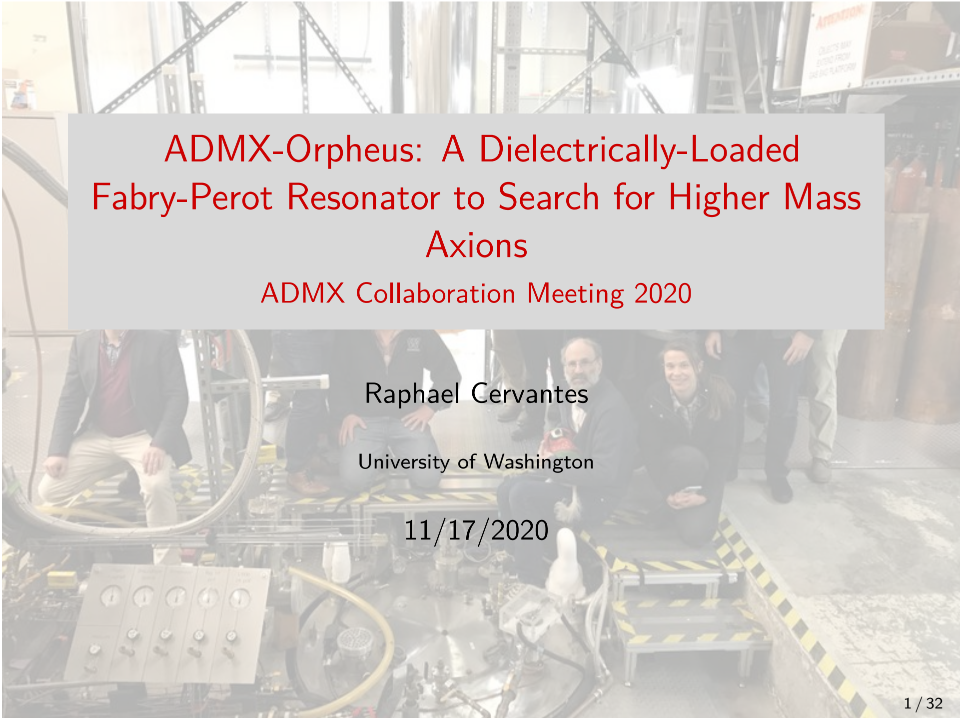


ADMX-Orpheus: A Dielectrically-Loaded Fabry-Perot Resonator to Search for Higher Mass Axions

ADMX Collaboration Meeting 2020

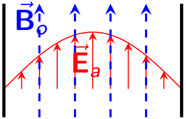
Raphael Cervantes

University of Washington

11/17/2020

ADMX haloscope difficult to implement higher frequency

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



V_{eff} is small.

ADMX haloscope difficult to implement higher frequency

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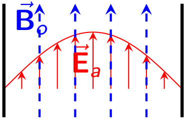
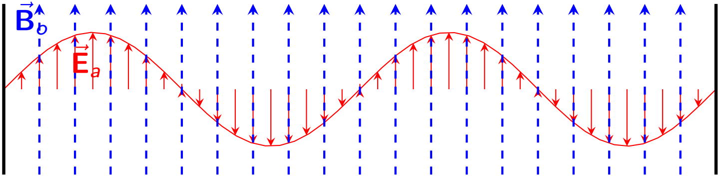


V_{eff} is small.



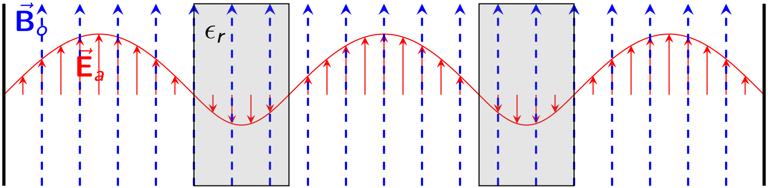
V is large, but $V_{eff} = 0$

Current Solution: Dielectric Haloscopes

Higher frequency with more volume and better axion coupling.

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

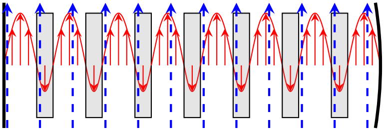
Low-loss dielectric $\sim \lambda/2$ thick placed every other half-wavelength.

