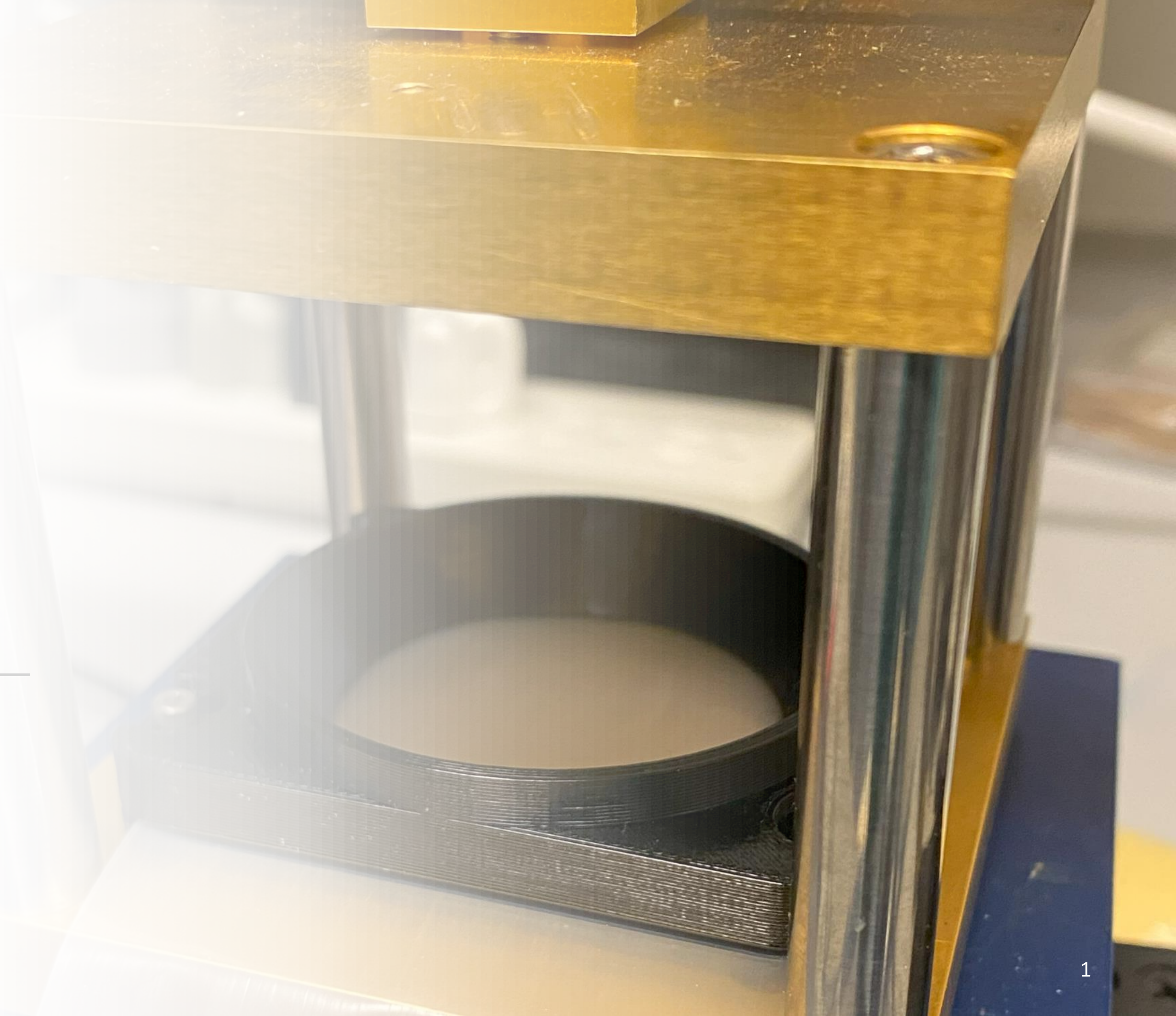
Fabry–Pérot Resonators in the Millimeter



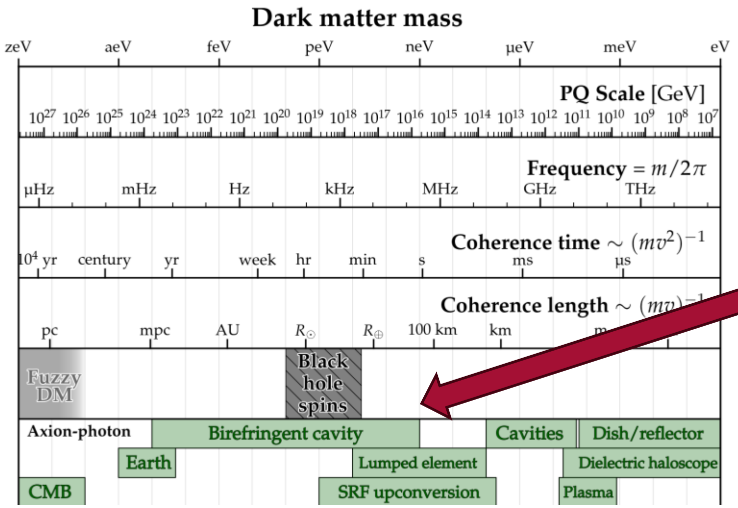
Brodi Elwood

BREAD Collaboration Workshop

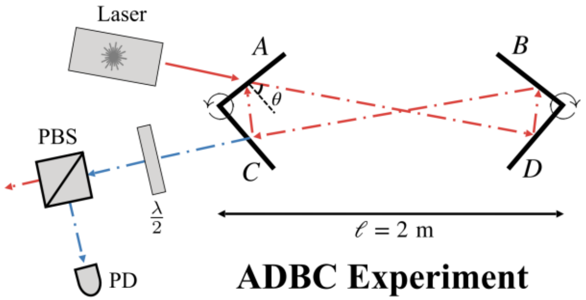
January 14, 2026

About

- Graduate student at Harvard working in John Kovac's group on the BICEP/Keck series of CMB polarimeters.
- Excited to be here, axion dark matter searches are where I cut my teeth on research.



O'Hare, *Zenodo* (2020)



Liu, Elwood, Evans & Thaler, *Phys Rev D.* (2019)

Outline

- Context and motivation for using high-Q resonant cavities for measuring the complex permittivity of dielectrics
- Design and implementation of high-Q Fabry–Pérot resonators
- Measurement technique and results
- Cryogenic measurements
- What's on the horizon?

Context & motivation

- In the CMB instrumentation community, we are interested in the **index and loss** of dielectrics from room to cryogenic temperatures.
- As receiver sensitivities improve, we become increasingly concerned with the uncertainty on loss in accounting for the white noise in our instruments.
- There is a growing need for rapid, **precise dielectric characterization under realistic operating conditions** to enable informed material selection for receiver optical design.
- Related applications of precise complex permittivity measurements in general mm/sub-mm instrumentation, such as with VLBI, line-intensity mapping, axion searches, and wide-field surveys.

What other complex permittivity measurements are reported in the literature?

