LOW FREQUENCY DARK MATTER WAVES: A FORECAST

UNIVERSITY OF CHICAGO, TEVPA

CHELSEA BARTRAM 2024

Wave-like dark matter

$$\lambda_{dB} \approx \frac{2\pi}{mv}$$ De Broglie wavelength

Dark matter that behaves more like a wave than a particle

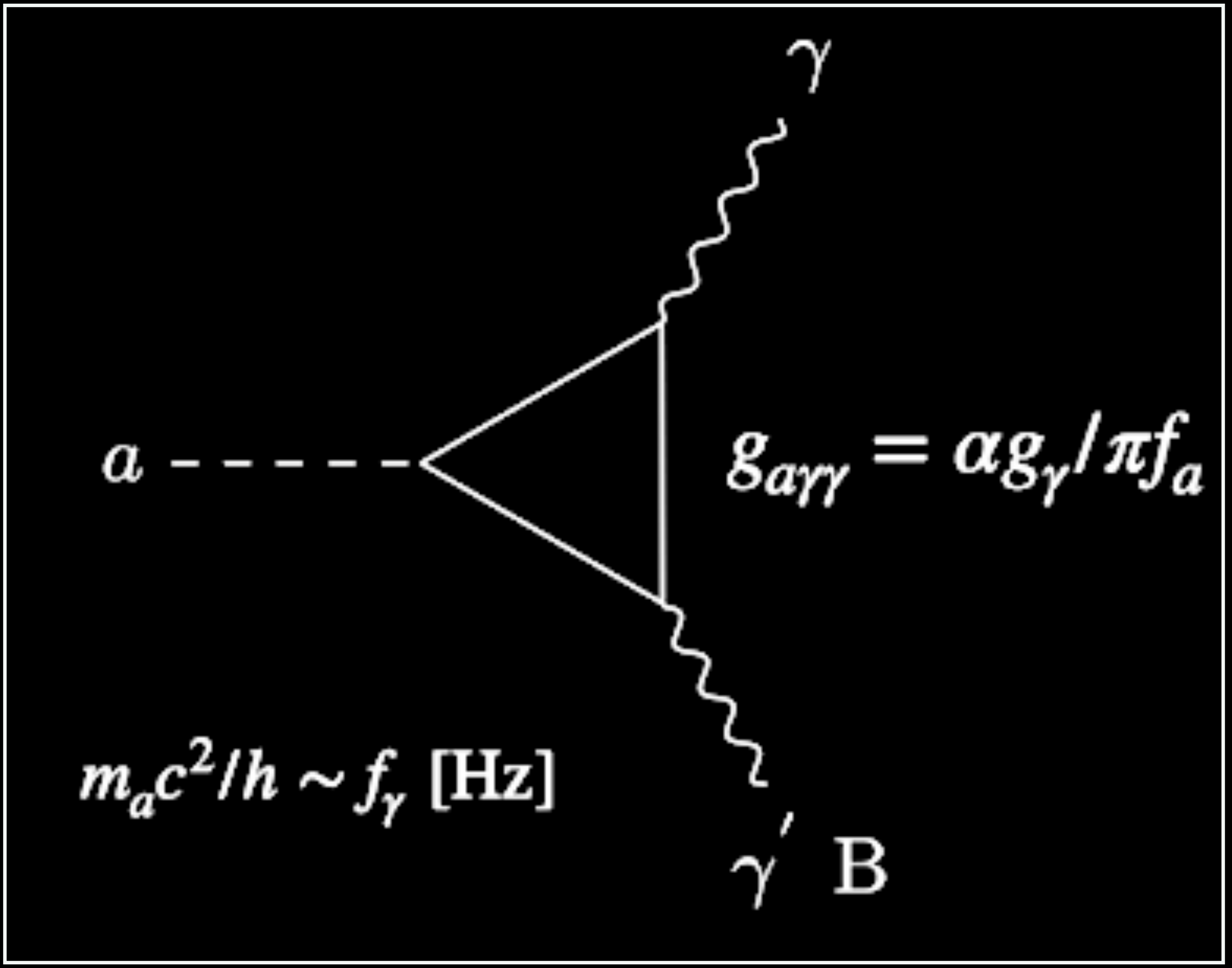
Proton in a linear accelerator: $\lambda \sim 10^{-12}$ m

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

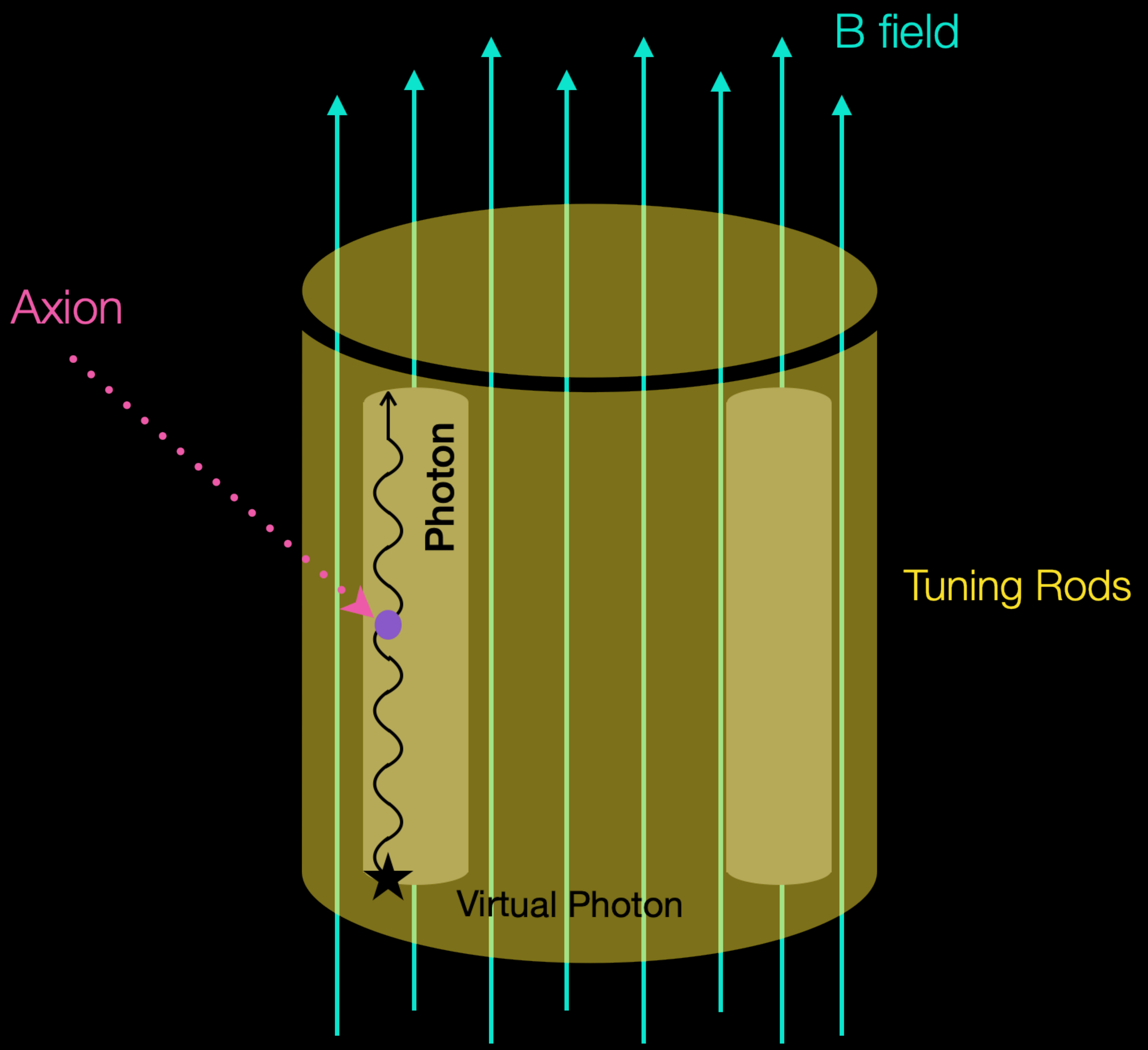
Axion Dark Matter ($m \sim 10^{-6}$ eV): $\lambda \sim 100$ m → Something completely different...

Detection: Axion Haloscope

Photon coupling: cleanest channel for discovery



Inverse Primakoff Effect



Resonant microwave cavity

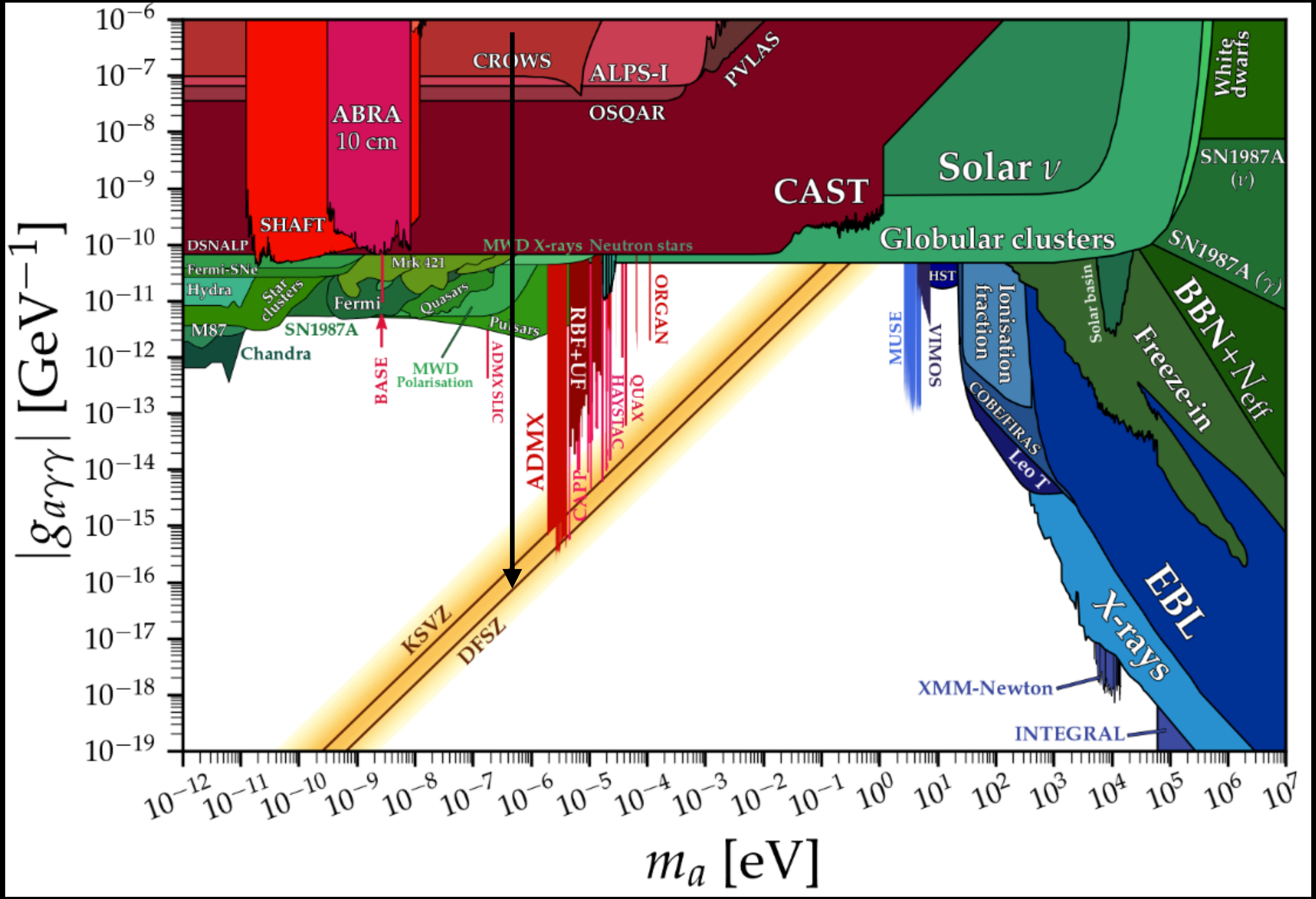
Axion Mass Range

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

Upper bound set by SN1987A and white dwarf cooling time

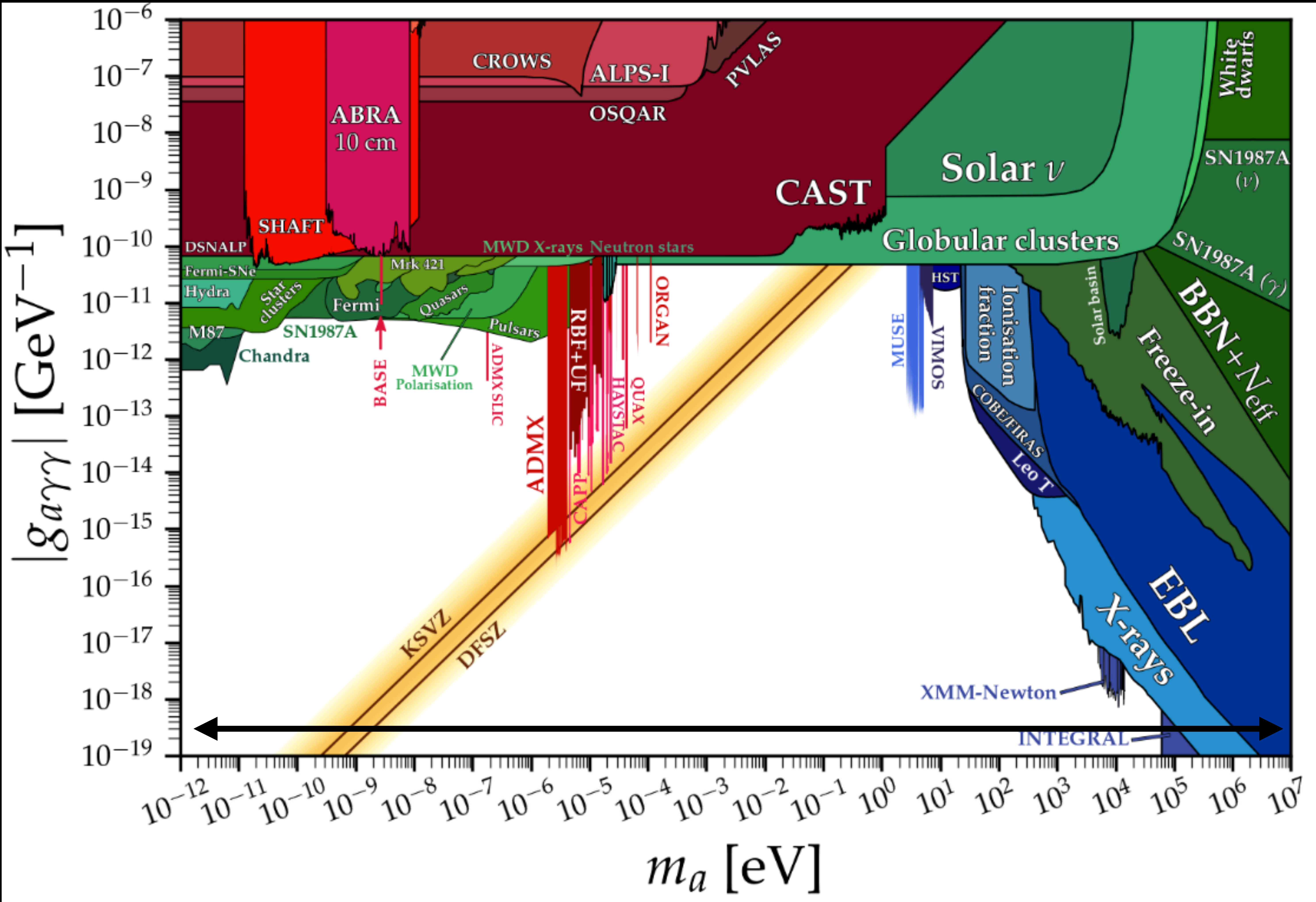
Adaptation of L. Winslow DPF Slide

Unexplored Parameter Space



Plot courtesy of Ciaran O'Hare

Unexplored Parameter Space



Plot courtesy of Ciaran O'Hare

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:
$\lambda_{comp} >> R_{exp}$
e.g. ABRA, DM Radio

Cavity Regime:
$\lambda_{comp} \sim R_{exp}$
e.g. ADMX

Radiation Regime:
$\lambda_{comp} << R_{exp}$
e.g. MADMAX

AXIONS AND WAVE-LIKE DARK MATTER

LUMPED ELEMENT REGIME

DM RADIO

DM Radio Collaboration

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Lumped Element Haloscope

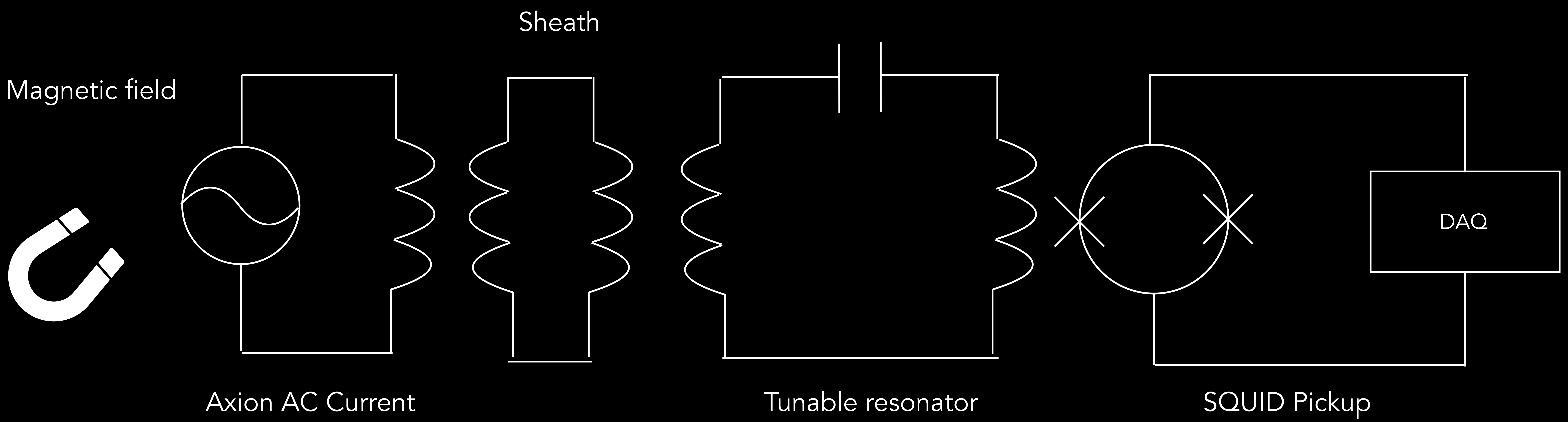
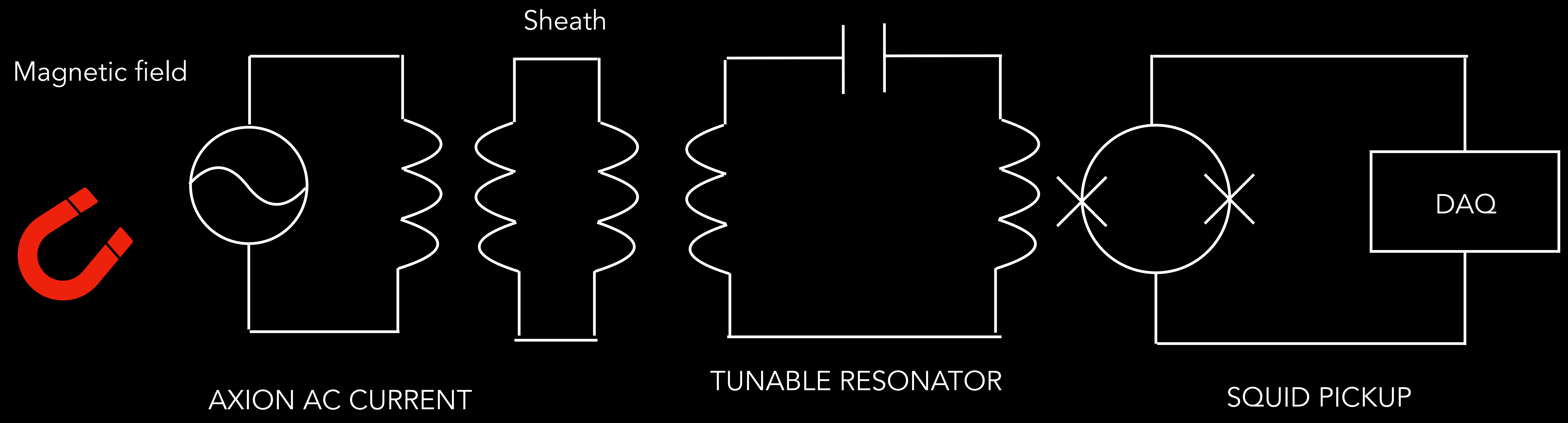


