# Quantum Physics Out of Equilibrium

**Resp. UE**: Marco Schiro’ (CNRS, JEIP Collège de France)

**Teachers**: Marco Schiro’ (CNRS, JEIP Collège de France)

**ECTS credits**: 3

**Language of instruction**: English

**Examination**: oral exam + homework

**Description**:

Recent years have seen enormous experimental progress in preparing, controlling and probing quantum systems in various regimes far from thermal equilibrium. Examples include systems as ultra-cold atomic quantum gases under time-dependent perturbations, driven non-linear cavity QED systems or strongly correlated electrons in solid-state materials under ultra-fast optical excitations.

These developments have brought fresh new interest around a set of fundamental questions concerning quantum systems and their dynamical behaviour, at the interface between quantum statistical physics, condensed matter, atomic physics and quantum optics.

The aim of this course is to introduce the students to the main concepts and motivations behind this active field of research. Only basic knowledge of quantum many-body physics will be needed (as provided by the compulsory courses of the 3 “parcours” (Condensed Matter Physics, Theoretical Physics, Quantum Physics). Lectures will be complemented by tutorials where concrete examples/problems will be discussed in detail with the students, through analytical and possibly numerical calculations.

Plan of the course (20h+ tutorials)

**1. Introduction to Quantum Nonequilibrium (2h)**

- Fundamentals on Equilibrium Quantum systems. Linear Response and Fluctuation-Dissipation Theorem. Different kinds of non-equilibrium: a first classification. Theoretical Challenges and Experimental Motivations. Overview of physical systems: from laser-excited solids to ultra-cold atoms and Cavity/Circuit QED systems.

**2. Thermalisation and its breakdown in Closed Quantum Many Body Systems (6h+ tutorial)**

- Experimental motivations: quantum dynamics of ultra-cold atoms. The simplest non-equilibrium protocol: a quantum quench. General properties of quantum dynamics, dephasing and diagonal ensemble. The paradox of quantum thermalisation. The role of interactions. Pre-thermalisation and Dynamical Transitions.

- Can quantum thermalisation break-down? Many-Body Anderson Localisation: basic properties, localised integrals of motions, effective model for the MBL phase. Experimental observation and open questions. Other mechanisms for quantum ergodicity breaking.

**3. Periodically Driven Closed Quantum Systems (4h+ tutorial)**

- Experimental motivations: Light control of quantum matter, from cold atoms to pumped electrons. Linear-response to a periodic drive and its breakdown. Energy absorption from the drive. Floquet Theorem for Periodic Quantum Dynamics. Floquet Hamiltonian and High-Frequency Expansions.

- Thermalisation to infinite temperature and Floquet Heating. Quantum Synchronisation and Period Doubling. Time-Crystals and their experimental observation.

**4. Open Markovian Quantum Many Body Systems (4h+ tutorial)**

- Experimental motivation: Cavity/Circuit QED systems, Losses and Heating in Cold Atoms; Quantum Measurements. Lindblad Master Equation. Stochastic Unravelling and Non-Hermitian Hamiltonian. Spectral Properties of Lindblad Super-operators. Vectorization and Thermofields. Diagonalisation of simple Lindbladians. Green's functions for Markovian systems.

- Dissipative Phase Transitions. Measurement-induced Phase Transitions.

**5. Selected Advanced Topics (4h + tutorial)**

- Keldysh Field Theory for closed and open quantum systems. Connection with MSRJD Field Theory for classical systems. Applications and Examples.