Kinetic transport is needed to reliably extract shear viscosity from pA and AA data.

Aleksi Kurkela

Kurkela, Wiedemann, Wu, 1805.04081
Kurkela, Wiedemann, Wu, 1803.02072

QM2018 , May 2018

Smooth onset of flow-like signatures motivates to revisit the fluid dynamical paradigm.

- pp: particle production + free streaming.
  No final state interactions.

- AA: particle production + hydrodynamics.
  Large number of final state interactions

Questions:

Are there mesoscopic systems with few final state interactions?

How many final state interactions are needed to produce the observed azimuthal anisotropies?

How much of the observed signals can be accounted for by a single final state interaction?

Study development of azimuthal harmonics in transport theory:

- Fully formed complex phenomenological setups with as many physics features included as possible

  BAMPS, AMPT,...
- Rely on convoluted assumptions

  Jamie Nagle's talk

or

- Generic and tractable
- Minimal sensitivity to model details.
  Maximal sensitivity to physics assumptions.

Simplified model: *Isotropization time approximation*

$$\underbrace{\partial_t + \vec{v}_\perp \cdot \partial_{\vec{x}_\perp} F}_{\text{Free stream}} = -C[F] = \underbrace{-\gamma\epsilon^{1/4} u \cdot v}_{\text{isotropization time}} \ (F - F_{iso})$$

- Particles free stream
- Scattering isotropize in *local rest frame* in time $\tau_{iso} \sim \gamma\epsilon^{1/4}$
- Keep track of only p-integrated distribution function $F(\Omega) = \int 4\pi p^3 dp f(\vec{p})$

$T^{\mu\nu} = \int d\Omega v^\mu v^\nu F(\Omega)$

- Single parameter γ related to isotropization time of p-scale dominating F.

Agrees well with QCD kinetic theory for $T^{\mu\nu}$ evolution Kurkela, Heller, Spalinski 1609.04803

Initial condition with harmonic perturbations δ_n with event plane orientations ψ_n:

$$F_0 \sim \delta(v_z)\varepsilon_0 e^{-r^2/R^2}(1 + \delta_2(r^2/R^2)\cos(2\theta - 2\psi_2) + \ldots)$$

Scaling variable:

$$\hat{\gamma} = \frac{\text{Transverse system size}}{\text{Mean free path}} = \gamma R^{3/4}(\epsilon_0\tau_0)^{1/4}$$

$\tau_0 \to 0$, $\epsilon_0\tau_0$ fixed

Single-hit calculation $\mathcal{O}(\hat{\gamma})$:

$$\frac{dE_\perp}{d\eta_s d\phi} \equiv \int dp_\perp^2 \frac{p_\perp \, dN}{dp_\perp^2 \, d\eta_s d\phi}$$

$$= \frac{1}{2\pi} \frac{dE_\perp}{d\eta_s}\Big|_{\hat{\gamma}=0,\delta_n=0} \Big\{ 1 - 0.21\,\hat{\gamma} + 0.02\,\hat{\gamma}\delta_2^2 + 0.04\,\hat{\gamma}\delta_3^2$$
$$- 0.21\,\hat{\gamma}\delta_2\,2\cos(2\phi - 2\psi_2) - 0.14\,\hat{\gamma}\delta_3\,2\cos(3\phi - 3\psi_3)$$
$$+ 0.06\,\hat{\gamma}\delta_2^2 2\cos(4\phi - 4\psi_2) + 0.11\,\hat{\gamma}\delta_3^2 2\cos(6\phi - 6\psi_3)$$
$$+ 0.08\,\hat{\gamma}\delta_2\delta_3 2\cos(5\phi - 3\psi_3 - 2\psi_2) \Big\}$$

