Observation of emergent hydrodynamic behavior in a mesoscopic 2D Fermi gas

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9th August, 2022

Based on: [Floerchinger, Giacalone, Heyen, Tharwat, **PRC 105, 044908 (2022)**]
[Brandstetter, Heintze, Lunt, Subramanian, Holten, Jochim, Heyen, Giacalone, Floerchinger, **in preparation**]

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OUTLINE

- 1. The quest for hydrodynamics in systems that are small.
- 2. Cold atom gases as a probe of hydrodynamics.
- 3. Elliptic flow as a function of particle number.
- 4. Experiment.
- 5. Preliminary results.
- Conclusion.

1.
The quest for hydrodynamics in systems that are small.

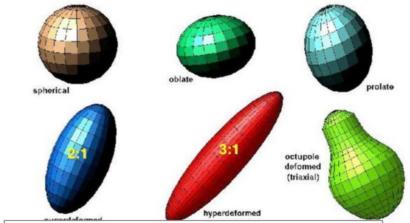
Emergent phenomena are among the most interesting in Nature.

"More is different", **[P. Anderson, 1972]**

https://en.wikipedia.org/wiki/Emergence

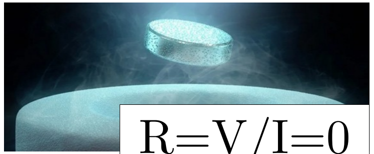
Examples relevant nuclear / cold atom physics:

Nuclear deformations

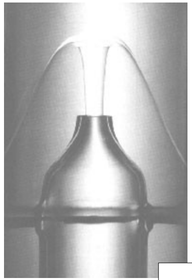


$$R = R_0\left(1 + \sum_n \beta_n Y_n^0\right)$$

Superconductivity



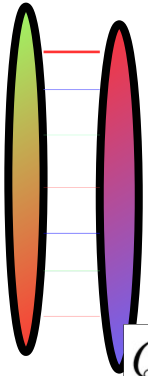
$$R = V/I = 0$$



$$\eta = 0$$

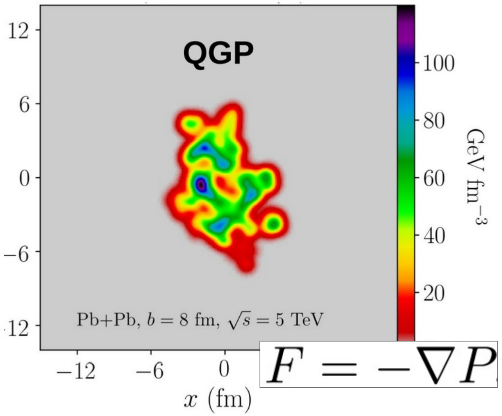
Superfluidity

color glass condensate



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

quark-gluon plasma



$$F = -\nabla P$$

Focus of this talk: Hydrodynamics, a prime example of emergent (macroscopic) behavior.

$$F = -\nabla P$$

Emergence in a particle system via collisions (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 (no collisions, but due to interactions in a Fermi gas).

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

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

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 require a mascroscopic scenario, i.e., very large particle numbers.

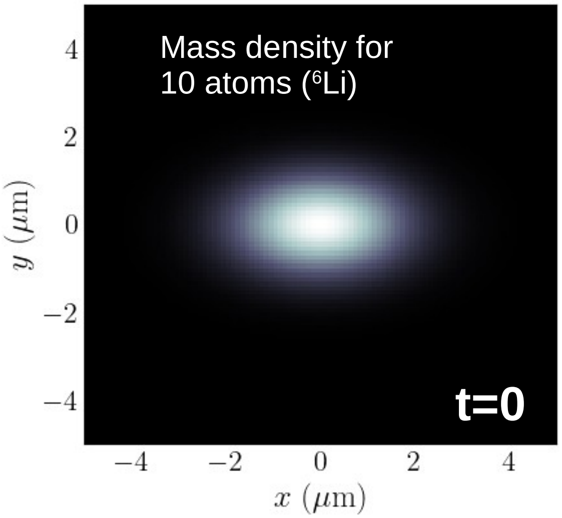
Frontier: behavior of mesoscopic systems? What if the particle number is small?

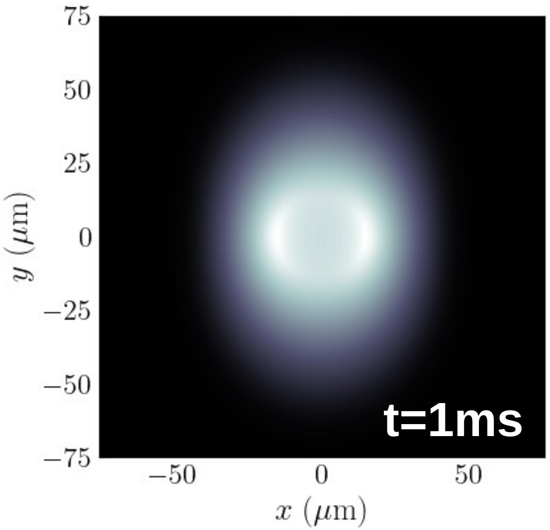
Tool to probe hydrodynamic behavior: Elliptic flow. Shape inversion of the gas due to asymmetry in pressure-gradient force.

[Ollitrault, **PRD 46 (1992) 229-245**

Does not really matter whether system is superfluid or collisional.

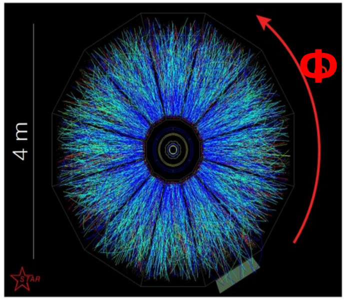
Realistic application: ideal Fermi gas in 2D at zero temperature.





In heavy-ion collisions:
2nd Fourier harmonic of the azimuthal particle distribution.

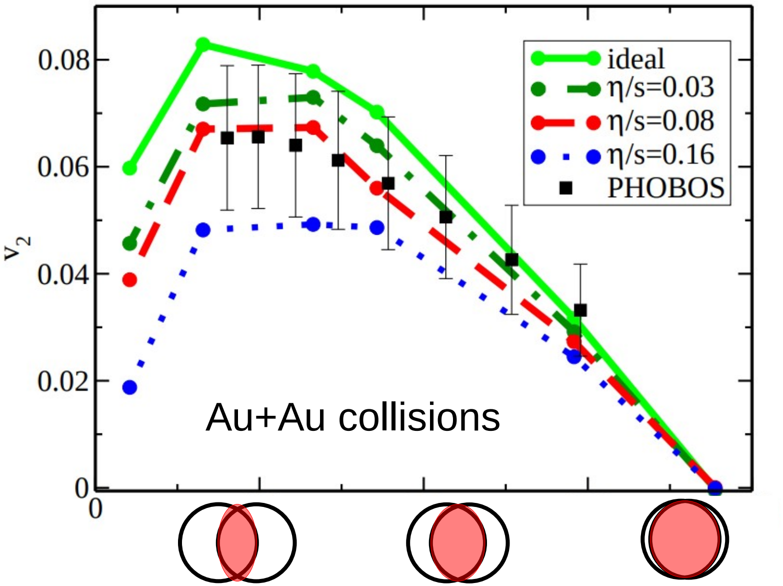
$$V_2 = \frac{1}{N}\int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-i2\phi_p}$$



[Romatschke & Romatschke, **PRL 99, 172301 (2007)**]

Elliptic flow is in sensitive to viscous corrections.

$$\rho\frac{d\mathbf{v}}{dt} = \underbrace{-\vec{\nabla}P}_{1/R} + \underbrace{\eta\vec{\nabla}^2\mathbf{v} + \vec{\nabla}\left[\vec{\nabla}\cdot\mathbf{v}\left(\zeta + \frac{2}{3}\eta\right)\right]}_{1/R^2}$$

