Finite Fermi systems in the crossover from few to many-body physics

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Few-body physics vs. many-body physics

The description of physical systems can usually be divided into:

many-body physics

e.g.: thermodynamical systems with temperature, pressure,…

description with macroscopic variables

Where is this transition from few to many-body physics?

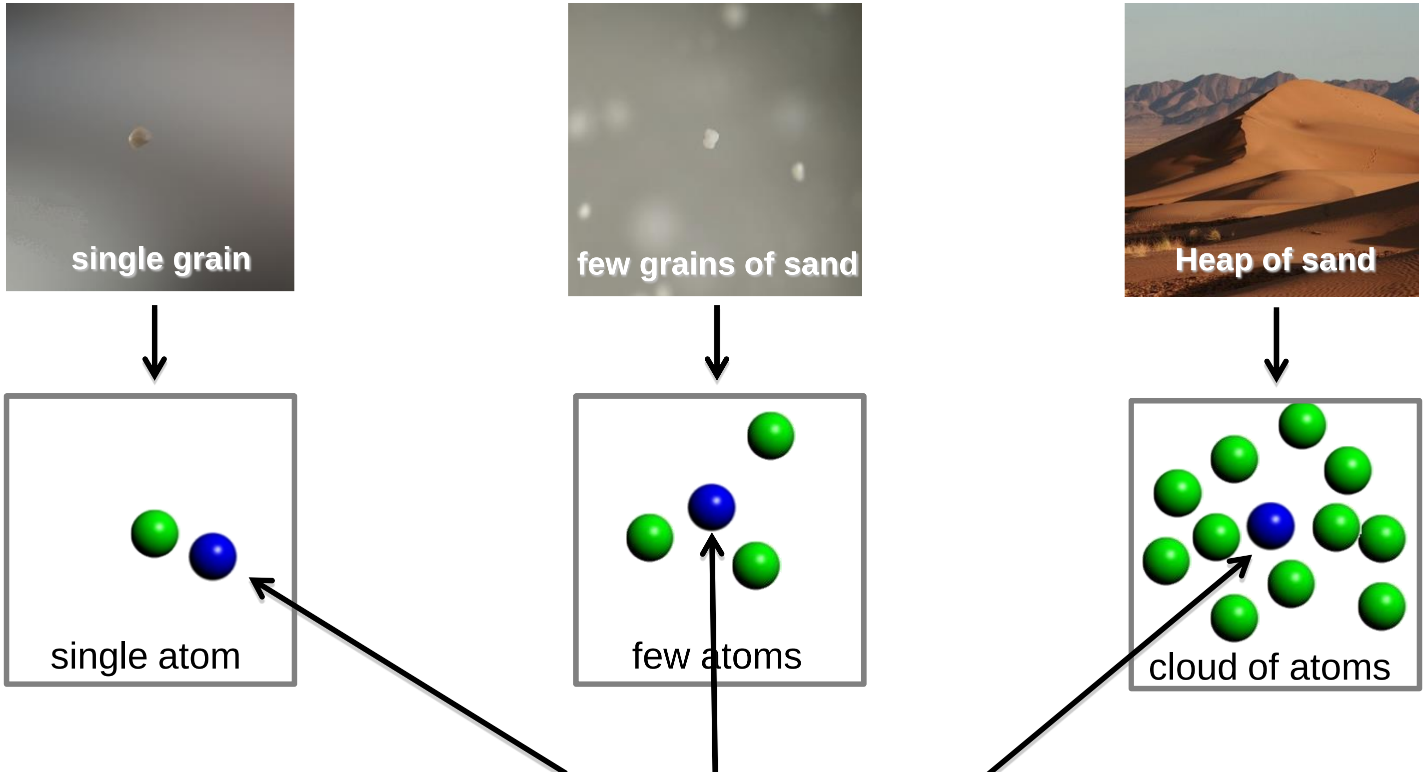
How to describe mesoscopic systems?

few-body physics

e.g.: scattering, hydrogen atom, …

description with microscopic variables

Our system and measurement



measure influence onto “test particle“

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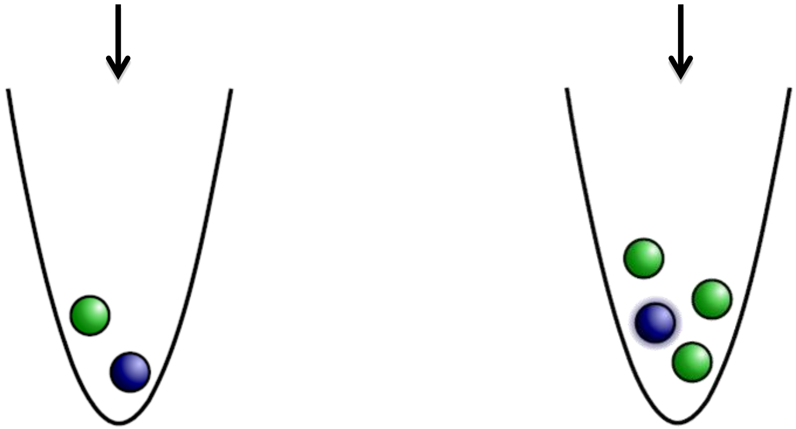
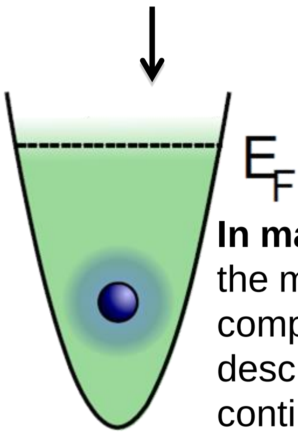
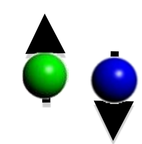
Our system and measurement





In many-body case: the majority component can be described as a continuous Fermi sea

in our case: fermionic ultracold atoms (^{6}Li) in two spin states trapped in a optical dipole trap



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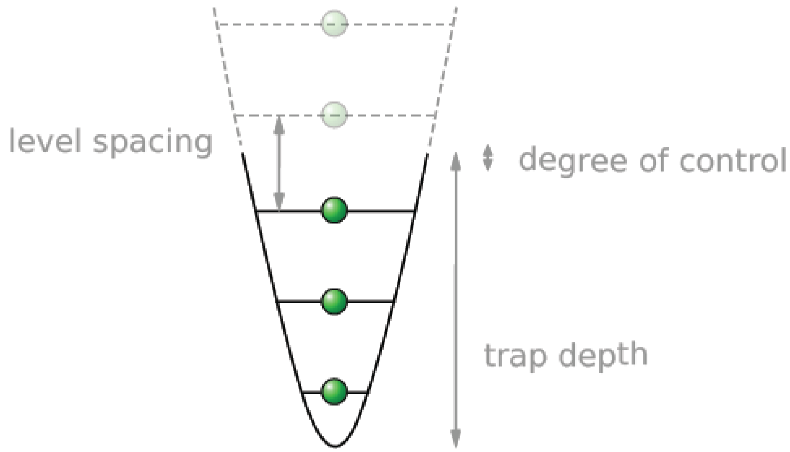
preparation scheme

idea: make use of the fermionic nature of the atoms
control the number of particles by controlling the number of states in the microtrap

control on trap depth must be better than
level spacing → need large level spacing

