# Nonequilibrium quantum condensates: from microscopic theory to macroscopic phenomenology

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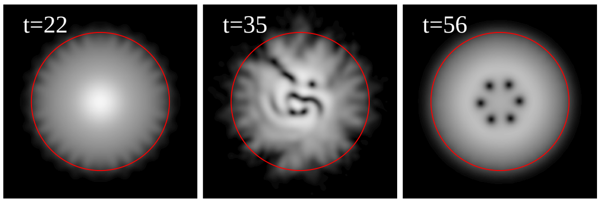
Microcavity polariton condensates provide an opportunity to explore a novel regime of nonequilibrium quantum systems, which both differ from the equilibrium Bose-Einstein condensate and also differ from any previous studied laser. In this talk, I will review our approach to microscopic modelling of an out-of-equilibrium polariton condensate [1, 2], discussing the distinction between those properties of quantum condensates that can be derived from mean-field (i.e Gross-Pitaevskii approaches), and those which involve correlations not described in mean-field theory.

Our microscopic theory starts from a model of disorder-localised excitons, coupled to propagating photon modes in a microcavity, where interactions between excitons are caricatured as exclusion [3]. This model is then driven out of equilibrium by coupling to baths that describe pumping and decay. We study the steady state behaviour of this non-equilibrium model by constructing the Keldysh path integral, and finding the saddle point (i.e. self-consistent steady state), and fluctuations around this state.

The Keldysh approach provides a natural formalism from which can be derived many of the other approximations used for non-equilibrium polariton systems, such as the Boltzmann equation and quantum kinetics; density matrix evolution, Dyson equations for the Keldysh Green's functions, and mean-field theory, i.e. Gross-Pitaevskii equations including pumping and decay. As such it provides a way to understand how these various methods relate to one another. The mean-field equation provides a clear way to understand how the steady state condition interpolates between that of an equilibrium condensate and that of a laser. By considering correlation functions for a finite two-dimensional non-equilibrium system one can gain further insights into the range of behaviour between the single mode laser, a polariton condensate and an equilibrium 2D weakly-interacting Bose gas.

To describe macroscopic phenomena such as the large scale spatial structure of the condensate, details of the microscopic theory become less important. This can be seen by noting that, in appropriate limits, the mean-field equation derived from the microscopic model can be written as a complex Gross-Pitaevskii equation, the form of which is strongly constrained by general symmetry considerations. Such an equation allows one to investigate how pumping and decay influence the spatial profile of the condensate. One dramatic consequence is that for harmonic trapping and uniform pumping, the Thomas-Fermi condensate profile can become unstable and is replaced by a non-stationary spontaneously rotating vortex lattice solution [4].




*Spontaneous vortex lattice formation from the competition of pumping and trapping.*

## References

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