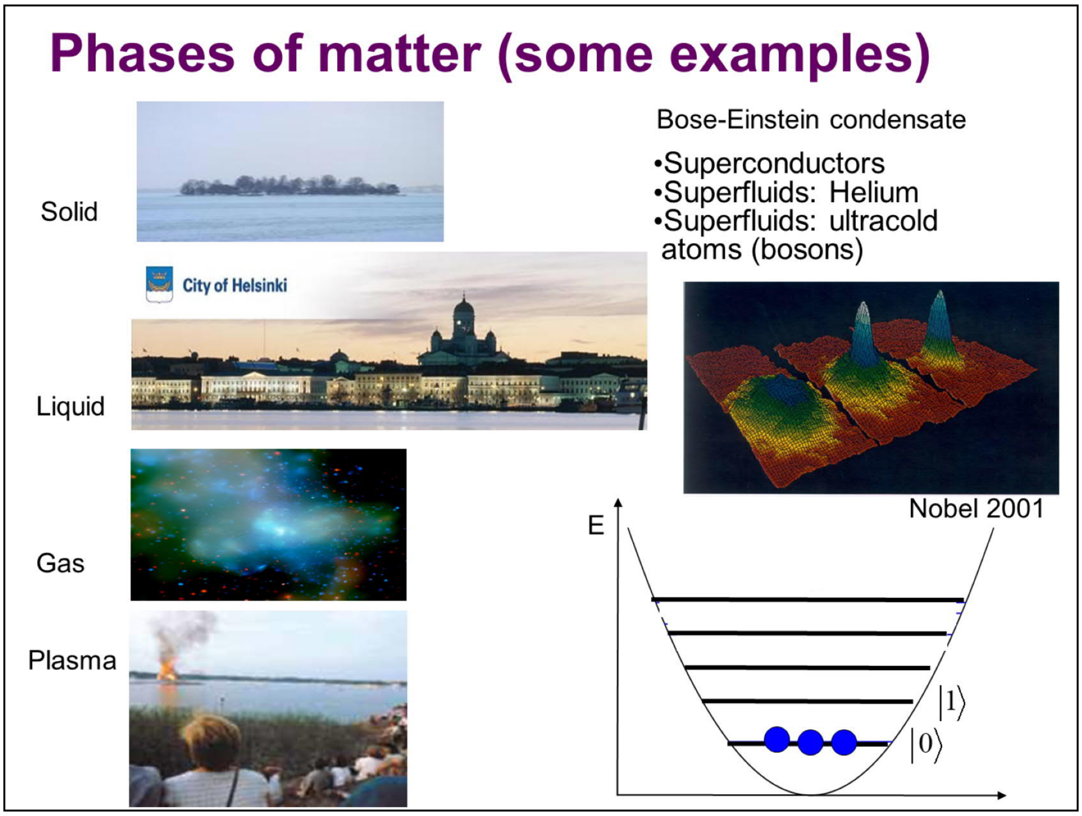
Lecture 8
Introduction to ultracold gases

- Key features of ultracold gases
- First observations of fermion pairing and superfluidity in ultracold Fermi gases
- Population imbalanced Fermi gases
- Quantum gas microscopes
- You will learn many of the concepts introduced here in more detail in the following lectures; you may come back to these slides afterwards, don’t worry if you don’t understand everything now, this is just introduction



Phases of matter (some examples)

