# Snowmass2021 Letter of Interest: Tunable Plasma Haloscope

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## Thematic Areas:

■ (CF2) Dark Matter: Wavelike
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■ (Other) IF2 Photon Detectors

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## Abstract:

We present a description of a tunable axion plasma haloscope, in which the plasma frequency of various metamaterials can be tuned to axion masses between 8–400 $\mu$eV with competitive sensitivities. The use of a resonant plasma target material means that the frequency of the experiment is independent of its size, an advantage over traditional cavity experiments which are limited by the axion Compton wavelength. In contrast, a plasma haloscope is limited in principle by the large axion de Broglie wavelength. This first full-scale demonstrator for the feasibility of detection of the axion-plasmon coupling opens up interesting technical challenges and presents a need for advances in quantum technologies including ultra-sensitive superconducting devices like Josephson parametric amplifiers (JPA), transition edge sensors (TES) and microwave kinetic inductance detectors (MKID).

## Axion-Plasmon mixing

In the presence of a magnetic field, the dark matter axion appears as an oscillating current in Maxwell's equations and sources an electric field. The axion de Broglie wavelength is very large, resulting in a spatially constant field oscillating at the axion frequency. To overcome the momentum mismatch and allow the massive axion to couple to the massless photon, traditional cavity [1] and dielectric [2] haloscopes break translational invariance by building experimental structures on the scale of the axion Compton wavelength.

To match dispersion relations, one can instead tune the photon mass to the axion mass. A tunable plasma haloscope was introduced in reference [3], in which the plasma frequency of a wire metamaterial can be tuned to axion masses between 8–400 $\mu$eV with competitive sensitivities. The use of a resonant plasma target material means that the frequency of the experiment is independent of its size. This is an advantage over traditional cavity experiments which are limited by the Compton wavelength, and require novel cavity structures to reach higher masses. A plasma haloscope is limited instead by the large de Broglie wavelength. When contrasted with dielectric haloscopes, plasma haloscopes offer a similar parameter space and sensitivity, but with different experimental challenges. Axion-plasmon mixing has been explored in [4, 5, 6], but has mostly been overlooked in the literature. Recent research has revived the discourse on axion-plasmon mixing, re-exploring the fundamental interaction [7, 8], application to experiments [9, 10] and use in astrophysics [11, 12]. Plasma haloscopes have also been shown to be sensitive to hidden photon dark matter, regardless of whether a magnetic field is present [13].

An international and multidisciplinary collaboration with members at Stockholm University, UC Berkeley, MIT, and ASU has been initiated with the ultimate aim of building a tunable, cryogenic axion-plasmon haloscope. This would be the first full-scale demonstrator for the feasibility of the detection of this coupling. We see wire metamaterials as the baseline design for the haloscope, as the detection and readout can be achieved with off-the-shelf components that are well-studied. In parallel to this baseline design, we are studying more novel, "blue sky" materials and detection mechanisms which are discussed in the following sections.

## Wire metamaterials

A finite volume of wires with thickness less than the wire spacing acts as an effective medium [14, 15]. The plasma frequency of the medium is set by the mutual inductance of the wires, and thus by the inter-wire spacing, with spacings on the order of cm giving plasma frequencies in the GHz range. Tuning of the plasma frequency would be a matter of mechanically changing the inter-wire spacing in at least one direction and swapping out wire grid inserts when mechanical limits are reached. Collaborators at UCB this year will make transmission/reflection measurements of various wire geometries to verify the plasma behavior and quality factor (Q factor) of the metamaterial.

Non-mechanical tuning of the wire metamaterial may be possible with the use of superconducting wires. It has been shown that the inductance of a superconducting wire can be tuned through a DC current applied to regularly spaced Josephson junctions along the wire [16, 17]. In addition, the low resistance of superconducting wires would in principle allow the creation of high-Q metamaterials.

