Universität Heidelberg

Observation of Ferromagnetic Spin Correlations in a 1D Fermi System

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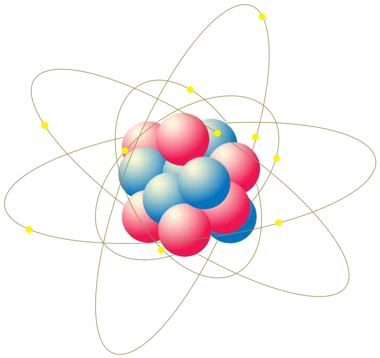
Motivation

few-fermion systems in nature:

- atoms, nuclei

  well defined quantum state

  limited tunability of interaction



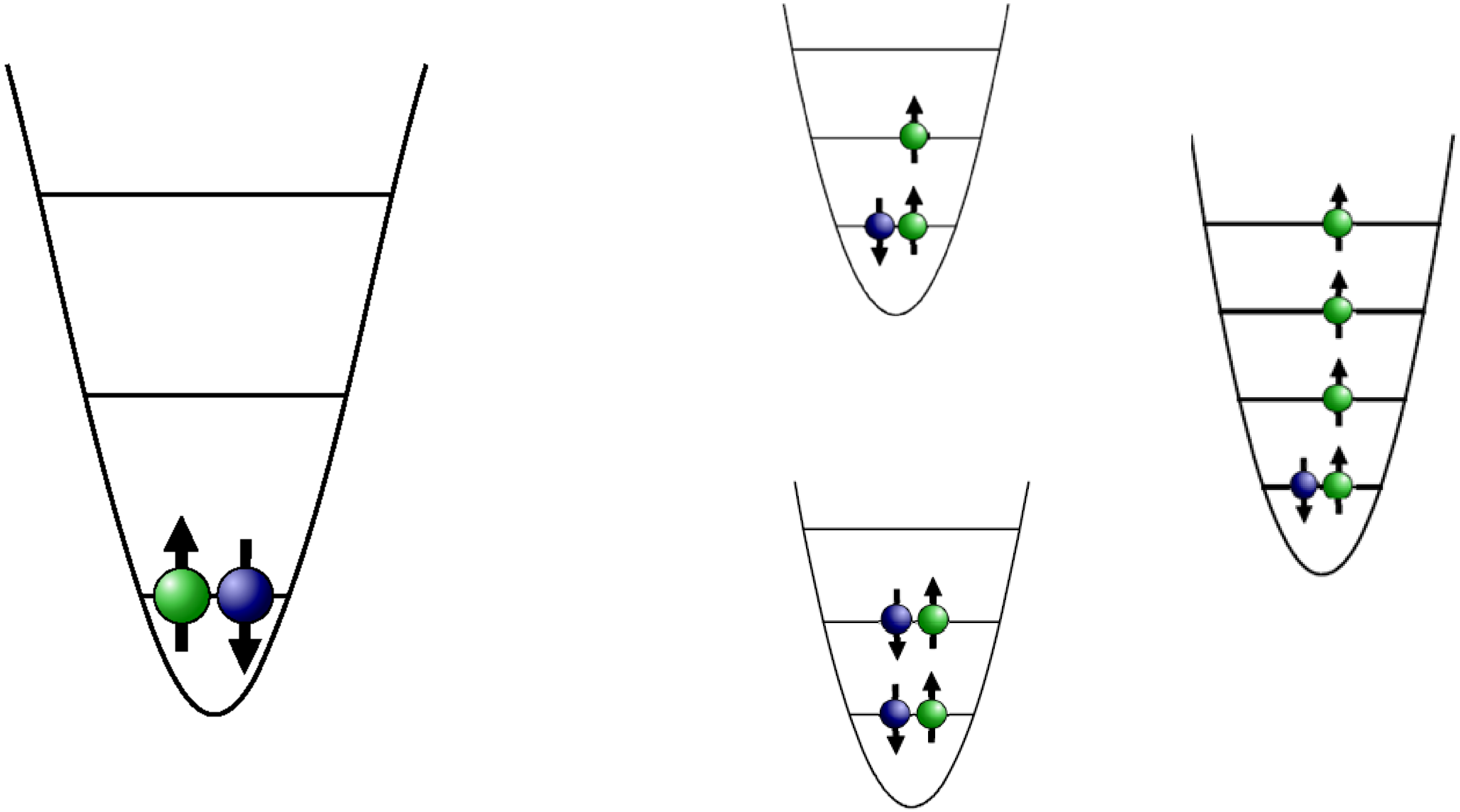
Crossover from few-body to many-body physics

With ultracold fermions:

→ Study this in a well-controlled and tunable system

Our Playground

Few-particle systems of Spin ½ fermions:



Outline

- Deterministic preparation of a few-fermion system

- Two repulsively interacting particles

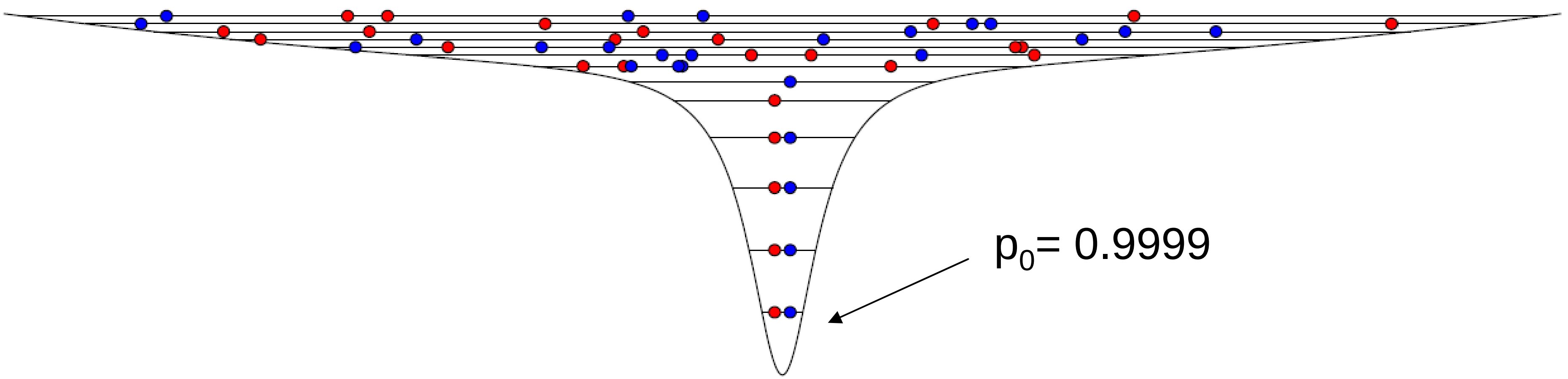
- Ferromagnetic correlations between fermions with repulsive interactions

High Fidelity Preparation

- 2-component mixture in reservoir T=250nK
- superimpose microtrap

  expected degeneracy: $T/T_F = 0.1$

- switch off reservoir



High Fidelity Preparation

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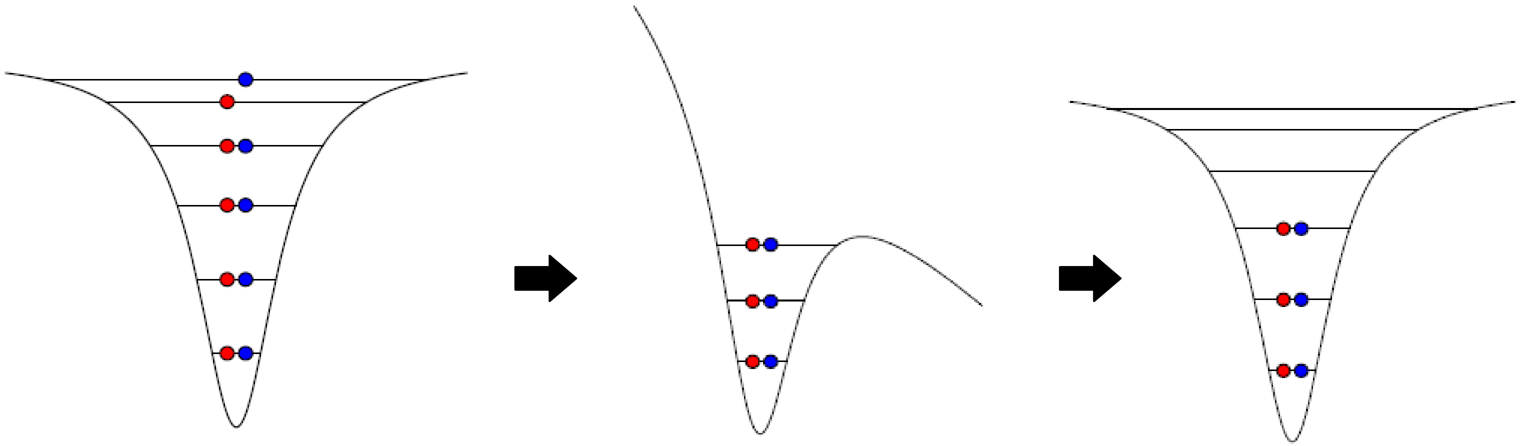
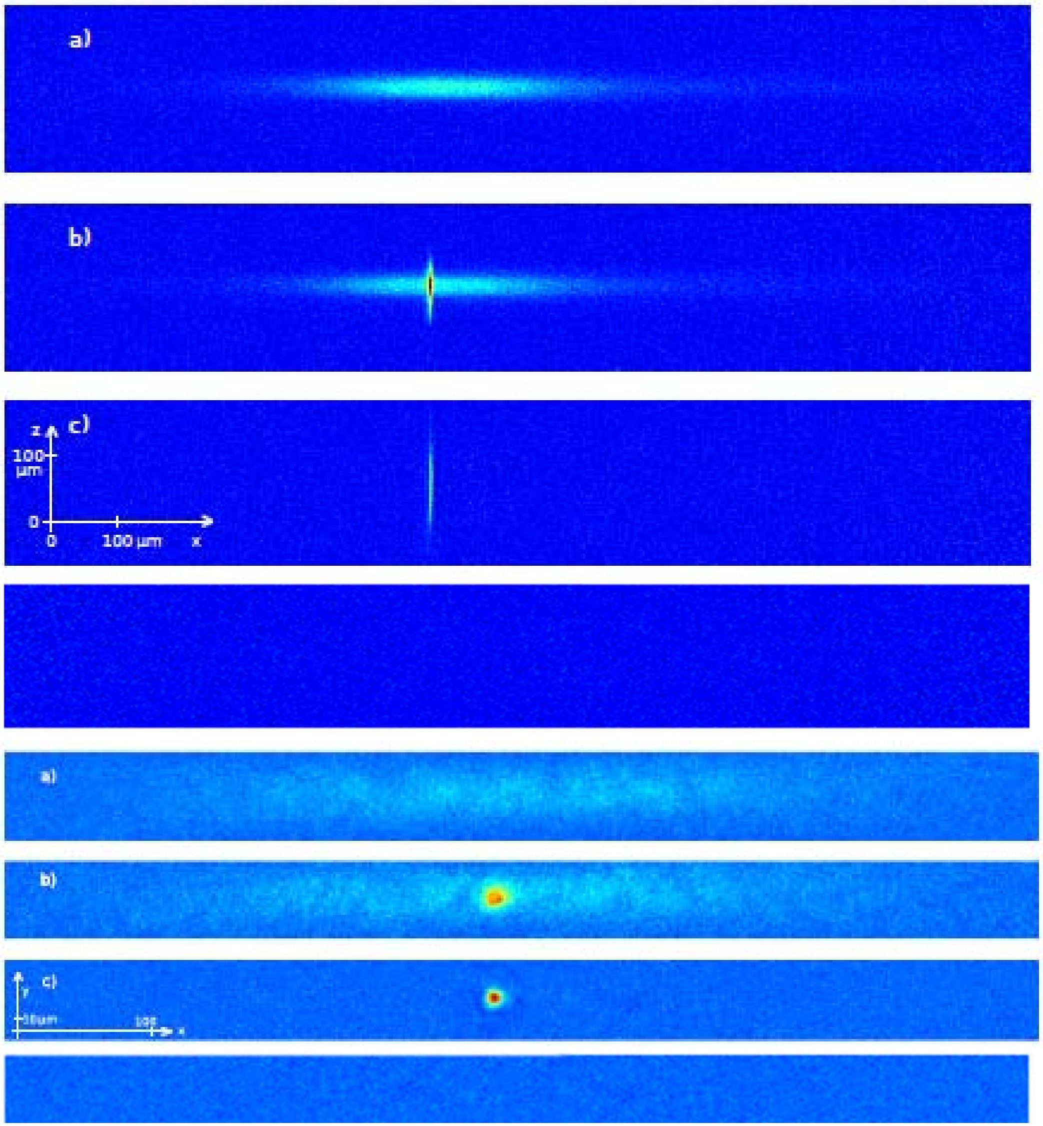


