Building a fluid particle by particle:

Real time imaging of the emergent hydrodynamic behavior of few strongly-interacting fermions

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August 24, 2023

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Based on: [Brandstetter *et al.*, arXiv:2308.09699]
[Floerchinger *et al.*, PRC **105**, 044908 (2022)]

52nd International Symposium on Multiparticle Dynamics (ISMD 2023)

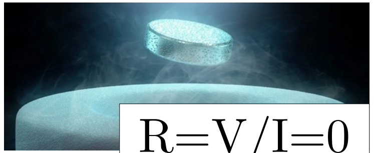
Aug 21 – 26, 2023

The physical world as an emergent phenomenon.

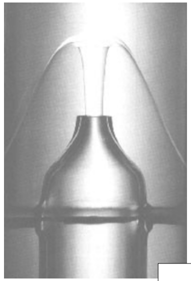
Describing interacting many-body systems through their emergent collective properties.

[Anderson, Science **177** no.4047, 393-396 (1972)]

Superconductivity



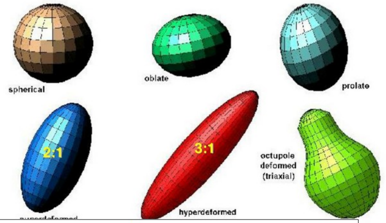
$R=V/I=0$



Superfluidity

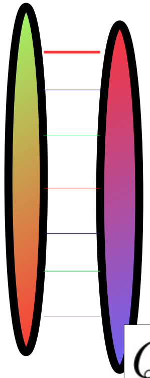
$\eta=0$

Nuclear deformations



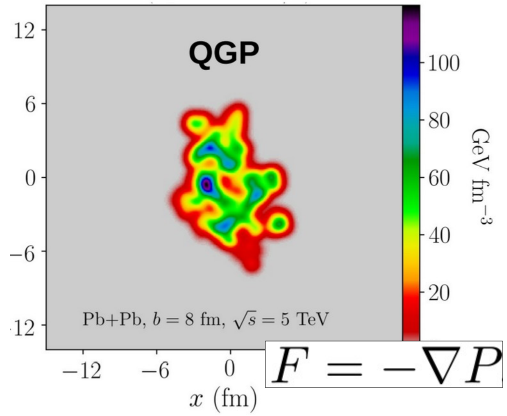
$$R = R_0\left(1+\sum_n \beta_n Y_n^0\right)$$