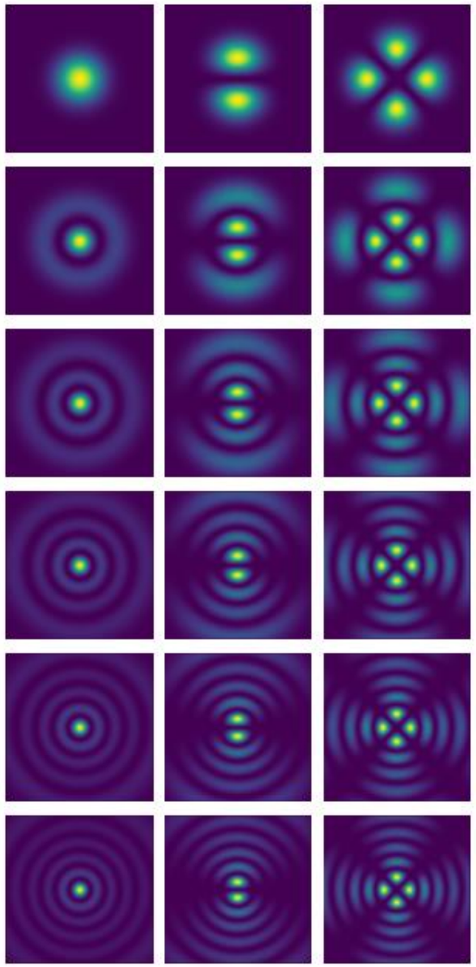
- For example, Lamb (1996) reports for Nylon:

Material	f (GHz)	T (K)	n	[illegible]	tan [illegible] 10^4	Ref.
Nylon	150 300 450	290	1.7267 1.7266 1.7268	2.9814 2.9812 2.9814	101 170 250	[36]
Nylon	100 200 300	300	1.730 1.729 1.729	2.993 2.993 2.995	8.8 12.5 16	[15]

- Index and loss depend on a dielectric's formulation, environmental, and thermal history.
  - How does Nylon's equilibrium moisture content impact loss?
- Waveguide-based methods for measuring complex permittivity tend to be narrowband, are impracticable at high frequencies (>75GHz), and suffer increased systematics at cryogenic temperatures.
- Methods using Fourier transform spectrometers suffer increased systematics for low-loss, thin materials.

Why open resonators?

- We seek a measurement with simple, directly observable quantities that depend strongly on refractive index and loss.
- The standing-wave modes of an open optical resonator are highly sensitive to both cavity optical length and round-trip loss.
- Field buildup in the cavity effectively integrates over many passes through the inserted dielectric sample.
- In particular, the TEM_{00} (fundamental) modes are readily measured.
    - By measuring how the resonance modes shift and broaden when the cavity is loaded, we can infer the sample material's index and loss.
- Inherently broadband



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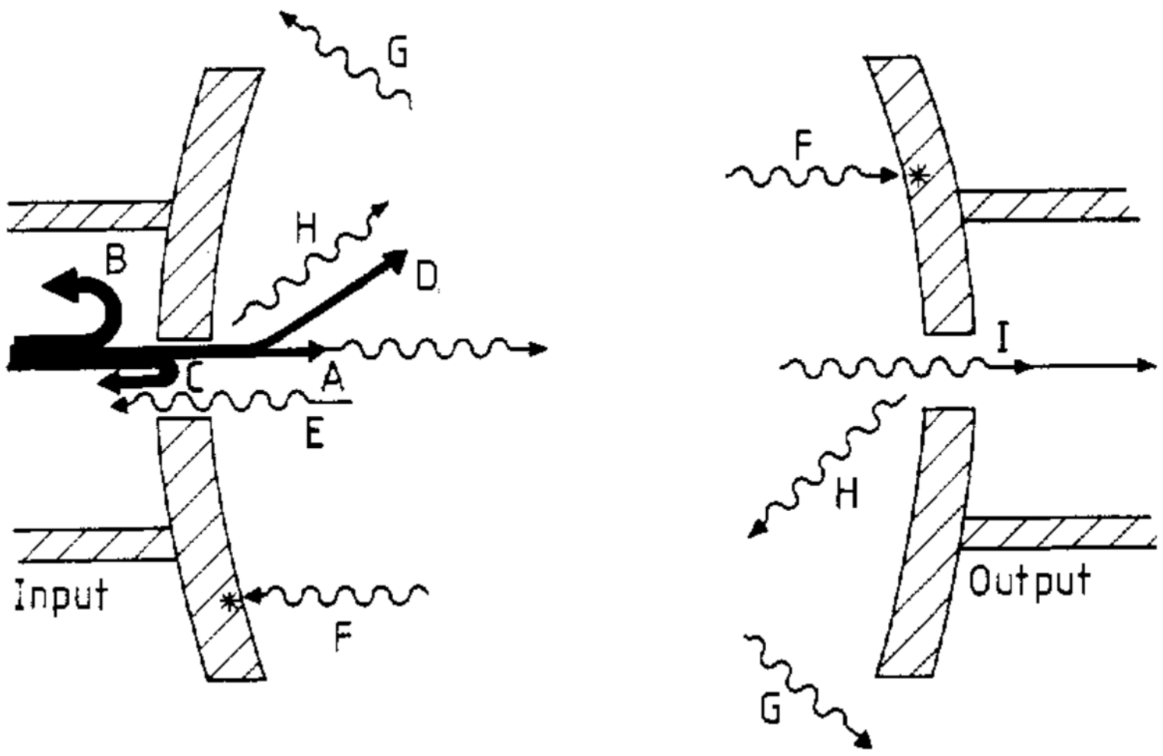
Losses in resonant cavities

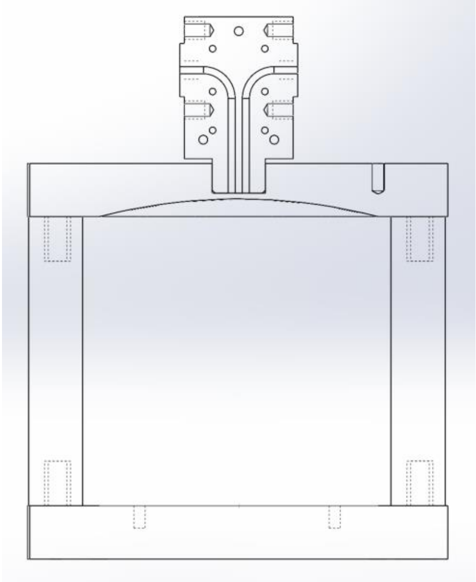
- To measure low-loss dielectrics, we must have high intrinsic quality factor.
  - Minimize cavity power losses and ensure effective coupling.
- We construct cavity quality factor such that we can measure low-loss materials while retaining enough transmitted power to stay above the transmission background of the apparatus.
- Must account for the sources of power loss intrinsic to the cavity:
  - Coupling losses from the aperture
  - Diffractive losses off the edges of the mirror and apertures
  - Resistive or scattering losses on the mirror surfaces



Clarke & Rosenberg (1982)

