Observation of nonequilirium effects in the collective flow

Piotr Bożek

AGH University of Kraków

Hydrodynamic regime

- energy-momentum tensor

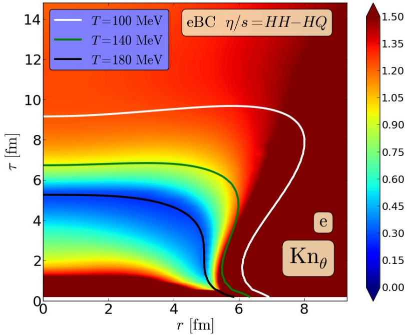
$$T_{id}^{\mu\nu} = (\epsilon + p)g^{\mu\nu} - Pu^{\mu}u^{\nu} + \pi^{\mu\nu}$$

- close to local equilibrium
- local energy density ϵ, pressure p, flow u^{μ}, stress (viscous) corrections $\pi^{\mu\nu}$
- local momentum distribution close to equilibrium

$$f(p) = f_{eq}(p) + \delta f(p)$$

Early times

Knudsen number $K = l_{micro}/L_{macro}$



H. Niemi, G. Denicol, , arXiv: 1404.7327

- large gradients
- viscous corrections dominant
- hydrodynamics $\longrightarrow$ kinetic evolution

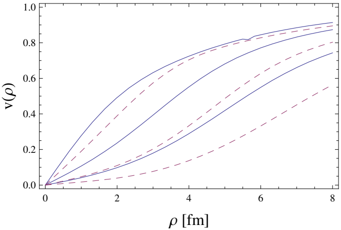
free-streaming + hydrodynamics

- free-streaming until τ_{hydro}
- matching to fluid $T^{\mu\nu}$ at τ_{hydro}

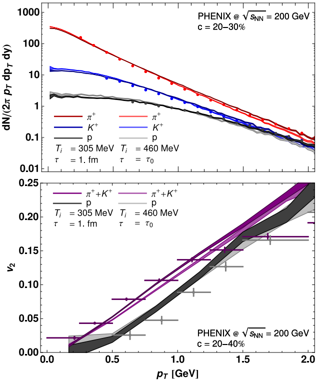
$\longrightarrow$ pre-equilibrium flow

$$v_T \simeq -\frac{\tau_{hydro} - \tau_0}{3} \frac{\nabla_T n(x,y)}{n(x,y)}$$

universal flow J. Vredevoogt, S. Pratt, arXiv: 0810.4325

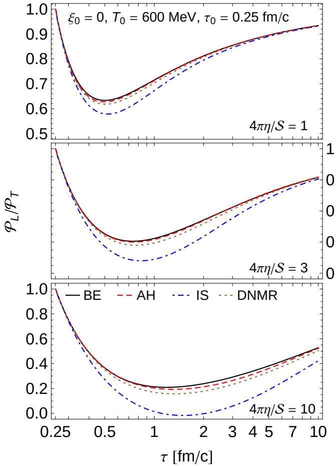


W. Broniowski, W. Florkowski, M. Chojnacki, A. Kisiel, arXiv: 0812.3393



testing hydrodynamics
- boost invariant solution of kinetic eq. in relaxation time app.

$$f(x,p) = f(t, p_\perp, x_\perp, w)$$



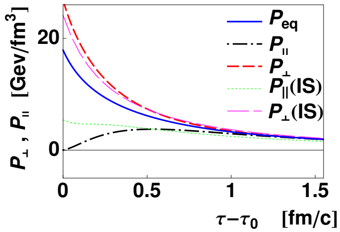
Nonequilibrium
$P_L \neq P_T$

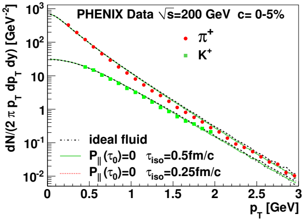
larger viscosity η
$\updownarrow$
larger relaxation time τ_{relax}
(less collisions)

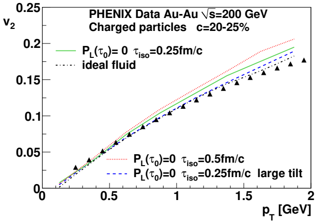
W. Florkowski, R. Ryblewski, M. Strickland,
arXiv 1304.0665

Effects od strong pressure asymmetry?

