Flow in AA and pA as an interplay of fluid-like and non-fluid like excitations

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Kurkela, Wiedemann, Wu, 1905.05139
Kurkela, Wiedemann, Wu, Taghavi 19011.xxxxx

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- **Observation** of signs of collectivity in pp, pA collisions is a qualitatively novel insight from the LHC.

- **Challenge**: what is the nature of collectivity in these small systems that likely go beyond perfect fluid paradigm?

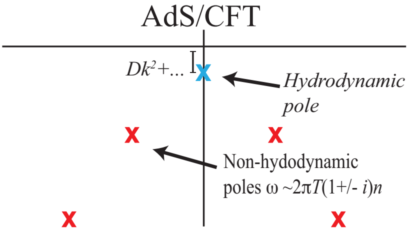
- **Opportunity:** Is there sensitivity to physics beyond fluid dynamics? Can data help distinguish between different microscopic dynamics?

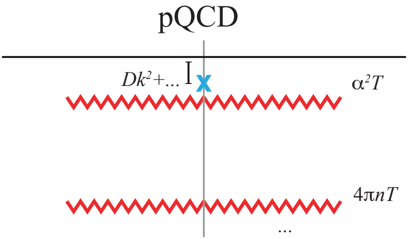
  "What is the microscopic structure of QGP"?

  NSAC Long Range Plan, HL-LHC WG5 report, arXiv:1812.06772

Non-hydro modes:

Different models of Quark-Gluon Plasma have different non-hydrodynamic properties:





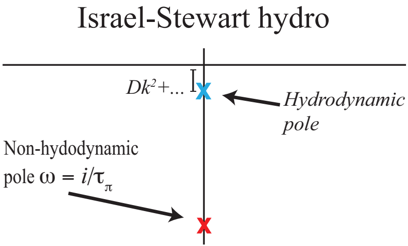
$$\langle T^{\mu\nu}\rangle = G_R^{\mu\nu\alpha\beta} h_{\alpha\beta}, \quad g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}$$

To understand the QGP beyond hydrodynamics,
we must confront the data
with models that go beyond hydrodynamics.

Non-hydro modes:

In fact, also Israel-Stewart hydro goes beyond hydrodynamics:

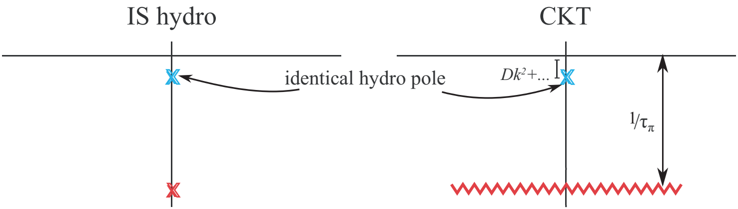
- Hydrodynamic pole
- Ad hoc non-hydro sector to keep theory causal and stable



$$\tau_\pi D\Pi^{\mu\nu} = -(\Pi^{\mu\nu} - \eta\sigma_{\mu\nu})$$

- Observables depend on both

Non-hydro modes:



How much difference can this make?

- Two models: same hydro, different non-hydro
- Same location of non-hydro structure, different form

Are experiments sensitive to the non-hydrodynamic sector?

Conformal Kinetic Transport:

$$\underbrace{(\partial_t + \vec{v}\cdot\partial_{\vec{x}})\,F}_{\text{Free stream}} = \underbrace{-\gamma\epsilon^{1/4}u\cdot v}_{\text{isotropization time}}\;(F - F_{iso})$$

- Scattering in isotropization time approximation

$$\tau_{iso} \sim 1/\gamma\epsilon^{1/4}$$

- Fluid dynamic limit known analytically: $(\frac{\eta}{s} = \frac{0.11}{\gamma}, \ldots)$
- As much hydrodynamics as Israel-Stewart. Think is as unpractical way of doing hydro.

