How many particles do make a fluid? Searching for fluiddynamic behavior with expanding clouds of few and many cold atoms

(based on https://arxiv.org/abs/2111.13591; to appear in PRC)

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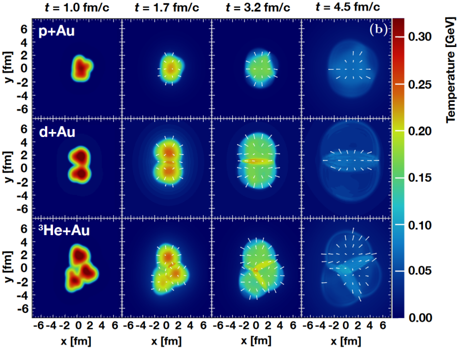
Fluidlike behavior observed in small systems

Hydrodynamic descriptions work for small collisional systems with low final state particle numbers

→ How many particles are necessary for fluidlike behavior?

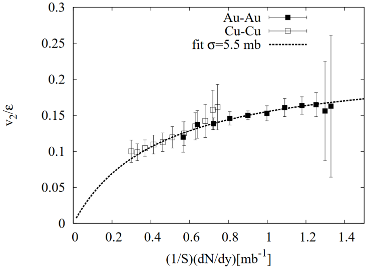


Monte Carlo Glauber model and hydrodynamic evolution of small systems; from: PHENIX collaboration, Nature Physics, 2019 [1]

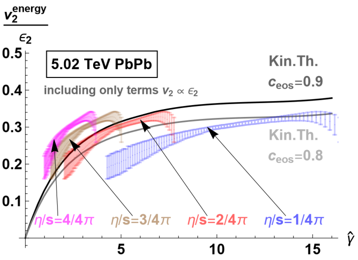
The observable: v_2/ϵ_2

$$\text{anisotropy in} \begin{cases} \text{the spatial distribution: } \epsilon_2 = \dfrac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \\ \text{the momentum distribution: } v_2 = \left\langle \dfrac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle \end{cases}$$

indicator for fluidlike behavior: elliptic flow normalized by initial conditions v_2/ϵ_2



v_2/ϵ_2 as a function of the multiplicity, ϵ_2 obtained using initial conditions from a Glauber model; from: Drescher et al., PRC, 2007 [2]



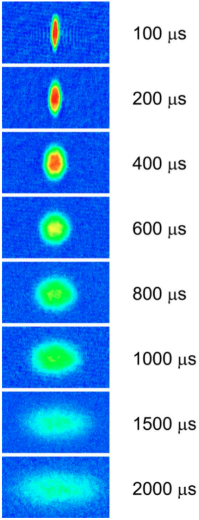
v_2/ϵ_2 as a function of opacity $\hat{\gamma}$, supplemented with kinetic theory calculation with non-ideal equation of state; from: Kurkela, Wiedemann, Wu, EPJ C, 2019 [3]

Analogy to cold atomic systems

Investigate a small number N of atoms in a trap. The geometry of the trap determines ϵ_2. Release the trap and make a time of flight measurement to obtain v_2.

Advantages:

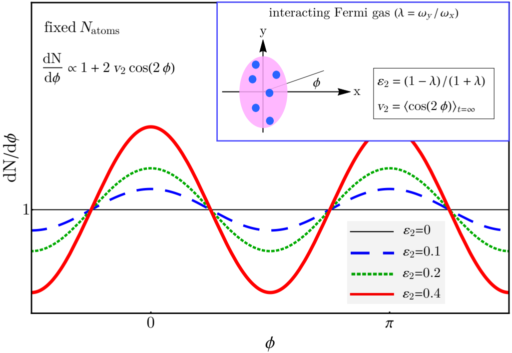
- control over geometry of the trap and thus the initial density profile
  - → due to known orientation we can use one-particle distributions instead of two-particle correlations
- control over interaction strength via Feshbach resonance
- control over particle number



False-color absorption images of a strongly interacting, degenerate Fermi gas; from: O'Hara et al., Science, 2002 [4]

Proposed experiments

Setup: N atoms in an anisotropic harmonic trap with frequencies ω_x, ω_y; switch off trap instantaneously and make a time of flight measurement of angular particle distribution at late times; repeat for different values of N.



Large figure: sketch of an angular particle distribution as would be measured; subfigure: sketch of the trapped fermi gas with the definitions of ϵ_2 and v_2; from Floerchinger et al., 2022 [5]

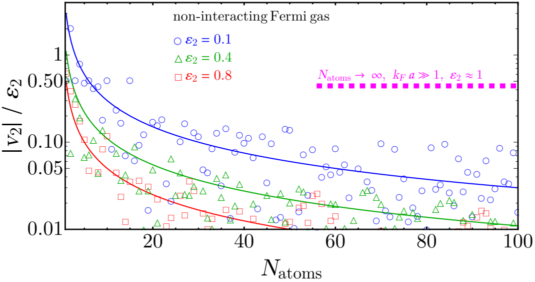
Evaluation: For the normalization we take ϵ_2 as its ground state value $\epsilon_2 = (1 - \omega_y/\omega_x)/(1 + \omega_y/\omega_x)$, entirely determined by the trap geometry. The elliptic flow can be obtained from the asymptotic angular distribution as $v_2 = \langle\cos(2\phi_p)\rangle$.

