

# Small systems - hydrodynamics

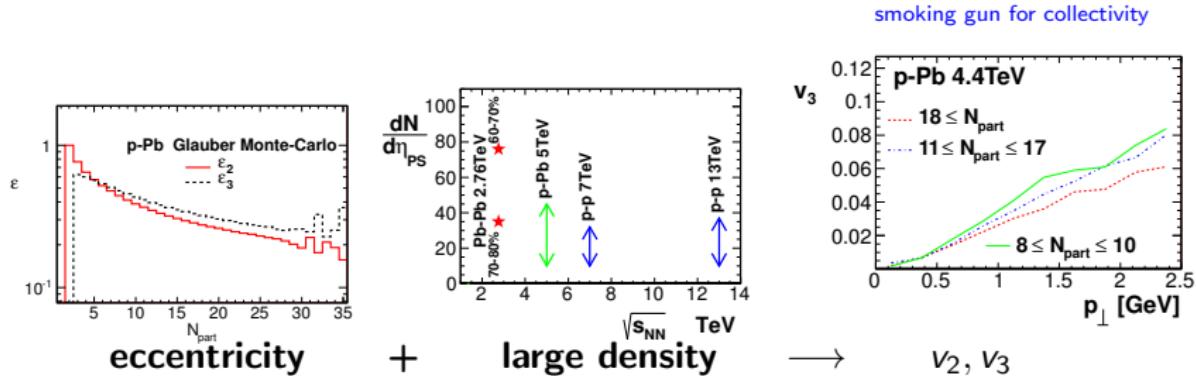
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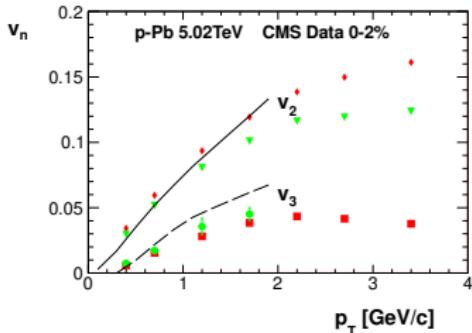
## Flow in p-Pb is expected

- ▶ multiplicity as in peripheral A-A → large energy density
- ▶ sQGP observed in A-A
- ▶ thermal models → stage close to local equilibrium
- ▶  $\eta/s = 0.08 \leftrightarrow$  mean free path  $\simeq 0.2 - 0.3\text{fm} \ll$  size of the system
- ▶ large eccentricity



# 1) Elliptic and triangular flow observed in p-Pb

- Glauber MC initial cond.
- agreement with data

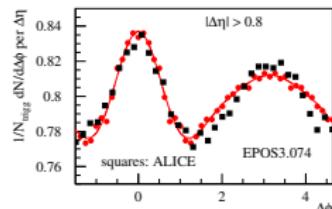


PB, W.Broniowski, G. Torrieri arXiv:1306.5442; G.Y. Qin, B. Müller 1306.3439; I. Kozlov et al. 1405.3976; A. Bzdak et al. 1304.34003, K. Kawaguchi et al. Poster 206

- ▶  $v_2, v_3$  consistent with hydro (Glauber MC, EPOS3)
- ▶ sensitive probe of init. cond.

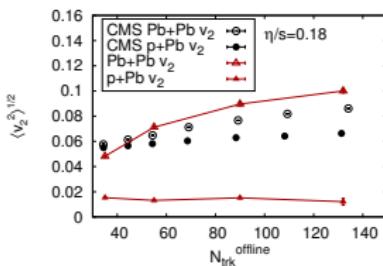
$v_{2,3}$  - hydro response to initial deformation !

- EPOS3 - agreement with data



K. Werner et al. 1307.4379

- IP-Glasma initial cond. - small  $v_2, v_3$  !

