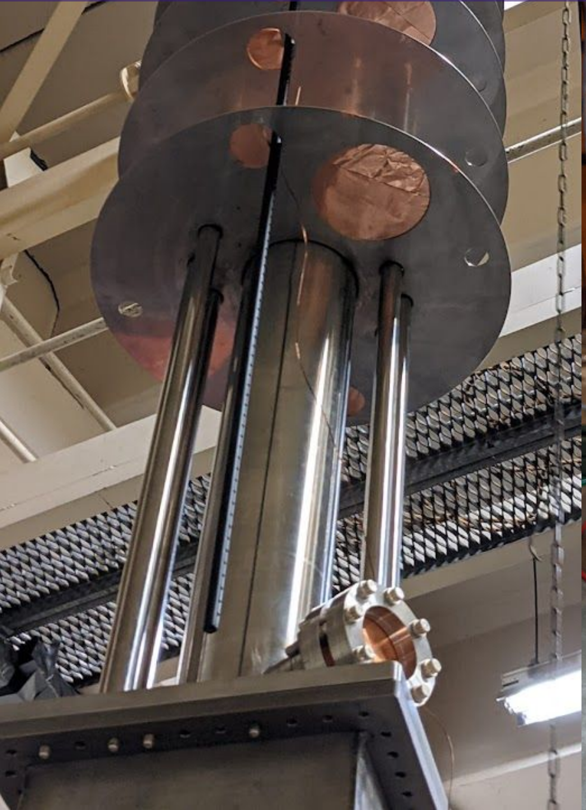
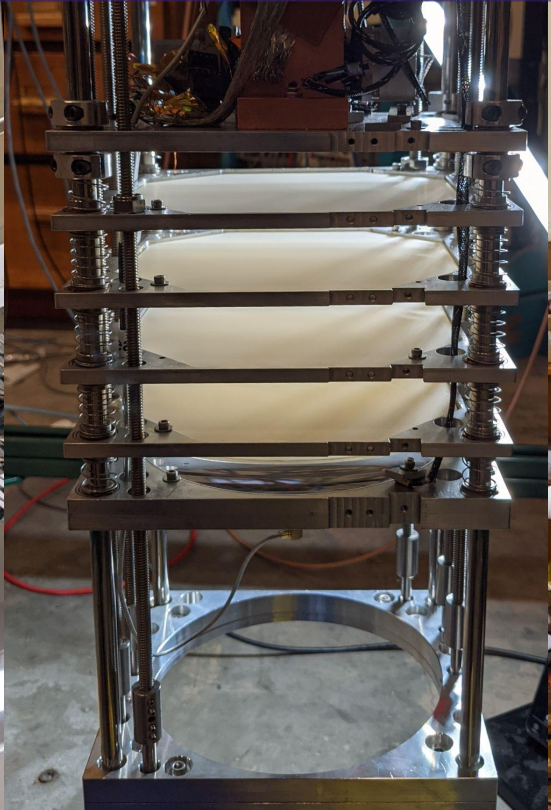
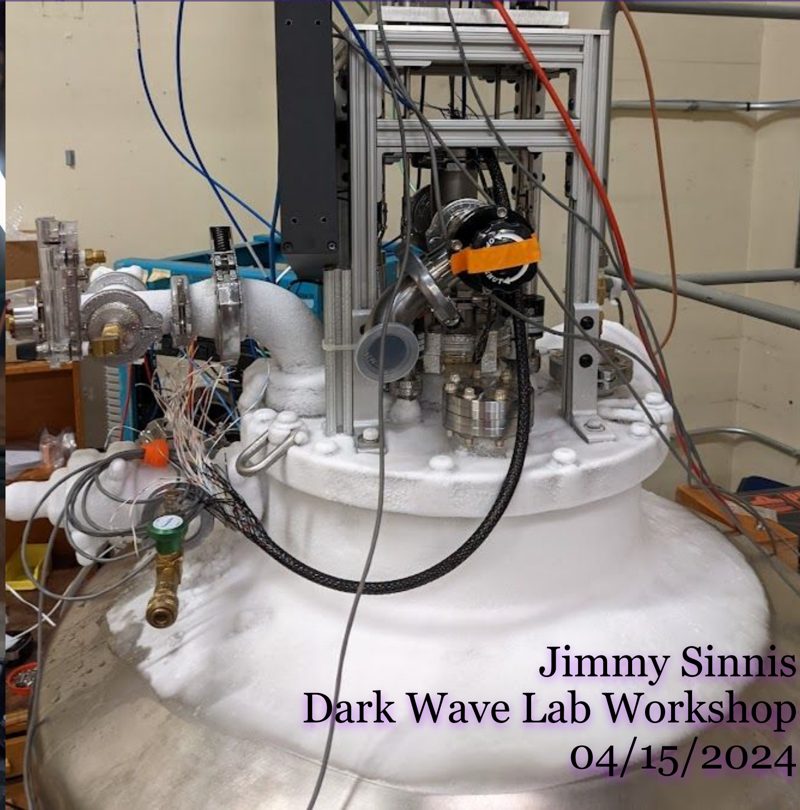
ADMX-Orpheus: a Tunable 16 GHz Cavity for Axion Searches



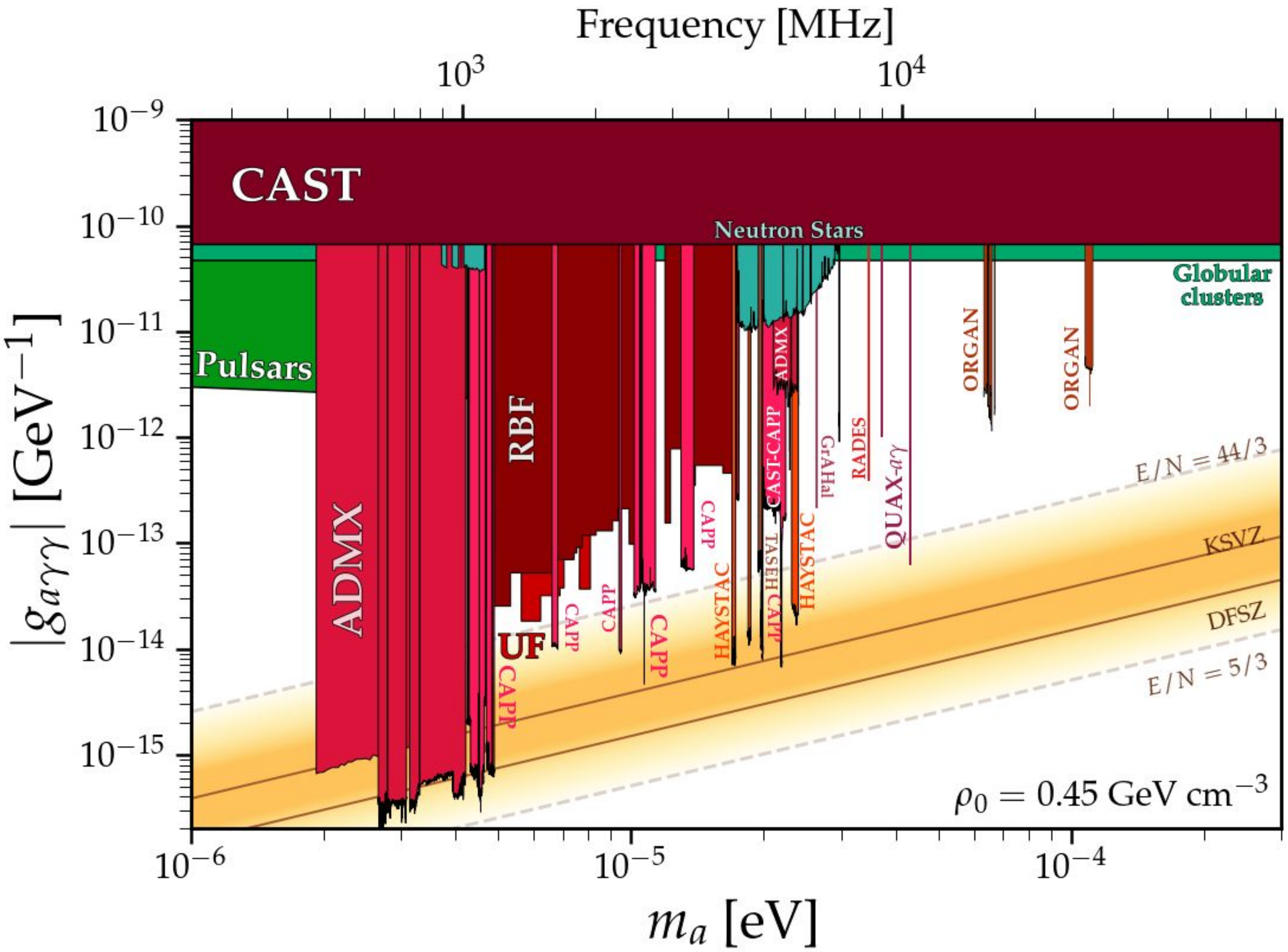




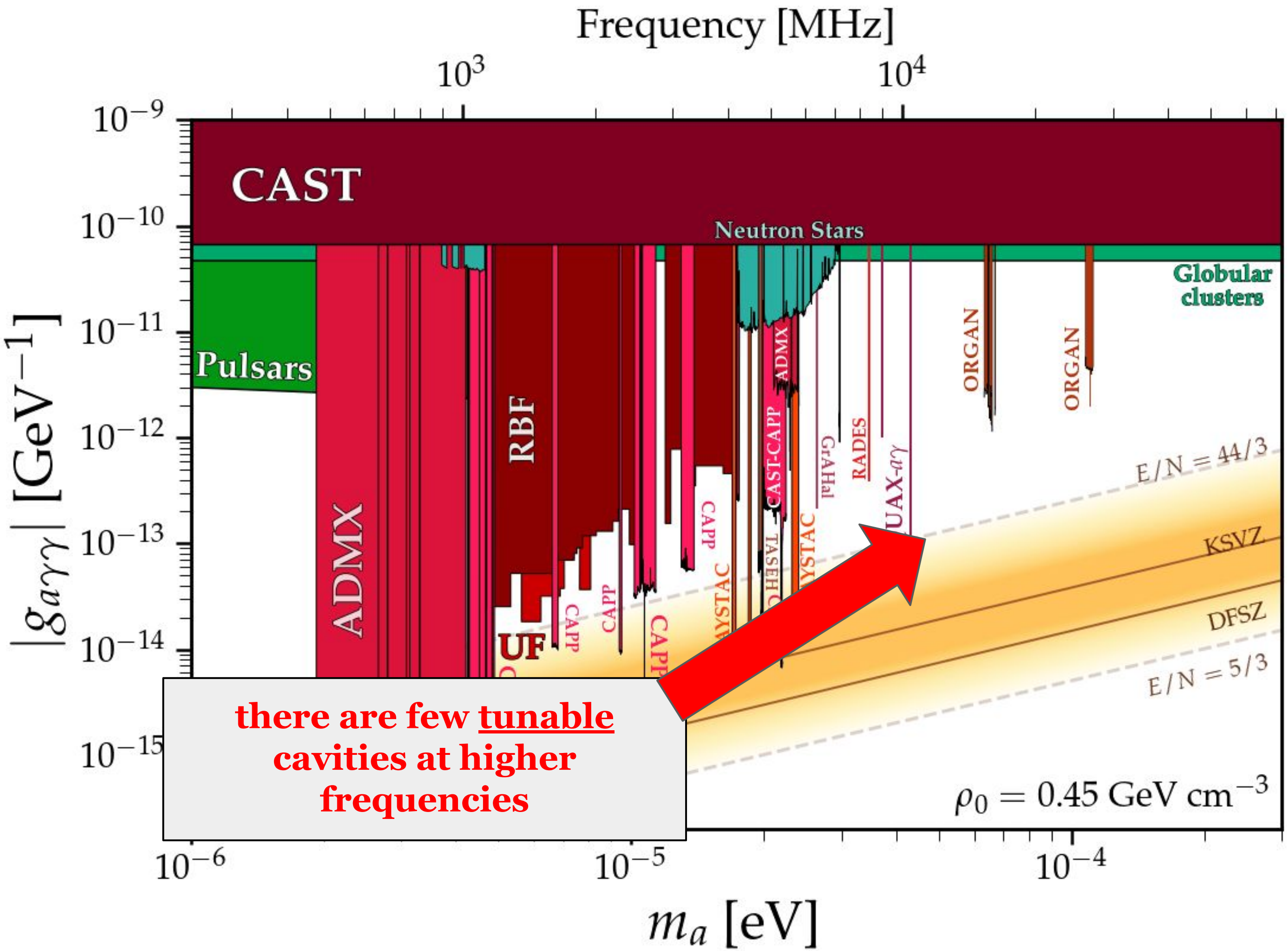
Jimmy Sinnis
Dark Wave Lab Workshop
04/15/2024

Overview of this talk

- How Orpheus searches higher frequencies
- Some technical details
- Current status and future work
- Points of improvement with existing technology



