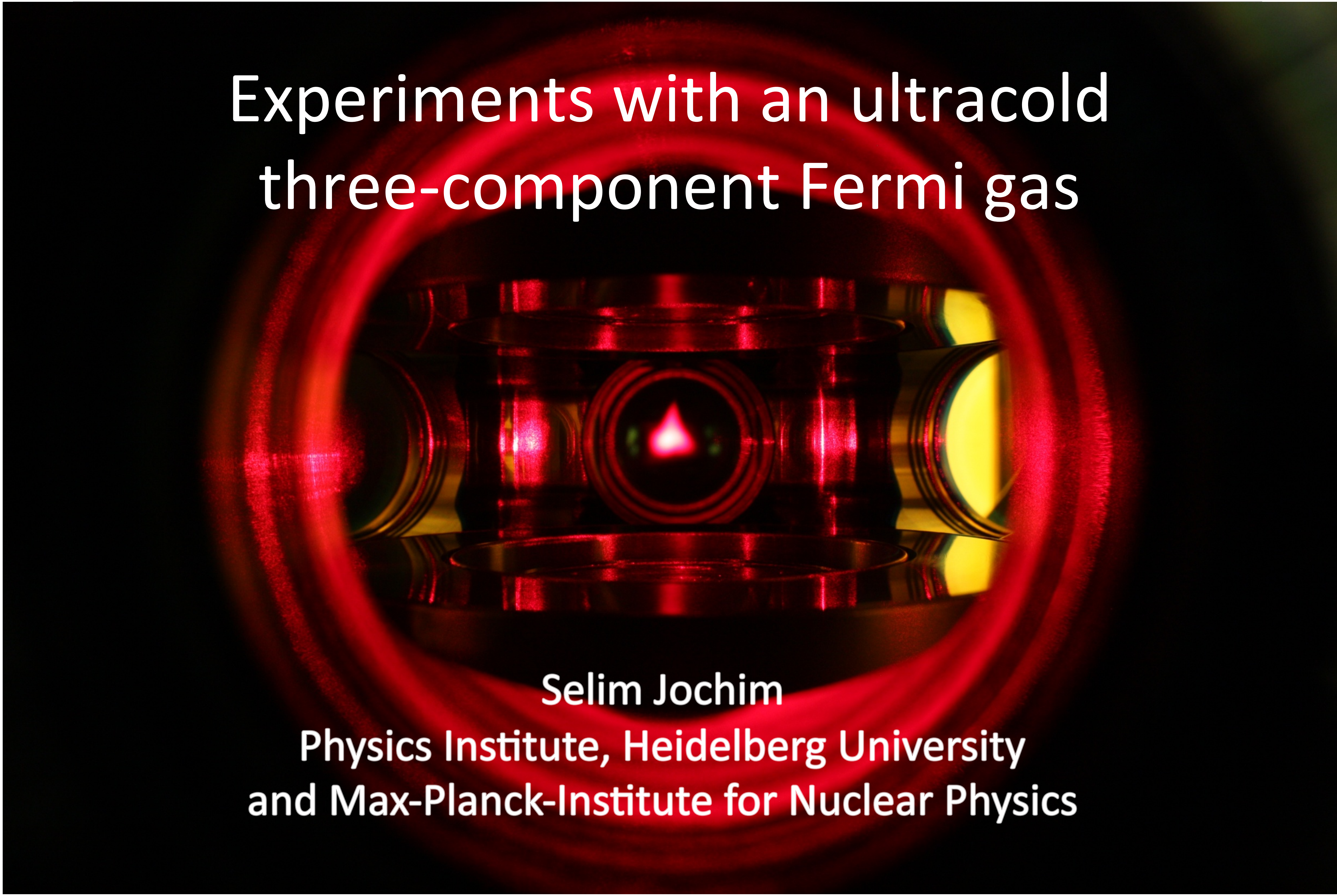
Experiments with an ultracold three-component Fermi gas

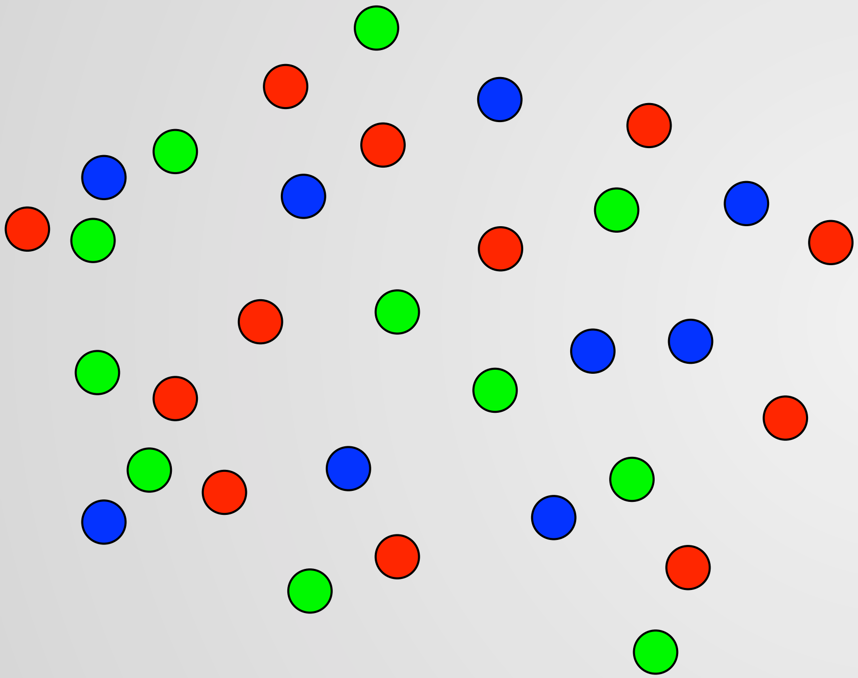


Selim Jochim
Physics Institute, Heidelberg University
and Max-Planck-Institute for Nuclear Physics

Ultracold experiments @ EMMI

Center for
Quantum
Dynamics

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!

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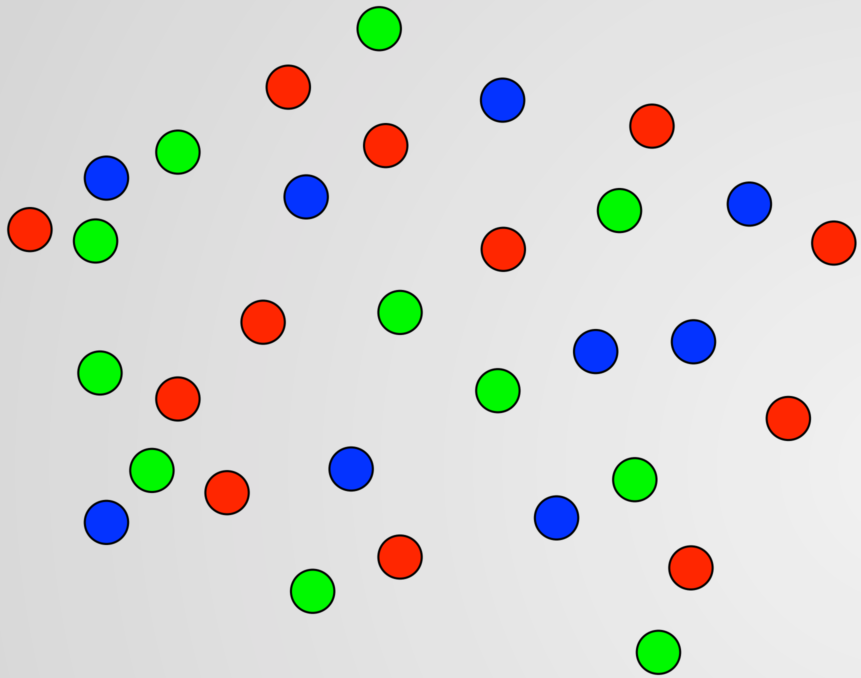
für Kernphysik

Important length scales



- interparticle separation

$\sqrt[3]{1/n} > 300\text{nm} \gg$ size of the atoms

- de Broglie wavelength

$\sqrt{\dfrac{h^2}{2\pi mkT}} > 300\text{nm} \gg$ 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!**

What we work on in the lab ....

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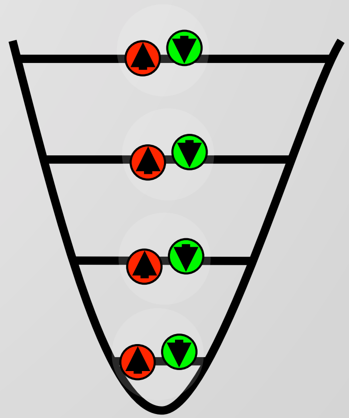
- **Three component Fermi gases**
  Radio frequency association of Efimov trimers
- ➢ **On the way to complex many-body phases**

- **Finite Fermi systems with tunable interaction**
  Very recent results!
- ➢ **Crossover from deterministic to thermodynamic ensembles**



Exciting many-body physics?

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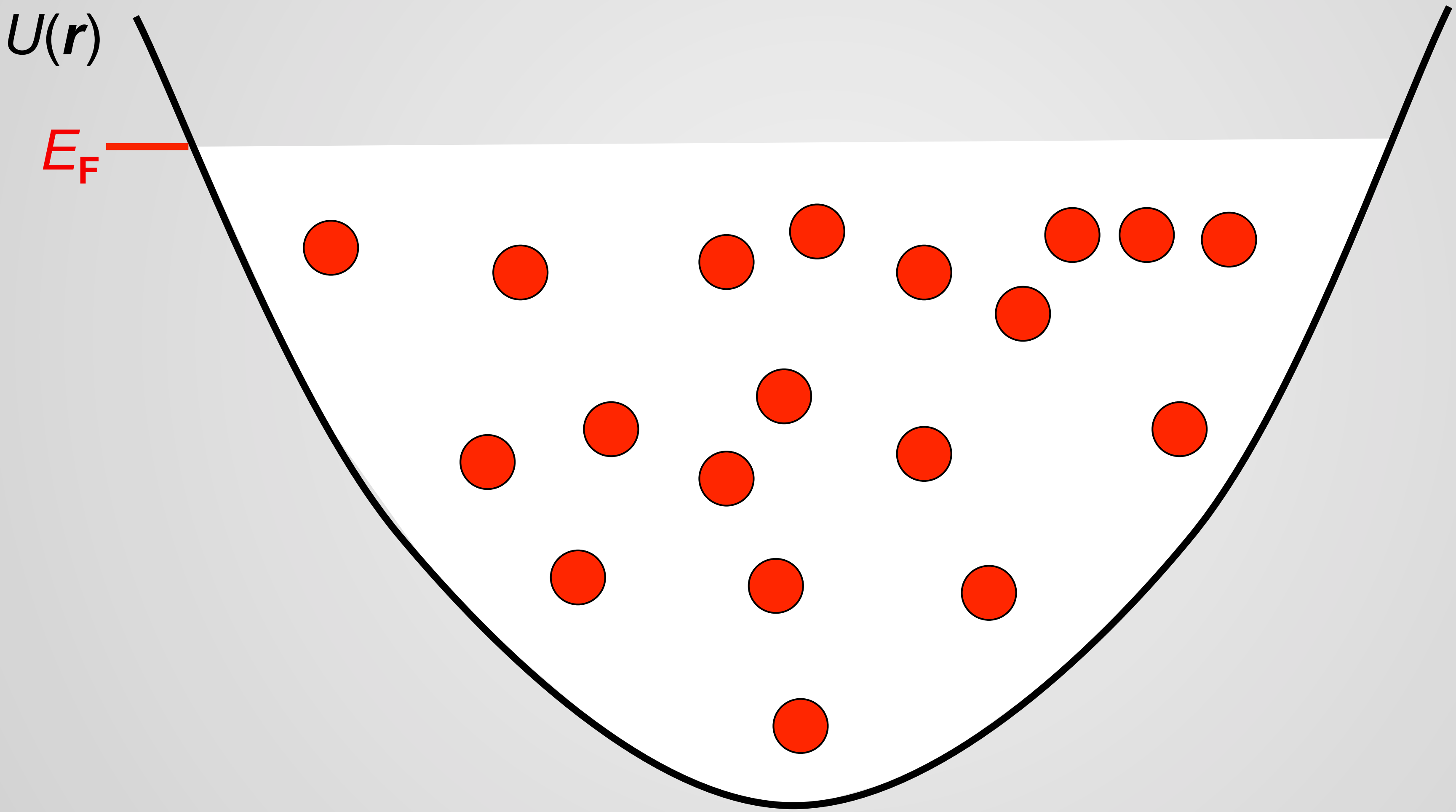
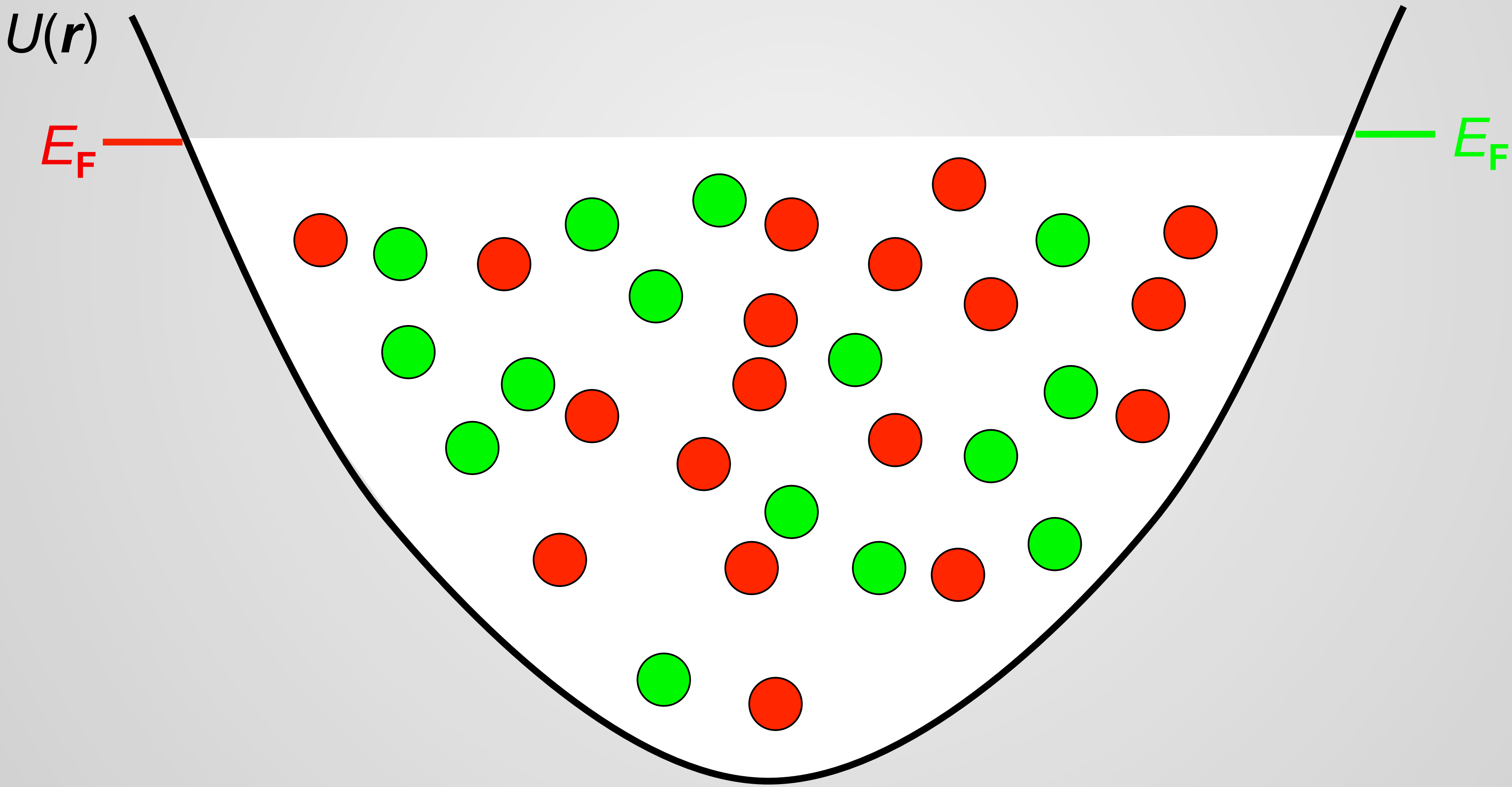
Atoms are trapped in a conservative potential



