Bulk and Shear Viscosity Effects in Event-by-Event Relativistic Hydrodynamics

J.Noronha-Hostler[1], G.Denicol[2], J.Noronha[1], R.Andrade[1], F.Grassi[1]

[1]Instituto de Física, Universidade de São Paulo, Brazil

[2]Department of Physics, McGill University, Canada

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Outline

I. WHY and HOW

II. Effect of viscosities on the fluid expansion

III. Effect of viscosities at decoupling

IV. Results

V. Conclusion

arXiv:1305.1981, to appear PRC

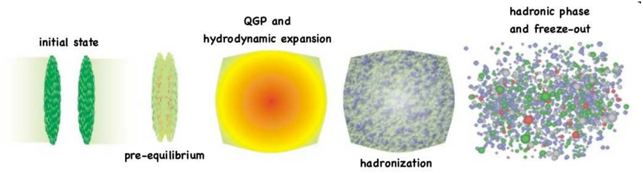
I. WHY and HOW

WHY?

• Ultra-high energy nuclear collisions have been performed at Brookhaven and CERN since 1986.

• (Main) aim: create and study the QGP.

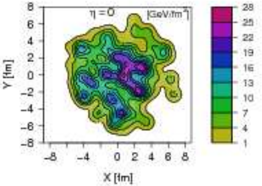
Evolution of a Heavy-Ion Collision



• Difficulty: reconstruct initial state (QGP) from final state (hadrons) $\rightarrow$ use hydrodynamics.

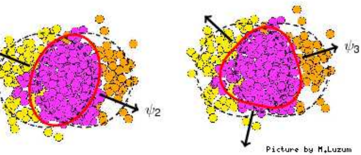
A tool: flow harmonics v_n's

Granular initial conditions $\longrightarrow$ Anisotropic angular distribution



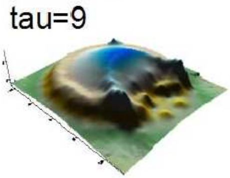
$$\frac{dN}{d\phi} = \frac{N}{2\pi}[1 + \sum_{n=1}^{\infty} 2\, v_n \cos n(\phi - \phi_n)]$$

Due to pressure gradients



Geometrical deformations.

OR



Outer tube pushes matter.

- Many works on hydro with shear viscosity and comparison with data.
  Additional difficulties: initial geometry, particle emission (δf), various formalisms, etc.
- The part played by bulk viscosity has not been so thorougly studied:
  - Monnai, Hirano, PRC80 (2009) 054906,
  - Denicol, Kodama, Koide, Mota, PRC80 (2009) 064901; JPG37 (2010) 094040,
  - Song, Heinz, PRC81 (2010) 024905,
  - Bozek, PRC81 (2010) 034909,
  - Roy, Chaudhuri, PRC85 (2012) 024909; erratum PRC85 (2012) 049902,
  - Dusling, Schafer, PRC85 (2012) 044909.
- $\longrightarrow$ Agree that $v_2(p_T)$ will be affected by bulk viscosity.
- No work on effect of bulk viscosity on higher order v_n's.
  (Above papers had smooth initial conditions.)

HOW

v-USPhydro
(viscous Ultrarelativistic Smooth Particle hydrodynamics)

Sucessor of NeXSPheRIO:

- First ($\sim$ 2000) event-by-event code for relativistic nuclear collisions (ideal fluid).
- Since 2010, various e-by-e codes have been appeared.

Description:

Modular event-by-event 2+1 hydrodynamical code that runs ideal & viscous hydro with nonzero ζ/s and η/s

- Initial conditions can easily be implemented from other sources.
- Equations of motion are solved using Smooth Particle Hydrodynamics

In progress:

- Particle decays
- 3+1

What is event-by-event hydrodynamics?

