Deterministic preparation and control of a few fermion system

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Max-Planck-Institut

Ultracold atoms experiments @ EMMI

Center for
Quantum
Dynamics

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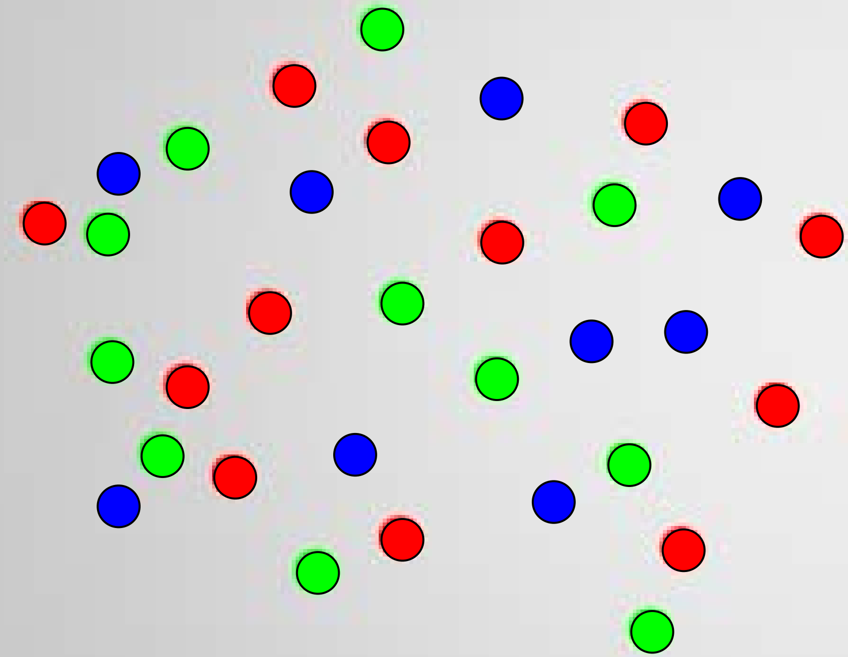
The matter we deal with



- T=40nK … 1µK
- Density n=10^9 … 10^{14}cm^{-3}
- Pressures as low as 10^{-17}mbar
- $k_B T$ ~ 5peV
- Extremely dilute gases, which can be strongly interacting!

Extreme matter!

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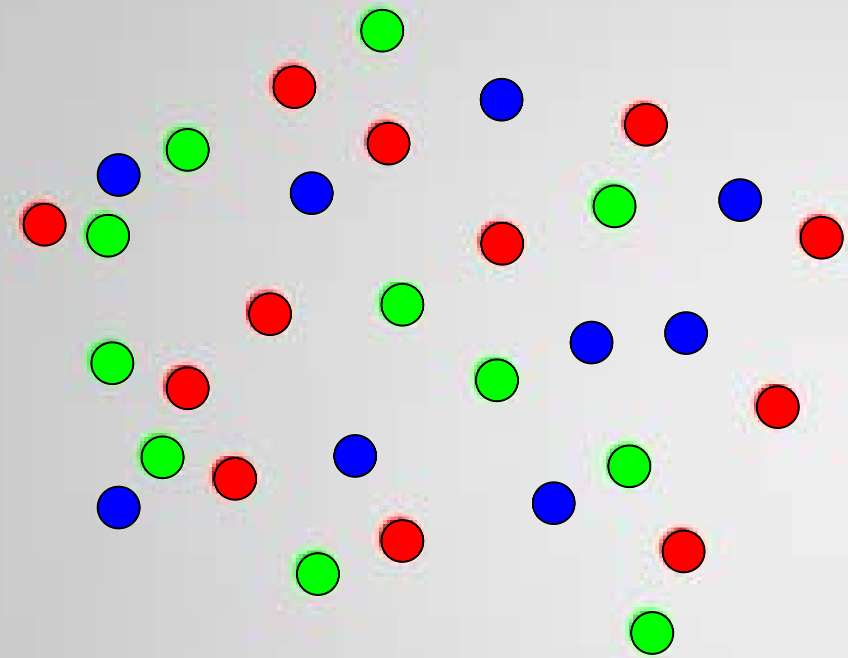
Important length scales



- interparticle separation

  $\sqrt[3]{1/n} \gg$ size of the atoms

- de Broglie wavelength

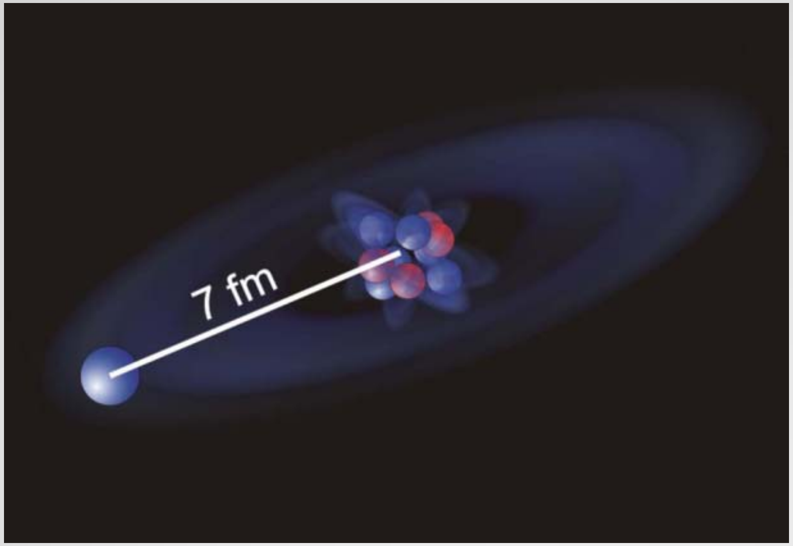
  $\sqrt{\frac{h^2}{2\pi mkT}} \gg$ size of the atoms

- scattering length *a* , only one length determines interaction strength

→ **Universal properties, independent of a particular system!**

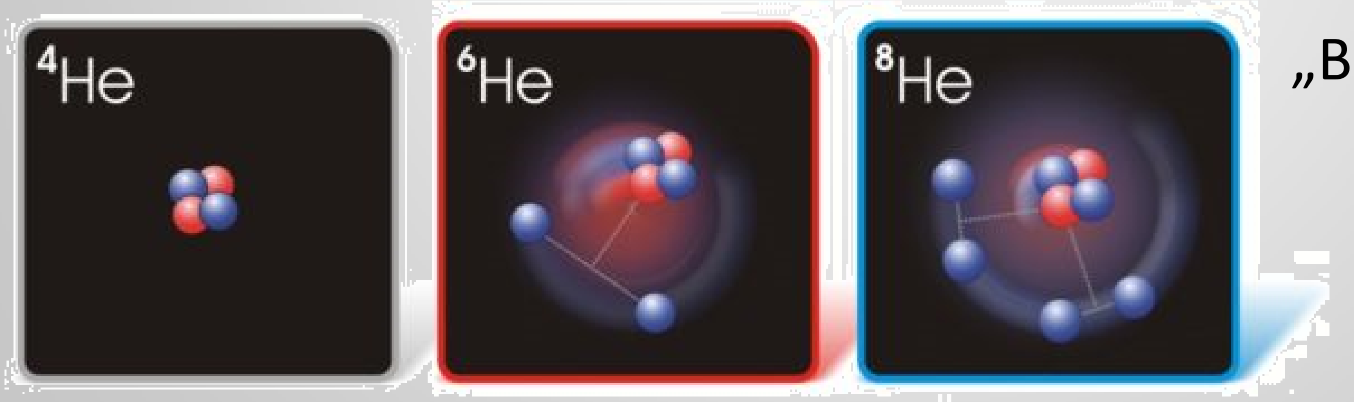
→ **We can tune all the above parameters in our experiments!**

Universality in nuclear systems …



„Halo dimer“

^{11}Be Nörtershäuser et al., PRL**102** 062503,2009



„Borromean“ states

Argonne Nat. Lab.

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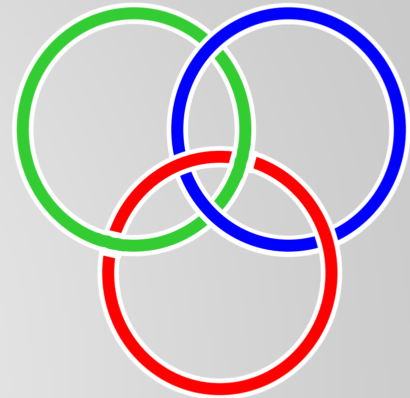
What we work on in the lab ….

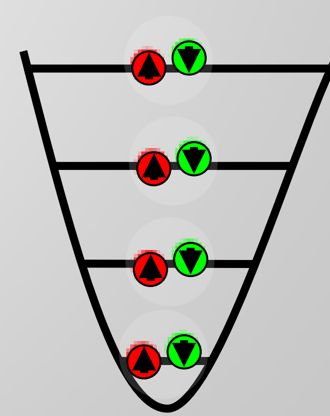
- **Three-body physics:**
  Radio frequency association of Efimov trimers

➢ **On the way to complex many-body phases**



- **Finite Fermi systems with tunable interaction**
  Very recent results!

➢ **Crossover from deterministic to thermodynamic ensembles**



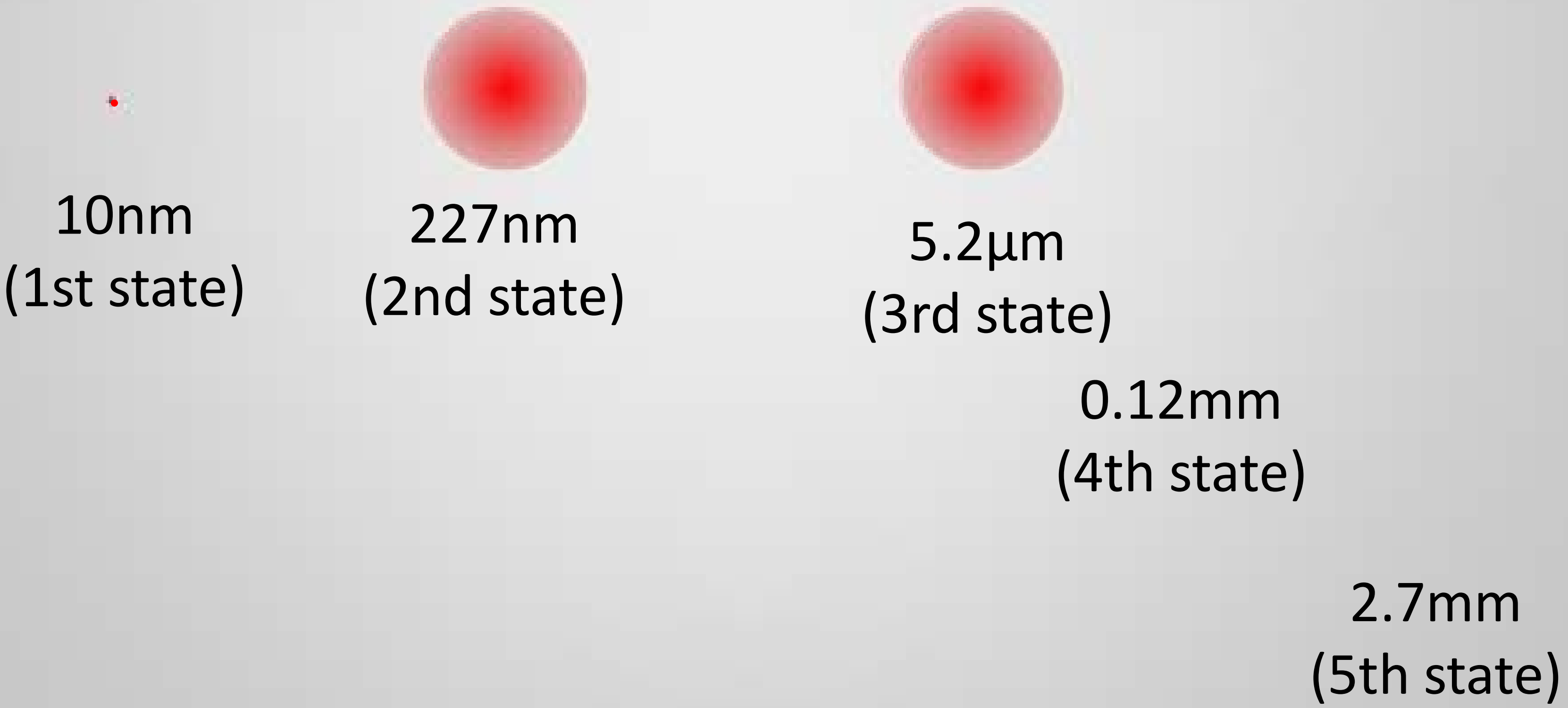
The Efimov effect (V. Efimov, 1970)