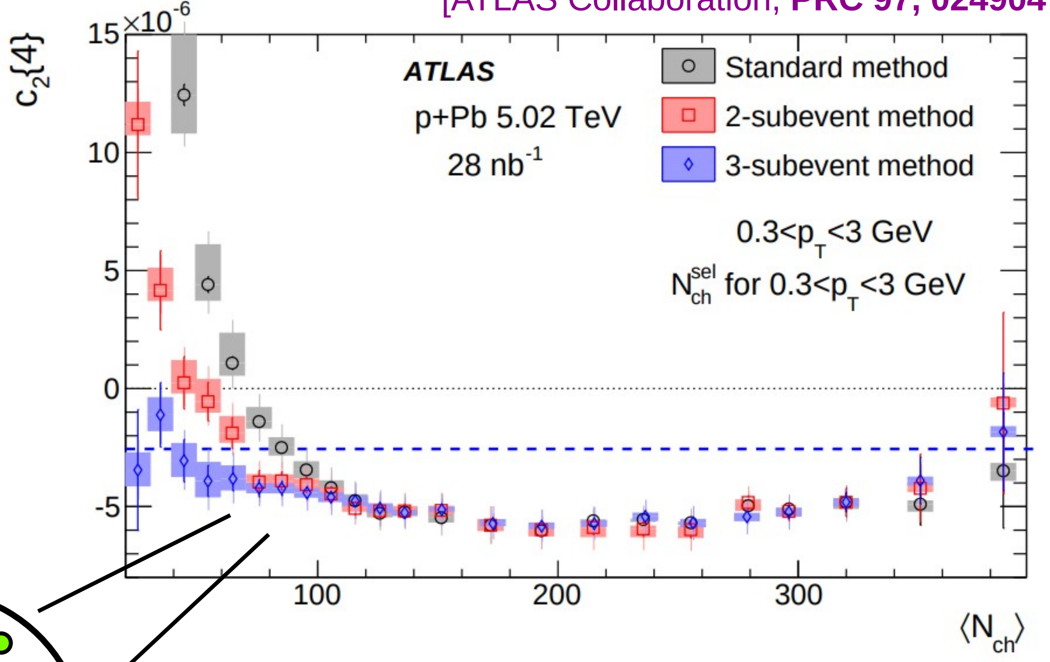


Provides convincing evidence that the QGP behaves like a strongly-coupled fluid.

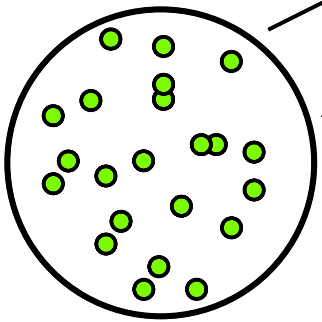
Why mesoscopic systems? Interesting motivation from high-energy collisions.
Signals of collective particle emission at low multiplicities.

[ATLAS Collaboration, **PRC 97, 024904 (2018)**]

$$2\langle v_2^2\rangle^2 - \langle v_2^4\rangle \;=$$

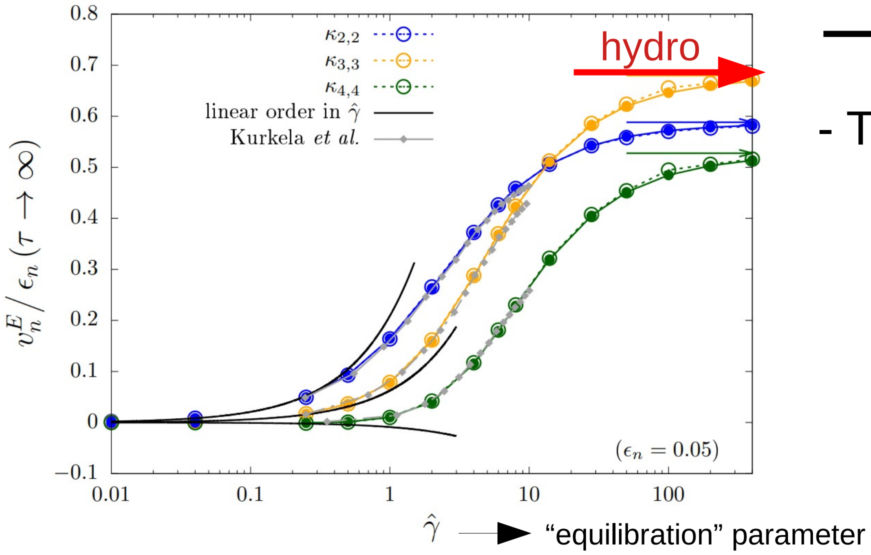


genuine 4-body
(non-Gaussian)
correlation.



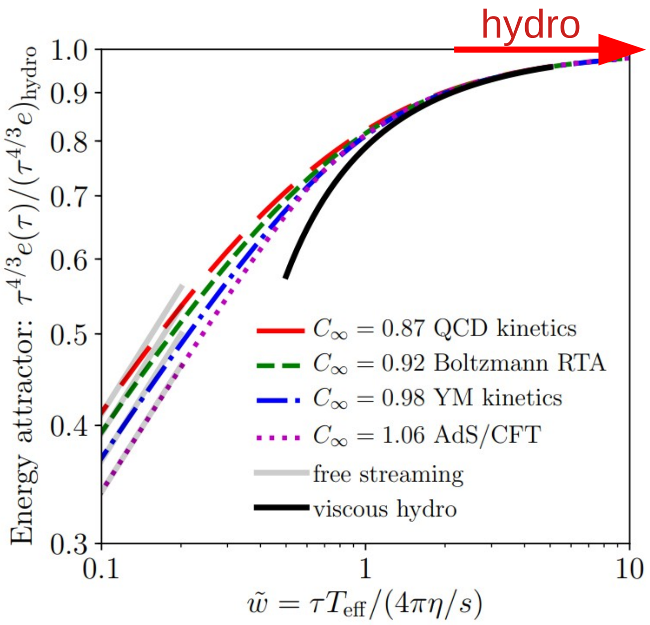
About 20 strongly-interacting particles per unit rapidity.
Can that make a fluid?

NB: understanding “small systems” is a very active research area.



- Transition to fluid dynamics.

[Kurkela, Wiedemann, Wu, **EPJC 79 (2019) 11, 965**]
[Ambrus, Schlichting, Werthmann, **PRD 105 (2022) 1, 014031**]



- Emergence of the hydrodynamic attractor.
  Out-of-equilibrium hydrodynamics.

[Romatschke & Romatschke, **arXiv:1712.05815**]
[Giacalone, Mazeliauskas, Schlichting, **PRL 123, 262301 (2019)**]
[Berges et al., **RMP 93 (2021) 3, 035003**]

Motivation: can we attack these questions with cold atom experiments?

