GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Effects of Dissipation in HIC

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H-QM | Helmholtz Research School Quark Matter Studies

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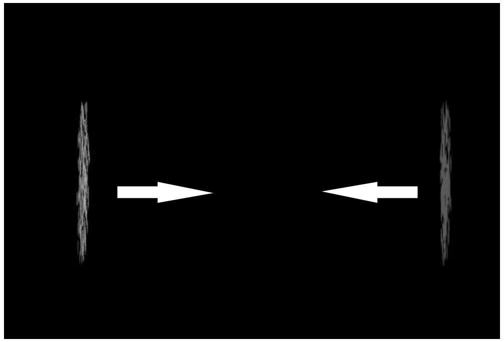
- Motivation/Introduction
- Hydrodynamics
- HIC
- Effective Viscosities
- Conclusions/Perspectives

Motivation I

- Success of the hydrodynamical aproach in describing many observables in the Relativistic Heavy Ion Colisions (QGP)

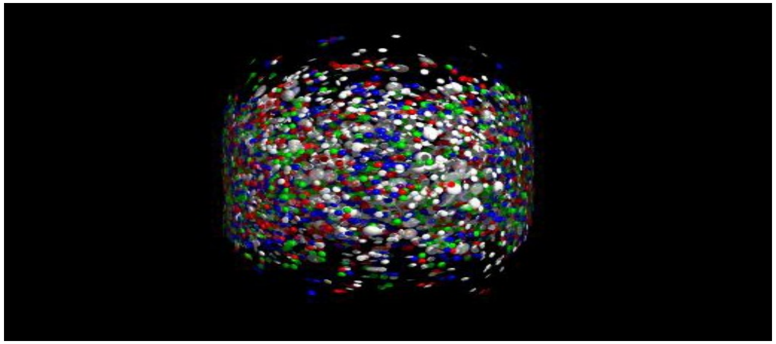
  - Created matter behaves as a fluid
  - Thermalization at very early times $\tau \sim 1\ \mathrm{fm}$
  - “small” viscosity (but important ...)

Rel. Heavy Ion Collision - Illustration



$\tau \sim 1$ fm

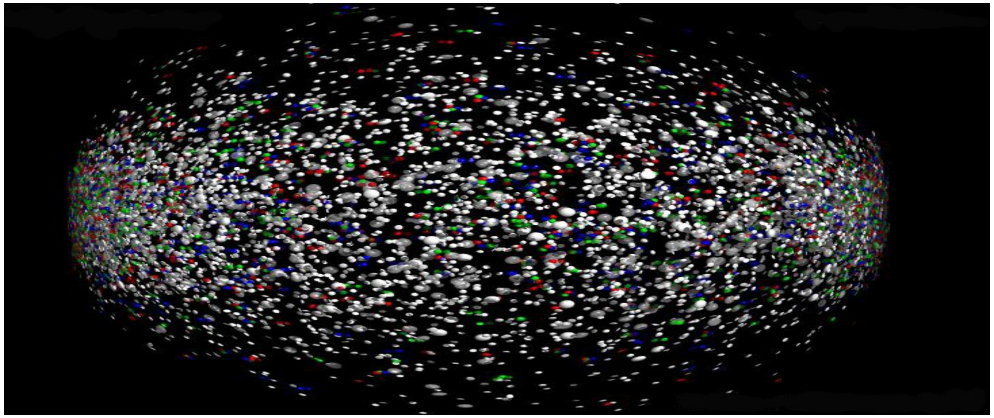
System achieves
local thermal equilibrium



Can be described
by Fluid Mechanics

EoS, η, τ_π ...

$\tau \sim 15$ fm



Negligible
interactions

Dissipative Hydro

Conservation Laws

$$\partial_\mu T^{\mu\nu} = 0, \qquad \partial_\mu N^\mu = 0.$$

bulk viscosity shear viscosity

$$T^{\mu\nu} = \varepsilon u^\mu u^\nu - \Delta^{\mu\nu}(P + \Pi) + \pi^{\mu\nu}$$
$$N^\mu = n u^\mu + n^\mu$$

Particle difusion

$$\varepsilon = \varepsilon(P)$$

EoS

$$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$$

We need eqs. for shear, ...

Hydro Equations

Relativistic Navier Stokes

Acausal

Unstable

$$
\begin{aligned}
\pi^{\mu\nu} &= 2\eta\nabla^{<\mu}u^{\nu>} \\
\Pi &= -\zeta\nabla_{\mu}u^{\mu} \\
n^{\alpha} &= \kappa\nabla^{\alpha}\left(\mu/T\right)
\end{aligned}
$$

$$
\begin{aligned}
A^{<\mu\nu>} &= \Delta^{\mu\nu\alpha\beta}A_{\alpha\beta} \\
\Delta^{\mu\nu\alpha\beta} &= \frac{1}{2}\left(\Delta^{\mu\alpha}\Delta^{\nu\beta}+\Delta^{\mu\beta}\Delta^{\nu\alpha}\right)-\frac{1}{3}\Delta^{\mu\nu}\Delta^{\alpha\beta}
\end{aligned}
$$

Retardation Effect

Second Order Theories

Can be causal (stable)!