- …xists when the

Drawing: V. Efimov

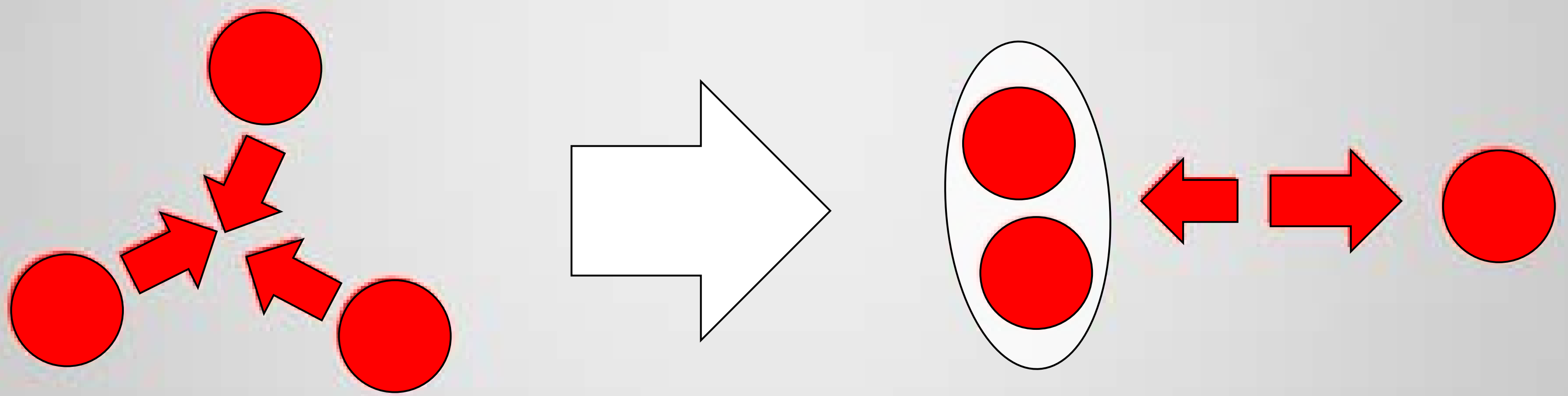
- Position of the series fixed by a three-body parameter, a_*

Observing an Efimov Spectrum?



What is observed in experiments?

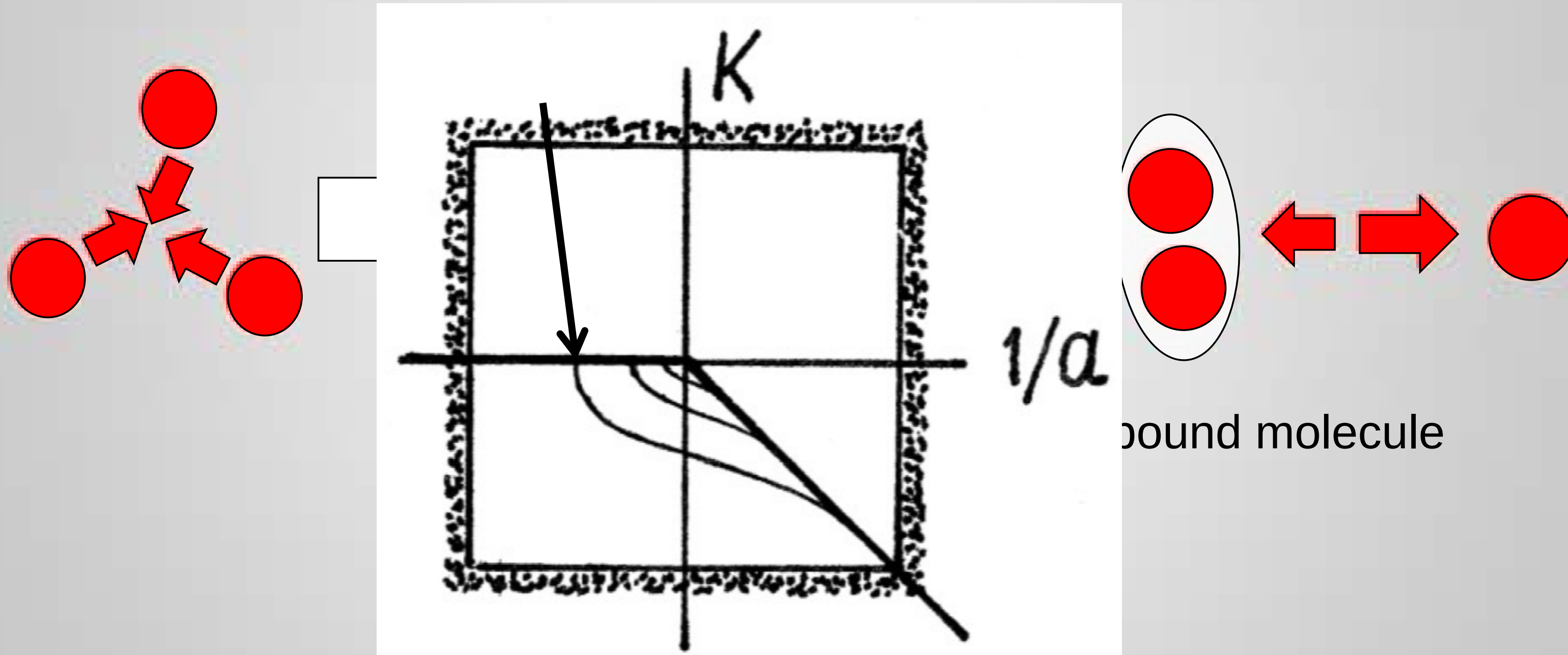
- three-body recombination



deeply bound molecule

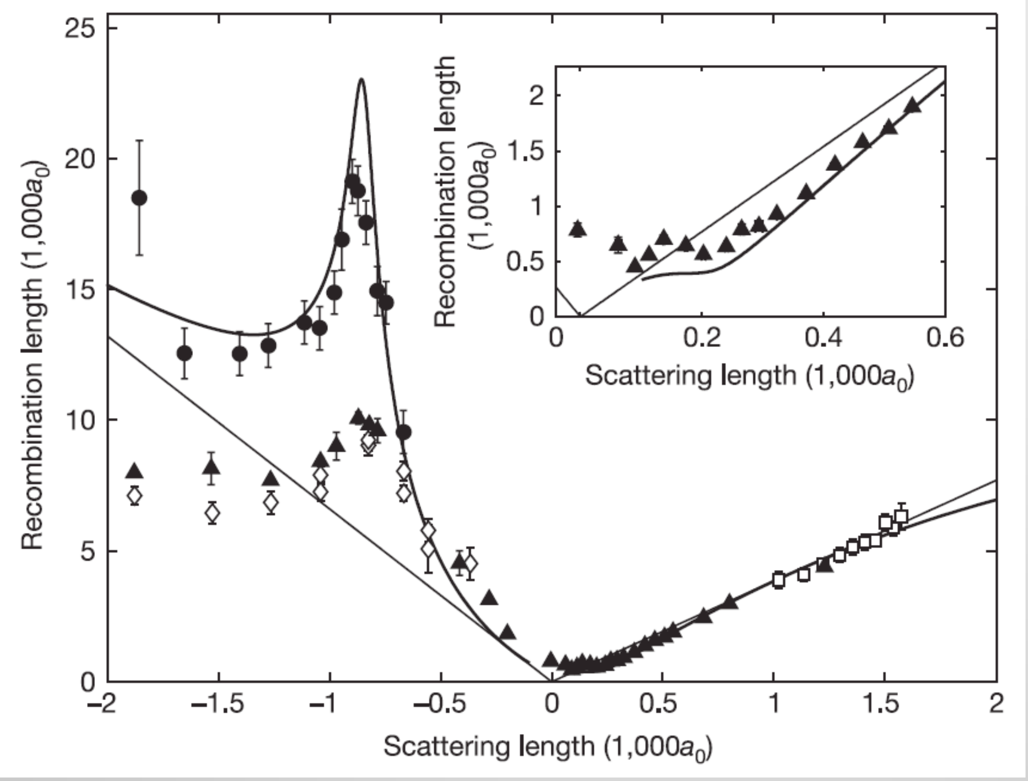
Enhanced recombination

- With an (Efimov) trimer at threshold recombination is enhanced:



What has been done in experiments?

- Observe and analyze collisional stability in ultracold gases
- pioneering experiment with ultracold Cs atoms (Innsbruck):

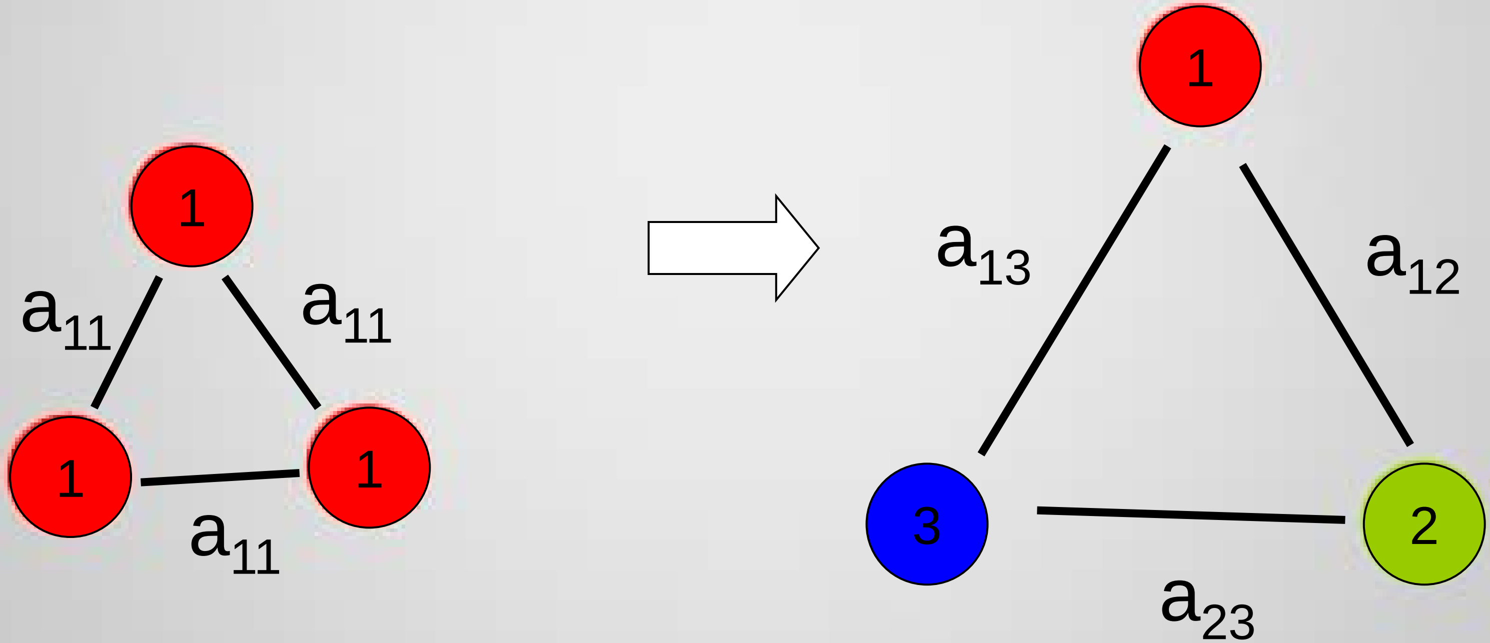


T. Krämer et al., Nature **440**, 315 (2006)

Efimov physics with Fermions?