Designing a high-Q cavity

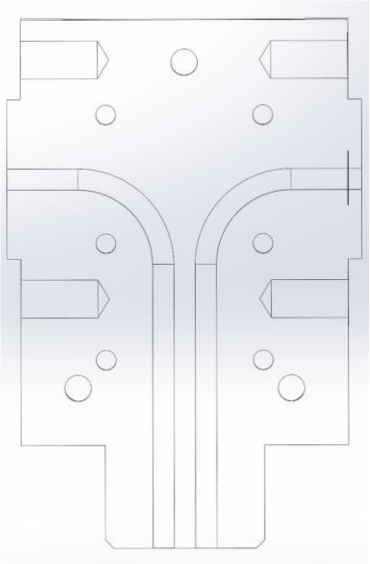
- We can limit diffraction losses by making the mirrors "large":
  - For mm-wave hemispherical cavities of reasonable lengths, the spot size at the spherical mirror is approx. 15 mm.
  - A spherical mirror diameter of approx. 50 mm results in minimal diffraction losses.
- In practice, intrinsic cavity loss is dominated by mirror losses and coupling.
- For our applications, the goal is to measure loss tangents on the order of $\approx 10^{-5}$, which requires a cavity with a Q-factor of ~100,000.

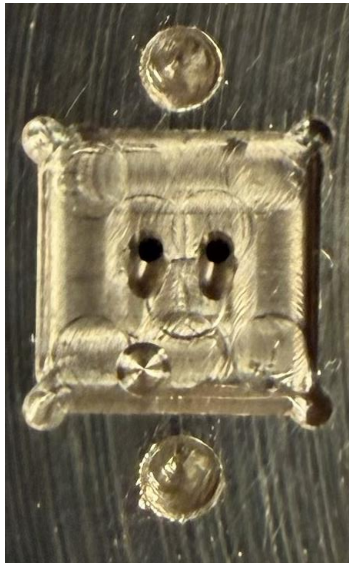


The coupling interface

$$Q_L = \frac{1}{1+\beta} Q_0$$

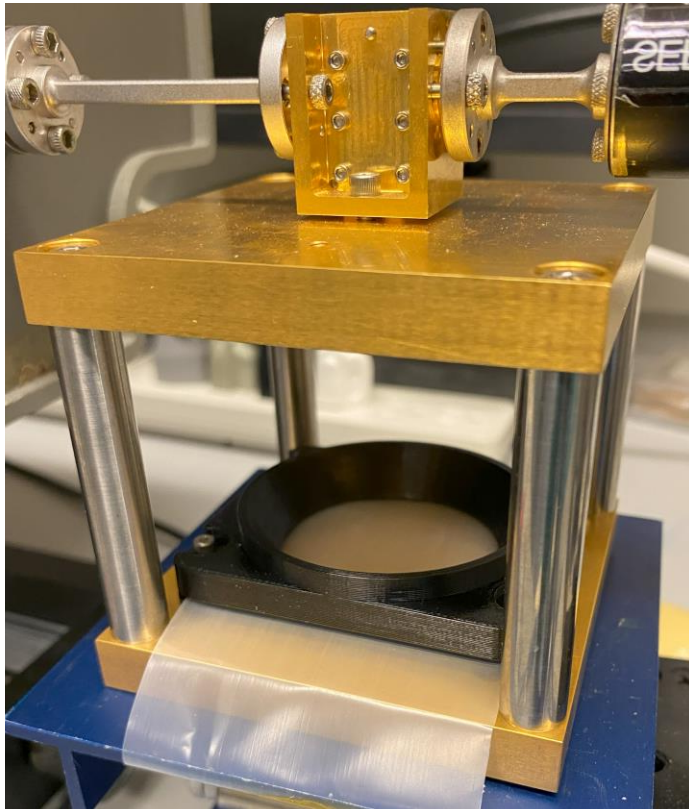
- Radiation is coupled into the cavity via a split-block waveguide butted into a recess in the spherical mirror.
- The coupling constant β (the ratio of cavity incident power to intrinsic power lost) parametrizes the power coupled into the cavity.
  - We use EMS to determine the aperture dimensions that give us the desired coupling.
  - Design balances sufficient signal coupling against the need to minimize cavity loss.

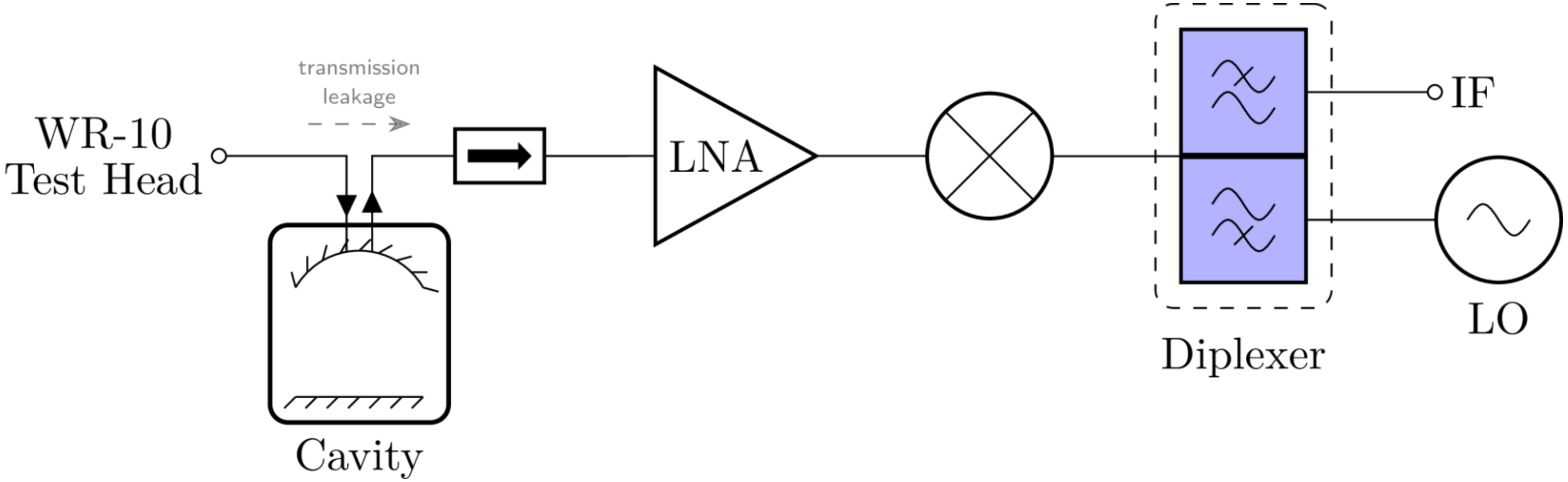




Quasioptical resonant cavities

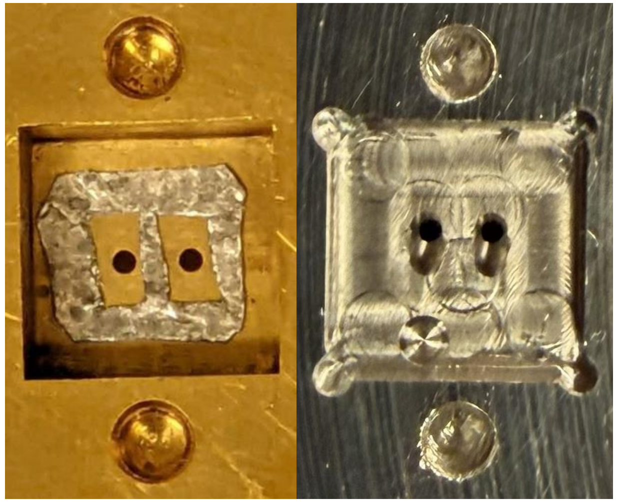
- A planar and a spherical mirror, separated by Invar struts, form a hemispherical open resonator.
- A low CTE material was chosen for the struts to minimize temperature-induced fluctuations in cavity length, which directly lead to fluctuations in resonant frequency.
- Dielectric samples are pressed against the flat mirror with a bracket fastened to the edges of the planar surface.

