Bjorken flow attractors and 2+1D flow observables

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Problem statement

- The hot QGP formed in heavy-ion collisions exhibits collective behaviour.
- Hydro is successful at capturing observables such as particle multiplicities, elliptic flow,...
- Problem 1: System is far from eq. when $\tau \to 0$.
- Problem 2: For pp, pPb, OO, the system size is small.
- Question: Can hydro work far from equilibrium?
- To answer, we take conformal kinetic theory (KT) in the relaxation time approximation (RTA) as a baseline and look at comparisons with hydro.

Problem setup

- System described via

$$f(\tau, \mathbf{x}_\perp, \eta, \mathbf{p}_\perp, y) = \frac{(2\pi)^3}{\nu_{\rm eff}} \frac{dN}{d^3x\, d^3p}(\tau, \mathbf{x}_\perp, \eta, \mathbf{p}_\perp, y),$$

with $\nu_{\rm eff} = 2(N_c^2 - 1) + \frac{7}{8} \times 4 N_c N_f = 42.25$.

- f evolves according to the Boltzmann eq.,

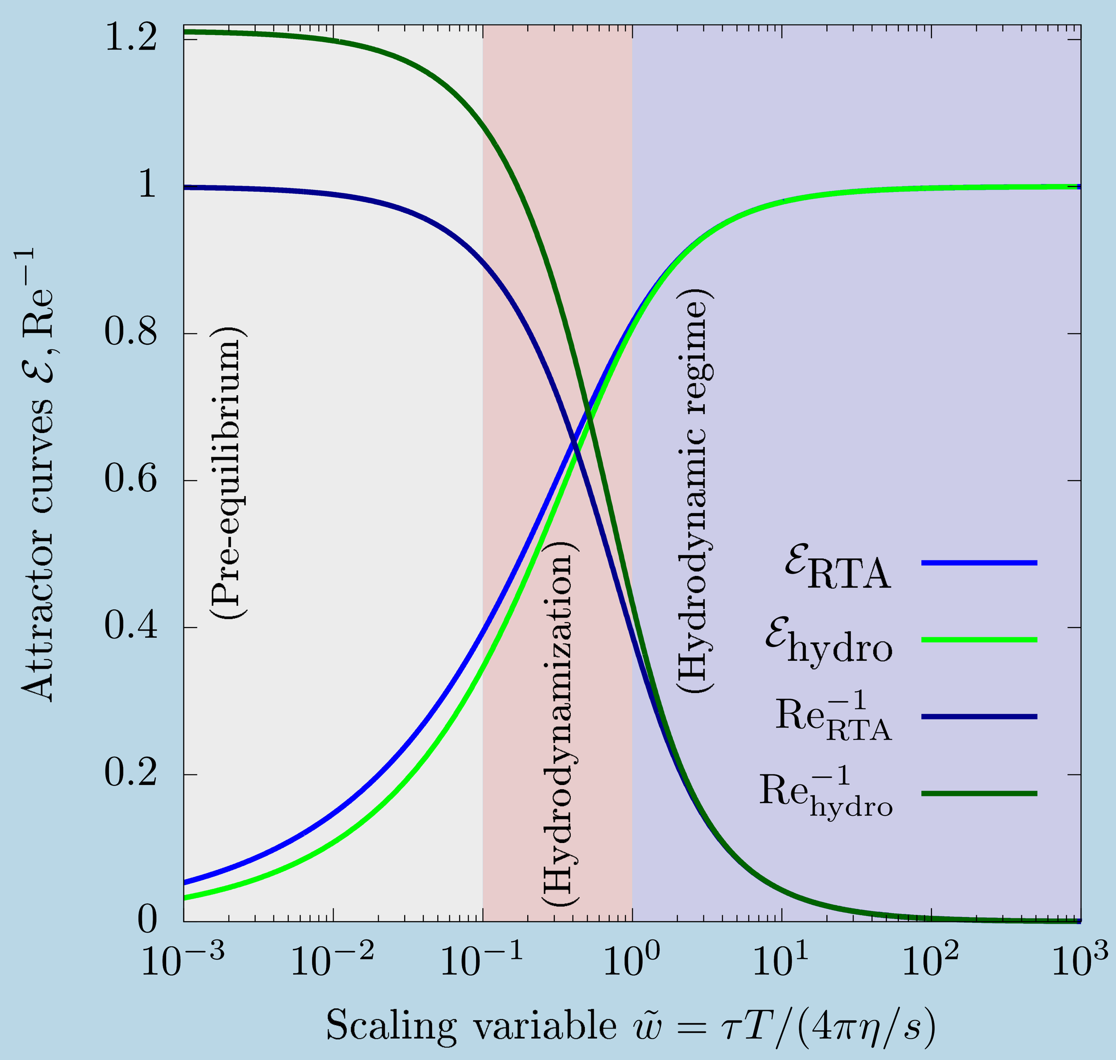
$$p^\mu \partial_\mu f = -\frac{p^\mu u_\mu}{\tau_R}(f - f_{\rm eq}), \qquad f_{\rm eq} = \frac{1}{e^{p^\mu u_\mu / T} - 1},$$

