# Orpheus: Extending the ADMX QCD Dark-Matter Axion Search to Higher Masses

## 3rd Workshop on Microwave Cavities and Detectors for Axion Research

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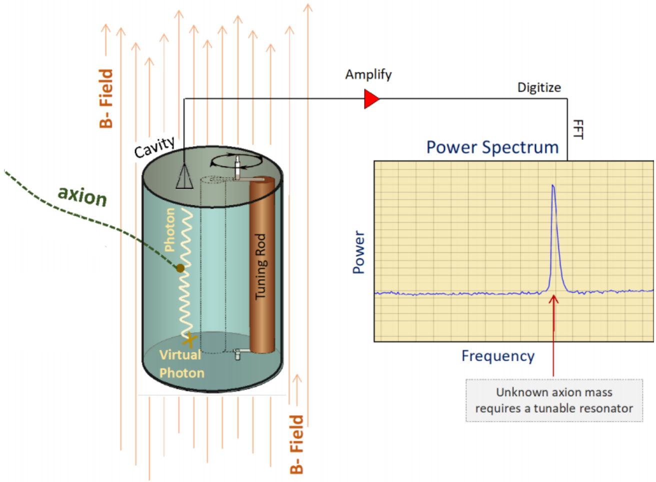
# Outline

1. Detecting Axions with Haloscopes.
2. Motivation for Dielectric Haloscopes and Open Resonators.
3. Orpheus Concept.
4. Orpheus Progress.
5. Outlook.

# Searching for Axions with the ADMX Haloscope

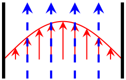



$$P_a \propto B_{ext}^2 Q V_{eff}\,, \qquad V_{eff} = \frac{\left|\int dV \vec{\mathbf{B}}_{ext} \cdot \vec{\mathbf{E}}_a\right|^2}{B_{ext}^2 \int dV \varepsilon_r \left|\vec{\mathbf{E}}_a\right|^2}$$

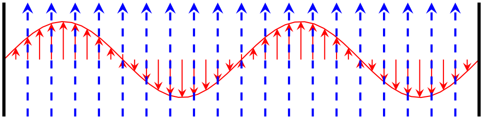
# Becomes increasingly difficult at higher frequency

$$P_a \propto B_{ext}^2 Q V_{eff}\,, \qquad V_{eff} = \frac{\left|\int dV \vec{\mathbf{B}}_{ext} \cdot \vec{\mathbf{E}}_a\right|^2}{B_{ext}^2 \int dV \varepsilon_r \left|\vec{\mathbf{E}}_a\right|^2}$$

| Resonator wall     $\vec{\mathbf{E}}_a$     $\vec{\mathbf{B}}_{ext}$



$\left|\int dV \vec{\mathbf{B}}_{ext} \cdot \vec{\mathbf{E}}_a\right| > 0$, V is small



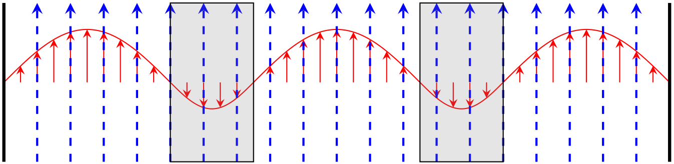
V is large, $\left|\int dV \vec{\mathbf{B}}_{ext} \cdot \vec{\mathbf{E}}_a\right| = 0$

# Solution: Dielectric Haloscopes

Higher frequency with more volume and better axion coupling.

$$P_a \propto B_{ext}^2 Q V_{eff}\,, \qquad V_{eff} = \frac{\left|\int dV \vec{\mathbf{B}}_{ext}\cdot\vec{\mathbf{E}}_a\right|^2}{B_{ext}^2 \int dV \varepsilon_r \left|\vec{\mathbf{E}}_a\right|^2}$$

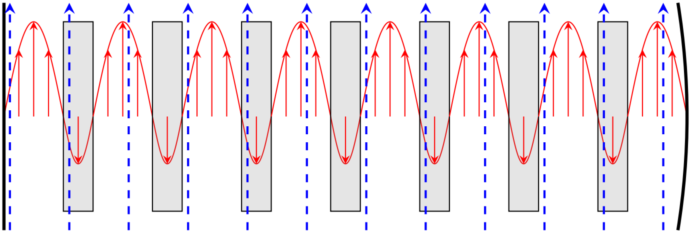

Low-loss dielectric $\sim \lambda/2$ thick placed every other half-wavelength.



$$\text{V is large,} \quad \left|\int dV \vec{\mathbf{B}}_{ext}\cdot\vec{\mathbf{E}}_a\right| > 0$$

# ADMX Orpheus Concept

**Goal**: Dielectrically Loaded Fabry-Perot Open Resonator threaded by a dipole magnet. Tunes with cavity length. Search for axion-like particles at 15-18 GHz.