Solid

Liquid

Gas

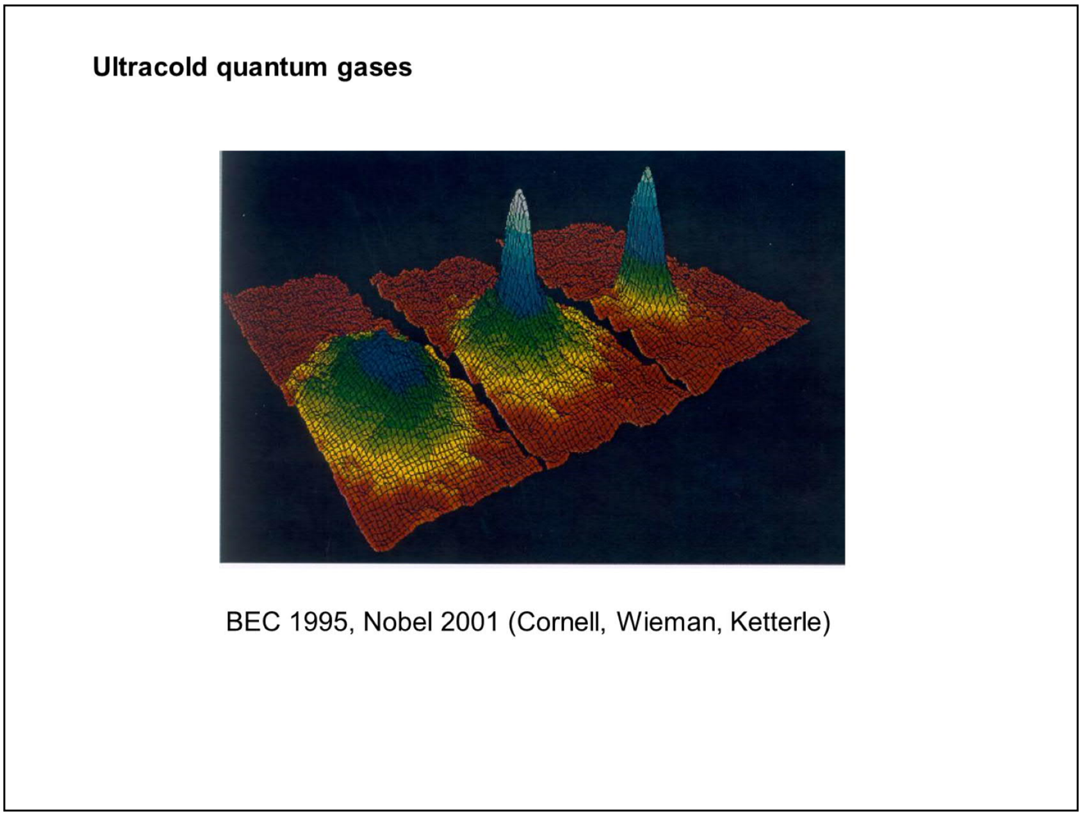
Plasma

Bose-Einstein condensate

- Superconductors
- Superfluids: Helium
- Superfluids: ultracold atoms (bosons)

Nobel 2001

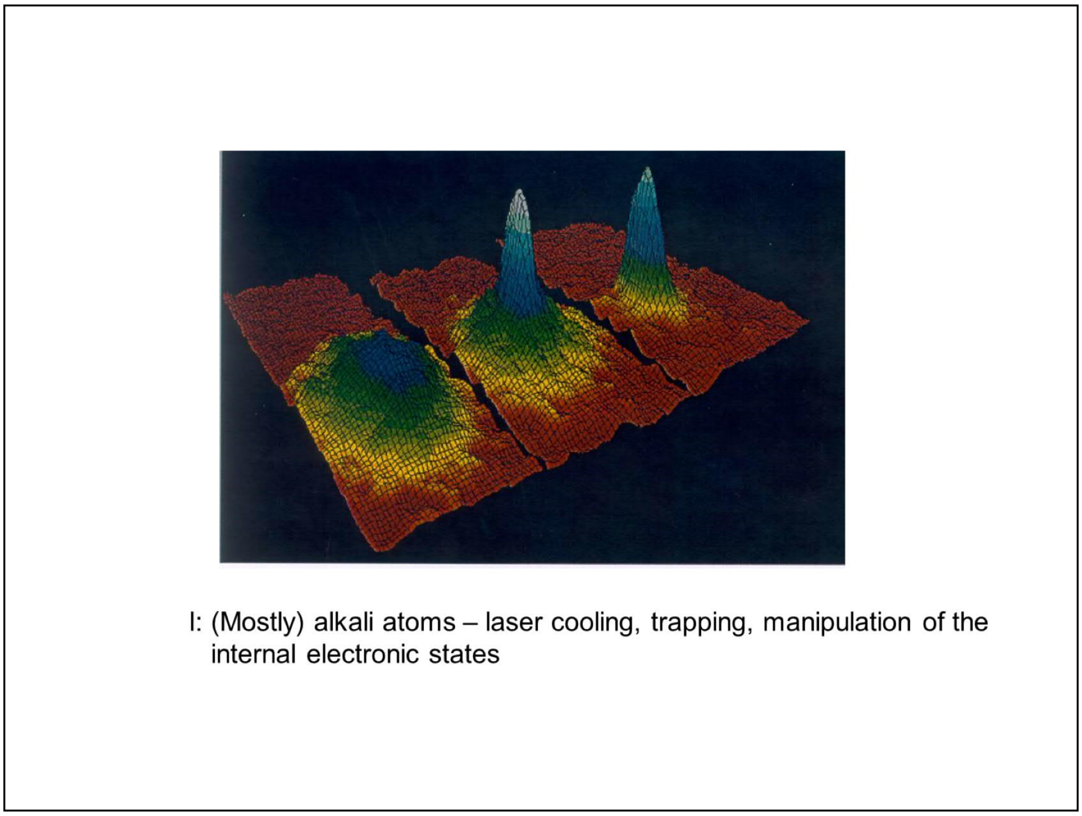
The phases of matter familiar for us from everyday life are: solid, liquid, gas and plasma (e.f. flames of fire). There are, however, many other phases of matter that have been experimentally observed, for instance superfluids of Helium or of ultracold gases, or superconducting phases in metals (superconductors and superfluids are conceptually similar, but the former involves charged particles). Furthermore, there are yet a large number of other phases or states of matter observed or predicted in physics, some of them very exotic in the sense that we do not have an everyday equivalent of them.



