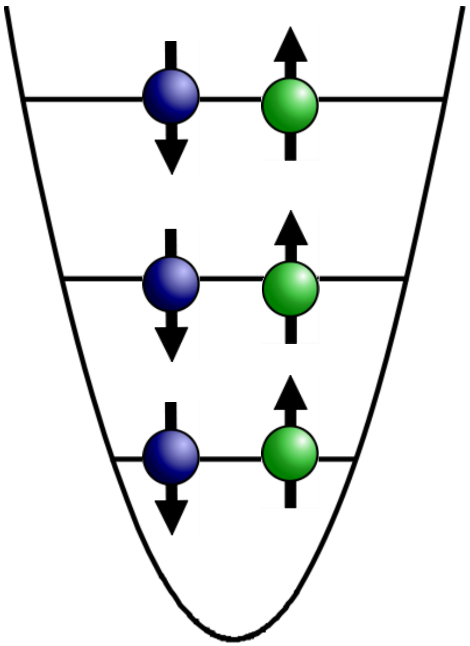
Few-body physics with ultracold atoms



Selim Jochim, Universität Heidelberg

Universität Heidelberg

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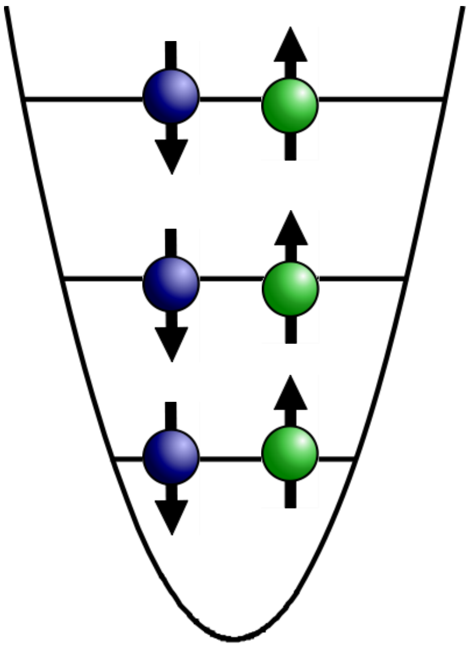
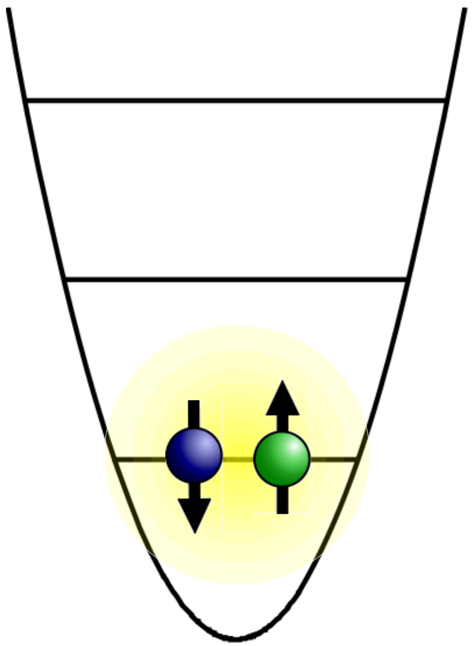


Selim Jochim, Universität Heidelberg

Physikalisches Institut

Two trapped interacting particles …

interacting singlet

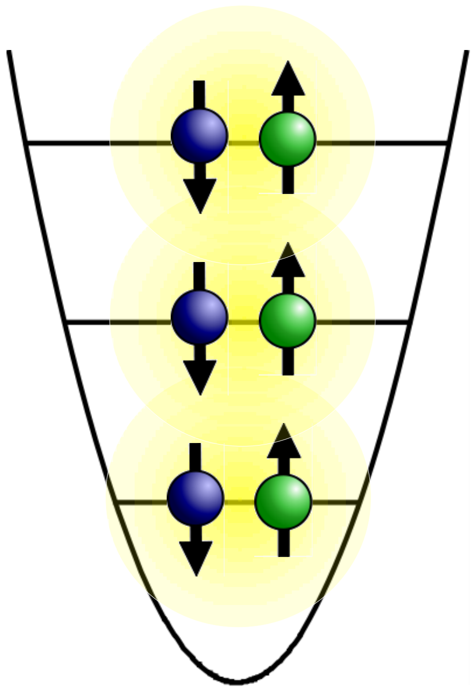


Ground state of the Helium atom:

No analytic solution available, we learn how to apply powerful numerical techniques: Hartree Fock method.

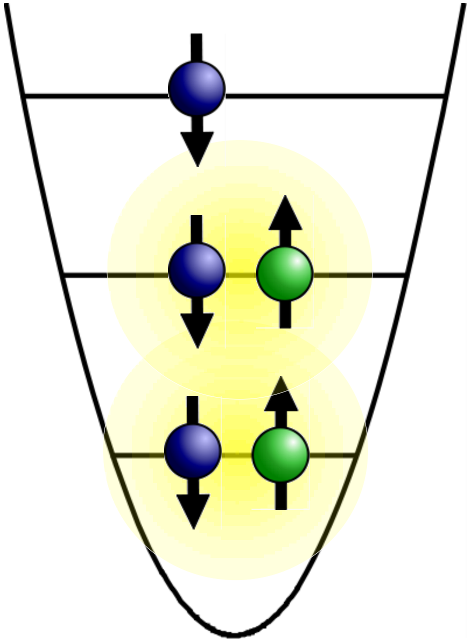
More particles …

The particles should pair up within shells ….



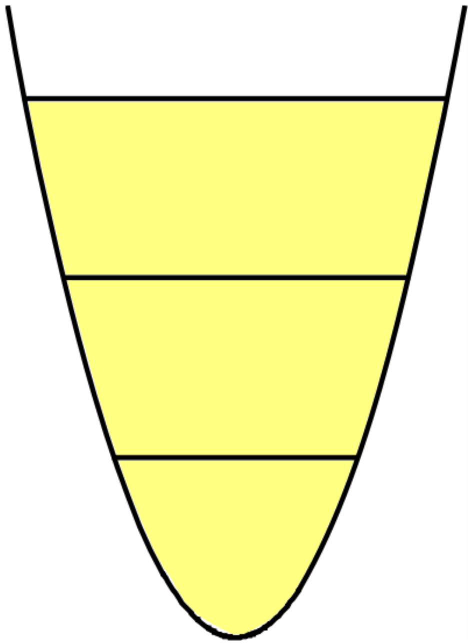
… or also beyond?

More particles …



Intershell pairing?
→ Pauli blocking should supress this!

Many body limit



Define quantities like the Fermi energy, density, pressure ….

… apply local density approximation …

But when are such approximations justified?

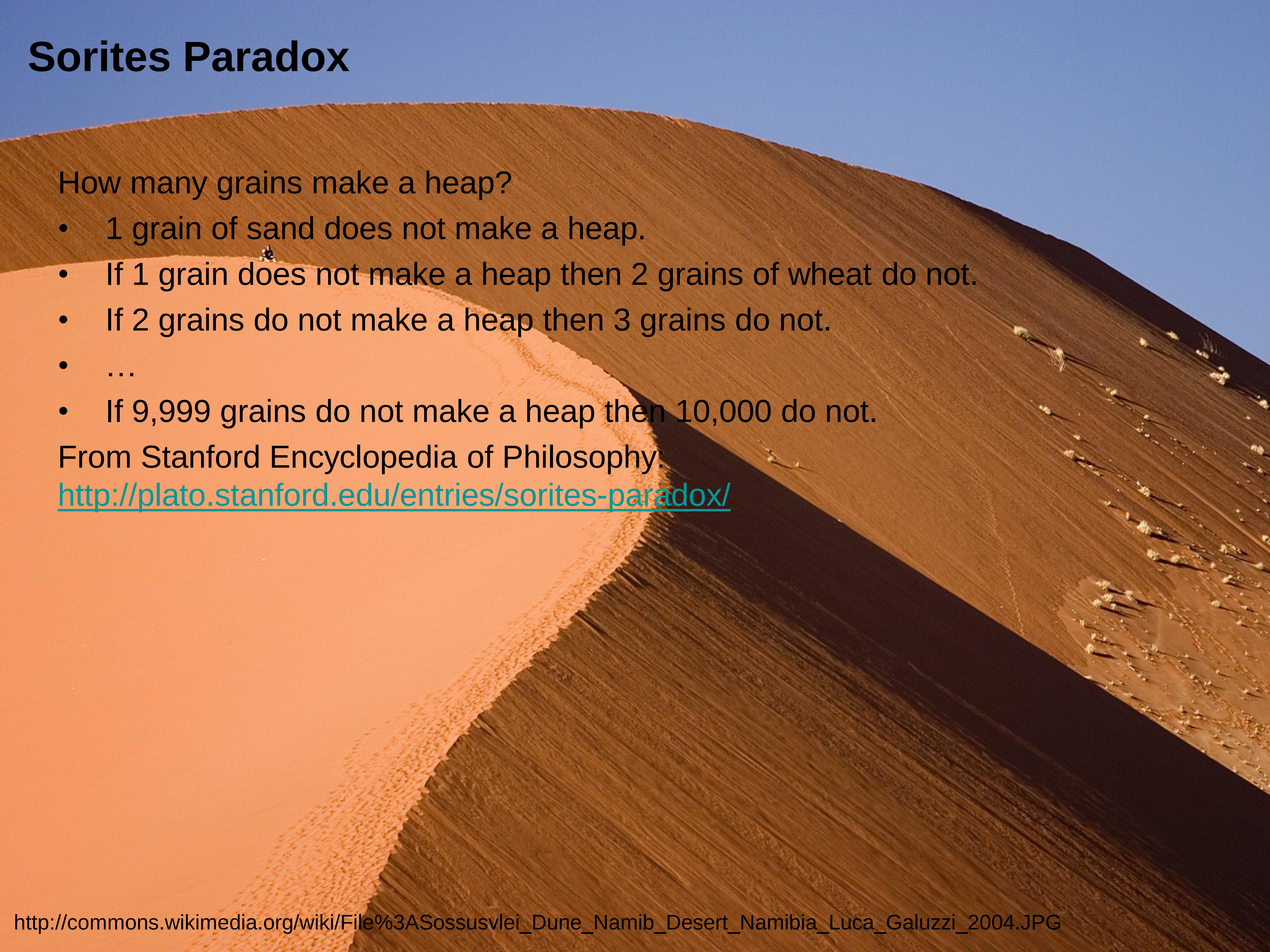
This is an ancient problem!

Sorites Paradox

How many grains make a heap?

- 1 grain of sand does not make a heap.
- If 1 grain does not make a heap then 2 grains of wheat do not.
- If 2 grains do not make a heap then 3 grains do not.
- …
- If 9,999 grains do not make a heap then 10,000 do not.

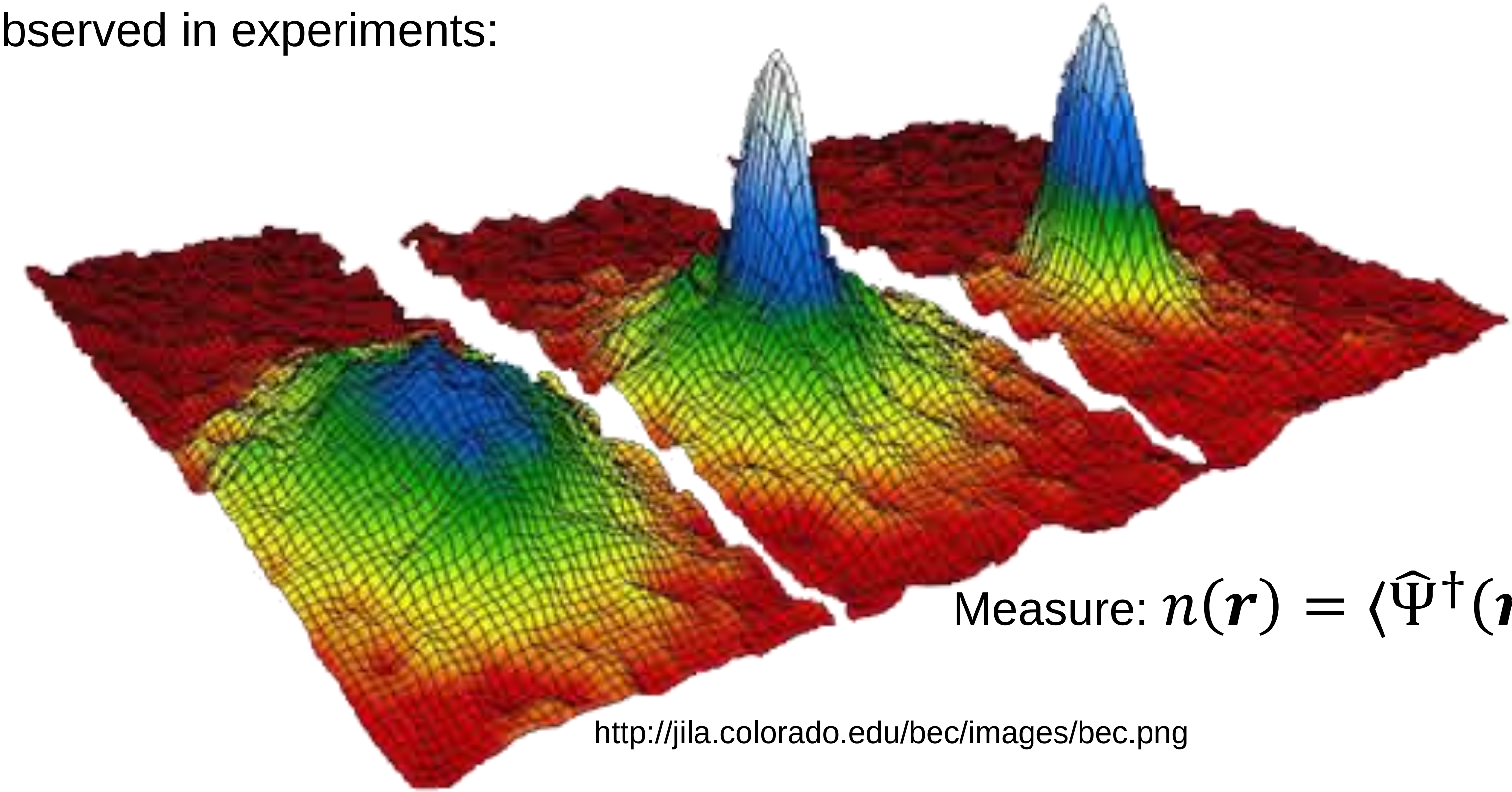
From Stanford Encyclopedia of Philosophy:
http://plato.stanford.edu/entries/sorites-paradox/



http://commons.wikimedia.org/wiki/File%3ASossusvlei_Dune_Namib_Desert_Namibia_Luca_Galuzzi_2004.JPG

Ultracold neutral atoms

Bose Einstein condensates of large samples of atoms: Macroscopic wave function: Number of particles is so large that a constant density of atoms is observed in experiments:



Measure: $n(\boldsymbol{r}) = \langle \hat{\Psi}^\dagger(\boldsymbol{r}) \hat{\Psi}(\boldsymbol{r}) \rangle$

http://jila.colorado.edu/bec/images/bec.png

Removing one single atom does not make a difference!

Our approach

Reduce the complexity of a system as much as possible

until only the essential parts remain!

In most physical systems:

Range of interaction
significantly complicates the description

Ultracold atoms are an ideal tool …

The interactions between ultracold atoms can be effectively pointlike

(contact interaction)

van der Waals interaction: range of $r_{vdW} \sim$ 1nm

In the experiments we have:

- extremely low density (interparticle spacing ~ 1µm)
- extremely low momentum, such that $\lambda_{dB} = \frac{h}{\sqrt{2\pi mkT}} \gg r_{vdW}$

Ultracold atoms are an ideal tool …

- extremely low momentum, such that $\lambda_{dB} = \frac{h}{\sqrt{2\pi mkT}} \gg r_{vdW}$

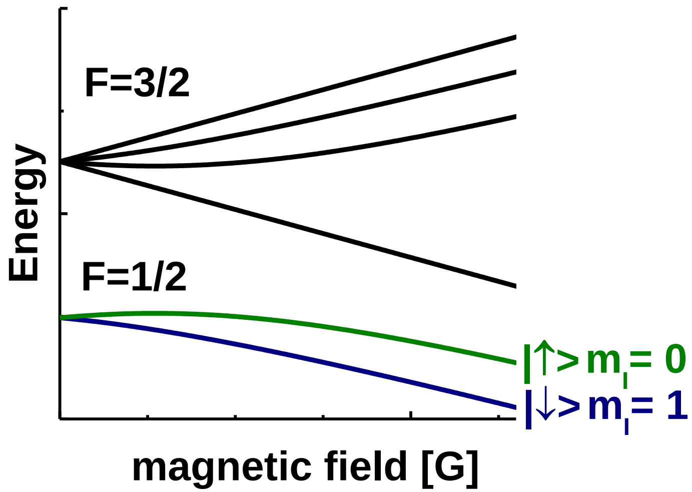
(This is the opposite limit desired in collision experiments: shorter wavelength enhances resolution)

Here:

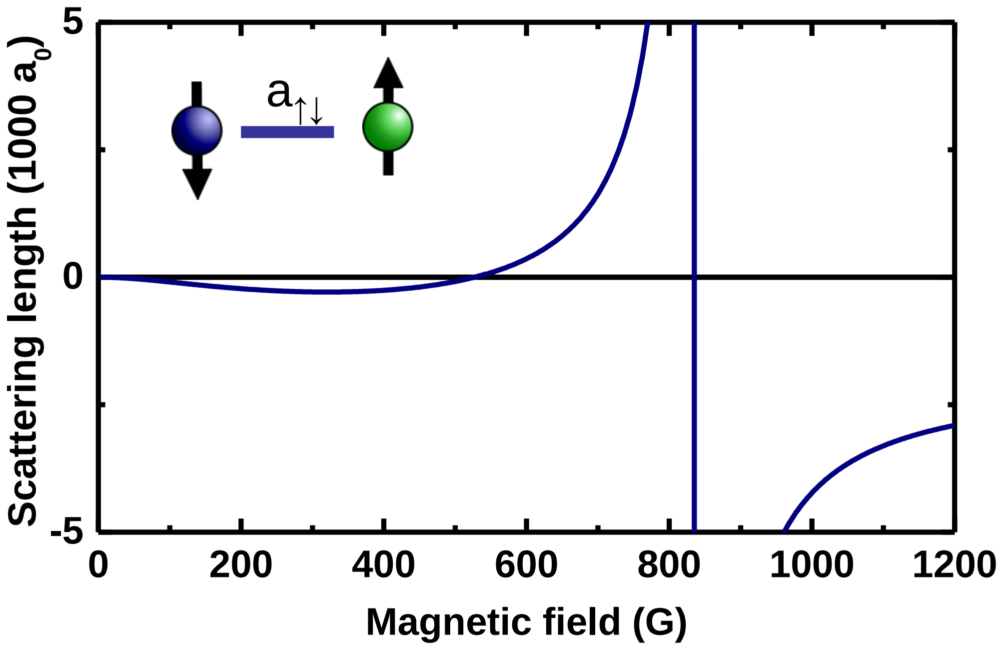
- If λ_{dB} is sufficiently large, all the information about internal structure of the atom is hidden in a single quantity, **the scattering length a**
- We can even tune the scattering length to any desired value by simply applying a magnetic field (<u>**Feshbach resonances**</u>).

