Demonstration of a High-Volume Tunable Haloscope Above 7 GHz

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ADMX-VERA (Volume-Enhanced Resonating Axion) Experiment

A new addition to the ADMX collaboration developing high-volume haloscopes above 4 GHz

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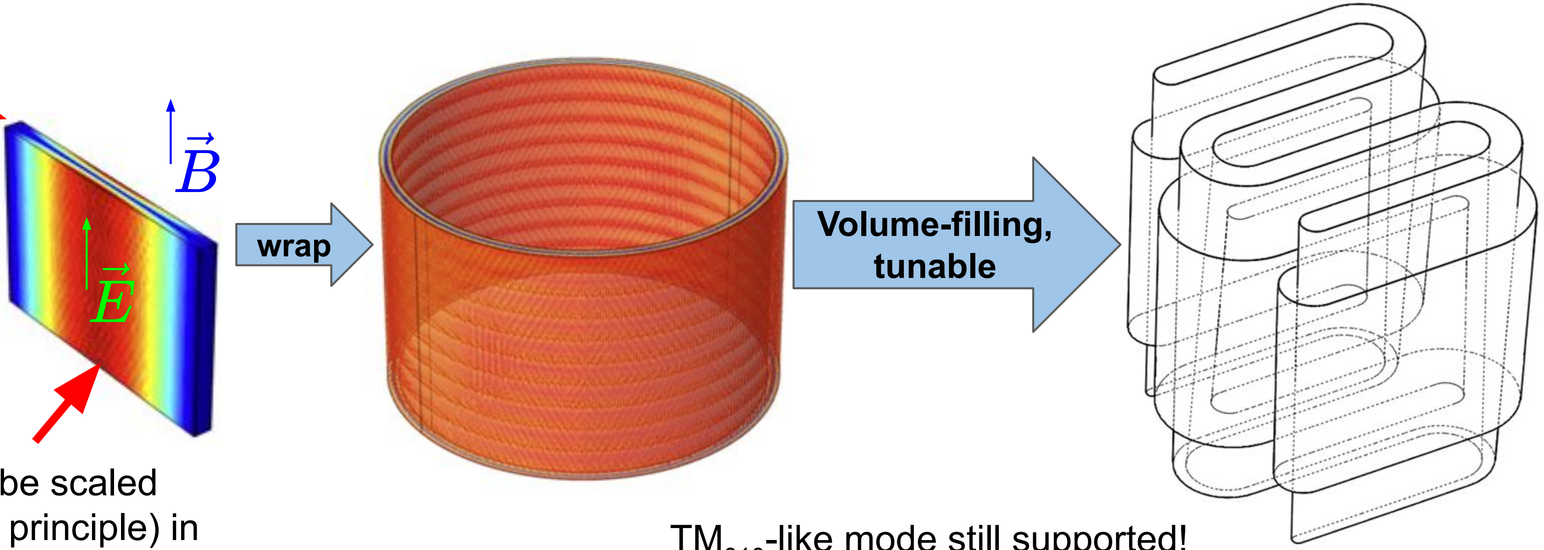
For haloscopes, $\frac{\mathrm{d}\nu}{\mathrm{d}t} \sim V^2$

Typically, $V \sim \nu^{-3}$

$\Rightarrow$ Cavity haloscopes are slow at high frequencies.

Decouple volume from resonant frequency:

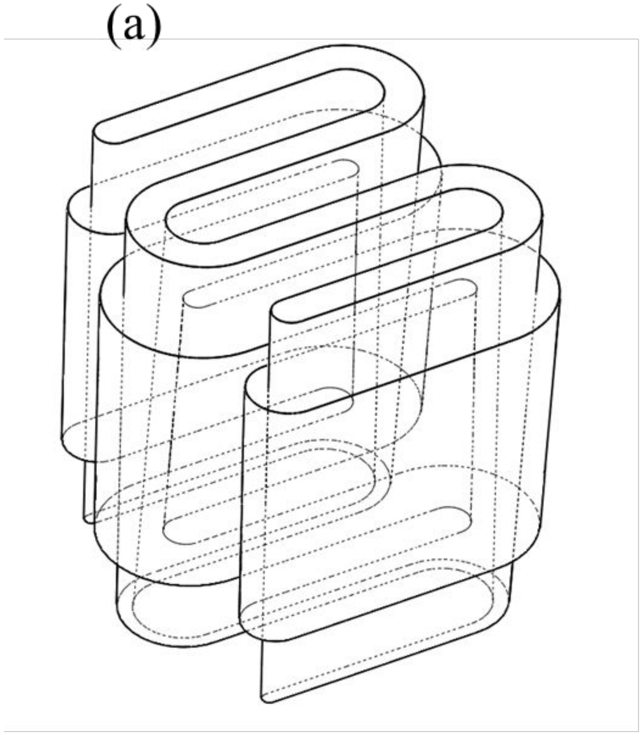
Width sets frequency of fundamental (TM_{010}) compatible with **solenoid B field**

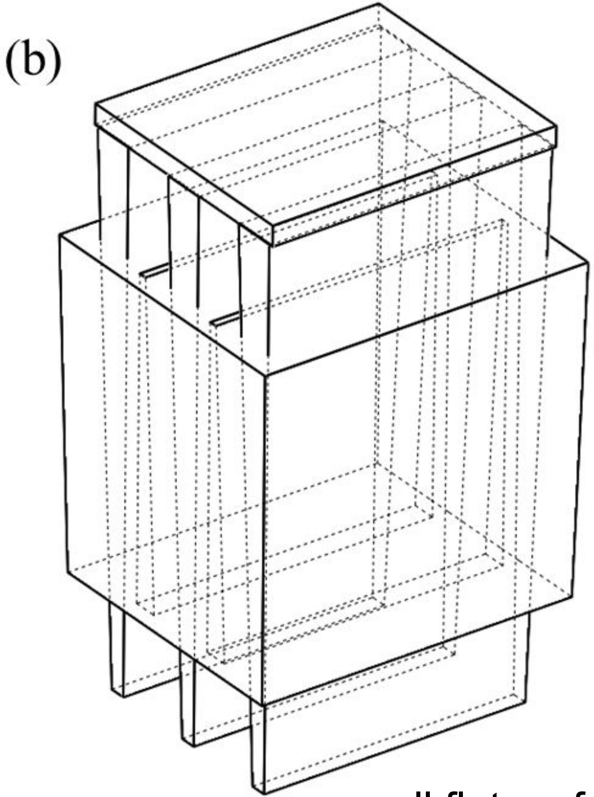


Volume can be scaled arbitrarily (in principle) in other dimensions

TM_{010}-like mode still supported!

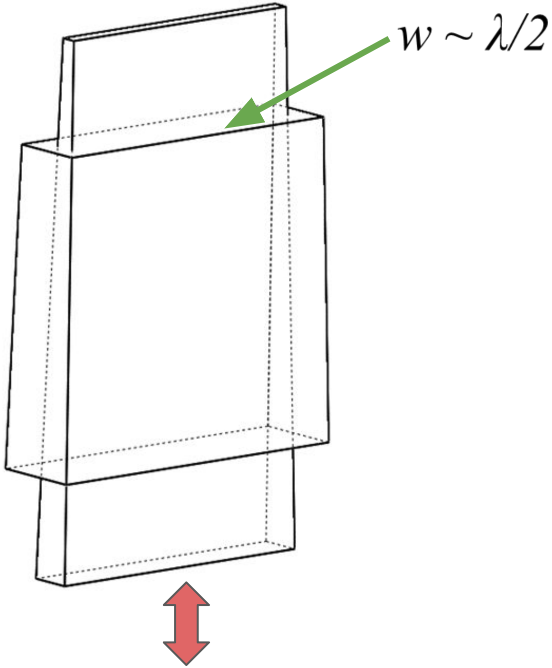
Tunable volume-filling cavities with $V > 100\lambda^3$





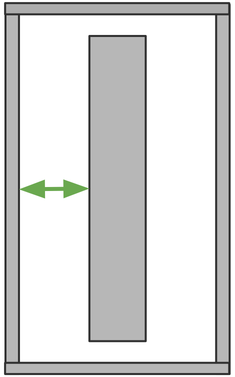
all flat surfaces !!