Ultracold quantum gases

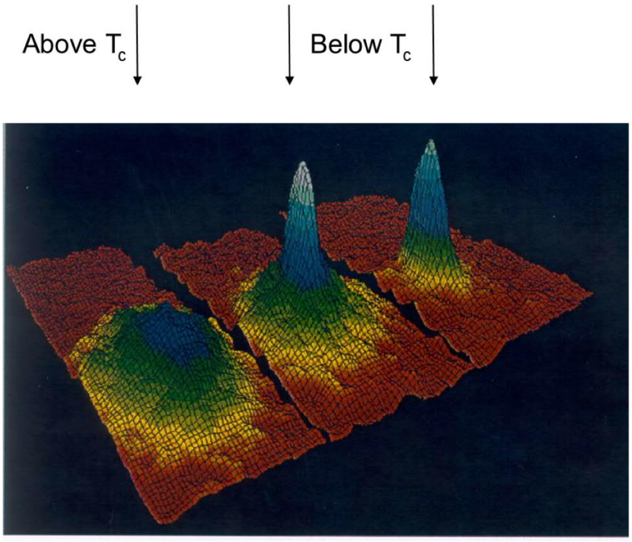
BEC 1995, Nobel 2001 (Cornell, Wieman, Ketterle)

The first BECs of ultracold alkali atoms were observed in 1995, and the Nobel prize was awarded to those observations 2001 (Eric Cornell and Carl Wieman, JILA, University of Colorado; Wolfgang Ketterle, MIT).