The ^{6}Li atom

^{6}Li ground state



Tuning interactions: Feshbach resonance in ^{6}Li



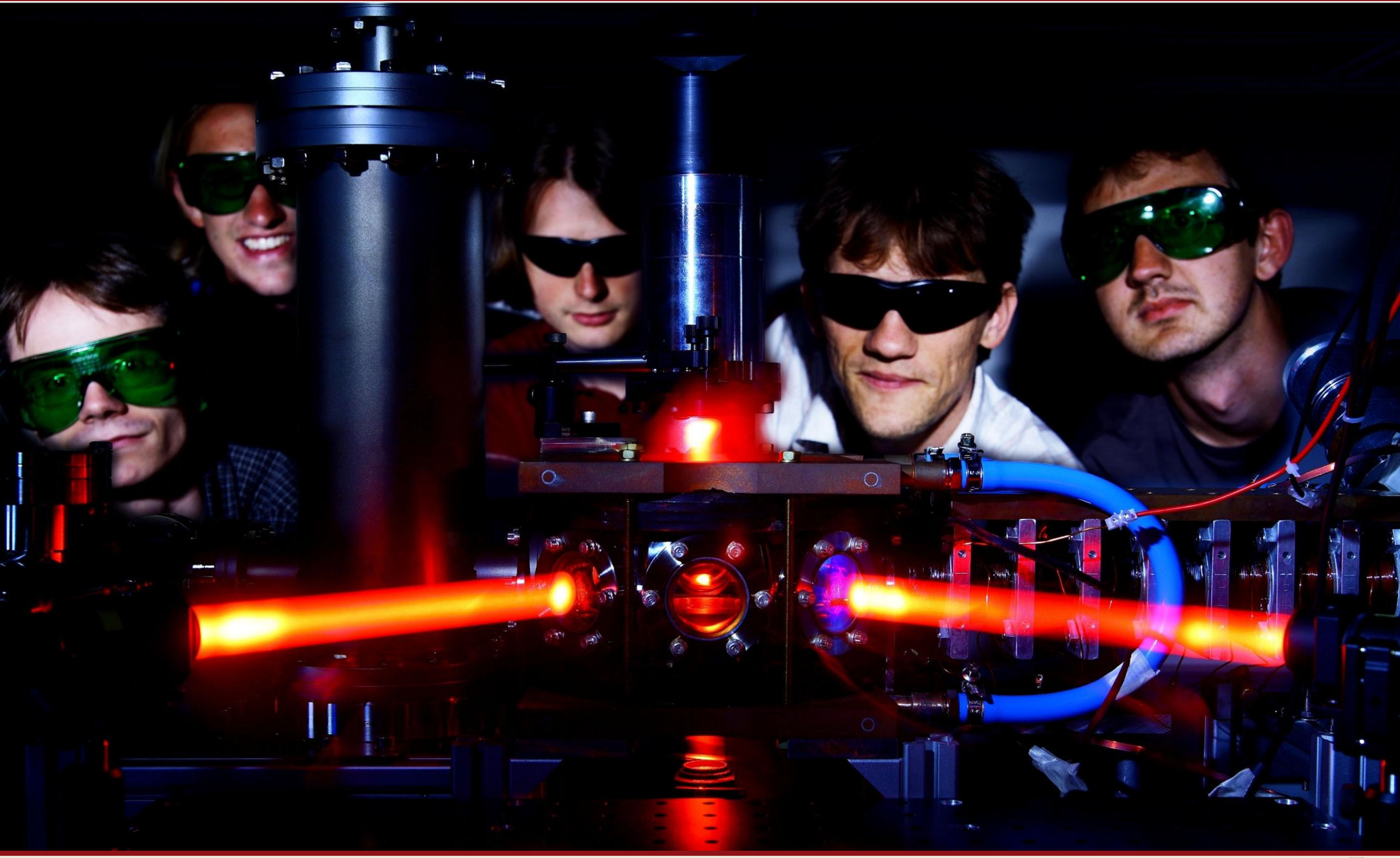
G. Zürn et al., **PRL** 110, 135301 (2013)

S=1/2, I=1
→ half-integer total angular momentum
→ ^{6}Li is a fermion

NO interaction between identical particles

C. Chin et al., Rev. Mod. Phys. **82**, 1225 (2010)

A picture from the lab …



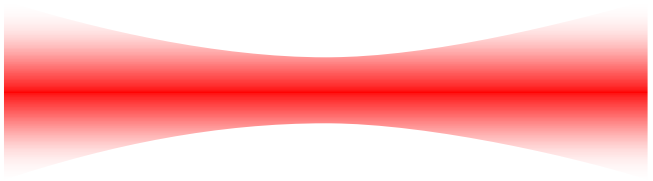
10^9 laser cooled atoms at ~1mK

A container for ultracold atoms

We need to isolate the atoms from the environment:

This might still work
for liquid nitrogen ….

… here we use the focus of a laser beam:



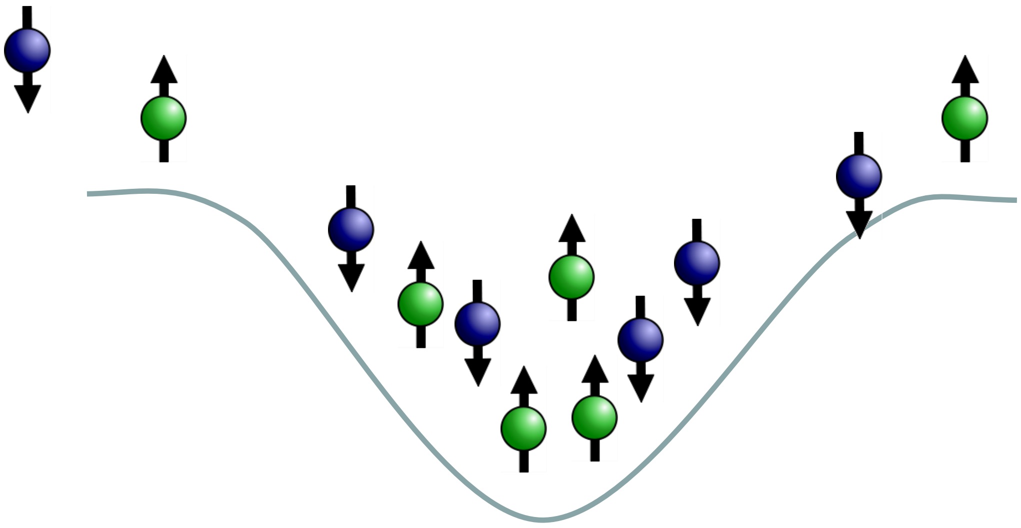
Optical dipole trap depth: $U \propto I(\boldsymbol{r})$

Evaporative cooling

It just works the same:

… and for our cold atoms:
Cool from ~1mK down to below 1µK

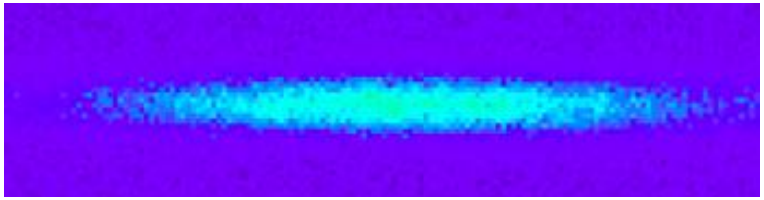
For our cup of coffee …



Just reduce the trap depth, i.e. laser power

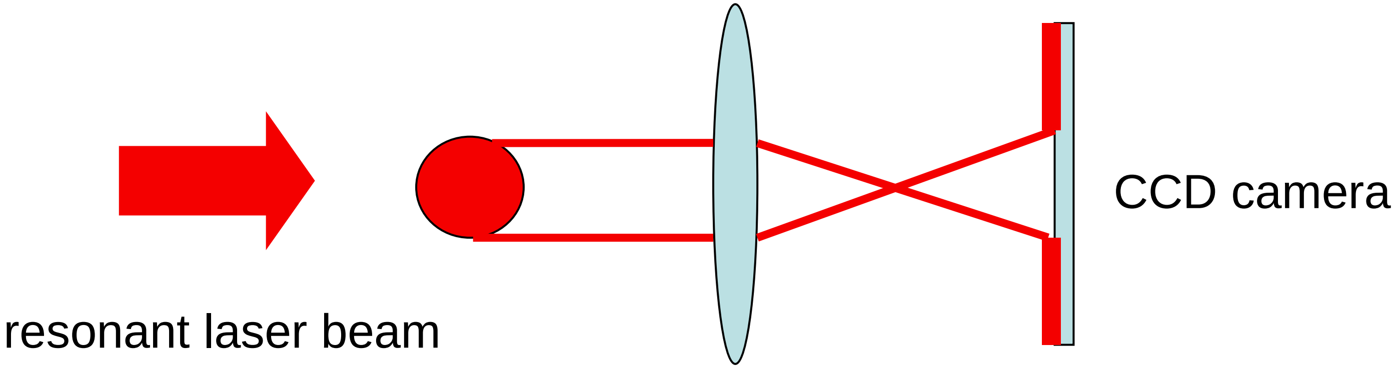
Ultracold gas of fermions

About 50000 atoms @ 250nK, T_F~1µK



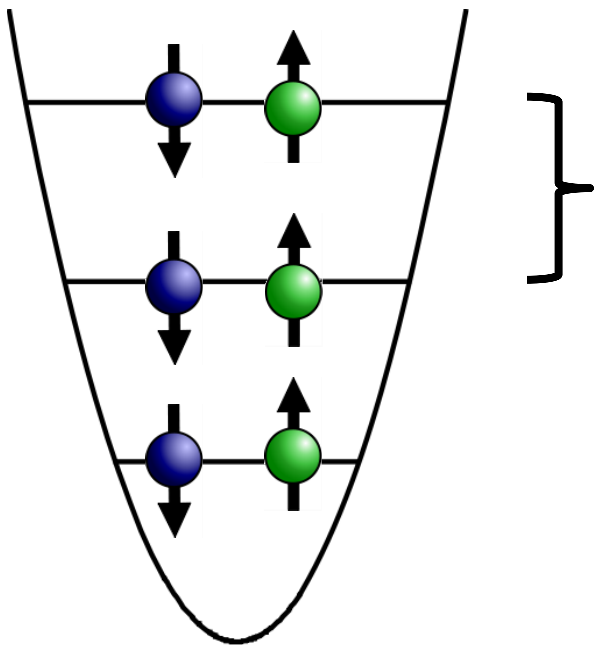
~100µm

Absorption imaging of ultracold clouds:



Towards a finite gas …

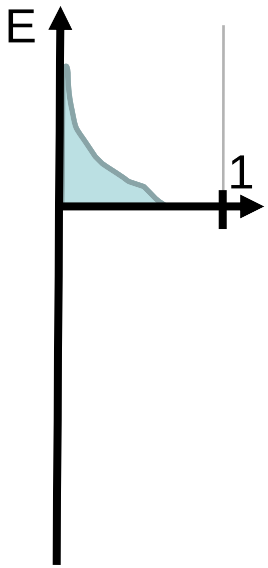
The challenge:

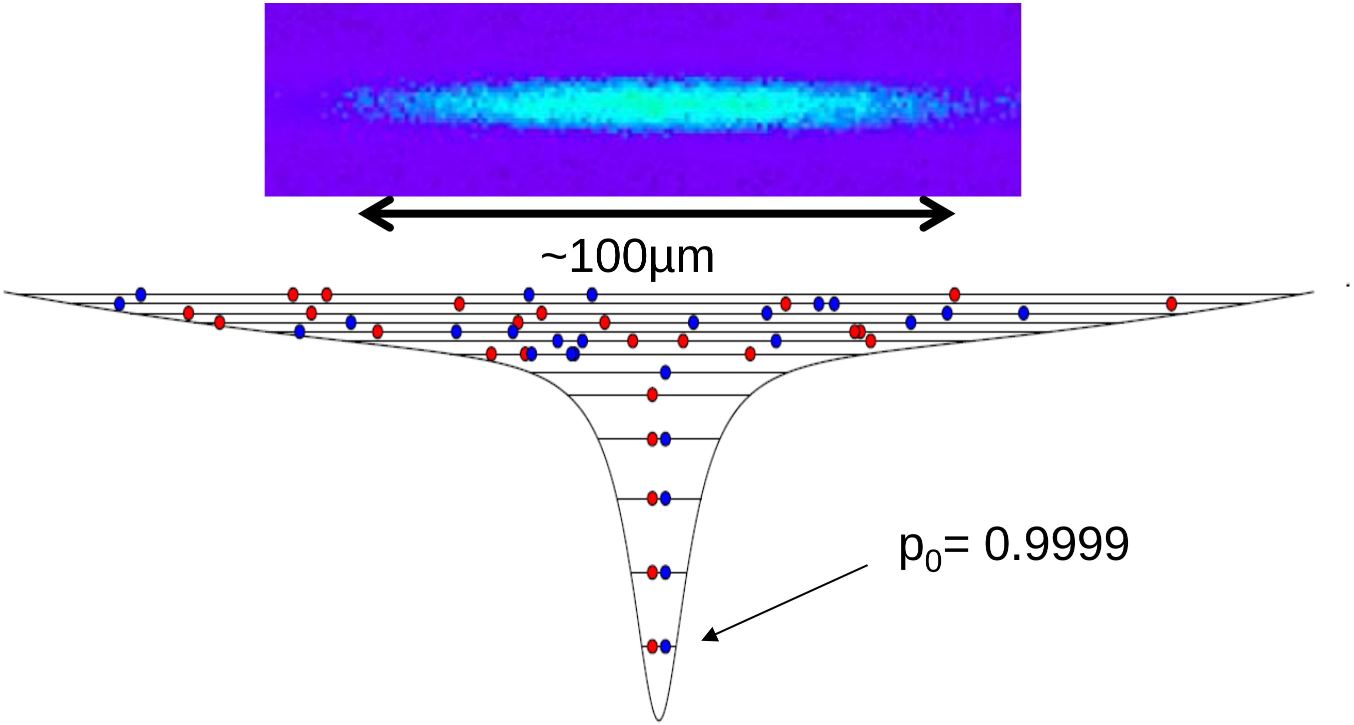


achieve $\hbar\omega \gg kT$

Creating a finite gas of fermions

Fermi-Dirac dist.