Figure inspired by Chiara Salemi

Lumped Element Haloscope

Case Study: Static Toroidal magnet

- Magnetic field $\mathbf{B_0}$



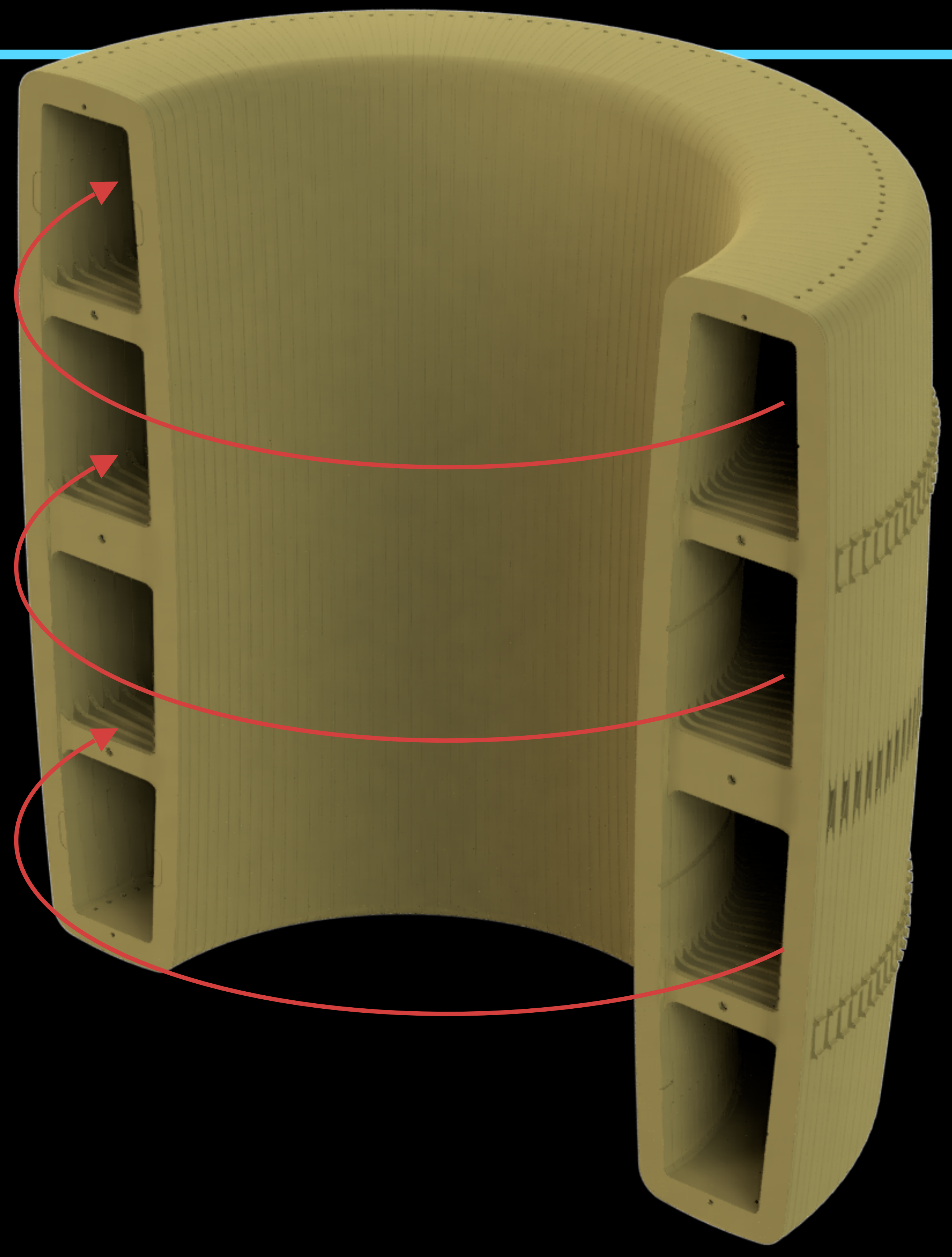
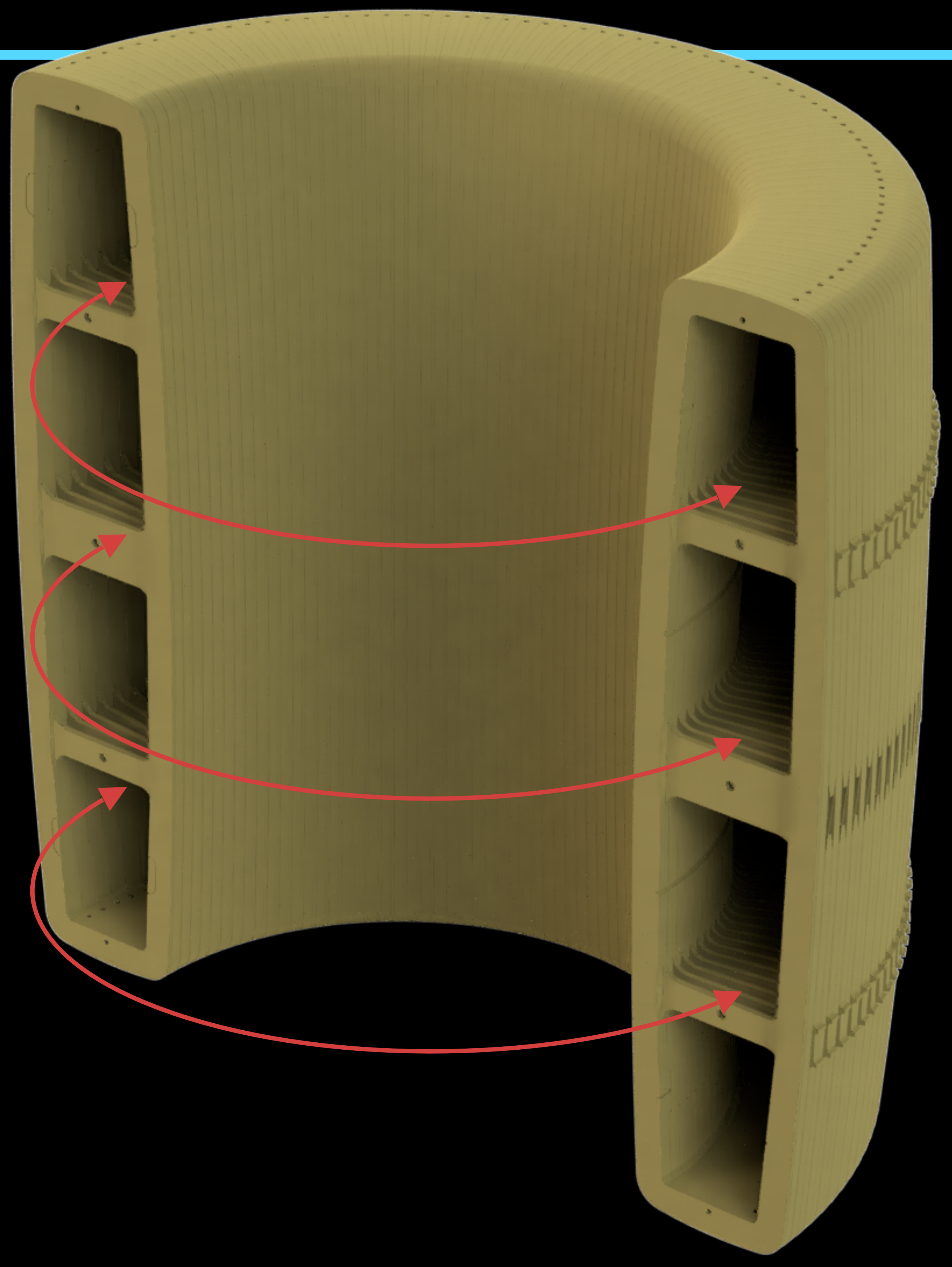


Figure courtesy of Chiara Salemi

Lumped Element Haloscope

Case Study: Static Toroidal magnet

- Magnetic field $\mathbf{B_0}$
- AC axion current $\mathbf{J_a}$



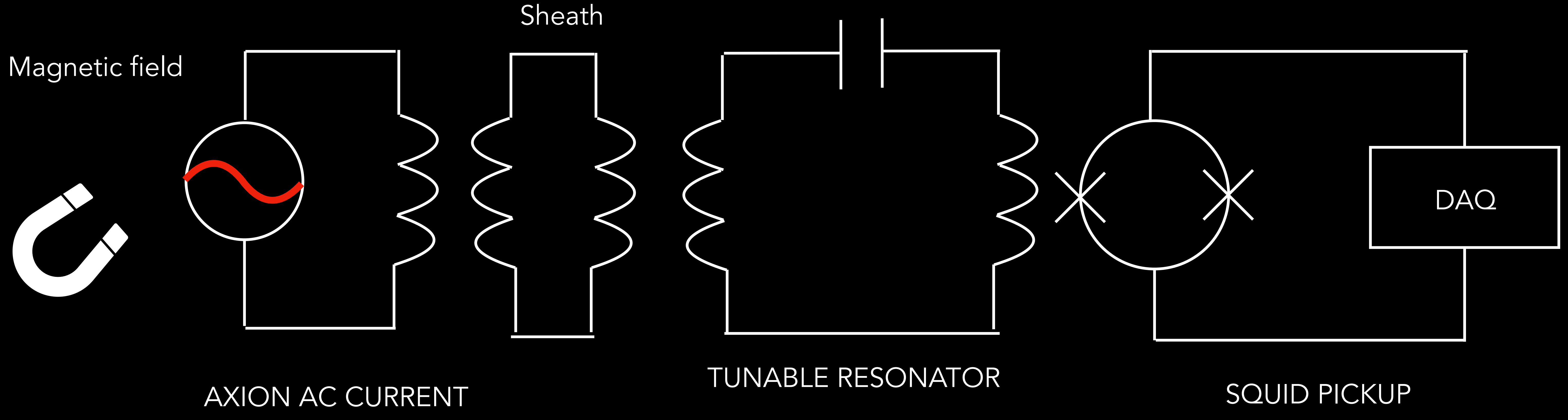
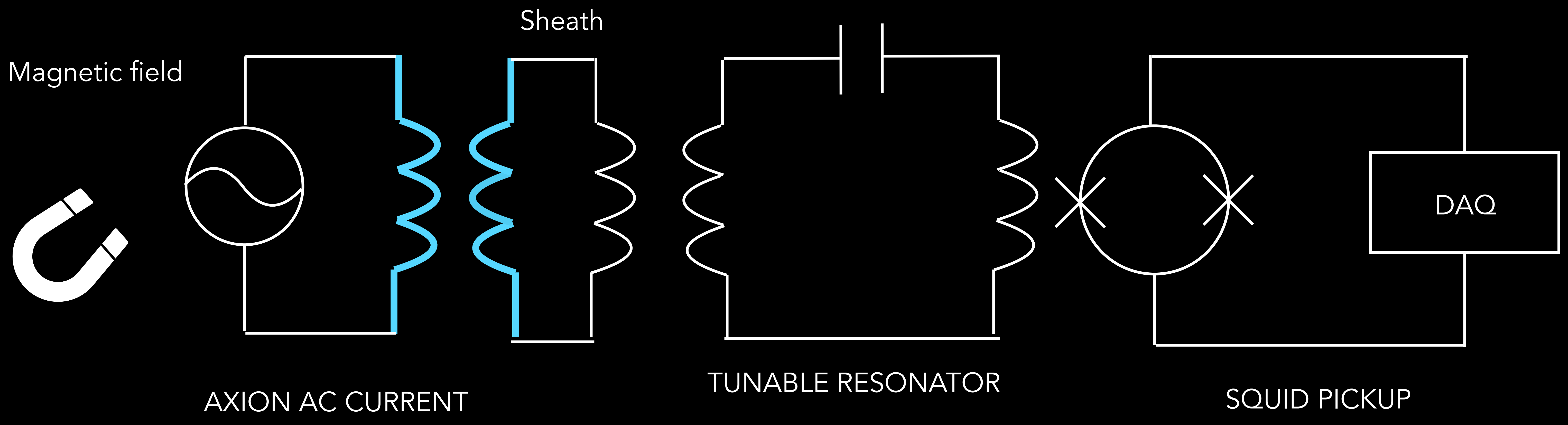


Figure courtesy of Chiara Salemi

Lumped Element Haloscope

Case Study: Static Toroidal magnet

- Magnetic field $\mathbf{B_0}$
- AC axion current $\mathbf{J_a}$
- Oscillating magnetic field



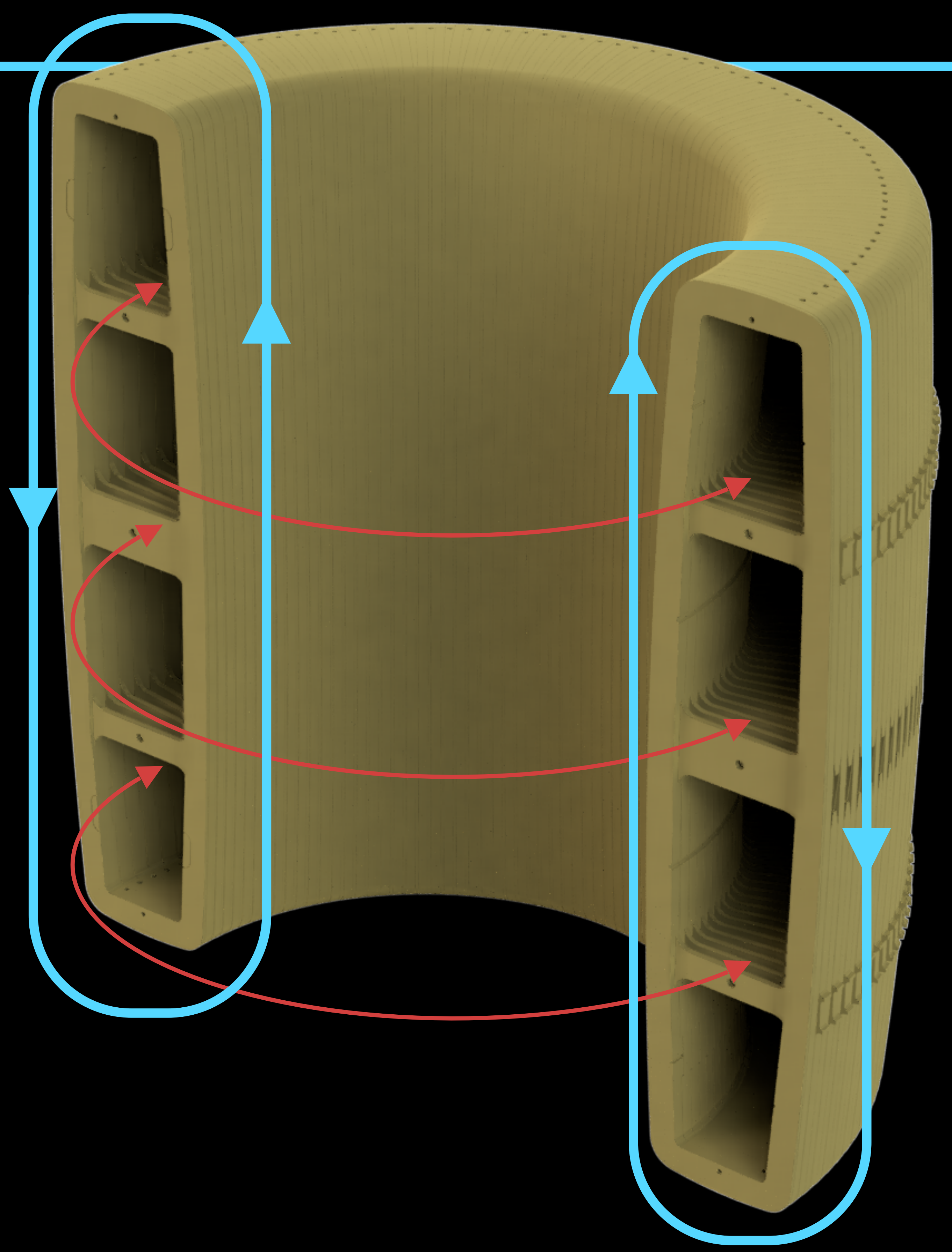


Figure courtesy of Chiara Salemi

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

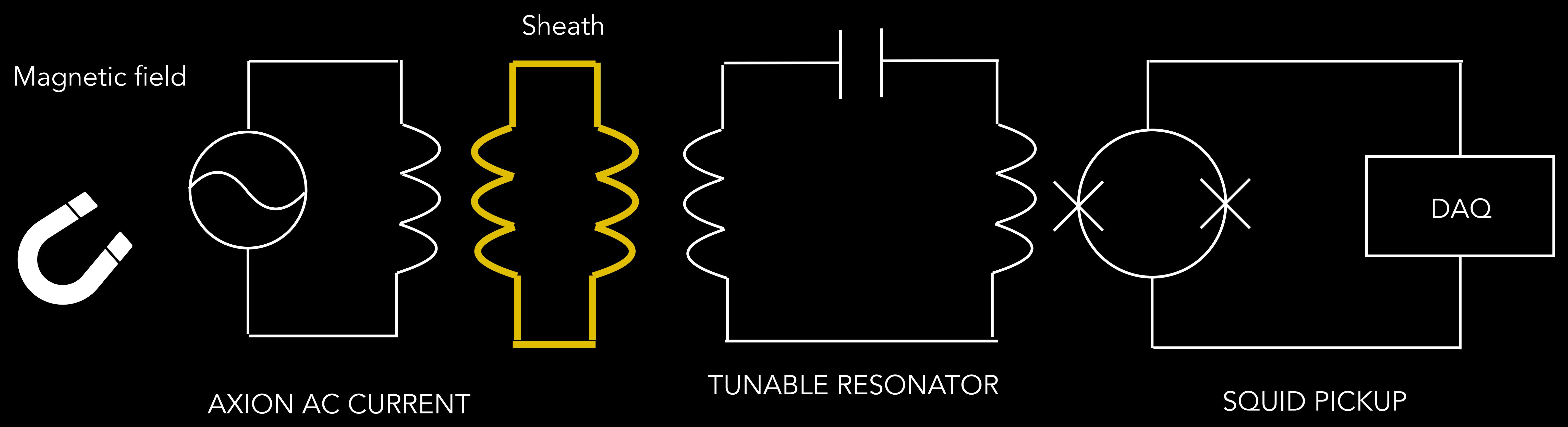
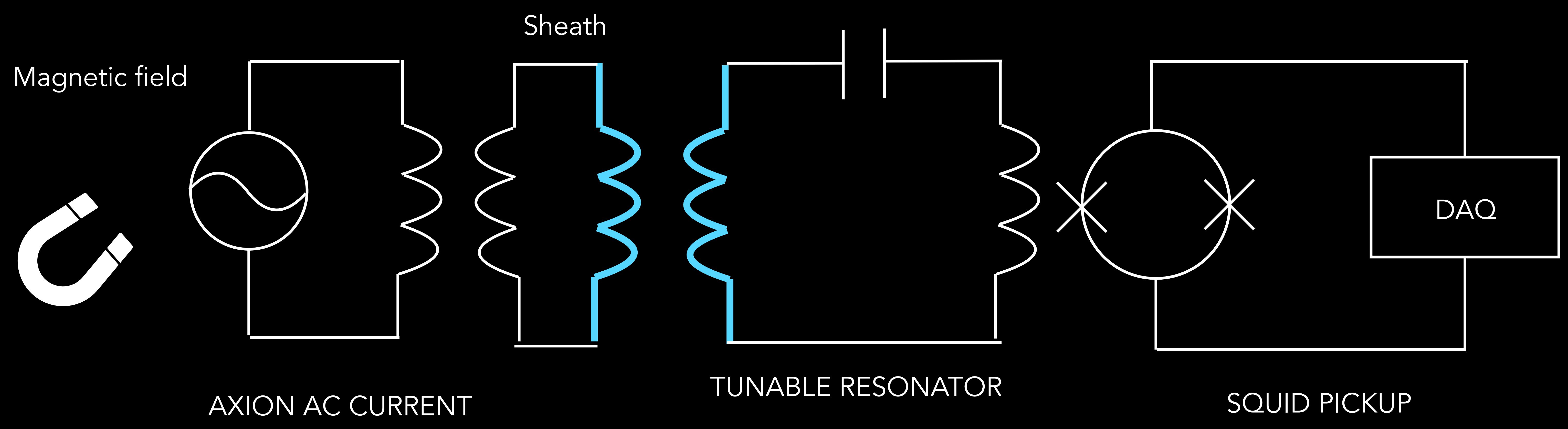


Figure courtesy of Chiara Salemi

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



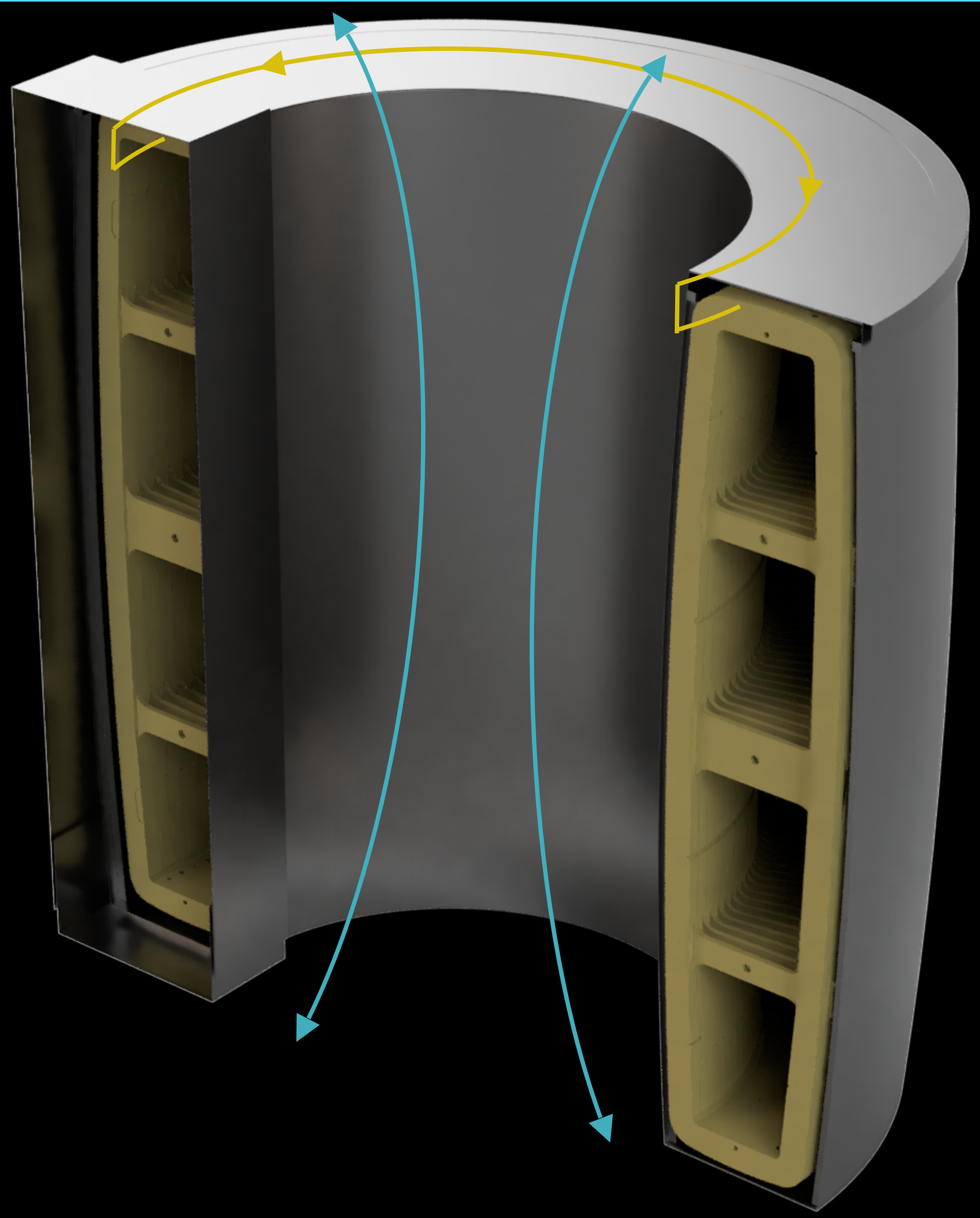
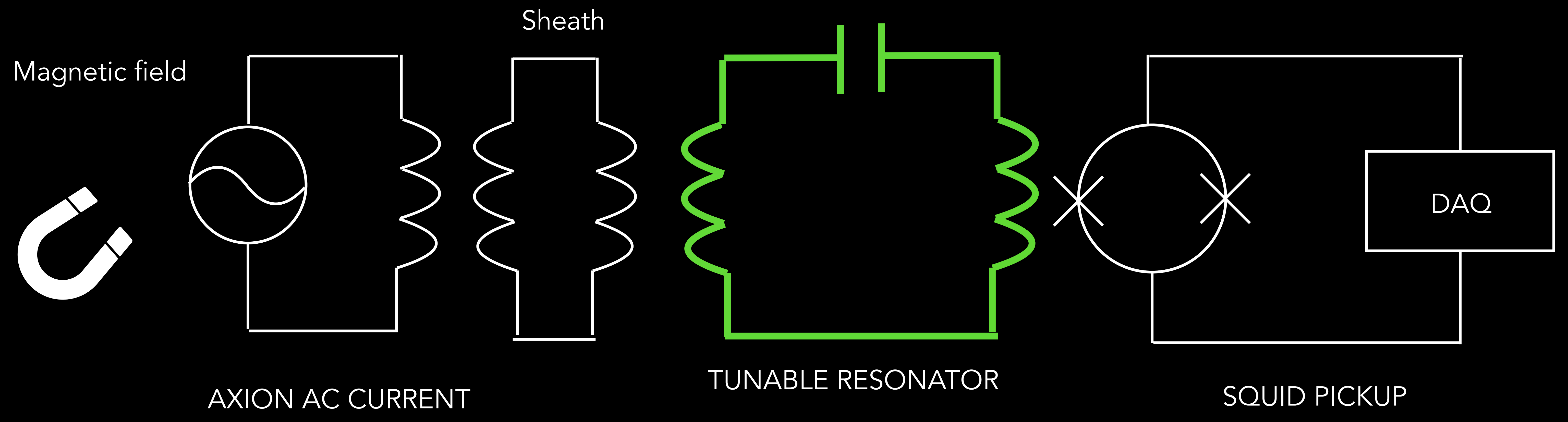


