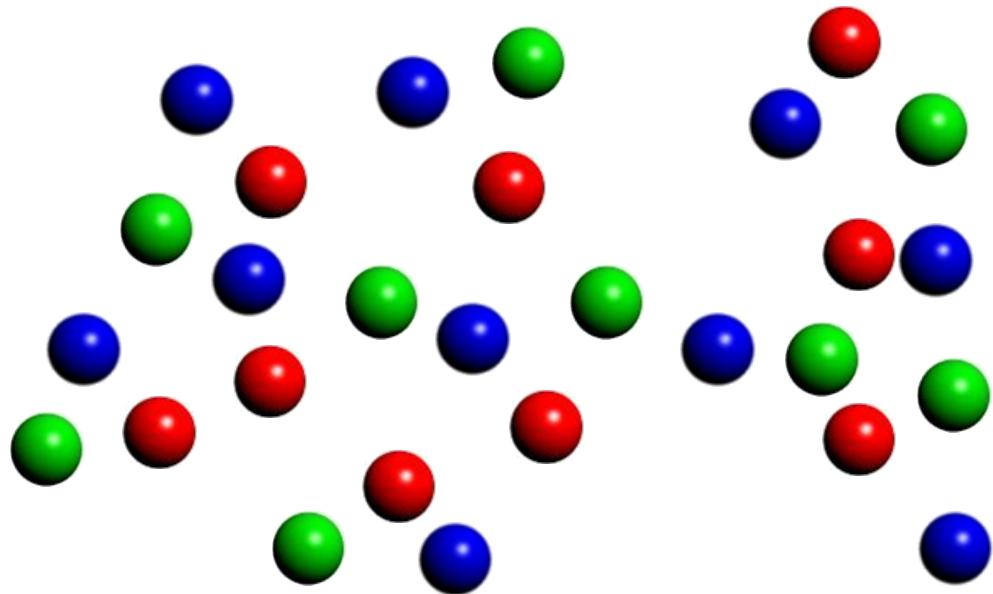




# Ultracold few-fermion systems with tunable interactions

Selim Jochim  
Physikalisches Institut  
Universität Heidelberg



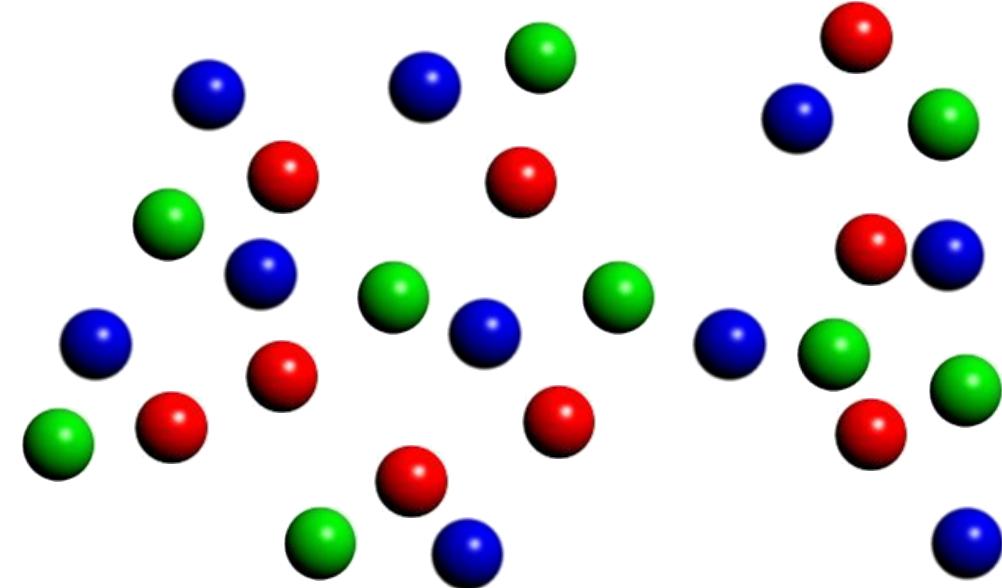


- $T=40\text{nK} \dots 1\mu\text{K}$
- Density  $n=10^9 \dots 10^{14}\text{cm}^{-3}$
- Pressures as low as  $10^{-17}\text{mbar}$
- $k_{\text{B}} T \sim 5\text{peV}$
- Extremely dilute gases,  
which can be strongly interacting!

## Extreme matter!



# Important length scales



- interparticle separation  
 $\sqrt[3]{1/n} \gg$  size of the atoms
- de Broglie wavelength  
$$\sqrt{\frac{h^2}{2\pi mkT}} \gg$$
 size of the atoms
- scattering length  $a$ , only one length determines interaction strength

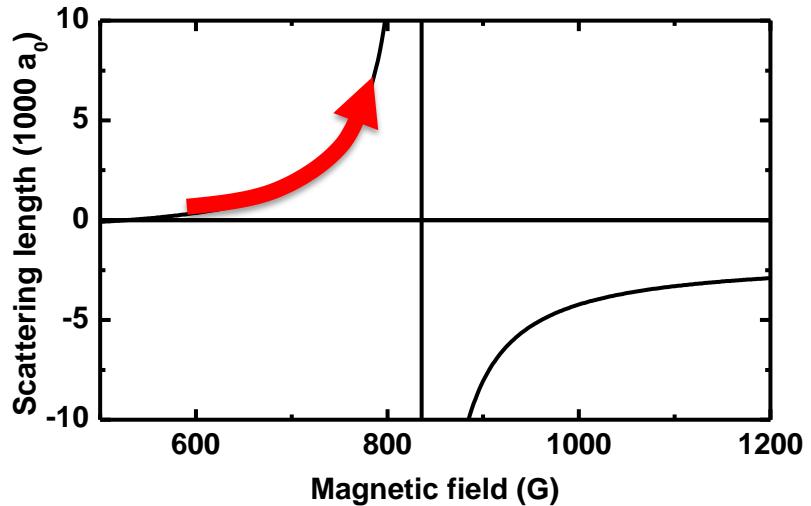
→ Universal properties, independent of a particular system!  
→ We can tune all the above parameters in our experiments!



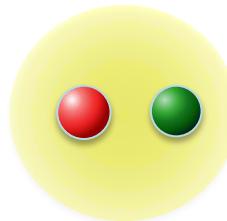
# Tunability of ultracold systems



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



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



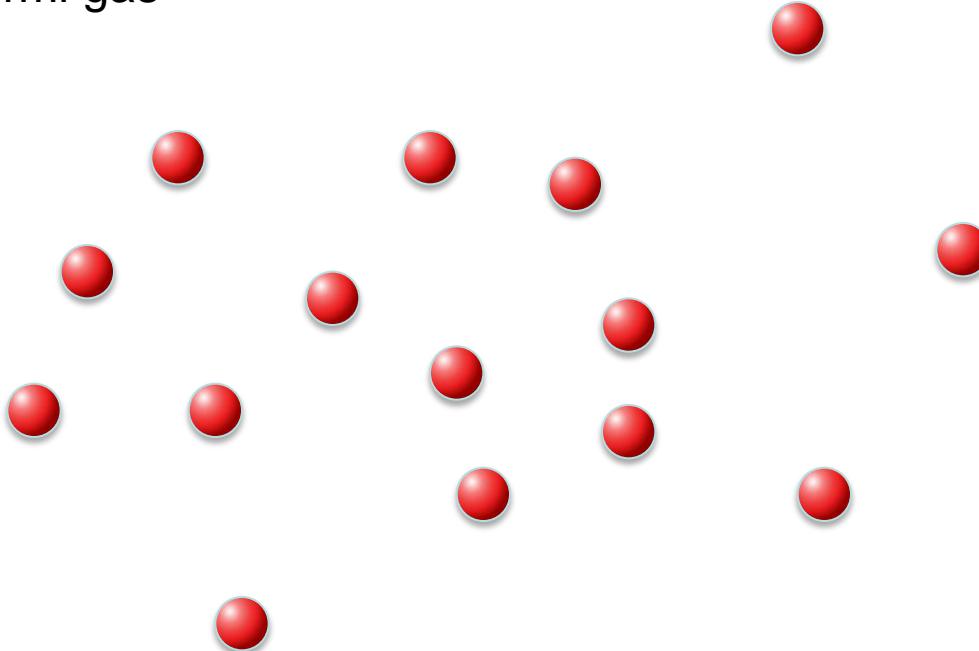
Size (>> range of interaction):  $\Psi(r) \propto e^{-r/a}$

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



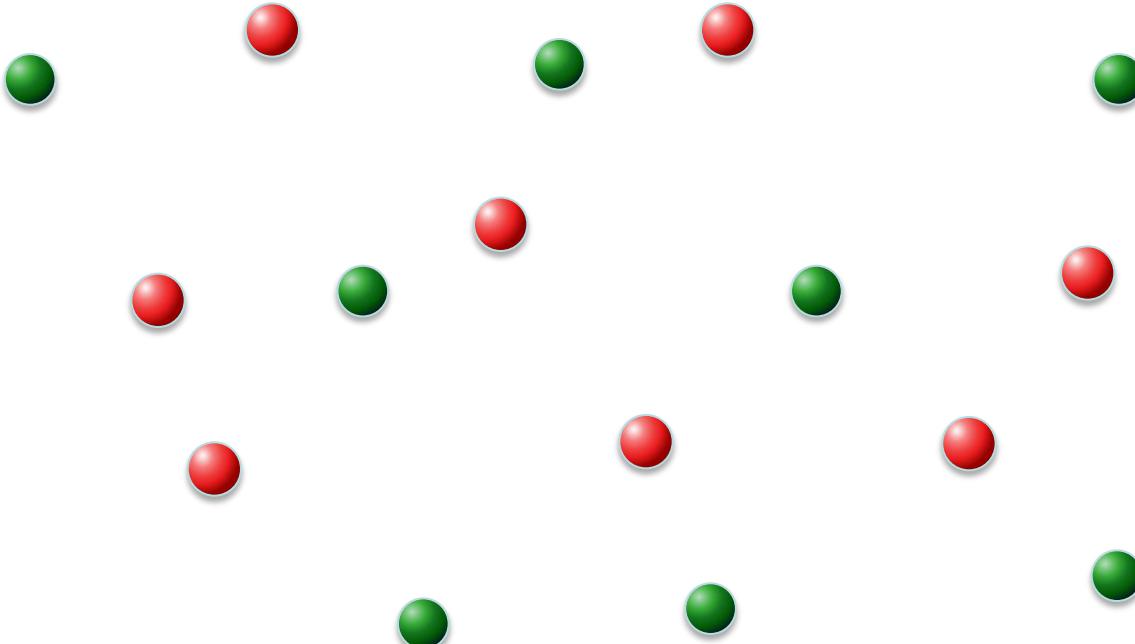


- At ultracold temperatures, a gas of identical fermions is noninteracting
- Ideal Fermi gas





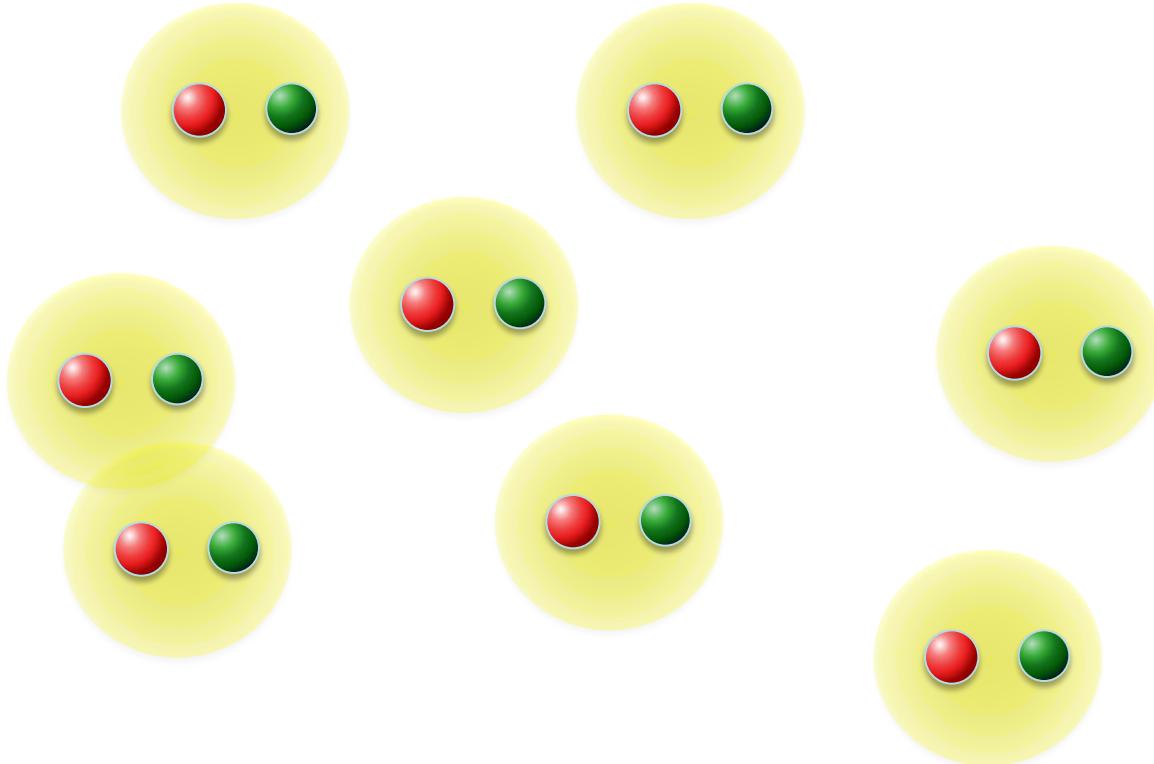
- Need mixtures to study interesting physics!
- Simplest implementation: spin mixtures ( $\uparrow, \downarrow$ )



# Ultracold Fermi gases



- Two (distinguishable) fermions form a boson .....
- ... molecules can form a Bose condensate ...