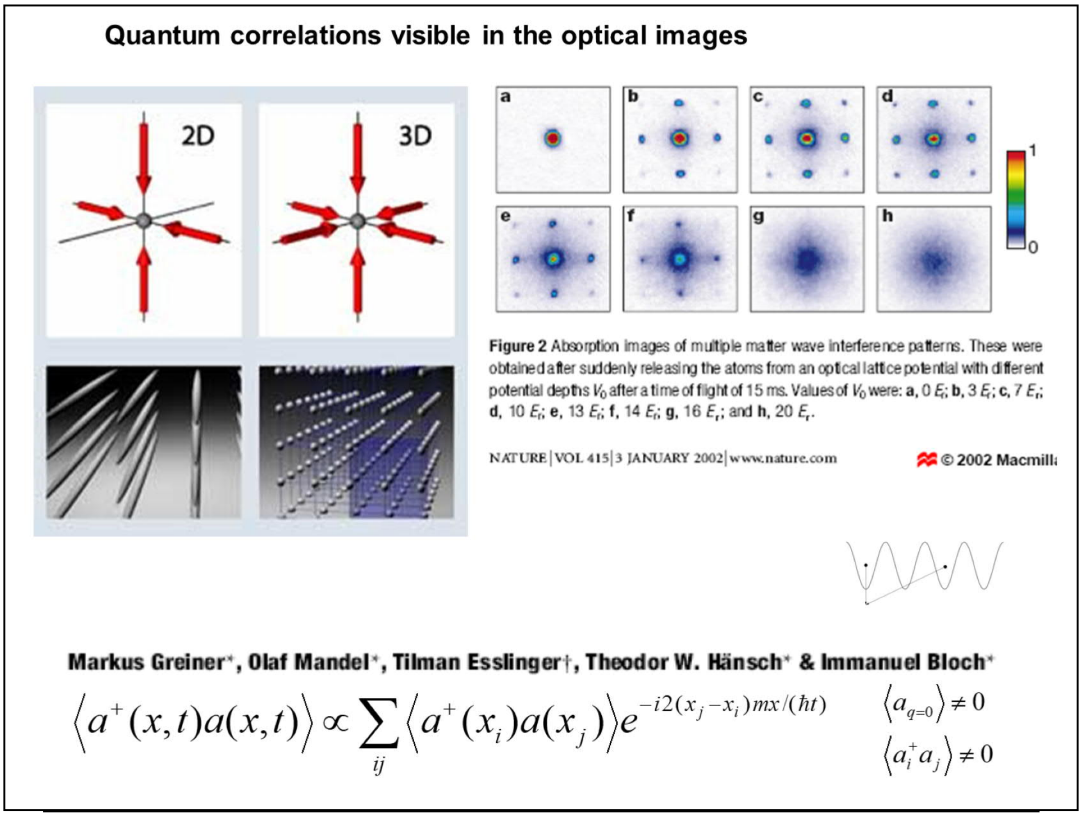
I: (Mostly) alkali atoms – laser cooling, trapping, manipulation of the internal electronic states

One basic feature is that the gases typically use alkali atoms which have only one electron at their outermost shell. This leads to a very clean and simple electronic level structure at optical frequencies, which allows easy laser cooling and electromagnetic trapping of the atoms, as well as manipulation of the internal degrees of freedom (the electronic states) with laser and RF fields. Note: nowadays also many non-alkali atoms are used, such as Er and Yb.



II: Optical imaging after time of flight – density distributions, interference effects

The trap is switched off. In the time of flight, momentum is mapped into. The picture shows the imaged density: high density in the middle means initial high occupation of the lowest momentum state: BEC. Phase coherence of the BEC was further demonstrated by interference experiments.



Quantum correlations visible in the optical images

Figure 2 Absorption images of multiple matter wave interference patterns. These were obtained after suddenly releasing the atoms from an optical lattice potential with different potential depths V_0 after a time of flight of 15 ms. Values of V_0 were: **a**, 0 E_r; **b**, 3 E_r; **c**, 7 E_r; **d**, 10 E_r; **e**, 13 E_r; **f**, 14 E_r; **g**, 16 E_r; and **h**, 20 E_r.

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Markus Greiner*, Olaf Mandel*, Tilman Esslinger†, Theodor W. Hänsch* & Immanuel Bloch*

$$\left\langle a^{+}(x,t)a(x,t)\right\rangle \propto \sum_{ij}\left\langle a^{+}(x_i)a(x_j)\right\rangle e^{-i2(x_j-x_i)mx/(\hbar t)}$$