Figure courtesy of Chiara Salemi

Lumped Element Haloscope

Case Study: Static Toroidal magnet

- Magnetic field B_0
- AC axion current J_a
- Oscillating magnetic field
- Induces currents on the sheath
- Oscillating magnetic field
- Ringing up a resonator



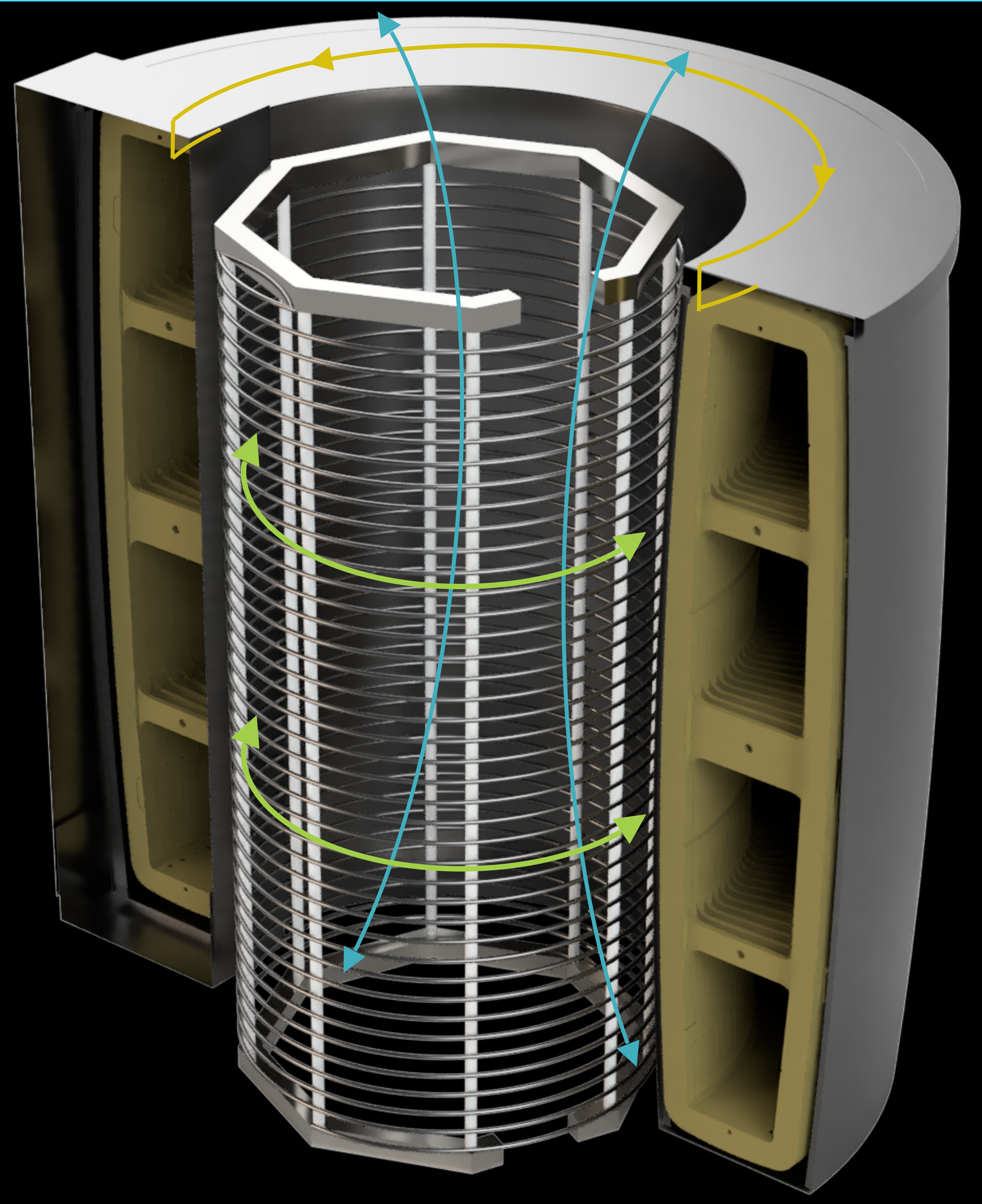


Figure courtesy of Chiara Salemi

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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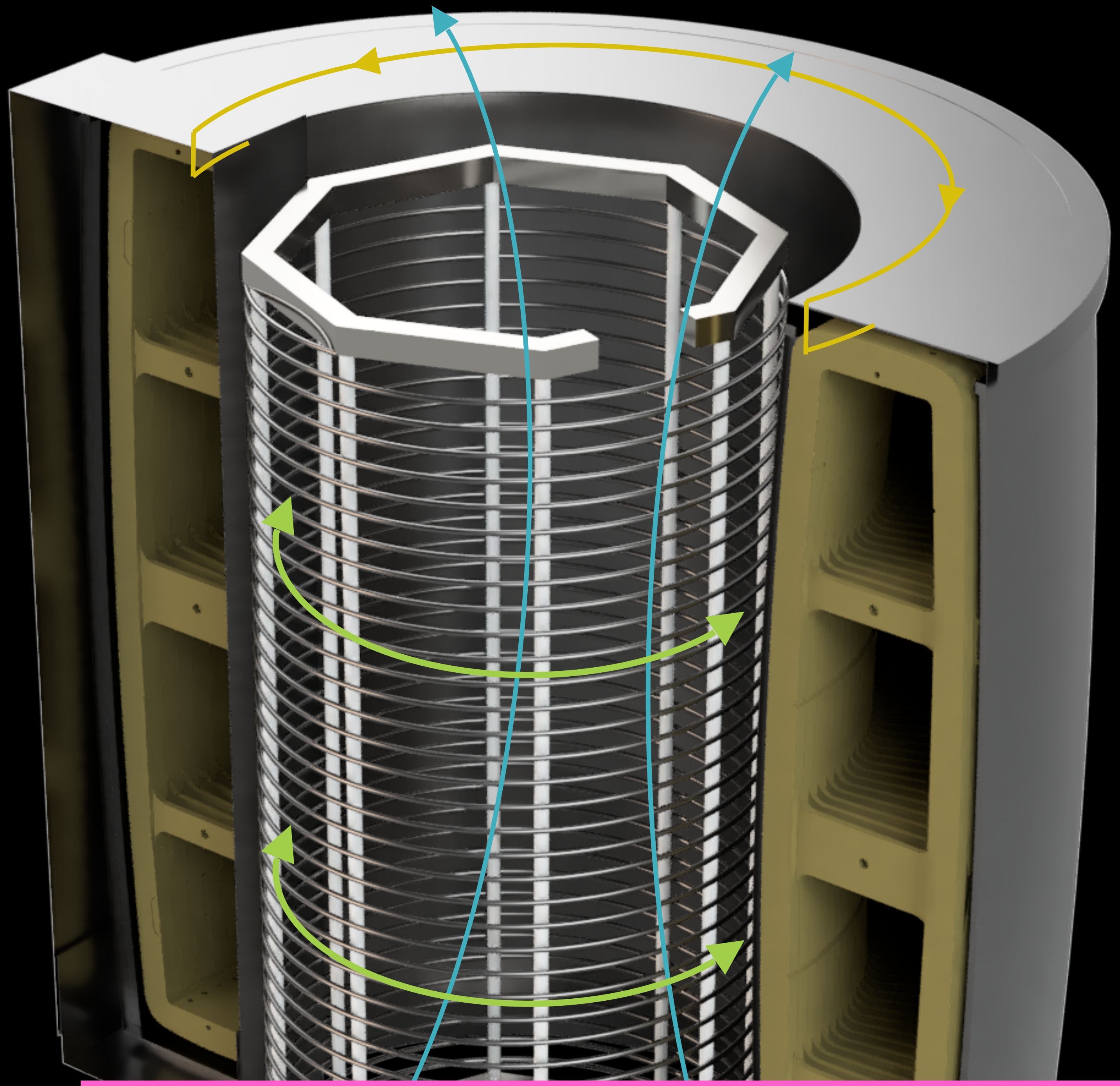
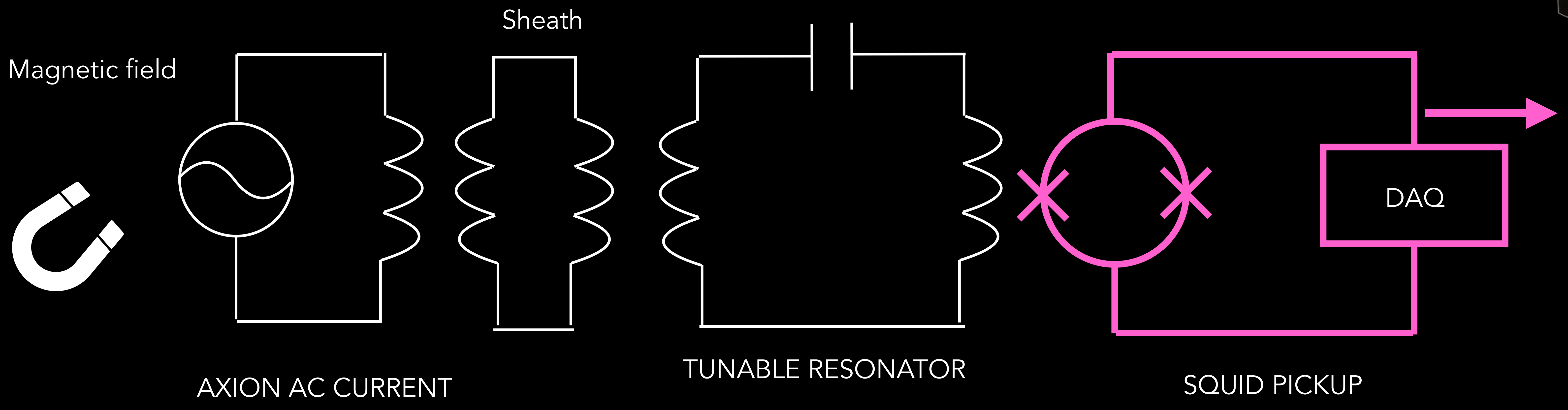




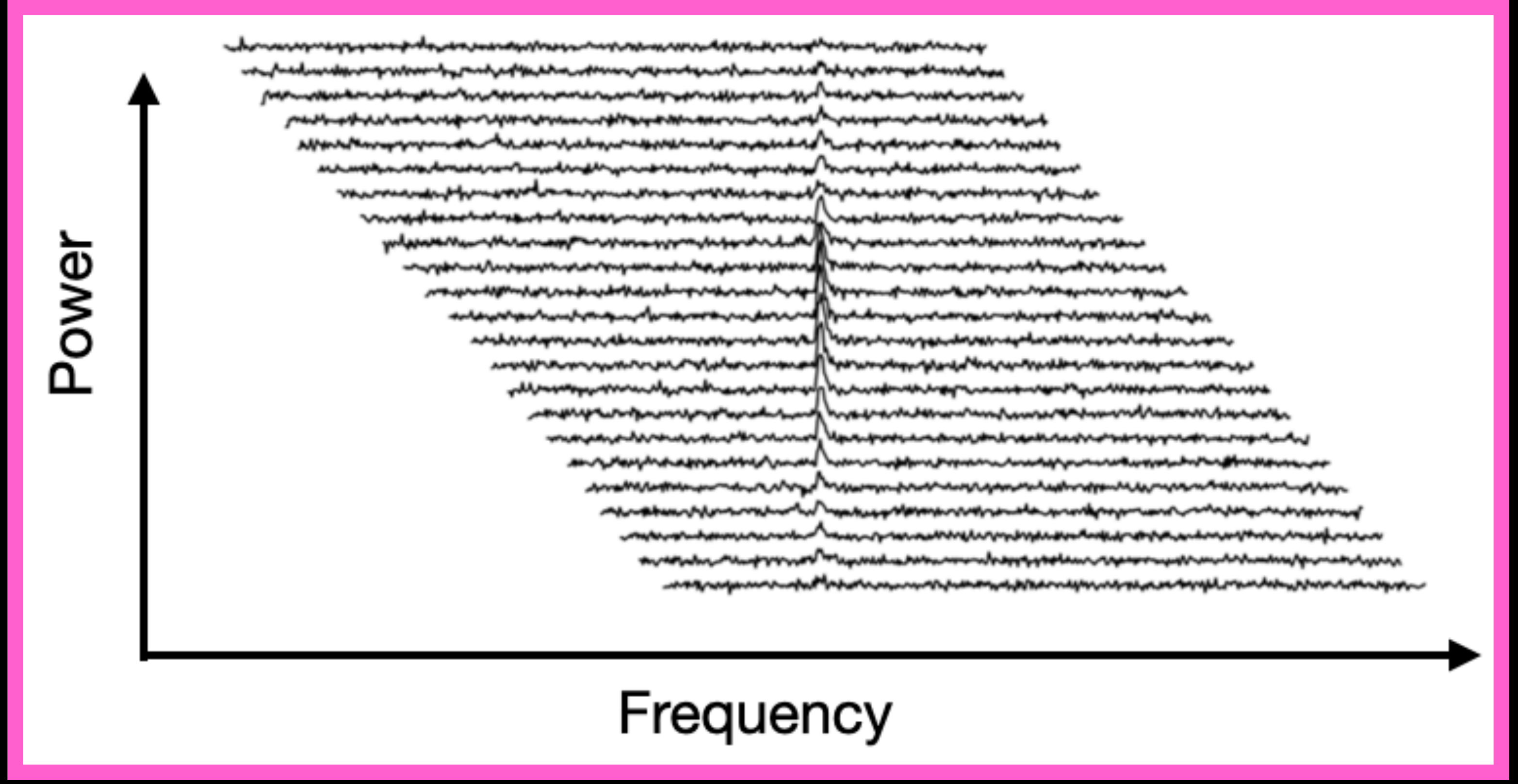
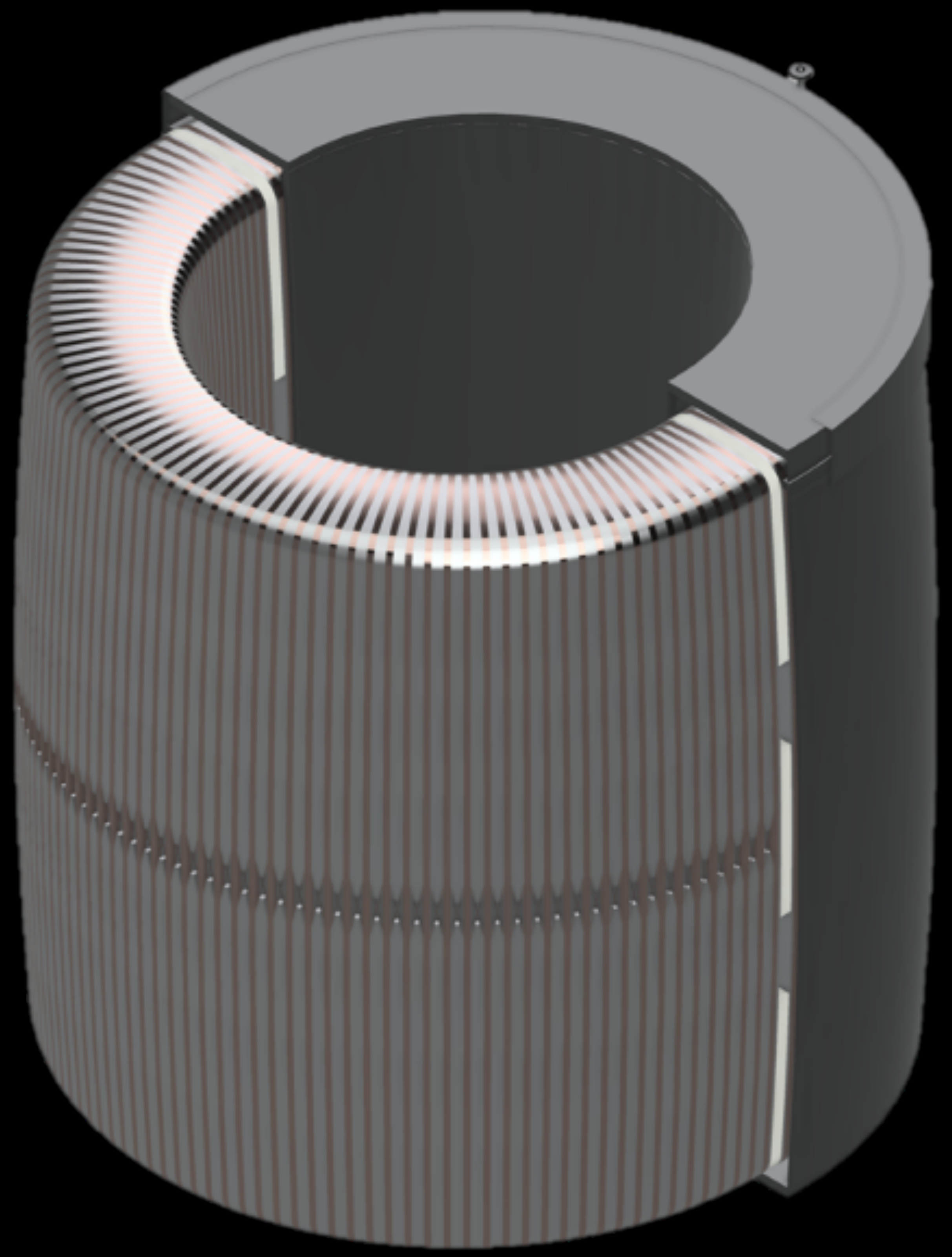


Figure courtesy of Chiara Salemi

DMRadio-50L Target

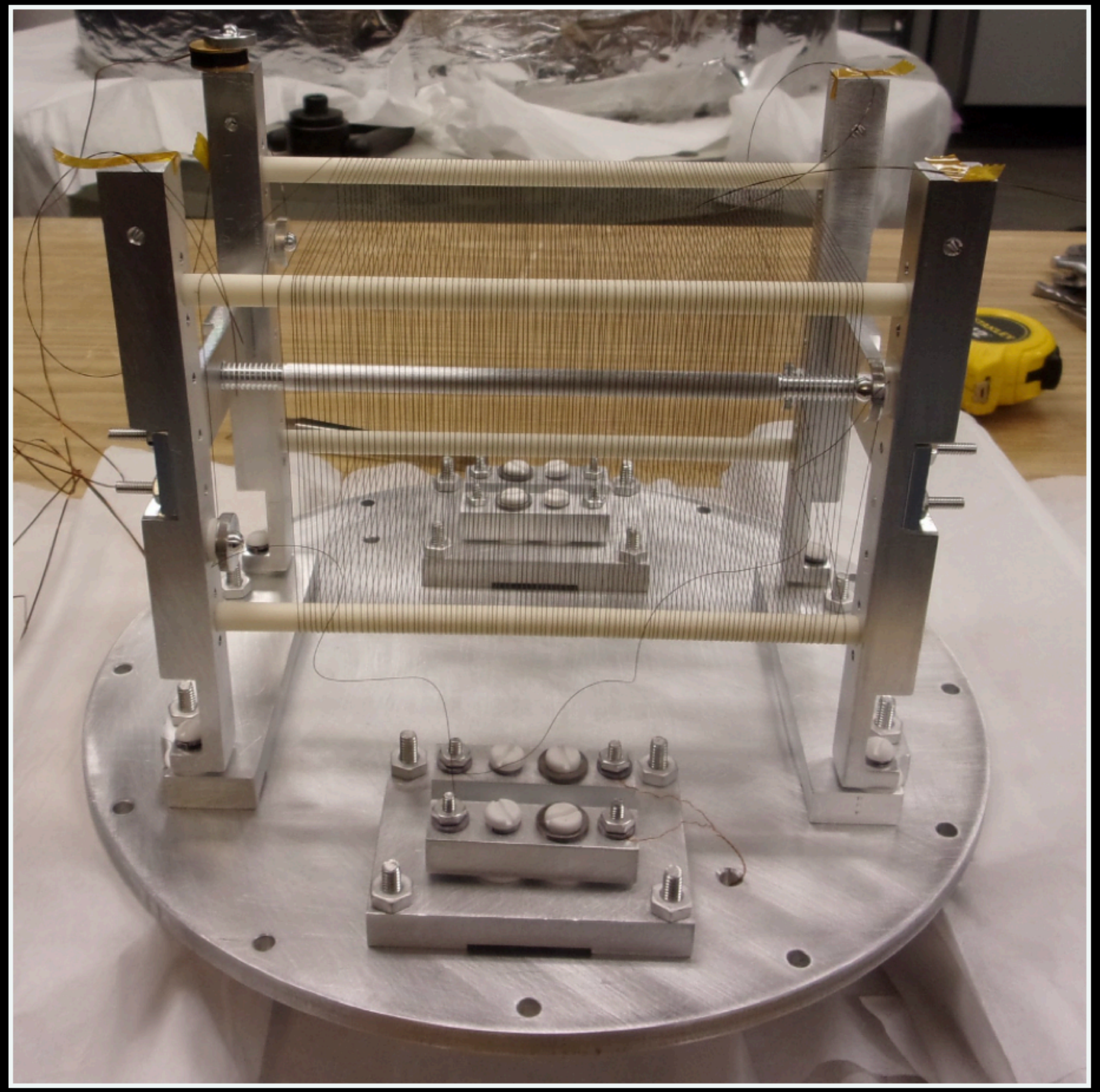
- 5 kHz — 5 MHz (20 peV — 20 neV)
- Will serve as a prototyping platform: Testbed for quantum readout technologies
- Toroidal magnet with field strength of 1 T (~113 A)
- 20 mK base temperature
- Sensitivity goal of $g_{a\gamma\gamma}=5\times10^{-15}$ GeV^{-1}