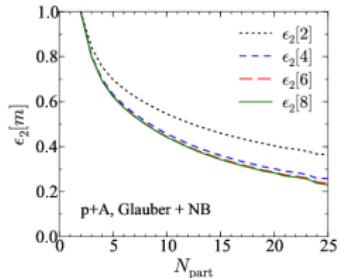


B. Schenke, R. Venugopalan 1405.3605

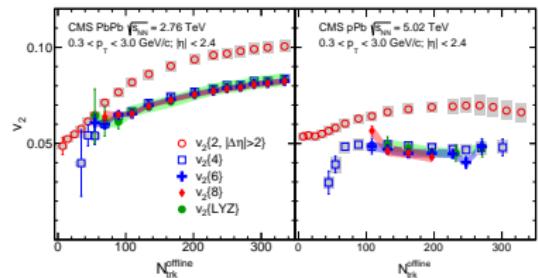
## 2) Flow from higher cumulants

- hierarchy of cumulants

$$\epsilon_2\{4\} \simeq \epsilon_2\{6\} \simeq \epsilon_2\{8\} < \epsilon_2\{2\} \rightarrow \text{hydro response} \rightarrow v_2\{4\} \simeq v_2\{6\} \simeq v_2\{8\} < v_2\{2\}$$



A. Bzdak, PB, L. McLerran, 1311.7325



CMS 1502.05382

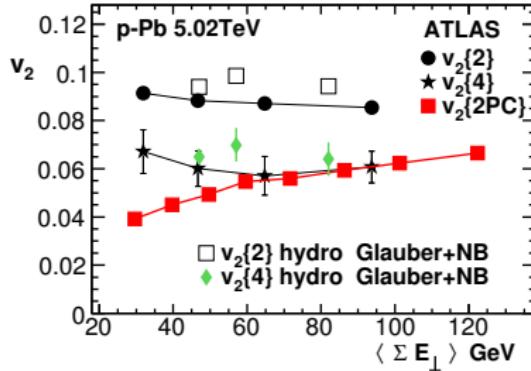
- detailed hierarchy of cumulants - consistent with data

universal prediction for differences  $v_2\{4\} \neq v_2\{6\} \neq v_2\{8\}$

L. Yan, J.Y. Ollitrault 1312.6555

$v_2\{n\}$  - hydro response to fluctuations of initial shape !

## $v_2\{4\}$ and $v_2\{2\}$ - hydro calculation



PB, W. Broniowski 1304.3044

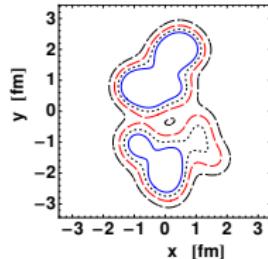
hierarchy  $v_2\{2\} > v_2\{4\} > 0$  confirmed in full hydro calculation

also: I. Kozlov et al. 1412.3147

**Note:**  $\epsilon_n + \text{hydro response} \rightarrow$  correct centrality dependence of  $v_n$

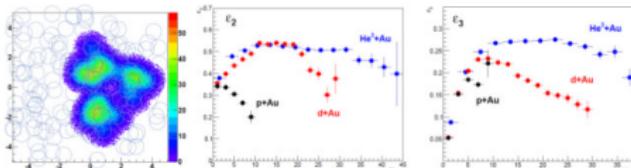
## Small system with large deformation

- deuteron projectile  
intrinsic deformation dominates over  
fluctuations → large  $v_2$



PB 1112.0915

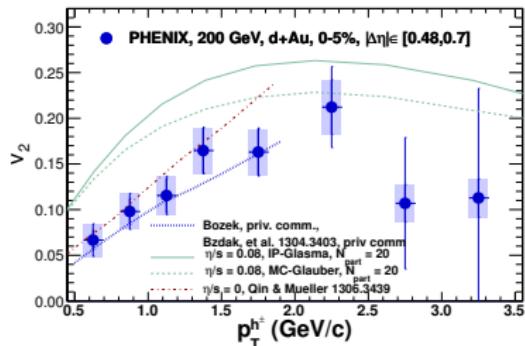
- $^3\text{He}$  projectile  
larger triangular flow



