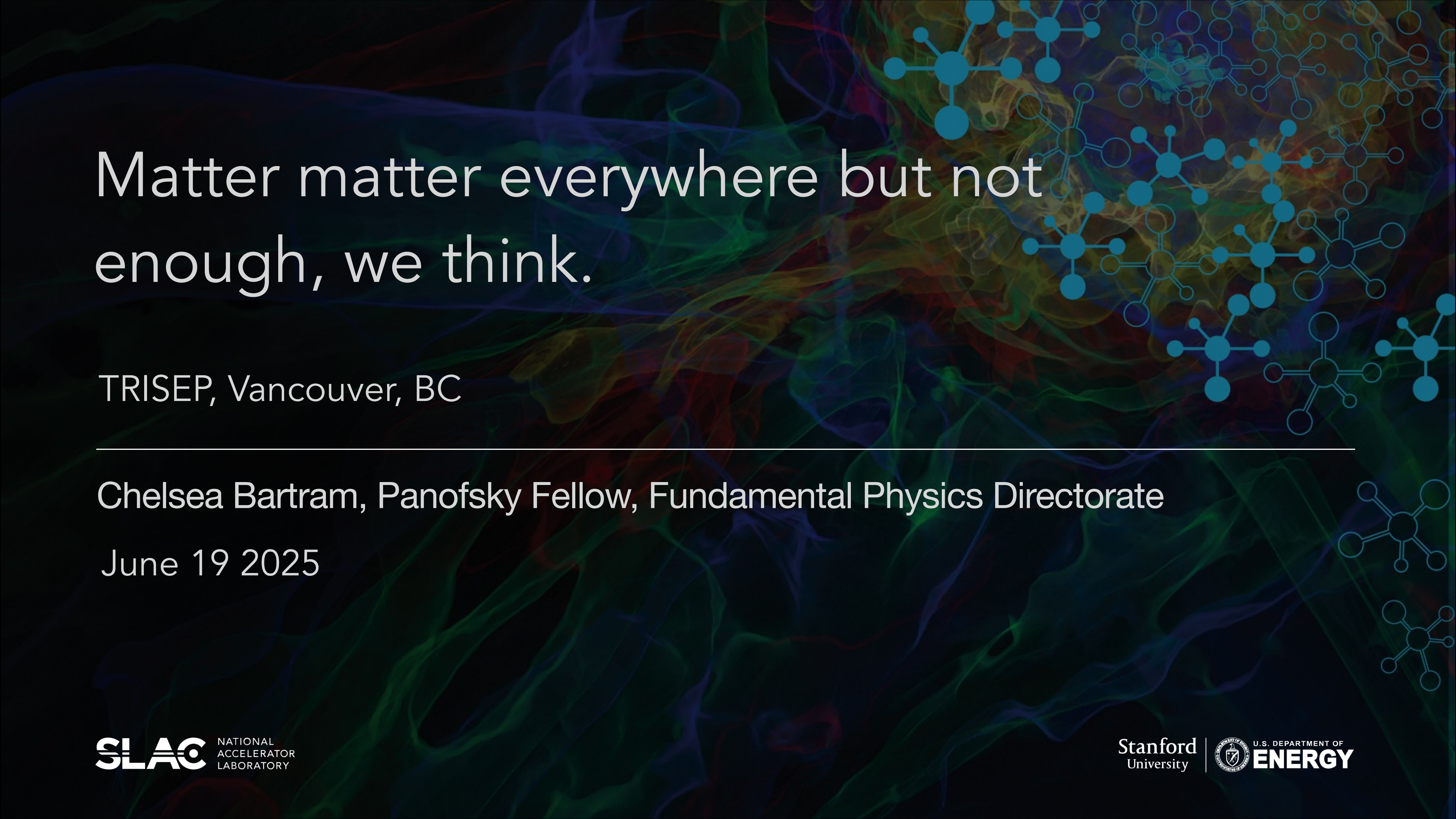




# Matter matter everywhere but not enough, we think.

TRISEP, Vancouver, BC

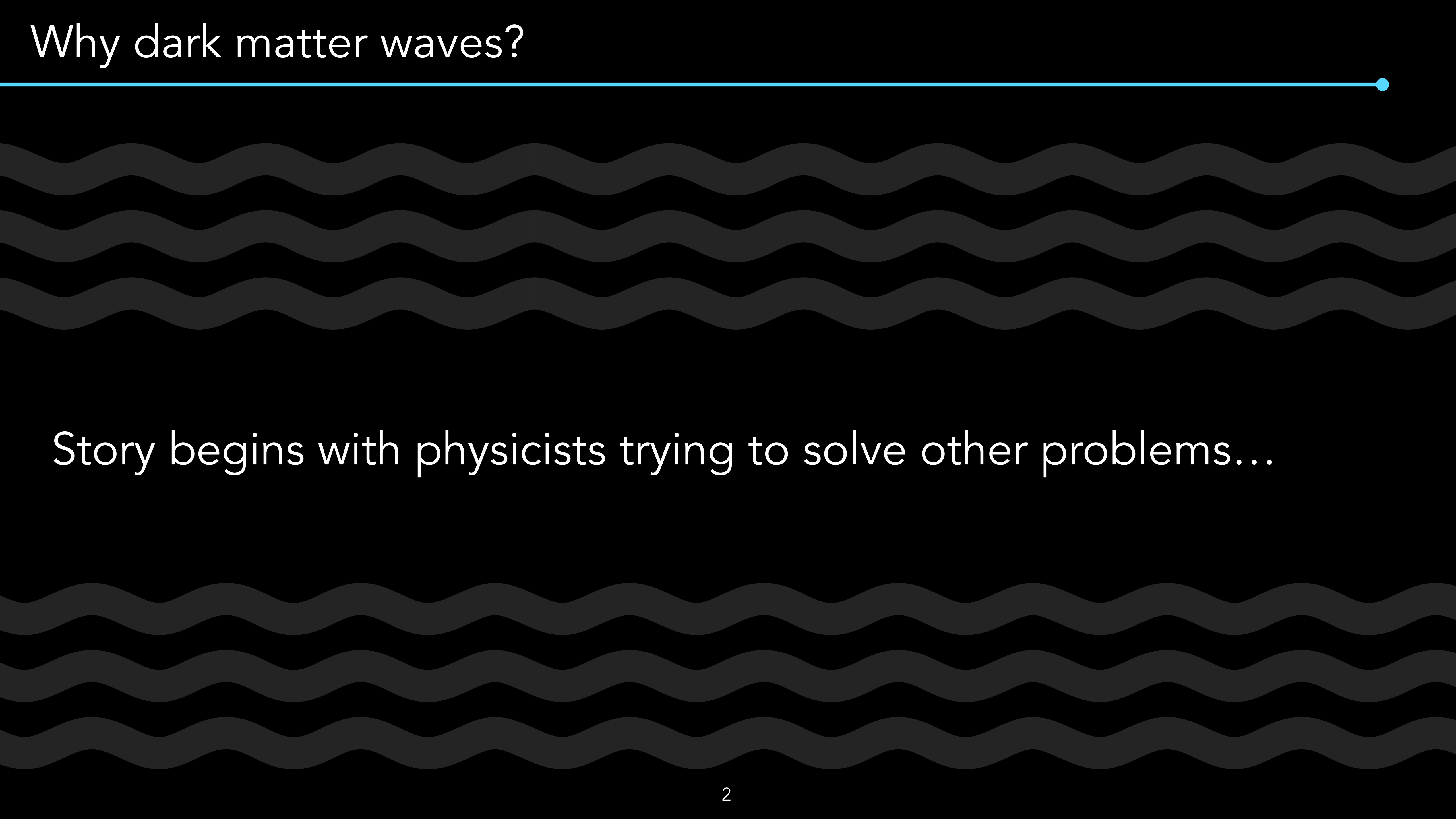
---

Chelsea Bartram, Panofsky Fellow, Fundamental Physics Directorate

June 19 2025



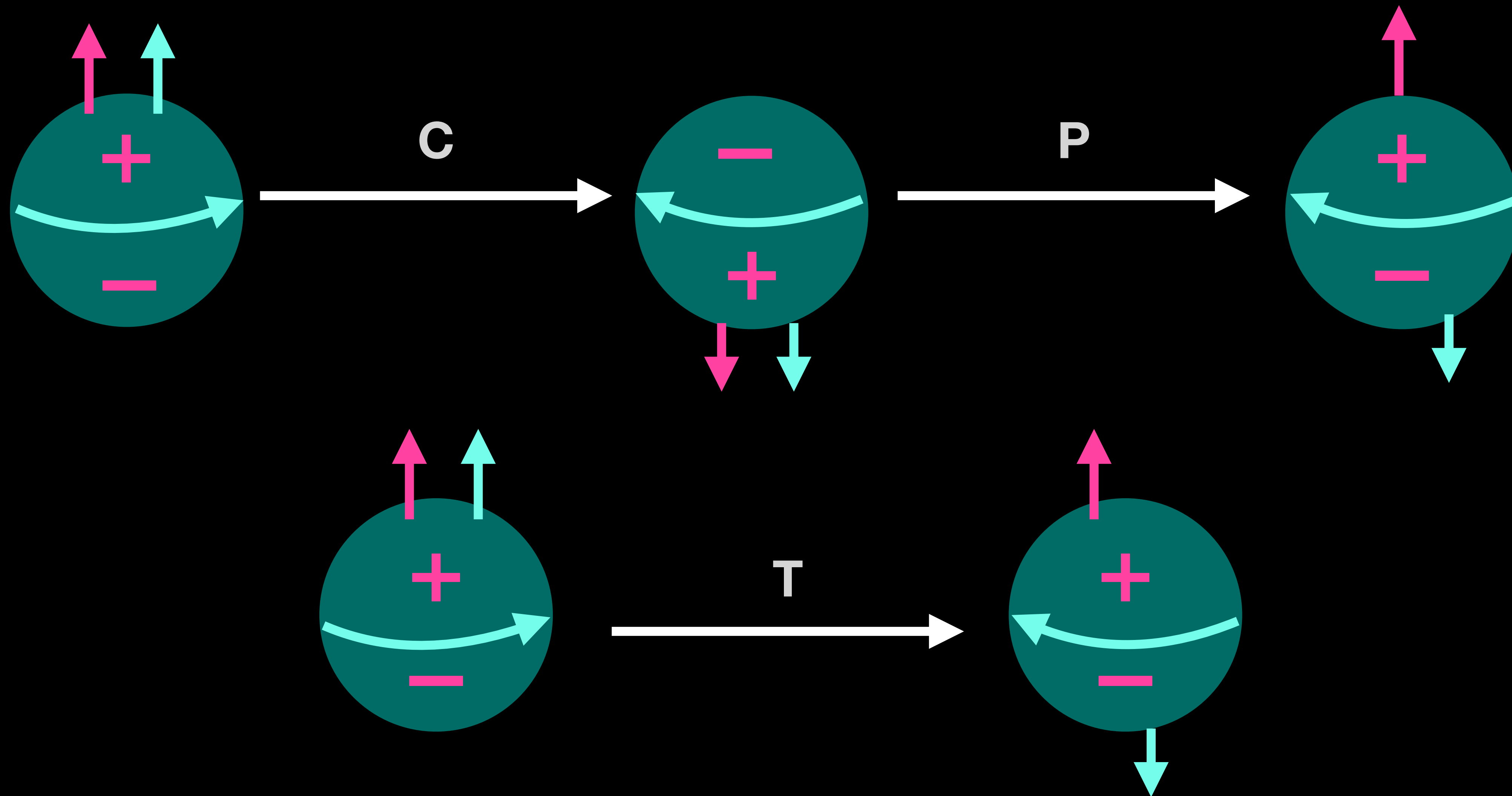
# Why dark matter waves?

The slide features a black background with several horizontal, wavy, light gray lines that resemble water or sound waves. A solid blue horizontal line spans the width of the slide, ending in a small blue dot on the right side.

Story begins with physicists trying to solve other problems...



# Fundamental symmetries in nuclear physics

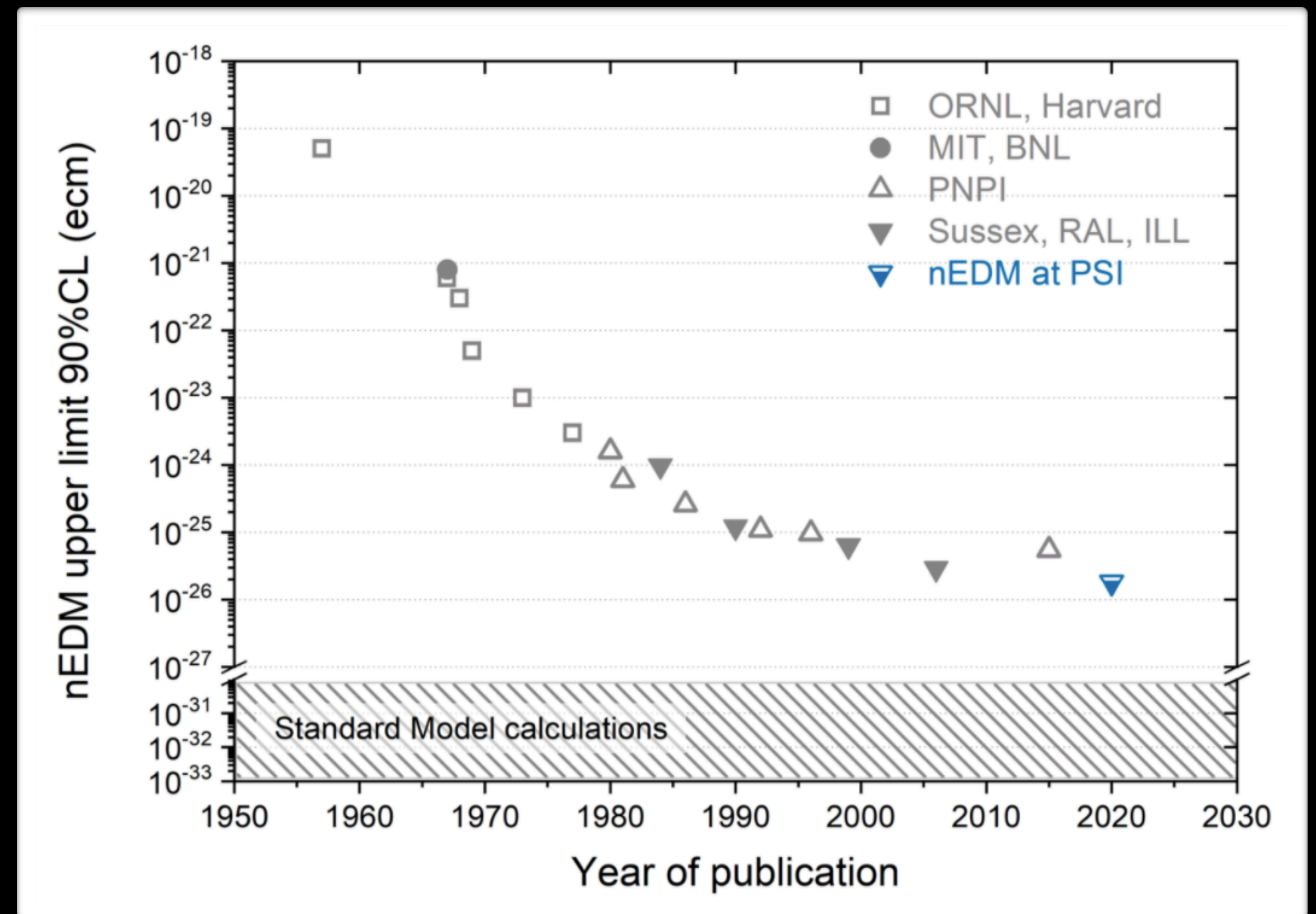




# Strong CP Problem

Quantum Chromodynamics (QCD) describes the binding of atomic nuclei

- Discrete fundamental symmetries known as Charge (C), Parity (P), and Time (T) and their combination (CP, CPT) describe symmetries in particle physics interactions.
  - P and CP symmetries could be violated with term in QCD Lagrangian
  - Search for an neutron electric dipole moment also search for violations of CP.
- 



# Strong CP Problem

---

No neutron electric dipole moment (n-EDM) has been observed so far!

Most recent search for the neutron electric dipole moment

C. Abel et al.

Phys. Rev. Lett. 124, 081803 — Published 28 February 2020

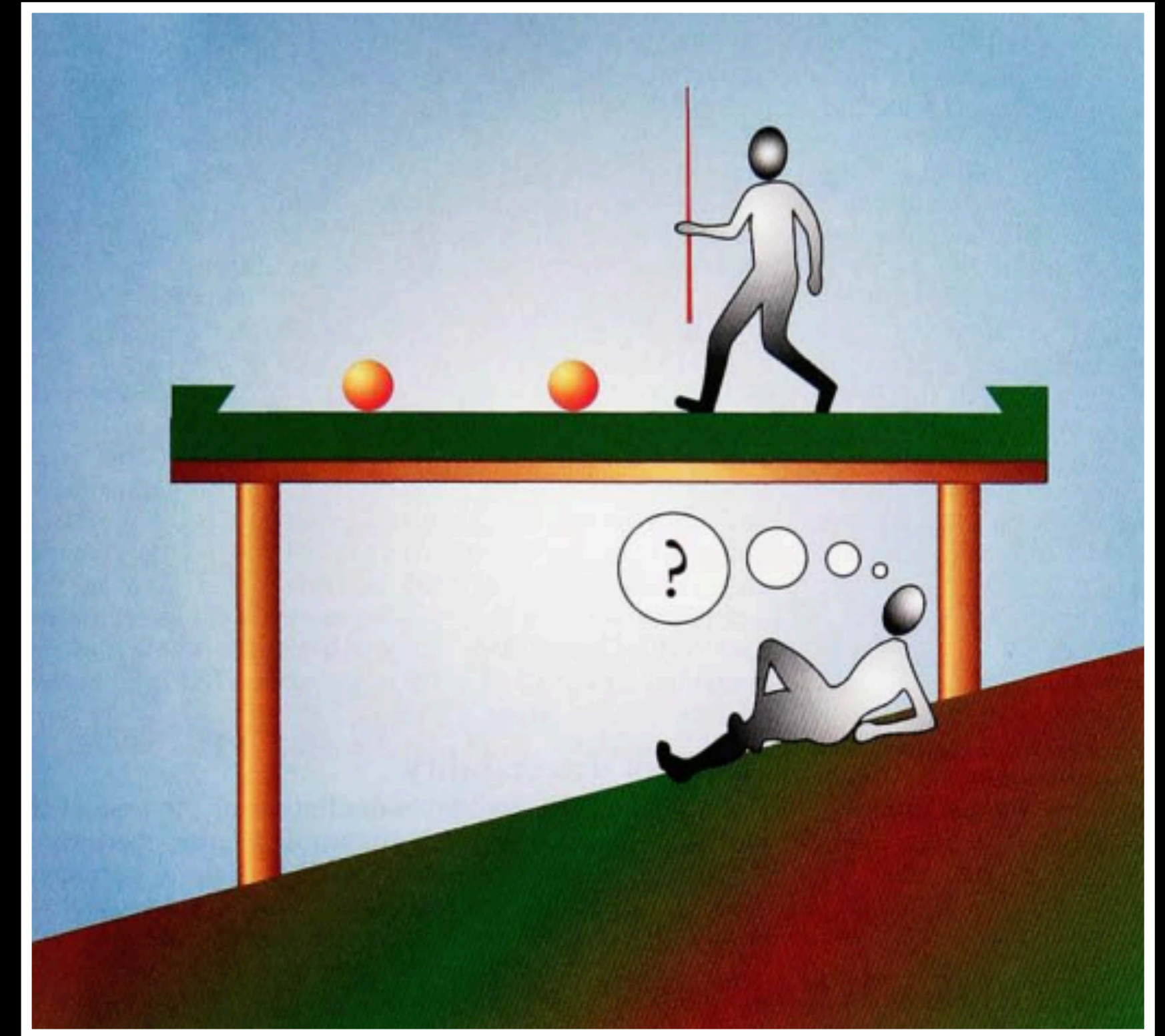
$$d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26} \text{e} \cdot \text{cm} \longrightarrow \theta_{\text{QCD}} < 10^{-10}$$




# The Pool Table Analogy

A story by Pierre Sikivie, 1996

- One imagines a pool table that appears *perfectly* horizontal.
- The occupants of the room realize one day that the room itself is slanted.
- Why is the pool table perfectly horizontal? This seems like an odd coincidence.



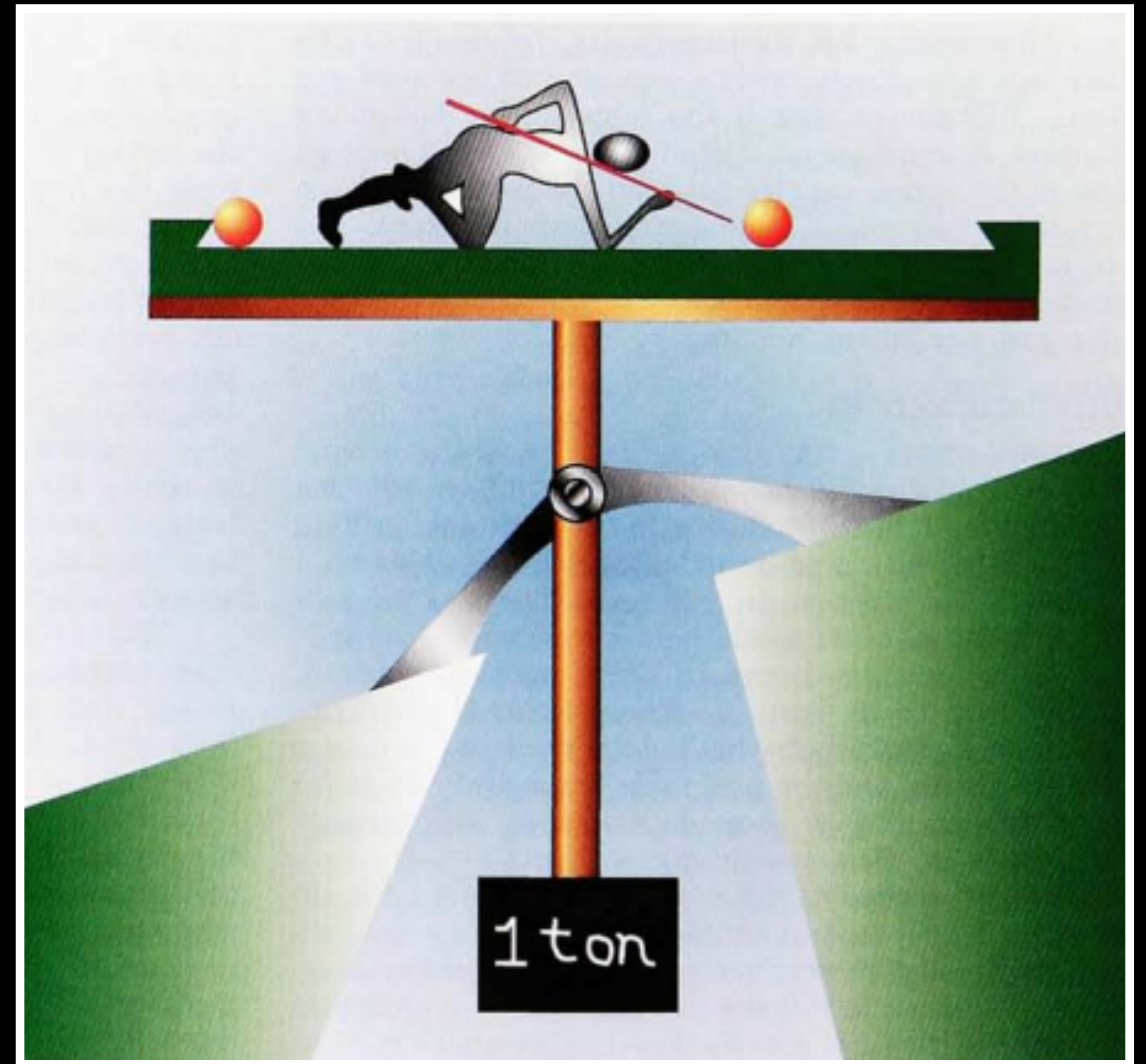
Sikivie, Pierre. "The Pool-Table Analogy with Axion Physics." *Physics Today* 49.12 (1996): 22-27.

The incline of the table is described by a made-up symmetry analogous to CP symmetry. The symmetry is perfectly preserved.

# Solution to Strong CP problem?

Perhaps there is a mechanism that uses gravity to level the pool table.

- Angle of pool table tilt =  $\theta_{\text{QCD}}$
- Physics of pool table = physics of QCD
- Gravity = Nonperturbative effects that make QCD depend on  $\theta_{\text{QCD}}$

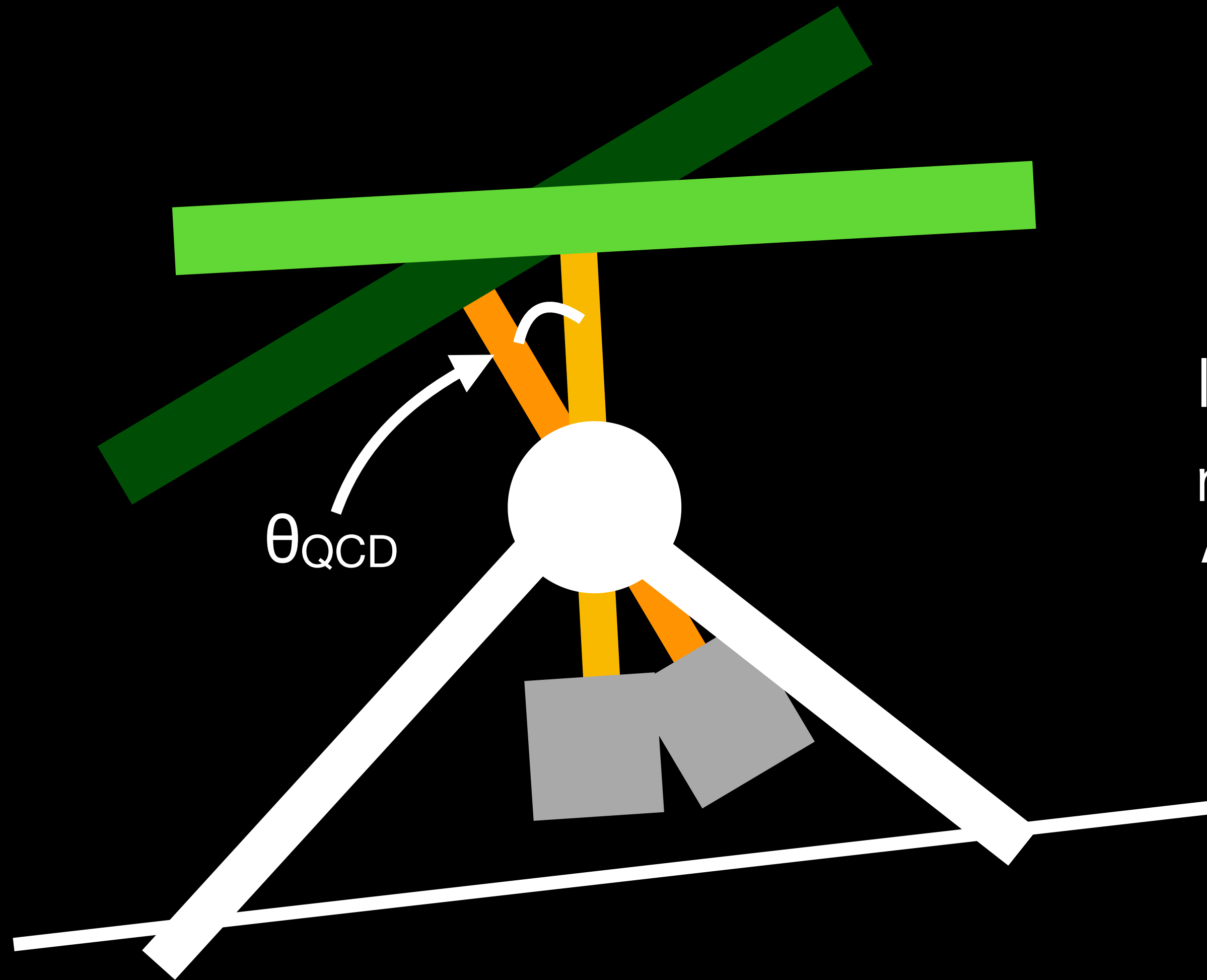


Sikivie, Pierre. "The Pool-Table Analogy with Axion Physics." *Physics Today* 49.12 (1996): 22-27.



# Angle $\theta_{\text{QCD}}$

$\theta_{\text{QCD}}$  might be a dynamical variable (moving with time)

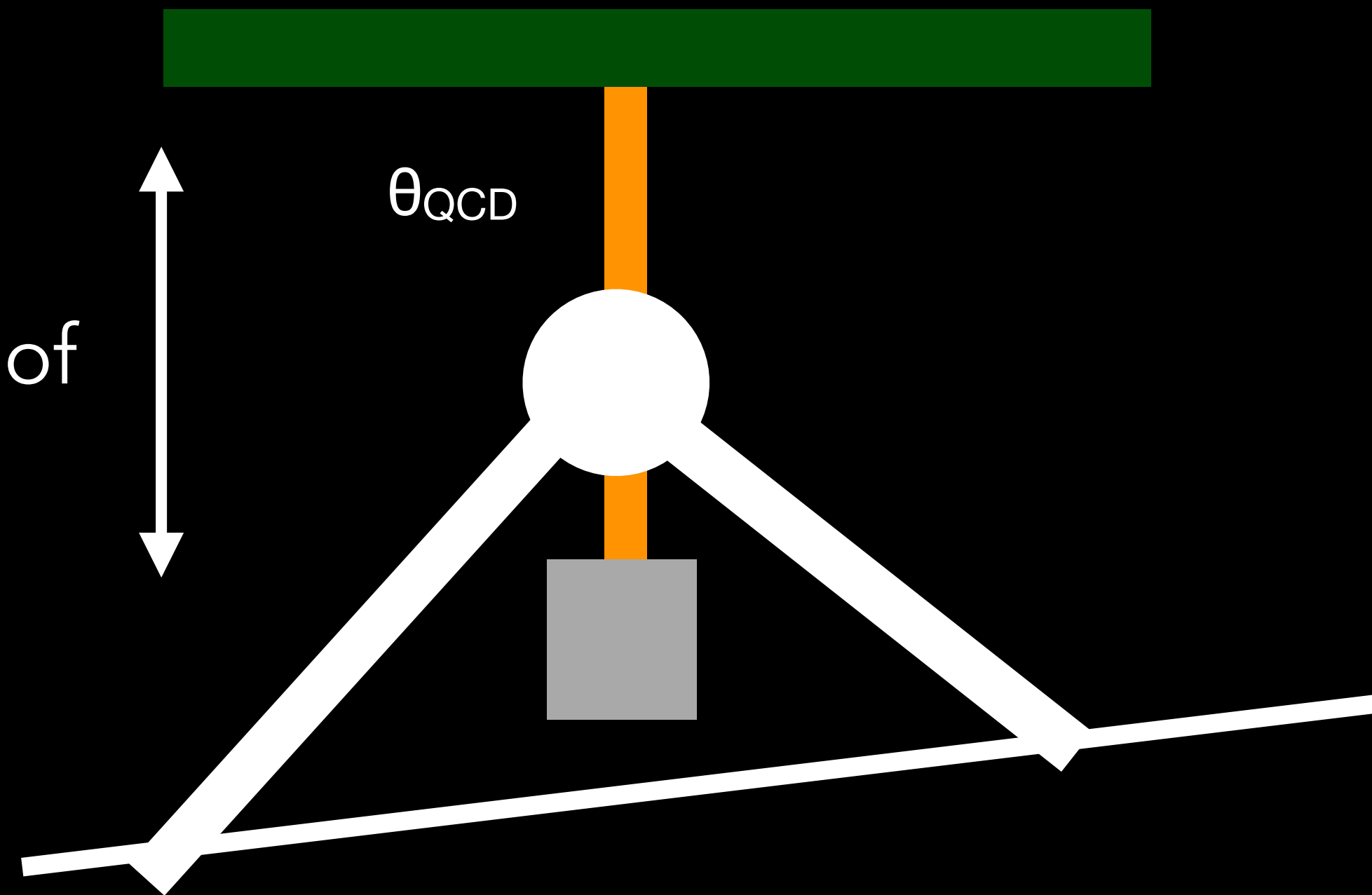


If  $\theta_{\text{QCD}}$  dynamical,  
mechanism is akin to  
"Peccei-Quinn Mechanism"

# How to test the hypothesis?

“Relic oscillation” that would depend on when gravity “turned on”

Length of lever arm  
determines strength of  
oscillation

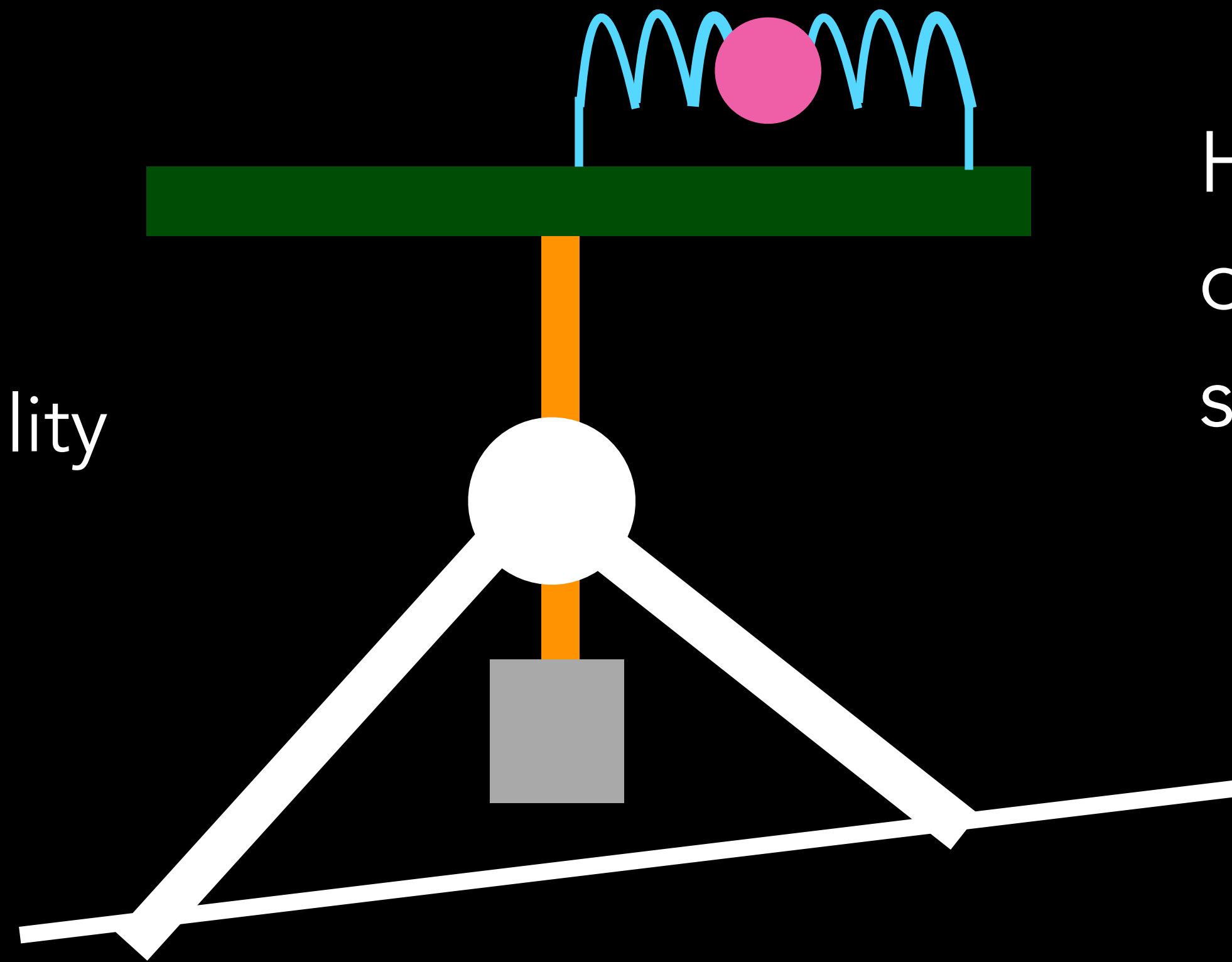


Maybe it's really long and  
the oscillation is hard to  
measure?  
Equivalently maybe the  
coupling is extremely small



# The pool table analogy

Associated quantum of oscillation = a particle call the axion!



High quality oscillator  
on the table could  
sense this!

More on high quality  
oscillators later...

# Axions as the dark matter

---

...“the most exciting phrase to hear in science...is not *Eureka* but *That’s funny...*”

-Isaac Asimov

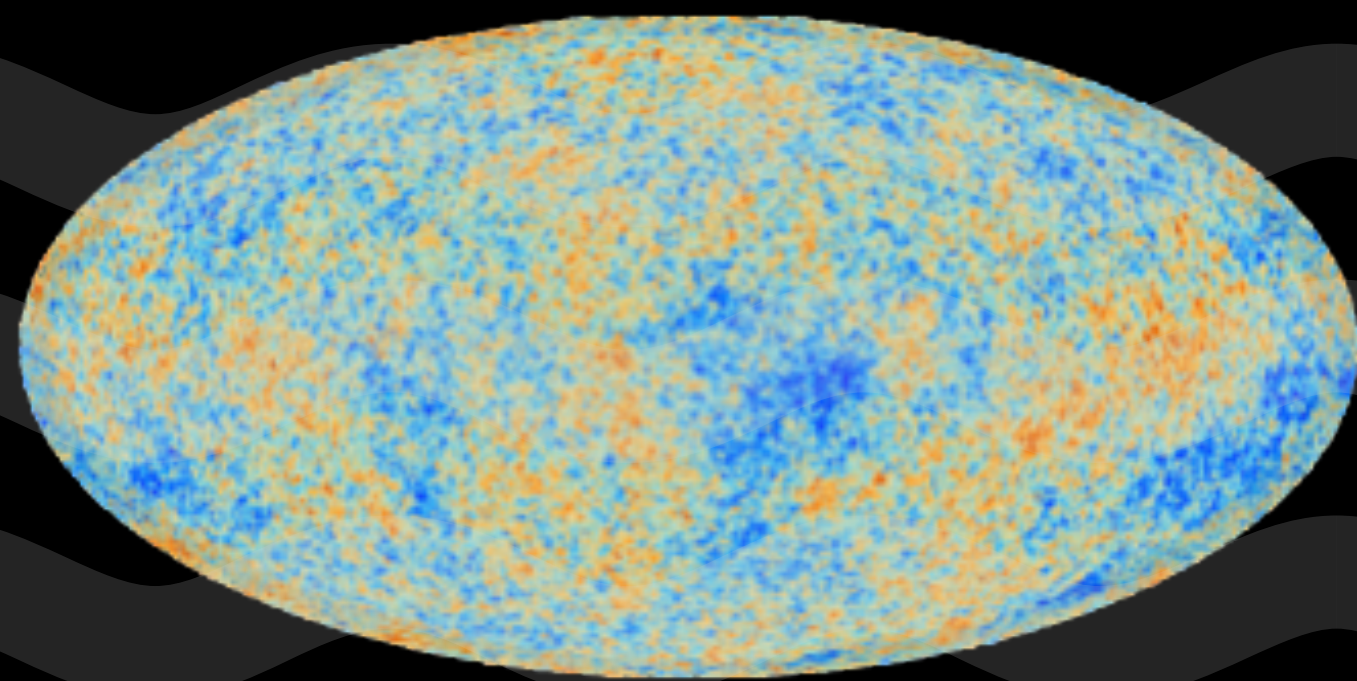


# Dark Matter

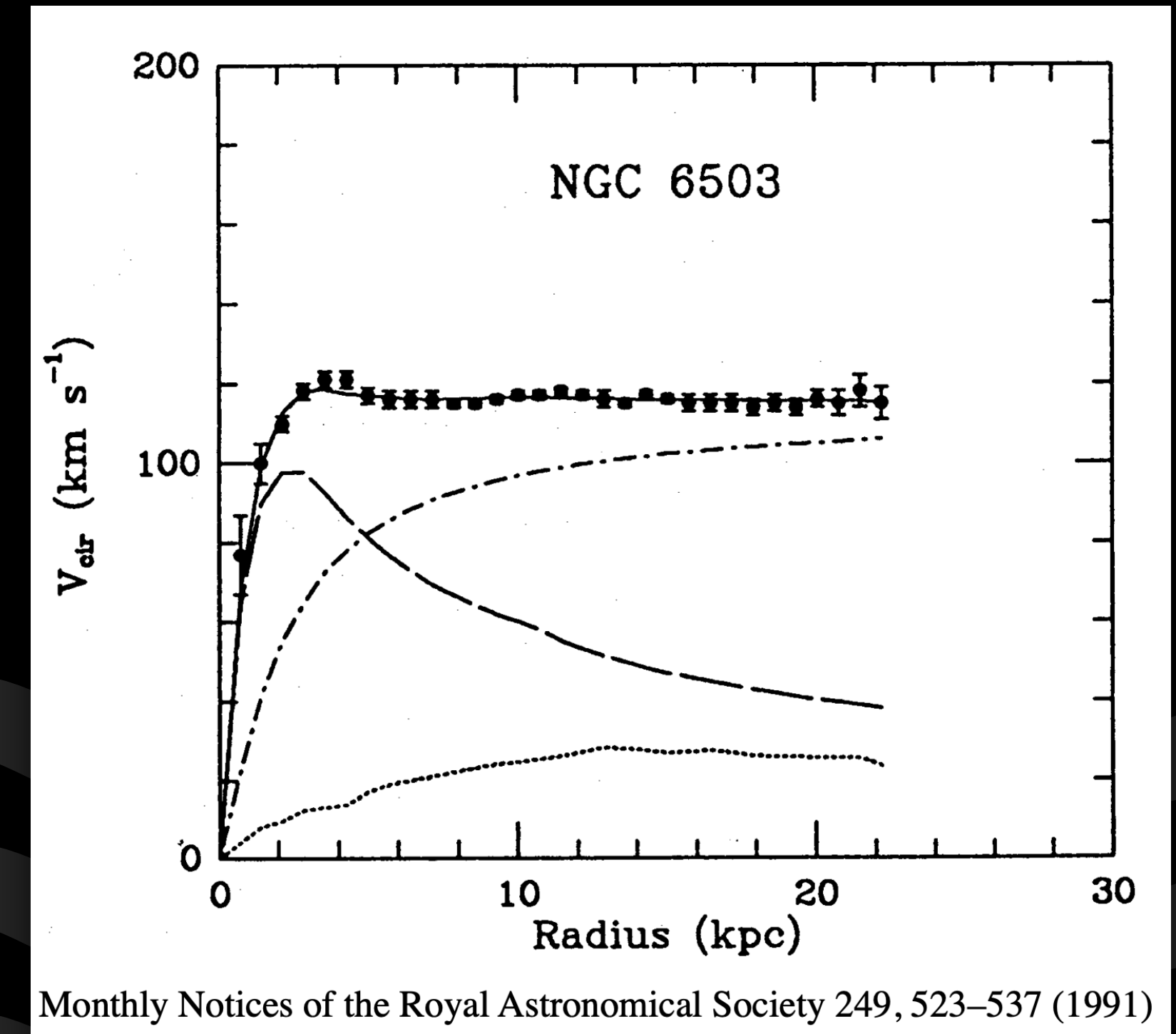
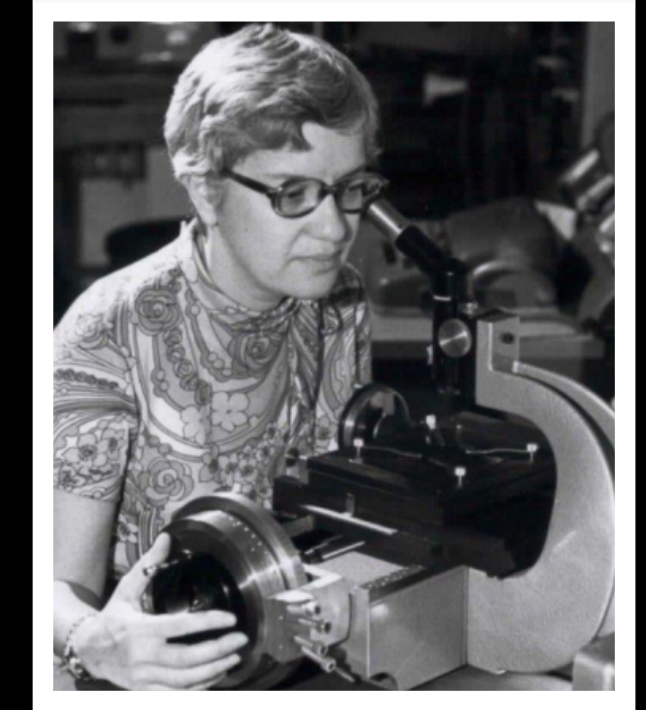
85% of the matter content of the universe. Likely to be non-relativistic, collisionless, dissipation less and non-baryonic.

## Evidence coming from:

- Anisotropies in the Cosmic Microwave Background
- Rotation curves of galaxies
- Behavior of galaxy cluster collisions
- Primordial nucleosynthesis
- Gravitational lensing
- Baryon Acoustic Oscillations



ESA and the  
Planck  
Collaboration



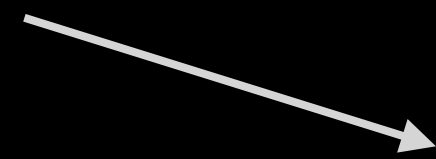
Monthly Notices of the Royal Astronomical Society 249, 523–537 (1991)

# Axions: why are they wave-like?

## Wave-particle duality

Proton:  $\lambda \sim 10^{-12}$  m

WIMP dark matter:  $\lambda \sim 10^{-13}$  m  Recoil experiments

Axion Dark Matter ( $m \sim 10^{-6}$  eV):  $\lambda \sim 100$  m  Something completely different...

Axion dark matter is associated with a huge wavelength!  
No longer behaves like a particle.

# So the axion could solve multiple problems in physics!

**Strong CP problem**

**Axion:  
wave-like dark matter  
candidate**

**5% of the matter  
unknown.**



# Axions modify Maxwell's Equations

$$\nabla \cdot \vec{E} = \rho - g_{a\gamma\gamma} \vec{B} \cdot \nabla a$$

Gradient of axion is very small

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Modification to Ampere's Law

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

...and has intriguing implications

---

Maxwell's equations

$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma\gamma} \mathbf{B}_0 \frac{\partial a}{\partial t}$$

Effective current oscillating at the frequency of the axion

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

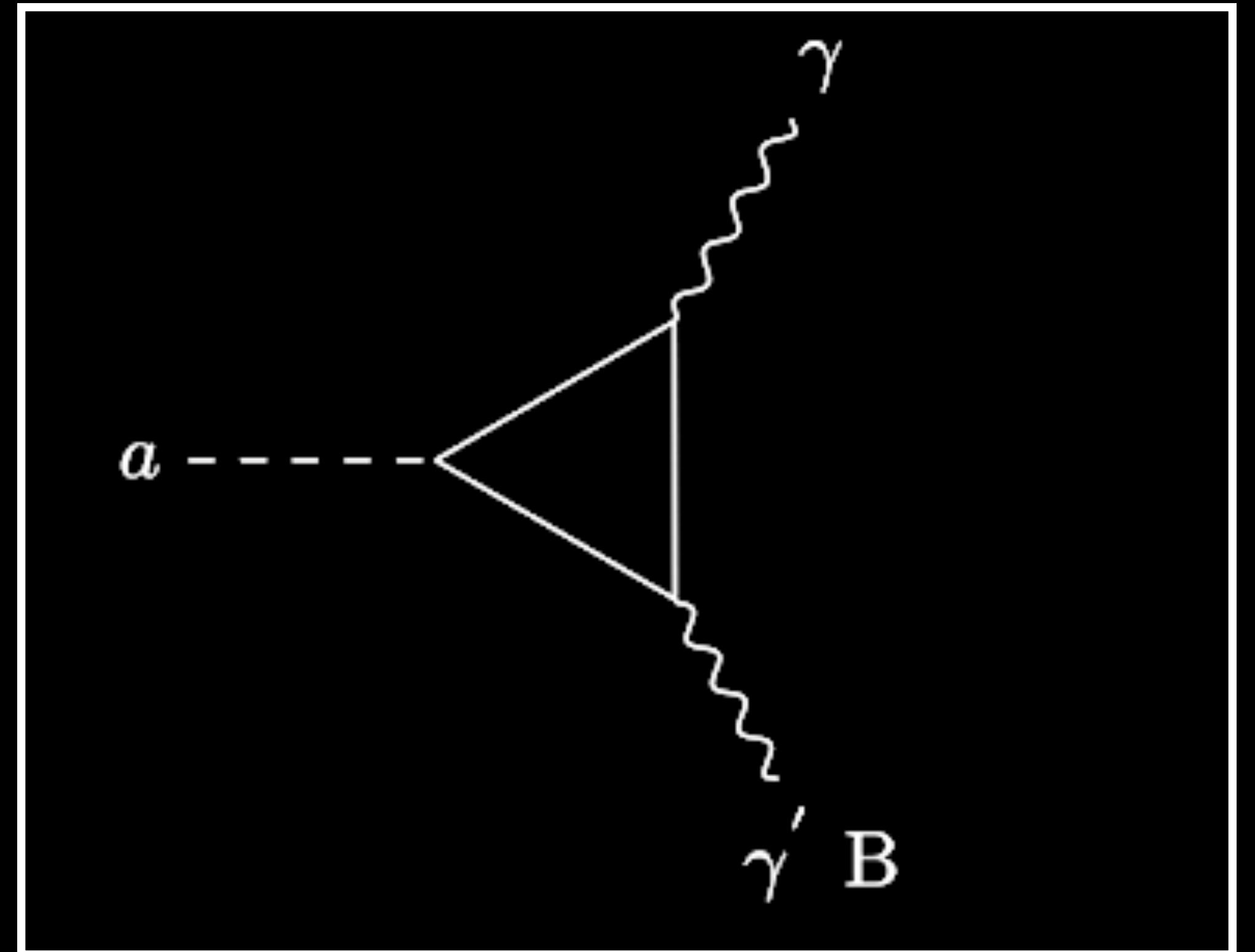
# Key Detection Mechanism

Axion turns into a photon (light particle) in a magnetic field!

Two key parameters:

$g_{a\gamma\gamma}$  Likelihood or 'strength' of interaction  
Units:  $1/\text{GeV}$

$m_a$  Mass of the axion  
Units: eV

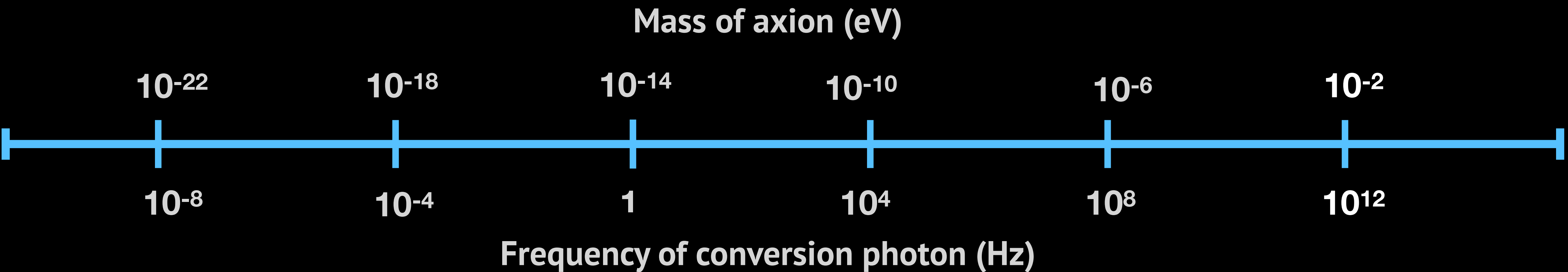




# Axion Mass Range

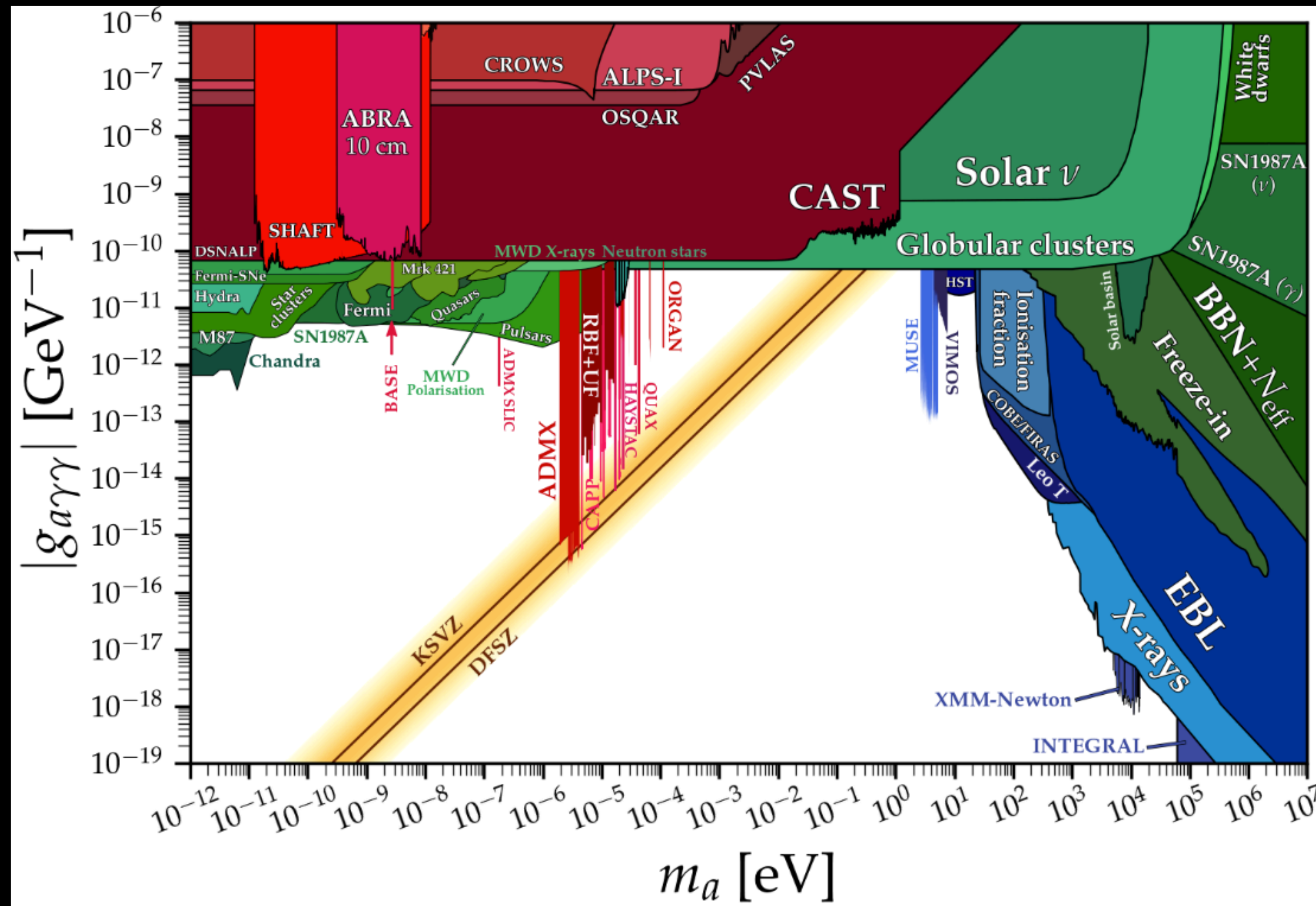
Lower bound set by size of  
dark matter halo size of dwarf  
galaxies

Upper bound set by  
SN1987A and white dwarf  
cooling time



What frequency (mass) exactly? We don't know.