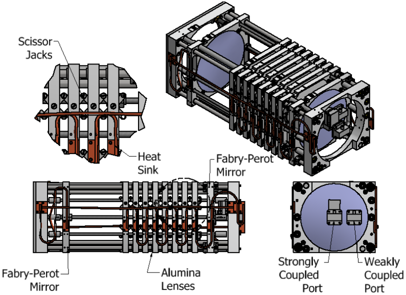


V_{eff} is large.

ADMX Orpheus Concept

Goal: Dielectrically-Loaded Fabry-Perot Open Resonator in dipole magnet. Tunes with length. Search for axions at 15-18 GHz.



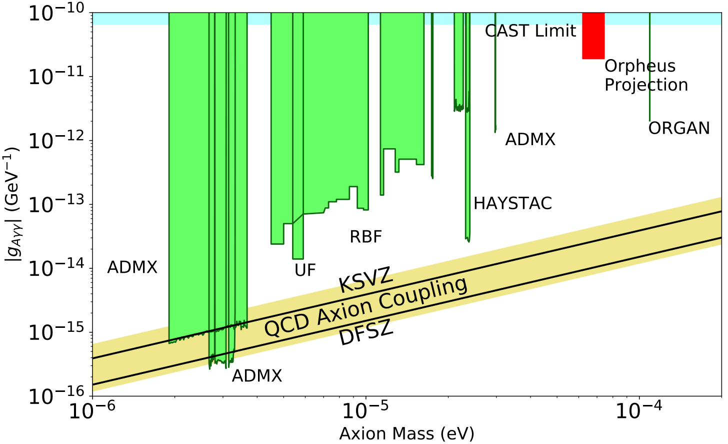


Additional Benefits:

- Less ohmic losses → higher Q.
- Sparser spectrum → easier to maintain axion-coupling mode.

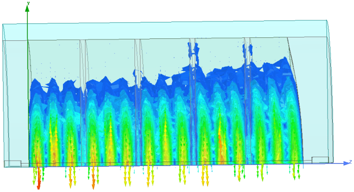
Orpheus Science Reach

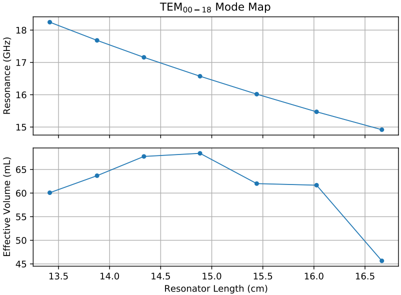
Proof-of-concept experiment. Preliminary results hopefully by Summer 2021.



$B = 1.5\,\mathrm{T},\ T_{sys} \sim 12\,\mathrm{K},\ V_{eff} \sim 65\,\mathrm{mL},\ Q = 10^4$, 1 week runtime.

TEM_{00-18} mode couples to axion

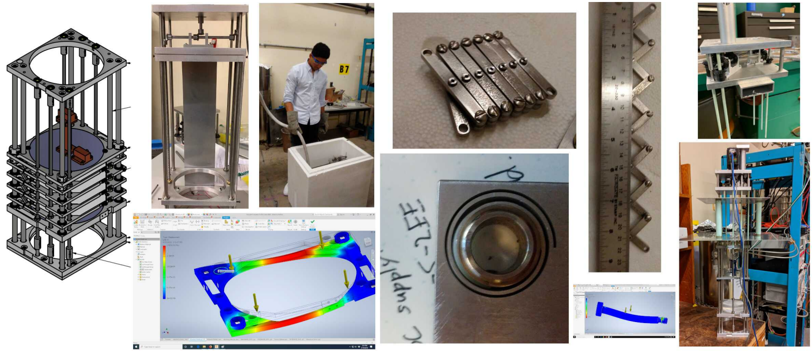




V_{eff} needs to be recalculated.

