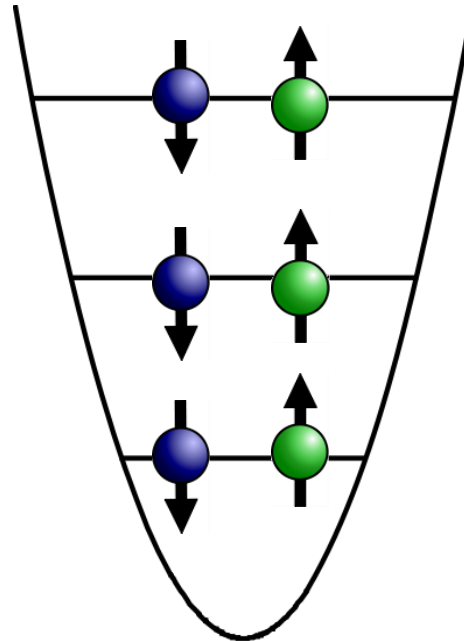


One, two, three, many

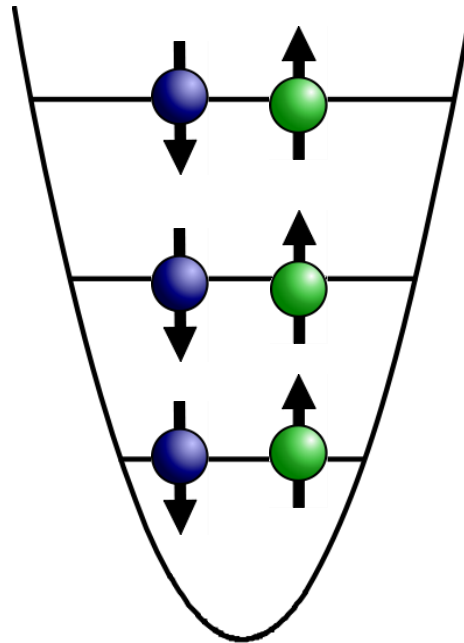
Creating quantum systems one atom at a time



Selim Jochim, Universität Heidelberg

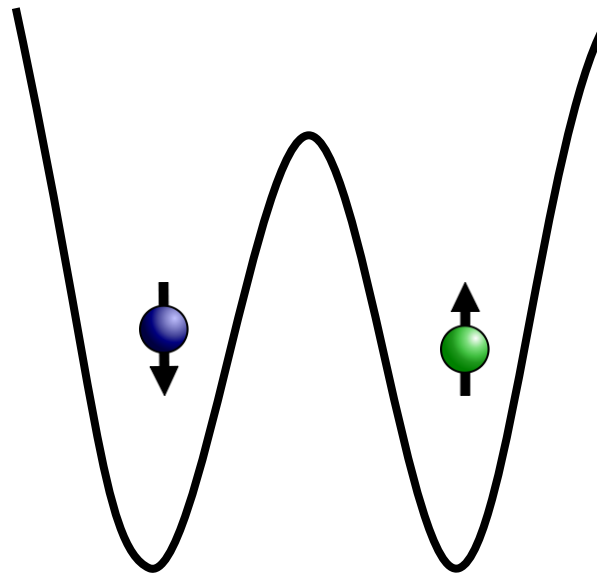
One, two, three, many

Creating quantum systems one atom at a time



Selim Jochim, Universität Heidelberg

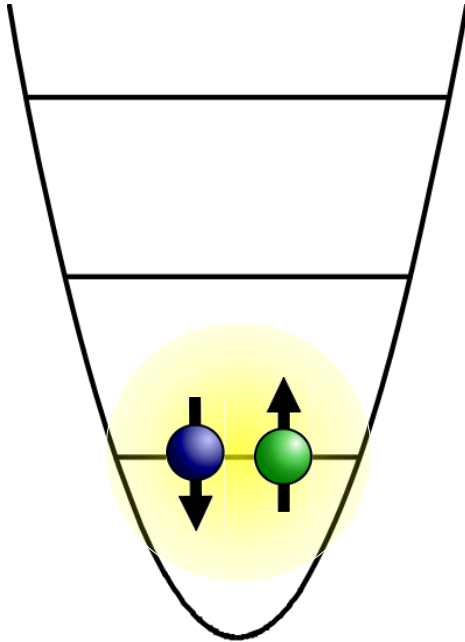
One, two, three, many
Creating quantum systems one atom at a time



Selim Jochim, Universität Heidelberg



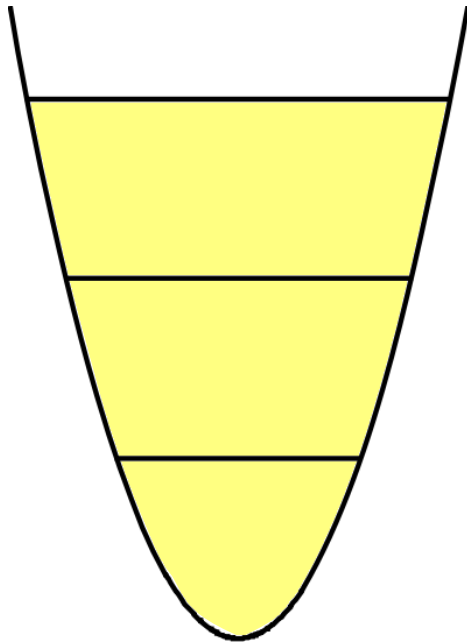
interacting singlet



Ground state of the Helium atom:

No analytic solution available, we learn how to apply powerful numerical techniques: Hartree Fock method.





Define quantities like the Fermi energy,
density, pressure

... apply local density approximation ...

**But when are such approximations
justified?**

This is an ancient problem!



Sorites Paradox

A large, smooth sand dune in the Namib Desert, showing a sharp ridge and a shadowed slope. The sky is clear and blue.

How many grains make a heap?

- 1 grain of sand does not make a heap.
- If 1 grain does not make a heap then 2 grains of sand do not.
- If 2 grains do not make a heap then 3 grains do not.
- ...

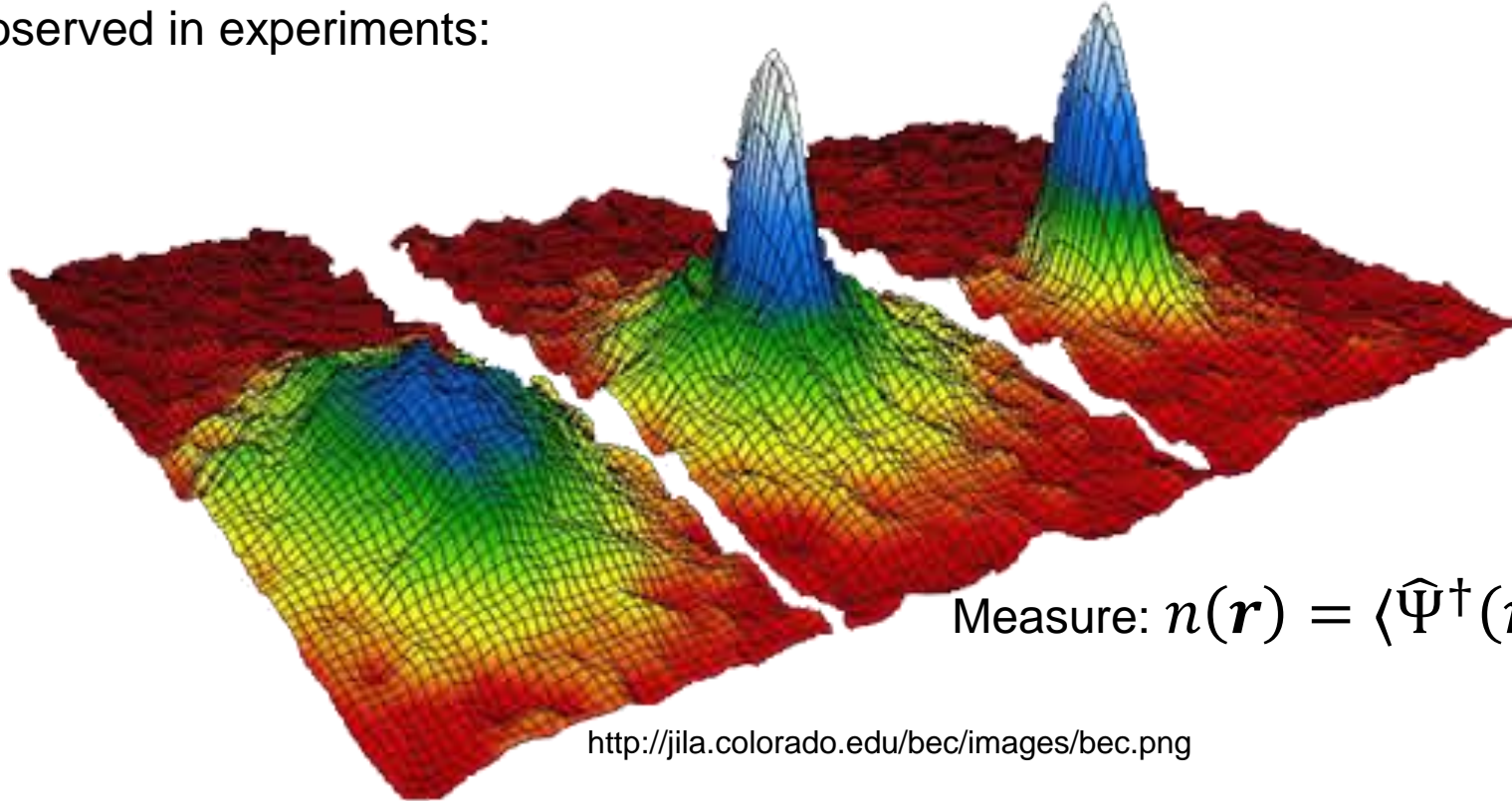
- If 9,999 grains do not make a heap then 10,000 do not.

From Stanford Encyclopedia of Philosophy:

<http://plato.stanford.edu/entries/sorites-paradox/>



Bose Einstein condensates of large samples of atoms: Macroscopic wave function: Number of particles is so large that a constant density of atoms is observed in experiments:



Measure: $n(\mathbf{r}) = \langle \hat{\Psi}^\dagger(\mathbf{r}) \hat{\Psi}(\mathbf{r}) \rangle$

<http://jila.colorado.edu/bec/images/bec.png>

Removing one single atom does not make a difference!



Reduce the complexity of a system as much as possible

until only the essential parts remain!

In most physical systems:

Range of interaction

significantly complicates the description





**The interactions between ultracold atoms can be effectively pointlike
(contact interaction)**

van der Waals interaction: range of $r_{vdW} \sim 1\text{nm}$

In the experiments we have:

- extremely low density (interparticle spacing $\sim 1\mu\text{m}$)
- extremely low momentum, such that $\lambda_{dB} = \frac{h}{\sqrt{2\pi mkT}} \gg r_{vdW}$



- extremely low momentum, such that $\lambda_{dB} = \frac{h}{\sqrt{2\pi mkT}} \gg r_{vdW}$

(This is the opposite limit desired in collision experiments:
shorter wavelength enhances resolution)

Here:

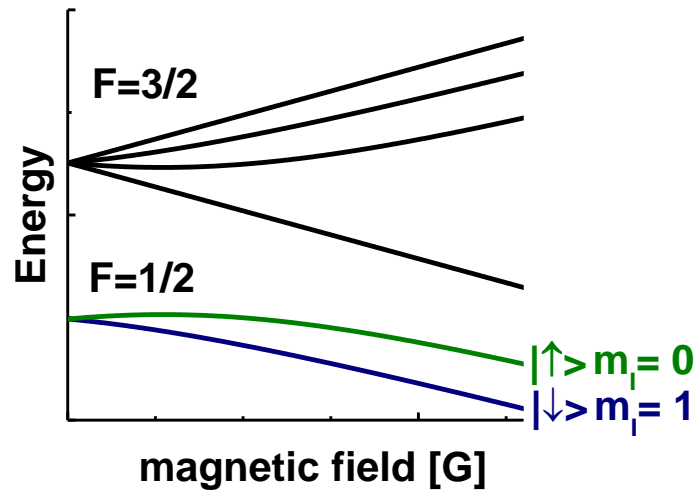
- If λ_{dB} is sufficiently large, all the information about internal structure of the atom is hidden in a single quantity, **the scattering length a**
- We can even tune the scattering length to any desired value by simply applying a magnetic field (**Feshbach resonances**).



The ${}^6\text{Li}$ atom



${}^6\text{Li}$ ground state

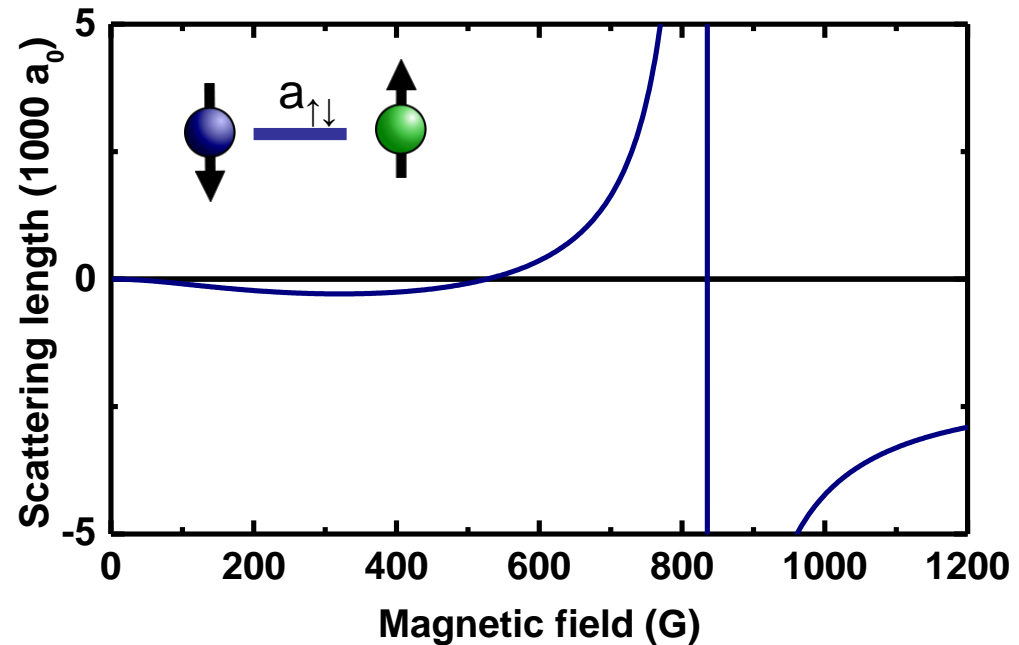


$S=1/2, I=1$

→ half-integer total angular momentum

→ ${}^6\text{Li}$ is a fermion

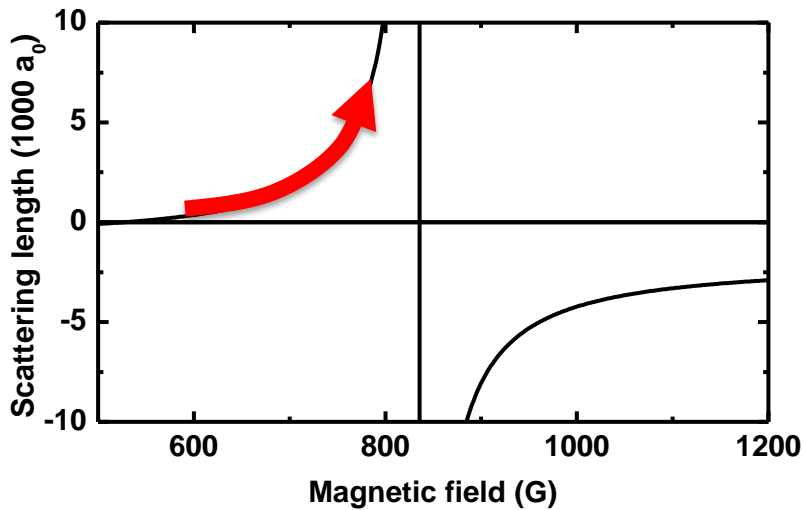
Tuning interactions: Feshbach resonance in ${}^6\text{Li}$



