Universität Heidelberg

Studying strongly correlated few-fermion systems with ultracold atoms

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Strongly correlated systems

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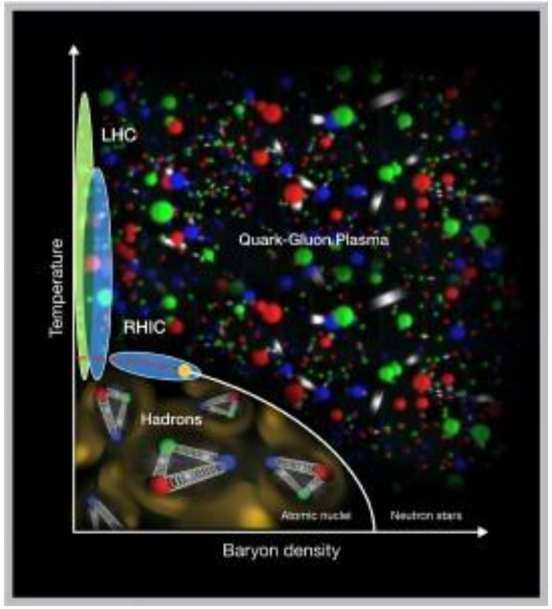
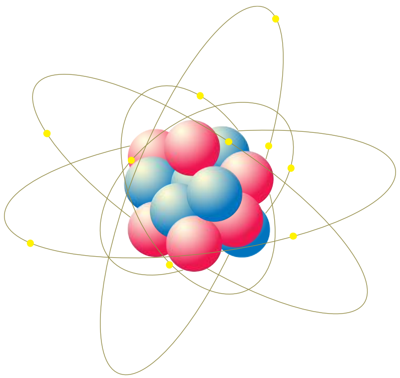
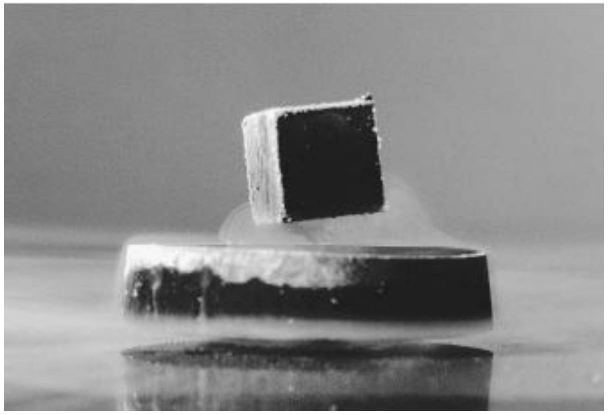


Taken from: www.phys.org/news/2012-08-border-primordial-plasma-ordinary





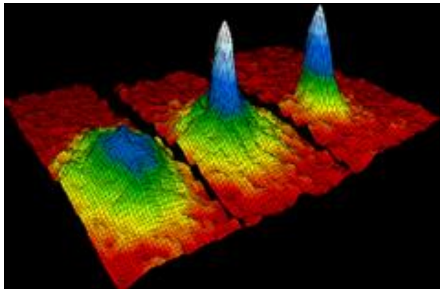
Taken from: http://www.chemistryexplained.com

Strong interaction + quantum nature!

→ Challenging to solve

→ Use quantum simulator

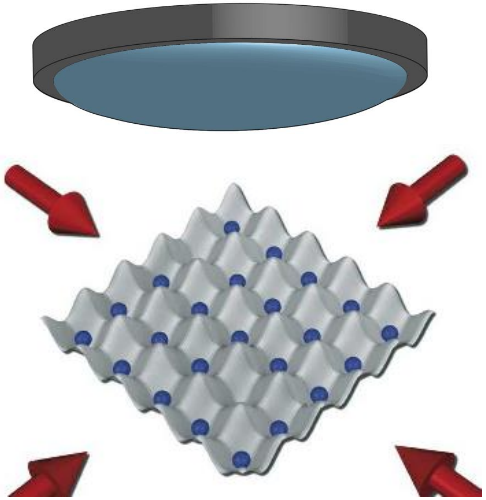
Ultracold gases



Quantum statistics is inherent

Controlled initialization of Hamiltonian:

- Tunable interaction strength
- Confinement with laser beams



Scales are convenient

- System size ~10-100µm
- Time scales ~µs

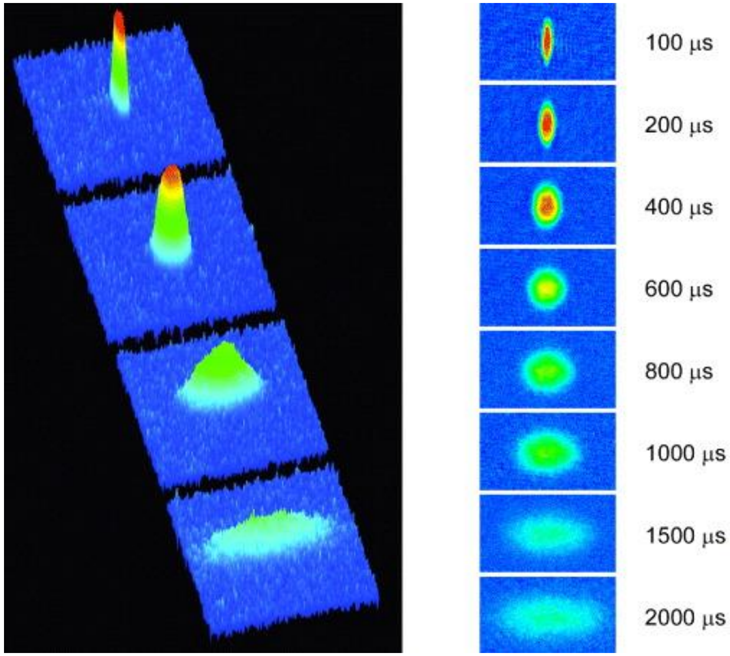
Measuring the state:

- Density distribution
- Single-atom sensitivity to detect correlations

➔ Perfect quantum simulators

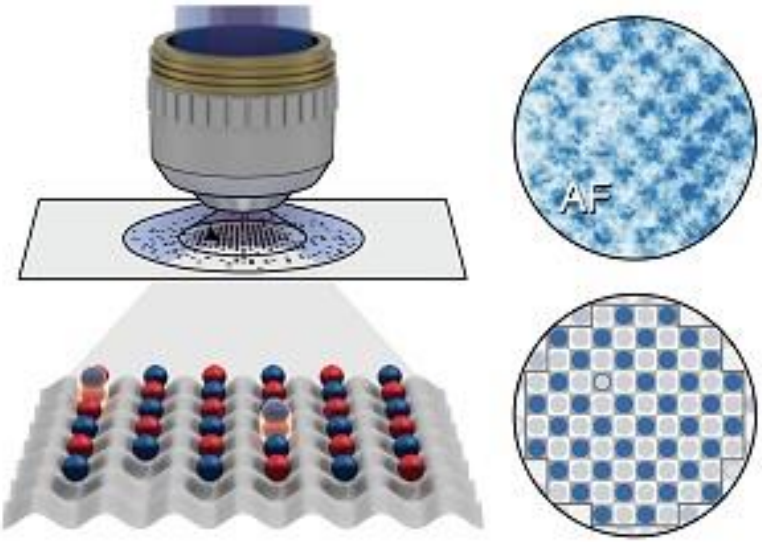
Ultracold gases

Hydrodynamic expansion



*O'Hara et al., Science **298** (2002) 2179*

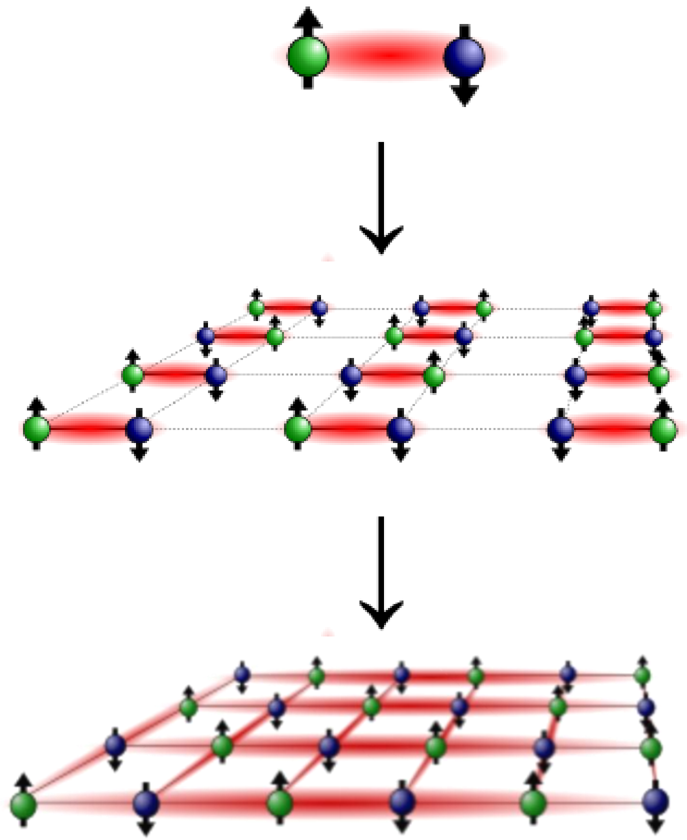
A cold-atom Fermi-Hubbard antiferromagnet