pressure asymmetry

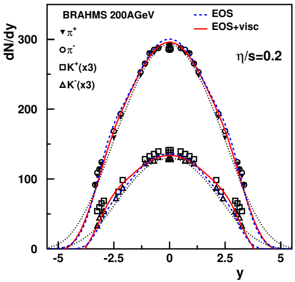


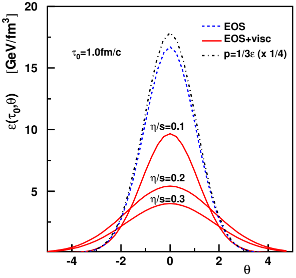




Very small effect on transverse expansion
Early nonequilibrium cannot be observed?

Longitudinal expansion



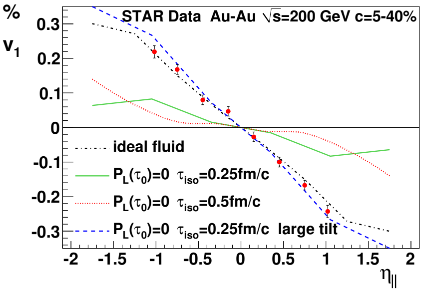


Strong differences in longitudinal colling and expansion

BUT: What is the initial longitudinal profile

Longitudinal and transverse expansion combined

Directed flow



rapidity odd directed flow is sensitive to pressure asymmetry!

Kinetic equations in RTA

- boost-invariant
- relaxation time approximation
- massless particles $\longrightarrow$ evolution of an integral (simplification)

$f(\tau, \vec{x}_T, \vec{p}_T, p_{\|}, w) \longrightarrow F(\tau, \vec{x}_T, \phi, v_z) = \int p^3 dp f(\tau, x_T, p_T, p_{\|}, w)$
at $z = 0$

$v = (1, \vec{v}_T, v_z) = (1, \sqrt{1-v_z^2} cos\phi, \sqrt{1-v_z^2} sin\phi, v_z)$

$\partial_\tau F + \vec{v}_T \partial_{\vec{x}_T} - \frac{v_z}{\tau}(1 - v_z^2)\partial_{v_z} F + \frac{4v_z^2}{\tau} = \frac{1}{\tau_{relax}}(F - F_{iso})$

Energy-momentum tensor can be reconstructed from F

$$T^{\mu\nu}(\tau, \vec{x}_T) = \int_0^{2\pi} \frac{d\phi}{2\pi} \int_{-1}^{1} \frac{dv_z}{2} F(\tau, \vec{x}_T, \phi, v_z)$$

A. Kurkela, U. Wiedemann, B. Wu : arXiv: 1803.02072 boost-invariant, relaxation-time approximation

- relaxation time approximation

$$p^\mu \partial_\mu f(x,p) = \frac{1}{\tau_{relax}} \left(f(x,p) - f_{eq}(x,p) \right)$$

$w = tp_{\|} - zE_p$

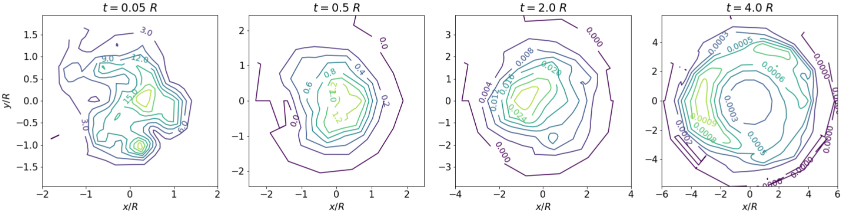
models preequilibrium transverse expansion only

Kinetic evolution in 2+1 dim

- boost-invariant
- relaxation time approximation
- massless particles $\longrightarrow$ evolution of an integral (simplification)

boost-invariant, small longitudinal pressure, $F = \delta(v_z)\tilde{F}$

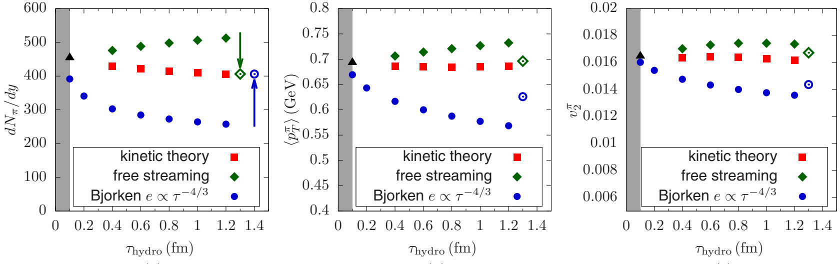
$$\partial_\tau \tilde{F} + v_T \partial_T \tilde{F} + \frac{1}{\tau}\tilde{F} = \frac{1}{\tau_{relax}}\left(\tilde{F} - \tilde{F}_{iso}\right)$$