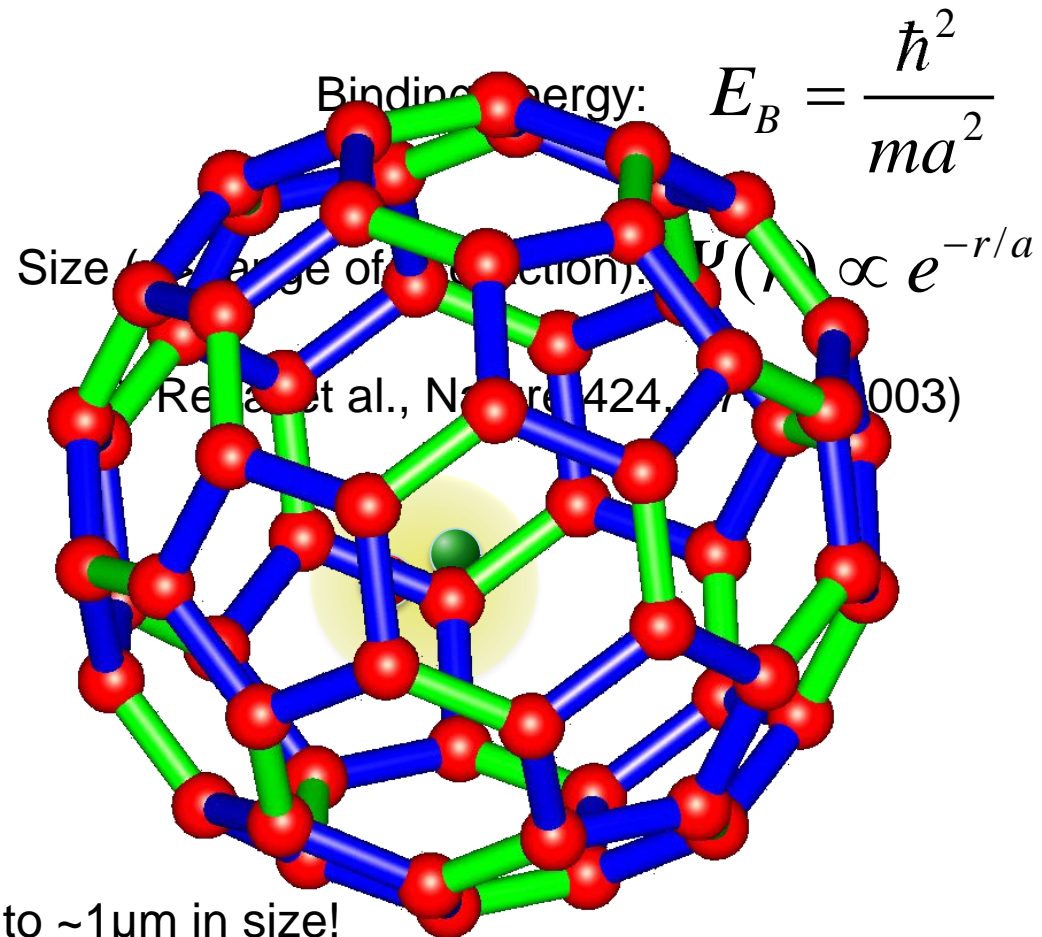
NO interaction between identical particles



Feshbach resonance: Magnetic-field dependence of s-wave scattering length

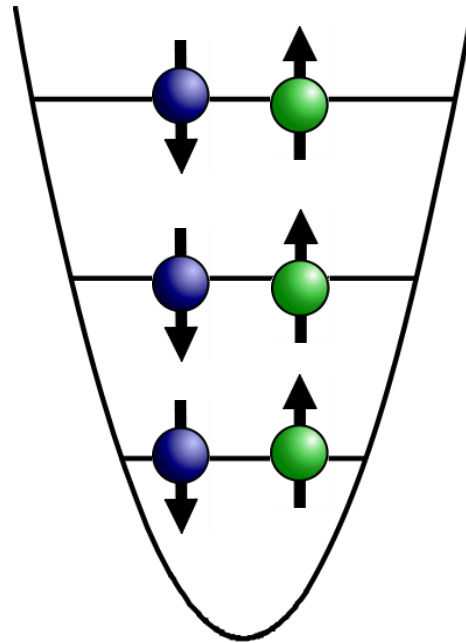


Two-body system: Tune the binding energy of a weakly bound molecule:



We have prepared such molecules up to ~1μm in size!

This talk





- How do we prepare our samples?
- How many particles do we need to form a heap?
- Controlling the motion of two particles in a double well

A picture from the lab ...

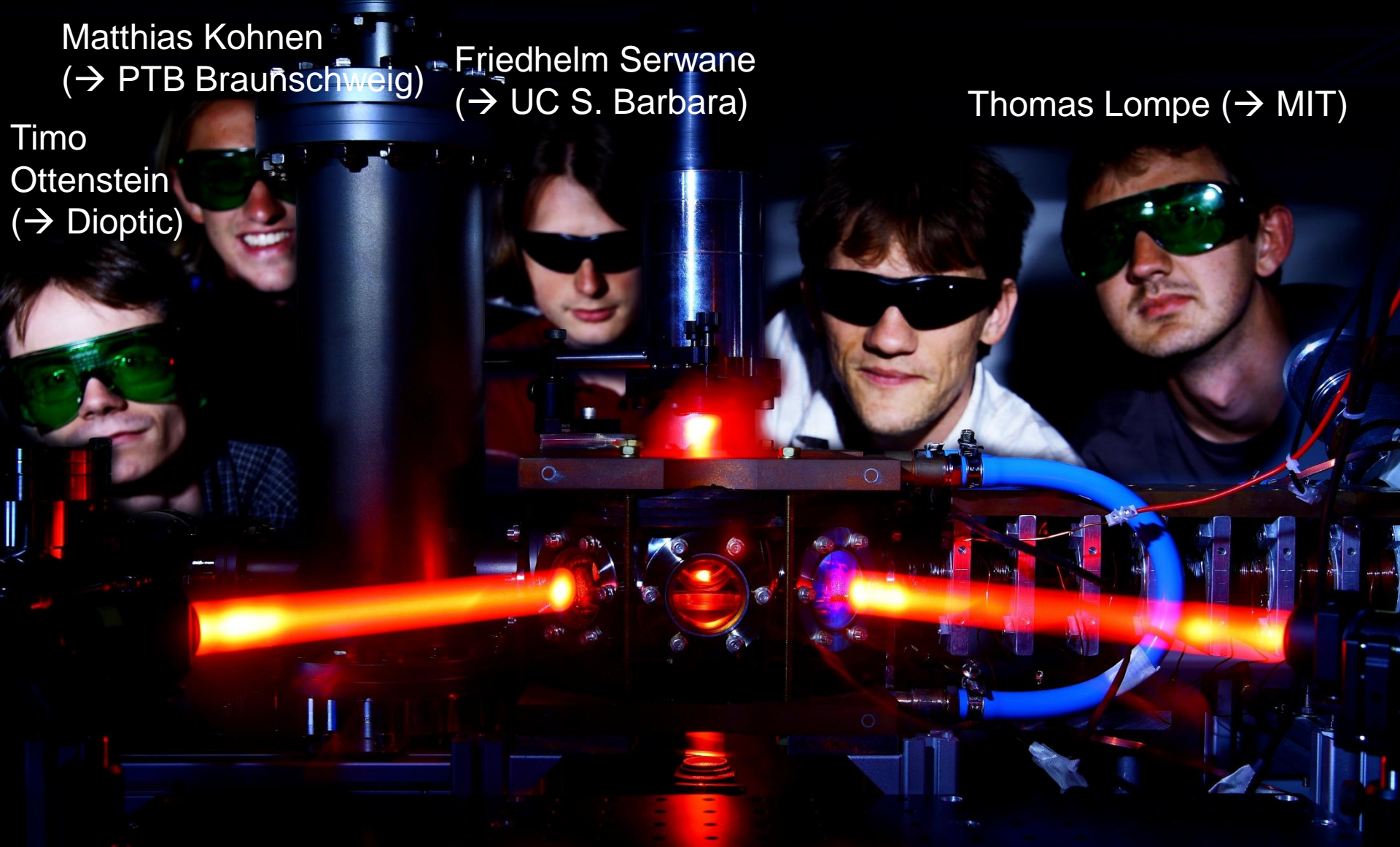


Matthias Kohnen
(→ PTB Braunschweig)

Friedhelm Serwane
(→ UC S. Barbara)

Thomas Lompe (→ MIT)

Timo
Ottenstein
(→ Diopic)



10^9 laser cooled atoms at $\sim 1\text{mK}$



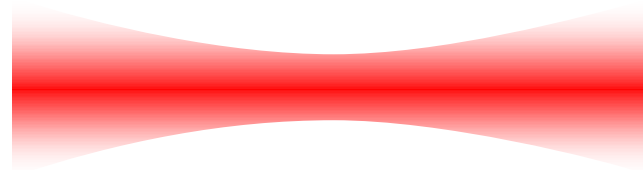


We need to isolate the atoms from the environment:



This might still work
for liquid nitrogen

... here we use the focus of a laser beam:



Optical dipole trap depth: $U \propto I(\mathbf{r})$



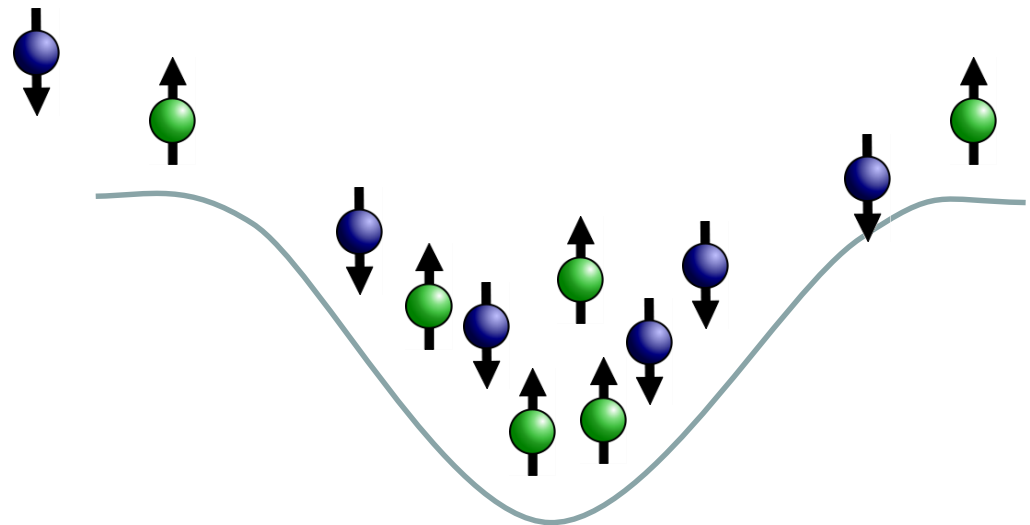


It just works the same:



For our cup of coffee ...

... and for our cold atoms:
Cool from $\sim 1\text{mK}$ down to
below $1\mu\text{K}$

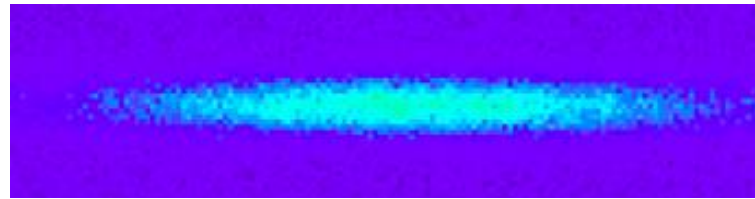


Just reduce the trap depth, i.e. laser power



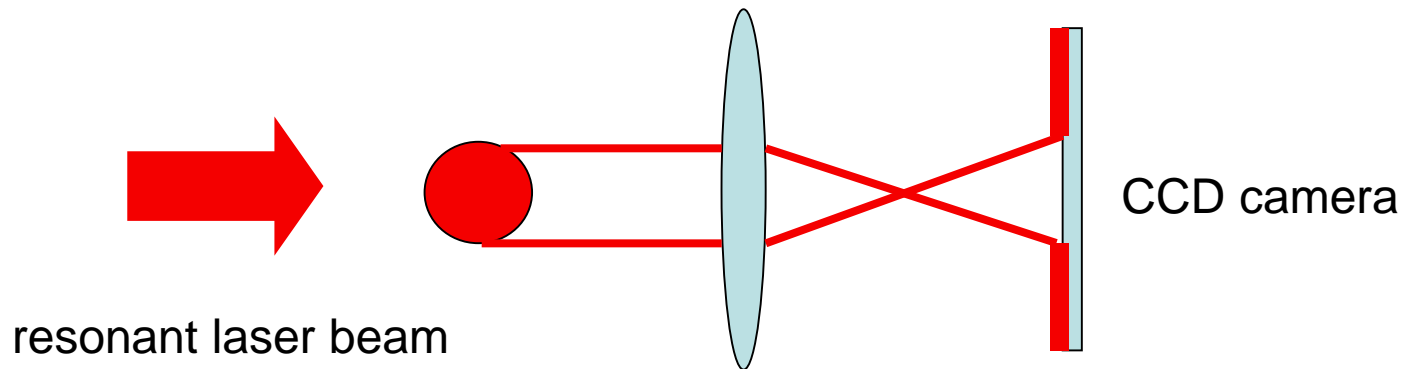


About 50000 atoms @ 250nK, $T_F \sim 1\mu\text{K}$

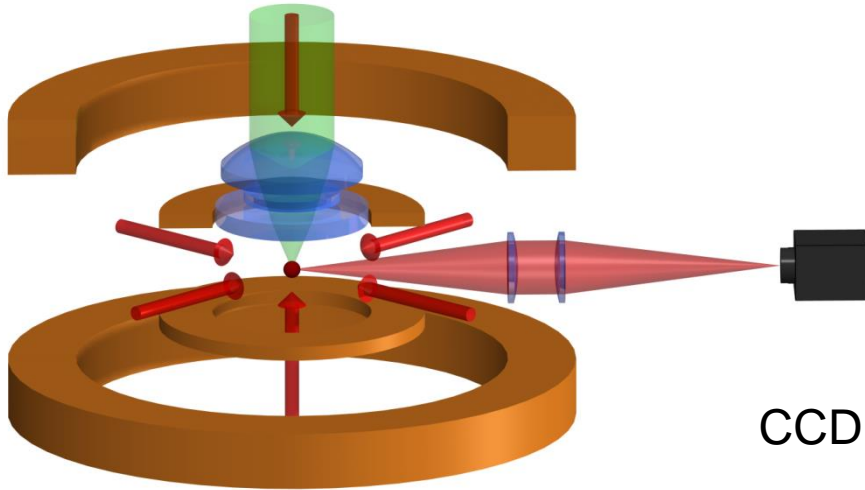


$\sim 100\mu\text{m}$

Absorption imaging of ultracold clouds:

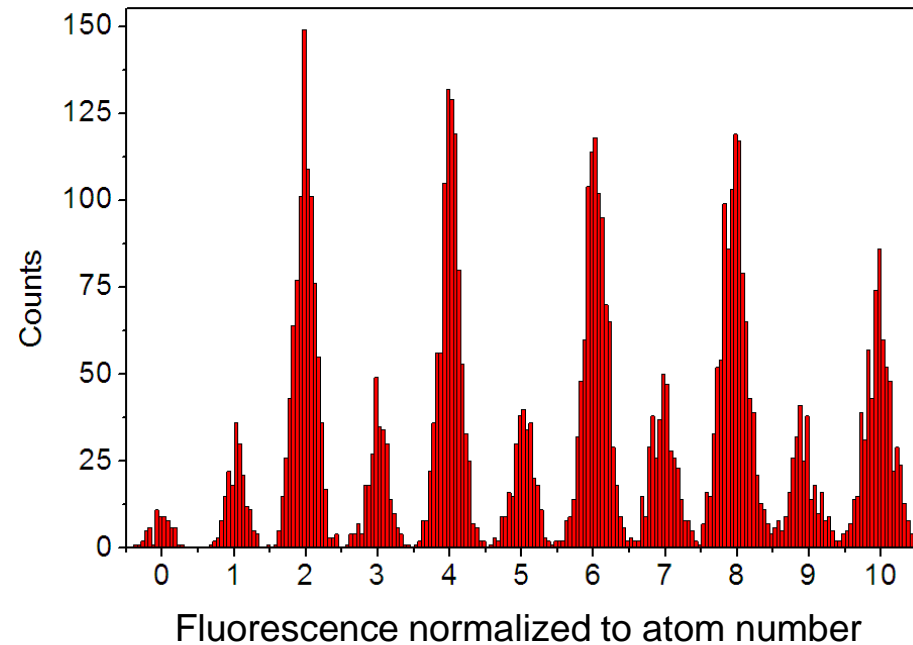
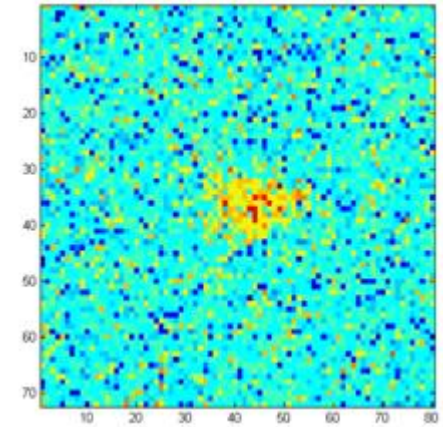


