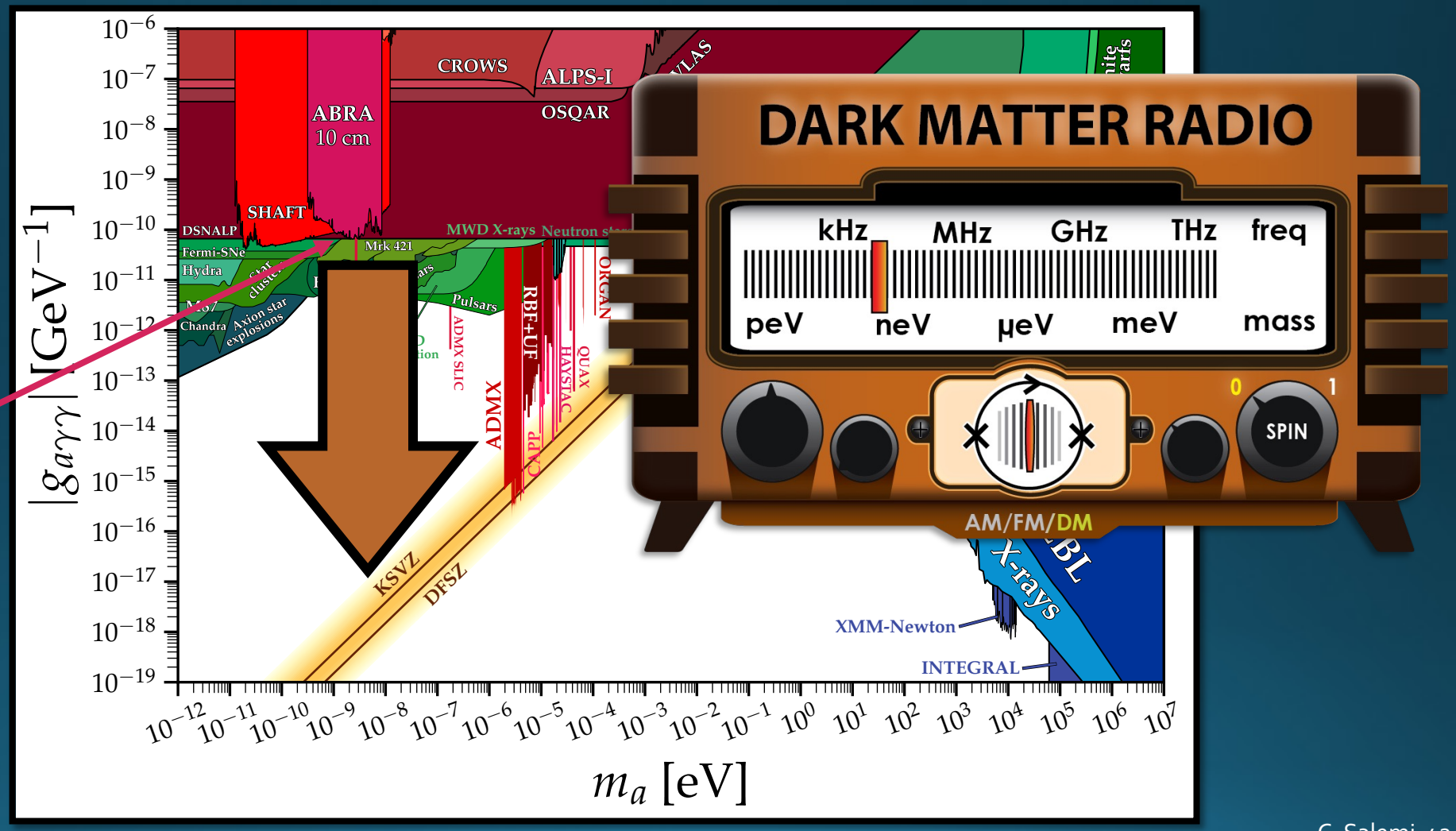
No axions found yet!



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

C. O'Hare

No axions found yet!



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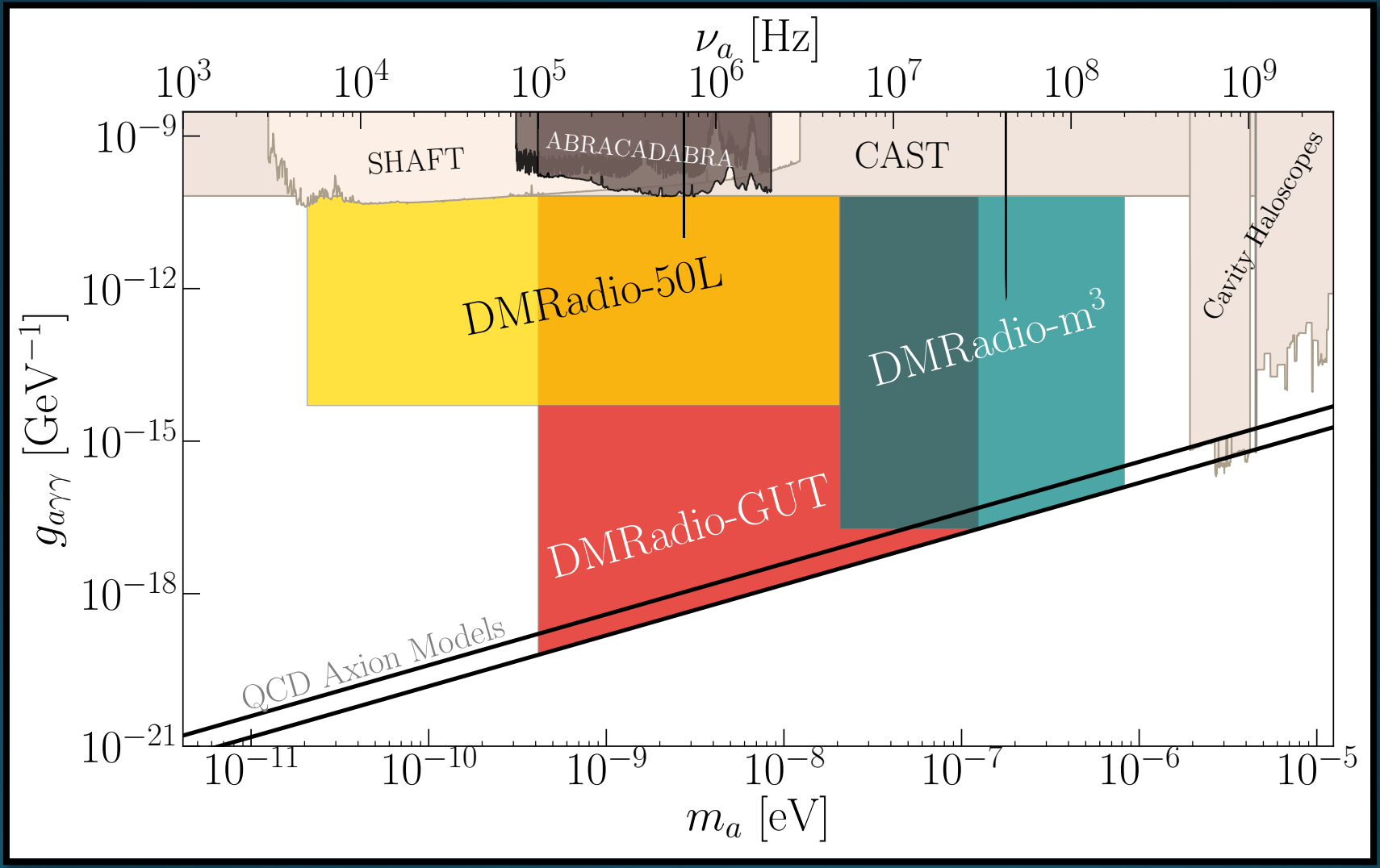
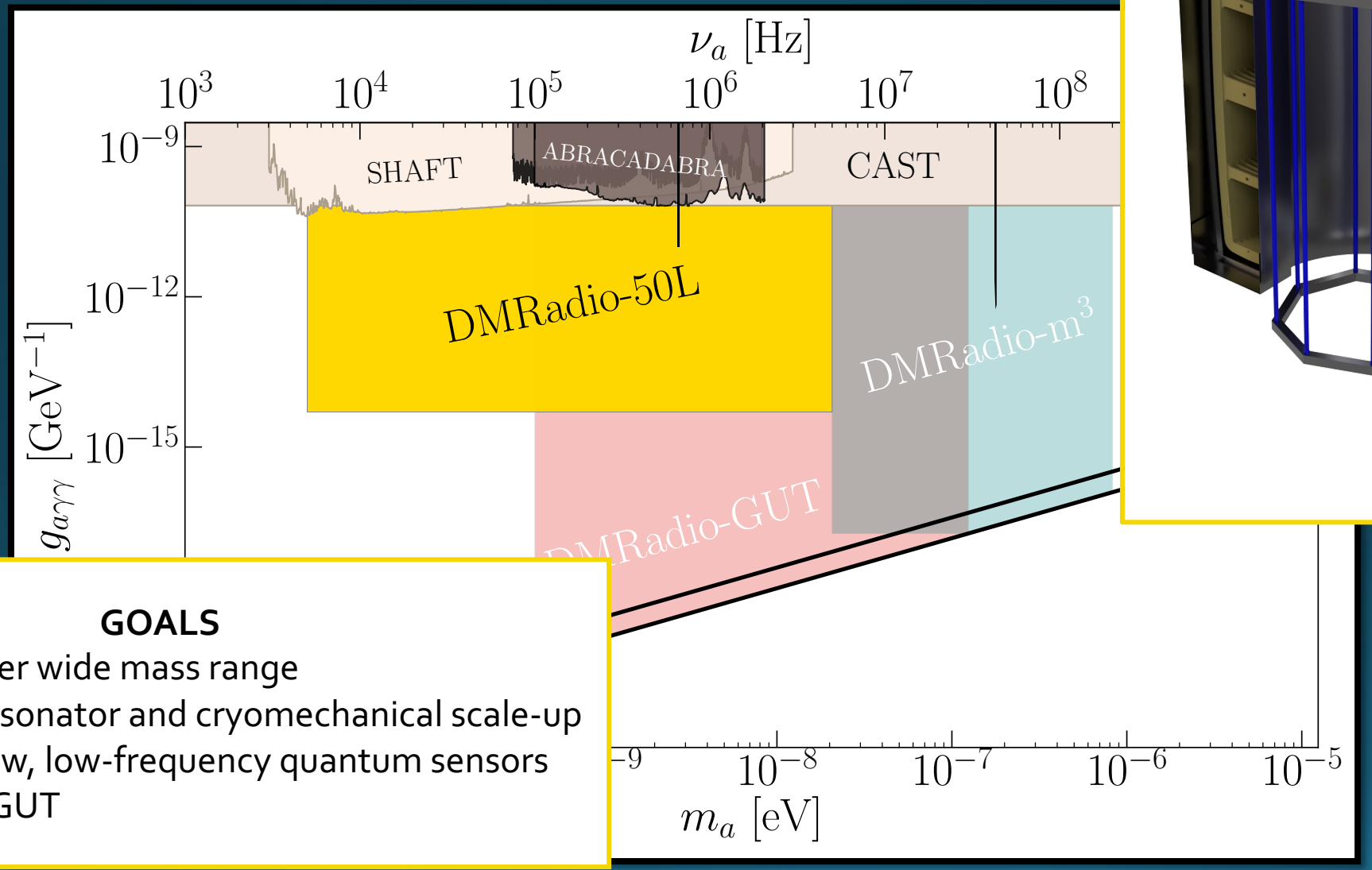
Ouellet, Salemi et al. *Phys.Rev.D* 2019

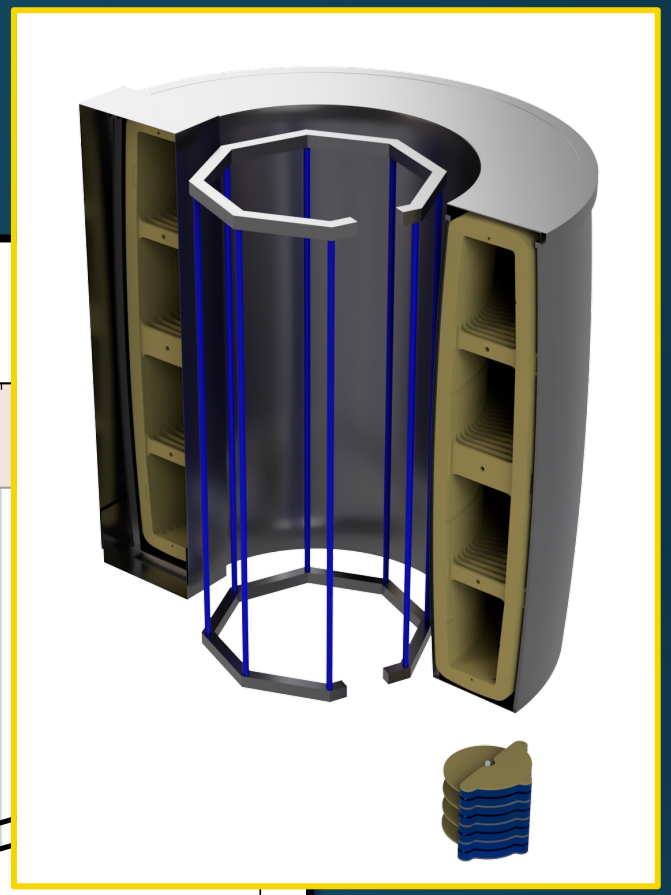
C. O'Hare

DMRadio program



DMRadio program—50L

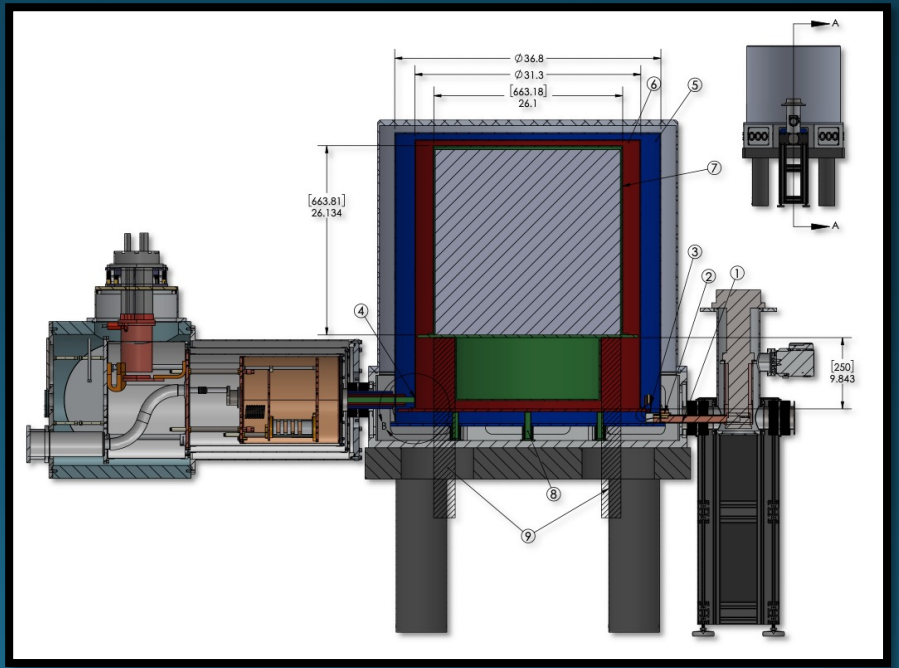




GOALS

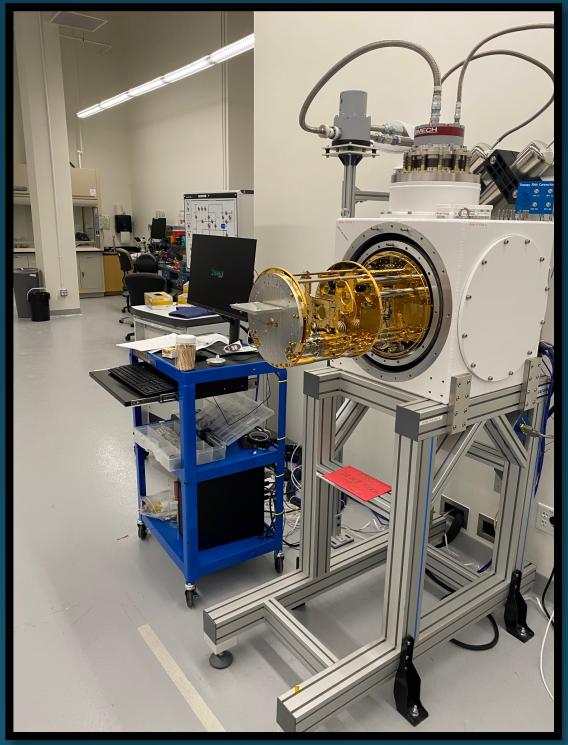
- ALP search over wide mass range
- Demo of LC resonator and cryomechanical scale-up
- Testbed for new, low-frequency quantum sensors for DMRadio-GUT

Under construction.
Site location is Stanford

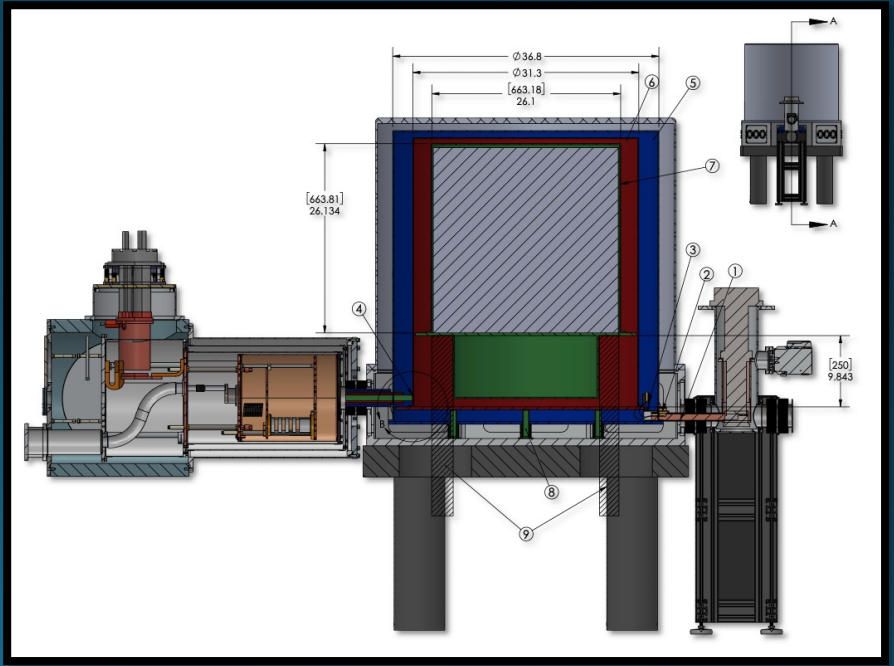


Dual cryogenic system design
(Maria Simanovskaia)

Under construction.
Site location is Stanford

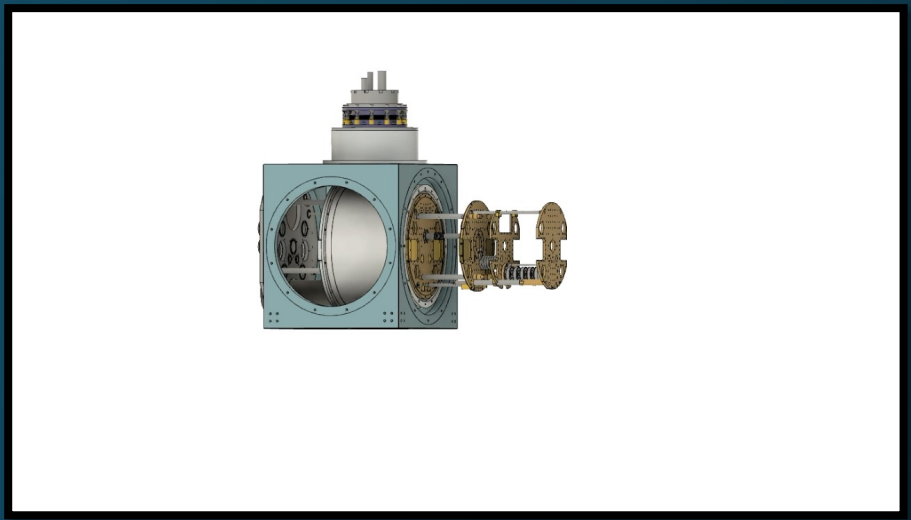


Dilution fridge testing of prototype capacitor
(Joe Singh)

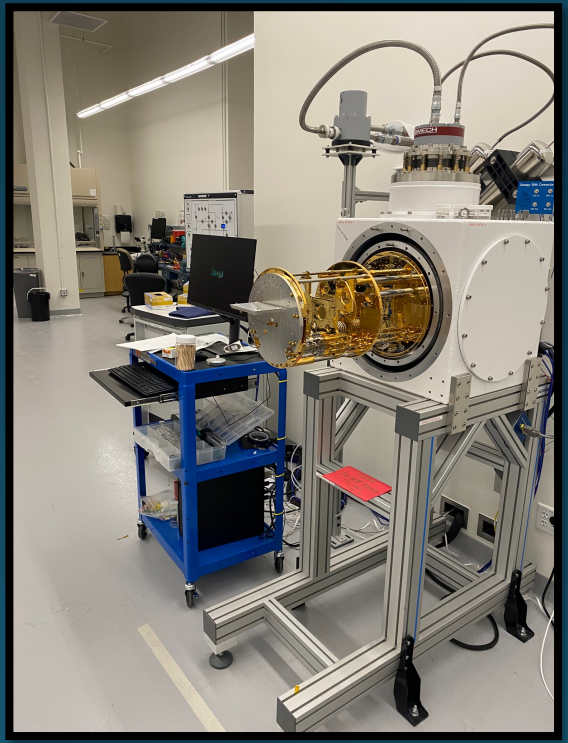


Dual cryogenic system design
(Maria Simanovskaia)

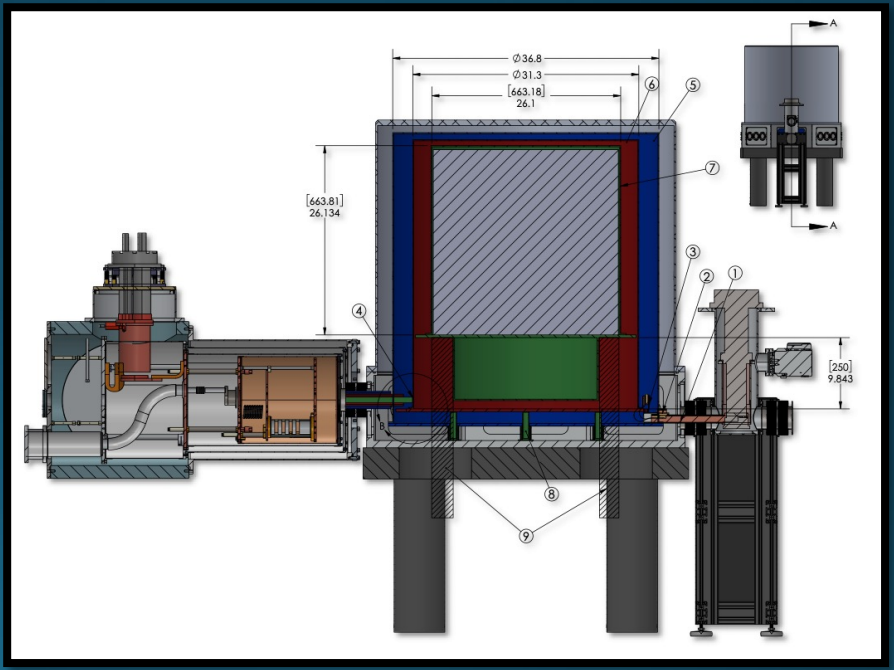
Under construction.
Site location is Stanford