A prototype tunable thin-shell cavity ($V = 40\lambda^3$)



Tuning by moving the "wedge"

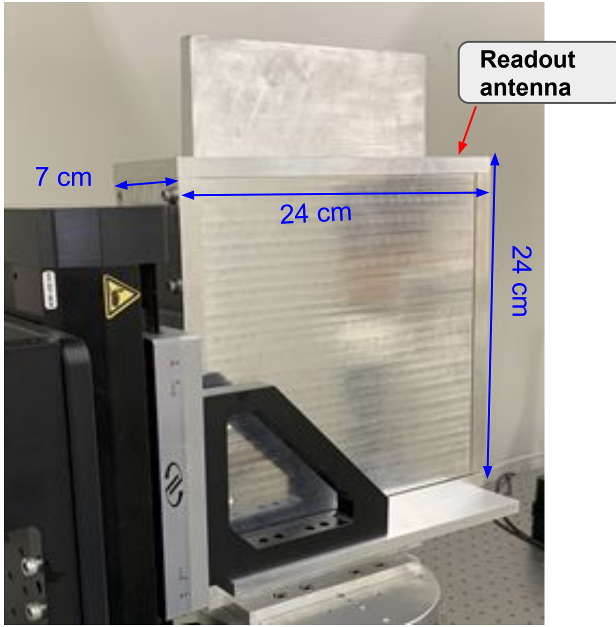
Top view:

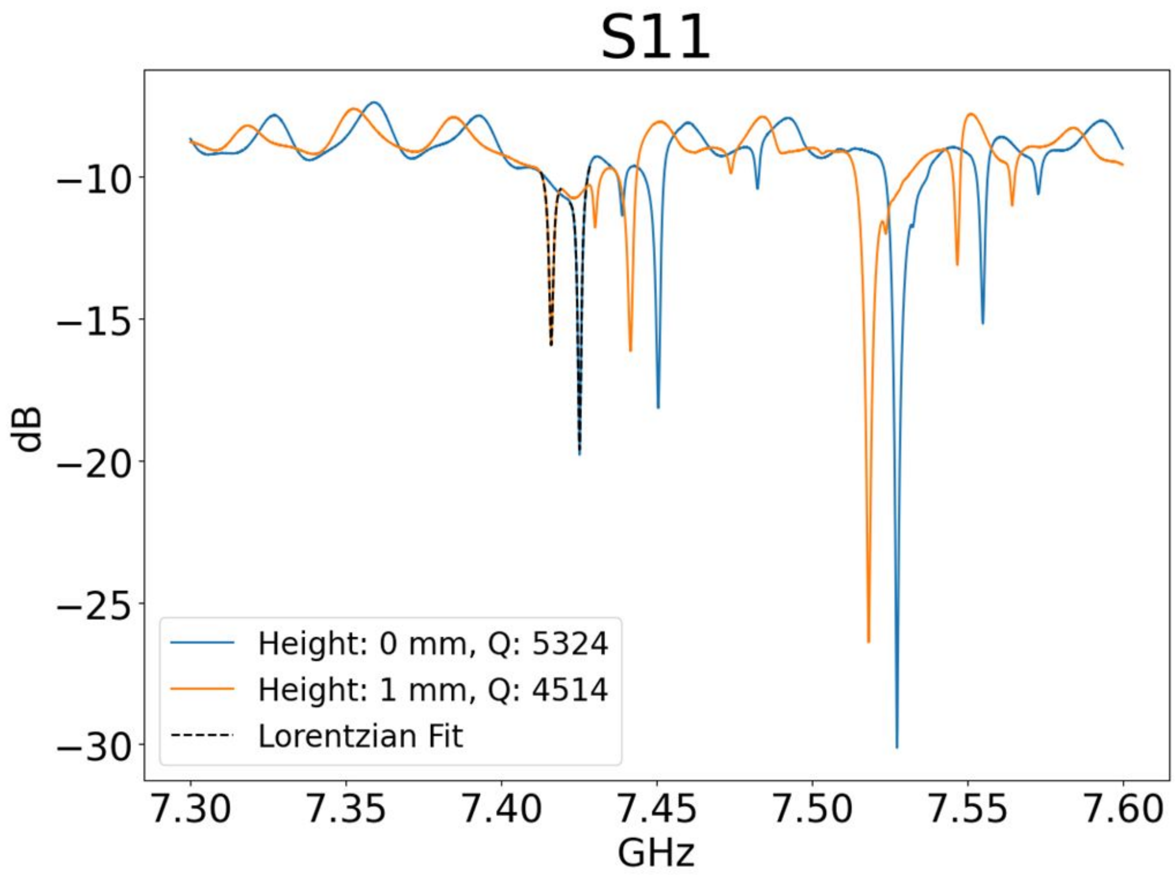


Resonant cavity formed by an inner wedge and an outer shell.

Tunable gap width sets TM_{010} frequency.

First prototype , $w \sim 2.0$ cm

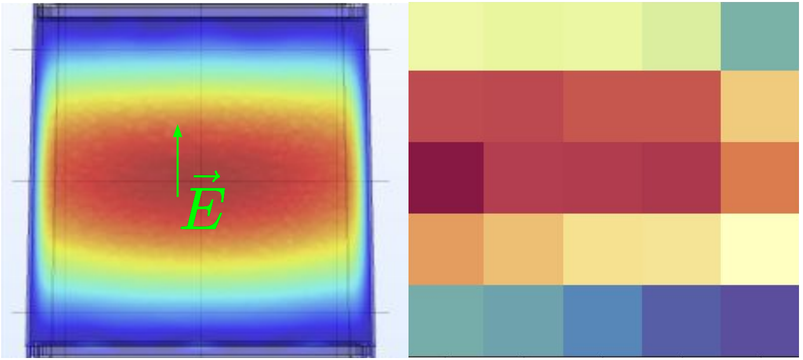



S11
dB
GHz
−10
−15
−20
−25
−30
7.30
7.35
7.40
7.45
7.50
7.55
7.60
Height: 0 mm, Q: 5324
Height: 1 mm, Q: 4514
Lorentzian Fit

Identifying the TM_{010}-like mode

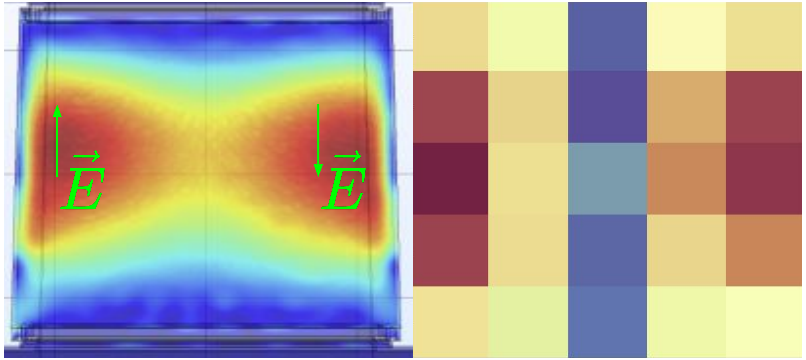
Simulation

Measured with foam disk



$|\mathbf{E}|$ (arb. units)

Lowest frequency mode. Identified in simulation as TM_{010}-like based on polarization.