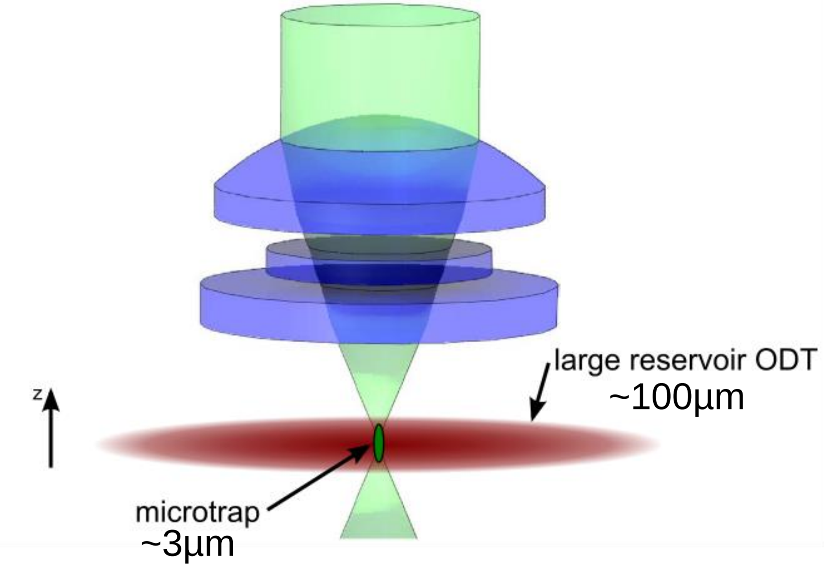


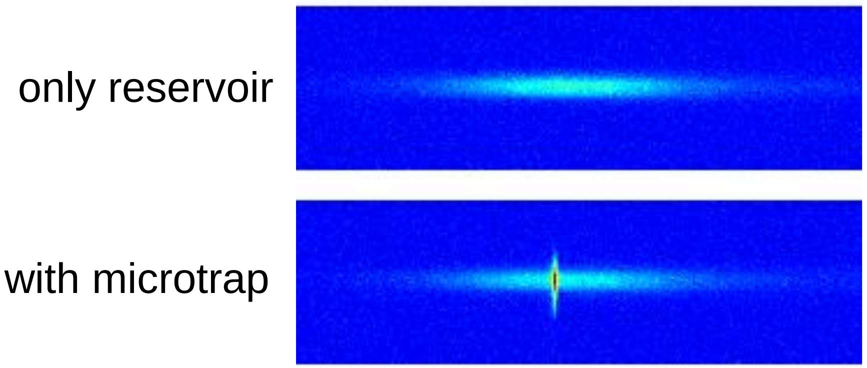
obtained by small focus and large trap depth

important: all states must be occupied (no holes)

Preparation of few fermion samples

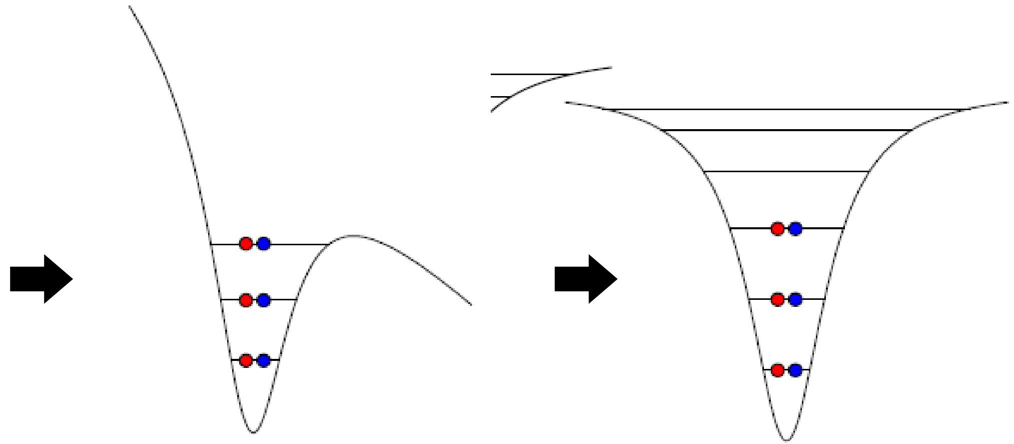
start from a large reservoir of ultracold atoms (40 000) and superimpose a small volume tightly focused optical microtrap





High Fidelity Preparation

- 2-component mixture in reservoir T=250nK (T/T_F~0.5)
- superimpose microtrap
  scattering → thermalization
  expected degeneracy: $T/T_F < 0.1$
- switch off reservoir



+ magnetic field gradient in axial direction

Single atom detection

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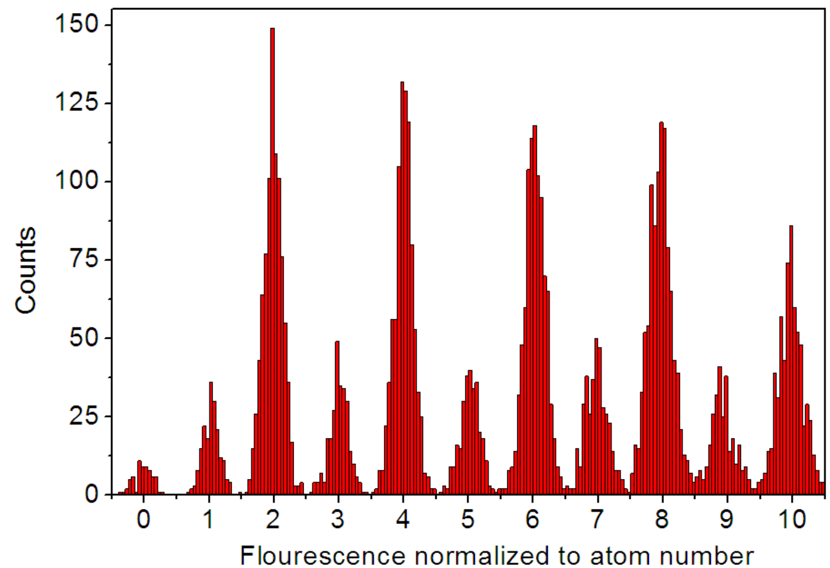
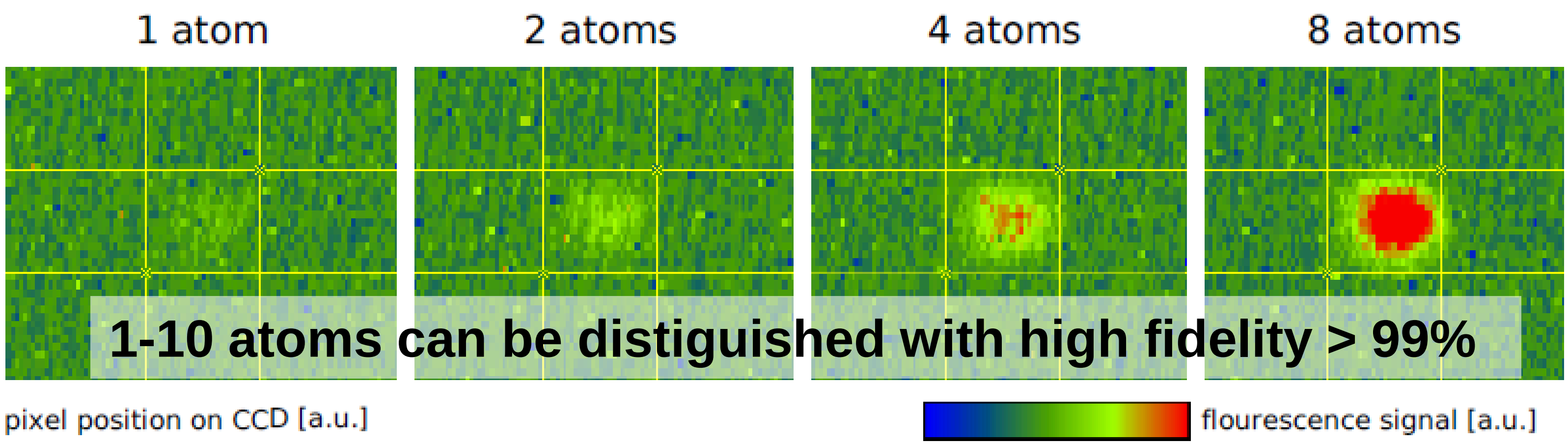
idea: count number of atoms by recapturing them in the MOT