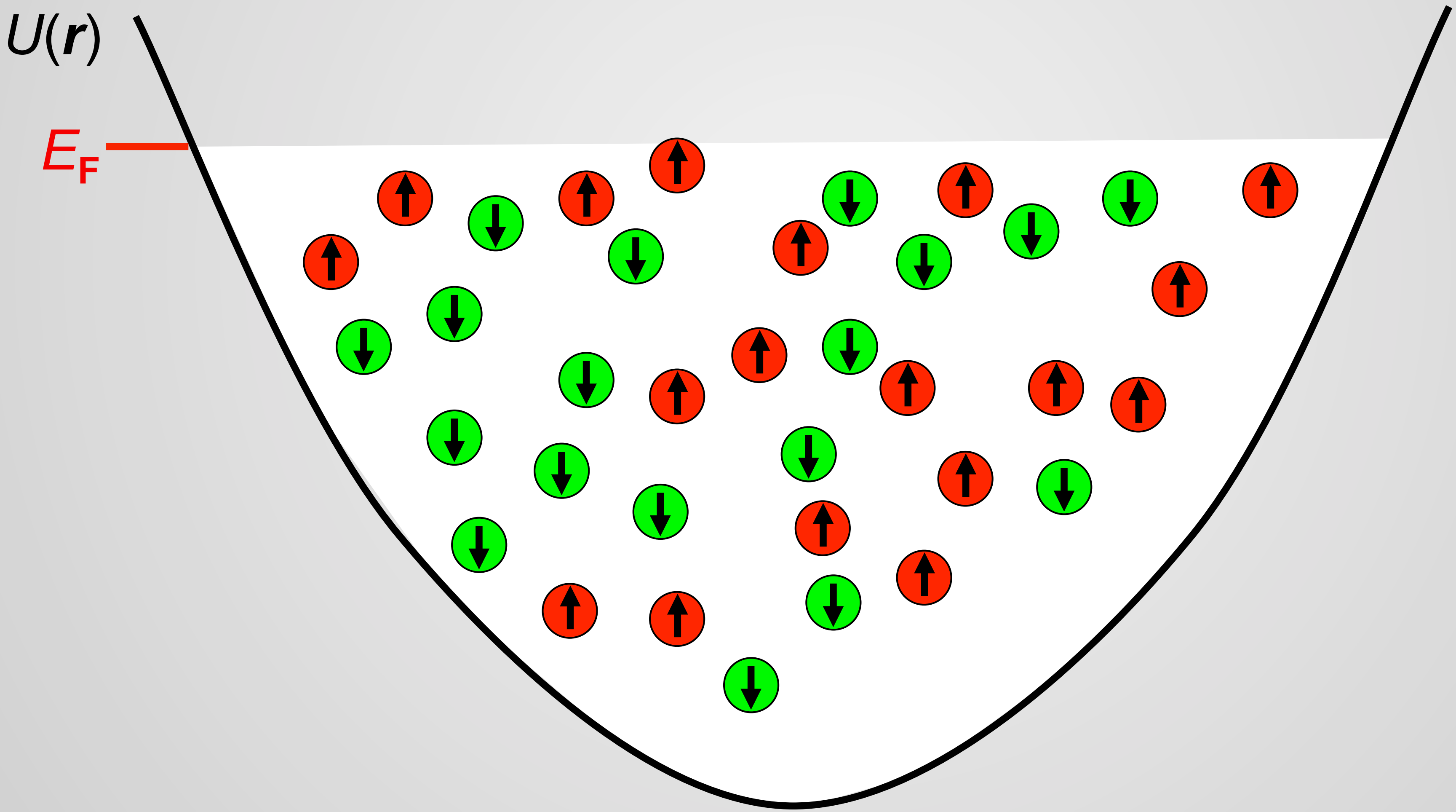
A spin polarized gas is noninteracting a ultracold temperature

Mixtures of fermions

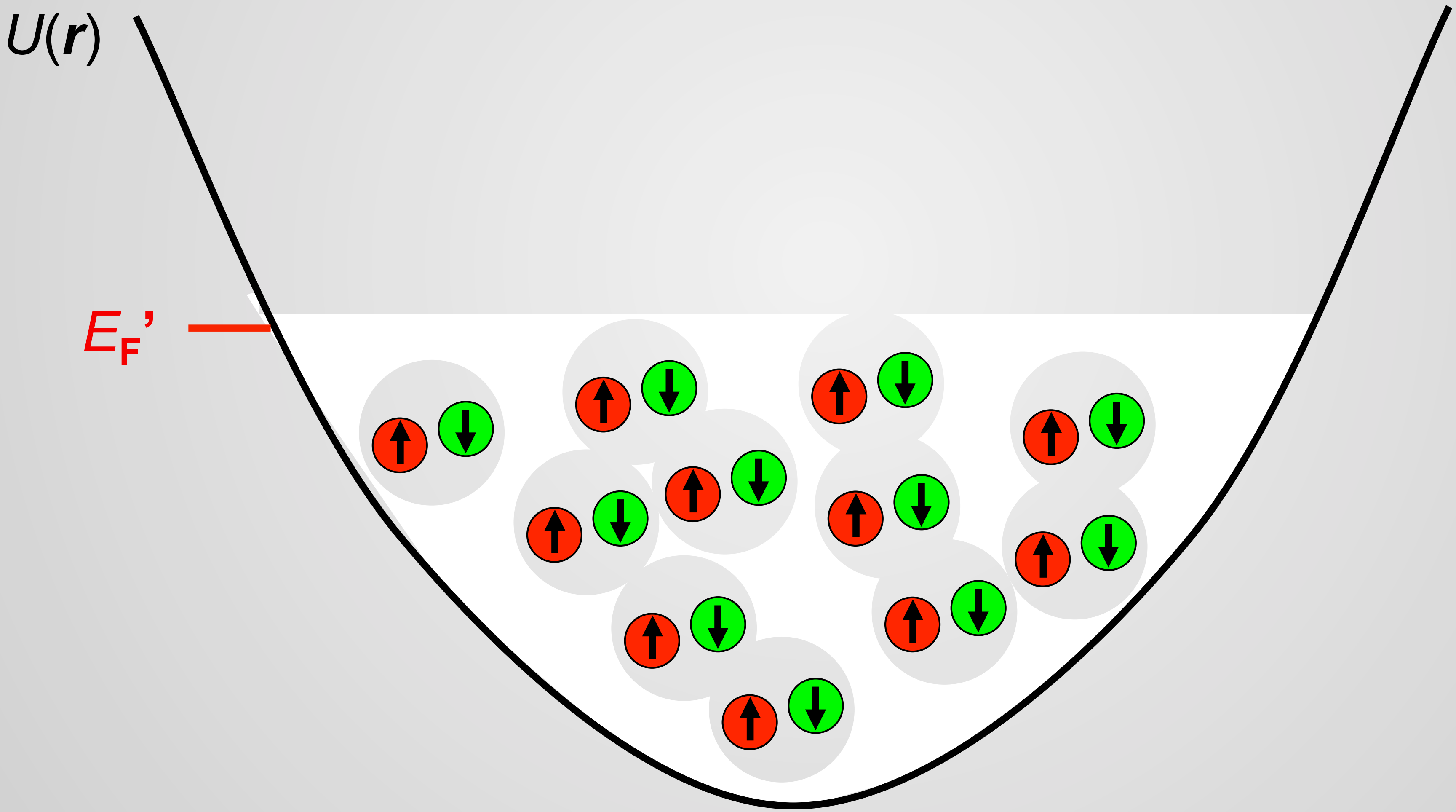
Exciting experiments in two-component mixtures!



Mixture of fermions



Strongly interacting fermions



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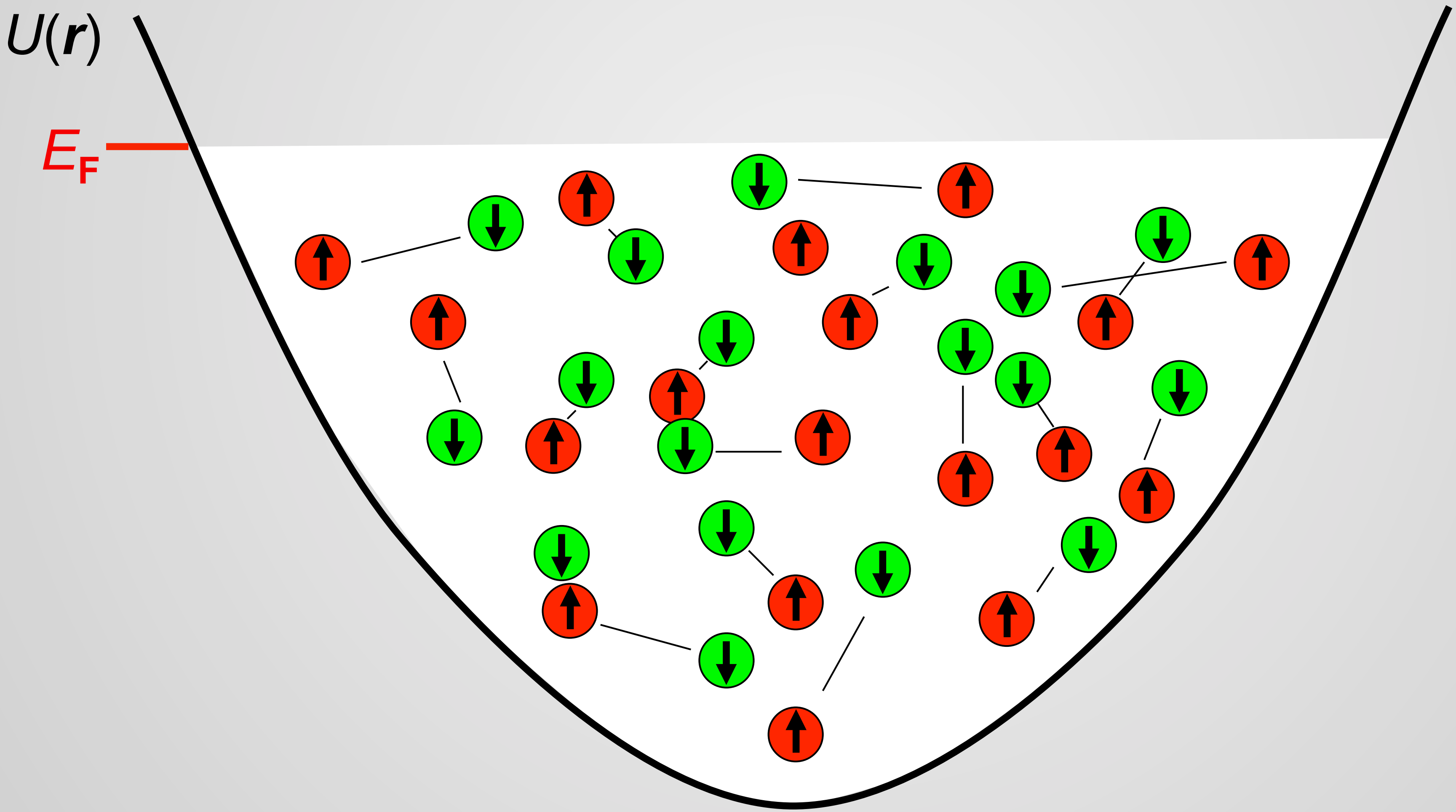
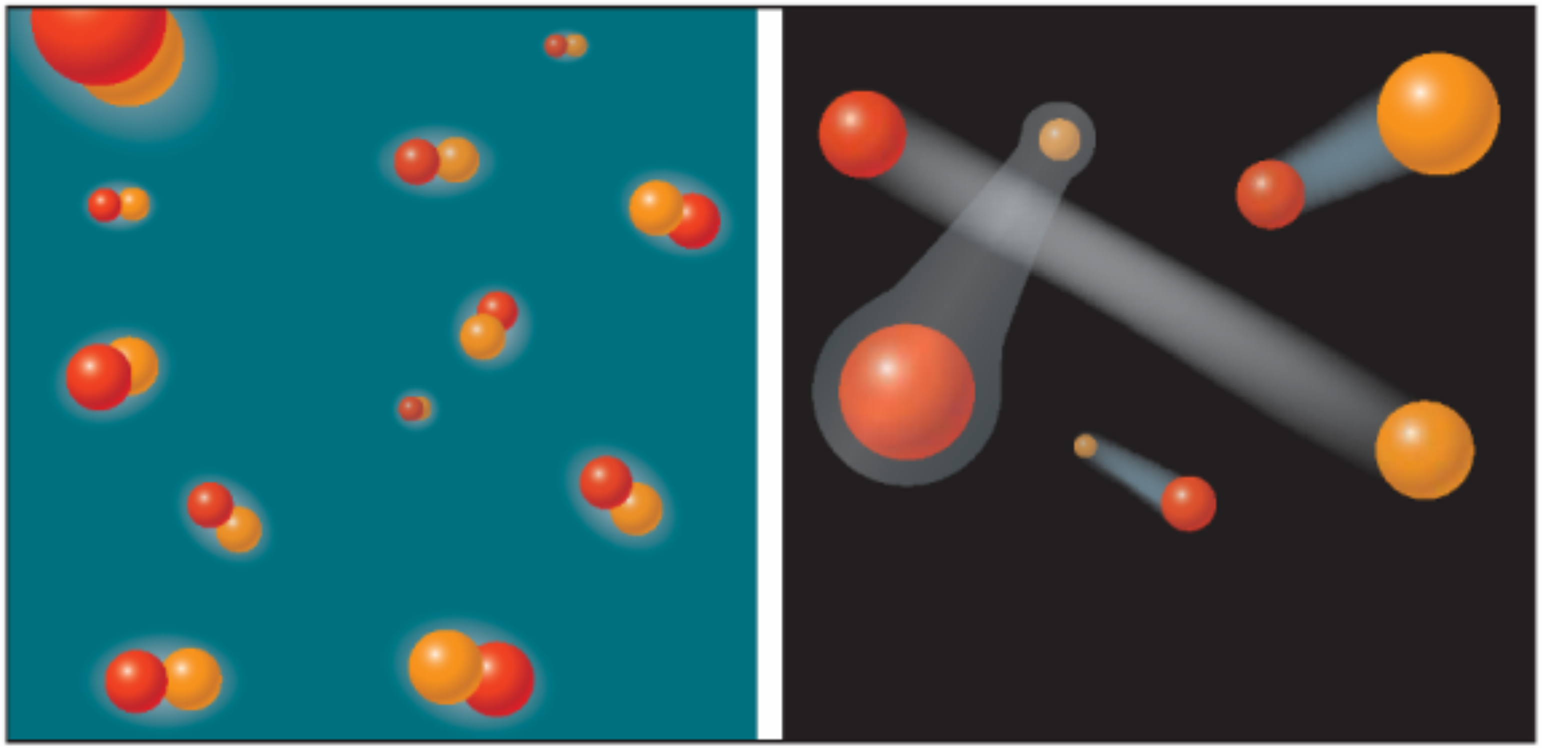
Tuning the interactions ....



A very exciting playground ....

... for many-body physics



Tango or twist? In a magnetic field, atoms in different spin states can form molecules (*left*). Vary the field, and they might also form loose-knit Cooper pairs.

