



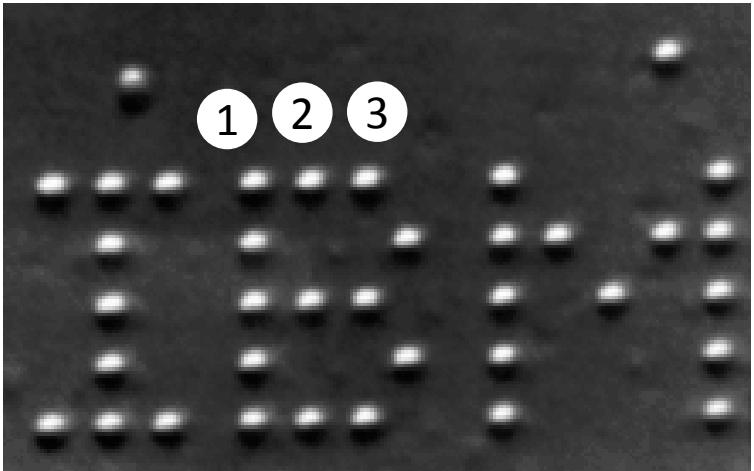
# Strong correlations in few-fermion systems

Andrea Bergschneider  
Group of Selim Jochim  
Physikalisches Institut  
Universität Heidelberg

# Controlling few particles

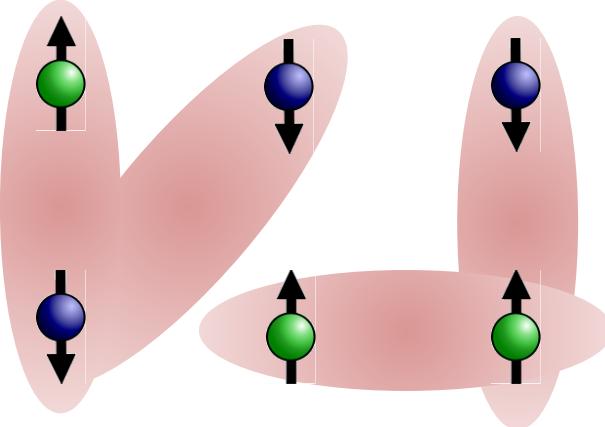


IBM:  
Control of single atoms



Browne, M. W. "Researchers Spell 'IBM,' atom by atom." *New York Times, New York* (1990).

Our vision:  
Control also **all correlations** between atoms



# Outline



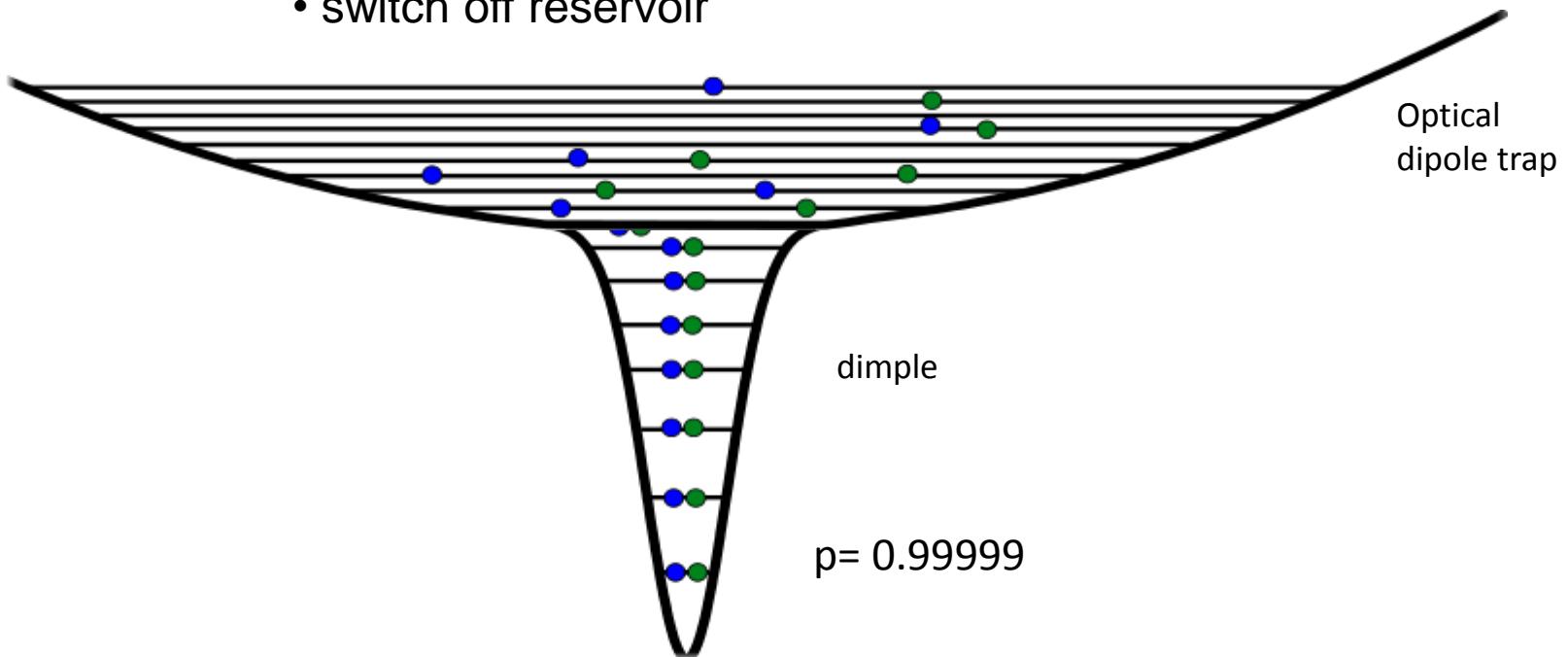
- How do we prepare our samples?
- How can we manipulate our sample?
- An antiferromagnet without a lattice
- Two atoms in a double well
- Assemble many body systems from individual building blocks?



# Getting few fermions ...



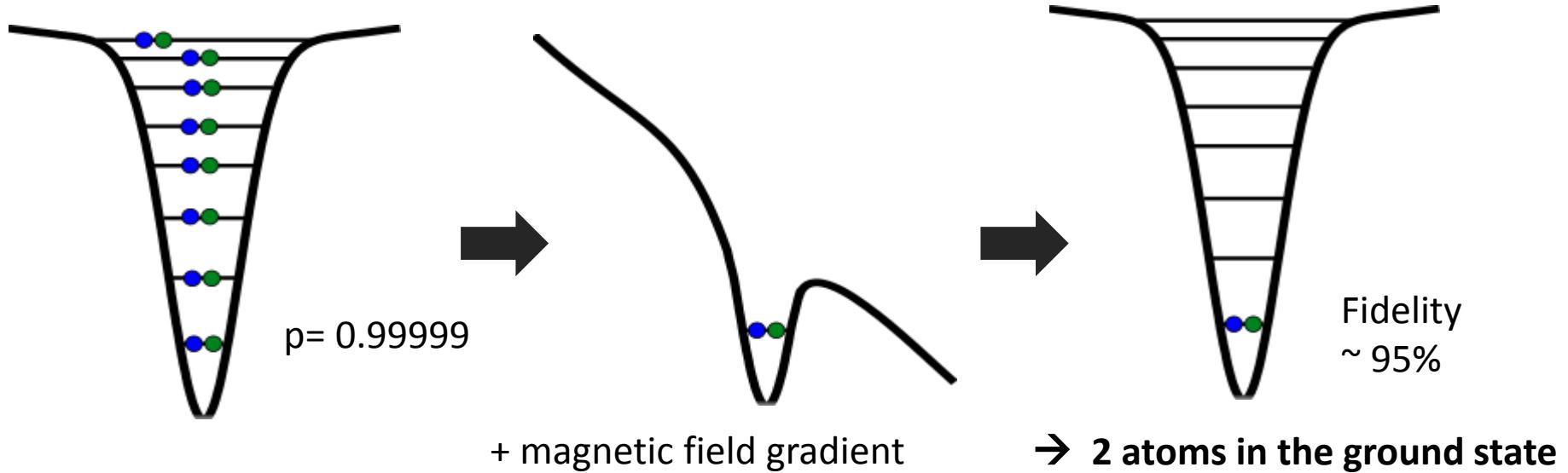
- 2-component mixture in reservoir  $T=250\text{nK}$
- superimpose microtrap  
scattering → thermalisation  
expected degeneracy:  $T/T_F \approx 0.1$
- switch off reservoir



