

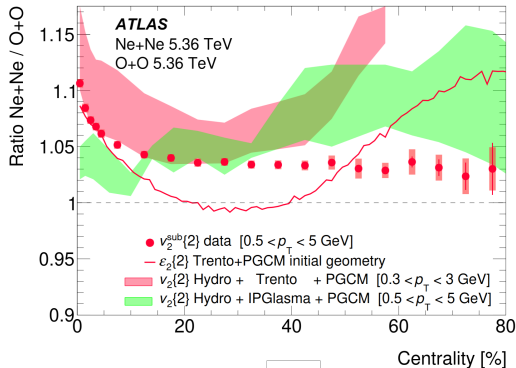
Anisotropic flow in O+O and Ne+Ne collisions

from kinetic theory and hydrodynamics

Clemens Werthmann

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based on WiP with Victor Ambruş, Giuliano Giacalone and Fabian Zhou



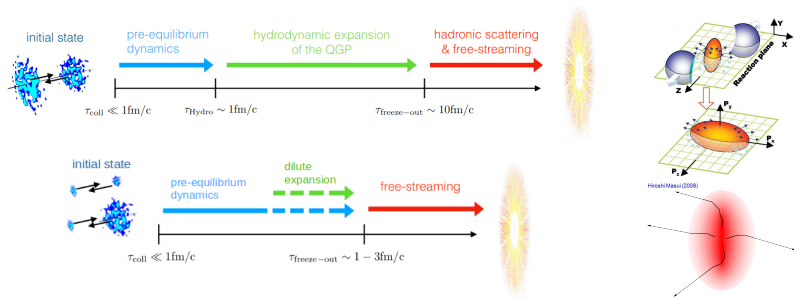
PRC 113 (2026) 045205

Dynamical modelling in small vs. large systems

large systems: dominated by hydrodynamic QGP, strong collectivity

↓ inbetween: **light ions**

small systems: might not fully equilibrate, few scatterings



measurable final state **flow** results from **dynamical response** to **initial state** ($v_n = \kappa_{n,n} \epsilon_n$)

⇒ assess applicability of hydrodynamics by comparing to more microscopic theory
e.g. kinetic theory: applicable on full range from free-streaming to hydrodynamic systems

Dynamical descriptions

kinetic theory in conformal relaxation time approximation (RTA): dynamics of $f = \frac{dN}{d^3p d^3x}$

- some microscopic info “integrated out”
⇒ no diluteness requirement
- dynamics depends only on opacity $\hat{\gamma}$

Aleksi Kurkela, Urs A. Wiedemann, Bin Wu, EPJC 79 (2019) 11, 965

$$p^\mu \partial_\mu f = -\frac{f - f_{\text{eq}}}{\tau_R}, \quad \tau_R = 5T^{-1} \frac{\eta}{s}$$

$$\hat{\gamma} = \left(5 \frac{\eta}{s}\right)^{-1} \left(\frac{1}{a\pi} R \frac{dE_\perp^{(0)}}{d\eta}\right)^{1/4}$$

total interactions $\hat{\gamma} \sim \text{Kn}^{-1}$: depends on **shear viscosity**, **transverse size** and **energy scale**

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viscous hydrodynamics:

- conformal equation of state $\mathcal{E} = 3P = aT^4$
- transport coefficients from RTA
- elliptic flow of energy ε_p : extracted directly from hydro, no need for particlization

