Shocks in sQGP

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plan
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• shocks and sounds generated by jets *(Do we see a Mach cone now? yes)*
example of a strong shock

Pressure (solid blue) jumps down, rapidity (dashed) up

Numerical example which is a solution of the NS Equations (without small parameters or expansion)

(Is it justified? What about other terms in the gradient expansion?)

Hot but slow (subsonic)

Cold but fast (supersonic)
AdS/CFT

Weak shocks are basically hydro, can be done systematically, see 1004.3803 by Khlebnikov, Kruczenski, Michalogiorgakis

So we jump to a strong case
If $y=\text{const}$, $h=\text{const}$, $A=B=0$ it is a boosted brane

V. SHOCKS IN THE ADS/CFT

We use coordinates $v, x_1 = x, x_2, x_3, r$ and write the nonzero component of the metric as

$$
g_{11} = -r^2 f c^2 + r^2 s^2;
g_{12} = g_{21} = -r^2 f c s + r^2 c s + A(x_1, r);
g_{22} = -r^2 f s^2 + r^2 c^2 + B(x_1, r);
g_{15} = g_{51} = c;
g_{25} = g_{52} = s;
g_{44} = g_{33} = r^2
$$

(5.1)

where

$T$ and rapidity are in $h$ and $y$

$$
f = 1 - h(x, r)^4 / r^4;
c = \cosh[y(x)]; \ s = \sinh[y(x)]
$$

(5.2)
Unfortunately the Einstein-Hilbert action $R$ is not bounded from below and cannot be used for variational studies. The so called conformal gravity, with a squared Weyl tensor in the Lagrangian, should work [22]. We propose to do is to use the covariantly squared (modified) Einstein tensor

$$\tilde{E}^2 = E_{mn} \tilde{E}^{mn}, \quad E_{mn} = E_{mn} + 6g_{mn} \quad (5.6)$$

which combines all the Einstein equations (in the AdS/CFT setting) into one (covariant scalar) combination

or the sum of squares.
Variational method

\[ E^2 \text{ and the sum of squares} \]
Variational result:

one function only $A(x, r) = 0$

$B(x, r) = -0.052r(1 - 0.3x)\exp[-.1(x + 0.3)^2]$

The physical meaning of $B$ is correction to the $g_{xx}$

Its **negative sign** and magnitude imply few percent reduction of the shock width, especially near the horizon

Conclusions: same as from LS resummation, Corrections to NS are quite small!
Expansion in gradients (colored) vs the LS resummation (black)

Red dash-dotted line includes all up to 8 derivatives, brown dotted up to 12 derivatives.

The solid line is the LS factor \[ \frac{1}{1 - \frac{f''}{8f}} \]
The sound from the initial state perturbations (ES, Staig: QM2011)

several harmonics is enough to draw quite complex pictures: **sonograms** of the fireball can be made

(Long propagation time till freezeout => large circles)
The “Mini-Bangs” as Signals of the QCD Phase Transition

Edward Shuryak and Pilar Staig

New idea: shocks/sounds from Rayleigh collapse of the QGP bubbles

H phase
phase separation in the "mixed phase"
=> surface tension makes bubbles spherical
=> as T<Tc the QGP pressure is less than p_H =>
Rayleigh collapse => energy of the bubble goes into the outgoing shock
Rayleigh collapse result in emission of a shock

\[ u_r = \partial_t \phi = \dot{R} \]  \hspace{1cm} (5)

where a dot means time derivative. It leads to a solution

\[ \phi = -\frac{\dot{R} R^2}{r} + \text{const} \]  \hspace{1cm} (6)

and putting it back into Euler equation in the form (3) one finds at \( r = R \) the equation for \( R(t) \)

\[ \rho (\dot{R} R + (2 - 1/2) \dot{R}^2) = p(r = \infty, t) \]  \hspace{1cm} (7)

where the \( (1/2) \) comes from the second term of (3) and the r.h.s. is the driving pressure.

