Effects of hydrodynamic fluctuations on 2-particle correlations in an expanding system

SOPHIA HADRON PHYSICS GROUP

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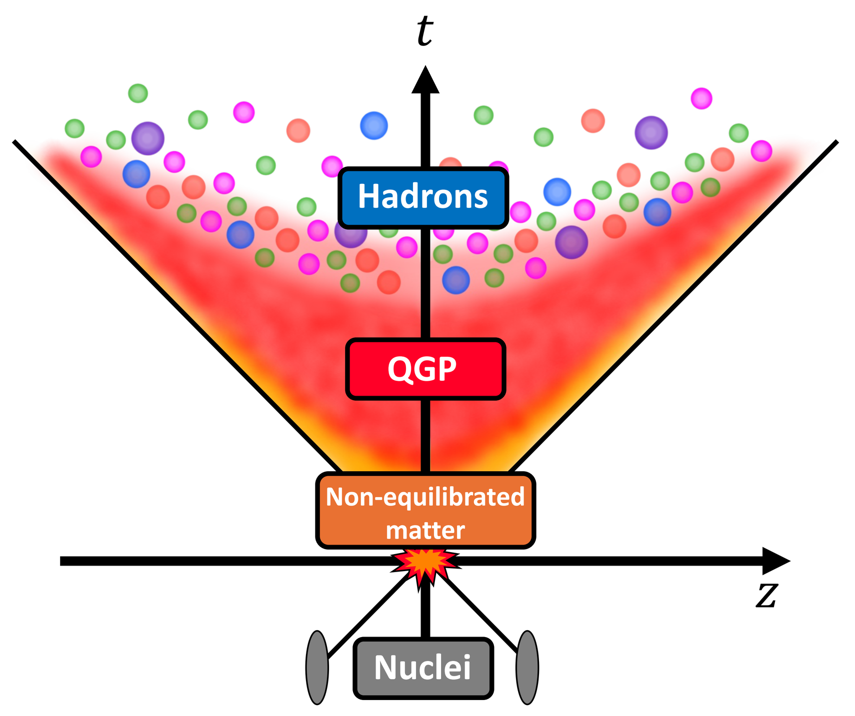
S. Fujii and T. Hirano, Phys. Rev. C **109**, 024916 (2024)

1. Introduction



Space-time evolution of Heavy Ion Collisions

Press release

Discovery of QGP's perfect fluid behavior

2005/04/18

https://www.bnl.gov/newsroom/news.php?a=110303

Standard description of space-time evolution by **"Relativistic hydrodynamics"**

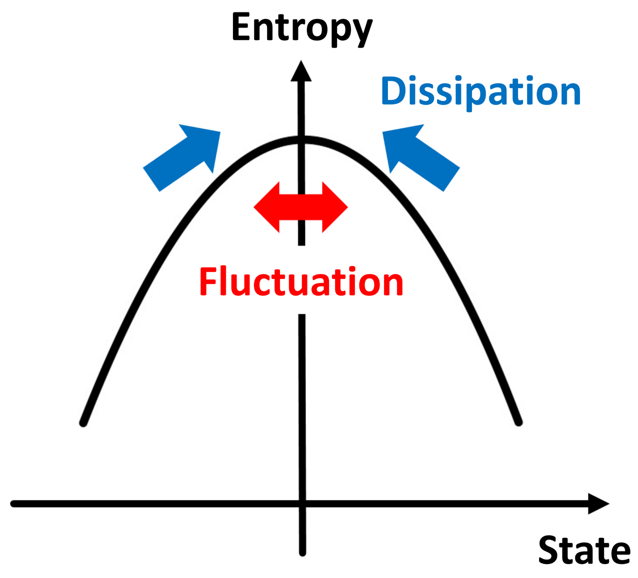
Fluctuation Dissipation Relation (FDR)