color glass condensate

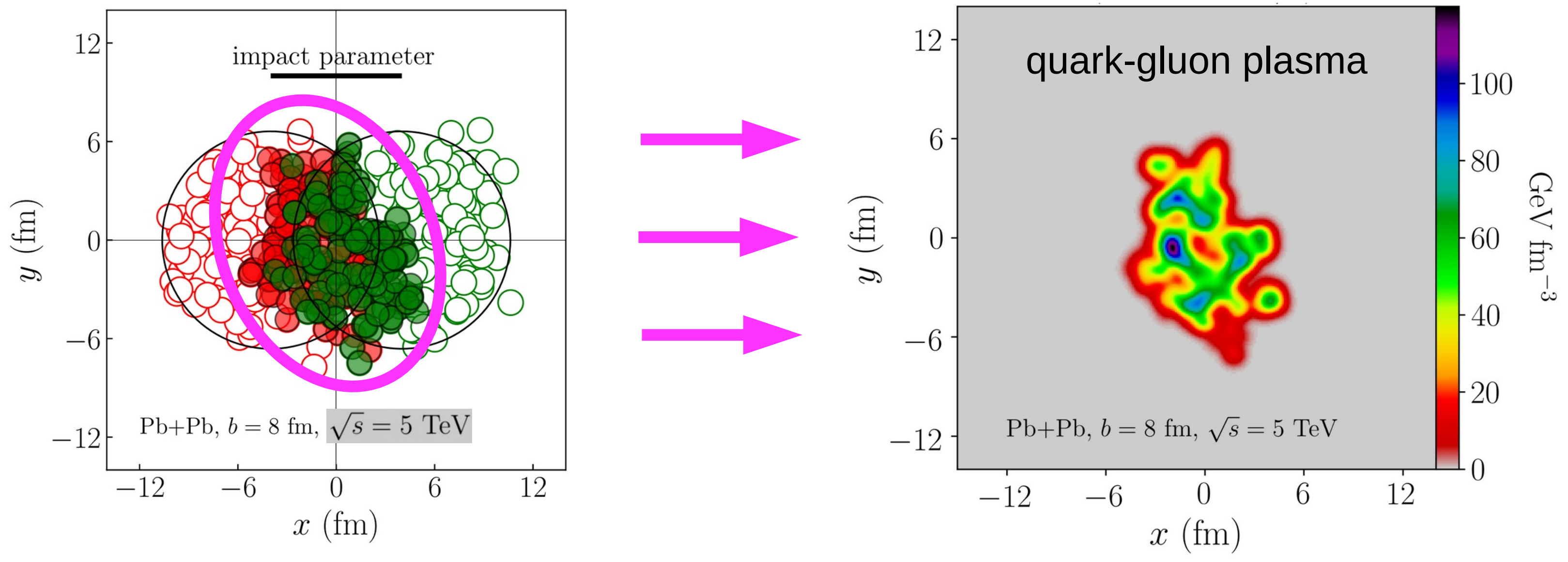


$Q_s^2(\mathbf{x})$

quark-gluon plasma



$F = -\nabla P$



THE HYDRODYNAMIC FRAMEWORK OF HIGH-ENERGY COLLISIONS

Effective fluid description: $T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$ [Romatschke & Romatschke, arXiv:1712.05815]

Equation of state from lattice QCD. [HoTQCD collaboration, PRD **90** (2014) 094503]
[Gardim, Giacalone, Luzum, Ollitrault, Nature Phys. **16** (2020) 6, 615-619]

Fluid is viscous (η/s **,** ζ/s **, …).** [Bernhard, Moreland, Bass, Nature Phys. **15** (2019) 11, 1113-1117]

Hydrodynamics, a prime example of emergent (macroscopic) behavior.

$$F = -\nabla P$$

- Emergence of collisional hydrodynamics (kinetic theory).

The *pressure tensor* is defined as the fluctuation of the velocities of the ensemble from the mean velocity, i.e. as the 2-nd order moment:

$$\mathbf{P} = m \int (\mathbf{v} - \mathbf{v}_b)(\mathbf{v} - \mathbf{v}_b) f(\mathbf{v}) d^3 v$$

- Emergence of superfluid motion in BEC (not collision-driven).

$$\frac{\partial}{\partial t} n + \nabla (v_S n) = 0$$

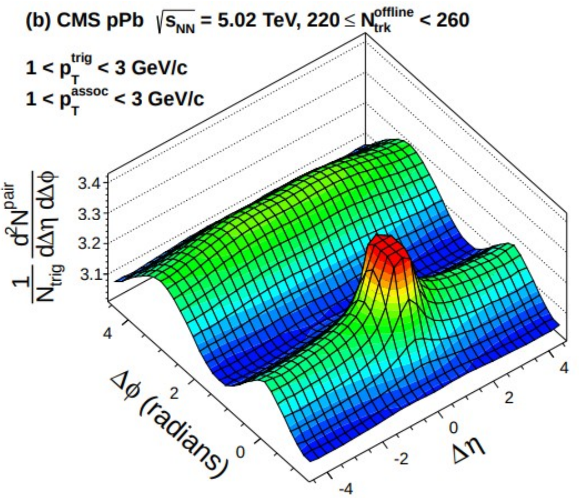
$$m \frac{\partial}{\partial t} v_S + \nabla \left(\frac{1}{2} m v_S^2 + \underbrace{\mu(n)}_{\text{EOS}} + V_{ext} \right) = 0$$

Hydrodynamic equations of superfluids (T=0)
Closed equations for n and v_S

[from S. Stringari, **Lectures at Collège de France (2004/2005)**]

Both situations based on a macroscopic scenario, i.e., very large particle numbers.

p+Pb



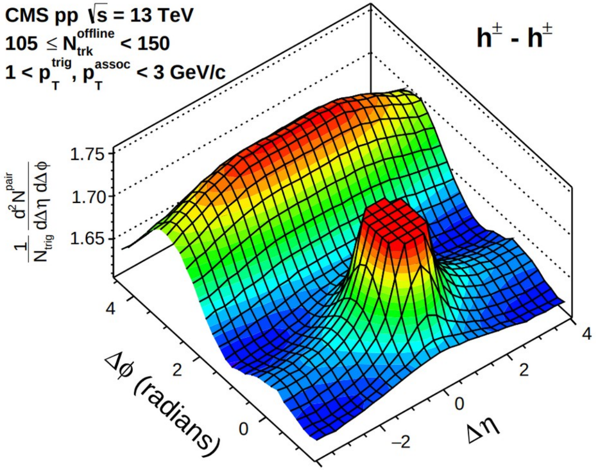
CHALLENGING HYDRODYNAMICS

COLLECTIVE FLOW IN SMALL-SYSTEM COLLISIONS

– How does collectivity emerge out of equilibrium?