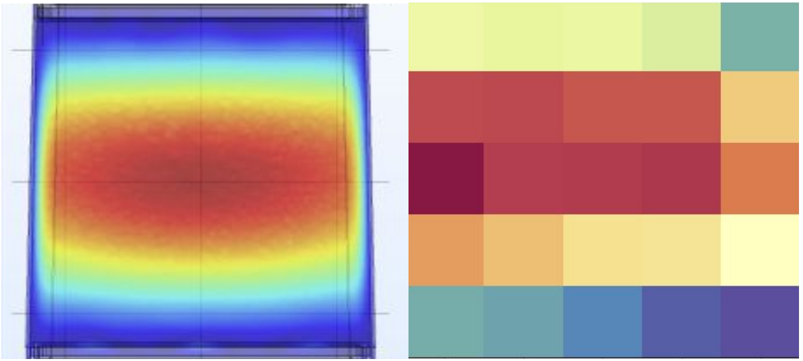
$|\mathbf{E}|$ (arb. units)

The second-lowest mode. Allows us to be confident that we have indeed found the TM_{010}-like mode.

The effect of misalignment

Simulation

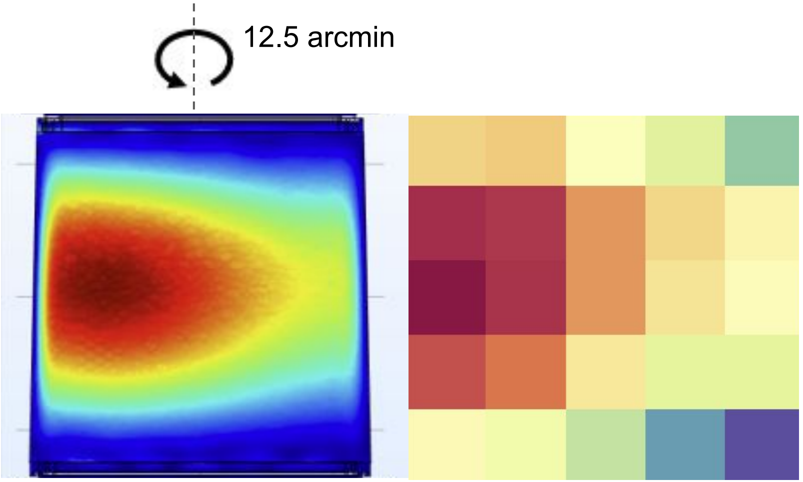
Measured with foam disk



$|\mathbf{E}|$ (arb. units)

$$C_{010} = 0.57$$

(simulated)



$|\mathbf{E}|$ (arb. units)

$$C_{010} = 0.32$$

(simulated)

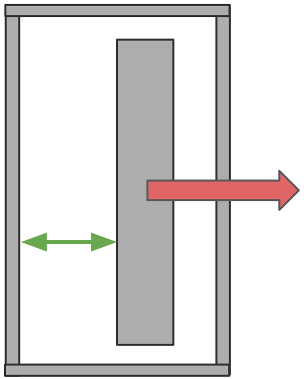
Alignment affects form factor.

We can't measure wedge position when it's in a fridge.

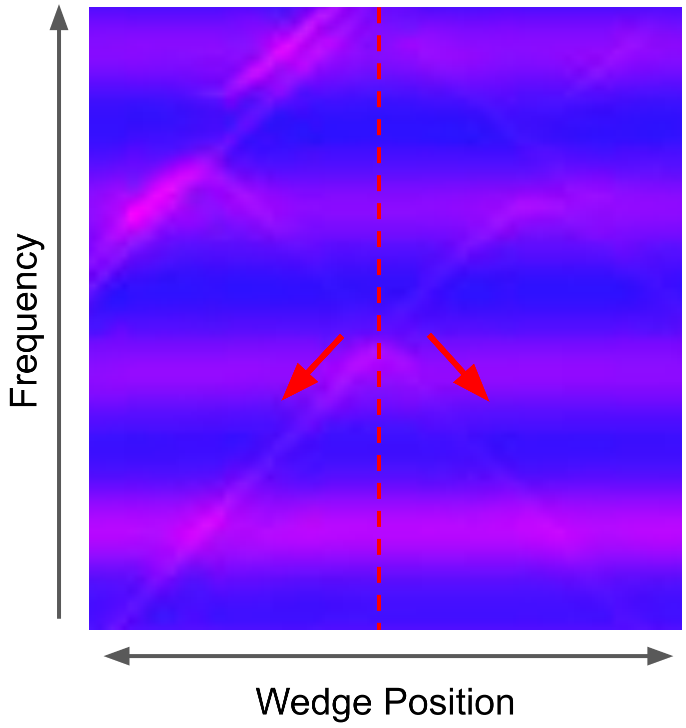
Fortunately, misalignment perturbs the resonant frequency:

Misalignment creates a larger gap width
⇒ Lower resonant frequency

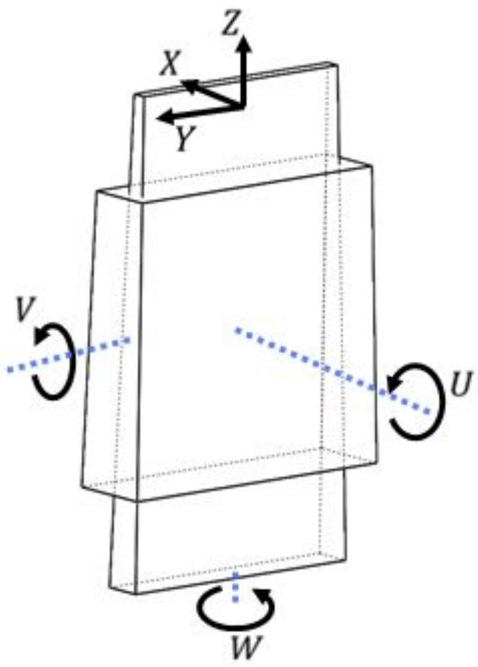
Top view:

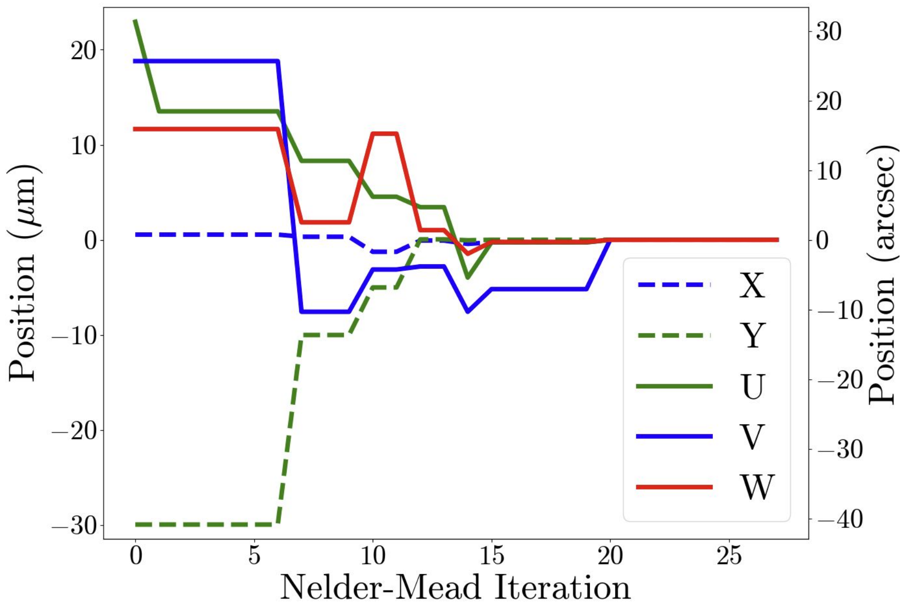


Mode Map



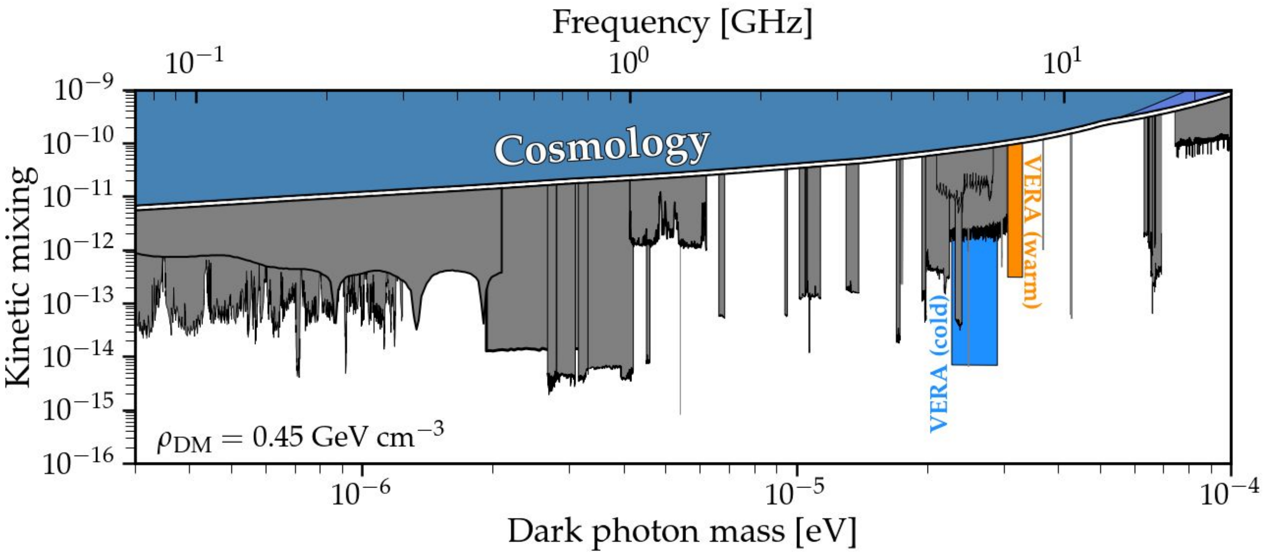
(Horizontal stripes are now-eliminated VNA artifacts)





Five DoF alignment based on Nelder-Mead optimization that only uses S_{11} measurements

Near-term Dark Photon Exclusion Forecasts



	Warm	Cold
f_0 (GHz)	7.4 – 8	5.5 – 7
V (L)	2.5	6
Q	5000	20000
$T_{\rm sys}$ (K)	300	0.4

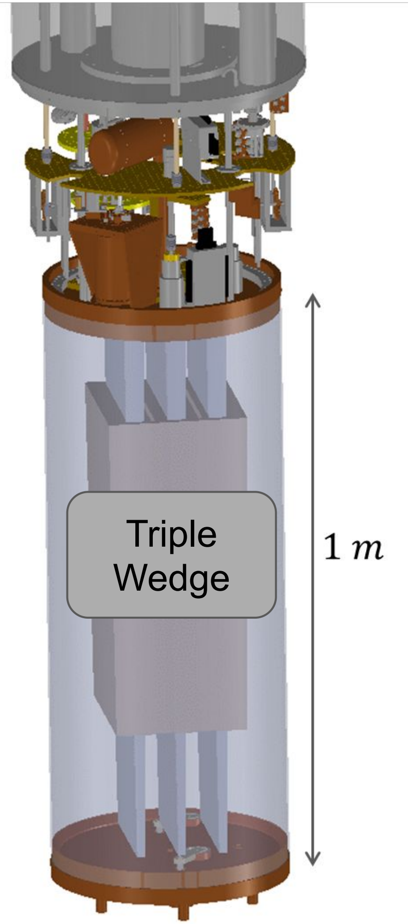
Plot used code and data from:
https://cajohare.github.io/AxionLimits/

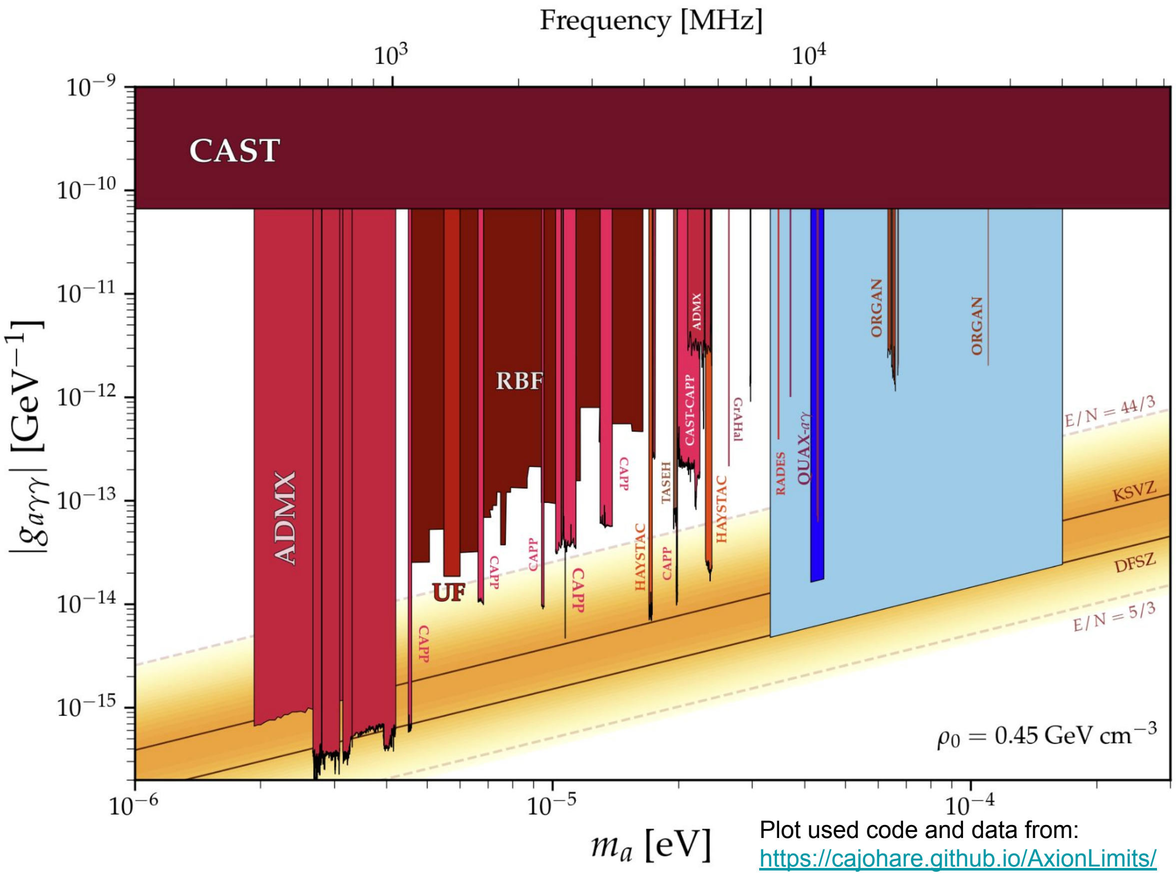
Projected limits for the current warm run and planned cold run, 1 month of uptime.

Next Steps - Triple Wedge Prototype

- Fabricated, now being assembled using precision metrology.
- The three wedges move together, so there remains only five parameters to align.

