Early Flow from Matching Pre-Equilibrium Dynamics to Viscous Hydrodynamics

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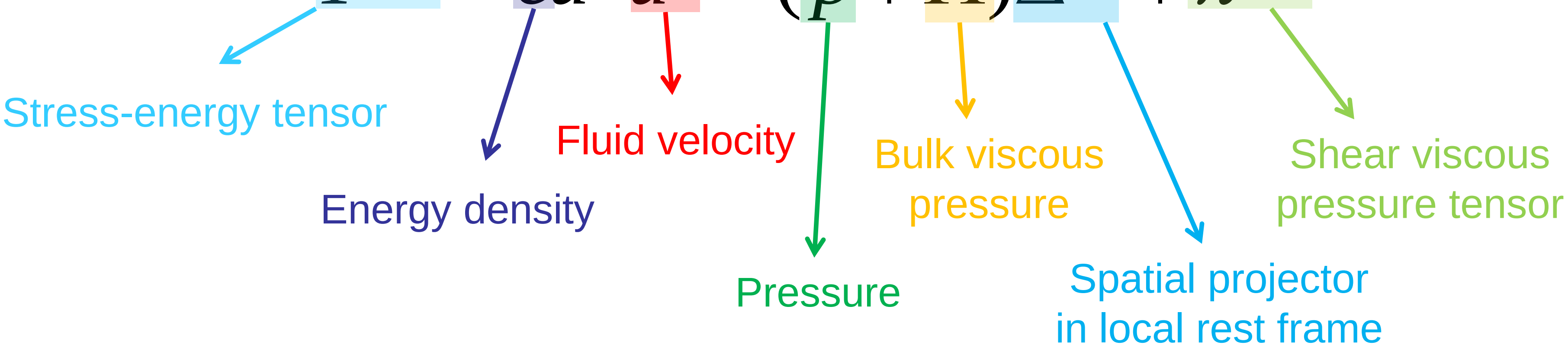
Introduction

- Quark-Gluon Plasma (QGP) described by viscous hydro
- What happens before thermal equilibrium?
  - Detailed microscopic dynamics presently unclear
  - Characterization by thermal parameters no longer meaningful
  - Ultimate goal: complete description of pre-equilibrium dynamics
- More immediate goal: explore sensitivity of the system on pre-equilibrium dynamics
  - Want to propagate pre-equilibrium effects through viscous hydro
  - Needed to establish uncertainties in late-time observables due to incomplete knowledge of early dynamics
  - To do so, need some way of converting pre-equilibrium dynamics to viscous hydrodynamics
  - Procedure: Matching the stress-energy tensor to viscous hydro parameters

The Matching Process

- Use the Landau matching condition $eu^{\mu} = T^{\mu\nu} u_{\nu}$
- Longitudinal boost invariance – match at $z = 0, \eta = 0$
- Allows us to look only at transverse plane – $u^{\mu} = \gamma(1, v_x, v_y, 0)$
- Compute other parameters from the standard expression:

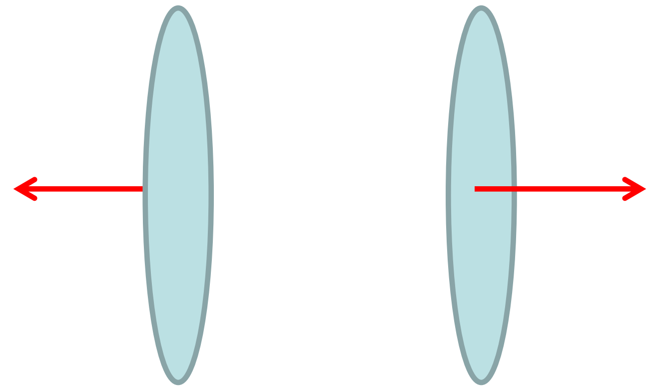
$$T^{\mu\nu} = eu^{\mu}u^{\nu} - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$



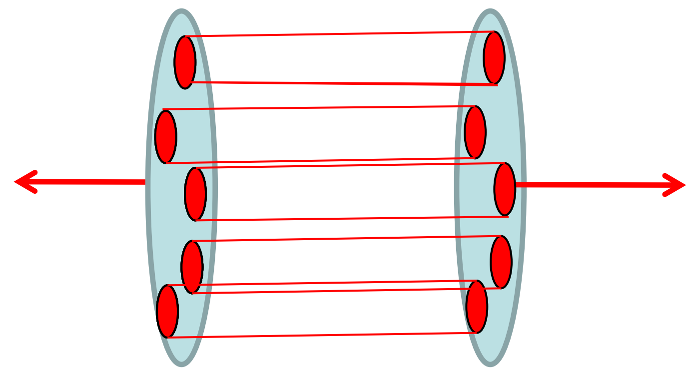
- (We use massless equation of state $p = e/3$ for simplicity)