$$\left\langle a_{q=0}\right\rangle \neq 0$$

$$\left\langle a_i^{+}a_j\right\rangle \neq 0$$

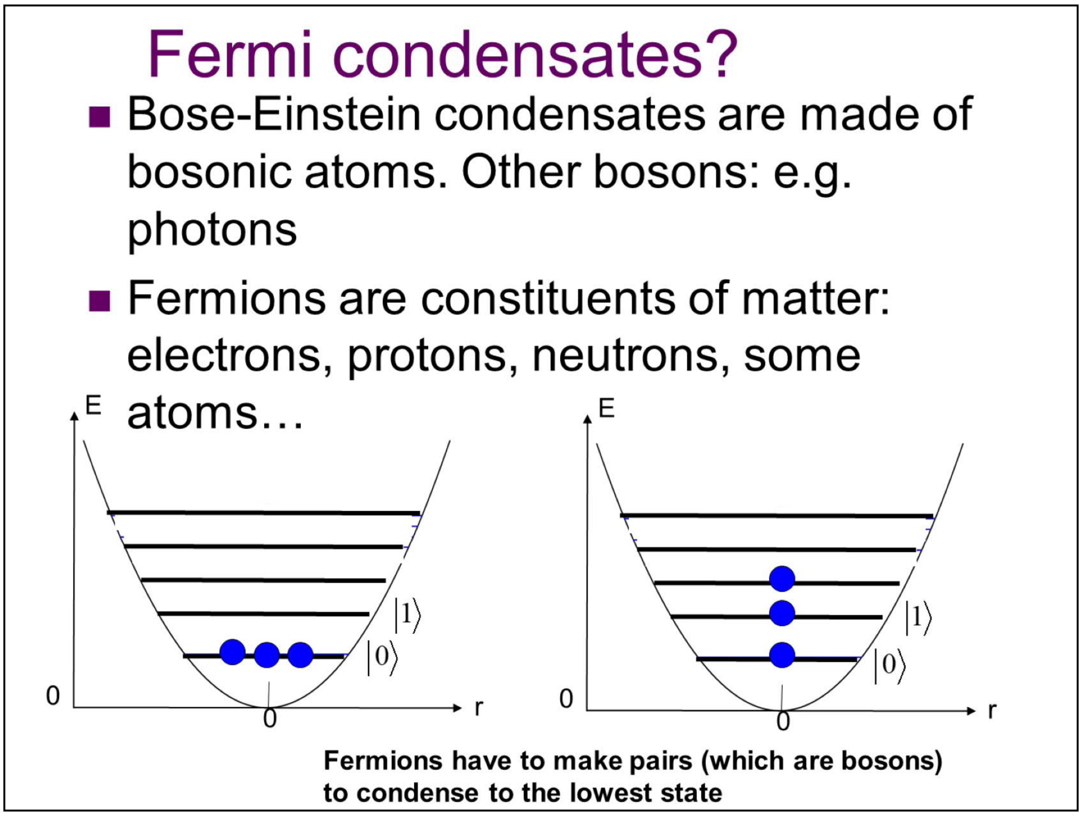
Counterpropagating laser beams create standing waves, and atoms can be trapped either in the minima or the maxima of the standing waves due to the dipole force the light field imposes on the atoms. Depending on whether one uses 2, 4, or 6 counterpropagating beams, a periodic structure in 1, 2 or 3 dimensions is created. The Figure 2 above is from the famous Mott insulator – BEC quantum phase transition experiment. The experiment was done at Max Planck Institute at Garching, Germany, and one of the co-authors, T. Esslinger, is now a professor at ETH Zurich. The pictures are absorption images after time of flight when the atoms have been released from the lattice.

If the atoms in the lattice are initially all coherent with each other, for instance they are in a BEC state, then the release of atoms from the lattice may, under certain conditions, form the type of interference patterns seen in Figures 2 b-f. Briefly, on can think that when one observes, after time of flight, an atom in a certain spot (see the small schematic picture below Figure 2), one cannot know whether it originated from one lattice site and had one momentum, or from another site but had another momentum and ended up in the same place. This type of lack of information always produces intereference both in quantum physics and in wave optics. This is expressed by the equation: the probablity includes interferences of amplitudes of particles from different sites. To see any interference, the amplitude coherence expectation value between two different sites has to be non-zero, as is the case for instance for a BEC.

Van der Waals → contact interaction with a scattering length a_S

III: ***Tunable interactions*** via Feshbach-resonances

The third important aspect of ultracold gases is the ability of tuning the interaction, using magnetic fields, via so-called Feshbach-resonances.