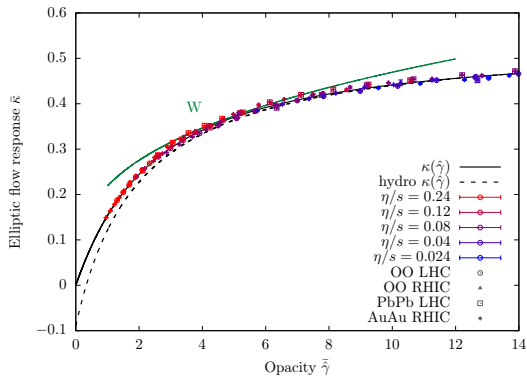
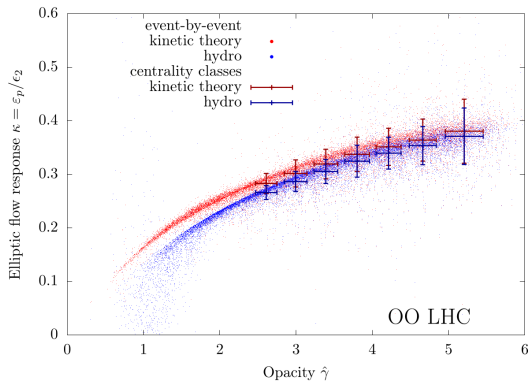
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$$\varepsilon_p = \frac{\int_{\mathbf{x}_\perp} T^{xx} - T^{yy} + 2iT^{xy}}{\int_{\mathbf{x}_\perp} T^{xx} + T^{yy}}$$

Previous results



- hydro $\rightarrow$ kinetic theory as $\hat{\gamma} \rightarrow \infty$, hybrid simulations accurate for $\hat{\gamma} \gtrsim 3$

Victor E. Ambruş, Sören Schlichting, CW PRD 107 (2023) 094013 and PRL 130 (2023) 152301

- some event-by-event spread, but mainly following universal curves

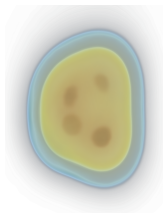
Victor E. Ambruş, Sören Schlichting, CW, PRD 111 (2025) 054024

- agnostic measurement of hydrodynamization via $W = \frac{2}{k} \frac{\Delta \log(c_2\{2k\})}{\Delta \log(dE_\perp/dy)} \approx \frac{d \log \kappa}{d \log \hat{\gamma}}$

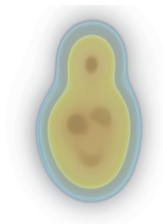
Victor E. Ambruş, Sören Schlichting, CW, PRD 111 (2025) 054025

Now: details of flow in NeNe and OO collisions incl. ratios, triangular flow

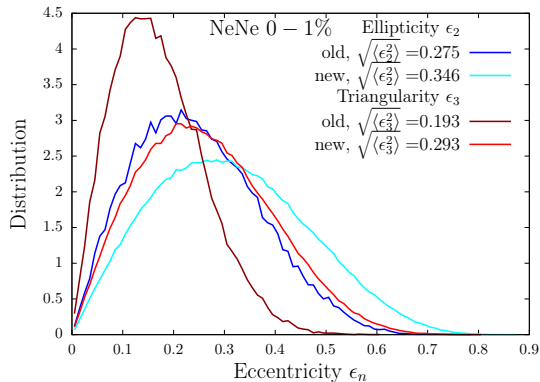
Initial state



^{16}O



^{20}Ne



- T_RENTo with nucleon positions from PGCM
- **old** parameters: VAH calibration with large nucleon width $w \approx 1$ fm

D. Liyanage, O. Sürer, M. Plumlee, S. M. Wild, U. Heinz, PRC 108 (2023) 054905

new parameters: Trajectum for 5.36 TeV, $w \approx 0.6$ fm and 3 constituents $v \approx 0.5$ fm

⇒ larger eccentricities!

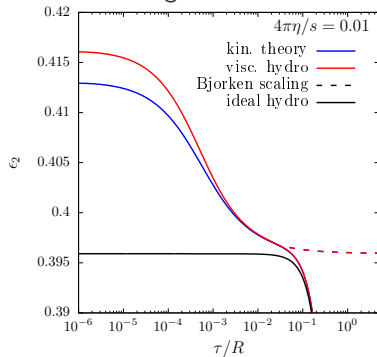
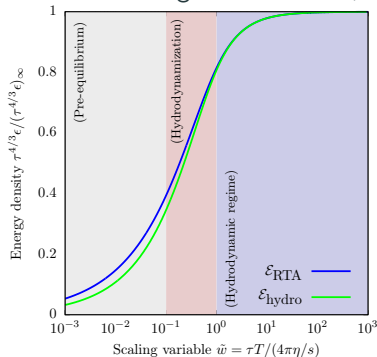
Govert Nijs, Wilke van der Schee, PRC 106 (2022) 044903 and PLB 872 (2026) 140061

