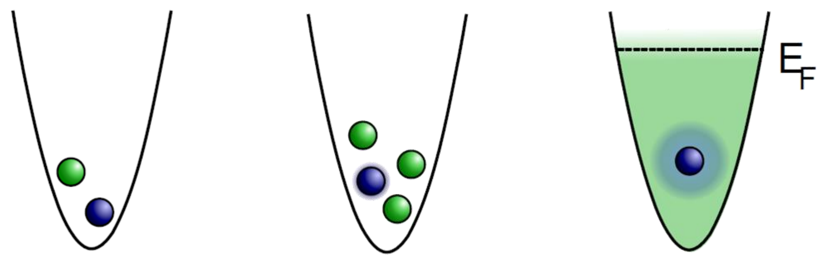
Universität Heidelberg

# Experiments on few fermion systems of ultracold atoms




…and the crossover to many-body systems

Workshop
Resonances and Non-Hermitian Quantum Mechanics in Nuclear and Atomic Physics
Trento, June 2014


Gerhard Zürn

Physikalisches Institut

# A tunable few-body system



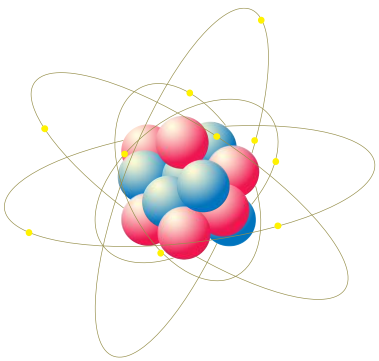
How can one study few body effects?

Few-fermion systems in nature:

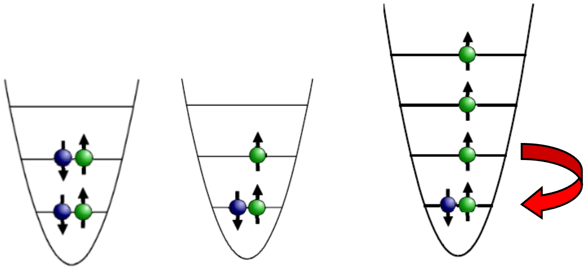
- atoms, nuclei

  well defined quantum state

  limited tunability of interaction

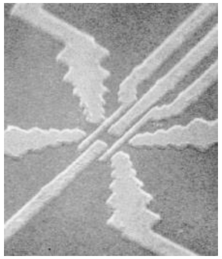


Artificial Quantum system:



interaction

- quantum dots
- atomic clusters



Wide tunability,

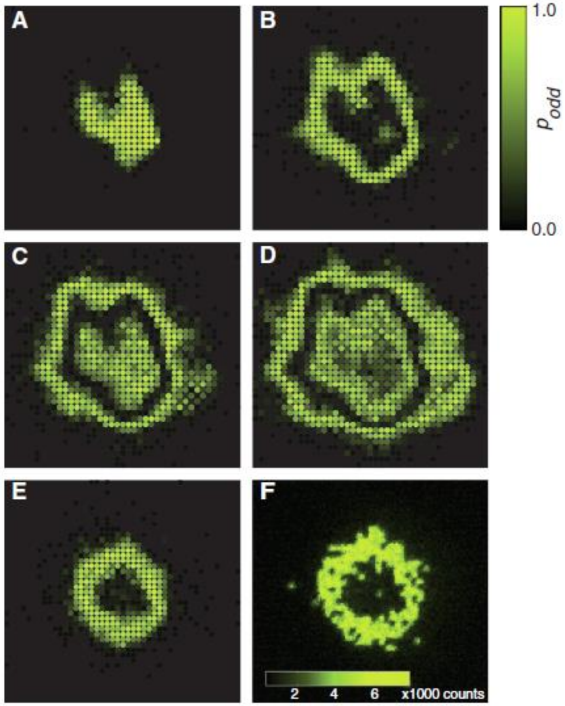
but no „identical“ systems

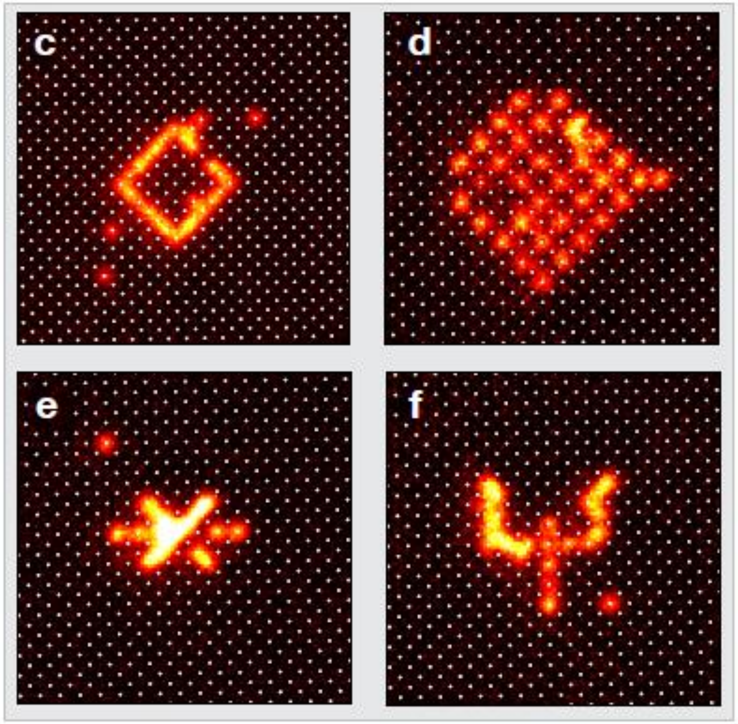
→ Realize a well-controlled and tunable quantum system using ultracold atoms

# Control at the single particle level



- Quantum control in a many-body system is becoming possible!




**W. Bakr et al., Science 329, 547, 2010**

**C. Weitenberg et al., Nature 471, 319-324, 2011**

→ We aim for bottom up approach:

Start with few-fermion system and then increase towards a many-body system

# Outline



- Preparation and control of few-fermion systems
- Pairing in a few-fermion system with attractive interactions
- From few to many: Building a Fermi sea from single particles
- (Two fermions in a double well)

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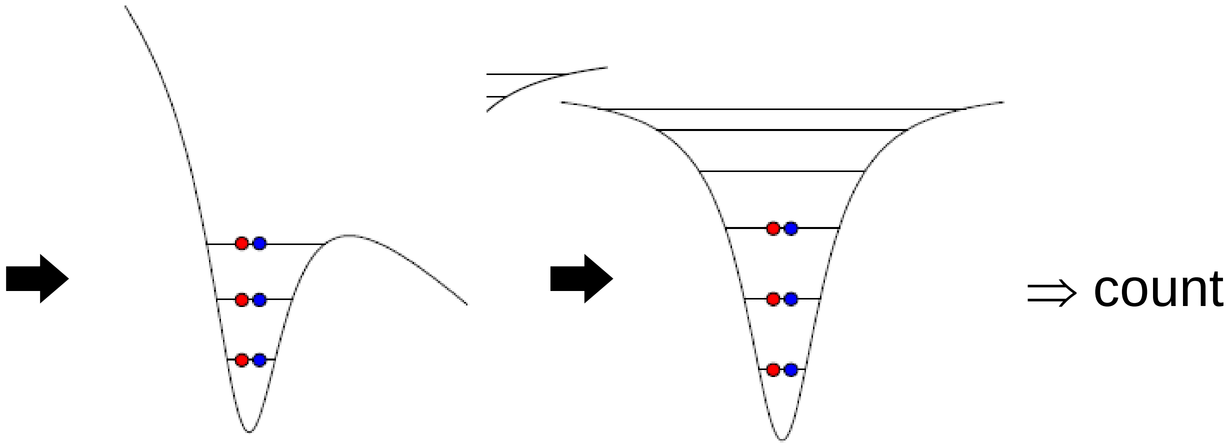
# High Fidelity Preparation



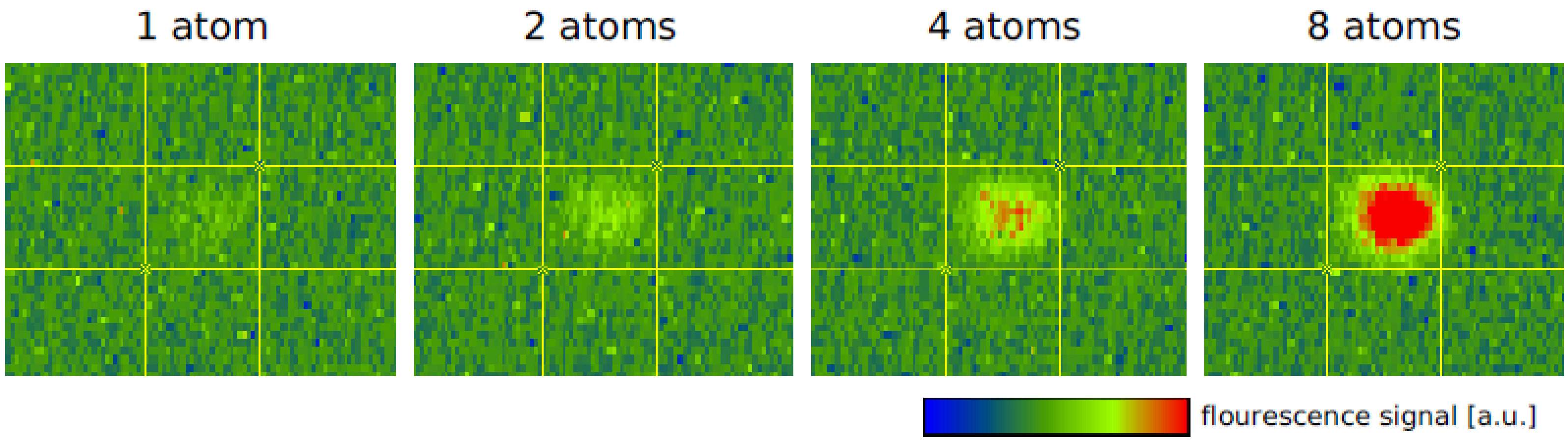
- 2-component mixture in reservoir T=250nK
- superimpose microtrap
  scattering → thermalisation
  expected degeneracy: $T/T_F = 0.1$
- switch off reservoir




+ magnetic field gradient in axial direction

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

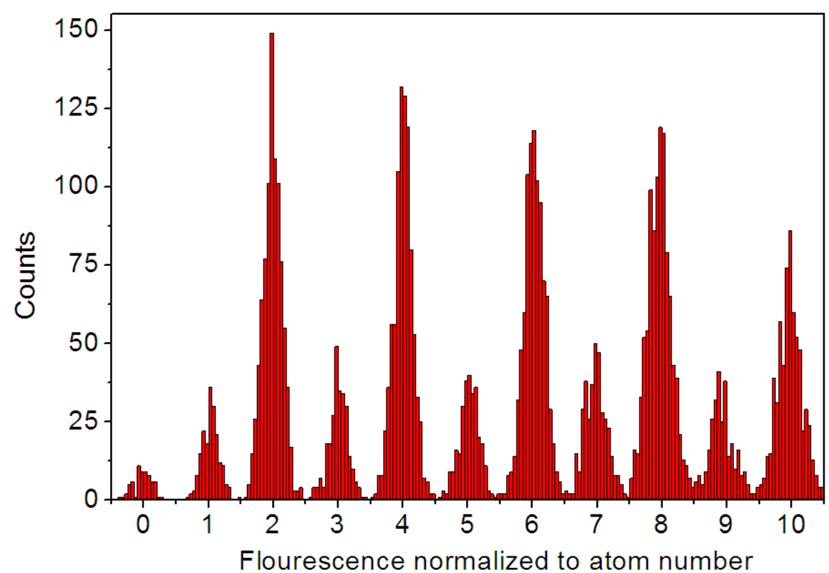
# Single atom detection




1/e-lifetime: 250s

Exposure time 0.5s

1-10 atoms can be distigiuished with high fidelity (> 99% )