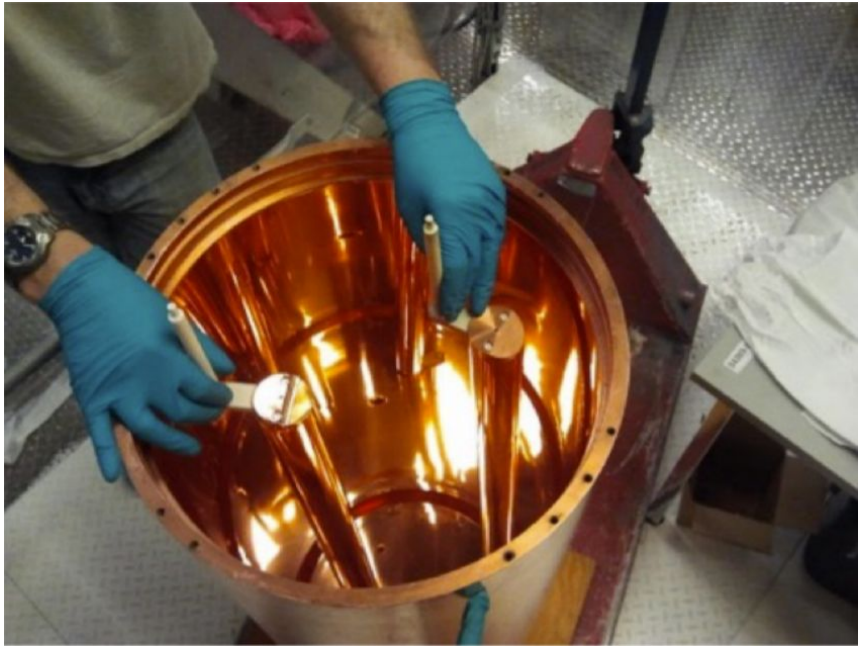
Frequency [MHz]
10^3
10^4
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
CAST
Neutron Stars
Globular clusters
Pulsars
ADMX
RBF
UF
CAPP
HAYSTAC
TASEH
CAST-CAPP
GrAHal
RADES
QUAX-$a\gamma$
ORGAN
E/N = 44/3
KSVZ
DFSZ
E/N = 5/3
$\rho_0 = 0.45$ GeV cm^{-3}
10^{-6}
10^{-5}
10^{-4}
m_a [eV]



there are few <u>tunable</u> cavities at higher frequencies

Axion haloscopes – ADMX

- Requirements to produce a signal:
  - Magnetic or electric field
  - Resonant structure
- Requirements to measure the signal:
  - Low temperatures
  - Coupling to resonator
- Innate constraints of conventional design:
  - Insensitive to higher-order modes
  - Smaller volumes for higher frequencies



$$P_a \propto V_{\mathrm{eff}} B_{\mathrm{ext}}^2 Q_L$$

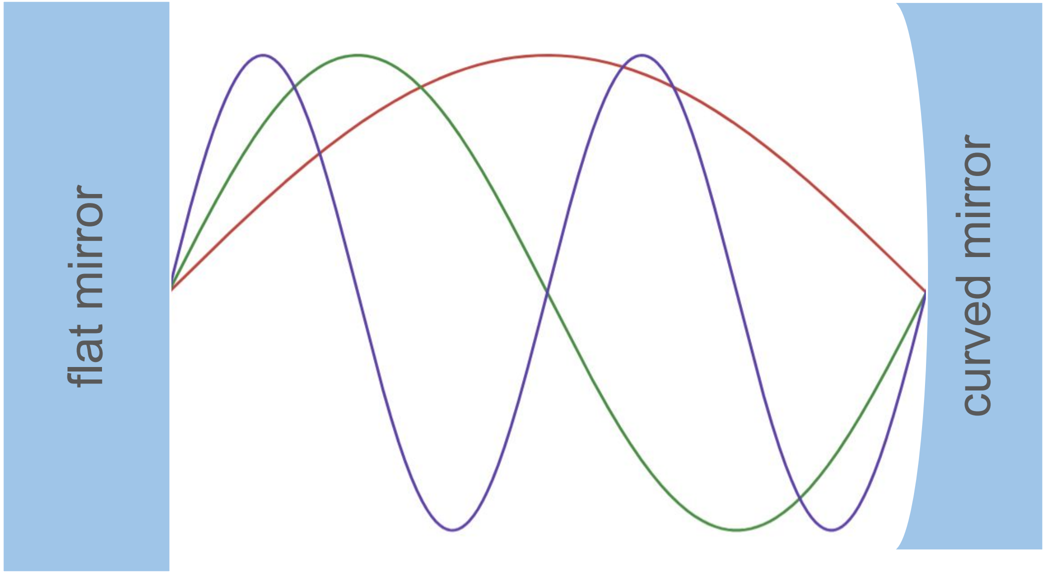
Effective volume decreases in higher frequency cavity modes.

$$V_{\text{eff}} \propto \left| \int \vec{E}(\vec{x}) \cdot \vec{B}_{\text{ext}} d^3x \right|^2$$

Design task: maintain large V_{eff} in a tunable cavity at higher frequencies

Design: Fabry-Perot Interferometers

- Standing waves between two mirrors
- We use the 18th order mode



Design: Fabry-Perot interferometers

- Fabry-Perot interferometers solutions:

$$u_{mn} = \frac{w_0}{w}\left[H_m\left(\sqrt{2}\frac{x}{w}\right)H_y\left(\sqrt{2}\frac{y}{w}\right)\exp\left(\frac{-\rho^2}{w^2}\right)\right]\exp\left(-i(kz-\varphi)-\frac{ik\rho^2}{2r}\right)$$

- The mode we search with has the form of a slightly modified sine wave:

$$u_{00} = \frac{w_0}{w}\exp\left(\frac{-\rho^2}{w^2}\right)\exp\left(-i(kz-\phi)-\frac{ik\rho^2}{2r}\right)$$

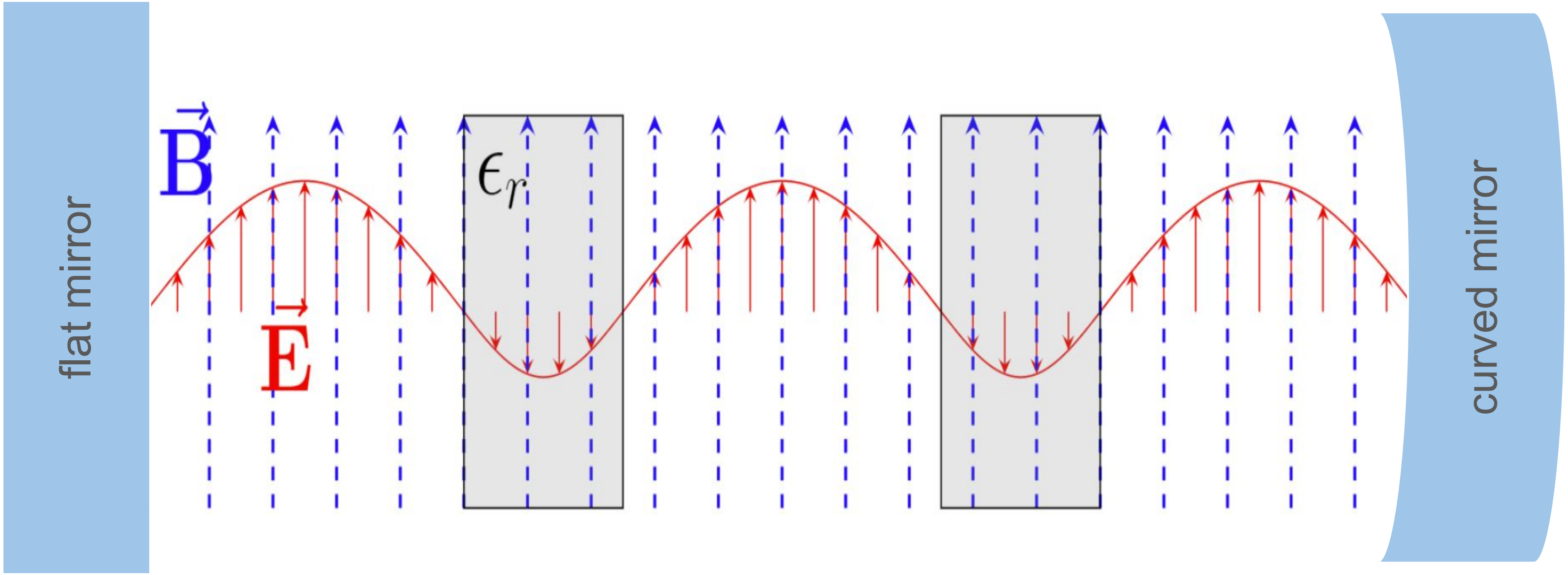
Design: Fabry-Perot interferometers

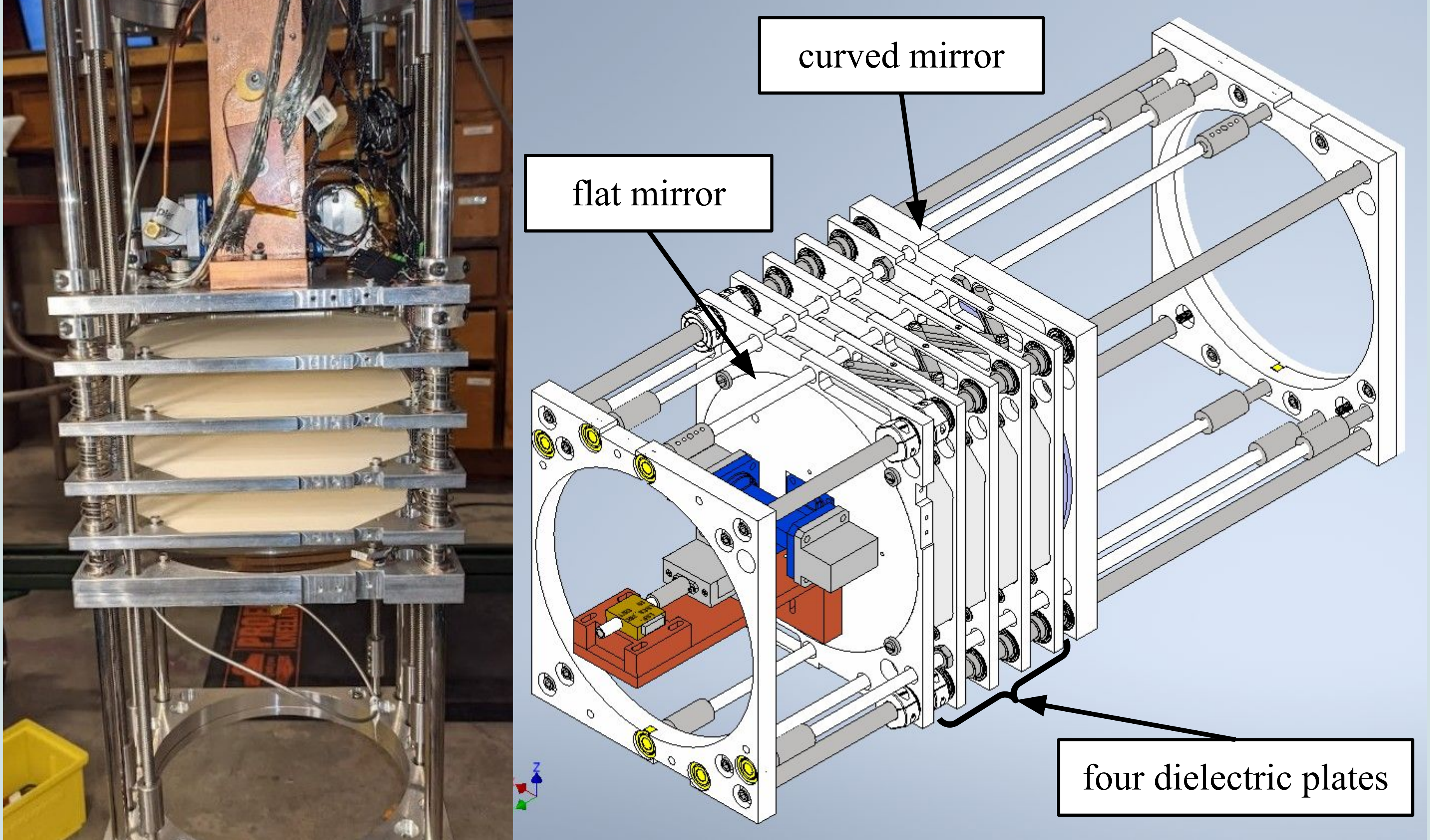
- Fabry-Perot interferometers solutions:

- The mode we search with has the form of a slightly modified sine wave:

$$u_{00} = \frac{w_0}{w} \exp\left(\frac{-\rho^2}{w^2}\right) \exp\left(-i(kz - \phi) - \frac{ik\rho^2}{2r}\right)$$

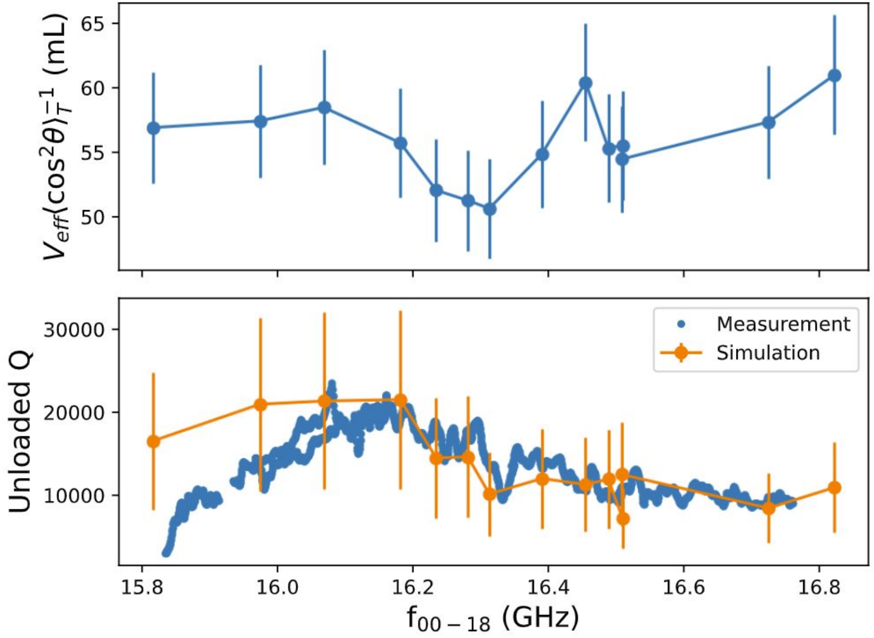
Apply a magnetic field and add dielectrics to couple axions to higher-order modes

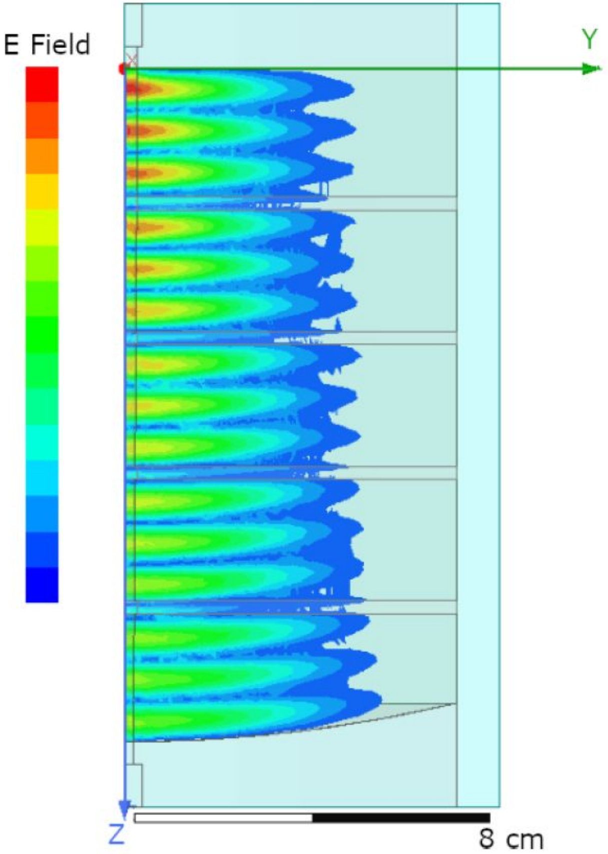



curved mirror
flat mirror
four dielectric plates

Simulations of the cavity

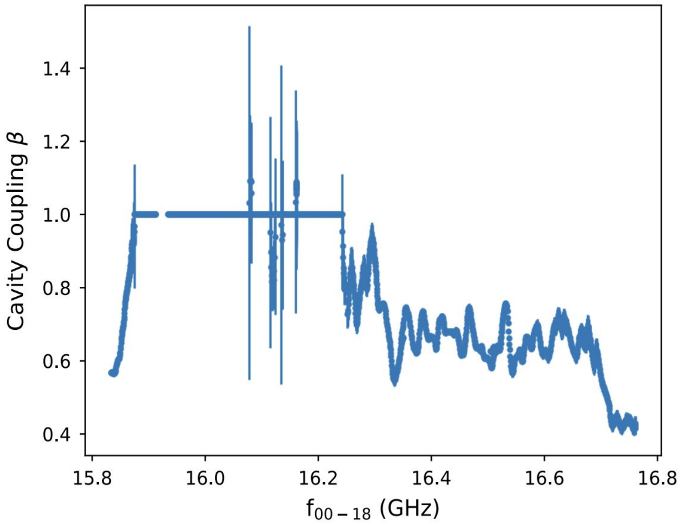
- 20 times the effective volume of traditional resonant cavity design at this frequency.