Interplay between dissipations (viscosities) and fluctuations

ex.) FDR for Shear stress tensor $\pi^{\mu\nu}$

$$\left\langle \xi_\pi^{\mu\nu}(x)\xi_\pi^{\alpha\beta}(x')\right\rangle = 4\eta T\delta^4(x-x')\Delta^{\mu\nu\alpha\beta}$$

$\xi_\pi^{\mu\nu}$: fluctuation η: viscosity



Evolution of relativistic hydrodynamic models

Ideal hydro	→ + viscosity →	Dissipative hydro	→ + FDR →	Fluctuating hydro
circa 2000		circa 2010		circa 2015

Hot Topic: Research on QGP properties using fluctuations

2. Formalisms

J. D. Bjorken, Phys. Rev. D **27**, 140 (1983)

Perturbative expansion around the Bjorken's solution

$$u^\mu_{\rm Bj} = (\cosh\eta_s, 0, 0, \sinh\eta_s)$$

$\eta_s = \frac{1}{2}\ln\left(\frac{t+z}{t-z}\right)$: coordinate rapidity

Small deviations

$$u^\mu \to \left(\cosh(\eta_s+\delta y(\tau,\eta_s)), 0, 0, \sinh(\eta_s+\delta y(\tau,\eta_s))\right)$$

$$e \to e_0(\tau) + \delta e(\tau,\eta_s) \quad \text{etc.}$$

e: energy density, $\tau=\sqrt{t^2-z^2}$: proper time

Energy-momentum conservation

Balance equation for Background (0th order perturbation)

Balance equation for Fluctuation (1st order perturbation)

Background

$$\frac{d}{d\tau}e_0 + \frac{1}{\tau}(w_0+\Pi_0-\pi_0) = 0 \quad \text{(Bjorken equation)}$$

$w=e+p$: enthalpy density

p: hydrostatic pressure

$\pi \equiv \pi^{00}-\pi^{33}$: shear pressure

Π: bulk pressure

Fluctuation

$$\frac{\partial}{\partial\tau}\begin{pmatrix}\delta e\\ \delta y(w_0+\Pi_0-\pi_0)\end{pmatrix} + \frac{1}{\tau}\frac{\partial}{\partial\eta_s}\begin{pmatrix}\delta y(w_0+\Pi_0-\pi_0)\\ \delta p+\delta\Pi-\delta\pi\end{pmatrix} + \frac{1}{\tau}\begin{pmatrix}\delta w+\delta\Pi-\delta\pi\\ 2\delta y(w_0+\Pi_0-\pi_0)\end{pmatrix} = 0$$

Causal constitutive equations

W. Israel and J. M. Stewart, Annals Phys. **118**, 341 (1979)

Israel-Stewart equation + noise $\quad (1+\tau_\pi D)\pi = \frac{4\eta}{3}\theta + \xi_\pi$

$D\equiv u^\mu\partial_\mu$, $\theta\equiv\partial_\mu u^\mu$, τ_π: relaxation time, ξ_π: noise

Perturbative expansion

Background

$$\left(1+\tau_{\pi 0}\frac{d}{d\tau}\right)\pi_0 = \frac{4\eta_0}{3\tau}$$

Fluctuation

$$\left(1+\tau_{\pi 0}\frac{\partial}{\partial\tau}\right)\delta\pi = -\frac{\delta\tau_\pi}{\tau_{\pi 0}}\left(\frac{4\eta_0}{3\tau}-\pi_0\right) + \frac{4\eta_0}{3\tau}\frac{\partial}{\partial\eta_s}\delta y + \frac{4\delta\eta}{3\tau} + \xi_\pi$$

Fluctuations from FDR

$$\langle\xi_\pi(\tau,\eta_s)\xi_\pi(\tau',\eta_s')\rangle = \frac{8\eta_0 T_0}{3\tau\Delta x\Delta y}G(\eta_s-\eta_s')\delta(\tau-\tau')$$

smeared by gaussian

η_0: shear viscosity (background)