need: long exposure time
low background light





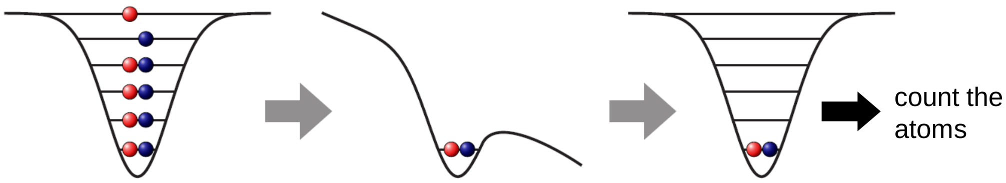
1-10 atoms can be distiguished with high fidelity > 99%

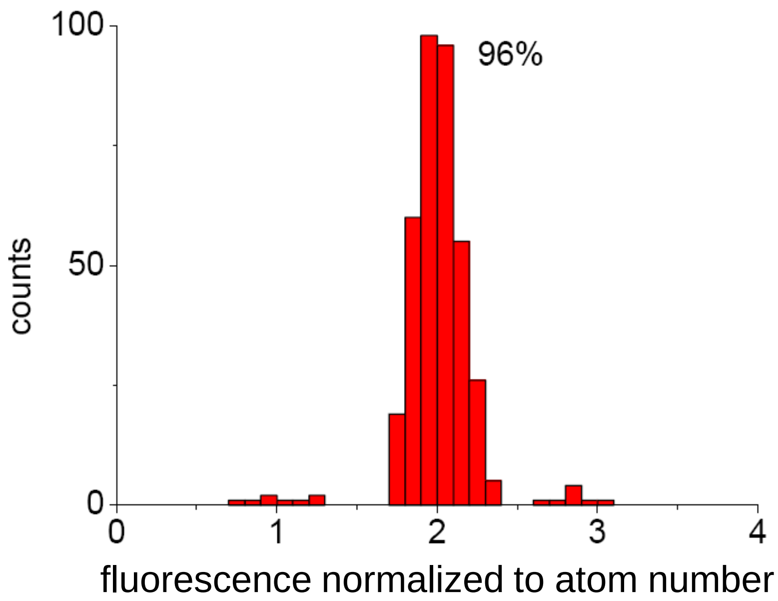
F. Serwane, G. Zürn, T. Lompe, T. Ottenstein, A. Wenz and S. Jochim, Science **332,** 336 (2011)

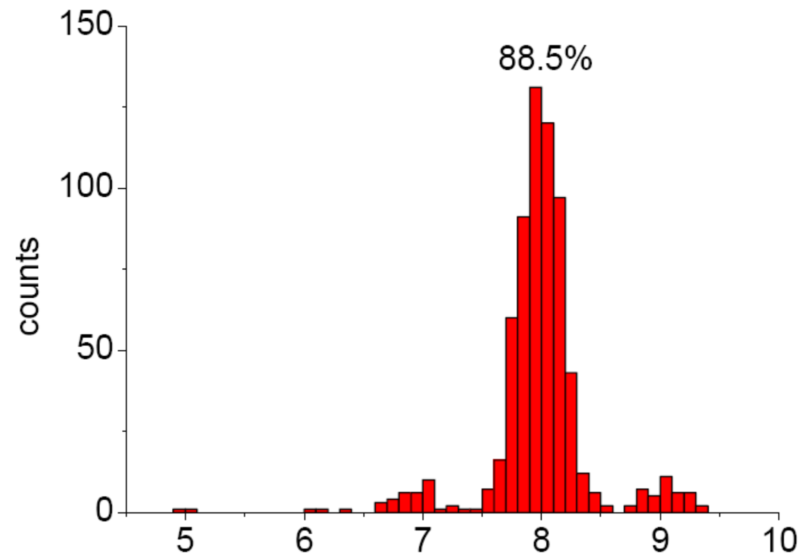
High Fidelity Preparation

2 atoms

8 atoms







lifetime in ground state ~ 60s

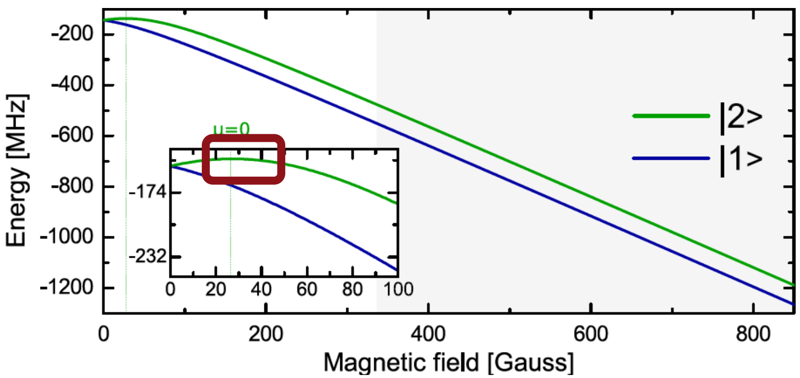
F. Serwane, G. Zürn, T. Lompe, T. Ottenstein, A. Wenz and S. Jochim, Science **332,** 336 (2011)

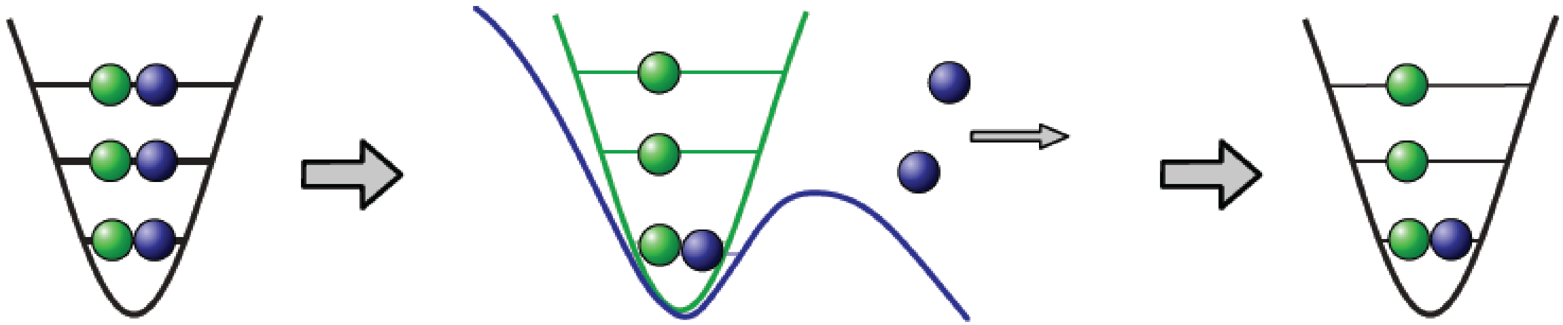
imbalanced systems

So far spilling at high field

→ same force on ↑ and ↓ atoms

At 27 G: magnetic moment of ↑ vanishes





can spill only atoms in ↓ → create imbalanced samples

but so far: no interactions!

