Emergent hydrodynamics in an mesoscopic Fermi system

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Experimental setup and observables

1 Mesoscopic Fermi system

- Fermionic particles interacting via contact interactions

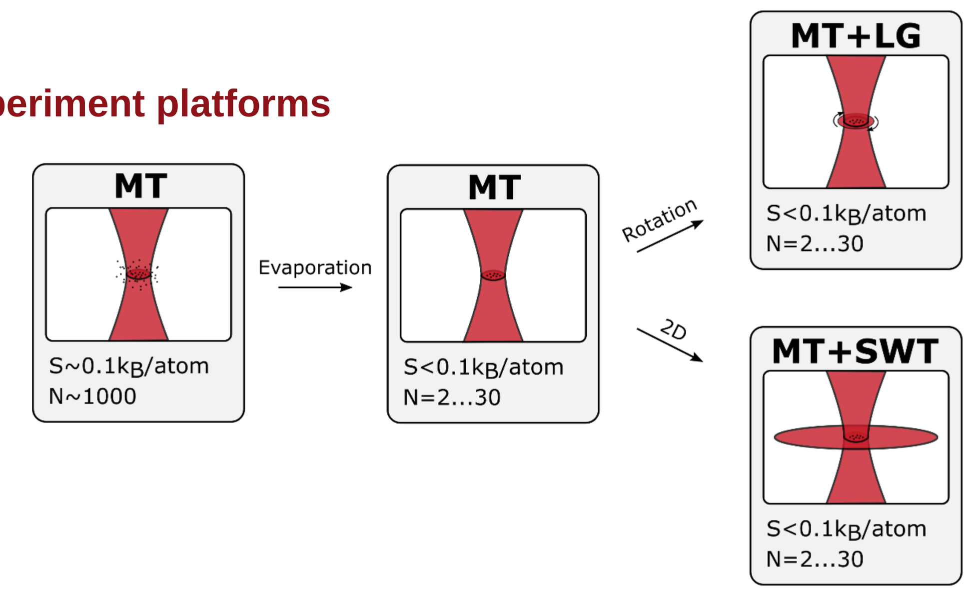
$$H = -\sum_i \frac{\hbar^2\Delta}{2m} + \sum_{i<j} g_0\delta^2(r_i - r_j) + V_{ext}$$

- Particles confined in external **harmonic** potential
- **Tunable aspect ratio** from 1D ($\omega_z \ll \omega_r$) to 2D ($\omega_z \gg \omega_r$)

Energy Scales

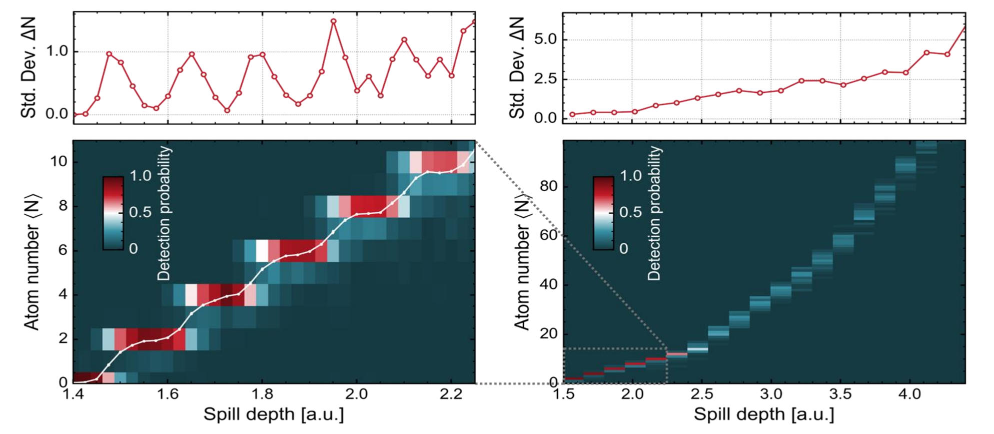
- Attractive interactions characterized by binding energy E_B
- E_B competes with shell-structure E_{ho} and Fermi energy E_F

