Searching for Axion Dark Matter with ADMX

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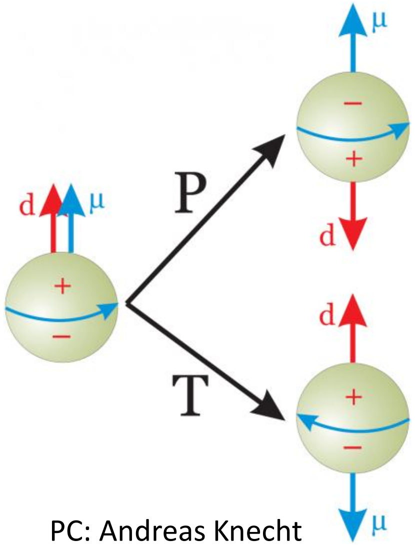
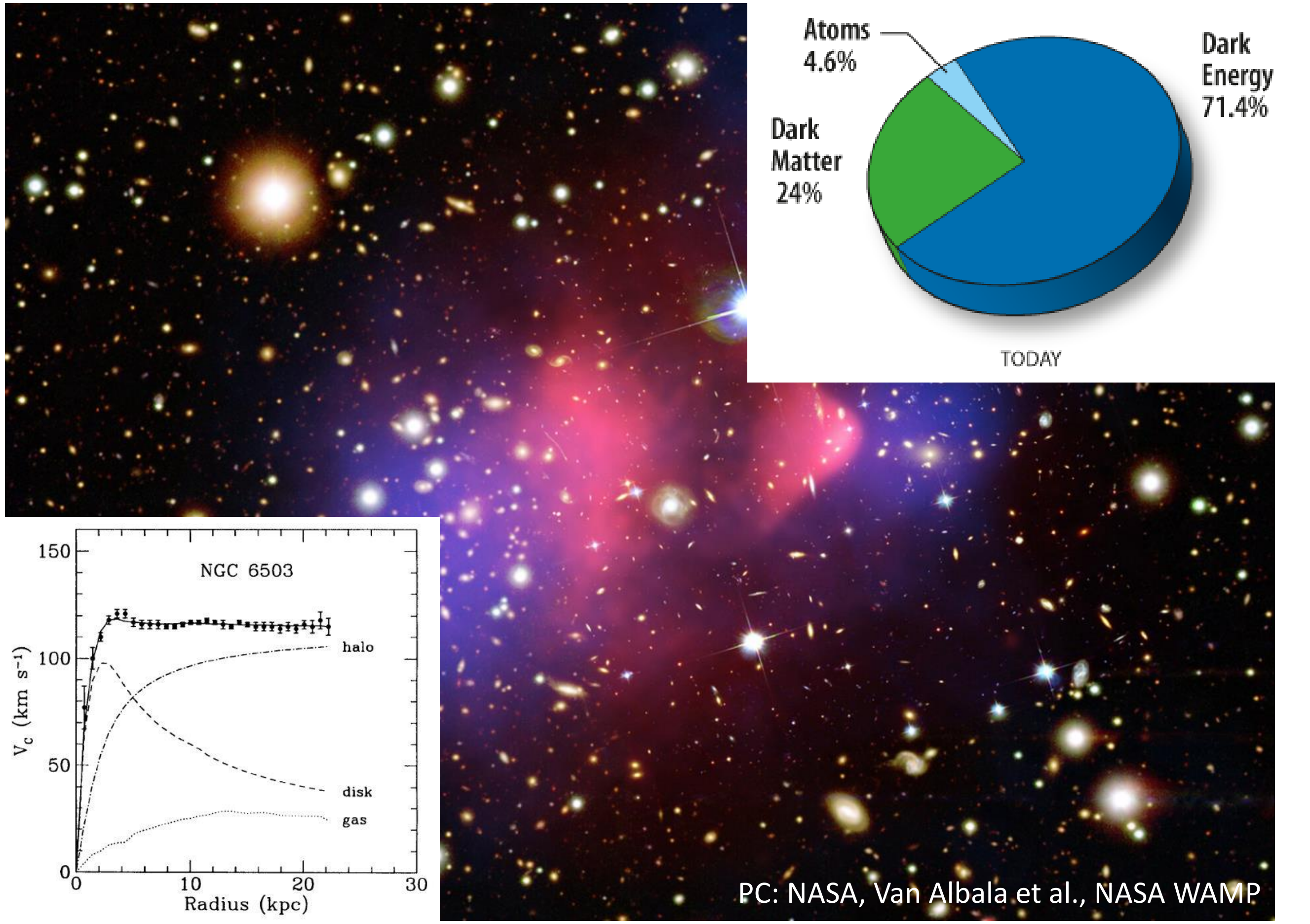
Axion Dark Matter

- Dark matter is a mysterious particle that makes up 24% of the mass in the Universe
- Axions are a theoretical particle that solves the Strong CP problem
- Properties of the axion make it a viable dark matter candidate