Inhomogeneous cooling and “scaled hydro”

“ $\tau \ll \langle \nabla_{\perp} \rangle^{-1}$ ”: system undergoes **local Bjorken flow** at each point in transverse plane

⇒ “Attractor behaviour”: quick convergence to universal evolution

⇒ hotter regions cool more, eccentricities change: amount differs between theories

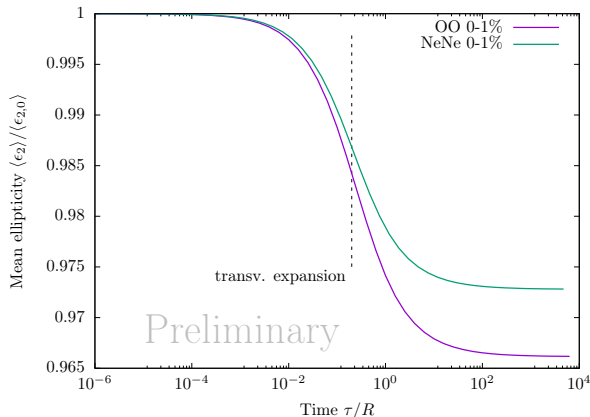


our hydro simulations:
scaled initial condition of
hydro in anticipation of
different pre-equilibrium

Ambruş, Schlichting, CW,
PRD 107 (2023) 094013

- eccentricity values at onset of transverse expansion determine final state flow
- typically changes eccentricities by $\mathcal{O}(1\%)$, but can be up to 10%

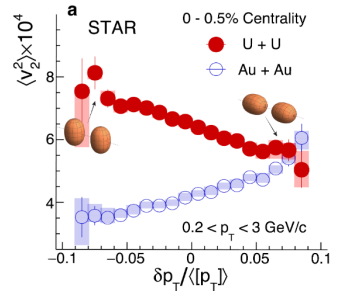
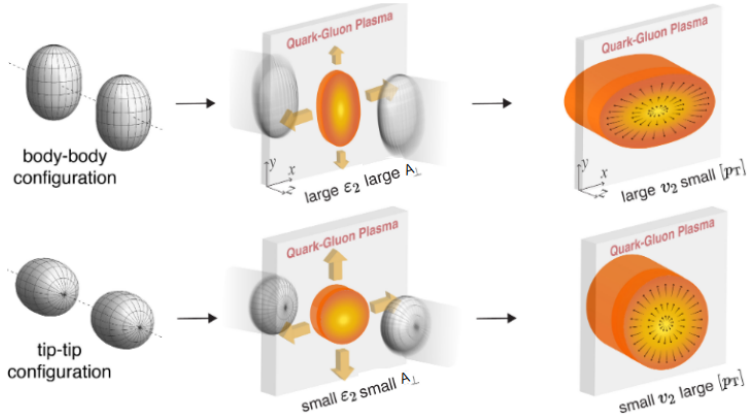
Early time eccentricity evolution in OO and NeNe



- OO: $\sim 3.4\%$, NeNe: $\sim 2.7\%$ total decrease
- when transverse expansion sets in, ϵ_2 has been reduced by a similar fraction $\sim 1.5\%$ in both systems $\Rightarrow$ good cancellation in ratio

Dependence on orientation of nuclei

Orientation of nuclei gives correlated fluctuations in flow and mean transv. momentum



STAR, Nature 635 (2024) 8037, 67-72

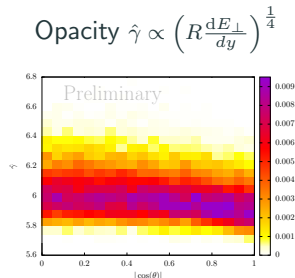
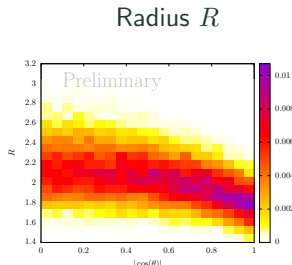
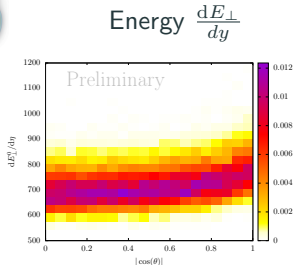
Orientation dependent response coefficient κ could also matter for v_2 !

