
ABSTRACT

This thesis examines the microscopic foundations of relativistic hydrodynamics in far-from-equilibrium systems, focusing on the quark–gluon plasma created in ultrarelativistic heavy-ion collisions. Experiments show that the quark–gluon plasma exhibits strong collective flow and behaves as an almost perfect fluid despite large initial anisotropies and rapid expansion, raising the question of why hydrodynamics applies when local equilibrium is not yet established.

Using the relativistic Boltzmann equation in the relaxation-time approximation, the thesis develops exact solutions for boost-invariant systems, analyses hydrodynamic attractors, and identifies the role of non-hydrodynamic modes in driving universal behaviour. A complete gradient expansion is constructed, its asymptotic character is demonstrated, and an operator-based decomposition is introduced to separate hydrodynamic and transient sectors. This leads to time-dependent, renormalised transport coefficients that encode far-from-equilibrium dynamics.

A central insight is the distinction between the Chapman–Enskog gradient expansion and fully relativistic causal hydrodynamics. The gradient expansion captures only long-wavelength perturbative contributions and is intrinsically acausal, whereas causal theories such as Israel–Stewart hydrodynamics promote dissipative quantities to independent dynamical fields with finite relaxation times. This promotion incorporates the fast transient modes already present in the Boltzmann equation, producing a consistent, stable, and causal macroscopic evolution. Hydrodynamics, therefore, emerges as a resummed effective theory that includes both long-lived collective behaviour and transient microscopic dynamics