Bourses postdoctorales Banting Postdoctoral Fellowships

McGill

Hydrodynamics and flow: theory perspective

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Strangeness in Quark Matter

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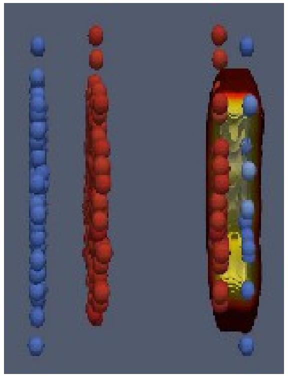
SQM DUBNA 2015

Main Motivation

- Relativistic **fluid dynamics** has played a key role in our current understanding of the novel **“near perfect”** fluid behavior displayed by the Quark-Gluon Plasma

  - ➔ Created matter behaves as a fluid
  - ➔ “thermalization” at very early times $\tau \sim 0.5$ fm
  - ➔ “Small”, but important, shear viscosity

Hydrodynamic modeling of heavy ion collisions

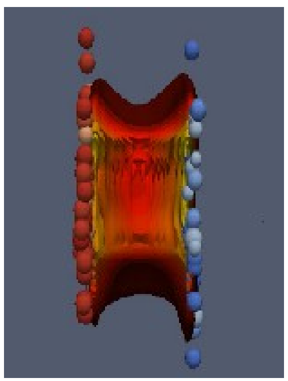


Initial state and pre-equilibrium dynamics

description of early time-dynamics and thermalization

"**initial condition**" for hydrodynamic evolution

(approach) thermalization



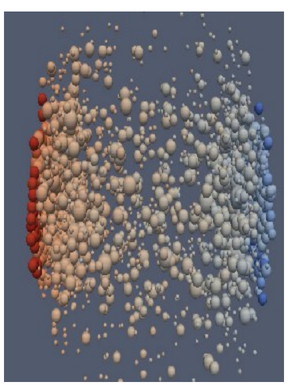
Fluid-dynamical expansion of QGP and Hadron Gas

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

+ EoM for dissipative currents

EoS, viscosities, diffusion coefficients...

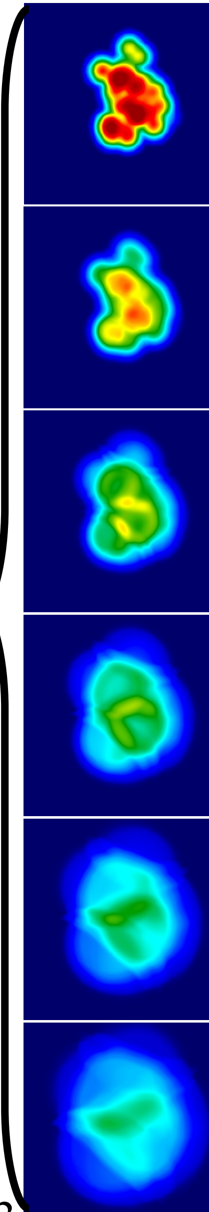
fluid elements converted to particles



Transport description of Hadron Gas

Matter described by cross sections and decay probabilities

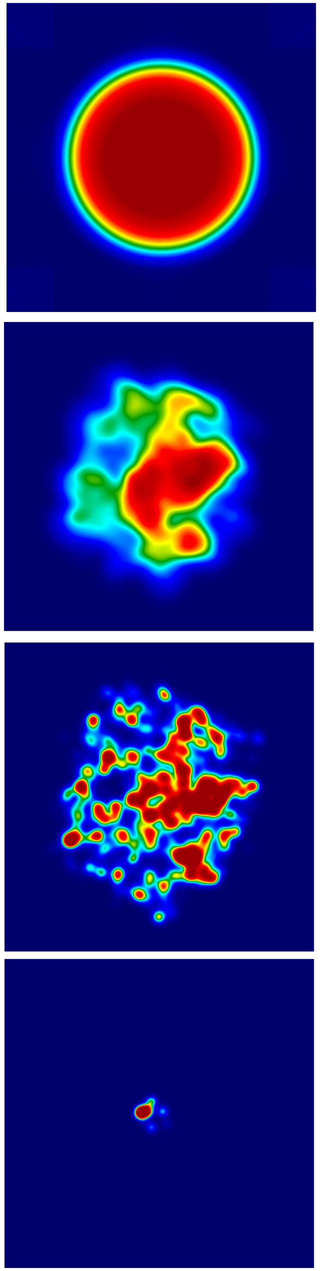
UrQMD, JAM, ...



Evolution of hydro model

$\varepsilon(x,y)$

Coarse-graining size



Smooth Initial conditions
($v2=0$ in central collisions) — $\lambda \sim 5$ fm

Fluctuations in nucleon positions
(odd harmonics) — $\lambda \sim 1$ fm

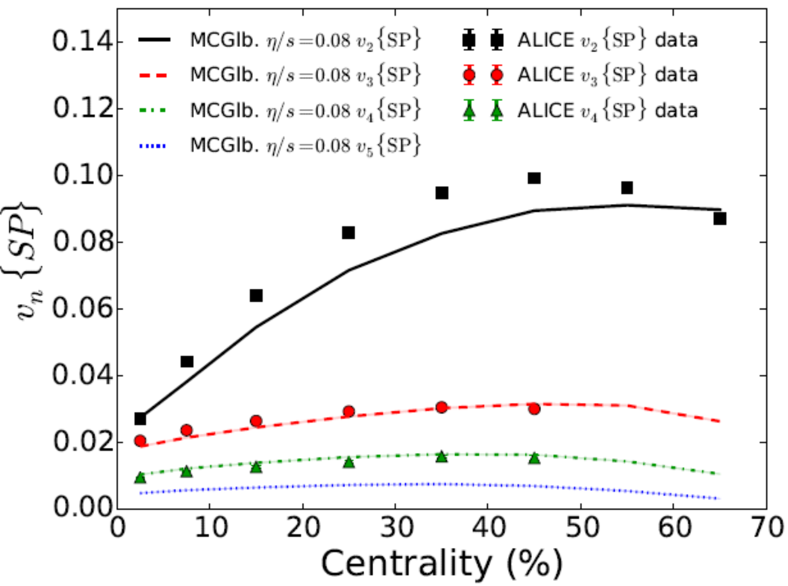
sub-fermionic fluctuations
(vn distributions&correlations) — $\lambda \sim 0.3$ fm

proton-Nucleus collisions — $\lambda \sim 0.3$ fm or smaller

Event-by-event fluctuations changed the game

Hydrodynamic models should describe, not only event-averaged observables, but also distributions/correlations of observables

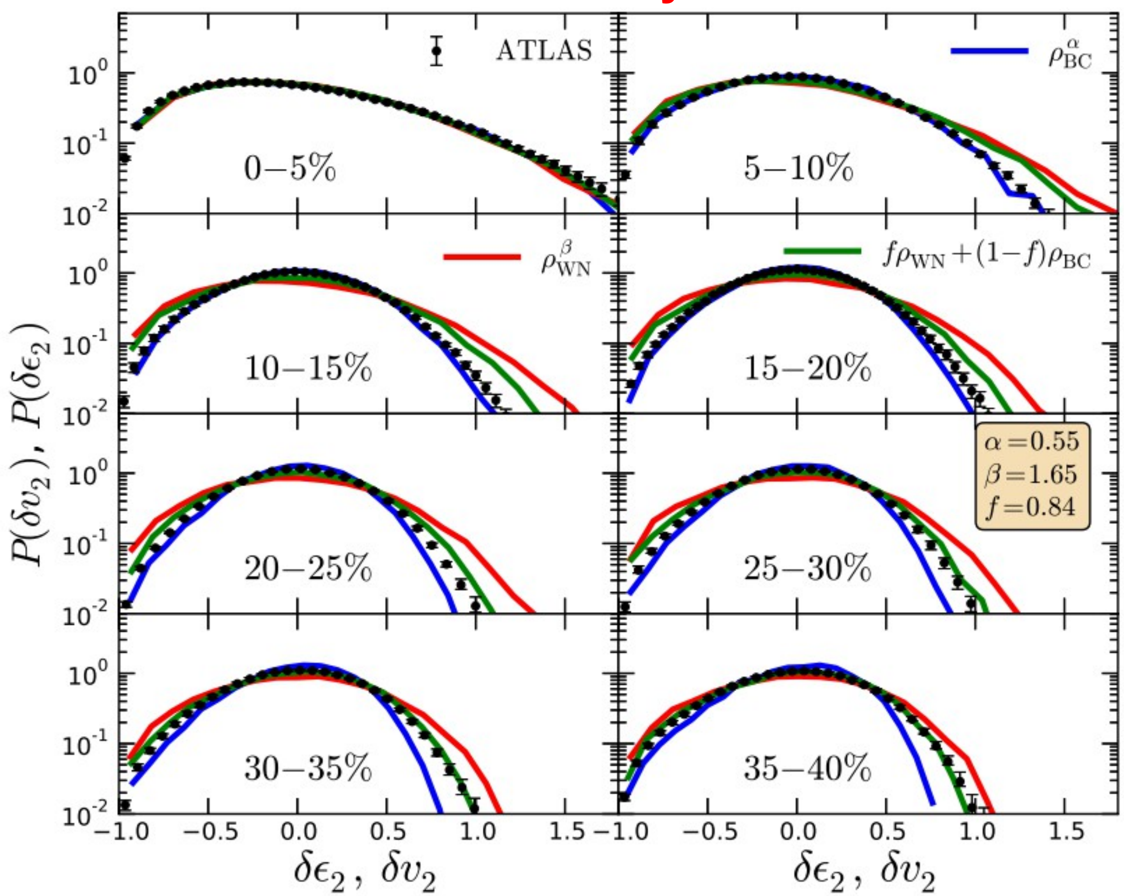
Centrality dependence of v_n



Difficult to describe v_2 and v_3 with the same shear viscosity

v_2 distributions (measured by ATLAS)