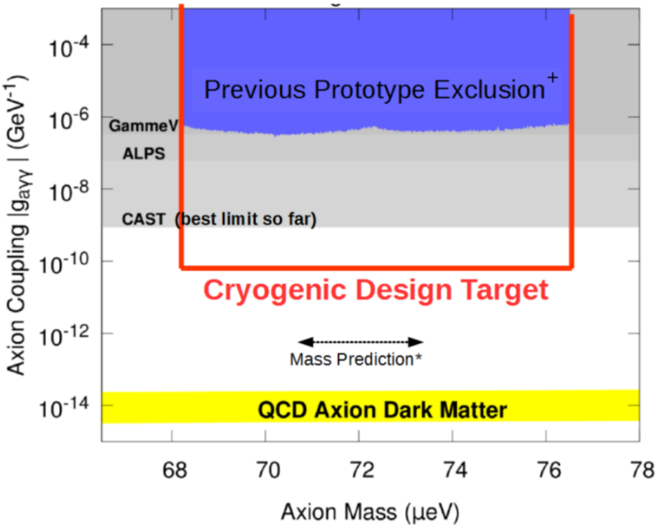
Open → Less ohmic losses → higher Q.
Open → Sparser spectrum → less mode crossings.

**Challenges**:

- Designing optics. Maintain good mode with high Q from 15-18 GHz.
- Moving mirror and dielectrics in LHe.
- Obtaining dipole magnet.

# Orpheus Science Reach

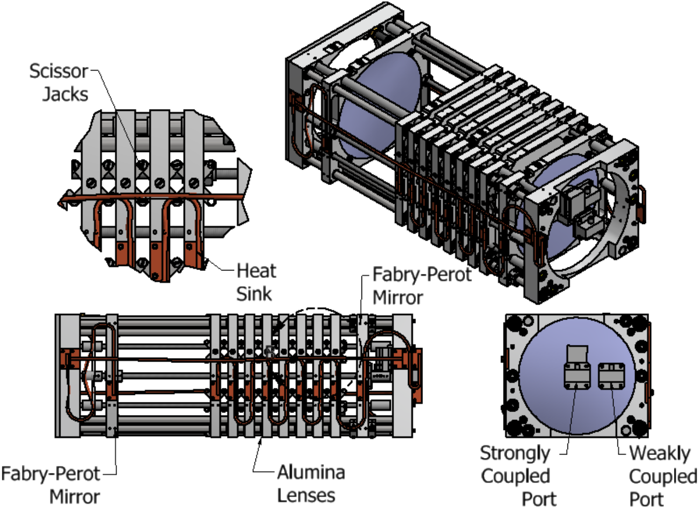
Within a few years.




+10.1103/PhysRevD.91.011701
*arXiv:1403.4594

# Progress Towards Orpheus: Preliminary Cryogenic Design

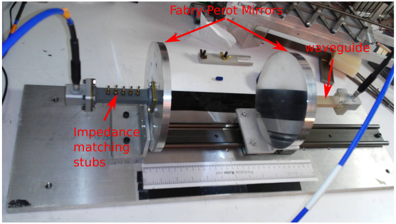
Submerged in LHe.

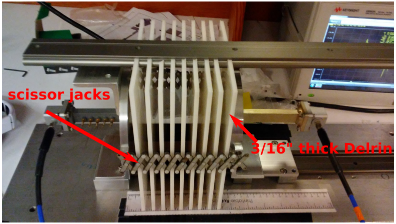



Think of an accordian!

# Room-Temperature Prototyping

Cheap and fast prototyping. Test mechanics and electronics.

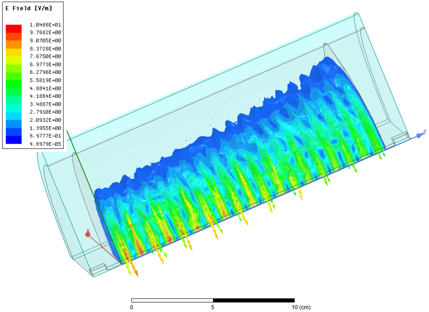



**Strategy**

1. Study empty cavity. Get analytical solution, simulations, and measurement to agree with each other. Gain confidence.
2. Load cavity with dielectrics. Simulate and measure. See if they agree.