where $\tau_R = 5 T^{-1} \eta/s$ and $\eta/s = \text{const}$.

- Assuming boost invariance, transverse homogeneity in f and initially vanishing P_L, evolution depends only on $\epsilon_0(\mathbf{x}_\perp)$ and **opacity** $\hat{\gamma}$ [1],

$$\hat{\gamma} = \left(5 \frac{\eta}{s}\right)^{-1} \left(\frac{R}{a\pi} \frac{dE_\perp^{(0)}}{d\eta}\right)^{1/4}, \qquad a = \frac{\pi^2}{30} \nu_{\rm eff}.$$

$0+1$-D Bjorken flow



- For $\tau \ll R$, system behaves as $0+1$-D Bjorken flows.
- Noneq. effects measured by $\text{Re}^{-1} = \sqrt{6\pi^{\mu\nu}\pi_{\mu\nu}/\epsilon^2}$, which depends only on $\tilde{w} = \tau T/(4\pi\eta/s)$.
- Energy density admits a universal scaling function, $\tau^{4/3}\epsilon = (\tau^{4/3}\epsilon)_\infty \mathcal{E}(\tilde{w})$, with

$$\mathcal{E}(\tilde{w}) \simeq \begin{cases} C_\infty^{-1} \tilde{w}^\gamma, & \tilde{w} \ll 1, \\ 1 - \frac{2}{3\pi\tilde{w}}, & \tilde{w} \gg 1, \end{cases} \qquad (\tau^{4/3}\epsilon)_\infty = \text{const.},$$

while $\gamma = 4/9$ (0.526) and $C_\infty \simeq 0.88$ (0.80) for KT (hydro).

- Hydro and KT agree when $\tilde{w} \gtrsim 1 \Leftrightarrow \text{Re}^{-1} \lesssim 0.4$.

Early-time evolution

- Using $\epsilon = aT^4$, $\tilde{w} = \frac{\tau T}{4\pi\eta/s}$ and $\mathcal{E}(\tilde{w} \ll 1) = C_\infty^{-1}\tilde{w}$, we find

$$\tilde{w}_{\rm early} \simeq \left[\frac{\tau^{2/3}}{C_\infty^{1/4}} (\tau^{-\frac{2}{3}}\tilde{w})_\infty\right]^{1/(1-\frac{\gamma}{4})}, \qquad (\tau^{-2/3}\tilde{w})_\infty = \frac{(\tau^{4/3}\epsilon)_\infty^{1/4}}{a^{1/4} 4\pi\eta/s}.$$

- When $\tilde{w}_0 \ll 1$, the asymptotic eq. state can be correlated to the initial state via

$$(\tau^{4/3}\epsilon)_\infty \simeq C_\infty \left(\frac{4\pi\eta}{s} a^{1/4}\right)^\gamma \left(\tau_0^{(\frac{4}{3}-\gamma)/(1-\gamma/4)} \epsilon_0\right)^{1-\gamma/4}.$$

- In KT, $(\tau^{4/3}\epsilon)_\infty^{\rm KT} \simeq C_\infty^{\rm KT} \left(\frac{4\pi\eta}{s} a^{1/4}\right)^{4/9} (\tau_0\epsilon_0)^{8/9}$.
- In hydro, $(\tau^{4/3}\epsilon)_\infty^{\rm hydro} \simeq C_\infty^{\rm hydro} \left(\frac{4\pi\eta}{s} a^{1/4}\right)^{0.526} (\tau_0^{0.93}\epsilon_0)^{0.868}$.