Cannot be described by Glauber and KLN



PhD thesis of C. Shen

Renk&Niemi, PRC 89 (2014) 6, 064907

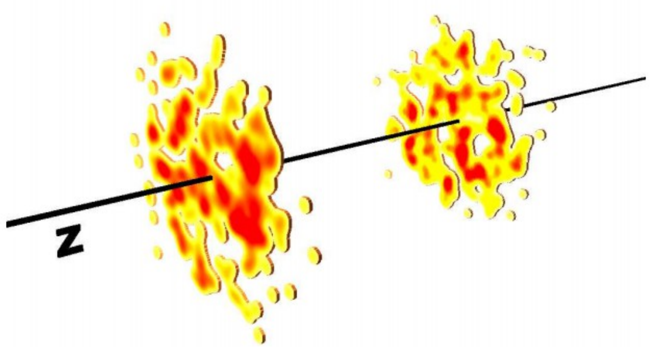
IP-Glasma: IPsat model + Yang-Mills evolution

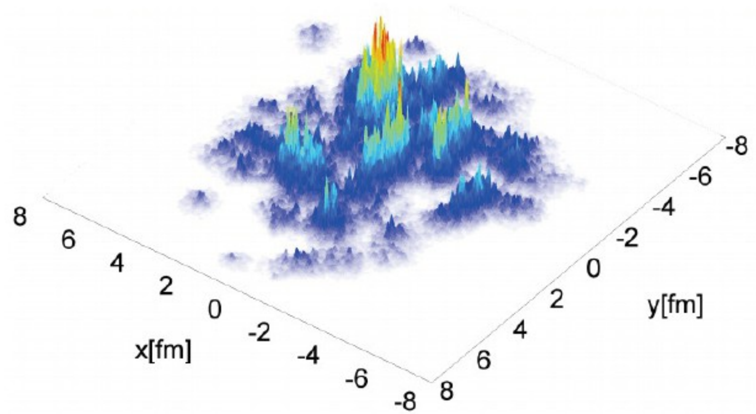
$\eta/s=0.2$

Very good description of flow harmonic coefficients

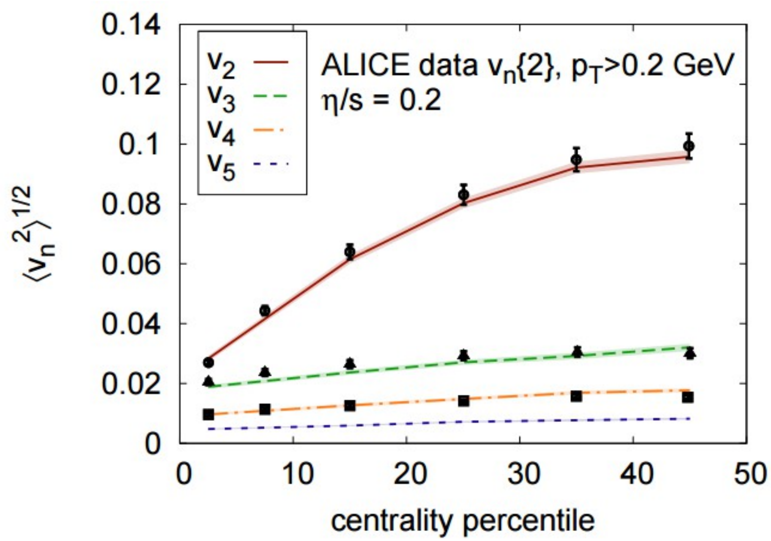
Prediction of v_n distribution

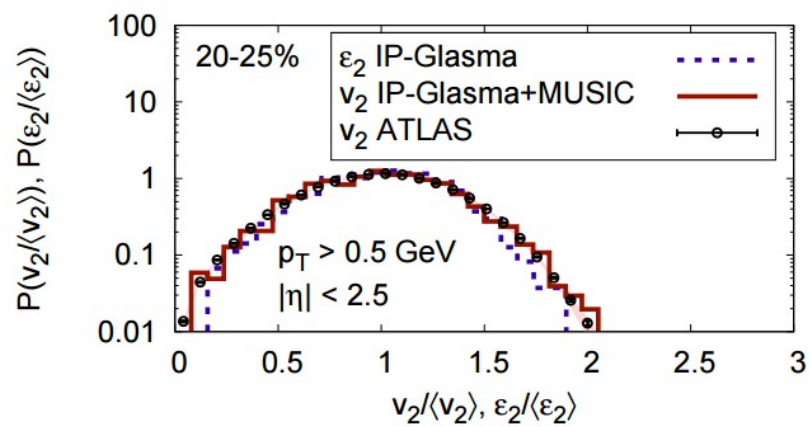
Gale *et al*, PRL 110 (2013) 1, 012302





Schenke *et al*, PRC86 (2012) 034908



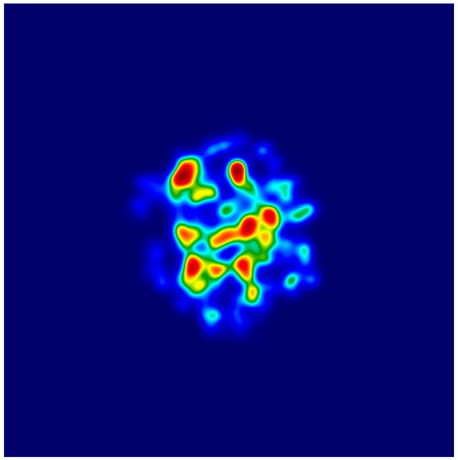


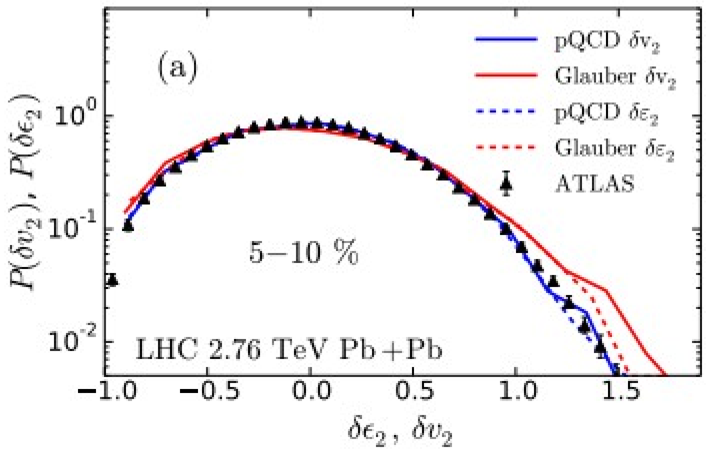
EKRT model: NLO-improved pQCD + saturation

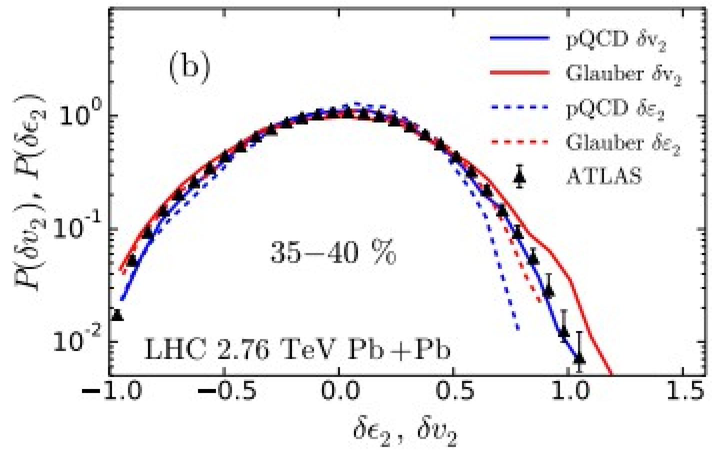
Niemi *et al*, arXiv:1505.02677

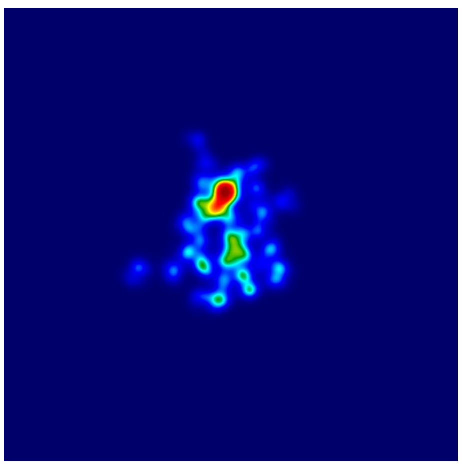
Also able to describe event-by-event distributions of flow

