Dissipative effects from transport and viscous hydrodynamics

Pasi Huovinen

Purdue University

Denes Molnar

RIKEN/BNL Research Center & Purdue University

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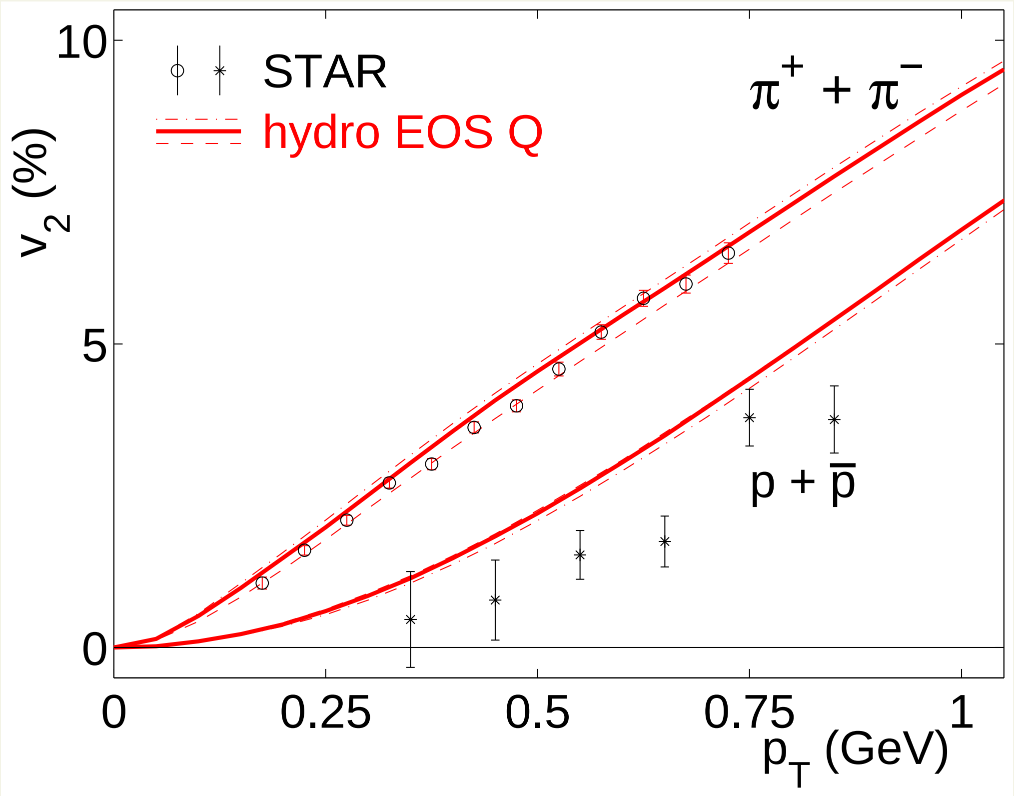
Success of ideal hydrodynamics

Kolb, Heinz, Huovinen et al ('01) **minbias Au+Au at RHIC**



$\Rightarrow$ **the idea of plasma as "perfect fluid"**

- **but how perfect? - what if $\eta/s > 0$, e.g., the conjectured $\eta/s \geq 1/(4\pi)$**

Two options to study dissipative effects at RHIC

- causal viscous hydrodynamics

Israel, Stewart; ... Muronga, Rischke; Teaney; Romatschke et al; Heinz et al...

- covariant transport

Israel, de Groot,... Zhang, Gyulassy, DM, Pratt, Xu, Greiner...

Viscous hydrodynamics

relativistic Navier-Stokes hydro: small corrections linear in gradients

$$T^{\mu\nu}_{NS} = T^{\mu\nu}_{ideal} + \eta(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}\partial^\alpha u_\alpha) + \zeta\Delta^{\mu\nu}\partial^\alpha u_\alpha$$

$$N^\mu_{NS} = N^\mu_{ideal} - \frac{n}{e+p}\kappa\nabla^\mu T$$

where $\Delta^{\mu\nu} \equiv u^\mu u^\nu - g^{\mu\nu}$, $\nabla^\mu = \Delta^{\mu\nu}\partial_\nu$

η, ζ **shear and bulk viscosities,** κ **heat conductivity**

two problems:

parabolic equations $\rightarrow$ **acausal** Müller ('76), Israel & Stewart ('79) ...

instabilities Hiscock & Lindblom, PRD31, 725 (1985) ...