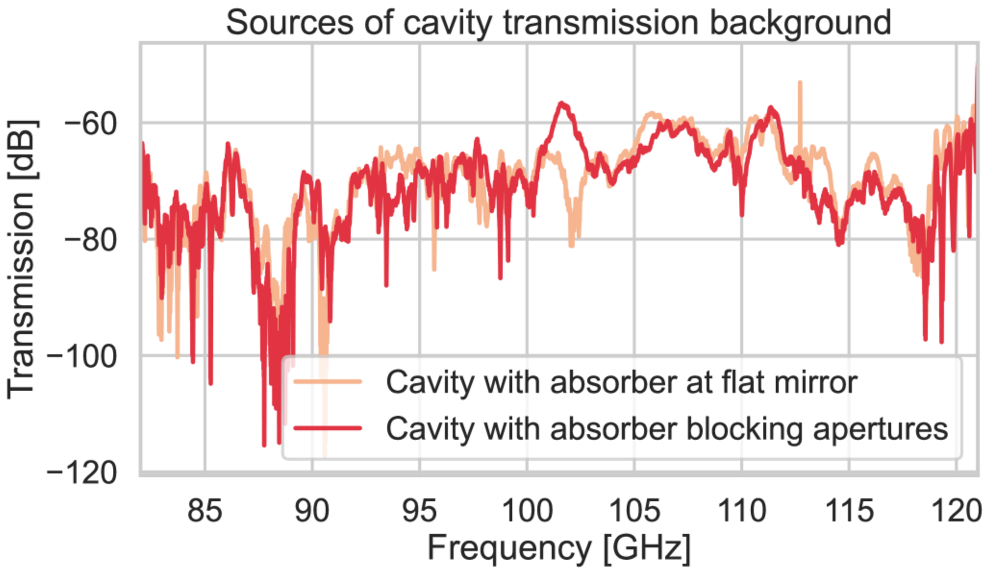




Mirror & coupling design

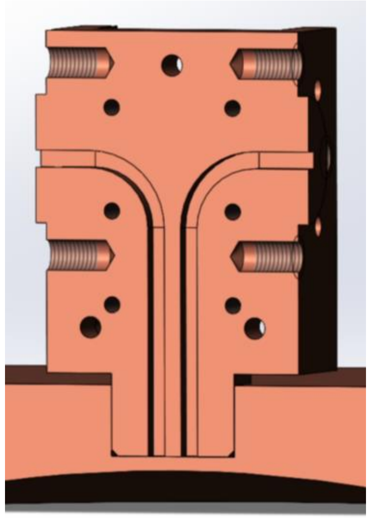
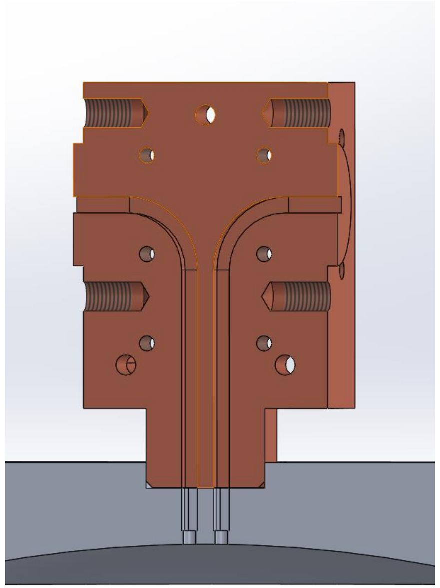
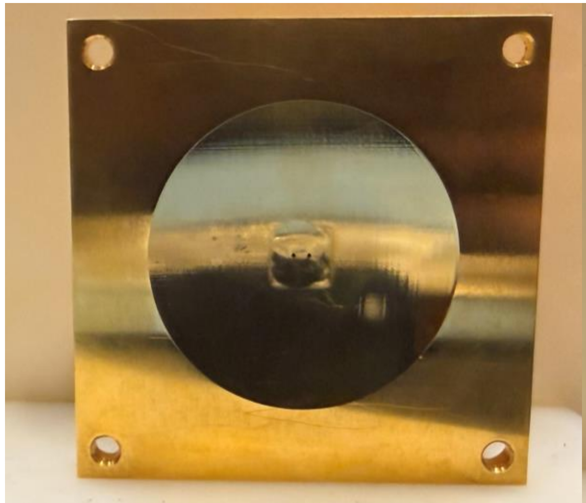
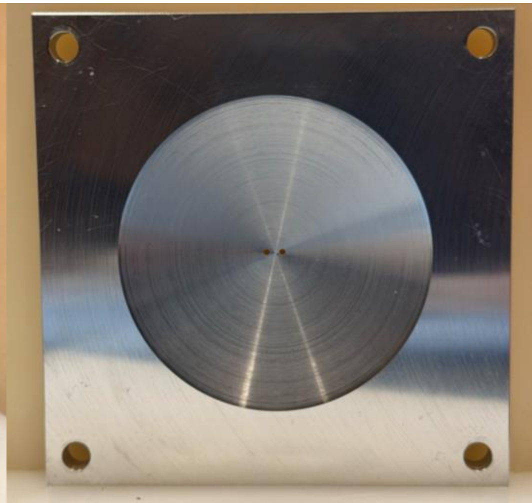
- High Q cavities output little power at the receiver; we can easily swamp out the signal by coupling power directly from the transmitter.
- There is coupling between the transmit and receive side at the mirror-coupling block interface.
- Without mitigation for this coupling, we cannot see the resonances!