→ realize the BEC-BCS crossover!

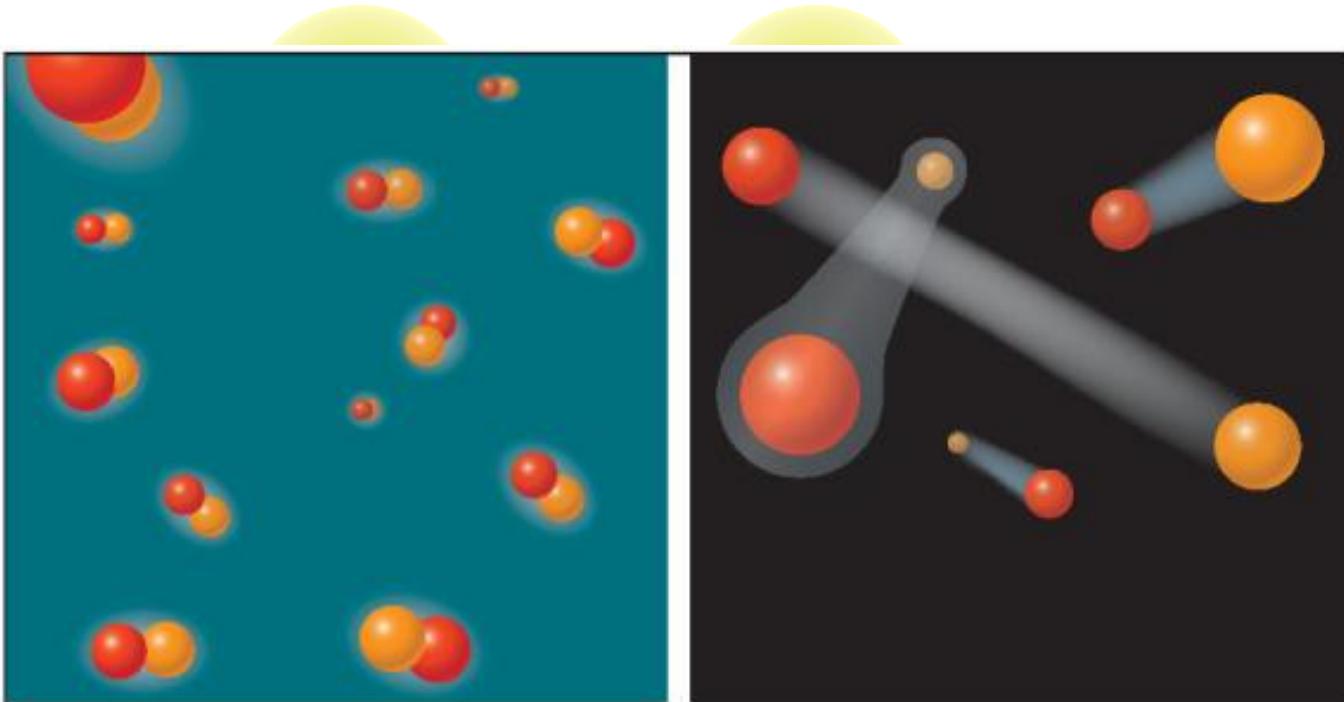


# Ultracold Fermi gases

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- Two (distinguishable) fermions form a boson .....
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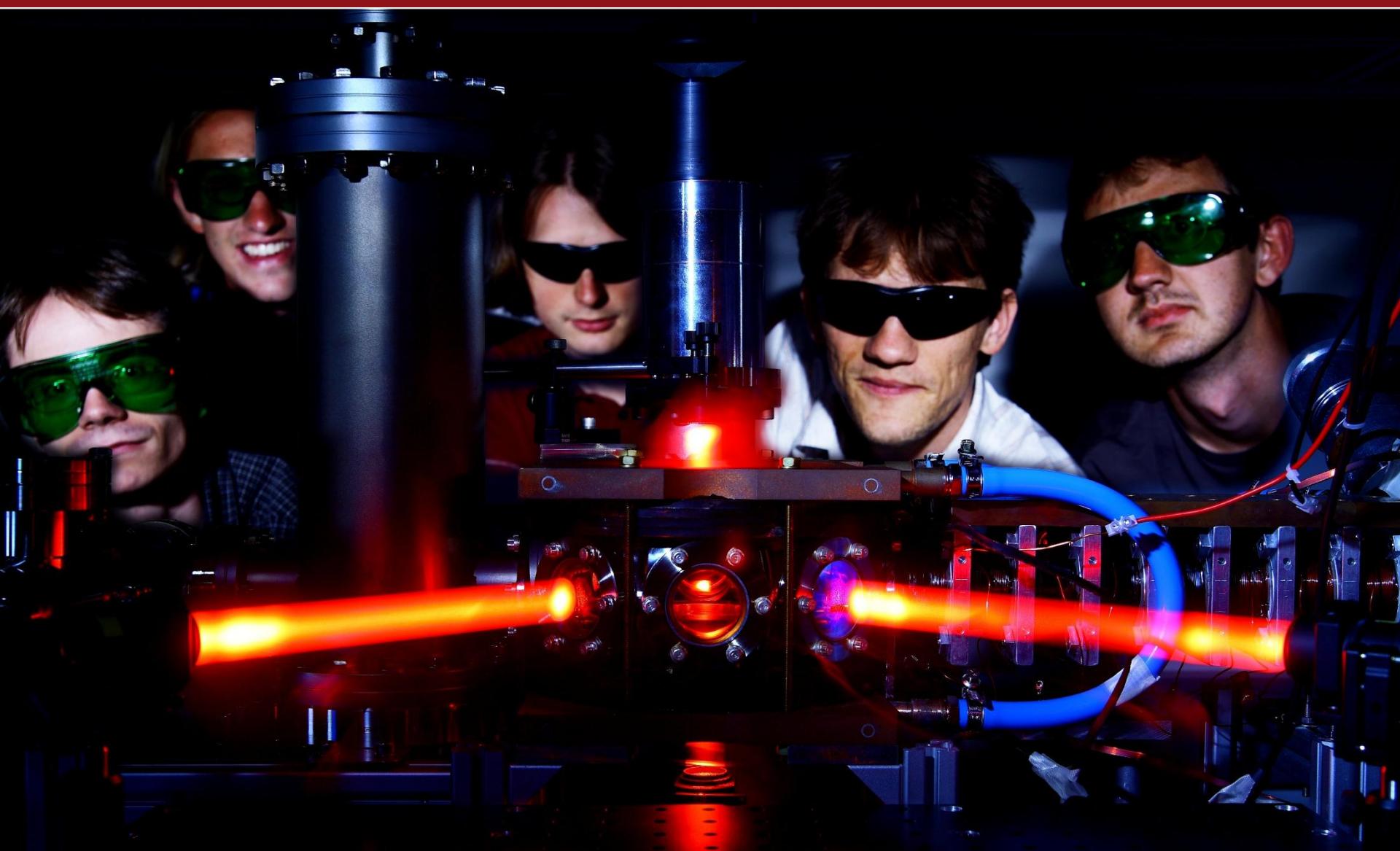
- ... tun

From A. Cho, Science 301, 751 (2003)

→ realize the BEC-BCS crossover!

# A picture from the lab ...

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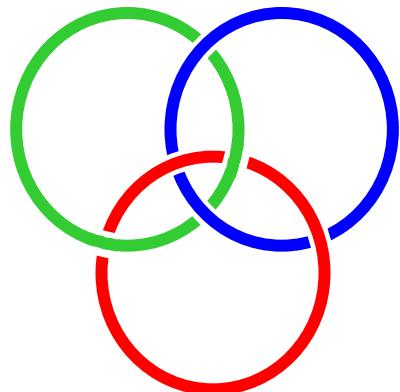




## 1. Universal three-body bound states

„Efimov“ trimers

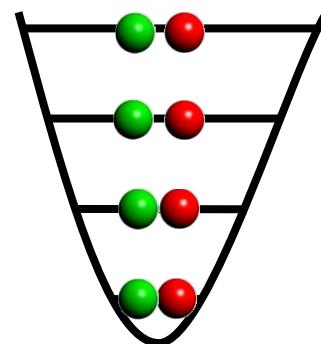
T. Lompe et al., Science **330**, 940 (2010)



## 2. Finite Fermi systems with controlled interactions

A new playground with control at the single atom level!

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

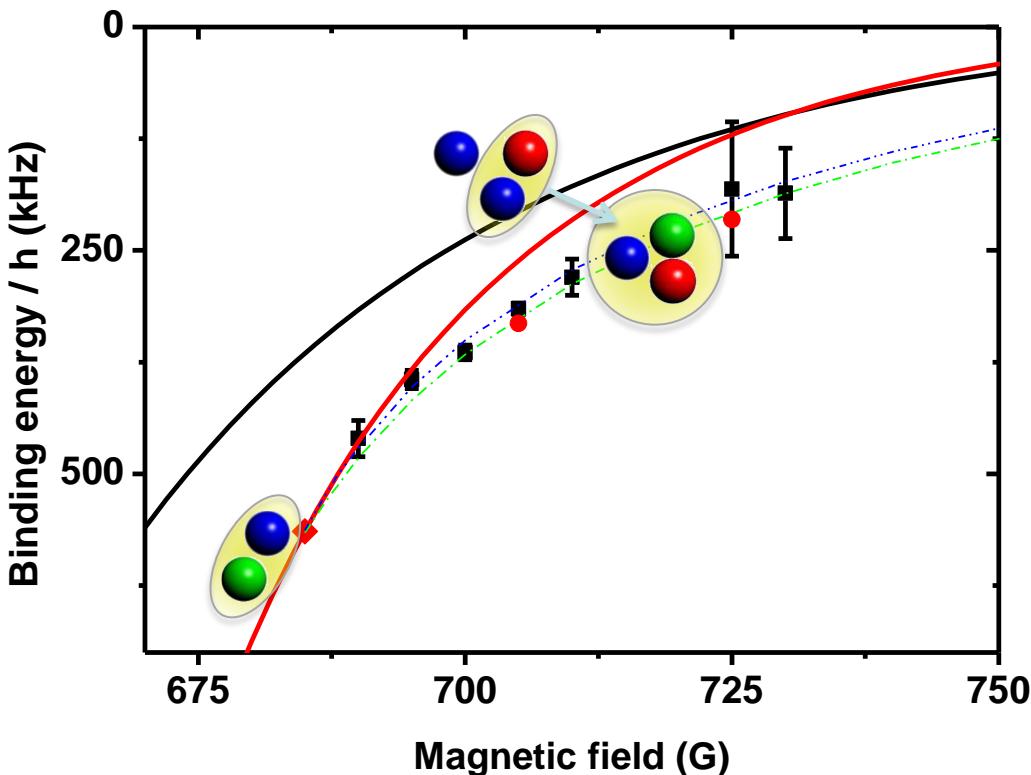


# Three-component Fermi gas: Experiments

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- Study of universal three-body bound states: **Efimov trimers**
- **First direct observation by measurement of the binding energy**
- Three-body loss prohibits study of many-body physics in free space



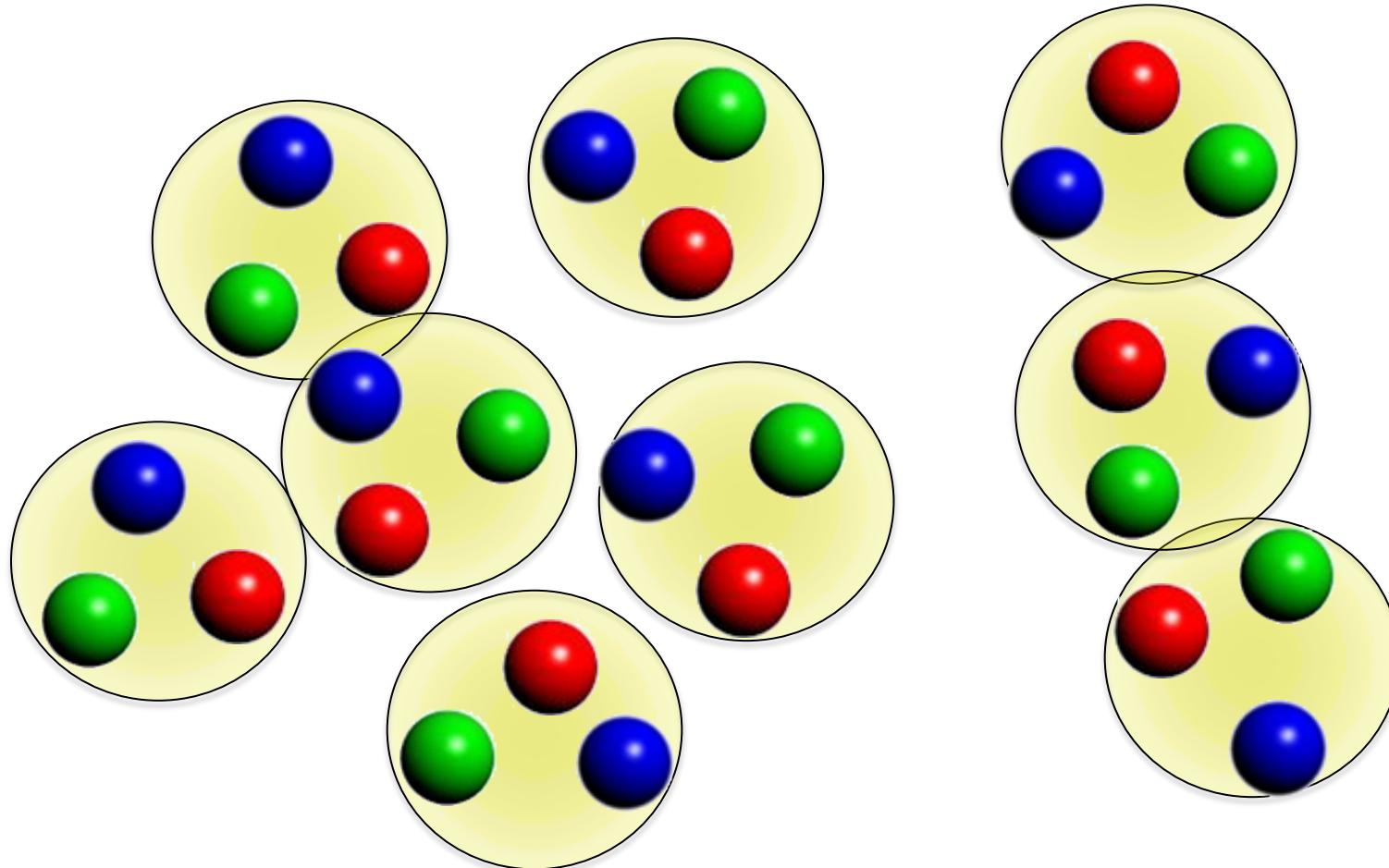
- T. Lompe *et al.*, Science **330**, 940 (2010)  
T. Lompe *et al.*, PRL **105**, 103201 (2010)  
A. Wenz *et al.*, PRA **80**, 040702(R) (2009)  
T. Ottenstein *et al.*, PRL **101**, 203202 (2008)