introducing interactions

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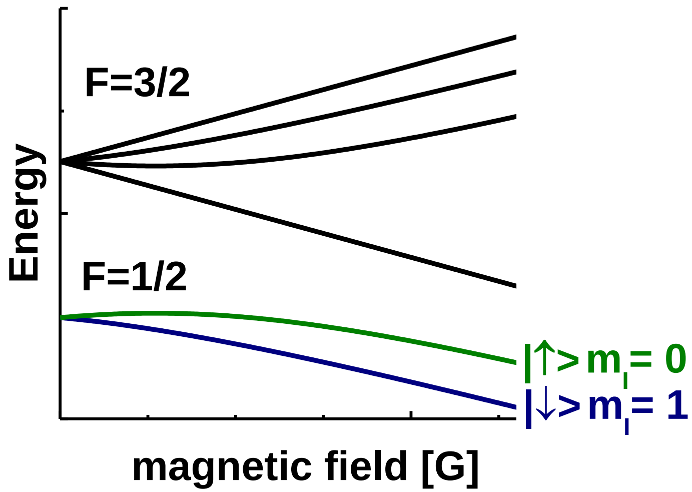
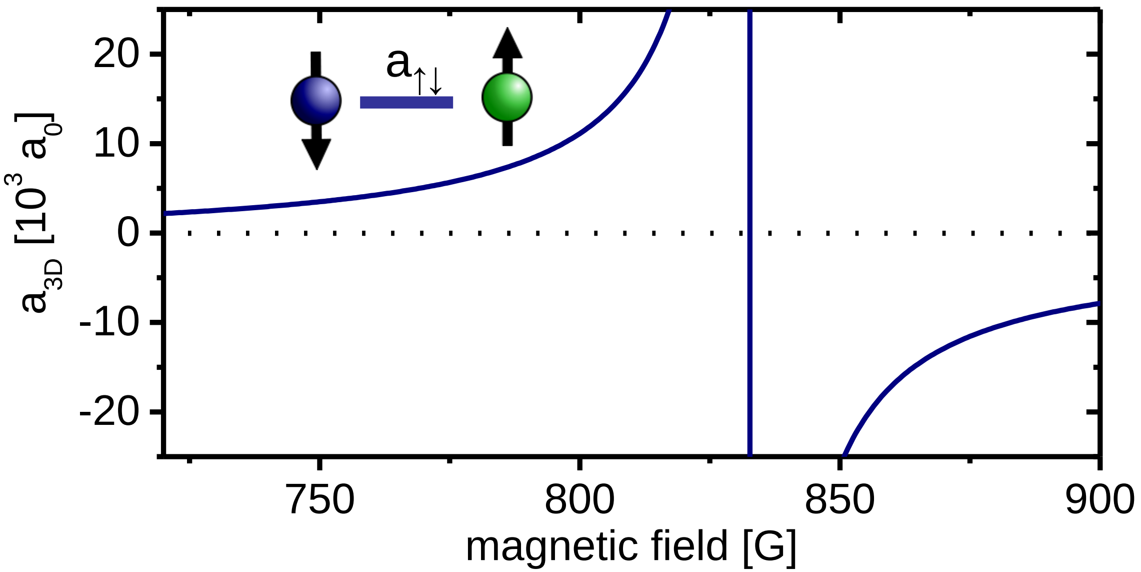
^{6}Li ground state



Tuning interactions: Feshbach resonance in ^{6}Li



^{6}Li is a fermion

NO interaction between identical particles

G. Zürn, T. Lompe, A. N. Wenz, S. Jochim, P. S. Julienne and J. M. Hutson, PRL **110,** 135301 (2013)

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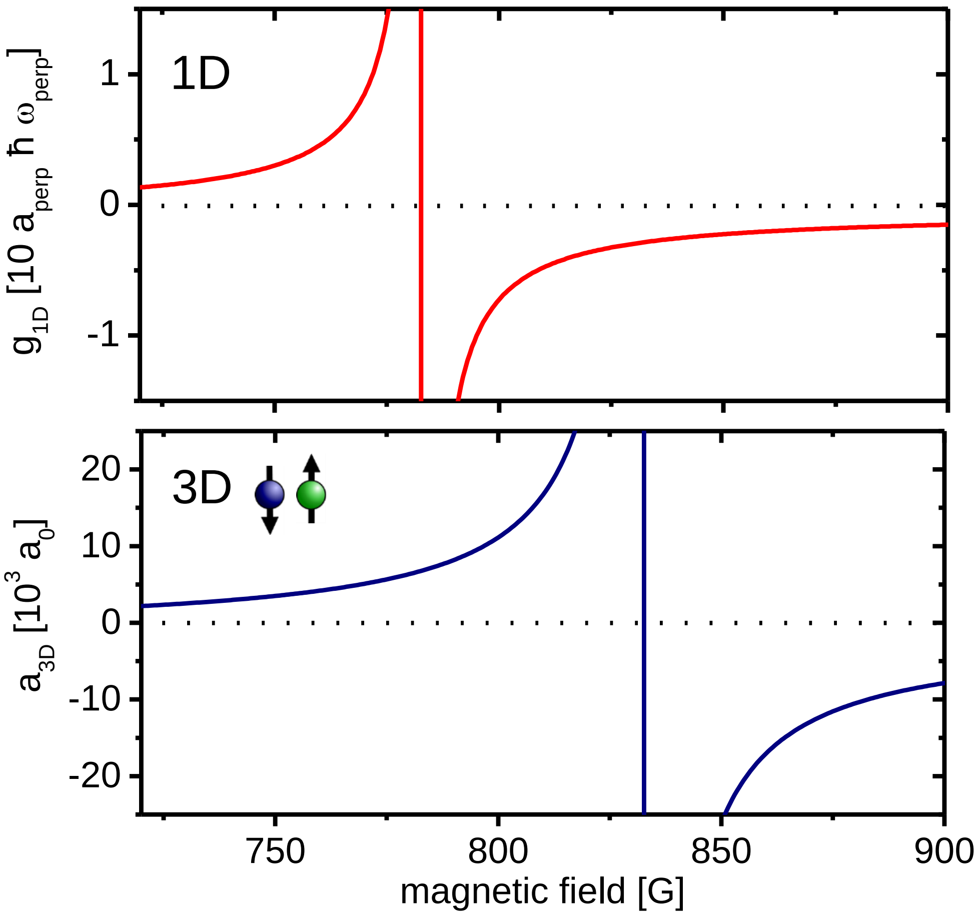
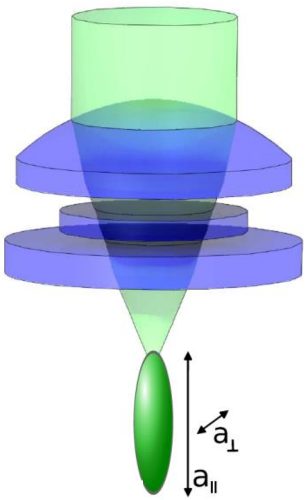
Interactions in 1D

Confinement induced resonance



Feshbach resonance in ^{6}Li

Trap has aspect ratio 1:10



→ 1D framework for lowest states

$$g_{1D} = \frac{2\hbar^2 a_{3D}}{m a_\perp^2} \frac{1}{1 - C a_{3D} / a_\perp}$$

