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Dynamics of causal hydrodynamic fluctuations in an expanding system

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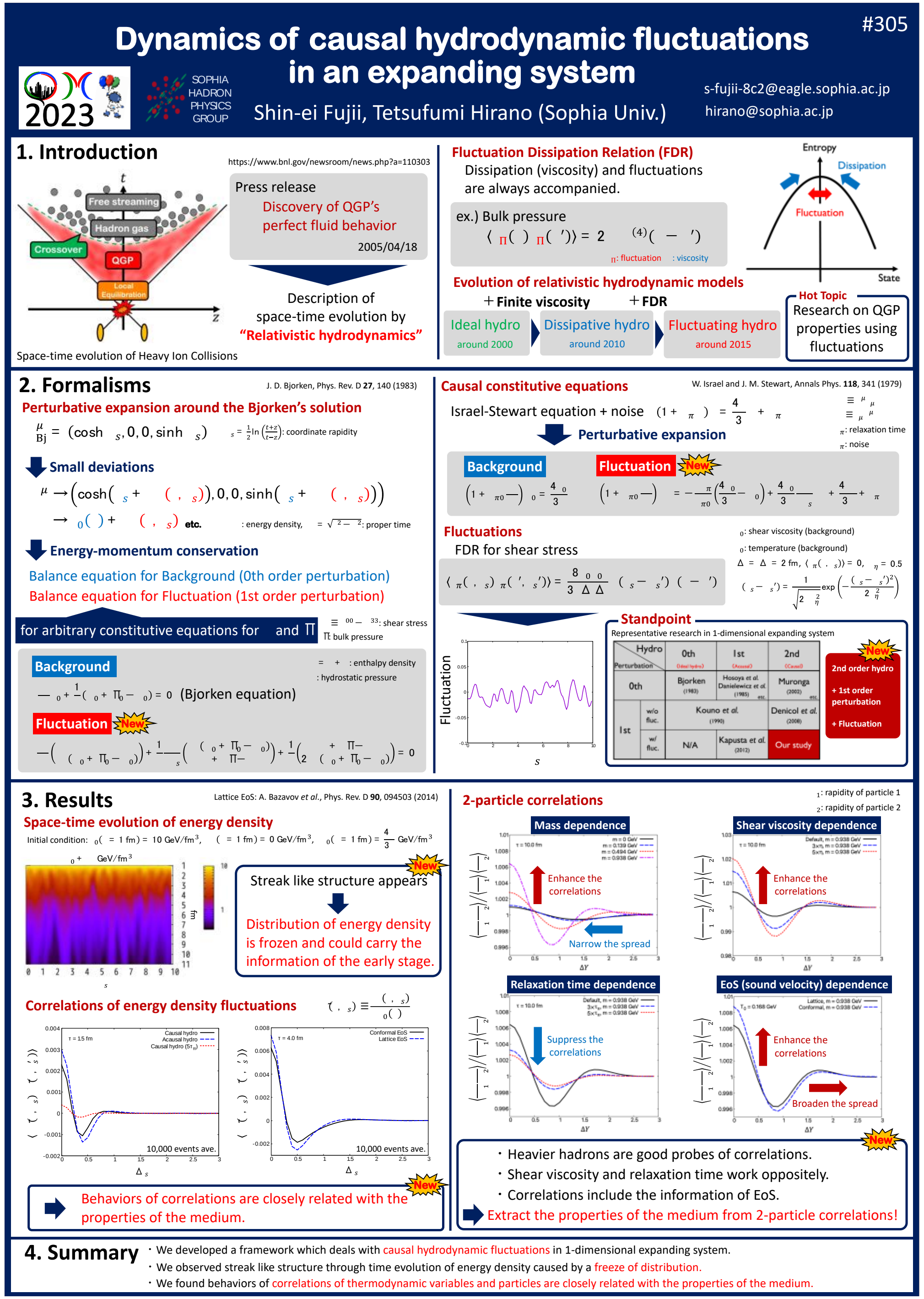


Introduction

QGP created in the HIC is successfully described by

"Relativistic Viscous Hydrodynamics"