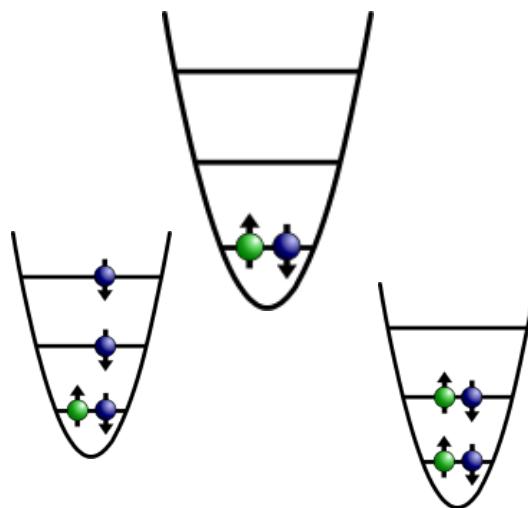
# Getting few fermions ...



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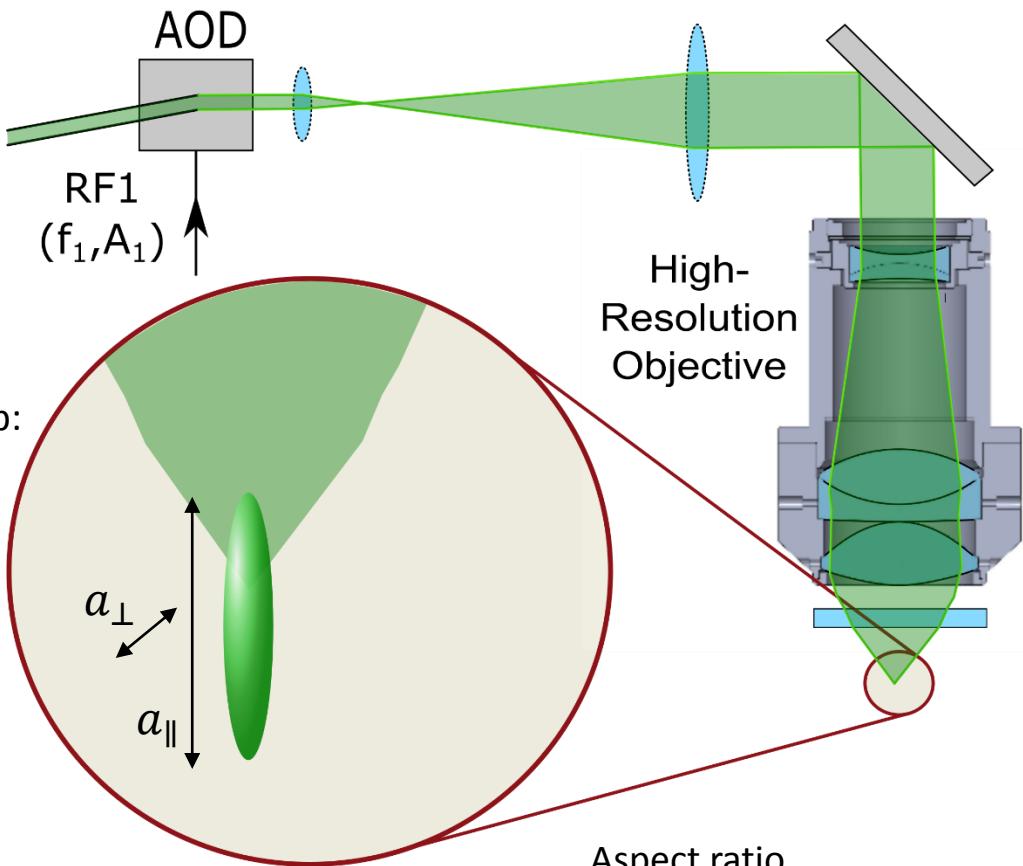
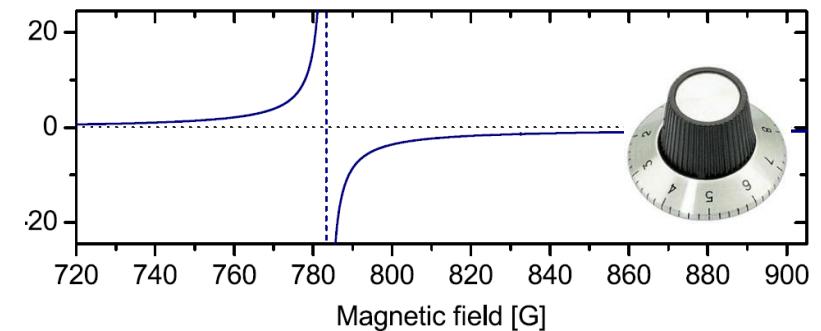


# Our experimental setup



Quasi-1D trap:

Tunable interaction

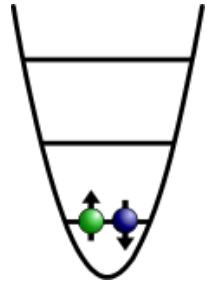


Aspect ratio

$$\eta = \frac{\omega_{\perp}}{\omega_{\parallel}} \sim 10$$



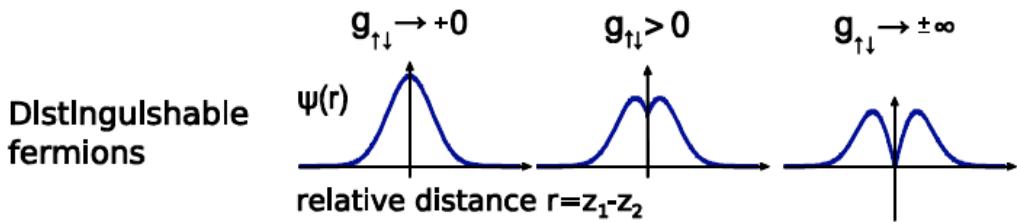
# Fermionization of distinguishable fermions



$$H_{1D} = \sum_i \left( -\frac{\hbar^2}{2m} \frac{d^2}{dx_i^2} - \frac{1}{2} m \omega^2 x_i^2 \right) + g \sum_{i < j} \delta(x_i - x_j)$$

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

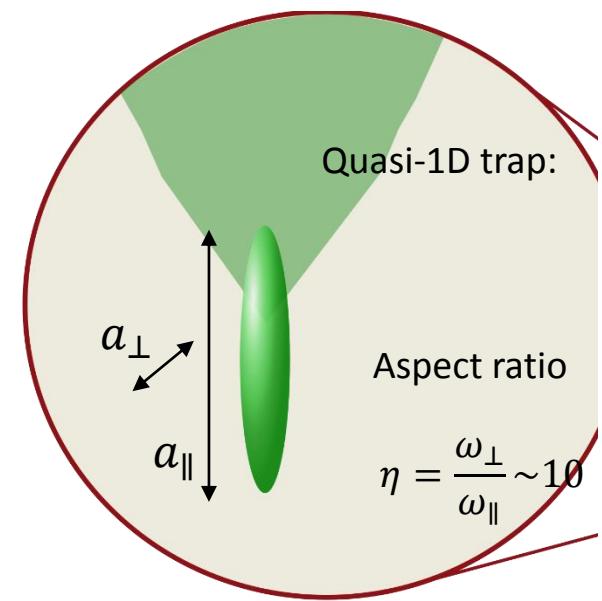
Relative wavefunction:



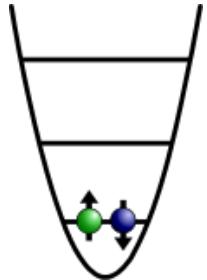
Identical fermions



→ Fermionization of two distinguishable fermions

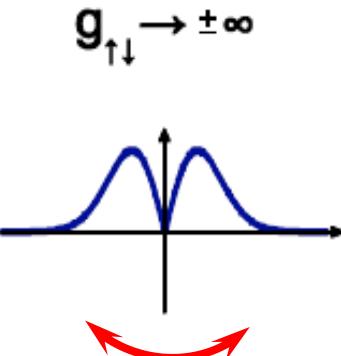
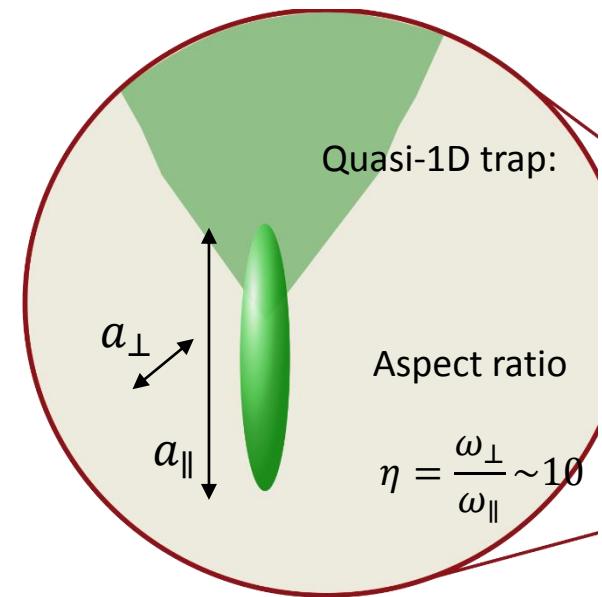


# Fermionization of distinguishable fermions



$$H_{1D} = \sum_i \left( -\frac{\hbar^2}{2m} \frac{d^2}{dx_i^2} - \frac{1}{2} m \omega^2 x_i^2 \right) + g \sum_{i < j} \delta(x_i - x_j)$$

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



$$J_{ex2} < 0 \quad J^{ex} = 0 \quad J_{ex2} > 0$$

$$H = \sum_i E_F^{(N)} n_i n_{i+1} + 2 \sum_i J_i^{ex} \left( \vec{S}_i \cdot \vec{S}_{i+1} - \frac{1}{4} n_i n_{i+1} \right)$$

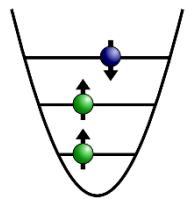


# Heisenberg Antiferromagnetic spin chain

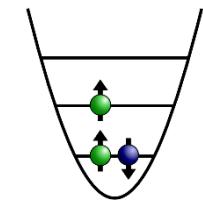
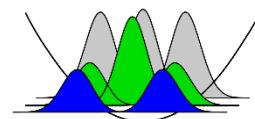
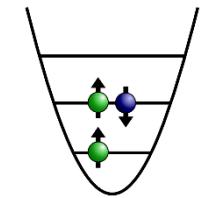
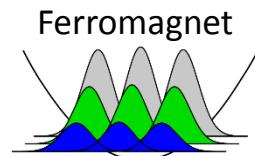