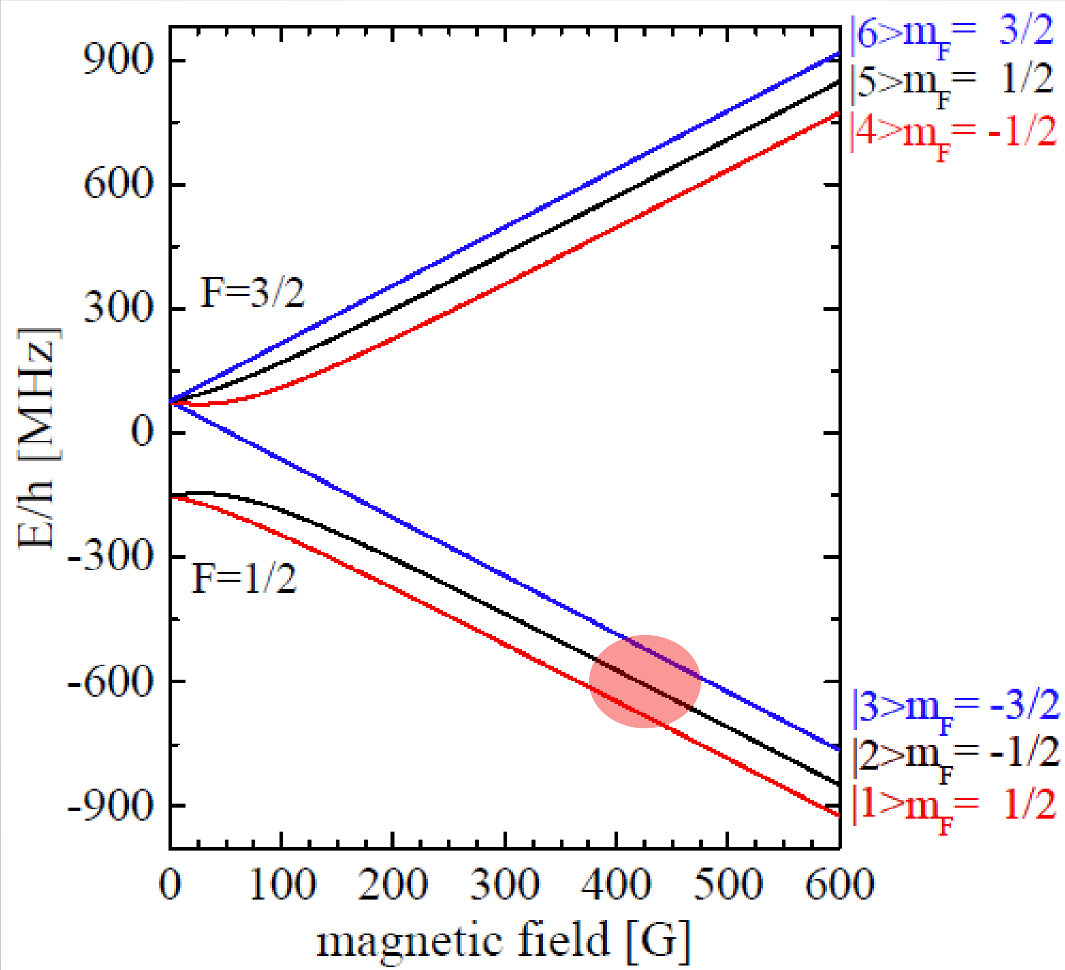
Efimov physics with fermions

- Need three distinguishable fermions with (in general) different scattering lengths:

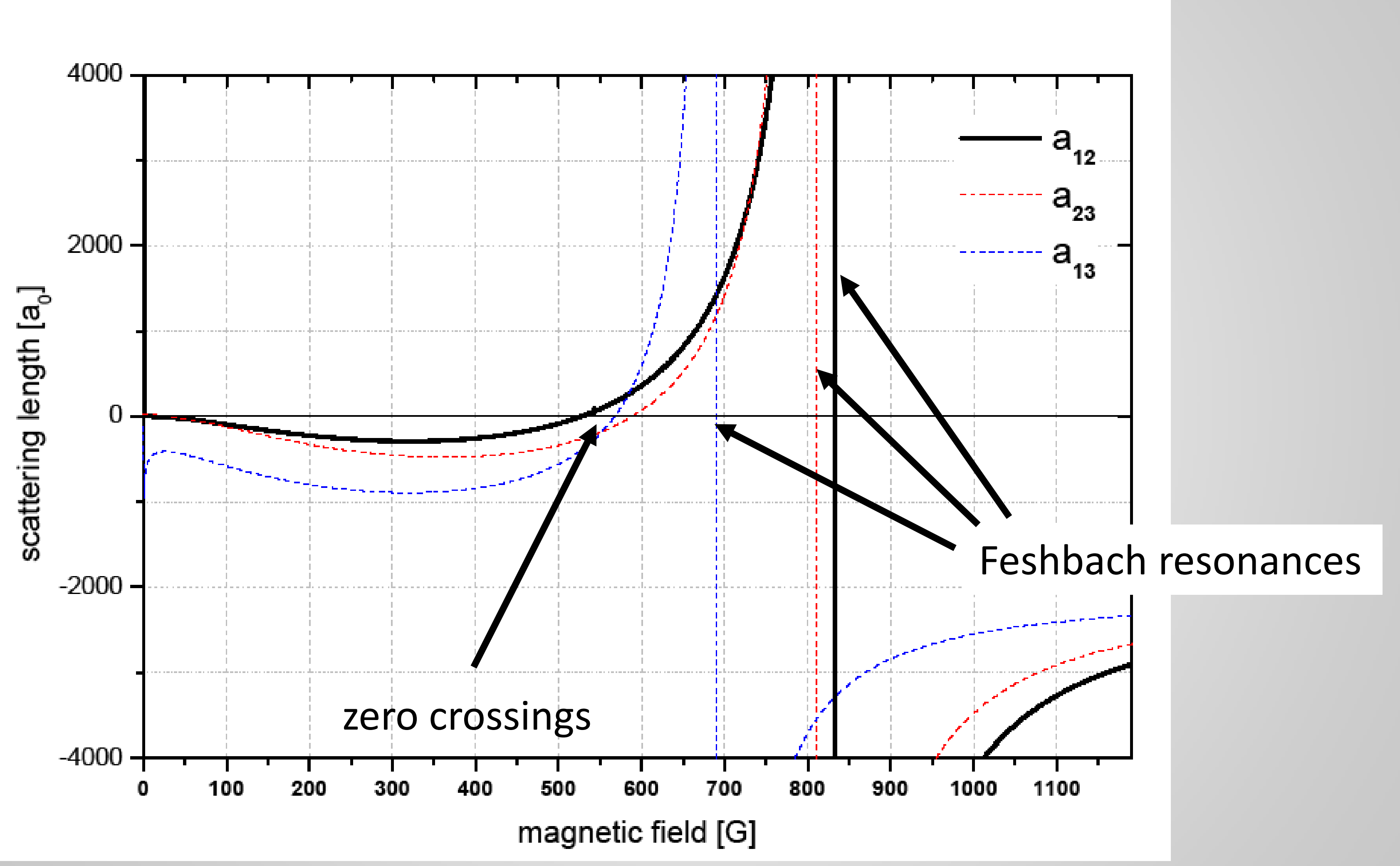


A three-component mixture of ^{6}Li

Ground state of ^{6}Li in magnetic field:



… three scattering lengths …



…are tuned with one knob: the magnetic field!

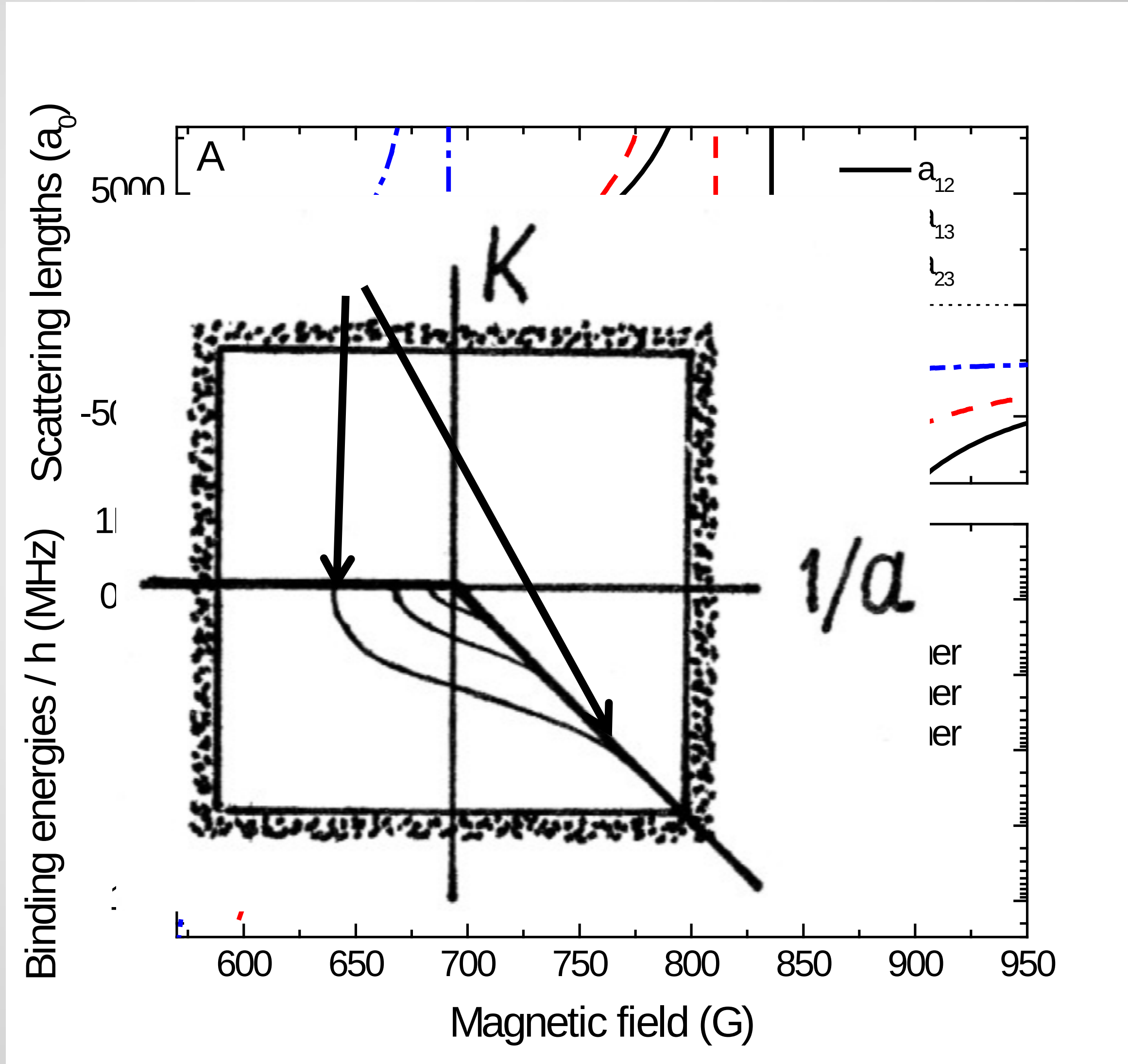
2- and 3-body bound states ….

Binding energies of dimers and trimers:

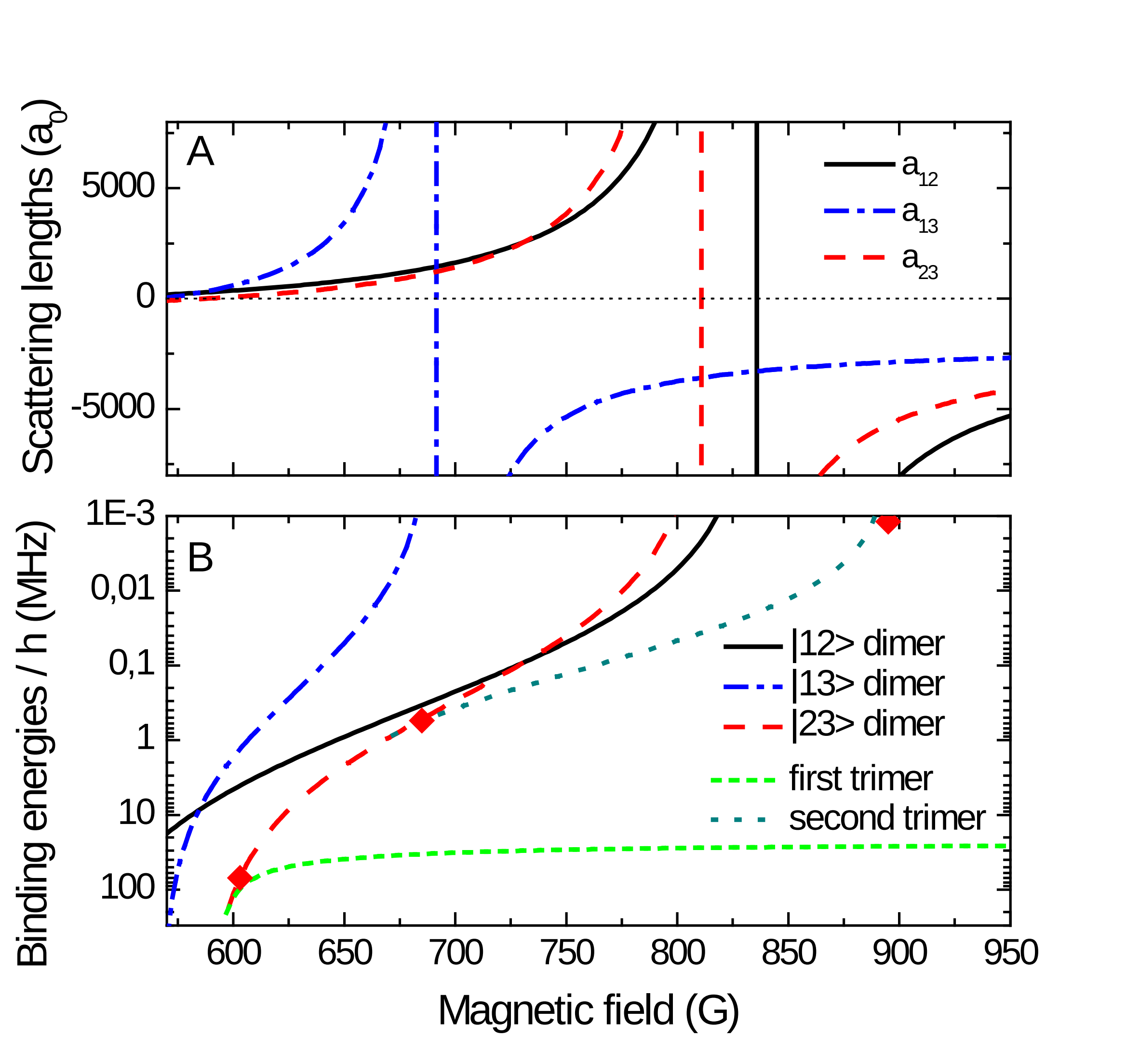
- Three different universal dimers with binding energy

$$E_B = \frac{\hbar^2}{ma^2}$$

- Where are trimer states?