# An ultracold three-component Fermi gas

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Fermionic trions, „Baryons“



Color Superfluidity and „Baryon“ Formation in Ultracold Fermions:  
A. Rapp *et al.*, PRL 98, 160405 (2007)

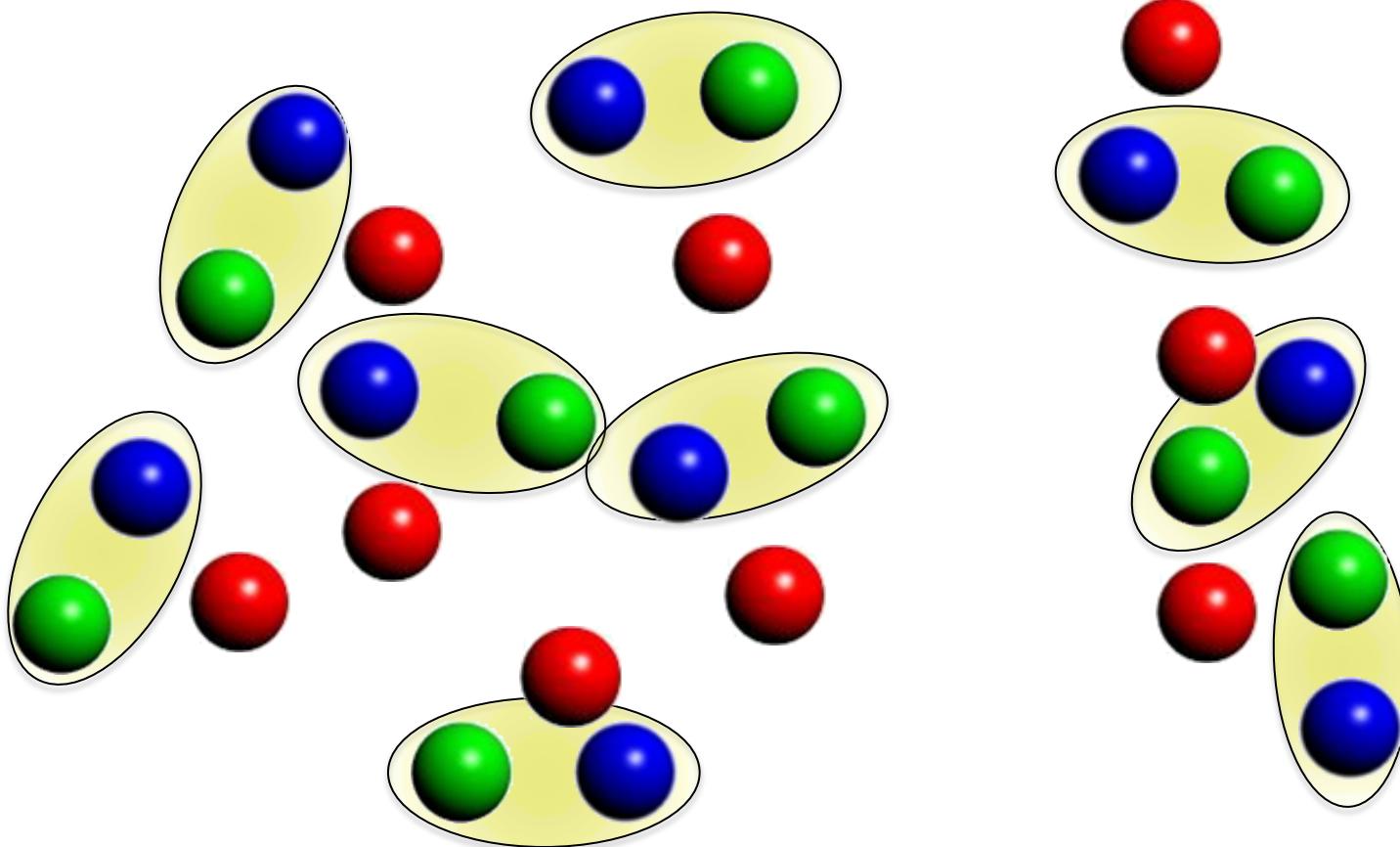


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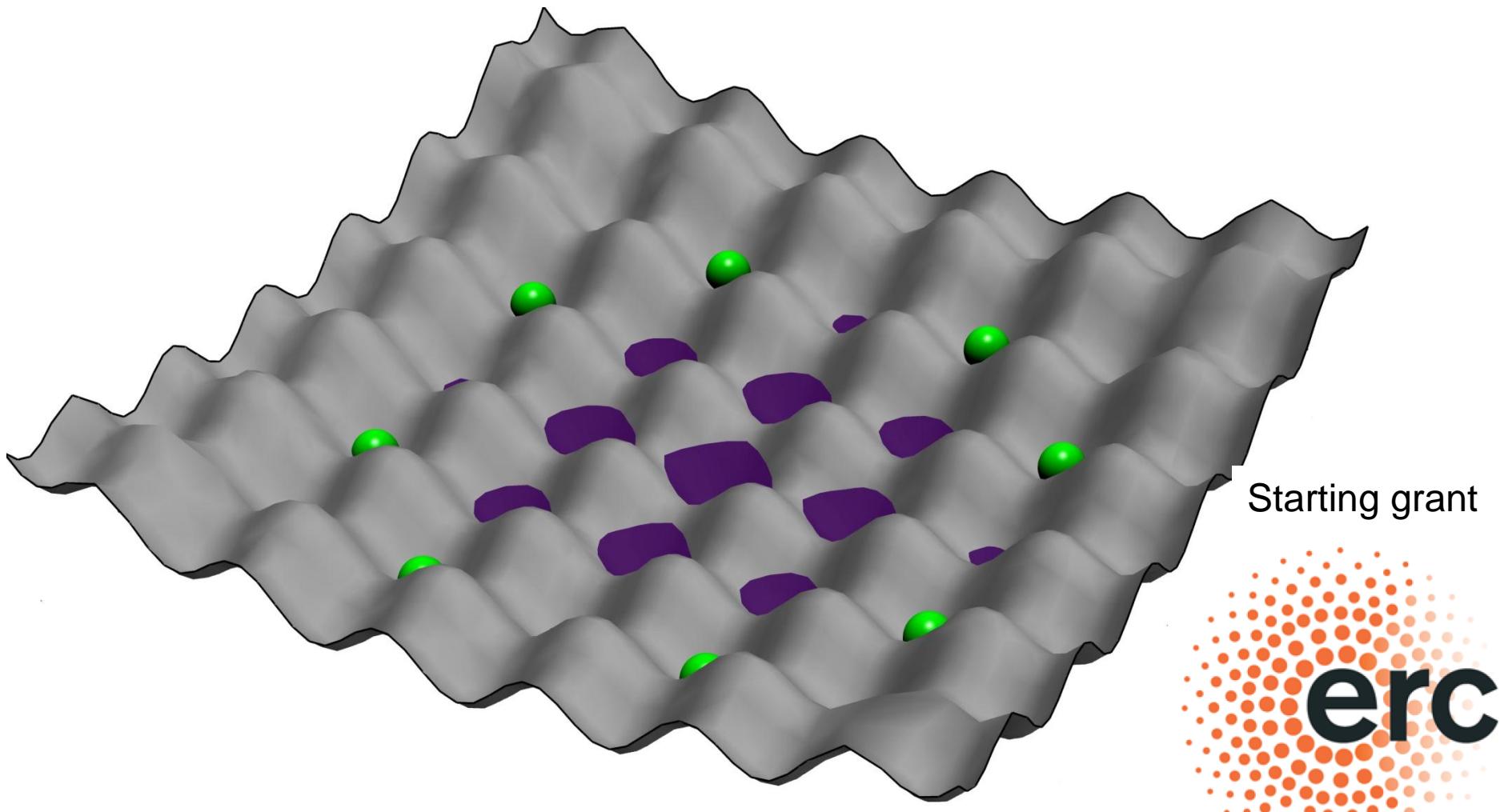
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A color superfluid



Color Superfluidity and „Baryon“ Formation in Ultracold Fermions:  
A. Rapp *et al.*, PRL 98, 160405 (2007)



- realize this in a 2 - dimensional lattice for optimal in-situ diagnostics

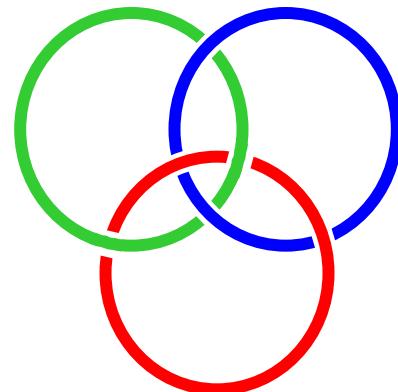




## 1. Universal three-body bound states

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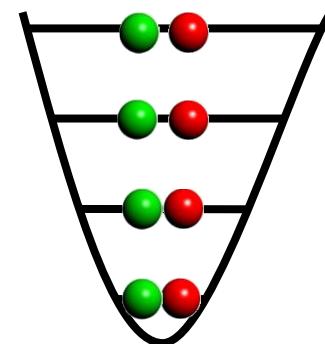
T. Lompe et al., Science **330**, 940 (2010)

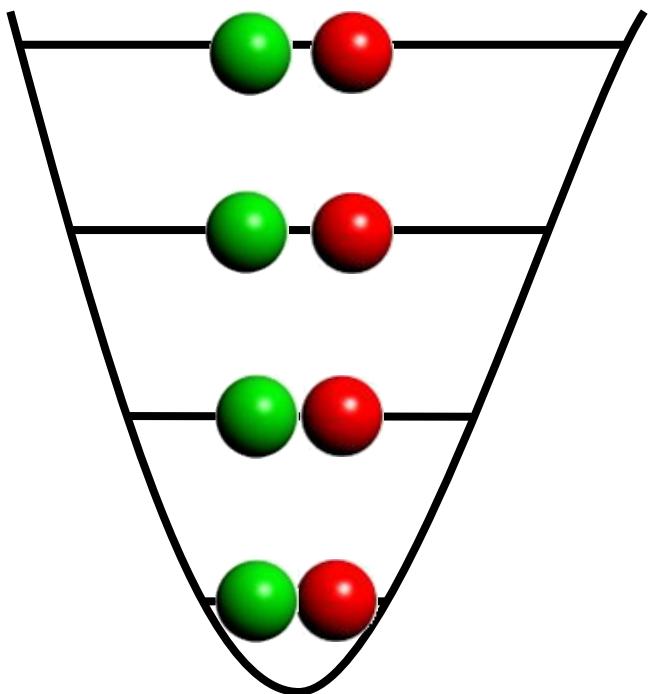


## 2. Finite Fermi systems with controlled interactions

A new playground with control at the single atom level!

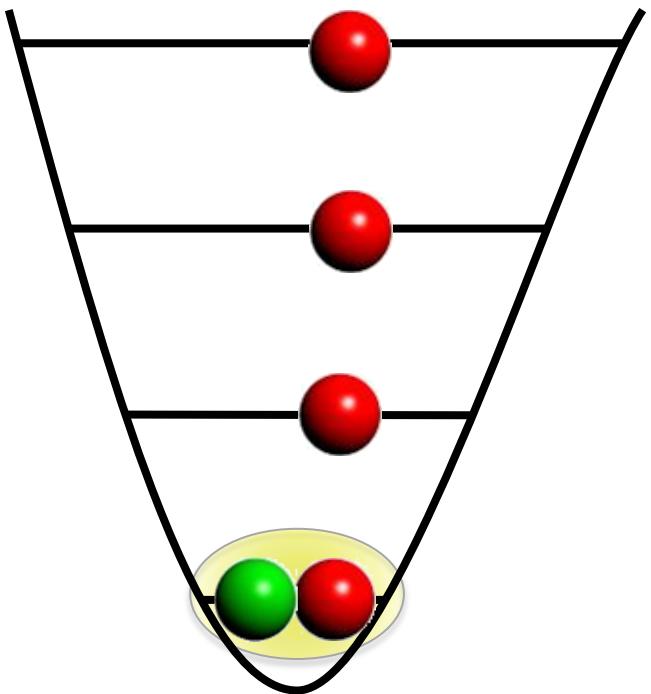
F. Serwane et al., Science **332**, 336 (2011)





