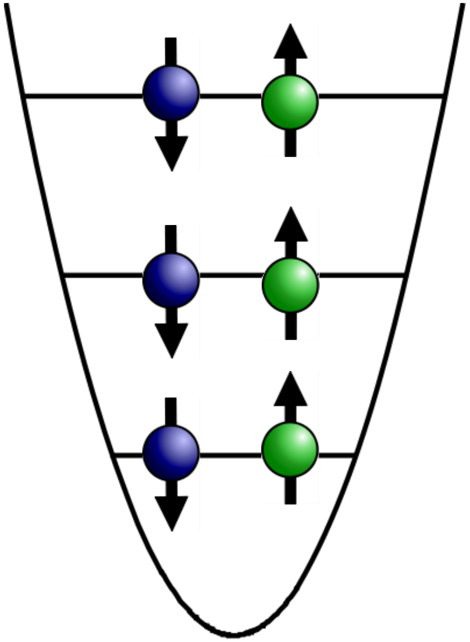
One, two, three, many
Creating quantum systems one atom at a time



Selim Jochim, Universität Heidelberg

One, two, three, many
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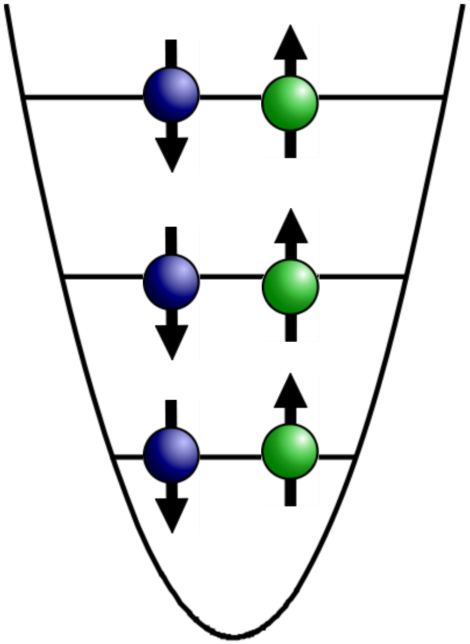

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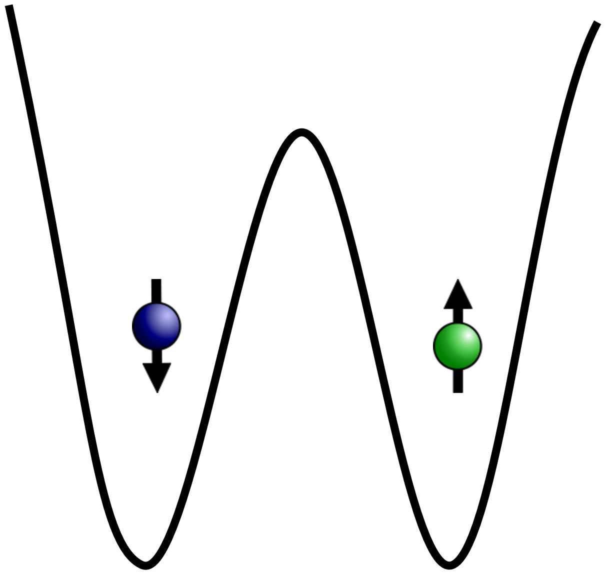
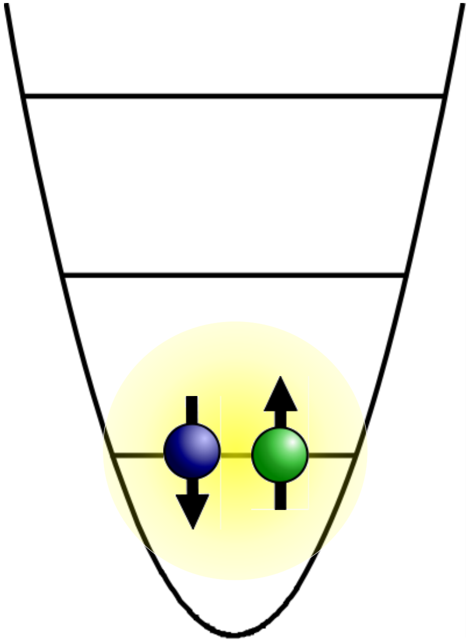


Selim Jochim, Universität Heidelberg

Two trapped interacting particles …

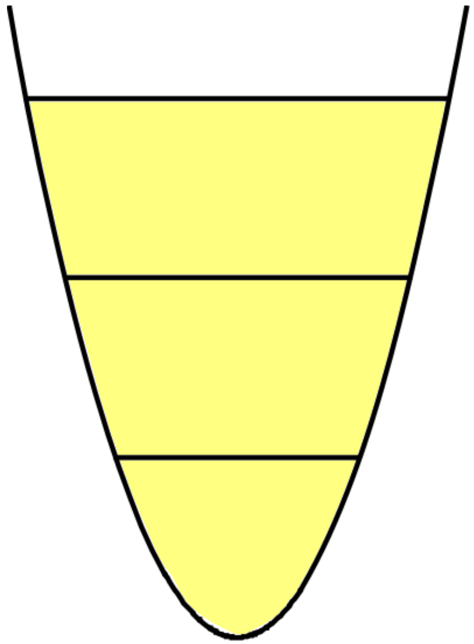
interacting singlet



Ground state of the Helium atom:

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

Many body limit



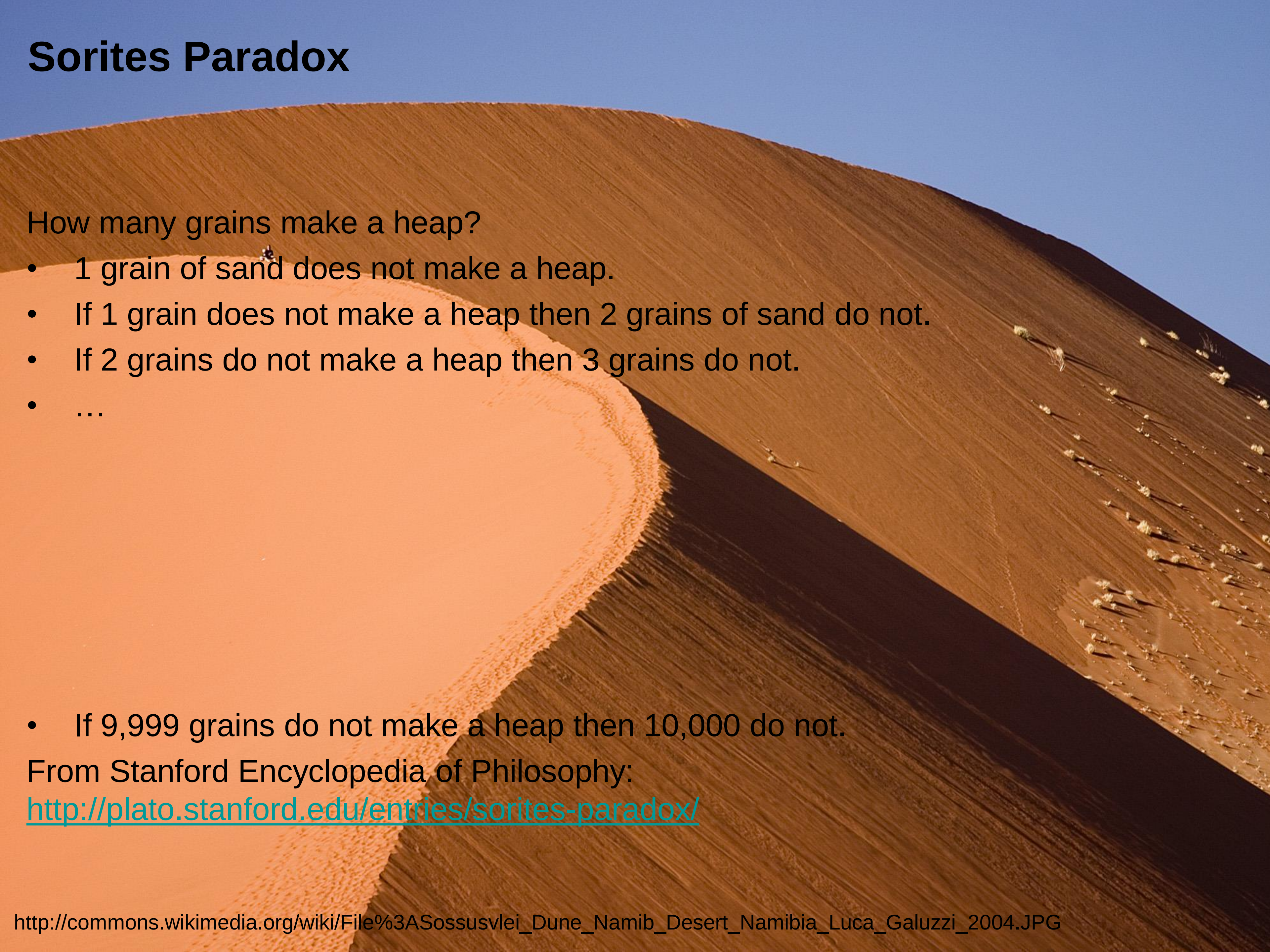
Define quantities like the Fermi energy, density, pressure ….

… apply local density approximation …

But when are such approximations justified?

This is an ancient problem!

Sorites Paradox



How many grains make a heap?

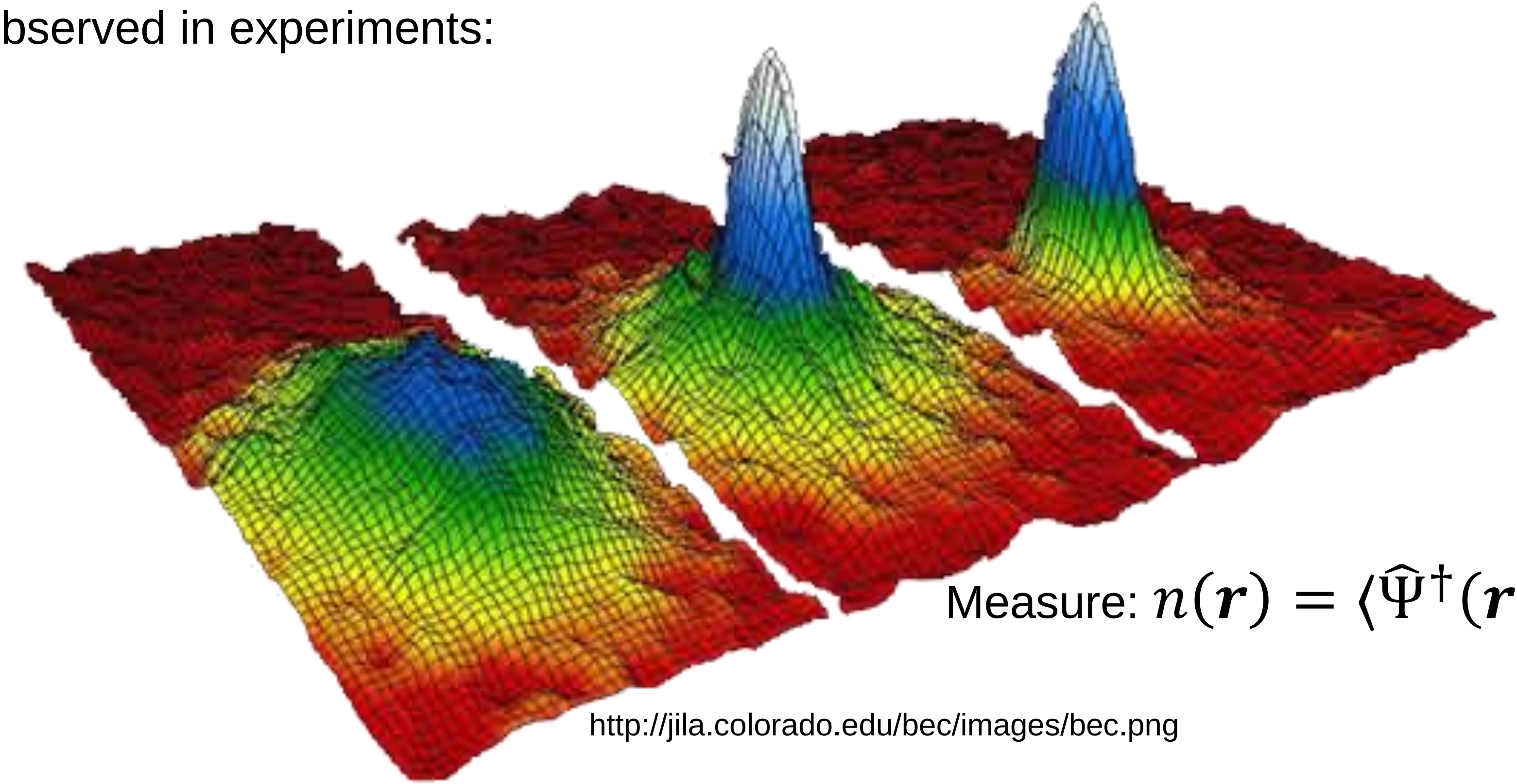
- 1 grain of sand does not make a heap.
- If 1 grain does not make a heap then 2 grains of sand do not.
- If 2 grains do not make a heap then 3 grains do not.
- …
- If 9,999 grains do not make a heap then 10,000 do not.

From Stanford Encyclopedia of Philosophy: http://plato.stanford.edu/entries/sorites-paradox/

http://commons.wikimedia.org/wiki/File%3ASossusvlei_Dune_Namib_Desert_Namibia_Luca_Galuzzi_2004.JPG

Ultracold neutral atoms

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

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

Removing one single atom does not make a difference!

Our approach

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

Ultracold atoms are an ideal tool …

The interactions between ultracold atoms can be effectively pointlike

(contact interaction)

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

In the experiments we have:

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

Ultracold atoms are an ideal tool …

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

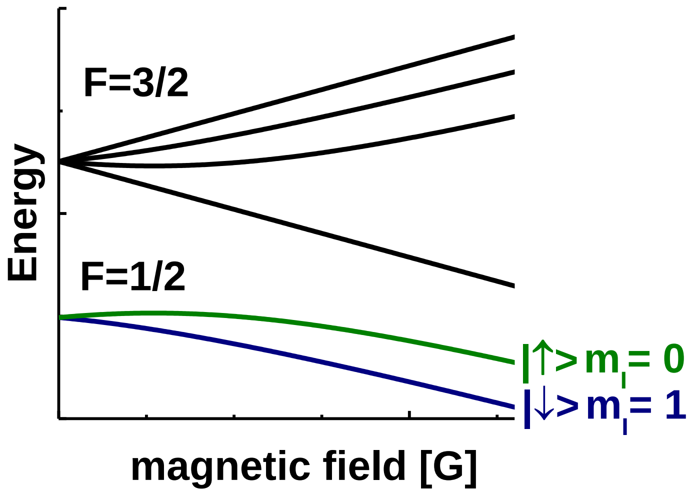
(This is the opposite limit desired in collision experiments:
shorter wavelength enhances resolution)

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 $\boldsymbol{a}$**
- We can even tune the scattering length to any desired value by simply applying a magnetic field (**<u>Feshbach resonances</u>**).

