Rotating traps, a Laughlin wave function, and the emergence of fluid behavior.

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Barcelona, September 2023

Selim Jochim, Heidelberg University

Outline

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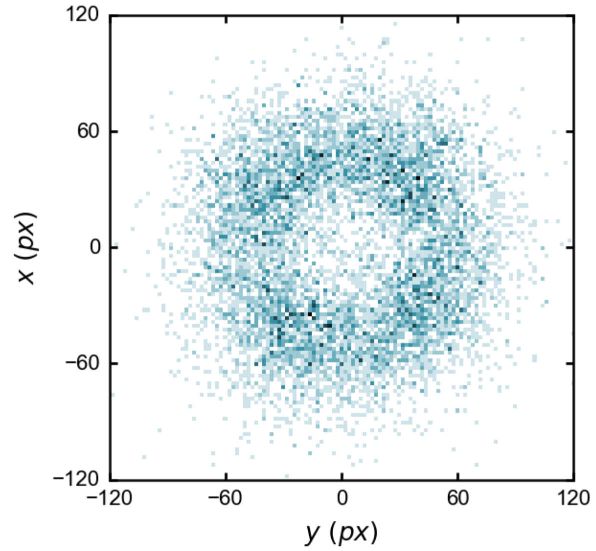
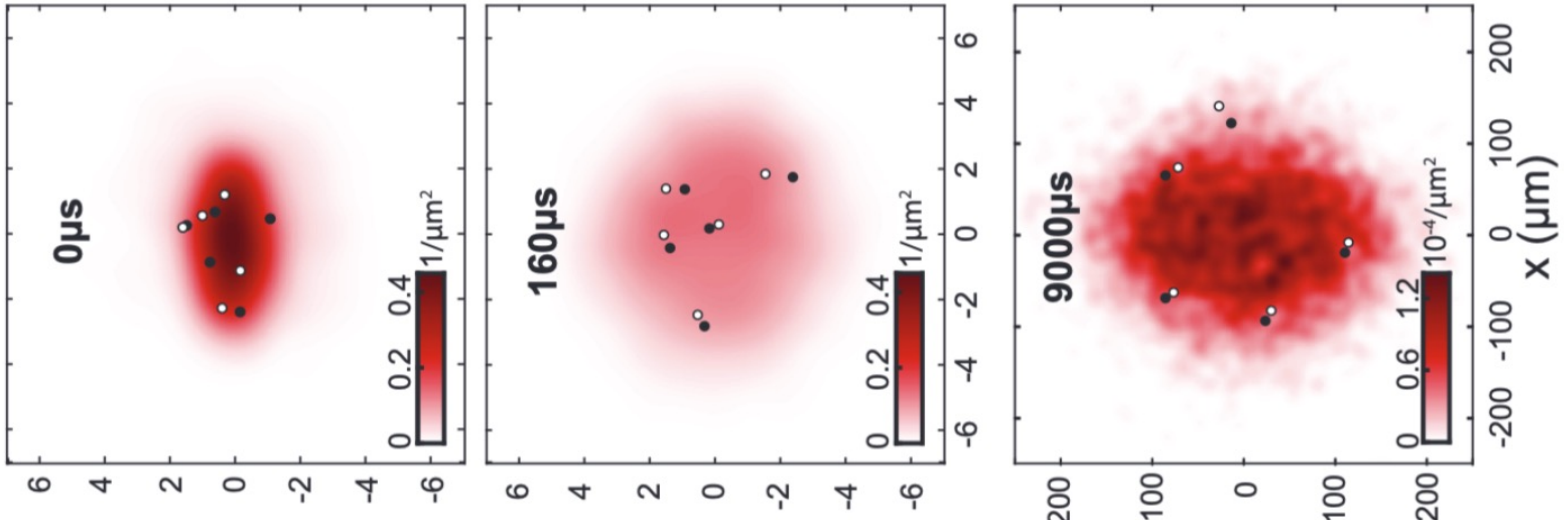
- Single atoms in discrete angular momentum states



- Two atoms turning around each other – a Laughlin state

- 10 atoms acting like a fluid



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Rotating two fermions

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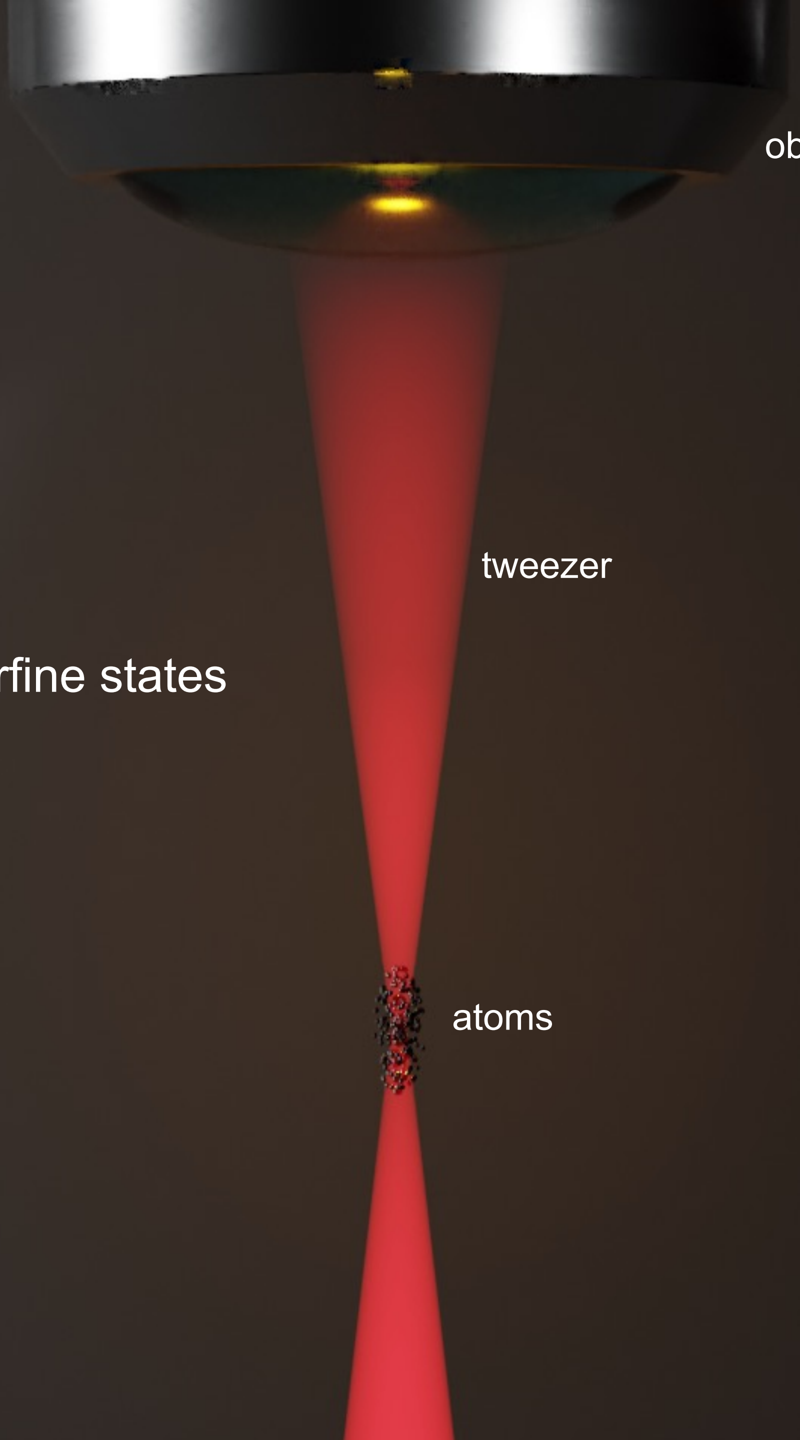


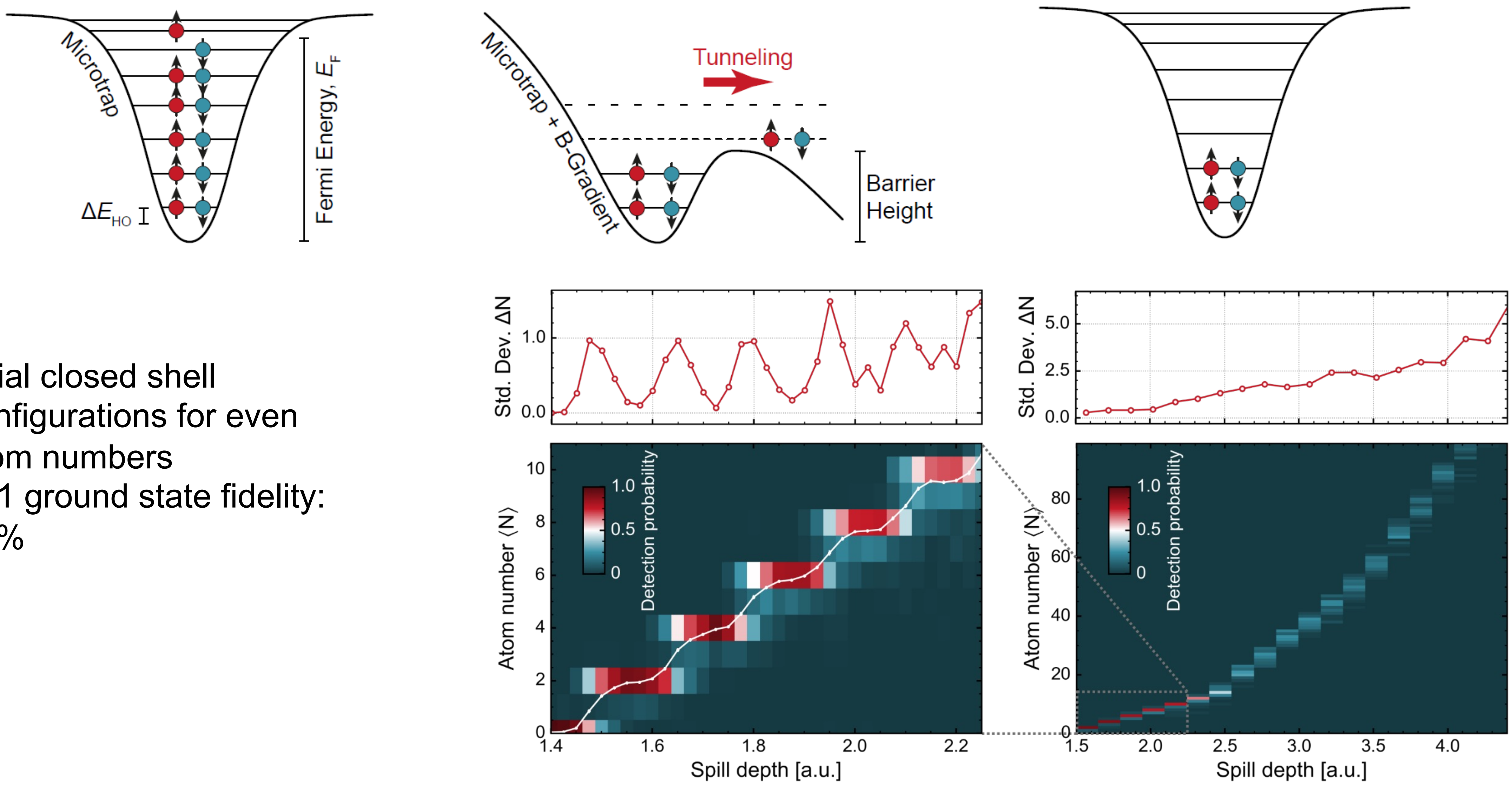
- Fermionic ^{6}Li atoms
  → balanced mixture of two hyperfine states
- Cigar-shaped trap

  $\omega_r \sim 52kHz$

  $\omega_r/\omega_z \sim 7$

- Interaction control
  → Feshbach resonance
- Observables:
  - Single-atom spin-resolved momentum space image
  - Spectroscopy

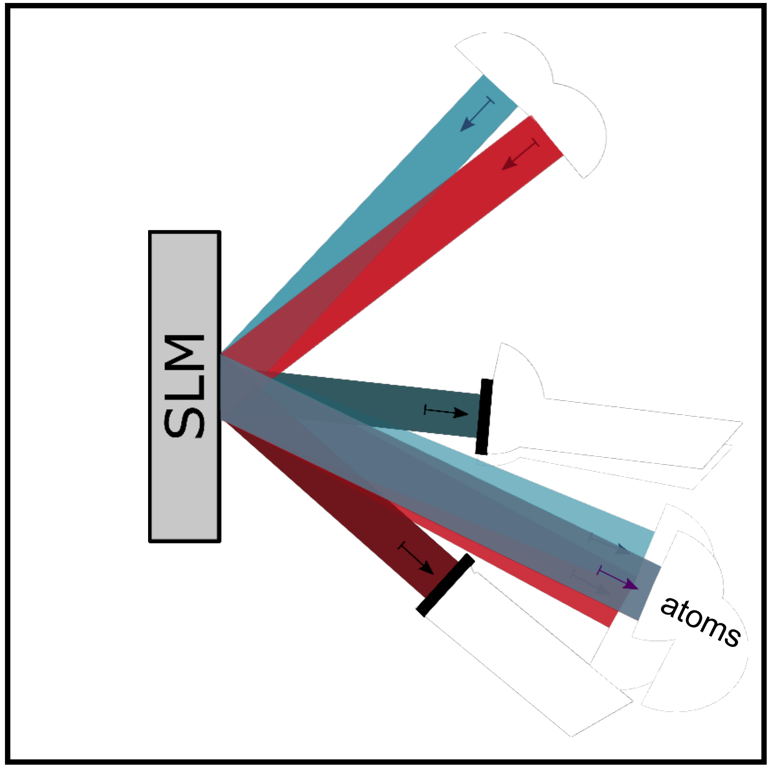
Deterministic preparation

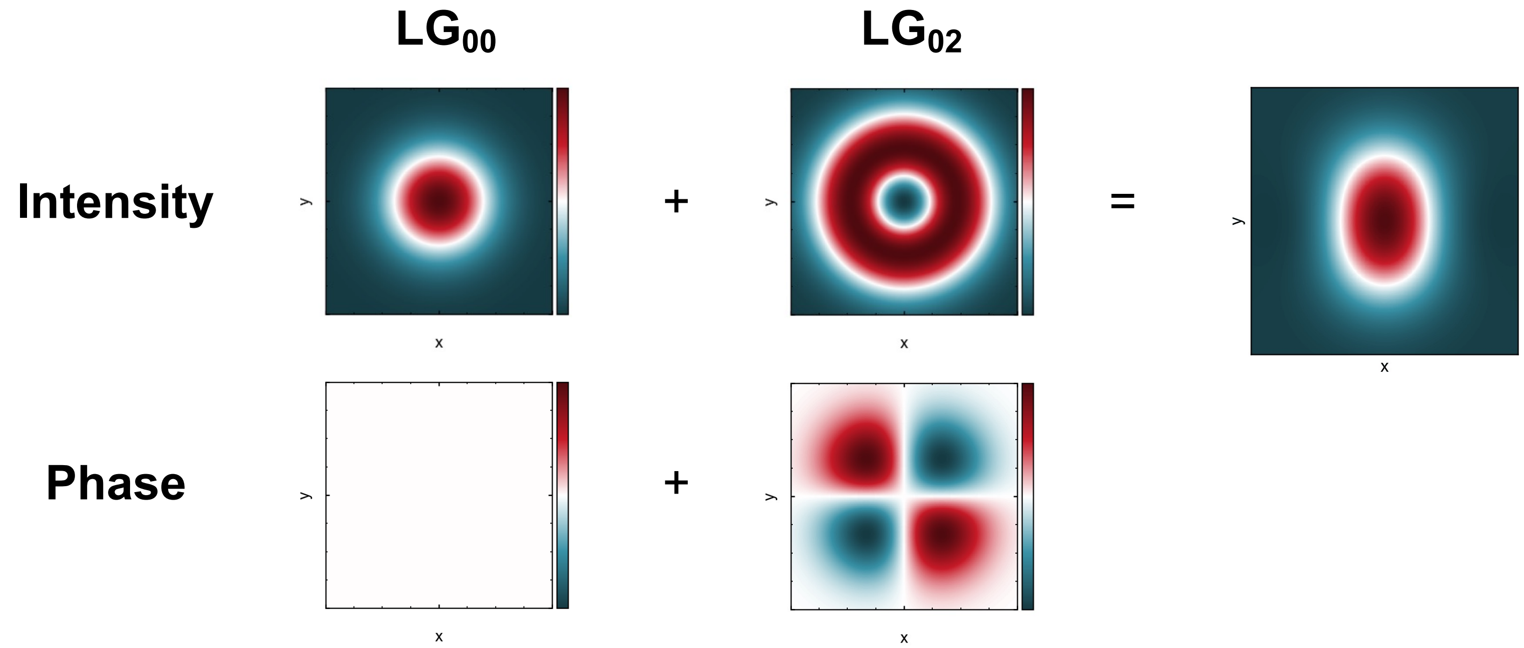


- Axial closed shell configurations for even atom numbers
- 1+1 ground state fidelity: 98%

