Search for the QCD Axion with ADMX

The Axion Quest- Recontres du Vietnam
August 5, 2024

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Postdoctoral Scholar

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Outline

- Axion Dark Matter
- Axion Haloscopes
- ADMX Run 1D
- Plans for Future Searches

Axion Dark Matter

- The nature of dark matter is one of the largest mysteries in physics
- Peccei-Quinn solution to the Strong CP problem predicts the axion
  - Axions have properties that make them compelling as a candidate for dark matter
- Axion dark matter would solve two huge mysteries in physics at once
  - This is very compelling!

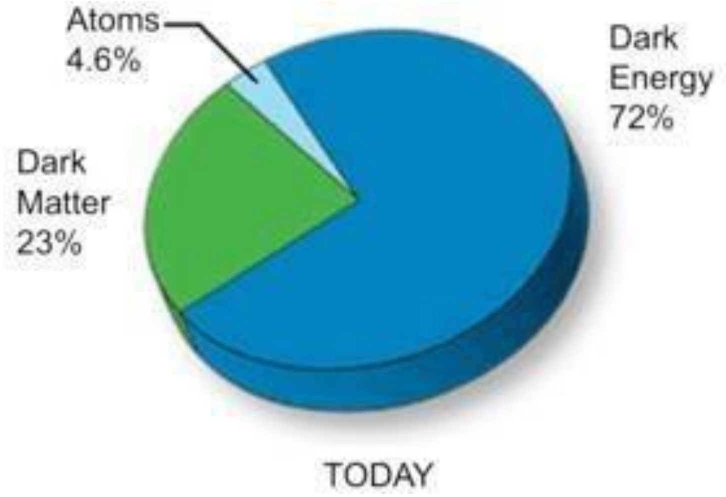
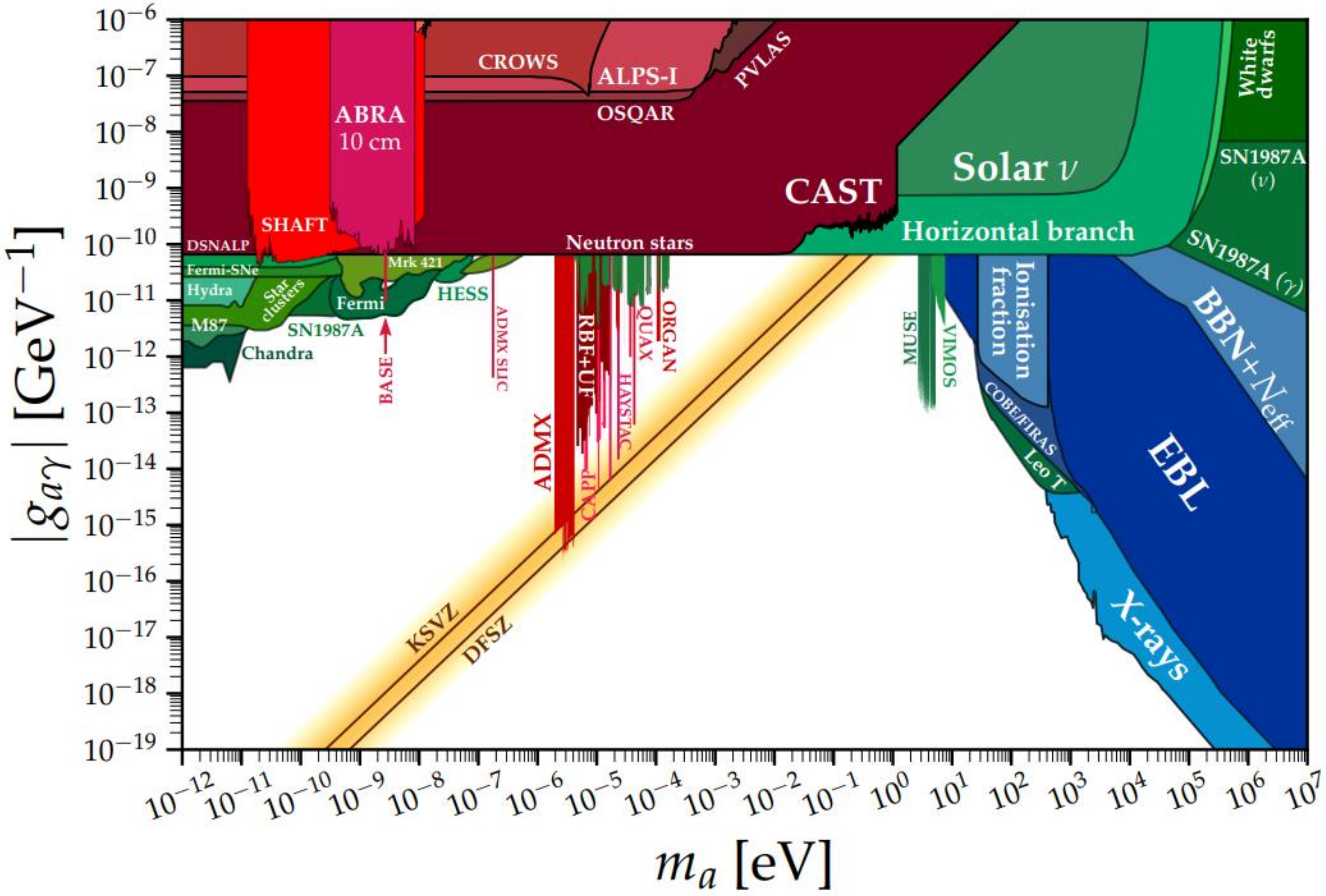


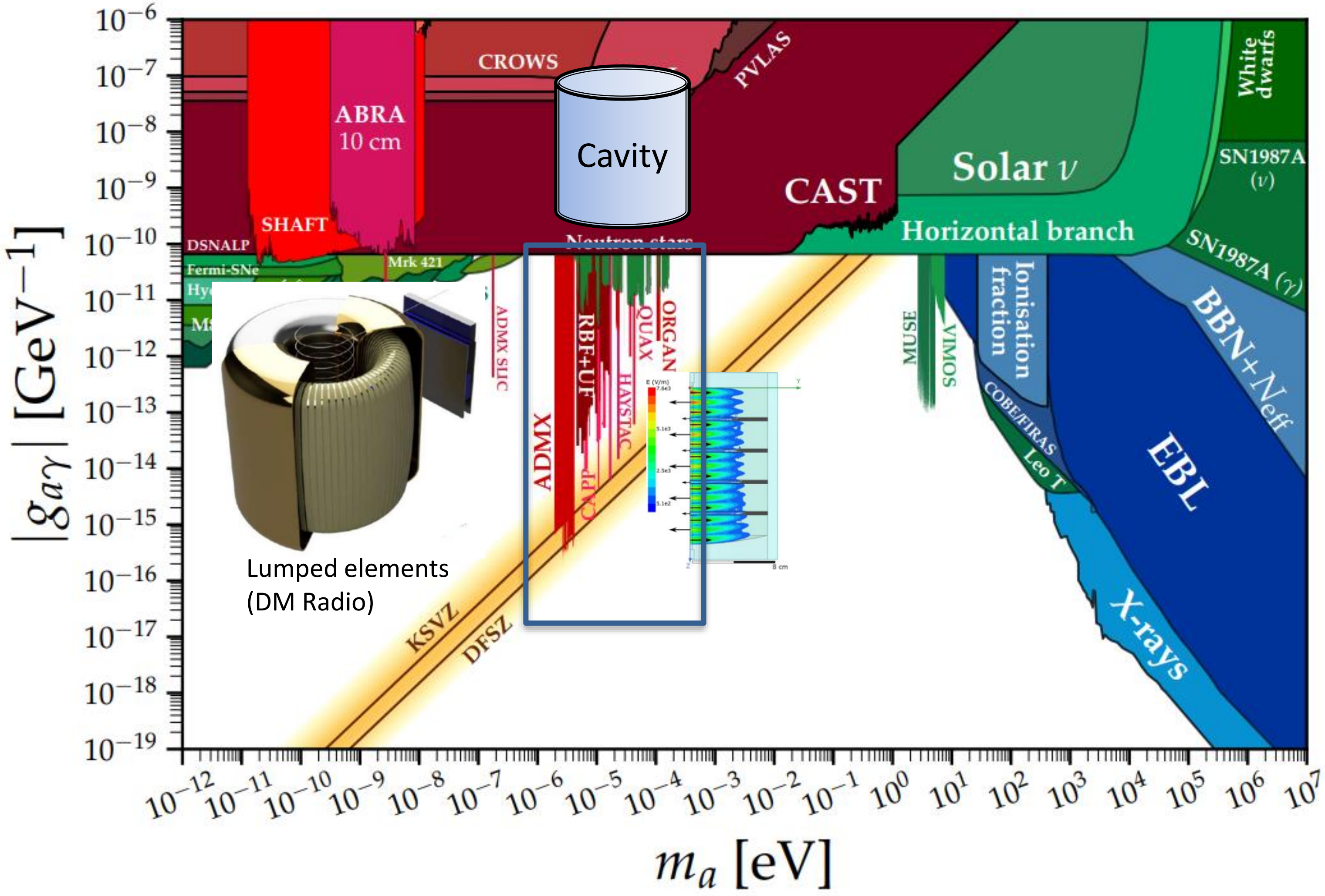
Photo: https://sanpedrosupermarket.com/product/axion-lime-dish-soap/