Single atom detection



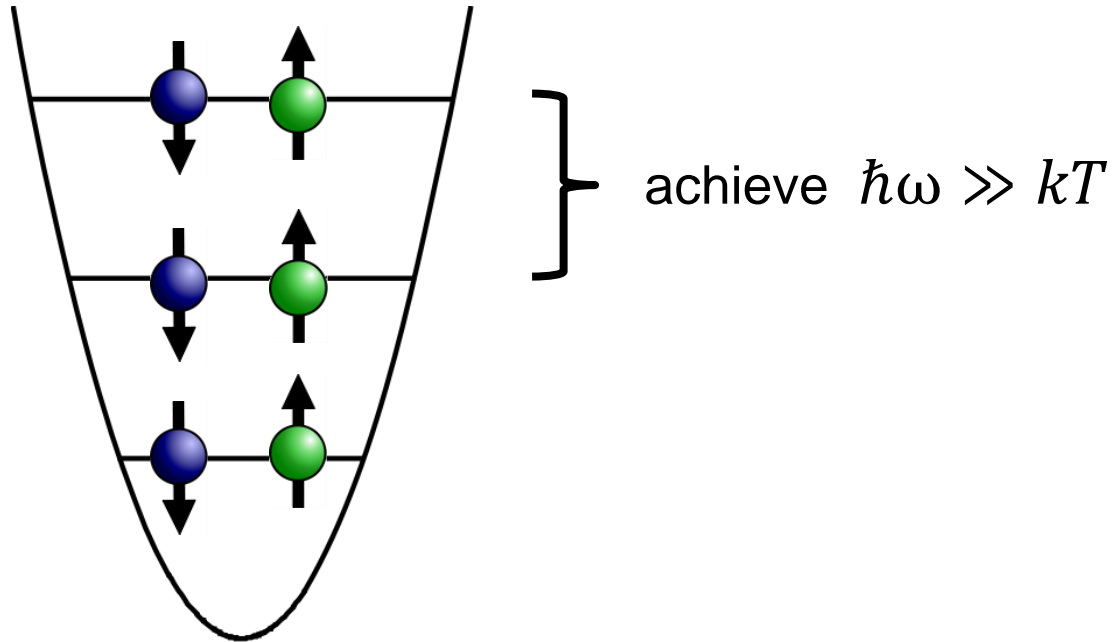
1-10 atoms can be distinguished with high fidelity > 99%

one atom in a MOT
 $1/e$ -lifetime: 250s
Exposure time 0.5s



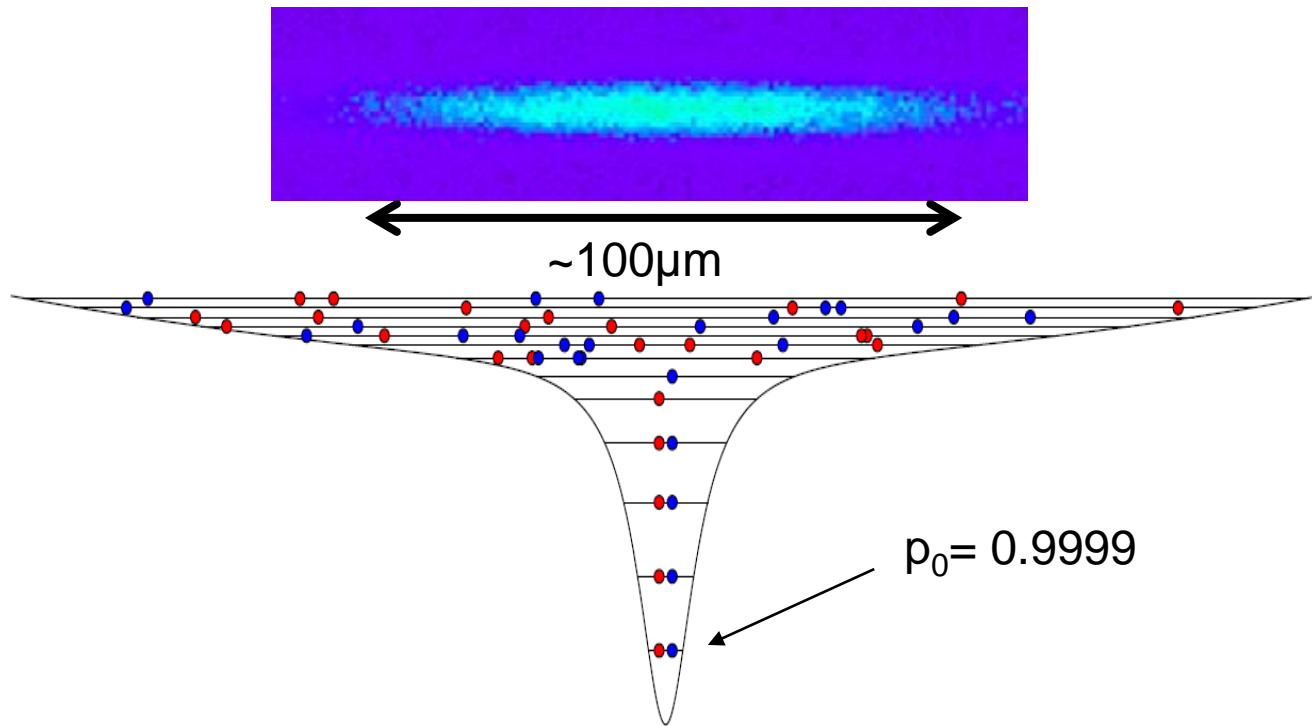
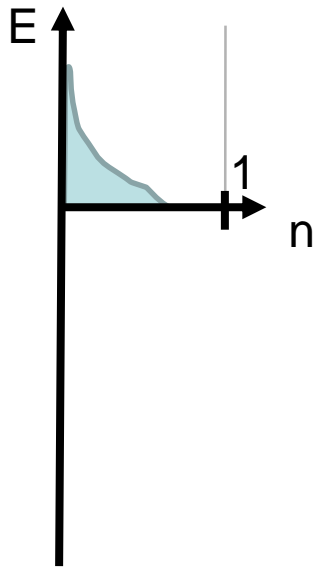


The challenge:





Fermi-Dirac dist.



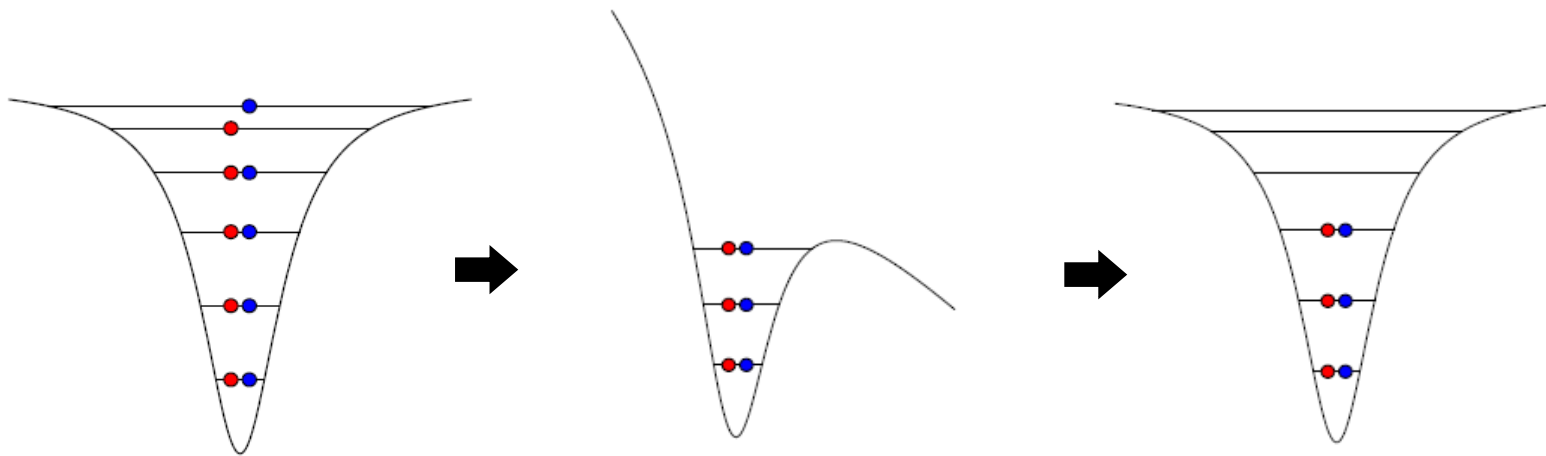
- 2-component mixture in reservoir
- superimpose microtrap ($\sim 1.8 \mu\text{m}$ waist)



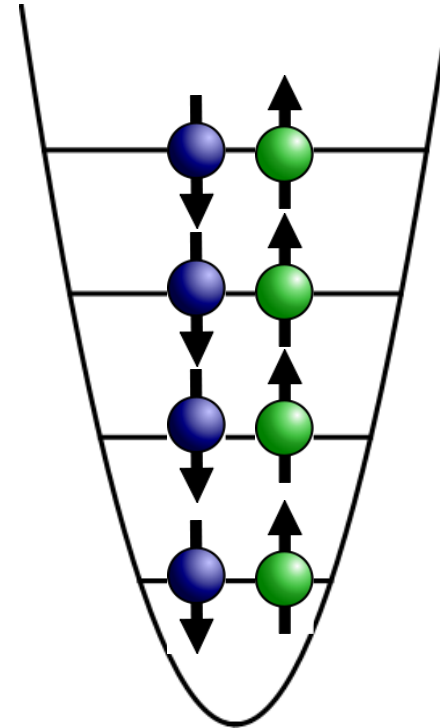
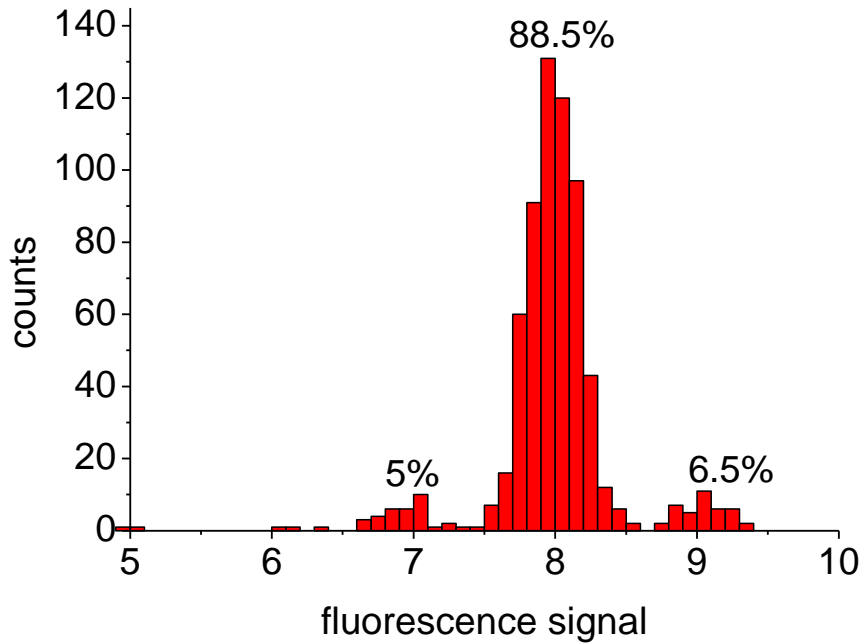
Creating a finite gas of fermions



- switch off reservoir



+ magnetic field gradient in
axial direction



- We can control the atom number with exceptional precision!
- Note aspect ratio 1:10: **1-D situation**
- **So far: Interactions tuned to zero ...**



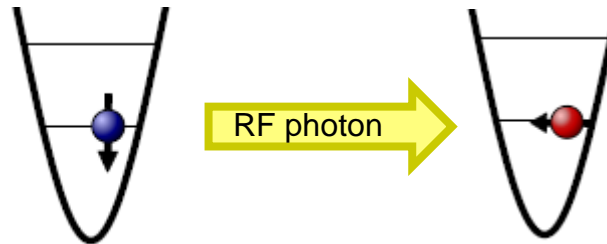
Let's study the interacting system!



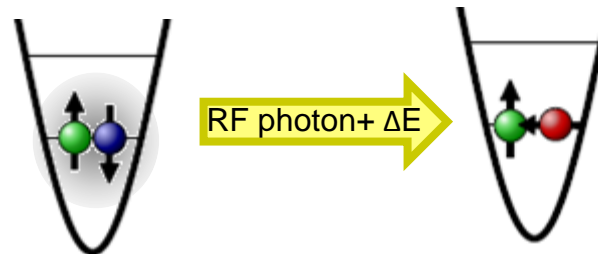


Radio Frequency spectroscopy

„bare“ RF – transition



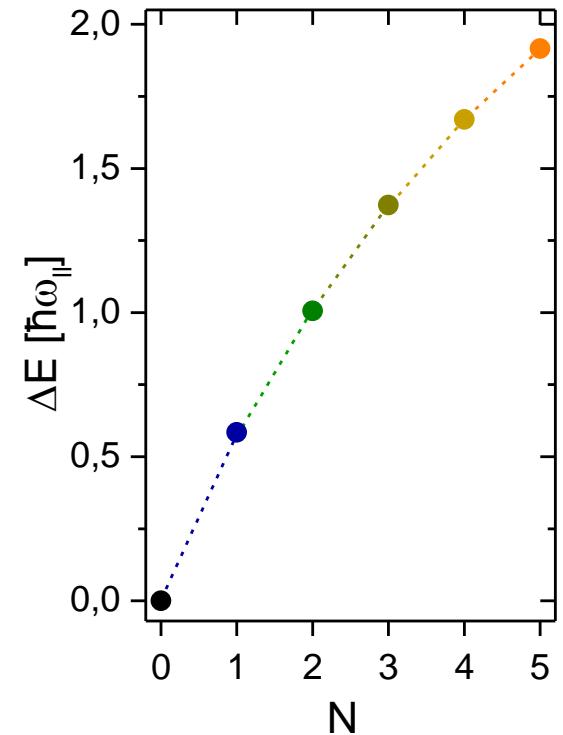
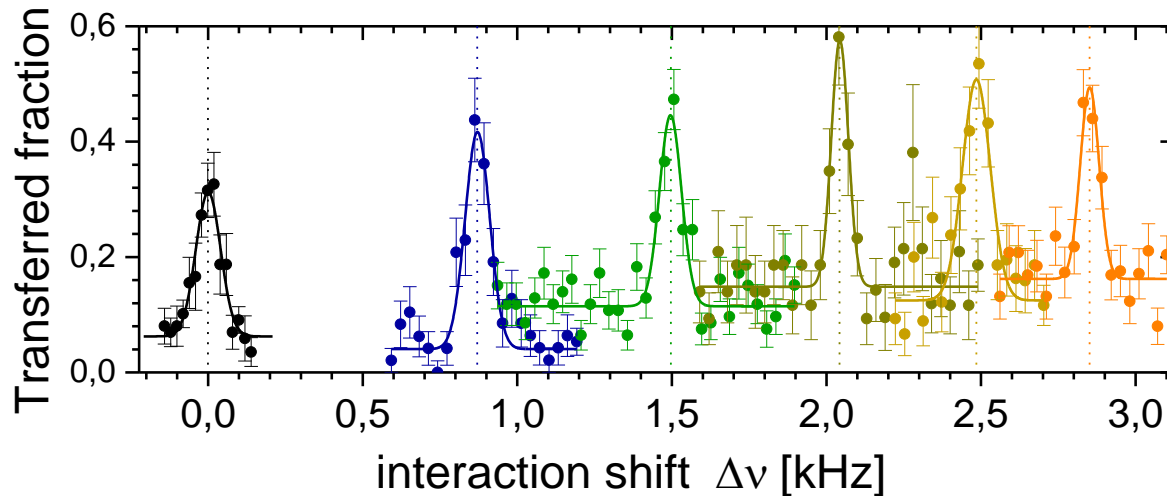
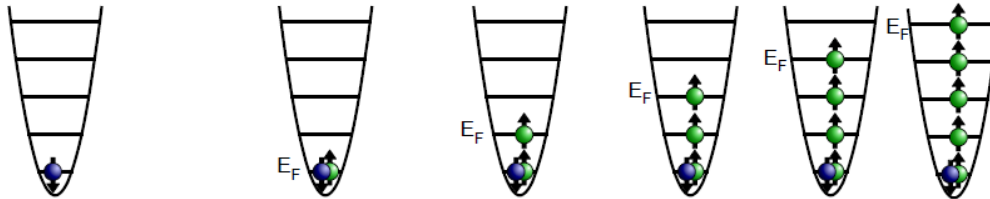
RF – transition with interaction