Experiment platforms



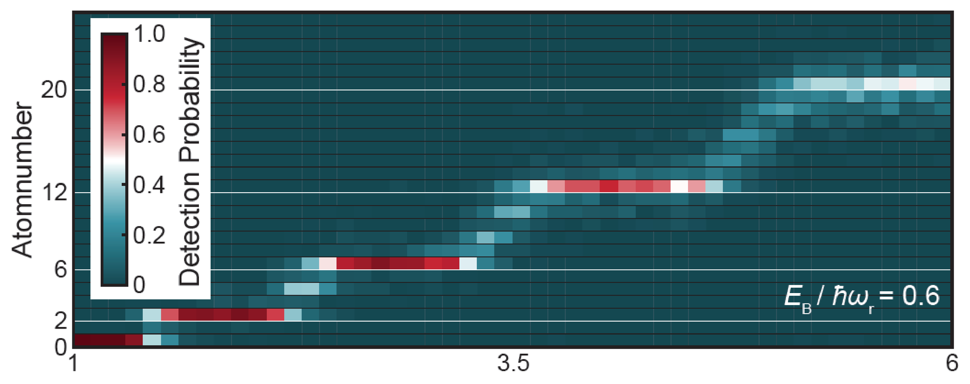
2 Deterministic Preparation in 1D and 2D

Microtrap (1D)



Low-entropy mesoscopic samples   Low-entropy mesoscopic samples

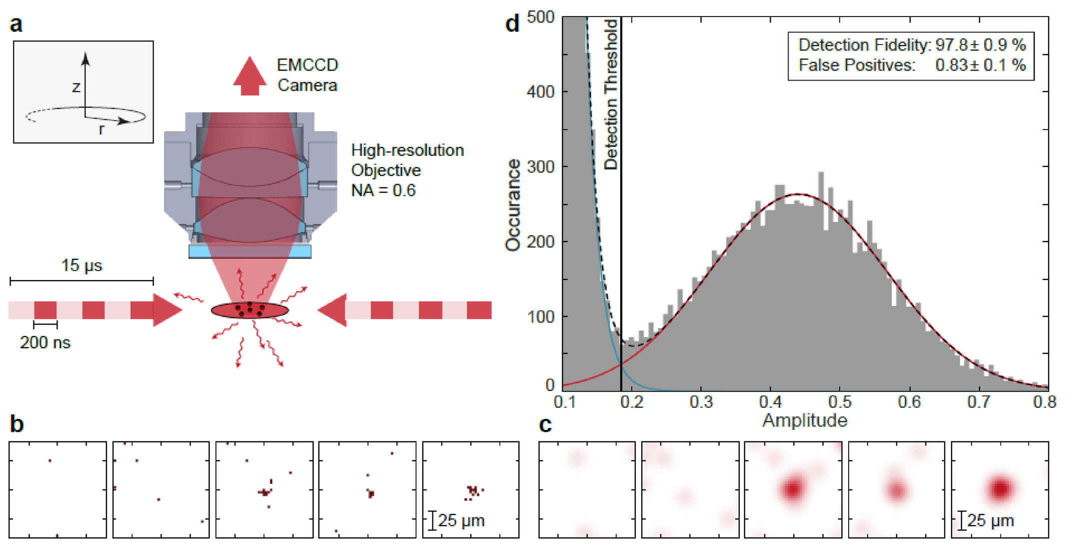
Microtrap and standing-wave trap (2D)



In 2D harmonic trap closed shells with 2, 6, 12, … atoms

F.Serwane *et al.* Science **15**, 6027 (2011)
Bayha et al. Nature **587**, 583-587 (2020)

3 Free-space fluorescence imaging



Characterization of imaging

- Random walk of atoms due to photon recoil
  - Limit to ~ 300 photons / atom
  - Around 20 photons / atom on EMCCD
- No cooling scheme required
- Works in free space