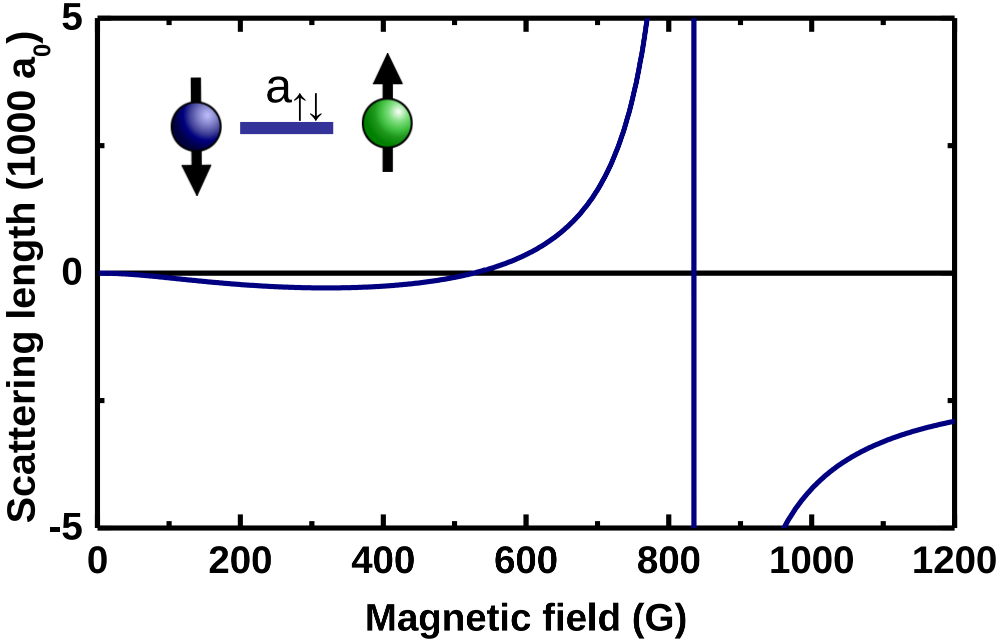
The ^{6}Li atom

^{6}Li ground state



S=1/2, I=1
→ half-integer total angular momentum
→ ^{6}Li is a fermion

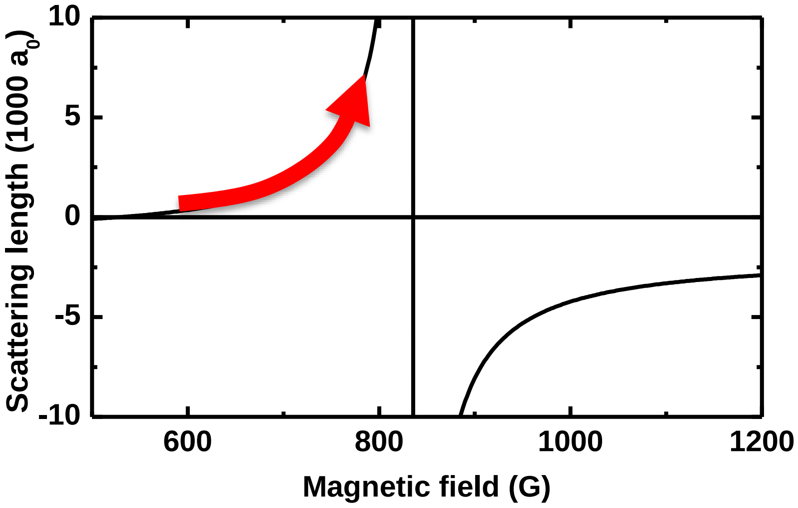
Tuning interactions: Feshbach resonance in ^{6}Li



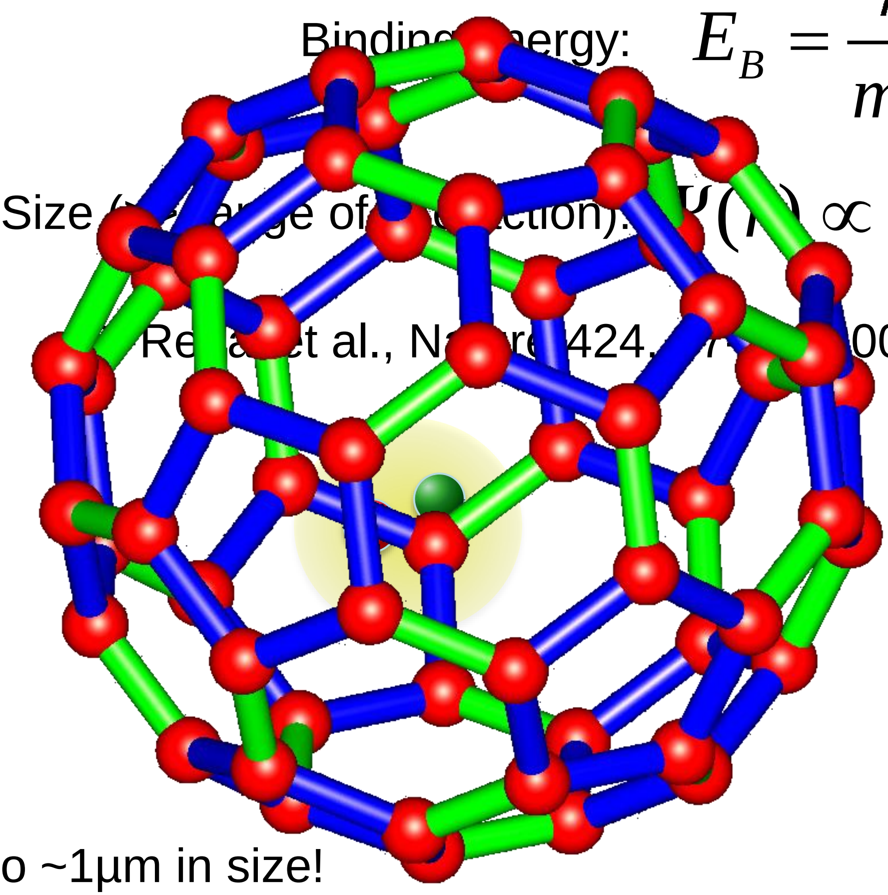
NO interaction between identical particles

Tunability of ultracold systems

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



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



Binding energy: $E_B = \frac{\hbar^2}{ma^2}$

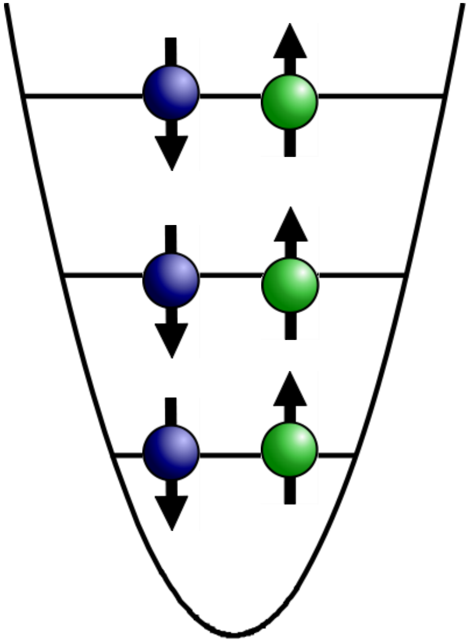
Size (~range of interaction): $\Psi(r) \propto e^{-r/a}$

Regal et al., Nature 424, 47 (2003)

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

G. Zürn et al., PRL **110**, 135301 (2013)

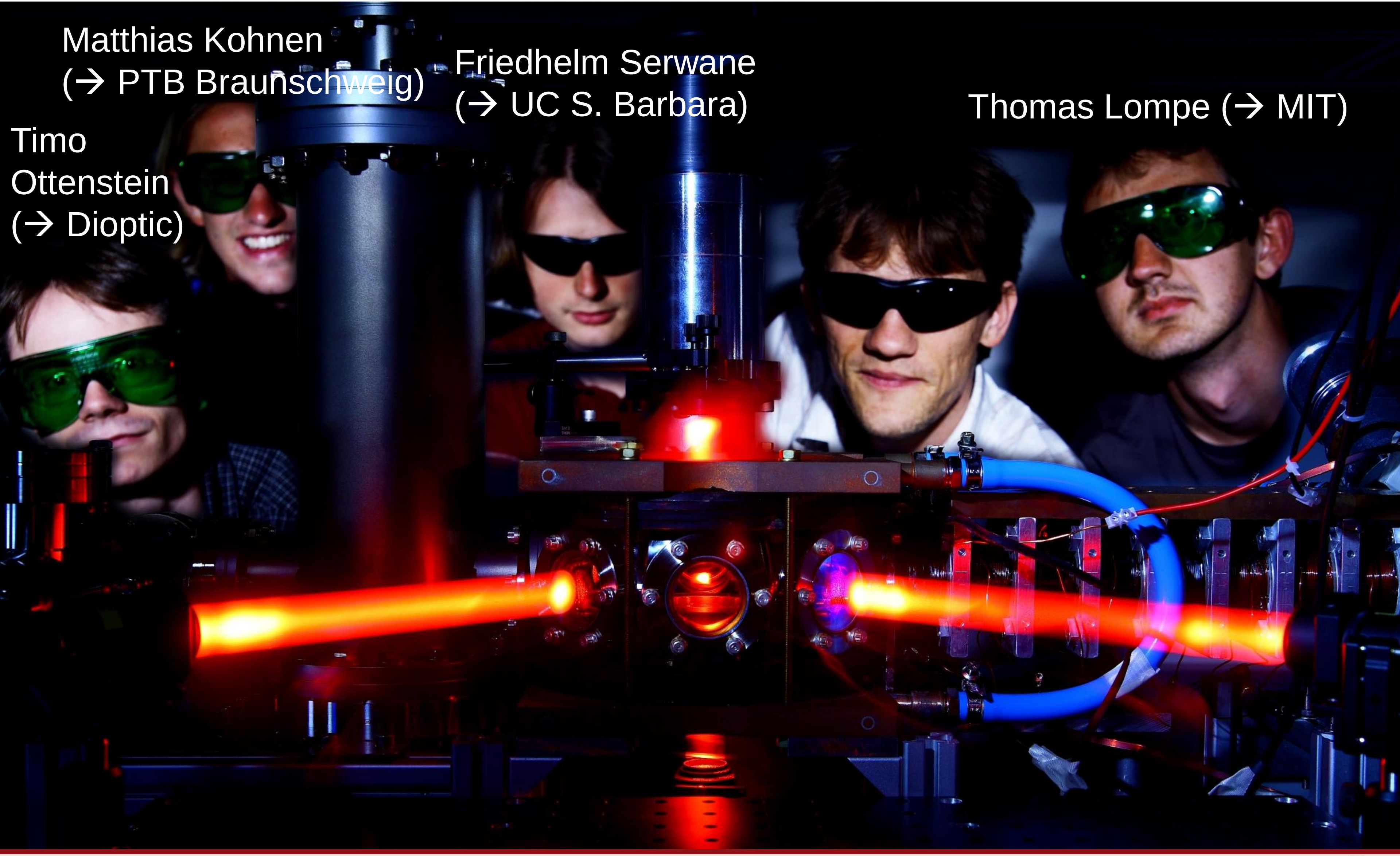
This talk



Outline

- 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 (→ Dioptic)

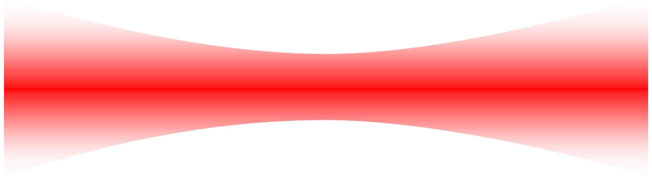
10^9 laser cooled atoms at ~1mK

A container for ultracold atoms

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:

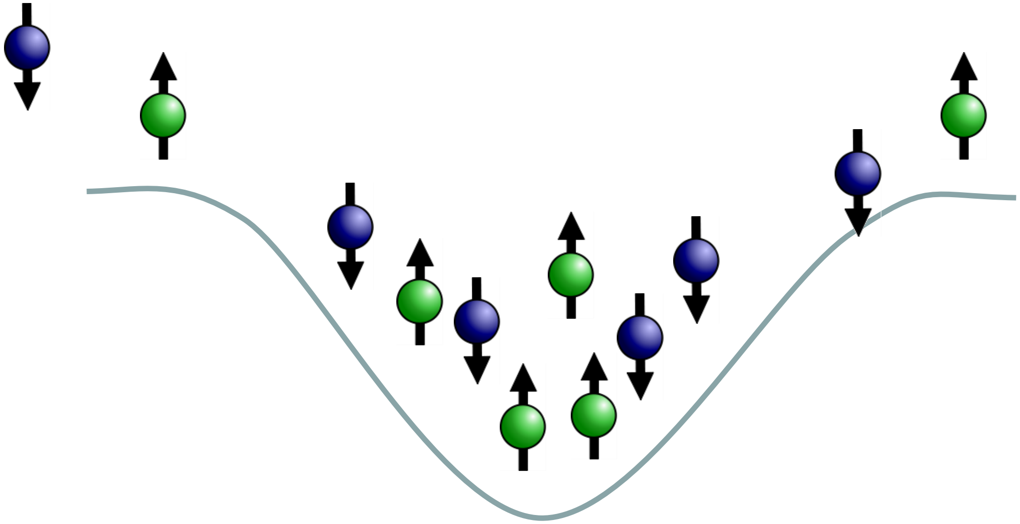


Optical dipole trap depth: $U \propto I(\boldsymbol{r})$

Evaporative cooling

It just works the same:

… and for our cold atoms:
Cool from ~1mK down to below 1µK

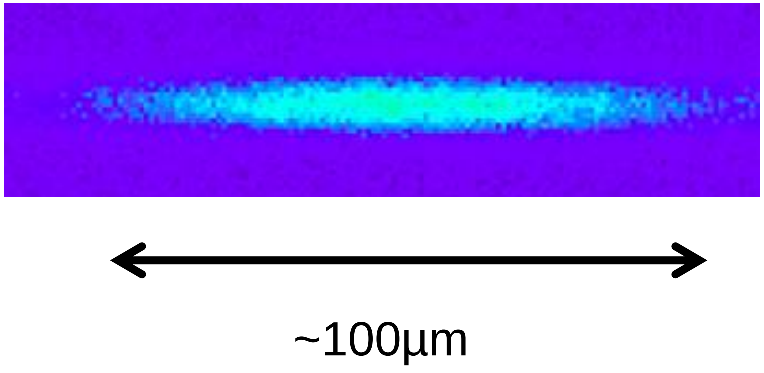


For our cup of coffee …

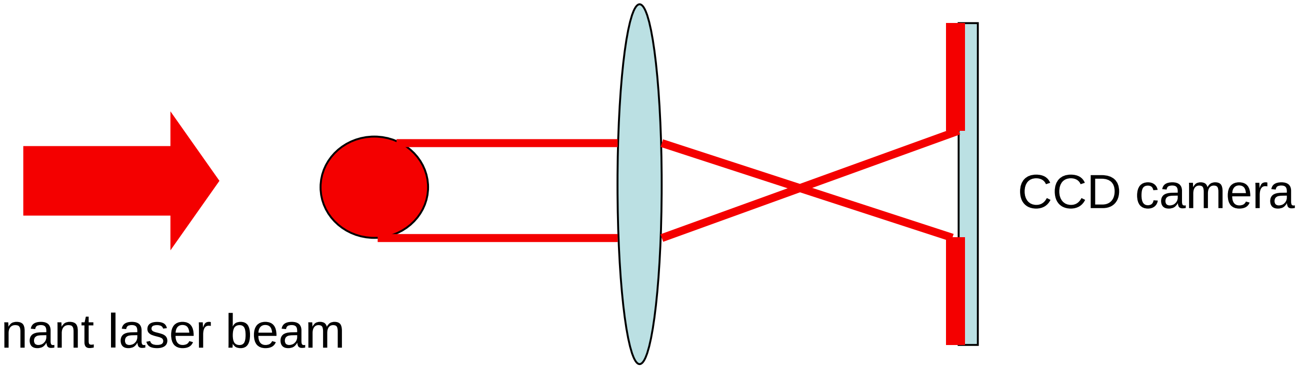
Just reduce the trap depth, i.e. laser power