+ magnetic field gradient in axial direction

1:10 aspect ratio
$\Rightarrow$ 1D system

High Fidelity Preparation

view radial direction



reservoir

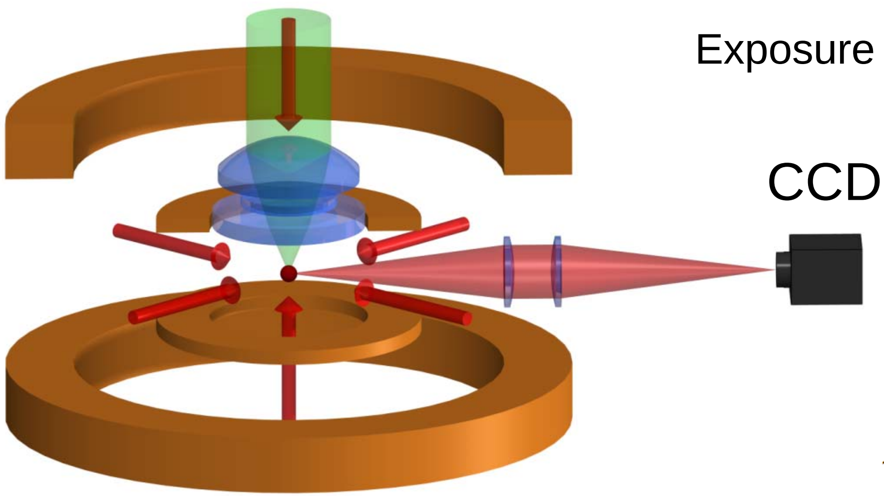
microtrap superimposed with the reservoir

microtrap only

microtrap with gradient applied

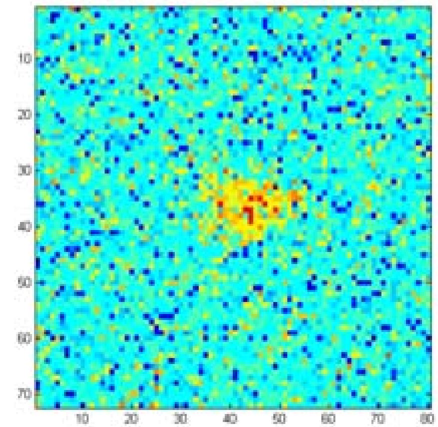
view axial direction

Single atom detection

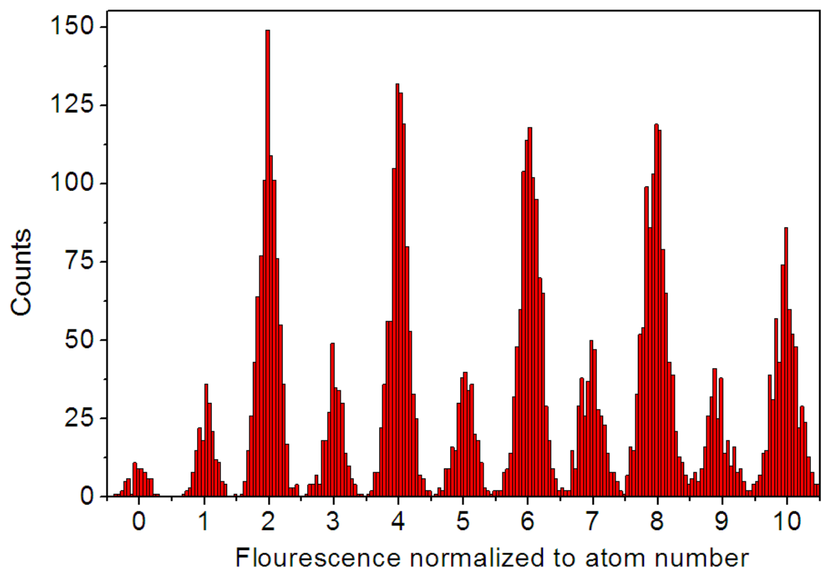


1/e-lifetime: 250s

Exposure time 0.5s



one atom in a Magneto Optical Trap



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

High Fidelity Preparation

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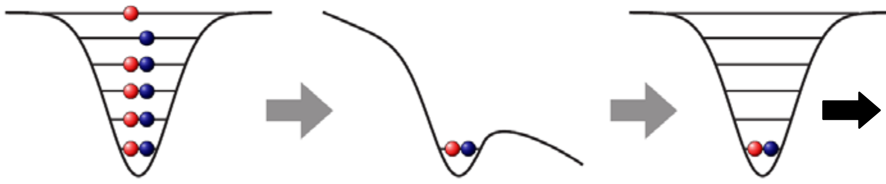
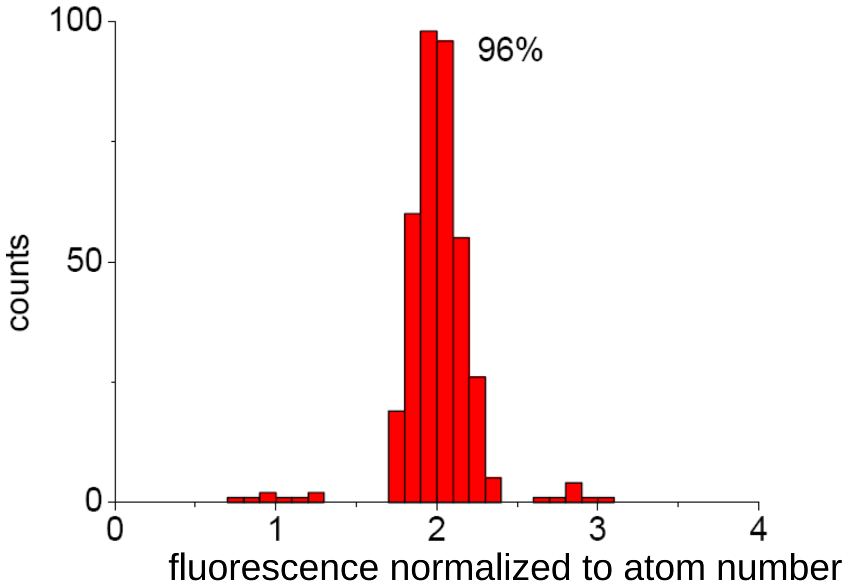
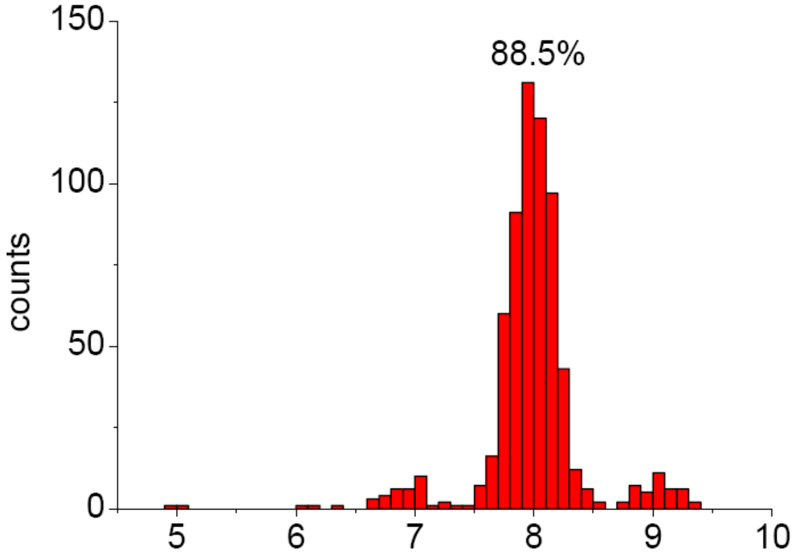
2 atoms