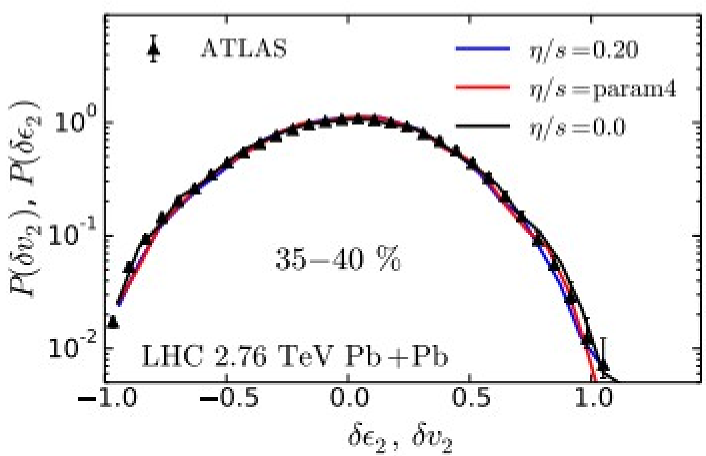
Central

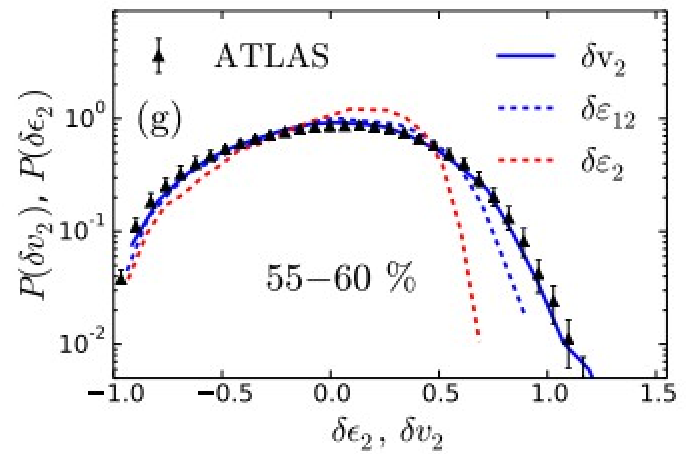












Peripheral

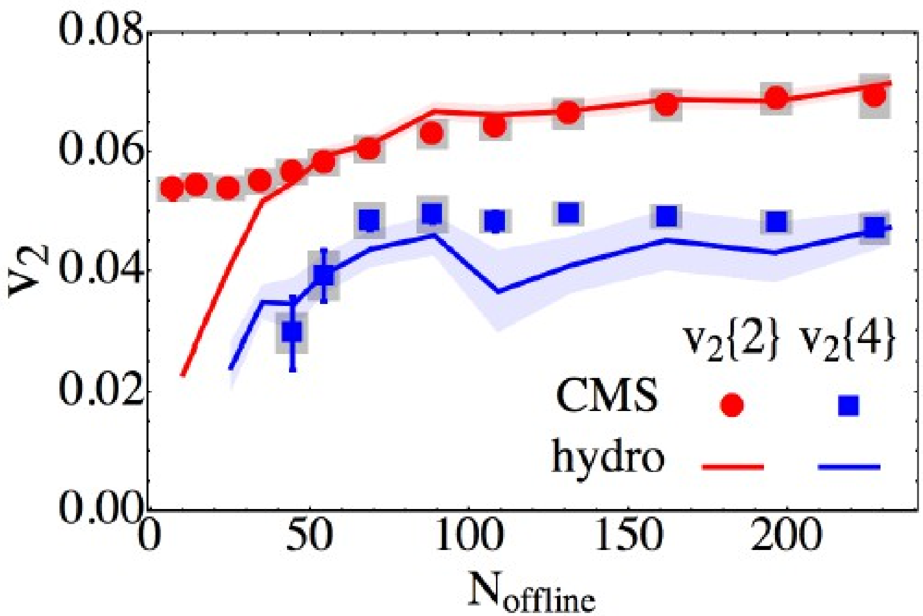
Why can only EKRT and IP-Glasma describe this data?

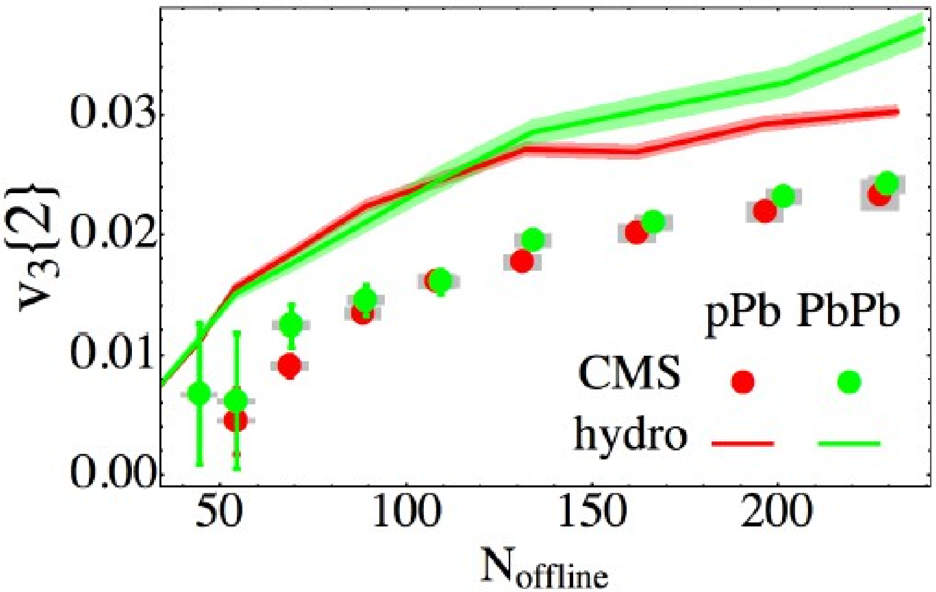
Hydrodynamics in small systems

Hydrodynamic description of small systems?

The same signals usually associated to flow in AA collisions are now also seen in pA

Nucl.Phys. A931 (2014) 1045-1050



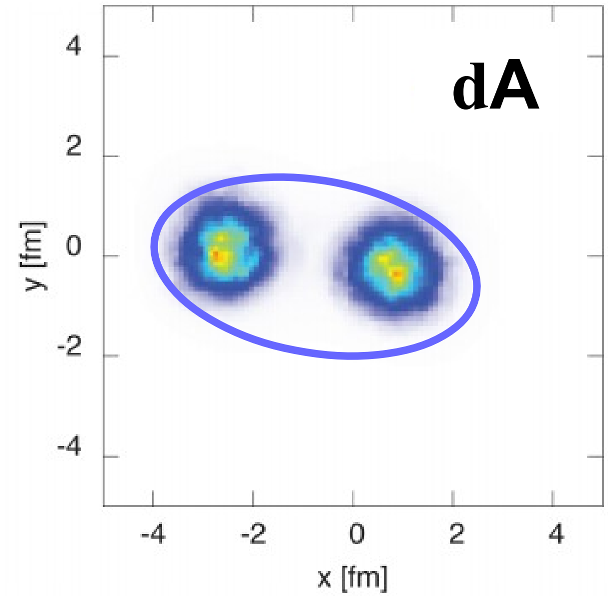


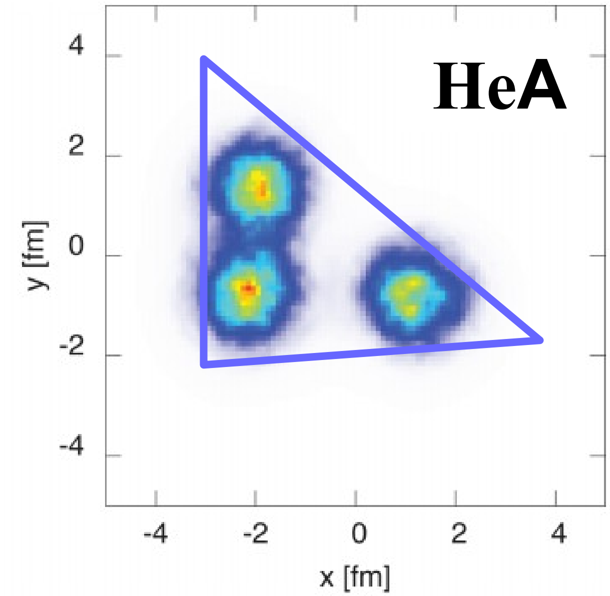
Large v_2 signal is also observed in p-N collisions

Hydrodynamic simulations seem to be able to describe it!

But how? What is a large volume for the QGP?

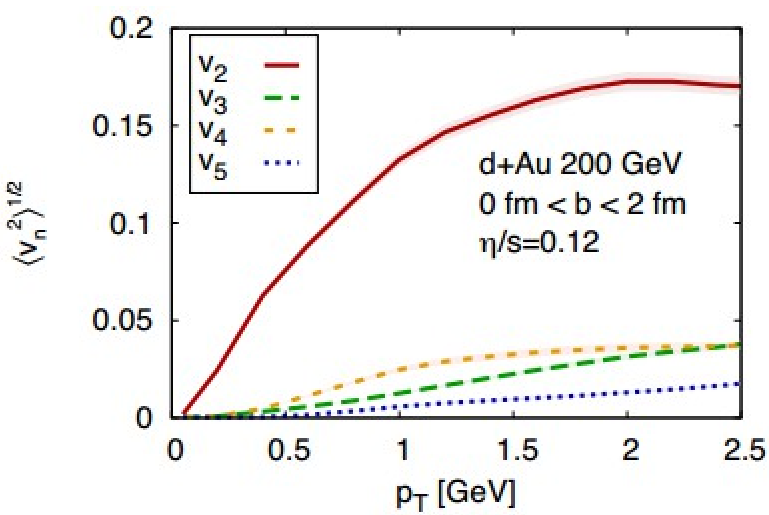
Hydrodynamic description of small systems?