Cold finger assembly
(Aya Keller)

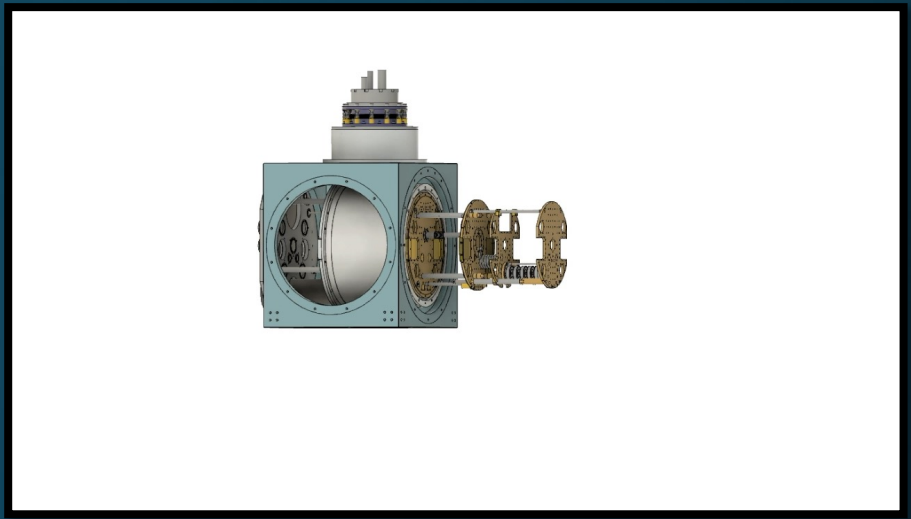


Dilution fridge testing of prototype capacitor
(Joe Singh)

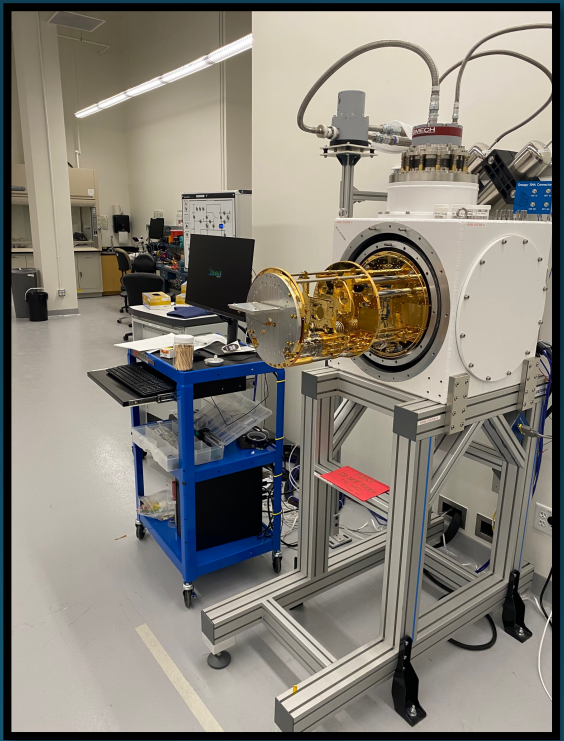


Dual cryogenic system design
(Maria Simanovskaia)

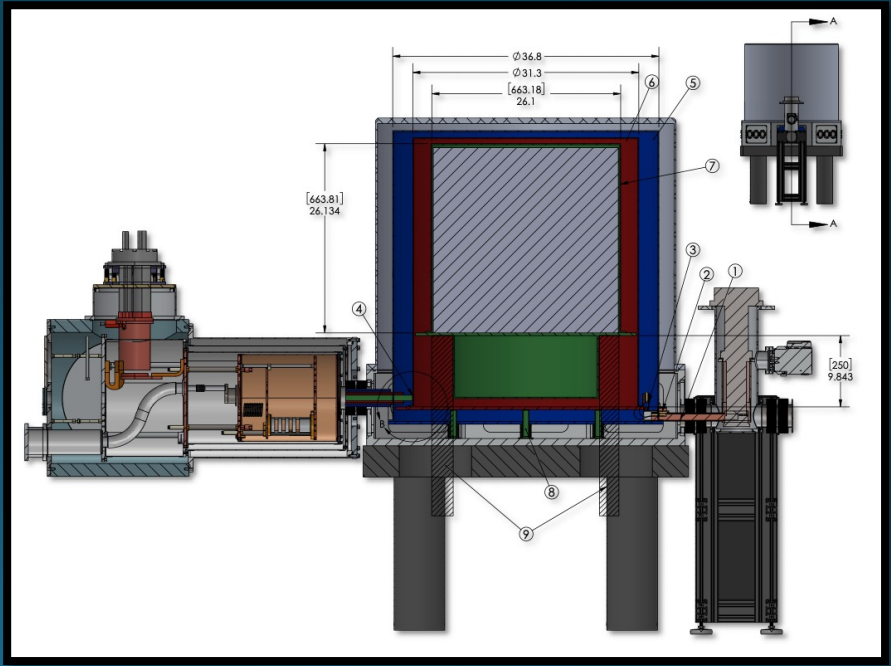
Under construction.
Site location is Stanford



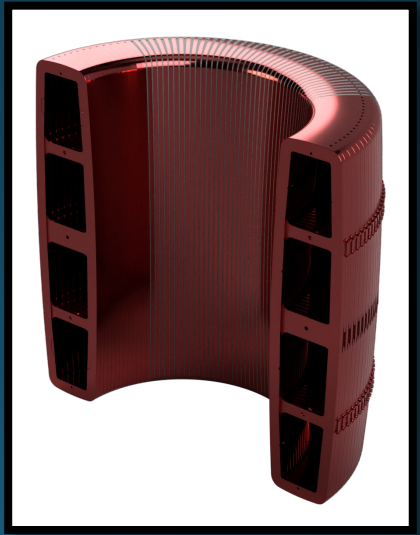
Cold finger assembly
(Aya Keller)



Dilution fridge testing of prototype capacitor
(Joe Singh)

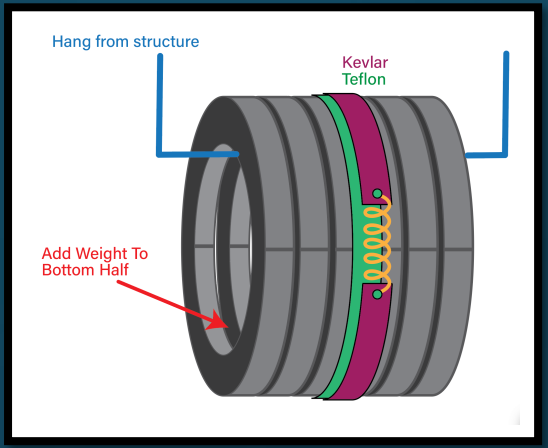


Dual cryogenic system design
(Maria Simanovskaia)

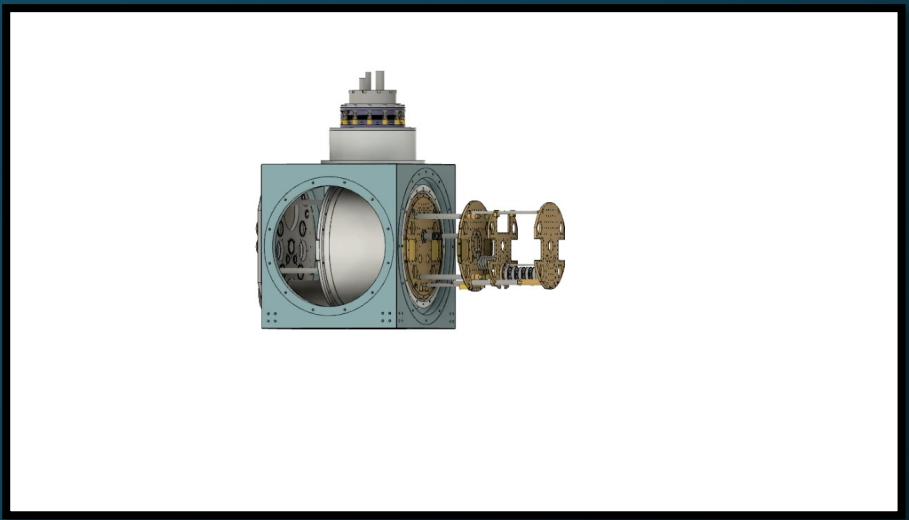


Magnet mandrel design
(Jon Ouellet)

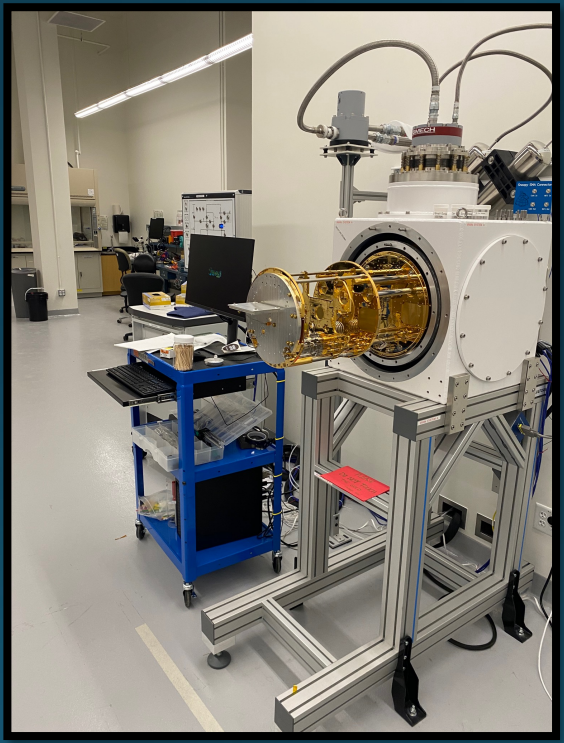
Under construction.
Site location is Stanford



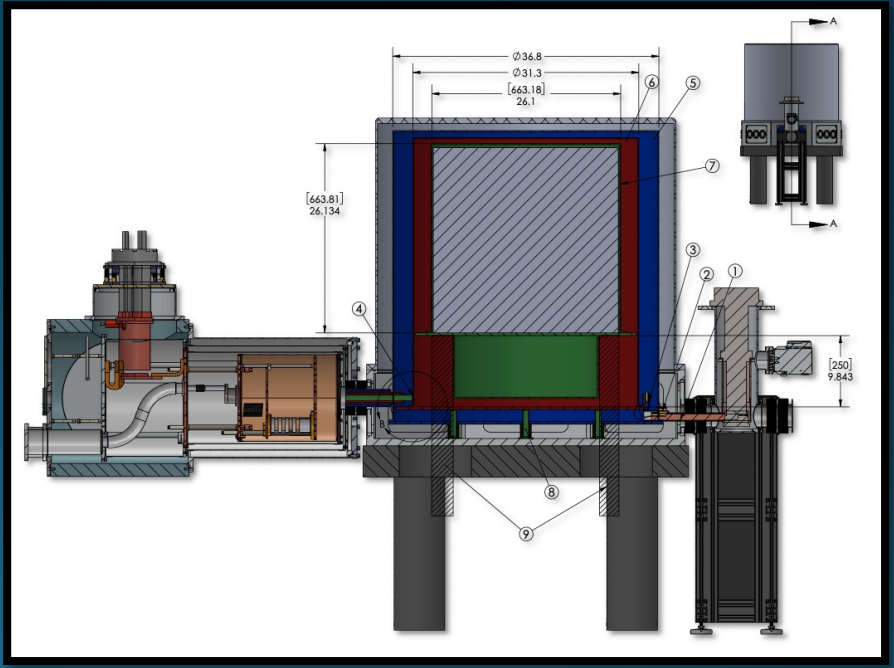
Setup for magnet strap testing
(Jessica Fry)



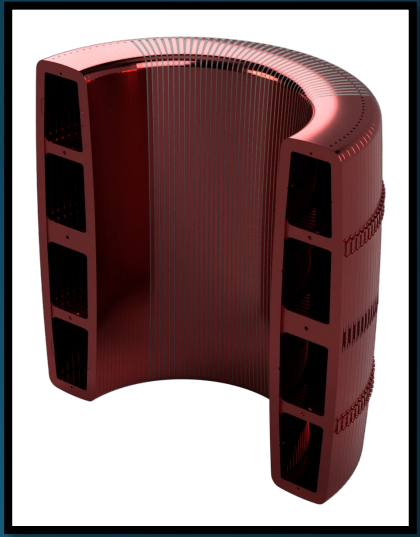
Cold finger assembly
(Aya Keller)



Dilution fridge testing of prototype capacitor
(Joe Singh)

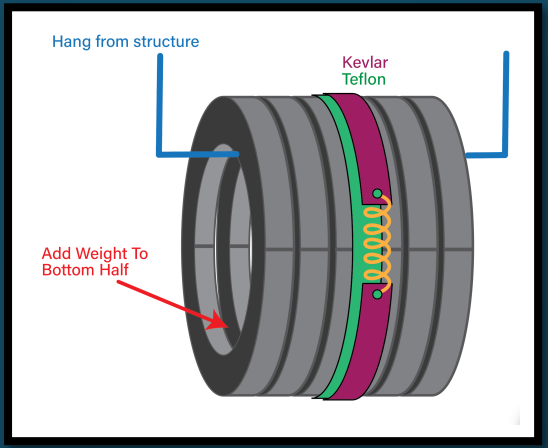


Dual cryogenic system design
(Maria Simanovskaia)

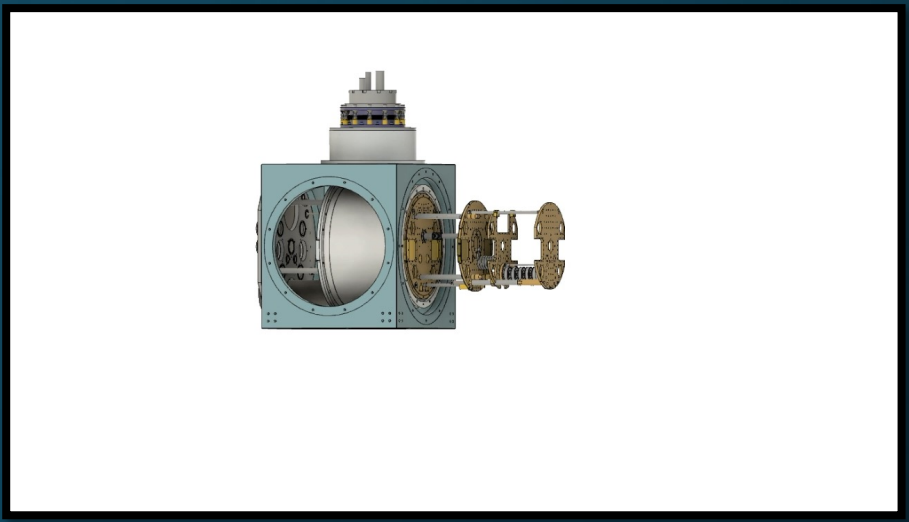


Magnet mandrel design
(Jon Ouellet)

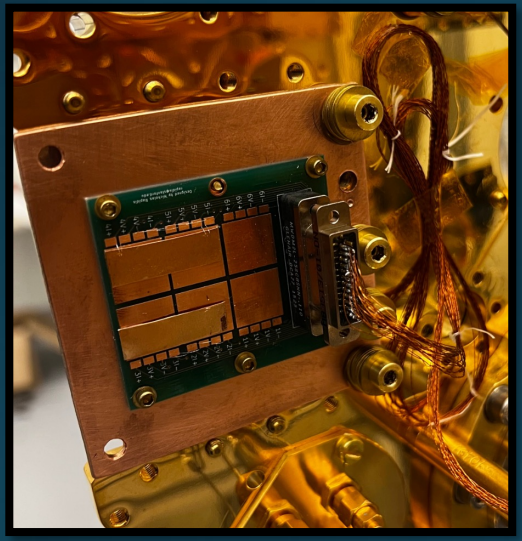
Under construction.
Site location is Stanford



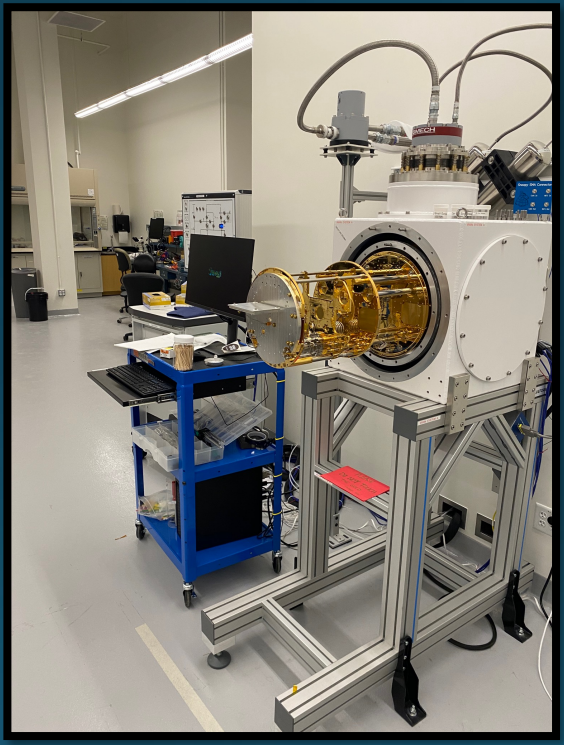
Setup for magnet strap testing
(Jessica Fry)



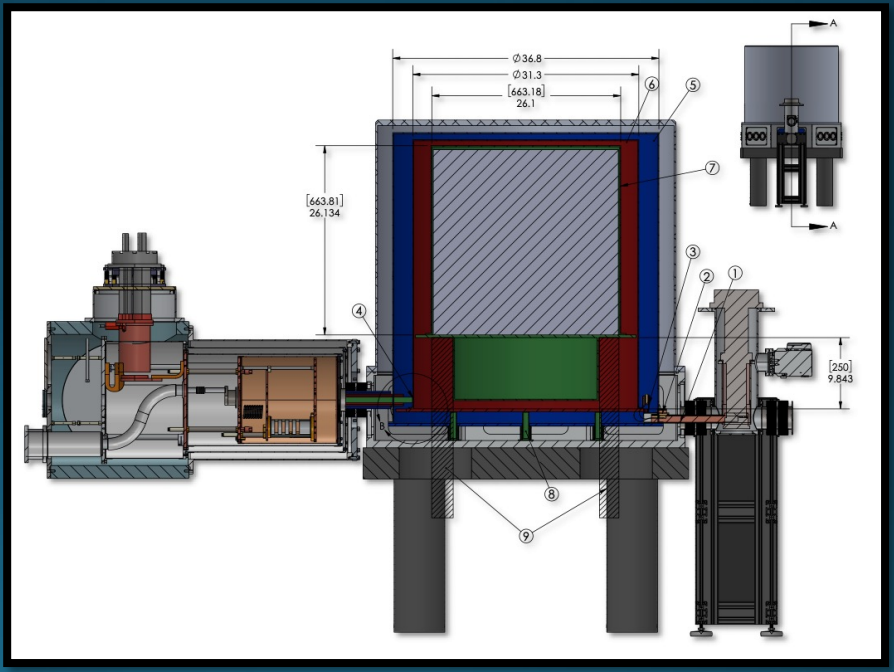
Cold finger assembly
(Aya Keller)



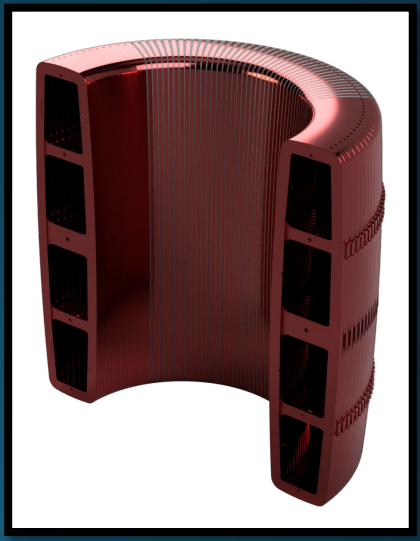
Materials testing for pickup sheath
(Nicholas Rapidis)



Dilution fridge testing of prototype capacitor
(Joe Singh)