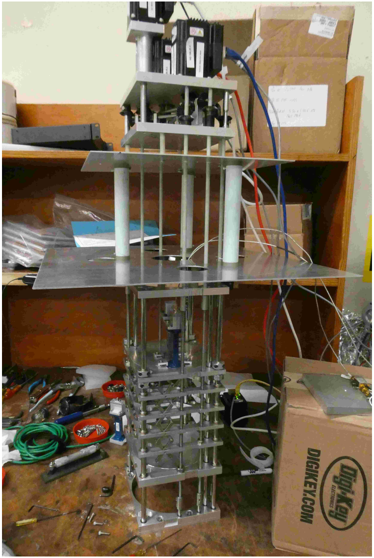
Mechanics for Cryogenic Orpheus

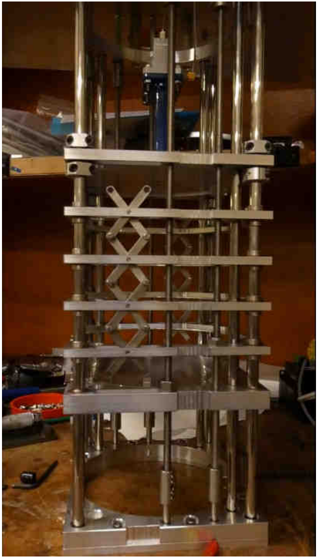
Lots of moving parts in vacuum, LHe.



Flexures, silver coating prevent galling and binding.
Gearbox allows for moving 3 plates independently.

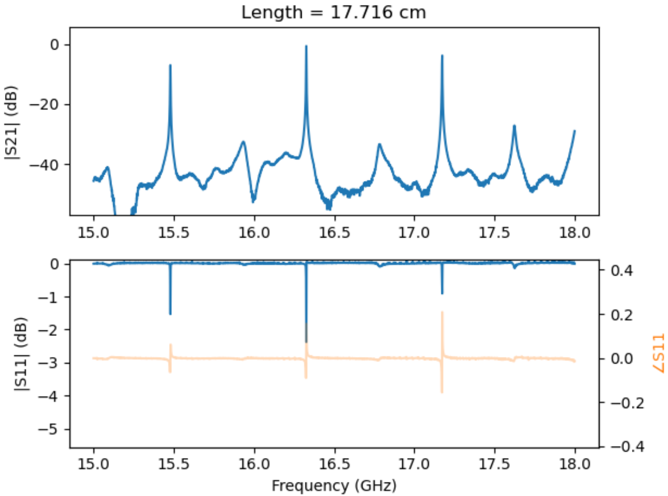
Orpheus Assembled



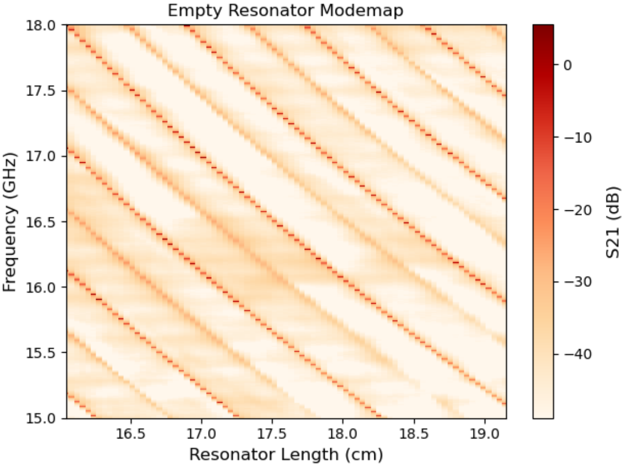


Empty Resonator

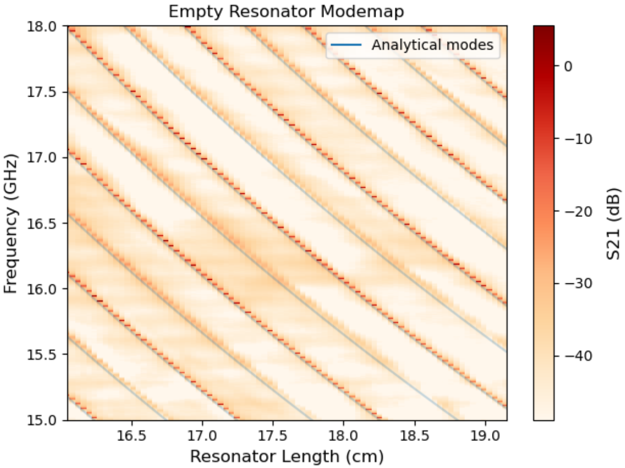
Resonances tune with length.