*Mazurenko et al., Nature **545** (2017)*

Our approach

Assemble a many-body quantum state from the bottom up



Outline

I A few-fermion quantum simulator

Fully deterministic preparation of fermions in a double-well potential

II Direct observation of two-particle correlations

Emergence of correlations between interacting atoms

III Characterization of the entanglement

Density matrix reconstruction and entanglement witness

Our playground

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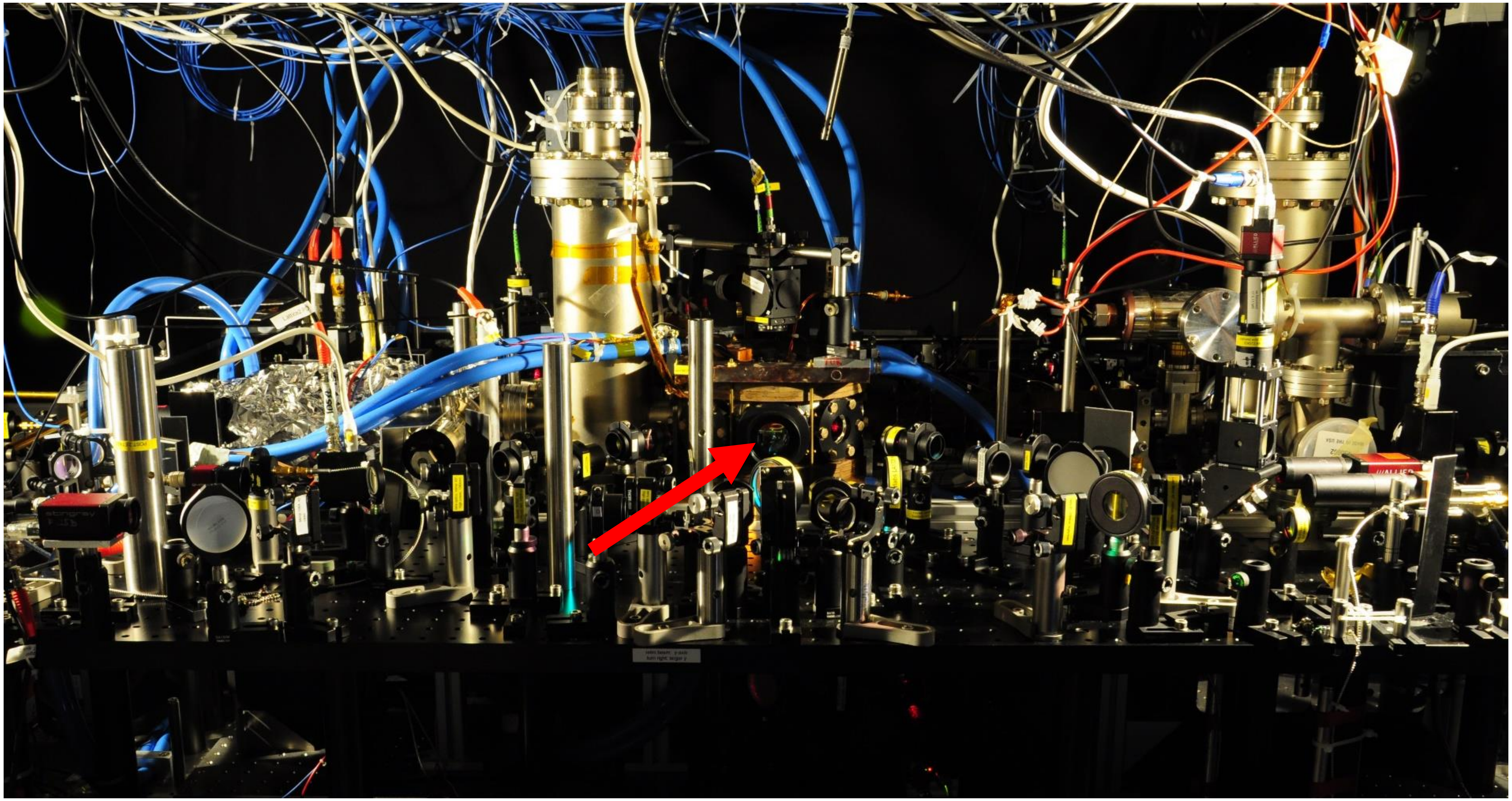
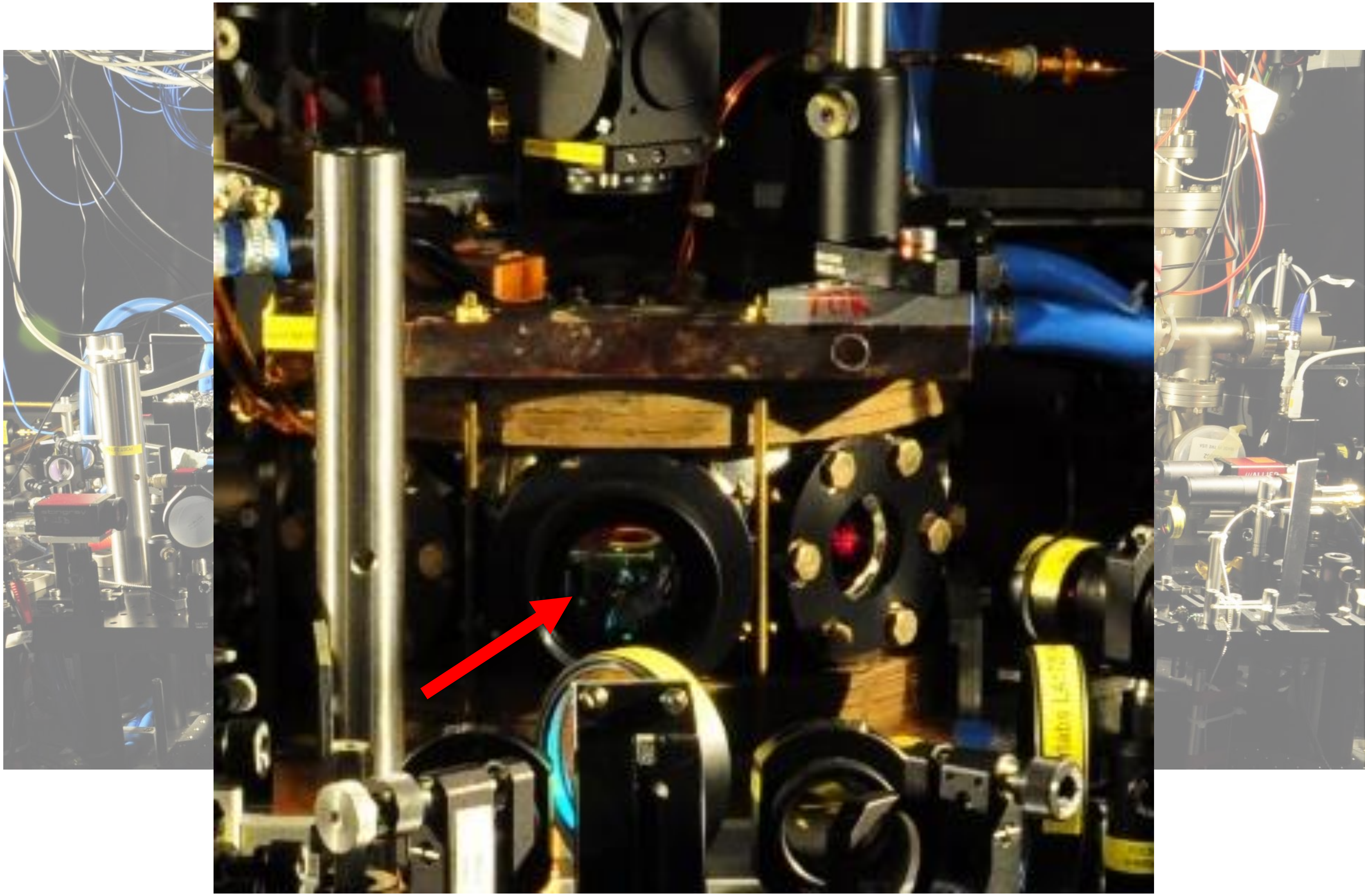


1.5 meter

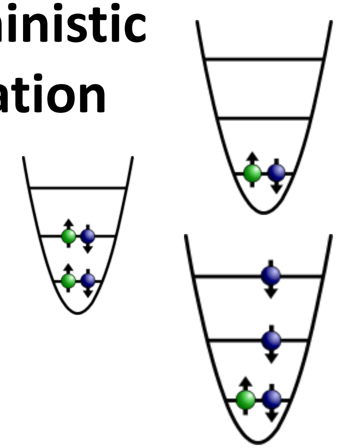
Our playground

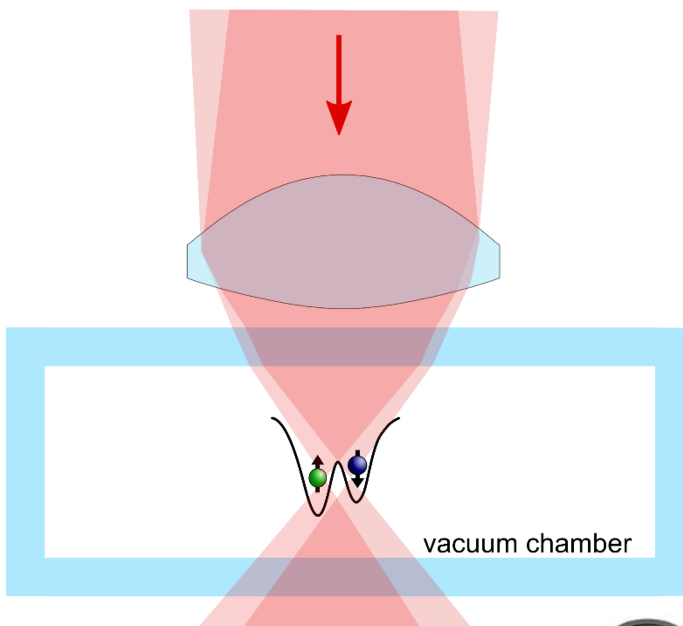


Our playground

^{6}Li:
→ Fermion statistics

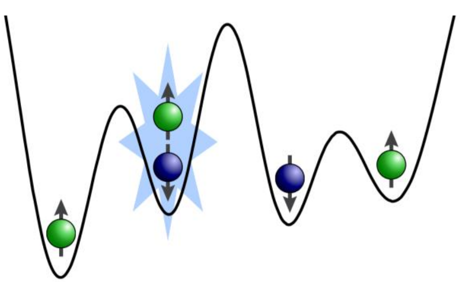
Deterministic preparation

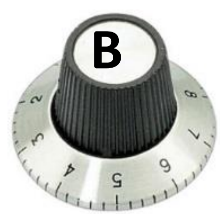




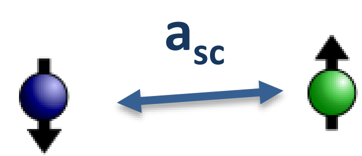
Zürn, G. et al., *PRL 108* (2012).
Zürn, G. et al., *PRL 111*(17) (2013).
Wenz, A. N. et al., Science 342 (2013).
Murmann, S. et al., *PRL 115*(21) (2015).

