# PHD PROJECT DESCRIPTION

## (4000 characters max., including the aims and work plan to de published online)

**Project title:** Quantum trajectories for collective emission from few solid-state emitters: superradiance, photon correlations, and engineered multiphoton output

## 1.1. Project goals

The main goal of this project is to develop a theoretical description of collective emission (such as superradiance and subradiance) in systems of a few quantum emitters, going beyond standard Markovian models. In particular, the project will investigate how emission processes are influenced by correlations in time carried by the electromagnetic field and how these correlations lead to memory effects in the system dynamics.

In the commonly used GKSL (Lindblad) approach, the environment is assumed to have no memory, and the system evolution is described by a time-local equation. However, in realistic situations—especially for few emitters interacting with non-classical light—the emitted photons can carry information that affects future evolution. This leads to non-Markovian dynamics, where the system "remembers" its past through the field. The project aims to describe such effects using methods that go beyond standard master equations, including approaches related to memory kernels and hierarchical equations of motion (HEOM).

A central objective is to use quantum trajectory methods to describe the dynamics at the level of individual emission events, while at the same time retaining the structure of correlations between different temporal modes of the field. This approach makes it possible to study how sequences of photon emissions are correlated in time and how these correlations give rise to collective effects such as enhanced or suppressed emission.

The project will focus in particular on systems with realistic multilevel structure (such as three-level emitters relevant to NV centers), where additional processes like shelving and non-radiative transitions introduce further time correlations and memory effects. The goal is to understand how these mechanisms modify collective emission and how they manifest in experimentally observable quantities such as photon correlation functions.

Finally, the project aims to explore how these memory effects and temporal correlations can be controlled and engineered, for example by tuning system parameters or the properties of the environment. This could enable the design of emission processes with tailored statistical properties and provide new insight into the role of correlations and memory in quantum optical systems.

## 1.2. Outline

The project will address collective emission in few-emitter quantum systems by going beyond standard Markovian descriptions and incorporating memory effects and temporal correlations using quantum trajectory methods. It will:

- analyse the limitations of standard GKSL (Markovian) approaches and identify regimes where memory effects become relevant
- develop theoretical descriptions incorporating temporal correlations, memory effects, and connections to non-Markovian dynamics and HEOM
- formulate and apply quantum trajectory methods to describe collective emission at the level of stochastic photon detection events
- extend models to few-emitter systems with multilevel structure, including three-level (NV-like) emitters and non-radiative processes
- analyse photon-counting statistics and reconstruct experimentally observable quantities such as $g(2)(\tau)$
- interpret experimental signatures of collective emission in terms of underlying dynamical mechanisms
- design strategies for controlling and engineering collective emission in realistic quantum systems

Applications include the development of tailored quantum light sources, improved understanding of cooperative effects in solid-state emitters, and potential contributions to quantum technologies such as sensing, communication, and random number generation.

## 1.3. Work plan

**Year 1:**
Introduction to open quantum systems and the GKSL formalism; learning quantum trajectory methods; reproduction of basic results for single- and few-emitter systems; development of numerical simulation tools.

**Year 2:**
Extension to few-emitter systems with multilevel structure; modelling of three-level (NV-like) emitters including pumping and non-radiative processes; formulation of corresponding quantum trajectory descriptions.

**Year 3:**
Study of temporal correlations and non-Markovian dynamics; analysis of correlations between time modes of the field; development of models incorporating memory effects (memory kernels, connections to HEOM).

**Year 4:**
Trajectory-level analysis of collective emission and connection to experimentally observable quantities; consolidation of results; preparation of scientific publications; thesis preparation.

## 1.4. Literature (max. 7 listed as a suggestion for a PhD candidate preliminary study)

1. H.-P. Breuer and F. Petruccione, *The Theory of Open Quantum Systems*, Oxford University Press (2002).

2. M. Ghosh Dastidar, A. Desikan, G. Sarbicki, and V. P. Bhallamudi, "Signatures of superradiance in intensity correlation measurements in a two-emitter solid-state system," arXiv:2408.01799 (2024)

3. A. Dąbrowska and G. Sarbicki,
"Quantum trajectories and output field properties for two-photon input field,"
*Journal of Physics A: Mathematical and Theoretical* 58, 015302 (2025)

4. M. Valipour, G. Sarbicki, K. Słowik, and A. Dąbrowska,
"Optimization of two-photon absorption for a three-level atom,"
*Physical Review A* 111, 033709 (2025)

5. H. J. Carmichael,
*An Open Systems Approach to Quantum Optics*, Springer (1993).

6. J. Dalibard, Y. Castin, and K. Mølmer,
"Wave-function approach to dissipative processes in quantum optics,"
*Physical Review Letters* 68, 580–583 (1992).

7. R. H. Dicke,
"Coherence in spontaneous radiation processes,"
*Physical Review* 93, 99–110 (1954).

## 1.5. Required initial knowledge and skills of the PhD candidate

- Master's degree in physics, mathematics, or a related field
- Basics of quantum mechanics and linear algebra
- Introductory knowledge of quantum optics and open quantum systems
- Some familiarity with probability theory and stochastic processes
- Programming skills (e.g., Python, MATLAB, or similar)
- Interest in theoretical and computational research
- Ability to read scientific literature in English and work independently

## 1.6. Expected development of the PhD candidate's knowledge and skills

The candidate will gain expertise in:

- open quantum systems and the GKSL formalism
- quantum trajectory methods and stochastic quantum dynamics
- collective emission phenomena (superradiance and subradiance)
- non-Markovian dynamics, memory effects, and temporal correlations
- modelling of multilevel quantum systems (e.g. NV-center-like emitters)
- numerical simulation of quantum systems and scientific programming
- analysis of photon statistics and correlation functions
- scientific writing, presentation, and research communication