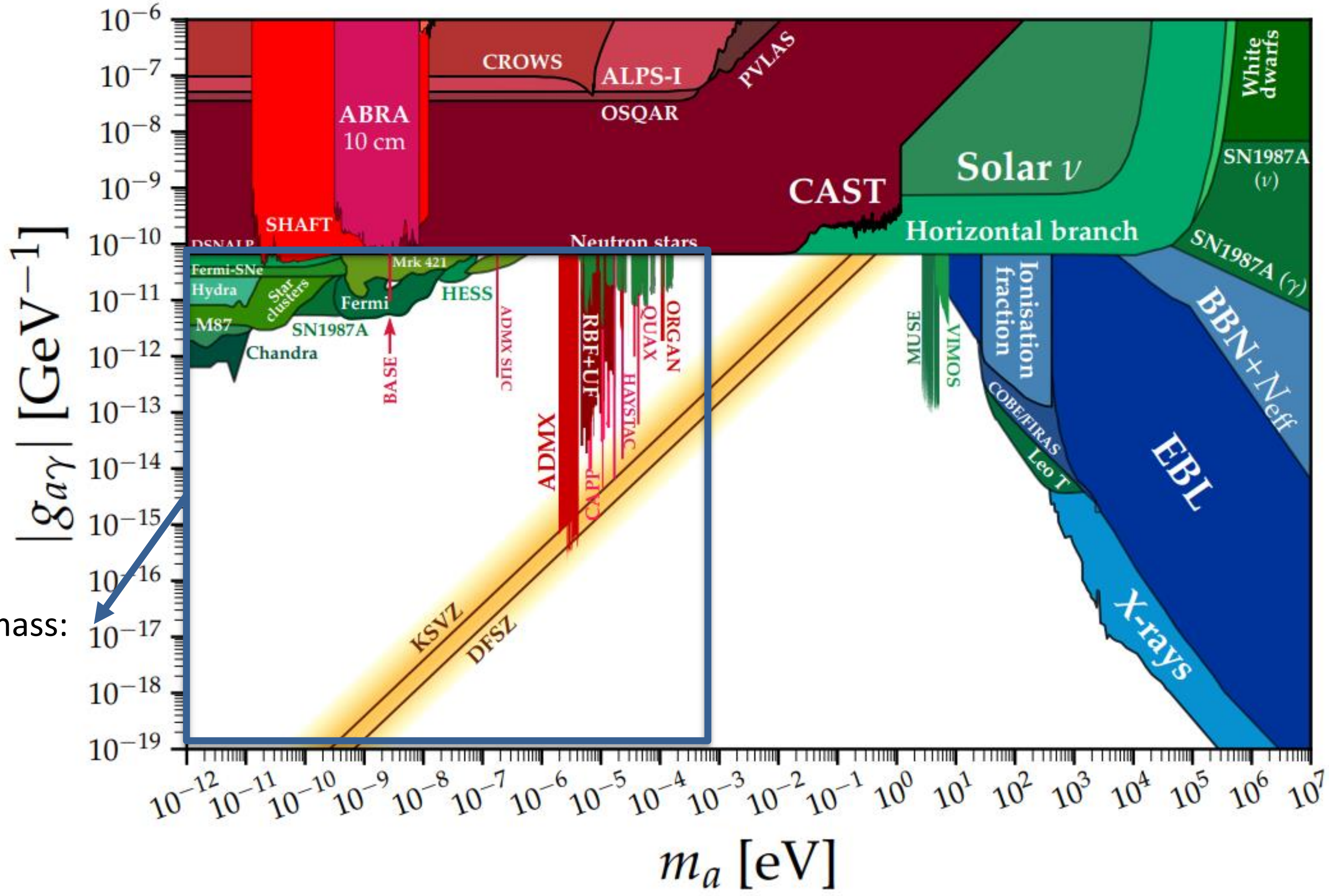


PC: Andreas Knecht



PC: NASA, Van Albala et al., NASA WAMP

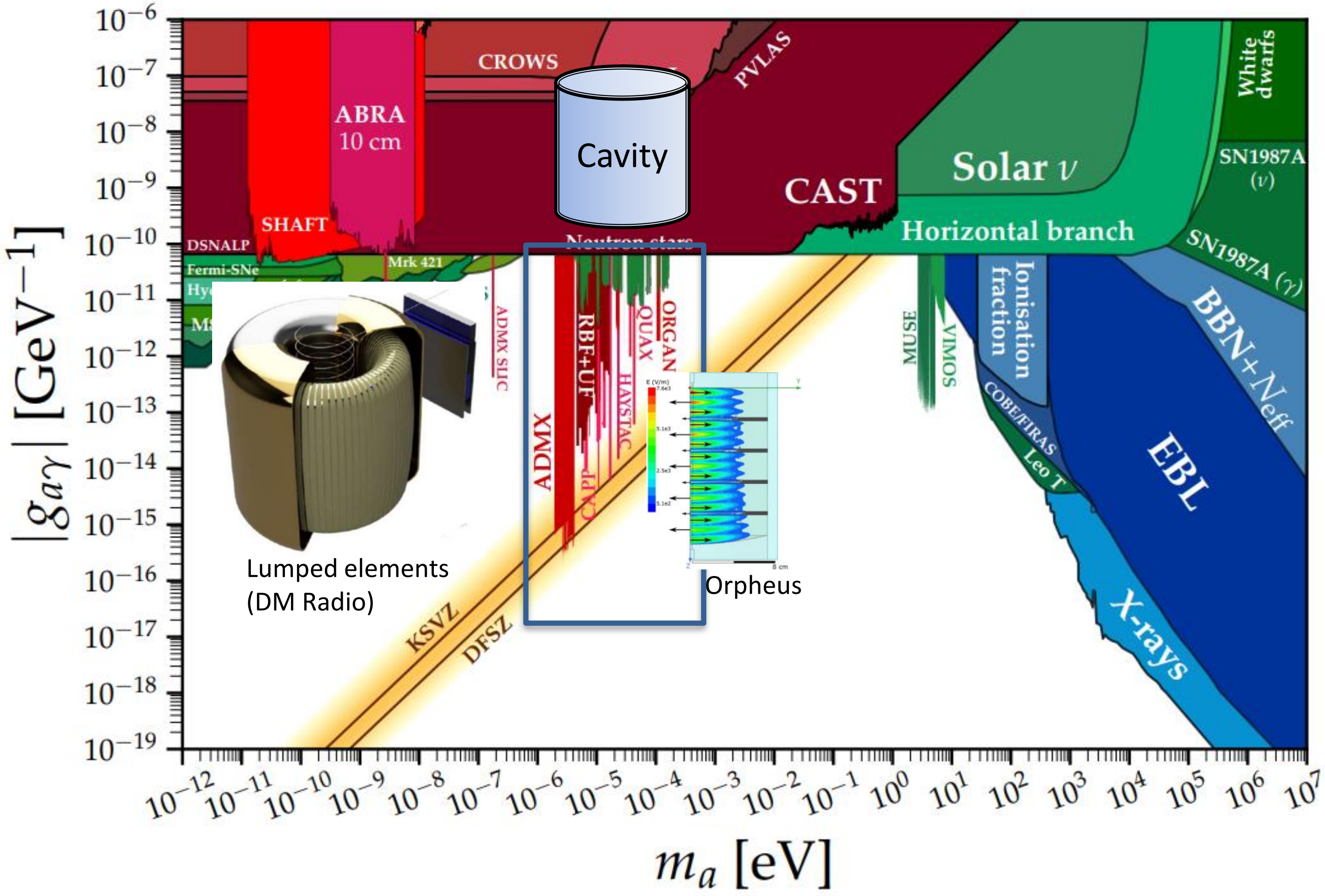
Axion Landscape



Cosmological constraints imply axion dark matter mass: $m_a = 1peV - 1eV$

Adapted from Ciaran O'Hare

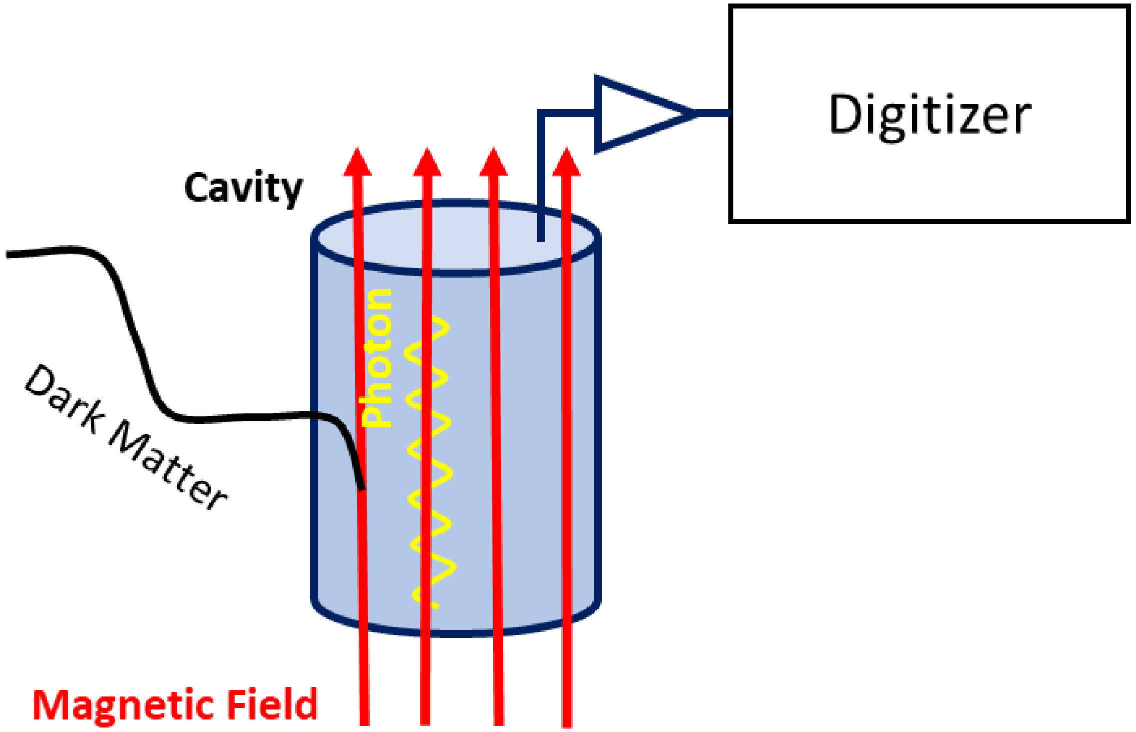
Axion Dark Matter Searches



Adapted from Ciaran O'Hare

Microwave Cavity Axion Haloscopes

- Axion haloscopes 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



Scan Rate for Cavity Axion Haloscopes

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

Theoretical Parameters

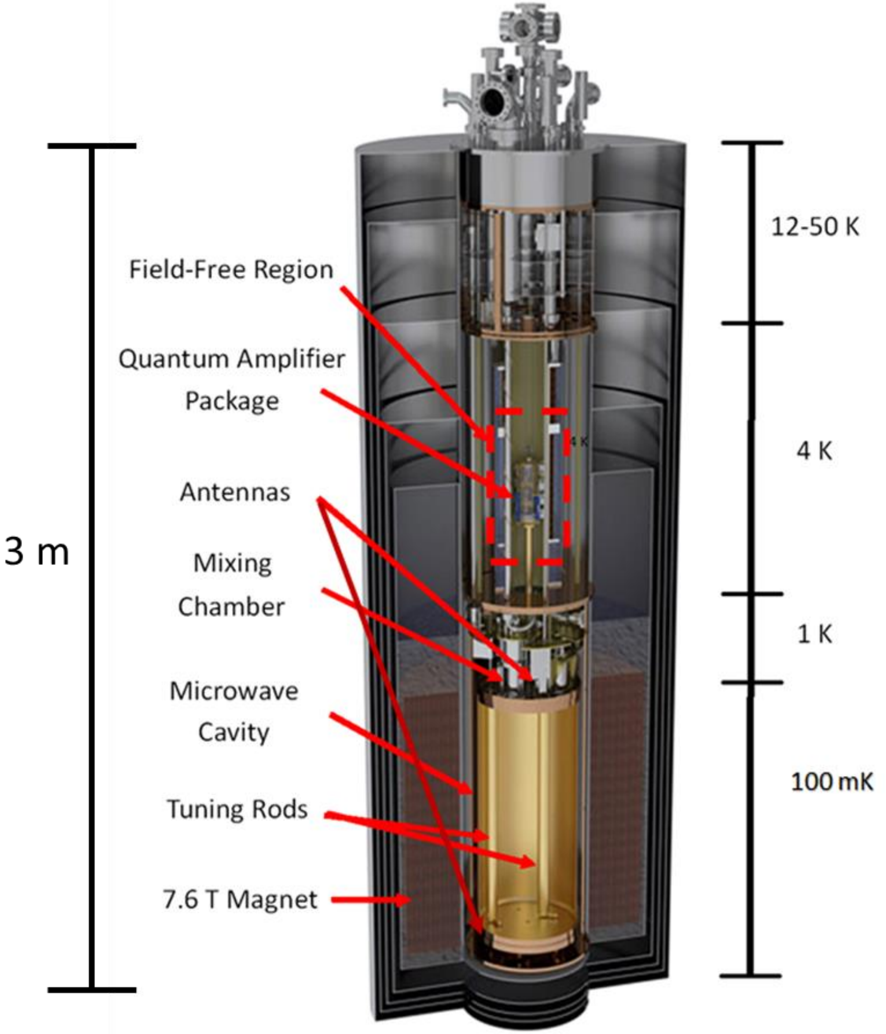
- g_γ – Dimensionless Coupling constant
- f – Axion frequency
- ρ_0 – Dark matter halo energy density

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

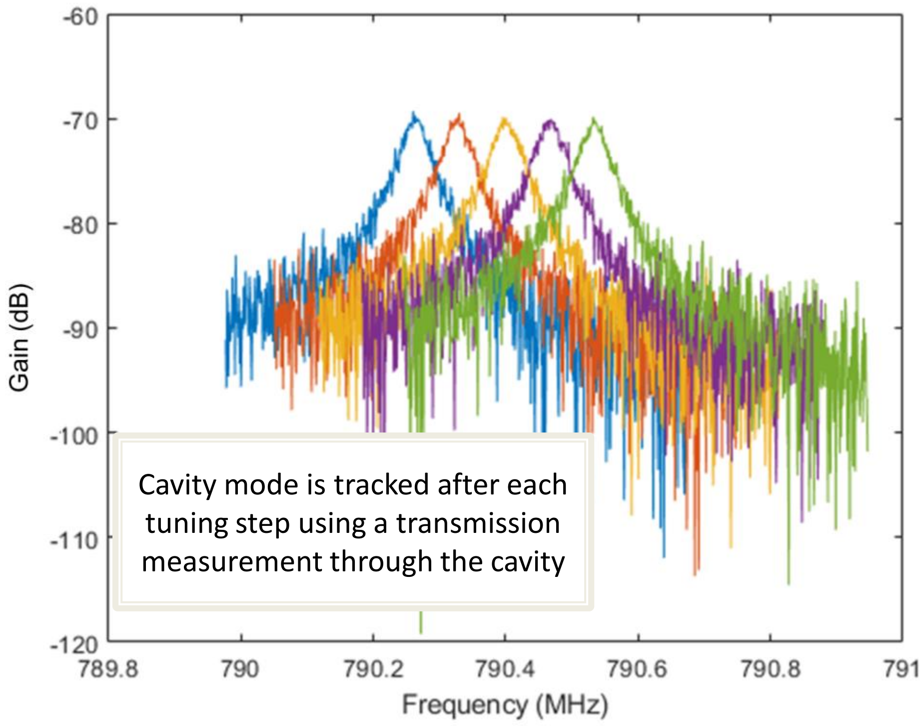
Axion Dark Matter Experiment (ADMX)

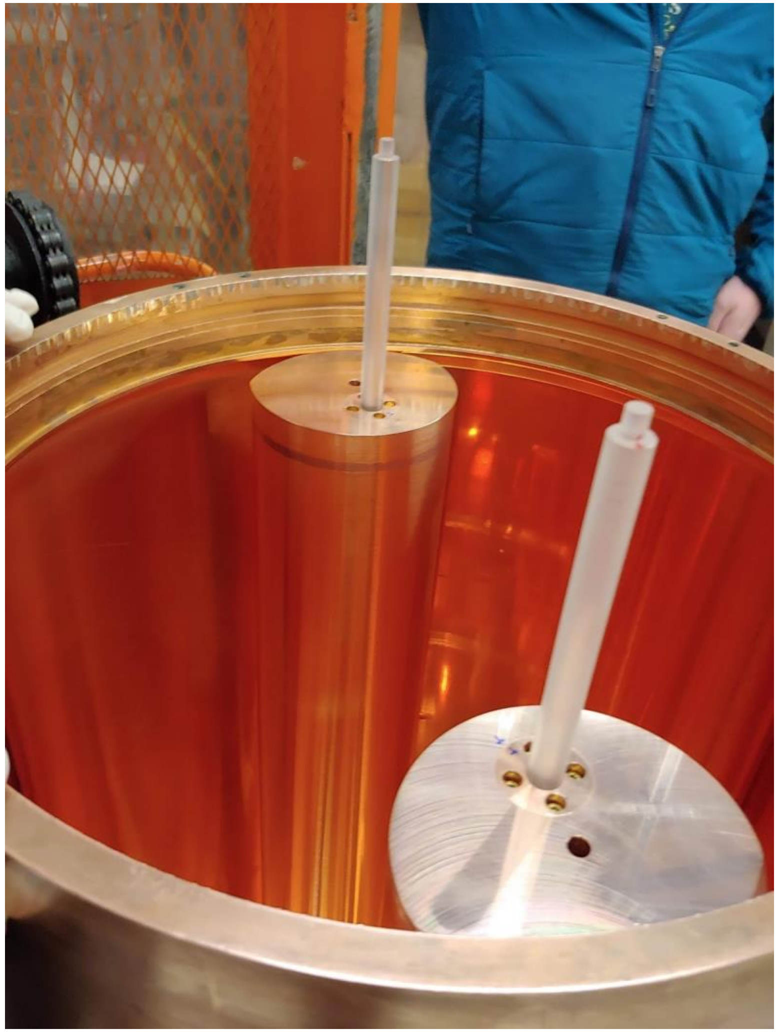
- Largest axion haloscope in the world
- Sited at the University of Washington
- ~50 collaborators



Tuning the Resonant Cavity

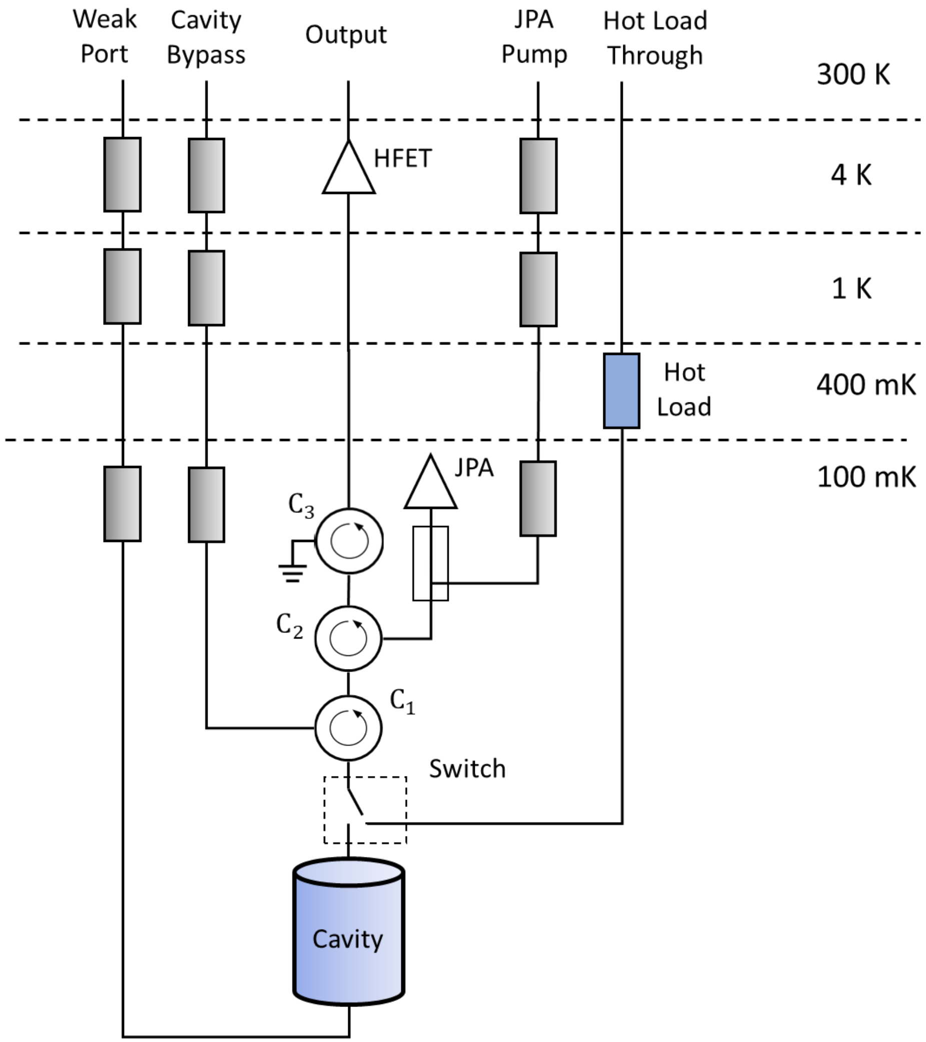
- Cavity resonant frequency is set by tuning rods inside the cavity
  - Tuning rods can be rotate from center of the cavity to the walls of the cavity





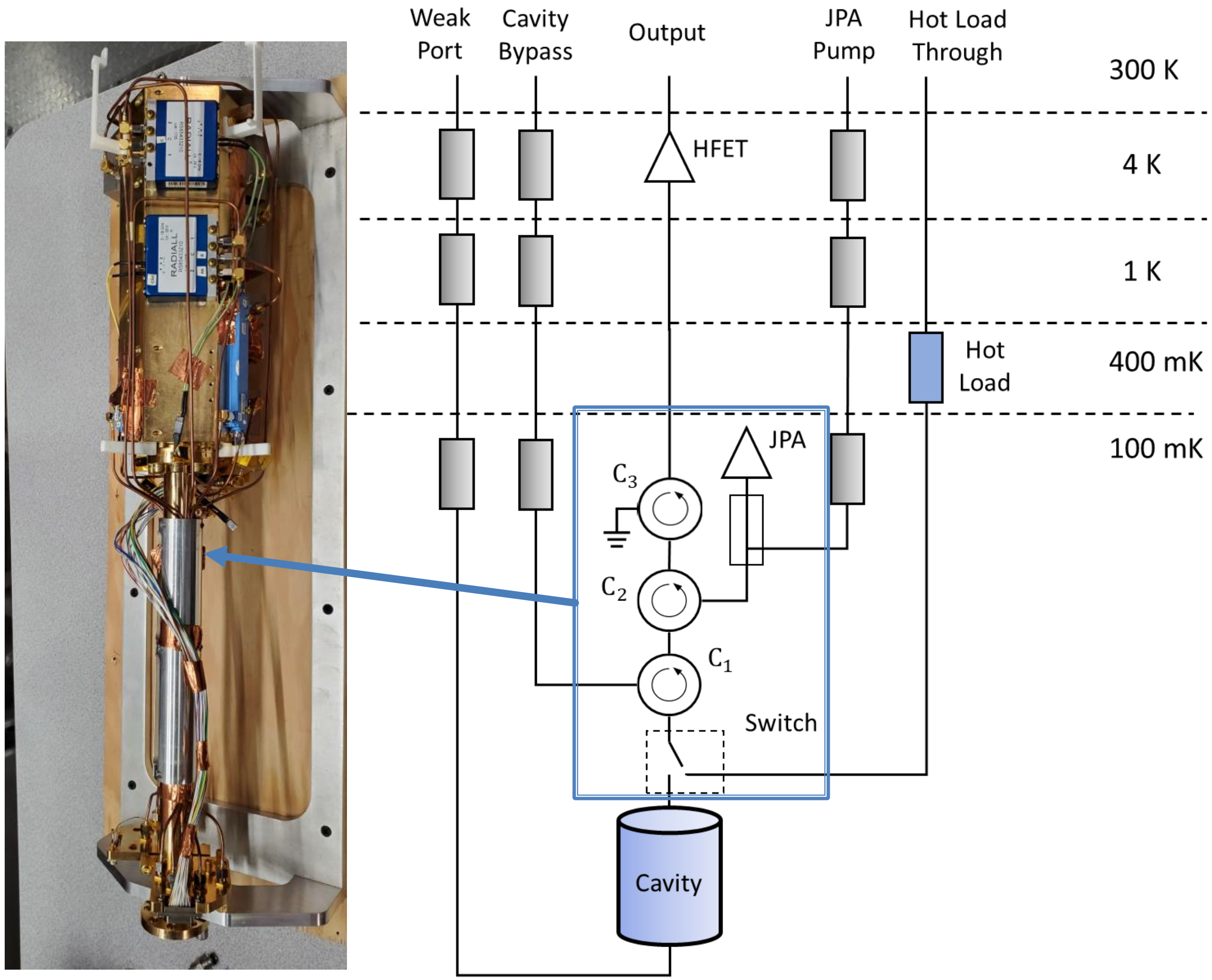
Sampling the Signal from the Cavity

- Dipole antenna couples signal from cavity into a low-noise microwave receiver



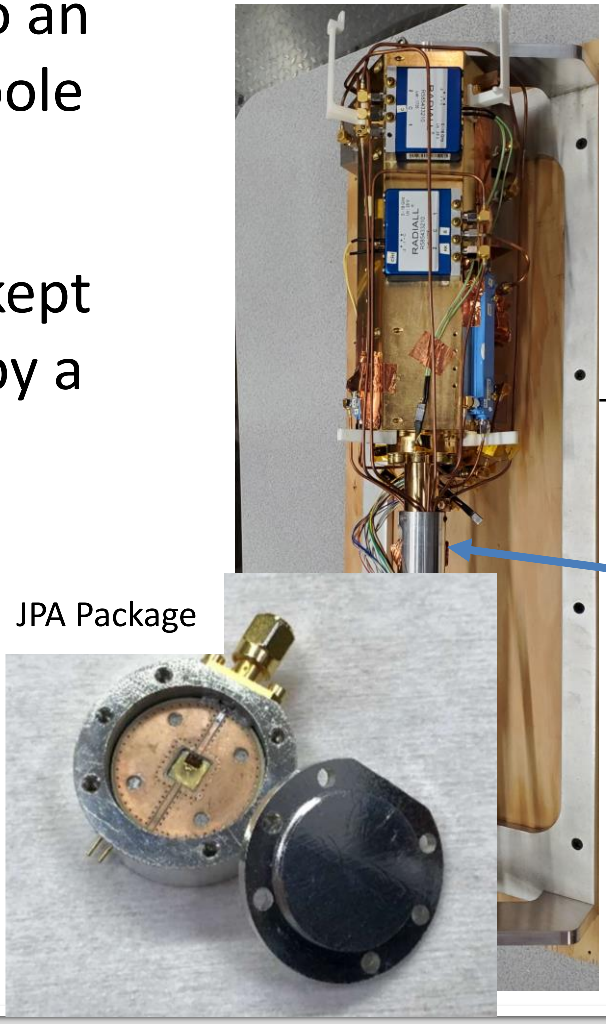
Sampling the Signal from the Cavity: Field Free Region