Causal viscous hydro

Müller, Israel & Stewart...

$$\Delta T^{\mu\nu} \equiv \pi^{\mu\nu} + \Pi\Delta^{\mu\nu} \quad , \qquad \Delta N^{\mu} = -\tfrac{n}{e+p} q^{\mu}$$

bulk pressure Π, shear stress $\pi^{\mu\nu}$ heat flow q^{μ} treated as independent dynamical quantities that relax toward their Navier-Stokes value on time scales $\tau_\Pi(e,n)$, $\tau_\pi(e,n)$, $\tau_q(e,n)$ - corresponds to keeping not only first but (certain) second derivatives

schematically

$$\dot{X} = -\frac{X - X_{NS}}{\tau_X}$$

restores causality (for not too small τ_X) telegraph eqn

In the literature

Romatschke & Romatschke, arXiv:0706.1522:

- Au+Au, minimum bias
- initial density different for ideal and dissipative evolution
- EoS with phase transition
- $T_{\rm fo} = 150$ MeV

Song & Heinz, arXiv:0709.0742 and 0712:3715:

- Cu+Cu, $b = 7$ fm
- ideal gas EoS or EoS with phase transition
- $T_{\rm fo} = 130$ MeV

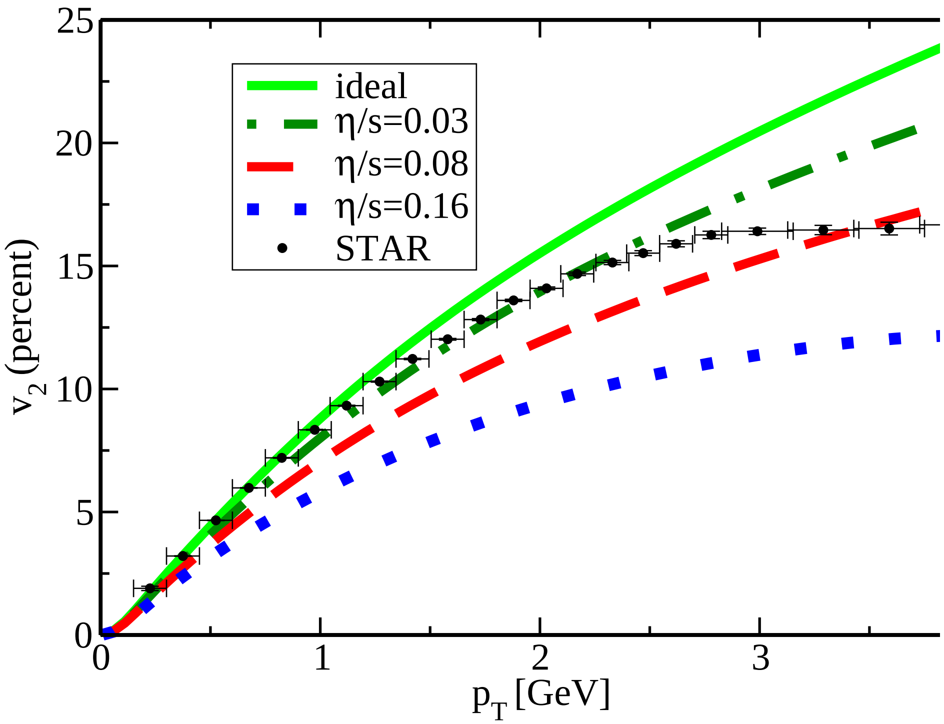
Dusling & Teaney, arxiv:0710.5932:

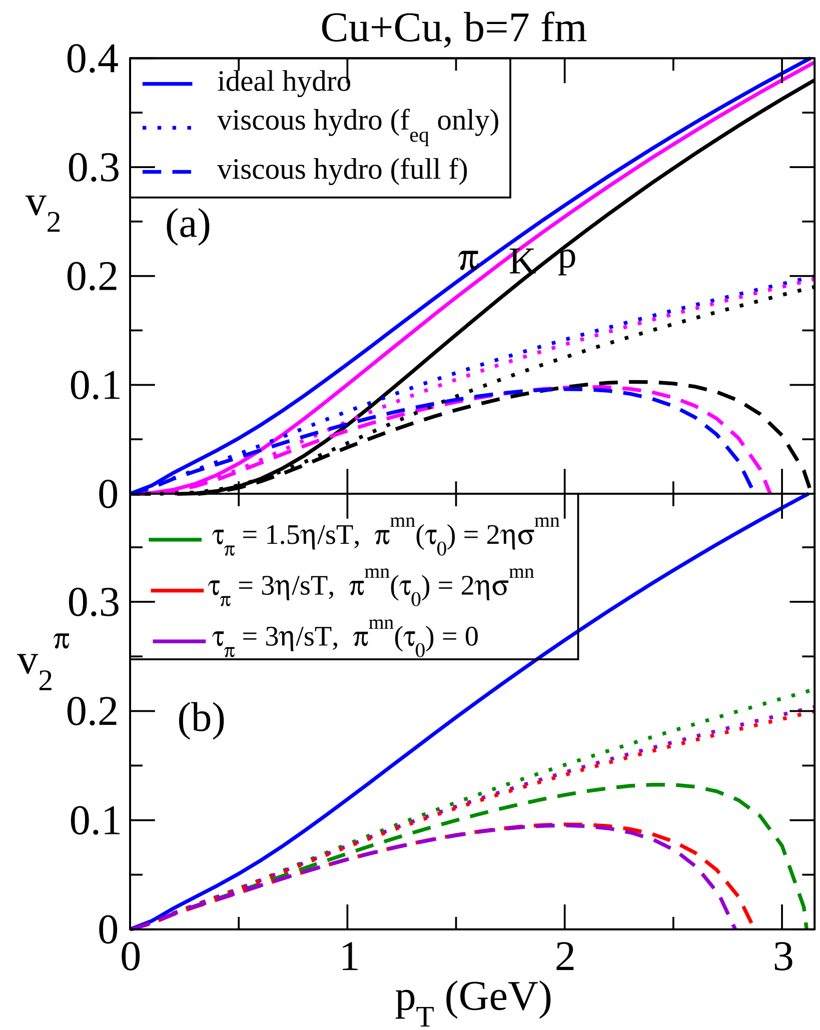
- equations by Öttinger and Grmela
- Au+Au, $b = 6.5$ fm
- ideal gas EoS
- Freeze-out at $\tau_R \sim \partial_\mu u^\mu$

