Letter of Interest for Snowmass 2021

Million-pixel Kinetic Inductance Detector Arrays for sub-GeV Light Dark Matter Search

Jiansong Gao[1,2*], Mike R. Vissers[1], Johannes Hubmayr[1], Clarence L. Chang[3], Pete Barry[3], Yonit Hochberg[4], Sae Woo Nam[1,2] and Joel N. Ullom[1,2]

[1]National Institute of Standard and Technology, Boulder, CO 80303

[2]University of Colorado at Boulder, Boulder, CO 80309

[3]Argonne National Laboratory, Lemont, IL 60439

[4] Hebrew University of Jerusalem, Jerusalem 91904, Israel

Understanding of nature of dark matter is one of most interesting and important open questions in fundamental physics, which is also among the top priority science goals for the Department of Energy. Despite significant effort to directly detect dark matter, statistically significant detection events still elude researchers today. Over the past few decades, the major effort has been focused on the search for a dark matter candidate called Weakly Interacting Massive Particles (WIMPs). As the WIMP parameter space continues to be excluded by search experiments in the ~GeV range, there has been a surge of ideas and proposals to explore the important sub-GeV mass range for a variety of different types of particles. Exploiting advances in photonic quantum information and superconducting quantum computing technologies, we propose to develop new detector technology to explore sub-GeV dark matter based on inelastic electron scattering in superconducting target materials. Building on a pilot experiment using a superconducting nanowire single photon detector (SNSPD) with a threshold of 0.8 eV and 4.3 ng of WSi target mass to place meaningful bounds on dark photon absorption [1], we propose to develop **low-energy threshold (<0.1 eV), million-pixel kinetic inductance detectors (KIDs)[2] arrays.** Such detector arrays would provide substantial new reach for dark matter masses below 1 MeV and dark photon masses below 1 eV.

Of all the quantum detectors, thus far MKIDs have the best combination of sensitivity (energy resolution) and scalability into large arrays (due to its multiplexing nature), which is a perfect match to the dark matter search application. For example, the state-of-the-art photon counting MKID has achieved energy resolution of 0.2 eV at 1550nm wavelength [3]. Recently, a 7000-pixel MKID array fabricated on a 6-inch wafer for the ToLTEC camera [4] was successfully developed.

The proposed work will concentrate on three areas:

- **Reducing the energy threshold of MKIDs**

The best energy resolution achieved by the state-of-the-art photon counting MKIDs is a factor of ~10 from the fundamental Fano limit and therefore there is still large room to improve. Using superconductors with lower Tc (currently Tc~1K) will also dramatically increase the detector sensitivity. Proximitized TiN/Ti and AlMn are two promising materials which have demonstrated tunable Tc below 1K. The emerging broadband quantum-limited parametric amplifier technology such as the kinetic inductance traveling-wave (KIT) amplifiers [5] may greatly reduce the readout noise which is another major limit to the energy resolution.

- **Increasing the array size (target mass)**

Using either TiN/Ti or AlMn, it should be straightforward to fabricate million-pixel scale dark matter MKID arrays out of 6-inch wafers, because 6-inch fabrication processes of these two materials have already been developed for submm astronomical detector (MKIDs and TES) arrays. In addition, applying the recently developed “tile-and-trim” [6] and “post-measurement lithographical correction” [7] techniques will ensure these million-pixel 6-inch arrays to be high quality and high yield. As for the readout of such large-scale MKID arrays, we can take advantage of the special properties of the dark matter search application. On one hand, dark matter MKIDs are expected to have very high quality factors because there

*Email contact: Jiansong.gao@nist.gov

is no background events or radiation load. It should not be difficult to achieve a factor of 10 higher multiplexing density than currently achieved in other MKID applications. On the other hand, the rare-event nature of dark matter search enables a special readout strategy, such as the "bandwidth recycling" scheme in which multiple MKID resonators can share the same RF bandwidth, potentially reducing the readout cost by a factor of 10 or more. With these dark-matter-detection oriented "smart" design and readout strategies, it should be possible to drive down the readout resources and cost by a factor of 100, to <$1 per pixel. Reductions in the readout costs of cryogenic detector arrays will also benefit other DOE programs including CMB-S4 and several potential neutrino-science experiments.

