Searching for Axion Dark Matter in the 3.3-4.2 μeV Mass Range with ADMX and Beyond

18th Patras Workshop on Axions, WIMPs, and WISPs

Nick Du
Postdoctoral Scholar

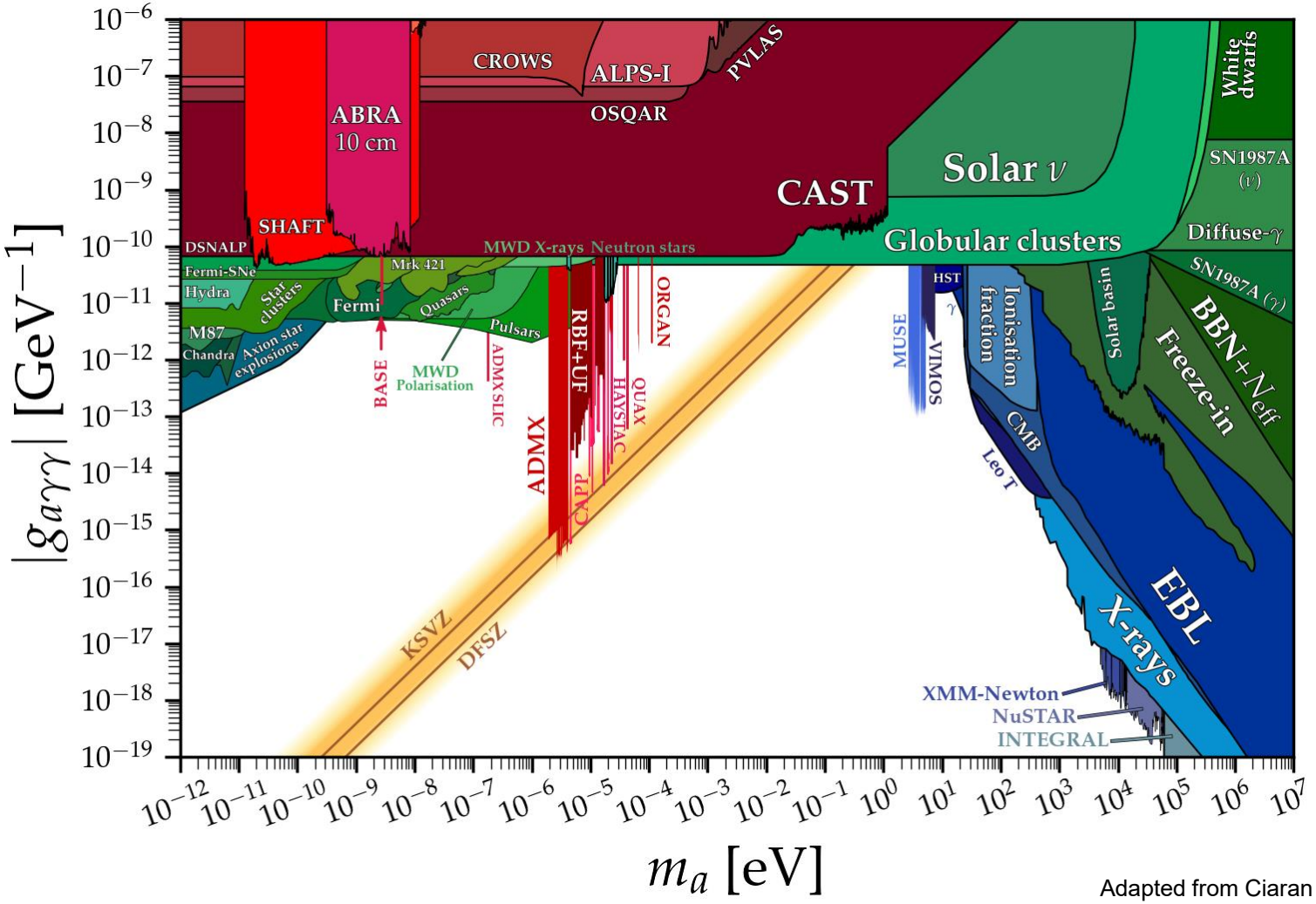
July 4, 2023

LLNL-PRES-1077320
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

Axion Landscape

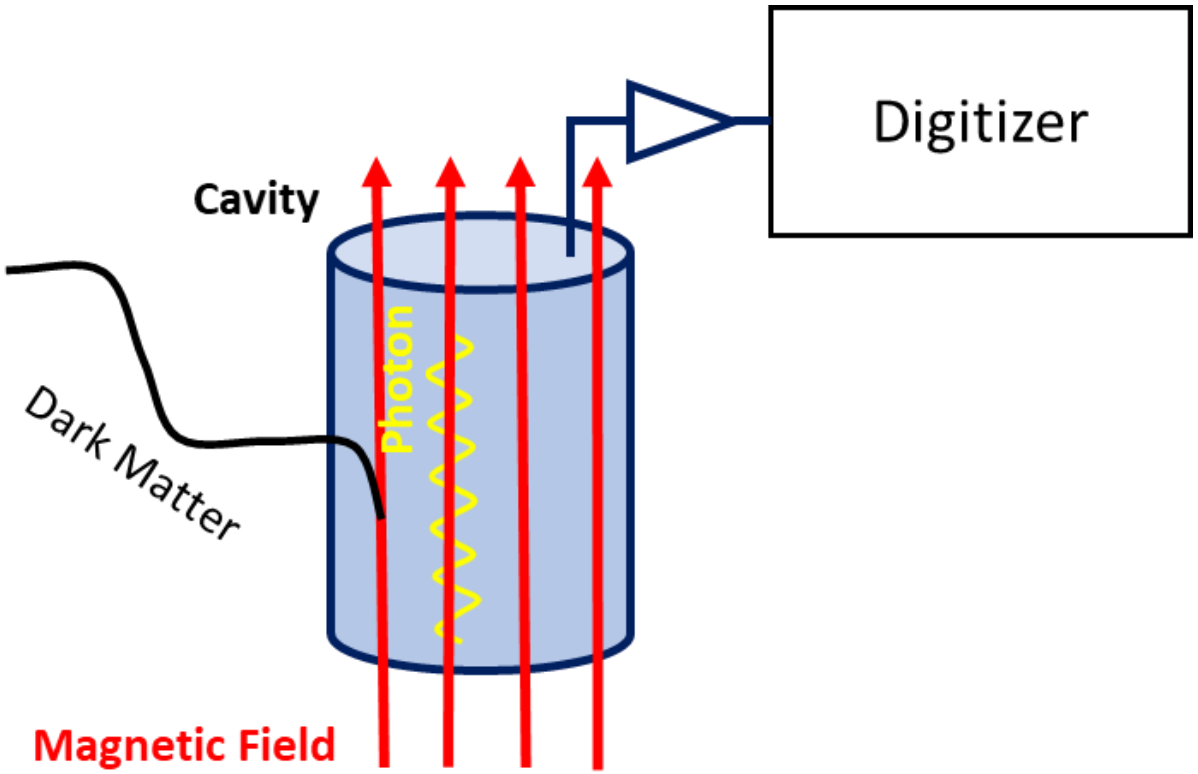
- Axion dark matter is a compelling particle
- Still lots of space to explore for the QCD axion
- An axion dark matter discovery would be very exciting!



