Going beyond hydro

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- Two mutually exclusive descriptions of hadronic collisions:
  - pp: no parton rescattering, *ideal gas* PYTHIA, Herwig, Sherpa ...
  - central AA: many rescatterings, *perfect fluid* viscous hydrodynamics
- LHC discovery of heavy-ion like behavior in pp, pPb challenges both paradigms. v_n, strangeness enhancement
- Plasmas without non-hydro modes do not exist in QFTs.

  Non-hydro modes become more important for decreasing system size.

- **The big question:** *Hydrodynamization*
  - How does one interpolate between *these two extremes*?
  - How is one sensitive to non-hydro modes in the plasma?

Hydrodynamization - progress in *simplified set-ups*

- boost-invariant 1+1D systems fully understood by now

  Almalool, Brewer, Blaizot, Chesler, Denicol, Heller, Kurkela, Janik, Martinez, Noronha, Romatschke, v.d. Schee, Shi, Spalinsky, Strickland, Svensson, Taghavi, Wiedemann, Witaszcyk, Wu, Yan

  - early- and late-time attractor solutions, resummation, resurgence
  - solved in weakly and strongly coupled theories

    But very few observables in 1+1D, essentially only p_L/ε and higher moments.

- boost-invariant 3+1D much recent progress by the above-mentioned + Borghini, Kersting, Roch, Werthmann, Schlichting ....

  - attractor solutions in 3+1D?
  - hydrodynamization of v_n's, or non-linear mode-mode couplings?

    Do all observables approach their hydro values under similar conditions ?

$\Longrightarrow$ study boost-invariant 3+1D Boltzmann equation

(Kurkela, Taghavi, Wiedemann, Wu, Phys.Lett. B811 (2020) 135901)

(Kurkela, v.d. Schee, Wiedemann, Wu, Phys.Rev.Lett. 124 (2020) 10, 102301)

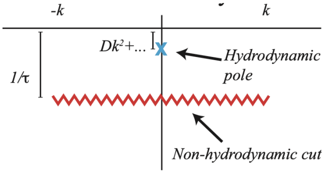
(Kurkela, Wiedemann, Wu, Eur. Phys. J C79 (2019) 9, 759), Eur.Phys. J C79 (2019) 11, 965

Boltzmann eq.: **Isotropization time approximation**

- interpolates btw. ideal gas ($\hat{\gamma} \to 0$) and perfect fluid ($\hat{\gamma} \to \infty$).

$$\boxed{\frac{1}{p} p^\mu \partial_\mu f = -C[f] = -\frac{[-v_\mu u^\mu]}{\tau_{\rm iso}} \left(f - f_{\rm iso}(p^\mu u_\mu)\right)}, \tau_{\rm iso} = \frac{1}{\gamma\, \epsilon^{1/4}}$$

- allows to study interplay btw.
  hydro modes with $\frac{\eta}{sT} = \frac{1}{5\gamma\varepsilon^{1/4}}$
  and quasi-particles with $1/\tau_{\rm iso}$



- We evolve for $F\,(t, r, \theta; \Omega(\phi, v_z)) = \int \frac{4\pi p^2 dp}{(2\pi)^3} p\, f$

  Integral over momentum space yields $T^{\mu\nu}(t, r, \theta) = \int d\Omega v^\mu v^\nu F$ and higher v^μ-moments.

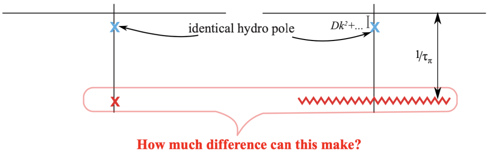
- The **price for propagating also non-hydro modes**:
  ~ 1000 times more expensive than viscous hydro.

  (We discretize ϕ with 20 and v_z with 50 points.)

Results

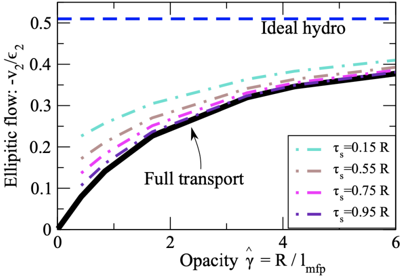
v_n's are sensitive to nature of non-hydro modes

Two theories:
Hydro, initial conditions & relaxation time **identical**.
Non-hydro mode **different**.