Ultracold gas of fermions

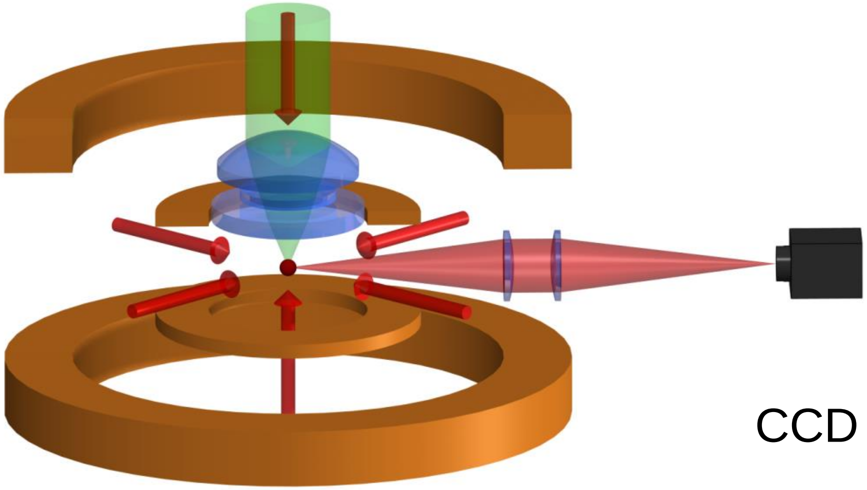
About 50000 atoms @ 250nK, T_F~1µK



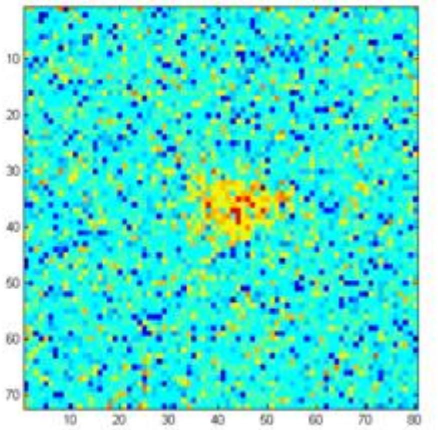
Absorption imaging of ultracold clouds:



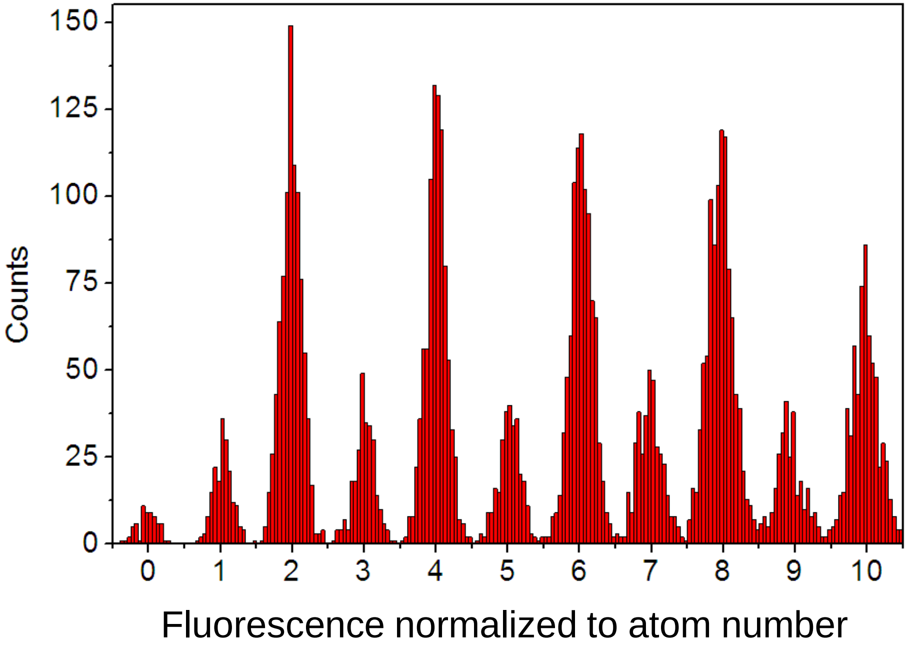
Single atom detection



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

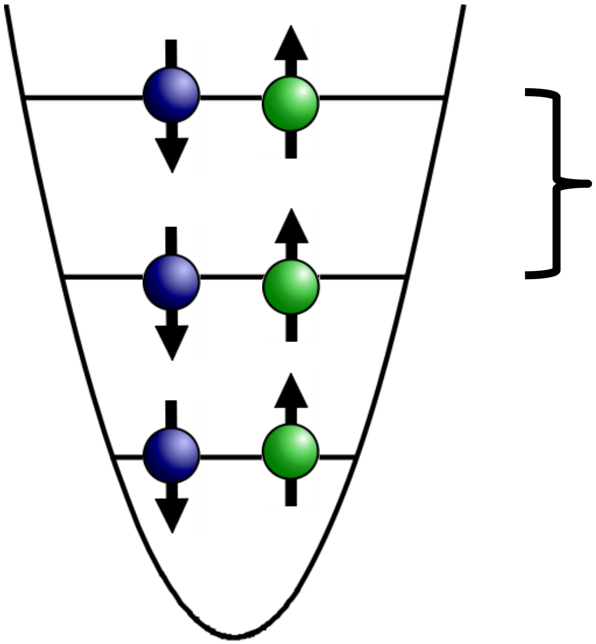


1-10 atoms can be distinguished with high fidelity > 99%



Towards a finite gas …

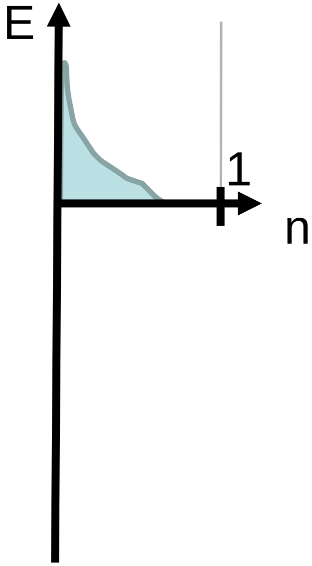
The challenge:

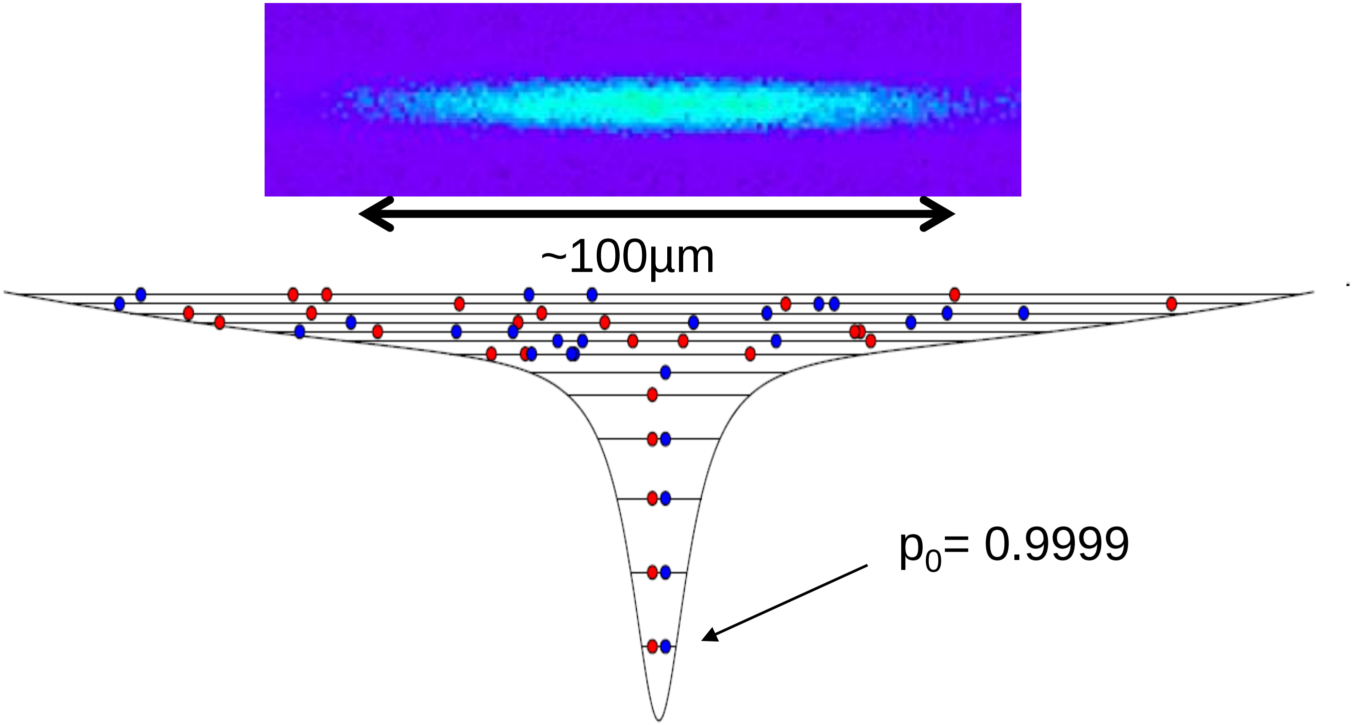


achieve $\hbar\omega \gg kT$

Creating a finite gas of fermions

Fermi-Dirac dist.

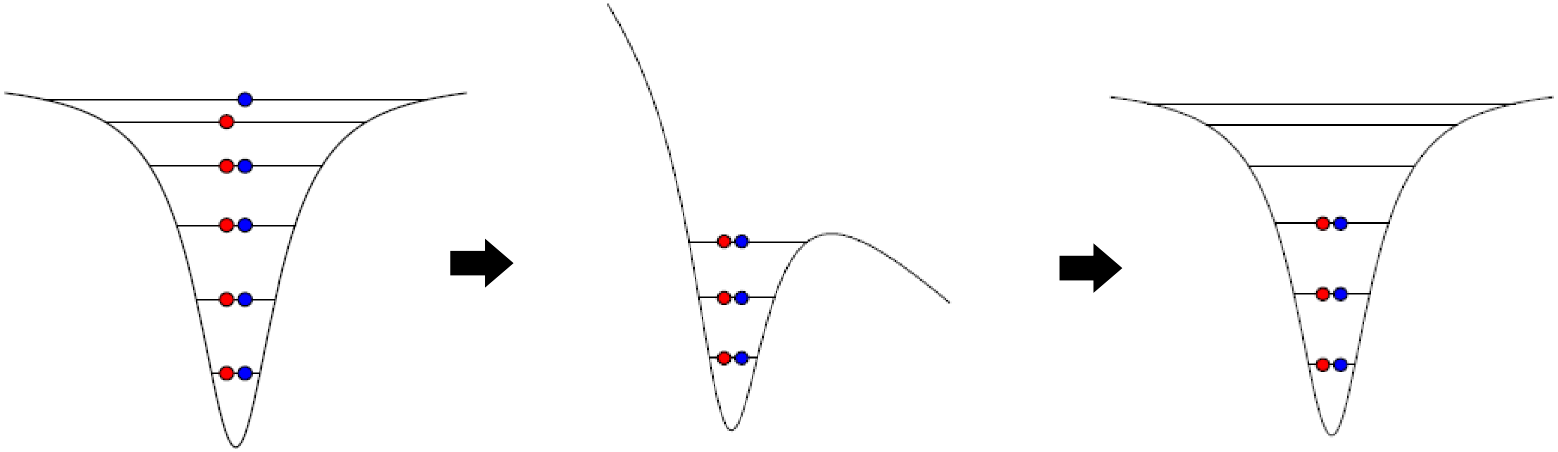




- 2-component mixture in reservoir
- superimpose microtrap (~1.8 µm waist)

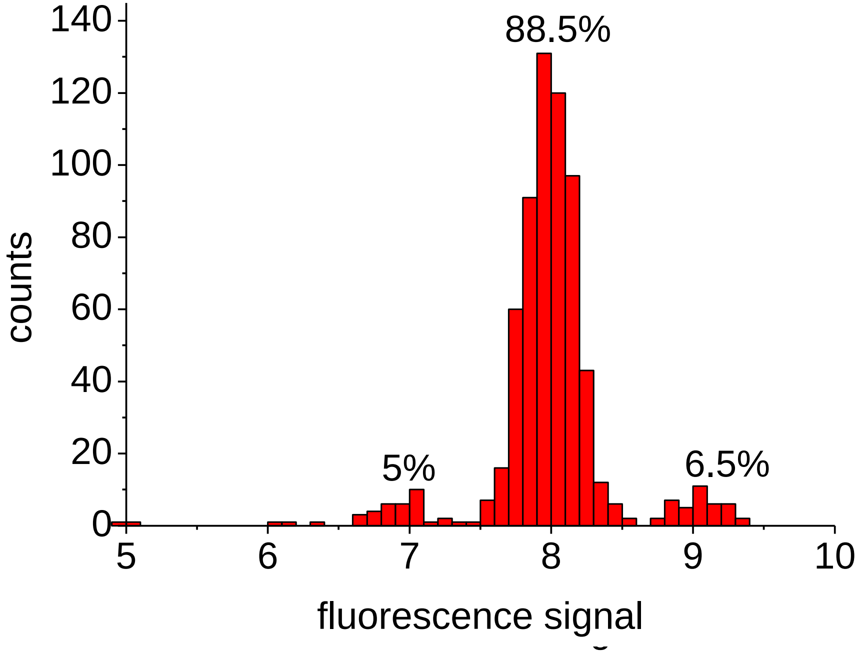
Creating a finite gas of fermions

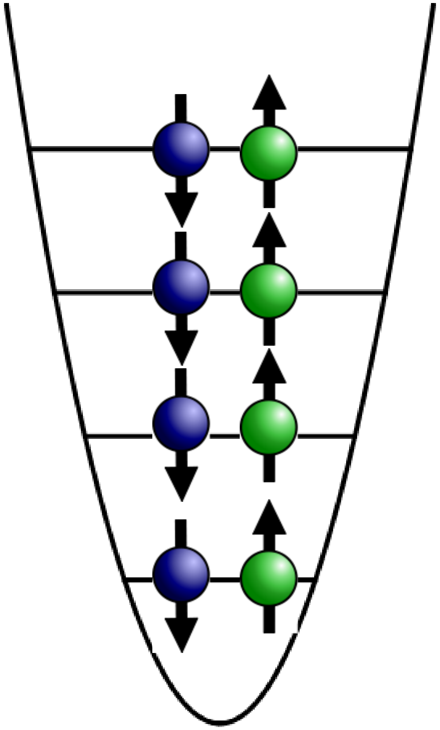
- switch off reservoir



+ magnetic field gradient in
axial direction

Spilling the atoms ….





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

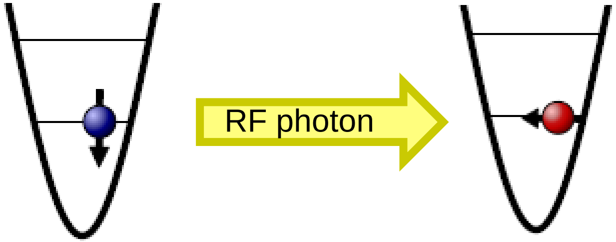
F. Serwane et al., Science **332,** 336 (2011)

Let‘s study the interacting system!