Creating a high-fidelity rotating potential:

Interference of Laguerre-Gaussian beams

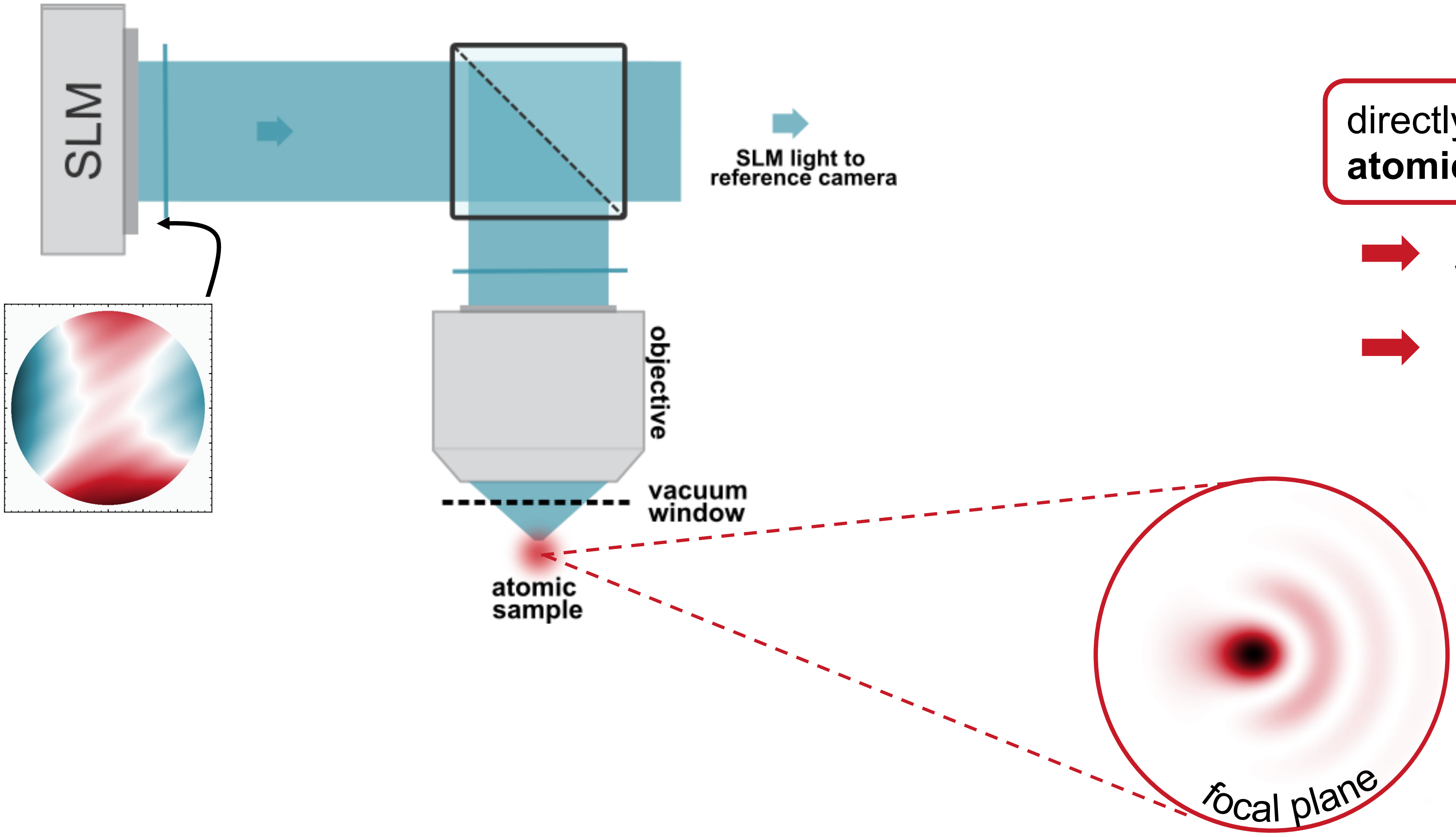




L. Palm *et al* 2020 *New J. Phys.* **22** 083037

Rotating Fermi systems:

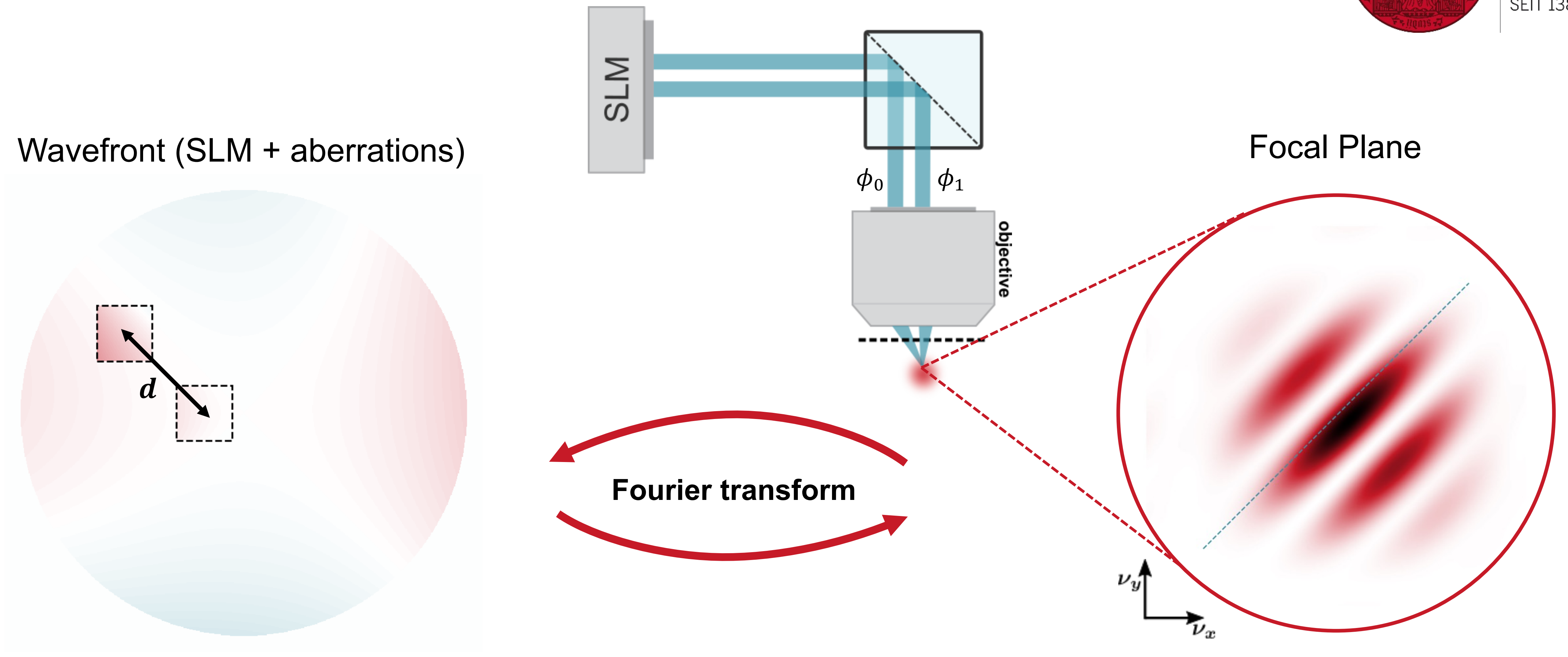
Aberrations in optical Setups



directly use atoms as
atomic wavefront-sensor

- measure aberrations where they matter
- map out inaccessible components

Measuring Aberrations



$$\sim 1 + \cos(2\pi \boldsymbol{d} \cdot \boldsymbol{\nu} + \Delta\phi)$$

Results (preliminary)

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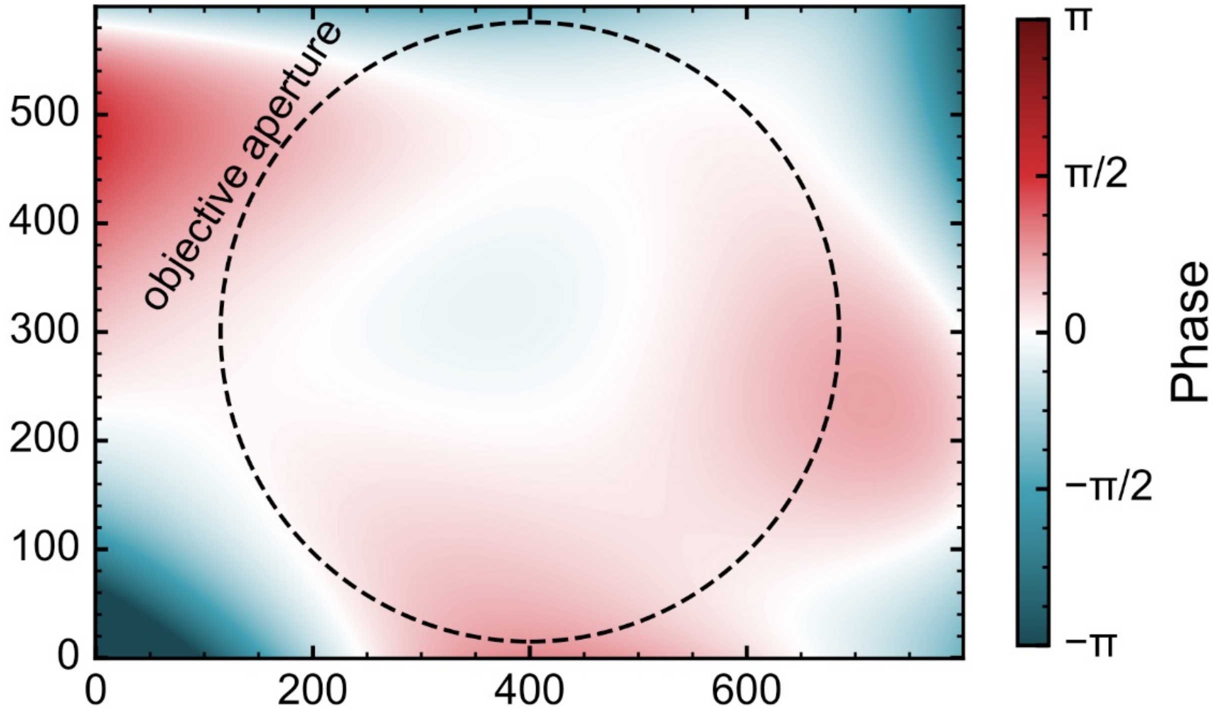

benchmarking

- rms deviation ~ $\lambda/13$
- peak-to-valley ~$\lambda/5$

Limitations

- patch size: sensitivity to spatial frequencies
- grid spacing: strength of shears limited to $(-\pi, \pi)$

Rotation of a single Fermion

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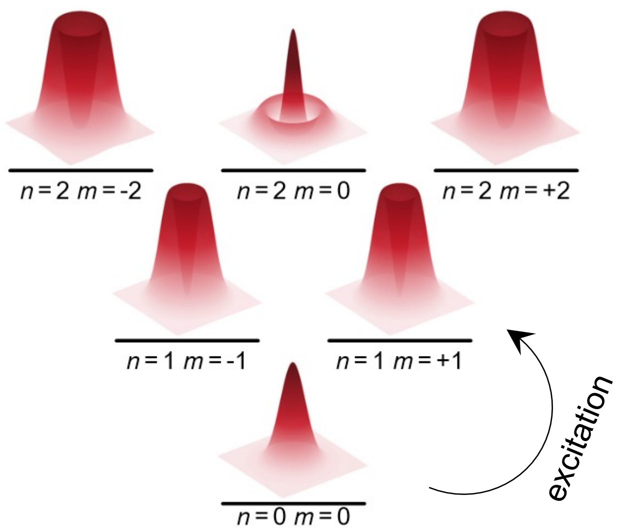
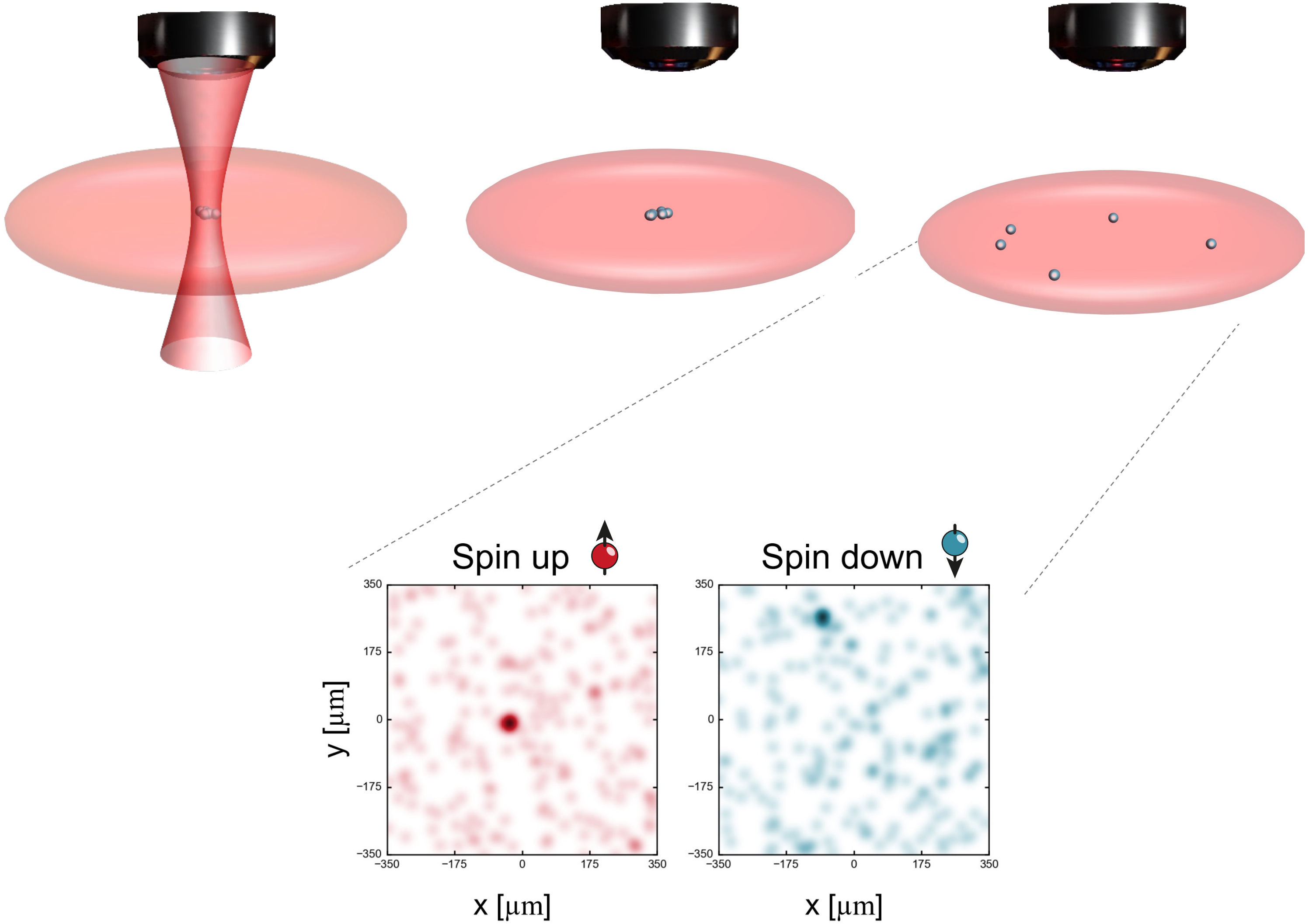
Preparation