[e.g. Soloviev, EPJC **82** (2022) 4, 319]

p+p



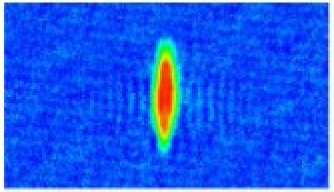
– Can systems made of only tens of particles even develop collective behavior driven by interactions?
Absence of a separation of scales?

We address this question by means of experiments on ultra-cold atomic gases.

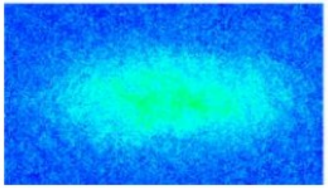
[CMS collaboration, PLB **724** (2013) 213-240]
[CMS collaboration, PLB **765** (2017) 193-220]

Why ultra-cold atomic gases? Interaction and system geometry can be controlled.

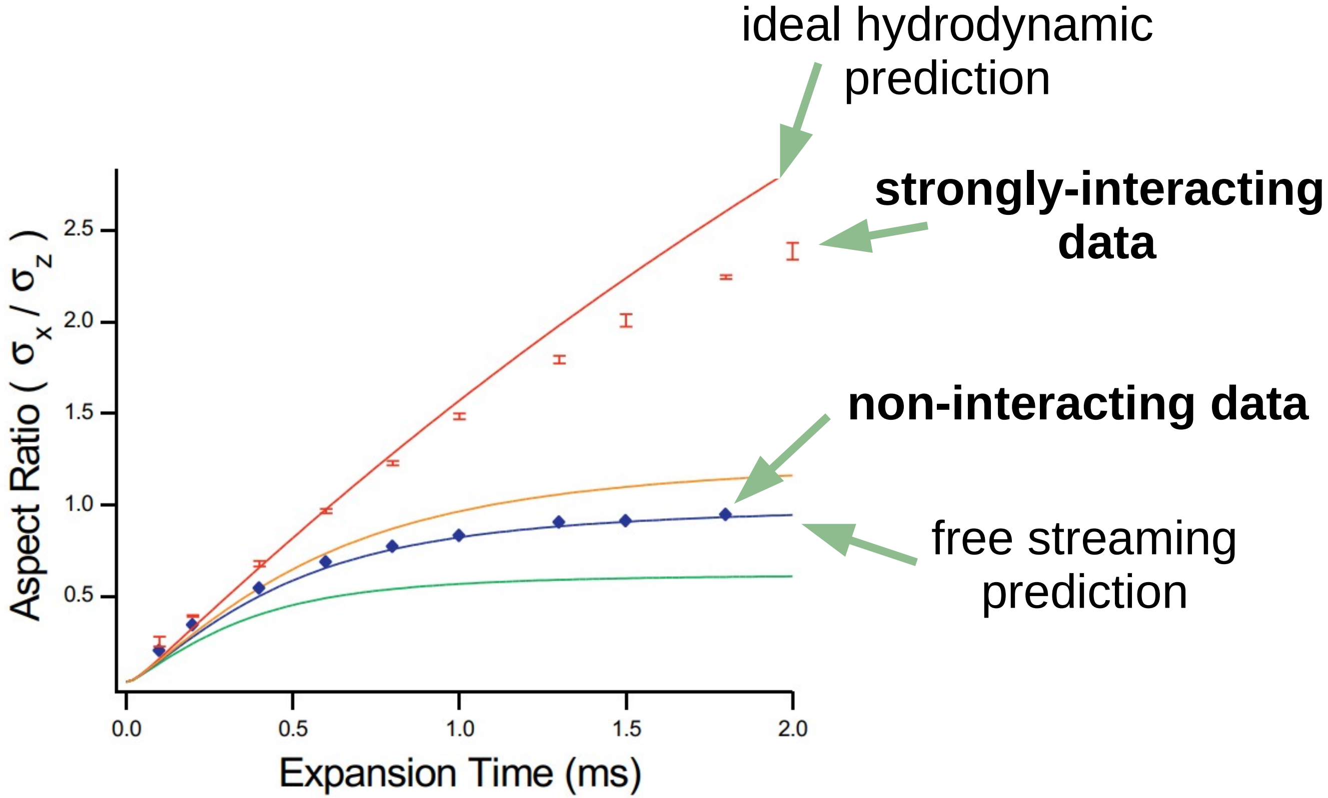
Elliptic flow used to analyze superfluid behavior of an ultracold Fermi gas.