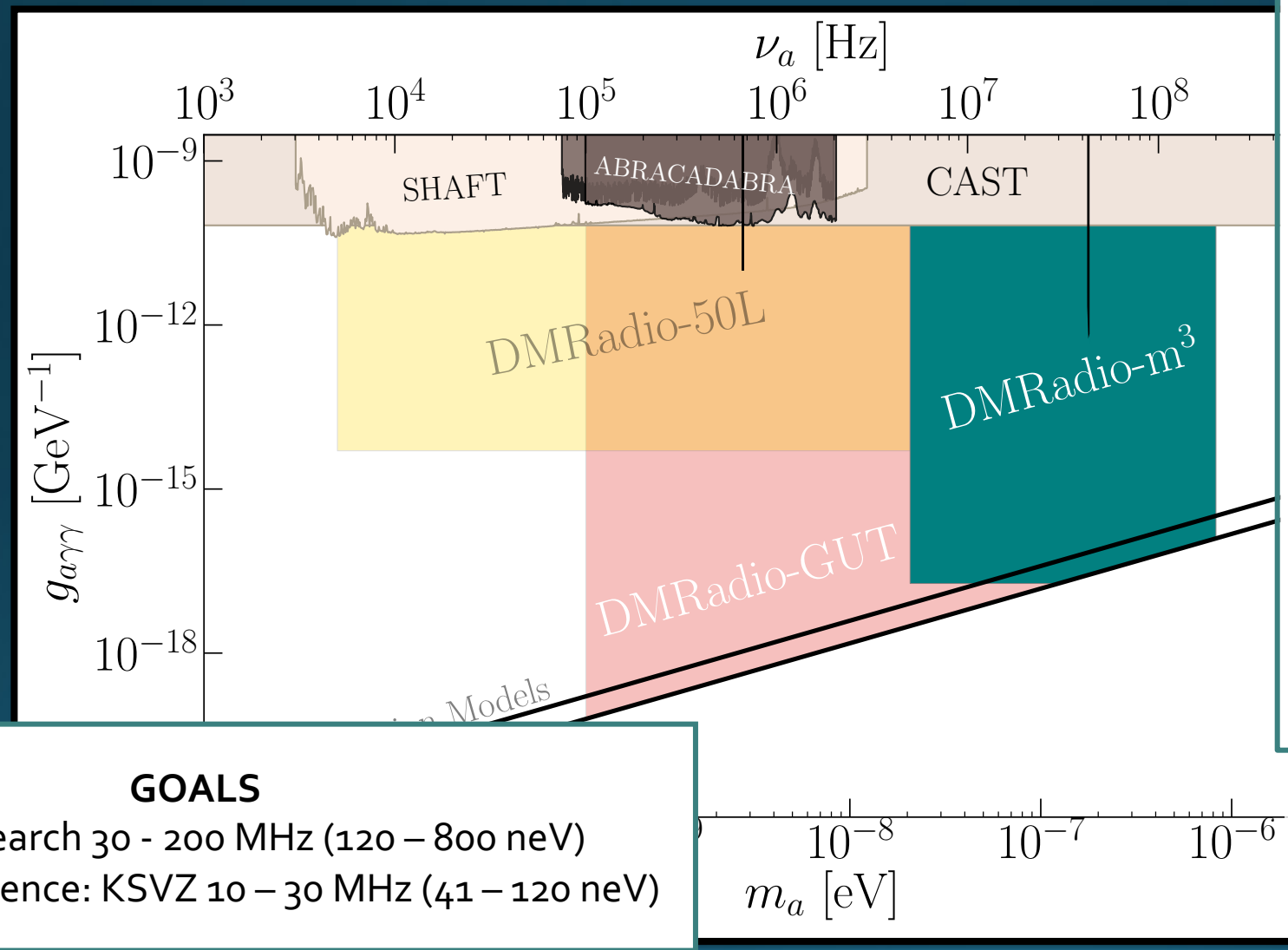


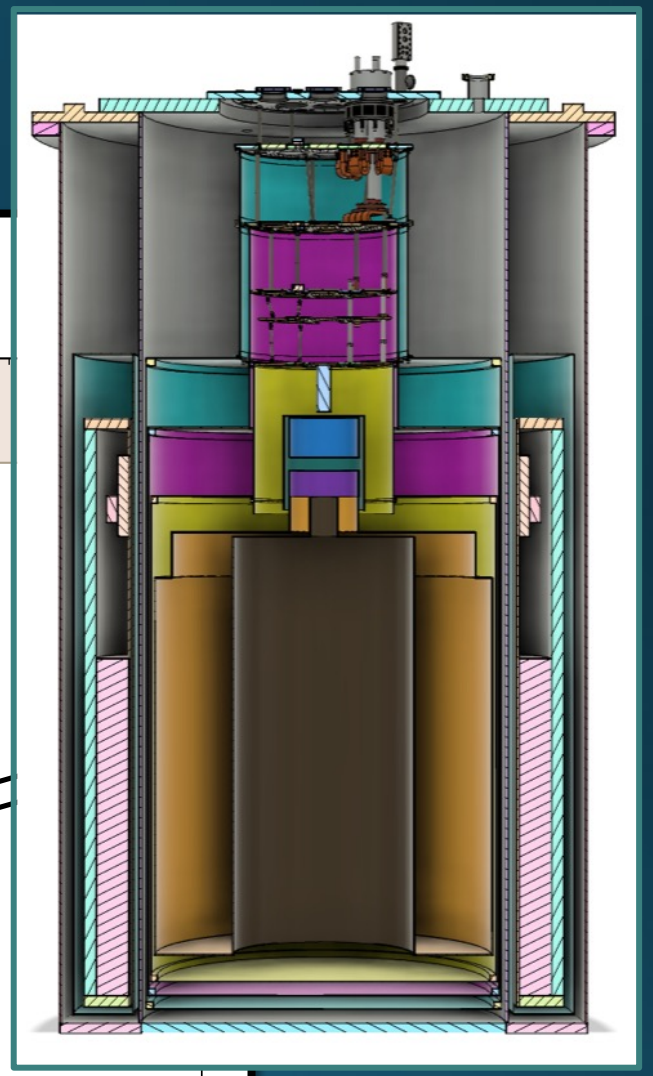
Dual cryogenic system design
(Maria Simanovskaia)



Magnet mandrel design
(Jon Ouellet)

DMRadio program—m³



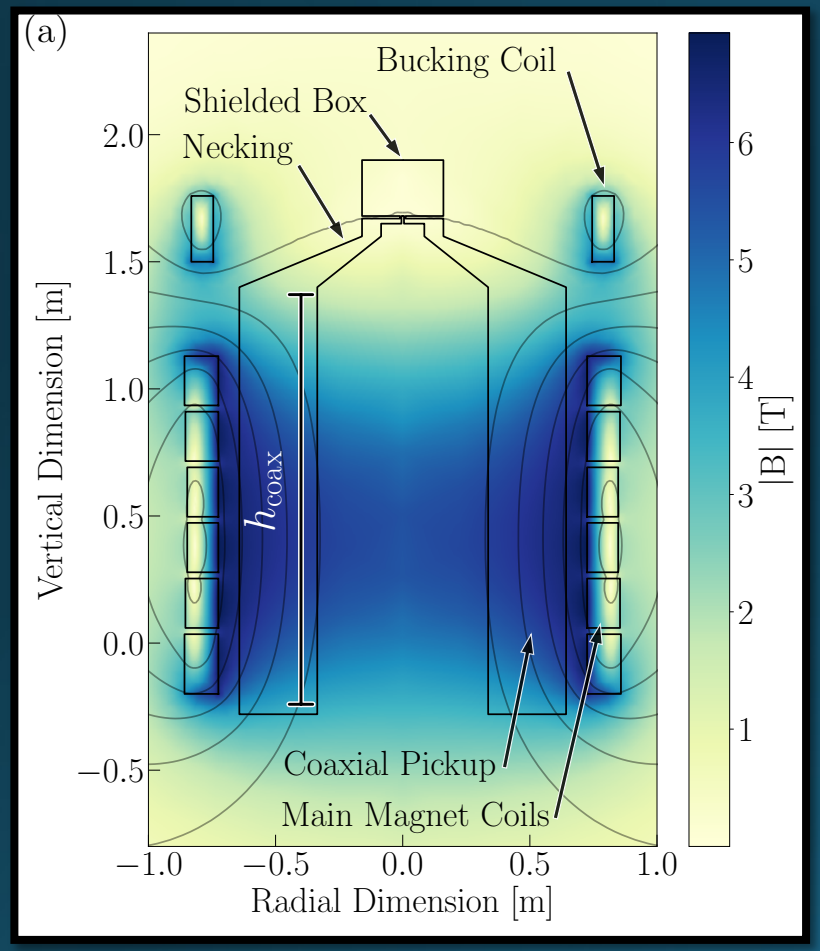


Brouwer et al. *Phys.Rev.D*, 2022a
Benabou et al. arxiv:2211.00008, 2022
AlShirawi et al. arxiv:2302.14084, 2023

GOALS

- DFSZ axion search 30 - 200 MHz (120 – 800 neV)
- Secondary science: KSVZ 10 – 30 MHz (41 – 120 neV)

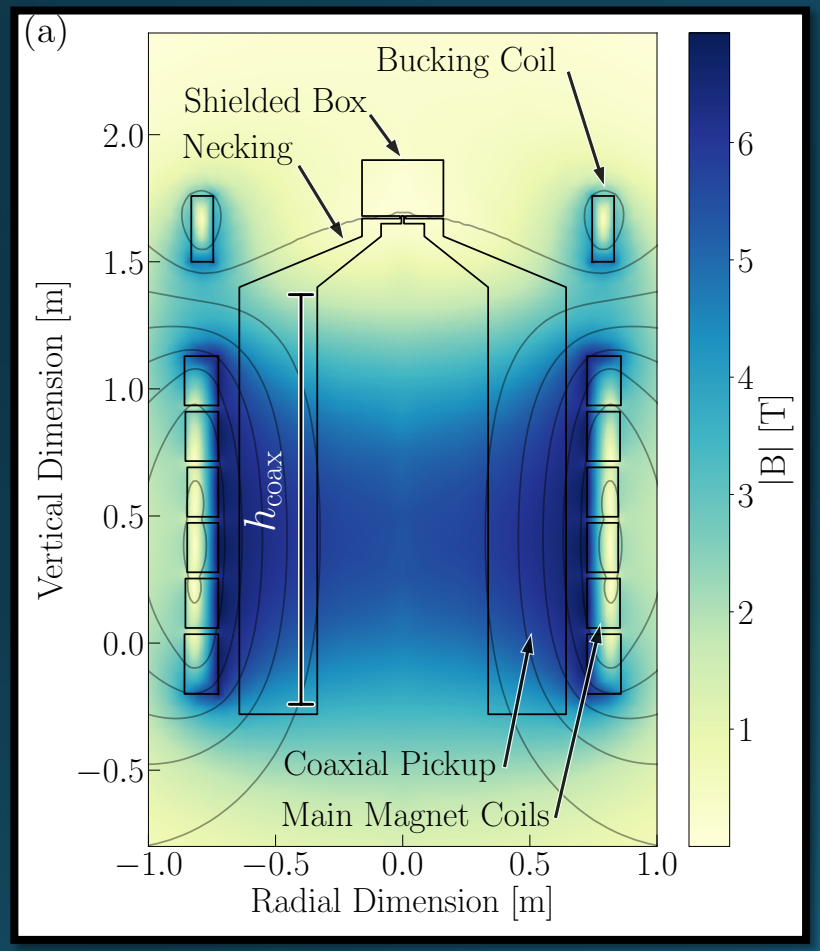
Preparing for design review.
Will be located at SLAC



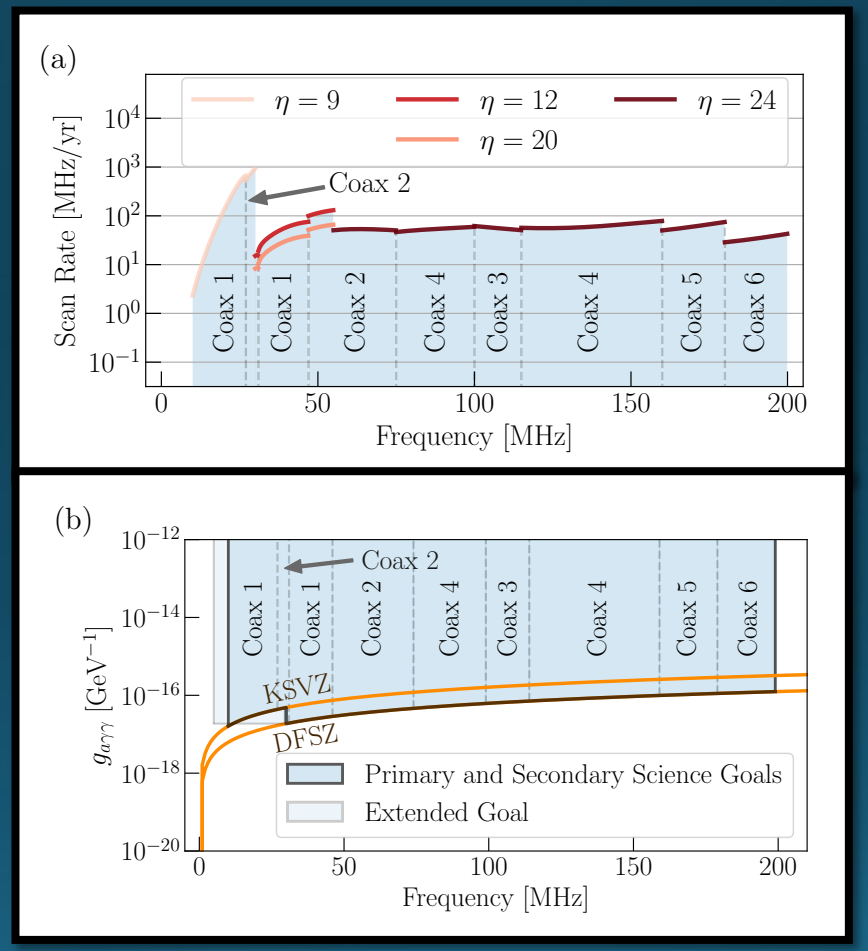
Axion fields simulation
(Nicholas Rapidis, Alex Droster, Josh Foster)

AlShirawi et al. arxiv:2302.14084, 2023

Preparing for design review.
Will be located at SLAC



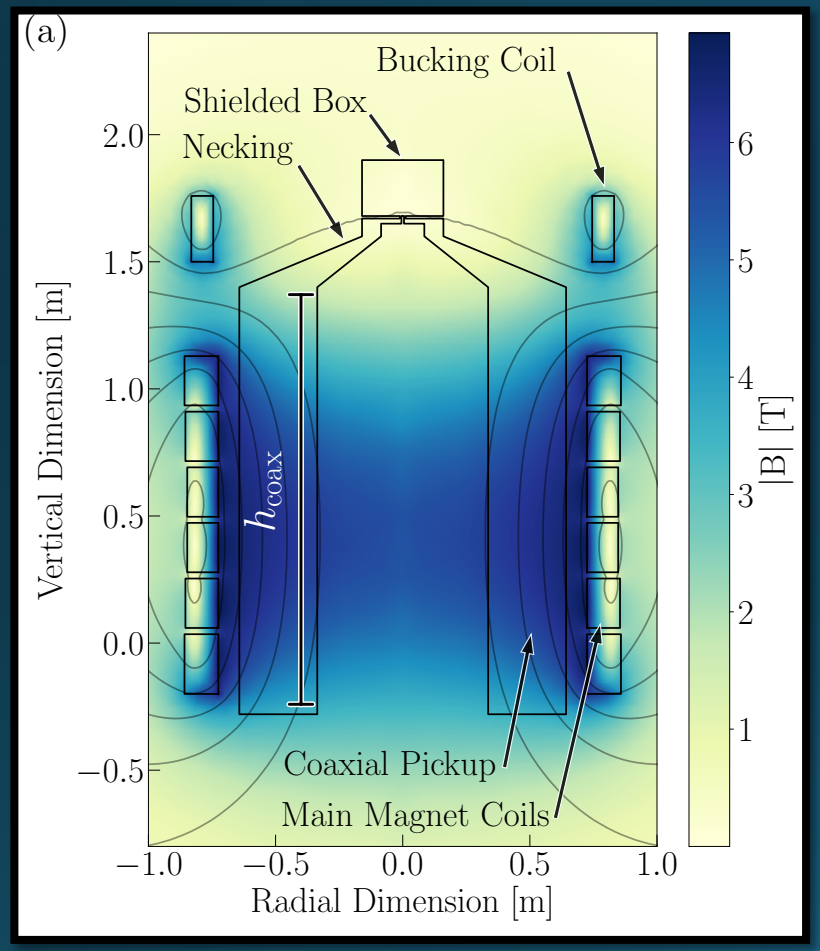
Axion fields simulation
(Nicholas Rapidis, Alex Droster, Josh Foster)



Calculated scan rate and $g_{a\gamma\gamma}$ reach with six coaxes
(Nicholas Rapidis)

AlShirawi et al. arxiv:2302.14084, 2023

Preparing for design review.
Will be located at SLAC



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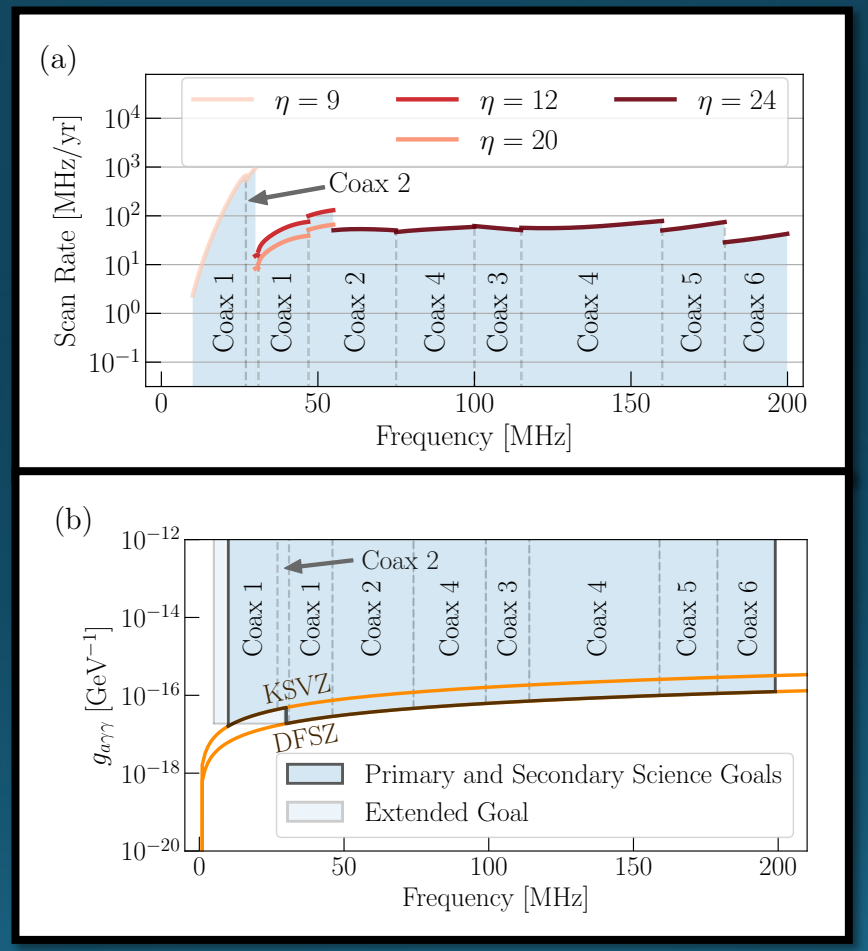

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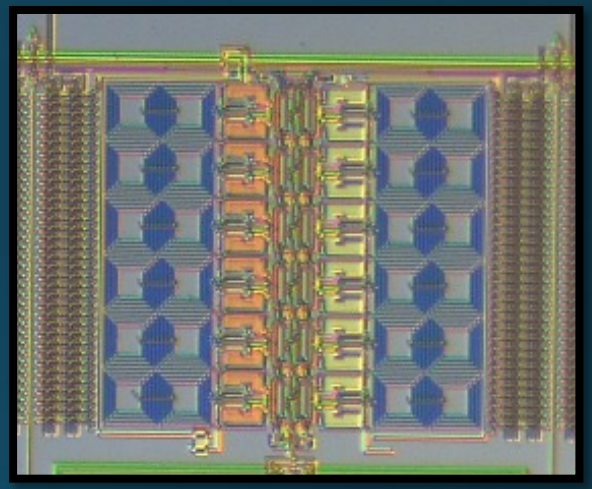


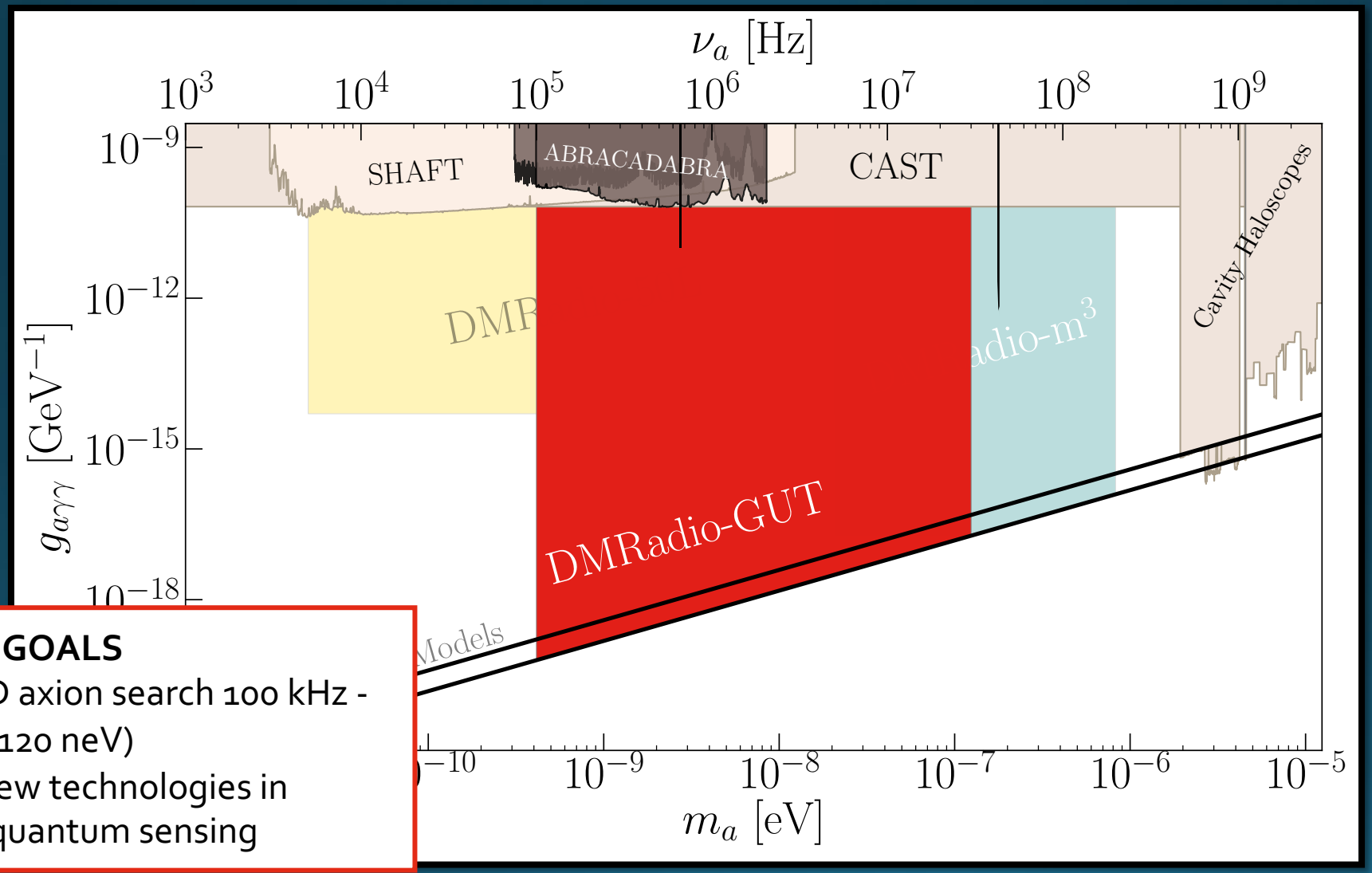
Developing SQUID readout chain
(Cady van Assendelft)

Bartram et al., in prep

AlShirawi et al. arxiv:2302.14084, 2023

DMRadio program—GUT

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



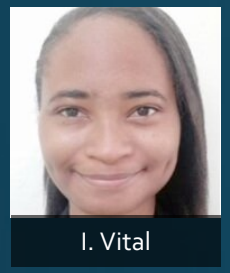
GOALS

- Definitive QCD axion search 100 kHz - 30 MHz (0.4 - 120 neV)
- Platform for new technologies in magnets and quantum sensing