# Red, green and blue show places we looked!



Plot courtesy of Ciaran O'Hare





# QCD axion: Product of the Peccei-Quinn Mechanism

Two classes of models:

•KSVZ:

•DFSZ:



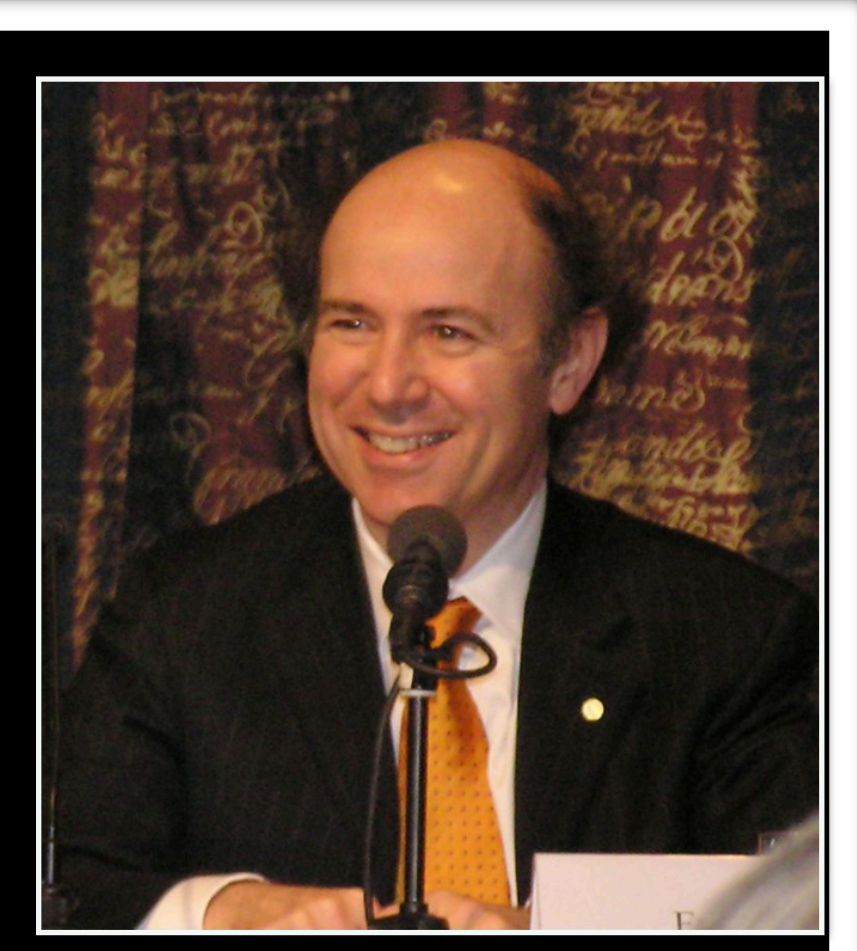
Helen Quinn



Roberto Peccei



Steven Weinberg



Frank Wilczek



# QCD axion: Solves longstanding nuclear physics problem

## Two classes of models:

- KSVZ:

- DFSZ:

Most difficult to detect but also most compelling because it can be included in Grand Unified Theories (GUT)



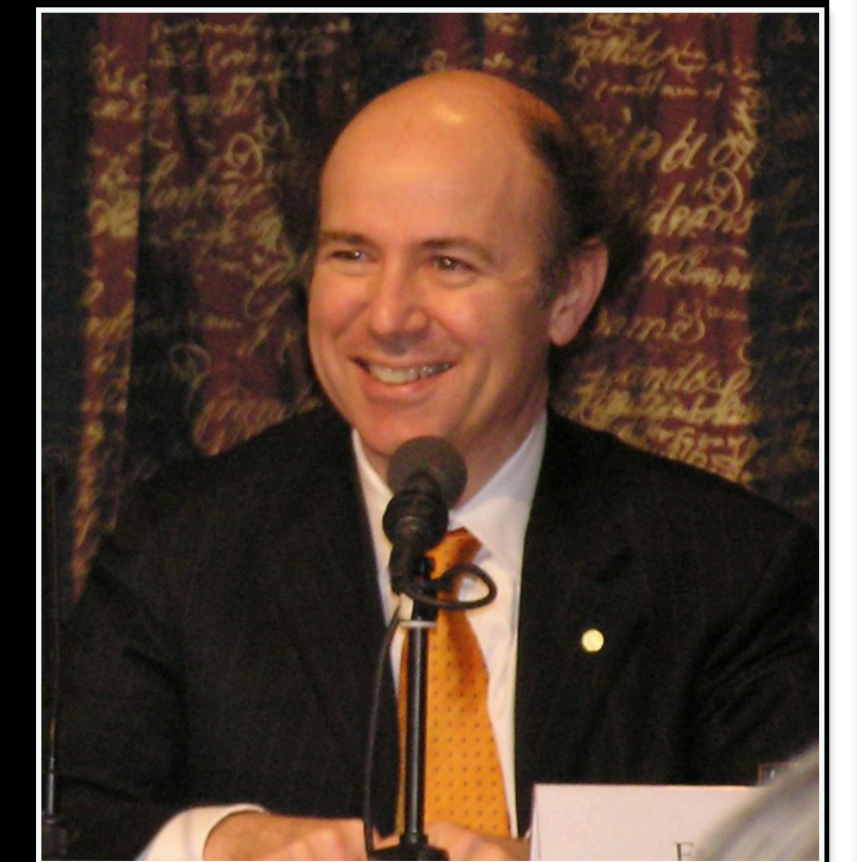
Helen Quinn



Roberto Peccei

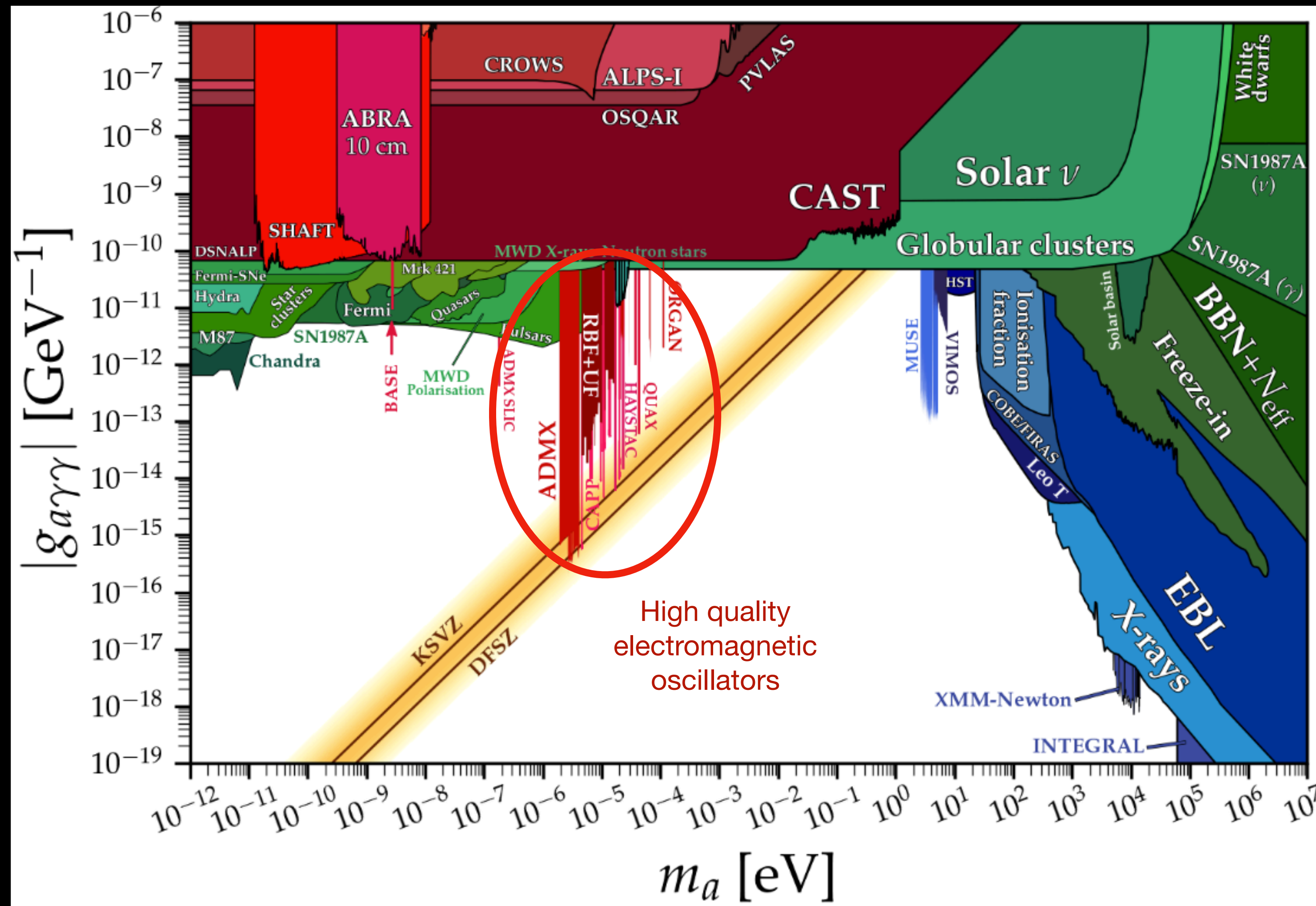


Steven Weinberg



Frank Wilczek

# QCD axion band is exceedingly difficult to reach

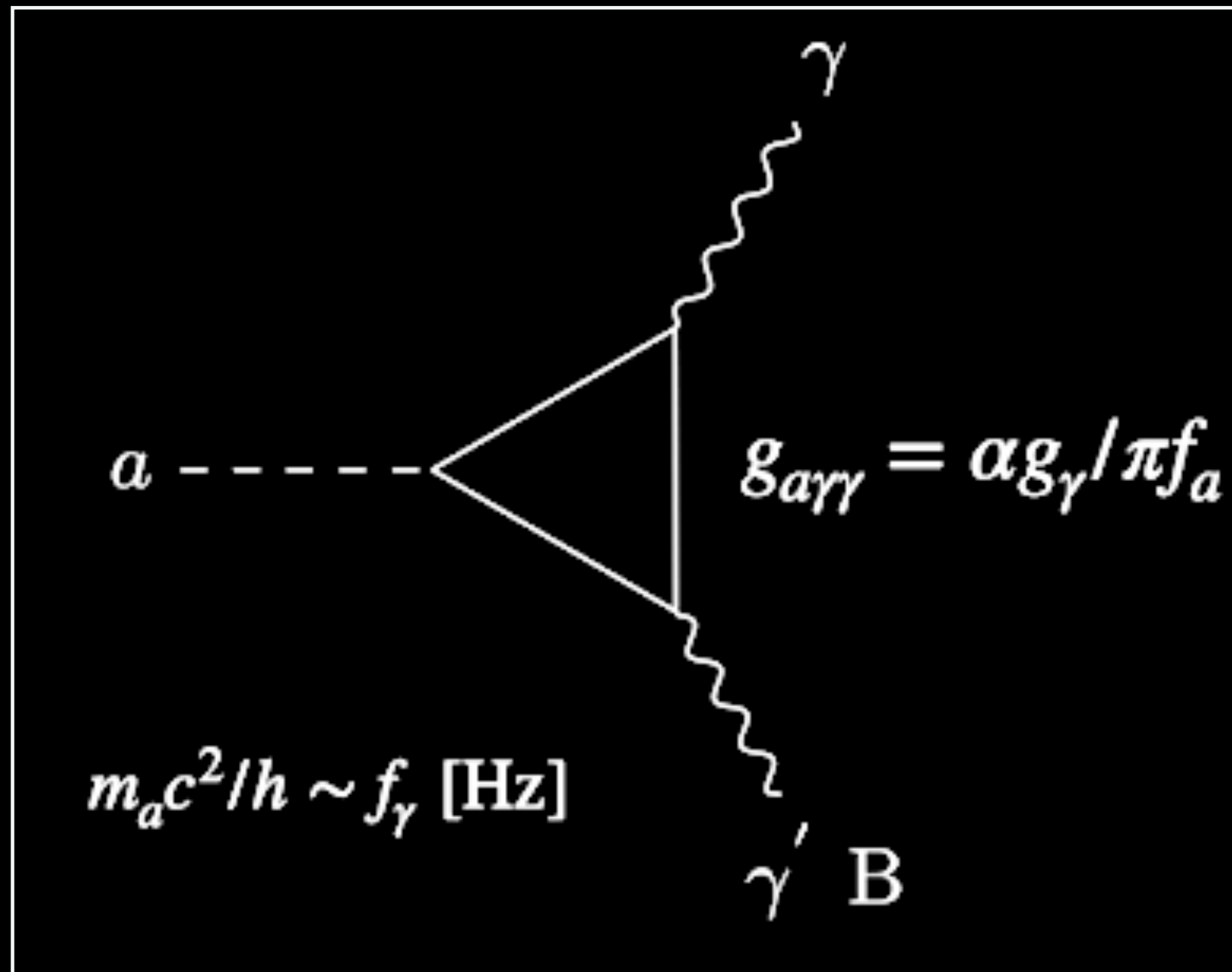


Plot courtesy of Ciaran O'Hare

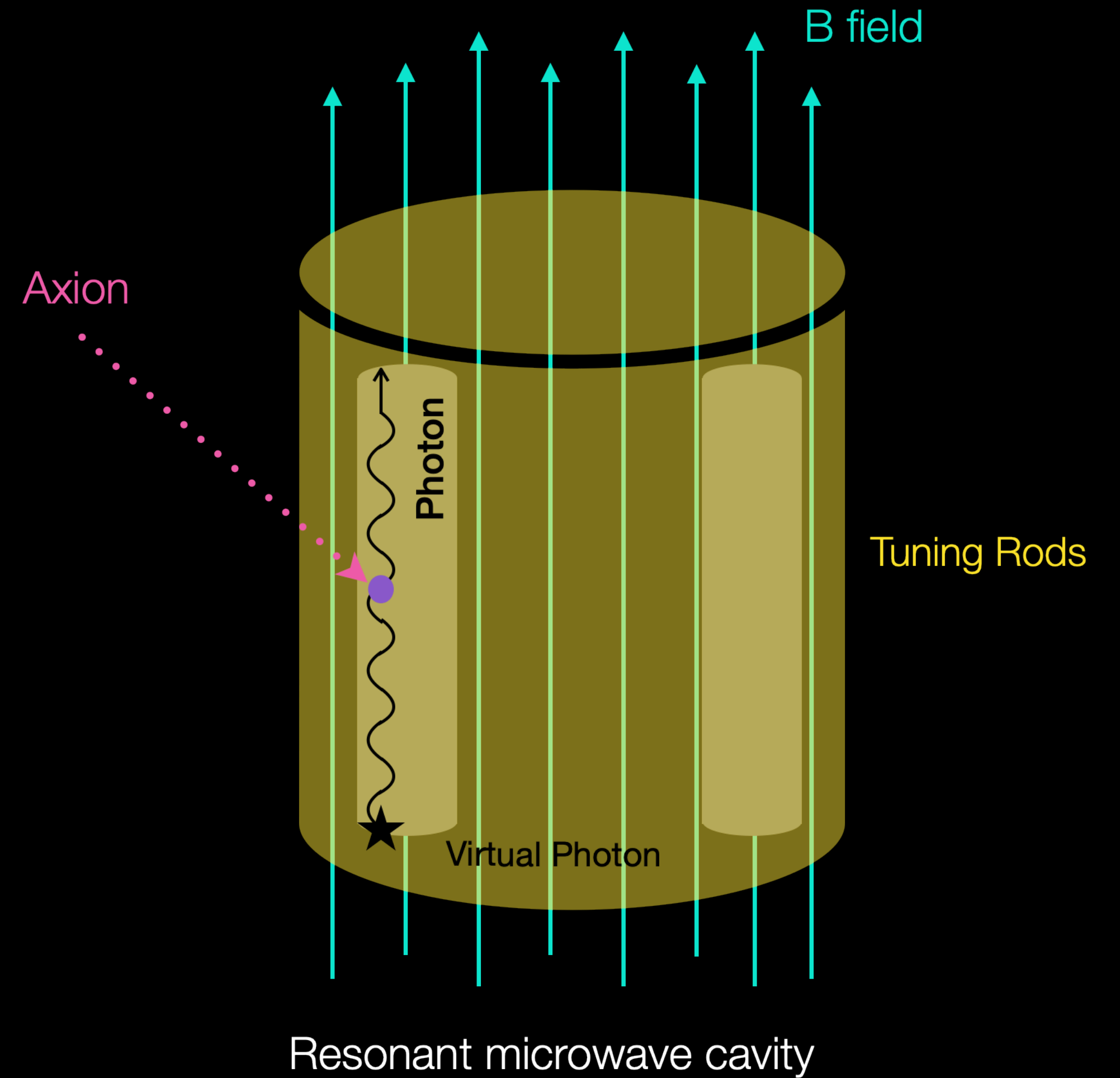


# Detection: Axion Haloscope

Photon coupling: cleanest channel for discovery



Inverse Primakoff Effect



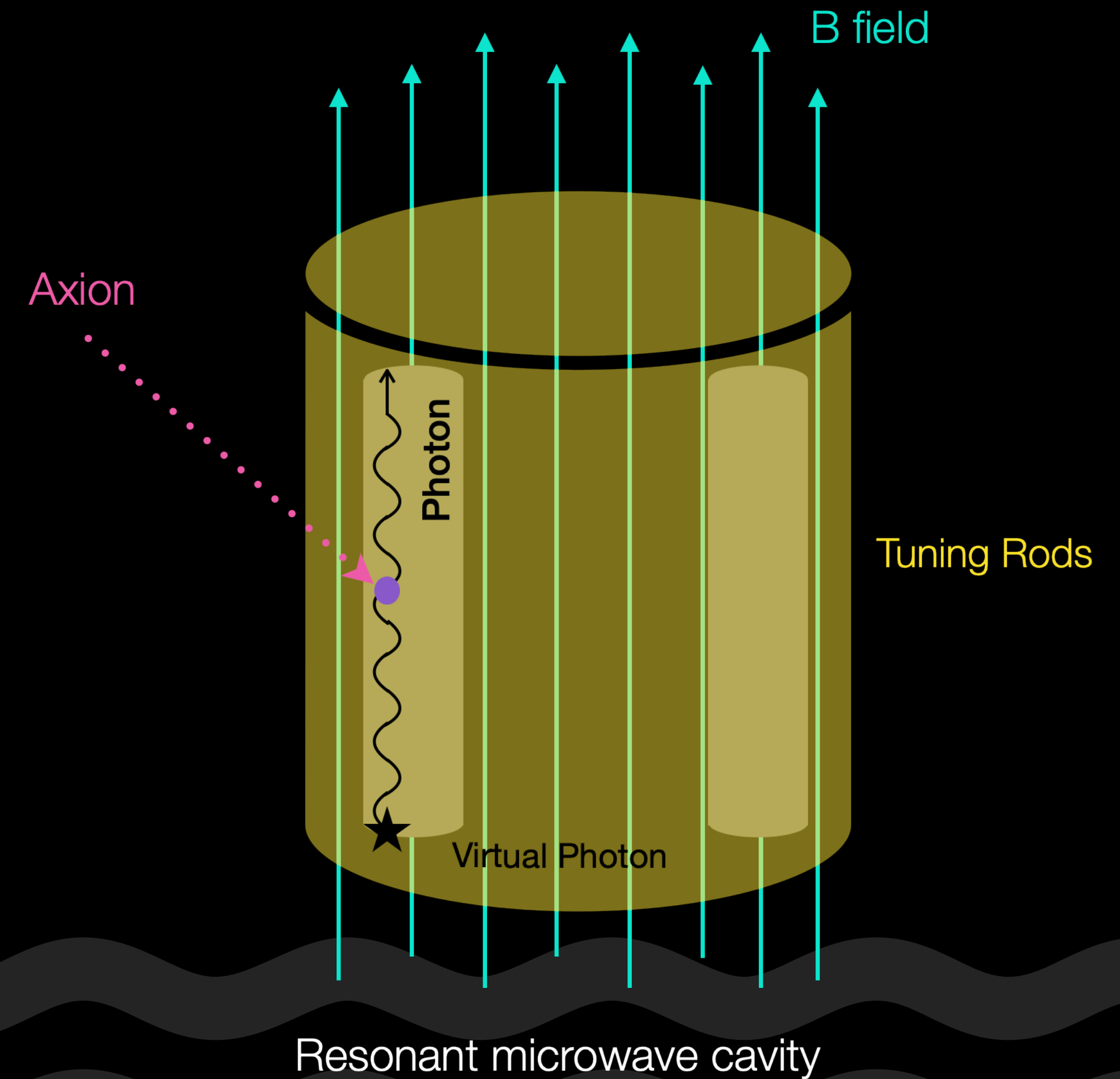
# How do you detect this?

## "Axion Haloscope"

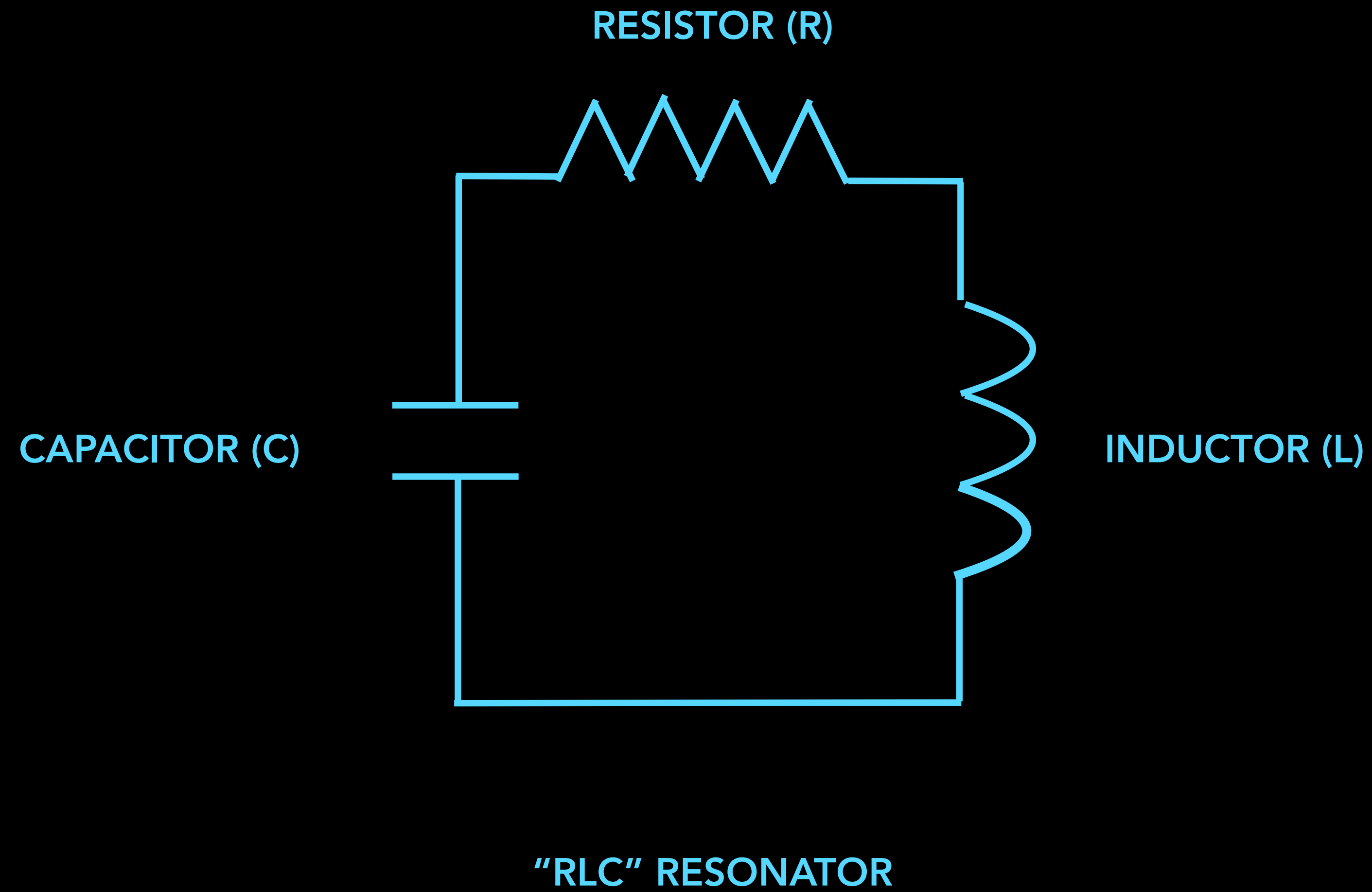
How to detect low frequency electromagnetic waves?

Detector that senses the electric current resulting from the axion conversion to photon in a magnetic field.

High quality electromagnetic oscillators (resonators) are the most sensitive detectors.

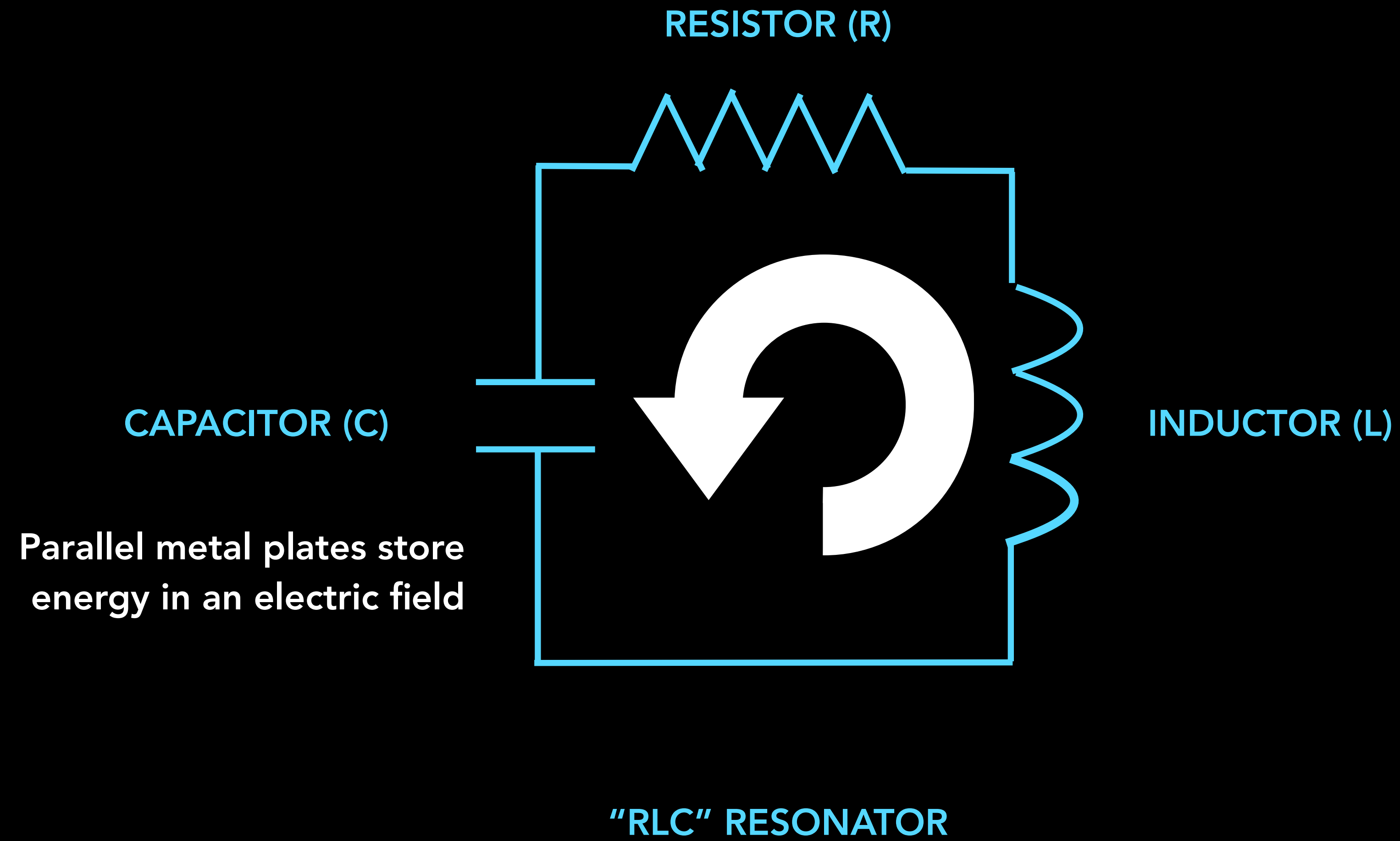


# HOW TO BUILD A RADIO

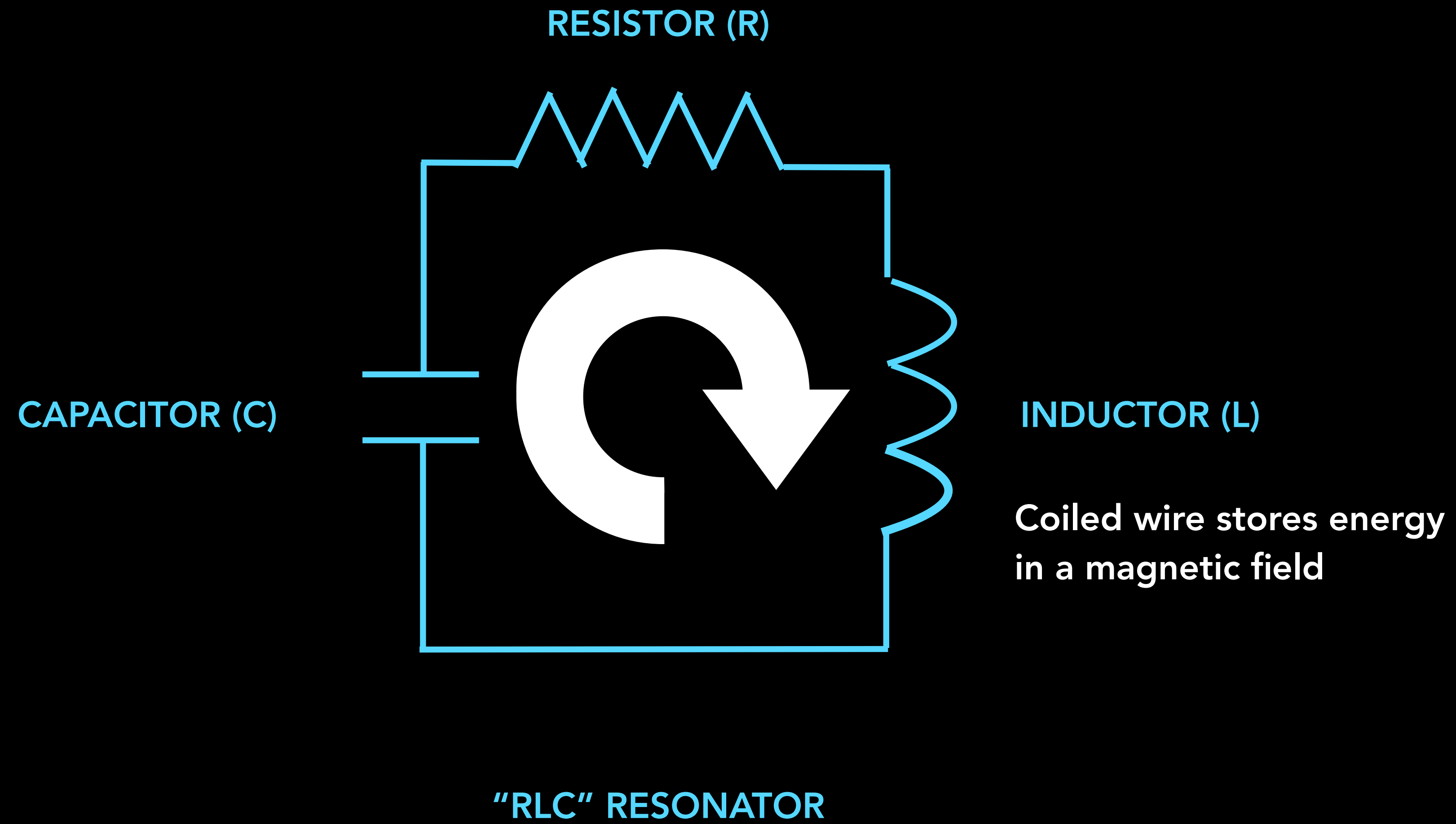




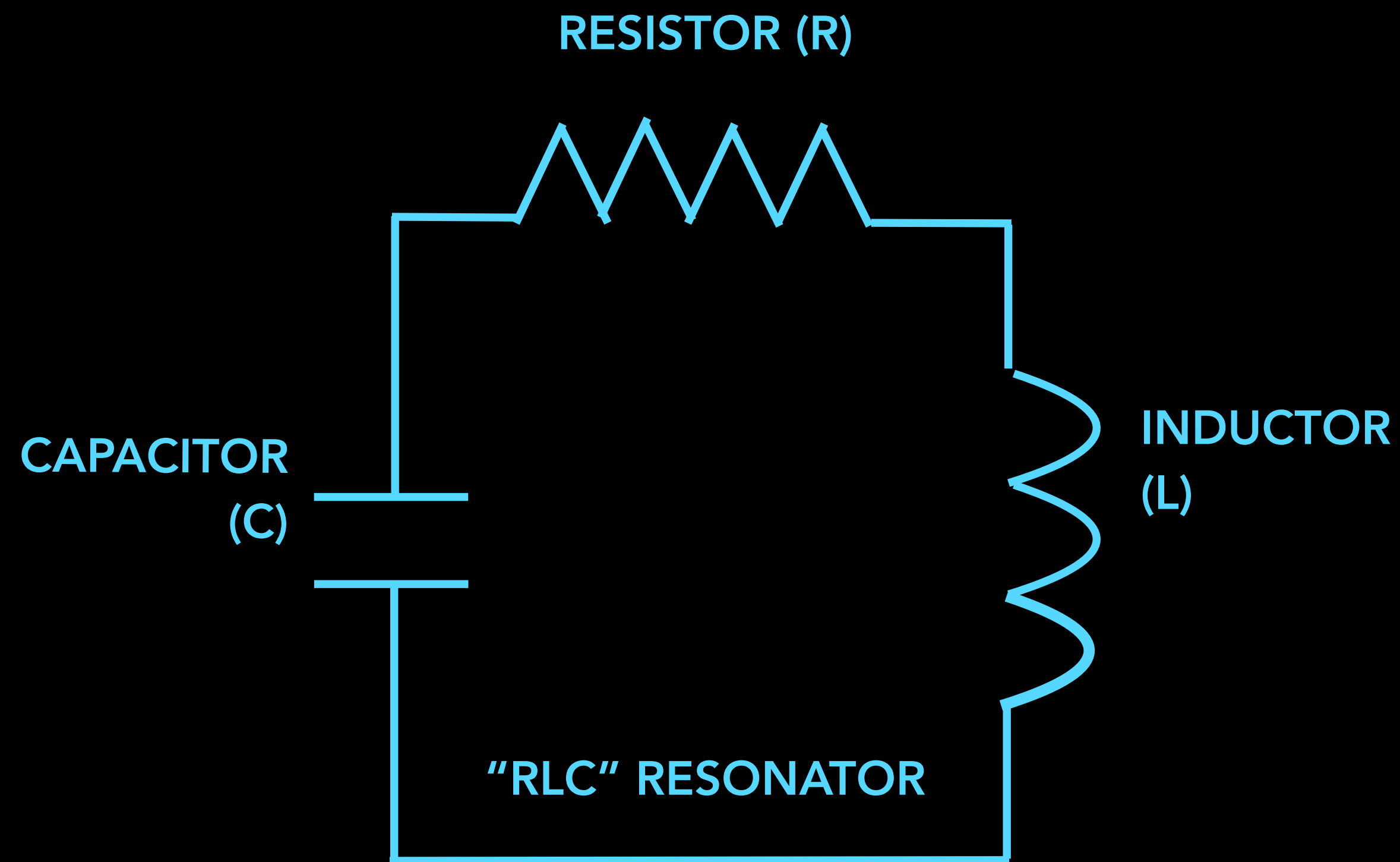
# HOW TO BUILD A RADIO



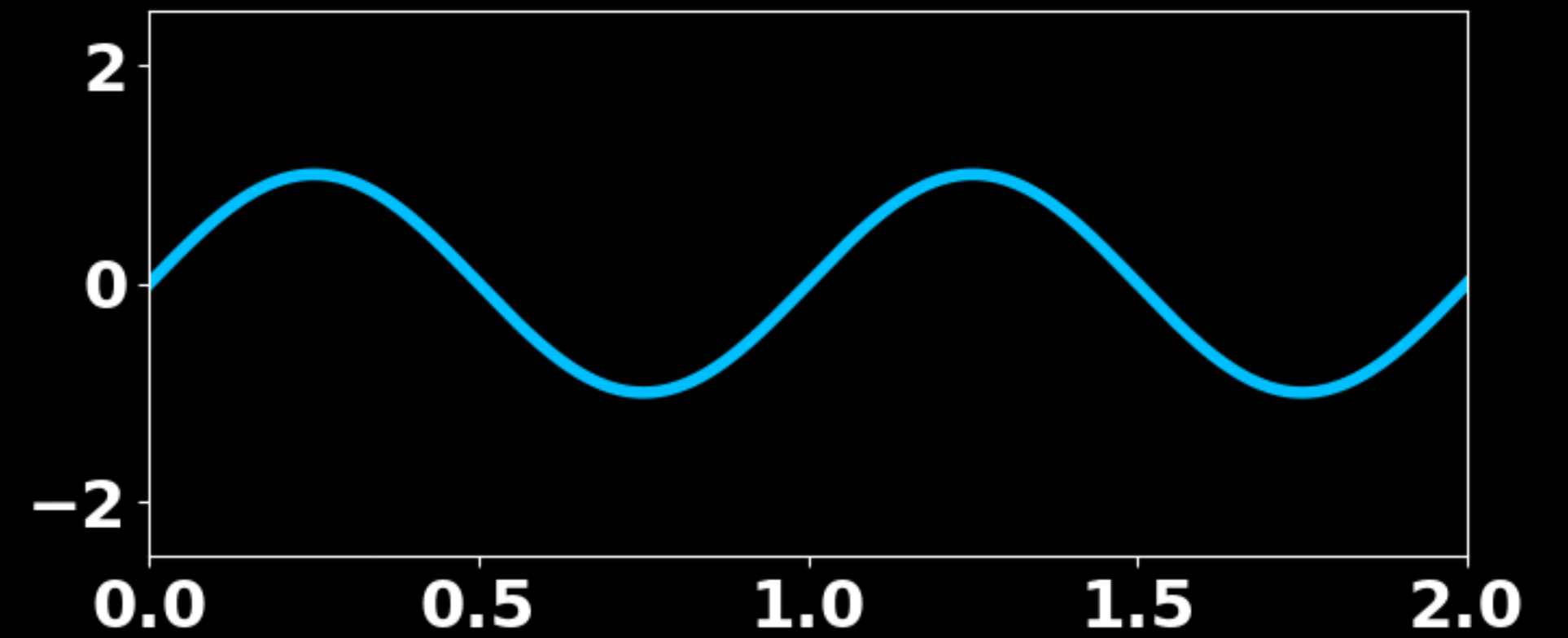
# HOW TO BUILD A RADIO



# HOW TO BUILD A RADIO



voltage (v)



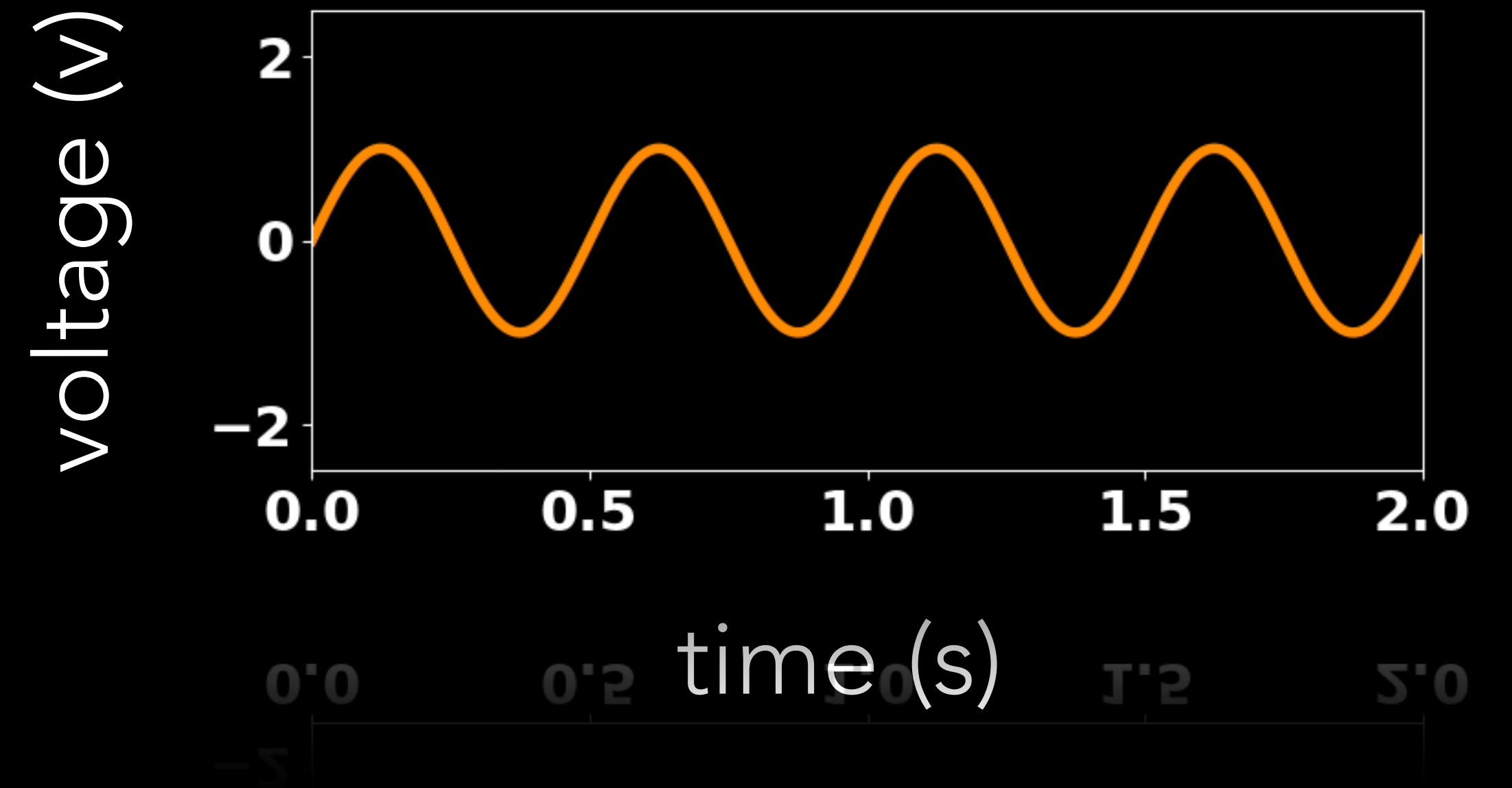
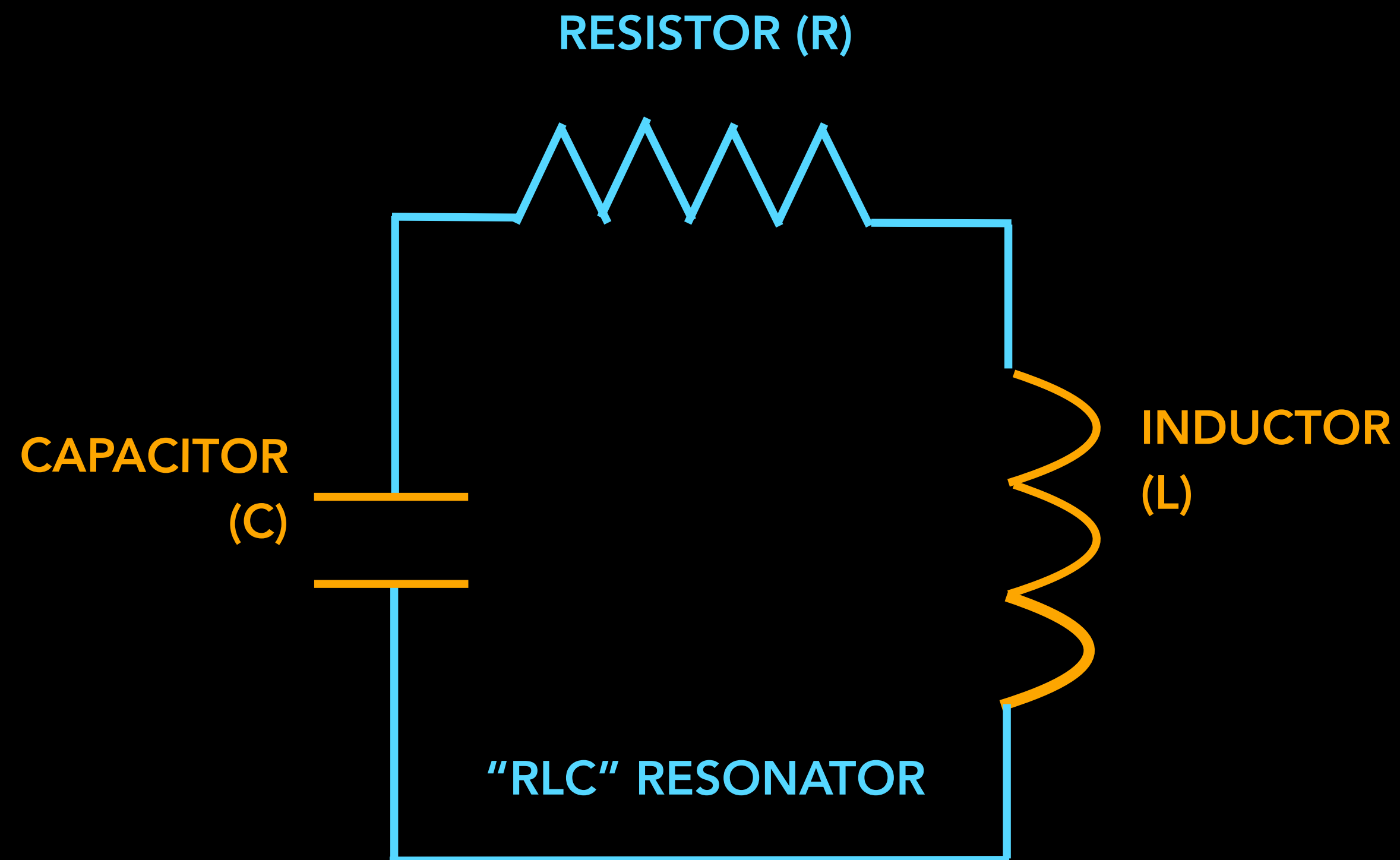
time (s)

Most sensitive to sine waves at  
the **resonant frequency**

$$\omega_0 = 1/\sqrt{LC}$$



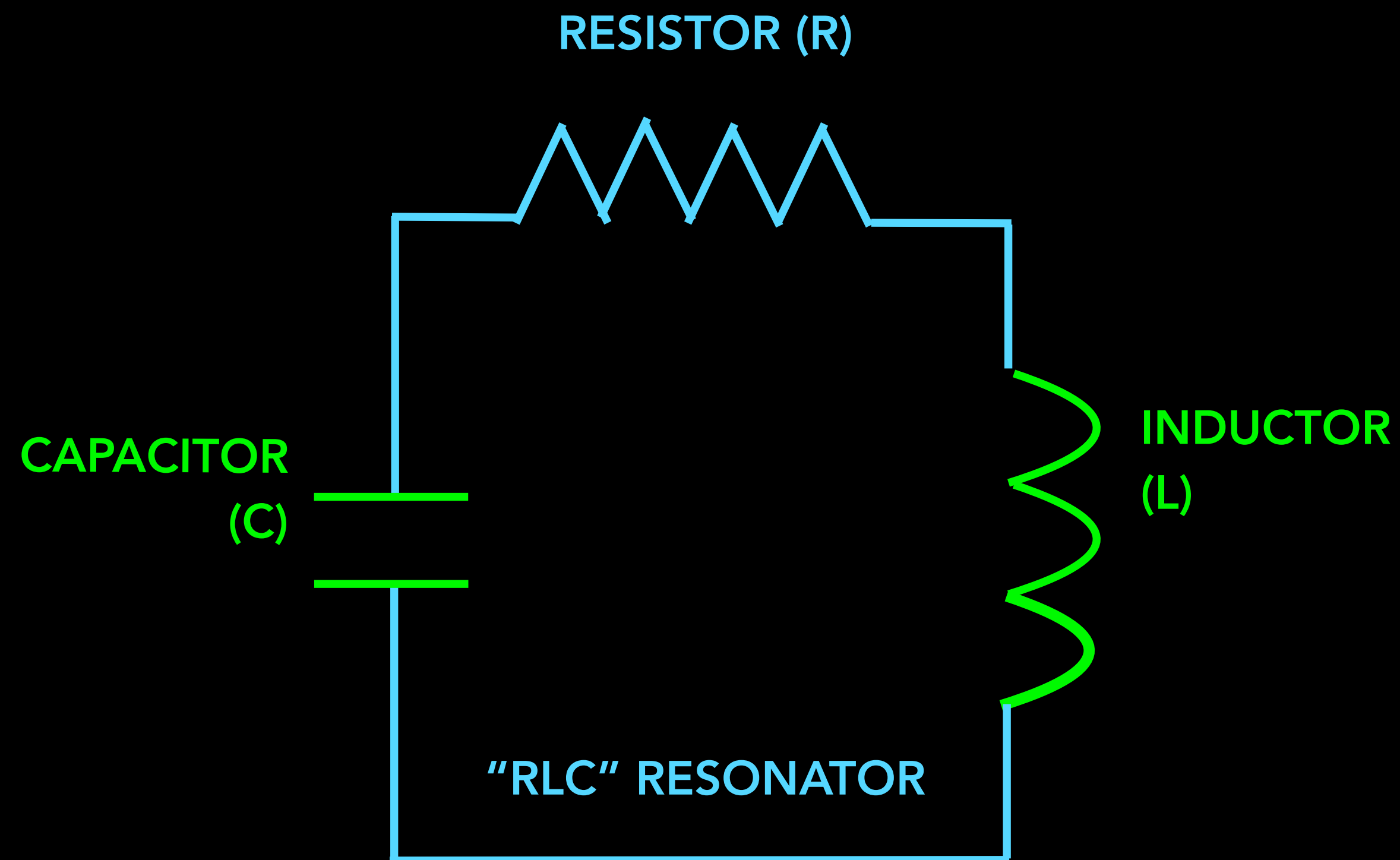
# HOW TO BUILD A RADIO



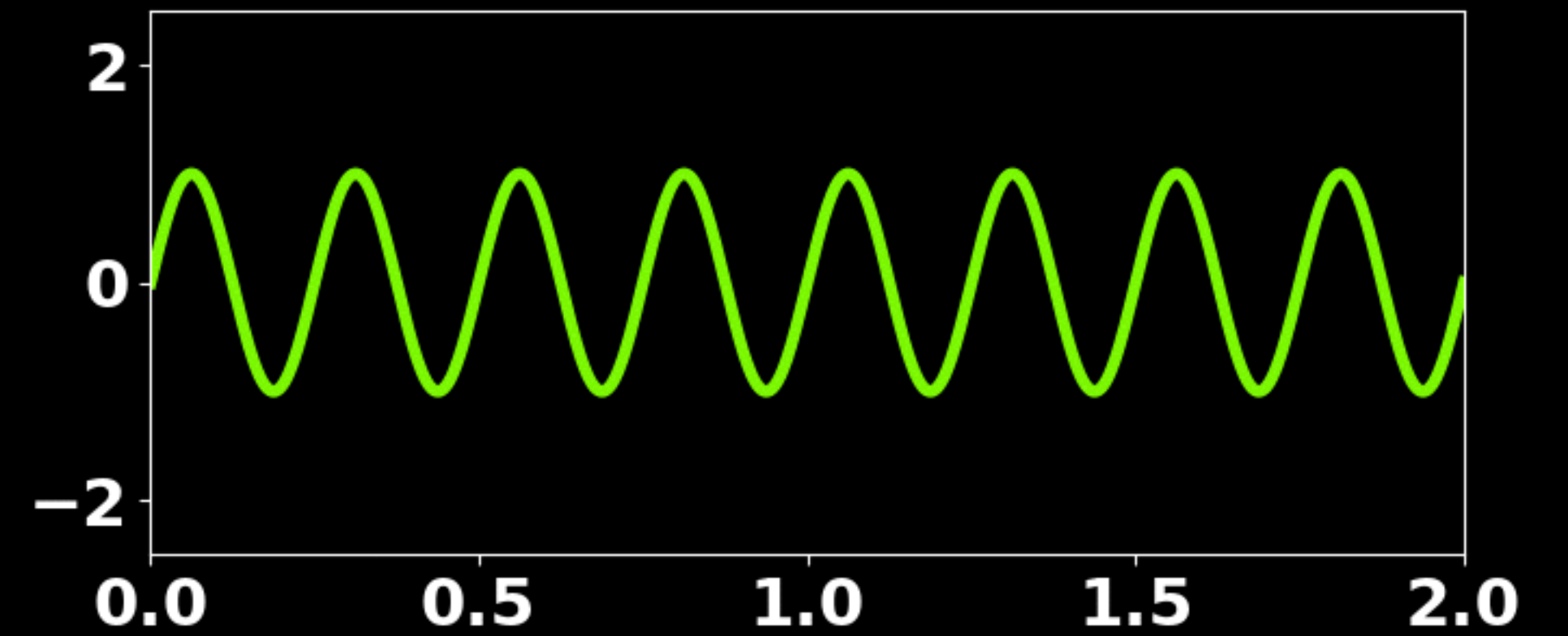
Most sensitive to sine waves  
with frequency

$$\omega_0 = 1/\sqrt{LC}$$

# HOW TO BUILD A RADIO



voltage (v)



time (s)

**Most sensitive to sine waves  
with frequency**

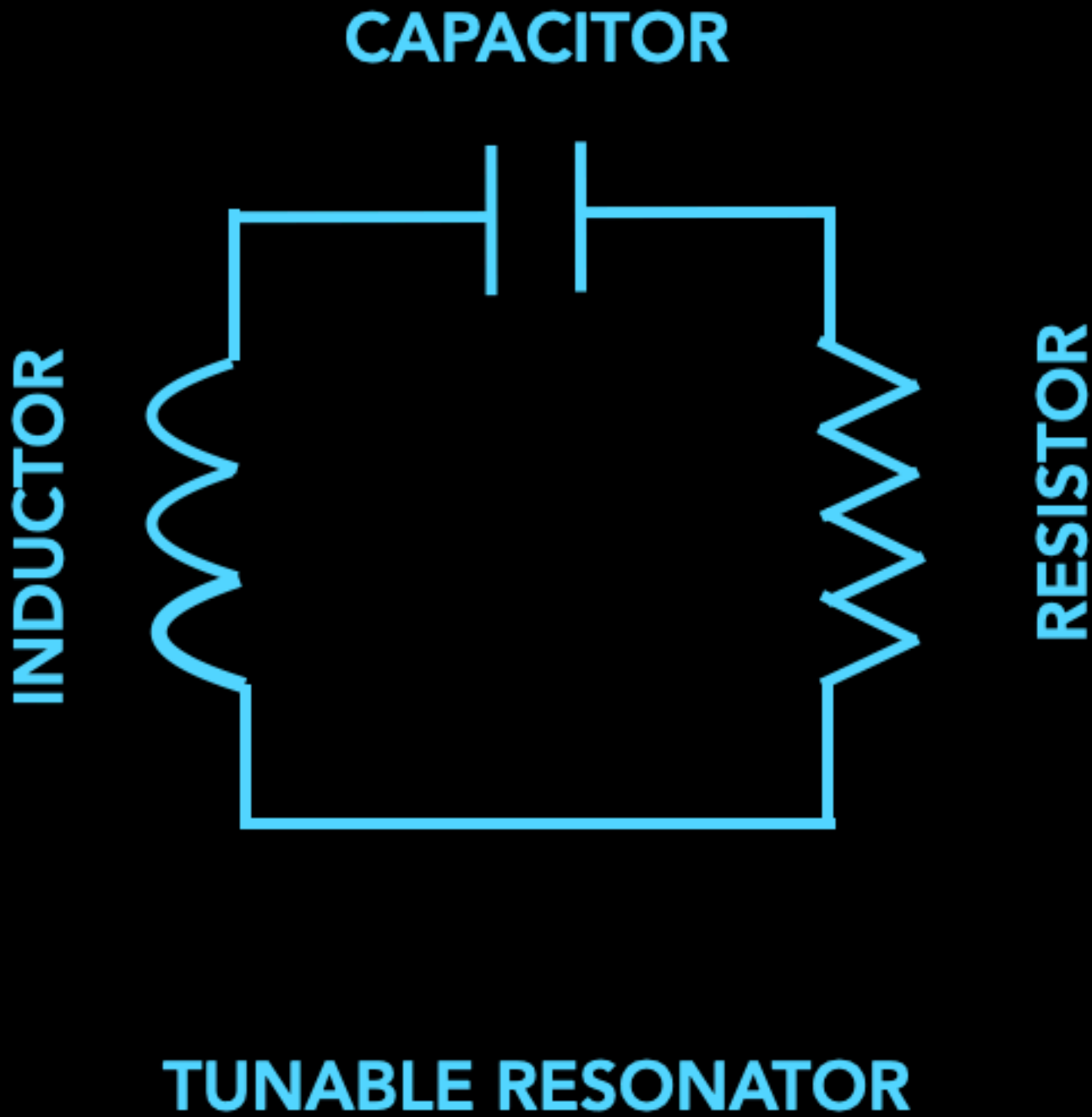
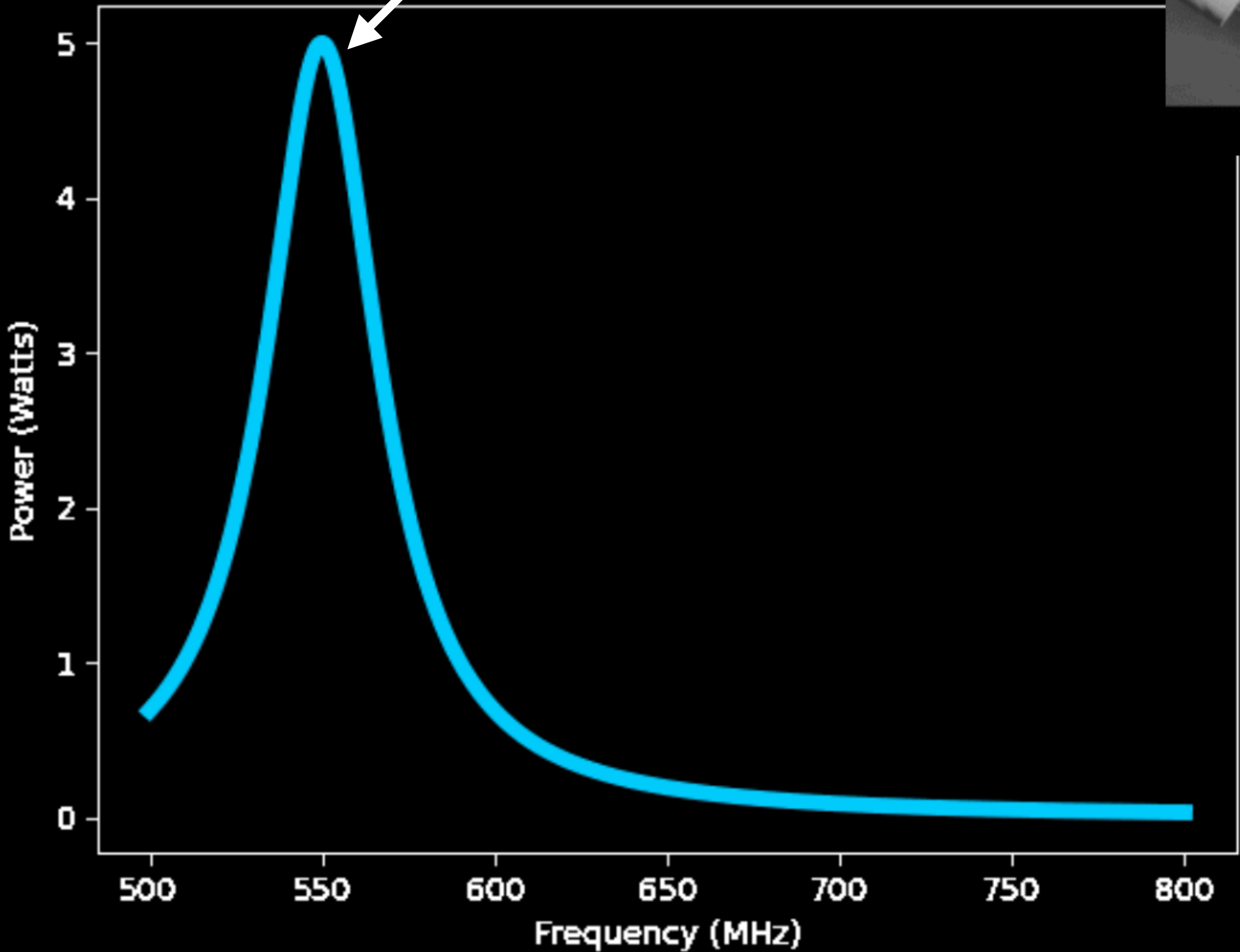
$$\omega_0 = 1/\sqrt{LC}$$