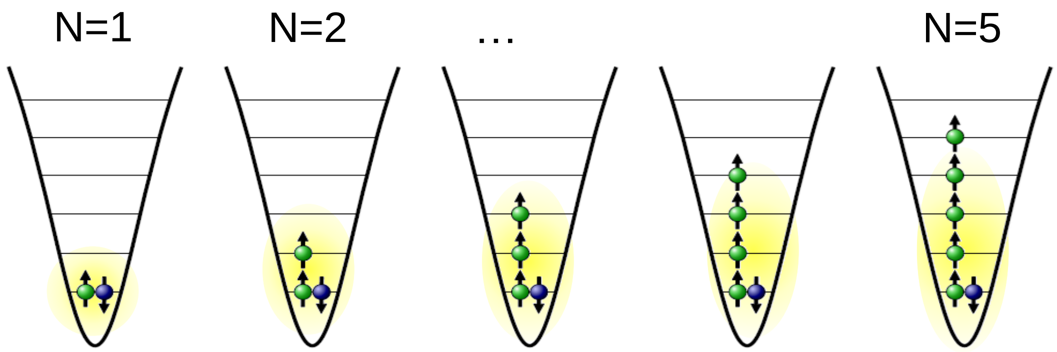
Z. Idziaszek and T. Calarco, PRA **74**, 022712 (2006)
M. Olshanii, PRL **81**, 938 (1998)
G. Zürn, F. Serwane, T. Lompe, A. N. Wenz, M. G. Ries, J. E. Bohn and S. Jochim, PRL **108**, (2012)

starting point

In 1D framework, the quantum impurity system is described by the following Hamiltonian:

$$H = \sum_{i=0}^{N} \left(-\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x_i^2} + \frac{1}{2} m \omega_\parallel^2 x_i^2 \right) + g_{1D} \sum_{i=1}^{N} \delta(x_i - x_0)$$

harm. trap **tunable 1D interaction**



now: need to measure influence of the majority particles ( ) onto the “test particle“ ( )

→ use RF spectroscopy

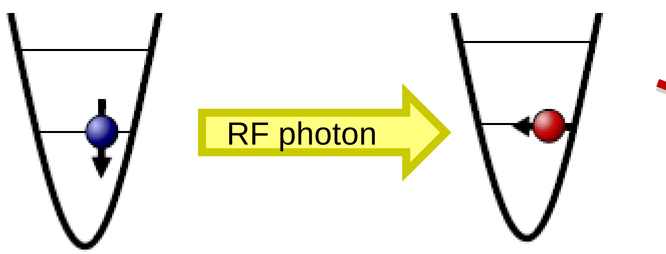
A. N. Wenz, G. Zürn, S. Murmann, I. Brouzos, T. Lompe and S. Jochim, Science **342,** 457 (2013)

Radio-frequency (RF) spectroscopy

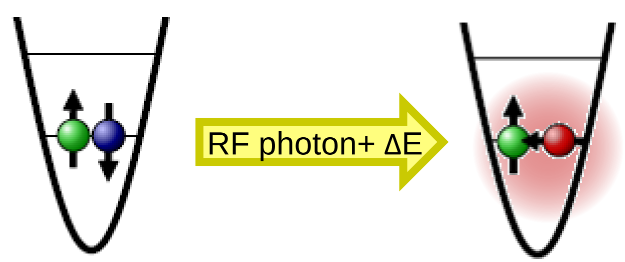
There are not only two spin states (,), but there is also a third state ( ).

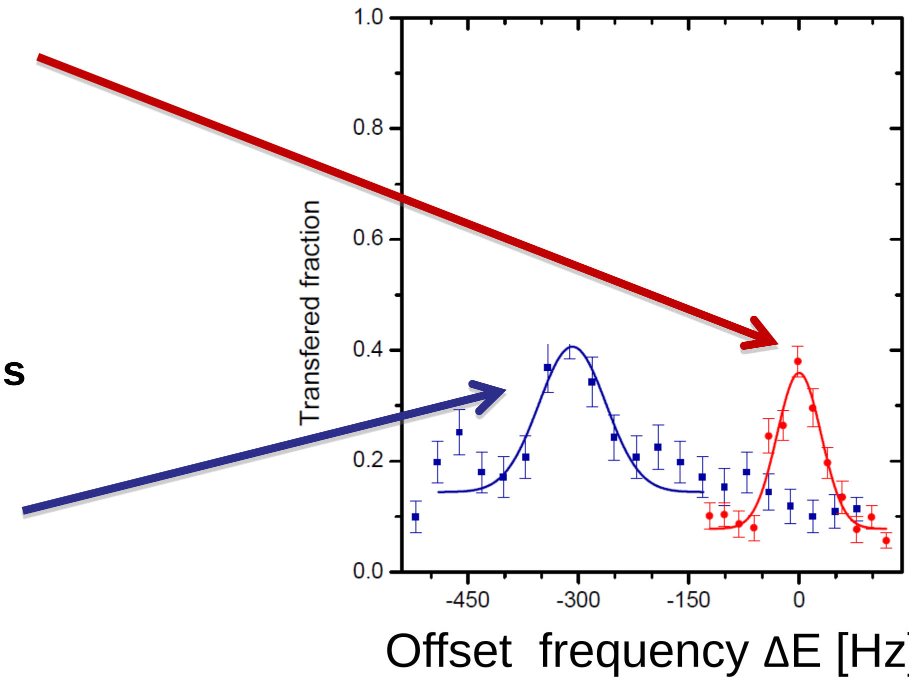
can drive transitions between the states using RF pulses (~80 MHz)

