Early Flow from Matching Pre-Equilibrium Dynamics to Viscous Hydrodynamics

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Introduction

- Heavy-ion collisions generate a thermalized QGP that evolves according to viscous hydrodynamics
- Dynamics prior to thermalization unclear
  - Potentially source of significant uncertainties
  - Presently-used initial conditions for hydrodynamics may not reflect realistic pre-equilibrium dynamics
- Assessing the relevant uncertainties requires exploration of a variety of pre-equilibrium models and matching them to viscous hydrodynamic parameters

- We developed a hydrodynamic matching algorithm
- We apply that algorithm to three toy models
  - Examine claim by Vredevoogd and Pratt* of universal early flow
  - Understand the pre-equilibrium features that lead to particular qualitative features in hydro parameters

*J. Vredevoogd and S. Pratt, Phys. Rev. C **79**, 044915 (2009)

The Matching Process ($\mu_b = 0$)

- Use the Landau matching condition $eu^{\mu} = T^{\mu\nu}u_{\nu}$ to get u^{μ}
- Separate $T^{\mu\nu}$ into ideal fluid components and viscous corrections by projection:

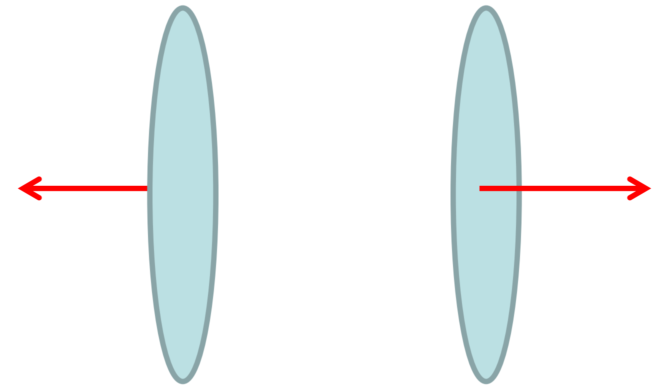
$$T^{\mu\nu} = eu^{\mu}u^{\nu} - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

- $T^{\mu\nu}$: Stress-energy tensor
- e: Energy density
- u^{ν}: Fluid velocity
- p: Pressure
- Π: Bulk viscous pressure
- $\Delta^{\mu\nu}$: Spatial projector in local rest frame
- $\pi^{\mu\nu}$: Shear viscous pressure tensor

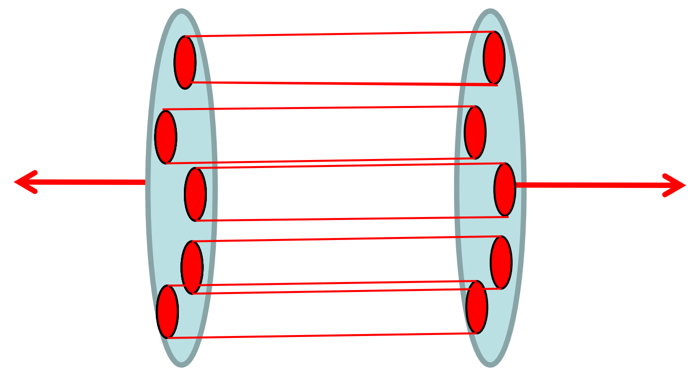
- Here: use longitudinal boost invariance (match at $z = 0, \eta = 0$)
- Allows us to look only at transverse plane: $u^{\mu} = \gamma(1, v_x, v_y, 0)$
- (We use massless equation of state $p = e/3$ for simplicity)
- Note: must be careful to use consistent definition of velocity and parameterization of $T^{\mu\nu}$

Three Toy Models

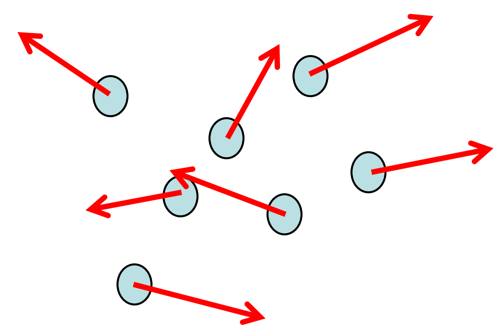
- Coherent electromagnetic
  - Discussed by Vredevoogd and Pratt
  - Dynamics governed by charge densities on receding nuclei