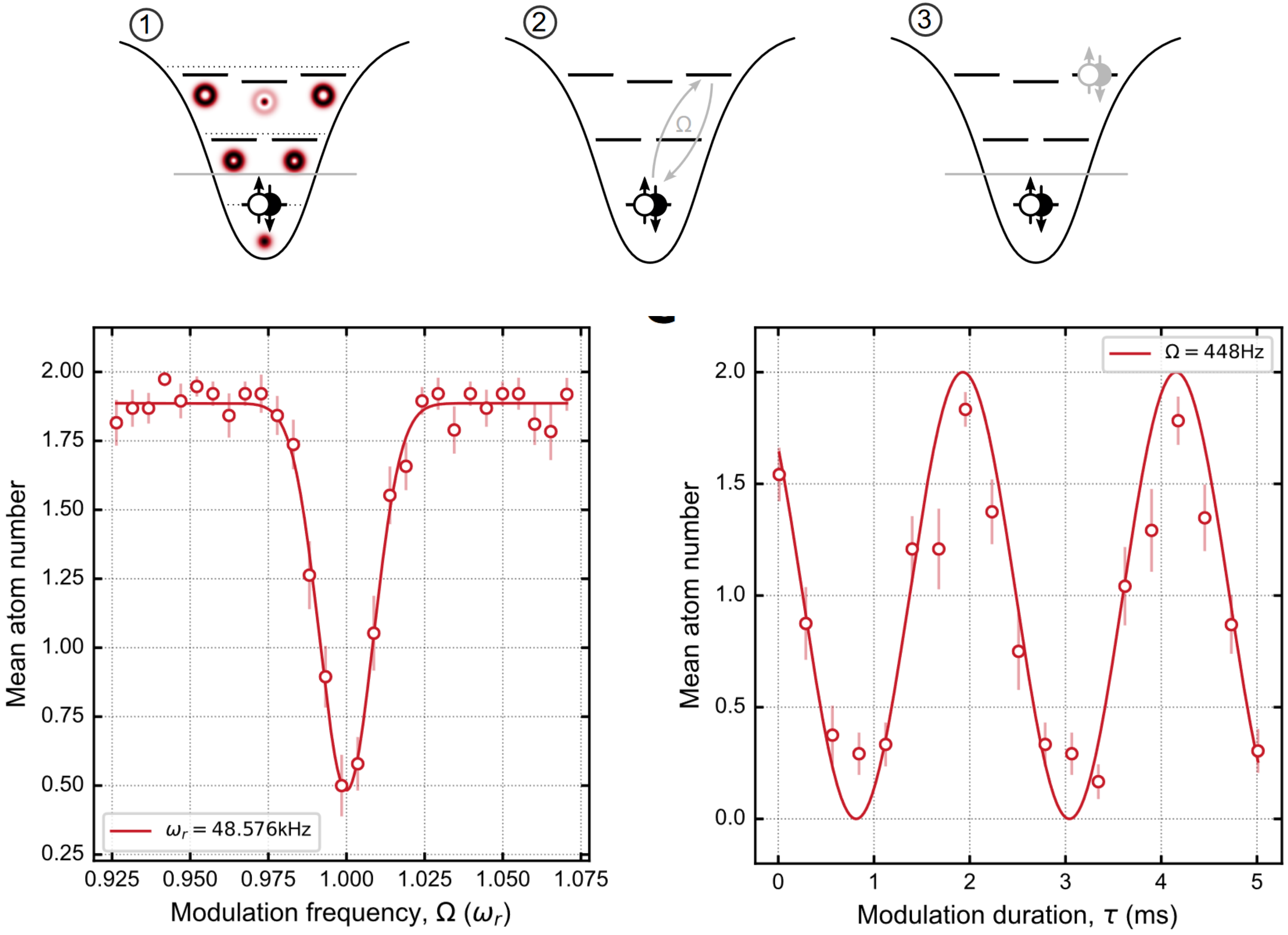
2D Harmonic oscillator levels



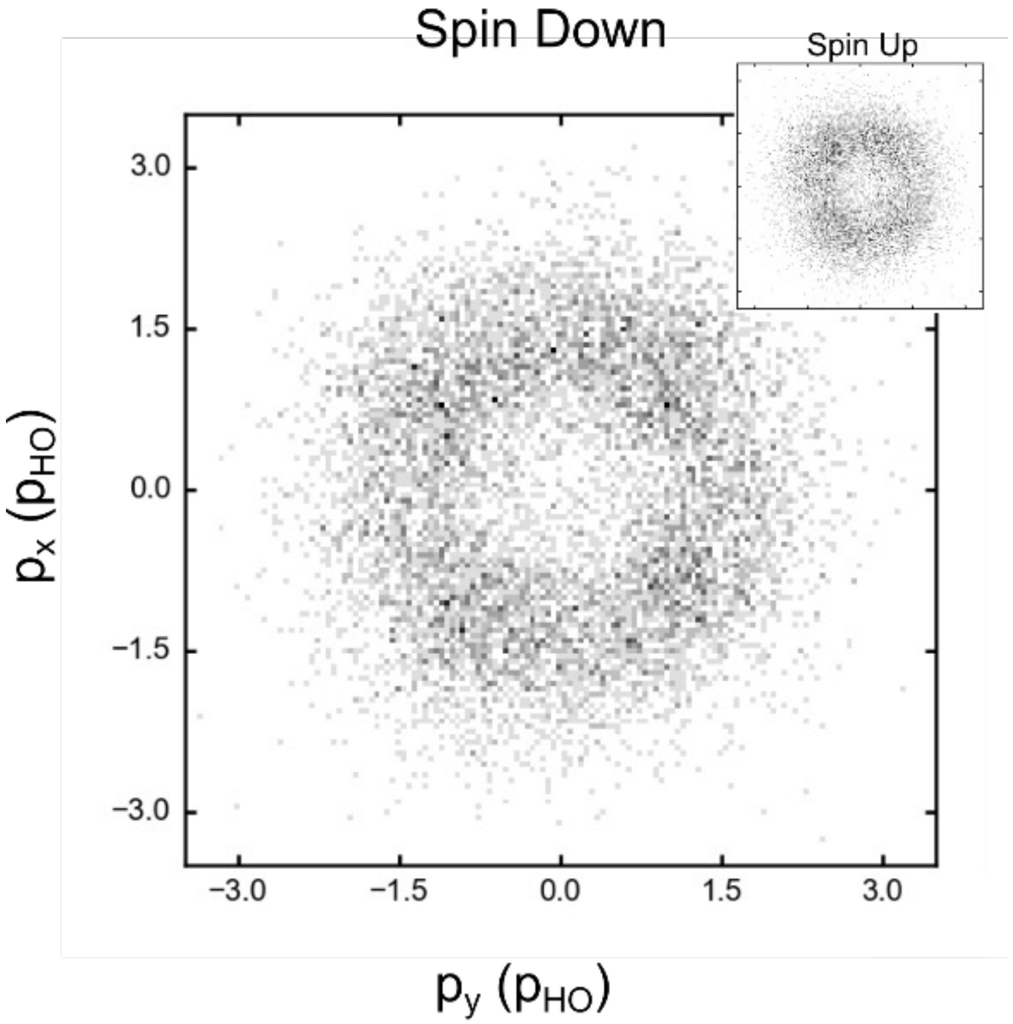
Detection

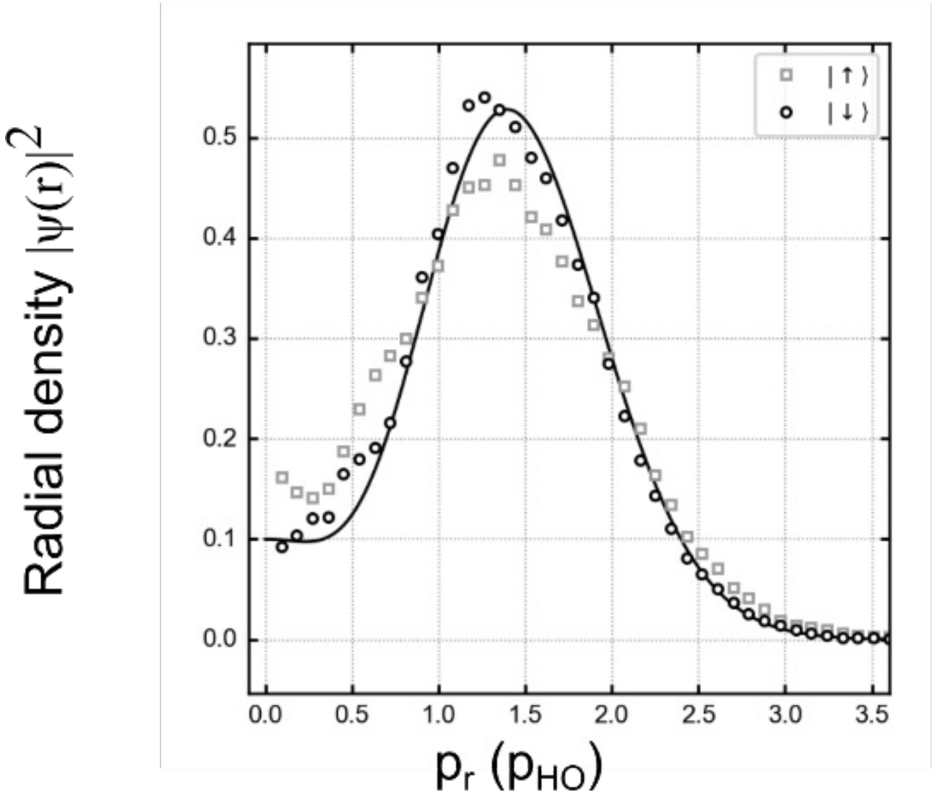


Atom loss spectroscopy



Rotation of two non-interacting fermions





$$|\psi|^2 = 0.05\,|\psi_{00}|^2 + 0.95\,|\psi_{22}|^2$$

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Control of the optical potential → control over motional states

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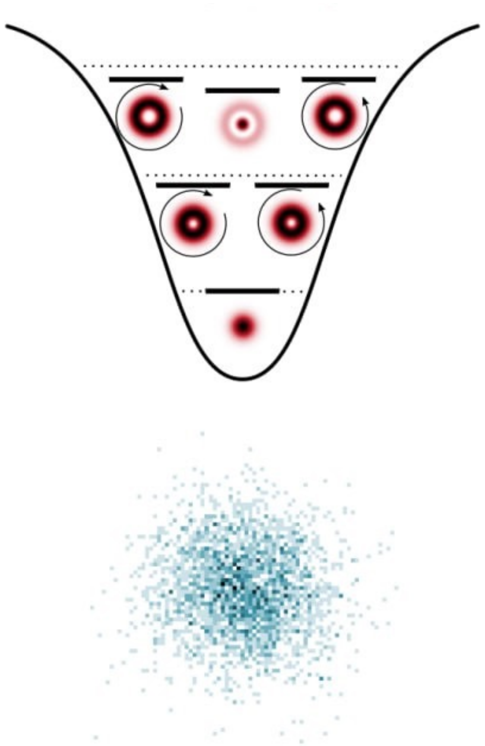

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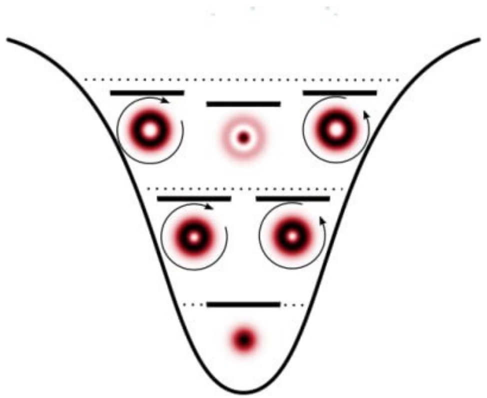
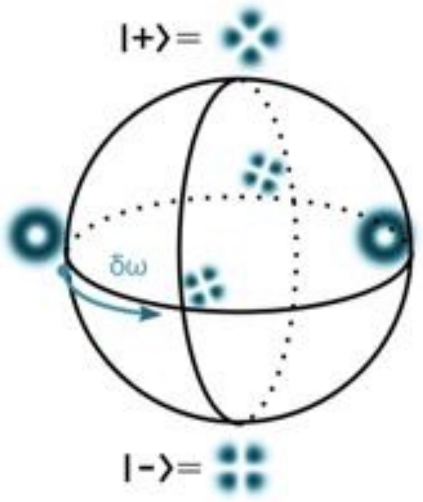
Do we know the sense of rotation?

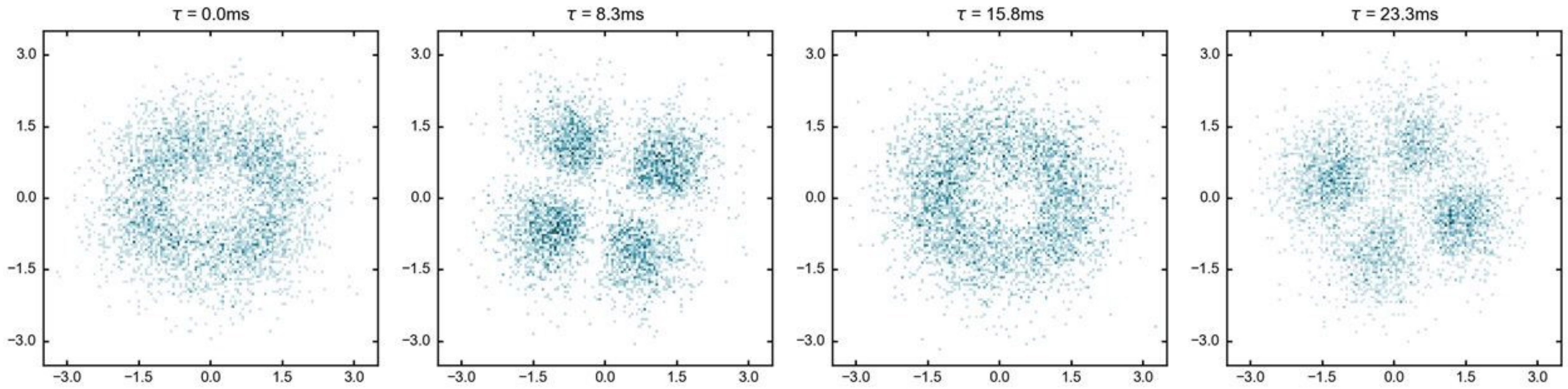


A slight anisotropy lifts degeneracies:
Angular momentum states are no longer eigenstates!