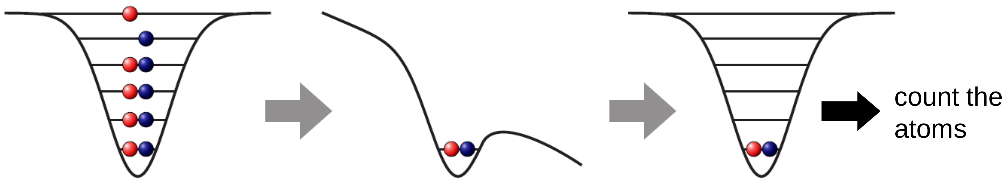

F. Serwane, G. Zürn, T. Lompe, T. Ottenstein, A. Wenz and S. Jochim, Science **332,** 336 (2011)

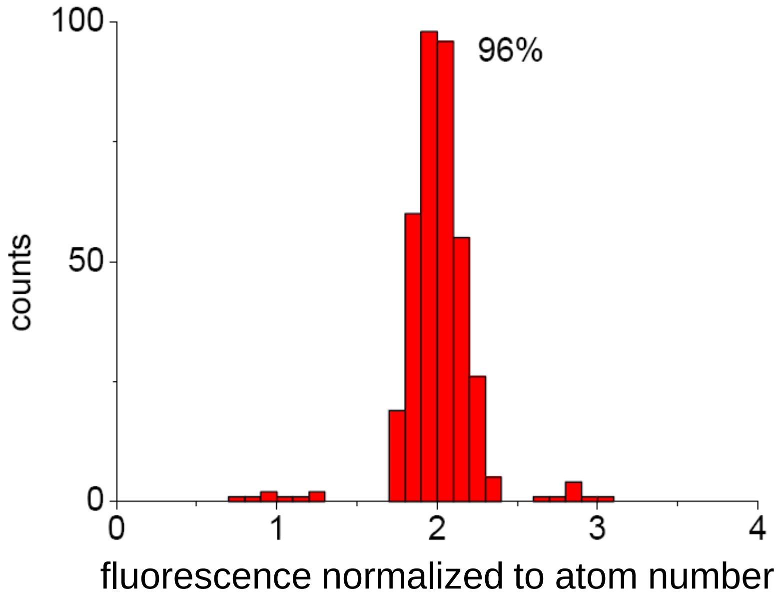
# High Fidelity Preparation

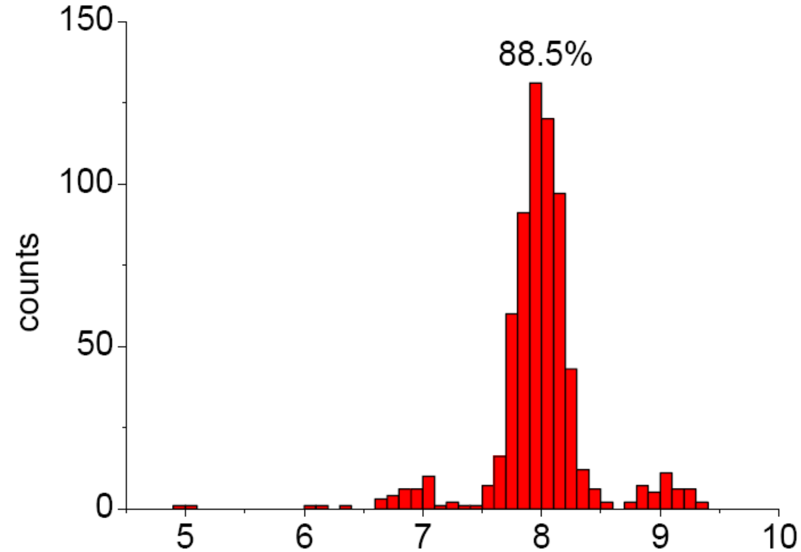


2 atoms

8 atoms



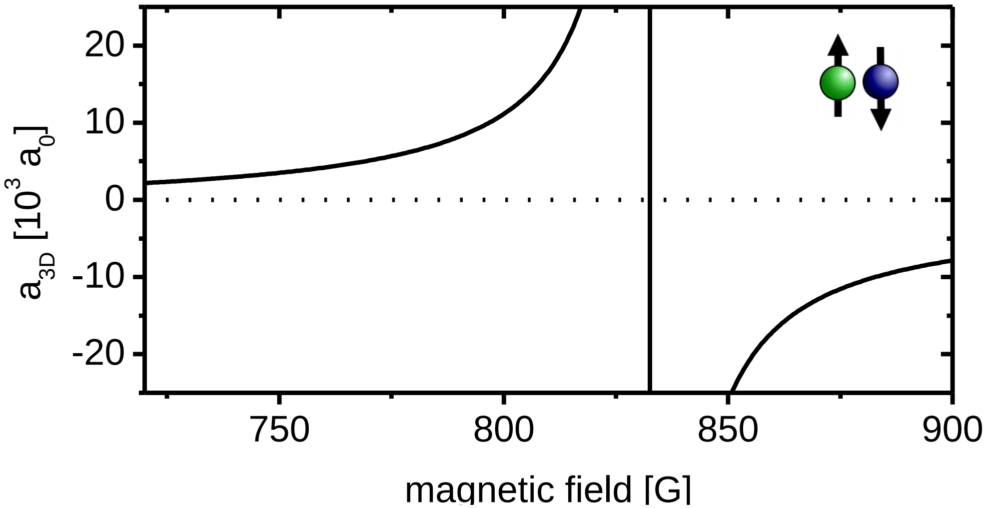

Lifetime in ground state ~ 60s

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

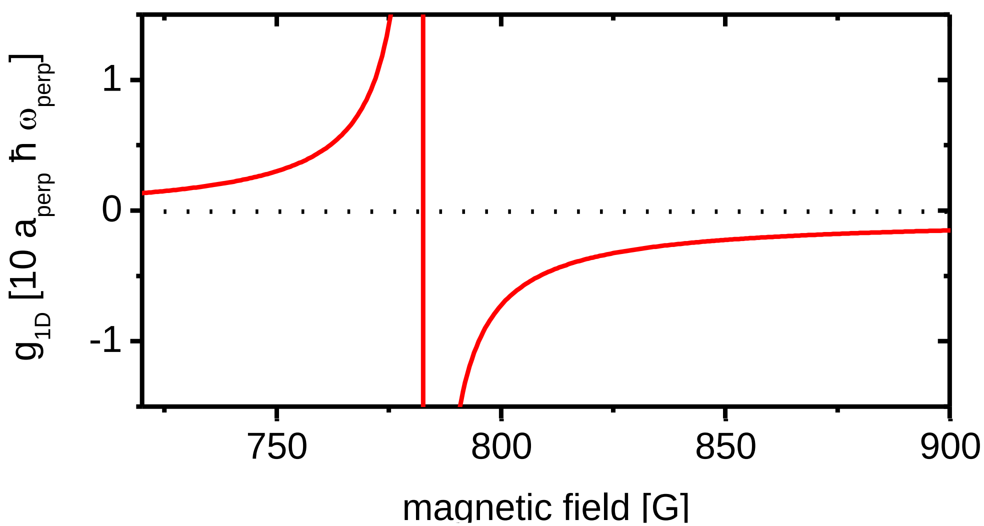
# Interaction in 1D



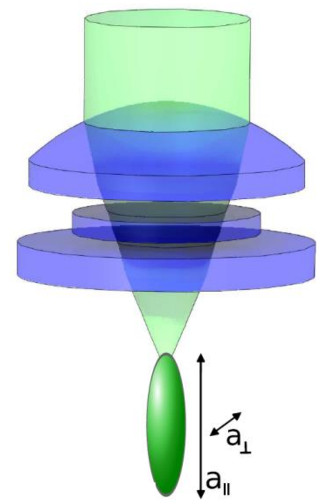
3D




1D




radially strongly confined




aspect ratio: $\omega_{\parallel}$ / $\omega_{perp}$ 1:10 → 1D

**Z. Idziaszek and T. Calarco, PRA 74, 022712 (2006)**

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

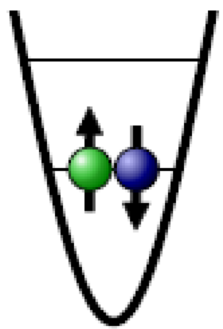
**M. Olshanii, PRL 81, 938 (1998)**

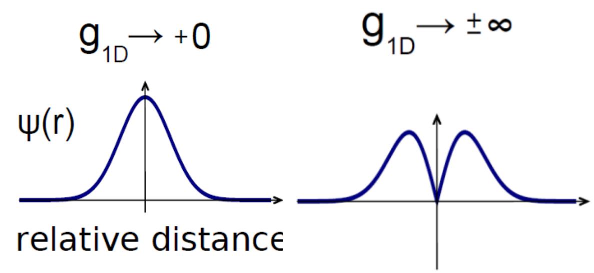
# Studying few-body physics

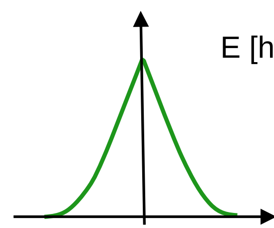
control of the particle number

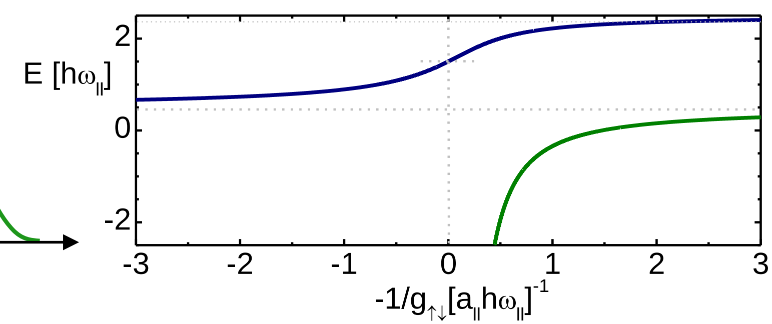
$$H = -\frac{\hbar^2}{2m}\sum_{i=1}^{N}\frac{\partial^2}{\partial x_i^2} + \frac{1}{2}m\omega_{\parallel}^2\sum_{i=1}^{N}x_i^2 + g_{1\mathrm{D}}\sum_{i<j}^{N}\delta(x_i - x_j)$$

tunability of the interpart. interaction








T. Busch et al., Found. Phys. **28**, 549 (1998)

# Outline



- Preparation and control of few-fermion systems
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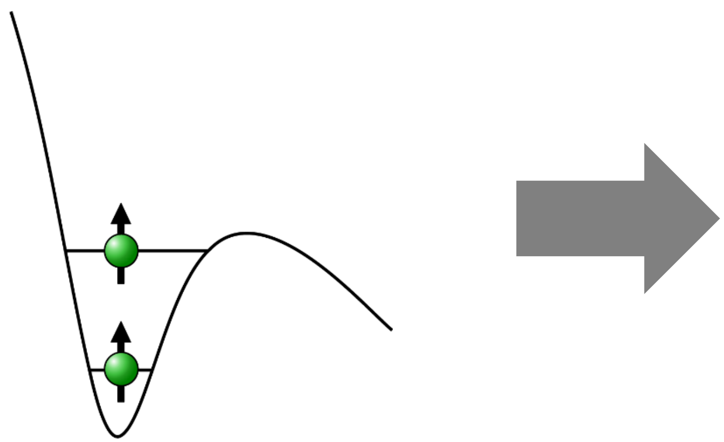
- (Two fermions in a double well)

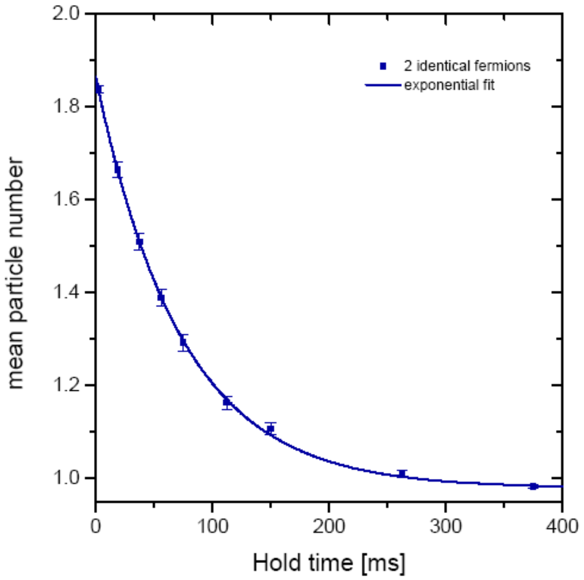
## Probing the system



Observe tunneling dynamics:

•Tilt the trap such that the highest-lying states have an experimentally accessible tunneling time of about 10-1000ms.

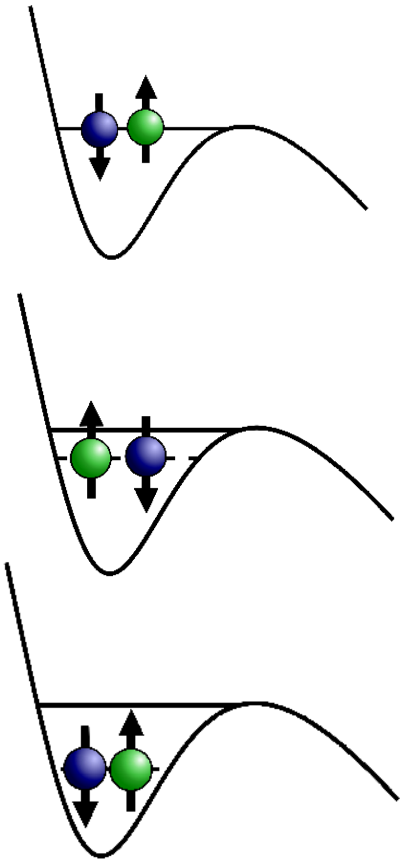


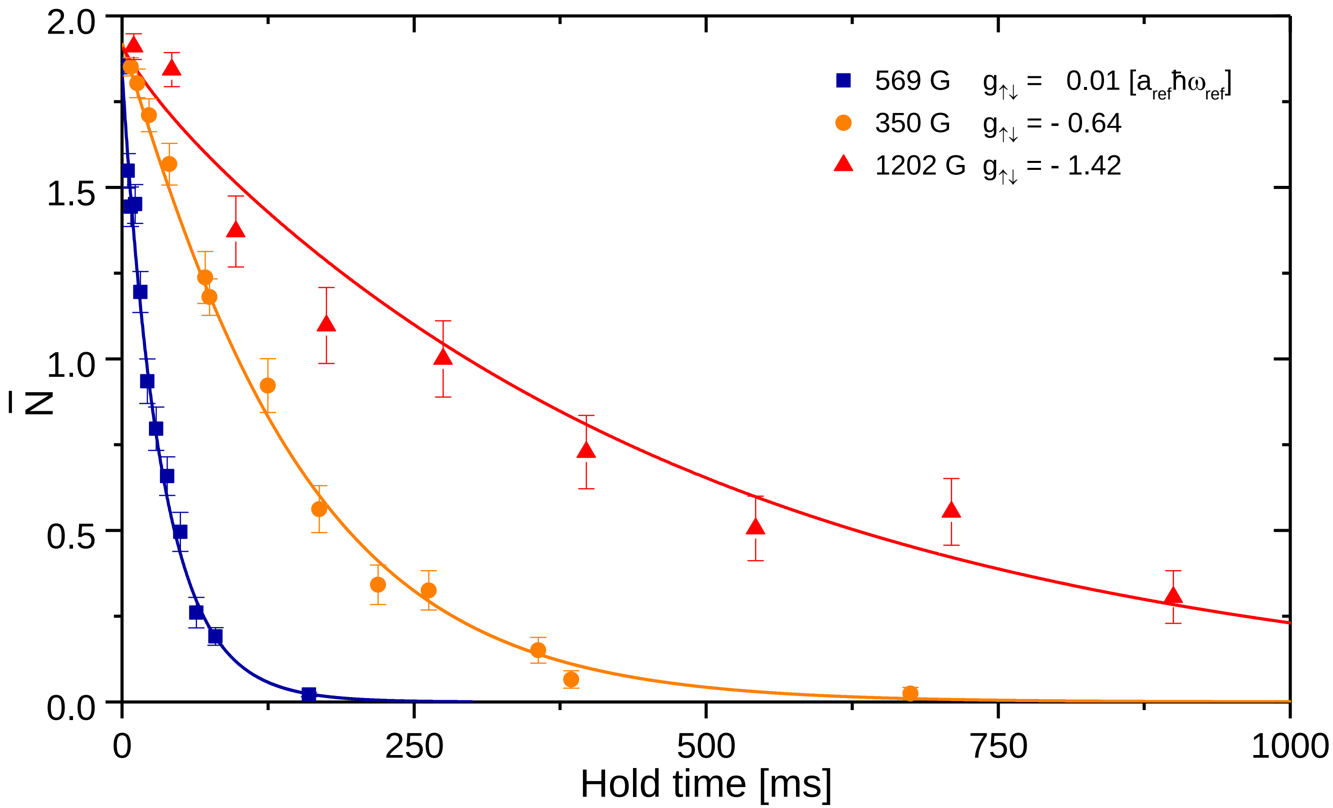



From the observed tunneling time scale we can then infer the total energy of the system