Non-interacting

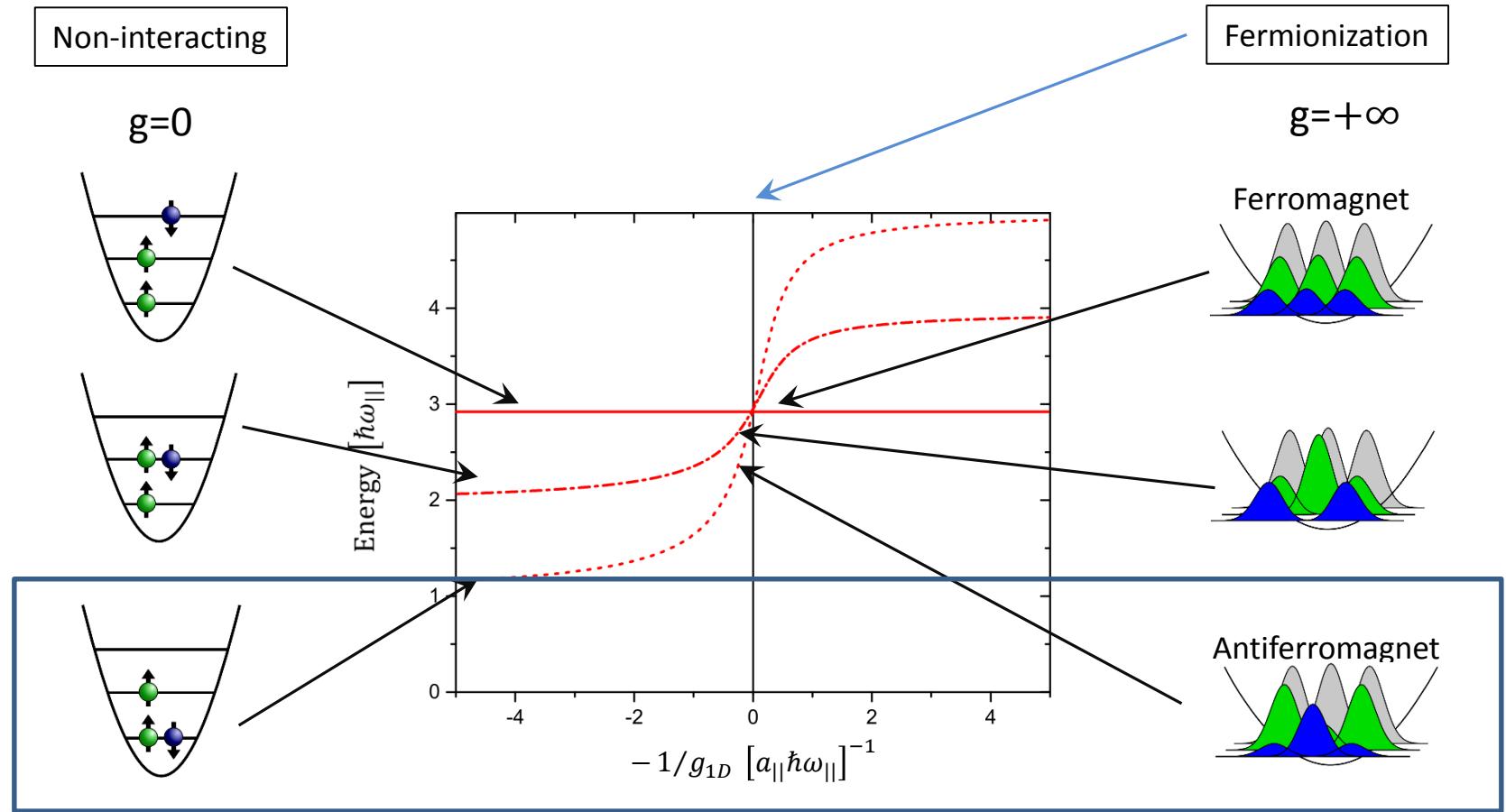
$g=0$



$g=+\infty$

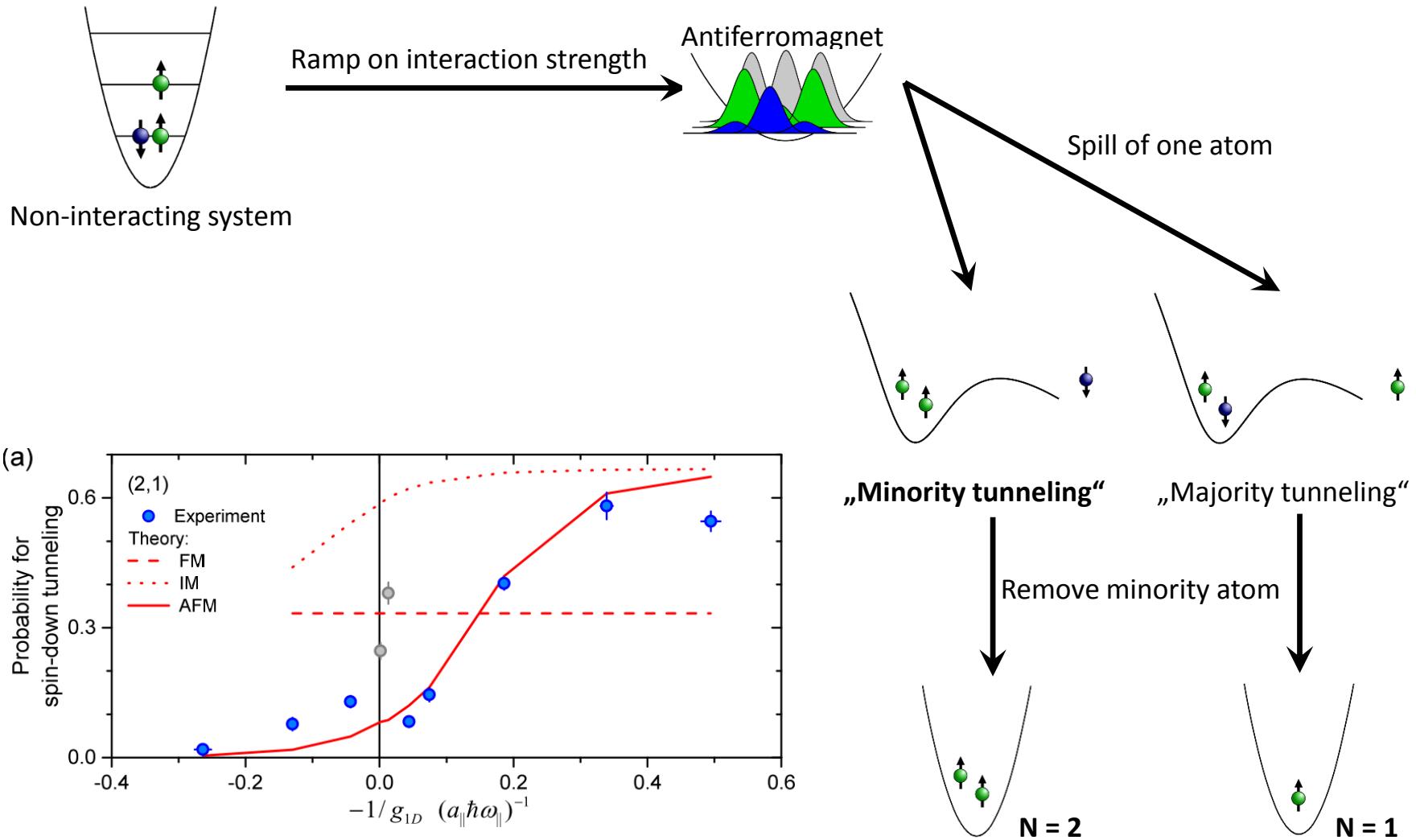


# Heisenberg Antiferromagnetic spin chain



# Heisenberg Antiferromagnetic spin chain

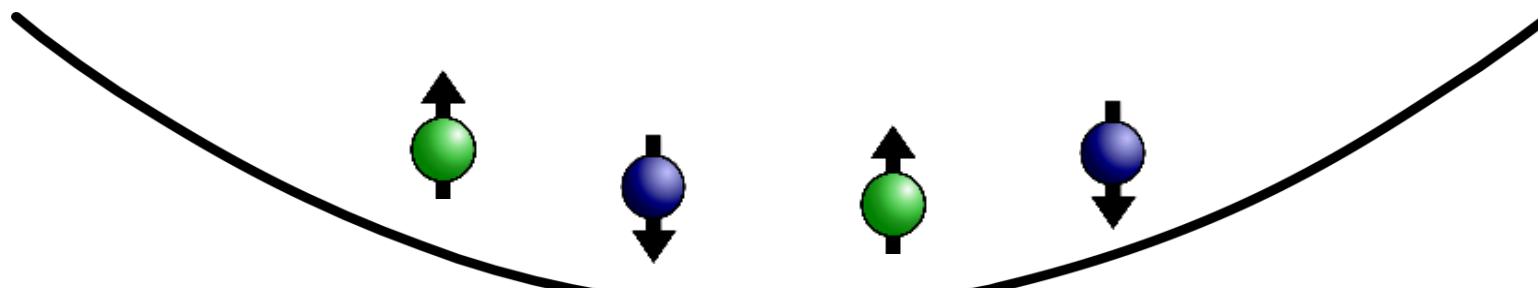
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HEIDELBERG



# Heisenberg Antiferromagnetic spin chain



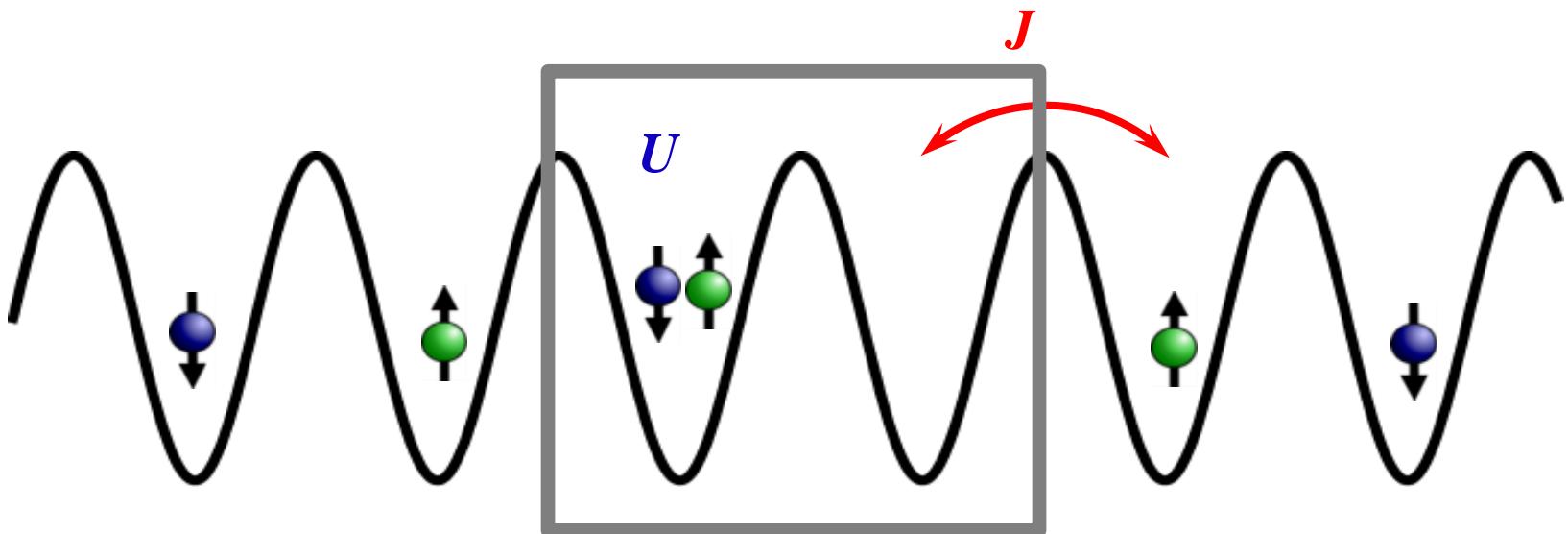
→ Experimental preparation of an AFM Heisenberg spin chain



