Snowmass2021 - Letter of Interest

Dark matter detection using layered materials and superconducting nanowires

Thematic Areas: (check all that apply □/■)

■ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (IF1) Quantum Sensors
■ (IF2) Photon Detectors
■ (TF09) Astro-particle physics and cosmology
■ (TF10) Quantum Information Science
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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Abstract:

We describe an ongoing project to design and build detectors for light bosonic dark matter in the $\sim 0.01\,\mathrm{eV}$ to $\sim 10\,\mathrm{eV}$ mass range. By utilising materials whose optical properties vary on the scale of the dark matter Compton wavelength, dark matter particles such as dark photons and axions convert coherently to photons, which can be be detected using superconducting nanowire single photon detectors (SNSPDs). Coherent conversion allows the signal photons to be focussed onto a small detector, reducing backgrounds and enhancing sensitivity. Existing prototypes have demonstrated very low dark count rates ($\lesssim 10^{-5}\,\mathrm{Hz}$), and should have sensitivity to unexplored parameter space for dark photon dark matter at masses $\sim 1\,\mathrm{eV}$. Future developments could increase this sensitivity to much smaller couplings and to a wider range of masses, as well as to other dark matter candidates, such as axion-like particles.

New, light particles occur in a wide range of theories beyond the Standard Model (SM). In many cases, there are early-universe production mechanisms which can give rise to a non-thermal, large-occupation-number abundance of such particles (if they are bosons), allowing them to be dark matter (DM). Well-known examples include the QCD axion[1–3], axion-like particles from string theory compactifications[4], and hidden-sector analogues of the SM photon[5;6].

Many experiments searching for light bosonic DM focus on the low frequency, high occupation number regime, where the DM mass is $\ll$ eV (e.g. microwave cavity experiments such as ADMX[7;8]). However, there are theoretically motivated DM models and production mechanisms for significantly higher DM masses. For example, if the QCD axion's PQ symmetry is broken post-inflation, then a network of axion strings is formed, whose contribution to the axion DM abundance is difficult to compute; plausible predictions can vary by orders of magnitude, corresponding to a large uncertainty in the axion mass that gives rise to the correct DM abundance[9–14]. In axion theories with additional new physics, there can be other production mechanisms which give a full axion DM abundance at higher masses[15–21], while for spin-1 particles, the simplest inflationary production mechanism only works for sufficiently heavy particles ($m \gtrsim 10^{-5}\,\mathrm{eV}$)[6]. Consequently, there are strong motivations to extend bosonic DM searches to higher masses.

To detect such DM particles, we want to absorb their energy into excitations of the detector. SM photons are a natural candidate for these target excitations; they possess a continuum of frequencies, and can easily be focussed and detected. However, DM is non-relativistic (with velocity $\sim 10^{-3}c$), while photons are relativistic, so the momentum mismatch must be made up for by the structure of the detector. This can be achieved by a target with optical structure on the scale of the DM's Compton wavelength. A simple example is a periodic structure of dielectric layers, with different layers having different refractive indices. Inside this 'photonic' structure, photon modes are modified, and can interact coherently with non-relativistic DM modes. This 'dielectric haloscope' concept was first proposed at microwave frequencies[22–24], and was extended to higher DM masses in[25;26].

The coherent conversion of DM to photons means that the produced photons are collimated within a narrow angle ($\theta \sim v/c \sim 10^{-3}$). As a result, they can be focussed onto a small detector, with only $\sim 10^{-6}$ of the target's area. This reduces backgrounds, and enables the use of very sensitive superconducting photon counters, as we discuss below. In addition, if a signal were seen, then the collimated nature of the signal photons would be a spectacular verification of the non-relativistic DM velocity distribution.

In this project, we aim to design and build such detectors for DM in the infrared to ultra-violet frequency range ($m \sim 0.01\,\mathrm{eV} - 10\,\mathrm{eV}$). For photon detection, we utilise superconducting nanowire single photon detectors (SNSPDs)[27]. SNSPDs are fabricated with common semiconductor technologies, produce large and unambiguous signals with few dark counts, and have matured to the point of enabling ambitious detection schemes[28]. As part of our work so far, SNSPDs with detector areas $(400\,\mu\mathrm{m})^2$ and $(1\,\mathrm{mm})^2$ have been fabricated and tested inside a dilution refrigerator at MIT. These have observed only a few dark count events over ~ 70 hours of data taking time, demonstrating a dark count rate of $\sim 10^{-5}\,\mathrm{Hz}$. In the near future, experiments are planned to determine the origin of these events (in particular, to determine whether they are due to cosmic rays), to allow the dark count rate to be reduced even further.