Response dependence on orientation of nuclei (θ : tip angle to beam axis)

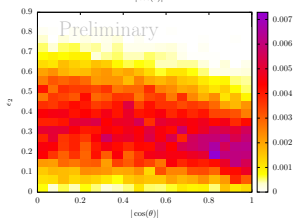
System: NeNe
5.36 TeV 0-1%



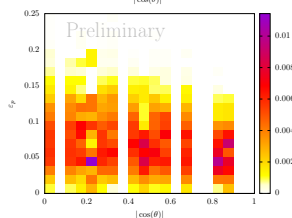
Initial state
properties
determining
response



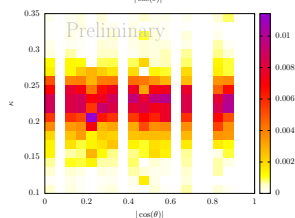
Actual ellipticity,
flow and response



Ellipticity ϵ_2



Elliptic flow ε_p



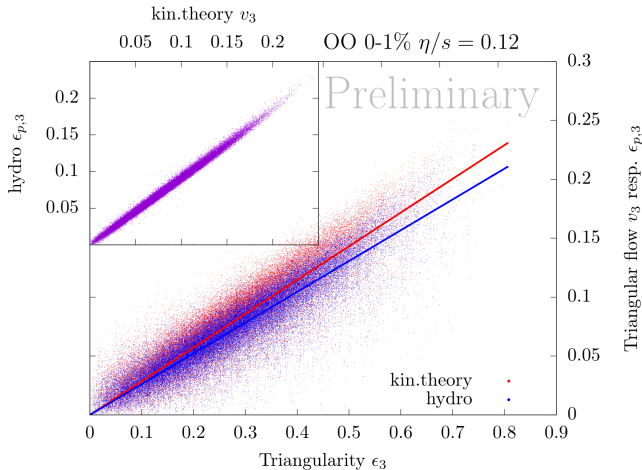
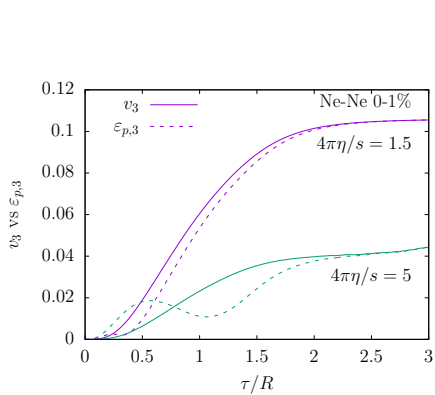
Flow response κ

$\Rightarrow$ no orientation dependence of response $\kappa(\hat{\gamma})$ in central NeNe!

$\varepsilon_{p,3}$: Triangular flow directly from hydro

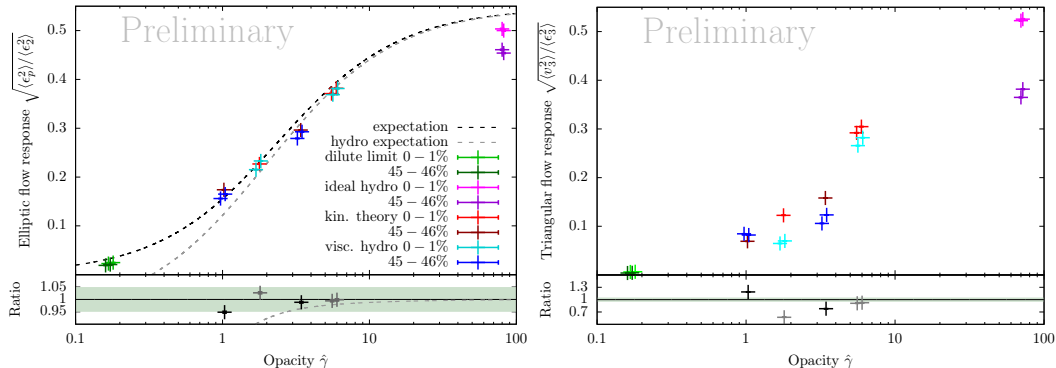
Ansatz: plug Chapman-Enskog expansion of distribution f to linear order into formula for v_3