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta \nabla_\alpha u^\alpha + \dots$$
$$\tau_n \dot{n}^{<\alpha>} + n^\alpha = \kappa \nabla^\alpha (\mu/T) + \dots$$
$$\tau_\pi \dot{\pi}^{<\mu\nu>} + \pi^{\mu\nu} = 2\eta \nabla^{<\mu} u^{\nu>} + \dots$$

(*) Relaxation times

(*) Viscous effects are not generated immediately

From Kinetic theory (Moments Method)

$$\dot{\Pi} + \frac{\Pi}{\tau_\Pi} = -\frac{\zeta}{\tau_\Pi}\nabla_\mu u^\mu + \tau_{\Pi n} n \cdot \dot{u} - \ell_{\Pi n}\partial \cdot n$$
$$-\hat{\zeta}_1 \Pi \nabla_\mu u^\mu + \hat{\zeta}_2 n \cdot \nabla\alpha_0 + \hat{\zeta}_3 \pi_{\mu\nu}\sigma^{\mu\nu}$$

Bulk

Particle Difusion

Shear

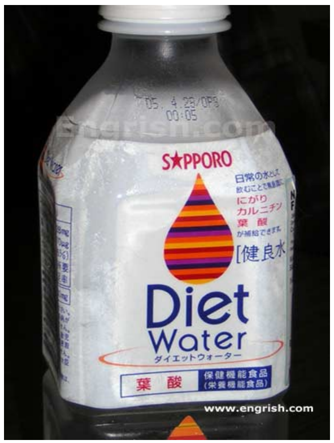
$$\dot{n}^{<\mu>} + \frac{n^\mu}{\tau_n} = \frac{\kappa}{\tau_n}\nabla^\mu \alpha_0 - \hat{\kappa}_1 n^\mu \nabla_\alpha u^\alpha - \hat{\kappa}_2 n_\alpha \nabla^{<\mu} u^{\alpha>} - \hat{\kappa}_3 \Pi \nabla^\mu (\mu/T) + \hat{\kappa}_4 \pi^{\mu\nu}\nabla_\nu (\mu/T)$$
$$+ n_\alpha \omega^{\mu\alpha} - \ell_{n\Pi}\nabla^\mu \Pi + \ell_{n\pi}\Delta^{\mu\alpha}\partial^\beta \pi_{\alpha\beta} + \tau_{n\Pi}\Pi \dot{u}^\mu + \tau_{n\pi}\pi^{\mu\nu}\dot{u}_\nu$$

$$\dot{\pi}^{<\mu\nu>} + \frac{\pi^{\mu\nu}}{\tau_\pi} = 2\frac{\eta}{\tau_\pi}\sigma^{\mu\nu} + 2\pi_\lambda^{<\mu}\omega^{\nu>\lambda} + 2\Pi\sigma^{\mu\nu}$$
$$-2\hat{\eta}_1 \pi_\lambda^{<\mu}\sigma^{\nu>\lambda} - 2\hat{\eta}_2 n^{<\mu}\nabla^{\nu>}\alpha_0 - \hat{\eta}_3 \pi^{\mu\nu}\nabla_\alpha u^\alpha + 2\hat{\eta}_4 \Pi \sigma^{\mu\nu}$$
$$-2\ell_{\pi n}\nabla^{<\mu} n^{\nu>} + 2\tau_{\pi n} n^{<\mu}\dot{u}^{\nu>}$$

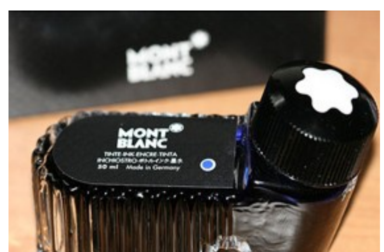
Israel&Stewart(1978)
Betz&Koide&Niemi&Rischke(2008)
GSD&Koide&Rischke(2010)