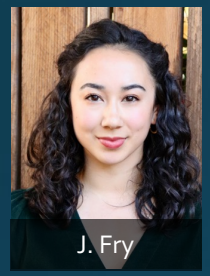
ABRACADABRA

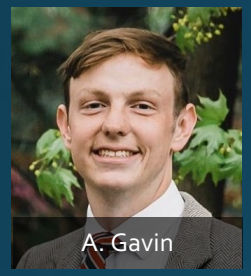
Undergraduate researchers

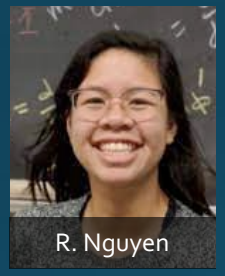

A. Colon Cesani

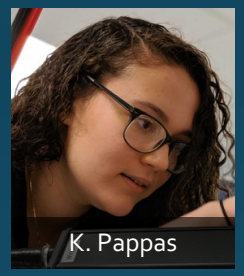

I. Vital

Graduate students

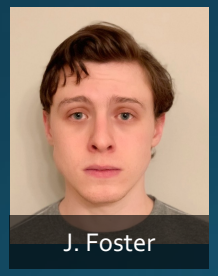

J. Fry


A. Gavin


R. Nguyen

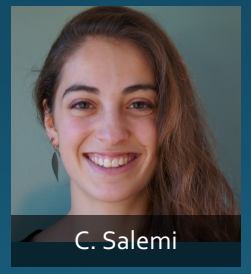

K. Pappas

Postdocs and research scientists

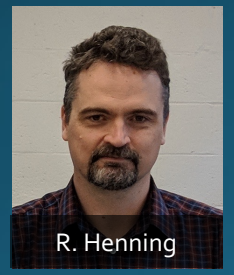

J. Foster

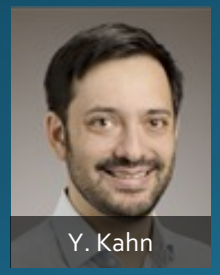

J. Ouellet

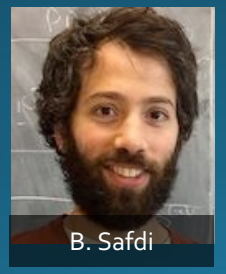

N. Rodd


C. Salemi

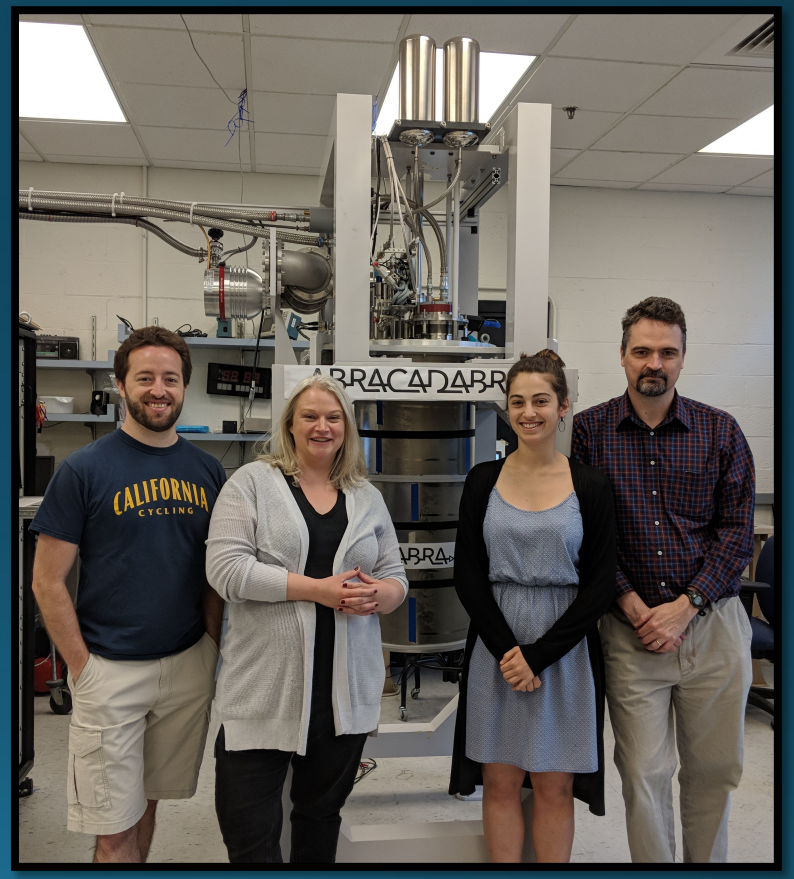
Principal investigators


R. Henning


Y. Kahn


B. Safdi


L. Winslow



DM RADIO

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. Simanovskaia, J. Singh, E. C. van Assendelft, K. Wells
Department of Physics,
Stanford University

A. Droster, A. Keller, A. F. Leder, K. van Bibber
Department of Nuclear Engineering,
University of California Berkeley

S. Chaudhuri, R. Kolevatov
Department of Physics,
Princeton University

L. Brouwer
Accelerator Technology and Applied Physics Division,
Lawrence Berkeley National Lab

B. A. Young
Department of Physics,
Santa Clara University

J. W. Foster, J. T. Fry, J. L. Ouellet,
K. M. W. Pappas, L. Winslow
Laboratory for Nuclear Science,
Massachusetts Institute of Technology

R. Henning
Department of Physics,
University of North Carolina Chapel Hill;
Triangle Universities Nuclear Laboratory

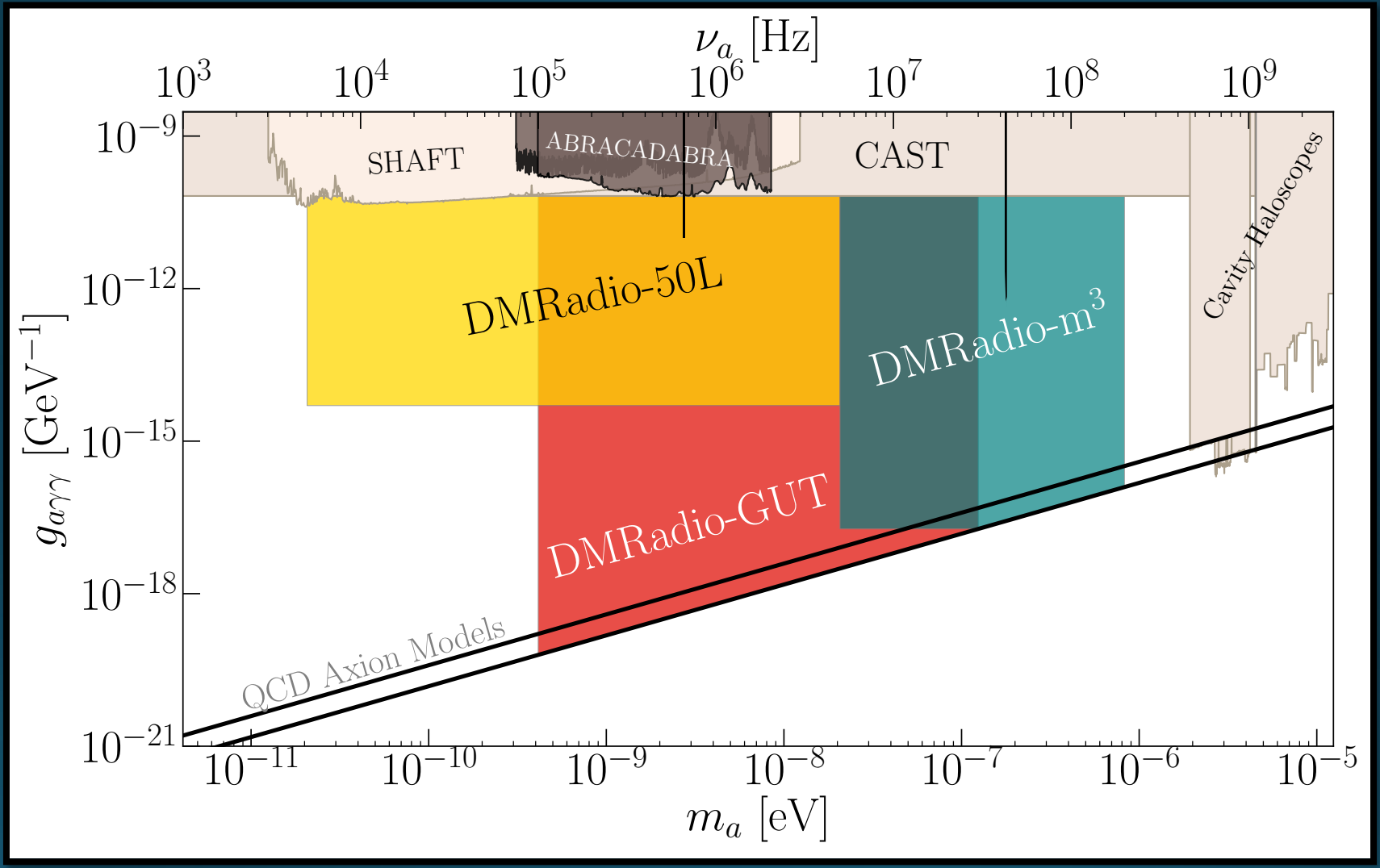
Y. Kahn
Department of Physics,
University of Illinois at Urbana-Champaign

A. Phipps
California State University, East Bay

J. N. Benabou, B. R. Safdi
Department of Physics
University of California Berkeley

GORDON AND BETTY MOORE FOUNDATION
NSF
U.S. DEPARTMENT OF ENERGY Office of Science
HEISING-SIMONS FOUNDATION

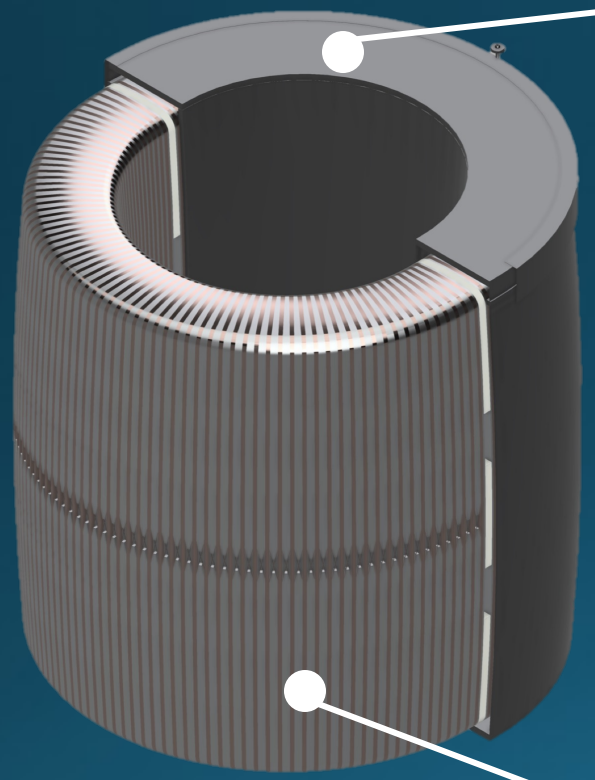
Thank you!

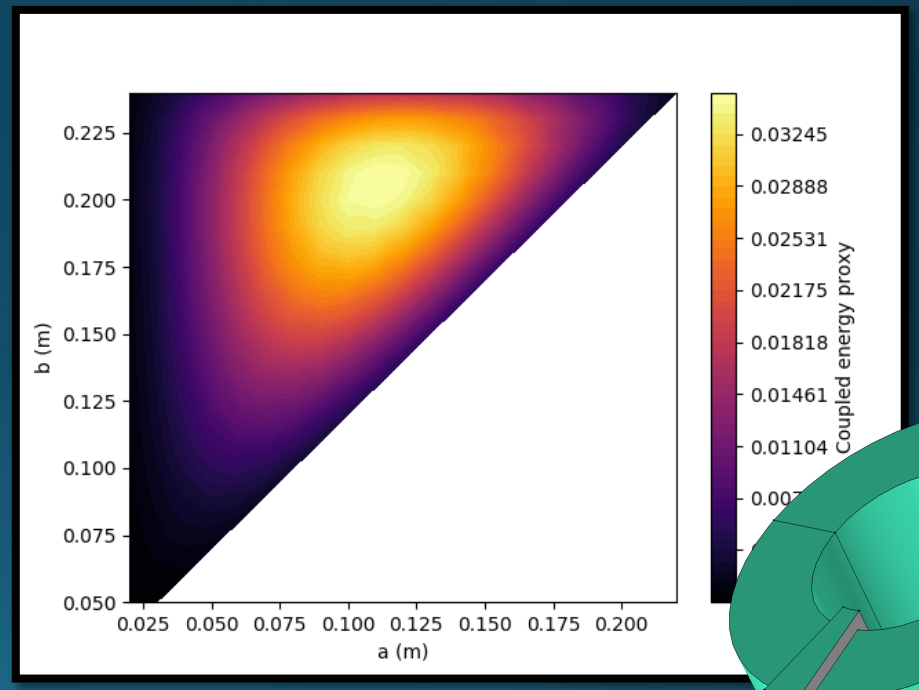

ν_a [Hz]
10^3
10^4
10^5
10^6
10^7
10^8
10^9
SHAFT
ABRACADABRA
CAST
Cavity Haloscopes
DMRadio-50L
DMRadio-m^3
DMRadio-GUT
QCD Axion Models
$g_{a\gamma\gamma}$ [GeV^{-1}]
10^{-9}
10^{-12}
10^{-15}
10^{-18}
10^{-21}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
m_a [eV]

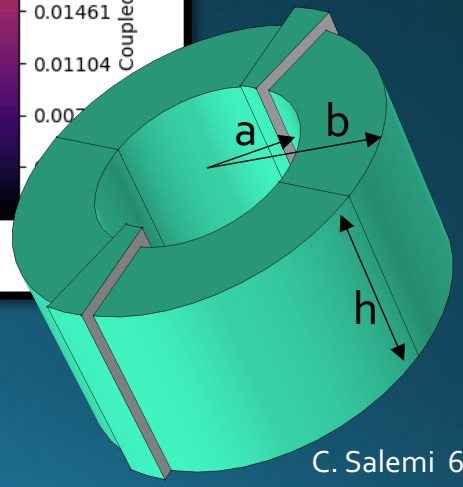
Backup slides

DMRadio-50 L

optimized axion-detector coupling with pickup sheath

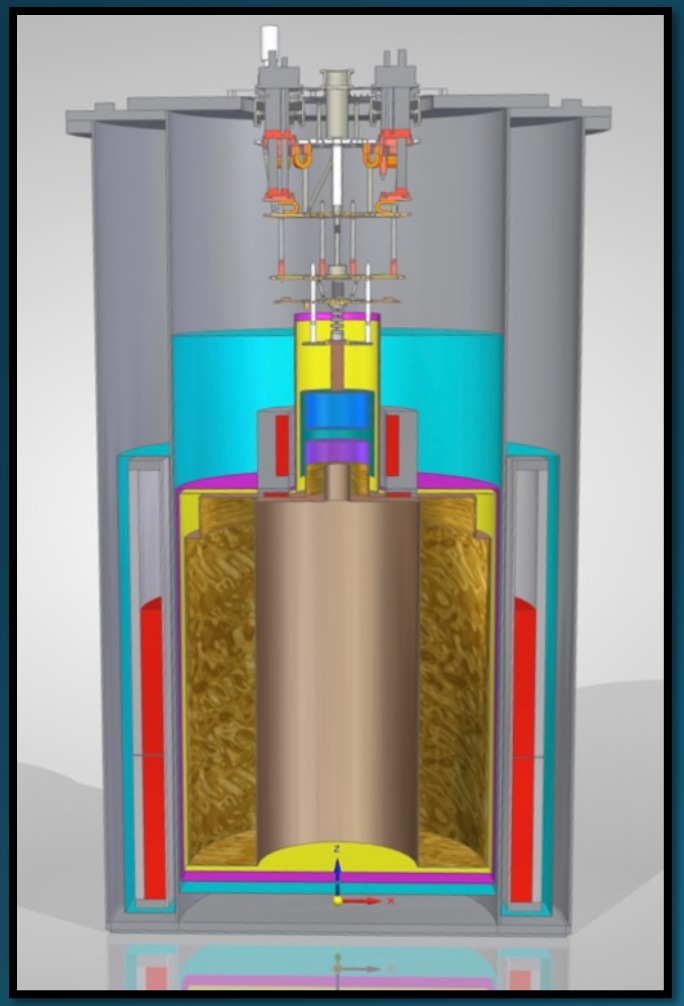




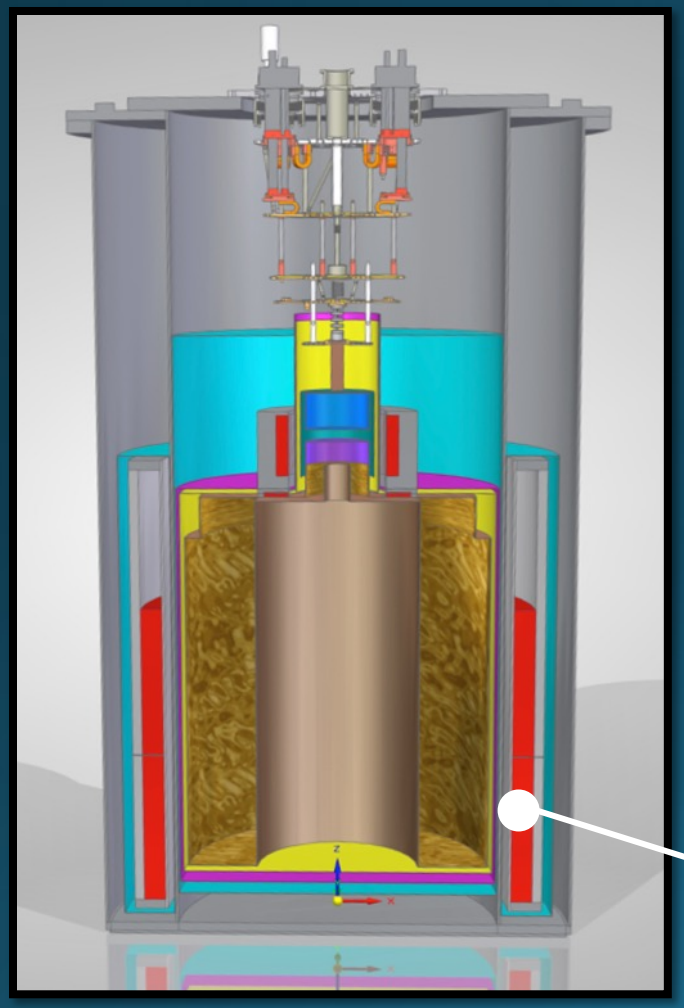


50 L volume, 1T field

DMRadio-m^3



DMRadio-m^3

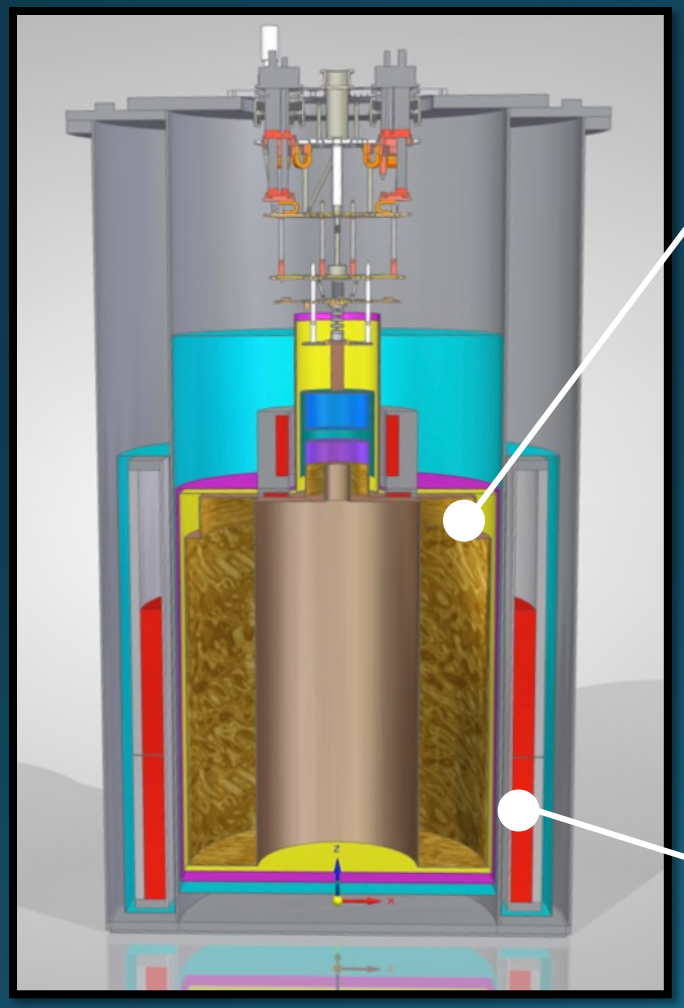


solenoidal magnet,
1 m^3 volume, 4-5T field

*ABRA-10cm ~ 0.9 L

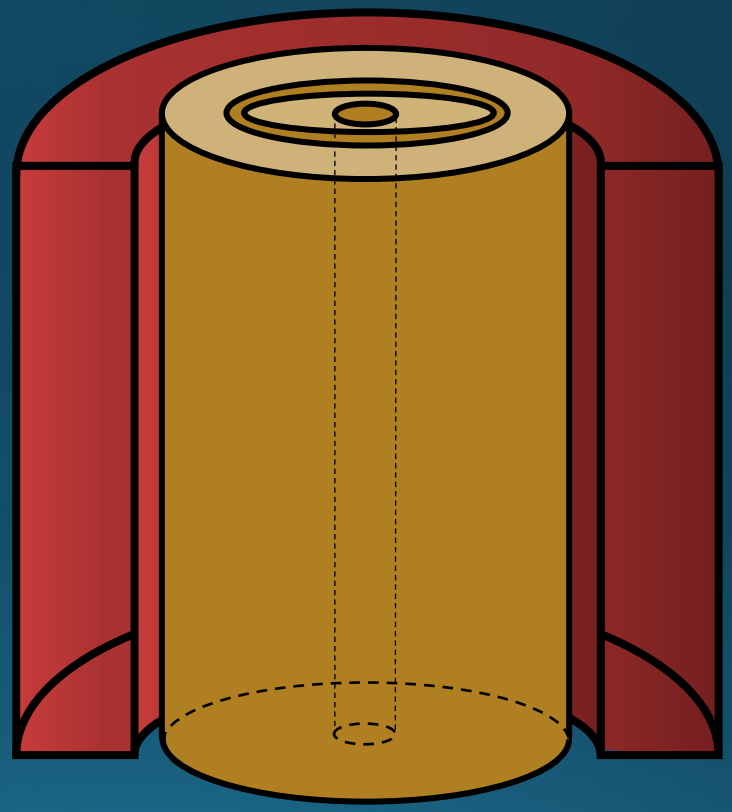
*1 m^3 = 1000 L

DMRadio-m^3



coaxial pickup sheath

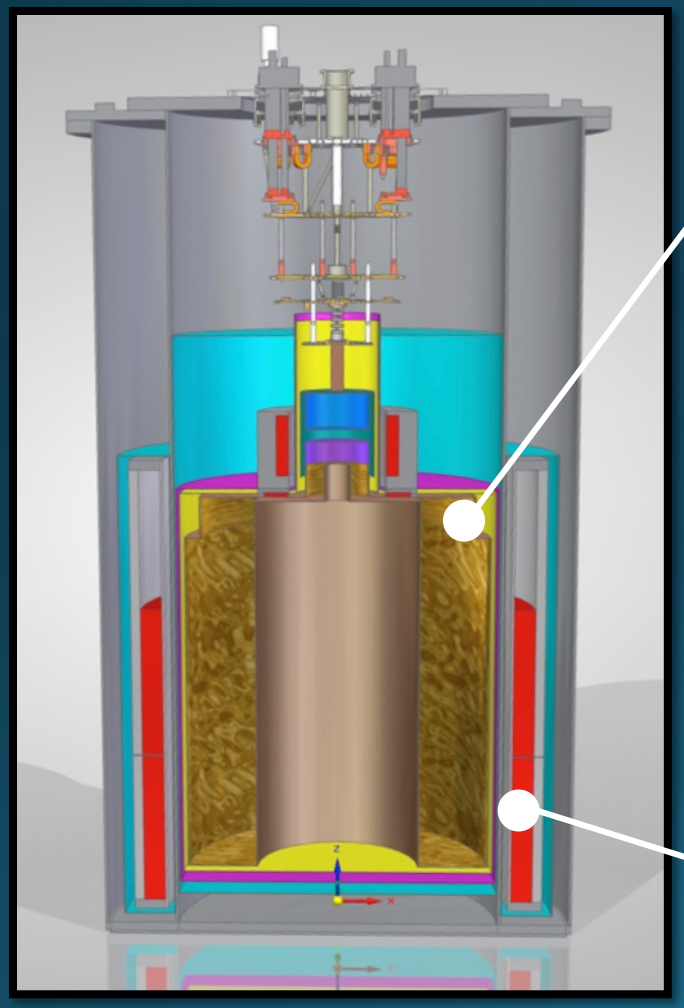
solenoidal magnet, 1 m^3 volume, 4T field