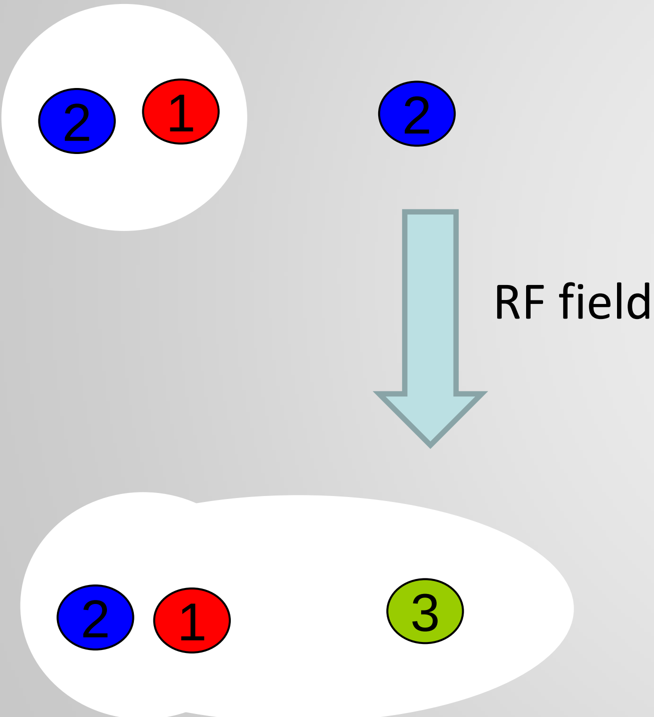
Where are the trimer states?



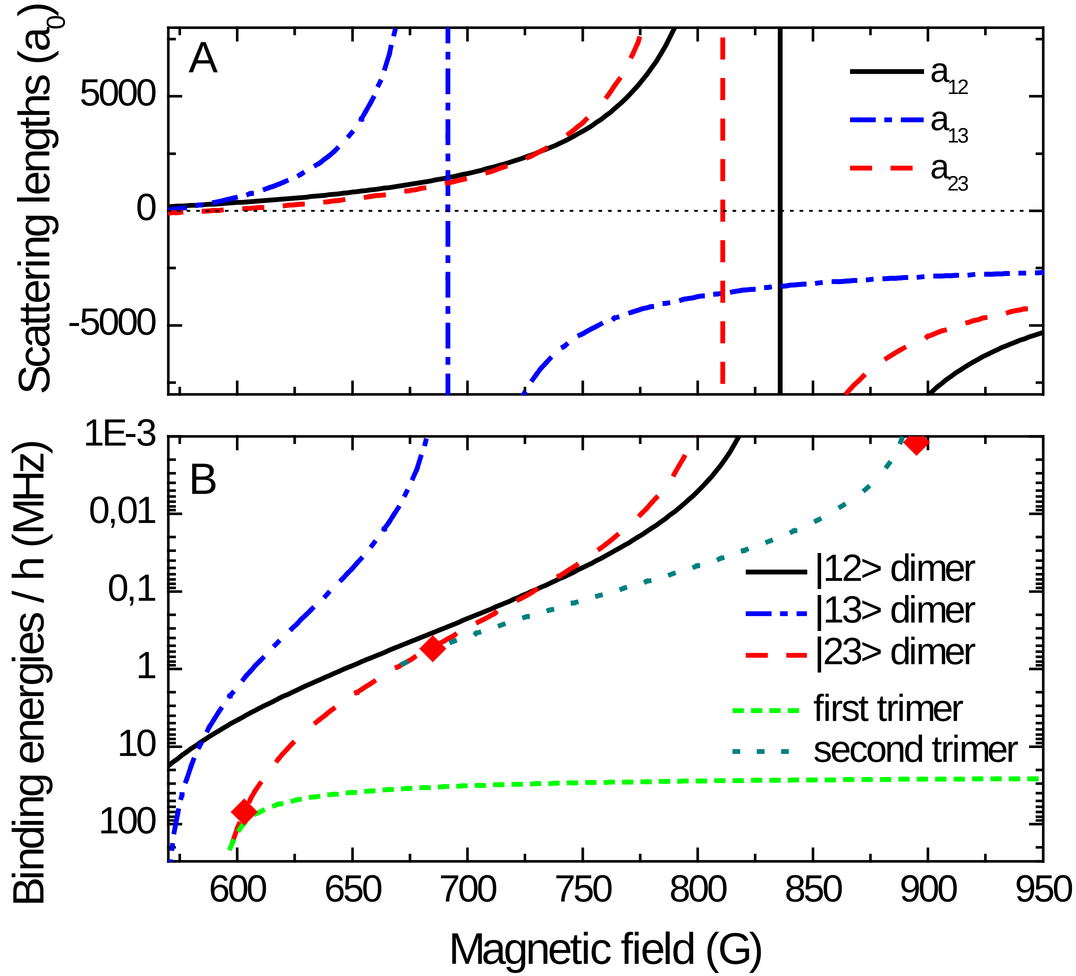
Theory data from: Braaten et al., PRA **81**, 013605 (2010)

Can we also measure binding energies?

Measure binding energies using RF spectroscopy!



Attach a third atom to a dimer!

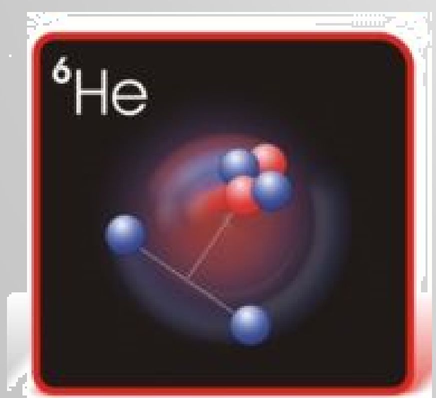


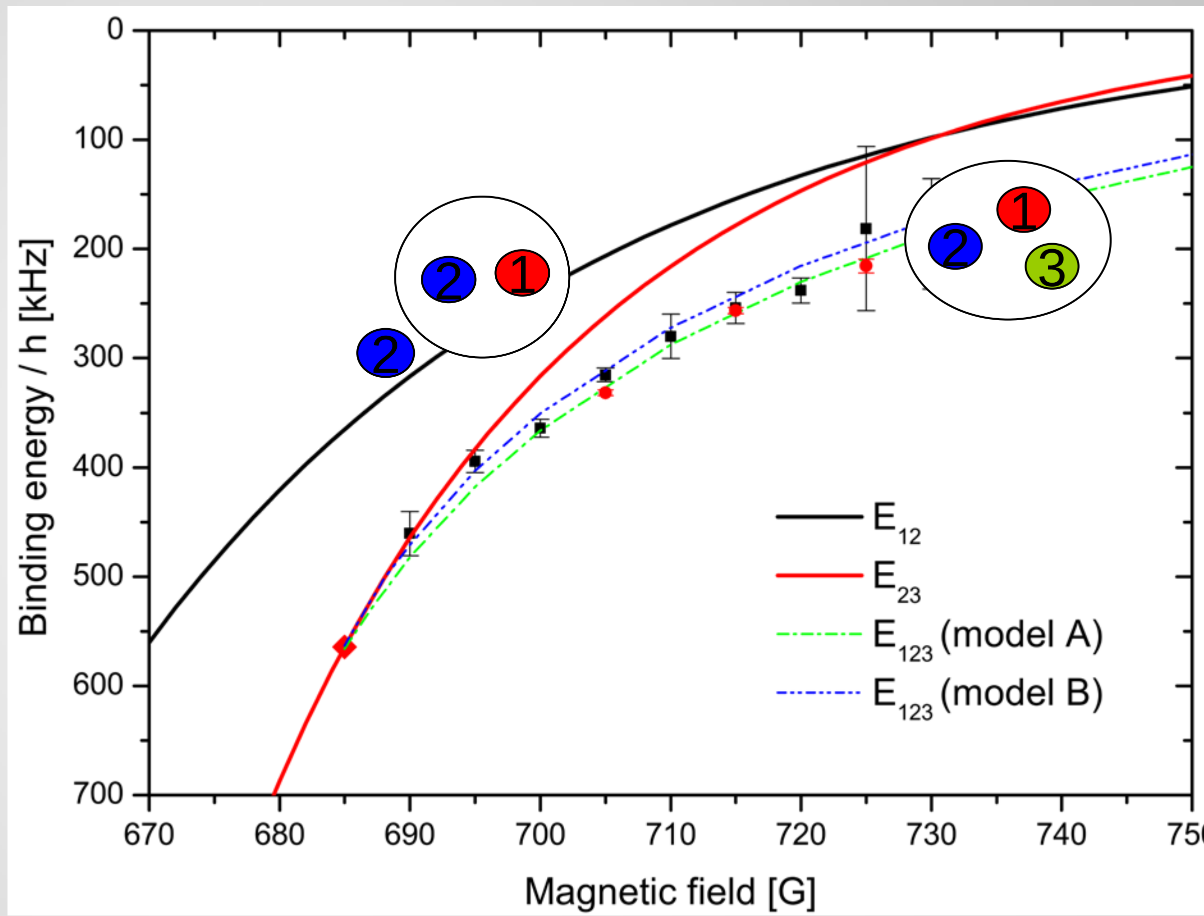
Theory data from: Braaten et al., PRA **81**, 013605 (2010)

Trimer binding energy

- With current precision: theoretical prediction of the binding energy confirmed: Need to include finite range corrections for dimer binding energies

- Same results for two different initial systems





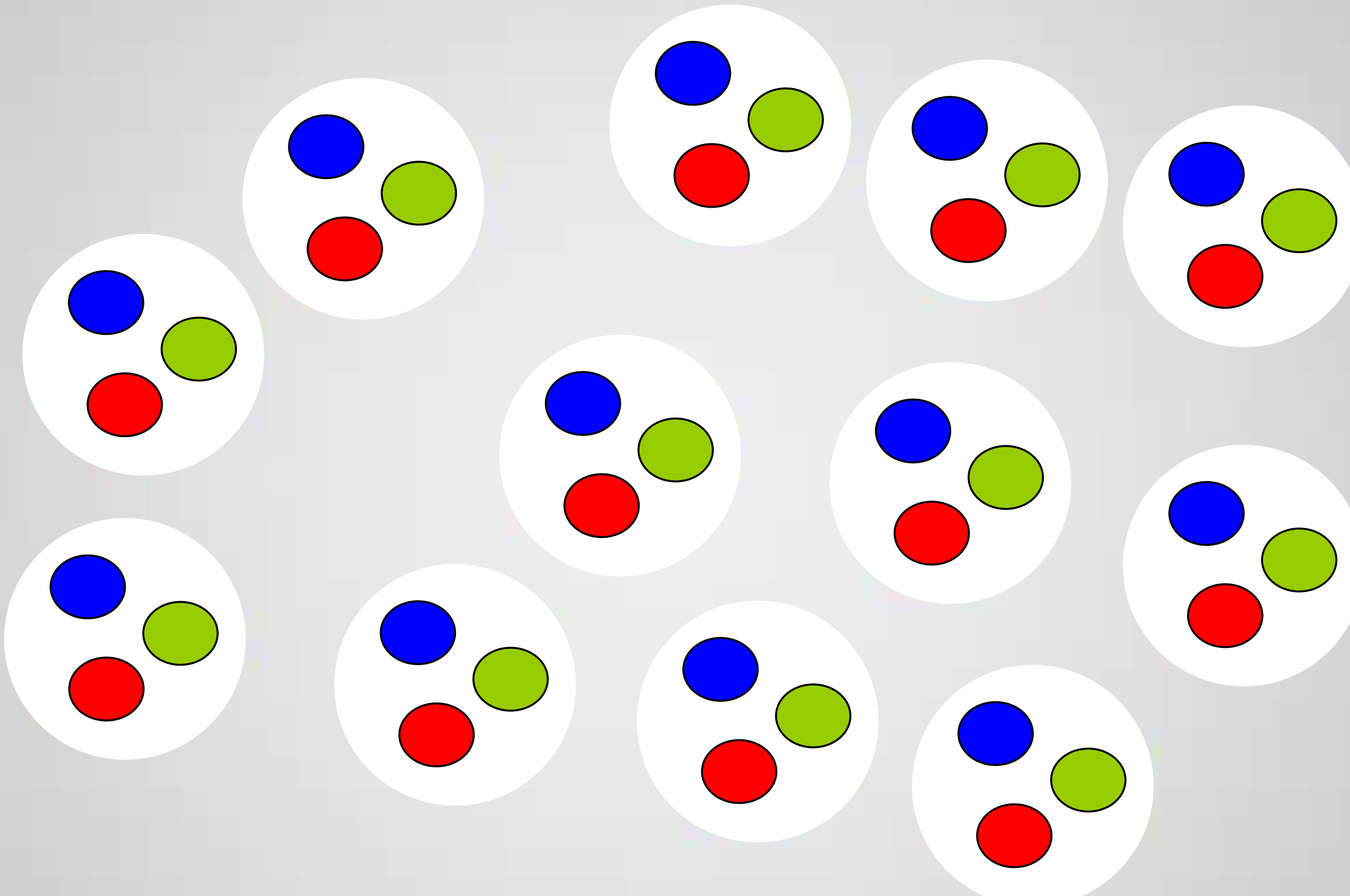
T. Lompe et al., arXiv:1006.2241, to be published

T. Lompe et al., PRL **105**, 103201 (2010)

See also Nakajima et al. arXiv:1010.1954

Theory curves from Nakajima *et al.*, PRL **105**, 023201 (2010)

Many-body physics with three components?



