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Snowmass2021 - Letter of Interest

Sub-eV Dark Matter Detection with MKID Haloscopes

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

■ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
□ (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]*
(IF1) Quantum Sensors
(IF2) Photon Detectors
(TF10) Quantum Information Science

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Abstract:

Light dark matter is an exciting new frontier in the search for dark matter candidates. We propose to use one of the most powerful energy sensors developed in the last twenty years, Microwave Kinetic Inductance Detectors (MKIDs), to search for dark matter in an optical haloscope. The advantage of MKIDs for this application is that they have already been proven as very low background energy-resolving photon sensors with sub-eV energy resolution for 1 eV photons. This energy range is of great interest for dark matter searches, and is difficult to achieve with semiconductor-based detectors. In addition, MKID arrays with over 20,000 pixels have been demonstrated, making them a mature technology and ready to be integrated into this experiment. The proposed research aims to discover or exclude light dark matter candidates with masses in the 0.25 eV – 2.5 eV range, covering a substantial region of dark matter parameter space and significantly exceeding existing constraints.

Dark matter has long been known to comprise 25% of the energy budget in our universe[1;2]. However, its precise nature remains undetermined despite extensive searches for candidate particles that cover many orders of magnitude in mass and couplings to Standard Model (SM) particles. Based on astrophysical observations, dark matter is known to be non-relativistic, but much less is known about its physical nature. Understanding the microscopic properties of dark matter is one of the central goals of modern astrophysics and particle physics. One direction has been the search for weakly-interacting massive particles (WIMPs) whose masses and couplings are comparable to those of the known weak gauge bosons, because the interactions of WIMPs in the early universe generically lead to present-day abundances consistent with observation. This has been the focus of an impressive experimental program including (for example) the liquid noble gas detectors LUX[3], PANDA-X[4], and Xenon1T[5], as well as the low temperature detector CDMS[6]. Together these experiments have excluded large swaths of parameter space for the WIMP particle. A more recent direction is the search for light, bosonic dark matter particles, which appear in many well-motivated extensions of the Standard Model. Such dark matter candidates are poorly constrained by existing experiments and require qualitatively new search strategies, one of which is pursued in this proposal.

A particularly well-known example of a light boson in beyond-SM theories is the QCD axion, proposed 40 years ago to solve the Strong CP problem[7–9]. More generally, 'axion-like' particles are common in theories beyond the Standard Model, including in string theory, where the complexity of compactifications of the many extra dimensions typically gives rise to light pseudoscalar particles[10–12]. These constructions also generically give rise to additional vector bosons, or 'dark photons'[13;14].

In addition to appearing in many well-motivated extensions of the Standard Model, axions and dark photons are also natural dark matter candidates that are easily produced in the early universe. Axions are produced during a period of inflation through the misalignment mechanism, where quantum fluctuations of the axion field are later converted into long-wavelength fluctuations that redshift as cold, pressureless dark matter[15–17].

A process similar to misalignment can produce dark photon dark matter during inflation[18]. Unlike axions, however, the amplitude of the long-wavelength dark photon modes redshifts rapidly during the early universe, resulting in fluctuations contributing to the dark matter abundance being at smaller scales. The dark photon abundance depends on the Hubble scale H_I of inflation at which these fluctuations are generated[18],

$$\frac{\Omega_{\rm DP}}{\Omega_{\rm DM}} \sim \left(\frac{m_{A'}}{\rm eV}\right)^{1/2} \left(\frac{H_I}{5\times 10^{12}\,{\rm GeV}}\right)^2 . \tag{1}$$

Bounds on the CMB tensor-to-scalar ratio constrain H_I to be $\lesssim 10^{14}\,\mathrm{GeV}$, so this mechanism can produce all of the DM for a range of dark photon masses centered around the eV scale.

Given its high occupancy number, light bosonic dark matter is best described as a coherent, classical field. These dark matter oscillations have a frequency set by the DM mass $m_{\rm DM}$, and amplitude proportional to $\sqrt{\rho_{\rm DM}}$, where $\rho_{\rm DM} \sim 0.3\,\mathrm{GeV/cm^3}$ is the local DM density. The light dark matter field exhibits macroscopic spatial coherence on a length scale of order its de Broglie wavelength, 10^3 times larger than its Compton wavelength. The coherence time is determined by the inverse kinetic energy spread, roughly 10^6 periods of oscillation. In our proposal, we aim to take advantage of the spatial coherence of dark matter to efficiently convert it into single photons at frequency given by the DM mass. In the case of dark photon dark matter, this conversion proceeds directly via the coupling to charged particles. For axions and axion-like particles, conversion occurs in the presence of a background magnetic field. In what follows we will focus on the conversion of dark photon dark matter, with the understanding that the proposal can be readily adapted to search for axion dark matter by the addition of a magnetic field.