Sheath Design
Nicholas Rapidis

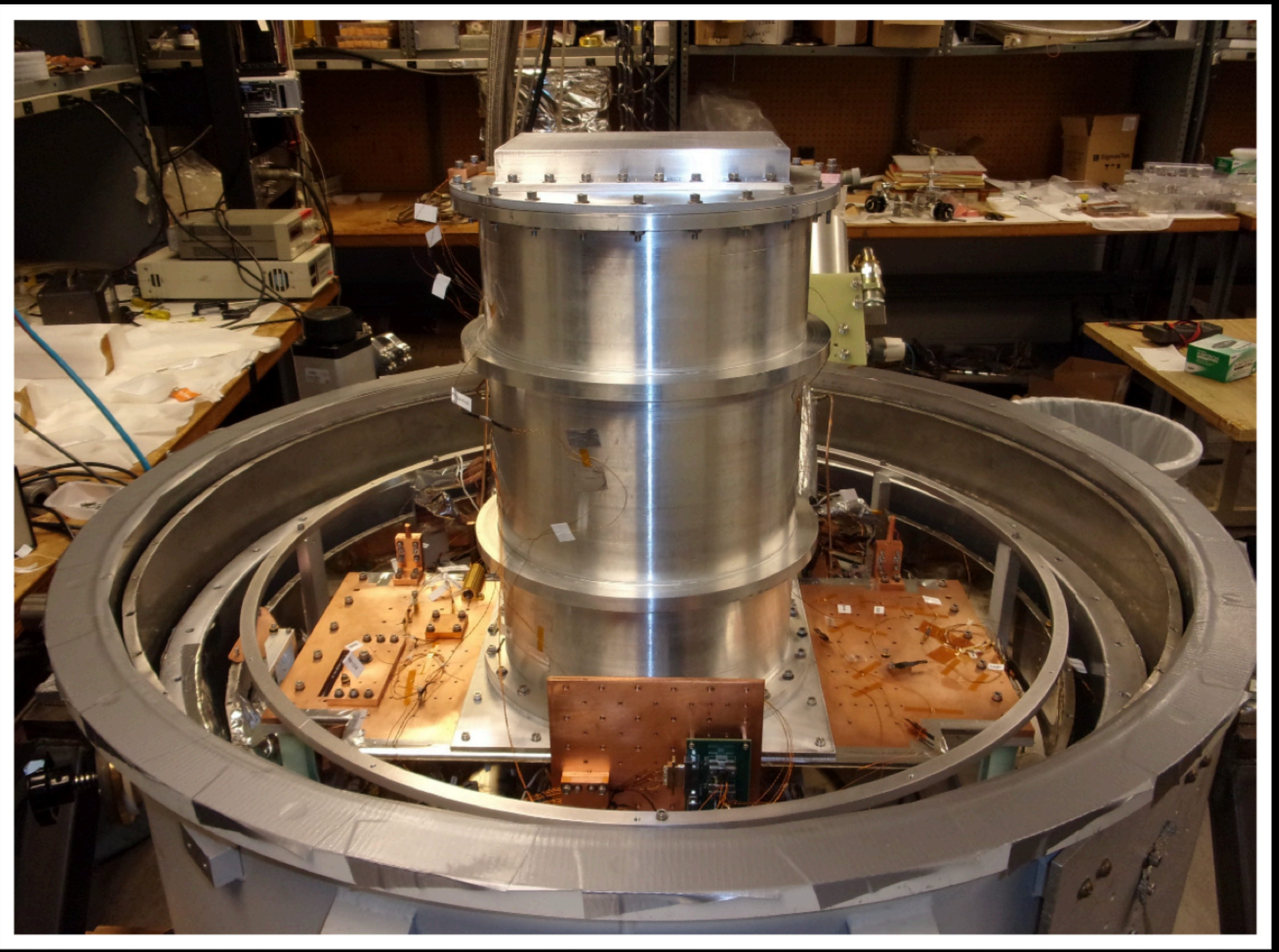


Aluminum mandrel with superconducting sheath

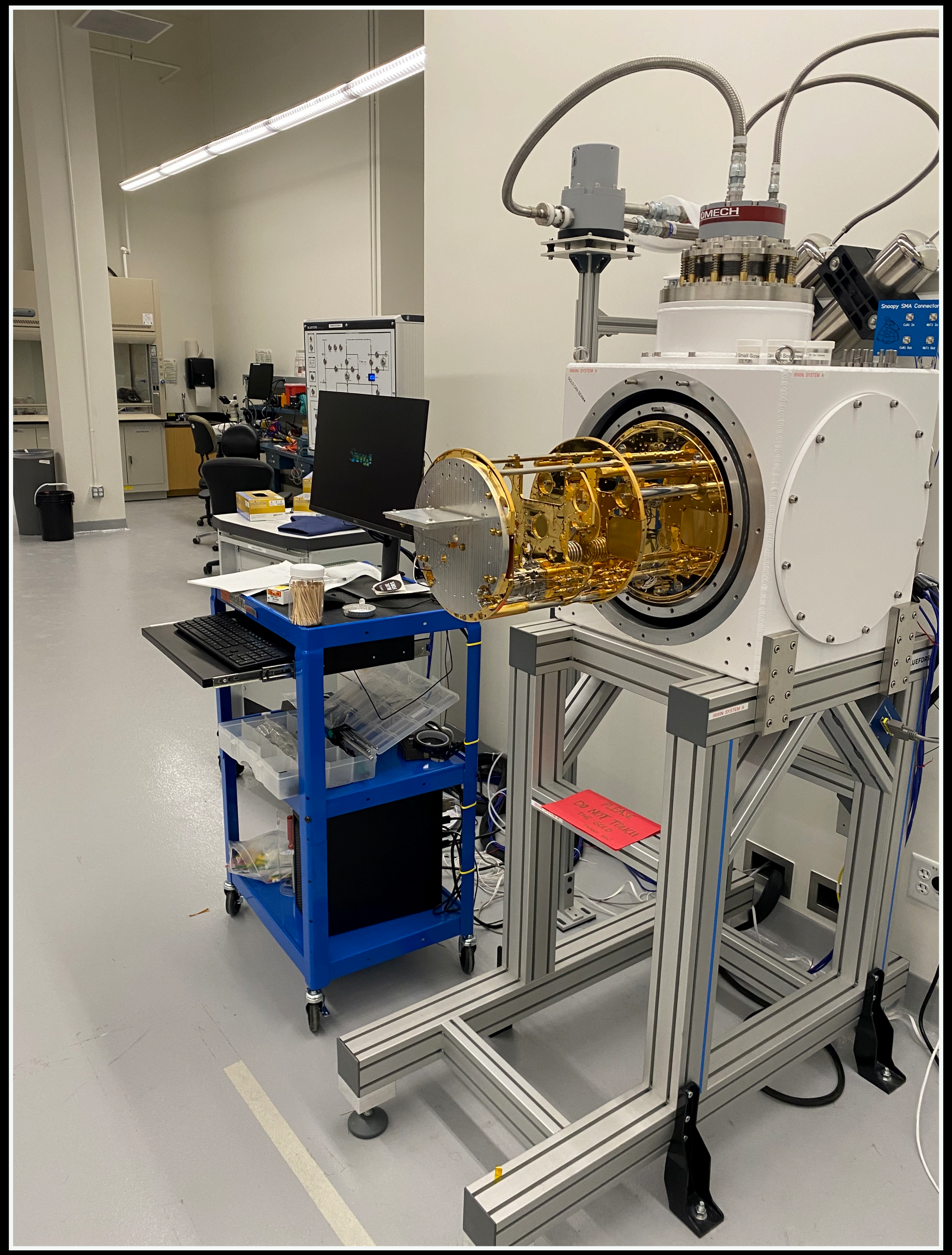
DMRadio-50L Resonator



Inductor winding
Saptarshi Chaudhuri
and Roman Kolevatov

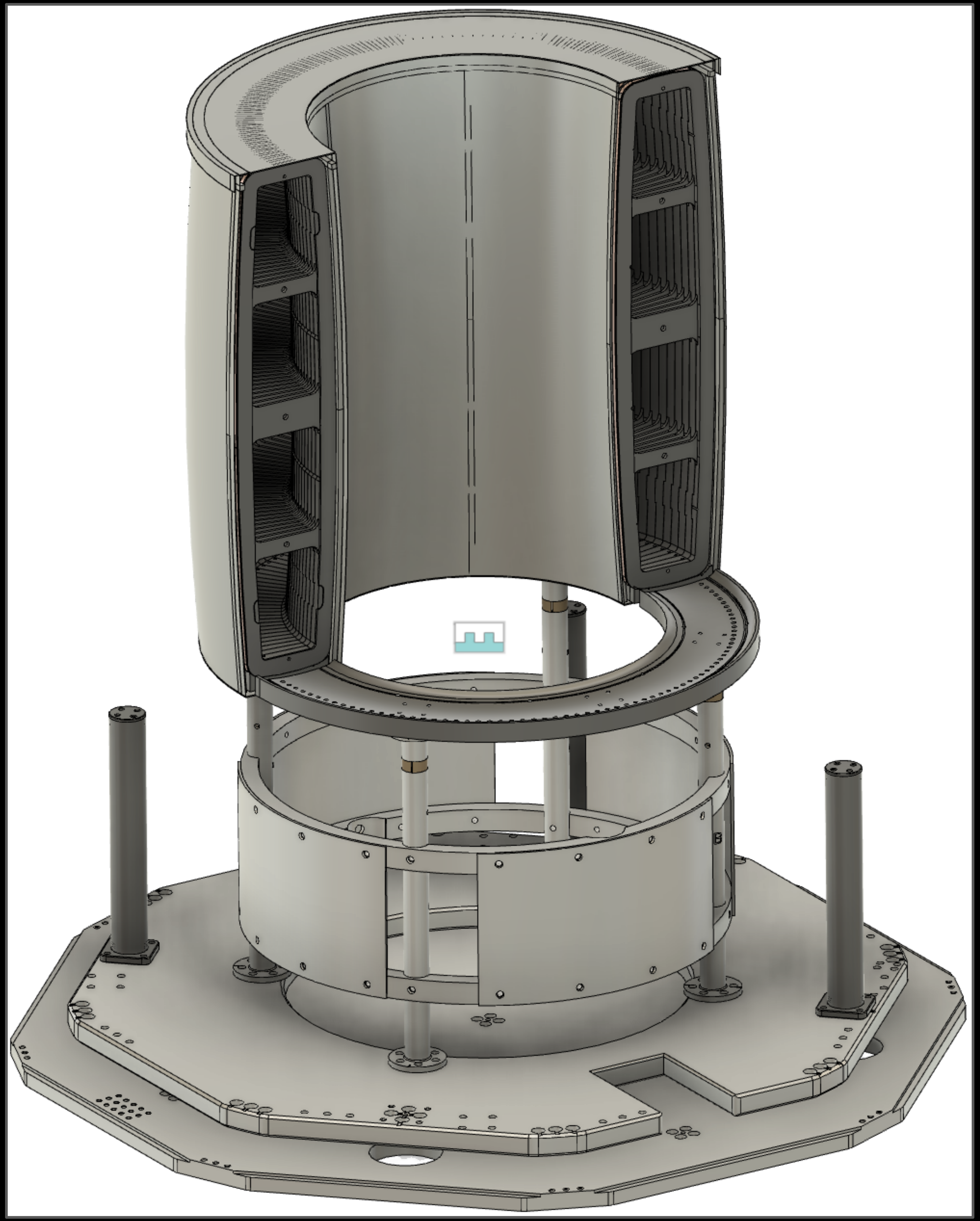


Resonator Q testing
Prototype Q = 374,000 at 300 kHz



Tunable Capacitor
Joe Singh

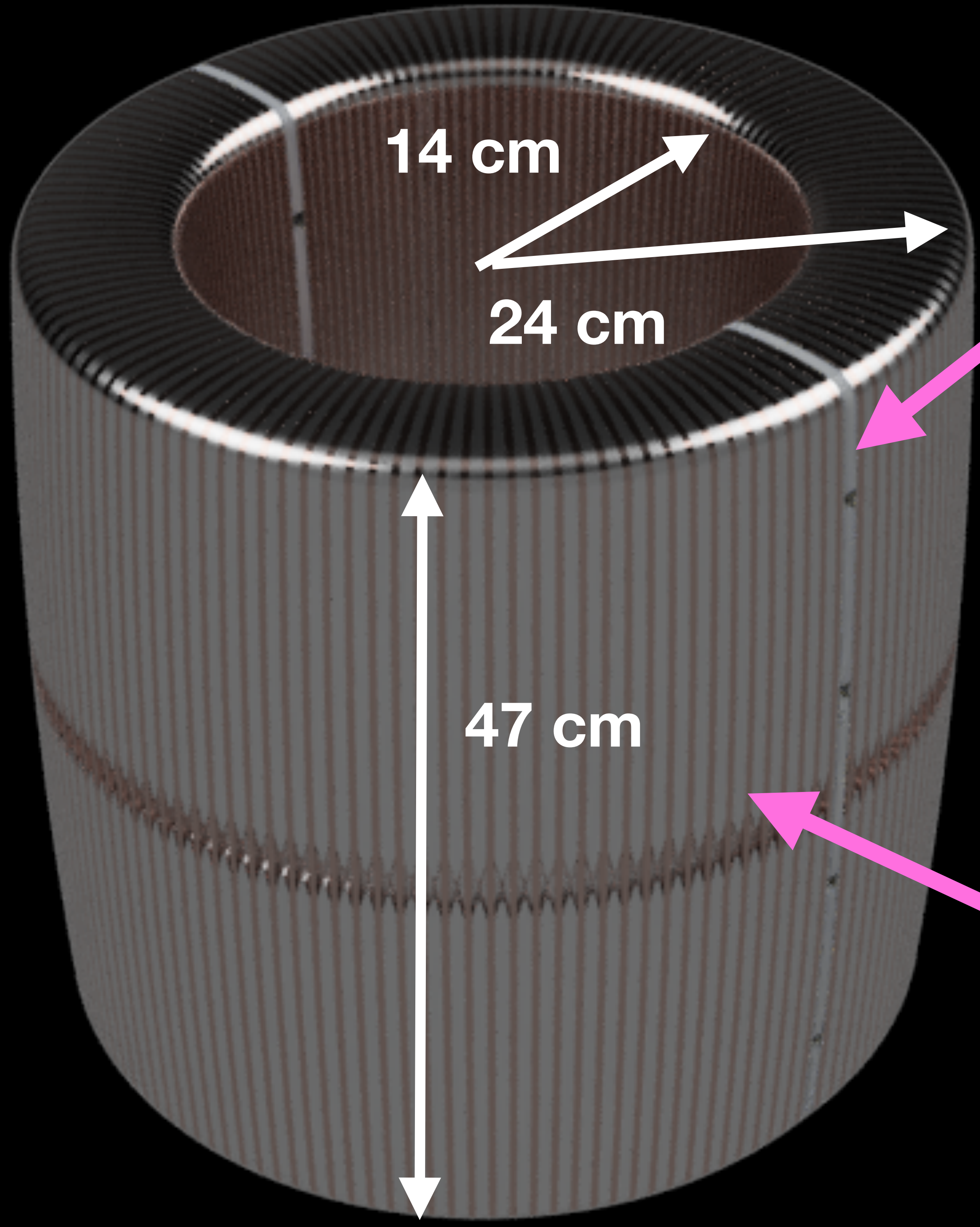
DMRadio-50L Magnet



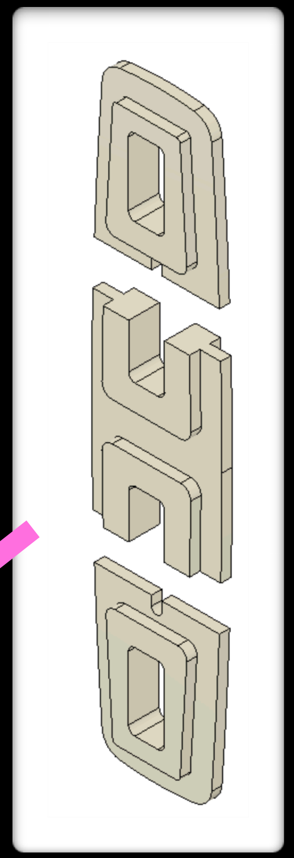
Structural and Thermal Connections
Alex Droster, Johny Echevers, Jessica Fry

Mandrel construction and winding

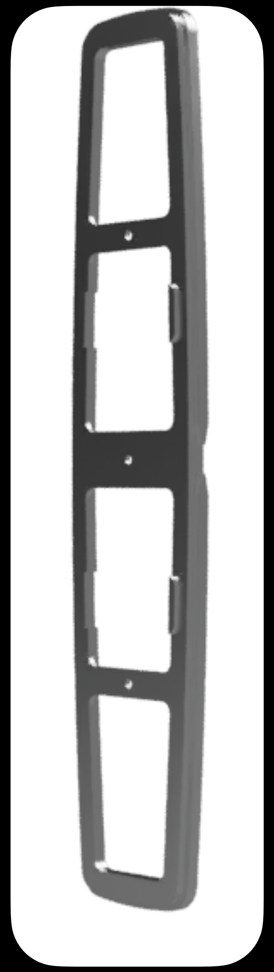
Superconducting Systems Inc



Aluminum mandrel

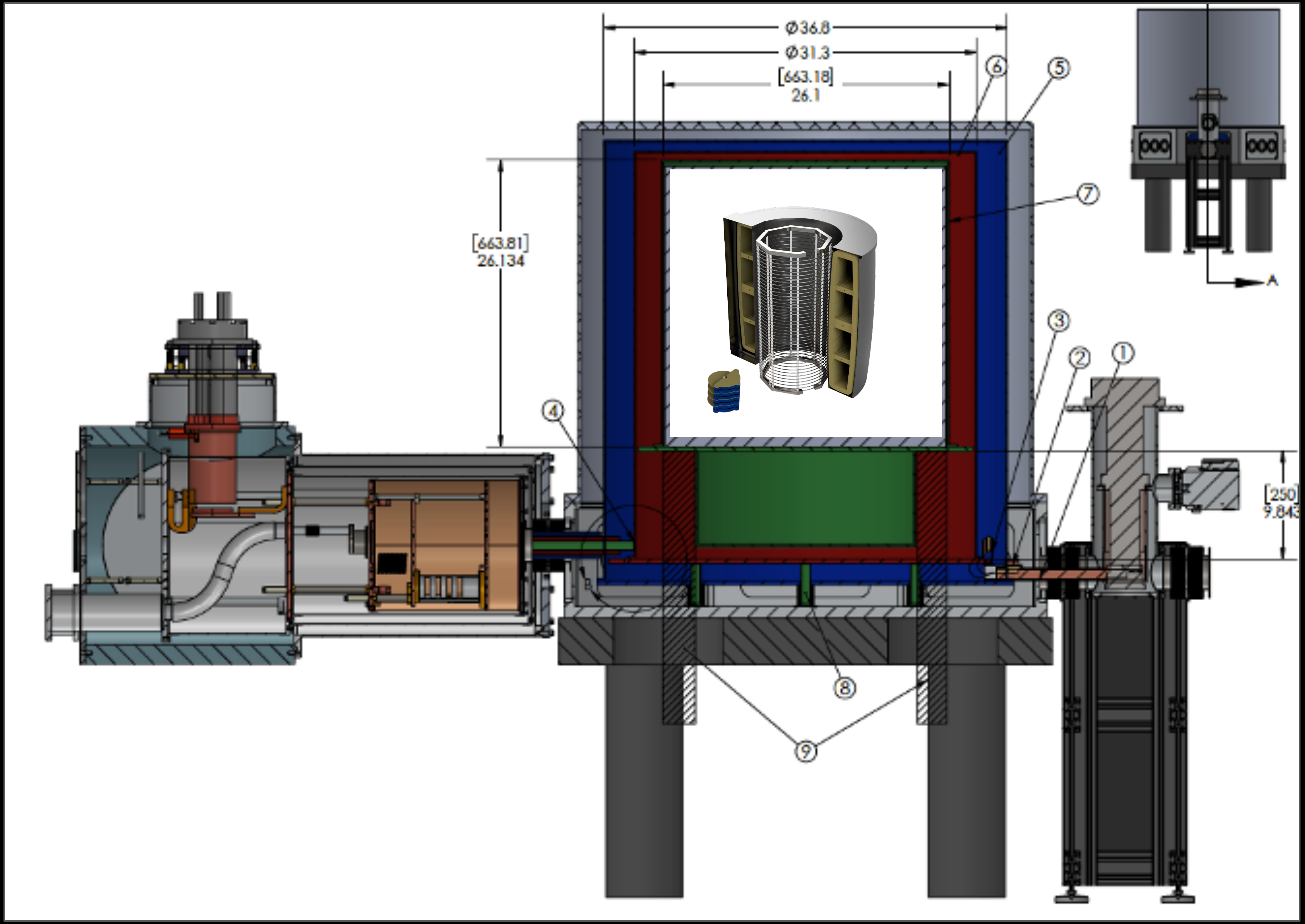


2 Insulating spacers



69x2 Mandrel wedges

DMRadio-50L Cryostat

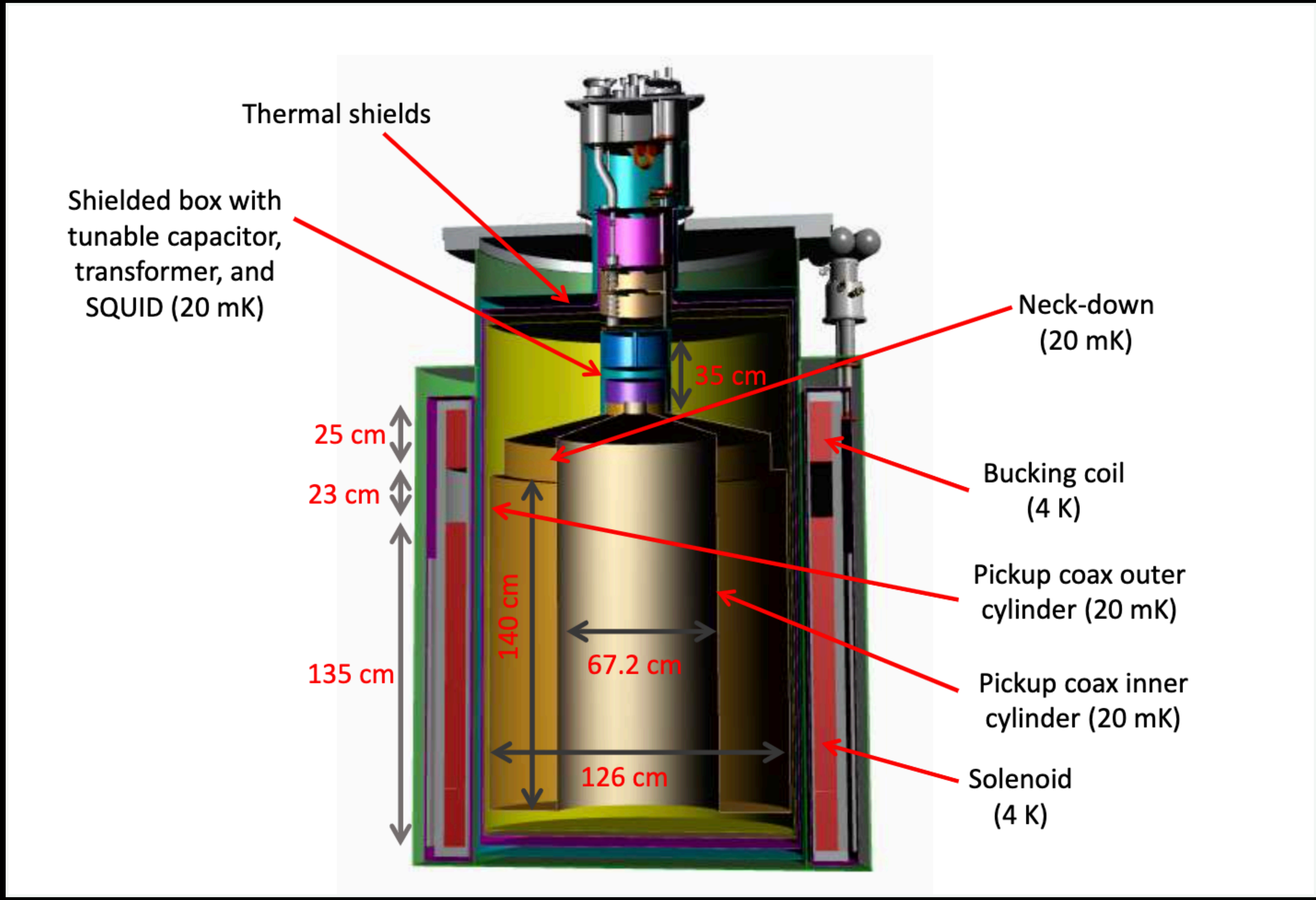


- Cryostat: Fournine Design
- BlueFors LH Dilution Refrigerator
- Cold snout to cool resonator