Non-flow / purely QM effects

In high-energy collisions: Non-flow effects (e.g. resonance decays) can influence the two-particle correlations used to calculate v2 (more important for small systems / multiplicities)."

In cold atomic systems: effects from quantum mechanics become relevant at low particle numbers and temperatures

$\Delta x_i \cdot \Delta p_i \geq 1/2$ stronger confinement in one direction → larger momentum in that direction (without interaction)

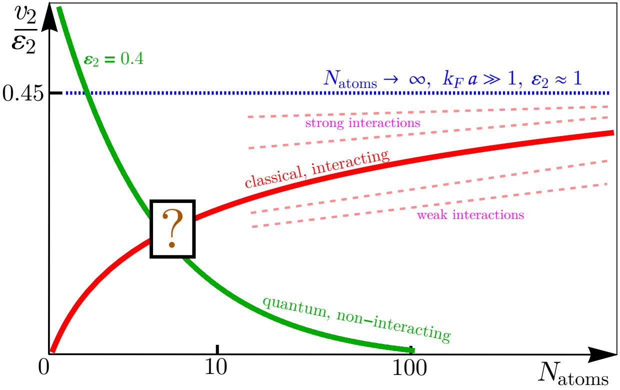


v_2/ϵ_2 for different numbers of non-interacting particles in a 2d harmonic trap; dots, triangles, squares: numerical results; solid lines: estimated fits, each proportional to $1/N$; dashed line: estimate of hydrodynamic limit; from Floerchinger et al., 2022 [5]

The effect of this becomes smaller with increasing particle number and temperature.

Expectations

We hope to find interplay between all these effects depending on the particle number and the convergence towards a fluiddynamic limit at high particle numbers and strong interactions (and high temperatures).

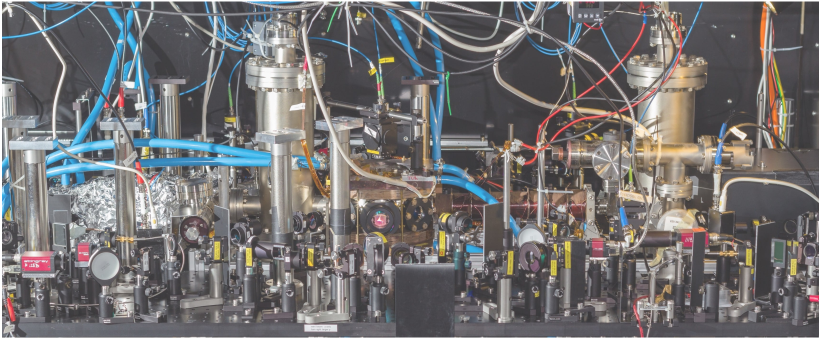


Sketch of the estimated scaling of the quantum effect (green solid line), classical interaction effects (red solid line) and the hydrodynamic limit (blue dashed line); the question mark at the crossing of the two solid lines marks the mesoscopic scale; from Floerchinger et al., 2022 [5]

Outlook

Theoretical side: multiparticle correlations, possible analogies to hydrodynamization

Experiments are in progress



Photograph of the experimental setup of the Ultracold Quantum Gases group, Physikalisches Institut, Heidelberg University; from: http://ultracold.physi.uni-heidelberg.de/

[1] C. Aidala et al. "Creation of quark–gluon plasma droplets with three distinct geometries". *Nature Physics* 15.3 (Mar. 2019), pp. 214–220. ISSN: 1745-2481. DOI: `10.1038/s41567-018-0360-0`. URL: `https://doi.org/10.1038/s41567-018-0360-0`.

[2] Hans-Joachim Drescher et al. "The Centrality dependence of elliptic flow, the hydrodynamic limit, and the viscosity of hot QCD". *Phys. Rev. C* 76 (2007), p. 024905. DOI: `10.1103/PhysRevC.76.024905`. arXiv: `0704.3553 [nucl-th]`.

[3] Aleksi Kurkela, Urs Achim Wiedemann, and Bin Wu. "Flow in AA and pA as an interplay of fluid-like and non-fluid like excitations". *Eur. Phys. J. C* 79.11 (2019), p. 965. DOI: `10.1140/epjc/s10052-019-7428-6`. arXiv: `1905.05139 [hep-ph]`.

[4] K. M. O'Hara et al. "Observation of a Strongly Interacting Degenerate Fermi Gas of Atoms". *Science* 298.5601 (2002), pp. 2179–2182. DOI: `10.1126/science.1079107`. eprint: `https://www.science.org/doi/pdf/10.1126/science.1079107`. URL: `https://www.science.org/doi/abs/10.1126/science.1079107`.

[5] S. Floerchinger et al. *How many particles do make a fluid? Qualifying collective behavior in expanding ultracold gases*. 2022. URL: `https://arxiv.org/abs/2111.13591`.