Extracting η/s in the presence of bulk viscosity in heavy ion collisions

Jacquelyn Noronha-Hostler
Columbia University

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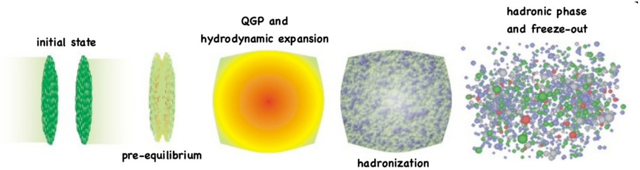
Outline

Evolution of a Heavy-Ion Collision

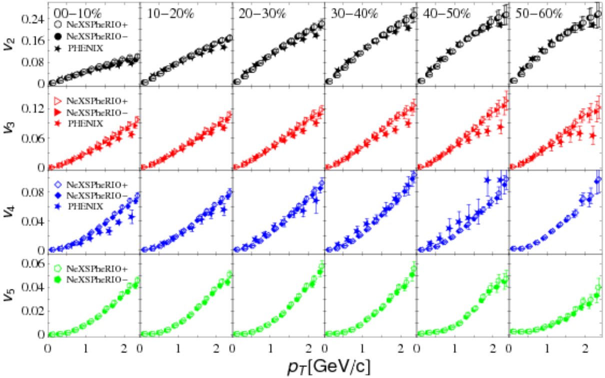


Heavy ion collisions are modeled through

- Initial Condition: Pre-equilibrium state using gluon saturation models/Glauber-like models
- Viscous hydrodynamical evolution/Lattice Equation of State
- Hadronization mechanism: Cooper Frye including viscous corrections
- Hadronic afterburner

Ideal hydrodynamics and Collective Flow

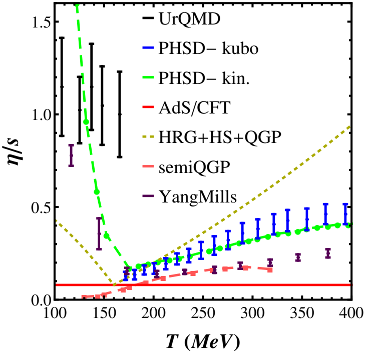
- Event-by-event NeXus initial conditions and 3+1 ideal relativistic hydrodynamics fit the flow harmonics well



Gardim, Grassi, Luzum, Ollitrault, Phys.Rev.Lett. 109 (2012) 202302

Shear Viscosity in Heavy-Ion Collisions

- Resistance against the deformation of a fluid
  $\Pi^{\mu\nu}_{Navier-Stokes} \sim \eta\partial^{\langle\mu}u^{\nu\rangle}$

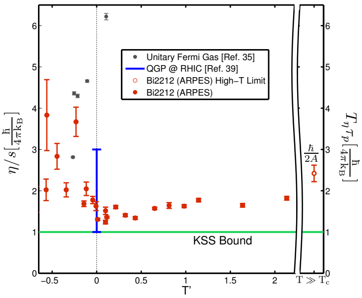


- Dyson-Schwinger Yang-Mills (arXiv:1411.7986)

- HRG+HS+QGP(JNH et al PRL103(2009)172302, Niemi et al PRL106(2011)212302)
- PHSD (PRC87(2013)064903)
- AdS/CFT -KSS limit (Kovtun,Son,Stairnets PRL94(2005)111601)
- UrQMD (Demir, Bass PRL(2009)102)
- semi-QGP- $\kappa = 32$ (Hidaka,Pisarski PRD81(2010)076002)
- Also, Csernai,Kapusta,McLerran PRL 97, 152303 (2006) (not shown)

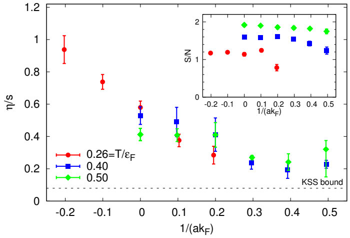
$\eta/s(T)$ in other nearly perfect fluids

High Temperature Superconductor



PRB 90, 134509 (2014)