Adapted from Ciaran O'Hare

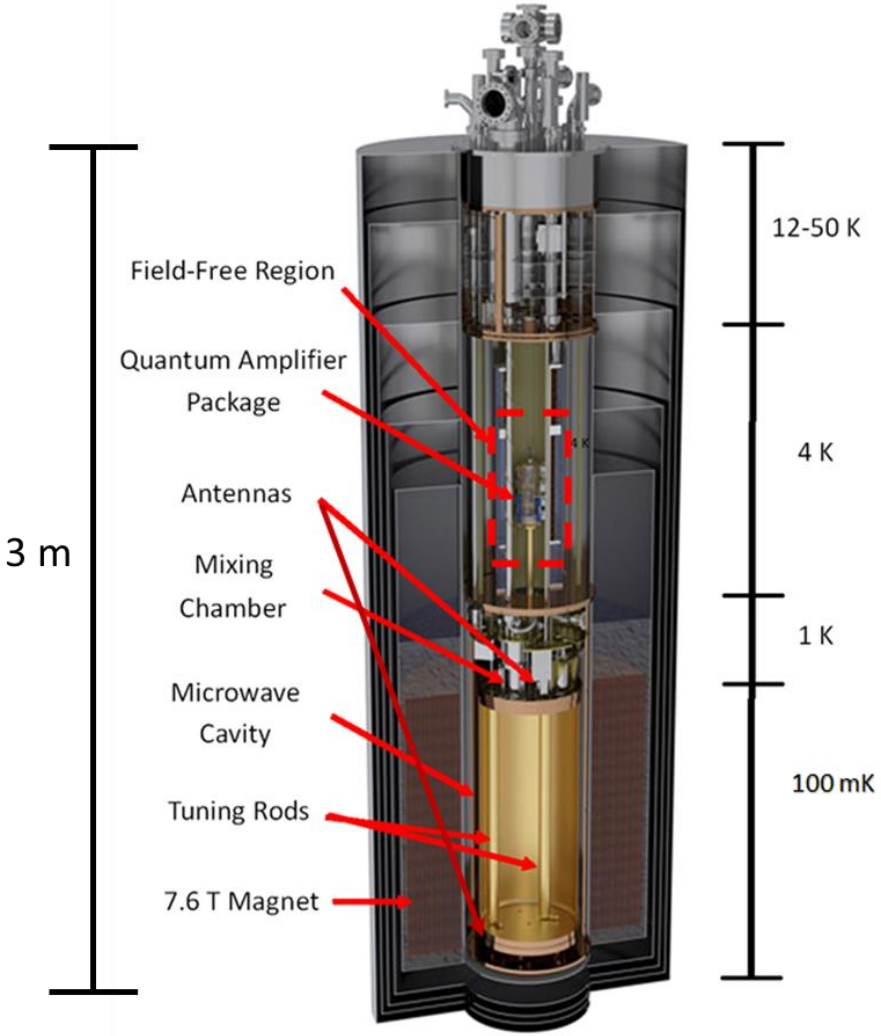
Axion Haloscopes

- P. Sikivie's axion haloscope probe for axion dark matter in the local Milky Way halo
  - Axion dark matter couples off static magnetic field to produce microwave photons
  - Conversion is enhanced when resonant cavity is tuned to the same frequency as the photon
- Signal is picked up by antenna, amplified by a low-noise receiver, then sampled



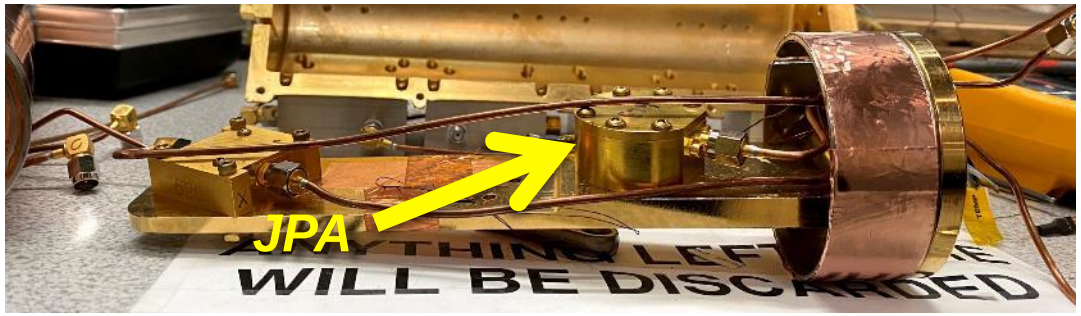
Axion Dark Matter Experiment (ADMX)

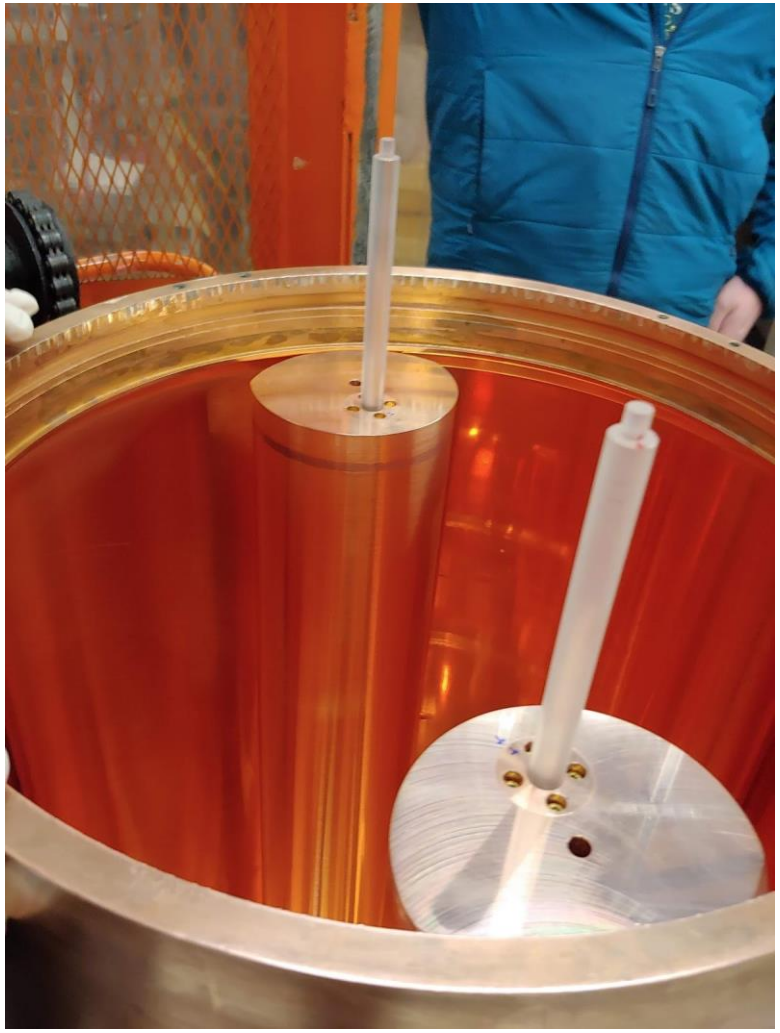
- First haloscope to reach DFSZ
- Sited at the University of Washington
- ~50 collaborators



ADMX Run 1C-Extended

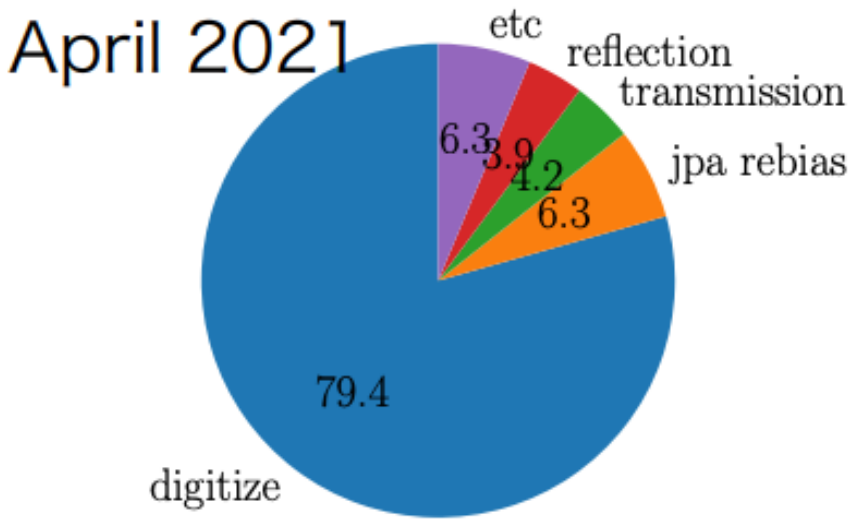
- Data run from June 2021-Dec 2022
  - Rescan previously explored range to DFSZ
  - Tuning problems restricted tuning range to 943-950 MHz
- Run Parameters
  - $T_{cav} = 100\ mK$
  - $Q_0 \approx 160{,}000$