Maria Simanovskaia,
Aya Keller

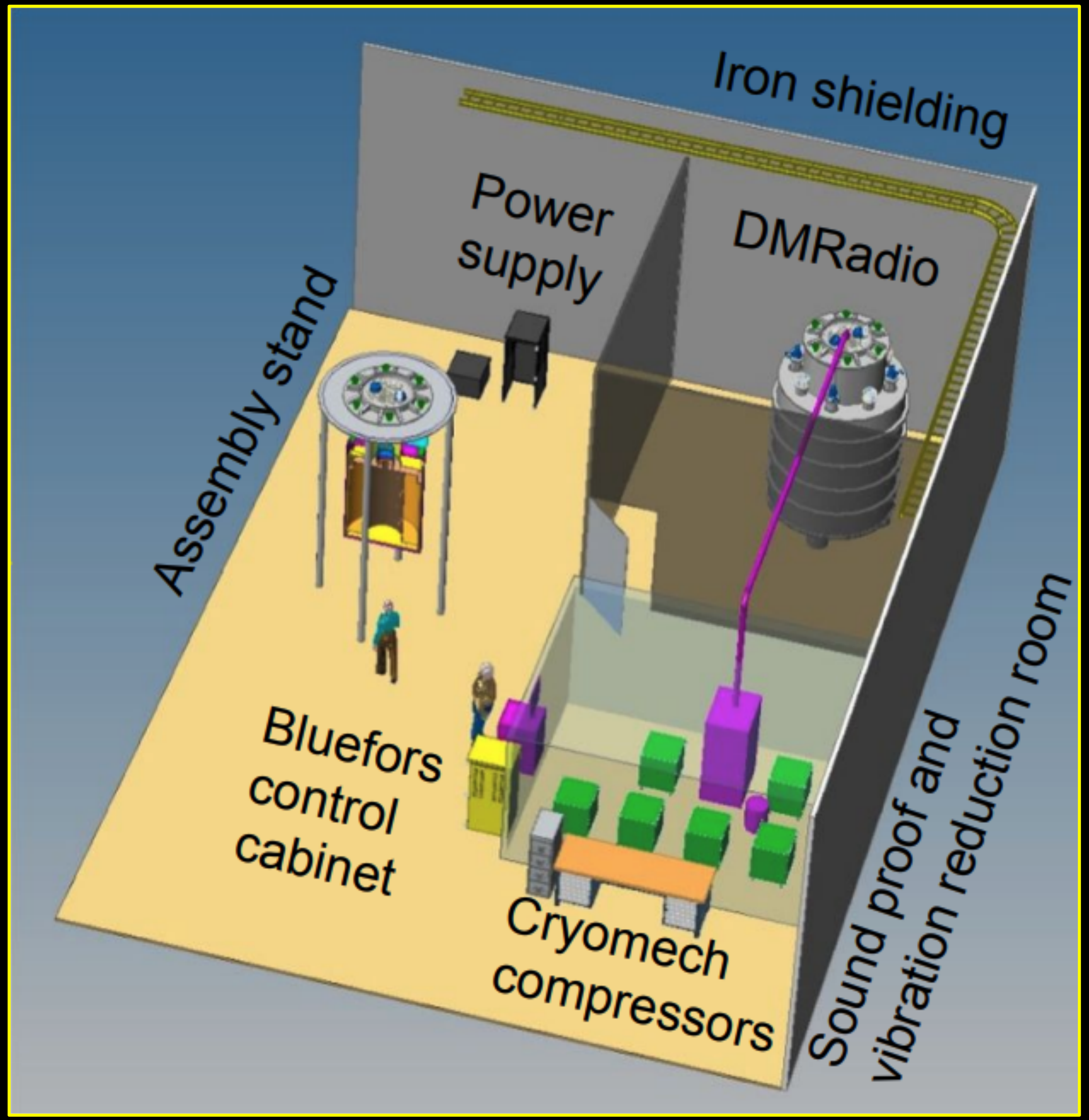
DMRadio-m³ Target

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

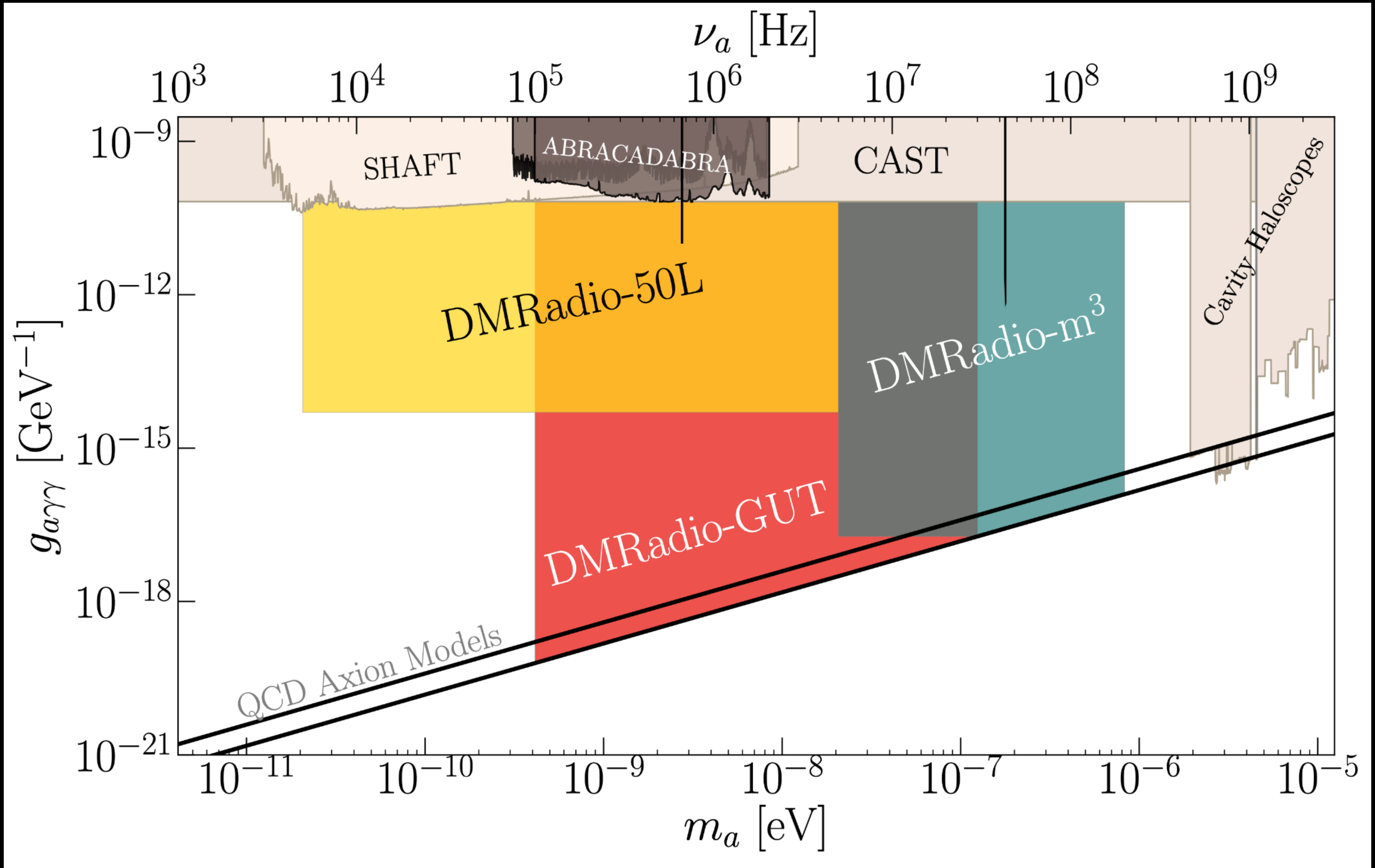


DMRadio-m^3 at SLAC

- DMRadio-m^3 has received DOE DMNI funding
- Will be constructed at SLAC National Lab
- Electromagnetic modeling and end-to-end sensitivity calculations are on the arXiv: *arXiv:2302.1408*
- Experience with design and operation of DMRadio-50L will inform design of DMRadio-m^3



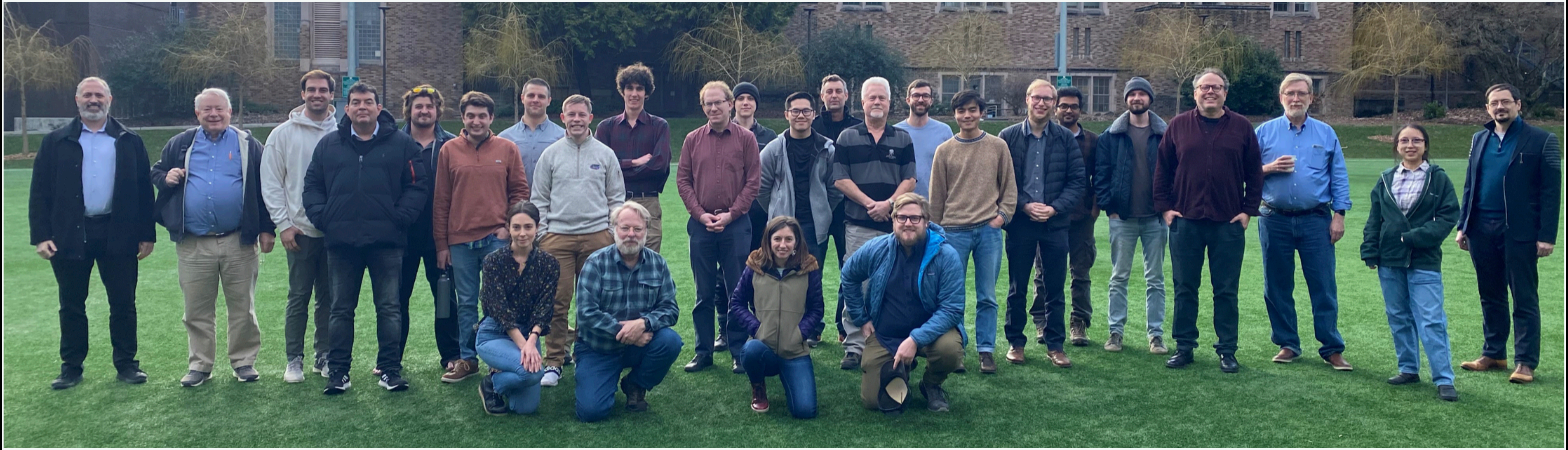
DMRadio Program



CAVITY REGIME

ADMX

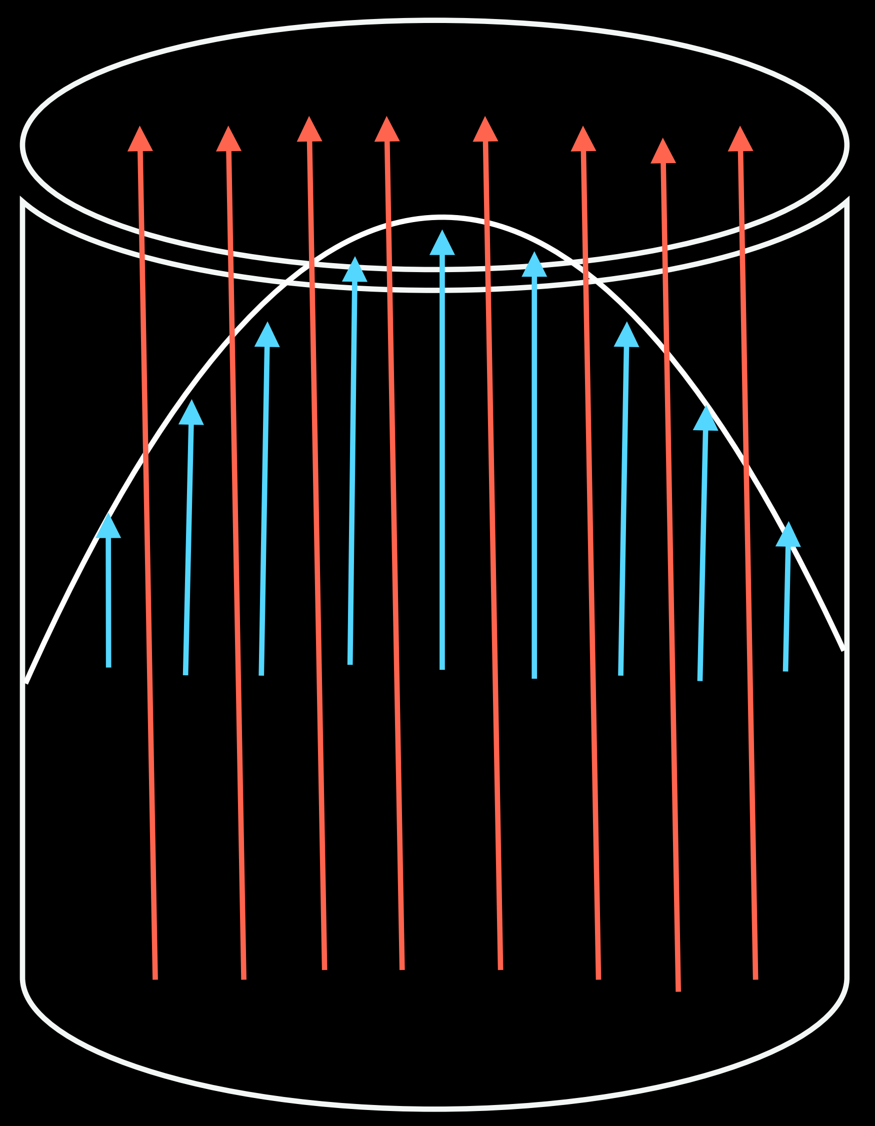
ADMX Collaboration



University of Washington 1861
Lawrence Livermore National Laboratory
Berkeley University of California
The University of Chicago 1890
Fermilab
Pacific Northwest National Laboratory
Washington University in St. Louis 1853
UF University of Florida
The University Of Sheffield.
The University of Western Australia
Illinois Institute of Technology
Los Alamos National Laboratory Est. 1943

Cavity Haloscope

Form factor describes coupling of the axion to the mode

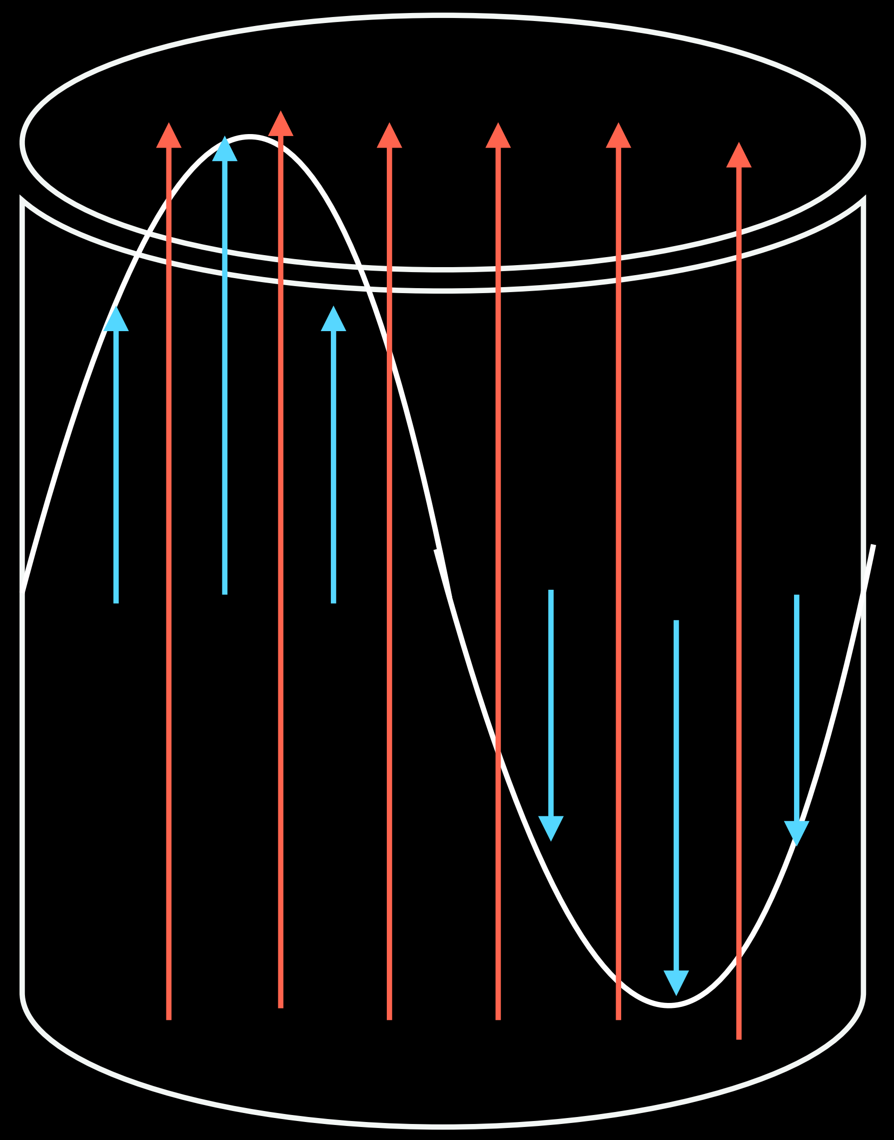


Non-zero form factor

Red is static magnetic field

Blue is axion electric field

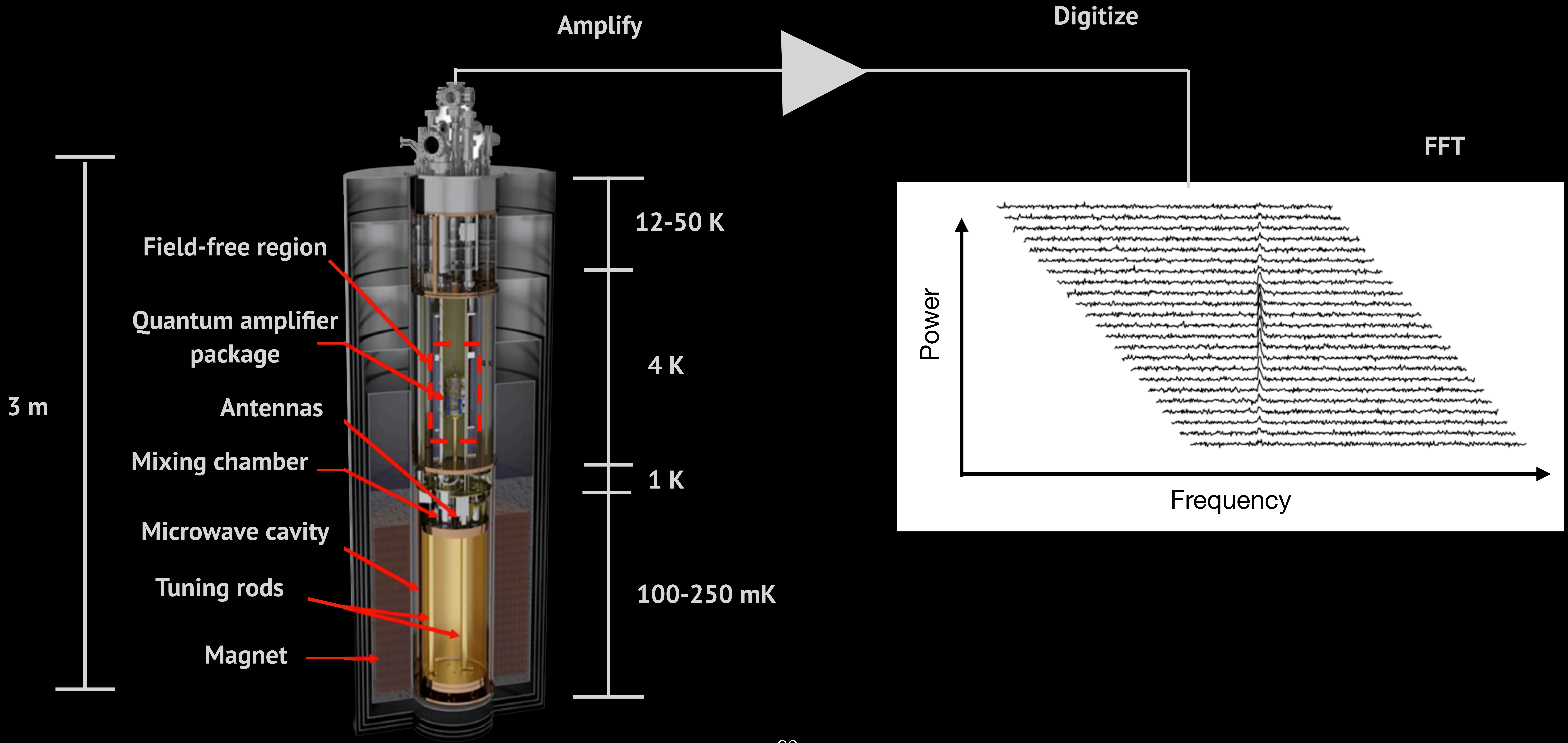
$$C_{010} = \frac{\left|\int dV\, \vec{B}_{\rm ext} \cdot \vec{E}_{\rm a}\right|^2}{B_{\rm ext}^2 \int dV\, \epsilon_{\rm r} |\vec{E}_{\rm a}|^2}$$