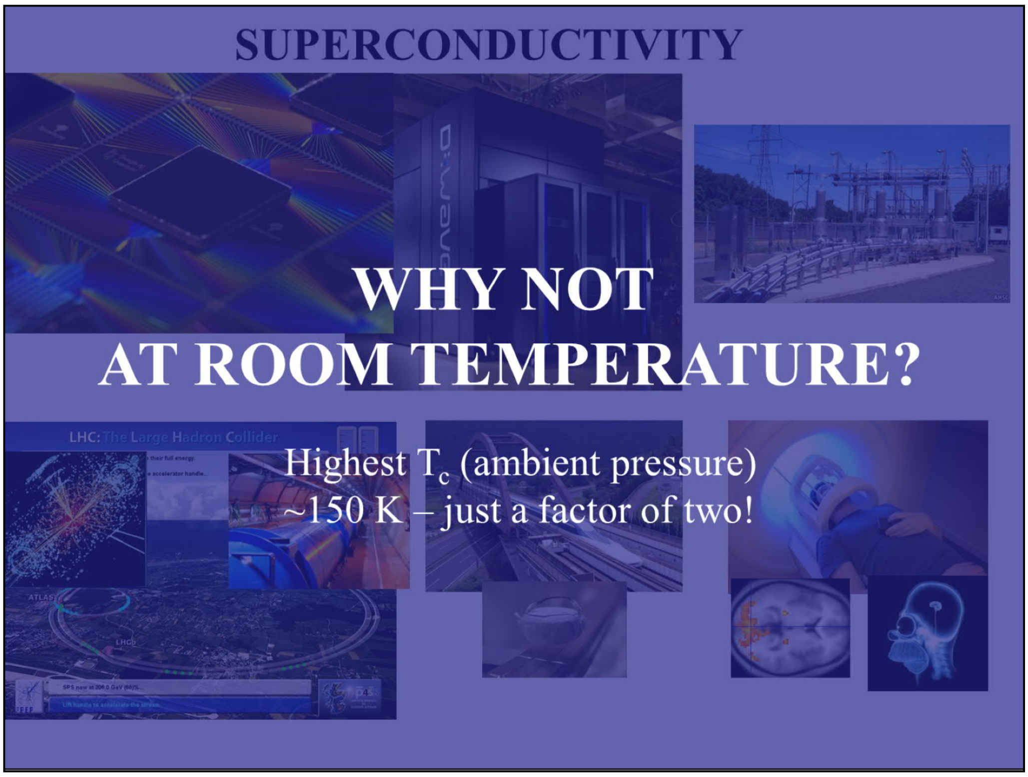


Fermi condensates?

- Bose-Einstein condensates are made of bosonic atoms. Other bosons: e.g. photons
- Fermions are constituents of matter: electrons, protons, neutrons, some atoms…

Fermions have to make pairs (which are bosons) to condense to the lowest state

We have learned about Bose-Einstein condensates. Is it possible to condense fermions? Fermions are important since they are the constituents of matter. However, fermions of one kind (indistinguishable fermions) cannot Bose-condense due to the Pauli exclusion principle. There is, however, a route to fermion condensates: if fermions make pairs which are effectively bosons, and those condense.