Axion Landscape



Adapted from Ciaran O'Hare

Axion Dark Matter Searches: Haloscopes



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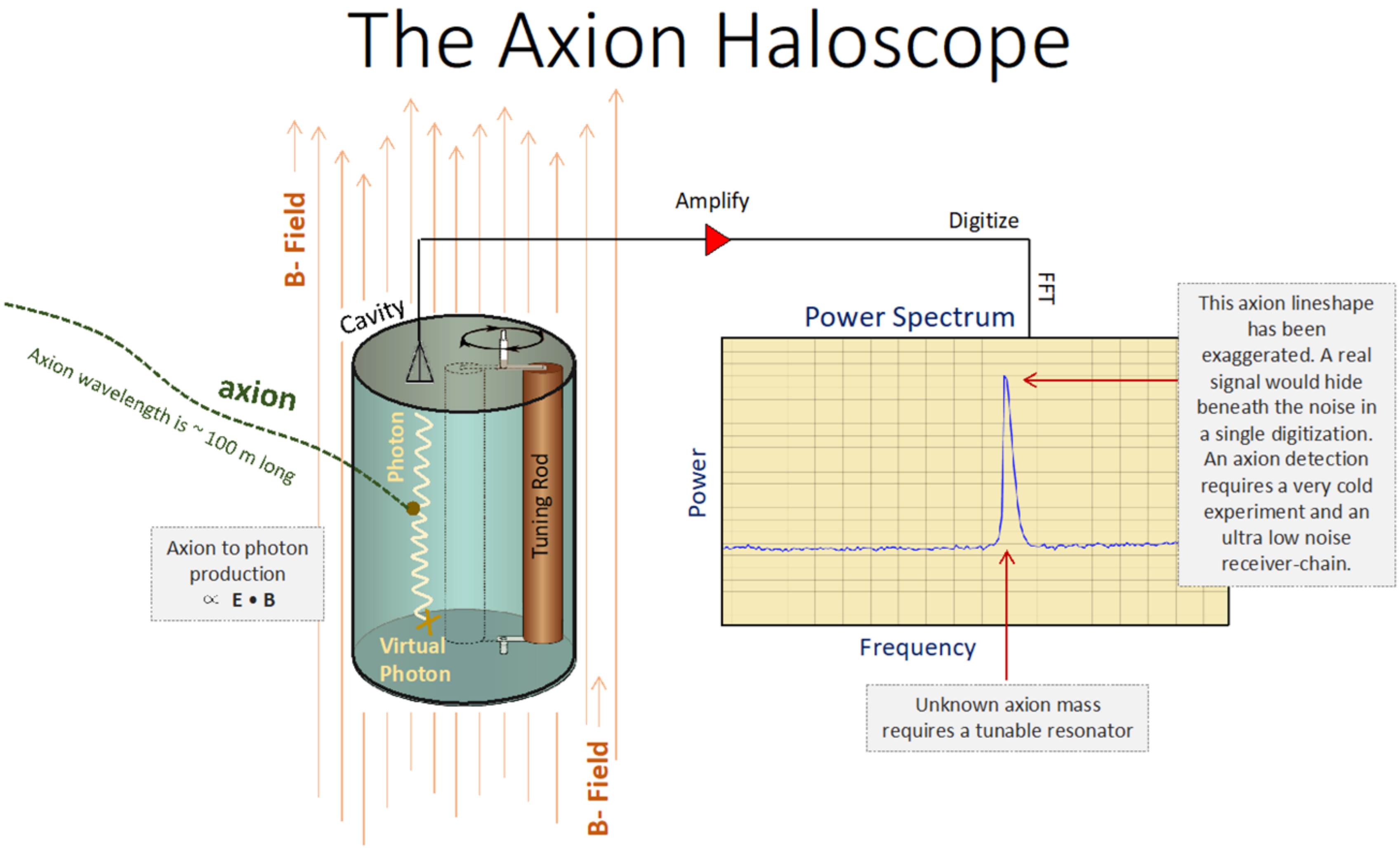
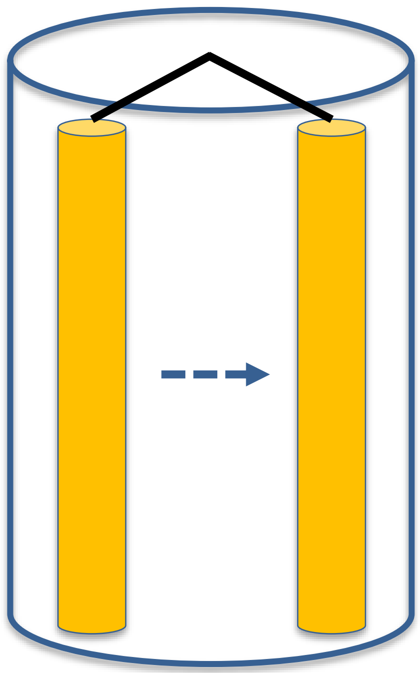
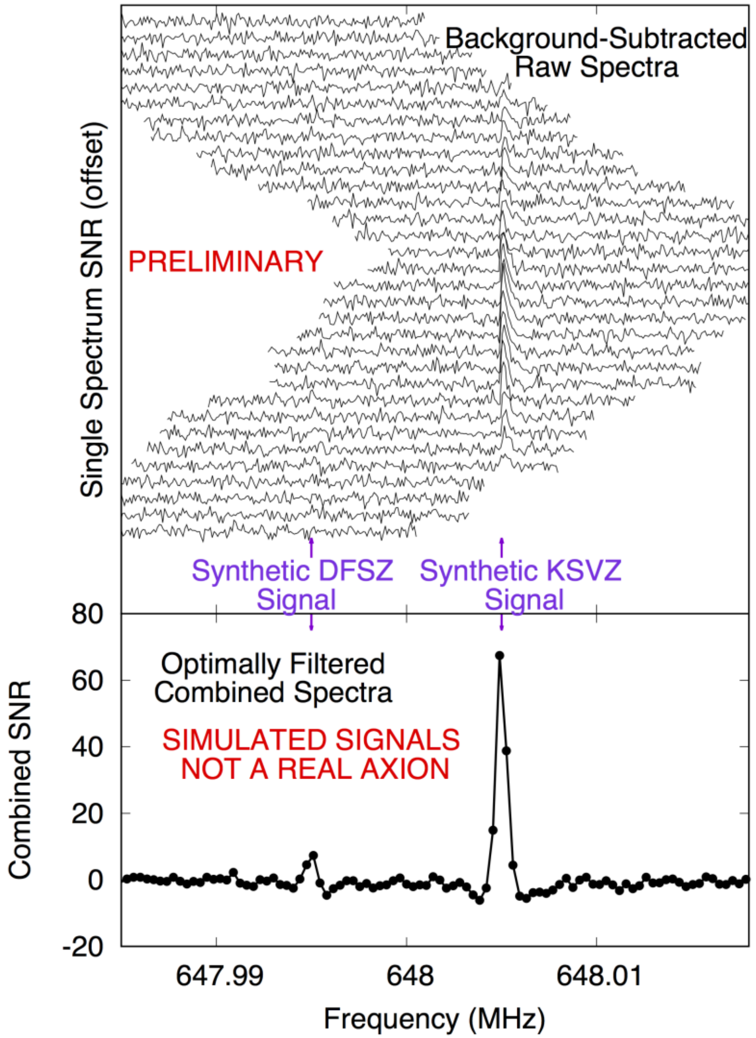
Axion Haloscopes



Scanning with Axion Haloscopes

- Axion mass is not known *a priori*
  - Axion haloscopes must be tunable across a wide frequency range
- Tuning rods set the resonant frequency of the cavity and are used to sweep the cavity resonant frequency target frequency range
  - Power from cavity is sampled then the cavity resonance is tuned and the procedure is repeated





Scan Rate for Cavity Axion Haloscopes

$$\frac{df}{dt} \approx 323\,\frac{\text{MHz}}{\text{year}} \left\{ \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1\ GHz}\right)^2 \left(\frac{\rho_0}{0.45\,\frac{GeV}{cc}}\right)^2 \right\} \cdot \left\{ \left(\frac{3.5}{SNR}\right)^2 \left(\frac{B_0}{7.6\ T}\right)^4 \left(\frac{V}{136l}\right)^2 \left(\frac{Q_L}{30{,}000}\right) \left(\frac{C_{lmn}}{0.4}\right)^2 \left(\frac{0.35\ K}{T_{sys}}\right)^2 \right\}$$

Parameters fixed by Nature

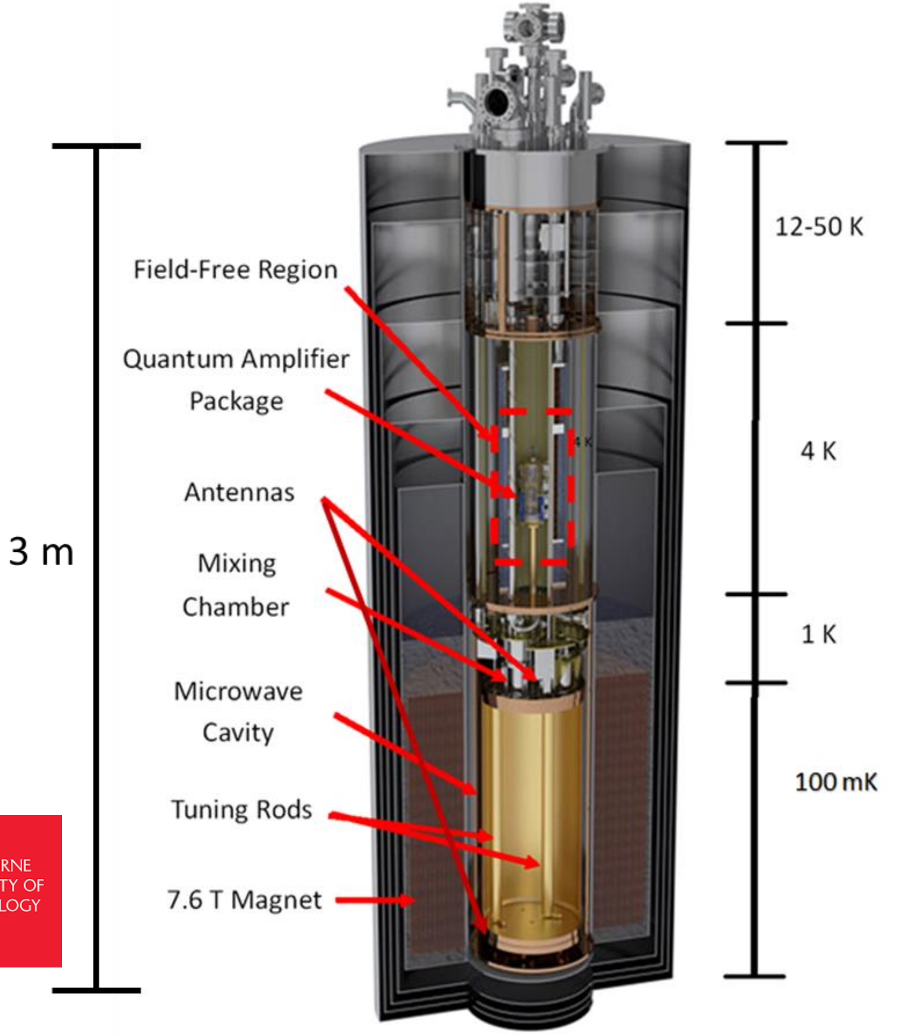
- g_γ – Dimensionless Coupling constant
- f – Axion frequency
- ρ_0 – Dark matter halo energy density