# Standing waves in FP Cavities




Sustain $\text{TEM}_{mnq}$ modes. Think of Gaussian beams.

m, n: nodes in transverse plane. q: nodes along cavity.

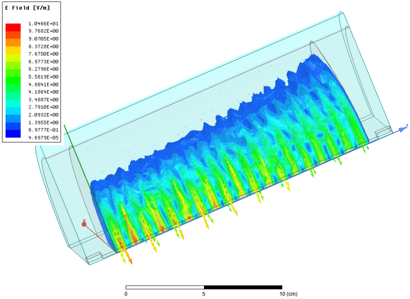
Analytical formula:

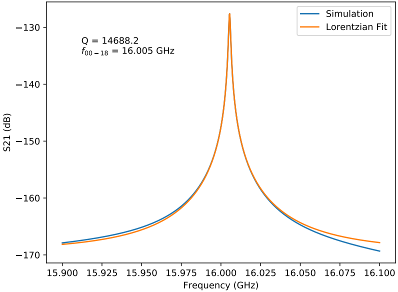
$f_{mnq} = (q+1)f_o + (f_o/\pi)(1+m+n)\cos^{-1}(1-2L/r_o)$, $f_o = \frac{c}{4L}$

Mirror focusing to reduce diffraction.

**Mode tunes with cavity length.**

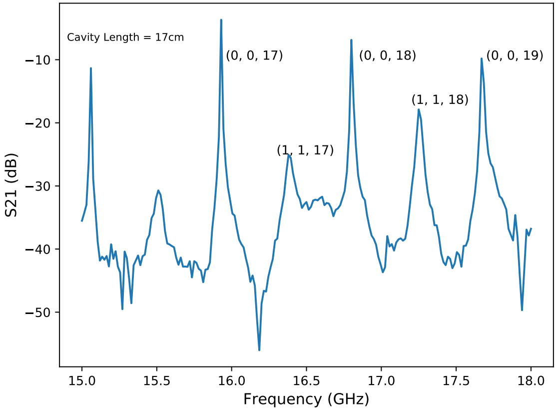
# Simulation Transmission of $TEM_{00-18}$ mode



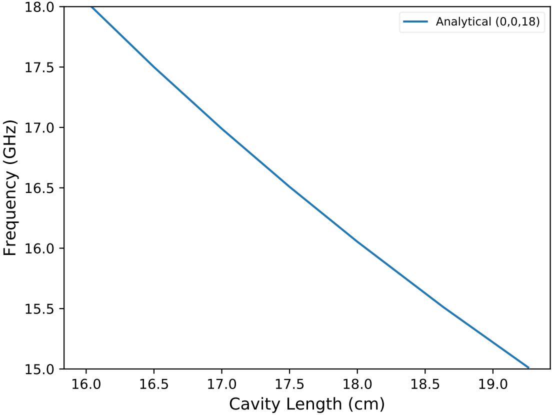

Simulated for different cavity lengths.

# Measure Transmission of $TEM_{00-18}$ mode




$Q_L$ between 1000 and 5000. Measured Qs don't match simulation, perhaps because of different coupling.

# Empty Orpheus Mode Map



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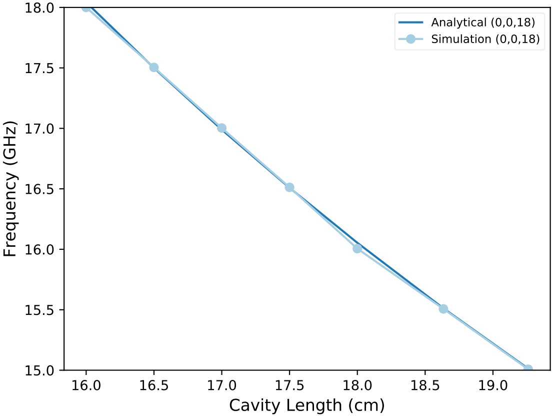
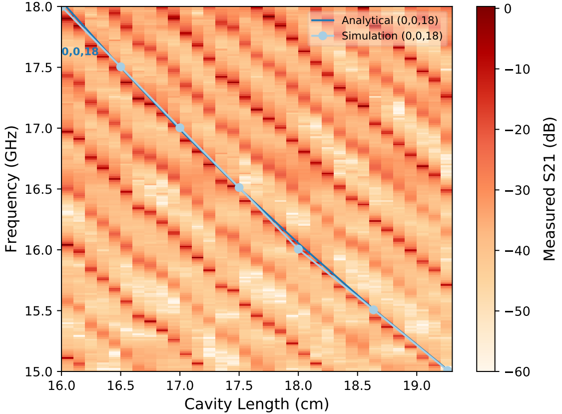


