The Beehive Haloscope: A Strongly Coupled, Phase-Coherent Cavity Array for Axion Detection

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Patras, Greece

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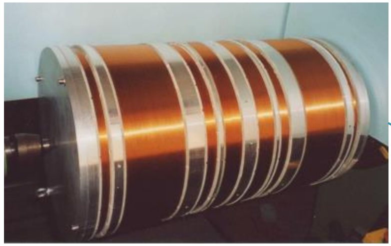
arXiv:2404.06627

Stanford University

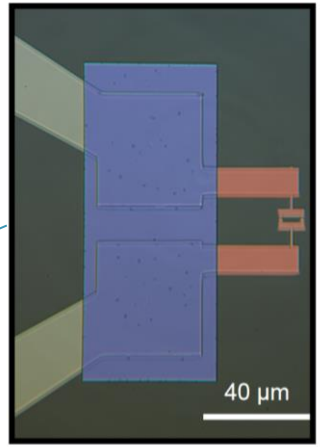
Outline

- ADMX-VERA: Volume-Enhanced Haloscopes
- Beehive Haloscopes
- Progress on Working Prototype
- Future Plans

High Frequency Haloscopes: Challenges and Opportunities



https://s.mriquestions.com/superconductive-design.html

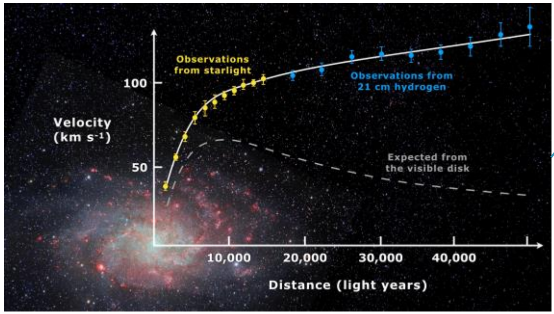


https://indico.fnal.gov/event/10138/contributions/1020/attachments/551/642/eddins_axionWorkshopSlides_20150824pdf.pdf

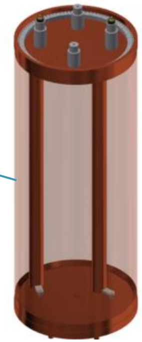
Magnet　　Detector

$$\frac{d\nu}{dt} \propto \boxed{g_\gamma^4 \rho^2}\,\boxed{B^4}\,\boxed{V^2 Q_L C^2}\,\boxed{T_{sys}^{-2}}$$

Nature　　Cavity

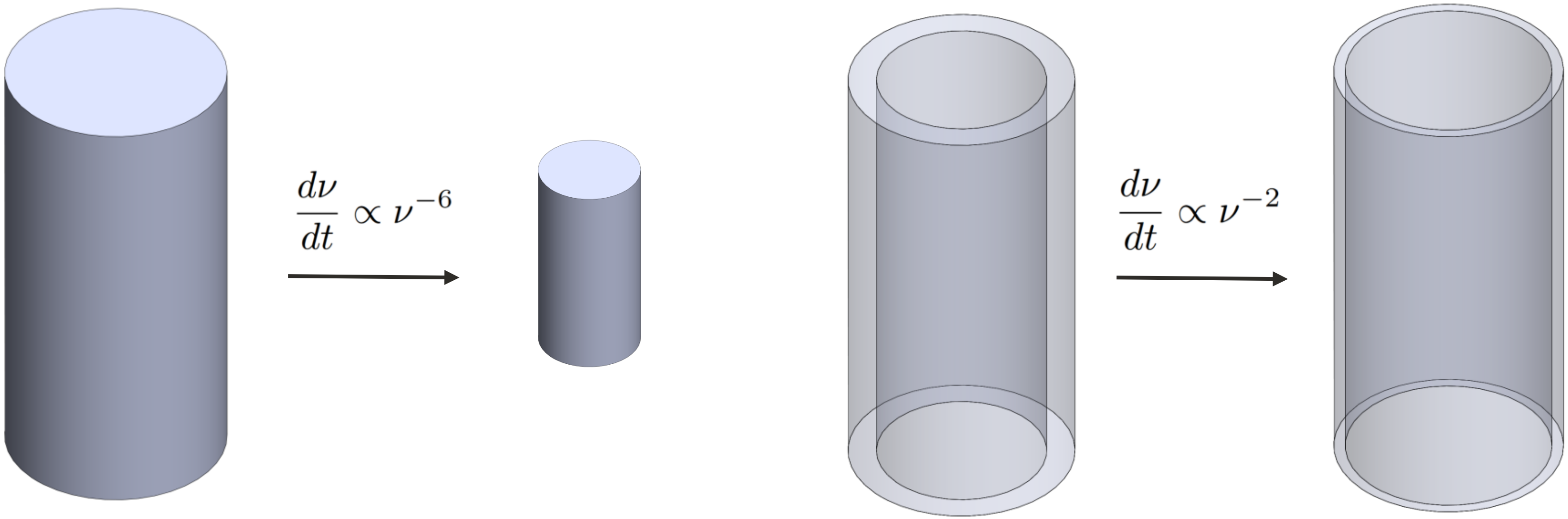


https://en.wikipedia.org/wiki/Galaxy_rotation_curve



C. Boutan *et al.* (ADMX Collaboration) Phys. Rev. D 109, 012009

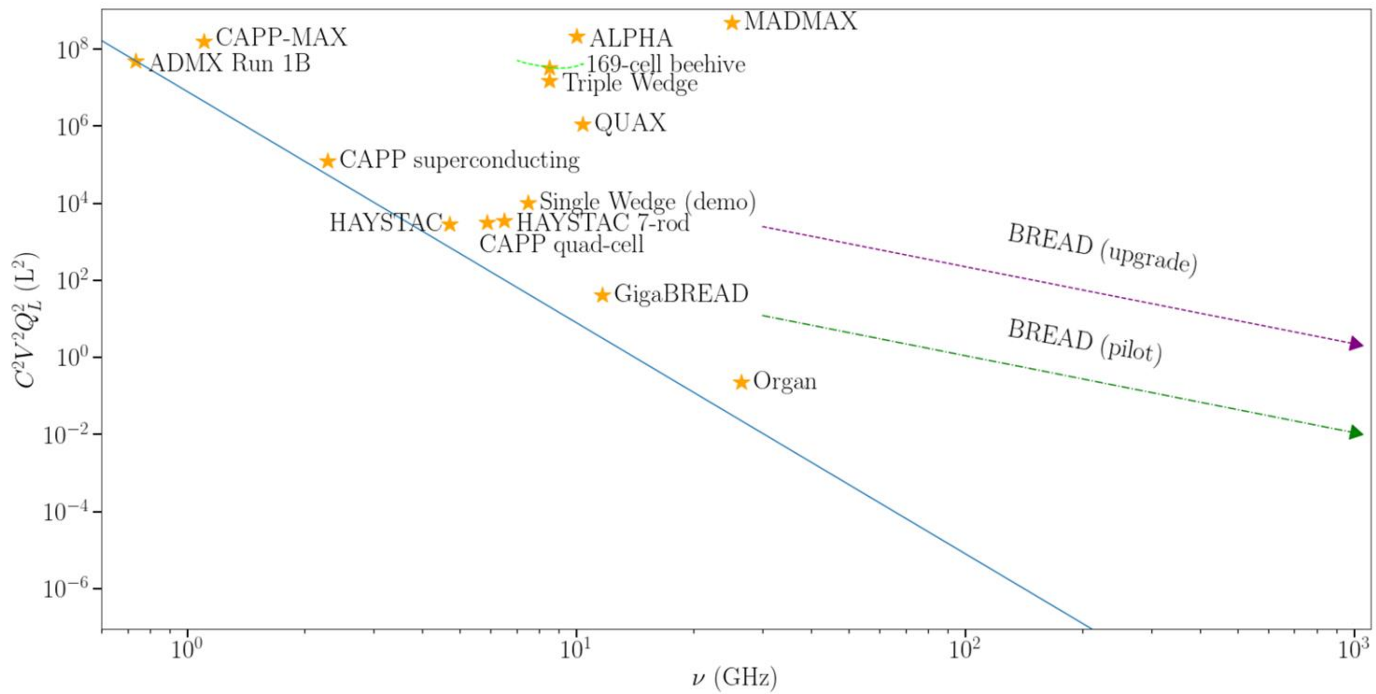
ADMX-VERA: Solving the Scan Rate-Volume Scaling Problem