# Attractive interactions





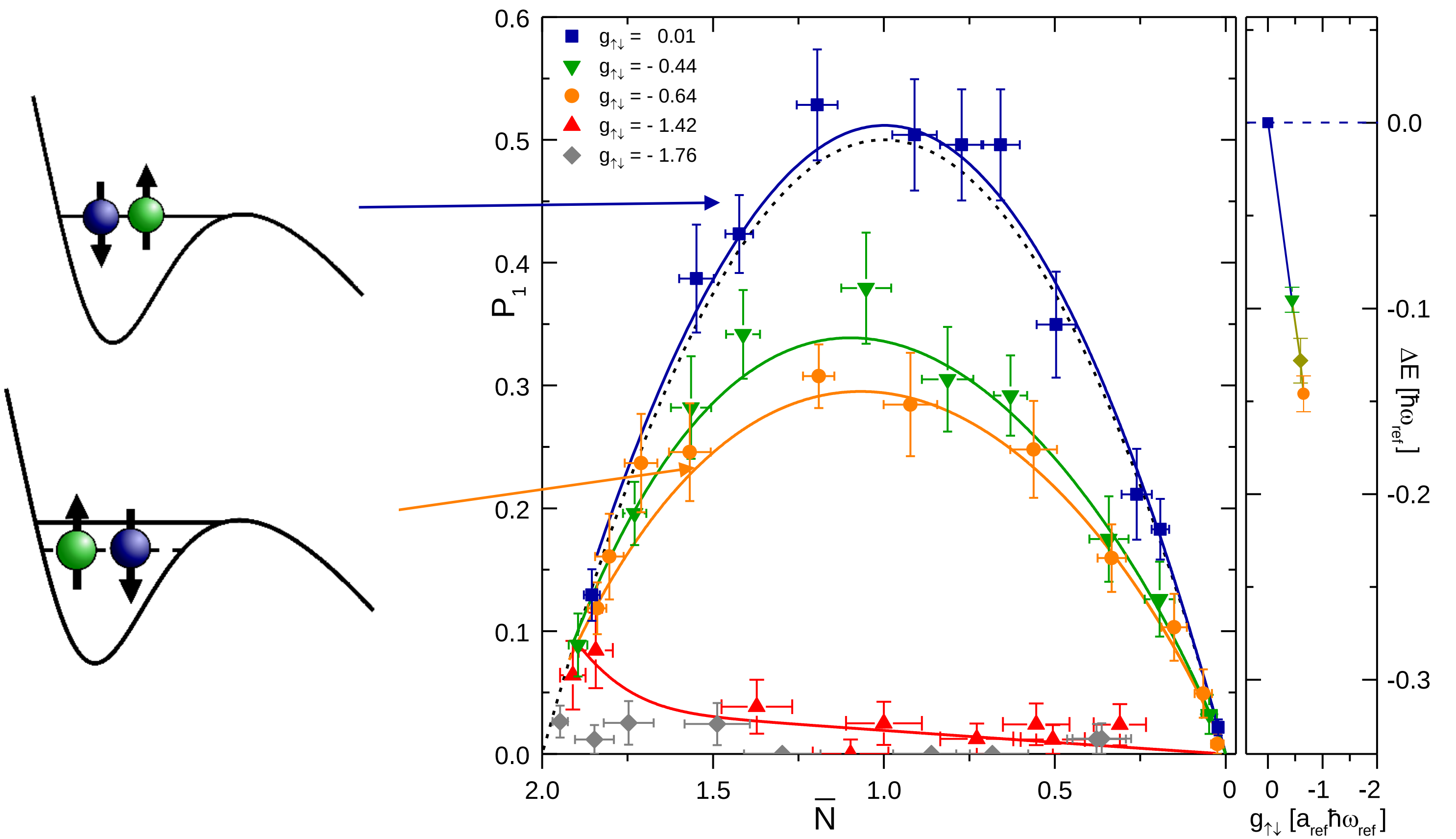



- Use this to determine the pairing energy
- Problem: tunneling of the two particles is correlated

G. Zürn, A. Wenz , S. Murmann, A. Bergschneider, T. Lompe, and S. Jochim, PRL **111**, 175302 (2013)

# Correlated tunneling

- Set up rate equation for tunneling
- Fit rate coefficients to the data (consistent with subsequent single particle tunneling)

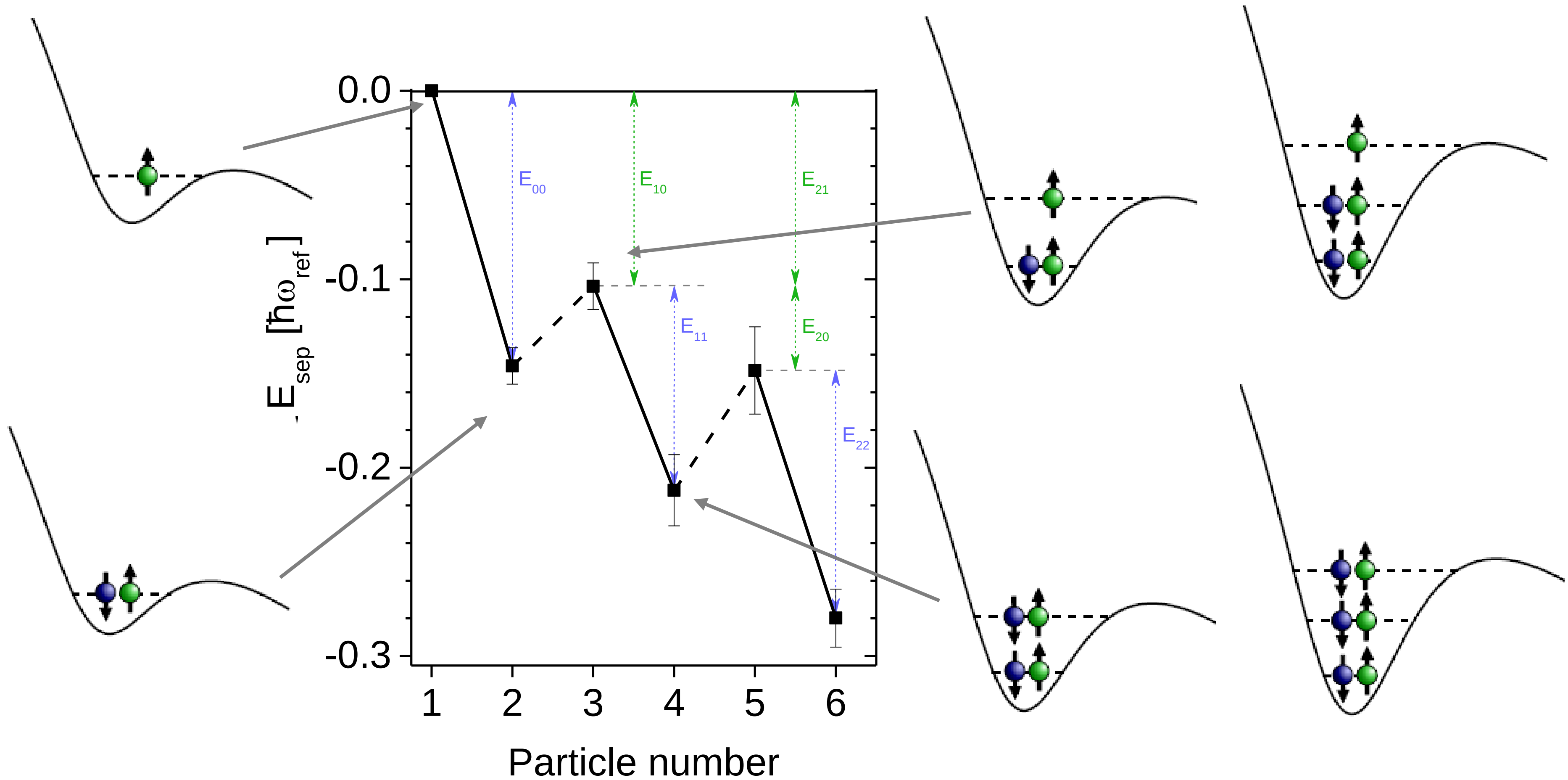



G. Zürn, A. Wenz , S. Murmann, A. Bergschneider, T. Lompe, and S. Jochim, PRL **111**, 175302 (2013)

# Odd-even effect with ultracold fermions



- How does the energy of the system evolve for larger systems?




G. Zürn, A. Wenz , S. Murmann, A. Bergschneider, T. Lompe, and S. Jochim, PRL **111**, 175302 (2013)

Prospects:

- Study non-perturbative regime
- Pairing in higher dimensions (2D, 3D)
- larger systems, superfluidity

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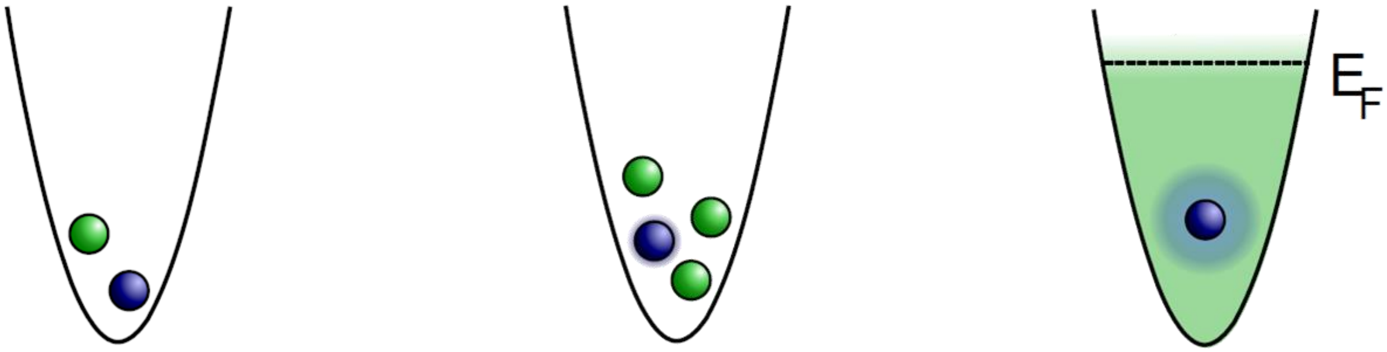
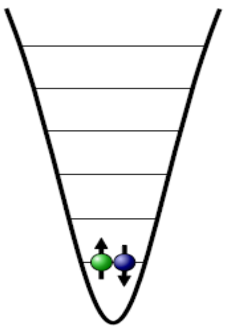