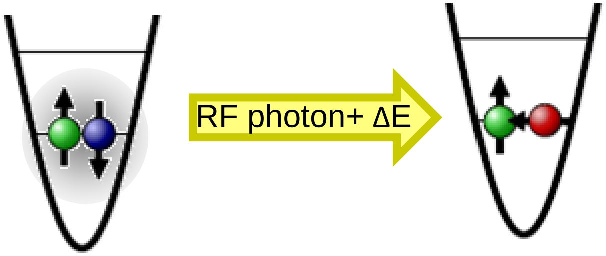
Precise energy measurements

Radio Frequency spectroscopy

„bare“ RF – transition

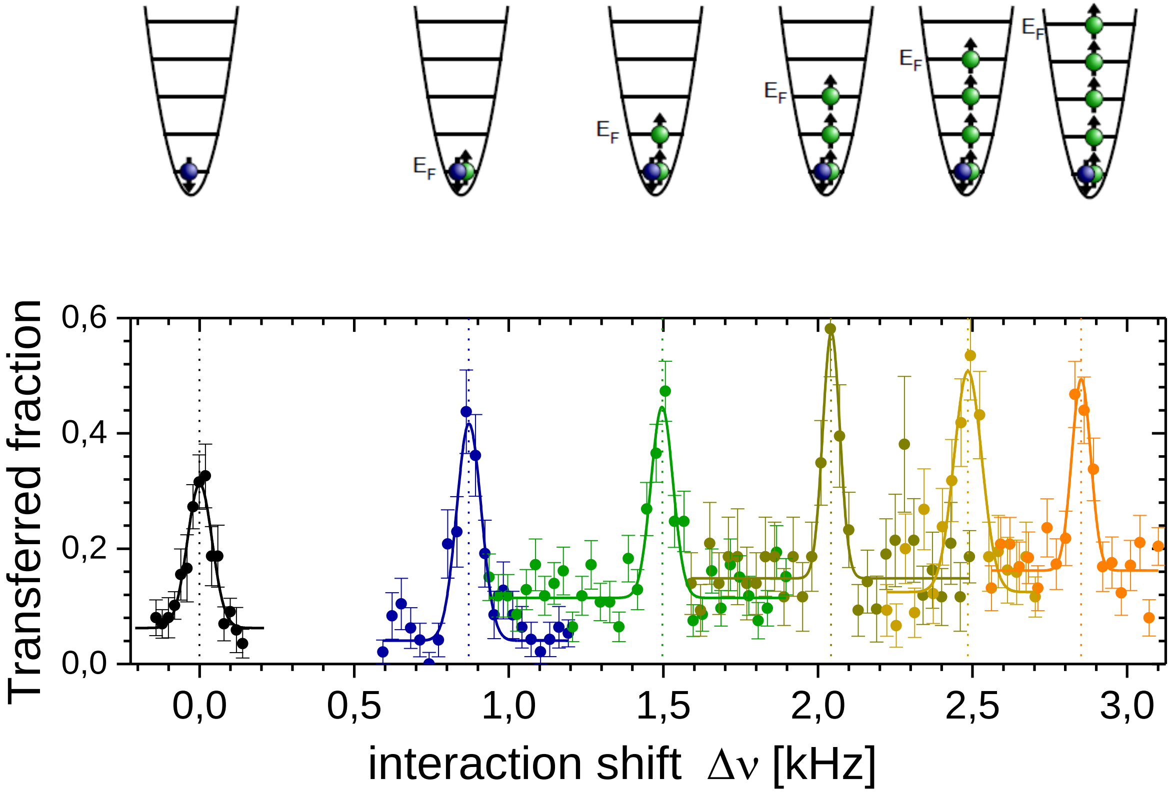


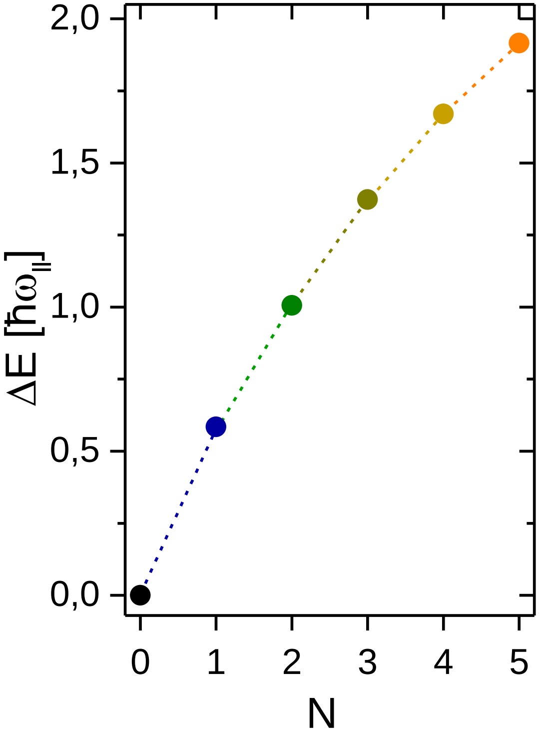
RF – transition with interaction



Measure the interaction energy

vary the number of majority particles:





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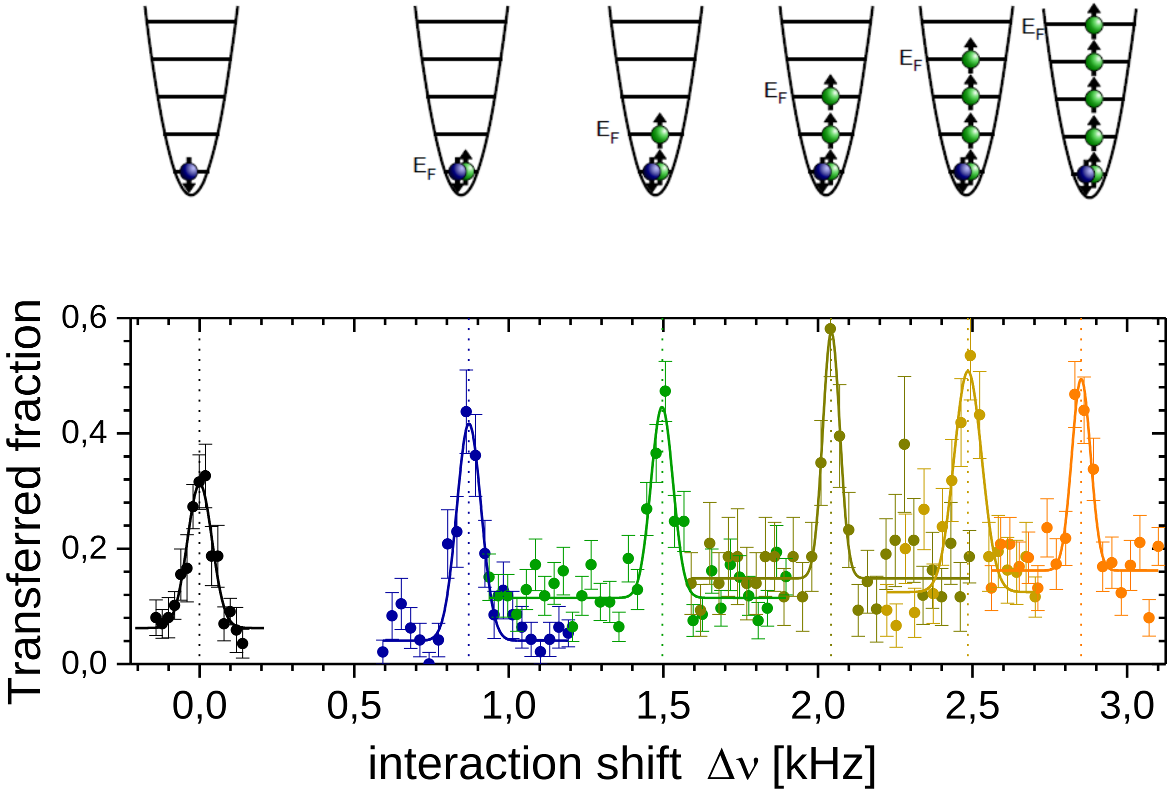
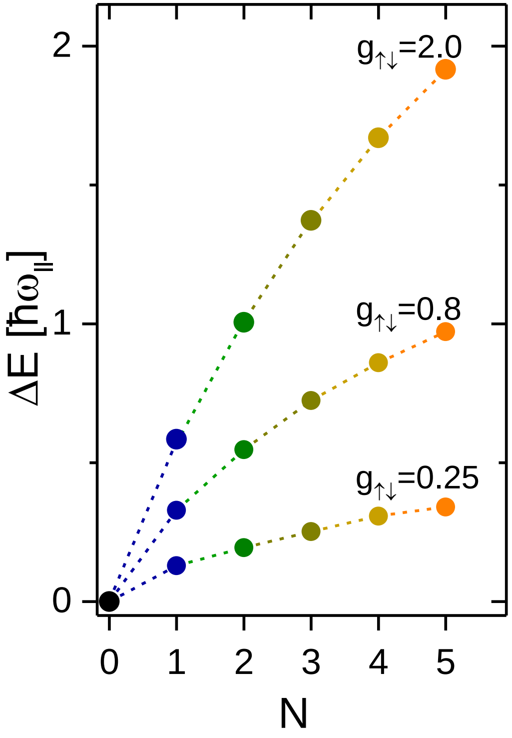
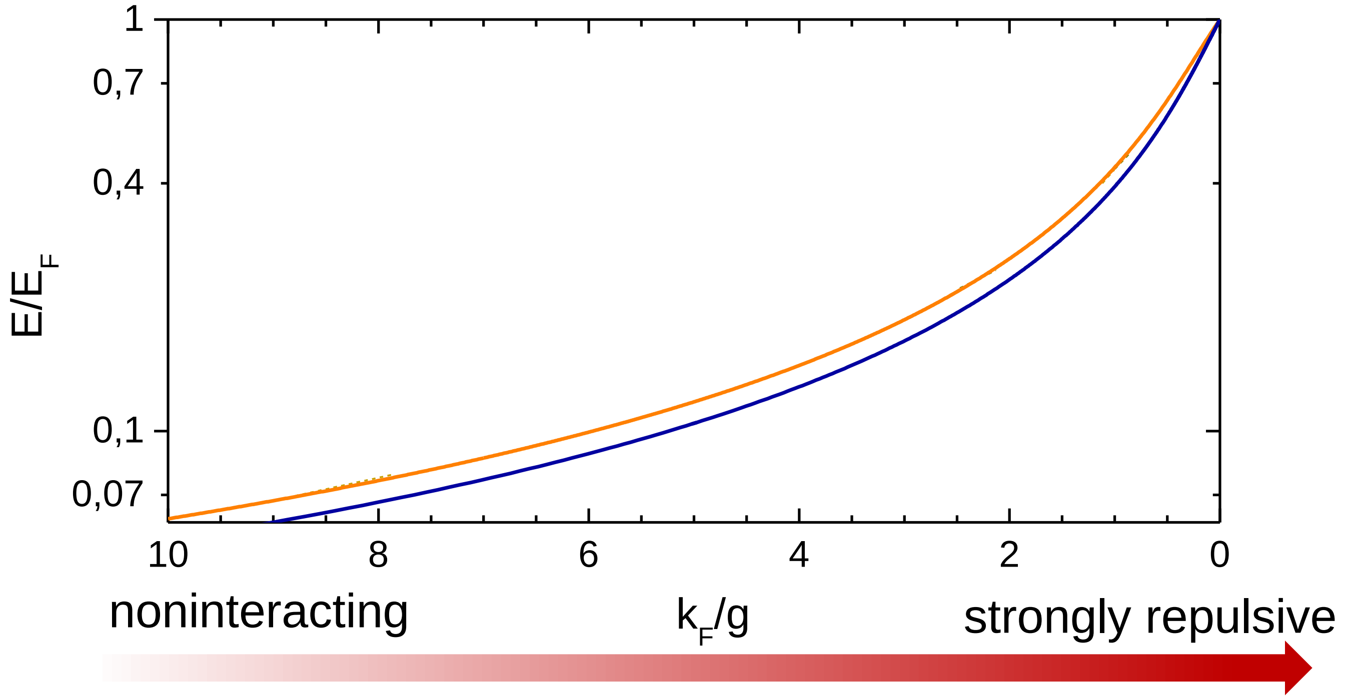
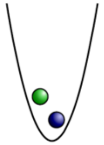




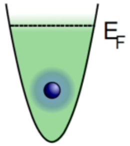
Interaction energy in dimensionless units



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

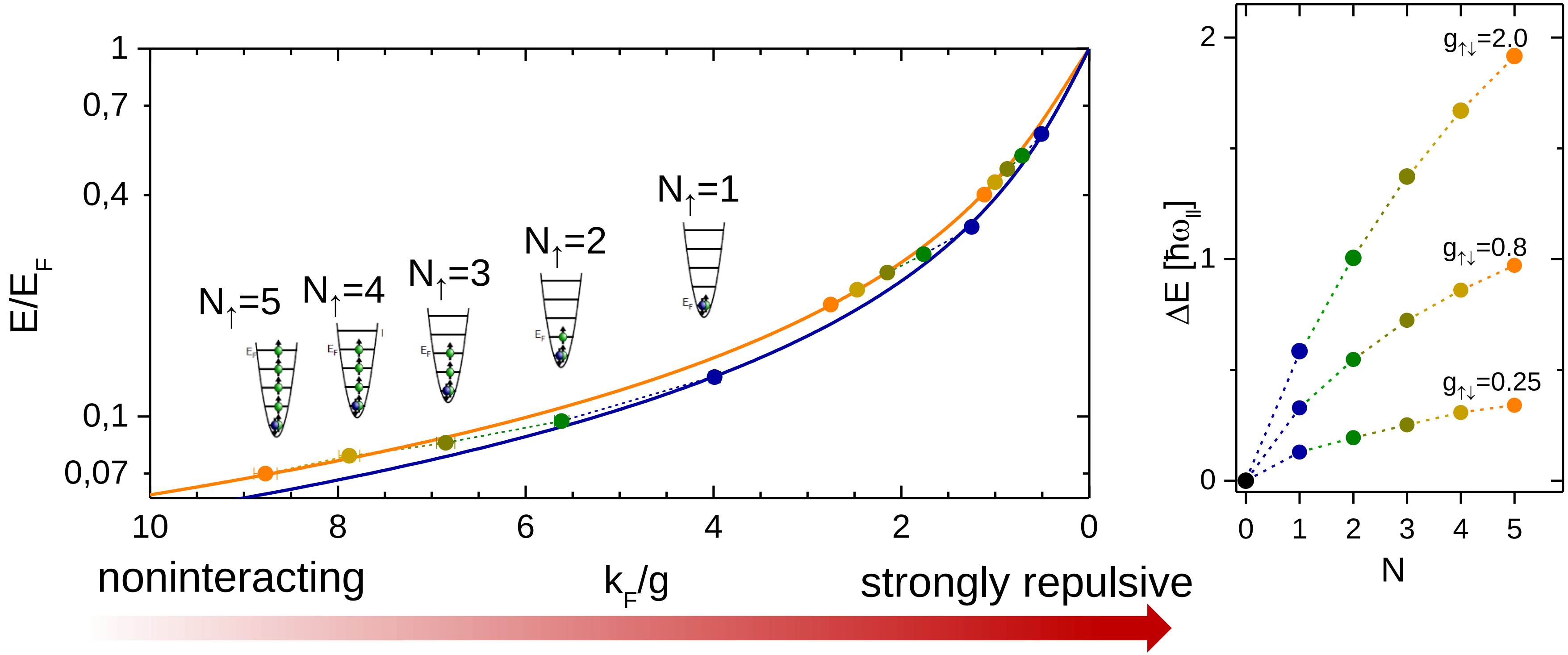


— Analytic solution for an infinite number of majority particles
J. McGuire, J. Math. Phys. 6,432 (1965)
(local density approximation)



A. Wenz et al., Science **342**, 457 (2013)

Interaction energy in dimensionless units



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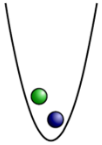

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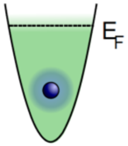
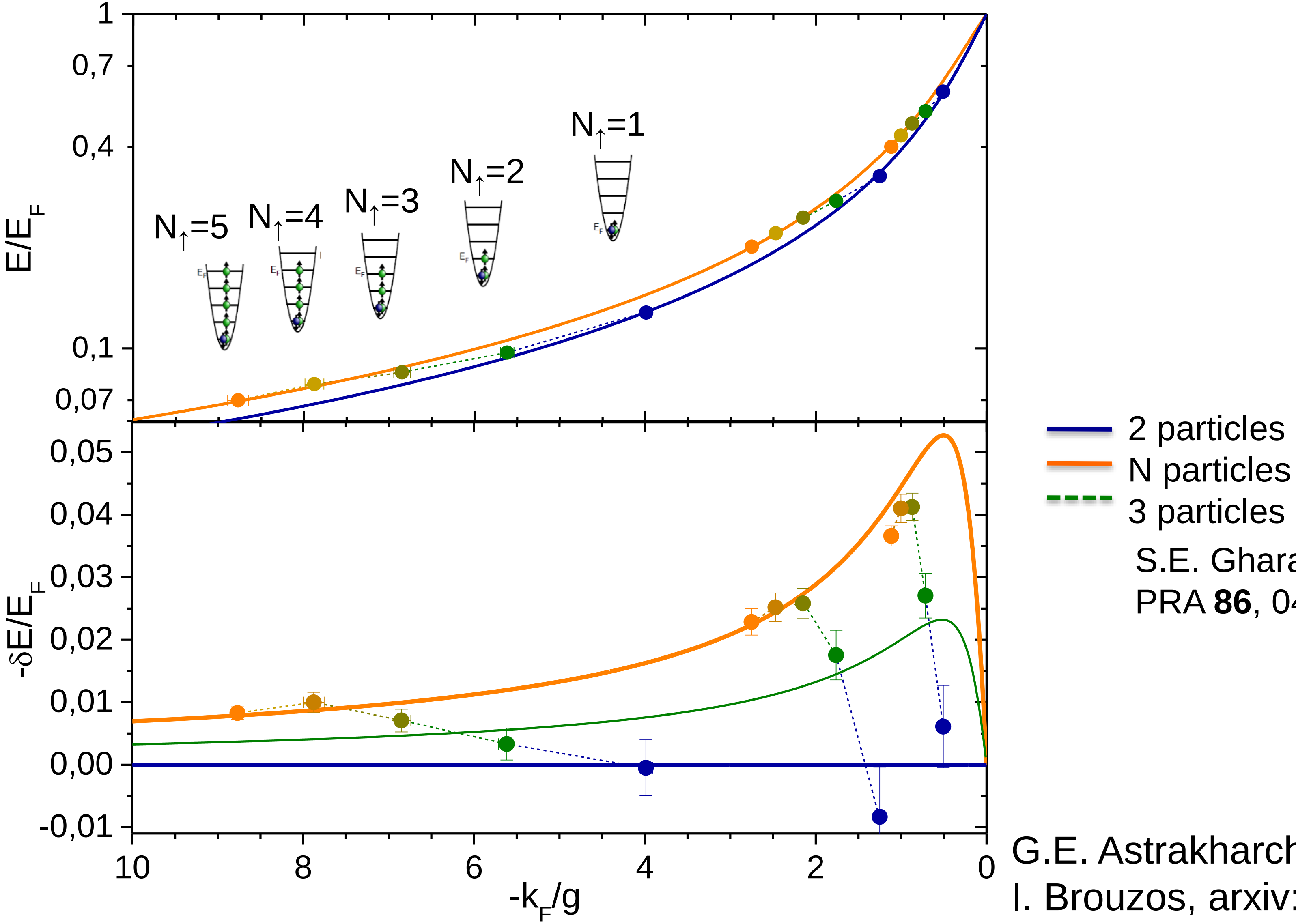