Single Atom Sensitivity

- Detection fidelity ≥ 97%
- Resolution ~10 µm

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

Hydrodynamic expansion

1 Observing elliptic flow

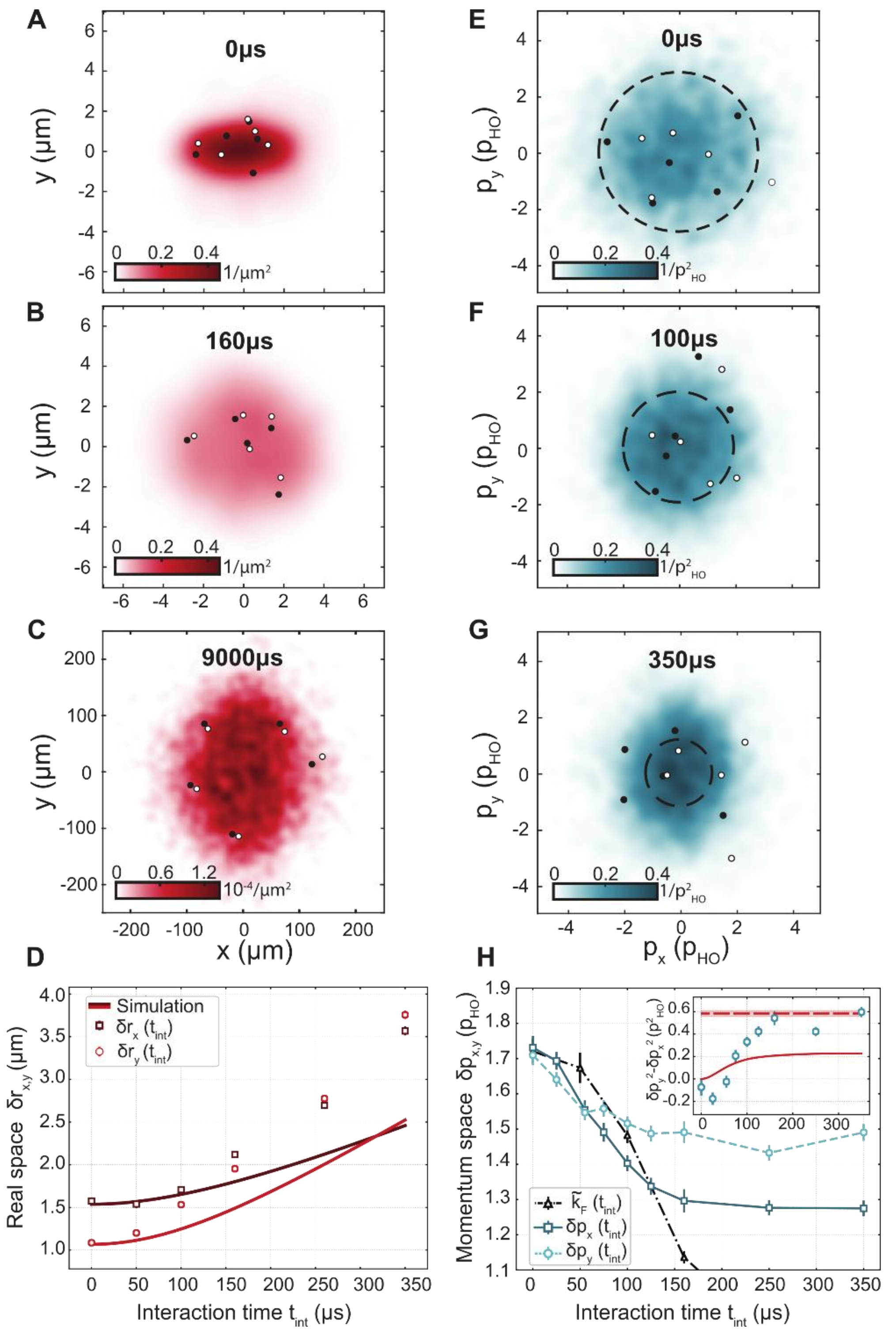
- How many particles make a fluid?
- Do phase transitions in the initial system manifest in the expansion?
- Is the hydrodynamic behaviour linked to the formation of pairs?