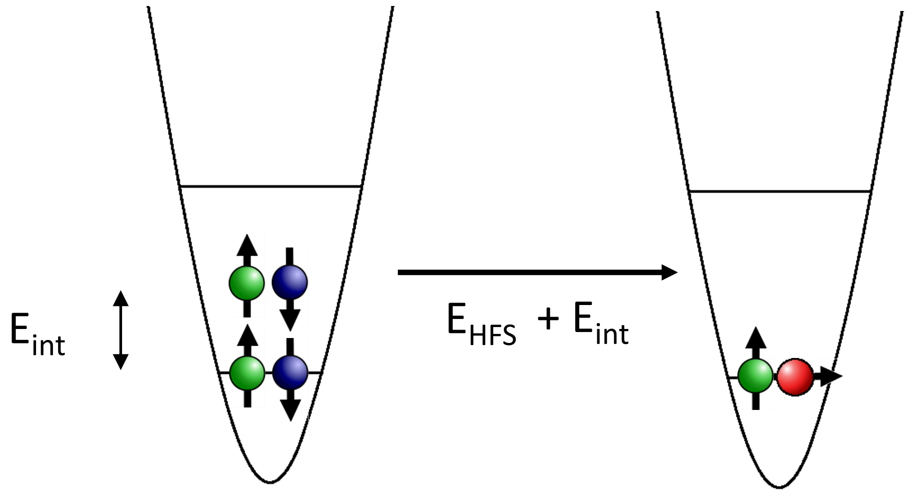

N=1

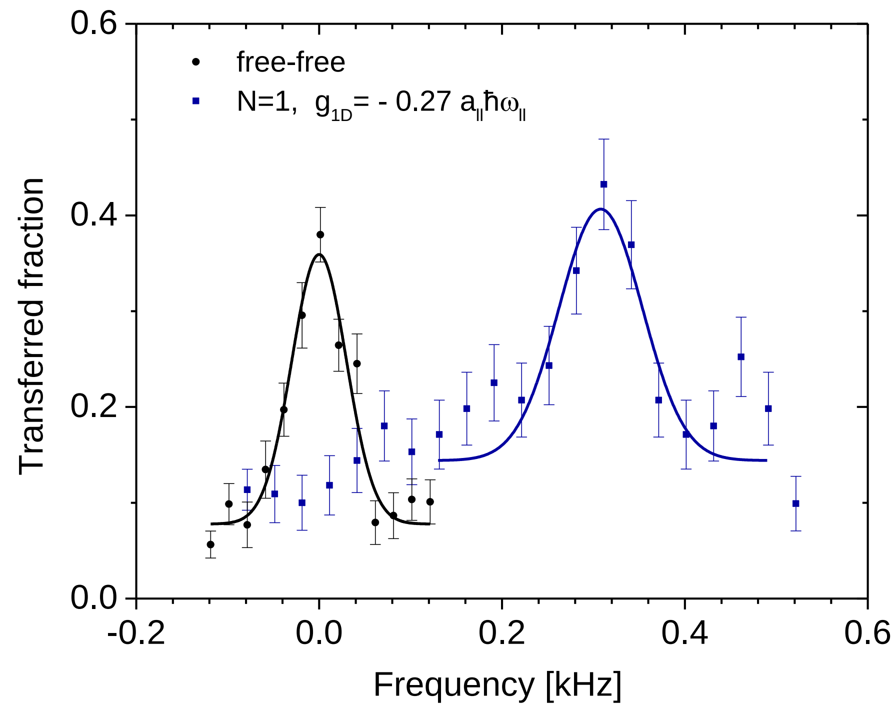


How many is many?

Observable: Interaction energy vs. particle number and interaction strength

# RF-Spectroscopy

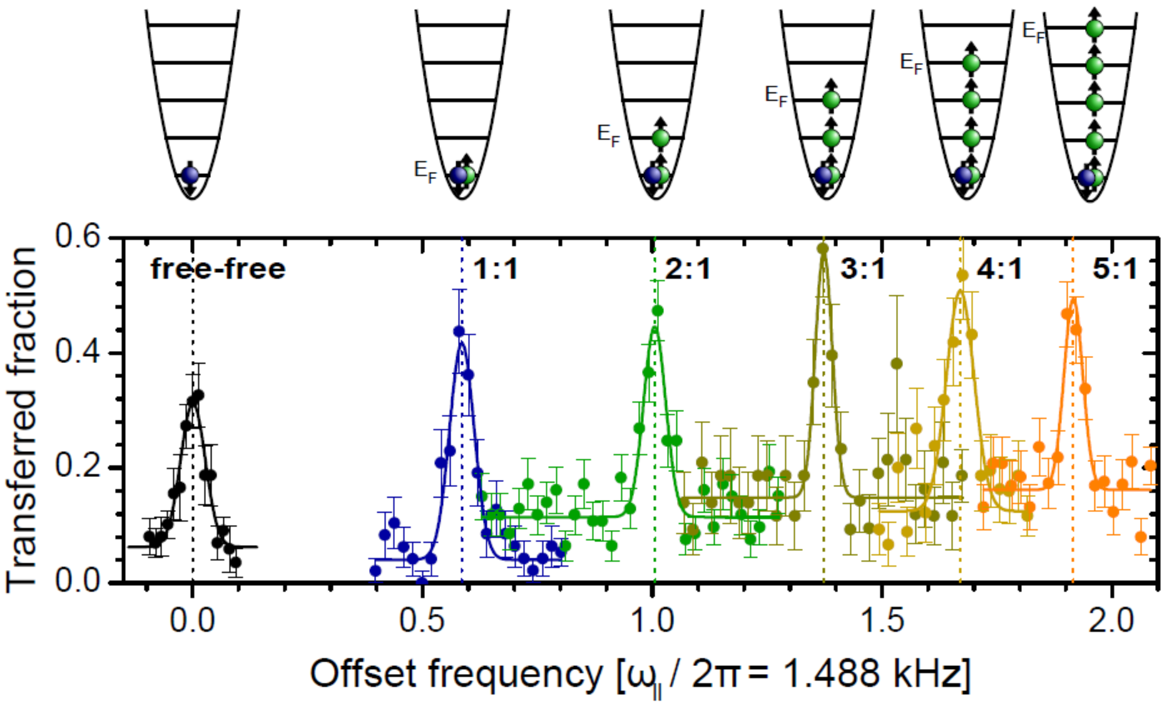


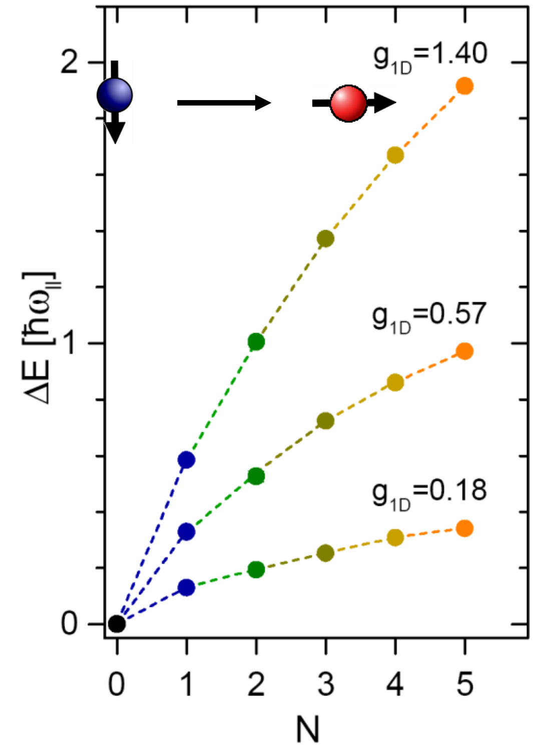



# Measure the interaction energy



A single impurity repulsively interacting
with an increasing 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:

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

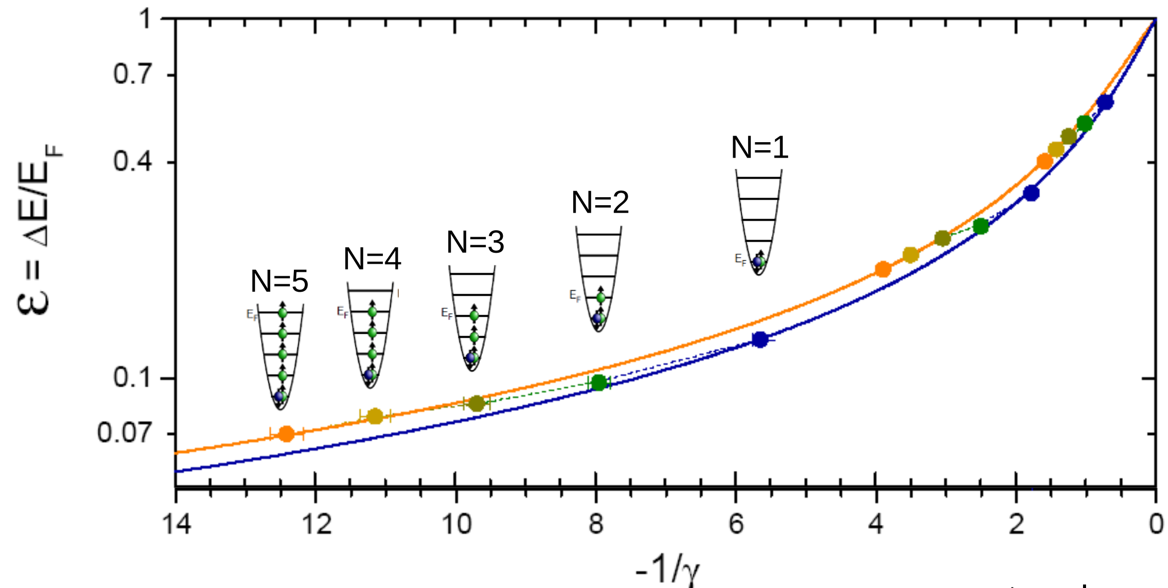
The interaction strength is rescaled with the Fermi momentum $k_F$ (~1/interparticle spacing) to obtain a dimensionless quantity:

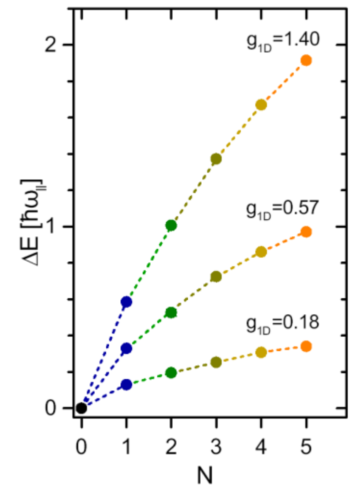
$$g_{1D} \rightarrow g_{1D}/k_F$$

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

# Measure the interaction energy



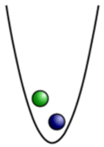


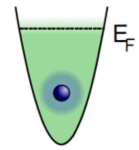

non interacting

strongly repulsive

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



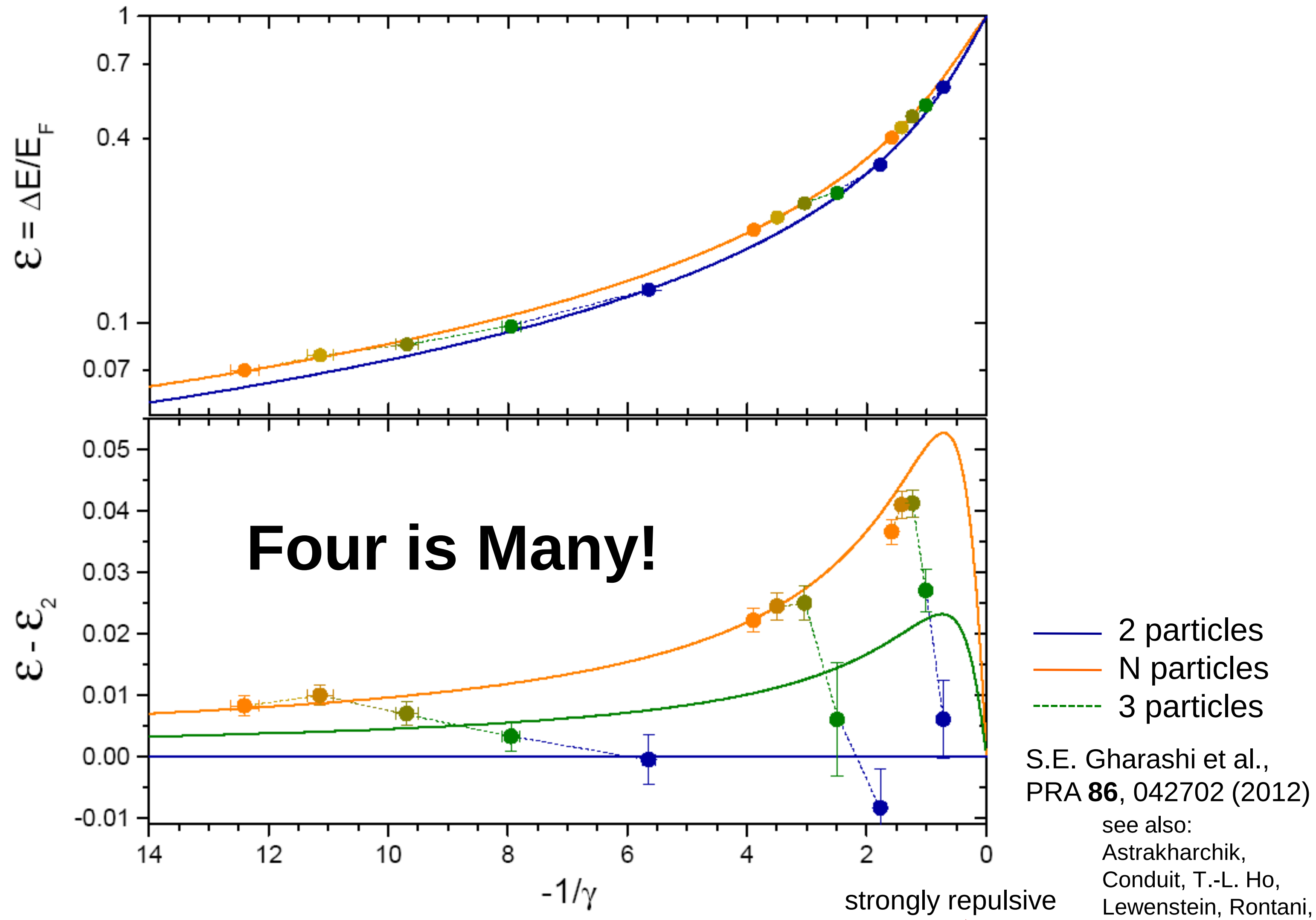
Analytic solution for an infinite number of majority particles
J. McGuire, J. Math. Phys. 6,432 (1965)
Adapted from homogeneous to trapped case by local density approximation