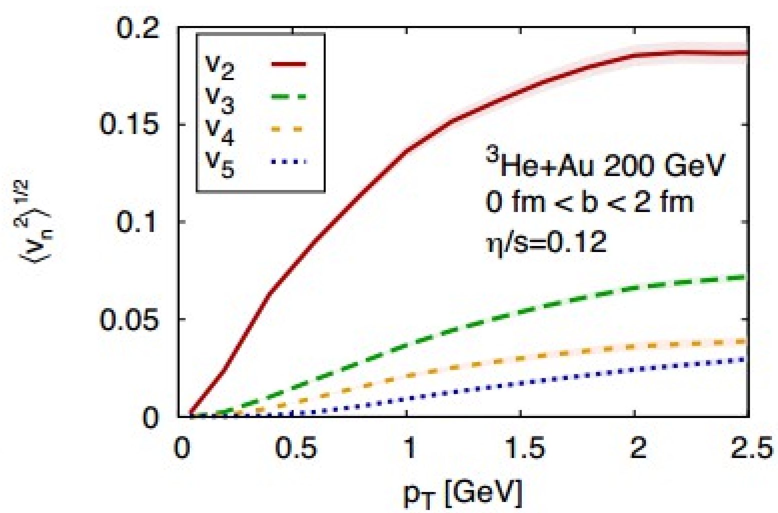




Large ellipticity

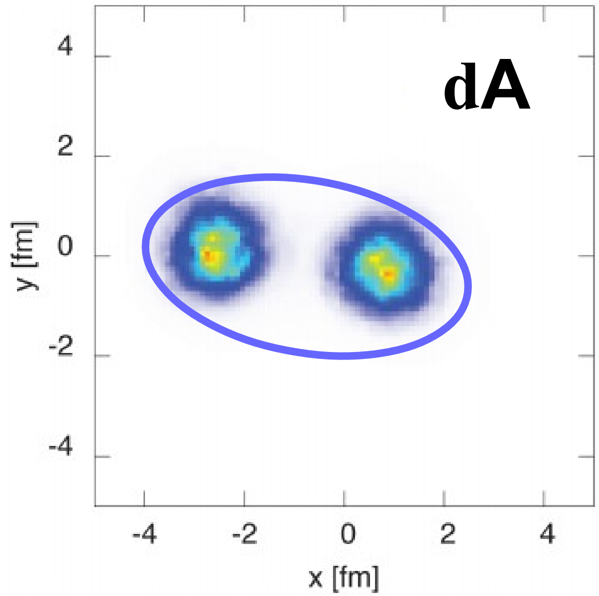
Large triangularity

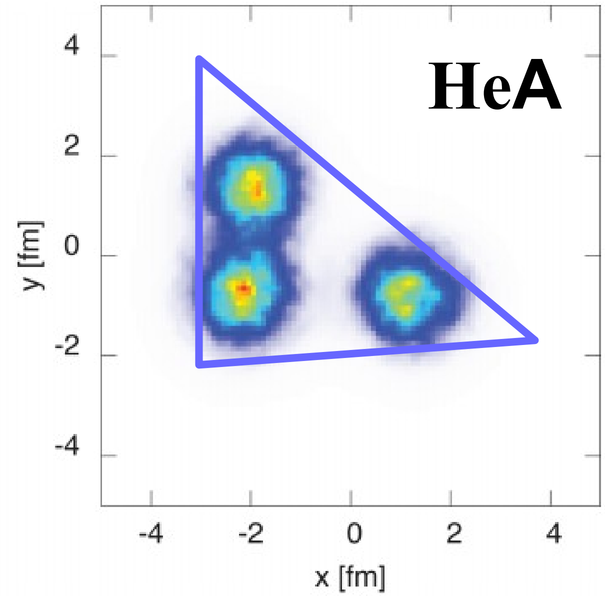




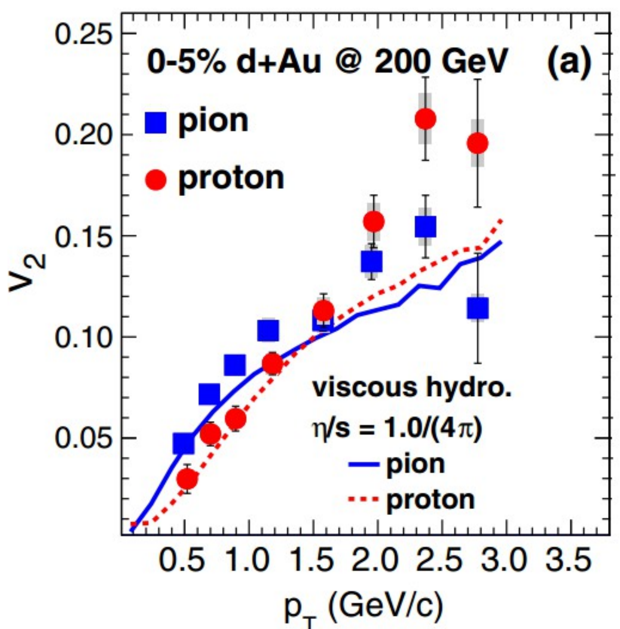
Schenke and Venugopalan, arXiv:1407.7557

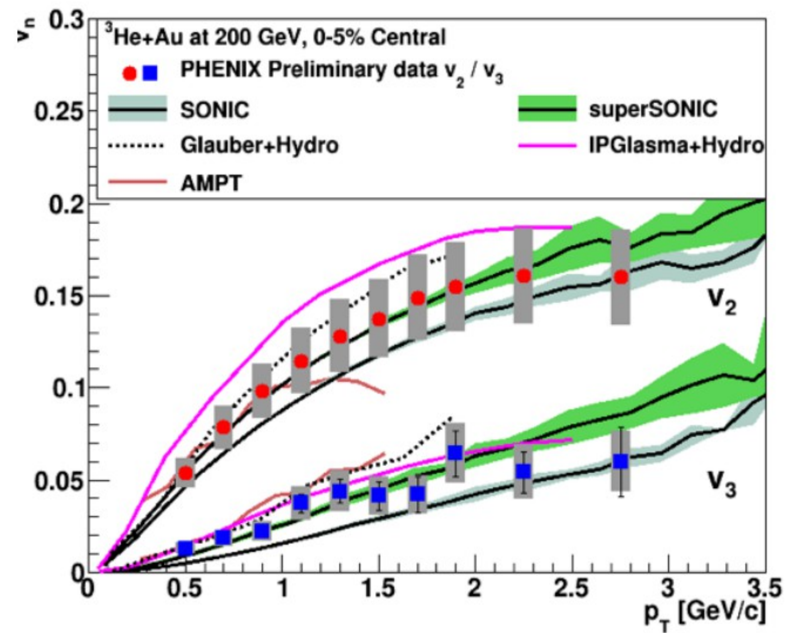
Hydrodynamic description of small systems?





Good agreement of hydro calc. with PHENIX data





Hydrodynamic description of small systems?

Apparent strong response to initial shape:
typical signature of hydrodynamic behavior

What is small?

Finite viscosity defines a length scale (mean free-path for dilute gases)

Relaxation time: $\tau_\pi = 5\frac{\eta}{\varepsilon + P}$

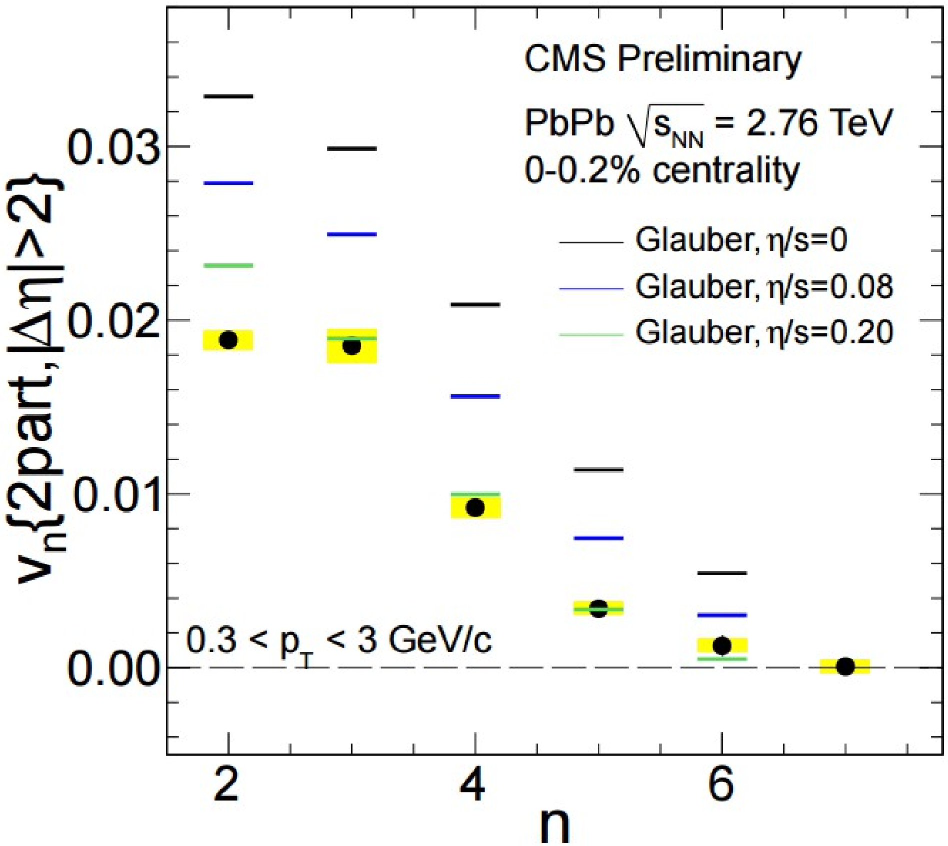
Right now, very small values of shear viscosity are being used: $\eta/s=0.08$

Unlike in AA collisions, not much room to increase the viscosity (hydro becomes not applicable)

Niemi&GSD, arXiv:1404.7327

Ultracentral Heavy ion collisions

- **Nonhydrodynamic**(?) behaviour in ultracentral PbPb collisions



$v_2 \sim v_3$

where is viscous damping?