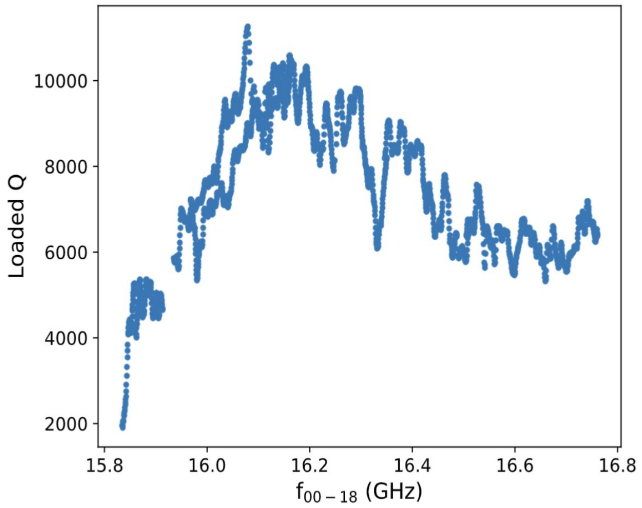


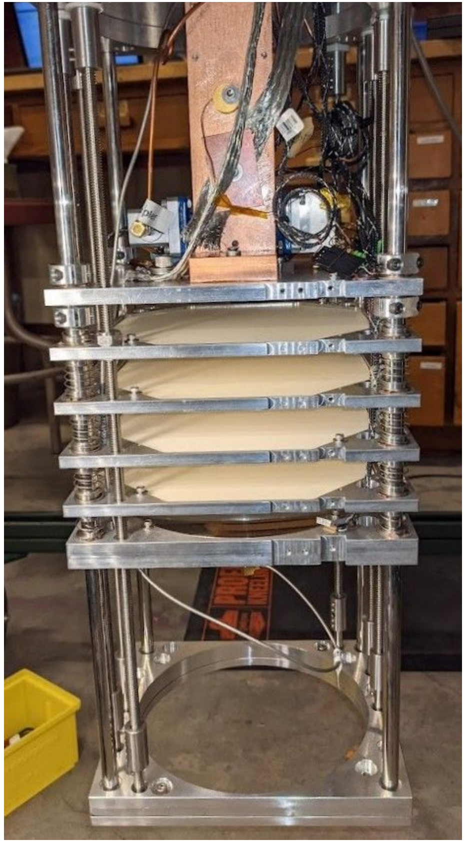


RF characterization of the real cavity

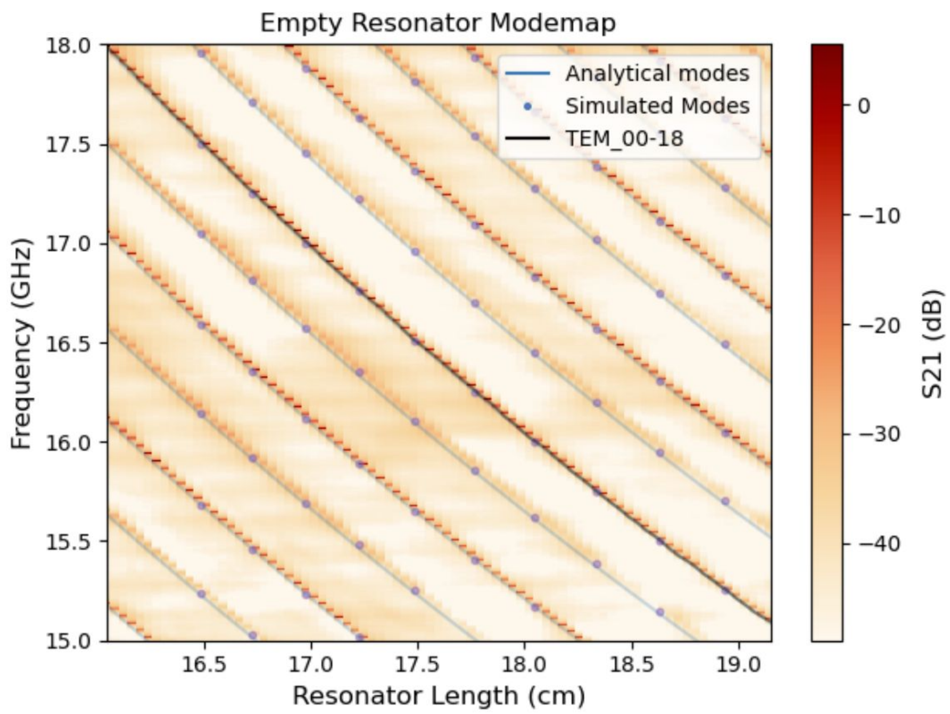
- Most losses are due to diffraction rather than ohmic losses
- We couple to the cavity with apertures in both mirrors



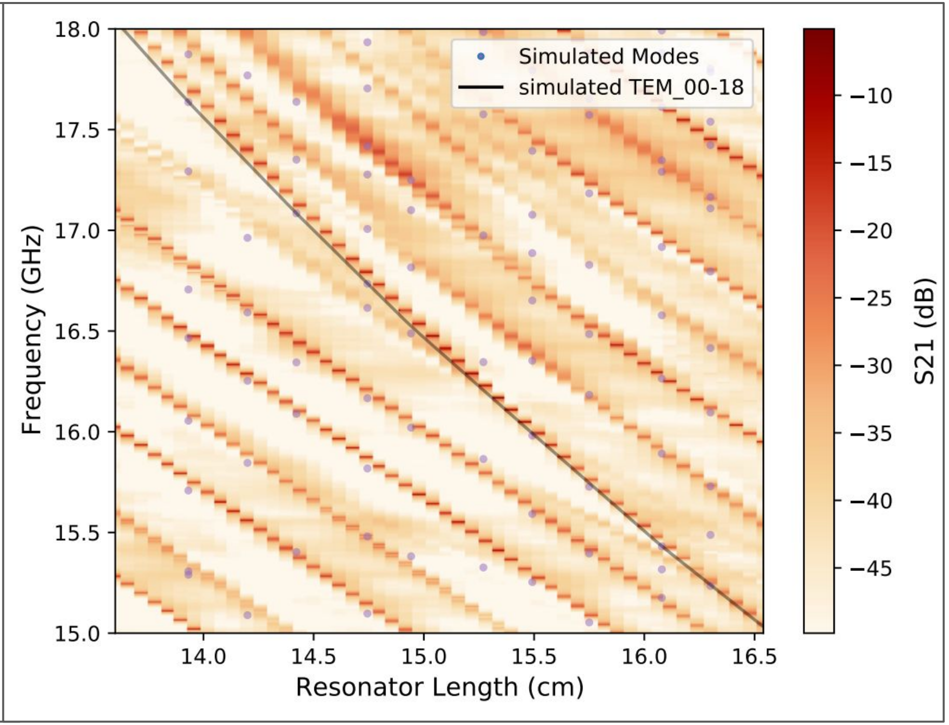




empty resonator

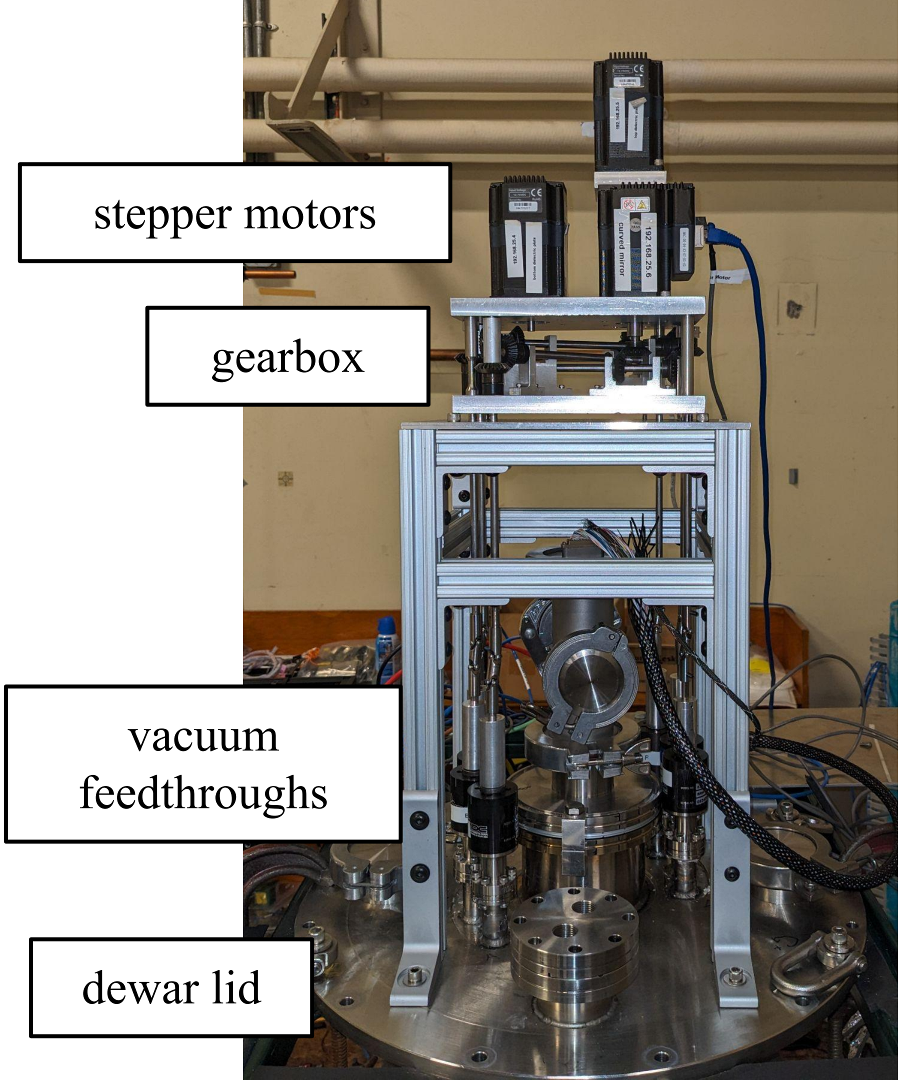


dielectrics added



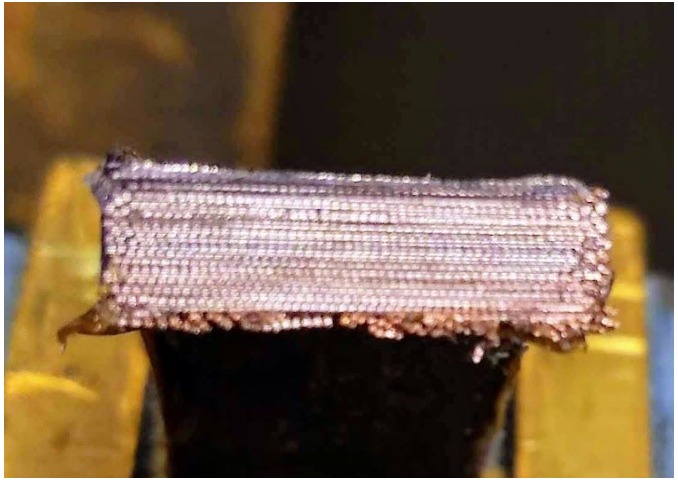
Tuning mechanism

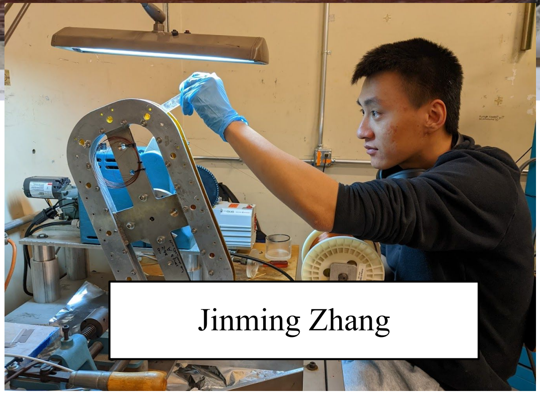
- Three stepper motors control:
    1. Curved mirror position
    2. Top dielectric plate position
    3. Bottom dielectric plate position
- The flat mirror is fixed and the spacing of the plates is regulated by scissor jacks
- steel and g-10 rods couple to the moving parts of the cavity
- We have tuned when the insert was cooled to 4K