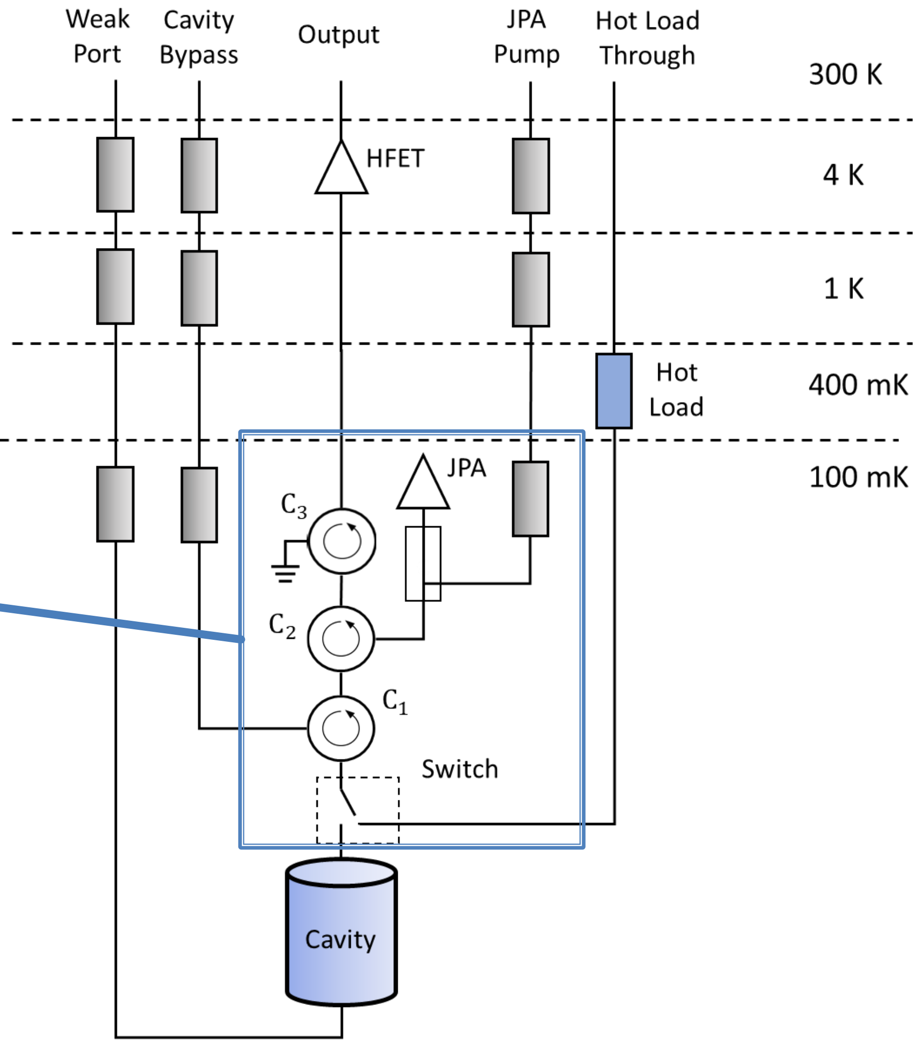
- Signal from cavity is coupled into an ultra-low noise receiver via a dipole antenna in the cavity
- Field sensitive components are kept in a field free region generated by a bucking coil magnet



Sampling the Signal from the Cavity

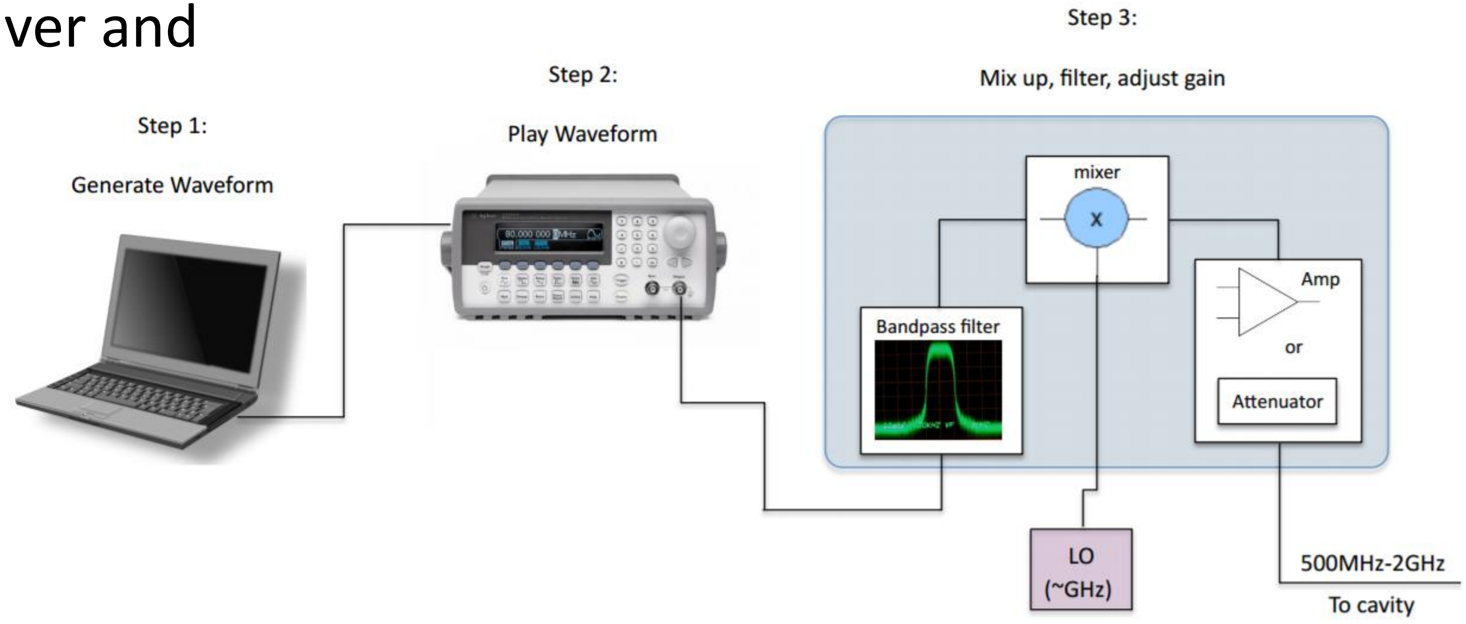
- Signal from cavity is coupled into an ultra-low noise receiver via a dipole antenna in the cavity
- Field sensitive components are kept in a field free region generated by a bucking coil magnet
  - System noise is optimized with low noise first-stage amplifier
    - Josephson Parametric Amplifier (JPA)
      - SQUID based technology





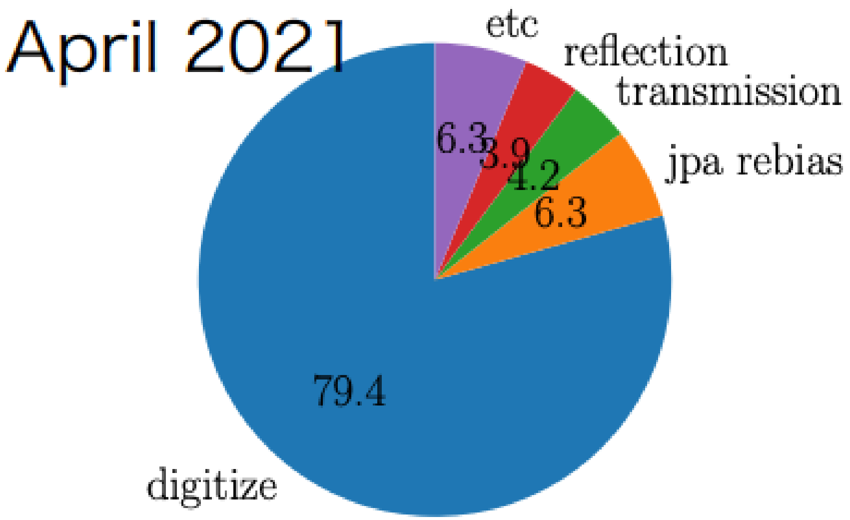
Synthetic Axion Injections

- 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



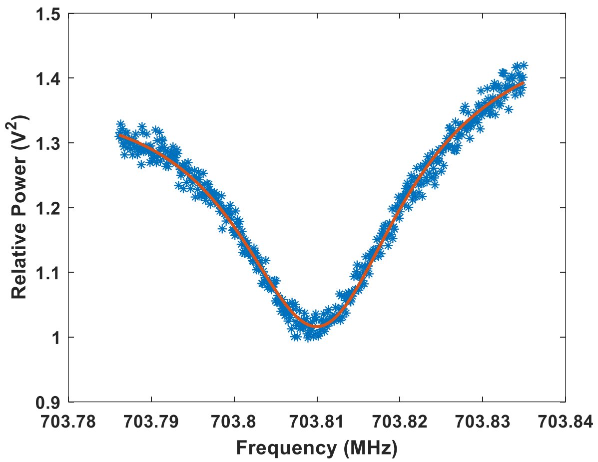
Data Taking Run with ADMX

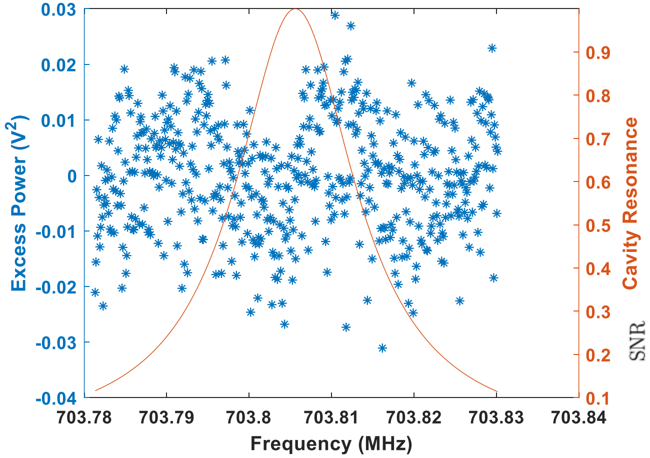
- Data run from June 2021-Dec 2022
  - Rescan previously explored range to DFSZ
  - Tuning Range: 800-950 MHz
- Data taking operations are controlled by an automated script

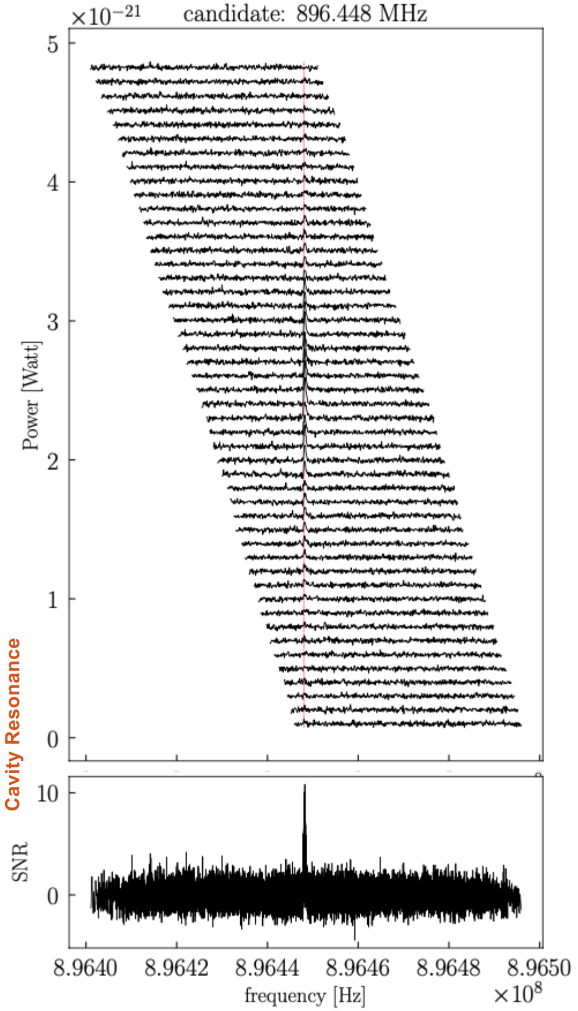


Identifying Axion Signals in Analysis

- Data run collects ~10,000 digitized power spectra
  - Analysis must search through these for axion signals
- Individual spectra are processed for background removal
  - Power in each frequency bin is weighted relative to distance from cavity resonant frequency
- Combine individual spectra into a "grand spectrum" to enhance the signal-to-noise ratio of potential axion signals