RF – transition without interactions



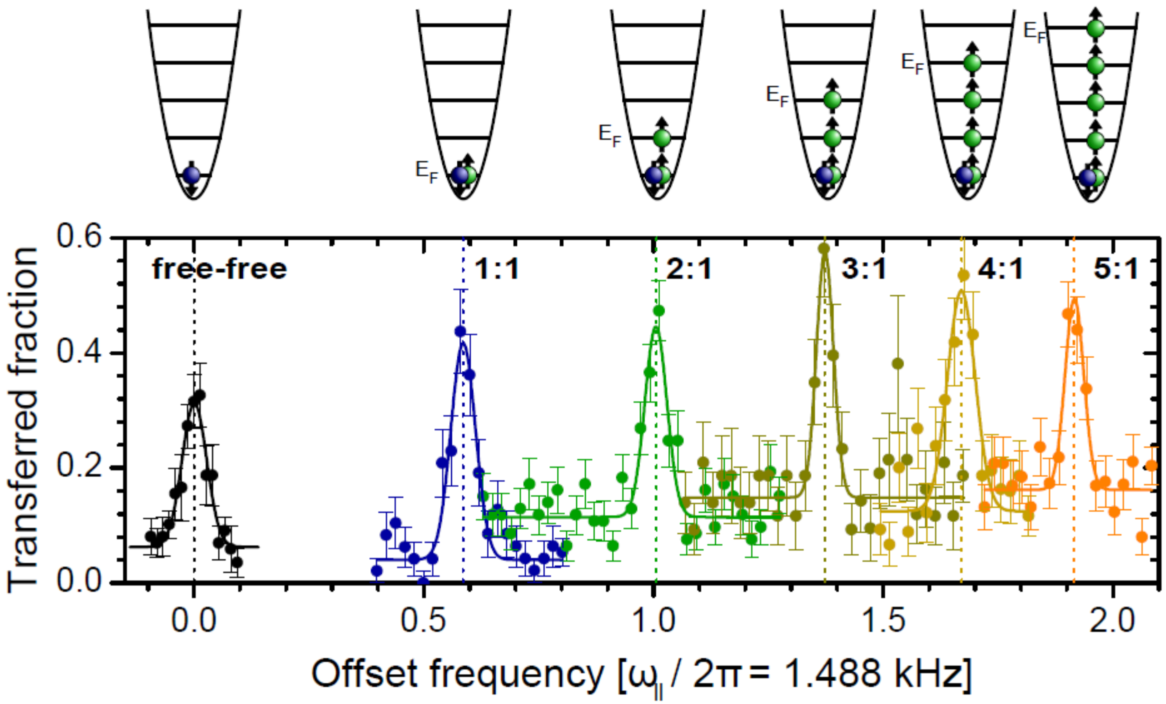
RF – transition with interactions

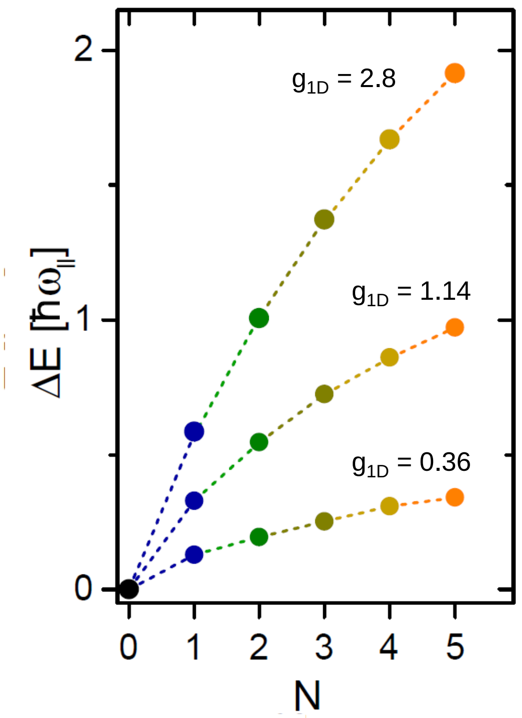




Measure the interaction energy

Use RF spectroscopy to determine the interaction energy as a function of the number of majority particles:

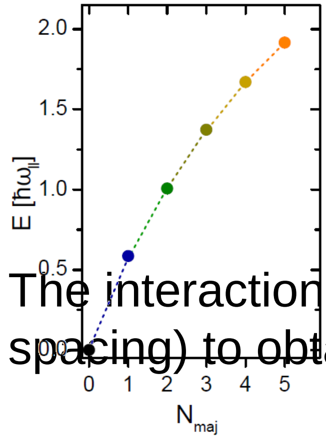




A. N. Wenz, G. Zürn, S. Murmann, I. Brouzos, T. Lompe and S. Jochim, Science **342,** 457 (2013)

Natural scales of the system

The interaction energy diverges for $N_{maj} \rightarrow \infty$. Therefore rescale E_{int} onto natural scale of a Fermi gas E_F to obtain a dimensionless quantity:



$$E_{int} \rightarrow E_{int}/E_F$$

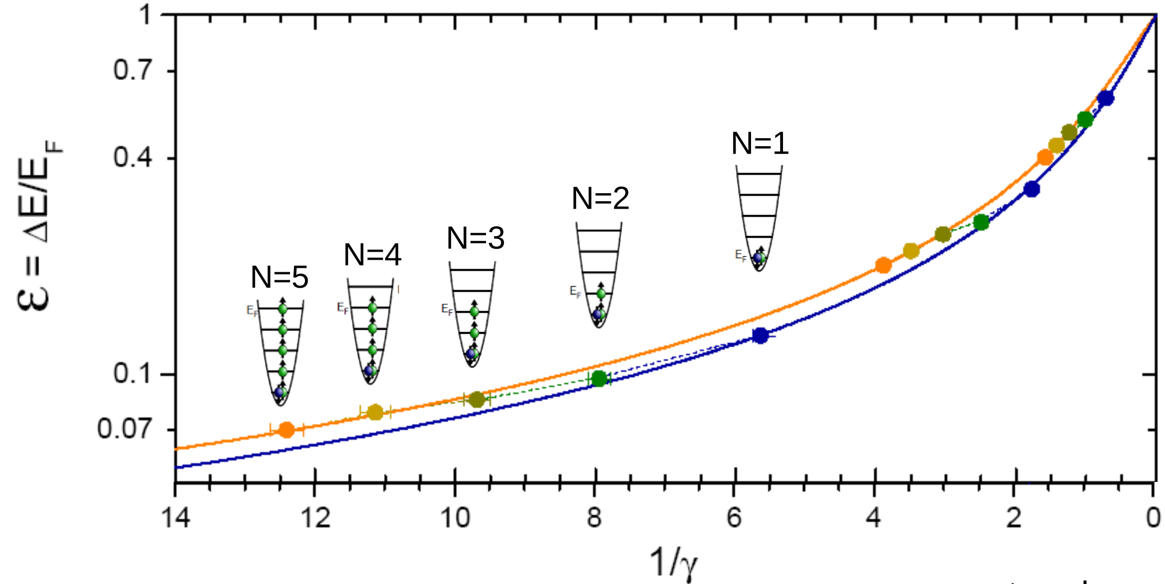
The interaction strength is rescaled with the Fermi momentum k_F (~1/interparticle spacing) to obtain a dimensionless quantity:

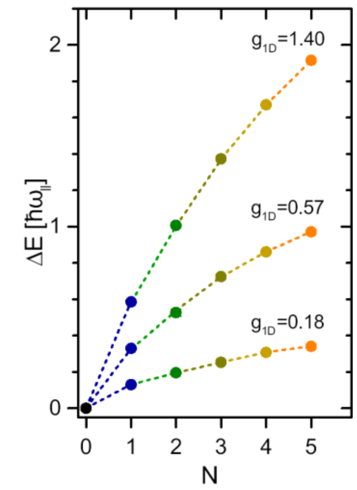
$$g_{1D} \rightarrow g_{1D}/k_F$$

$g_{1D}/k_F \sim \gamma$ the Lieb-Liniger parameter

it is the 1D equivalent of $(k_F\ a_{3D})$ in 3D

Measure the interaction energy

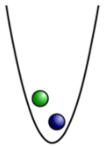




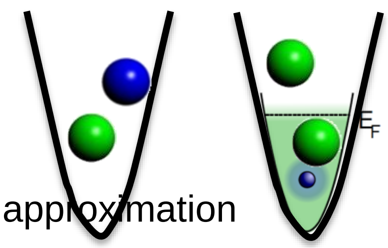
non interacting

strongly repulsive

Analytic solution of the two particle problem
T.Busch et al., Found. Phys. 28, 549 (1998)