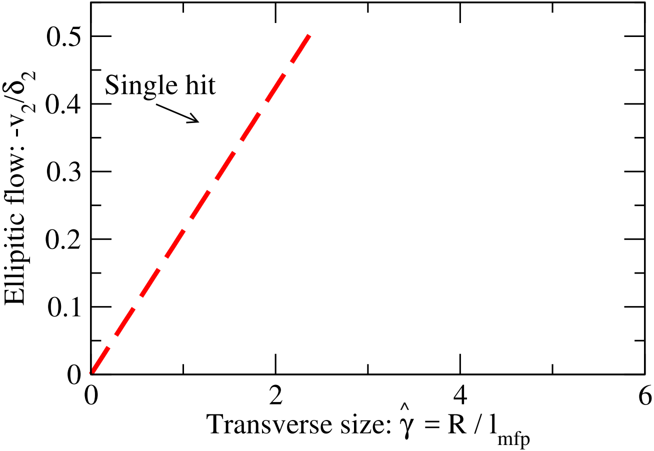
Kurkela, Wiedemann, Wu, 1803.02072

All linear and non-linear structures observed in the azimuthal anisotropies arise.

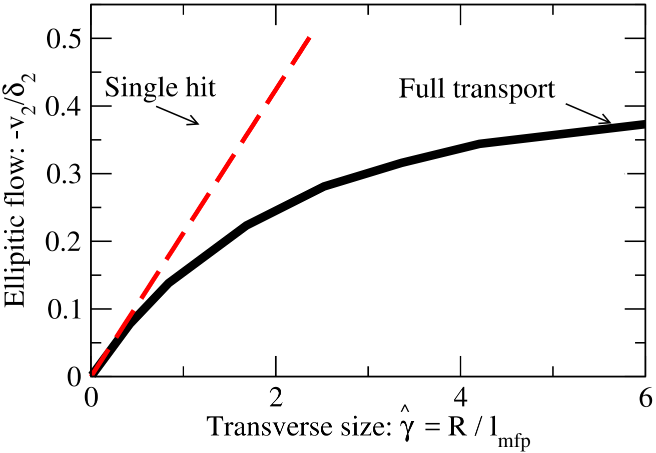
v_2/ϵ_2, mode-mode coupling, event plane correlations...

It swims like a duck, it quacks like a duck, it's probably a ...