$$f \approx f^{(0)} + f^{(1)}, \quad f^{(0)} = \frac{1}{e^{\beta p^\mu u_\mu} - 1}, \quad f^{(1)} = \frac{\beta \tau_R}{p^\mu u_\mu} f^{(0)} \tilde{f}^{(0)} p^{\langle \mu} p^{\nu \rangle} \frac{\pi_{\mu\nu}}{2\eta}, \quad v_3 = \frac{\int_{\mathbf{x}_\perp} \int d^3 p p_\perp e^{3i\varphi_p} f}{\int_{\mathbf{x}_\perp} \int d^3 p p_\perp f}$$



Flow response coefficients in OO and NeNe

Compiled results for $\sqrt{\langle v_n^2 \rangle / \langle \epsilon_n^2 \rangle}$ from NeNe and OO (2 centrality classes each)

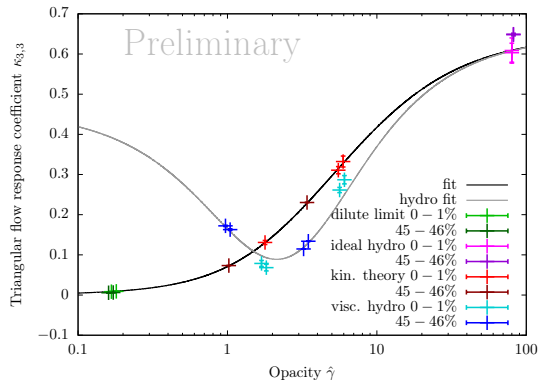
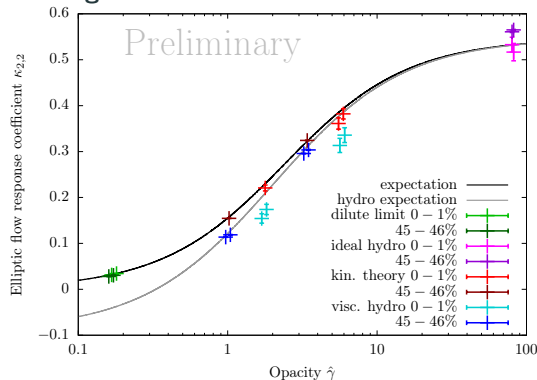


- elliptic flow now agrees better
- triangular flow response decreases faster with decreasing $\hat{\gamma}$, strong deviations in hydro!
- no universal response curve, difference between central and peripheral

Linear response coefficients

response coefficients from fitting $v_n = \kappa_{n,n}(\hat{\gamma})\epsilon_n + \kappa_{n,nnn}(\hat{\gamma})\epsilon_n^3$ to events with small $\epsilon_m, m \neq n$

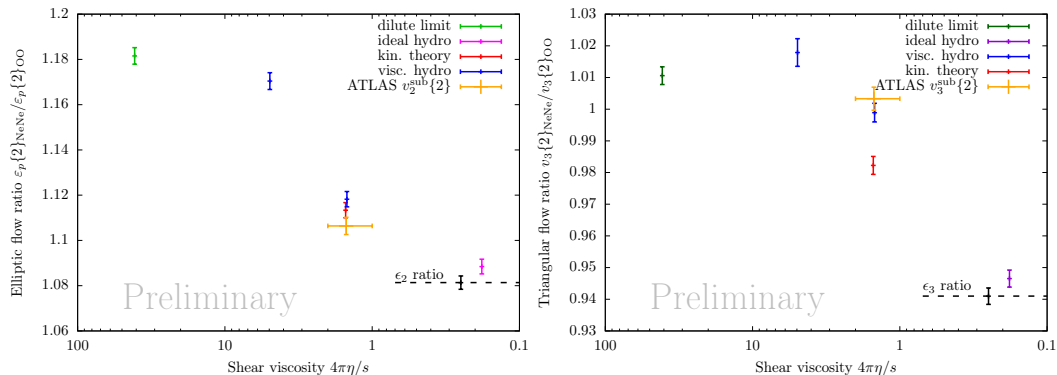
$\Rightarrow$ again follow universal curves:



Full flow is likely sum of many responses with different opacity dependences:

$$v_n \sim \kappa_{n,n}(\hat{\gamma})\epsilon_n + \sum_m \kappa_{n,m,|n-m|}(\hat{\gamma})\epsilon_m\epsilon_{|n-m|} + \sum_m \kappa_{n,m,n+m}(\hat{\gamma})\epsilon_m\epsilon_{n+m} + \dots$$

Flow Ratio



ATLAS data: PRC 113 (2026) 045205

- ideal hydro agrees with ε_n ratio; for finite fixed η/s NeNe has larger $\hat{\gamma} \Rightarrow$ larger response
 - up to 10% difference in ε_p , 7% in v_3
- differences hydro vs. kinetic theory not as big in ratios
 - still, hydro $\varepsilon_{p,3}$ ratio is 2% off of a few % signal

Summary

- found elliptic and triangular flow in OO and NeNe from simulations in hydrodynamics and kinetic theory, extracted response coefficients and flow ratios
 - formula for triangular flow $\varepsilon_{p,3}$ allows for direct extraction from hydro
- deviation of hydrodynamic response less apparent in flow ratios, but **triangular flow shows significant deviations**
- when eccentricities are large, flow responses no longer follow a universal curve in opacity
 - likely due to larger nonlinear flow responses, which have different opacity dependence

Backup

$\varepsilon_{p,3}$: Formula for triangular flow directly from hydro

Ansatz: plug Chapman-Enskog expansion of distribution f to linear order into formula for v_3

$$f \approx f^{(0)} + f^{(1)}, \quad f^{(0)} = \frac{1}{e^{\beta p^\mu u_\mu} - 1}, \quad f^{(1)} = \frac{\beta \tau_R}{p^\mu u_\mu} f^{(0)} \tilde{f}^{(0)} p^{\langle \mu} p^{\nu \rangle} \frac{\pi_{\mu\nu}}{2\eta}, \quad v_3 = \frac{\int_{\mathbf{x}_\perp} \int d^3 p p_\perp e^{3i\varphi_p} f}{\int_{\mathbf{x}_\perp} \int d^3 p p_\perp f}$$

$$\Rightarrow \varepsilon_{p,3} = \frac{\frac{4\gamma\epsilon}{3} e^{3i\varphi_u} \beta^3 \gamma + \frac{1}{2} [\beta e^{i\varphi_u} \Pi_+ (6 - 3\beta^2 + \beta^4) - \beta^3 e^{3i\varphi_u} \Pi_\times (5 - 2\beta^2) + \beta^5 e^{5i\varphi_u} \Pi_-]}{\frac{\gamma\epsilon}{6} [(7 + \beta^2)\text{Ei} - 4\text{Ki}] + \frac{1}{32\beta^2\gamma} \left\{ \Pi_\times [(6 + 14\beta^2 - 4\beta^4)\text{Ei} - 2(3 + \beta^2)\text{Ki}] \right. \\ \left. - \frac{2\pi^{00}}{\beta^2} [(6 - 15\beta^2 + 5\beta^4 - 4\beta^6)\text{Ei} - 2(3 - 6\beta^2 + \beta^4)\text{Ki}] \right\}},$$

$$\text{Ei} \equiv \text{Ei}(-\beta^2 \gamma^2), \quad \text{Ki} \equiv \text{Ki}(-\beta^2 \gamma^2), \quad \Pi_\times = \pi^{xx} + \pi^{yy}, \quad \Pi_\pm = \pi^{xx} \pm 2i\pi^{xy} - \pi^{yy}$$