Three Toy Models

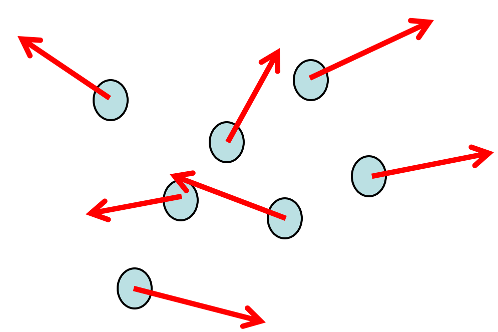
- Coherent electromagnetic
  - Discussed by Vredevoogd and Pratt*
  - Dynamics governed by charge densities on receding nuclei



- 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

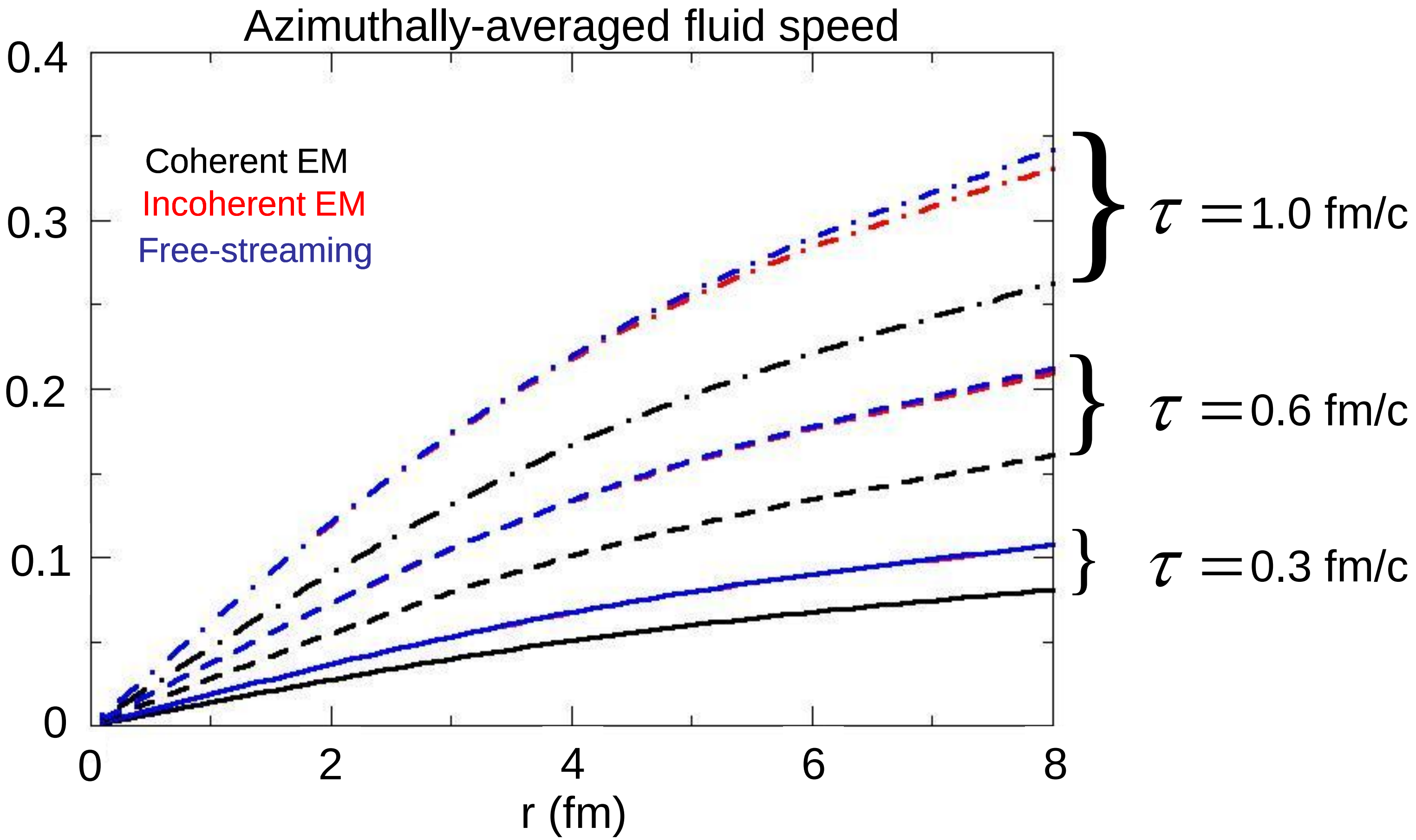


*J. Vredevoogd and S. Pratt, Phys. Rev. C **79**, 044915 (2009)

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 here)