Experimental Parameters

- SNR – Signal-to-noise ratio
- B_0 – External magnetic field
- V – Cavity volume
- Q_L – Cavity quality factor
- C_{lmn} – Cavity form factor
- T_{sys} – System noise temperature

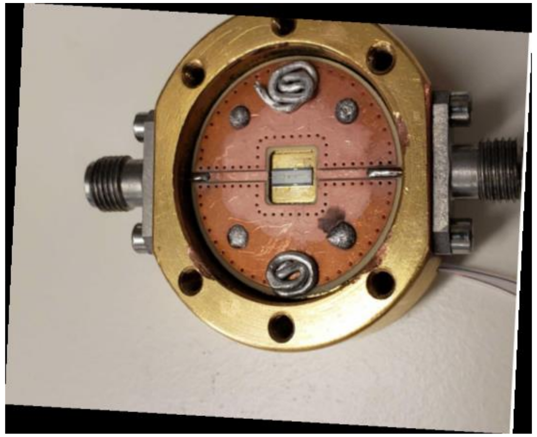
Axion Dark Matter Experiment (ADMX)

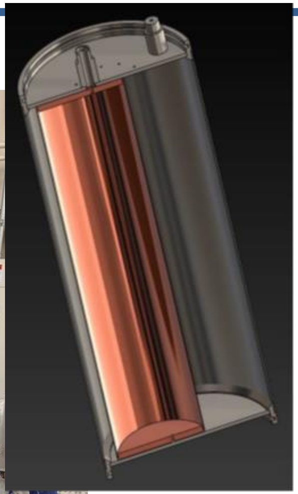
- Largest axion haloscope in the world
- Was originally based in LLNL
  - Moved to University of Washington in 2010
- ~50 collaborators



ADMX Run 1D

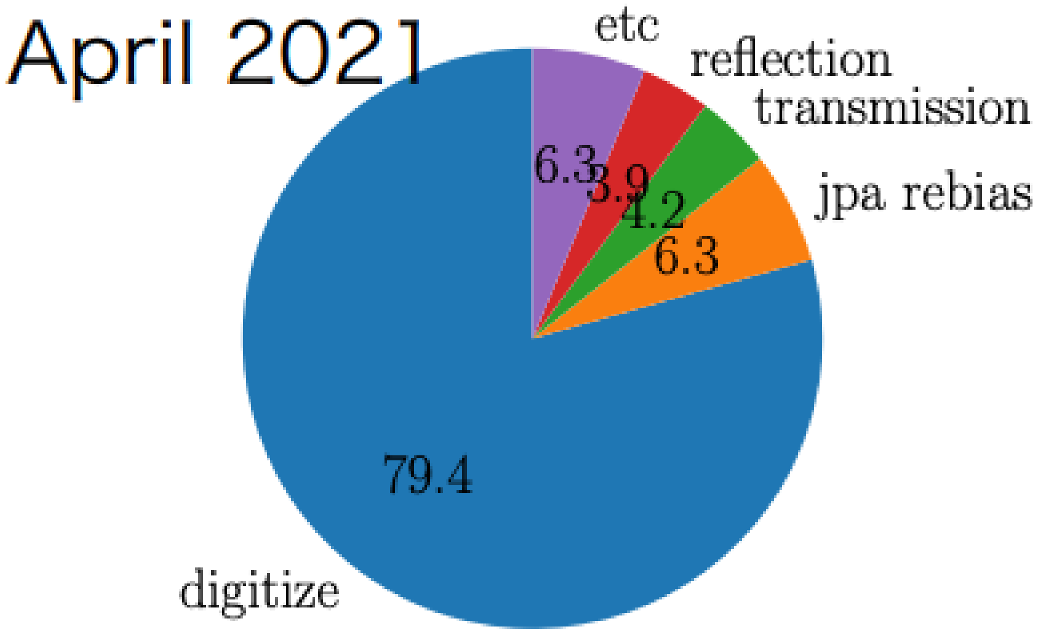
- Run 1D
  - Began January 2024
  - Search for axion in the 1-1.4 GHz frequency range
- Resonator design
  - Same tube but with larger tuning rod to reach a higher frequency
- Receiver design
  - Tunable current-pumped JPA enables quantum-limited noise across entire range
  - Anticipating transition to a flux-pumped JPA by Washington University





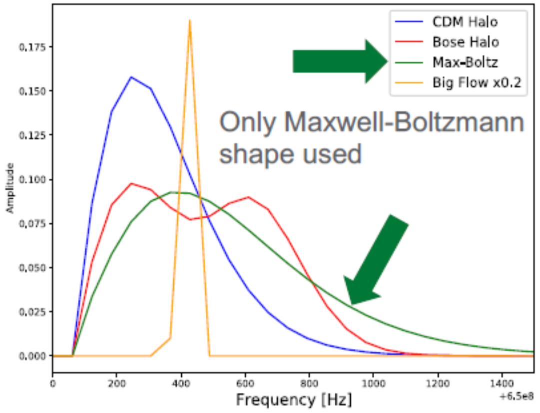
Data Taking Run with ADMX

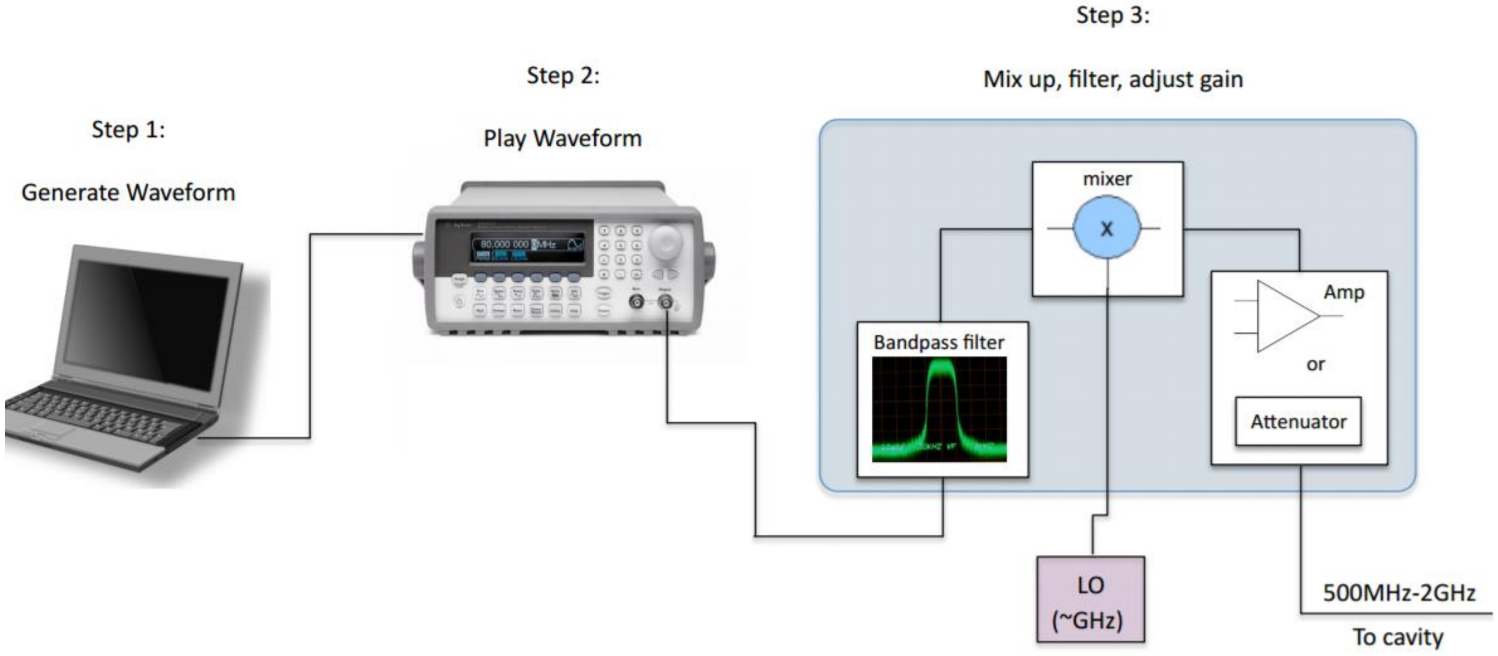
- Data taking operations are controlled by an automated script
- Multiple measurements are required at each tuning step to monitor status and optimize the noise temperature of the experiment



Synthetic Axion Injections

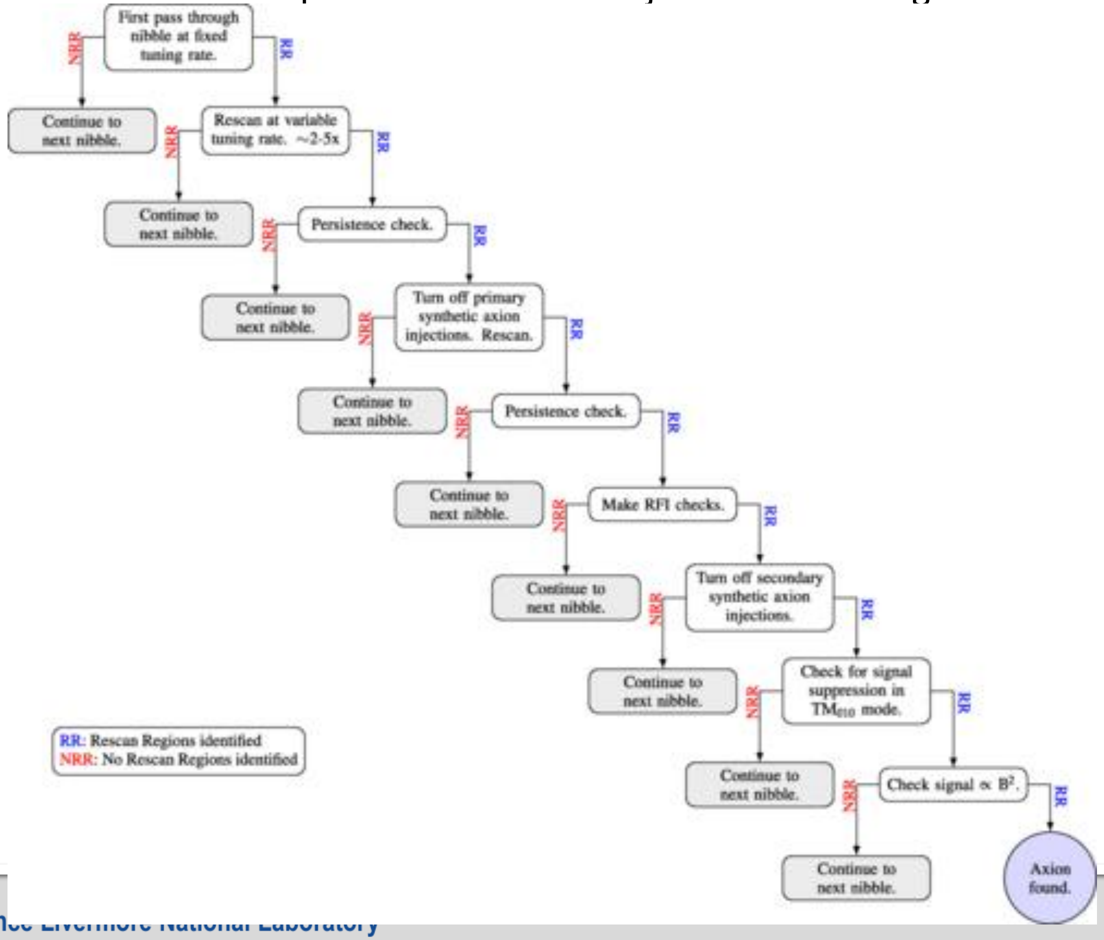
- Synthetically generated axion waveforms are injected into the cavity via a weakly coupled antenna
- Enables testing of RF receiver and candidate identification methodology
  - Blinded axion injections
- We regularly inject synthetic axions into our system to ensure a robust test of our identification methodology