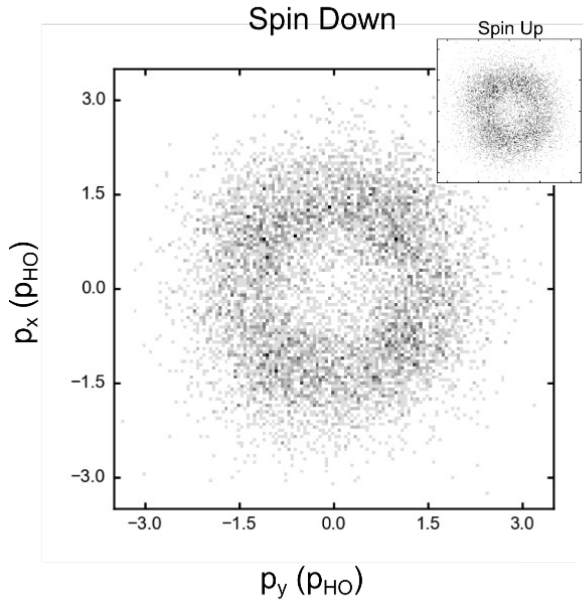
$\nu_r \sim 30kHz, \nu_x - \nu_y \sim 30Hz$

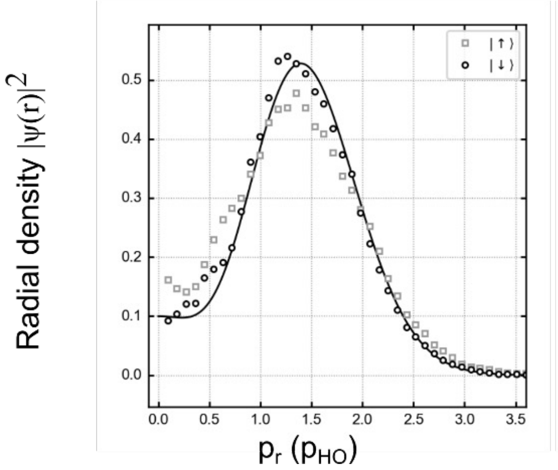


Time evolution of the roational state:



Center of mass & relative motion





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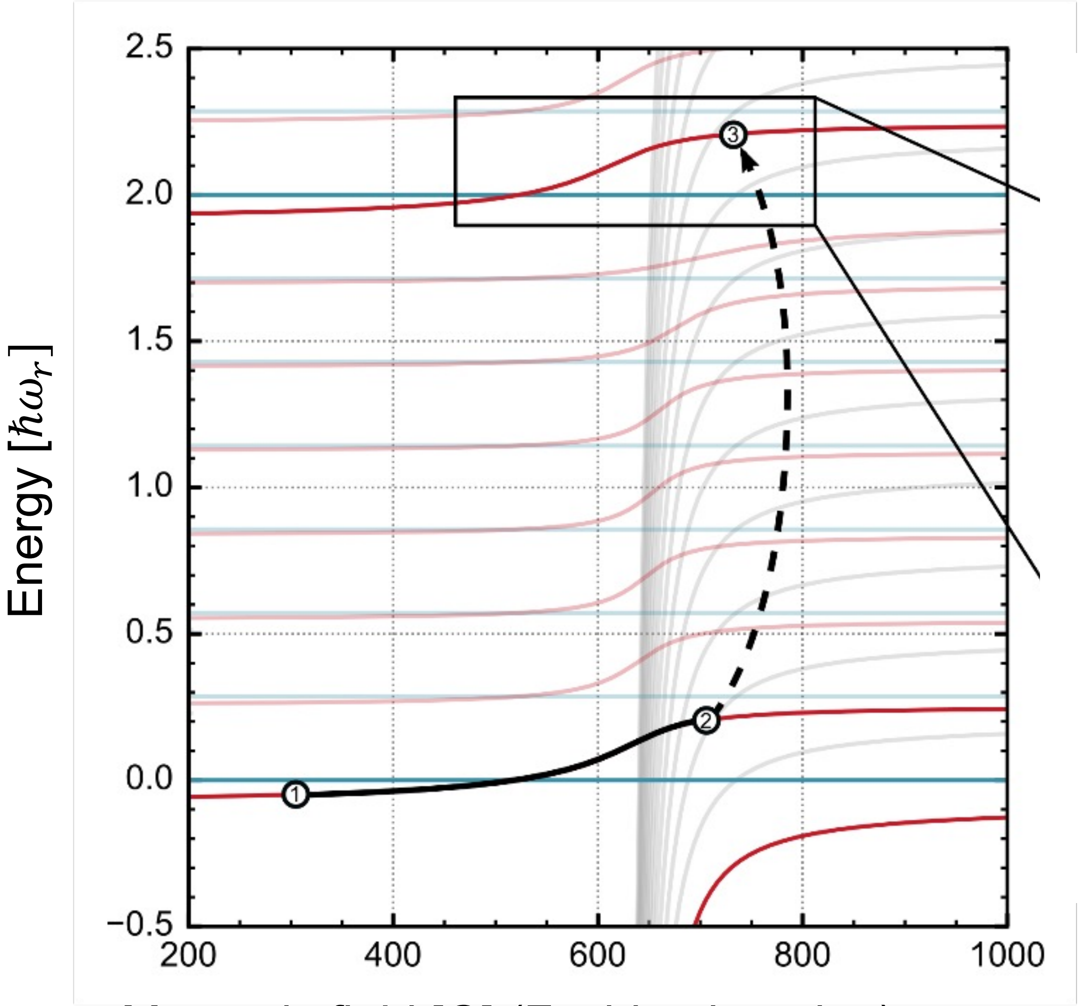
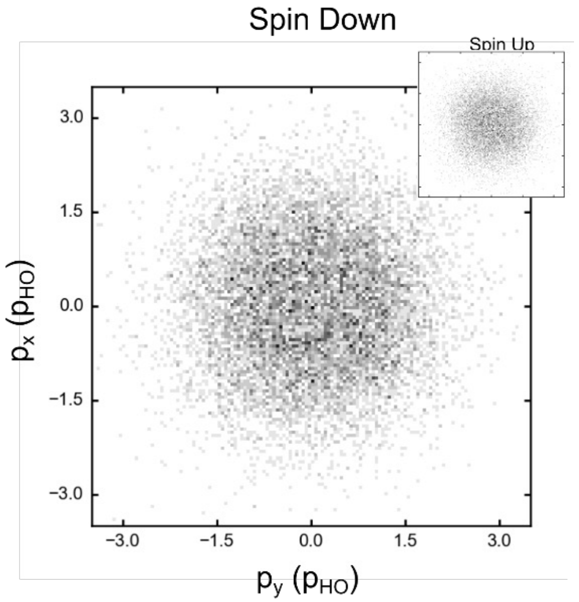
States with relative anglular momentum: Laughlin states

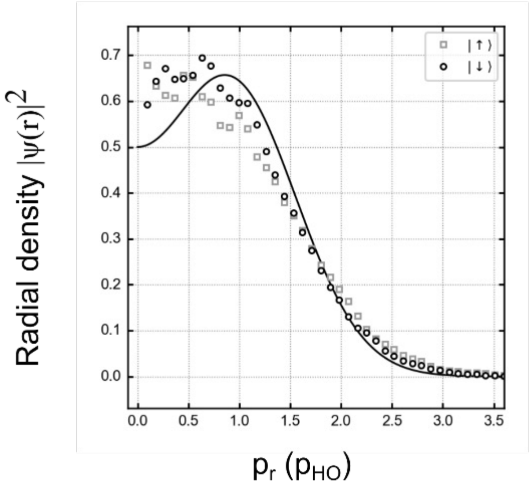


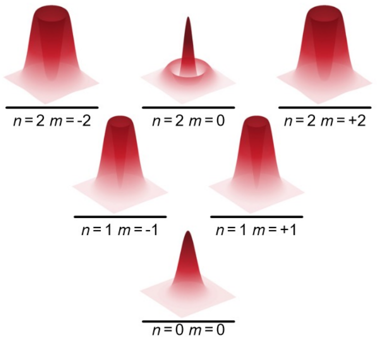
Magnetic field [G] (Feshbach tuning)

Idziaszek,, Calarco, Phys. Rev. A **74**, 022712 (2006)   L. Palm *et al* 2020 *New J. Phys.* **22** 083037

Laughlin state

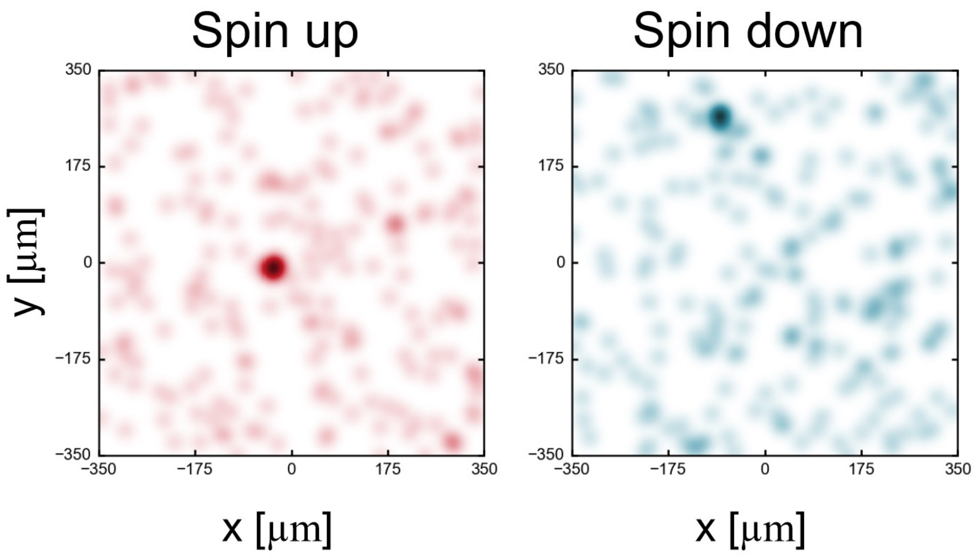


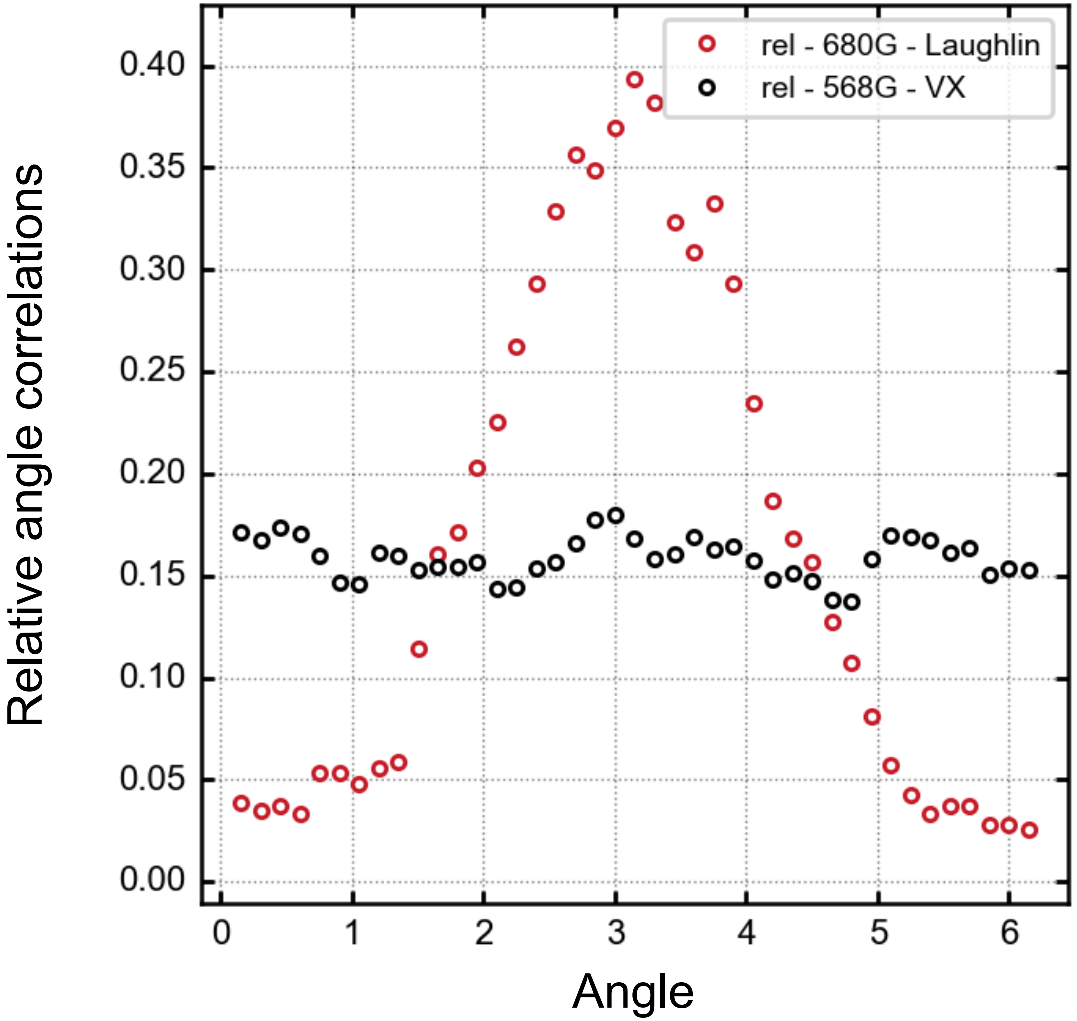




See also: Clark et al., Nature **582**, 45 (2020), Léonard et al., Nature **619**, 495 (2023)

Angular correlations





- Measure angle ϕ_1 , ϕ_2
- Relative angle $\Phi = \phi_1 - \phi_2$
- $\mathrm{Mod}(\Phi, 2\pi)$

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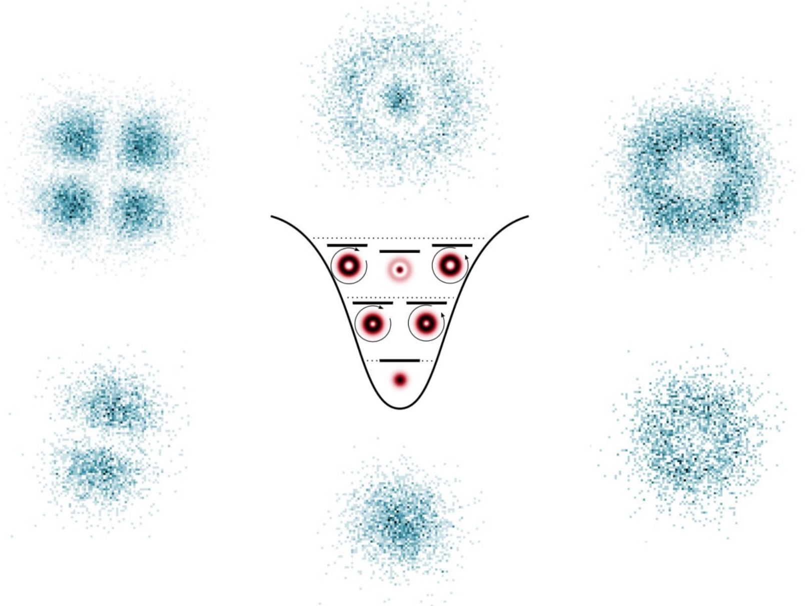
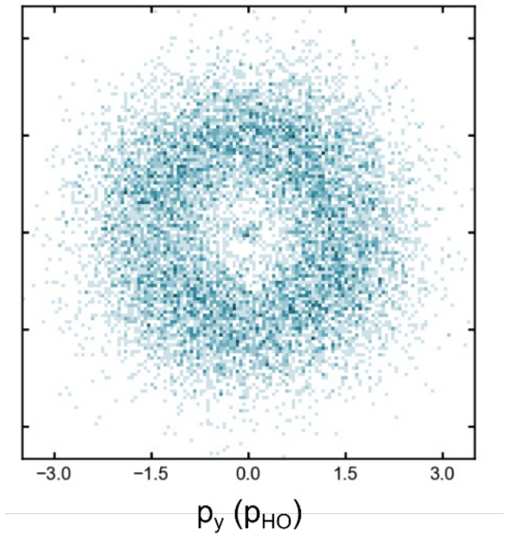
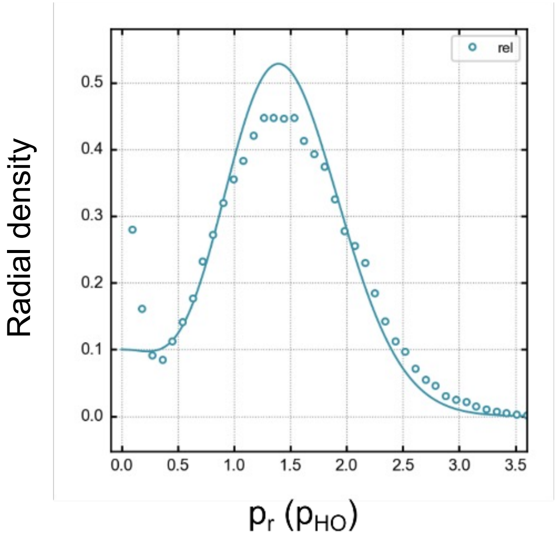
Summary rotating states