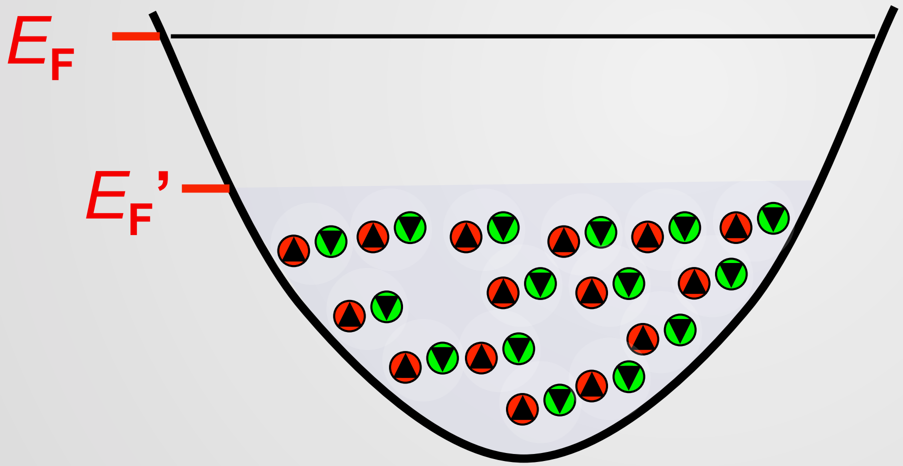
Cho, Science (2003)

BEC-BCS crossover:

- Establish the link between Bose-Einstein Condensation and Superconductivity

A unitary Fermi gas

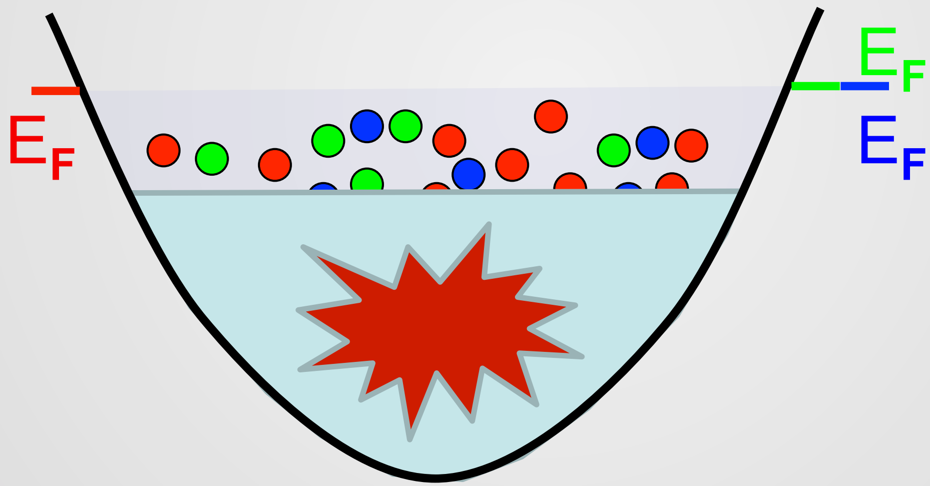
At infinite scattering length: only one length scale: Interparticle distance
Fermi energy is rescaled by a universal factor:



$E_F' = (1-\beta) * E_F$, $\beta \approx -0.58$

A unitary Fermi gas with more components?

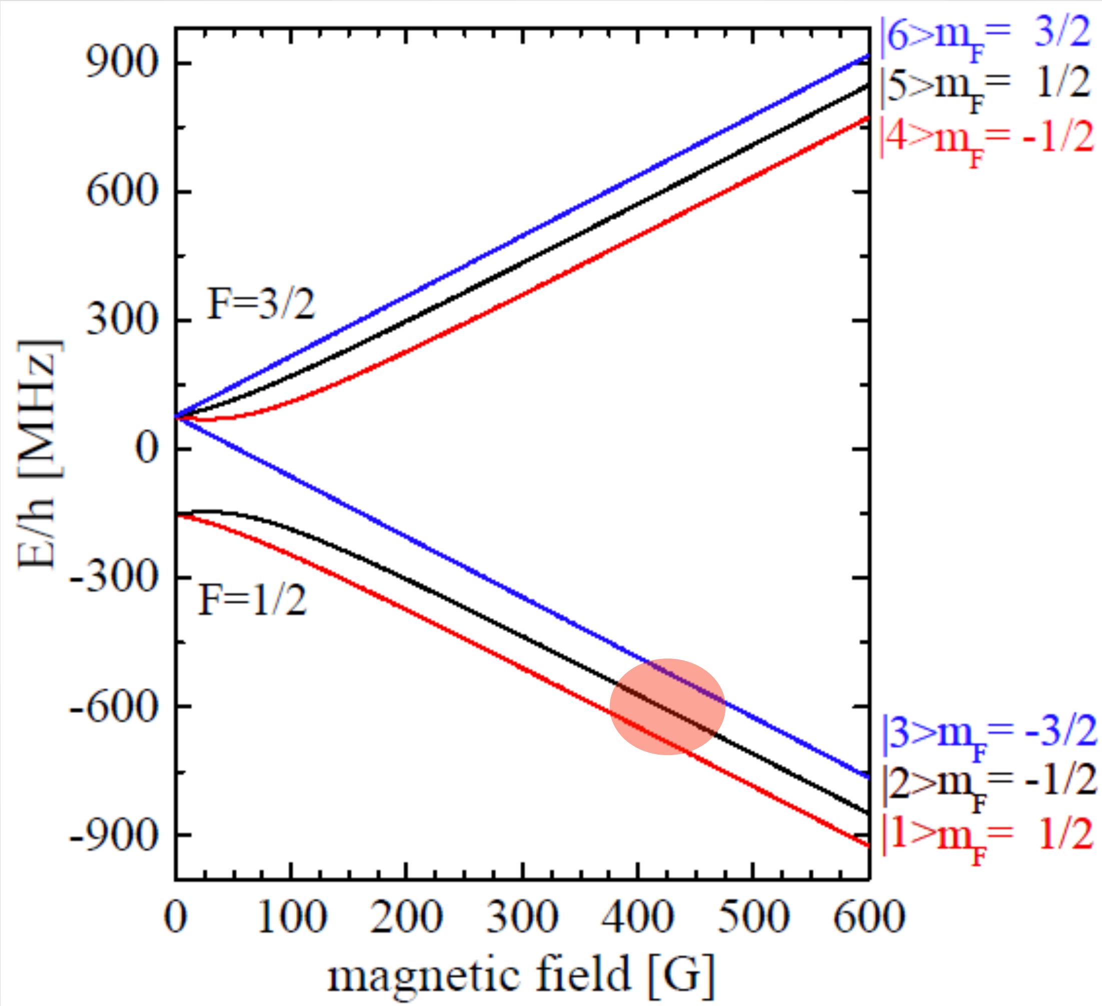
For three components: Will there be just another universal factor that rescales the energy?
… or will the gas not be mechanically stable at all?
… is that a fundamental question???



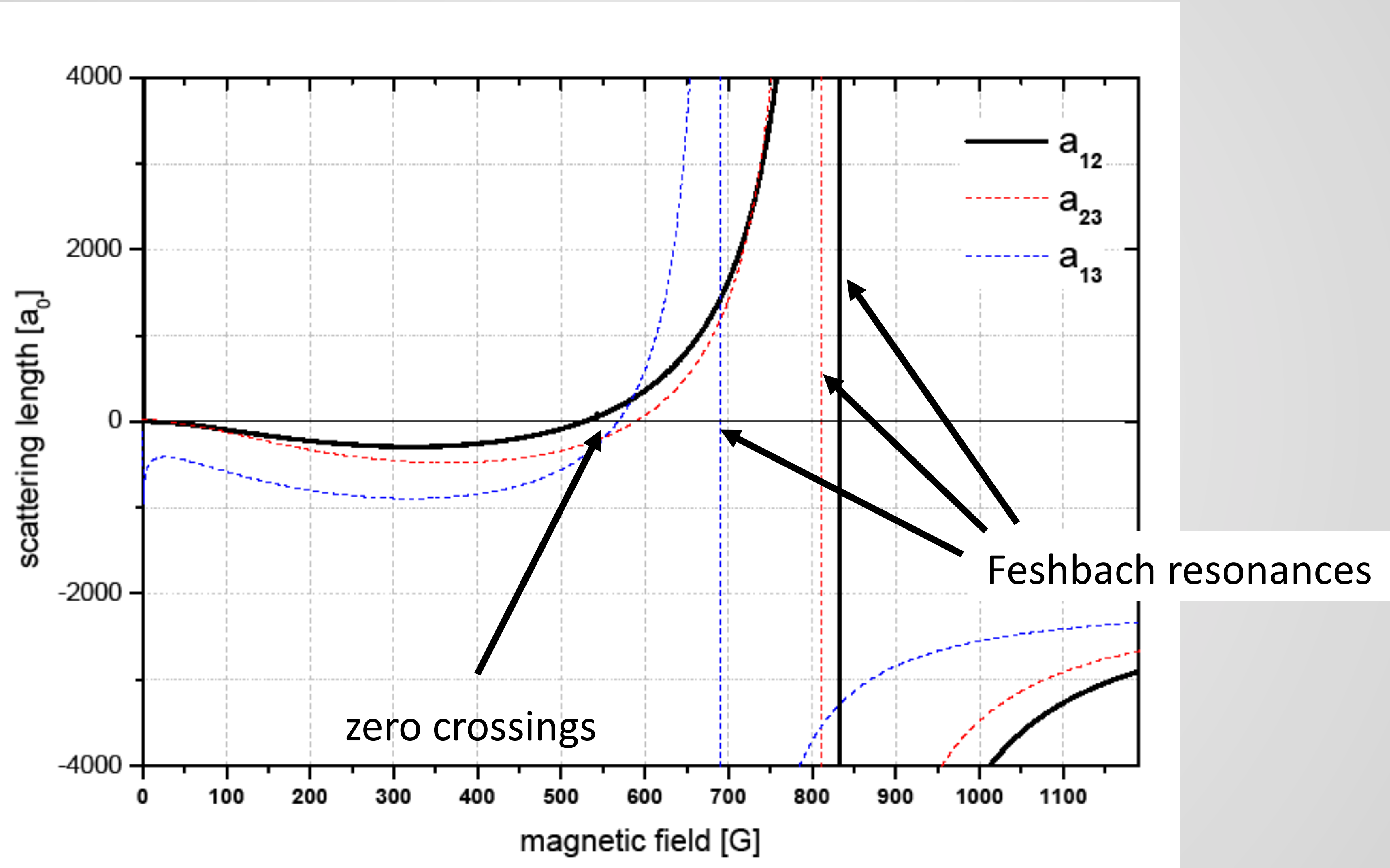
H. Heiselberg, PRA **63**, 043606 (2001)
D. Blume *et al.*, PRA **77**, 033627 (2008)

A three-component mixture of ^{6}Li

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



… Tuning the interactions …

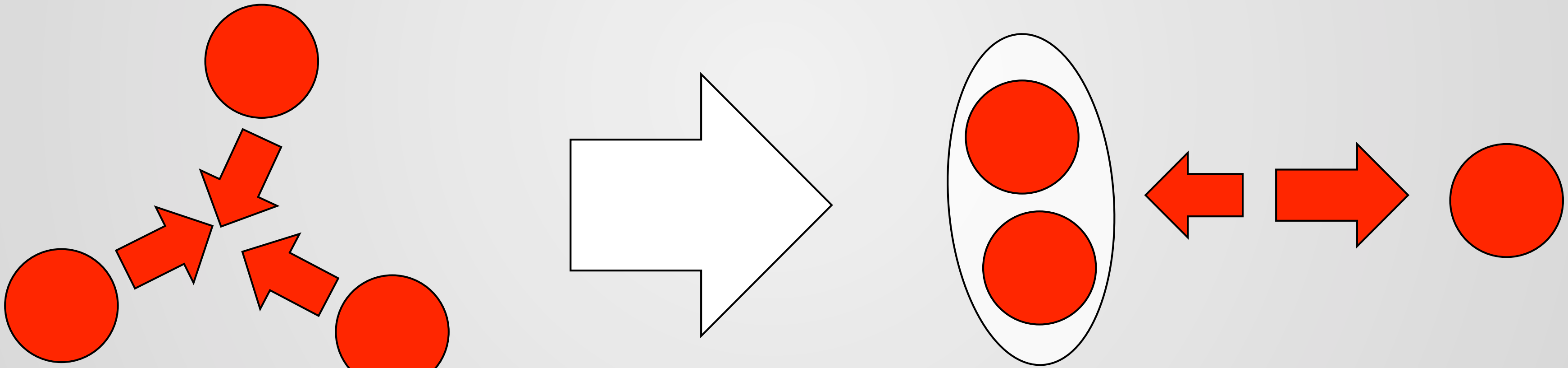


…are tuned with one knob: the magnetic field!

What is observed in experiments?

Unexpectedly large three-body recombination!!!

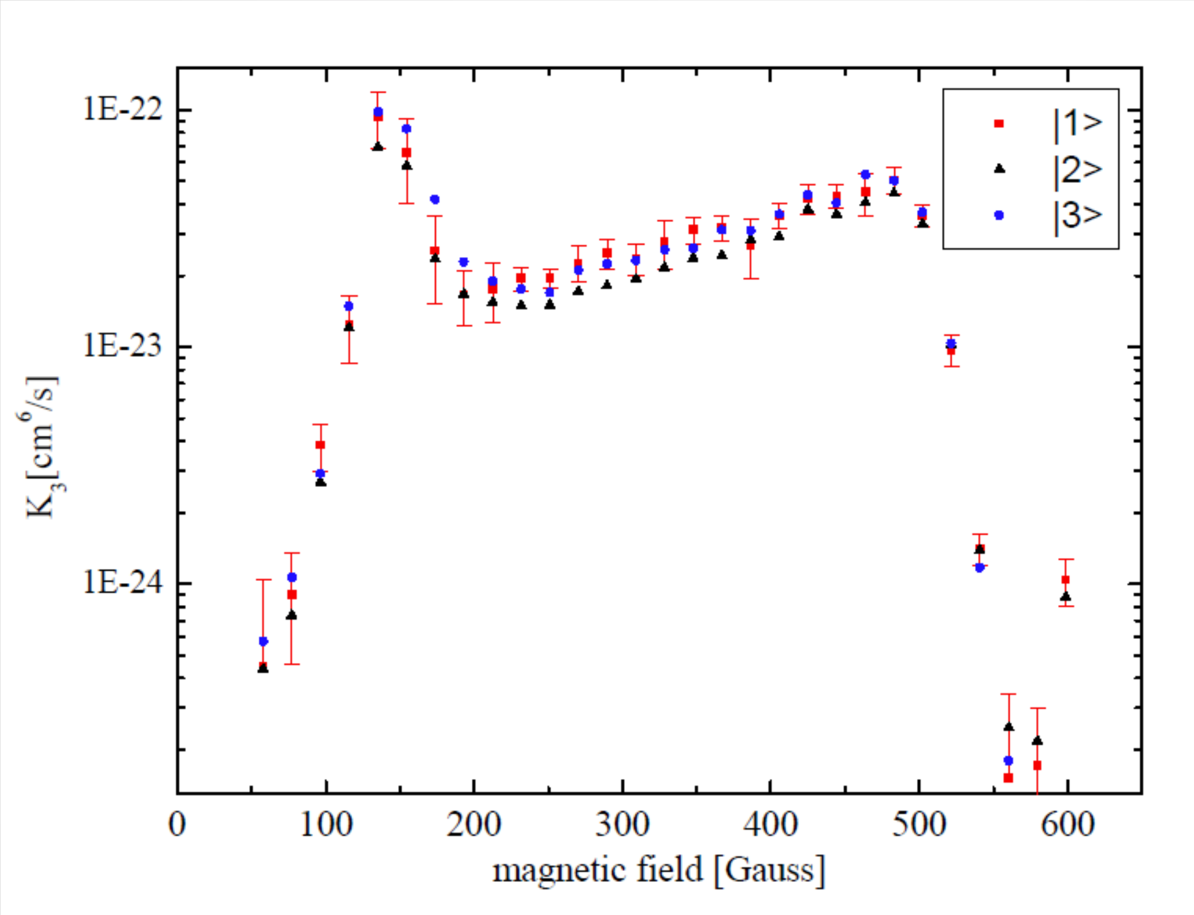
Few-body physics dominates ...



deeply bound molecule

Inelastic decay rate vs. magnetic field

Tune interaction strength using magnetic field



T. Ottenstein *et al.*, PRL **101**, 203202 (2008)

Similar experiments at:
Penn State: J. Huckans *et al.*, PRL **102**, 165302 (2009), also at Tokyo U. and MIT

The Efimov effect (V. Efimov, 1970)

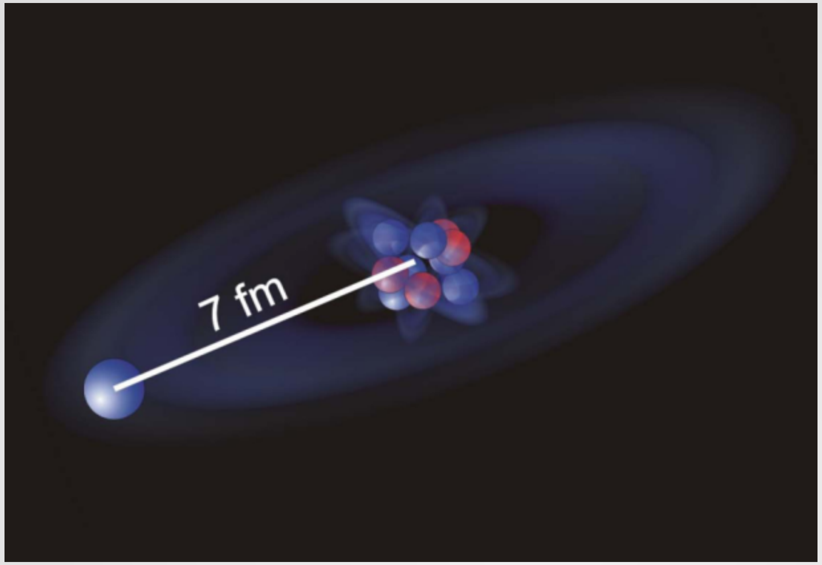
- An i… number of 3-body bound states exists when the sc… ngth diverges: (3 identical bosons)
- A…
- Sc… ngt… Efim… mers become unbound