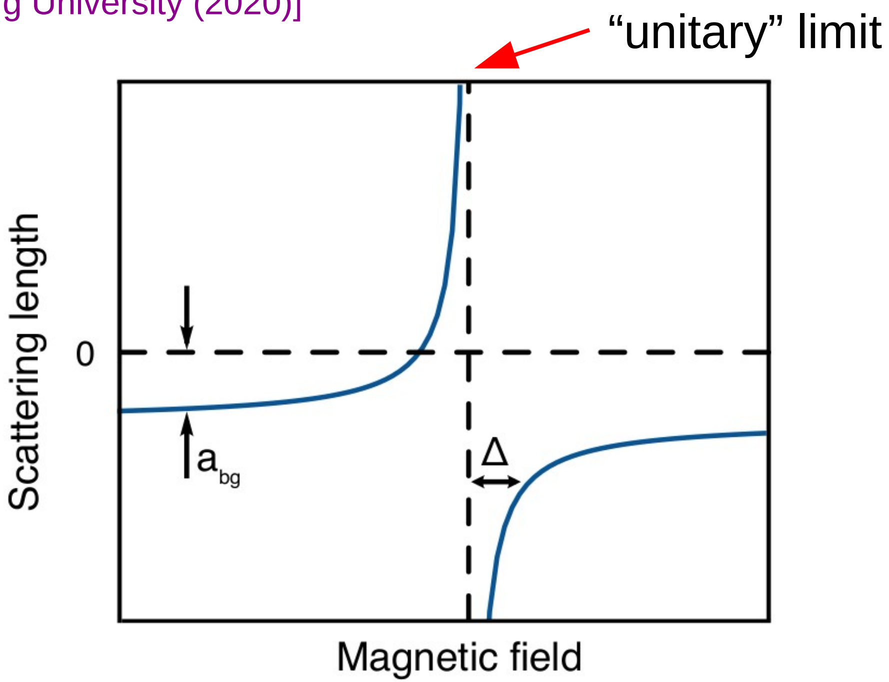
2.
Cold atom gases as a probe of hydrodynamics.

Why ultracold atom gases? First reason: interactions are tunable.

Interactions at low momenta described by an s-wave scattering length parameter.

Tunable via a Feshbach resonance in presence of an external magnetic field.

[from Luca Bayha, PhD thesis, Heidelberg University (2020)]



$$a_{3D} = a_{bg}\left(1 + \frac{\Delta}{B - B_0}\right)$$

Values for lowest states of ^{6}Li:

$$a_{bg} = -2100\, a_{\mathrm{Bohr}}$$

$$B_0 = 690\,\mathrm{G}$$

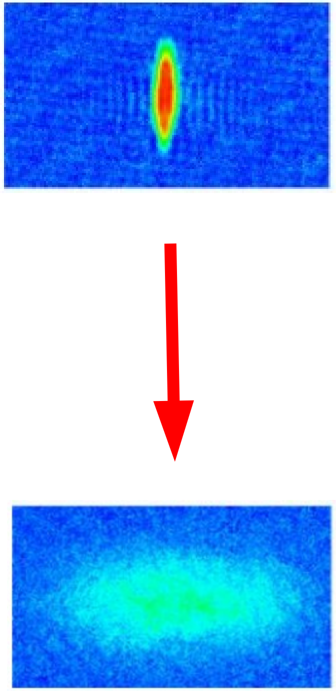
$$\Delta = 200\,\mathrm{G}$$

We can move from non-interacting to strongly-interacting systems.

Second reason: we can play with the geometry of the system.

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

NB: at low temperature, strongly-interacting Fermi gas is a gas of pairs (bosons).

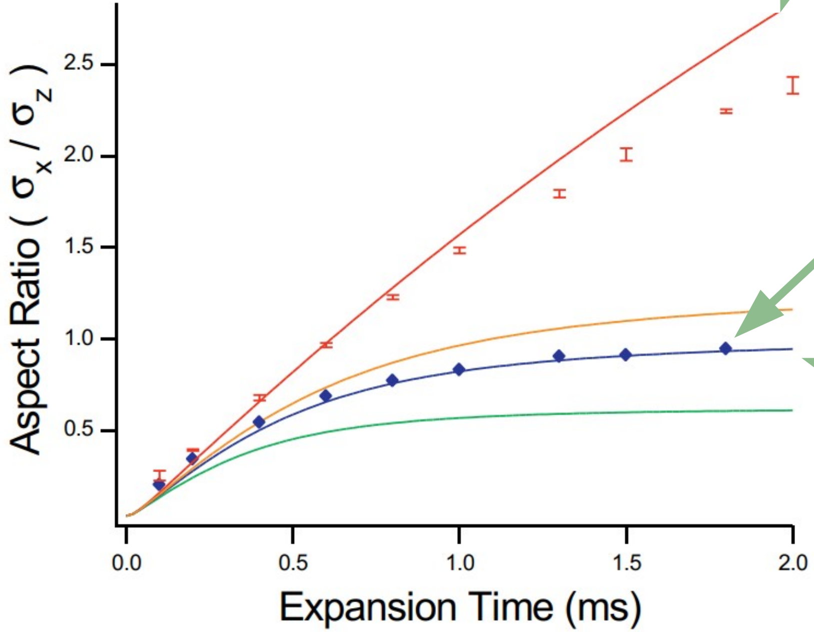


100 μs

2000 μs

ideal hydrodynamics

strongly-interacting gas



non-interacting gas

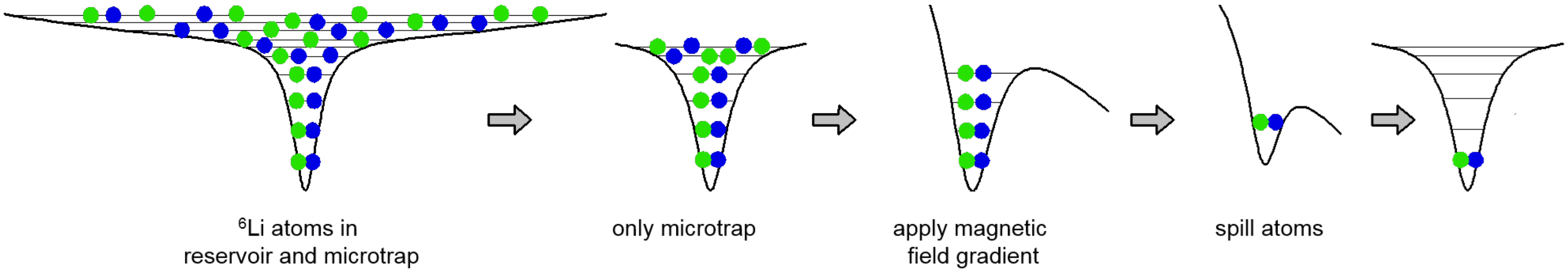
ballistic expansion

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

Third reason [focus of this talk]: much less explored, the particle number is tunable!

Going “cold” brings dramatic advantages. Effective control over the number of particles.

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



[from http://ultracold.physi.uni-heidelberg.de/02research/]

Transition from few-body to many-body physics.

Our proposal:
Study elliptic flow to assess emergent hydrodynamic behavior as a function of particle number (in two dimensions).

3.
Elliptic flow as a function of particle number.

[Floerchinger, Giacalone, Heyen, Tharwat, **PRC 105, 044908 (2022)**]

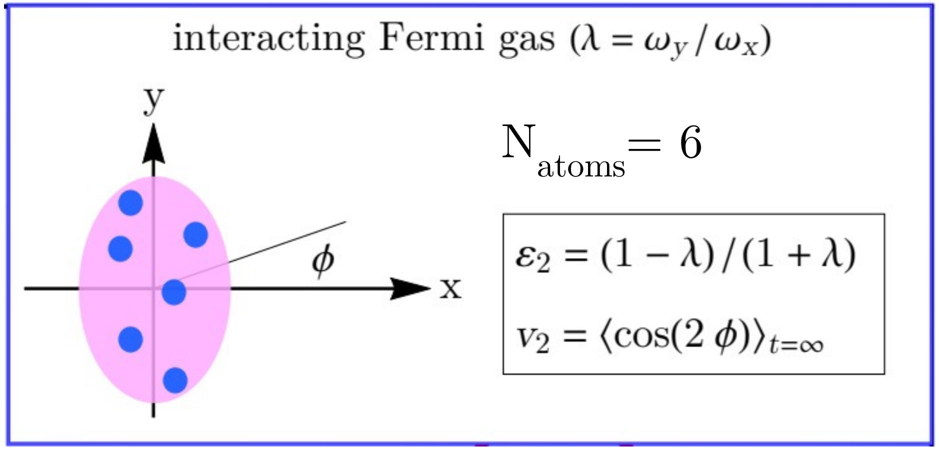
Measuring elliptic flow in mescoscopic samples.