100 μs



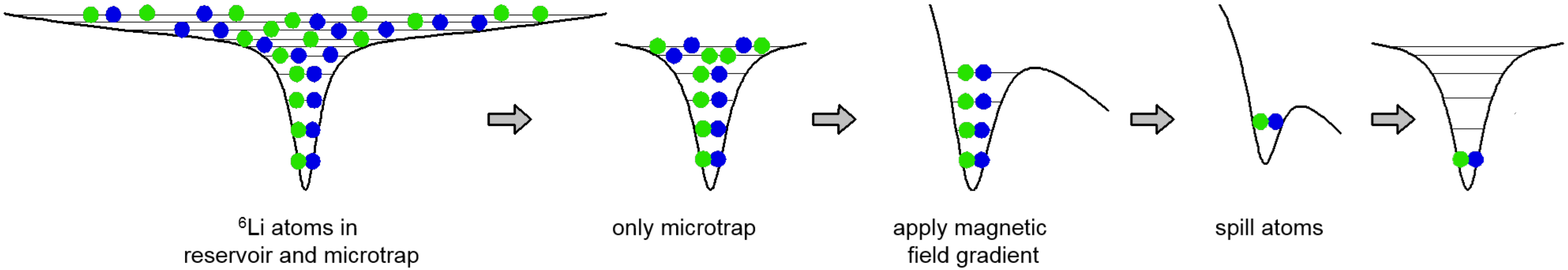
2000 μs



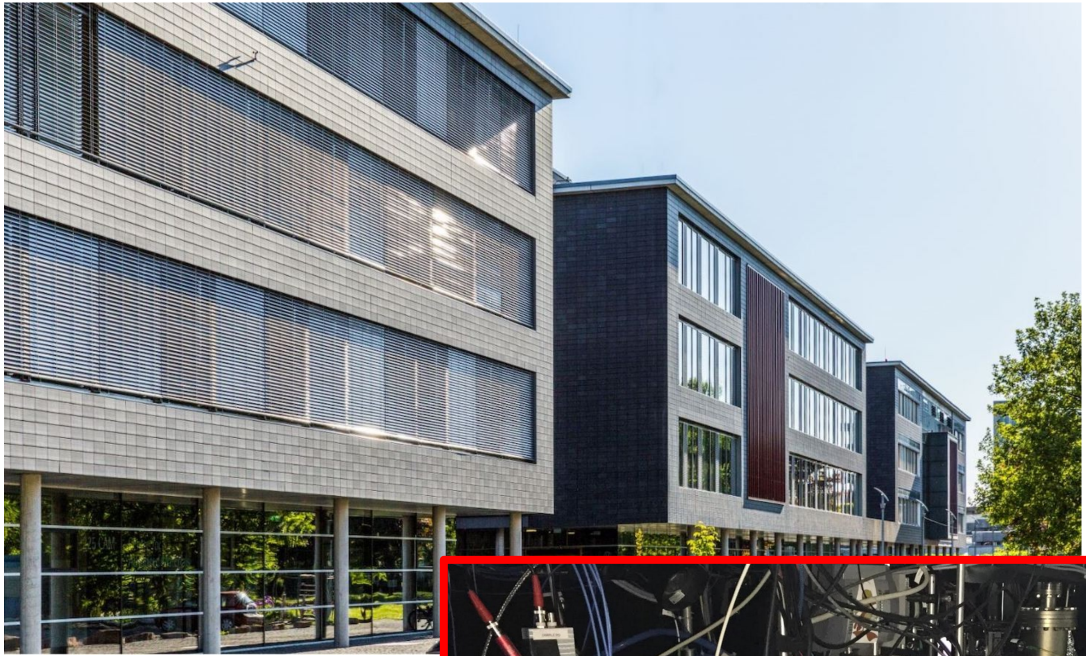
[O'Hara et al., Science **298** (2002) 2179-2182]
[Menotti, Pedri, Stringari, PRL **89**, 250402 (2002)]

Furthermore, controlled transition from few-body to many-body physics.