Chaudhuri, arXiv:0704.0134 and 0801.3180:

- Au+Au, various centralities
- initial shear from Navier-Stokes
- ideal EoS or EoS with phase transition

$\eta/s = 1/(4\pi)$ corrections from IS hydro

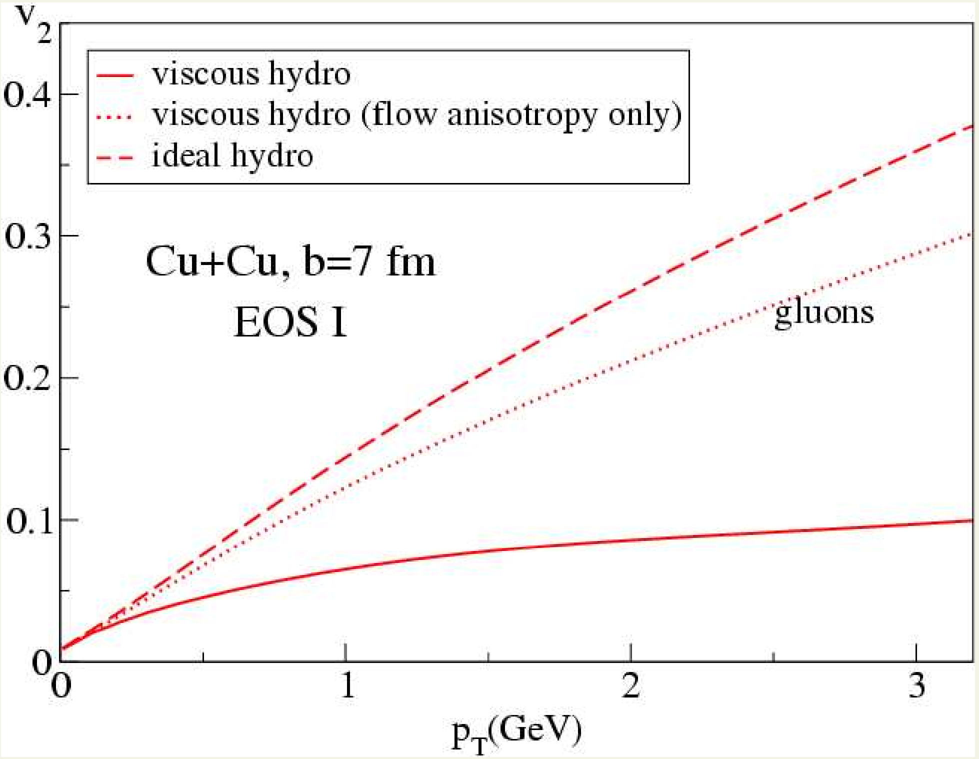


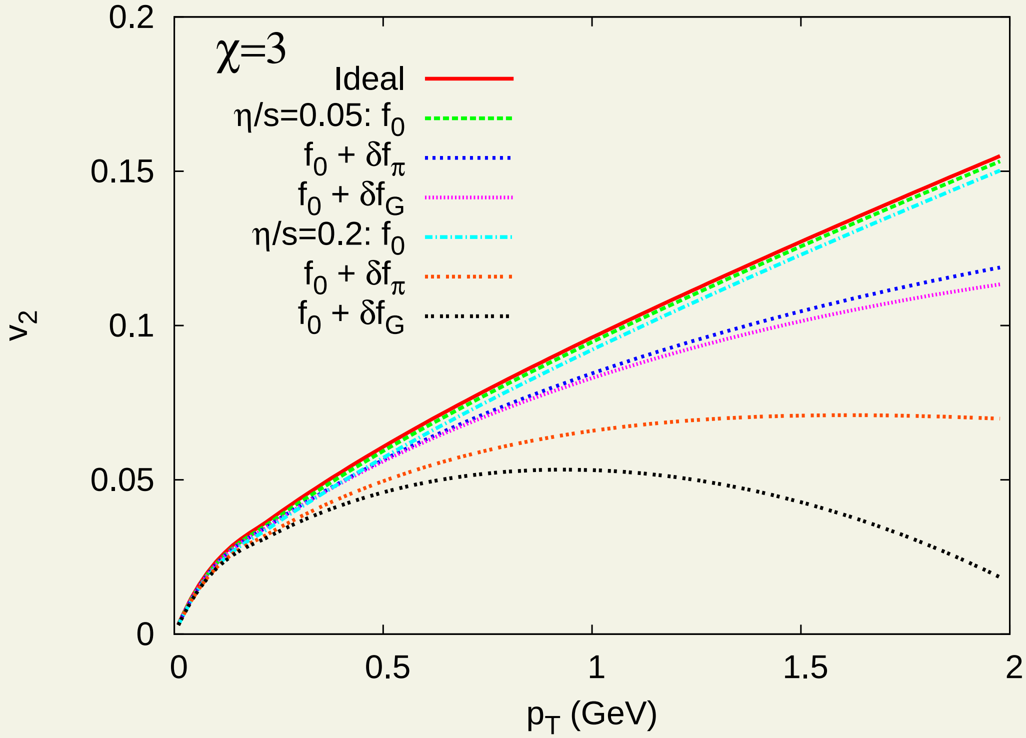


Romatschke & Romatschke, arxiv:0706.1522

Song & Heinz, arxiv:0709.0742

10-20% **or** **50+% reduction??**





Song & Heinz, arXiv:0712:3715

Dusling & Teaney, arxiv:0710.5932

corrections to flow or **only to distributions**?

Potential caveat

Whereas Navier-Stokes is an expansion in λ/R (keeps only first derivatives), Israel-Stewart hydro is NOT a controlled approximation (retains certain second derivatives). For example in kinetic theory, it corresponds to Grad's 14-moment approximation

$$f(x,p) \approx [1 + C_{\alpha\beta} p^\alpha p^\beta] e^{(\mu - p^\mu u_\mu)/T}$$