8 atoms







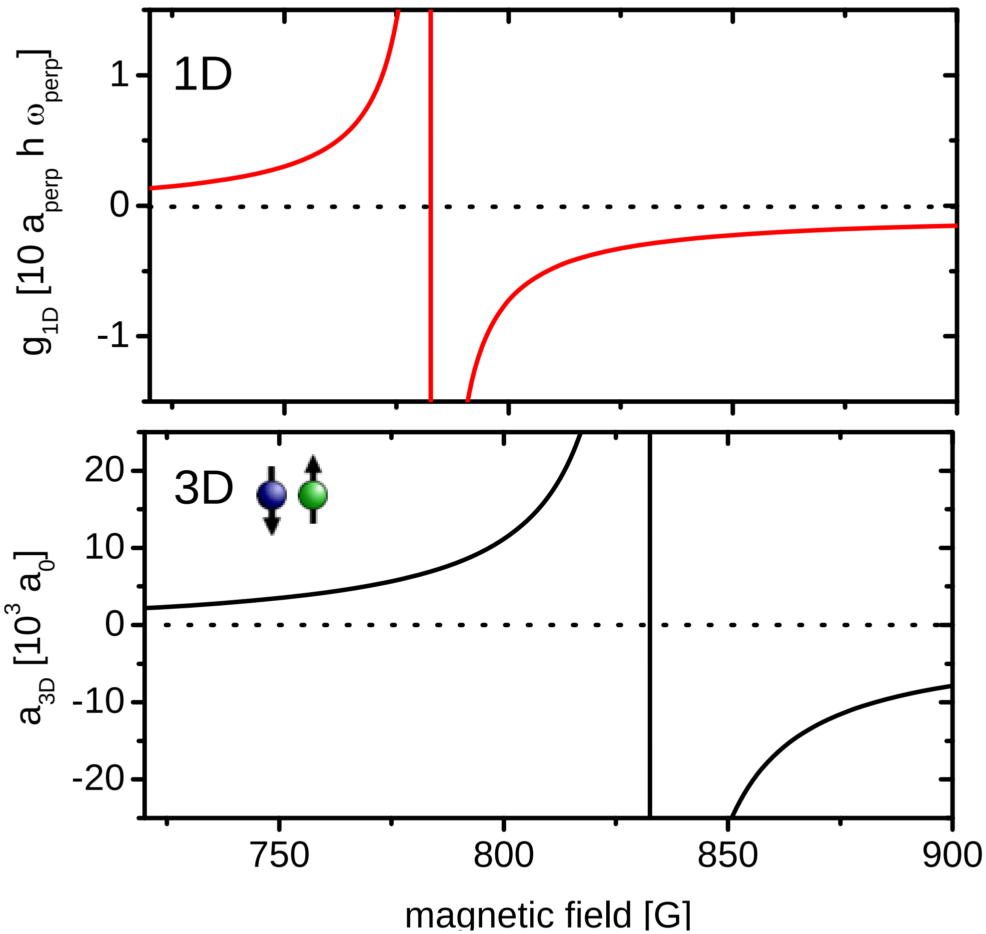
fidelity for ground state preparation: ~ 93 %

lifetime in ground state ~ 60s

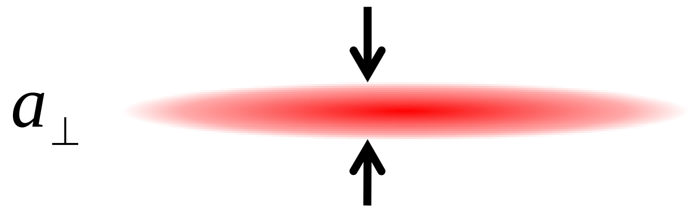
F. Serwane, G. Zürn, T. Lompe, T. Ottenstein, A. Wenz and S. Jochim,
Science **332,** 336 (2011)

Interactions in 1D

Confinement induced resonance



Trap has aspect ratio 1:10



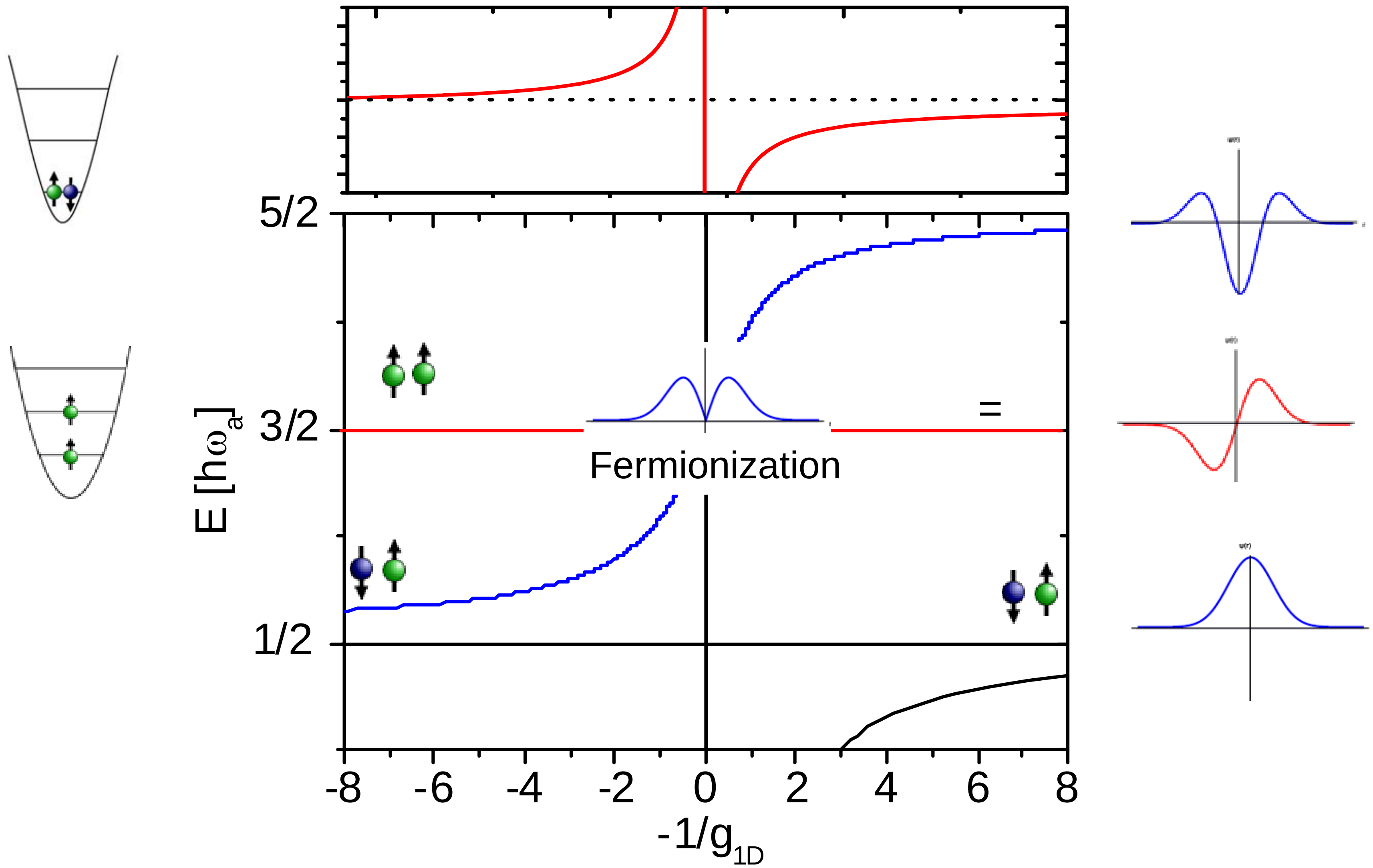
$$g_{1D} = \frac{2\hbar^2 a_{3D}}{m a_\perp^2} \frac{1}{1 - C a_{3D} / a_\perp}$$

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

Contact interaction:

$$V(x_1 - x_2) = g_{1d}\delta(x_1 - x_2)$$

Energy of 2 atoms in a harmonic trap

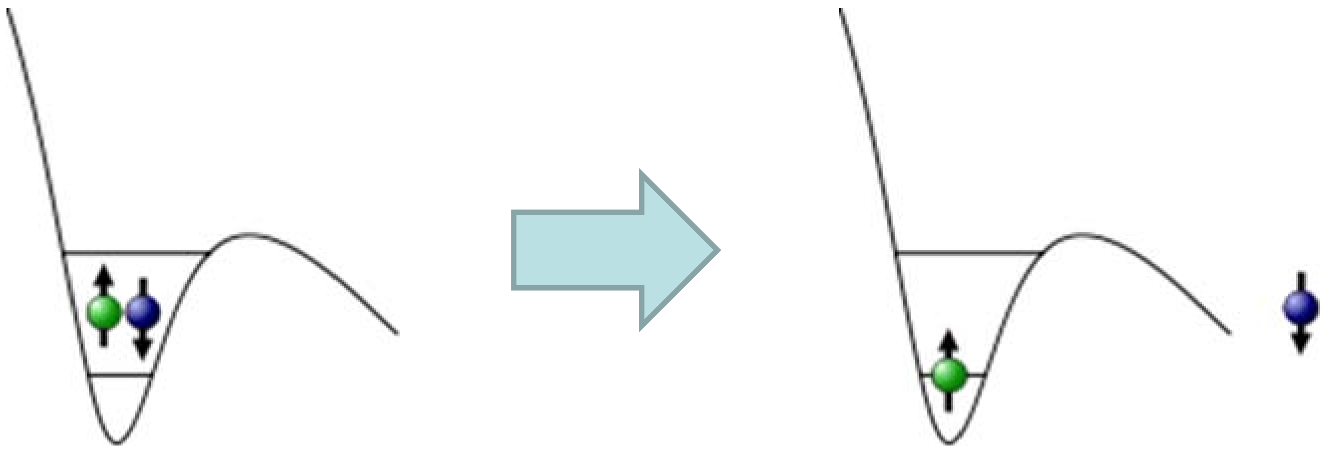


T. Busch et al., Foundations of Physics **28**, 549 (1998)

How to measure the energy?

Observe tunneling dynamics:

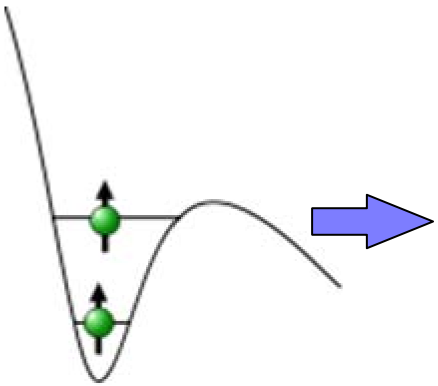
•Tilt the trap so much that the highest-lying states have an experimentally accessible tunneling time (~10-1000ms).