Provide initial conditions → Solve hydrodynamics equations → Compute observables

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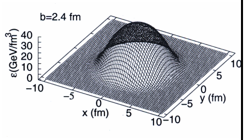
Provide initial conditions	$\rightarrow$	Solve hydrodynamics equations	$\rightarrow$	Compute observables

Traditional approach ($<$ 2010):

smooth initial conditions: $\epsilon_0(x, y)$



$\rightarrow$ run once

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Provide initial conditions	$\rightarrow$	Solve hydrodynamics equations	$\rightarrow$	Compute observables

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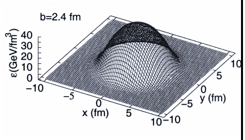
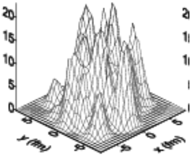


$\rightarrow$ run once

Event-by-event approach:

fluctuating initial conditions: $\epsilon_0(x, y)$



$\rightarrow$ run many times
should mimic experiment better

Event-by-event hydrodynamics:

NeXSPheRIO initial ($\sim$ 2001) team:

C.Aguiar, Y.Hama, T.Kodama & T.Osada

More on wednesday afternoon:

Event-by-event hydrodynamics:

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More on wednesday afternoon:

v-USPhydro collaborators $\sim$ 2001

II. Effect of viscosities on the fluid expansion

Equations of Motion for bulk

Conservation of Energy and Momentum

$$D_\mu T^{\mu\nu} = 0 \quad (1)$$

The energy-moment tensor contains a bulk viscous pressure Π

$$T^{\mu\nu} = (\epsilon + p + \Pi)\, u^\mu u^\nu - (p + \Pi)\, g^{\mu\nu} \quad (2)$$

Using memory function method
(Denicol, Kodama, Koide, Mota, PRC75(2007)034909, PRC78(2008)034901,JPG36 (2009)035103),
Π obeys

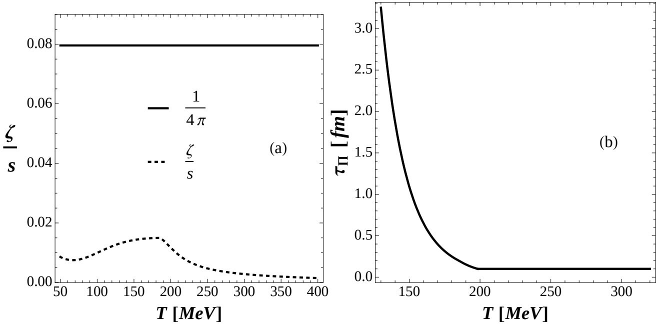
$$\tau_\Pi u^\mu D_\mu \Pi + \Pi = -\left(\zeta + \tau_\Pi \Pi\right) D_\mu u^\mu$$

$\Pi_{Navier-Stokes} = -\zeta D_\mu u^\mu$: it acts as a negative pressure, slowing expansion and cooling $\Rightarrow$ small effect if ζ small.

Description of Bulk Viscosity

$$\left(\frac{\zeta}{s}\right) = \frac{1}{4\pi}\left(\frac{1}{3} - c_s^2\right), \qquad \tau_\Pi = 9\,\frac{\zeta}{\epsilon - 3p}$$

Inspired by Buchel,PLB663,286(2008) and Huang, Kodama, Koide, Rischke PRC83,024906(2011)



Using altice-based equation of state: Huovinen, Petreczky, NPA837 (2010) 26.

Conservative estimate: $\zeta/s \sim 0.2(1/4\pi)$

Equations of Motion and description of Shear Viscosity:

Energy-moment tensor

$T^{\mu\nu} = (\epsilon + p)\, u^{\mu} u^{\nu} - p\, g^{\mu\nu} + \pi^{\mu\nu}$

Equation for shear stress tensor

$\tau_{\pi} \Delta^{\mu\nu\lambda\rho} u^{\alpha} D_{\alpha} \pi_{\lambda\rho} + \pi^{\mu\nu} = \eta \sigma^{\mu\nu} - \tau_{\pi} \pi^{\mu\nu} D_{\alpha} u^{\alpha}$ (standard notations)

PRELIMINARY:

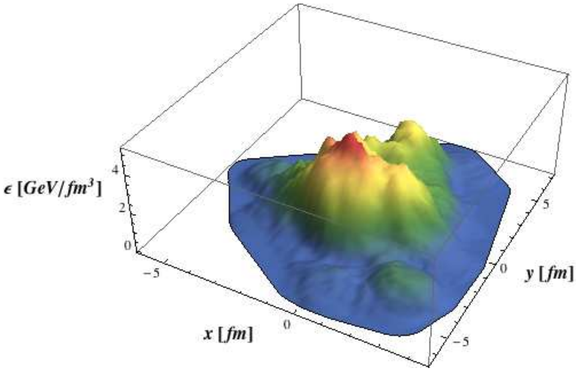
$\frac{\eta}{s} = \frac{1}{4\pi}$, $\tau_{\pi} = 5\, \frac{\eta}{sT}$

$\pi^{\mu\nu}_{Navier-Stokes} = \eta \sigma^{\mu\nu}$: it tends to prevent deformations of fluid cell.