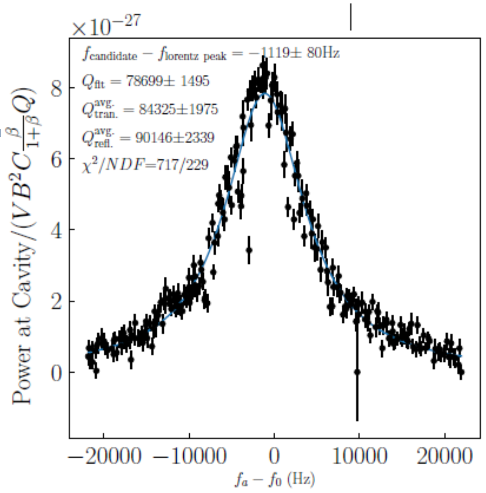


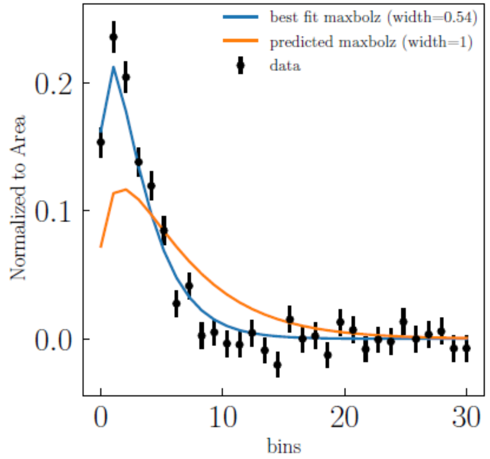


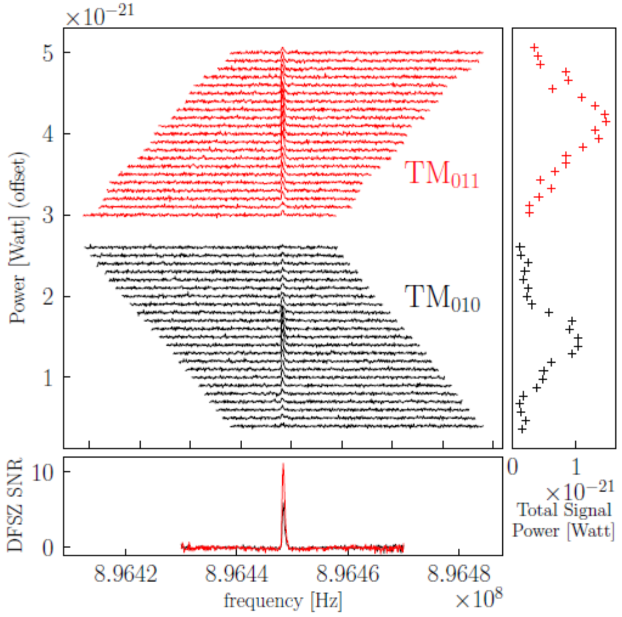
Vetoing Candidate Signals

- Candidates are always expected due to blind injections, noise fluctuations, RFI
  - Candidate veto procedure ensures reject non-axion signals