- Incoherent electromagnetic
  - Also discussed by Vredevoogd and Pratt
  - Similar to coherent model, but only pairs of nucleons interact
  - Abelian approximation of color flux tubes



- Free-streaming
  - Initialize with distribution of particles
  - Allow distribution to evolve without interactions

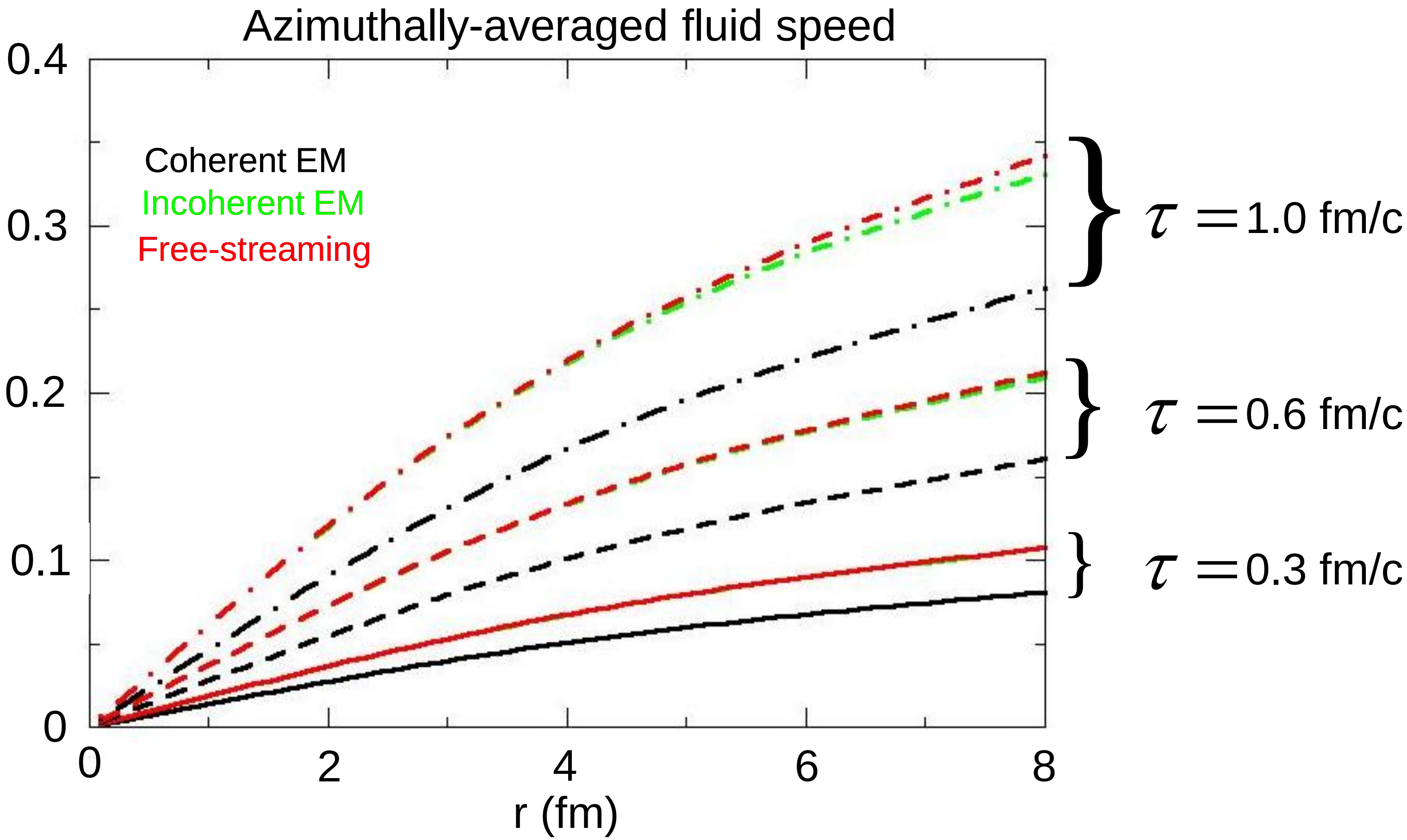


*J. Vredevoogd and S. Pratt, Phys. Rev. C **79**, 044915 (2009)

Model Comparison

Initialize each model by $T^{00}(\tau=0) \propto \exp\left[-\frac{x^2}{2R_x^2}-\frac{y^2}{2R_y^2}\right]$

(we set $R_x = 2.0$ fm, $R_y = 3.0$ fm, $\varepsilon = 0.385$ here)



No universal early flow!