Traditional Haloscope
Scale 3 Dimensions

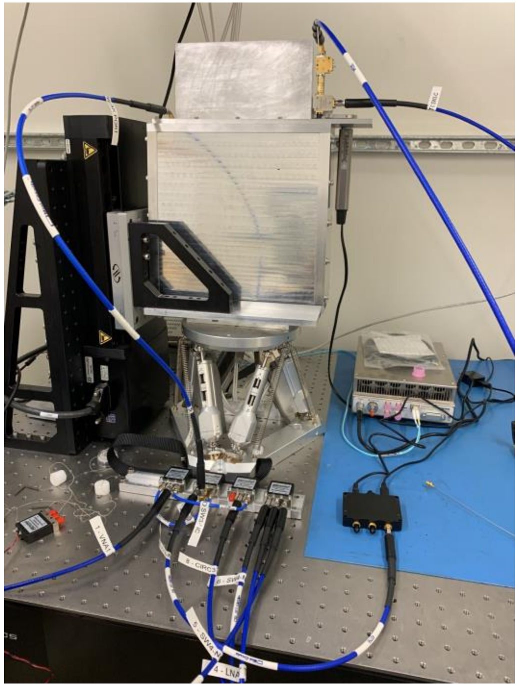
Thin-Shell Haloscope
Scale 1 Dimension

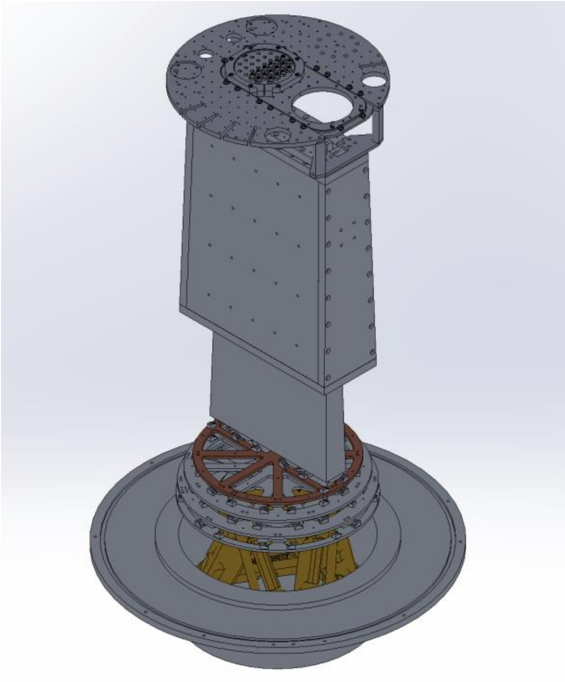
High Frequency Haloscopes: Challenges and Opportunities

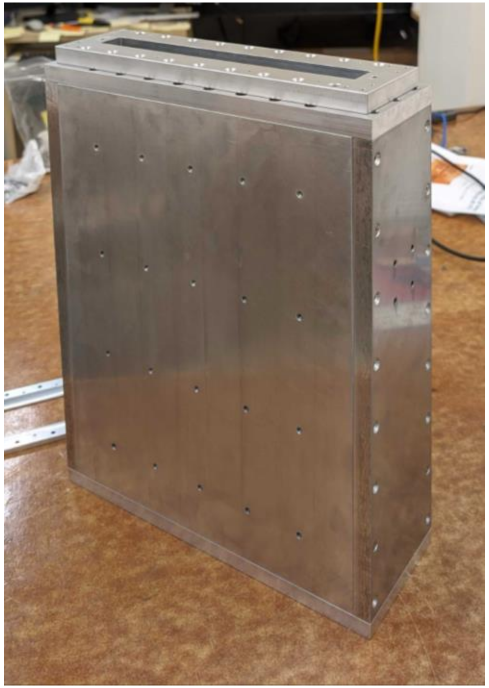


ADMX-VERA: Current Prototypes

* Includes work by T. Dyson, S. Ruppert, M. Salatino, and many summer students



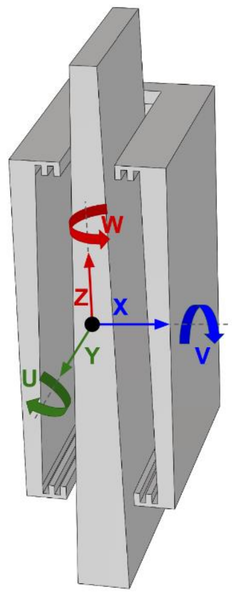


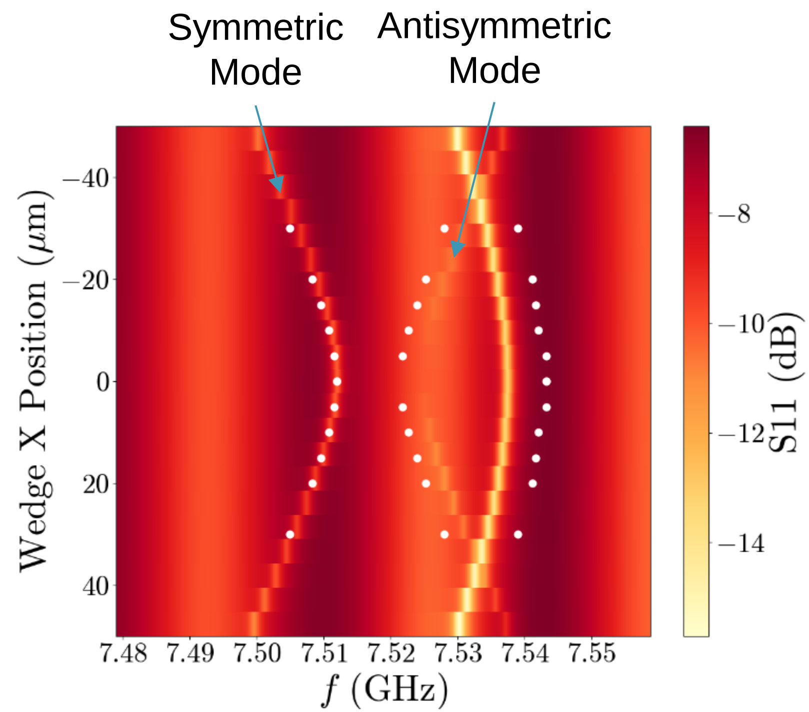


Warm “Single-Racetrack” Prototype

Cryogenic “Single-Racetrack”

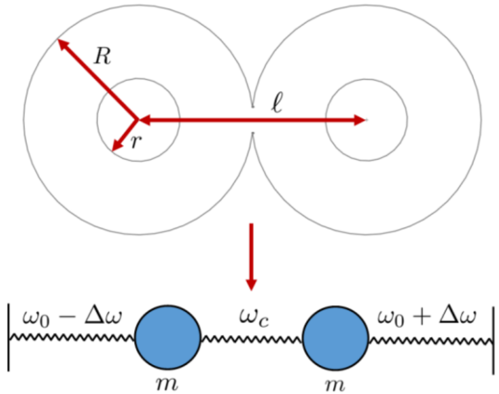
Strong Coupling and Passive Coherence

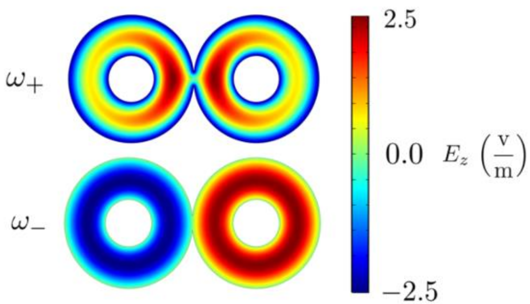


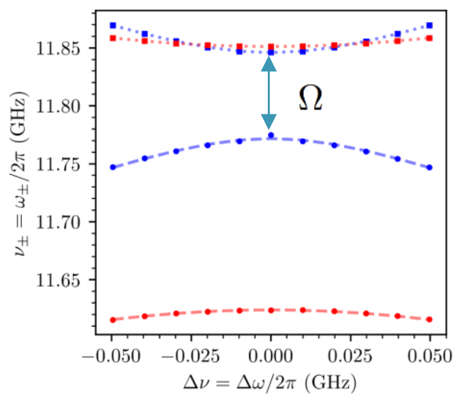


Dyson T., et al. 2024 Phys. Rev. Applied 21, L041002

Strong Coupling and Passive Coherence







Mode splitting depends on coupling:

$$\Omega \equiv \omega_- - \omega_+ \sim \frac{\omega_c^2}{\omega_0}$$

Form factor high when $\Delta\omega < \Omega$:

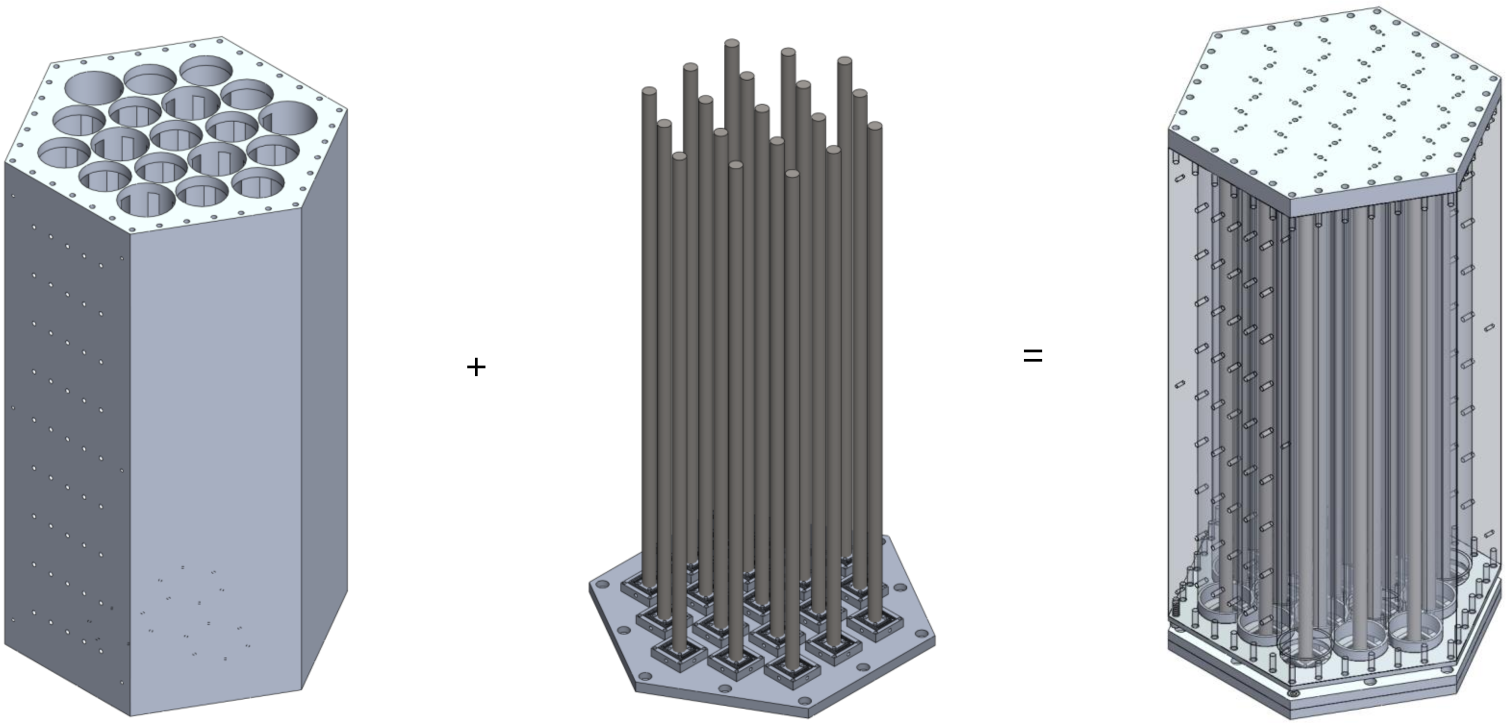
$$C_p = \frac{(1 + \sqrt{1+\zeta^2} - \zeta)^2}{2[1 + (\sqrt{1+\zeta^2} - \zeta)^2]}$$

$$\zeta \equiv 2\omega_0 \frac{\Delta\omega}{\omega_c^2} \sim \frac{2\Delta\omega}{\Omega}$$

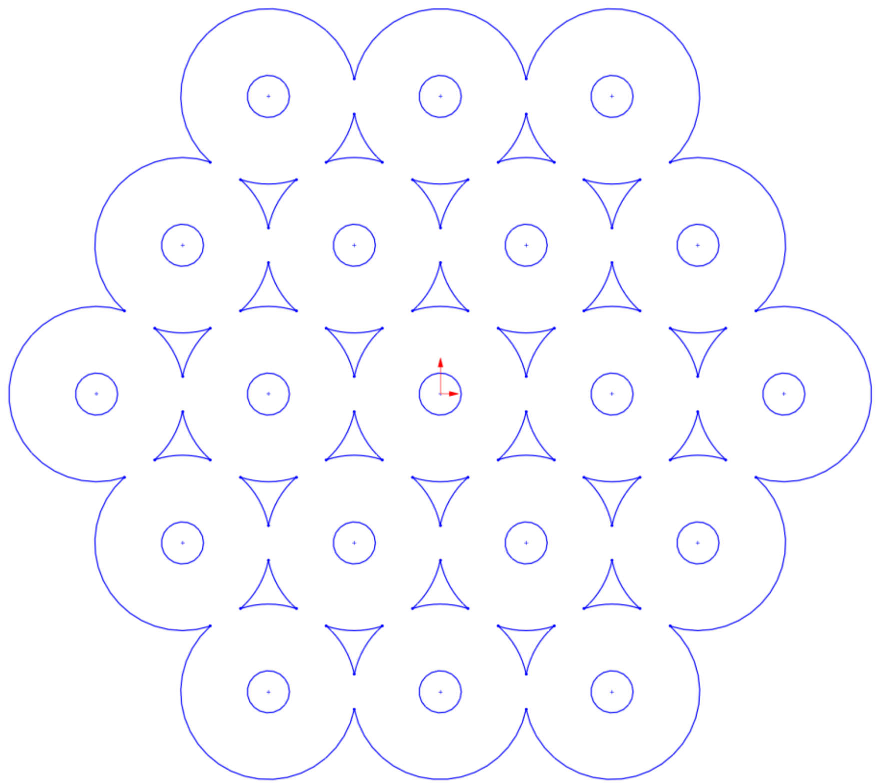
Conclusion: Line width criterion replaced by mode splitting criterion

$$\Delta\omega < \frac{\omega_0}{Q} \longrightarrow \Delta\omega < \Omega \sim \frac{\omega_c^2}{\omega_0}$$

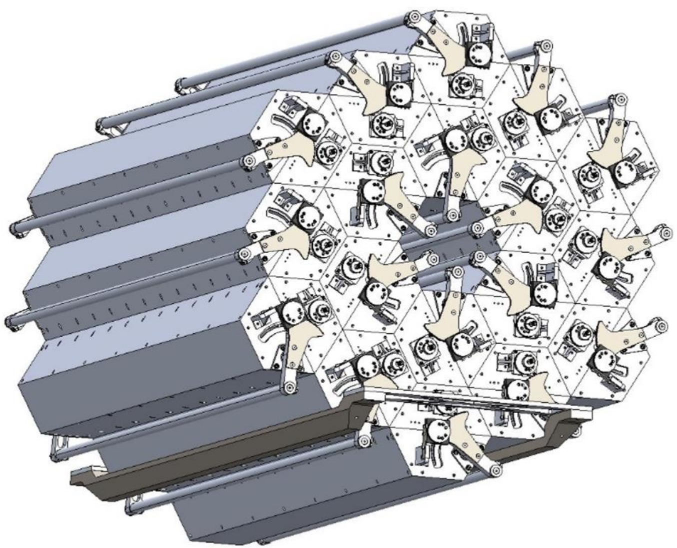
Maximizing Passive Coherence: Beehive Geometry



Maximizing Passive Coherence: Beehive Geometry



Beehive: Combining Cavity Arrays and Thin Shell Haloscopes



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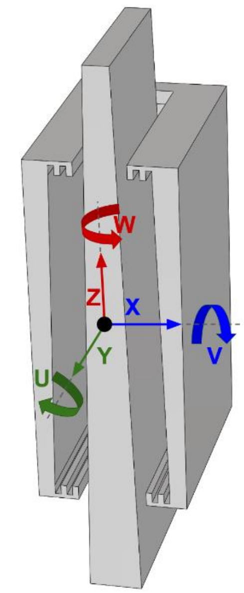
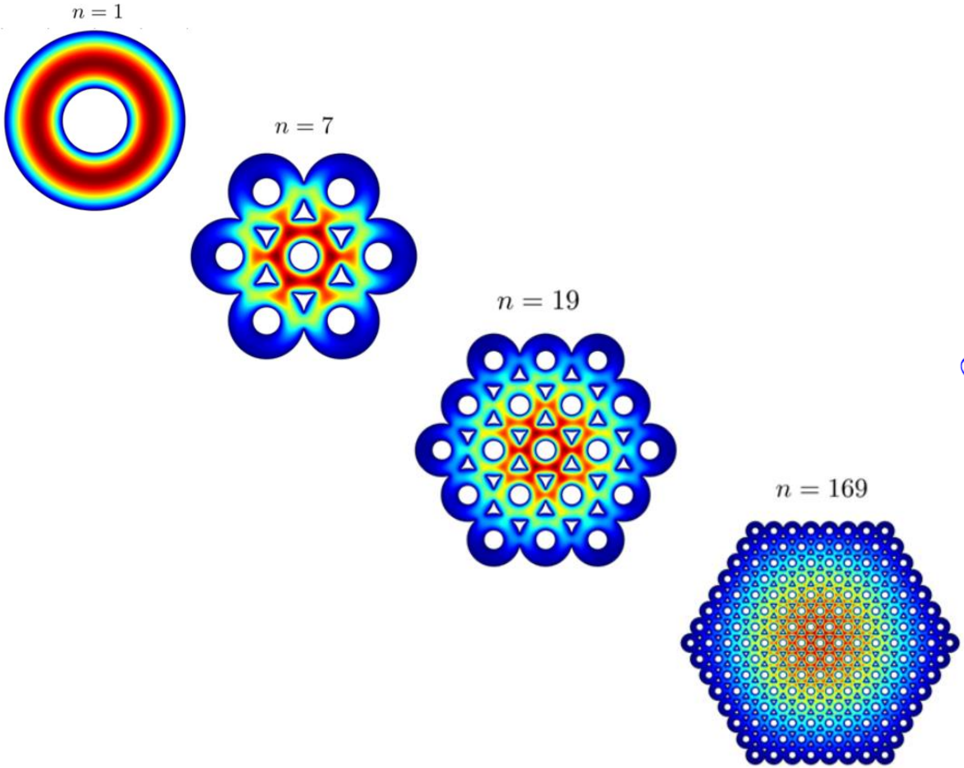
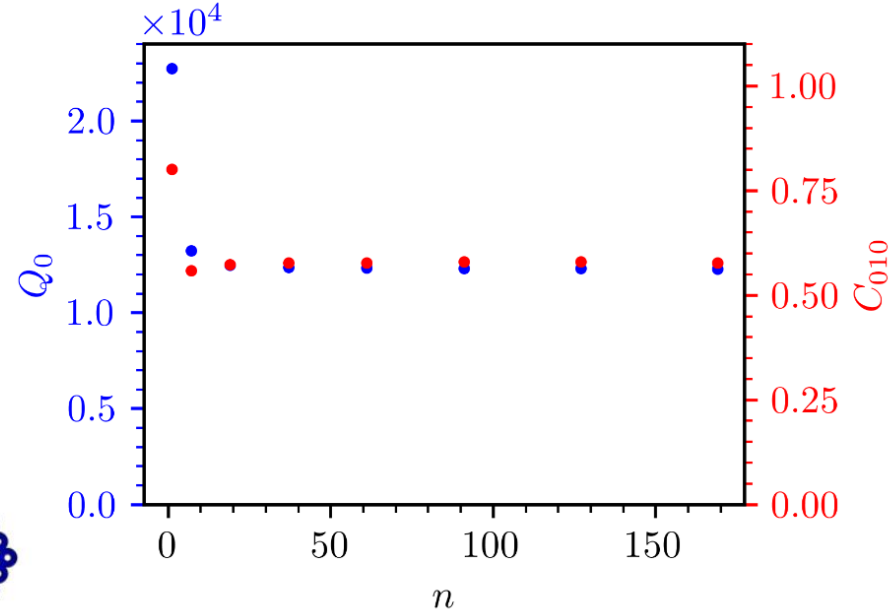


