Opening the terahertz axion window

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This *Letter of Interest* summarizes plans to propose a broadband search for weakly-coupled dark matter, notably the QCD axion, with 1 meV to 100 meV masses. This corresponds to terahertz photon frequencies, where there are no direct-detection haloscope constraints in part due to a historical technology gap between the microwave and infrared at the interface of electronics and photonics. Opening sensitivity at the terahertz frontier is an important science driver for the coming decade that requires investment in novel single-photon-counting quantum sensor instrumentation.

■ (CF2) Dark Matter: Wave-like ■ (IF1) Quantum Sensors ■ (IF2) Photon Detectors
■ (AF7) Accelerator Technology R&D ■ (UF02) Underground Facilities for Cosmic Frontier

This *Letter of Interest* describes our planned contribution outlining a broadband axion dark matter detection strategy in the terahertz frequency range. This work is part of rapidly emerging community interest for novel dark matter probes and quantum sensing technology [1–4]. We plan to describe ongoing work towards exploring necessary investments in both overall detector design and novel quantum sensor instrumentation for low-rate photon counting in the context of next-generation axion dark matter direct detection searches in the coming decade.

Motivational questions—Two longstanding pressing questions in fundamental physics aim to 1) reveal the fundamental nature of dark matter and 2) resolve the strong CP problem. The axion, a pseudoscalar field, is among the most motivated solution to these problems. Many theories beyond the Standard Model also generically predict new weakly-coupled light particles. Their photon coupling modifies Maxwell's equations and thus experimental searches are equivalently precision tests of QED at the low-rate quantum regime. We argue that addressing these exciting but challenging problems requires the community to invest in several areas of science. The cornerstone axion haloscope for the past decade has been ADMX [5–7] but its microwave resonance cavity approach currently provides narrowband search coverage around 2 μeV masses and the sensitivity of this technique is not expected to scale beyond about 40 μeV.

Recent phenomenological work motivates mass ranges around the milli-eV scales [8], which corresponds to THz photon frequencies. Exploring this range has historically been limited by a technology gap in sources and detectors. We wish to overcome this hurdle for these masses and define new next-generation flagship axion detection experiments.

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Physics targets—Ambient dark matter targets: axion-like particles, dark photons in the milli-eV ranges with the QCD axion and relic density as benchmark targets. We could consider axions from solar or other production mechanisms. Furthermore, we could explore other motivated models that modify laboratory QED.

There is a gap in sensitivity around 1 meV to 100 meV (0.3 THz to 30 THz frequency), in particular reaching the QCD axion benchmarks. This is an important, but challenging region to probe for the coming decade. Dish antenna-type experiments operating in large volume magnets may feasibly produce signal rates in the range of a few photons per day in this regime for the QCD axion (rates may be orders of magnitude higher for generic axion-like particles or dark photons) [9]. A target sensitivity of 1 photon per day corresponds to 10^{-26} W. These parameters present a formidable experimental challenge for suppressing environmental and instrumental noise. We could also consider the experiment as both a haloscope and helioscope for e.g. solar axions.

At around 10 meV, the target sensitivity to couplings corresponds to surpassing the CAST limit of $g_{a\gamma\gamma} \sim 10^{-10}$. This is possible with order days of running using a 10 T magnet and 1 m^2 area reflector. The long-term target of the region favoured by QCD axion solutions are around $g_{a\gamma\gamma} \sim 10^{-12} - 10^{-13}$ [9]. This is the similar order of magnitude for dark photon A' kinematic mixing parameter $\epsilon_{A'}$. As dark photons have similar signatures but can proceed without an external magnet, this can proceed as a pilot search.

Instrumentation opportunities—Superconducting quantum sensing devices have been shown to couple to terahertz radiation with single photon absorption [10]. One such technology is a Transition Edge Sensor (TES) [11–13]. Other devices include the microwave kinetic inductance detector (MKID) [14–17] and superconducting nanowire single-photon detector (SNSPD).

Characterising the performance of these sensors across a wide range of (terahertz) frequencies is a key goal. Resonant enhancement in THz may be possible using axion quasiparticle materials (topological insulators) [18].

Calibration strategy: we wish to define strategies for absolute energy calibration, ideally in situ for this broadband detector. This is traditionally challenging in the THz range given emerging source, filter, detector technologies. We discuss preliminary explorations in constructing a THz Fourier Transform Spectrometer for this characterisation, which bridge standard setups for microwave and infrared.

Signal amplification: we propose a parabolic reflector to focus emitted radiation from an antenna [9], and consider materials and manufacturing technology, simulation, single vs. secondary reflector, costs for further study.

Data acquisition and processing: we plan to investigate methods of coupling of photon counter to readout, terahertz photo-electronics, spectrum analyzers, and fast electronics.

Infrastructure: we wish to study available magnets (cold vs. warm), cryogenics, host locations, shielding (assess the necessity for underground facility), and scalability potential.

Synergies and applications—Complementary strategies with overlapping sensitivity is important both for cross-correlating discovery and also post-discovery measurements of dark matter. The greater Chicago area is an emerging hub for quantum information science. Collaborations between the University of Chicago, Fermilab, University of Illinois, Argonne National Laboratory, and relevant expertise elsewhere are envisioned. We envision that dark matter science will drive developments in photon counting in the THz regime that could benefit both fundamental and applied sciences. Examples include next-generation sub-millimeter astronomy and cosmology missions. The enabling hardware is similar to those used to develop quantum computation, communications and related technologies. We could also consider applications in the imaging, medical, industrial, communications, and security communities.

Community—As an emerging science crossing several fields, we consider community engagement integral to growing and sustaining the science on decades-long timescales. We wish to consider innovative mechanisms to attract, train and support newcomers from diverse backgrounds to this area. Being cross-disciplinary, we wish to reach out to those who may not traditionally consider but would thrive pursuing this science, in addition to those under-represented in this field to foster an inclusive environment for terahertz axion research.

Snowmass Frontiers and topical groups—This work cuts across many of the Snowmass Frontiers and Topical Groups, which we list to foster communication and collaboration for a Snowmass White Paper. Our main science resides in Cosmic Frontier CF2 Dark Matter: Wave-like [19] with the detector development in Instrumentation frontier IF1 quantum sensors [20] and IF2 photon detectors [21]. Long term, this work could benefit from high-field magnet R&D in AF7 and low-background requirements may require Underground Facilities [22].

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