Potential landscape

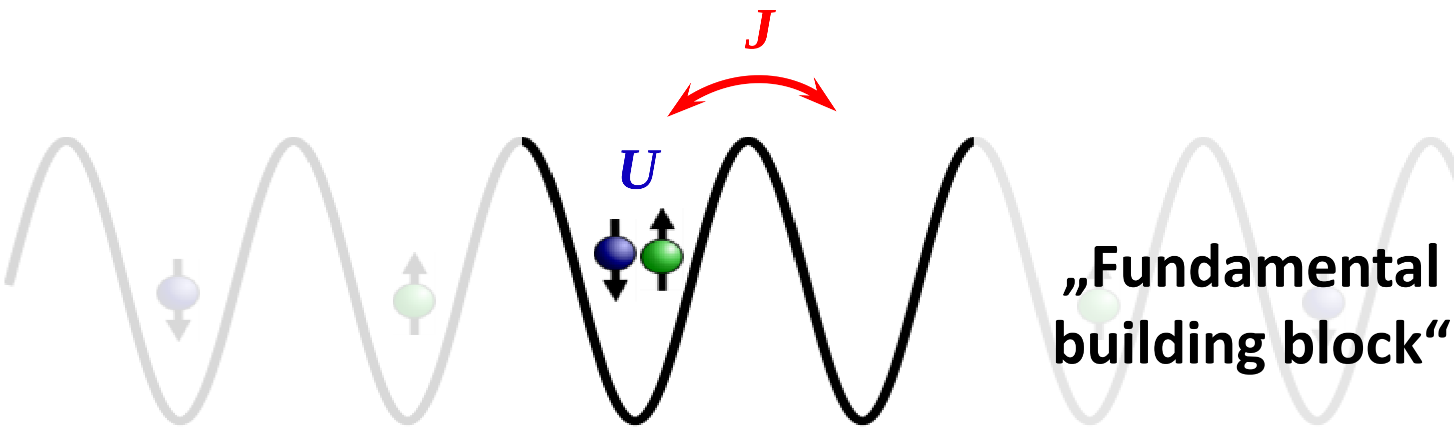




Tunable interaction



Two atoms in a double well

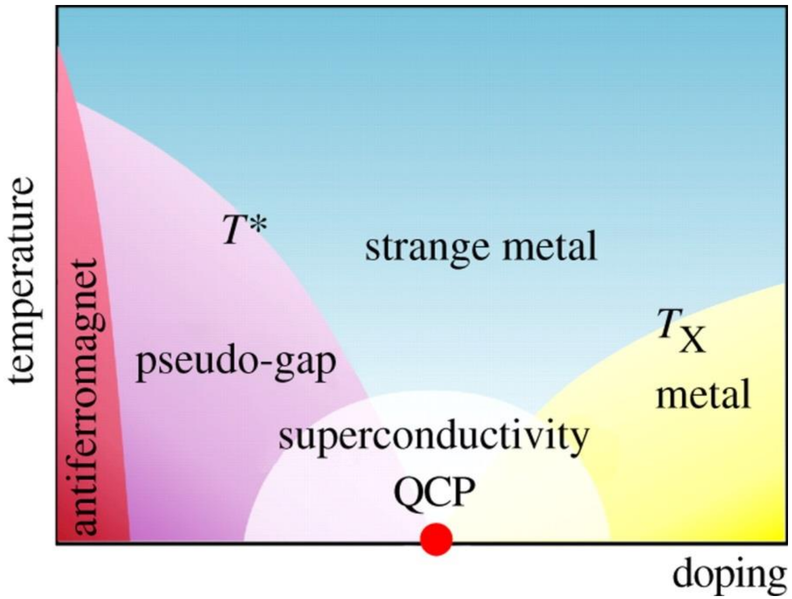


„Fundamental building block“

Hubbard model:

- Only hopping between adjacent sites
- Only on-site interactions

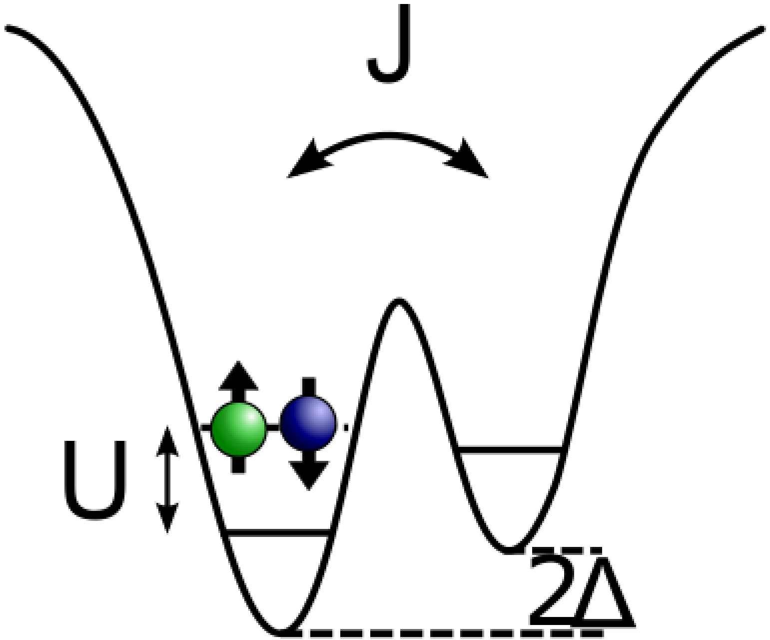
→ „Simplest model“



Galanakis et al., Galanakis, D., et al., Philos. Trans. Royal Soc. A, 369.1941 (2011): 1670-1686

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

Two atoms in a double well



Experimental control of:

- Distance
- Tilt
- Tunnel coupling
- Interaction

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

Preparation of the ground state

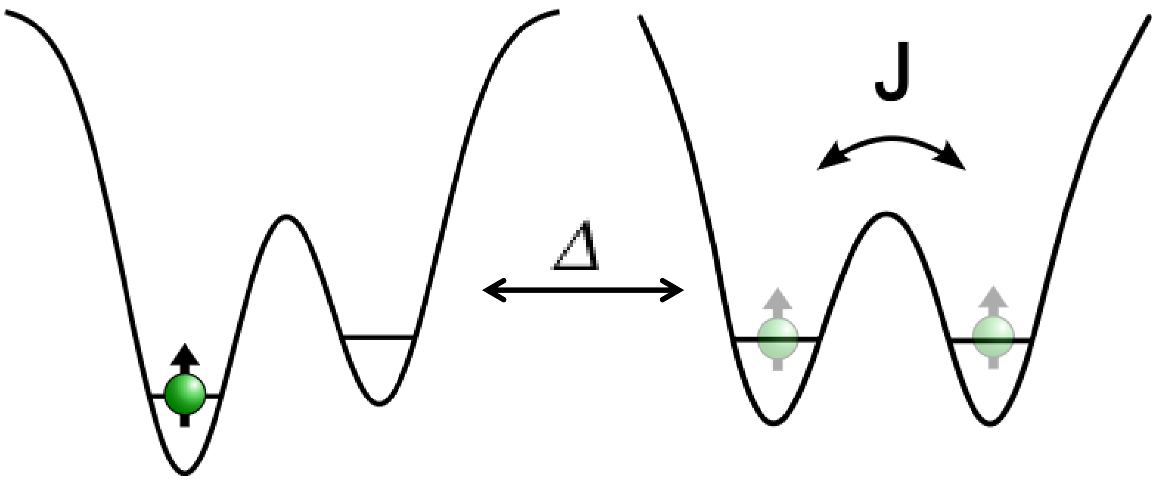
$\Delta \ll 0$

Adiabatic passage

$\Delta = 0$

$|L\rangle$

$$\psi_+ = \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle)$$



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

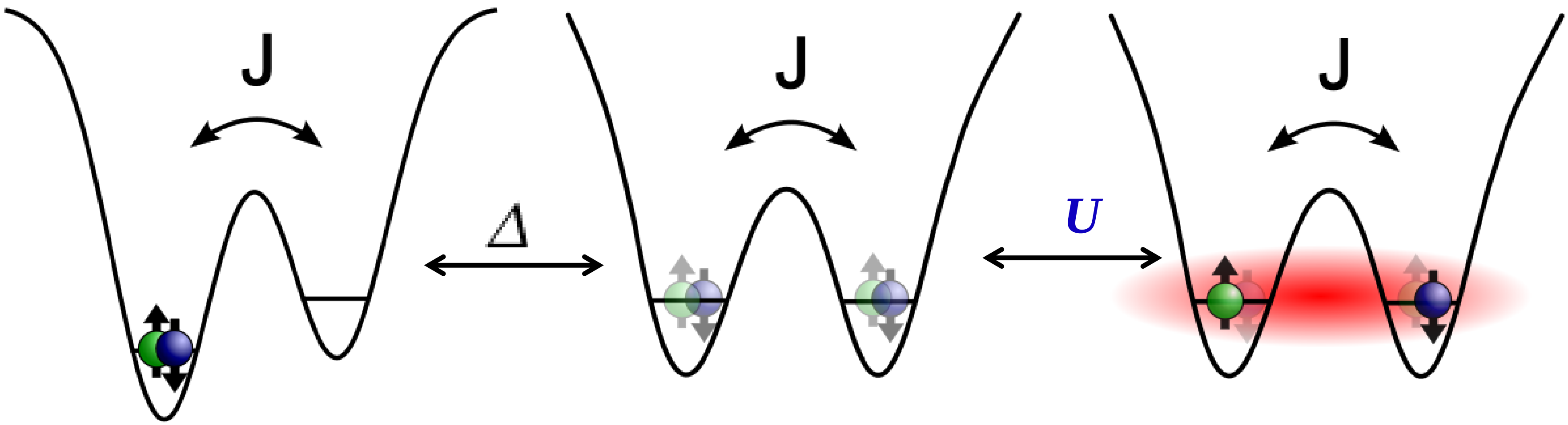
Preparation of the ground state

$\Delta \ll 0$		$\Delta = 0$		$\Delta = 0$
U = 0	Adiabatic passage	U = 0	Adiabatic passage	U ≠ 0