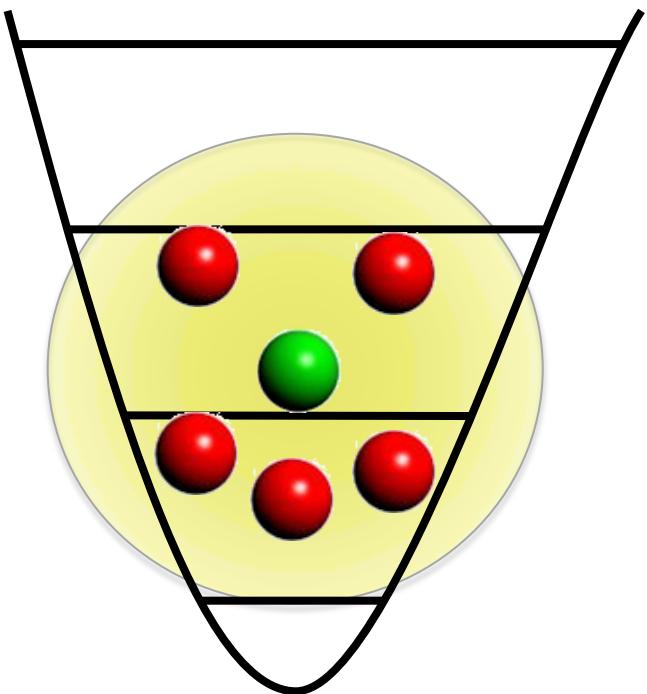
- An isolated quantum system in which all degrees of freedom can be controlled
- Study pairing in different interaction regimes, weak or strong
- Study the time evolution of an isolated system (transition from a deterministic to thermal system)





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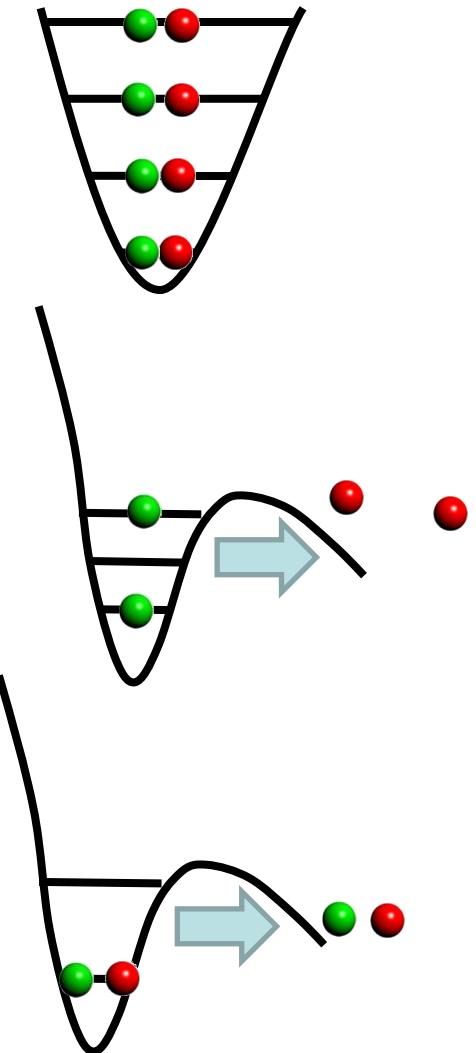


- An isolated quantum system in which all degrees of freedom can be controlled
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# Outline

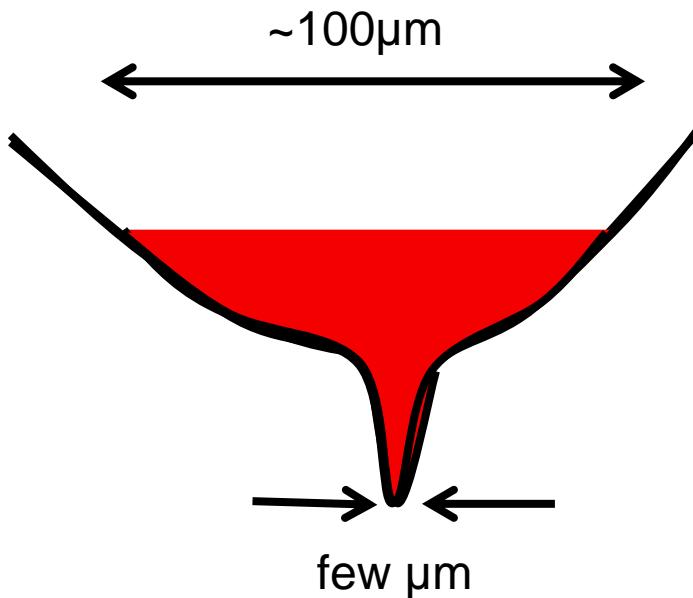
1. Preparation and manipulation of deterministic microscopic ensembles
2. Study of the repulsive few-particle system:  
Fermionization and magnetism
3. Study of the attractive system: correlated tunnelling, and odd-even effect



# Creating a finite gas of fermions



1. A conventional ultracold Fermi gas  
 $T \sim 250\text{nK}$ ,  $T_F \sim 0.5\mu\text{K}$
2. Superimpose microtrap, depth  $U \sim 3\mu\text{K}$   
 $\rightarrow T_F \sim U \sim 3\mu\text{K}$ ,  $T/T_F \sim 0.08$
3. Occupation probability of the lowest energy state:  $> 0.9999$   
(assuming thermal equilibrium)

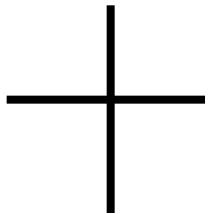
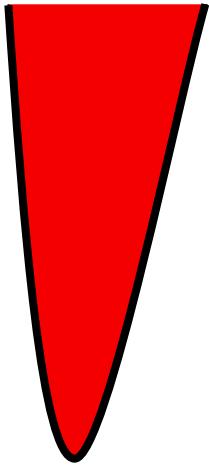


# Creating a finite gas of fermions

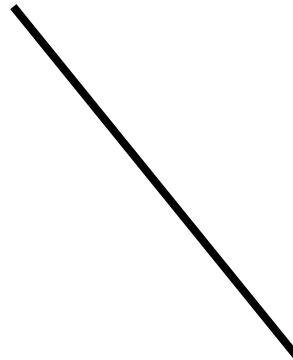


Lower trap depth

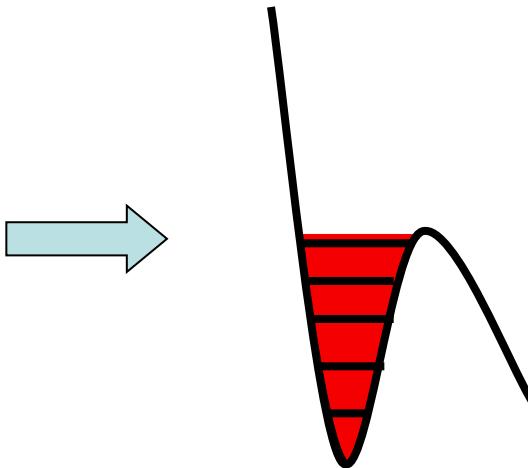
Use a magnetic field gradient to spill:



~600 atoms



$$\mu \times B$$



~2-10 atoms

# Classical atom culling machine

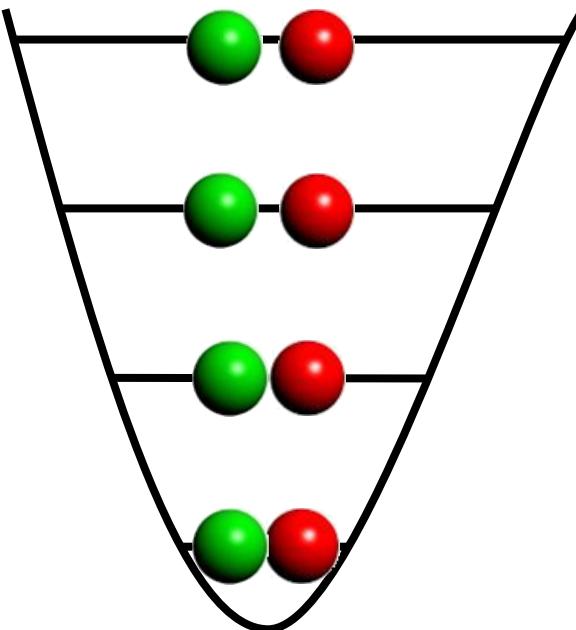
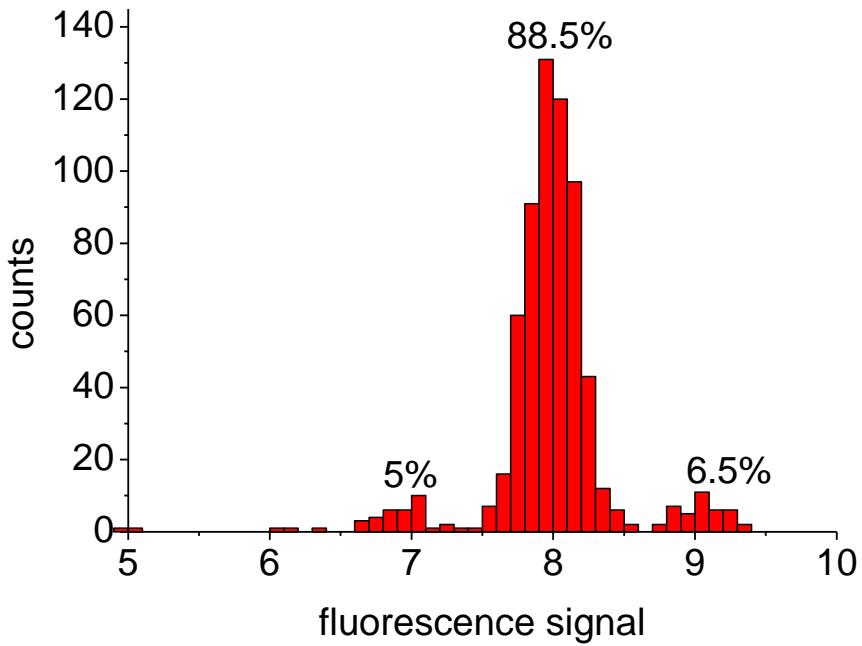
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# Spilling the atoms ....



- We can control the atom number with exceptional precision!
- Note aspect ratio 1:10: 1-D situation

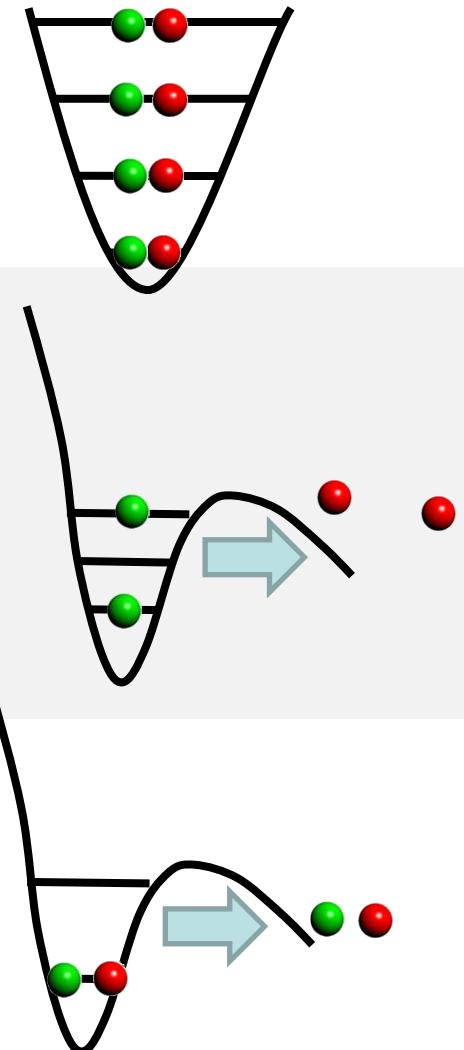


# Outline

1. Preparation and manipulation of deterministic microscopic ensembles

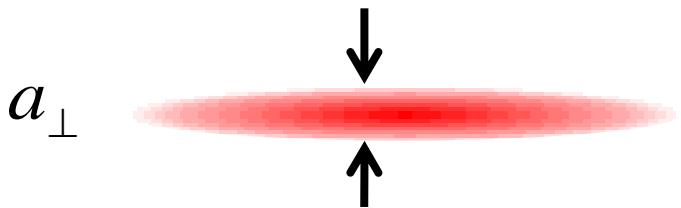
2. Study of the repulsive few-particle system:  
Fermionization and magnetism

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Trap has aspect ratio 1:10

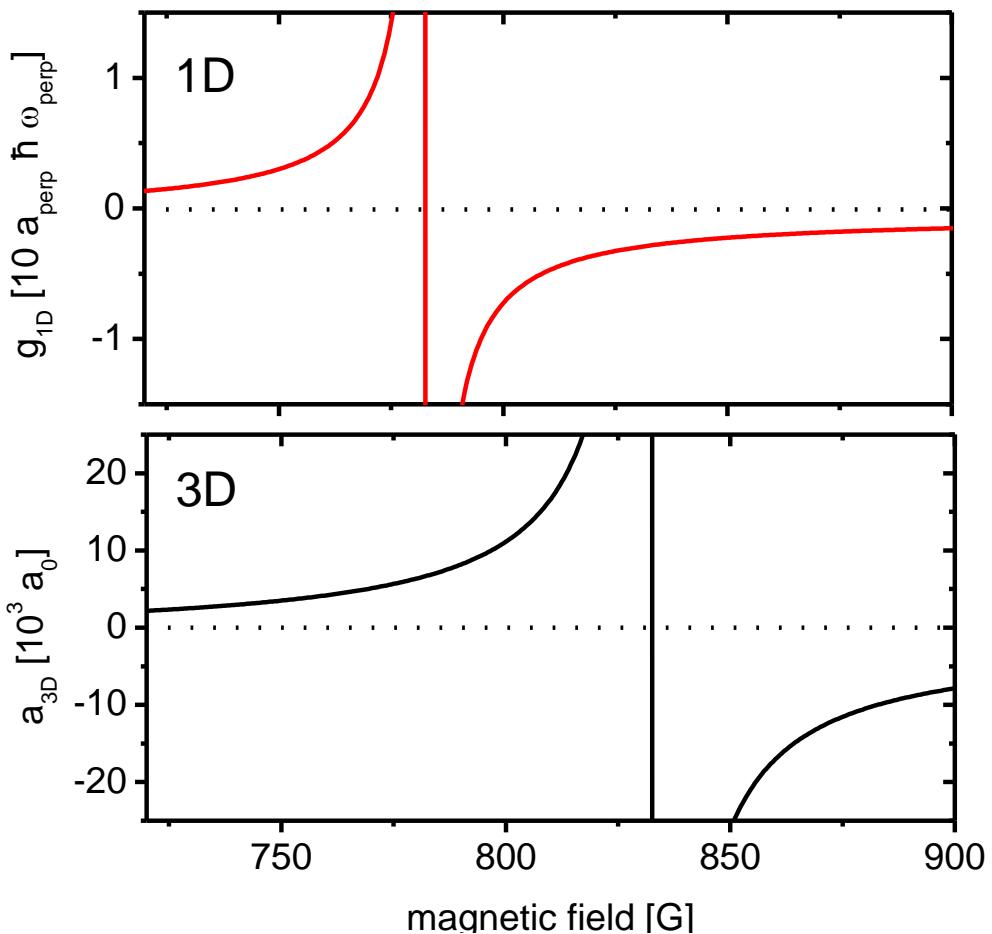


$$g_{1D} = \frac{2\hbar^2 a_{3D}}{m a_{\perp}^2} \frac{1}{1 - C a_{3D} / a_{\perp}}$$