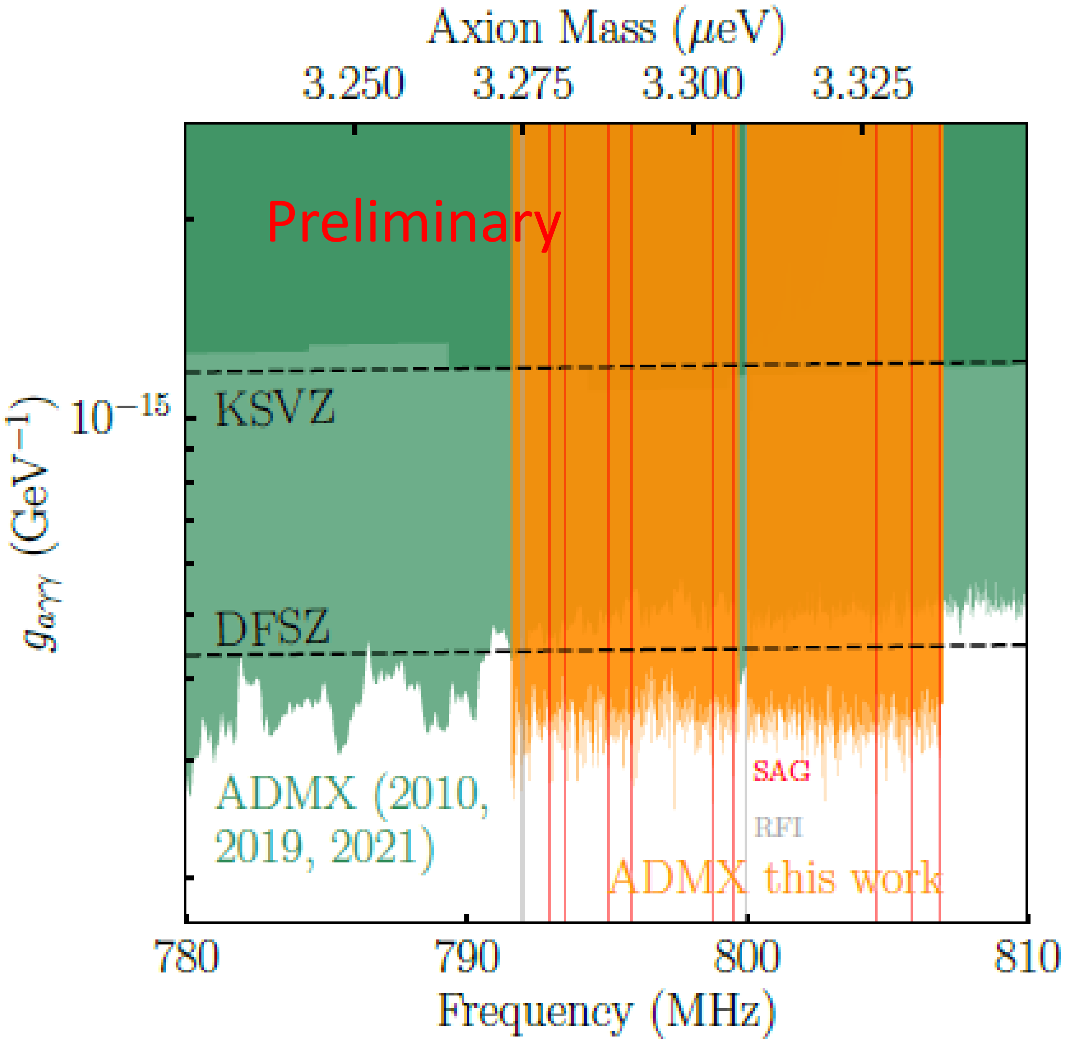


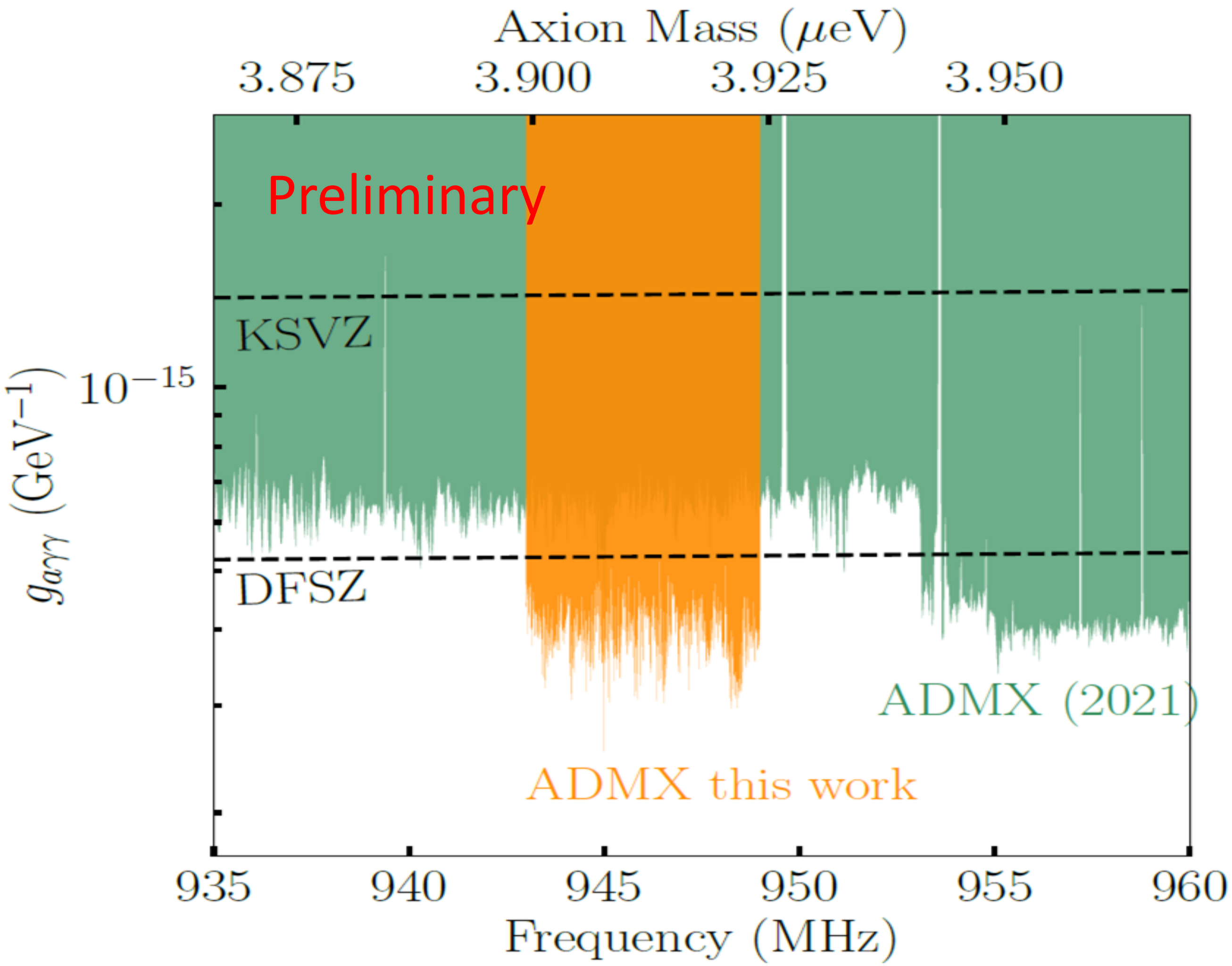






Upcoming Limits on the Axion with ADMX Run 1C Extend





Probing for Higher Mass Axions

- The target mass of your axion search sets the length scale of your resonant cavity
- As resonant frequency of the cavity goes up
  - Volume decreases as $V \sim 1/f^3$
  - Quality factor decreases as $Q \sim 1/f^{2/3}$
  - Noise power increases at $T_{amp} \sim f$
- To maintain an adequate scan rate need new developments (Multiple cavities, Stronger magnets, Higher Q cavities, etc.)

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Stronger magnets

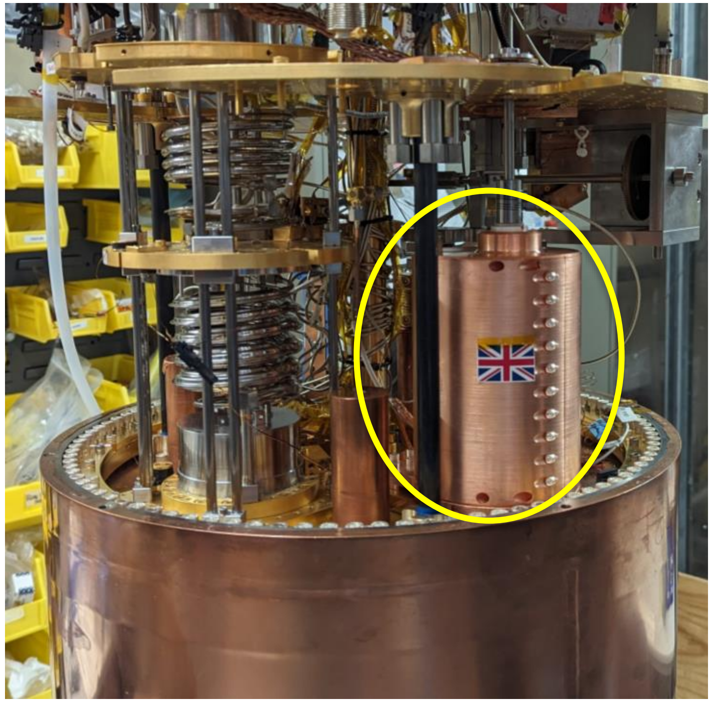
Larger cavities to maintain volume

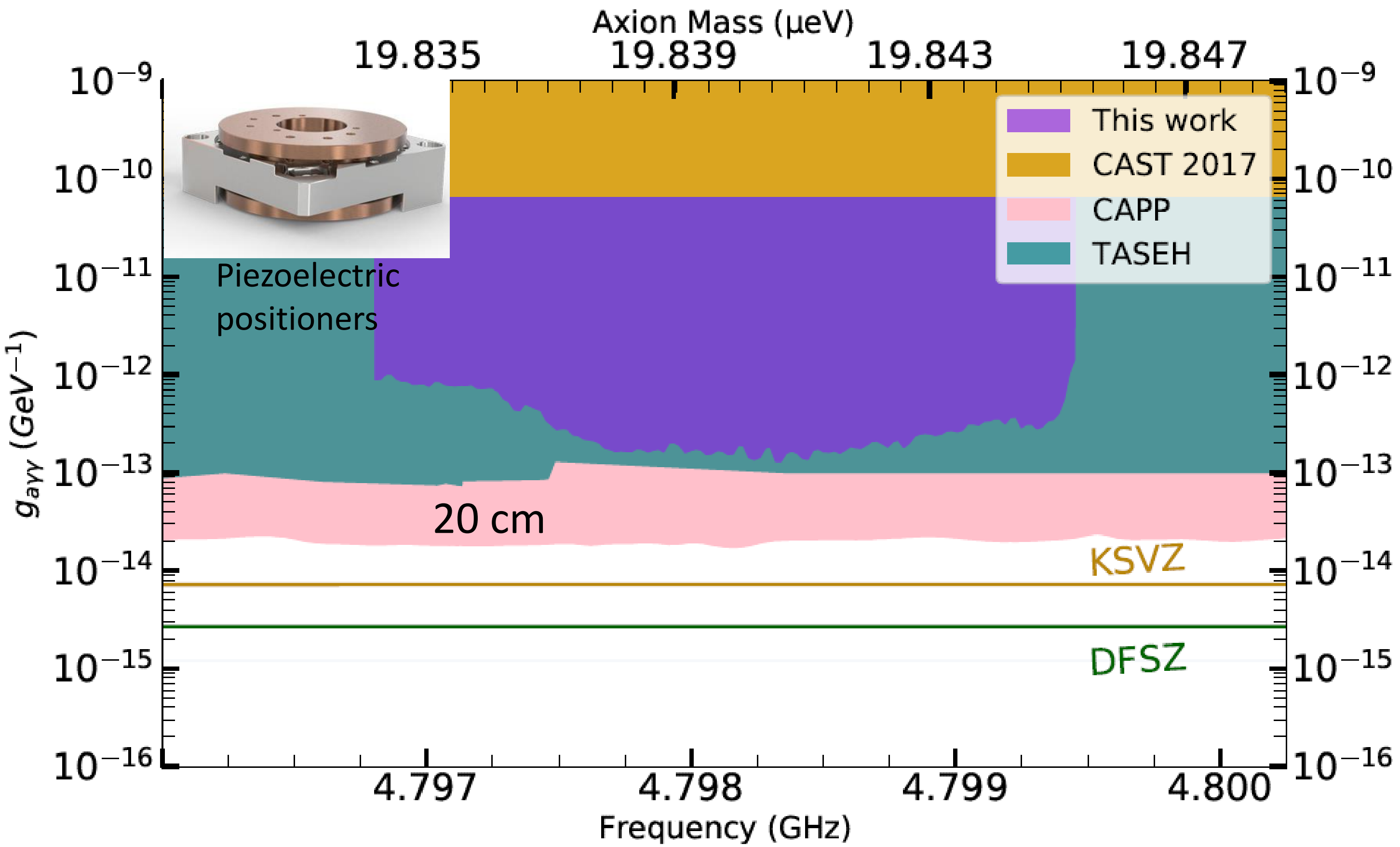
Lower loss materials to improve Q factor

Below SQL noise (?)

ADMX Sidecar: High Frequency Testbed

- Higher frequency cavity mounted above the main cavity
  - Testbed for new resonator designs and technology
- Sidecar is also an axion search!

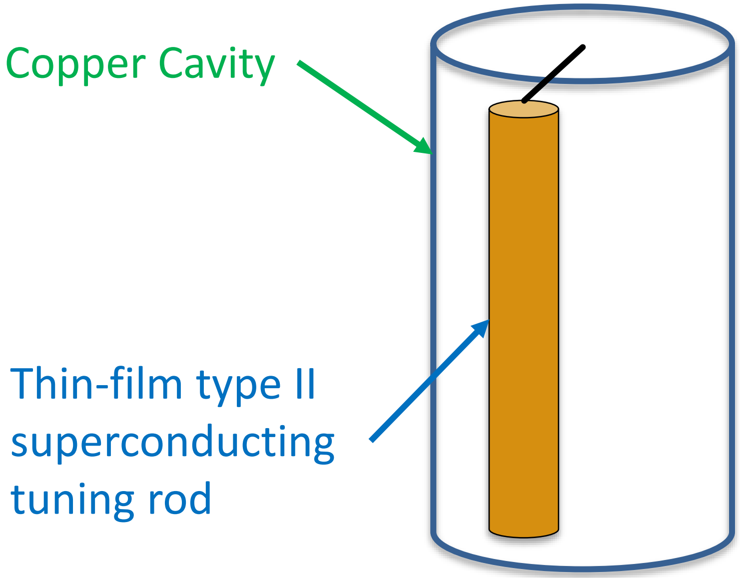


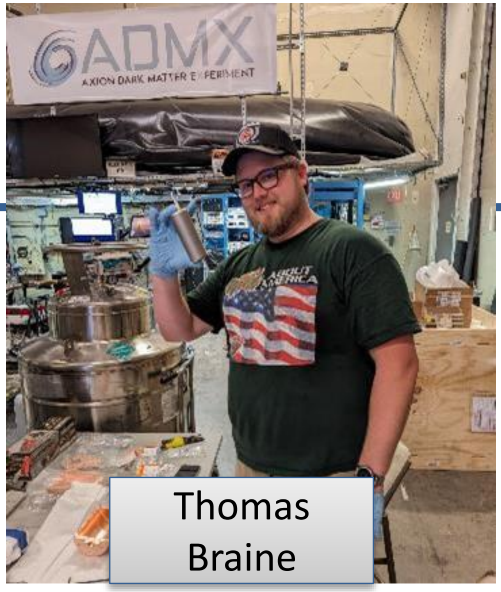


Bartram et. al., Rev. Sci. Instrum. 94. 044703 (2023)