[Serwane et al., Science **332** (2011) 6027]



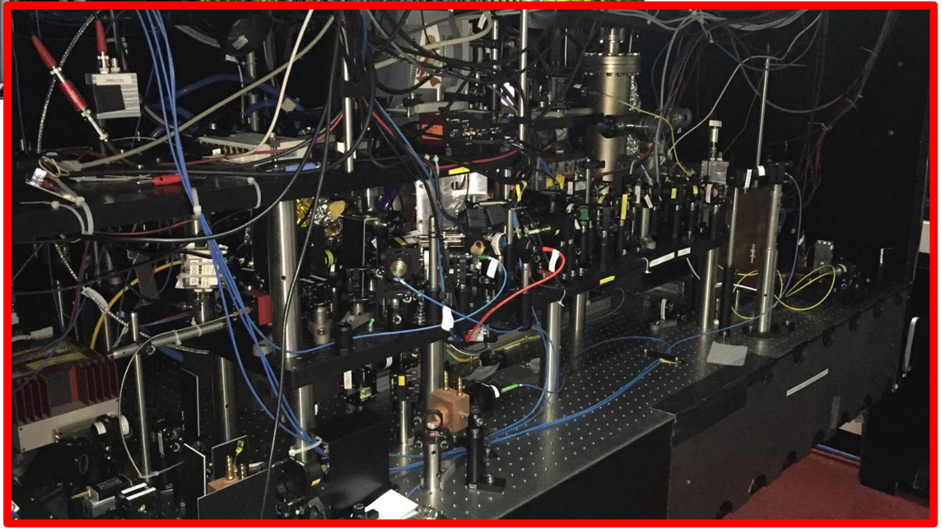
Our proposal:
Study elliptic flow to assess emergent hydrodynamic behavior in the limit of small particle numbers.



Few-body experiments at the
Physics Institute of Heidelberg University.

http://ultracold.physi.uni-heidelberg.de/

Main collaborators:
Sandra Brandstetter (PhD student)
Philipp Lunt (PhD student)
Carl Heintze (PhD student)
Selim Jochim (PI)



Experimental setup.

[Holten et al., Nature **606**, 287-291 (2022)]