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

(for radial harmonic confinement)

Confinement induced resonance

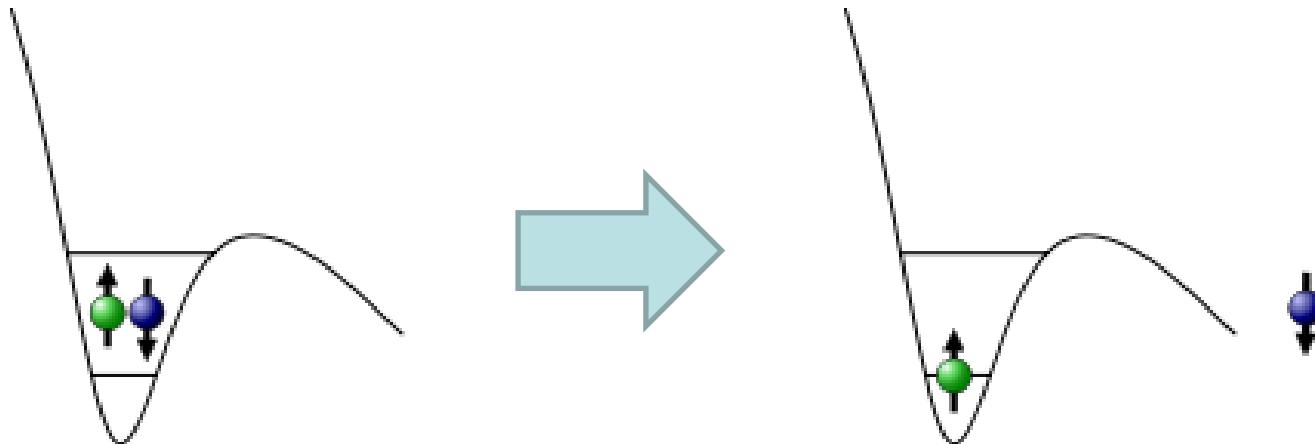


# Our major tool:



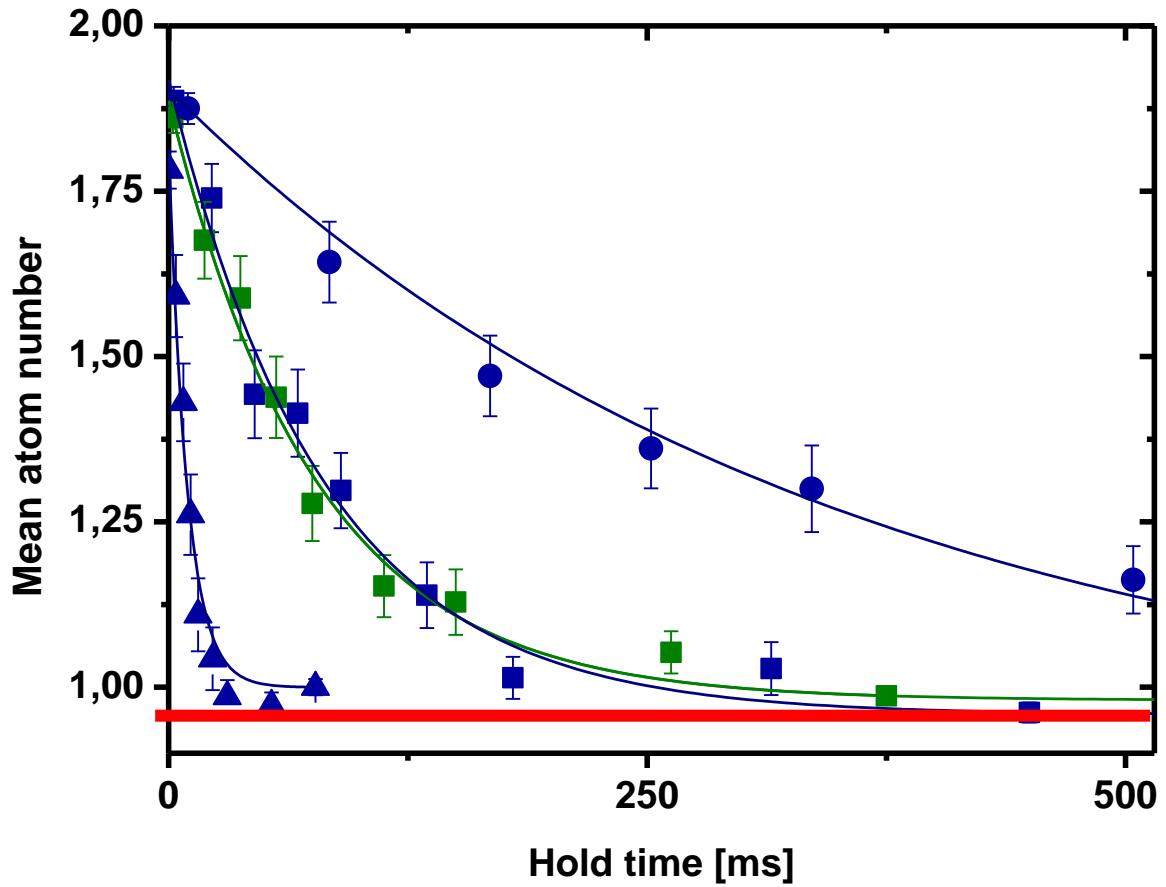
Observe tunneling dynamics:

- Tilt the trap so much that the highest-lying states have an experimentally accessible tunneling time ( $\sim 10\text{-}1000\text{ms}$ ).



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

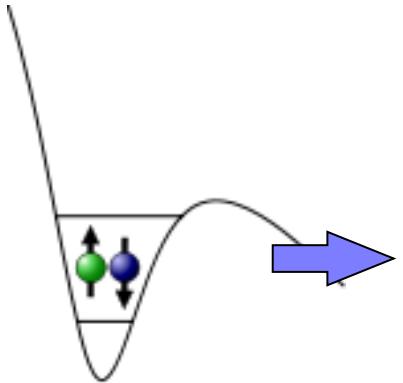
# Repulsive few-body interactions



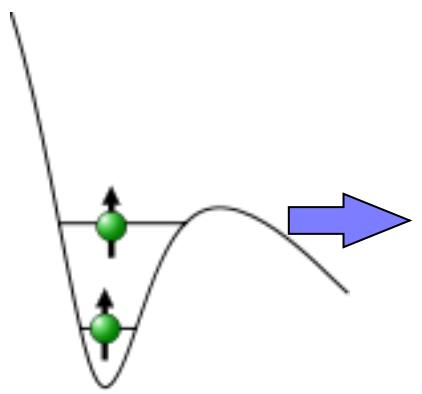
One atom tunnels out of the trap with time  $\tau$  while the second remains trapped.



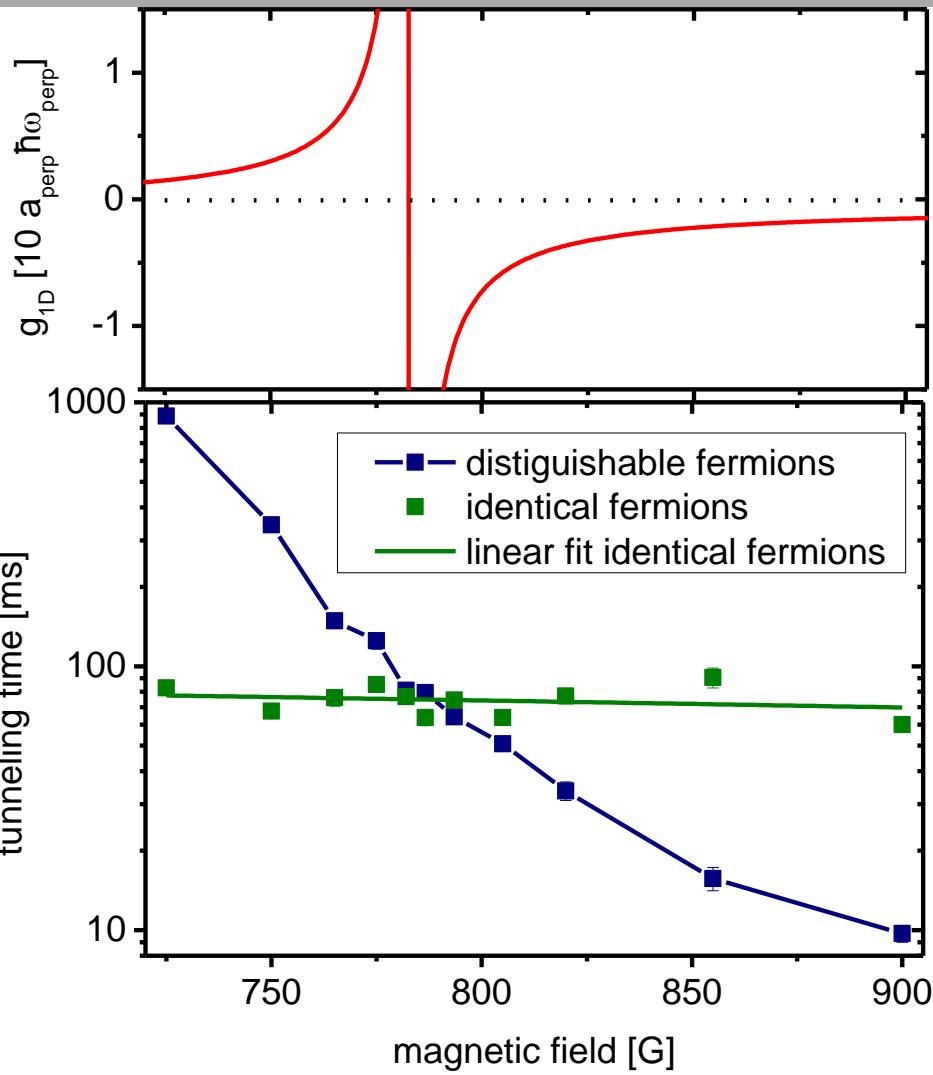
# 2 distinguishable vs. 2 identical fermions



2 distinguishable atoms



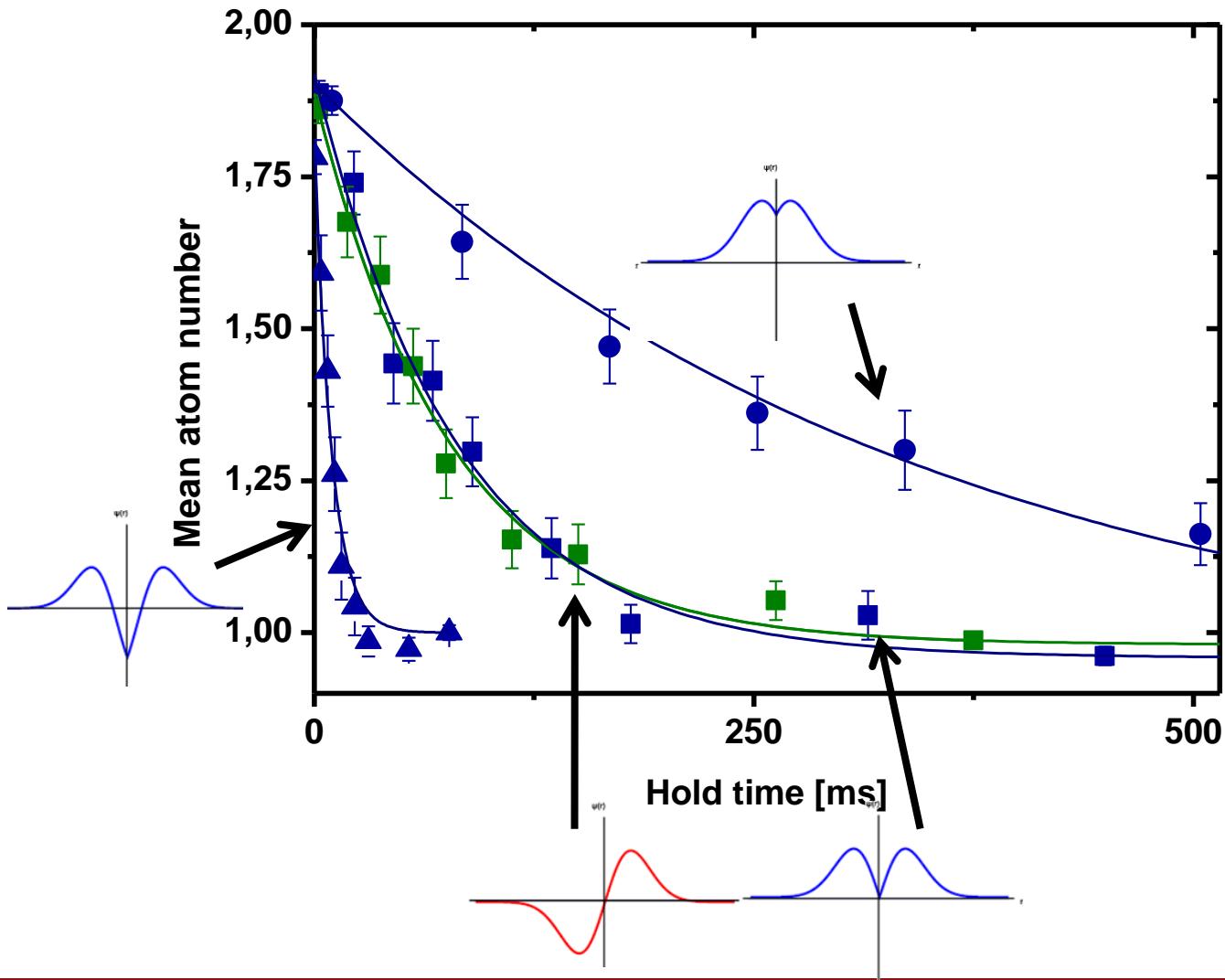
2 identical fermions



Tunneling time equal to case of two identical fermions: the system is „fermionized“



