Measuring the thermalization time

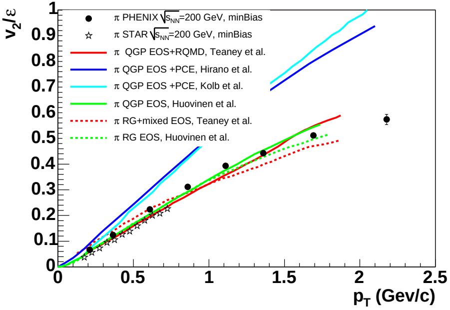
Piotr Bożek

Rzeszów University/Institute of Nuclear Physics Kraków

with Iwona Wyskiel

Fluid expansion at RHIC

- HBT requires hard EOS
  Broniowski et al. Phys. Rev. Lett. 101, 022301 (2008); Pratt Phys. Rev. Lett. 102, 232301 (2009)
- Early transverse expansion



PHENIX white paper

Have we seen a 3D expanding fireball?

Transverse / Longitudinal Pressure

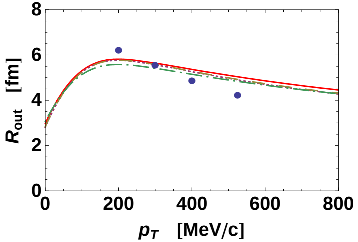
Non-equilibrium and/or viscosity
Early stage

$$T^{\mu\nu} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p + \pi/2 & 0 & 0 \\ 0 & 0 & p + \pi/2 & 0 \\ 0 & 0 & 0 & p - \pi \end{pmatrix}$$

$$\pi = \frac{4}{3}\frac{\eta}{\tau} \quad \text{Navier-Stokes}$$

more general π possible - (initial value, dynamics, far off-equilibrium)

What signatures of isotropization?
What measure of thermalization time?

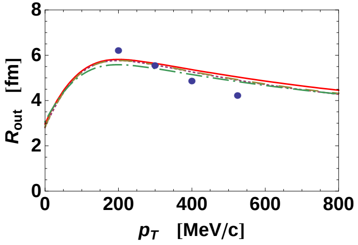


$$(P_\perp - P_\parallel) \propto exp\left(-\frac{\tau}{\tau_{iso}}\right)$$

phenomenological ansatz
thermalization time τ_{iso}

Bozek, Acta Phys. Polon. B39, 1375 (2008)

Early dissipation



$$(P_\perp - P_\parallel) \propto exp\left(-\frac{\tau}{\tau_{iso}}\right)$$

phenomenological ansatz

thermalization time τ_{iso}

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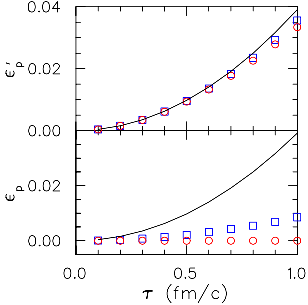
BUT

Universal flow

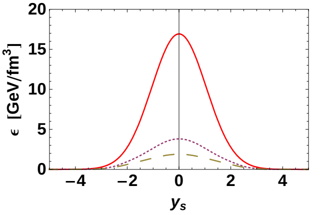


Vredevoogd, Pratt, Phys. Rev C79 044915 (2009)

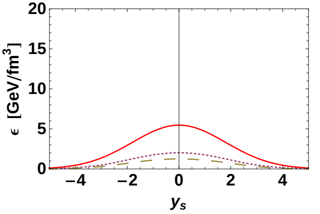
No sensitivity of transverse flow to early dissipation !

Longitudinal expansion - cooling

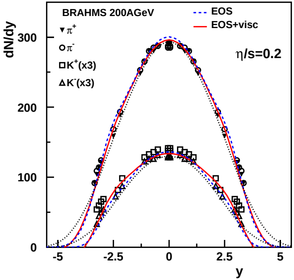
Ideal hydro



Viscous hydro $\eta/s = 0.2$



Bozek, Phys. Rev. C77, 034977 (2008)



Cannot be observed in final distributions !