ADMX Collaboration. 2023.
arXiv:2203.14923v3

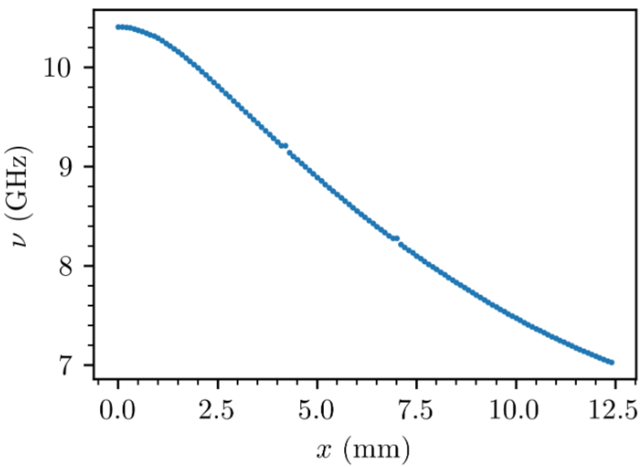
Dyson T., et al. 2024 Phys. Rev.
Applied 21, L041002

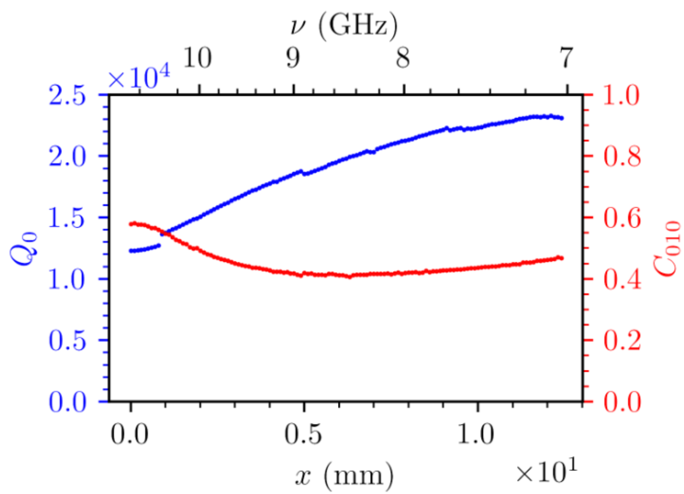
Beehive Features: Scalability

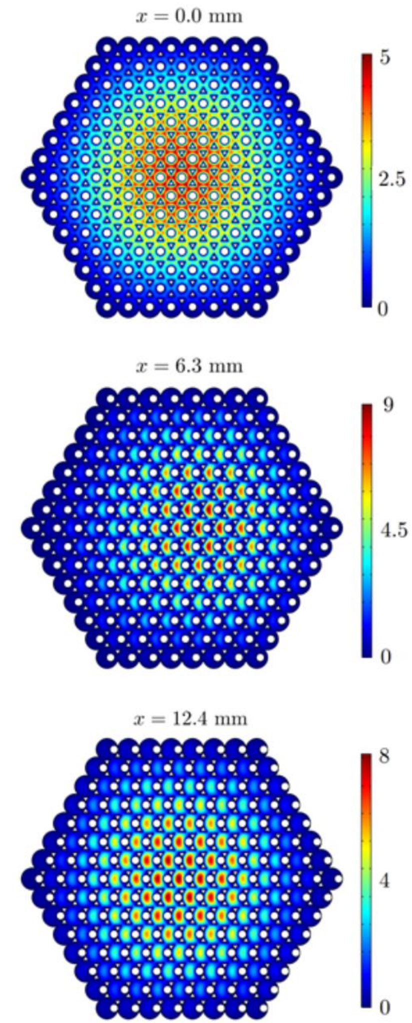




Beehive Features: Tunability

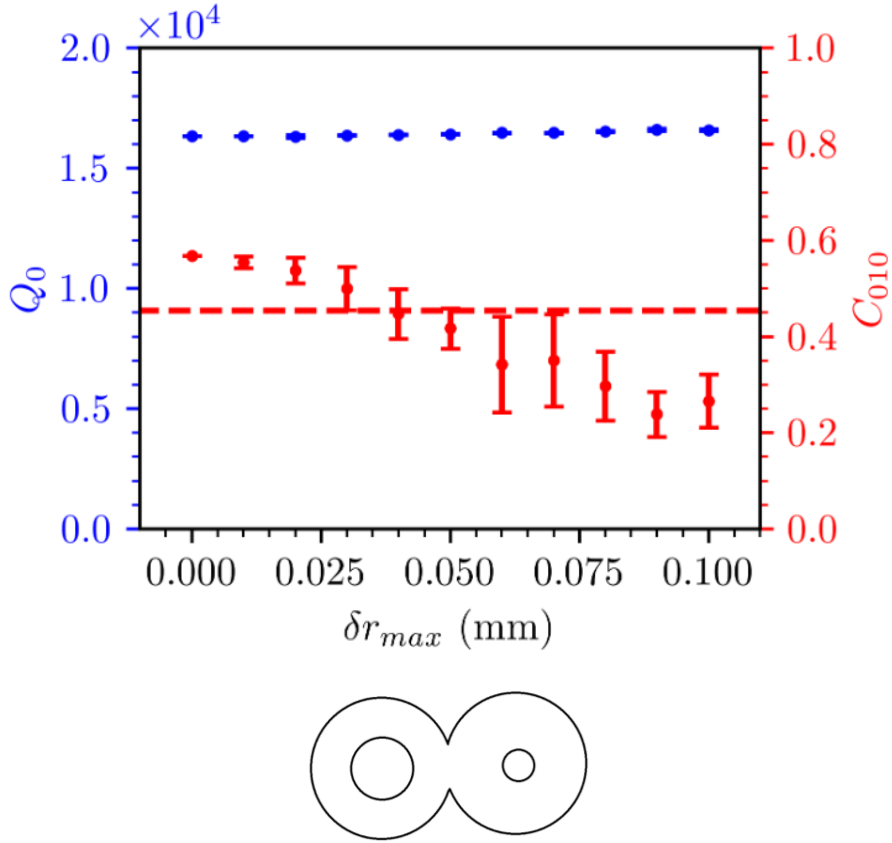




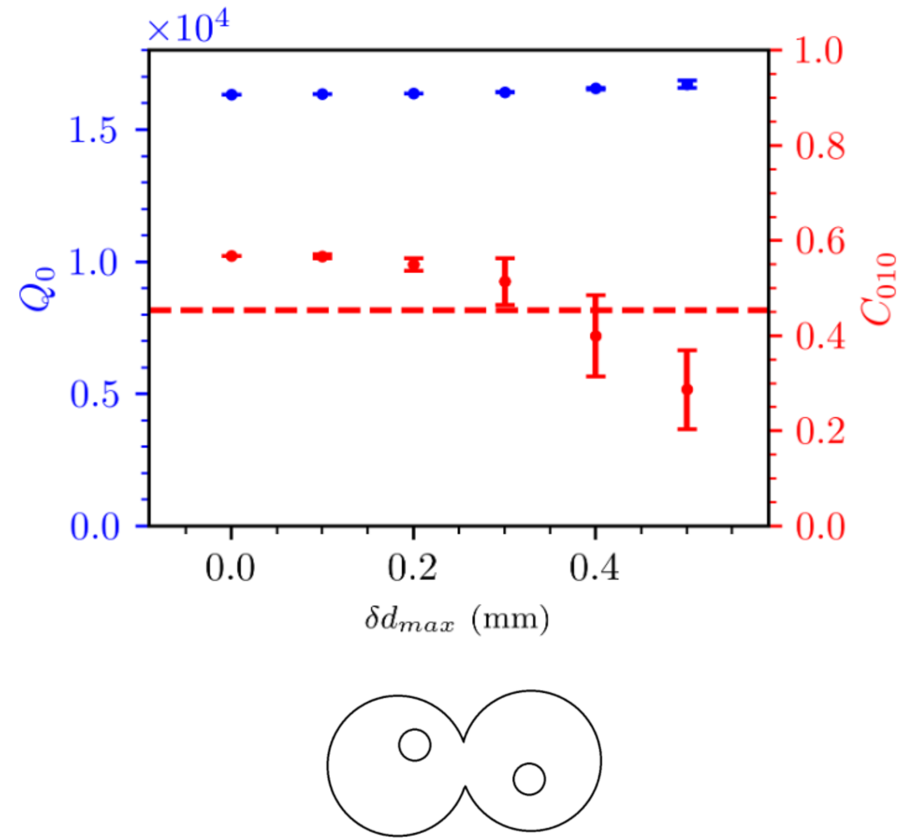


Beehive Features: Resilience

Machining Tolerance Example:
Rod Radius Variation

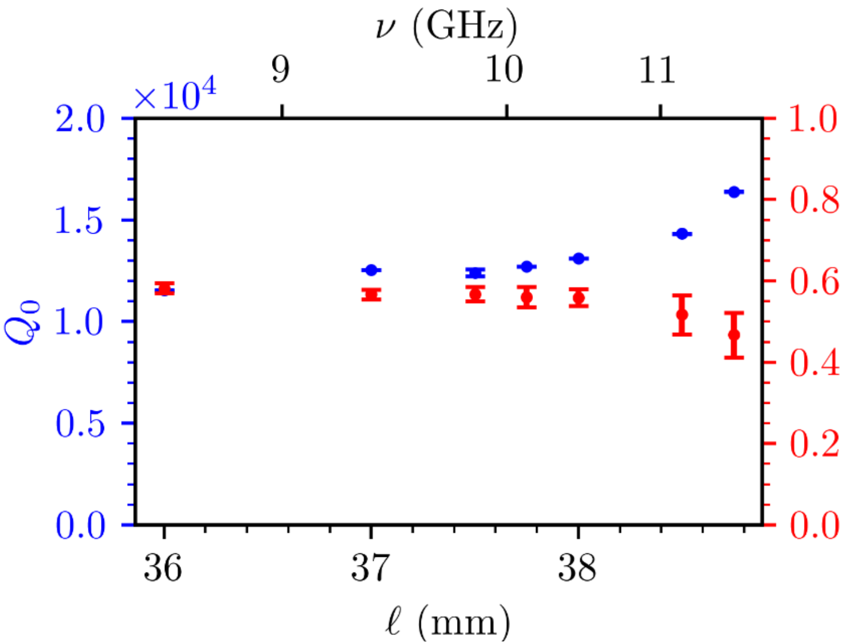


