Exploration of Wire-Array Metamaterials for the Plasma Axion Cavity

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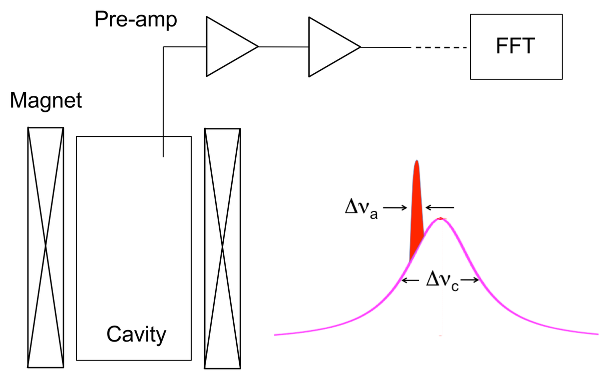
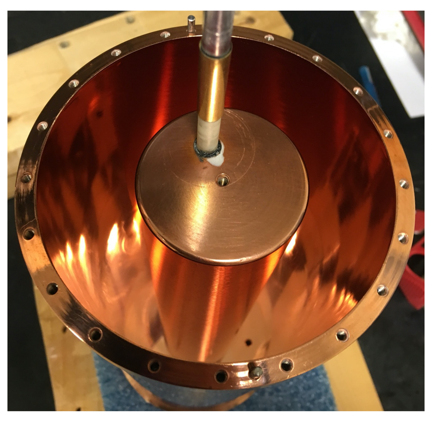
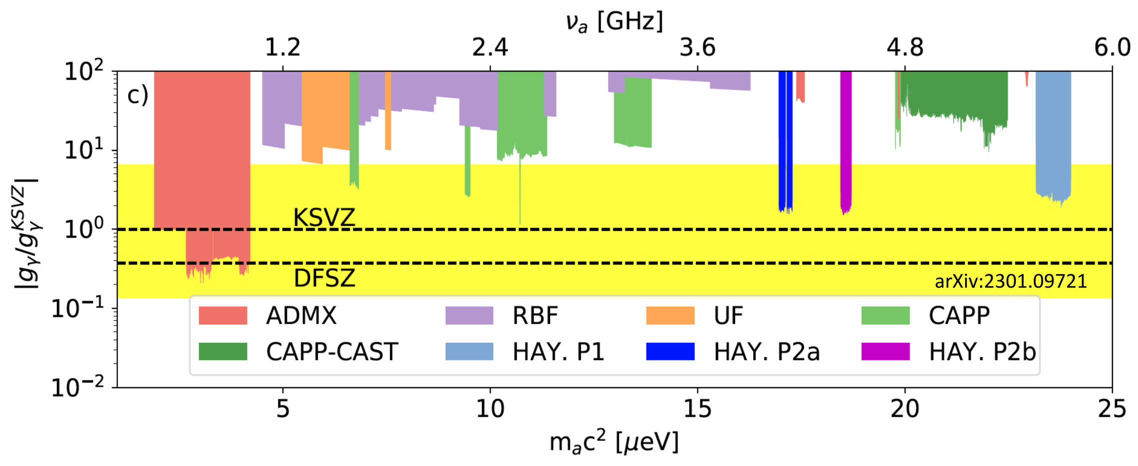
Metamaterials – A Path to Higher Frequency Axion Haloscopes

The Sikivie Axion Haloscope[1]

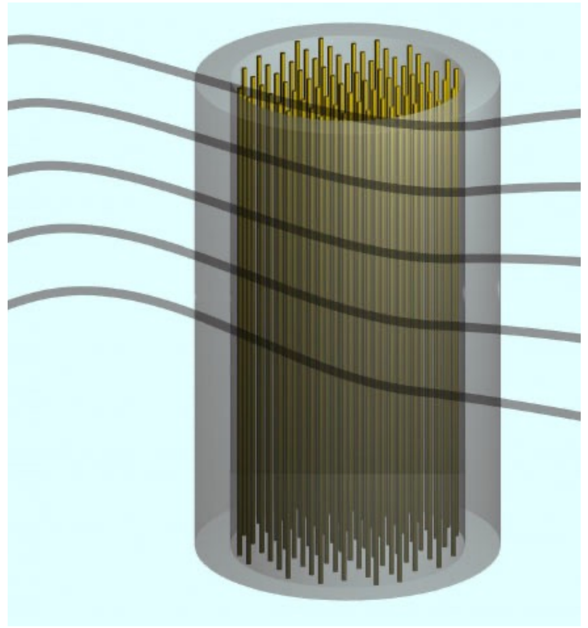




- The conversion power $P_{a\to\gamma} \propto g_{a\gamma\gamma}^2 B^2 VCQ$
  - With $g_{a\gamma\gamma}$ the coupling, B magnetic field strength, and V, C, Q the microwave cavity volume, form factor and quality factor.
- The relationship between cavity size and frequency has restricted traditional haloscopes to ≈ 0.5 - 5 GHz.