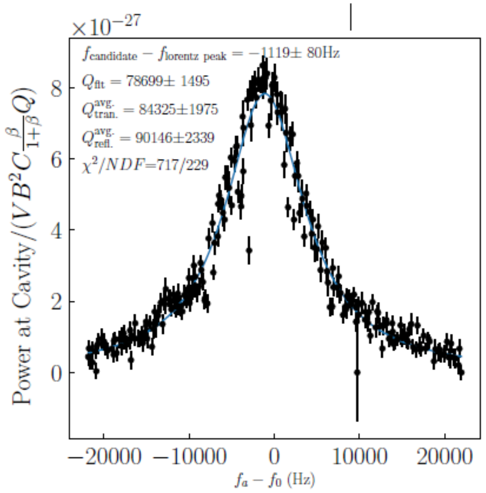


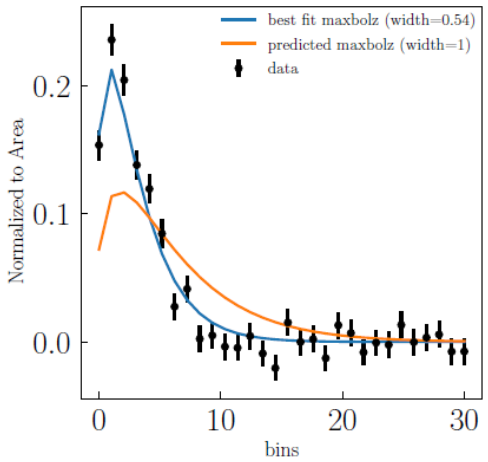


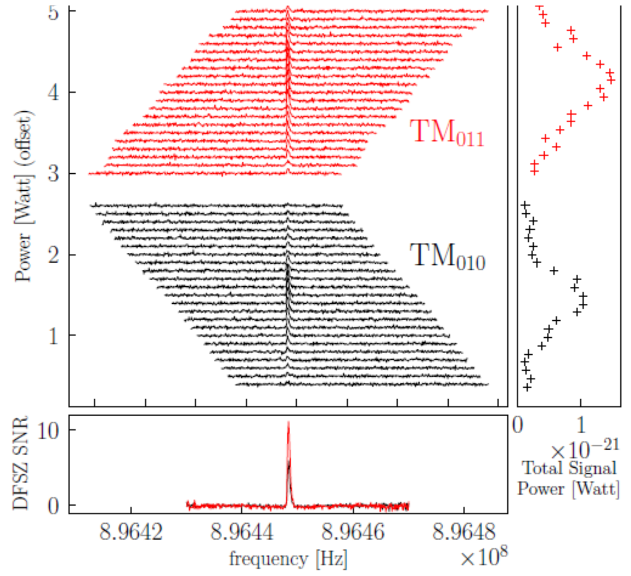


Vetoing Candidate Signals

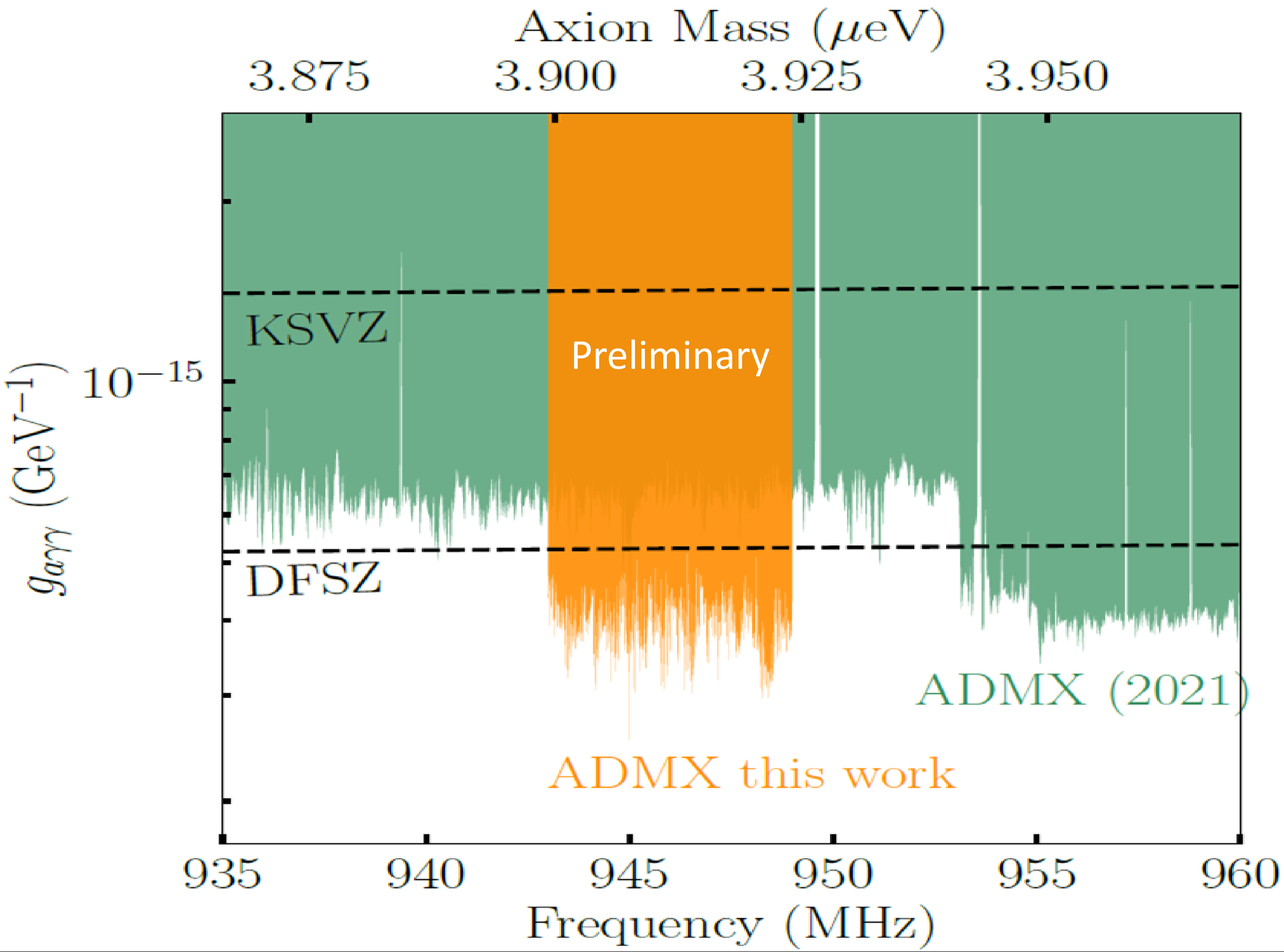
- Candidates are always expected due to blind injections, noise fluctuations, RFI
- Candidates that are identified as potential axion signals undergo a rigorous series of tests
  1. Is the signal persistent?
  2. Is the signal enhanced by the cavity resonance?
  3. Does the signal lineshape follow a Maxwell-Boltzmann distribution?
  4. Does the power of the signal scale correctly?
     - Change the magnetic field magnitude and search mode







Results: Limits on Axion-to-Photon Coupling



- Problems with tuning systems prevented coverage of full frequency range
  - Covered 943-950 MHz

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

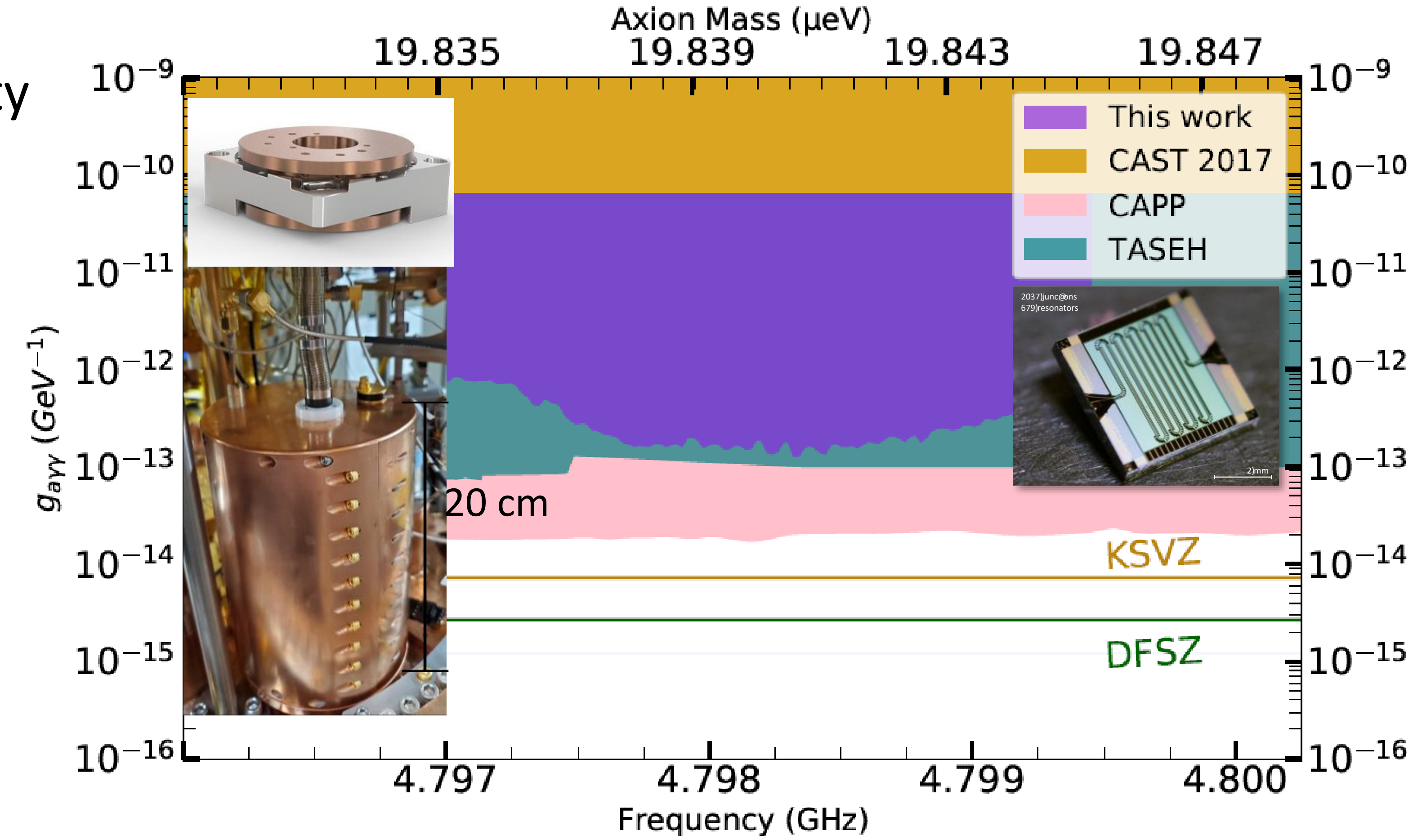
Larger cavities to maintain volume

Lower loss materials to improve Q factor

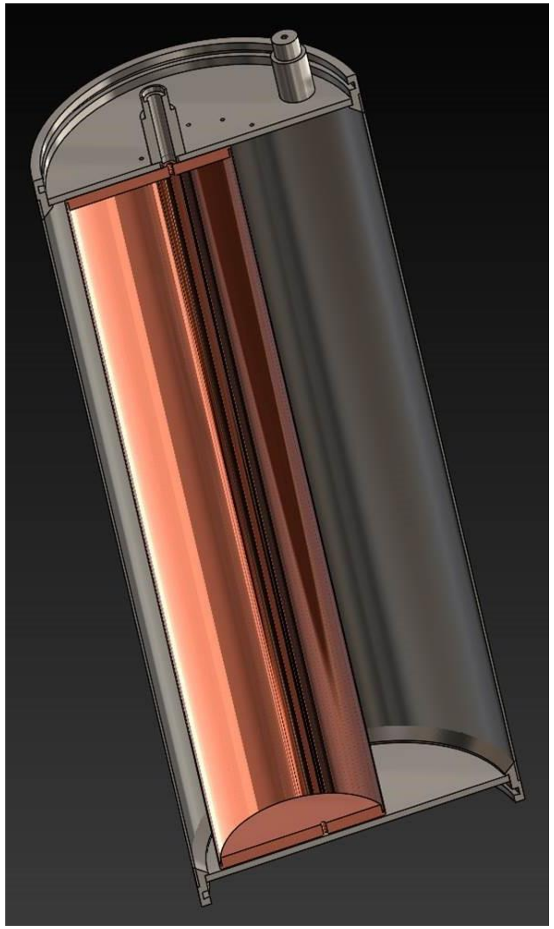
Below SQL noise (?)

ADMX Sidecar

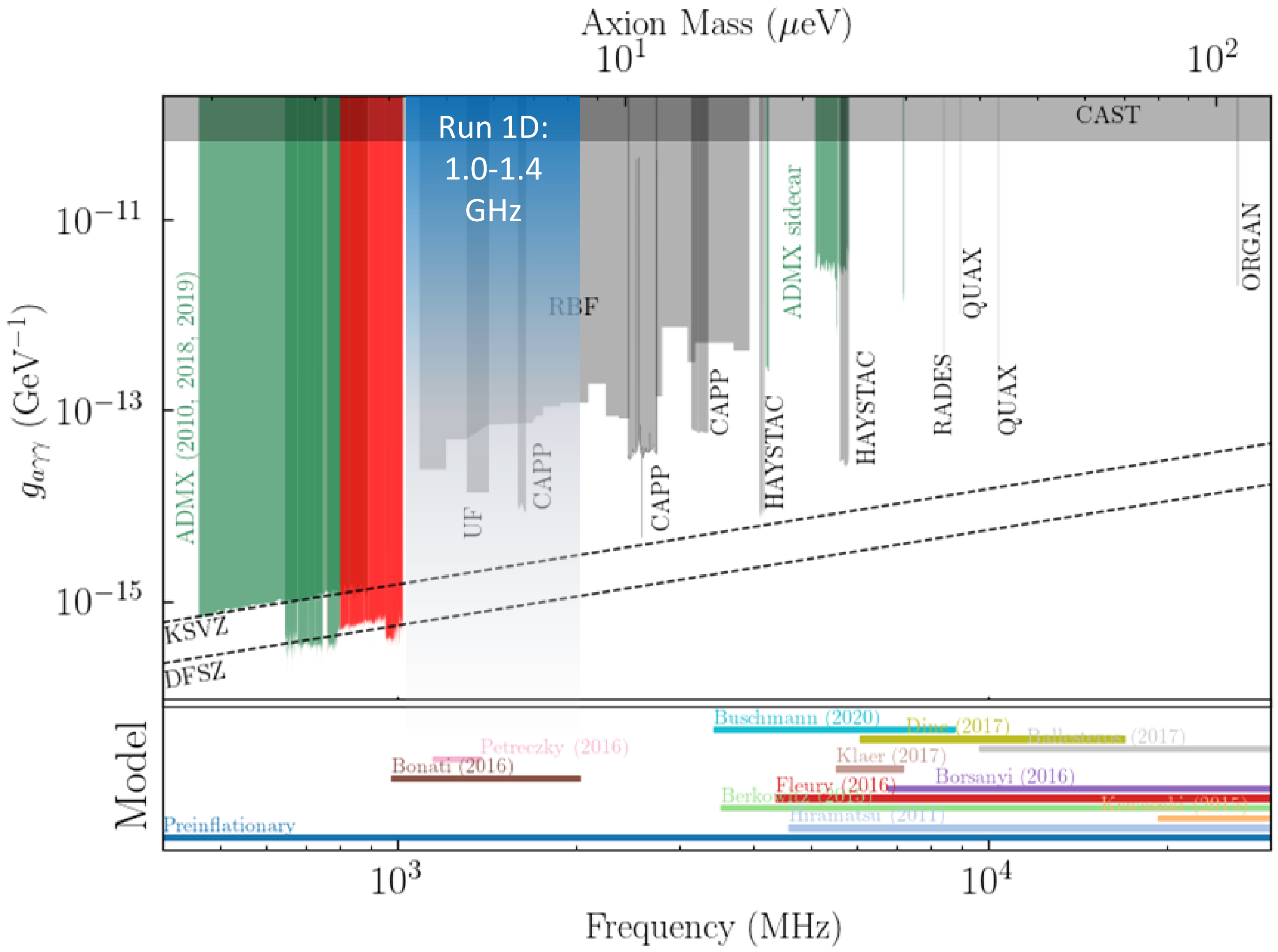
- Higher frequency cavity mounted above the main cavity
  - Testbed for higher frequency resonator designs
- Research into
  - Piezo-electric based tuning systems
    - Fine control over tuning
  - Josephson Traveling Wave Parametric Amplifiers (JTWPA)
    - Broadband low noise amplification



