Project title: Open quantum systems beyond Markovian semigroup

1.1. Project goals:

- To provide detailed comparative analysis for time local generators and time non-local memory kernels which give rise to legitimate quantum evolution.
- Analysis of spectral properties of super-operators
- To find new indicators of quantum non-Markovianity for general quantum evolution and characterize non-Markovian quantum dynamical maps using tools from quantum information theory (like e.g. well known entropic quantities).

1.2. Outline

A real quantum system is never perfectly isolated and since it always interacts with the external world (environment). A typical example is an atom which interacts with electromagnetic field even if the field is in its vacuum state. Hence, if we are interested in the evolution of the system alone the standard Schroedinger does no longer provide a proper description of the quantum evolution. For example unitary evolution governed by the Schroedinger equation does not allow a pure state to evolve into a mixed state. It is, therefore, clear that one is forced to go beyond closed (isolated) systems and use already well developed theory of *open quantum systems*. 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 `big' 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 (the system's degrees of freedom are `slow' and that of the environment are `fast'). 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 field). Quantum Markovian semigroups were fully characterized in 1976 by Gorini, Kossakowski and Sudarshan and independently by Lindblad (GKSL).

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, that is, completely positive and trace-preserving (CPTP) maps, they define at the same time one of the most fundamental object of quantum information theory. A dynamical map maps operators in the system's Hilbert space to itself. A Markovian semigroup is defined in terms of the following dynamical map exp(tL), where `L' stands for the corresponding GKSL generator.

Going beyond Markovian semigroup one is faced with a problem of *quantum non-Markovianity*. The are two basic approaches to define the evolution of the system beyond Markovian semigroup: one is based on time-local master equation with time-dependent generator L(t) The other is based on non-local memory kernel master equation governed by time dependent kernel K(t). In this PhD project we will analyze both approaches to find appropriate conditions for L(t) and K(t) which guarantee that the corresponding mathematical solution is physically legitimate, i.e. completely positive and trace-preserving. It is also interesting to link mathematical properties of L(t) and K(t) to physical properties of the quantum system and appropriate characteristics of memory effects in quantum evolution.

1.3. Work plan

- Student learns basic tools from open quantum systems, quantum information, and operator algebras,
- provides comparative analysis for time local generators and time non-local memory kernels,
- applies quantum information tools to analysis of quantum non-Markovian dynamical maps,
- analyzes quantum evolutions governed by non-local mamory kernel master equation.

1.4. Literature

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- A. Rivas, S. F. Huelga, and M. B. Plenio, Rep. Prog. Phys. **77**, 094001 (2014).
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- L. Li, M. J.W. Hall, and H. M. Wiseman, Phys. Rep. **759**, 1 (2018).
- D. Chruściński, A. Kossakowski and A. Rivas, Phys. Rev. A **83**, 052128 (2011).
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- S. Chakraborty, D. Chruściński, Phys. Rev. A. **99** (2019), 042105
- D. Chruściński, C. Machiavello, S. Maniscalco, Phys. Rev. Lett. **118** (2017), 080404

1.5. Required initial knowledge and skills of the PhD candidate

- Basic knowledge of algebraic and analytical methods in quantum physics (operator algebras, functional analysis),
- Eager to learn
- Basic knowledge of quantum information theory
- Basic knowledge of open quantum systems
- Eager to work hard

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

  - Better understanding of mathematical methods used in quantum information and open quantum systems

- Understanding of quantum decoherence and dissipation

- Fluency in modeling open quantum system evolution

1.7.