Magnet design: dipole racetrack magnet

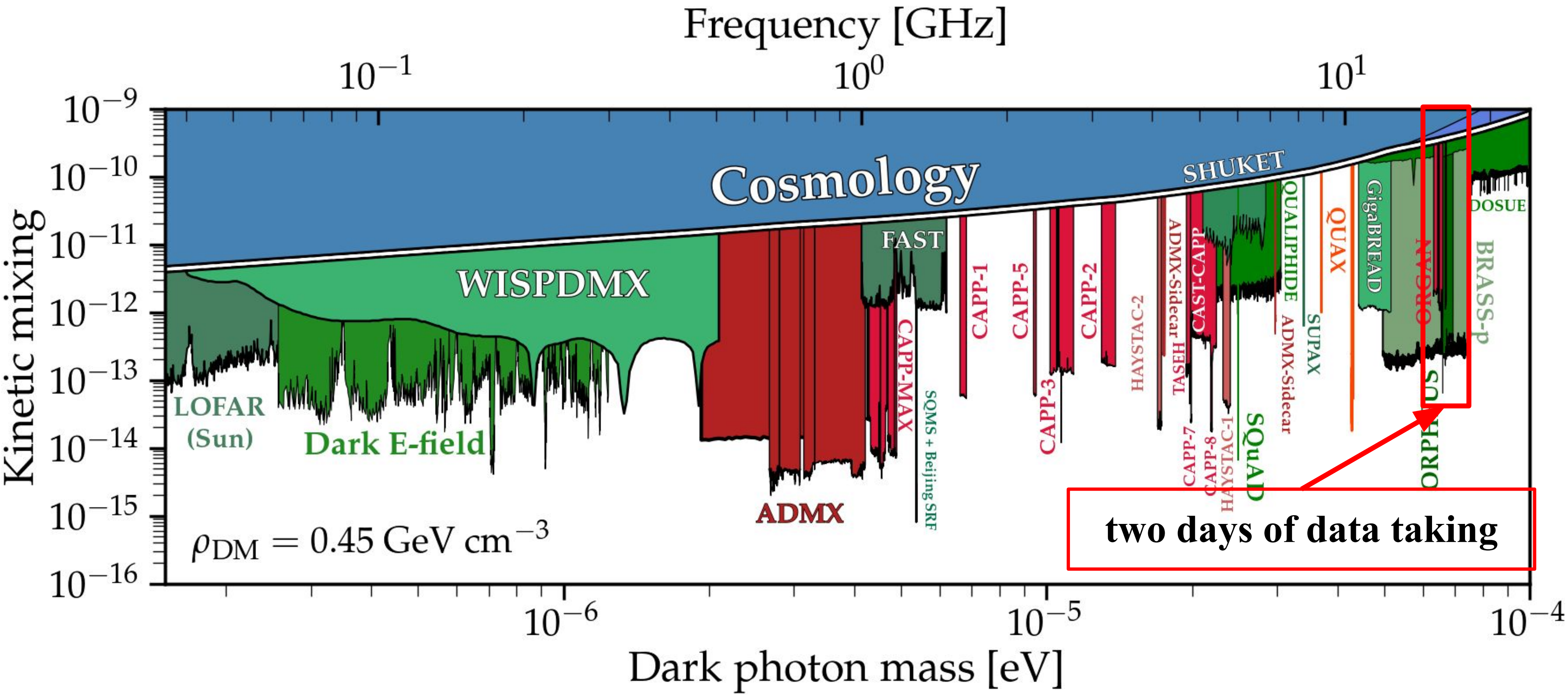
- Two sided
- Expected field is roughly 0.8-0.9 Tesla
- Wound and potted by hand at CENPA





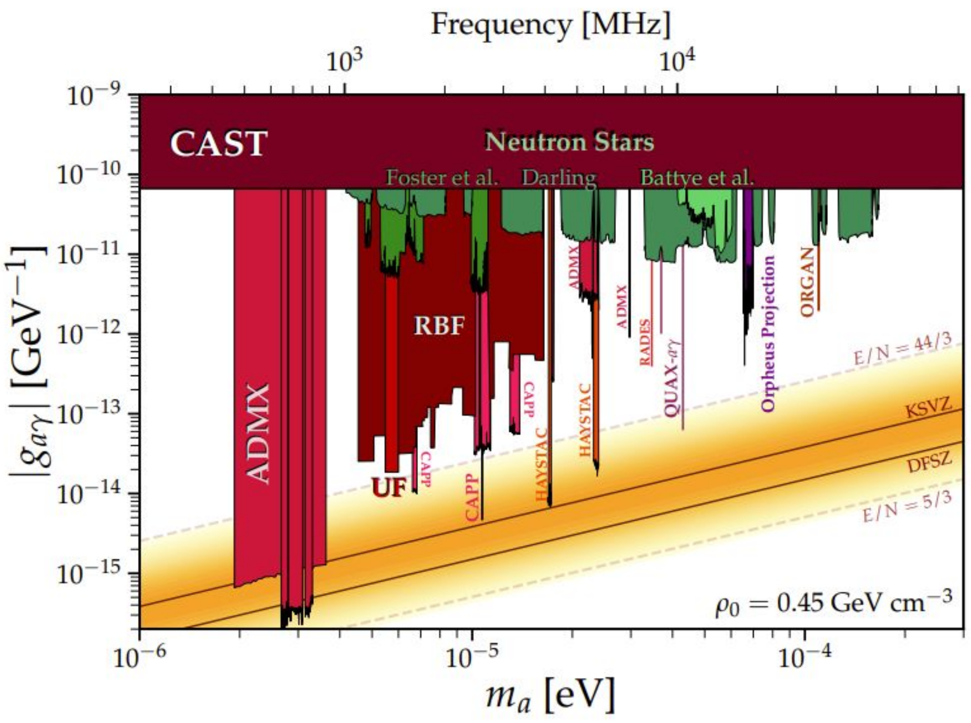
Jinming Zhang

LHe dark photon data run



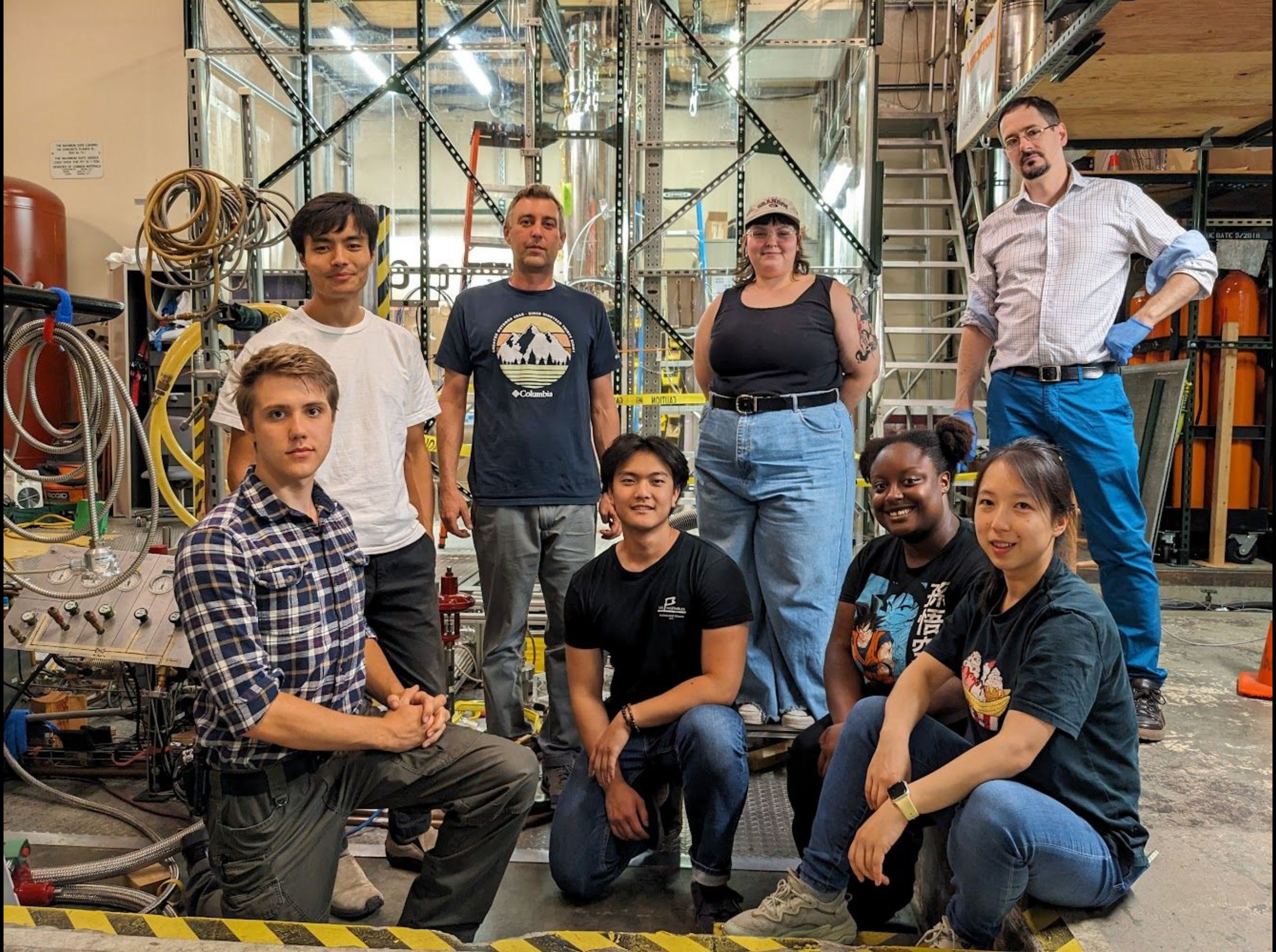
Current and future work

- We are preparing to test the magnet
    - Adding Orpheus to the ADMX helium recovery system
- Simulations to improve effective volume and avoid the mode crossing
- If the magnet works, an axion data run will follow



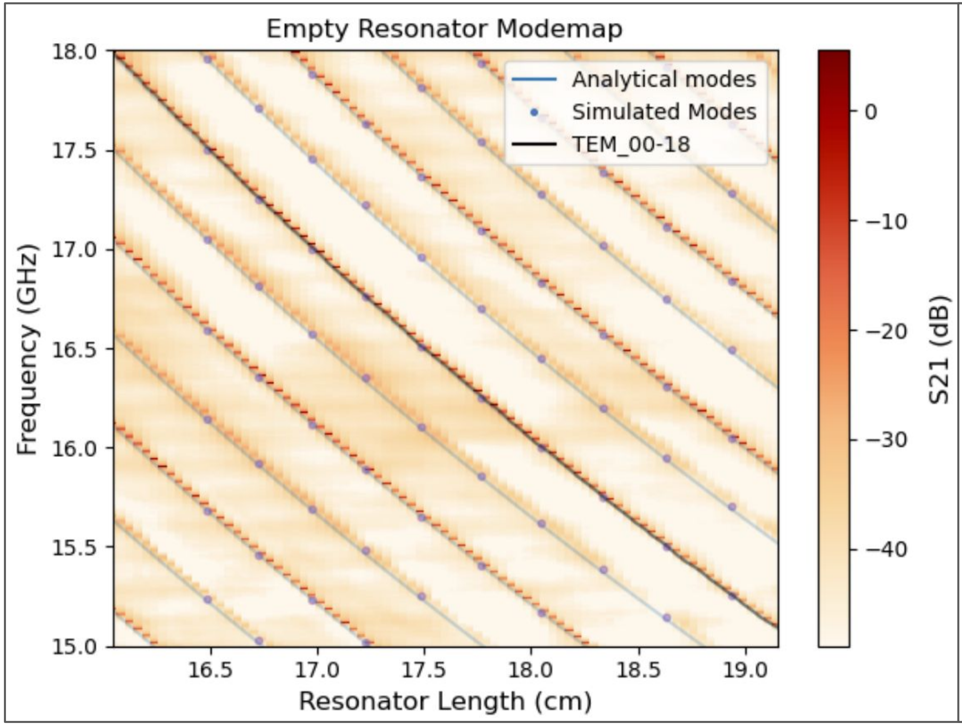
Ways to improve Orpheus with existing technology

- A stronger and larger dipole magnet
- A larger resonator
    - This increases both volume and Q
- A dilution fridge
- More dielectric plates
- A quantum amplifier