1 – Resort to a statistical description, i.e., repeat the experiment many times like in heavy-ion collisions.

2 – Unlike in heavy-ion collisions, the orientation of the ellipse and the initial ellipticity, ε_2, can be chosen.

3 – Let the system expand and measure the anisotropy of the system (e.g. $<\cos 2\Phi_p>$) with respect to the fixed axis. **single-particle measurement!**

4 – Repeat the experiments for different number of atoms in the cloud.



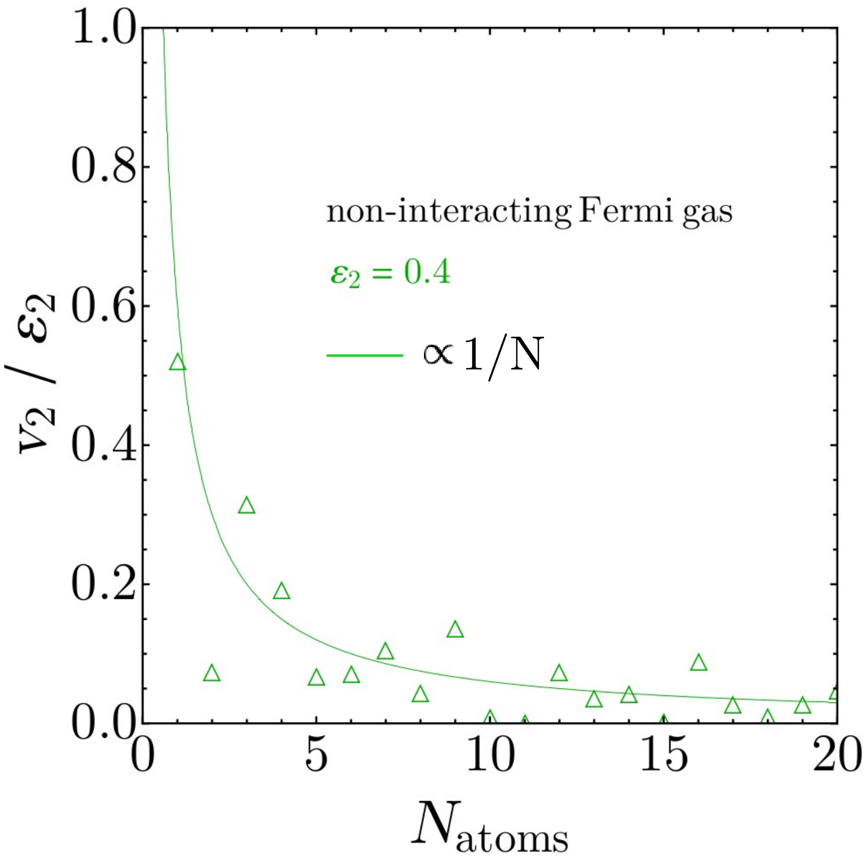
Imposing an elliptical potential has a strong impact on the initial momentum distribution.

$$\Delta p_x \Delta x \geq \frac{h}{4\pi}$$

Calculate v2 from the quantum harmonic oscillator (initial momentum anisotropy).

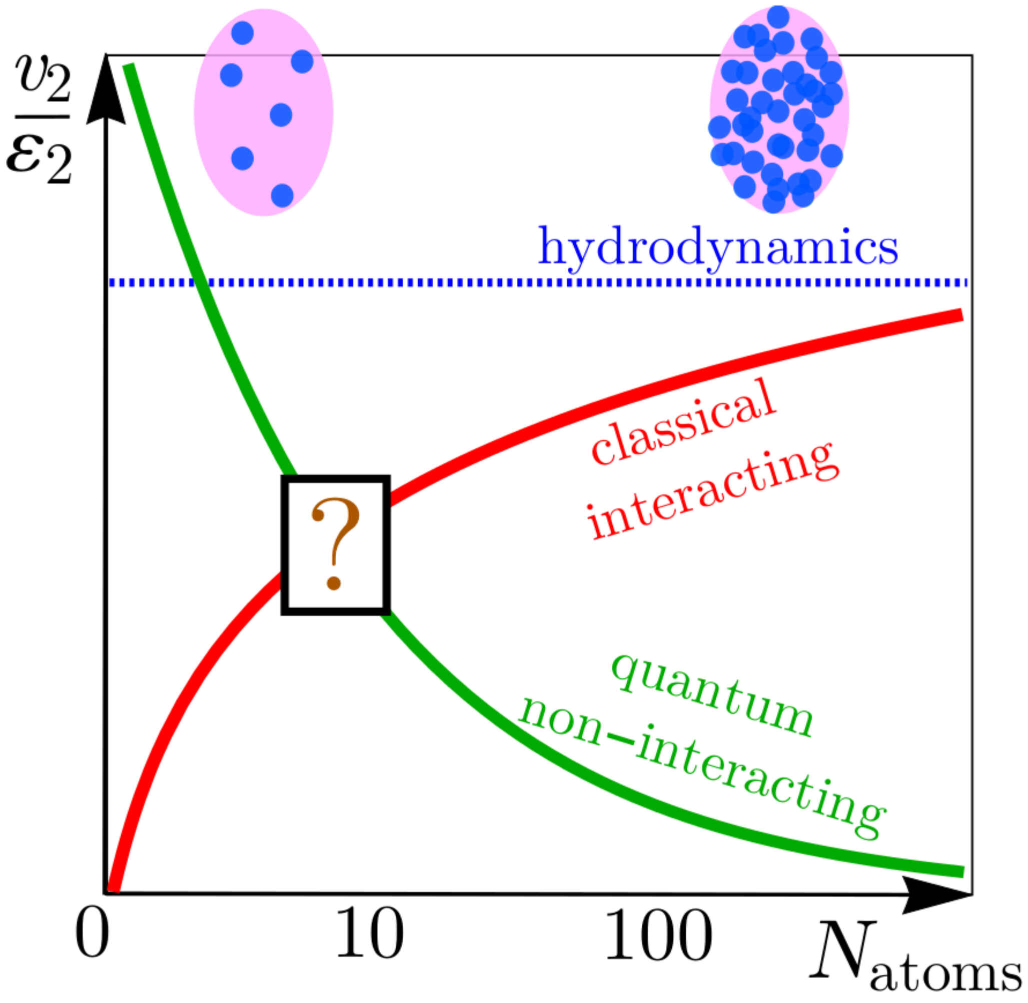
$$v_2 = \langle \cos(2\phi_p) \rangle_{\Psi}$$

trapped non-interacting fermions



Very important if we only have 2-3 particles.
However, it disappears quickly, like 1/N.