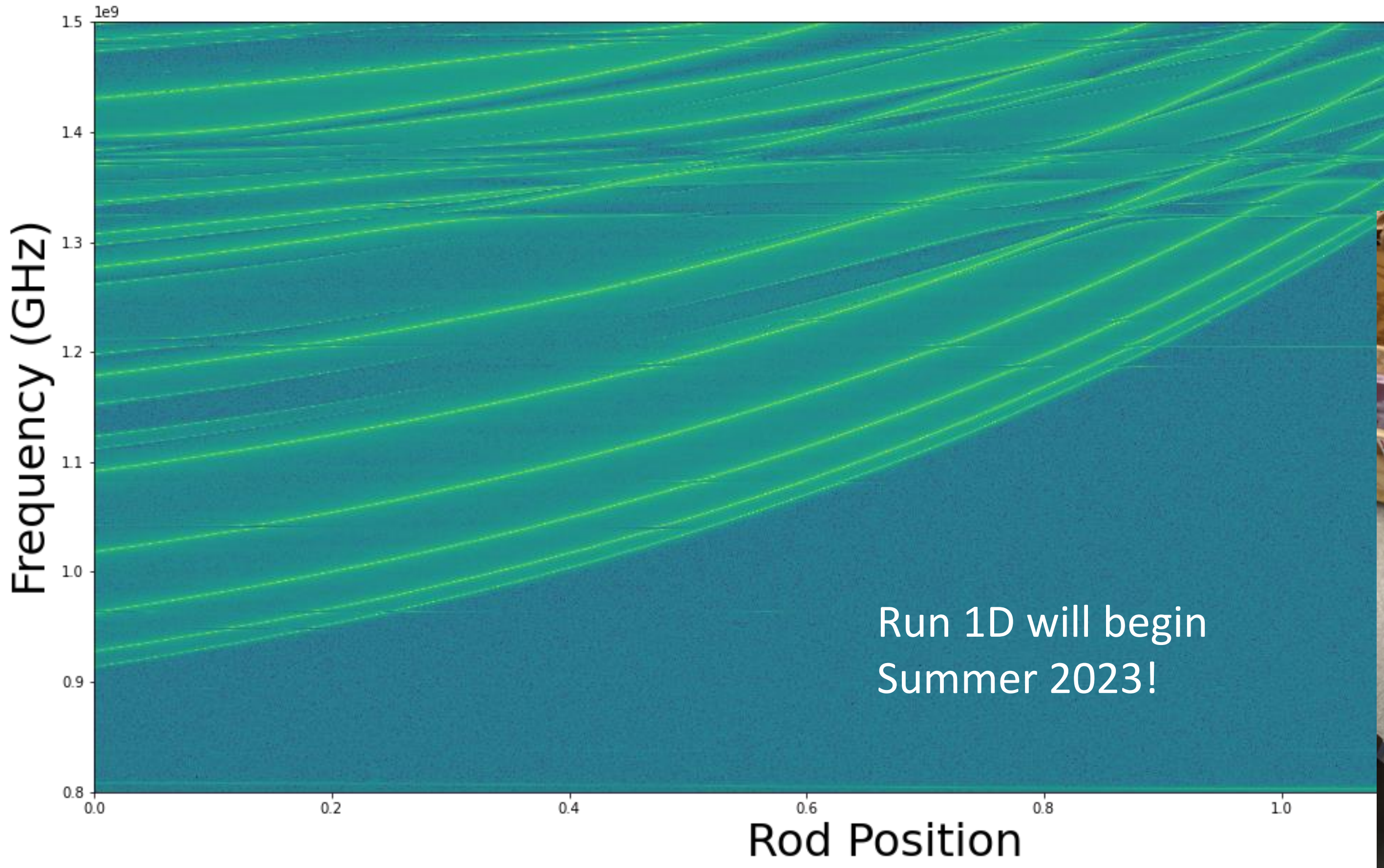
Pursing Higher Mass Axion: Run 1D



Single “Large” Rod

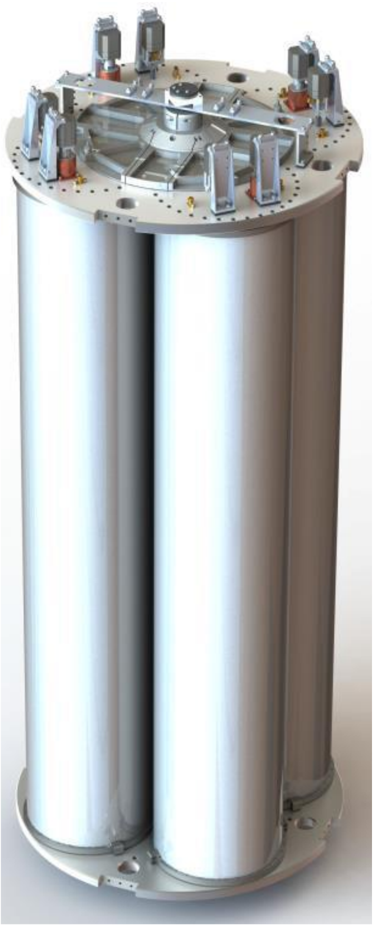


Preparations for Run 1D

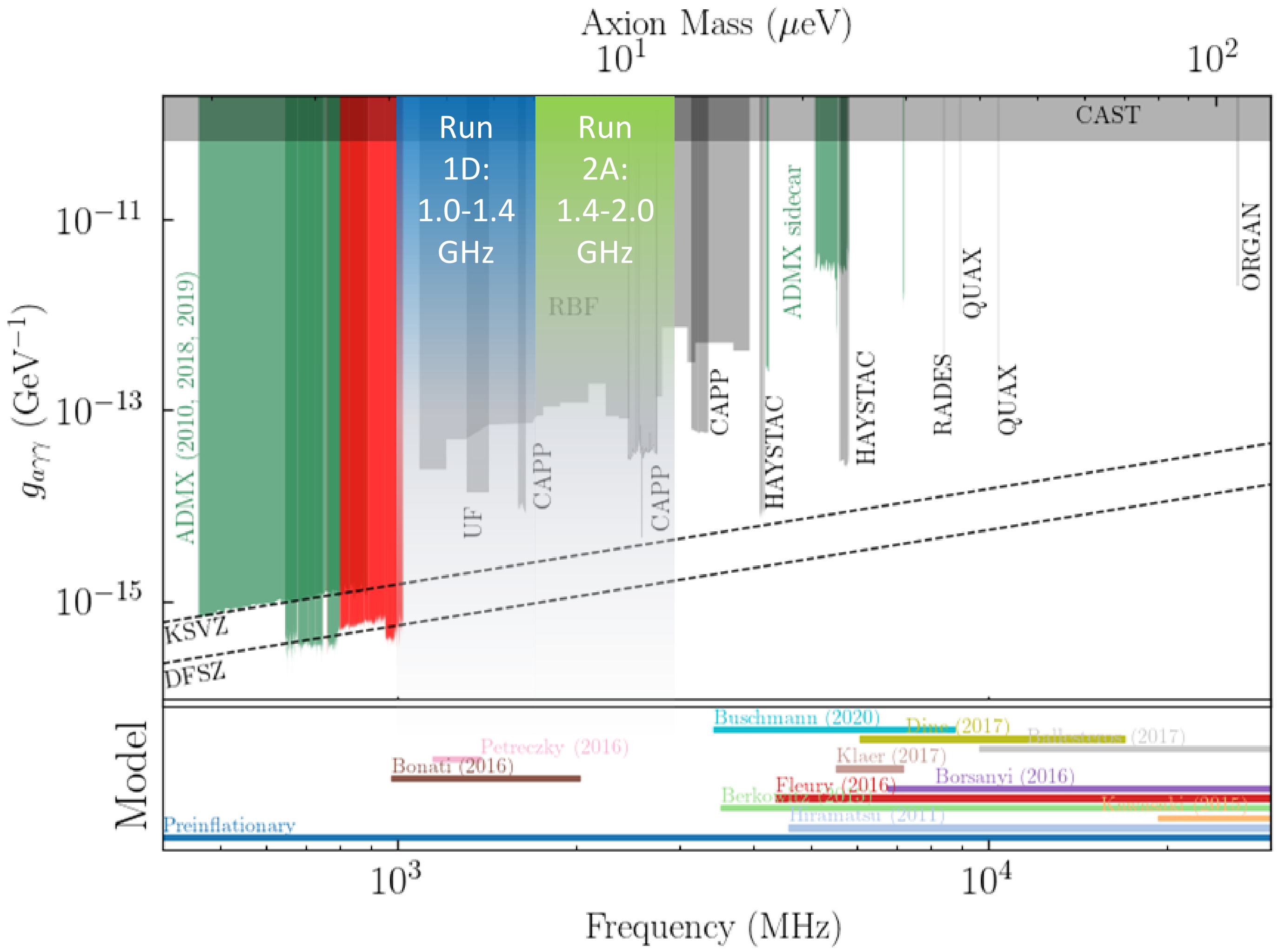


Run 1D will begin
Summer 2023!