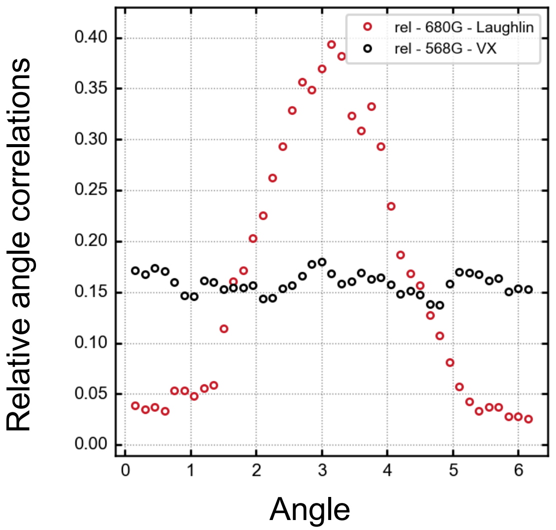
- Control of the optical potential



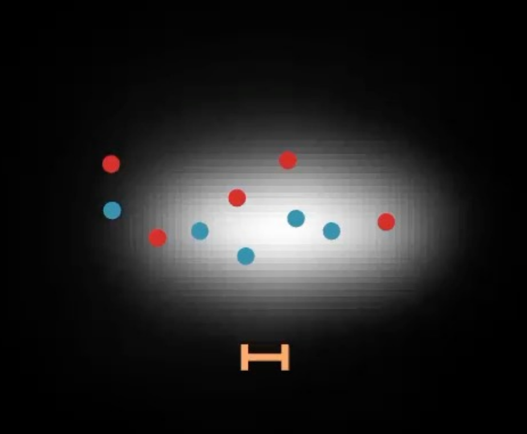
- Observation of Laughlin state







A fluid composed of 10 atoms



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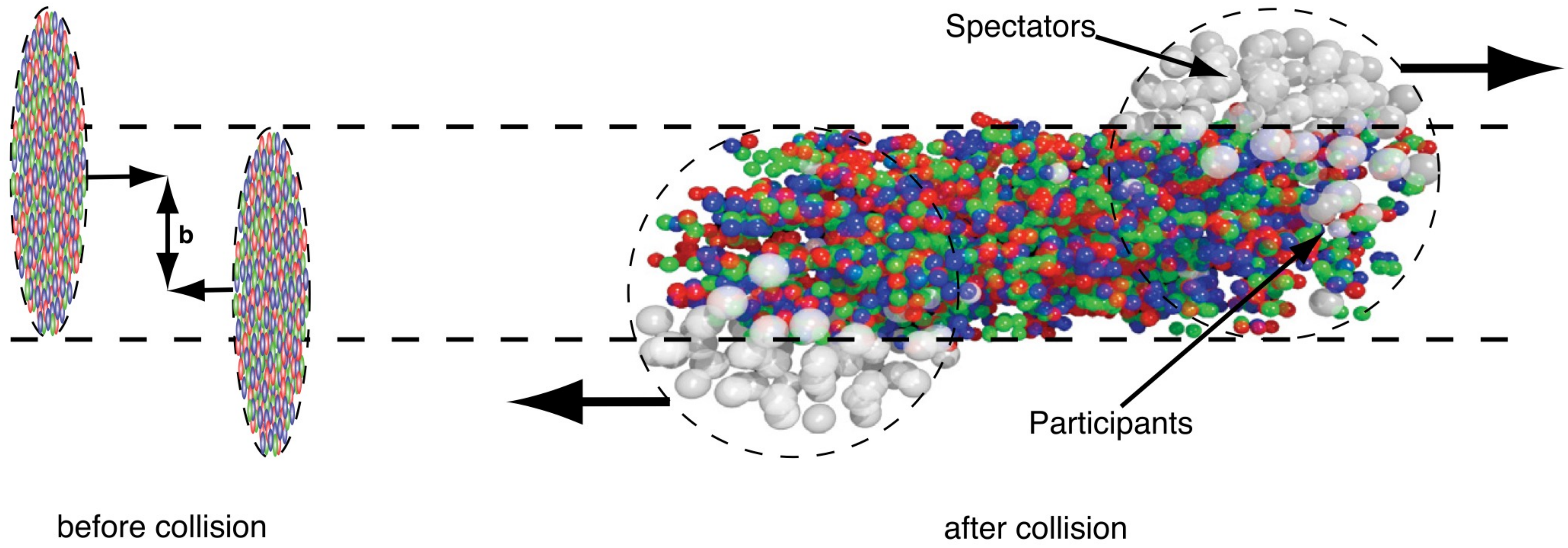
Let's look at some dynamics!

How many particles does one need to see hydrodynamics?

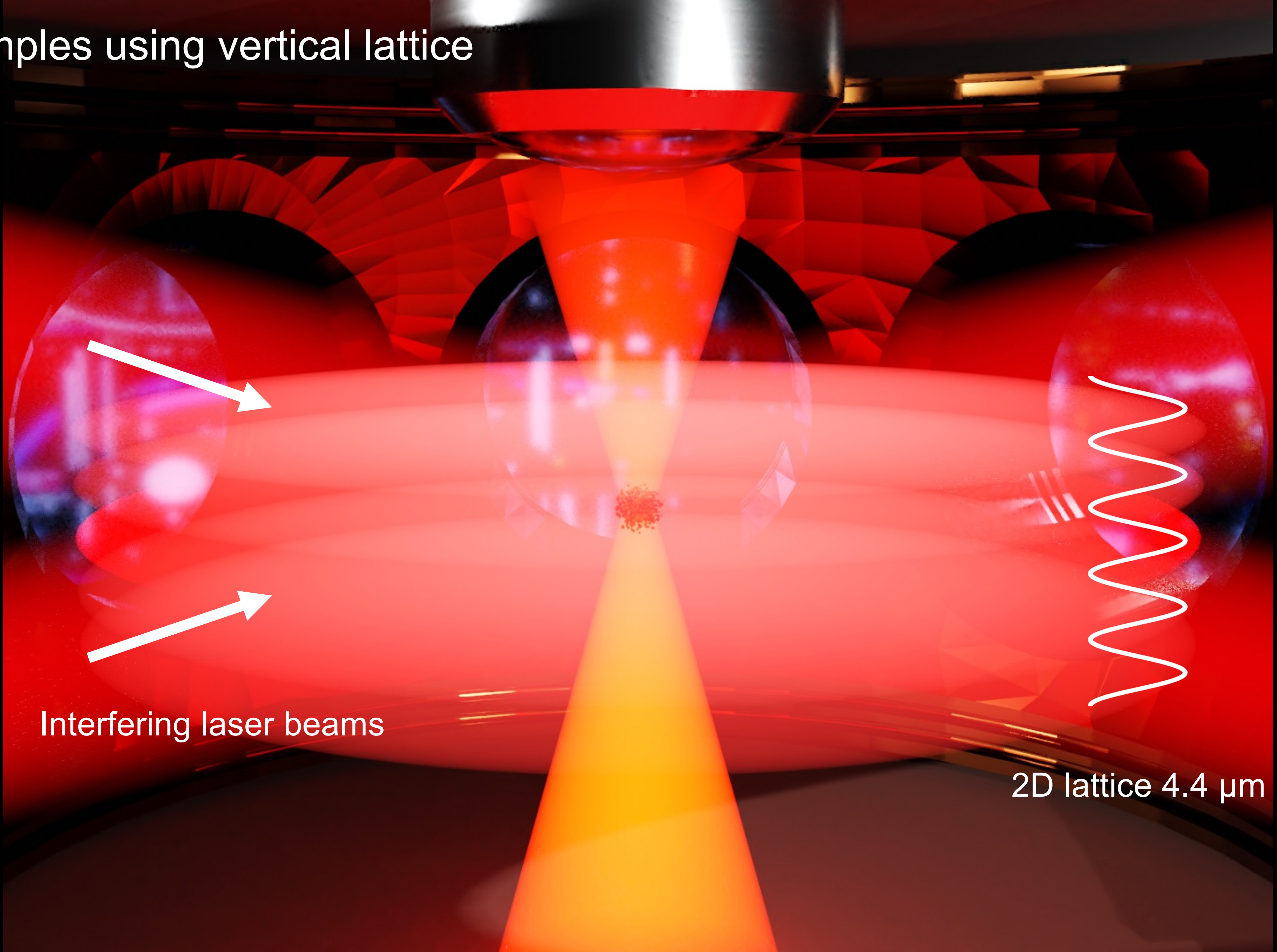
Inspired by nuclear physics:

Hydrodynamic „elliptic flow“ is observed in Pb-Pb collisions:



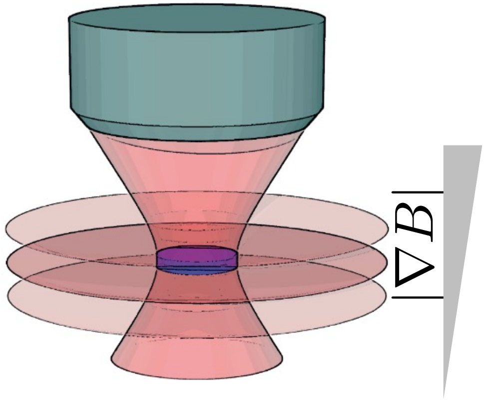
R. Snellings, New Journal of Physics **13** (2011) 055008

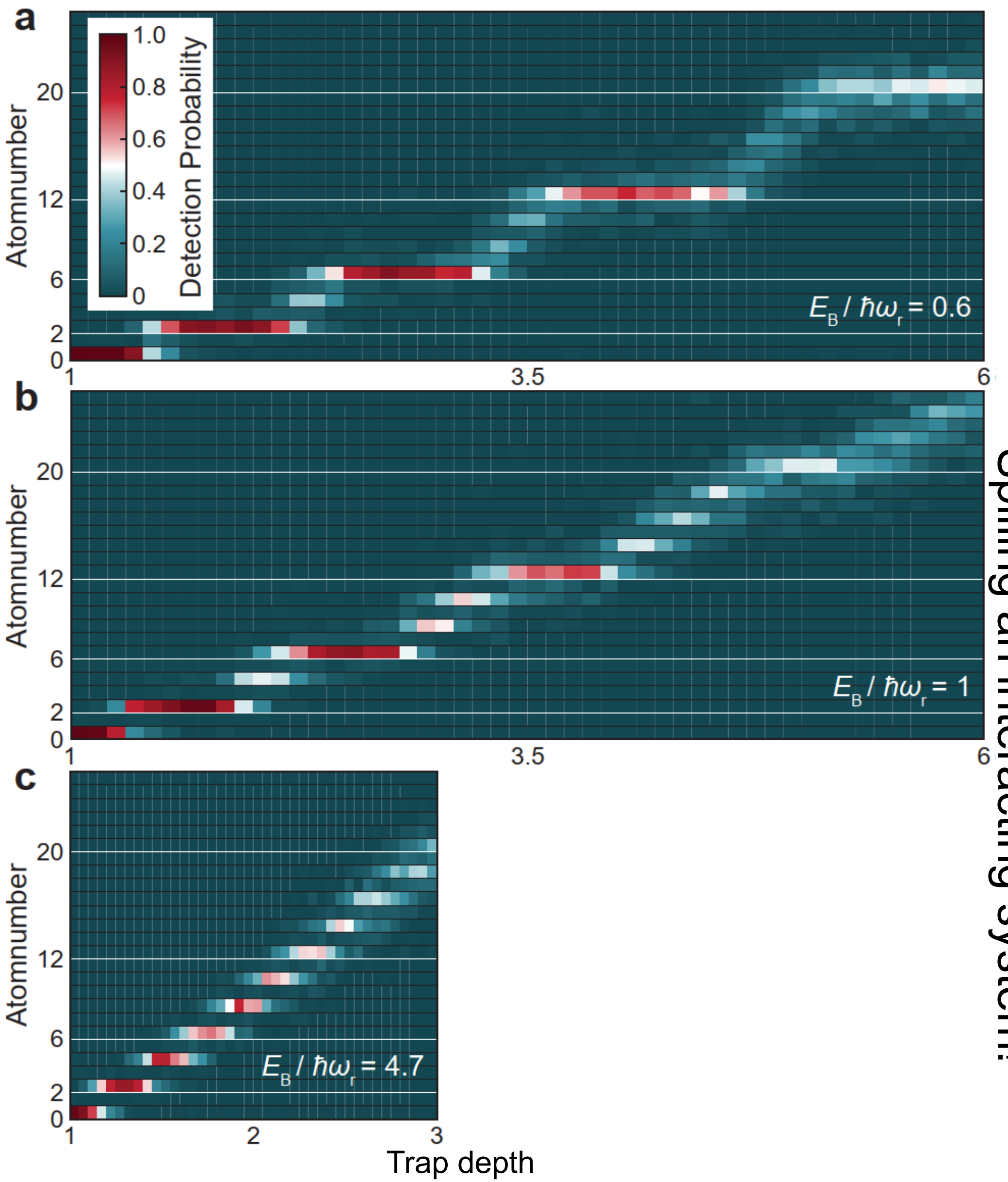
2D Samples using vertical lattice



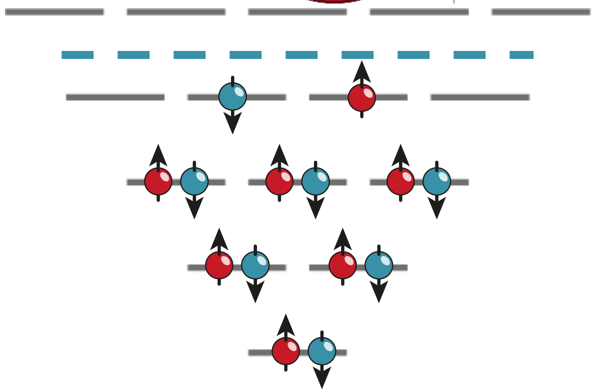
Controlling the particle number

Spilling particles from a 2D tra





Spilling an interacting system!



