Snowmass2021 - Letter of Interest

Superconducting Qubit Advantange for Dark Matter (SQuAD)

Thematic Areas:

- ■ (CF2) Dark Matter: Wavelike
- ■ (IF1) Quantum Sensors
- ■ (IF2) Photon Detectors

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Abstract:

This LOI describes two complementary strategies that utilize superconducting transmon qubits[1] to enable future dark matter searches. First, we discuss a novel photon counting technique[2] harnessing the quantum non demolition (QND) nature of the qubit-photon interaction[3–7] which allows us to subvert the quantum limit. We have demonstrated an unprecedented counting error rate equivalent to noise 15.7 dB[2] below the standard quantum limit. Second, we enhance the dark matter induced signal by initializing a microwave cavity in a large n-photon Fock state using the non-linearity of the qubit. This transfer of technology from the quantum information community opens up new frontiers for dark matter searches in the 3-30 GHz range. To further advance these techniques, it is necessary to investigate quasi particle rejection, background photon filtering, and high-Q cavity designs.

Introduction

Current searches for low mass bosonic dark matter (e.g. axion[8–15], hidden photon[16,17]) involve accumulating the induced electromagnetic signal in a resonant microwave cavity[18] and reading it out with a quantum limited linear amplifier[19–22]. This technique encounters steep challenges as the search for dark matter extends above the GHz region. The detector volume must be reduced to ensure the resonance condition is met, thereby drastically reducing the signal. Additionally, the quantum noise from linear amplification overwhelms the signal making the search untenable.

Photon counting

We develop a photon counting strategy in order to evade the quantum limit that linear amplification is subject to. We couple a superconducting qubit to the electromagnetic field of a microwave cavity that accumulates the dark matter induced signal (Fig. 1). The QND interaction between the qubit and signal allows us to make repeated measurement of a single photon[23–25], resulting in an exponential suppression of detector-based false positives. We reach unprecedented sensitivities, 15.7 dB better than a quantum limited linear amplifier, with the detector performance limited only by sources of background photons. This sets the detector noise to a background photon probability of 7.3×10^{-4} per measurement. As a demonstration of the capabilities of this technique, we use this detector to conduct a hidden photon search[2]. We constrain the kinetic mixing angle to $\epsilon \leq 1.82 \times 10^{-15}$ in a 3 kHz band around 6.011 GHz as shown in Fig. 1. The exclusion is obtained with an integration time of 8.33 s and a duty cycle of 65%.

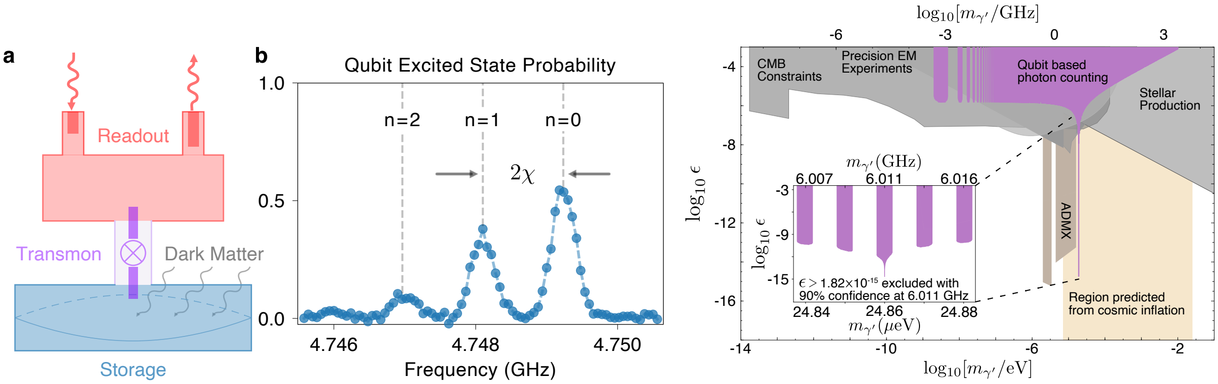

Figure 1: **Left.** Schematic of a transmon qubit coupled to a cavity that accumulates the dark matter signal (storage) and a cavity used to read out the qubit state (readout). The interaction between the qubit and cavity results in a photon number dependent shift of the qubit transition frequency. We harness this interaction to devise a QND counting protocol. **Right.** Hidden photon parameter space excluded by qubit based counting search is shown in purple. The maximum sensitivity occurs for candidates on resonance with the cavity. Additionally, the qubit search is sensitive to off resonant candidates in regions where the the photon number dependent qubit frequency shift is an odd multiple of 2χ. With the sensitivities already achieved, large swaths of parameter space can be excluded with a tuned narrow band search strategy.

Further suppression of background photons will increase the sensitivity of the detector. Cavity photon occupation can be mitigated by further reducing the operating temperature and ensuring better thermalization of the system. Additional attenuation and isolation of the microwave control lines could also reduce the cavity photon population[26,27]. Another source of backgrounds includes quasiparticles generated in the superconducing film of the qubit that result in athermal qubit excitations[28,29], which are then converted to cavity photons due to the qubit-cavity interactions. Mitigating quasiparticle production can be achieved via several methods; shielding against terrestrial and cosmic radiation sources[30], decoupling the qubit structure for the target substrate, engineering quasiparticle traps[31], increased infrared absorption, and use of higher $\mathrm{T_c}$ materials in the production of the circuits (e.g. Tantalum[32], Niobium, Titanium Nitride).