Signatures of hydrodynamics

- **Inversion of the aspect ratio**
- Collective excitations

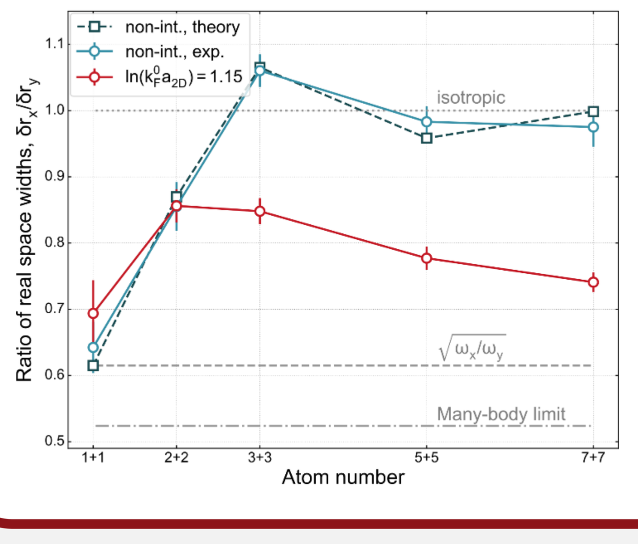
Measurement scheme

- Prepare interacting particles in the harmonic oscillator ground state → **elliptical potential**
- Switch off initial trap
- **Interacting expansion**
- Single atom and spin resolved imaging → **momentum or position measurement** at different times



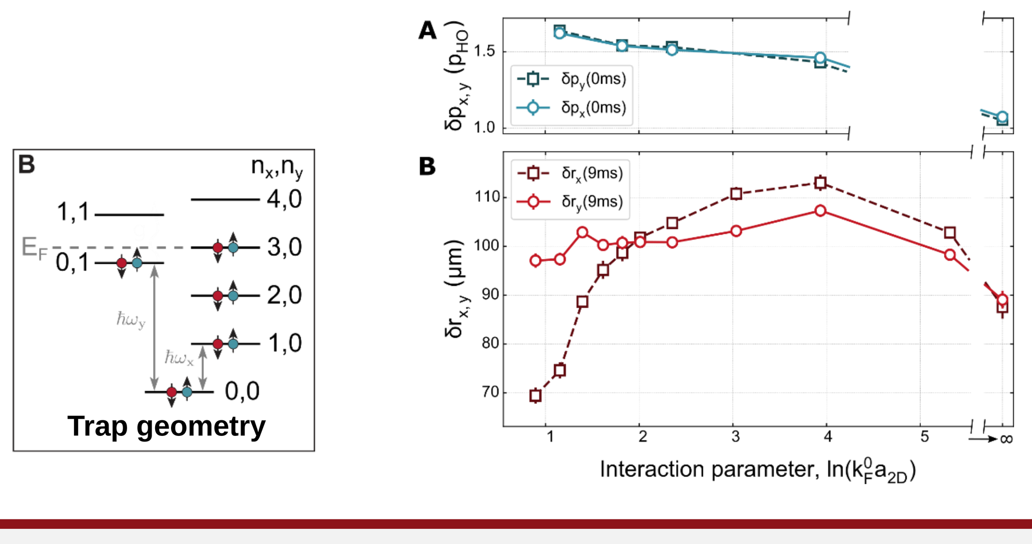
2 Building a fluid atom by atom

- Single atom in elliptic trap → inverts already the aspect ratio
- Discriminate between pure quantum and interaction effects



3 Tuning interactions

- Tunable interactions through Feshbach resonance
- Measurement of
  - **In-situ momentum**
  - **Real space with interacting expansion**