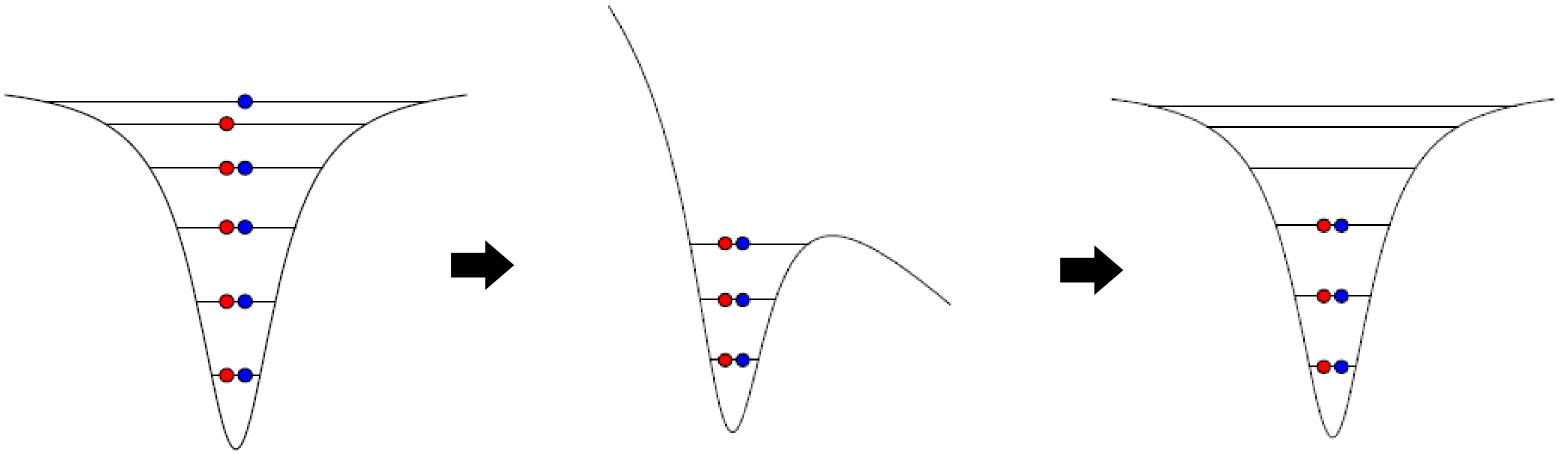




- 2-component mixture in reservoir
- superimpose microtrap (~1.8 μm waist)

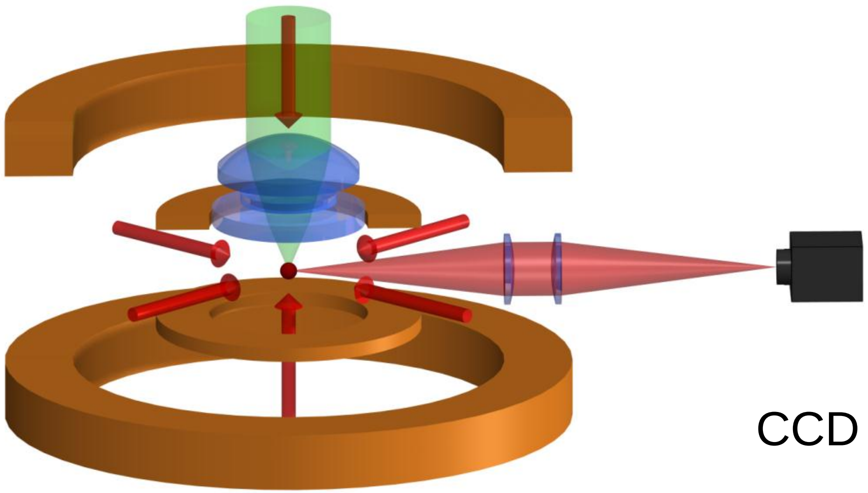
Creating a finite gas of fermions

• switch off reservoir

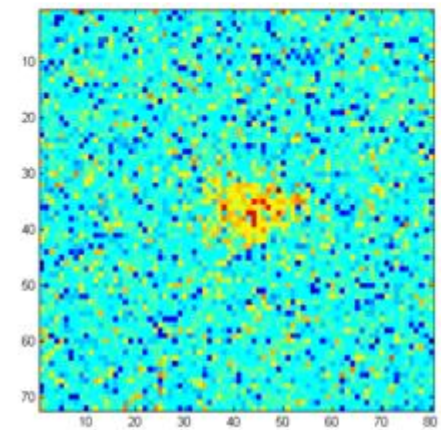


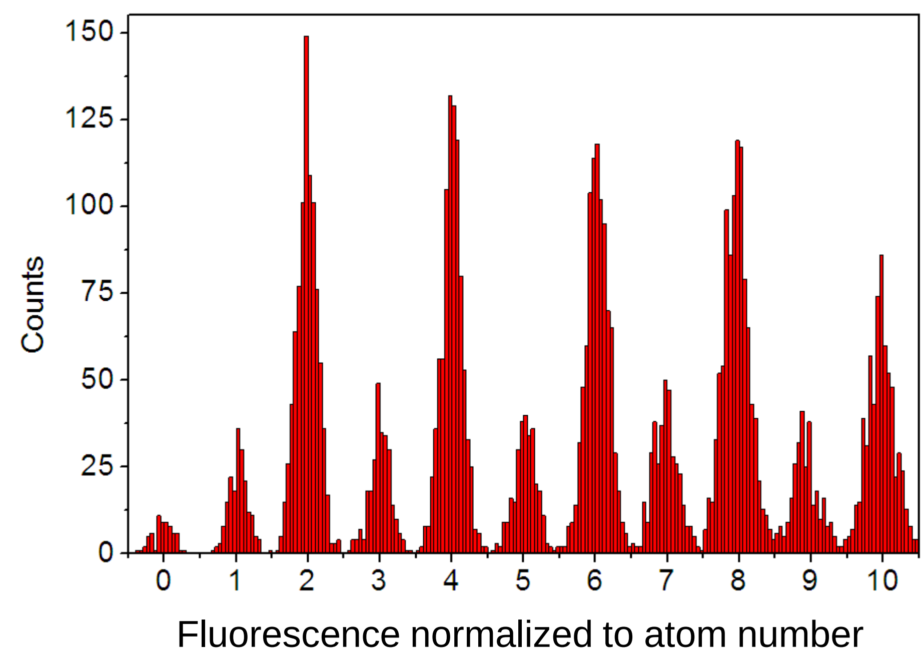
+ magnetic field gradient in axial direction

Single atom detection



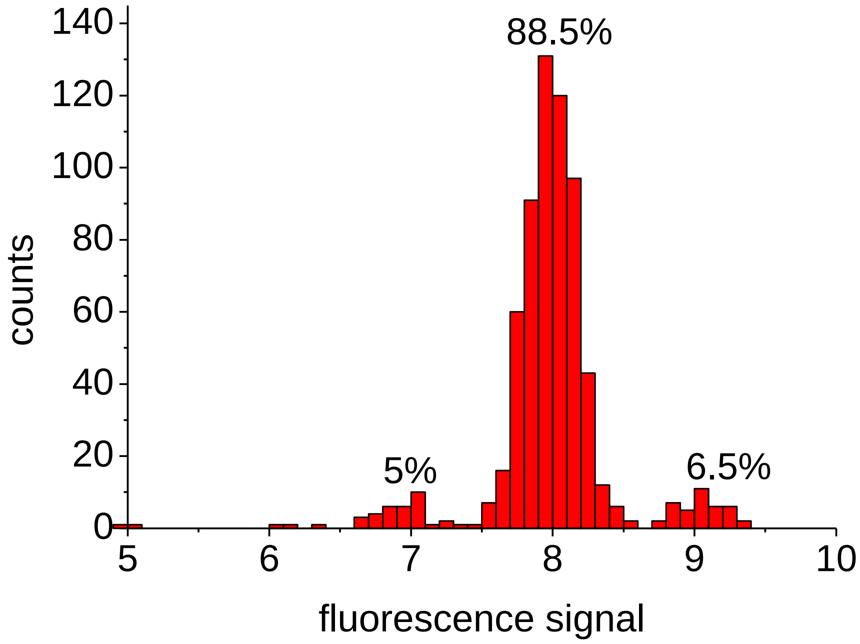
one atom in a MOT
1/e-lifetime: 250s
Exposure time 0.5s

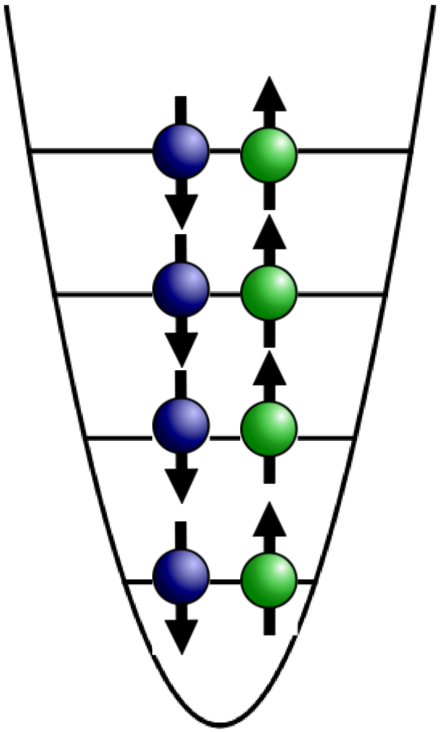




distance between 2 neighboring atom numbers : ~ 6σ
1-10 atoms can be distinguished with high fidelity > 99%

Spilling the atoms ….





- We can control the atom number with exceptional precision!
- Note aspect ratio 1:10: 1-D situation
- **So far: Interactions tuned to zero …**

Let‘s study interacting systems!

Let´s look at two atoms in the trap

$$H = \frac{p_1^2}{2m} + \frac{p_2^2}{2m} + \frac{1}{2} m\omega^2 x_1^2 + \frac{1}{2} m\omega^2 x_2^2 + g_{1D}\delta(x_2 - x_1)$$

Separate the center-of-mass motion from relative motion

$$x = x_2 - x_1;\ X = x_2 + x_1$$

$$H_{\text{RelMotion}} = \frac{p^2}{2\mu} + \frac{1}{2}\mu\omega^2 x^2 + g_{1D}\delta(x)$$

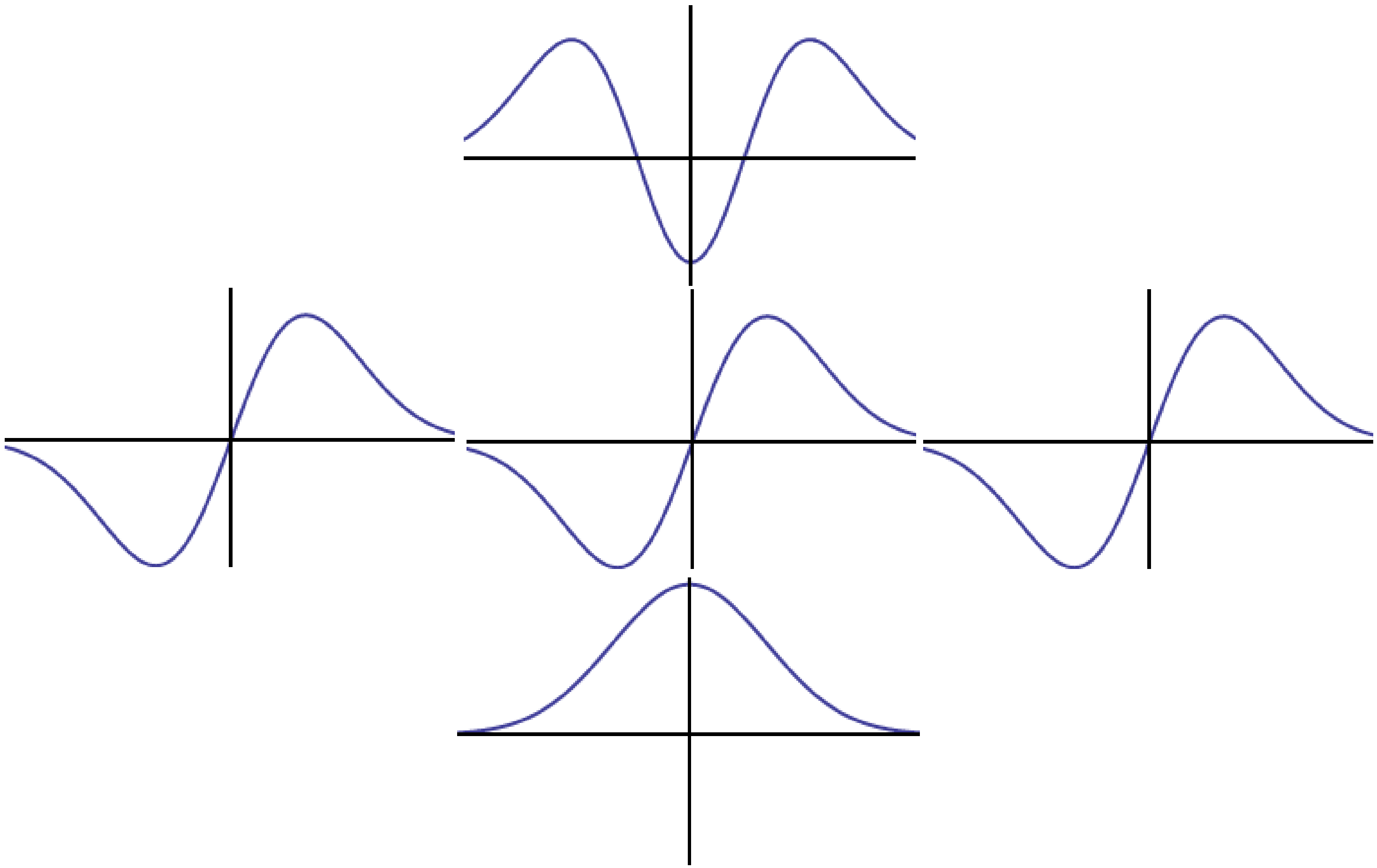
This can be solved exactly!

(All antisymmetric solutions of the harmonic oscillator are solutions!)

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

Solutions for the two particles:

repulsive $g > 0$ | noninteracting | attractive $g < 0$



spatially symmetric, $S = 0, m_S = 0$ $|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

spatially antisymmetric, $S = 1, m_S = 0, \pm 1$ $|\uparrow\uparrow\rangle, |\downarrow\downarrow\rangle, |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$

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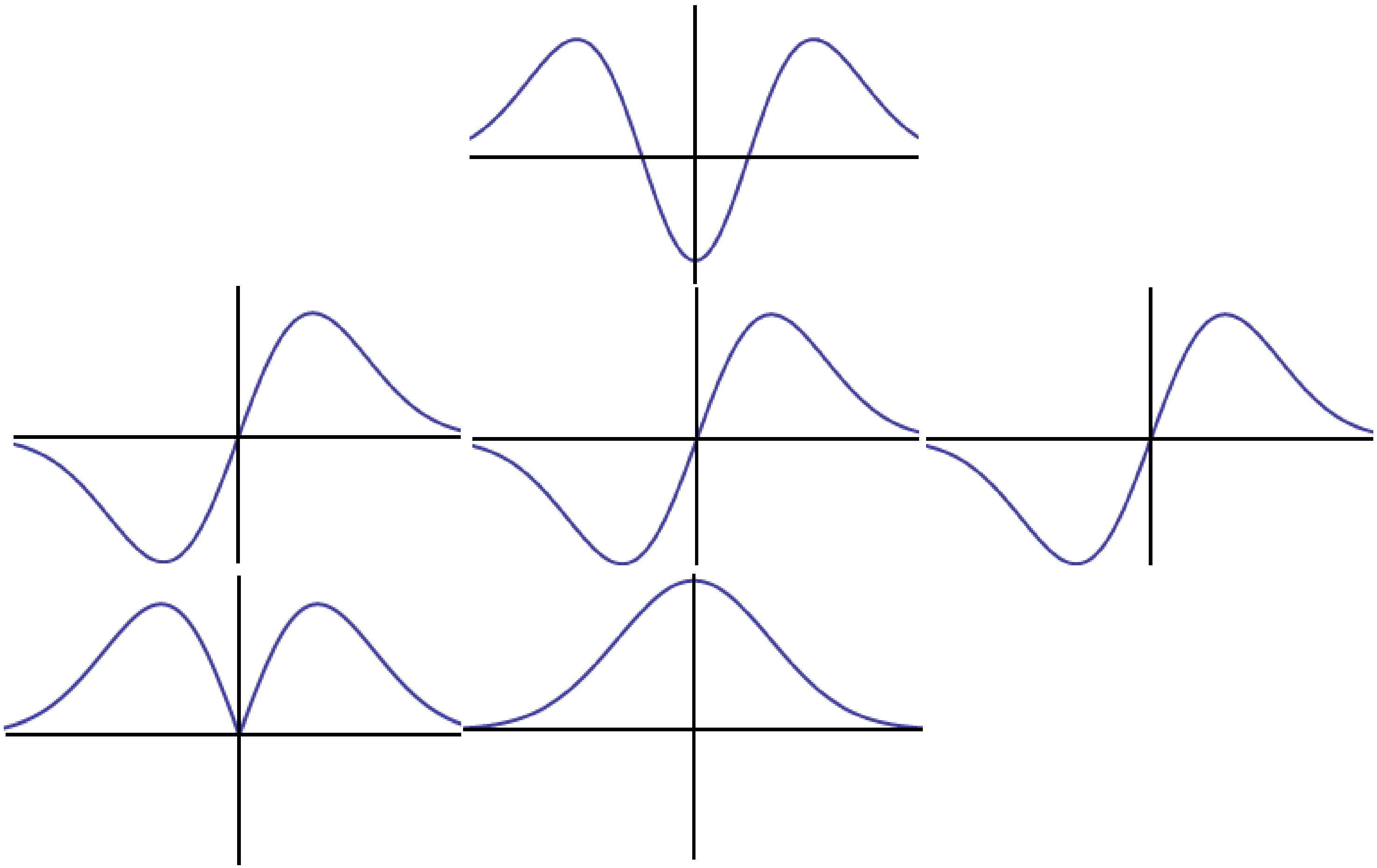