A. Wenz et al., Science **342**, 457 (2013)

Interaction energy in dimensionless units



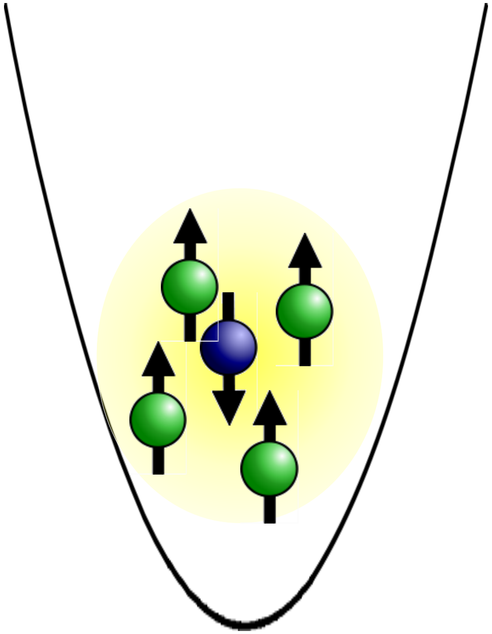
S.E. Gharashi et al.,
PRA **86**, 042702 (2012)

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

A. Wenz et al., Science **342**, 457 (2013)

Approaching the many body limit…

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



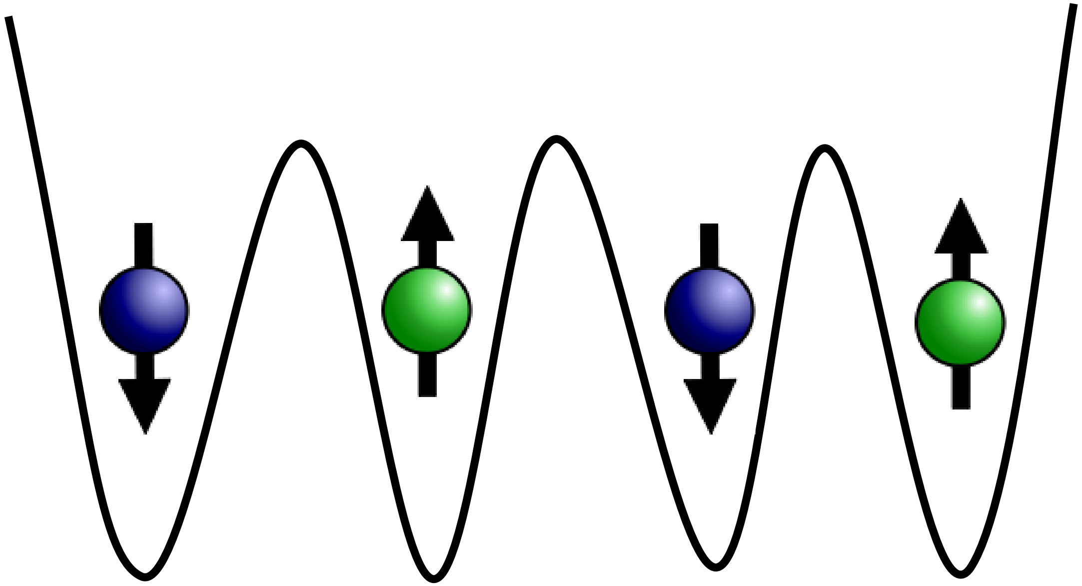
Interesting things to look at:

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

A. Wenz et al., Science **342**, 457 (2013)

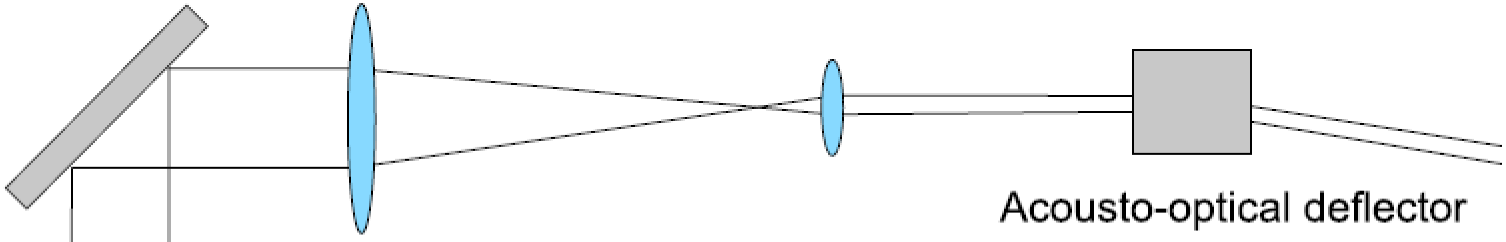
Realize multiple wells …

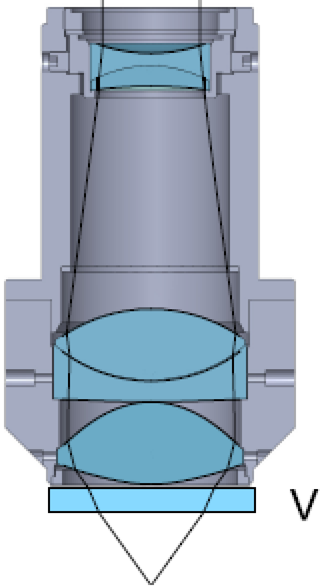
….. with similar fidelity and control?

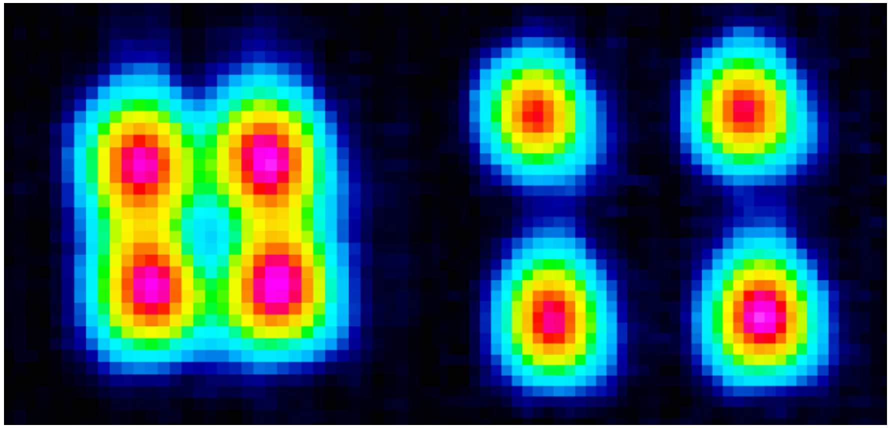


Basic building blocks of matter!

The setup

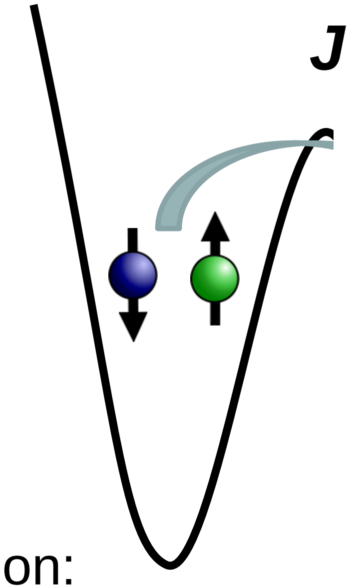






Light intensity distribution

A tunable double well



initial spatial wave function:

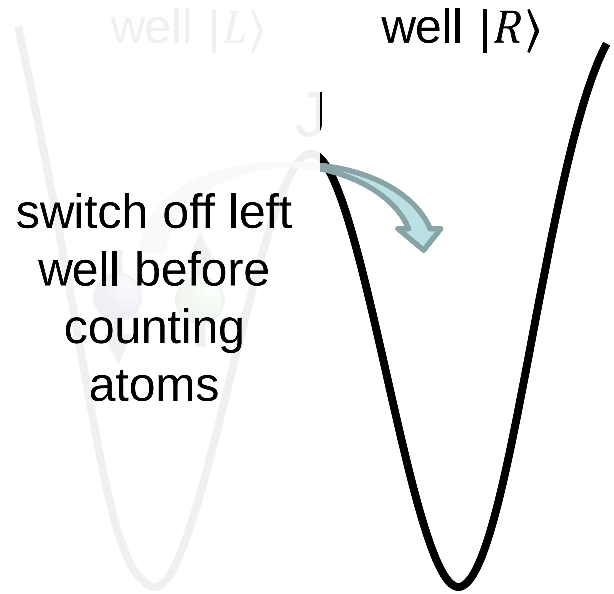
$$|\Psi(t=0)\rangle = |L\rangle_1 |L\rangle_2 = |LL\rangle$$

spin wave function (stationary)

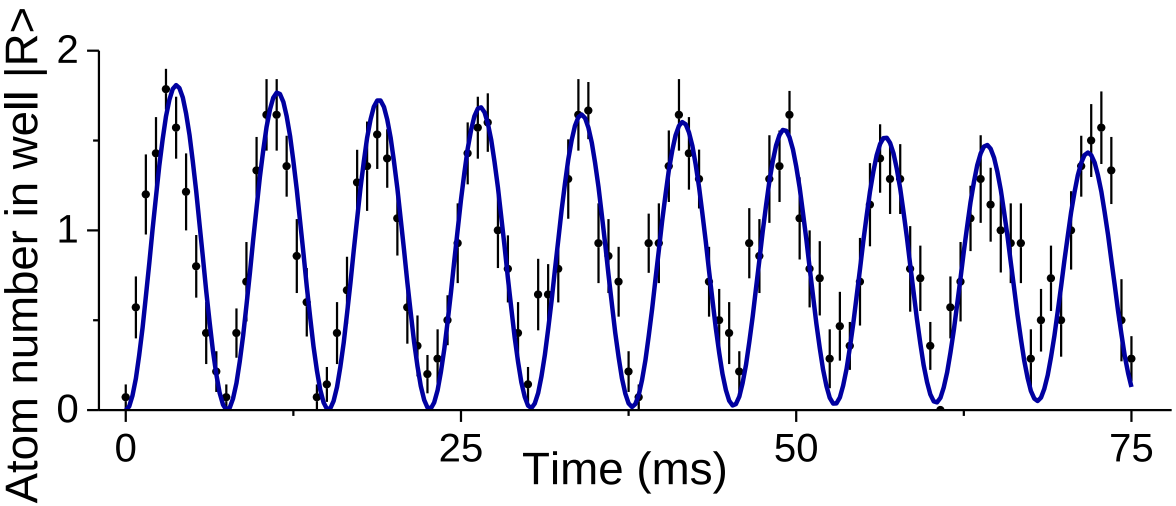
$$|\chi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2) = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

A tunable double well

- Interactions switched off:



switch off left well before counting atoms

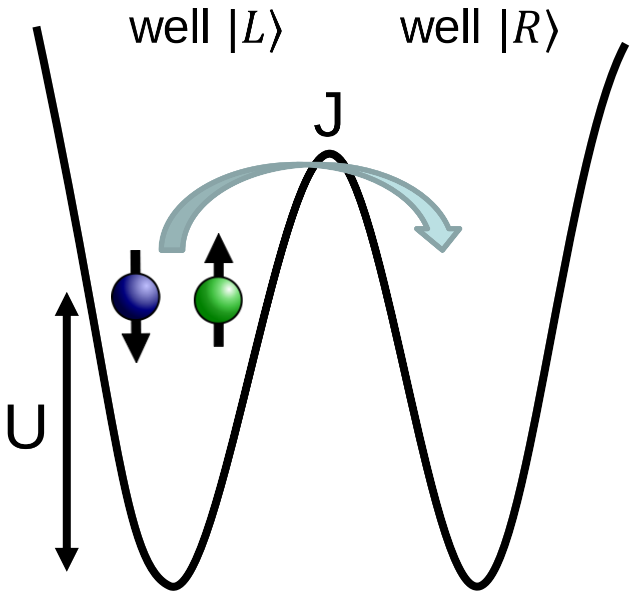


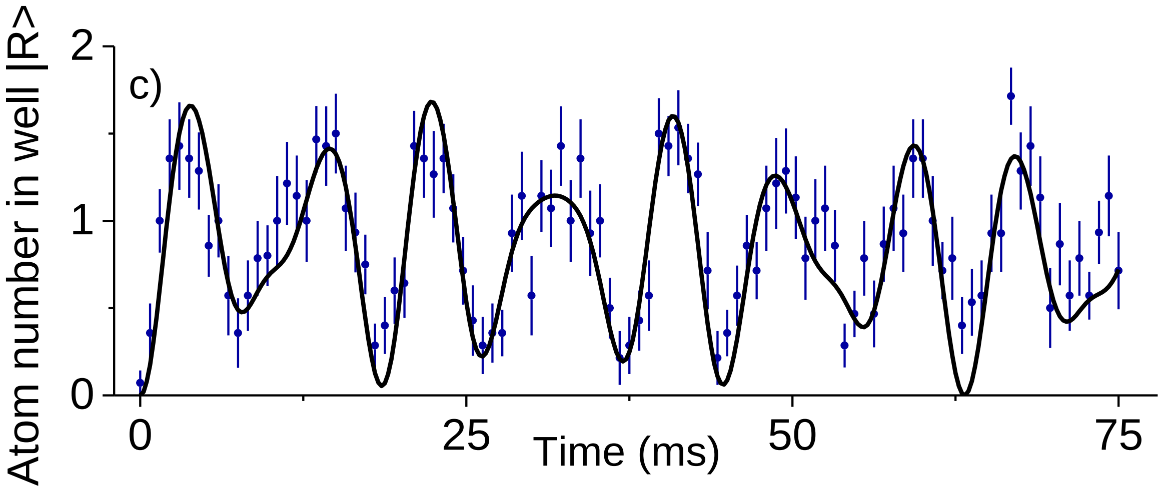
$$|\Psi(t)\rangle = |\psi(t)\rangle_1 \, |\psi(t)\rangle_2$$

$$|\psi(t)\rangle_1 = \tfrac{1}{2}\left(\left(|L\rangle_1 + |R\rangle_1\right) + \left(|L\rangle_1 - |R\rangle_1\right) e^{-i\Delta E t/\hbar}\right)$$