Kurkela, Wiedemann, Wu, 1805.04081

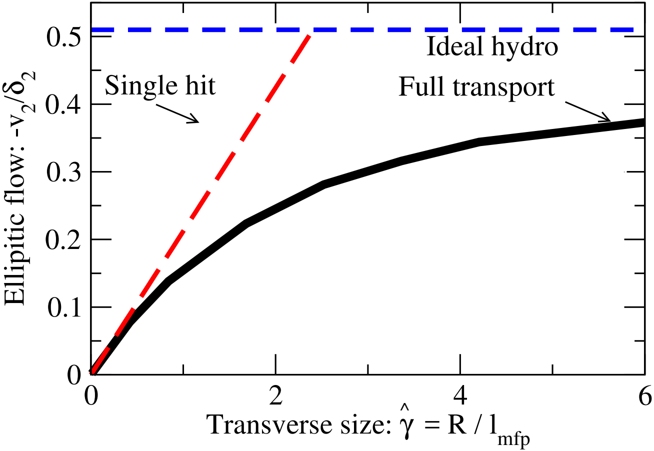


Kurkela, Wiedemann, Wu, 1805.04081

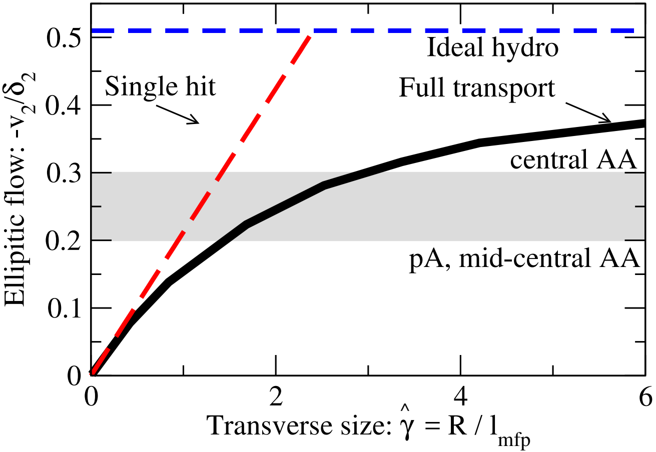


All orders in $\hat{\gamma}$: v_2/δ_2 saturates

Kurkela, Wiedemann, Wu, 1805.04081



Large systems approach ideal fluid dynamics



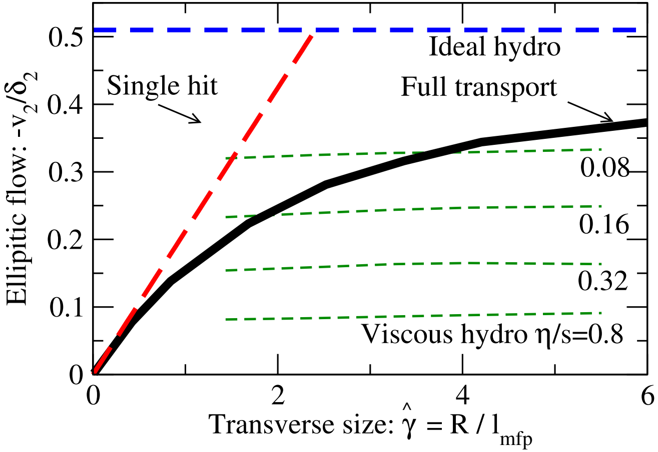
Central pA: $\frac{v_2}{\delta_2} \approx 0.2$, Central AA: $\frac{v_2}{\delta_2} \approx 0.3$

- Closer to single hit regime than ideal hydro

$$\eta/s \gtrsim 0.5$$

$\eta/s = 0.11/\gamma = 0.11/\hat{\gamma} \times R^{3/4}(\epsilon_0\tau_0)^{1/4}$

Kurkela, Wiedemann, Wu, 1805.04081

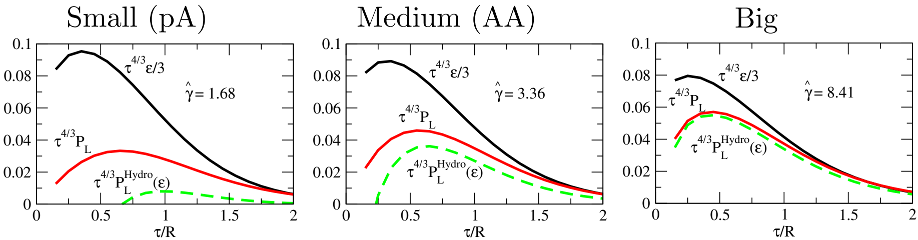


The approach to ideal hydro is *not* described by viscous hydro

$\epsilon_0 = 1000\text{fm}^4,\ \tau_0 = 0.26\text{fm},\ R = 2 - 12\text{fm}$

No system size dependence in hydro!

What happened?



Kurkela, Wiedemann, Wu, 1805.04081

Constitutive equations (at $r = 0$) fulfilled better and better with increasing system size

$$\Pi^{\mu\nu} = -2\eta\sigma^{<\mu\nu>}$$

Hydrodynamization at large anisotropy

What happened?

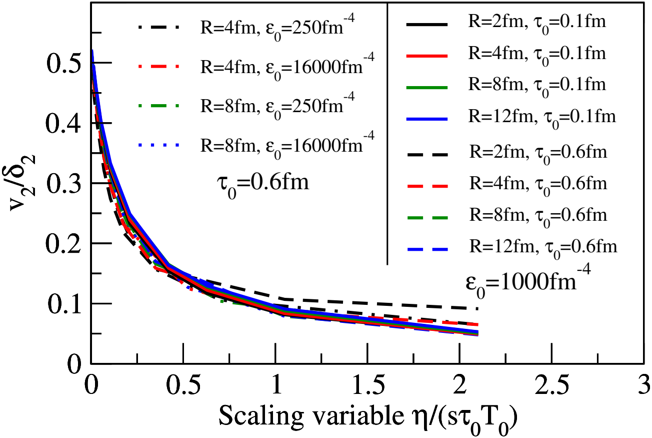
$$\partial_\mu T^{\mu\nu} = 0, \qquad \tau_\pi \partial_\tau \Pi^{\mu\nu} = -\left(\Pi^{\mu\nu} + 2\eta\sigma^{\mu\nu}\right)$$

