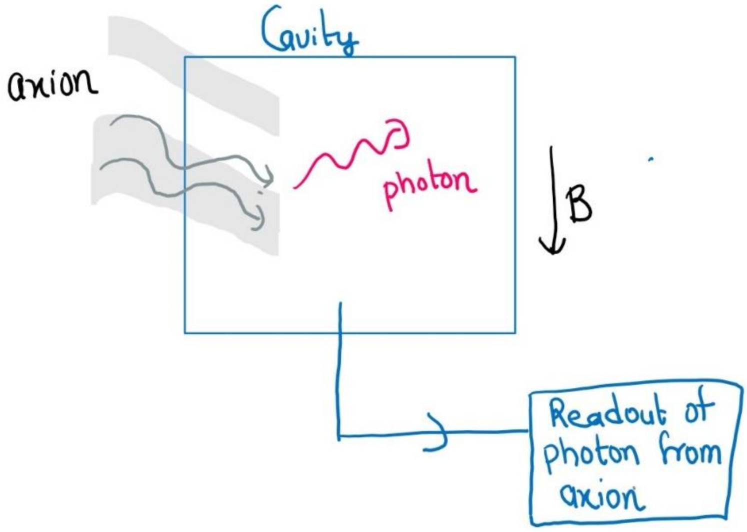
Overcoming the limits of the nature to disclose the biggest mystery of the universe

-Singh Shrestha Yaman

Dark matter is one of the biggest mysteries in the world of physics. Various cosmological observations show that nearly 80% of the matter in the universe is completely invisible to us. This unaccounted matter is believed to arise from dark matter which has almost zero interaction with normal matter that surrounds us. Since dark matter has extremely weak interaction with normal matter, the nature of dark matter is completely unknown to us. One of the candidates for dark matter is *axion*. Postulated by Roberto Peccei and Helen Quinn, axions have a very weak interaction with normal matter and can explain the unexplained mass of the universe. Despite the weak interaction, theoretical predictions show that in the presence of a strong magnetic field, axions can be converted to photons, whose frequency is determined by the axion mass. By trapping these photons inside a hollow metallic cavity (resonator) with the frequency corresponding to the axion mass, detection of axions should be possible. This detection signal from axions though, is extremely weak and is obscured by different noises, which make axion detection extremely difficult.

The biggest obstacle in the detection of axions is generating signals stronger than the background noises, in other words, attaining a strong Signal to Noise Ratio (SNR). Since the axion signals are expected to be extremely weak, suppressing noises to the minimum is of the utmost importance for the detection of axion signals. Noises in the signal depend largely on the detection mechanism employed for the measurement. In the paper titled *"Analysis of single-photon and linear amplifier detectors for microwave cavity dark matter axion searches"*, Lamoreaux, S. K., et al. compare the noises from two major axion detection techniques: a) linear amplifier detectors and b) single photon detectors. They also demonstrate how single photon detectors can surpass the more common linear amplifier detectors in terms of noise suppression and thus open up new possibilities in the field of axion detection.



The most common method for detection of axions is the linear amplifier technique. Since the photon signal generated from axion conversion in a cavity resonator is expected to be extremely weak *(0.3 photons per second at 5 GHz for ADMX-HF),* a linear amplifier is used to amplify the axion signals before they can be readout and analysed. The major source of noise in such a detector is the random photons generated due to thermal noises. These thermal noises can be suppressed by reducing the temperature, but at lower temperatures, linear amplifiers are again limited by the quantum fluctuations in the vacuum. This quantum fluctuation noise is the result of the *Heisenberg's uncertainty principle,* which puts a fundamental limit on the accuracy of the measurement of the overall state of any system. Since the entire signal (i.e., both the amplitude, and the phase) is readout in the linear amplifier detectors, the resulting measurement cannot escape the inherent noises from the quantum fluctuations of the system. Furthermore, along with the inherent quantum noises of the resonator system, additional quantum noise is added by the linear amplifier too. Thus, the quantum fluctuations from the resonator and the amplifier place a constraint called the Standard Quantum Limit (SQL) on the sensitivity of linear amplifier detectors. As a result, even at low temperatures, the noise level cannot be reduced beyond the Standard Quantum

Limit (equal to 1 photon per measurement), which makes generating a high Signal to Noise Ratio extremely time-consuming.

This Standard Quantum Limit on axion detection can be avoided by using a single photon detector which involves the counting of axion-generated photons in the cavity resonator. Single photon detector, unlike the linear amplifier detector, only measures the amplitude of the signal (which corresponds to the number of axion-generated photons) without measuring the signal phase. Since only one of the two quantities that define the overall system is measured, quantum fluctuations resulting from the Heisenberg's uncertainty principle do not affect the single photon detectors. As a result, single photon detectors are not constrained by the Standard Quantum Limit like the linear amplifier detectors. Without the Standard Quantum Limit, single photon detectors are only constrained by the thermal noise which can be reduced by decreasing the temperature of the system. This makes single photon detectors far more sensitive to axions than linear amplifier detectors at low temperatures. At the temperature of 10mK (close to -273 ^{0}C, which can be achieved using devices such as Dilution Refrigerator), the noise in single photon detectors is expected to be 17,000 times lower than linear amplifier detectors. As a result, using single photon detectors, a high Signal to Noise Ratio can be generated within much shorter measurement time.

Currently, we have very limited knowledge about axions and their parameters. Therefore, a huge frequency space must be scanned to detect axions. The development of single photon detectors can greatly accelerate our search for axions. In recent years, single photon detectors have been experimentally realized using superconducting qubits (the fundamental component of quantum computers). Thus, employing superconducting qubits as single photon detectors, a more rapid search of axions should be possible in the yet unscanned frequency regime near 10GHz.

This current development in axion search has paved a way for us to not only overcome the natural constraint on measurement set up by the *Heisenberg's uncertainty principle,* but also hopefully reveal the hidden mystery of dark matter. A deeper understanding of dark matter can help us understand not just the composition of our universe but also its origin and its evolution to its present form. Furthermore, a direct detection of dark matter would fill several gaps in our current model of physics and help us to paint a more complete picture of our universe. Thus, accelerating our search of dark matter is extremely important and using single photon detectors can help us achieve this goal.

Reference:

Lamoreaux, S. K., et al. “Analysis of Single-Photon and Linear Amplifier Detectors for Microwave Cavity Dark Matter Axion Searches.” *Physical Review D*, vol. 88, no. 3, 2013, https://doi.org/10.1103/physrevd.88.035020.