while NS comes from the Chapman-Enskog expansion in small gradients

$$E \partial t f + \epsilon \cdot \vec{p} \vec{\nabla} f = C[f] \quad , \qquad f = f_0 + \epsilon f_1 + \epsilon^2 f_2 + \ldots$$

If relaxation effects important, NS and IS are different

$\Rightarrow$ **control against a nonequilibrium theory is crucial**

Covariant transport

Boltzmann ..., Israel, Stewart, de Groot, ... Pang, Zhang, Gyulassy, DM, Vance, Csizmadia, Pratt, Cheng, Xu, Greiner ...

Covariant, causal, nonequil. approach - formulated in terms of local rates.

$$e.g.,\ \Gamma_{2\to 2}(x) \equiv \frac{dN_{scattering}}{d^4x} = \sigma v_{rel} \frac{n^2(x)}{2}$$

This theory has a hydrodynamic limit (i.e., it equilibrates) Boltzmann

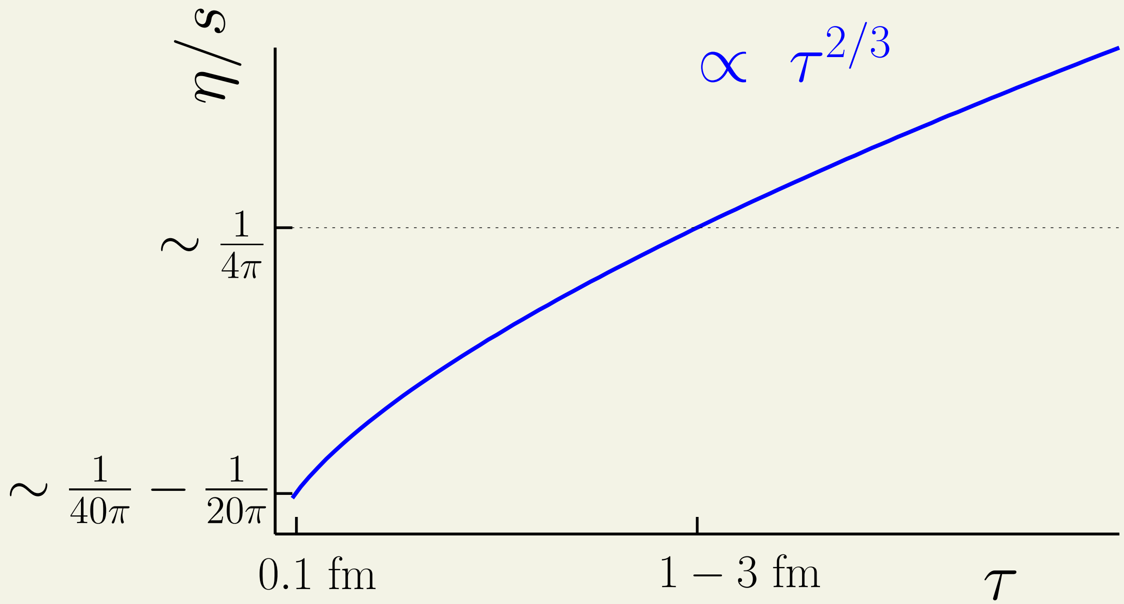
Parameter σ controls transport coefficients and relaxation:

$$\eta \approx 0.8 \frac{T}{\sigma_{tr}} \qquad\qquad \tau_\pi = 1.2\lambda_{tr}$$

solvable numerically: HERE, utilize MPC algorithm DM & Gyulassy, NPA 697 ('02)

In transport $\eta/s \sim \lambda_{tr} T \sim 1/(\sigma T^2)$

e.g., for $\sigma \approx 50$ mb ($\sigma_{tr} \approx 14$ mb)

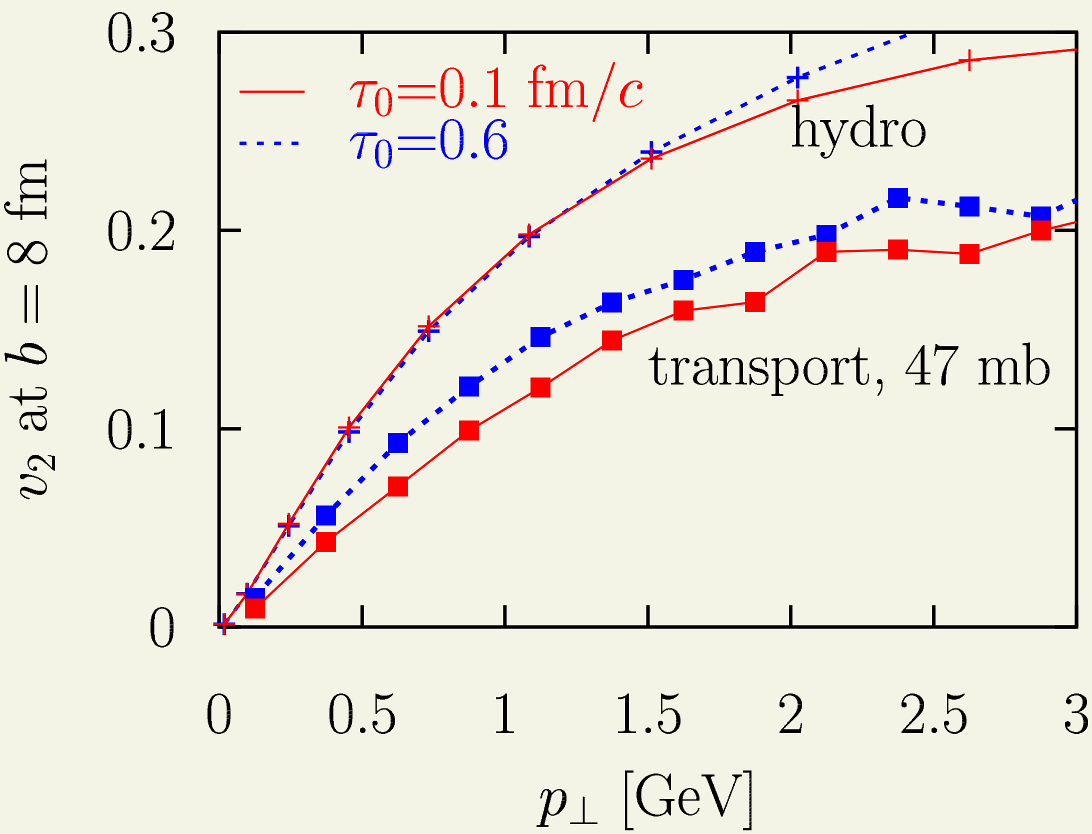


$\Rightarrow \eta/s = const$ **needs growing** $\sigma(\tau) \propto 1/T^2 \propto \tau^{2/3}$