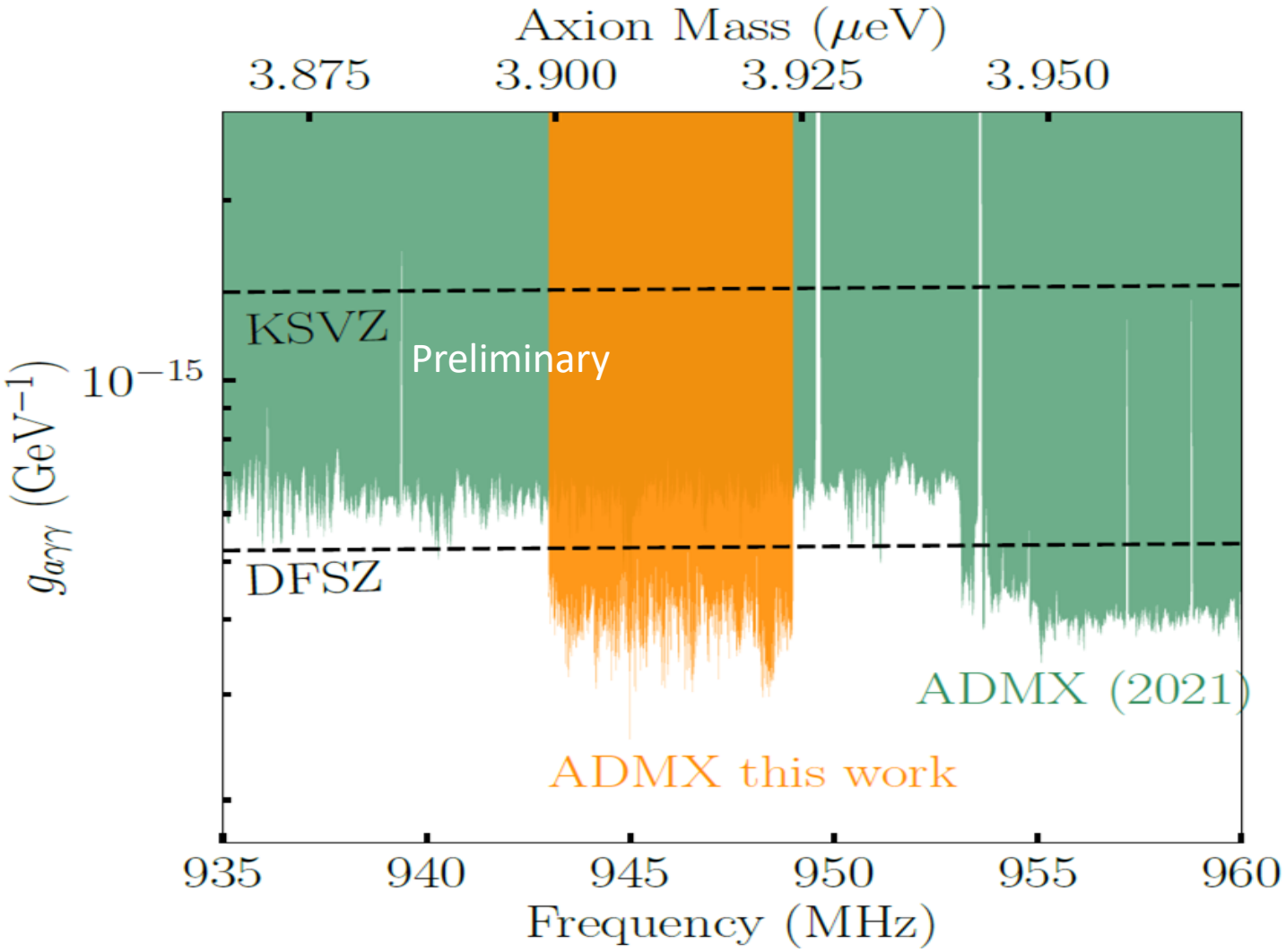


Data Taking Run with ADMX

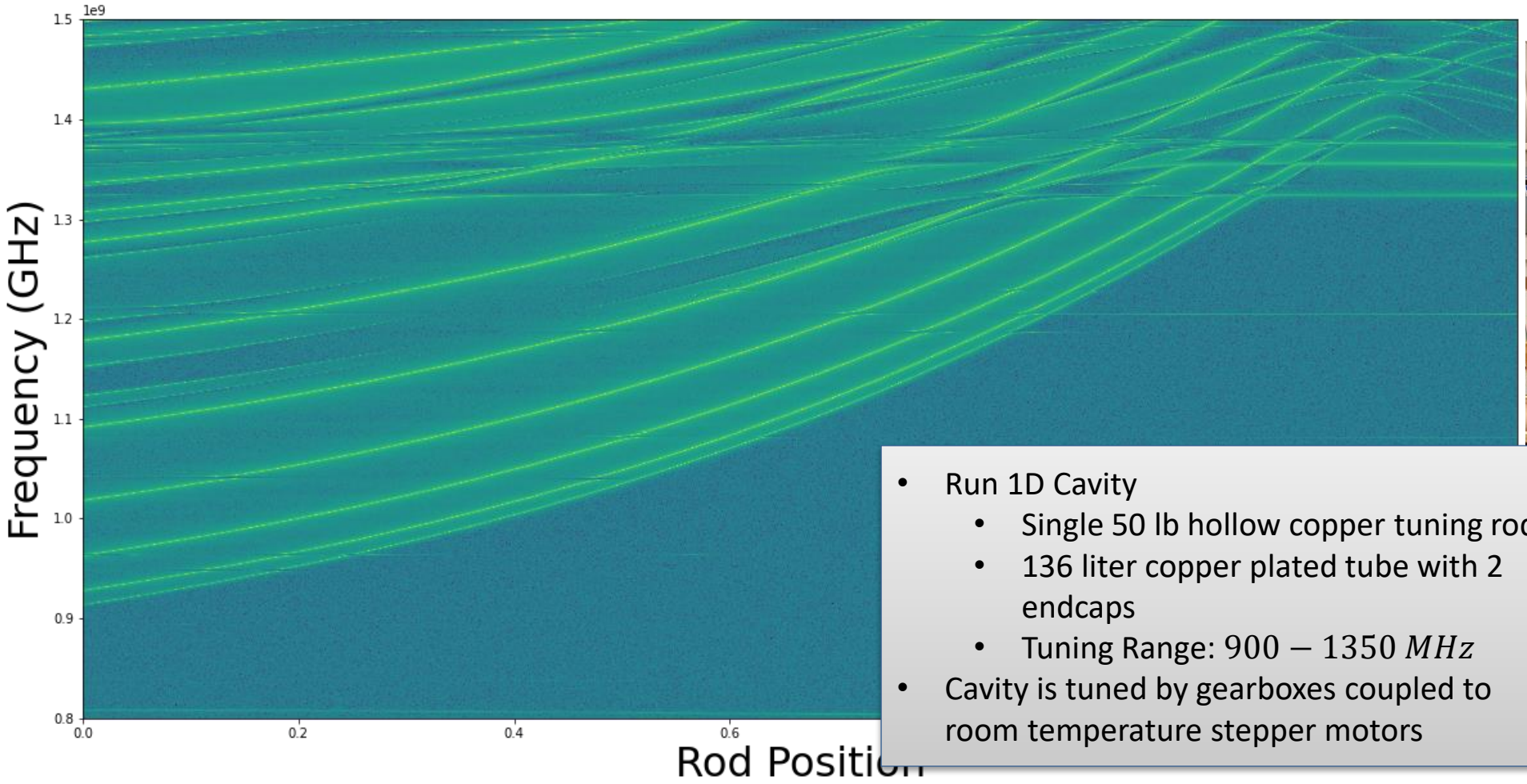
- Data taking operations are controlled by an automated script
- Cavity is tuned every ~100 seconds
  - Signal from cavity is sampled for 100 seconds