No non-hydrodynamical elements: no pre-equilibrium, no freeze-out

- Flow builds up at times $\sim R$.
- *Difference* between ideal and viscous builds when the gradients are the largest
- Gradients are largest at earliest times
- For small η/s, hydro equations depend on

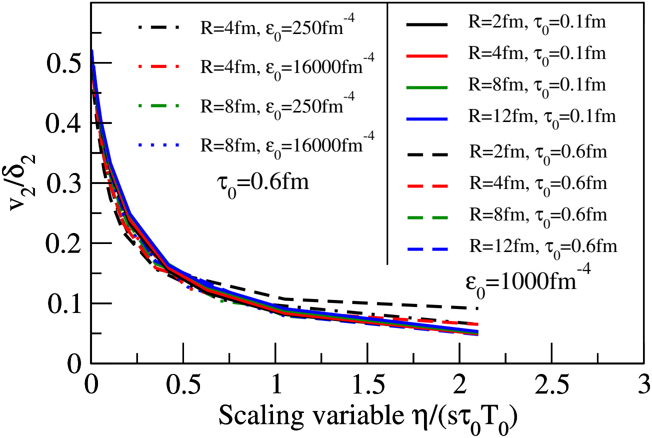
$$\frac{v_2}{\delta_2} \simeq \frac{v_2}{\delta_2}\Big|_{\text{ideal}} - f_L^{(1)} \frac{\eta}{sT_0} \underbrace{\frac{1}{\tau_0}}_{\partial_z} - f_\perp^{(1)} \frac{\eta}{sT_0} \underbrace{\frac{1}{R}}_{\partial_\perp}$$

- By assumption: $\tau_0 \ll R$, initial condition dependence dominates over transverse geometry



Pure hydro exhibits nearly perfect scaling with

$$\frac{v_2}{\delta_2} \simeq \frac{v_2}{\delta_2}\Big|_{\text{ideal}} - f_L\left(\frac{\eta}{sT_0}\frac{1}{\tau_0}\right)$$



- In systems of all sizes: the sensitivity of hydro to η/s arises from the earliest time τ_0, where hydro is least reliable.

Conclusions:

- Viscous hydro is a coarse grained effective description of transport theory.

- In this model, for v_2, even if the transport theory hydrodynamizes, qualitative features not descried by viscous hydro.

- This is because of the rapid expansion: η/s-sensitivity arises from ∂_z, not $\partial_\perp$. Increasing η/s increases sensitivity to initialization time, not to transverse geometry.

- In phenomenological applications, hydro can be supplemented with additional non-hydro elements that lead to violation of scaling. But these are not hydro.

Perturbative pre-equilibrium evolution: Talk by Mazeliauskas

Conclusions:

- All the observed structures in azimuthal harmonics arise already from single final state interaction
- Single hit dynamics most efficient at transferring spatial anisotropy to momentum anisotropy
- This explains in the most natural way the observation of v_2/ϵ_2 in the smallest pp, pA collisions

Conclusions:

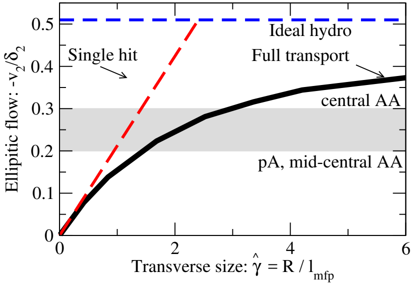
- Observed signal sizes suggest that hadronic collisions create a system with significant dissipation