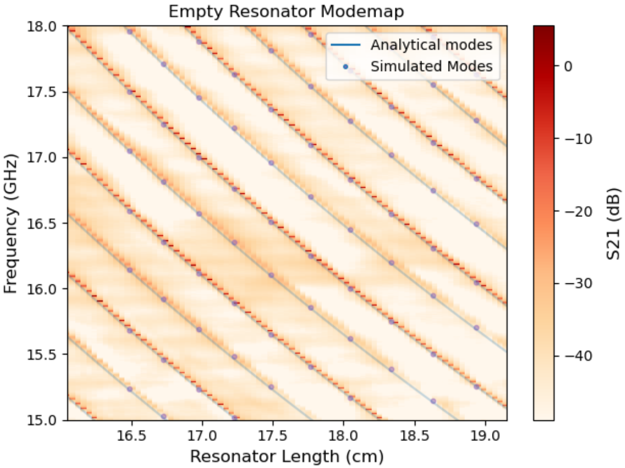
Empty Resonator Modemap



Empty Resonator Modemap

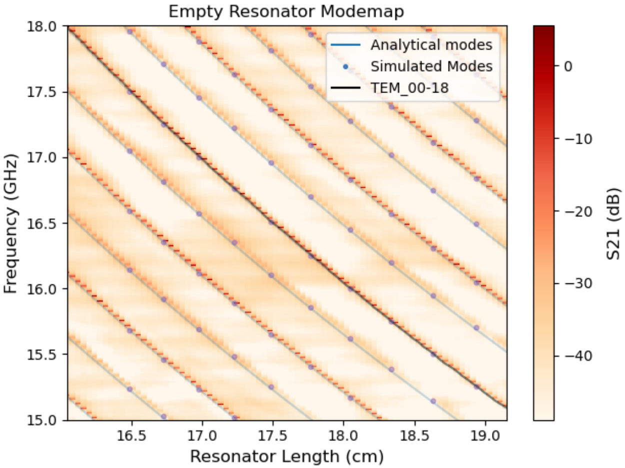


Empty Resonator Modemap



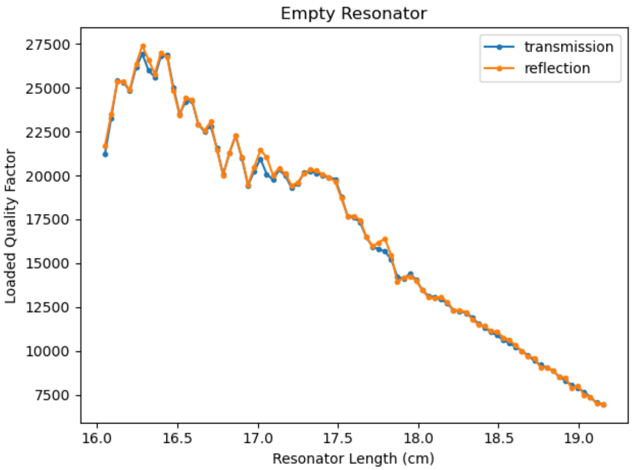
Resonant frequencies between measured, analytical formula, and simulation agree.

Empty Resonator Modemap



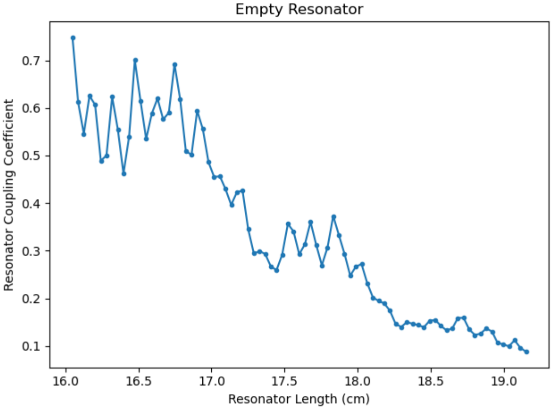
Resonant frequencies between measured, analytical formula, and simulation agree.