# Tunneling dynamics

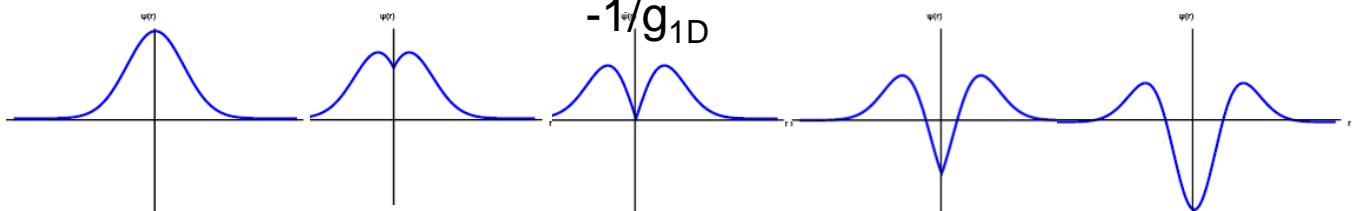
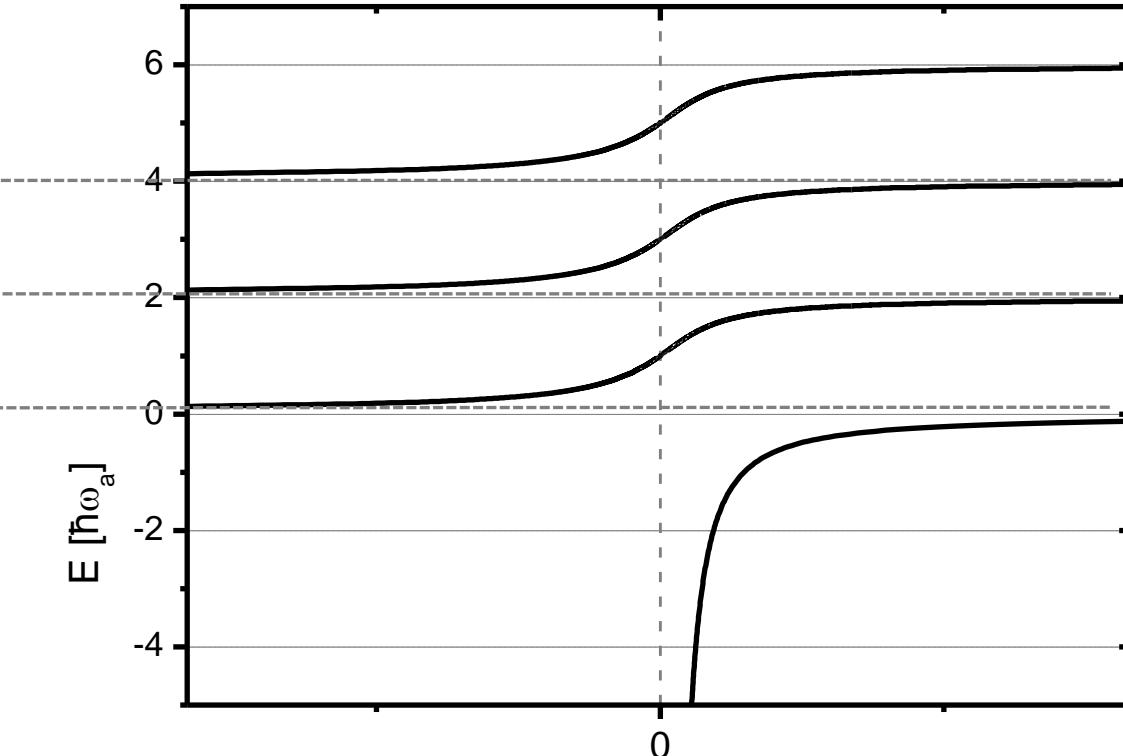
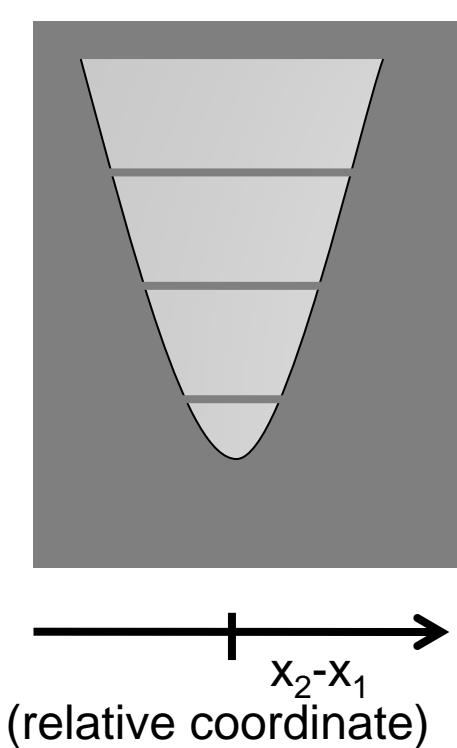


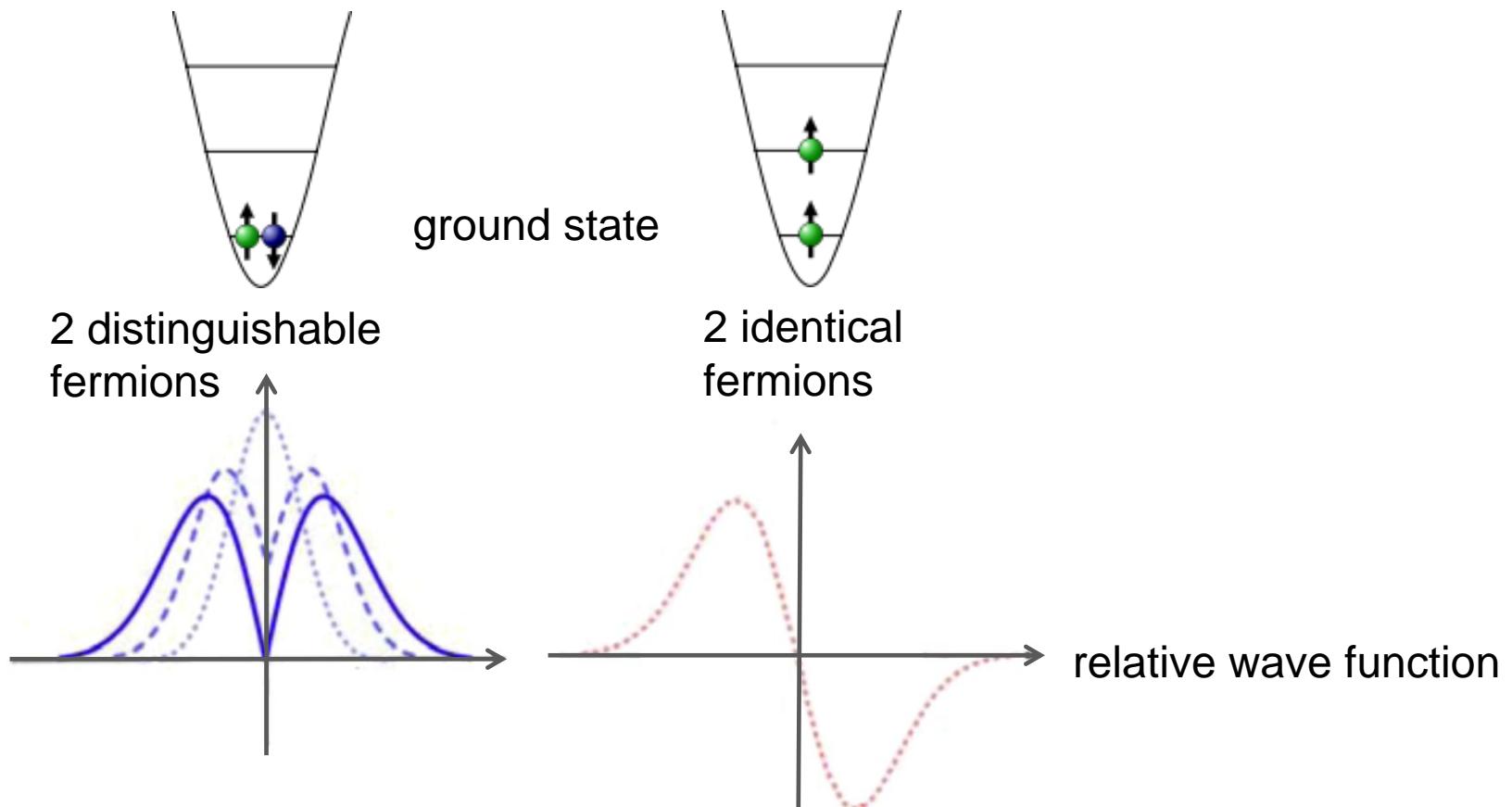
# Energy of 2 atoms in the trap



Relative kinetic energy of two interacting atoms (exact solution!)

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

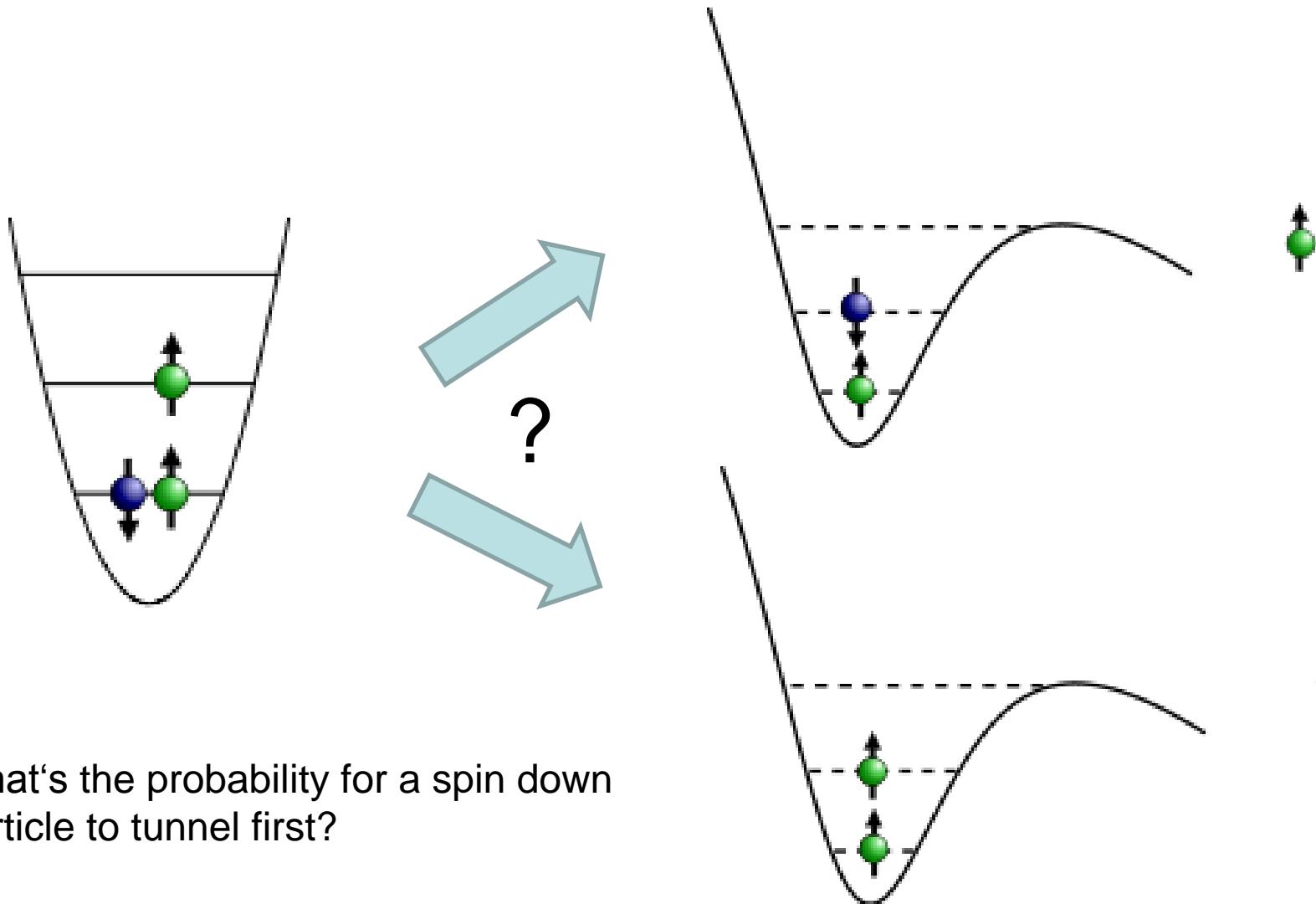




From equal tunneling time in 1D we infer:  
Wave function square modulus, and energy are identical