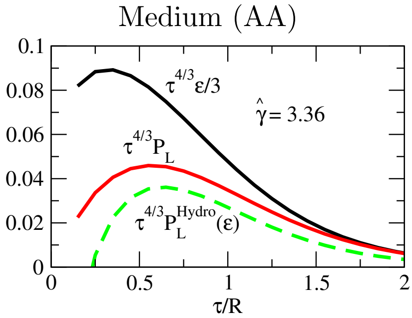
$$\hat{\gamma} \sim R/l_{mfp} \sim 1.5 - 3,$$

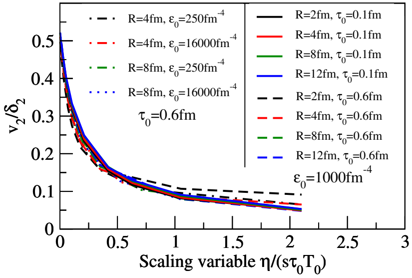
- and do not require that system hydrodynamizes at any point of evolution.
- These imply values of

$$\eta/s \gtrsim 0.5,$$

at least 6 times more than the perfect fluid value (0.08) and closer to perturbative expectation.


Ideal hydro
Single hit
Full transport
central AA
pA, mid-central AA
Elliptic flow: $-v_2/\delta_2$
Transverse size: $\hat{\gamma} = R / l_{mfp}$

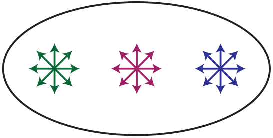

Medium (AA)
$\tau^{4/3}\varepsilon/3$
$\hat{\gamma} = 3.36$
$\tau^{4/3}P_L$
$\tau^{4/3}P_L^{Hydro}(\varepsilon)$
τ/R


R=4fm, ε_0=250fm^{-4}
R=4fm, ε_0=16000fm^{-4}
R=8fm, ε_0=250fm^{-4}
R=8fm, ε_0=16000fm^{-4}
τ_0=0.6fm
R=2fm, τ_0=0.1fm
R=4fm, τ_0=0.1fm
R=8fm, τ_0=0.1fm
R=12fm, τ_0=0.1fm
R=2fm, τ_0=0.6fm
R=4fm, τ_0=0.6fm
R=8fm, τ_0=0.6fm
R=12fm, τ_0=0.6fm
ε_0=1000fm^{-4}
v_2/δ_2
Scaling variable $\eta/(s\tau_0 T_0)$

Extra slides

Generation of v_2 far from equilibrium

Kurkela, Wiedemann, Wu, 1803.02072

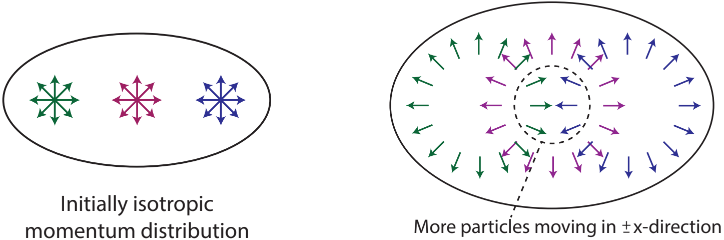


Initially isotropic
momentum distribution

- Initial condition initially isotropic in momentum space, anisotropic in coordinate space

Generation of v_2 far from equilibrium

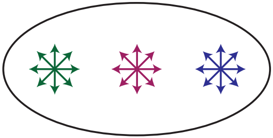
Kurkela, Wiedemann, Wu, 1803.02072

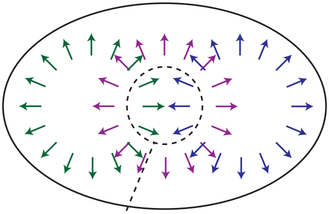


- Initial condition initially isotropic in momentum space, anisotropic in coordinate space
- Free streaming makes local patches anisostropic

Generation of v_2 far from equilibrium

Kurkela, Wiedemann, Wu, 1803.02072





- Initial condition initially isotropic in momentum space, anisotropic in coordinate space
- Free streaming makes local patches anisostropic
- Collisions isotropize the distribution in the center $\Rightarrow$ Reduction of horizontal movers and increase of vertical movers

Related closely to *anisotropic parton escape mechanism*, He et al. PLB753 (2016)