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

# Measure the interaction energy

UNIVERSITÄT HEIDELBERG




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

see also: Astrakharchik, Conduit, T.-L. Ho, Lewenstein, Rontani, Santos, Zinner …

non interacting

strongly repulsive

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

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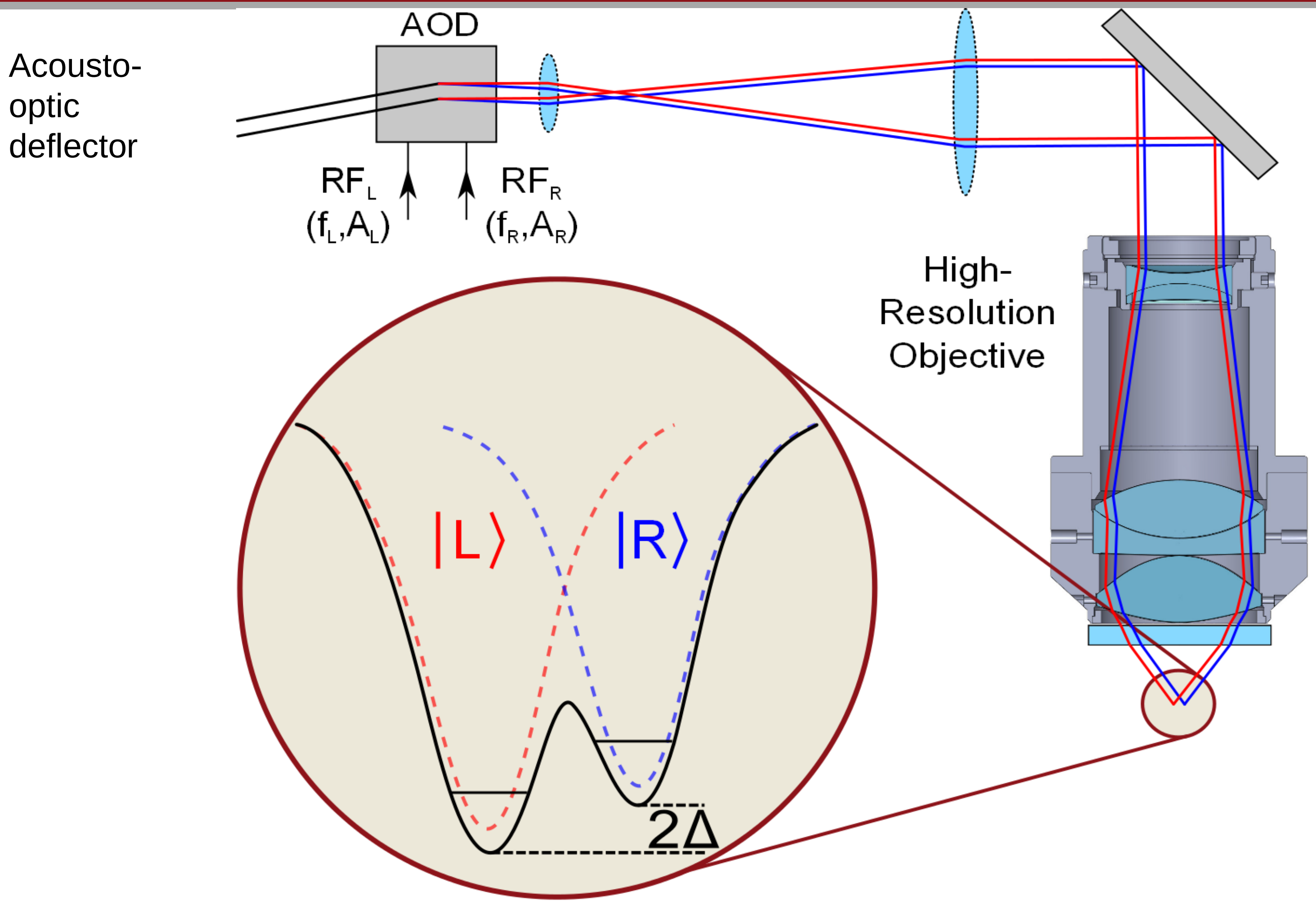
# Outline



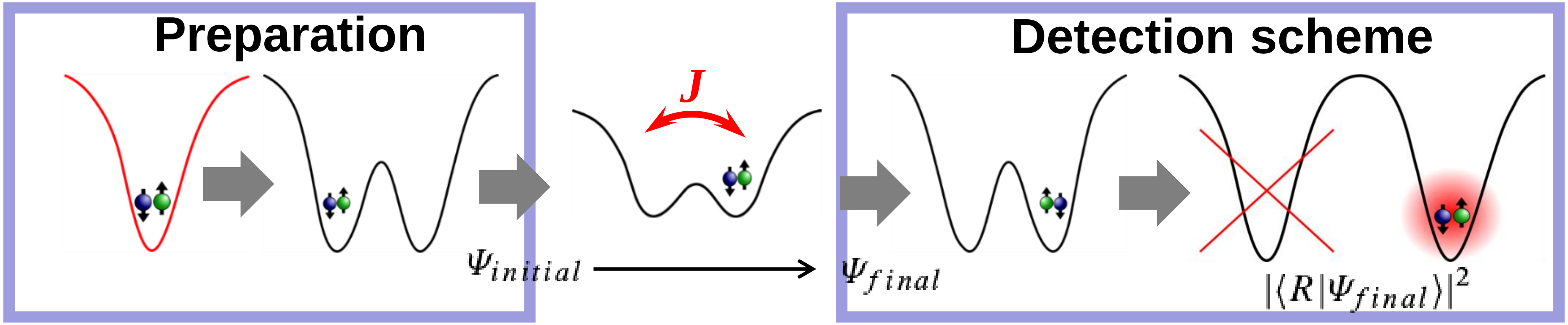
- Preparation and control of few-fermion systems
- Pairing in a few-fermion system with attractive interactions
- From few to many: Building a Fermi sea from single particles
- Realize a tunable potential

# Creating  a tunable potential

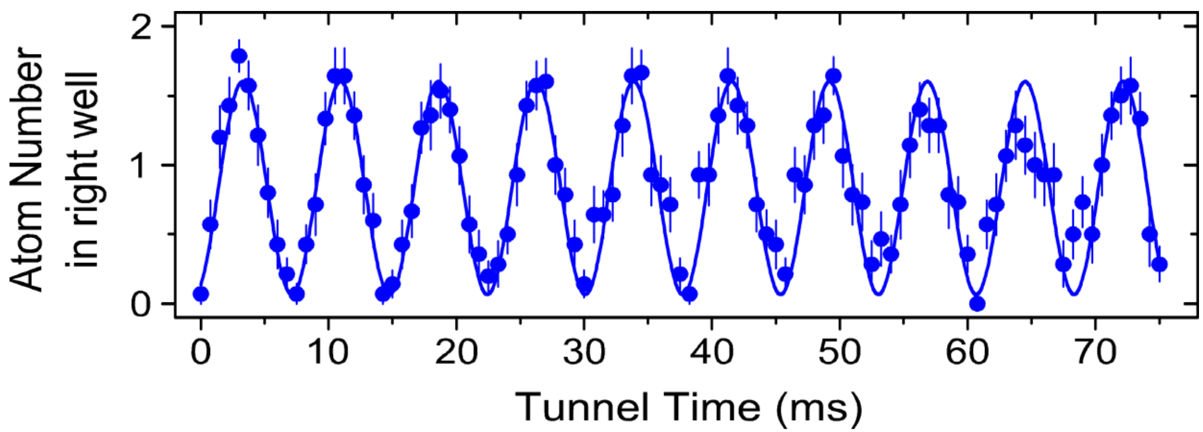




# Tunneling in a double-well




$\sim 1/2J$

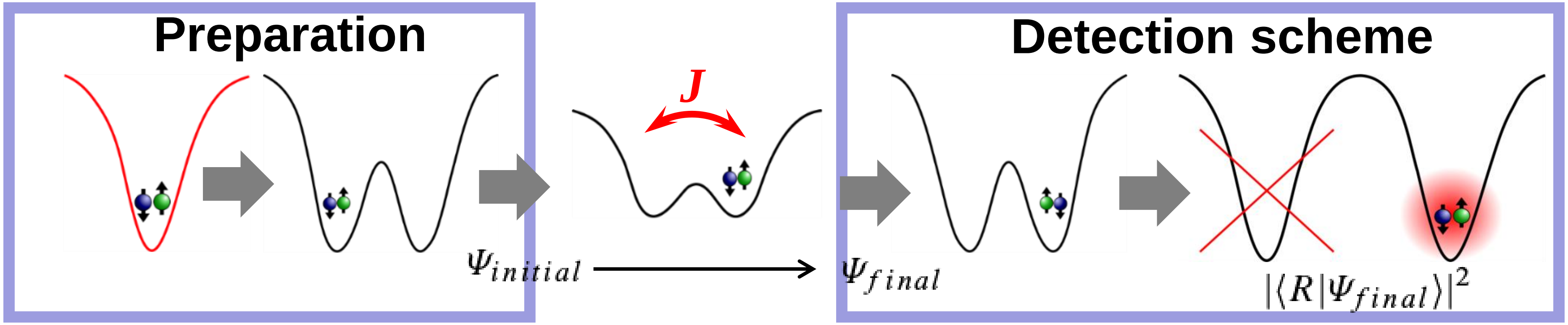


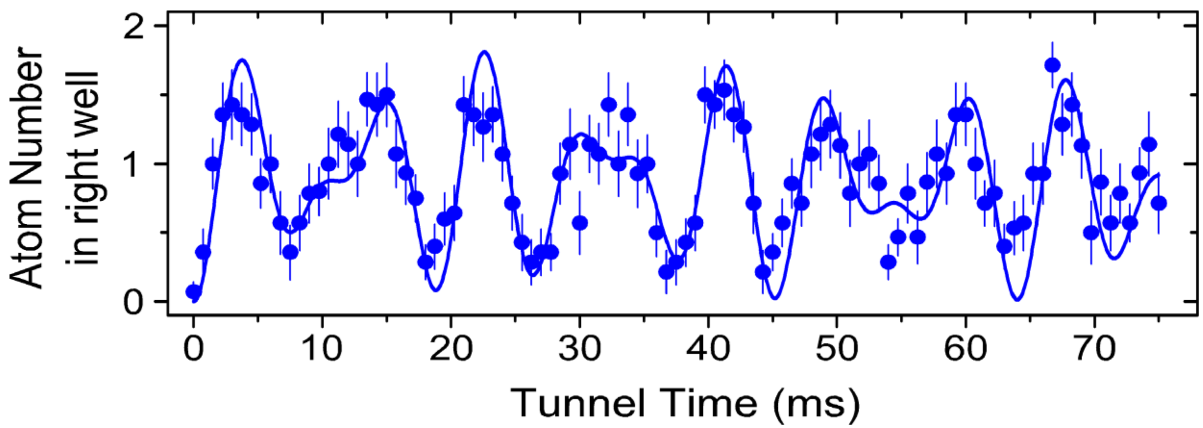

***U = 0***

$$\Psi_{1,2}(t) = \psi_1(t)\,\psi_2(t)$$

- Single-part. tunneling
- Calibration of $J$

# Tunneling in a double-well




***U ≠ 0***

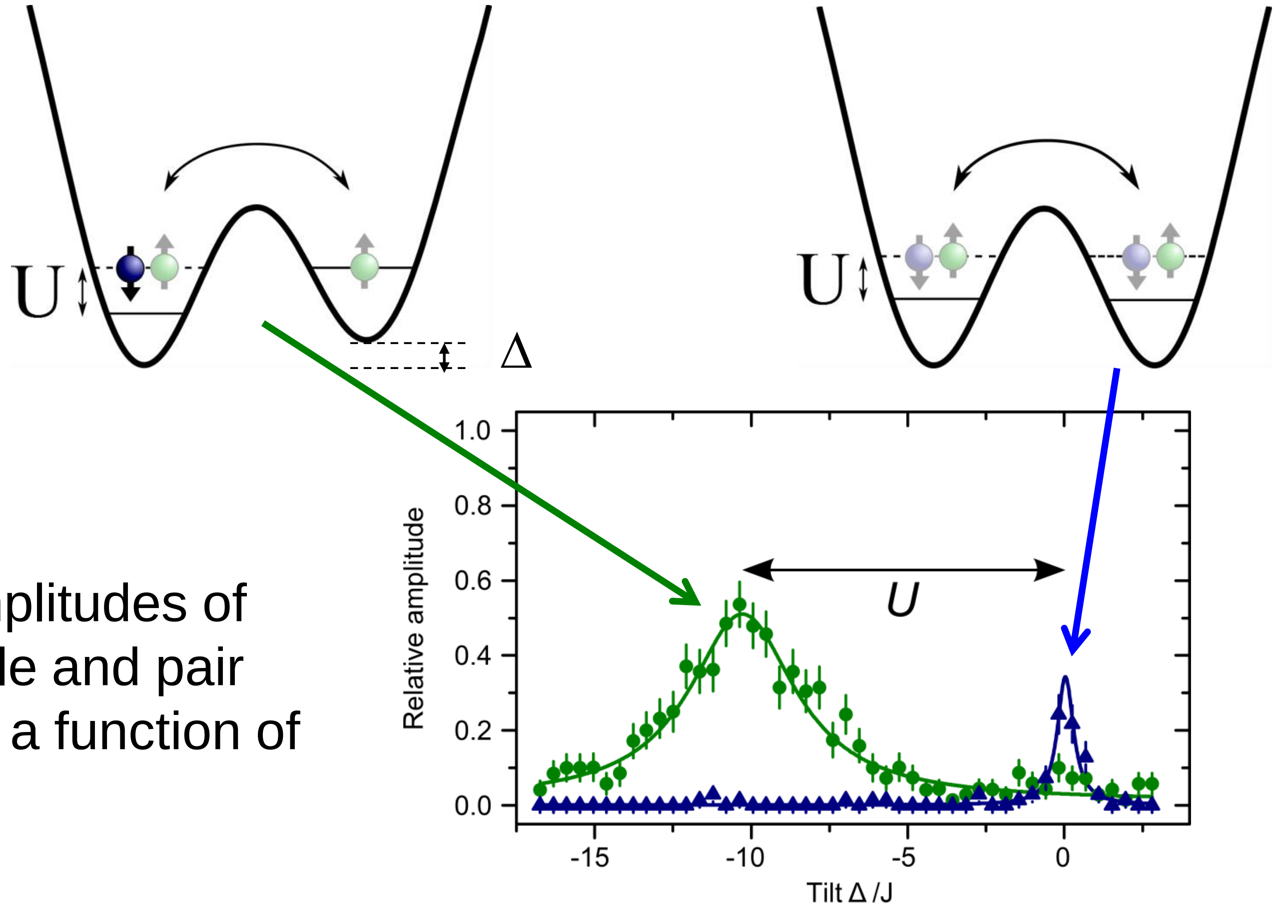
$$\Psi_{1,2}(t) \neq \psi_1(t)\,\psi_2(t)$$