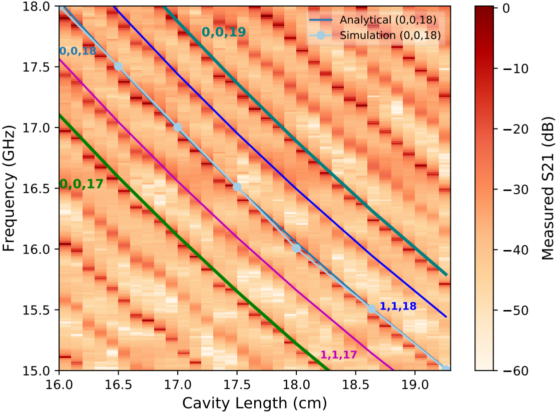

Simulations agree with analytical formula.

# Empty Orpheus Mode Map




Resonant frequencies for analytical formula, simulation, and experiment agree!

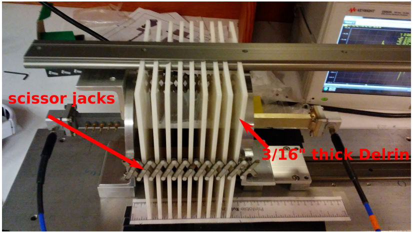
# Empty Orpheus Mode Map

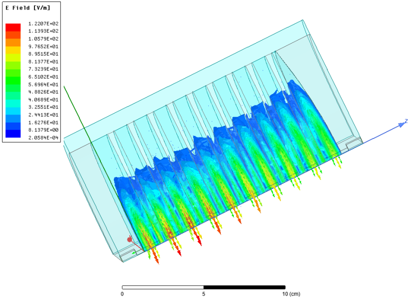



Resonant frequencies for analytical formula, simulation, and experiment agree!

Other modes where predicted. No mode crossings!

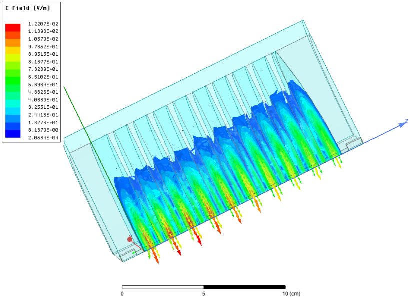
# Room-Temperature Prototyping with Delrin

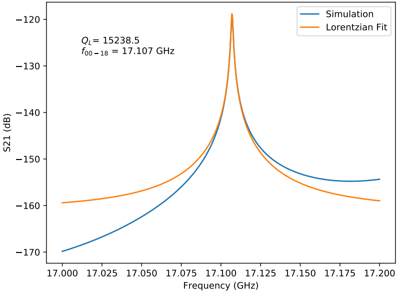



$\text{TEM}_{00-18}$ mode is the good mode for axion coupling.
Can we track this mode while we tune it?

# Delrin: Predict resonant frequency through simulation



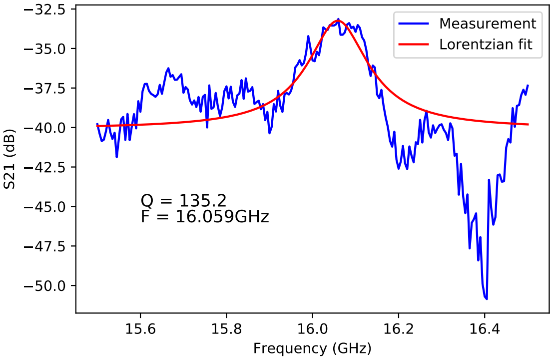




$\varepsilon_r = 3.7$ at 100 Hz. Don't know at 15-18 GHz.

Simulation done with lossless Delrin. $Q_L$ comparable to empty resonator for this frequency at this cavity length.

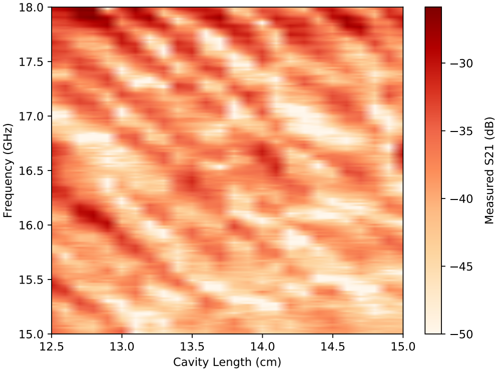
Q depends highly depends on loss tangent and impedance changing parameters (e.g. mirror thickness, hole aperture size).