ADMX Insert





Plot used code and data from: https://cajohare.github.io/AxionLimits/

Conclusions

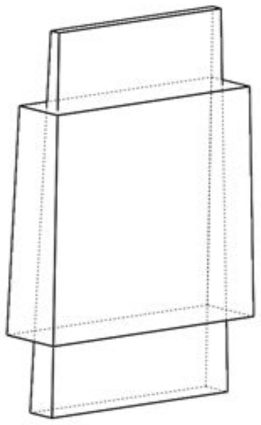
- ADMX-VERA uses novel geometries which decouple volume from frequency in haloscopes, allowing for feasible designs from 4 GHz to tens of GHz potentially with a volume of 10^2 - 10^3 cubic wavelengths.
- Resonance, tuning, and alignment have been shown at room temperature.
- A warm dark photon search is underway, to be followed by a larger cryogenic run.
- Testing of higher volume enhancement cavities underway.

The dark blue corresponds to a conservative projection reaching KSVZ. The parameters are as follows.

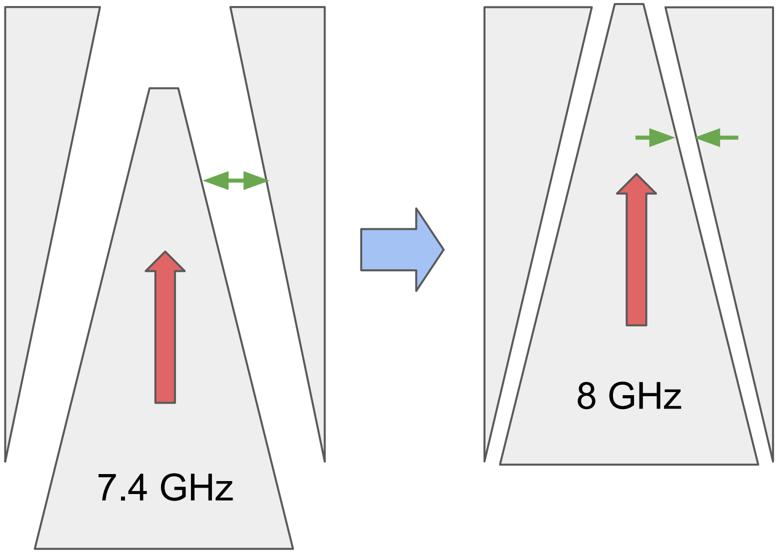
Acquisition live time: 1 month at 80% uptime
Frequency range: 10 to 10.745 GHz
Coupling: beta = 1 (critical)
SNR: 3.5
Field strength: 5 T
Q: 15000 at 10 GHz (scaling w/ anomalous skin depth)
Form factor: 0.57
Total system noise: 900 mK

Light blue is a "futuristic" projection reaching DFSZ with the same parameters as above except:

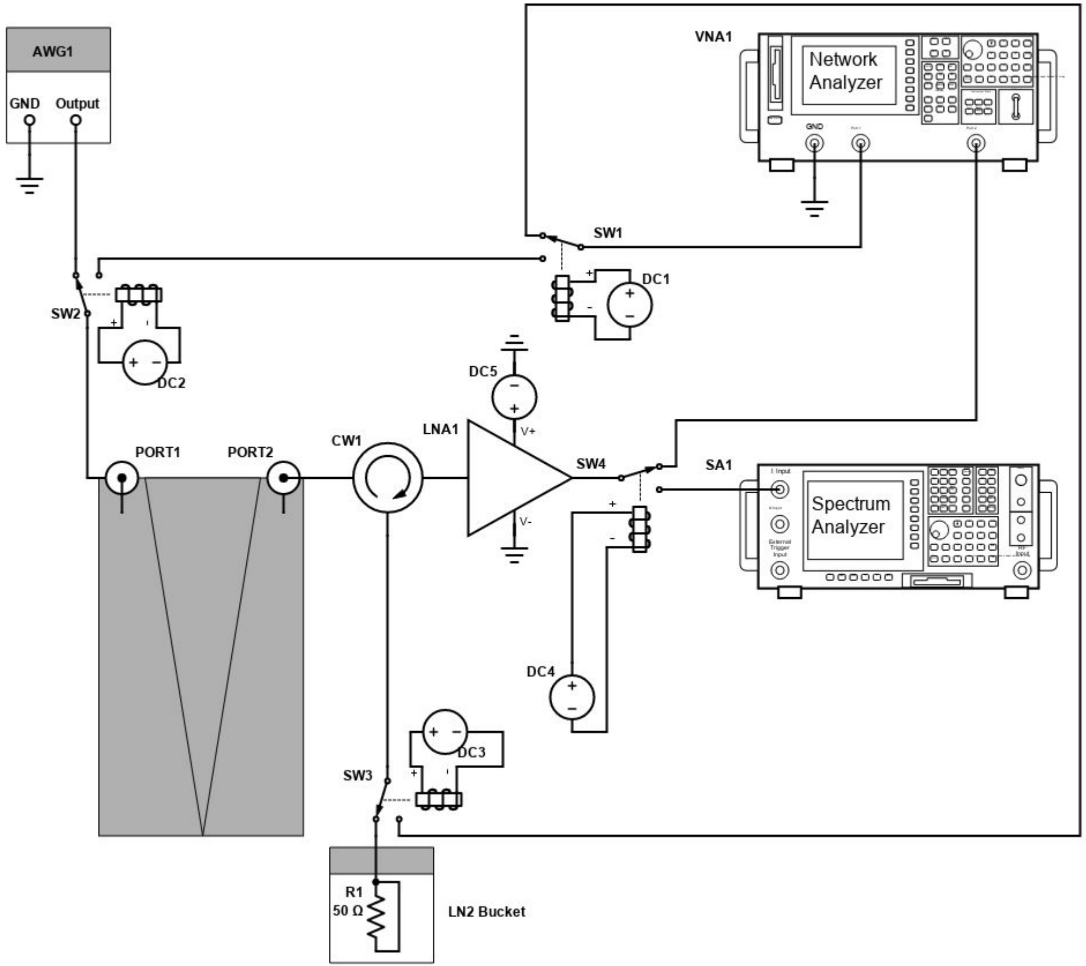
Acquisition live time: 1 year at 80% uptime
Frequency range: 10 to 40 GHz
Field strength: 15 T
Total system noise: 1/6.09 * SQL