solenoidal magnet

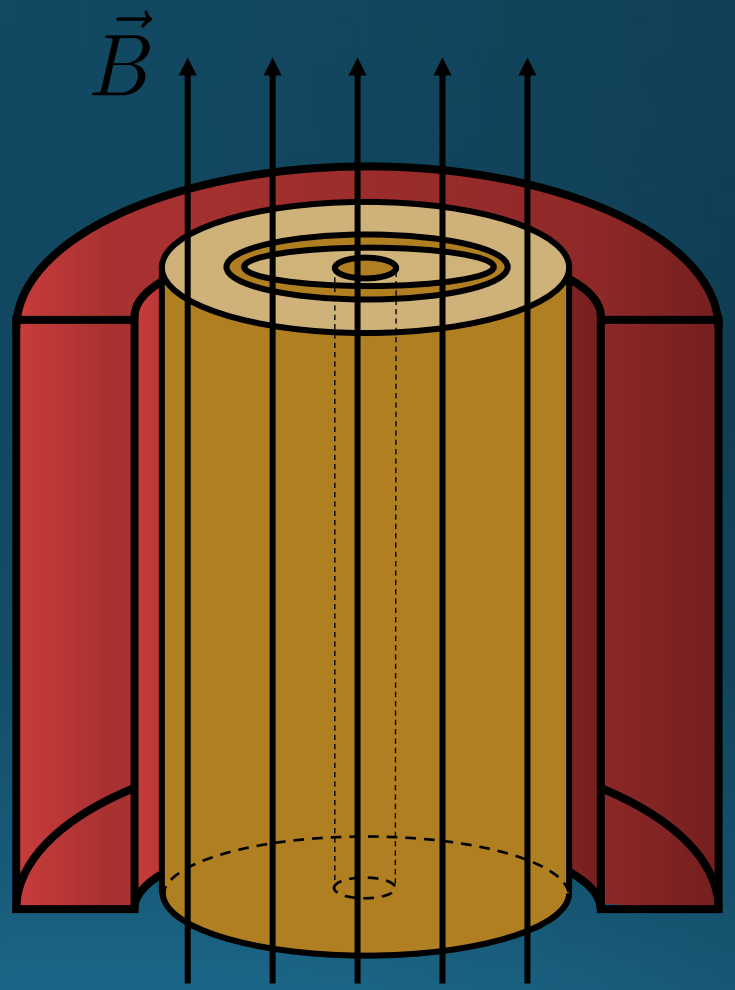
coaxial sheath

DMRadio-m³



coaxial pickup sheath

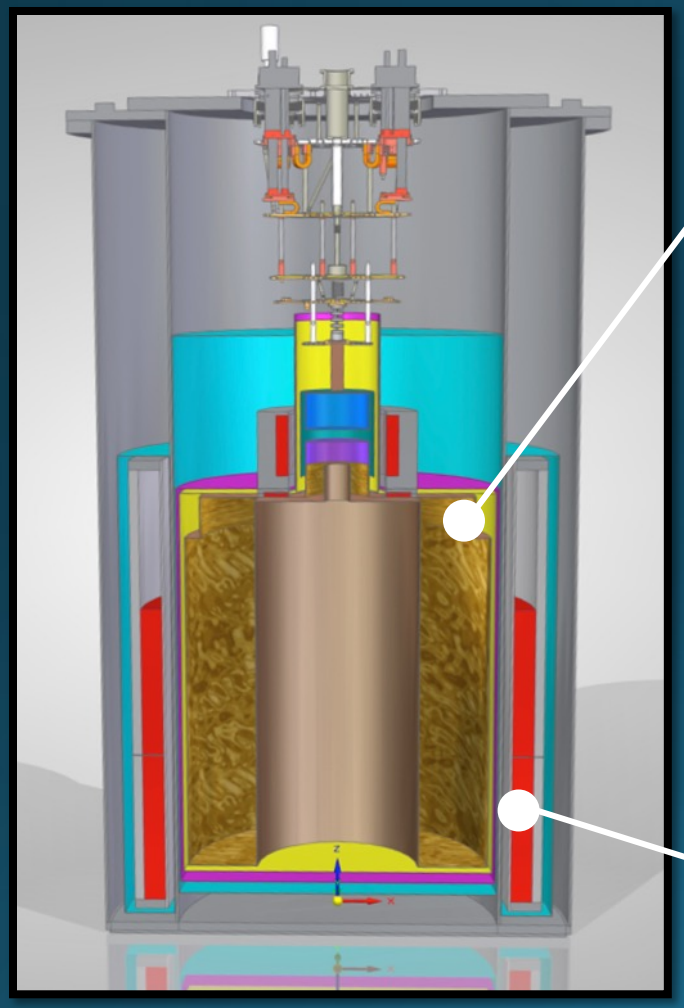
solenoidal magnet, 1 m³ volume, 4T field



solenoidal magnet

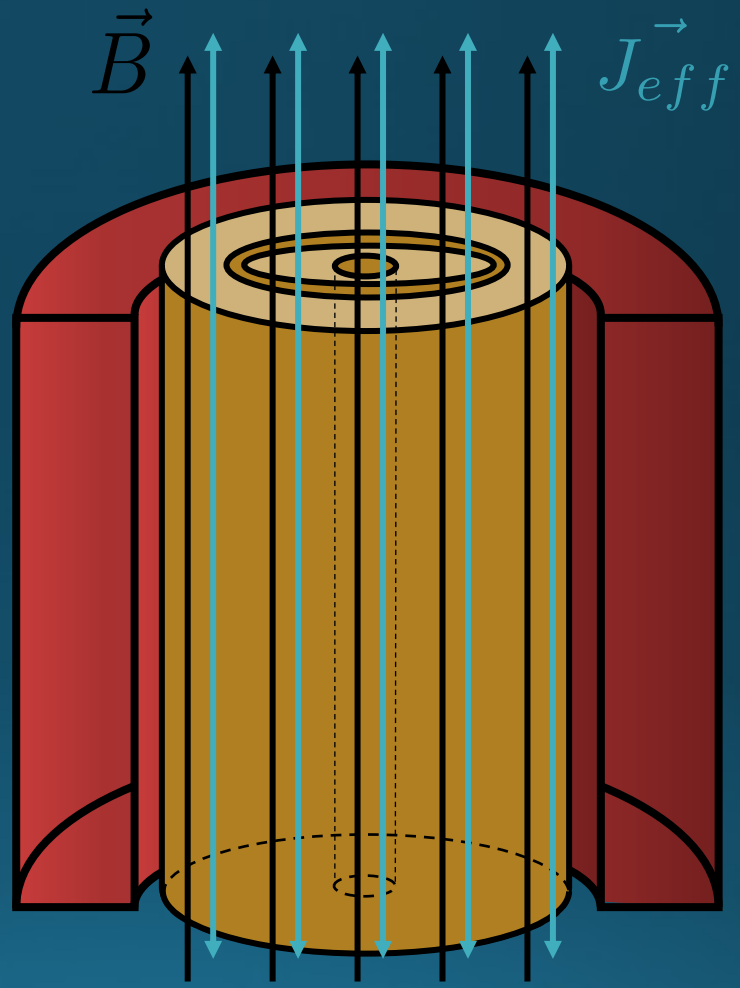
coaxial sheath

DMRadio-m³



coaxial pickup sheath

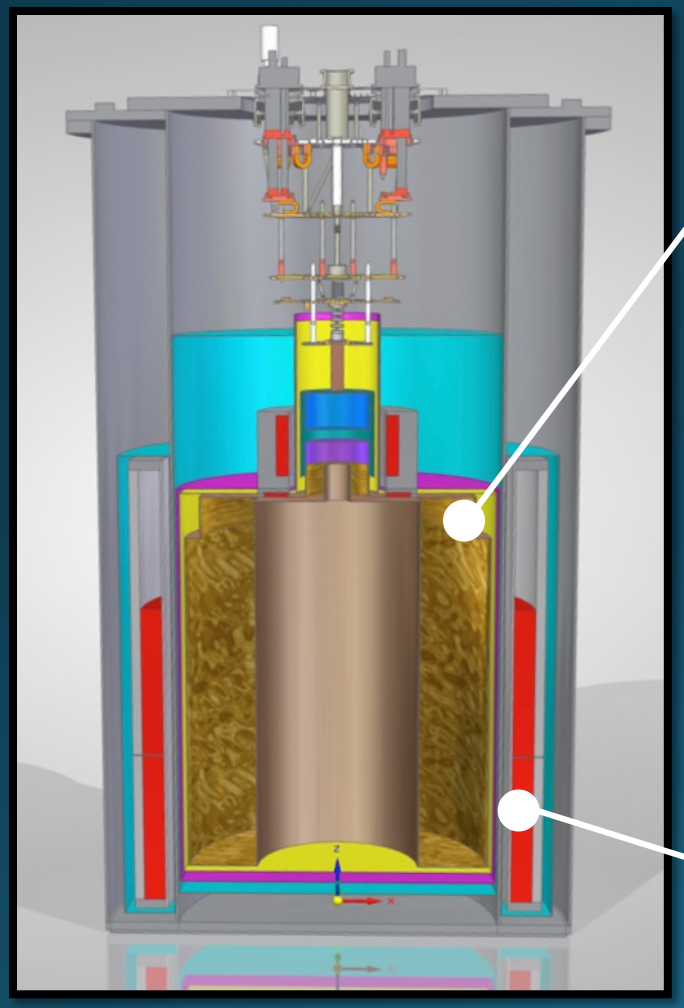
solenoidal magnet, 1 m³ volume, 4T field



solenoidal magnet

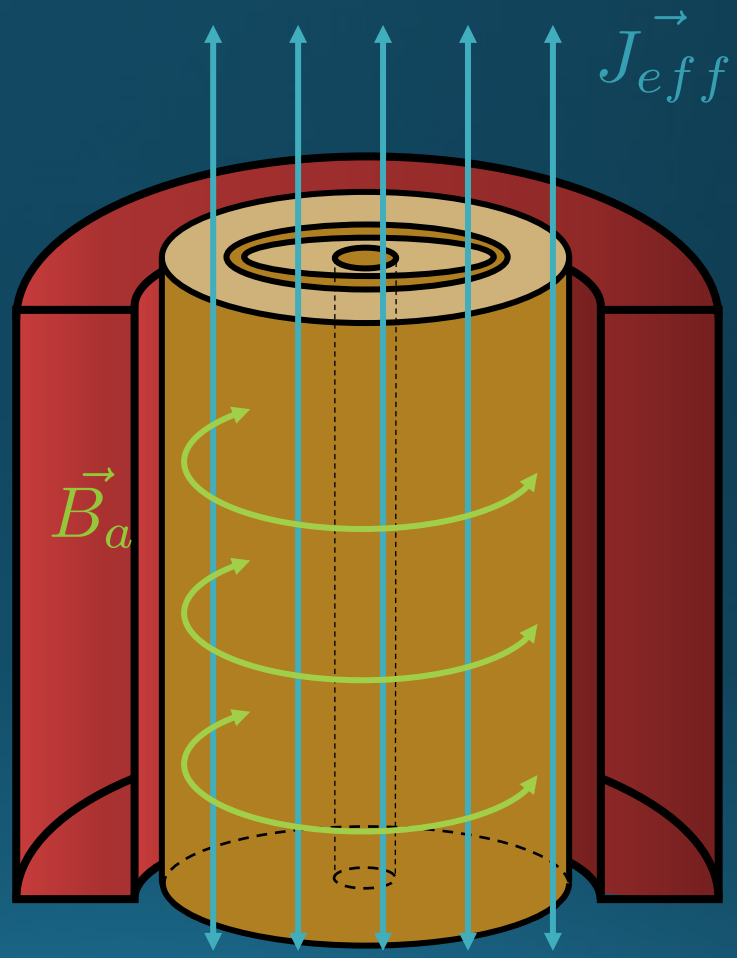
coaxial sheath

DMRadio-m³



coaxial pickup sheath

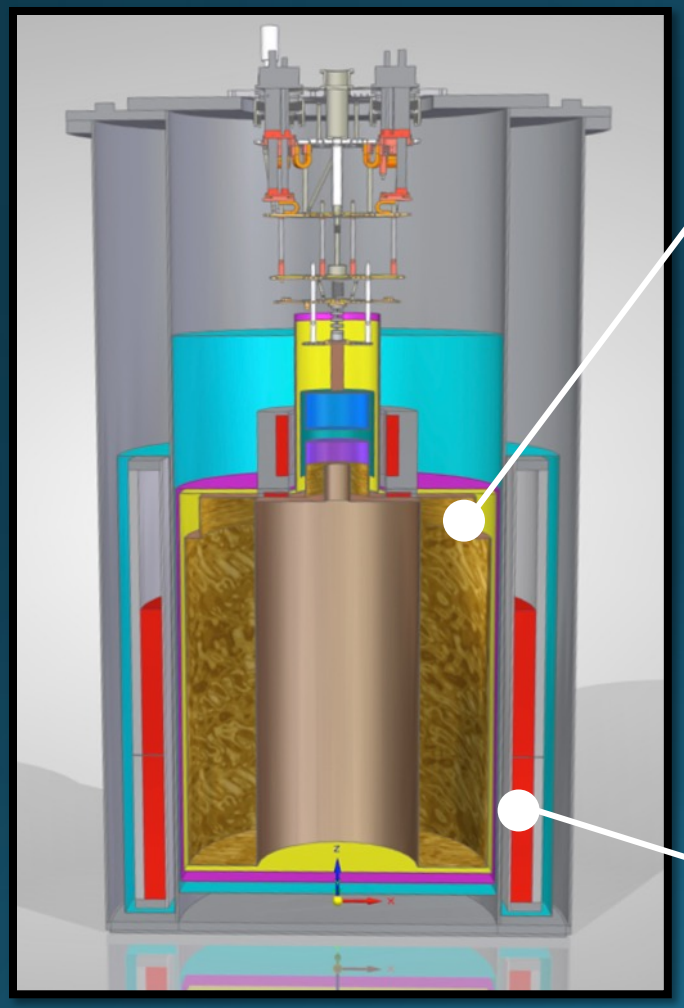
solenoidal magnet,
1 m³ volume, 4T field



solenoidal magnet

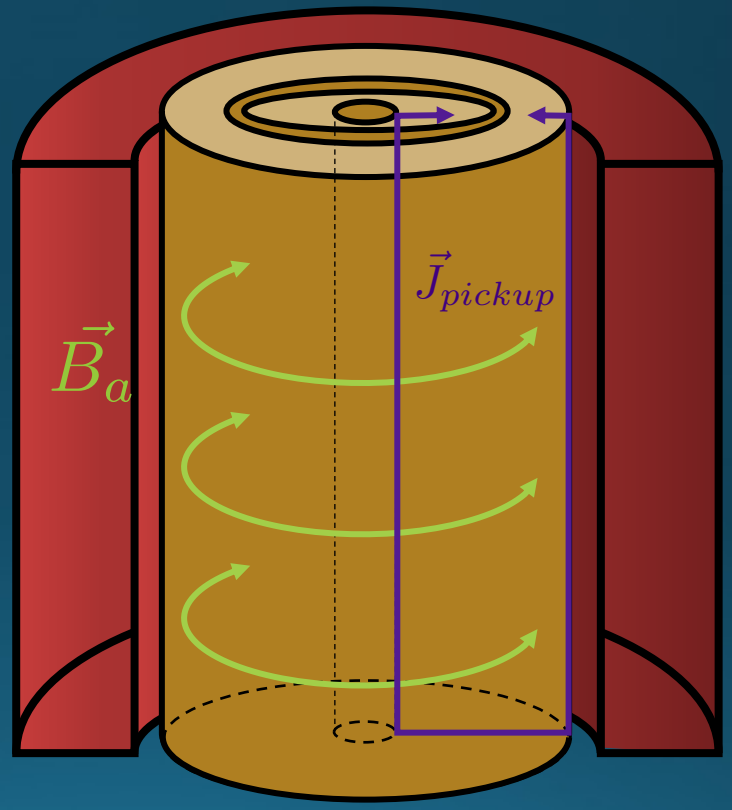
coaxial sheath

DMRadio-m³



coaxial pickup sheath

solenoidal magnet, 1 m³ volume, 4T field

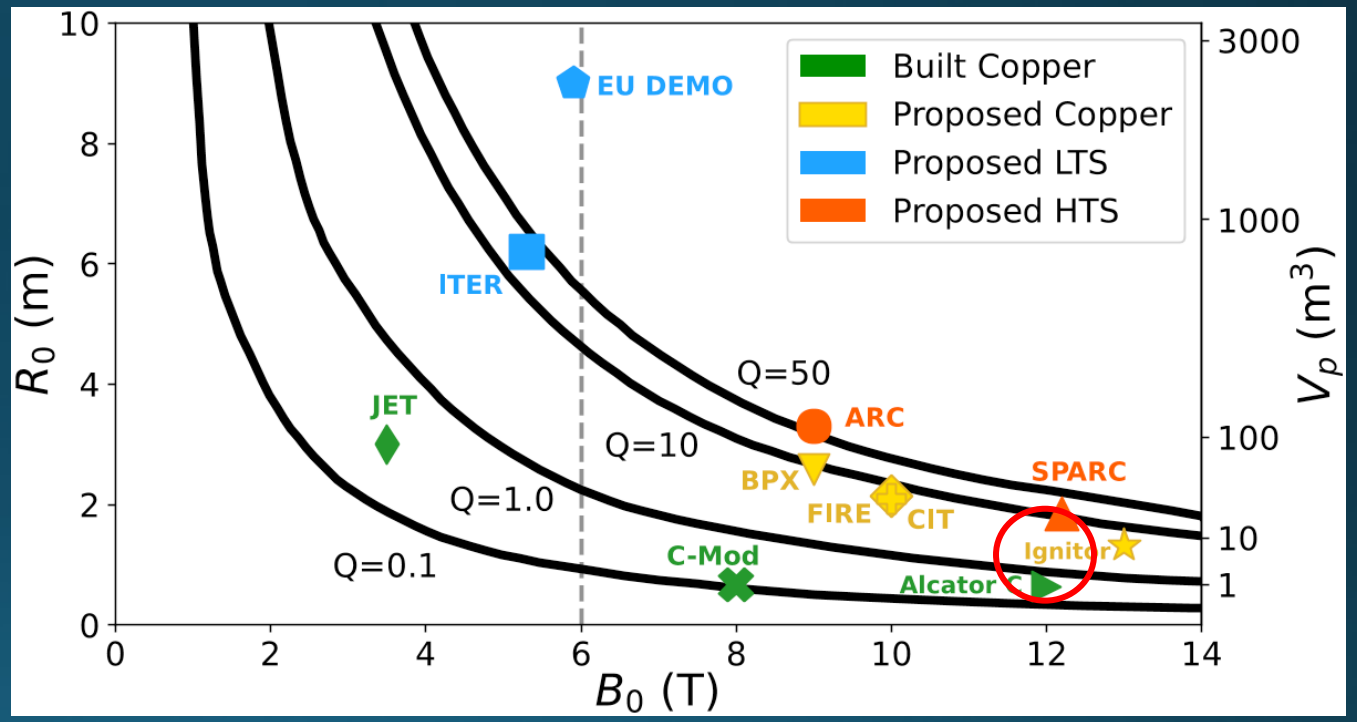


solenoidal magnet

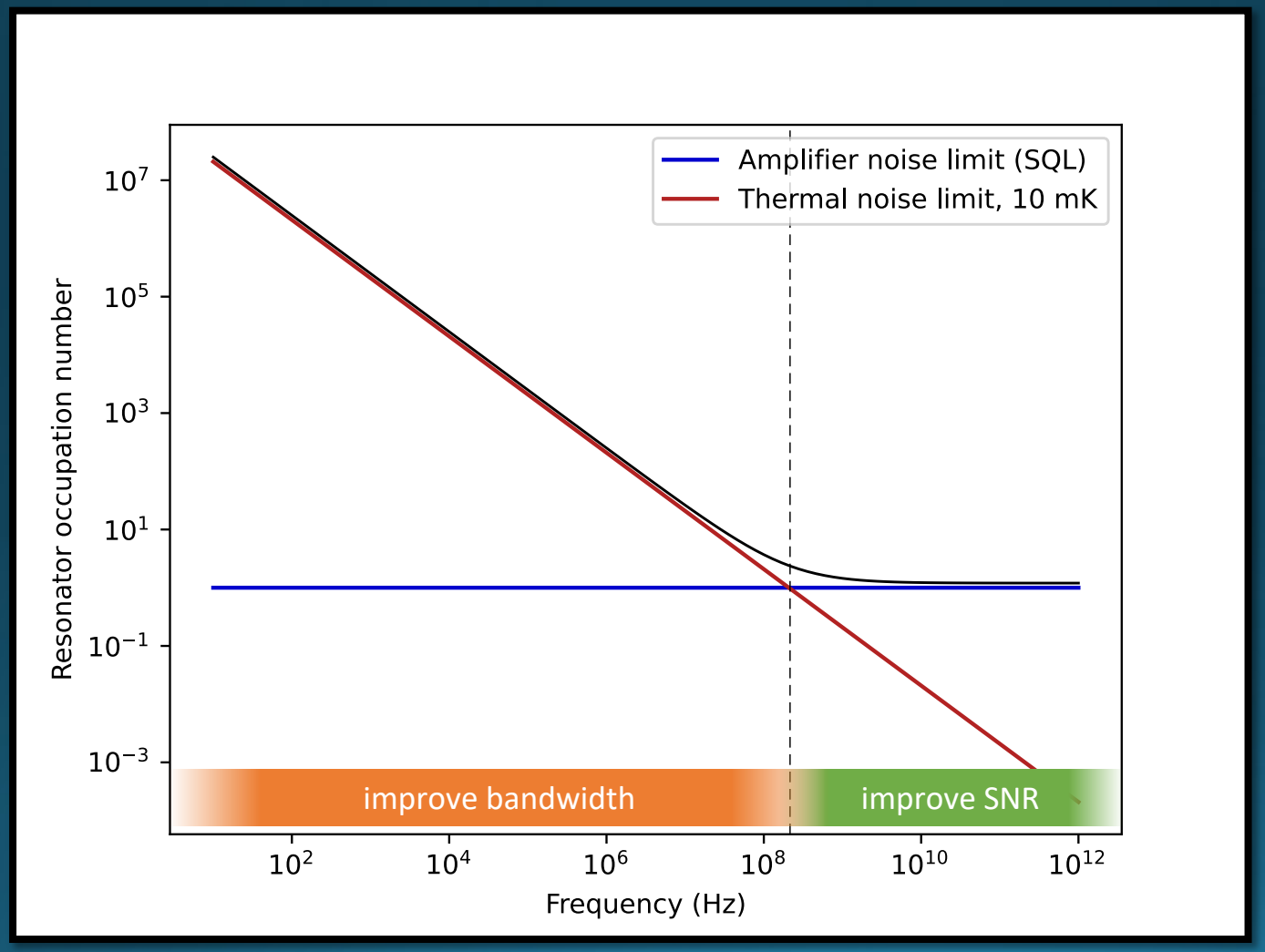
coaxial sheath

DMRadio-GUT

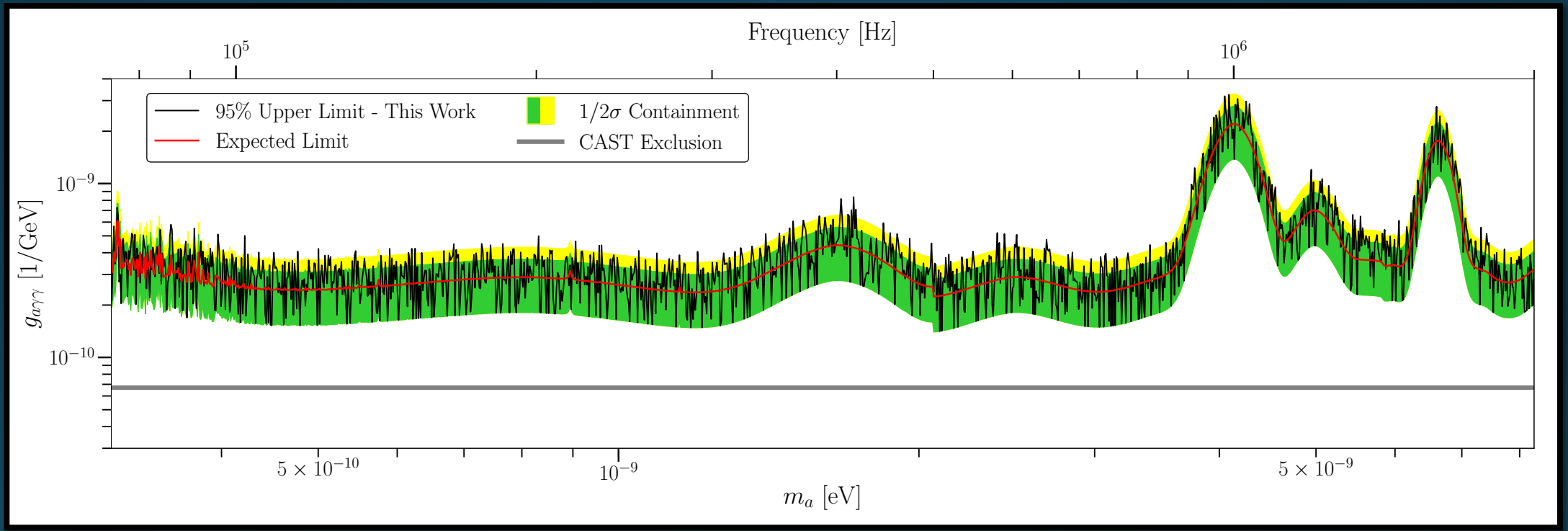
- B_0 ~ 16 T (12 T RMS)
- V ~ 10 m^3
- m_a ~ 400 peV — 125 neV
  (ν_a ~ 100 kHz — 30 MHz)
- ~7 year scan time
- ~20 dB below SQL amplifiers
- $T_{resonator}$ ~ 10 mK
- Q ~ 20 × 10^6