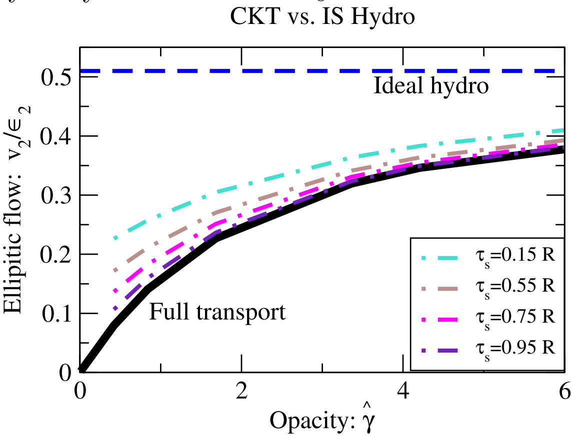
- Physics depends on only one dimensionless parameter: **opacity**

$$\hat{\gamma} = \gamma(\epsilon_0\tau)^{1/4}R^{3/4},$$

For small $\hat{\gamma}$, mean number of final-state scatterings per particle

Sensitivity to non-hydro modes

- Keep hydrodynamic modes fixed, change the non-hydrodynamic sector at τ_s

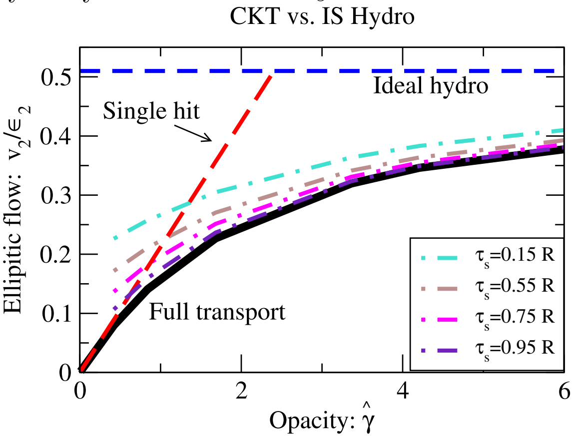


AK, Wiedemann, Wu, 1805.04081

- Sensitivity to non-hydro sector for small opacity

Sensitivity to non-hydro modes

- Keep hydrodynamic modes fixed, change the non-hydrodynamic sector at τ_s



AK, Wiedemann, Wu, 1805.04081

- Sensitivity to non-hydro sector for small opacity
- Small opacity limit understood as perturbation of free streaming of particle-like excitations

∼ escape mechanism

How fluid-like is the system?

Hydrodynamic gradient expansion relates the different components of the energy-momentum tensor:

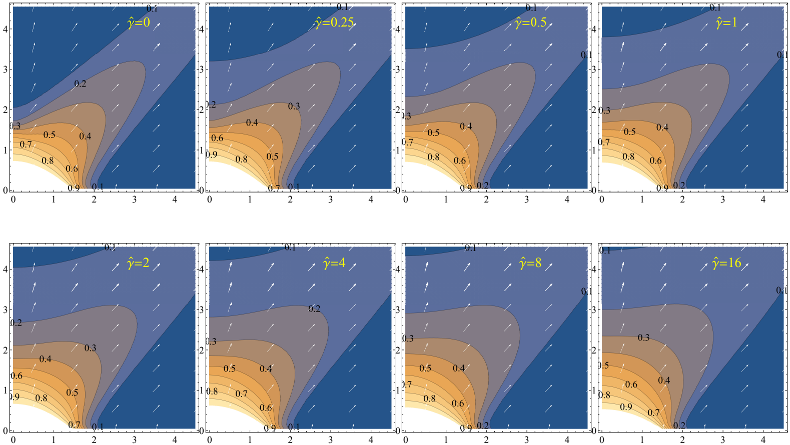
$$T^{\mu\nu}_{hyd} = T^{\mu\nu}_{\text{id}} - \eta(\epsilon)\underbrace{\sigma^{\mu\nu}}_{\sim\partial_\mu} + \underbrace{\dots}_{\sim\partial^2_\mu}$$