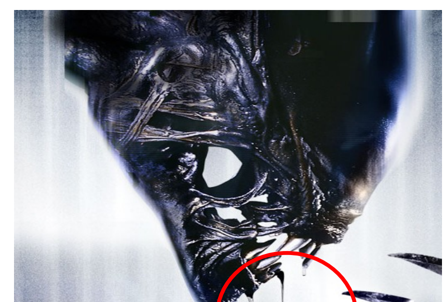
Different types of Fluids

Newtonian Fluids



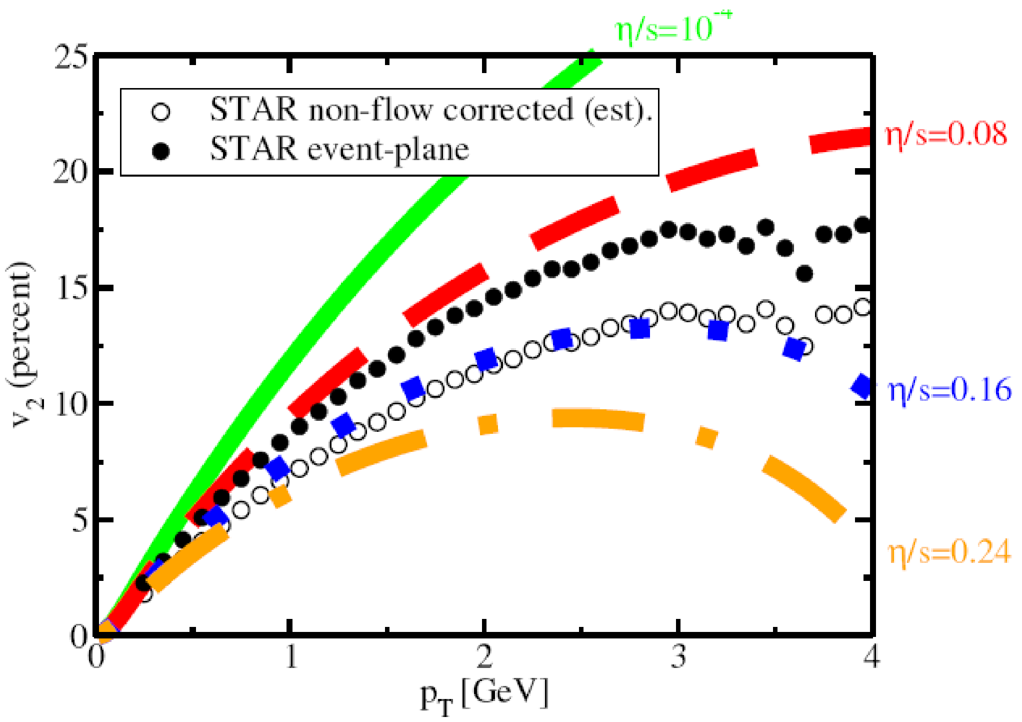
Non-Newtonian Fluids





Relativistic Fluids cannot be Newtonian

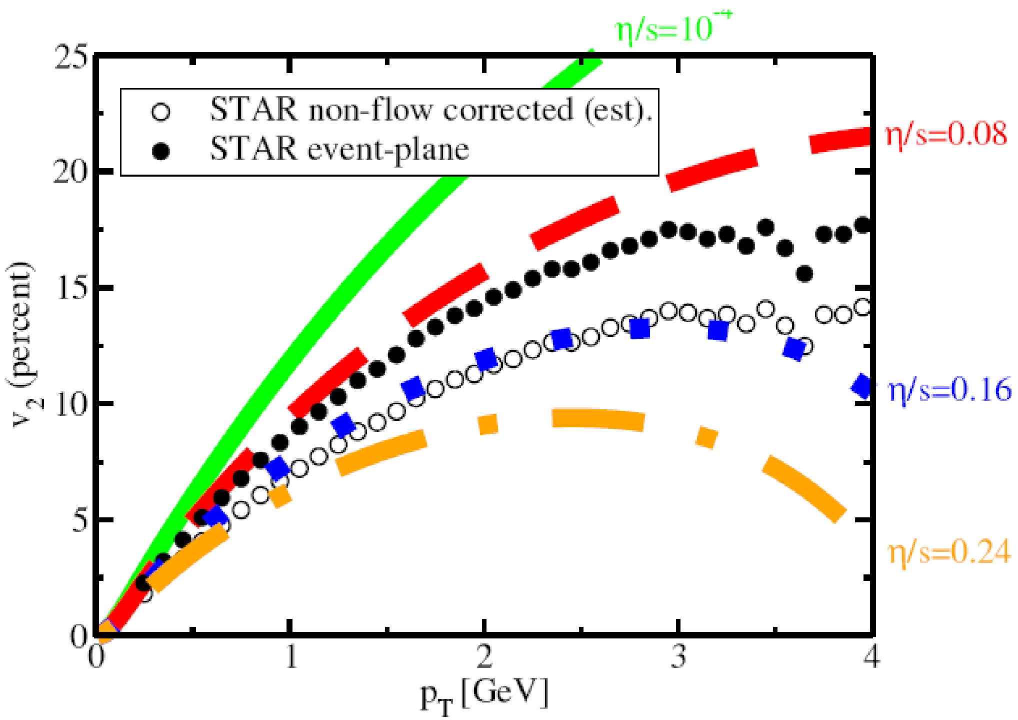
Constraining η/s from data



$\eta/s \sim 0.15$

Luzum&Romatschke

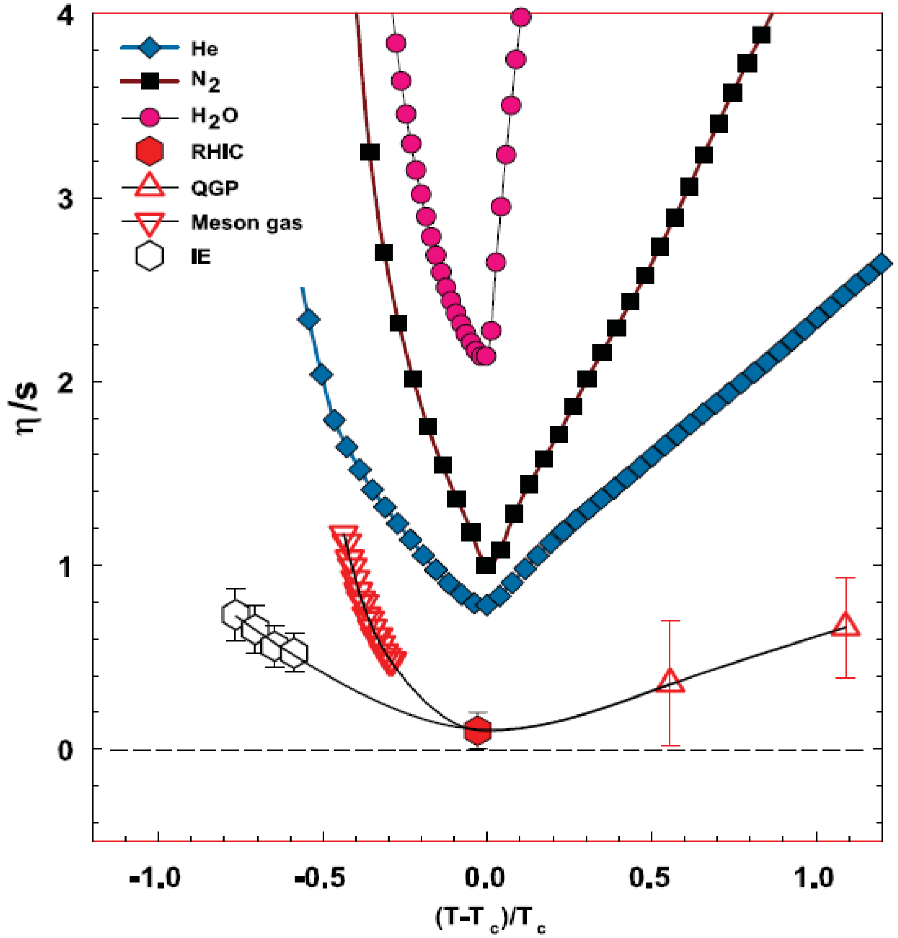
Constraining η/s from data



$\eta/s \sim 0.15$

However, η/s is not constant !

Old News ...



Lacey *et al*(2007)

η/s is minimum

at Tc

effective η/s ?

Before:

Hirano&Gyulassy(2006)

Csernai&Kapusta&McLerran(2006)

What we do