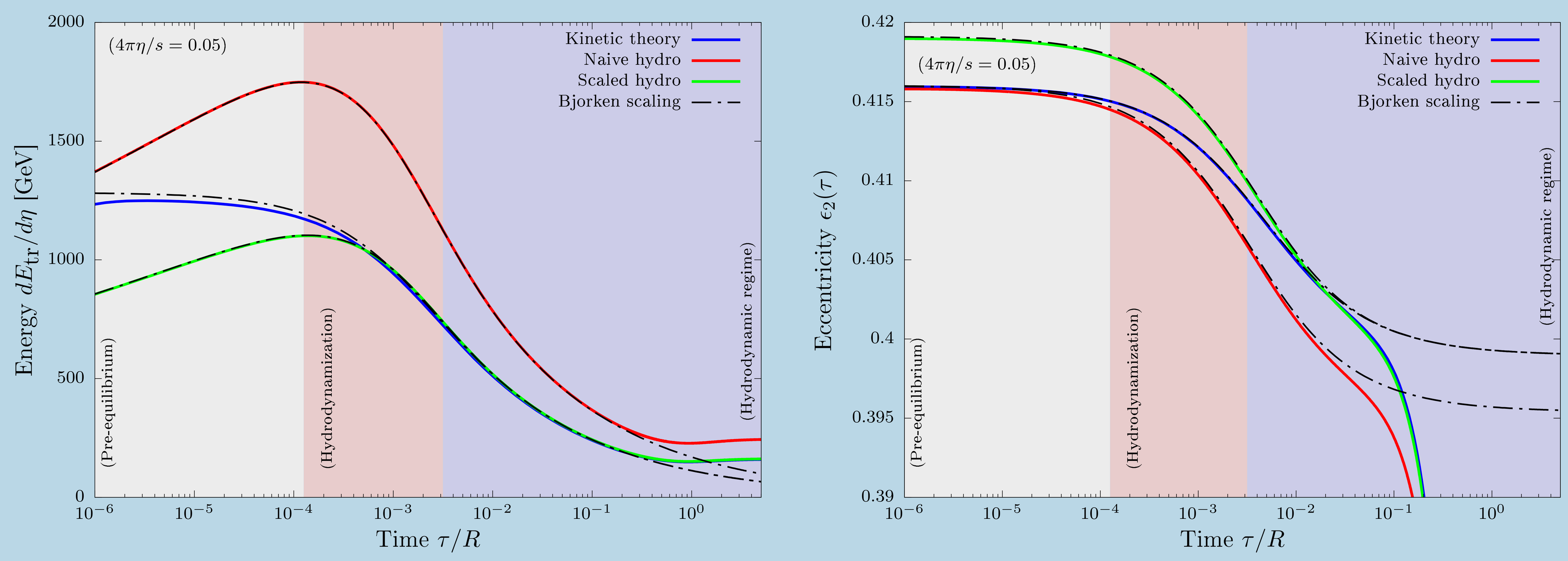
Transverse plane observables

- Consider now ICs corresp. to PbPb at $\sqrt{s_{NN}} = 5.02$ TeV.
- If hydro and KT use **the same** ICs, at late times hydro overestimates energy:

$$\frac{(\tau^{4/3}\epsilon)_\infty^{\rm KT}}{(\tau^{4/3}\epsilon)_\infty^{\rm hydro}} \simeq \frac{C_\infty^{\rm KT}}{C_\infty^{\rm hydro}} \tilde{w}_0^{\gamma_{\rm hydro} - \gamma_{\rm KT}} \simeq 1.1 \times \tilde{w}_0^{0.082}.$$

