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Heavy ion collisions and cosmology

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Abstract

There are interesting parallels between the physics of heavy ion collisions and cosmology. Both systems are out-of-equilibrium and relativistic fluid dynamics plays an important role for their theoretical description. From a comparison one can draw interesting conclusions for both sides. For heavy ion physics it could be rewarding to attempt a theoretical description of fluid perturbations similar to cosmological perturbation theory. In the context of late time cosmology, it could be interesting to study dissipative properties such as shear and bulk viscosity and corresponding relaxation times in more detail. Knowledge and experience from heavy ion physics could help to constrain the microscopic properties of dark matter from observational knowledge of the cosmological fluid properties.

Keywords: Relativistic fluid dynamics, Cosmological perturbation theory, Dissipation, Backreaction

1. The analogy

The analogy between ultra-relativistic heavy ion collisions and cosmology has often been emphasized. What distinguishes the physics there from typical situations in condensed matter physics is the aspect of history or dynamical evolution. Experimentally, one cannot probe a static quark gluon plasma with external probes as it is possible for solid state systems. All information must be reconstructed from the final state, which contains essentially the decay products of the quark-gluon plasma. In cosmology, this is very similar. The cosmic microwave background allows to see back in time until photon decoupling but information about earlier times is not directly available. Similarly, one can observe the large scale structure today and, by looking at more distant galaxies, in the recent past, but large parts of the history of structure formation are not accessible.

On first sight there are big differences: cosmological and nuclear scales differ by many orders of magnitude, late time cosmology is dominated by gravity, QED and the still rather poorly understood physics of dark matter and dark energy, while heavy ion collisions are governed by QCD. Another difference is that only a single event can be studied in cosmology, in contrast to very many heavy ion collisions. However, from a more abstract viewpoint, there are many interesting parallels. In the theoretical description, a particularly nice one is that many aspects of the dynamics can be described in both cases by relativistic fluid dynamics.

While the fluid produced in high energy nuclear collisions consists initially of a quark-gluon plasma which then expands and cools down and eventually undergoes a transition to hadronic degrees of freedom, the cosmological fluid has many more different stages. Very shortly after the big bang, there is also one

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epoch where it was dominated by quarks and gluons but this will actually not be in the focus of this talk. The first reason is that, unfortunately, only little information is transmitted to later times from this era, the other is that the biggest theoretical problems in current cosmology research actually arise from the latter epoch of structure formation. As I will argue, there are interesting parallels between heavy ion collision physics and late time cosmology although on a slightly more abstract level.

Before going deeper into the comparison, it is instructive to compare briefly the symmetries in both cases. They are actually of statistical nature: Concrete realizations break them but the statistical properties are symmetric. In cosmology the statistics arises from comparing different regions of space while in heavy ion collisions the statistical properties are for ensembles of events. Now, for the universe, the cosmological principle implies a three-dimensional translation and rotation symmetry whereas central heavy ion collisions have only a one-dimensional rotation symmetry and an approximate one-dimensional Bjorken boost invariance in the central rapidity region. Only the very central region in the transverse plane has also an approximate two-dimensional translation invariance.

From these considerations follow practical consequences: For the treatment of inhomogeneities or perturbations around an homogeneous and isotropic universe, it is very useful to work with three-dimensional Fourier transforms. Perturbations can be classified according to their transformation behavior with respect to rotations (into scalar, vector and tensor excitations) and translations (by a three dimensional wave vector). For heavy ion collisions, a Bessel-Fourier transform has similar advantages [1, 2] although not as far going as for cosmology because of less degree of symmetry in total.

2. The problem of initial conditions

A problem shared by both cosmology and heavy ion physics is the one of initial conditions. Due to obvious reasons it is not possible to directly access the initial conditions for a fluid dynamic description in cosmology, say very shortly after the big bang, or for heavy ion collisions shortly after the collision.[1] Despite this principle problem, cosmology has evolved over the last decades into a precision science - a success that heavy ion physics would certainly like to follow. It is instructive to compare the treatment of initial conditions in both cases.

The main source of information in cosmology are perturbations. They can be classified according to their transformation properties with respect to rotations and translations into scalar, vector and tensor modes with different wave vectors. Vector modes and some scalar modes are decaying and need not be specified further. Tensor modes correspond to gravitational waves and can be neglected for many considerations. The most prominent role is played by growing scalar modes. For the relevant range of wavelengths it turns out that their statistical properties are close to Gaussian with an almost scale invariant initial spectrum,

$$\langle \delta(\mathbf{k})\, \delta(\mathbf{k}') \rangle = P(k)\, \delta^{(3)}(\mathbf{k} + \mathbf{k}'),$$

with $P(k) = c\, k^{n_s - 1}$. In this way, initial conditions for very many modes are actually specified by two numbers: the spectral index n_s and the overall amplitude c. These are finally determined from observations. It is this simplicity or universality of initial conditions that allows to learn so much from the observed temperature spectrum of the cosmic microwave background and the large scale structure.

In contrast, in heavy ion collisions, the current state of the art are explicit realizations of initial conditions in terms of various Monte-Carlo models. These have typically many parameters and the resulting initial conditions, say for the energy density, usually have features at many different length scales. The question arises, whether the success of cosmology in characterizing initial conditions could be repeated here. This would imply to characterize statistical properties instead of explicit realizations and to focusing on the relevant modes in the relevant range of wavelengths. First steps in this direction have been made [2, 3, 4, 5, 6] but more progress seems possible.

[1] One may argue that the situation is better for heavy ions because the wavefunction of nuclei that determines the initial state can be probed by other experiments such as proton-ion or electron-ion collisions.