Measured TEM_{00-18} Qs



Q will decrease with better coupling.
Q will increase with lower resistivity mirrors and cryogenic temperatures.

Resonator Coupling Coefficient



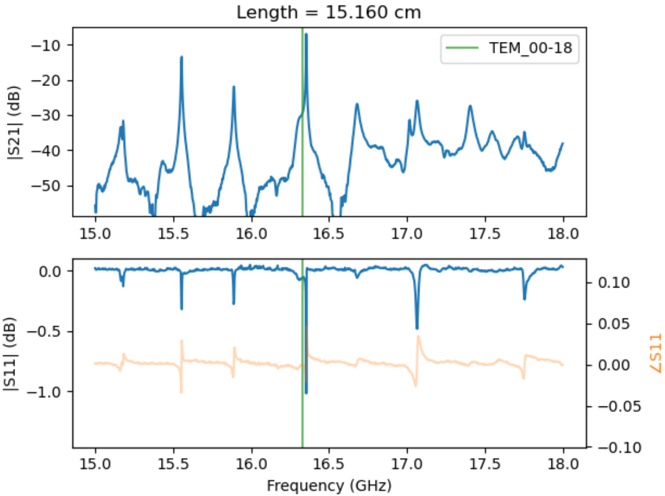
$\frac{df}{dt} \propto \left(\frac{\beta}{1+\beta}\right)^2$. Need better coupling to have reasonable scan rate. β can be increased by increasing Q_0 or by building impedance matching network. Work in progress.

Now let's add dielectrics!

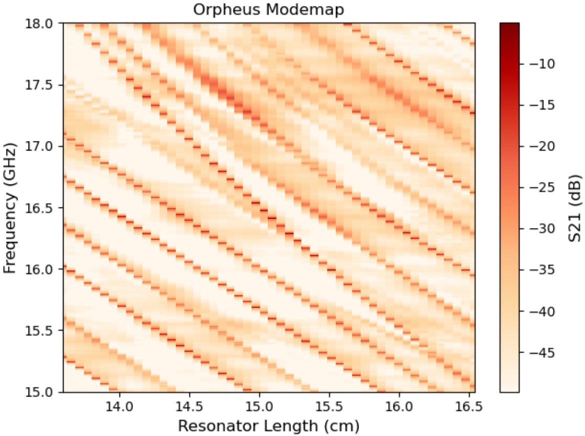
99.5% Alumina from Superior Technical Ceramics.
3 mm thick. 6" wide.
$\epsilon_r \sim 9.8$
$\tan\delta \sim 0.0002$?

Orpheus modes

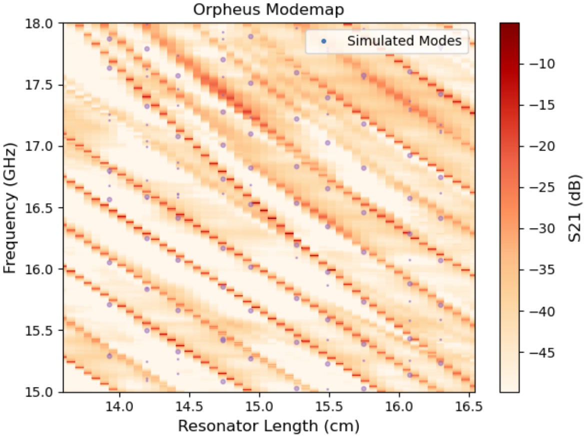
Modes tune with length.