Hydrodynamic models always over-predict the elliptic flow

CMS coll., CMS-PAS-HIN-12-011
Calculations by Luzum, arXiv:1210.6010

So far, all hydro models cannot get this right

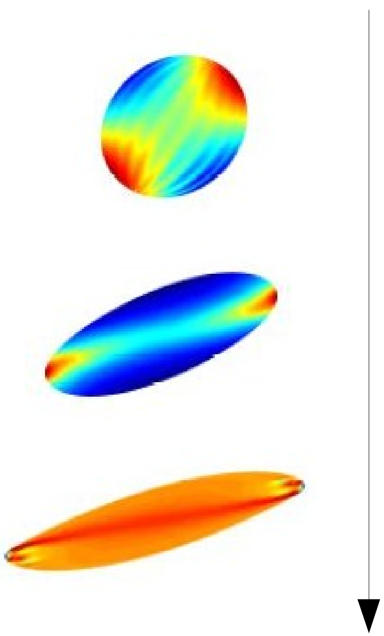
Transport coefficients

Sources of viscosity and dissipation

Shear viscosity

Resistance to deformation

$$\pi^{\mu\nu} = 2\eta\nabla^{\langle\mu}u^{\nu\rangle}$$



very studied

Bulk viscosity

Resistance to expansion

$$\Pi = -\zeta\nabla_{\mu}u^{\mu}$$

little studied

Charge/particle diffusion

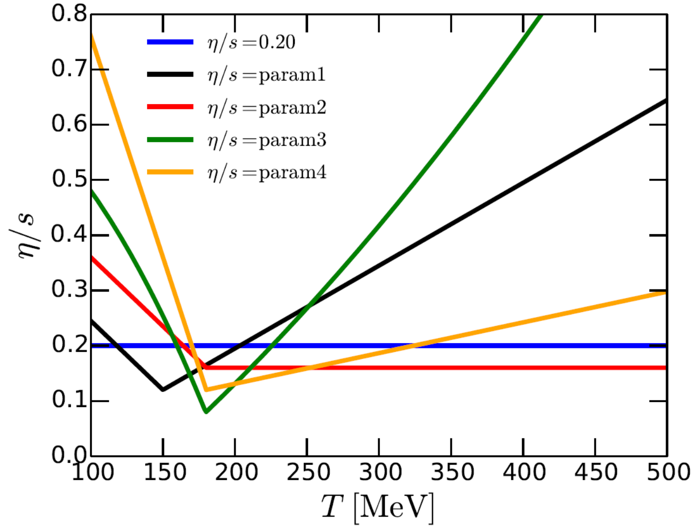
$$q^{\mu} = \kappa\nabla^{\mu}\frac{\mu_B}{T}$$

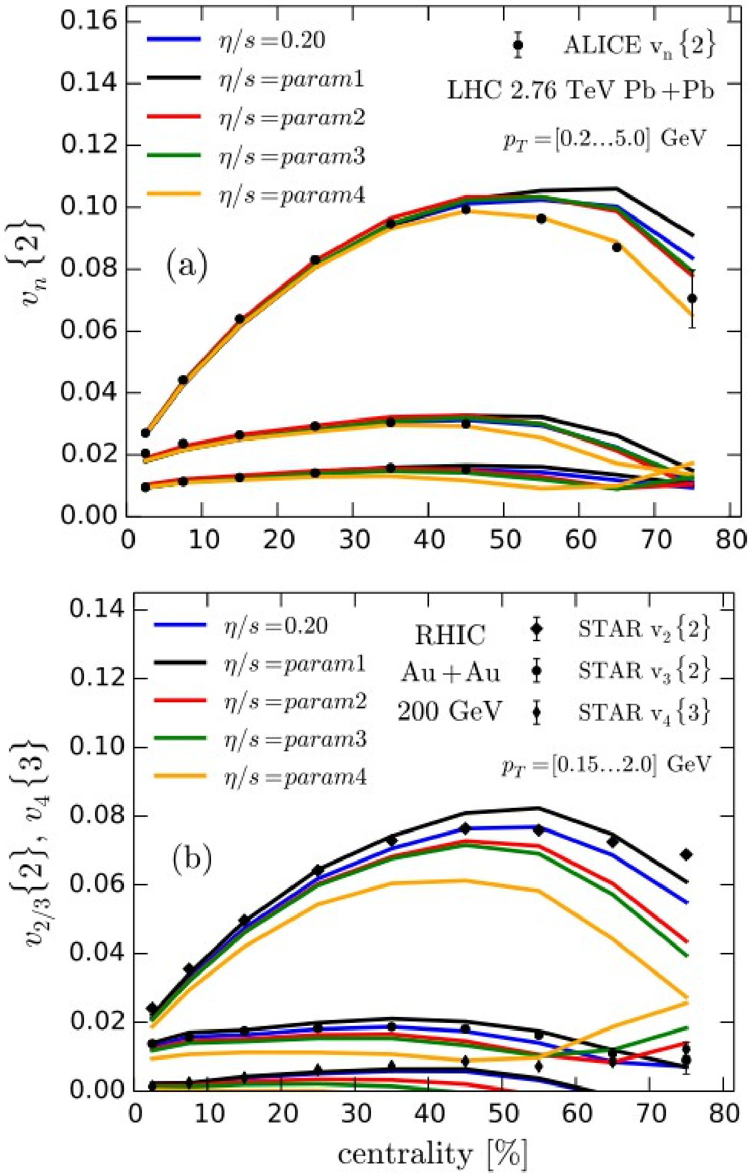
Not yet … but coming

EKRT model + second order viscous hydro

Niemi *et al*, arXiv:1505.02677

η/s(T)





LHC

RHIC

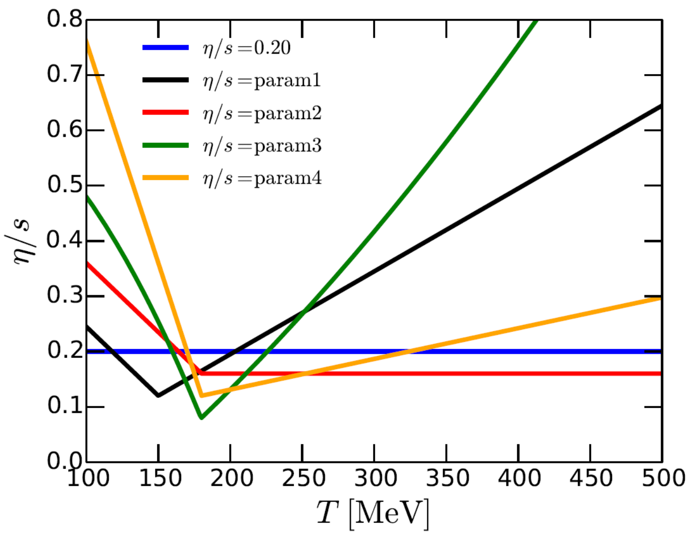
What happens when we change η/s(T) ?

Can we extract it ?

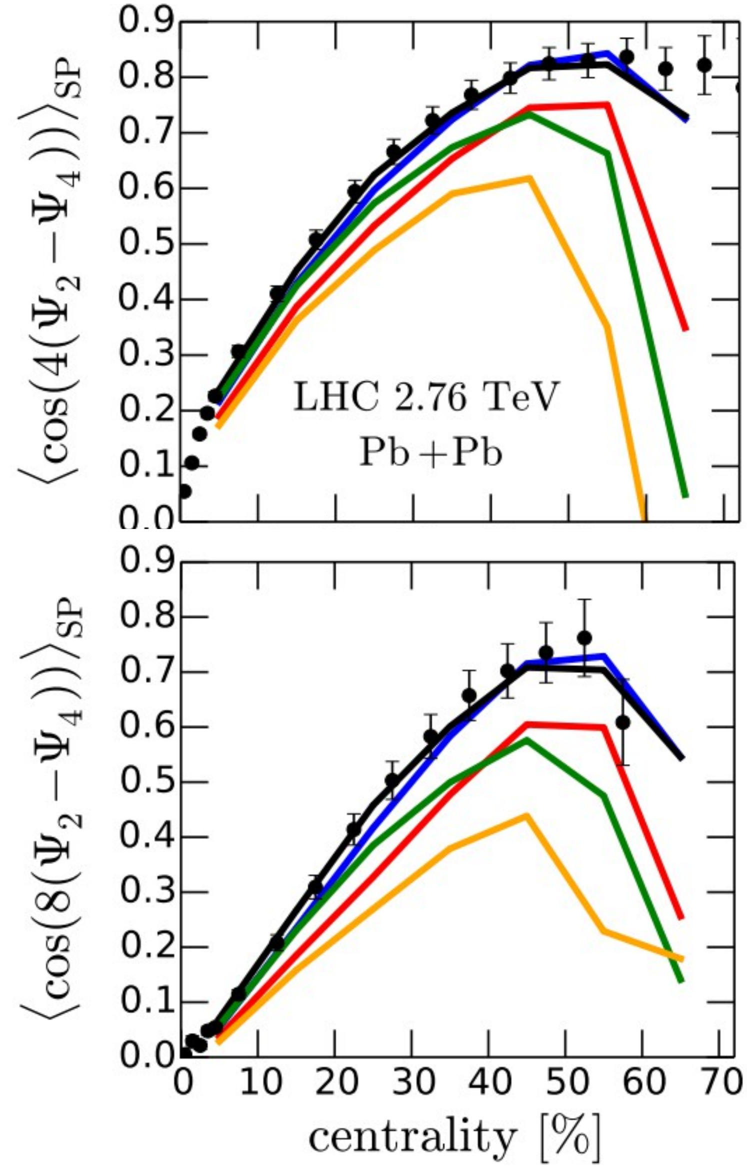
EKRT model + second order viscous hydro

Niemi *et al*, arXiv:1505.02677

η/s(T)



event-plane correlations

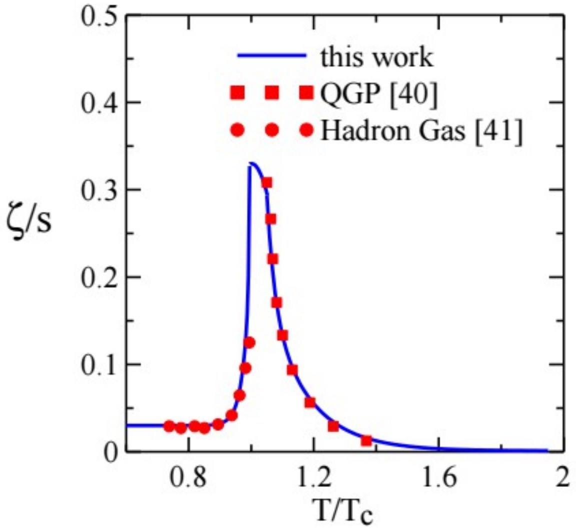


It is necessary to look at more than $v_{2,3}$ to obtain η/s(T)