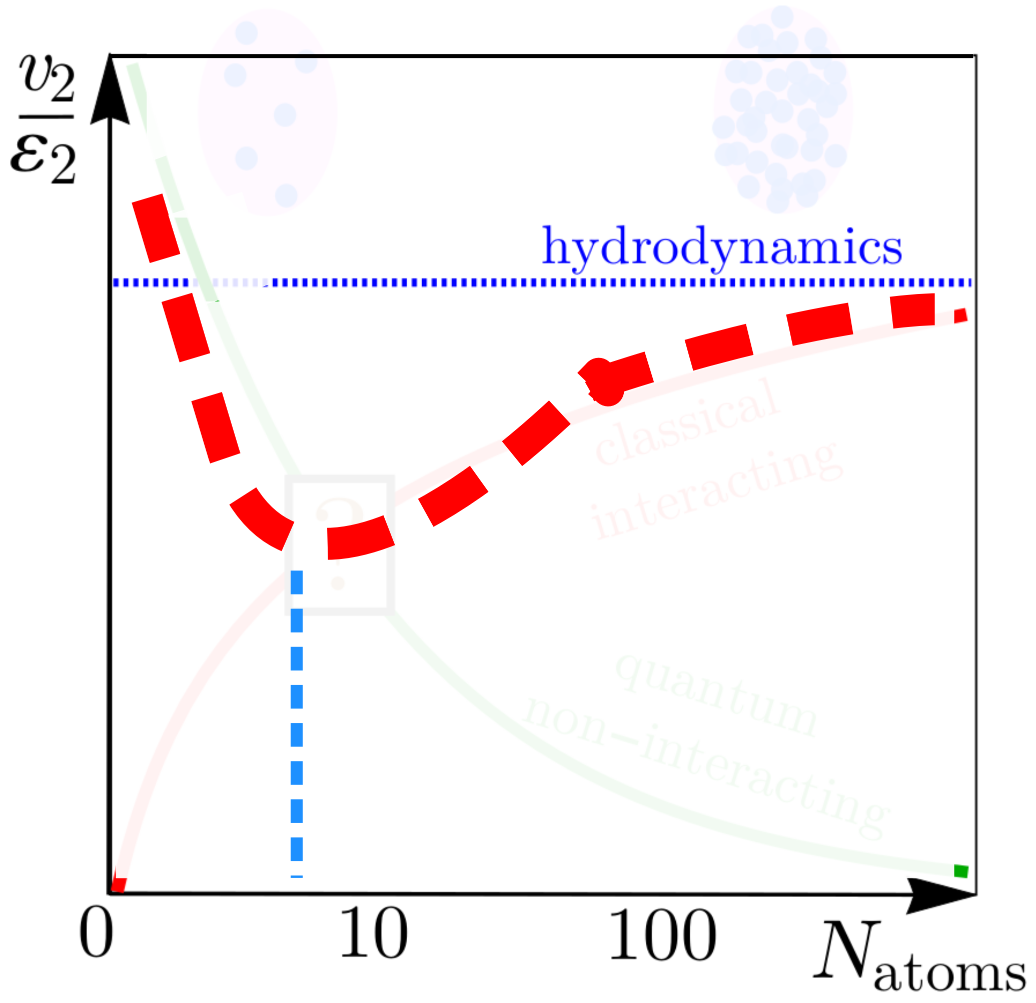
Qualitative expectations.



Combining the curves…

Could there be a minimum?

Transition from quantum effects to interaction effects?

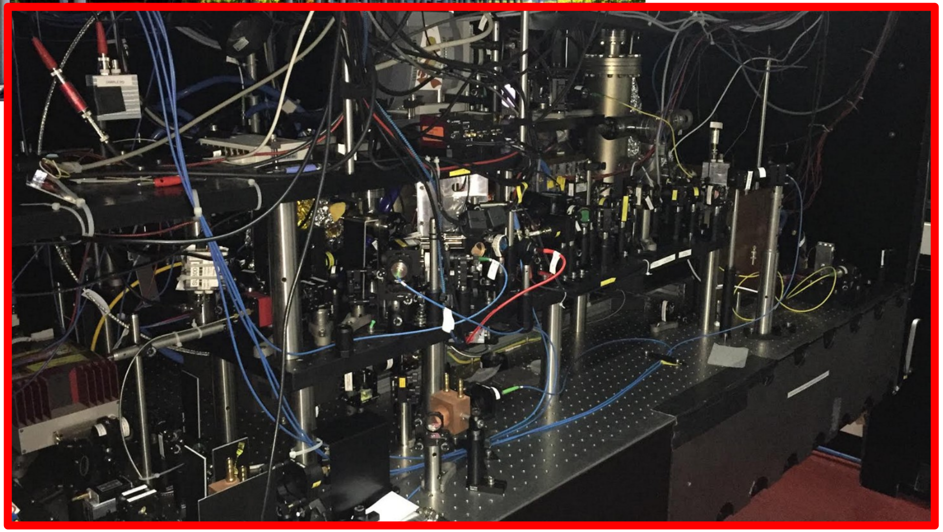


4.
Experiment.

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

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

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

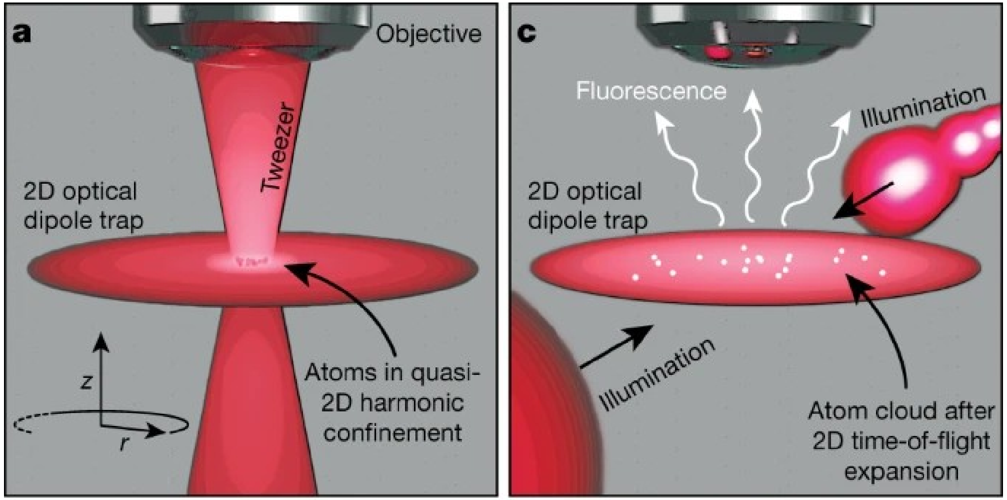


Atoms trapped on this optical bench.

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

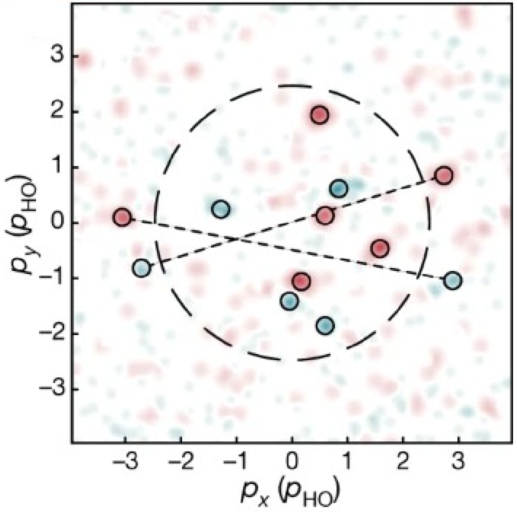
Unique method to determine atom positions and momenta in an expanding cloud.

[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: Collapse of the wavefunction while system expands,
not when the expansion starts!
Fundamental difference w.r.t. heavy-ion collisions?

APPLICATION: Observing the Pauli exclusion principle “by eye” (**Pauli crystals**).

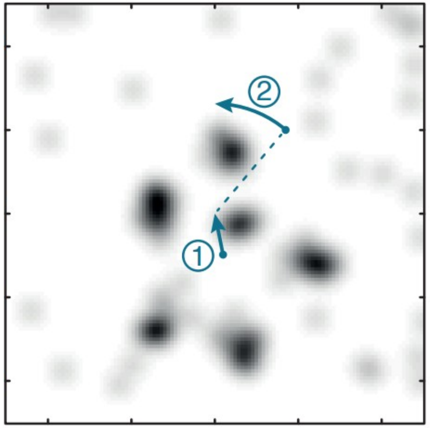
[Holten et al., **PRL 126, 020401 (2021)**]

Identify (non-interacting) atoms after some time of flight (magnification).