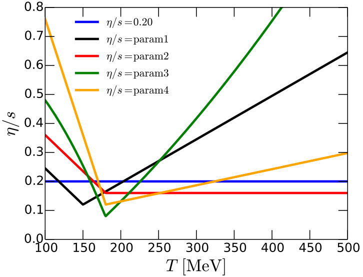
Dilute Fermi Gas

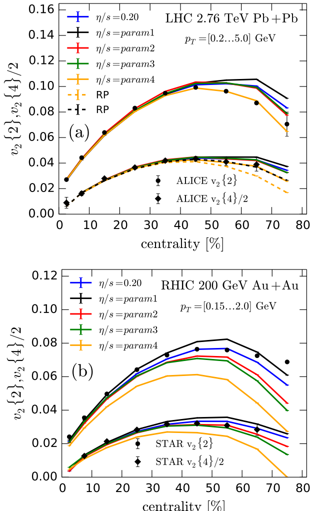


Wlazlowski, Quan, Bulgac arXiv:1504.02560

Shear Viscosity in Heavy-Ion Collisions

Varying η/s: Niemi et al. arXiv:1505.02677

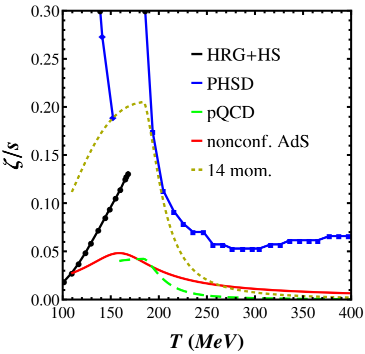




- RHIC probes lower temperatures, $\eta/s = 0.2$ (for EKRT), LHC prefers $\eta/s(T)$ that is small in the hadron gas phase

Bulk Viscosity in Heavy-Ion Collisions

- Resistance against the radial expansion or compression of a fluid $\Pi_{Navier-Stokes} \sim -\zeta(\partial_\mu u^\mu)$



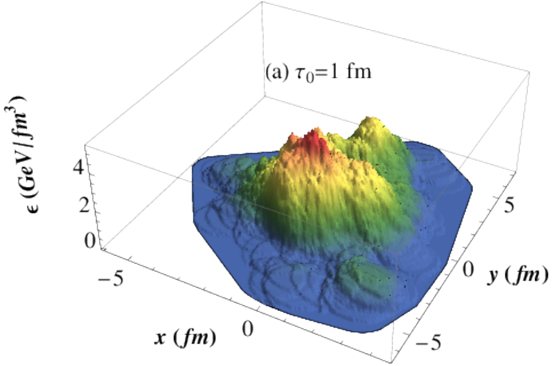
Peak also seen in:
JNH, PRL 103 (2009) 172302,
Kharzeev JHEP 0809 (2008) 093

- HRG+HS(Kadam and Mishra arXiv:1408.6329)
- PHSD (PRC 87, 064903 (2013))
- non-conformal holographic model (Finazzo et al - JHEP 1502 (2015) 051)
- pQCD (Arnold, Dogan, Moore Phys.Rev. D74 (2006) 085021)
- 14 mom. (Denicol et al, PRC90(2014)024912)

Viscosity in Heavy-Ion Collisions

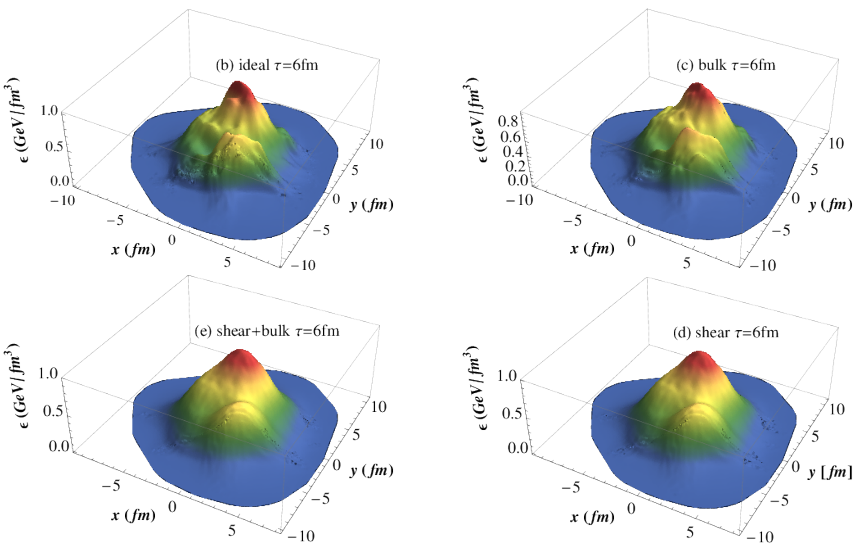
JNH et al, Phys.Rev. C90 (2014) 3, 034907