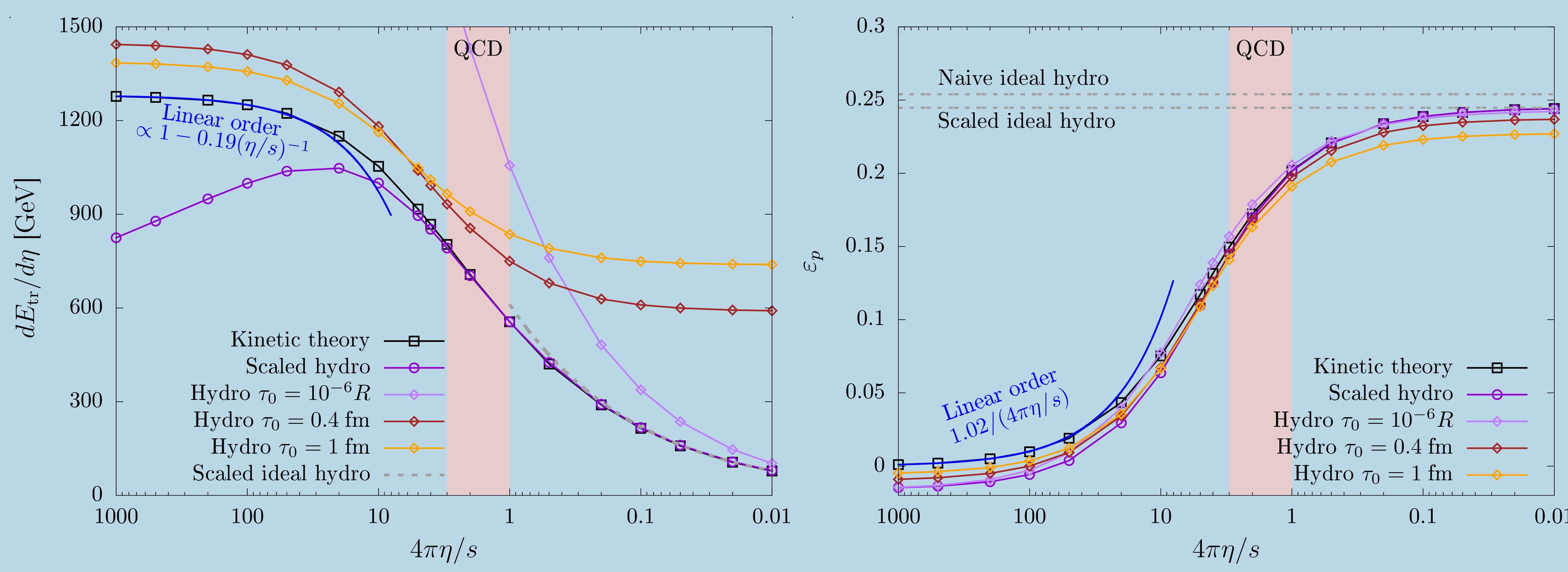
- Late-time agreement $(\tau^{4/3}\epsilon)_\infty^{\rm KT} = (\tau^{4/3}\epsilon)_\infty^{\rm hydro}$ achieved if hydro ICs are **scaled** [1, 2]:

$$\epsilon_0^{\rm hydro} = \left[\left(\frac{4\pi\eta/s}{\tau_0} a^{1/4}\right)^{\frac{1}{2} - \frac{9\gamma}{8}} \left(\frac{C_\infty^{\rm KT}}{C_\infty^{\rm hydro}}\right)^{9/8} \epsilon_0^{\rm KT}\right]^{\frac{8/9}{1-\gamma/4}}.$$



- Local inhomogeneities lead to inhomogeneous cooling, affecting the eccentricity ϵ_2.

Final-state observables [3]



- Naïve hydro (unscaled) overestimates $dE_{\rm tr}/d\eta$ and understimates ε_p.
- At low $\hat{\gamma}$, scaled hydro no longer works, as equilibration is interrupted by transv. exp.
- In this study, **hydro loses applicability when** $\hat{\gamma} \lesssim 4$ **[2].**
- Hybrid schemes, where hydro takes over from KT at threshold Re^{-1} can improve over scaled hydro [1, 2]: **See poster by C. Werthmann!**

References

[1] VEA, S. Schlichting, C. Werthmann, Phys. Rev. D **107** (2023) 094013.
[2] VEA, S. Schlichting, C. Werthmann, Phys. Rev. Lett. **130** (2023) 152301.
[3] V. E. Ambruș, S. Schlichting and C. Werthmann, [arXiv:2302.10618 [nucl-th]].