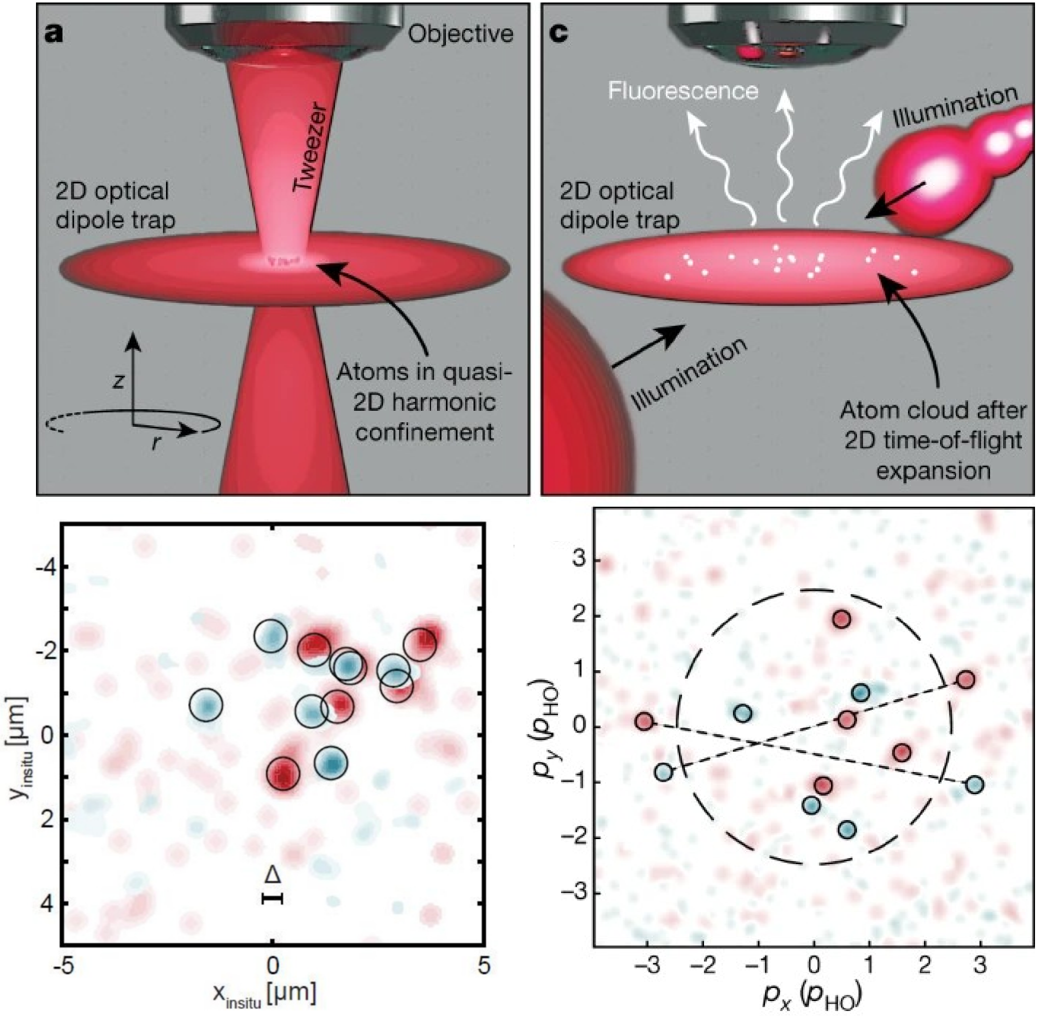
Unique method to determine atom positions and momenta in “free space”.

[Bergschneider et al., PRA **97**, 063613 (2018)]

For each atom one detects about
20 photons per 20μs of exposure.

Localization fidelity: 99.4 ± 0.3%

NB:
The measurement can be carried out in either real or momentum space.



Addressing the small system question.

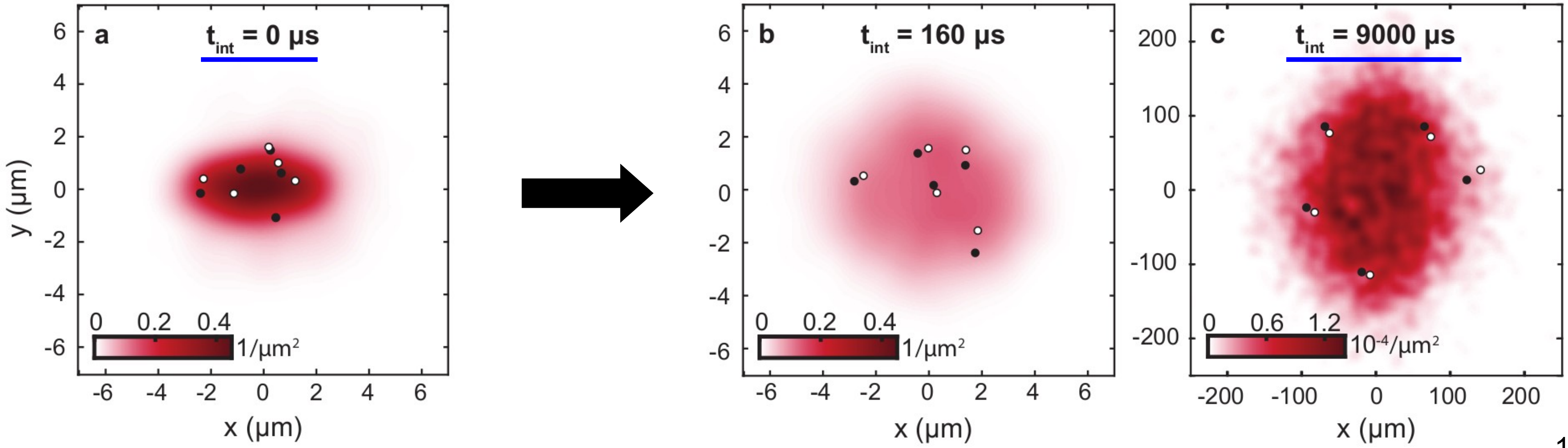
[Brandstetter *et al.*, arXiv:2308.09699]
[Flörchinger *et al.*, PRC **105** (2022) 4, 044908]

Strongly-interacting ^{6}Li atoms in a trap. Imaging the expansion driven by interactions.

