The cornerstone of the Standard Model of elementary particles is Yang-Mills theory: the theory of spin 1 particles somewhat similar to the photon, but endowed with very specific self interactions. These self interactions are crucial throughout the Standard Model, but they are especially spectacular in the case of gluons, which are responsible for the strong nuclear force which, in particular, confines quarks within nucleons.

While a lot is known about the Standard Model in situations when interactions can be assumed to be weak, much is still unknown about the behaviour of fundamental constituents of matter in situations where interactions are strong. This includes many features of the phase diagram of nuclear matter which captures answers to questions such as what happens to it at high temperatures and/or high densities. Such questions are very interesting from the perspective of studies of the early Universe or the physics of neutron stars. One thing however is known for certain: when nuclear matter is heated to temperatures of above 200MeV, it turns into a state of matter called the Quark-Gluon Plasma (QGP).

The goal of this project is to find an effective description of the dynamics of QGP, which here on Earth is produced in experiments where heavy nuclei collide in accelerators such as the Relativistic Heavy Ion Collider (RHIC) at Brookhaven, or in the ALICE experiment at the LHC at CERN. In the aftermath of a nuclear collision typically tens of thousands of particles are registered. Already Fermi and Landau in the 1940s and 1950s had guessed that a statistical approach in terms of relativistic hydrodynamics should apply. Almost 20 years ago these expectations were decisively confirmed. It was not obvious that they would be, since we expect that at sufficiently high collision energies we should see a gas of weakly interacting quarks and gluons: this expectation follows from asymptotic freedom, which is one of the basic features of the strong nuclear force. However both at RHIC and the LHC we clearly observe collective effects characteristic of fluids, not gases: the distributions of detected particles carry information about the collision geometry (this is the so called "elliptic flow"). The fluid is called quark-gluon plasma, even though it is far from clear whether one can in a useful way regard it as a collection of individual quarks and gluons rather than a quantum state which does not possess such a particle description. It is also significant that the flow of quark-gluon plasma is dissipative: it is associated with entropy increase. This effect is due to viscosity of the fluid. It turns out that the viscosity of quark-gluon plasma is small relative to its entropy density, and for this reason one sometimes speaks of "the most perfect fluid in nature". It is also worth noting that in the ALICE experiment the temperature of quark-gluon plasma exceeds 5 trillion degrees.

The fundamental theory of the strong interactions – Quantum Chromodynamics – is a part of the Standard Model. Because of the strong interactions between quarks and gluons on nuclear scales this theory is difficult theory to solve, and we do not have the mathematical tools necessary to effectively use it to describe quark-gluon plasma in a quantitative way. Fortunately, even nonequilibrium states show certain universal properties. These properties, which follow from very general conservation principles, are captured by the theory of relativistic fluid dynamics. The emergence of this kind of description has been the focus of intense research in recent years, primarily because of its applications to the physics of quark-gluon plasma. It is however an extremely important task to understand when this hydrodynamic description is valid and derive its parameters from the underlying microscopic theory, even in some approximate way. One surprising fact which has emerged is that some physical quantities behave in a universal way even when the system is far from local equilibrium. This behaviour is due to the rapid expansion of QGP right after the collision and goes by the name of a far-from-equilibrium attractor. In this research project we will formulate and explore models which provide a tractable theoretical laboratory where the emergence of the hydrodynamic behaviour, and in particular attractor behaviour, can be studied. We plan to explore ways in which traces of the initial state can survive and leave experimentally accessible consequences.