ADMX Sidecar: Hybrid Superconducting Cavities

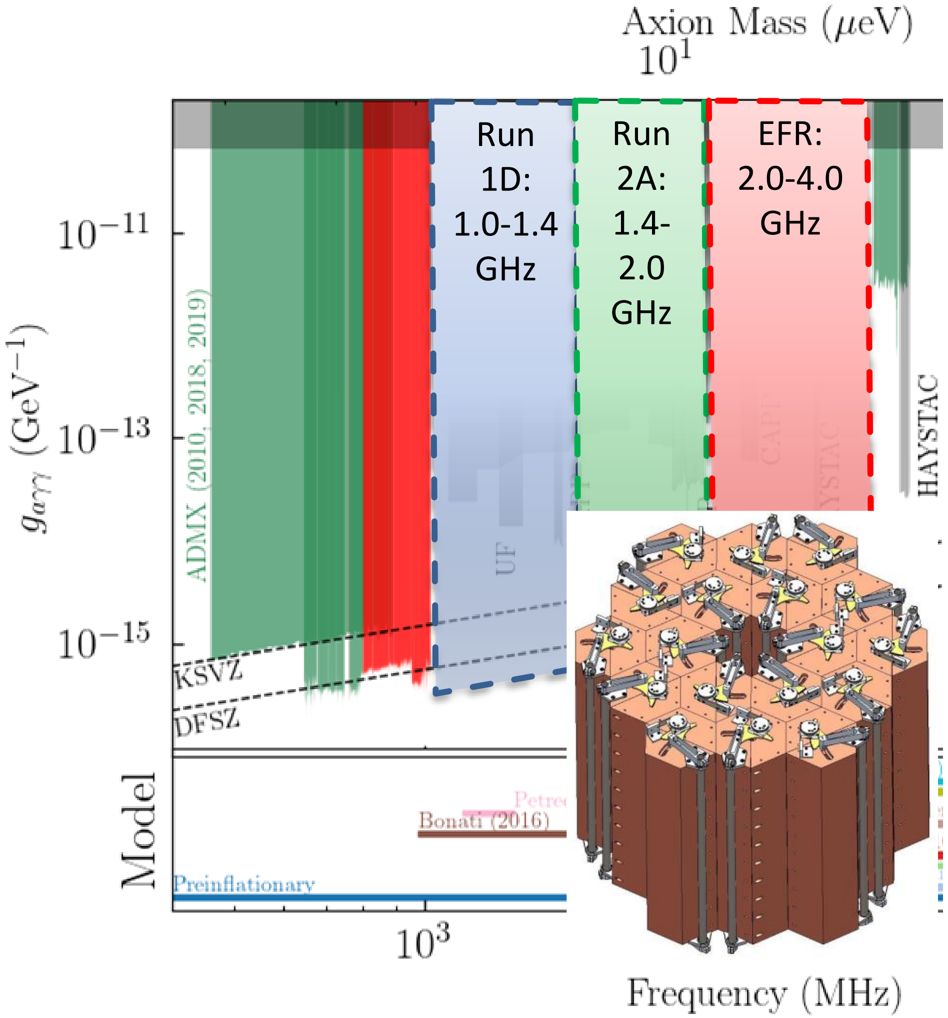
- Hybrid cavity will utilize superconducting tuning rod with copper cavity
  - Superconducting tuning rod will reduce signal losses from tuning rod
  - Expecting a 30% increase in quality factor
- Using Nb_3Sn thin-film super conductor
  - Demonstrated to maintain superconductivity in high magnetic fields
  - Provided by S. Posen at FNAL

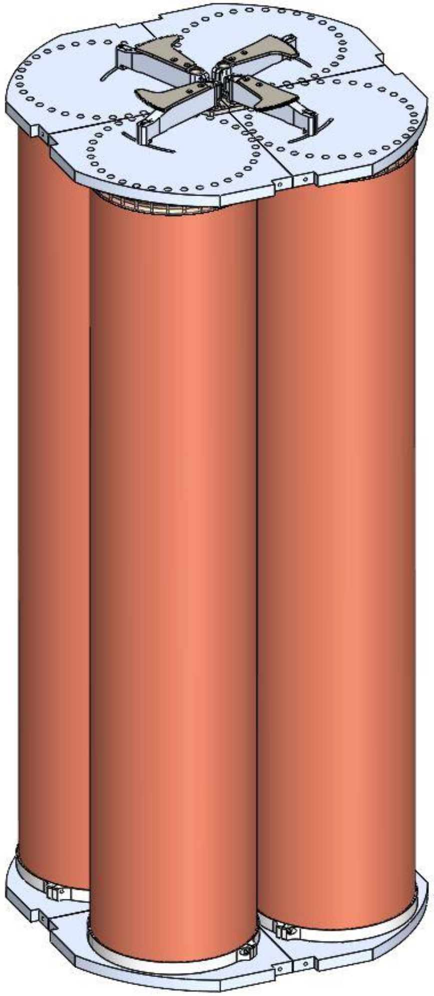




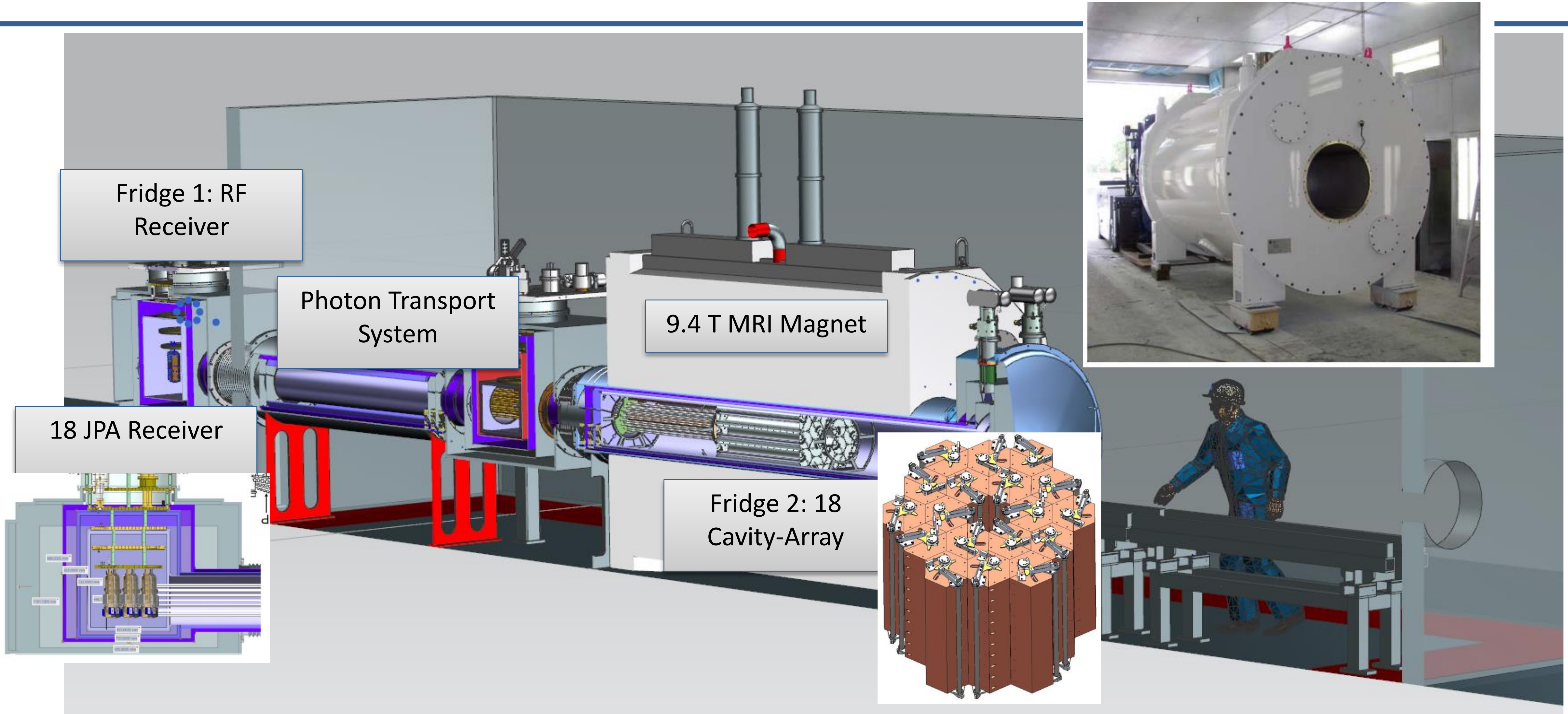
ADMX 2A: Multi-Cavity Searches

- Multiple cavities combined in a phase-matched method scan scale the SNR of an axion by the number of cavities
- Run 2A: 1.4-2 GHz
  - Utilize 4 co-tuned cavities
  - Tuning will be done with piezoelectric motors for faster frequency matching
- Extended Frequency Range: 2-4 GHz
  - 18 cell cavity array
  - To be run in 9.4 T MRI magnet at Fermilab



