Qubit based Single-Photon Sensors for Dark Matter Searches

Rakshya Khatiwada, Fermilab.

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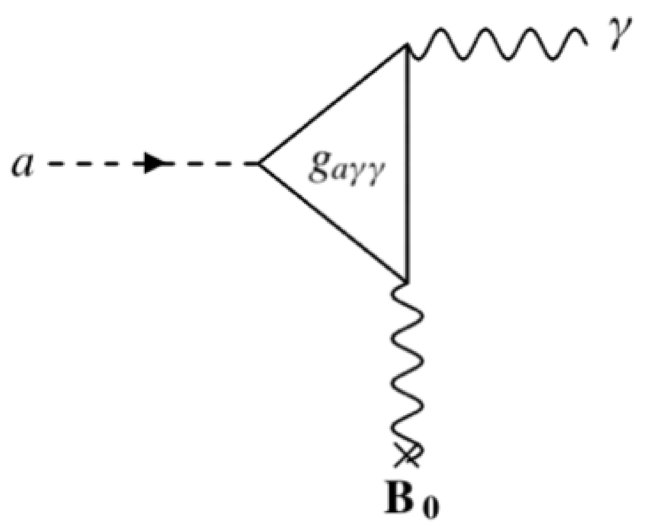
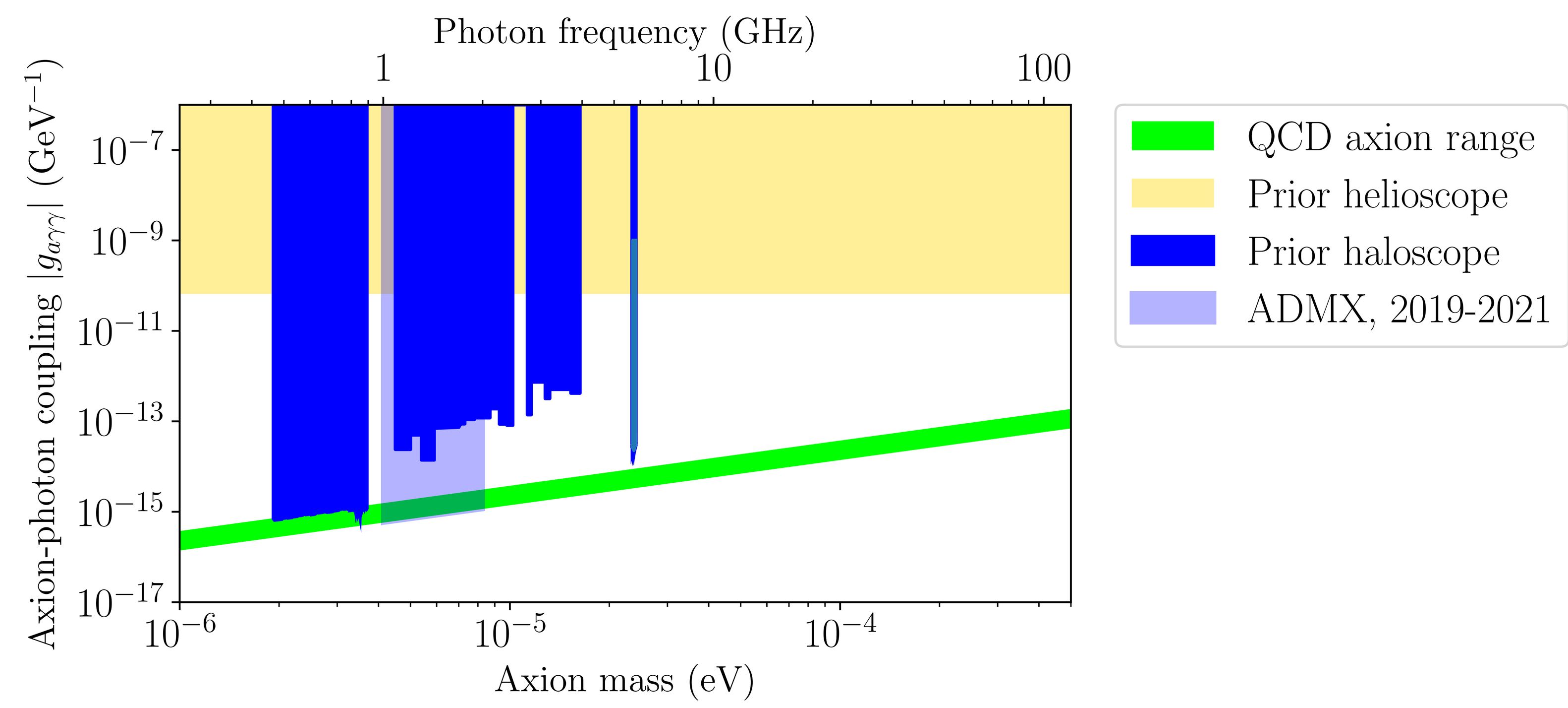
Project Synopsis: Quantum Bits for Dark Matter Detection

This experimental program will adapt low-noise qubit readout techniques for use in particle physics experiments. As an end goal, this research will deliver a technical demonstration of low-noise quantum sensors, as well as the results of a proof-of-principle axion search in a narrow but previously unexamined mass range. This program would form the basis for a technical design report outlining a next-generation axion dark matter search.