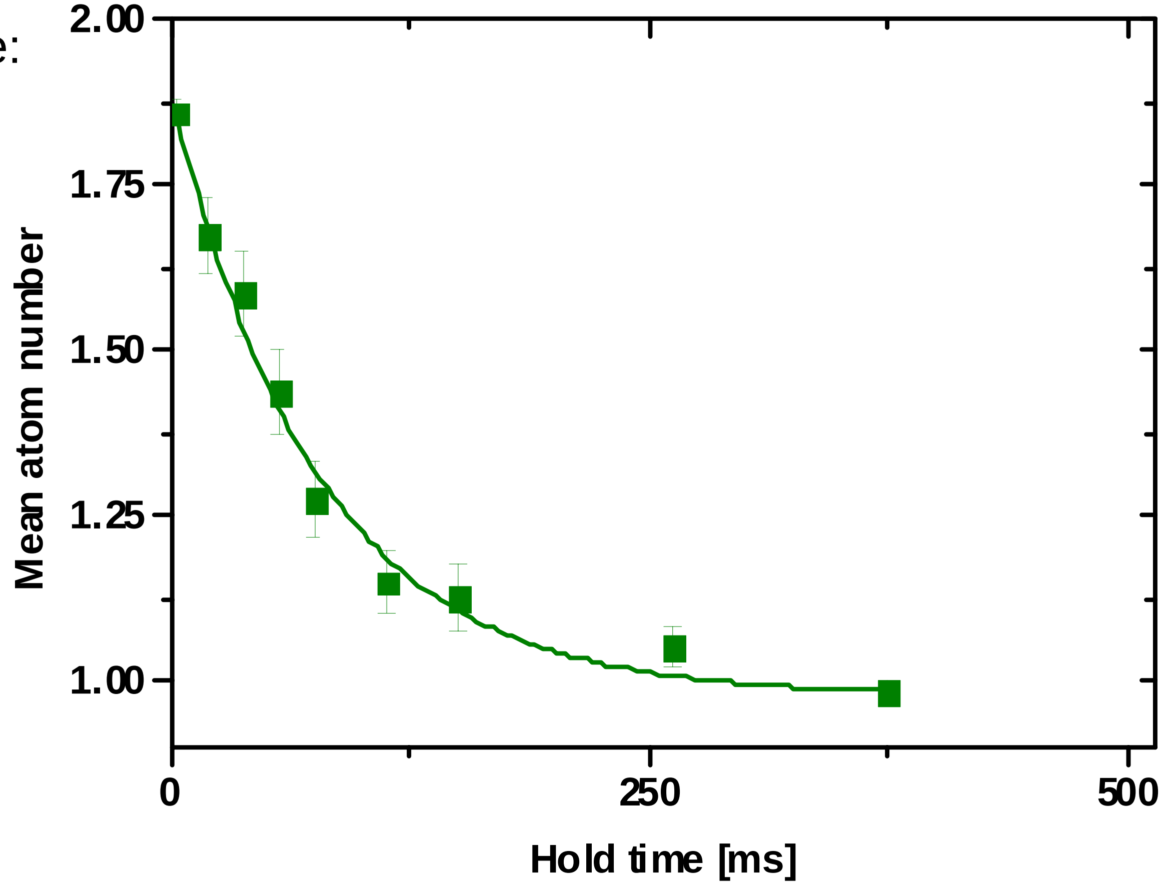


•From observed tunneling time scale infer total energy of the system

Two atoms …

First the spin polarized case:

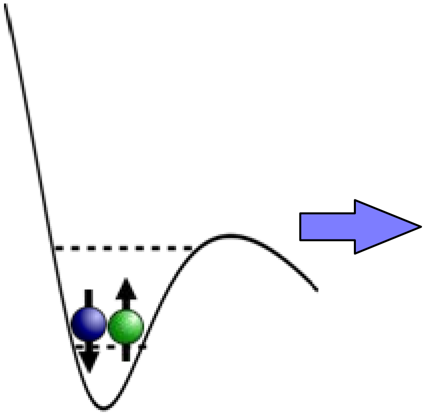


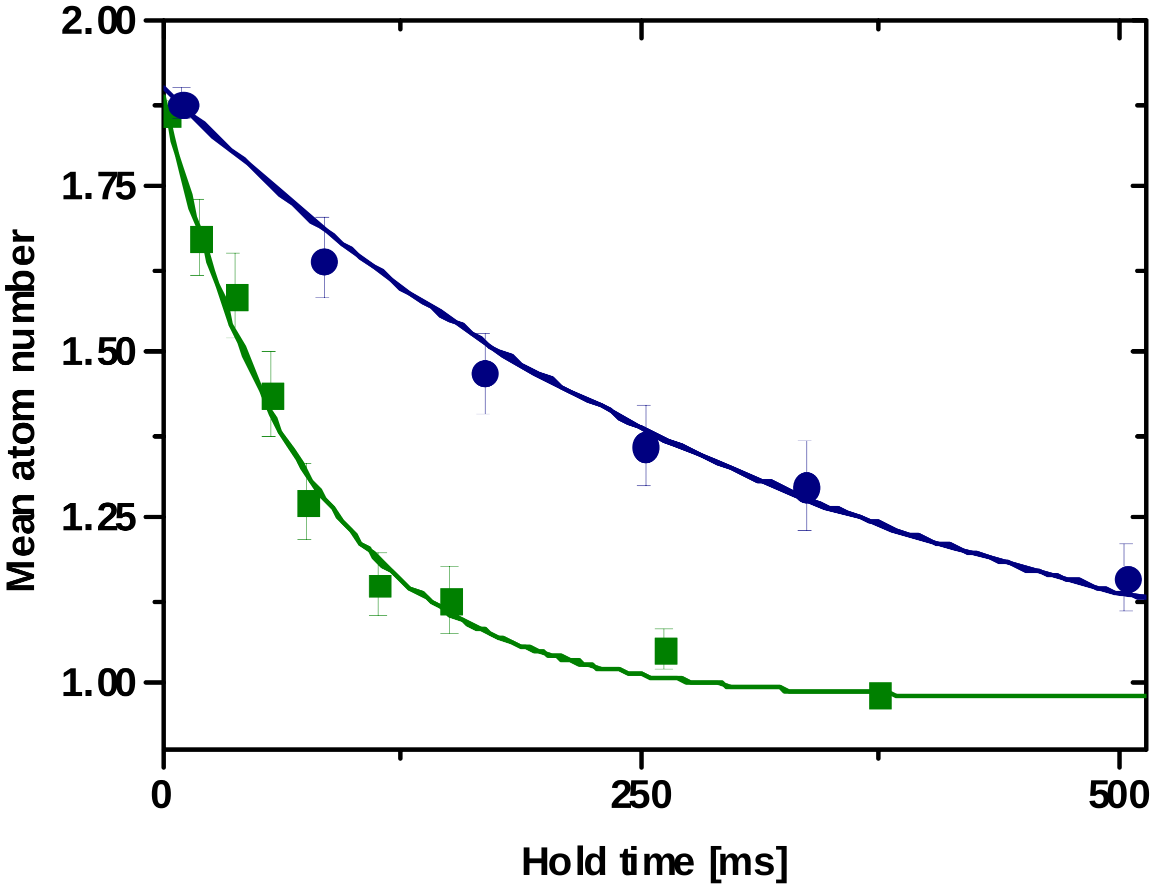


One atom tunnels out of the trap with time τ while the second remains trapped.

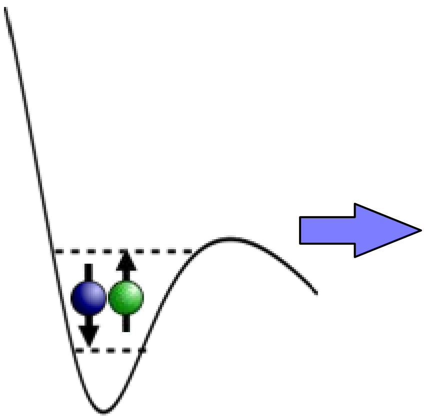
G. Zürn et al., PRL **108**, 075303 (2012)