$|L\rangle * |L\rangle$

$$|\Psi\rangle = \frac{1}{2}(|L\rangle + |R\rangle)_1 \otimes (|L\rangle + |R\rangle)_2$$

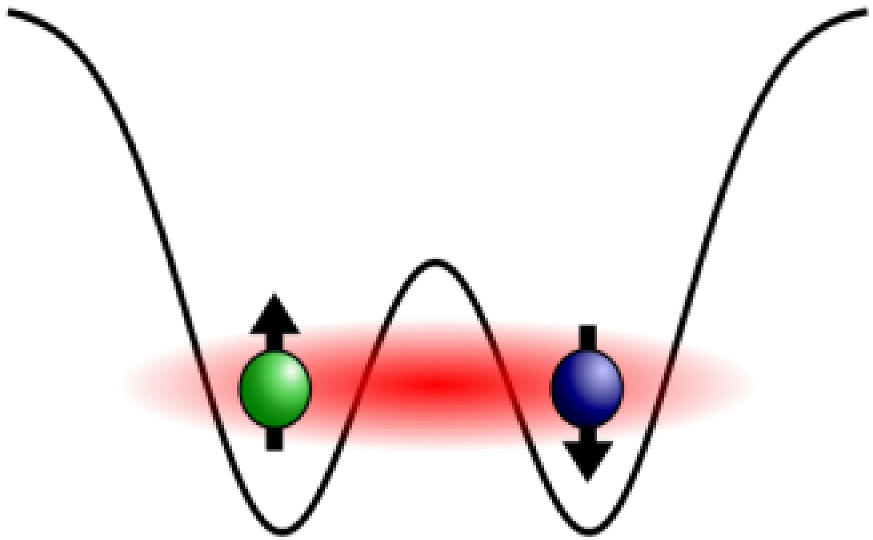
$$\frac{1}{\sqrt{2}}(|LR\rangle + |RL\rangle)$$



→ Adiabatic ramp to ground state with interaction

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

Hubbard dimer



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

Free-space single-atom imaging

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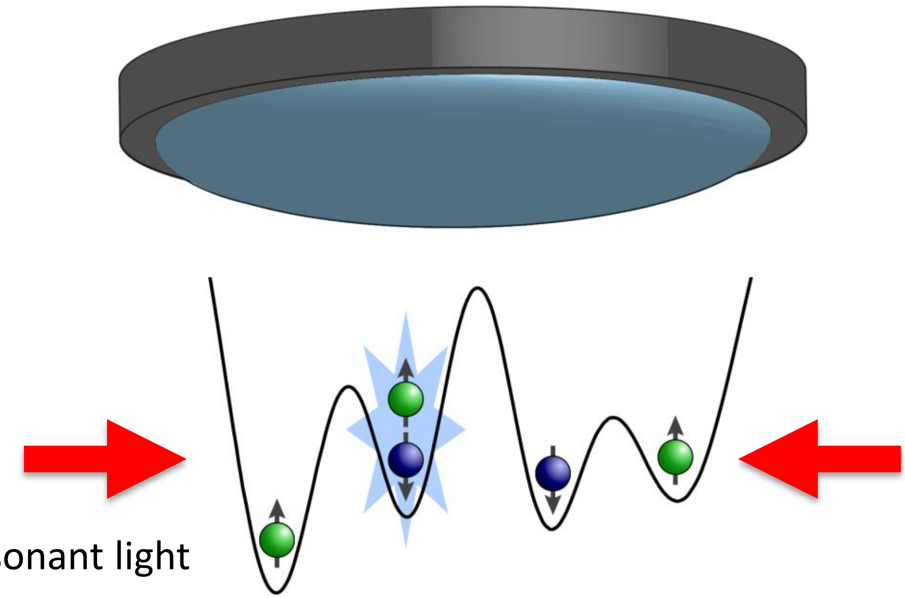
High-resolution objective



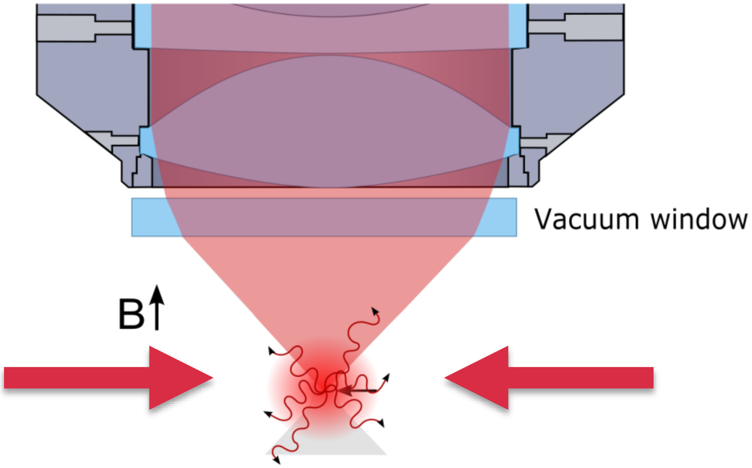
resonant light

Free-space fluorescence imaging

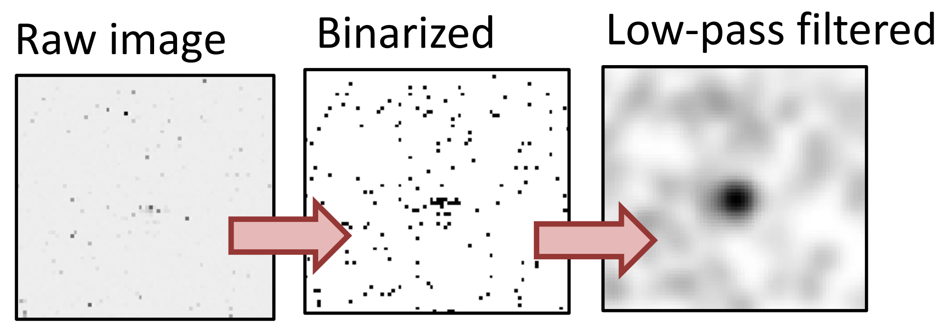
- Extremely simple
- No trapping potential, no special cooling scheme
- Resolve hyperfine state

Fermi gas microscopy: Greiner, Bloch, Zwierlein, Kuhr, Thywissen, Bakr…
Free-space imaging of Rb: Bücker *et al.*, NJP **11** 103039 (2009)

Single-atom imaging



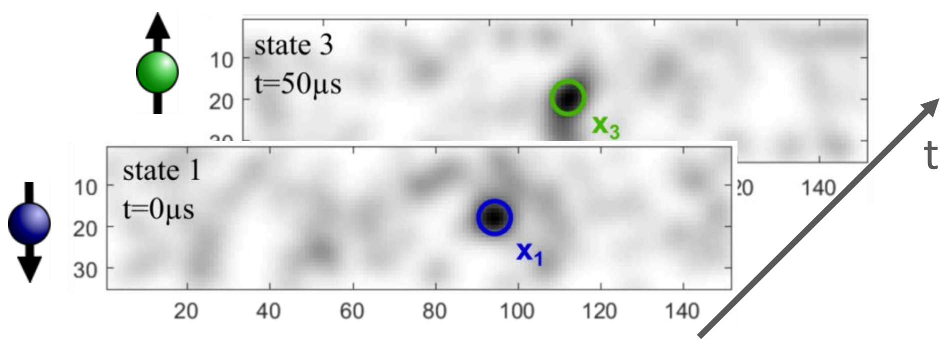
Identification and position resolution:



97% detection fidelity

- Fluorescence imaging
- Collect ≈20 photons with the objective
- Single-photon sensitive camera
- Image processing

Hyperfine spin resolution:



Free-space imaging of Rb: Bücker *et al.*, NJP **11** 103039 (2009)

Measuring occupation statistics

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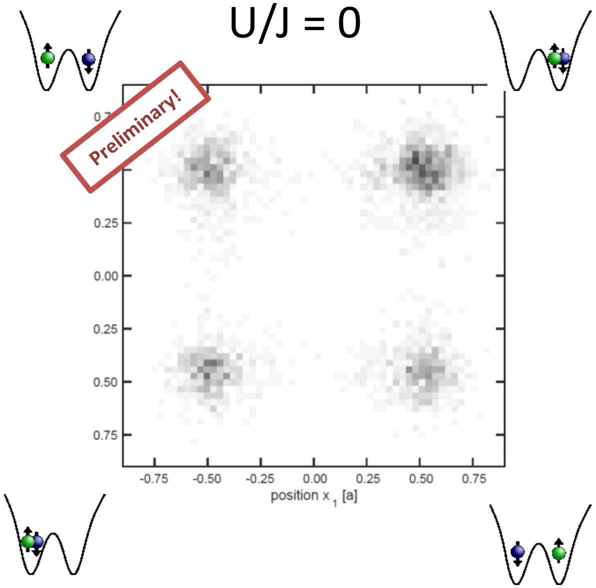
Repulsive interaction