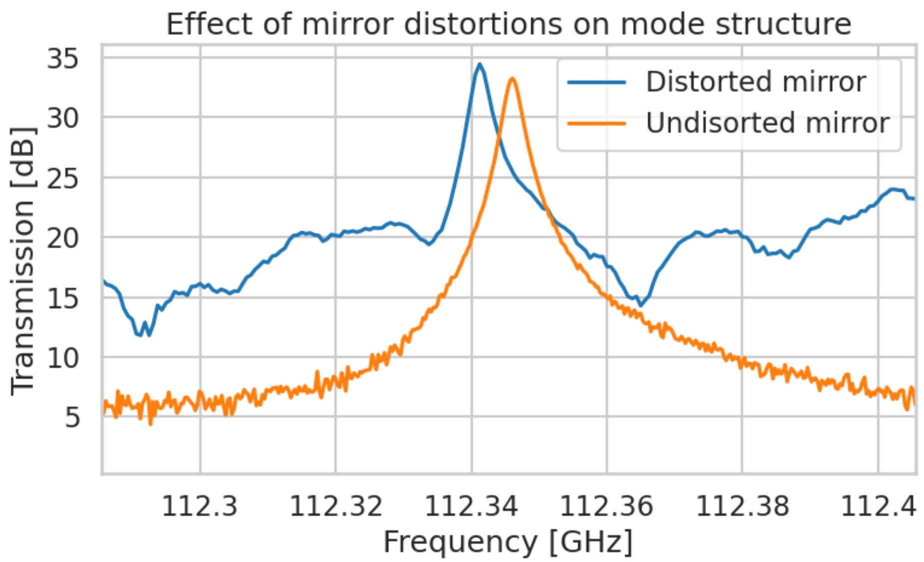
Improving mirror design

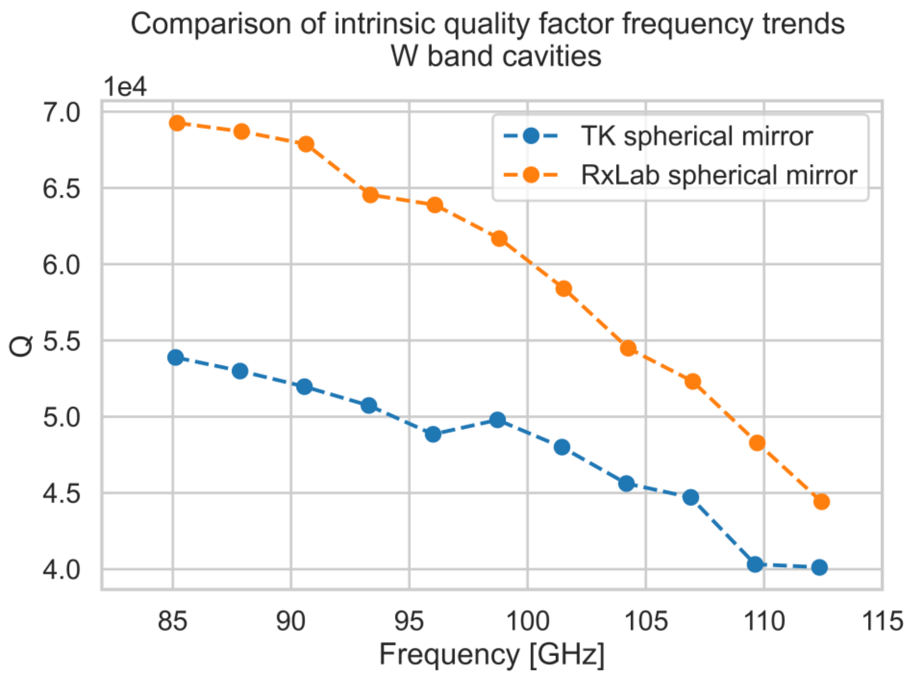
- Suppressing direct transmission requires good contact pressure on the mirror-coupling block interface.
- Increased attenuation by using a small indium gasket.
- Unfortunately, attempting a high-pressure mate tended to distort the spherical mirror.
- Solution: increase depth by machining waveguide structures into the spherical mirror.

Improved mirror design performance

- Demonstrated that the improved design performs to spec for W band.
- Mirrors are machined in-house, so we can rapidly iterate on designs.
  - Decided to use Al for ease of machining and increased hardness.
- New design more robust to reassembly of cavity or general mechanical perturbations to the coupling block (such as experienced on cooldown).
- Indium gasket no longer necessary, but we still would like ~60 dB of suppression.
  - Working on modeling choke structures in parallel.





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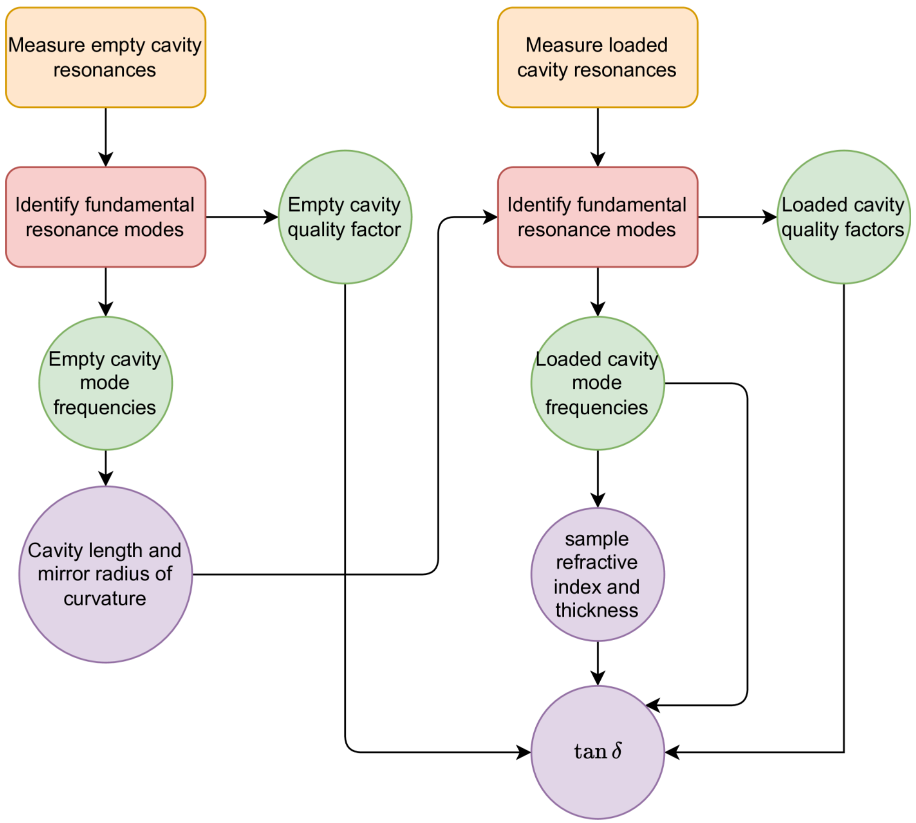
Overview of measurement procedure

- By perturbing the cavity with a dielectric sample, we can compare the loaded and unloaded fundamental modes to infer index and loss.
- Practically, two approaches to scanning cavity modes: sweep in frequency or sweep in cavity length.
    - **Frequency-variation method**
        - Natural way to approach with a VNA
    - Length variation method
        - Harder to implement, but cavity intrinsic coupling is the same between loaded and unloaded configurations, reducing systematics when measuring loss.