TUNING A RADIO

Resonant frequency



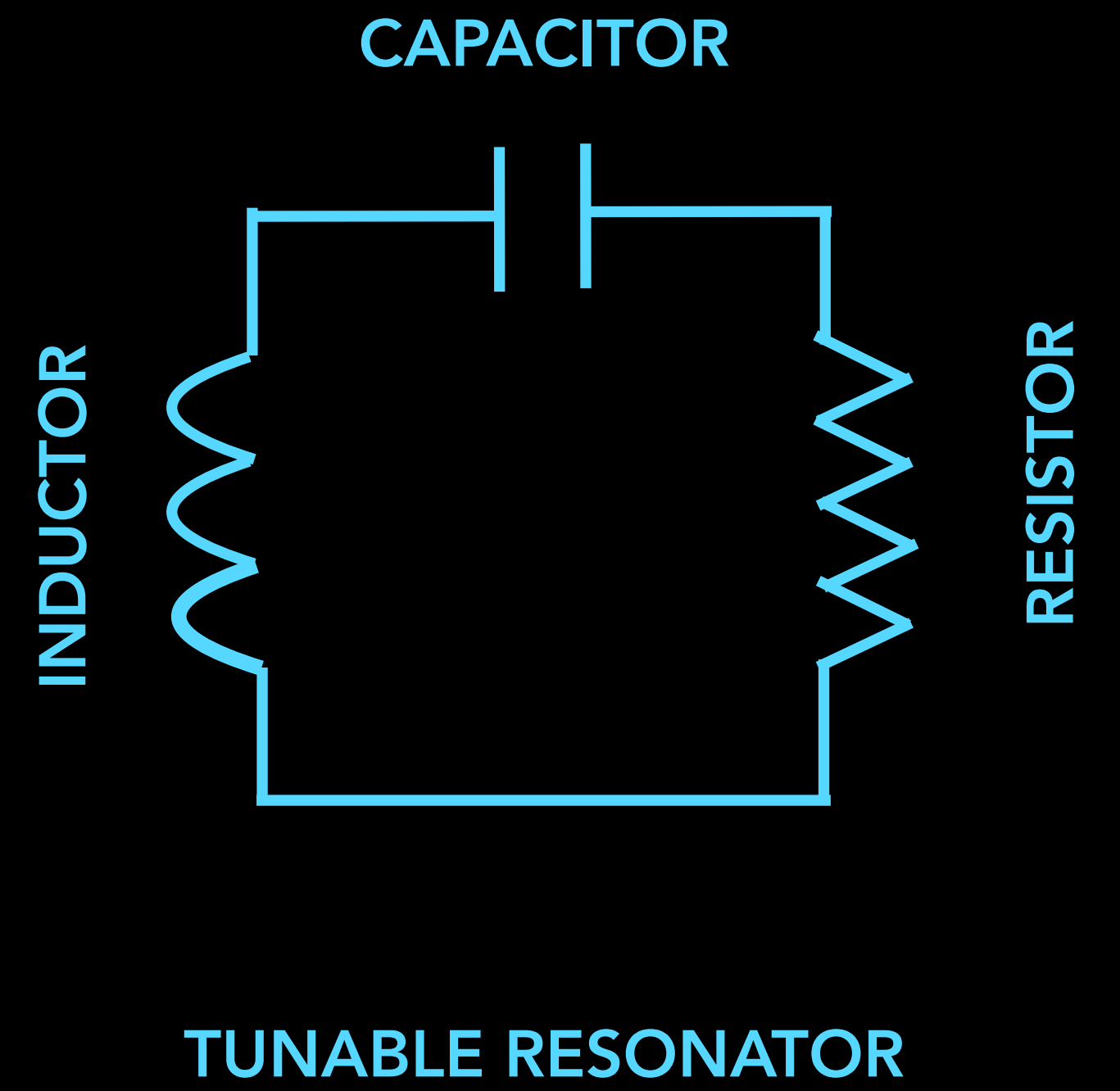
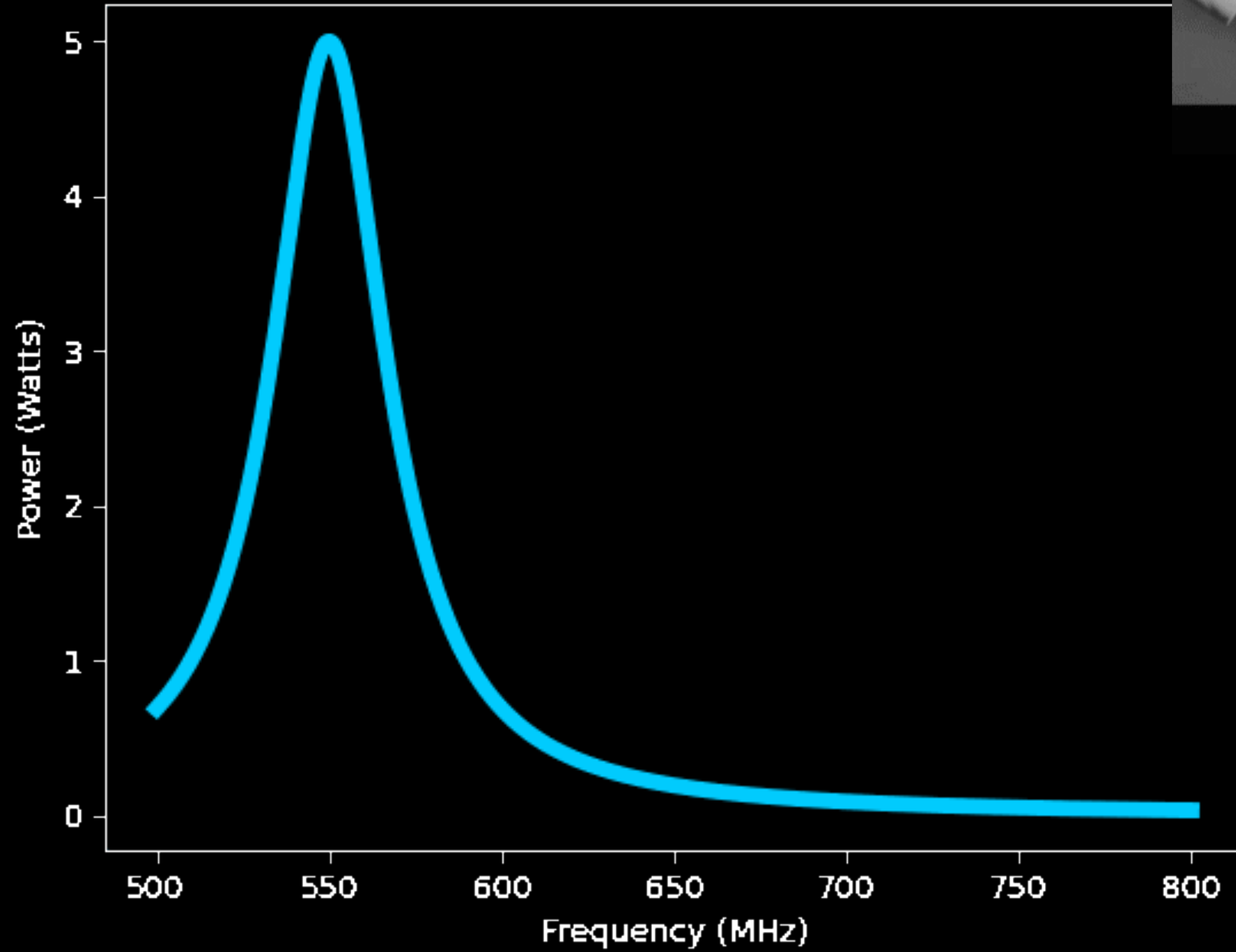
More power = greater sensitivity





# TUNING A RADIO

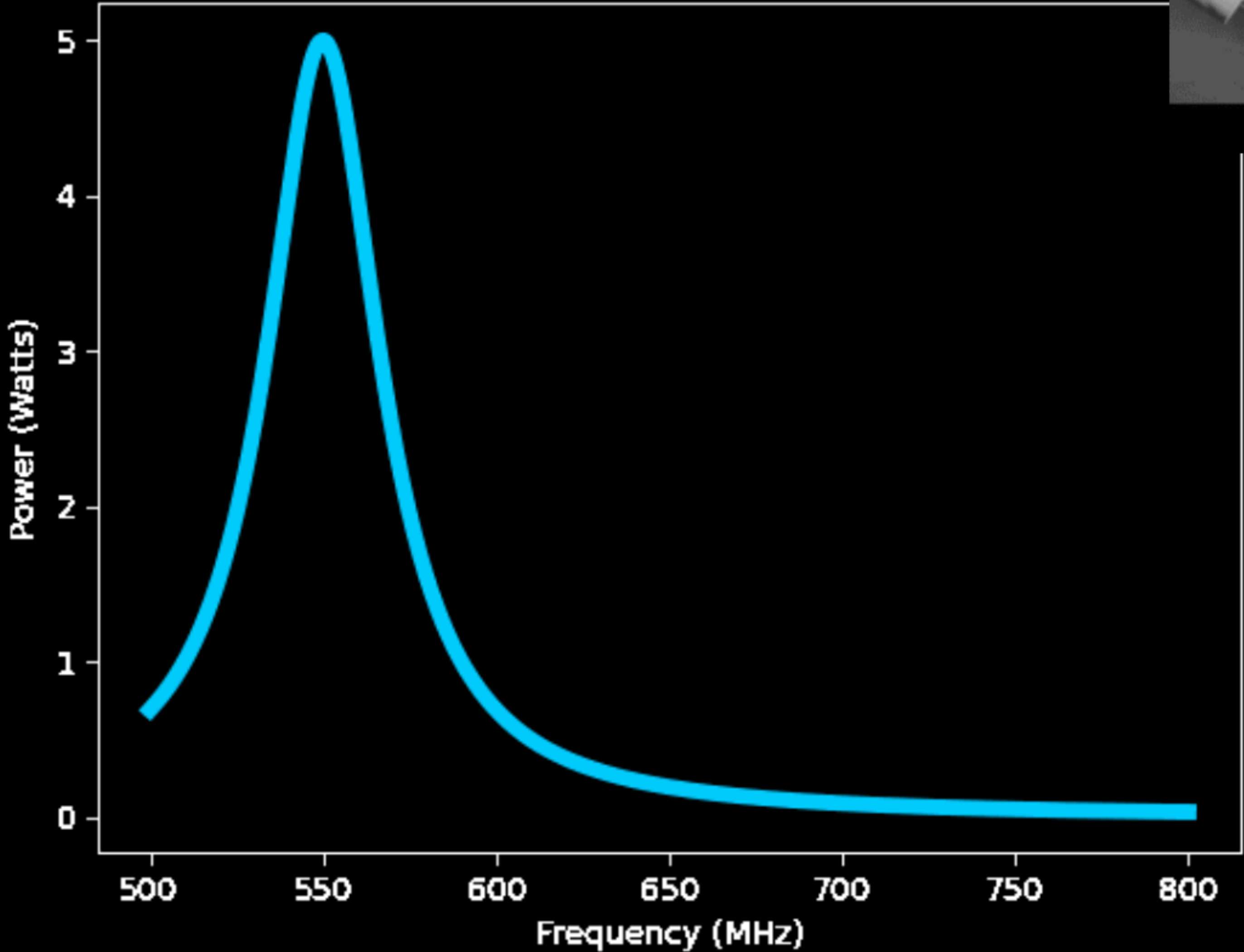
More power = greater sensitivity



TUNING A RADIO



More power = greater sensitivity



INDUCTOR

CAPACITOR

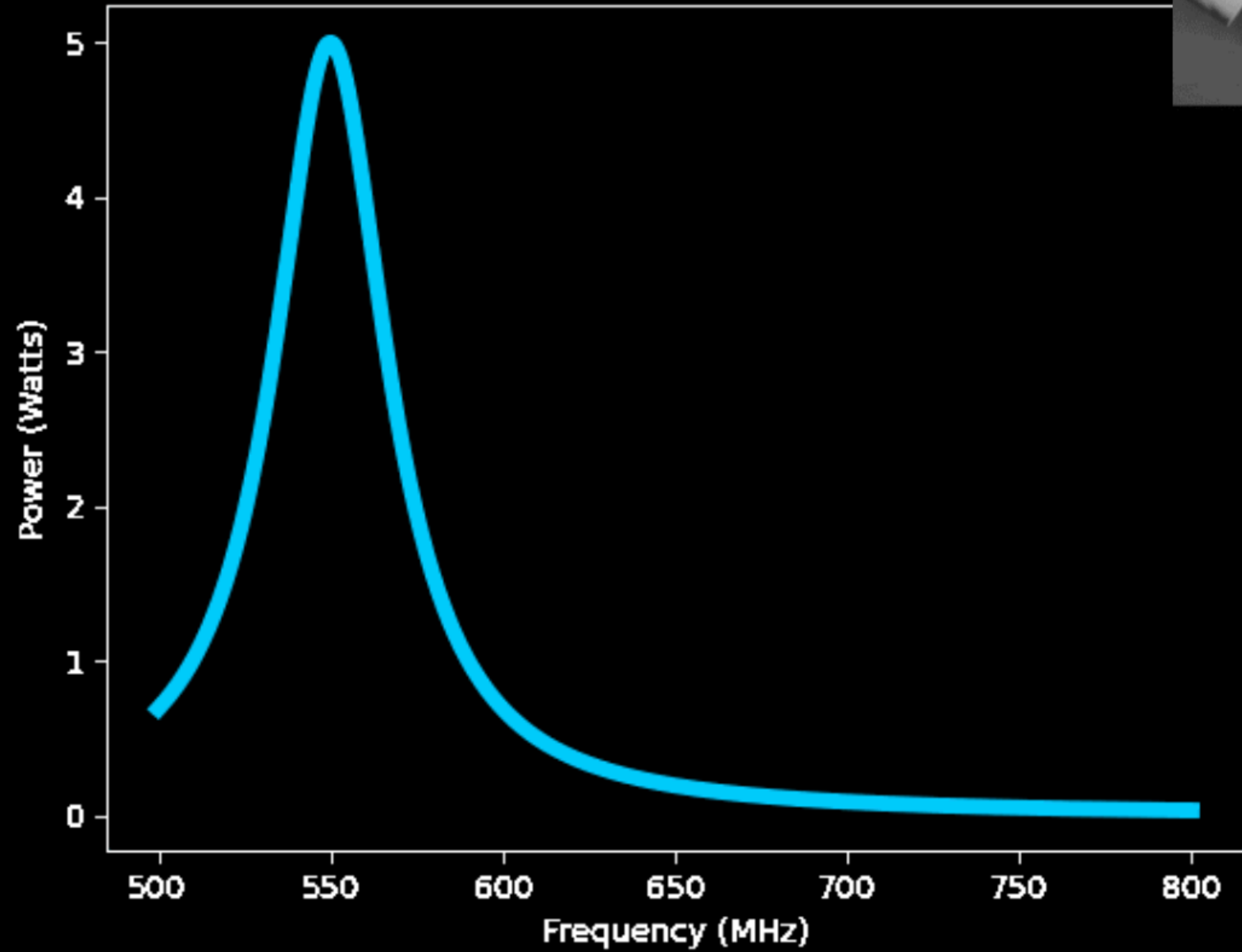
?

RESISTOR

TUNABLE RESONATOR

## TUNING A RADIO

More power = greater sensitivity



**EVEN A COFFEE CAN IS A  
RESONATOR!**



# Modified Electromagnetism

$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma\gamma} \mathbf{B}_0 \frac{\partial a}{\partial t}$$

Modified Ampère's Law

Quasistatic Regime:

$$\lambda_{\text{comp}} \gg R_{\text{exp}}$$

e.g. ABRA, DM Radio

Cavity Regime:

$$\lambda_{\text{comp}} \sim R_{\text{exp}}$$

e.g. ADMX

Radiation Regime:

$$\lambda_{\text{comp}} \ll R_{\text{exp}}$$

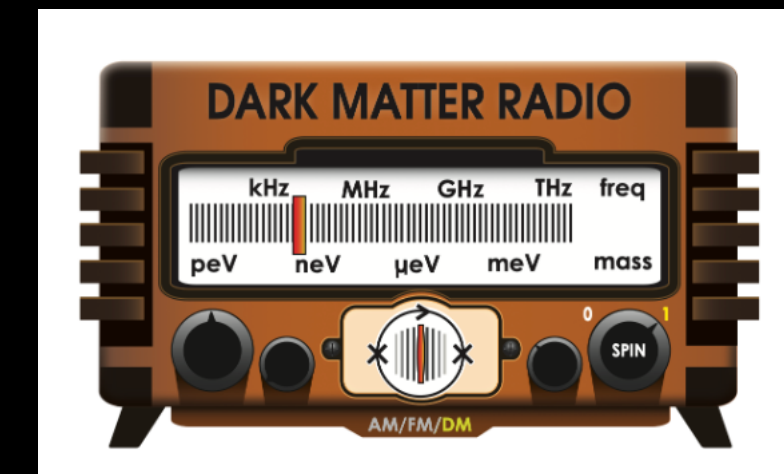
e.g. MADMAX



AXIONS AND WAVE-LIKE DARK MATTER

# LUMPED ELEMENT REGIME

DM RADIO



# DM Radio Collaboration

H.M. Cho, W. Craddock, D. Li, W. J. Wisniewski  
Stanford Linear Accelerator Center

C. Bartram, J. Corbin, C. S. Dawson, P. W. Graham, K. D. Irwin, F. Kadribasic, S. Kuenstner, N. M. Rapidis, 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. Kolevator  
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, C. P. Salemi, L. Winslow  
Laboratory of Nuclear Science  
Massachusetts Institute of Technology

R. Henning  
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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

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



# Lumped Element Haloscope

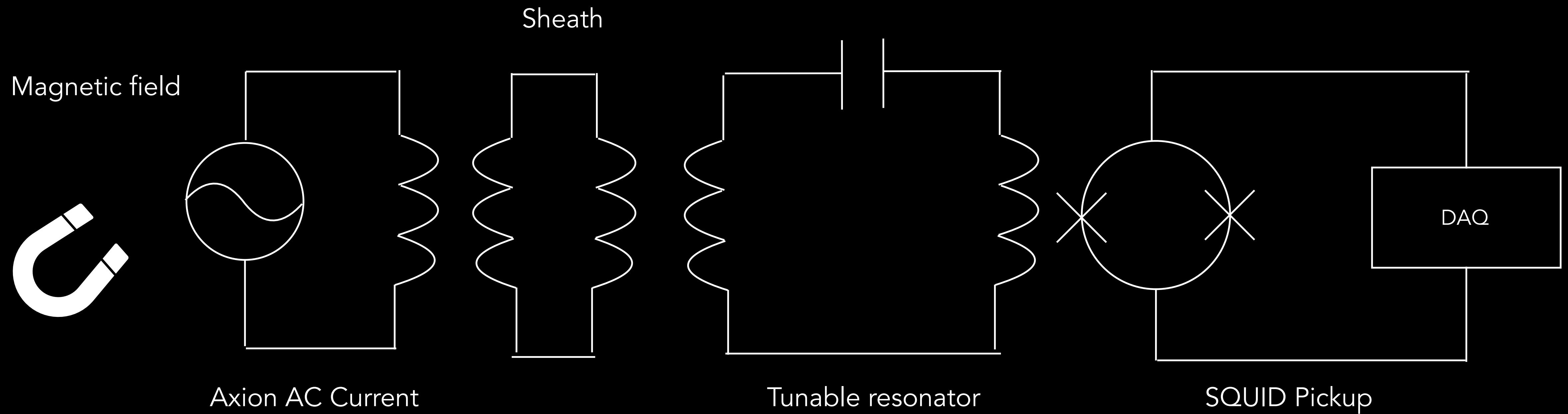


Figure inspired by Chiara Salemi



# Lumped Element Haloscope

Case Study: Static Toroidal magnet

- Magnetic field  $B_0$

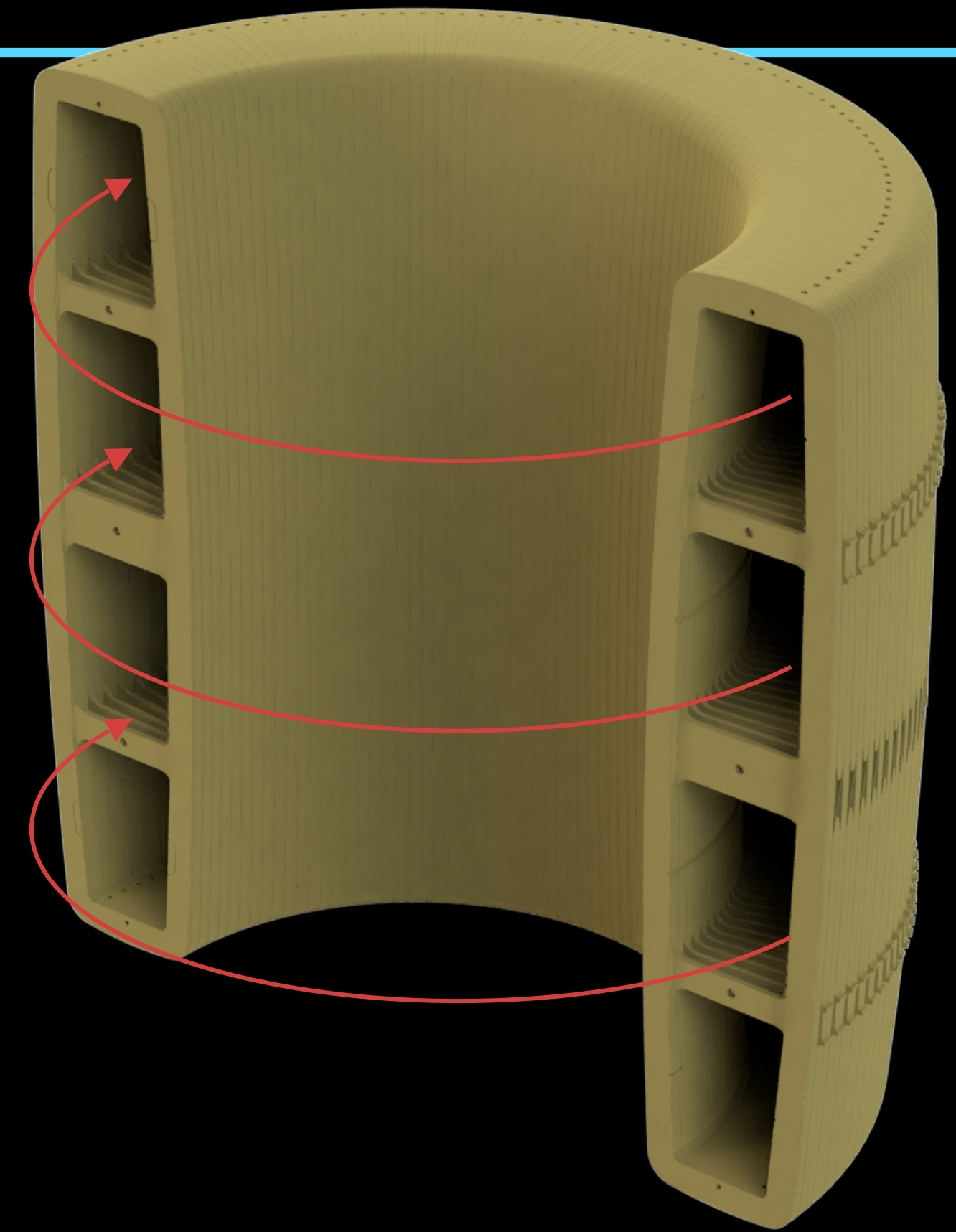
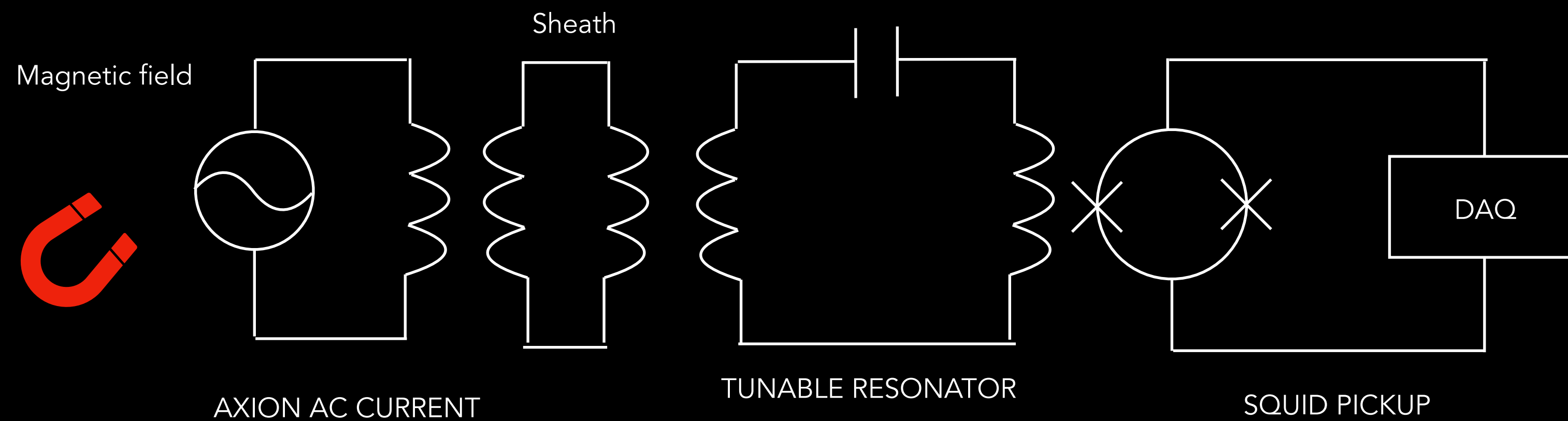


Figure courtesy of Chiara Salemi



# Lumped Element Haloscope

Case Study: Static Toroidal magnet

- Magnetic field  $\mathbf{B}_0$
- AC axion current  $\mathbf{J}_a$

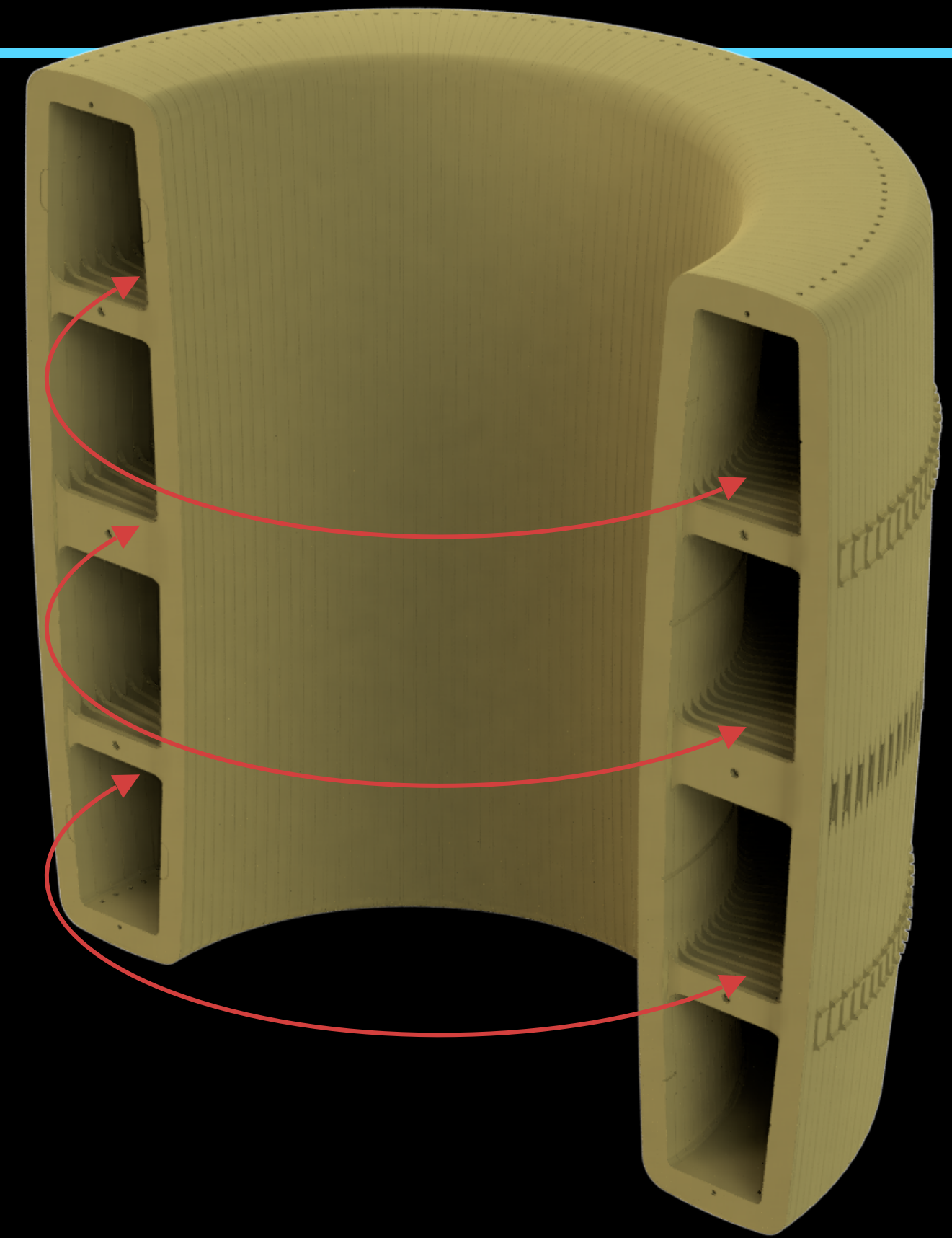
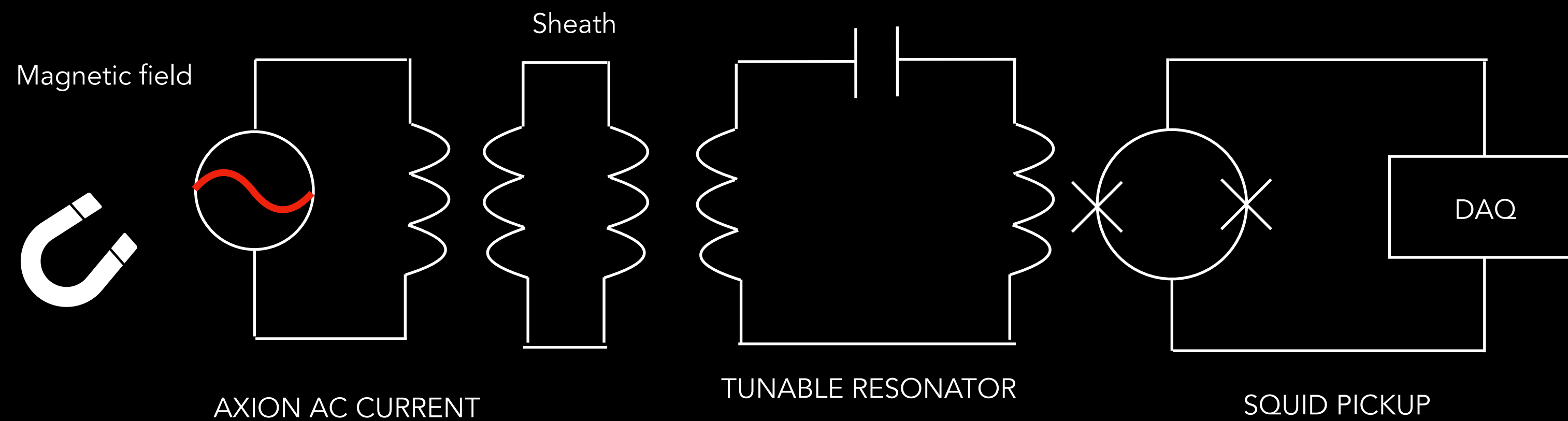


Figure courtesy of Chiara Salemi

# Lumped Element Haloscope

Case Study: Static Toroidal magnet

- Magnetic field  $\mathbf{B}_0$
- AC axion current  $\mathbf{J}_a$
- Oscillating magnetic field

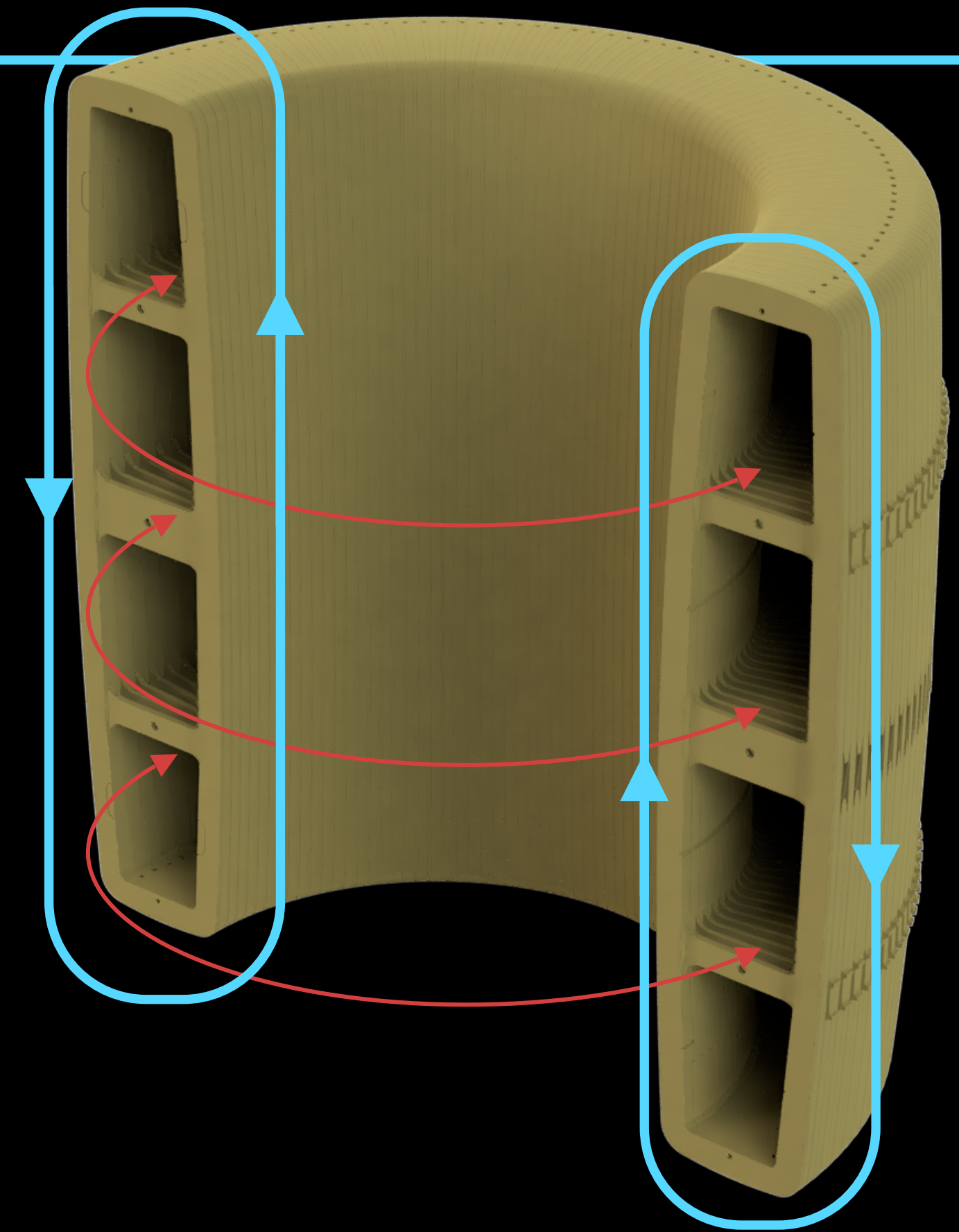
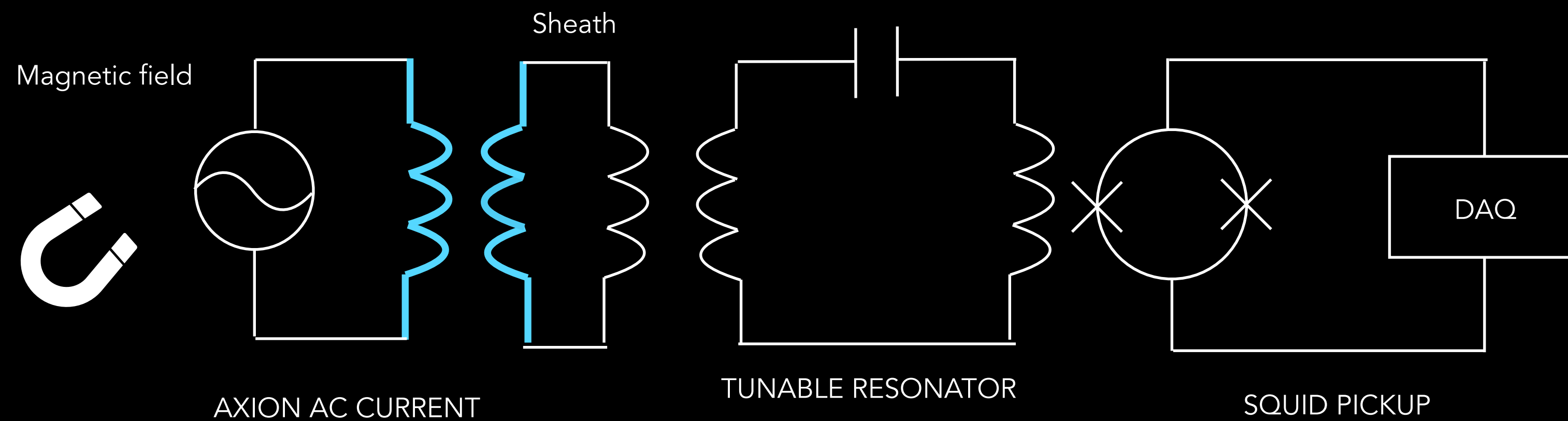


Figure courtesy of Chiara Salemi

# Lumped Element Haloscope

Case Study: Static Toroidal magnet

- Magnetic field  $B_0$
- AC axion current  $J_a$
- Oscillating magnetic field
- Induces currents on the sheath

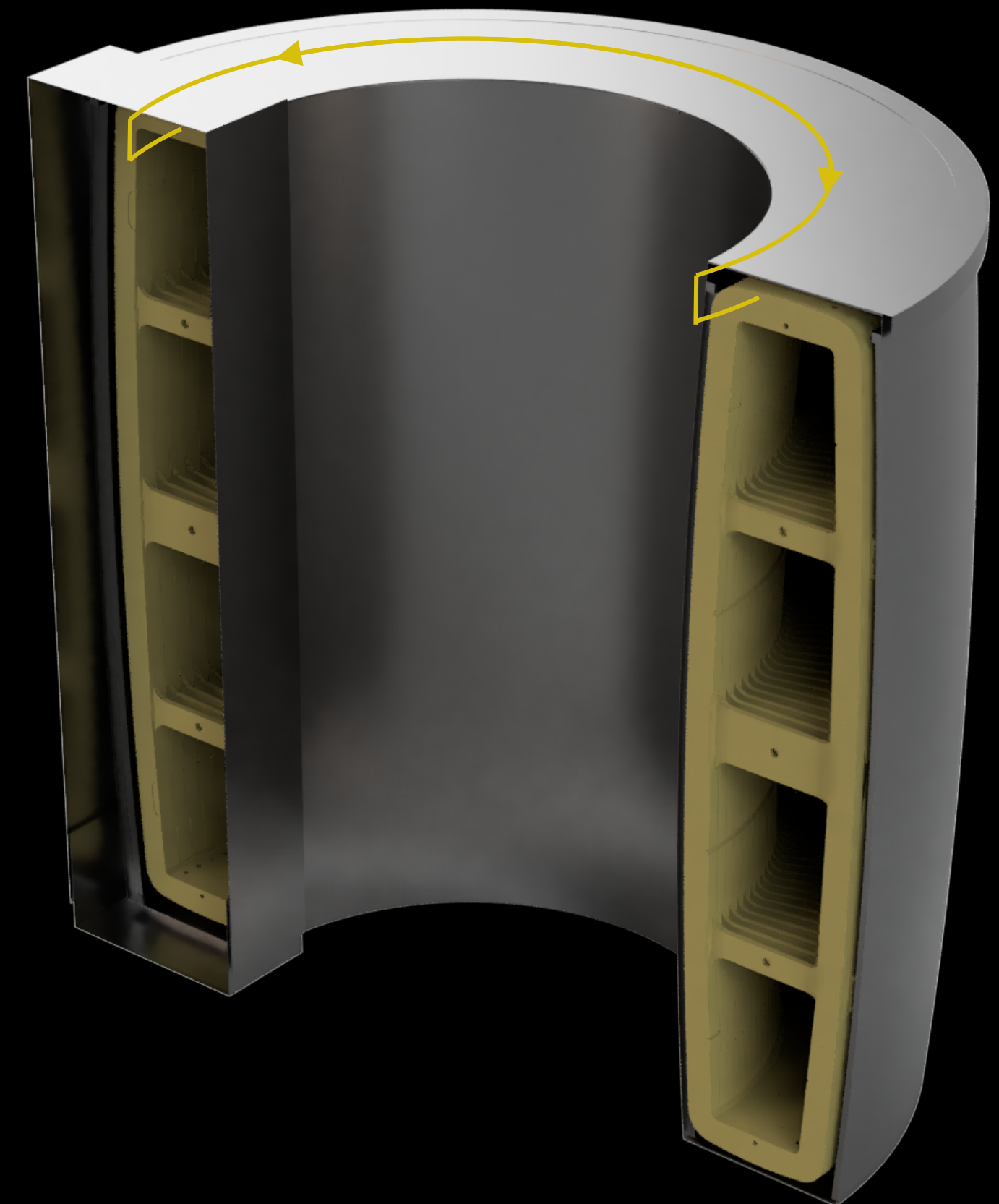
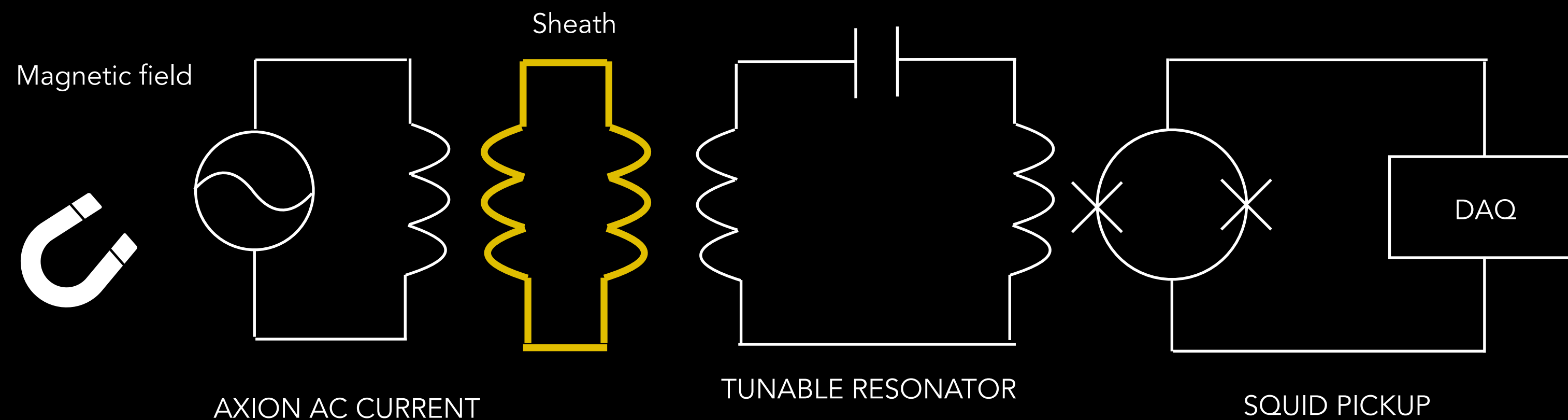


Figure courtesy of Chiara Salemi



# Lumped Element Haloscope

## Case Study: Static Toroidal magnet

- Magnetic field  $B_0$
- AC axion current  $J_a$
- Oscillating magnetic field
- Induces currents on the sheath
- Oscillating magnetic field

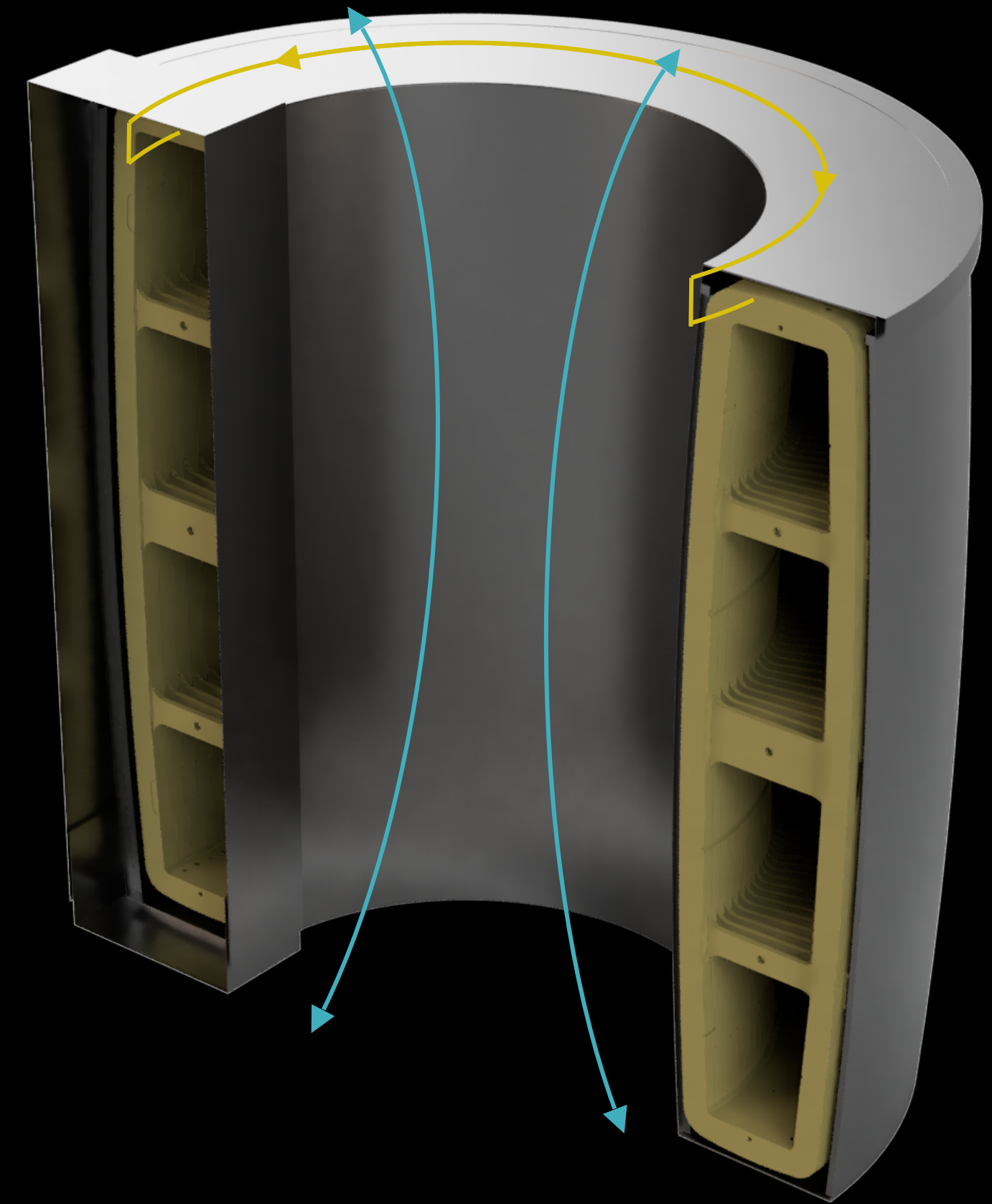
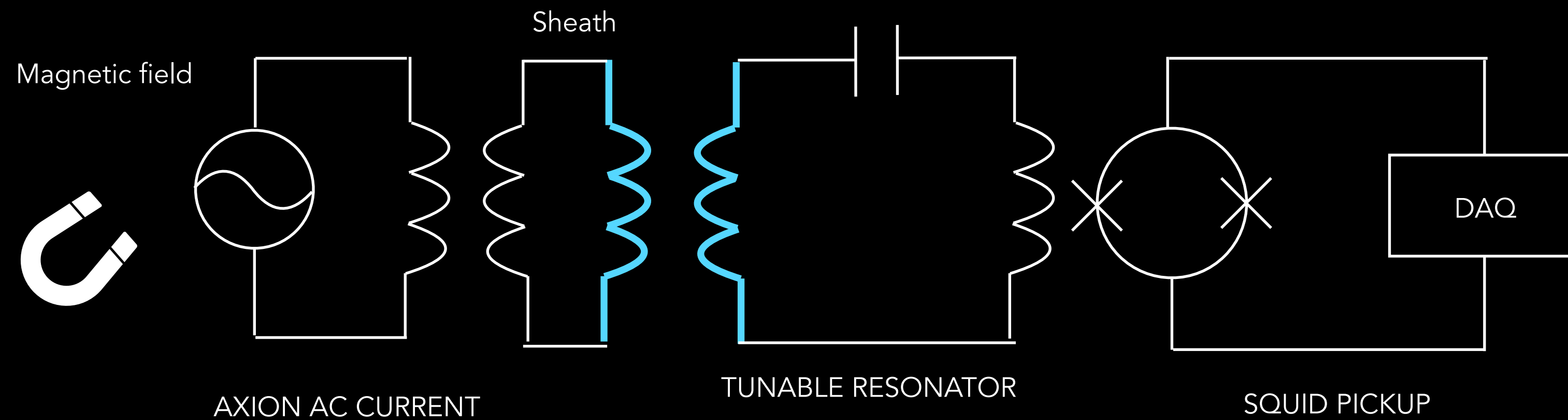


Figure courtesy of Chiara Salemi



# Lumped Element Haloscope

## Case Study: Static Toroidal magnet

- Magnetic field  $\mathbf{B}_0$
- AC axion current  $\mathbf{J}_a$
- Oscillating magnetic field
- Induces currents on the sheath
- Oscillating magnetic field
- Ringing up a resonator

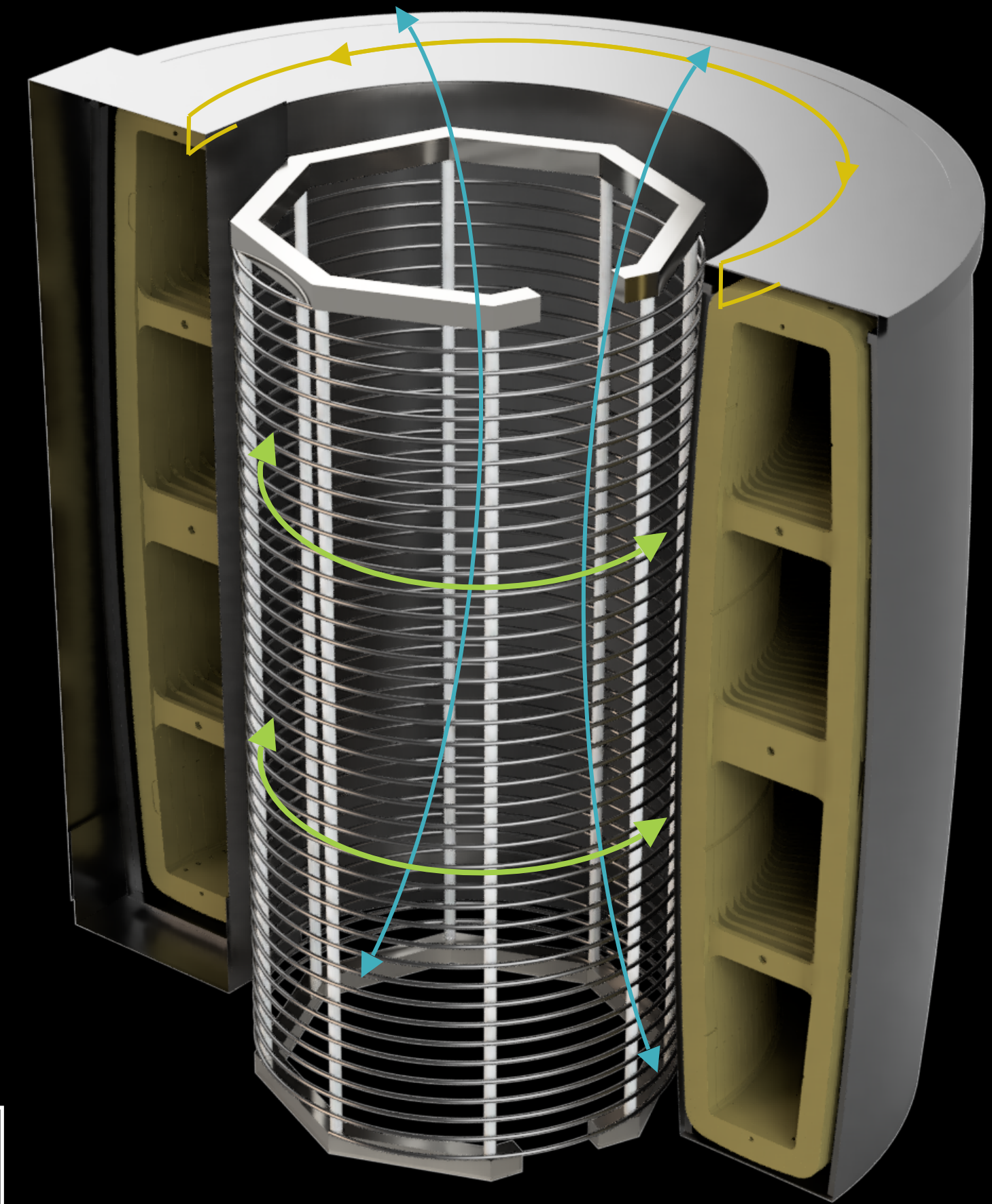
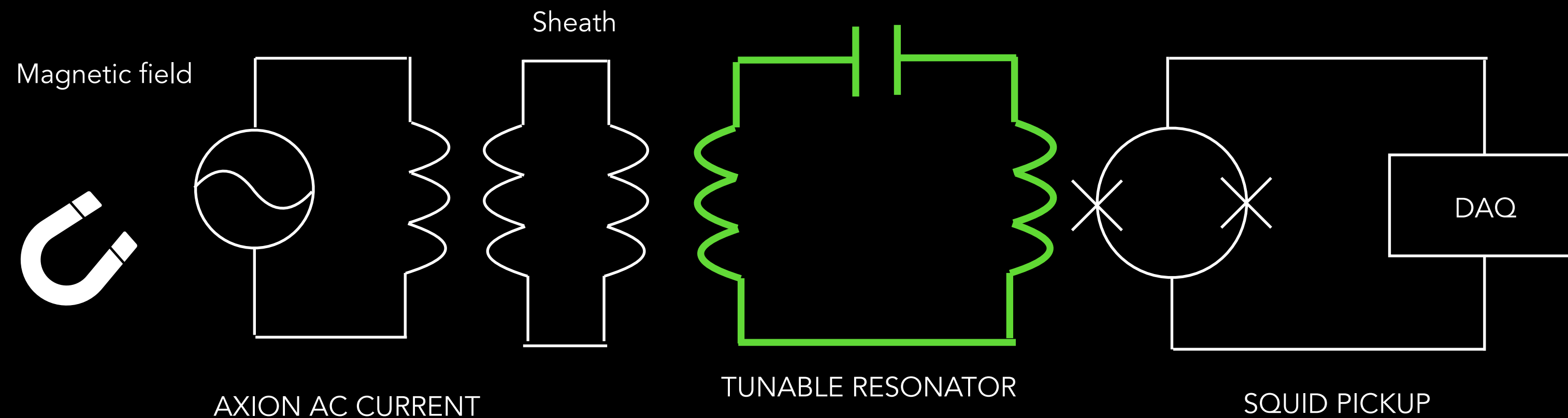