$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

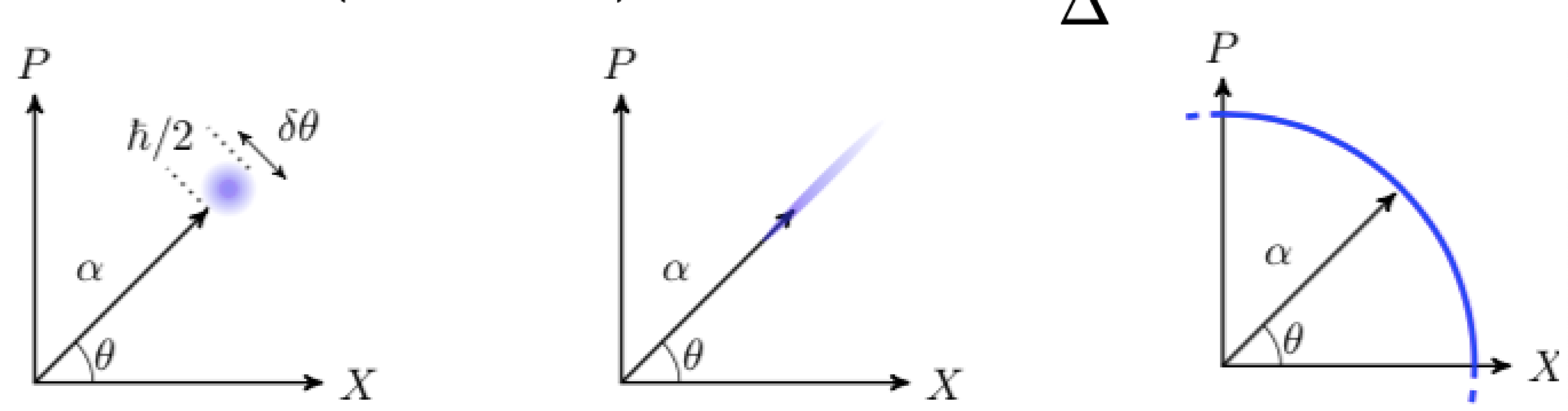
Axions convert to photons in the presence of a magnetic field, with coupling coefficient $g_{a\gamma\gamma}$.



Axion mass is only loosely constrained by theory. Scanning over three orders of magnitude in mass/frequency may be required. *New technologies are required to perform this search efficiently.*

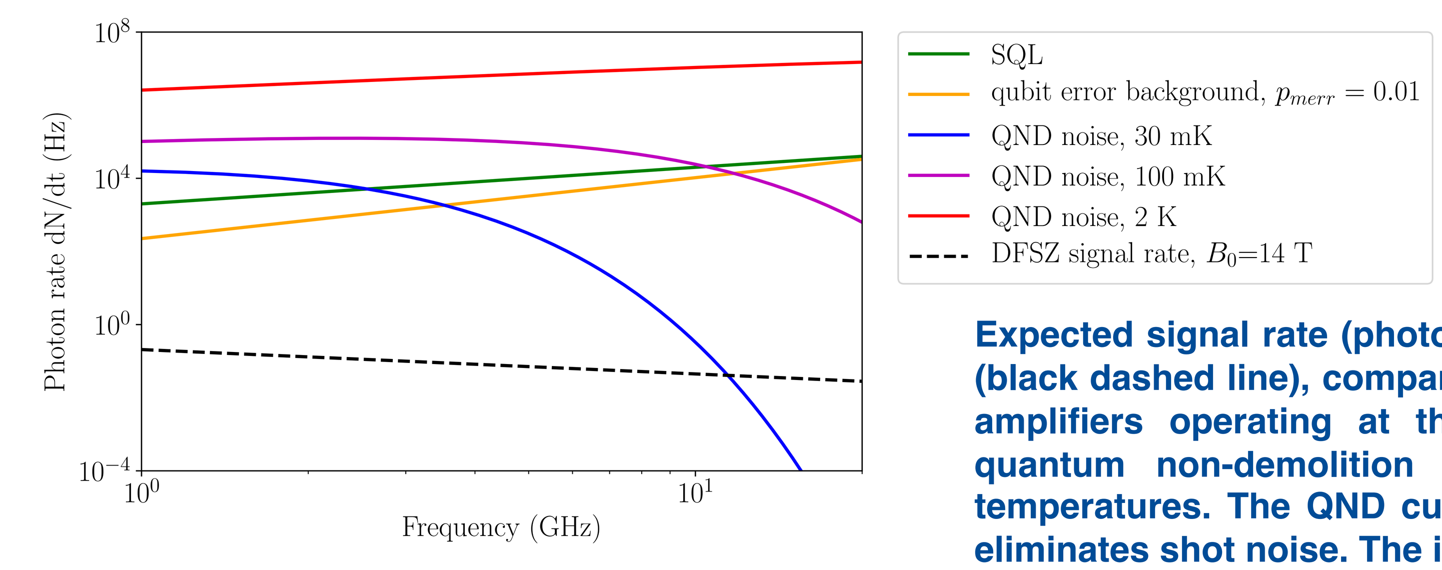
Quantum non-demolition (QND) techniques allow repeated measurement of Fock states, to arbitrary precision.