A. Kurkela, S.F. Taghavi, U. Wiedemann, B. Wu, arXiv: 2007.06851

also: free streaming, KOMPOST

Early dynamics gives a transverse push



A. Kurkela, A. Mazeliauskas, J. F. Paquet, S. Schlichting, D. Teaney arXiv: 1805.00961

hydrodynamics - free streaming - kinetic equations : SMALL differences

kinetic equations in 1+1+1 dim

- nonboost invariant dynamics
- full treatement of longitudinal and transverse momenta
- at least one nontrivial transverse diemnsion

set up for directed flow studies

- evolution in time t, longitudinal z, and one transverse direction x

$$\partial_t F + v_x \partial_x F + v_z F = \frac{1}{\tau_{relax}} (F - F_{iso})$$

- variables τ, x, η, ϕ, v_z : $F(\tau, x, \eta, \phi, v_z)$

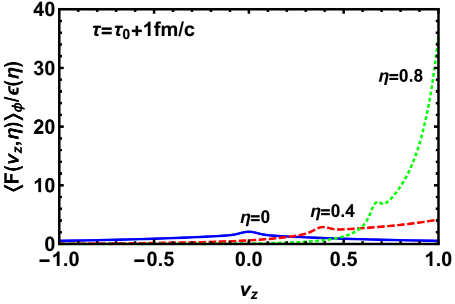
- solved in the global frame

F in boosted frame

Initial conditions $F = \epsilon(\tau_0, x, \eta)\ g\,[\,v_z\,]$ (note $v_z = cos(\theta)$)

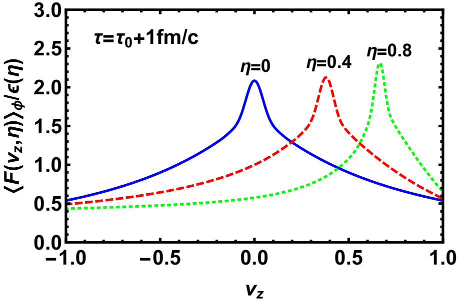
after boost by rapidity $y = \eta$ (Bjorken flow)

$$F = \epsilon(\tau_0, x, \eta)\ \frac{g[\,(v_z cosh(y) - sinh(y))/(cosh(y) - v_z sinh(y)\,]}{(cosh(y) - v_z sinh(y))^4}$$

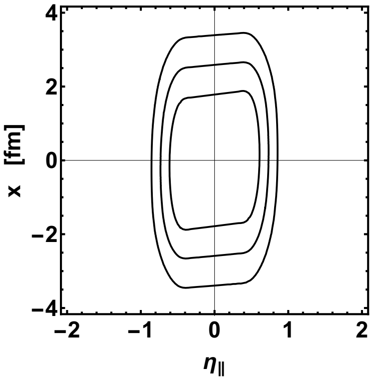


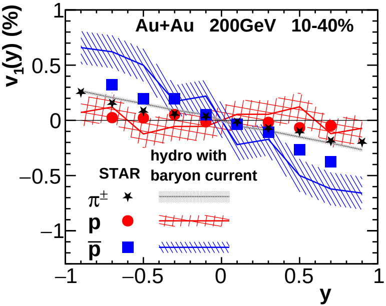
- difficult numerics at large rapidities