Fluid quality quantifies "fluid" the kinetic dynamics is:

$$Q(t,r) = \sqrt{\left(T^{\mu\nu}_{\text{kin}} - T^{\mu\nu}_{\text{hyd}}\right)^2 / \left(T^{\mu\nu}_{\text{id}}\right)^2}$$

$T^{\mu\nu}_{\mathrm{kin}}$ as a function of opacity:

$$F_0(\tau_0, r) = \epsilon_0 \delta(v_z) P_{\mathrm{Woods-Saxon}}(r/R)$$



Plotting local energy density in rest frame $\epsilon(t, r)$
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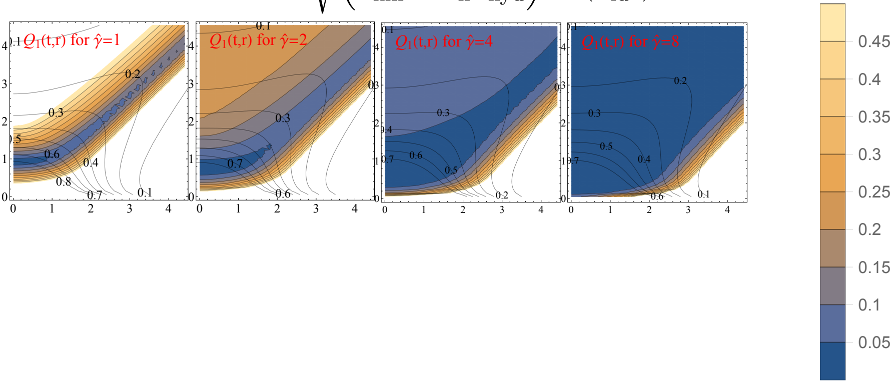
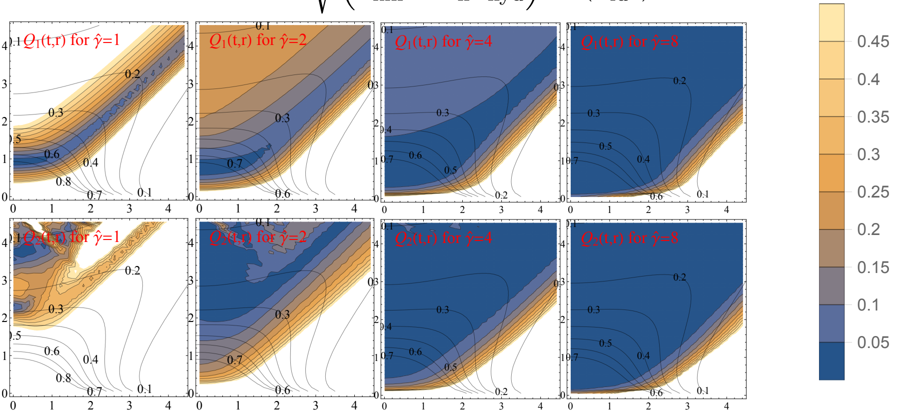
How fluid-like is the system?

$$Q_n(t,r) = \sqrt{\left(T^{\mu\nu}_{\text{kin}} - T^{\mu\nu}_{\text{n-hyd}}\right)^2 / \left(T^{\mu\nu}_{\text{id}}\right)^2}$$



How fluid-like is the system?

$$Q_n(t,r) = \sqrt{\left(T^{\mu\nu}_{\rm kin} - T^{\mu\nu}_{\rm n-hyd}\right)^2 / \left(T^{\mu\nu}_{\rm id}\right)^2}$$