Measure the interaction energy



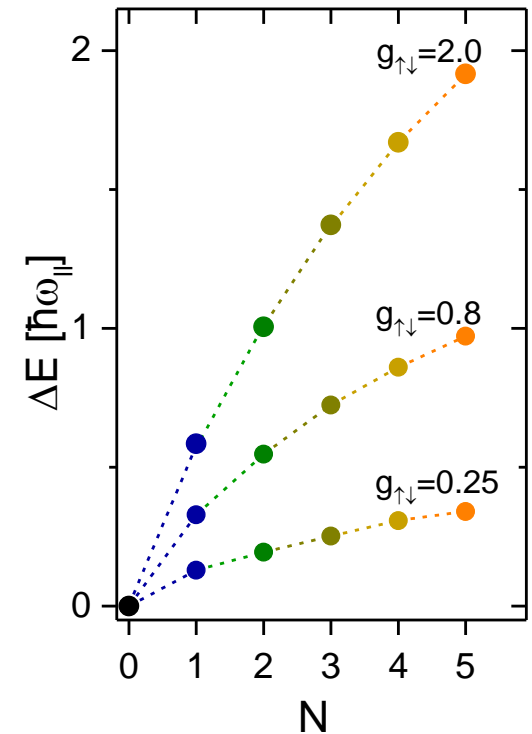
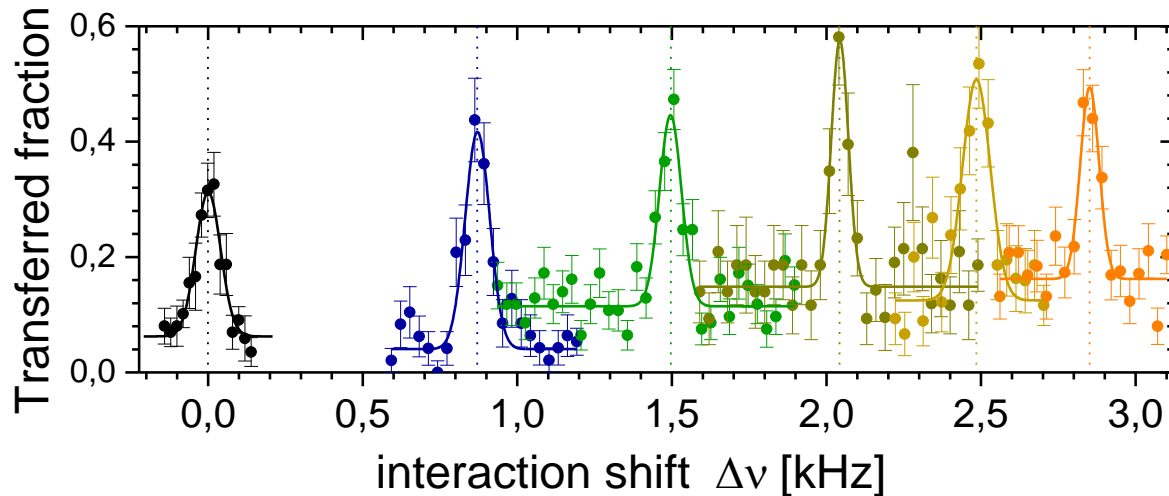
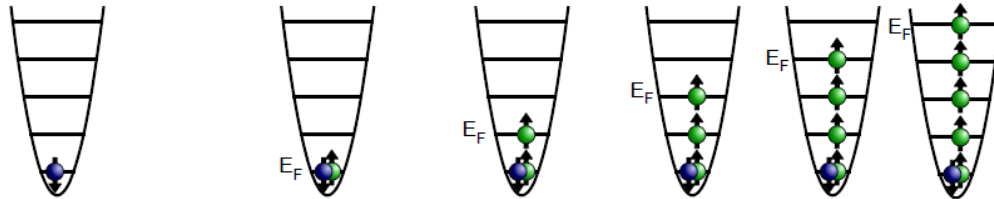
vary the number of majority particles:

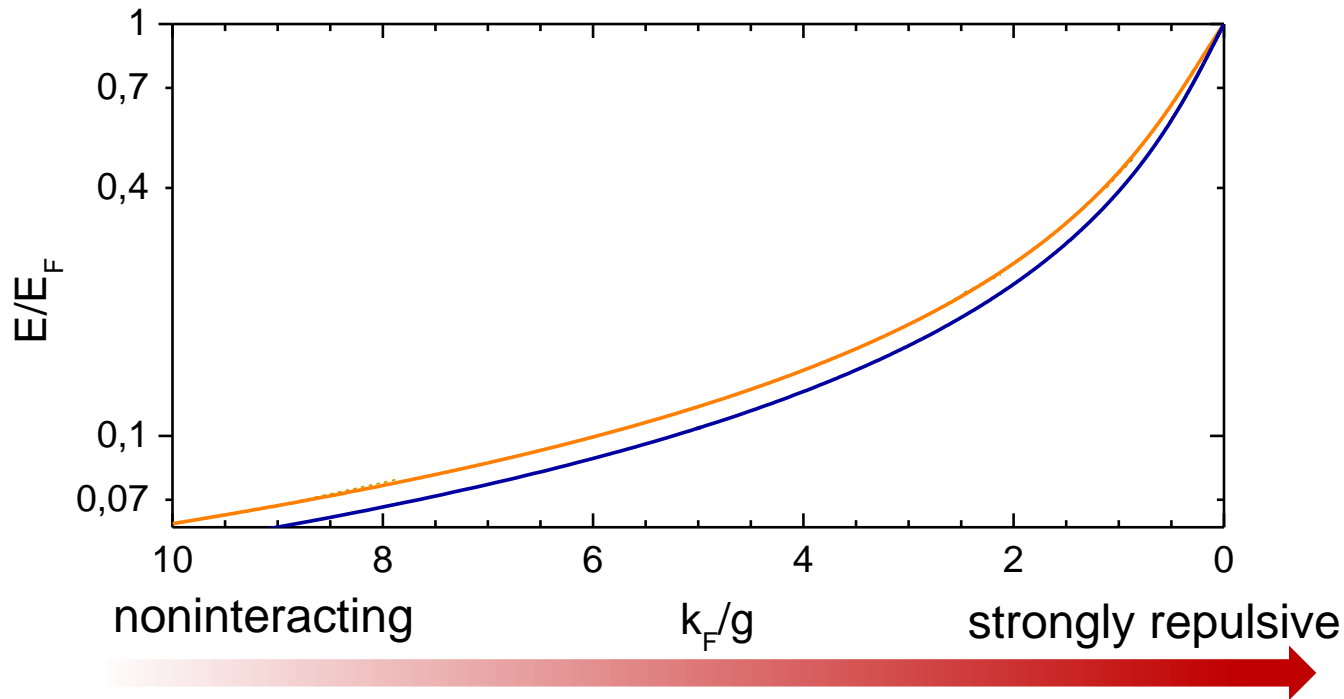


Measure the interaction energy




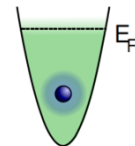
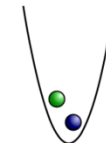
vary the number of majority particles:

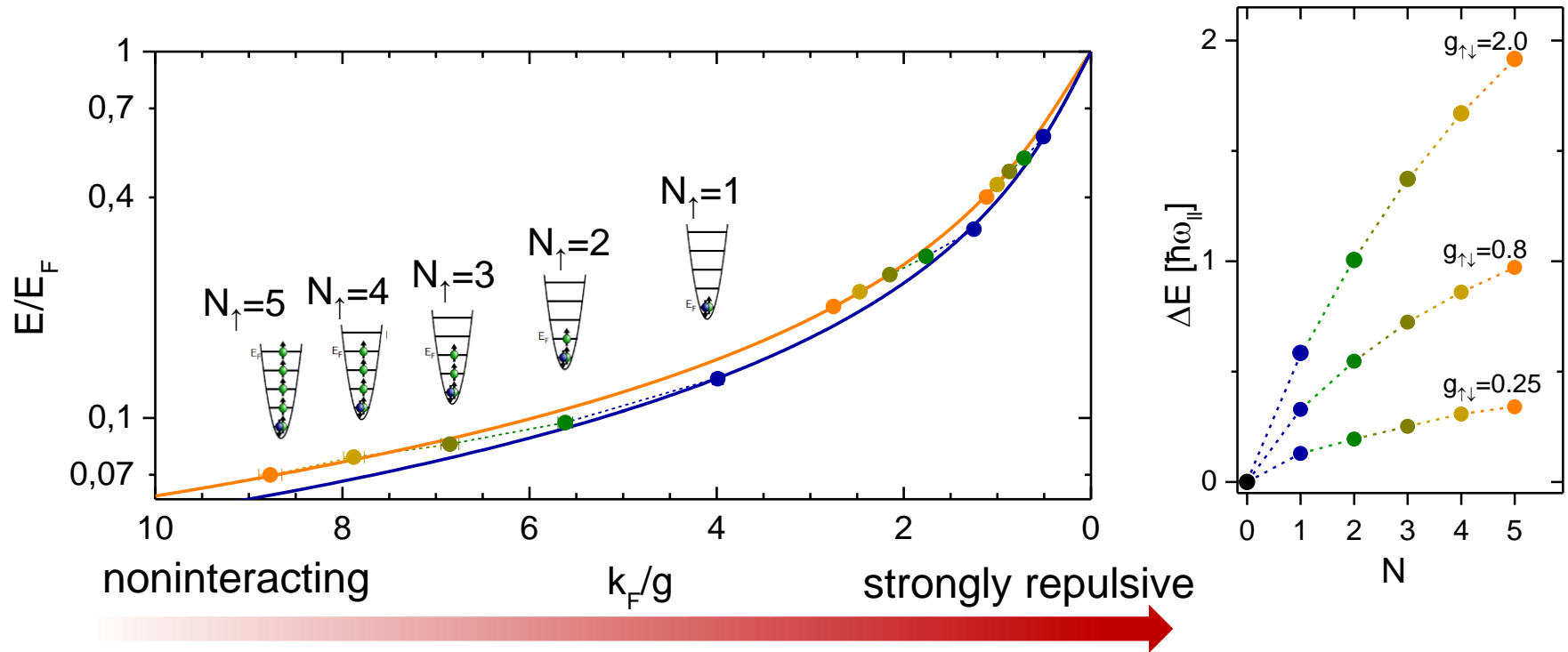





 Analytic solution of the two particle problem
T.Busch et al., Found. Phys. 28, 549 (1998)

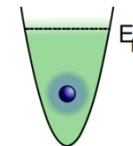
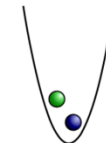
 Analytic solution for an infinite number of majority particles
J. McGuire, J. Math. Phys. 6,432 (1965)
(local density approximation)

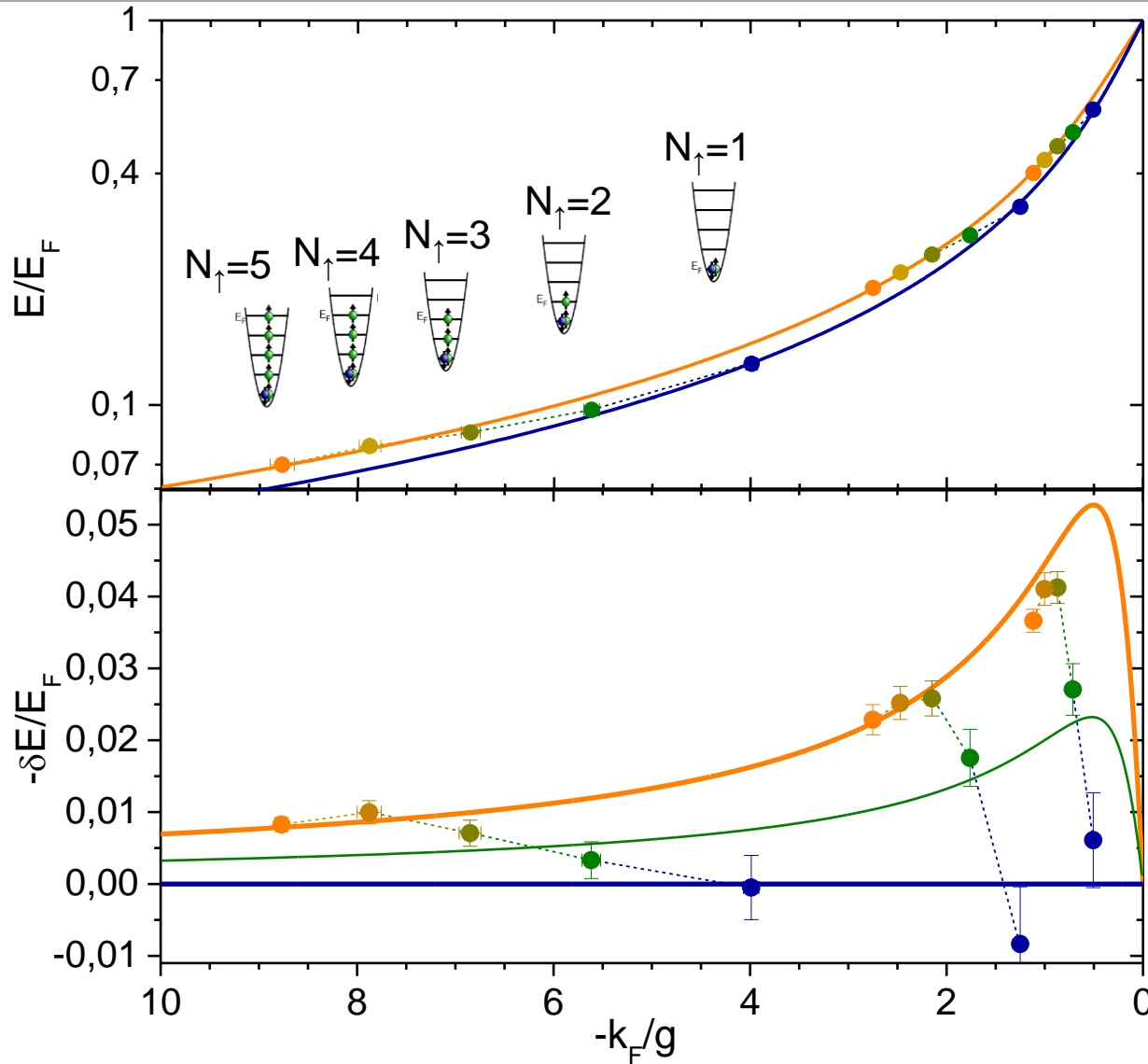




 Analytic solution of the two particle problem
T.Busch et al., Found. Phys. 28, 549 (1998)