Fluid expansion

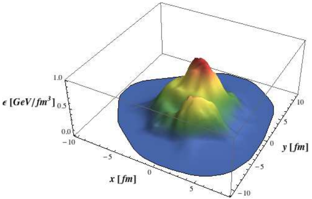
Initial Conditions:

- MC-Glauber: energy density $= c n_{coll}(\vec{r})$ (c adjusted to get midrapidity multiplicity)
- $\tau_0 = 1\,fm$ (tested)

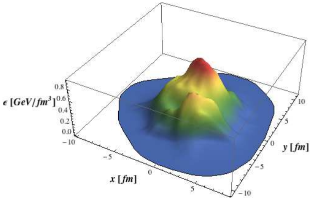


$h = 0.3, N_{SPH} \sim 3\,10^4$, nb.events/window=150.

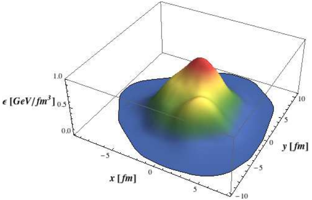
Ideal after $\tau = 5.6fm$



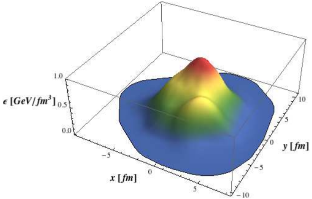
Bulk after $\tau = 5.6fm$



Shear+Bulk after $\tau = 5.6fm$



Shear after $\tau = 5.6fm$



- Viscosity attenuates other forces $\rightarrow$ smearing of granularity.
- Shear dominates, bulk barely affects expansion (expected since $\zeta/s << \eta/s$) [smaller ζ/s only in this slide].

III. Effect of viscosities at decoupling

Compute observables with Cooper-Frye formula:

Particle spectra: $E\frac{d^3N}{dp^3} = \int_{f.o.} f(x,p)p^\mu d\sigma_\mu$

$f = f_{eq} + \delta f_{shear} + \delta f_{bulk}$

Problem: compute δf.

In what follows:

Shear results: not (yet) ours

Bulk results: v-USPhydro.

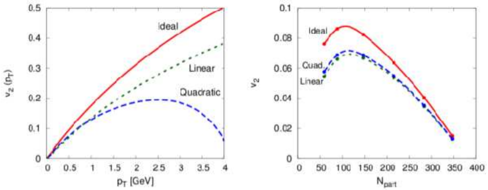
δf_{shear}

Common ansatz: $\delta f_{shear} \sim \pi_{\mu\nu} p^\mu p^\nu [(\epsilon + p)T^2]$.

Navier-Stokes limit, $\delta f_{shear} \propto (\eta/s)p^2$

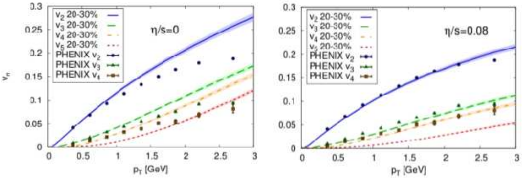
$\rightarrow$ stronger effect for larger η/s and p.

- $v_2(p_T)$: shape dominated by δf_{shear}:



Dusling, Moore, Teaney PRC81 (2010) 034907.