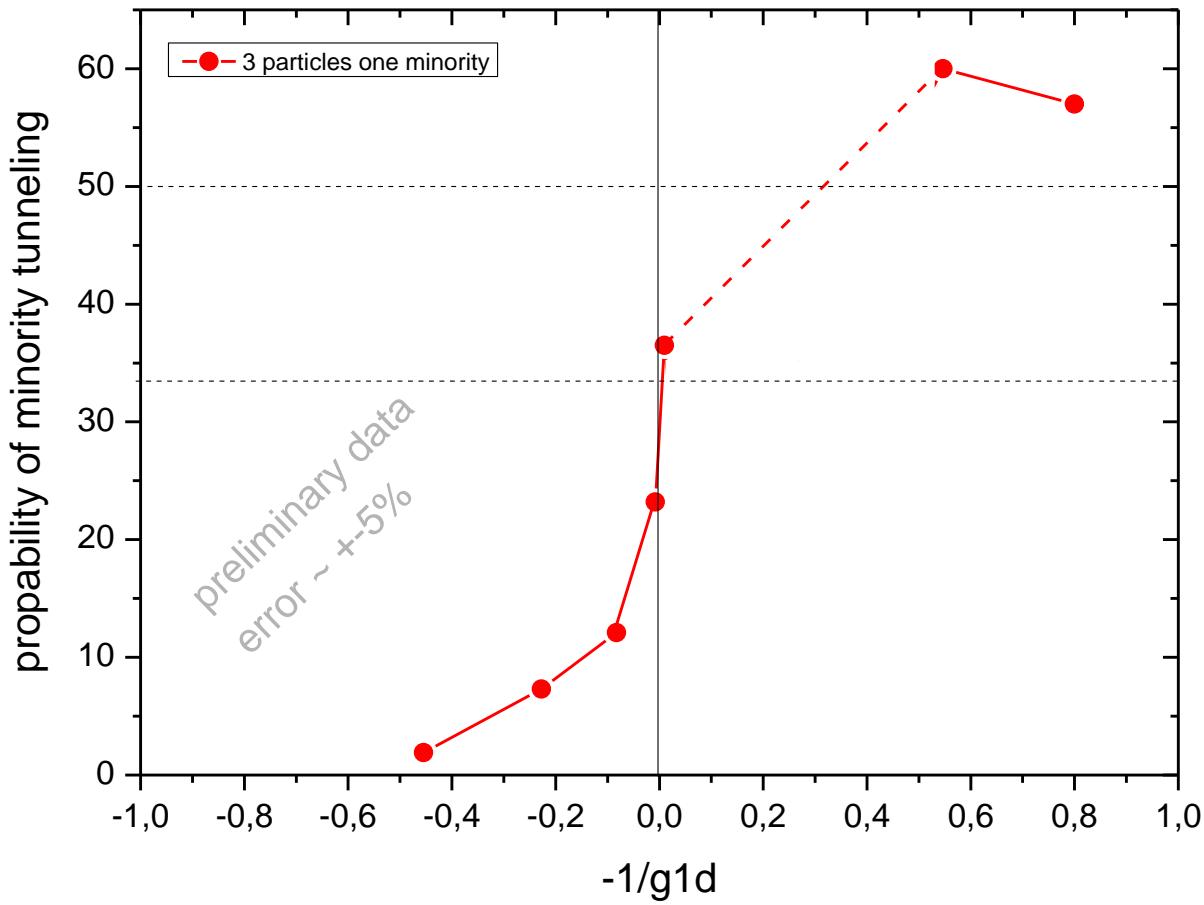


# Three particles



What's the probability for a spin down particle to tunnel first?

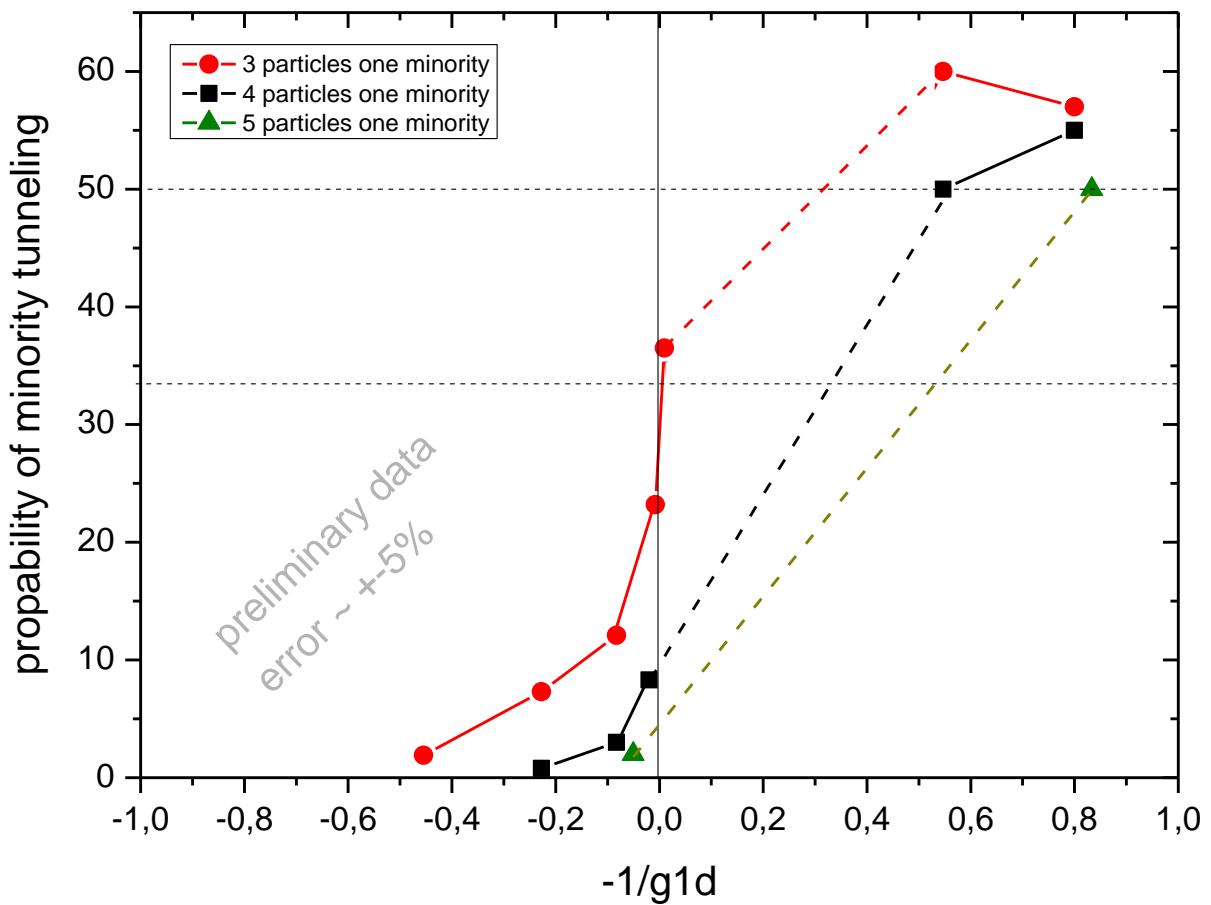
# Three particles



- On resonance, expect 1/3 ...

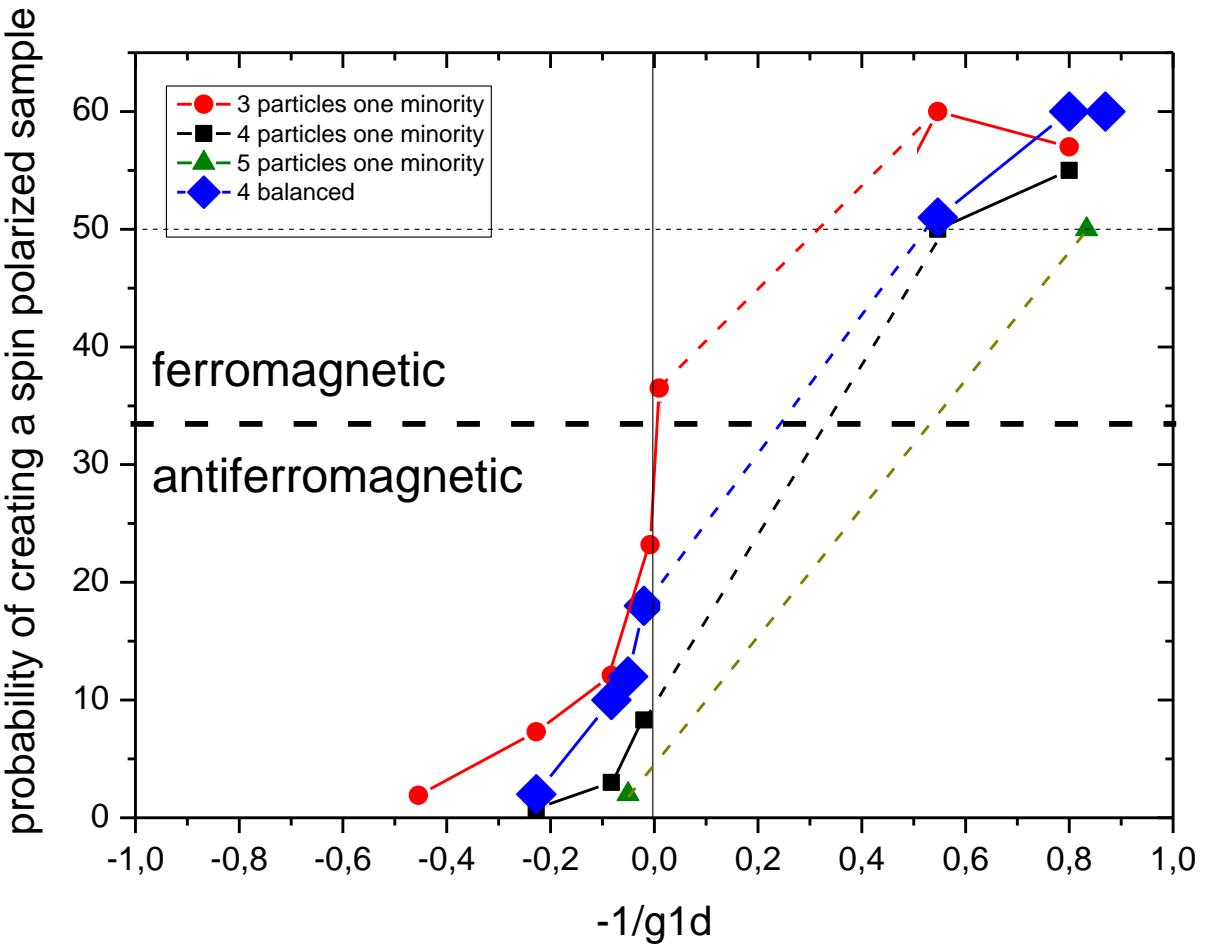
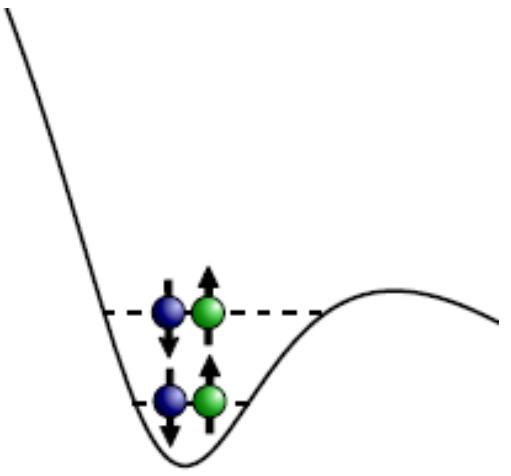


# ... more particles



- On resonance, expect 1/3 and 1/4, and so on ....

Preliminary data!



Crossover from antiferromagnetic to ferromagnetic correlations !