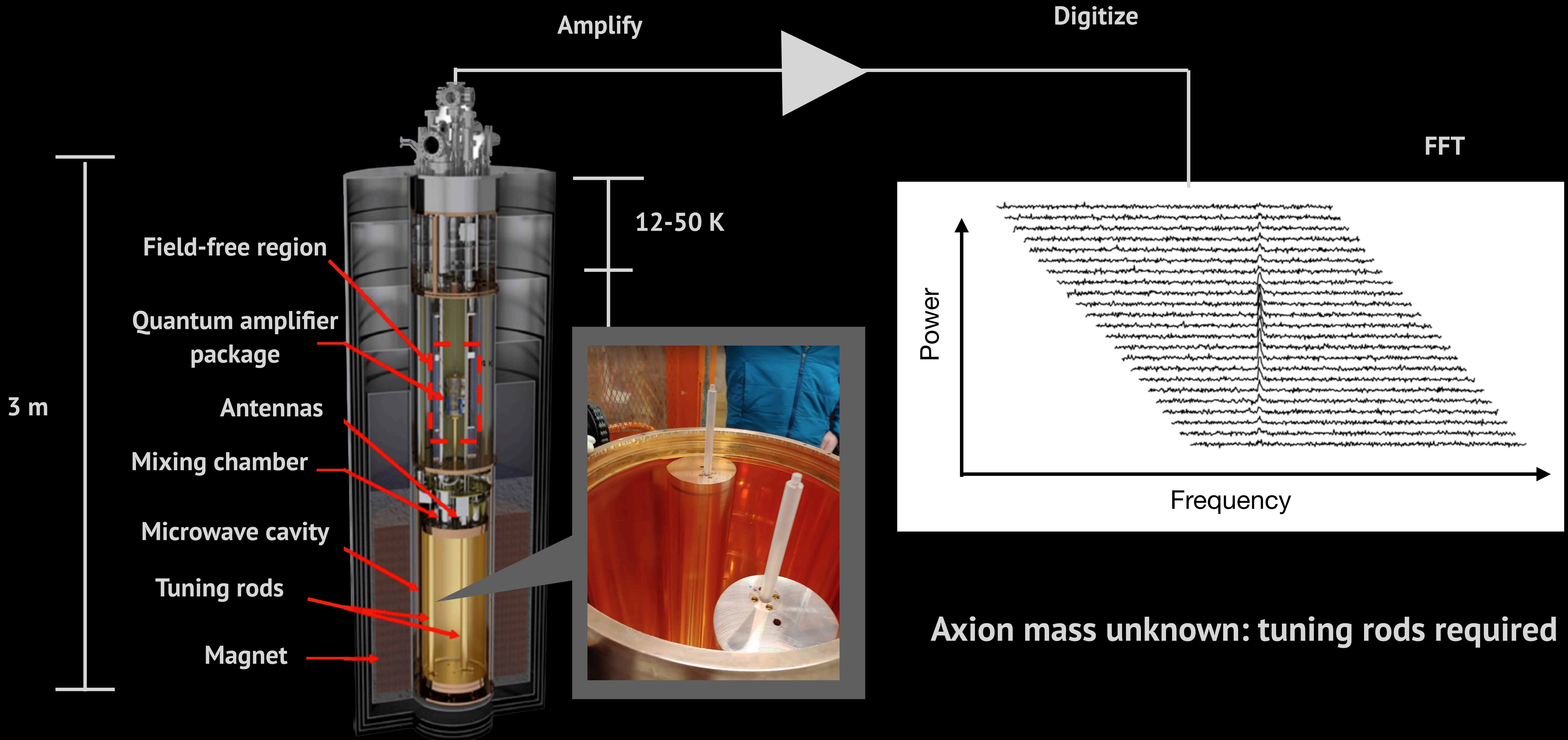
Zero form factor

ADMX: Axion couples most strongly to TM010 mode

Cavity Haloscope

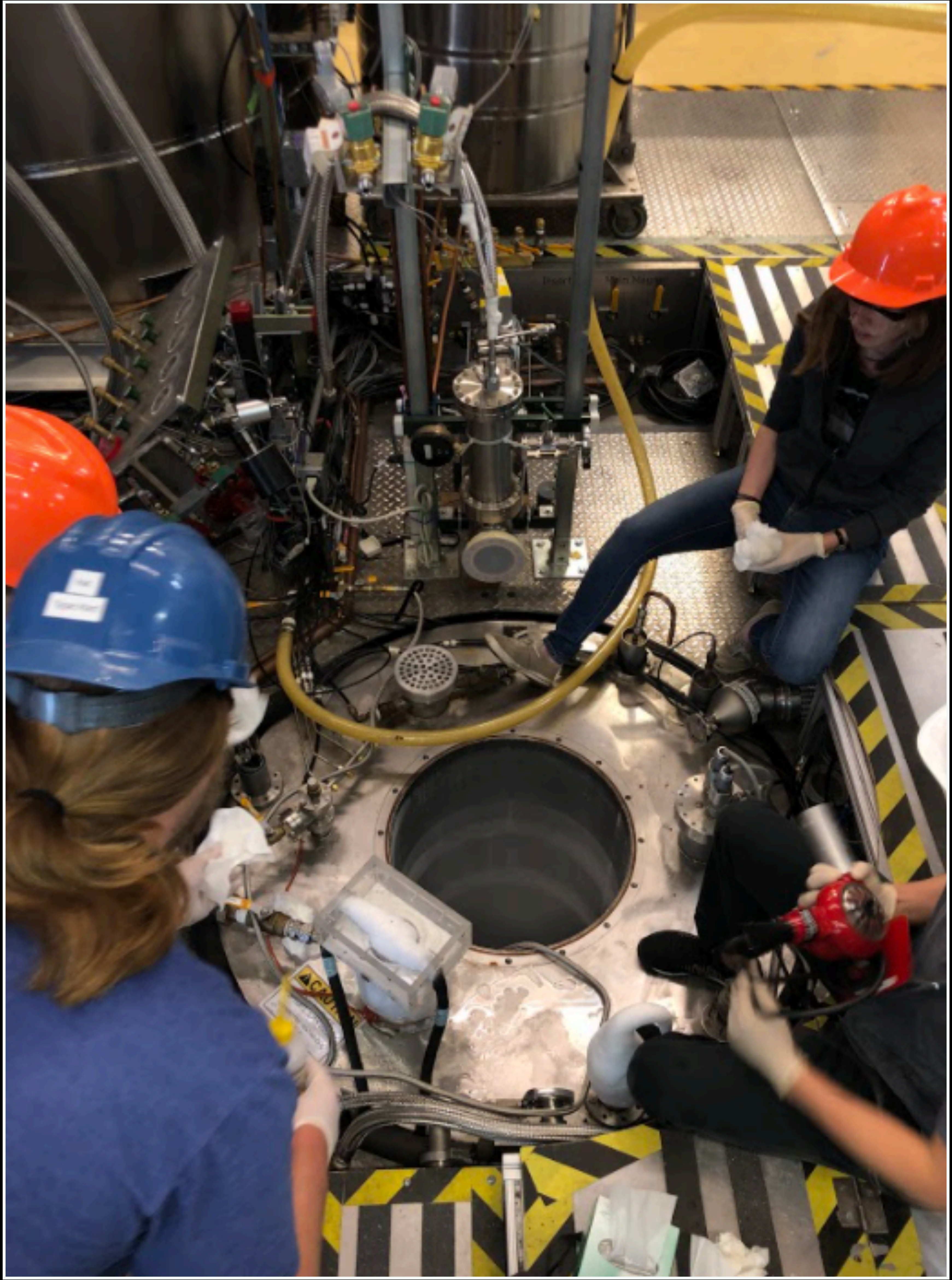


Cavity Haloscope

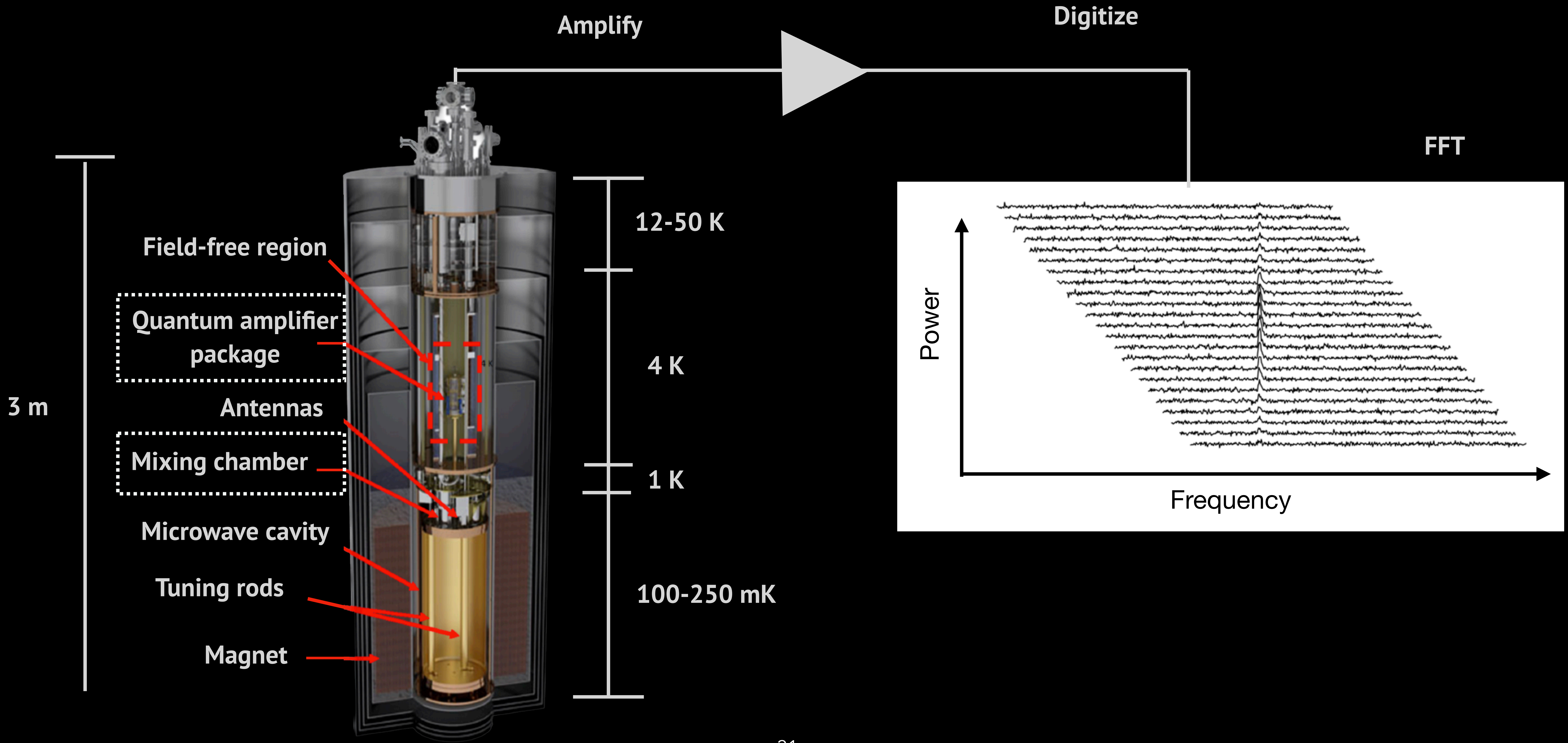


Axion mass unknown: tuning rods required

Cavity Haloscope



Ultra low noise receiver

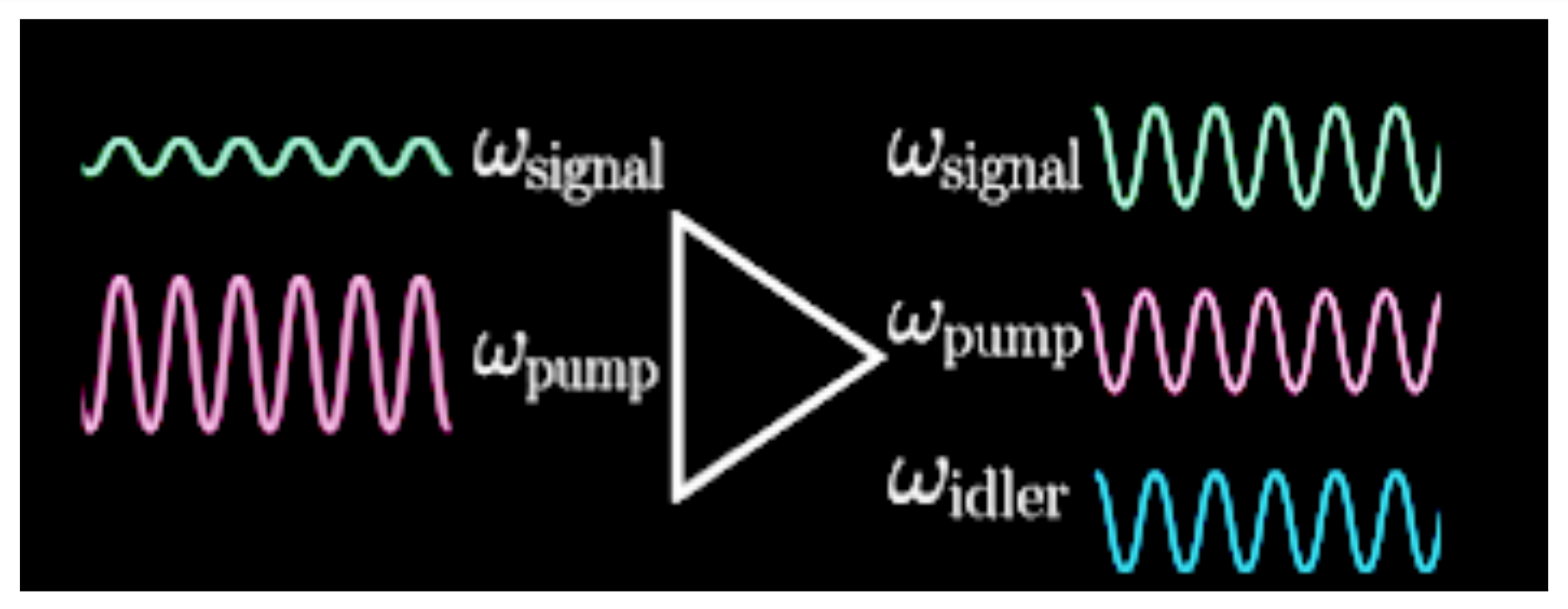


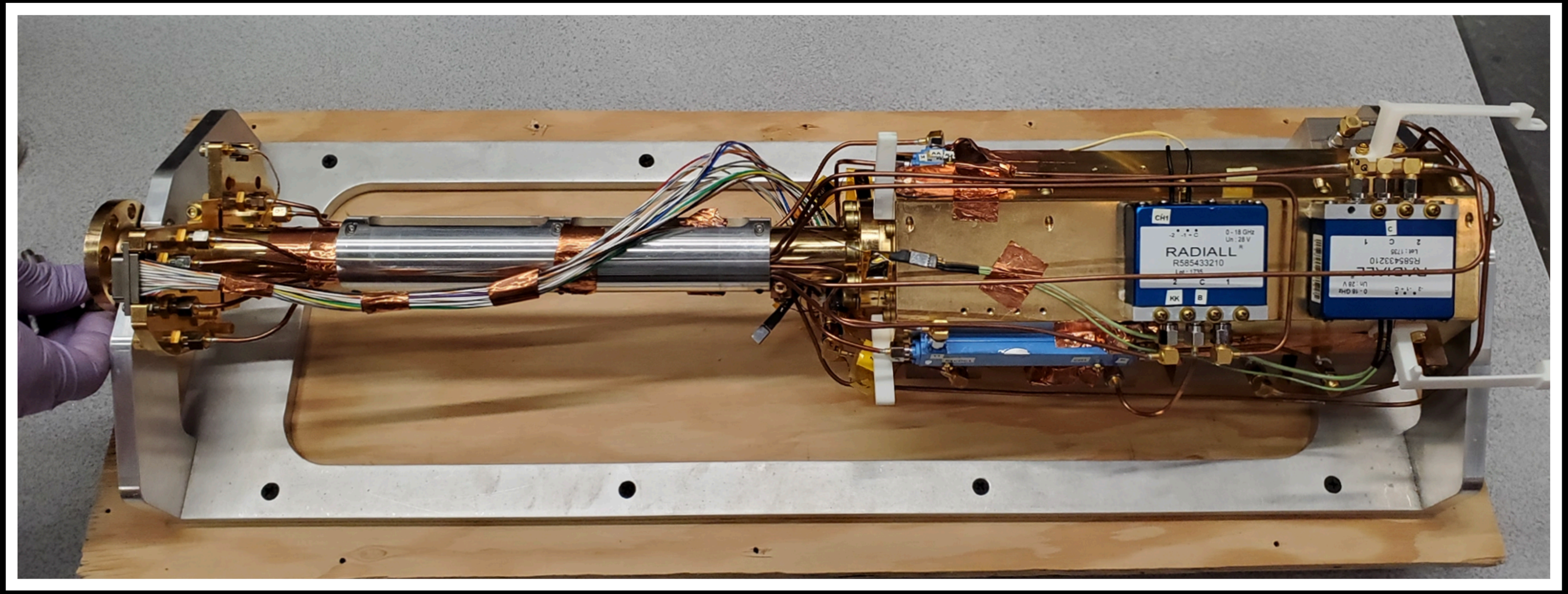
Quantum Amplification

JPA courtesy of
Irfan Siddiqi

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

Figures courtesy of Shahid Jawas

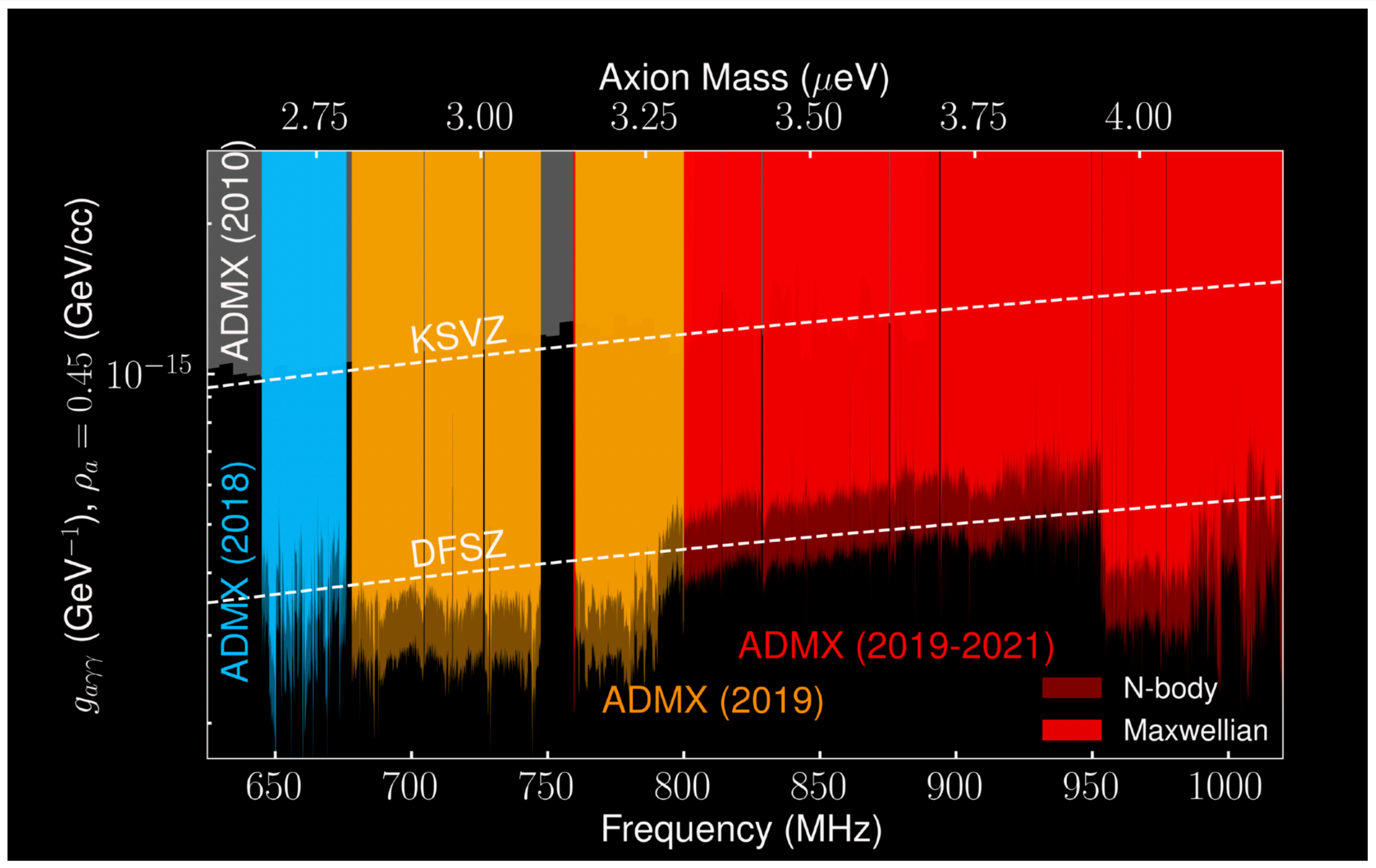




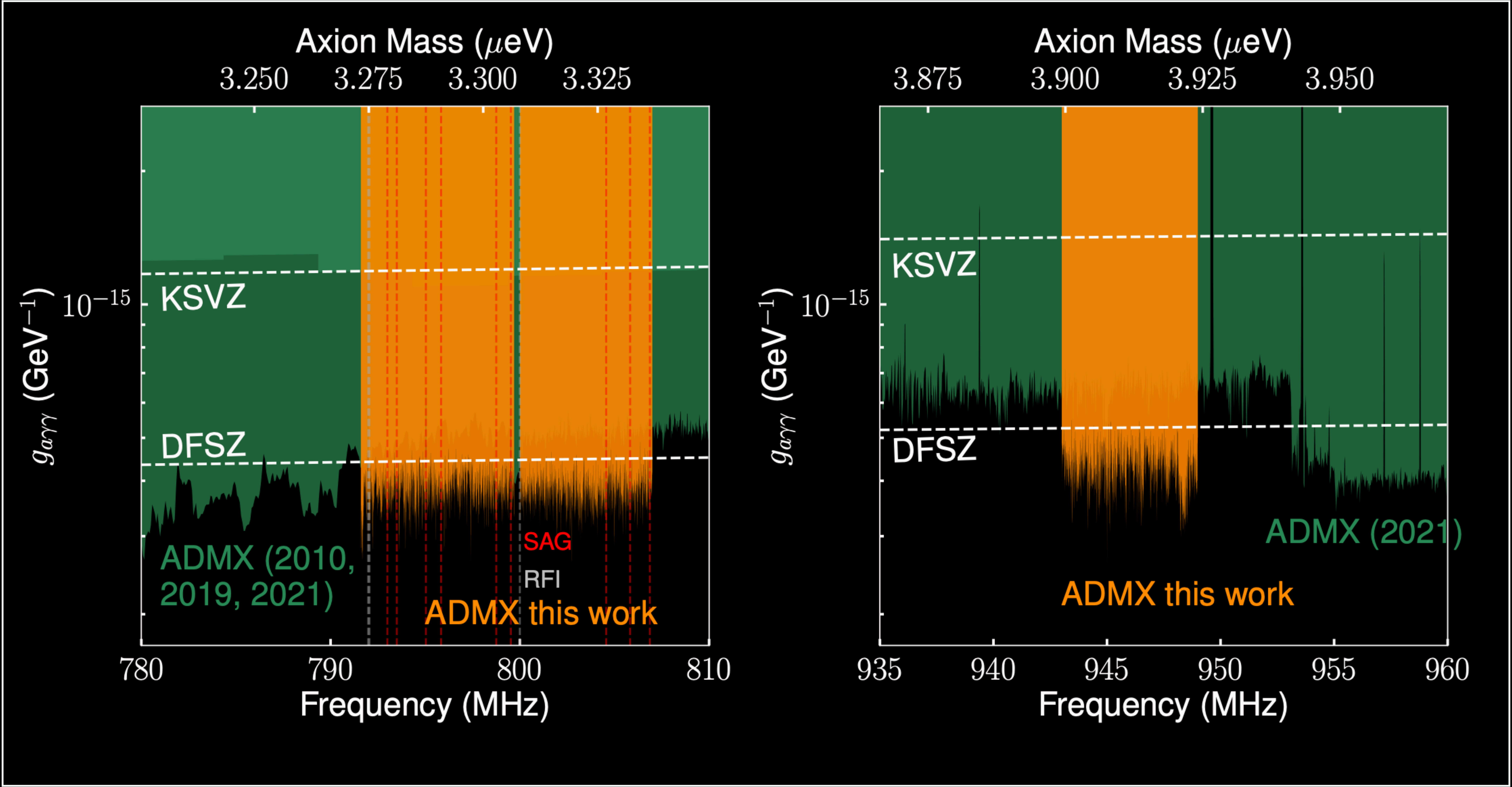
~2 ft

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