- $v_N(p_T)$ decreased



Schenke, Jeon, Gale PRC85 (2012) 024901

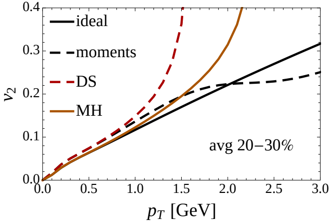
δf_{bulk}

Using method of moments as in Denicol, Niemi NPA904-905 (2013) 369c

$$\delta f_{bulk}^{(\pi)} = f_{eq} \times \Pi \times [B_0^{(\pi)} + D_0^{(\pi)} u.p + E_0^{(\pi)} (u.p)^2]$$

where

$B_0^{(\pi)} = -65.85\, fm^4$, $D_0^{(\pi)} = 171,27\, fm^4/GeV$, $E_0^{(\pi)} = -63.05\, fm^4/GeV^2$



MH: Monnai, Hirano, PRC80 (2009) 054906

DS: Dusling, Schafer, PRC85 (2012) 044909

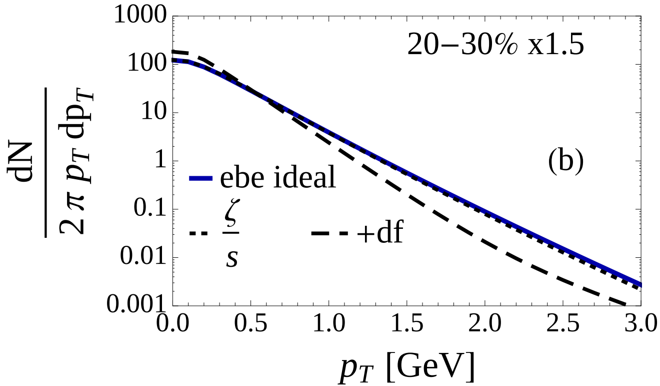
- $v_2(p_T)$: shape dominated by δf_{bulk}:
  Similar to δf_{shear}.
- $v_2(p_T)$ is enhanced relative to ideal case.
  δf_{bulk} has opposite effect to that of δf_{shear}
- Moment method leads to well-behaved $v_2(p_T)$ at high p_T.

IV. Results

π^+ Spectrum (Direct π^+'s Only)

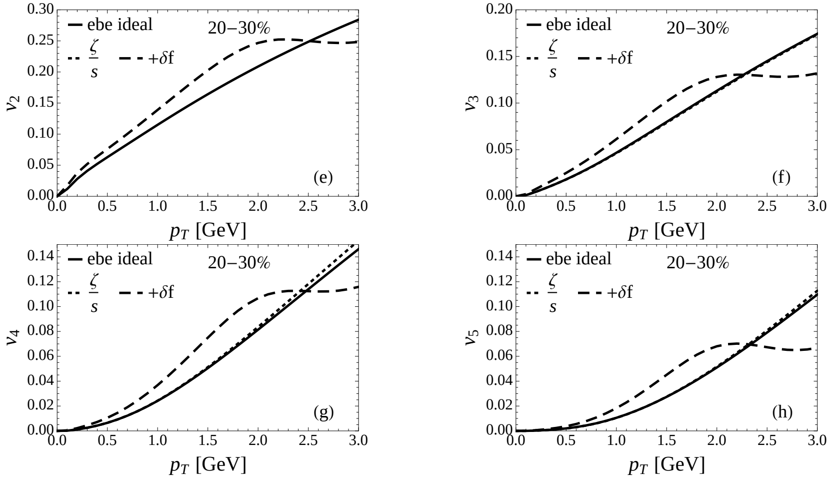
$T_{f.o.} = 150$ MeV

Direct $\pi^+ \approx 54$



As expected: more slow/less fast particles.

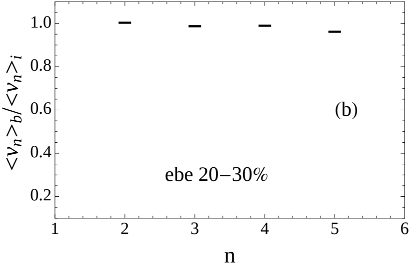
Event-by-Event higher flow harmonics



- $v_n(p_T)$ are significantly enhanced, even though ζ/s is small.
- HOW TO DISENTANGLE shear and bulk effects? (may cancel each other)