In order to convert non-relativistic dark matter into relativistic photons, the target must have optical structures on the scale of the dark matter Compton wavelength, correcting the momentum mismatch between

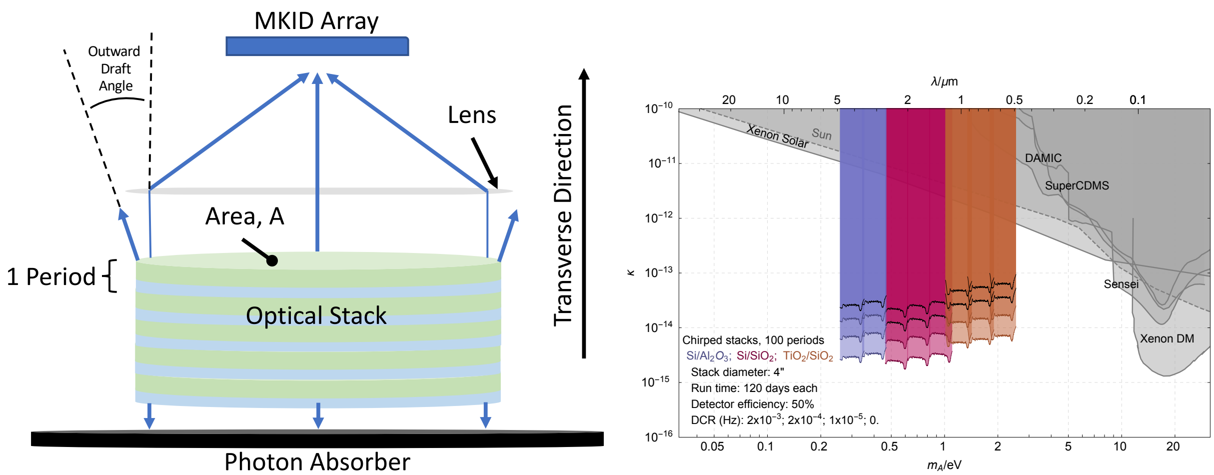

Figure 1: Left: Proposed experimental setup: stack of dielectric layers, with alternating indices of refraction. In the presence of the right type of background DM oscillation (e.g. dark photon DM), at a frequency corresponding to the inverse spacing between the layers, the layers will emit photons in the transverse direction from both sides of the stack. On one side the photons are extinguished. On the other side, a lens focuses them onto an MKID photon detector array. To detect axion DM with a coupling to photons, a magnetic field should be applied parallel to the layers. Tight: Projected sensitivity in the plane of dark photon mass (m_A) and coupling (κ) with 8 chirped stacks, at 95% C.L., assuming respective dark count rates (DCRs) of $2 \times 10^{-3}, 2 \times 10^{-4}, 10^{-5}$ Hz, and no background in the MKID detector array.

the dark matter and the photon. A simple example of such a structure is a series of dielectric layers, with different refractive indexes[19], e.g. n_1 and n_2. We will use the terminology 'optical stack' to refer to these structures. Each stack has alternating layers of two dielectric materials, $n_1 n_2 n_1 n_2 \cdots n_1 n_2$. The adjacent occurrence of each dielectric material is what we call a 'period', e.g. $n_1 n_2$.

These layered structures modify the dispersion relation of the photon mode inside the dielectric materials, such that dark matter can resonantly convert to photons at the same frequency. Due to the spatial coherence of dark matter, the converted photon can add coherently over the entire stack as long as the stack is not thicker than the dark matter coherence length. The converted photon signal, in terms of emission rate, is enhanced quadratically by the number of repeated layers in the stack.

We propose to combine the concept of a Dark Matter Haloscope with the most powerful detectors currently available for photon detection, Microwave Kinetic Inductance Detectors, or MKIDs. MKIDs are superconducting detector arrays that can determine the energy of each arriving photon without read noise or dark current, and with microsecond temporal resolution. An illustration of the experimental design is shown in the left panel of Figure 1, where an optical stack converts dark photons originating from the transverse direction to real photons collimated in the transverse direction out of the stack where a lens focuses the light down onto an MKID array. As such this is a directional dark matter detector. The entire setup will be in a dilution refrigerator to allow operation of the MKID and eliminate the background of blackbody photons. Detailed simulations have been carried out to evaluate the relevant backgrounds and ultimate sensitivity of this experiment, as shown in the right panel of Figure 1. Even modest initial experiment can set extremely low limits over a wide range of potential dark matter masses.

References

[1] Vera C. Rubin and W. Kent Ford, Jr. Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions. *Astrophys. J.*, 159:379–403, 1970.