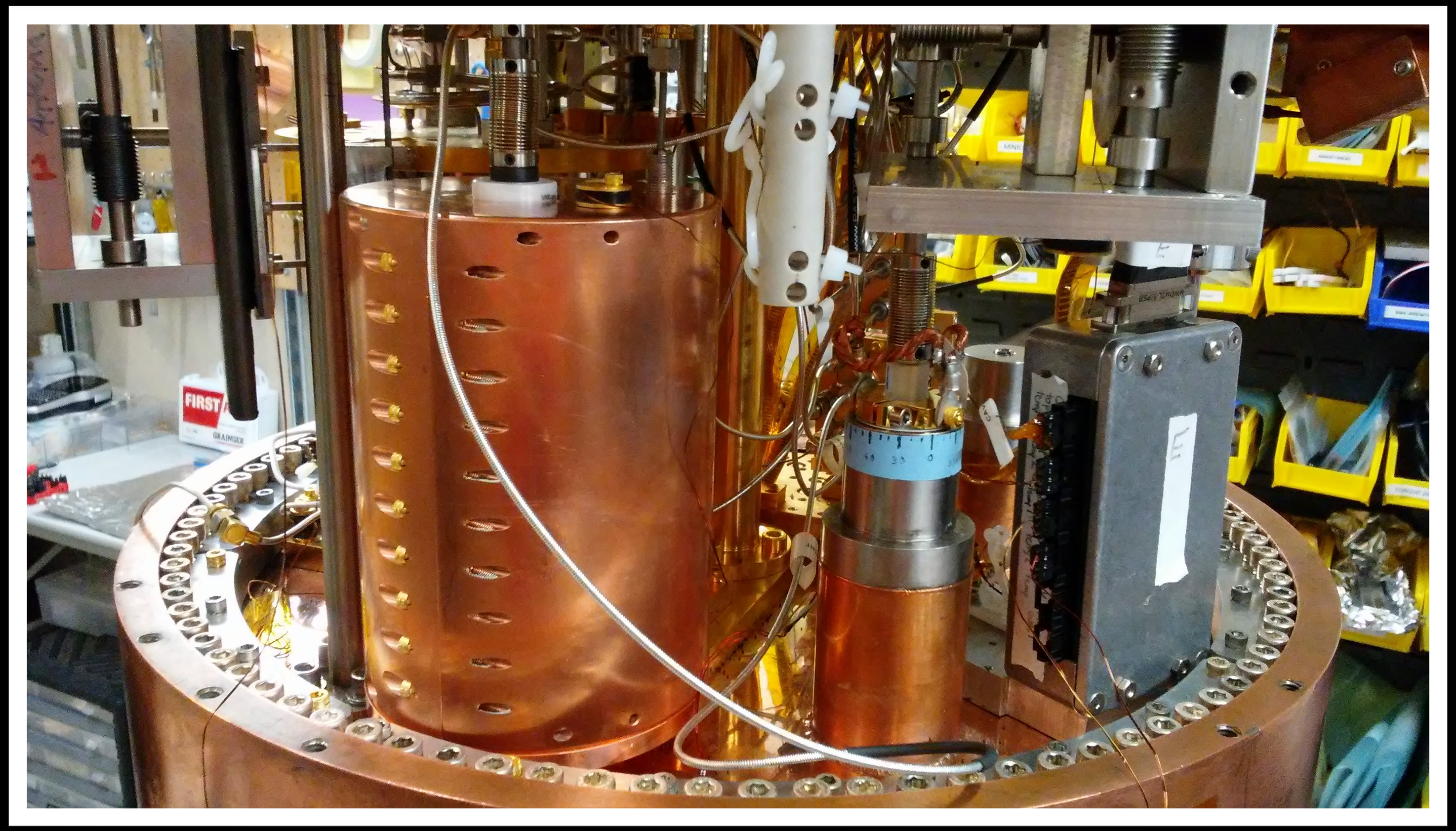
ADMX Exclusion Limits (Published)

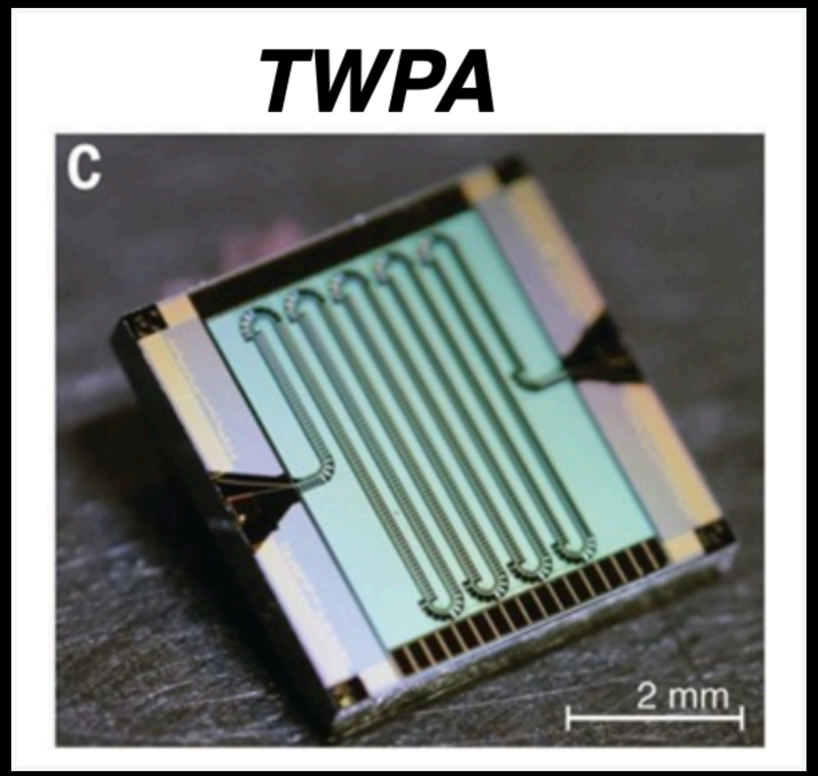


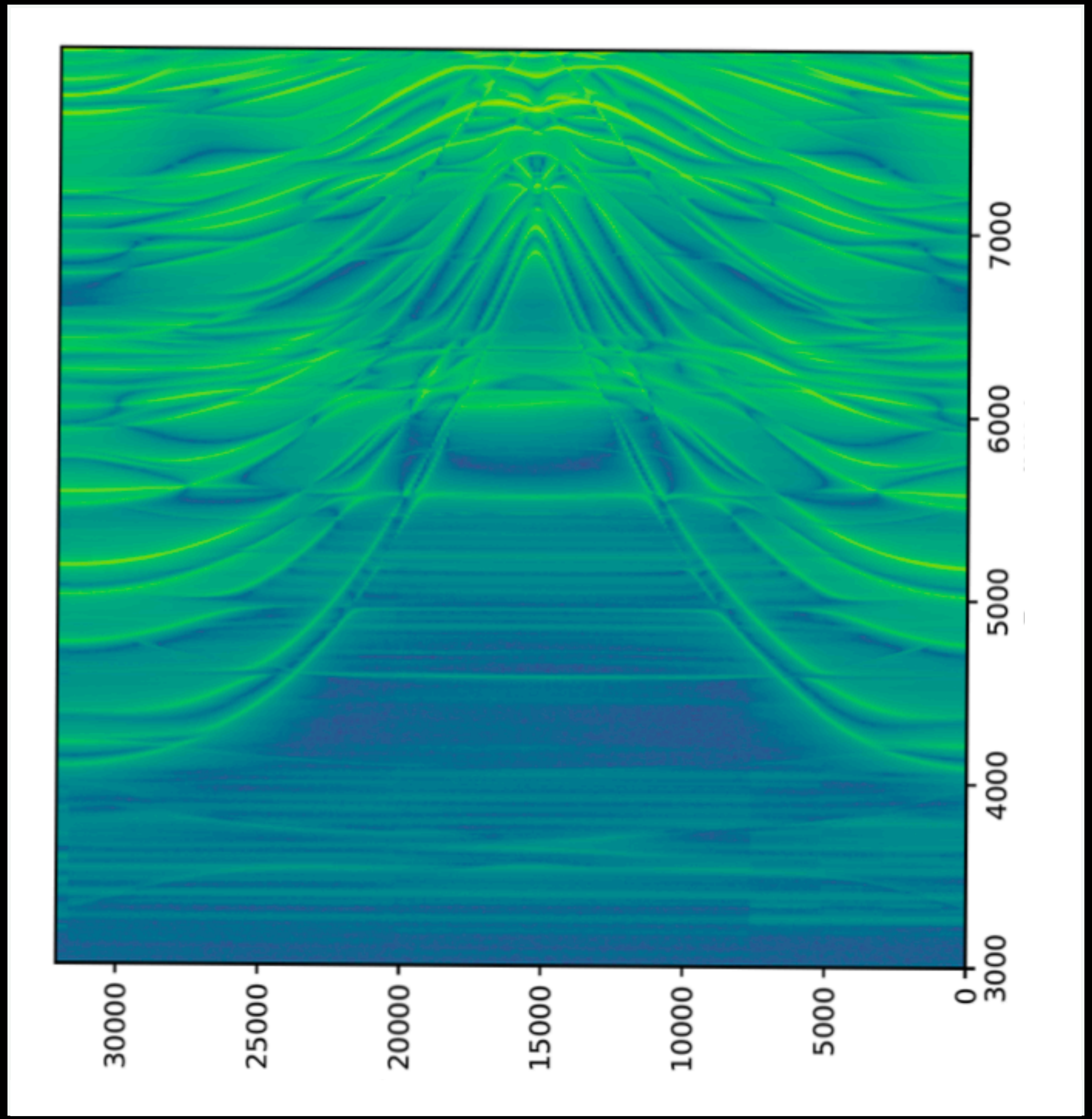
ADMX Preliminary Sensitivity



ADMX high frequency prototype





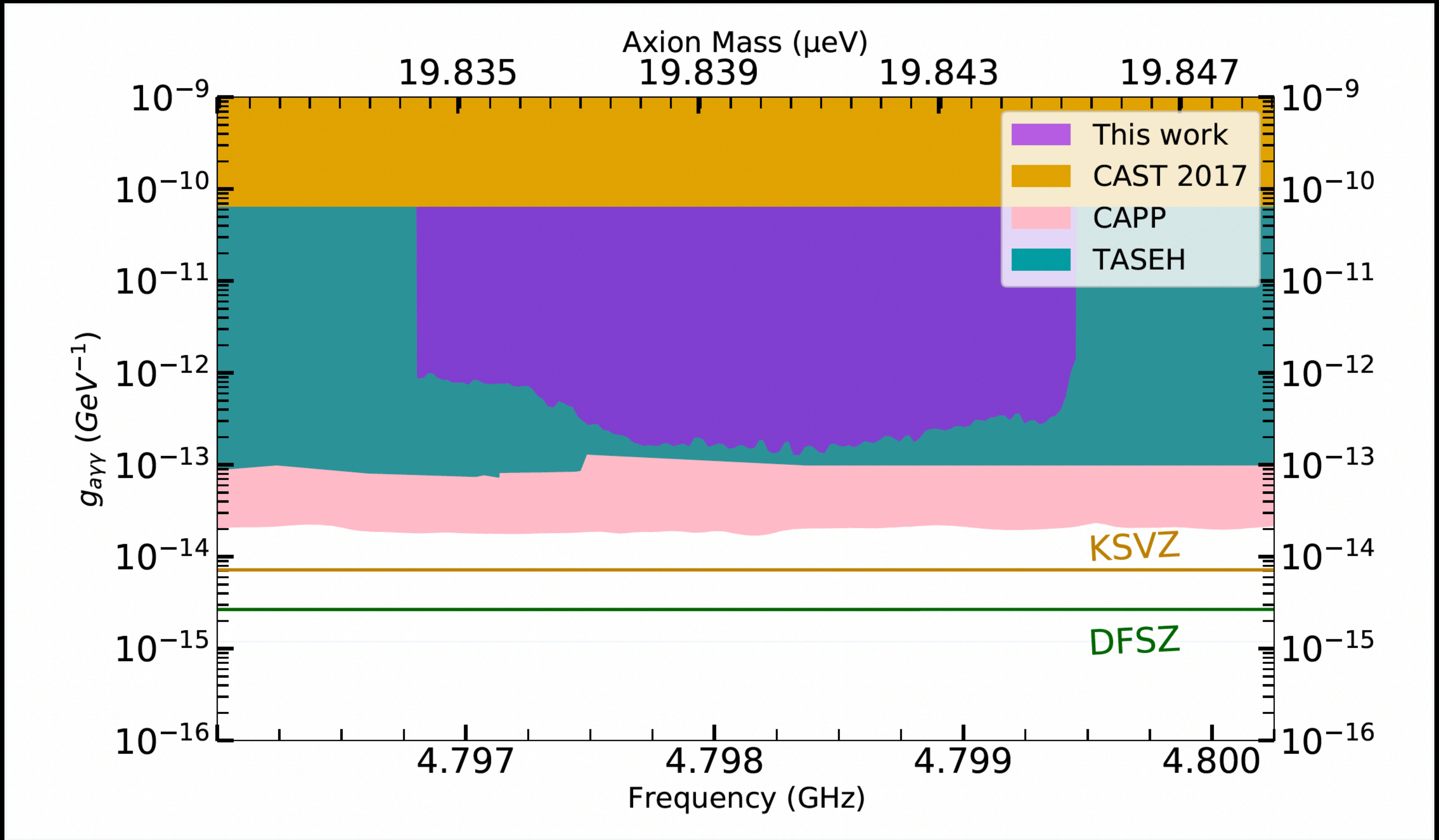


Sidecar mode map

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

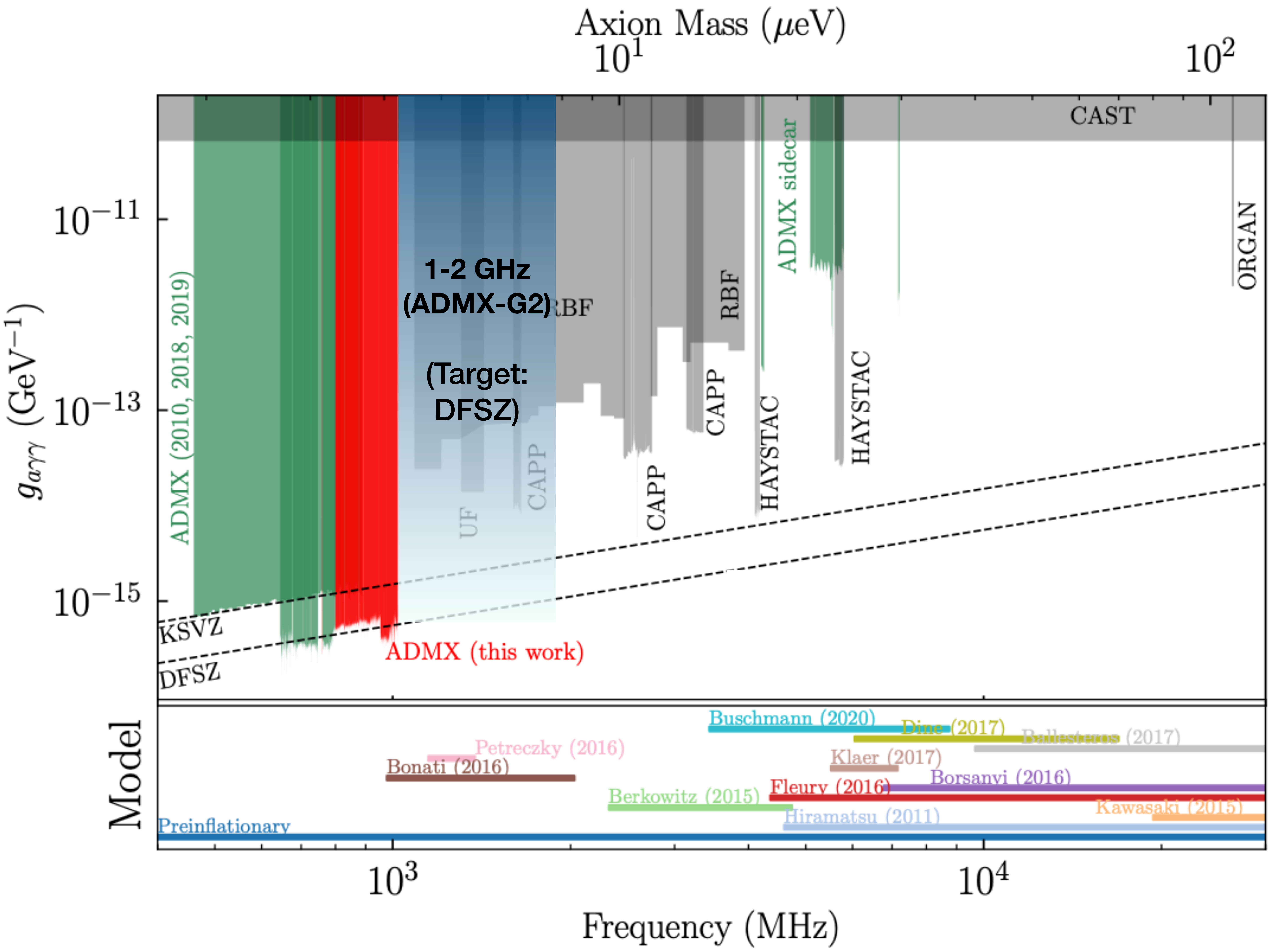
First axion search with a JTWPA



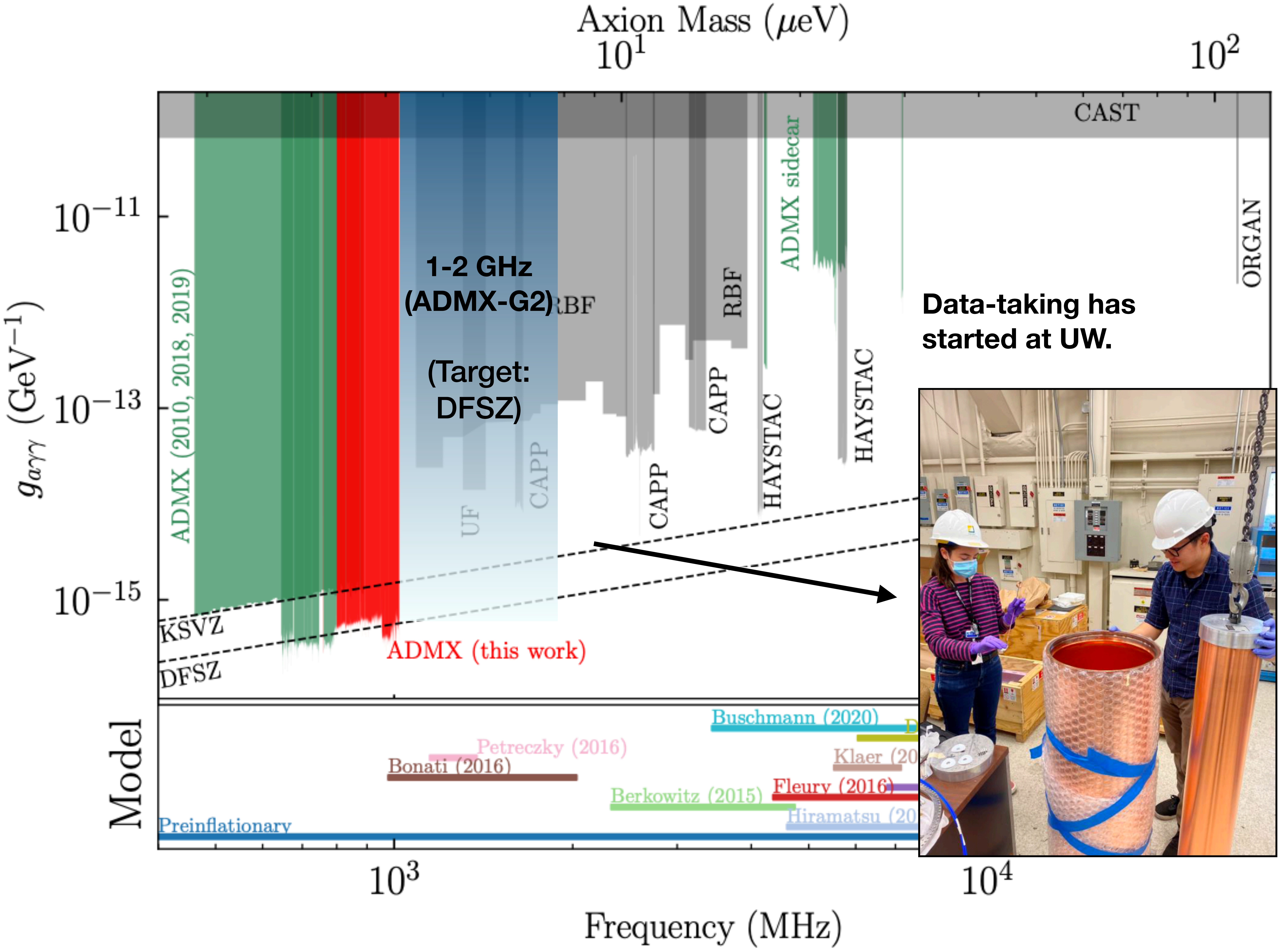
Bartram, C., et al. "Dark matter axion search using a Josephson traveling wave parametric amplifier". Review of Scientific Instruments 94.4 (2023): 044703

Sidecar now taking data at 5.2-5.6 GHz at 10x KSVZ with a Nb3Tn superconducting tuning rod!