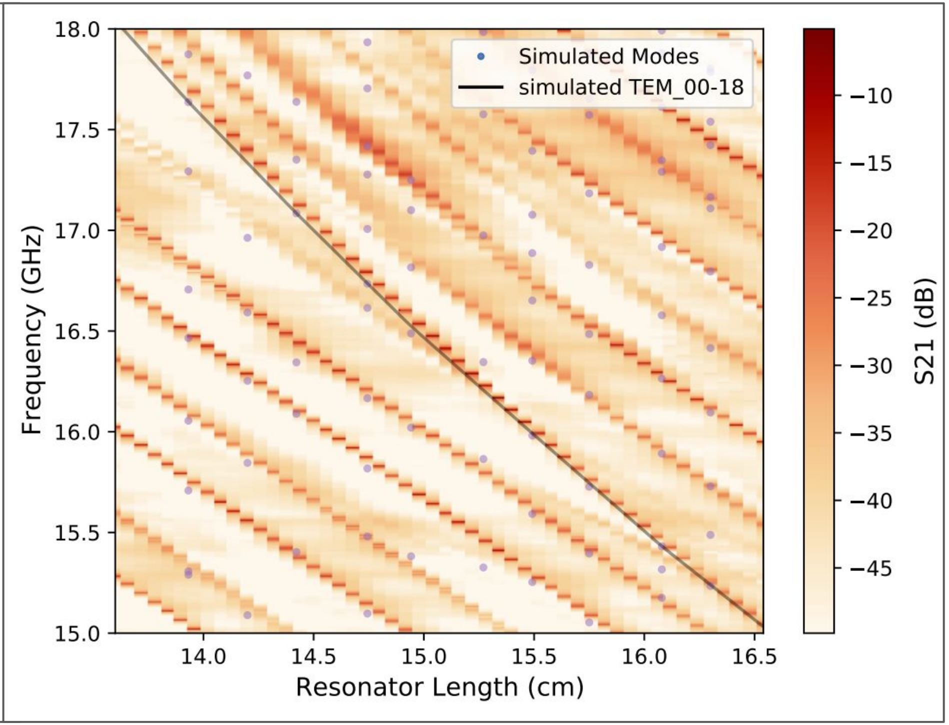

Columbia

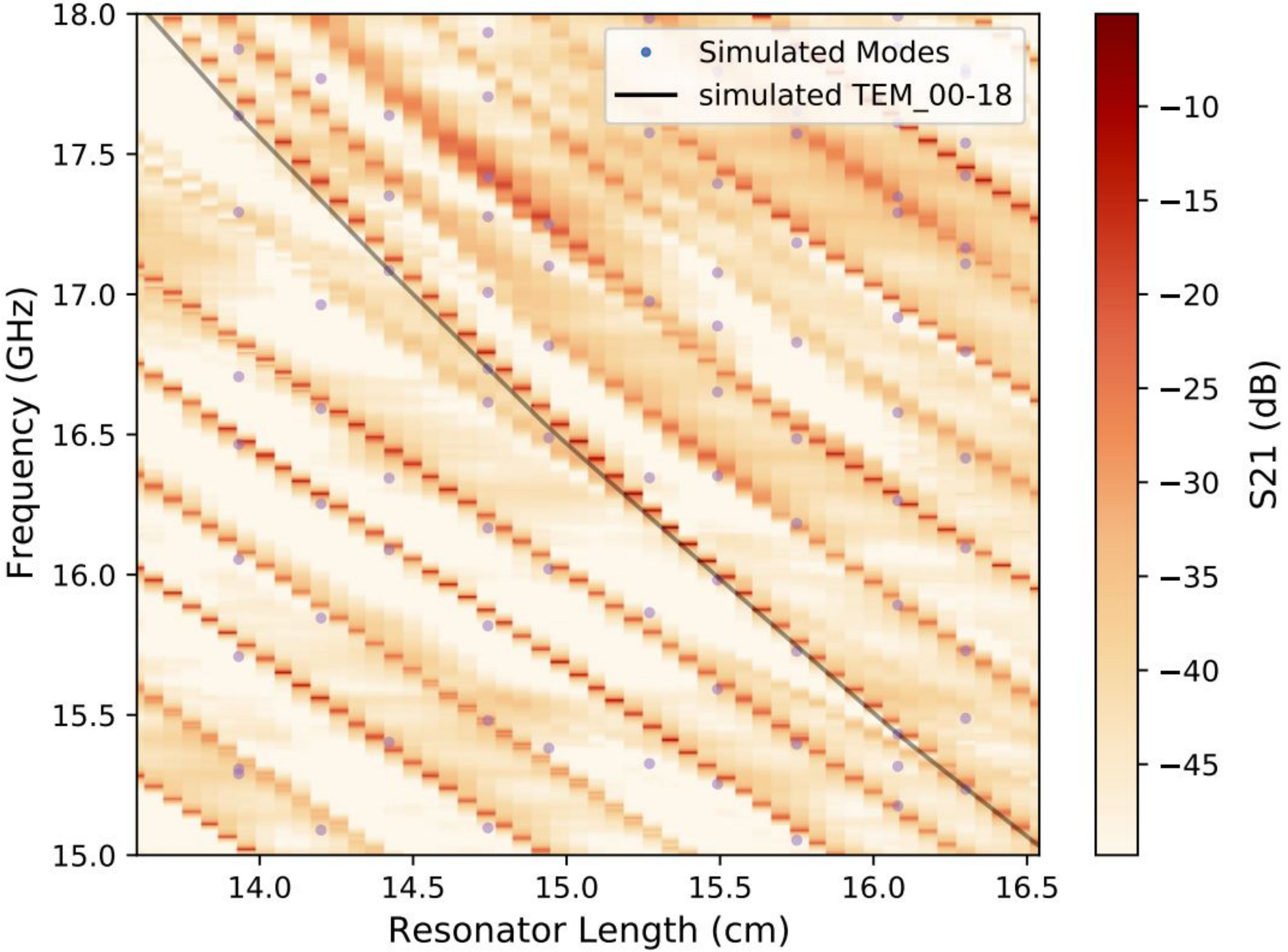
Backup slides

empty resonator

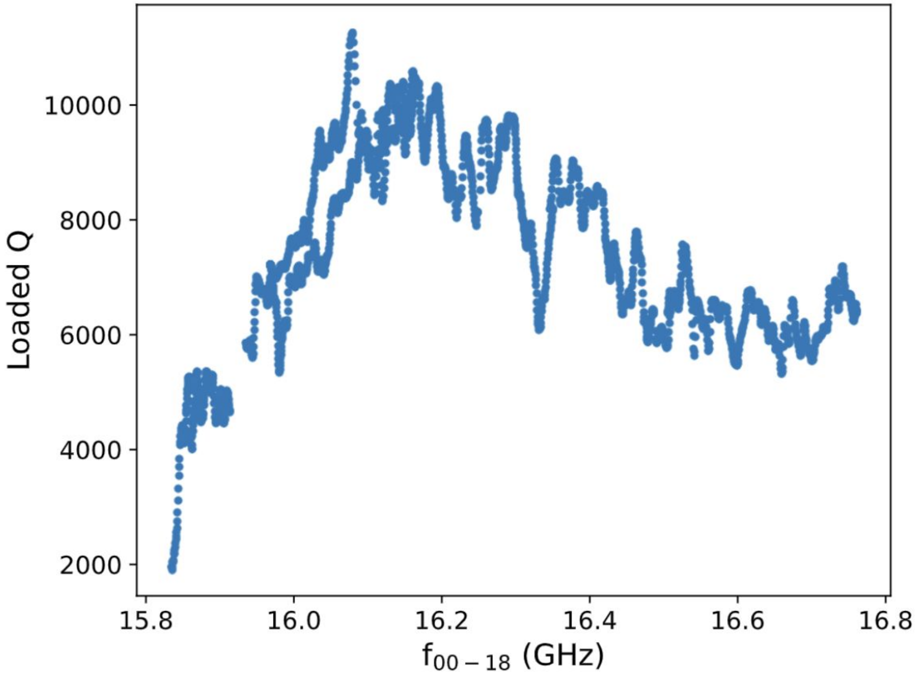


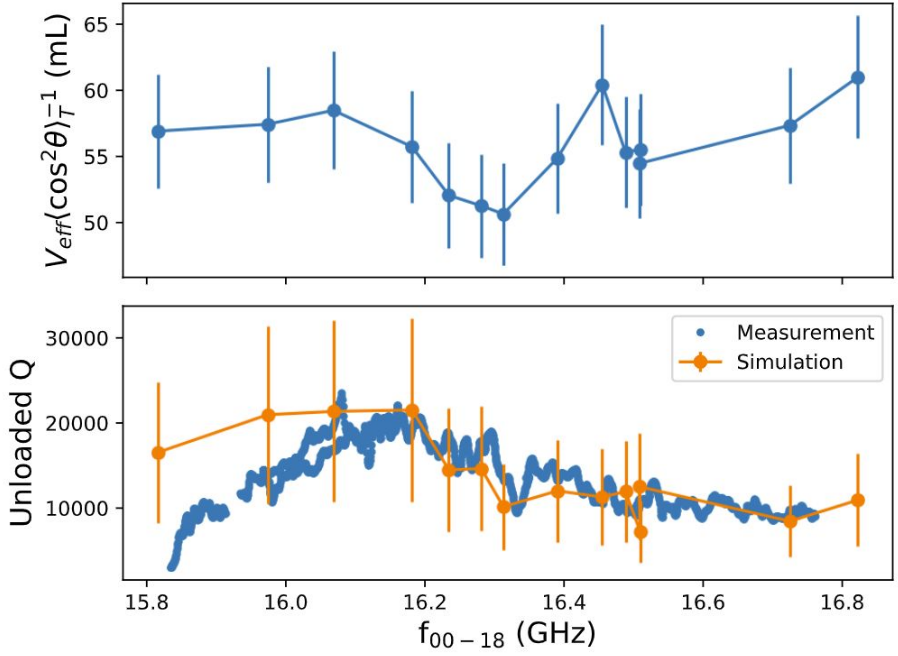
dielectrics added

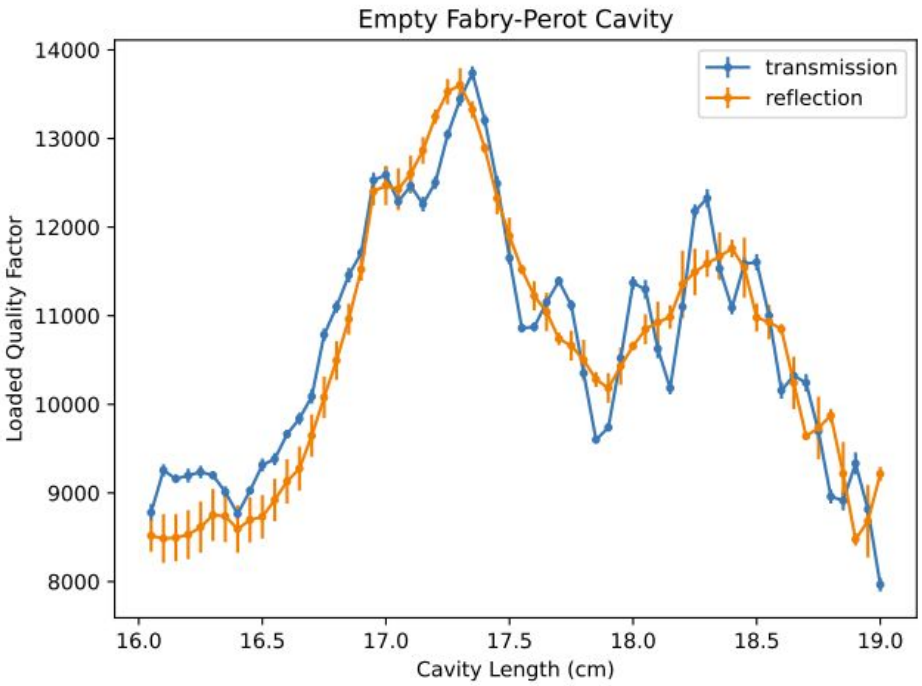



Simulated Modes
simulated TEM_00-18
Frequency (GHz)
18.0
17.5
17.0
16.5
16.0
15.5
15.0
14.0
14.5
15.0
15.5
16.0
16.5
Resonator Length (cm)
−10
−15
−20
−25
−30
−35
−40
−45
S21 (dB)

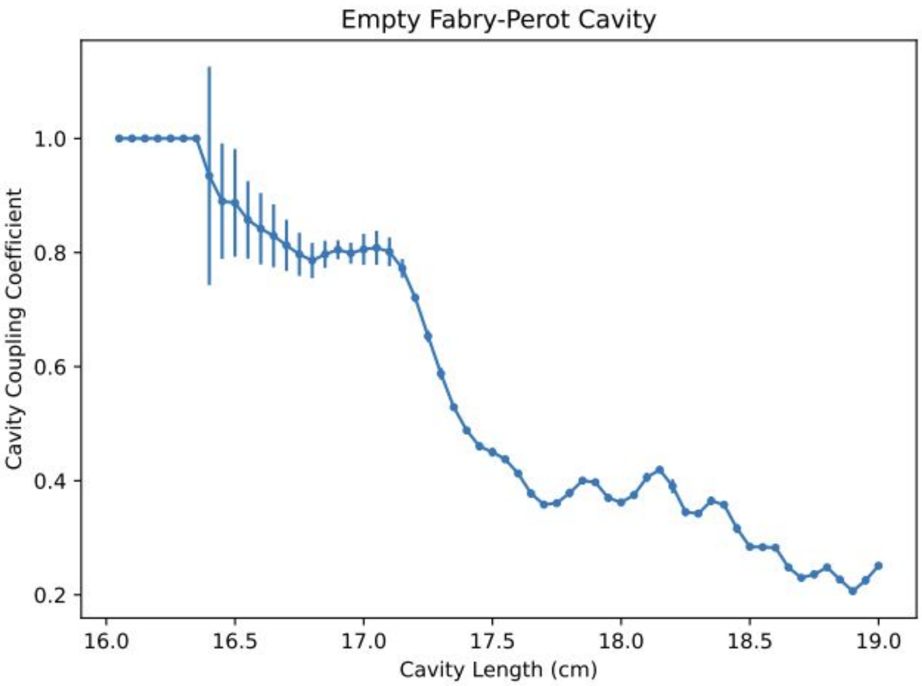
RF characterization of the Orpheus resonator:



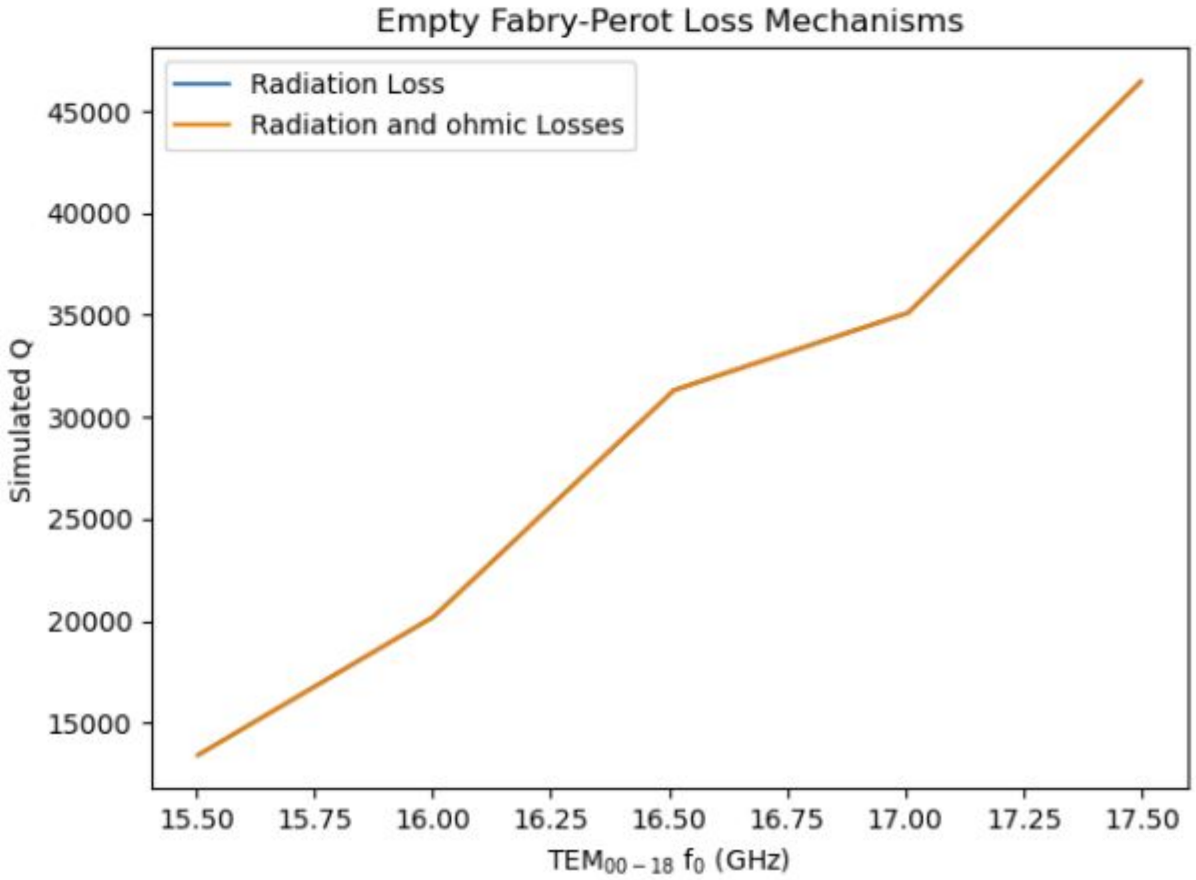



Empty Fabry-Perot Cavity
Loaded Quality Factor
Cavity Length (cm)
transmission
reflection
14000
13000
12000
11000
10000
9000
8000
16.0
16.5
17.0
17.5
18.0
18.5
19.0