[2] D. N. Spergel, L. Verde, H. V. Peiris, E. Komatsu, M. R. Nolta, C. L. Bennett, M. Halpern, G. Hinshaw, N. Jarosik, A. Kogut, M. Limon, S. S. Meyer, L. Page, G. S. Tucker, J. L. Weiland, E. Wollack, and E. L. Wright. First year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Determination of cosmological parameters. *Astrophys. J. Suppl.*, 148:175–194, 2003.

[3] D.S. Akerib, S. Alsum, H.M. Araújo, X. Bai, A.J. Bailey, J. Balajthy, P. Beltrame, E.P. Bernard, A. Bernstein, T.P. Biesiadzinski, E.M. Boulton, R. Bramante, P. Brás, D. Byram, S.B. Cahn, M.C. Carmona-Benitez, C. Chan, A.A. Chiller, C. Chiller, A. Currie, J.E. Cutter, T.J.R. Davison, A. Dobi, J.E.Y. Dobson, E. Druszkiewicz, B.N. Edwards, C.H. Faham, S. Fiorucci, R.J. Gaitskell, V.M. Gehman, C. Ghag, K.R. Gibson, M.G.D. Gilchriese, C.R. Hall, M. Hanhardt, S.J. Haselschwardt, S.A. Hertel, D.P. Hogan, M. Horn, D.Q. Huang, C.M. Ignarra, M. Ihm, R.G. Jacobsen, W. Ji, K. Kamdin, K. Kazkaz, D. Khaitan, R. Knoche, N.A. Larsen, C. Lee, B.G. Lenardo, K.T. Lesko, A. Lindote, M.I. Lopes, A. Manalaysay, R.L. Mannino, M.F. Marzioni, D.N. McKinsey, D.M. Mei, J. Mock, M. Moongweluwan, J.A. Morad, A.St.J. Murphy, C. Nehrkorn, H.N. Nelson, F. Neves, K. O'Sullivan, K.C. Oliver-Mallory, K.J. Palladino, E.K. Pease, P. Phelps, L. Reichhart, C. Rhyne, S. Shaw, T.A. Shutt, C. Silva, M. Solmaz, V.N. Solovov, P. Sorensen, S. Stephenson, T.J. Sumner, M. Szydagis, D.J. Taylor, W.C. Taylor, B.P. Tennyson, P.A. Terman, D.R. Tiedt, W.H. To, M. Tripathi, L. Tvrznikova, S. Uvarov, J.R. Verbus, R.C. Webb, J.T. White, T.J. Whitis, M.S. Witherell, F.L.H. Wolfs, J. Xu, K. Yazdani, S.K. Young, and C. Zhang. Results from a search for dark matter in the complete LUX exposure. *Phys. Rev. Lett.*, 118(2):021303, 2017.

[4] Xiangyi Cui, Abdusalam Abdukerim, Wei Chen, Xun Chen, Yunhua Chen, Binbin Dong, Deqing Fang, Changbo Fu, Karl Giboni, Franco Giuliani, Linhui Gu, Yikun Gu, Xuyuan Guo, Zhifan Guo, Ke Han, Changda He, Di Huang, Shengming He, Xingtao Huang, Zhou Huang, Xiangdong Ji, Yonglin Ju, Shaoli Li, Yao Li, Heng Lin, Huaxuan Liu, Jianglai Liu, Yugang Ma, Yajun Mao, Kaixiang Ni, Jinhua Ning, Xiangxiang Ren, Fang Shi, Andi Tan, Cheng Wang, Hongwei Wang, Meng Wang, Qiuhong Wang, Siguang Wang, Xiuli Wang, Xuming Wang, Qinyu Wu, Shiyong Wu, Mengjiao Xiao, Pengwei Xie, Binbin Yan, Yong Yang, Jianfeng Yue, Dan Zhang, Hongguang Zhang, Tao Zhang, Tianqi Zhang, Li Zhao, Jifang Zhou, Ning Zhou, and Xiaopeng Zhou. Dark Matter Results From 54-Ton-Day Exposure of PandaX-II Experiment. *Phys. Rev. Lett.*, 119(18):181302, 2017.