Increasing the measurement cadence and reducing the number of repeated measurements required to achieve the error probabilities needed for a dark matter search will involve reducing readout errors, mitigating qubit and readout spurious population, and increasing qubit coherence times. A parametric amplifier can be used as a part of the readout of the qubit state, improving readout fidelity as well as a reducing the number of probe photons needed to resolve the qubit state[33]. The wait time between measurements can be decreased by actively emptying the readout cavity with shaped pulses[34]. Further attenuation of readout cavity residual population will result in increased qubit coherence times (T_2) and qubit fabrication techniques (novel materials and designs) can improve qubit lifetimes (T_1).

Stimulated Emission

We propose two methods to enhance the diminishing signal rate at higher frequencies. Firstly, we use photonic bandgap cavities[35,36] made out of low-loss dielectric material to achieve Q's $> 10^8$, significantly higher than the Q $\sim 10^4$ with copper cavities currently used. Second, by initializing the cavity in a n-photon Fock state, we can stimulate the conversion of dark matter to cavity photons and achieve an enhancement factor of $n+1$ in the signal rate[37]. In the background free regime, we would initialize the cavity in the largest n possible to accumulate the dark matter signal as the SNR scales as $\sqrt{n+1}$.

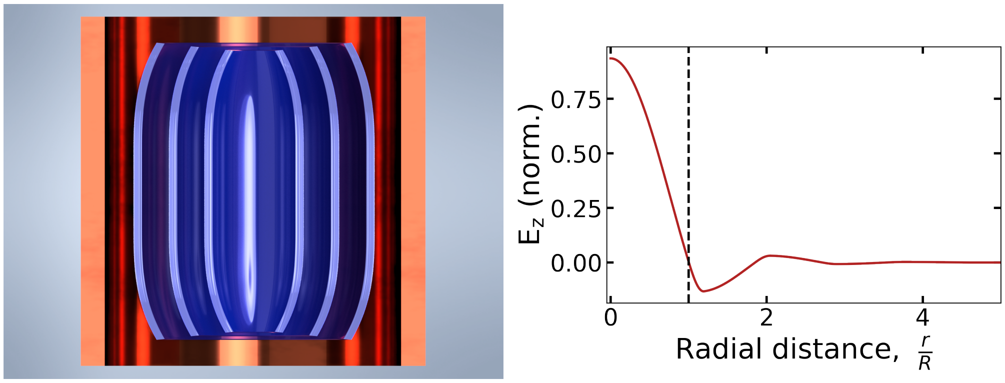

Figure 2: **Left.** Rendered image of a nested dielectric cylinder cavity surrounded by copper to minimize the radiation loss along the radial direction. The tapered structure along the axial direction prevents any loss to the radiation by smoothly varying the cut-off frequency. **Right.** Exponential attenuation of the electric field along the radial direction ensures low Ohmic losses on the metallic walls.

Using numerical simulation methods to generate quantum optimal control[38–40](QOC) pulses, we have successfully created Fock states up to n=10. The QND interaction allows us to detect the $|n+1\rangle$ state by repeatedly applying number resolved[41,42] qubit π pulses, which suppresses detector based false positives.

The largest n-Fock state we can prepare the cavity in is limited by the coherence time of the Fock state[43], which is set by T_1/n, where T_1 is the coherence time of the cavity. This necessitates the development of high Q cavities that can operate in a magnetic field for axion searches. Recent developments of novel cavities with type-II superconductors[44] or low loss sapphire[36,45] show the feasibility of Q up to 10^6 in X band. Further improvements by design optimizations (as shown in Fig: 2), by type-II superconducting coating, and by using high purity sapphire[46] could achieve a quality factor of 10^8 allowing us to initialize cavity Fock states up to $n = 100$. For hidden photons, SRF[47] cavities with Q$\sim 10^{10}$ will allow even higher Fock number.

Summary

In order to implement these two strategies in a full scale axion or hidden photon search further R&D must be undertaken to overcome the challenges outlined above. Additionally, an efficient photon transport mechanism must be developed to bridge the two techniques described in this LOI. One possible technology that could perform this function is a Josephson parametric converter[48] that can facilitate the swap of the signal photon from the high Q cavity in the magnetic field to the field free region where the qubit based photon counter resides. Plans for testing this developing technology in the presence of high magnetic field is already under way. To reach 30 GHz, we must fabricate and test qubits and nonlinear elements at frequencies above where they are conventionally fabricated ($\leq$ 15 GHz). This will involve new techniques and novel materials that must be studied.

By integrating superconducting qubit technology with dark matter searches, we pave the path toward a new generation of dark matter searches in the 3-30 GHz range targeting DFSZ sensitivity. Photon counting and stimulated emission are two complementary strategies that can be used to overcome the quantum noise and diminishing signal of a conventional dark matter search.

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