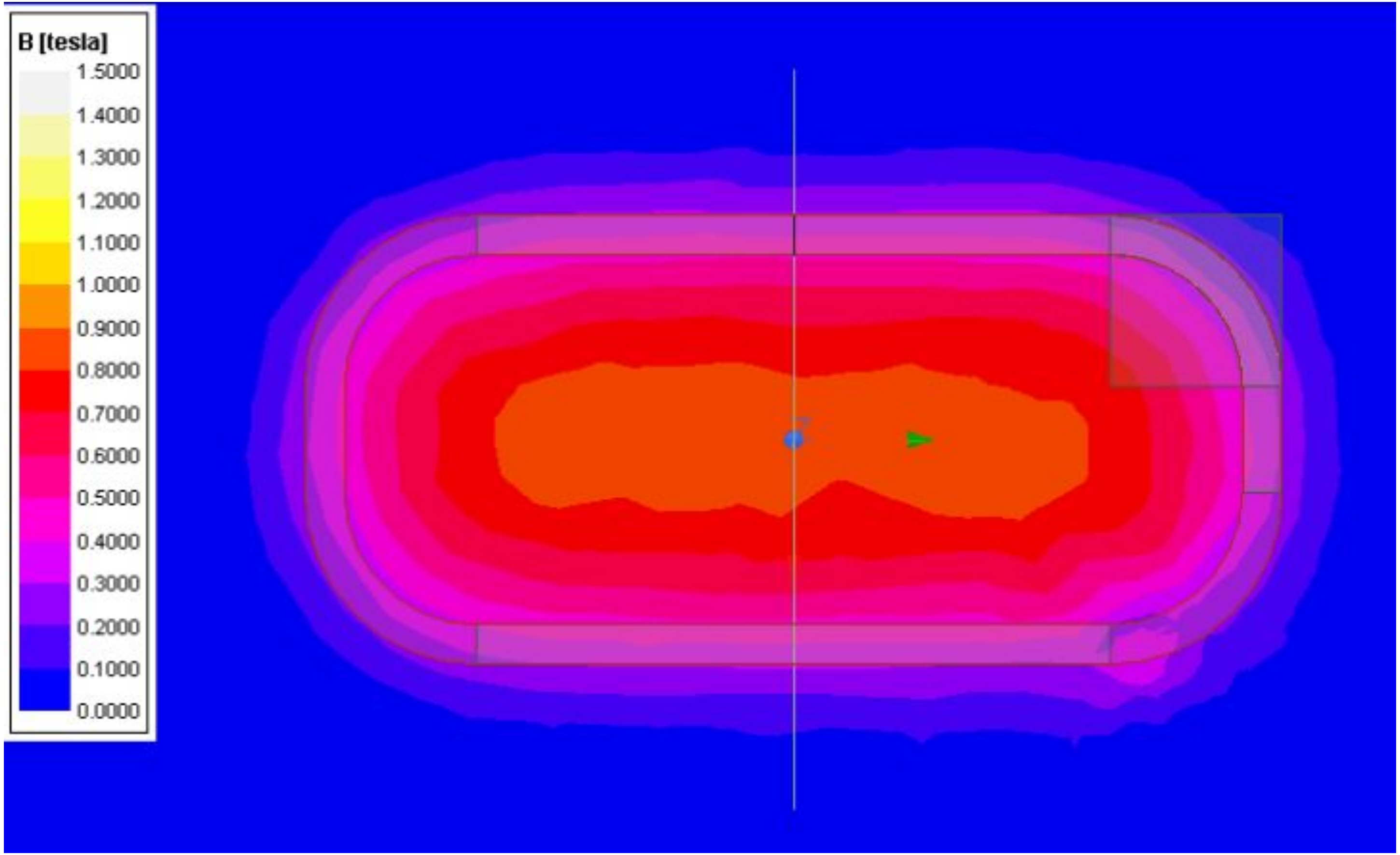
(a)


Empty Fabry-Perot Cavity
Cavity Coupling Coefficient
Cavity Length (cm)
1.0
0.8
0.6
0.4
0.2
16.0
16.5
17.0
17.5
18.0
18.5
19.0

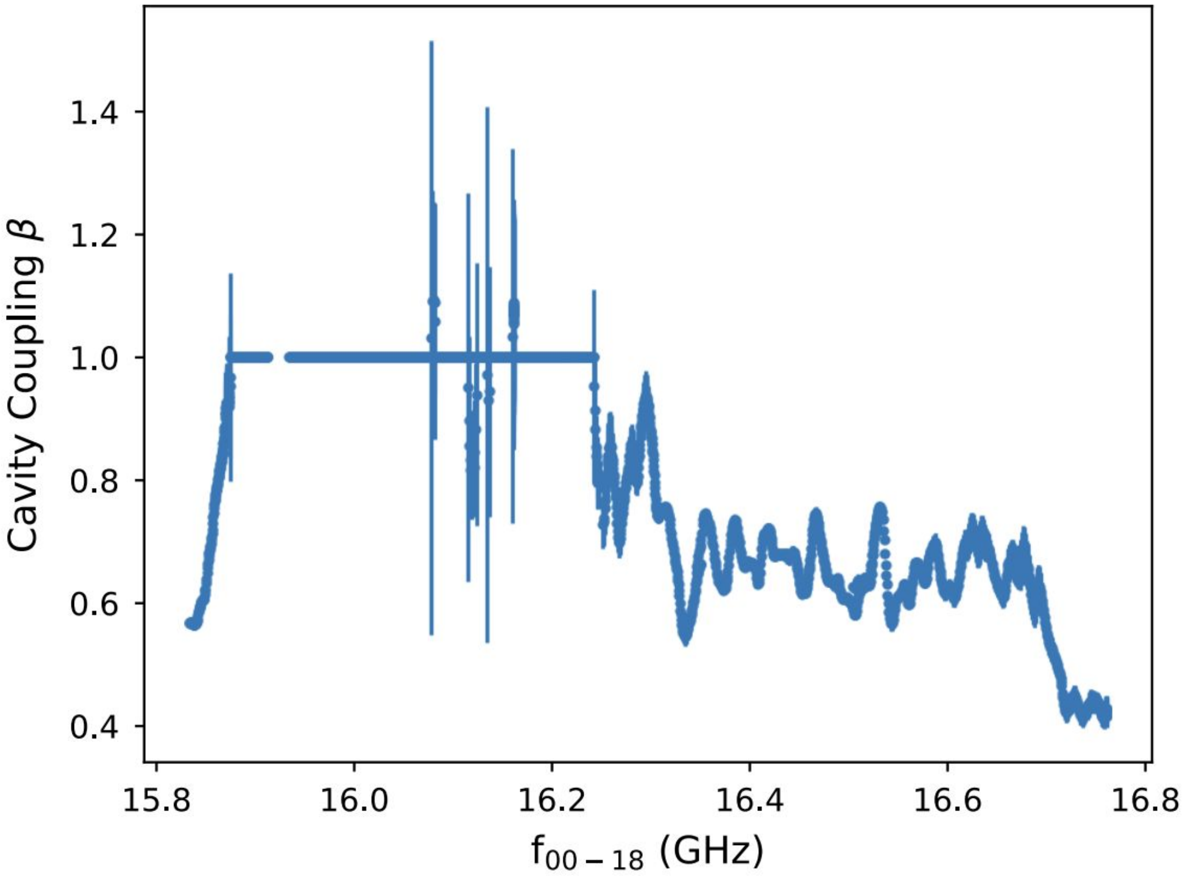
(b)

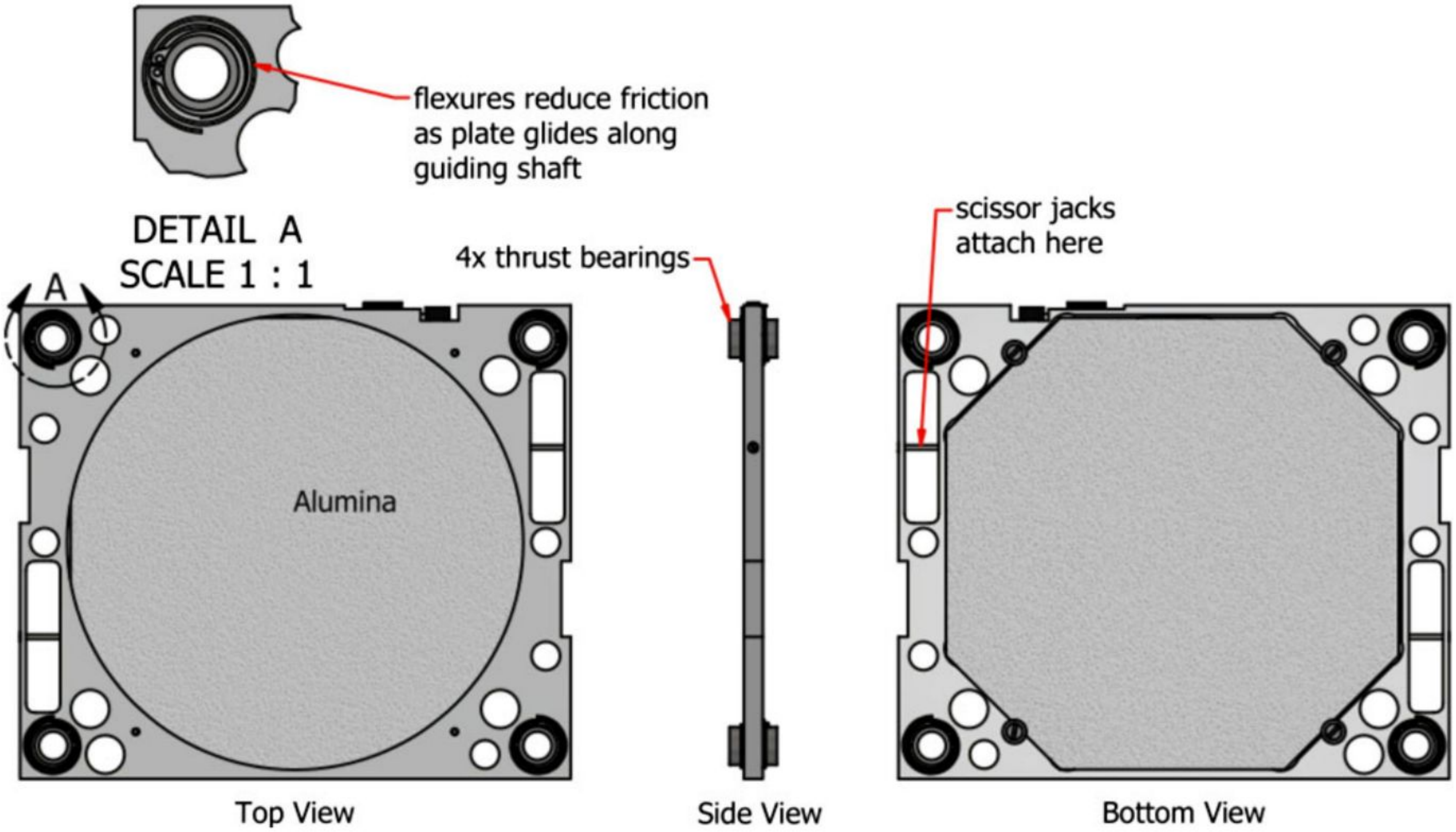

Empty Fabry-Perot Loss Mechanisms
Radiation Loss
Radiation and ohmic Losses
45000
40000
35000
30000
25000
20000
15000
Simulated Q
15.50
15.75
16.00
16.25
16.50
16.75
17.00
17.25
17.50
TEM_{00-18} f_0 (GHz)