IP-Glasma + MUSIC + UrQMD

ζ/s(T)   η/s=0.095

Ryu *et al*, arXiv:1502.01675

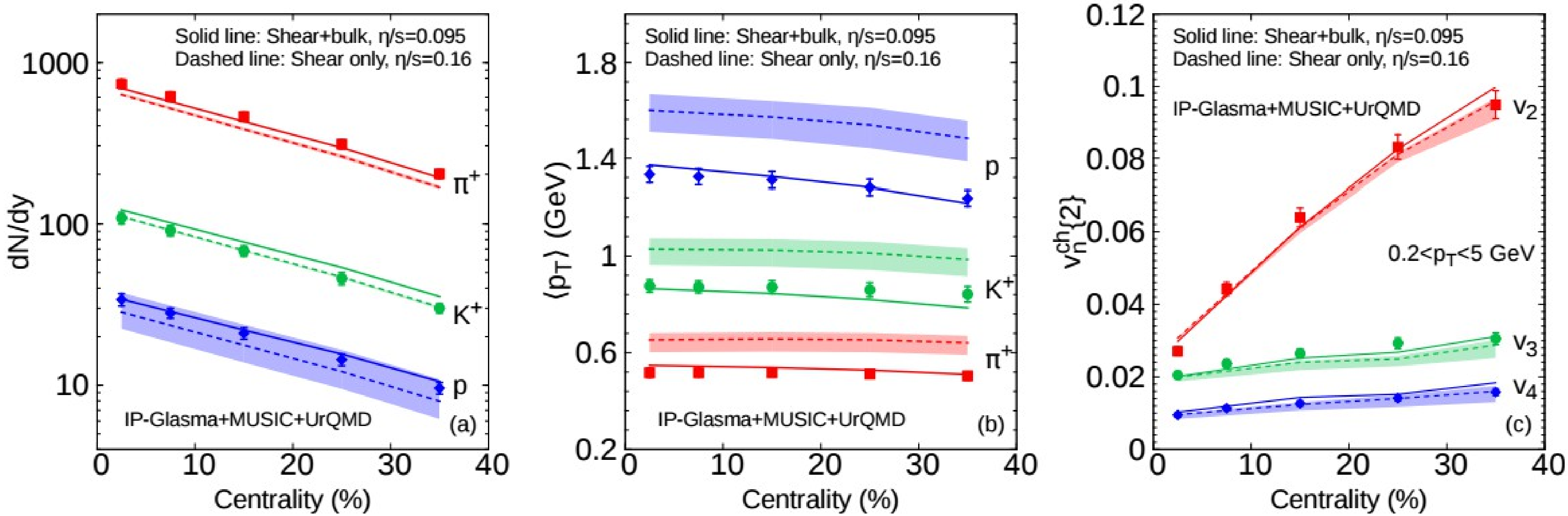


IP-Glasma initial conditions lead to high mean pt (sub-fermionic fluctuatons?)

Need bulk viscosity to explain the mean pt of identified hadrons

Value of shear viscosity extracted changes

η/s=0.16 ⟶ 0.095



UrQMD + Hydro + UrQMD

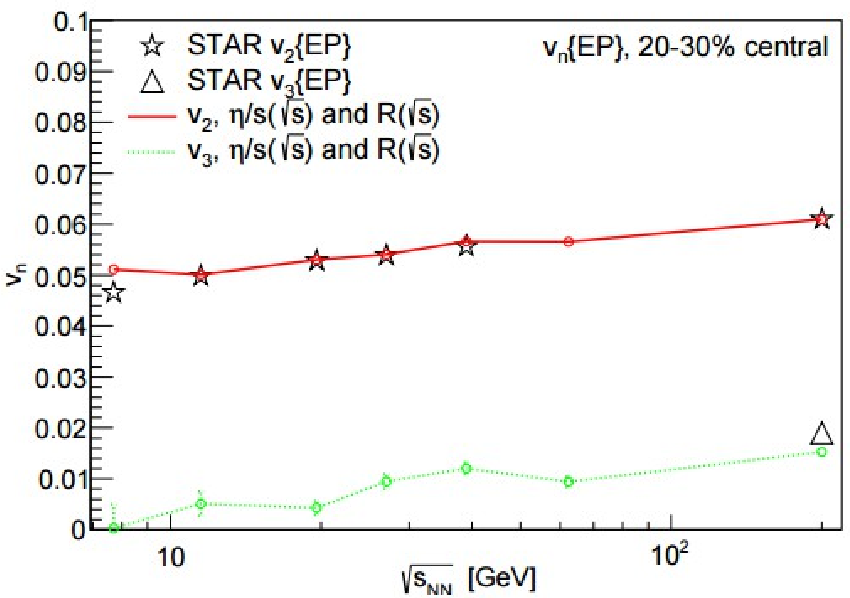
η/s vs collision energy

Karpenko *et al*, Phys.Rev. C91 (2015) 6, 064901

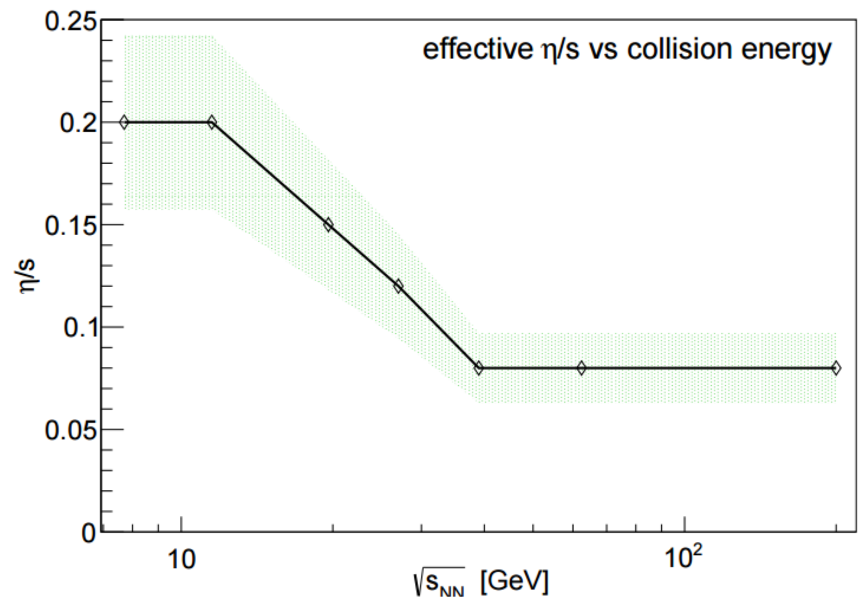
Modeling of heavy ion collisions at lower energies

Finite baryon number, isospin, and electric charge must be included

Effective EoS is employed Steinheimer&Schramm&Stocker, J. Phys. G 38, 035001 (2011).



Good description of v_2 as a function of energy



η/s estimated

Hydrodynamics with diffusion

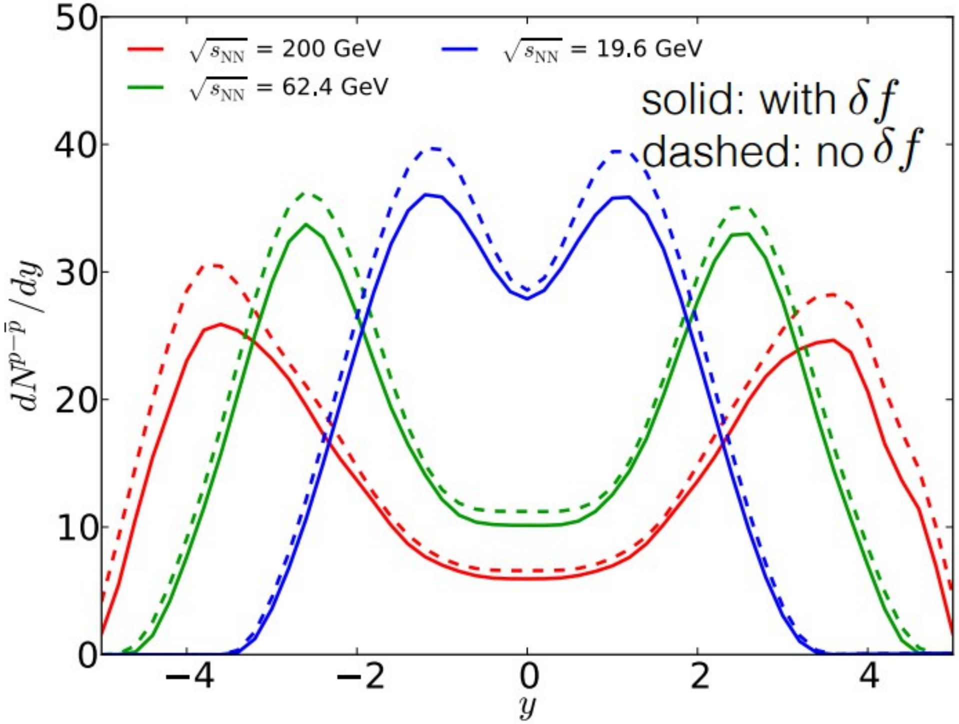
C. Shen *et al*, Preliminary

Modeling of heavy ion collisions at lower energies

$$\Delta^{\mu\alpha}\Delta^{\nu\beta}D\pi_{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu}) - \frac{4}{3}\pi^{\mu\nu}\theta$$

$$\Delta^{\mu\nu}Dq_\nu = -\frac{1}{\tau_q}\left(q^\mu - \kappa\nabla^\mu\frac{\mu_B}{T}\right) - q^\mu\theta - \frac{3}{5}\sigma^{\mu\nu}q_\nu$$

Effect on multiplicity can be large



Can we use RHIC and SPS data to understand this transport coefficient?

Maybe we will know the answer soon

Summary

✔ Hydrodynamic models are being applied with sucess to describe small systems and subfermionic fluctuations in AA

Will this hold? Too soon to say ...

✔ But ultracentral AA collisions still cannot be described ...