Standard observables are not sensitive to early dissipation

transverse or longitudinal expansion alone is insufficient

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transverse + longitudinal expansion = directed flow

Standard observables are not sensitive to early dissipation

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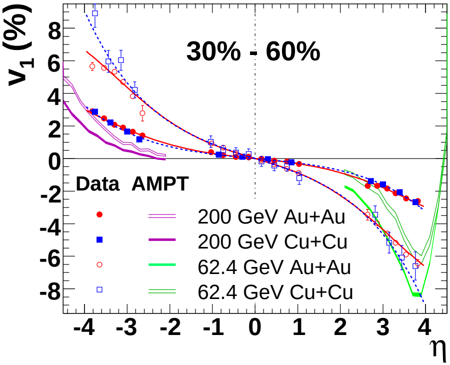
transverse + longitudinal expansion = directed flow

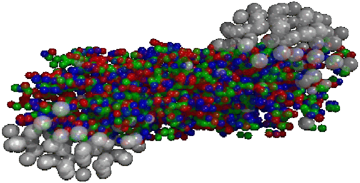
and

it happens very early

Directed flow - v_1

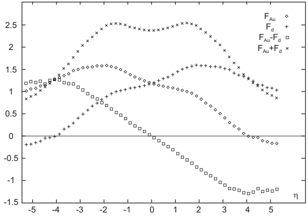
URQMD





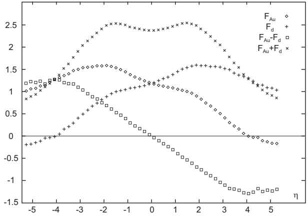
- large flow at 200GeV
- anti-flow
- Au-Au similar to Cu-Cu
- Dynamics: early, 3D

$$\frac{dN}{d^2p\,dy} = \frac{dN}{2\pi p\,dp}dy\,(1 + 2{\color{red}v_1}\cos\phi + 2v_2\cos 2\phi + \dots)$$



Asymmetric emission

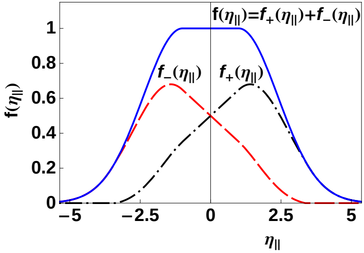
(Białas, Czyż, Acta Phys.Polon.B36, 905 (2005)

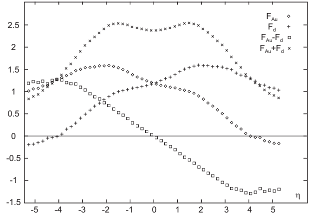


Asymmetric emission

(Białas, Czyż, Acta Phys.Polon.B36, 905 (2005)

$$\rho(\eta, x, y) \propto f_+(\eta) N_+(x, y) + f_-(\eta) N_-(x, y)$$





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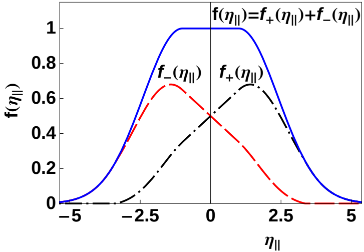
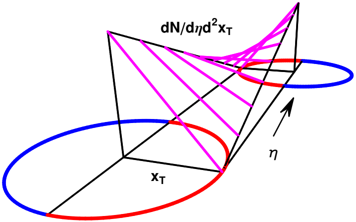
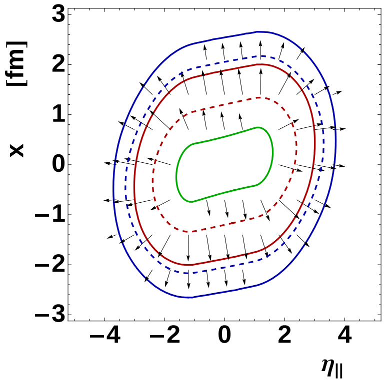




bremsstrahlung (Adil Gyulassy, Phys. Rev. C72, 034907 (2005))