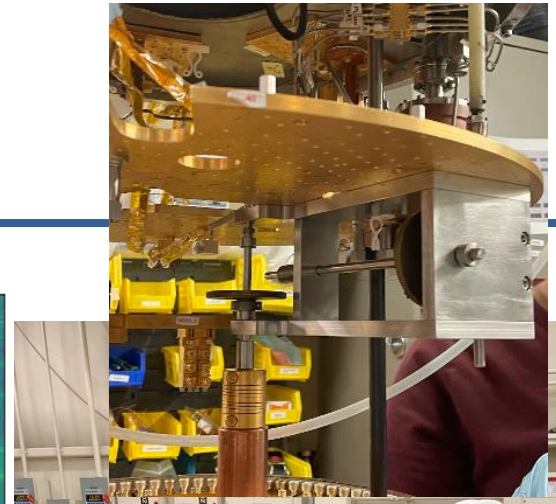


Results: Limits on Axion-to-Photon Coupling



Preparations for Run 1D: Cavity

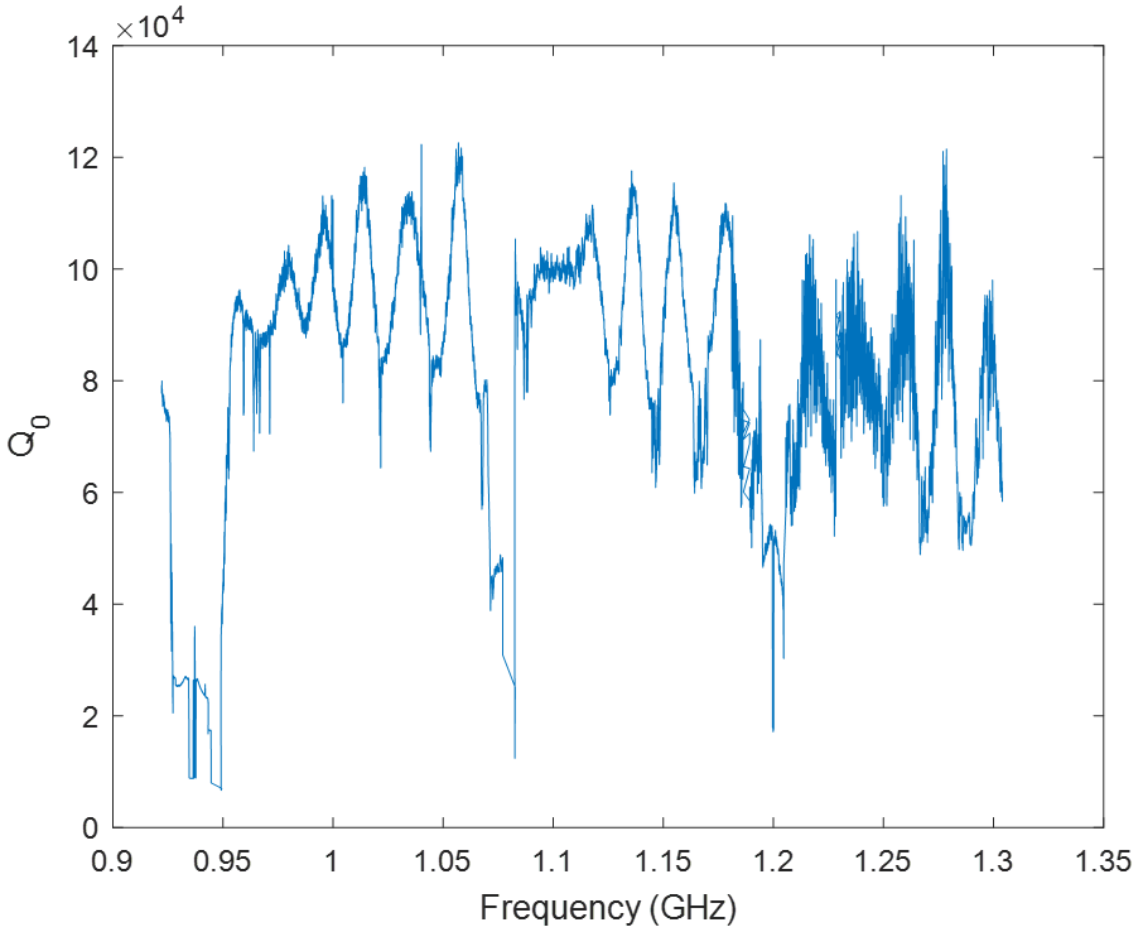




- Run 1D Cavity
  - Single 50 lb hollow copper tuning rod
  - 136 liter copper plated tube with 2 endcaps
  - Tuning Range: $900 - 1350\ MHz$
- Cavity is tuned by gearboxes coupled to room temperature stepper motors

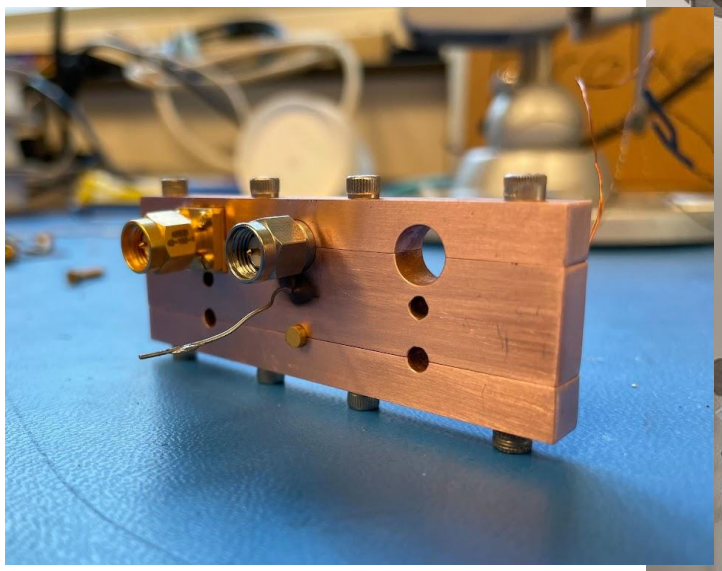
Preparations for Run 1D: Cryogenic Cavity Tests

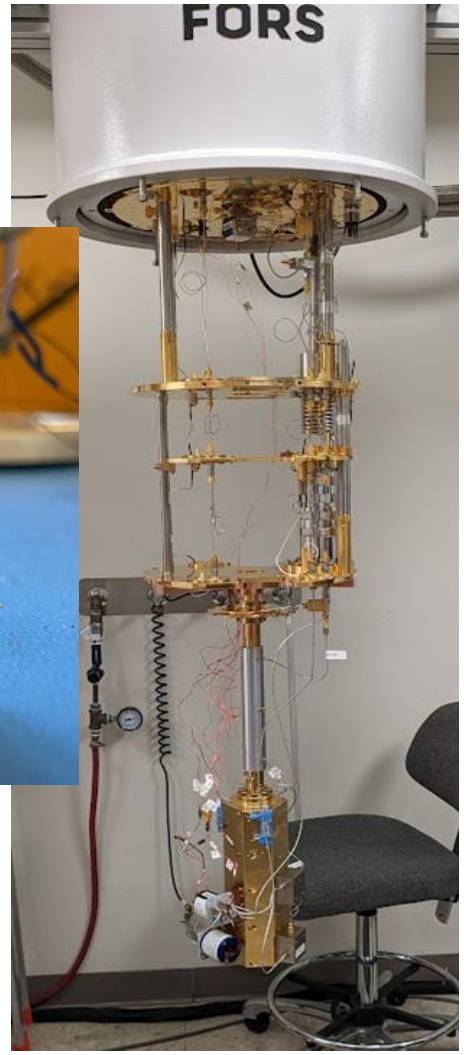
- System was installed in Fermilab 4K cryogenic test stand
- Tuning system operated successfully of 4K
- Cavity Q_0: $80{,}000 - 100{,}000$



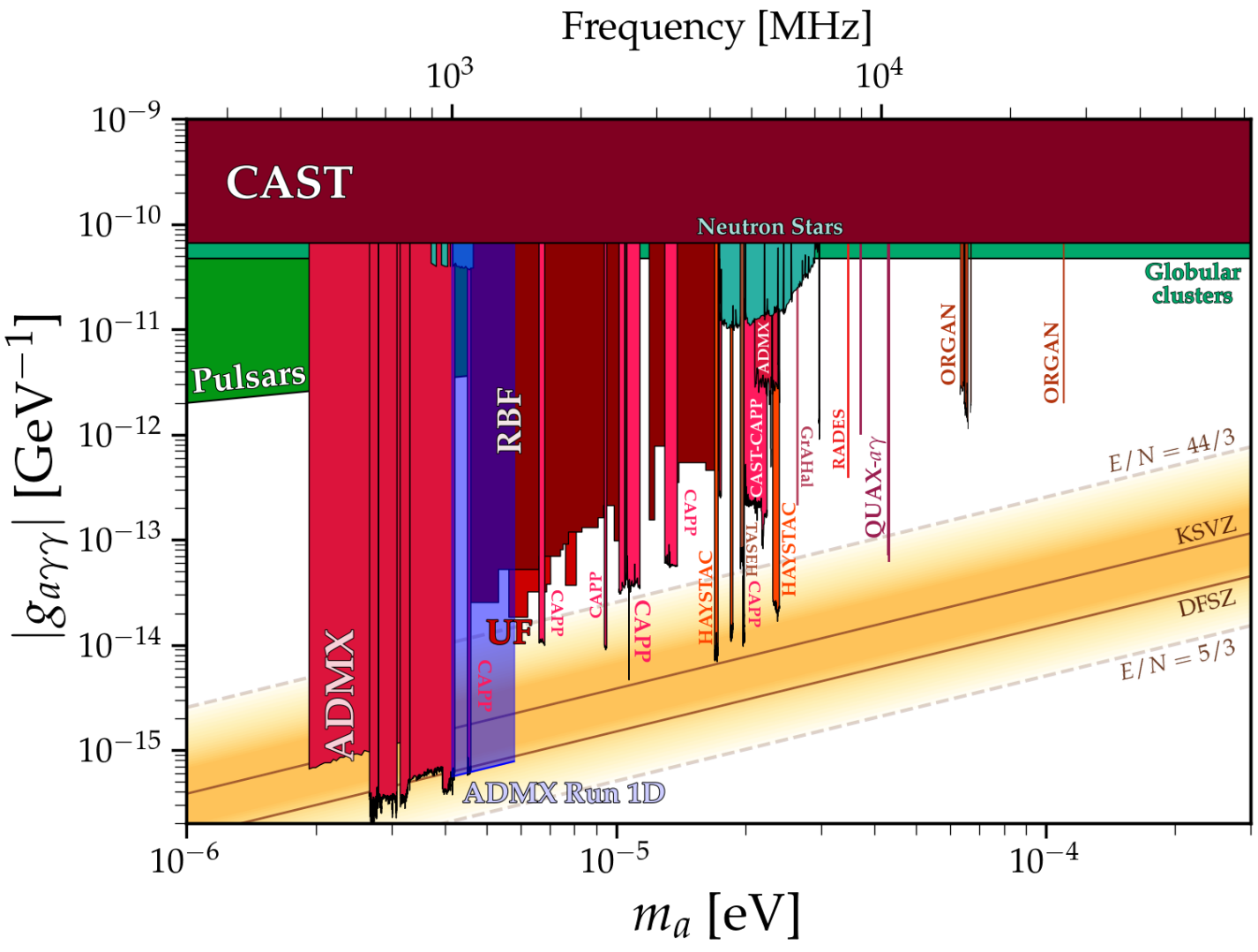
Preparations for Run 1D: Cryogenic Electronics

- Cryogenic receiver tested at Washington University
- Run 1D: Current-pumped JPA
  - >25 dB gain at 1.35 GHz w/ 18 dB SNRI
  - ~15 dB gain at 980 MHz with 12 dB SNRI
- New hot load operable between 100-400mK for Y-factor calibration of JPA
- Flux-pumped JPAs are in development for future runs





ADMX Run 1D: Installation



Data taking to begin summer 2023!