✔ Some progress in understanding transport coefficients:

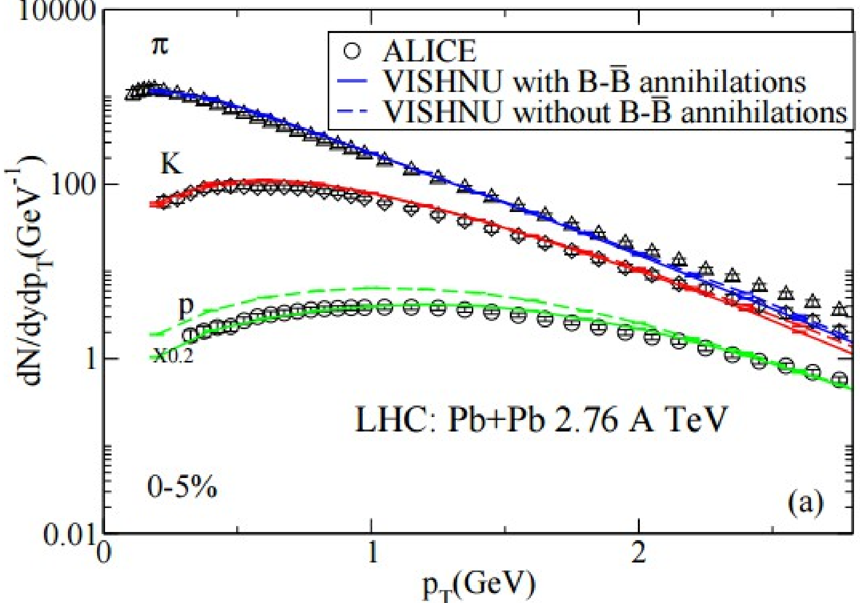
1) possibility to extract $\eta/s(T)$ also using event-plane correlations

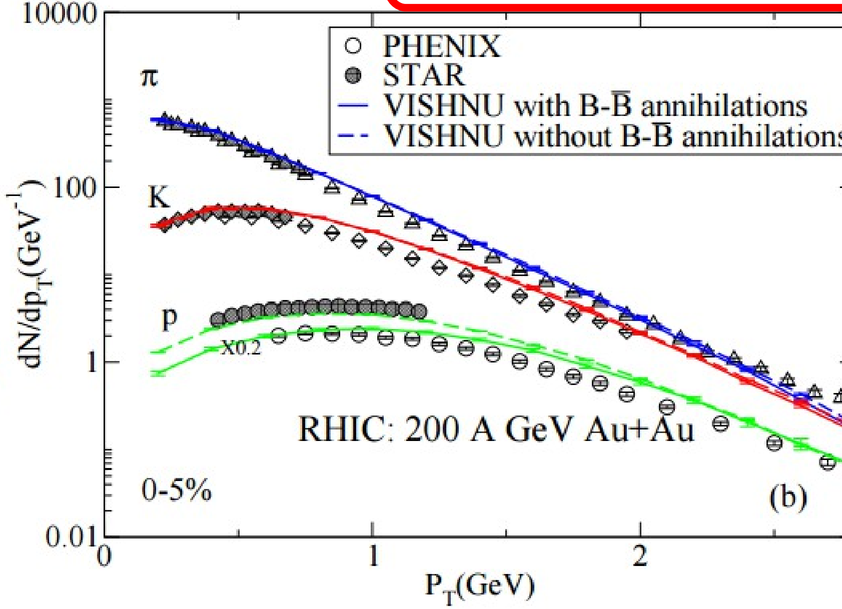
2) IP-Glasma IC suggests a finite bulk viscosity around Tc

3) First estimation of η/s at lower energies

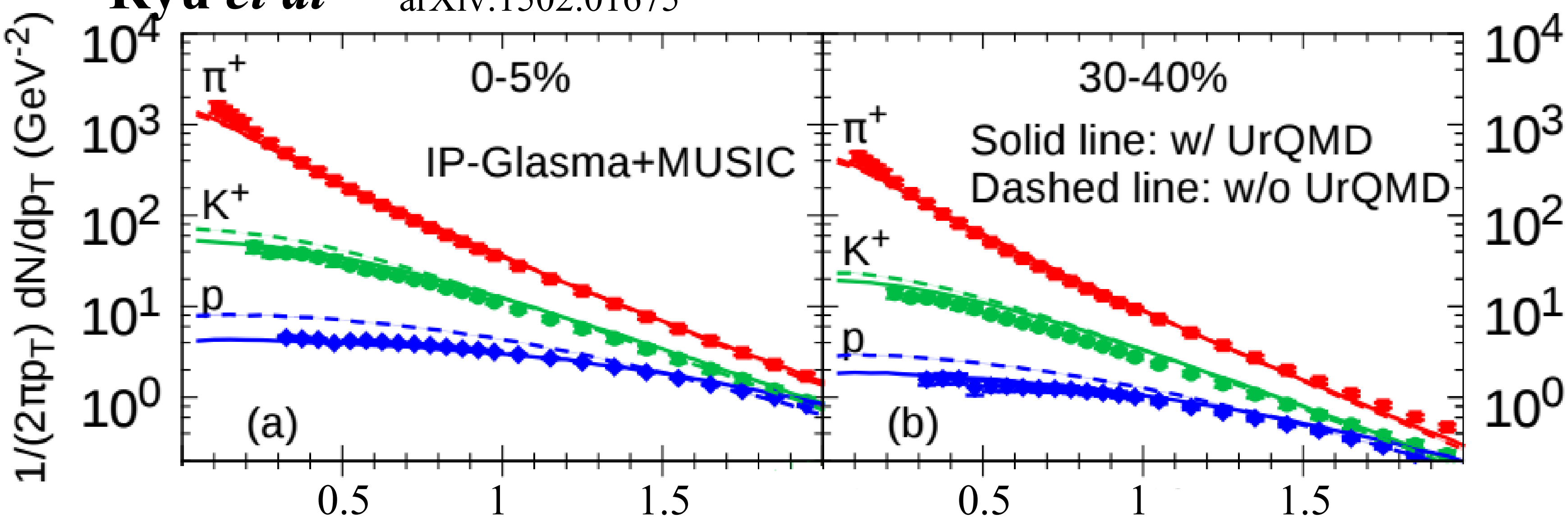
Song *et al* arXiv:1311.0157

talk by X. Zhu today



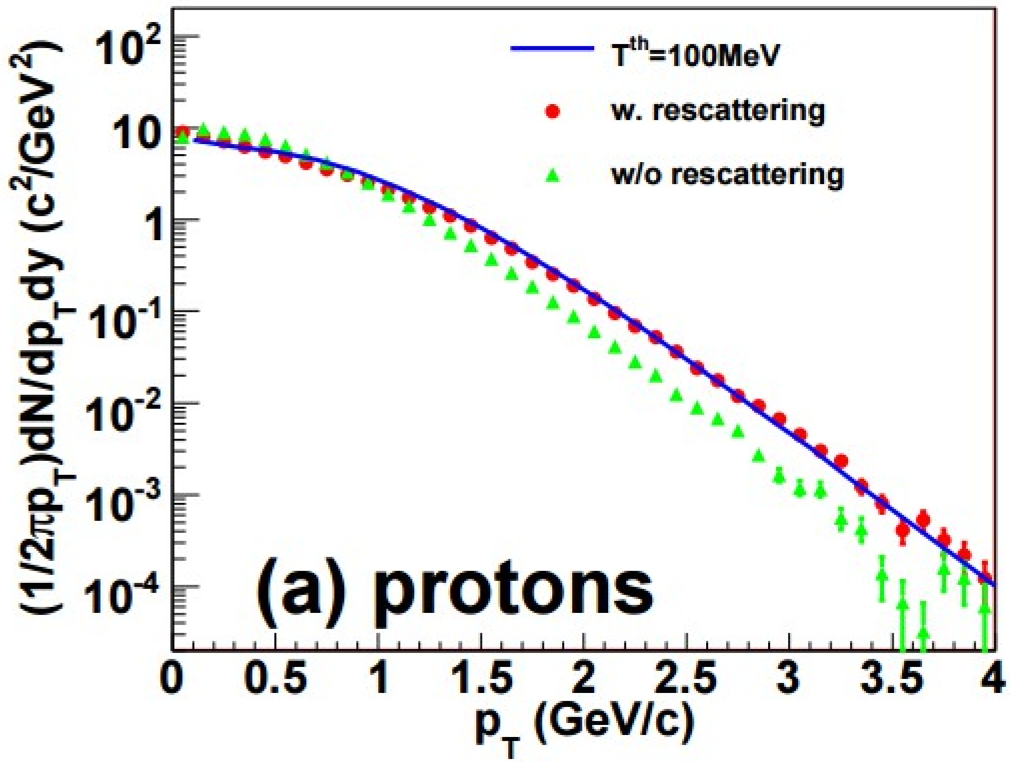


Ryu *et al* arXiv:1502.01675



Both calculations show an important effect from annihilation as first shown by Steinheimer&Aichelin&Bleicher arXiv:1203.5302