When the r.h.s. is positive the system is stable, but as it crosses into negative the collapse takes place. What was discovered by Rayleigh, even if the r.h.s. is put to zero, the equation admits simple analytic solution known as “the Rayleigh collapse”

\[ R(t) \sim (t_s - t)^{2/5} \]  \hspace{1cm} (8)

corresponding to the infinite velocity \( \dot{R} \sim (t_s - t)^{-3/5} \)

\[ \text{FIG. 1: The time evolution of the drop radius } R(t), \text{ for the values of } \eta/\rho = 0.01..0.1 \text{ with the 0.01 step.} \]

\[ \text{FIG. 2: The time evolution of the quantity } |\tilde{V}(t)|^2, \text{ entering the sound radiation intensity, for the values of } \eta/\rho = 0.06, 0.07, 0.08, 0.09, 0.1. \]
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FIG. 2: The time evolution of the quantity \( |\hat{V}(t)|^2 \), entering the sound radiation intensity, for the values of \( \eta/\rho = 0.06, 0.07, 0.08, 0.09, 0.1 \).

FIG. 22. Outgoing shock wave from a collapsing bubble: (a) Streak image of the emitted outgoing shock wave from the collapsing bubble and (b) an intensity cross section along the line \( AA' \). From Pecha and Gompf (2000).
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\[ R(t) \sim (t - \tau)^{2/5} \]

from which the infinite velocity \( \dot{R} \sim (t - \tau)^{-3/5} \)

![FIG. 1: The time evolution of the drop radius \( R(t) \), for the values of \( \eta/\rho = 0.01..0.1 \) with the 0.01 step.](image)

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- \( V_{\text{shock}} = 4 \text{km/s} \)
- \( C_{\text{sound}} = 1.4 \text{km/s} \)
- \( p = 40-60 \text{ kbar} \)
- \( T = 1 \text{ ev} ! \)
Sound propagating in rapidity direction

\[
\frac{\partial \delta(\rho)}{\partial \rho} = \frac{l(l + 1) \nu_s(\rho)}{3 \cosh^2(\rho)} - \frac{1}{3} i k \nu_\eta(\rho)
\]

\[
\frac{\partial \nu_s(\rho)}{\partial \rho} = \frac{2}{3} \tanh(\rho) \nu_s(\rho) - \delta(\rho)
\]

\[
\frac{\partial \nu_\eta(\rho)}{\partial \rho} = \frac{2}{3} \tanh(\rho) \nu_\eta(\rho) - i k \delta(\rho)
\]

The temperature perturbation at freeze-out as a function of \( \eta \) for different \( r \).
The temperature perturbation at freeze-out as a function of $\eta$ for different $r$.

Summing up those curves one gets a double-hump distribution.
The temperature perturbation at freeze-out as a function of $\eta$ for different $r$. Summing up those curves one gets a double-hump distribution.

Scale uncertainty: 20%
$\Delta \phi$ projection in $|\Delta \eta| < 0.80$
$\Delta \eta$ projection in $|\Delta \phi| < 0.87$
clusters in rapidity at LHC: first evidences for “mini-bangs”?

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The temperature perturbation at freeze-out as a function of $\eta$ for different $h$.

Summing up those curves one gets a double-hump distribution.

Hump separation corresponds to propagation duration of about 2 fm/c (to freezeout): makes sense at LHC.
sound from a jet on top of expanding fireball (Gubser flow): the old Mach cone
ALICE: very preliminary: peaks perhaps due to 4 points (A-B,A’B’) are there
summary

- strong shocks: out-of-equilibrium but stationary problem. LS hydro and ADS/CFT confirm small corrections to Navier-Stokes

- sounds from initial perturbations have many harmonics => sonogramms possible

- shocks and Mach cones from jets are becoming observable

- Rayleigh collapse of the QGP bubble: the sound of the QGP phase transition?
The angular edge of the jets: matter inside is few % HOTTER => SHOULD BE SEEN at tuned pt

- ATLAS very high energy event, in which there is no identifiable jet
  - Tracks pt>2.6 GeV, cal. E>1GeV/cell
- Note the sharp edge of the away-side perturbation! Is it a “frozen sound”?

Large $O(100 \text{ GeV})$ energy deposition into the medium should create strong shocks, and thus a different (larger) propagation distance