- A gas of fermionic “trions”, “baryons”

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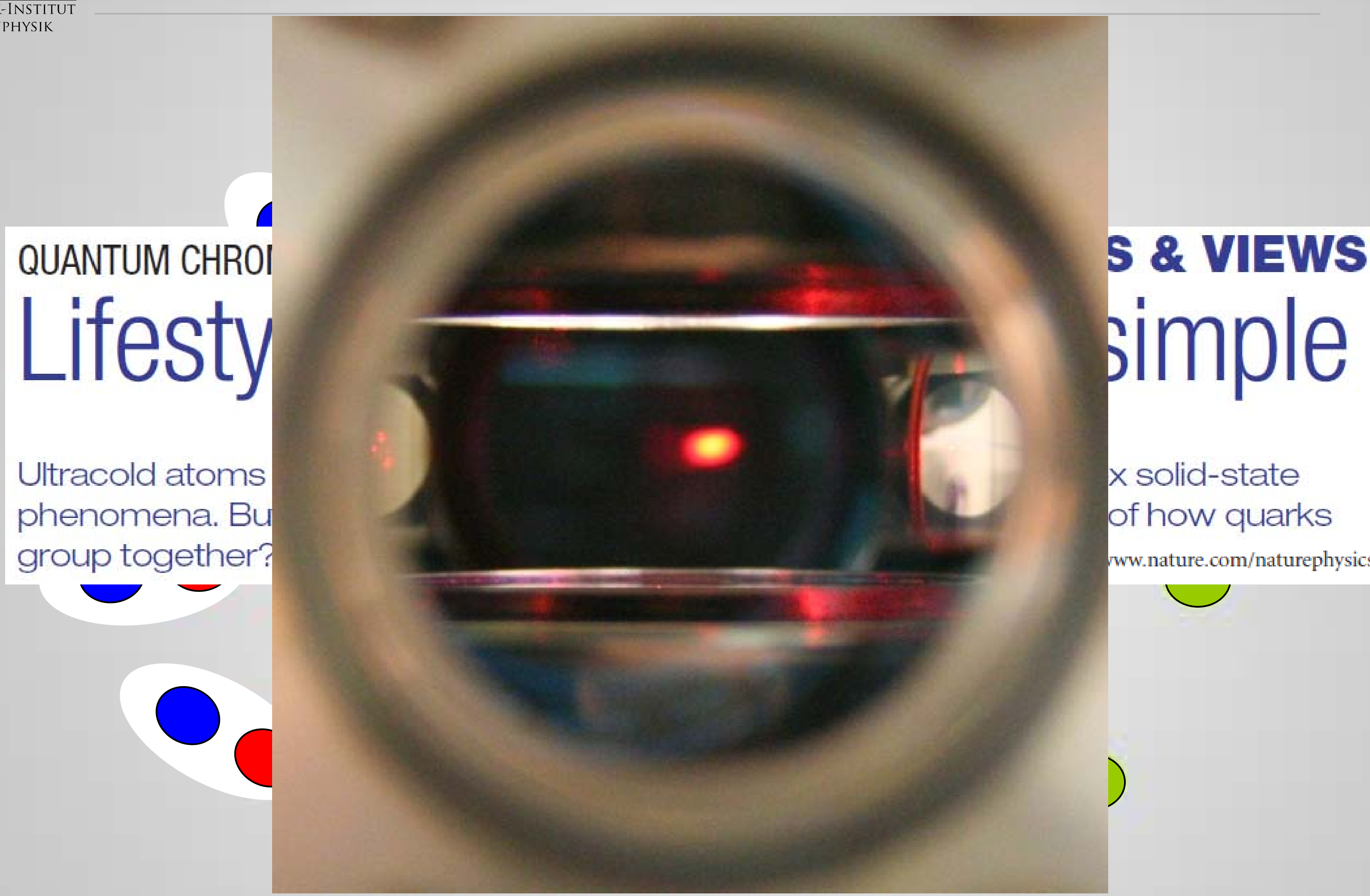
… many different phases are expected



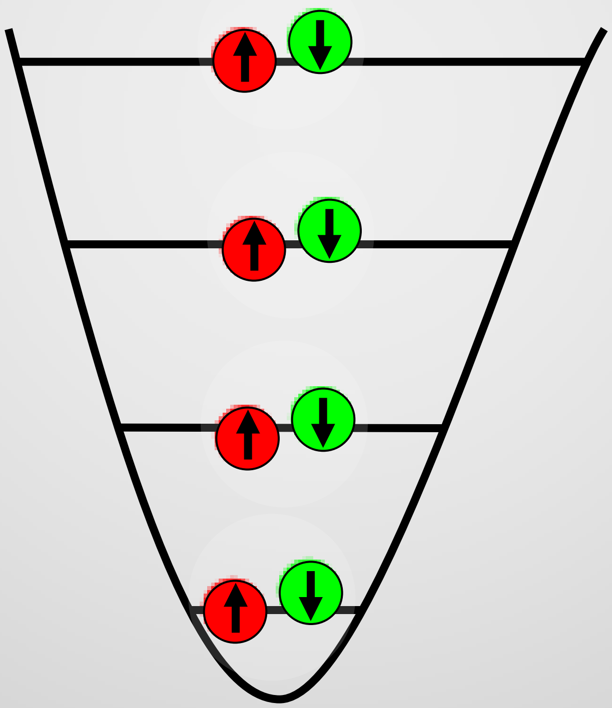
- A “color superfluid”?

A. Rapp et al., PRL **98**, 160405 (2007)
A. Kantian et al., PRL **103**, 240401 (2009)

In between three and many ….

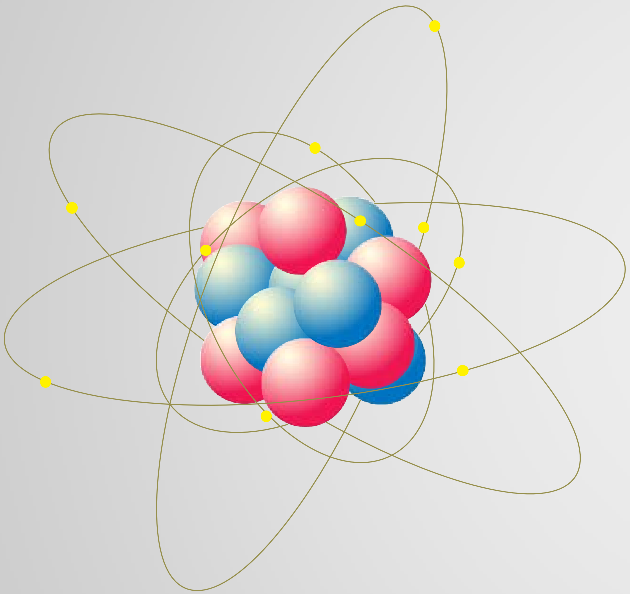
Very recent results:

- Create a system of a few fermions with tunable interactions!

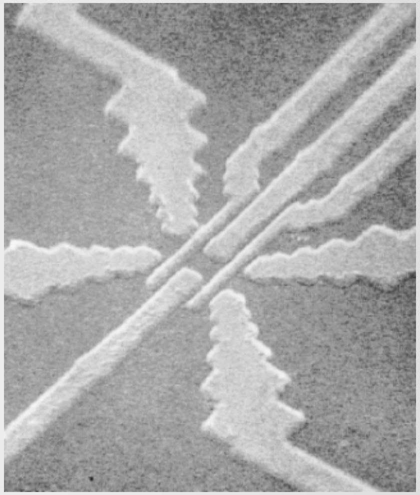


Other finite quantum systems …

- Atoms, nuclei …



- Quantum dots, clusters …



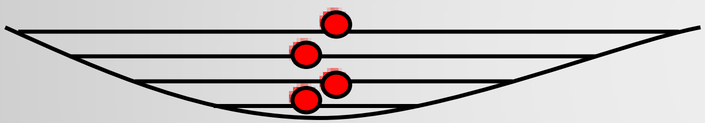
- Extreme repeatability and control over all degrees of freedom, but limited tunability
- Wide tunability, but no „identical“ systems

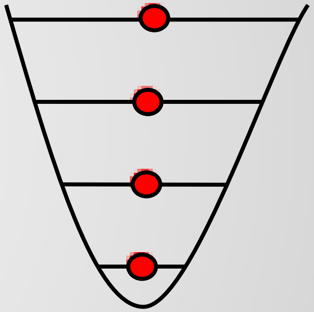
Creating a finite gas of fermions

Control the number of quantum states in the trap!

Conventional trap
like a soup plate!

Shot glass
type trap

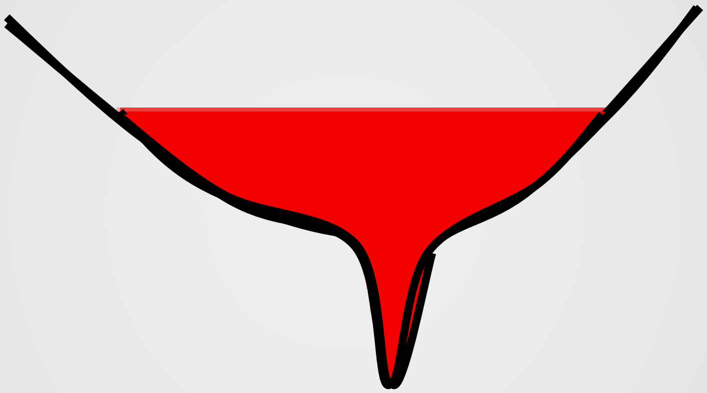




Large density of states ...

...small density of states

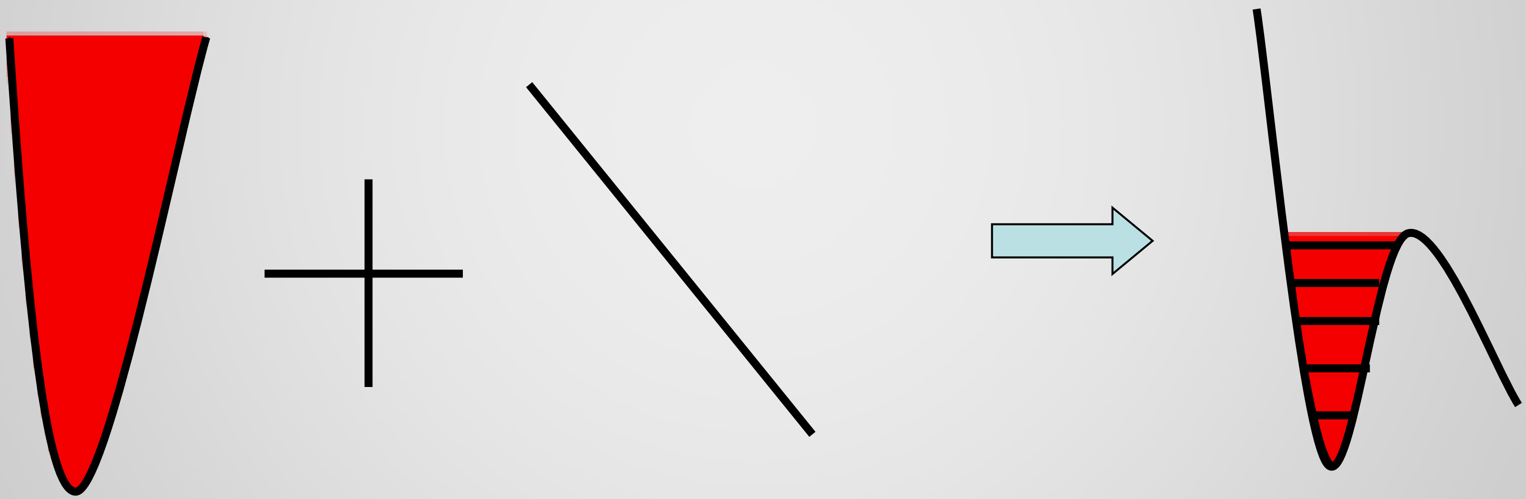
Transfer atoms to microtrap …



Spill most of the atoms:

Lower trap depth

Use a magnetic field gradient to spill:



~200 atoms

μ x B

~2-10 atoms

→ What is the population of the ground state?