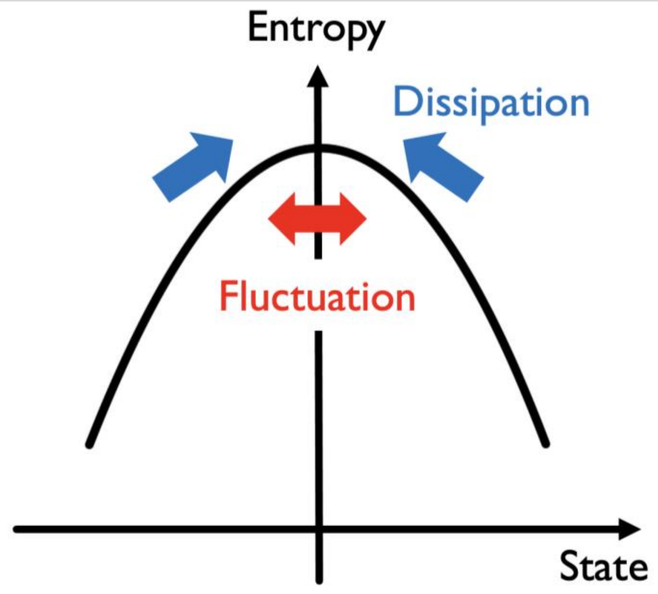
Fluctuation Dissipation Relation (FDR)

Dissipation (viscosity) and fluctuations are always accompanied.

Ex.) FDR for shear stress tensor

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

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



Purpose

To see the effect of hydrodynamic fluctuations on observables

Formalism

J. D. Bjorken, Phys. Rev. D **27**, 140 (1983)
W. Israel and J. M. Stewart, Annals Phys. **118**, 341 (1979)

Perturbative expansion around the Bjorken's solution

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

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

Small deviations

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

$$e \to e_0(\tau) + \delta e(\tau,\eta_s)$$

etc.

e: energy density

$\tau = \sqrt{t^2 - z^2}$: proper time

Energy-momentum conservation

Background

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

(Bjorken equation)

Fluctuation

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

$w = e + p$: enthalpy density $\quad$ p: hydrostatic pressure $\quad$ $\pi \equiv \pi^{00} - \pi^{33}$: shear stress $\quad$ Π: bulk pressure

Formalism

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Perturbative expansion aro

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

Small deviations

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

$$e \to e_0(\tau) + \delta e(\tau,\eta_s)$$ **etc.**

Energy-momentum co

Background $\frac{d}{d\tau}e_0 + \frac{1}{\tau}(w_0 + \Pi_0 - \pi_0) = 0$ (Bjork ation)

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

$w = e + p$: enthalpy density p: hydrostatic pressure $\pi \equiv \pi^{00} - \pi^{33}$: shear stress Π: bulk pressure

