From full stopping to transparency in a holographic model of heavy ion collisions

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Fast “Thermalization” at RHIC and LHC

There are overwhelming evidences that relativistic heavy ion collision programs at RHIC and LHC created strongly coupled quark-gluon plasma (sQGP).

Successful description of experimental data is based on hydrodynamic simulations of an almost perfect fluid of $\eta/s = O(1/4\pi)$ starting on very early ($< 1 \text{ fm}$).
“Thermalization” at strong coupling

Recent progress in numerical relativity in AdS opened a possibility to study equilibration processes in holographic (strongly coupled) gauge theories

0812.2053 [hep-th], 0906.4426 [hep-th], 1011.3562 [hep-th] P. Chesler & L. Yaffe
1202.0981 [hep-th], 1304.5172 [hep-th] MPH, D. Mateos, W. van der Schee + others
...

The key lesson from these developments is that “thermalization” at strong coupling proceeds over a time scale set by the inverse of the “final” temperature

holography: \( t_{\text{equil}} \times T_{\text{final}} \bigg|_{\lambda=\infty} = \mathcal{O}(1) \) (LHC estimate: \( 0.25 \text{ fm} \times 500 \text{ MeV} = 0.63 \))

From this perspective, fast applicability of hydrodynamics at RHIC and LHC might not be so surprising given that the coupling there is not parametrically small
A typical holographic thermalization process

\[ \langle T_{\mu\nu} \rangle = \text{diag} \left\{ \epsilon, \frac{1}{3} \epsilon - \frac{2}{3} \Delta P(t), \frac{1}{3} \epsilon + \frac{1}{3} \Delta P(t), \frac{1}{3} \epsilon + \frac{1}{3} \Delta P(t) \right\} \]

Initial profile for the bulk metric

Absorption by the horizon

MPH, D. Mateos, W. van der Schee, D. Trancanelli

1202.0981 [hep-th]
The main problem

HUGE FREEDOM OF CHOICE

Which far from equilibrium initial condition is the closest to the experiment?
Towards a holographic „heavy ion collision”

Operational view:

collide holographically two lumps of matter moving at relativistic speeds

unfortunately necessarily deconfined, i.e. with $\langle T^{\mu \nu} \rangle = \mathcal{O}(N_c^2)$

State of the art as of July 2013: colliding gravitational shock wave solutions
Gravitational shock wave solutions


dual stress tensor:

\[ T^{tt} = T^{zz} = +T^{t\zeta} = \frac{N_c^2}{2\pi^2} h(t - z) \]

Solution of Einstein’s equations with the negative CC for any longitudinal profile \( h(x_-) \)

We will specialize to \( h(t \pm z) = \mathcal{E}_0 \exp \left[ -\frac{(t \pm z)^2}{2\sigma^2} \right] \). But we’re in a CFT, so the only qty that matters is

\[ e = \mathcal{E}_0^{1/4} \sigma \quad \text{(in real HIC } e \sim \gamma^{-1/2}) \]
Colliding shocks at $e_{CY} \approx 0.64$

$e_{CY} \approx 0.64$ is roughly the value corresponding to Pb nuclei boosted to RHIC energies

$\mu \sim$ total energy\*
\[ \mathcal{E} \sim T^{00} \]

significant stopping:
15\% slow-down of $T^{00}$ maxima

is it the full story?

large anisotropy at hydrodynamization!
Dynamical crossover


\[ e_{\text{left}} = 2 e_{CY} \]

„low energy”

\[ e_{\text{right}} = \frac{1}{8} e_{CY} \]

„high energy”

\[ \rho t = 10 \]

\[ \rho z = 10 \]

\[ \frac{\mathcal{E}}{\rho^4} \]

\[ \frac{\mathcal{E}}{\rho^4} \]

again, significant stopping:

12% slow-down of \( T^{00} \) maxima \( (v \approx 0.88) \)

\[ T^{00} < 0 \]

no stopping:

\( T^{00} \) maxima move with \( v \approx 1 \)
ties are close to zero, in close similarity with the Landau
expansion with initial conditions in which all the veloci-
that the thick-shocks collisions results in hydrodynamic
smaller as the width of the shocks increases. We conclude
applicable extends from
the hydrodynamic description can be seen in Fig. 3(left)
line. This is not constant in time, but at late times it
from the same figure as the inverse slope of the dotted

FIG. 3. Energy flux for collisions of thick (left) and thin (right) shocks. The dotted curves show the location of the maxima of
energy flux.

FIG. 2. Energy and pressures for collisions of thick (left column) and thin (right column) shocks. The grey planes lie at the
origin of the vertical axes.

A dynamical cross-over.

FIG. 1. Energy and pressures for collisions of thick (left) and thin (right) shocks. The white areas indicate the vacuum regions outside the light cone.

Dynamical crossover


e_{left} = 2 e_{CY}

„low energy”

\frac{3 \Delta P_{L}^{loc}}{\mathcal{E}_{loc}}

\rho t

max. energy flux

\rho z

hydro kicks in soon after the outer parts of incoming shocks meet
more like the old Landau picture (at \rho t = 0.58 (max. \mathcal{E}) \nu < 0.1)

hydro applicable only at mid-
rapidities and late enough!!!

more like what seems to be happening at RHIC and LHC

\frac{e_{right}}{e_{CY}} = \frac{1}{8}

„high energy”

\rho z

deviation from viscous hydro
Assume boost-invariance: $\mathcal{P}_L = -\mathcal{E} - \tau \mathcal{E}'$ and $\mathcal{P}_T = \mathcal{E} + \frac{1}{2} \tau \mathcal{E}'$

$\mathcal{E}\big|_{\tau=0} \sim 1$ leads to $\mathcal{P}_L \big|_{\tau=0} = -1$ and $\mathcal{P}_T \big|_{\tau=0} = 1$

$\mathcal{E}\big|_{\tau=0} \sim \tau^2$ leads to $\mathcal{P}_L \big|_{\tau=0} = -3$ and $\mathcal{P}_T \big|_{\tau=0} = 2$
Rapidity distribution at hydrodynamization

The dynamics is not boost-invariant in the sense introduced by Bjorken but nevertheless with decreasing e the rapidity distribution flattens out.
Summary

Dispels the myth that strong coupling necessarily leads to stopping*

Plasma creation and hydrodynamization (≠ isotropization!)

$$\frac{P_L}{E} \quad \text{and} \quad \frac{P_T}{E}$$

$$\left. \frac{P}{E} \right|_{\text{equilibrium}} = \frac{1}{3}$$

Fast hydrodynamization