- Correlated tunneling
- Calibration of *U*

# Measuring Energies in a DW

Conditional
single-particle tunneling

Resonant pair tunneling



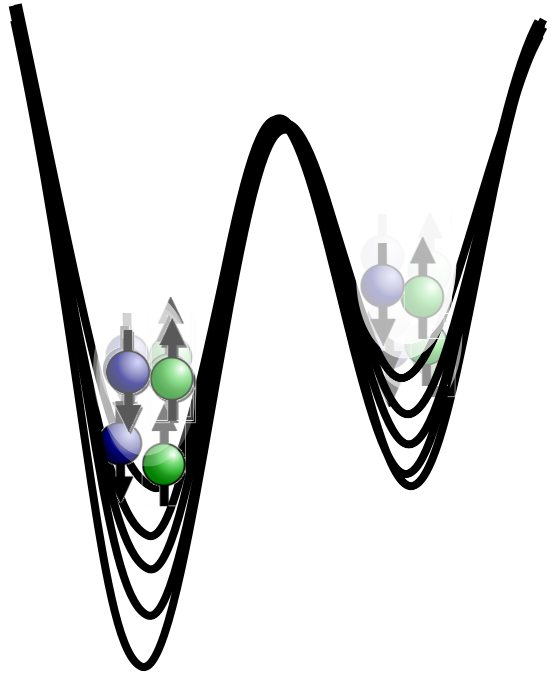

Measure amplitudes of single-particle and pair tunneling as a function of tilt

# Preparation of the ground state



$\Delta \ll 0$ $\quad\quad$ $\Delta = 0$ $\quad\quad$ $\Delta \gg 0$

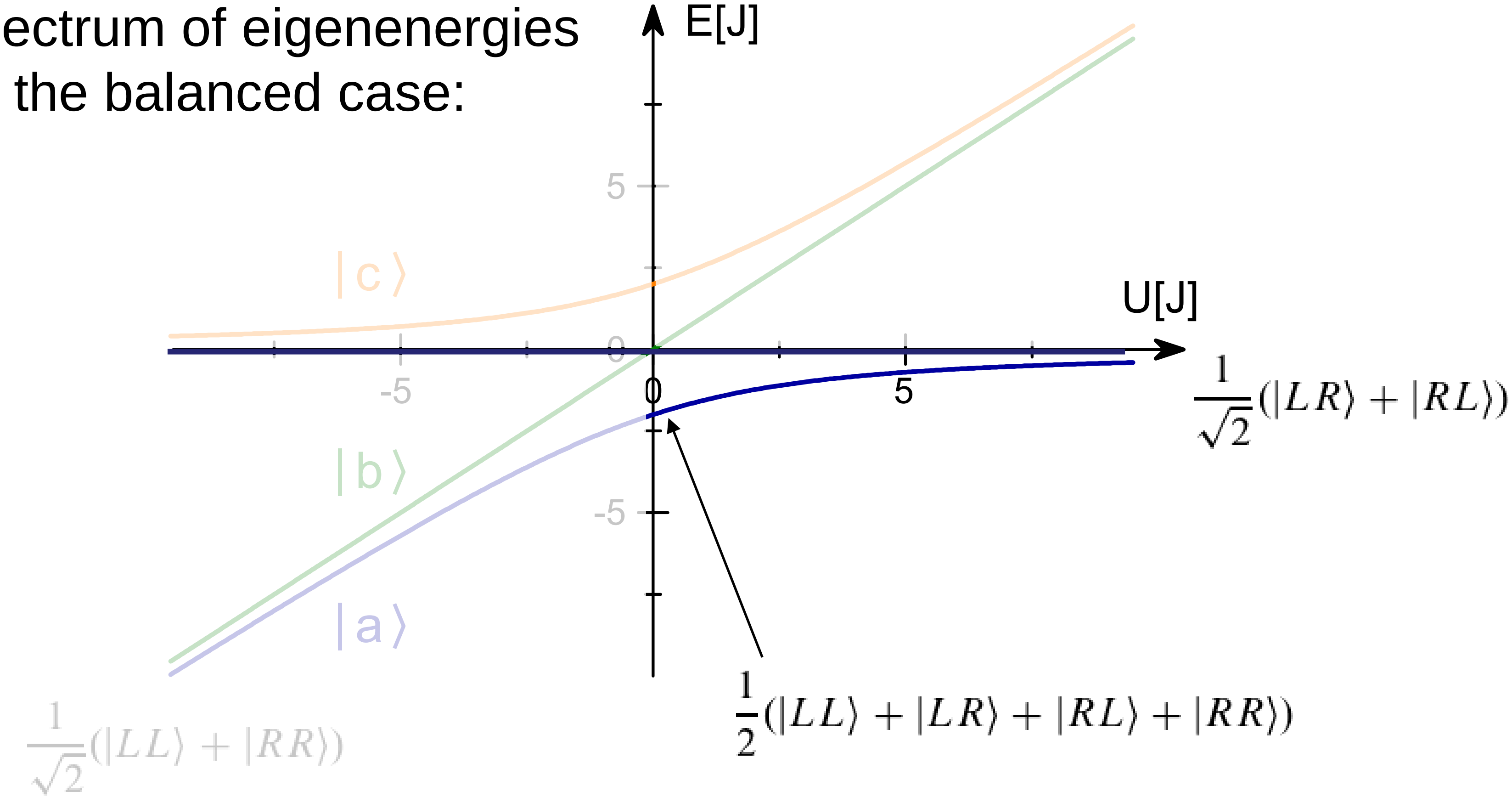
$$|LL\rangle \longleftarrow \frac{1}{2}(|LL\rangle + |LR\rangle + |RL\rangle + |RR\rangle) \longrightarrow |RR\rangle$$



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

# The eigenstates

Spectrum of eigenenergies for the balanced case:

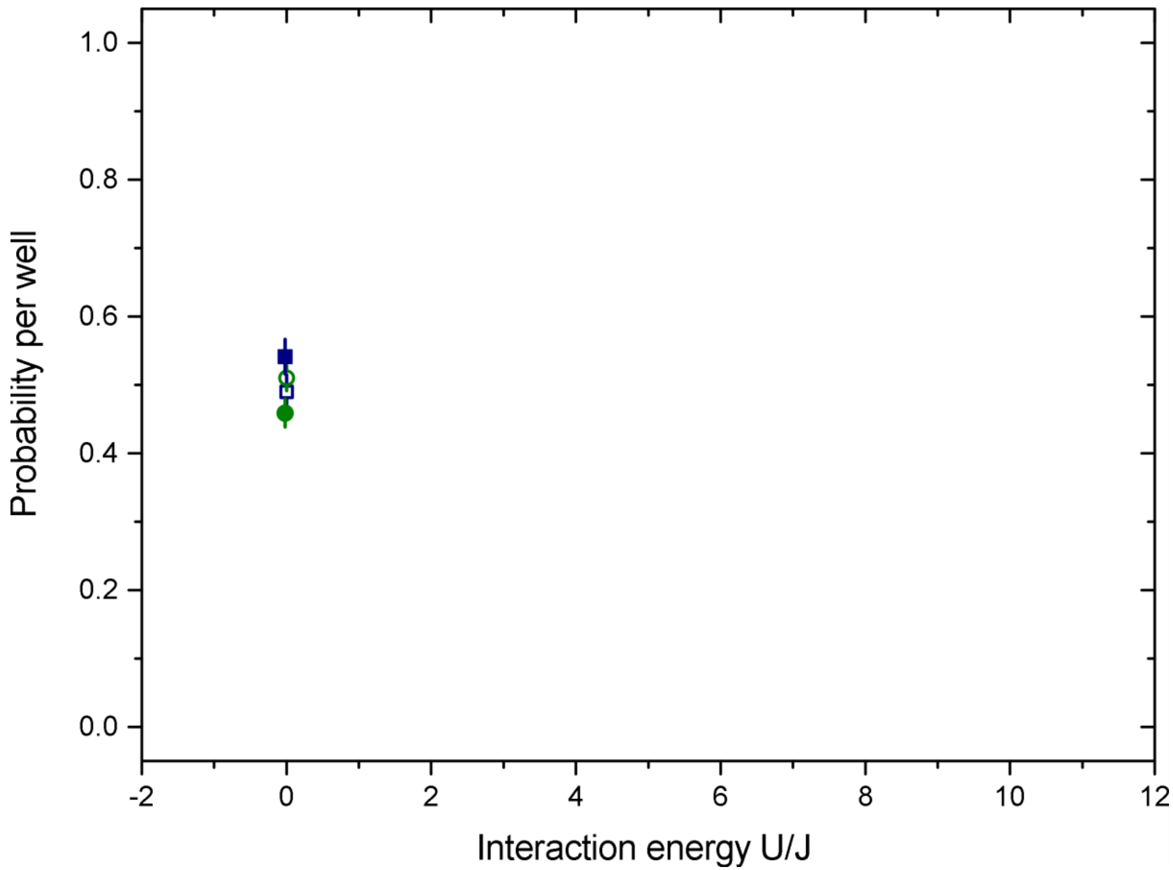


# Occupation statistics

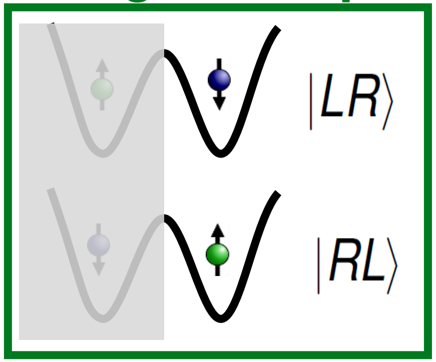


Number statistics for the balanced case depending on the interaction strength:

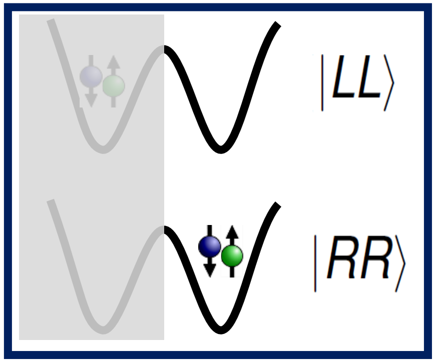
$$\frac{1}{2}(|LL\rangle + |LR\rangle + |RL\rangle + |RR\rangle)$$