Figure courtesy of Chiara Salemi



# Lumped Element Haloscope

Case Study: Static Toroidal magnet

- Magnetic field  $\mathbf{B}_0$
- AC axion current  $\mathbf{J}_a$
- Oscillating magnetic field
- Induces currents on the sheath
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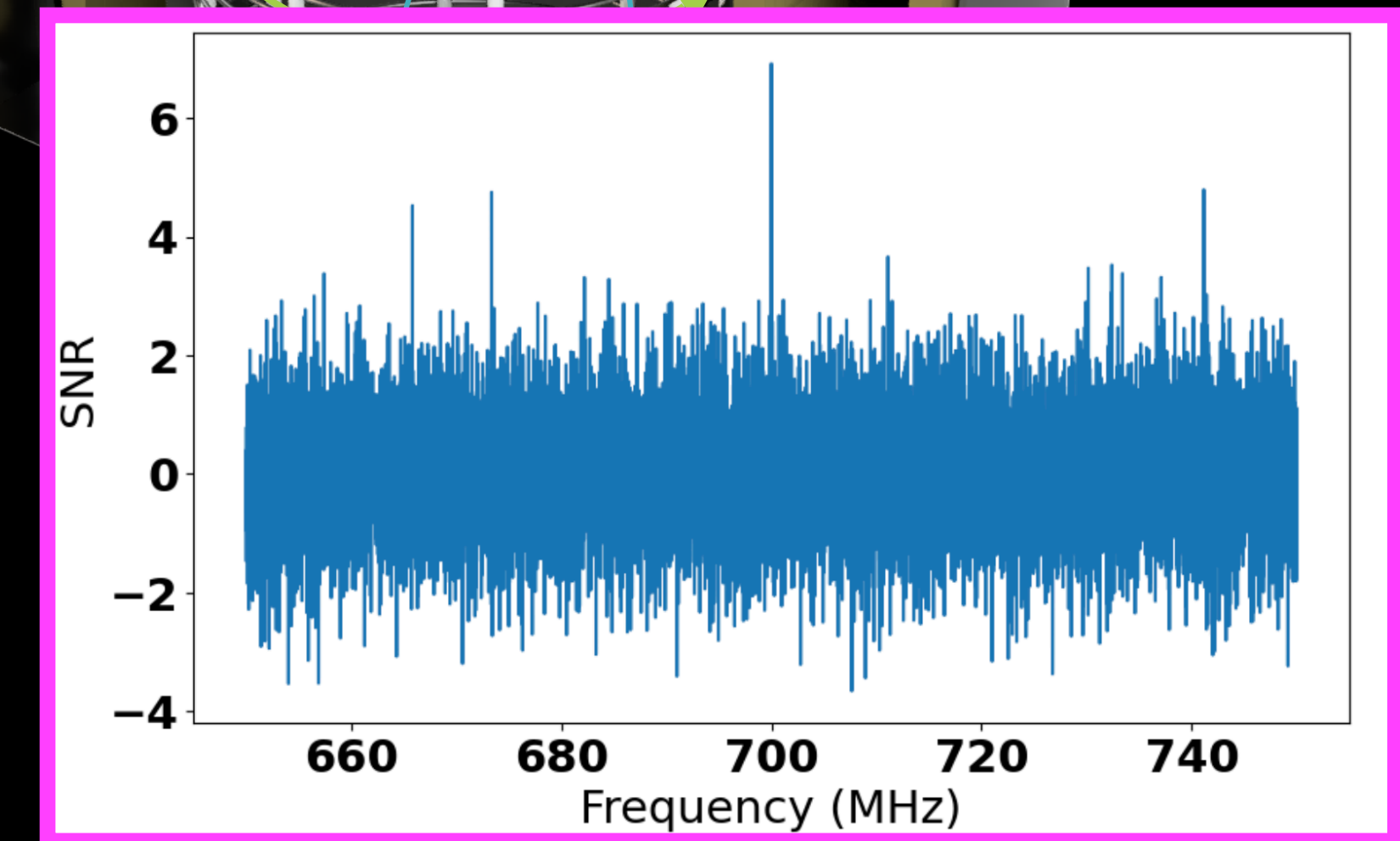
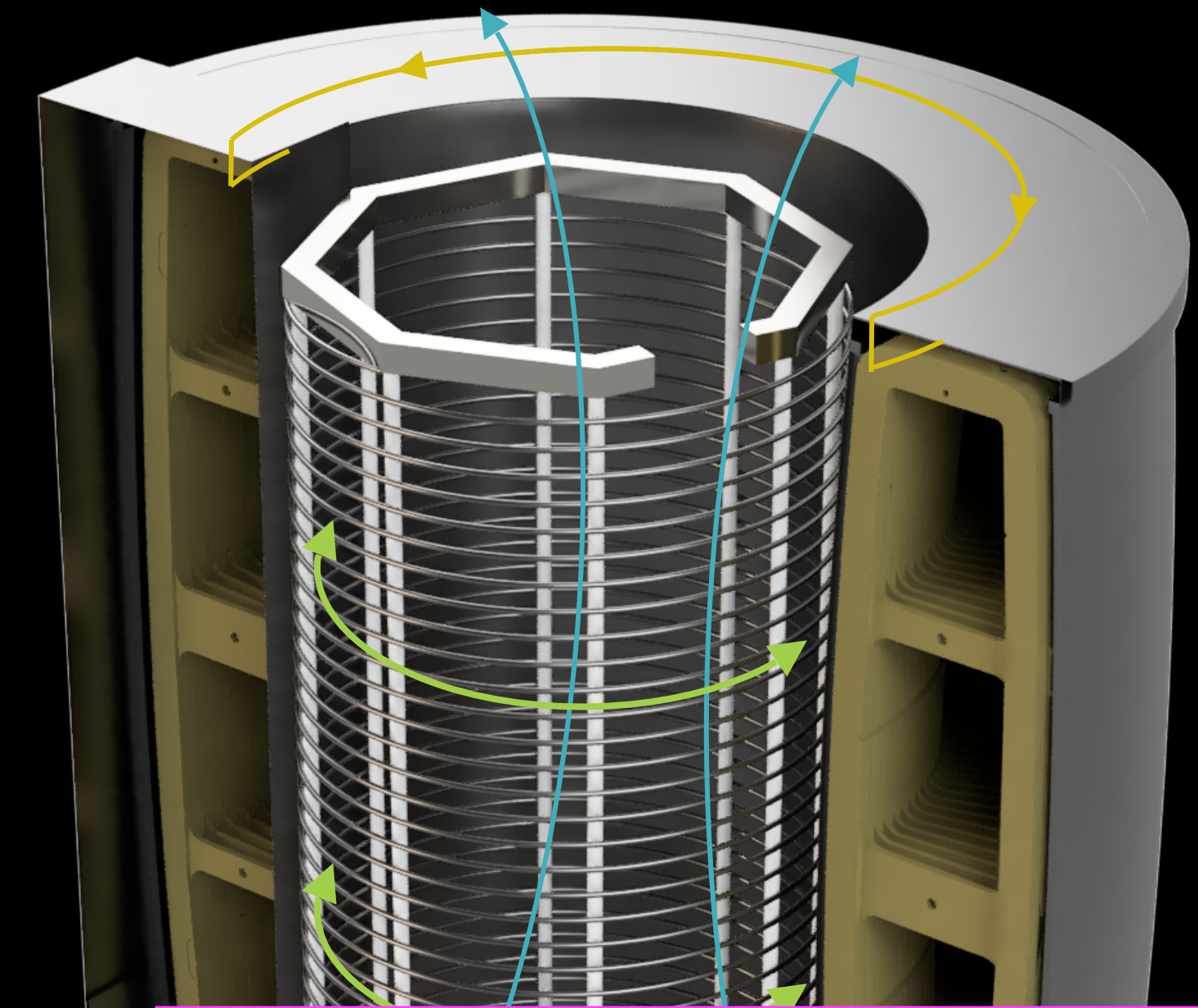
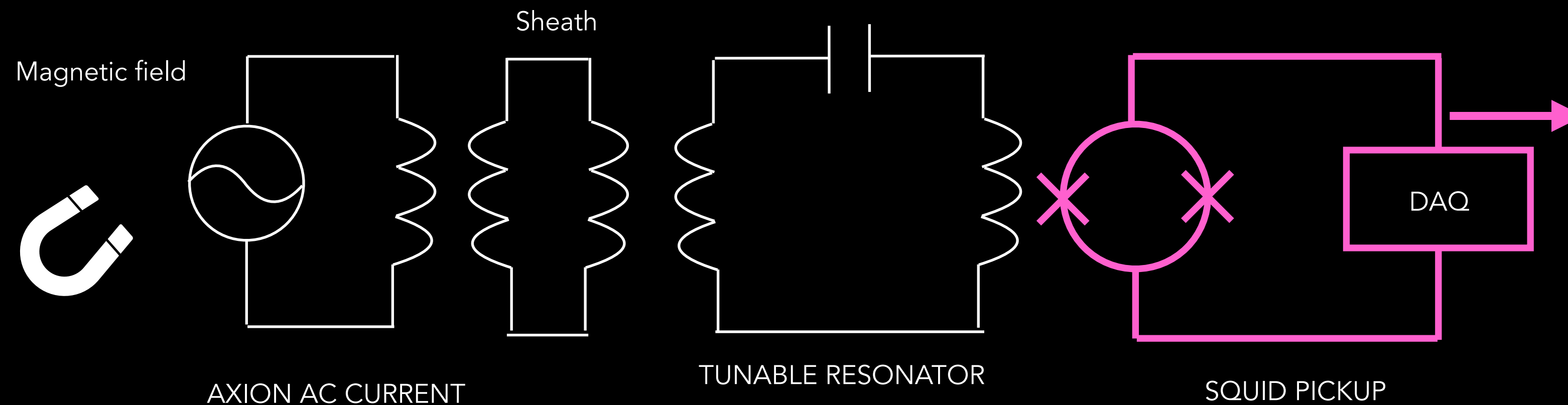
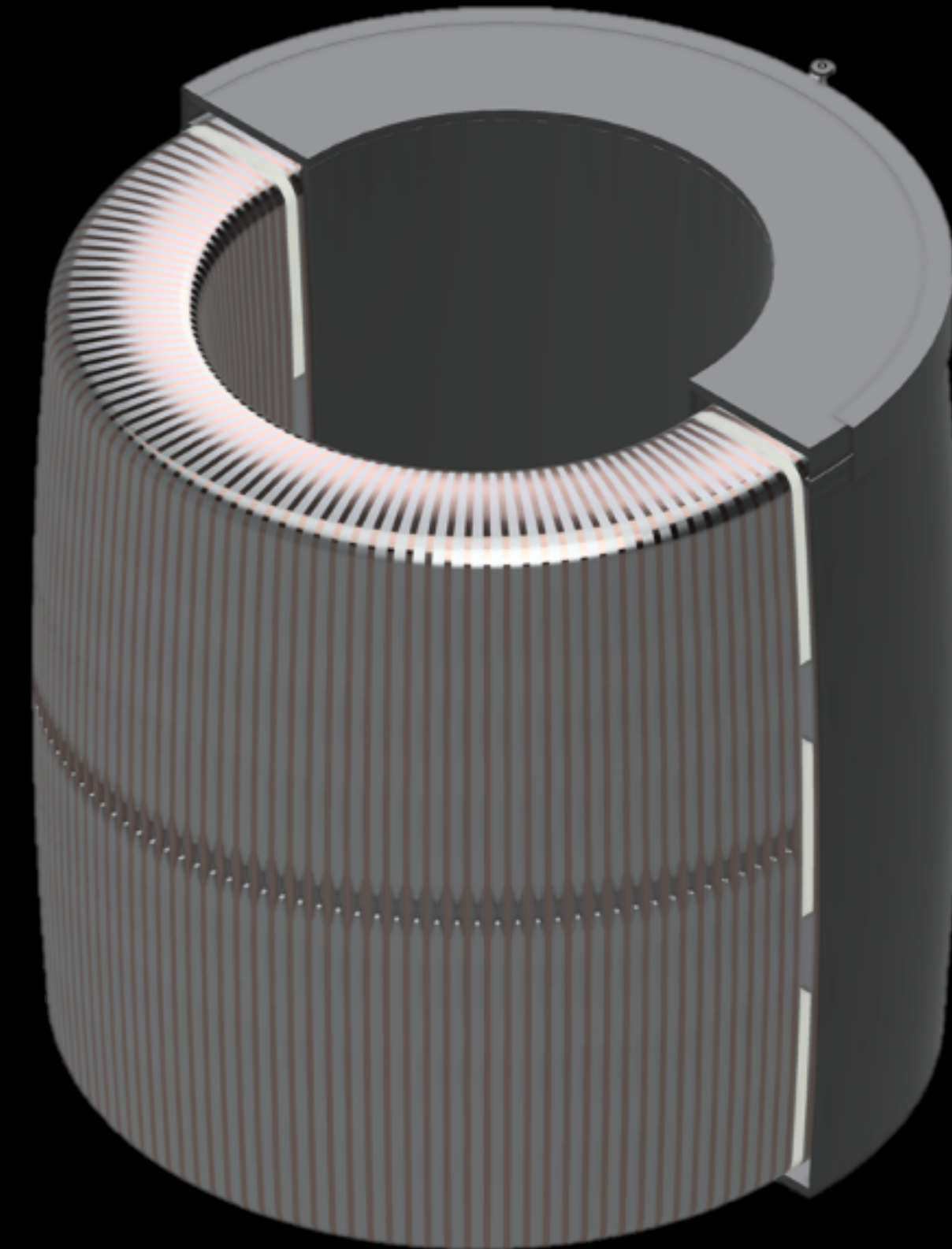


Figure courtesy of Chiara Salemi

# DMRadio-50L Target

- 5 kHz — 5 MHz (20 peV — 20 neV)
- Will serve as a prototyping platform:  
Testbed for quantum readout technologies
- Toroidal magnet with field strength of 1 T  
(~113 A)
- 20 mK base temperature
- Sensitivity goal of  $g_{a\gamma\gamma}=5\times 10^{-15} \text{ GeV}^{-1}$

Sheath Design  
Nicholas Rapidis



Aluminum mandrel with  
superconducting sheath



# DMRadio-50L Experiment

- Searching for axions between 5 kHz and 5 MHz
- Quantum sensing testbed
- Commissioning to happen this fall at Stanford University

Superconducting sheath surrounding the toroidal magnet

BF-LH400

Panel in octagonal vacuum base chamber for feedthroughs

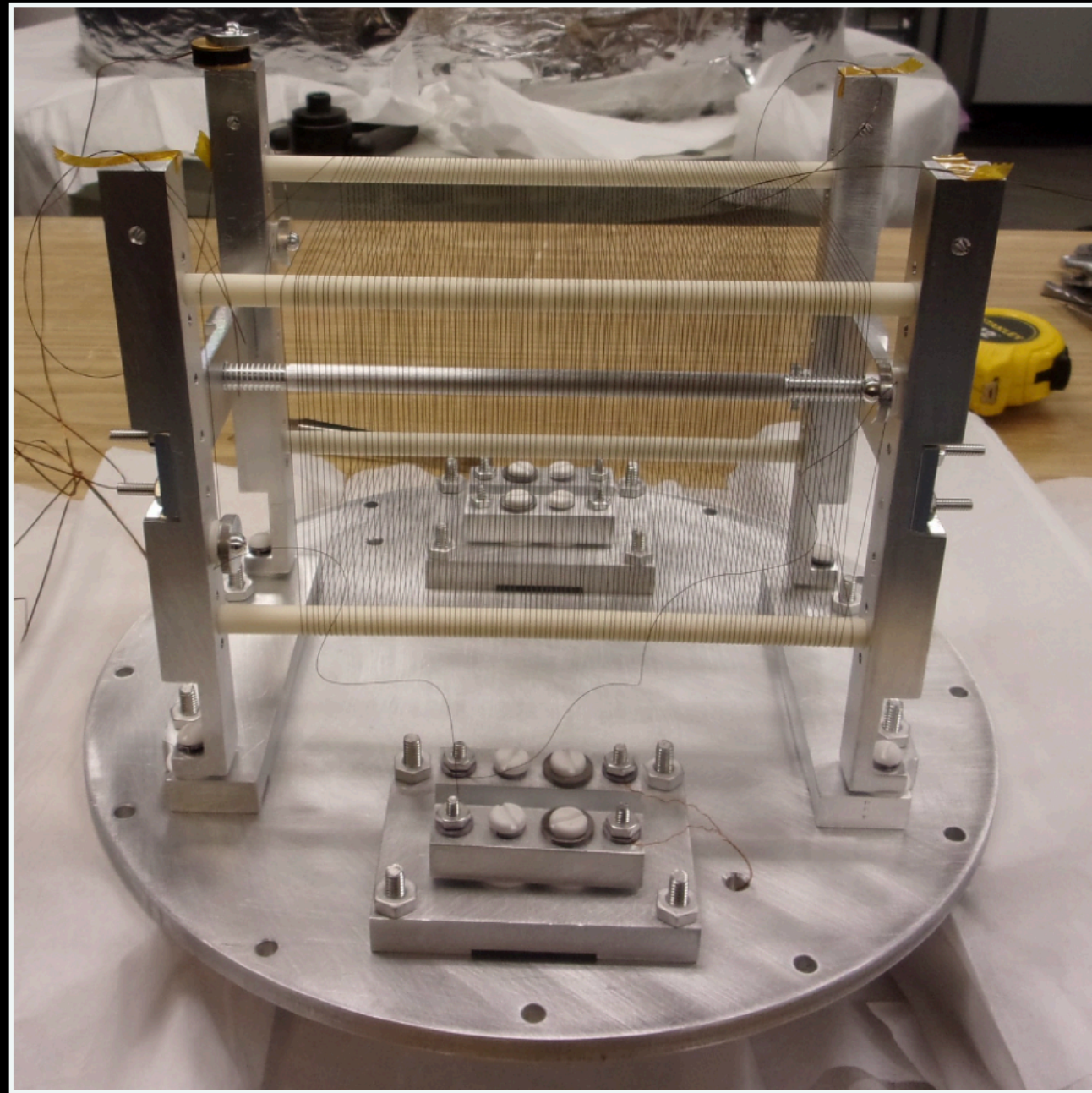
Inductor in the center

PT425-RM to cool 4 K and 40 K plates in custom cryostat

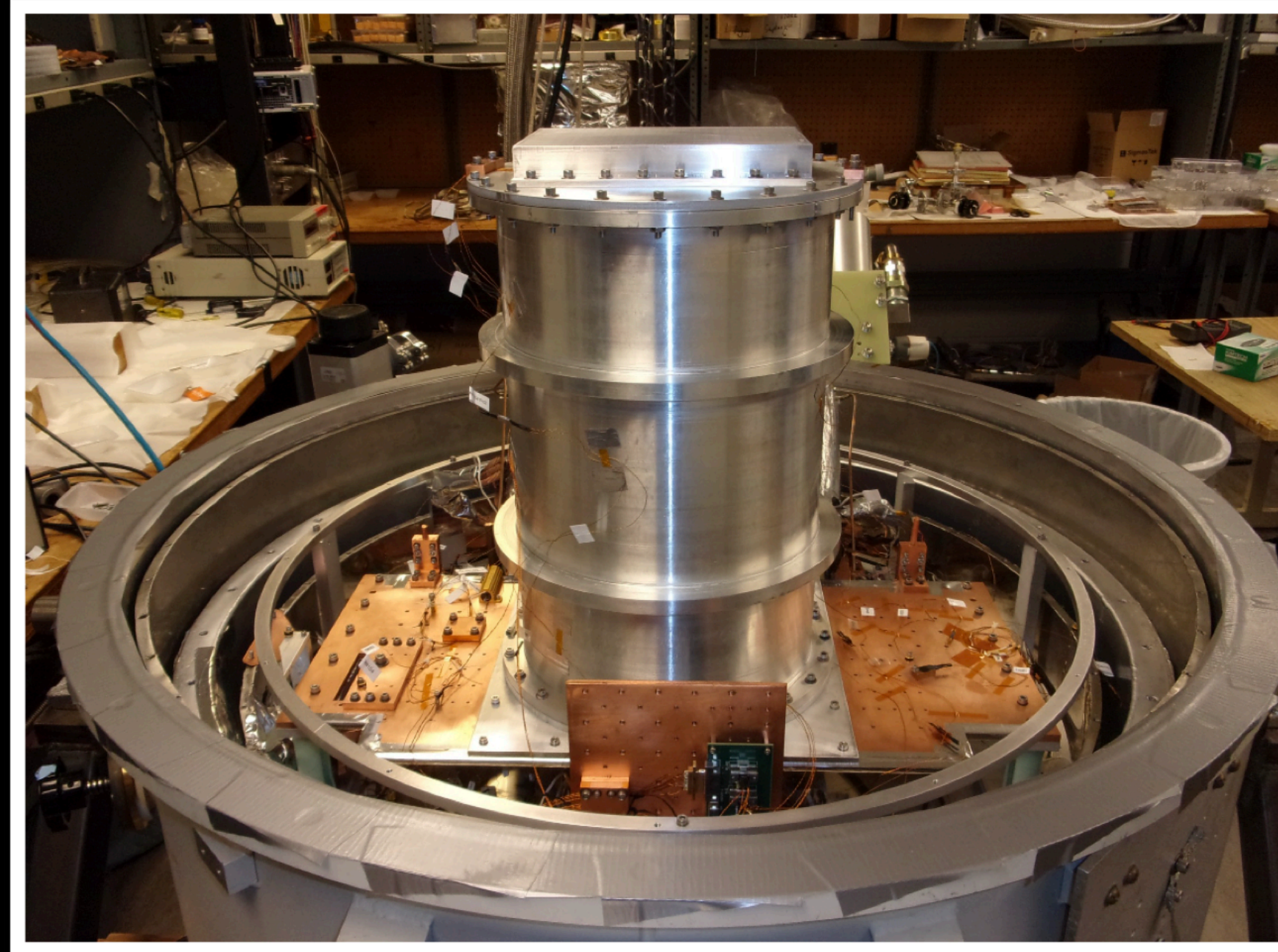
1 K plate with 20 mK plate underneath



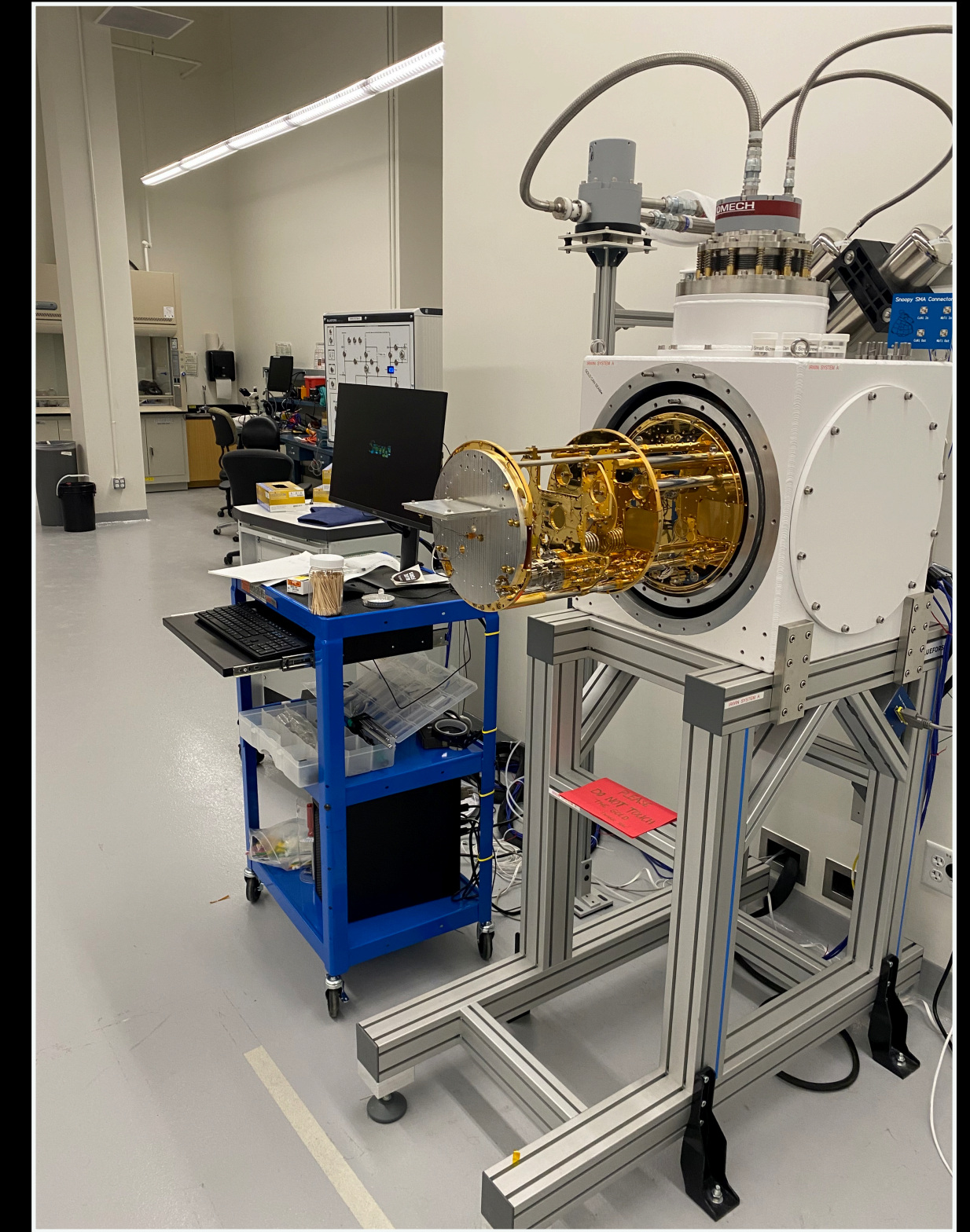
# DMRadio-50L Resonator



Inductor winding  
Saptarshi Chaudhuri  
and Roman Kolevator



Resonator Q testing  
Prototype  $Q = 374,000$  at 300 kHz



Tunable Capacitor  
Joe Singh



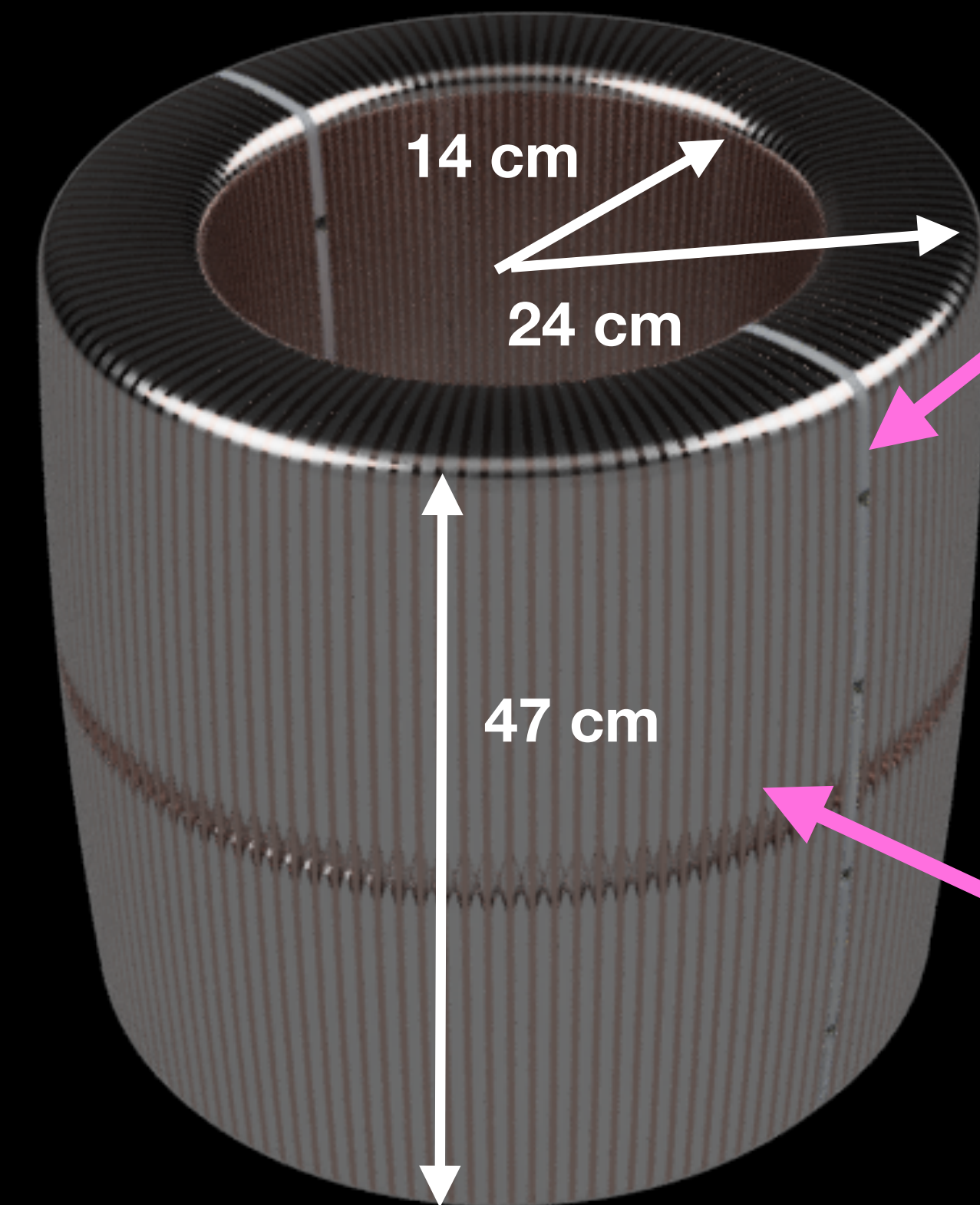
# DMRadio-50L Magnet



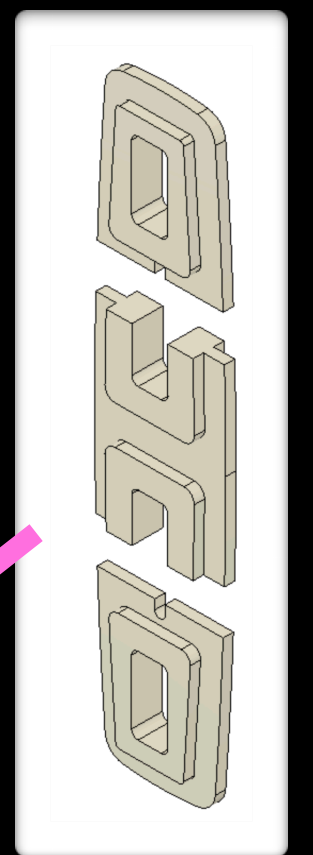
Structural and Thermal Connections  
Alex Droster, Johny Echevers, Jessica Fry



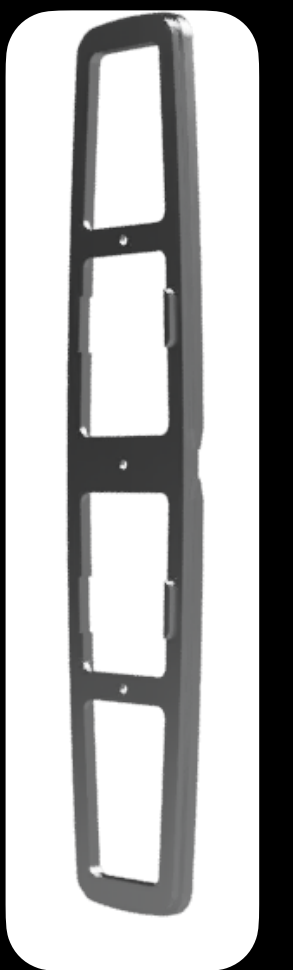
Mandrel construction  
and winding  
Superconducting  
Systems Inc



Aluminum mandrel



2 Insulating  
spacers



69x2 Mandrel  
wedges



# DMRadio-50L Cryostat

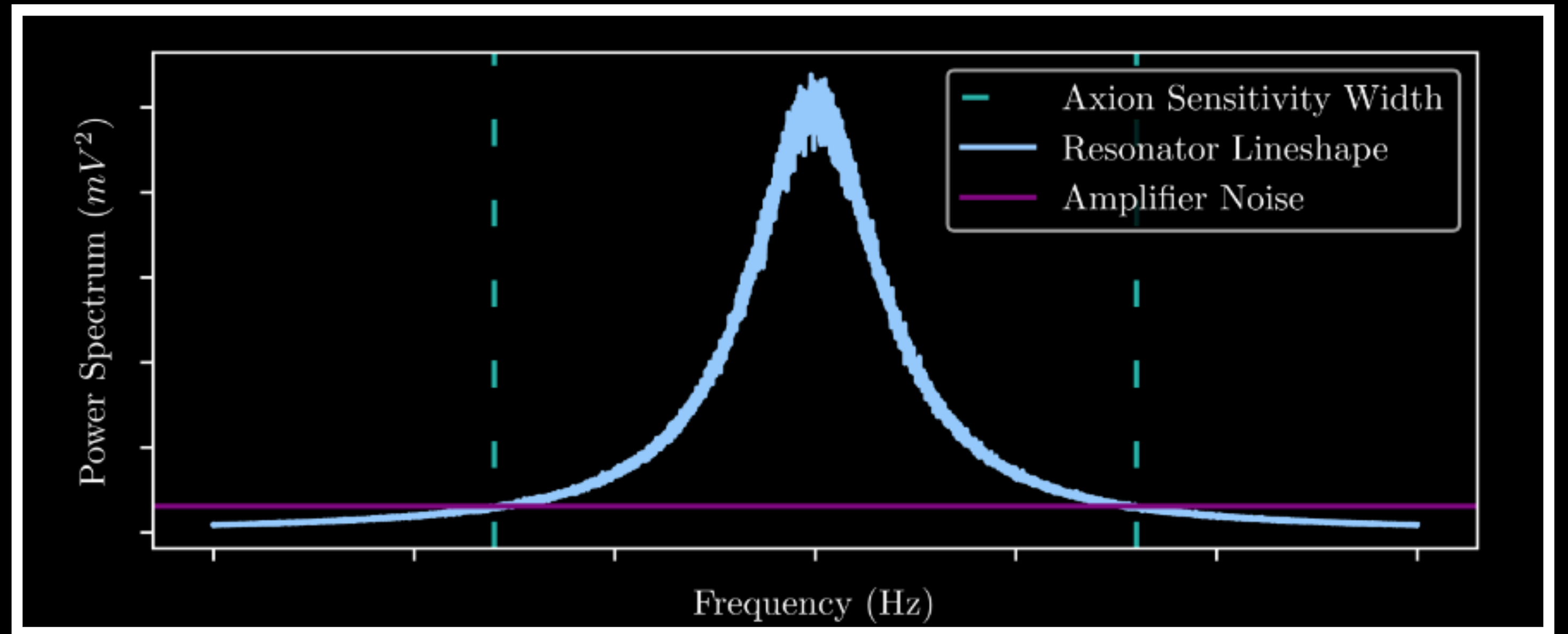


- Cryostat: Fournine Design
- BlueFors LH Dilution Refrigerator



# Quantum sensing techniques + R&D

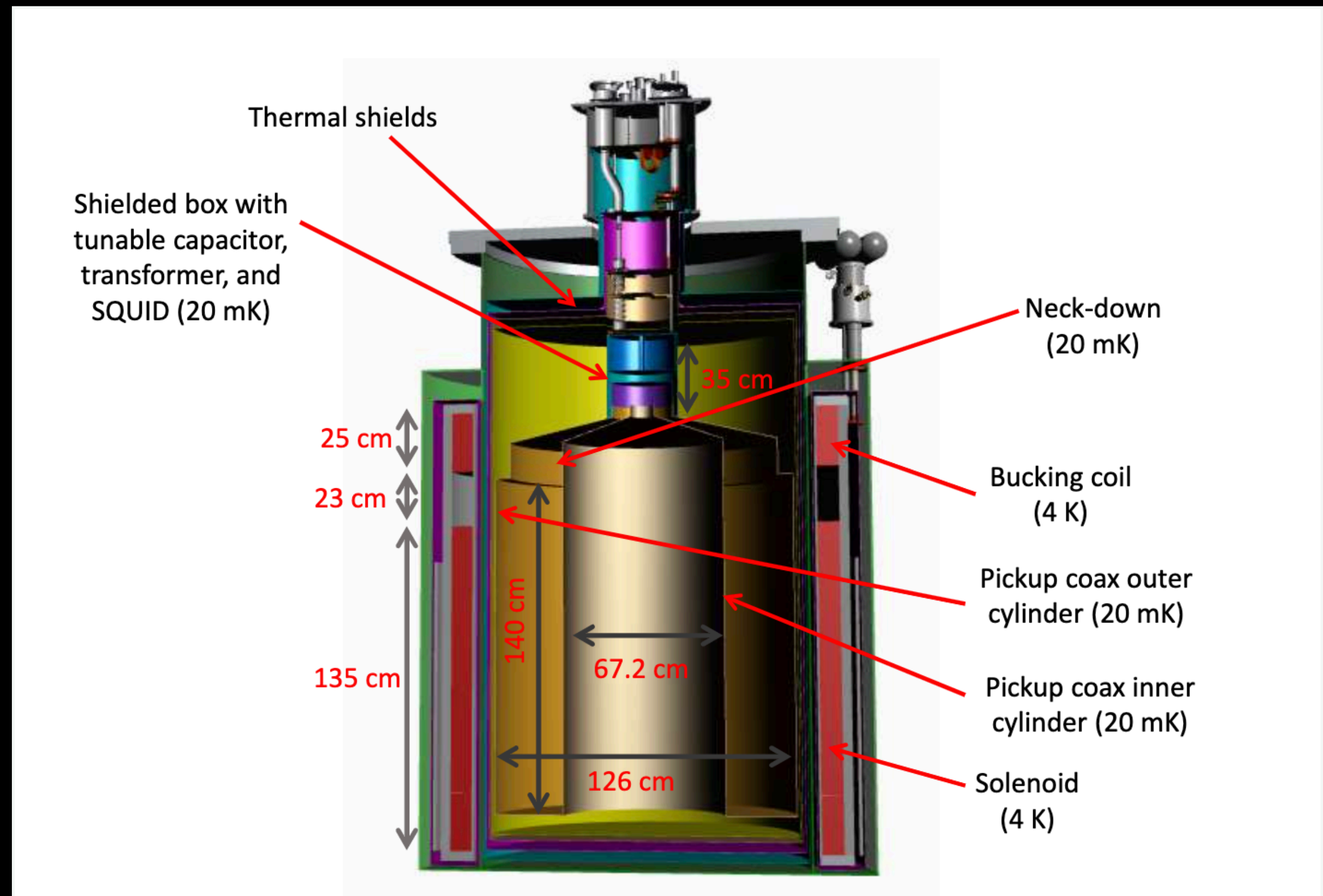
- Increasing the bandwidth via SQUID coupling to the resonator
- Radiofrequency Quantum Upconverters (RQUs)
- Bode-Fano Evasion



...happy to field more questions later!

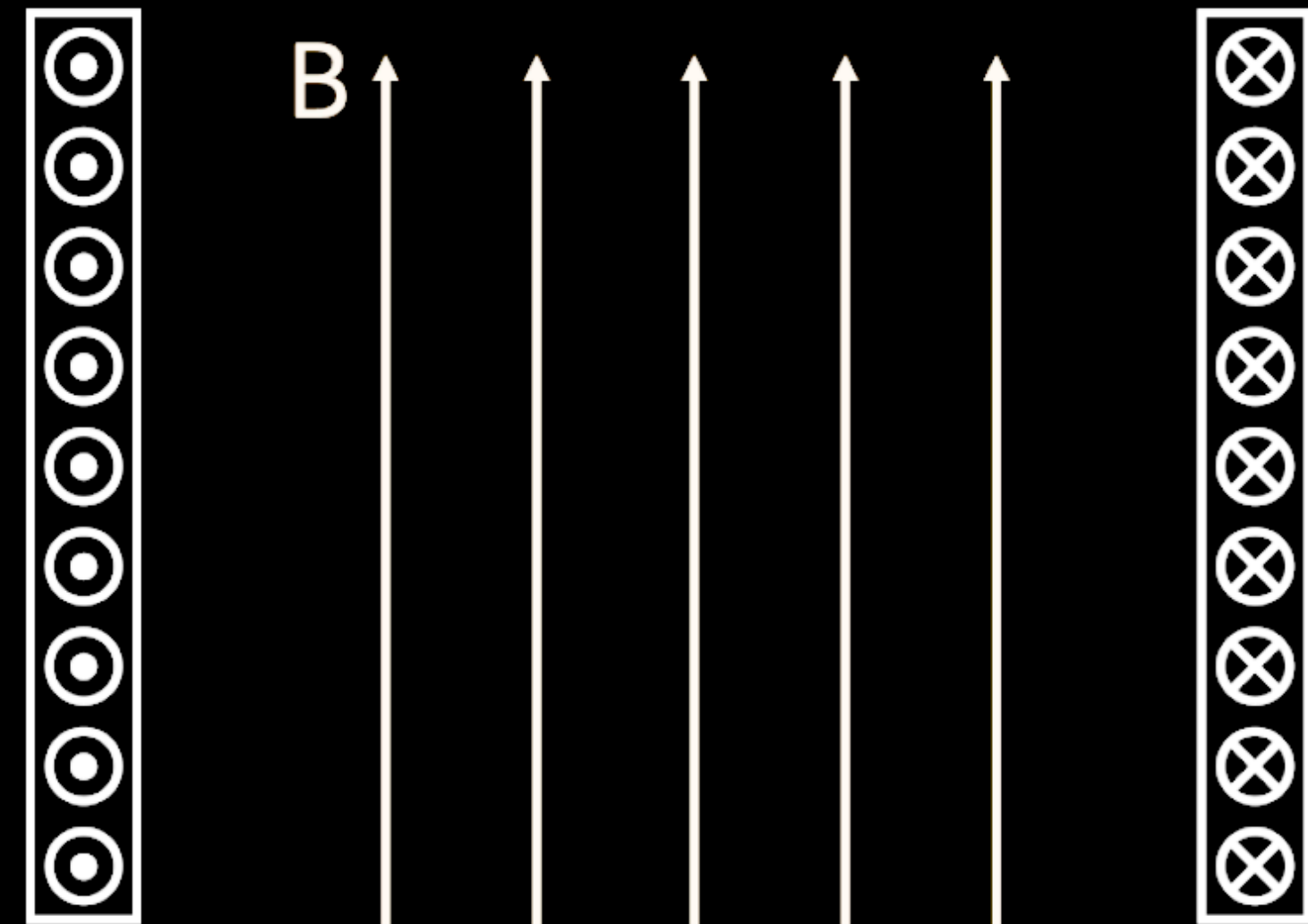
# DMRadio-m<sup>3</sup> Target

- 10 — 200 MHz (40 neV — 1.2  $\mu$ eV)
  - 30 — 200 MHz at DFSZ sensitivity
- Solenoidal magnet
- Coaxial copper pickup structure
- 20 mK base temperature
- 4.7 T magnetic field



# DMRadio-m<sup>3</sup> Target

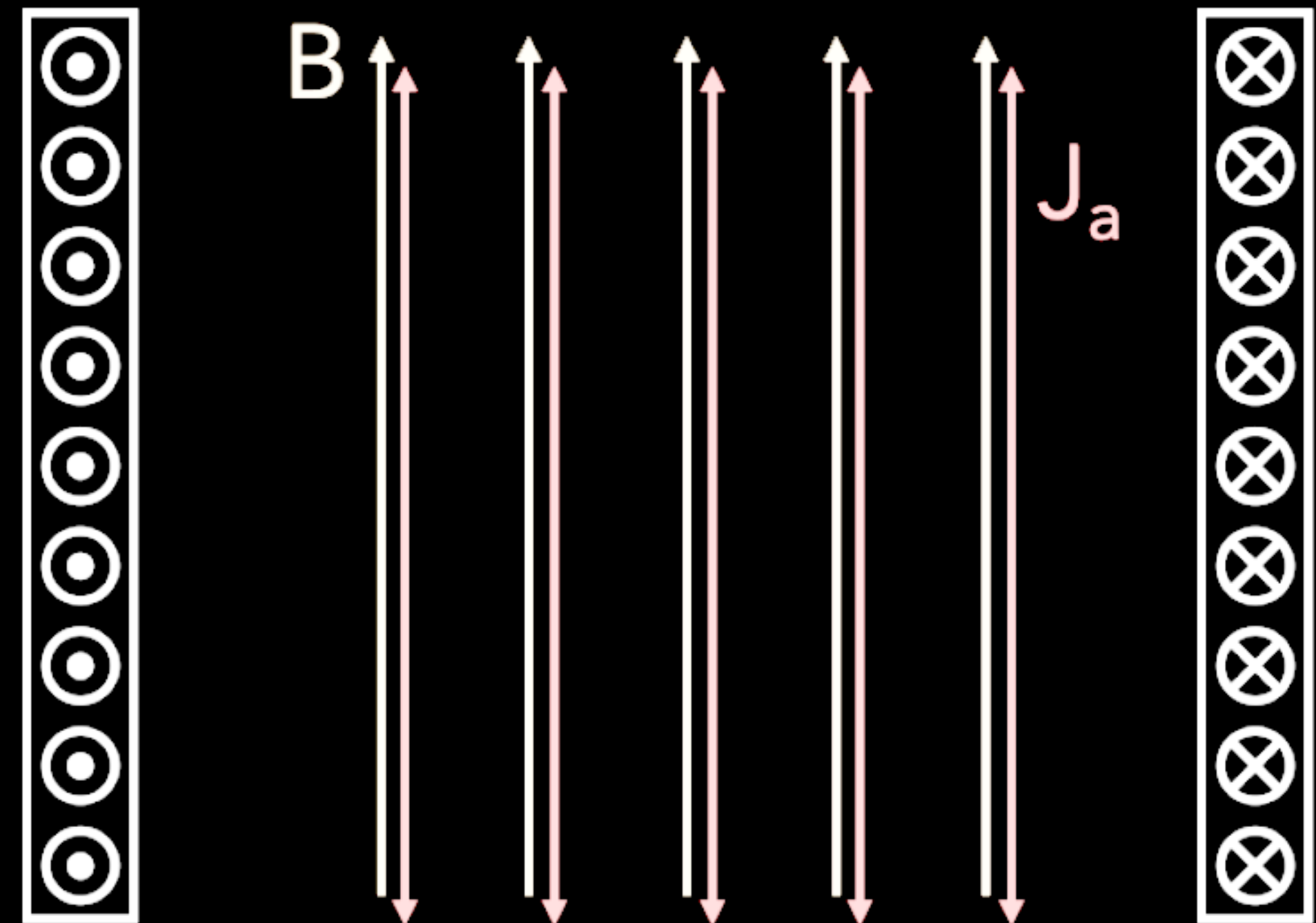
- **Static magnetic field in z-direction**





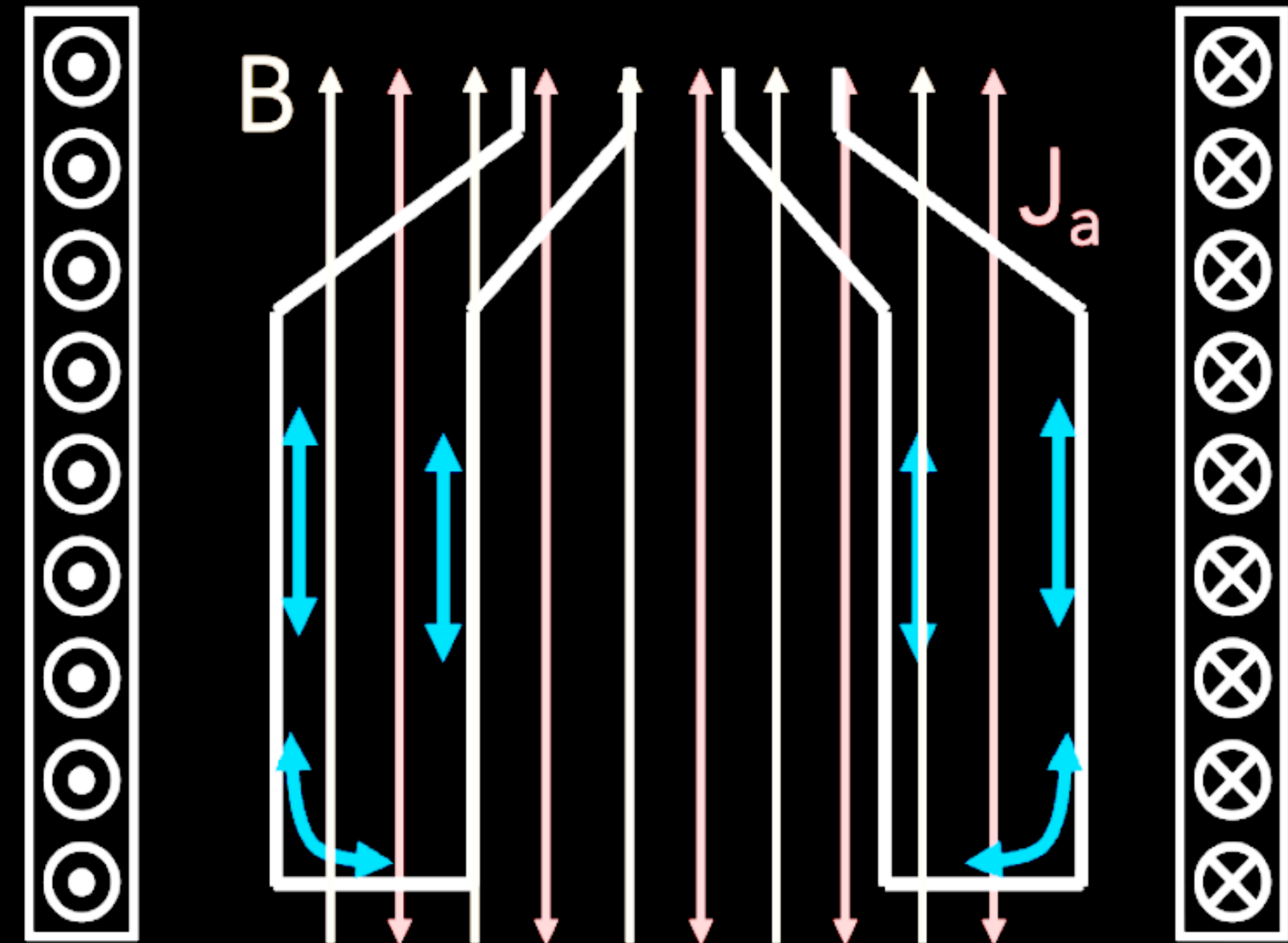
# DMRadio- $m^3$ Target

- Static magnetic field in z-direction
- **Magnetic field and axions are coupled to a surface current,  $J_a$**



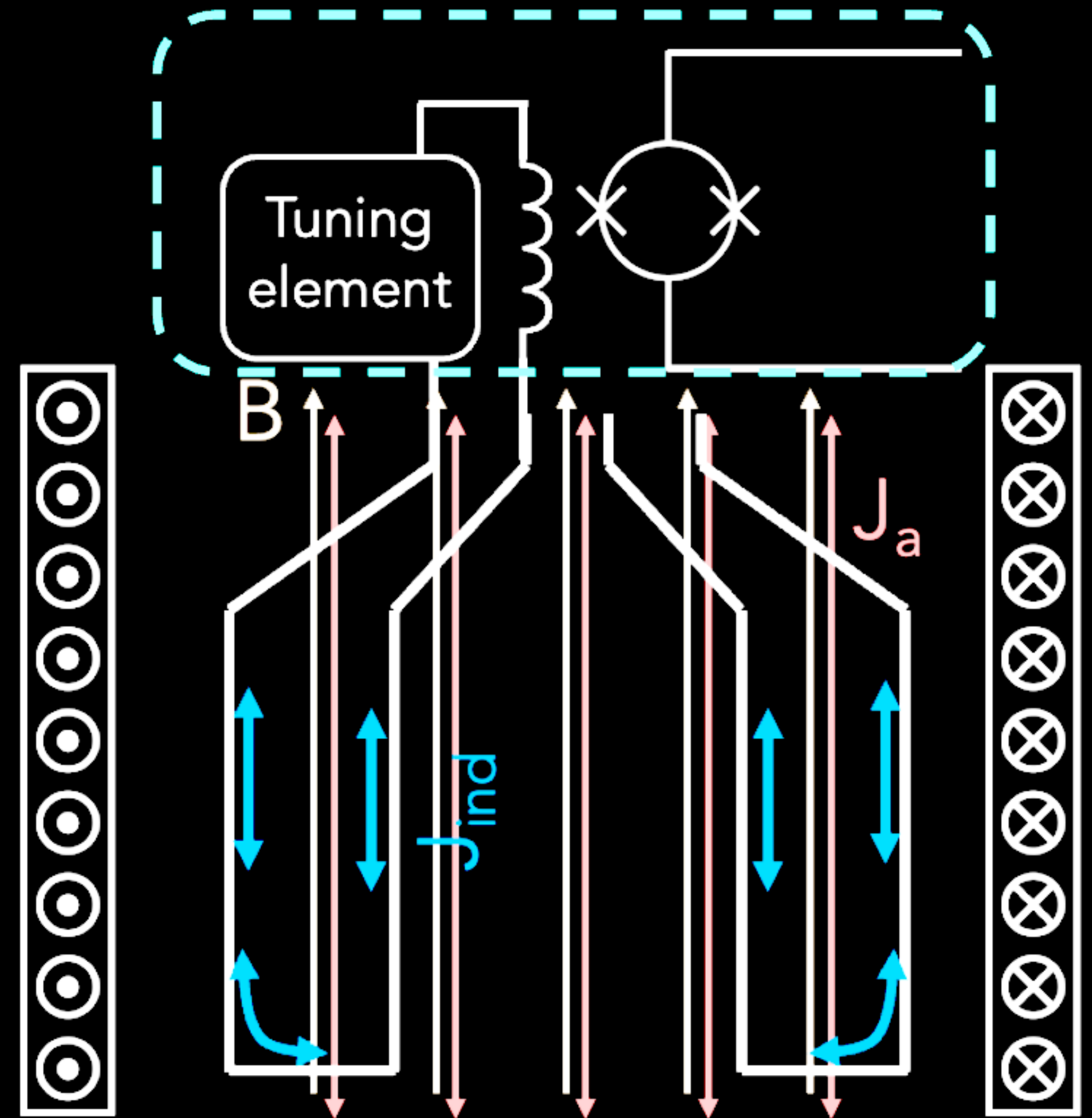
# DMRadio-m<sup>3</sup> Target

- Static magnetic field in z-direction
- Magnetic field and axions are coupled to a surface current,  $J_a$
- **Surface-current-induced magnetic field is picked up by coaxial inductor**



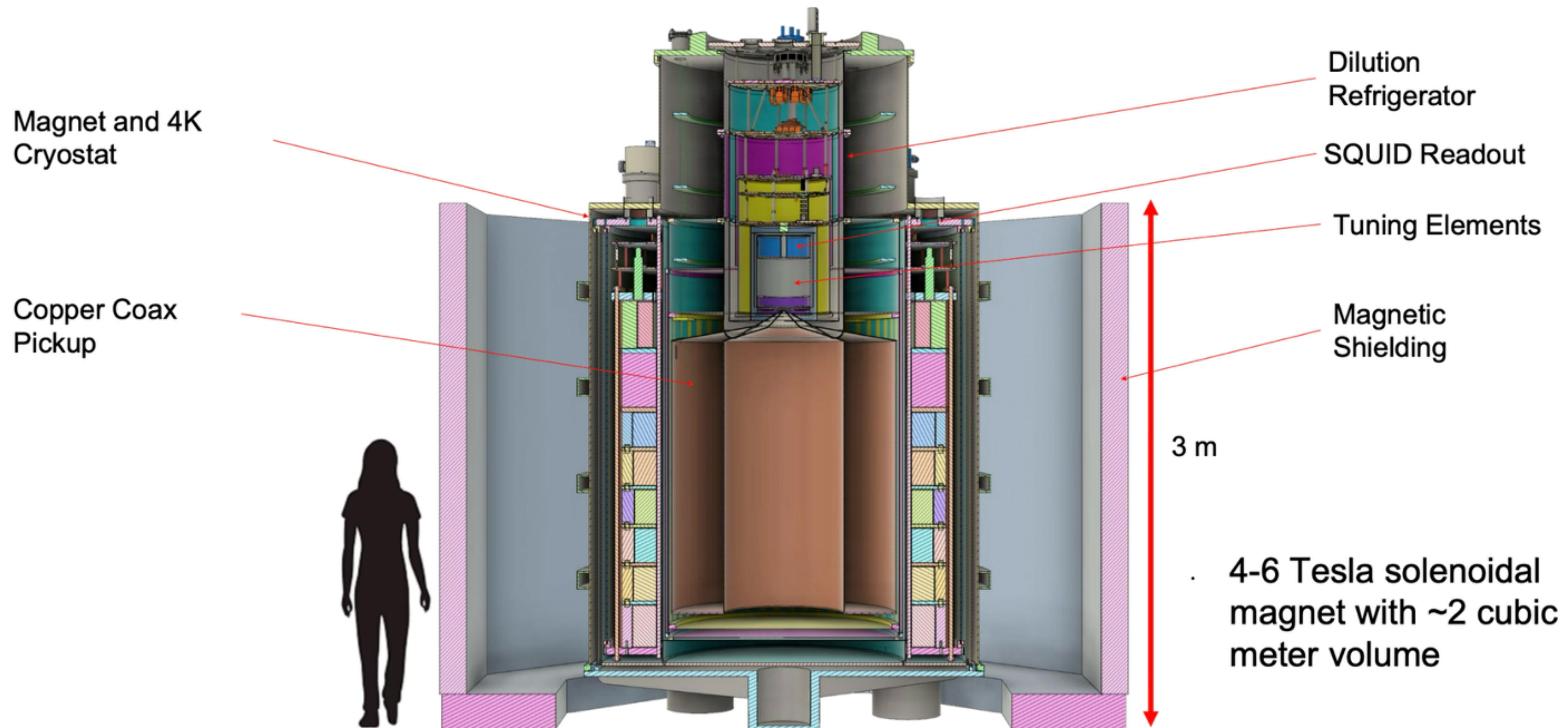
# DMRadio-m<sup>3</sup> Target

- Static magnetic field in z-direction
- Magnetic field and axions are coupled to a surface current,  $J_a$
- Surface-current-induced magnetic field is picked up by coaxial inductor
- **Tuning elements control resonance frequency that couples into a SQUID**
- **Low field region generated with bucking coils and shielding**

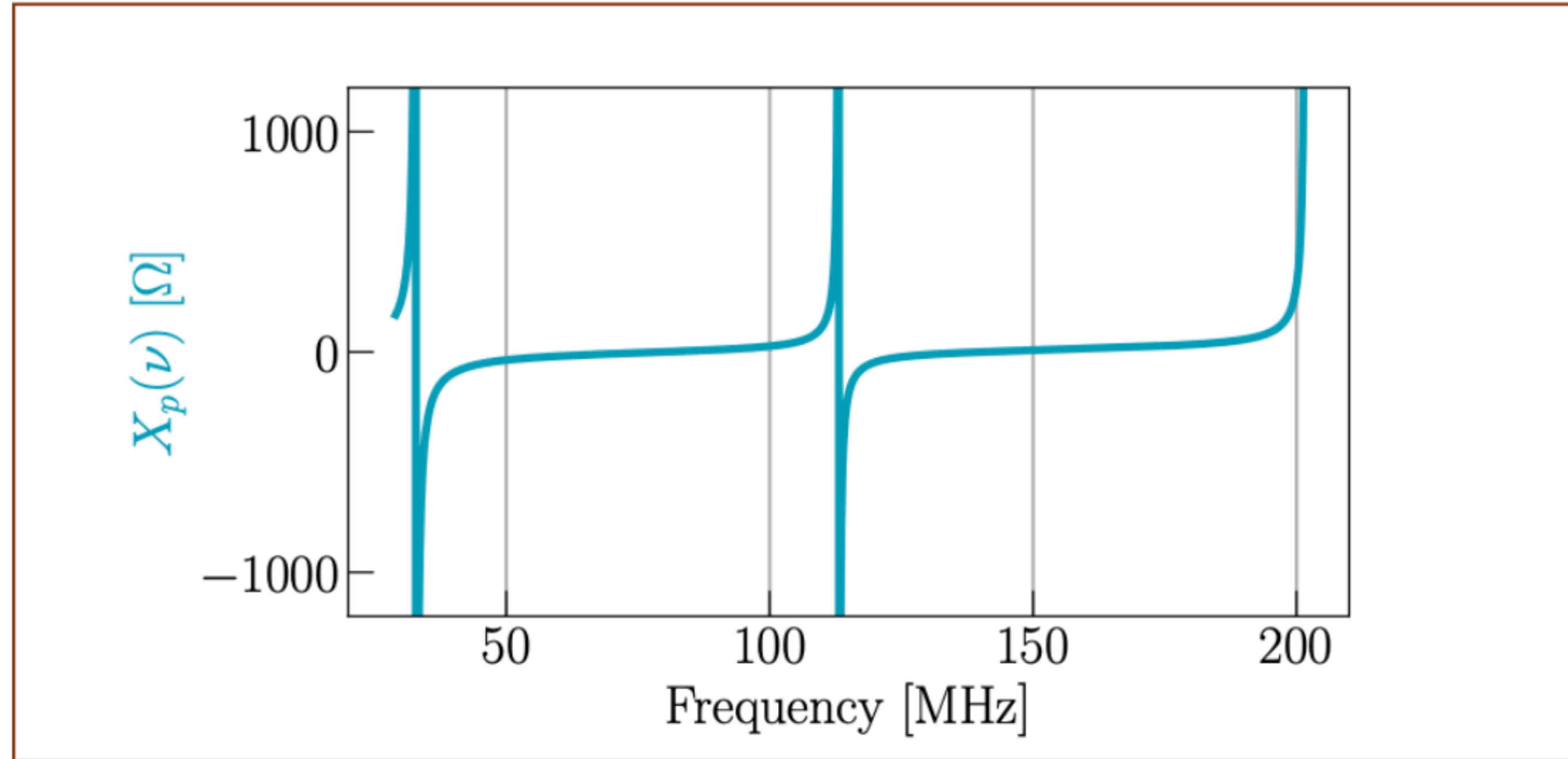




# DMRadio-m<sup>3</sup> Target



# DMRadio-m<sup>3</sup> Tuning



Images courtesy of N. Rapidis

$$Z_p(\nu) = R_p(\nu) + iX_p(\nu)$$

Taylor expand the impedance in terms of frequency-specific RLC series circuit components

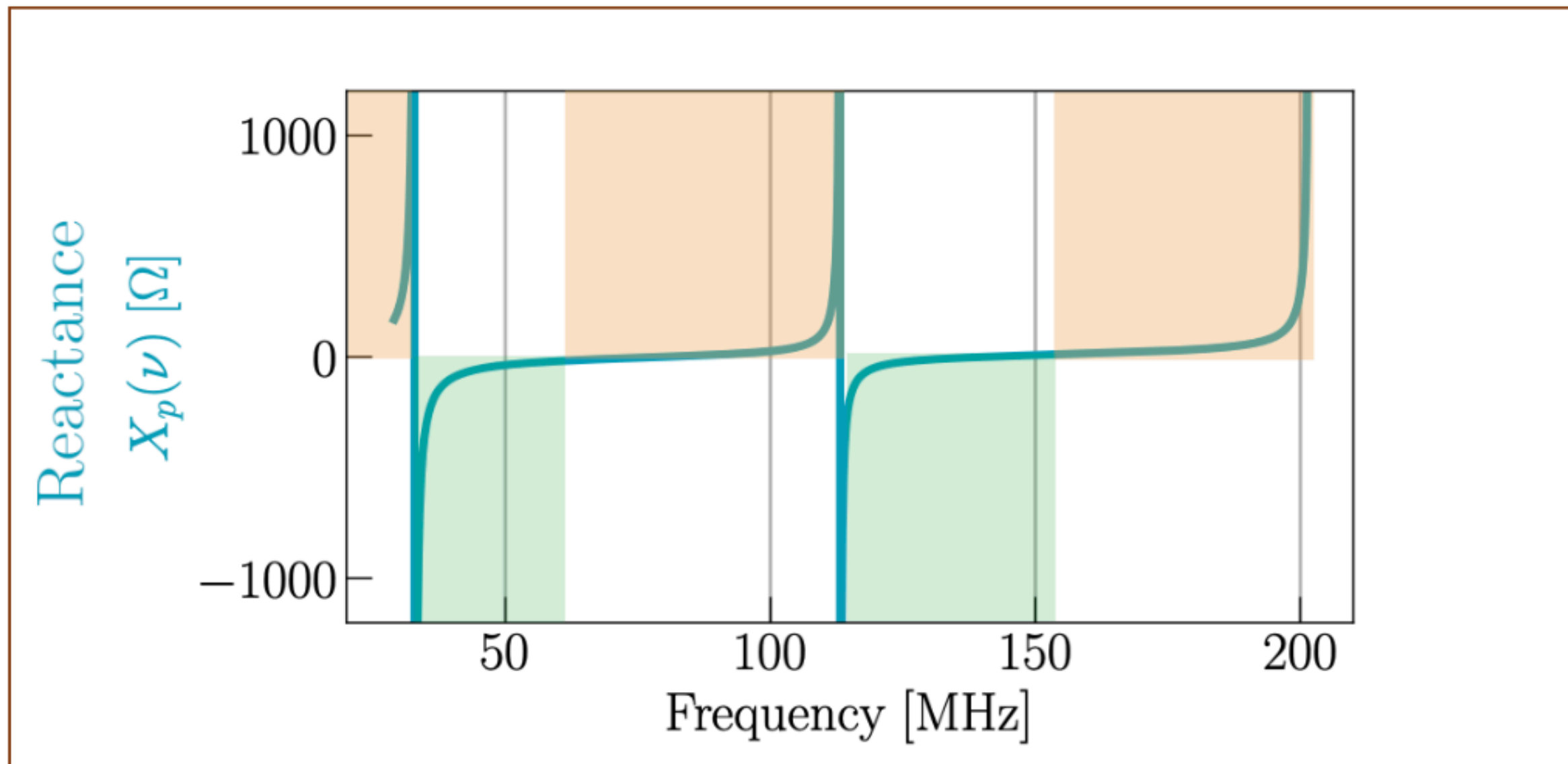
To be extracted

$$Z_p(\nu_0) = R_p(\nu_0) + iX_p(\nu_0) = \underbrace{R(\nu_0)}_{\text{Simulation}} + i2\pi\nu_0 L_{\text{eff}}(\nu_0) - \frac{i}{2\pi\nu_0 C_{\text{eff}}(\nu_0)}$$

Simulation

# DMRadio-m<sup>3</sup> Tuning

capacitive tuning



inductive tuning

$$Z_p(\nu) = R_p(\nu) + iX_p(\nu)$$

Images courtesy of N. Rapidis

To achieve resonance at a given frequency, the reactance must be tuned to zero.