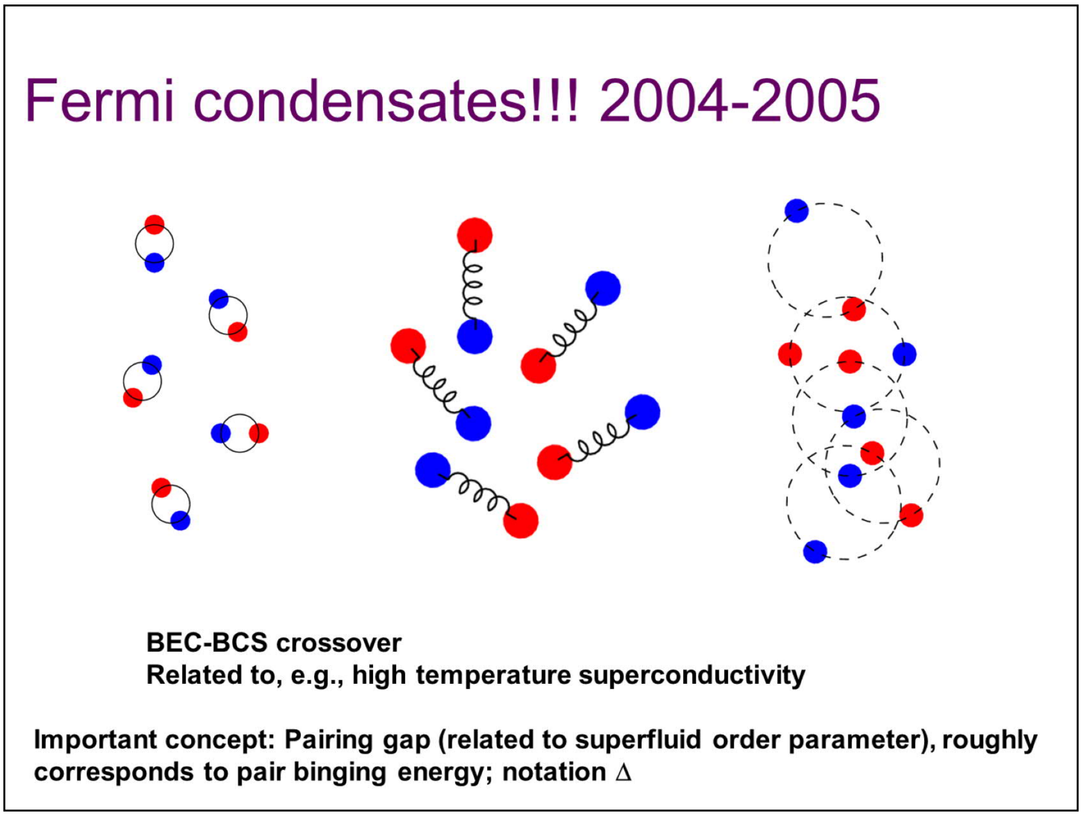


SUPERCONDUCTIVITY

WHY NOT
AT ROOM TEMPERATURE?

Highest T_c (ambient pressure)
~150 K – just a factor of two!

It would be of tremendous impact, if materials that are superconducting at room temperature could be found or designed. For instance, superconducting (classical) logic would be 100 000 times more energy efficient in principle, but the cooling takes 1000 more power than room temperature operation; also the speed could be 770 GHz instead of 5 GHz. Physicists have been struggling to understand the underlying mechanism of high-temperature superconductivity (occuring for cuprates and pnictides at temperatures in the 100 Kelvin range) since the discovery of first high-temperature superconductors by J.G. Bednorz and K.A. Mueller at the IBM Zurich Labs in 1986. One of the motivations for studies of ultracold Fermi gases is to use them as a quantum simulator in exploring physics that may enable us to reach room temperature superconductivity one day in the future.



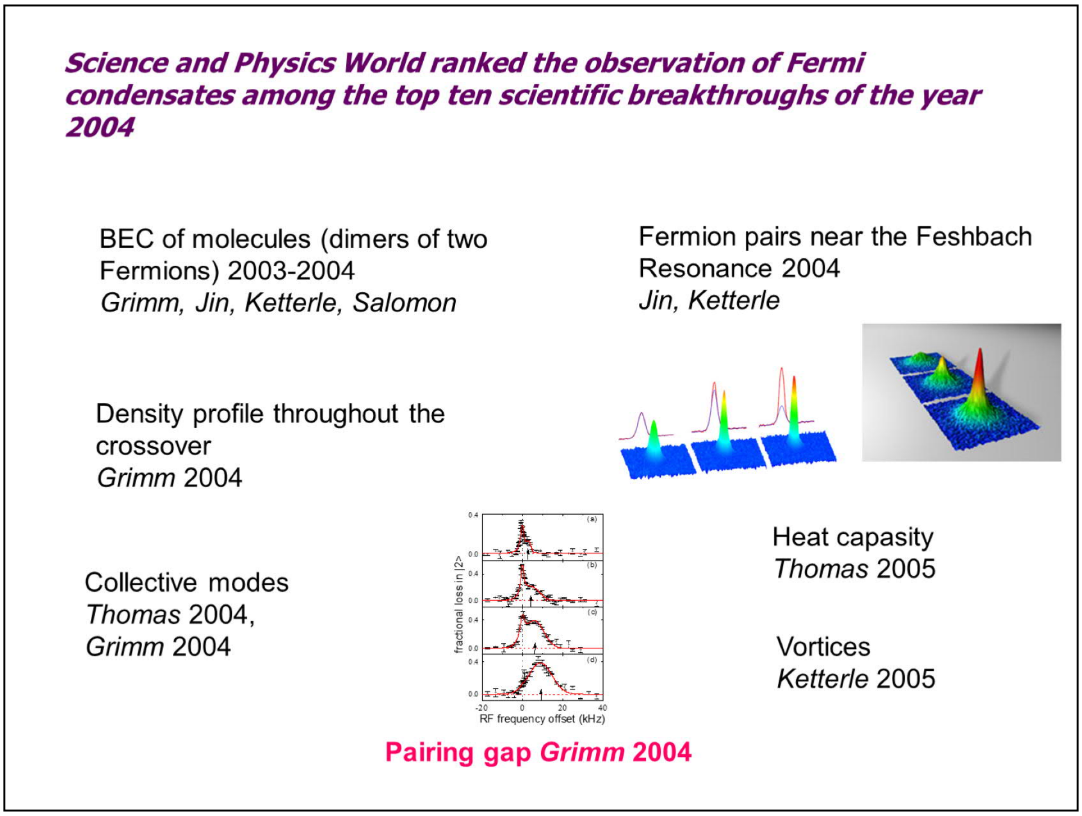
Fermi condensates!!! 2004-2005

BEC-BCS crossover
Related to, e.g., high temperature superconductivity

Important concept: Pairing gap (related to superfluid order parameter), roughly corresponds to pair binging energy; notation Δ