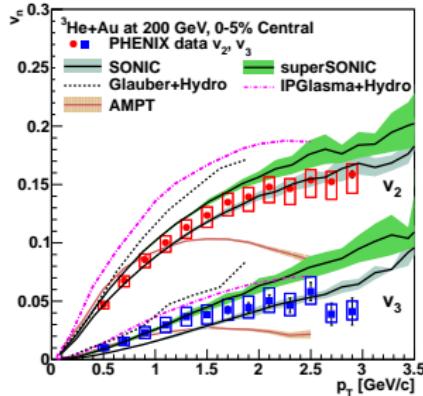
Nagle et al. arXiv:1312.4565

central collisions - deformed fireball, **control of initial geometry**

### 3) Elliptic and triangular flow in d-Au, ${}^3\text{He}$ -Au and p-Au (QM15)



PHENIX, arXiv:1303.1794



PHENIX, arXiv:1507.06273

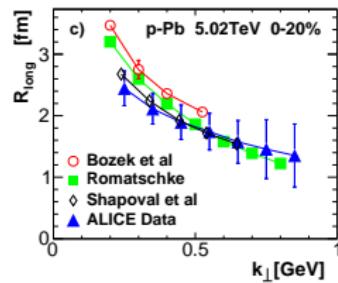
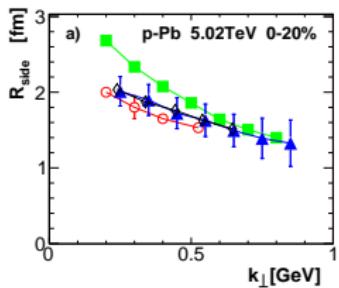
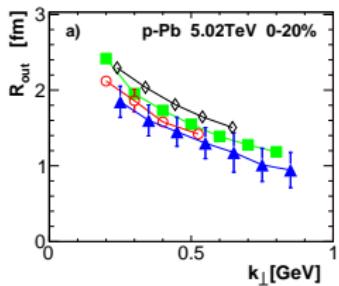
- ▶ observed  $v_3 \rightarrow$  collectivity
- ▶ hierarchy of  $v_2$  and  $v_3$  consistent with collective response on fireball geometry

hydrodynamic calculations reproduce the data

sensitivity to details, limits of applicability of hydro - systematic model uncertainty

large eccentricity - large flow component  
collective response to geometry

## 4) Interferometry radii



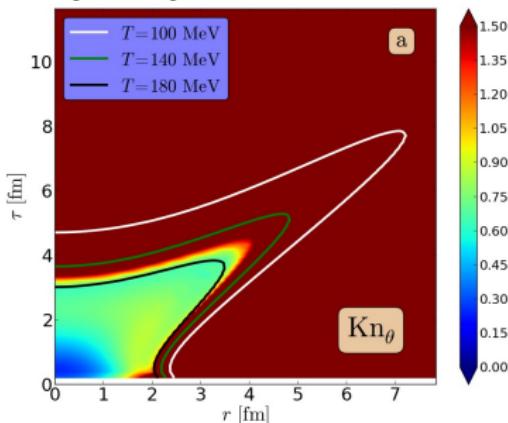
-  $k_{\perp}$  dependence of  $R_{o,I,s}$   
 $R_{side}, R_{out}$  consistent with hydro  
- similar results for d-Au