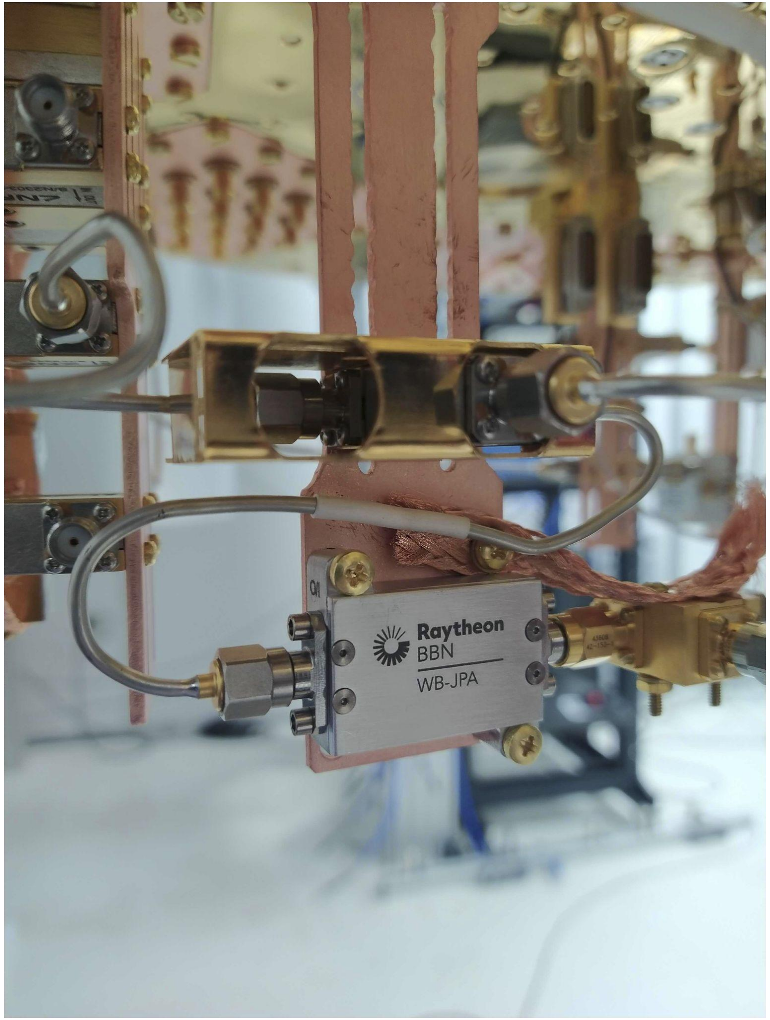


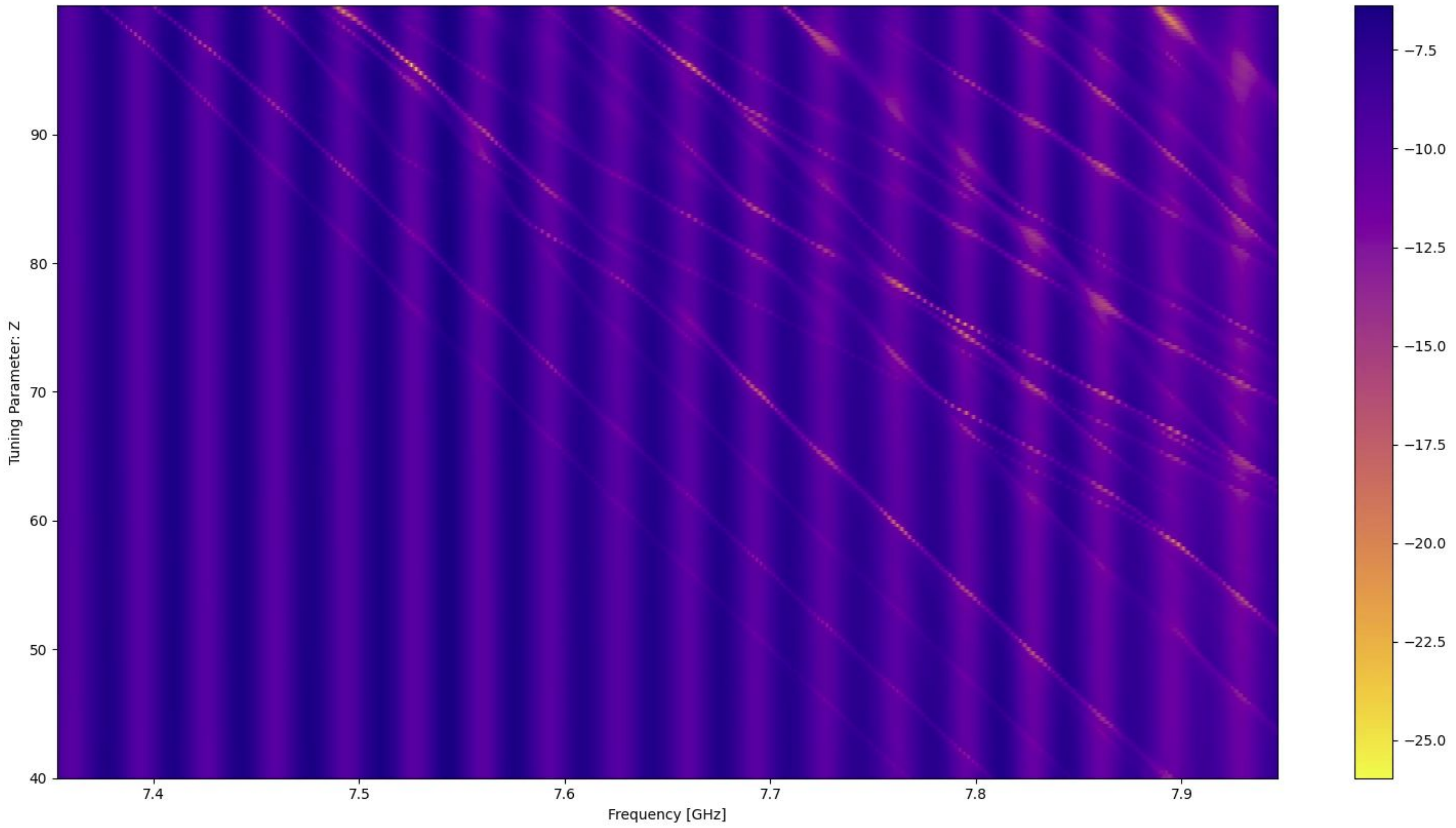
Tuning (side view):

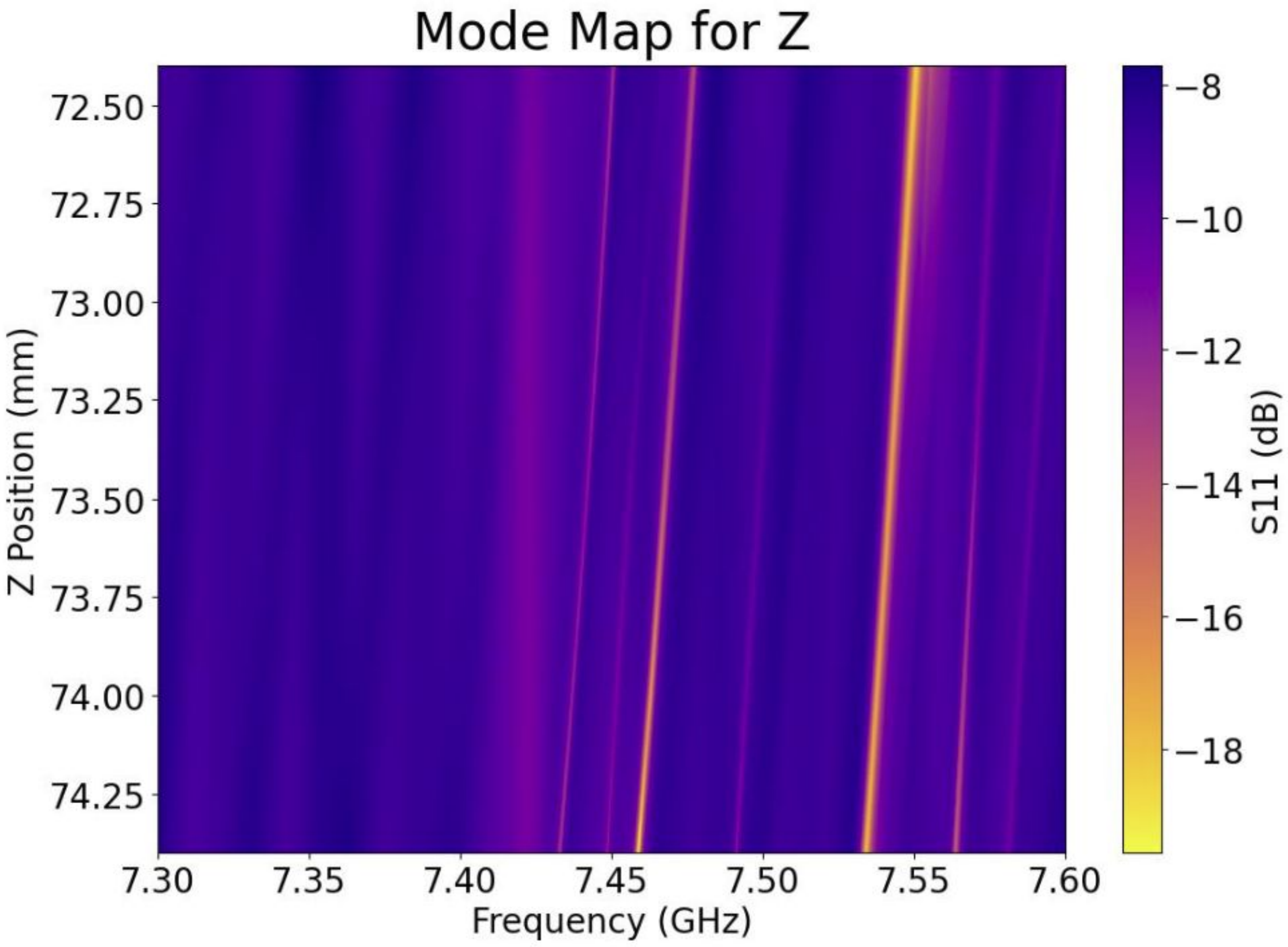


Resonant frequency set by gap width, which tunes as the wedge moves vertically.