U/J

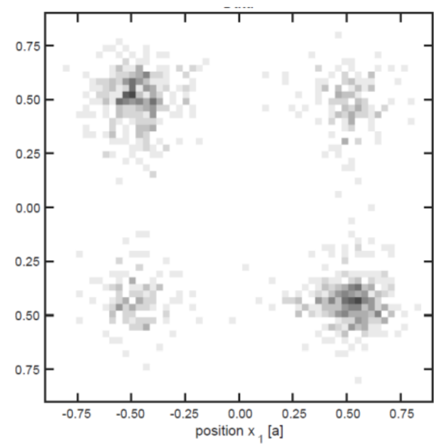
$$|\Psi\rangle = \frac{1}{2}(|L\rangle + |R\rangle)_1 \otimes (|L\rangle + |R\rangle)_2$$

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

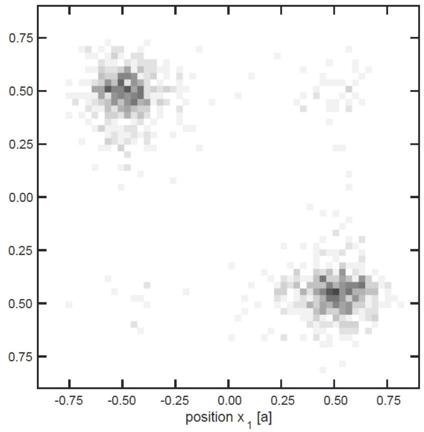
U/J = 0

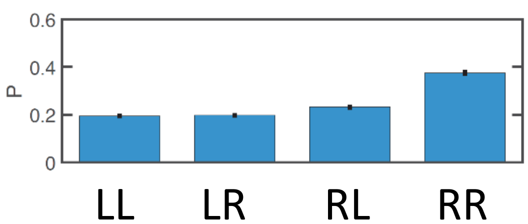


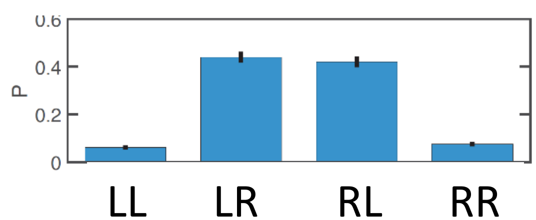
U/J = 3.8

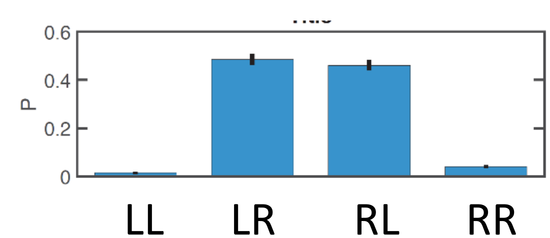


U/J = 15

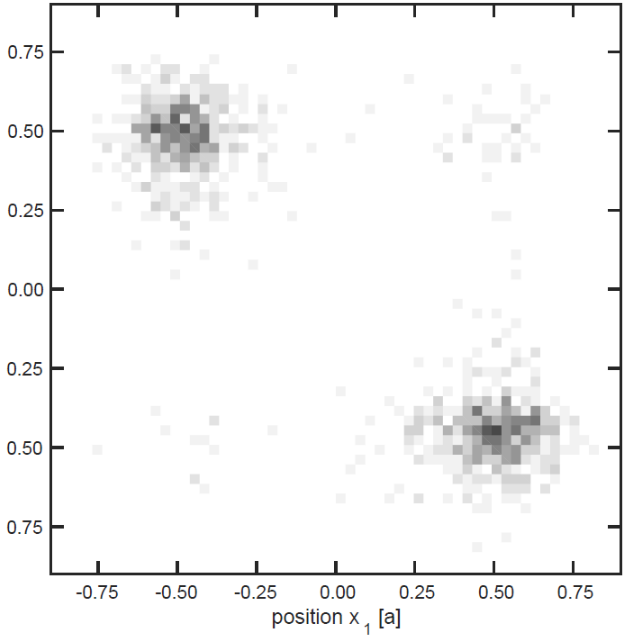








Pure or mixed state?



Pure state

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|LR\rangle + |RL\rangle\right)$$

or

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|LR\rangle - |RL\rangle\right)$$

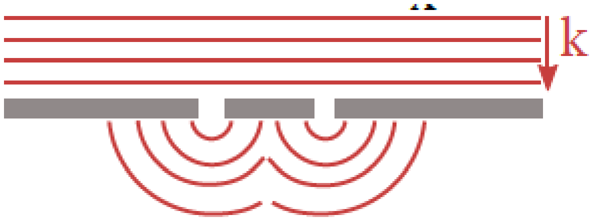
or mixed state

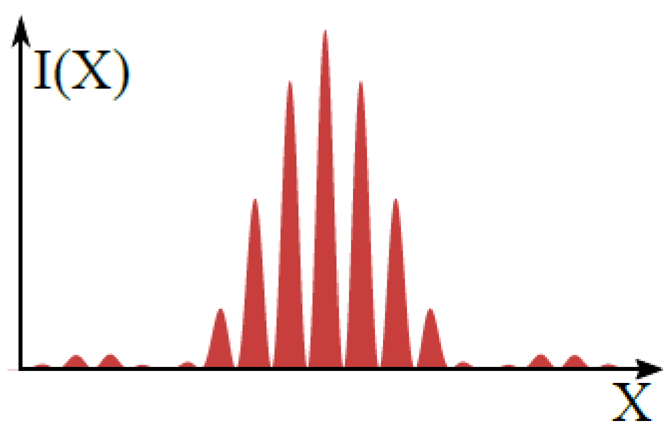
$$\rho = 0.5\,|LR\rangle\langle LR| + 0.5|RL\rangle\langle RL|$$

→ Measure coherence!

Study coherence

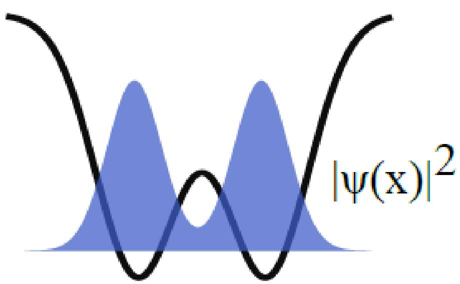
Measuring coherence in optics:

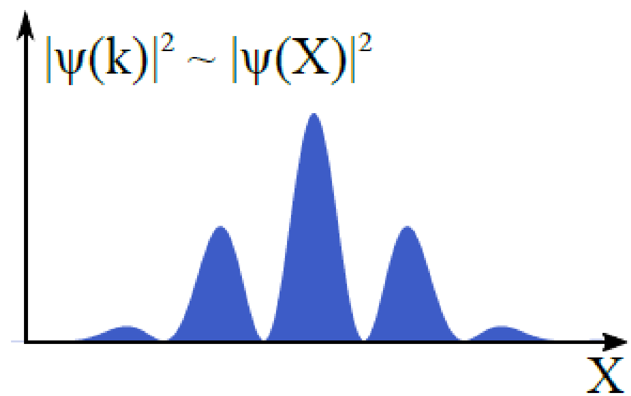




Young‘s double slit with a single atom

$$\psi_+ = \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle)$$





Two non-interacting particles

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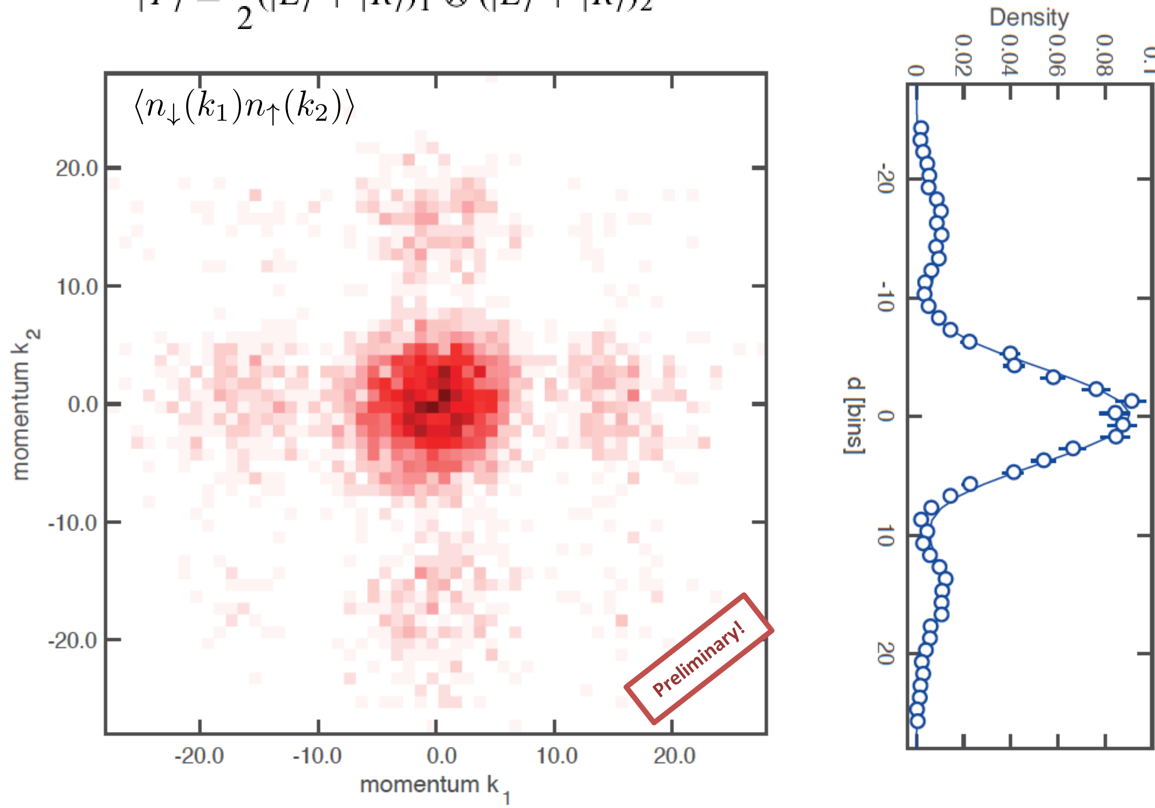
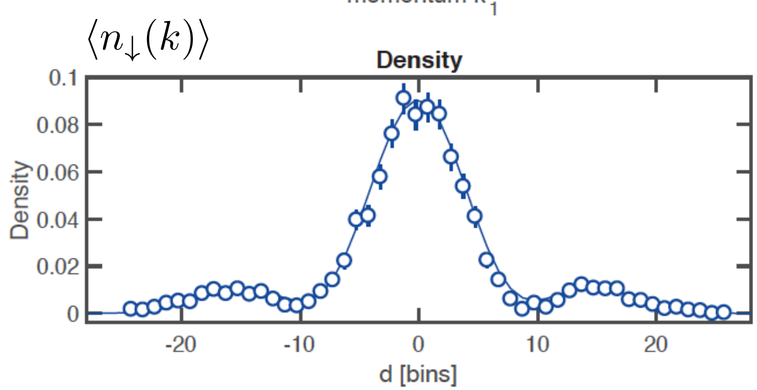
$$|\Psi\rangle = \frac{1}{2}(|L\rangle + |R\rangle)_1 \otimes (|L\rangle + |R\rangle)_2$$

