1. PHD PROJECT DESCRIPTION (4000 characters max., including the aims and work plan)

Project title: Characterizing quantum dynamical maps beyond Markovian regime

- **Project goals**

- **Characterize physically legitimate time-local master equation**
- **Characterize admissible time non-local memory kernel master equations**
- **Provide comparative analysis of time-local generators vs. non-local memory kernels**
- **Provide spectral analysis of time-local generators and quantum dynamical maps**
- **Provide new tools to characterize memory effects in open quantum systems dynamics**
- **Find the connection between Markovianity and classicality of the quantum process**

1.1. Outline:

Open quantum systems are of paramount importance in the study of the interaction between a quantum system and its environment that leads to important physical processes like dissipation, decay, and decoherence. Very often to describe the evolution of a `small' system neglecting degrees of freedom of the environment one applies very successful Markovian approximation leading to the celebrated quantum Markovian semigroup. This approximation usually assumes a weak coupling between the system and environment and separation of system and environment time scales. A typical example is a quantum optical system where Markovian approximation is often legitimate due to the weak coupling between a system (atom) and the environment (electromagnetic eld). Quantum Markovian semigroups were fully characterized in 1976 by Gorini, Kossakowski and Sudarshan and independently by Lindblad. Current laboratory techniques and technological progress call, however, for more refined approach taking into account non-Markovian memory efects. A mathematical representation of the evolution of open quantum system is provided by a quantum dynamical map - a family of quantum channels parameterized by time. Nowadays dynamical maps define one of the basic ingredient of modern quantum theory. Being quantum channels they define at the same time one of the most fundamental object of quantum information theory. It is therefore clear, that the proposed research project belongs to the very fruitful intersection of quantum theory, open quantum systems and quantum information theory. The proper mathematical language to deal with these kind of problems is a theory of operator algebras and completely positive maps. Completely positive maps in operator algebras were invented by Stinespring in 1955 and found elegant application in physics already in the 60. with seminal papers of Kraus and collaborators. Finally, in the 90. of the last century they proved to be the key concept of quantum information theory. The aim of the project is to incorporate the above mathematical tools to study open quantum systems beyond the standard Markovian regime.

1.2. Work plan

- **Formulating general conditions for legitimate master equations**: Analyze time-local master equations and Nakajima-Zwanzig memory kernels giving rise to physically admissible quantum dynamics.

- **Performing spectral analysis of dynamical maps and time-local generators:** Study spectra of quantum maps. Special attention is devoted to the analysis of so called exceptional points which define spectral singularities of non-Hermitian operators that exhibit a strong spectral response to perturbations. Explore potential applications in quantum metrology.

- **Developing new unraveling tools for non-Markovian memory kernel master equations:** study Feshbach projection methods in connection to open quantum systems

- **Studying non-Markovianity and non-classicality of open-system evolutions:** Define non-classicality via violation of Kolmogorov consistency conditions. Study violation of the Leggett-Garg inequalities (temporal analogues of Bell inequalities).

1.3. **Literature** *(max. 10 listed, as a suggestion for a PhD candidate)*

- H.-P. Breuer and F. Petruccione, The Theory of Open Quantum Systems, OUP, Oxford, 2007

- A. Rivas and S. Huelga, Open Quantum Systems. An Introduction, Springer, Heidelberg, 2011.

- A. Rivas, S. F. Huelga, and M. B. Plenio, Quantum Non-Markovianity: Characterization, Quantification and Detection, Rep. Prog. Phys. **77**, 094001 (2014).

- H.-P. Breuer, E.-M. Laine, J. Piilo, and B. Vacchini, Colloquium: Non-Markovian dynamics in open quantum systems, Rev. Mod. Phys. **88**, 021002 (2016).

- L. Li, M. J.W. Hall, and H. M. Wiseman, Concepts of quantum non-Markovianity: a hierarchy, Phys. Rep. **759**, 1 (2018).

- D. Chruściński, Dynamical maps beyond Markovian regime, Phys. Rep. **992**, 1-85 (2022)

- D. Chruściński, A. Rivas, and E. Størmer, Divisibility and Information Flow Notions of Quantum Markovianity for Noninvertible Dynamical Maps, Phys. Rev. Lett. **121**, 080407 (2018).

- D. Chruściński, A. Kossakowski, Sufficient conditions for a memory-kernel master equation, Phys. Rev. A **94** (2016) 020103(R).

- D. Chruściński, G. Kimura, A. Kossakowski, and Y. Shishido, On the universal constraints for relaxation rates for quantum dynamical semigroup, Phys. Rev. Lett. **127**, 050401 (2021)

- D. Chruściński and S. Maniscalco, Degree of Non-Markovianity of Quantum Evolution, Phys. Rev. Lett. **112**, 1204 (2014).

1.4. Required initial knowledge and skills of the PhD candidate

o basic experience in the following fields: open quantum systems, quantum information, entanglement theory, operator algebras,

o numerical skills in Mathematica and/or Matlab (advantageous),

o motivation to conduct research and to turn challenges to opportunities,

o independence in doing research and strong interest in the topic (quantum dynamical maps, quantum information, entanglement theory, operator algebras),

o developed written and verbal communication skills (English required, Polish not required),

o willingness to work in a research team

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

- Develops mathematical skills in the field of operator algebras, functional analysis and stochastic processes.
- Gains new knowledge on the evolution of open quantum systems beyond Markovian approximation.
- Develops new skills and techniques to deal with non-Markovian quantum stochastic processes.