The easiest DM candidate to search for is a dark photon. Simply combining a dielectric stack, a focussing mechanism and a photon counter is enough to search for dark photon DM[25], and even an inexpensive apparatus is enough to explore new parameter space. A prototype experiment, schematically illustrated in the left panel of Fig 1, has already been constructed at MIT and NIST. Using only 10 dielectric layers, a runtime of a few weeks should be able to explore new DM parameter space (as illustrated in the right-hand panel of Fig 1), either discovering or ruling out these models.

Future developments of this experiment, utilising larger volumes of layered materials, lower dark count

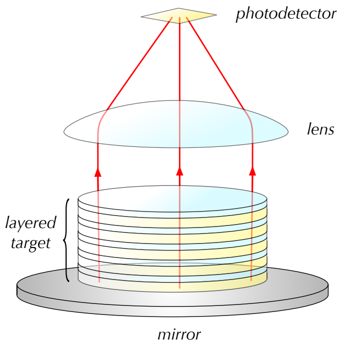

Figure 1: *Left panel:* schematic illustration of DM detection scheme. DM particles convert to photons inside the layered material, which are then focussed onto a small photodetector.

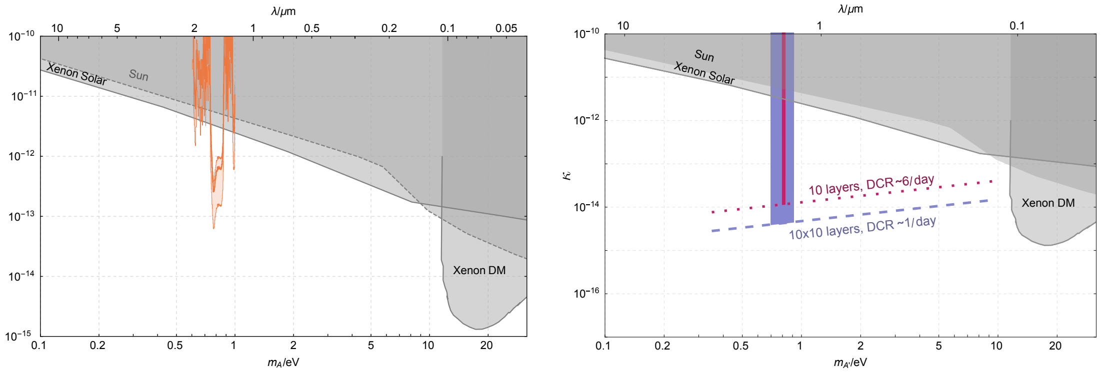

Figure 2: *Left panel:* projected sensitivity reach for our prototype detector, assuming dark photon DM with kinetic mixing parameter κ.[5] The prototype uses a 10-layer Si/SiO$_2$ half-wave stack[25], with central wavelength $1550\,\mathrm{nm}$, and diameter 2 inches. The sensitivity projection is for a runtime of 21 days, assuming dark count rate 10^{-5} Hz. *Right panel:* Nominal sensitivity reach for the next phase of the experiment, with multi-layered targets of silica and gas, 3 inches in diameter. The red (blue) dotted curve shows the reach for a stack with 10 (100 non-periodic) layers. The red and blue vertical bar shows the parameter space that would be covered by a single such stack.

detectors, and different layer thickness, will be able to probe a wider range of dark photon couplings and masses. Similar setups would also be able to search for other DM candidates. For example, placing the layered material in a magnetic field would enable axion-like particle DM to be absorbed, via the axion-photon coupling[22;25]. In this context, SNSPDs with sensitivity to lower-frequency photons are particularly interesting, since the best-motivated QCD axion masses correspond to infrared frequencies and below. Alternatively, using spin-polarised materials could allow absorption via axion-fermion couplings[26].

Another potential avenue for development is tunability of the target's optical properties. For example, if some of the dielectric layers were replaced by a gas, whose molecules have a resonant optical response, then the response of the target to DM could be modified by changing the pressue of the gas[26].

Summary: the combination of coherent DM conversion in structured materials, with state-of-the-art superconducting photon counters, enables even straightforward and inexpensive experiments to explore new DM parameter space for dark photons at $\sim$ optical frequencies. Future developments, including lower dark count rates, expanded frequency ranges, and larger targer volumes, will cover more parameter space, while modifications such as a background magnetic field will allow sensitivity to axion DM.

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