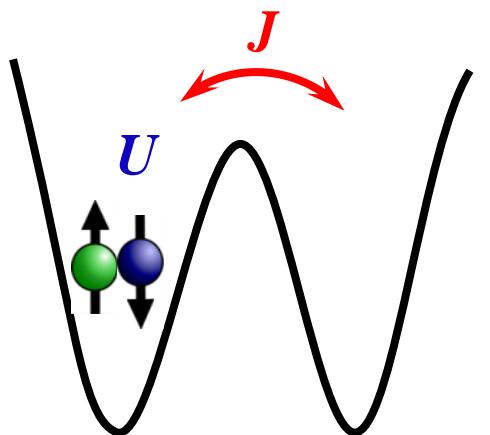
# The Fermi-Hubbard model



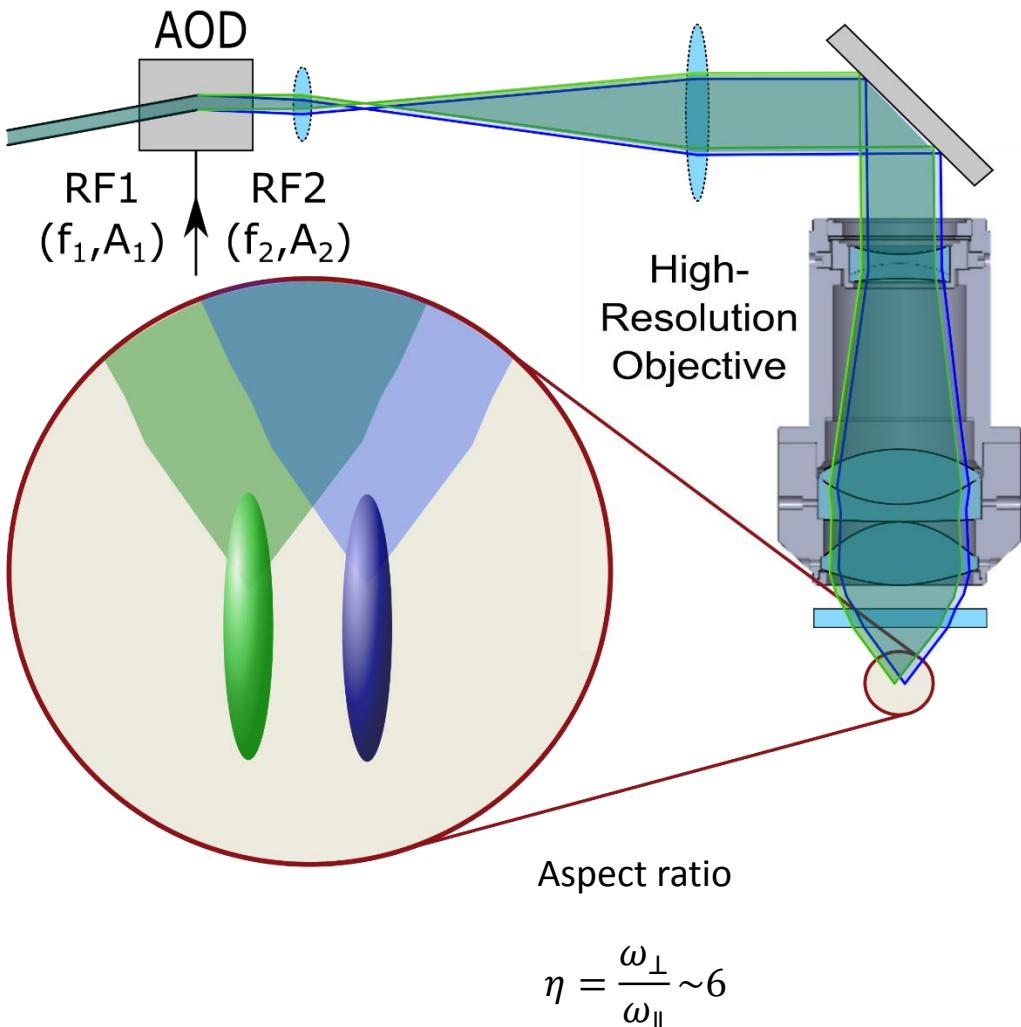
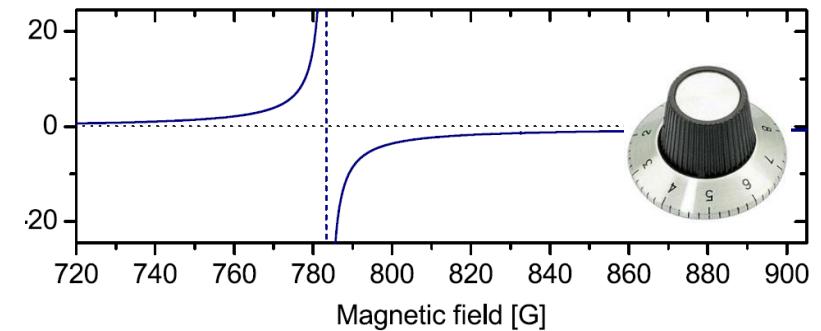
$$H_{FH} = -\mathbf{J} \sum_{\langle i,j \rangle} (a_{i\uparrow}^\dagger a_{j\uparrow} + a_{i\downarrow}^\dagger a_{j\downarrow}) + \mathbf{U} \sum_j n_{j\uparrow} n_{j\downarrow}$$



# Our experimental setup

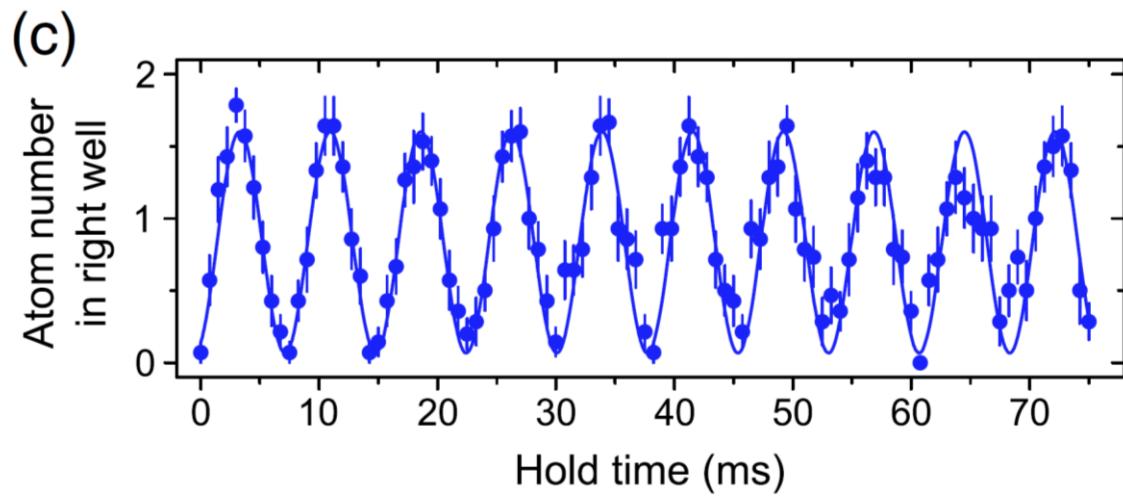
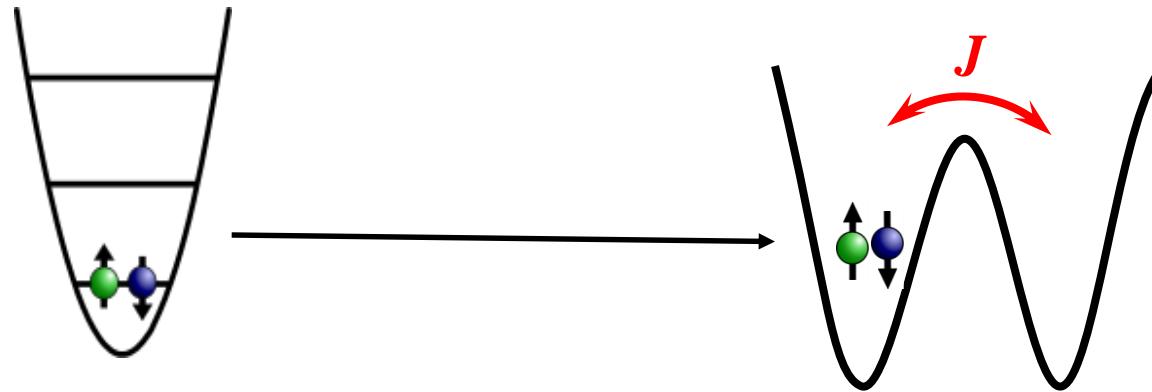