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.)

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

Stronger magnets

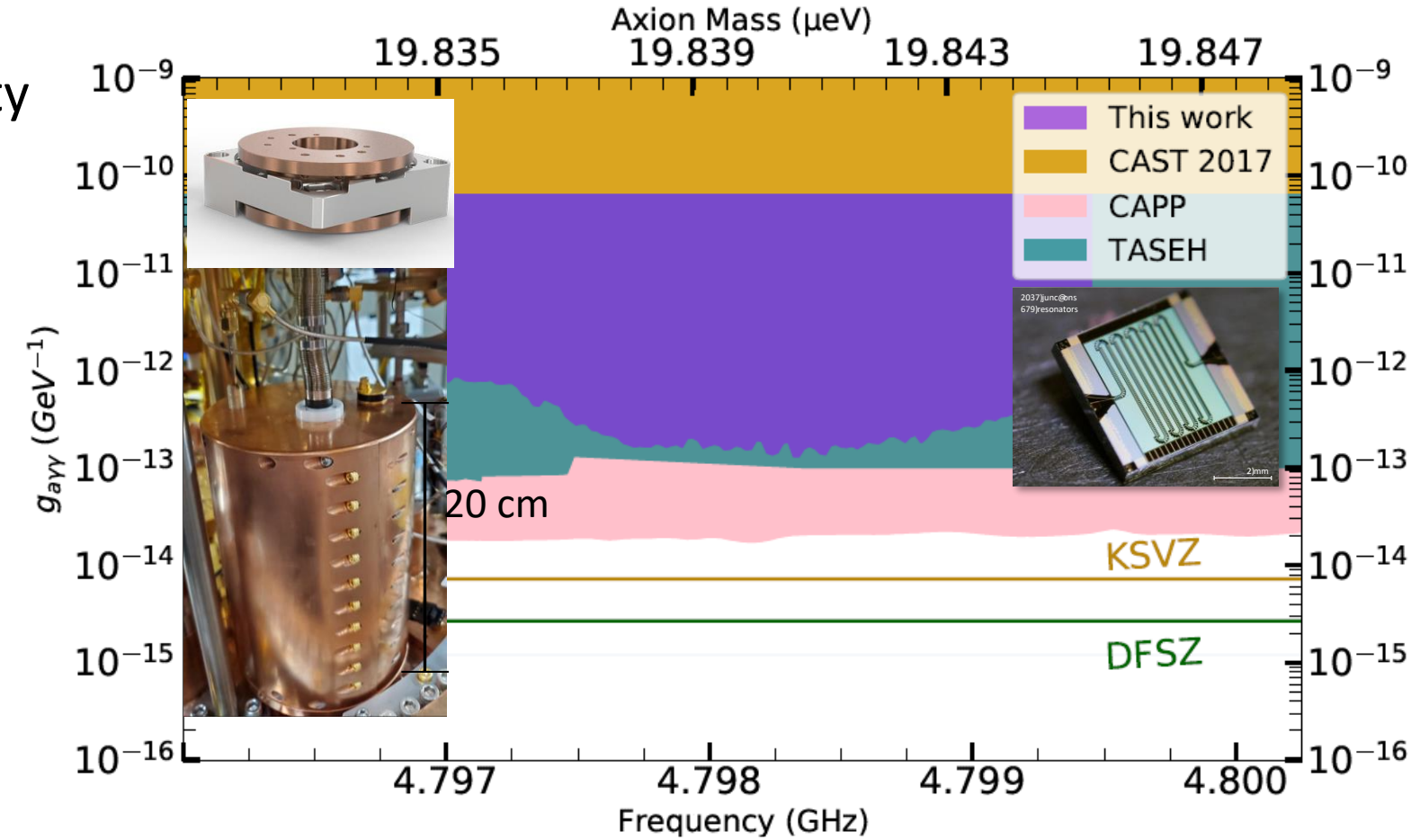
Larger cavities to maintain volume

Lower loss materials to improve Q factor

Below SQL noise (?)

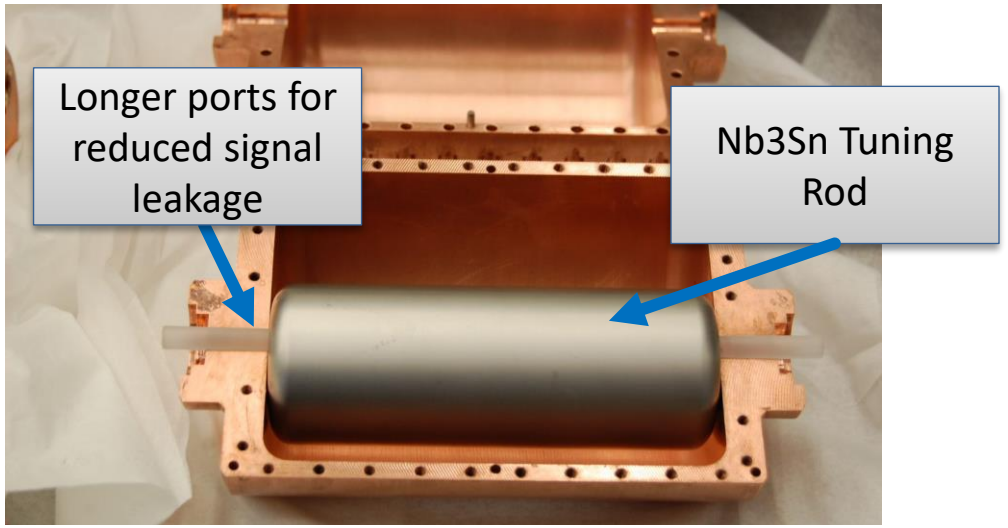
ADMX Sidecar

- Higher frequency cavity mounted above the main cavity
  - Testbed for higher frequency resonator designs
- Research into
  - Piezo-electric based tuning systems
    - Fine control over tuning
  - Josephson Traveling Wave Parametric Amplifiers (JTWPA)
    - Broadband low noise amplification

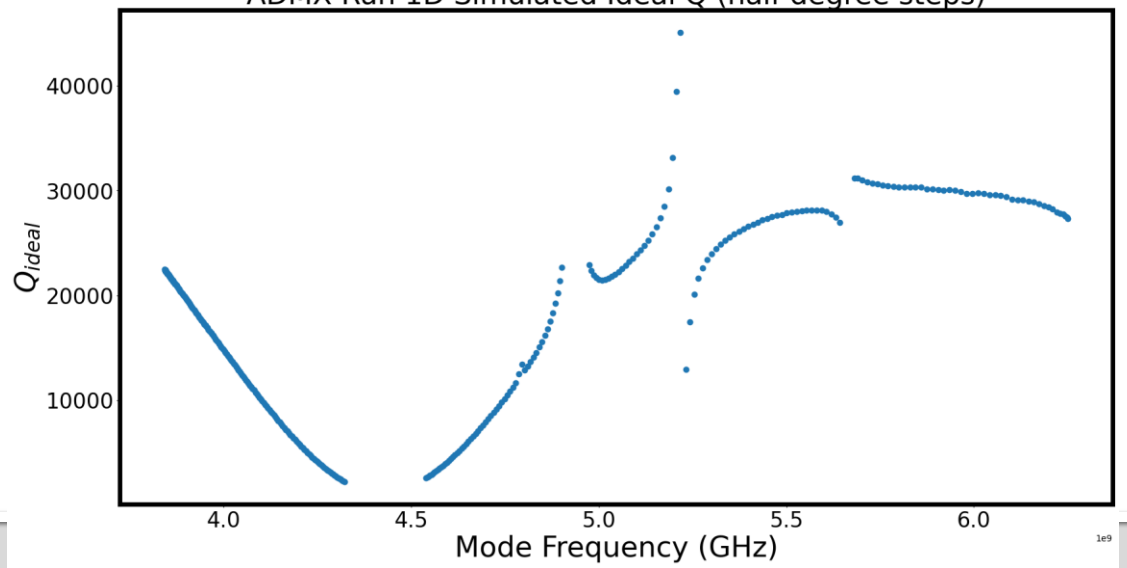


ADMX Sidecar: Upgrades

- Nb3Sn tuning rod fabricated by SQMS center
- Copper cavity fabricated by University of Sheffield
- Repaired broken 2nd stage amplifier
  - Broken FET in previous run caused a high system noise temperature