Given the Glauber Initial Condition $\tau = 1\,fm$



Viscosity in Heavy-Ion Collisions

JNH et al, Phys.Rev. C90 (2014) 3, 034907



Initializing the Energy-Momentum Tensor

Hydrodynamics boils down to:

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

$$T^{\mu\nu} = \varepsilon u^\nu u^\nu - (p + \Pi)\,\Delta^{\mu\nu} + \pi^{\mu\nu} \quad (2)$$

$$(3)$$

where we obtain an initial $T^{\mu\nu}$ from NEXUS/IP-Glasma or $\varepsilon(\mathbf{r})$ from Glauber/MCKLN/EKRT/URQMD etc.
From $T^{\mu\nu}$ we get:

$$\varepsilon(\mathbf{r}), u^\mu, \pi^{\mu\nu}, \Pi$$

but we only use $\varepsilon(\mathbf{r}), u^\mu$!!!
Precision hydrodynamics necessitates the entire $T^{\mu\nu}$, so BOTH bulk and shear are needed!

Effects of viscosity with hydrodynamics (hydro only)

JNH et al, Phys.Rev. C90 (2014) 3, 034907

Compare percentage change of mean and variance in the presence of shear+bulk vs. bulk only (or shear only)

Effects of shear on Π

- The mean has almost no variation
- Shear increases the variation in bulk (at late times)
- Variation decreases significantly at early times

Effects of bulk on π^{00} and π^{12}

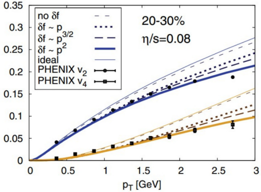
- Bulk suppresses the $\pi^{\mu\nu}$
- Largest effect at late times.
- Variation decreases across the board

Cooper-Frye Freeze-out

Hydro into Particles: $\left(E_p \frac{dN}{d^3p}\right)_i = g_i \int_\Sigma d\Sigma_\mu p^\mu f_i$