## Lightly doped semiconductors

The plasma frequency of semiconductors can be tuned using the dependence of the carrier concentration on the temperature and magnetic field. It is also possible to tune the number of carriers by exciting electron-hole pairs through irradiation with laser light [18]. The Q factors and possible carrier concentrations for plasma resonances in various semiconductors are being studied, as well as possible readout systems. The choice of semiconductor and operating conditions would give frequencies at the lower range of $\sim 50\,$GHz and up to the THz range. Frequencies within the THz regime are historically very challenging, with only one competing proposal [19]. Thus any new possibility of exploring this space is very interesting for axion detection.

## Detection technologies

Detector limitations and the dominant plasmon decay modes within the target frequency range guide the choice of technology. For axion masses between 10–40 GHz, we expect to measure the electric field, which will require a unique antenna design. Any antenna within the volume would be electrically small compared to the effectively infinite wavelength of the spatially constant EM wave induced by the axion. However, any antenna larger than $\sim 1\,\mathrm{cm}$ would not couple efficiently due to its length being larger than the Compton wavelength of the light in the antenna, with the finite propagation time effectively "shorting out" the signal. Thus we plan to couple the electric field to an array of small antennas and a phase-matched summing network followed by cryogenic low noise amplification with high-electron-mobility transistors (HEMT). HEMTs are already widely used in radio astronomy experiments [20], and within coherent elastic neutrino scattering [21] and low-mass WIMP searches [22].

The sensitivity of the experiment will be limited by the noise temperature of the preamplifier. State of the art off-the-shelf devices have noise temperatures in the realm of 5 K for frequencies below 40 GHz generally with a roughly linear relationship with frequency, with best results usually a factor of 2-3 above the quantum limit. Further development in amplifiers at or below the quantum noise limit must be developed for higher frequencies. Recent experiments using squeezed states have shown to be a promising avenue [23] for detection below the quantum limit. Extending these techniques using Josephson parametric amplifiers (JPA) to higher frequency would be of great importance to any axion experiment operating above $\sim 10\,\mathrm{GHz}$.

Instead of reading out the electric field, the decay products of the plasmons (photons or phonons) can be detected with quantum sensors. Plasma haloscopes constructed from semiconductors, which operate in the THz range, could use transition edge sensor (TES) technologies that are currently deployed in WIMP dark matter detectors [24] and CMB experiments [25] which detect quanta with frequencies above $\sim 100\,\mathrm{GHz}$. Active R&D in low frequency TESs and microwave kinetic inductance detectors (MKIDs) would benefit our search in the parameter space below 100 GHz. TES bolometer arrays with a reach as low as 27 GHz have been deployed in ground based telescopes [26] , and planned CMB experiments have also developed prototypes towards this range [27]. Our experiment would also benefit from ongoing research in low-frequency MKIDs using alloy superconductors [28, 29], multi-metallic-layer superconductors [30, 31], and the application of DC-bias currents [32].

As the primary driver behind detector choice comes from the operating frequency, we stress that advancements in this field would benefit axion detection regardless of the exact type of experiment realized. Over the last few years, a great focus of the axion community has been on extending the range of experiments outside of the classical window. Plasma haloscopes and similar ideas provide a compelling indication that experiments will, in the near future, push into previously inaccessible parameter space, motivating serious exploration of detector technology at these frequencies for axion detection.

## Summary

Plasma haloscopes open up a new parameter space for axion detection. A cryogenic, tunable plasma haloscope is being designed, with measurements of wire metamaterials and studies on semiconductors already underway. The detection and readout of very low axion masses opens up interesting technical challenges and presents a need for advances in quantum technologies including ultra-sensitive superconducting devices like JPAs, TESs, and MKIDs. As the range of frequencies that can potentially be reached by plasma haloscopes is very large $O$(GHz–THz), both "bottom up" and "top down" approaches are motivated, either extending near or sub quantum-limited detection to higher frequencies or extending single photon/phonon counting to lower frequencies.

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