T_0: temperature (background)

$\Delta x = \Delta y = 2$ fm, $\langle\xi_\pi(\tau,\eta_s)\rangle = 0$, $\sigma_\eta = 0.5$

$$G(\eta_s-\eta_s') = \frac{1}{\sqrt{2\pi\sigma_\eta^2}}\exp\left[-\frac{(\eta_s-\eta_s')^2}{2\sigma_\eta^2}\right]$$

Particle spectra

$$E\frac{dN}{d^3p} = \frac{d}{(2\pi)^3}\int f(p^\mu u_\mu, T)\, p_\mu d\sigma^\mu \;\Rightarrow\; \frac{dN}{dY} = \frac{d\tau A}{(2\pi)^2}\int_{-\infty}^{\infty}d\eta_s\int_m^\infty dm_T\, m_T^2\cosh(Y-\eta_s)\, f$$

F. Cooper and G. Frye, Phys. Rev. D **10**, 186 (1974)

d: degrees of freedom, A: transverse area

Distribution function

$$f_{\rm ideal}(p^\mu u_\mu, T) = \exp\left(-\frac{p^\mu u_\mu}{T}\right) = \exp\left(-\frac{m_T\cosh(Y-\eta_s-\delta y)}{T_0+\delta T}\right)$$

including fluctuations

Viscous correction

$$f = f_{\rm ideal} + f_{\rm vis}$$

1st vis.

A. Monnai and T. Hirano, Phys. Rev. C **80**, 054906 (2009)

Perturbative expansion

$$f = f_{0,\rm ideal} + f_{0,\rm vis} + \delta f_{\rm ideal} + \delta f_{\rm vis}$$

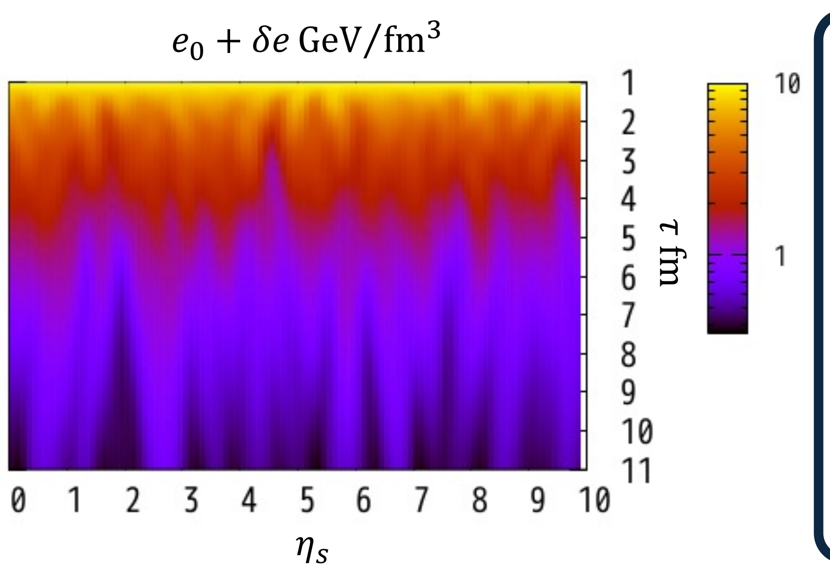
1st vis.; 1st per.; 1st vis., 1st per.