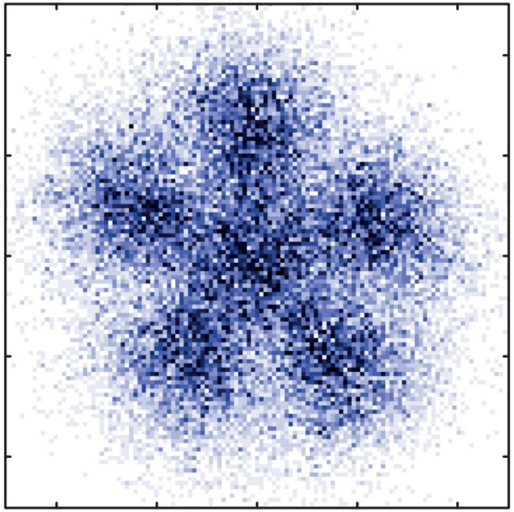
Rotate images and shift center-of-masses to common reference.

Exclusion principle drives the average geometry away from isotropy.

single image



average image

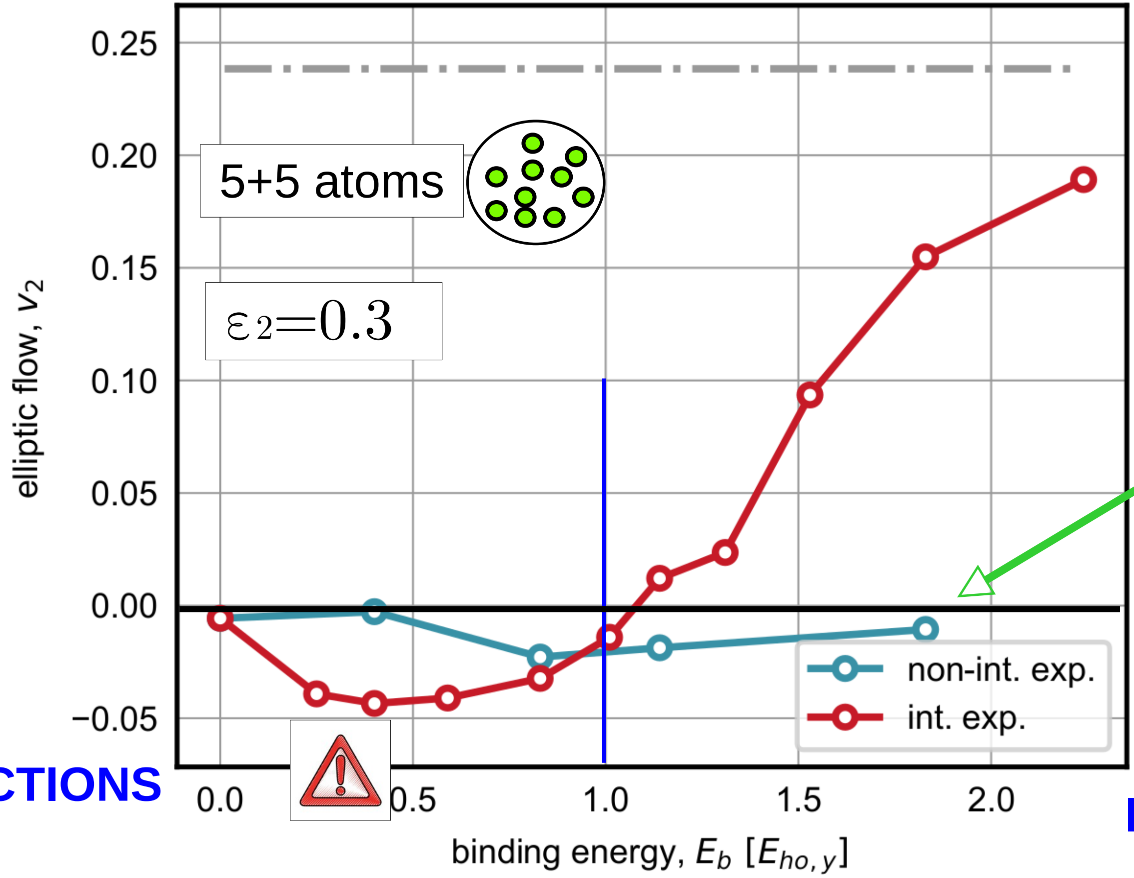


5.
Preliminary results.

Emergence of v_2 from interactions.

***E_b* = binding energy of one pair**
***E_{ho}* = harmonic oscillator energy**

When $E_b = E_{ho}$, bosonic pairs appear. Onset of superfluidity?
Energy dependence of effective viscosity? (superfluid = zero viscosity)



Interactions switched off right after trap is released.

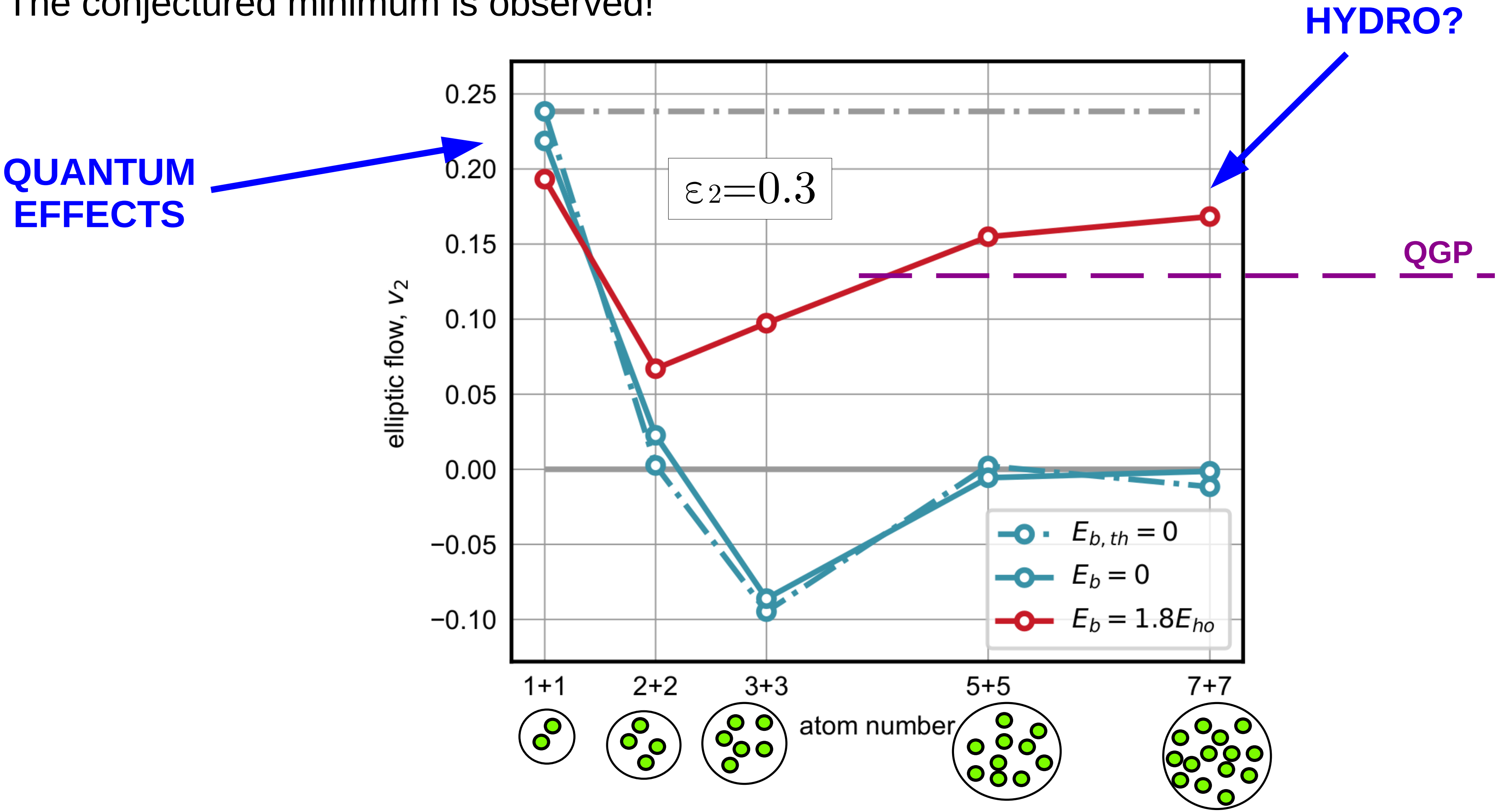
Remaining v_2 is from the initial state, i.e., the initial momentum anisotropy.