  $a_{n+1}=22.7a_n$

Drawing: V. Efimov

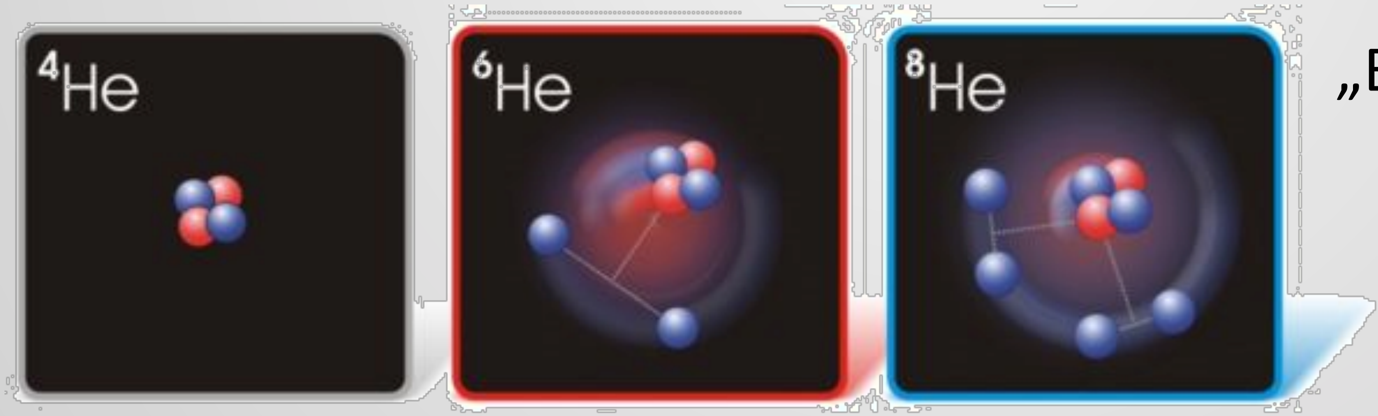
- Position of the series fixed by a three-body parameter, a_*

Universality in nuclear systems …



„Halo dimer“

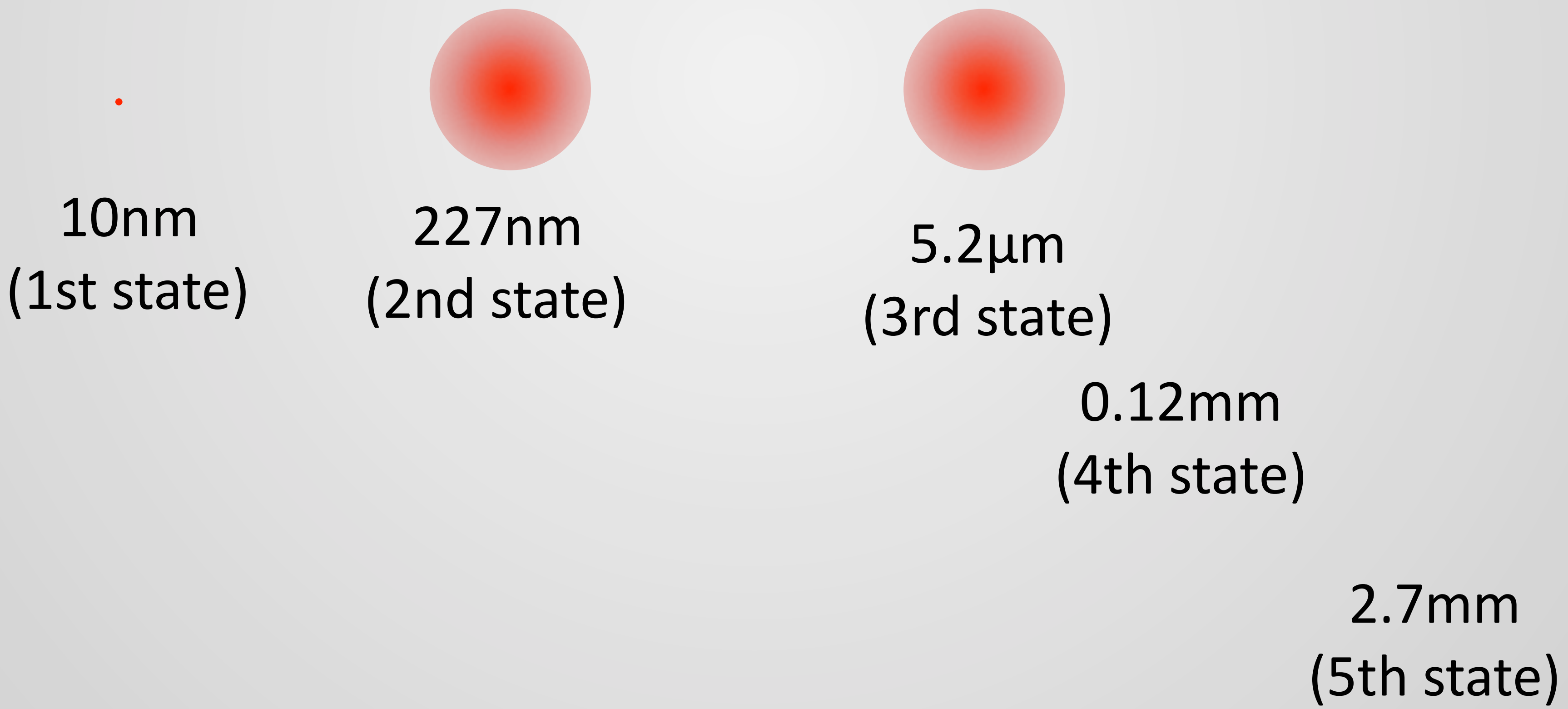
^{11}Be Nörtershäuser et al., PRL**102** 062503,2009



„Borromean“ states

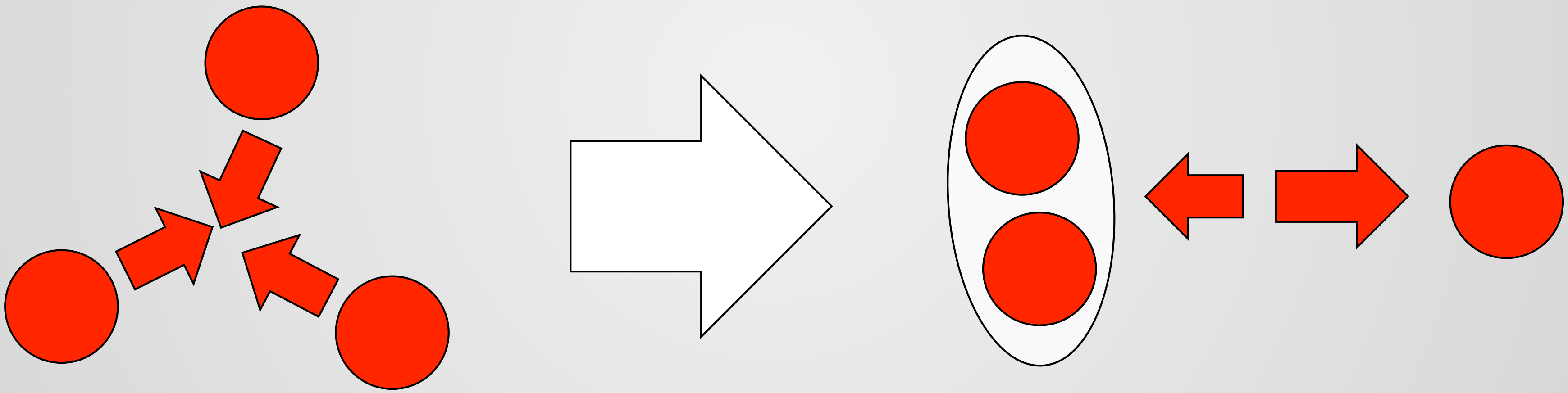
Argonne Nat. Lab.

Observing an Efimov Spectrum?



What is observed in experiments?

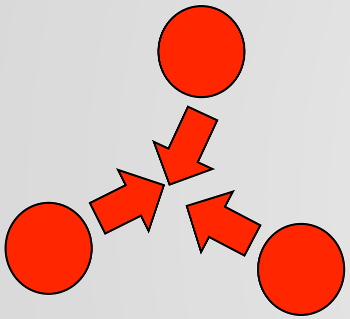
- three-body recombination

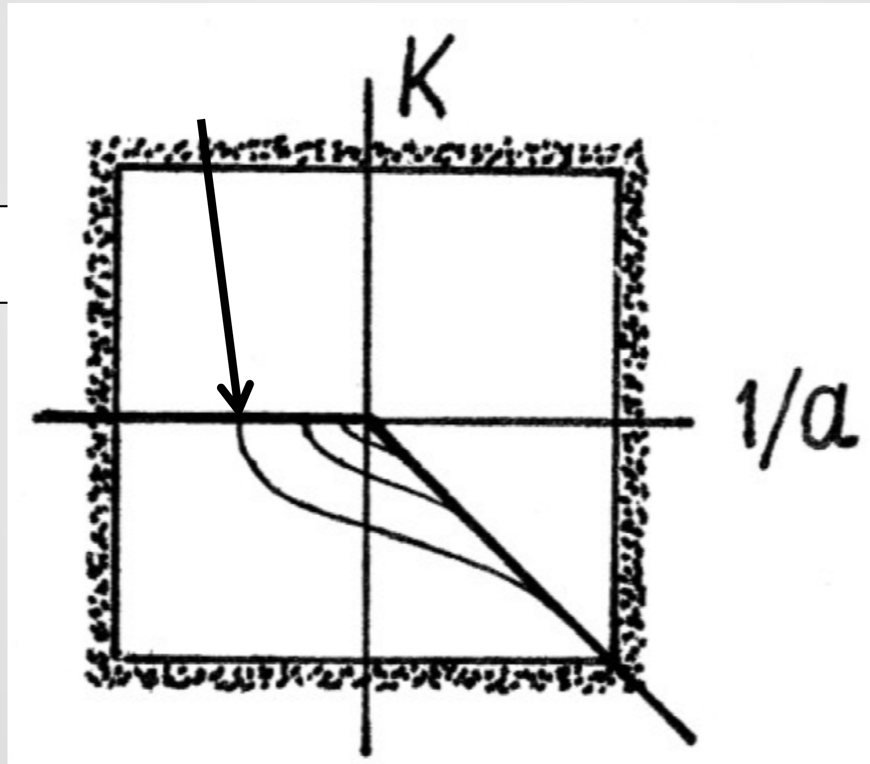


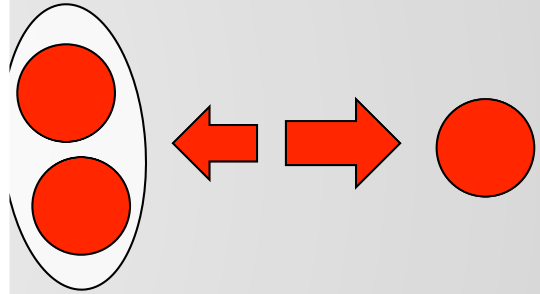
deeply bound molecule

Enhanced recombination

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



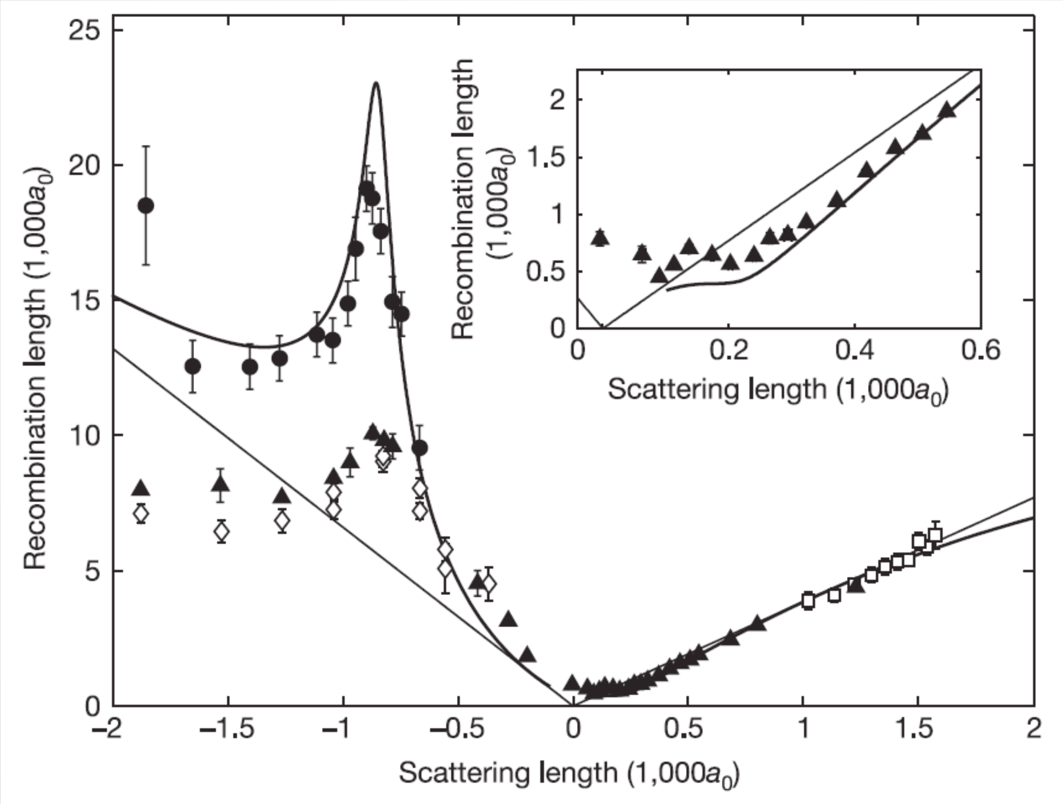




ound molecule

What has been done in experiments?

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

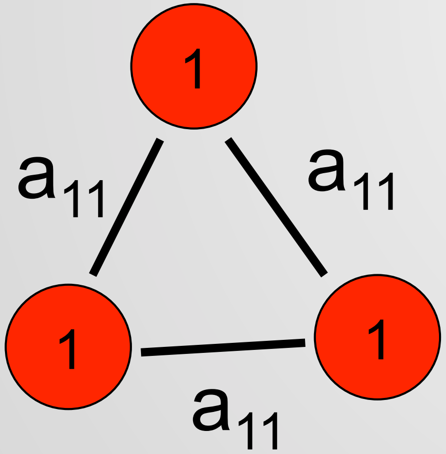


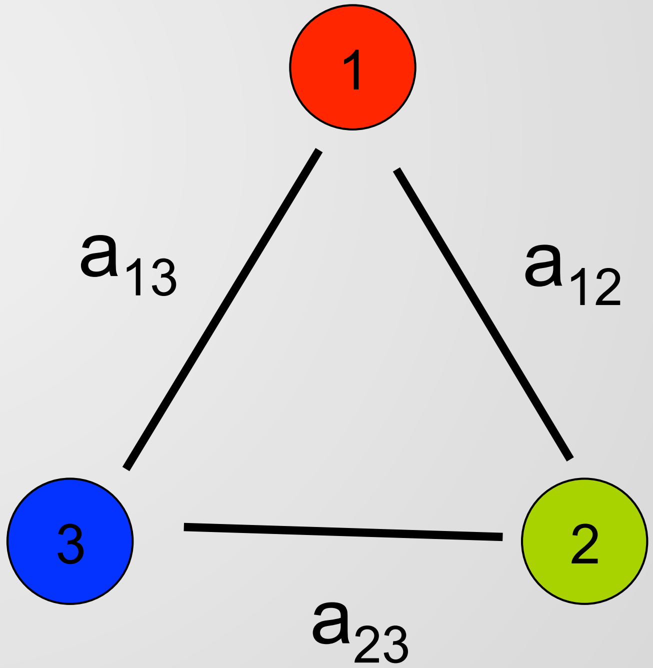
T. Krämer et al., Nature **440**, 315 (2006)

Efimov physics with Fermions?