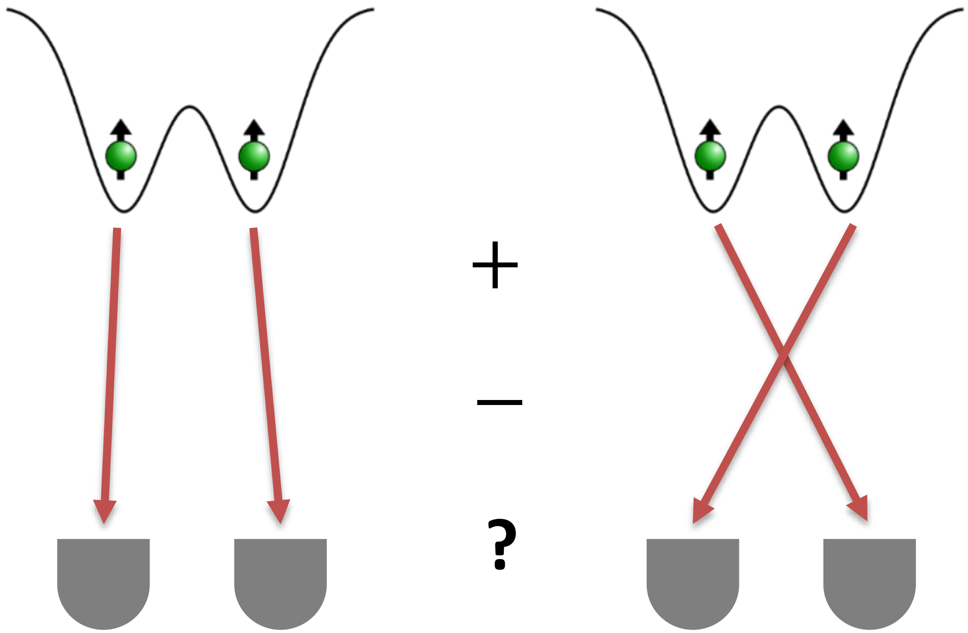
U/J=0





→ **Observe single-particle coherence**

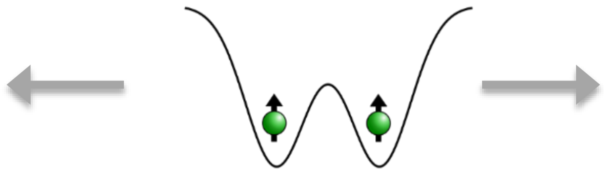
Two-particle correlations



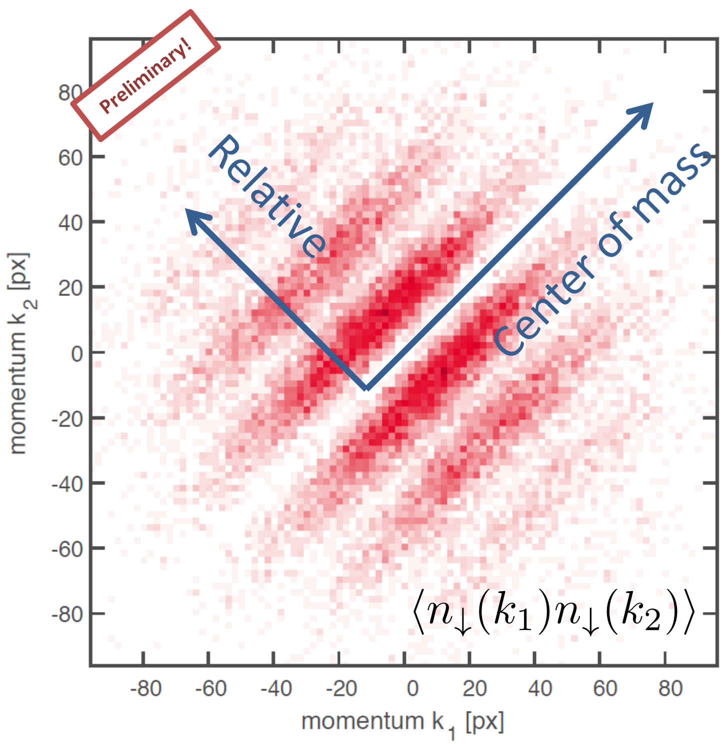
Antibunching in lattice: T. Rom *et al.,* Nature **444**, 733-736 (2006)

Fermionic HBT (Helium): T. Jeltes *et al.,* Nature **445**, 402-405 (2007)

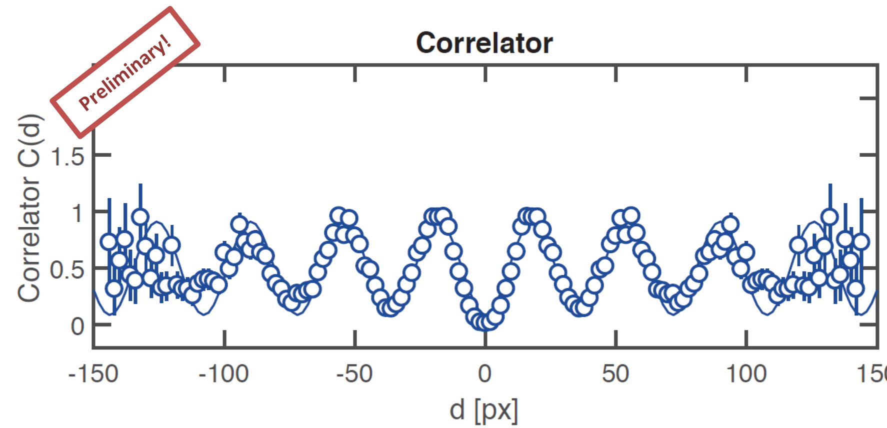
Two-particle correlations



Two-dimensional probability distribution



One-dimensional correlation function



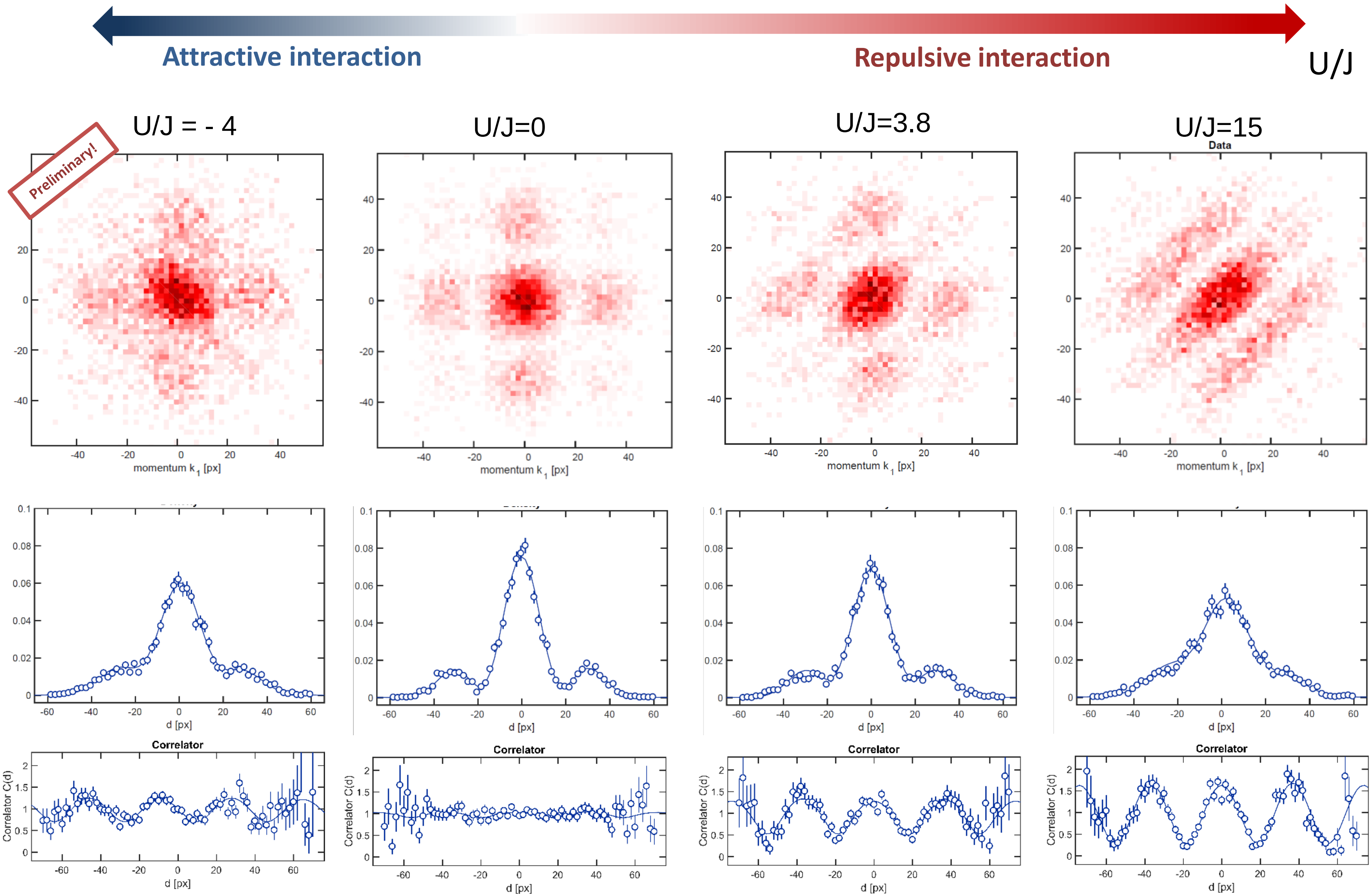
$$C(\boldsymbol{d}) = \frac{\int \langle \hat{n}(\bar{\boldsymbol{x}} - \boldsymbol{d}/2) \hat{n}(\bar{\boldsymbol{x}} + \boldsymbol{d}/2) \rangle d\bar{\boldsymbol{x}}}{\int \langle \hat{n}(\bar{\boldsymbol{x}} - \boldsymbol{d}/2) \rangle \langle \hat{n}(\bar{\boldsymbol{x}} + \boldsymbol{d}/2) \rangle d\bar{\boldsymbol{x}}}$$