The Plasma Axion Haloscope[2]



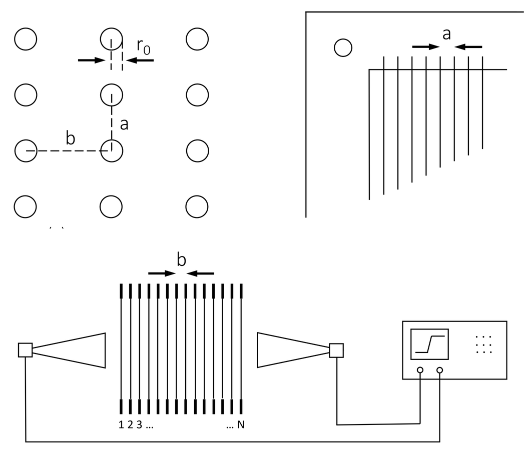
- Lawson et al. have proposed the use of a wire-array metamaterial to replace a conventional cavity[2]
- The plasma frequency ν_p is a function of the unit cell, rather than the overall size of the resonator
  - Wire-array metamaterials have been extensively studied theoretically, with some limited experimental validation[3-5]
- As an example, for a simple square lattice of wire radius r_0, and spacing a, the plasma frequency is

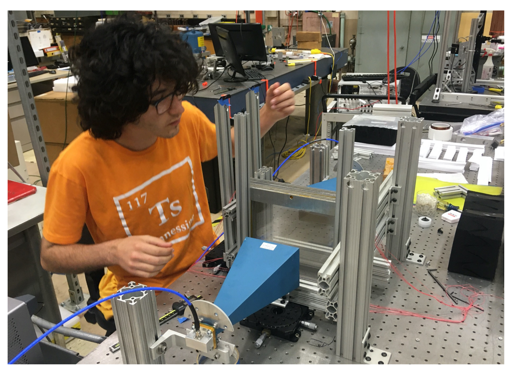
$$\nu_p^2 = \frac{c^2}{2\pi a^2 \ln\left(\frac{a}{r_0}\right)}$$