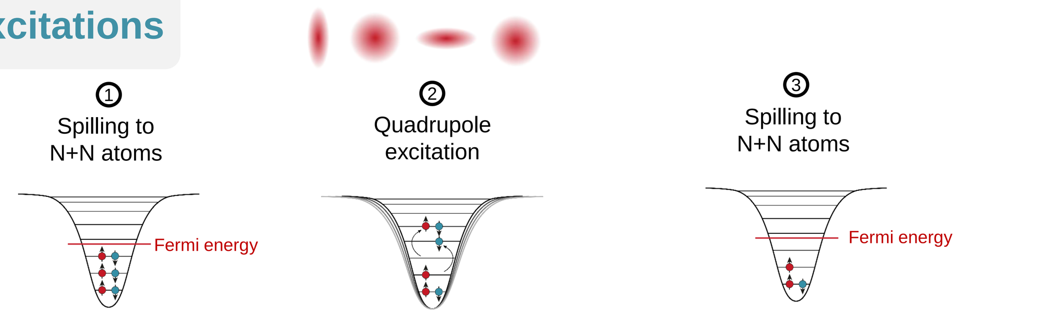


Collective excitations

1 Emergence of Collective excitations

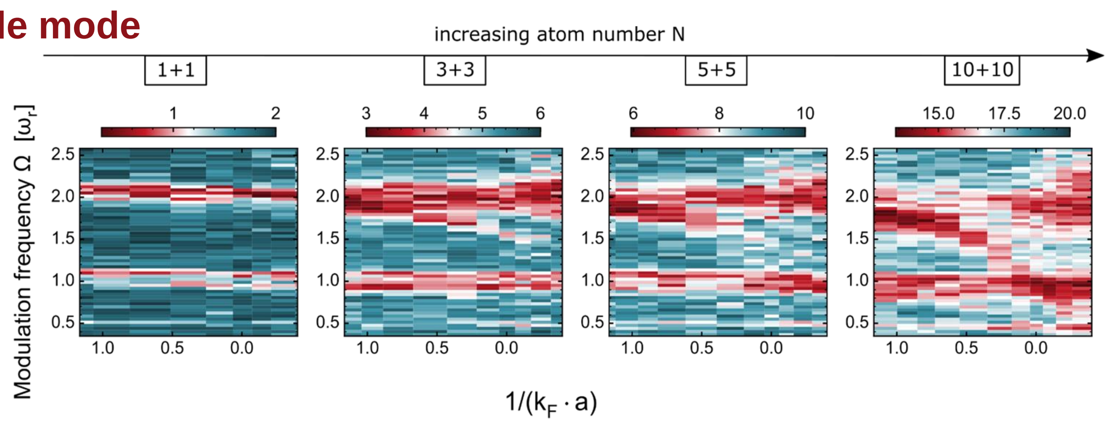
Atom loss spectroscopy

- Atoms are lost on resonance



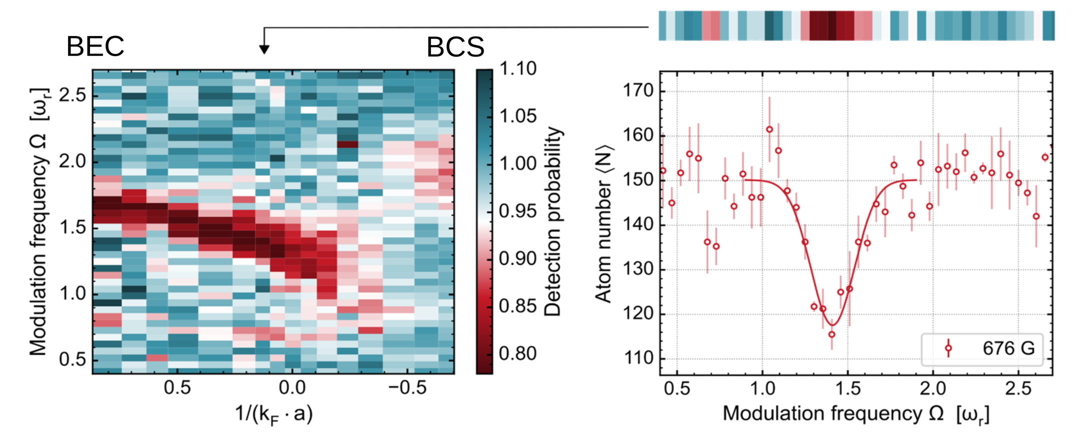
Emergence of the quadrupole mode

- Emergence of an interaction dependent collective branch from the confinement dominated excitation spectrum