3D simulations with Bulk and Shear viscosities, considering realistic transport coefficients

What we investigate

- ✓ Can we use a constant η/s ?
- ✓ What does it mean ?

effective η/s ?

- ✓ Effect of Relaxation time ?
  (deviations from NS ?)

Scheme

✔We solve the dissipative hydrodynamical equations using the SPH method

GSD&Koide&Kodama&Mota(2009)

J. Phys. G36, 035103

✔Freeze-out via SPH method

Aguiar&Kodama&Osada&Hama (2001)

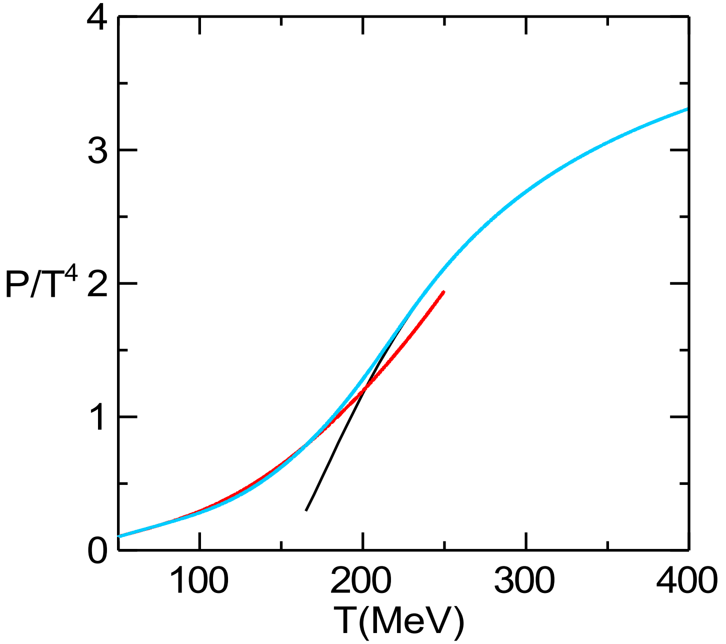
J. Phys. G27, 75

No out-of-equilibrium corrections ...

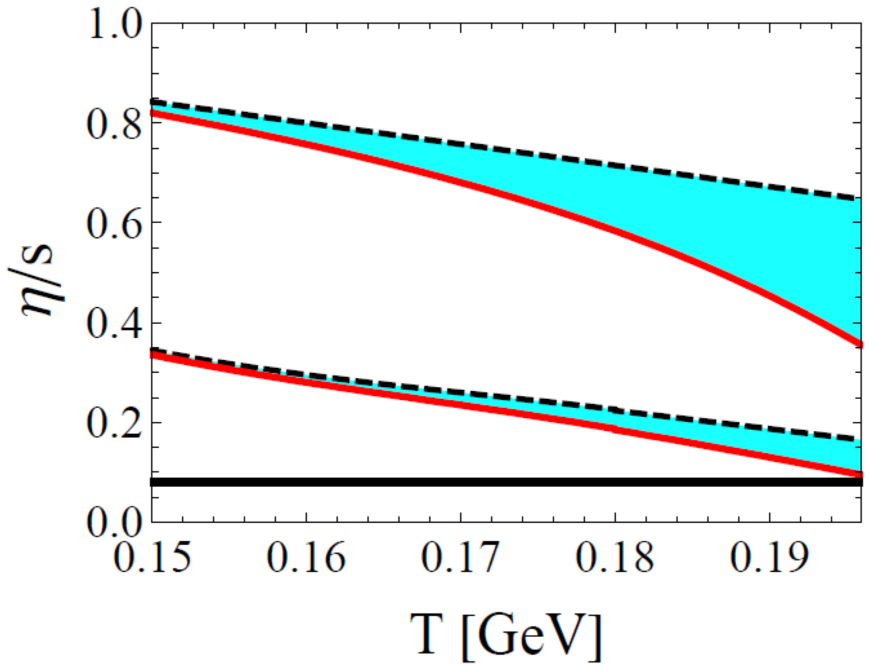
✔Initial Condition: Glauber Model $\tau_0 = 0.6$ fm