 Analytic solution for an infinite number of majority particles
J. McGuire, J. Math. Phys. 6,432 (1965)
(local density approximation)





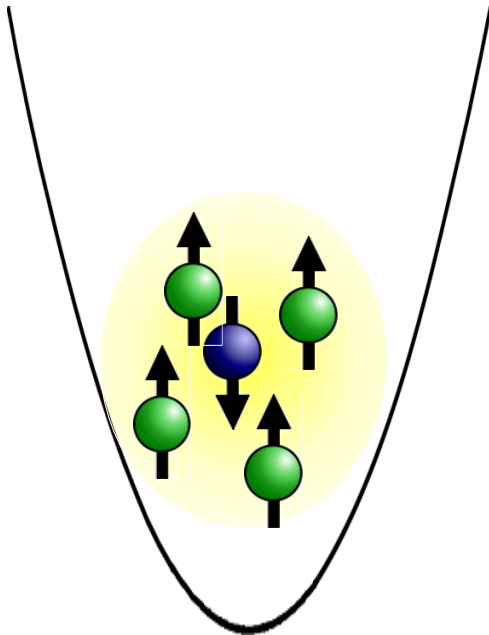
— 2 particles
— N particles
- - - 3 particles

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

G.E. Astrakharchik and
I. Brouzos, arxiv:1303.7007



... with very few particles (in a one-dimensional system)

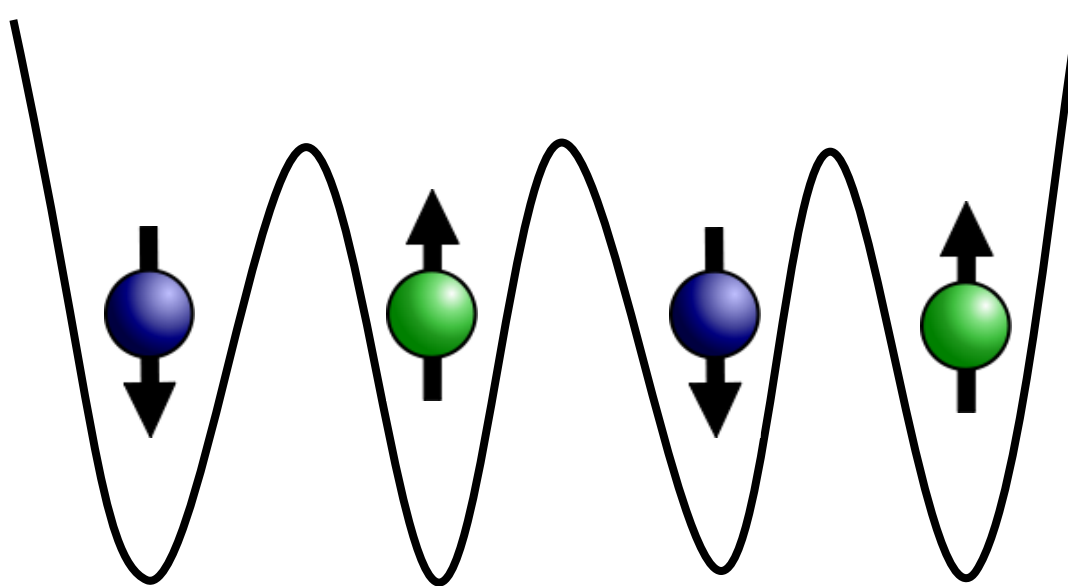


Interesting things to look at:

- Polaron physics in various dimensions
- The Kondo problem
- Anderson's orthogonality catastrophe

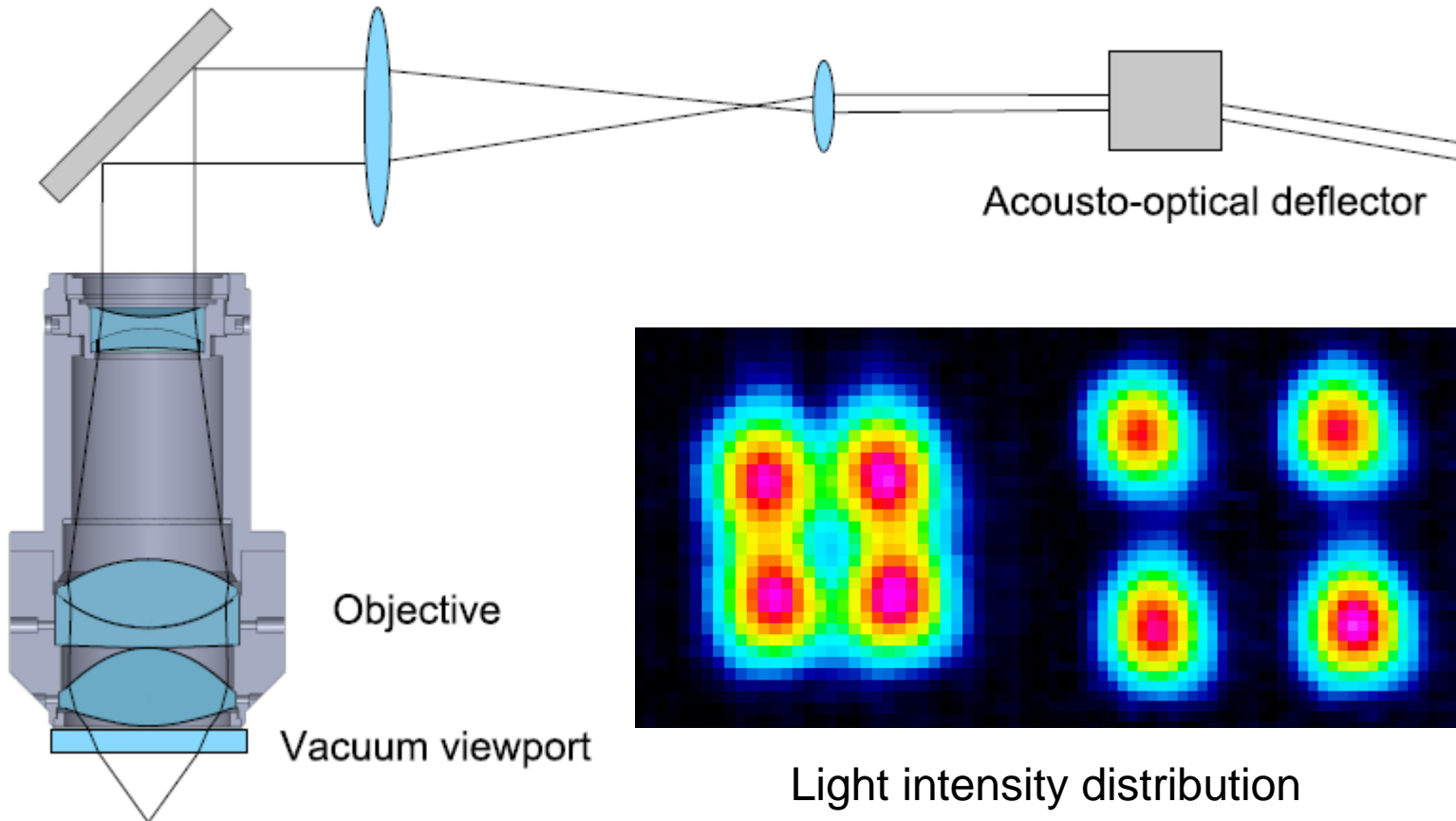


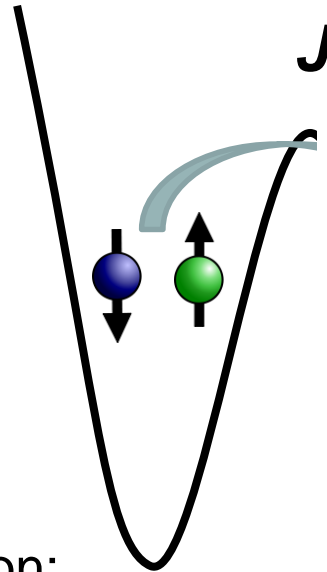
..... with similar fidelity and control?



Basic building blocks of matter!

The setup





initial spatial wave function:

$$|\Psi(t = 0)\rangle = |L\rangle_1 |L\rangle_2 = |LL\rangle$$

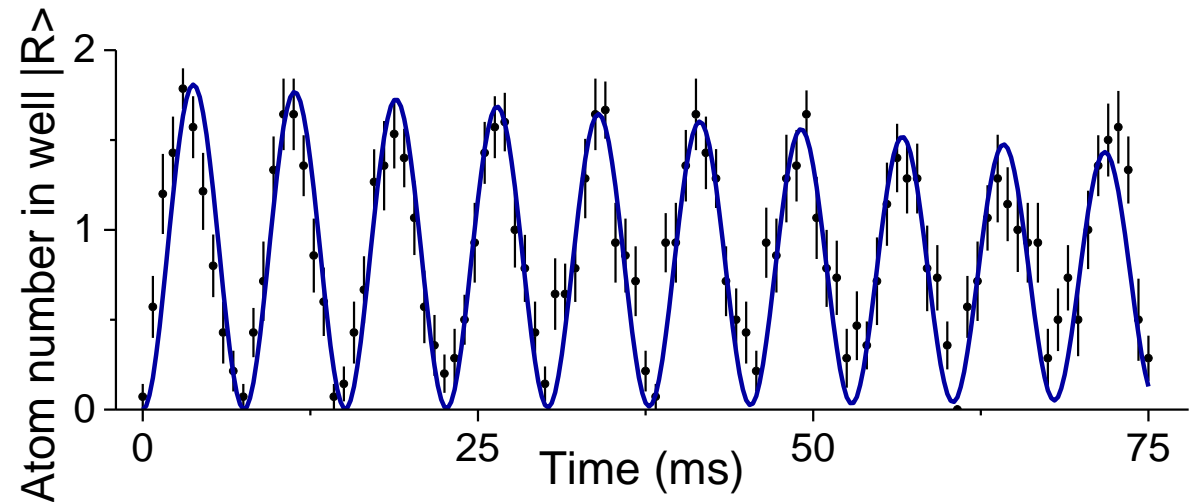
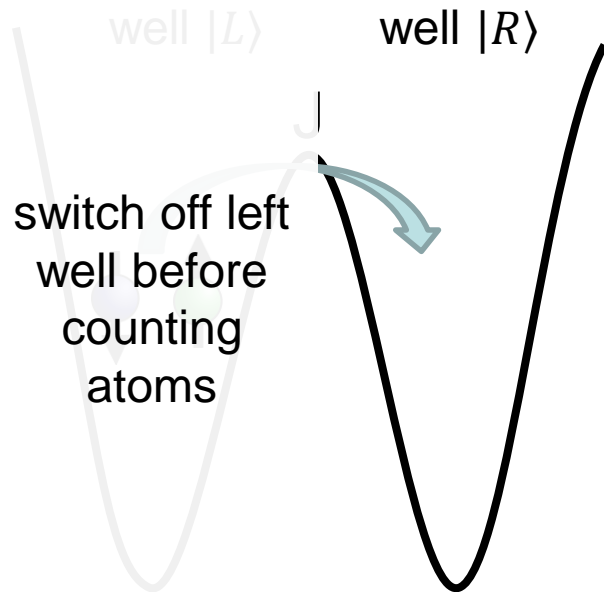
spin wave function (stationary)

$$|\chi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2) = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$





- Interactions switched off:



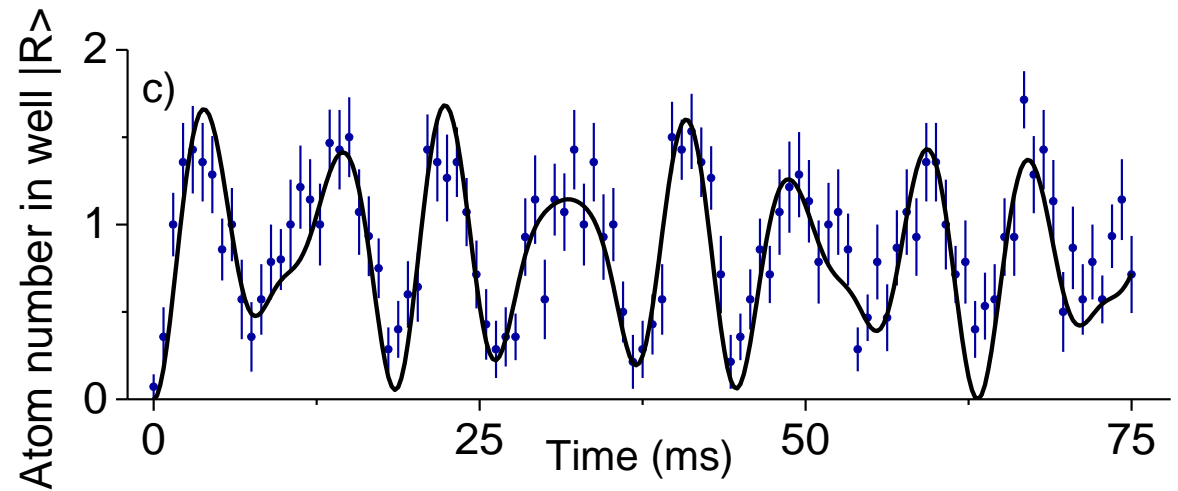
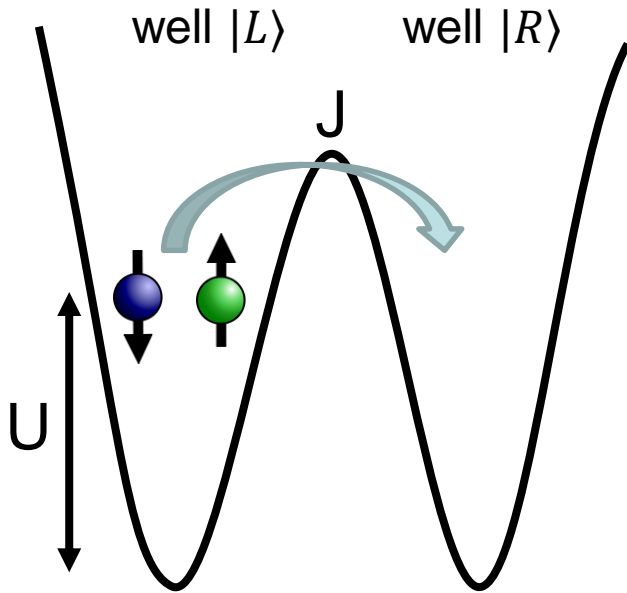
$$|\Psi(t)\rangle = |\psi(t)\rangle_1 |\psi(t)\rangle_2$$

$$|\psi(t)\rangle_1 = \frac{1}{2}((|L\rangle_1 + |R\rangle_1) + (|L\rangle_1 - |R\rangle_1)e^{-i\Delta Et/\hbar})$$