Efimov physics with fermions

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





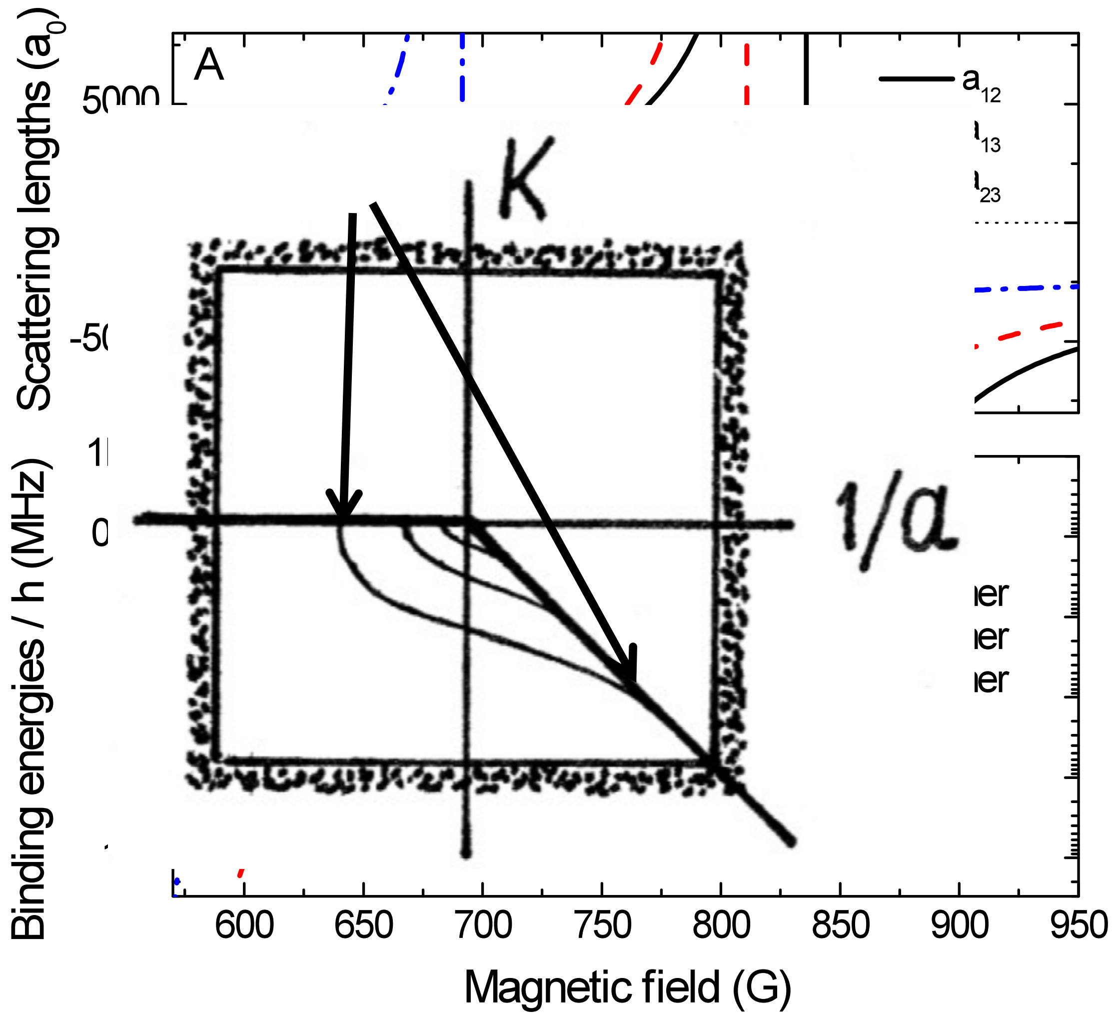
2- and 3-body bound states ….

Binding energies of dimers and trimers:

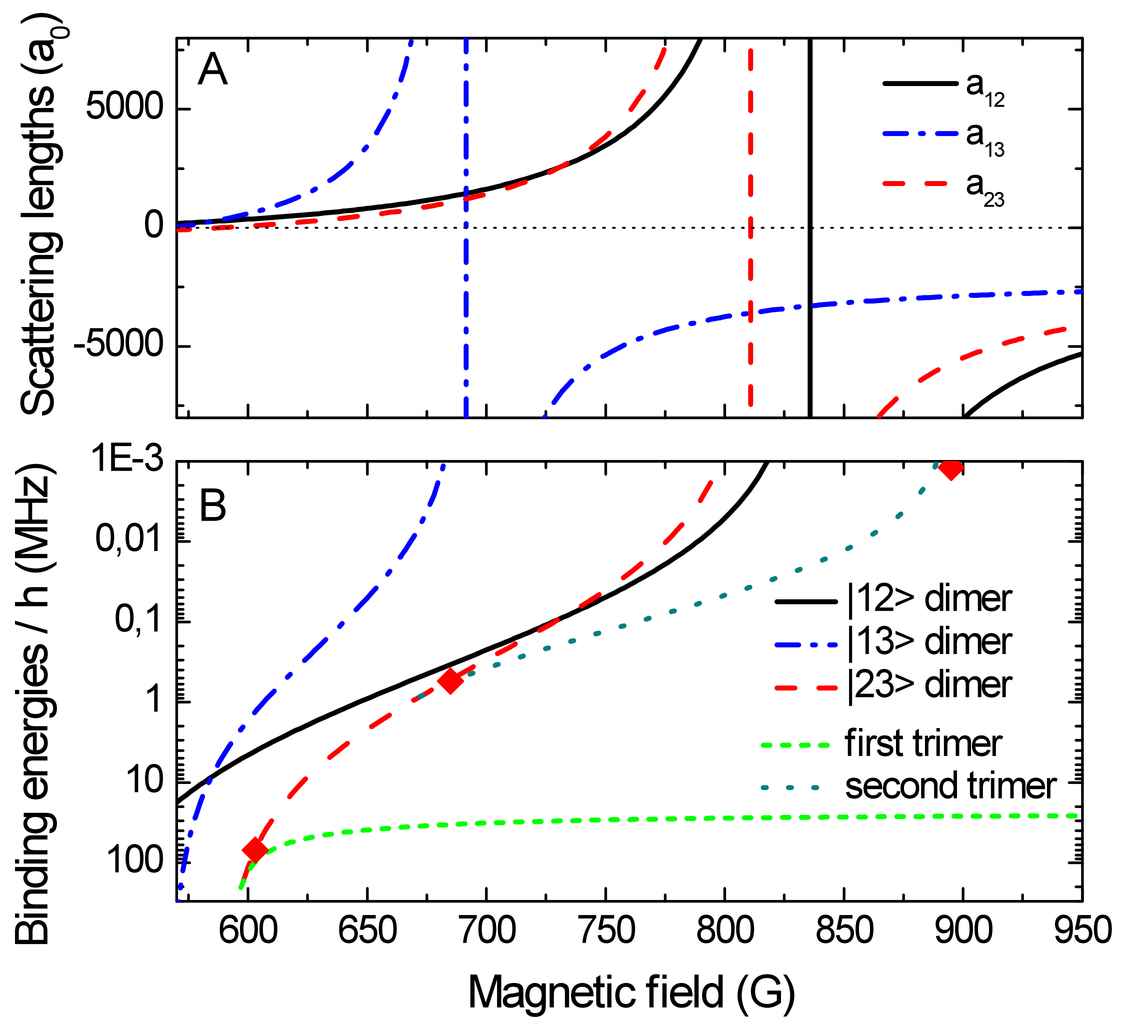
- Three different universal dimers with binding energy

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

- 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?

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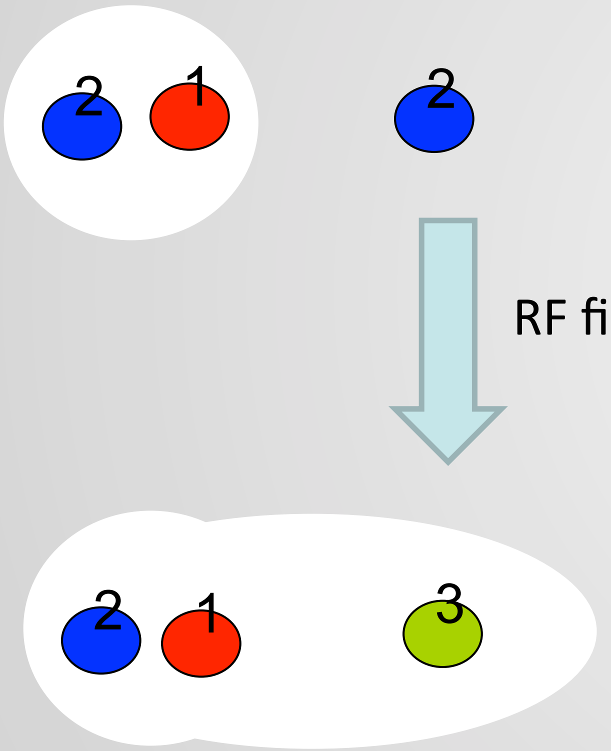
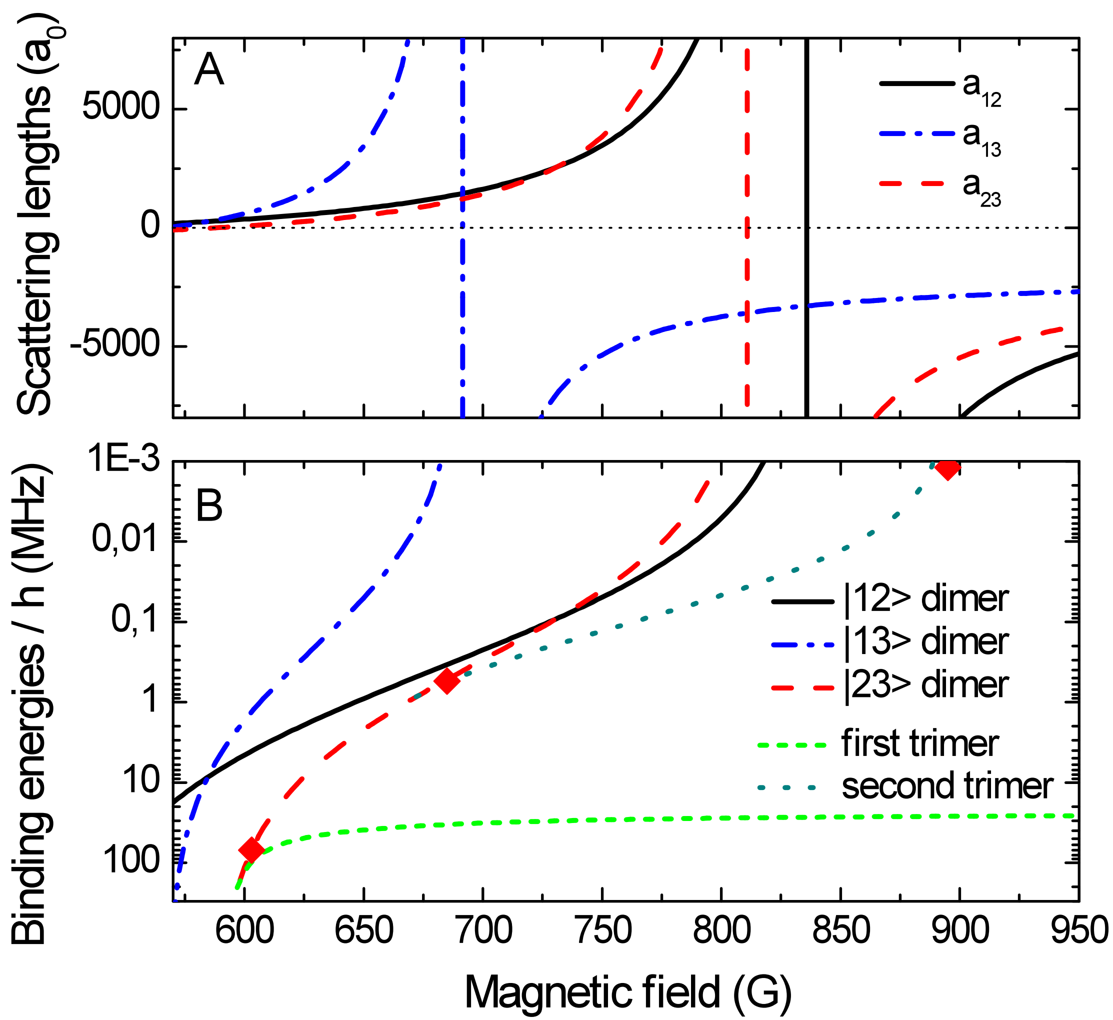
Measure binding energies using RF spectroscopy!

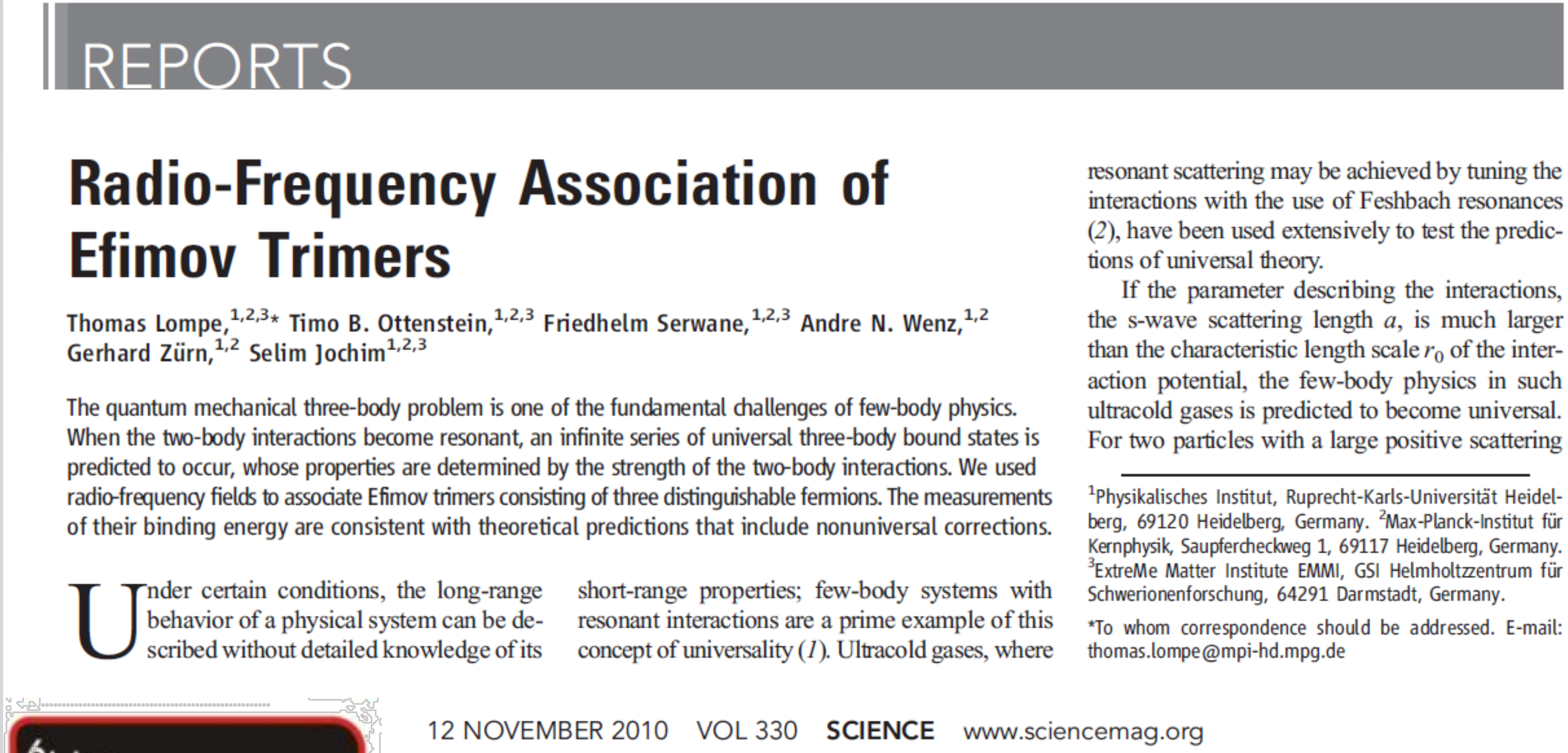


Attach a third atom to a dimer!



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

Trimer binding energy



REPORTS

Radio-Frequency Association of Efimov Trimers

Thomas Lompe,[1,2,3]* Timo B. Ottenstein,[1,2,3] Friedhelm Serwane,[1,2,3] Andre N. Wenz,[1,2] Gerhard Zürn,[1,2] Selim Jochim[1,2,3]

The quantum mechanical three-body problem is one of the fundamental challenges of few-body physics. When the two-body interactions become resonant, an infinite series of universal three-body bound states is predicted to occur, whose properties are determined by the strength of the two-body interactions. We used radio-frequency fields to associate Efimov trimers consisting of three distinguishable fermions. The measurements of their binding energy are consistent with theoretical predictions that include nonuniversal corrections.