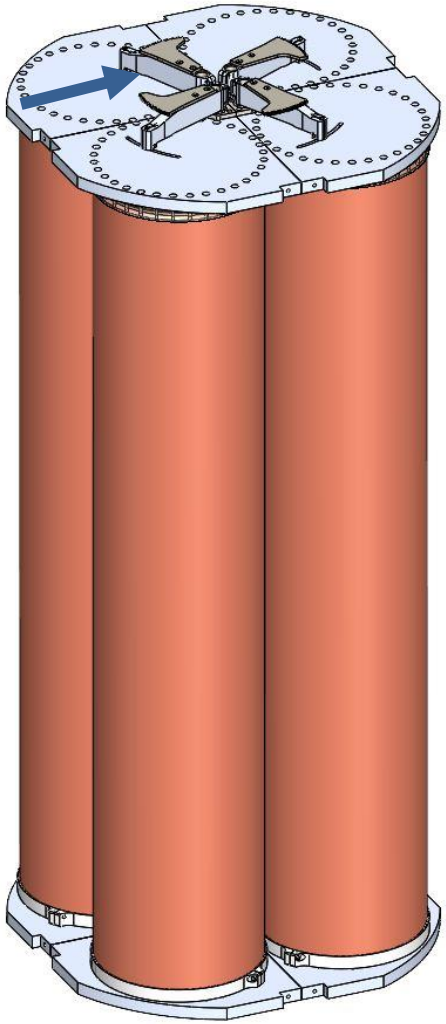


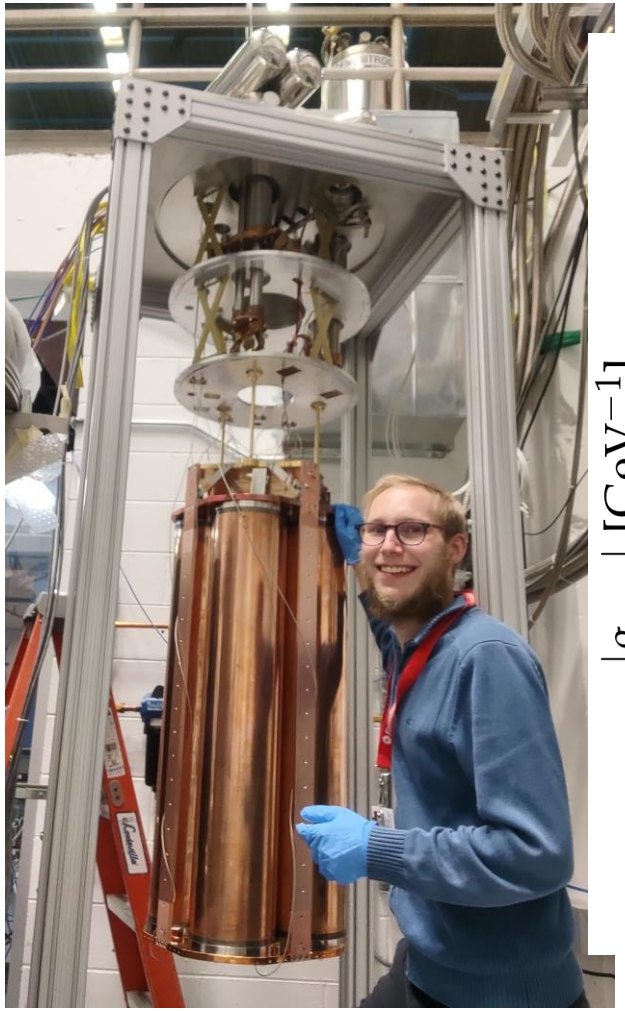
ADMX Run 1D Simulated Ideal Q (half degree steps)

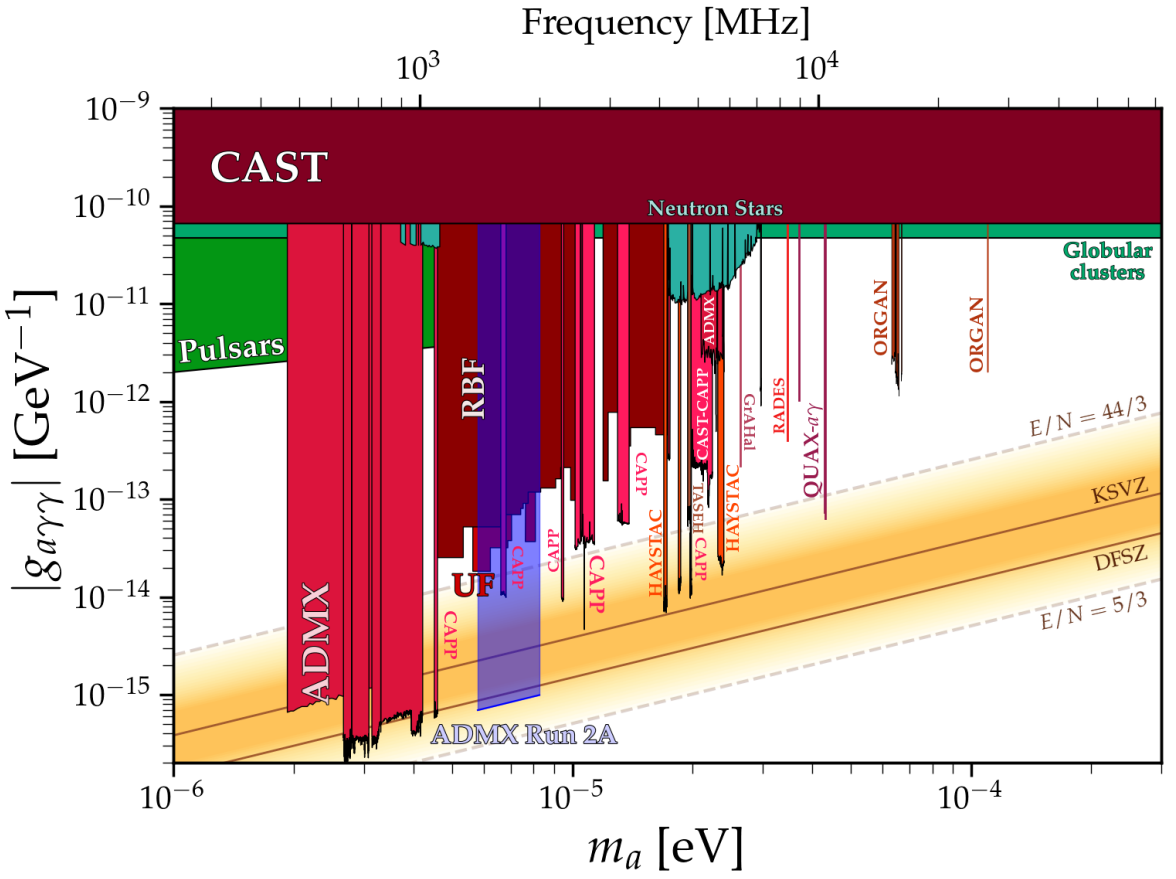


ADMX Run 2A: 4-Cavity Array (1.4-2 GHz)