Shear Viscosity

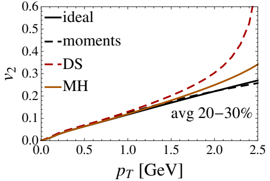
$\delta f_{shear} \propto p^2$



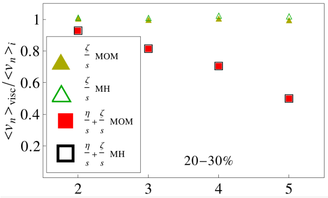
Schenke, Jeon, Gale,PRC85(2012)024901

Bulk Viscosity

$\delta f_{bulk} \propto B_0 + D_0(u\cdot p) + E(u\cdot p)^2$



JNH et al, Phys.Rev. C88 (2013) 044916



- Shear ⇑ flow, bulk ⇓ flow
- Bulk is highly model dependent for higher p_T

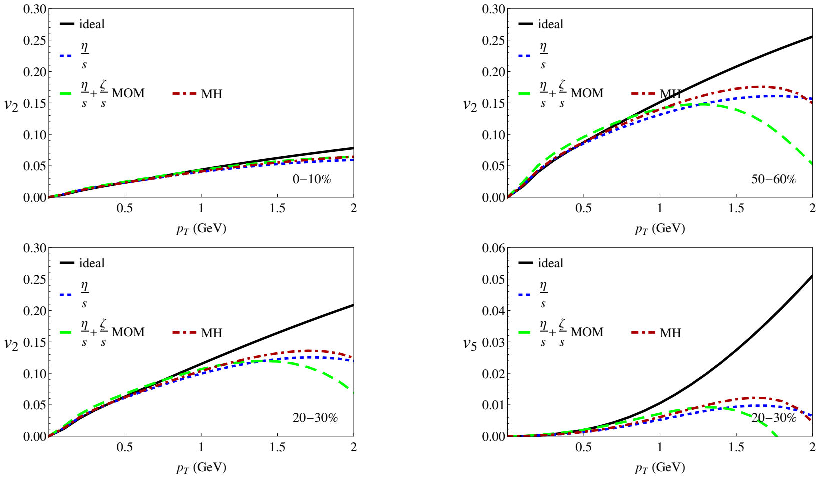
	E_0 $[fm^4]$	D_0 $\left[\frac{fm^4}{GeV}\right]$	B_0 $\left[\frac{fm^4}{GeV^2}\right]$	
mo	-65.85	171.27	-63.05	PRC88(2013)044916
DS	-71.96	121.50	0	PRC85(2012)044909
MH	-0.69	-38.96	49.69	PRC80(2009)054906

- Integrated v_n's not affected by δf

Outline

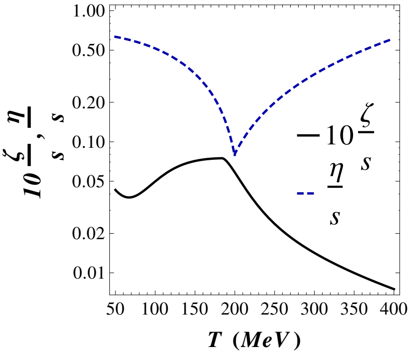
Event-by-Event v_2 at RHIC in v-USPhydro

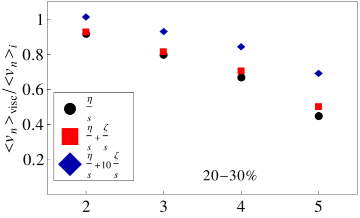
JNH, Noronha, Grassi, PRC90(2014)034907



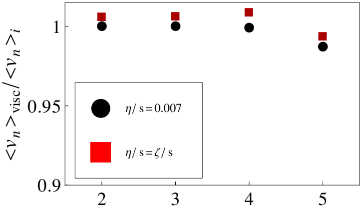
Integrated v_n's at RHIC in v-USPhydro - Comparing ζ/s

JNH, Noronha, Grassi, PRC90(2014)034907





$\zeta/s = \eta/s = 0.007$

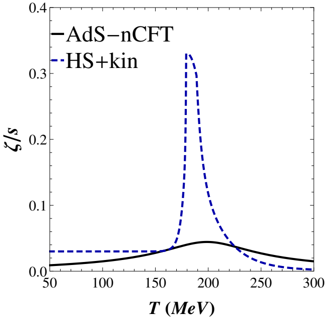


- ζ/s increases the integrated v_n's

Outline

ζ/s Description

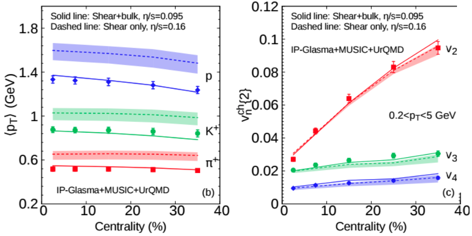
- ζ/s^1 Hagedorn States
  (JNH et al,PRL103(2009)172302)
  +kinetic theory
  (Denicol et al,PR90(2014)no.2,024912)
- ζ/s^2 non-conformal AdS
  (Finazzo et al,JHEP1502(2015)051)



- $\tau_\pi^1 = 5\frac{\zeta}{(1-c_s)^2(e+p)}$
- $\tau_\pi^2 = 9\left(-0.0506\frac{T_c}{T^2} + \frac{10.453}{T\sqrt{0.156658+(T/T_c-1.131)^2}}\right)$

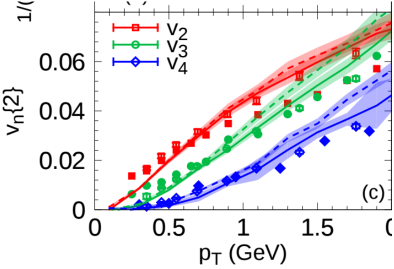
Bulk viscosity at LHC in IP-Glasma+MUSIC