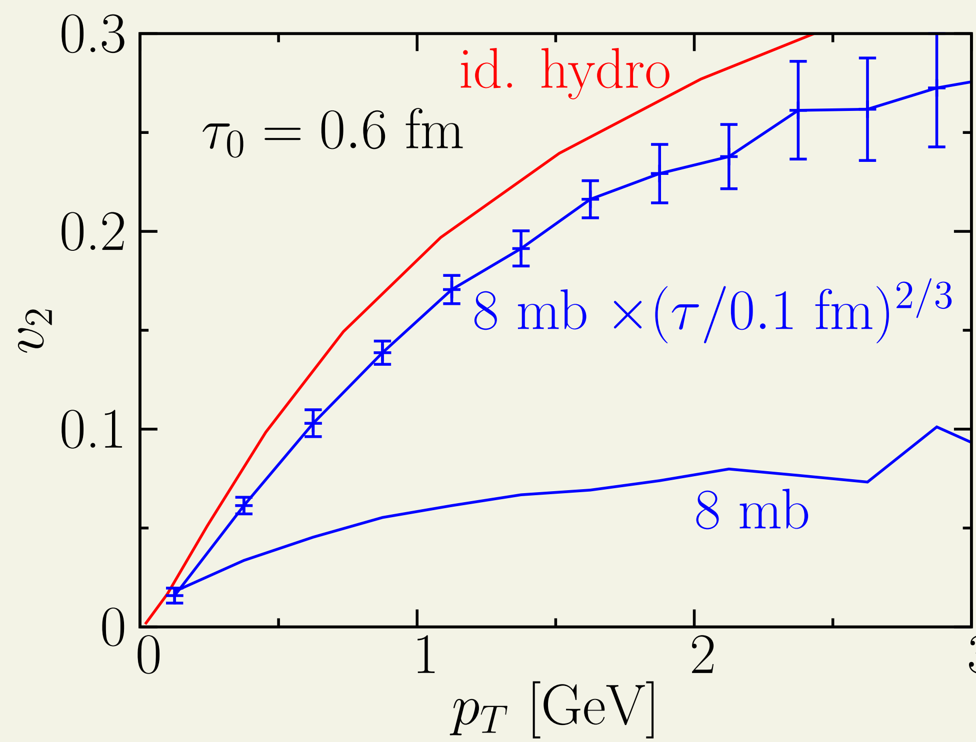
already encoded in perturbative QCD: $\sigma_{tr} \sim \frac{\alpha_s^2}{s} ln \frac{s}{\mu_D^2} \sim \frac{g^4}{T^2} ln \frac{1}{g^2}$

Ideal hydro vs transport

$\sigma \approx 50$ **mb** DM & Huovinen, PRL94 ('05)



$\eta/s \approx 1/(4\pi)$ DM @ QM2006



$15 - 30\%$ **reduction of v_2 from transport due to dissipation**

Viscous hydro vs transport

We solve the full Israel-Stewart equations, including vorticity terms from kinetic theory, in a 2+1D boost-invariant scenario. **Shear stress only.**

Mimic a known reliable transport model:

- **massless Boltzmann particles** $\Rightarrow \epsilon = 3P$
- **only** $2 \leftrightarrow 2$ **processes, i.e. conserved particle number**
- $\eta = 4T/(5\sigma_{\rm tr})$
- **either** σ **= const.** $= 47$ **mb** **(**$\sigma_{tr} = 14$ **mb)** $\leftarrow$ **the simplest in transport**
  or $\sigma \propto \tau^{2/3}$ $\Rightarrow \eta/s \approx 1/(4\pi)$