Causal constitutive equations + noise

η: shear viscosity

τ_π: relaxation time

Background

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

Fluctuation

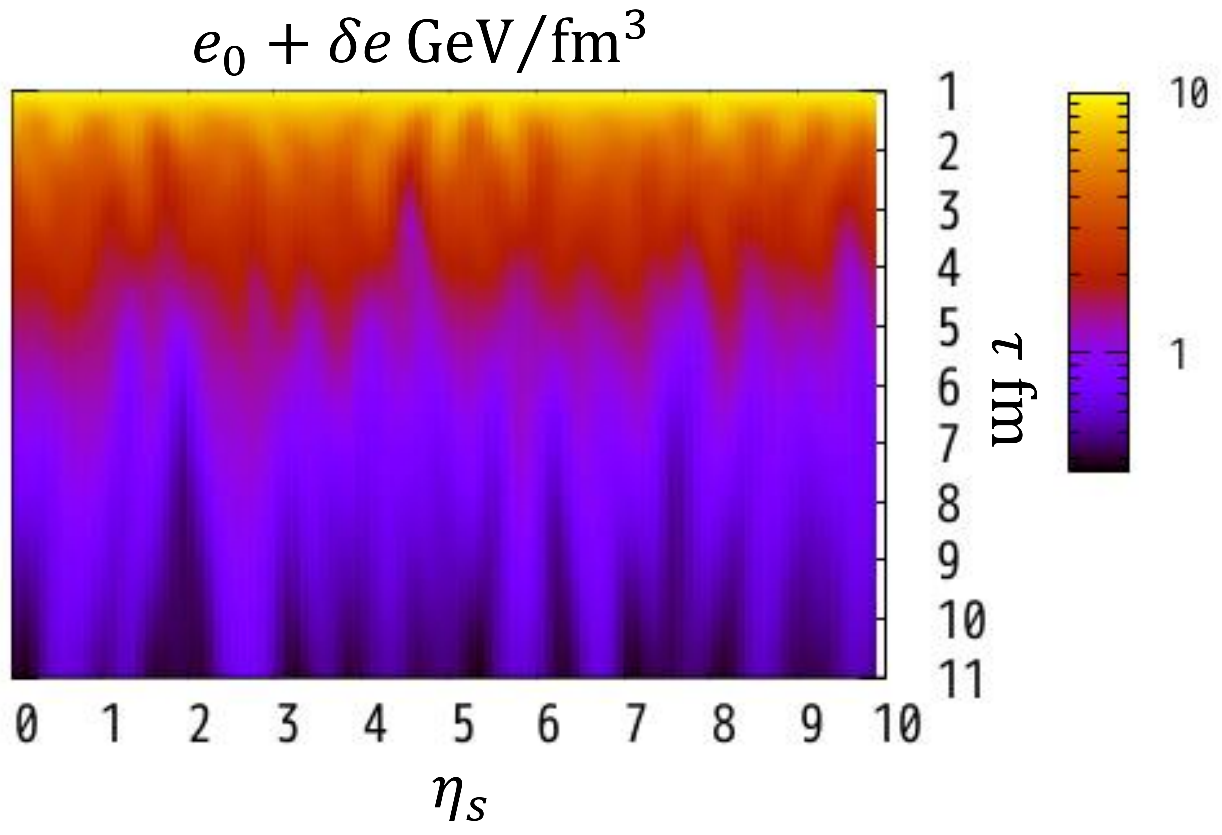
noise term

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

Results

Space-time evolution of energy density

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



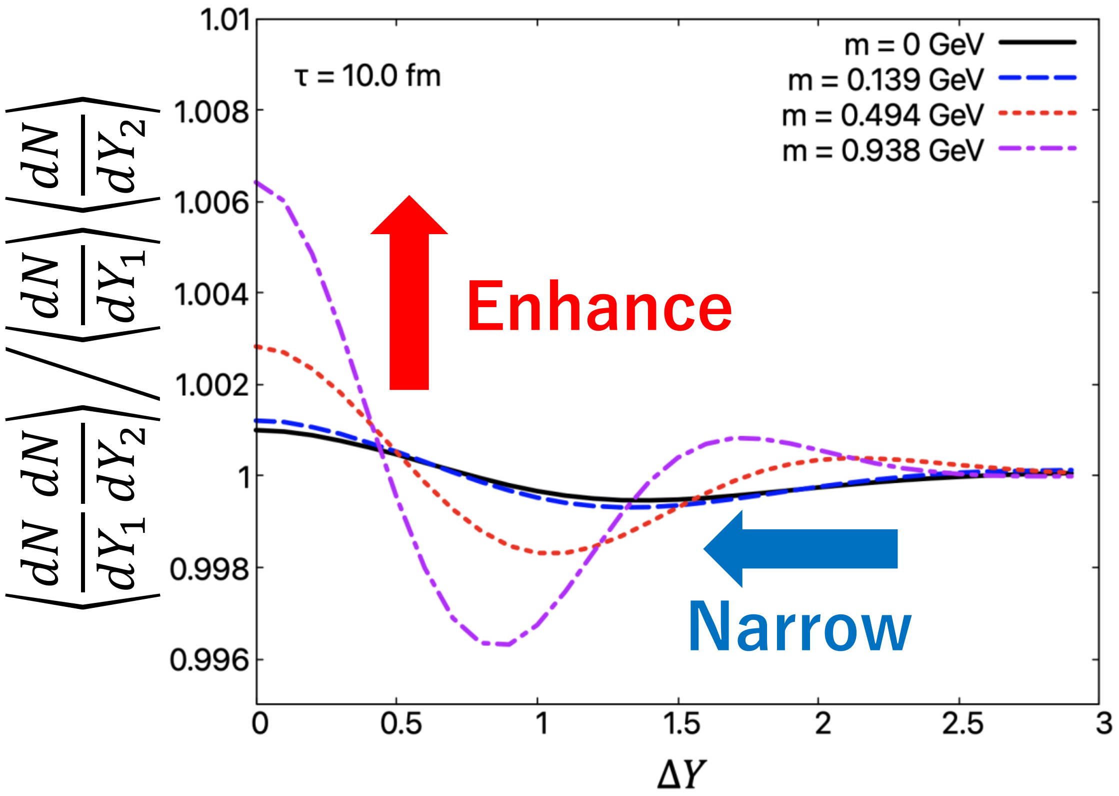
Distribution is frozen ▶ Carry the information of early stage