ADMX-G2

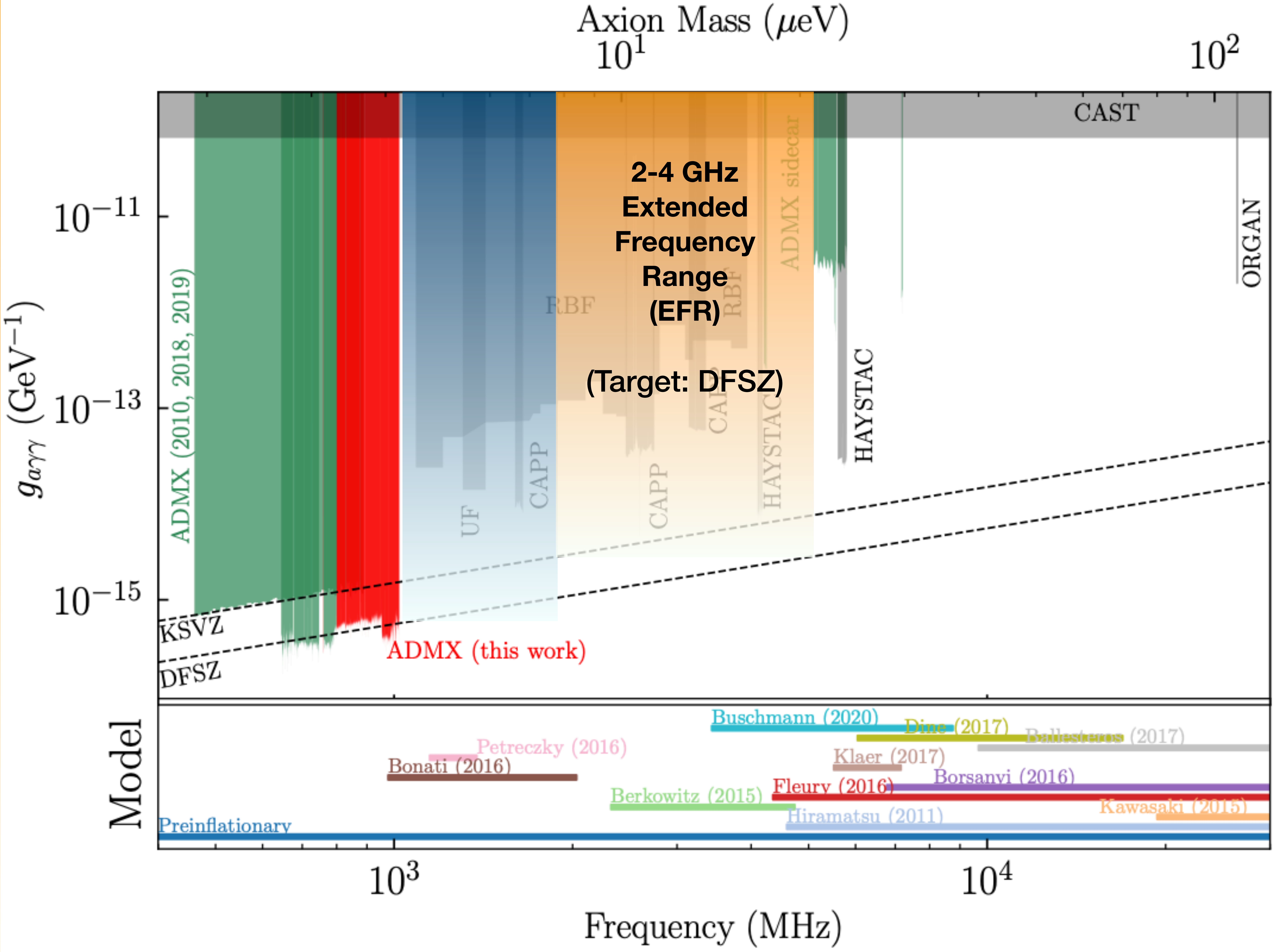

Axion Mass (μeV)
10^1
10^2
CAST
1-2 GHz
(ADMX-G2)
(Target:
DFSZ)
RBF
RBF
ADMX sidecar
ORGAN
ADMX (2010, 2018, 2019)
CAPP
UF
CAPP
CAPP
HAYSTAC
HAYSTAC
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-11}
10^{-13}
10^{-15}
KSVZ
DFSZ
ADMX (this work)
Model
Buschmann (2020)
Dine (2017)
Ballesteros (2017)
Petreczky (2016)
Klaer (2017)
Bonati (2016)
Borsanyi (2016)
Fleury (2016)
Berkowitz (2015)
Kawasaki (2015)
Hiramatsu (2011)
Preinflationary
10^3
10^4
Frequency (MHz)

ADMX-G2



Axion Mass (μeV)
10^1
10^2
CAST
ORGAN
ADMX sidecar
RBF
CAPP
HAYSTAC
UF
ADMX (2010, 2018, 2019)
ADMX (this work)
KSVZ
DFSZ
10^{-11}
10^{-13}
10^{-15}
$g_{a\gamma\gamma}$ (GeV^{-1})
Model
Buschmann (2020)
Petreczky (2016)
Bonati (2016)
Klaer (20
Berkowitz (2015)
Fleury (2016)
Hiramatsu (20
Preinflationary
10^3
10^4
Frequency (MHz)
1-2 GHz
(ADMX-G2)
(Target:
DFSZ)
Data-taking has
started at UW.

ADMX-EFR



Axion Mass (μeV)
10^1
10^2
CAST
2-4 GHz
Extended
Frequency
Range
(EFR)
(Target: DFSZ)
ADMX sidecar
ORGAN
RBF
HAYSTAC
CAPP
UF
ADMX (2010, 2018, 2019)
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-11}
10^{-13}
10^{-15}
KSVZ
DFSZ
ADMX (this work)
Model
Buschmann (2020)
Dine (2017)
Ballesteros (2017)
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Borsanyi (2016)
Fleury (2016)
Berkowitz (2015)
Kawasaki (2015)
Hiramatsu (2011)
Preinflationary
10^3
10^4
Frequency (MHz)

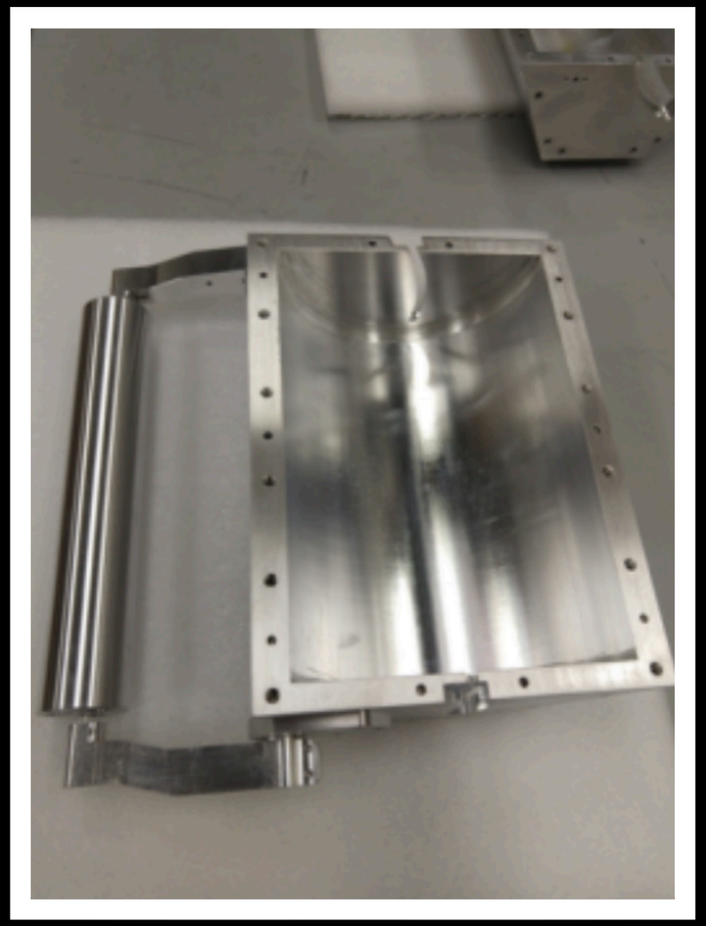
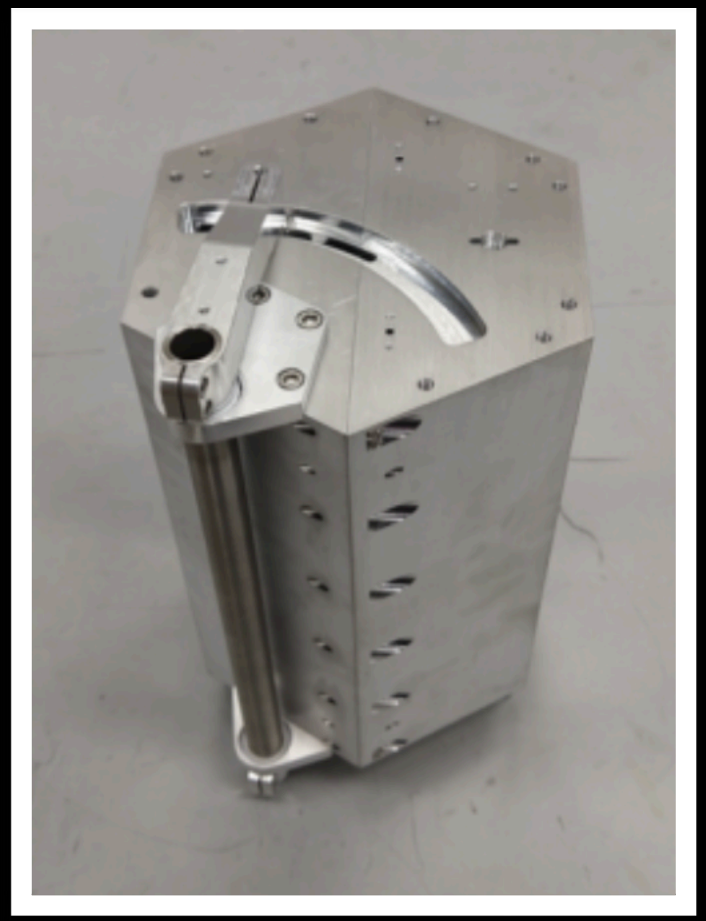
Scan speed for cavity haloscope

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

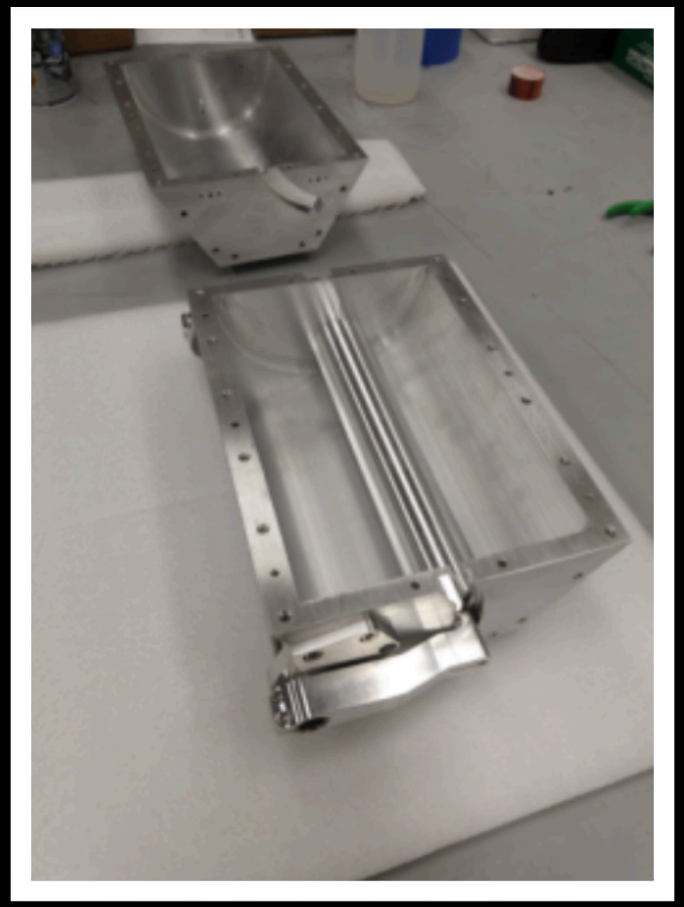
Maximize	Can't Control	Minimize
• B Field • Volume • Quality Factor • Form Factor	• Frequency • Coupling • Dark Matter Density	• System noise: • Amplifier Noise • Physical Noise

***Similar equation for quasistatic haloscope**

ADMX EFR (2-4 GHz)

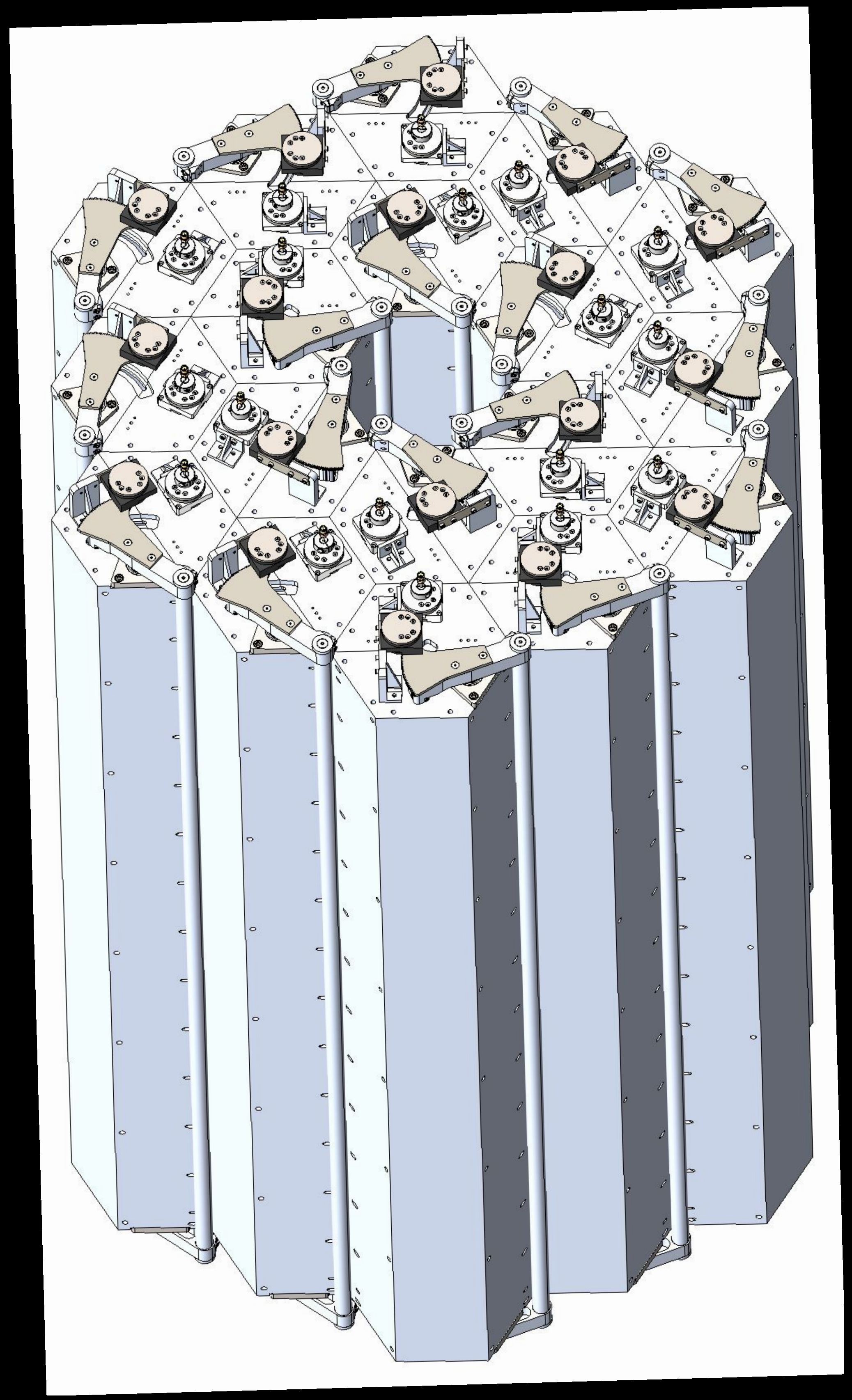



Prototype cavity testing



18-JPA receiver

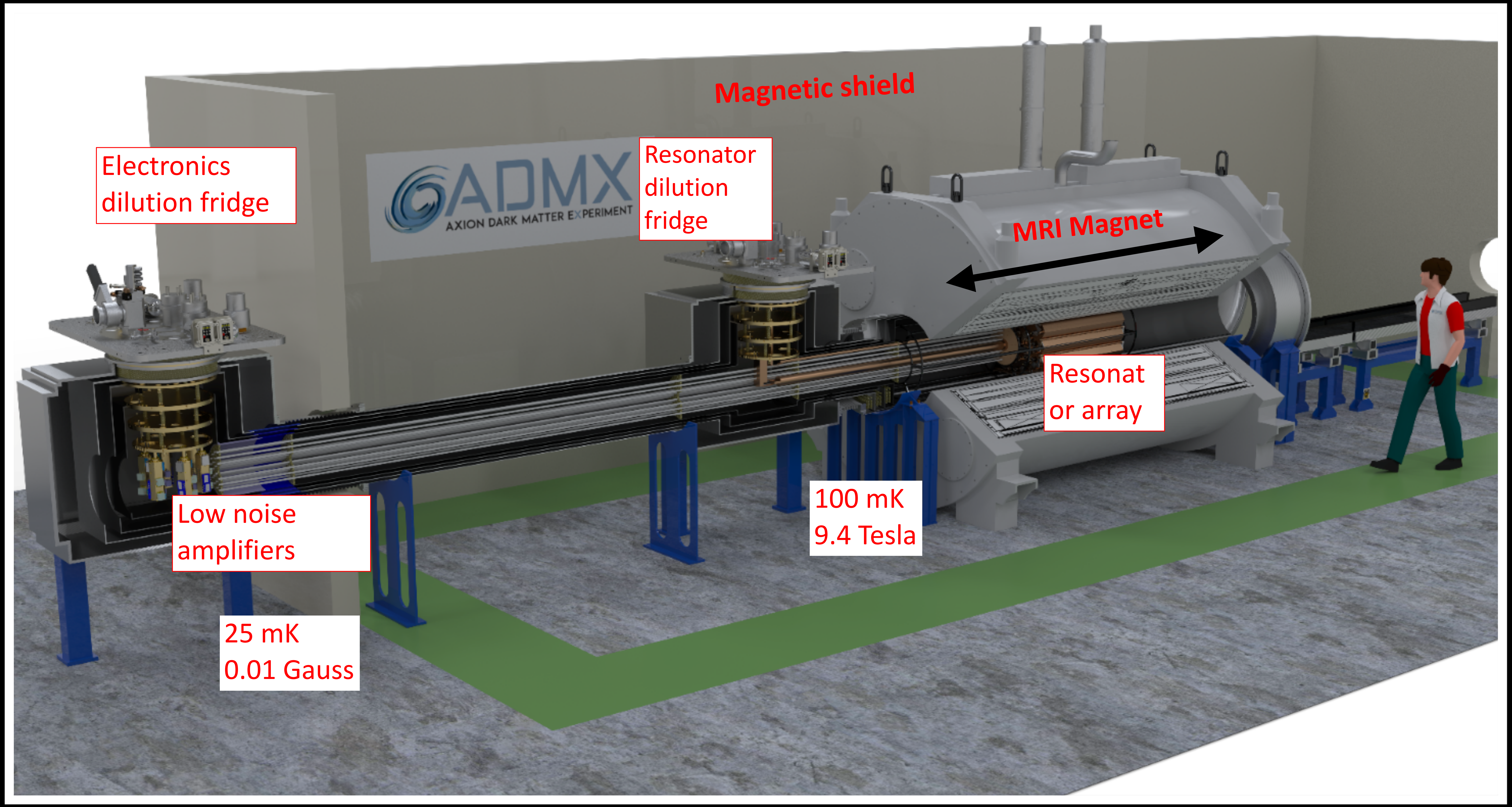
9.4 T Magnet



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)

Conclusions

- Variety of haloscopes to search for axions over a range of frequencies. Low frequency microwave signals leverage established technology (microwave antennas) and novel techniques (quantum sensing).

- Field is growing rapidly.

- New results on the horizon for ADMX and DM Radio.