# Delrin setup: Measure Transmission of $TE_{00-18}$ mode



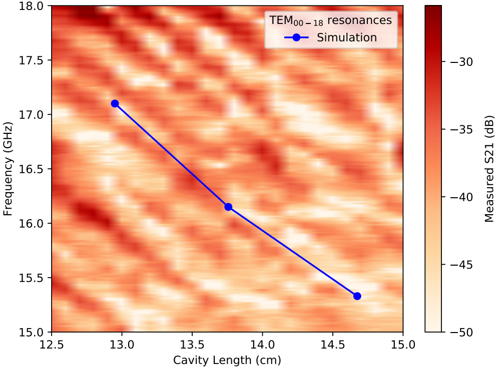

Q is much lower, as expected. Delrin is very lossy.
Will need better dielectrics to understand substructure.

# Delrin setup mode map




Mode structure is apparent but messier. Expected with lower Q.

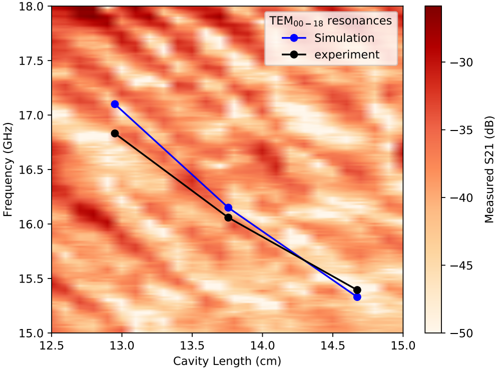
# Delrin setup mode map




Mode structure is apparent but messier. Expected with lower Q.

Simulation resonances agree with experiment. Should be better with improved mechanical structure. Also, don't know $\varepsilon_r$.

# Delrin setup mode map



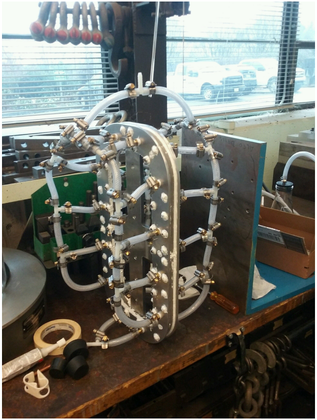

Mode structure is apparent but messier. Expected with lower Q.

Simulation resonances agree with experiment. Should be better with improved mechanical structure.

Better Q would allow us to understand substructure.

# Progress Towards Orpheus: Magnet Making

3,250 windings. Niobium titanium wire 0.3 mm in diameter. 1 T.



Prototyping different manufacturing methods.

# Next Steps

- Improve mechanical design.
- Improve and understand optics.
- Develop DAQ, electronics, and motor systems.
- Cryogenic tests.

First results in 2-3 years.

# How to get to DFSZ sensitivity

Scan rate equation from ADMX

$$\frac{df}{dt} \approx 1.68 \text{ GHz/year } \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1 \text{ GHz}}\right)^2 \left(\frac{\rho_0}{0.45 \text{ GeV/cc}}\right)^2 \cdot \left(\frac{5}{SNR}\right)^2 \left(\frac{B_0}{8 \text{ T}}\right)^4 \left(\frac{V}{100\text{l}}\right)^2 \left(\frac{Q_L}{10^5}\right) \left(\frac{C_{010}}{0.5}\right)^2 \left(\frac{0.2 \ K}{T_{sys}}\right)^2$$

Assume Quantum Limited Amplifiers. Then $T_{sys} = \frac{hf}{2k_B} = 0.43\text{K}$. Let $Q_L = 10^5, \text{SNR} = 3.5, V_{eff} = VC_{lmn}, f = 18\text{GHz}$. If

$\frac{df}{dt} = 1\text{GHz/year}$, then $\boxed{B^2 V_{eff} = 200\text{LT}^2}$

# Summarize

1. Dielectric haloscopes could look for $\sim 100\mu$eV axions.
2. ADMX Orpheus experiment is a haloscope consisting of a Fabry-Perot Cavity loaded with evenly-spaced dielectrics. It will explore 15 to 18 GHz.
3. Room-temperature table top resonators have been characterized. Improvements underway.
4. Cryogenic setup in development.
5. First results in 2-3 years.

# Acknowledgements

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