Hydrodynamic flow in heavy-ion collisions at RHIC and LHC

Pasi Huovinen
Uniwersytet Wrocławski

The 2nd International Conference on Particle Physics and Astrophysics

Oct 14, 2016, Moscow, Russia

The speaker has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 665778 via the National Science Center, Poland, under grant Polonez DEC-2015/19/P/ST2/03333
Strongly interacting matter

- interaction between constituents QCD, not QED
- matter in condensed matter physics sense
- so many particles that thermodynamical concepts
  - temperature
  - pressure
  - etc.
  apply
Phase diagram of strongly interacting matter
Transition temperature from hadrons to QGP $\sim 2 \cdot 10^{12}$ K, $\sim 160$ MeV

- temperature on the surface of the Sun $\sim 5800$ K
- temperature in the core of the Sun $\sim 1.6 \cdot 10^7$ K
Heavy-ion collision
Hydrodynamics

local conservation of energy, momentum and baryon number:

\[ \partial_\mu T^{\mu\nu}(x) = 0 \quad \text{and} \quad \partial_\mu N^\mu(x) = 0 \]

\[ T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - (P + \Pi)g^{\mu\nu} + \pi^{\mu\nu} \]

\[ N^\mu = n u^\mu + \nu^\mu \]

local, macroscopic variables: energy density \( \epsilon(x) \)
pressure \( P(x) \)
flow velocity \( u^\mu(x) \)

matter characterized by: equation of state \( P = P(T, \{\mu_i\}) \)
transport coefficients \( \eta = \eta(T, \{\mu_i\}) \)
\( \zeta = \zeta(T, \{\mu_i\}) \)
\( \kappa = \kappa(T, \{\mu_i\}) \)

Unknowns: initial state, final state
Elliptic flow $v_2$
Elliptic flow $v_2$

Spatial anisotropy $\rightarrow$ Final azimuthal momentum anisotropy

- Anisotropy in coordinate space $+$ rescattering $\Rightarrow$ Anisotropy in momentum space

- Pressure gradients convert spatial anisotropy to momentum anisotropy

  Sensitive to speed of sound $c_s^2 = \frac{\partial p}{\partial e}$ and shear viscosity $\eta$
Initial state fluctuates

temperature profiles in transverse plane
Characterising initial state

Shape of the initial density quantified by eccentricities:

\[ \epsilon_n e^{in\Phi_n} = -\frac{\{r^n e^{in\phi}\}}{\{r^n\}} \]

\[ \{\ldots\} = \int dx\, dy\, e(x, y, \tau_0)(\ldots) \]

- \( \epsilon_n \) eccentricity
- \( \Phi_n \) “participant plane” angle
From fluid to distribution

\[ \epsilon_n, \Psi_n \implies \nu_n, \Phi_n \]

\[ \frac{dN}{dyd\phi} = \frac{dN}{dy} \left[ 1 + \sum_n 2v_n \cos(n(\phi - \Psi_n)) \right] \]
From fluid to distribution

\[ \epsilon_n, \Psi_n \implies \nu_n, \Phi_n \]

\[ \frac{dN}{dyd\phi} = \frac{dN}{dy} \left[ 1 + \sum_n 2\nu_n \cos(n(\phi - \Psi_n)) \right] \]
$\epsilon_n, \Psi_n \implies \nu_n, \Phi_n$

$$\frac{dN}{dyd\phi} = \frac{dN}{dy} \left[ 1 + \sum_n 2v_n \cos(n(\phi - \Psi_n)) \right]$$
From fluid to distribution

\[ \epsilon_n, \Psi_n \iff \nu_n, \Phi_n \]

\[ \frac{dN}{dyd\phi} = \frac{dN}{dy} \left[ 1 + \sum_n 2\nu_n \cos(n(\phi - \Psi_n)) \right] \]
From fluid to distribution

\[ \epsilon_n, \Psi_n \quad \rightarrow \quad \nu_n, \Phi_n \]

