# Abstract

In this work, I present experimental studies of cavity quantum electrodynamics (cQED) with a focus on superradiant emission from a hybrid system of nitrogen-vacancy (NV) centers in diamond strongly coupled to a microwave cavity. The research centers on two key experiments that investigate superradiance, a collective phenomenon where synchronized emitters generate a coherent burst of radiation with nonlinear intensity scaling, facilitated by their common coupling to the cavity mode.

First, I demonstrate a protocol for generating and storing a uniformly inverted spin ensemble, enabling the controlled release of a superradiant burst. By extending the inversion storage time for up to tens of milliseconds, I achieve a fully upright, metastable spin state with vanishing transverse spin components. I explore the onset of superradiance, revealing that weak microwave trigger pulses on the order of $10^{-11}$ photons per spin are sufficient to influence the superradiant decay in both timing and phase.

Second, following the initial decay, I observe unexpected self-induced superradiant dynamics that evolve from a periodic pulsing regime into quasi-continuous masing, lasting up to a millisecond. This behavior, which cannot be explained by known cQED effects, is driven by direct spin-spin interactions that redistribute the spectral spin inversion within the inhomogeneously broadened NV ensemble. These findings reveal a new role for spin-spin interactions as an active drive of superradiant emission, rather than merely a source of decoherence.

The experimental results are prefaced by a theoretical framework and numerical simulations. Additionally, I present microwave cavity designs aimed at achieving strong and uniform spin coupling with reduced mode volumes. These designs, realized through finite-element simulations and experiments, explore a range of resonator types — from bulk copper and superconducting niobium to on-chip, nano-fabricated structures — paving the way for future cQED experiments and quantum technology applications.