- For e.g. a = 5 mm and r_0 = 25 μ, ν_p = 10.4 GHz

Determination of Wire-Array Metamaterial Parameters

S_{21} (Transmission) Measurements of Metamaterial Parameters



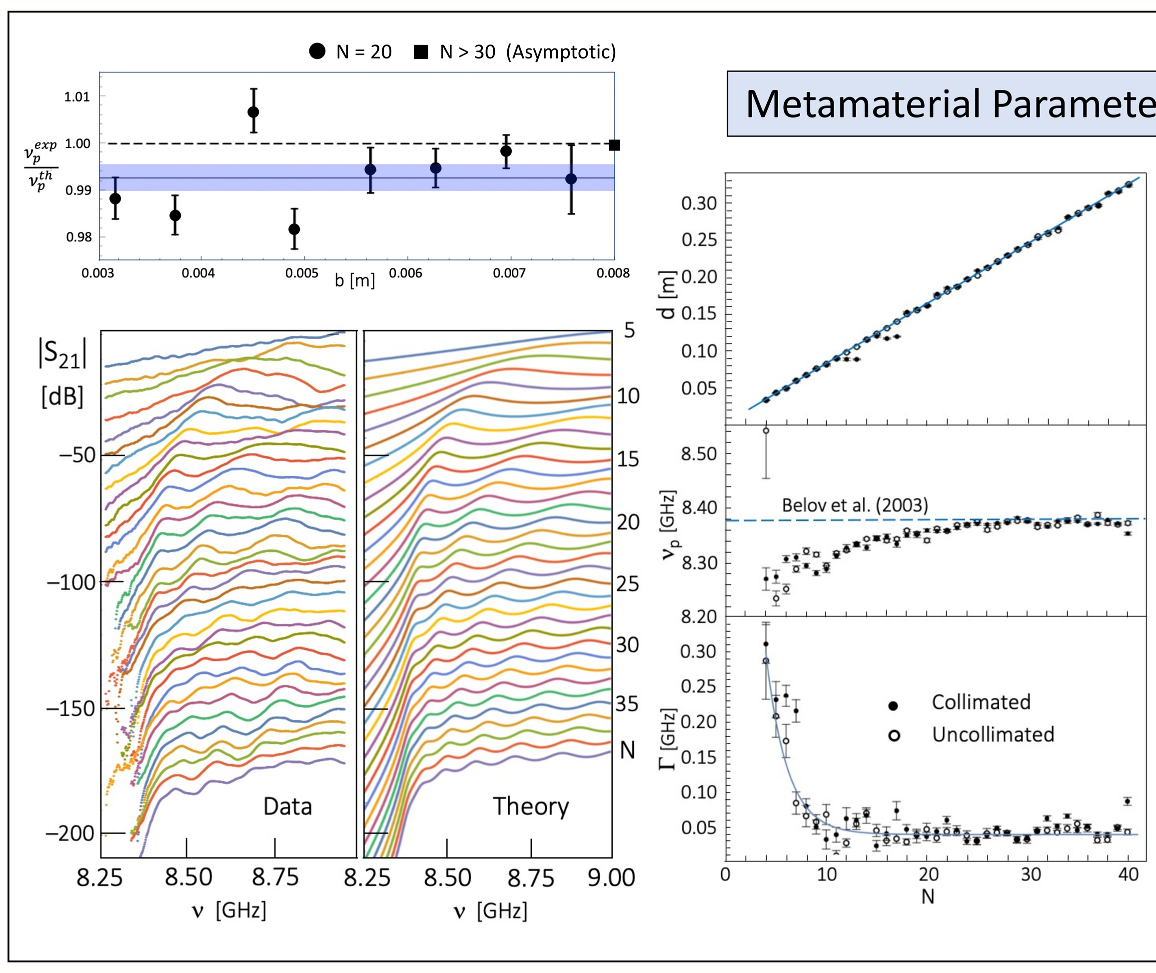


- In a Drude model, with a complex permittivity $\epsilon(\nu) = \epsilon'(\nu) - i\epsilon''(\nu)$:

$$\epsilon' = 1 - \frac{\nu_p^2}{\nu^2+\Gamma^2} \quad , \quad \epsilon'' = \left(\frac{\nu_p}{\nu}\right)^2 \frac{\frac{\Gamma}{\nu}}{1+\left(\frac{\Gamma}{\nu}\right)^2}$$

- The fitted transmission function, S_{21} is very sensitive to the metamaterial parameters ν_p [GHz], the loss term Γ [GHz], and the array width d [mm].
- Extensive measurements were performed at Berkeley of rectangular lattices assembled by stacking planes of gold-on-tungsten wires.
- For these measurements, the wire radius and spacing in the plane were r_0 = 25 μ, a = 5.88 mm; the plane separation for most tests was b = 8 mm.
- The metamaterial parameters were investigated as a function of N = 5-40.

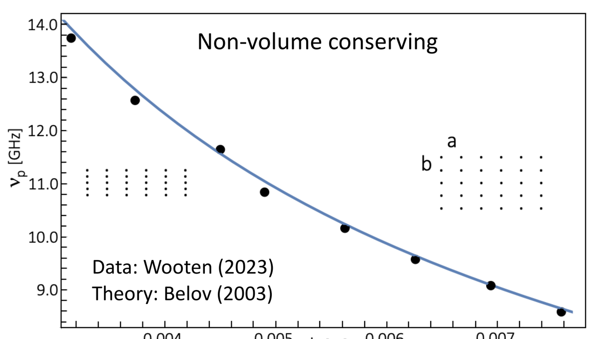
Metamaterial Parameters – Experiment and Theory

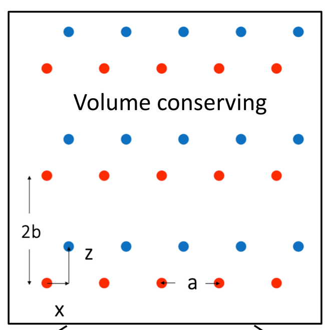


- Plasmonic behavior is already well established for N ~ 5 planes.
- The semianalytic theory of Belov[4] is in excellent agreement with the experiment with the asymptotic ν_p, at the ~0.1% level.
- The asymptotic loss term Γ~ 0.038 implies a quality factor $Q = \nu_p / \Gamma$~220, in good agreement with the theoretical value of 260.
- While Q is low, the radius & spacing can be changed to maintain the same ν_p, but maximizing Q.[6] For r_0~1 mm, a~10 mm, the theoretical quality factor is projected to be ~4000, and thus at cryogenic temperatures, > 10^4.
- For a description of the experiments and modeling, see Ref. 7.