➔ Fermionic antibunching

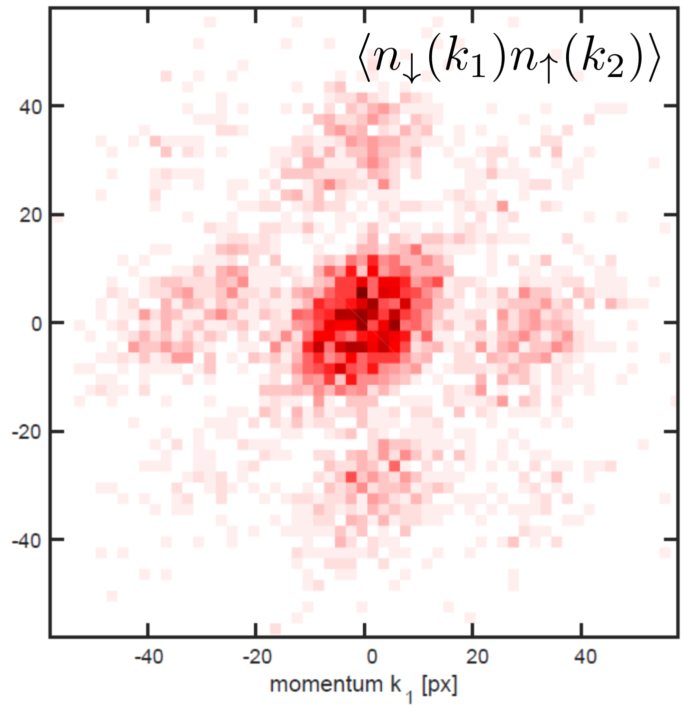
Antibunching in lattice: T. Rom *et al.,* Nature **444**, 733-736 (2006)

Fermionic HBT (Helium): T. Jeltes *et al.,* Nature **445**, 402-405 (2007)

Correlations for interacting fermions



Two-particle correlations



What information can we extract?

- Pureness of state?
- Information on the density matrix?

In principle

measuring all correlation functions should fully characterize a system

We combine

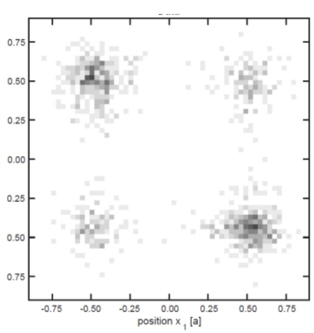
- momentum correlation
- insitu correlations

Density matrix reconstruction

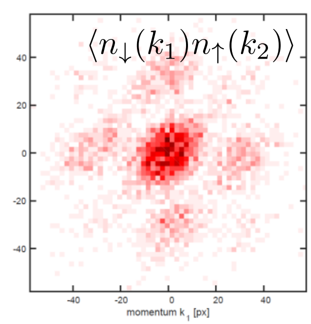
Density matrix of the two-mode Hubbard model:

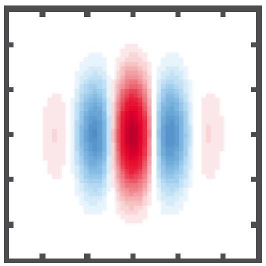
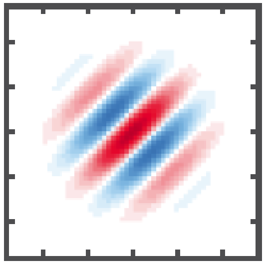
$$
\begin{array}{c}
\begin{array}{cccc} |\mathrm{LL}\rangle & |\mathrm{LR}\rangle & |\mathrm{RL}\rangle & |\mathrm{RR}\rangle \end{array} \\
\rho = \begin{pmatrix} P_{\mathrm{LL}} & \rho_{1,2} & \rho_{1,3} & \rho_{1,4} \\ & P_{\mathrm{LR}} & \rho_{2,3} & \rho_{2,4} \\ & & P_{\mathrm{RL}} & \rho_{3,4} \\ & \text{h.c.} & & P_{\mathrm{RR}} \end{pmatrix}
\end{array}
$$

Real space density:
→ populations



Momentum space density:
→ coherences/correlations

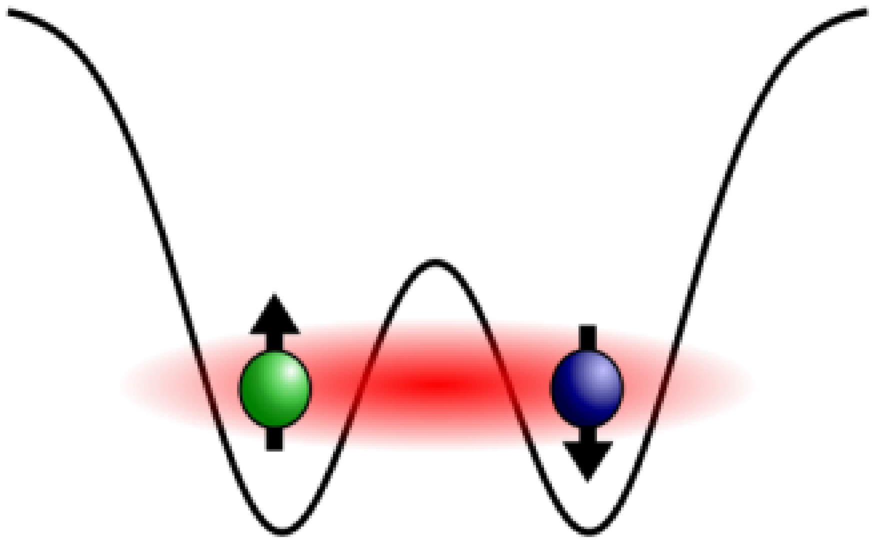


$= \begin{pmatrix} \rho_{1,2} \\ + \\ \rho_{3,4} \end{pmatrix}$  $+\ \rho_{2,3}$ 

→ **Study entanglement**

similar: M. Bonneau et al., arXiv 1711.08977

Hubbard dimer



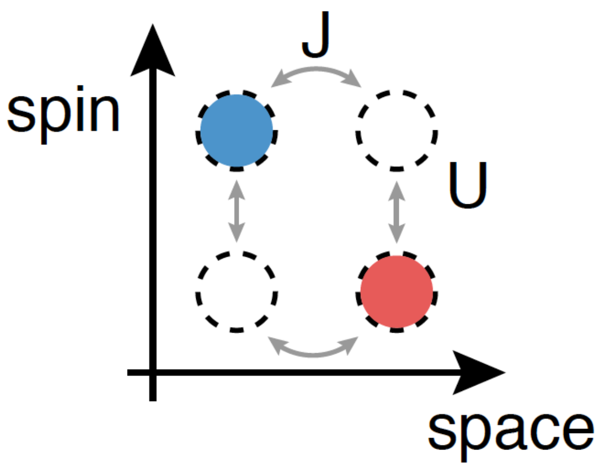
$$\frac{1}{\sqrt{2}}(|LR\rangle + |RL\rangle)$$

Can we observe entanglement?

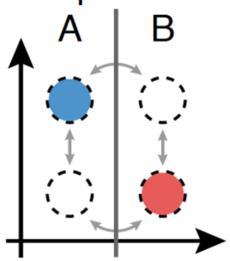
Entanglement witness

Entanglement depends on **partitioning !**

Hubbard double well

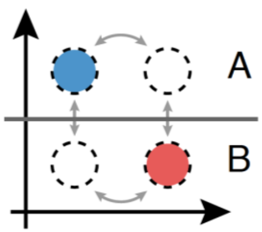


Mode partitioning



"Is the left well entangled with the right well?"

Spin partitioning



"Are the two particles entangled?"