PRC78 024902

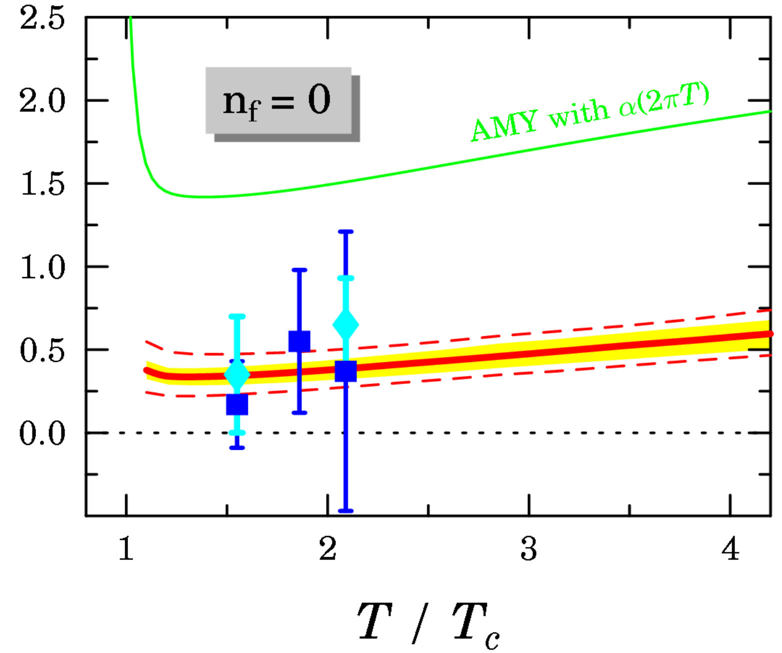
✔EoS: Hadron Ressonance Gas + Lattice QCD - Crossover



Transport Coef.

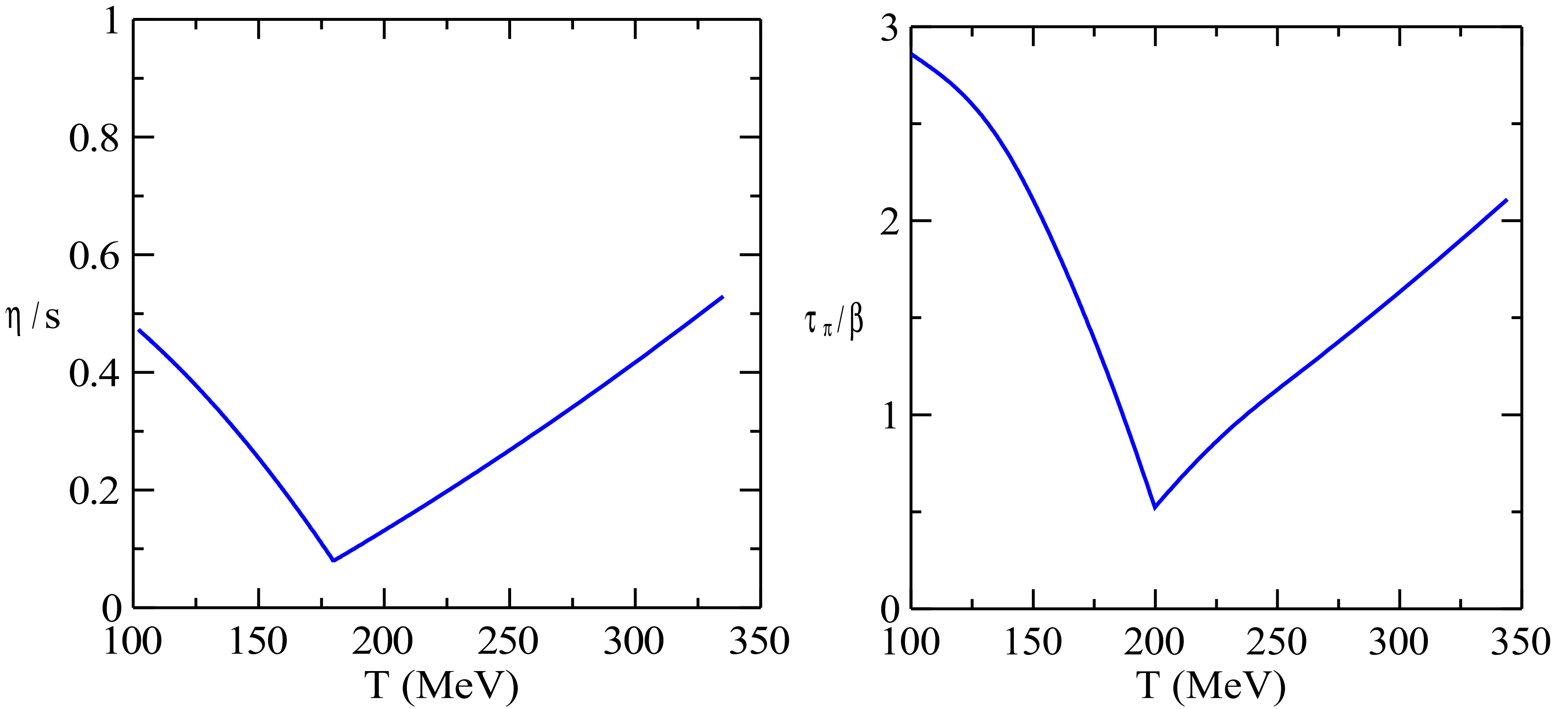


Noronha-Hostler&Noronha&Greiner



AMY, LQCD,A. Peshier

Transport Coefficients (Fits)