Under certain conditions, the long-range behavior of a physical system can be described without detailed knowledge of its short-range properties; few-body systems with resonant interactions are a prime example of this concept of universality (*1*). Ultracold gases, where resonant scattering may be achieved by tuning the interactions with the use of Feshbach resonances (*2*), have been used extensively to test the predictions of universal theory.

If the parameter describing the interactions, the s-wave scattering length a, is much larger than the characteristic length scale r_0 of the interaction potential, the few-body physics in such ultracold gases is predicted to become universal. For two particles with a large positive scattering

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*To whom correspondence should be addressed. E-mail: thomas.lompe@mpi-hd.mpg.de

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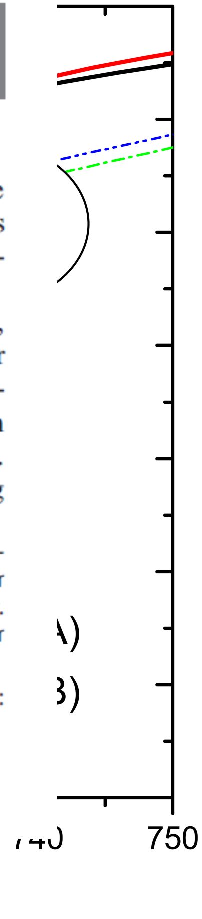
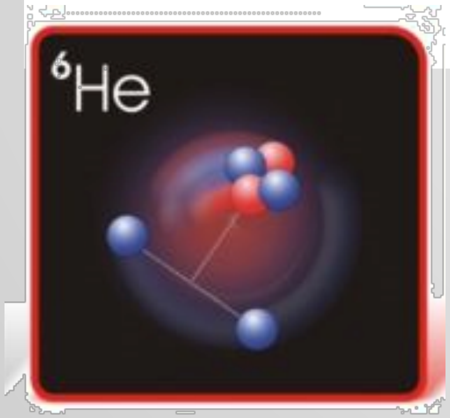
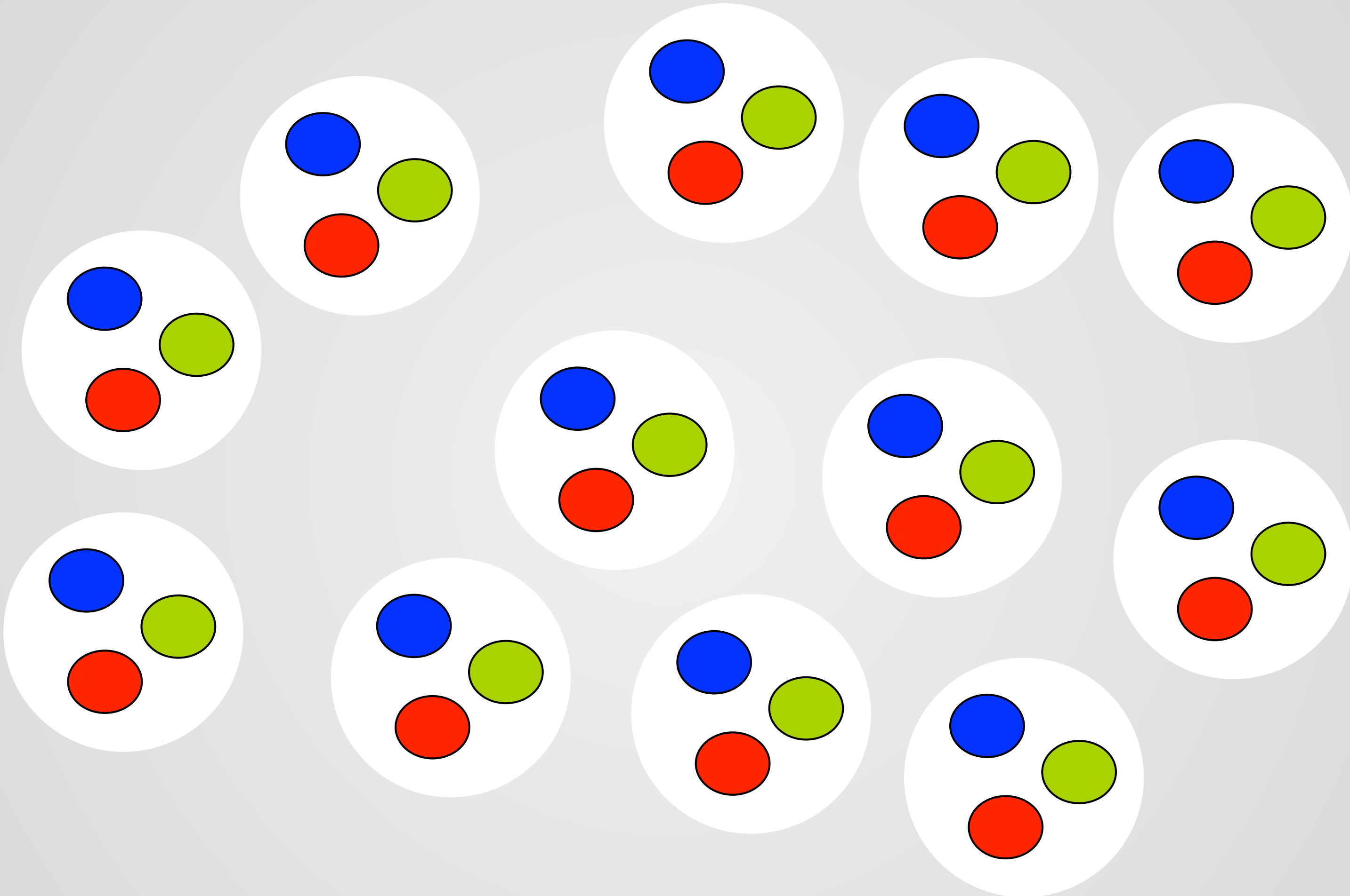




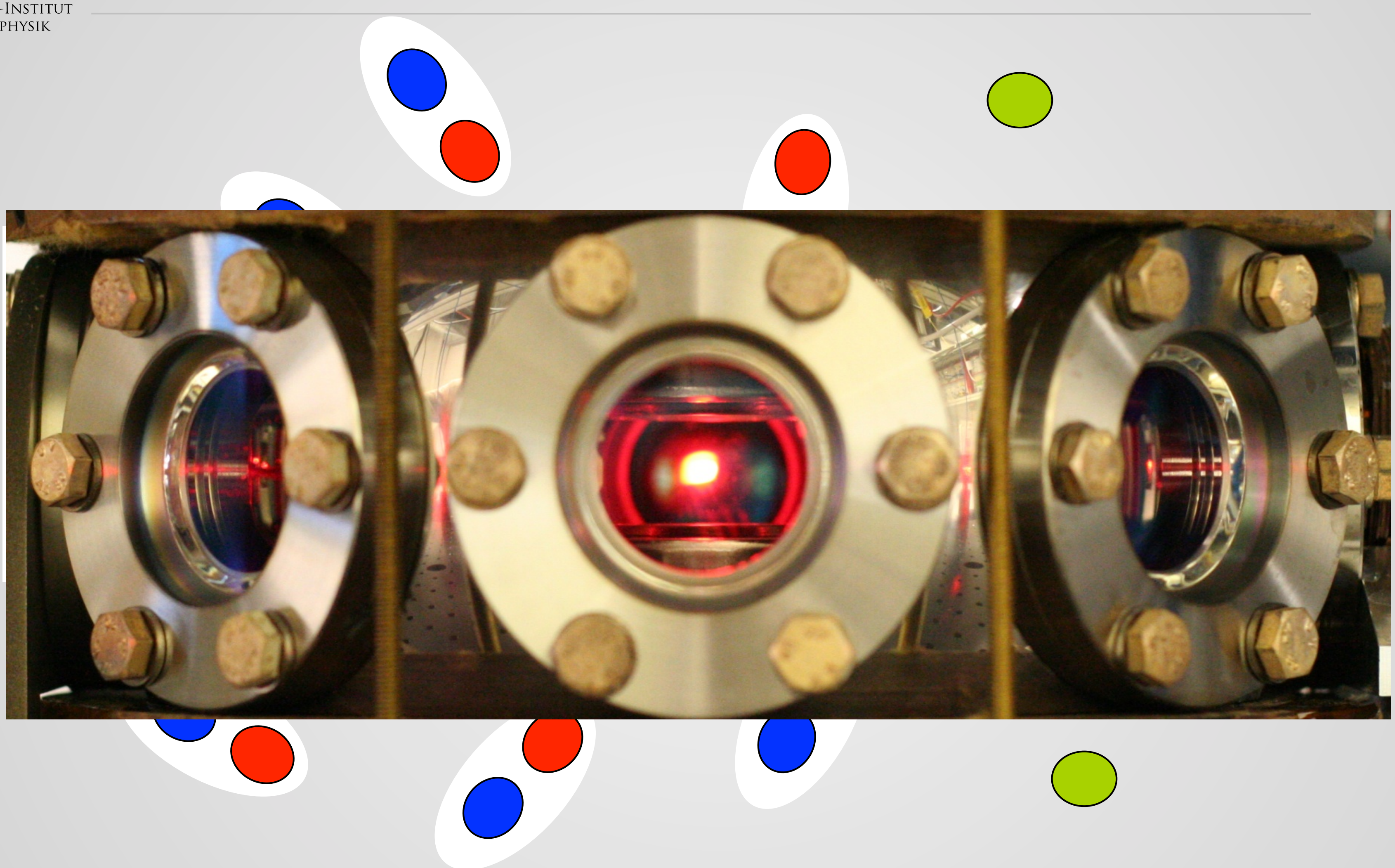
T. Lompe et al., Science 330, 940 (2010)
T. Lompe et al., PRL **105**, 103201 (2010)
See also Nakajima et al. arXiv:1010.1954
Theory curves from Nakajima *et al.*, PRL **105**, 023201 (2010)

Many-body physics with three components?



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

… many different phases are expected



- A “color superfluid”?

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

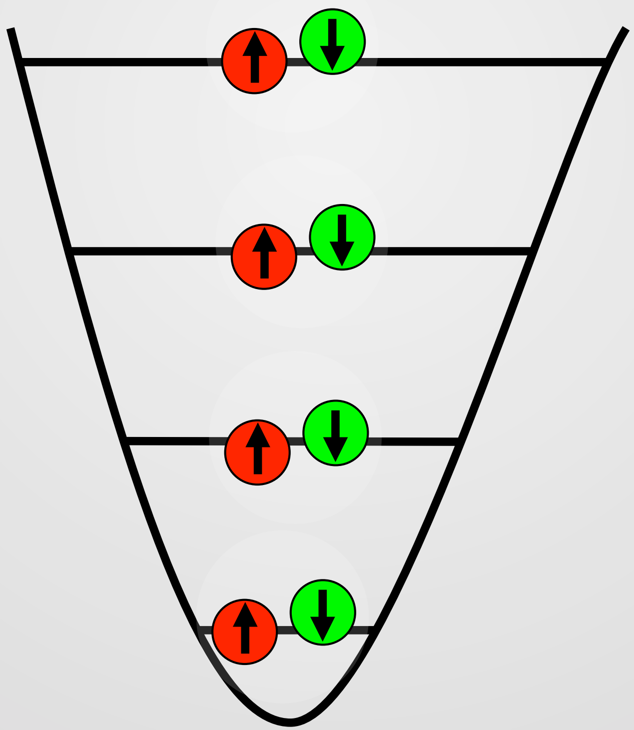
Conclusion

- Few-body physics in a three-component Fermi gas is governed by the Efimov effect.
- First direct observation of universal Efimov states.
- We are currently setting up an experiment to perform many-body physics with a three-component Fermi gas.

In between three and many ….

Very recent results:

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



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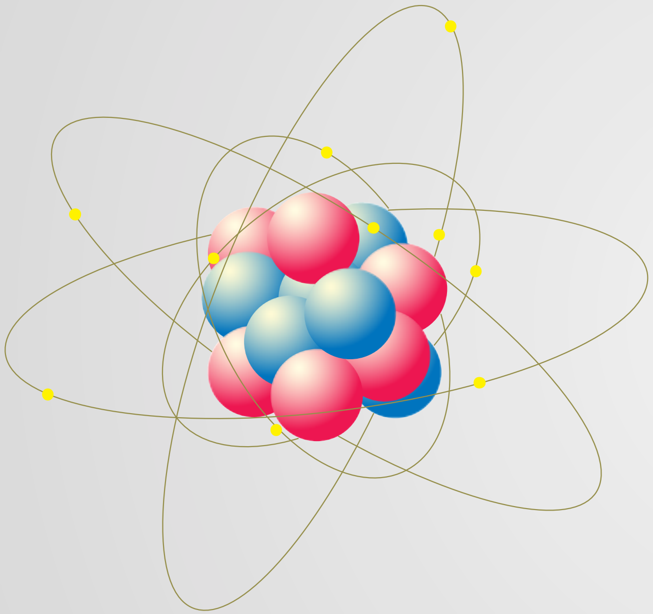
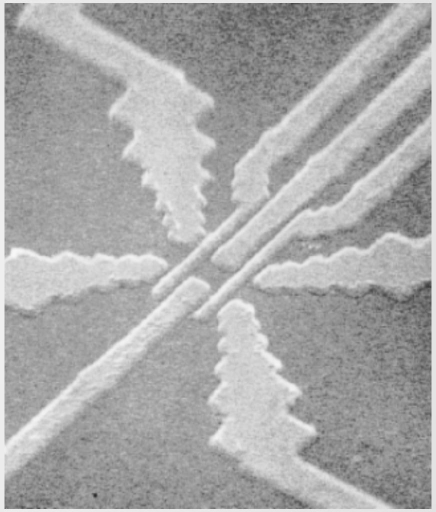
Other finite quantum systems …

- Atoms, nuclei …

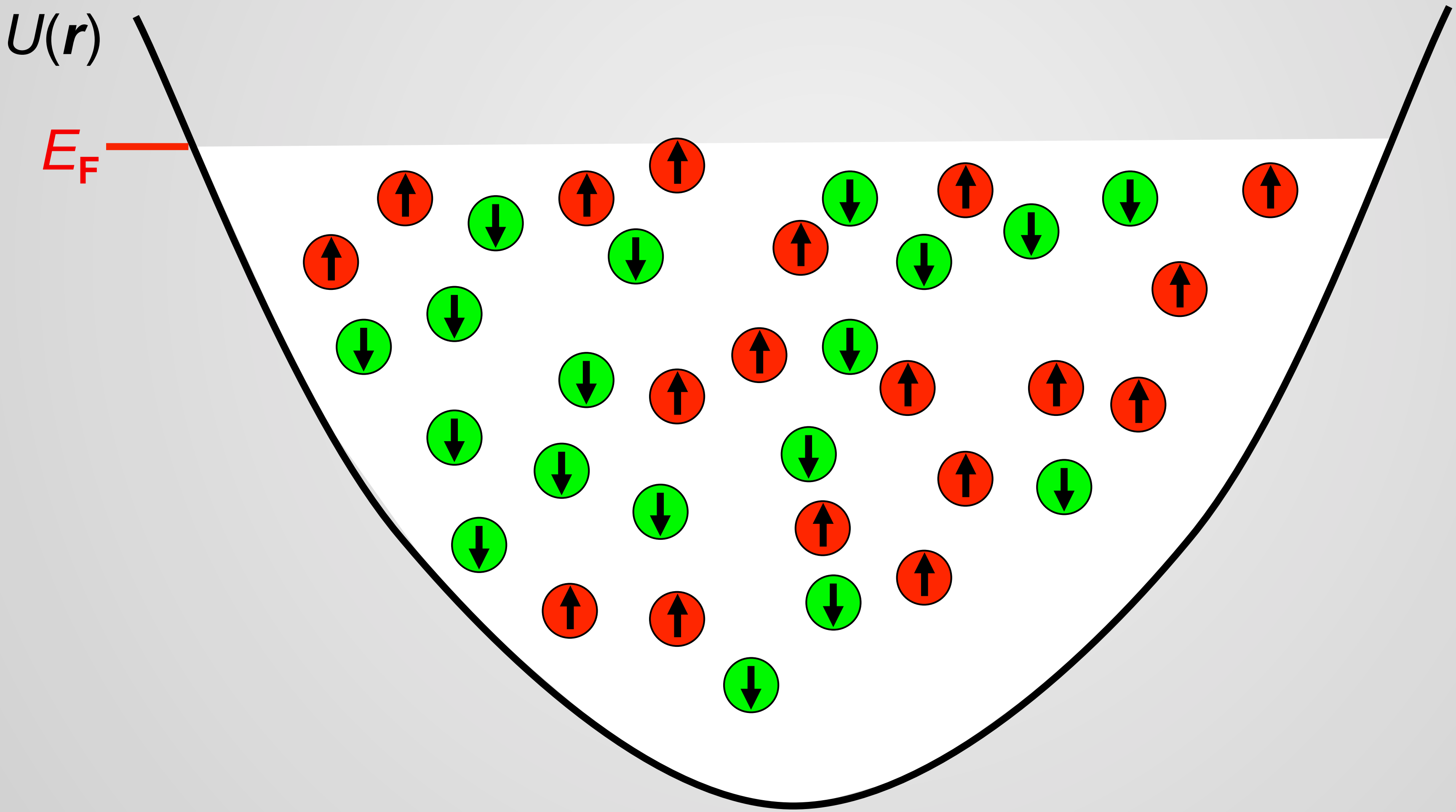


- Quantum dots, clusters …

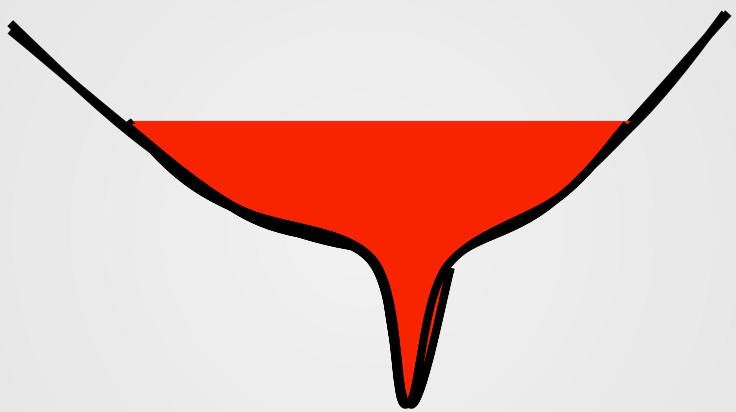


- Extreme repeatability and control over all degrees of freedom, but limited tunability
- Wide tunability, but no „identical“ systems