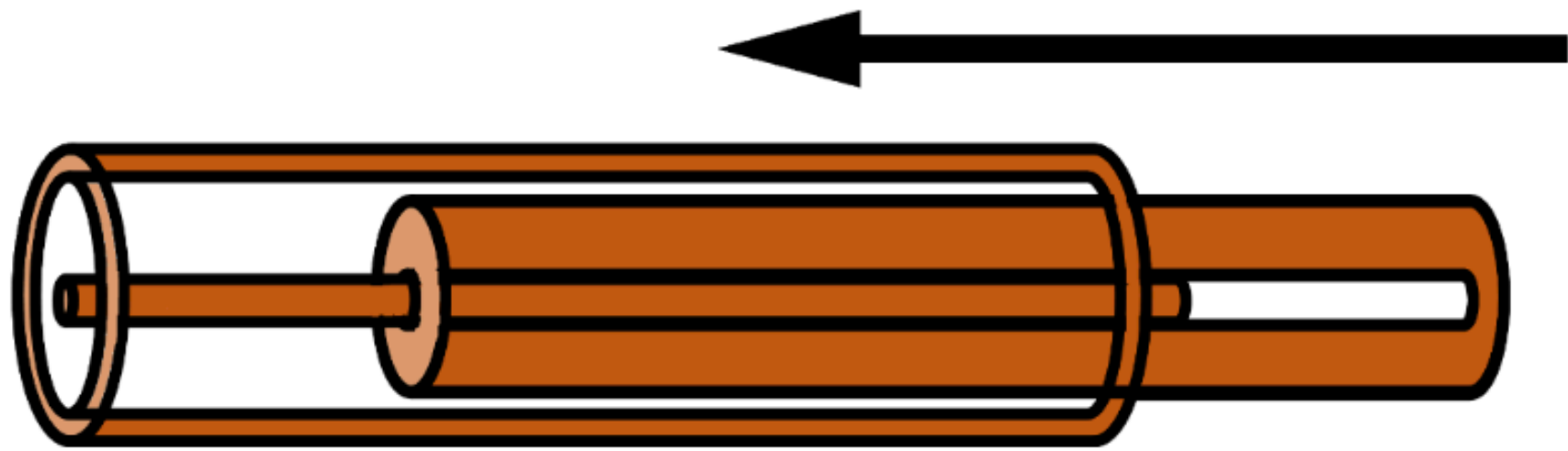
$$X_{\text{tot}}(\nu_0) = X_{\text{tuning}}(\nu_0) + X_p(\nu_0) = 0$$

selected  
reactance

reactance to  
cancel

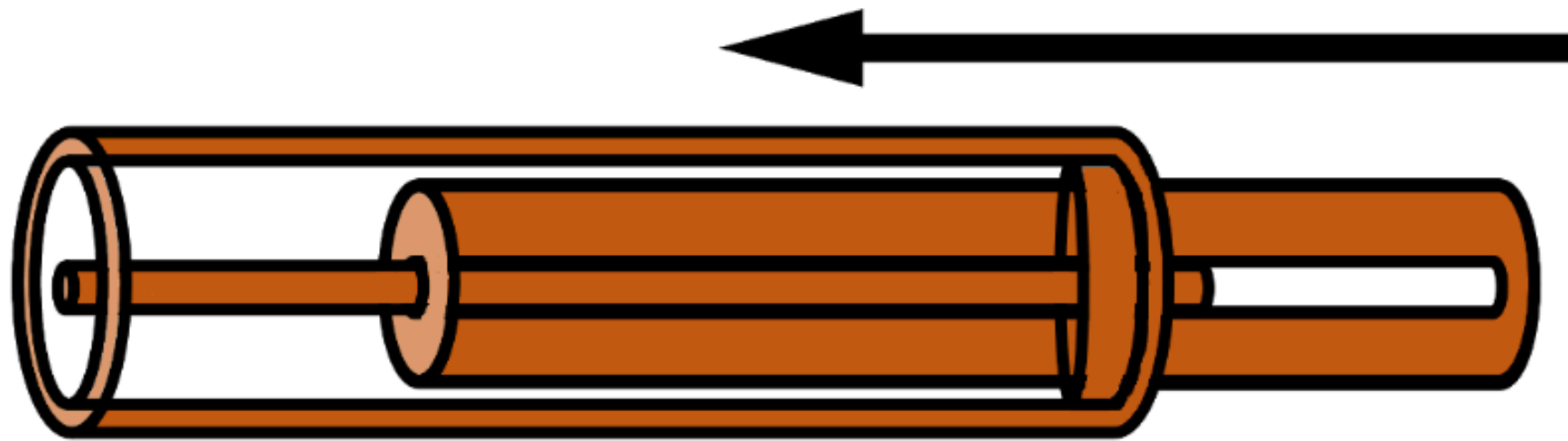


# DMRadio-m<sup>3</sup> Tuning Elements



Sliding rod increases capacitance in direction of arrow

Simple modification to go from capacitive to inductive tuning element: short the tubes.



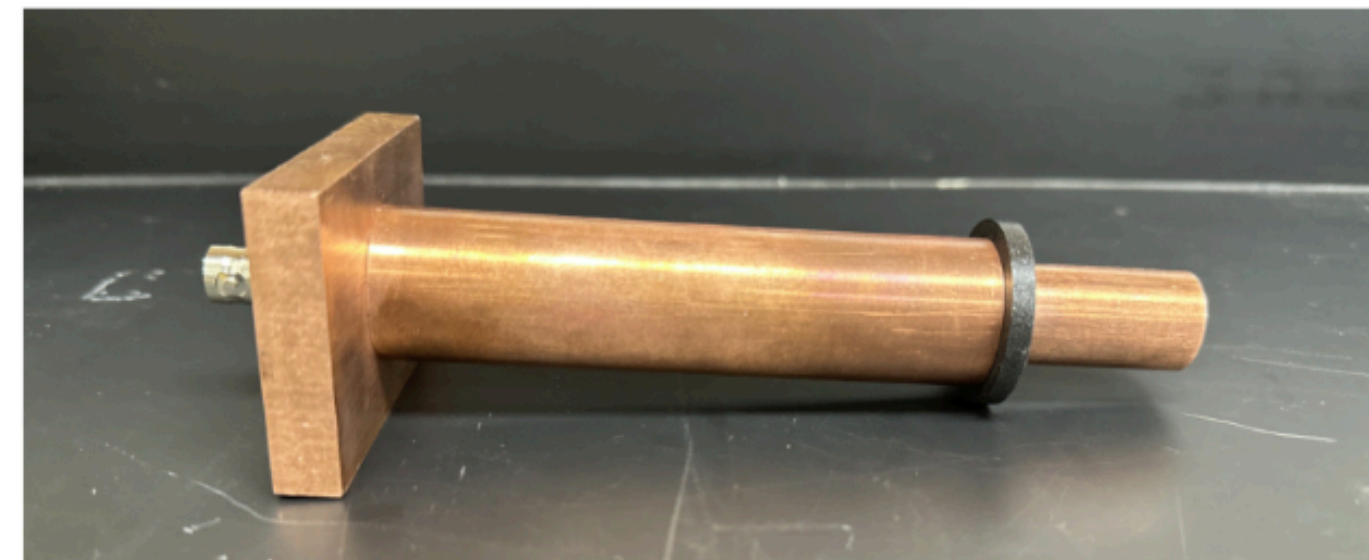
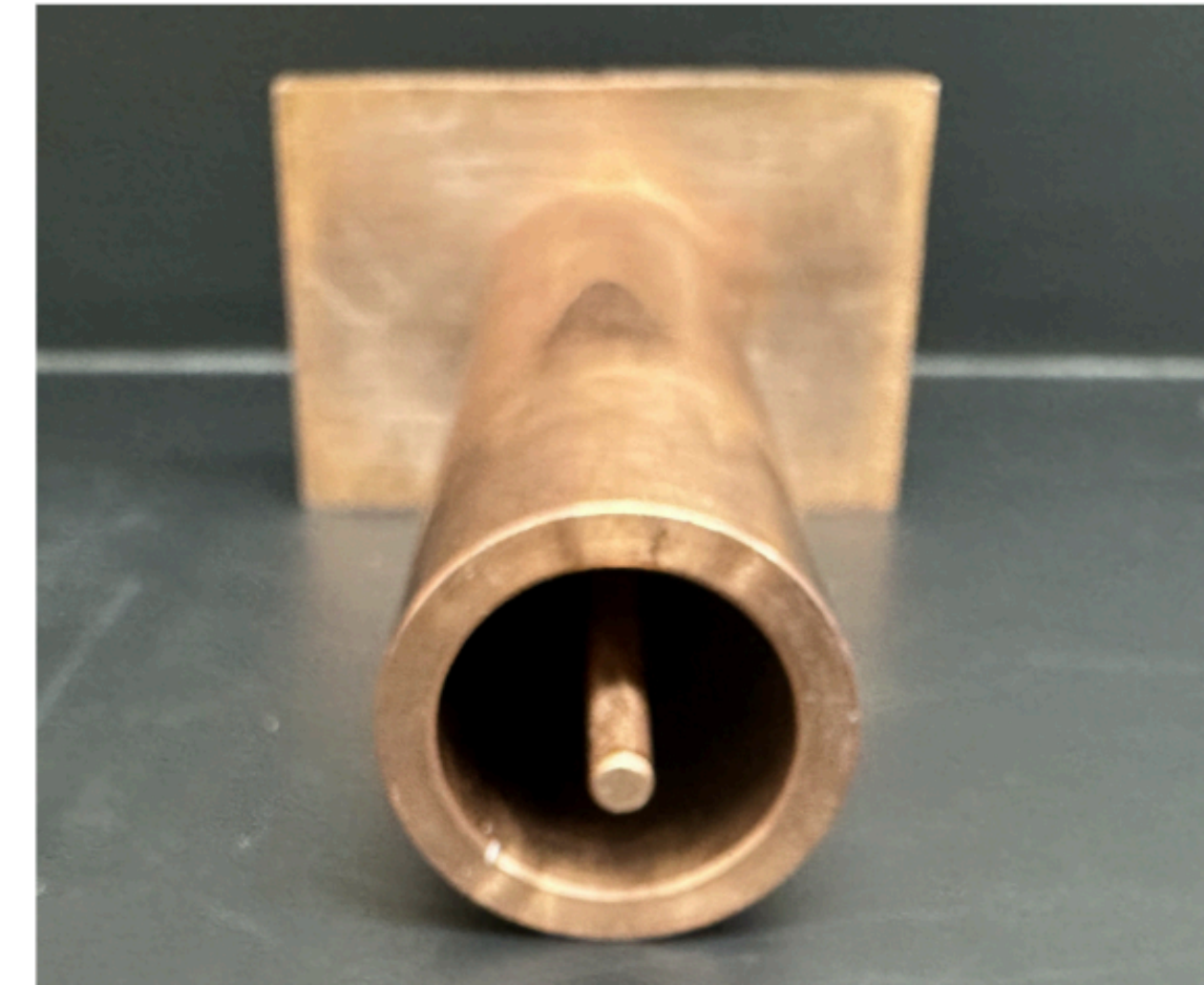
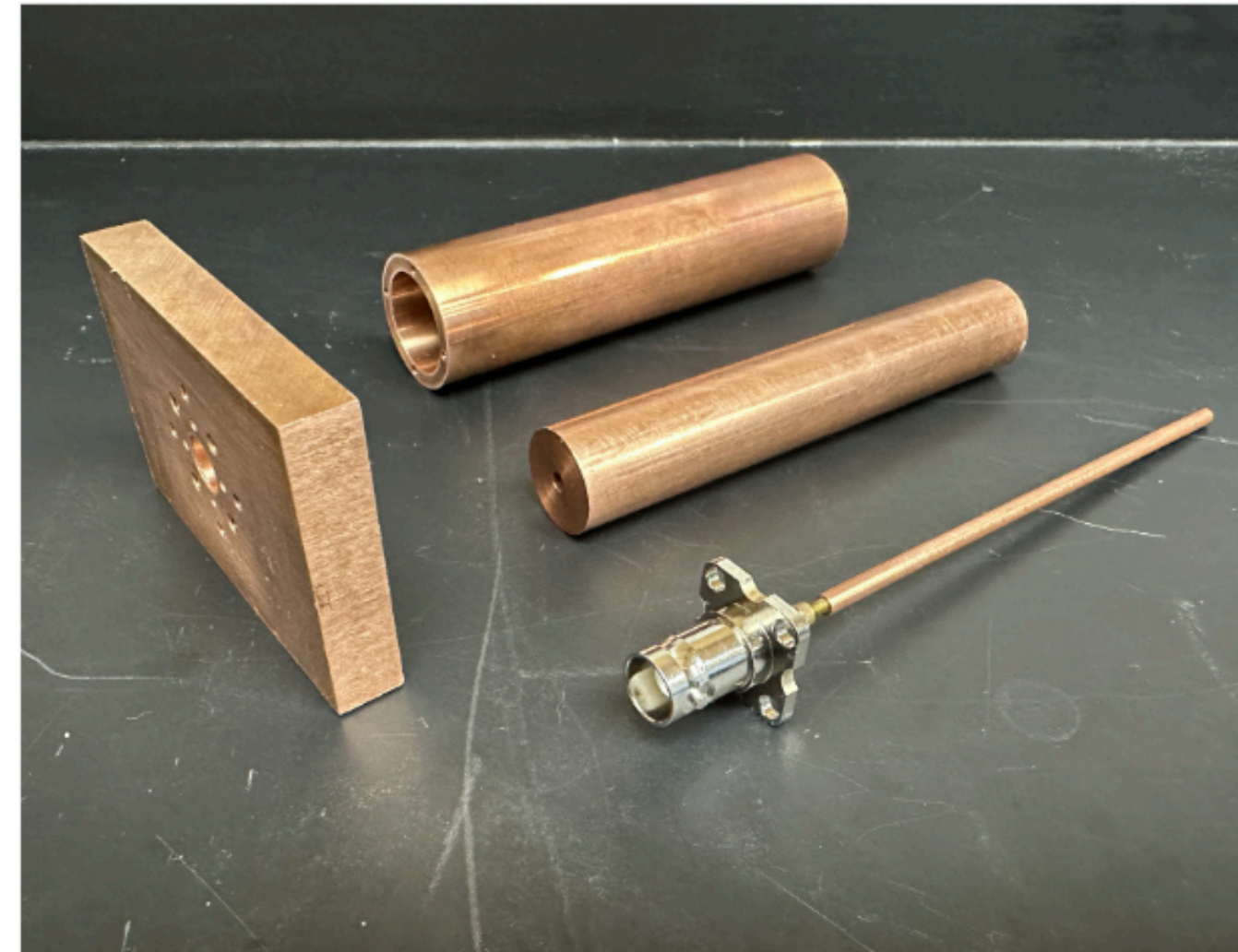
Sliding rod increases inductance in direction of arrow



# DMRadio-m<sup>3</sup> Tuning Elements

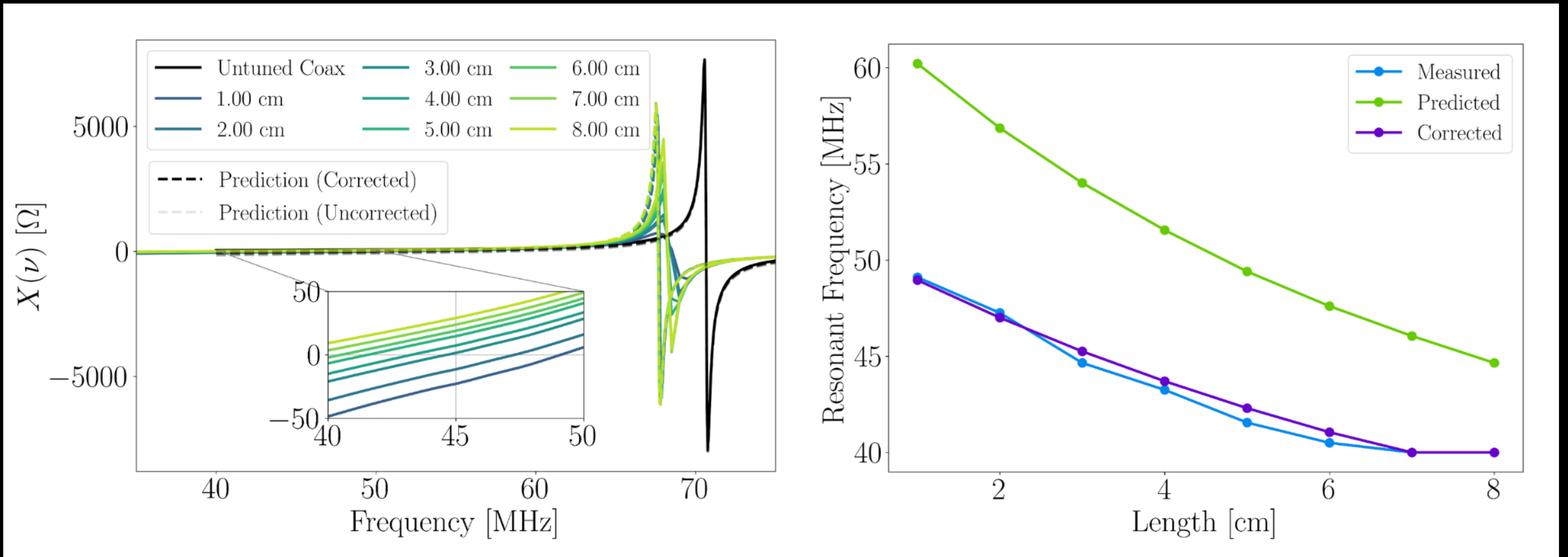
- Pieces machined out of copper
- BNC connector screws into inner rod
- 3D printed spacer to stabilize sliding rod in capacitive mode.
- Copper spacer shorts the tubes in inductive mode.
- Studied with antenna analyzer.

Images courtesy of E. Berzin



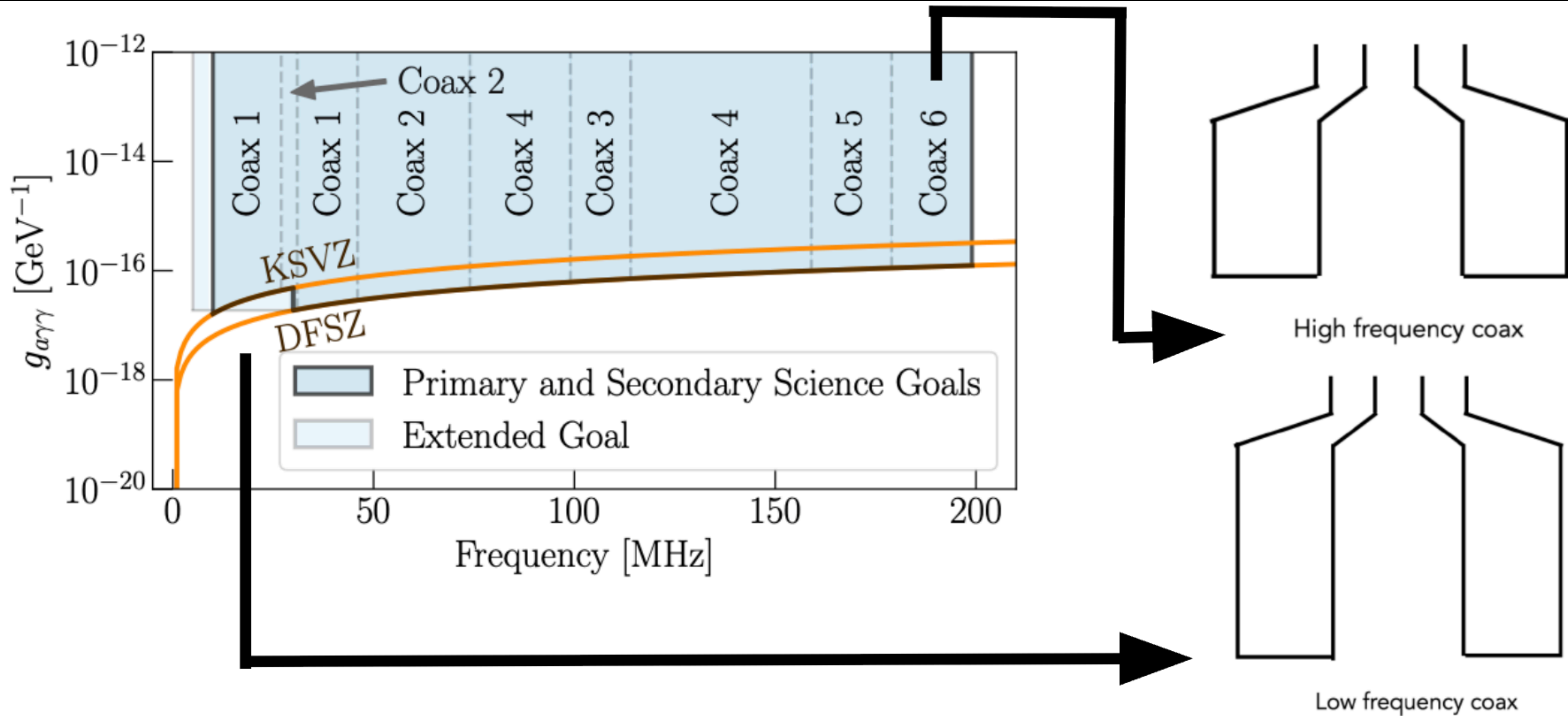


# DMRadio-m<sup>3</sup> Tuning Elements: Example of capacitive tuning



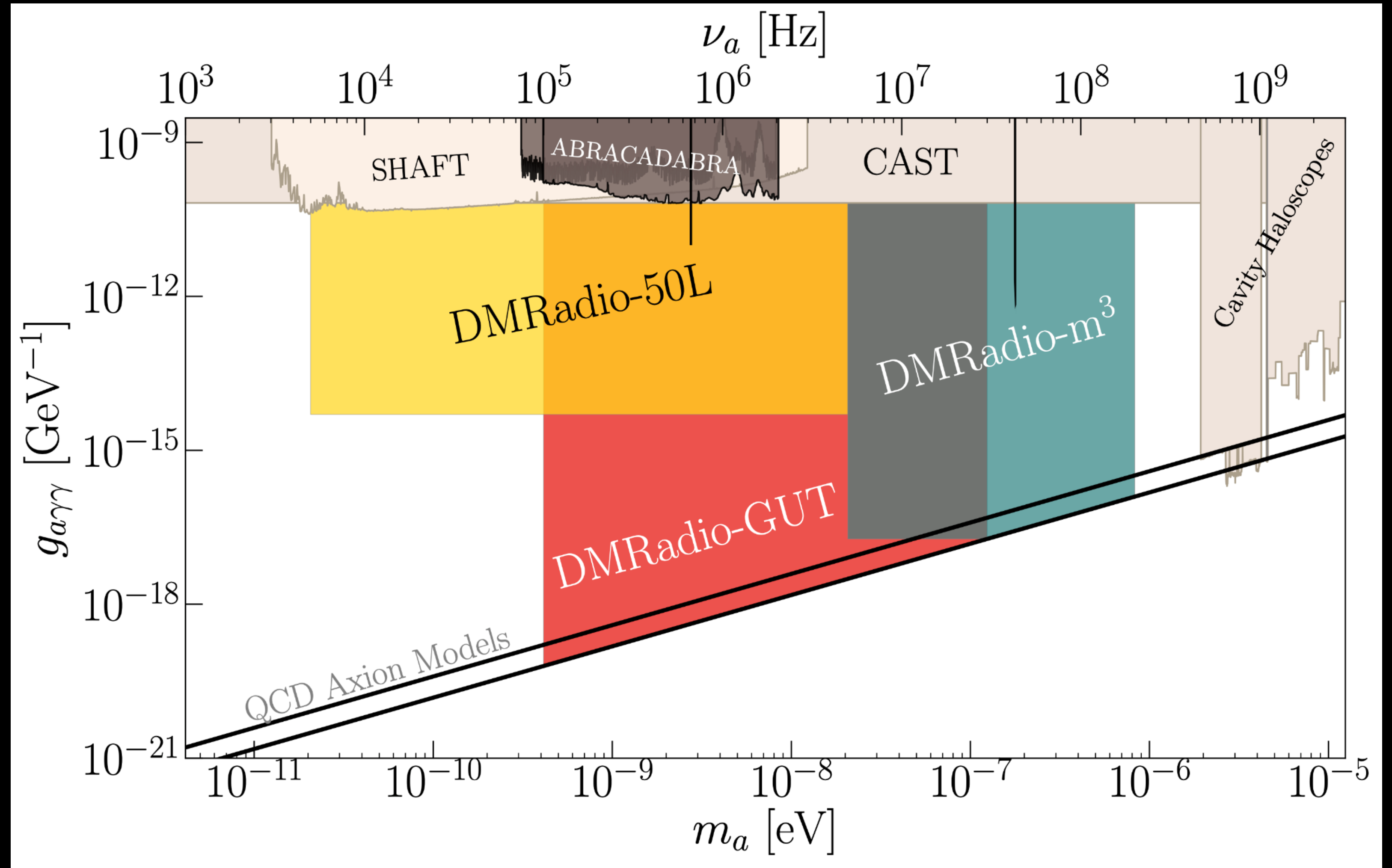


# DMRadio-m<sup>3</sup> Tuning Elements: Example of capacitive tuning



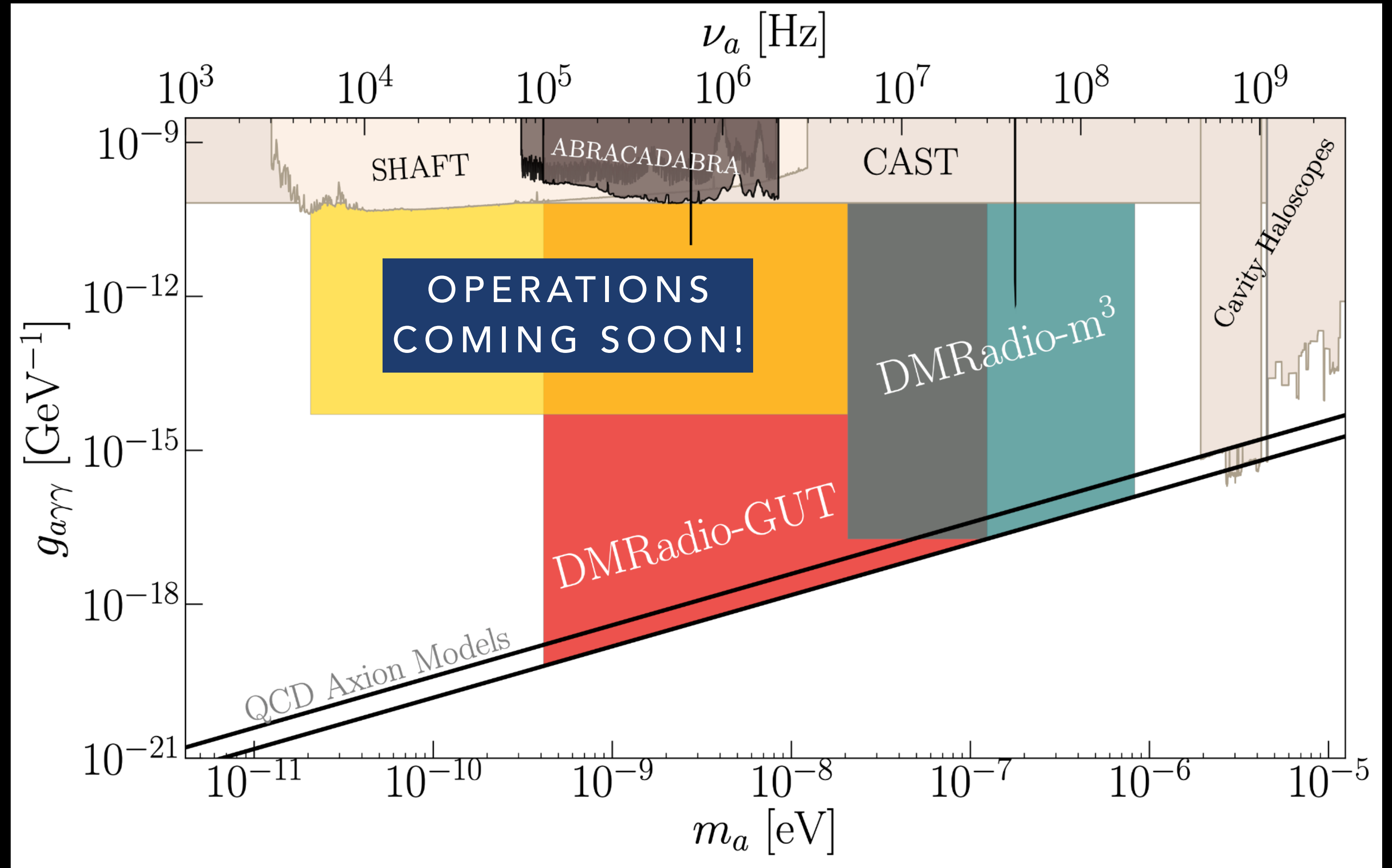
# DMRadio Sensitivity Targets

- DMRadio-50L:
  - 20 peV - 20 neV
  - 5 kHz - 5 MHz
- DMRadio-m3:
  - DFSZ
    - 100 neV - 800 neV
    - 30 - 200 MHz
  - KSVZ
    - 40 neV - 100 neV
    - 10 - 30 MHz
- DMRadio-GUT: arXiv:2203.11246
  - DFSZ
    - 0.4 - 100 neV
    - 100 kHz - 30 MHz

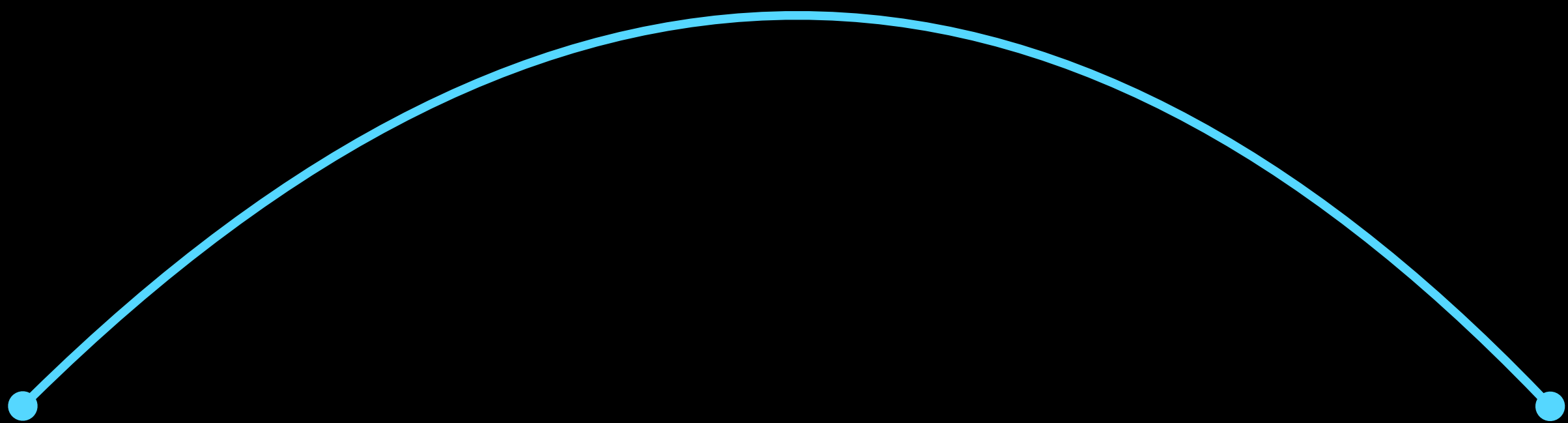


# DMRadio Sensitivity Targets

- DMRadio-50L:
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    - 30 - 200 MHz
  - KSVZ
    - 40 neV - 100 neV
    - 10 - 30 MHz
- DMRadio-GUT: arXiv:2203.11246
  - DFSZ
    - 0.4 - 100 neV
    - 100 kHz - 30 MHz







AXIONS AND WAVE-LIKE DARK MATTER

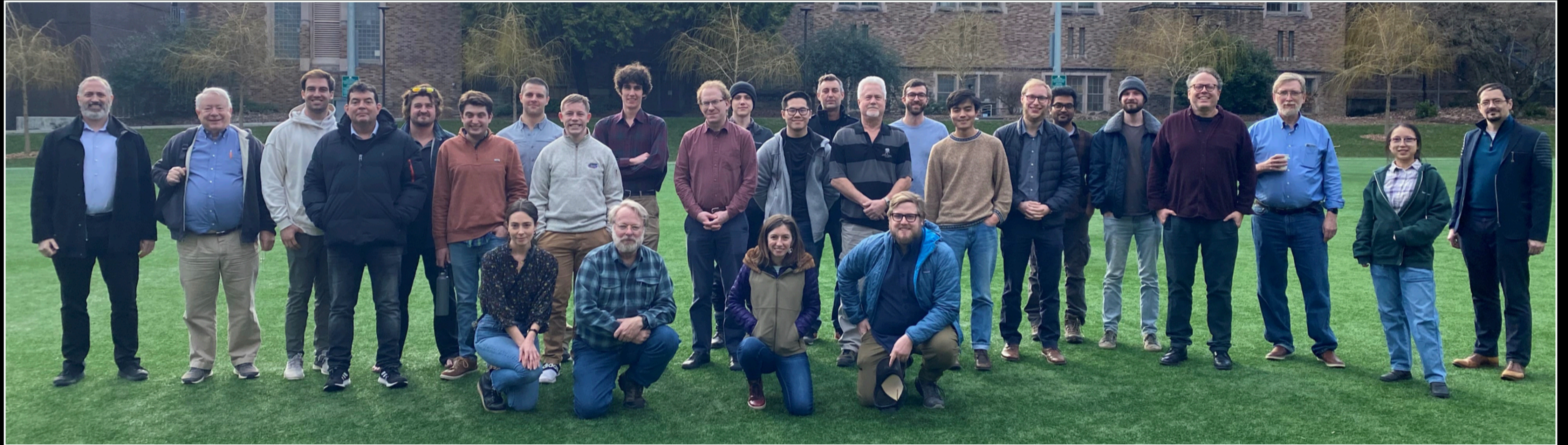
# CAVITY REGIME

ADMX, CAPP, HAYSTAC, ORGAN...





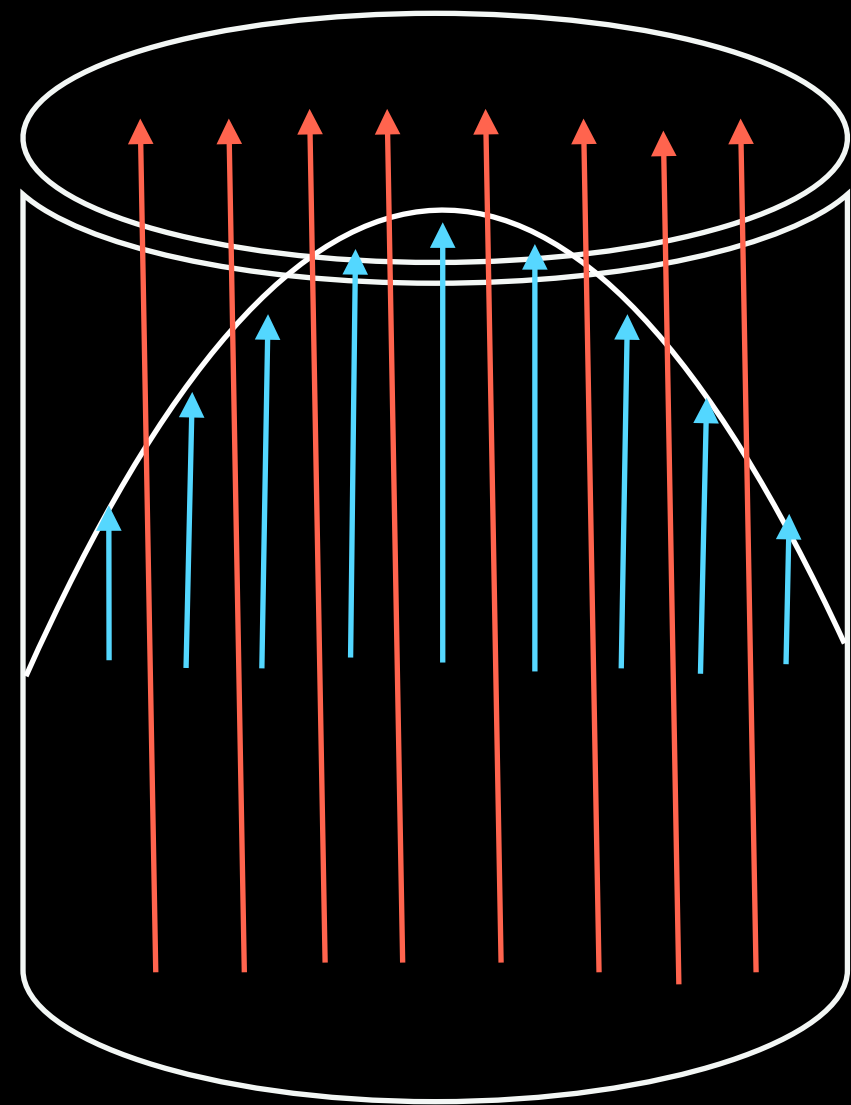
# ADMX Collaboration





# Cavity Haloscope

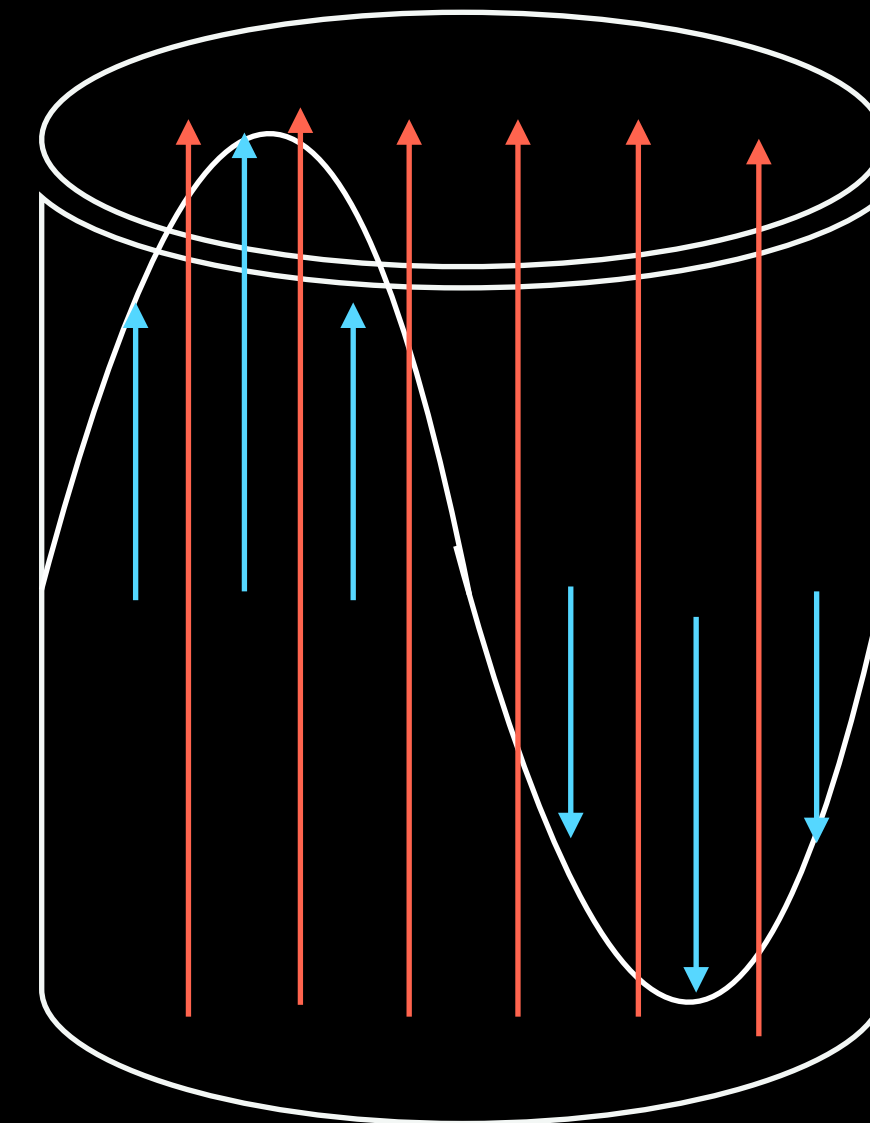
Form factor describes coupling of the axion to the mode



Non-zero form factor

Red is static magnetic field  
Blue is axion electric field

$$C_{010} = \frac{|\int dV \vec{B}_{\text{ext}} \cdot \vec{E}_a|^2}{B_{\text{ext}}^2 \int dV \epsilon_r |\vec{E}_a|^2}$$

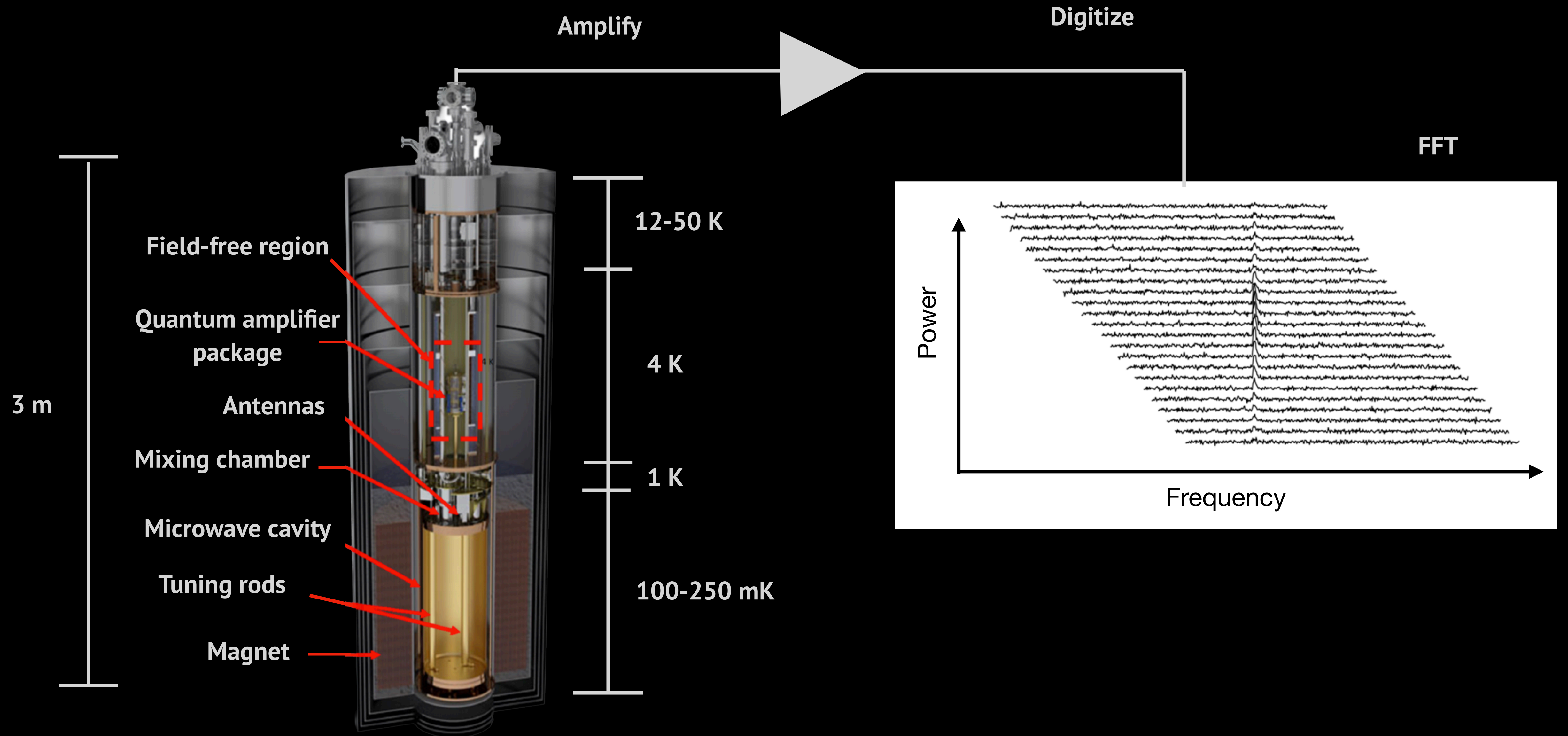


Zero form factor

ADMX: Axion couples most strongly to TM010 mode

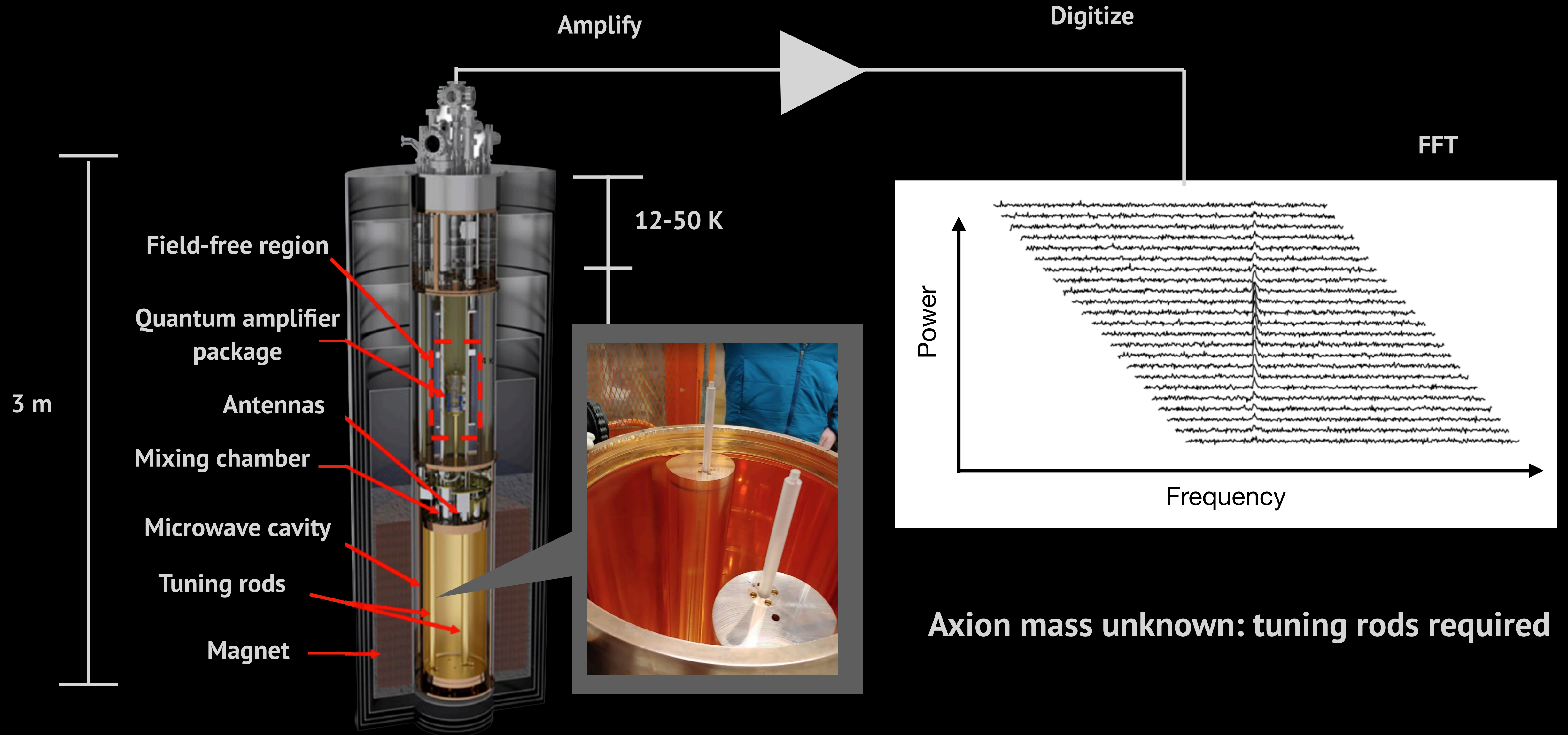


# Cavity Haloscope



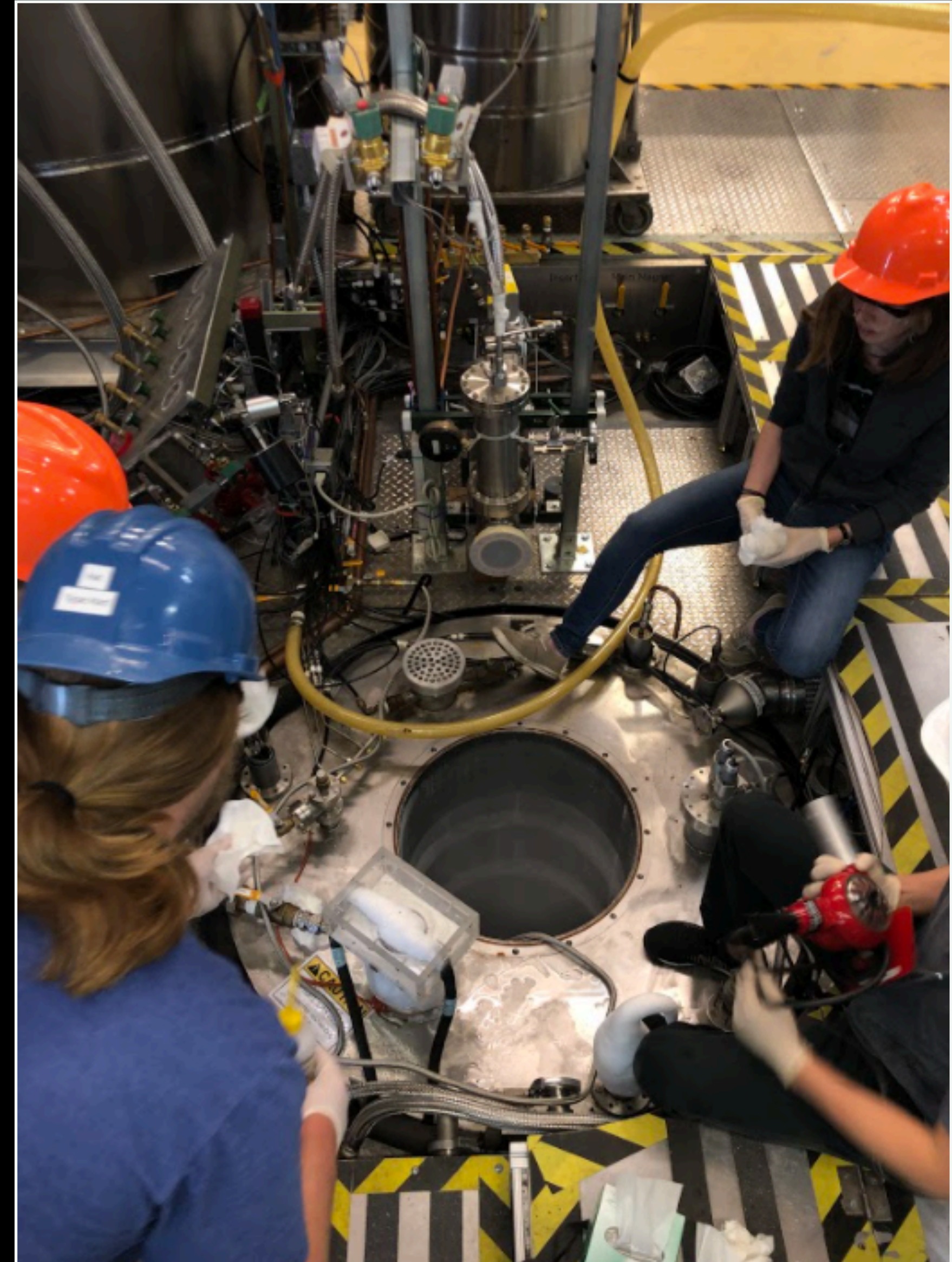


# Cavity Haloscope



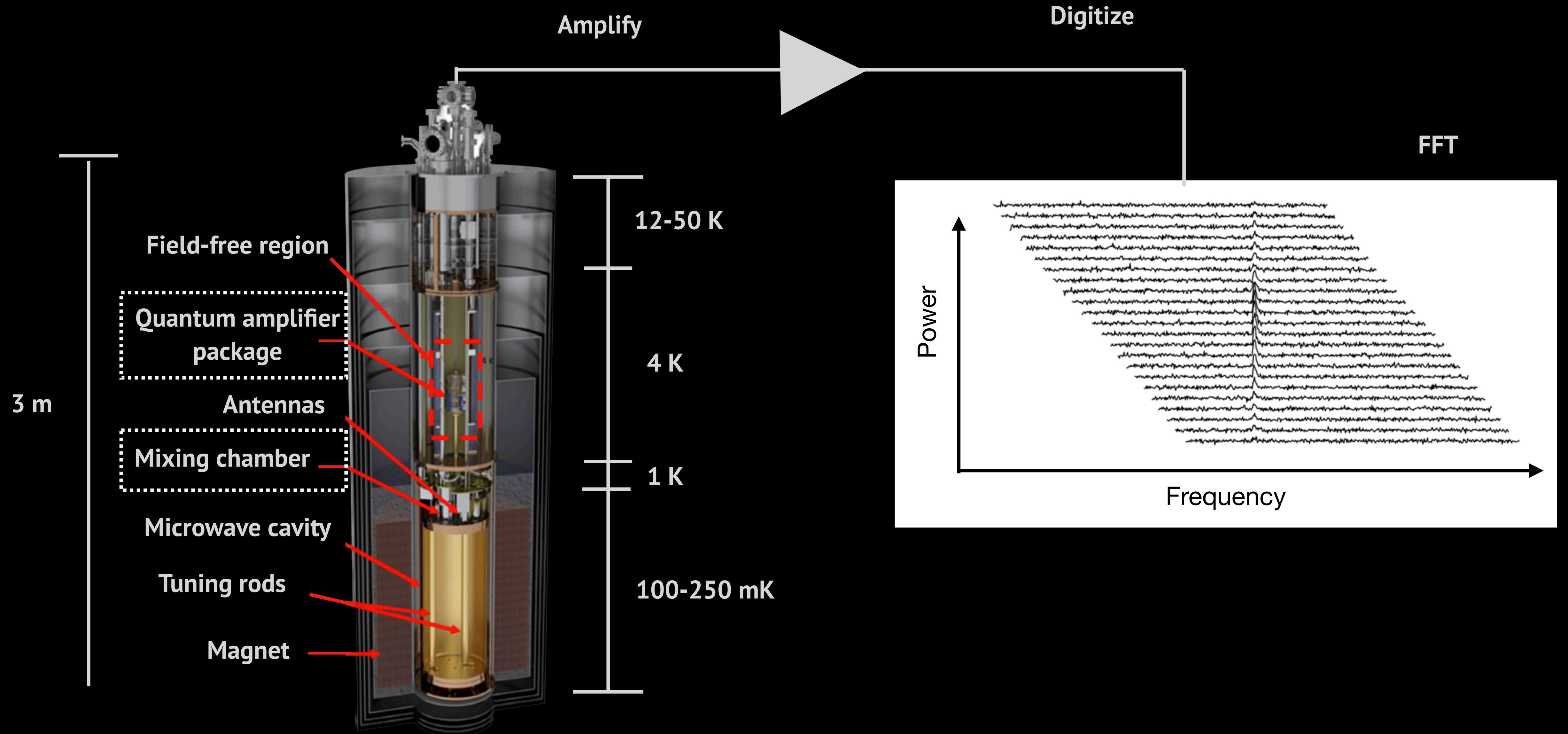


# Cavity Haloscope





# Ultra low noise receiver





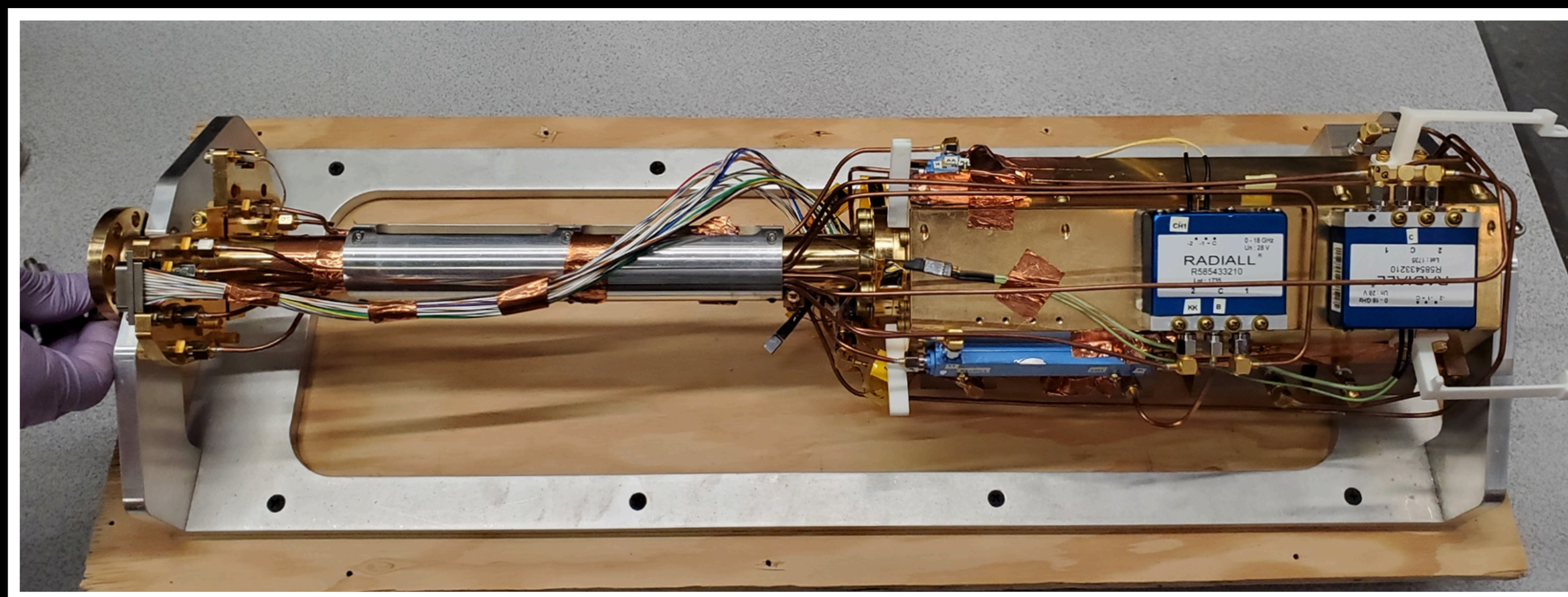
# Quantum Amplification

- Microstrip SQUID Amplifier (2017)
- Josephson Parametric Amplifier (2018–today)
  - Anharmonicity leads to energy transfer from pump to signal
  - Josephson Junction is non-linear element