Results

Y_1: rapidity of particle 1
Y_2: rapidity of particle 2

2 particle correlations

Mass dependence



Heavier hadrons are good probes of correlations

Results

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

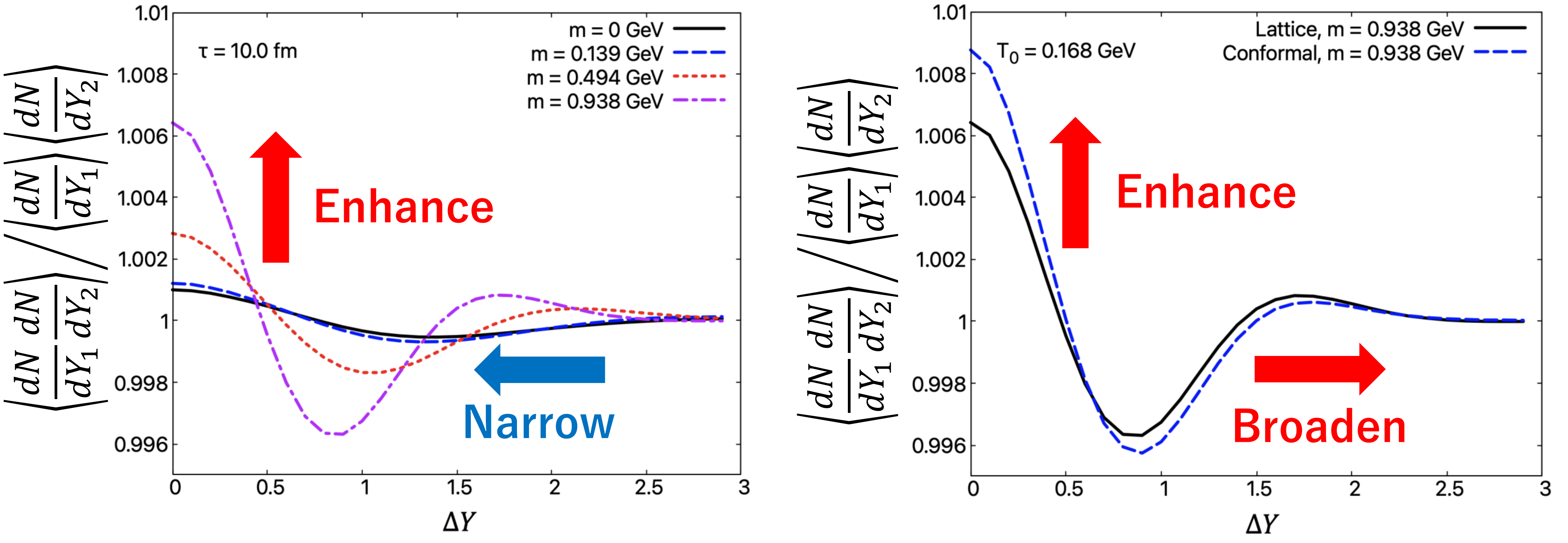
2 particle correlations

Y_1: rapidity of particle 1