Two interacting atoms



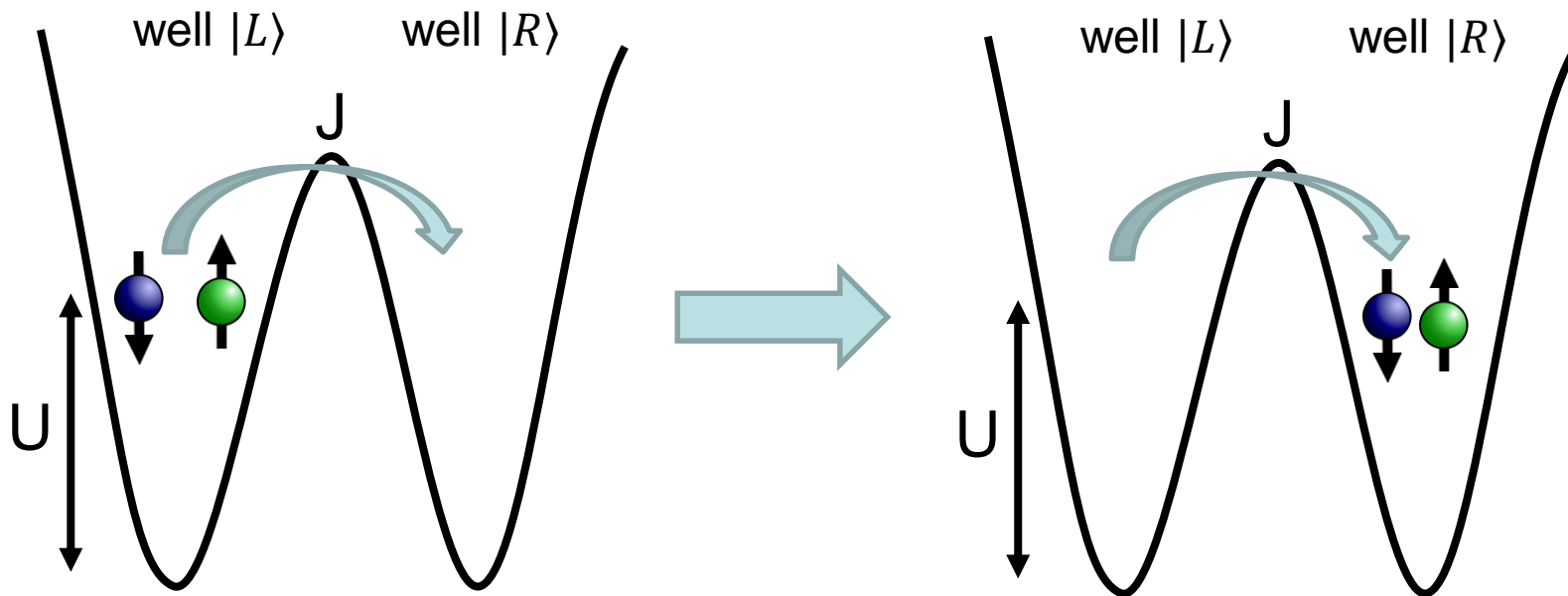
Interaction leads to entanglement:



$$|\Psi(t)\rangle \neq |\psi(t)\rangle_1 |\psi(t)\rangle_2$$

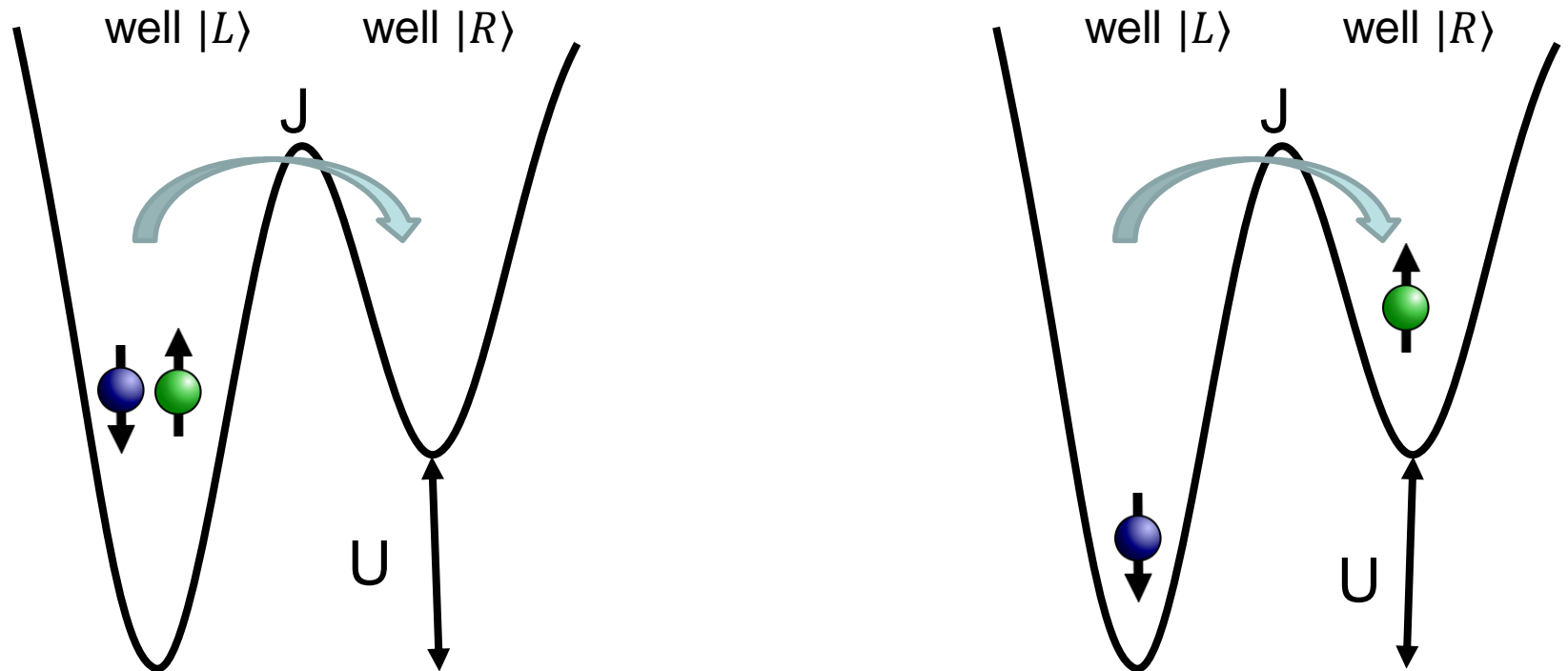


Two strongly interacting atoms



In a balanced double well, they can only tunnel together!

Two strongly interacting atoms



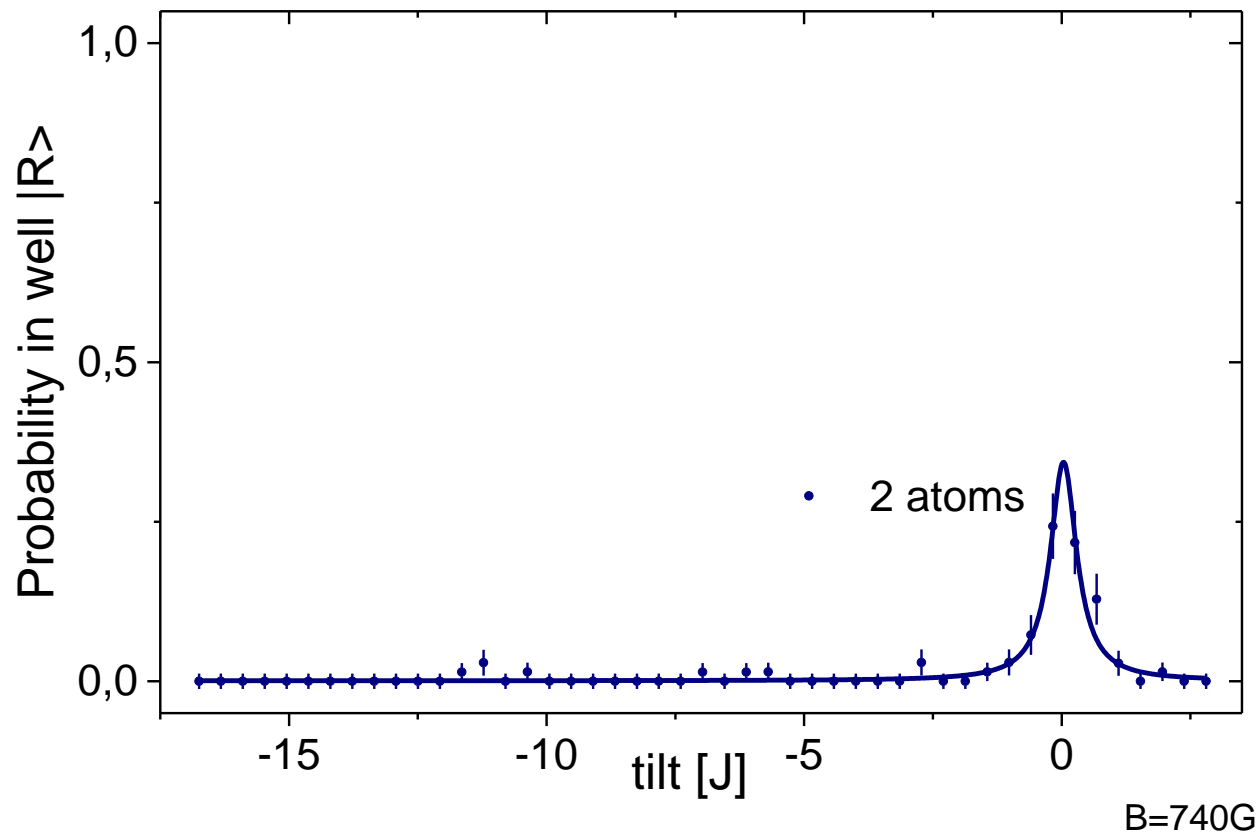
We can compensate for the interaction energy by applying a tilt!



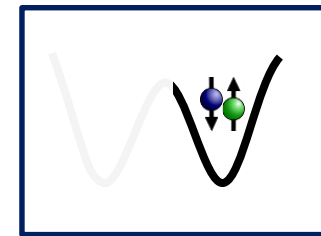
Two strongly interacting atoms



- Observe number statistics in the right well (time averaged)



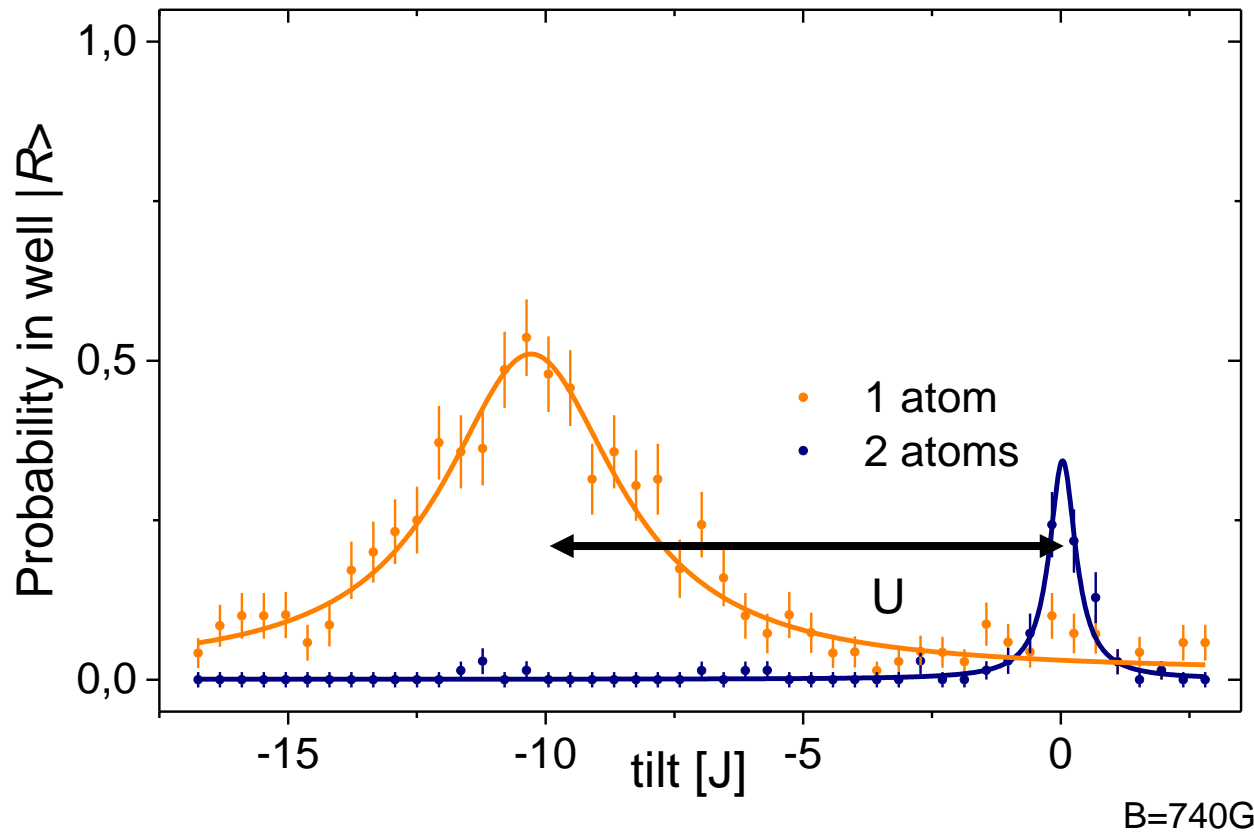
two atoms



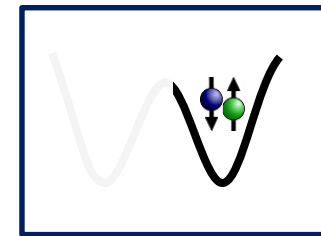
Two strongly interacting atoms



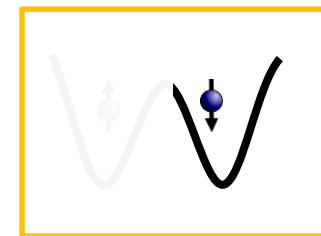
- Observe number statistics in the right well (time averaged)



two atoms



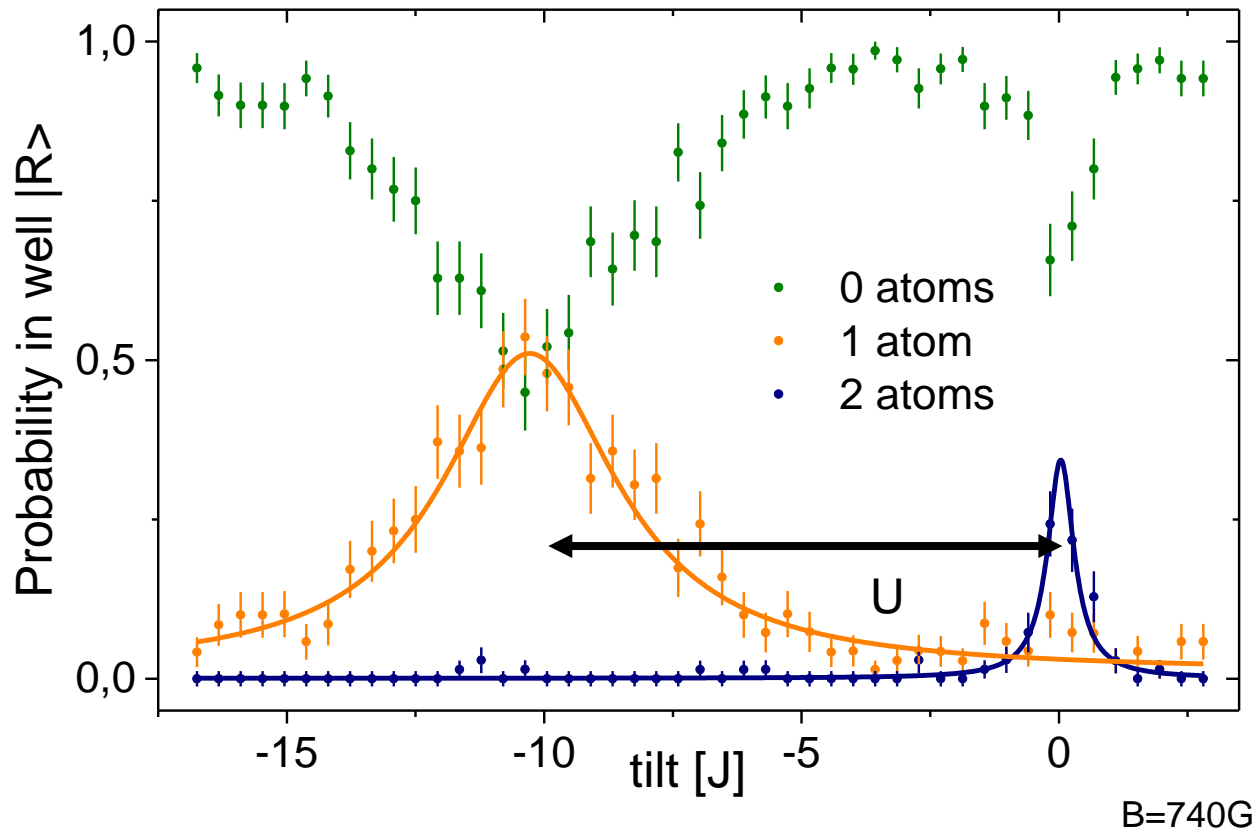
one atom



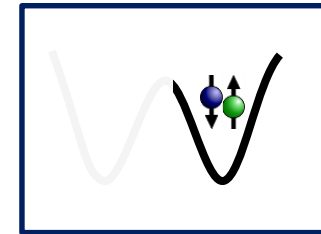
Two strongly interacting atoms



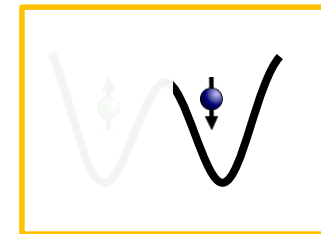
- Observe number statistics in the right well (time averaged)