Index & loss results

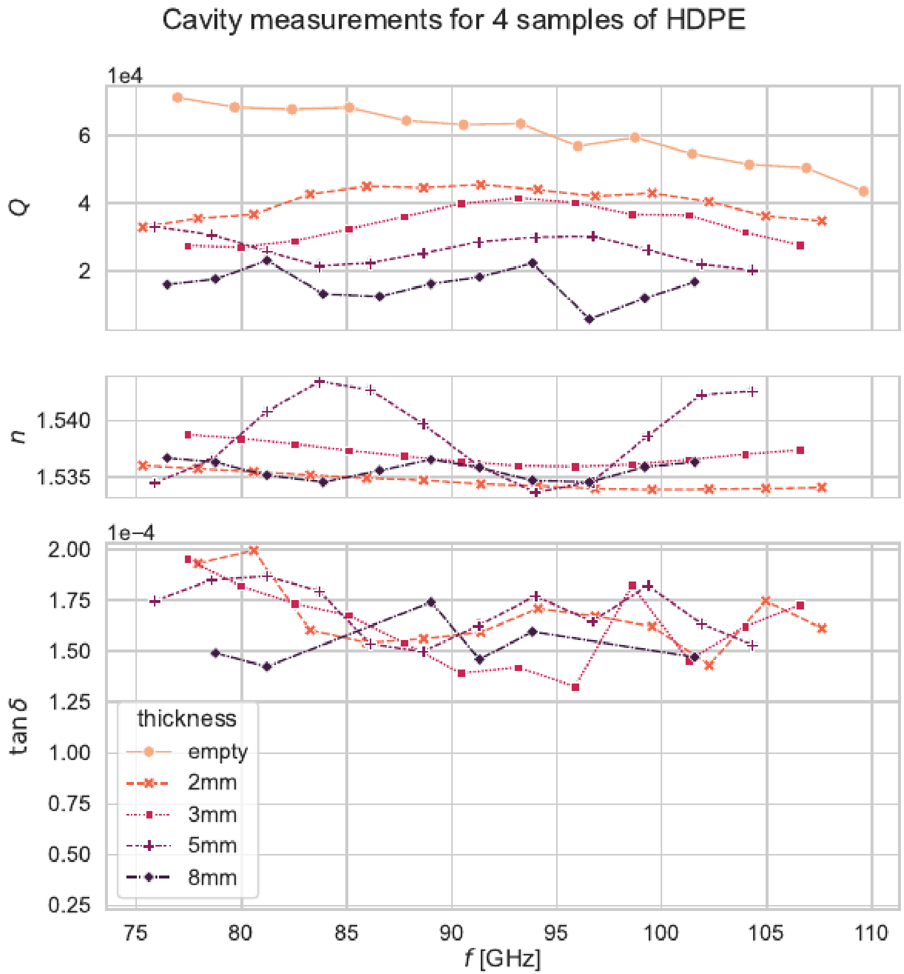
W-band Measurements

material	n	$\tan\delta$ ($\times 10^{-4}$)	**loss** (dB)
HDPE	1.537 ± 0.003	1.66 ± 0.18	-31
annealed HDPE	1.541 ± 0.004	1.48 ± 0.24	-32
UHMWPE	1.526 ± 0.007	1.43 ± 0.21	-32
LDPE			-52
low-loss Si	3.4230 ± 0.0001	1.47 ± 0.63	-30
Kyocera A479G Alumina	3.140 ± 0.005	3.94 ± 0.60	-

Preliminary

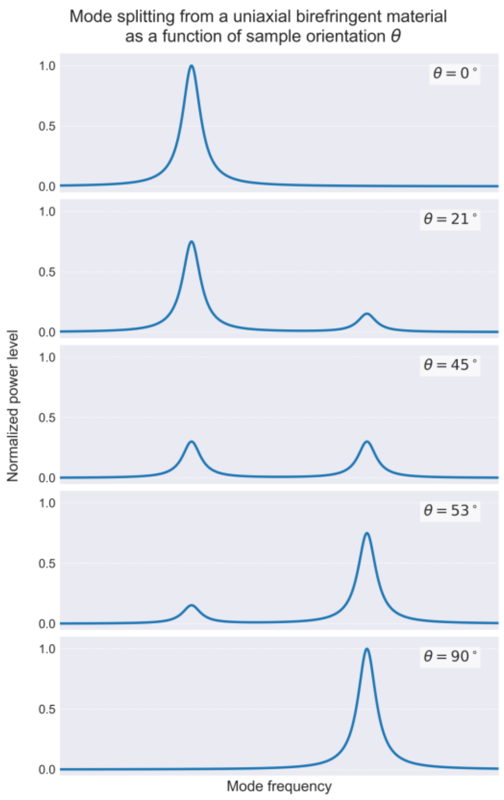
D-band Measurements

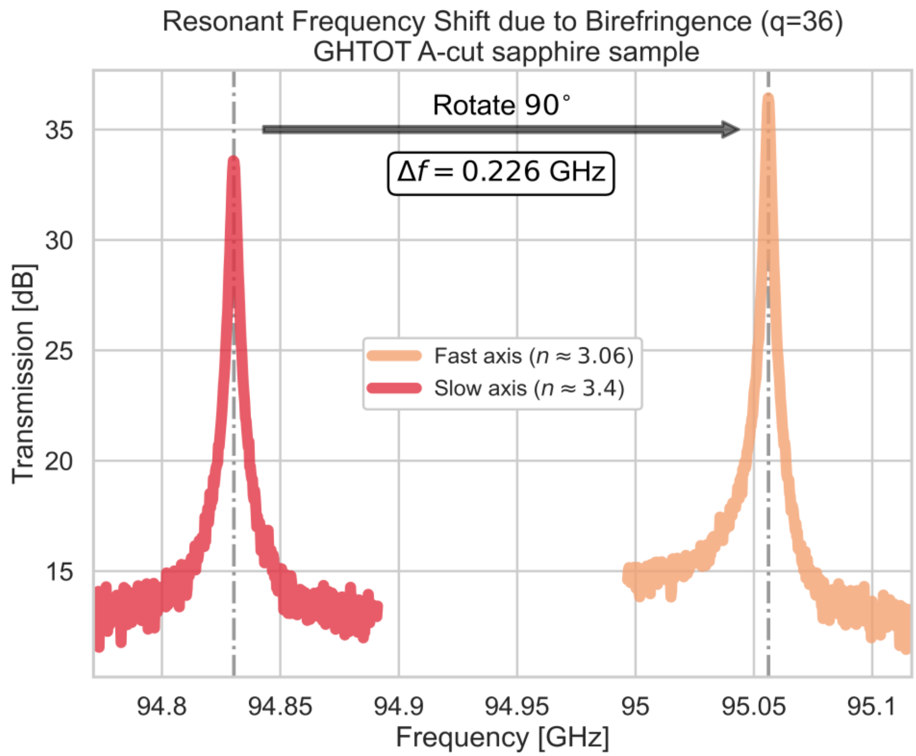
material	n	$\tan\delta$ ($\times 10^{-4}$)	**loss** (dB)
GHTOT Sapphire C cut	3.0647 ± 0.0007	2.3 ± 1.4	-



Birefringence

- By resolving the electric field vector along a uniaxial sample's two permittivity axes, we can obtain both permittivity values from the resulting two resonance modes.
- We can find the principal axes by rotating until we maximize the power in the fundamental modes.





