

SURF@IFISC 2026 Proposals

1. Measurement-Induced Transport in Photonic Phase Space

Advisor: Luisa Toledo Tude

Quantum transport in lattice systems is a central topic in modern quantum physics due to its relevance for quantum algorithms, quantum simulation, and the control of information flow in quantum devices. In contrast to classical dynamics, quantum transport can exploit genuinely quantum features such as superposition, interference, and entanglement, enabling the exploration of a richer state space. A paradigmatic example is the quantum walk, which has been extensively studied as the quantum analogue of the classical random walk. Unlike classical random walks, which exhibit diffusive spreading, quantum walks can display ballistic transport, leading to faster spreading and enhanced performance in algorithmic and simulation tasks.

In this project, we will study a measurement-driven transport protocol in a photonic system that exhibits a quantum-walk-like behavior. The setup consists of photons confined in a microcavity, where two operations are applied sequentially: a fixed displacement in phase space and a photon parity measurement. Repeating these operations drives the system into a stochastic evolution, with the dynamics conditioned on the outcomes of the parity measurements. The student will investigate transport properties in this system using numerical simulations (in python) and analytical methods. The project will focus on how the measurement strength controls the crossover from quantum to classical behavior and its impact on transport.

2. Comparing computational invariance across constrained reservoir substrates

Advisor: Miguel C. Soriano

The project will investigate how structural and dynamical constraints shape computational performance across different reservoir substrates, including biologically inspired networks and abstract recurrent systems. By systematically varying network topology, sign structure, and weight distributions, the student will characterize invariance properties of memory capacity and kernel richness across nonlinear dynamical regimes. The aim is to identify general dynamical principles underlying robust computation, bridging biological neural networks and reservoir computing theory, with relevance for machine learning and physical reservoir implementations.

3. A simple model of active reproducing matter

Advisors: Emilio Hernandez-Garcia

Active matter consists of individual units—such as cells, bacteria, synthetic particles, or even animal groups—that continuously consume energy to move or exert forces. This persistent activity gives rise to striking behaviors, including spontaneous flows, swarming, and flocking, which have become central topics in modern statistical physics. One aspect that remains relatively unexplored is how replication or reproduction influences the dynamics of such systems. This proposal aims to generalize what is probably the simplest stochastic model of reproducing and motile individuals [1] by incorporating an active component into their motion. Comparing this extended model with more complex frameworks that also include particle interactions [2] will help clarify the interplay between active motion, growth, and interactions in nonequilibrium multiparticle systems.

[1] Young, W., Roberts, A. & Stuhne, G. Reproductive pair correlations and the clustering of organisms. *Nature* 412, 328–331 (2001). <https://doi.org/10.1038/35085561>

[2] Takamura, S. & Saito, N. Spatially structured flocking in a proliferating population of self-propelled organisms without explicit alignment interactions. *Physical Review Research* 7, 033299 (2025). <https://doi.org/10.1103/v3gm-vhry>

4. Quantum synchronization and associative memories in a system of coupled quantum van der Pol oscillators

Advisor: Albert Cabot

A quantum van der Pol oscillator (QvdP) is a quantum system consisting of a single bosonic mode subject to driving and nonlinear dissipation [1]. It can be implemented in a variety of physical platforms (e.g. trapped ions, superconducting circuits, or optomechanical oscillators), by engineering the dynamics of a motional degree of freedom or a cavity mode. The QvdP provides a paradigmatic setting for extending synchronization into the quantum regime. This has enabled researchers to address fundamental questions such as how quantum fluctuations affect synchronization, how to identify synchronization in a quantum system, and even how to generalize a phenomenon so deeply rooted in classical phase-space trajectories to a regime where such trajectories are generally not available. Recently, QvdP-like systems have also been proposed as candidates for implementing quantum associative memories, in which metastable states of a quantum system are used to store and retrieve multiple patterns [2].

In this project, the student will first study the dynamics of two coupled QvdP oscillators subject to a two-photon [3] drive and characterize the synchronization diagram under different types of coupling (coherent vs. dissipative). This characterization will initially be carried out at the mean-field level; later, the full quantum dynamics will be explored by analyzing the system's master equation, with particular attention to quantum effects on synchronization and on how to detect these effects. Subsequently, the student will either investigate the capabilities of such a system as an associative memory or examine the dynamics of more complex arrays of QvdP oscillators.