Y_2: rapidity of particle 2

Mass dependence

EoS (sound velocity) dependence



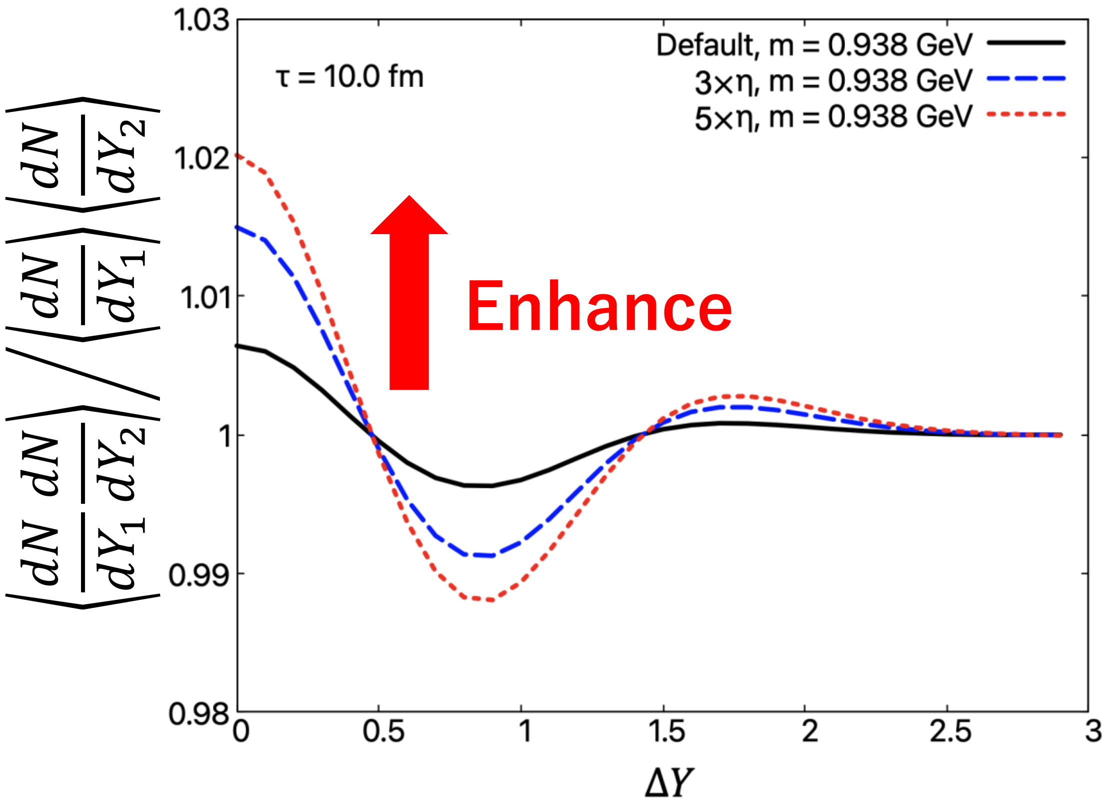
Correlations include information of EoS

Results

Y_1: rapidity of particle 1
Y_2: rapidity of particle 2

2 particle correlations

Shear viscosity dependence



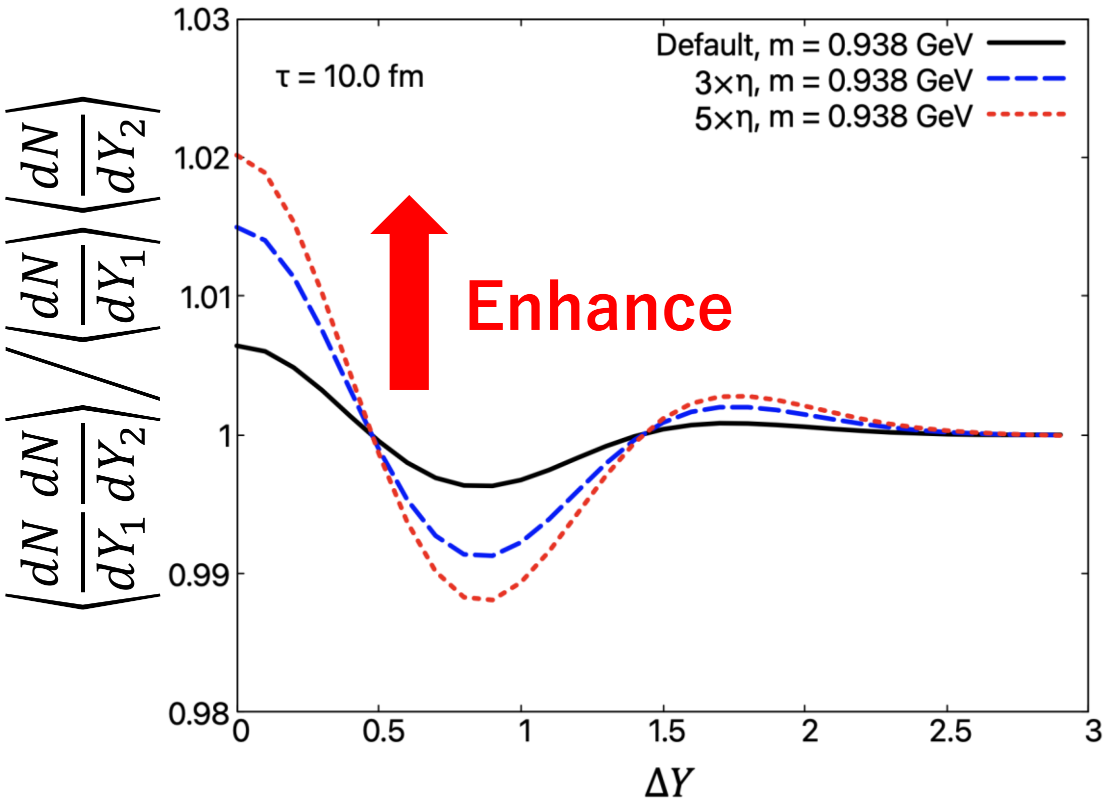