But Hirano *et al* does not see it ... arXiv:0710.5795

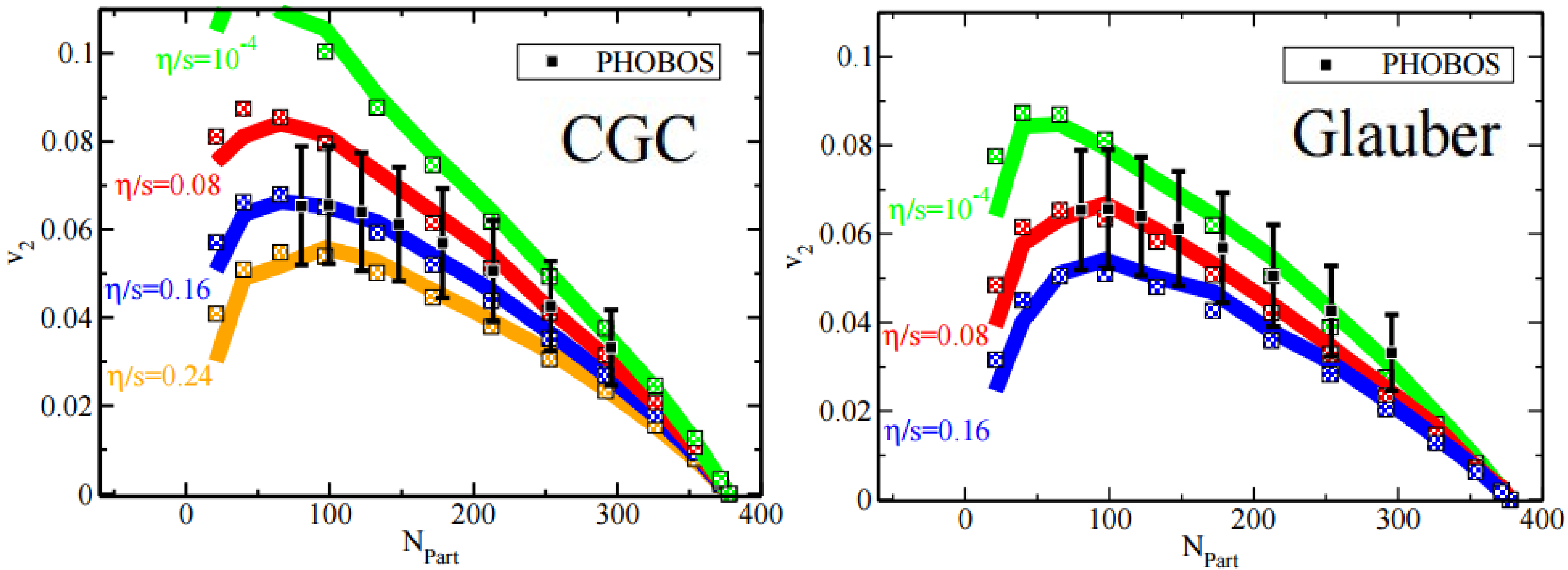


And is still able to describe protons and multi-strange hadrons ... arXiv:1505.05961

Why? Is hadronic transport under control?

Event-by-event fluctuations changed the game

BEFORE: different initial state models could fit the same data by changing the shear viscosity



Luzum&Romatschke PRC 78, 034915 (2008)

Initial state enters as an uncertainty in the extraction of shear viscosity

Song *et al*, PRL 106, 192301 (2011)

Hydrodynamic description of small systems?

What is small?

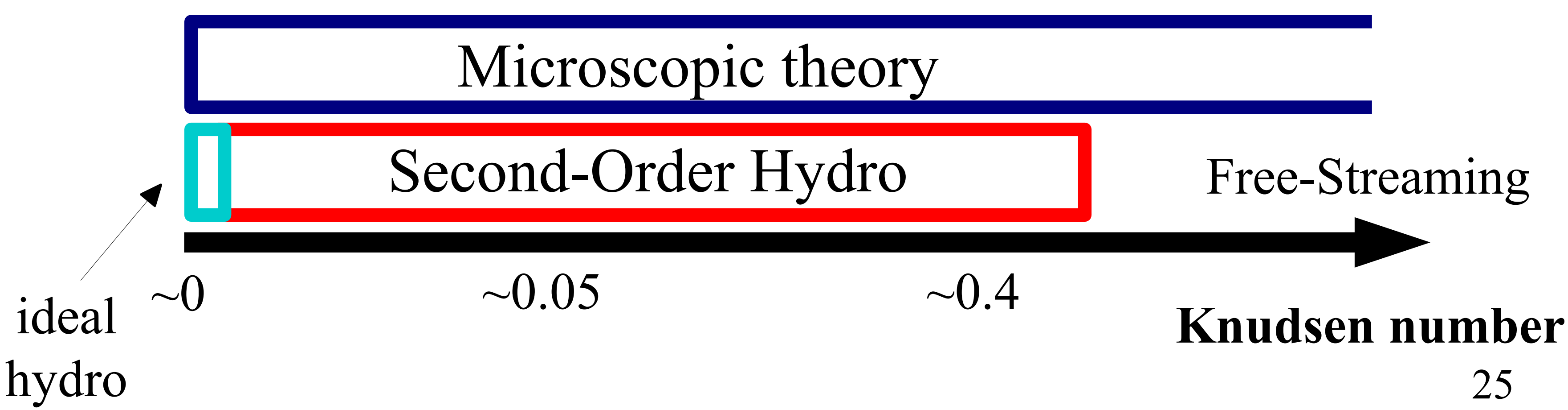
Finite viscosity defines a length scale (mean free-path for dilute gases)

Relaxation time: $\tau_\pi = 5\frac{\eta}{\varepsilon + P}$

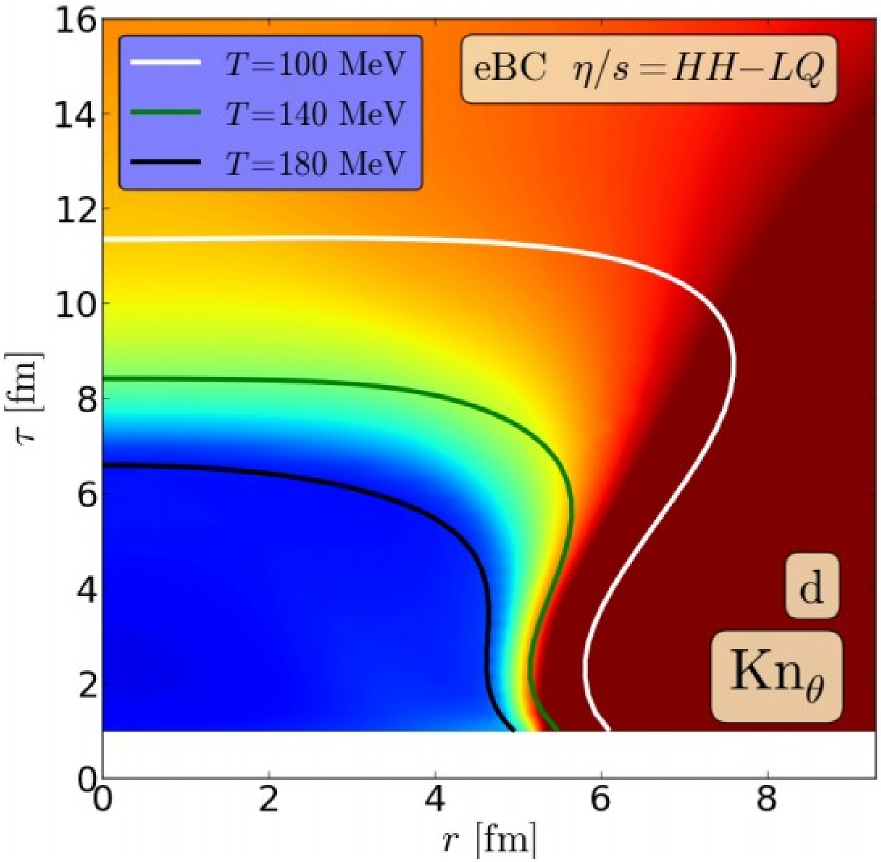
Validity of fluid dynamics defined by Knudsen number:

$\mathrm{Kn}_i = \tau_\pi / L^i_{\mathrm{macro}}$

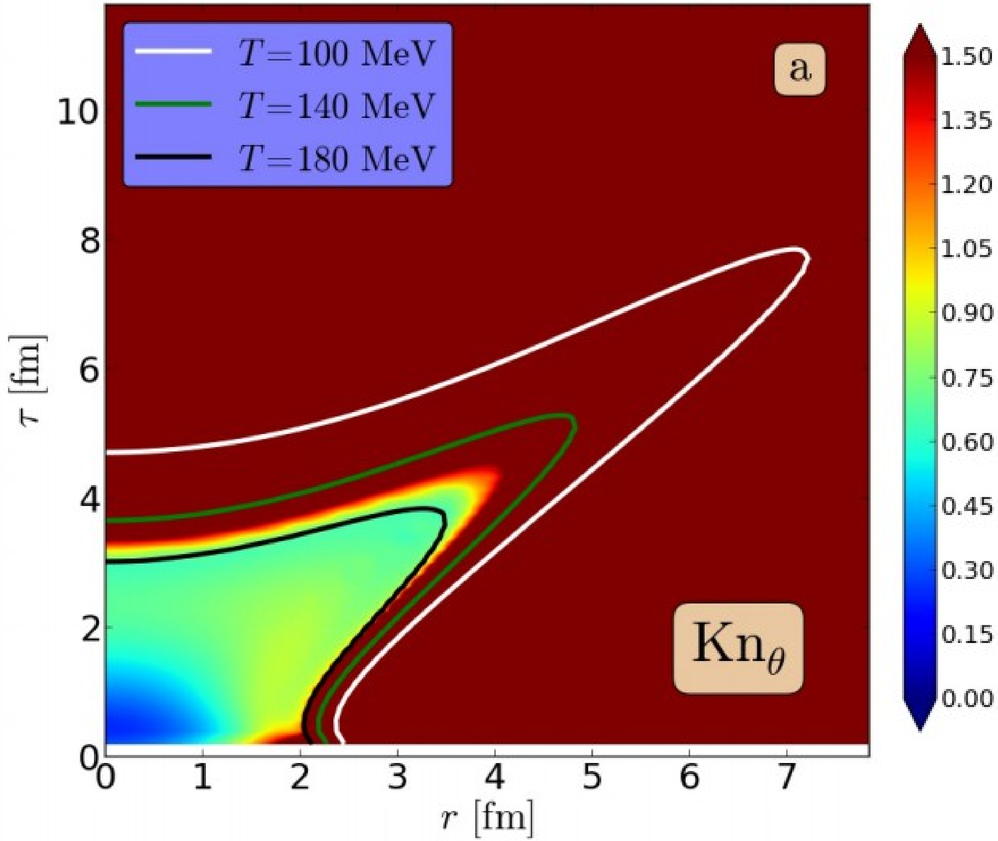
L_{macro} ~ expansion rate



Snapshot of a collision: Kn in τ,x=y plane



Noncentral collision, LHC
τ_0=0.6 fm, η/s=0.08 in QGP



Ultracentral pA collision, LHC
τ_0=0.2 fm, η/s=0.08 in QGP

pA: hydro applies at early times, but breaks down quickly

Viscosity has to be small

Niemi&GSD, arXiv:1404.7327