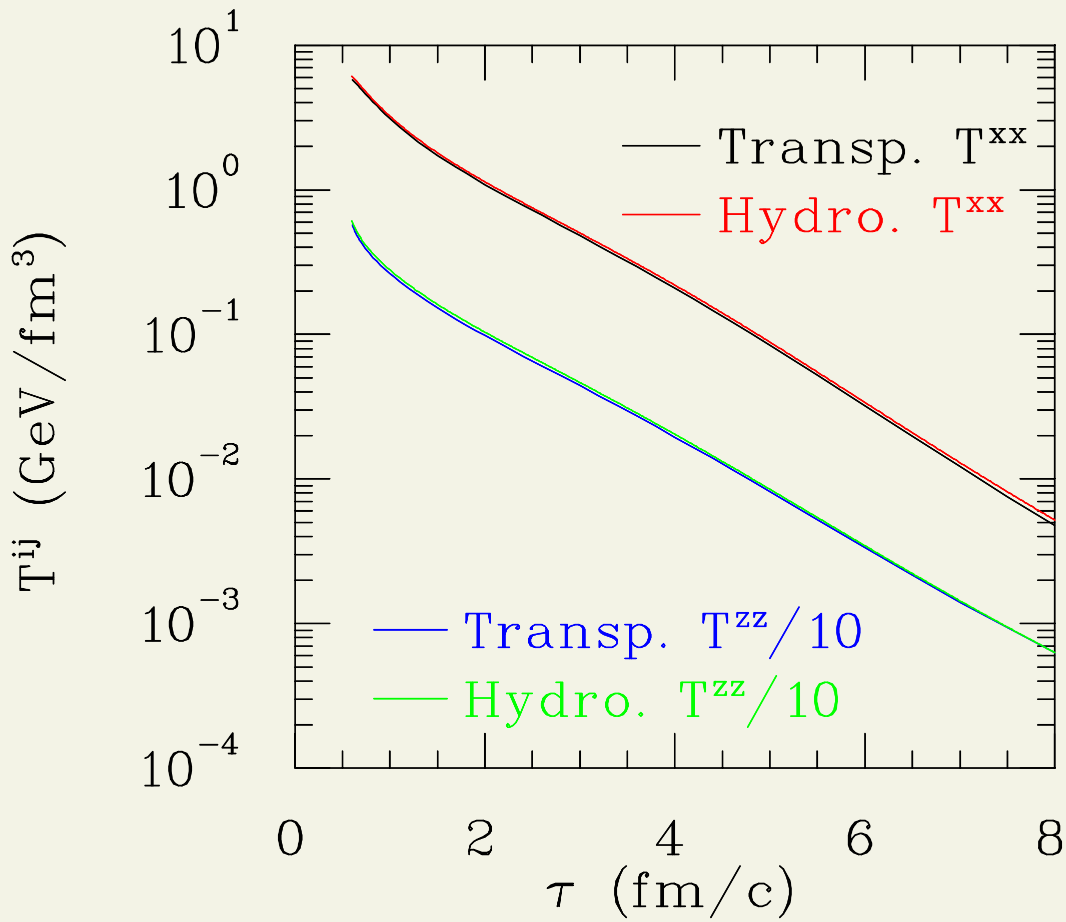
"RHIC-like" initialization:

- $\tau_0 = 0.6$ **fm/**c
- $b = 8$ **fm**
- $T_0 = 385$ **MeV and** $dN/d\eta|_{b=0} = 1000$
- **freeze-out at constant** $n = 0.365$ **fm**$^{-3}$

Pressure evolution in the core

T^{xx} **and** T^{zz} **averaged over the core of the system,** $r_\perp < 1$ **fm:**

$\boldsymbol{\eta/s \approx 1/(4\pi)}$ $(\sigma \propto \tau^{2/3})$

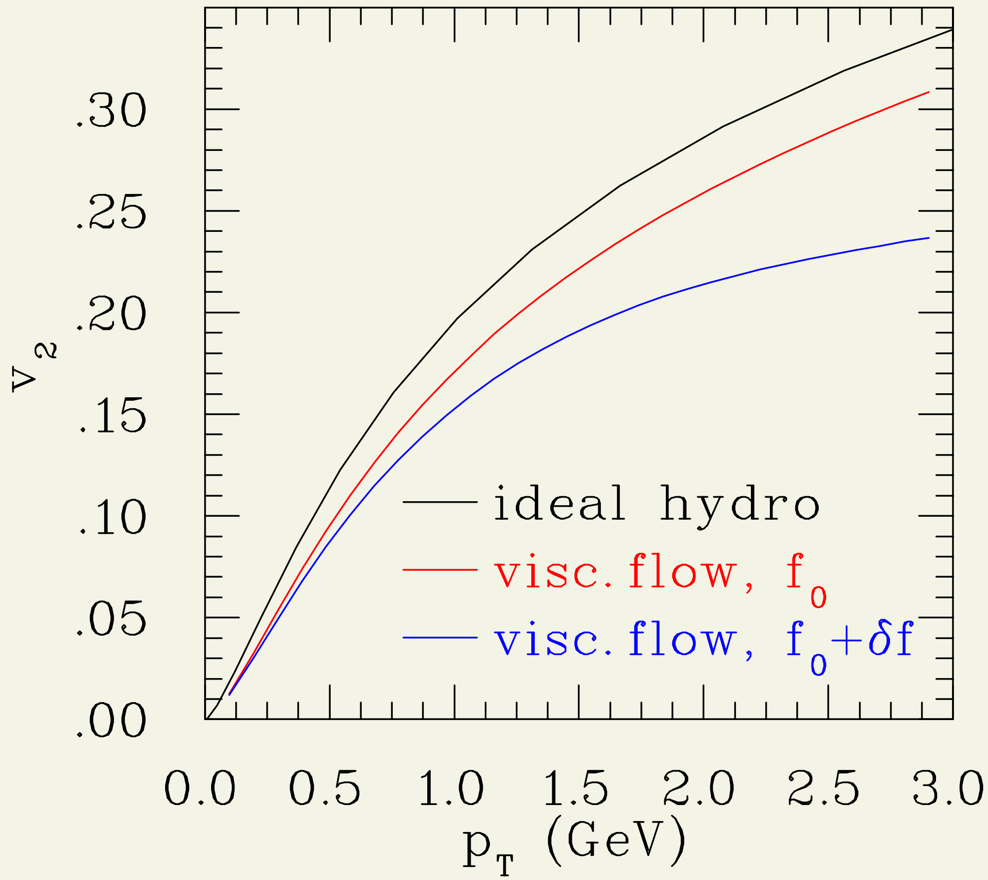


remarkable similarity!