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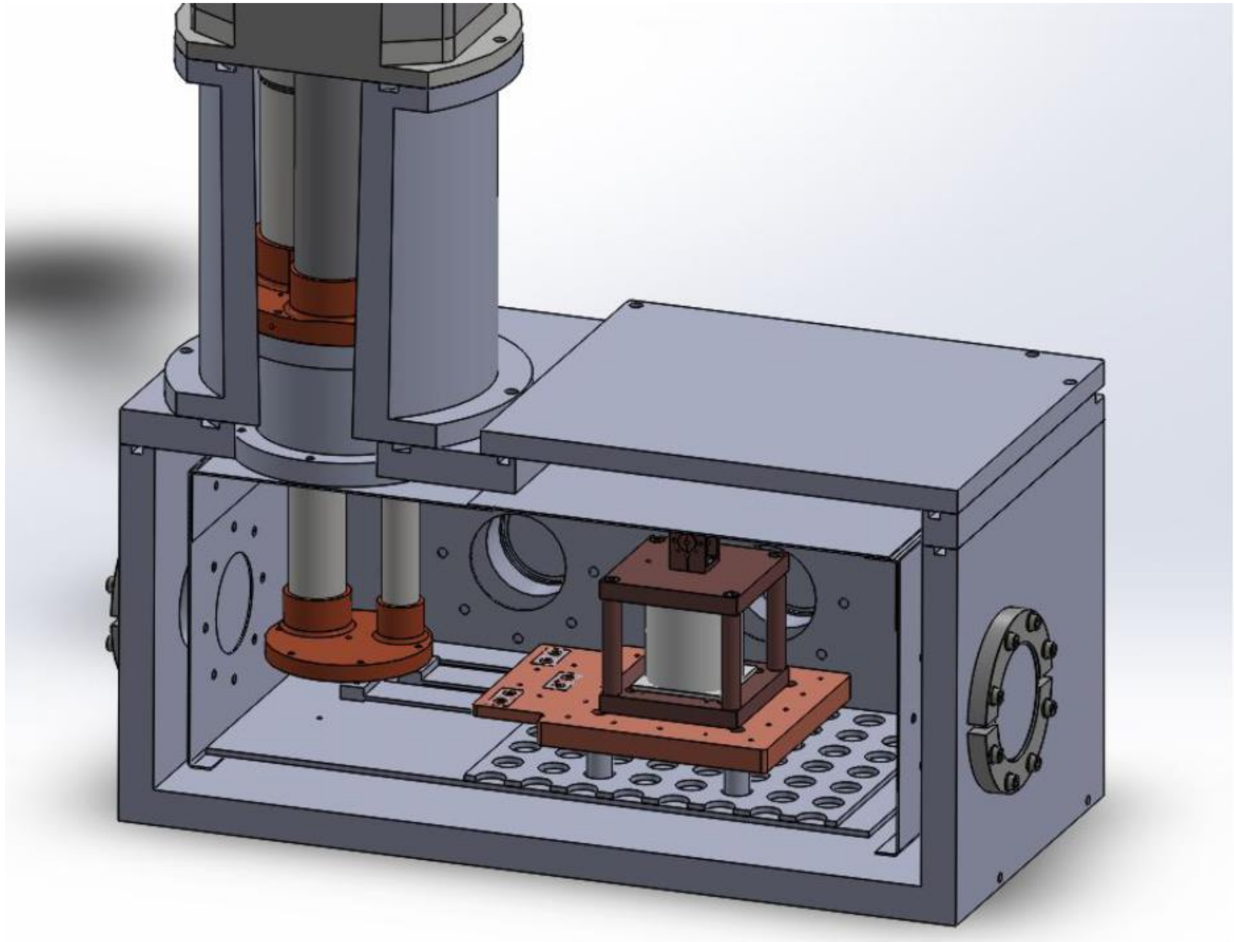
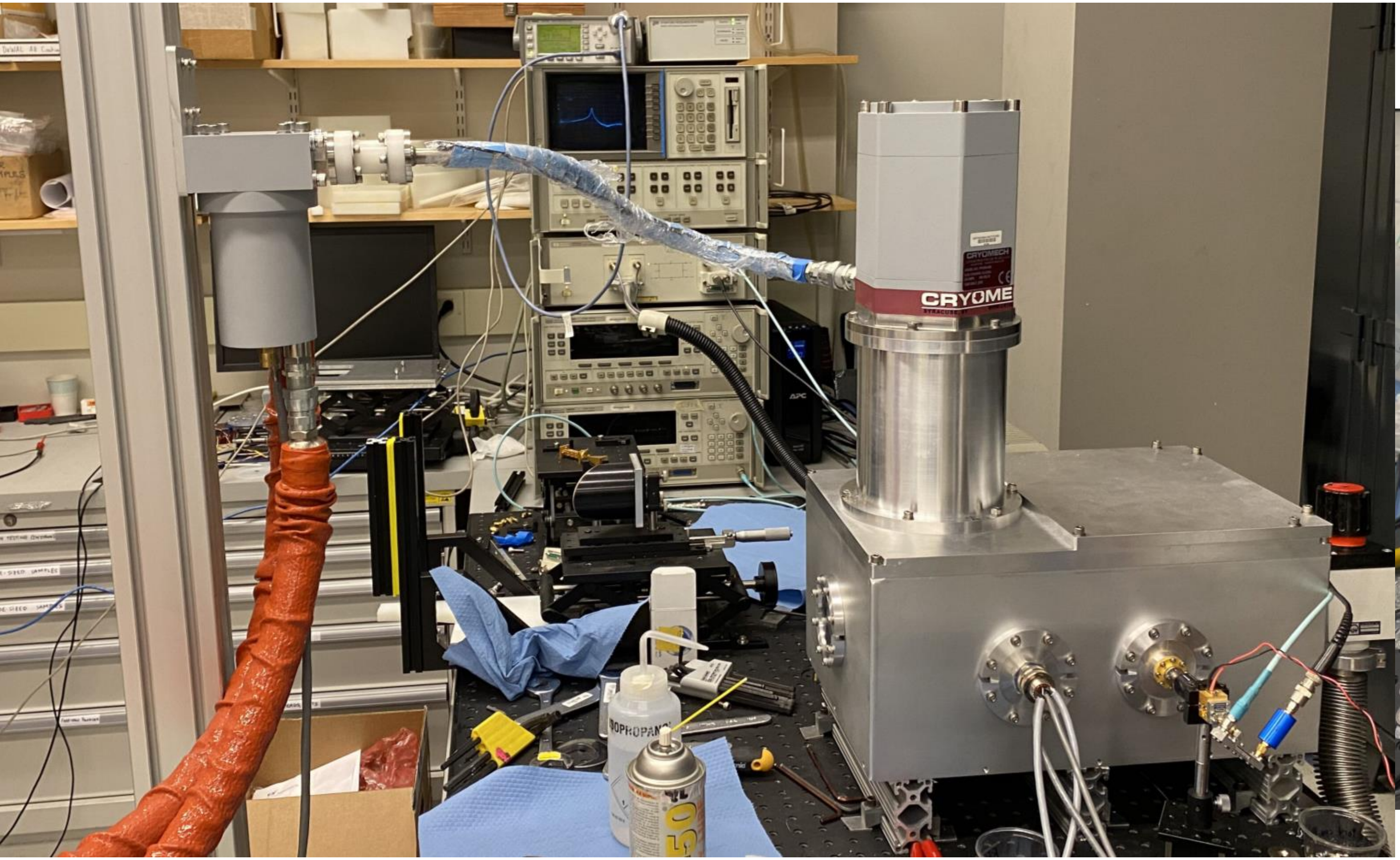
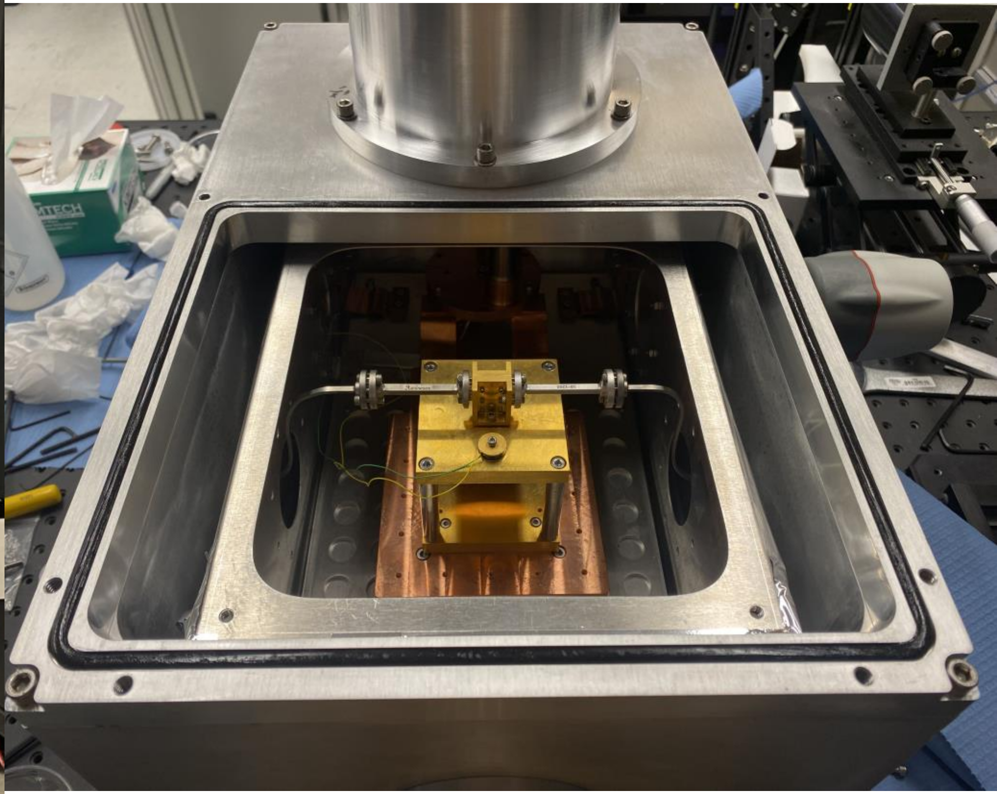
A quick-turnaround cryostat