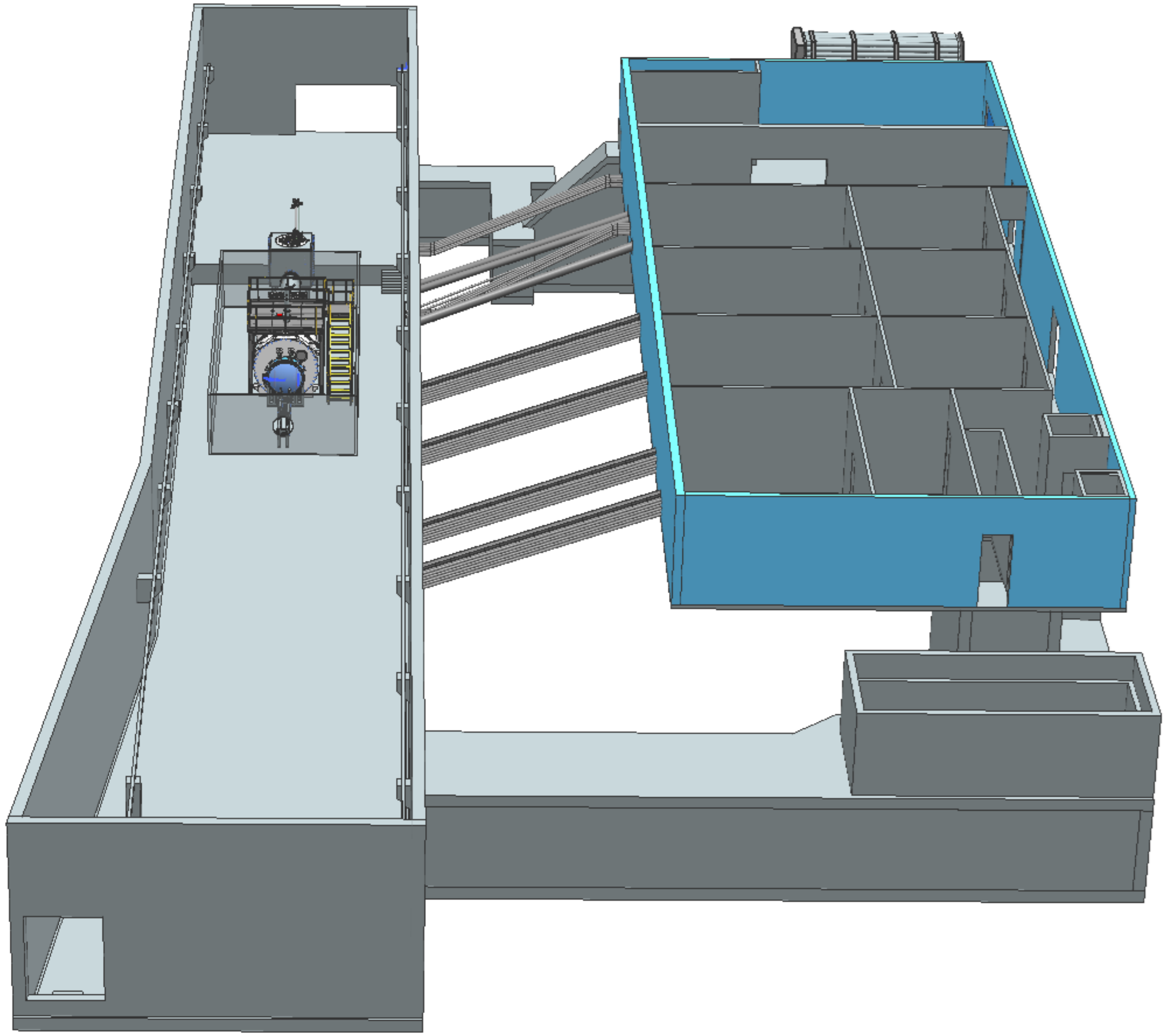


ADMX-EFR: Cryostat Design



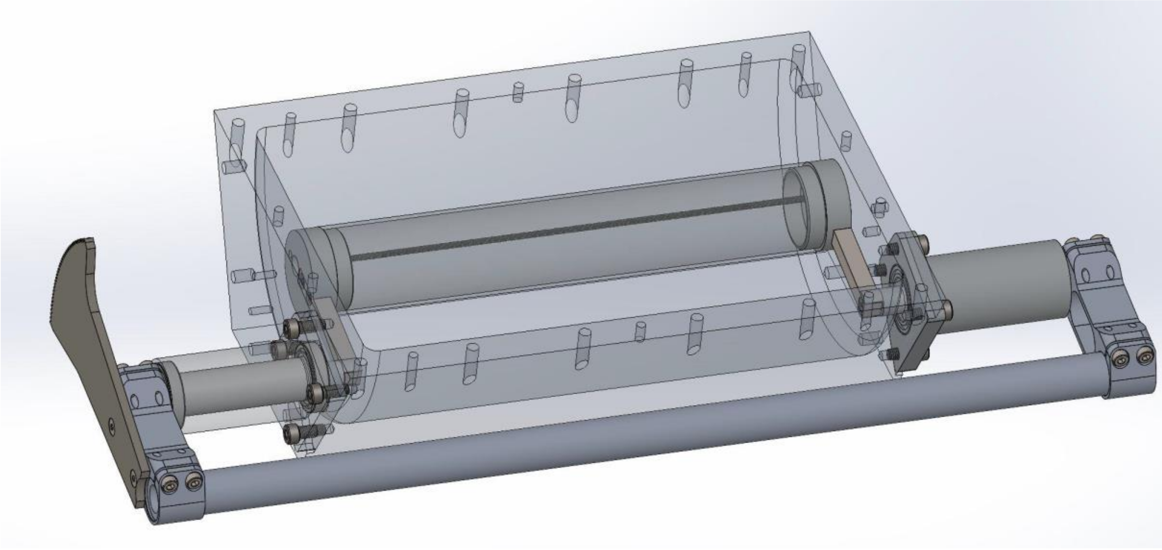
ADMX-EFR: Magnet Installation

- Magnet has been installed at Fermilab
- Currently undergoing diagnostics before it will undergo ramping



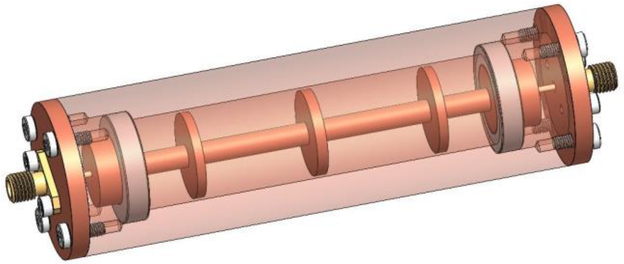
ADMX-EFR Cavity Prototype

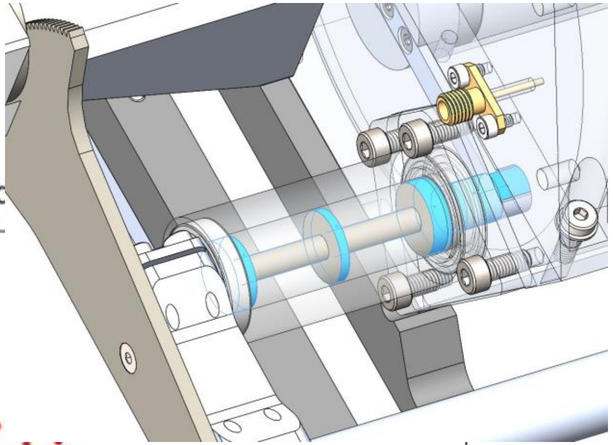
- ADMX EFR will consist of an array of 18-cavities
  - Cavities are 1 m long, 128 mm diameter
  - Cavities will be horizontally mounted inside the magnet
    - Tuning rod armature acts as a counterweight for the tuning rod
- Different diameter tuning rods will change the frequency range
  - 32 mm rods: 2.0-3.1 GHz
  - 54 mm rods: 3.1-3.9 GHz

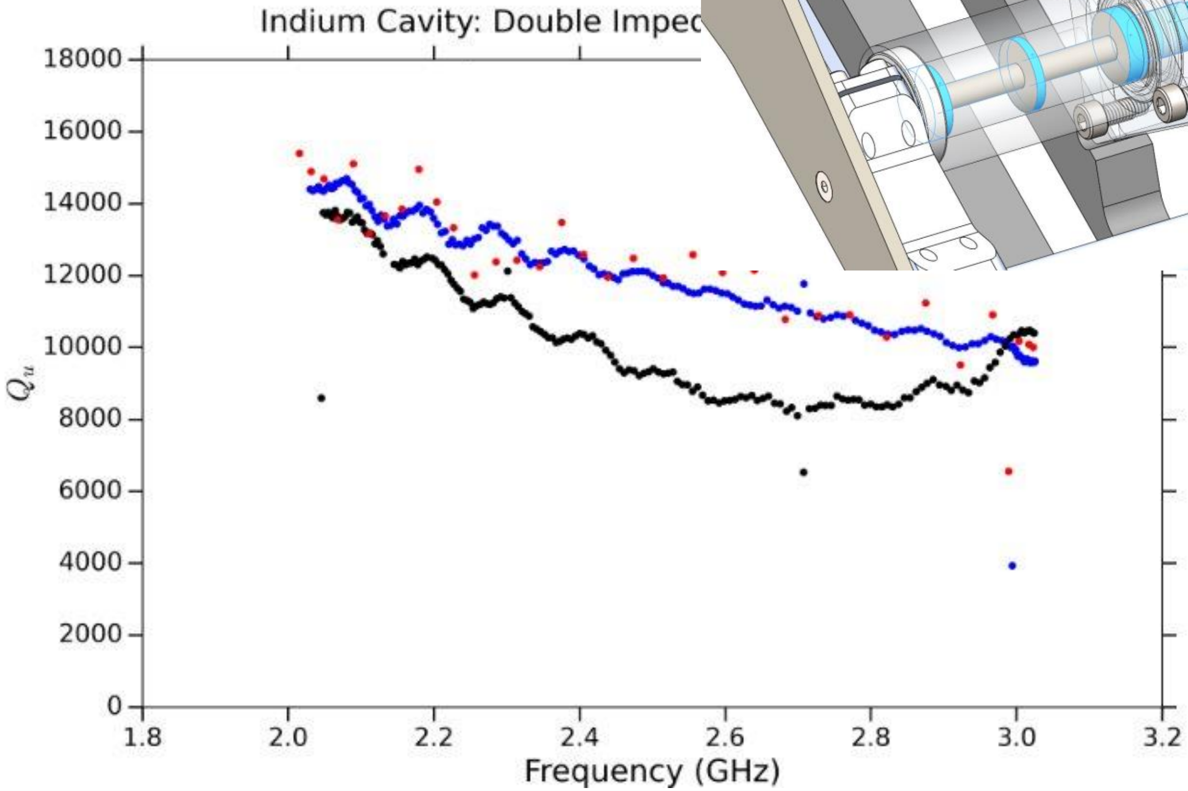


ADMX-EFR Tuning Impedance Filter

- Stepped impedance filter on the axles of tuning rods prevent coupling of power out of cavity by tuning rod axles
  - Enables fabrication of metal tuning rod axles, instead of classical dielectric
    - Easier fabrication
    - Improved thermalization
    - Reduced dielectric losses