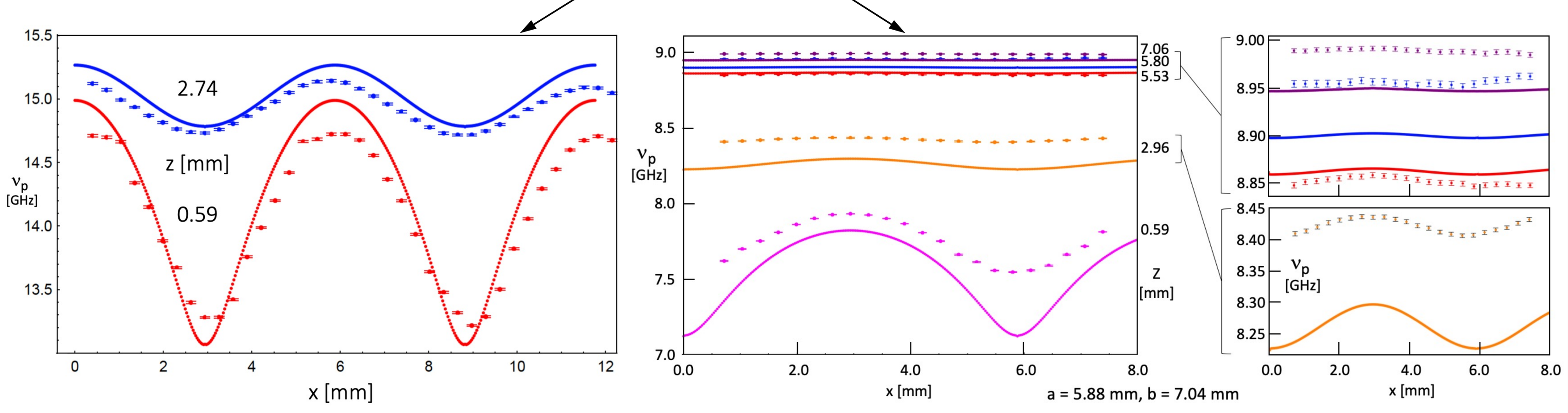
Study of the Plasma Frequency Dependence on the Unit Cell