3. Results

Lattice EoS: A. Bazavov *et al.*, Phys. Rev. D **90**, 094503 (2014)

Space-time evolution of energy density

Initial conditions $\tau_0 = 1$ fm, $e_0(\tau_0) = 10$ GeV/fm^3, $\pi_0(\tau_0) = \frac{4\eta}{3\tau}$, $\delta e(\tau_0) = \delta y(\tau_0) = \delta\pi(\tau_0) = 0$



New

Streak-like structure

↓

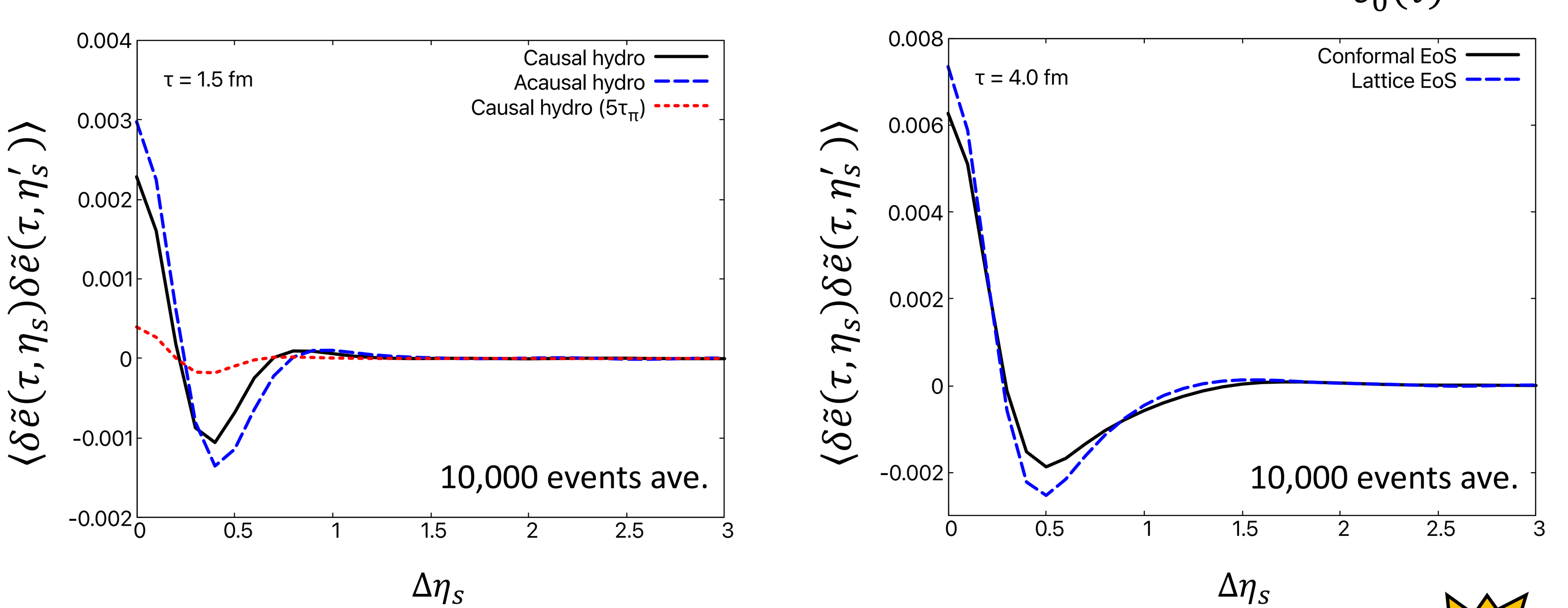
Frozen distribution of energy density

↓

Information on the early stage

Correlations of energy density fluctuations

$$\delta\tilde{e}(\tau,\eta_s) \equiv \frac{\delta e(\tau,\eta_s)}{e_0(\tau)}$$



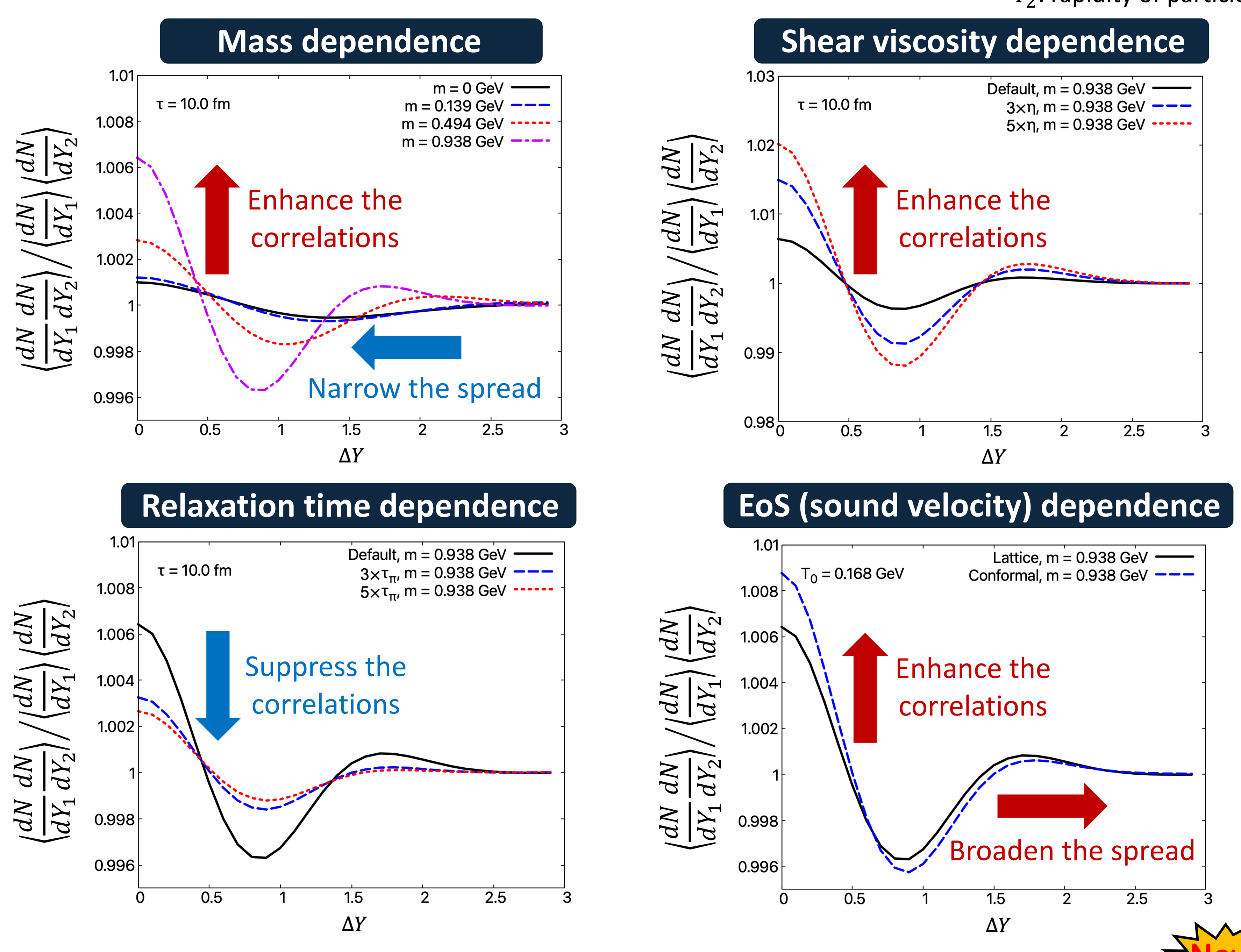
New

→ Effects of bulk and transport properties of the medium on energy density correlations

2-particle correlations

Y_1: rapidity of particle 1

Y_2: rapidity of particle 2



New

- Heavier hadrons as better probes of correlations
- Opposite behavior between shear viscosity and relaxation time
- Effects of EoS (sound velocity) on correlations

→ Extract the properties of the medium from 2-particle correlations!

4. Summary

- We developed a framework which deals with causal hydrodynamic fluctuations in 1-dimensional expanding system.
- We observed a streak-like structure through the time evolution of energy density caused by a freeze of distribution.
- We found behaviors of correlations of thermodynamic variables and particles are closely related to the properties of the medium.