Switch non-hydro mode from Boltzmann to Israel-Stewart at τ_s:
Nature of non-hydro mode matters! (more for small systems)

(Kurkela, Wiedemann, Wu, Eur. Phys. J C79 (2019) 9, 759)



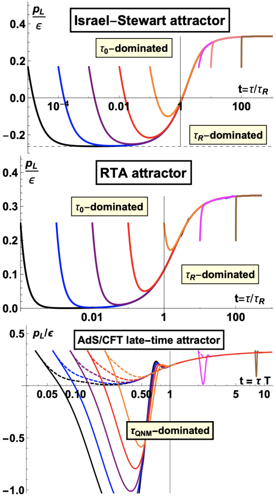
Attractors in 1+1D (for Israel-Stewart, Boltzmann eq. & AdS/CFT)

(Kurkela, v.d. Schee, Wiedemann, Wu, PRL124 (2020) 10, 102301)

- IS similar to weakly coupled Boltzmann
  - expansion-driven early time attractor
  - hydrodynamic late-time attractor
- strongly coupled QFT different
  - no universal early time attractor
- 1+1D forgets initial conditions

Thermalization is about forgetting.
Hydrodynamization remembers sth.

e.g. initial eccentricities are remembered after hydrodynamization

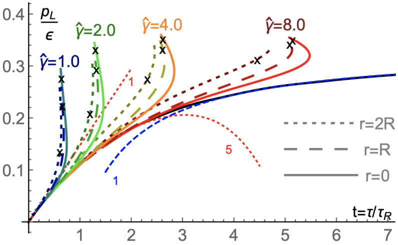


$\Longrightarrow$ need 3+1D to learn how observables that are remembered hydrodynamize

3+1D attractor (for Boltzmann eq.)

(Kurkela, v.d. Schee, Wiedemann, Wu, Phys.Rev.Lett. 124 (2020) 10, 102301)

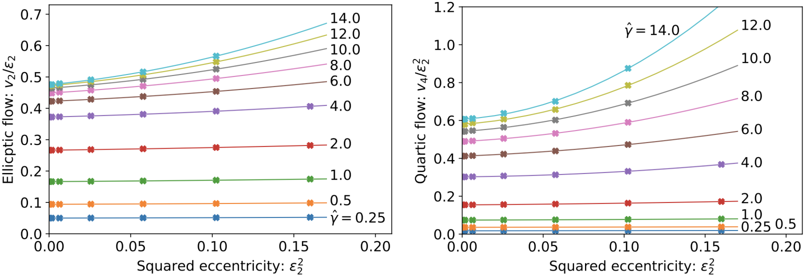
- As a function of system size
  - expansion-driven early-time attractor **is universal** (longitudinal gradients dominate over transverse ones)
  - less opaque systems deviate earlier from the attractor
  - hydrodynamic late-time attractor **is not universal**



$v_n(\{\epsilon_m\})$ - linear and non-linear response coefficients

$$V_2 = w_{2,2}\epsilon_2 + w_{2,222}\left(\epsilon_2\epsilon_2^*\right)\epsilon_2 + O\left(|\epsilon_2|^5\right), \quad V_4 = w_{4,22}\epsilon_2^2 + O\left(|\epsilon_2|^4\right)$$

(Kurkela, Taghavi, Wiedemann, Wu, Phys.Lett. B811 (2020) 135901)



- ▷ consistent with Borghini, Feld, Kersting EPJC78 (2018) 832 if $\hat{\gamma} \sim \bar{N}_{resc}$
- ▷ Non-linear couplings grow with $\hat{\gamma}$ when linear ones are saturated

Comparing IS hydro to Boltzmann

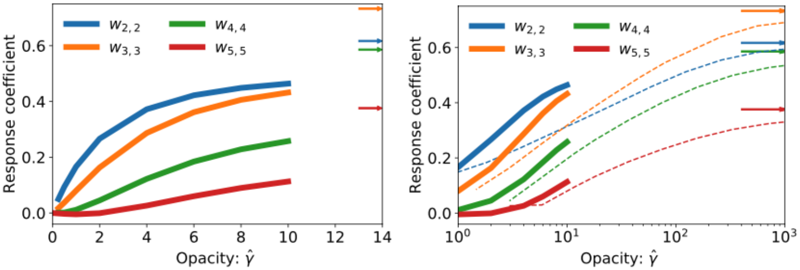
$$\hat{\gamma} = \gamma R \left(\frac{\varepsilon_R}{f_{0\to R}(\hat{\gamma})} \right)^{1/4} , \qquad \text{for } f_{0\to R}(\hat{\gamma}) = \frac{\varepsilon_R R}{\varepsilon_0 \tau_0} \propto \hat{\gamma}^{-4/9} \qquad (1)$$

- to relate IS viscous hydro to $\hat{\gamma}$:
  - initialize viscous hydro from same initial conditions as Boltzmann for $\tau_0 < R$ and evolve for varying $\frac{\eta}{s}$ and ε_0.
  - This yields ε_R, η/s (and v_n) from fluid dynamics.
  - With ε_R, η/s , solve (1) for $\hat{\gamma}$.
- $\tau_0 \to$ 0-limit
  - exists as consequence of universal early-time attractor.