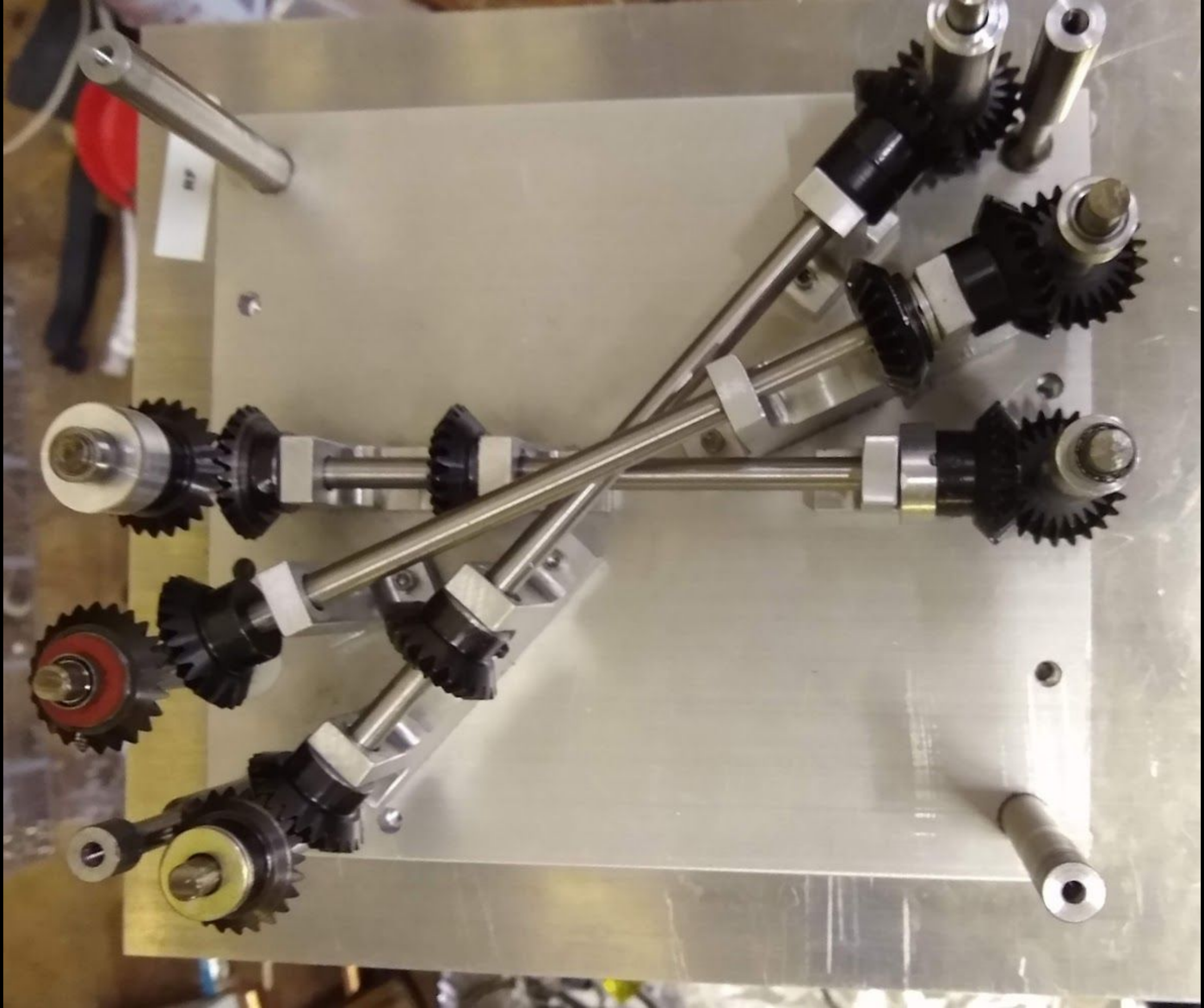
Magnetic field simulation

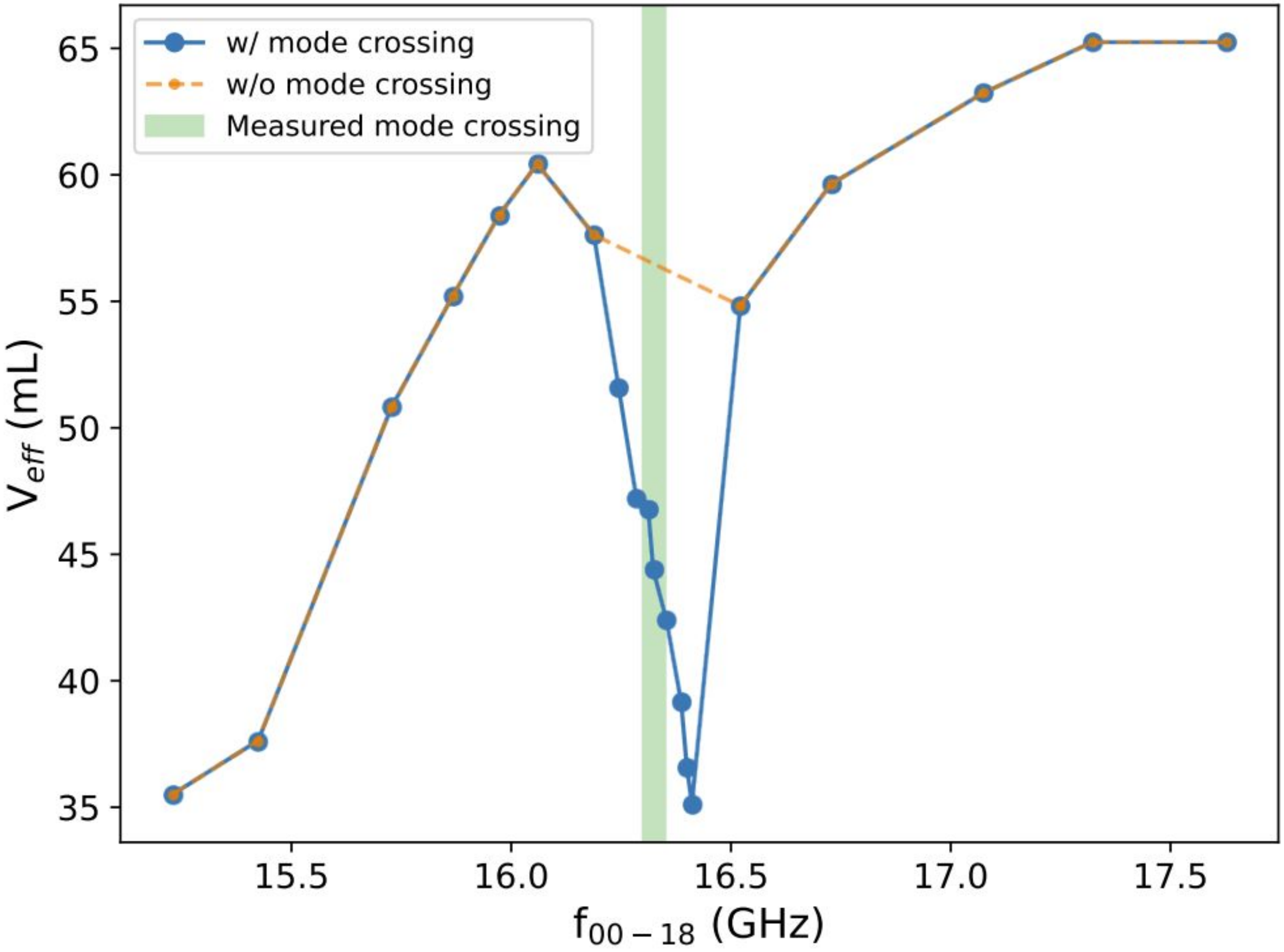


Cavity coupling coefficient – the flat part is a safe guess due to poor fitting



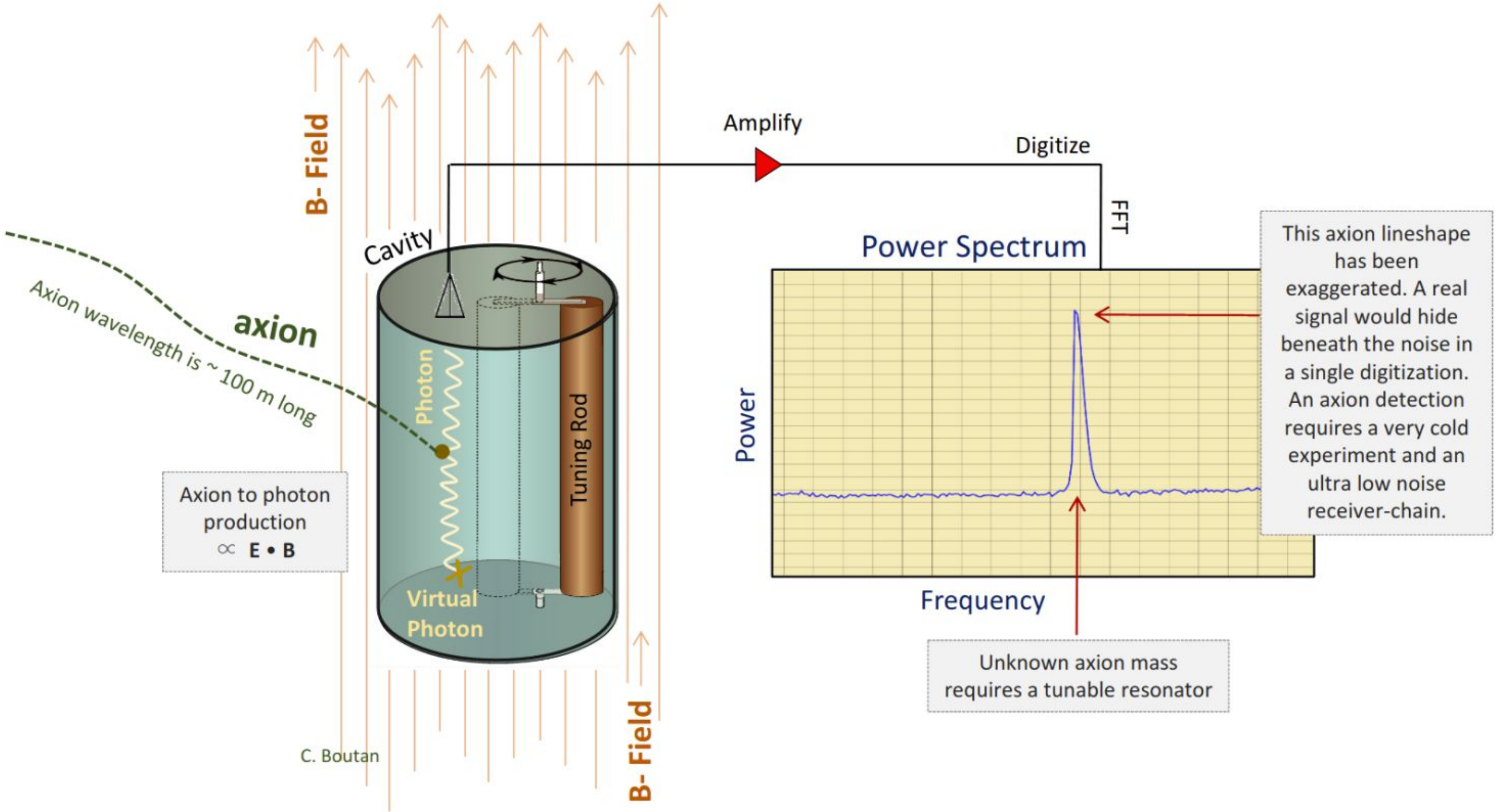

flexures reduce friction
as plate glides along
guiding shaft
DETAIL A
SCALE 1 : 1
A
4x thrust bearings
scissor jacks
attach here
Alumina
Top View
Side View
Bottom View





w/ mode crossing
w/o mode crossing
Measured mode crossing
65
60
55
50
45
40
35
V_{eff} (mL)
15.5
16.0
16.5
17.0
17.5
f_{00-18} (GHz)

Haloscope detection scheme:



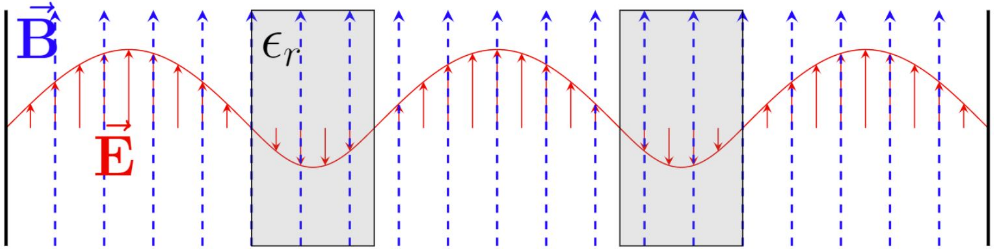
$$w^2 = w_0^2[1 + (z^2/z_0^2)]$$

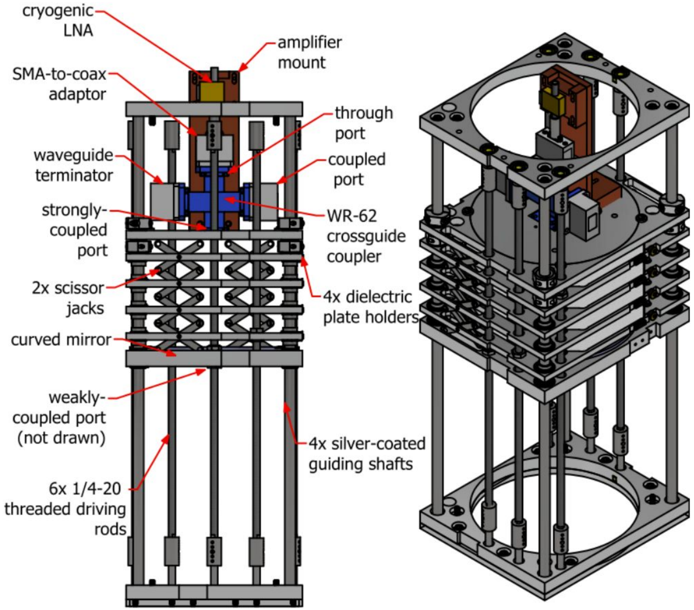
$$r = z[1 + (z_0^2/z^2)]$$

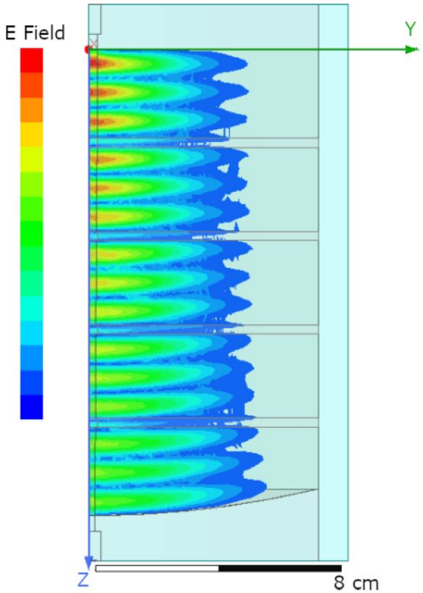
$$z_0 = kw_0^2/2$$

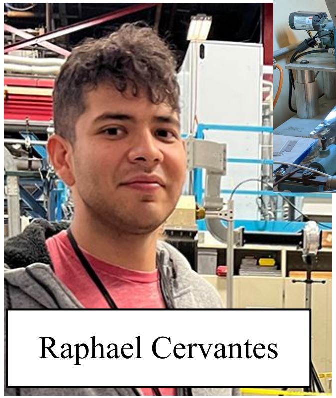
Orpheus uses dielectrics to couple axions to higher-order modes.