What's the Difference?

- This result contradict other studies!
- They used generalized form of the Eckart matching condition

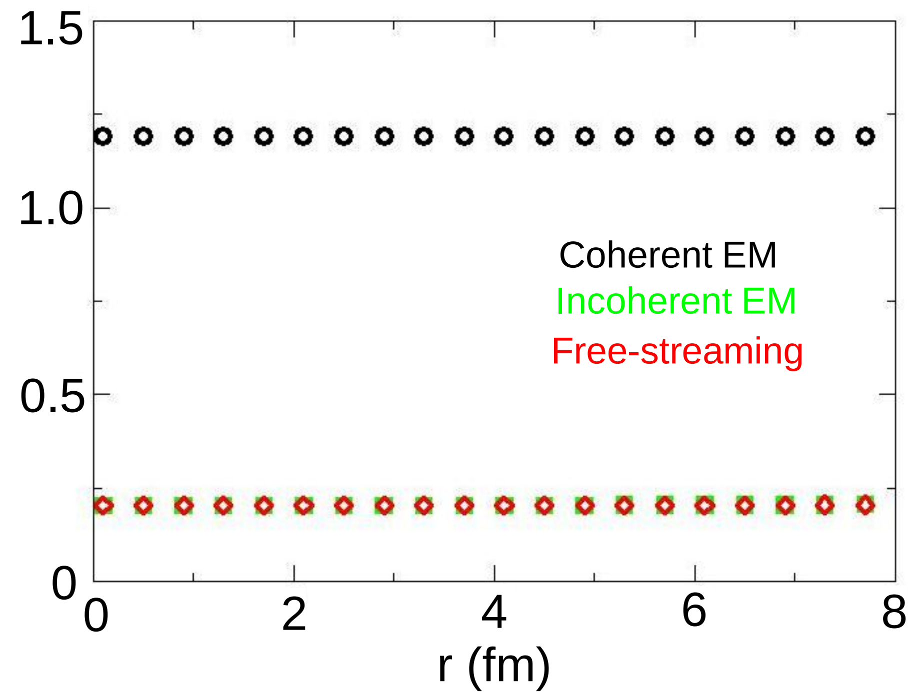
$$u^\mu = \frac{N^\mu}{\sqrt{N^\nu N_\nu}} \xrightarrow{\text{(Free-Streaming Model)}} u^\mu = \frac{T^{0\mu}}{\sqrt{T^{0\nu}T_{0\nu}}}$$

  - Only true for the free-streaming model
  - No physical meaning for others
- They match to ideal hydro
  - As measure of viscous corrections:

$$\sqrt{\frac{\pi^{\mu\nu}\pi_{\mu\nu}}{T_{ideal}^{\mu\nu}T_{ideal,\mu\nu}}} = \frac{\sqrt{\pi^{\mu\nu}\pi_{\mu\nu}}}{e+p}$$