Noise regimes

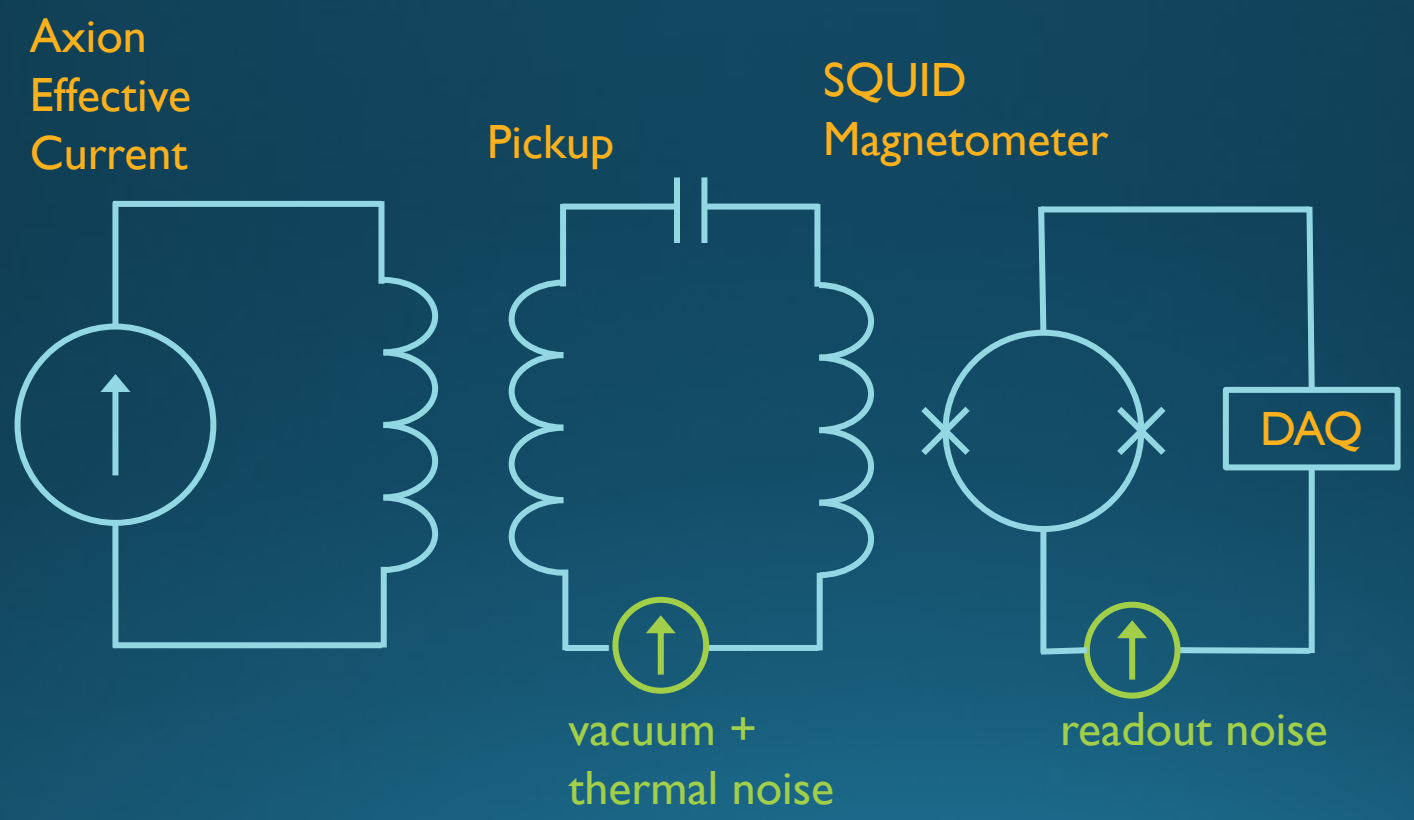


Limits on $g_{a\gamma\gamma}$ (run 1)

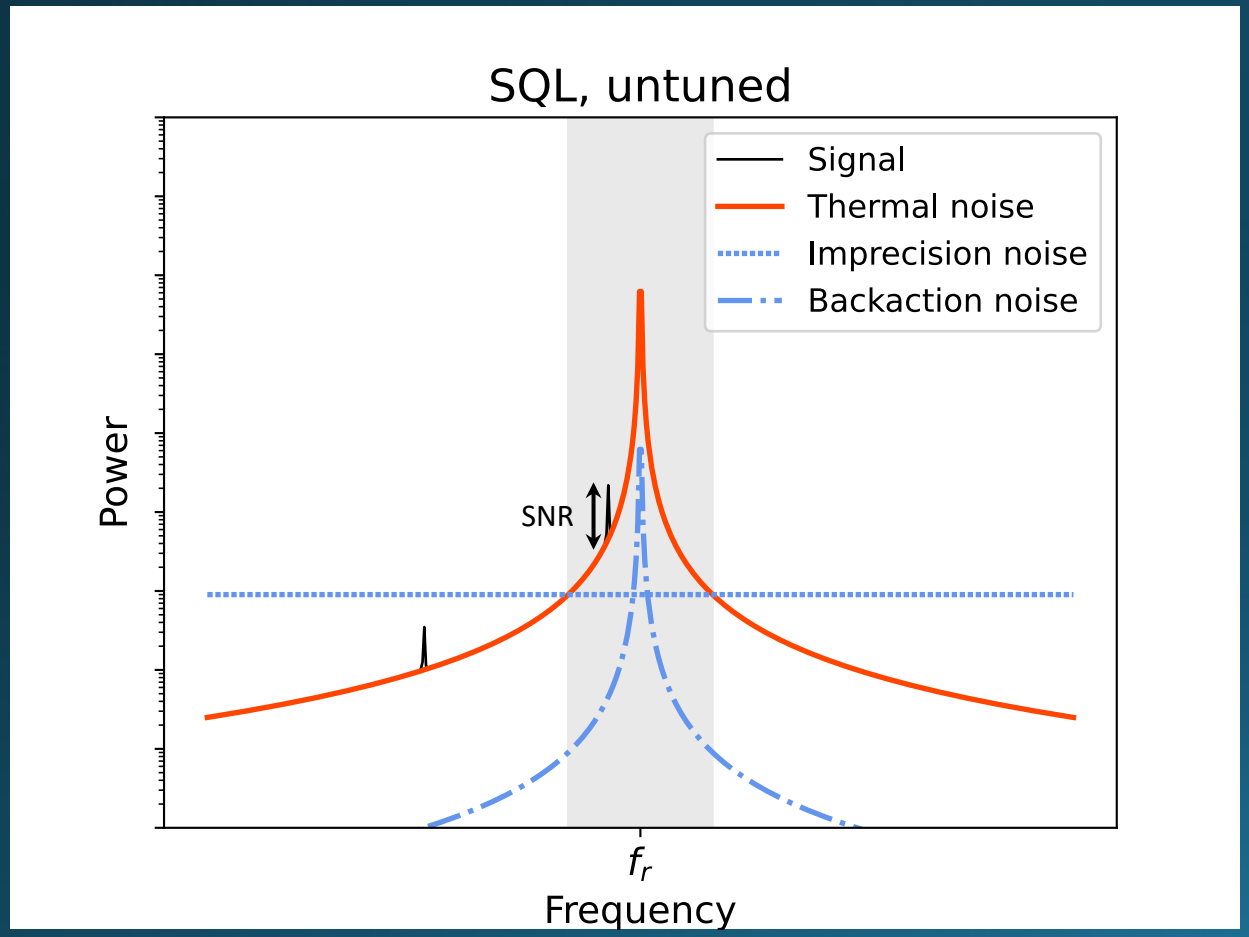


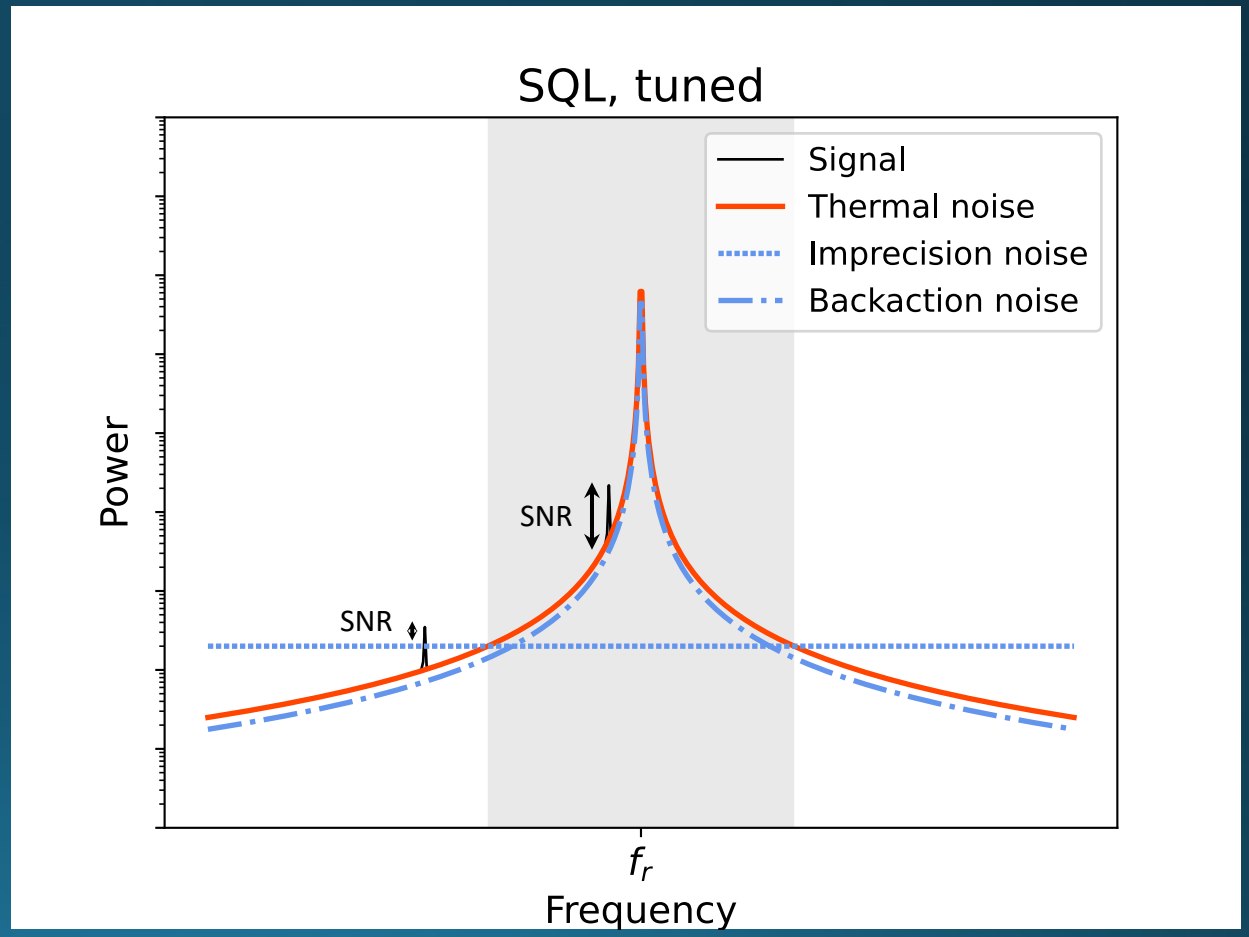
Ouellet, Salemi et al. *Phys.Rev.Lett.* 2019
Ouellet, Salemi et al. *Phys.Rev.D* 2019

Resonant readout —improving the scan rate

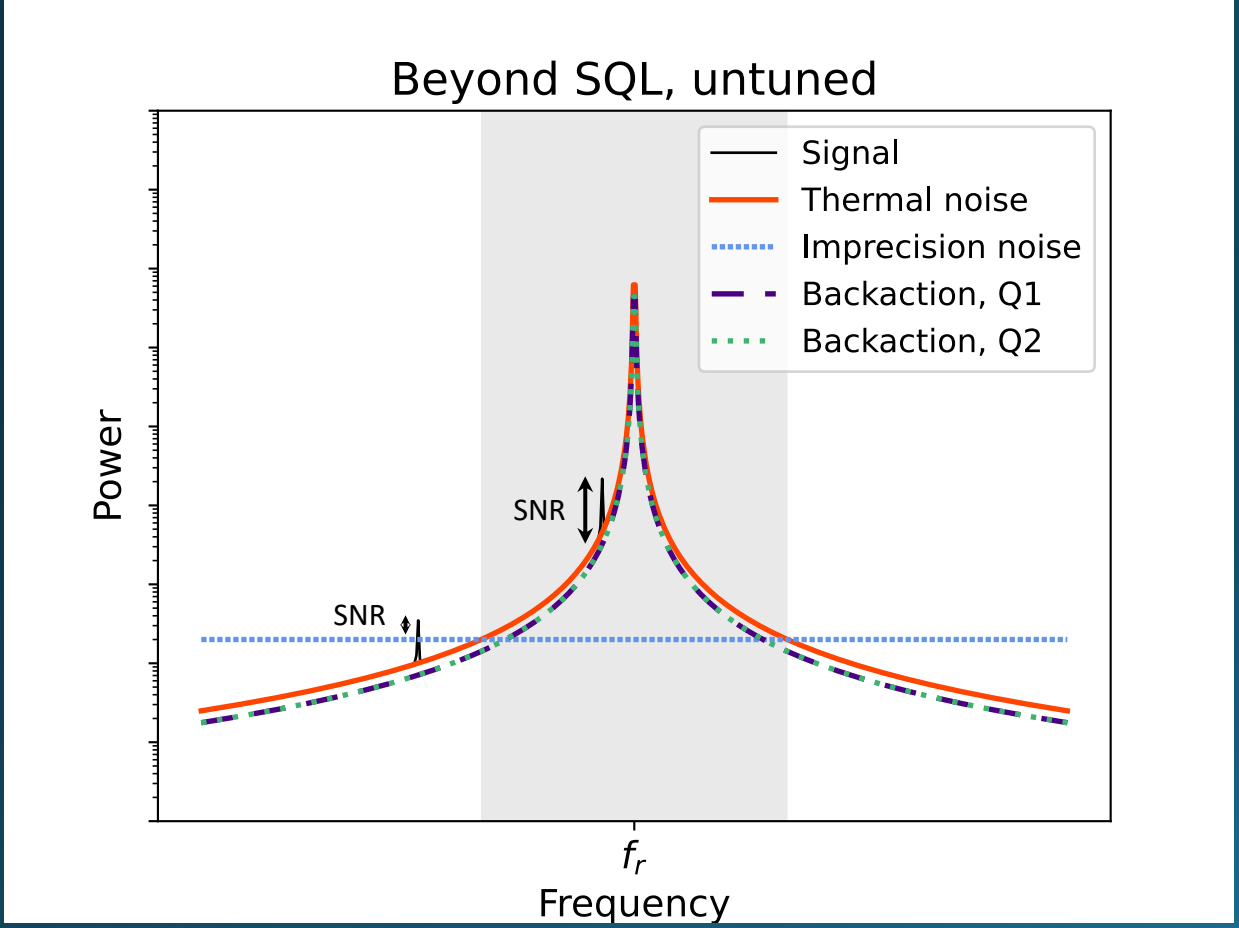


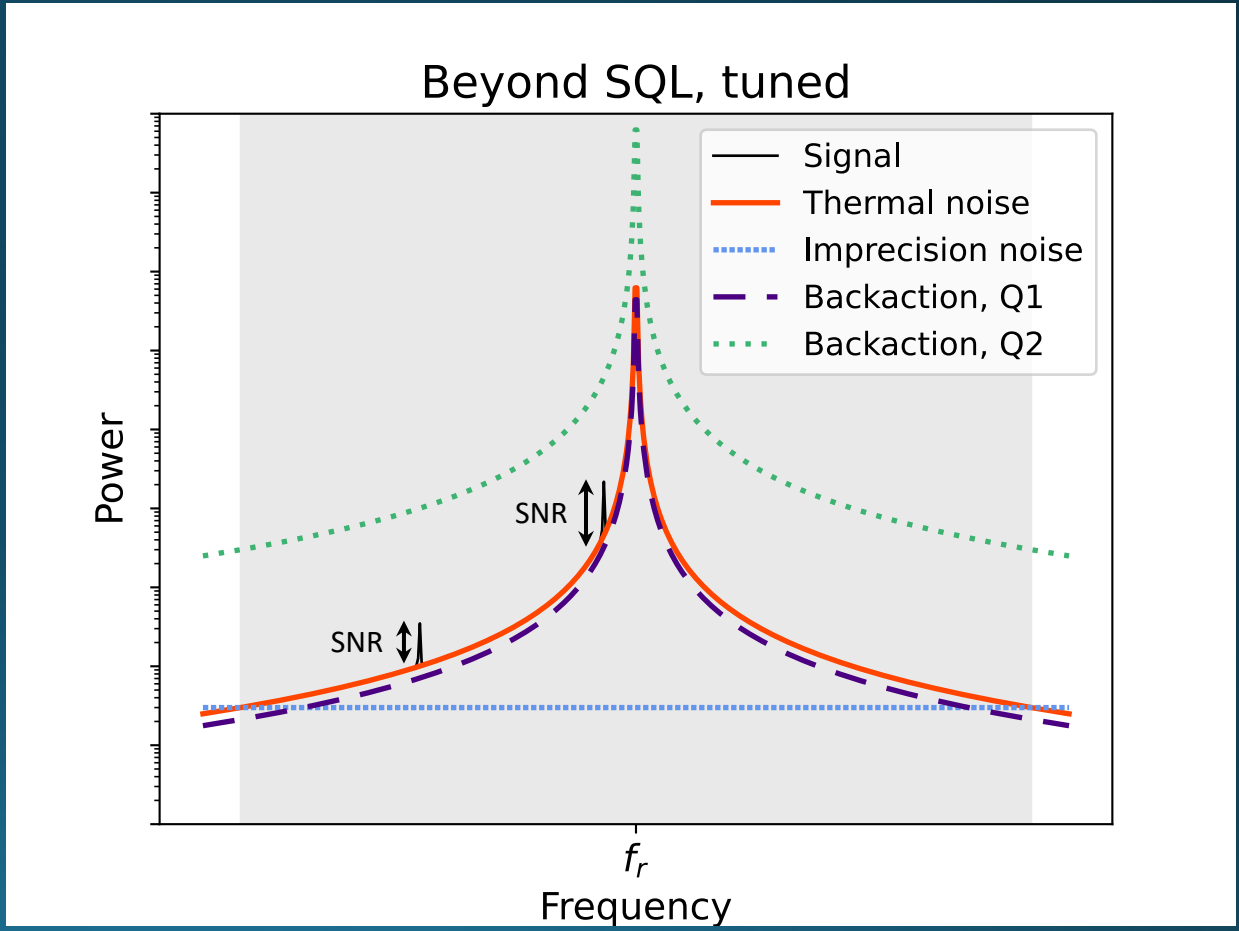
Improving the bandwidth





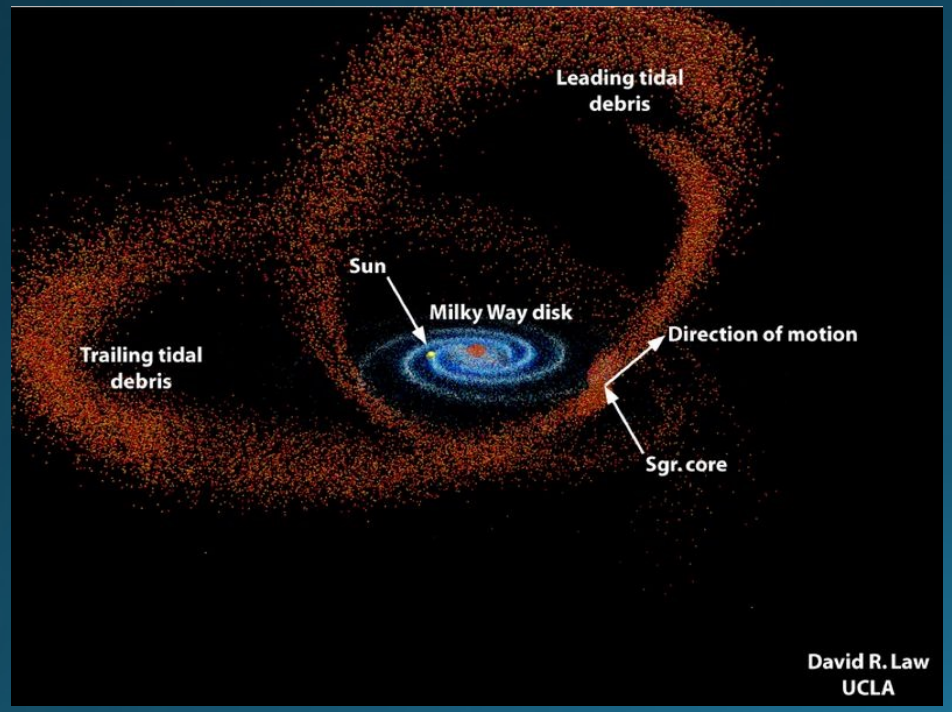
Backaction evasion

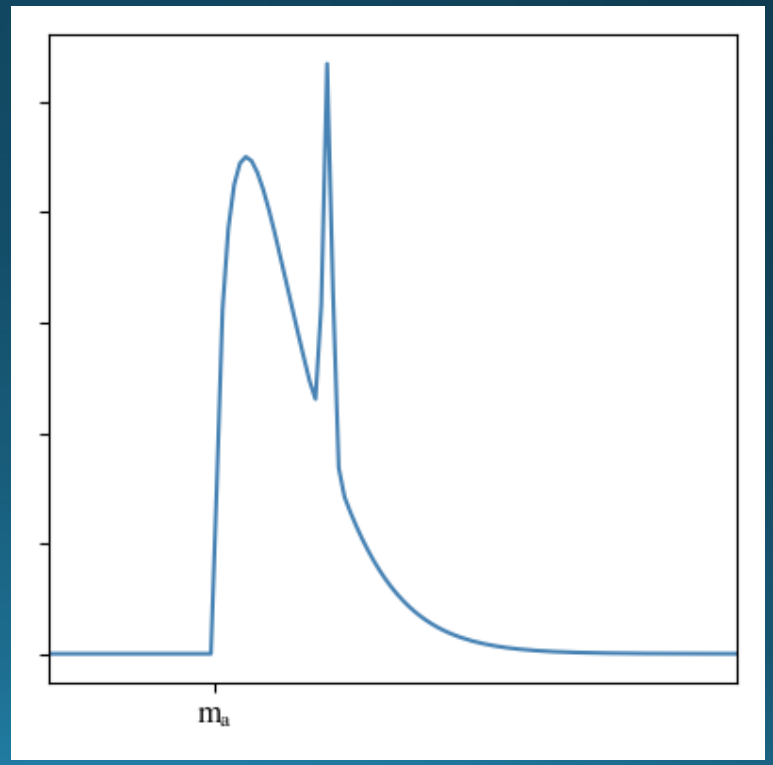




Axion astrophysics?