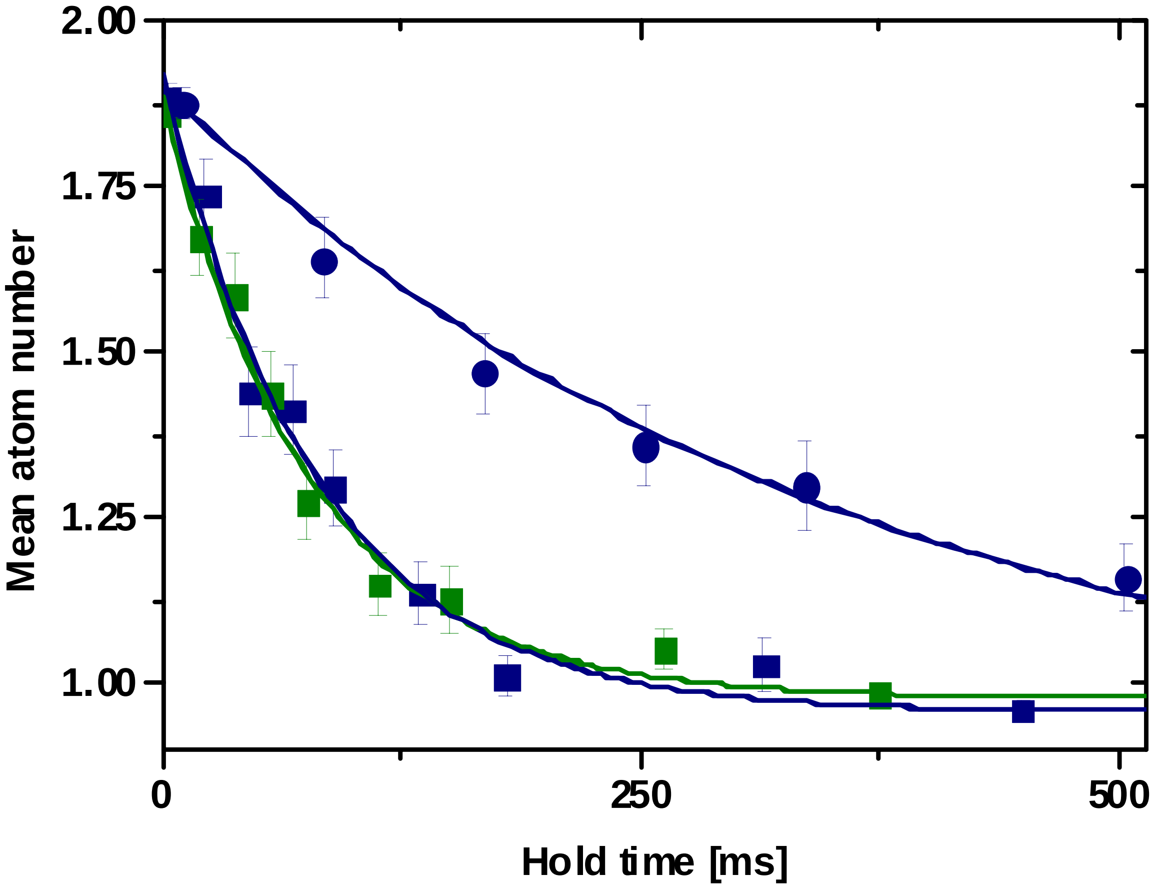
Two atoms …





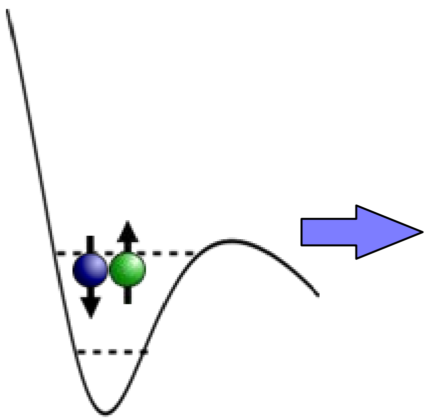
Two atoms …

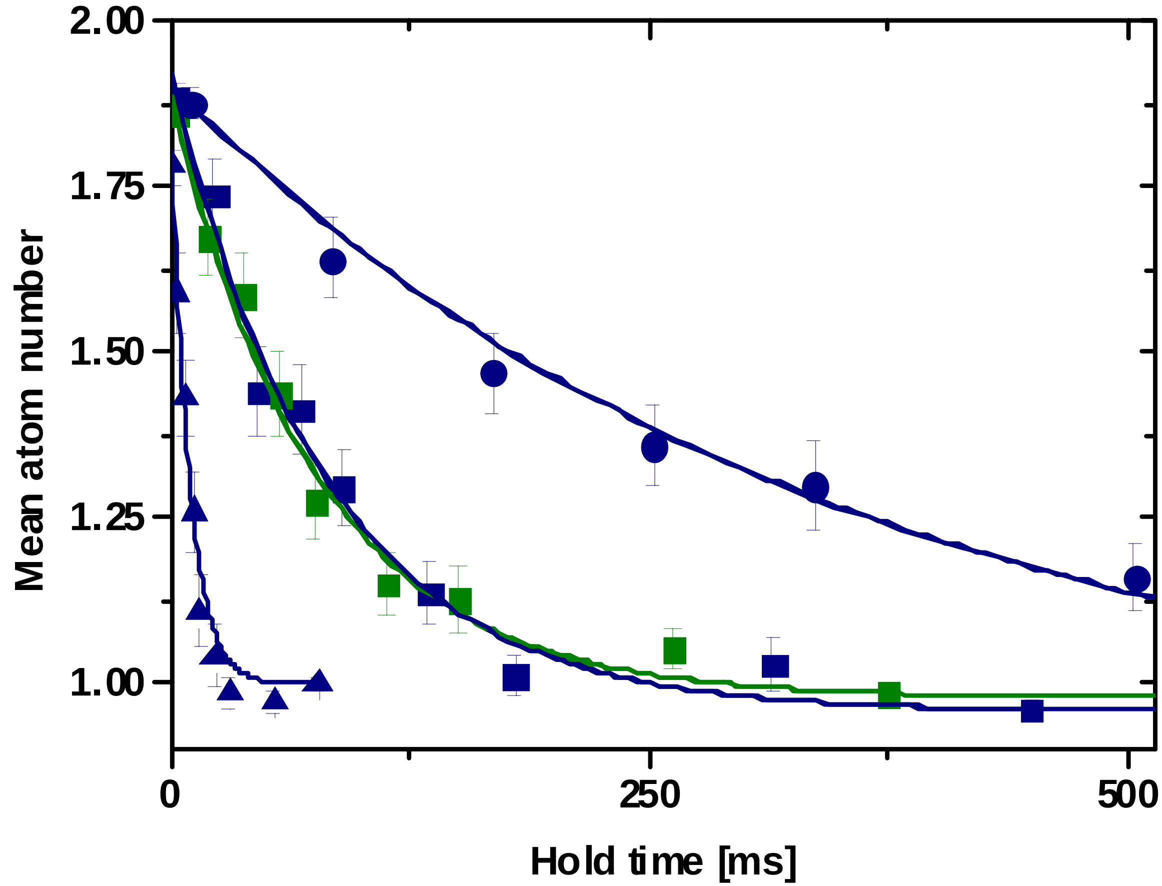




G. Zürn et al., PRL **108**, 075303 (2012)

Two atoms …

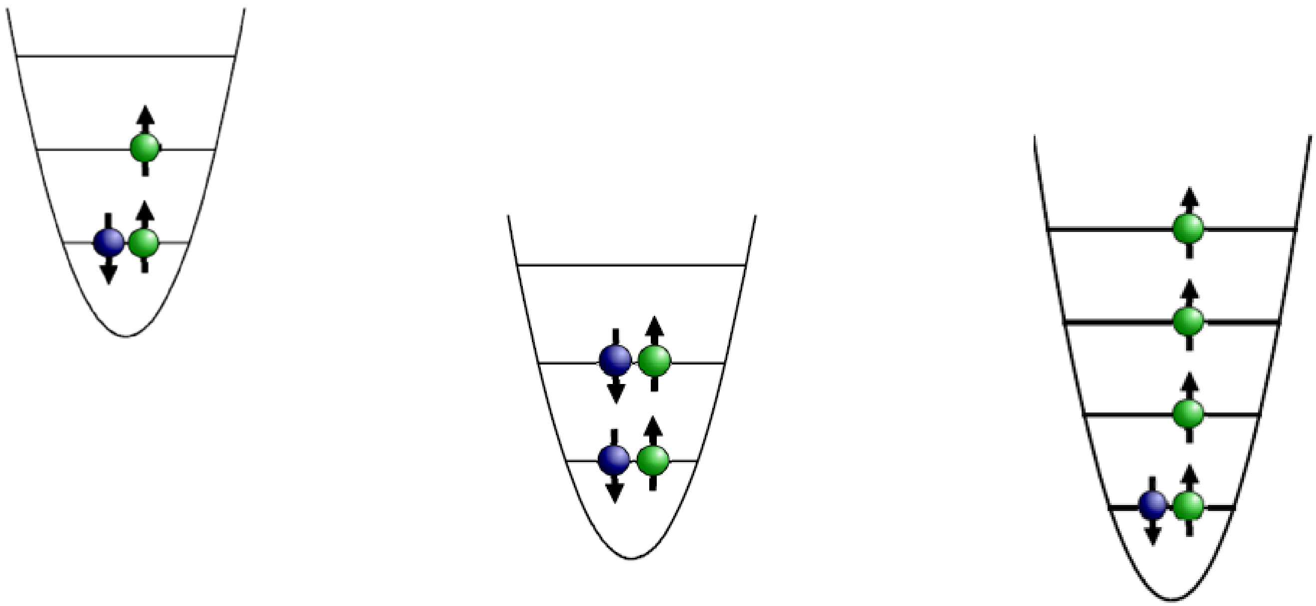




G. Zürn et al., PRL **108**, 075303 (2012)

More particles

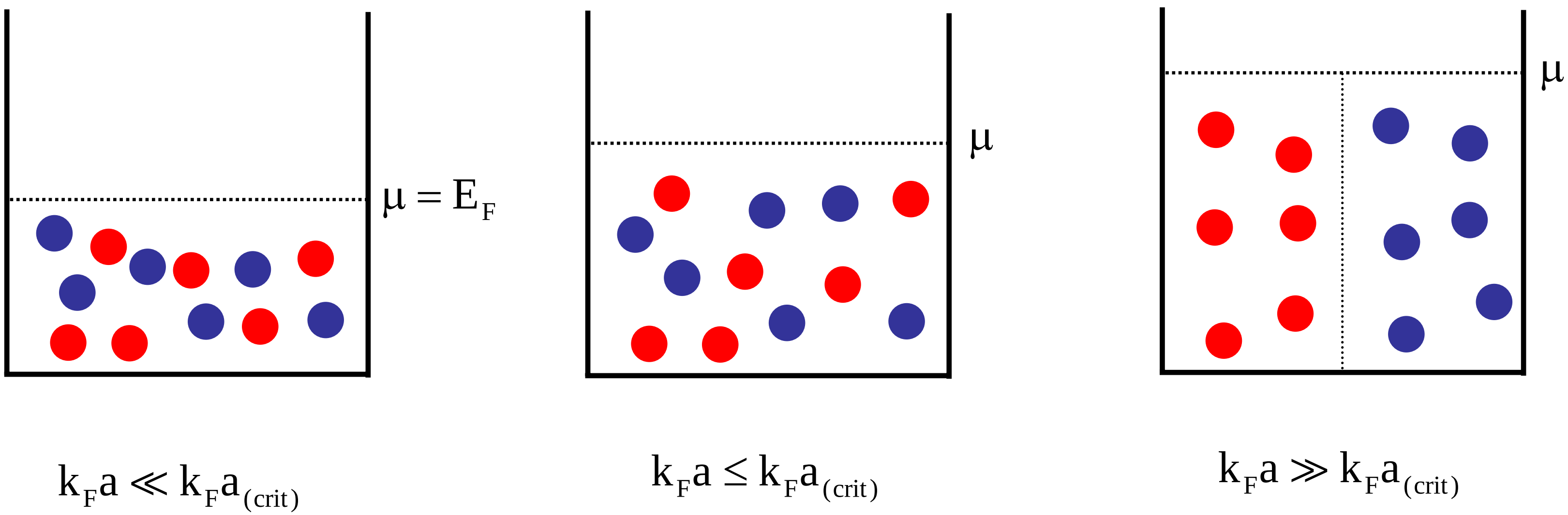
Now we are ready to study many-particle systems!