  - We find large viscous corrections; matching to viscous hydro necessary

Measure of viscous corrections at 0.6 fm/c

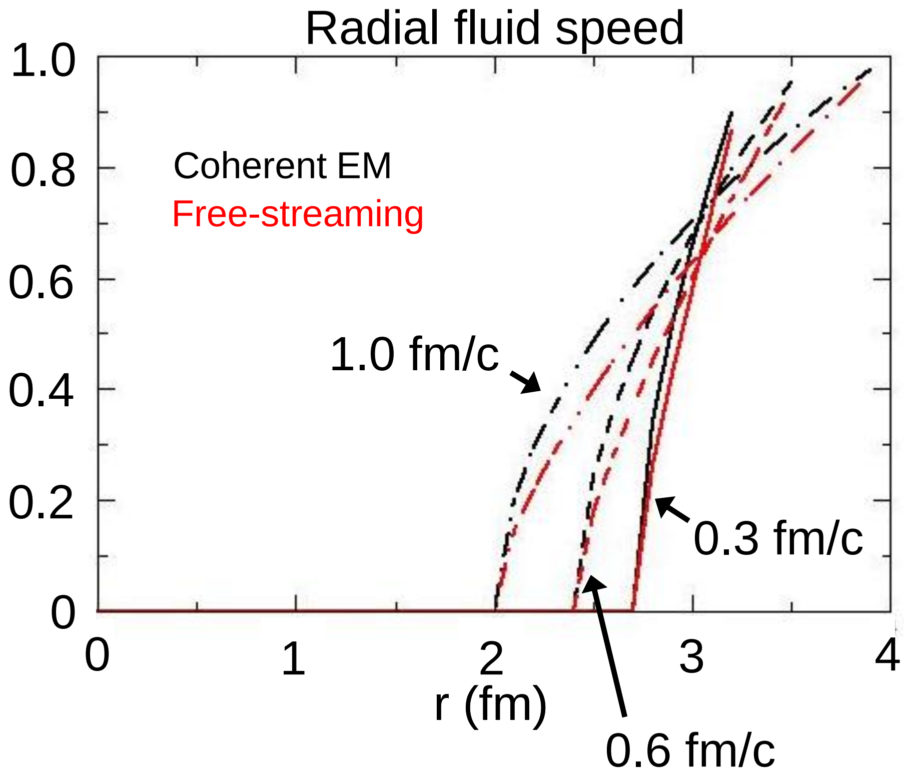


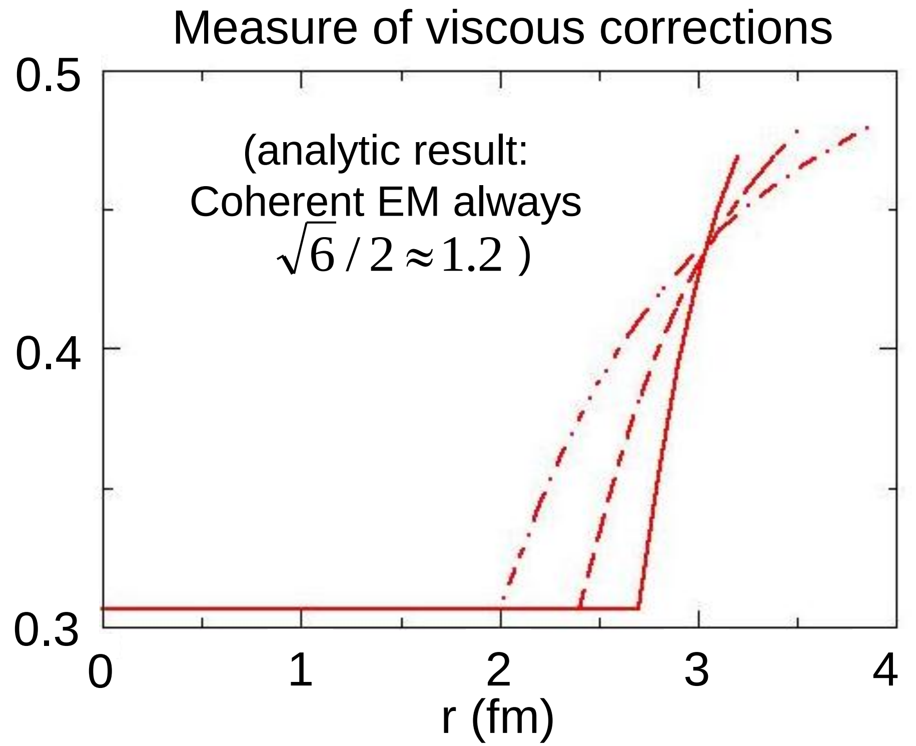
Model Comparison (cont'd)

A second initialization: $T^{00}(\tau=0) \propto \theta(R^2 - r^2)$

Easily computed for coherent and free-streaming models

(we set $R = 3.0$ fm here)





Coherent model generates larger flows for this initialization!

Conclusions and Outlook

Initial conditions for hydrodynamics are sensitive to pre-equilibrium dynamics and initializations

Large viscous terms in $T^{\mu\nu}$ at the matching time require use of viscous hydrodynamics

Outlook: Study more realistic pre-equilibrium models and initializations (e.g. free-streaming with CGC initialization)

Further examine properties of matching condition (e.g. do particular features in matched parameters correspond to properties of $T^{\mu\nu}$?)