Tunable interaction



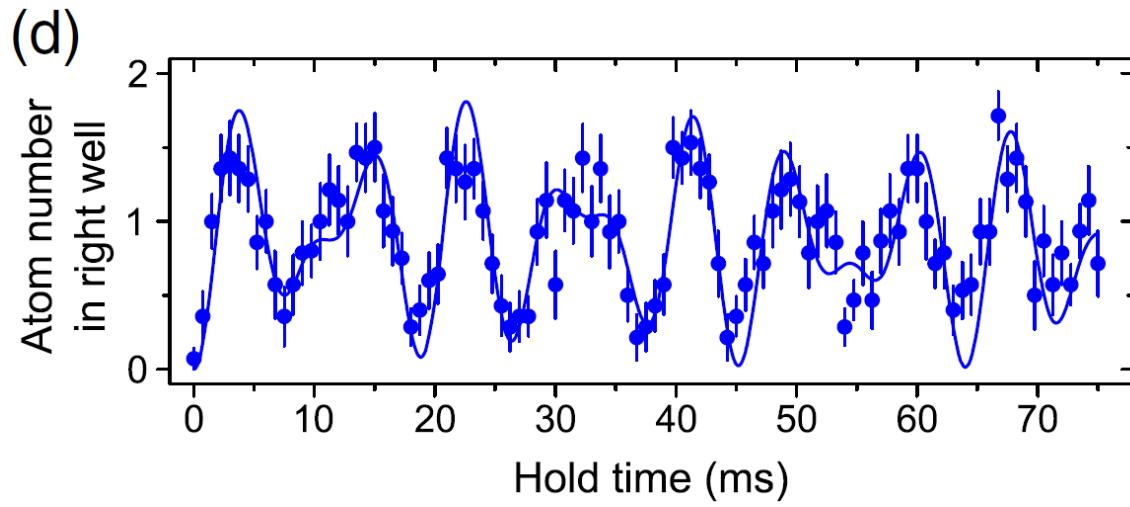
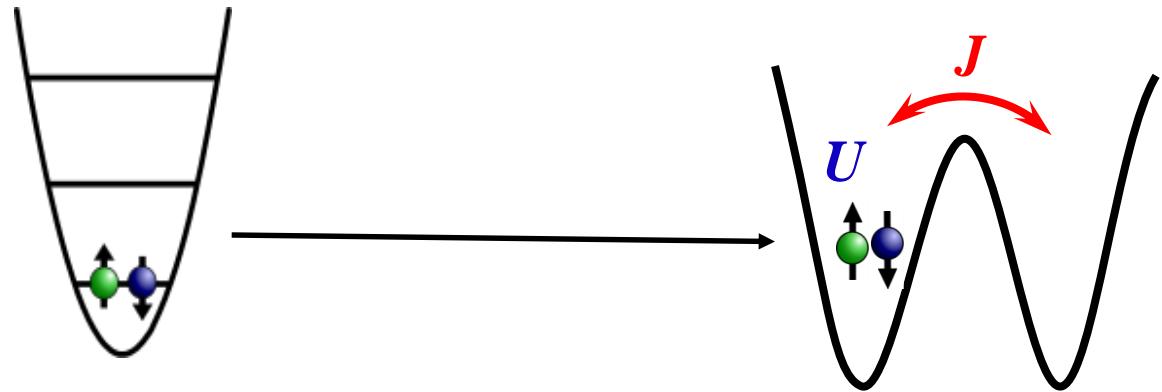
# Building block of the Hubbard model

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# Building block of the Hubbard model

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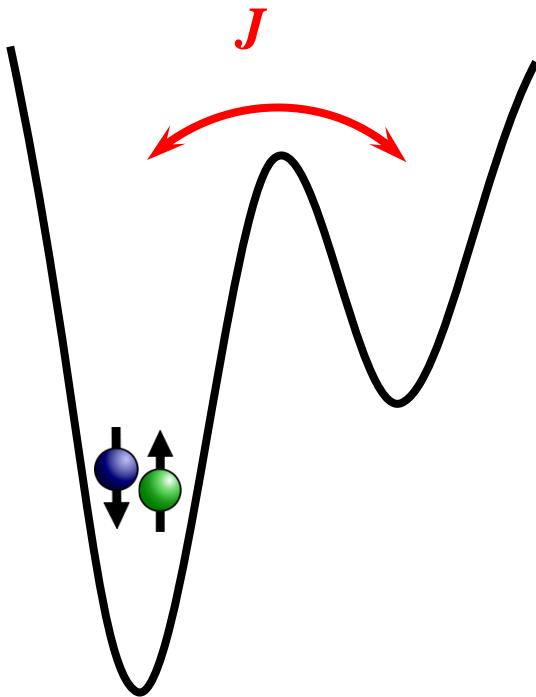


# Preparation of the ground state



$\Delta \ll 0$

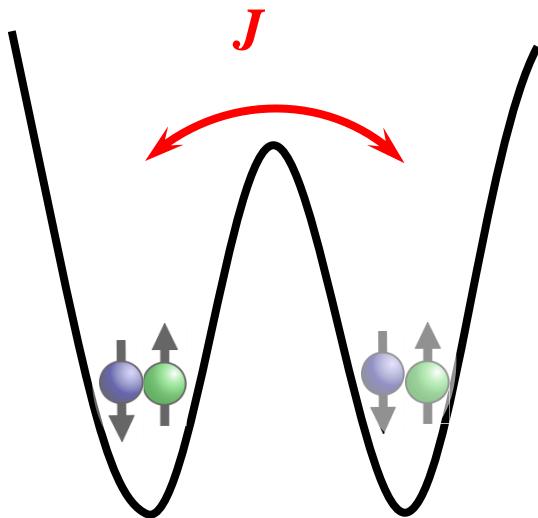
$|LL\rangle$



# Preparation of the ground state



$$\Delta \ll 0 \quad \Delta = 0 \quad \Delta \gg 0$$
$$|LL\rangle \xleftarrow{\hspace{1cm}} \frac{1}{2}(|LL\rangle + |LR\rangle + |RL\rangle + |RR\rangle) \xrightarrow{\hspace{1cm}} |RR\rangle$$