**Single occupancy**




**Double occupancy**

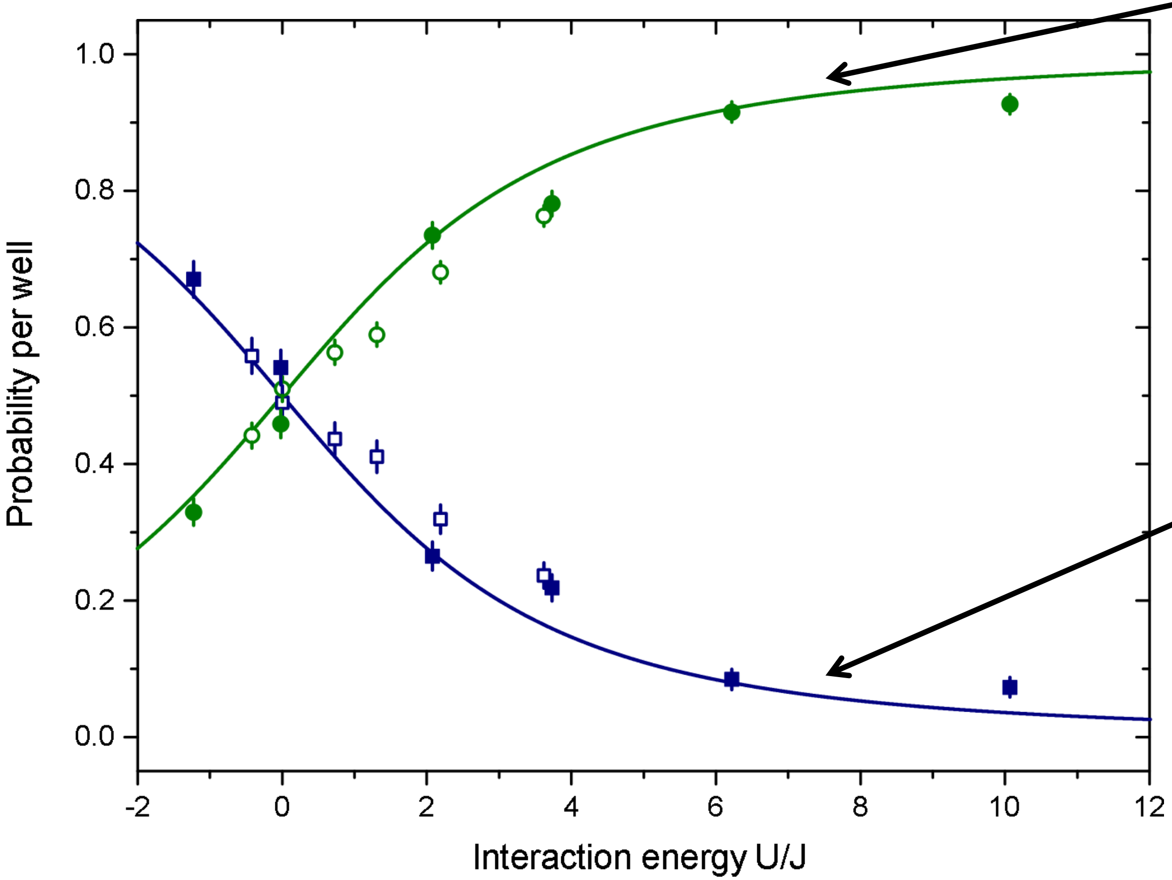


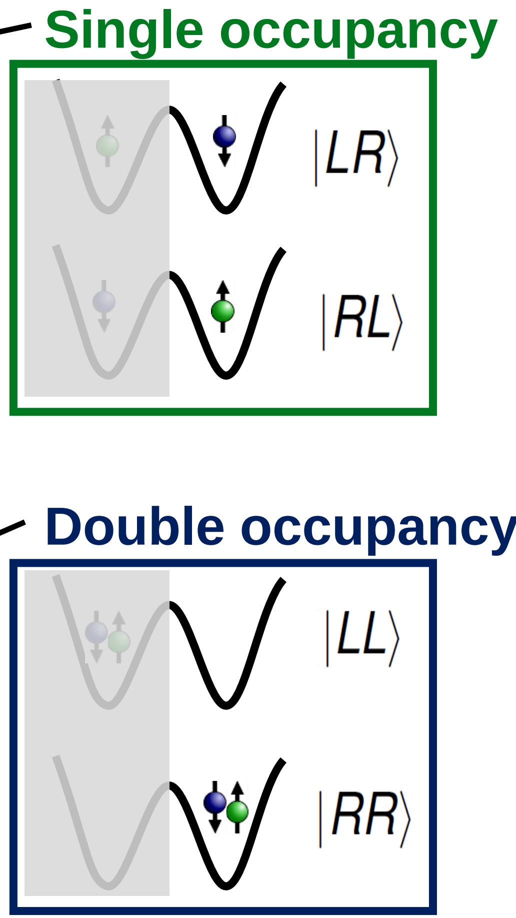
# Occupation statistics



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

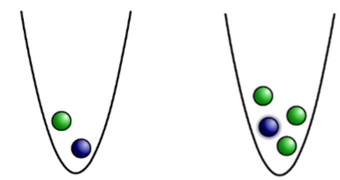
$$\frac{1}{2}(|LL\rangle + |LR\rangle + |RL\rangle + |RR\rangle)$$



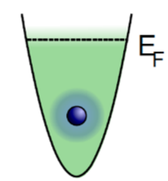



# Summary

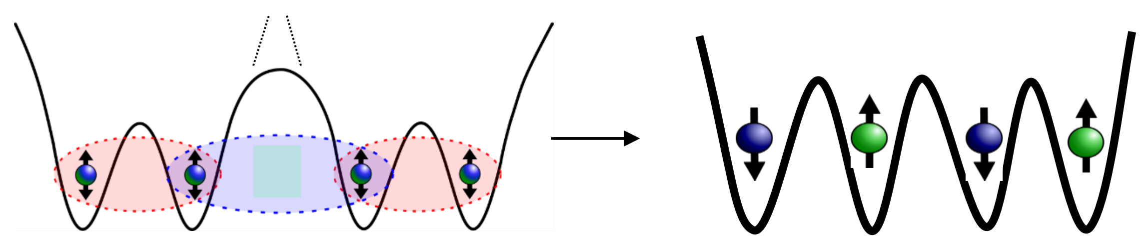
- We can prepare and control few-fermion systems

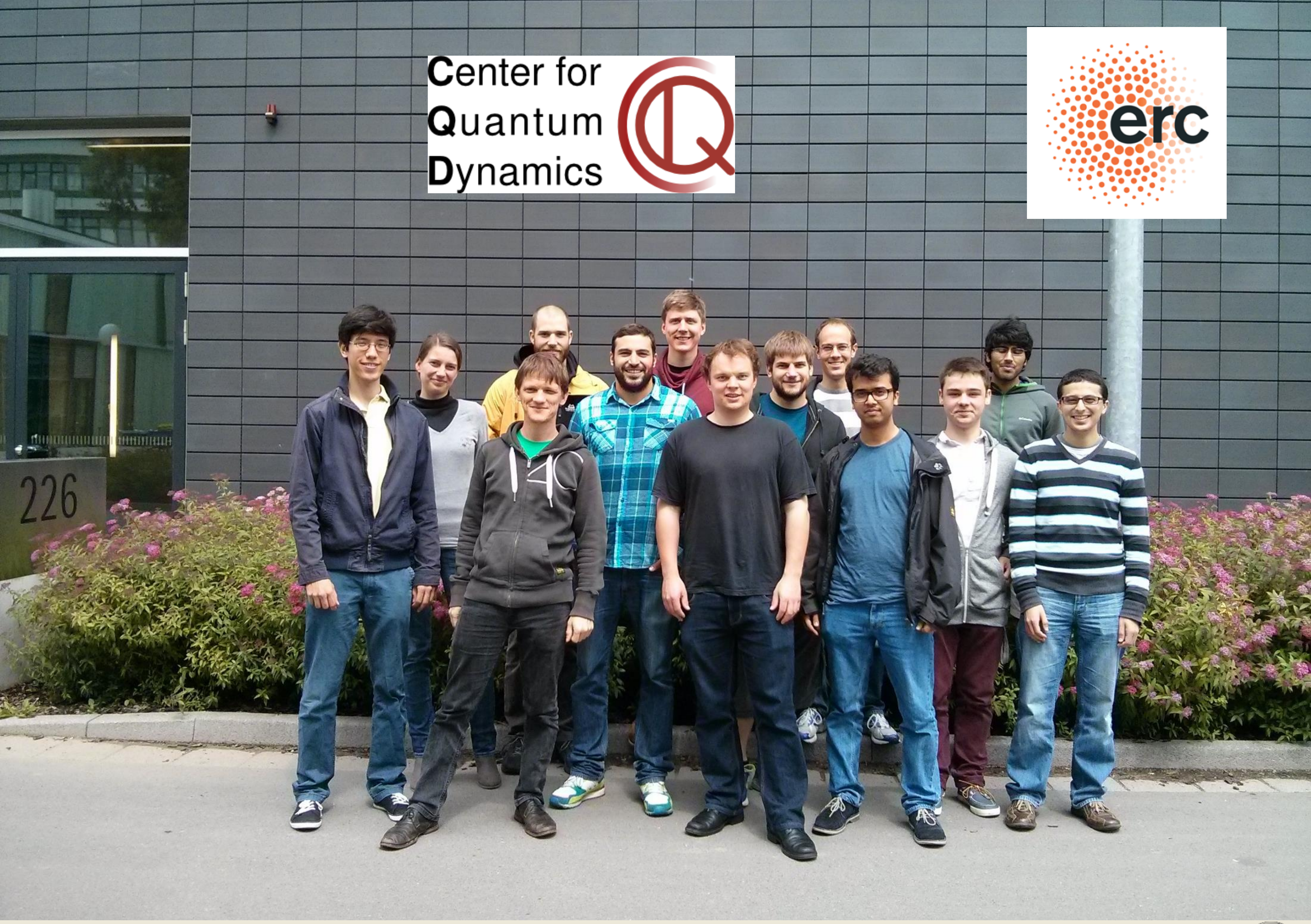


- Observed Crossover from few- to many-body regime




- Next: Fermi-Hubbard physics

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Quantum
Dynamics
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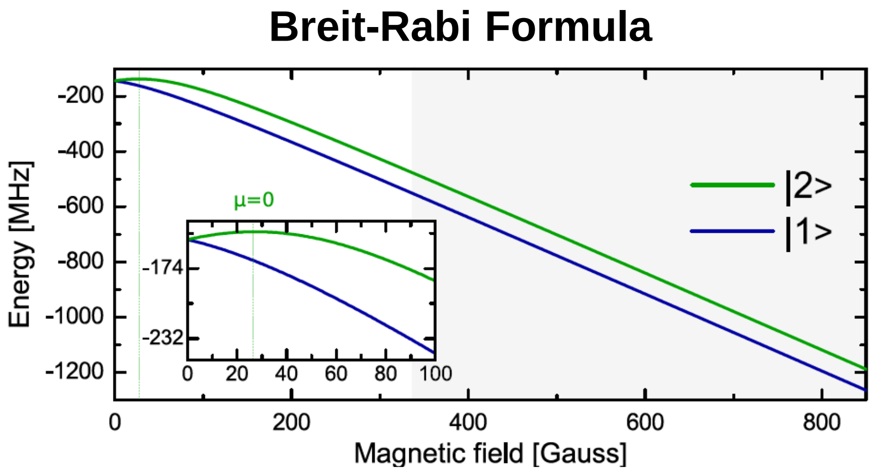
226

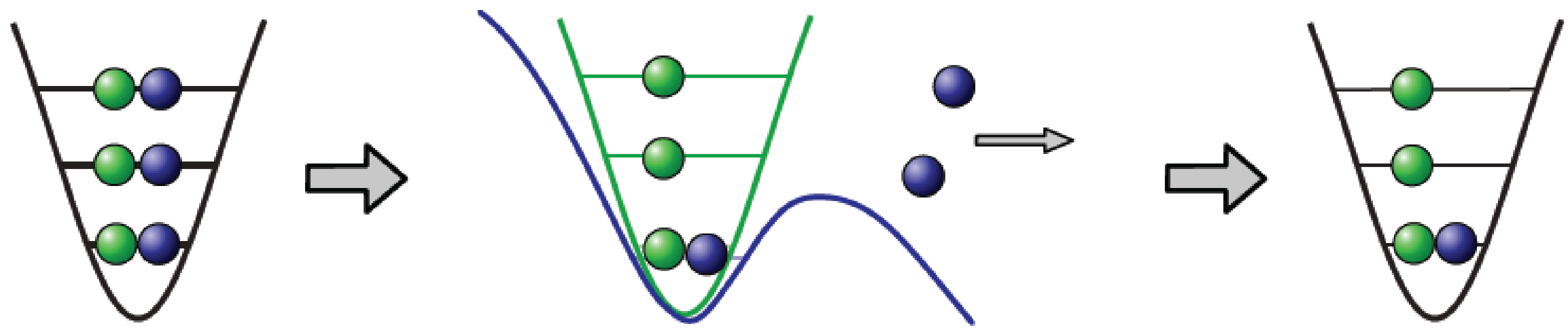
# Creating imbalanced systems



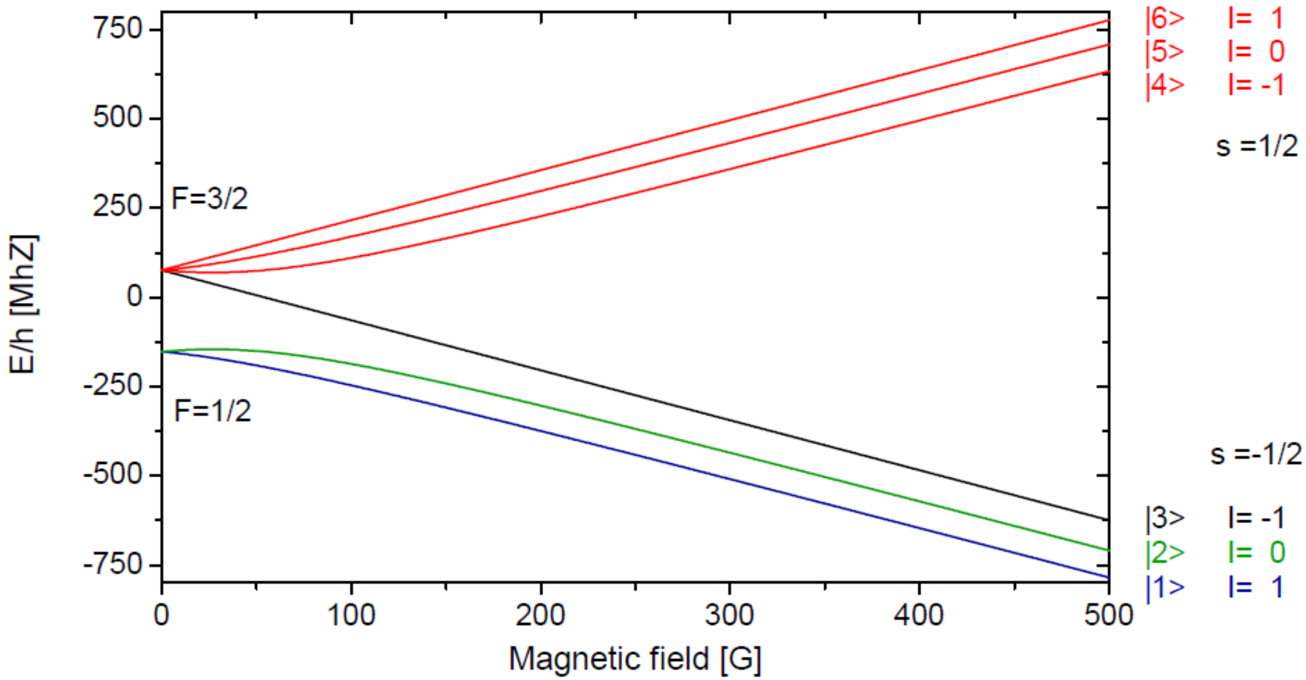
How to prepare systems which are not balanced in spin ?