Degeneracies in a 2D harmonic trap

F. Serwane et al., Science **332**, 336 (2011)

M. Holten et al., Nature **606**, 287 (2022)

Energy scales

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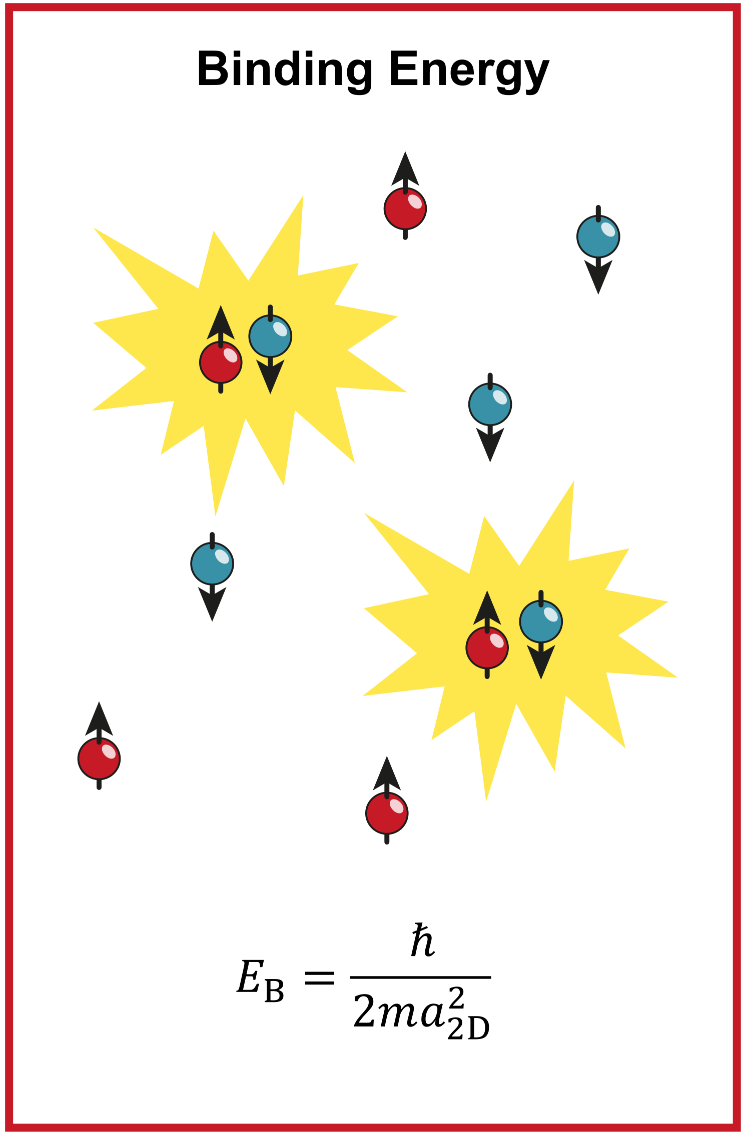

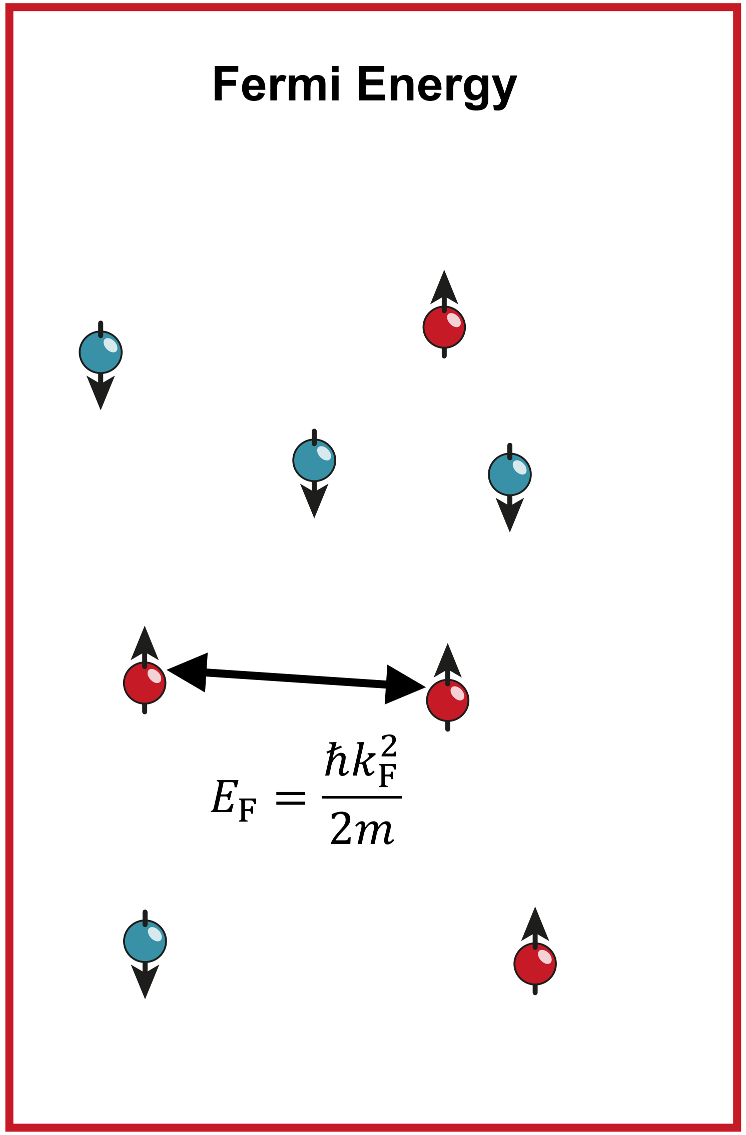

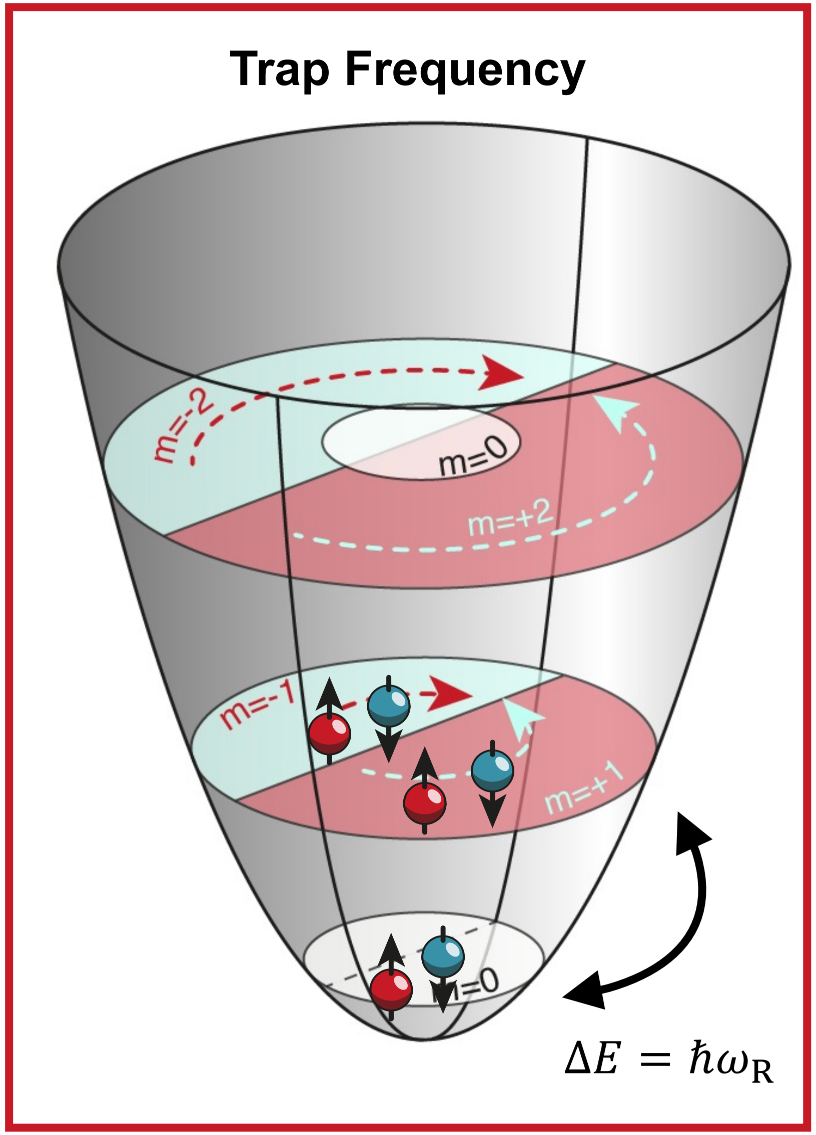

Tuning interations

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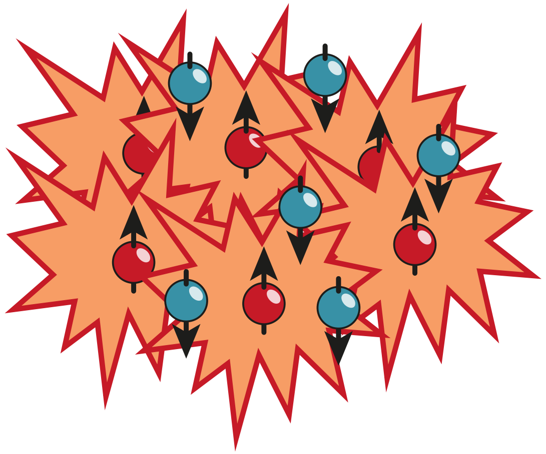
- Interactions can be tuned at will using Feshbach resonances!
- Goal: Measure their in-situ momenta
- Essential ingredient: Fast switch-off of interactions using Raman induced spin flip



M. Holten et al., Nature **606**, 287 (2022)

Our new tool: A matterwave microscope

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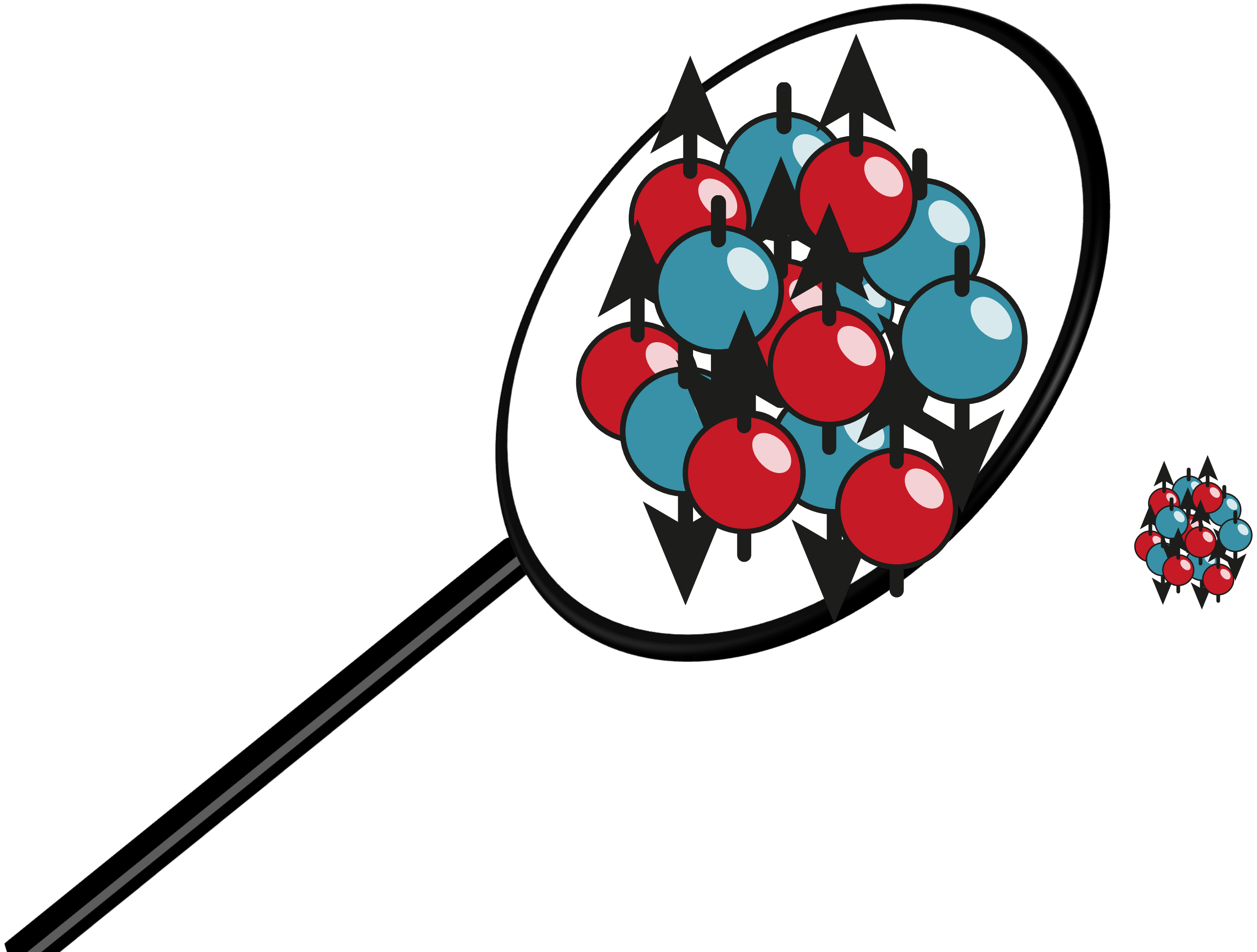
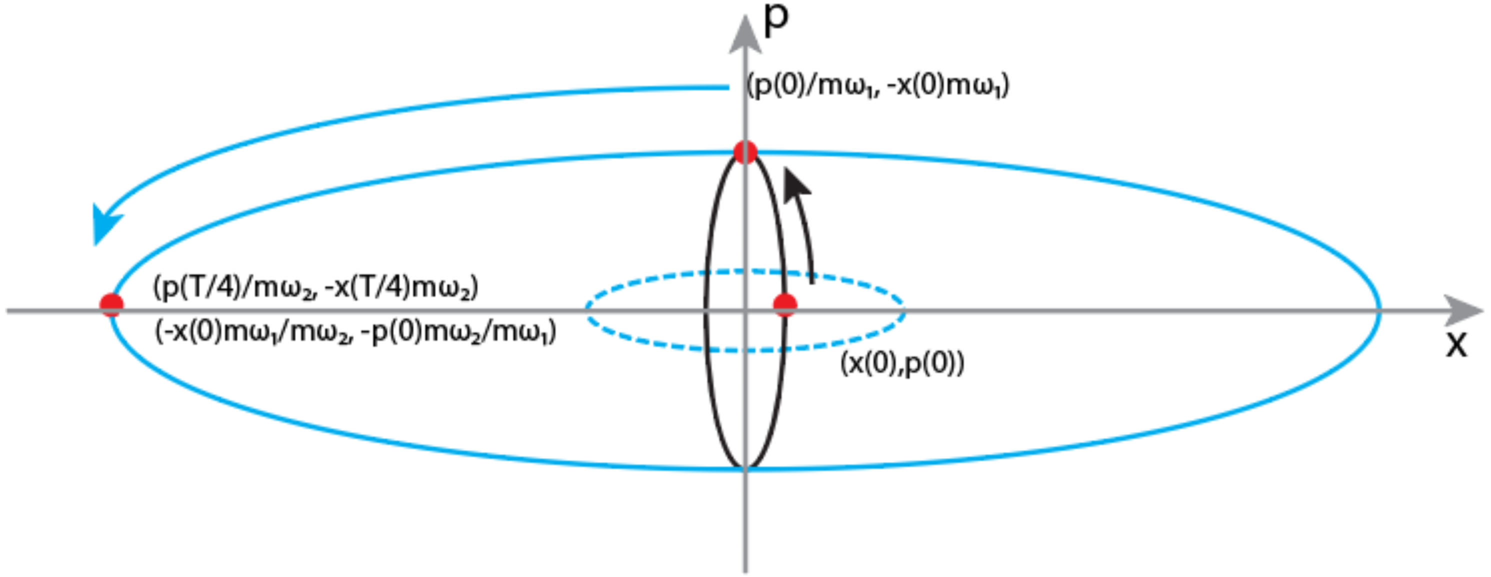