Orpheus modemap

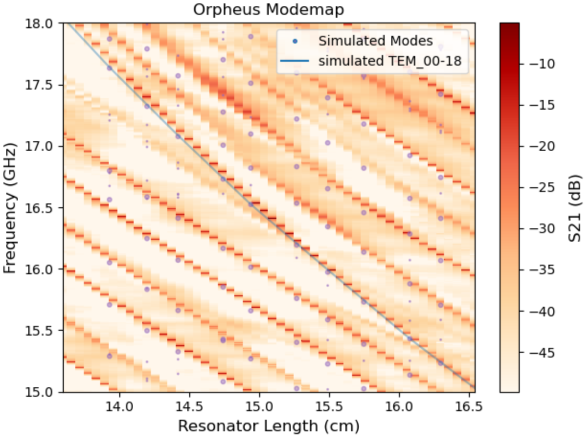


Orpheus modemap



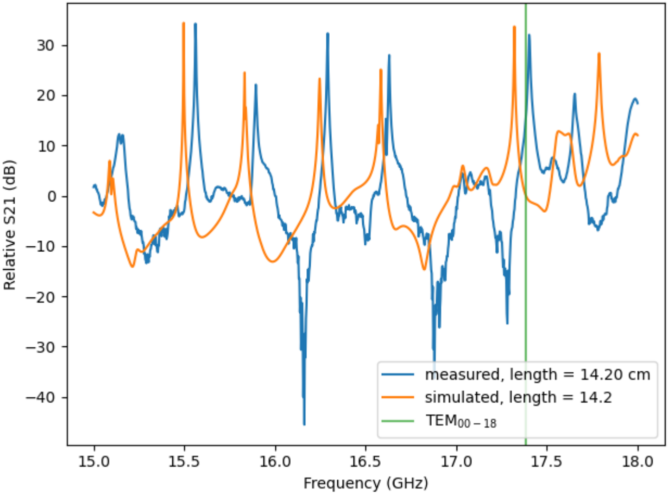
Simulation and measurement diverge at higher frequencies, likely because of unaccounted ϵ_r frequency dependence.

Orpheus modemap

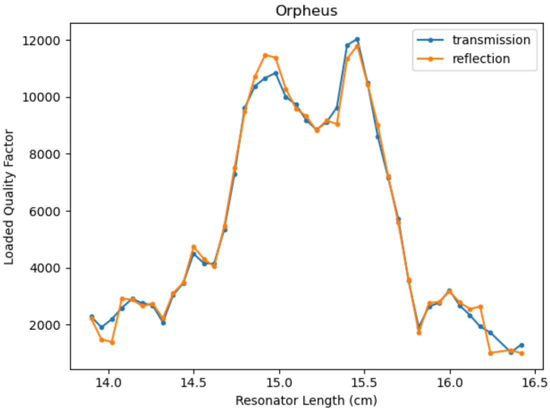


Simulation and measurement diverge at higher frequencies, likely because of unaccounted ϵ_r frequency dependence.
TEM_{00-18} mode clear.

Simulated vs Measured Transmission

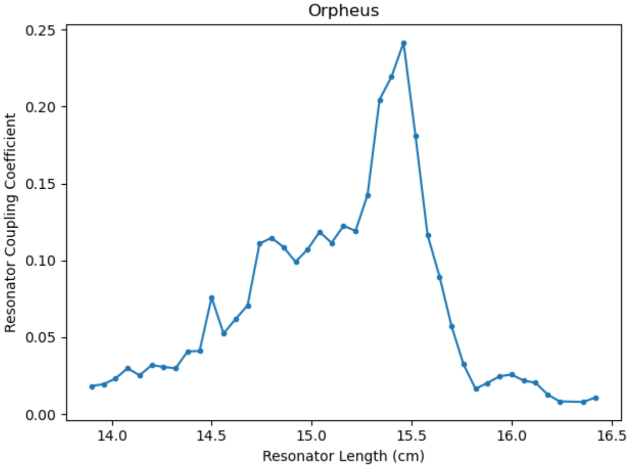


Orpheus Quality Factor



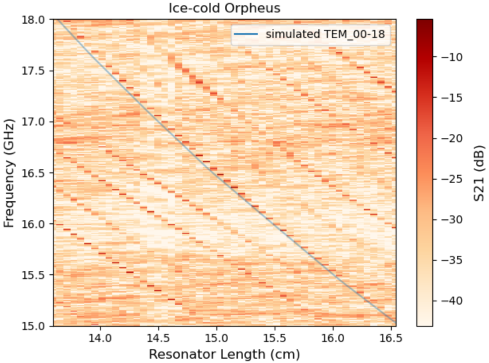
Q lower because of lossy dielectrics. Will increase at lower temperatures.
Dip in center from mode crossing.
Suggests practical BW: 15.7 GHz-17.2 GHz.