Eqs. solved for $\tilde{F} = F\left(cosh(y) - v_z sinh(y)\right)^4$



tilted fireball initial conditions

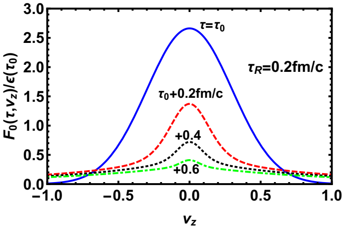


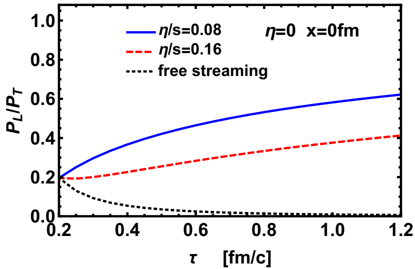


can describe the directed flow with early start of hydrodynamics

τ_{hydro}=0.2fm/c

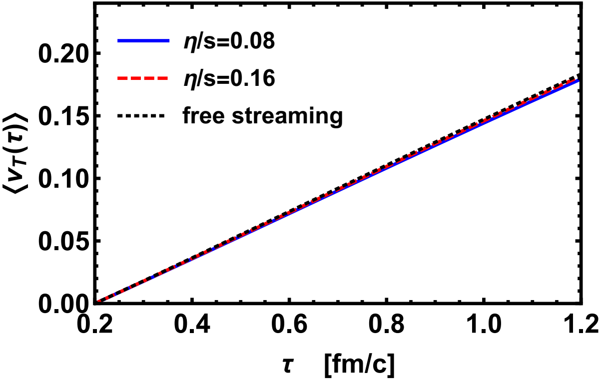
evolution of momentum distribution





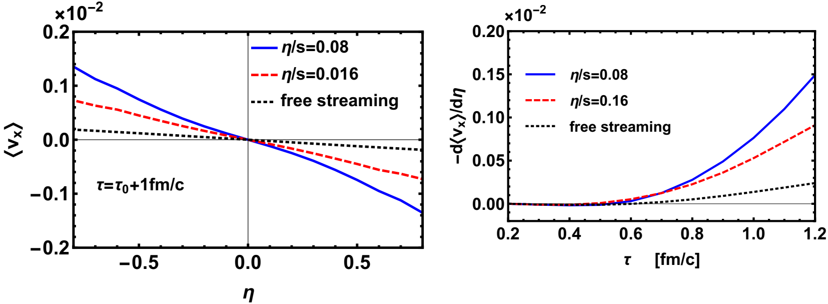
- redshift $\longrightarrow$ reduction of longitudinal pressure
- collisions $\longrightarrow$ isotropization

transverse flow



universal transverse flow J. Vredevoogt, S. Pratt, arXiv: 0810.4325

directed flow



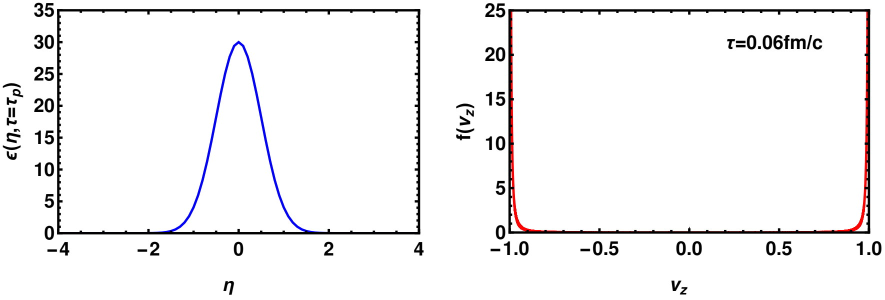
directed flow probes equlibration rate !

- Kinetic equation for early dynamics
- Non-boost invariant solutions
- Early formation of directed flow
- Directed flow sensitive to pressure anisotropy
- Preequilibrium dynamics in 3+1D ?

pre-Bjorken flow in 1+1 dim

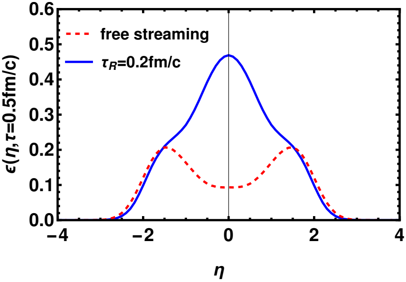
two streams of partons in the initial state