- **Background event rejection**

A real event, from dark matter hitting a single detector, is expected to appear only in one detector, while a substrate event, from other particles hitting the Si substrate, is expected to show as correlated pulses in multiple detectors. This mechanism provides a reliable and easy to implement way to reject substrate events which are expected to dominate the background. In addition, effective background event screening/rejection techniques from other dark matter projects (e.g., ionization veto technique used in CDMS) may also be adapted for and implemented in MKIDs.

The predicted reach in dark mark mass space of the proposed MKID arrays as compared to other major projects is shown in Fig. 1. In summary, we envision that in a 3-5 year long program, a new detector technology tailored for light dark matter search based on million-pixel low-energy threshold MKID arrays can be developed from the today's state-of-the-art, which may provide significant new reach into the unexplored sub-GeV dark matter parameter space.

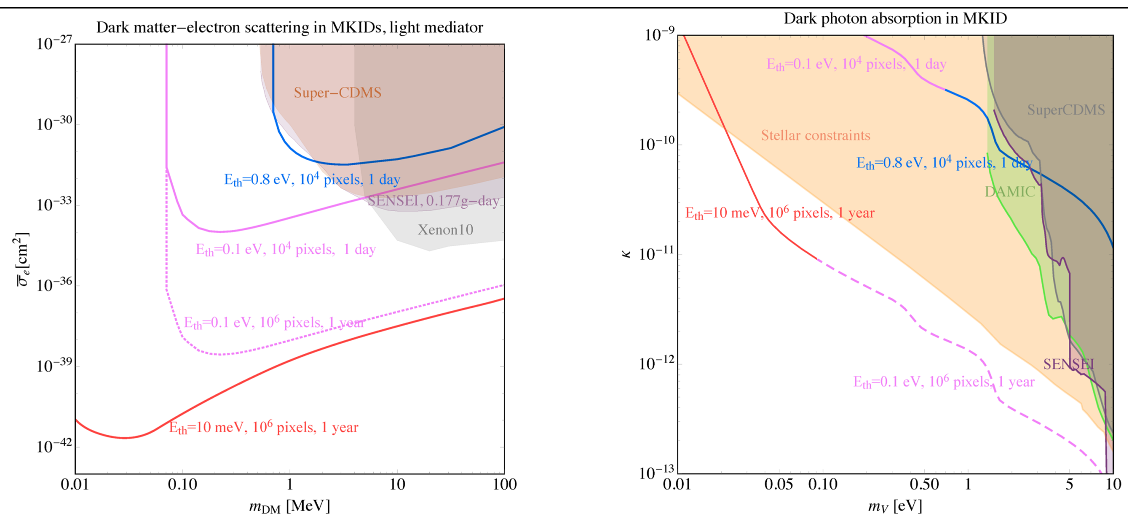

FIG. 1: Projected reach for DM-electron scattering via a light mediator (left) and for absorption of kinetically mixed relic dark photons (right) of a MKID array with different energy threshold, number of pixels and exposure time in comparison with other major dark matter search projects.

[1] P. Day, et al., Nature 425, 817 (2003)

[2] Y. Hochberg, et al., PRL 123, 151802 (2019)

[3] W. Guo, et al., Appl. Phys. Lett. 110, 212601 (2017)

[4] J. E. Austermann, et al., Low Temp Phys 193, 120–127 (2018)

[5] S. Chaudhuri, APL 110, 152601 (2017)

[6] C. M. McKenney, RSI 90, 023908 (2019)

[7] X. Liu, Appl. Phys. Lett. 111, 252601 (2017)

*Email contact: Jiansong.gao@nist.gov