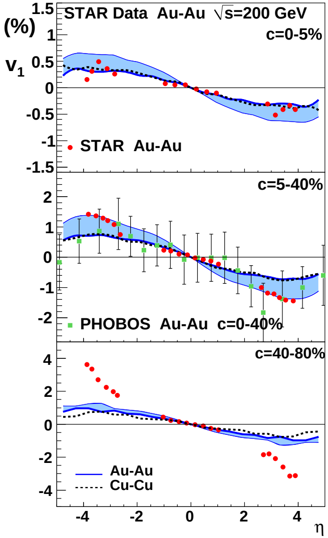
Tilted source



$$\partial_\tau u_x = -\frac{\partial_x p_\perp}{p+\epsilon}$$

$$\partial_\tau Y = -\frac{\partial_\eta p_{||}}{\tau(p+\epsilon)}$$

tilted source $\rightarrow$ transverse pressure + longitudinal pressure
Glauber model



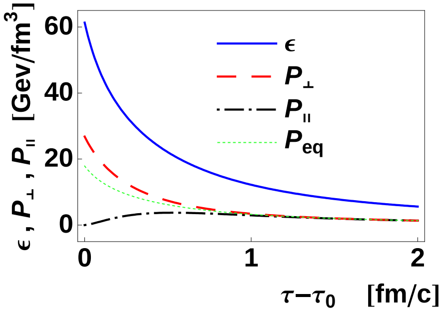
- Anti-flow explained!
- System size dependence
- Consistent with asymmetric emission

3+1D expansion with off-equilibrium pressure

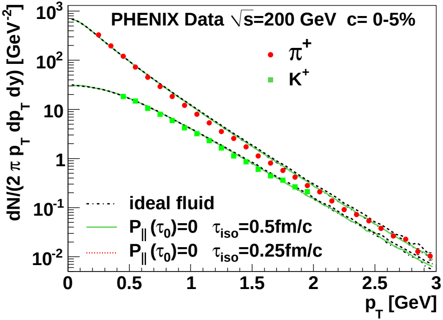
$$T^{\mu\nu} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p_\perp & 0 & 0 \\ 0 & 0 & p_\perp & 0 \\ 0 & 0 & 0 & p_\parallel \end{pmatrix}$$

$$\partial_\mu T^{\mu\nu} = 0$$

in $3+1$D

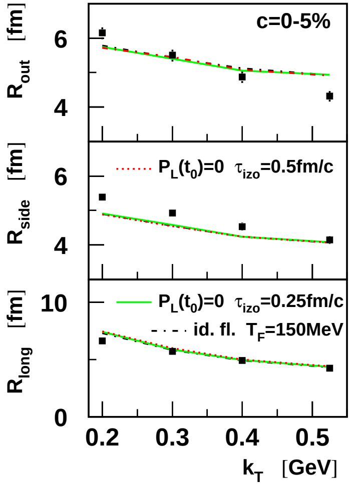


Central collisions - **spectra**



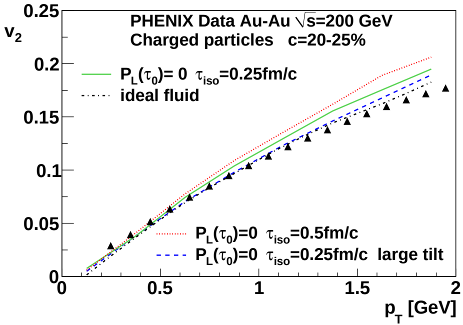
No sensitivity to off-equilibrium pressure

Central collisions - **HBT**



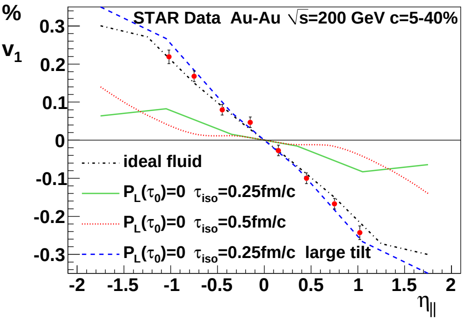
No sensitivity to off-equilibrium pressure