$$H = \hbar\omega_r\left(a^\dagger a + 1/2\right) + \hbar\omega_q\sigma_z/2 + \frac{\hbar g^2}{\Delta}(a^\dagger a + 1/2)\sigma_z$$



Even amplifiers operating at the quantum limit can be too noisy for efficient axion detection. Phase-preserving linear amplifiers simultaneously measure the occupation number and phase of a system, and these parameters have a nonzero commutator; they cannot be measured simultaneously to arbitrary precision. In a QND experiment, the phase of a photon state is randomized at every measurement so that amplitude (i.e. photon number) can be measured repeatedly and with high precision.

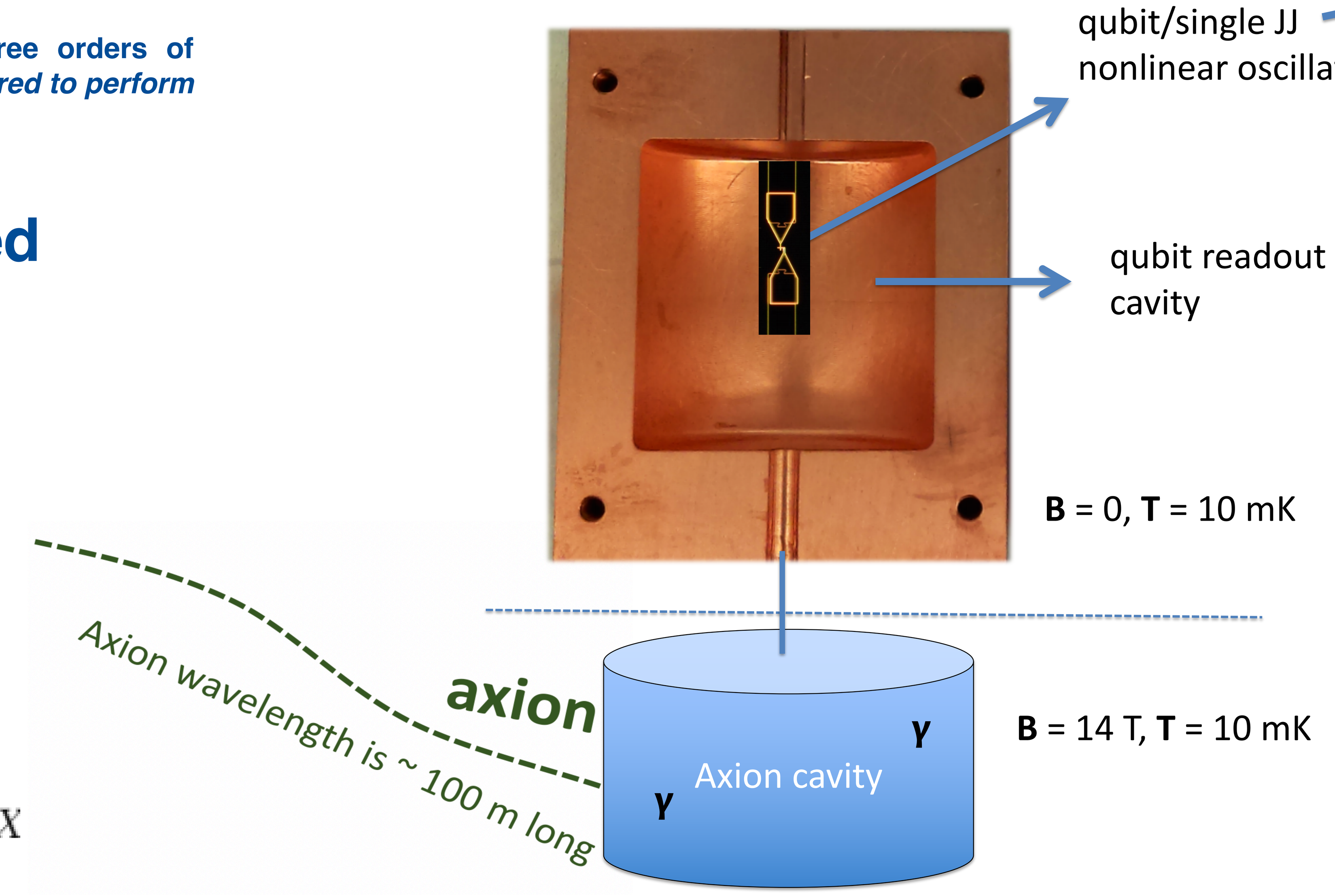
Quantum sensors enable low-noise photon sensitivity "beyond the standard quantum limit".