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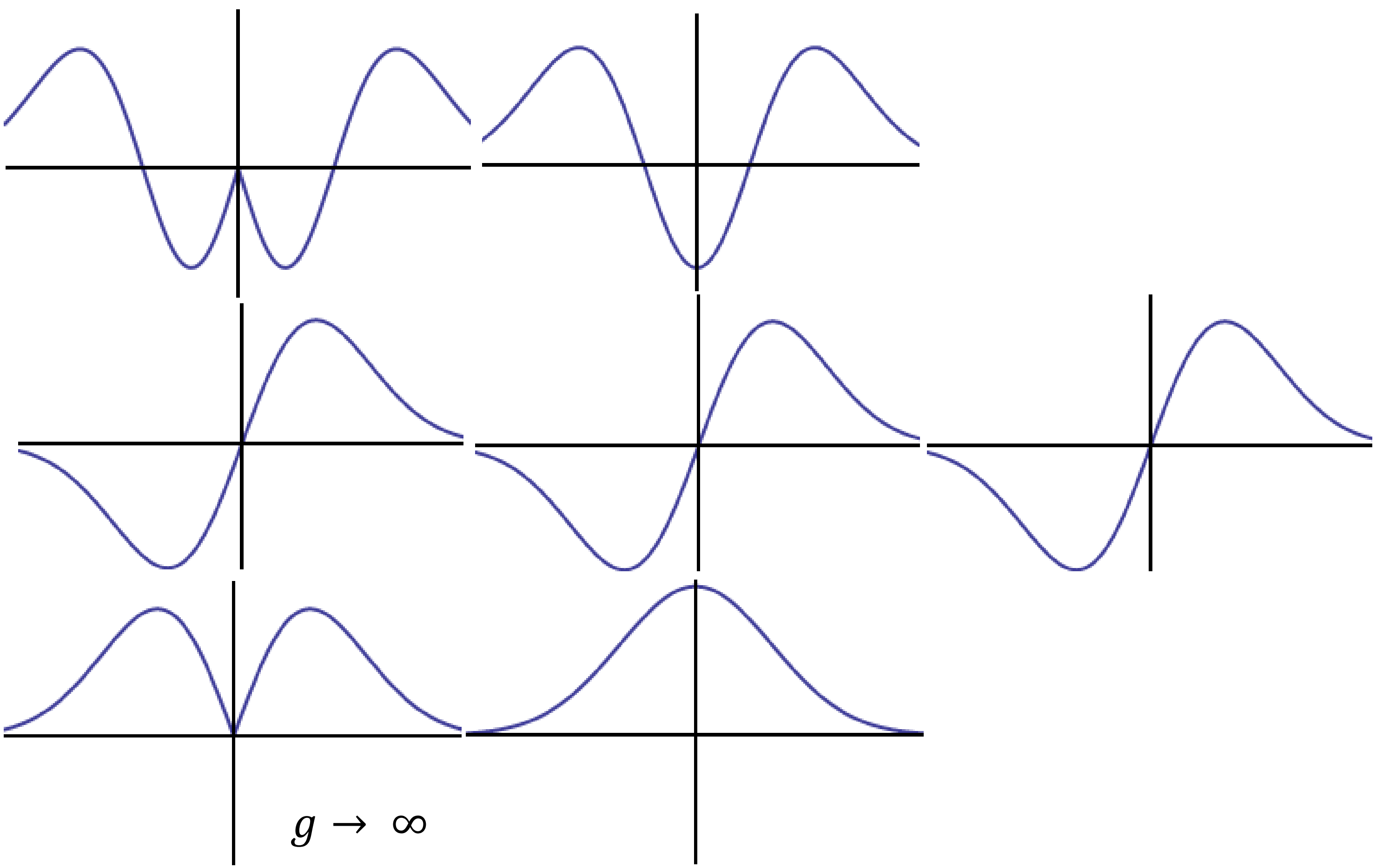

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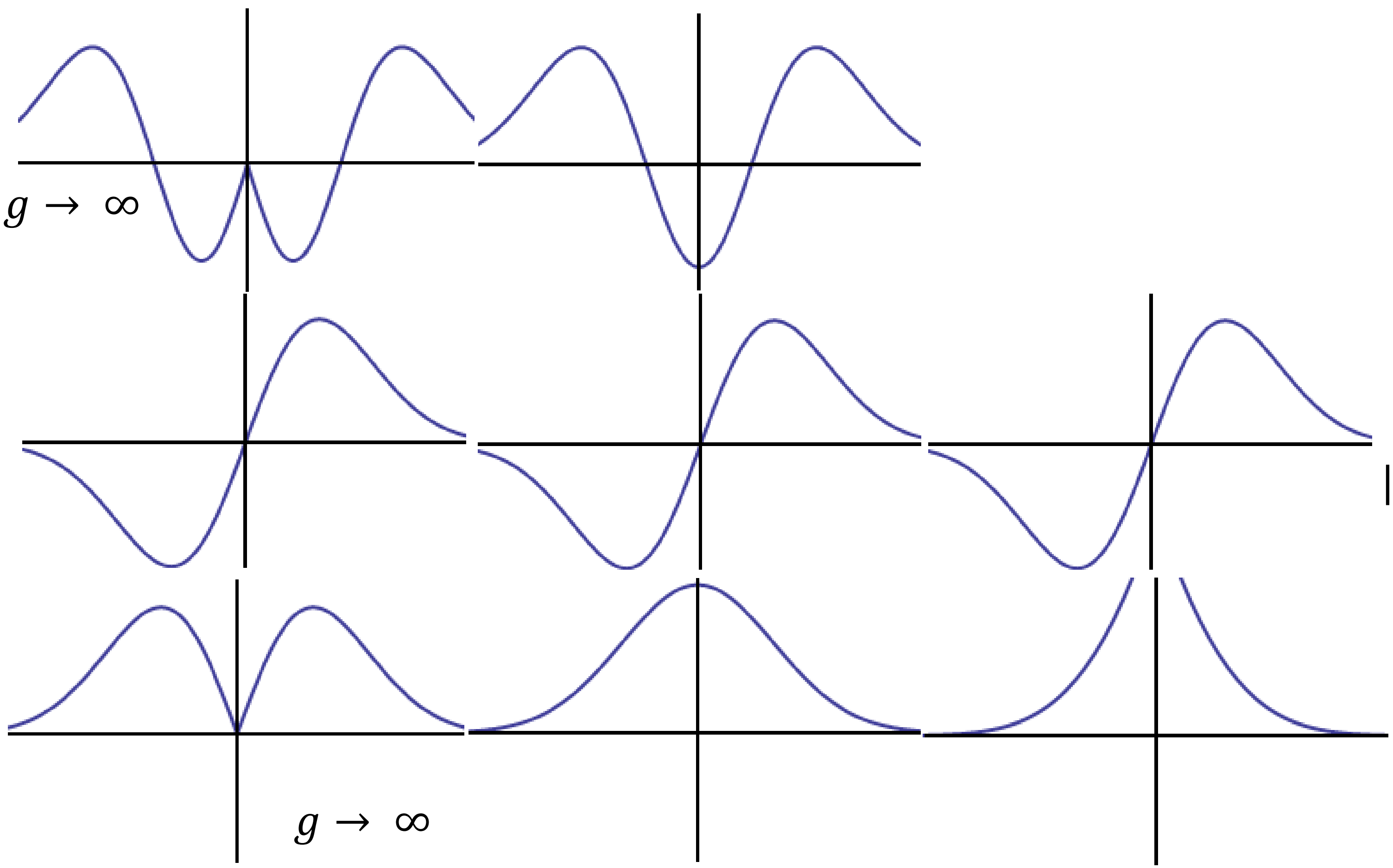

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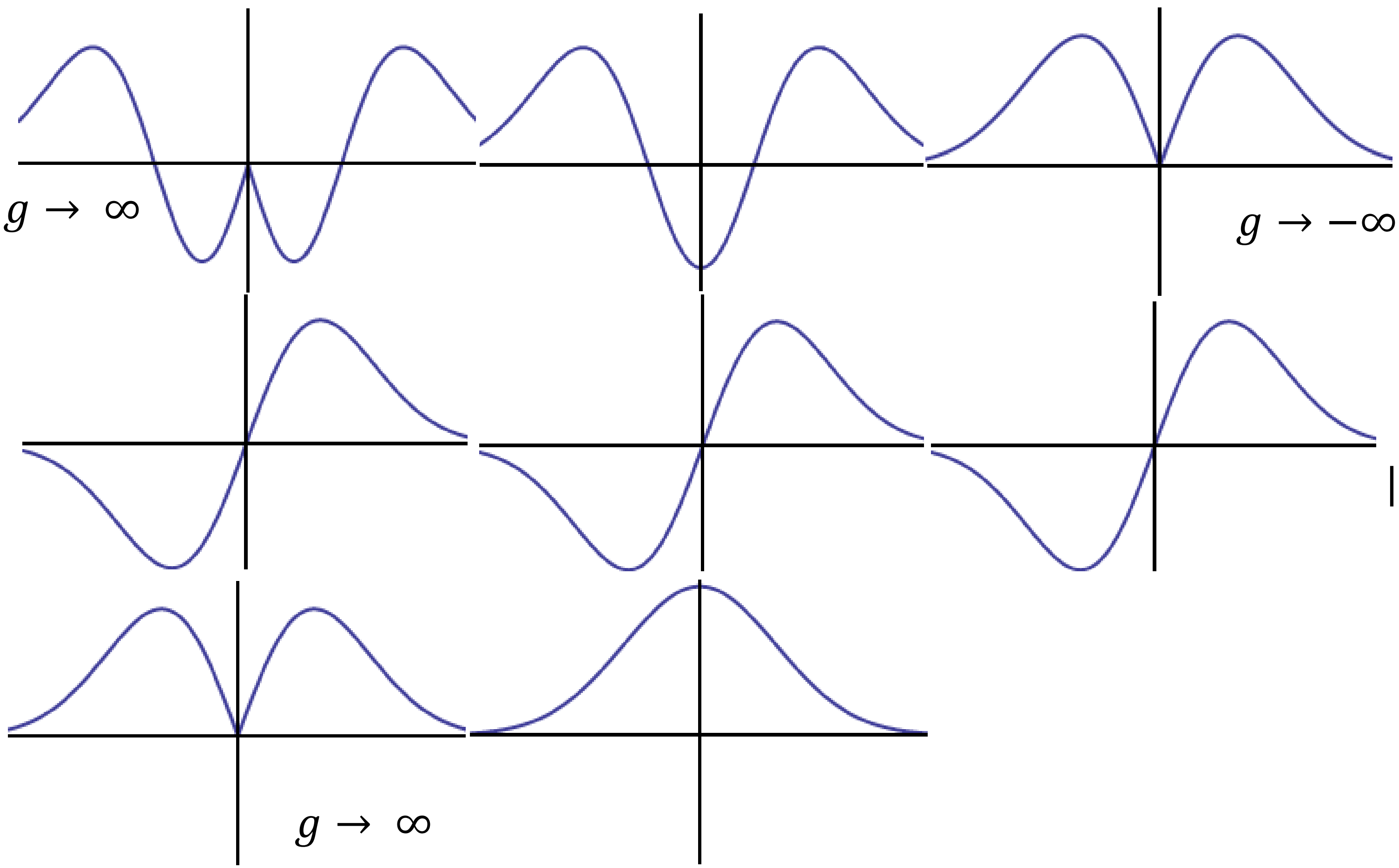

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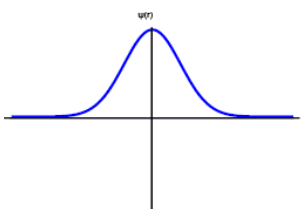
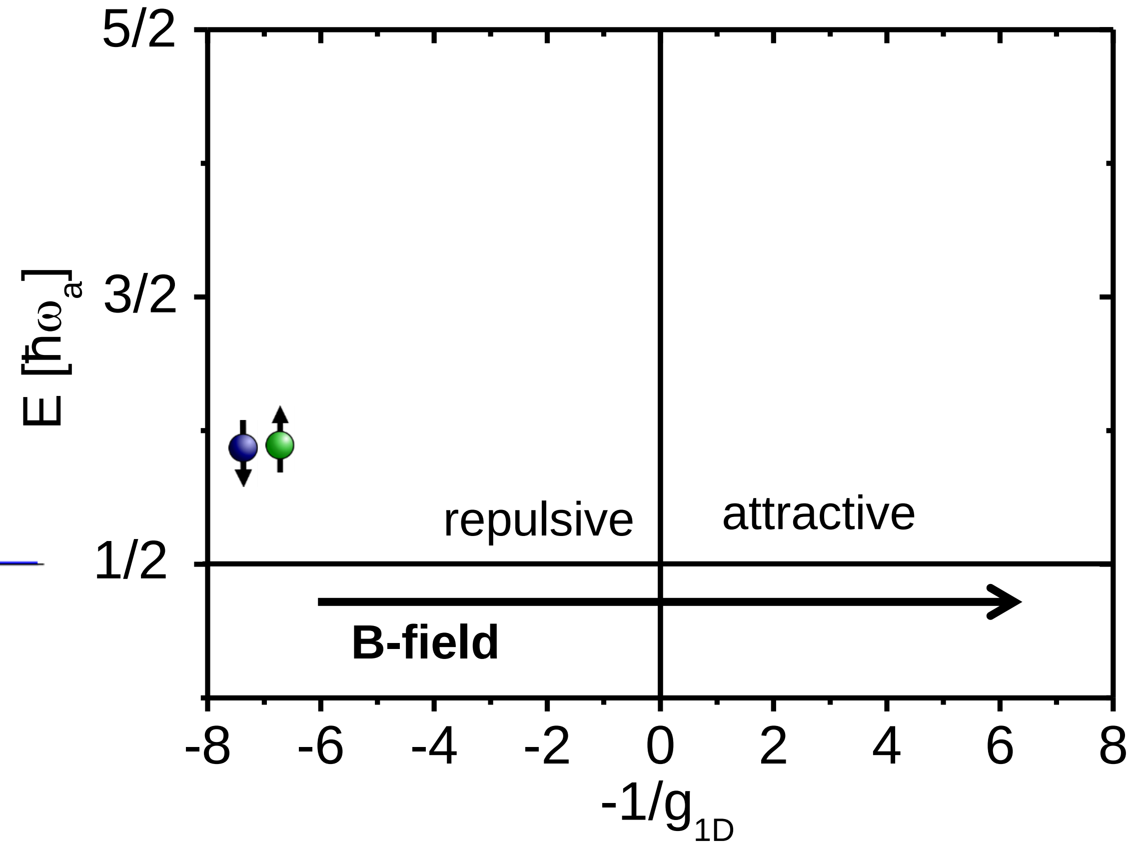
Energy of 2 atoms in a harmonic trap

Relative energy of two contact-interacting atoms: $V(x) = \frac{1}{2}\mu\omega^2 x^2 + g_{1D}\delta(x)$





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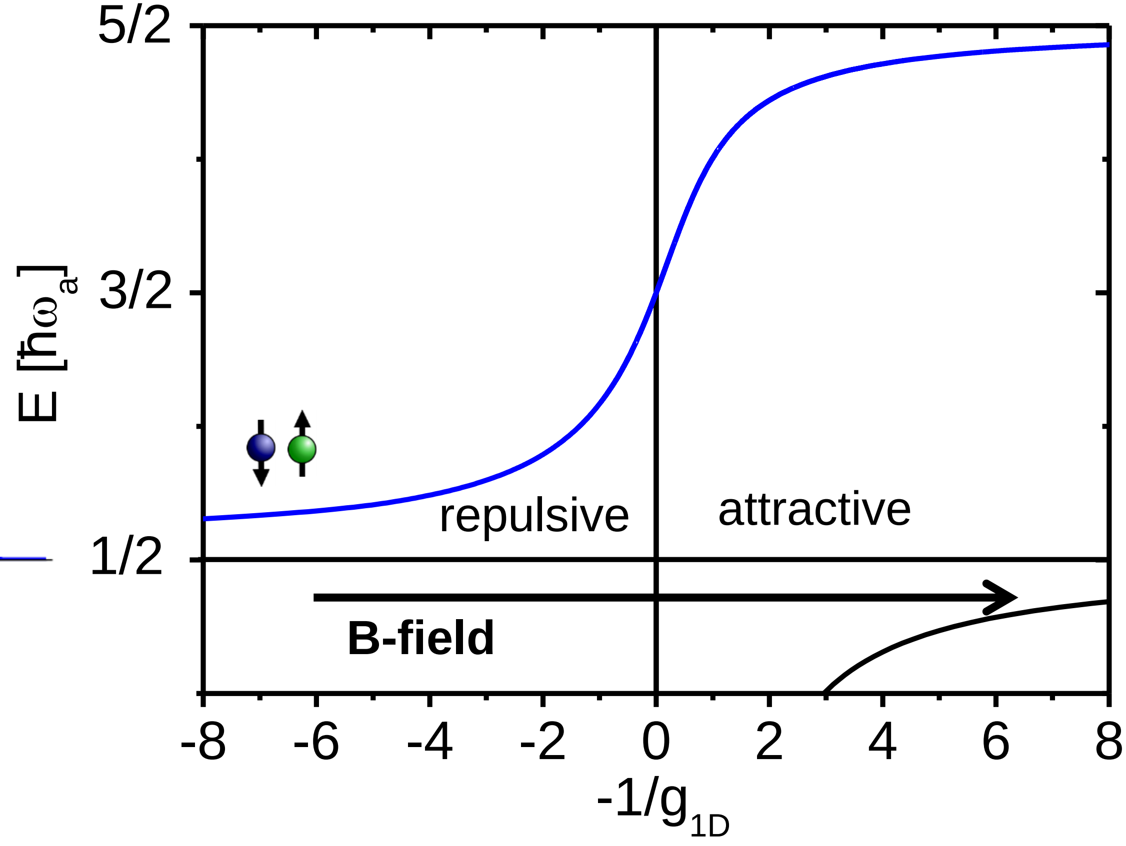

