Tunable metamaterials and the search for dark matter

There is a mismatch between astrophysical observations and theory. Observations of galaxy dynamics and gravitational lensing (Fig. 1) are consistent with there being considerably more mass in galaxies than we can see. The prevailing theory postulates new species of "dark matter" particles, which have significant mass but insignificant interaction with the electromagnetic field [1], thus being invisible to close to earth observations of astrophysical objects. This project builds on recent proposals to use resonant wire-medium based metamaterials [2,3,4] as the basis for detectors that enhance the interaction between candidate dark matter particles and the electromagnetic field.

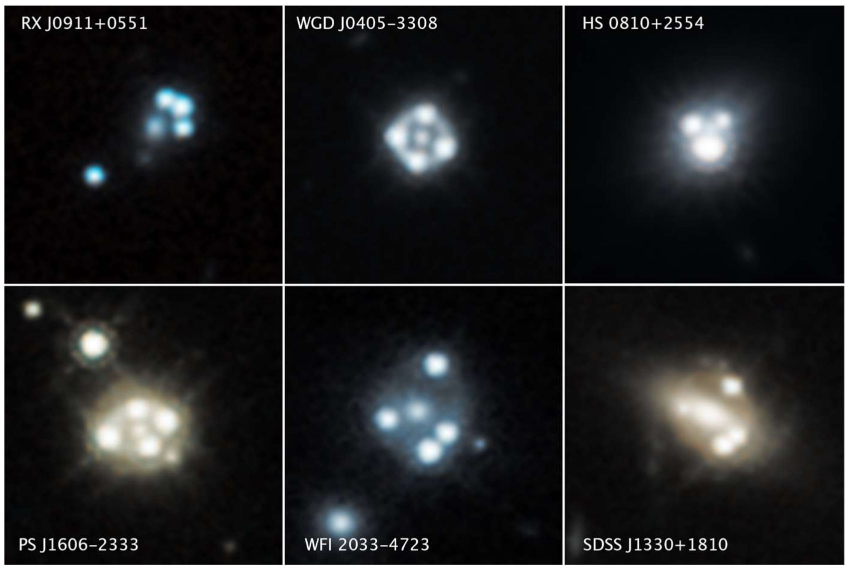

Figure 1: Hubble space telescope images of Dark Matter distribution, inferred from anomalous gravitational lensing of light from distant quasars.

One candidate dark matter particle is the axion, a field introduced in 1977 to explain the observation of zero (or at least very weak) CP violation by the strong force [5]. This theory modifies the Lagrangian density $\mathcal{L}$ for the standard model to contain both our usual massless electromagnetic field$F_1^{\mu\nu}$, and an axion field $F_2^{\mu\nu}$with mass$m_{A'}$. The interaction between the two is parametrized by an interaction constant χas follows,

$$\mathcal{L} = \frac{1}{4}\left(F_1^{\mu\nu}F_{1\mu\nu} + F_2^{\mu\nu}F_{2\mu\nu} - 2\chi F_1^{\mu\nu}F_{2\mu\nu} - 2m_{A'}^2 A'^2\right).$$

In infinite free space, conservation laws prevent photon creation from the axion field, hence this matter being "dark". However, within a plasma subject to a strong magnetic field, the interaction can be greatly increased [2-4], becoming resonant when the axion rest mass frequency $m_a c^2/\hbar$equals the plasma frequency. The theoretically expected axion mass of $m_a c^2 \leq 60$meV puts this resonant frequency in the terahertz or lower. In this frequency range, artificial plasma wire-based metamaterials have been developed [3], with a tunable plasma frequency . This makes it feasible to develop metamaterial based detectors for axionic dark matter particles. This theoretical project will investigate the design and feasibility of these detectors.

In this project we will:

(1) Examine the theory of electromagnetism coupled to axions and understand the general conditions for enhancing their interaction with materials, as well as how to numerically simulate these effects through e.g. modifying COMSOL multiphysics. We will consider a broader class of materials than the wire media in [2], including both dielectrics and metasurfaces.

(2) Search for candidate metamaterials for enhancing the rate of axion to photon conversion. This will be done using both analytic theory and numerical simulations using e.g. adjoint optimization to develop inhomogeneous tunable structures where the coupling to axions is maximized within some region, analogous to increasing the local density of states for an antenna [6].

(3) Compare metamaterial based axion detectors to existing cavity based designs.

(4) More broadly explore the topic of axion electrodynamics and the similarity between bianisotropic metamaterials and coupling to the proposed axion field. This may allow us to also use the designs developed in (1-2) to enhance the usually small resonant bianisotropic response of metamaterials.

References:

[1] J. L. Feng "*Dark Matter Candidates from Particle Physics and Methods of Detection*", *Annu. Rev. Astron. Astrophys.* **48**, 495 (2010).
[2] M. Lawson, A. J. Millar, M. Pancaldi, E. Vitagliano, and F. Wilczek, "*Tunable Axion Plasma Haloscopes*", *Phys. Rev. Lett.* **123**, 141802 (2019)
[3] R. Balafendie, C. Simovski, A. Millar, P. Belov, "*Wire metamaterial use for dark matter detection*", *2022 Sixteenth International Congress on Artificial Materials for Novel Wave Phenomena (Metamaterials)*, 1-3 (2022).
[4] R. Cervantes et al/. "*Search for 70 μeV Dark Photon Dark Matter with a Dielectrically Loaded Multiwavelength Microwave Cavity*" *Phys. Rev. Lett.* **129**, 201301 (2022).
[5] R. D. Peccei and H. R. Quinn, "*CP Conservation in the Presence of Instantons*", *Phys. Rev. Lett.* **38**, 1440 (1977).
[6] S. Mignuzzi, S. Vezzoli, S. A. R. Horsley, W. L. Barnes, S. A. Maier, and R. Sapienza "*Nanoscale Design of the Local Density of Optical States*", *Nano Lett.* **19**, 113-117 (2019).