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# Equilibration and hydrodynamics at strong and weak coupling

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## Abstract

We give an updated overview of both weak and strong coupling methods to describe the approach to a plasma described by viscous hydrodynamics, a process now called hydrodynamisation. At weak coupling the very first moments after a heavy ion collision is described by the colour-glass condensate framework, but quickly thereafter the mean free path is long enough for kinetic theory to become applicable. Recent simulations indicate thermalization in a time $t \sim 40(\eta/s)^{4/3}/T$ [1], with $T$ the temperature at that time and $\eta/s$ the shear viscosity divided by the entropy density. At (infinitely) strong coupling it is possible to mimic heavy ion collisions by using holography, which leads to a dual description of colliding gravitational shock waves. The plasma formed hydrodynamises within a time of $0.41/T$. A recent extension found corrections to this result for finite values of the coupling, when $\eta/s$ is bigger than the canonical value of $1/4\pi$, which leads to $t \sim (0.41 + 1.6(\eta/s - 1/4\pi))/T$ [2]. Future improvements include the inclusion of the effects of the running coupling constant in QCD.

*Keywords:* hydrodynamisation, holography

## 1. Introduction

The creation of a strongly coupled plasma at relativistic nucleus-nucleus collisions is one of the most striking discoveries at RHIC and LHC. One of the hallmarks resulting from this program is the understanding that this plasma is described by viscous relativistic hydrodynamics very quickly, within 1 fm/c. This is surprising since the gradients at that time result in a small longitudinal pressure, even with the small viscosity present. This process of going to a regime described by hydrodynamics is now called hydrodynamisation and depending on the gradients present this can take much shorter than the process of equilibration.

It is profoundly challenging to describe the entire process from collision to hydrodynamics fully within QCD itself. This is partly because at high energy scales a perturbative treatment can be appropriate, while at energy scales of the temperature of the plasma formed a strong coupling picture should be used.

A perturbative treatment is not straightforward, since at higher energies the gluon concentration in nuclei increases. After the collision it is hence natural to expect an overoccupied state of gluons, which act coherently in a state called colour-glass condensate (CGC). At weak coupling the CGC undergoes classical expansion, up to the point where the mean-free path is long enough to allow for a description using kinetic theory. At strong coupling there are currently no theoretical tools to do such a description within QCD itself, although within holography it is possible to try and mimic QCD as close as possible [3].

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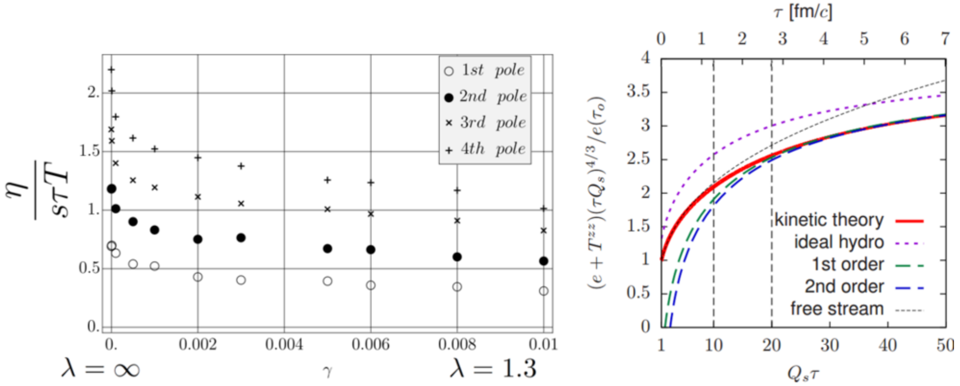

Fig. 1. Left we show relaxation times $\tau$ as a function of the 't Hooft coupling $\lambda$ for a partially resummed supersymmetric Yang-Mills theory, in units of the temperature $T$ and the viscosity over entropy ratio $\eta/s$ (from [11], see also [12]). Even though the $\eta/s$ ranges from 0.08 to 1.05 in the range plotted, the ratio is remarkably constant. Right we show the relaxation of the energy density for a particular evolution using gluonic kinetic theory (from [13]), for $\lambda = 10$ (i.e. $\eta/s \approx 0.6$ [14]). It can be seen that the system is well described by (viscous) hydrodynamics within approximately 2 fm/c.

This talk will review both weak and strong coupling approaches from a far-from-equilibrium initial stage to a plasma described by relativistic hydrodynamics. This includes both the timescale of the process, as well as the evolution of the flow and energy density during the process.

## 2. Hydrodynamisation at weak and strong coupling

At weak coupling the first stage of a heavy ion collision is described by classical Yang-Mills [4, 5]. After a short time the mean free path of the gluons becomes long enough that evolution using kinetic theory becomes feasible. For pure Yang-Mills this was first achieved in [6], where it was found that for 't Hooft coupling $\lambda = 10$ a typical state hydrodynamises within a time of $\tau \sim 10/Q_s$, with $Q_s$ the saturation scale. In terms of the temperature at hydrodynamisation and the shear viscosity this translates into $\tau \sim 40(\eta/s)^{4/3}/T$ [1]. More recently, this has been extended to also include dynamics in the transverse plane [7], which is useful since among else it can shed light on the early time dynamics of radial flow. At early times this pre-flow in the transverse plane grows linearly with time and for any approximately boost-invariant conformal theory is given by [8]

$$v_\perp = -\frac{\tau}{2}\frac{\nabla_\perp e}{e+P_\perp}, \tag{1}$$

where $e$ is the energy density profile, and $P_\perp$ the transverse pressure. For accurate initial hydrodynamic conditions the relevant question is then what the (average) transverse pressure is during the far-from-equilibrium evolution. For strong coupling the transverse pressure starts out high, at $P_\perp = e$, but decreases fast, giving an average effective pressure of approximately $P_\perp \approx e/2$ [9, 10]. In [7] it is instead found that at weak coupling the transverse pressure starts at $e/2$ and does not change much at early times. In the end both weak and strong coupling approaches hence give rise to very similar transverse flow.

For hydrodynamisation at strong coupling there have been studies in a homogeneous [15, 16] and boost-invariant setting [17, 18], finding a far-from-equilibrium regime almost immediately followed by a near-equilibrium regime described by quasi-normal modes. These systems were always well described by hydrodynamics within a time of $1/T$, with $T$ the temperature at that time of hydrodynamisation, which is non-trivial for the varying energy density in the boost-invariant case.

Recently, there have been elaborate studies studying similar dynamics in theories of higher derivative gravity [12, 11] (see also [19]). These are especially interesting for heavy ion collision, as these higher derivative terms can correspond to inverse coupling constant corrections on the field theory side, and can