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

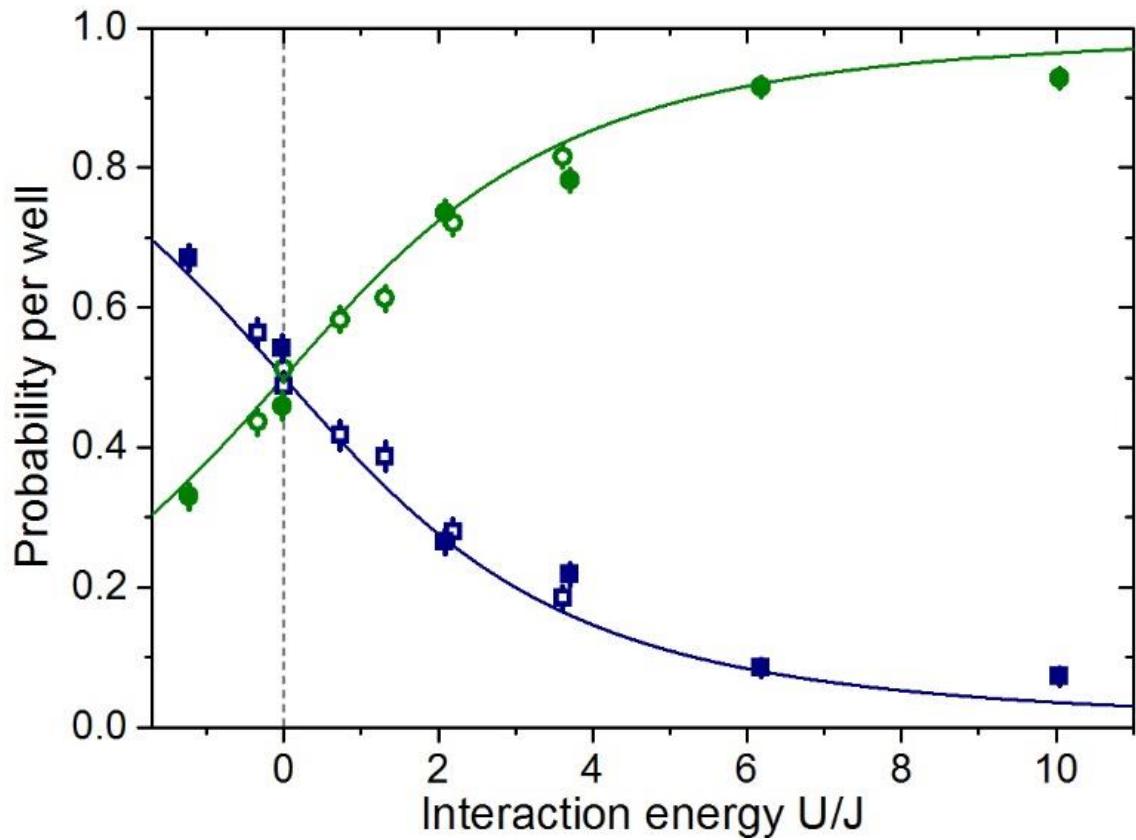


# Measuring Occupation statistics

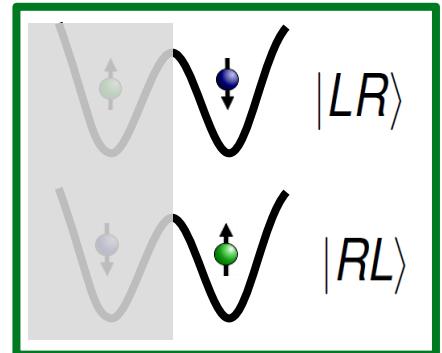


$$\frac{1}{2}(|LL\rangle + |LR\rangle + |RL\rangle + |RR\rangle)$$

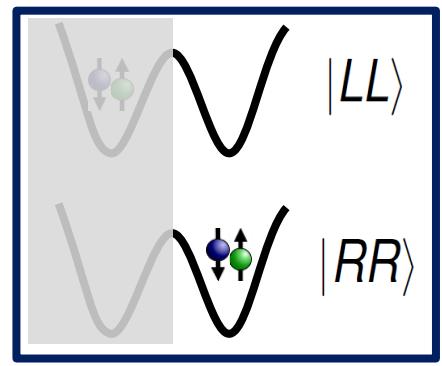
$$\frac{1}{\sqrt{2}}(|LR\rangle + |RL\rangle)$$



Single occupancy



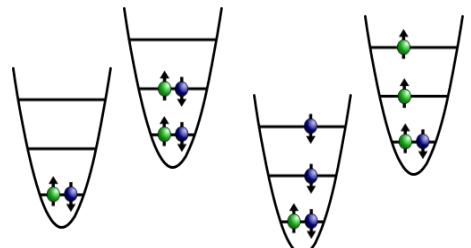
Double occupancy



# Summary

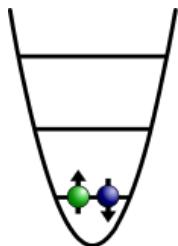


Prepare atom number:



F. Serwane et al.,

Science **332**, 336 (2011)



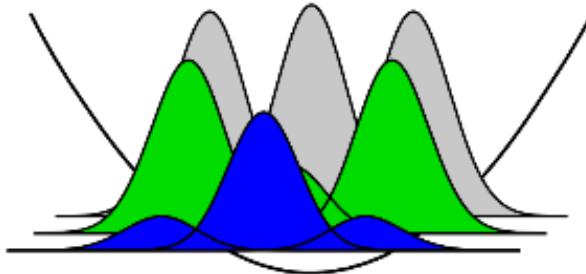
+

Tunable interaction  
Tailor potential



→ Fidelity 95%

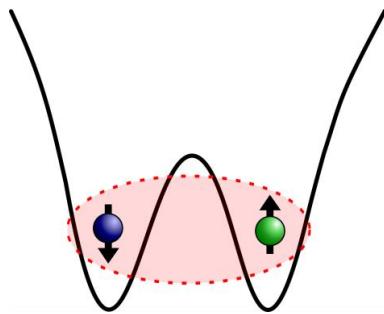
Realizing an Antiferromagnetic  
Heisenberg spin chain



S. Murmann, A. Bergschneider et al., PRL **114**, 080402 (2015)

S. Murmann, F. Deuretzbacher et al., PRL **115**, 215301 (2015)

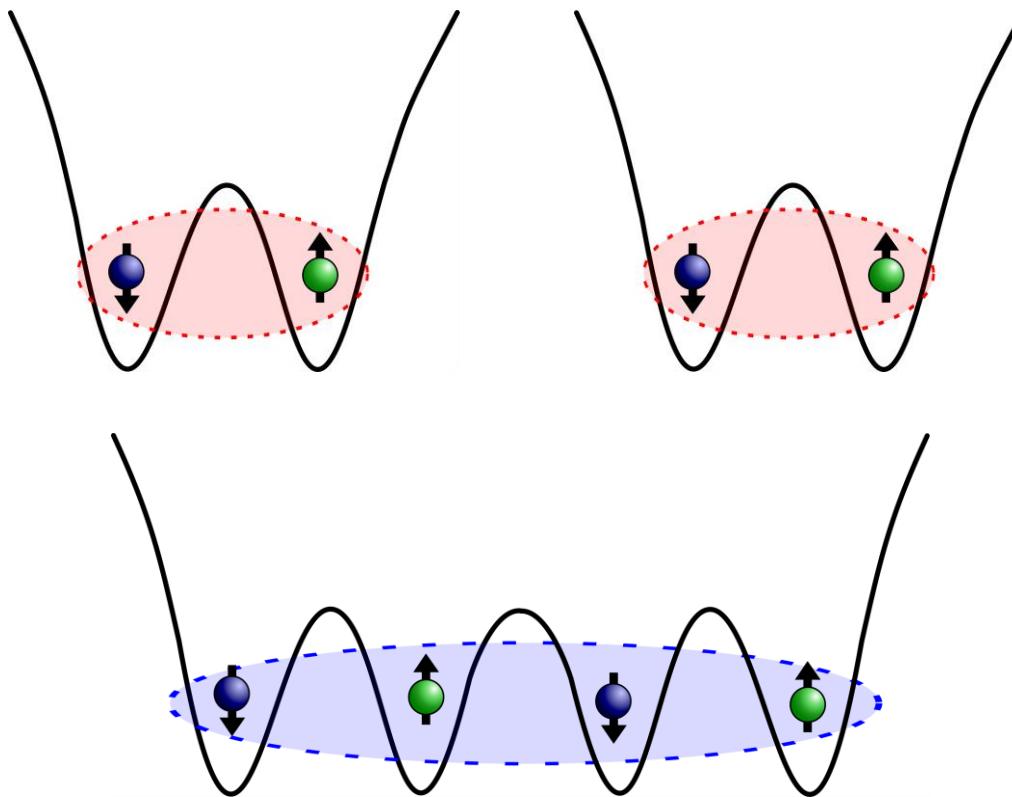
Preparation of ground state  
of fundamental building block  
of Hubbard model