- Bulk decreases $\langle p_T \rangle$ at LHC
- Fits integrated v_n well



Ryu et al, arXiv:1502.01675

- $v_n(p_T)$ has a steeper slow

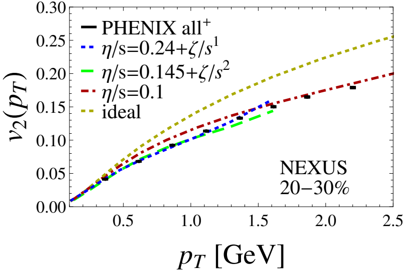


Ryu et al, arXiv:1502.01675

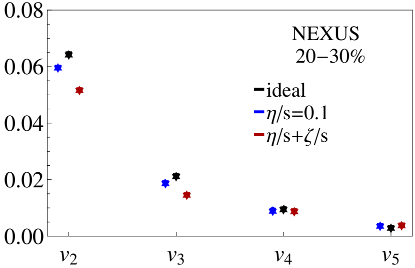
Here bulk viscosity $\Downarrow \eta/s$ to fit the v_n's (for IP-Glasma+MUSIC)

Bulk viscosity at RHIC in NEXUS+v-USPhydro- preliminary!!

- Bulk viscosity has smaller model dependencies for δf below $p_T = 1.5$ GeV
- Bulk require twice as large η/s



- Bulk contributes little to v_n's
- Same ζ/s as in IP-Glasma arXiv:1502.01675



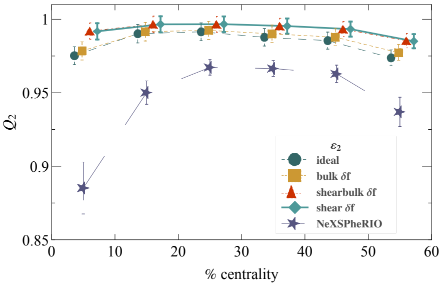
Here bulk ⇑ η/s to fit v_n's (NEXUS-v-USPhydro) - differences in 2^{nd} order transport coef.? UrQMD? RHIC vs. LHC? δf? NEXUS vs. IP-Glasma?

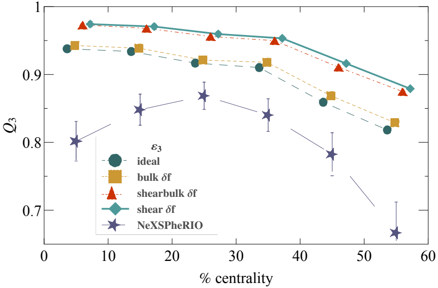
Outline

Shear and bulk effects on the mapping of eccentricities

Gardim, JNH, Luzum, Grassi, arXiv:1411.2574

- But in the end, the eccentricities are vital!
- If the initial eccentricities are wrong, there is only so much that shear/bulk can do
- Shear and bulk increase the mapping between initial eccentricities and v_n's

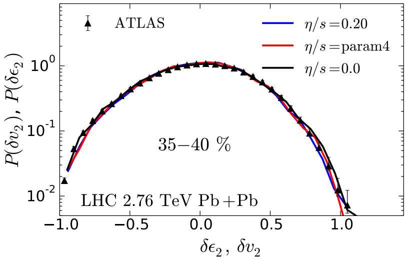




Where do we go from here?

- $\langle p_T \rangle$ with different initial states
- δf improvements- current models don't converge!
- Effects of bulk viscosity in hard probes?
- *pA* (see Niemi and Denicol arXiv:1404.7327)
- Non-zero initial shear stress tensor/bulk pressure (free streaming checked Liu et al arXiv:1504.02160 but need QCD inspired initializations)
- Effects of granularity

- Shear viscosity doesn't affect $P(v_2)$, what about bulk?



Niemi et al. arXiv:1505.02677

Conclusions

- Bulk viscosity and shear viscosity have a non-trivial interplay for the flow harmonics
- Depending on the initial conditions/RHIC vs. LHC etc bulk viscosity either increases are decreases η/s!
- You can't escape the initial eccentricities- viscosity just strengthens that relationship
- So much more work to be done...