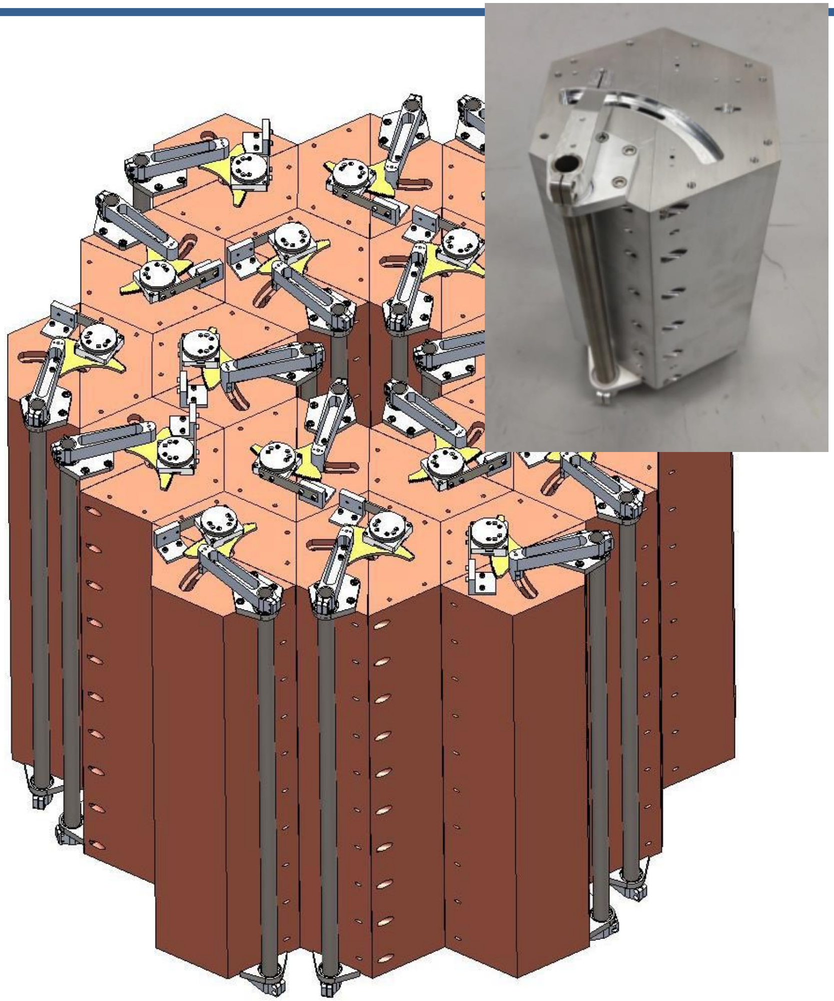
ADMX 4-Cavity Array



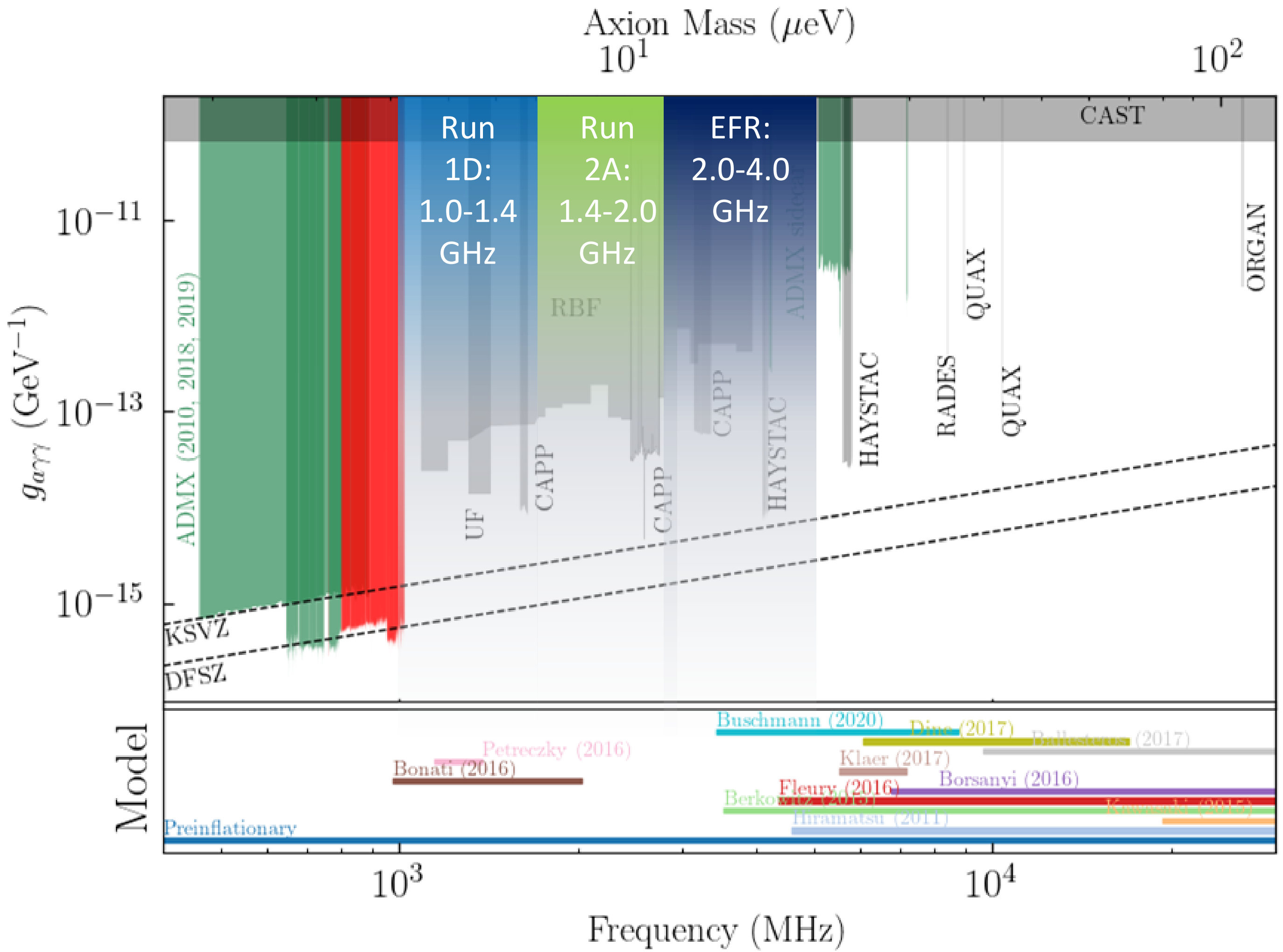
4-Cavity System



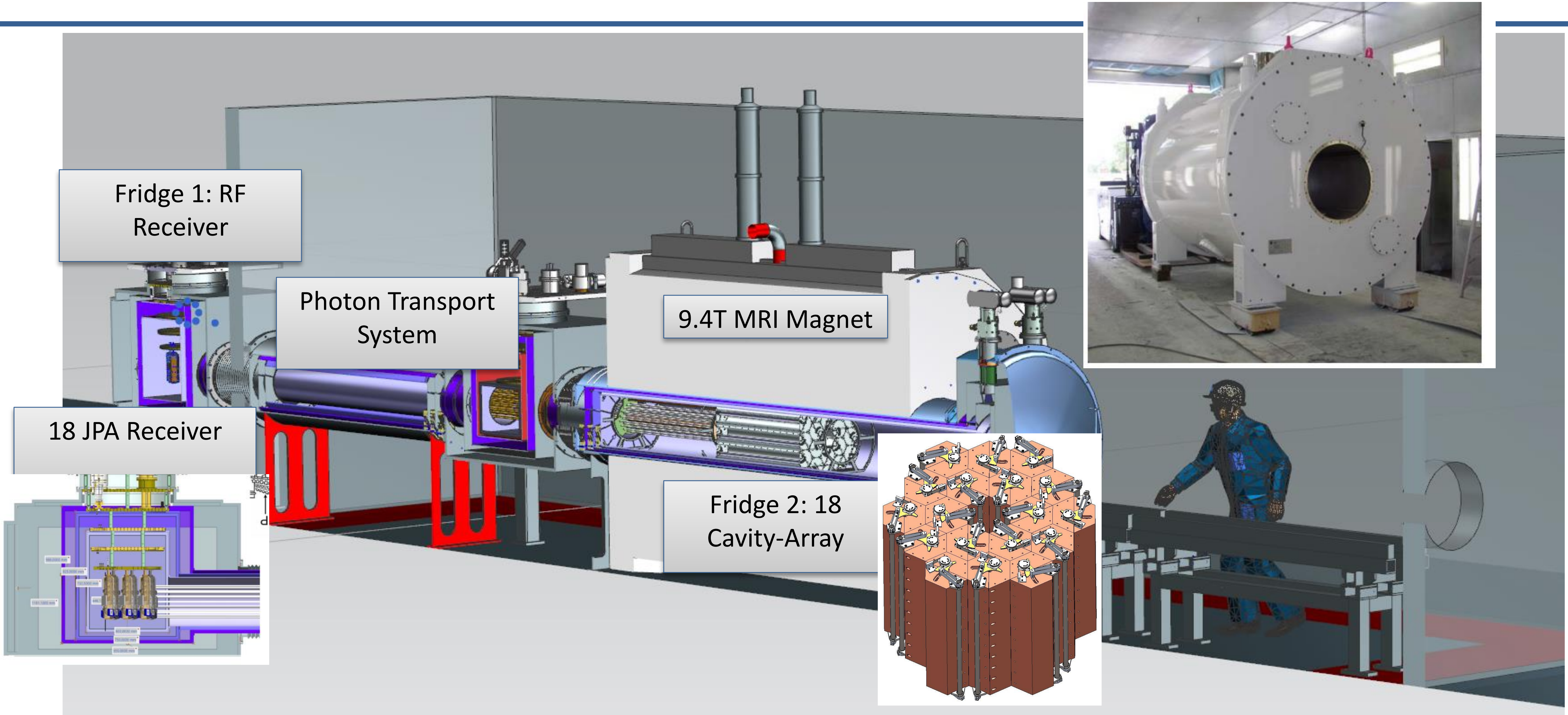
ADMX-Extended Frequency Range (EFR)



18-Cavity Array

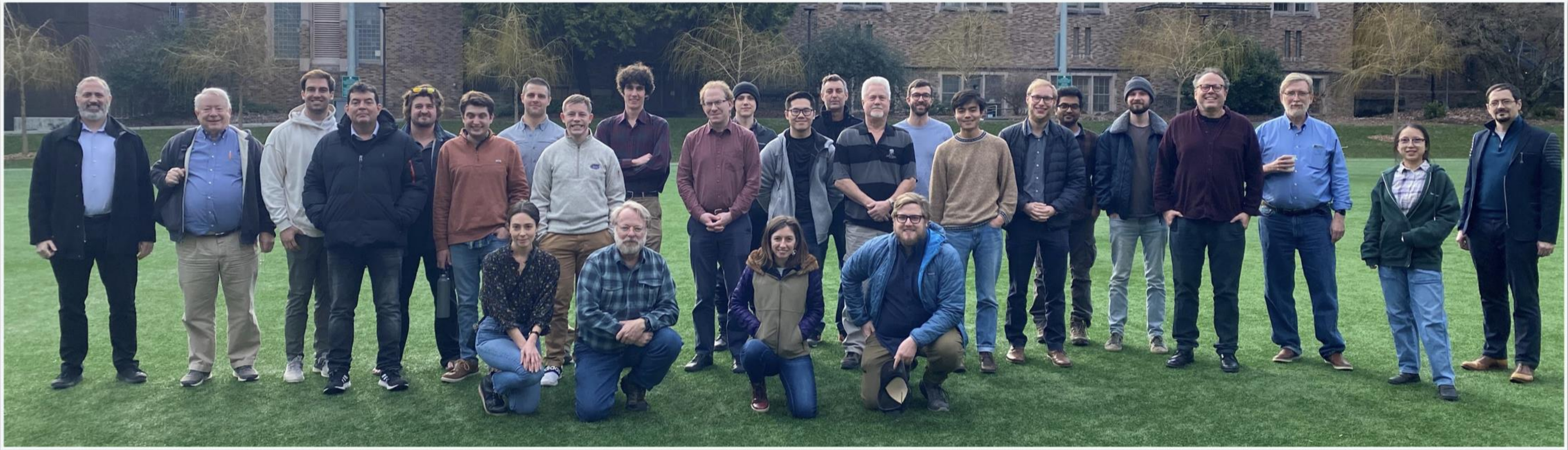


ADMX-EFR Cryostat Design



Summary

- Axion dark matter is exciting field!
- 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 $m_a = 4.2 - 5.8\ \mu eV$



Acknowledgements

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Questions

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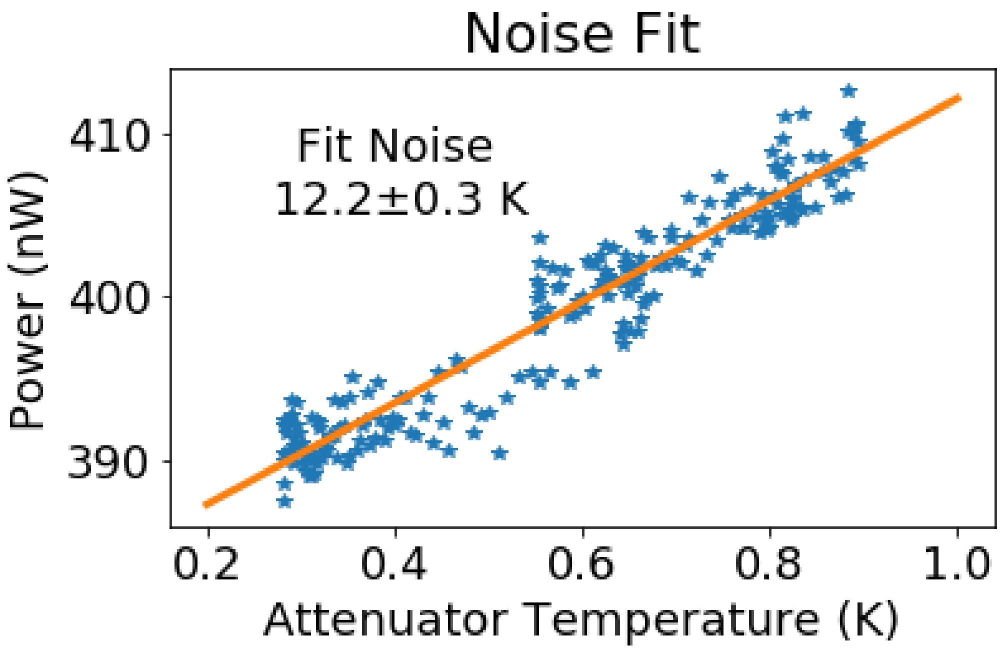
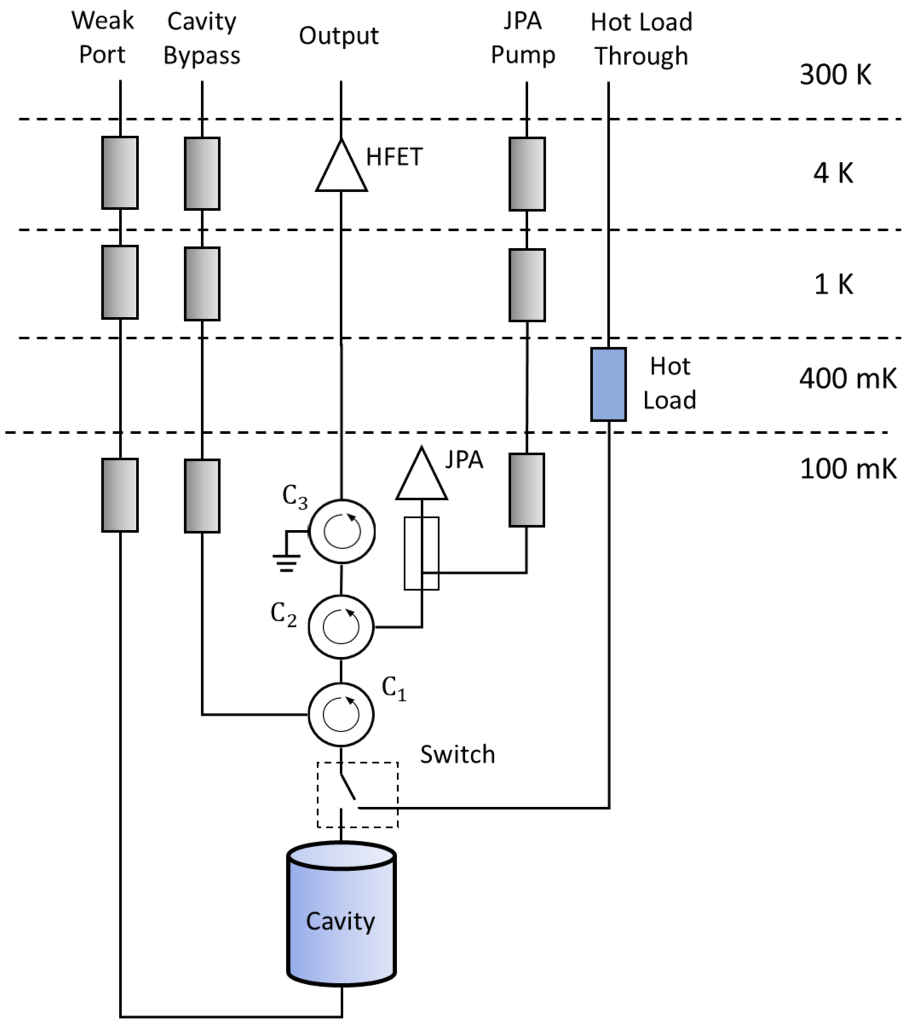
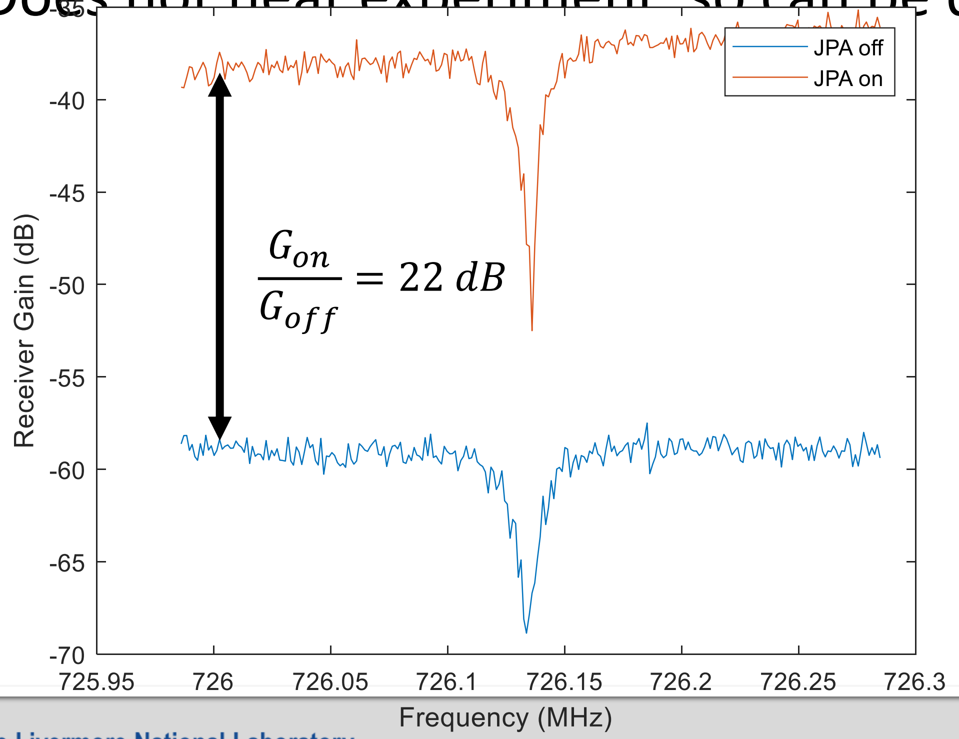
Backup slides