Orpheus Coupling



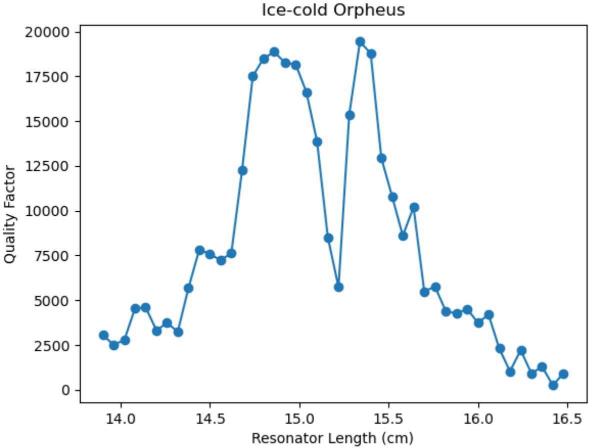
Coupling lower likely because of lower Q.

Try cooling the resonator



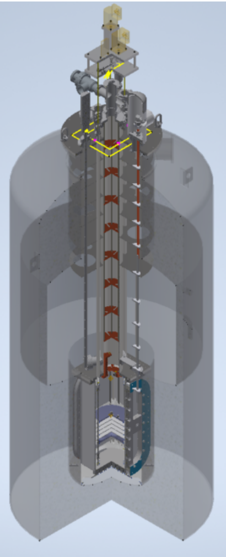
Mechanics work even while submerged LN2! Smooth tuning.
Noisier in metallic canister.
Resonator characterized while in contact with LN2, but not submerged. Resonator ice-cold.

Orpheus Q when Colder



Q increases by $\sim 60\%$. Will increase more when in contact with liquid helium bath.

Outlook



Build liquid helium setup. In progress.

Build magnet.

Improve impedance matching.

Take data at 4 K for 2 weeks.

First results hopefully by the end of summer.

Thank you!

ADMX Collaboration, especially UG Parashar Mohapatra

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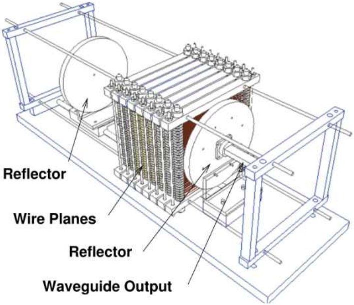
Summary

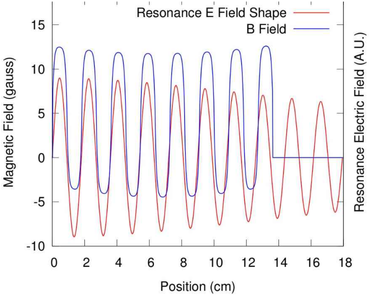
1. Orpheus is a dielectric haloscope that will push axion search to $\sim 70\,\mu$eV.
2. Orpheus mechanics and microwave properties have been tested.
3. Experiment being built to search for axions at 4 K.

Backup slides.

Orpheus Experiment 2014 *

Increase V_{eff} by alternating $\vec{\mathbf{B}}$ to match $\vec{\mathbf{E}}$

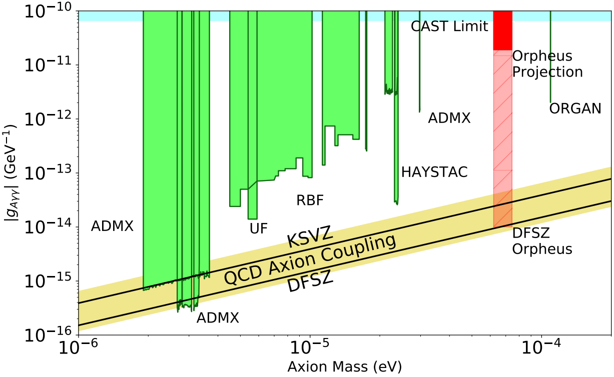




Difficult to scale to Tesla.