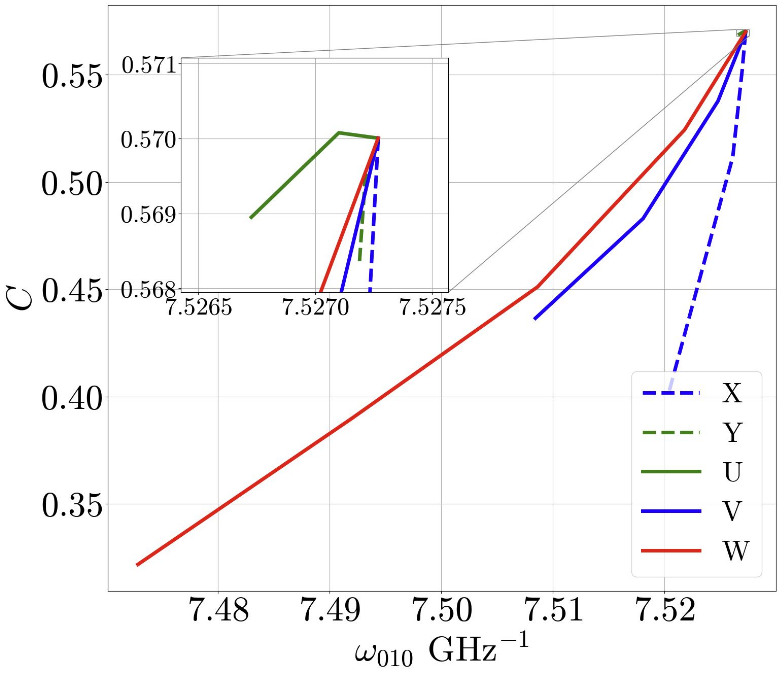

AWG1
GND
Output
VNA1
Network Analyzer
GND
SW1
DC1
SW2
DC2
DC5
LNA1
V+
V-
SW4
SA1
Spectrum Analyzer
PORT1
PORT2
CW1
DC4
DC3
SW3
R1
50 Ω
LN2 Bucket


Raytheon
BBN
WB-JPA

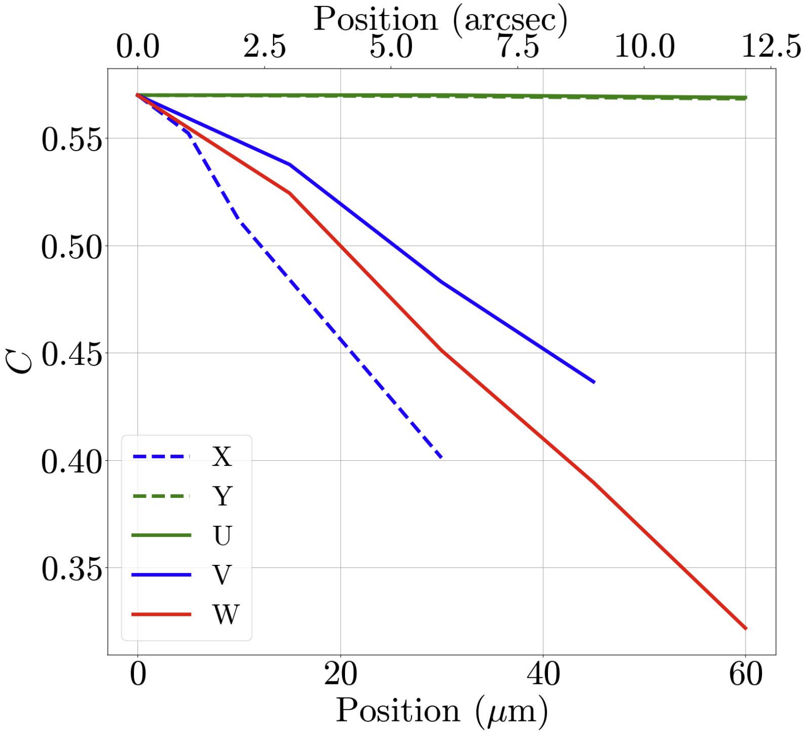

90
80
70
60
50
40
Tuning Parameter: Z
7.4
7.5
7.6
7.7
7.8
7.9
Frequency [GHz]
−7.5
−10.0
−12.5
−15.0
−17.5
−20.0
−22.5
−25.0



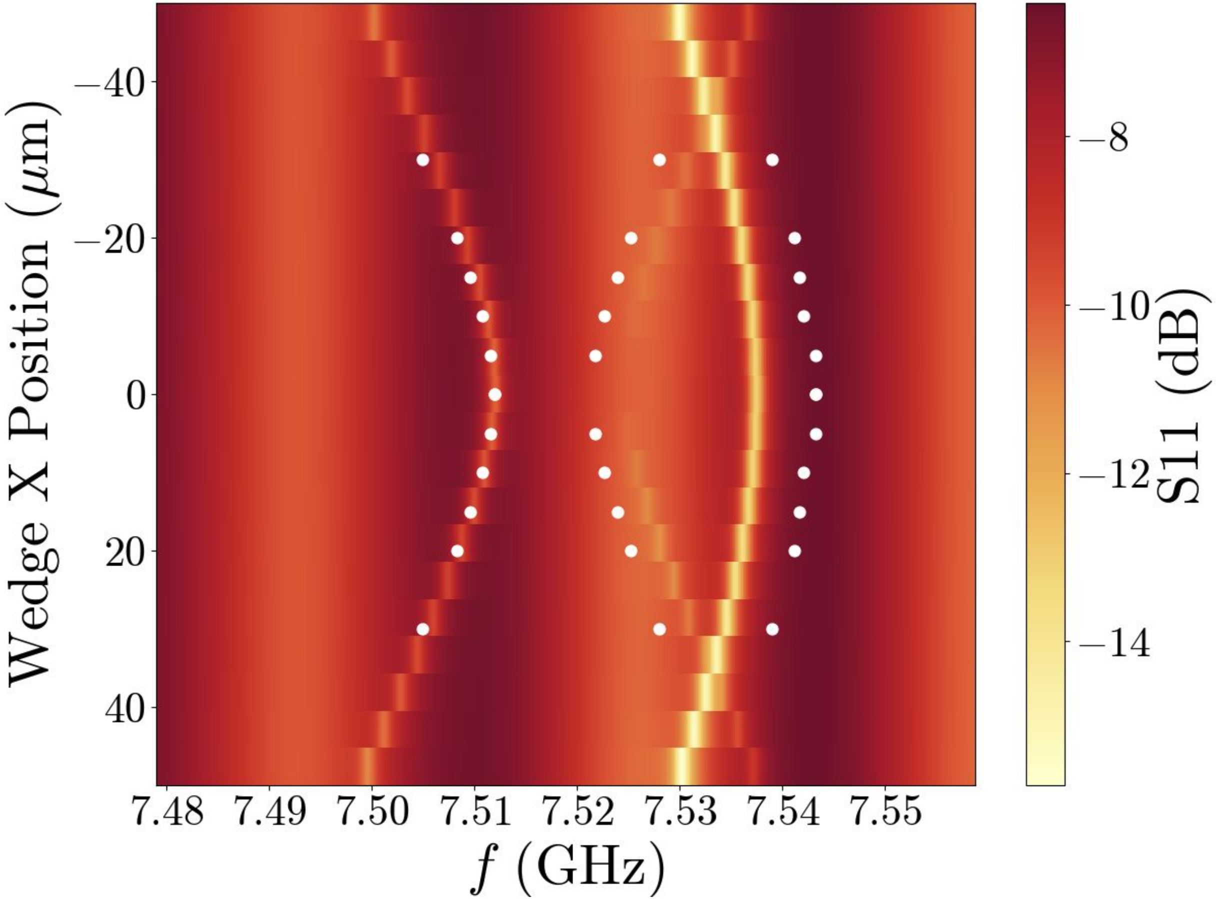
Retuning required every ~1 mm = ~10 MHz. Each realignment takes ~2 minutes.