**right magnitude and  $k_{\perp}$  dependence of HBT radii support collective scenario**

HBT: p-Pb in between p-p and Pb-Pb - **as predicted by hydro**

# Hydrodynamics in small systems?

## Hydrodynamics $K < 1$



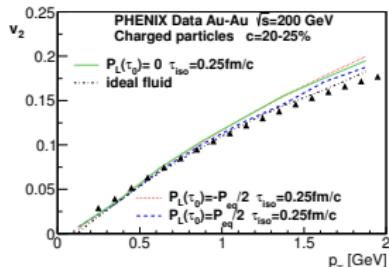
H. Niemi, G. Denicol 1404.7327

large gradients in the evolution

higher order corrections,

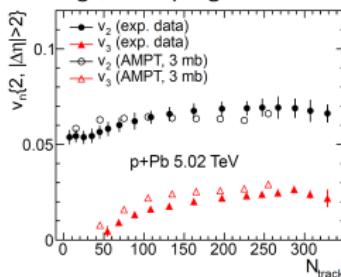
**effective viscosity reduced**

### 1. Early stage, pressure asymmetry $P_L \ll P_{\perp}$



PB, I. Wyskiel-Piekarska 1011.6210; J. Vredevoogt, S. Pratt 0810.4325  
early pressure asymmetry - irrelevant

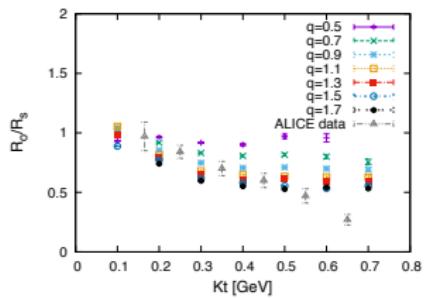
### 2. Late stage, decoupling at freeze-out



A.Bzdak, G.L. Ma 1404.4129; L. He et al. 1502.05572  
hydrodynamics similar to AMPT cascade

# Stronger flow in p-p ?

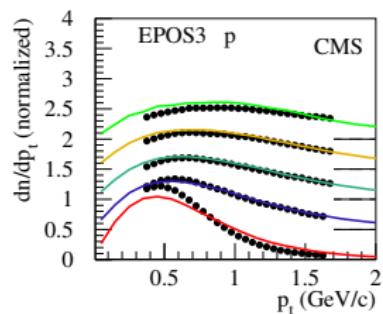
## Interferometry



Y. Hirono, E. Shuryak 1412.0063

stronger transverse flow in p-p !

## Spectra



K. Werner et al 1312.1233,

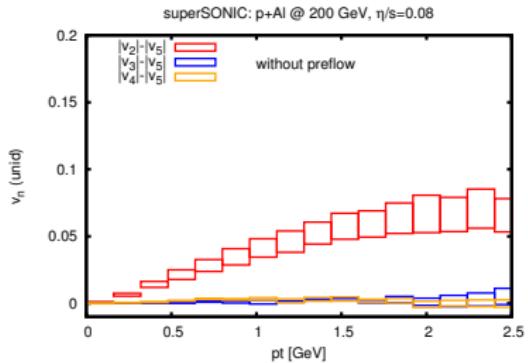
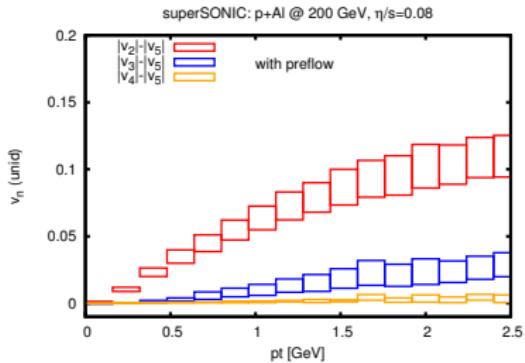
T. Kalaydzhyan, E. Shuryak 1503.05213

Hardening of spectra for high multiplicity events

but: quantitative predictions for flow asymmetry  
less robust in p-p, no smoking gun