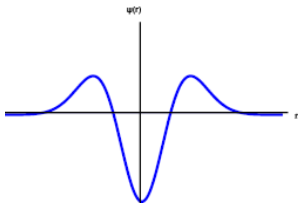

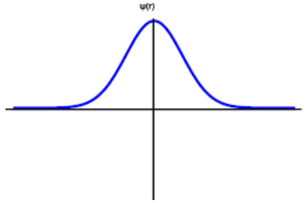

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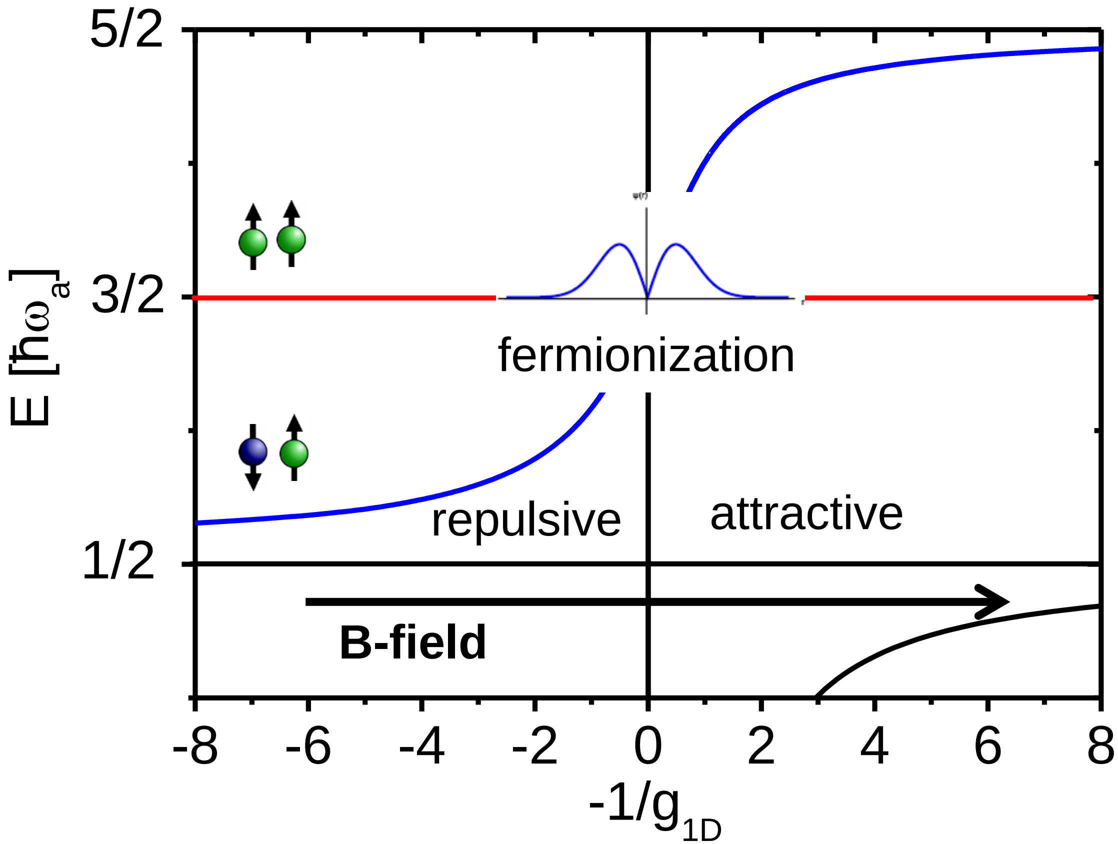
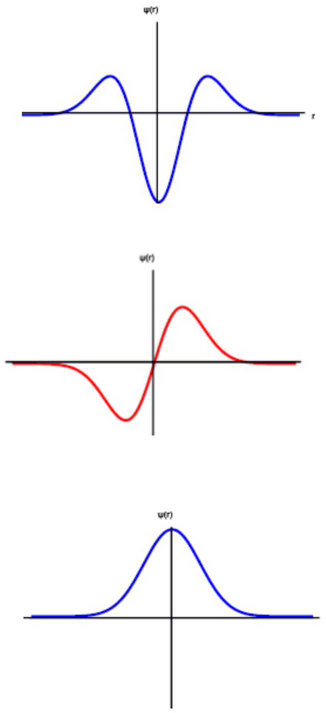
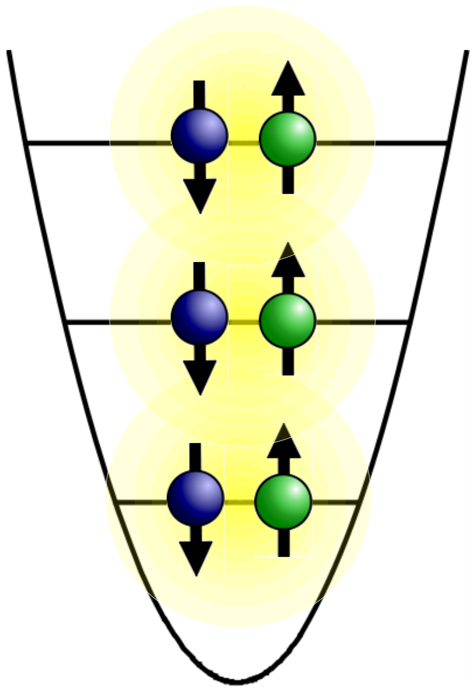




G. Zürn et al., PRL **108**, 075303 (2012)

More particles …

The particles should pair up within shells ….



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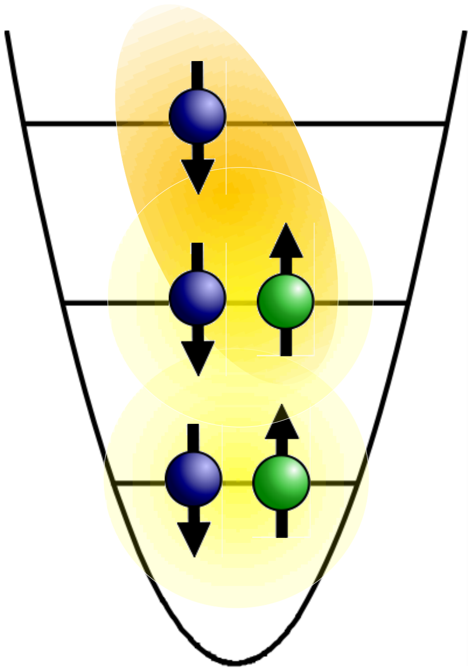
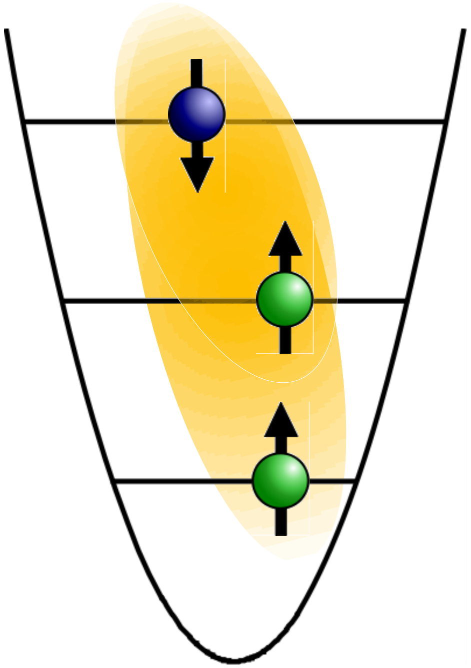
More particles …



Intershell pairing?

More particles …



Intershell pairing?

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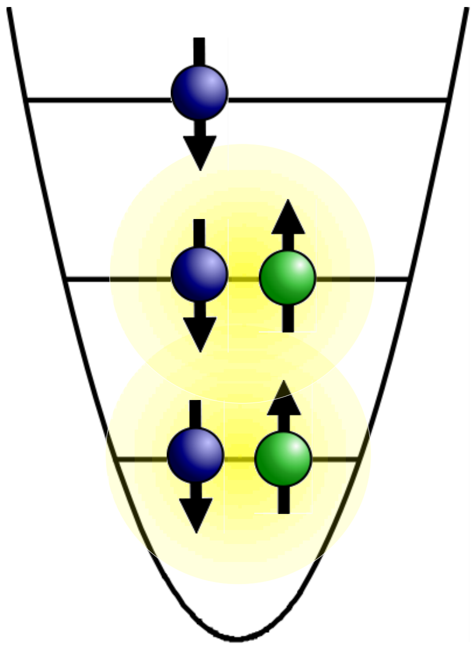
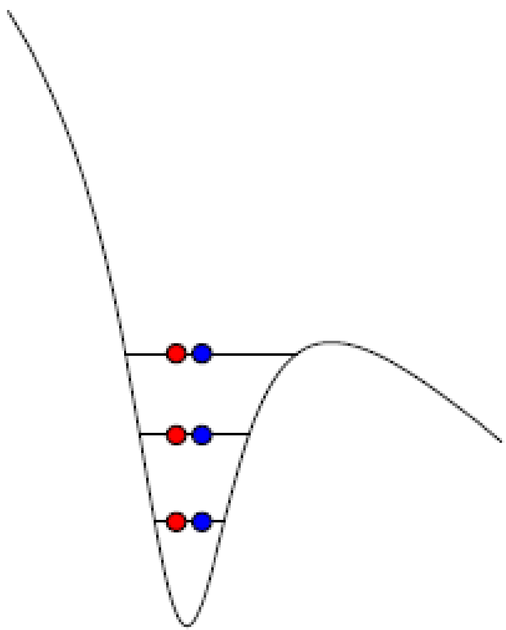
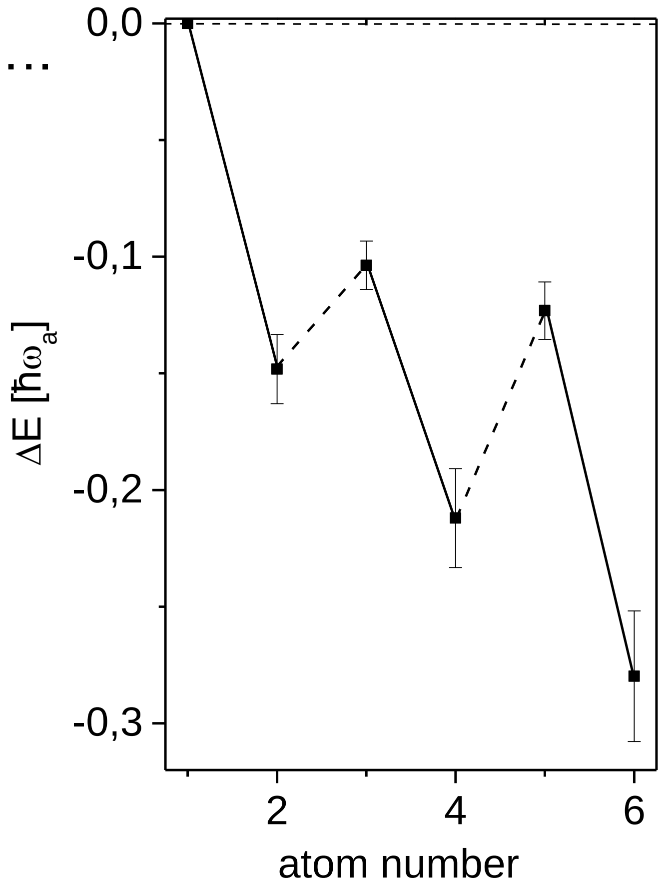


Intershell pairing?
→ Pauli blocking should supress this!

Attractive interactions

The energy it costs to remove one particle….



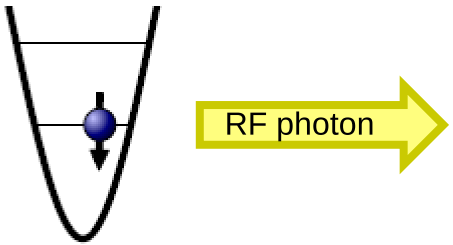


… compared to a noninteracting system

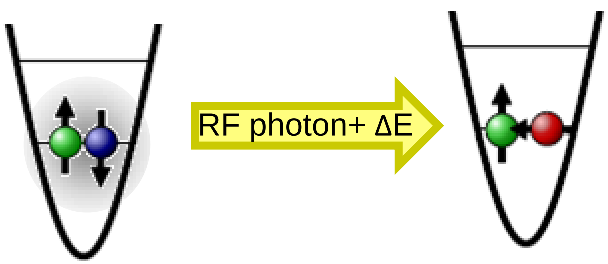
Precise energy measurements

Radio Frequency spectroscopy

„bare“ RF – transition

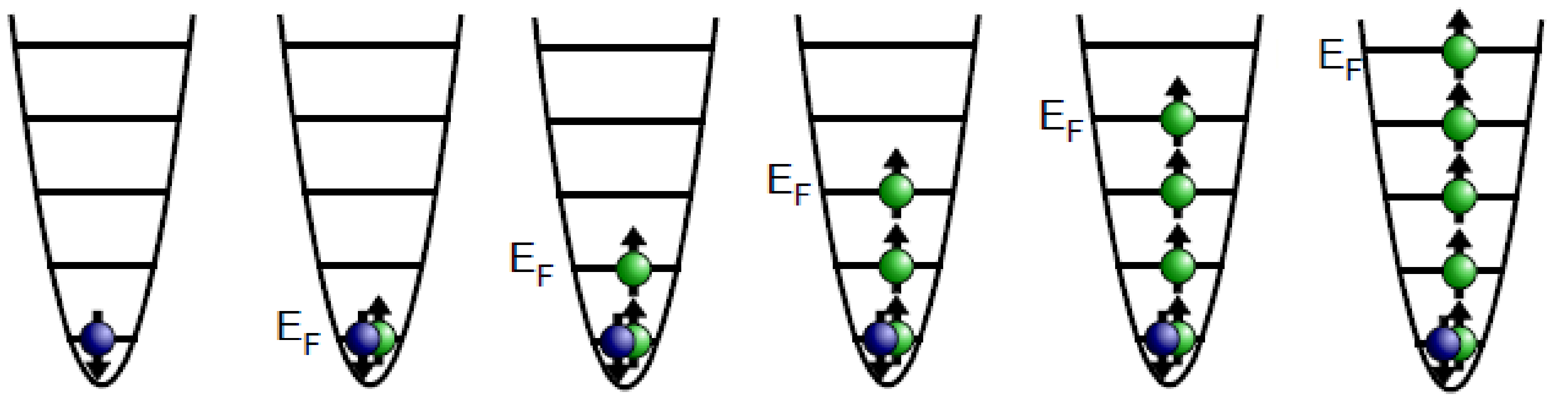


RF – transition with interaction



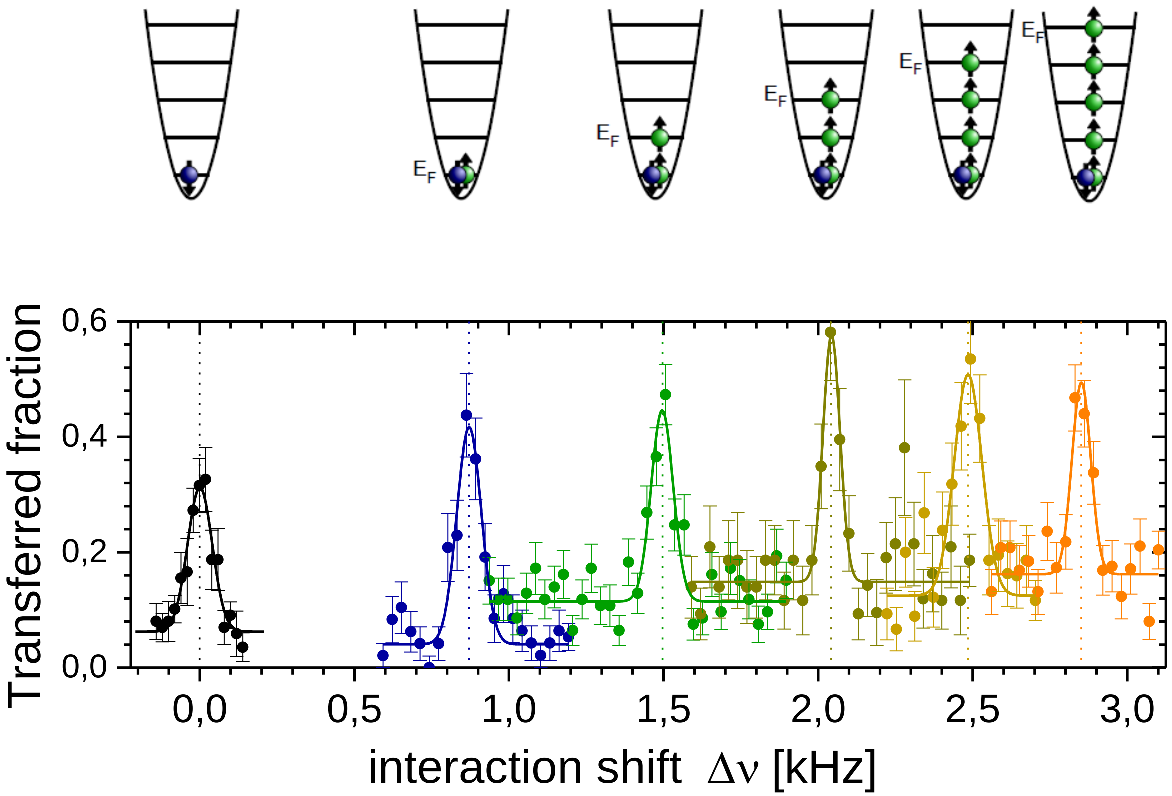
Approaching the many body limit?