[5] E. Aprile, J. Aalbers, F. Agostini, M. Alfonsi, L. Althueser, F.D. Amaro, M. Anthony, F. Arneodo, L. Baudis, B. Bauermeister, M.L. Benabderrahmane, T. Berger, P.A. Breur, A. Brown, A. Brown, E. Brown, S. Bruenner, G. Bruno, R. Budnik, C. Capelli, J.M.R. Cardoso, D. Cichon, D. Coderre, A.P. Colijn, J. Conrad, J.P. Cussonneau, M.P. Decowski, P. de Perio, P. Di Gangi, A. Di Giovanni, S. Diglio, A. Elykov, G. Eurin, J. Fei, A.D. Ferella, A. Fieguth, W. Fulgione, A. Gallo Rosso, M. Galloway, F. Gao, M. Garbini, C. Geis, L. Grandi, Z. Greene, H. Qiu, C. Hasterok, E. Hogenbirk, J. Howlett, R. Itay, F. Joerg, B. Kaminsky, S. Kazama, A. Kish, G. Koltman, H. Landsman, R.F. Lang, L. Levinson, Q. Lin, S. Lindemann, M. Lindner, F. Lombardi, J.A.M. Lopes, J. Mahlstedt, A. Manfredini, T. Marrodán Undagoitia, J. Masbou, D. Masson, M. Messina, K. Micheneau, K. Miller, A. Molinario, K. Morå, M. Murra, J. Naganoma, K. Ni, U. Oberlack, B. Pelssers, F. Piastra, J. Pienaar, V. Pizzella, G. Plante, R. Podviianiuk, N. Priel, D. Ramírez García, L. Rauch, S. Reichard, C. Reuter, B. Riedel, A. Rizzo, A. Rocchetti, N. Rupp, J.M.F. dos Santos, G. Sartorelli, M. Scheibelhut, S. Schindler, J. Schreiner, D. Schulte, M. Schumann, L. Scotto Lavina, M. Selvi, P. Shagin, E. Shockley, M. Silva,

H. Simgen, D. Thers, F. Toschi, G. Trinchero, C. Tunnell, N. Upole, M. Vargas, O. Wack, H. Wang, Z. Wang, Y. Wei, C. Weinheimer, C. Wittweg, J. Wulf, J. Ye, Y. Zhang, and T. Zhu. Dark Matter Search Results from a One Ton-Year Exposure of XENON1T. *Phys. Rev. Lett.*, 121(11):111302, 2018.

[6] R. Agnese, A. J. Anderson, T. Aramaki, M. Asai, W. Baker, D. Balakishiyeva, D. Barker, R. Basu Thakur, D. A. Bauer, J. Billard, A. Borgland, M. A. Bowles, P. L. Brink, R. Bunker, B. Cabrera, D. O. Caldwell, R. Calkins, D. G. Cerdeno, H. Chagani, Y. Chen, J. Cooley, B. Cornell, P. Cushman, M. Daal, P. C. F. Di Stefano, T. Doughty, L. Esteban, S. Fallows, E. Figueroa-Feliciano, M. Ghaith, G. L. Godfrey, S. R. Golwala, and J. Hall. New Results from the Search for Low-Mass Weakly Interacting Massive Particles with the CDMS Low Ionization Threshold Experiment. *Phys. Rev. Lett.*, 116(7):071301, 2016.

[7] Steven Weinberg. A New Light Boson? *Phys.Rev.Lett.*, 40:223–226, 1978.

[8] Frank Wilczek. Problem of Strong p and t Invariance in the Presence of Instantons. *Phys.Rev.Lett.*, 40:279–282, 1978.

[9] R.D. Peccei and Helen R. Quinn. CP Conservation in the Presence of Instantons. *Phys.Rev.Lett.*, 38:1440–1443, 1977.

[10] Peter Svrcek and Edward Witten. Axions In String Theory. *JHEP*, 06:051, 2006.

[11] Asimina Arvanitaki, Savas Dimopoulos, Sergei Dubovsky, Nemanja Kaloper, and John March-Russell. String Axiverse. *Phys. Rev.*, D81:123530, 2010.

[12] Renata Kallosh, Andrei D. Linde, Dmitri A. Linde, and Leonard Susskind. Gravity and global symmetries. *Phys. Rev.*, D52:912–935, 1995.

[13] Michele Cicoli, Mark Goodsell, Joerg Jaeckel, and Andreas Ringwald. Testing String Vacua in the Lab: From a Hidden CMB to Dark Forces in Flux Compactifications. *JHEP*, 07:114, 2011.

[14] Asimina Arvanitaki, Nathaniel Craig, Savas Dimopoulos, Sergei Dubovsky, and John March-Russell. String Photini at the LHC. *Phys. Rev.*, D81:075018, 2010.

[15] Andrei D. Linde. Inflation and Axion Cosmology. *Phys. Lett.*, B201:437–439, 1988.

[16] Andrei D. Linde. Axions in inflationary cosmology. *Phys. Lett.*, B259:38–47, 1991.

[17] John Preskill, Mark B. Wise, and Frank Wilczek. Cosmology of the Invisible Axion. *Phys. Lett.*, B120:127–132, 1983. [,URL(1982)].

[18] Peter W. Graham, Jeremy Mardon, and Surjeet Rajendran. Vector Dark Matter from Inflationary Fluctuations. *Phys. Rev.*, D93(10):103520, 2016.

[19] Masha Baryakhtar, Junwu Huang, and Robert Lasenby. Axion and hidden photon dark matter detection with multilayer optical haloscopes. *Phys. Rev.*, D98(3):035006, 2018.