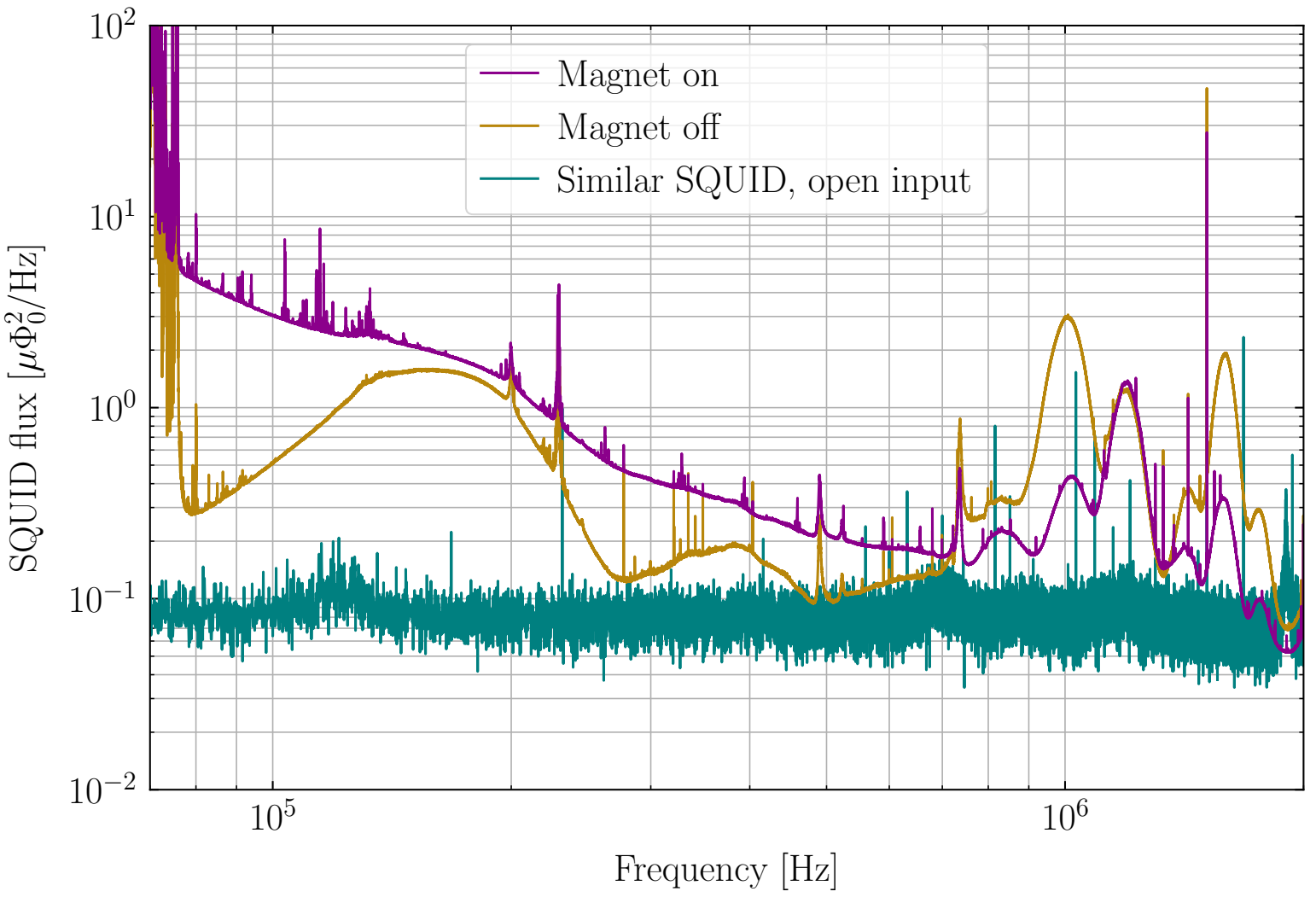
- Could see substructure within dark matter halo
- Low velocity distribution: sharp, narrow peak



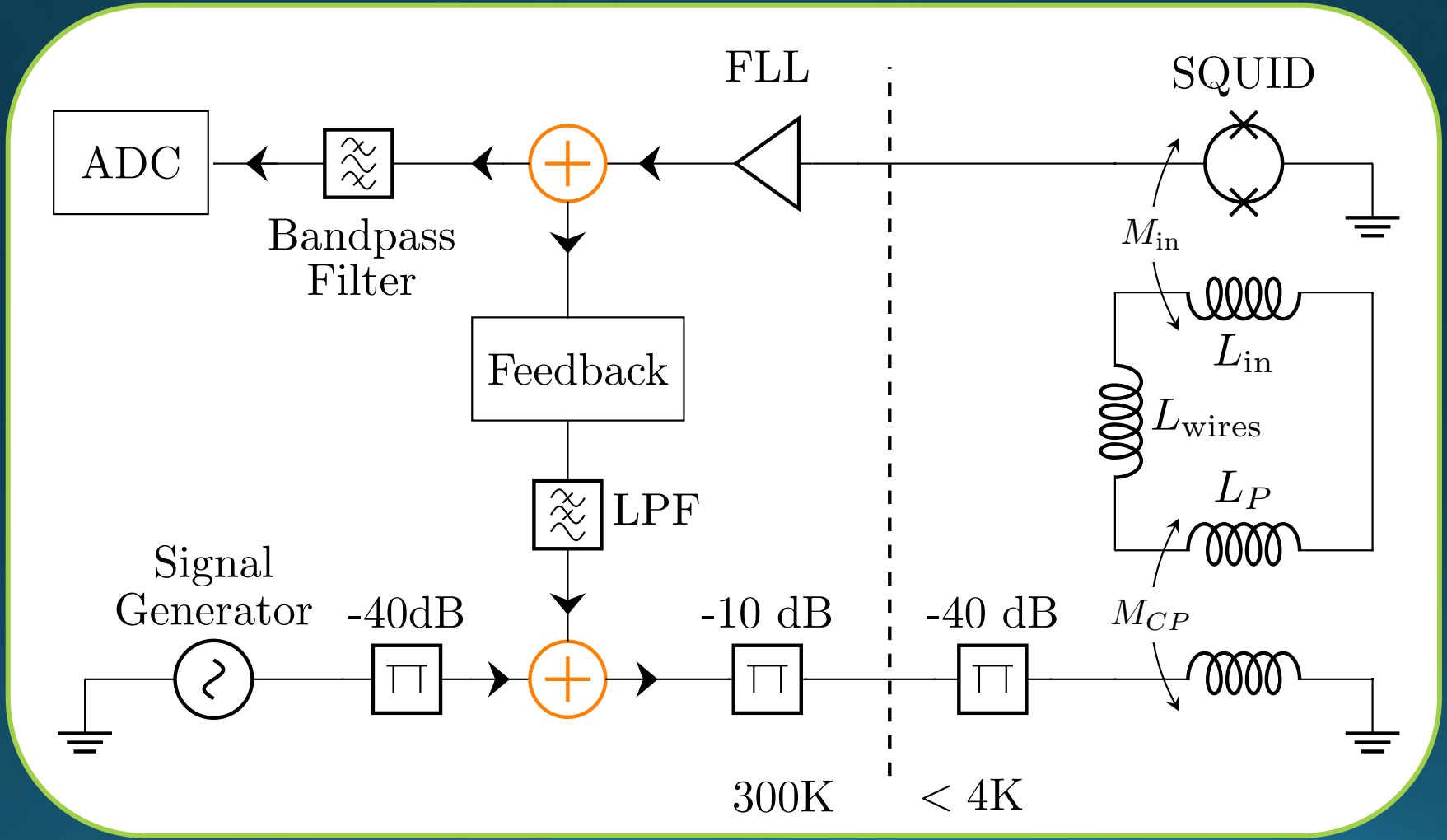


Foster, Rodd, Safdi 2018

Run 3 noise


Magnet on
Magnet off
Similar SQUID, open input
SQUID flux [$\mu\Phi_0^2$/Hz]
Frequency [Hz]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^5
10^6

Calibration circuit



Likelihood

$$\mathcal{L}(d|m_a, A;\, \mathbf{a}, \sigma) = \prod_k \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(d_k - As_k - \mu_k(\mathbf{a}))^2}{2\sigma^2}\right]$$

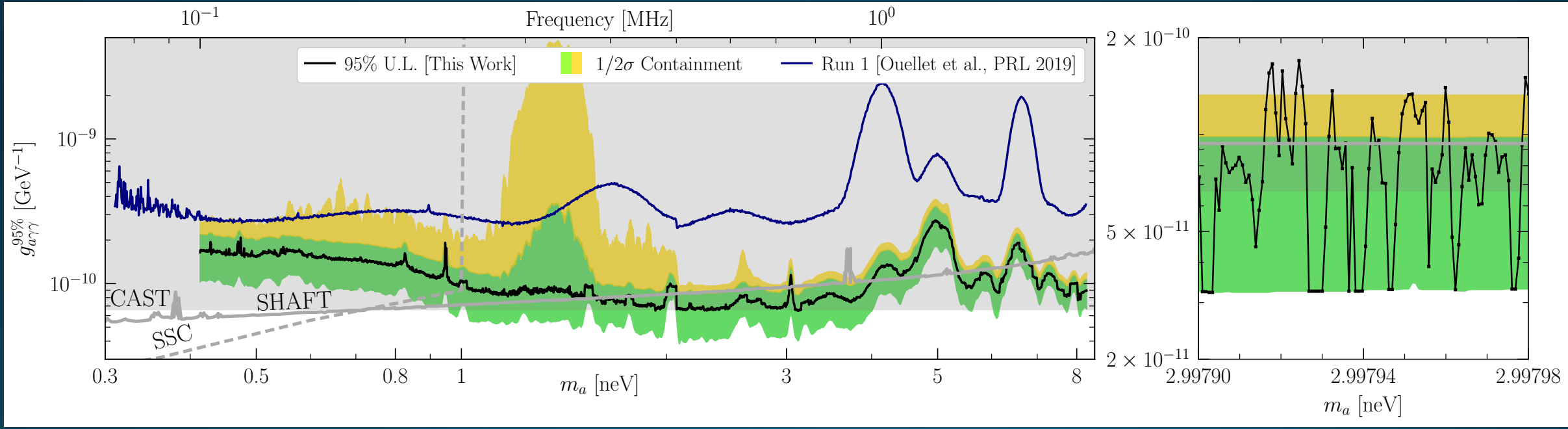
$$t(m_a, A) = 2\ln\left[\frac{\mathcal{L}(d|m_a, A;\, \hat{\mathbf{a}}, \hat{\sigma})}{\mathcal{L}(d|m_a, A=0;\, \hat{\mathbf{a}}, \hat{\sigma})}\right]$$

- Corrected for LEE and correlation of nearby search windows
- TS_{thresh}=55 for 5σ discovery
- Modified likelihood with nuisance parameter

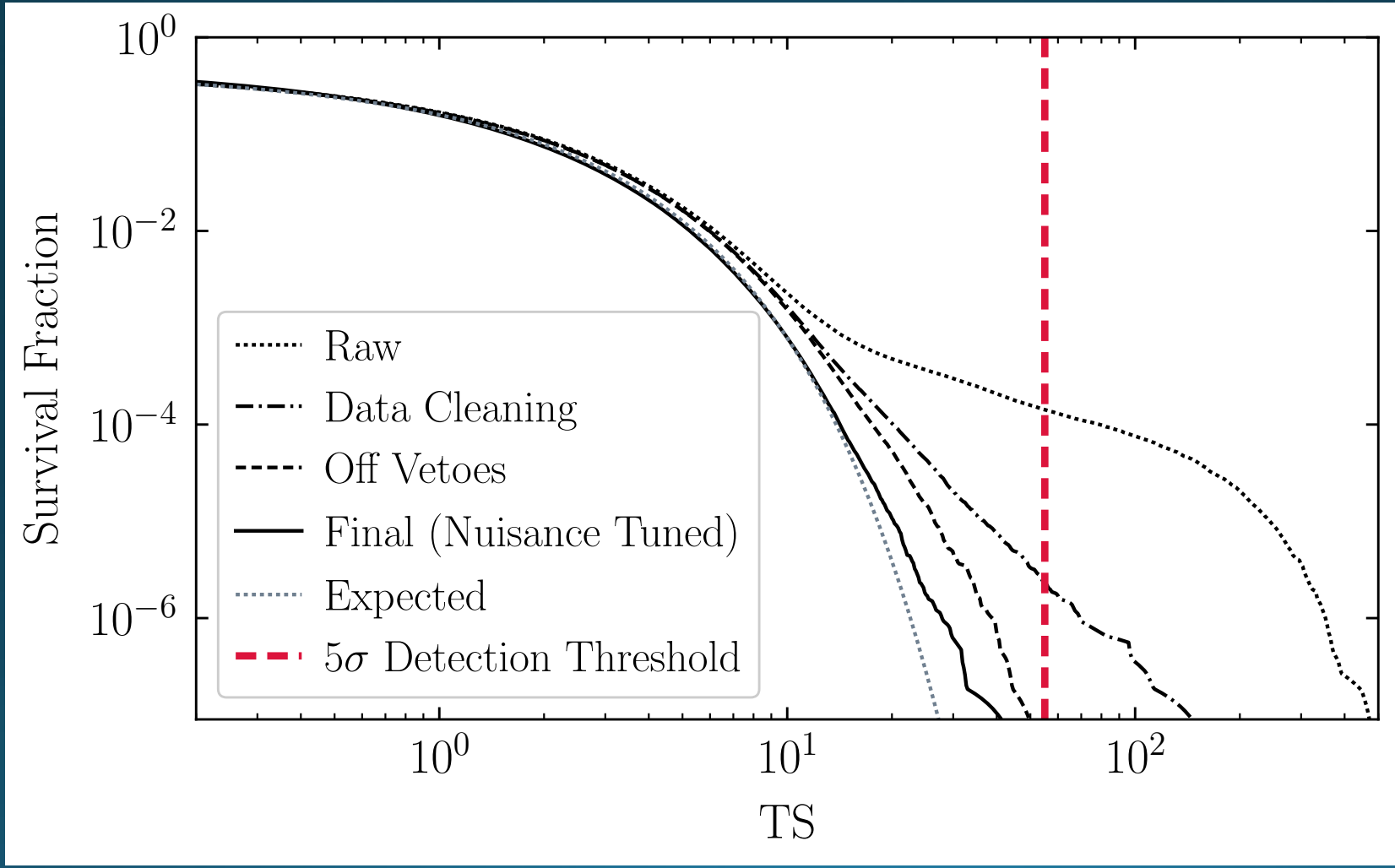
Analysis procedure

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

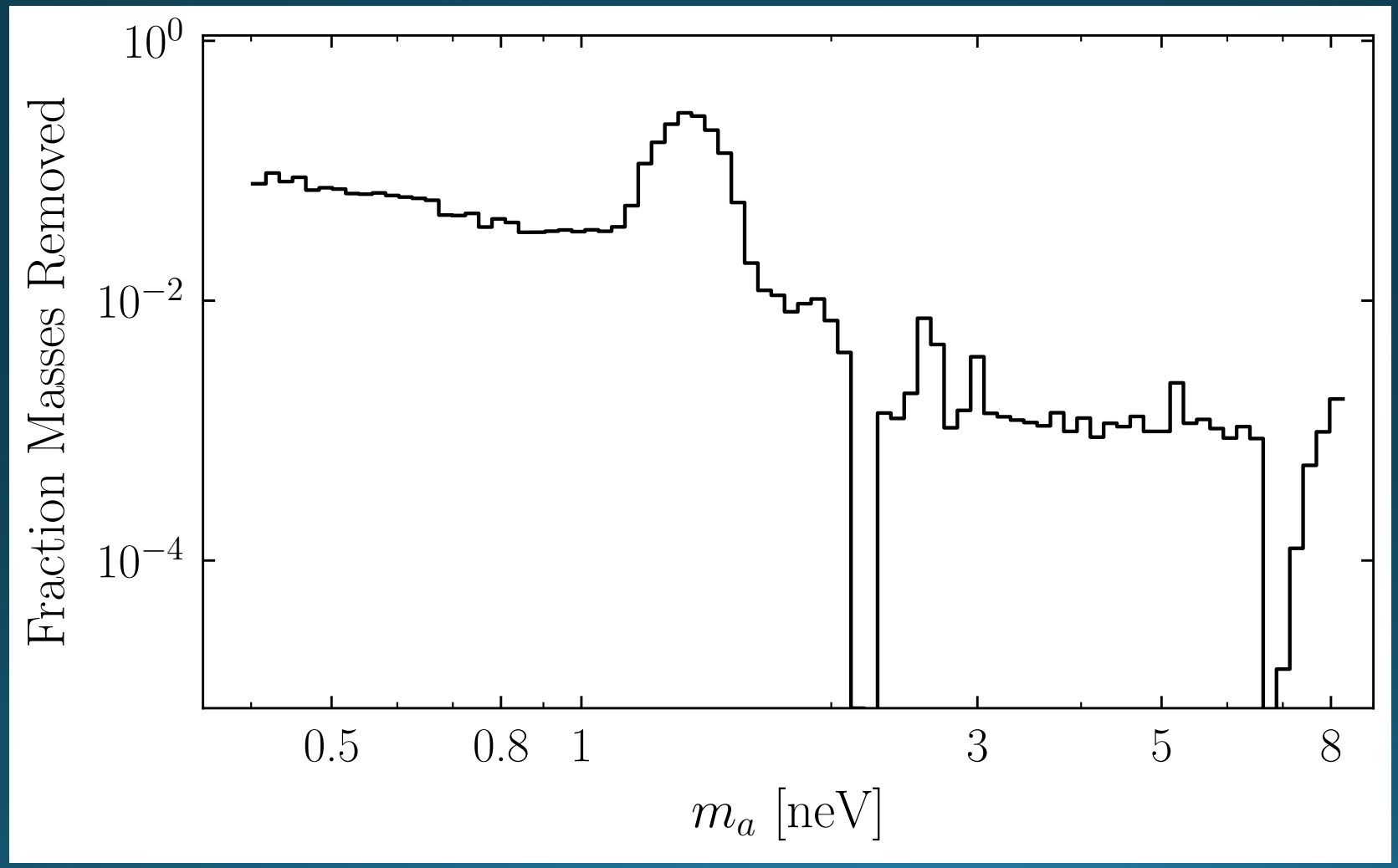
Joint limit


Frequency [MHz]
10^{-1}
10^{0}
95% U.L. [This Work]
1/2σ Containment
Run 1 [Ouellet et al., PRL 2019]
$g_{a\gamma\gamma}^{95\%}$ [GeV^{-1}]
10^{-9}
10^{-10}
CAST
SHAFT
SSC
0.3
0.5
0.8
1
3
5
8
m_a [neV]
2×10^{-10}
5×10^{-11}
2×10^{-11}
2.99790
2.99794
2.99798
m_a [neV]