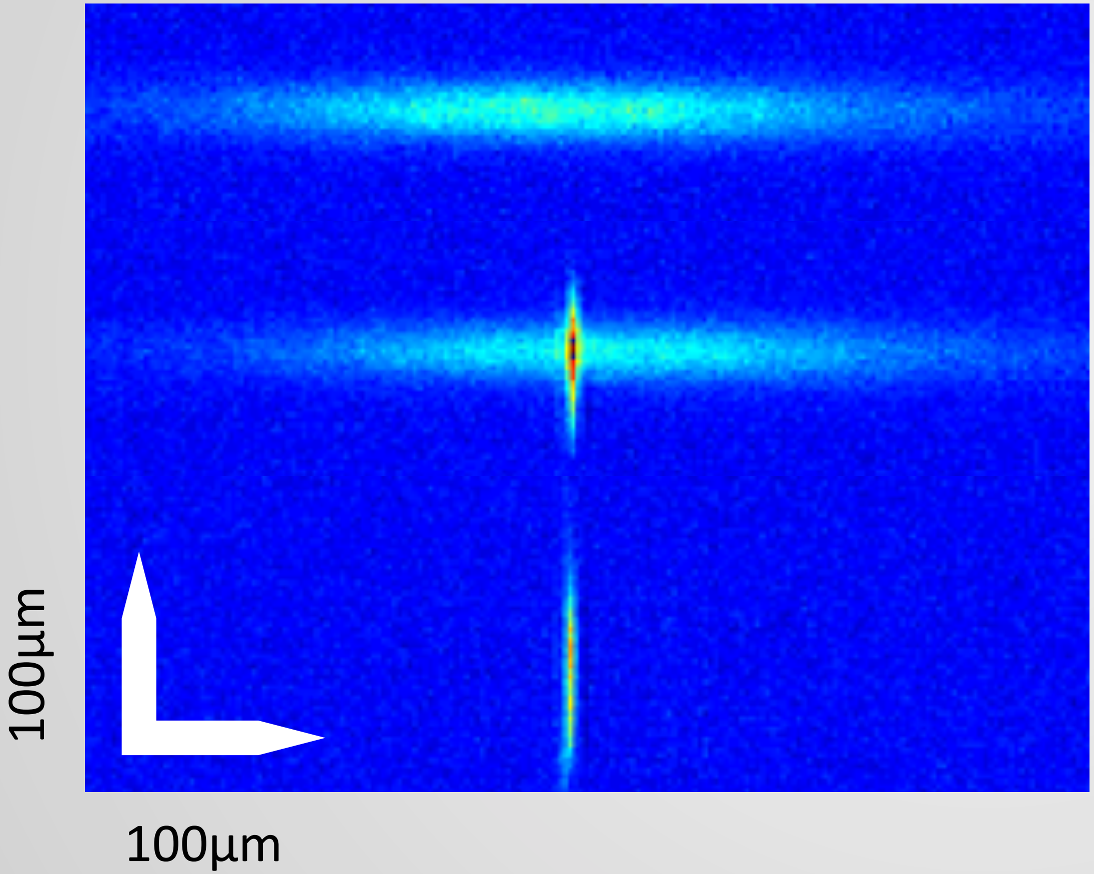
Mixture of fermions



Transfer atoms to microtrap …



Starting conditions



Reservoir temperature ~250nK

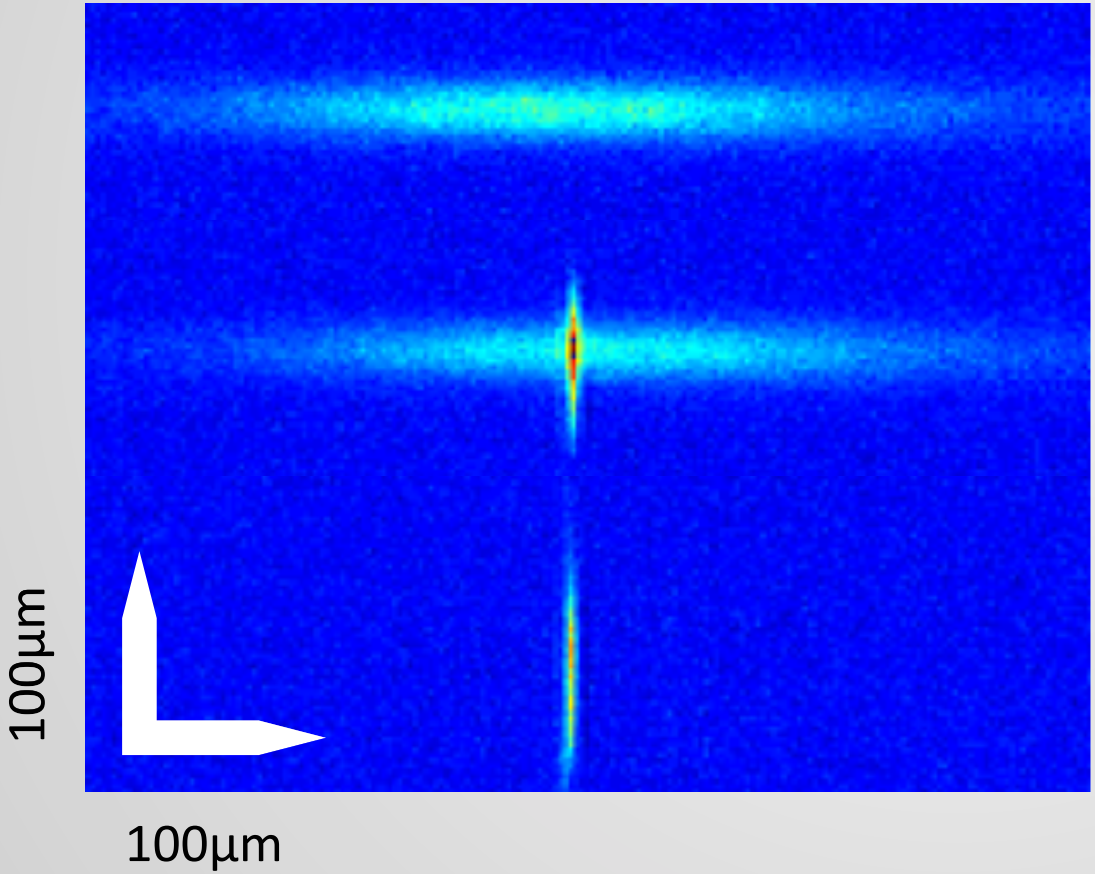
Depth of microtrap: ~3µK

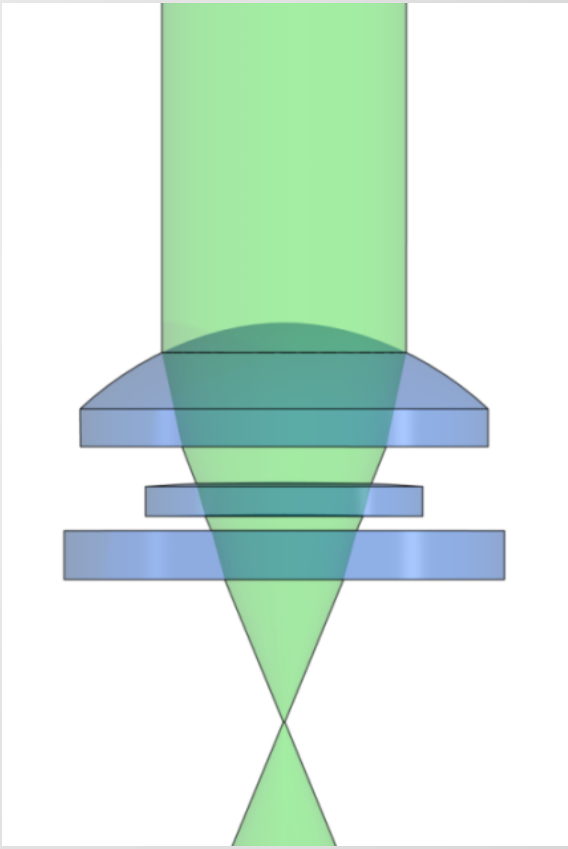
⇒Expect $T \approx 0.08 T_F$

⇒Occupation probability of the lowest energy state: > 0.9999

Atoms in a microtrap

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





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

Spill most of the atoms:

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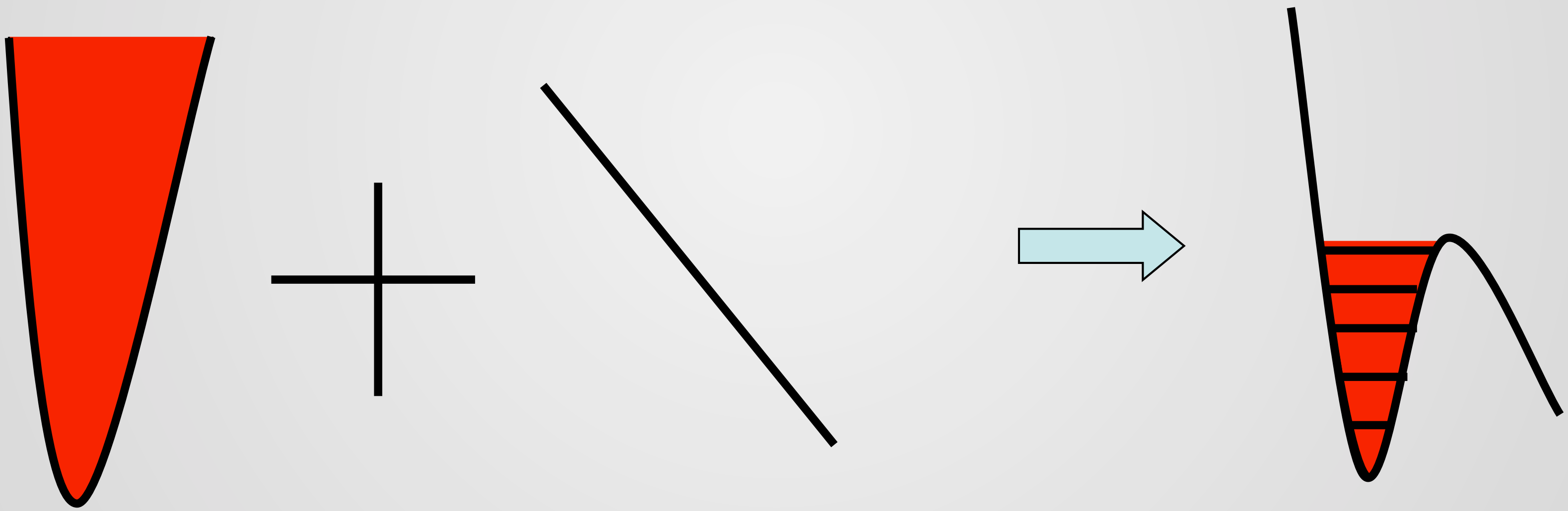
Lower trap depth

Use a magnetic field gradient to spill:



~200 atoms

μ x B

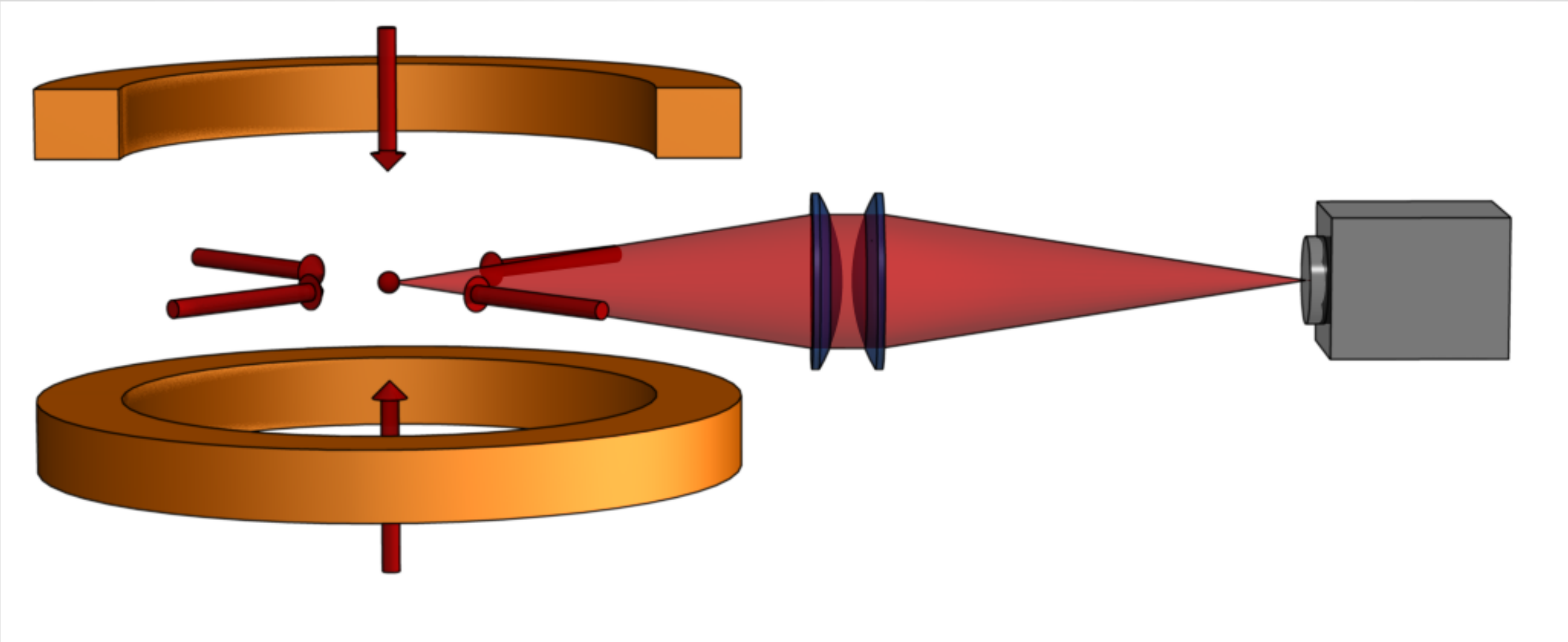
~2-10 atoms

→ What is the population of the ground state?