Study Spin correlations as a function of interaction strength

Stoner model for Ferromagnetism:

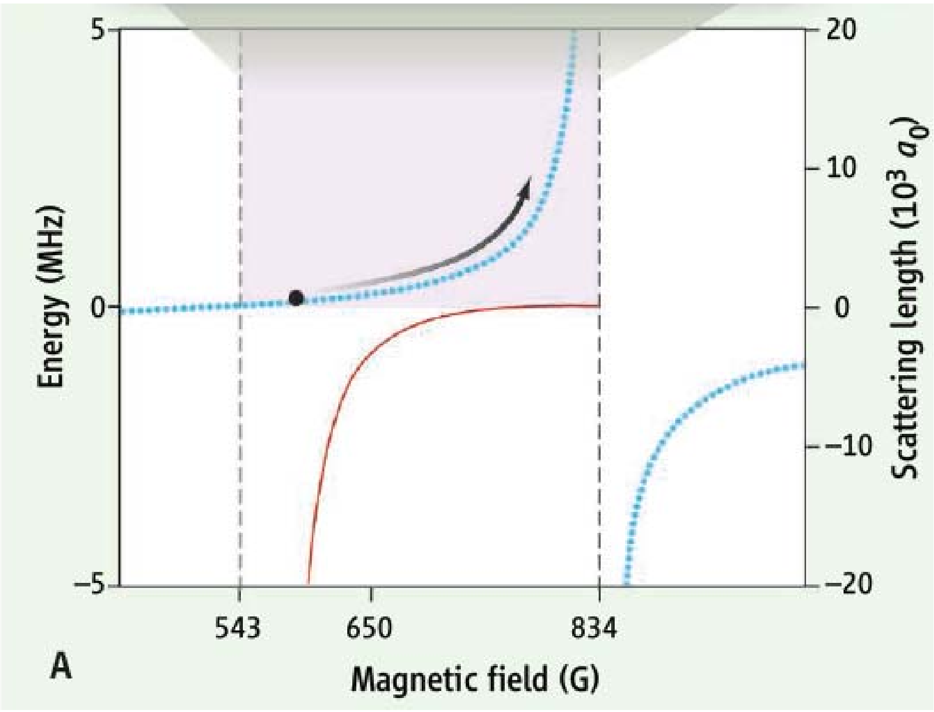
- Basic idea: compare Fermi pressure with interactions:

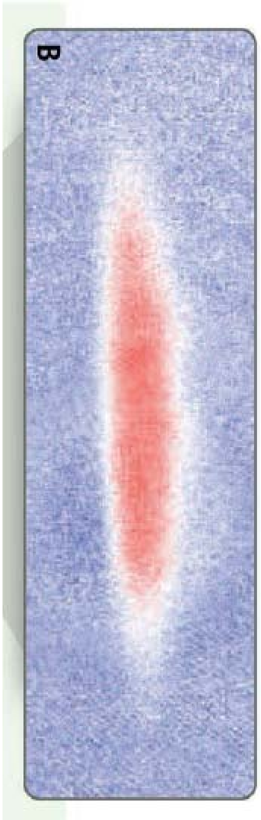


Prediction: Ferromagnetic phase for $k_F a > k_F a_{(crit)}$

Itinerant Ferromagnetism in a Fermi Gas of Ultracold Atoms

Gyu-Boong Jo,[1*] Ye-Ryoung Lee,[1] Jae-Hoon Choi,[1] Caleb A. Christensen,[1] Tony H. Kim,[1] Joseph H. Thywissen,[2] David E. Pritchard,[1] Wolfgang Ketterle[1]

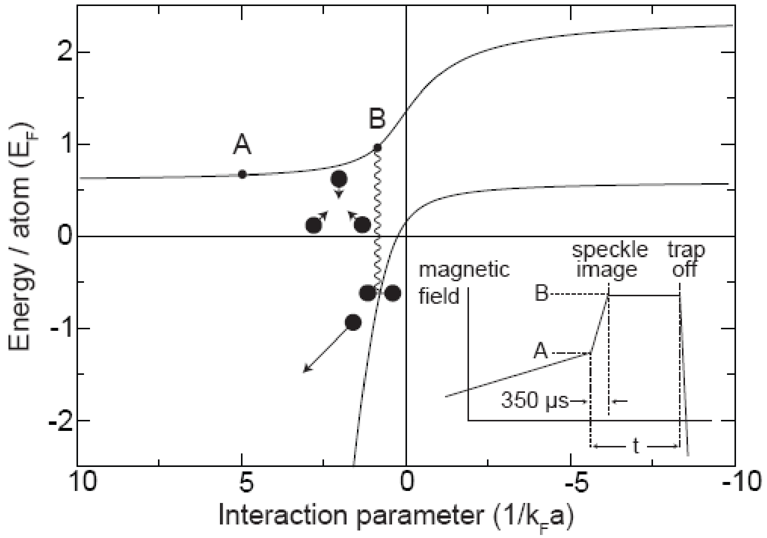


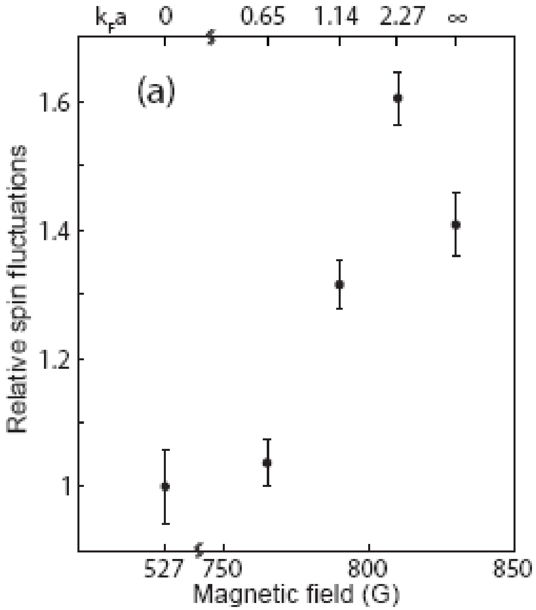


The Ketterle Experiment

Correlations and Pair Formation in a Repulsively Interacting Fermi Gas

Christian Sanner, Edward J. Su, Wujie Huang, Aviv Keshet, Jonathon Gillen, and Wolfgang Ketterle
MIT-Harvard Center for Ultracold Atoms, Research Laboratory of Electronics,
and Department of Physics, Massachusetts Institute of Technology, Cambridge Massachusetts 02139, USA





Can we study this?

In one dimension: Ground state has been proven to be unmagnetized:

PHYSICAL REVIEW VOLUME 125, NUMBER 1 JANUARY 1, 1962

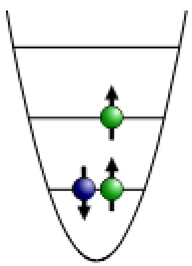
Theory of Ferromagnetism and the Ordering of Electronic Energy Levels

ELLIOTT LIEB AND DANIEL MATTIS
Thomas J. Watson Research Center, International Business Machines Corporation, Yorktown Heights, New York

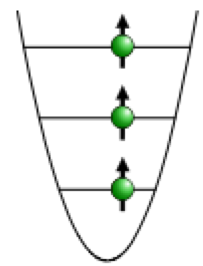
(Received May 25, 1961; revised manuscript received September 11, 1961)

Consider a system of N electrons in one dimension subject to an arbitrary symmetric potential, $V(x_1,\cdots,x_N)$, and let $E(S)$ be the lowest energy belonging to the total spin value S. We have proved the following theorem: $E(S)<E(S')$ if $S<S'$. Hence, the ground state is unmagnetized. The theorem also holds

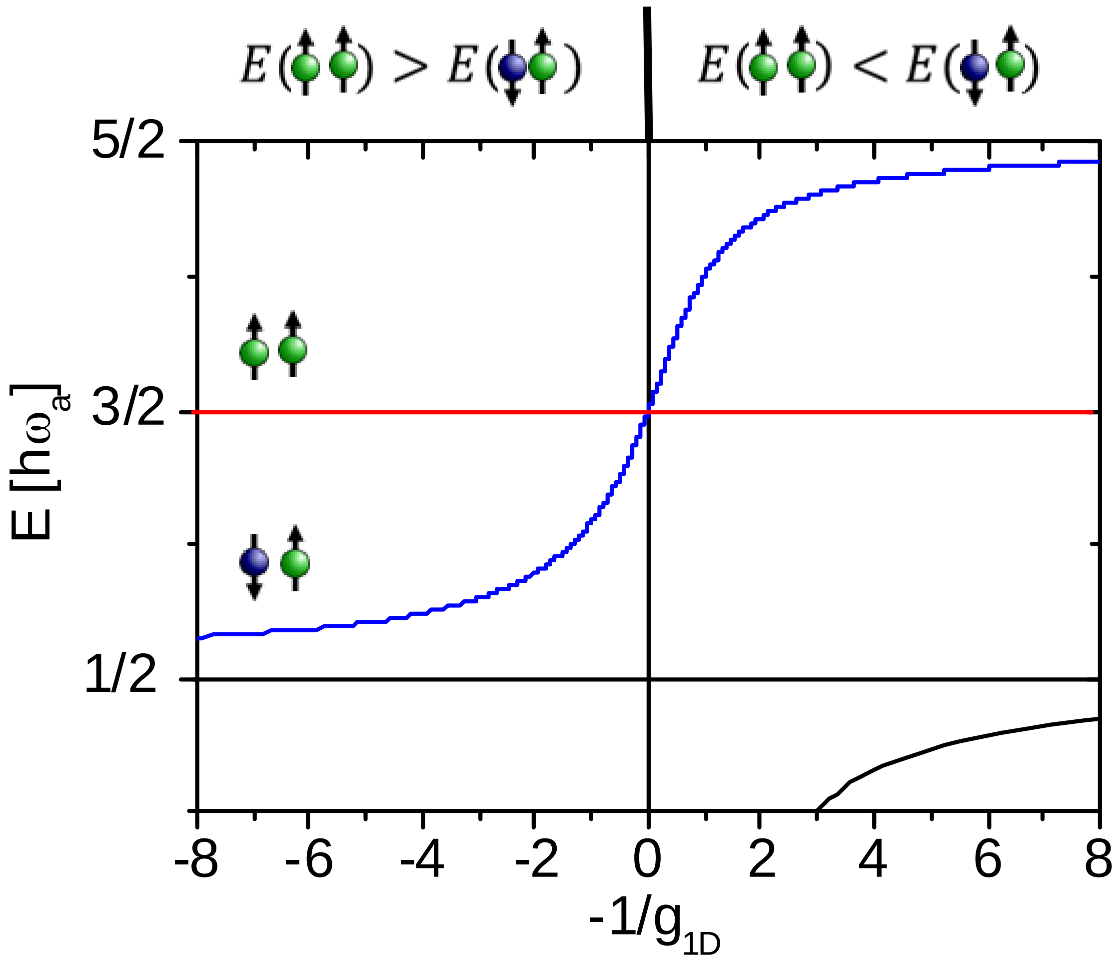
This system



has lower energy than this one



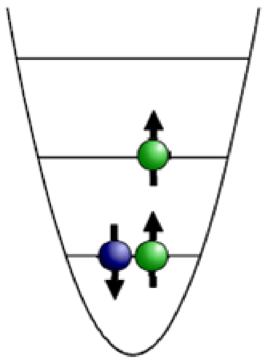
Can we study this?

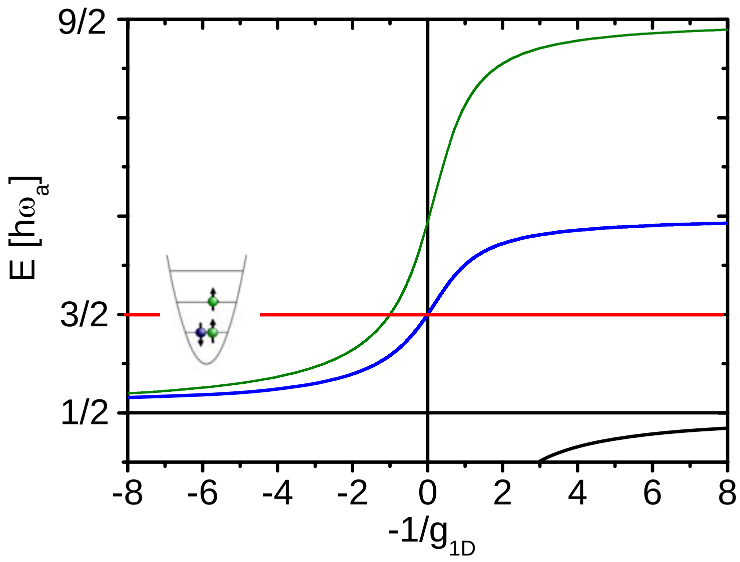


Can we see magnetism in the metastable state?