- A relatively compact cryostat that enables cooling the cavity and samples down to 4K.
  - Approx. 3-4-hour turnaround time
- Use an off-the-shelf PT405 pulse tube cryocooler to cool an active area and radiation shield.

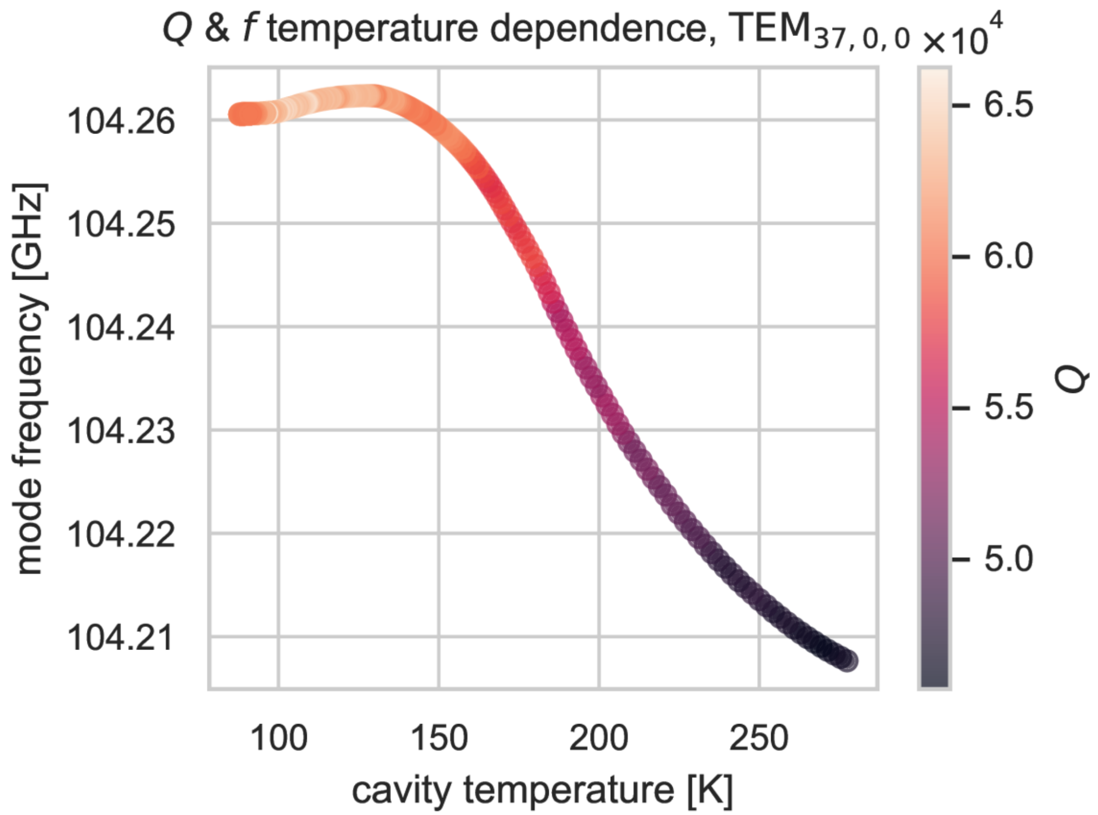






Empty cavity, cryogenic

- W-band cavity behaves as expected cryogenically.
  - Mode frequencies shift by amount expected by cavity length contraction.
  - In the first few cooldowns did not see issues from coupling-block induced distortions or worsening transmission leakage.
- Suspect improved mirror design will make cryogenic cavity more robust.



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  - We are planning on a measurement campaign this spring, targeting room temperature W-band measurements.
  - Hope to compile and publish our measurement results in the near future!