"laser culling of atoms": M. Raizen *et al*., Phys. Rev. A 80, 030302(R)

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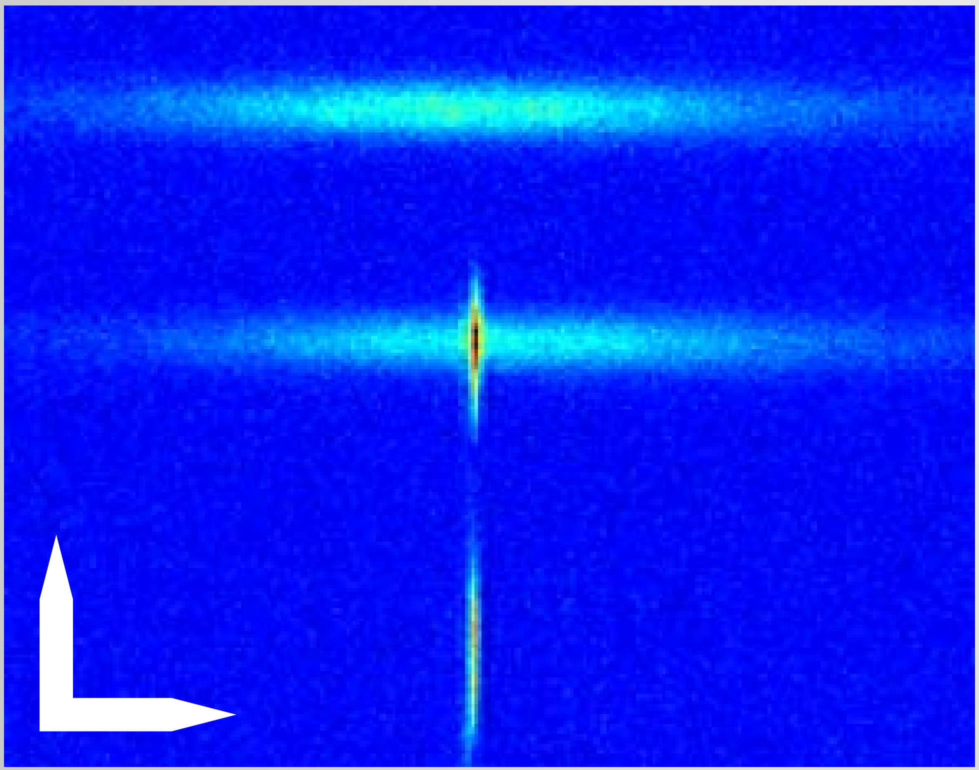
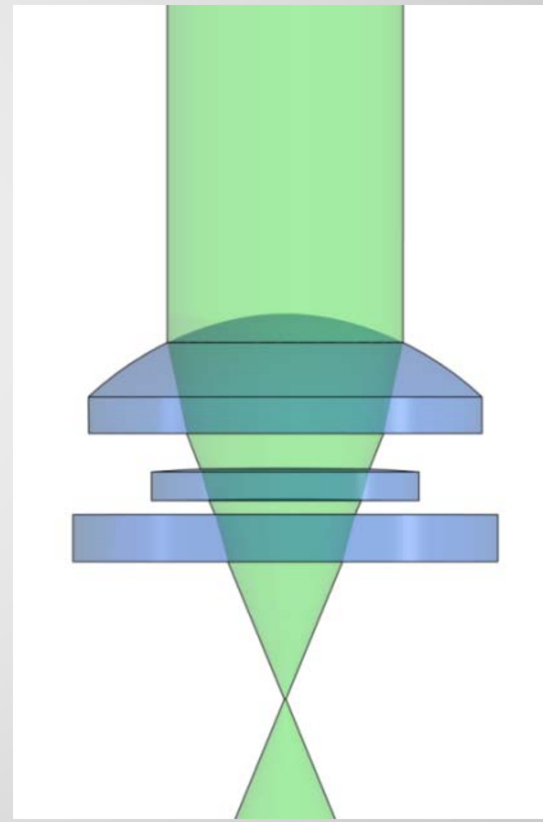
Atoms in a microtrap

Transfer a few 100 atoms into a tightly focused trap (~1.8µm in size)



100µm

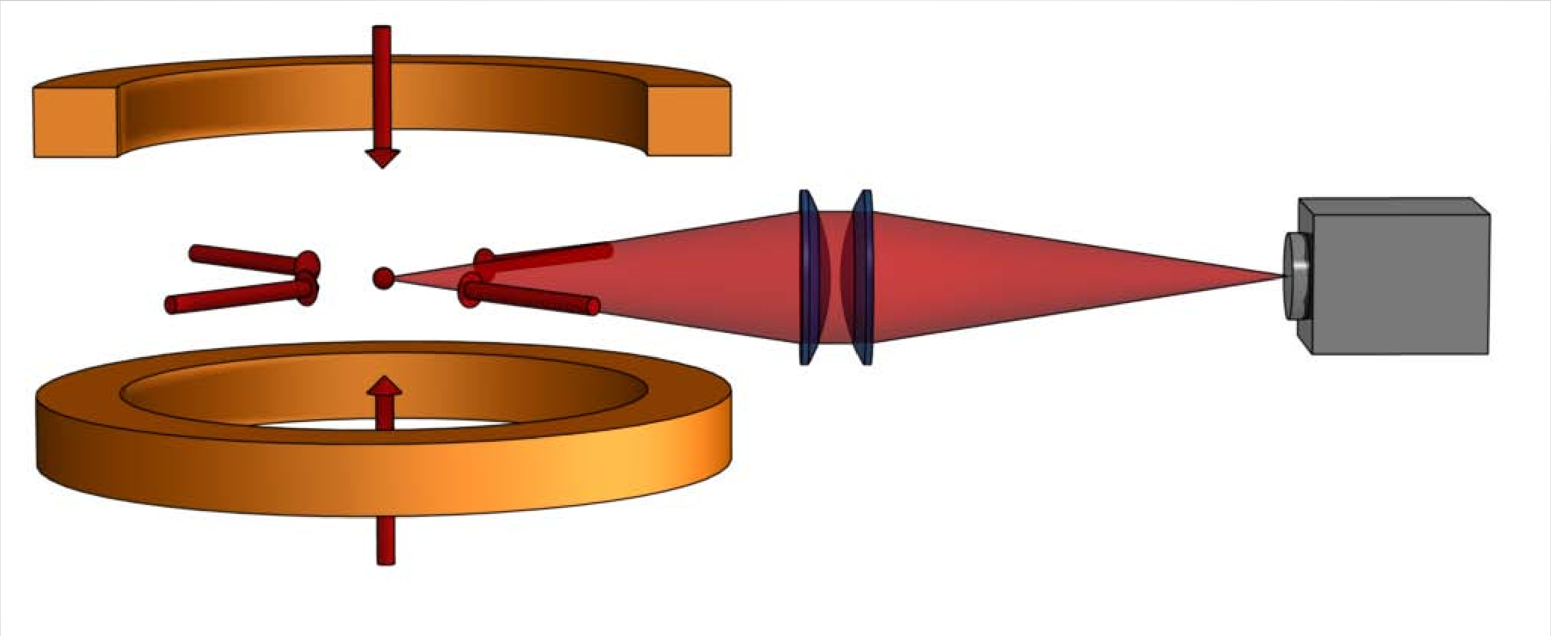
100µm



We use the infrared emission of a green laser pointer! (1064nm)

Detection of single atoms

Measure fluorescence signal of single atoms in a compressed Magneto-optical trap.



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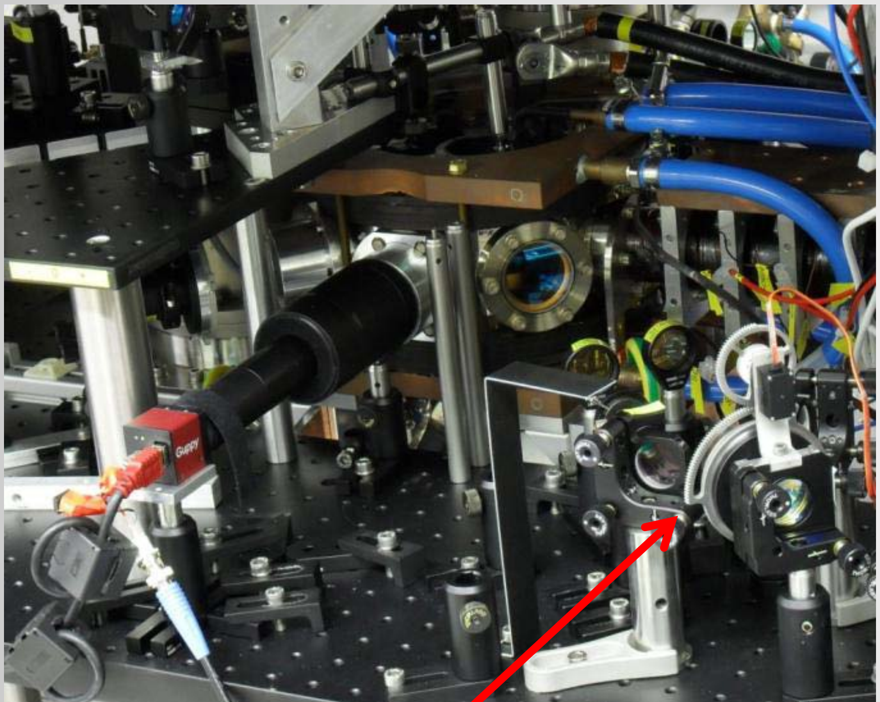
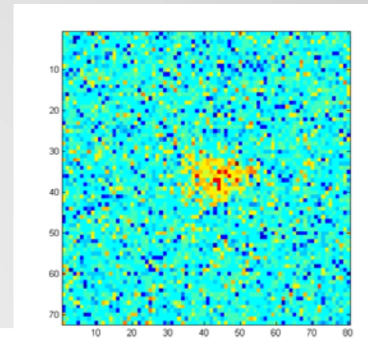
Detection of single atoms

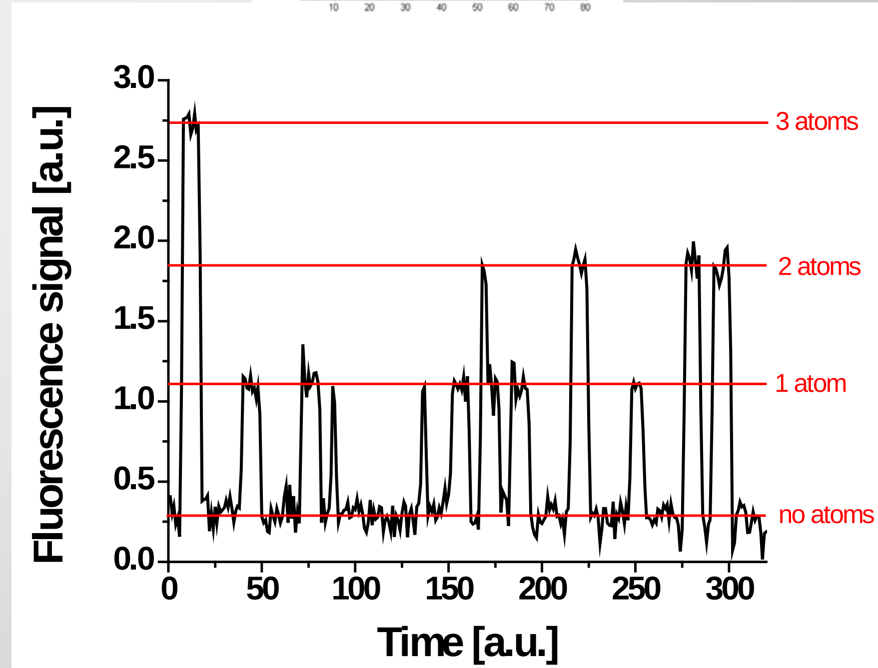
Essential ingredients: Low background and MOT lifetime