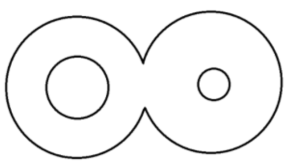
Assembly Tolerance Example:
Rod Position Variation



Beehive Features: Resilience

Machining Tolerance Example:
Rod Radius Variation





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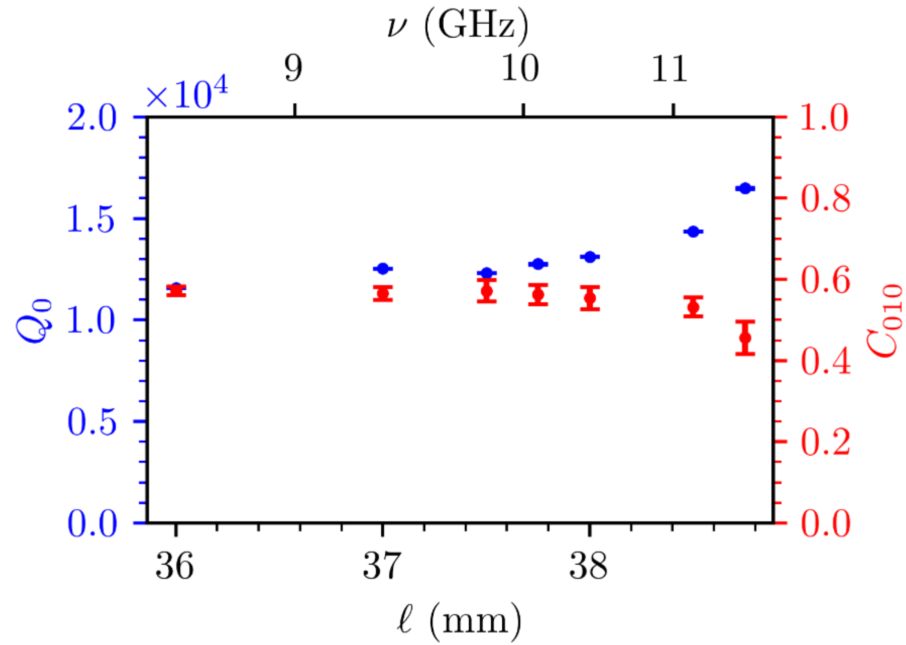
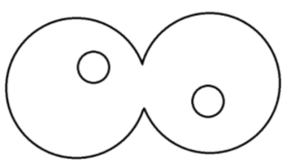
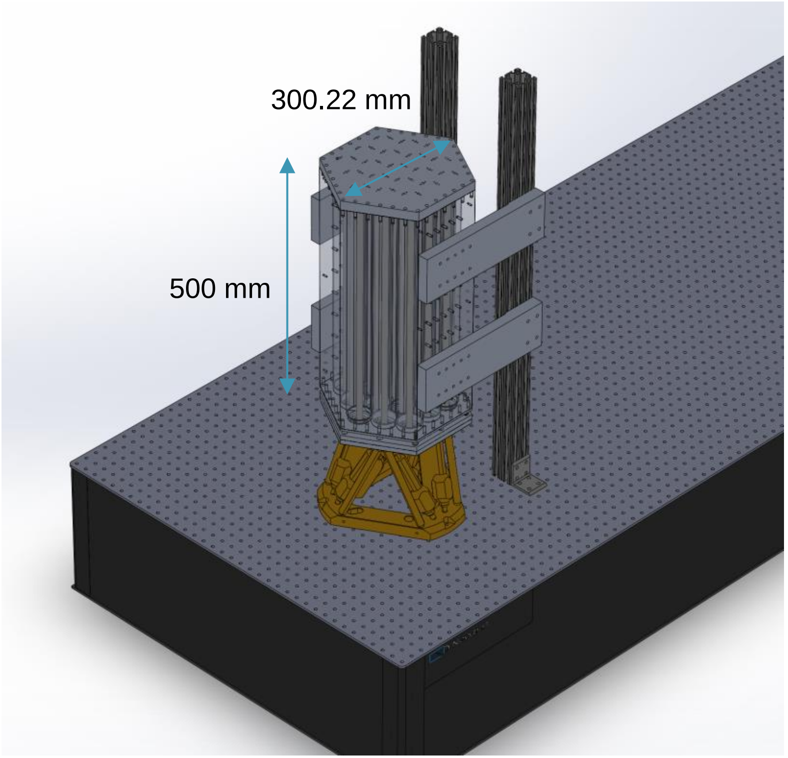




Production Model

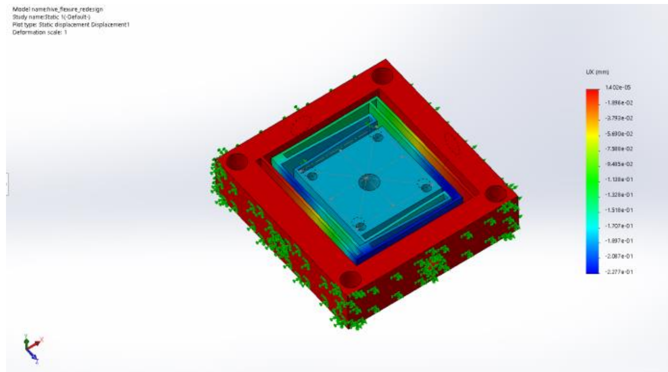


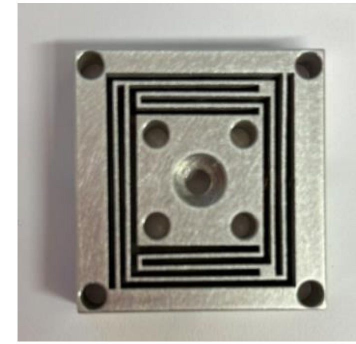
Quick Statistics:

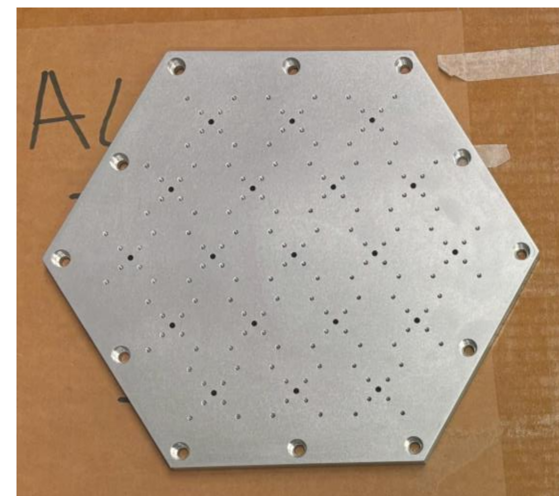
Parameter	Value
Tuning Range (GHz)	5-7 GHz
Q (center of tuning range; Cu at cryogenic temp.)	24,897
C (center of tuning range)	0.34
V (L)	16.73 (19 cells)

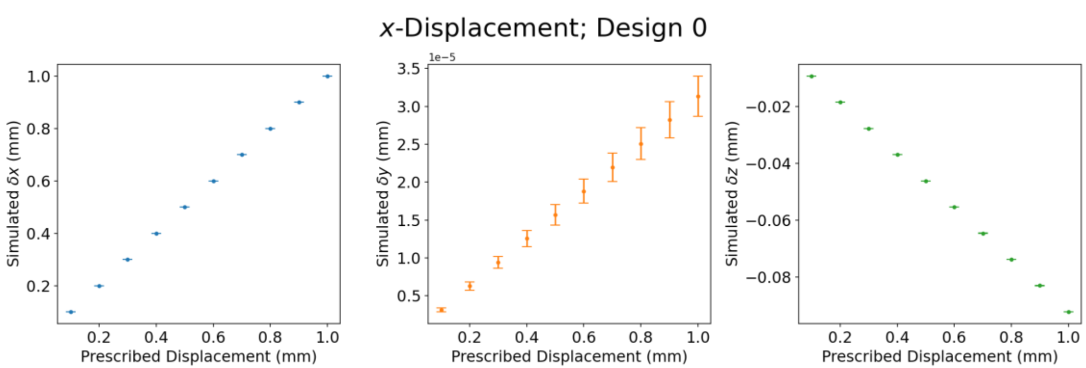
Improving Form Factor: Precise Rod Alignment

* Building on and in conjunction with work by Sephora Ruppert (Stanford graduate student)

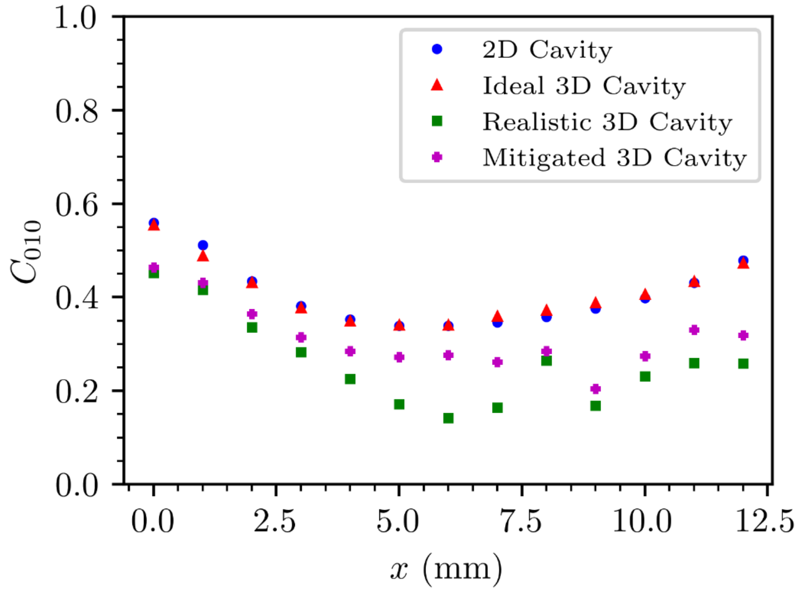


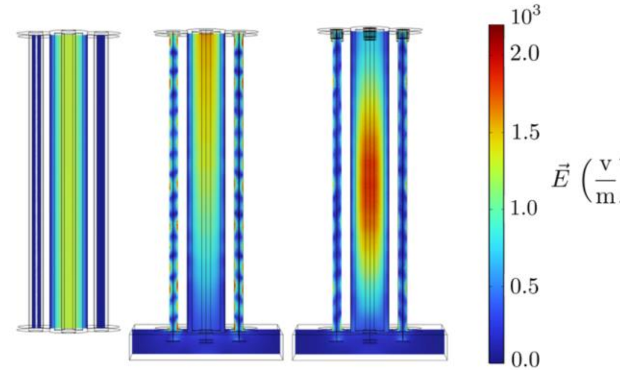


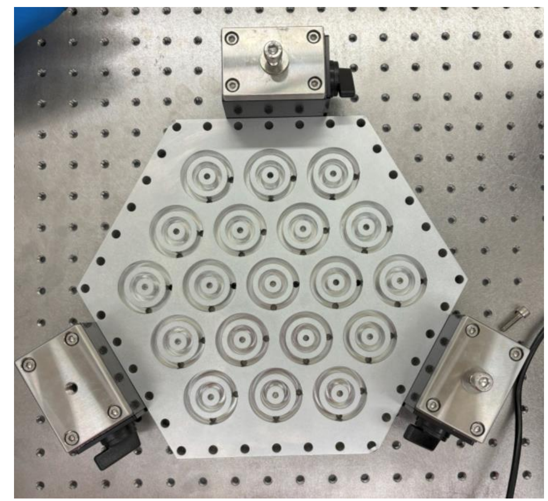




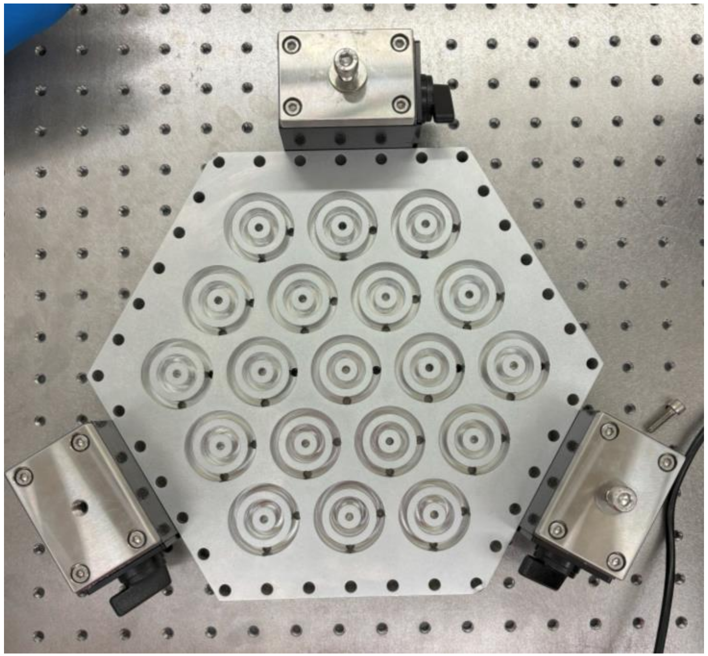
Improving Form Factor: Mode Shaping with Corrugations