Integrated v_n's: PRELIMINARY no δf

For small ζ/s, expect $v_n^{bulk} \sim v_n^{ideal}$

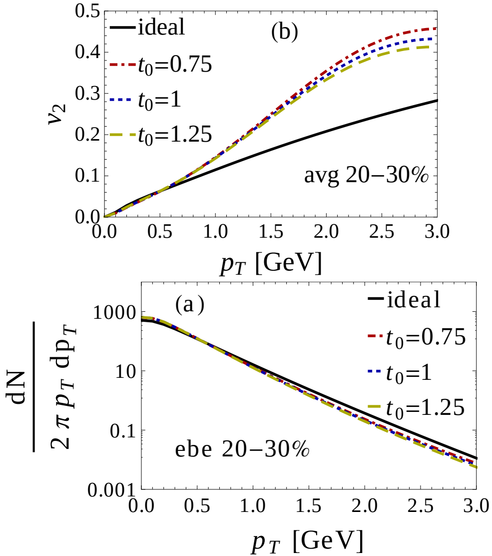


V. Conclusion

- v-USPhydro: Lagrangian 2+1 hydro code with bulk and shear viscosity, running event-by-event.
- $v_n(p_T)$ enhanced by bulk viscosity while it is decreased by shear ciscosity.
  - How to disentangle to extract η/s and ζ/s?
  - Higher ζ/s do not seem excluded.
- Integrated v_n's (or other integrated quantities) may be useful.
- δf_{bulk} plays a crucial part.
  (Here computed with moment method.)

BACK UP SLIDES

Dependence on τ_0

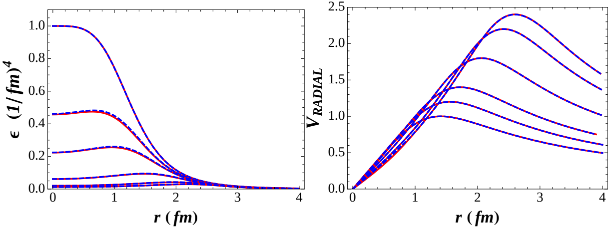


Checks

- Reproduce analytical sol. from 2+1 conformal ideal hydro

$$\epsilon = \frac{\epsilon_0}{\tau^{4/3}} \frac{(2q)^{8/3}}{\left[1 + 2q^2\left(\tau^2 + x_\perp^2\right) + q^4\left(\tau^2 - x_\perp^2\right)\right]^{4/3}}$$

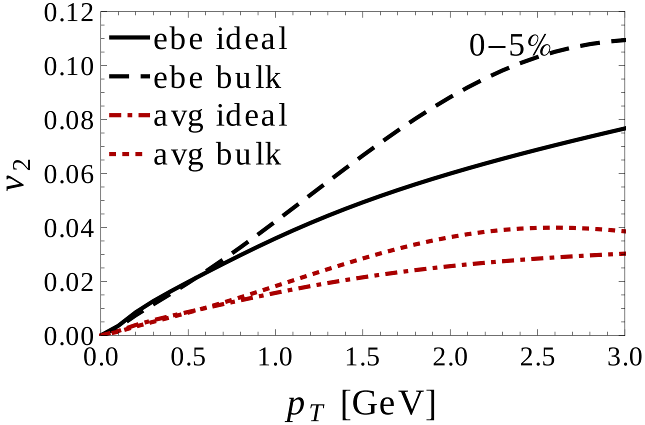
Gubser,PRD**82**,085027(2010), Marrochio et. al. 1307.6130 [nucl-th] (first analytical solution of Israel-Stewart hydro)



- The viscous bulk evolution converges to that computed within ideal hydrodynamics for sufficiently small ζ/s.

Averaged Initial Conditions vs. Event-by-Event

- No decays are included. We use Monte Carlo Glauber initial conditions.



- The effect of the bulk viscosity is enhanced in event-by-event studies

Comparison between papers

Monnai, Hirano, PRC80 (2009) 054906,	bulk visc. not in evol. but in δf	$v_2(p_T) \nearrow$
Denicol, Kodama, Koide, Mota, PRC80 (2009) 064901; JPG37 (2010) 094040,	bulk visc. in evol. but not δf bulk and shear visc. in evol. but not δf	
Song, Heinz, PRC81 (2010) 024905,	bulk and shear visc. in evol. and only (?) δf_{shear}	
Bozek, PRC81 (2010) 034909,	bulk visc. in evol. and in δf	agrees w. MH
Roy, Chaudhuri, PRC85 (2012) 024909; erratum PRC85 (2012) 049902,	bulk visc. in evol. and in δf	$v_2(p_T) \nearrow$ for $p_T > 0.5$
Dusling, Schafer, PRC85 (2012) 044909	bulk visc. in evol. and in δf	$v_2(p_T) \nearrow$