Motorized irises
control beam diameter

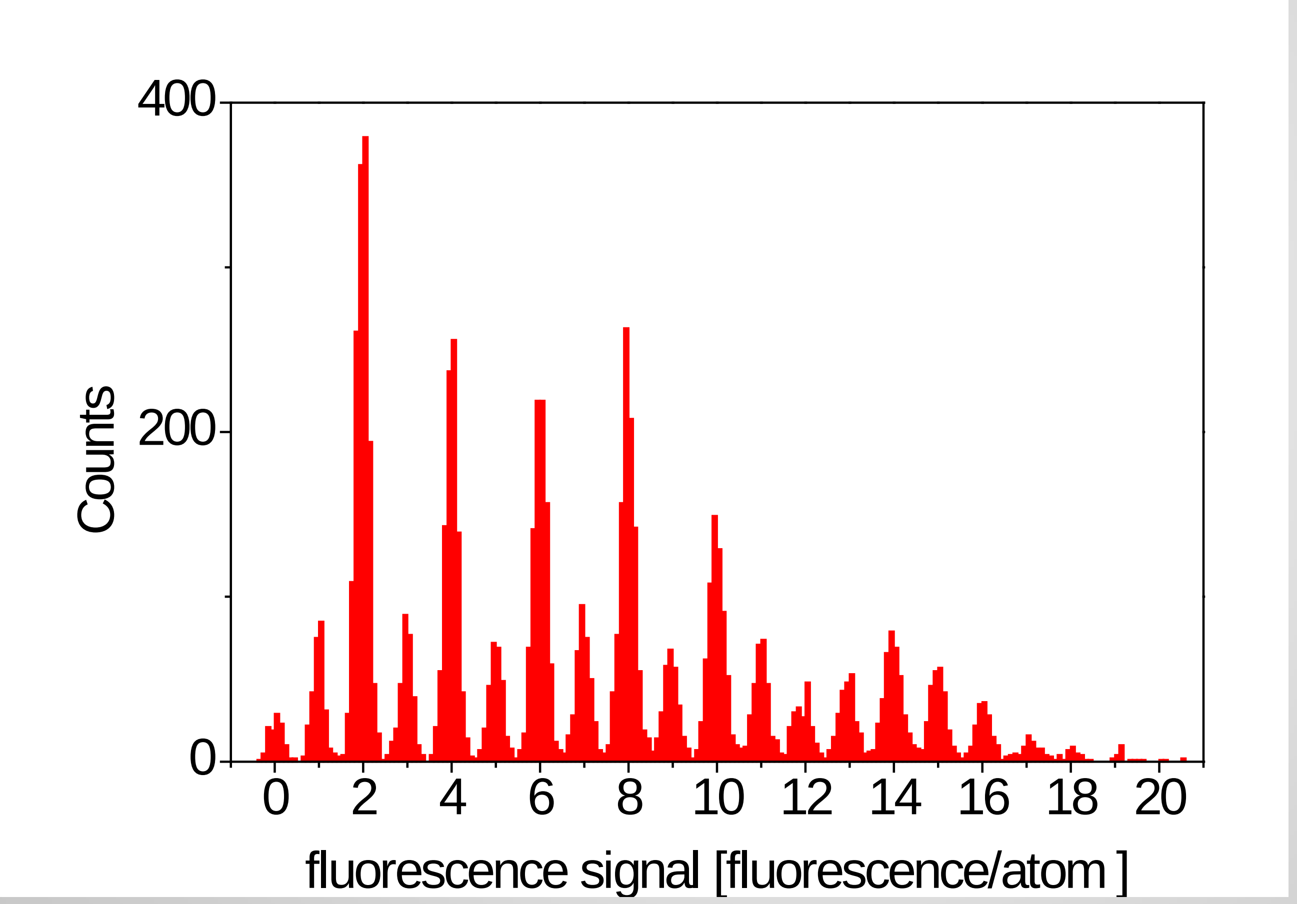
1 atom in the MOT





Detection fidelity

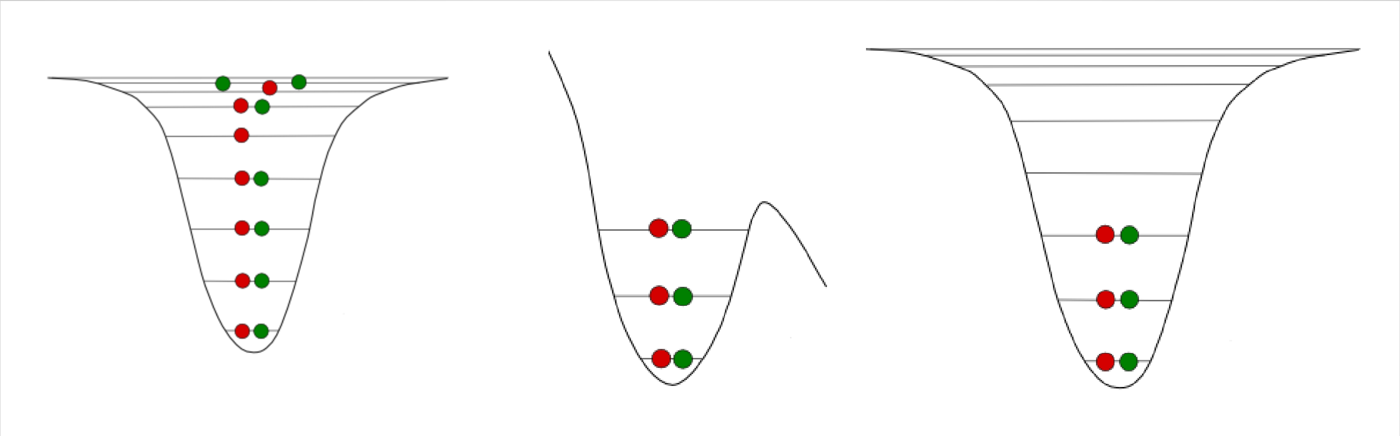
- 1-10 atoms can be distinguished: fidelity > 99,7 % (3 σ)



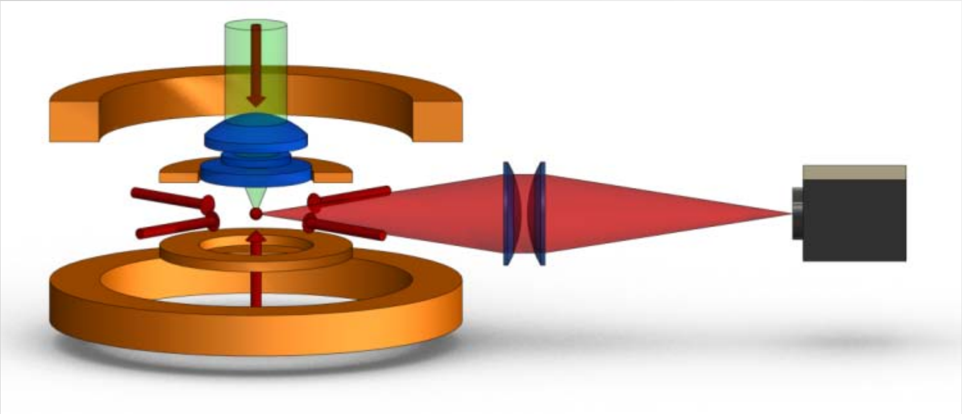
Let‘s prepare ultracold few-fermions systems!

Preparation sequence

1. Spill atoms in a controlled way



2. Recapture prepared atoms into Magneto Optical Trap



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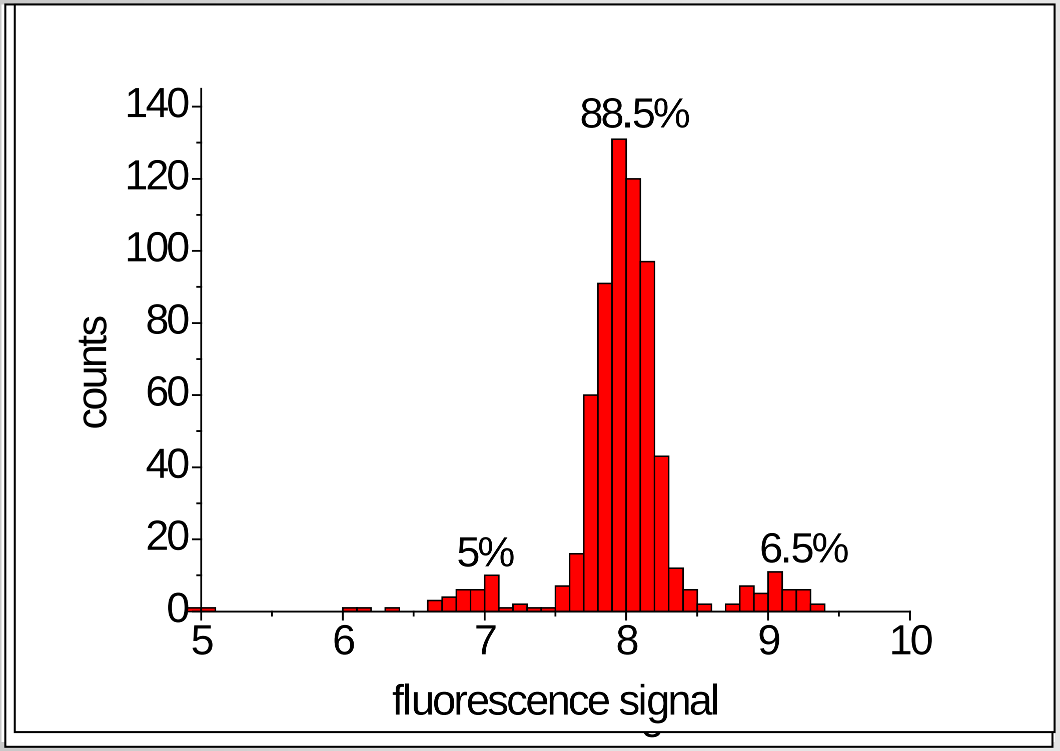
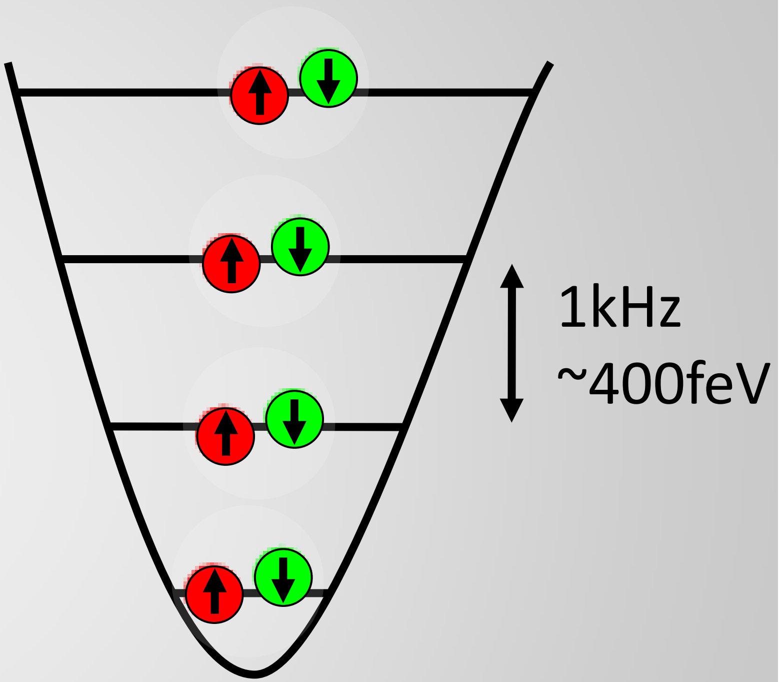
Spilling the atoms ….