Can we study this?

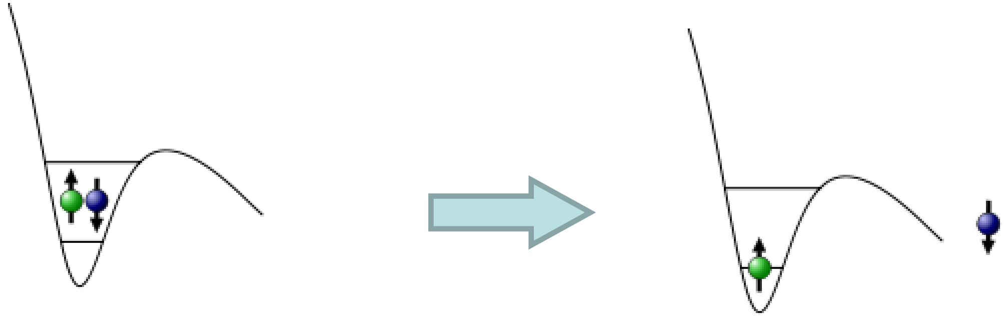
- Start with a many-particle system
- Ramp across the resonance



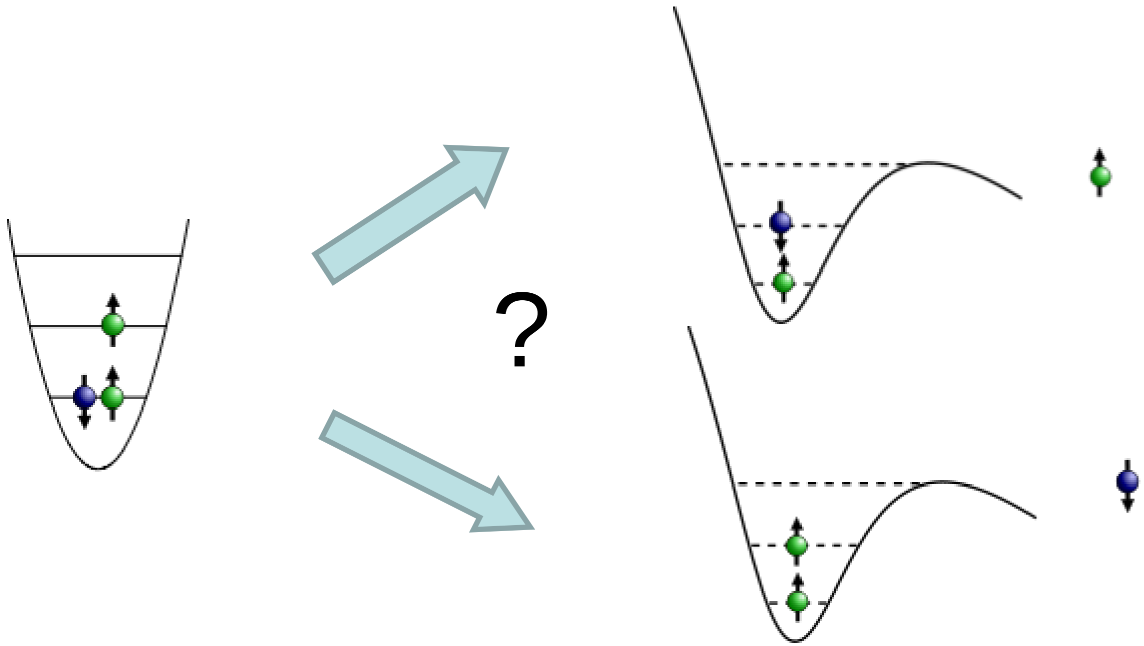


Lifetime of the metastable state > 5s!