\[
\frac{dN}{dyd\phi} = \frac{dN}{dy} \left[ 1 + \sum_n 2\nu_n \cos(n(\phi - \Psi_n)) \right]
\]
From fluid to distribution

\[
\epsilon_n, \Psi_n \quad \xrightarrow{\iff} \quad \nu_n, \Phi_n
\]

\[
\frac{dN}{dyd\phi} = \frac{dN}{dy} \left[ 1 + \sum_n 2\nu_n \cos(n(\phi - \Psi_n)) \right]
\]
From fluid to distribution

\[ \epsilon_n, \Psi_n \rightarrow \nu_n, \Phi_n \]

\[ \frac{dN}{dy\,d\phi} \frac{dN}{dy} = 1 + \sum_n 2\nu_n \cos(n(\phi - \Psi_n)) \]
\[ \frac{\eta}{s} \text{ from } v_2 \]


- **MC-Glauber initialization:** \( \eta/s = 0.08 \)
- **MC-KLN initialization:** \( \eta/s = 0.2 \)
Sensitivity to $\eta/s$


- higher coefficients are suppressed more by dissipation

- models can be distinguished
- MC-Glauber slightly favoured
Distributions of $v_n$ event-by-event

Scale out the average

$$\delta v_2 = \frac{v_2 - \langle v_2 \rangle}{\langle v_2 \rangle}$$

$$P(\delta v_2) = P(\delta \epsilon_2)$$

independent of viscosity


$\langle v_2 \rangle = 0.061$ ($\eta/s = 0.0$)
$\langle v_2 \rangle = 0.043$ ($\eta/s = 0.16$)
Flow fluctuations


\( P(v_2) \) compared to MC-Glauber and MC-KLN \( P(\varepsilon_2) \)

- MC-Glauber initialization: too wide
- MC-KLN initialization: too narrow
• IP-Glasma
  (Color Glass + Yang-Mills)

and

• EKRT
  (pQCD + saturation)

initial states work

\begin{align*}
\left( \frac{v_2}{\langle v_2 \rangle} \right)^2, \left( \frac{\epsilon_2}{\langle \epsilon_2 \rangle} \right)^2
\end{align*}

\begin{align*}
p_T > 0.5 \text{ GeV} \\
|\eta| < 2.5
\end{align*}

\begin{align*}
20-25\% \epsilon_2 \text{ IP-Glasma} \\
v_2 \text{ IP-Glasma+MUSIC} \\
v_2 \text{ ATLAS}
\end{align*}

Niemi et al., PRC 93, 024907 (2016)

\begin{align*}
P(\delta v_2), P(\delta \epsilon_2)
\end{align*}

\begin{align*}
35-40\% \\
LHC 2.76 \text{ TeV Pb+Pb}
\end{align*}

\begin{align*}
\eta/s = 0.20 \\
\eta/s = \text{param4} \\
\eta/s = 0.0
\end{align*}
State of the art

- IP-Glasma initial state: Color Glass plus Yang-Mills evolution

\begin{figure}
\centering
\includegraphics[width=\textwidth]{graph.png}
\caption{ALICE data $v_n\{2\}, p_T > 0.2$ GeV $\eta/s = 0.2$}
\end{figure}

- $\eta/s = 0.2$ favoured
State of the art

- IP-Glasma initial state: Yang-Mills evolution plus Color Glass

- $\eta/s = 0.2$ favoured at LHC

- $\eta/s = 0.12$ favoured at RHIC
$$\frac{\eta}{s} = \text{const.} \rightarrow (\frac{\eta}{s})(T)$$
sensitivity to $(\eta/s)(T)$

- weak dependence on QGP $\eta/s$ at RHIC
- increasing sensitivity to QGP $\eta/s$ with collision energy at LHC
- sensitive to minimum of $\eta/s$
Summary

• hydrodynamics can describe the anisotropies of particle emission observed in ultrarelativistic heavy-ion collisions

• the minimum specific shear viscosity of matter formed in these collisions is very low, $\eta/s \lesssim 2.5/(4\pi)$

• temperature dependence of $\eta/s$ is to be determined