# Snowmass2021 - Letter of Interest

# *Augmenting Axion Haloscopes With Light-Shining-Through-Walls Experiments*

**Thematic Areas:** (check all that apply ☐/■)

■ (CF2) Dark Matter: Wavelike
☐ (IF01) Quantum Sensors
☐ (RF3) Fundamental Physics in Small Experiments

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**Abstract:** Significant effort has been put into developing haloscope-style detectors for the QCD axion, enabling unprecedented sensitivities. We propose feasible light-shining-through-walls (LSW) experiments that can operate in tandem with these existing haloscope experiments and be integrated into future development plans.

[1]

# 1 Introduction

Weakly Interacting Slim Particles, or WISPs, are natural consequences of solutions to problems with the Standard Model via the proposition of a new, spontaneously broken symmetry. In order to constitute some fraction of the observed dark matter density, these particles must be both cold and of low mass. Further, to account for the fact that no such candidates have been observed, these particles must be feebly interacting. Generally speaking, there are two forms of WISPy dark matter which can be detected through coupling to photons: axion-like particles (ALPs) and hidden sector photons (HSPs). The QCD axion is a uniquely compelling form of WISP because it both solves the strong CP problem and can be produced in sufficient quantities in the early universe to be a significant fraction of the dark matter[1–3]. The QCD axion mass is linked to its coupling via the symmetry-breaking scale $f_a$ providing a target range which has attracted several significant experimental efforts. The majority of experiments use the dark matter halo as a particle source as this provides a significant energy density. However, making this assumption introduces a vulnerability in the experiment, as it assumes knowledge of the dark matter composition and distribution. In an LSW search, the WISP is both generated and detected within the experiment, removing the model dependence of any results. In this LOI, we will outline LSW techniques targeting the mass range of existing QCD axions microwave resonance searches and comment on the extending the mass range.

# 2 Microwave Haloscopes as LSW Experiments

Any bright photon source can also be a HSP source. Furthermore, the addition of a magnetic field in the vicinity of such a source can facilitate the production of ALPs. Thus, if a high-powered microwave resonator is positioned next to a microwave detector there is some probability of detecting a WISP converting back to a photon[4]. The maximum probability of transmitting a photon from one cavity to another in an LSW experiment is proportional to the quality factor of the two resonators. In the $1 - 40$ μeV mass range, axion dark matter haloscopes have become increasingly sensitive, with the ADMX collaboration achieving sensitivity to signals as low as $10^{-24}$ W[5]. These experiments present an opportunity to run a parallel LSW experiment passively, capitalizing on the investments already made in the detector. This search technique has already been demonstrated, with dedicated experiments having been performed at CERN[6], The Cockcroft Institute[7], Yale[8], and The University of Western Australia[9] and the ADMX collaboration[10]. Nevertheless, a concerted effort to run LSW experiments in parallel with operational haloscopes is currently lacking. Such an approach could exploit the sensitivity of axion searches to probe deeper into the HSP parameter space.

A possible, simple design for such an experiment would be to use an RF generator, a power amplifier and a microwave resonator with a tuning mechanism to frequency-match the haloscope as the WISP emitter. Attention would need to be paid to leakage between the emitter and detector, but a suitably designed set of nested Faraday cages would be sufficient. Figure 1 shows the schematic of a simple LSW extension to the existing ADMX experiment with an emitter (quality factor of $10^4$) powered by a 100 W source. The expected exclusion in the 1-2 GHz region beats previous dedicated results by greater than a decade. The layout in Figure 1 is sub-optimal due to the space required for the magnet coils separating the cavities, approximately 0.8 m. Another possibility is to make use of existing space above the haloscope cavities: for example, in previous incarnations of ADMX, a smaller prototype cavity known as sidecar has been operated in tandem with the main experiment. Such a cavity would significantly reduce the geometric reduction in signal while also benefiting from being within the magnetic field, enabling a simultaneous ALPs search. Finally, higher mass haloscopes targeting DFSZ axions are being designed with multiple, simultaneously-operated cavities neatly confined within the bore of existing magnets. It is a relatively simple operation to power one of these cavities to enable a LSW search between adjacent cavities.

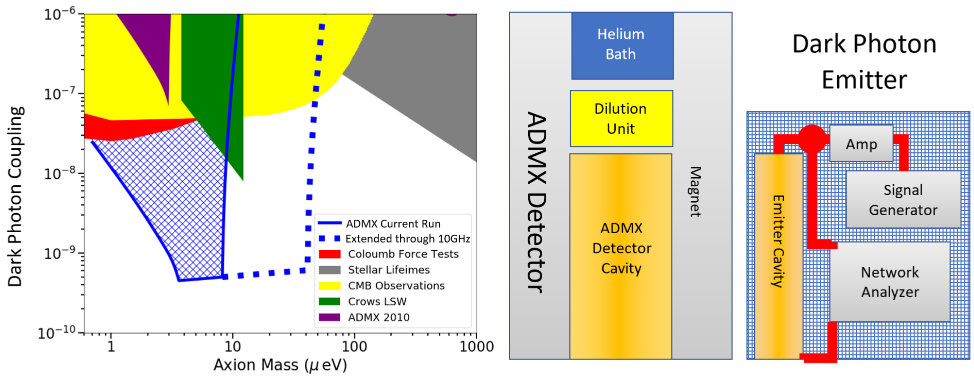


Figure 1: Left: Exclusion plot showing the expected sensitivity of an HSP search running in parallel with the ADMX 1-2 GHz run. The emitter is assumed to be a $10^4$–$Q$ cavity with equivalent geometry as the ADMX detector cavity powered by a 100 W pump and placed on the perimeter of the magnet. Right: A schematic of emitter cavity assembly. The emitter system is fully independent of the ADMX system allowing for such a system to be retrofitted to existing experiments. The blue hashed area indicates components which would be housed in the Faraday cage only requiring power through-puts.

# 3 Extended Mass Range

One promising technique to extend the reach of LSW searches to higher masses is to leverage the high-$Q$ of superconducting cavities which compensates for the effect of reduced volume and allows the stored energy for the emitter to be increased. Quality factors as high as $10^{10} - 10^{12}$ have been obtained [11] with such superconducting cavities. The challenge of operating superconducting cavities in high magnetic fields limits the use of this technique for detecting ALPs. One possible means of avoiding this issue and searching for low mass WISPs is described in this article[12], which uses a gapped toroid and two superconducting rf cavities outside the high field region. Projected sensitivities reach down to ALP masses of $10^{-8}$, reaching axion-photon couplings just lower than $10^{-11}$. This novel approach capitalizes on the high-$Q$ of superconducting RF cavities without putting them in a high-field region.

The LSW technique can also be used to extend sensitivity of existing axions searches to lower mass ALPs. The emitter cavity will excite any ALP or HSP field with a rest mass lower than energy of the resonant frequency. This produces a finite probability of detecting an ALP or HSP with any mass below the resonant energy rather than the narrow slice produced by haloscopes, although to avoid kinematic suppression it may be necessary to adapt the detector. An example of a simple adaptation to enhance the off-resonance detection in the case of HSPs is to alter the relative orientation of the detector and emitter cavities to make more optimal use of the longitudinal polarisation mode. Strategies to increase the tunability of the detector further include the use of metamaterials as proposed for the development of plasma haloscopes[13].

# 4 Conclusion

HSPs and ALPs remain viable dark matter candidates, and existing experiments possess the ability to search for them with small, minimal cost extensions. Initiatives should be taken to design and integrate LSW experiments in parallel with these haloscope searches to maximize the possibility of discovery.

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