Two interacting atoms

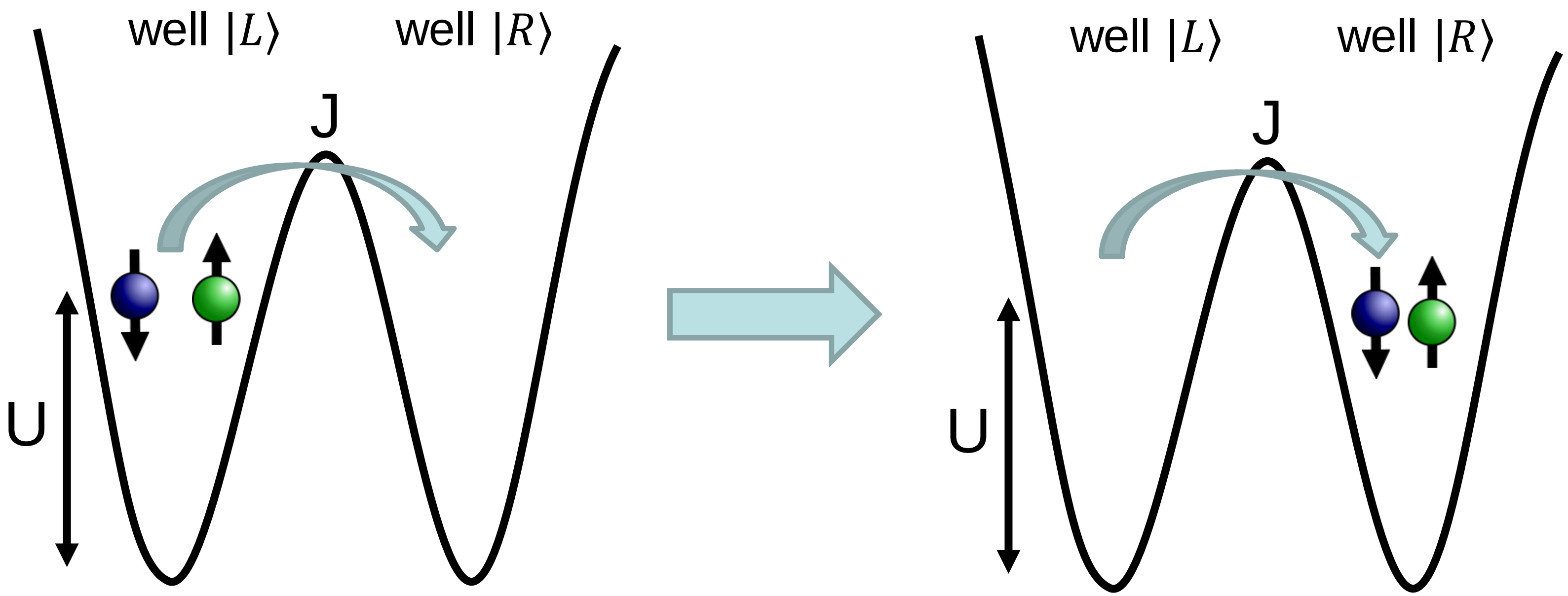
Interaction leads to entanglement:





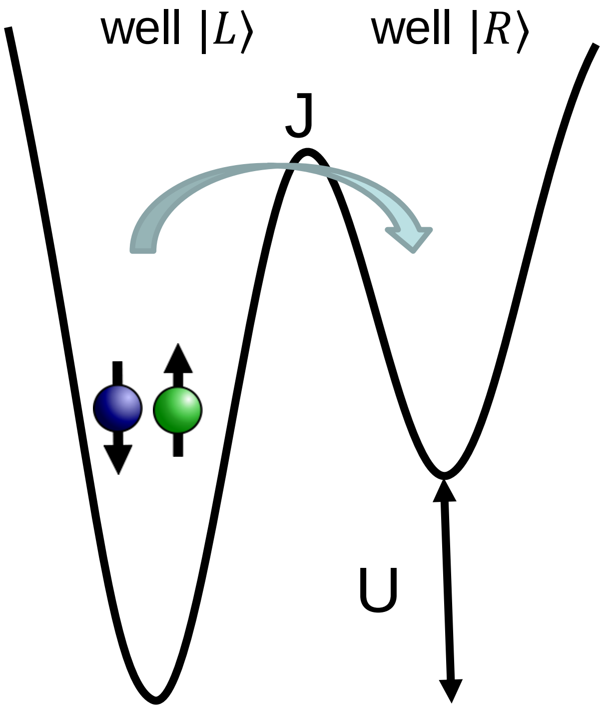
$$|\Psi(t)\rangle \neq |\psi(t)\rangle_1 \, |\psi(t)\rangle_2$$

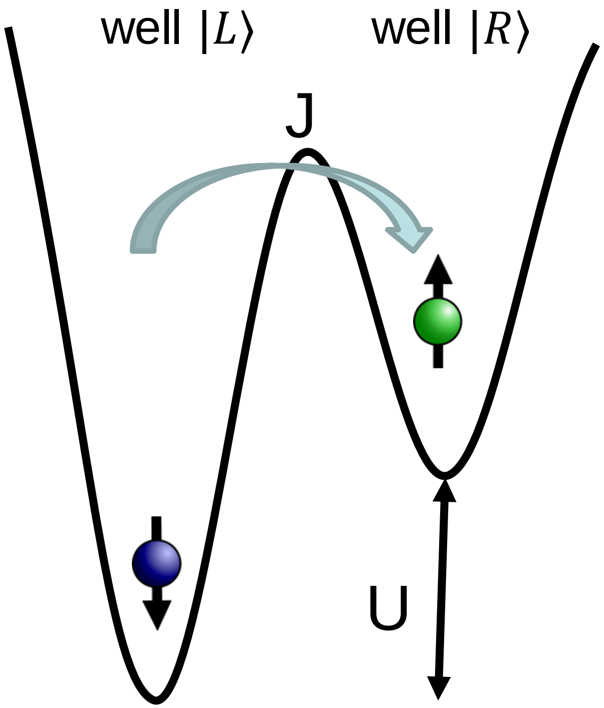
Two strongly interacting atoms



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

Two strongly interacting atoms

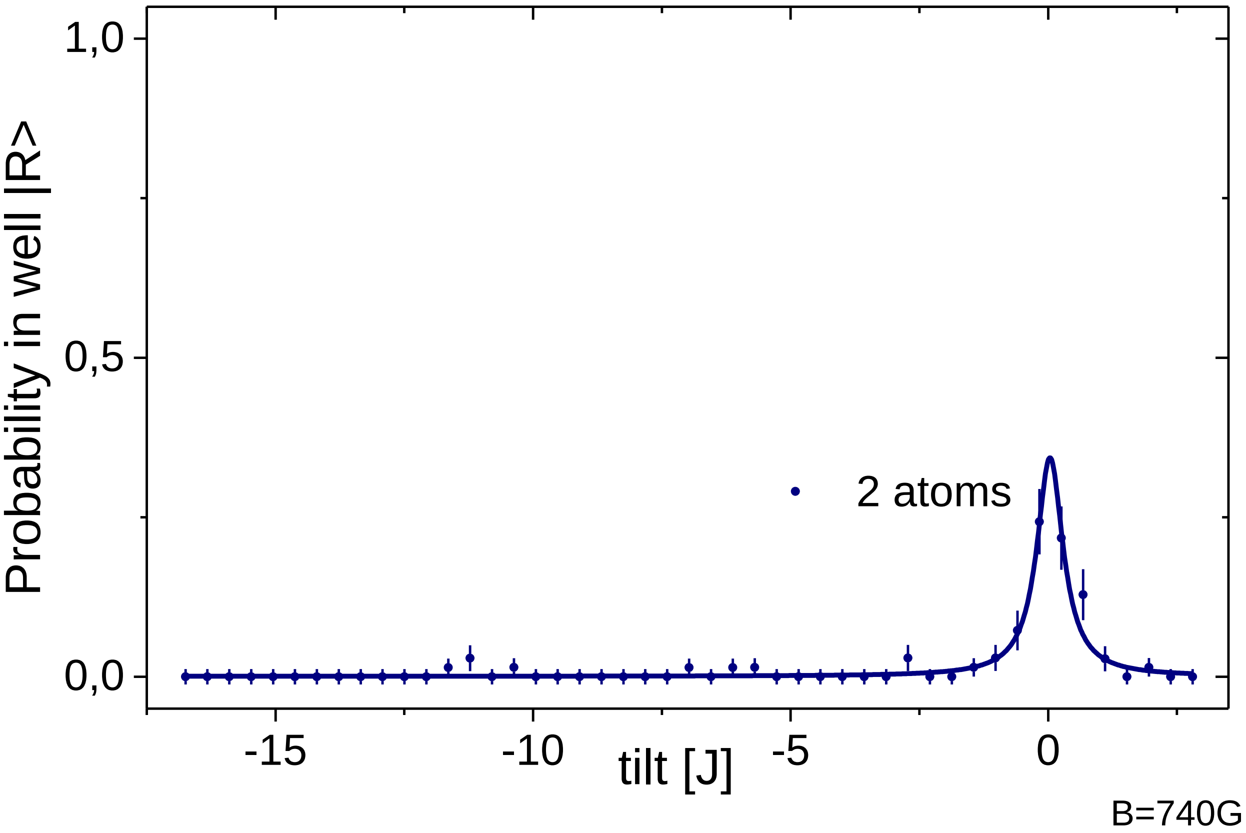




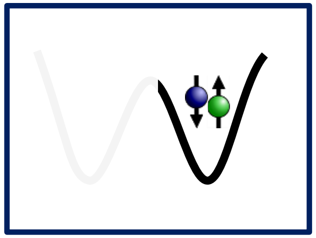
We can compensate for the interaction energy by applying a tilt!

Two strongly interacting atoms

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



two atoms



Two strongly interacting atoms

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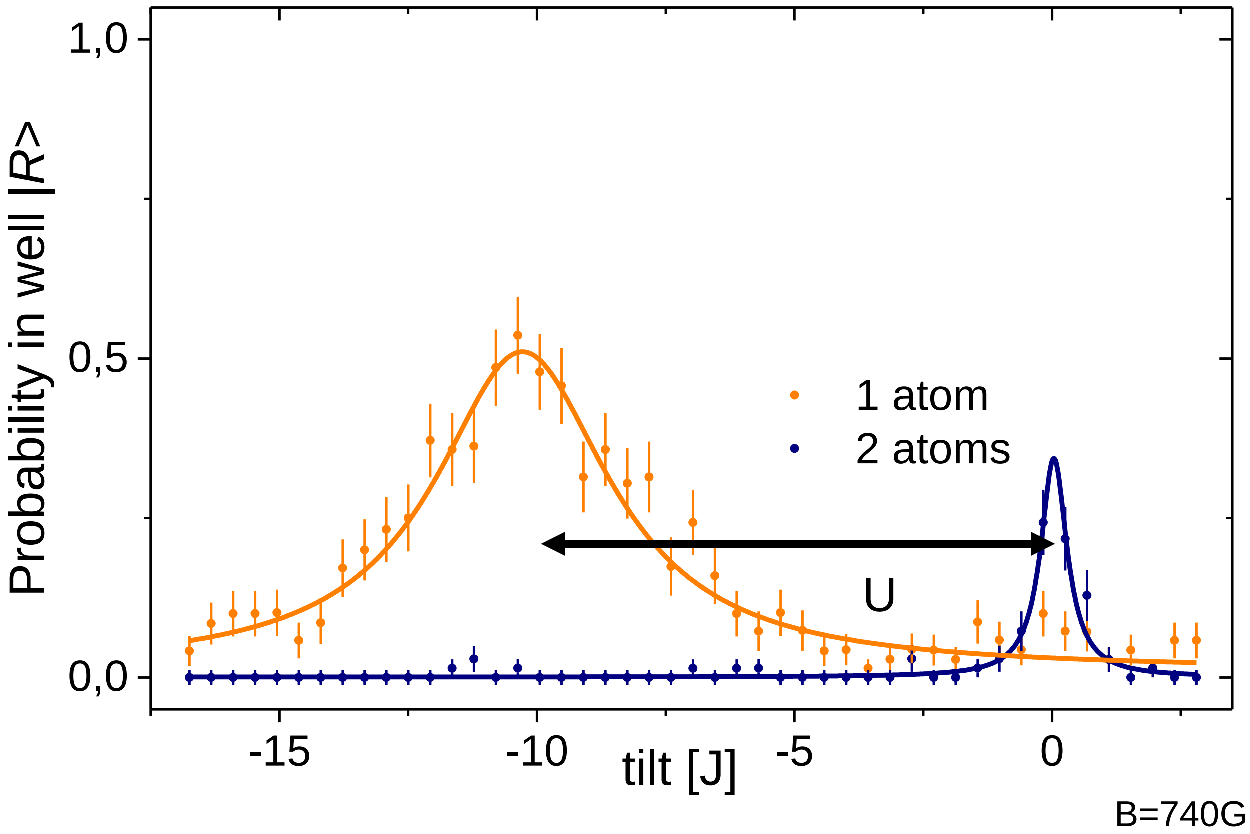
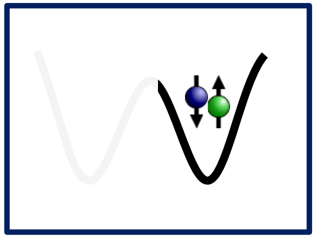
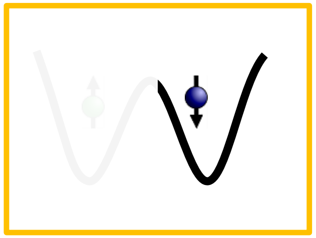


two atoms

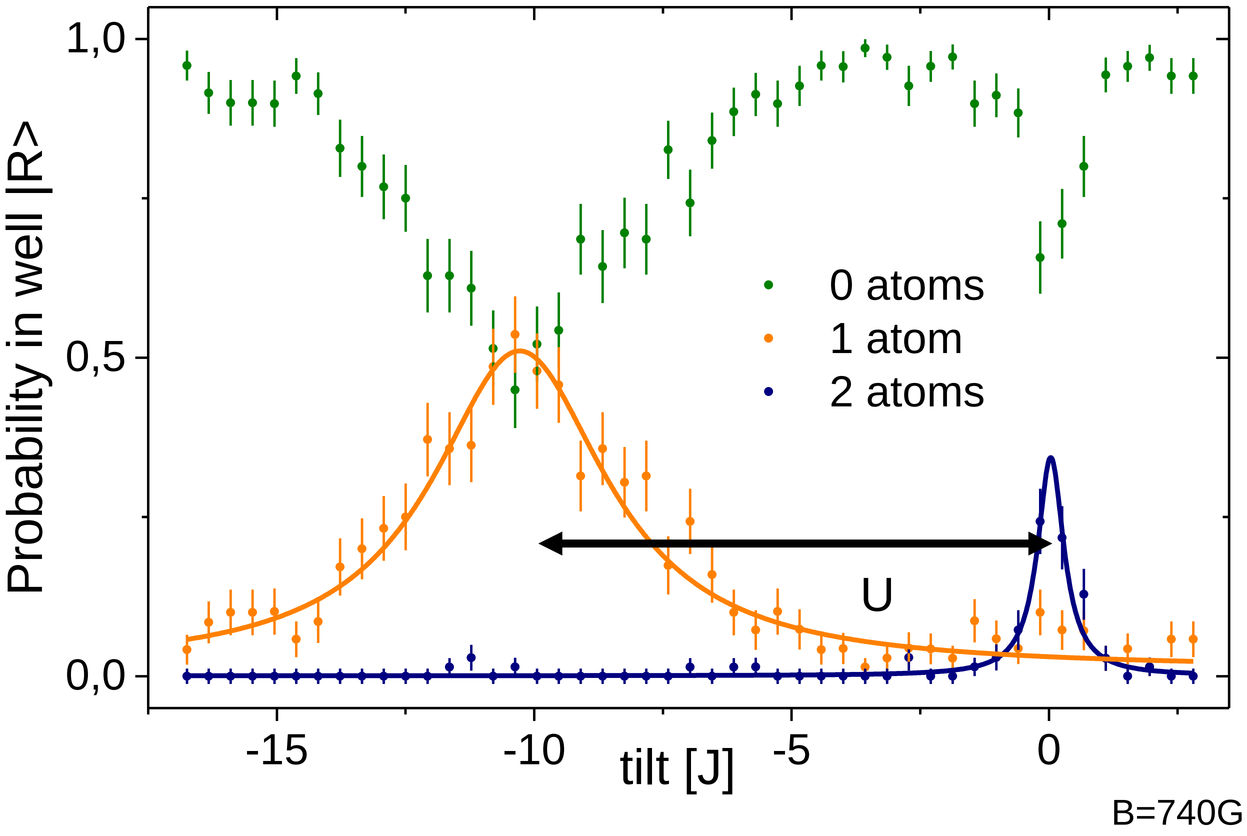


one atom

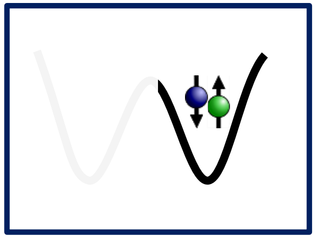


Two strongly interacting atoms

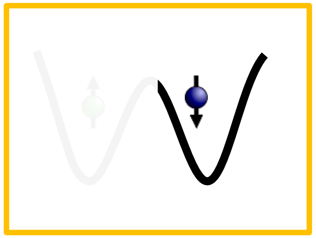
- Observe number statistics in the right well (time averaged)