2 Towards the many-body limit

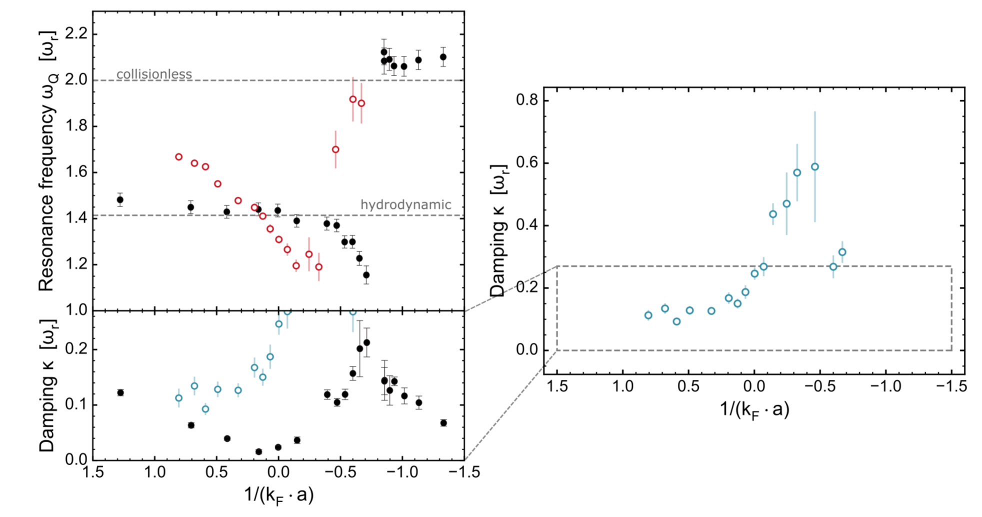
- System of 80 + 80 atoms
- Downshift of the collective mode frequency below the hydrodynamic expectation of $\sqrt{2}\omega$
- Sudden jump from the collective into the collisionless branch



Comparison to the many-body limit

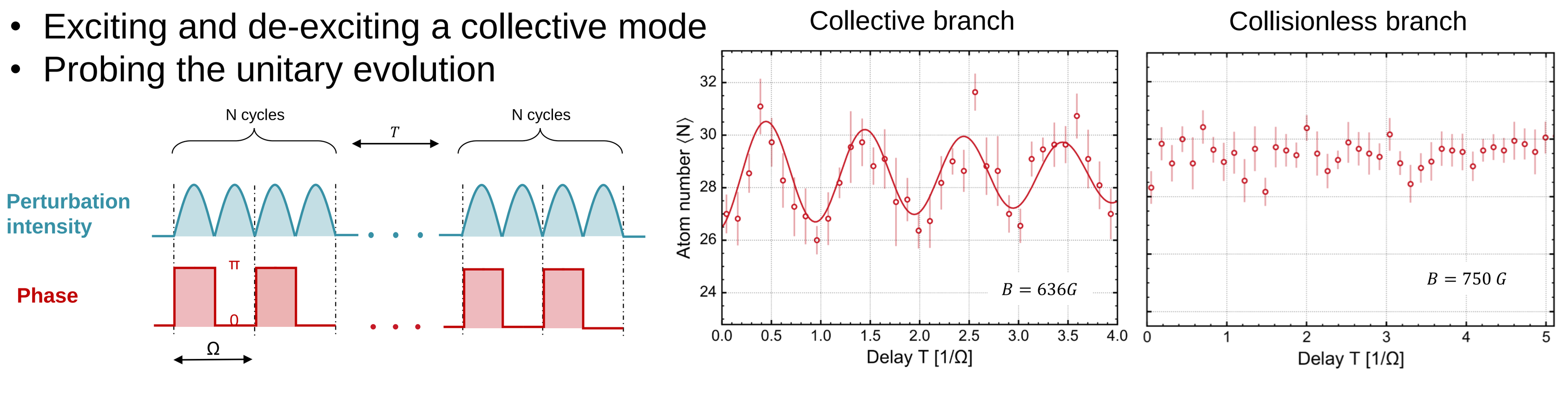
- **Altmeyer et al. (2007)** Phys. Rev. A 76, 033610
- **Resonance frequencies** and **damping** in our system with 160 atoms