    For Boltzmann transport ($\varepsilon\tau = \mathrm{const.}$), for Israel-Stewart ($\varepsilon\tau^{\frac{4}{15}(\sqrt{5}-5)} = const.$)
  - differs from phenomenological practice, removes unphysical τ_0.
  - informs us to what extent entire v_n of Boltzmann can be built up by IS viscous fluid dynamics.

Comparing Israel-Stewart viscous hydro to Boltzmann

Boltzmann (full), viscous (dashed) & ideal hydro (arrows). (Kurkela, Taghavi, UAW, Wu, PLB811 (2020) 135901)

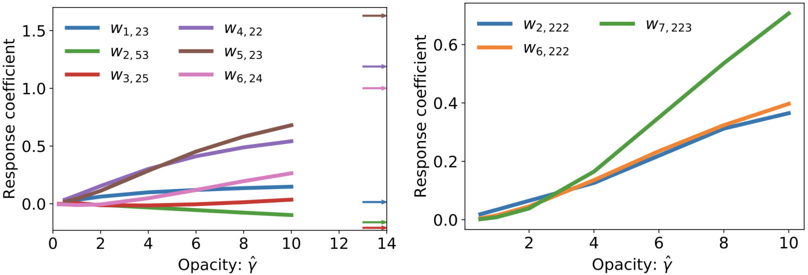


- IS viscous hydro approaches ideal hydro for $\hat{\gamma} \sim O(10^3)$.
- Boltzmann qualitatively similar to IS viscous hydro for $\hat{\gamma} \sim O(10)$

  $\hat{\gamma} \sim O(10) \sim$ central PbPb. Non-hydro comtributions to v_n are still significant .
- Inversion of hierarchy between elliptic and triangular linear response.

Non-linear response coefficients

Boltzmann (full), viscous (dashed) & ideal hydro (arrows). (Kurkela, Taghavi, UAW, Wu, PLB811 (2020) 135901)

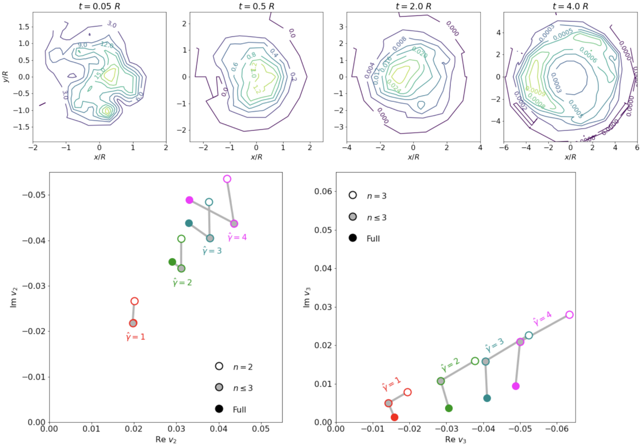


- Hierarchy of non-linear response coefficients qualitatively similar in Boltzmann for $\hat{\gamma} \sim O(10)$ and in viscous hydrodynamics.
- for studies of non-lin response coefficient in IS hydro as fct of system size

  Sievert & Noronha-Hostler, Phys.Rev. C100 (2019), 2, 024904

Evolving a full Trento event in Boltzmann

- linear (open circle) and non-linear (full circle) response coefficients capture collectivity in *real* events. (Kurkela, Taghavi, Wiedemann, Wu, Phys.Lett. B811 (2020) 135901)



Final remarks

- Main challenge: A consistent phenomenology of collectivity across all system sizes from $pp \to pPb \to PbPb$.
- Non-hydrodynamic degrees of freedom
  - are important part of that phenomenology (all causal theories contain them!)
  - address the fundamental question:
    what are the microscopic constituents of the QGP?
  - become quantitatively more important for smaller systems
  - may dominate collectivity in the smallest systems
- IS2021 features many hydrodynamization studies in *simplified set-ups.*
  - These can inform us about the interplay of fluid and non-fluid modes in building up collectivity.
  - going to 3+1 D and going beyond hydro is relevant for phenomenology.