Viscosity → Enhance

Results

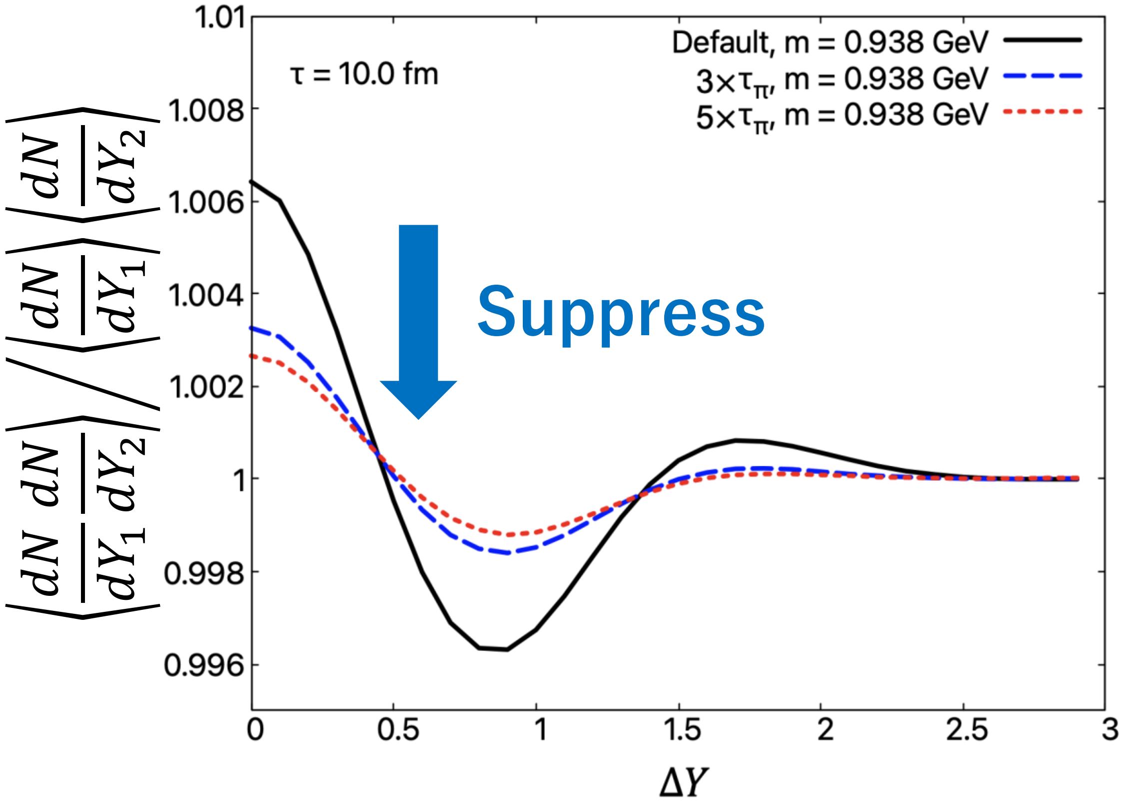
2 particle correlations

Y_1: rapidity of particle 1
Y_2: rapidity of particle 2

Shear viscosity dependence



Relaxation time dependence



Viscosity → Enhance　　Relaxation time → Suppress

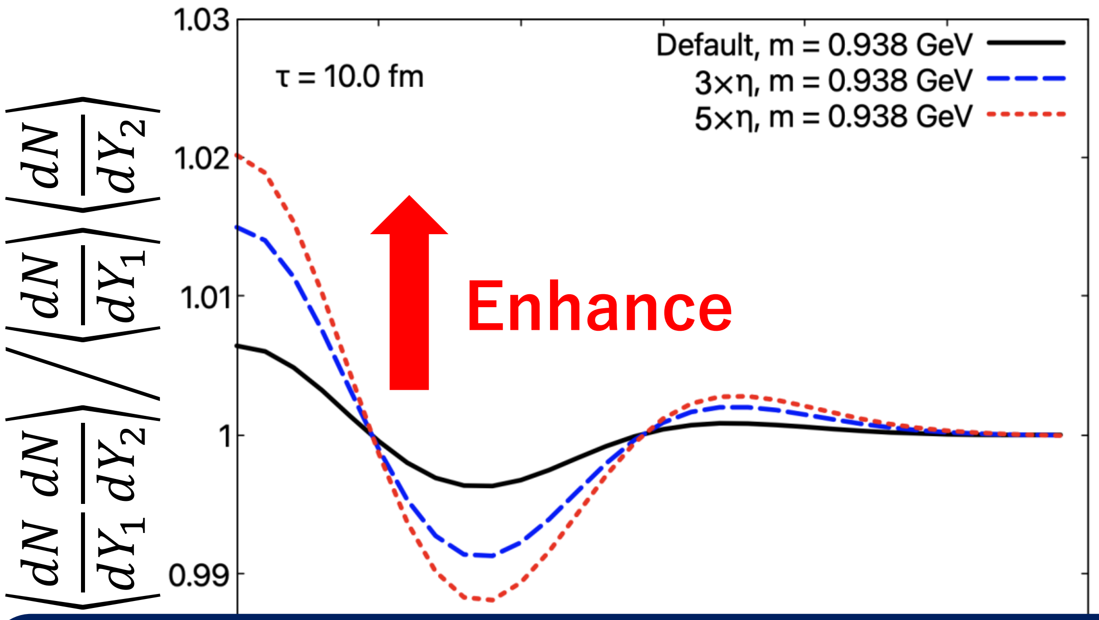
Results