Generalized Kubo Formula (Koide *et al*):

Leading order, η is the same

$$\tau_\pi = \frac{\eta}{P}$$

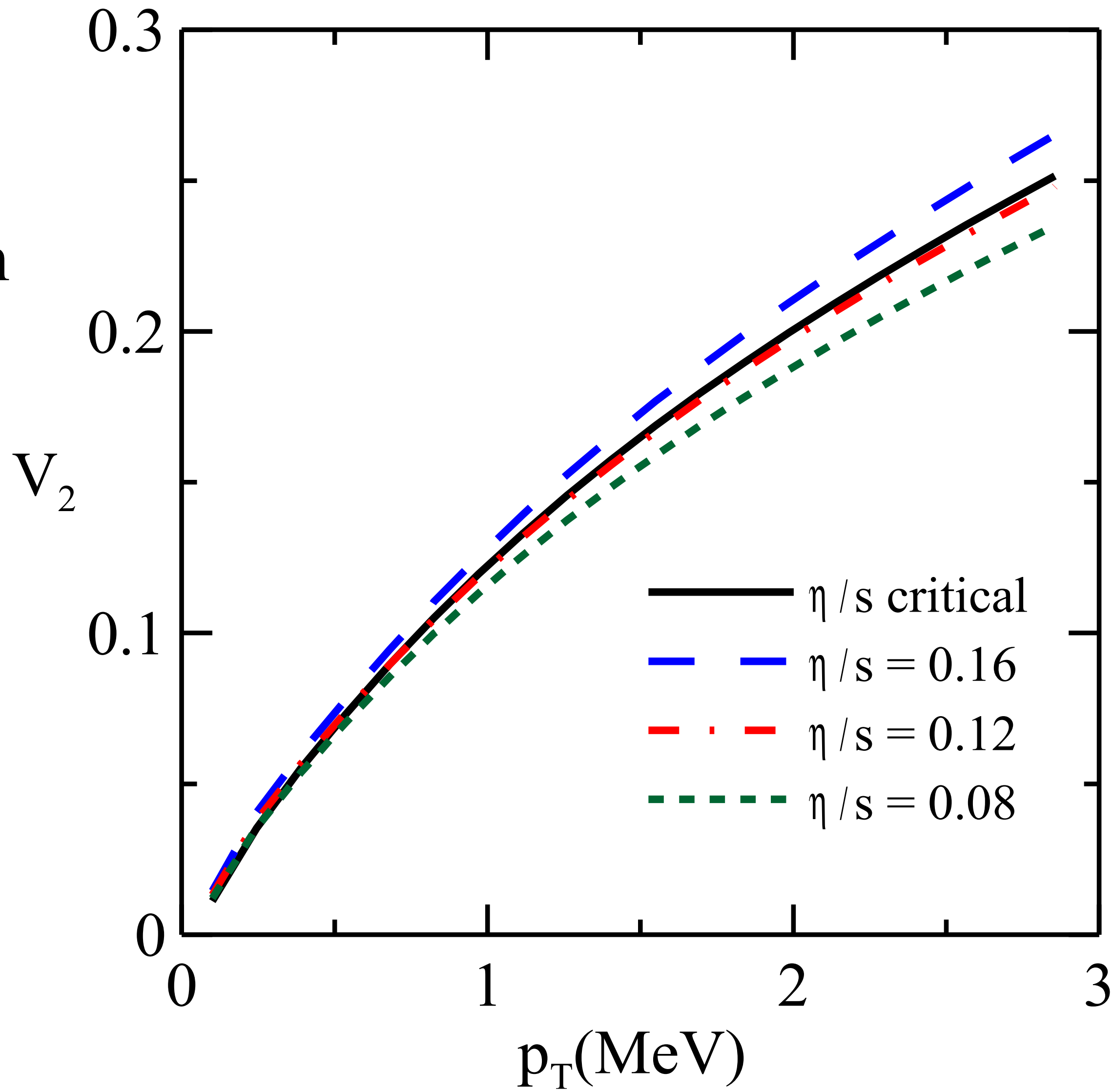
Results:

T_F=130MeV

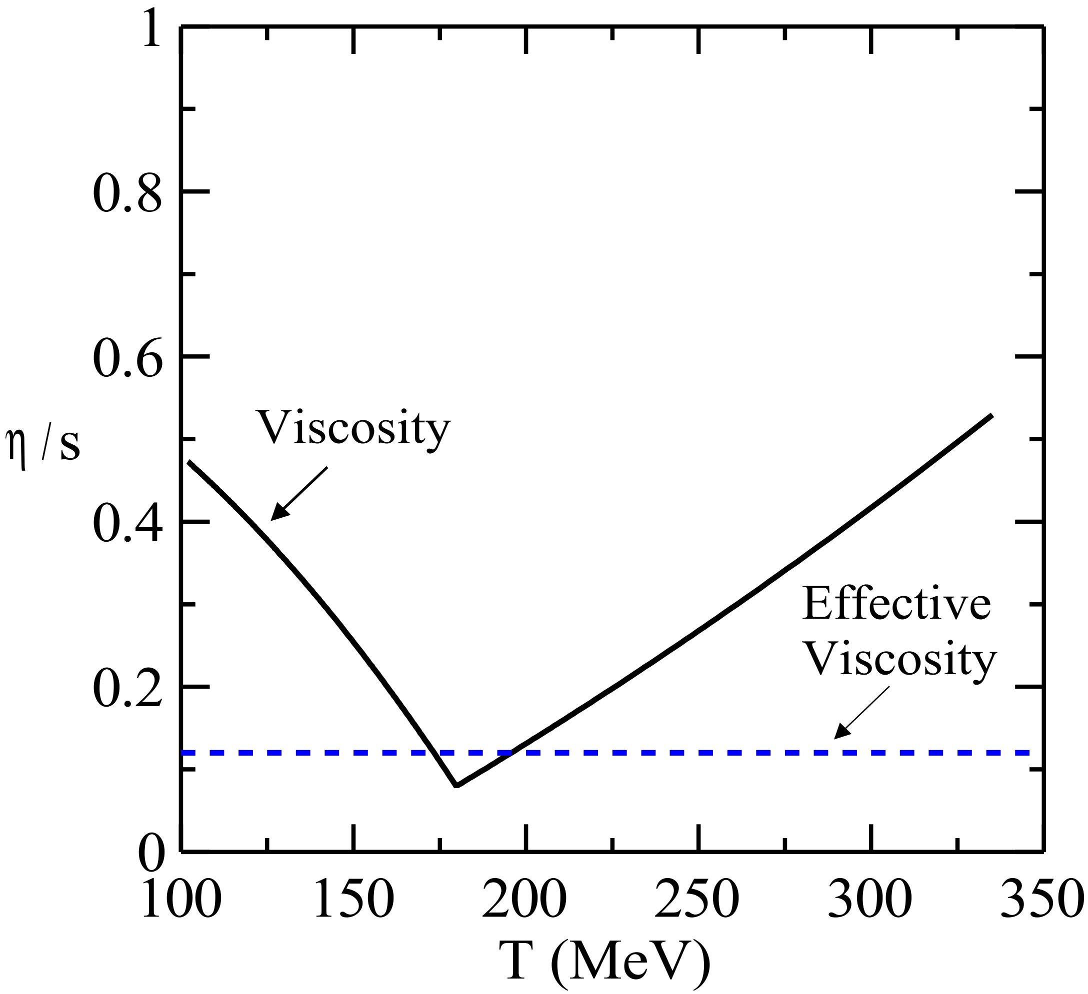
pions - b=7.53

For shear, we found an effective viscosity of

$\eta / s \approx 0.12$



Small "Effective" shear viscosity



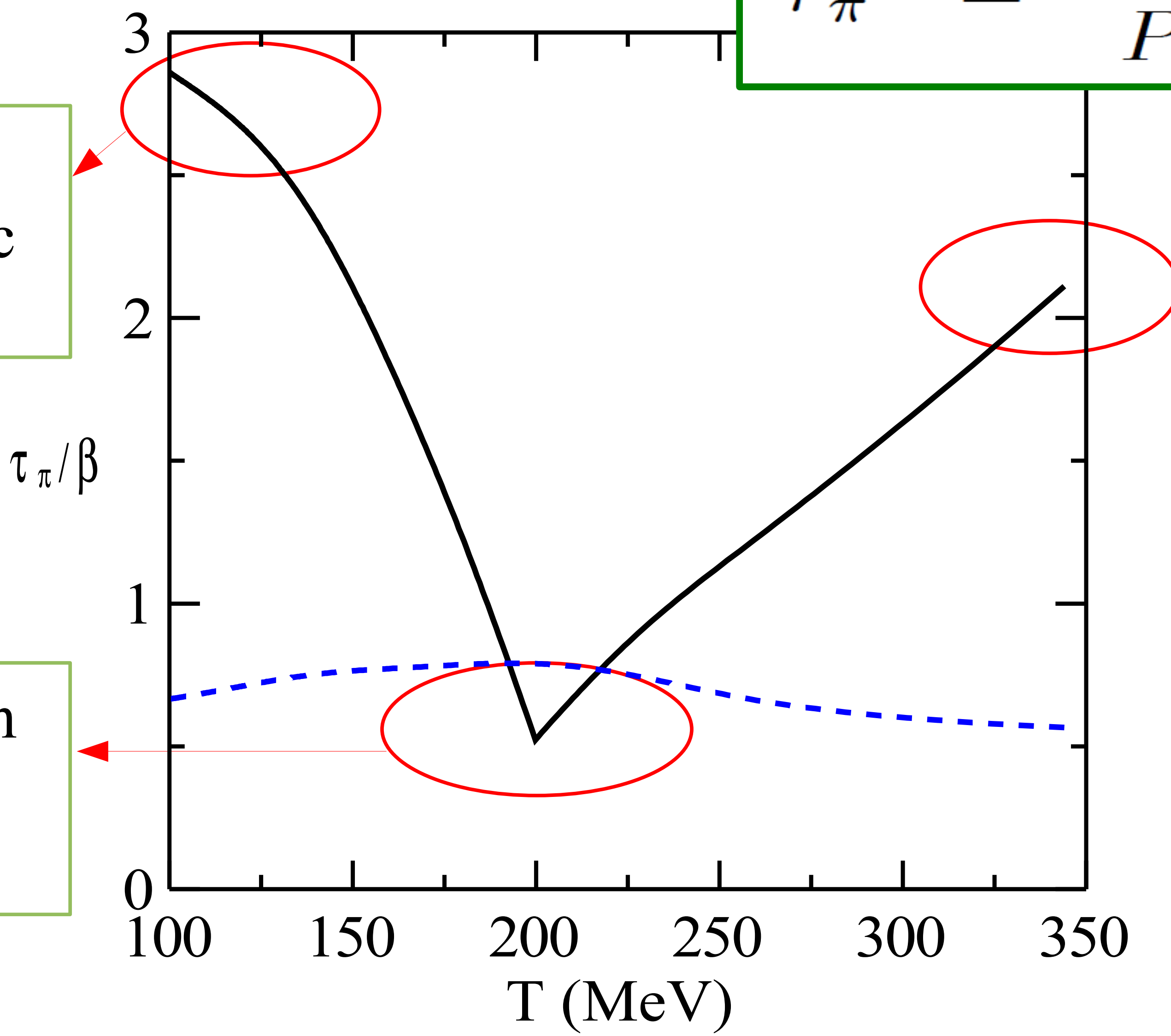
Effetively, viscosity is small

Effects from viscosity come mostly from the phase transition region

Relaxation Time - shear

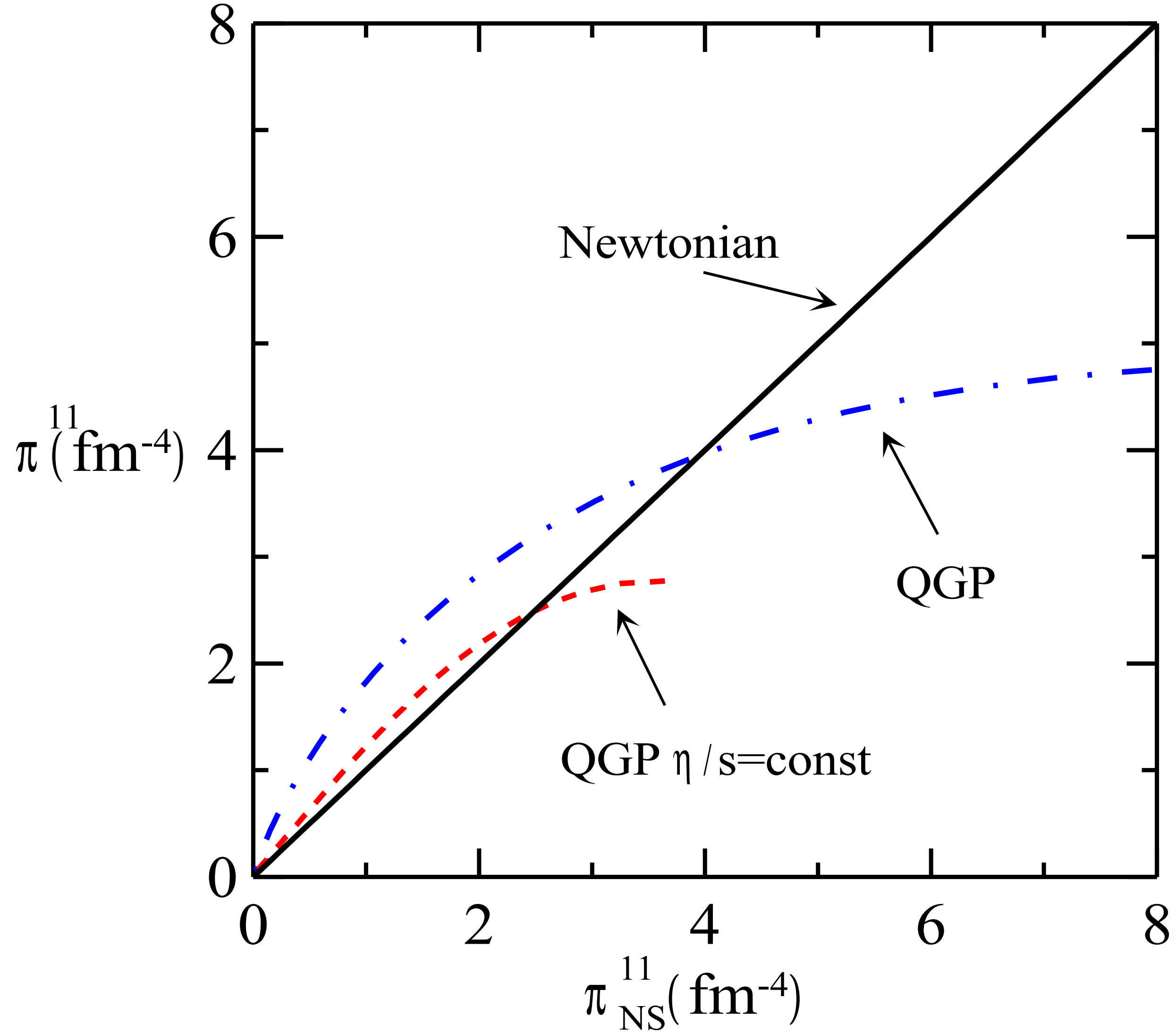
$$\tau_\pi = \frac{\eta}{P}$$

huge relaxation times at hadronic phase



Small Relaxation time at phase transition

Deviations from Navier-Stokes



Comment

if

$$\tau_\pi = 3\frac{\eta}{P}$$

The effective viscosity becomes smaller than the minimum value of η/s

The value of the effective viscosity does not necessarily relate to the actual viscosity

We need to know relaxation time !

Conclusions

Viscous Effects are generated mainly near the phase transition

Relaxation Time is very important to determine the effective viscosity of the system

LHC → More time in QGP phase → higher "effective" η/s ?