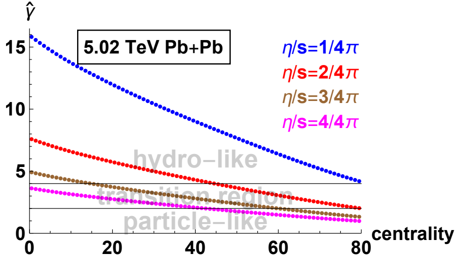
$\hat{\gamma} < 2$, **Particle-like**

$4 < \hat{\gamma}$, **Hydro-like**

$2 < \hat{\gamma} < 4$, **Transition region**

How fluid-like are hadronic collisions?

$$\hat{\gamma} = \gamma R^{3/4} (\epsilon_0 \tau_0)^{1/4} = \underbrace{\frac{0.11}{\eta/s}}_{\text{need to know}} \quad R^{1/4} \quad \underbrace{f_{\text{work}}^{-1/4}(\hat{\gamma})}_{\text{from calculation}} \underbrace{\left(\frac{dE_\perp}{d\eta}\right)^{1/4}}_{\text{from data}}$$



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Opacity $\hat{\gamma}$ in PbPb from data

Data comparison (I), inputs:

1. In hydrodynamics:

$$\left.\frac{\partial v_n}{\partial \epsilon_n}\right|_{\epsilon=0}(c_s^2) = c_{\rm eos} \left.\frac{\partial v_n}{\partial \epsilon_n}\right|_{\epsilon=0}(c_s^2 = 1/3)$$

   $c_{\rm eos}$ applied to KT

   $c_{\rm eos} = 0.86 \dots 0.93$

2. Non-linear eccentricity dependence

$$v_n(\epsilon_n) \propto \epsilon_n(1 + c_{\rm nl}\epsilon_n^2)$$

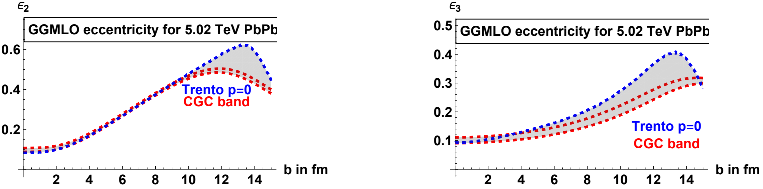
   fit to hydrodynamics $c_{\rm nl} \approx 0.75$, Niemi, Eskola, Paatelainen, 1505.02677

3. Here, energy flow harmonics

$$v_n^{\rm energy} = \frac{\int dp_\perp \frac{dN}{dp_\perp d\eta_s} p_\perp v_n(p_\perp)}{\int dp_\perp \frac{dN}{dp_\perp d\eta_s} p_\perp} = c_{\rm energy} v_n\{2\}$$

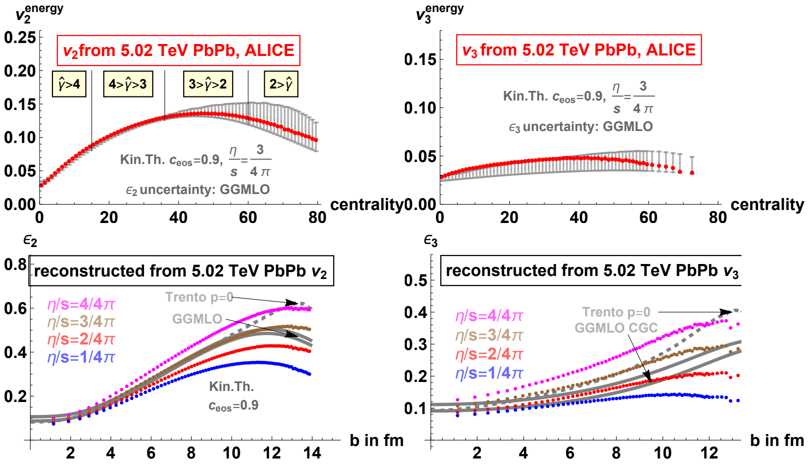
   For ALICE 5 TeV PbPb, $c_{\rm energy} = 1.34$