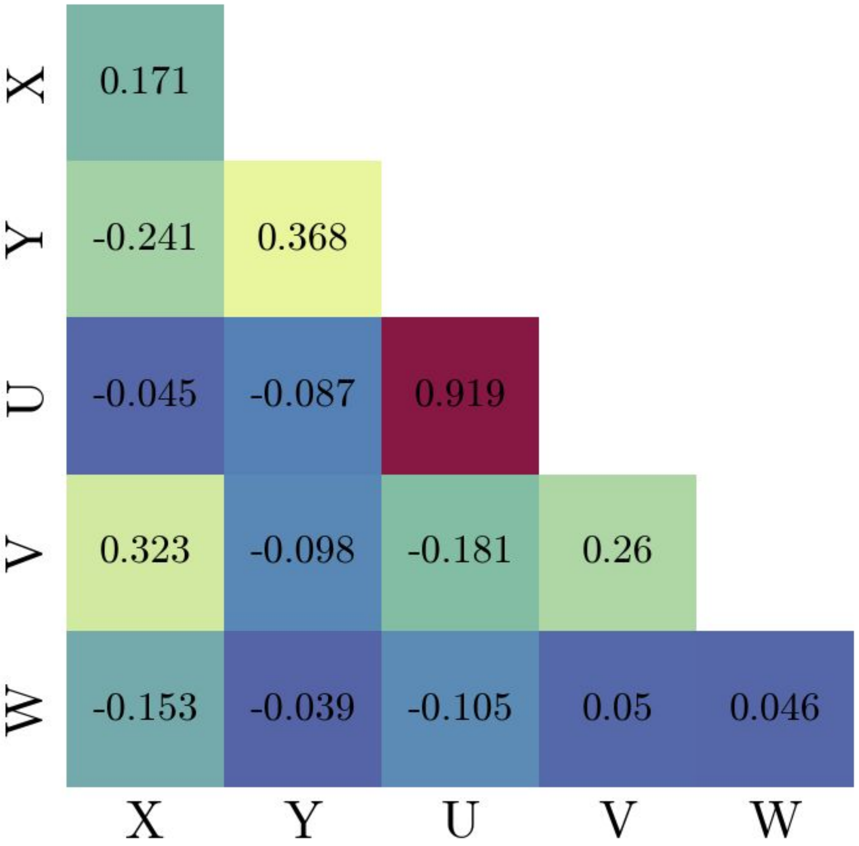
0.571
0.570
0.569
0.568
7.5265
7.5270
7.5275
0.55
0.50
0.45
0.40
0.35
C
7.48
7.49
7.50
7.51
7.52
ω_{010} GHz^{-1}
X
Y
U
V
W

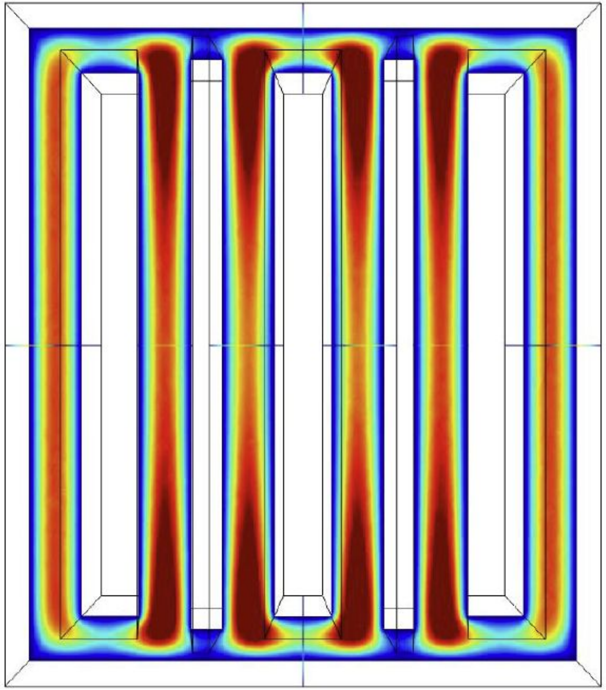


Position (arcsec)
0.0
2.5
5.0
7.5
10.0
12.5
0.55
0.50
0.45
0.40
0.35
C
0
20
40
60
Position (μm)
X
Y
U
V
W



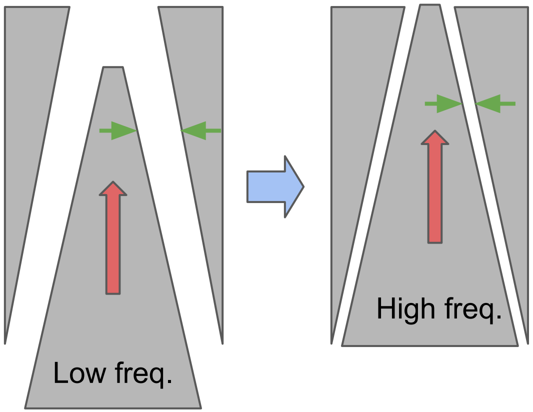
Wedge X Position (μm)
−40
−20
0
20
40
7.48
7.49
7.50
7.51
7.52
7.53
7.54
7.55
f (GHz)
S11 (dB)
−8
−10
−12
−14


X
Y
U
V
W
0.171
-0.241
0.368
-0.045
-0.087
0.919
0.323
-0.098
-0.181
0.26
-0.153
-0.039
-0.105
0.05
0.046
X
Y
U
V
W



Tuning, how it works (in simple case)

New figure depicting tuning with vertical motion in simple annular case (similar to below).



Gap width is tuned as the wedge moves vertically.

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We present results from a first experimental demonstration of a tunable thin-shell axion haloscope, as proposed in [JCAP02(2021)018]. This novel geometry decouples the overall volume of the haloscope from its resonant frequency, thereby evading the steep sensitivity degradation in scaled high-frequency haloscopes. An aluminum 4 L pathfinder (designed for 6.8-8.2 GHz) has been fabricated and measured at room temperature. A singly polarized, axion-sensitive, TM_{010}-like mode is clearly identified against a background of spurious resonances. The on-resonance E-field distribution is mapped, verifying results from numerical calculations. With high-precision alignments, we achieve robust tuning over a representative frequency range. Anticipating future cryogenic operations, we demonstrate successful cavity alignments relying only on microwave reflection measurements, achieving a form factor of 0.57 and a room temperature Q of 5,000.