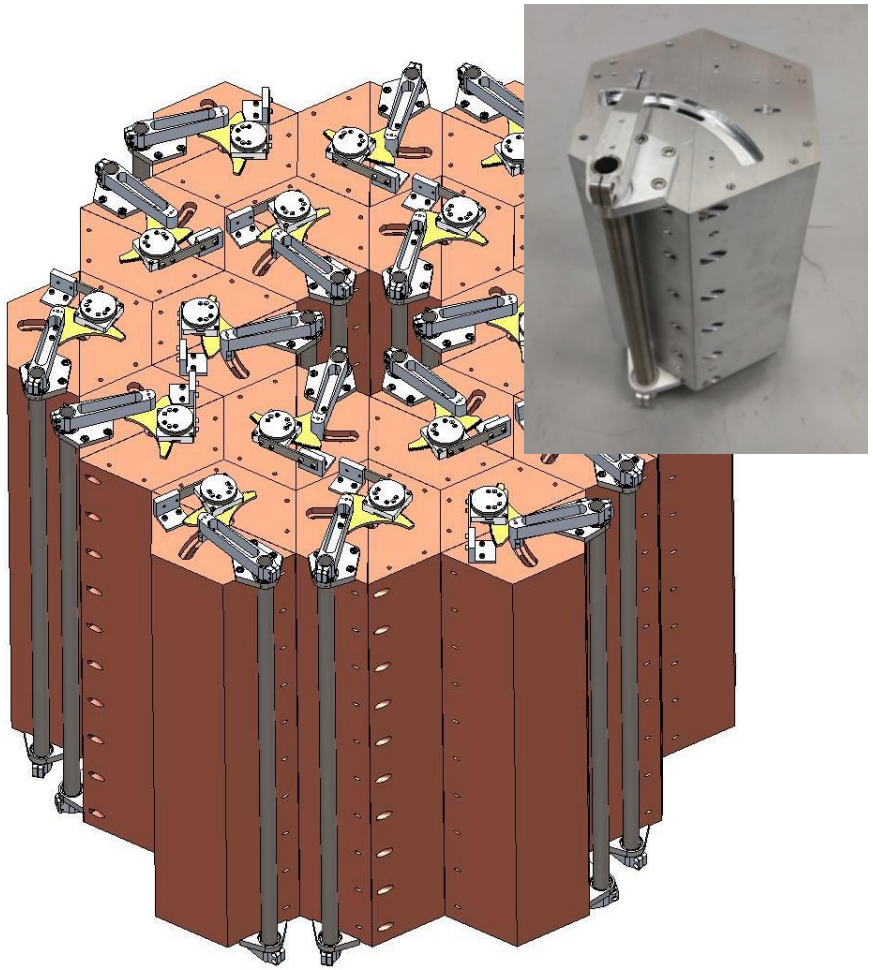
4 individual cavities tuned by rotors



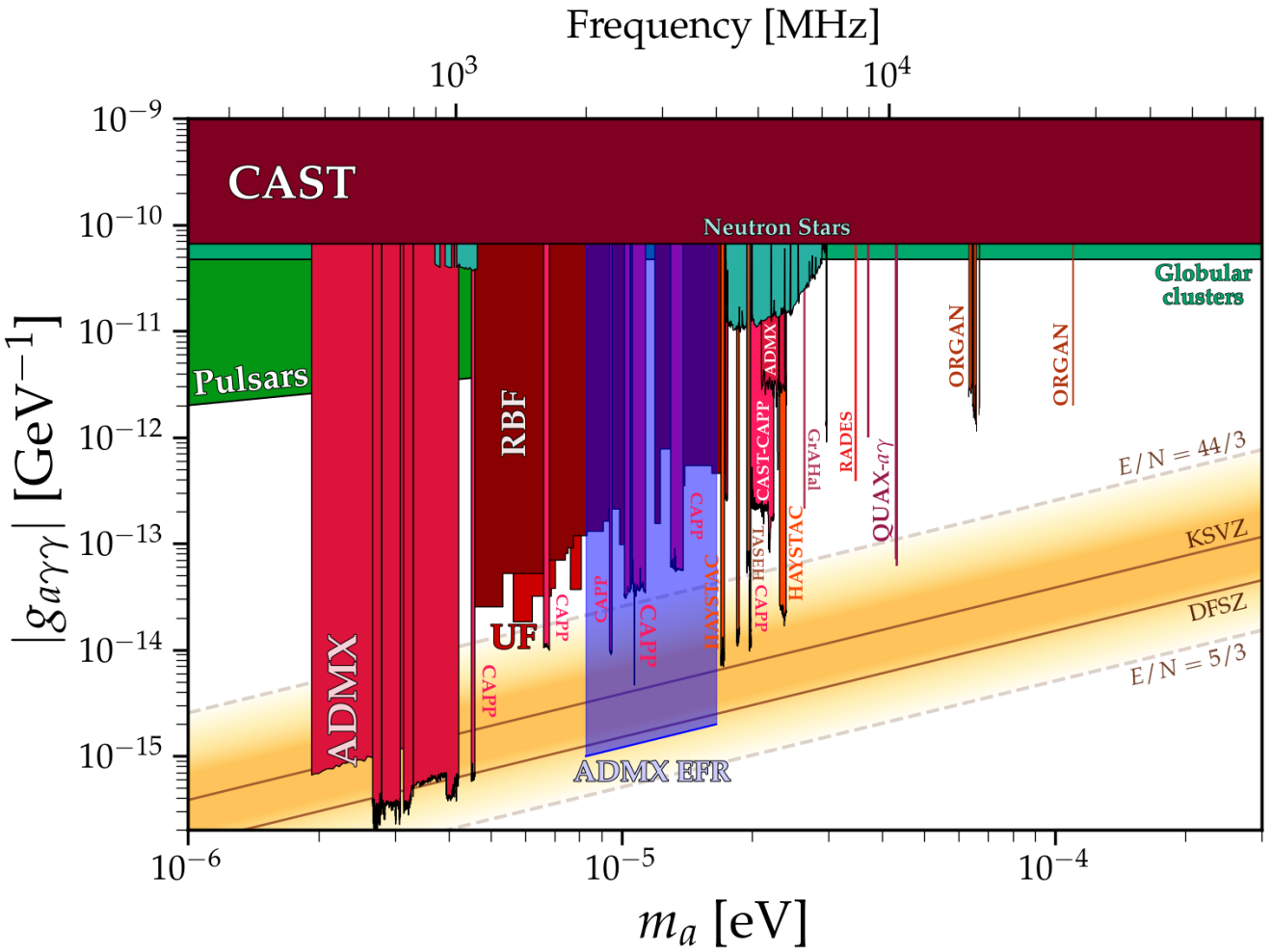




ADMX Extended Frequency Range (EFR): 2-4 GHz

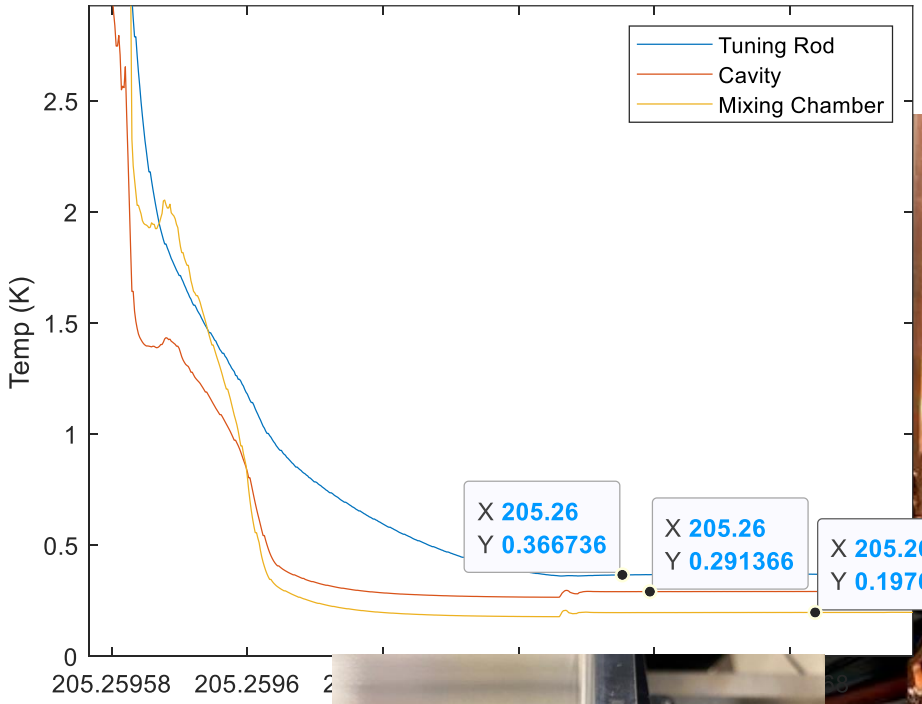


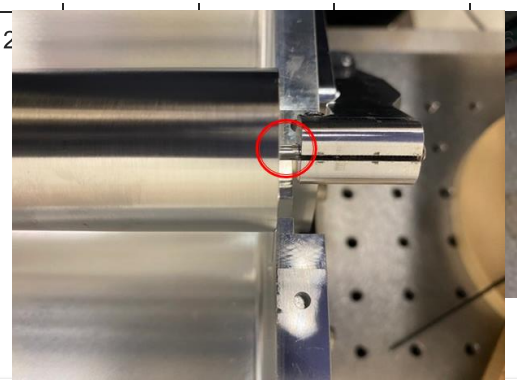
18-Cavity Array

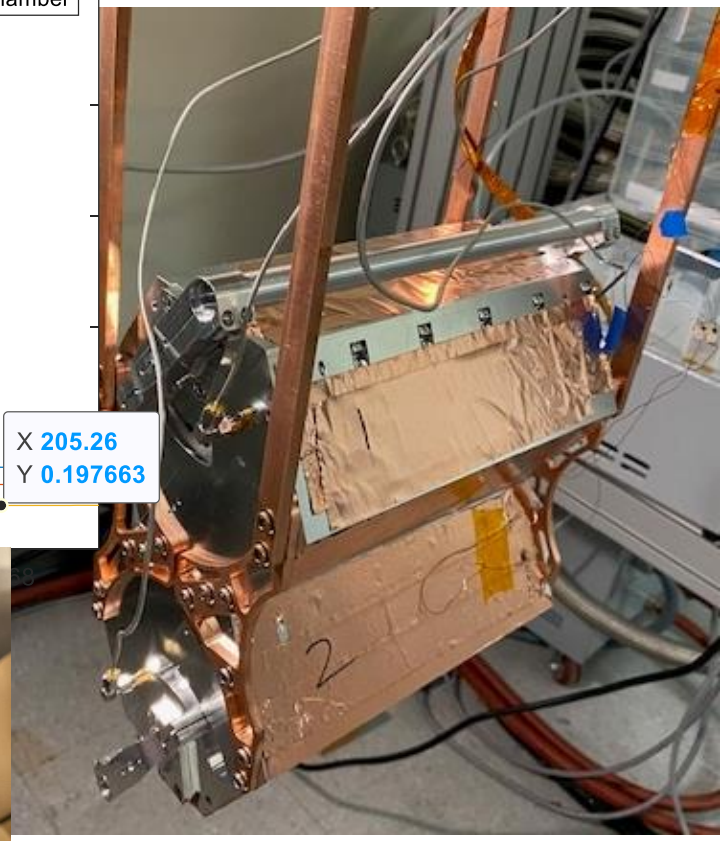


ADMX EFR-Testing

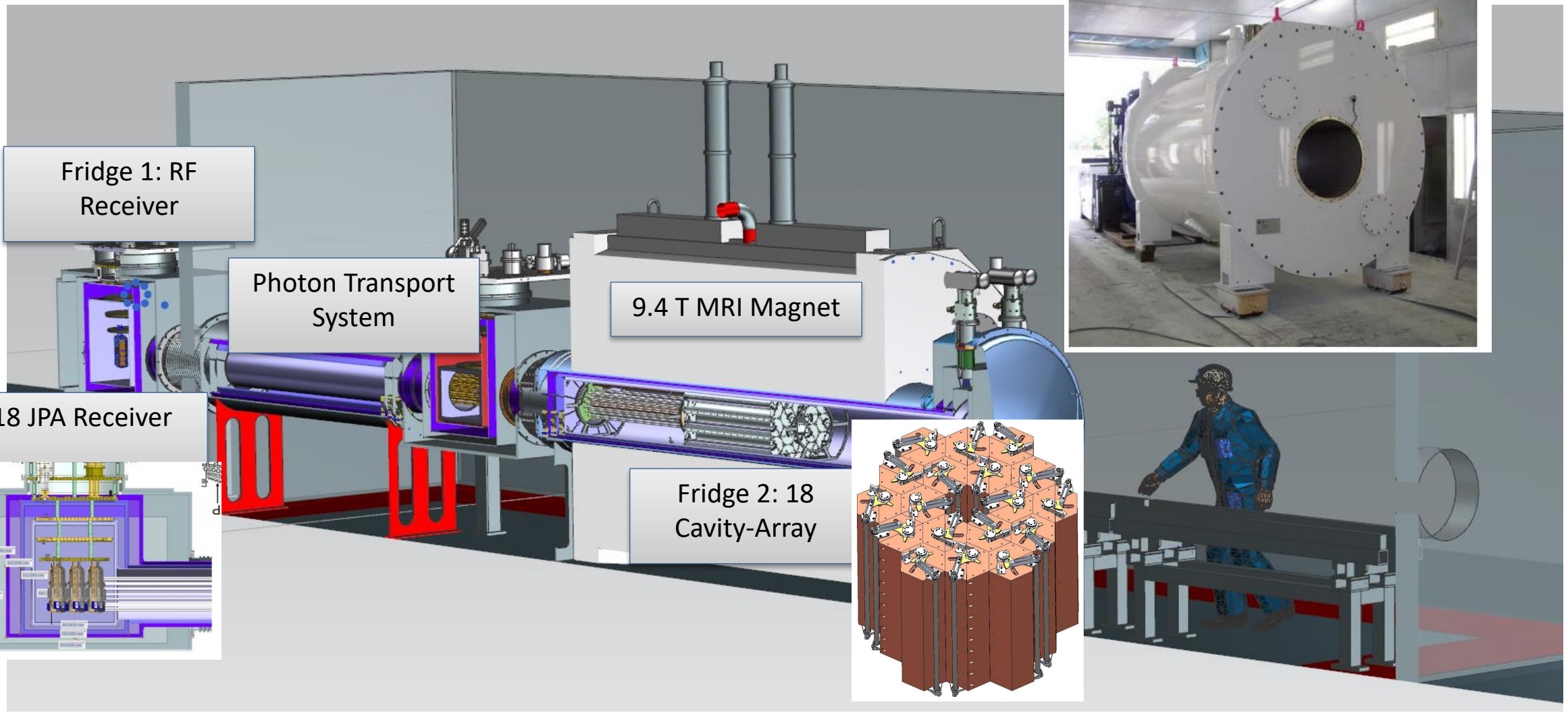
- Began cryogenic testing of two-cavity system in dilution refrigerator
  - Tuning failed due to DC resistance in power to piezo motors
    - Switching to lower resistance lines
  - Demonstration of tuning rod thermalization to within 70 mK with sapphire axles over an hour