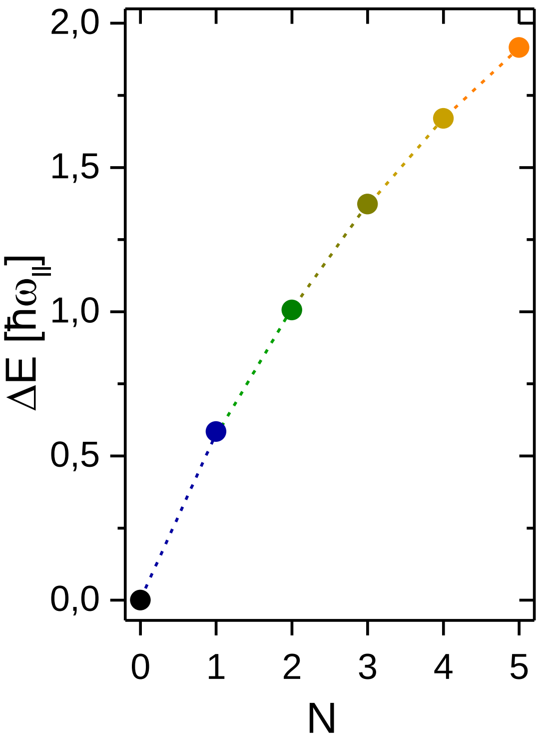
Grow a Fermi sea:
add a growing number of majority atoms to a single minority



Measure the interaction energy

vary the number of majority particles:





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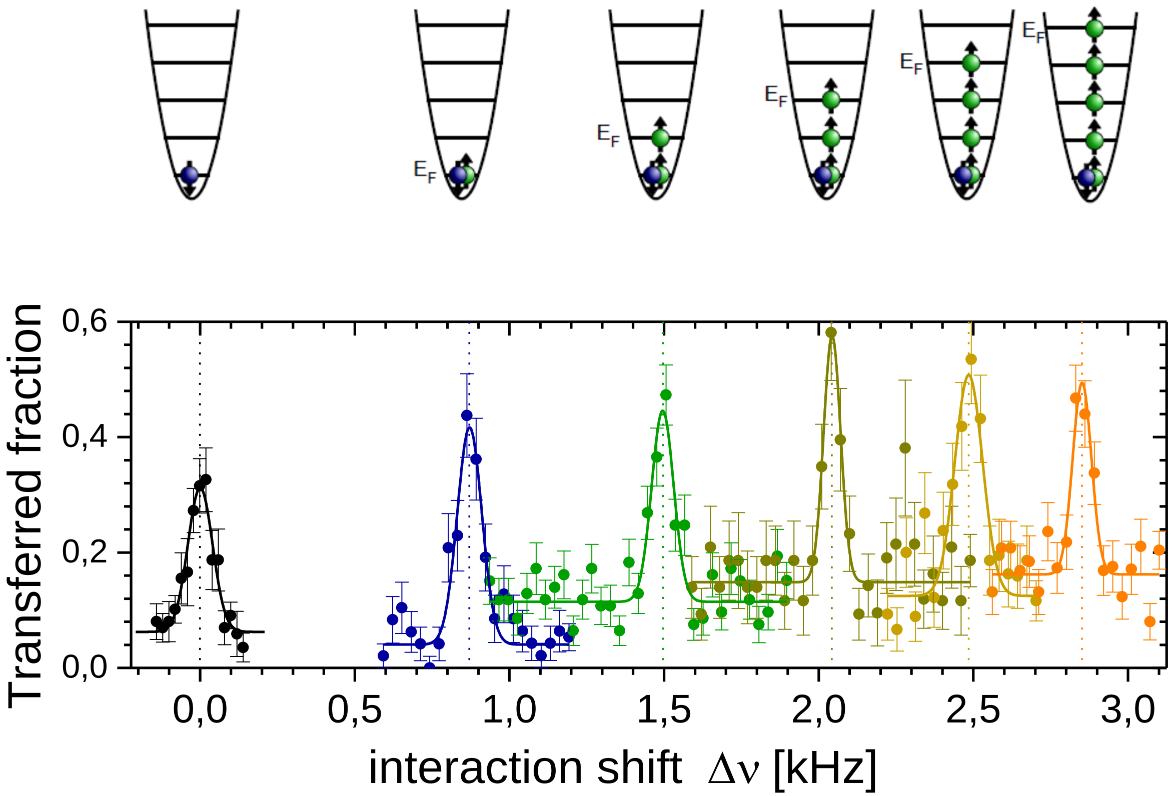
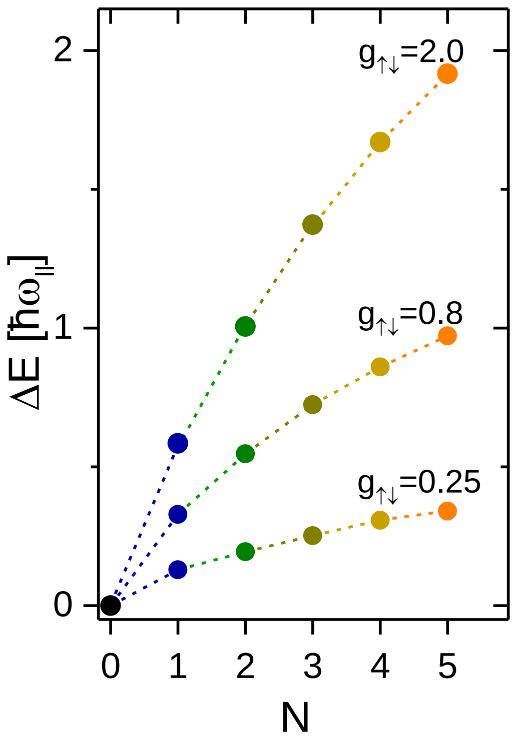
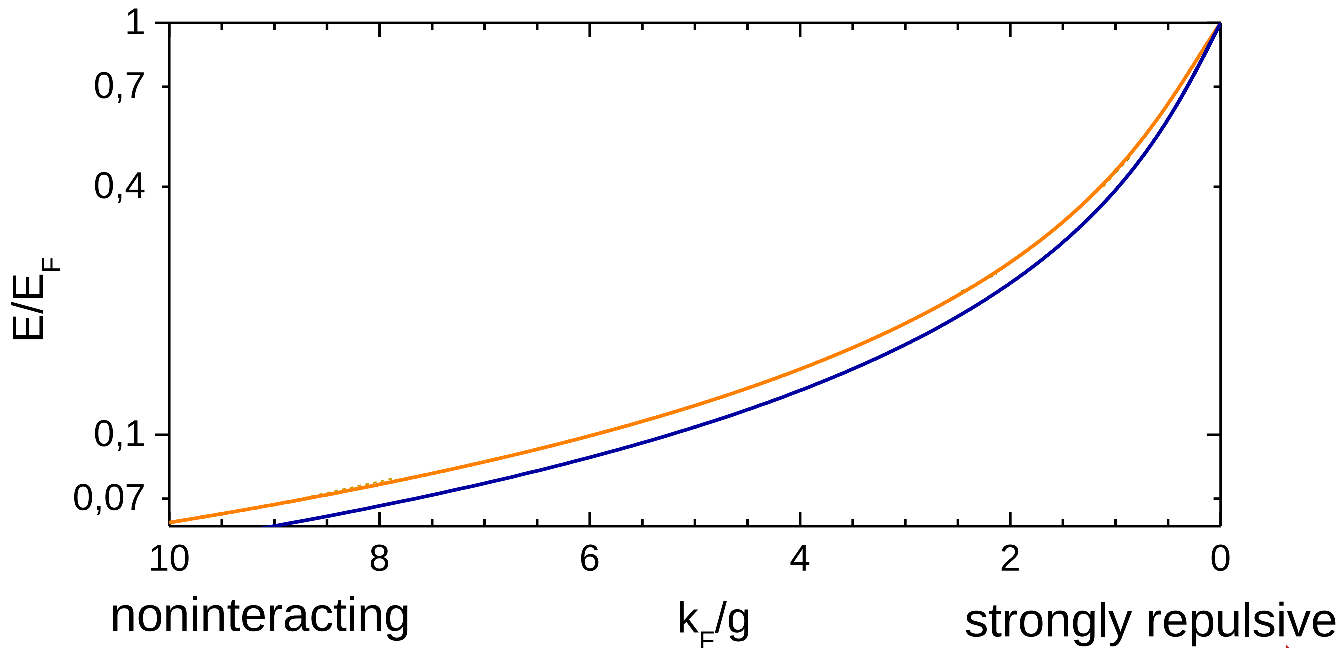
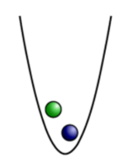


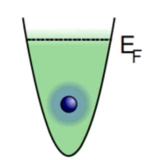


Interaction energy in dimensionless units



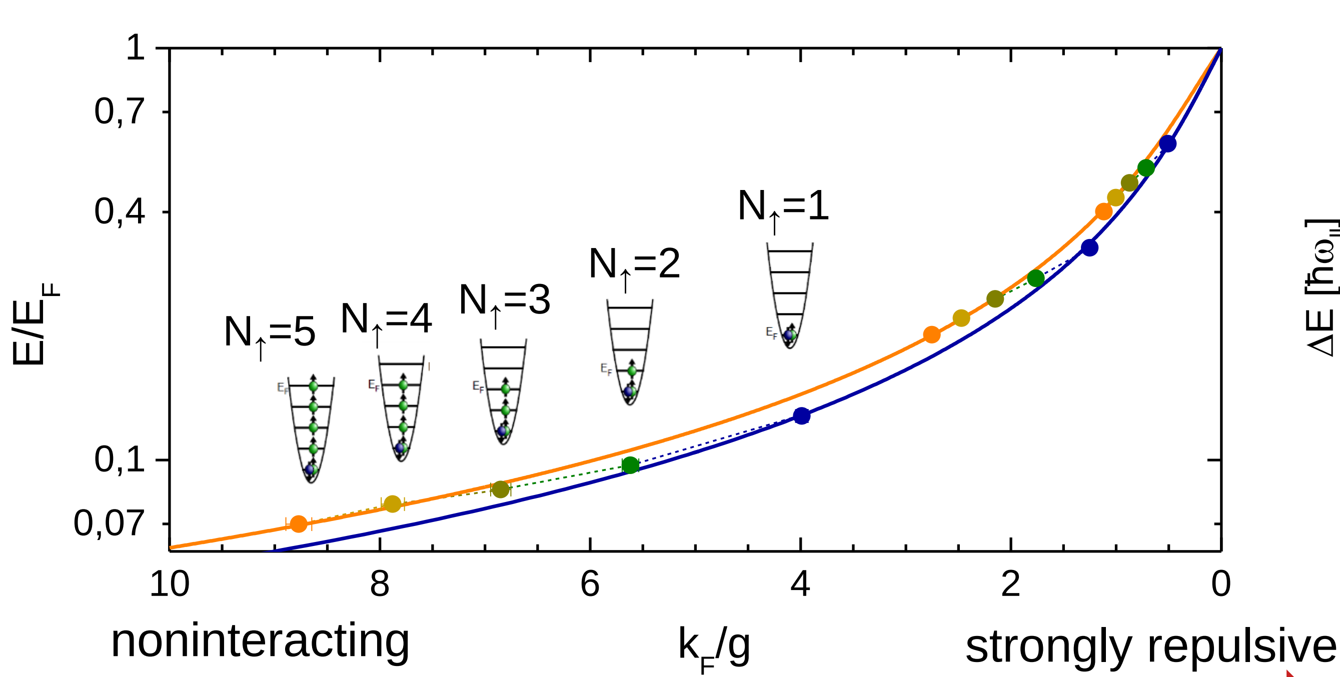


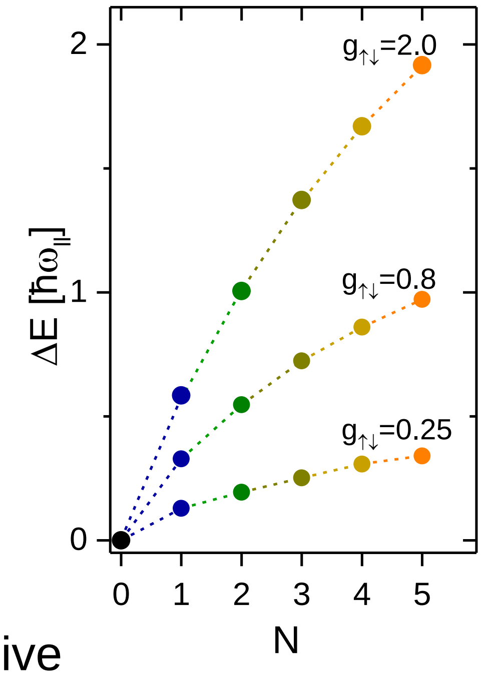
Analytic solution of the two particle problem
T.Busch et al., Found. Phys. 28, 549 (1998)



Analytic solution for an infinite number of majority particles
J. McGuire, J. Math. Phys. 6,432 (1965)
(local density approximation)

Interaction energy in dimensionless units





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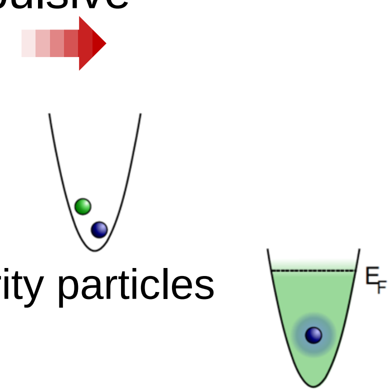

Interaction energy in dimensionless units

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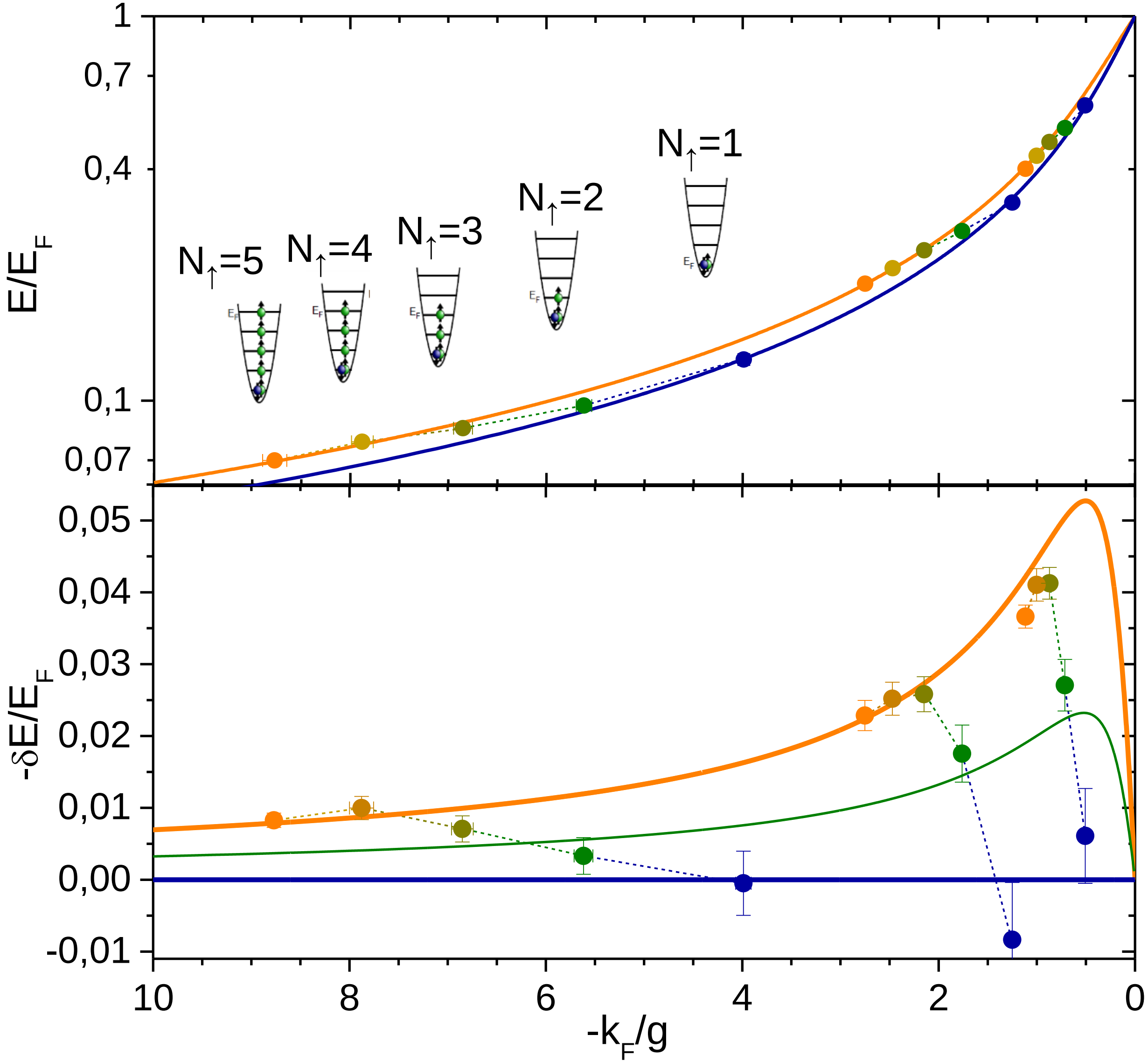

- 2 particles
- N particles
- 3 particles

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

A.Wenz et al., arXiv:1307.3443 (Science, in press)

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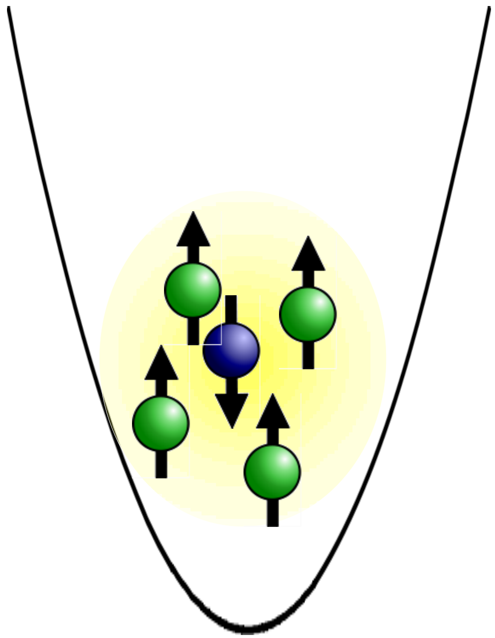
Approaching the many body limit…

… with very few particles (in a one-dimensional system) …

… a 1-D polaron?