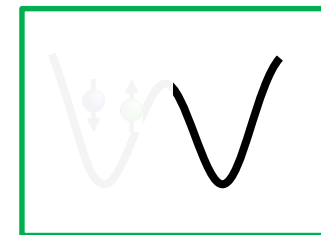
two atoms



one atom

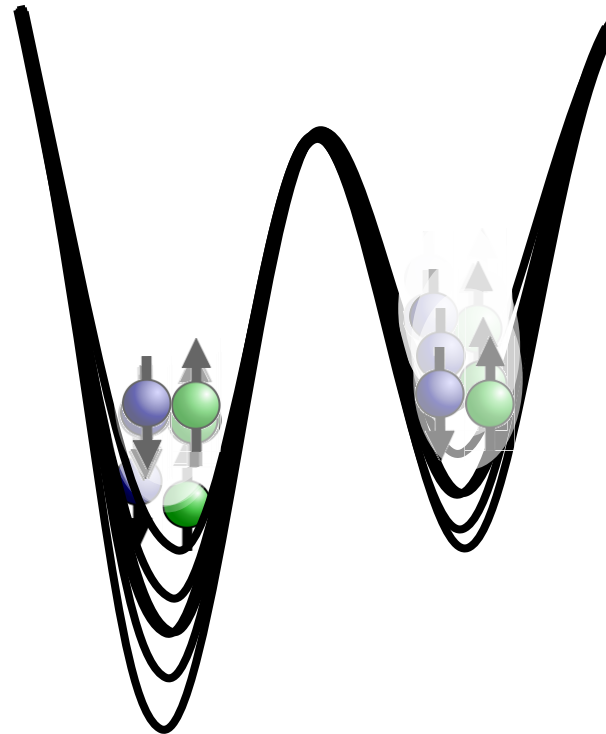


no atoms

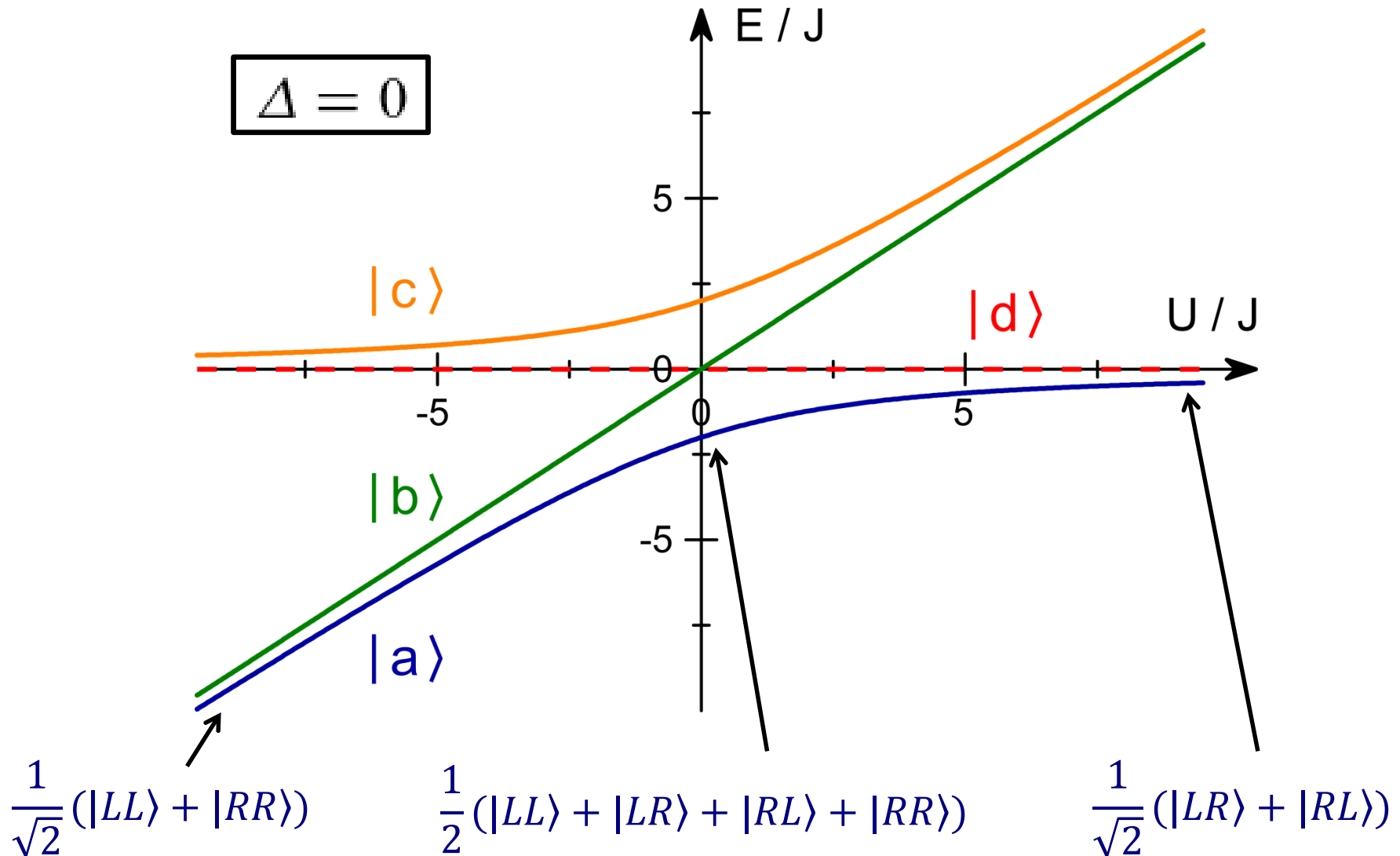




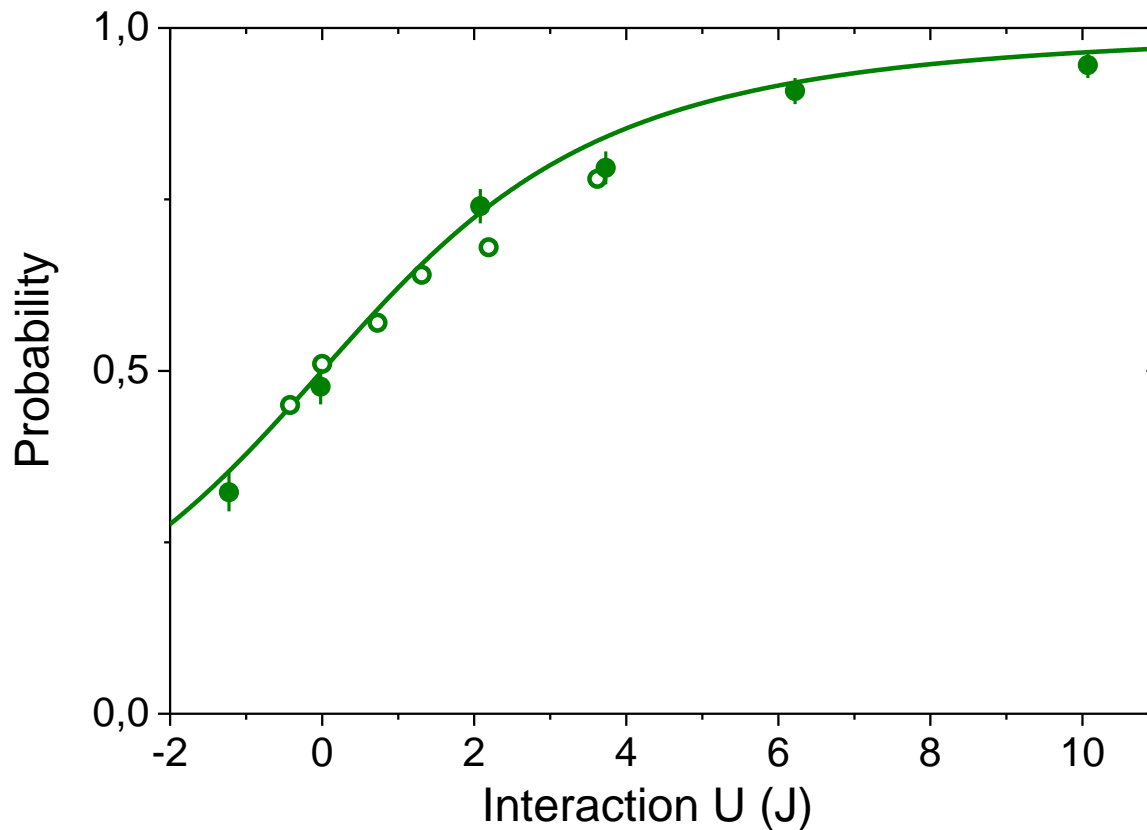
- If we ramp on the second well slowly enough, the system will remain in its ground state:



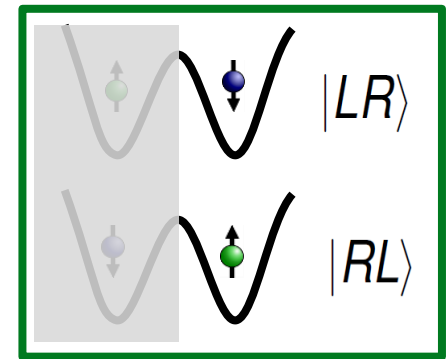
Eigenstates of a symmetric DW



- Number statistics for the balanced case depending on the interaction strength:



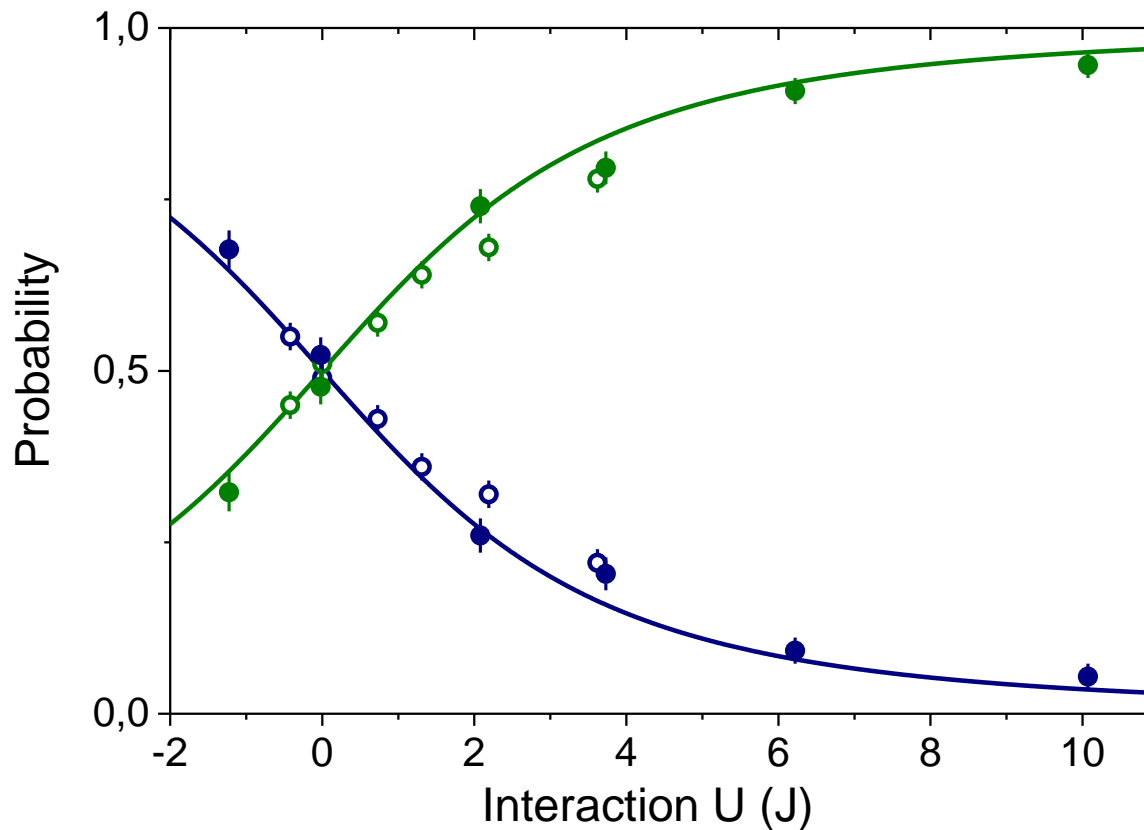
Single occupancy



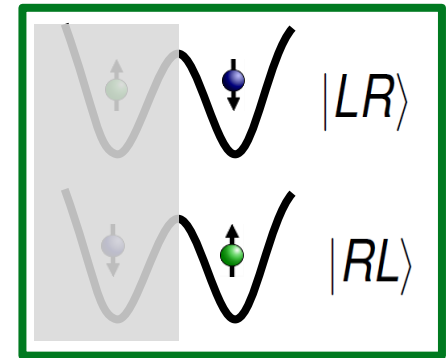
Preparing stationary states



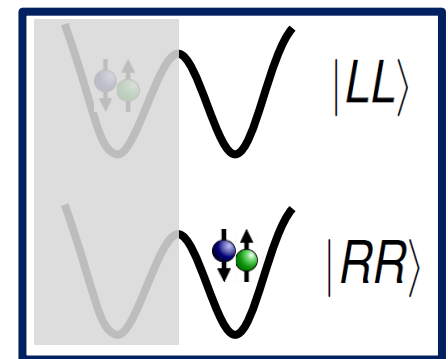
- Number statistics for the balanced case depending on the interaction strength:

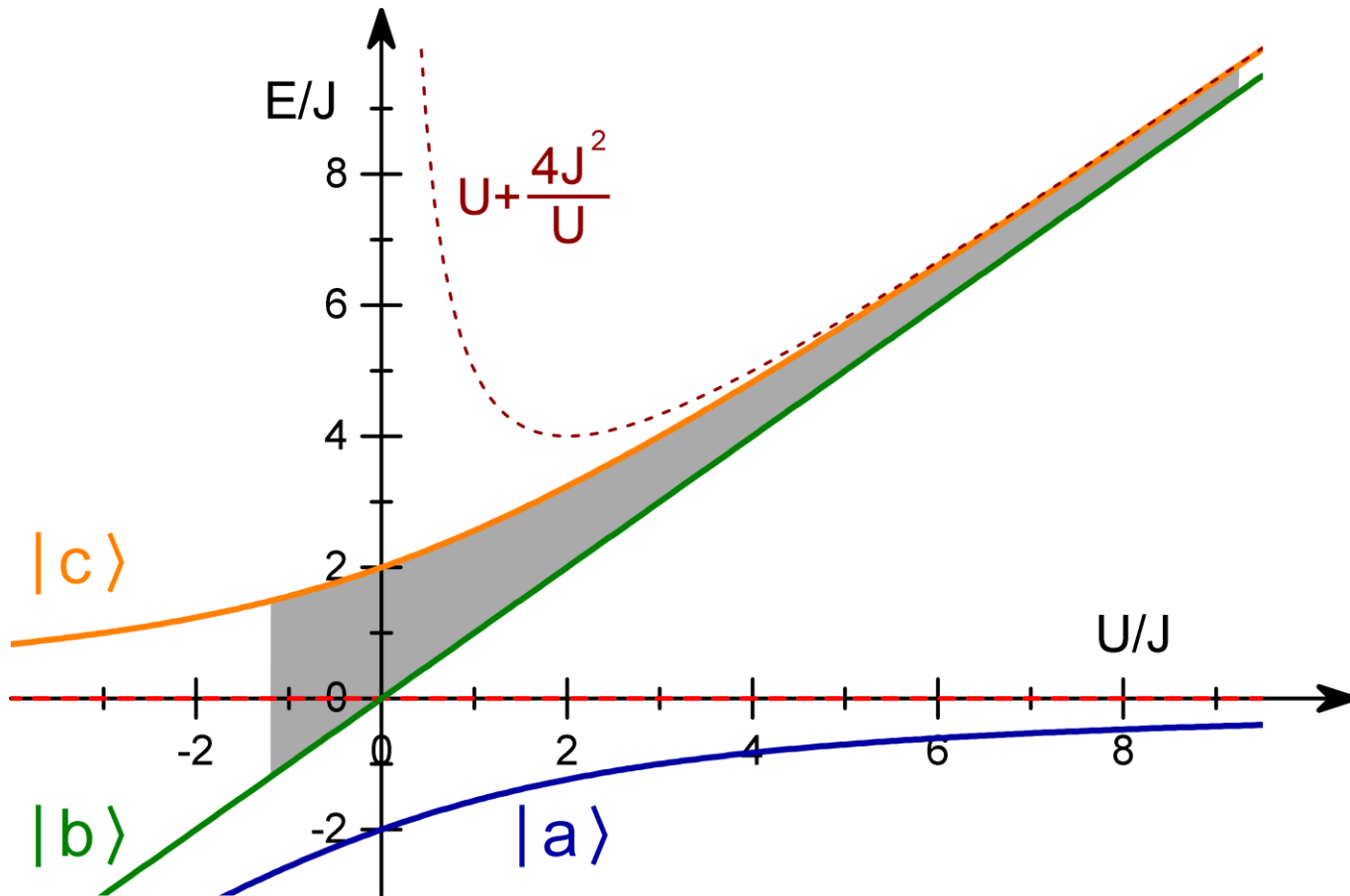


Single occupancy

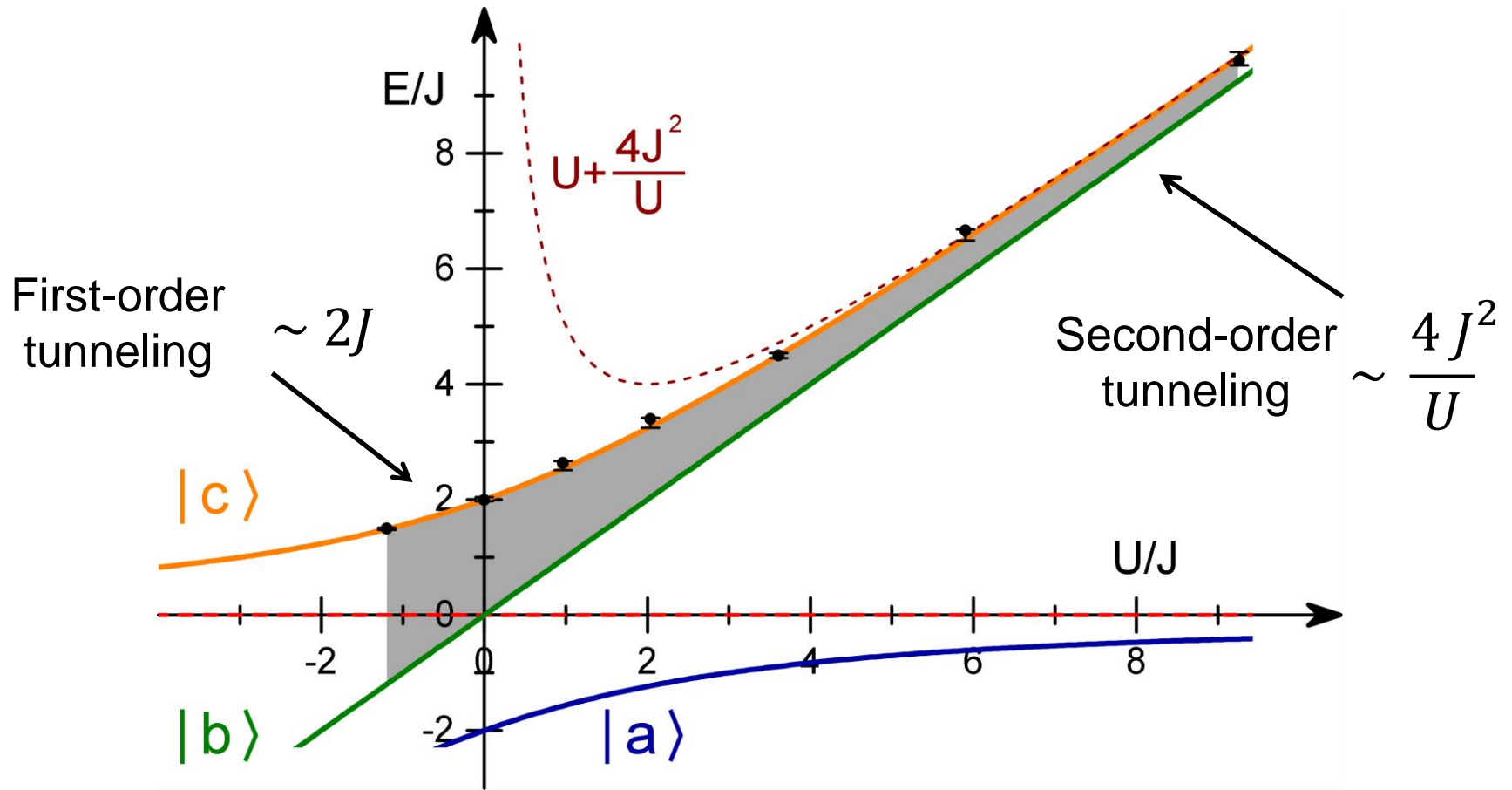


Double occupancy

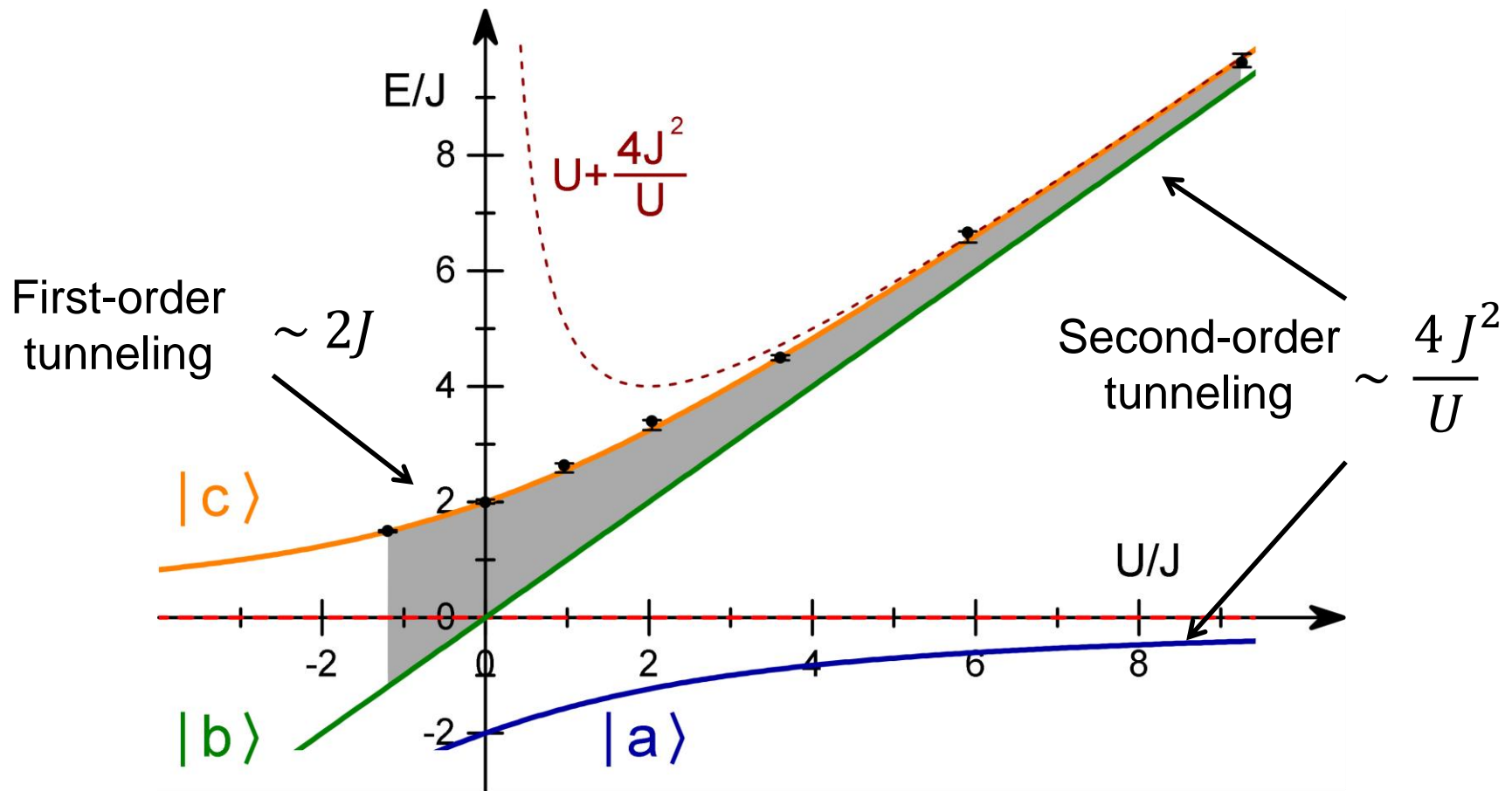




Trap modulation spectroscopy



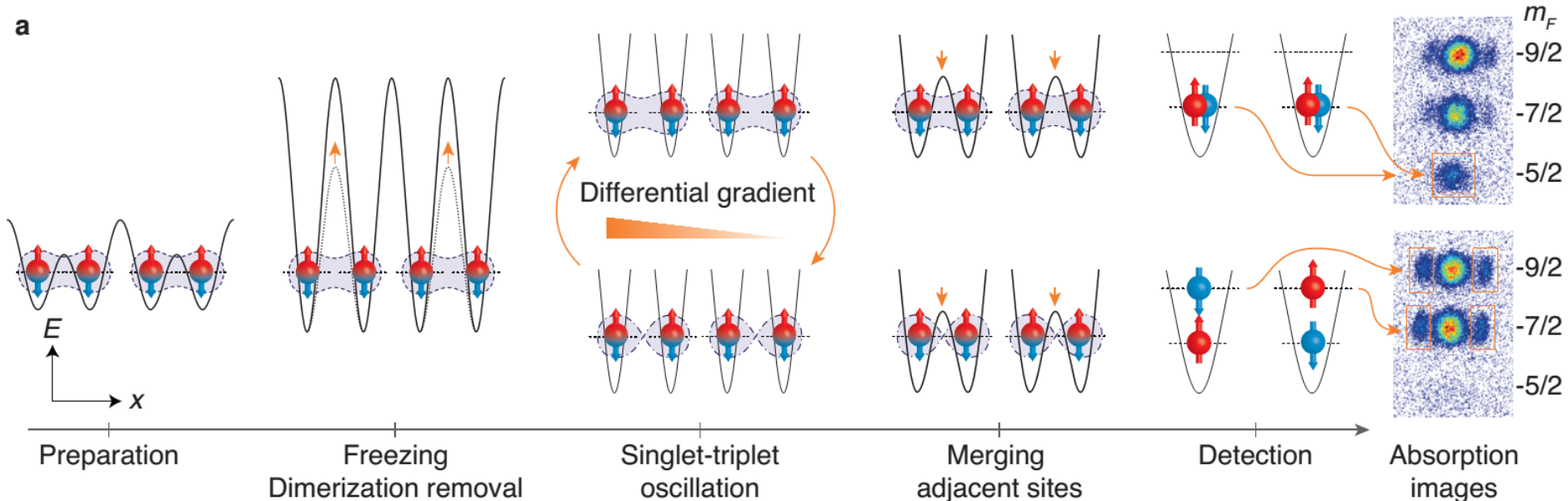
Trap modulation spectroscopy



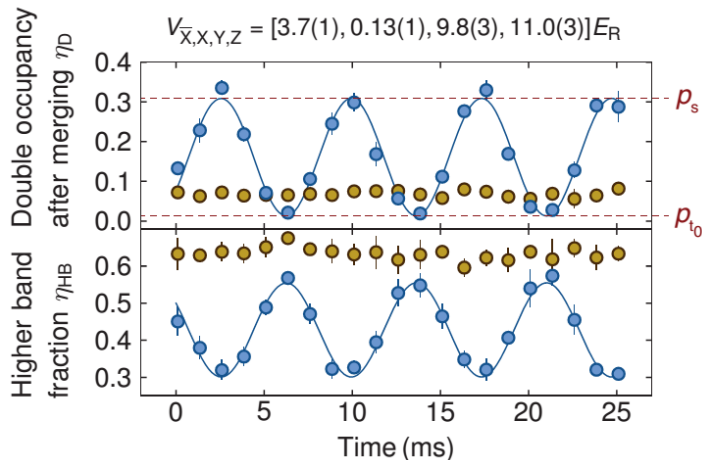
Super exchange energy!
responsible for spin ordering in the many body ground state

How to go to a many-body system?

- Inspired by a top-down approach: D. Greif et al., Science **340**, 1307-1310 (2013) (ETH Zürich)



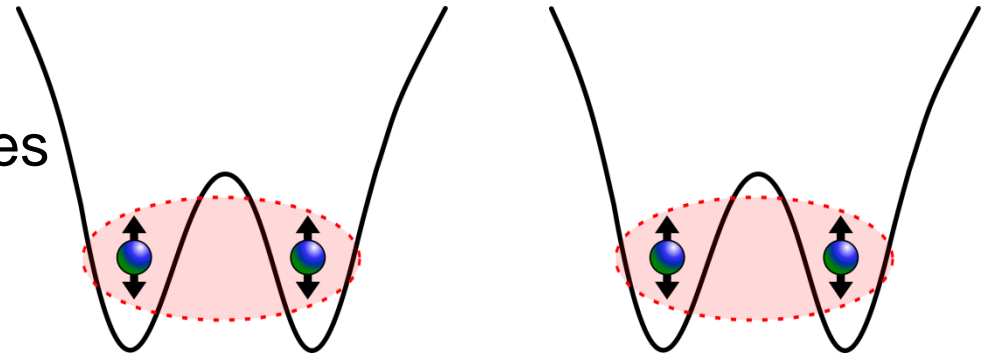
- Dimerize a lattice filled with spin-1/2 fermions to observe spin correlations



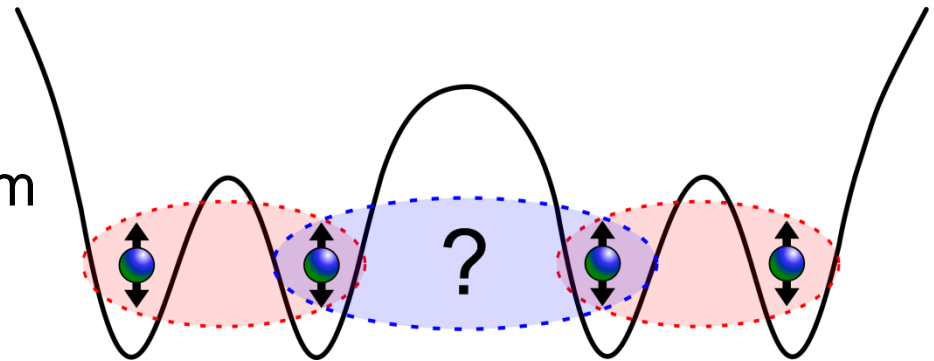


Combination of multiple double wells

- Preparation of ground states in separated double wells



- Combination to larger system



Can this process be done adiabatically ?
Can it be extended to larger systems ?

Thomas Lompe
(-> MIT)



Andre
Wenz



Mathias Neidig

Martin Ries

Simon Murmann

Sebastian Pres

Puneet Murthy

Dhruv
Kedar



Andrea Bergschneider

Selim
Jochim

Gerhard Zürn

Vincent Klinkhamer

Thank you for your attention!

Funding:

Center for
Quantum
Dynamics