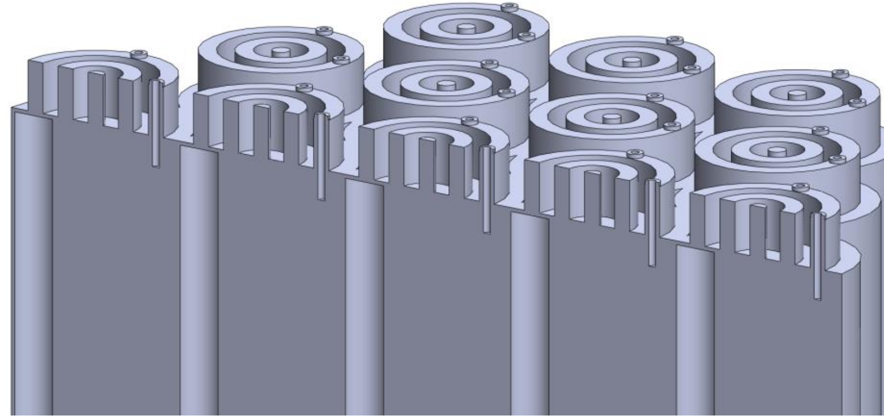


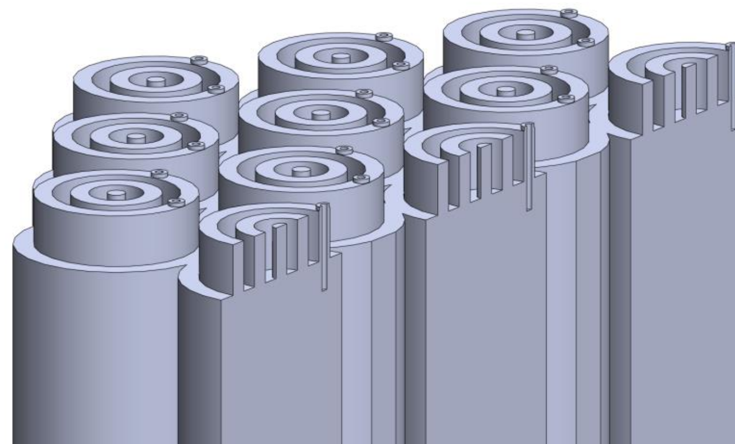




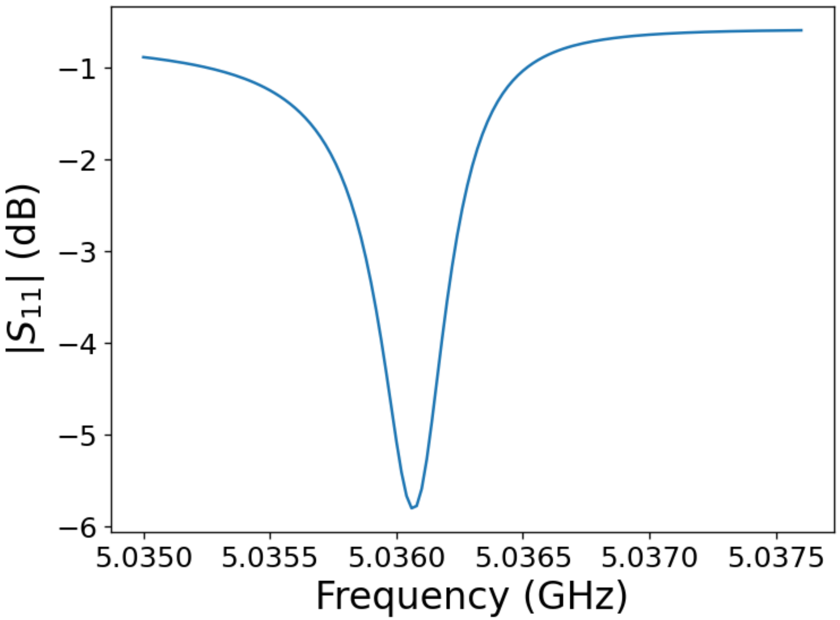
Coupling Scheme



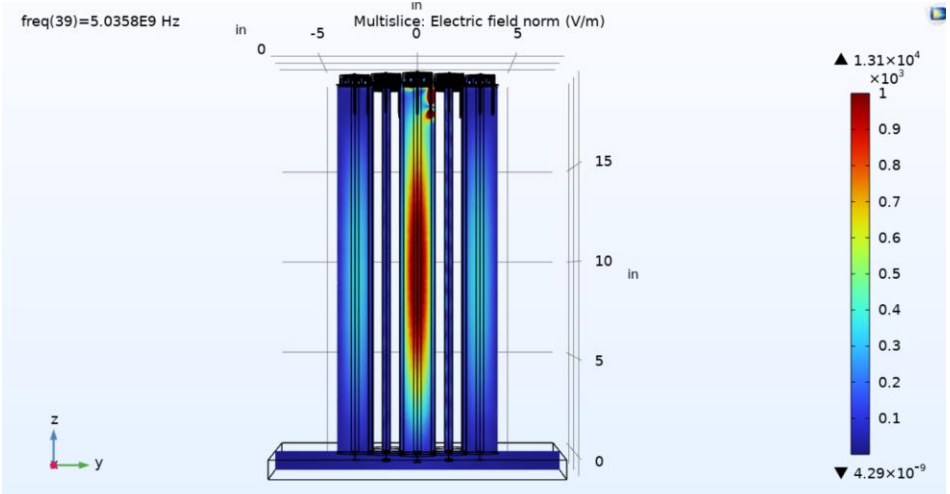


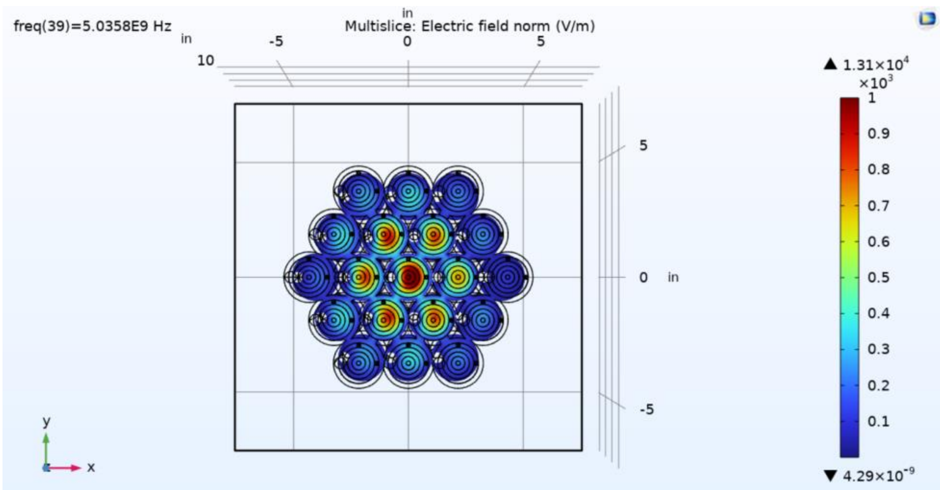


Simulating Coupling: S11



$$Q_0 = 26372$$
$$Q_L = 13252$$
$$\beta = 0.9899$$





Metrology Plan

https://hexagon.com/products/absolute-arm-compact

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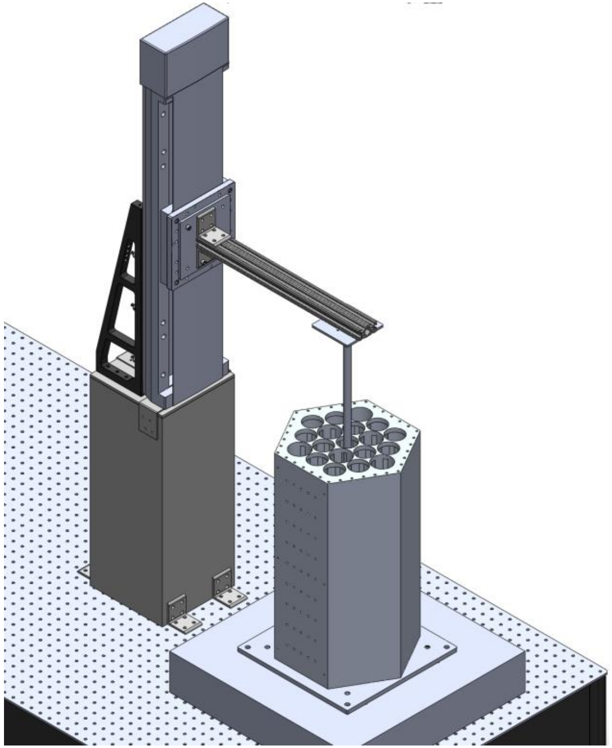
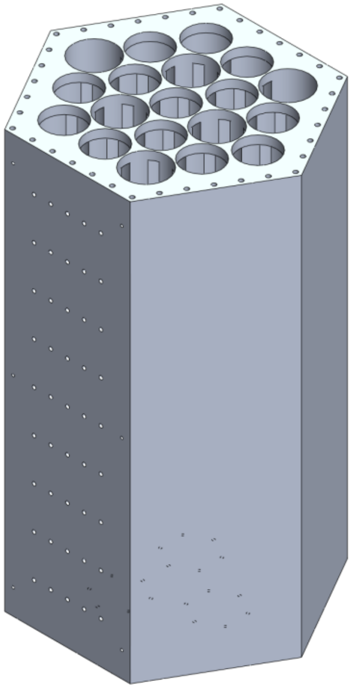


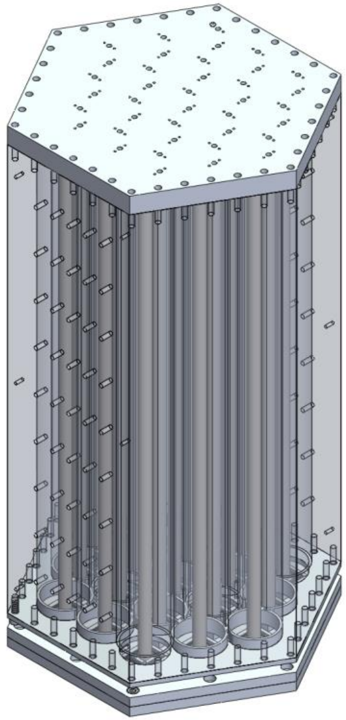
Future Experiment Plans

- Shell machining under consultation
- Assembly and metrology of shell and tuning mechanism
- Cavity parameter measurements:
  - Quality factor
  - Electric field maps
  - Mode maps
- Dark photon exclusion limit run