ADMX-EFR Cryostat Design



Summary

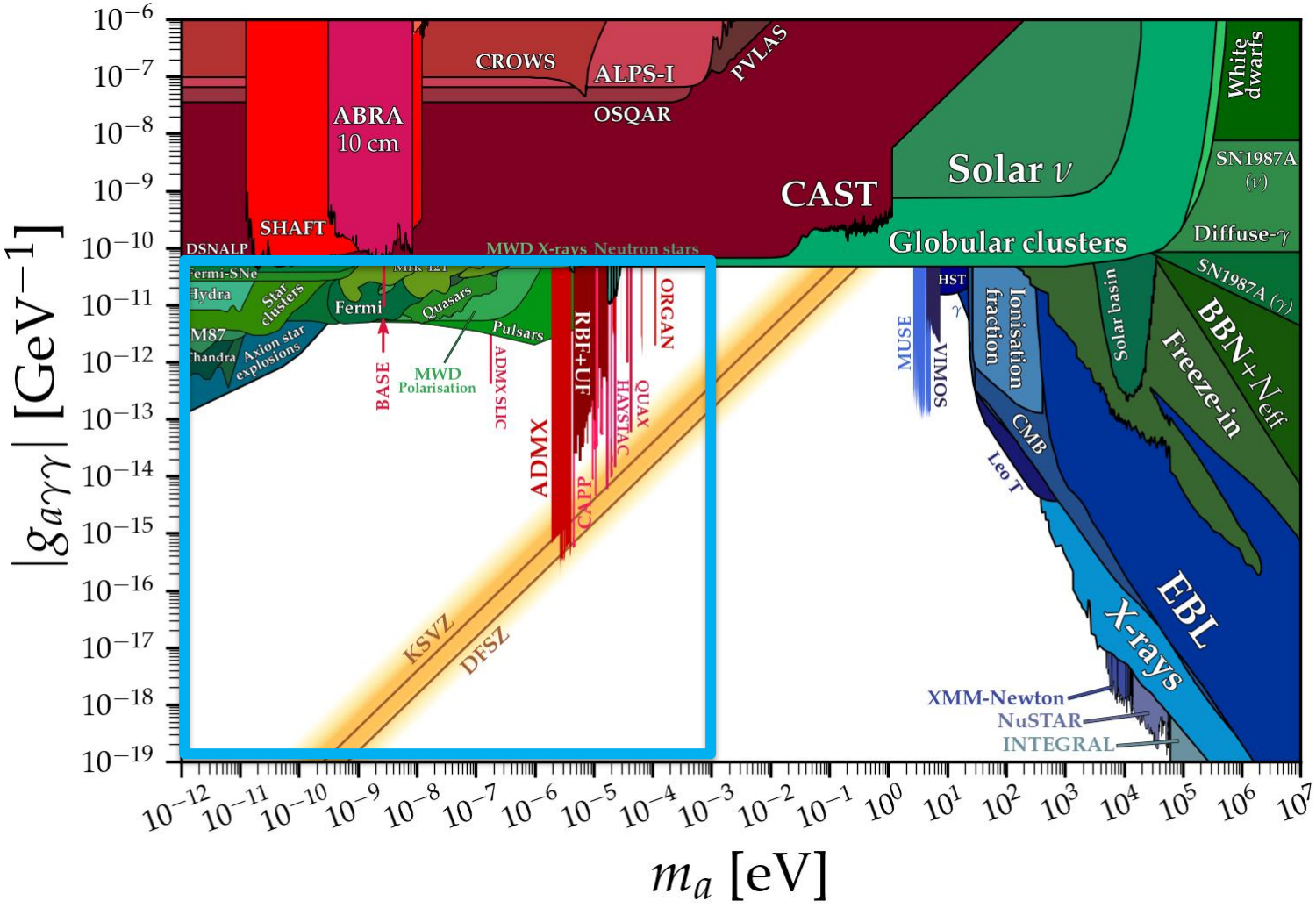
- ADMX has excluded axion dark matter between $m_a = 3.9 - 3.93\ \mu eV$
- We are currently preparing for a new run searching for axions between $m_a = 4.2 - 5.8\ \mu eV$
- Developments on the way for searches from $1.4 - 4\ GHz$

Acknowledgements

This work was supported by the U.S. Department of Energy through Grants No DE-SC0009800, No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, No. DE-C03-76SF00098 and No. DE-SC0017987. Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory LDRD offices.

Thanks!

Axion Landscape



Adapted from Ciaran O'Hare