- We observe the energy of the finite system to approach the many body energy

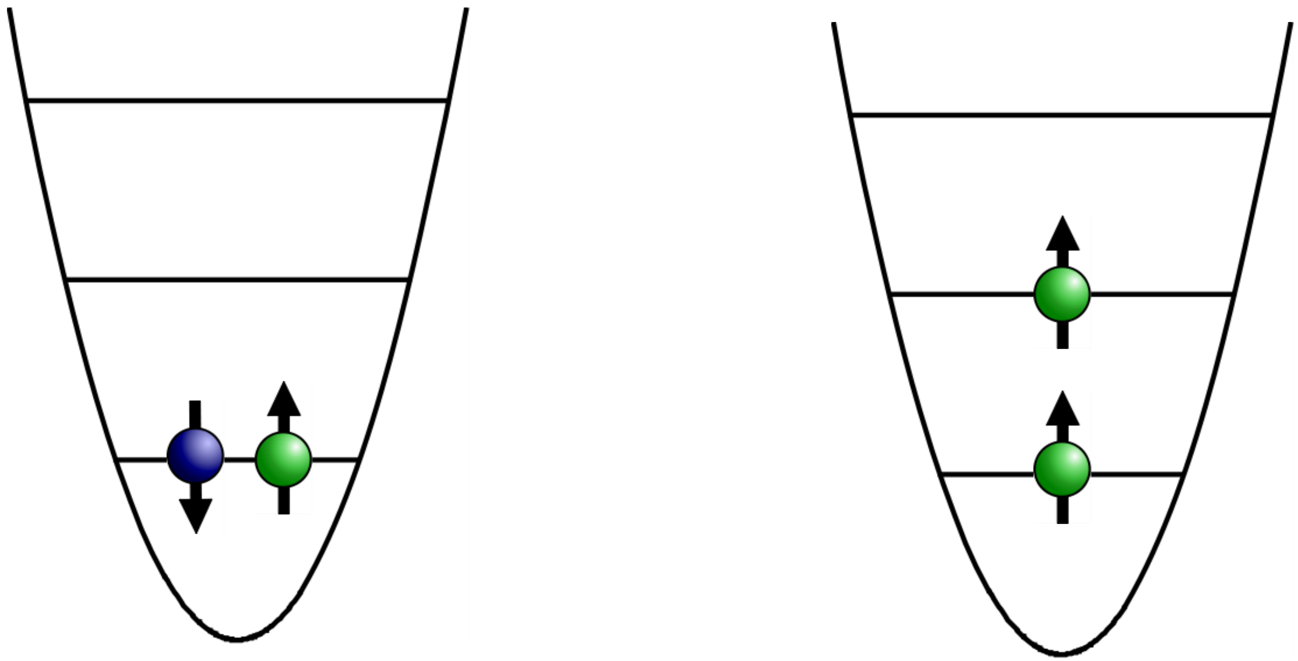
- We do not measure a spectrum an excitation spectrum from which a quasi particle residue could be deduced.

Can we also learn something about correlations?

Spin correlations

Let us first go back to the two-particle case:

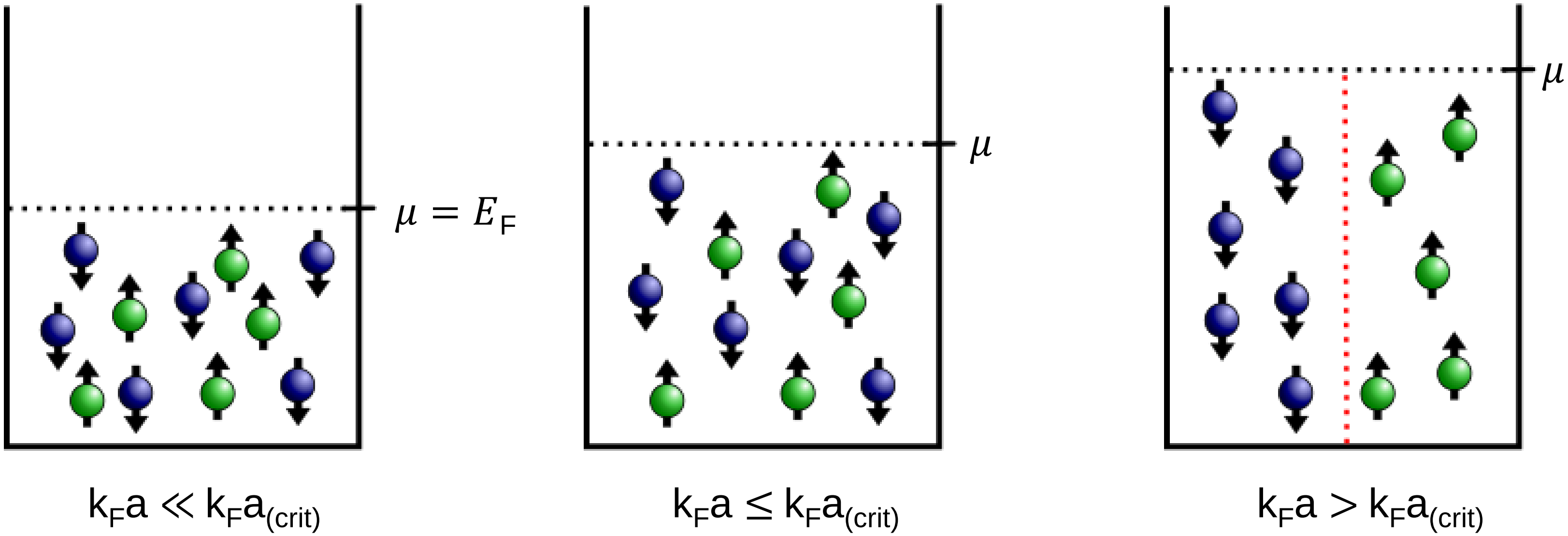
- Without any interactions, the singlet has lower energy:



- Can we make the repulsion so strong that the triplet becomes the ground state?

Many spins

We can ask a similar question for a many body system:

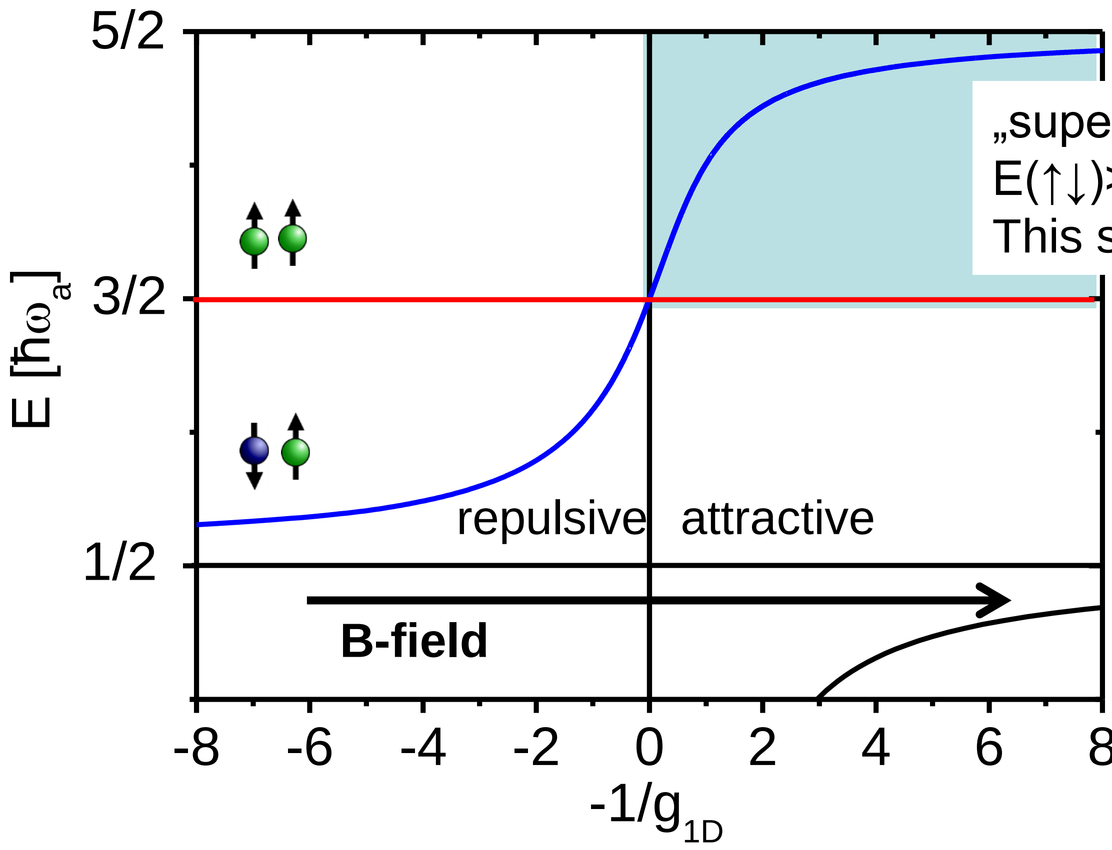


Can the repulsion between the different spins be so strong such that they separate?

→ The Stoner model of itinerant ferromagnetism

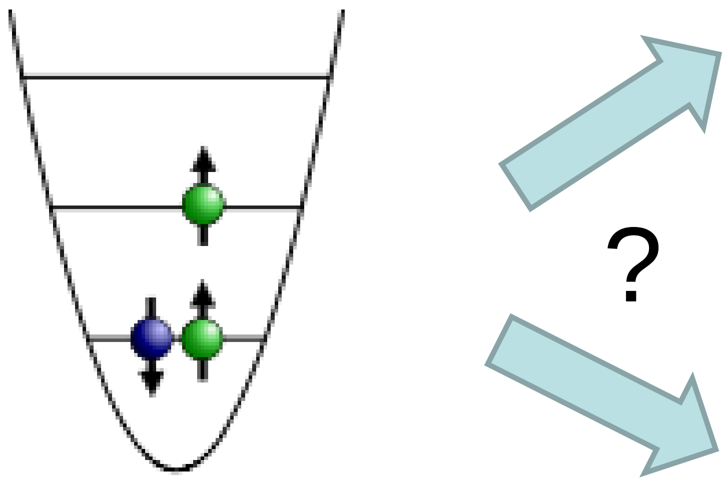
E. Stoner, Philos. Mag. **15**, 1018 (1933)

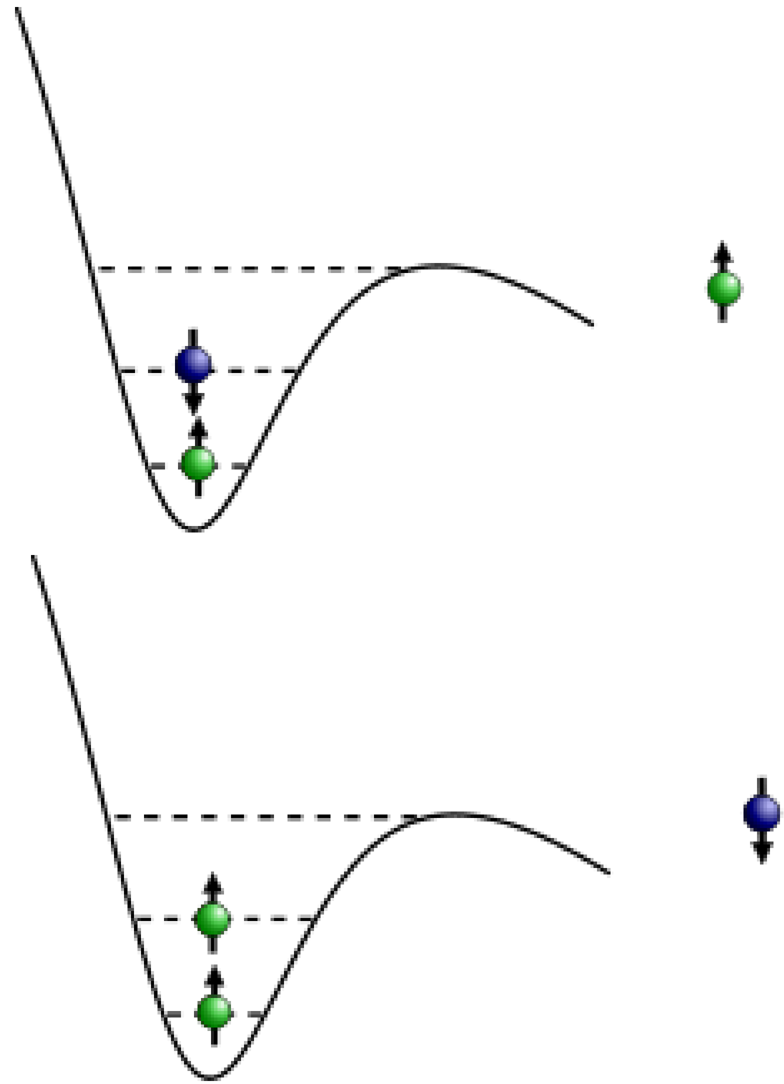
Energy of more than two atoms?