Fermi energy $E_F/\hbar\omega$	# atoms N
41.7	400 000
4.3	160



3 Coherence of the quadrupole mode

- Exciting and de-exciting a collective mode
- Probing the unitary evolution

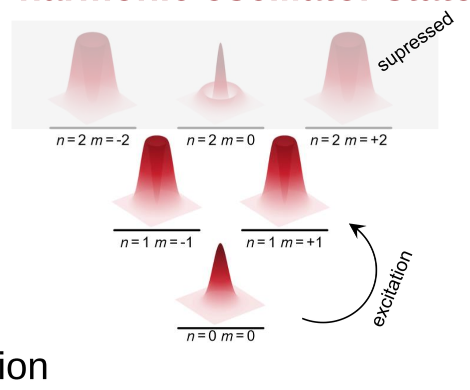


Outlook

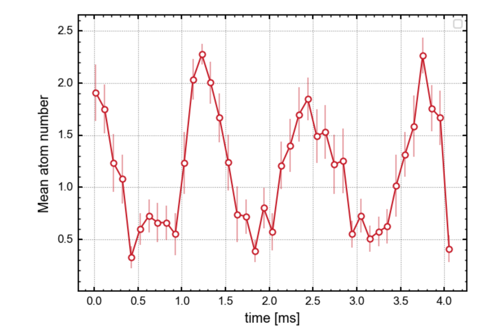
1 Rotation of a single atom

- Preparation of a single atom in the ground state
- Excitation into L=1 state via rotation
- Drive Rabi oscillations between (0,0) and (1,1) → coupling to higher states is suppressed due to anharmonicity
- π –pulse → Measure the momentum space distribution

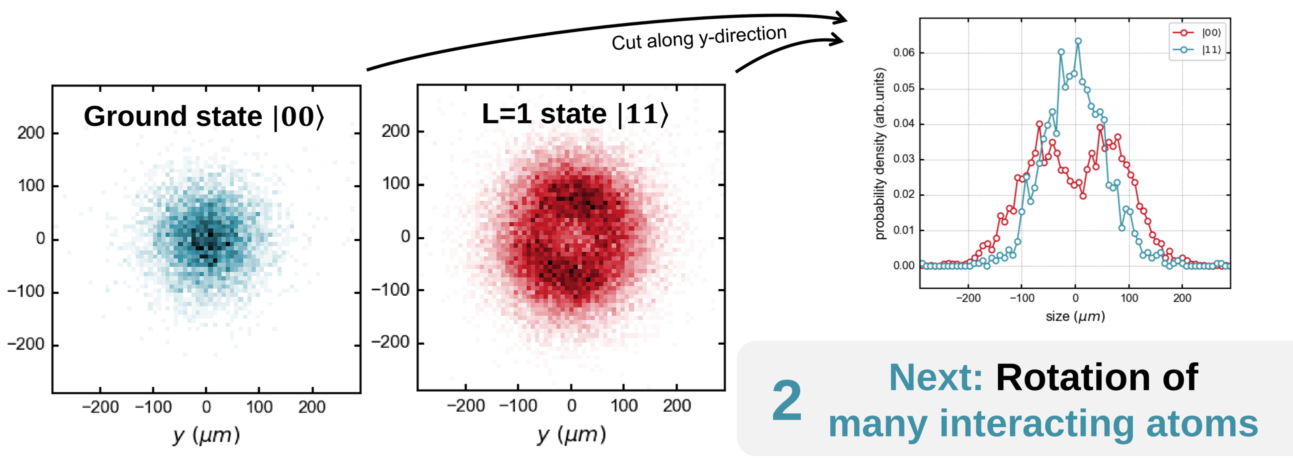
2D harmonic oscillator states



Rabi oscillations between |00⟩ and |11⟩



Momentum distribution



2 Next: Rotation of many interacting atoms