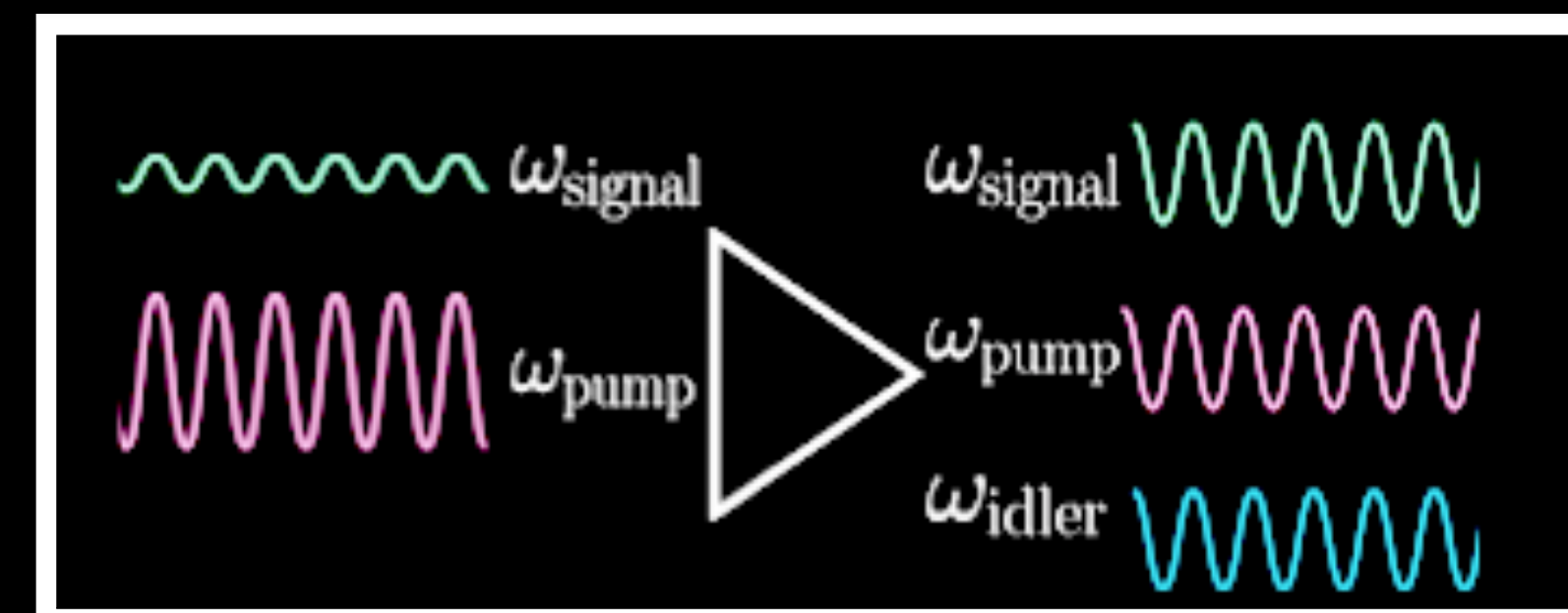


JPA courtesy of  
Irfan Siddiqi

Figures courtesy of Shahid Jawas



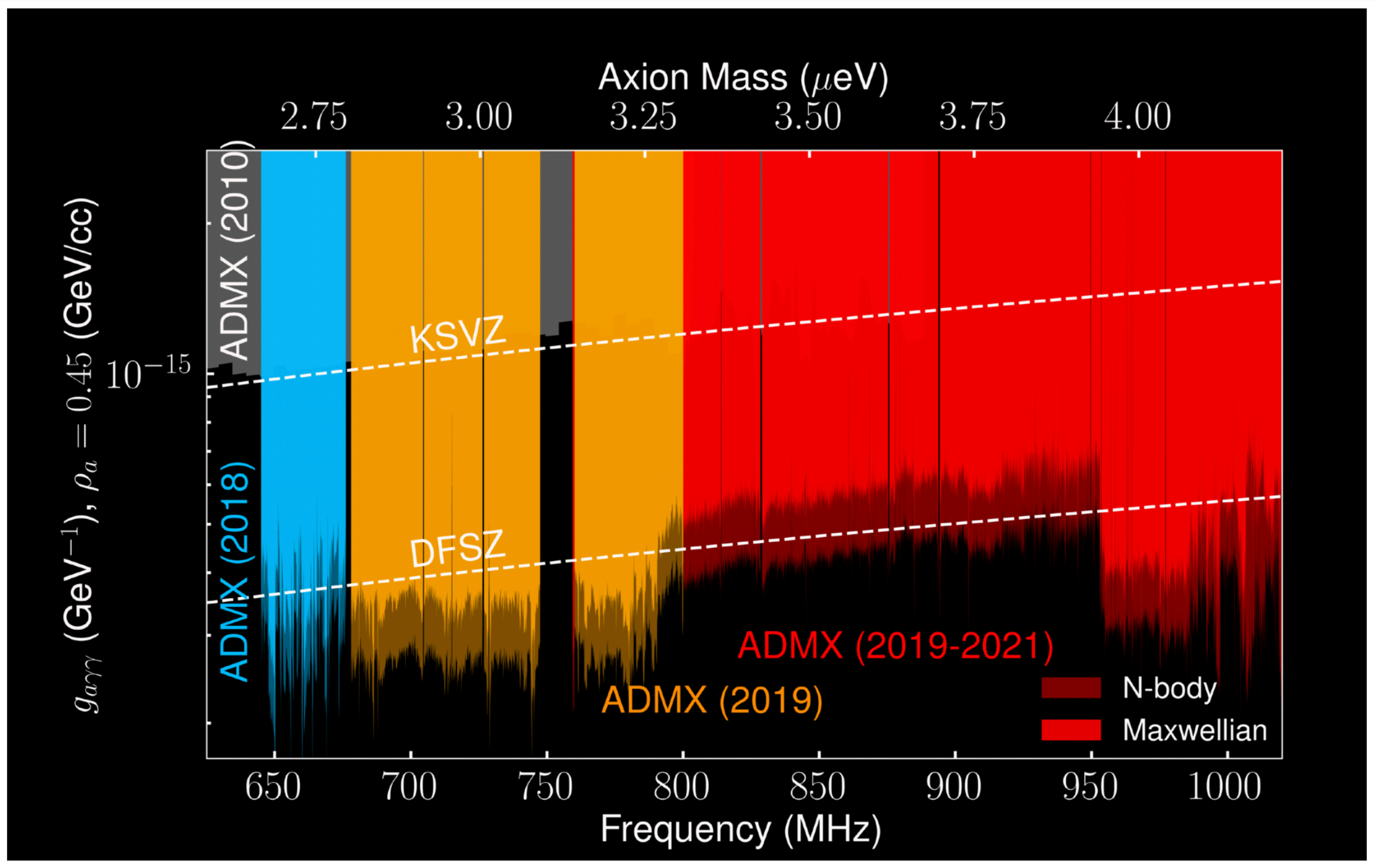
~2 ft



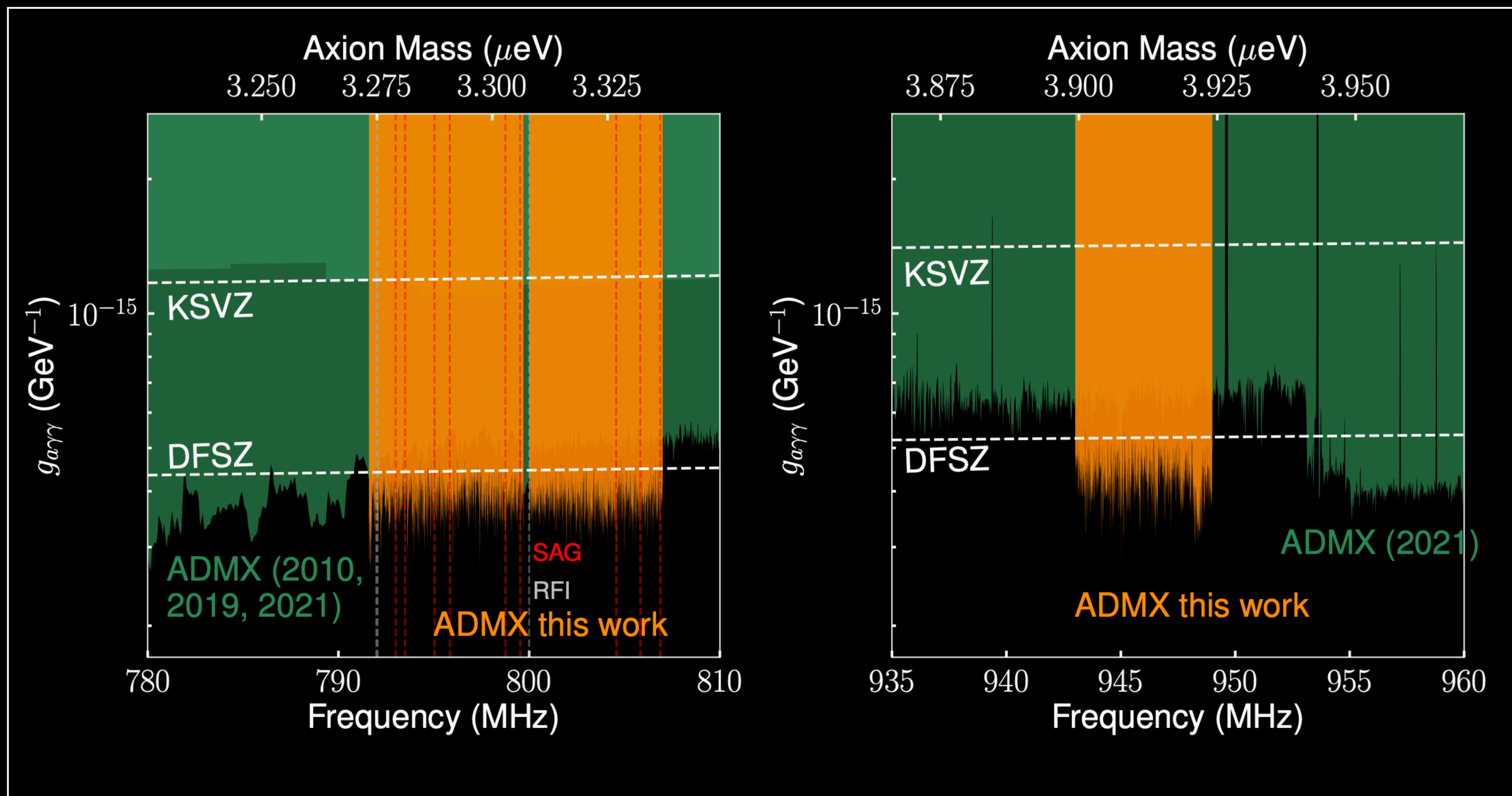
Field cancellation coil + Mu-metal  
shielding required for optimal  
performance



# ADMX Exclusion Limits (Published)

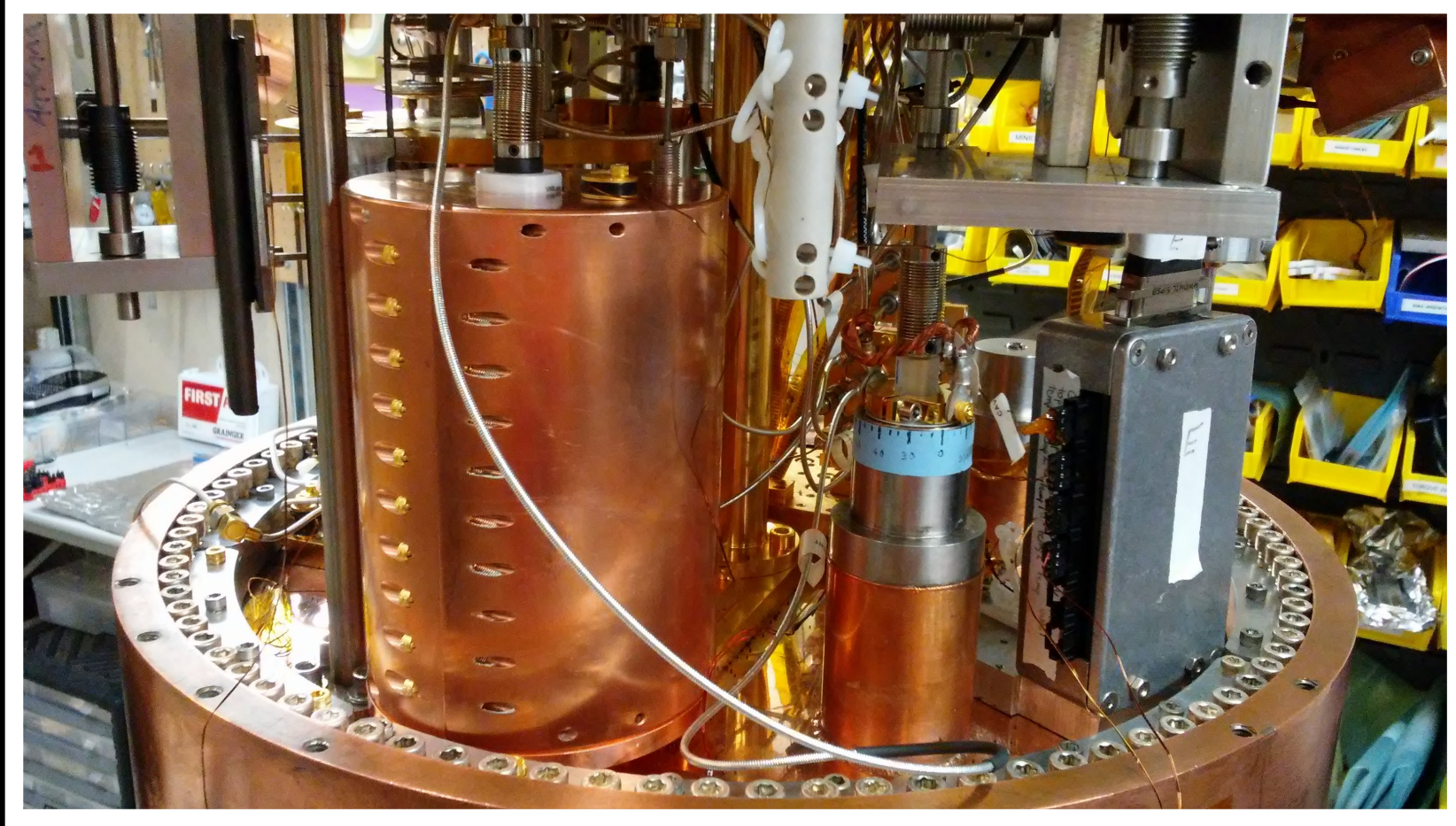


# ADMX Preliminary Sensitivity



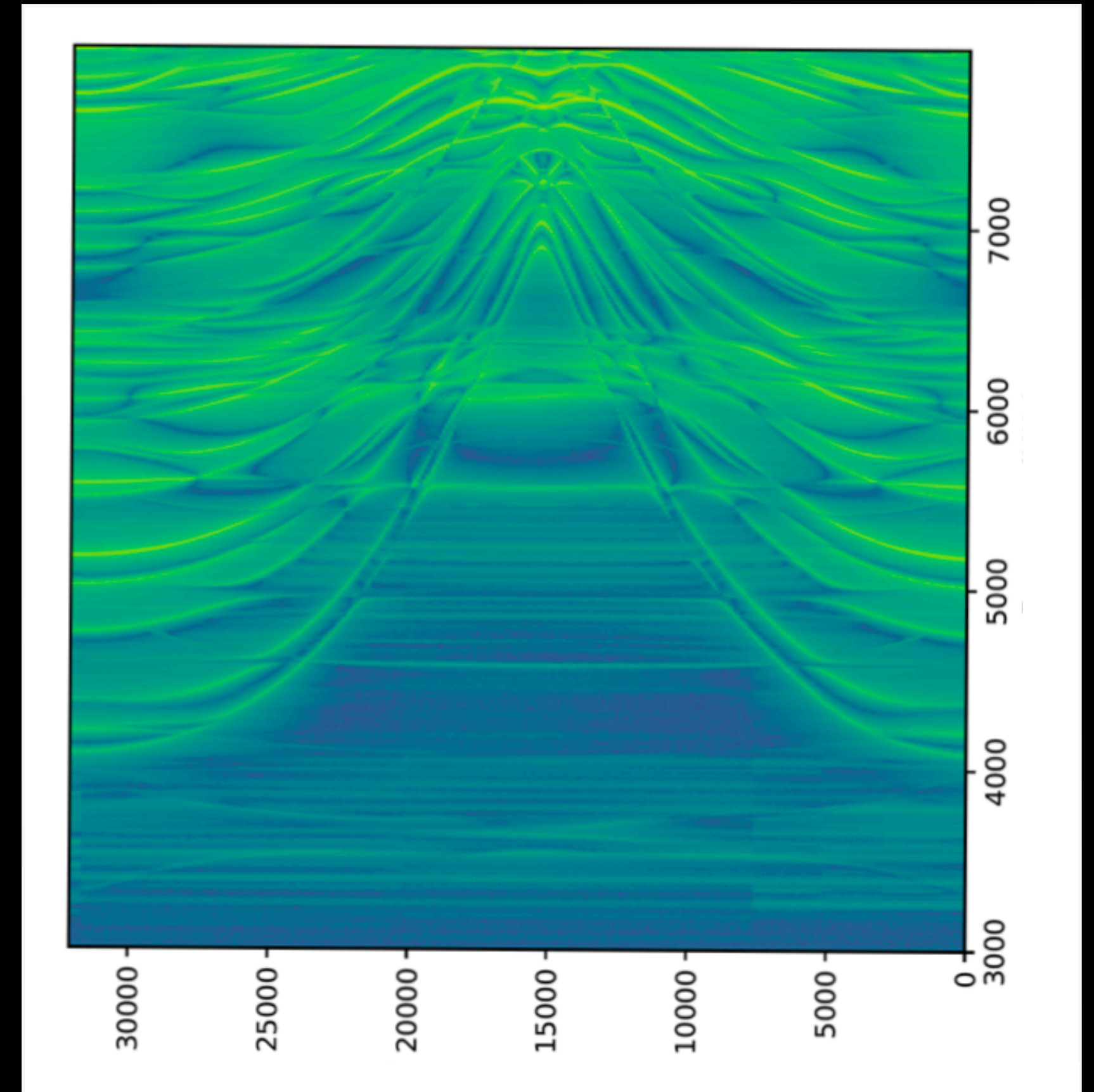
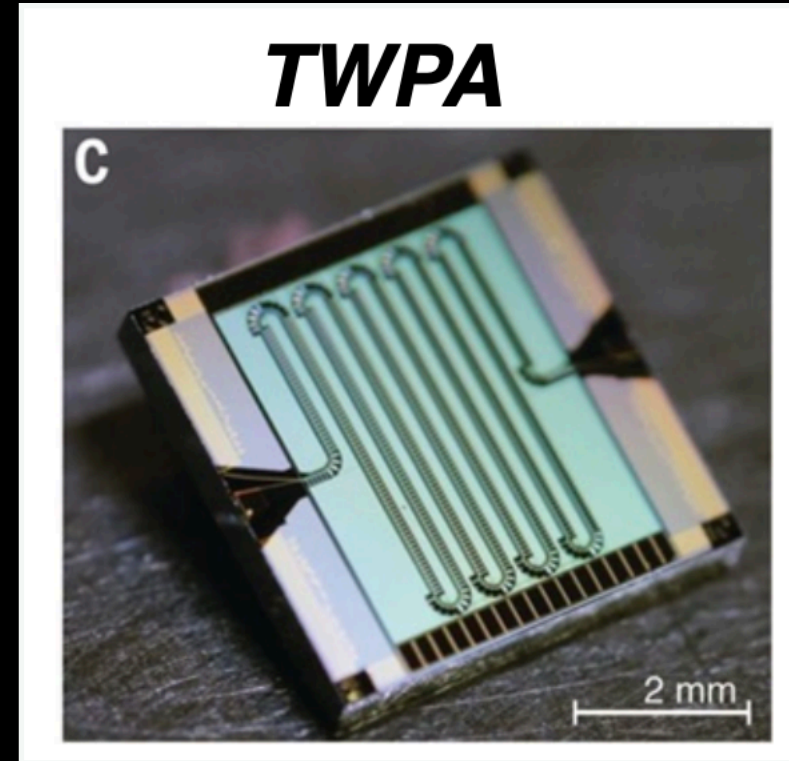


# ADMX high frequency prototype



Sidecar is a small prototyping cavity that sits on top of the main cavity.

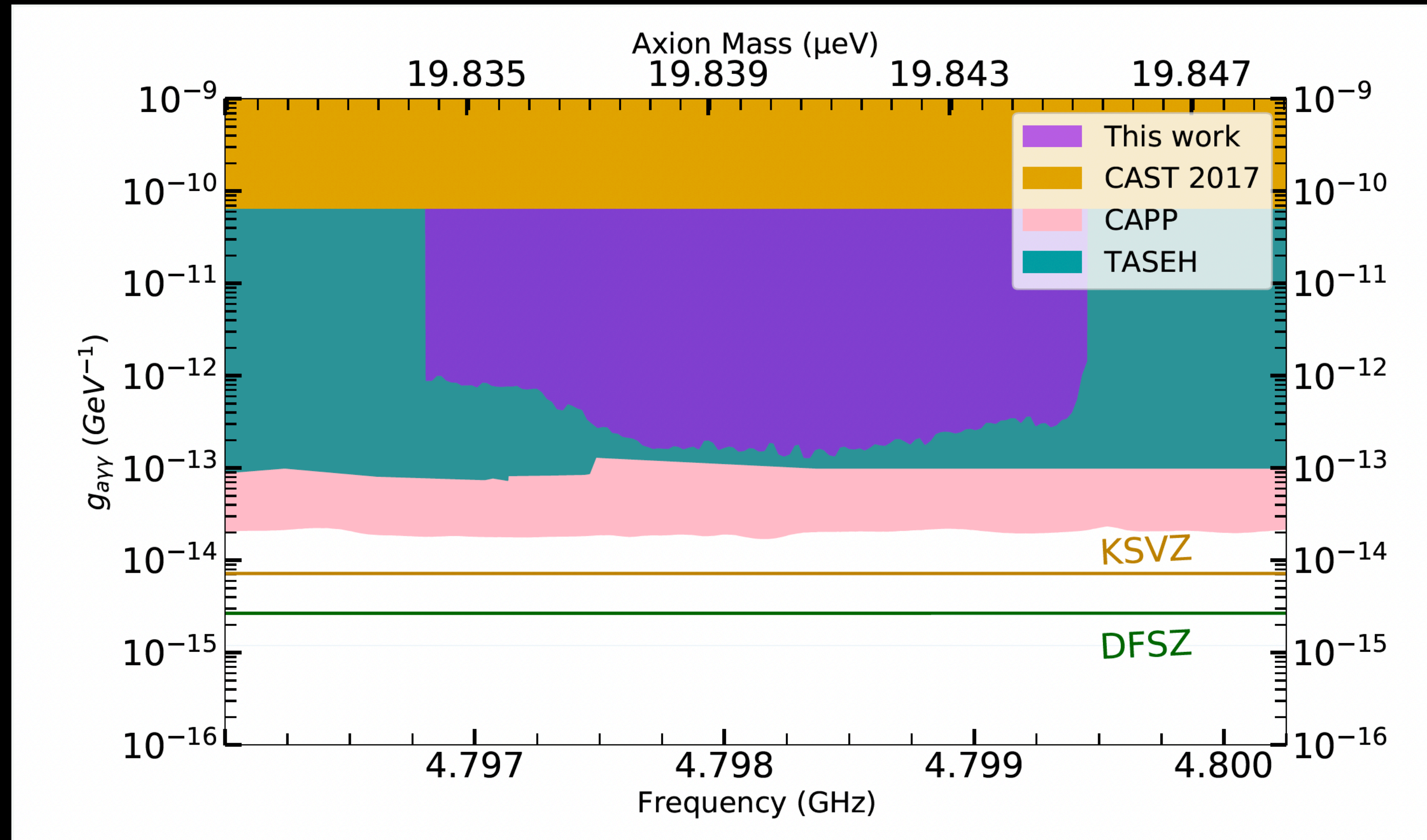
- Testing:
  - Traveling Wave Parametric Amplifier (TWPA)
  - Clamshell cavity design
  - Piezo motors for antenna and tuning rod



Sidecar mode map



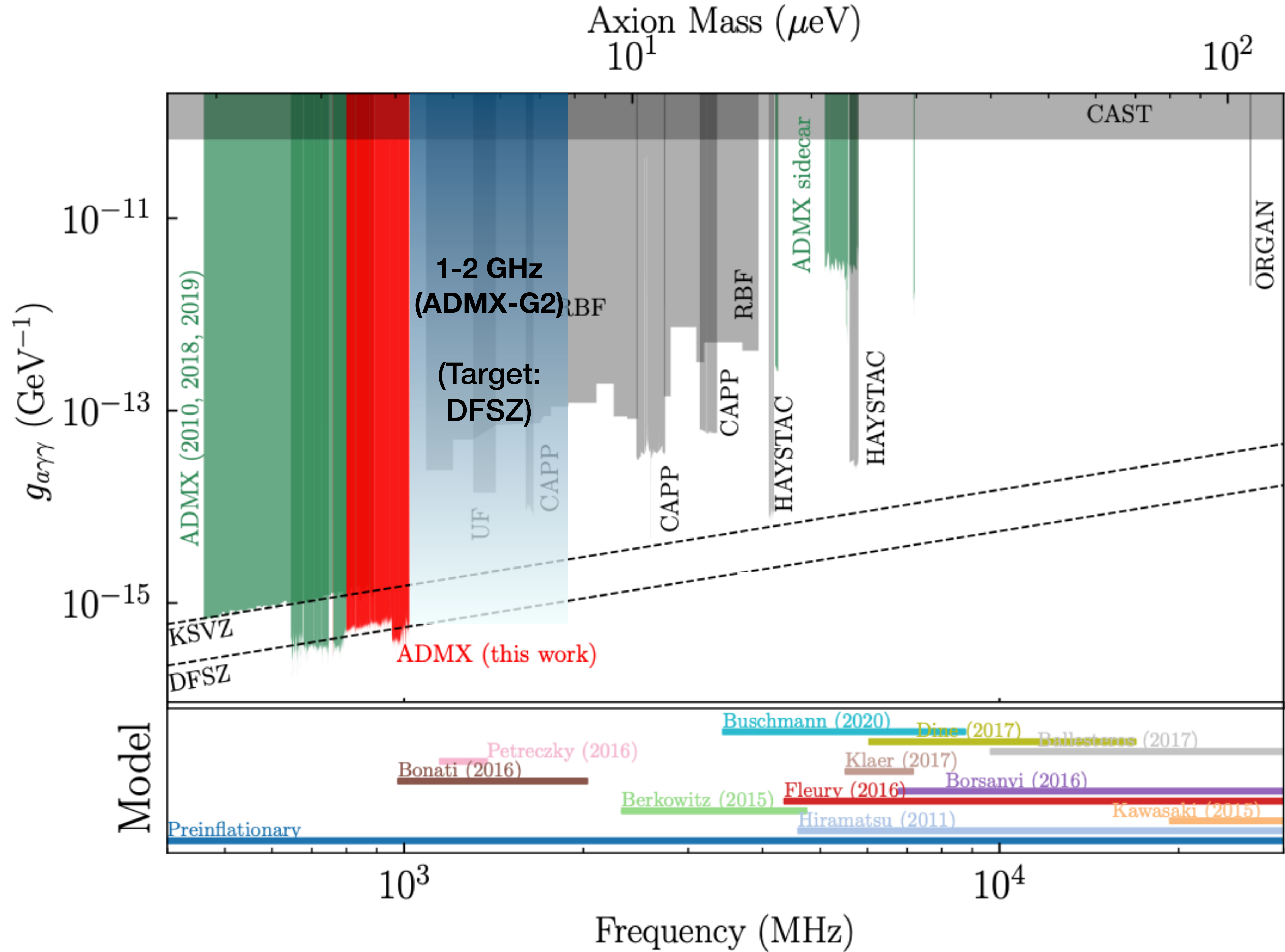
# First axion search with a JTWPA

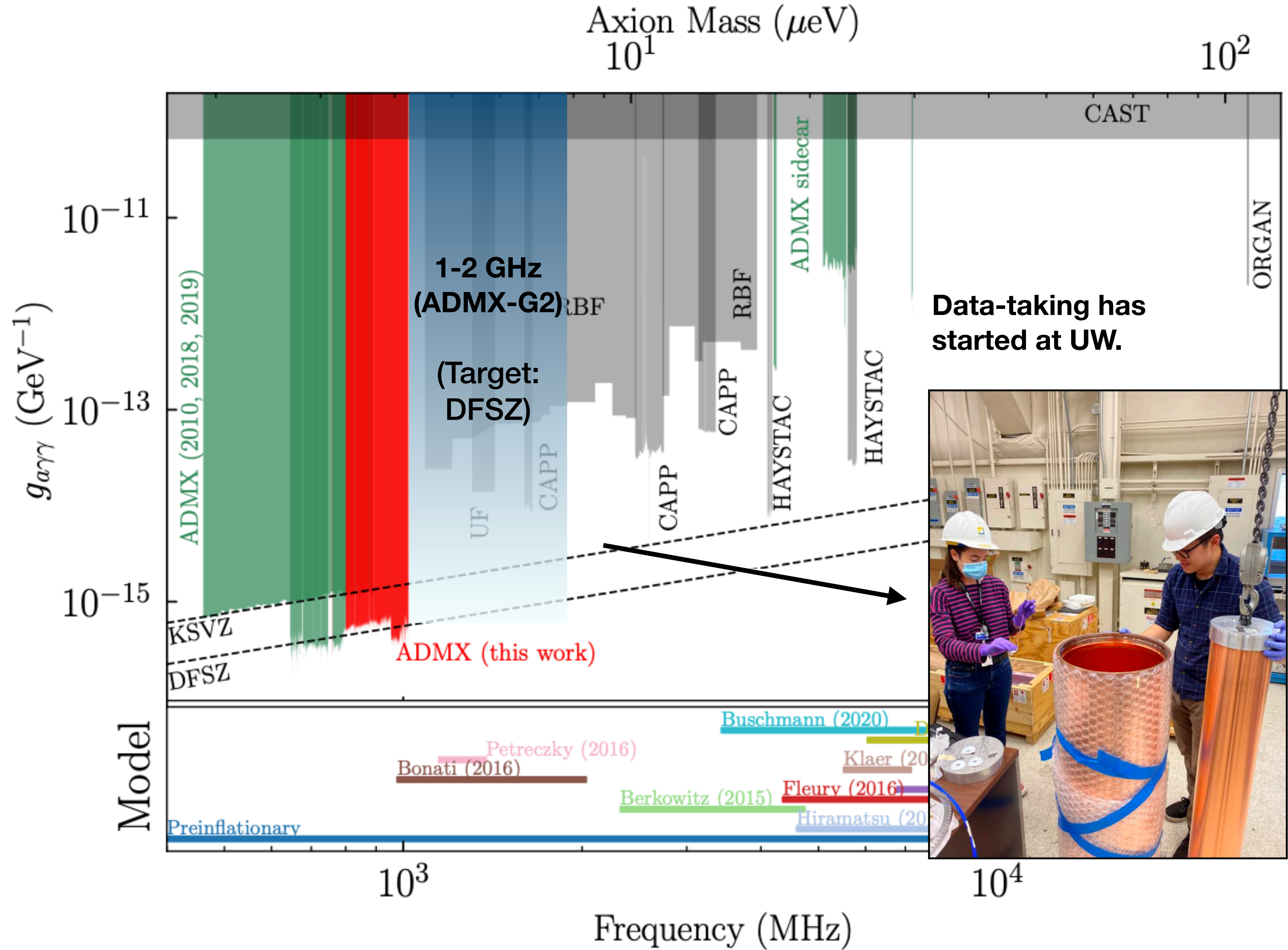


Bartram, C., et al. “Dark matter axion search using a Josephson traveling wave parametric amplifier”. Review of Scientific Instruments 94.4 (2023): 044703

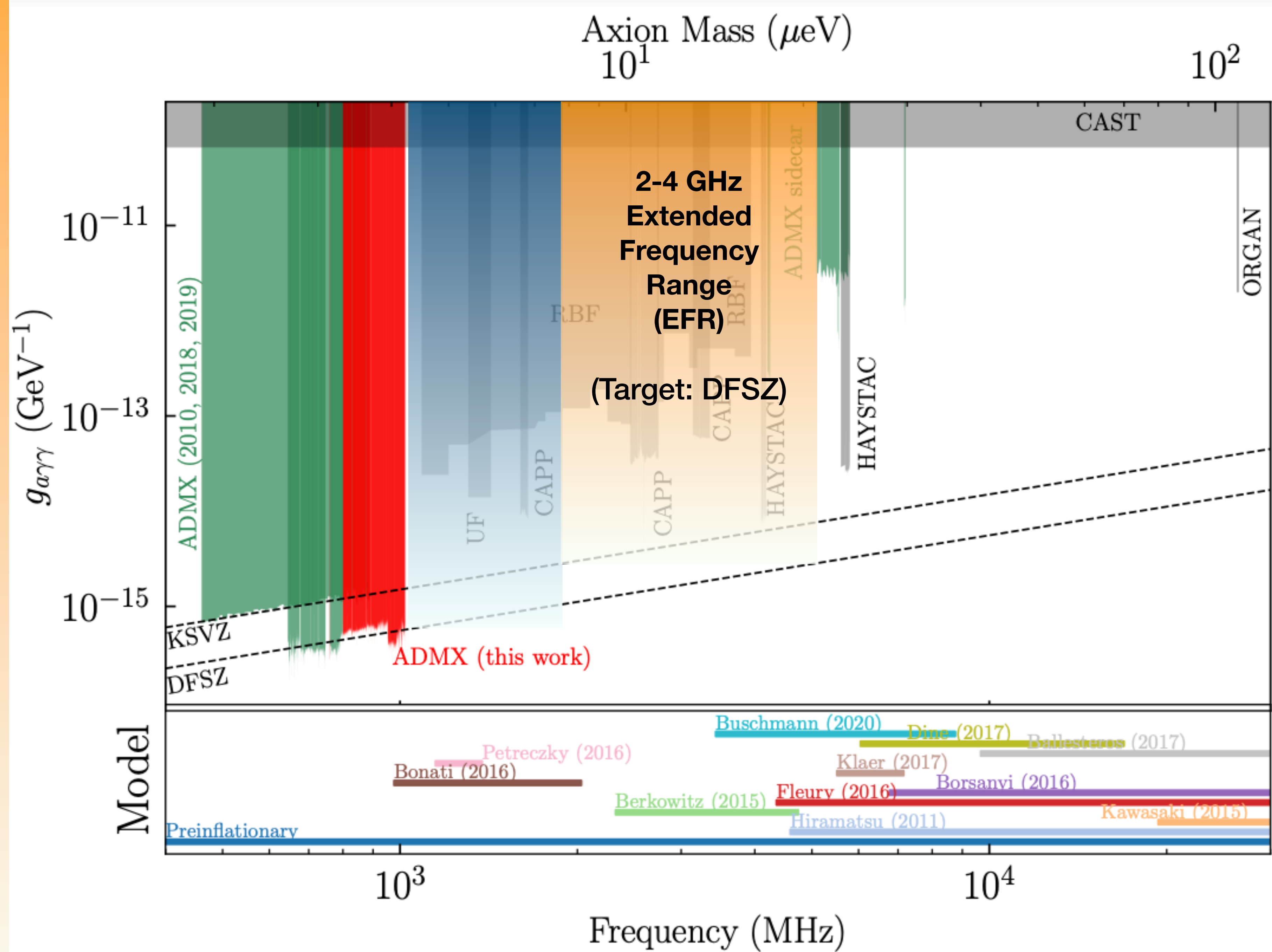
Sidecar now taking data at 5.2-5.6 GHz at 10x KSVZ with a Nb<sub>3</sub>Tn superconducting tuning rod!











# Scan speed for cavity haloscope

$$\frac{df}{dt} \approx 323 \frac{\text{MHz}}{\text{yr}} \left( \frac{g_\gamma}{0.36} \right)^2 \left( \frac{\rho}{0.45 \text{ GeV/cm}^3} \right)^2 \left( \frac{f}{1 \text{ GHz}} \right)^2 \left( \frac{3.5}{\text{SNR}} \right)^2 \left( \frac{B_0}{7.6 \text{ T}} \right)^4 \left( \frac{V}{136 \ell} \right)^2 \left( \frac{Q_L}{30,000} \right) \left( \frac{C_{lmn}}{0.4} \right)^2 \left( \frac{0.35 \text{ K}}{T_{\text{sys}}} \right)^2$$

## Maximize

- B Field
- Volume
- Quality Factor
- Form Factor

## Can't Control

- Frequency
- Coupling
- Dark Matter Density

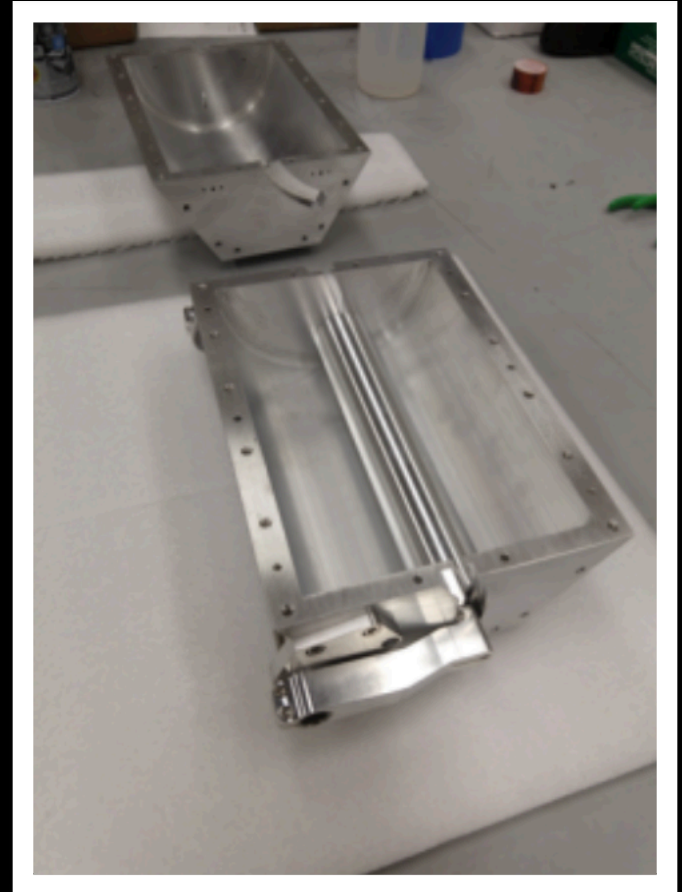
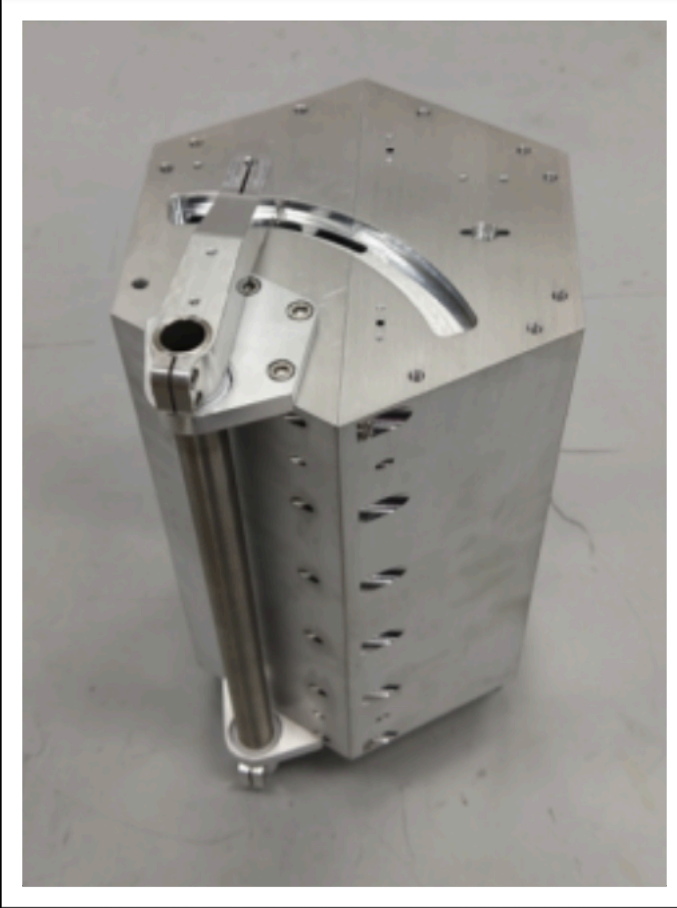
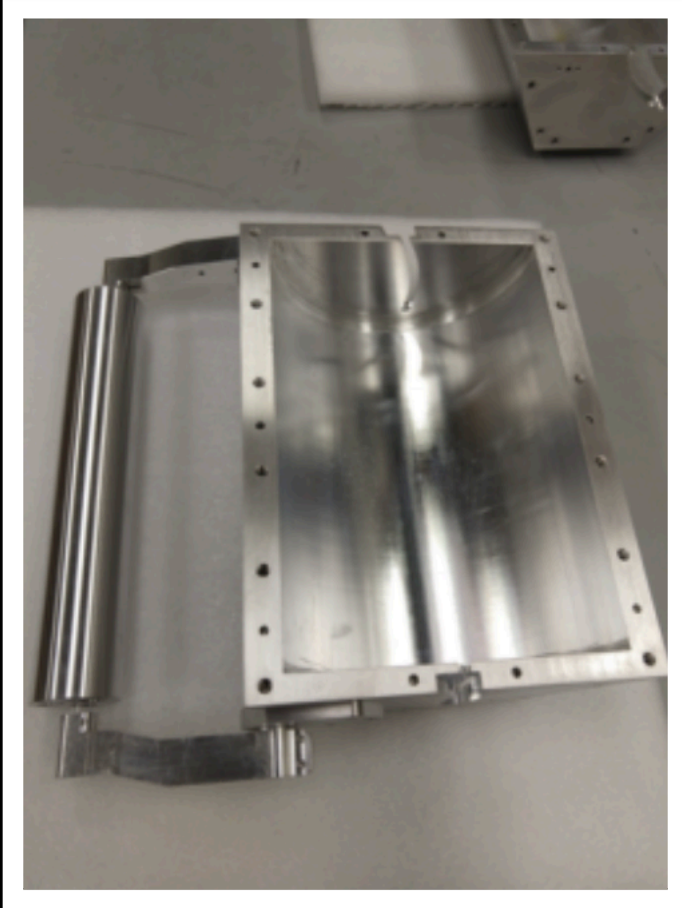
## Minimize

- System noise:
- Amplifier Noise
- Physical Noise

**\*Similar equation for quasistatic haloscope**



# ADMX EFR (2-4 GHz)

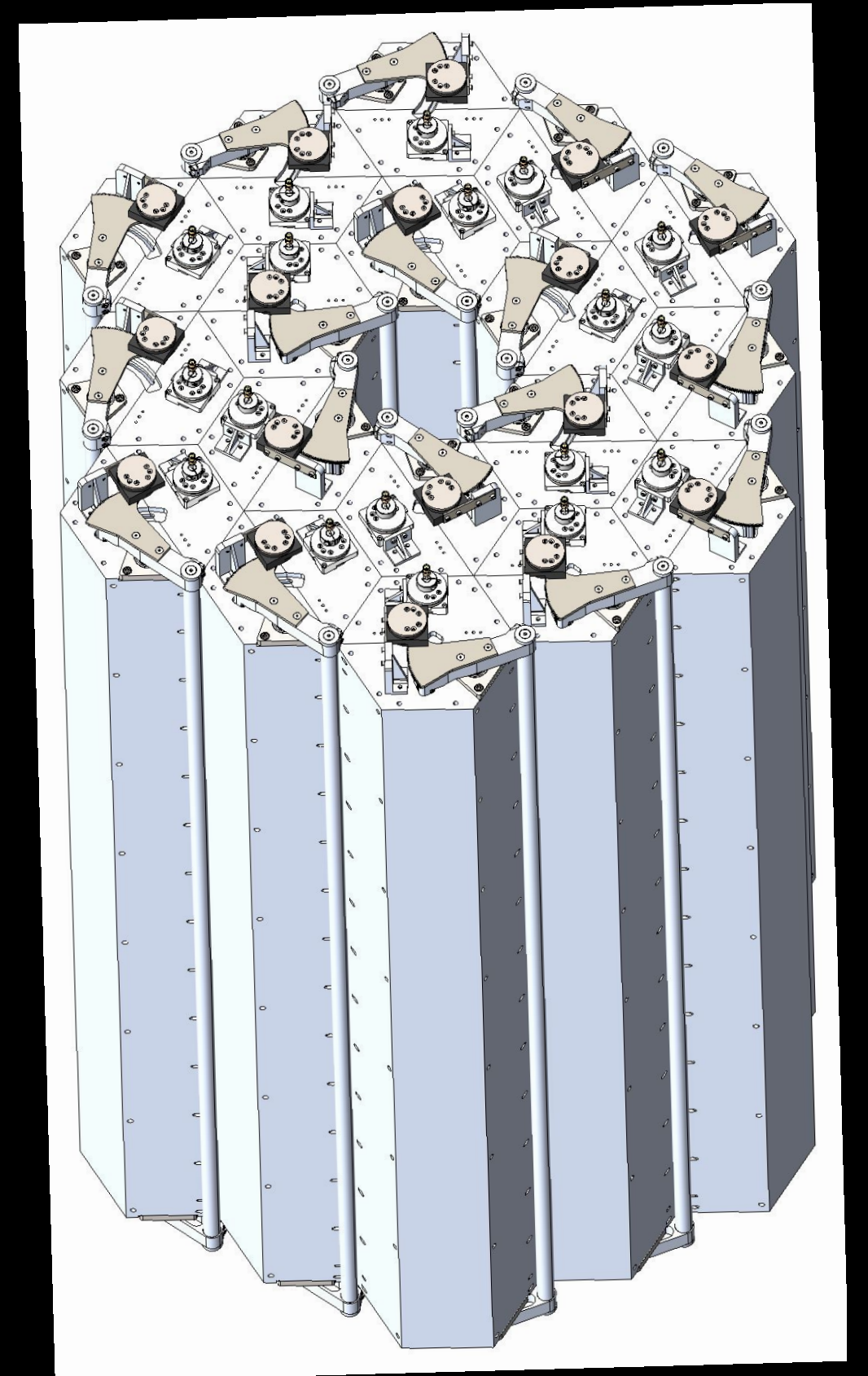


Prototype  
cavity  
testing

18-JPA receiver



9.4 T Magnet

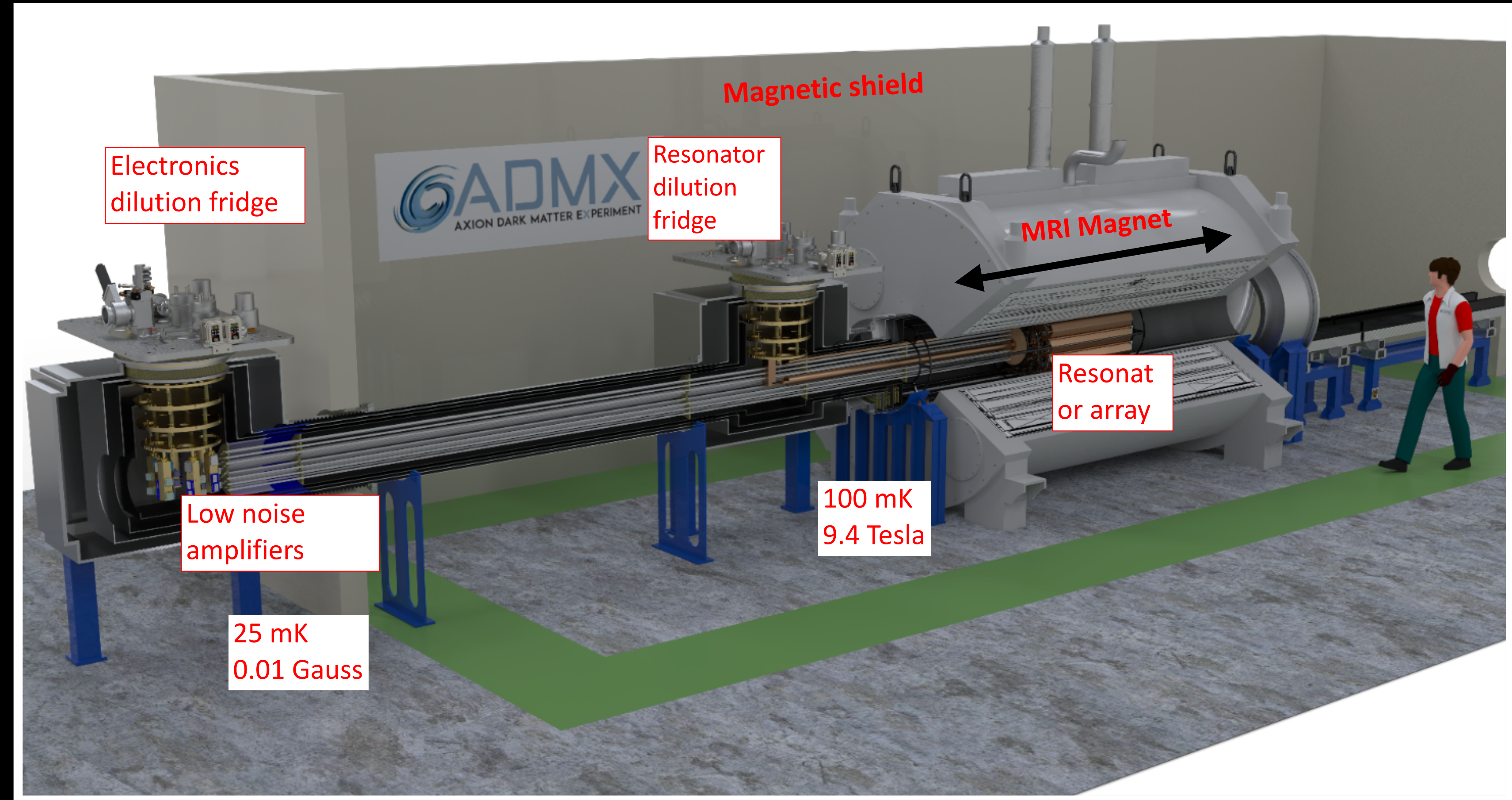


18-cavity array  
simulations



# ADMX EFR (2-4 GHz)

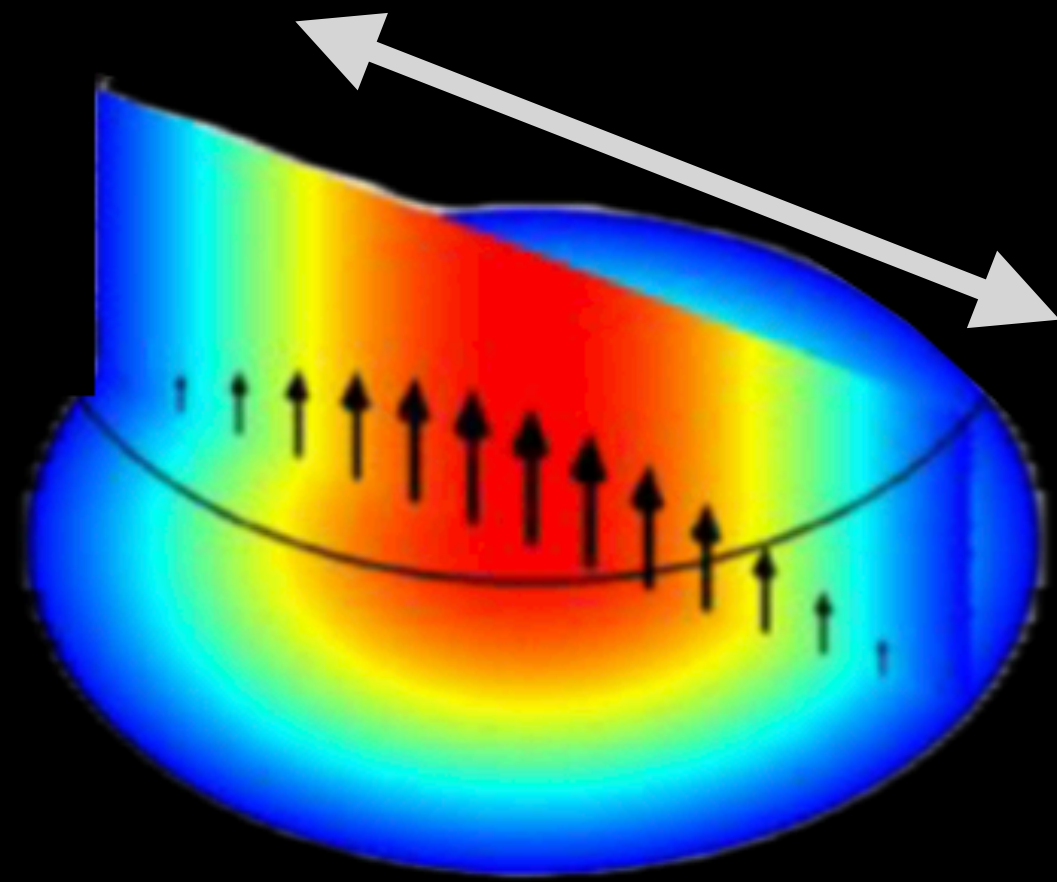
- Horizontal magnet bore
- Extra modularity: cavity electronics are separate from magnet bore
- Large magnet volume: 258 liters
- Other: Squeezing? Superconducting cavities?



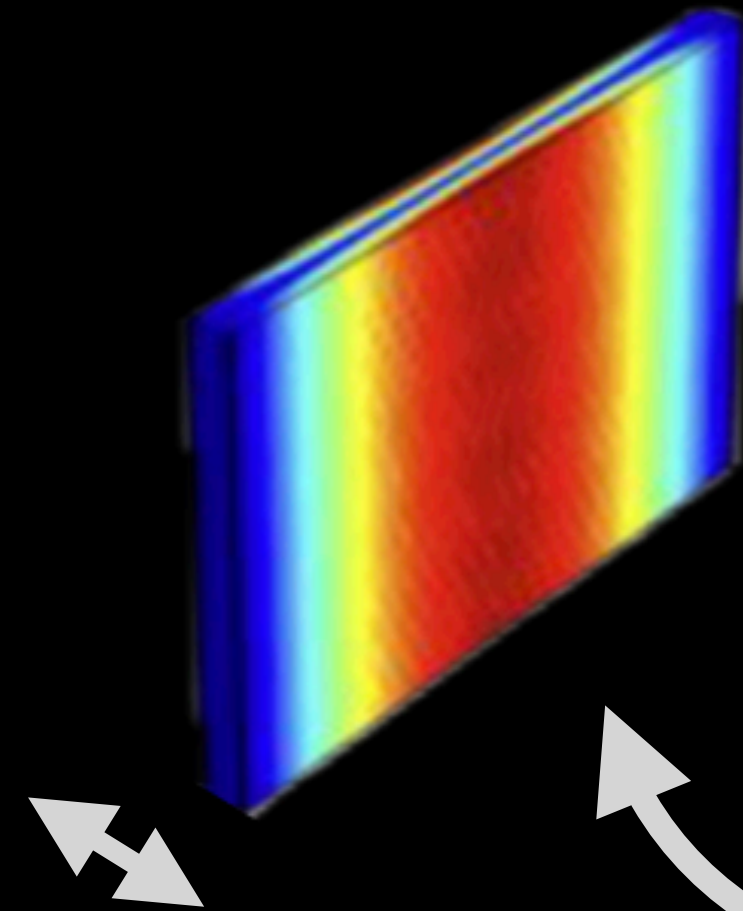
(ADMX EFR Design)



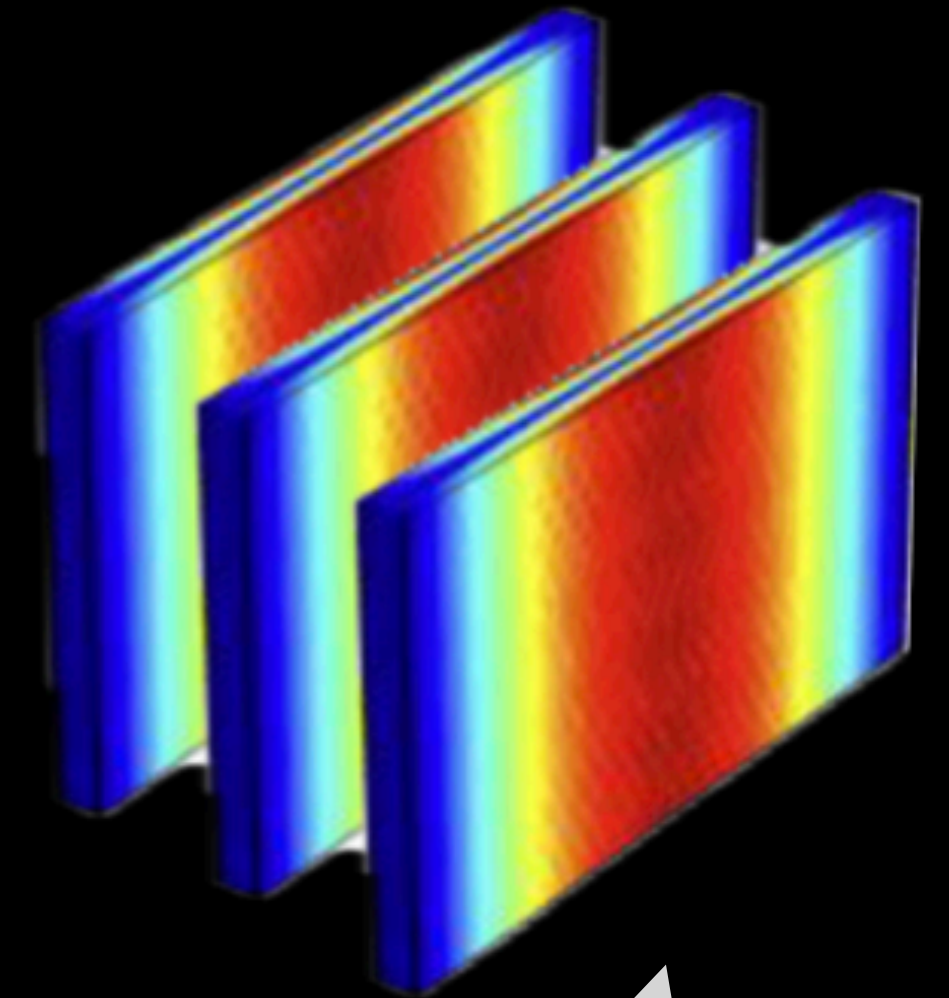
# ADMX-VERA



Cavity haloscope  
Cavity frequency  
determines cavity  
volume.



Width sets  
frequency of  
TM010 mode.

