Towards understanding hybrid strong/weak thermalisation of the QGP

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Outline

- Motivation
- Semiholography in heavy ion collisions
- Kinetic theory/hydrodynamics
- Some results
Motivation

**Challenge**: To develop a consistent framework which combines weak and strong degrees of freedom

To understand the evolution of Quark-Gluon Plasma (QGP), need weak and strong degrees of freedom interacting at various energy scales

How does this interplay affect thermalization?
Competing descriptions:

- pQCD – good for hard momentum scales
- Gauge/gravity duality – good for fluid description

\[ \frac{\eta}{s} = \frac{1}{4\pi} \]
Semiholographic models

Original proposal by Iancu and Mukhopadhyay\textsuperscript{1}
Refined by Mukhopadhyay, Rebhan, Preis, Stricker\textsuperscript{2}

Dynamical boundary theory coupled to a strongly coupled conformal sector with a gravity dual

**UV theory:** captured by classical YM theory for overoccupied gluon modes at $Q_s$

**IR theory:** described by N=4 Super Yang-Mills theory for effective theory of strongly coupled soft gluon modes

\textsuperscript{1}JHEP06(2015)003
\textsuperscript{2}JHEP05(2016)141
Semiholography at late times

- At late times, gluons are not in an overoccupied state
  → Classical YM description of glasma fails
  → Use kinetic theory instead
- Soft radiation seems to undergo hydrodynamization
The model

Nearly free streaming limit:

- Hard partons (UV) described by kinetic theory
- Soft radiation (IR) described via hydrodynamics (approximation due to fluid/gravity correspondence)
Coupling

The two theories know about each other through the metric deformation

\[ g_{\mu\nu} = \eta_{\mu\nu} + \frac{\gamma}{Q_s^4} t_{\mu\nu} \sqrt{-g} \]

Both sectors have a respective conservation law

\[ \nabla_\mu t^{\mu}_{\nu} = 0 \]  \[ \nabla_\mu t^\mu_{\nu} = 0 \]
Equations

Kinetic sector (UV)

\[ t^\mu_\nu = \int \frac{d^3 p}{\sqrt{-gp^0}} p^\mu p_\nu f(x^\mu, p_j) \]

\[ \left[ p^\mu \partial_\mu + \Gamma^\mu_{\nu\rho} p^\nu p_\mu \right] f(x^\mu, p_j) = C(f, f) \]

Hydrodynamic sector (IR)

\[ t^\mu_\nu = (\epsilon + \mathcal{P}) u^\mu u_\nu + \mathcal{P} \delta^\mu_\nu - \eta \sigma^\mu_\nu \]

\[ \nabla_\mu t^\mu_\nu = 0 \]
Total energy-momentum tensor

Can construct a stress tensor of full system:

\[ T_{\mu \nu} = t^\mu_{\nu} \sqrt{-g} + t^\mu_{\nu} \sqrt{-g} - \frac{\gamma}{Q_s^4} t^\alpha_{\beta} \sqrt{-g} t^\beta_{\alpha} \sqrt{-g} \delta^\mu_{\nu} \]

This is conserved in the flat background!

\[ \partial_\mu T^\mu_{\nu} = 0 \]
Linear response

The linear response of both the UV and IR theories is known.

Linear response for the complete theory?

We find that the shear viscosity is additive

$$\eta = \eta(1 + \gamma \frac{\varepsilon}{2}) + \eta(1 + \gamma \frac{\varepsilon}{2})$$
Bi-hydro

- Look at the effective change of the hydrodynamic degrees of freedom in both sectors
- Study eigenmodes of the complete system
- Find the total system has a hydro mode, which is just the sum of the eigenmodes of the two sectors
Shear viscosity

\[ \frac{T \text{Im} \omega}{k^2} \]

- **Numerical solution**
- **Analytic solution for** \( k^2/T^2 \ll \gamma T^4 \)
- **Analytic solution for** \( k^2/T^2 \gg \gamma T^4 \)
Outlook

- Understanding the thermodynamics of the complete system
- Moving away from conformal limit (e.g. adding bulk viscosity)
- Moving from linearization to numerics
- Dependence on initial conditions?