NO INTERACTIONS

STRONG INTERACTIONS

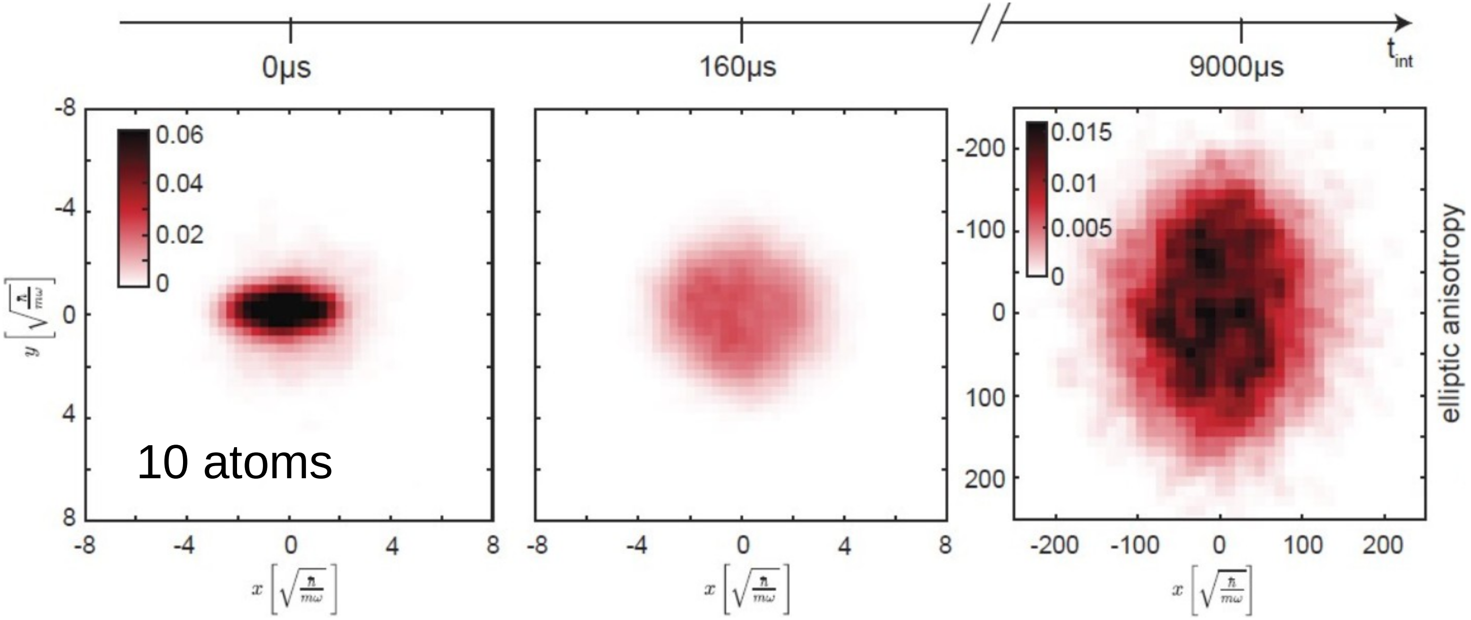
v_2 as a function of particle number.

The conjectured minimum is observed!



Have we observed hydrodynamics?
Elliptic flow defined in momentum space. Not directly computable in hydro.

Probe: Temporal evolution of the shape of the average cloud in coordinate space.



Is this a fluid expansion?

Hydrodynamic prediction?

$$F = -\nabla P$$

We only need the pressure.

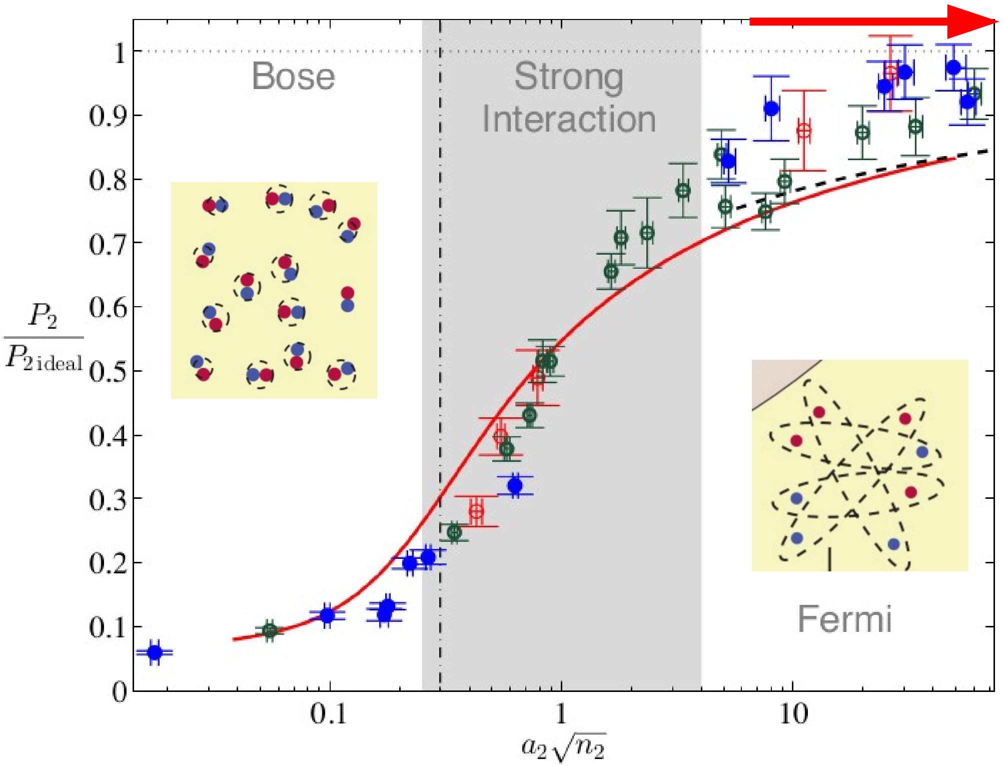
For a 2D Fermi gas at zero temperature, this has been extensively studied.

[Levinsen, Parish, **Annual Review of Cold Atoms and Molecules, arXiv:1408.2737**]

EoS for ideal Fermi gas (Pauli pressure):

$$P_{\mathrm{ideal}} = \frac{\pi\hbar^2}{2M} n^2$$

Mass of ^{6}Li



In the experiment:

$$a_{2D} \approx 1\ \mu\mathrm{m}$$
$$n \approx N/\pi \approx 3\ \mu\mathrm{m}^{-2}$$
$$\Rightarrow \quad P \approx 0.53 P_{\mathrm{ideal}}$$