Backup Slides

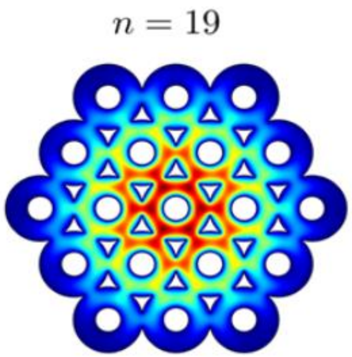
Beehive vs. Plasma Haloscopes

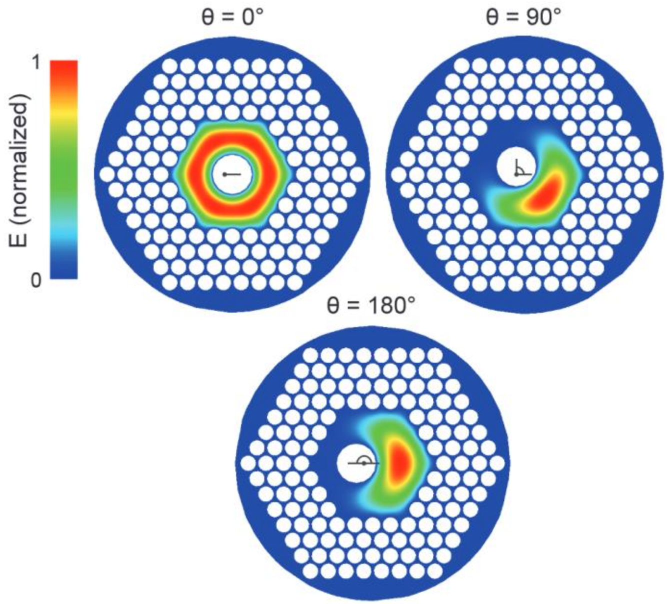




Alpha Collaboration. 2023. https://arxiv.org/pdf/2210.00017

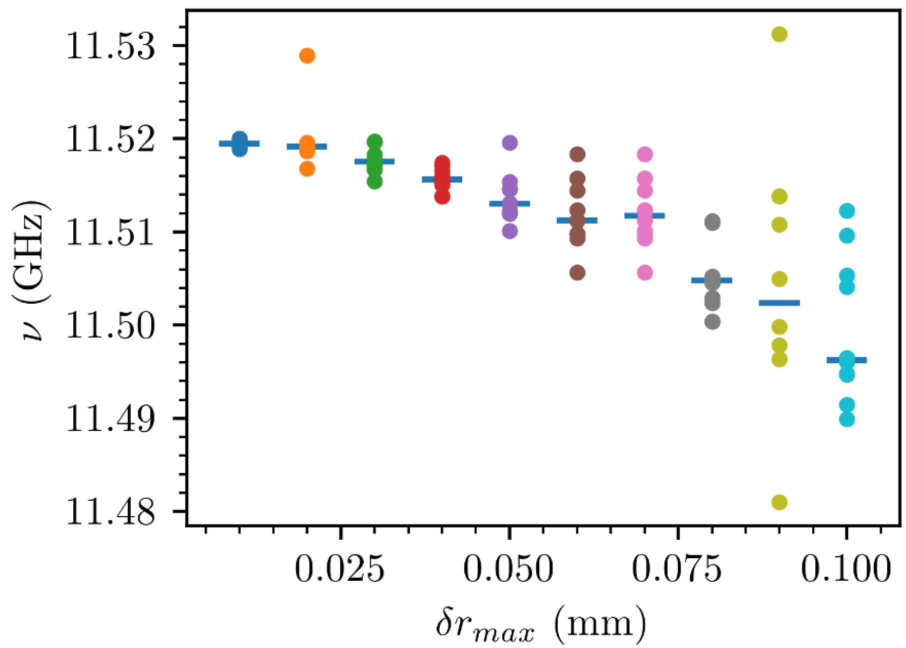
Beehive vs. Photonic Band Gap Haloscopes

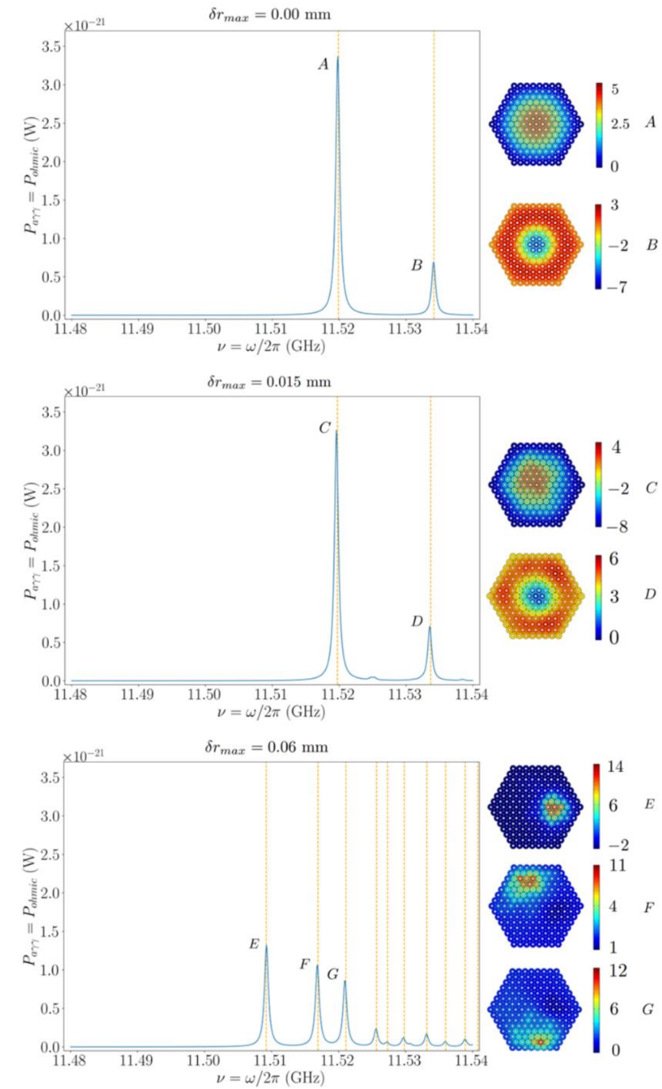




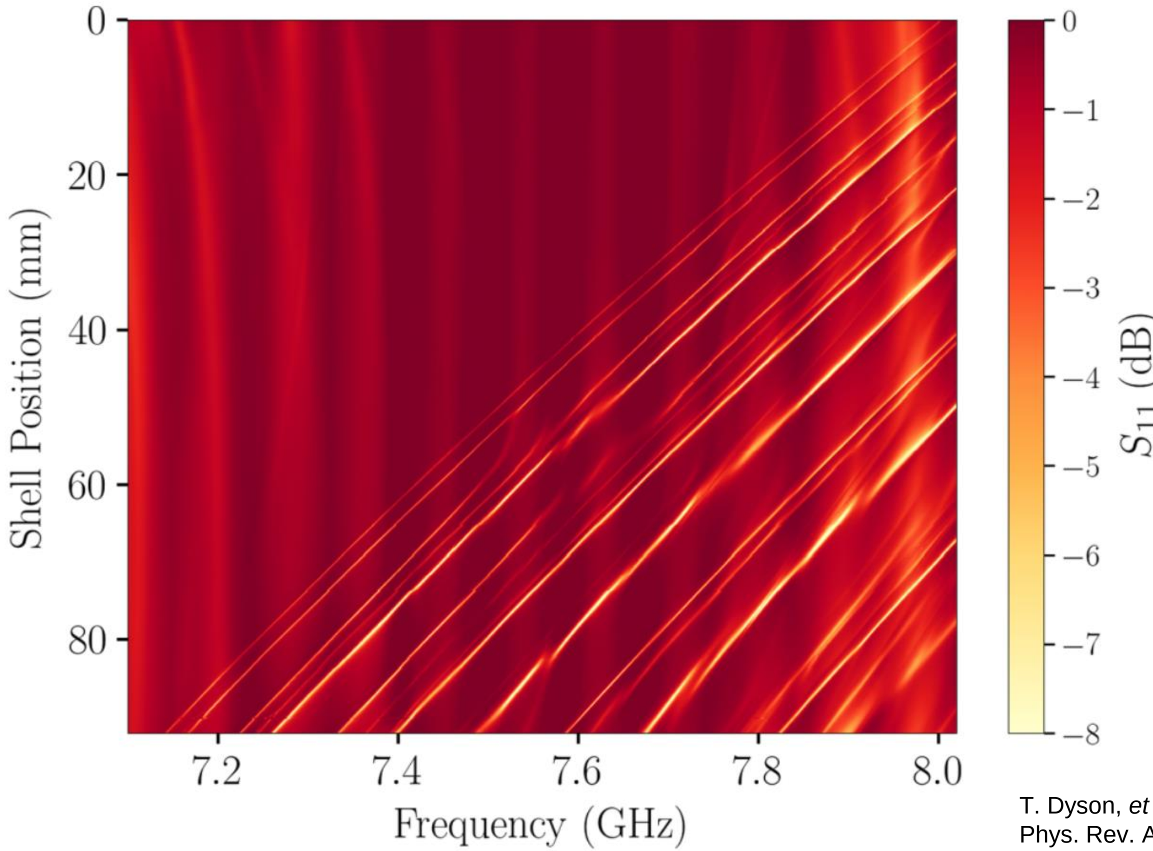
S. M. Lewis, *et al.* 2024. https://arxiv.org/pdf/2408.03861v1

Cavity Decoherence





Thin-Shell Mode Map



T. Dyson, *et al*.
Phys. Rev. Applied 21, L041002