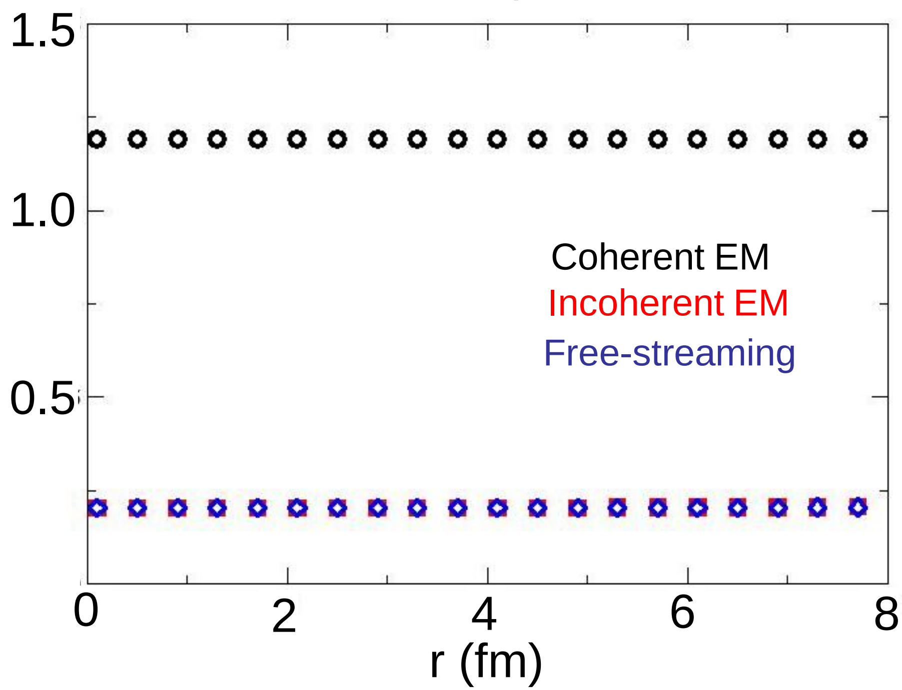
No universal early flow!

Model Comparison (cont'd)

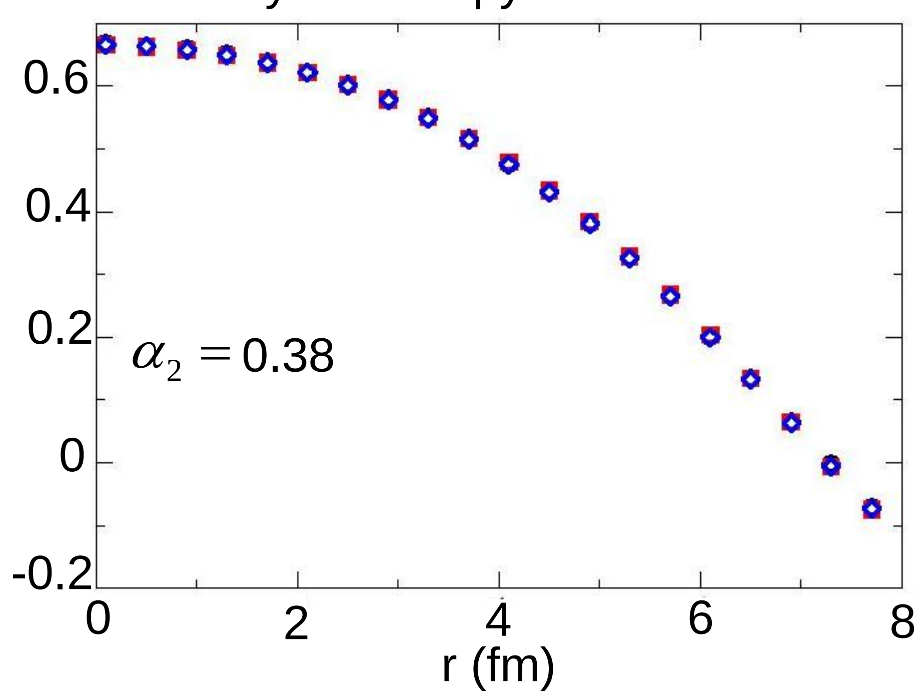
Also look at deviation from local equilibrium $\sqrt{\dfrac{\pi^{\mu\nu}\pi_{\mu\nu}}{T^{\mu\nu}_{ideal}T_{ideal,\mu\nu}}} = \dfrac{\sqrt{\pi^{\mu\nu}\pi_{\mu\nu}}}{e+p}$

and velocity anisotropy $\alpha_2(r) = \dfrac{\int_{-\pi}^{\pi} d\phi\, \gamma e\left(v_x^2 - v_y^2\right)}{\int_{-\pi}^{\pi} d\phi\, \gamma e\left(v_x^2 + v_y^2\right)}$ and $\alpha_2 = \dfrac{\int_0^{\infty} r\,dr \int_{-\pi}^{\pi} d\phi\, \gamma e\left(v_x^2 - v_y^2\right)}{\int_0^{\infty} r\,dr \int_{-\pi}^{\pi} d\phi\, \gamma e\left(v_x^2 + v_y^2\right)}$

Deviation from local equilibrium at 0.6 fm/c



Velocity anisotropy at $\tau = 0.6$ fm/c



Summary

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

Radial flow and magnitude of viscous effects vary between models, but flow anisotropies seem to be more universal