Viscous hydro elliptic flow

TWO effects: **- dissipative corrections to hydro fields** u^μ, T, n
- dissipative corrections to thermal distributions $f \to f_0 + \delta f$

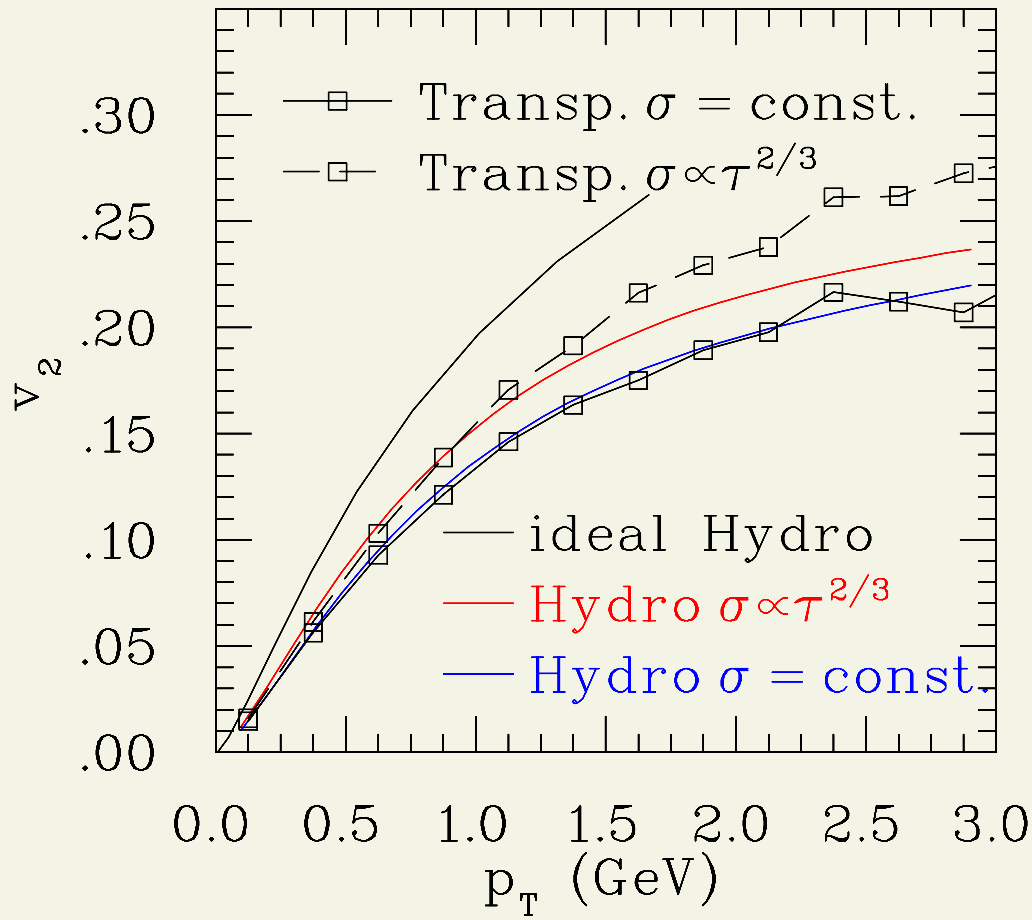
$\boldsymbol{\eta/s \approx 1/(4\pi)}$ $(\sigma \propto \tau^{2/3})$



$$\delta f = f_0 \left[1 + \frac{p^\mu p^\nu \pi_{\mu\nu}}{8nT^6}\right]$$

calculation for $\sigma_{\rm tr} = const \sim 15mb$ **shows similar behavior**

Viscous hydro vs transport v_2



- **excellent agreement when $\sigma =$ const $\sim 47mb$**
- **good agreement for $\eta/s \approx 1/(4\pi)$, i.e., $\sigma \propto \tau^{2/3}$**

- **BUT results sensitive to freeze-out criterion, especially at high pT**

Conclusions

Prospects for applicability of Israel-Stewart causal hydrodynamics at RHIC look promising, based on comparisons with covariant $2 \to 2$ transport in 2+1D Bjorken scenario.

Dissipative effects change both flow and distributions.

Dissipation reduces $v_2(p_T)$ by $20 - 30\%$, for $\eta/s = 1/(4\pi)$ and conditions expected at RHIC

NOTE: hydrodynamical results are sensitive to the freeze-out procedure

$\to$ being investigated

This is just the beginning, stay tuned.

- detailed cross-checks of other calculations, exploration of parameter space, etc, etc