No separation of scales in the initial system: system size = interparticle spacing.

TEXTBOOK FLUID DYNAMICS DOES NOT APPLY …

… but shape inversion is observed!

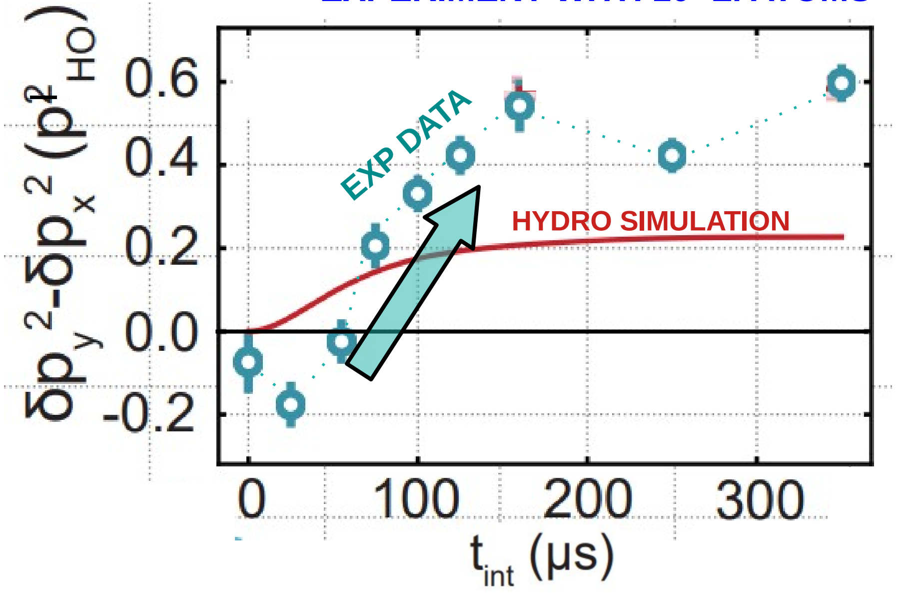


Real time imaging of the emergence of elliptic flow (momentum space).

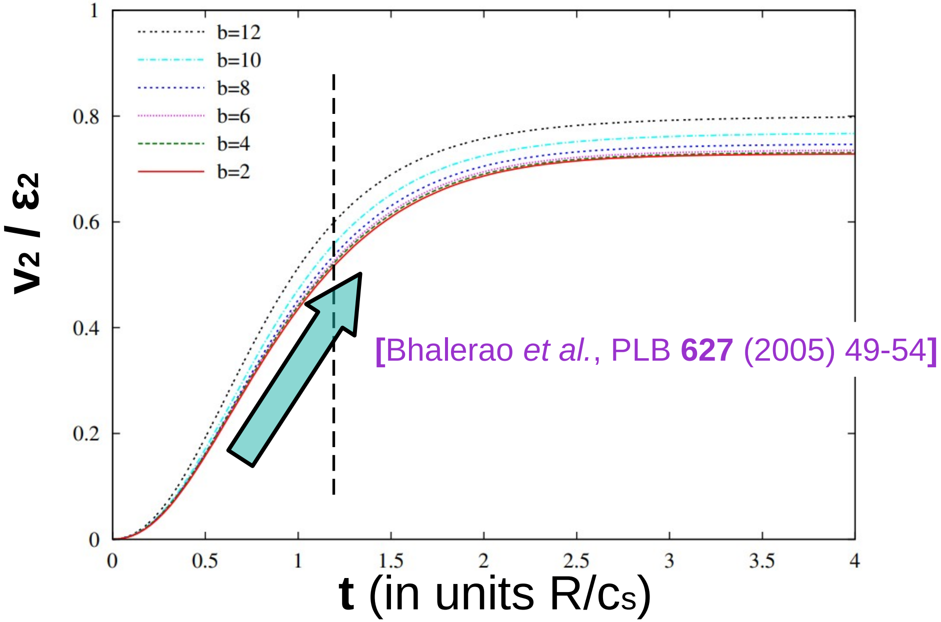
From data alone it behaves in all respects like a fluid.