Entanglement witness

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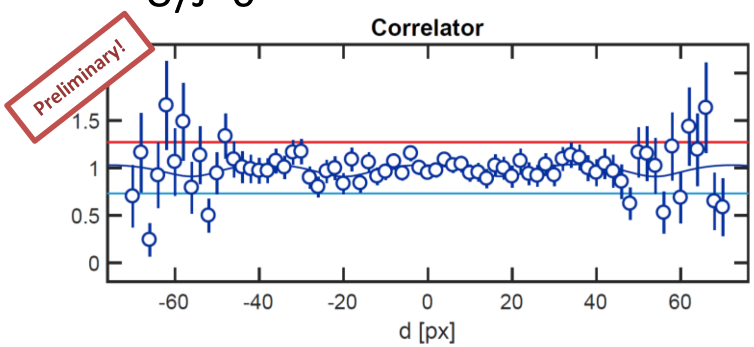
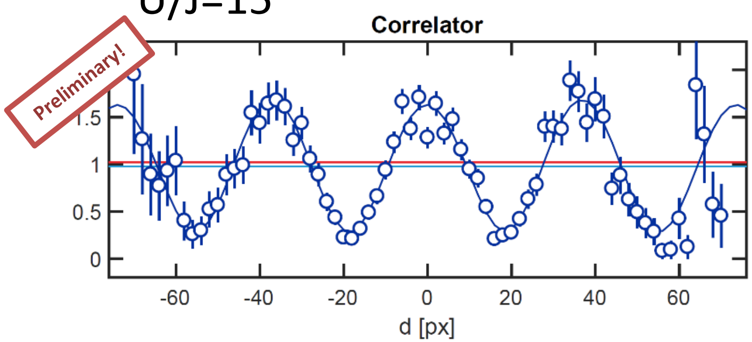
$$
\begin{array}{cc}
 & \begin{array}{cccc} |\mathrm{LL}\rangle & |\mathrm{LR}\rangle & |\mathrm{RL}\rangle & |\mathrm{RR}\rangle \end{array} \\
\rho = & \begin{pmatrix} P_{\mathrm{LL}} & \rho_{1,2} & \rho_{1,3} & \rho_{1,4} \\ & P_{\mathrm{LR}} & \rho_{2,3} & \rho_{2,4} \\ & & P_{\mathrm{RL}} & \rho_{3,4} \\ & \text{h.c.} & & P_{\mathrm{RR}} \end{pmatrix}
\end{array}
$$

U/J=0



U/J=15



Entanglement witness

- Use fringe contrast *C* as a witness
- Assuming a separable state between the spins

$$\rho = \rho_\uparrow \otimes \rho_\downarrow$$

- Measured populations provide bound on *C*

$$4\,C \leq \sqrt{P_{LL} P_{RR}} \quad \rightarrow \text{separable}$$

$$4\,C \geq \sqrt{P_{LL} P_{RR}} \quad \rightarrow \text{non-separable}$$

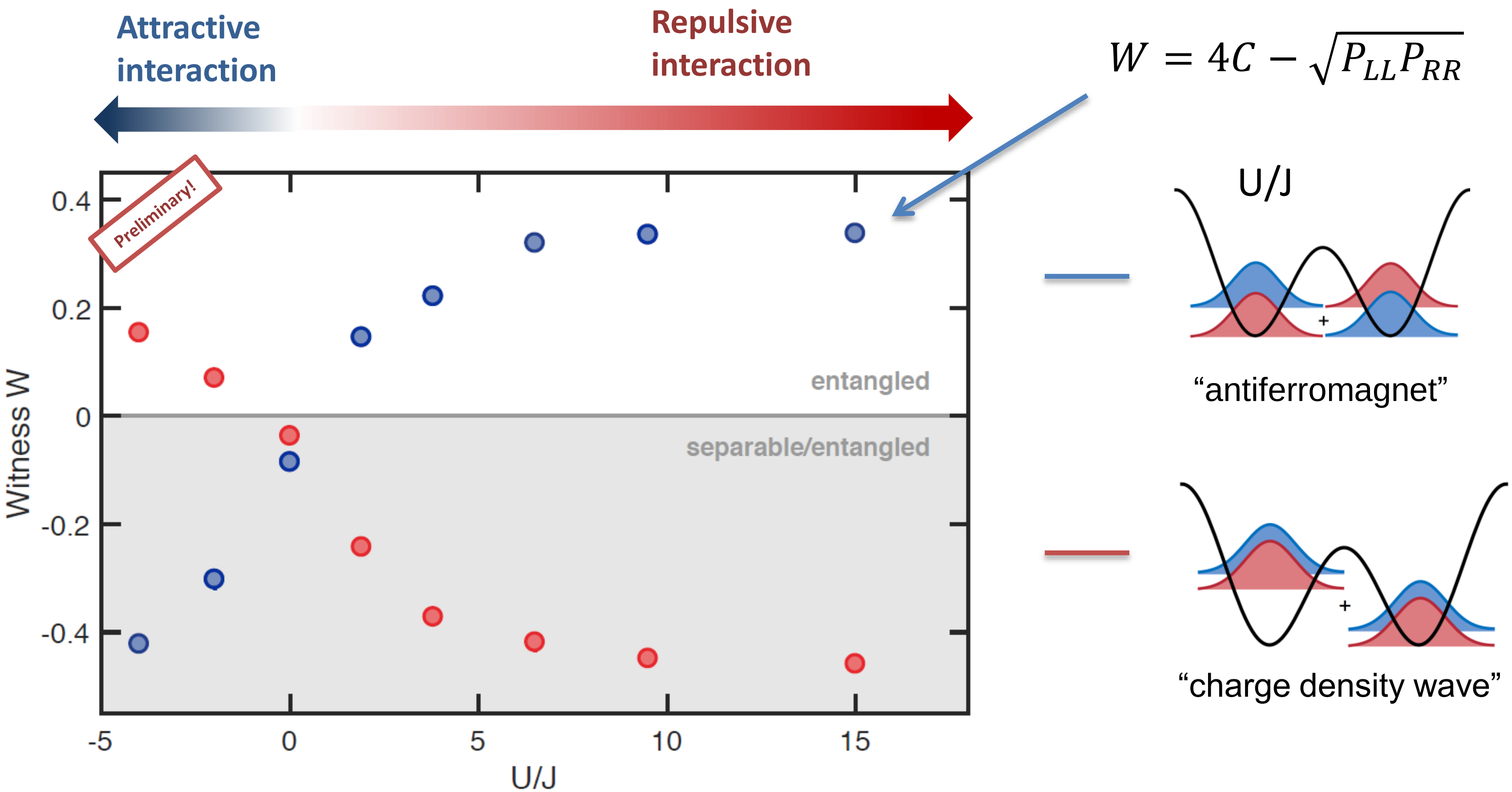
Interacting state is non-separable!

Witness construction Kaufman *et al.*, Nature **527**, 208 (2015).

Entanglement witness

Entanglement between spins

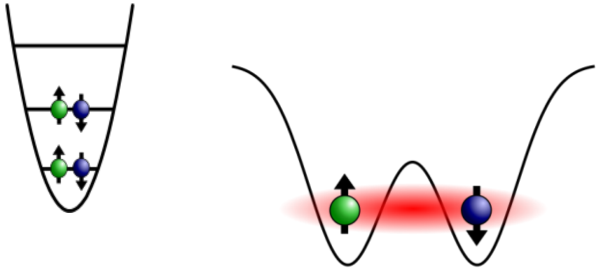
$$W = 4C - \sqrt{P_{LL} P_{RR}}$$



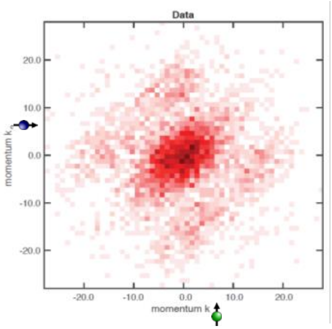
Particles become entangled through interaction

Summary

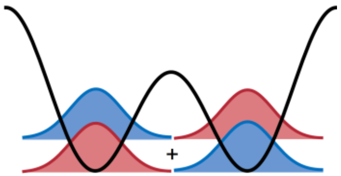
Preparation of strongly interacting few-fermion systems



Single-atom imaging allows to access coherences/correlations



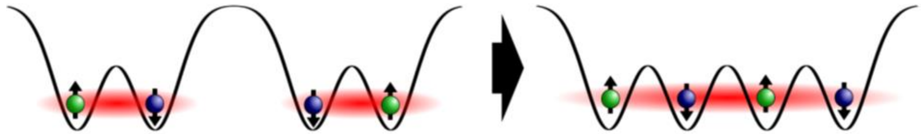
Reconstruct the density matrix and certify entanglement



“antiferromagnet”

Outlook

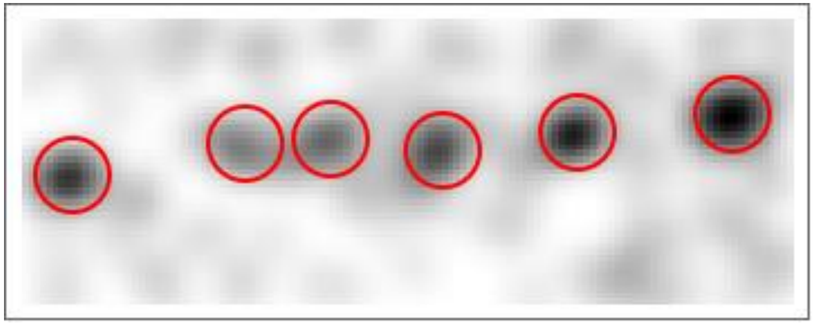
Create larger systems



Imaging of more than two particles:

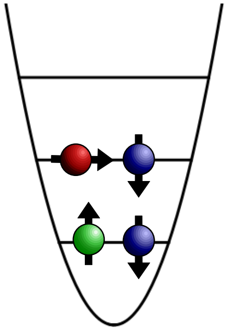
→ Beyond two-particle correlations

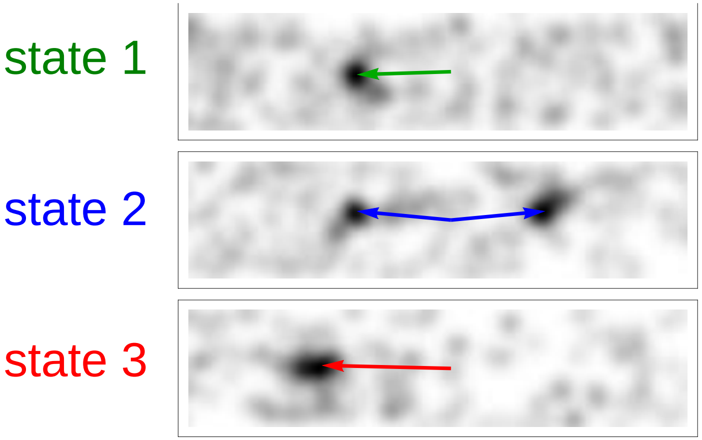
$$\langle n(\mathbf{k}_1)n(\mathbf{k}_2)n(\mathbf{k}_3)...\rangle$$



Imaging three different hyperfine states:

→ SU(3) systems





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Thank you for your attention!

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