Mid-peripheral collisions - **elliptic flow**

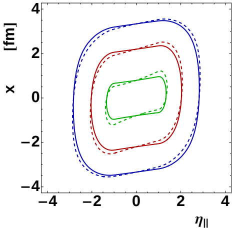


No sensitivity to off-equilibrium pressure

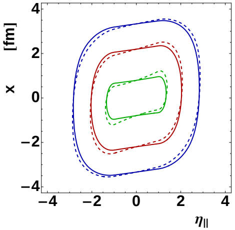
Mid-peripheral collisions - **directed flow**



- **Sensitive to off-equilibrium pressure**
- **RHIC data indicate early thermalization**



tilt →**HYDRO**→ v_1



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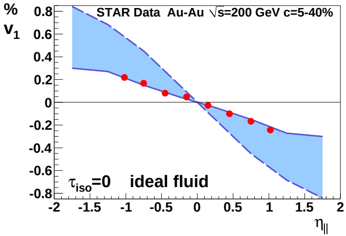
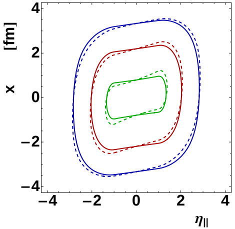


$0 \leq \tau_{iso}$



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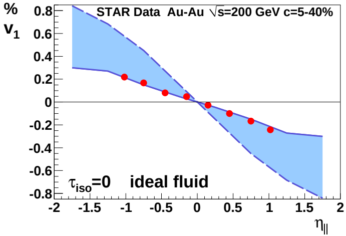
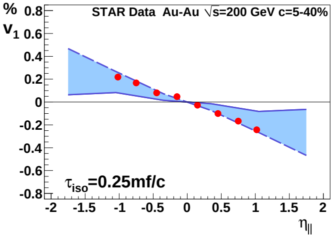
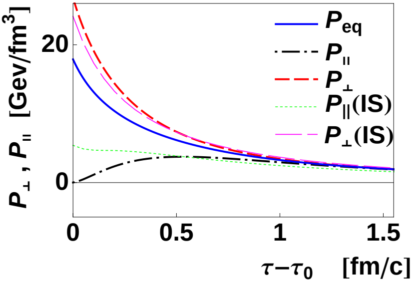




$$0 \leq \tau_{iso} \leq 0.25\mathrm{fm}/c$$

Viscosity- minimal pressure anisotropy

$$\Pi \simeq \frac{4\eta}{3\tau} \qquad \frac{\eta}{s} = \frac{1}{4\pi}$$



Pressure anisotropy compatible with small shear viscosity

Directed flow

New observable for early stages

- Directed flow sensitive to longitudinal and transverse pressure
- Directed flow develops early
- Need 3+1D model

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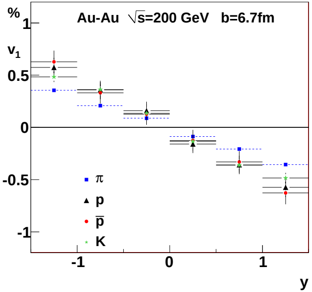
Conclusions