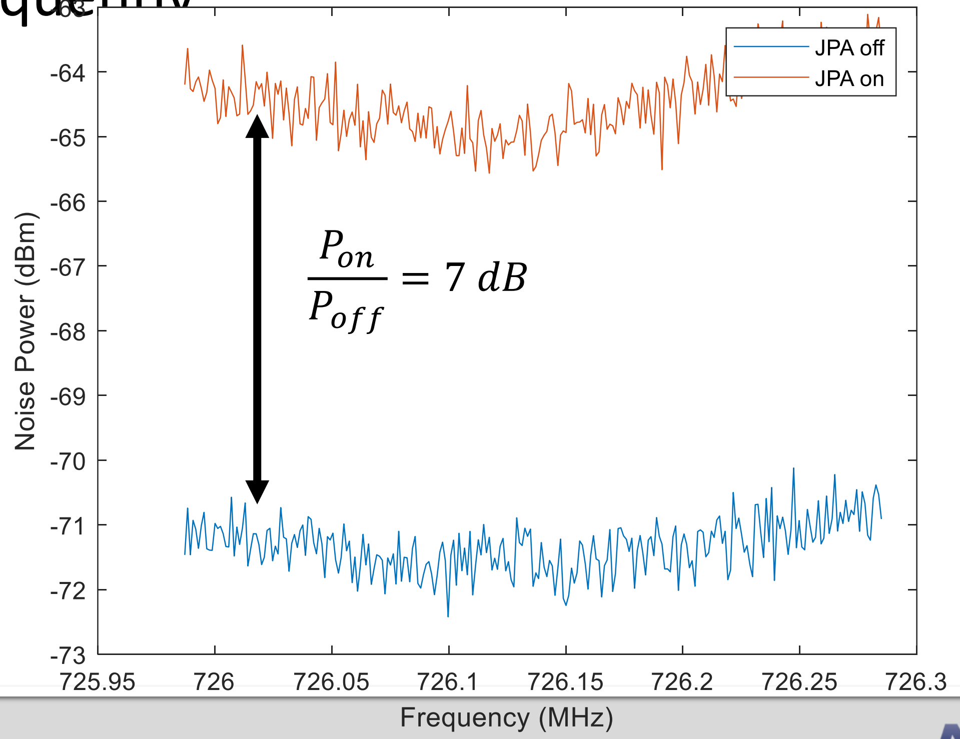
Calibrating the Signal Power





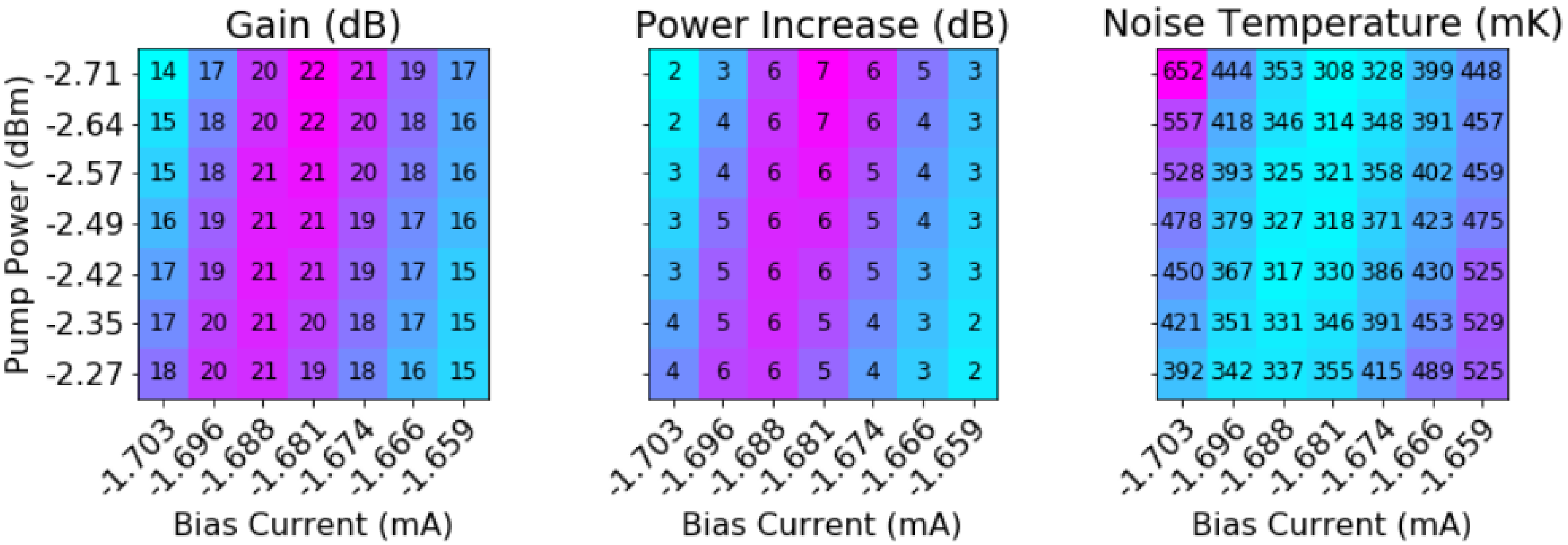
- Measure improvement in signal-to-noise of receiver with JPA on and off
- $SNRI = \frac{G_{on}}{G_{off}} / \frac{P_{on}}{P_{off}}\ ;\ T_{sys} = \frac{T_{HFET}}{SNRI}$
- Does not heat experiment, so can be done frequently



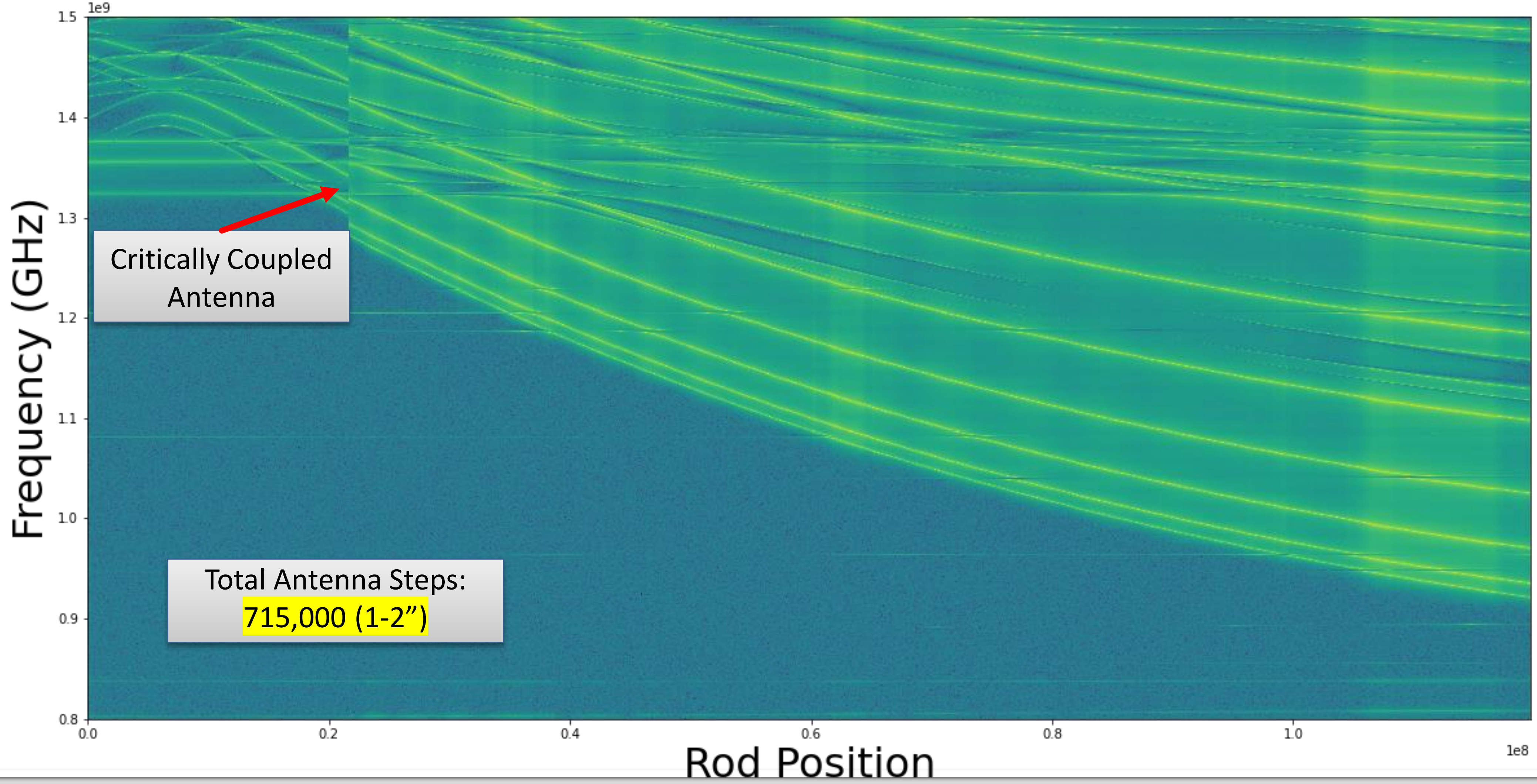


SNRI: Optimizing the System Noise Temperature

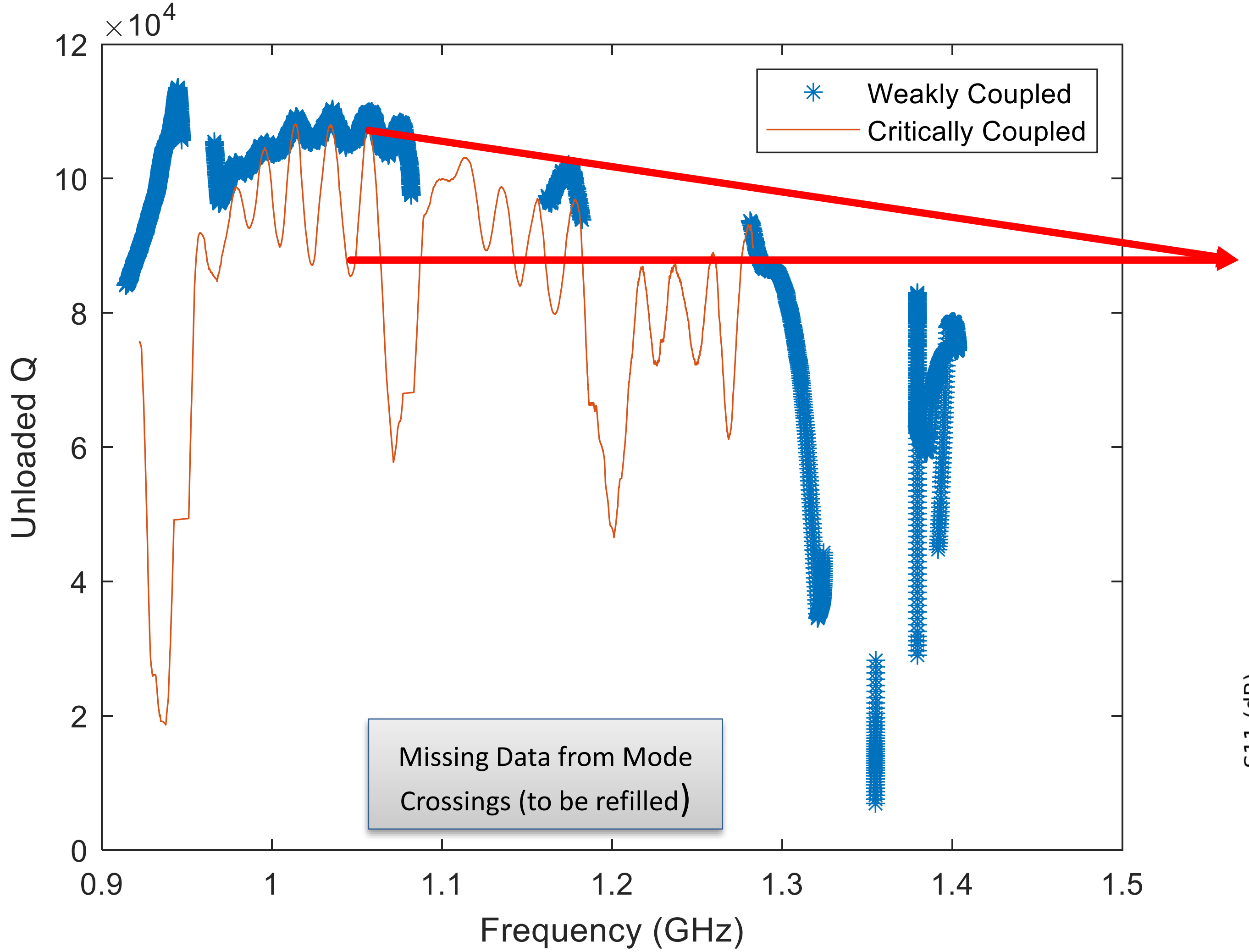
- Noise temperature of JPA is dependent on bias parameters of JPA
- JPA SNRI is optimized by adjusting the power of the JPA-pump tone and the JPA-bias current