*Rybka et al.:PhysRevD.91.011701

Reaching DFSZ

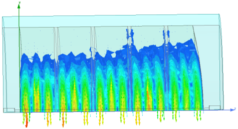


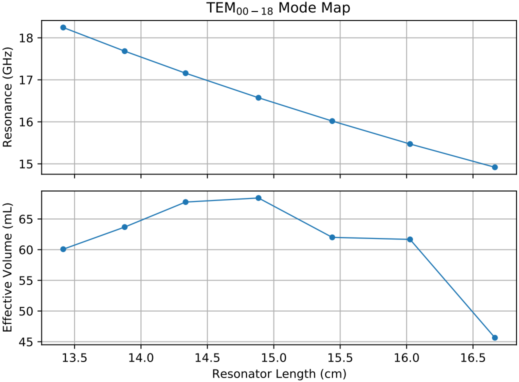
Assume Quantum Limited Amplifiers. Then $T_{sys} \sim \frac{hf}{2k_B} = 0.43\text{K}$.
Let $Q_L = 10^5, \text{SNR} = 3.5, f = 18\text{GHz}$.

If $\frac{df}{dt} = 1\text{GHz/year}$, then $\boxed{B^2 V_{eff} = 200\text{LT}^2}$ $\quad (V_{eff} = V \times C)$

Orpheus Simulations

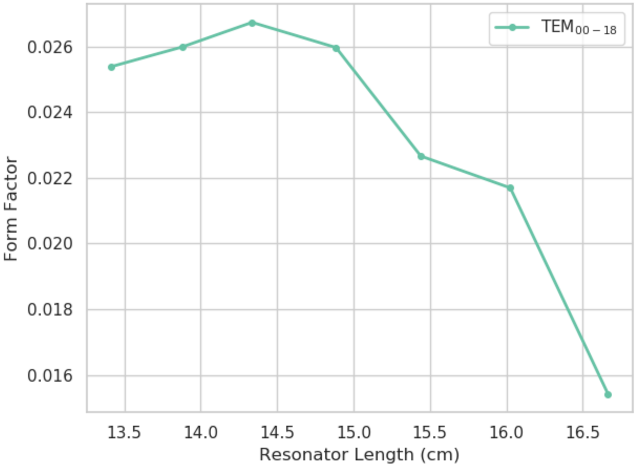
For simulations: $\epsilon_r = 9.4$, $\tan\delta = 0.0005$, thickness $= 1/8$".





Factor of 40 improvement over cylindrical cavity haloscope (2-to-1 aspect ratio) operating at same frequency.

Simulated TEM_{00-18}



But this isn't the right quantity to think about.

Far future: How to reach DFSZ sensitivity

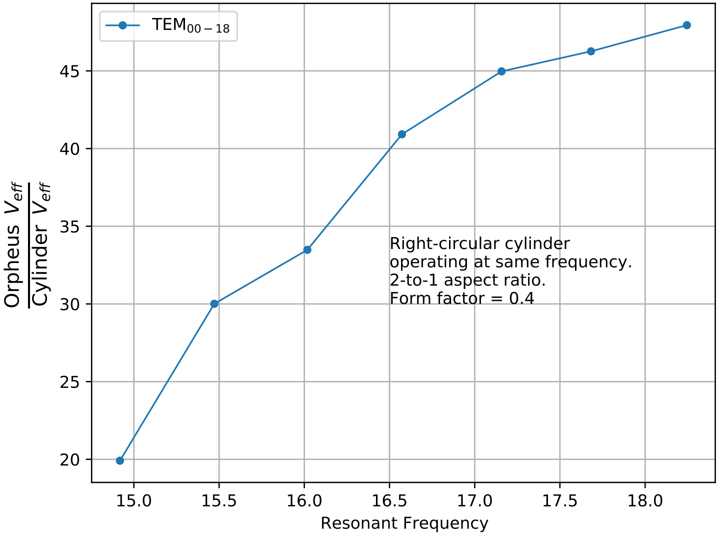
Scan rate equation from ADMX

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

Assume Quantum Limited Amplifiers. Then $T_{sys} \sim \frac{hf}{2k_B} = 0.43\text{K}$. 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 $\boxed{B^2 V_{eff} = 200\text{LT}^2}$

Orpheus vs Cylindrical Cavity



How is Orpheus different from MADMAX?

1. We are treating this like a resonator problem. Design choices come from resonator intuition.
2. We want high Q. They want a broadband measurement.
3. We are less ambitious. We are going to search from 70-80 μeV. They want to cover 40-400 μeV.

Orpheus Gearbox