Scheme

- A T/4 – propagation in a harmonic trap corresponds to a Fourier transform:

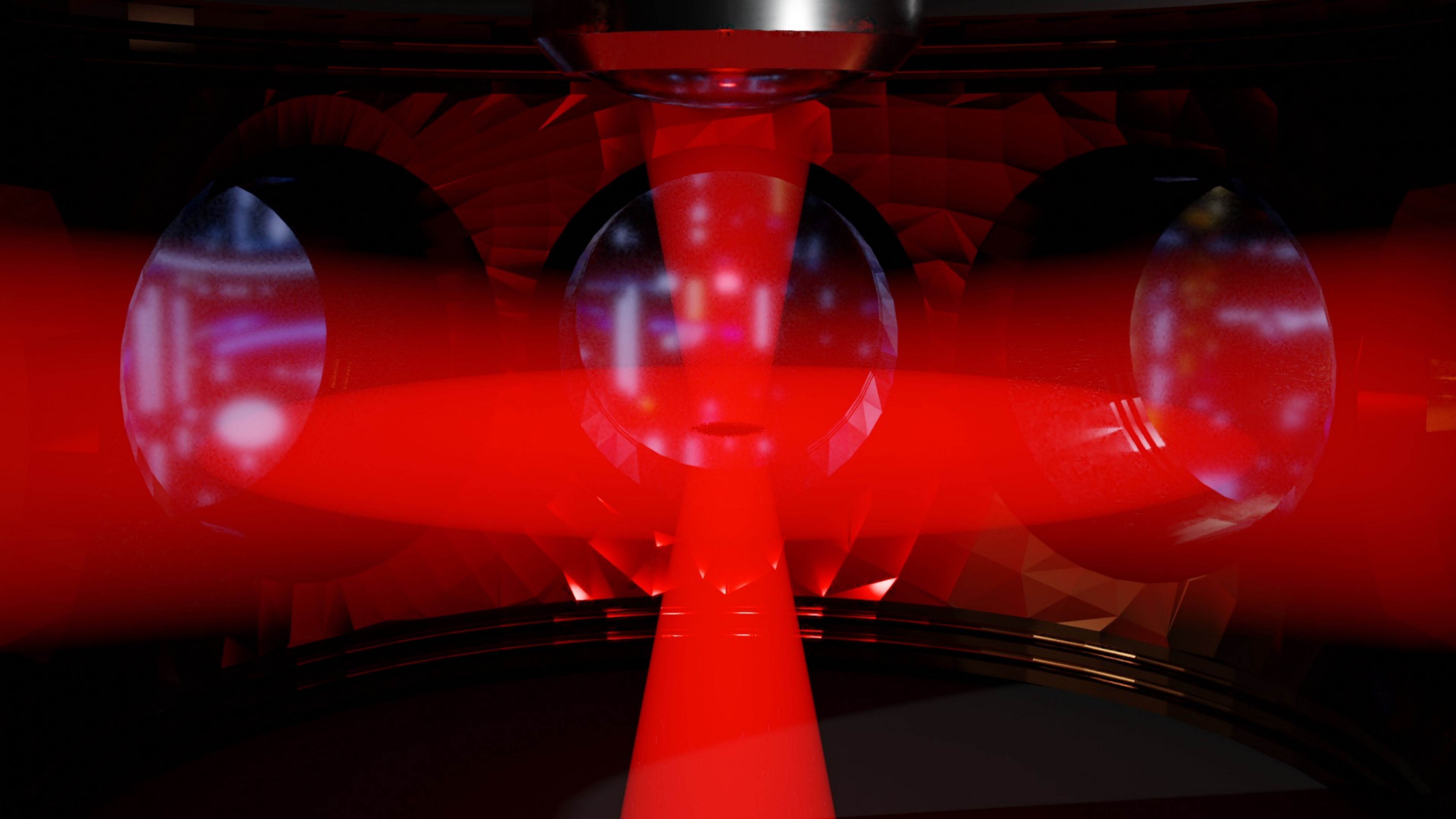
$$\begin{bmatrix} x(t) \\ p(t) \end{bmatrix} = \begin{bmatrix} \cos\omega t & \frac{1}{m\omega}\sin\omega t \\ -m\omega\sin\omega t & \cos\omega t \end{bmatrix} \begin{bmatrix} x(0) \\ p(0) \end{bmatrix}$$

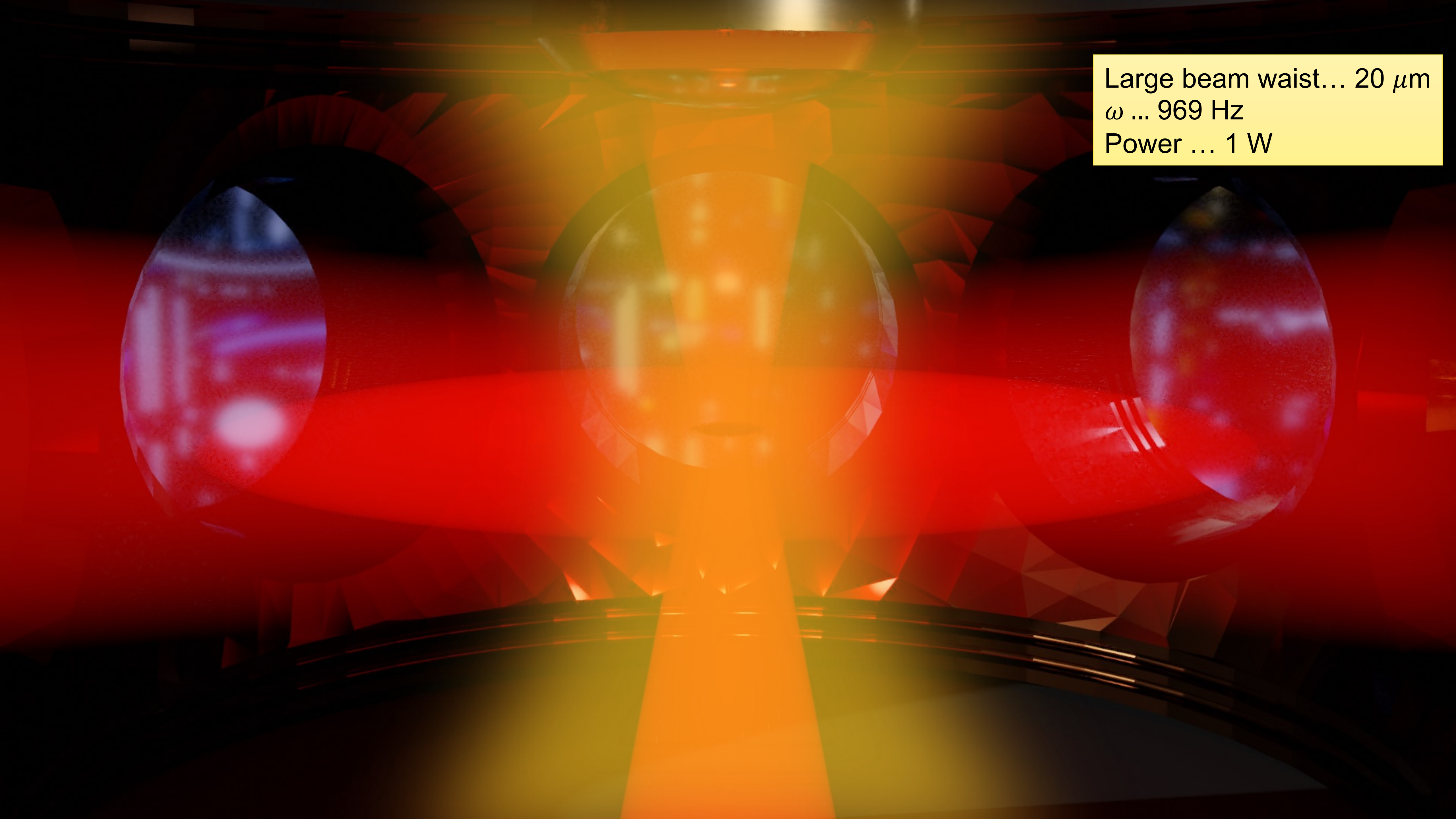
- Use two Fourier transforms with different magnification



Asteria *et al.*, *Nature* ***599****, 571 (2021)*
Murthy *et al.*, arXiv:1911.10824
Murthy *et al.*, *Phys. Rev. A* **90** (2014), 043611

I Svarchuk et al., PRL **89**, 270404 (2002)
A. H. van Amerongen et al., PRL**100**, 09040 (2008)
S. Tung et al., PRL **105**, 230408 (2010)
T. Jacqmin et al., PRA **86**, 043626 (2012)




Large beam waist… 20 μm
ω ... 969 Hz
Power … 1 W

We now have a matterwave microscope!

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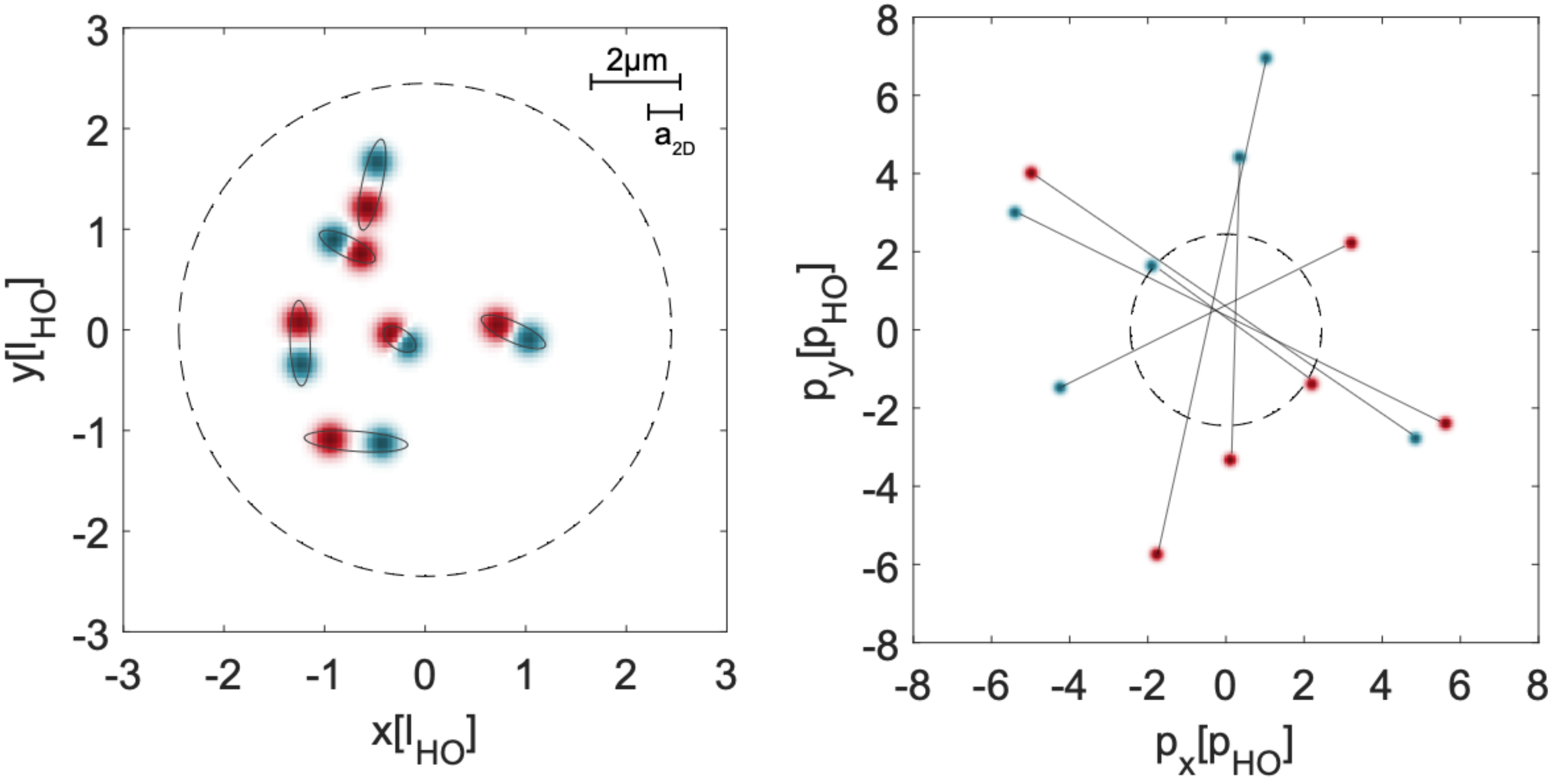
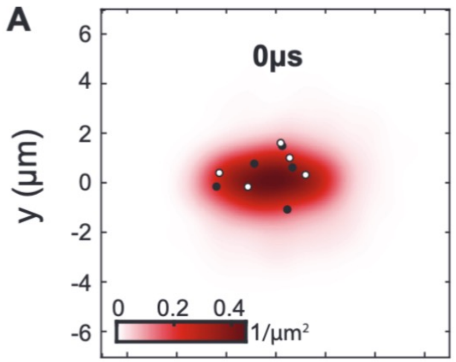
Imaging of molecules in real space



- Magnification about 50x
- Sufficient to resolve all relevant length scales for our systems

Creating a model system for elliptic flow:

- prepare an elliptic system,
- release it from the trap
- and wait …

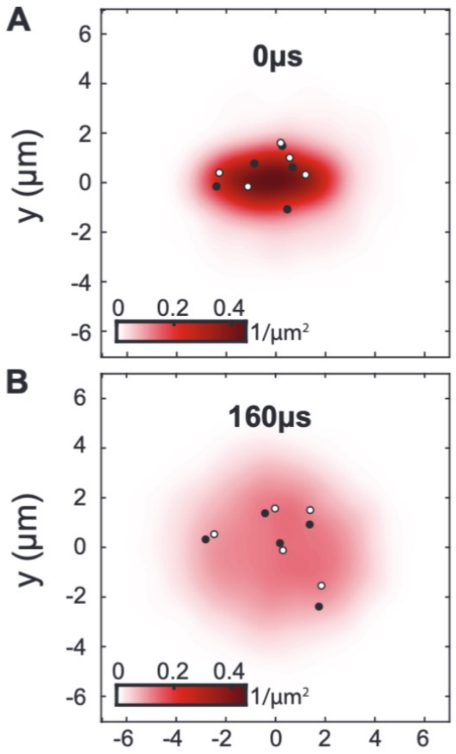


Brandstetter, Lunt et al., arXiv:2308.09699

Creating a model system for elliptic flow:

- prepare an elliptic system,
- release it from the trap
- and wait …

- The cloud becomes round



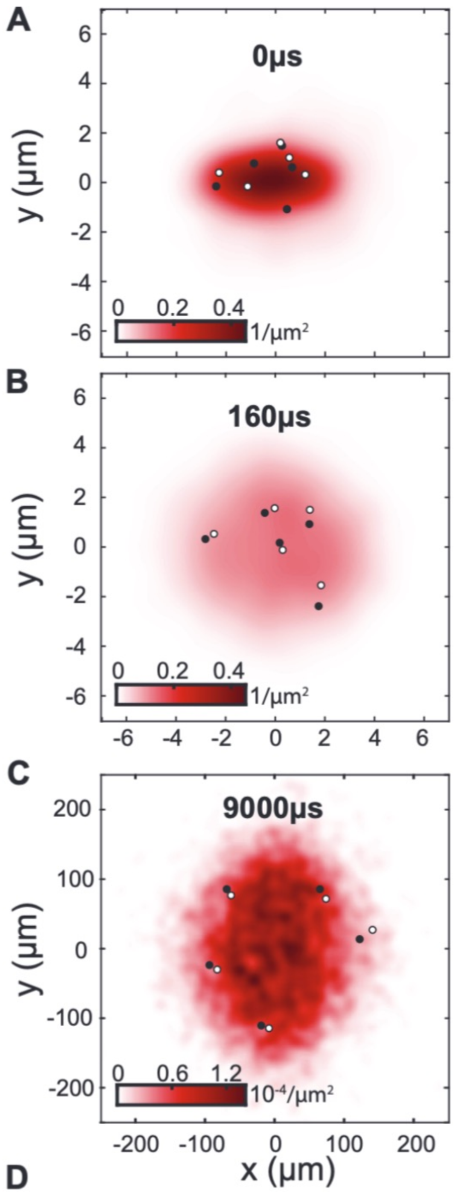
Brandstetter, Lunt et al., arXiv:2308.09699

Creating a model system for elliptic flow:

- prepare an elliptic system,
- release it from the trap
- and wait …

- The cloud becomes round …

- … and inverts!