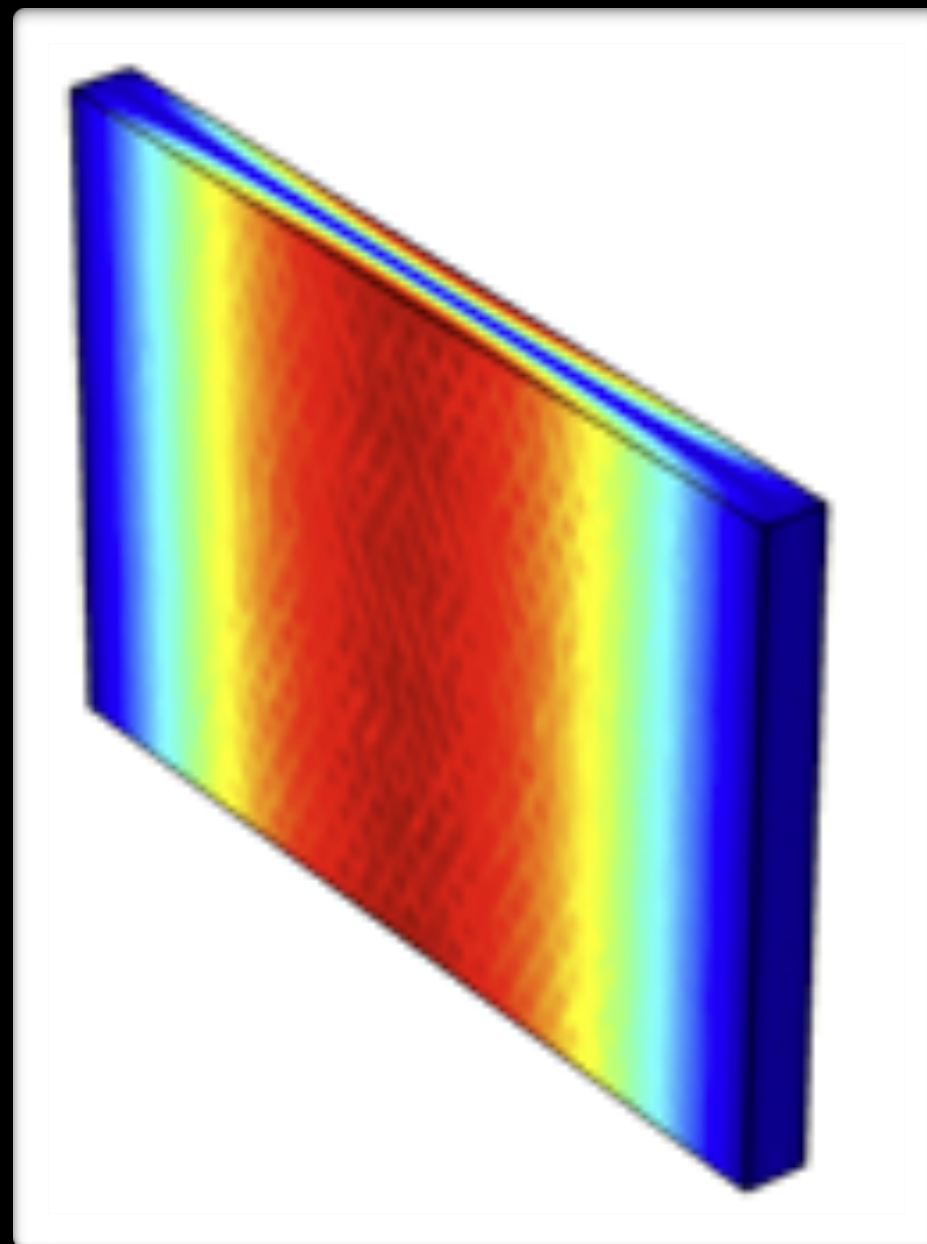


VERA haloscope  
Cavity frequency decoupled from  
cavity volume. Volume can be  
scaled arbitrarily in other  
dimensions.

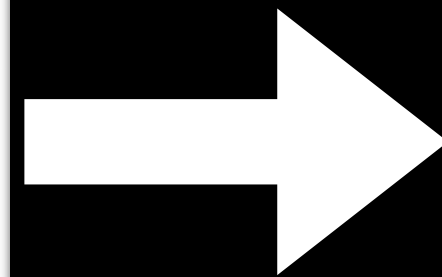
# ADMX-VERA

Width sets frequency  
of fundamental ( $TM_{010}$ )  
compatible with  
**solenoid B field**

Volume can be  
scaled arbitrarily  
in other  
dimensions



Wrap



$TM_{010}$  mode  
still supported.

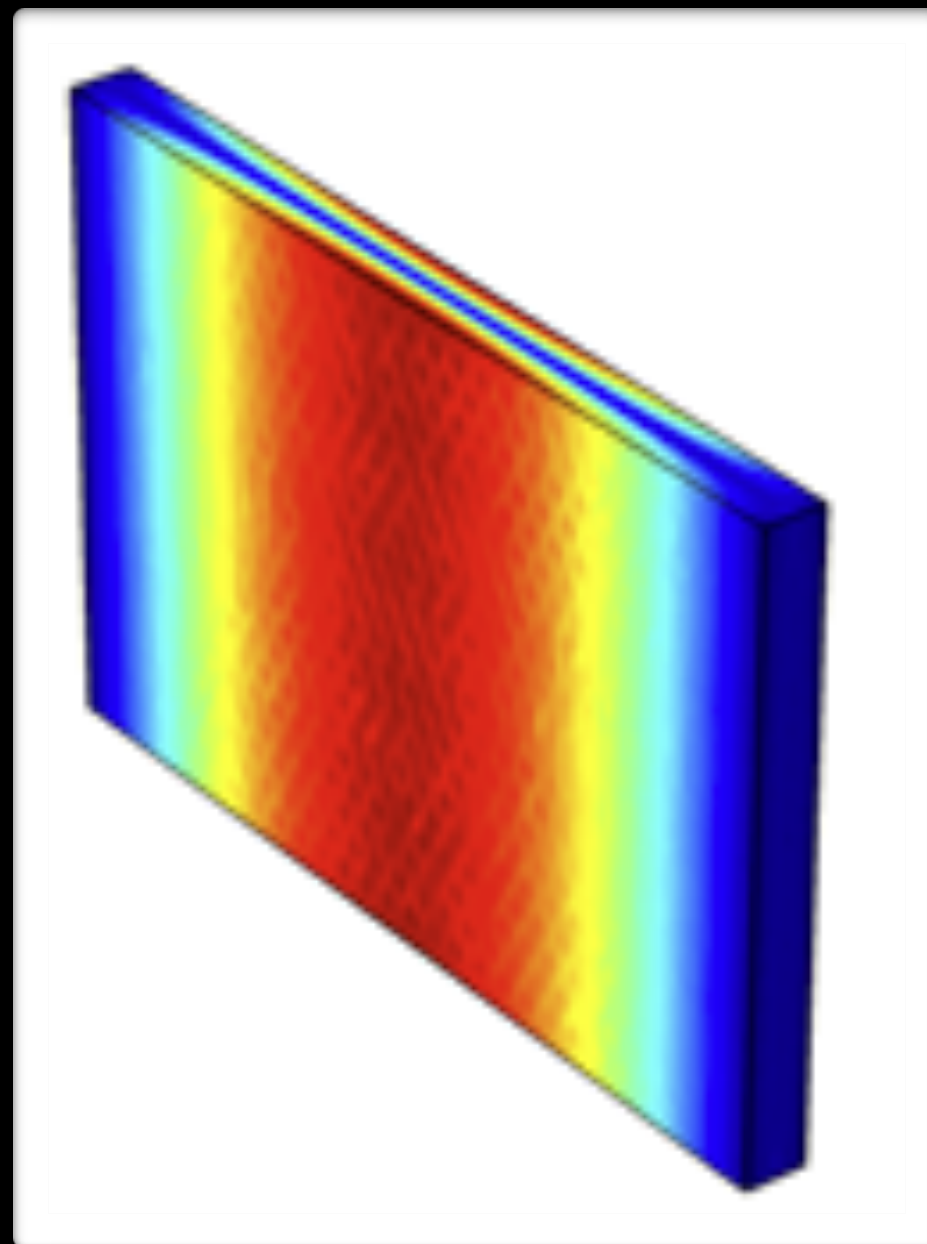


## Decouple frequency and volume.



Width sets frequency  
of fundamental ( $TM_{010}$ )  
compatible with  
**solenoid B field**

Volume can be  
scaled arbitrarily  
in other  
dimensions

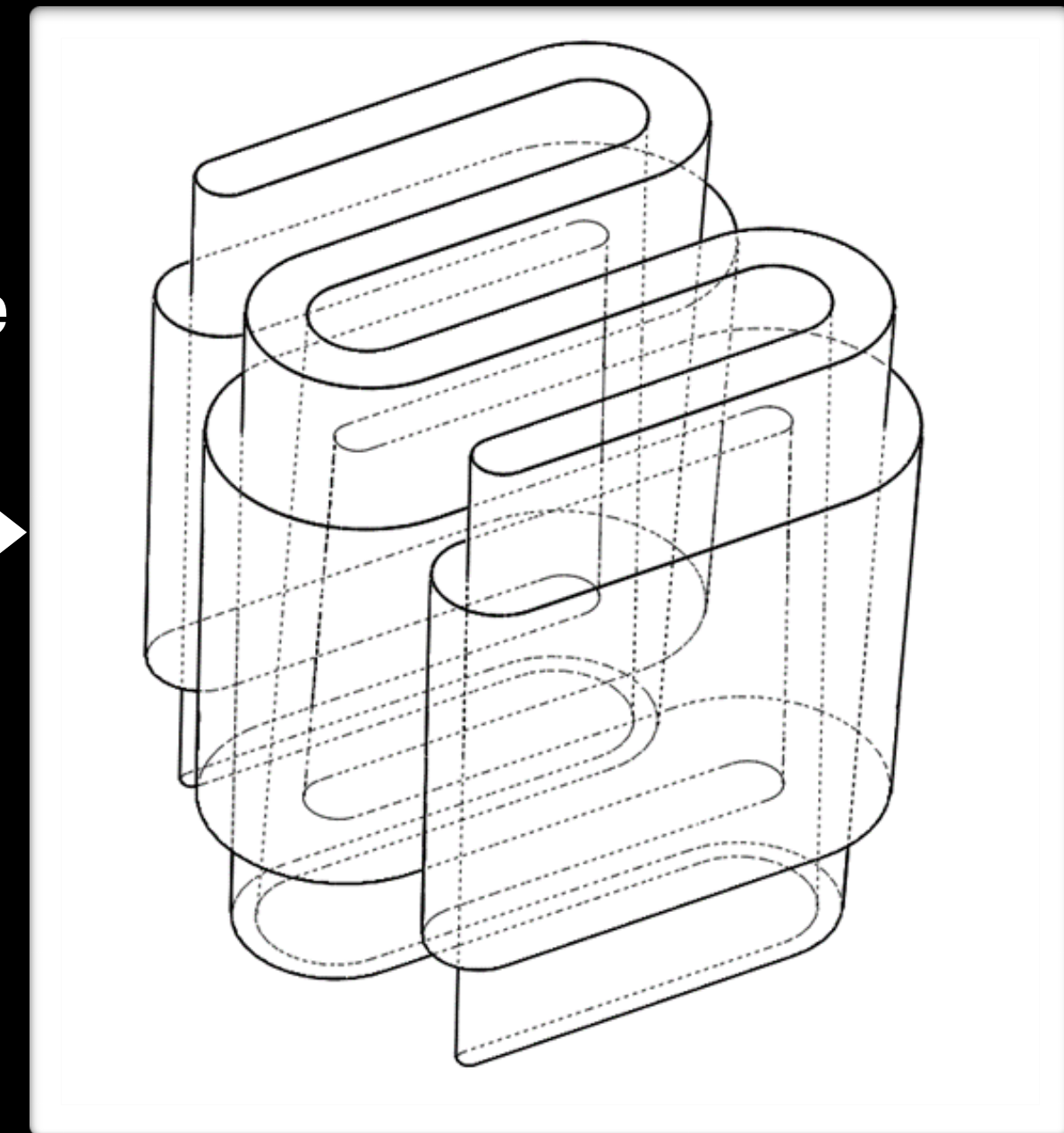


Wrap



TM010 mode  
still supported.

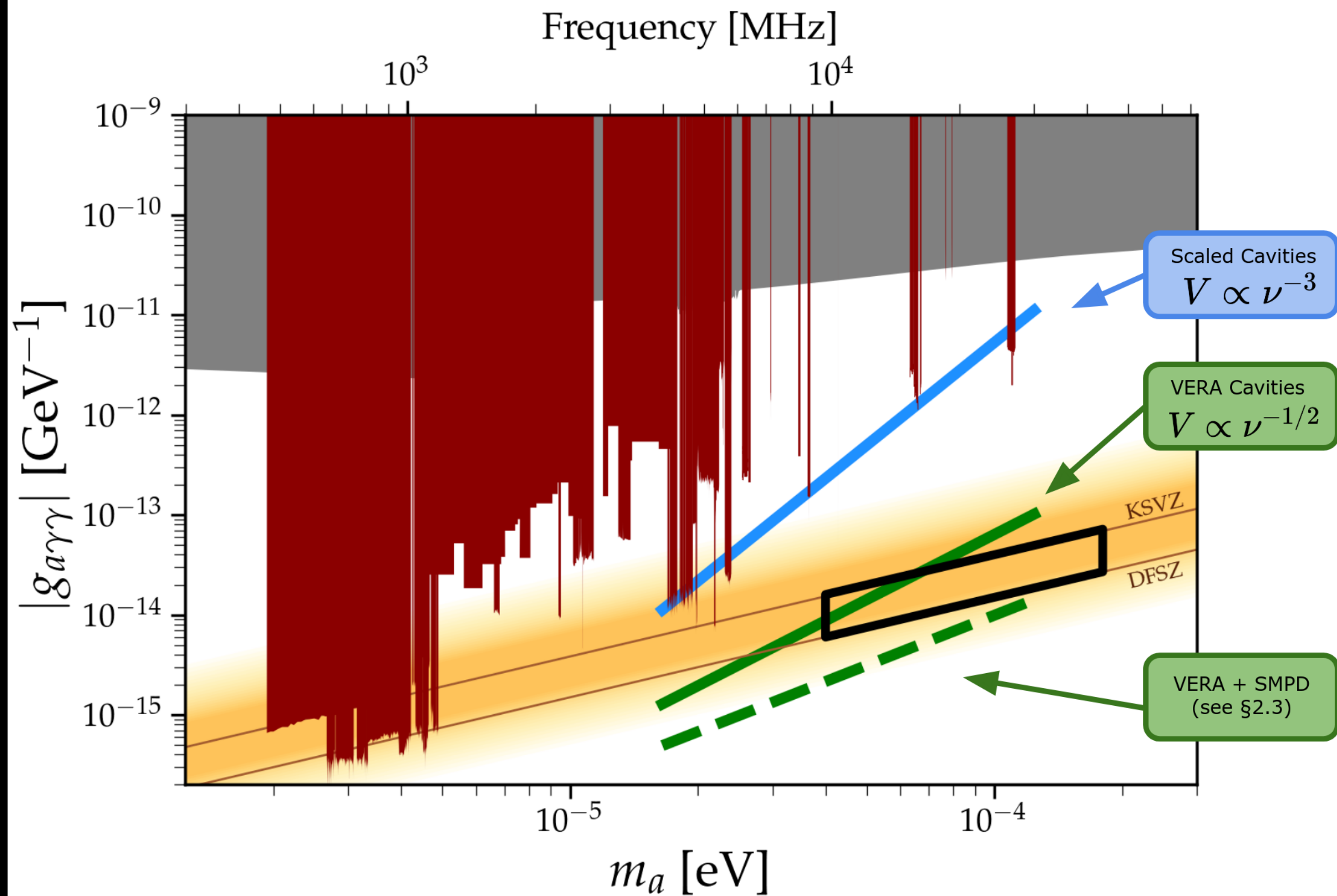
Convolute



JCAP 02 (2021) 018  
JCAP 06 (2020) 010

## Decouple frequency and volume.

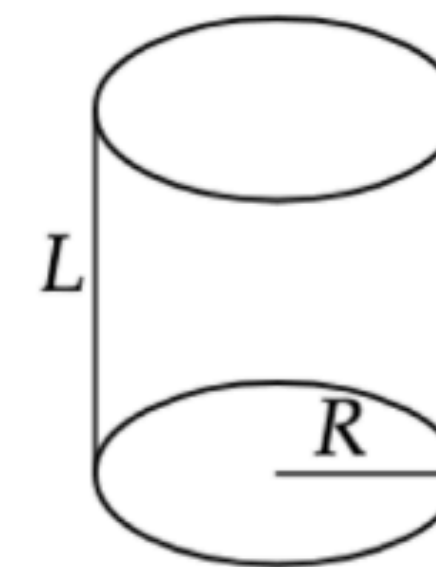
# ADMX-VERA



- CP-conserving theory band
- classical window
- astrophysics constraints
- cavity haloscope constraints
- ADMX projections

$$\nu_r \propto \sqrt{\frac{1}{R^2} + \frac{1}{L^2}} \Rightarrow$$

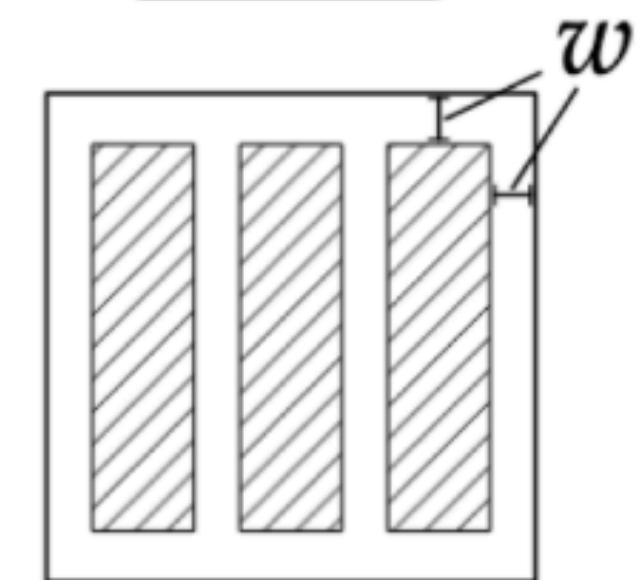
$$V \propto \nu_r^{-3}$$



$$V = \lambda^3$$

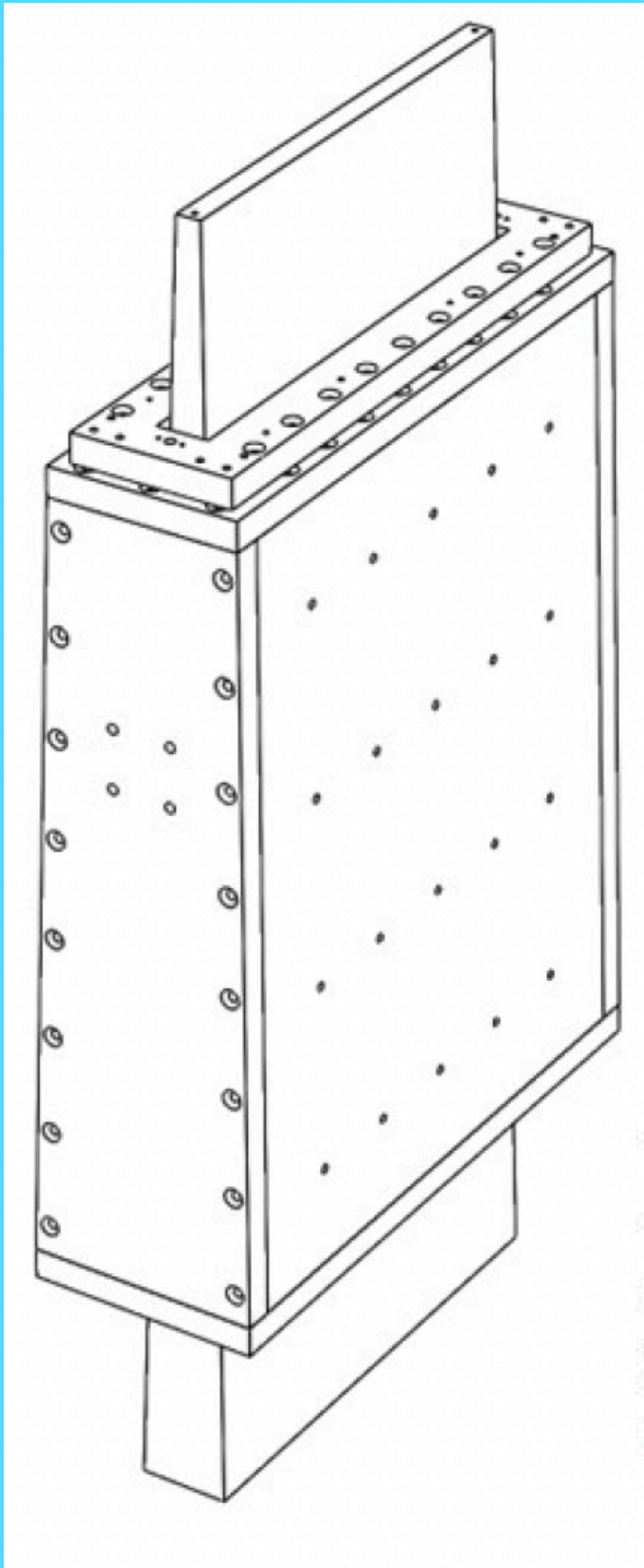
$$\nu_r \propto w^{-1} \Rightarrow$$

$$V \propto \nu_r^{-1}$$



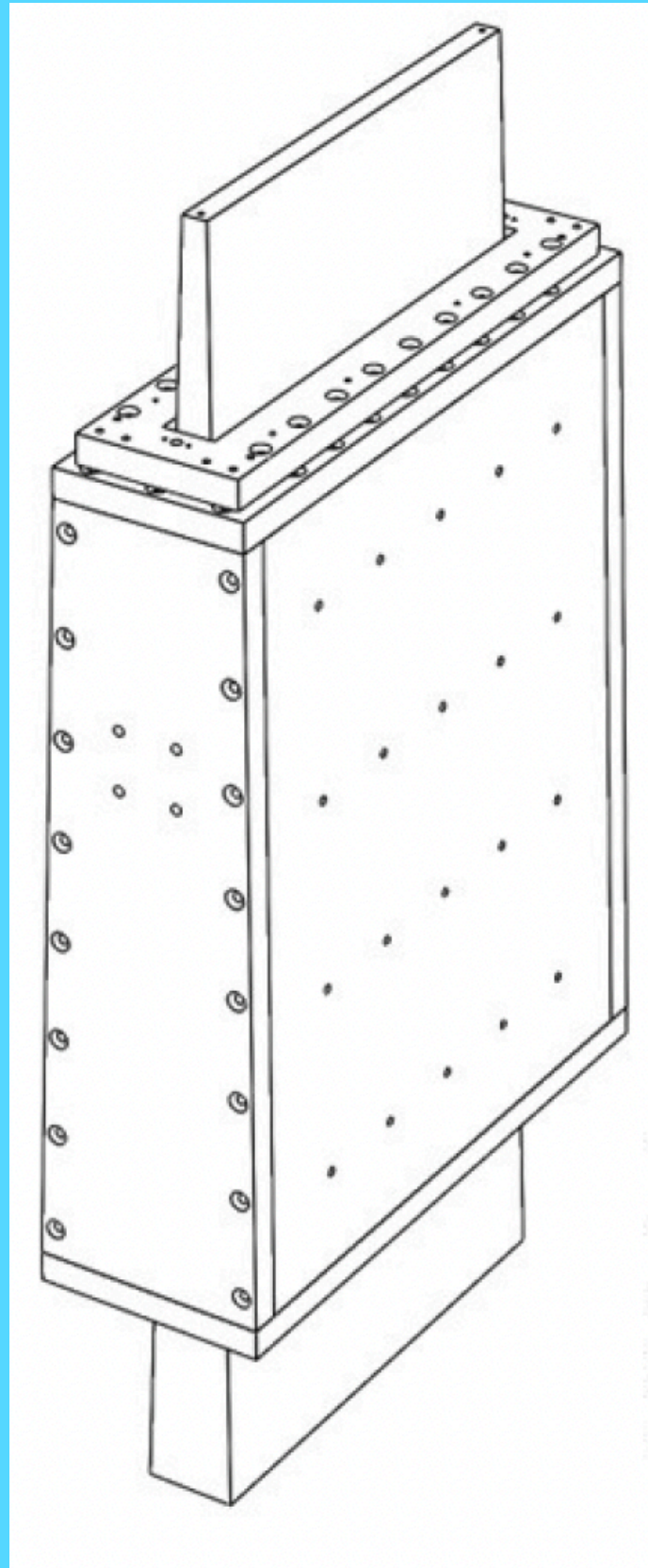
$$V = 100\lambda^3$$



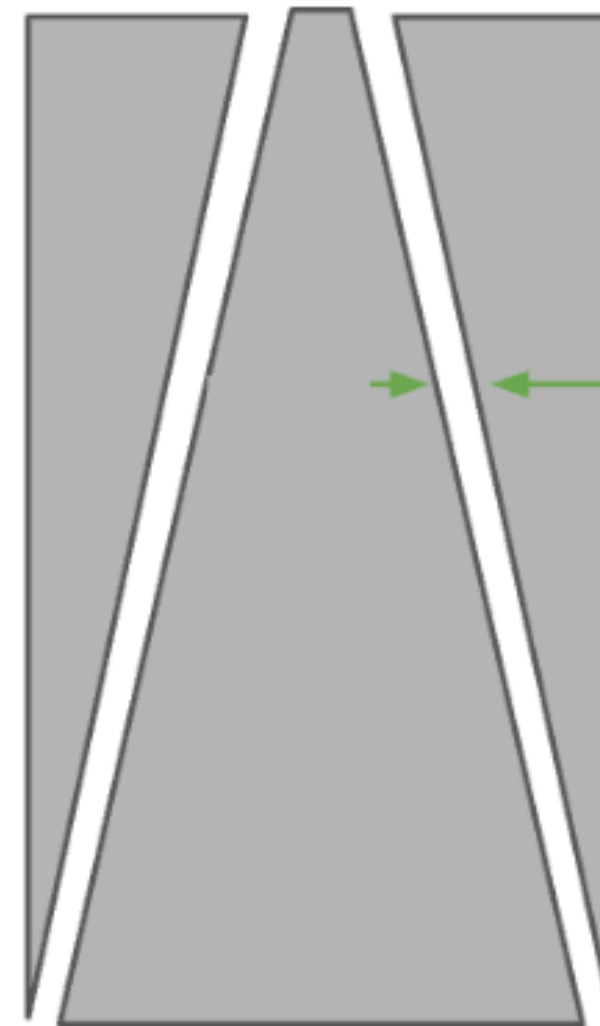


|                           |                                   |
|---------------------------|-----------------------------------|
| Volume (V)                | 2.6L (41 $\lambda^3$ ) at 7.5 GHz |
| Frequency Range           | 7 to 8 GHz                        |
| Quality Factor (Q)        | 4000                              |
| Form Factor ( $C_{010}$ ) | 0.57                              |

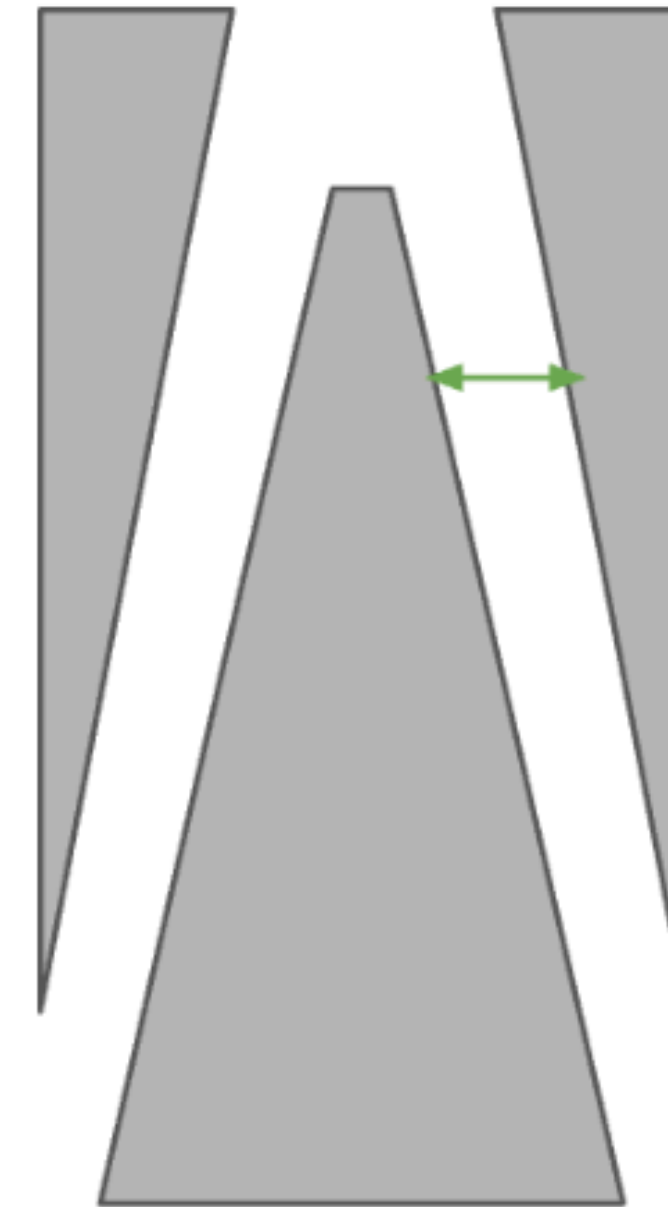
# ADMX-VERA



High frequency

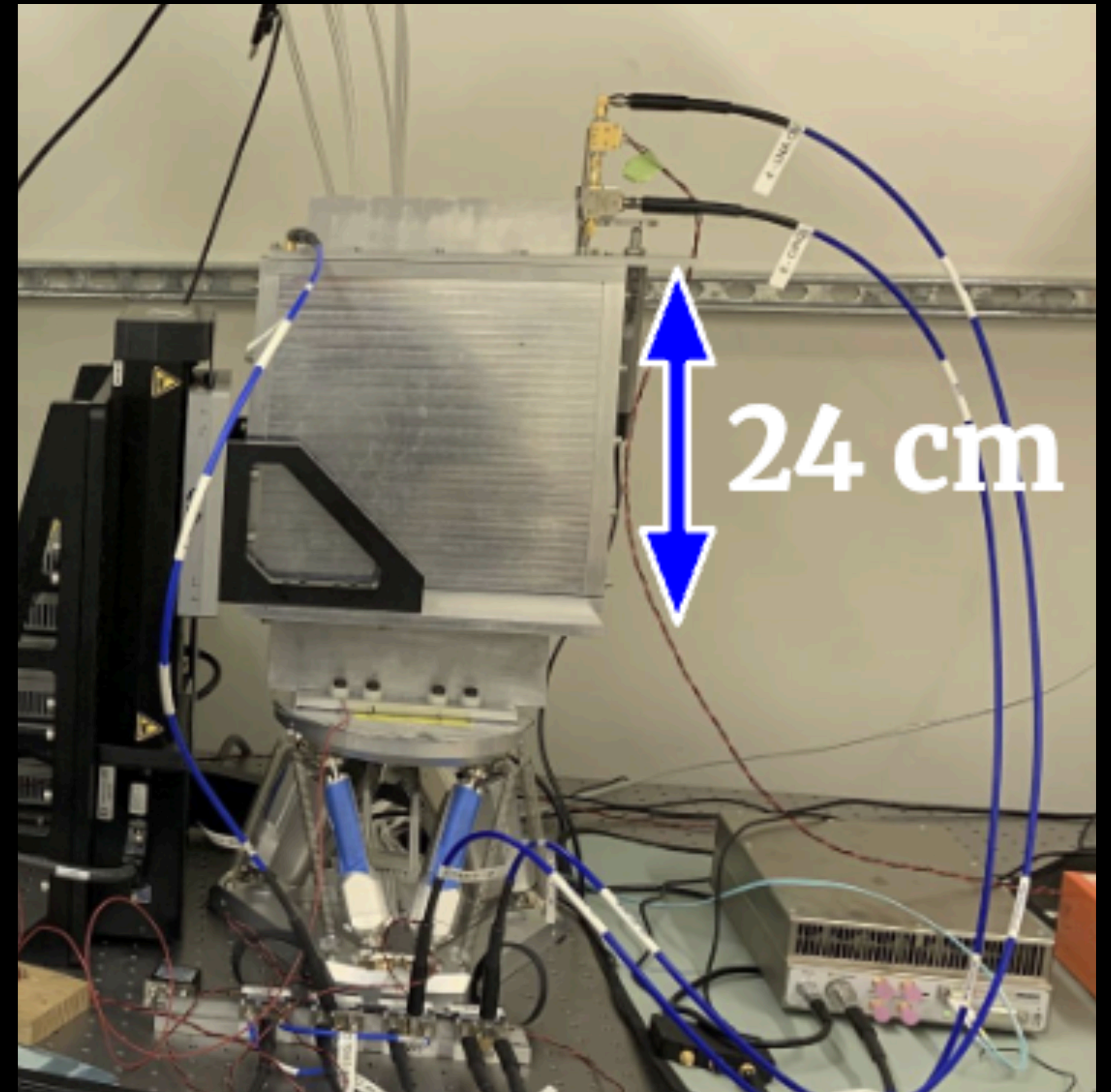
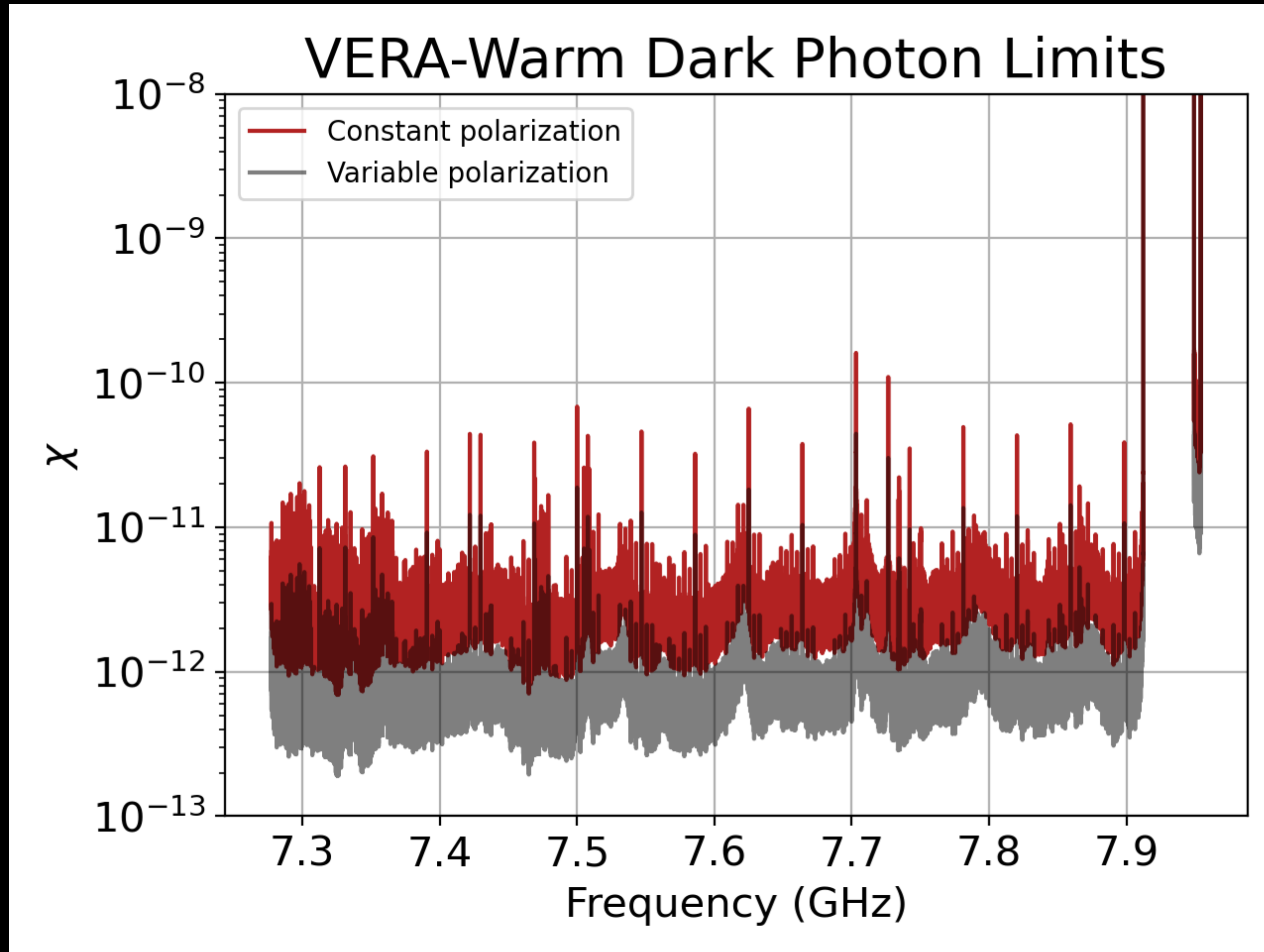


Low frequency





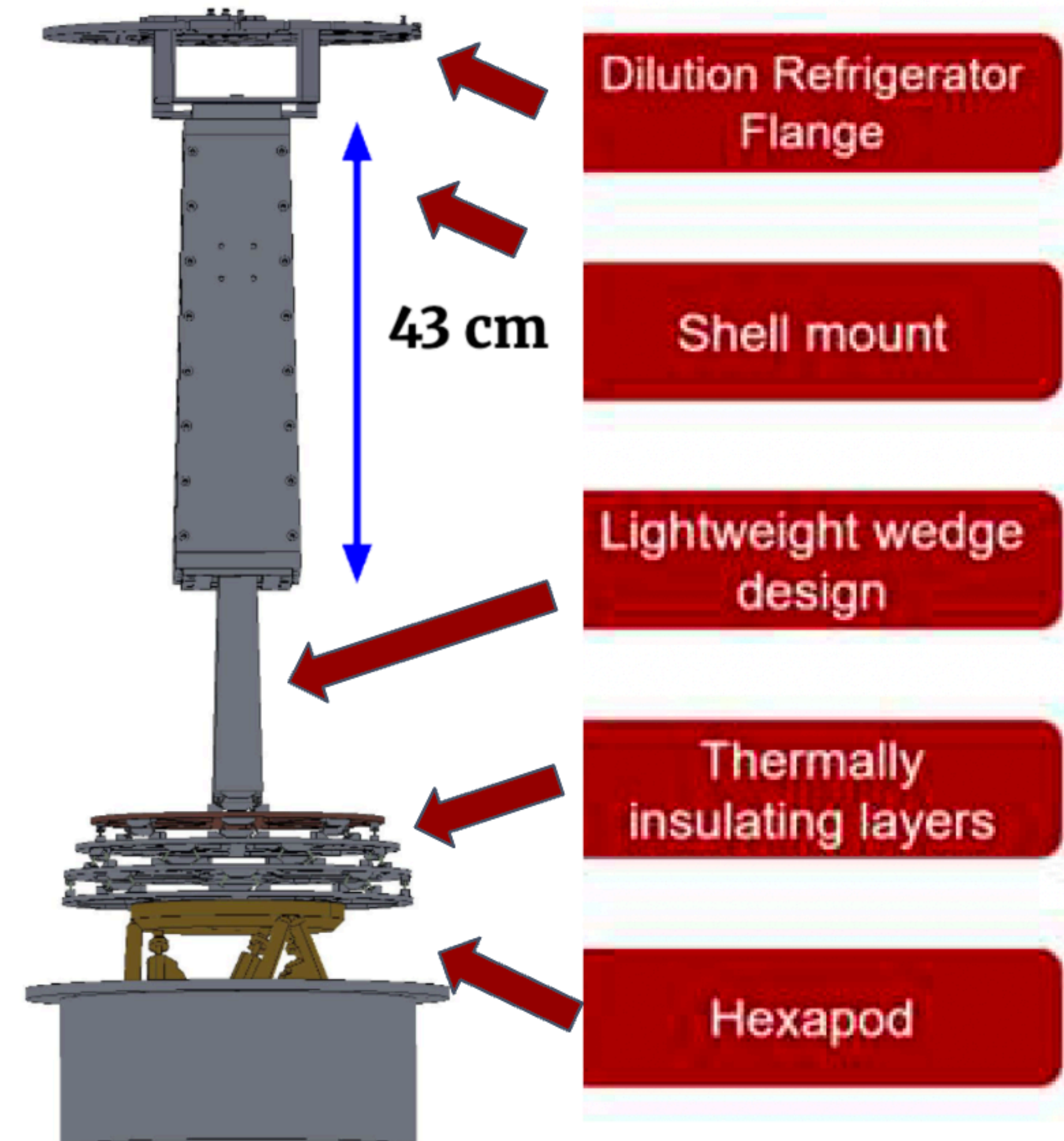
# ADMX-VERA



# ADMX-VERA

|                           |                                |
|---------------------------|--------------------------------|
| Volume (V)                | 6L ( $51 \lambda^3$ ) at 6 GHz |
| Frequency Range           | 5 to 7 GHz                     |
| Quality Factor (Q)        | 20,000                         |
| Form Factor ( $C_{010}$ ) | >0.5                           |

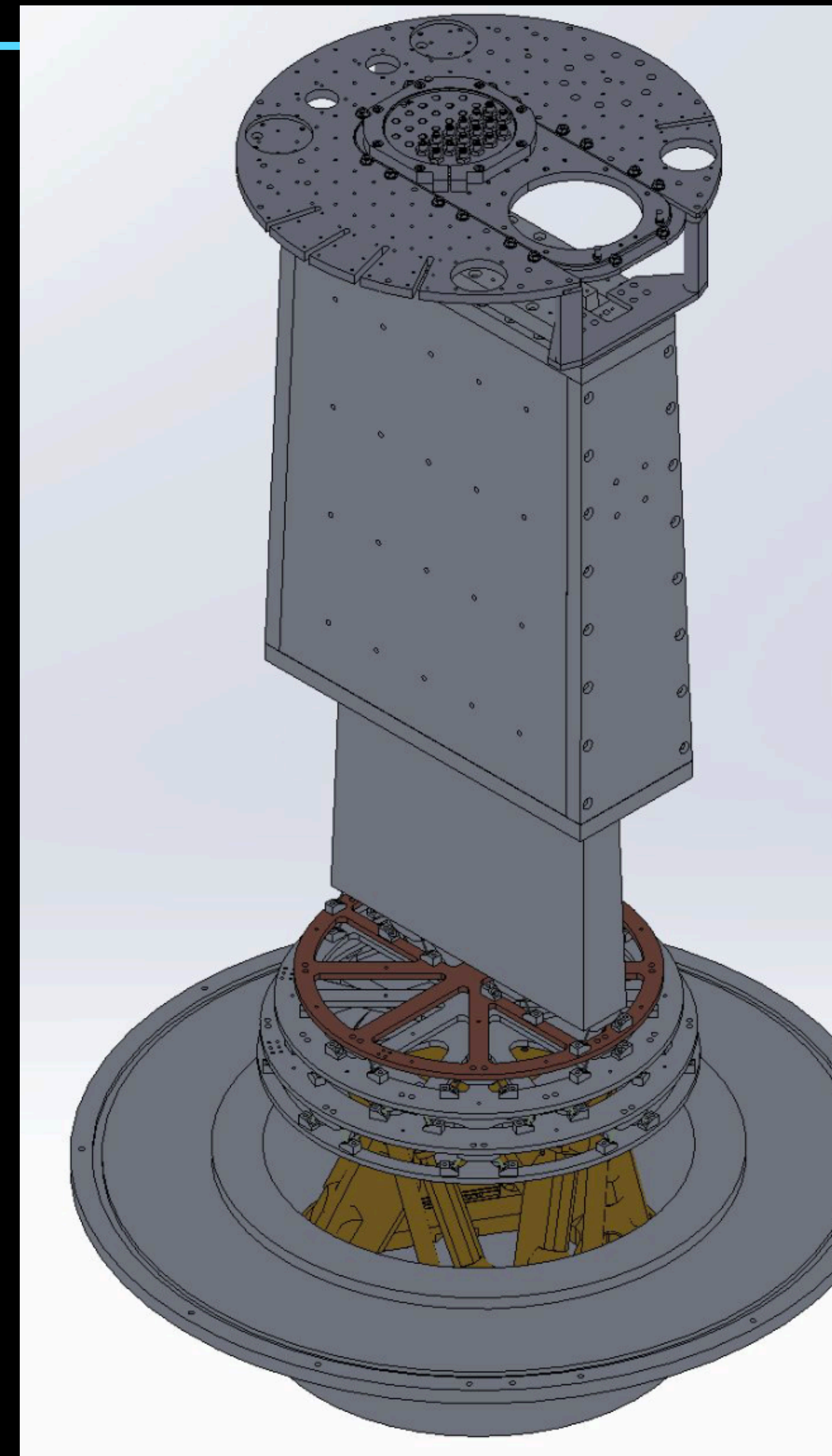
Simulated!





# ADMX-VERA

- Leverages “wedding cake” cryostat design from CMB experiments
- Hexapod motion transferred through wedding cake layers for precision alignment
- Designed to mount to Oxford fridge at SLAC milliKelvin Facility (SMF)





# ADMX-VERA

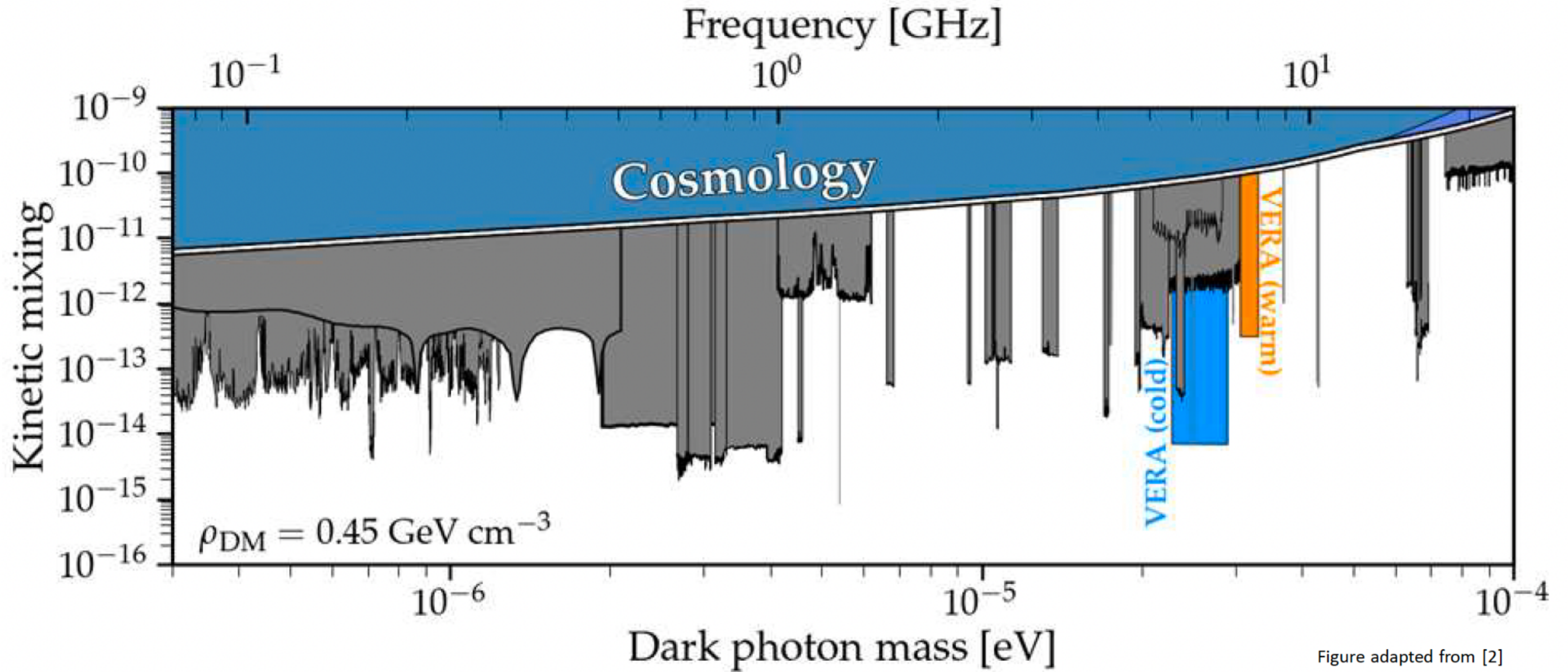
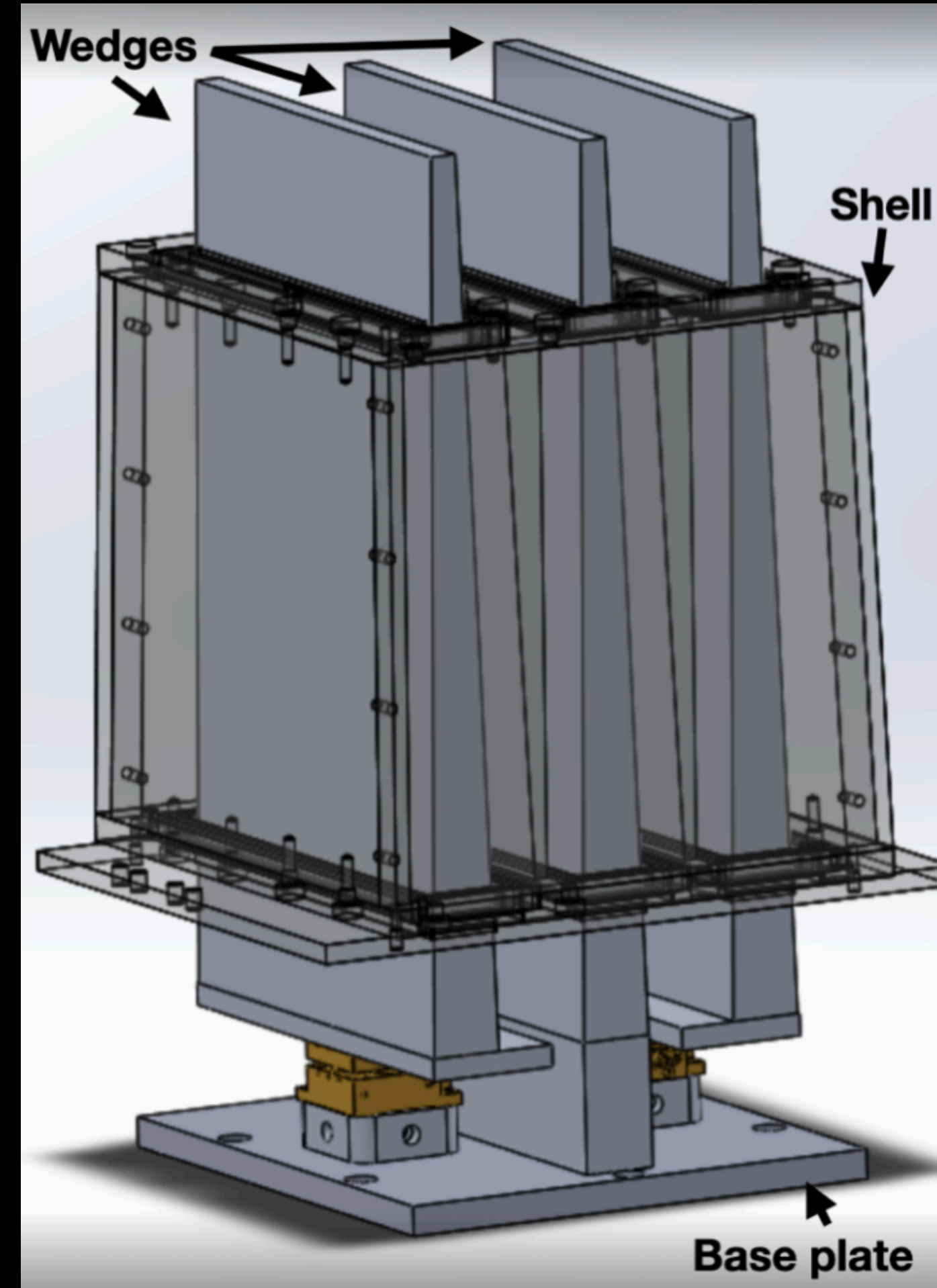
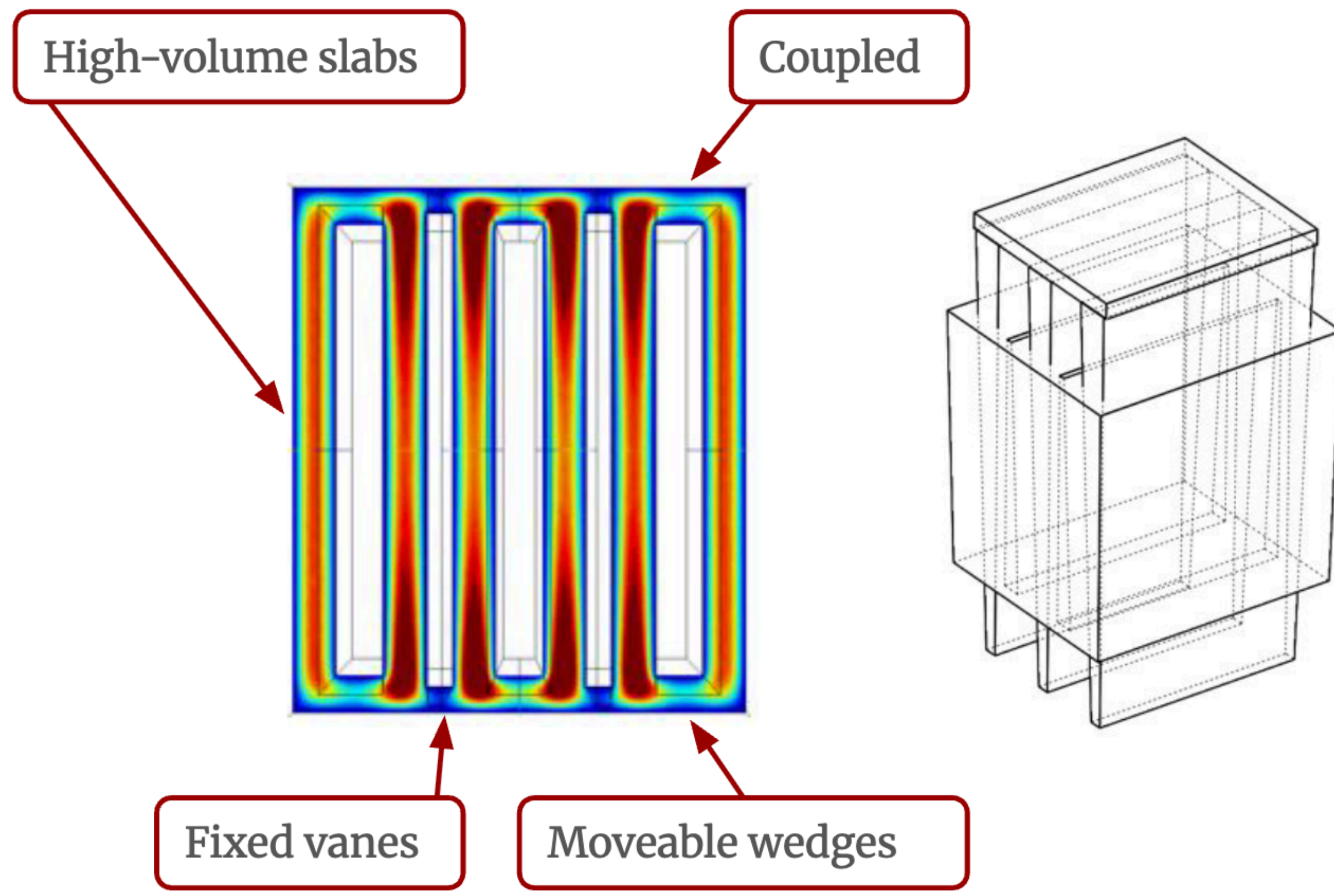


Figure adapted from [2]