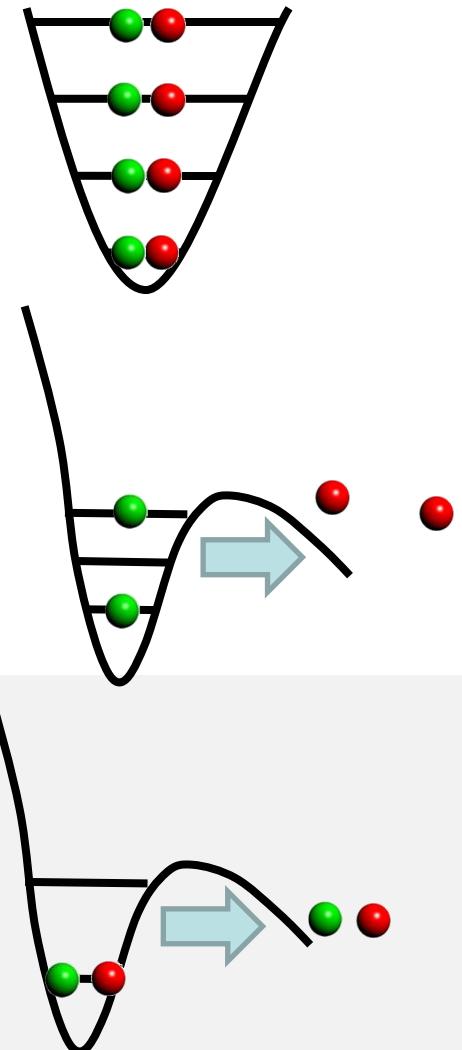


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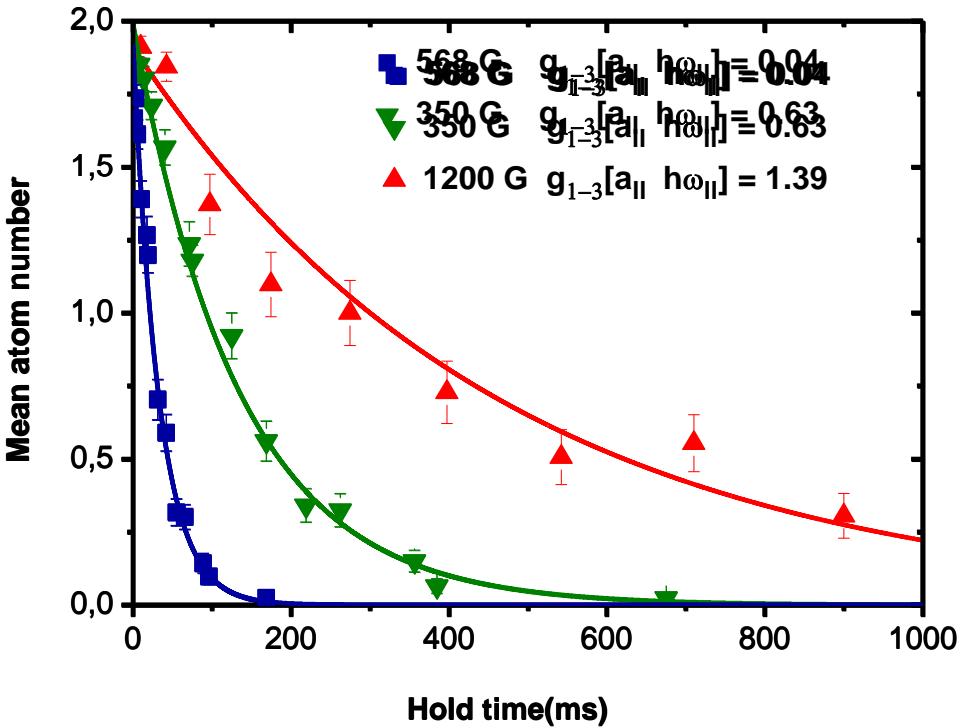
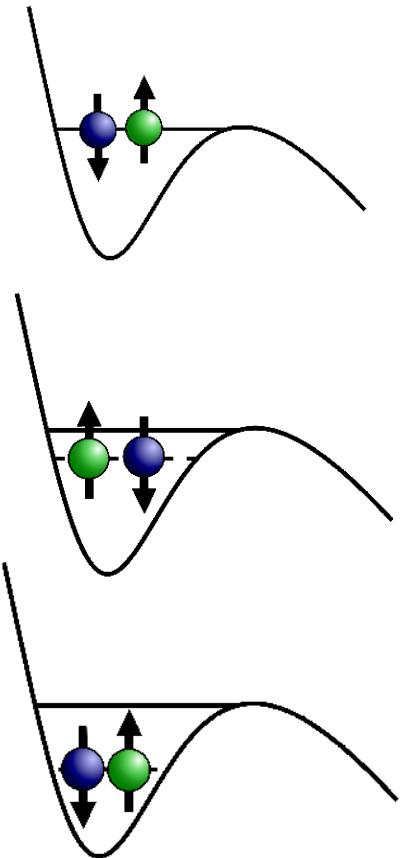
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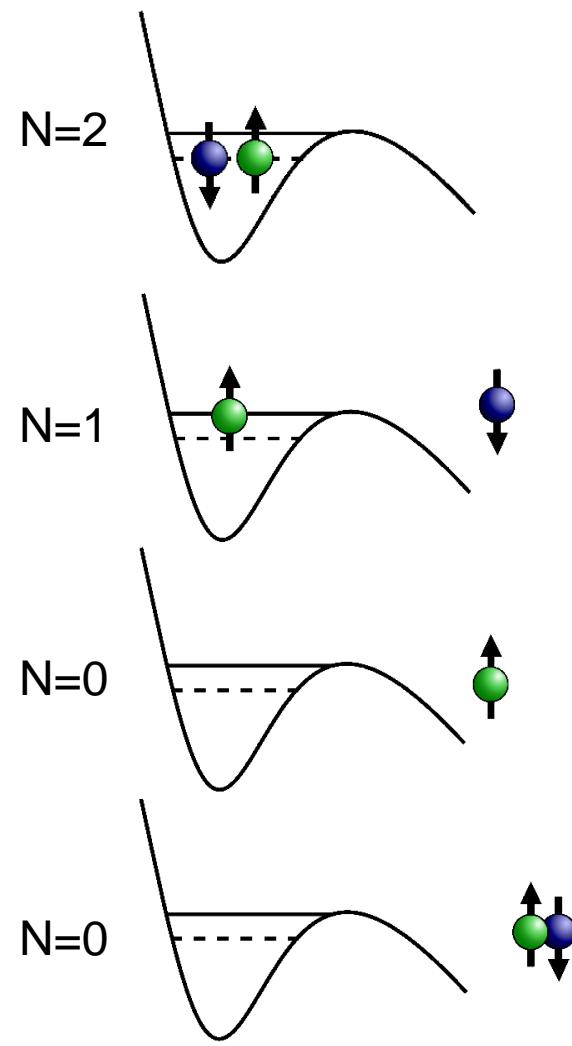
# Attractive interactions



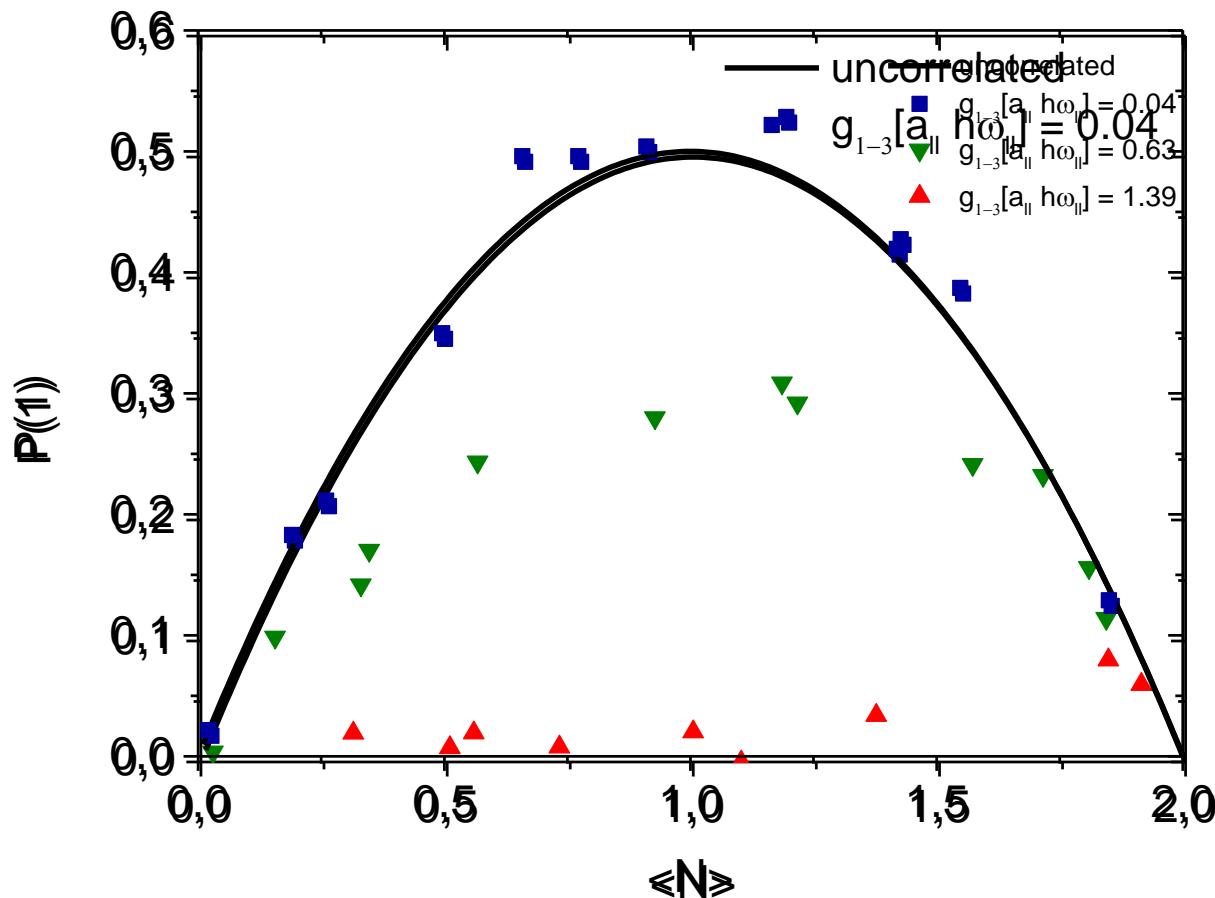
- Tunneling out of an interacting system is more complex, as the two particles can influence each other.
- What can we learn from correlated tunneling?



# Correlated tunneling



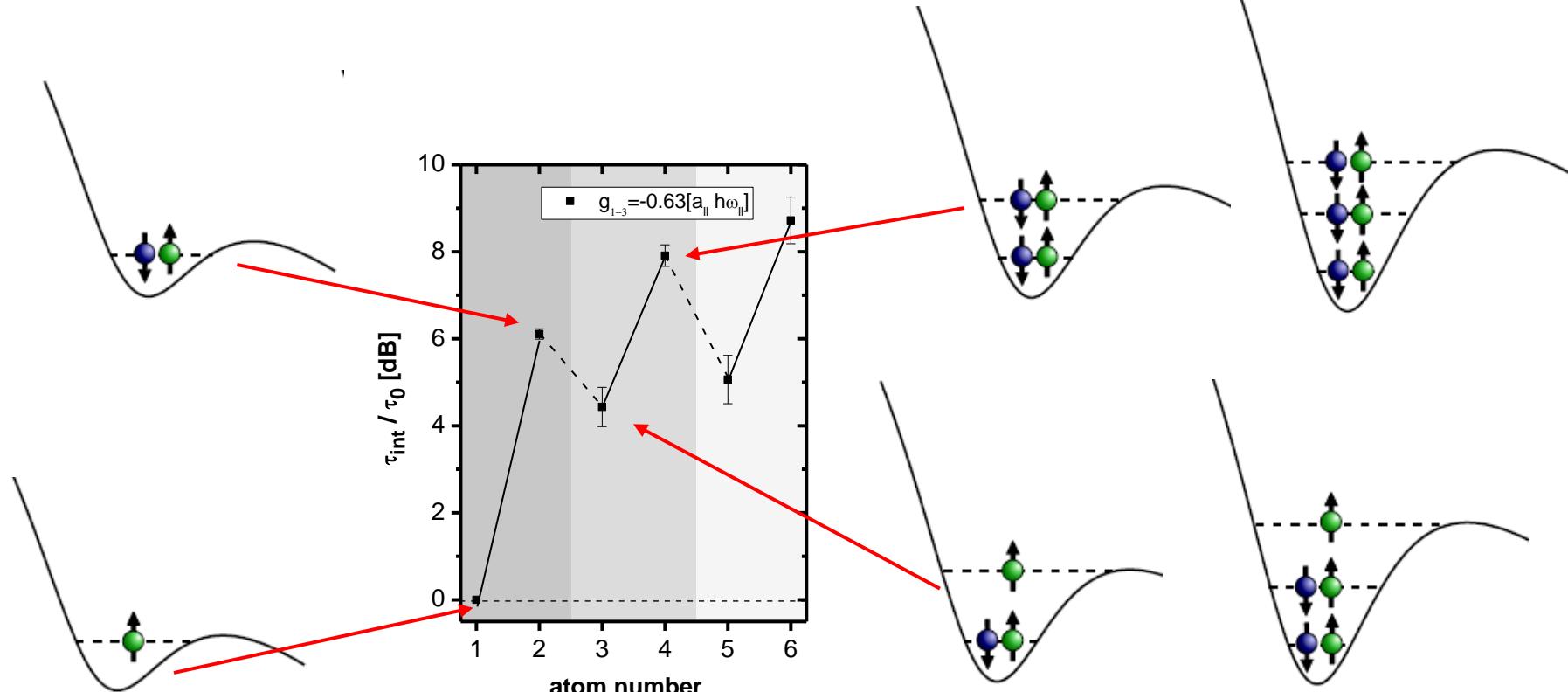
Depending on the interaction strength, the two atoms can tunnel independently, correlated in time or as pairs



# Odd-even effect with ultracold fermions



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



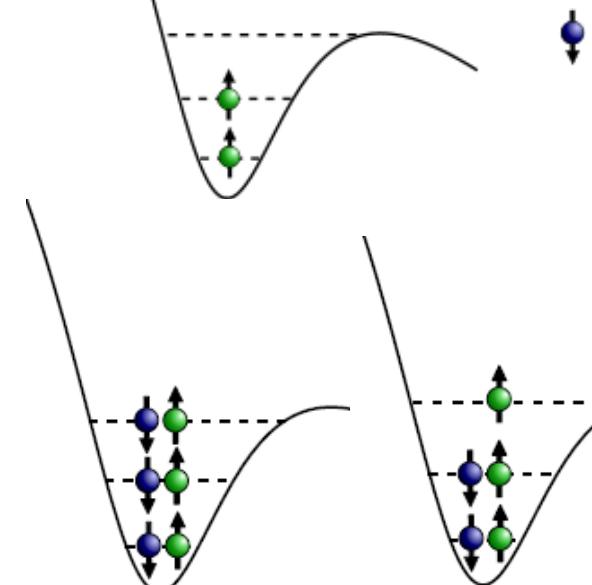
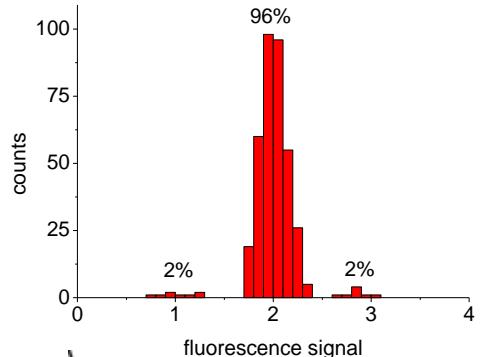
Systems with closed shells are more stable against decay



# Summary



- We prepare few-fermion systems with unprecedented control
- Control over both attractive and repulsive interactions
  - a) We fermionized two distinguishable atoms
  - b) Observe magnetic correlations in the repulsive few-body system
  - c) Observe correlated tunneling and odd-even effect with attractive interactions



# Thank you very much for your attention!



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