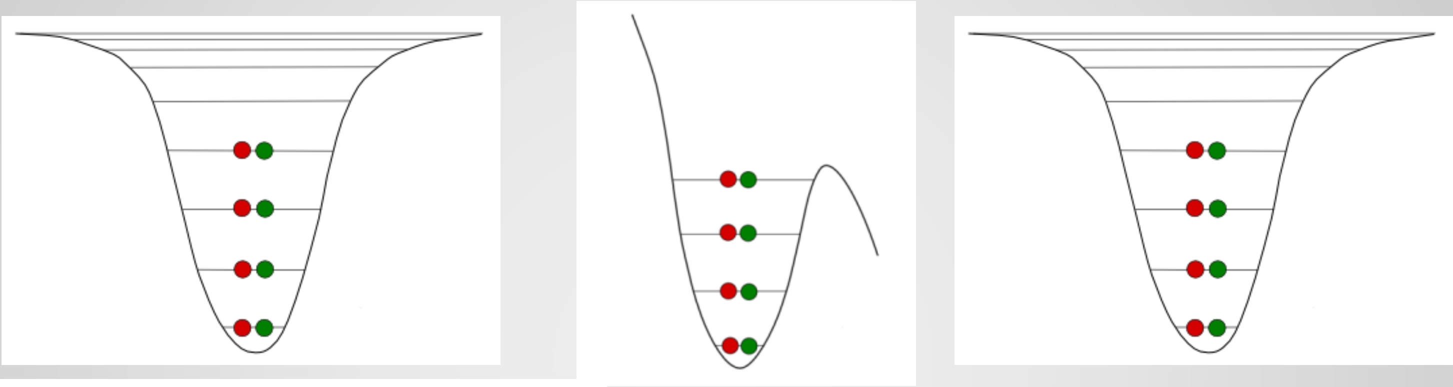


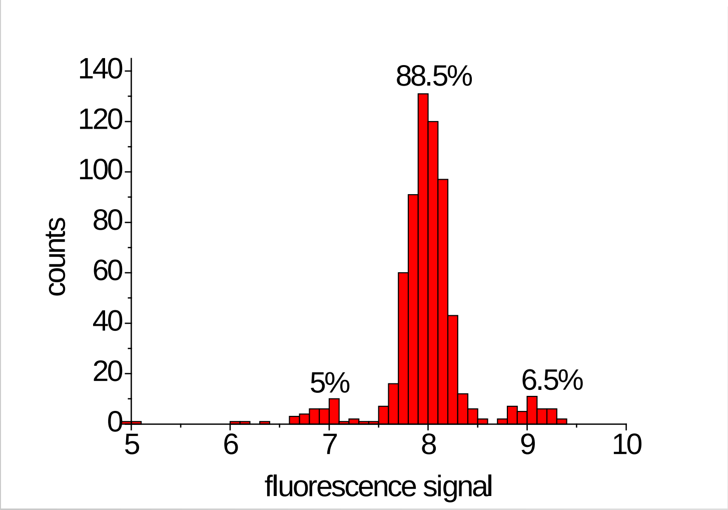


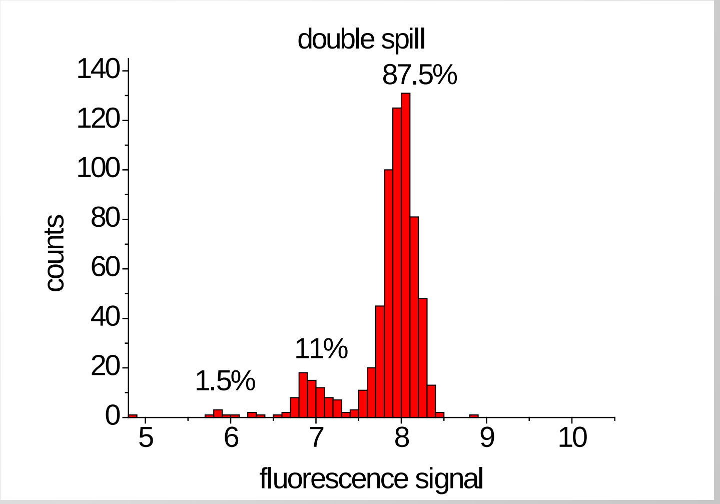
- We can control the atom number with exceptional precision!

Ground state systems ?

Spill twice!

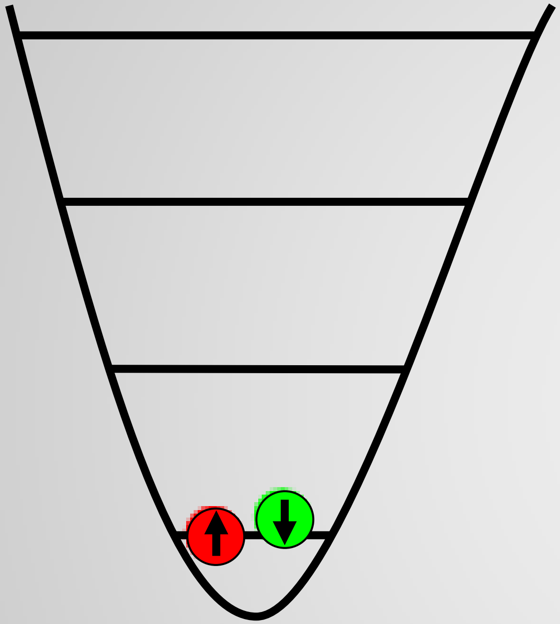




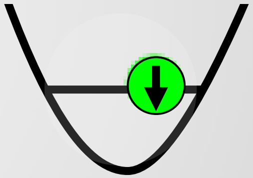


Lifetime of the system in the ground state: > 60s

First few-body interactions



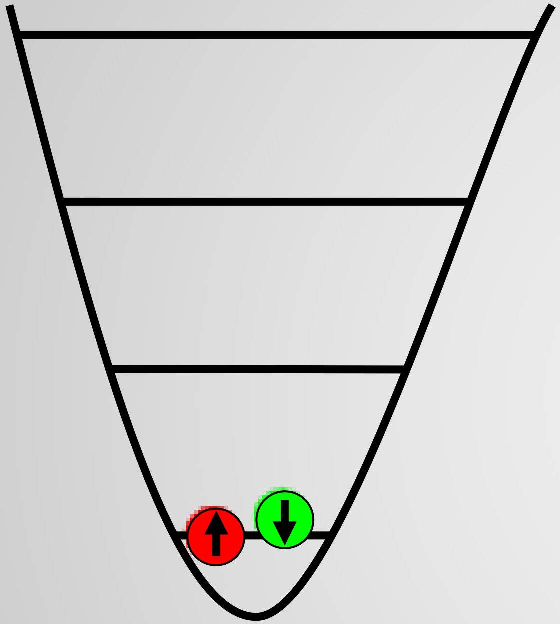
a~0



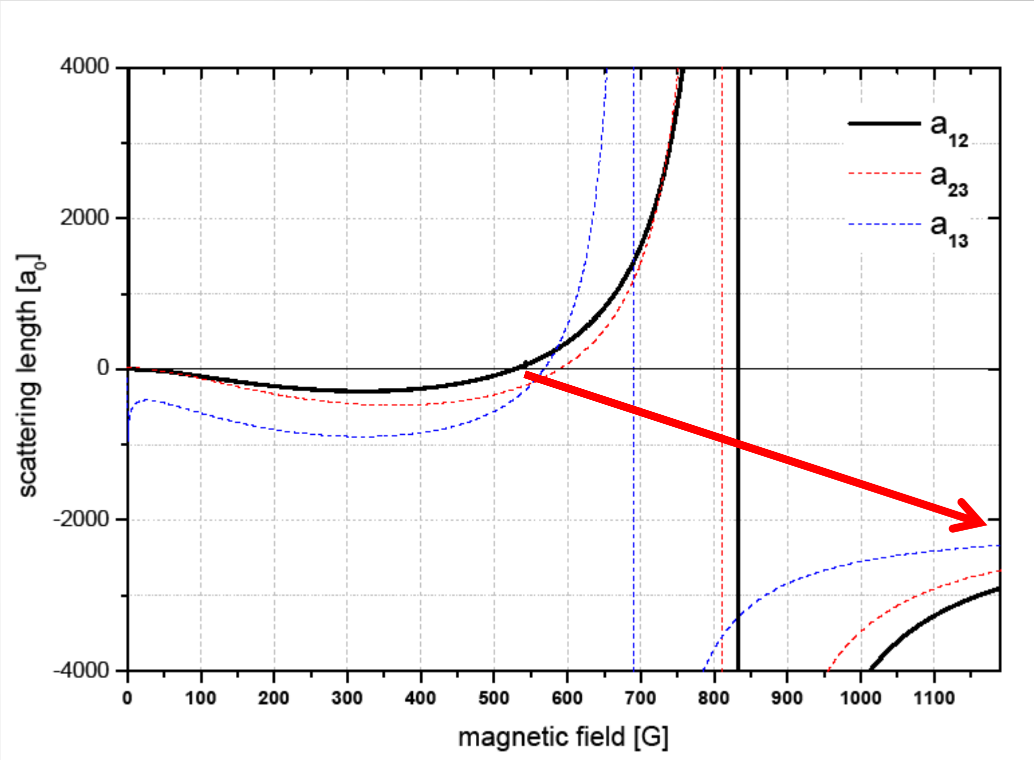
a>0

- What happens if we switch on some (repulsive) interactions?
- We observe only one atom in ν=0!

First few-body interactions

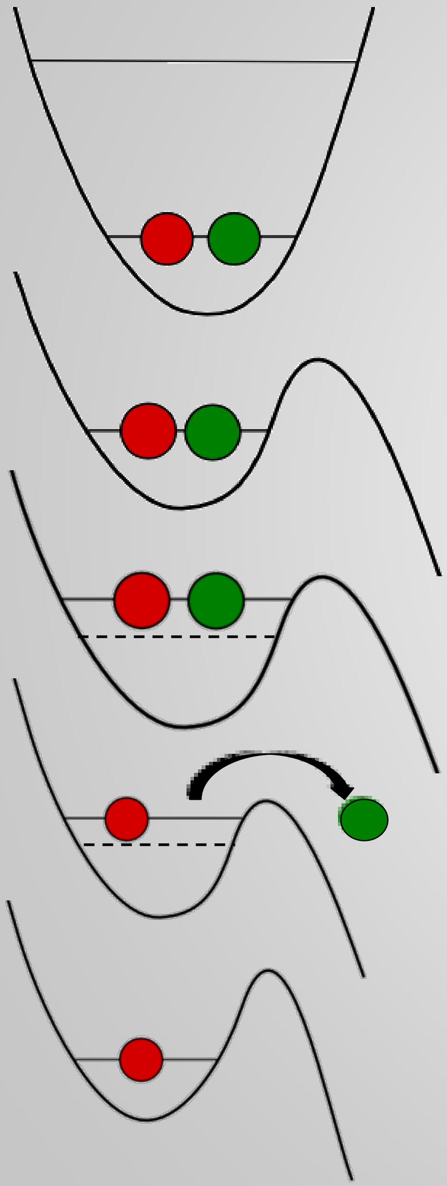


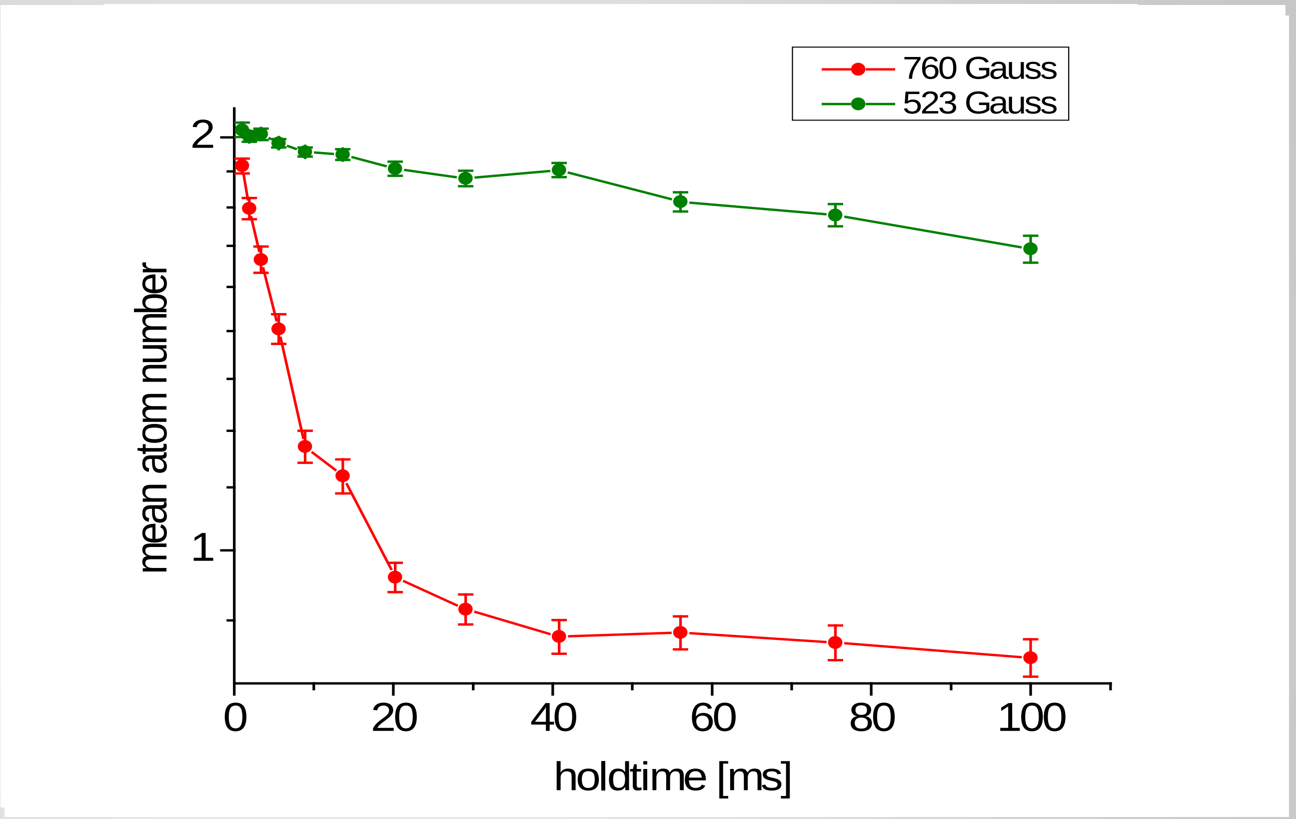
a~0



- What happens if we bring the two atoms in the ground state across the Feshbach resonance
- One atom is observed in ν~2

More interactions …





Interaction-induced spilling!

Conclusion

- We detect and count single atoms with very high fidelity
- We prepare few-fermion systems with unprecedented control
- We control the interactions in the few-fermion system

Future:

- Investigate interacting few-body systems in the ground state
- Study dynamics of few-fermion systems: How many atoms do we need to have a thermal ensemble?

Thank you very much for your attention!