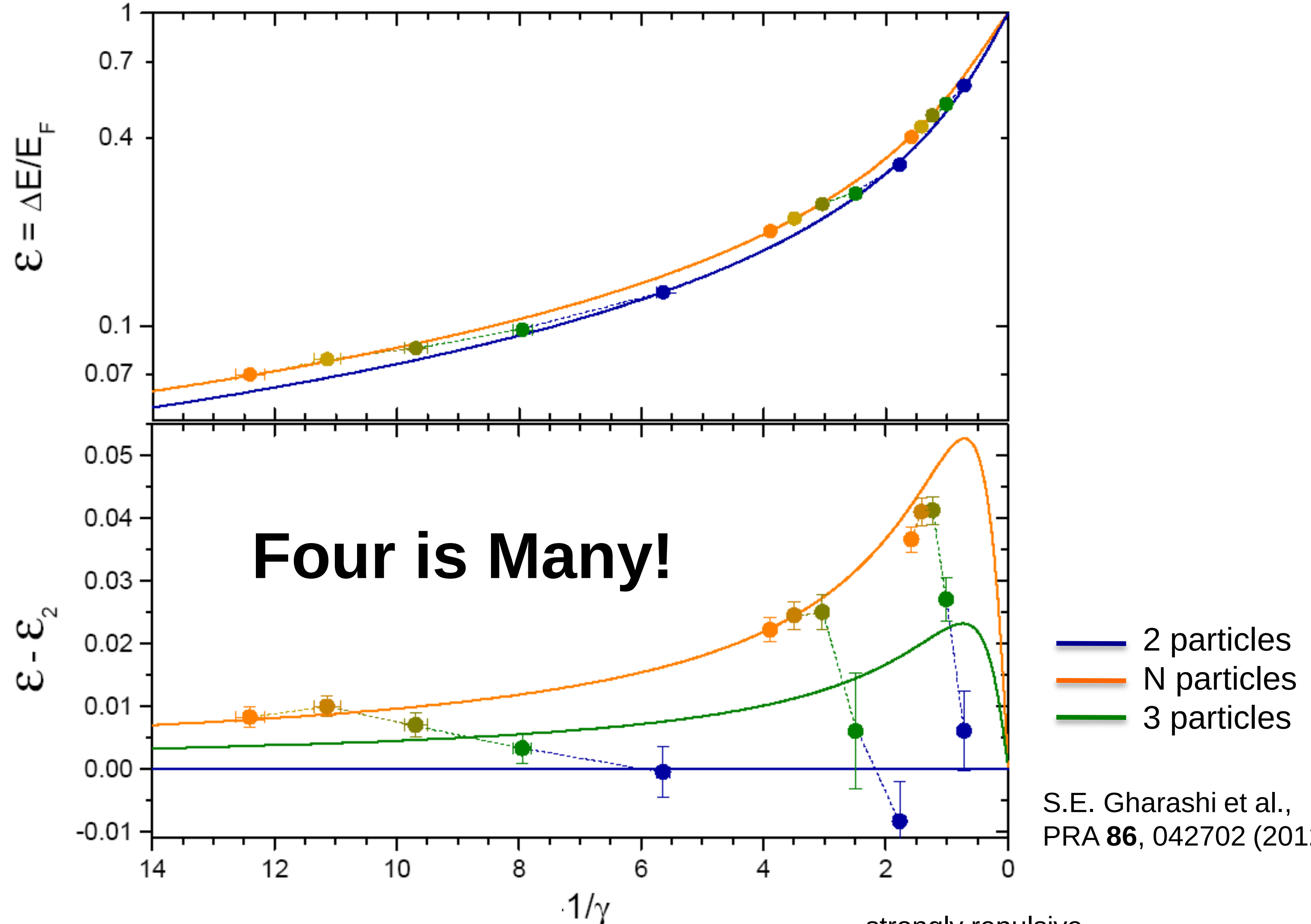


“Fermionzation”



Analytic solution for an infinite number of majority particles
J. McGuire, J. Math. Phys. 6,432 (1965)
Adapted from homogeneous to trapped case by peak density approximation

Measure the interaction energy



S.E. Gharashi et al., PRA **86**, 042702 (2012)

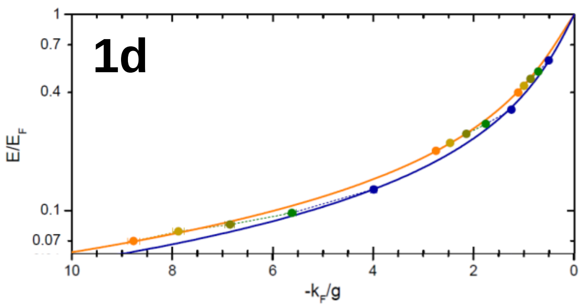
non interacting → strongly repulsive

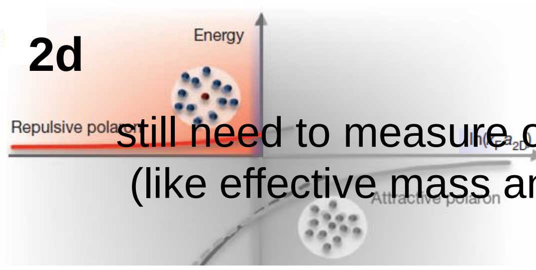
Conclusion

- We can deterministically prepare few fermion systems in the ground state with control over the motional and the spin state of the atoms

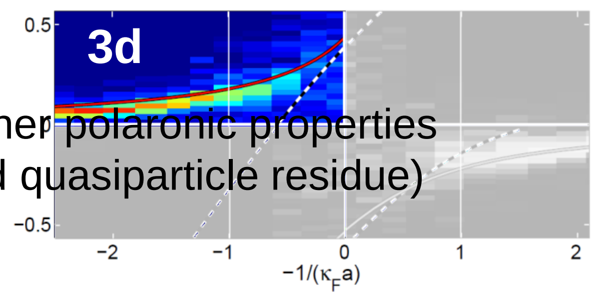
- We observed crossover from a few to a many-body description
  → 4 particles are already many!

- For N→∞ one obtains the one-dimensional analogue of the repulsive Fermi polaron





M. Koschorreck et al., Nature **485**, 619 (2012)



C. Kohstall et al., Nature **485**, 615 (2012)

still need to measure other polaronic properties
(like effective mass and quasiparticle residue)

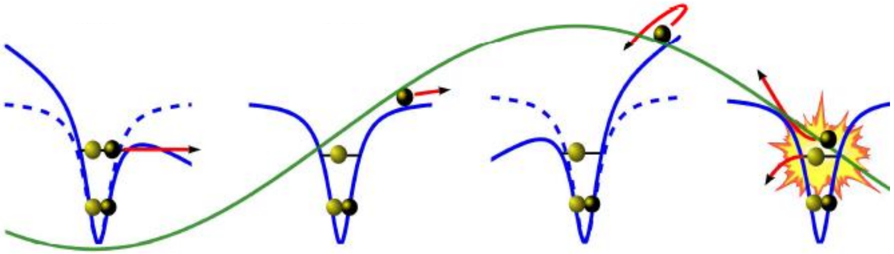
We also studied:

repulsive two-particle systems and fermionization (PRL 108, (2012))
coherent molecule formation at CIR (PRL 110, 203202 (2013))
attractively interacting systems for N=2-8 (PRL 111, 175302 (2013)).

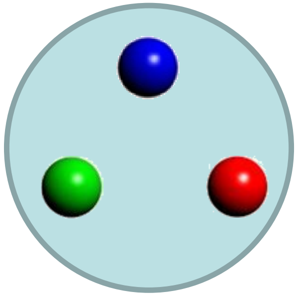
the future

We just started to explore these rich finite Fermi systems
and there is still a lot to discover

simulate attosecond physics
by applying time dependent gradient
(proposal: S. Sala et al., arXiv 1311.230)



study universal few-body physics and the
Efimov effect for three particles
(for bulk systems: PRL 101, 203202 (2008))



study influence of many-body physics
(e.g. superfluidity in finite systems, see e.g. Yan & Blume, arXiv:1406.5546)