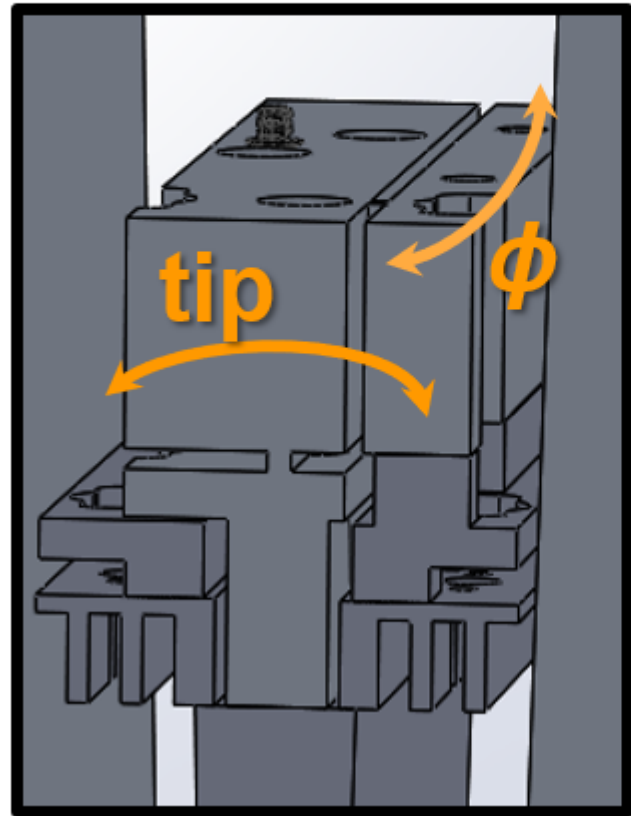
# ADMX-VERA

## Geometry



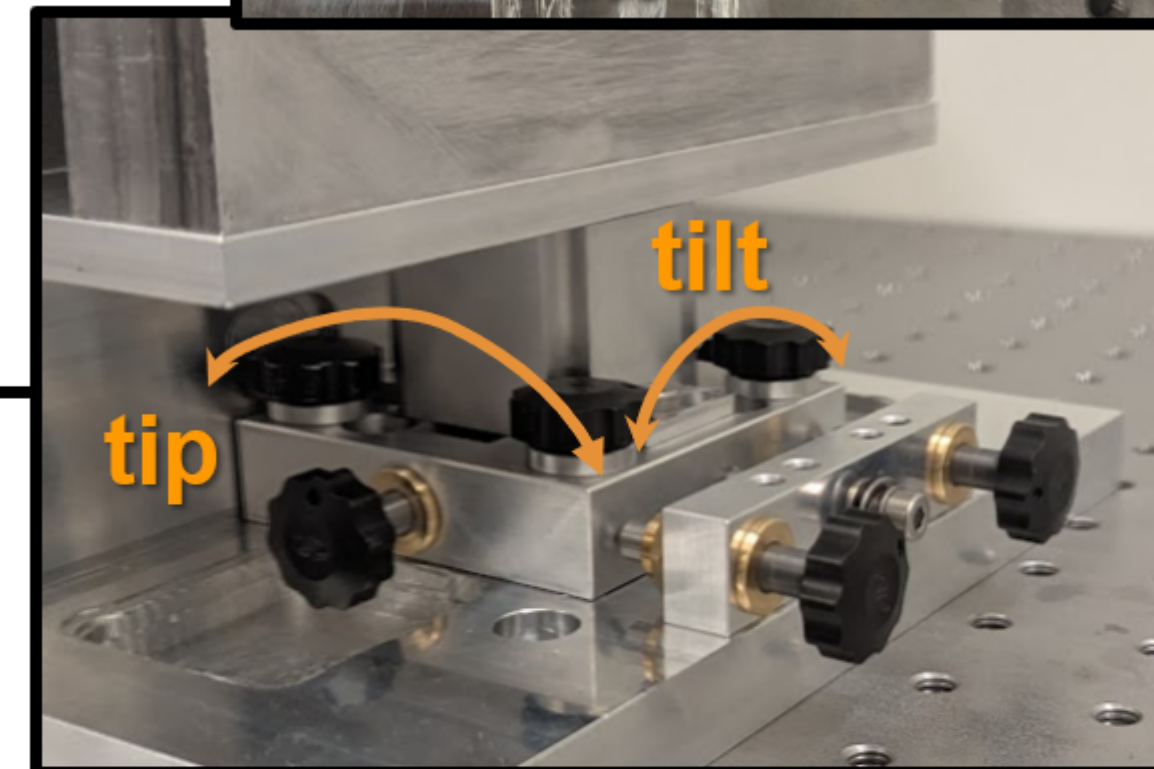
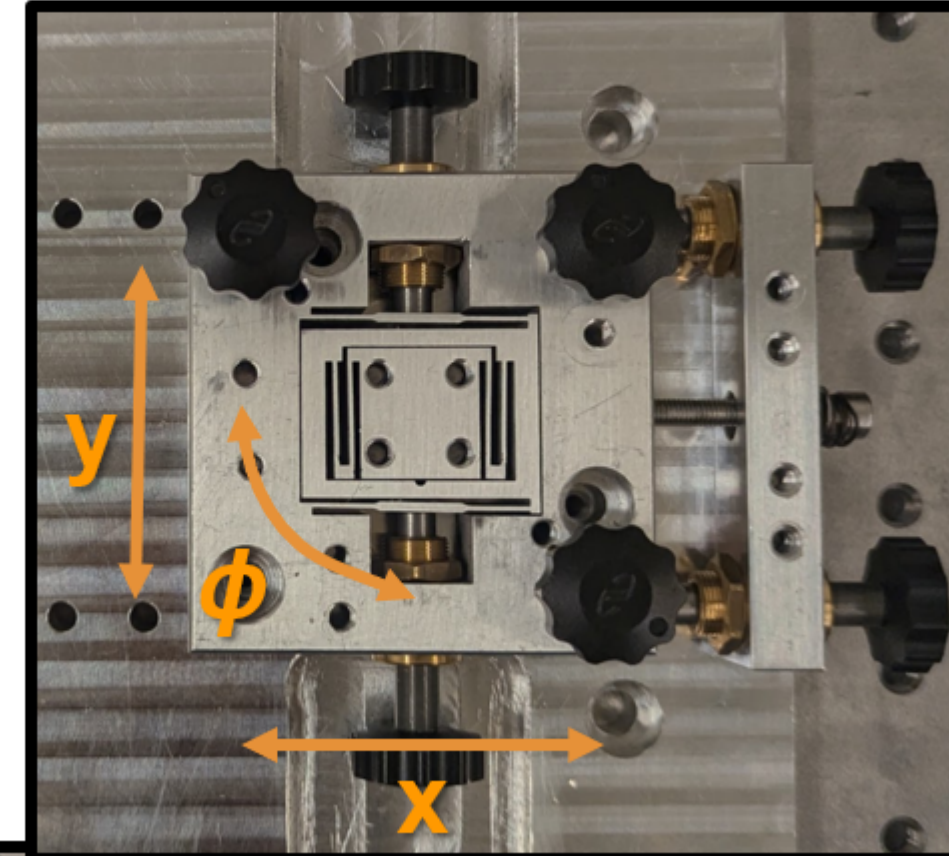
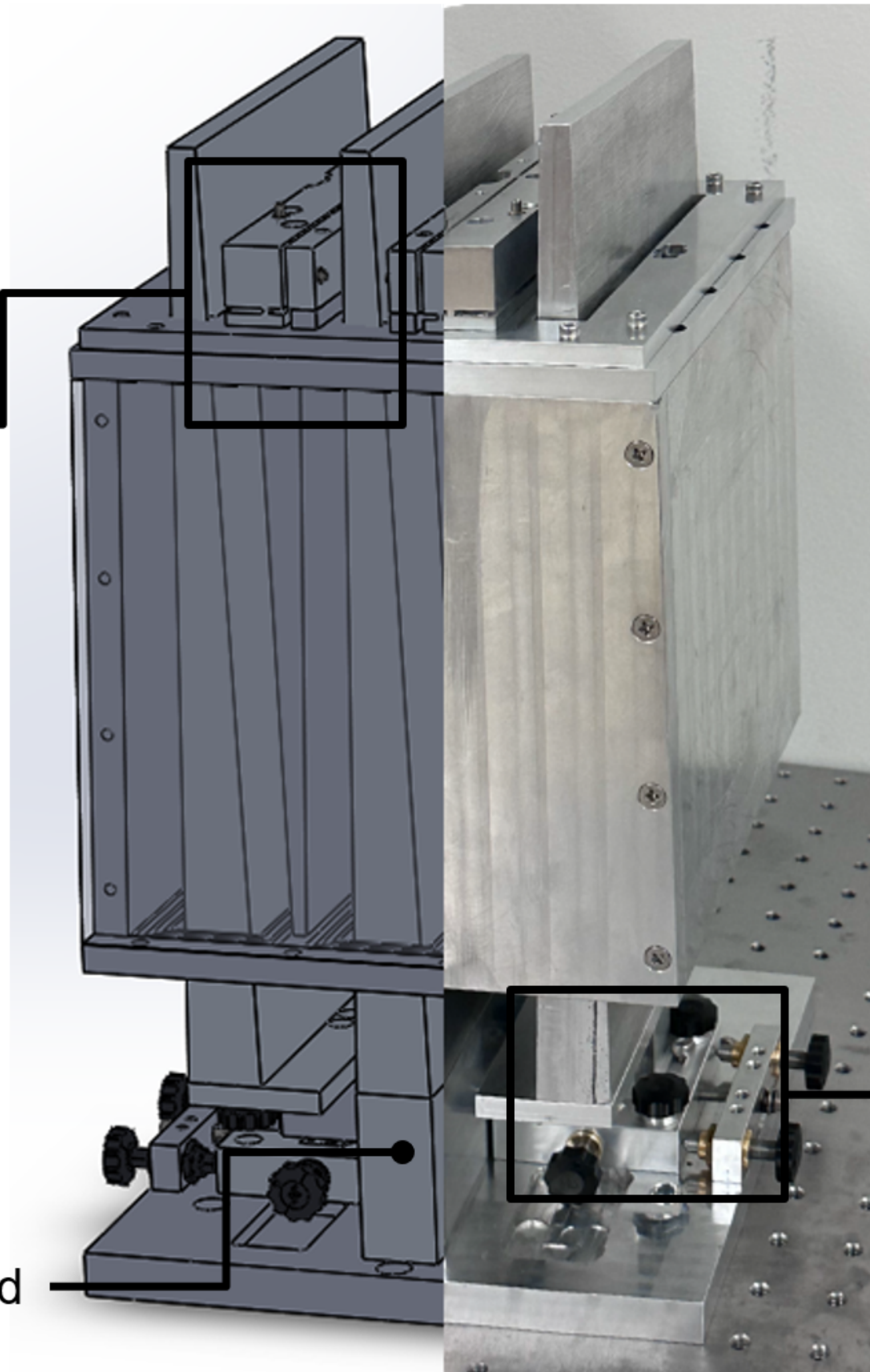


# ADMX-VERA



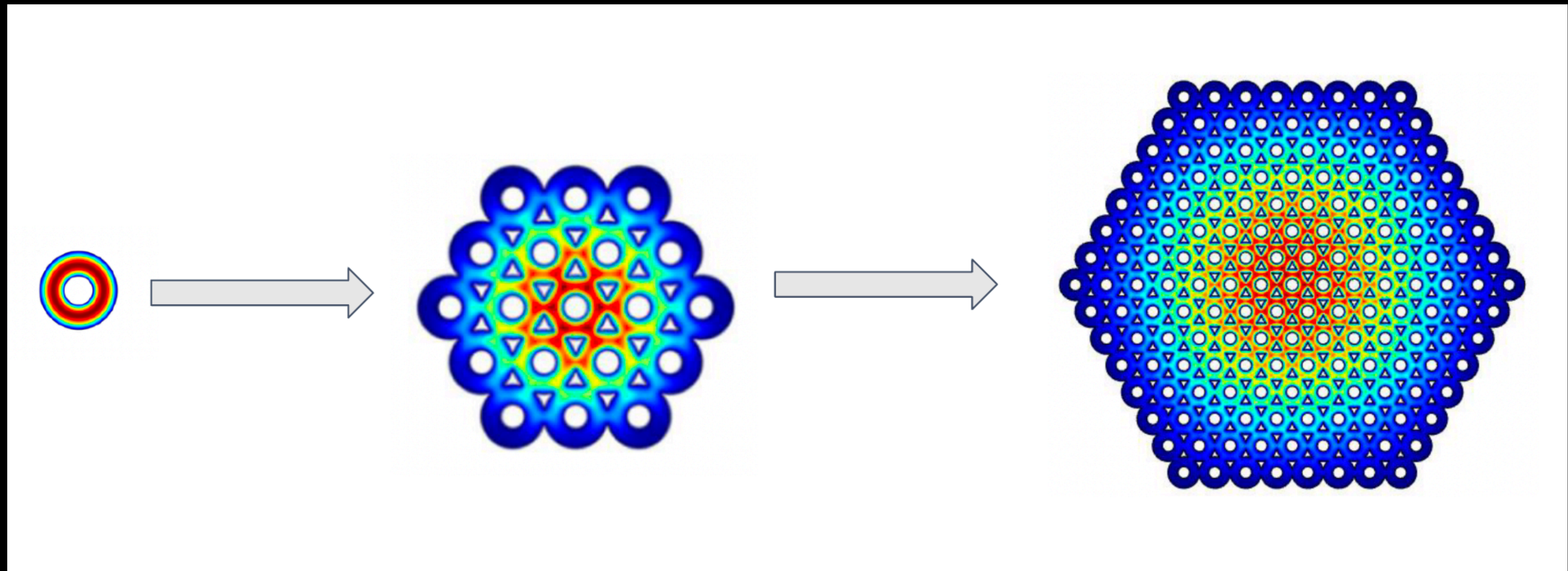
Shell dividers are positioned by 2-DoF flexure design

Center wedge is fixed



Outer wedges are positioned by 5-DoF fine adjustment stage

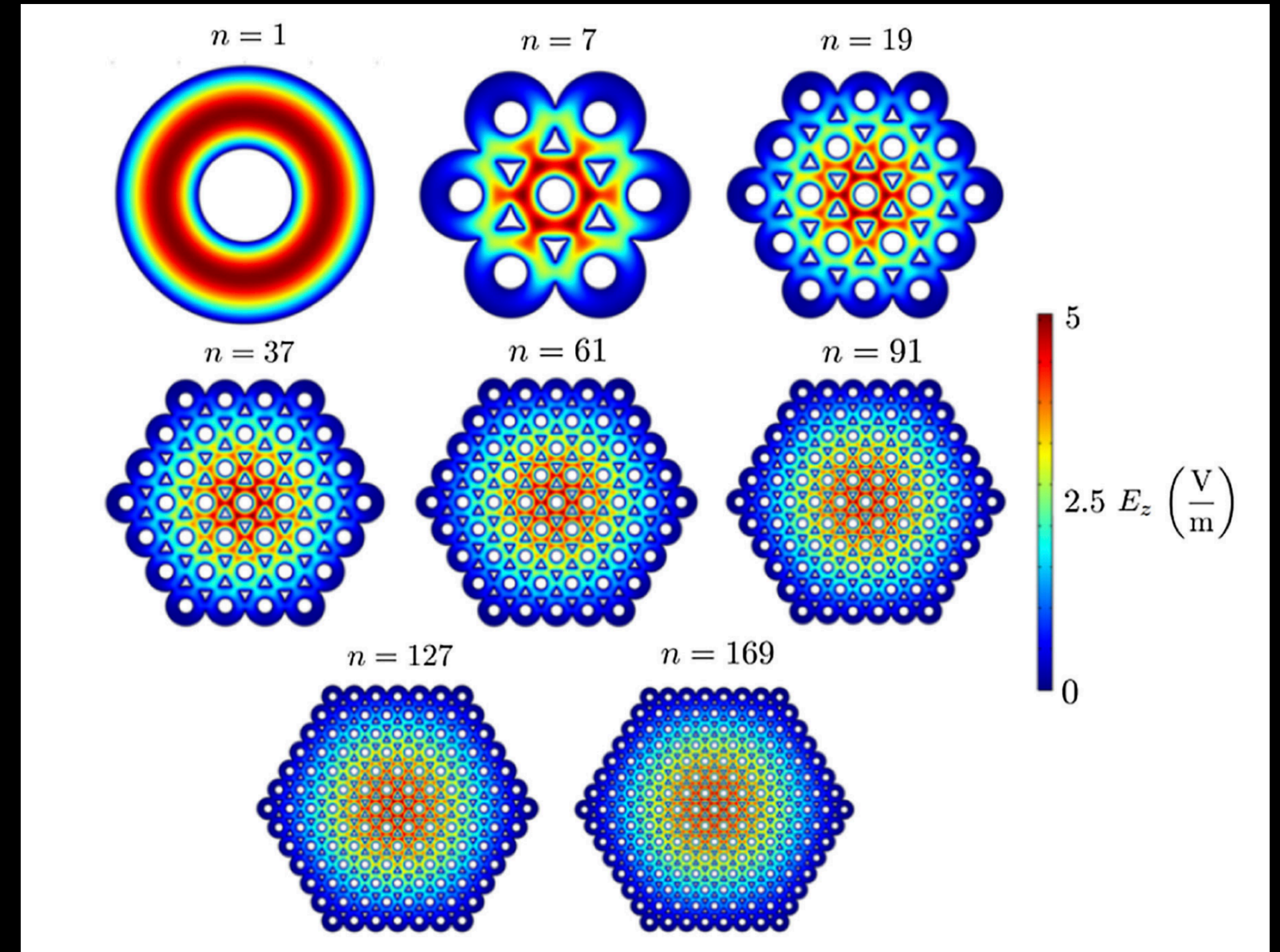






# ADMX-VERA

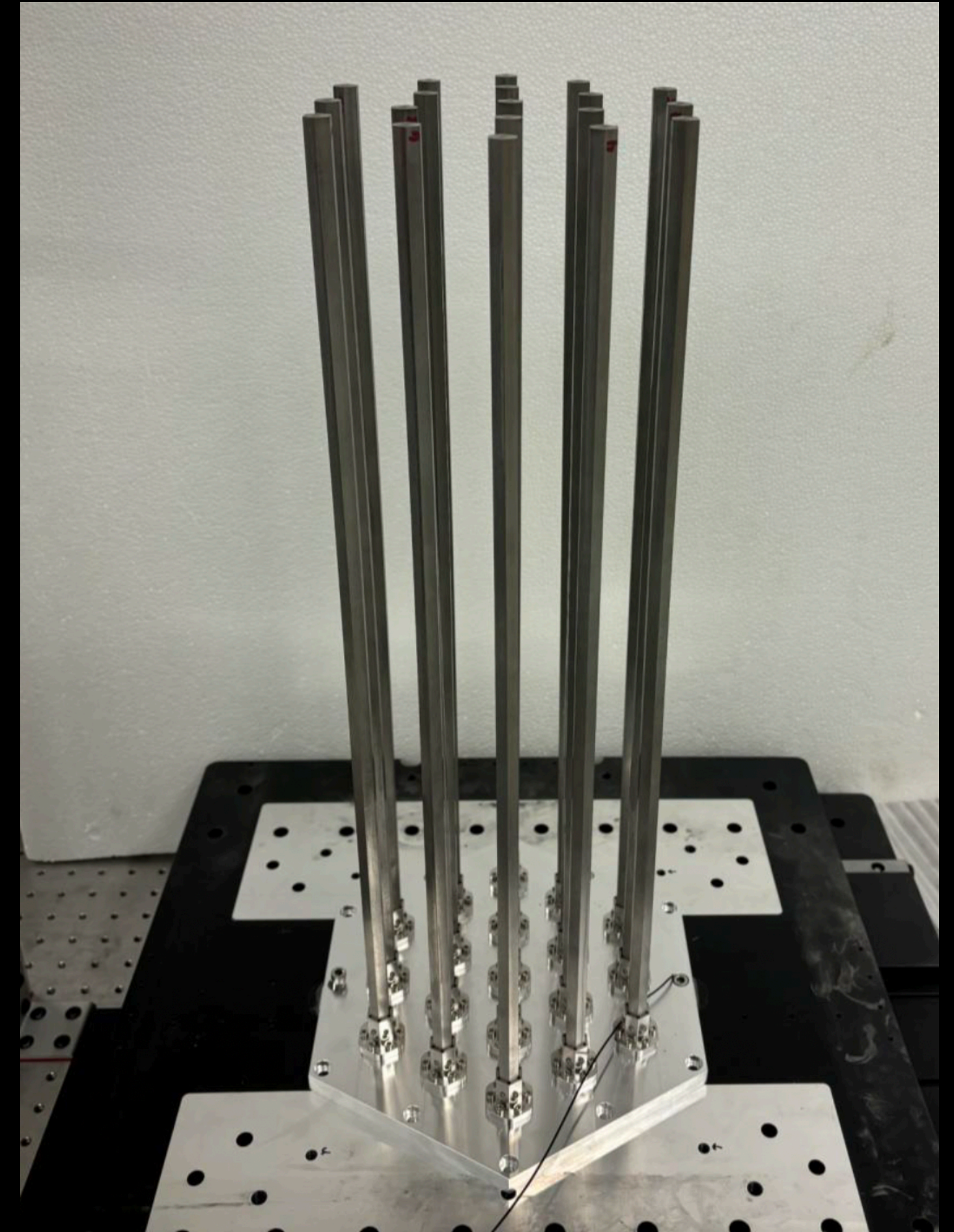
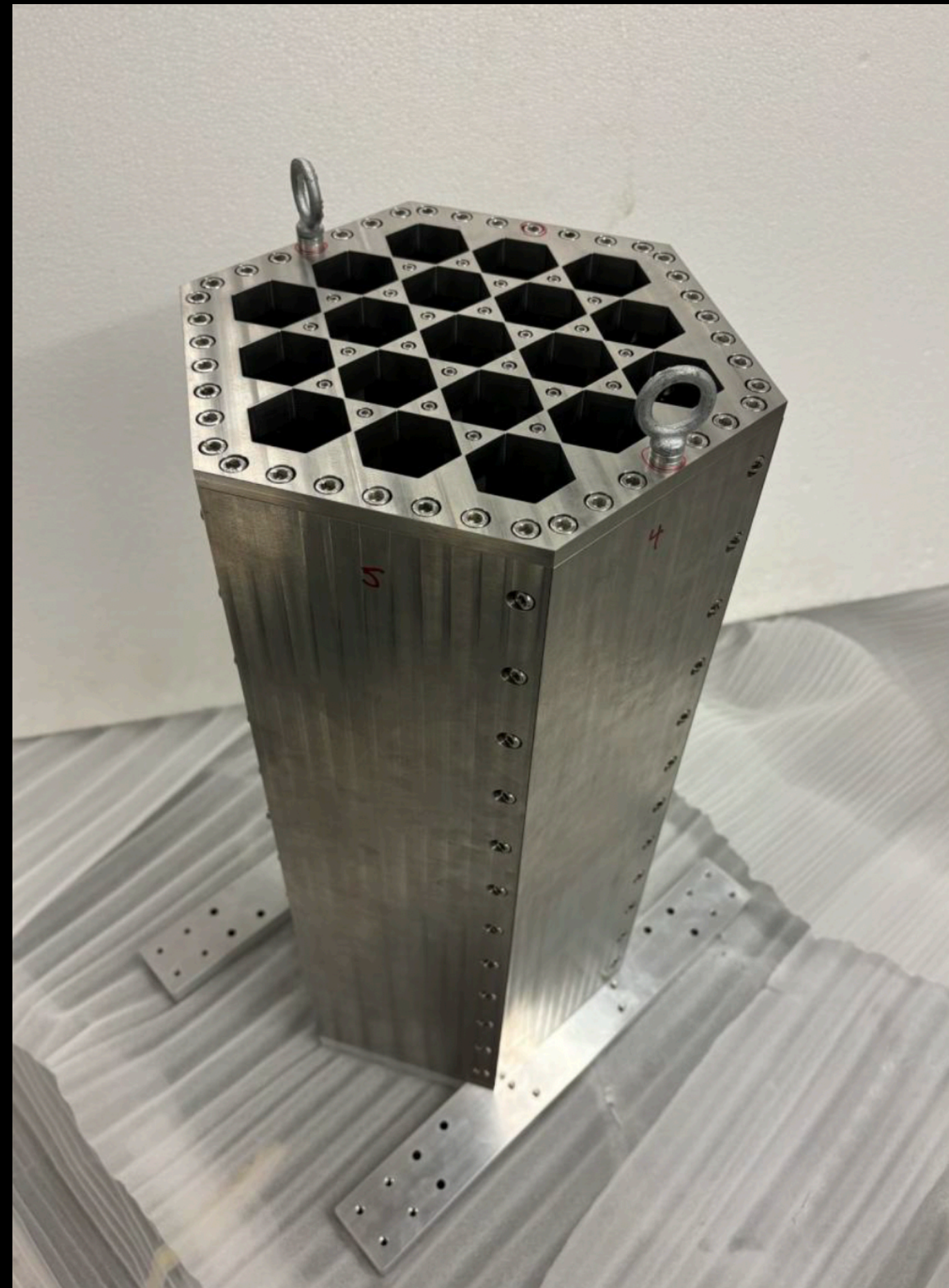
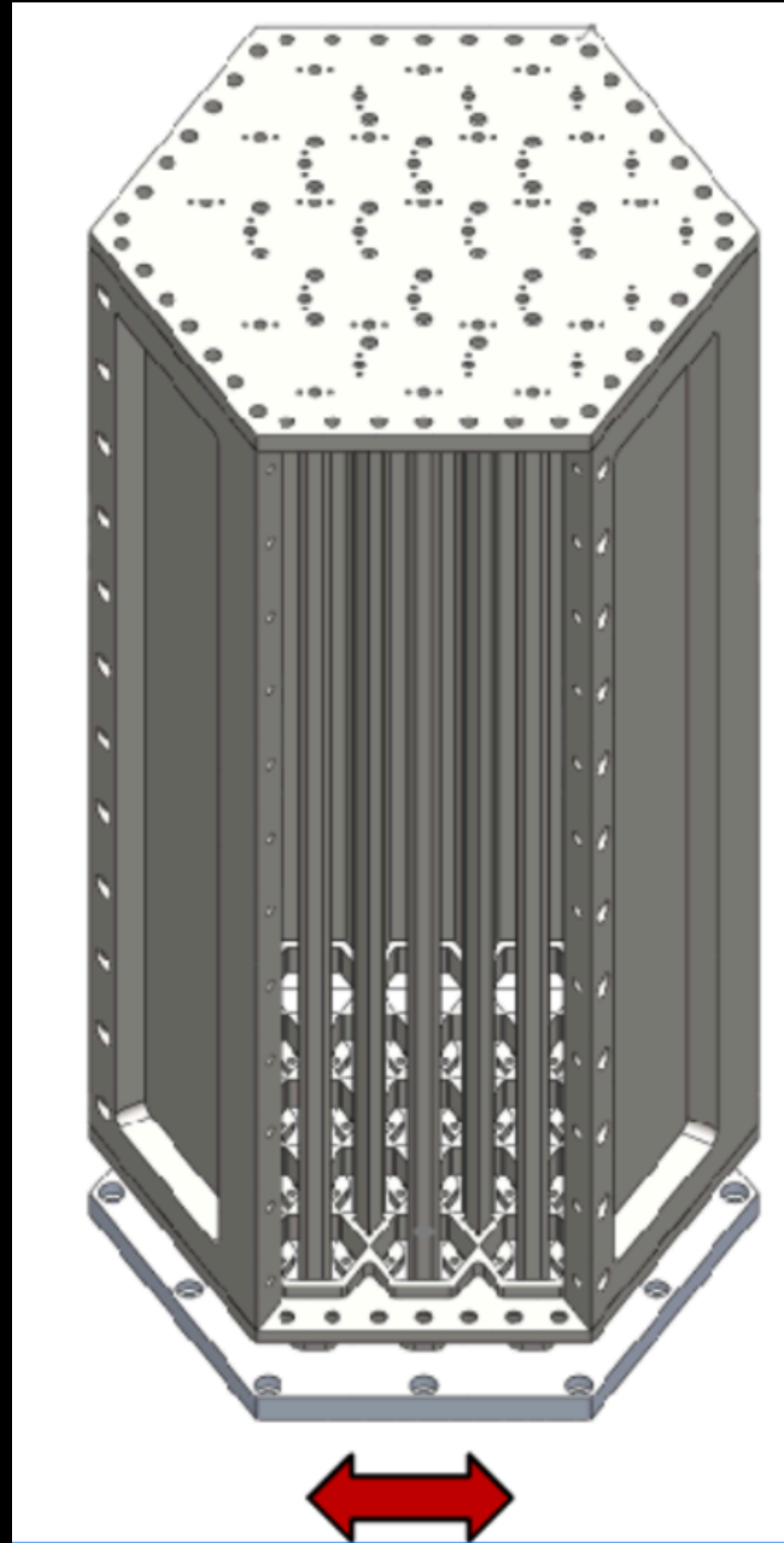
- Closely packed overlapping cavities.
- Resonant frequency determined by cells oscillating in phase.
- Global eigenmode that has high (40%) form factor in a 169-element resonator.
- Tunable by moving center rods laterally in unison.



Withers, Matthew O., and Chao-Lin Kuo. "Beehive haloscope for high-mass axion dark matter." *Physical Review D* 111.7 (2025): 072011.

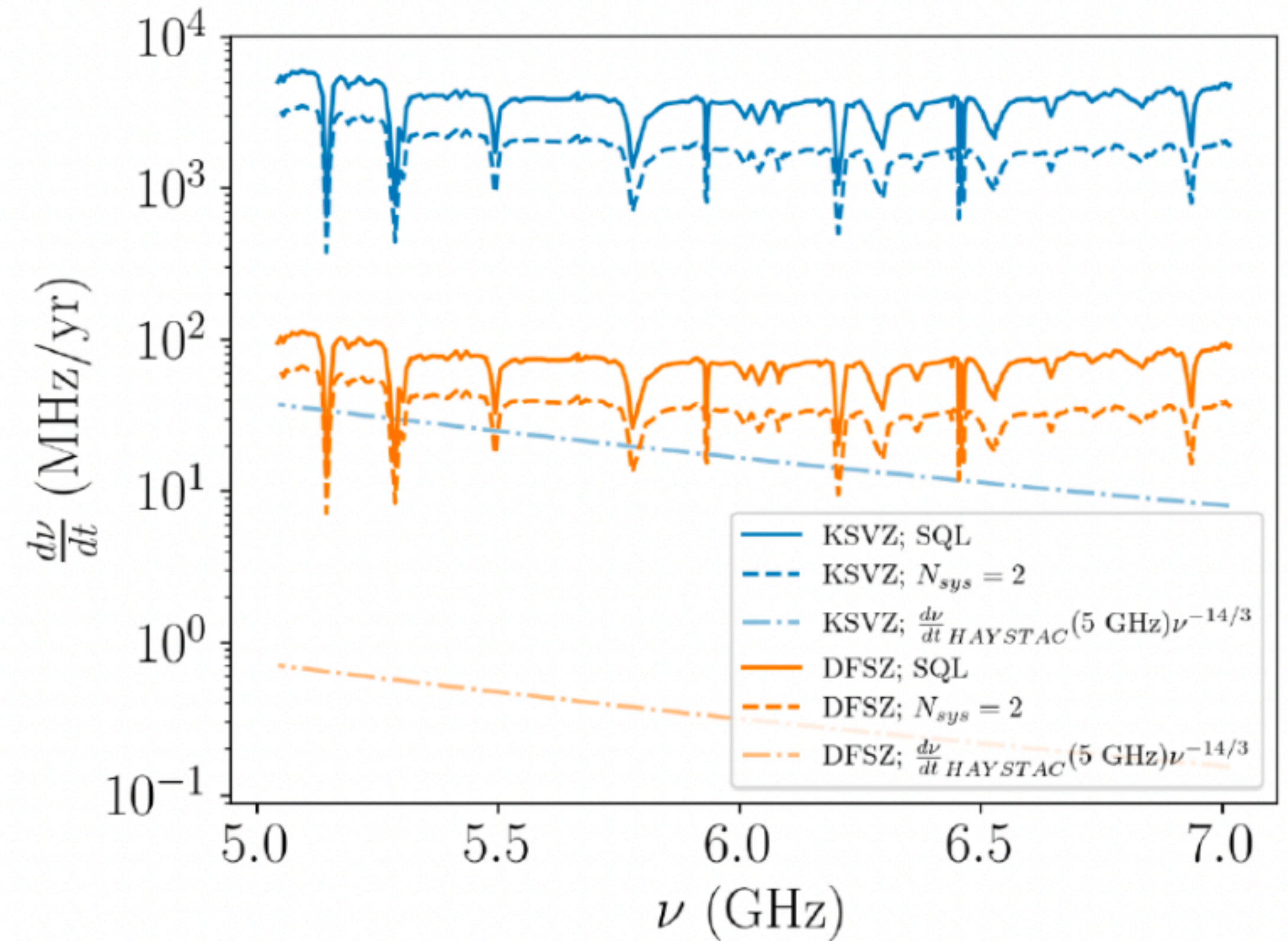
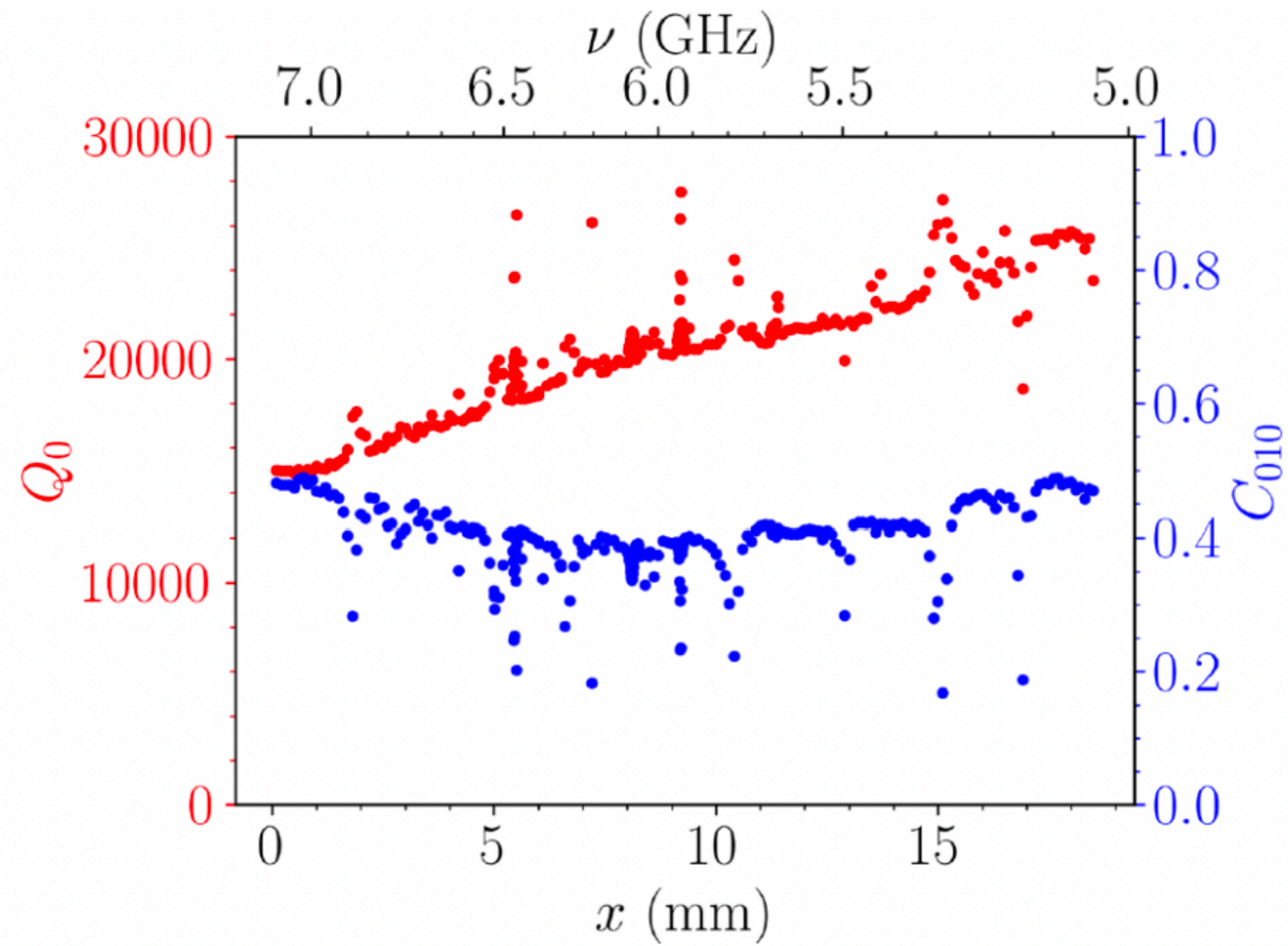


# ADMX-VERA





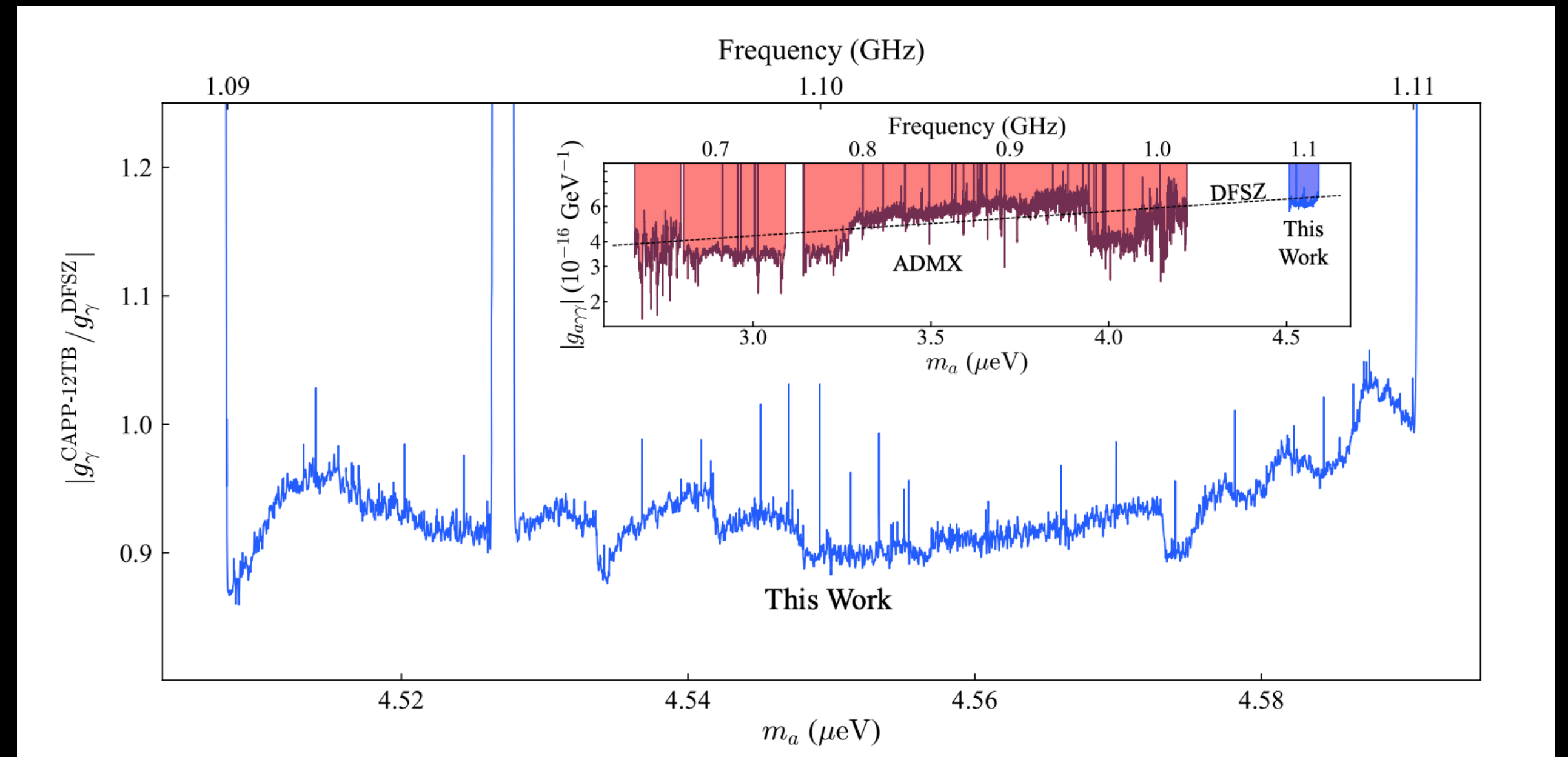
# ADMX-VERA





## CAPP-12TB

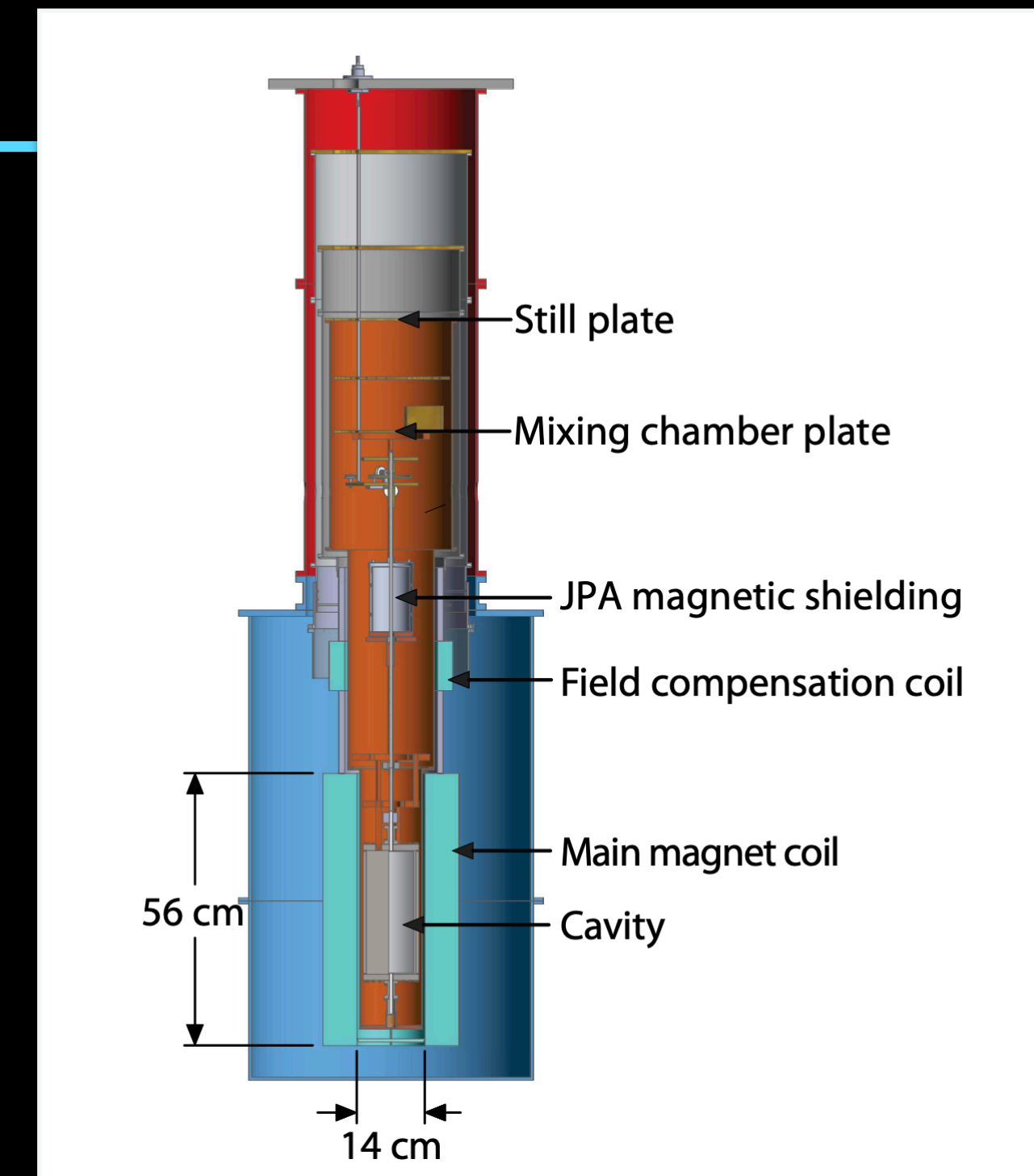
- Second cavity search at DFSZ
- ~10 T superconducting magnet
- 25 mK base temperature
- 36.85 L cavity



Andrew, K. Yi, et al. "Axion Dark Matter Search around  $4.55 \mu\text{eV}$  with Dine-Fischler-Srednicki-Zhitnitskii Sensitivity." *Physical Review Letters* 130.7 (2023): 071002.

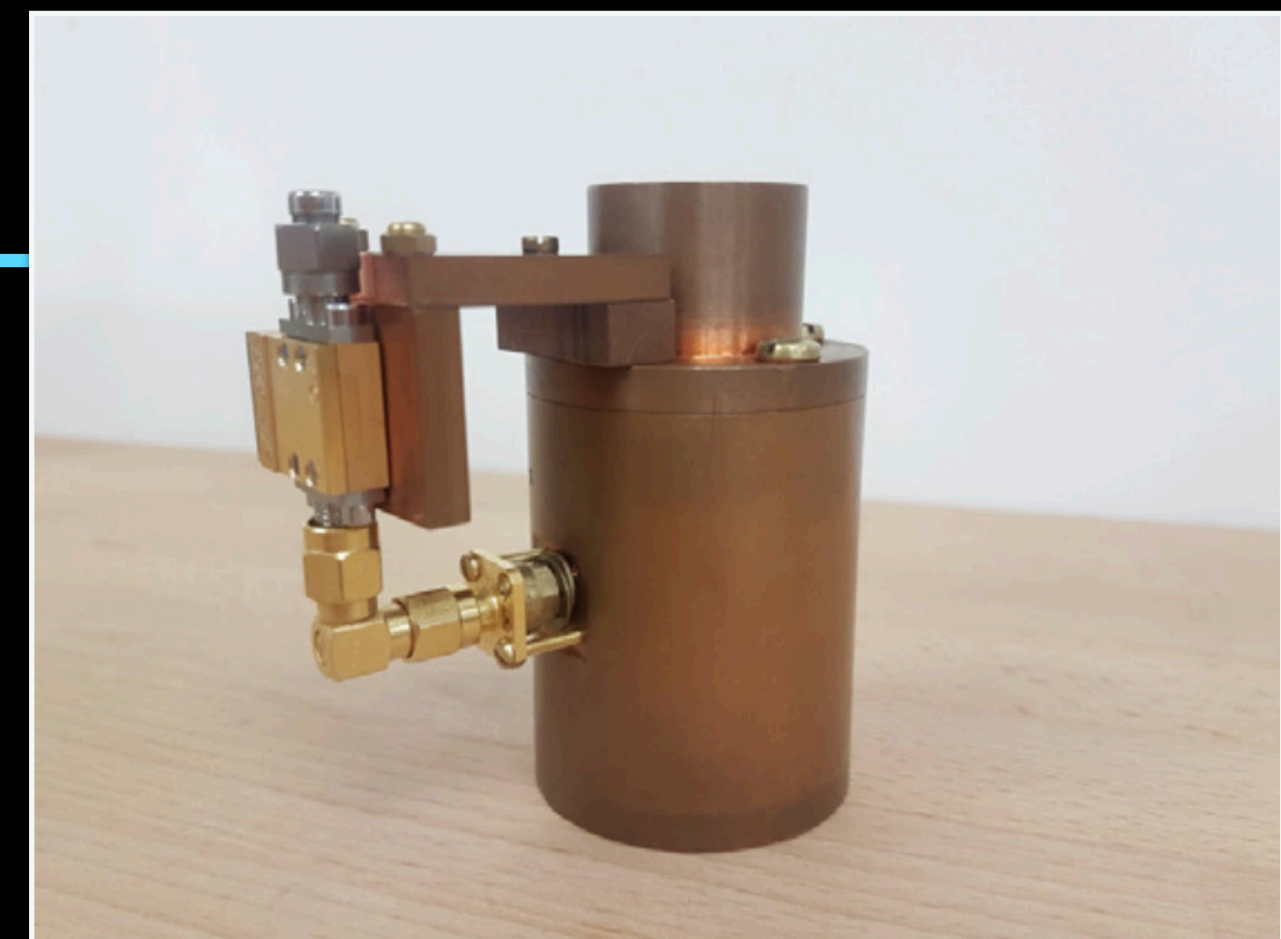
# HAYSTAC

- Exploring higher frequency axions
- Using squeezed state receiver:
- Phys. Rev. X 9, 021023 (2019)
- Exploring Bayesian techniques:
- Phys. Rev. D 101, 123011 (2020)
- Phase 1 results complete
- Phase 2 underway

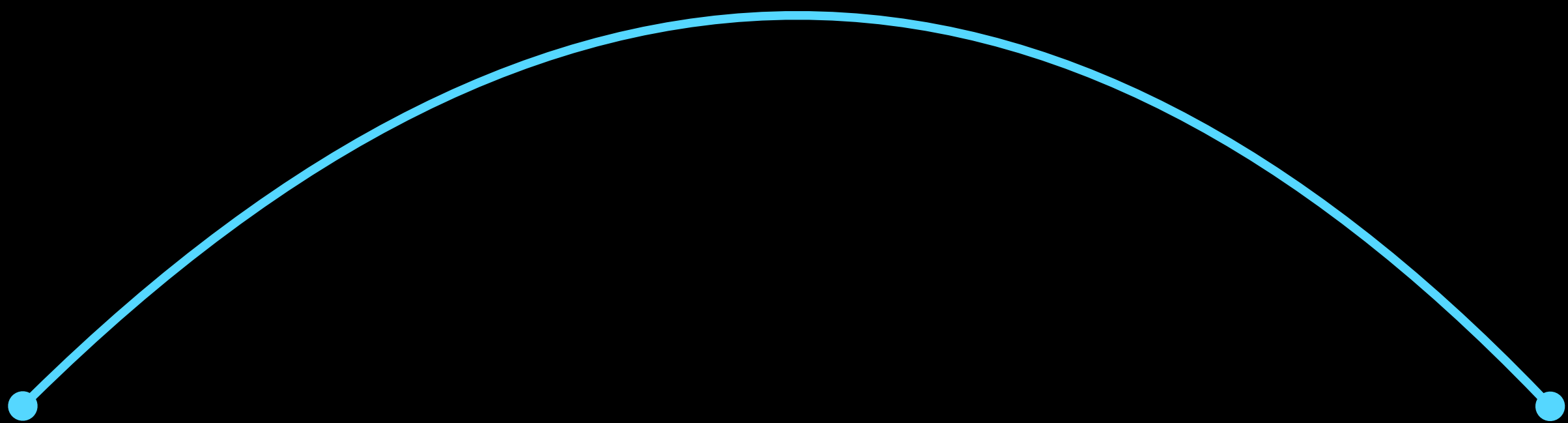


# ORGAN

Higher frequencies 26.6 ~GHz (110  $\mu$ eV)







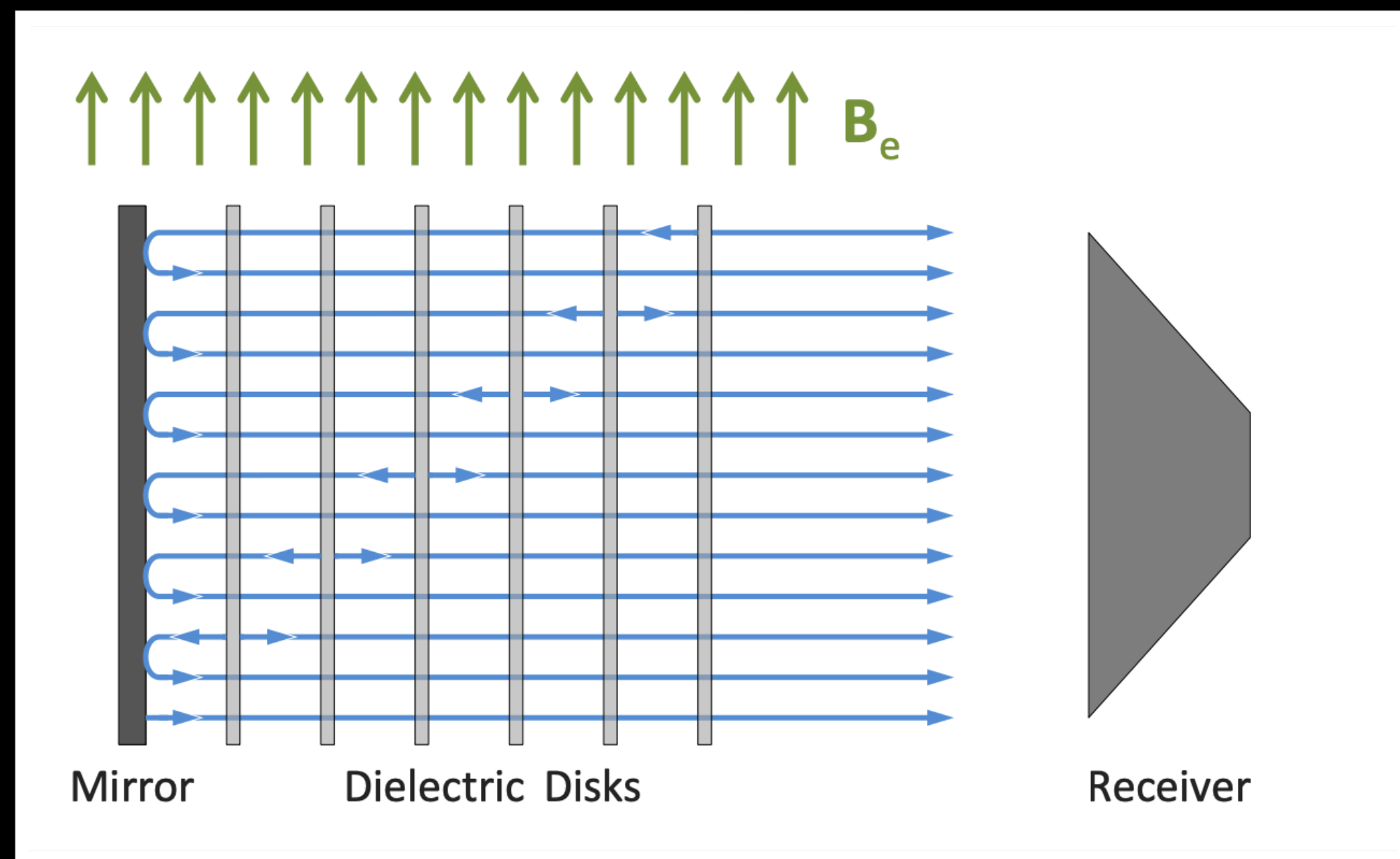
AXIONS AND WAVE-LIKE DARK MATTER

# RADIATION REGIME

MADMAX, BREAD AND MORE...



# MADMAX: Dielectric Haloscope



- Will probe 40-400  $\mu\text{eV}$  range (10-100 GHz)
- 10 T field
- ~80 disks
- Prototype phase using dipole magnet at CERN

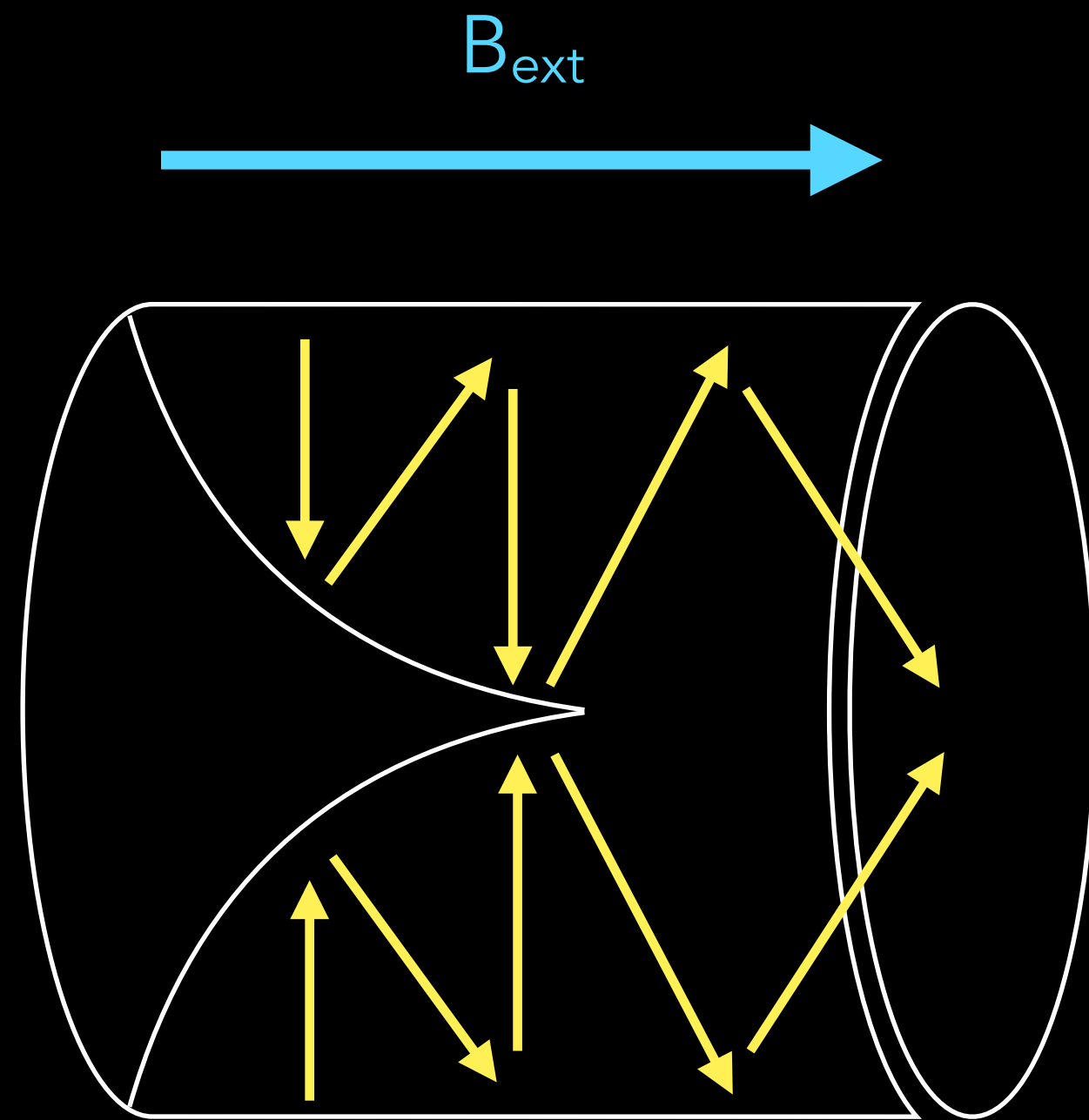
B. Majorovits and MADMAX interest group 2020 J. Phys.: Conf. Ser. 1342 012098

Stefan Knirck and MADMAX interest group 2020 J. Phys.: Conf. Ser. 1342 012097

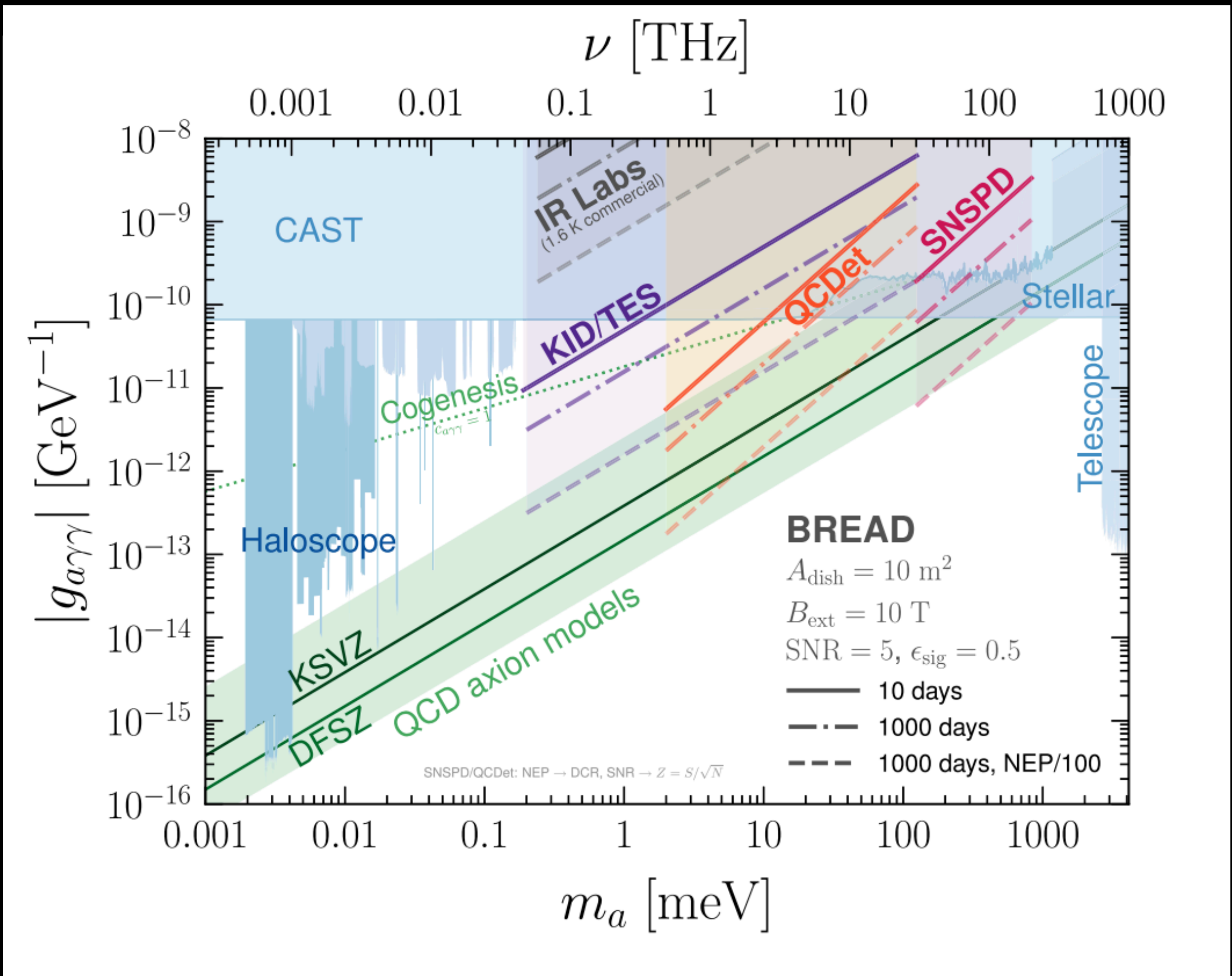


# BREAD: Inverted Dish Antenna

Conical structure focuses the light to a single photon detector.



Liu, Jesse, et al. "Broadband solenoidal haloscope for terahertz axion detection." *Physical Review Letters* 128.13 (2022): 131801.





# Conclusions

- Variety of haloscopes to search for axions.
  - Lumped element detectors
  - Cavity resonators
  - Dielectric haloscopes and more
- Field is growing rapidly
- New techniques from fields of quantum information and quantum measurement (more tomorrow!)





# Backup Slides