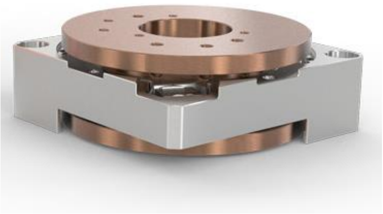


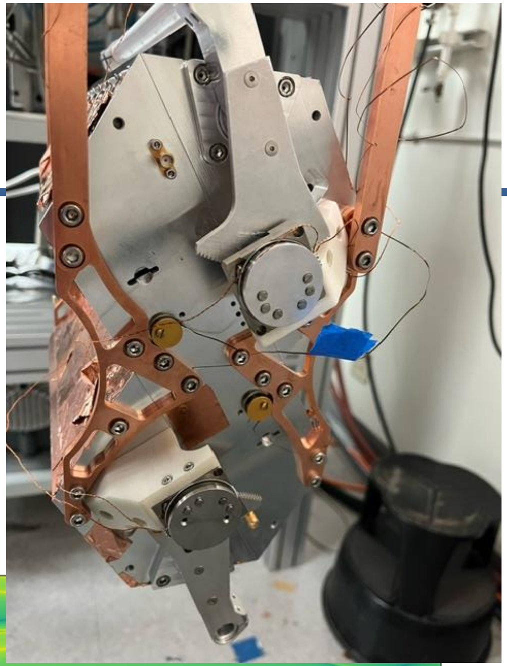


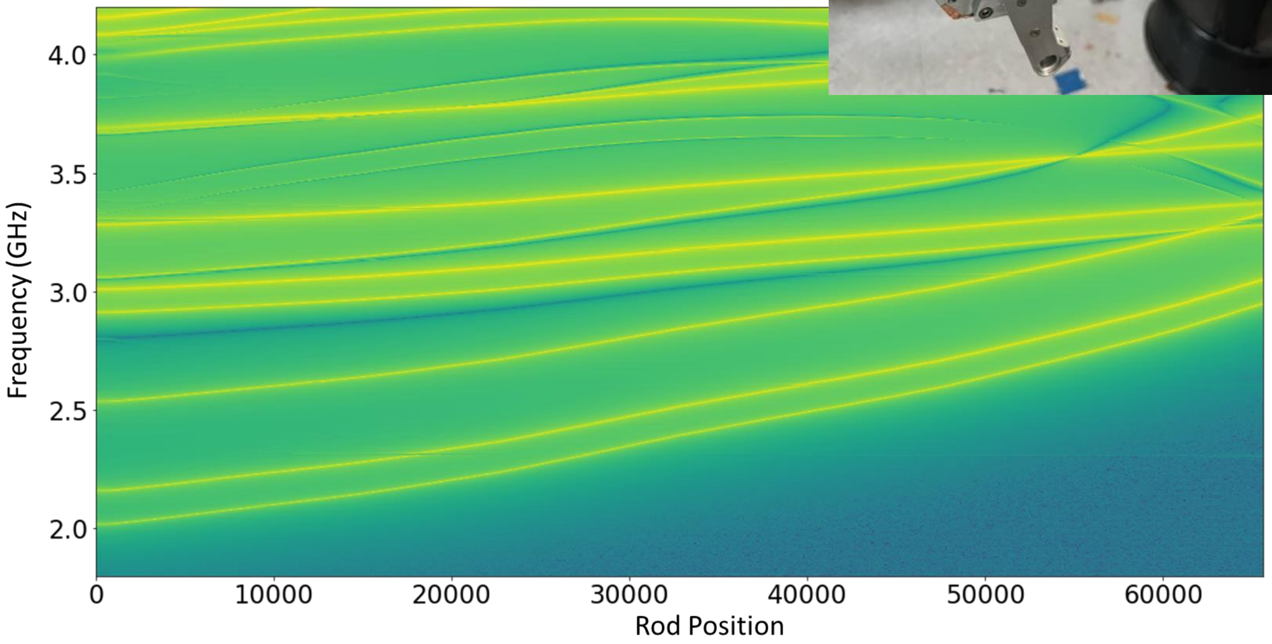


ADMX-EFR: Tuning System

- Each tuning rod is rotated by a rotary piezoelectric motor coupled to the cavity via a gear
  - Angular resolution on the rotary motors is $1\ \mu deg$
- A linear piezoelectric motor will adjust the insertion depth of a dipole antenna to control coupling to the cavity
- We can vary coupling and rod position with fine control

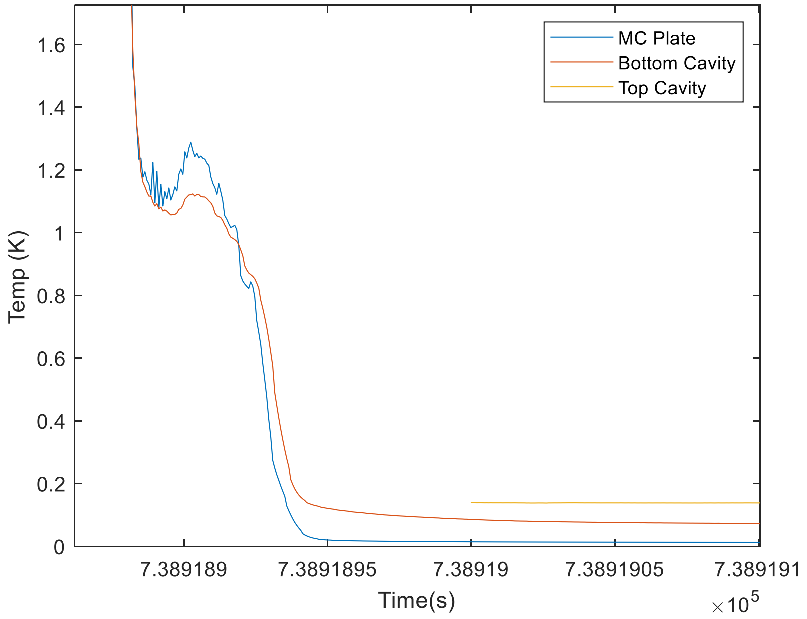


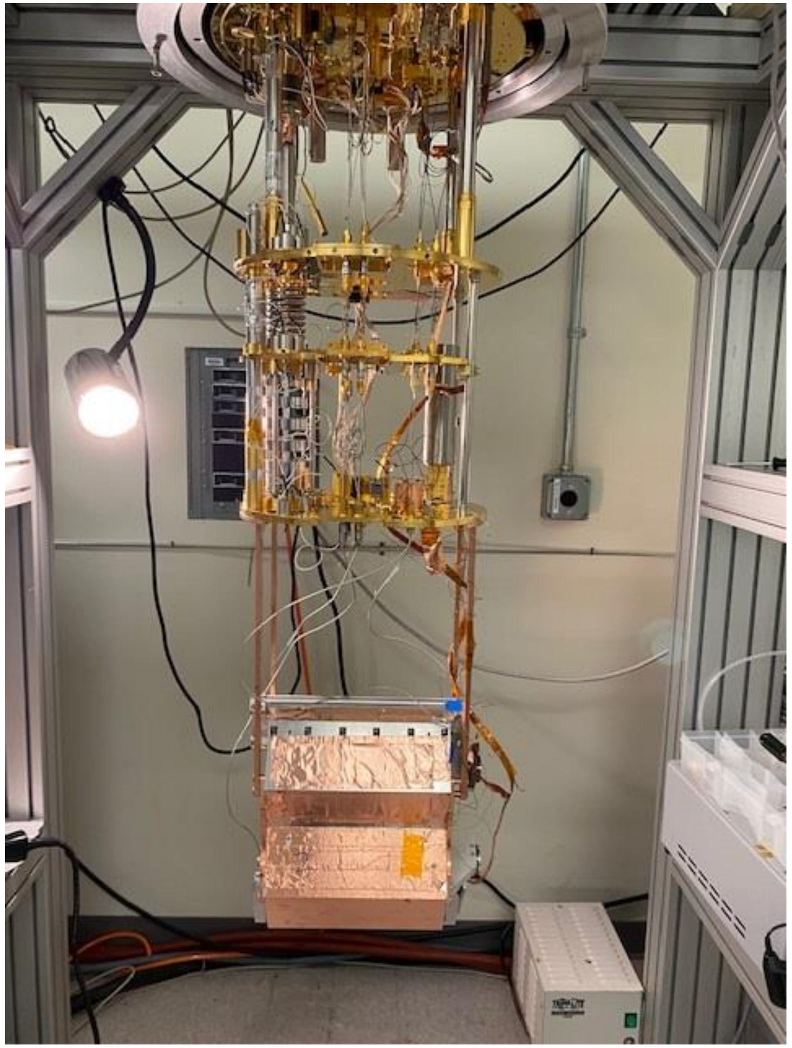




ADMX-EFR: Two-Cavity System Cooldown

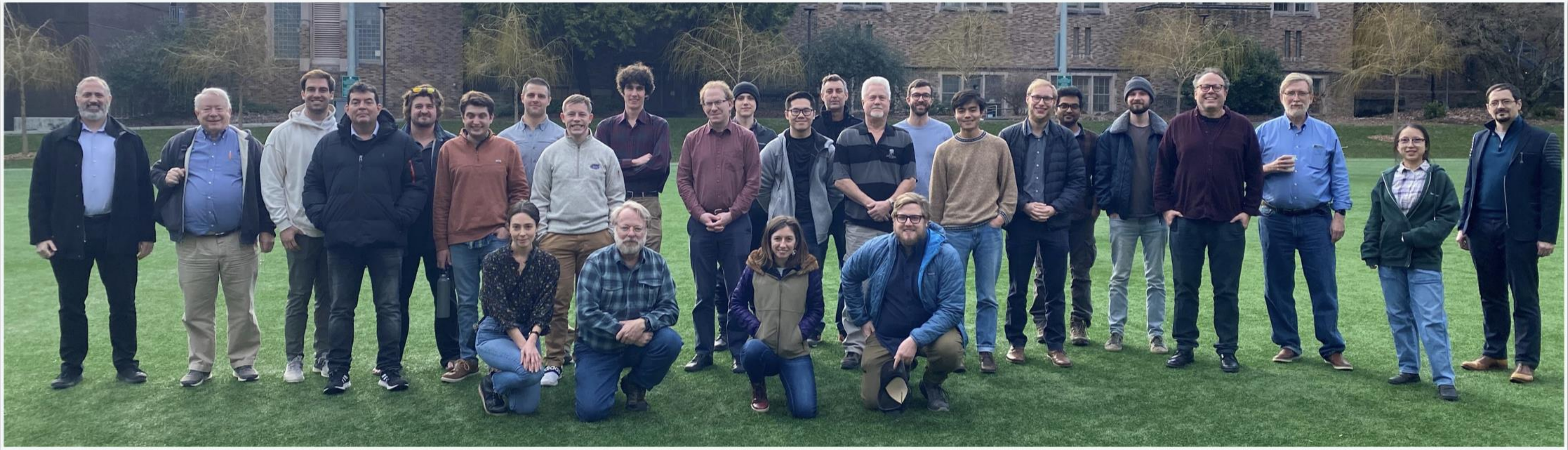
- Cryogenic testing of the EFR prototype is underway at LLNL!
- Cavities were cooled to 100 mK
- Two-cavity testbed has been useful to demonstrate mode-locking and tuning in a cryogenic environment





Summary

- Axion dark matter is exciting field!
- ADMX is currently searching for axion dark matter in the 1.0-1.4 GHz frequency regime
- Multicavity arrays will improve on the sensitivity for higher frequency axion searches



Acknowledgements

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Questions

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