4. Geometry:



arXiv:1902.07168

Data comparison (II):



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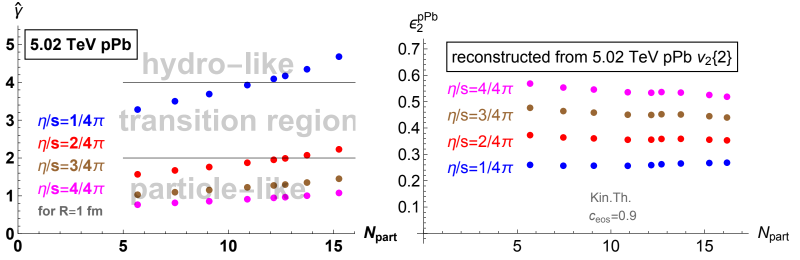
Data comparison (II):



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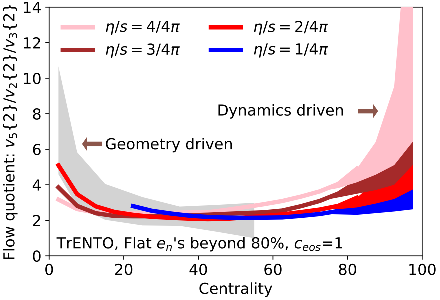
- Fluid-like interpretation disfavoured
- Reconstructed N_{part}-dependence flat for ϵ_2: **Event activity $\neq$ centrality**

Nonlinear quotients:

- In hydro: $w_n = \frac{v_n}{\epsilon_n} \sim \text{const}$
- In kinetic transport at particle-like regime: $w_n = \frac{v_n}{\epsilon_n} \sim \#\hat{\gamma}$

$$\frac{v_5}{v_2 v_3} \sim \frac{\epsilon_5 w_5 + w_{5,23}\epsilon_2\epsilon_3}{\epsilon_2 w_2 \;\; \epsilon_3 w_3} \sim \frac{1}{\hat{\gamma}}$$

w_5 in single-hit regime very small



PRELIMINARY

Kurkela, Wiedemann, Wu, Taghavi, in progress

- Expect rise in $\frac{v_5\{2\}}{v_2\{2\}v_3\{2\}}$ for sufficiently peripheral collisions

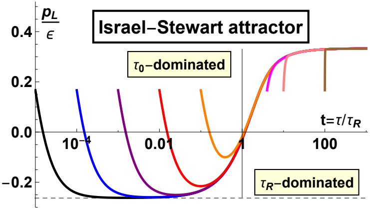
Similarly for $\frac{v_4\{2\}}{v_2\{2\}v_2\{2\}}$

Conclusions:

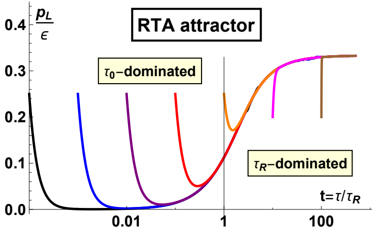
- Hydrodynamics is an effective description of a more complete microscopic dynamics
- In practical calculations, hydrodynamics is always supplemented with some completion, Israel-Stewart
- Flow harmonics in pA and peripheral AA sensitive to how the hydrodynamics is supplemented
- One-parameter kinetic transport model captures well the centrality (and $\sqrt{s}$) dependence of v_2, v_3
  - Can other microscopically motivated models be similarly successful?

AdS/CFT?

Extra slide:



Israel−Stewart attractor
$\frac{p_L}{\epsilon}$
0.4
0.2
0.0
−0.2
τ_0−dominated
τ_R−dominated
t=τ/τ_R
10^{-4}
0.01
1
100



RTA attractor
$\frac{p_L}{\epsilon}$
0.4
0.3
0.2
0.1
0.0
τ_0−dominated
τ_R−dominated
t=τ/τ_R
0.01
1
100