Analysis pathway

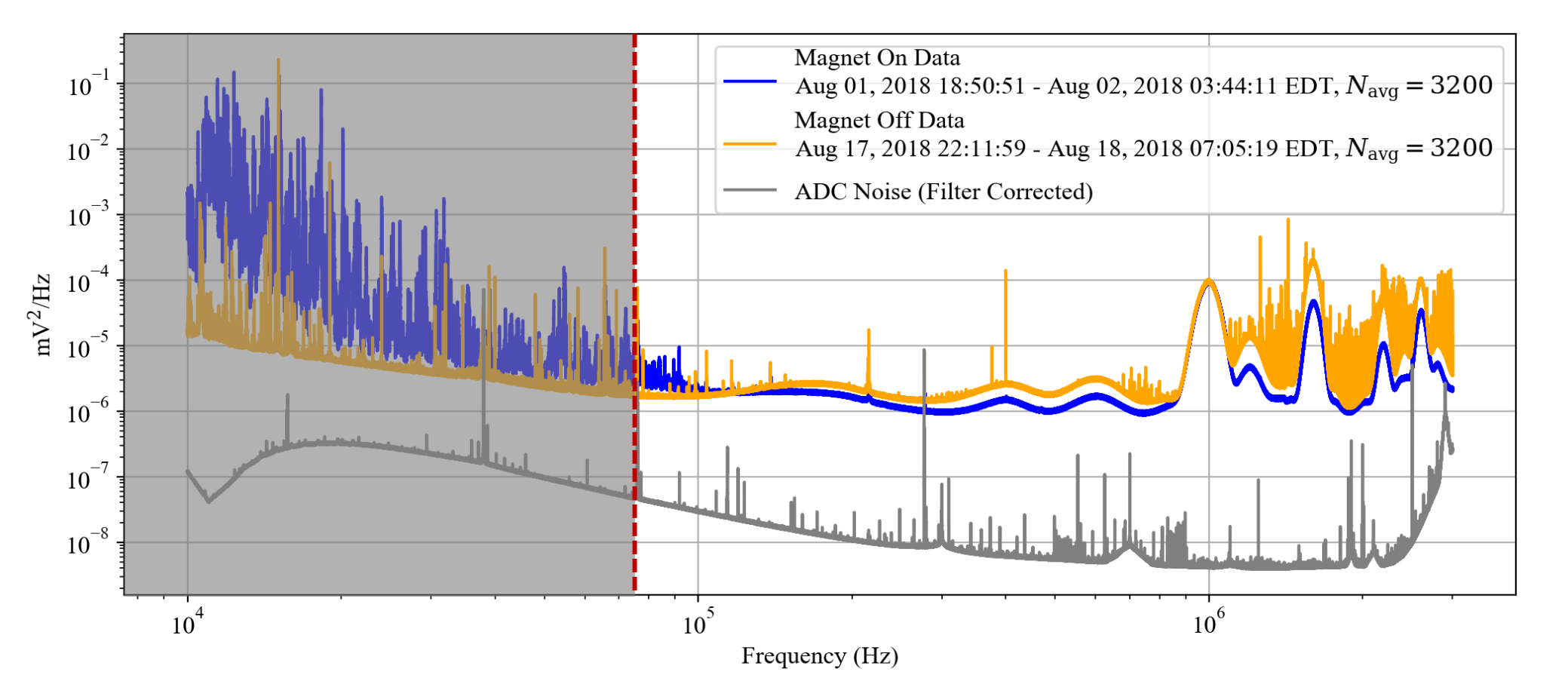


Masking fraction



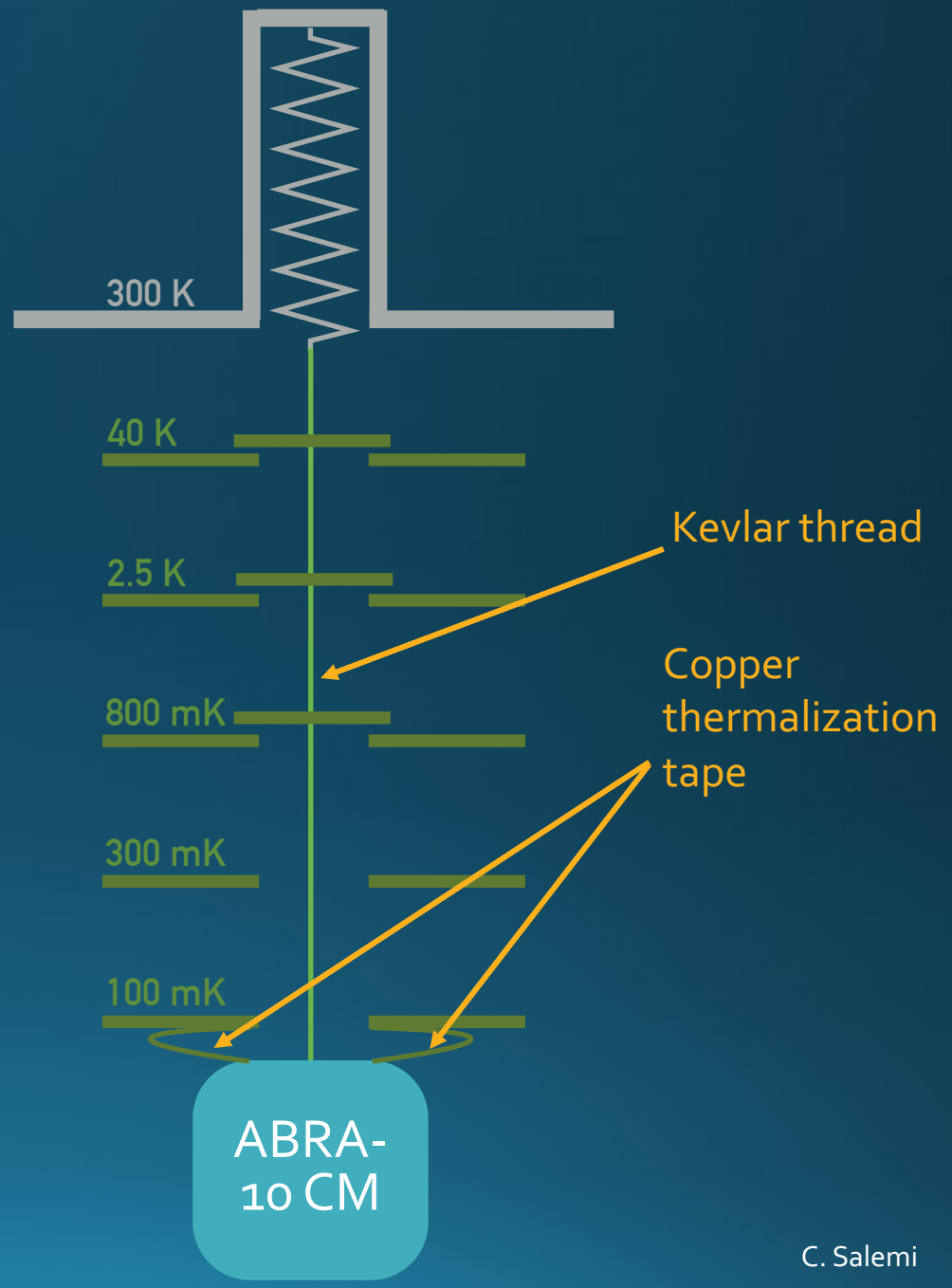
Real Spectra, run 1

m_a~neV, "GUT-scale"



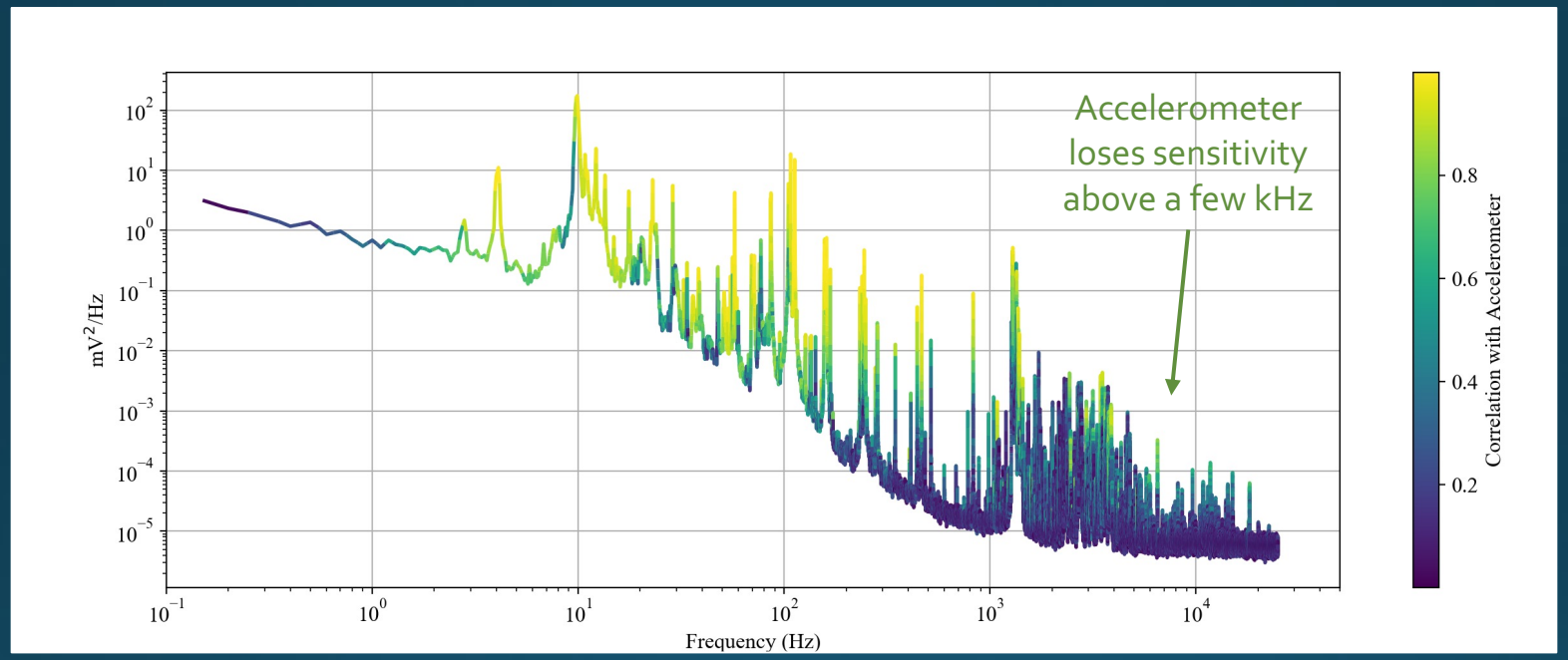
Vibration Isolation

- 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)



C. Salemi

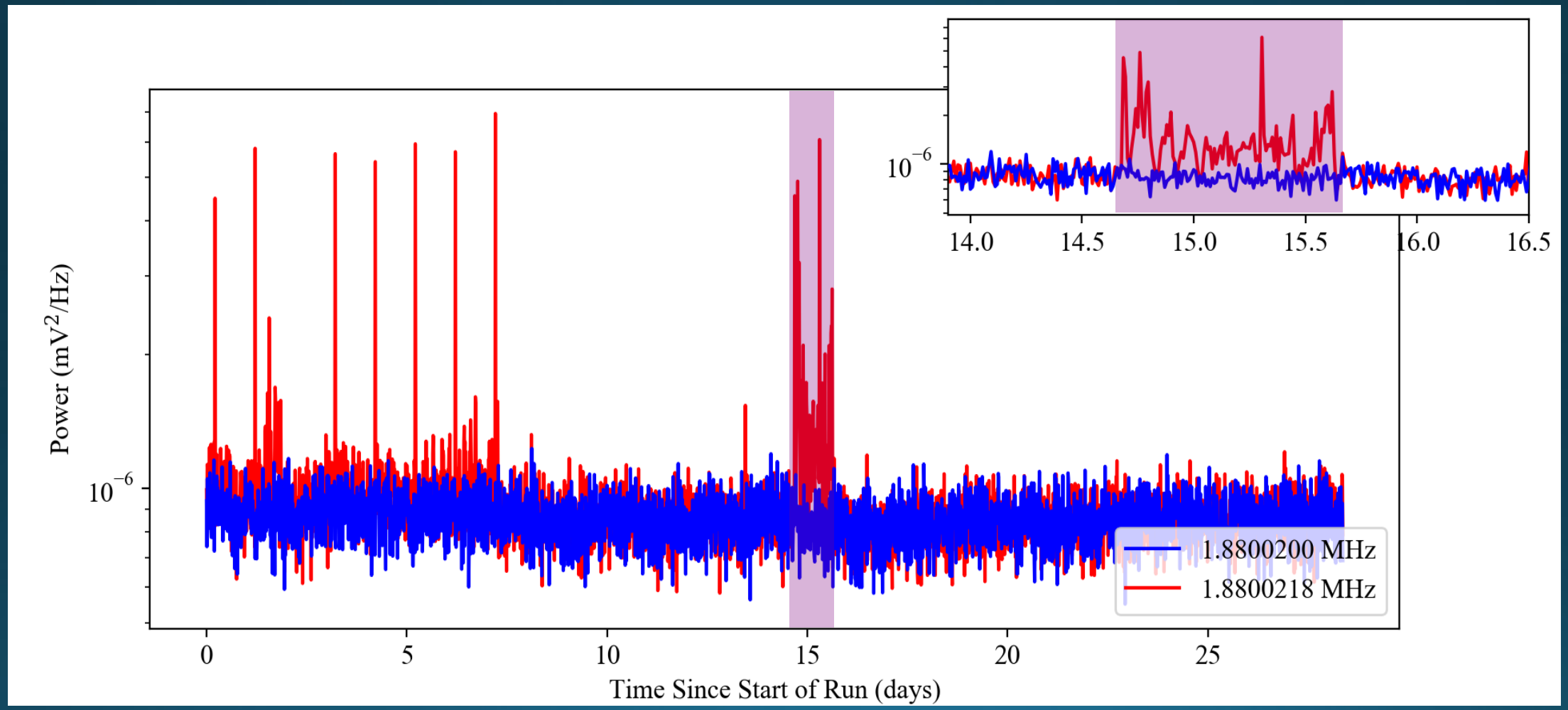
Vibrational Noise



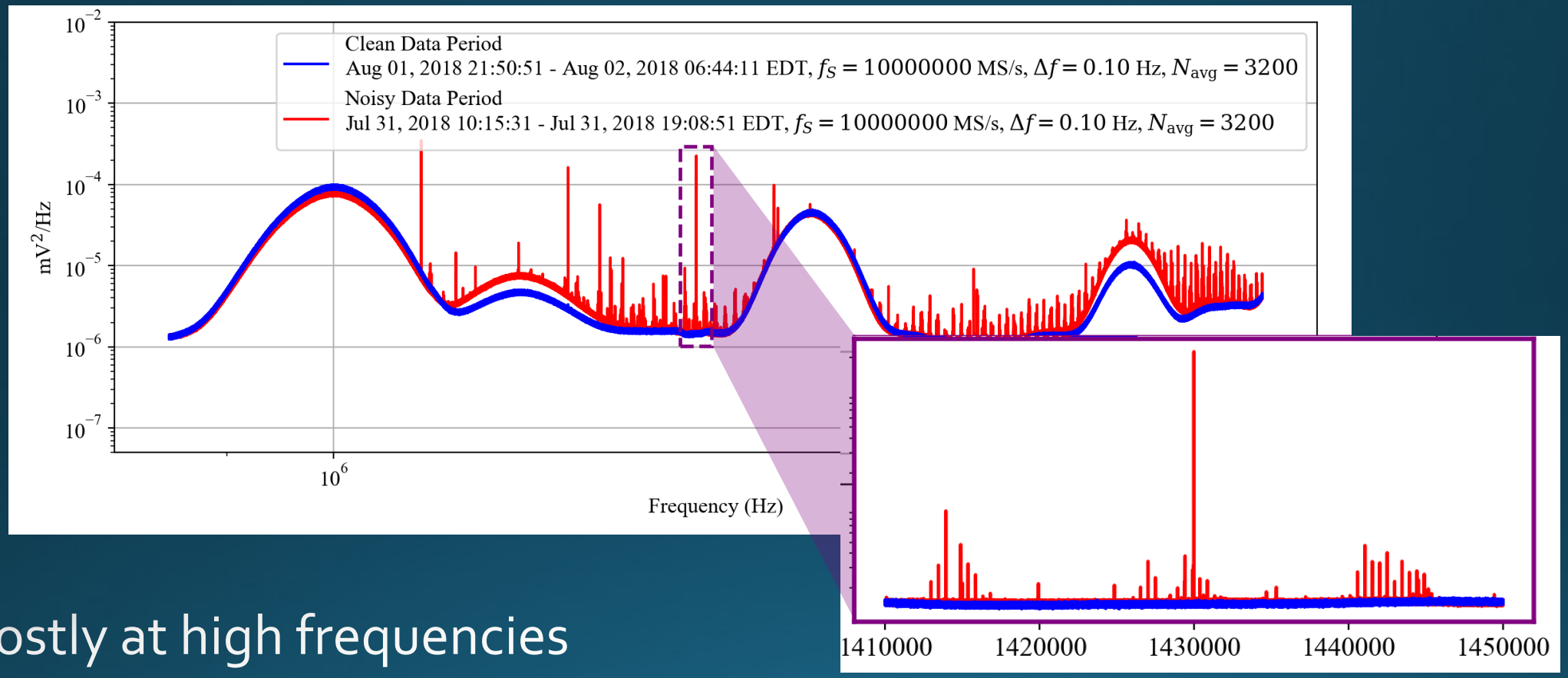
- Huge amount of noise below ~10 kHz, strongly correlated with vibration on the 300K plate
- Had to use a 10kHz high pass filter to get the data to fit in the digitizer window
- Hard limit on the low end of the search window

C. Salemi

Transient Noise

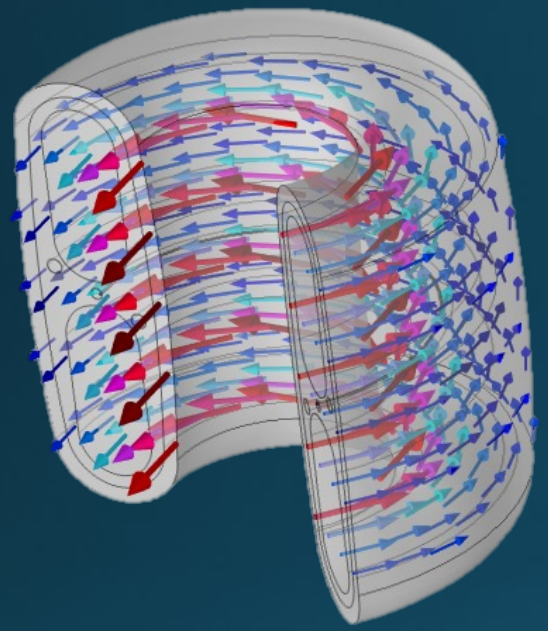


Transient Noise

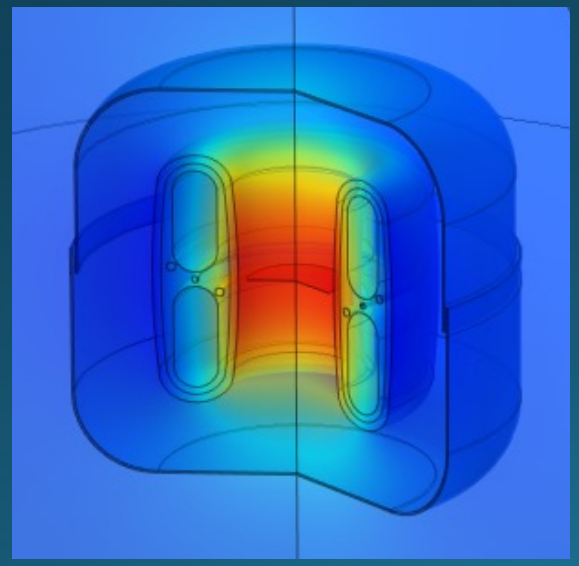


- Mostly at high frequencies
- Investigating building power, grounding schemes, shielding, etc…
- In the present analysis, we discarded ~30% of the data

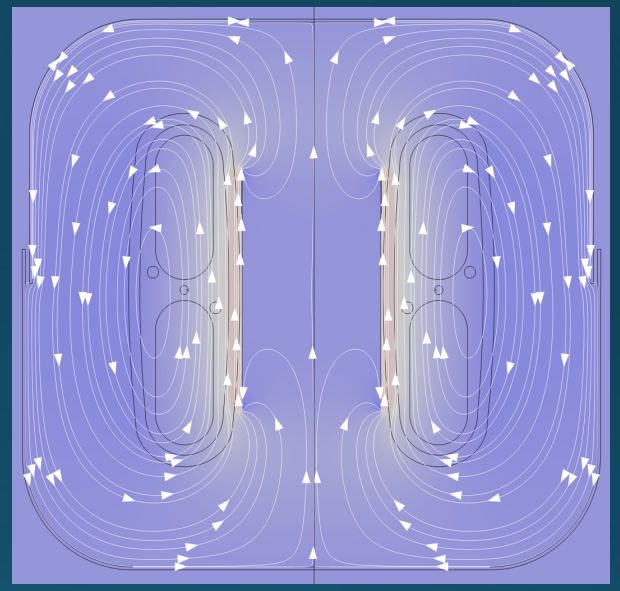
COMSOL simulations



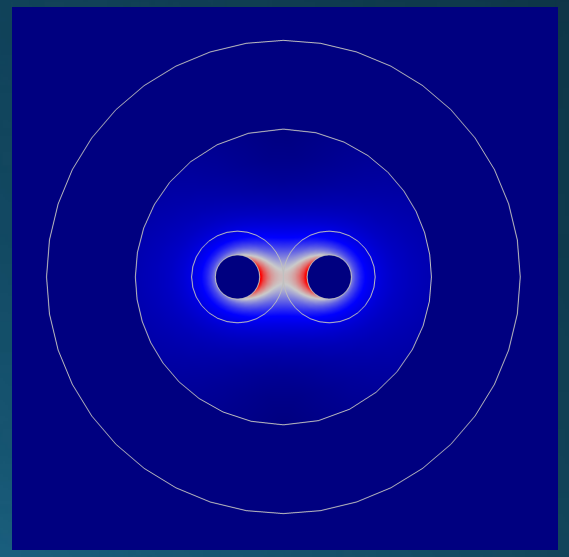
Axion effective current distributed in magnetic field



Axion magnetic field oscillates in toroid bore

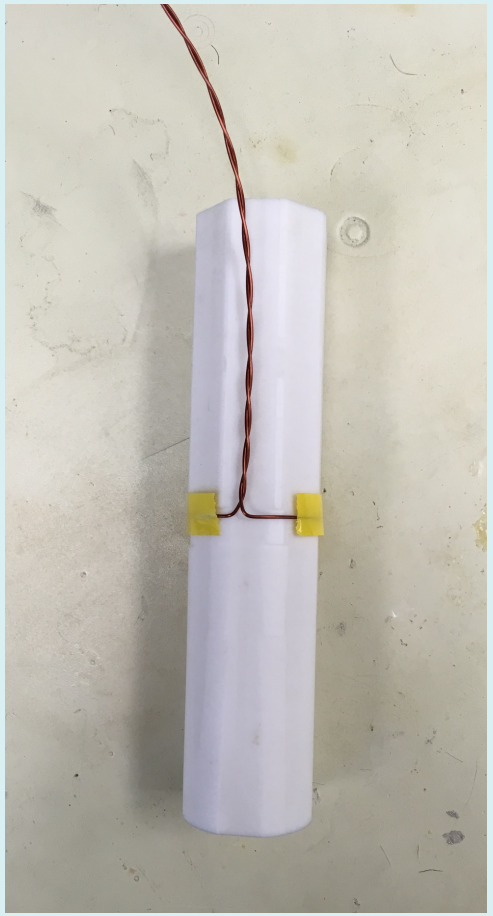


Current induced in pickup

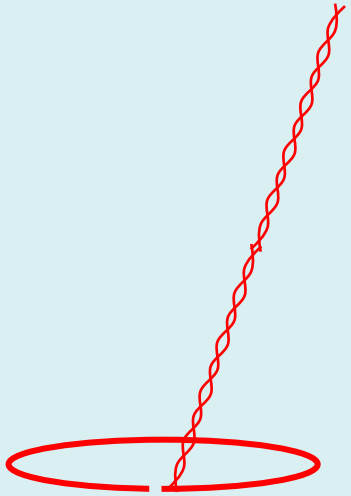


Current propagates through wiring

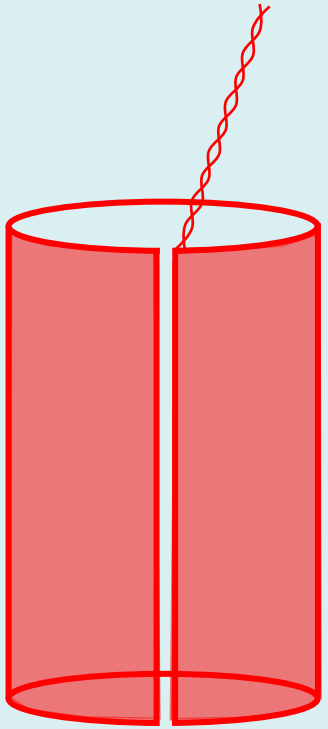
Replacing the pickup circuit



Run 1



Runs 2&3



Improved sensitivity