Tuning the Resonator by Modifying the Unit Cell

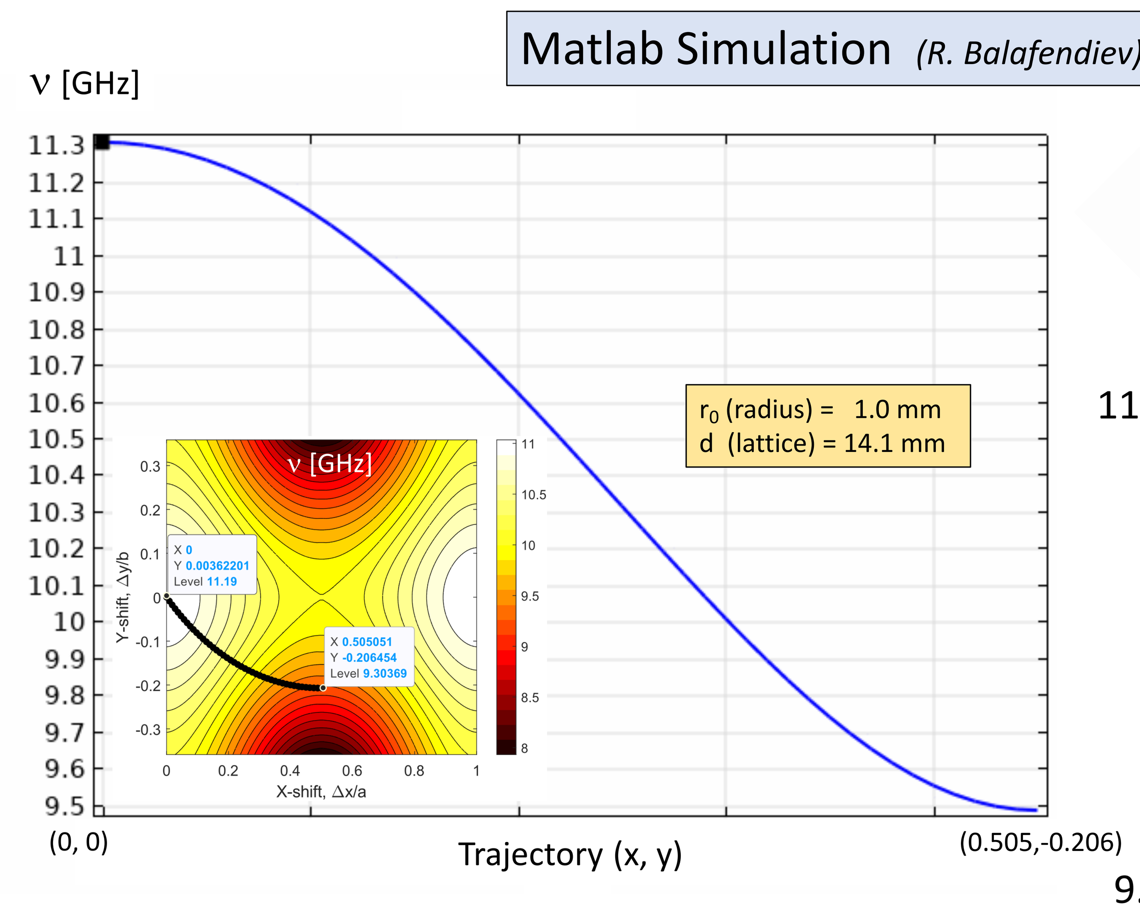


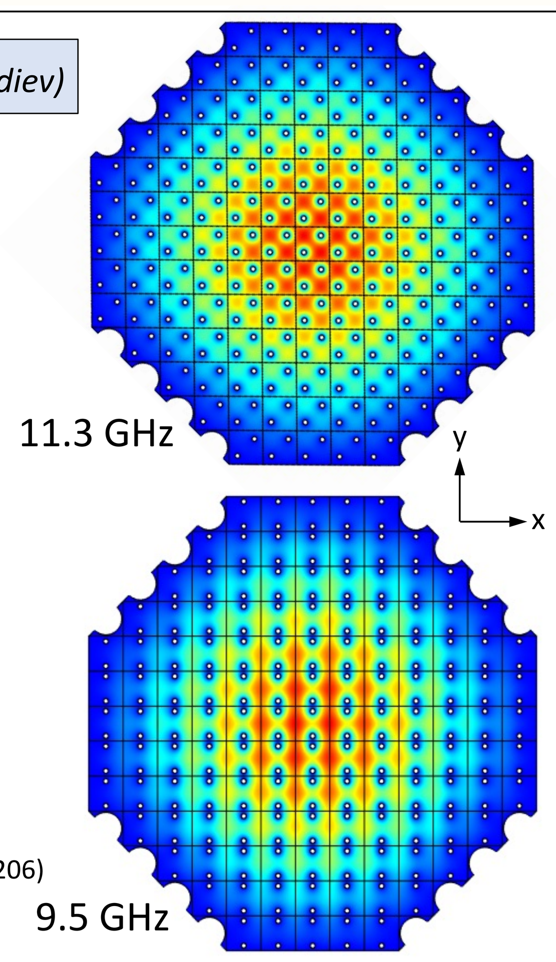


- Changing the plane spacing yields a large dynamic range in frequency, but may be impractical for a haloscope.
- Shifting alternate planes in the parallel or perpendicular direction yields a smaller but useful dynamic range for a haloscope, and can be easily implemented mechanically.
- Simulations are in good agreement with data, at the few percent level (Kowitt *et al.*, manuscript in preparation).



Matlab Simulation (*R. Balafendiev*)





Summary and Future Work

- Wire-array metamaterials are a promising route to reach higher frequencies in the dark matter axion search, as motivated by recent calculations of the mass of the post-inflation axion.[8]
- Fixed-frequency prototypes validate the expected room temperature quality factor[9] (see below); tunable prototypes are being designed and built.
- Optimal coupling of the resonator with the quantum preamplifier is under active study.
- A complete discussion of metamaterial resonators and the ALPHA proposal has recently appeared.[10]
- See talk of Andrea Gallo Rosso (Saturday, April 1, 10:15 a.m., PAB-1-425)

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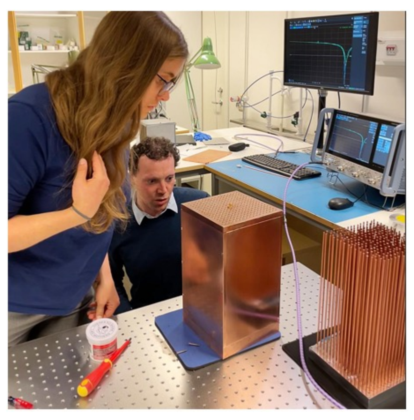

Acknowledgements

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