- Open resonator with dielectric plates
- 20 times the effective volume of traditional resonant cavity design at this frequency.

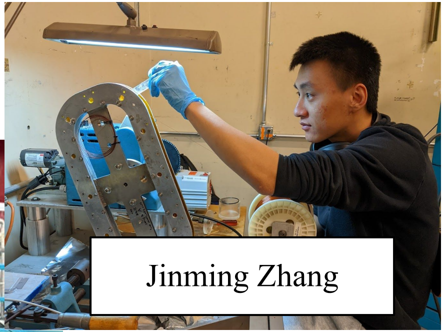




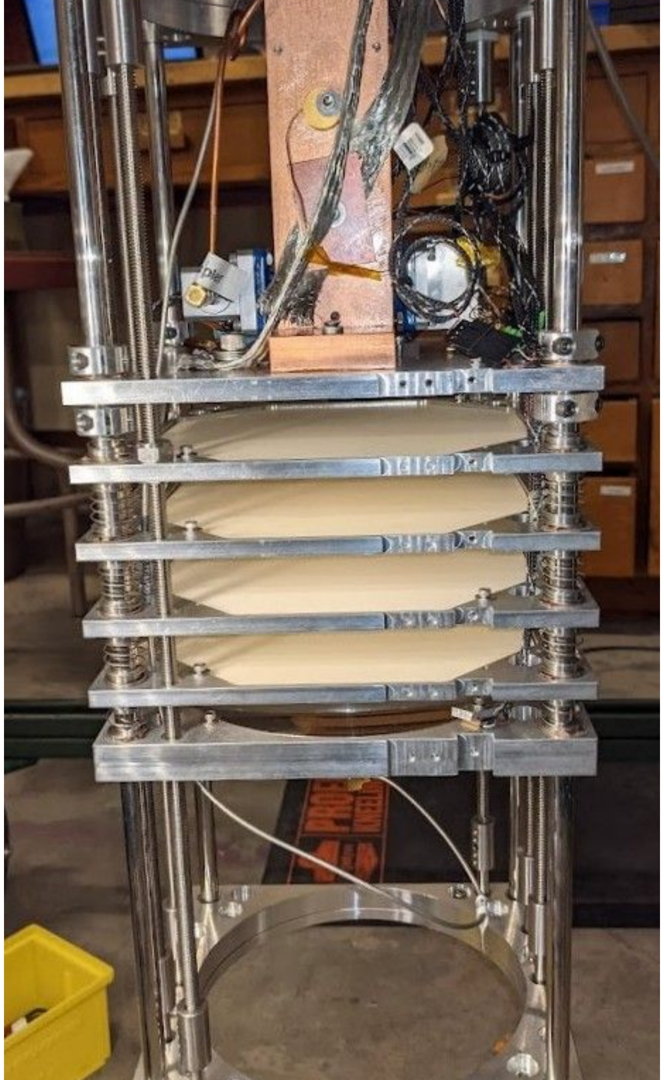


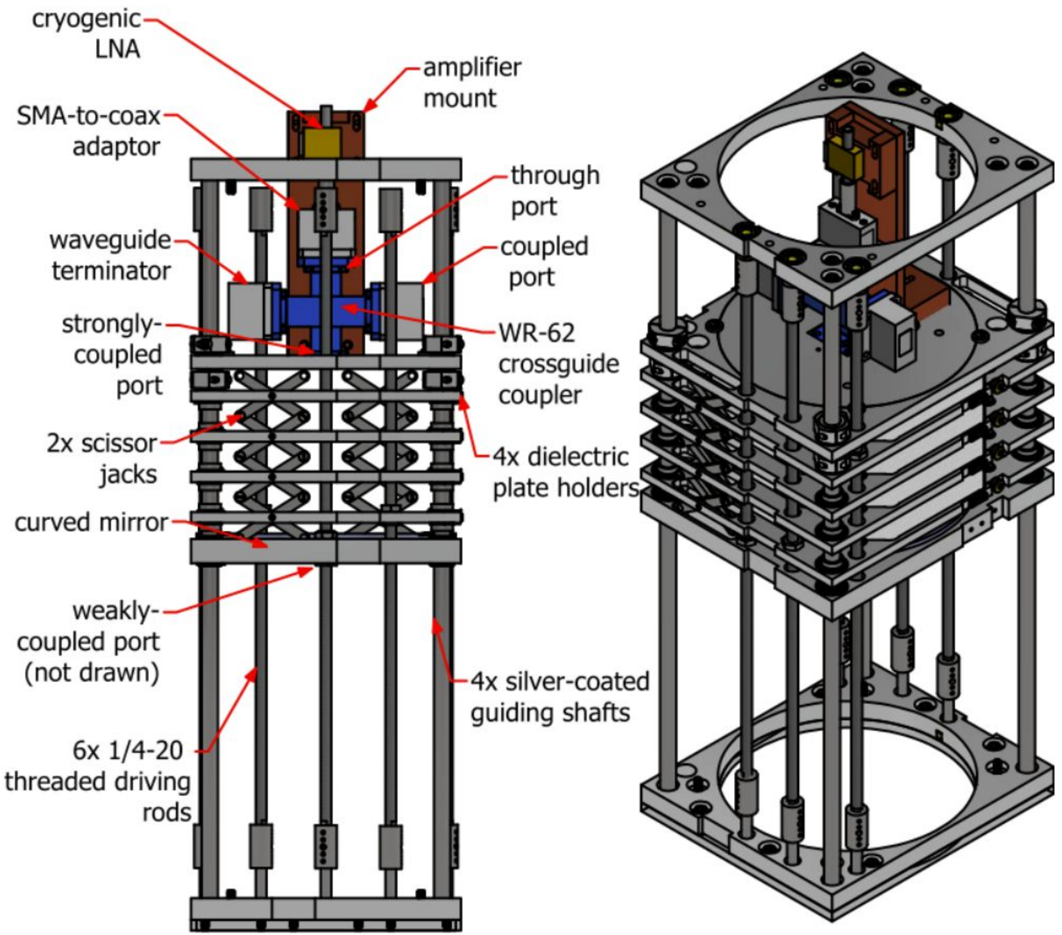


Raphael Cervantes



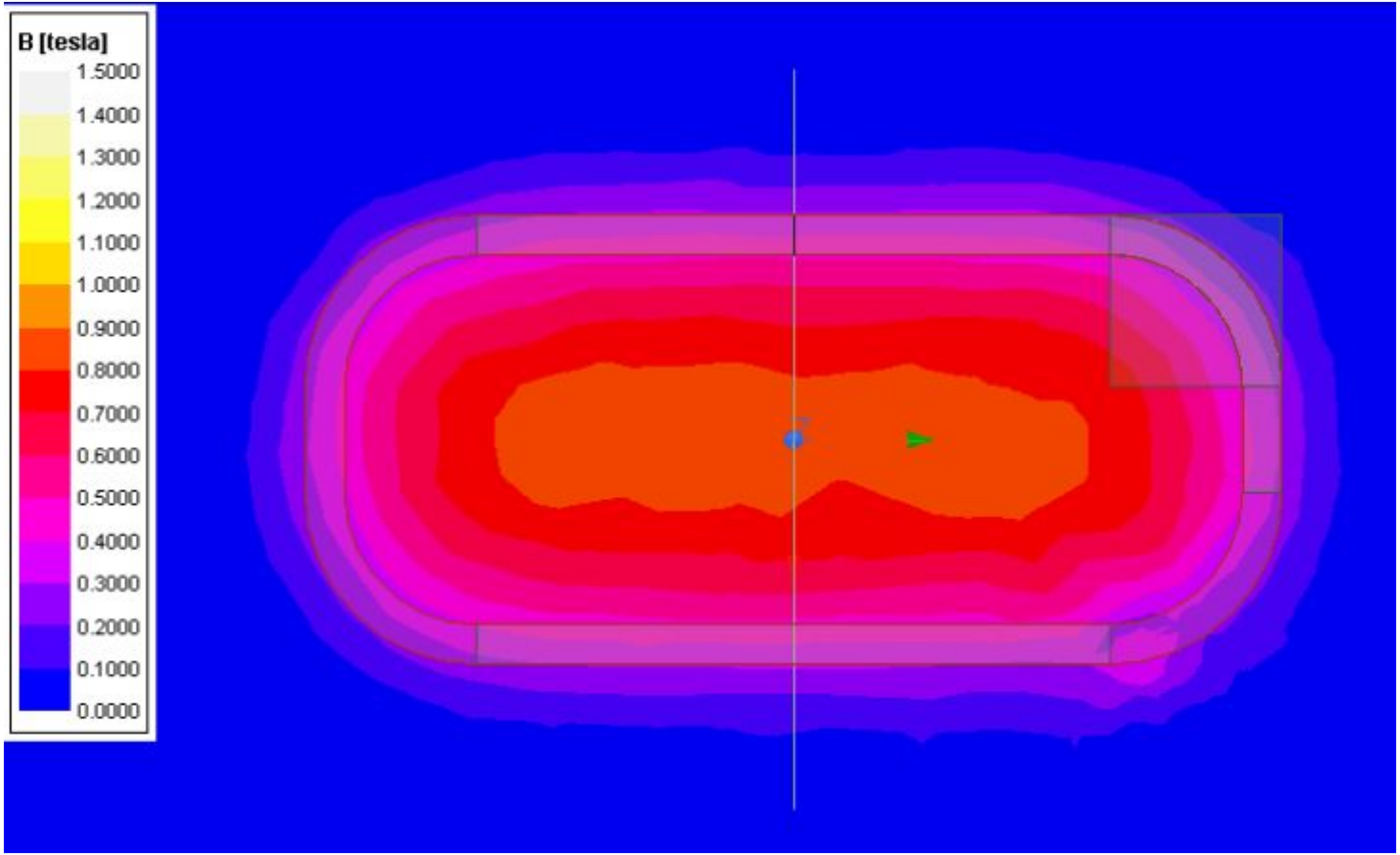
Jinming Zhang

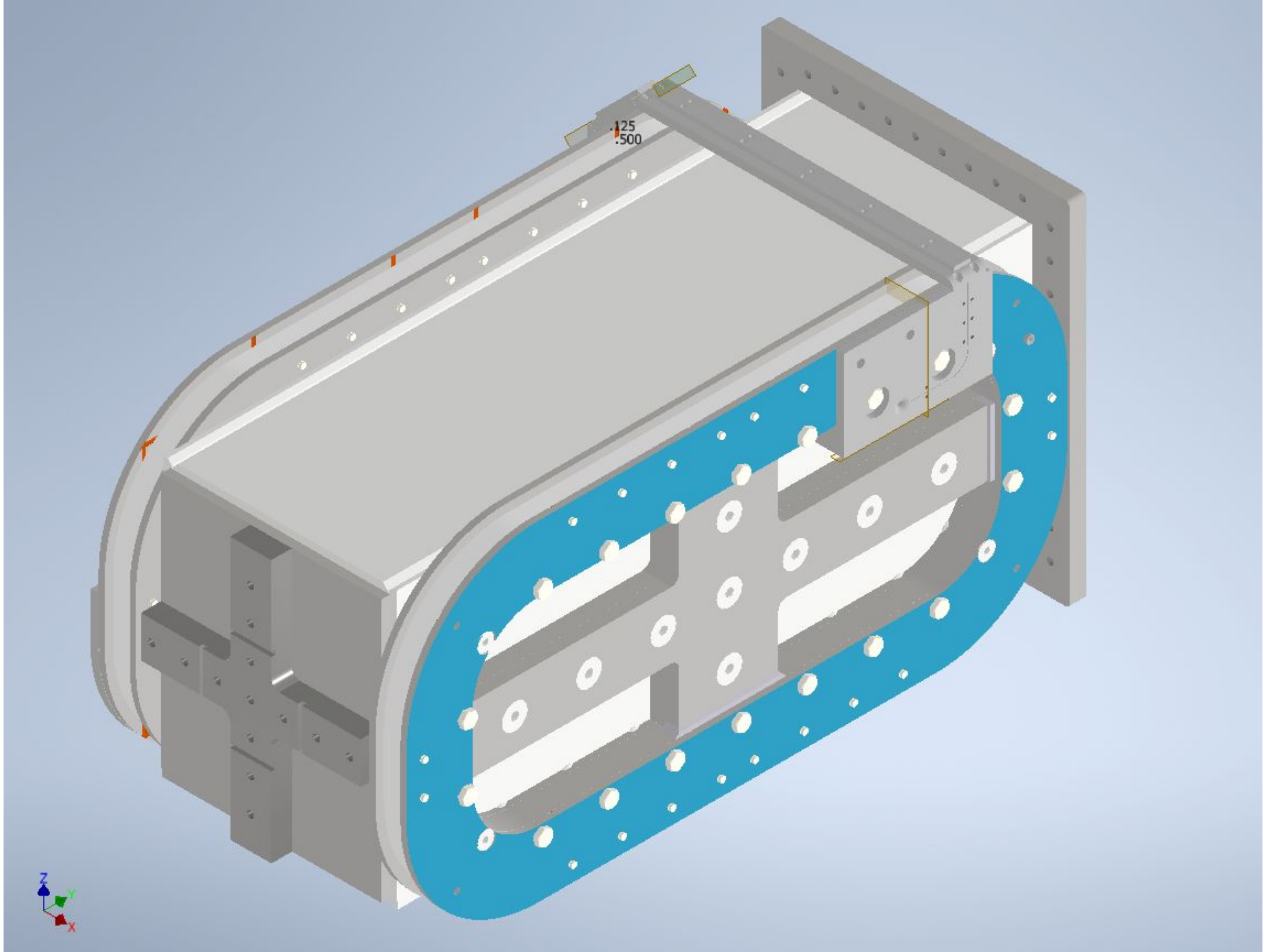




cryogenic LNA
amplifier mount
SMA-to-coax adaptor
through port
waveguide terminator
coupled port
strongly-coupled port
WR-62 crossguide coupler
2x scissor jacks
4x dielectric plate holders
curved mirror
weakly-coupled port (not drawn)
4x silver-coated guiding shafts
6x 1/4-20 threaded driving rods

Magnetic field simulation




.125
.500
Z
Y
X