HYDRODYNAMIC RESULTS

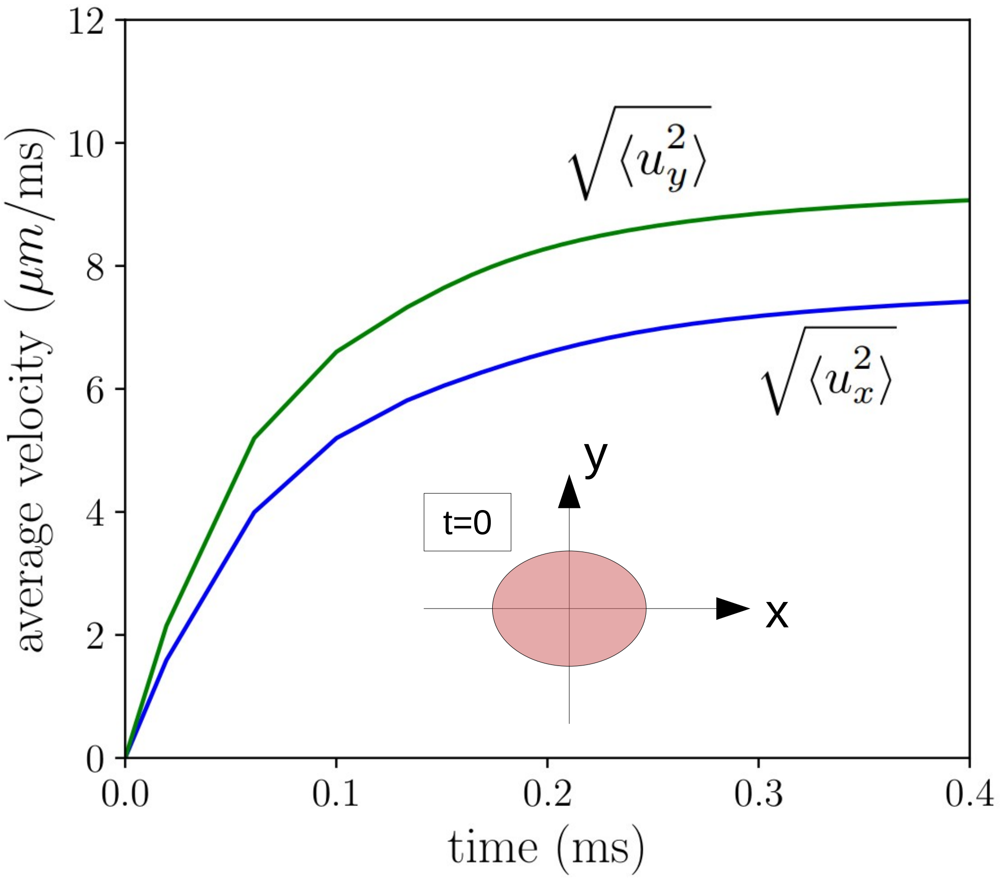
Over what time scales are gradients effective?

Compressible hydro solver developed at Stony Brook:
https://pyro2.readthedocs.io/en/latest/index.html#

Typical velocity is lower than speed of sound.
(Mach number ~ 0.5)

R~1 μm c_s~25 μm/ms

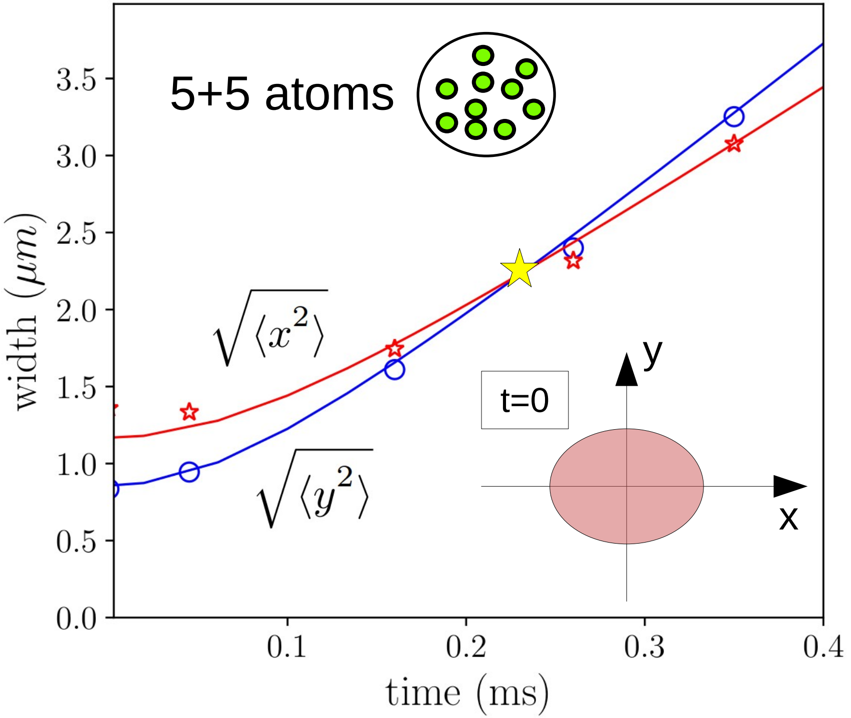
Expansion is fairly "slow".

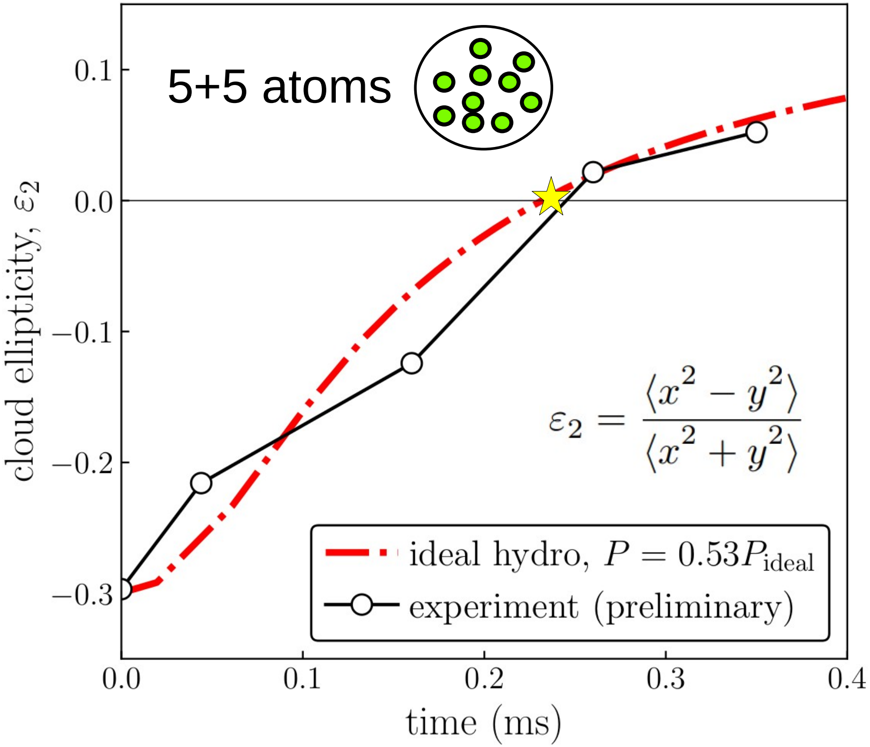


HYDRODYNAMIC RESULTS

Average shape directly comparable to experimental data.

Ideal hydrodynamics naturally captures the time scale of shape inversion.





The first mesoscopic fluid.

CONCLUSION

- Hydrodynamics is an emergent behavior observed in systems across vastly different energy scales (superfluids at T=0, QGP at $T \sim 10^{12}$ K)
- Cold atom experiments permit us to study emergent hydrodynamic behavior as a function of particle number and tunable interactions.
- Quantum effects leading to elliptic flow vanish quickly with the particle number and as soon as interactions are turned on.
- We observe a large elliptic flow driven by interactions in a cloud of N~10 strongly interacting fermions. Ideal hydrodynamic results naturally explain the data.

PROSPECTS

- Study more observables (e.g. triangular flow, mean momentum).

- Further signals of superfluidity (rotational properties).

- Connection with small systems in heavy-ion collisions?

  Certainly possible. We need to formulate conceptual issues.

- Alternative theoretical descriptions? Microscopic dynamics?

THANK YOU!
(and stay tuned)

Intersection of nuclear structure and high-energy nuclear collisions

Jan 23rd - Feb 24th 2023

Organizers:
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Jiangyong Jia (Stony Brook & BNL)
Dean Lee (Michigan State & FRIB)
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