„super-repulsive“ regime
E(↑↓)>E(↑ ↑)
This should also apply to many spins

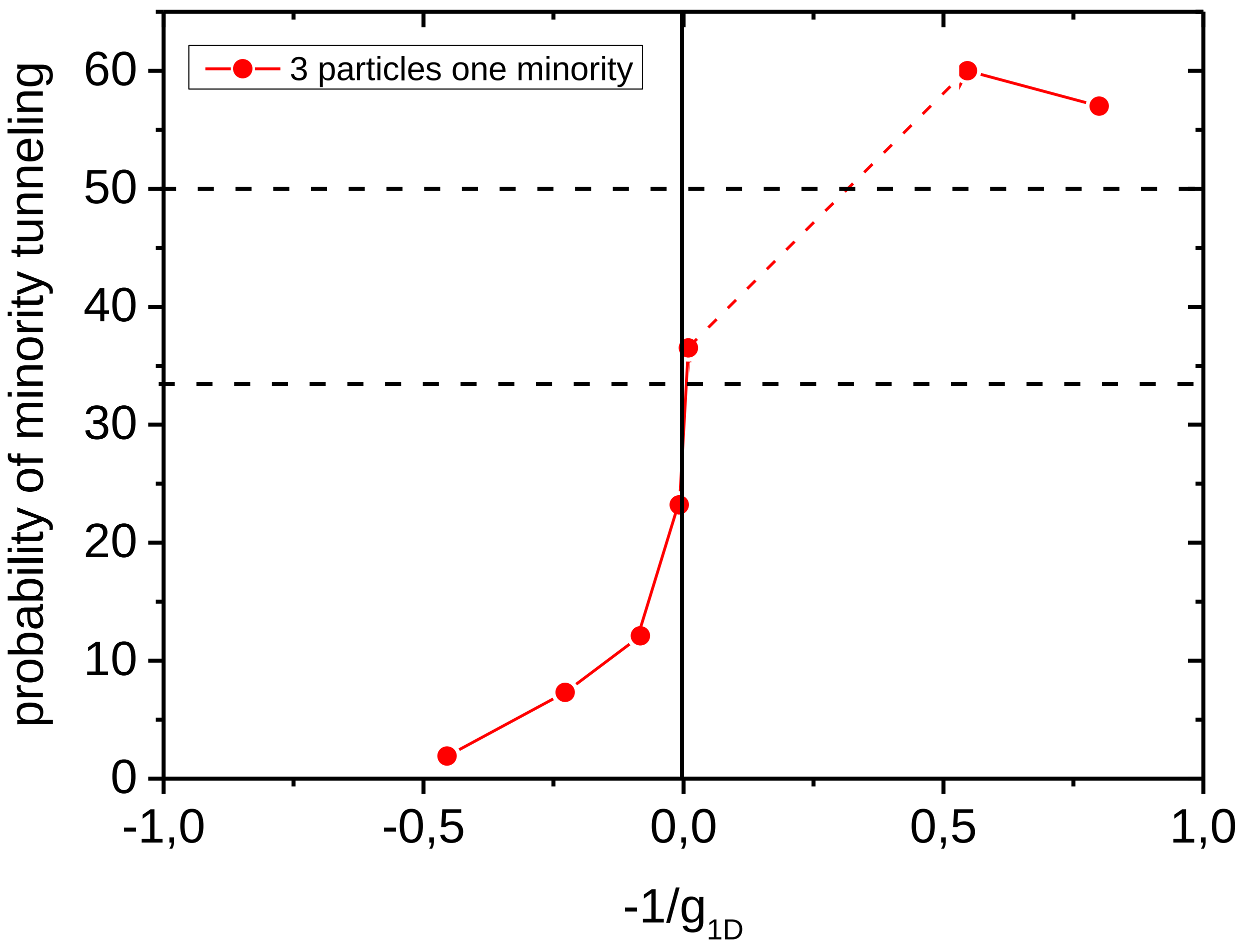
Three particles

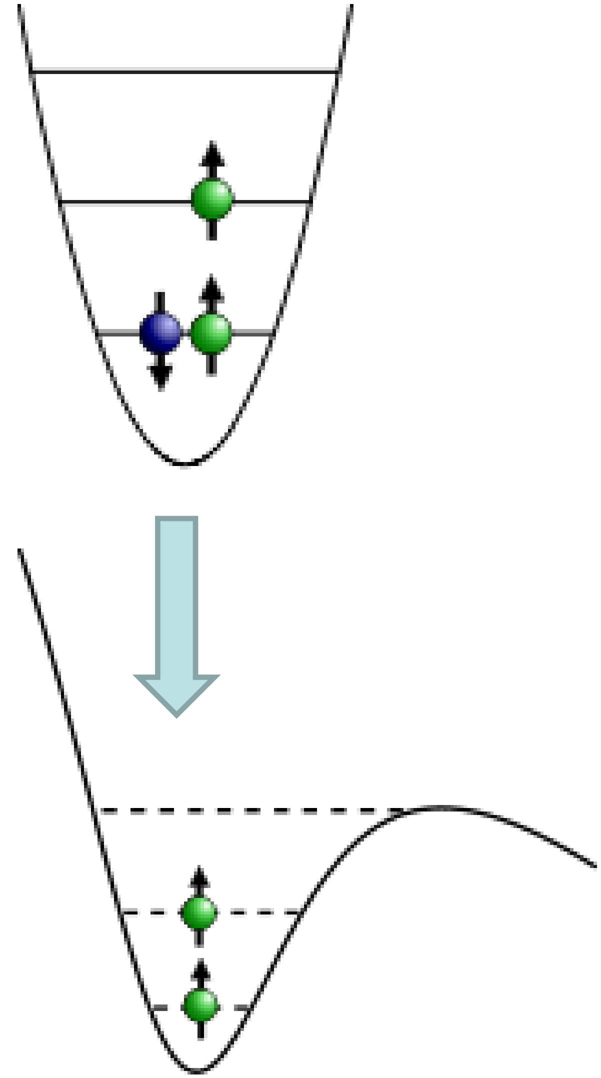




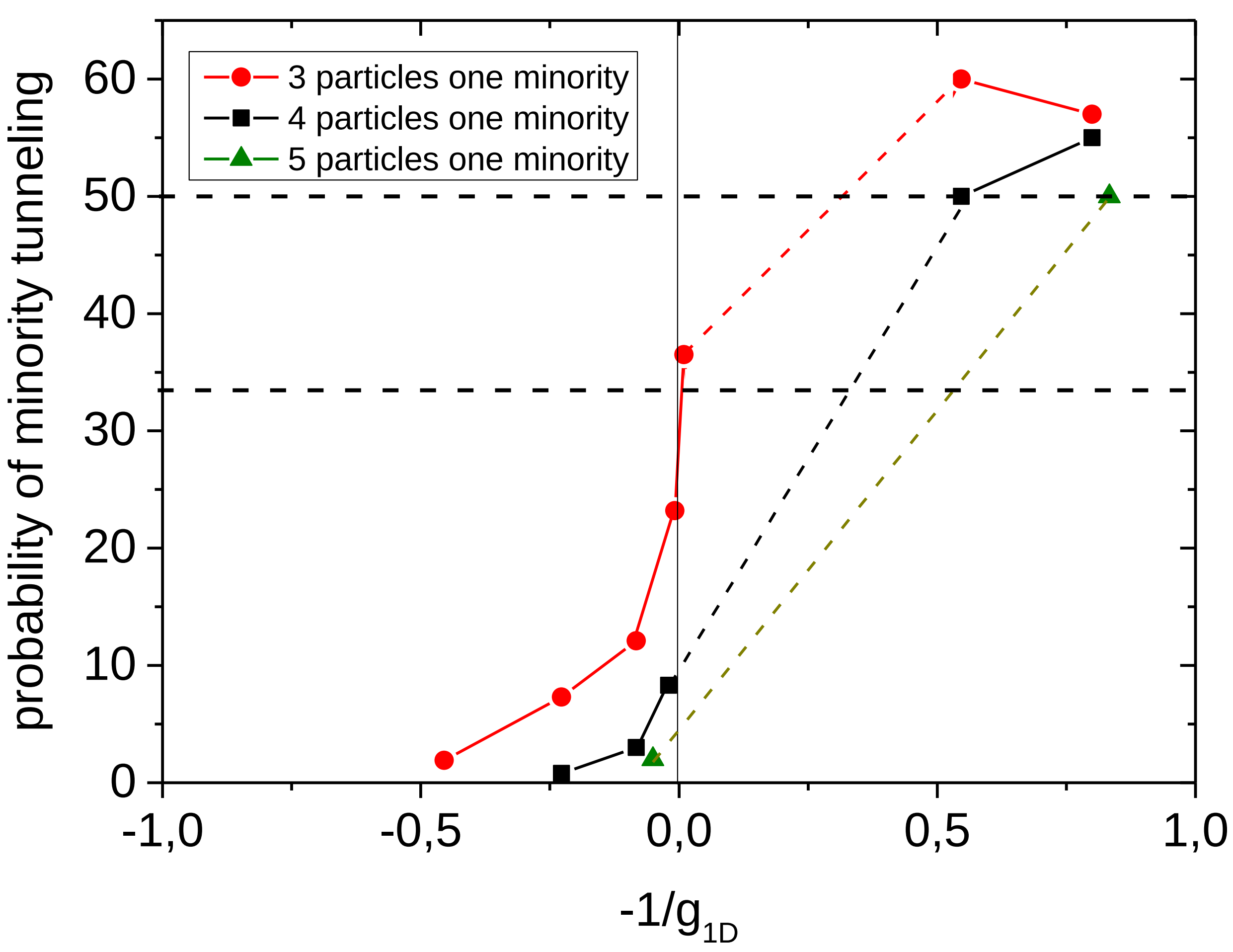
What‘s the probability for a spin down particle to tunnel first?

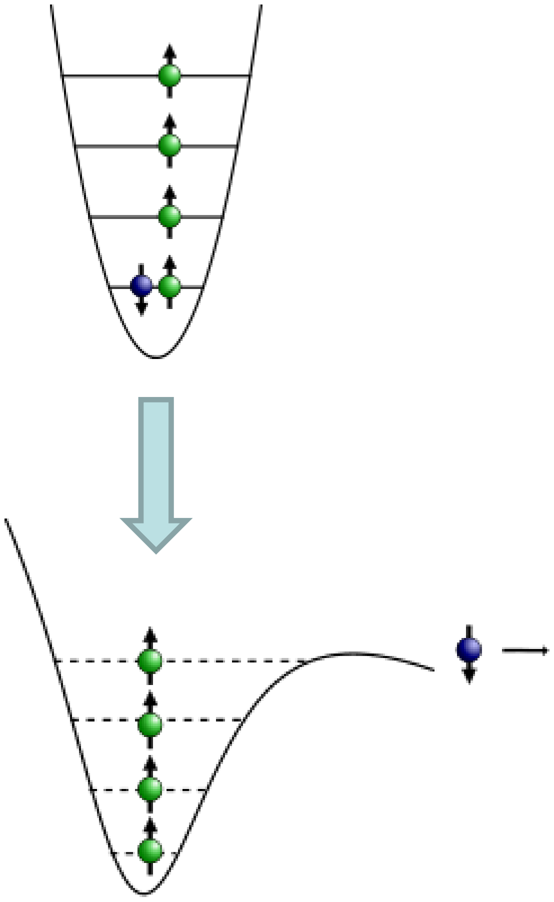
Three particles





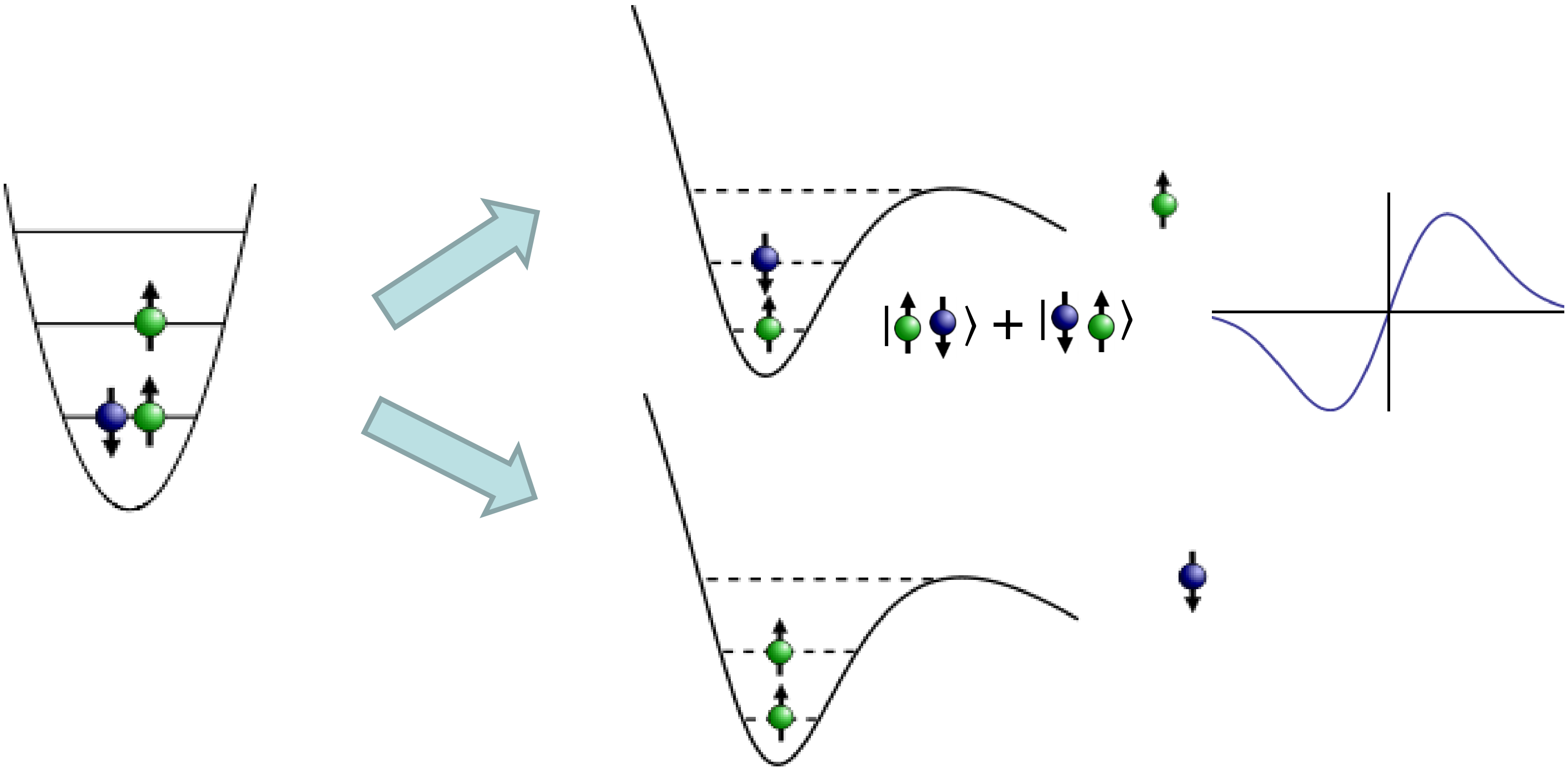
… more particles





What happens to the remaining atoms?

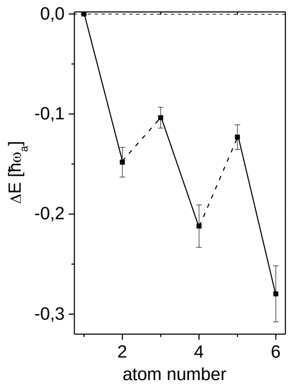
We can show that the two remaining particles **always have total spin S=1**



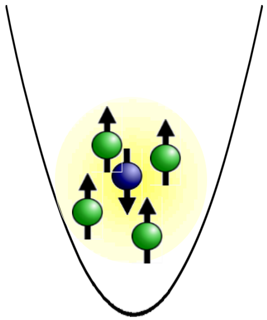
Are we separating the „cloud“ along a „domain wall“?

Summary

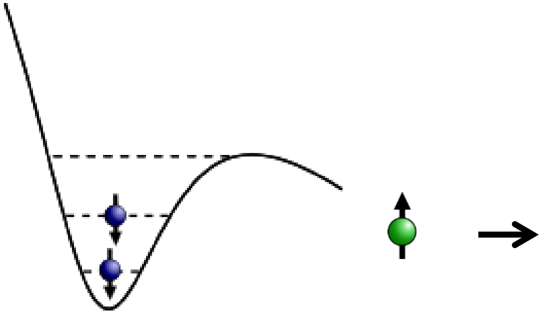
- We can see a strong odd-even effect:



- We can observe the few particle system approach the many body limit in 1-D

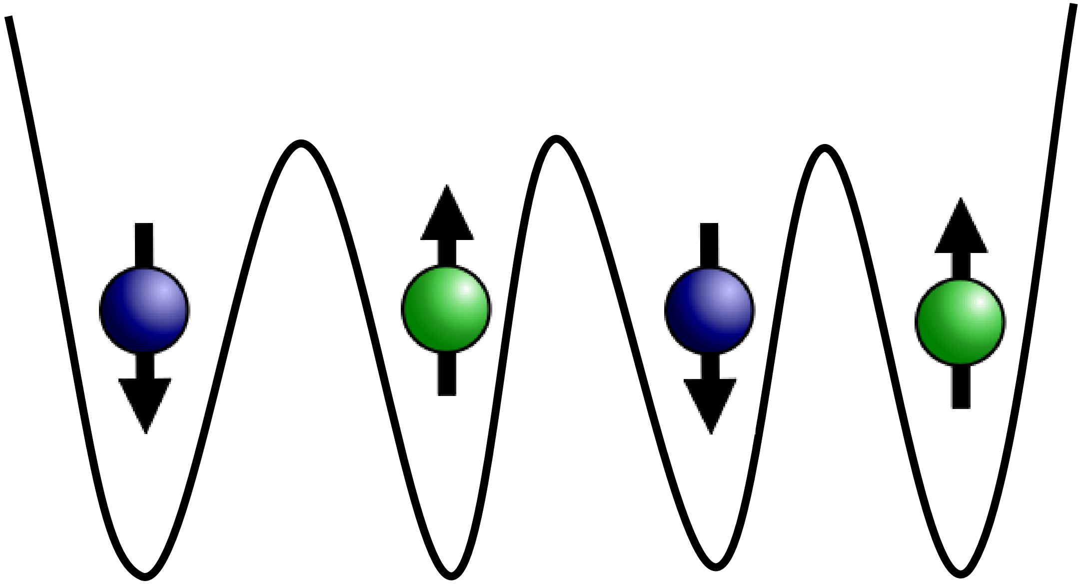


- We can observe correlations in a strongly repulsive few-body system



Outlook

Realize multiple wells with similar fidelity and control



Basic building blocks of condensed matter!

We moved to a new building

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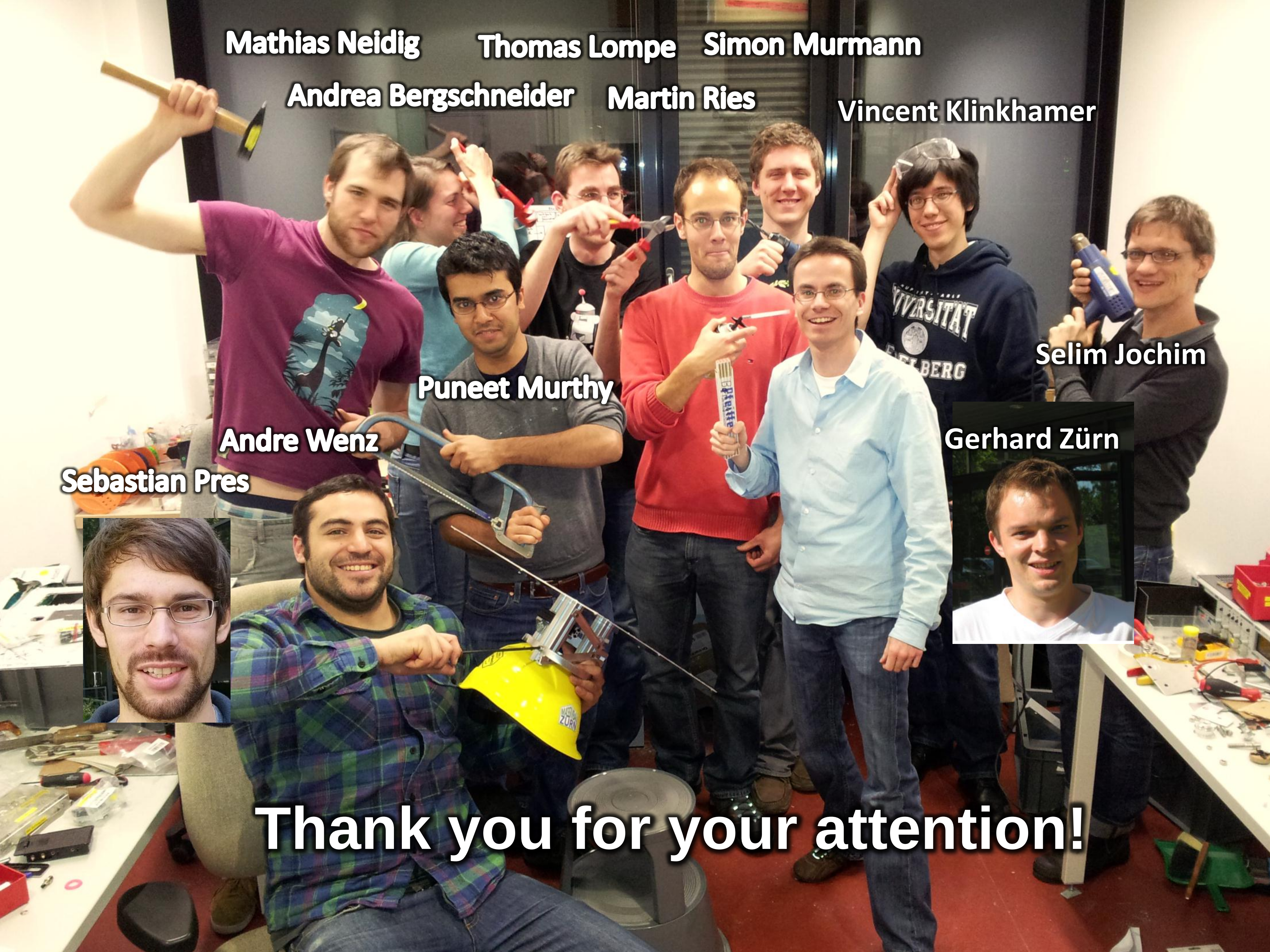
All the experiments presented have been performed at the MPI für Kernphysik

Entering the new building

By now, all experiments are operational again!


Mathias Neidig
Thomas Lompe
Simon Murmann
Andrea Bergschneider
Martin Ries
Vincent Klinkhamer
Selim Jochim
Puneet Murthy
Andre Wenz
Gerhard Zürn
Sebastian Pres
Thank you for your attention!