The student will learn about the following topics:

- How to model a quantum system subject to Markovian dissipation.
- How to simulate the dynamics of a quantum system using a computer (e.g., writing Python code).
- How to derive mean-field nonlinear equations from quantum equations of motion.
- How to analyze nonlinear dynamical systems.
- Current research topics such as quantum synchronization, quantum associative memories, and how platforms like trapped ions can be used to engineer interesting quantum dynamics.

[1] T. E Lee, H. R. Sadeghpour, *Phys. Rev. Lett.* 111, 234101 (2013) [arXiv: <https://arxiv.org/abs/1306.6359>]; S. Walter, A. Nunnenkamp, C. Bruder *Phys. Rev. Lett.* 112, 094102 (2014) [arXiv: <https://arxiv.org/abs/1307.7044>]

[2] A. Labay-Mora, R. Zambrini, G. L. Giorgi, *Phys. Rev. Lett.* 130, 190602 (2023) [arXiv: <https://arxiv.org/abs/2205.09491>]

[3] A. Cabot, G. L. Giorgi, R. Zambrini, *New J. Phys.* 23, 103017 (2021) [arXiv: <https://arxiv.org/abs/2109.01438>]

5. Quantum reservoir computing in multiphoton Jaynes-Cummings systems

Advisors: Sreetama Das and Roberta Zambrini

Quantum reservoir computing (QRC) [1] is a recently proposed quantum machine learning approach. It harnesses the natural dynamics of quantum systems to process complex time-series data—ranging from weather and financial markets to signals in quantum devices.

A promising platform for QRC is provided by the Jaynes-Cummings (JC) model, which describes the interaction between a two-level atom (or spin) and a single quantized electromagnetic mode (a “bosonic mode”). Even though the standard JC model involves a simple single-photon exchange between the atom and the mode, it can already generate non-classical, non-Gaussian states that are highly valuable for quantum computation and information processing.

In this project, we aim to push beyond the standard JC model and explore multiphoton Jaynes-Cummings interactions, in which multiple photons can be exchanged simultaneously between the atom and one or more bosonic modes. These interactions are largely unexplored in the context of QRC, and they offer exciting opportunities:

1. Enhanced computational power: Multiphoton interactions could increase the dynamical complexity and memory capacity of the quantum reservoir, potentially improving its predictive performance compared to a standard JC reservoir [2].
2. Experimental relevance: Such interactions naturally emerge in the ultrastrong coupling regime—where the atom-boson interaction is comparable to the atomic or bosonic energies—and can be engineered efficiently in superconducting qubit systems.
3. Scalable architectures: By extending the interaction to two or more bosonic modes [3], we can expand the reservoir’s Hilbert space, opening the door to richer quantum dynamics and enhanced QRC capabilities.

This project will combine theoretical modeling with numerical simulations to explore how multiphoton JC systems can serve as powerful quantum reservoirs. The outcomes could have broad implications for quantum information processing, complex time-series prediction, and the design of next-generation quantum computing architectures.

References:

- [1] K Fujii and K Nakajima, *Phys. Rev. Applied* 8, 024030 (2017).
- [2] S. Das, G. L. Giorgi, and R. Zambrini, [arXiv:2510.00171](https://arxiv.org/abs/2510.00171).
- [3] P. Laha, P. A. Ameen Yasir, and P. Van Loock, *Phys. Rev. Research* 6, 033302 (2024)

6. Modeling Opinion Polarization: From Binary Choices to Continuous Spectra

Advisor: Antonio Fernández Peralta

Opinion models provide a simple mathematical framework to study how individual opinions evolve through social influence, interaction, and exposure to information. Each person is represented as an “agent” with an internal state: its opinion. Agents update their state according to prescribed rules, typically shaped by an underlying network of interactions.

Prototypical models are often grouped into two broad categories. In continuous models, an opinion is represented by a real value along a spectrum, for example from extreme left to extreme right. In discrete models, opinions take values from a finite set. The simplest case is a binary choice, such as left vs right.

A key collective phenomenon captured by these models is polarization. Opinions do not converge to consensus and may instead segregate into distinct groups. Introducing bias can enable or amplify polarization. Bias can enter the dynamics through information perception, interaction patterns, or the update mechanism. The resulting opinion clusters are often shaped by the network’s community structure.

We propose to explore the relationship between continuous and discrete opinion models. We will identify conditions under which they are equivalent, meaning they produce the same macroscopic behavior. We will then compare how different forms of bias operate across both approaches. In particular, we will clarify when they lead to similar polarization outcomes and when they generate different patterns of opinion segregation.