- No room for early pressure anisotropy
- Very fast thermalization

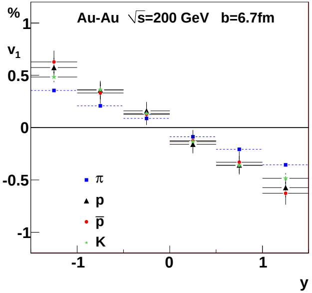
$$\tau_{iso} \leq 0.25 \mathrm{fm}/c$$

PID v_1



Hydro : mass scaling

PID v_1



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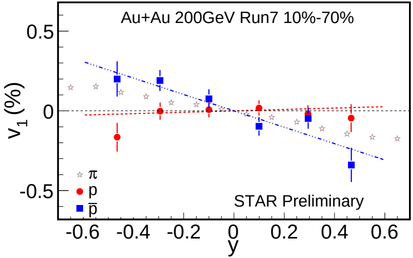
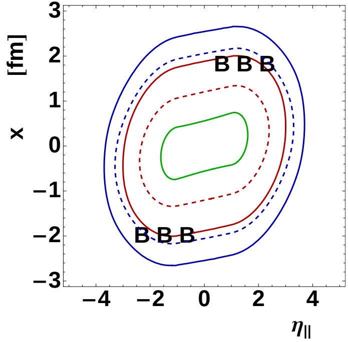


Zero baryon flow! (STAR)

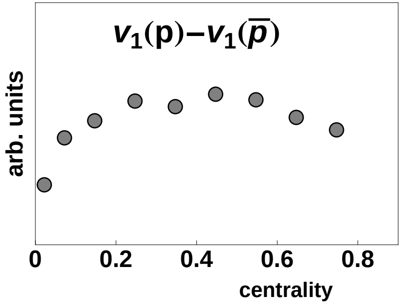
Baryon asymmetry!

fragmenting nucleons

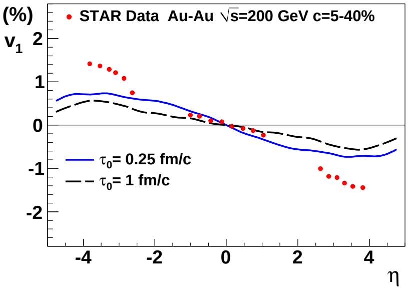


baryons pushed to $v_1 > 0$

$$\Delta v_1 \propto \frac{\mu}{T} \frac{N_+ - N_-}{N_+ + N_-}$$

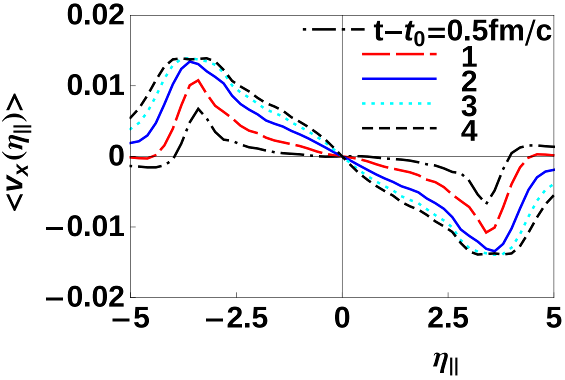


Transverse + Longitudinal Expansion = Directed Flow



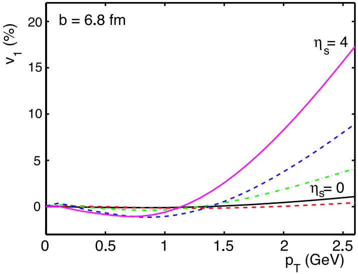
longitudinal pressure appears before 1fm/c
fast isotropization

Early collectivity



v_1 develops before v_2

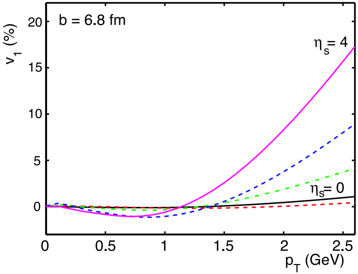
$p_\perp$ dependence



deformed source
(Kolb Heinz)

$$< p_x >= 0$$

$p_\perp$ dependence



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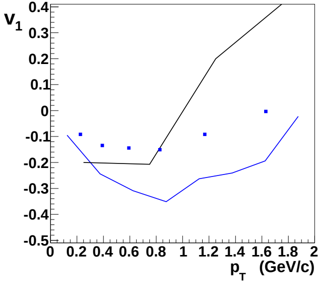

3+1D $\rightarrow$ shift to $v_1 < 0$