PHYSIKALISCHES  
I N S T I T U T



# Outlook: Increasing the system size

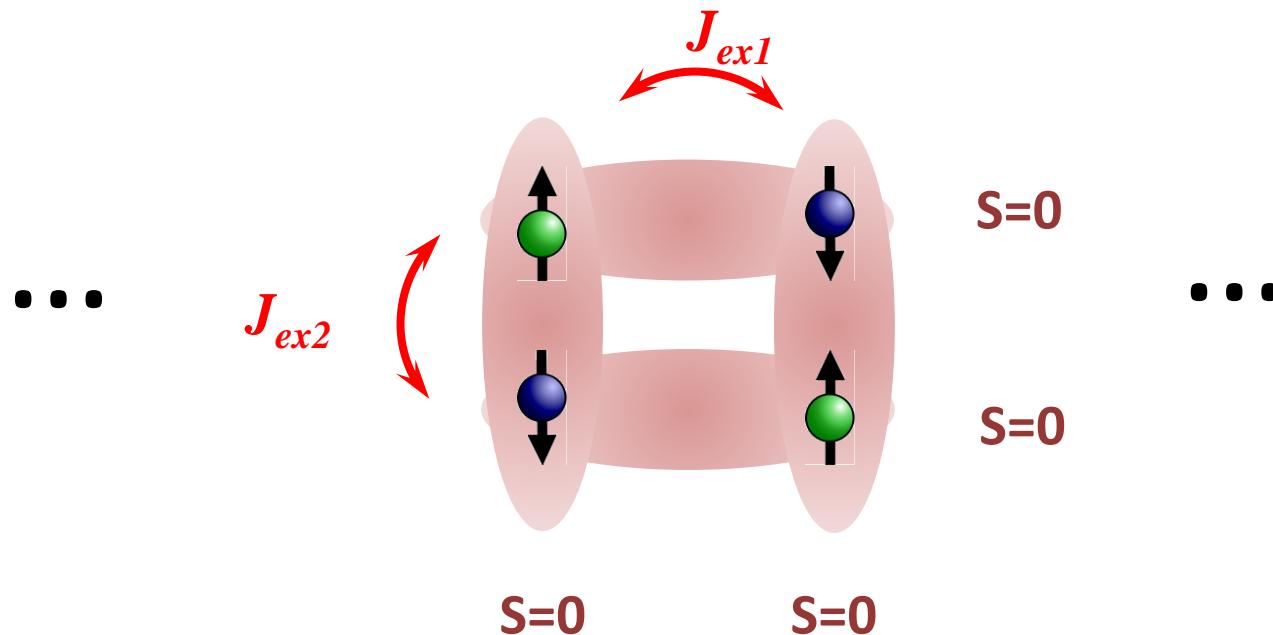


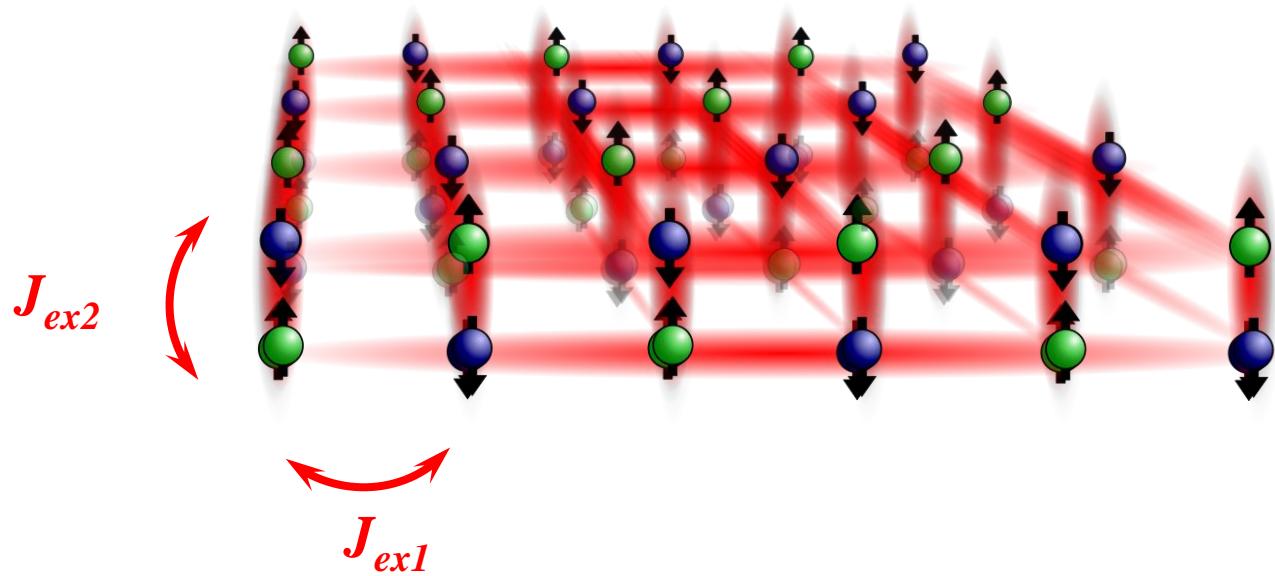
preparation of ground state  
in a finite lattice



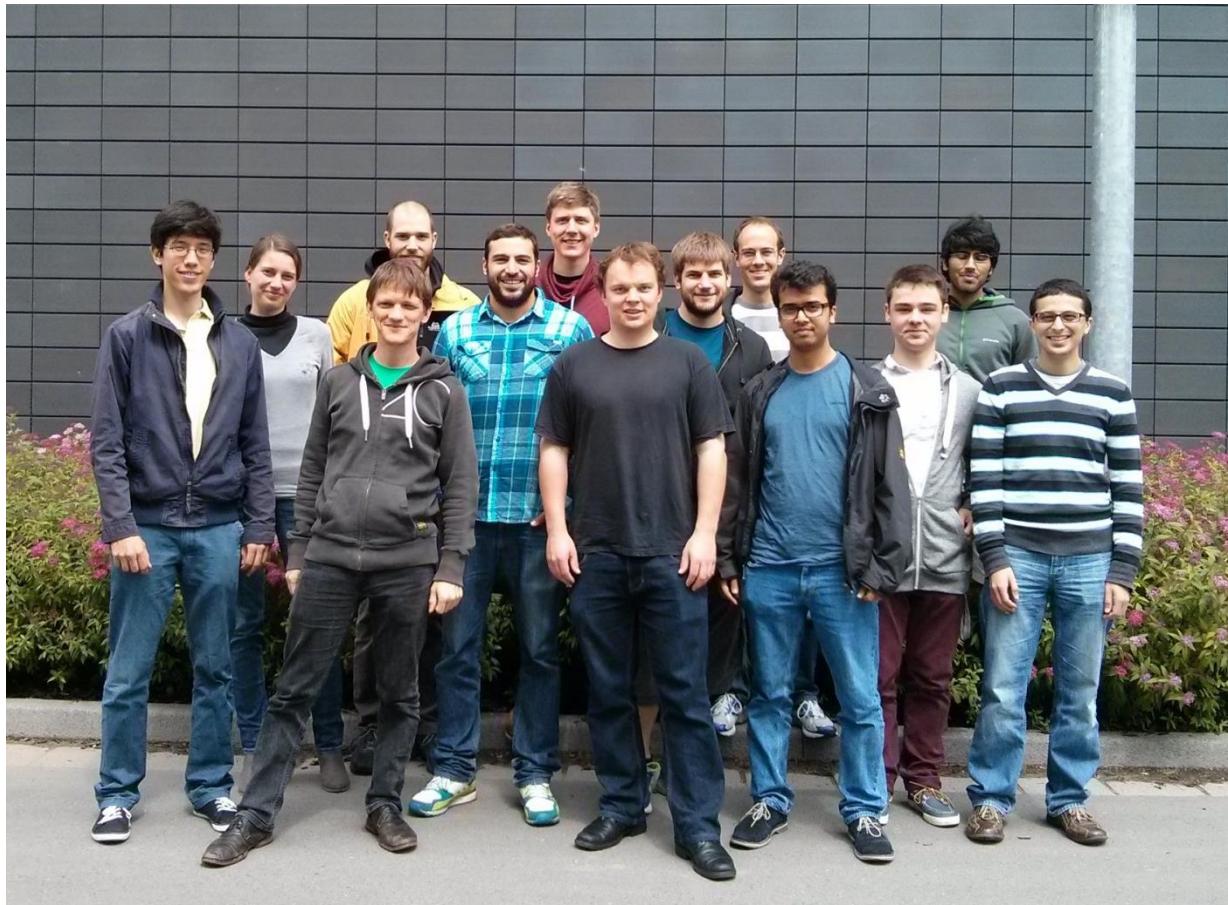


Can we couple many individual spin chains ?





# The team



Selim Jochim

## Few-fermion Team

Gerhard Zürn  
Philipp Preiss  
Andrea Bergschneider  
Vincent Klinkhamer  
Jan Hendrik Becher  
Michael Dehabe

## Theory collaboration:

Frank Deuretzbacher  
Luis Santos  
Johannes Bjerlin  
Stephanie Reimann

## Former members:

Simon Murmann  
Thomas Lompe (→ H. Moritz)

Center for  
Quantum  
Dynamics



**Thank you for your attention!**