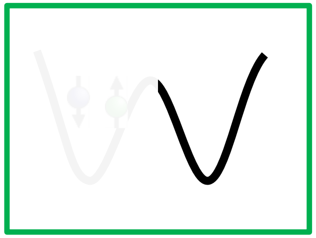
two atoms



one atom

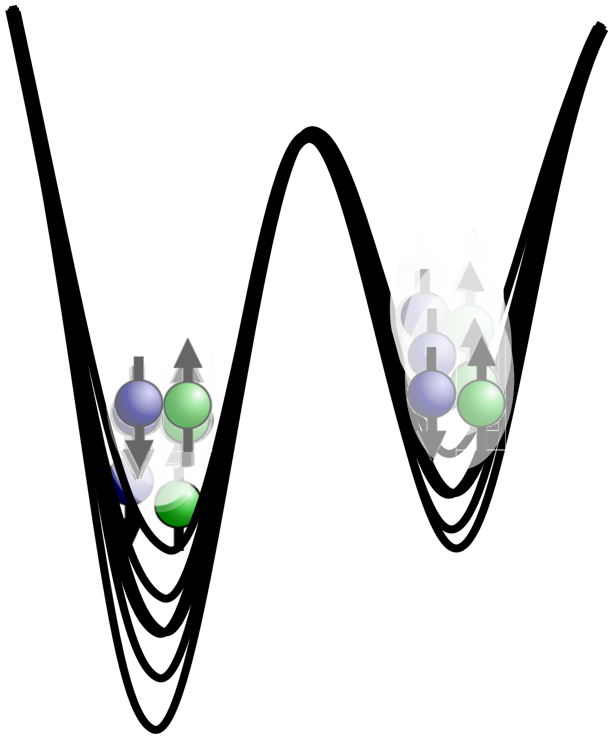


no atoms

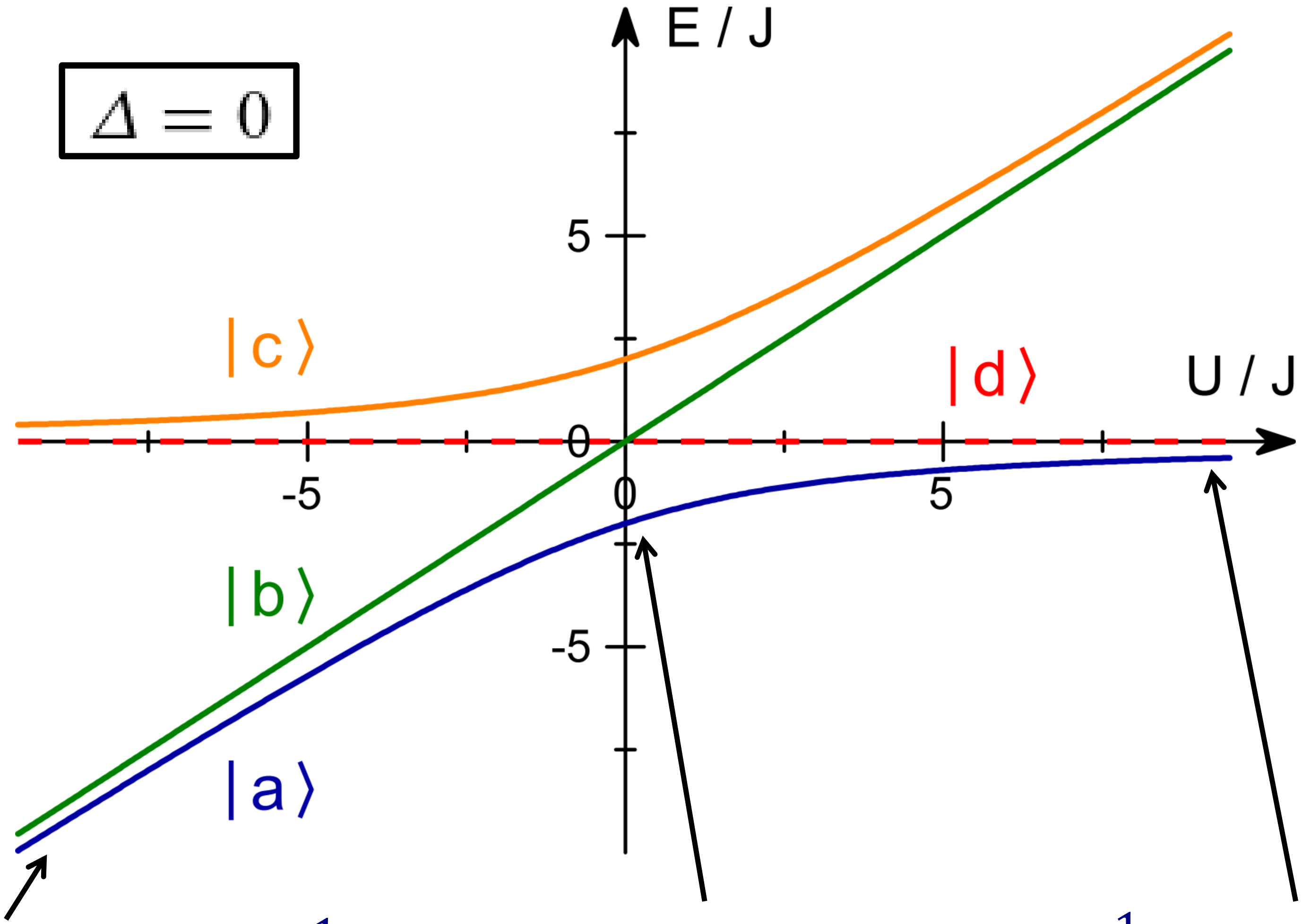


Preparing stationary states

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



Eigenstates of a symmetric DW



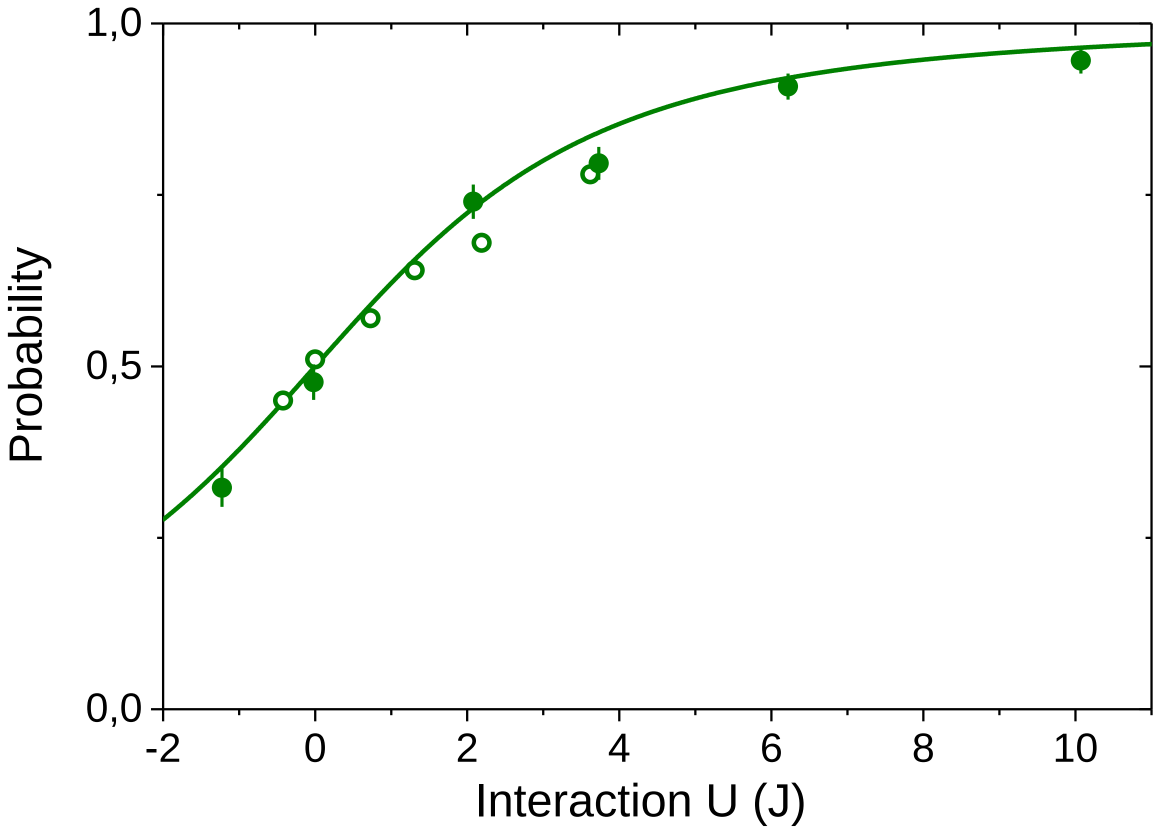
$$\frac{1}{\sqrt{2}}(|LL\rangle + |RR\rangle)$$

$$\frac{1}{2}(|LL\rangle + |LR\rangle + |RL\rangle + |RR\rangle)$$

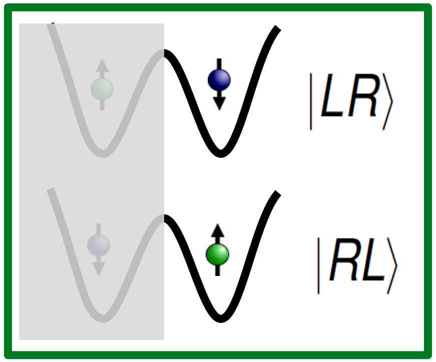
$$\frac{1}{\sqrt{2}}(|LR\rangle + |RL\rangle)$$

Preparing stationary states

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

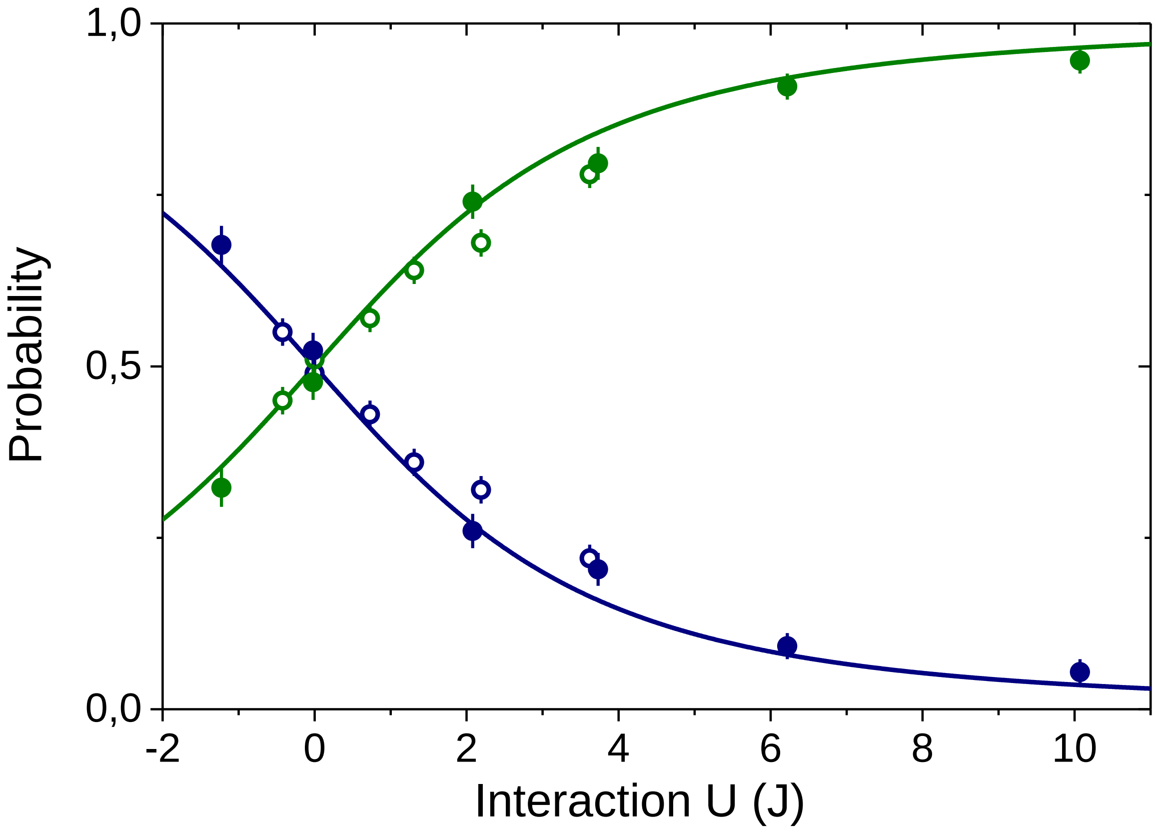


Single occupancy

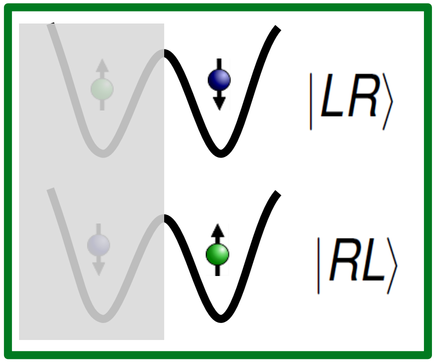


Preparing stationary states

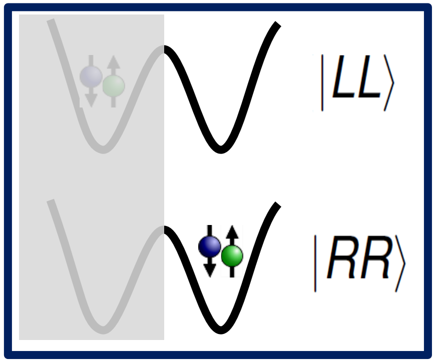
- Number statistics for the balanced case depending on the interaction strength:



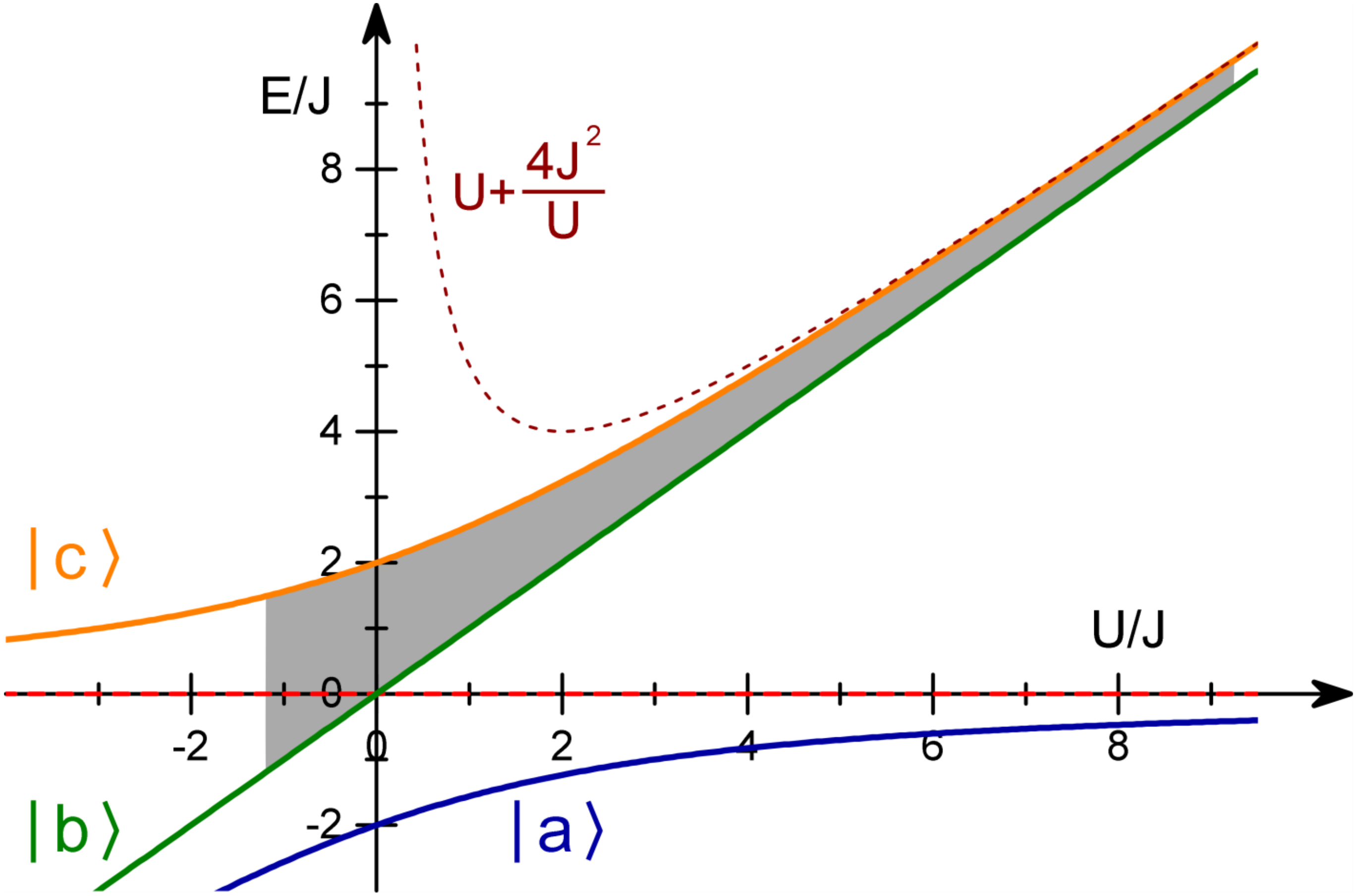
Single occupancy



Double occupancy

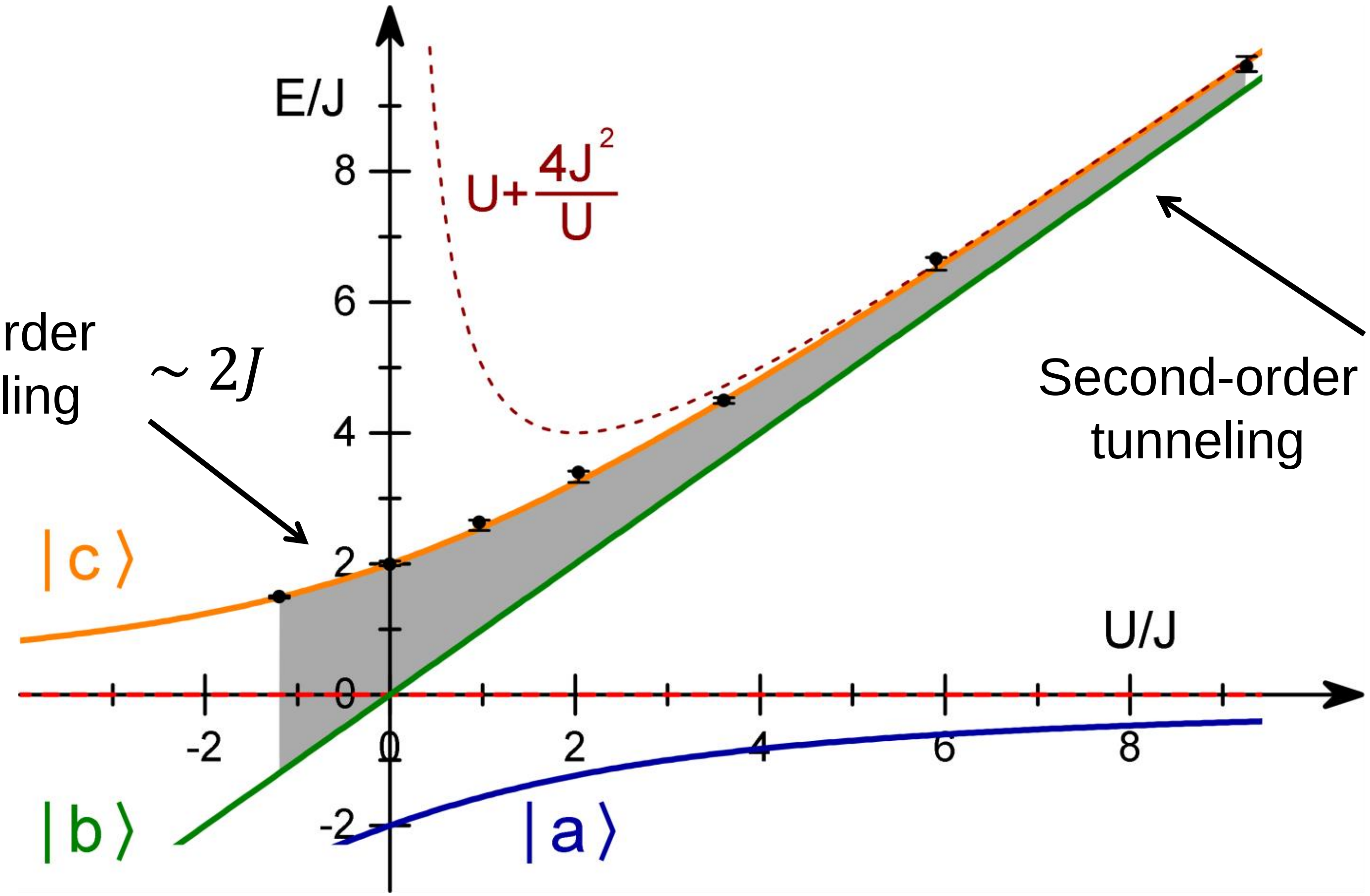


Measuring energies



Trap modulation spectroscopy

Measuring energies

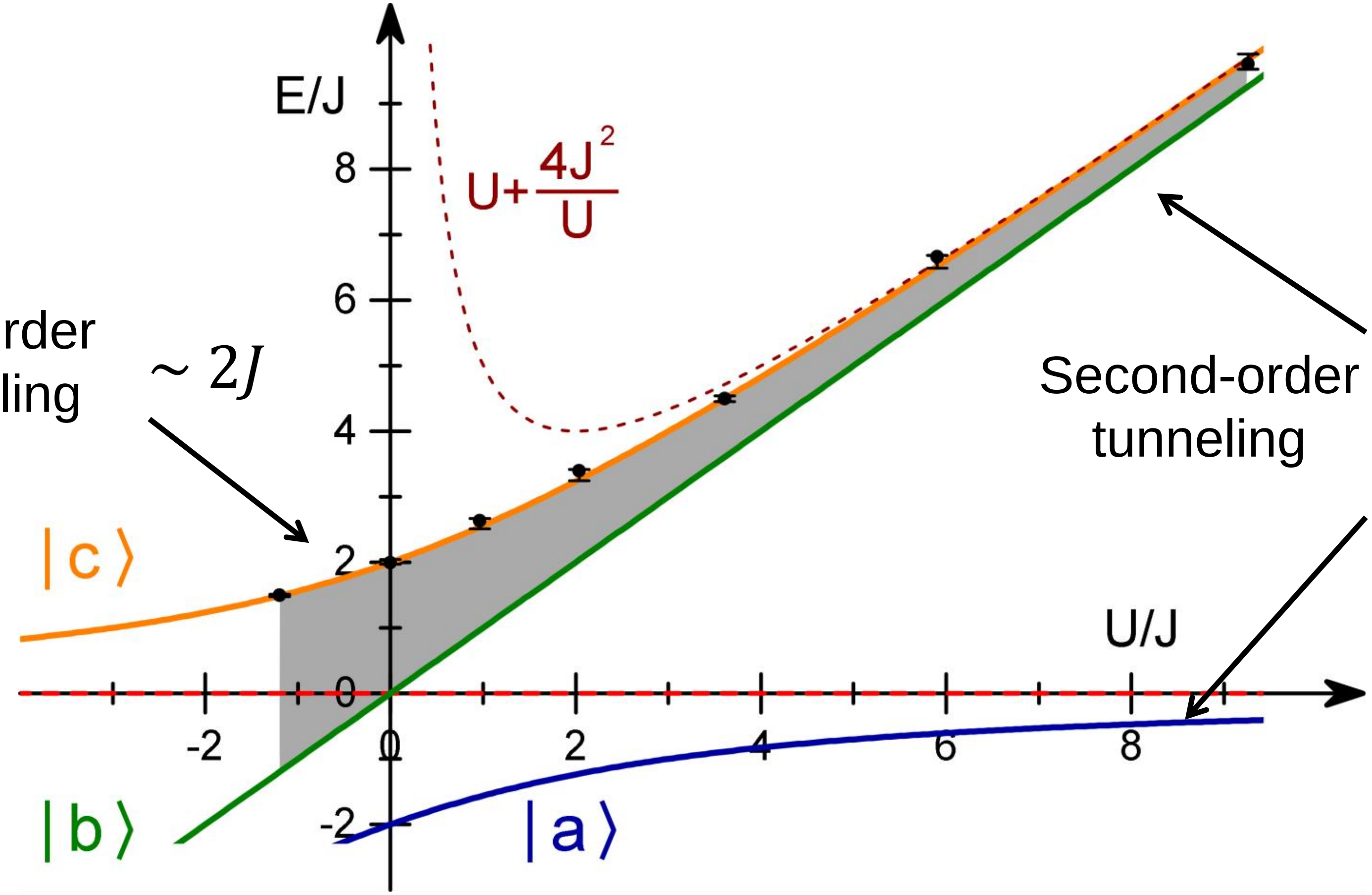


First-order tunneling $\sim 2J$

Second-order tunneling $\sim \frac{4J^2}{U}$

Trap modulation spectroscopy

Measuring energies



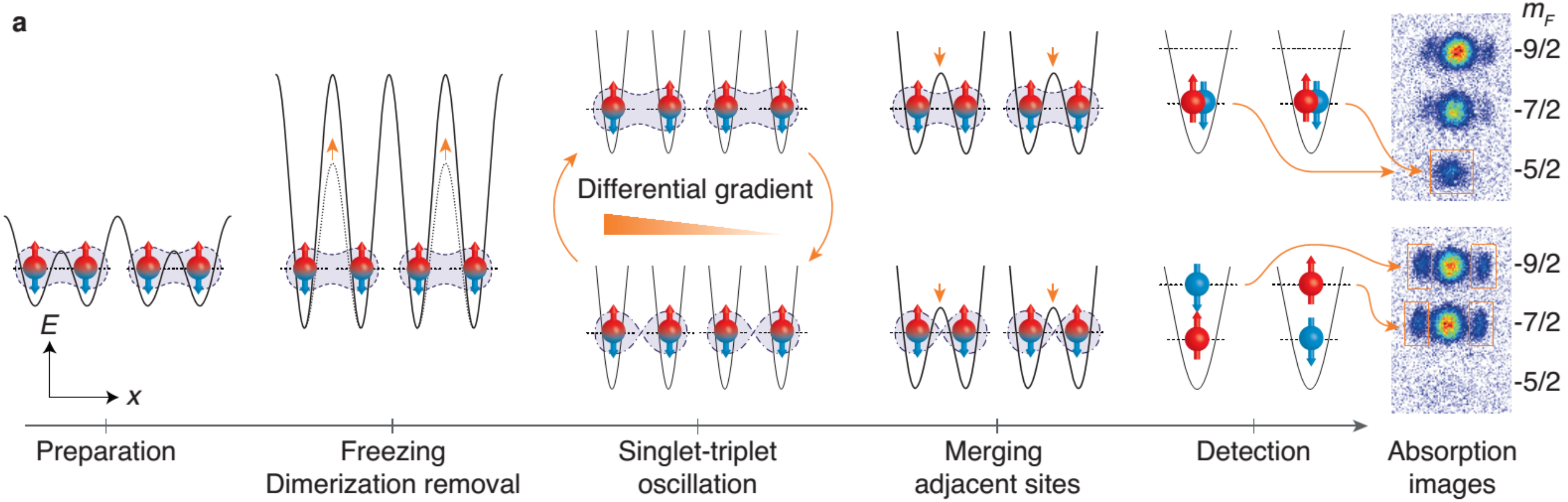
First-order tunneling $\sim 2J$

Second-order tunneling $\sim \frac{4J^2}{U}$

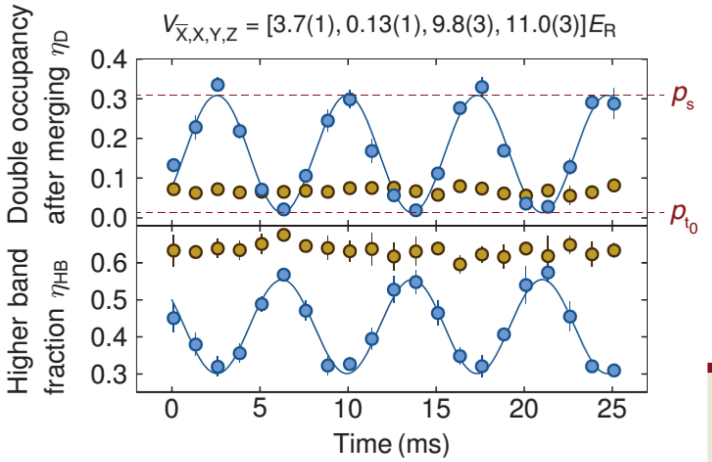
Super exchange energy!
responsible for spin ordering in the many body ground state

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)



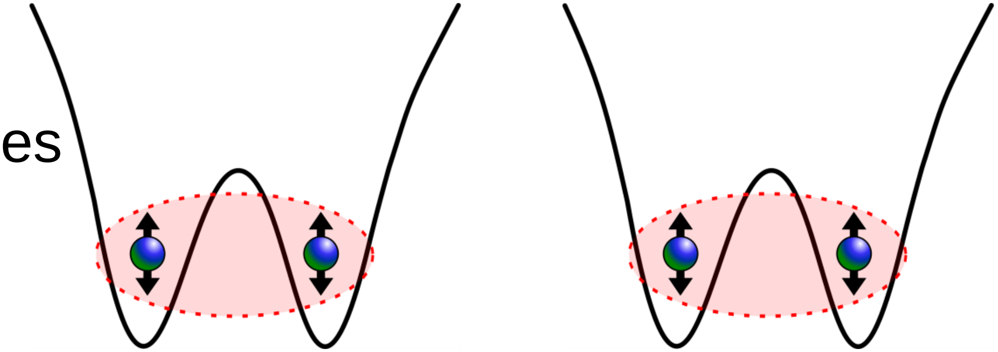
- Dimerize a lattice filled with spin-1/2 fermions to observe spin correlations



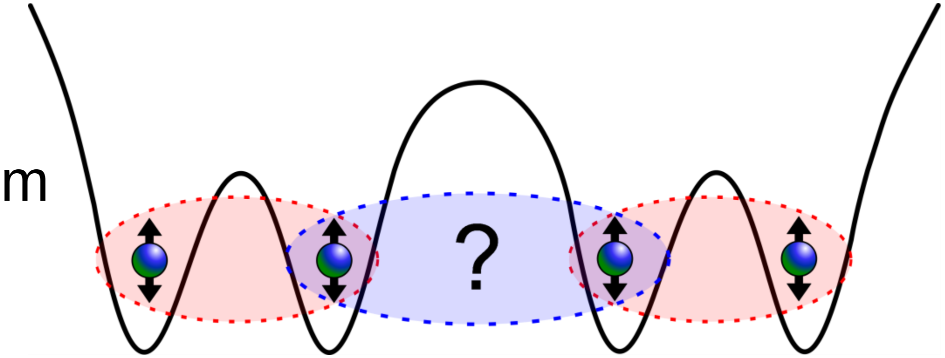
Outlook

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 ?

Thank you for your attention!

Funding:

Center for
Quantum
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