Y_1: rapidity of particle 1

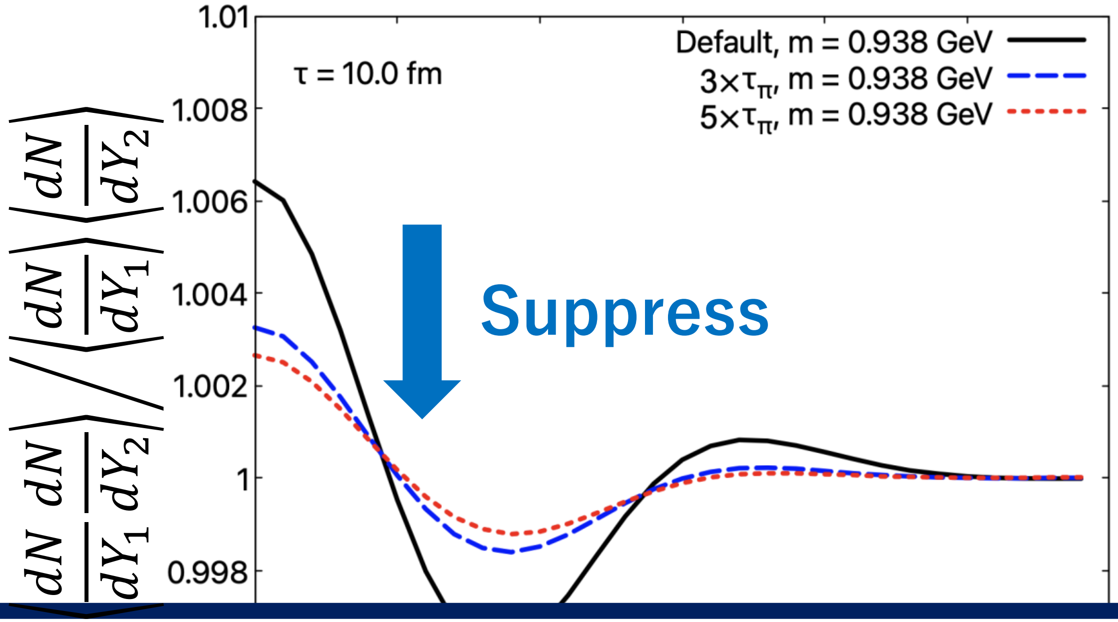
Y_2: rapidity of particle 2

2 particle correlations

Shear viscosity dependence



Relaxation time dependence



Summary

New framework of causal hydrodynamic fluctuations in (1+1)D system

➡ Hydrodynamic fluctuations provide a multidimensional analysis