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

Detection of single atoms

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



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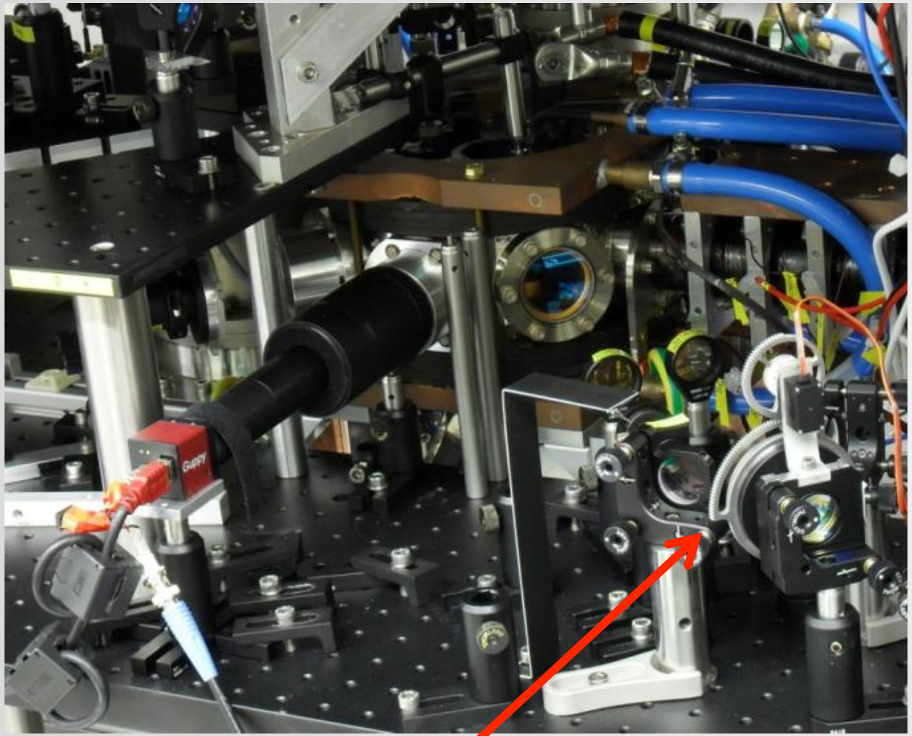
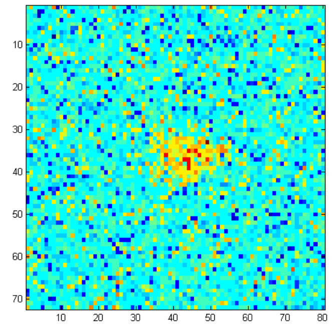
Detection of single atoms

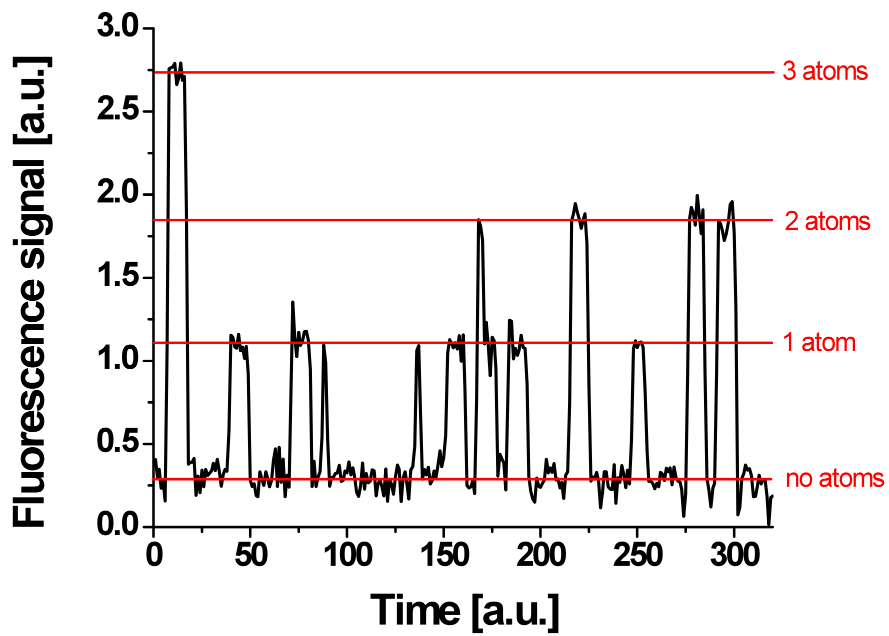
Essential ingredients: Low background and MOT lifetime



Motorized irises
control beam diameter

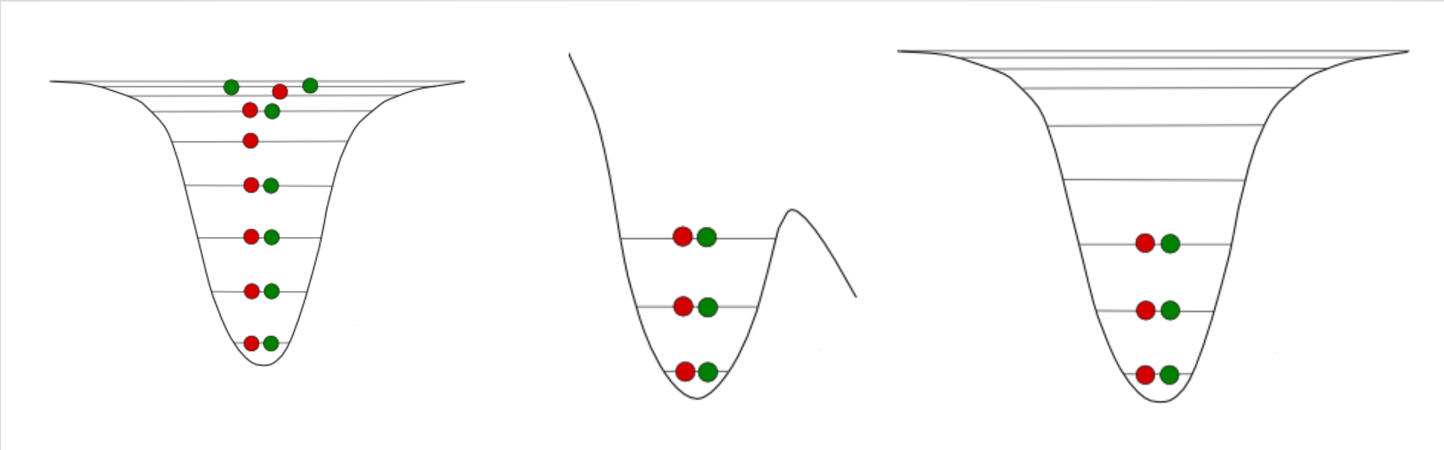
1 atom in the MOT



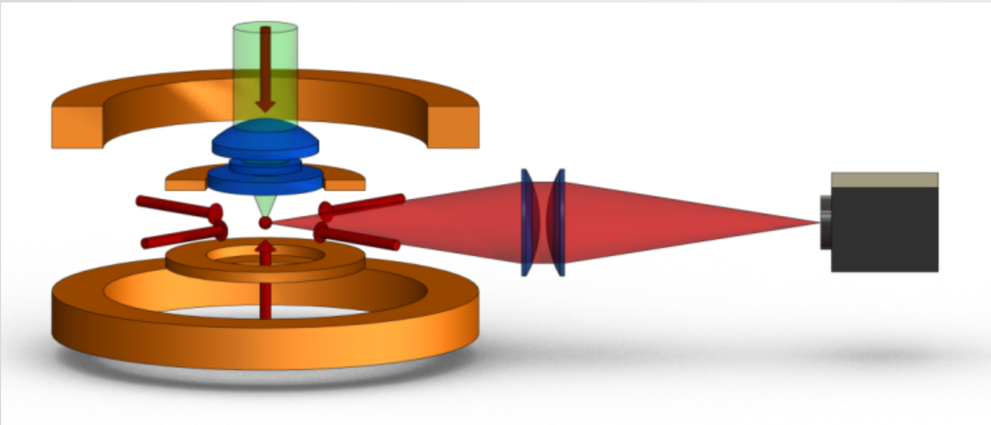


Preparation sequence

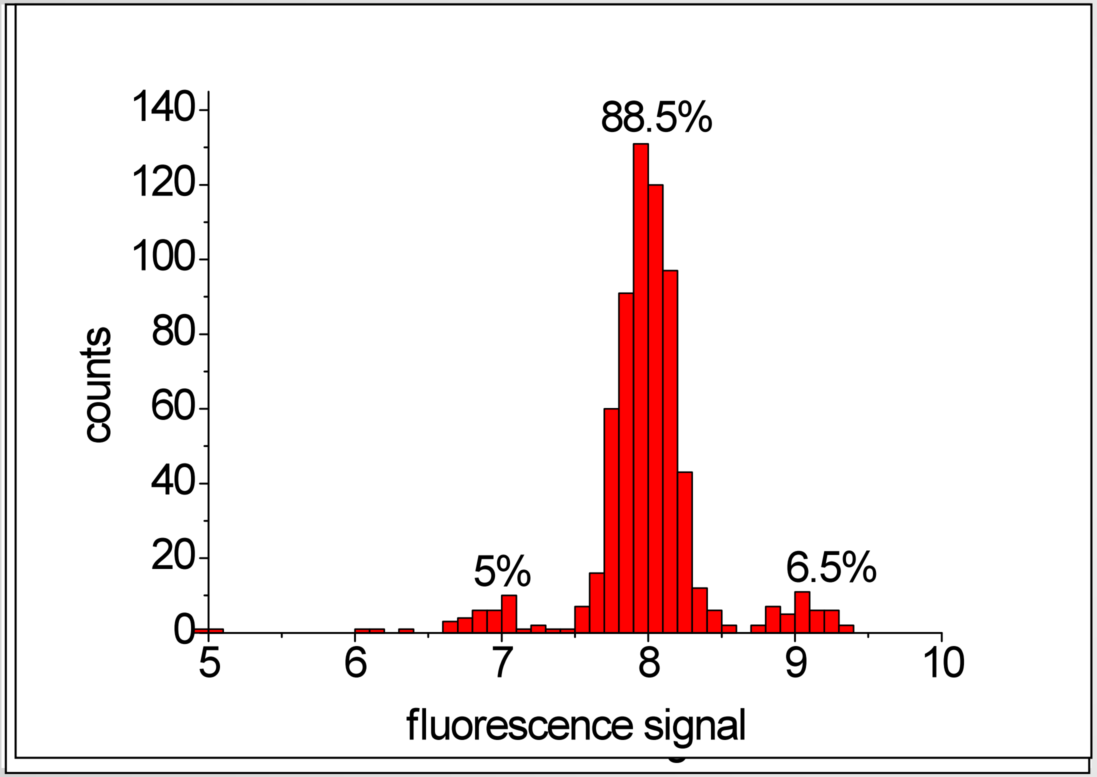
1. Spill atoms in a controlled way

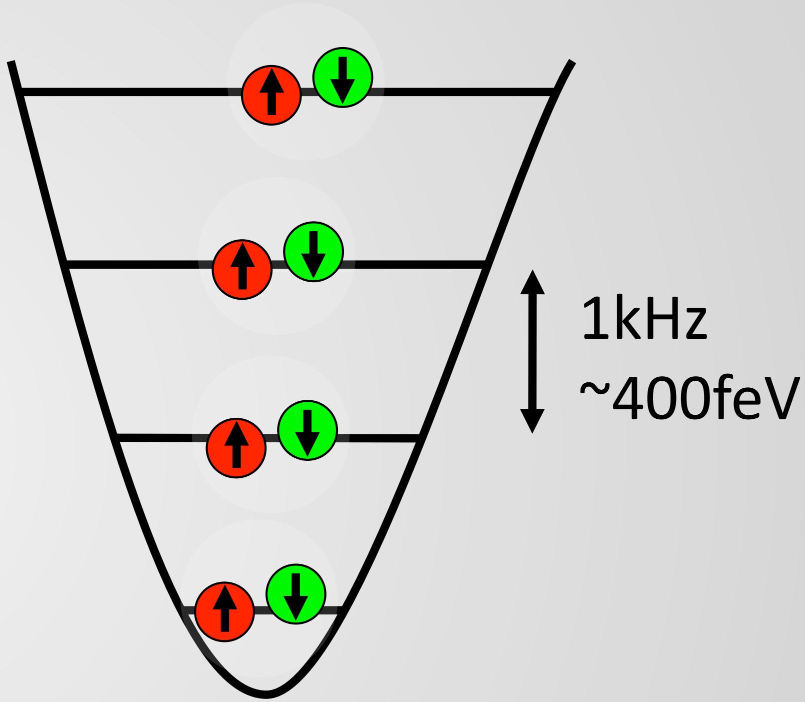


2. Recapture prepared atoms into Magneto Optical Trap



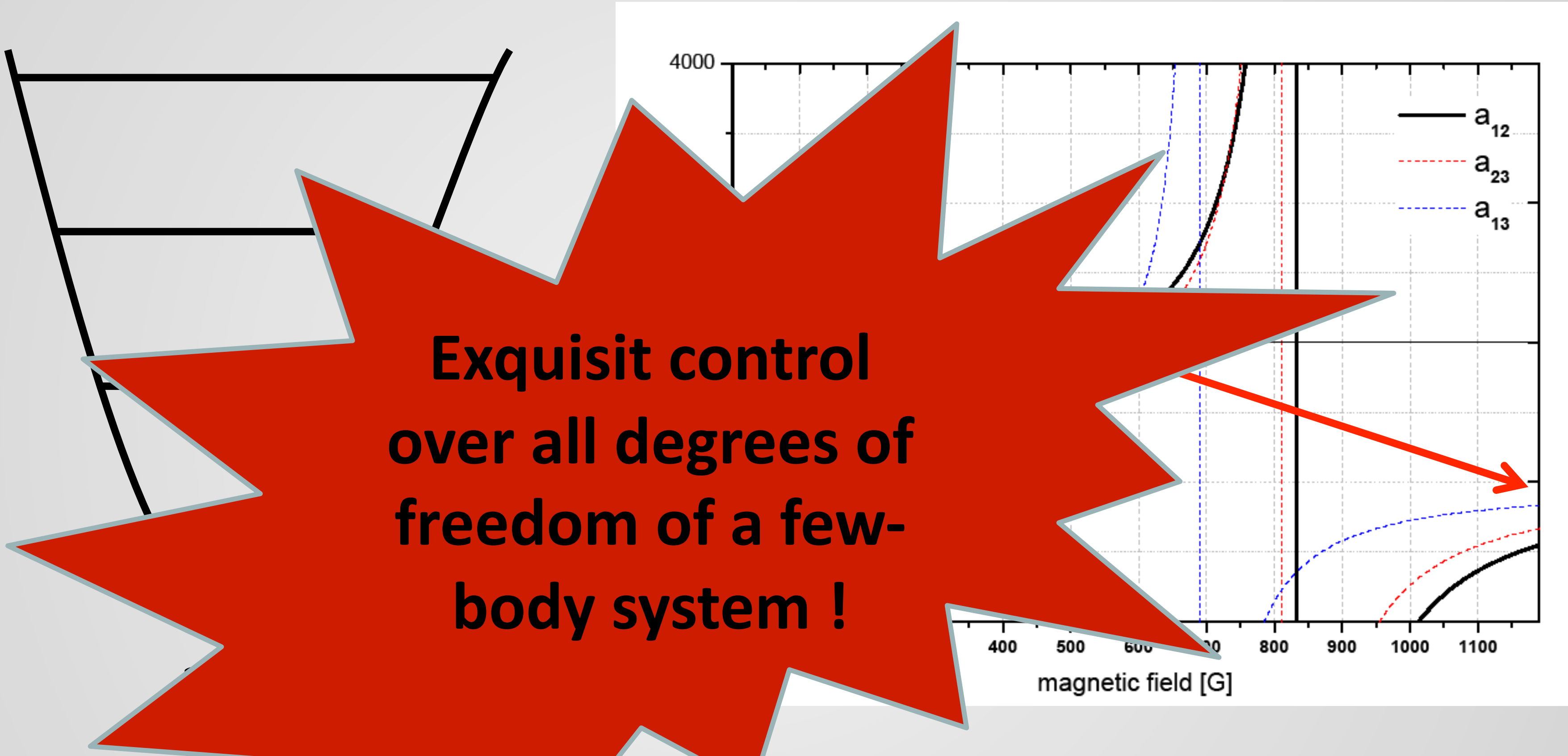
Spilling the atoms ….





- We can control the atom number with exceptional precision!

First few-body interactions



- What happ… we…ing the two atoms in the ground state across the …shbach resonance
- One atom is observed in ν~2

F. Serwane et al., in preparation


Thank you very much for your attention!
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HAPPY BIRTHDAY
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