## flow in small systems - what can we learn

### 1. onset of collectivity

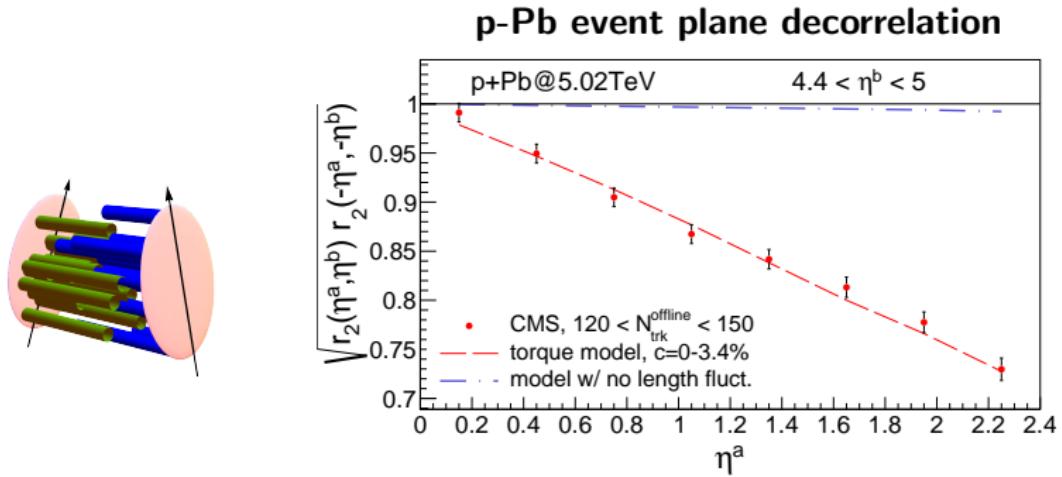


P. Romatschke 1502.02529

sensitivity to preequilibrium flow

- no reason to expect sudden turn off of flow
- decisive between AMPT and hydro? (spectra and  $v_n$ )

## 2. mapping of space time distribution by flow



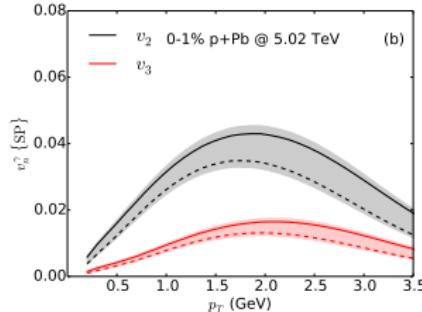
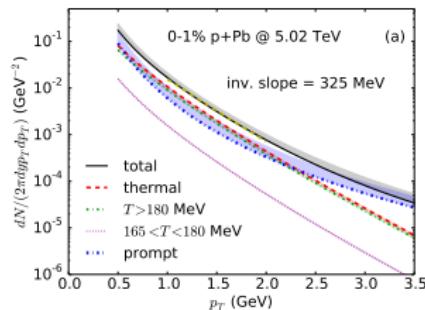
PB, W. Broniowski 1506.04362

sensitivity to fluctuations in energy deposition  
event-plane decorrelation in p-Pb indicates the presence of  
longitudinal fluctuations - random flux tubes

# flow in small systems - what can we learn

## 3. what flows?

medium probes in small systems: photons, jets, heavy flavors, balance functions



direct photons: S. Shen et al. 1504.07989

# SIGNS OF COLLECTIVITY IN SMALL SYSTEMS

1. **Elliptic and triangular flow**
2. **Flow from higher cumulants**  
all particles flow
3. **Hierarchy of  $v_2$  and  $v_3$  in p-A, d-A, He-A**  
collective response to geometry (final state effect)
4.  **$k_\perp$  dependence of HBT radii**
5. **Factorization at intermediate  $p_\perp$  and large  $\Delta\eta$**   
particles at intermediate  $p_\perp$ , large  $\eta$ , correlated to geometry
6. **Mass splitting of  $v_2$**
7. Mass hierarchy of spectra ( $\langle p_\perp \rangle$ )

- ▶ **Density driven collective expansion**
- ▶ **Hydrodynamics describes data for  $p_\perp < 1.5\text{GeV}$**