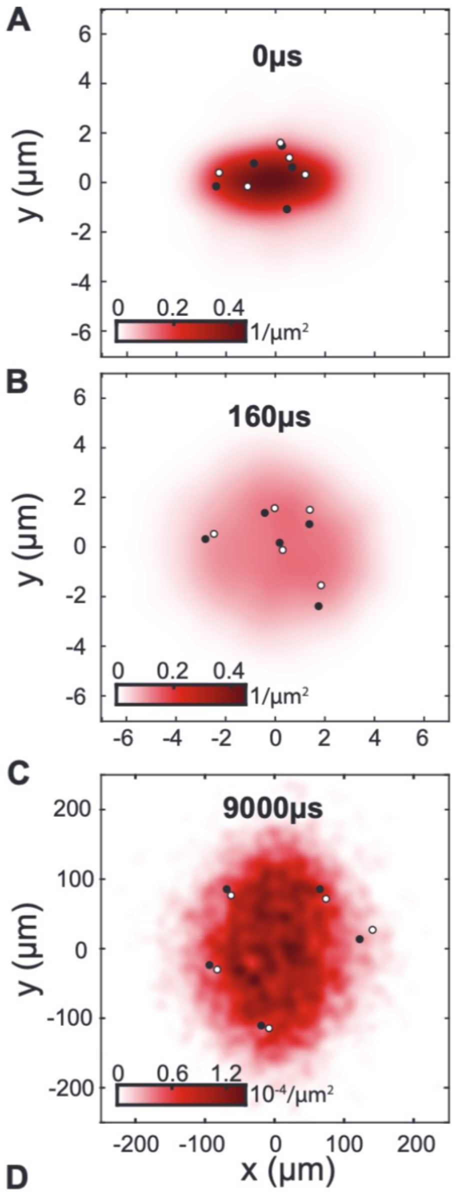
Brandstetter, Lunt et al., arXiv:2308.09699

Creating a model system for elliptic flow:

- prepare an elliptic system,
- release it from the trap
- and wait …

- The cloud becomes round …

- … and inverts!
- At the same time: Molecules are formed!



Brandstetter, Lunt et al., arXiv:2308.09699

We can also observe the evolution of momenta

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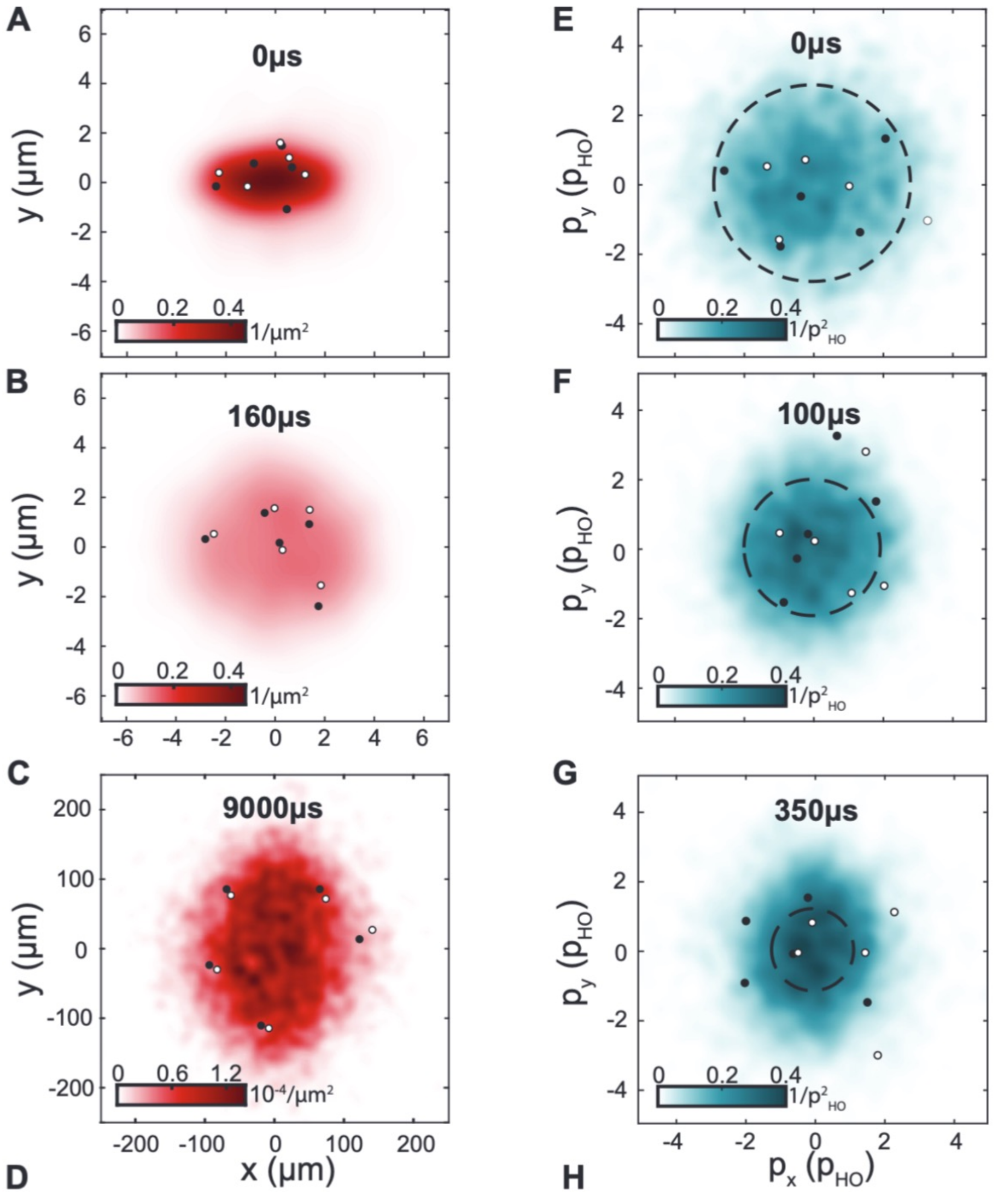
- prepare an elliptic system,
- release it from the trap
- and wait …

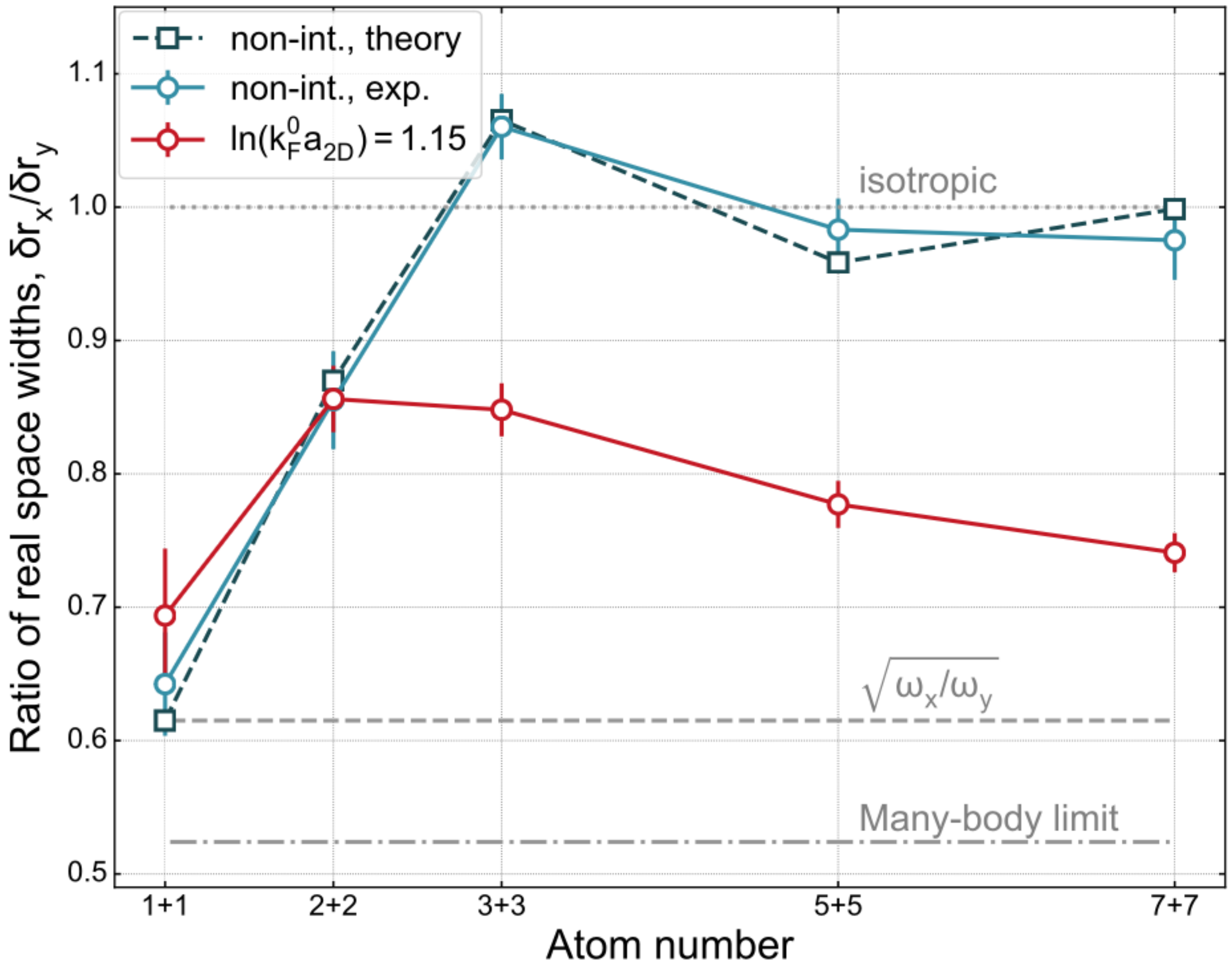
- The cloud becomes round …

- … and inverts!
- at the same time:
  molecules are formed!



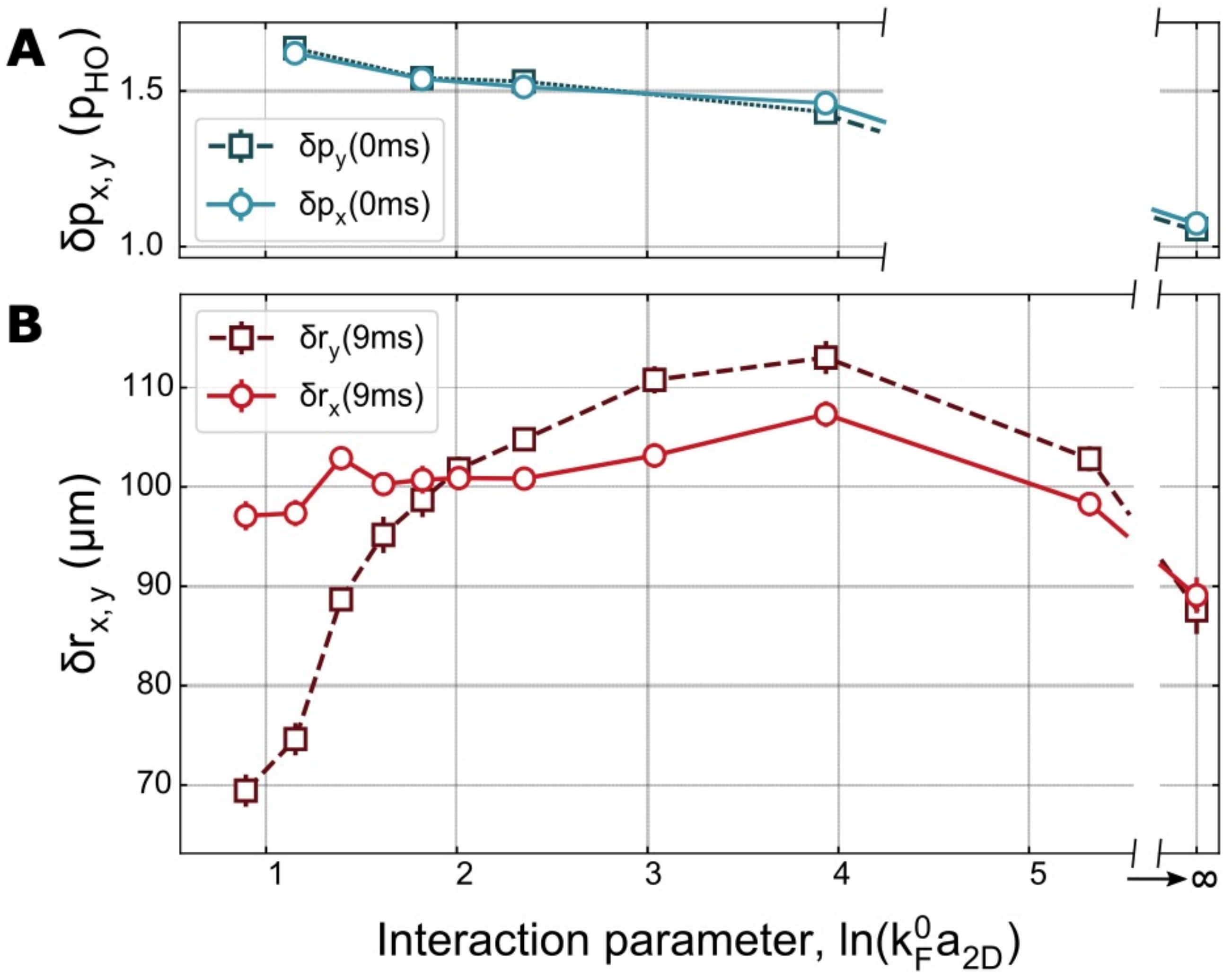
Brandstetter, Lunt et al., arXiv:2308.09699

Emergence of hydrodynamic behavior



Brandstetter, Lunt et al., arXiv:2308.09699

Dependence on interaction strength



Brandstetter, Lunt et al., arXiv:2308.09699

We have a lot of questions

What do we associate with hydrodynamics?

A system described by

- equation of state: Density determined by (local) density, temperature
- Velocity field: define (local) velocity

What we observe:

Redistribuion of momenta leading to deformation of the system consistent with „elliptic flow“

Can we sort out a contribution from nonlocal entanglement in the system?

→ The formation of pairs during expansion is a very strong indicator

Thank you for your attention!

Want to join?
jochim@uni-heidelberg.de

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