- Go to 27G, where magnetic moment of state $|2\rangle$ vanisches
- Gradient only affects atoms in state $|2\rangle$
- Further changes between hyperfine states with RF transfer



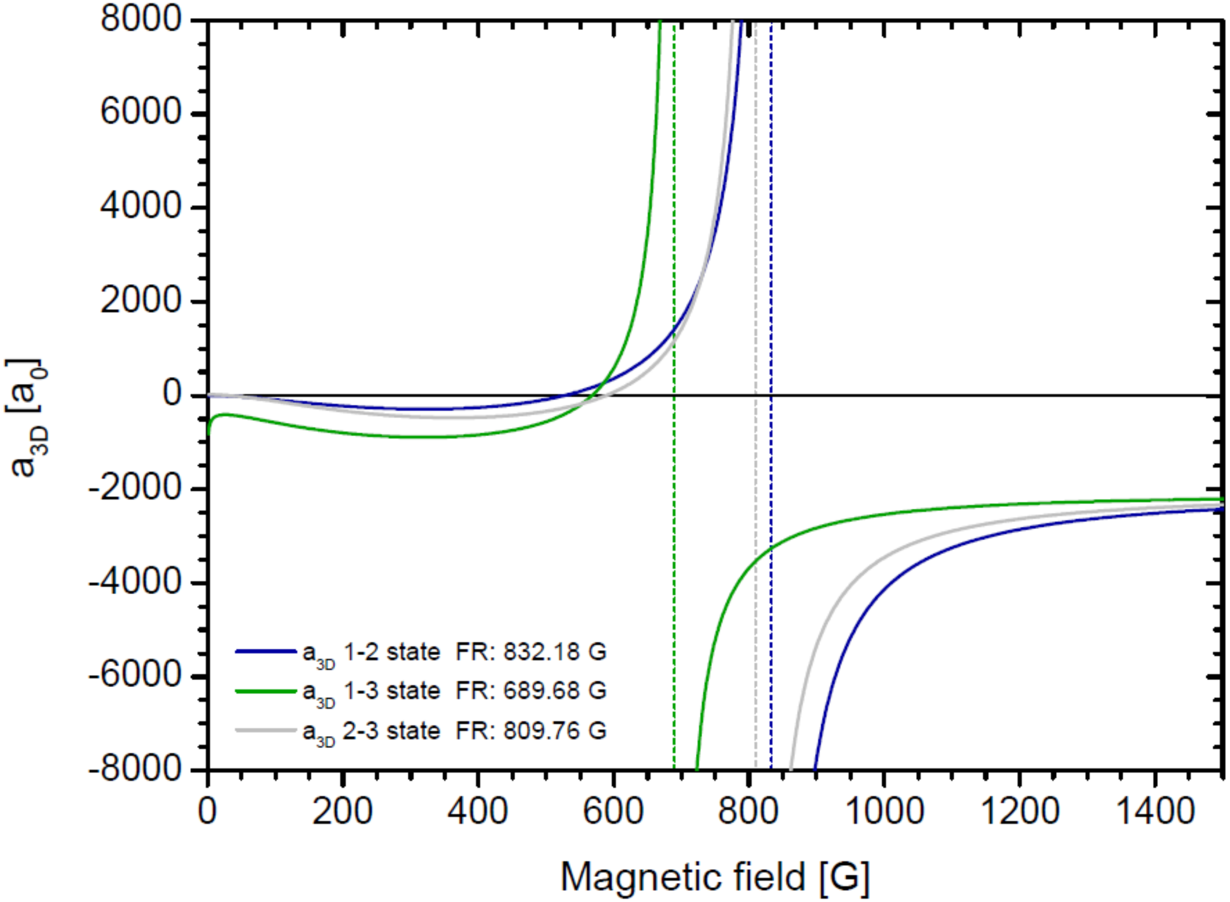



# . $^6$Li level scheme



# Feshbach resonances in 6Li

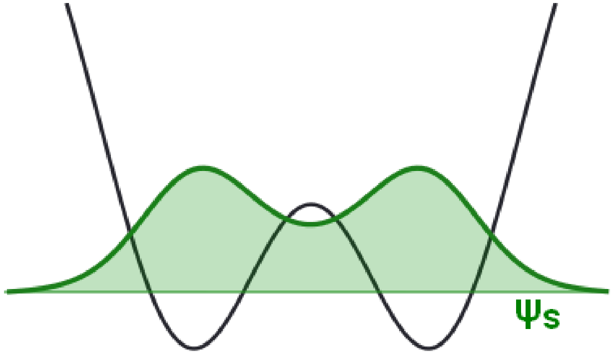




# The ground state of the double well

One particle:

- basis $|L\rangle \quad |R\rangle$
- Ground state $\psi_S = \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle)$




Two non-interacting particles:

$$\Psi_{1,2}(t) = \psi_1(t)\,\psi_2(t)$$

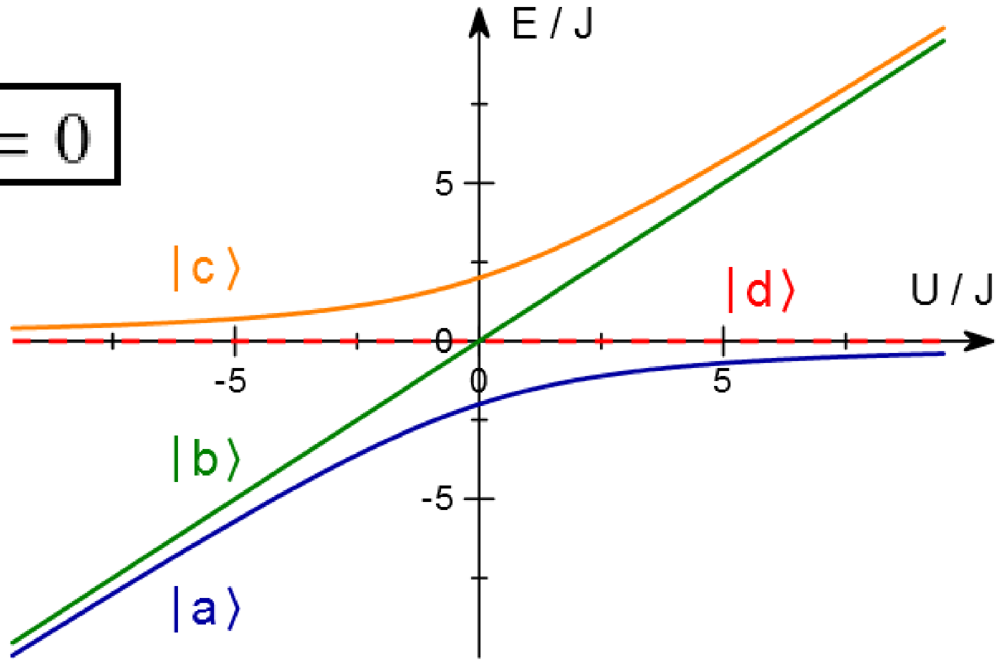
- Ground state at U=0

$$|\Psi\rangle = \frac{1}{2}(|L\rangle + |R\rangle)_1 \otimes (|L\rangle + |R\rangle)_2 \quad = \frac{1}{2}(|L_1 L_2\rangle + |L_1 R_2\rangle + |R_1 L_2\rangle + |R_1 R_2\rangle)$$

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

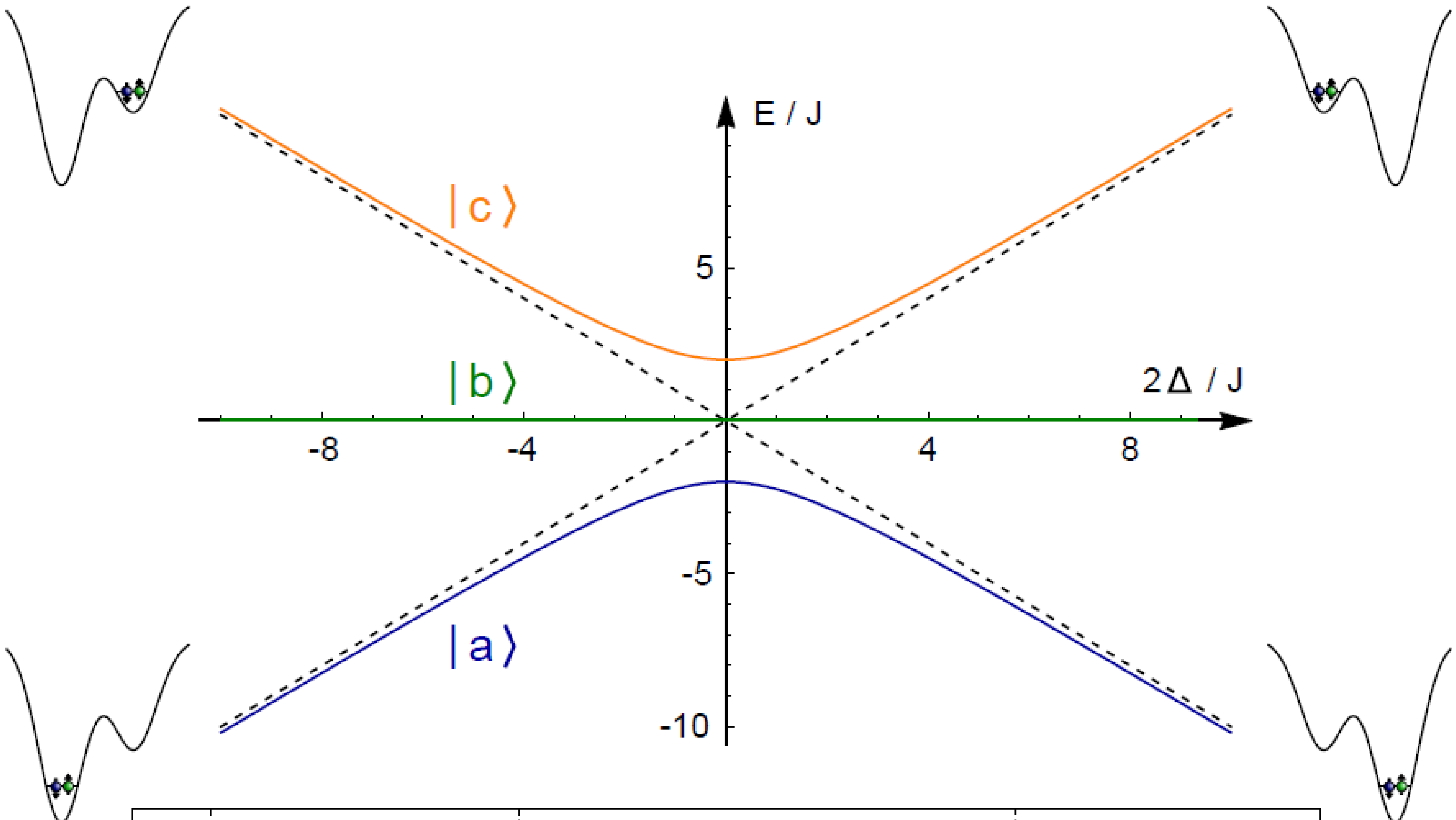
# Eigenenergies in the Hubbard Model

$\boxed{\Delta = 0}$




| | $U \to -\infty$ | $U = 0$ | $U \to +\infty$ |
|---|---|---|---|
| $\lvert a\rangle$ | $\frac{1}{\sqrt{2}}(\lvert LL\rangle + \lvert RR\rangle)$ | $\frac{1}{2}(\lvert LL\rangle + \lvert RR\rangle + \lvert LR\rangle + \lvert RL\rangle)$ | $\frac{1}{\sqrt{2}}(\lvert LR\rangle + \lvert RL\rangle)$ |
| $\lvert b\rangle$ | | $\frac{1}{\sqrt{2}}(\lvert LL\rangle - \lvert RR\rangle)$ | |
| $\lvert c\rangle$ | $\frac{1}{\sqrt{2}}(\lvert LR\rangle + \lvert RL\rangle)$ | $\frac{1}{2}(\lvert LL\rangle + \lvert RR\rangle - \lvert LR\rangle - \lvert RL\rangle)$ | $\frac{1}{\sqrt{2}}(\lvert LL\rangle + \lvert RR\rangle)$ |
| $\lvert d\rangle$ | | $\frac{1}{\sqrt{2}}(\lvert LR\rangle - \lvert RL\rangle)$ | |

How to measure energy differences between eigenstates?




| | $\Delta \to -\infty$ | $\Delta = 0$ | $\Delta \to +\infty$ |
|---|---|---|---|
| $\vert a\rangle$ | $\vert LL\rangle$ | $\frac{1}{2}(\vert LL\rangle + \vert RR\rangle + \vert LR\rangle + \vert RL\rangle)$ | $\vert RR\rangle$ |
| $\vert b\rangle$ | $\frac{1}{\sqrt{2}}(\vert RL\rangle + \vert LR\rangle)$ | $\frac{1}{\sqrt{2}}(\vert LL\rangle - \vert RR\rangle)$ | $\frac{1}{\sqrt{2}}(\vert RL\rangle + \vert LR\rangle)$ |
| $\vert c\rangle$ | $\vert RR\rangle$ | $\frac{1}{2}(\vert LL\rangle + \vert RR\rangle - \vert LR\rangle - \vert RL\rangle)$ | $\vert LL\rangle$ |