New "small system question" outside of the field of high-energy collisions.

EXPERIMENT WITH 10 ^{6}Li ATOMS



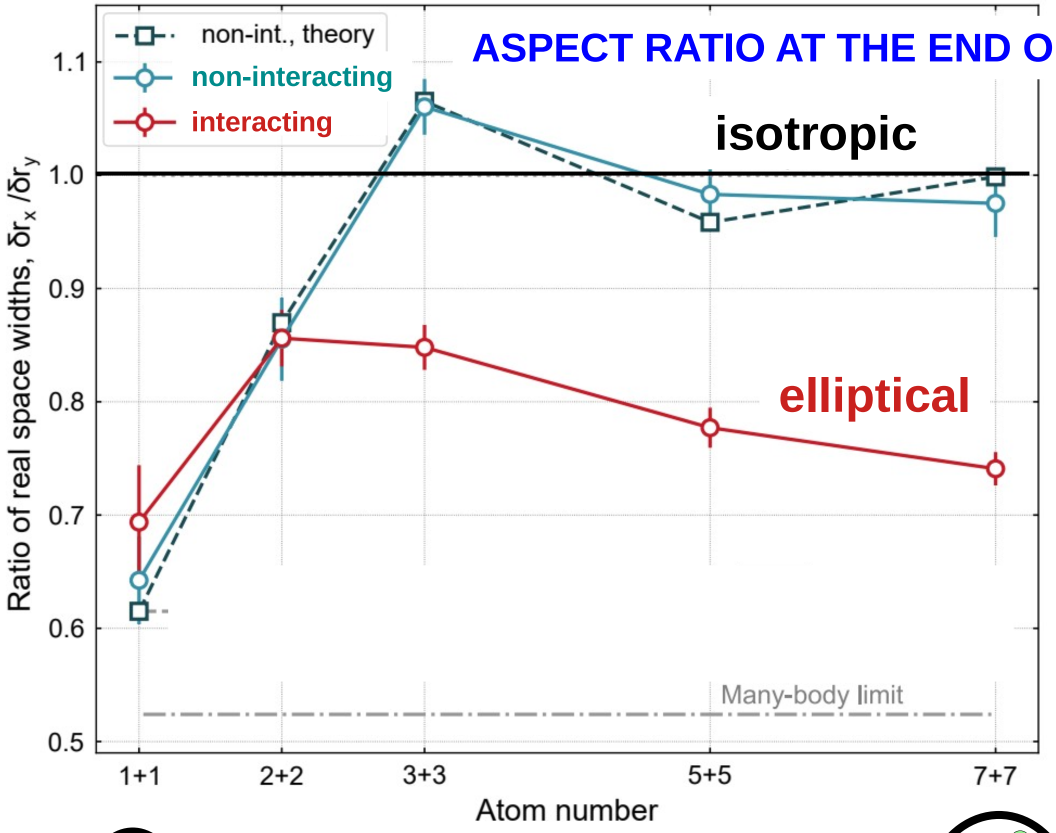
HYDRO SIMULATION OF Au+Au COLLISION

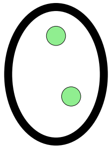


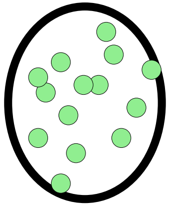
NB: Hydro calculation based on corresponding many-body EOS does not work.

Ruling out elliptic flow driven by Heisenberg uncertainty relations. $\Delta p_x \Delta x \geq \frac{h}{4\pi}$

ASPECT RATIO AT THE END OF EXPANSION







Up to N_{atoms}=4, anisotropy is an initial-state effect sourced by uncertainty relations.

Beyond N_{atoms}=6, elliptic flow is solely determined by inter-atom interactions.

$\downarrow$

Hydrodynamic interpretation

BUILDING A FLUID PARTICLE BY PARTICLE

SUMMARY

- Criteria for applicability of hydrodynamics have been challenged by the observation of collectivity in small collision systems.

- Exploit exquisite degree of control of cold atomic gases to address the issue of the emergence of hydrodynamic behavior.

- **Novel "small system question" with flow of ultracold atoms:**
  Few strongly-interacting particles without a separation of scales display fluid-like behavior (elliptic flow).

- Paves the way for detailed characterizations of the emergence of fluid dynamics as a function of particle number and interaction strengths.

THANK YOU!