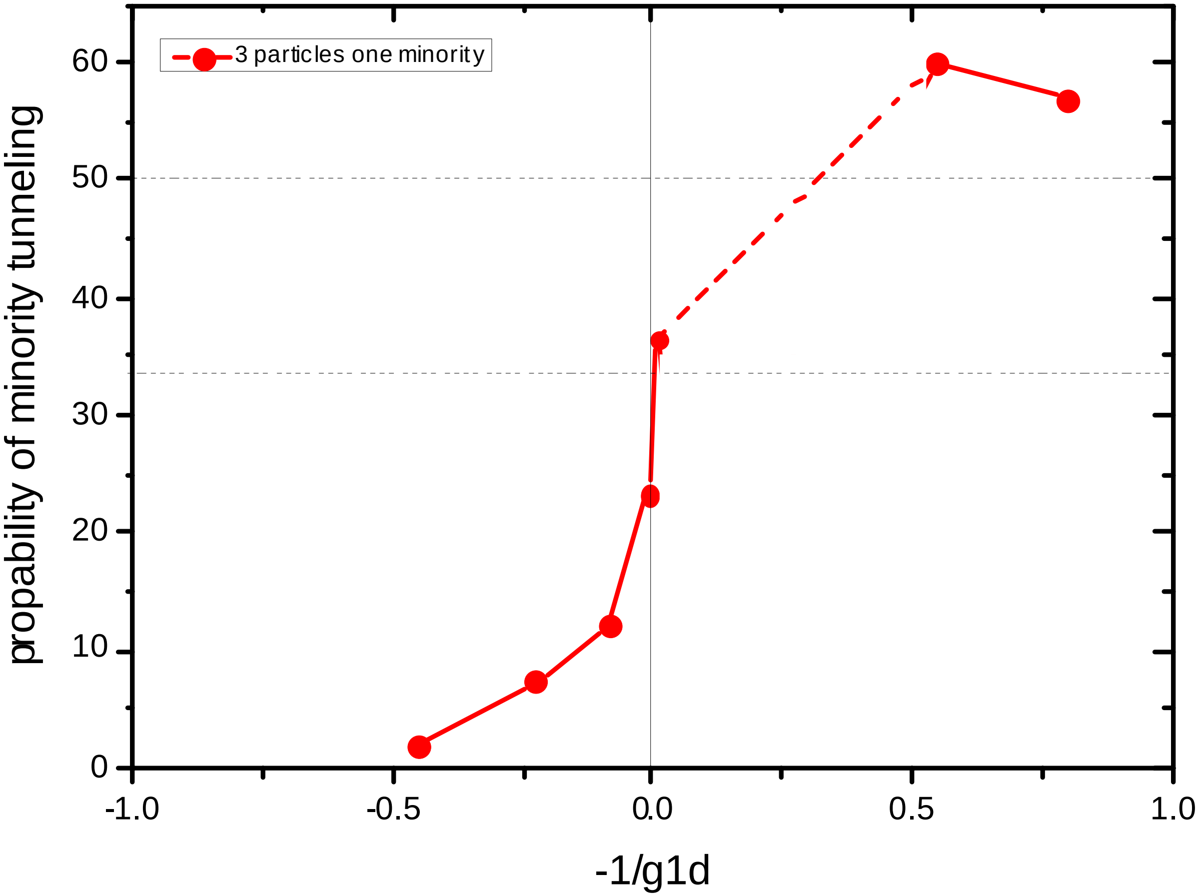
Remove one particle

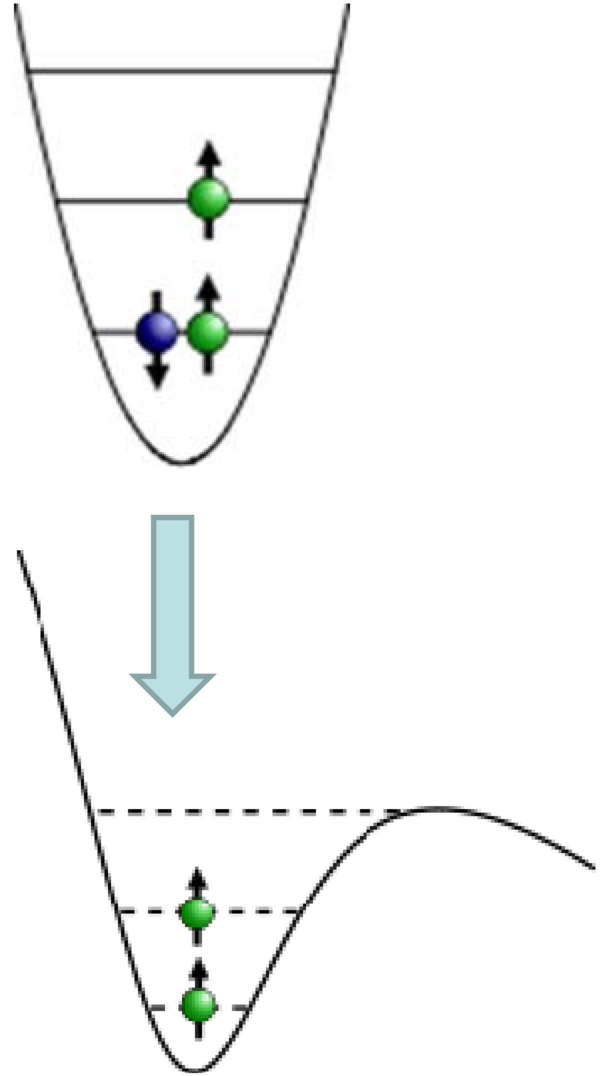


ratio of up/down independent of interaction strength



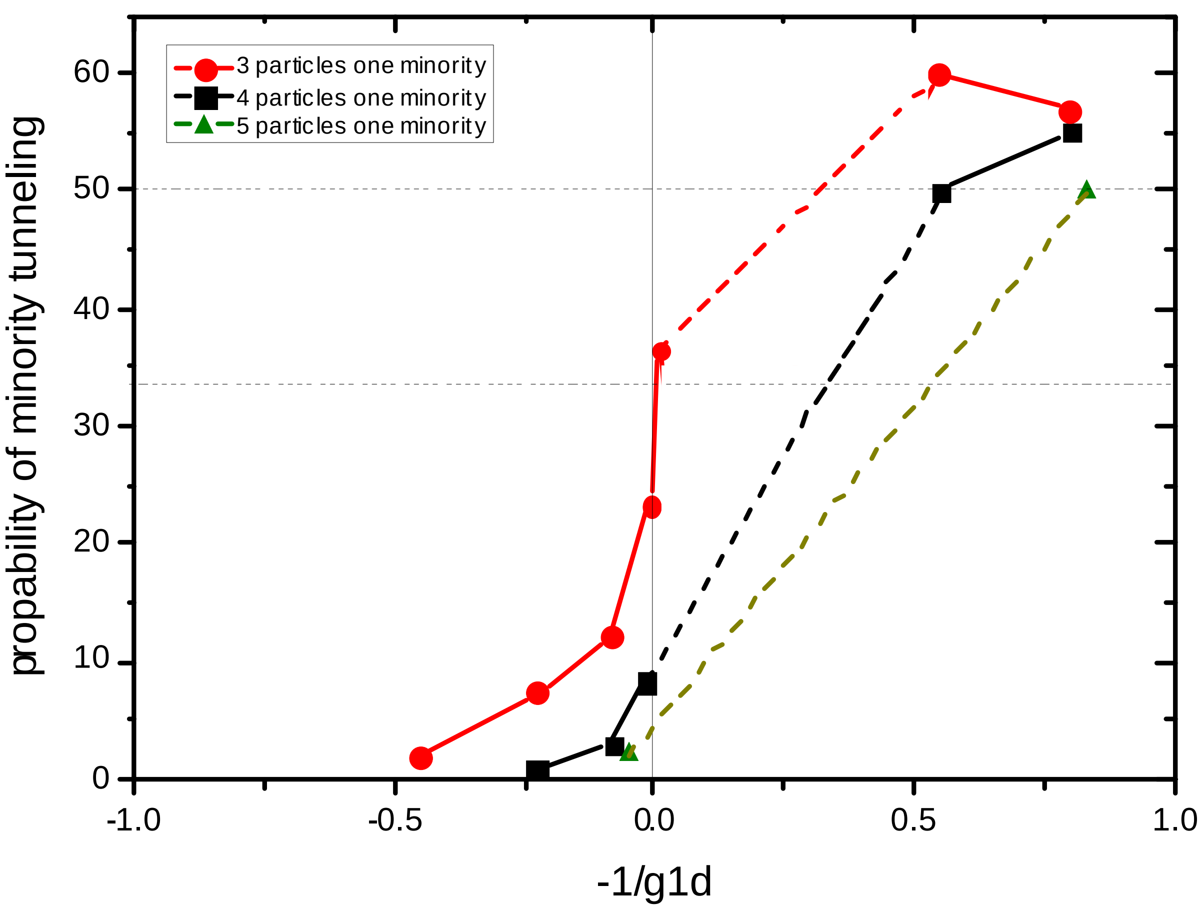
Probability of minority tunnelling

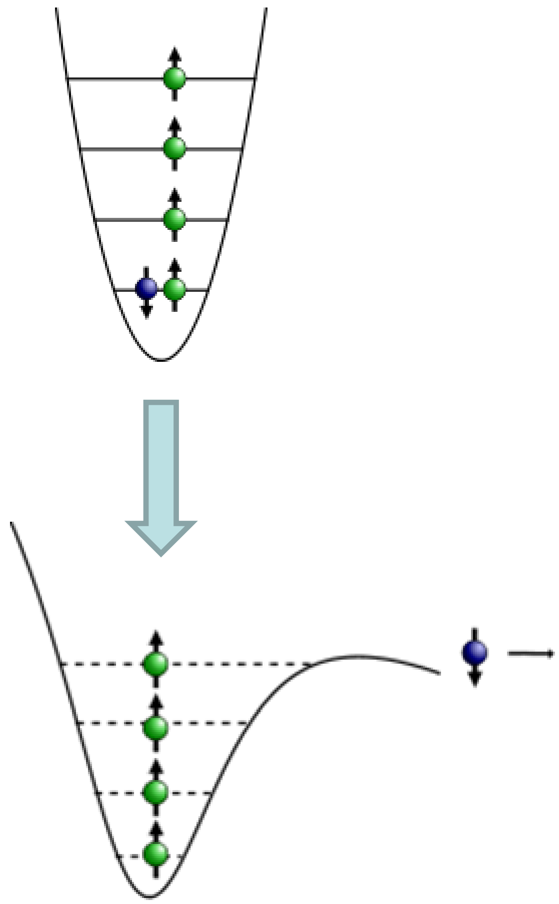




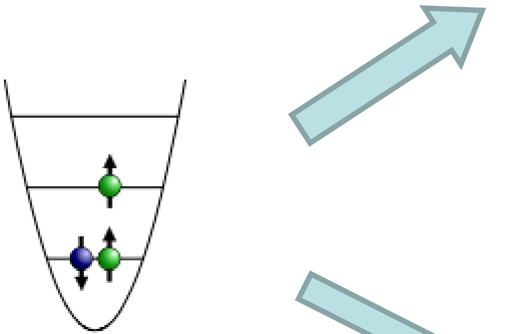
- On resonance, expect 1/3 …

Probability of minority tunnelling

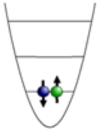




The final state

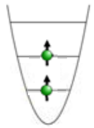


S=0:

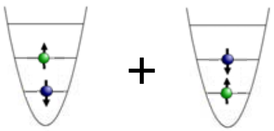


~~$|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$~~ ~0%

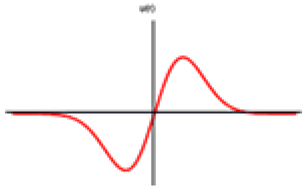
S=1:

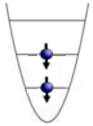


$|\uparrow\uparrow\rangle$ ~50%



$|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$ ~50%



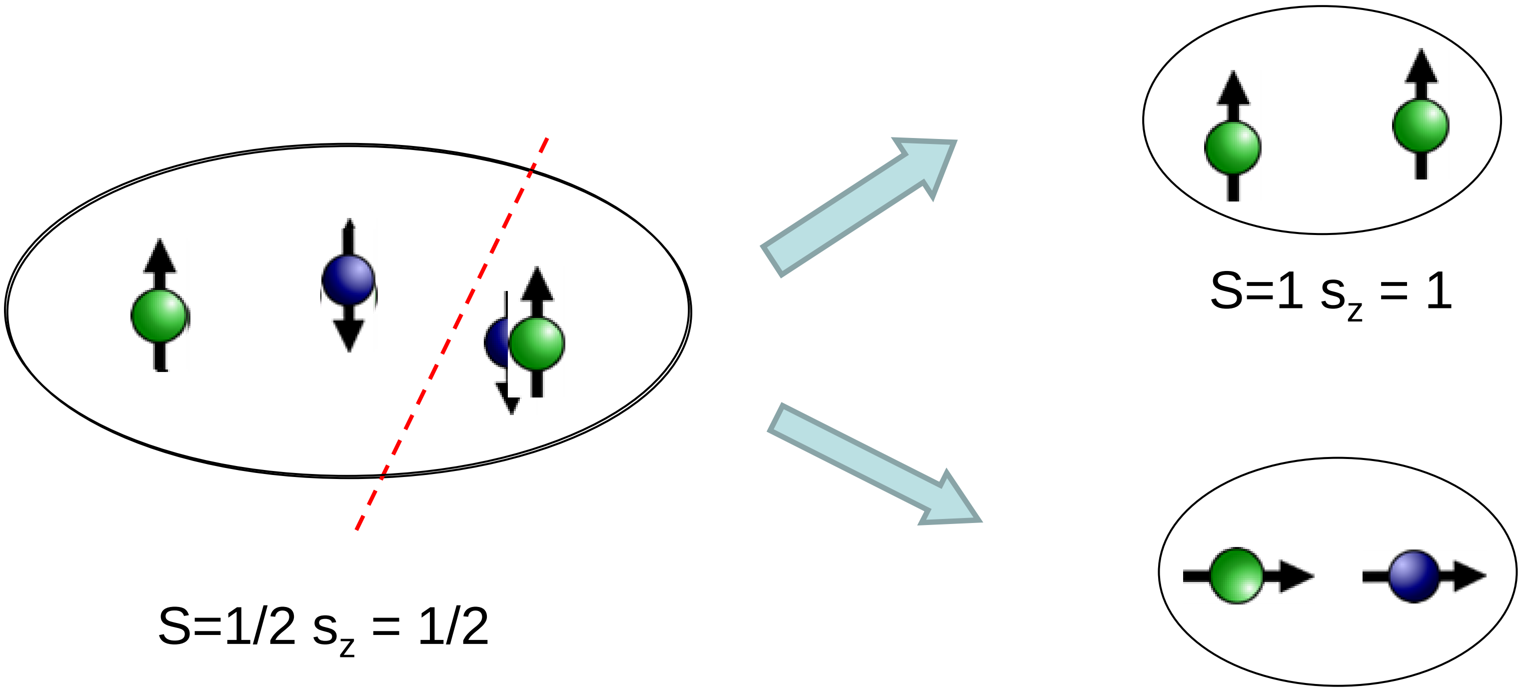


~~$|\downarrow\downarrow\rangle$~~ 0%

$\Rightarrow$ We always get a spin-polarized system

Conclusion

The spilling is spin-independent



S=1 s_z = 1

S=1/2 s_z = 1/2

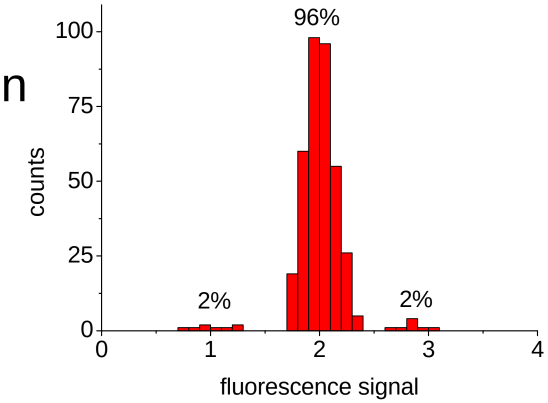
We always get a spin-polarized final state

S=1 s_z = 0

$\Rightarrow$ The initial state must have a finite magnetization?

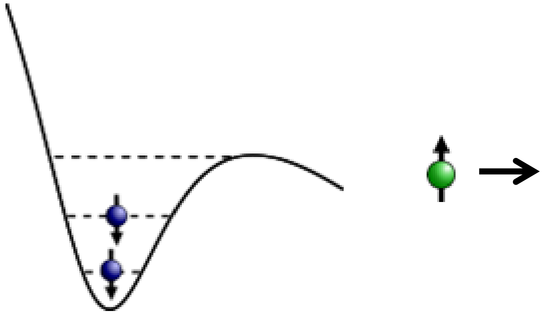
Summary

- We can deterministically prepare few-fermion systems in well-defined quantum states



- We can control the interacterparticle interactions

- We can use this system to study interesting physics



Thank you very much for your attention!