$\tau = 0.06 \text{fm/c}$, passage time for the colliding nuclei

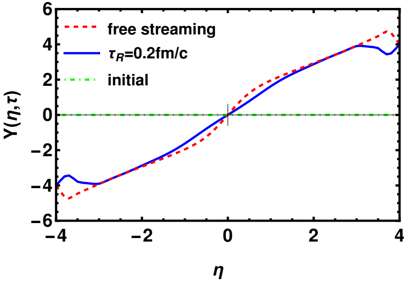


τ=0.5fm/c , after kinetic evolution

stopping due to relaxation

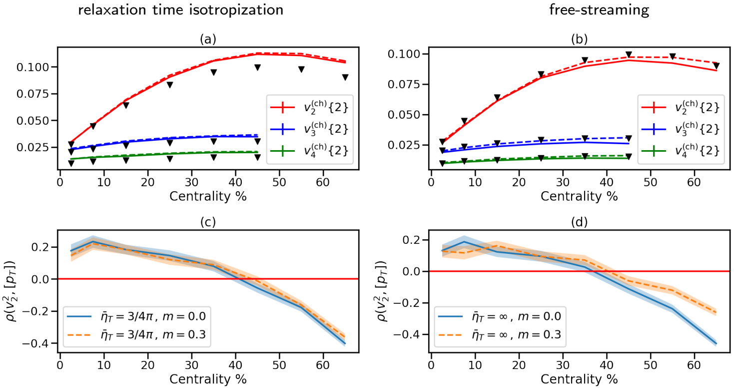


close to Bjorken flow



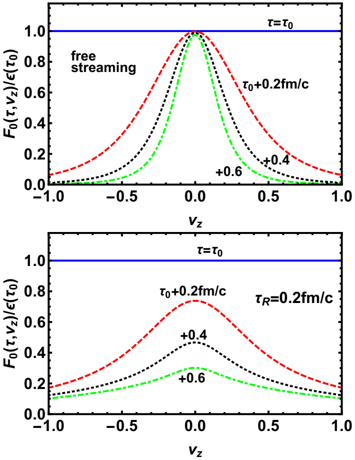
prequilibrium longitudinal flow
non-Bjorken initial flow for hydrodynamics

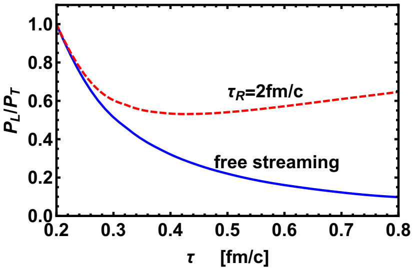
RTA pre-equilibrium + hydrodynamics



D. Liyanage, D. Everett, C. Chattopadhyay, U. Heinz arXiv: 2205.00964

longitudinal evolution





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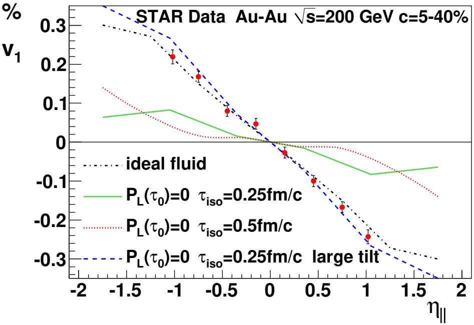
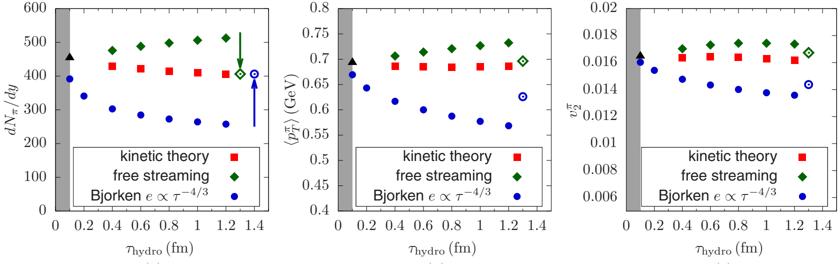
Longitudinal and transverse expansion combined

Directed flow



Early dynamics gives a transverse push



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hydrodynamics - free streaming - kinetic equations : SMALL differences

Kinetic equation

equation for the phase-space distribution $f(x,p)$

$$p^\mu \partial_\mu f(x,p) = C\left[f(x,p)\right]$$

$C\left[f(x,p)\right]$ collisions integral ($2 \leftrightarrow 2$ and $1 \leftrightarrow 2$ processes)

- for on-shell particles $f(t,\mathbf{x},\mathbf{p})$ 7-dimensional function

- more general than viscous hydrodynamics

- most solutions for boost-invariant geometry