For most of these studies it is beneficial to have a tunable trapping potential…

Right now: two fermions in a double well

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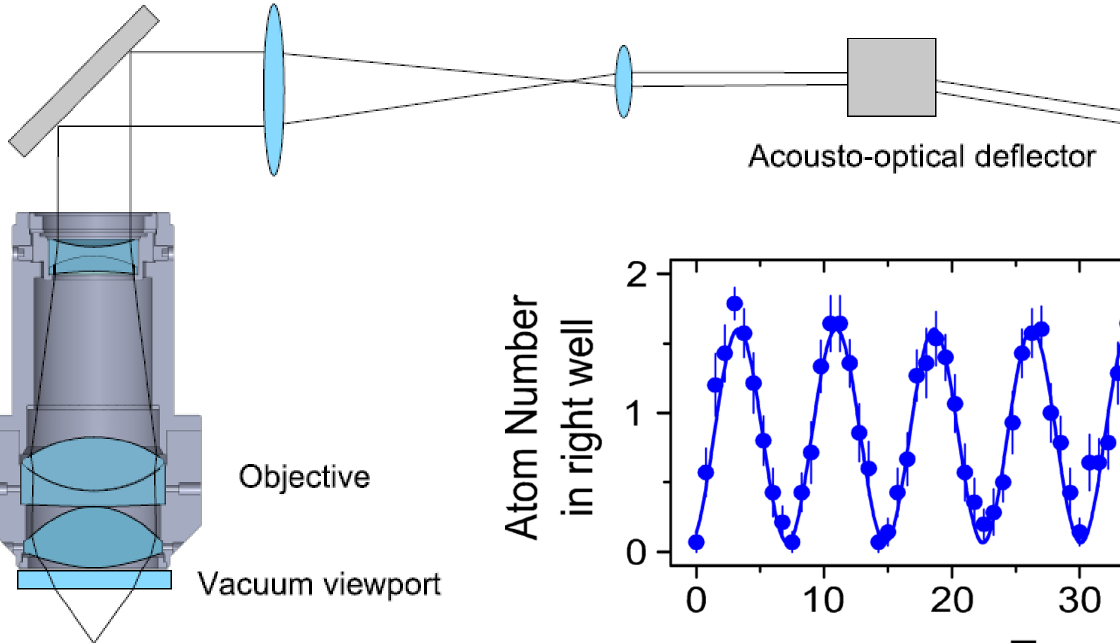
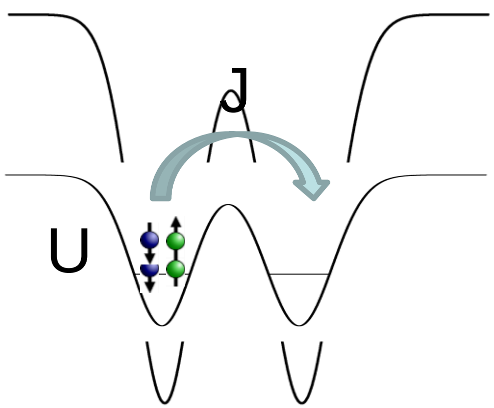
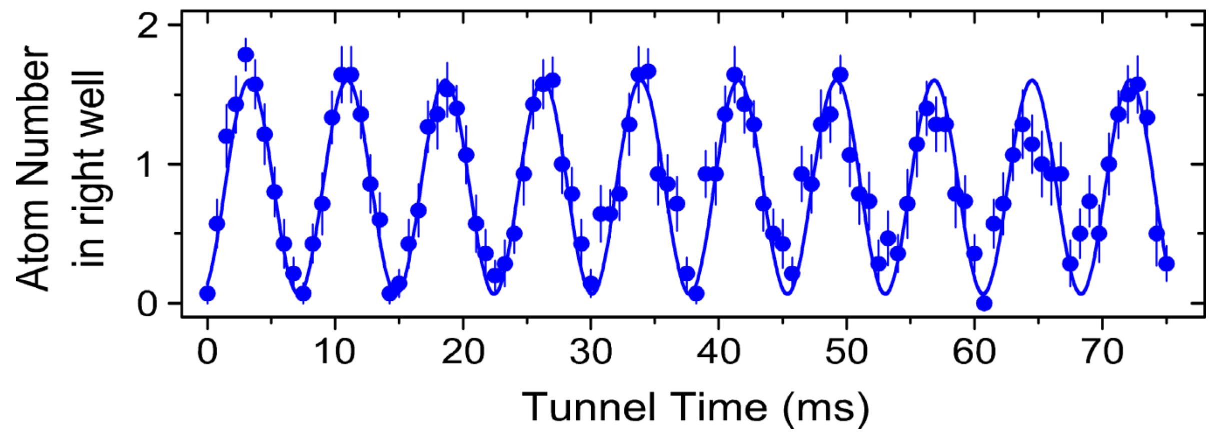
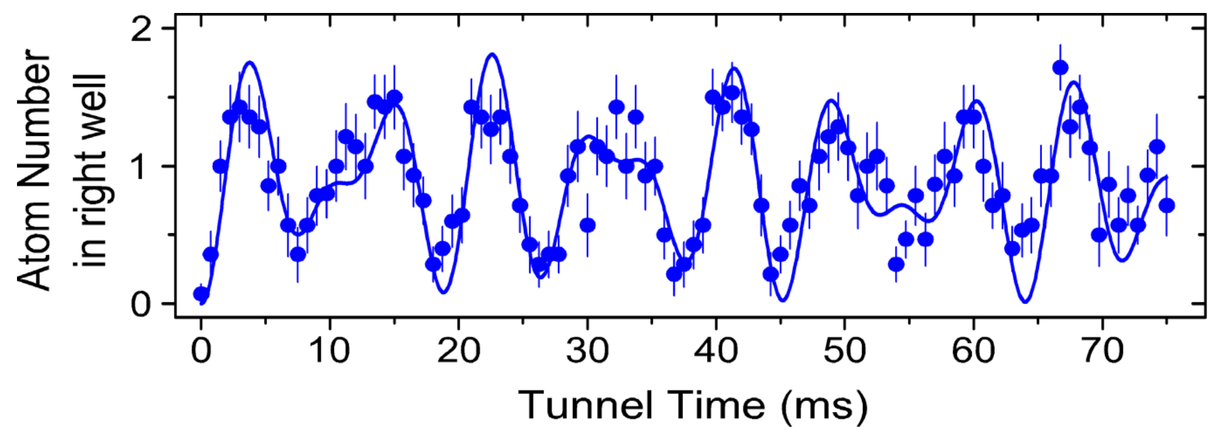
S. Murmann et al., in preparation (2014)









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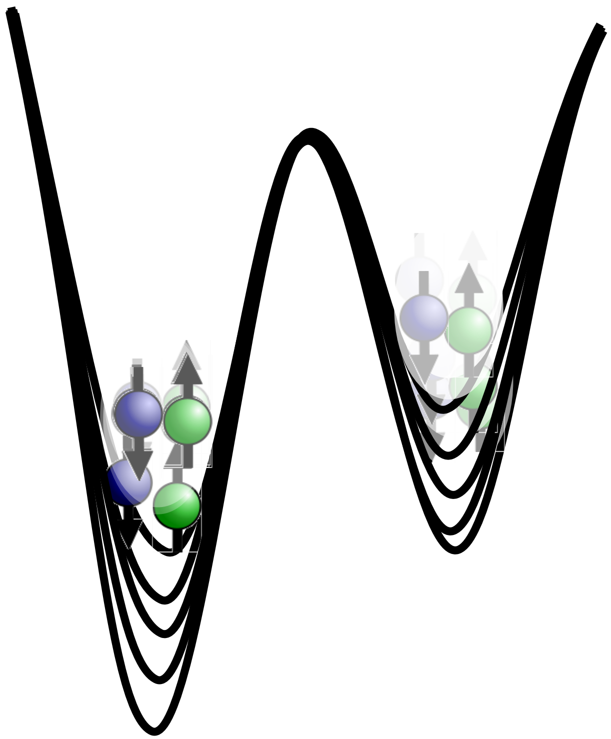
preparing stationary states

If we tilt the potential, we can initialize the system in the ground state (i.e. the singlet state):



currently: introduce interactions and study 1D double well version of the „superfluid“ to Mott insulator transition

S. Murmann et al., in preparation (2014)

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