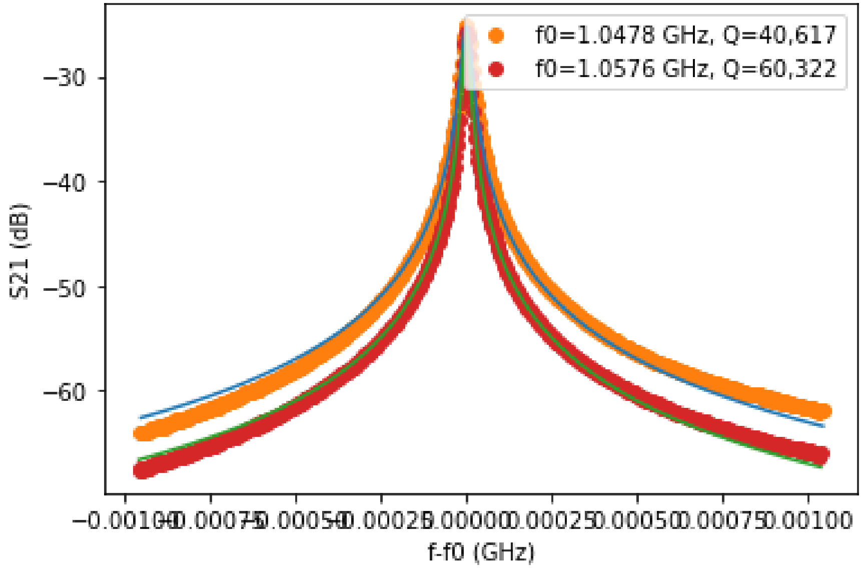


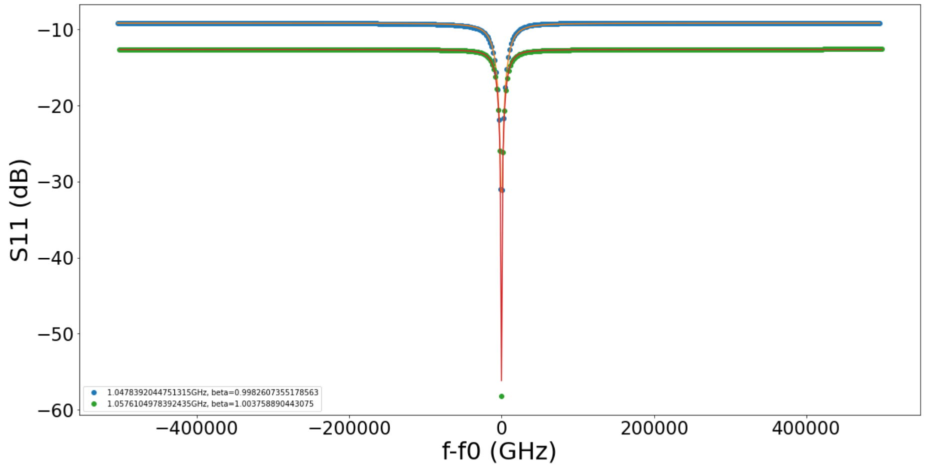
Critically Coupled: Modemap



1D: Quality Factor

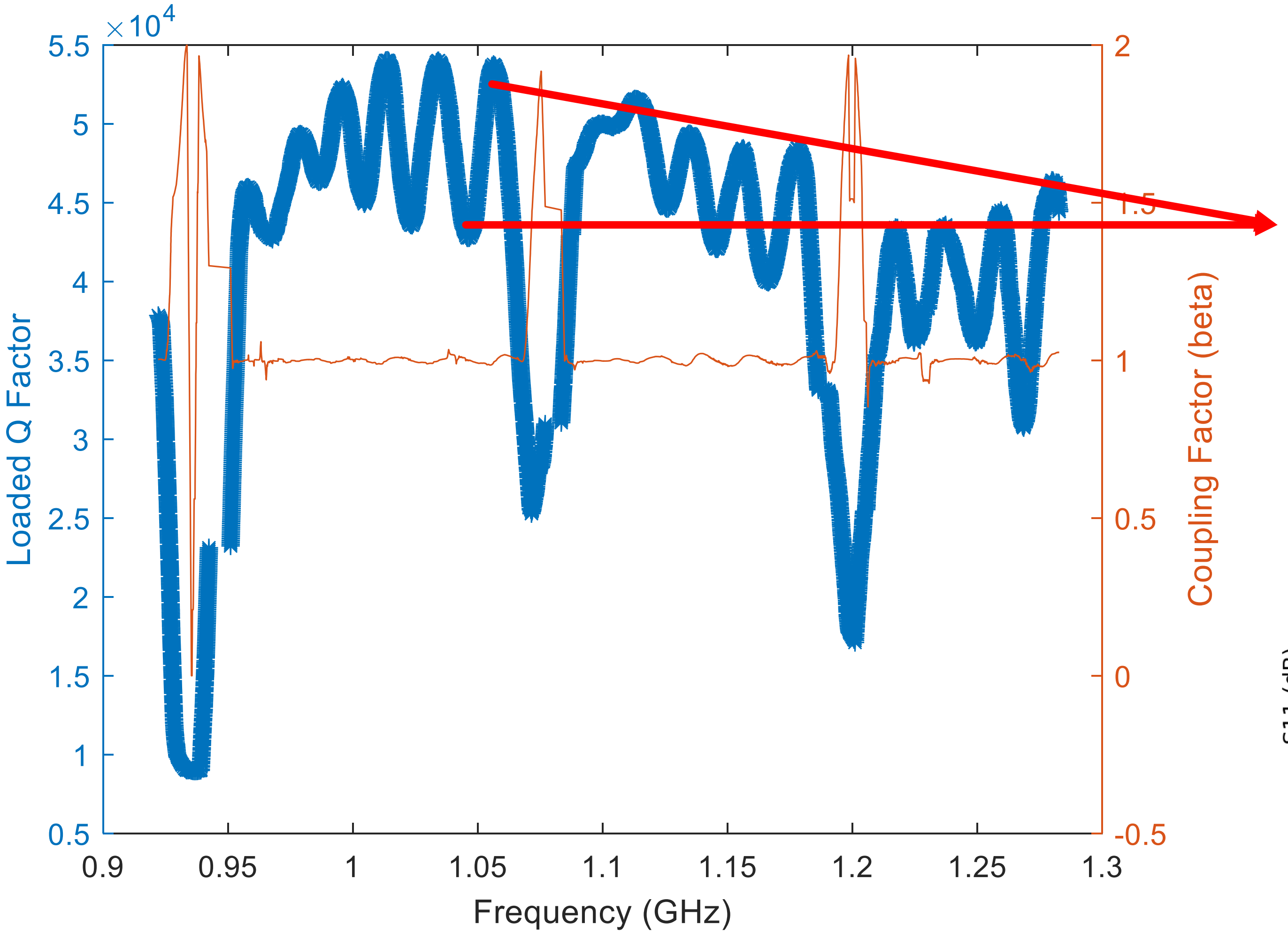


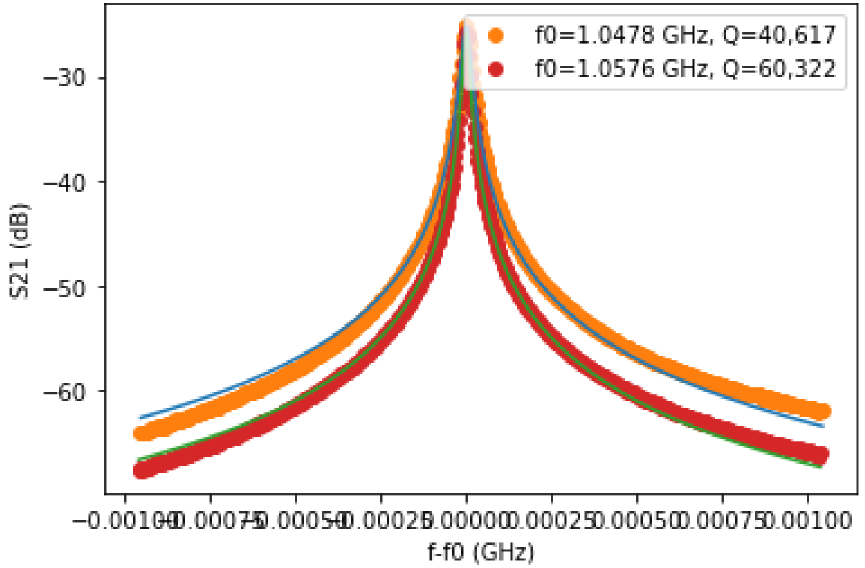


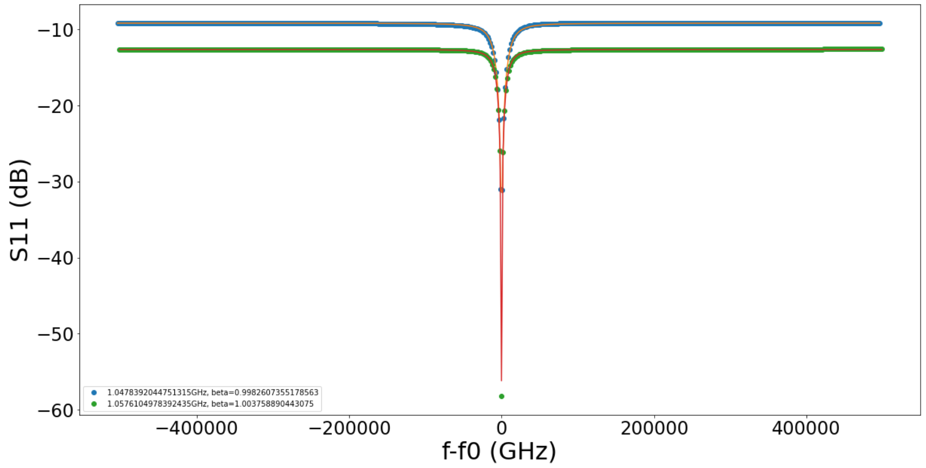


Change window zoom i

Critically Coupled: Quality Factor







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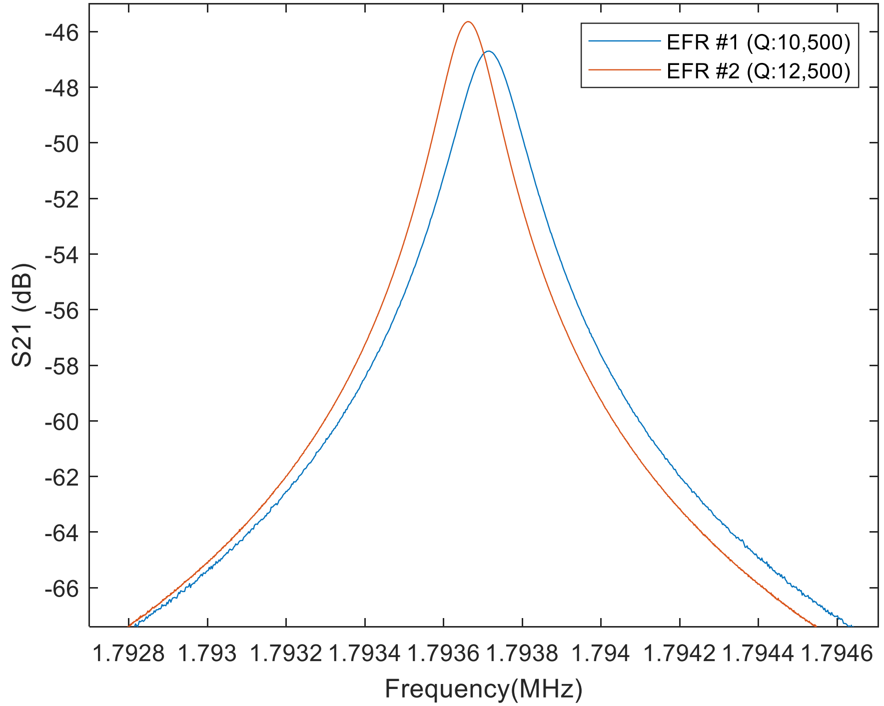
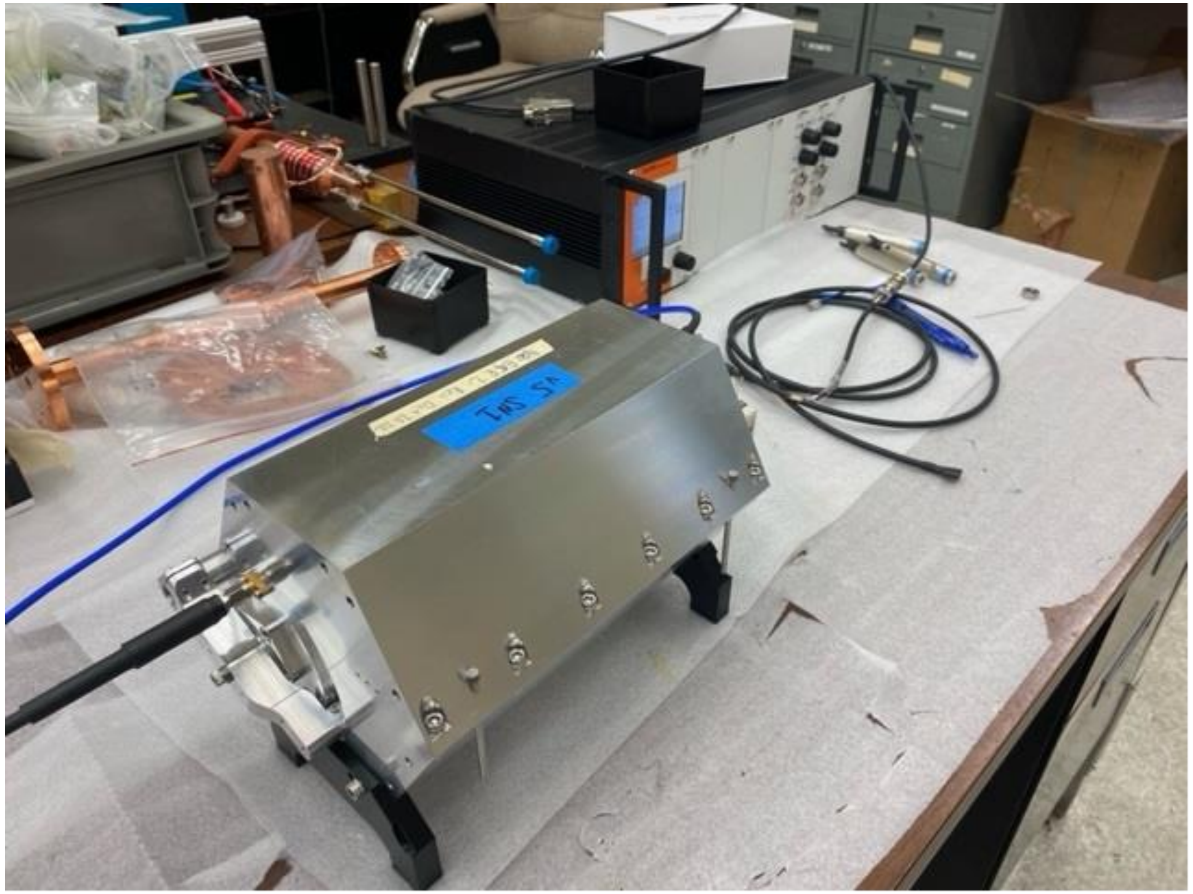
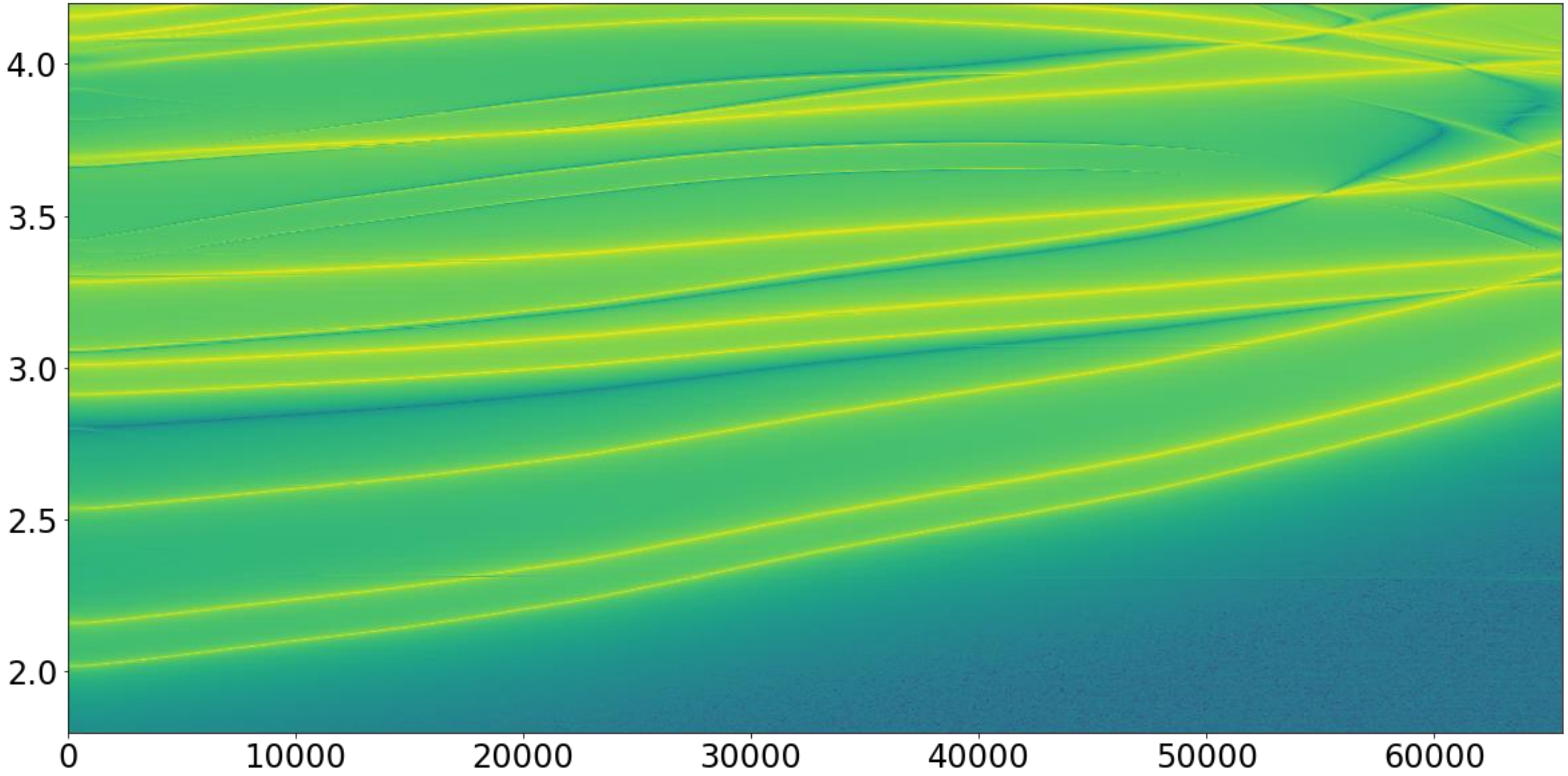
Warm Cavity Assembly

- Two cavities received from UF assembled warm
  - Slight difference in empty cavity Q's, surface finish?





Warm Modemap



Cryogenic Mounting of EFR

- Two-cavity system was mounted into LLNL DF unit
  - Cavities mounted in horizontal orientation with rotary piezo for tuning each cavity
    - Swapped sapphire axles with copper to improve on tuning rod thermalization
    - Rotary piezos heat sunk to still plate via copper braid; isolated from cavity via nylon space
  - Using fixed antenna (No room for linear drive)
- Run Objectives (Cooldown Jan. 27)
  - Demonstrate rotary motion of horizontal cavity system at mK temperatures
  - Obtain cryogenic modemap of EFR cavity
  - Understand thermalization of system
  - Implement two-cavity mode locking (Stretch!)