Nonequilibrium Field Theory of Open Quantum Fluids

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The stochastic Gross–Pitaevskii equation (SGPE) is commonly described as a finite-temperature correction to mean-field Bose gas dynamics. This characterisation understates its scope. The SGPE is a controlled nonequilibrium field theory for driven, dissipative, and fluctuating Bose fluids, derived systematically from reservoir theory and valid across the condensation transition.

I present the complete first-principles structure of the theory. Number damping and energy damping arise from distinct reservoir interactions and generate a stochastic partial differential equation with explicit fluctuation–dissipation structure. A third process, evaporative damping, follows directly from the underlying master equation. Together these mechanisms provide a unified dynamical framework for vortex nucleation, defect proliferation through the phase transition, and relaxation toward equilibrium.

A central result is that energy damping is not a secondary correction but the dominant dissipation channel for condensate excitations. I will discuss quantitative agreement with finite-temperature vortex dynamics experiments, resolution of the vortex mutual friction problem, the role of energy damping as a coherent relaxation pathway, and applications to the formation and decay of persistent currents.

The SGPE should therefore be understood not as a numerical convenience, but as an effective nonequilibrium field theory of open quantum fluids, capable of predictive simulations of Bose–Einstein condensate experiments and analytical insights in reduced-dimensional systems.