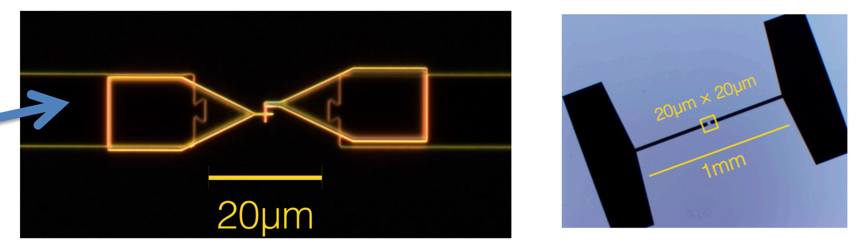


Expected signal rate (photons per second) for the DFSZ family of axion models (black dashed line), compared with noise/error rates for phase-preserving linear amplifiers operating at the standard quantum limit (SQL, green), and for quantum non-demolition (QND, blue/purple/red) measurements at various temperatures. The QND curves reflect thermal photon populations, since QND eliminates shot noise. The industry-typical qubit false-positive error rate of 1% is shown in yellow.

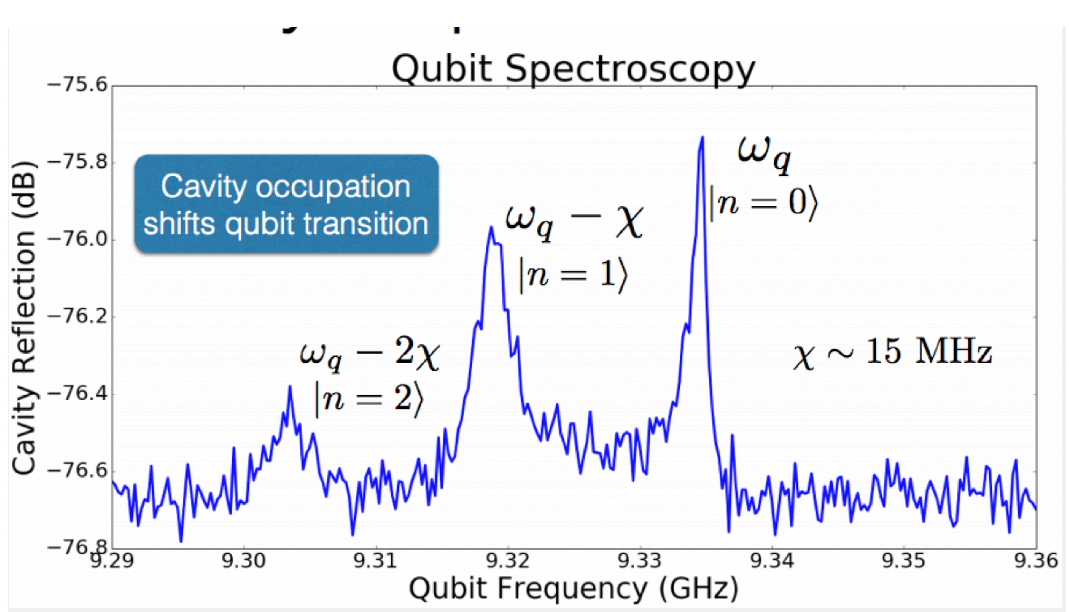
This measurement technique represents a novel application of quantum information technology to the field of particle physics. It has the potential to enhance axion search speeds by four orders of magnitude while enabling sensitivity to weak axion-photon coupling models.

Current Work





Collaborators at U. Chicago fabricate and characterize superconducting qubits (Schuster Lab). We use "transmon" superconducting qubits with aluminum /aluminum oxide Josephson junctions. The qubit capacitively couples to microwave cavity modes.



An AC Stark effect causes the cavity frequency to shift by (15 MHz) when a signal photon interacts with the qubit.

Background Suppression

false-positive rates for transmon qubits are ~ 1%. Several qubits, all measuring the same photon state, can reduce this rate. For N qubits: $p_{err} \rightarrow (0.01)^N$

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