Single Microwave Photon Detection with Superconducting Qubits for Fundamental Physics

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The detection of individual microwave photons is one of the most formidable challenges in quantum sensing, as their energy lies four to five orders of magnitude below that of optical photons, making conventional detector technologies insufficient for registering individual quantum events. The circuit quantum electrodynamics (cQED) platform has emerged as the leading framework to overcome this barrier. Superconducting transmon qubits, offering long coherence times and photolithographic flexibility, enable microwave photon detection through two complementary strategies. In the first, based on cQED and waveguide quantum electrodynamics principles, an incoming itinerant photon conditionally flips the qubit state via a Quantum Non-Demolition (QND) interaction, and subsequent dispersive readout reveals the photon occupation number. In the second, the qubit couples directly to the dark matter field and its presence drives slow Rabi oscillations in the qubit, which are monitored to set limits on the kinetic mixing parameter.

This technology is being actively advanced through coordinated research programmes within the INFN. The SIMP project first established the INFN's capabilities in single microwave photon detection, and then the Qub-IT and QUART&T projects built on this foundation with the goal of developing advanced quantum architectures targeting enhanced efficiency and suppressed dark-count rates, with direct applications to light dark matter searches. At the largest scale, GravNet, funded as an ERC Synergy Grant, proposes a global network of microwave cavity sensors exploiting the inverse Gertsenshtein effect to search for gravitational waves in the MHz-to-GHz band, for which qubit-based single photon detectors represent a key readout technology. Together, these initiatives illustrate how superconducting qubit-based microwave photon detection is becoming a cornerstone of quantum-enhanced searches in particle astrophysics and beyond.

In this contribution, we review the working principles of single microwave photon detectors based on superconducting qubits, discuss the state of the art within the INFN projects and future possible applications.