A series of experiments in ultracold gases (^{6}Li and ^{40}K were the atoms used) by several groups proved the existence of fermionic many-body pairing, condensation and superfluidity in 2004-2005. Such Fermi condensates are analogous to superconductors (although not charged) and to ^{3}He (although much more dilute systems with higher condensate fractions and more controllable interactions). There are also analogies to nuclear matter and to quark matter.

One of the important results was the study of the so-called BEC-BCS crossover. It had been suggested in the 80’s by the Nobel laureate Leggett, and by Nozieres and Schmitt-Rink (and in the 60’s by Eagles), that Bose-Einstein condensates of bosons and superconductors of Cooper pairs are actually two sides of the same coin, that is, they are extreme cases of the same phenomenon and there is simply a crossover between them, no (quantum) phase transition. In ultracold gases, it was for the first time possible to study this question experimentally and show that indeed it is only a crossover. The phenomenon of Feshbach resonance was used to tune the interaction between two types of fermions (e.g. two hyperfine states of Li atoms) so that they evolved from tightly bound molecules into a loosely bound Cooper pairs. The BCS-BEC crossover is related to the puzzle of high-temperature superconductivity, a phenomenon yet without deep theoretical understanding, in the sense that high-T_c superconductors are known to be in the intermediate regime between the BEC and BCS ends. In ultracold gases, this regime is called the unitarity regime, because there the scattering length formally diverges and in practise the only energy scale describing the interactions will be the Fermi energy. Thus, ultracold gases are expected to provide new insight to the problem of high-temperature superconductivity, possibly even solve it. In one of the following lectures in this course, we will learn physics of the BCS-BEC crossover more thoroughly.



Science and Physics World ranked the observation of Fermi condensates among the top ten scientific breakthroughs of the year 2004

BEC of molecules (dimers of two Fermions) 2003-2004
Grimm, Jin, Ketterle, Salomon

Fermion pairs near the Feshbach Resonance 2004
Jin, Ketterle

Density profile throughout the crossover
Grimm 2004

Collective modes
Thomas 2004,
Grimm 2004

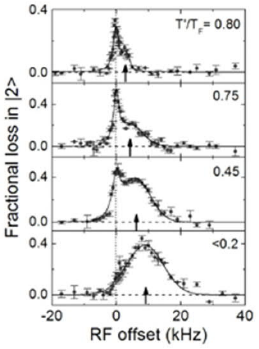
Heat capasity
Thomas 2005

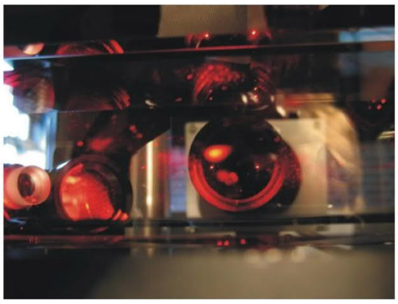
Vortices
Ketterle 2005

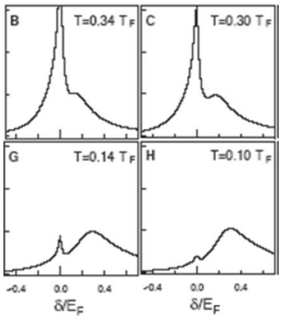
Pairing gap *Grimm* 2004

Several groups contributed to the creation of fermionic pairing and condensation. Superfluidity was demonstrated by quantized vortices. The observation of the pairing gap was done by the group of Prof. R. Grimm in Austia, with theory collaboration by the group of P. Törmä, Finland.

The pairing gap in strongly interacting Fermi gases







C. Chin, M. Bartenstein, A. Altmayer,
S. Riedl, S. Jochim, J.H. Denschlag,
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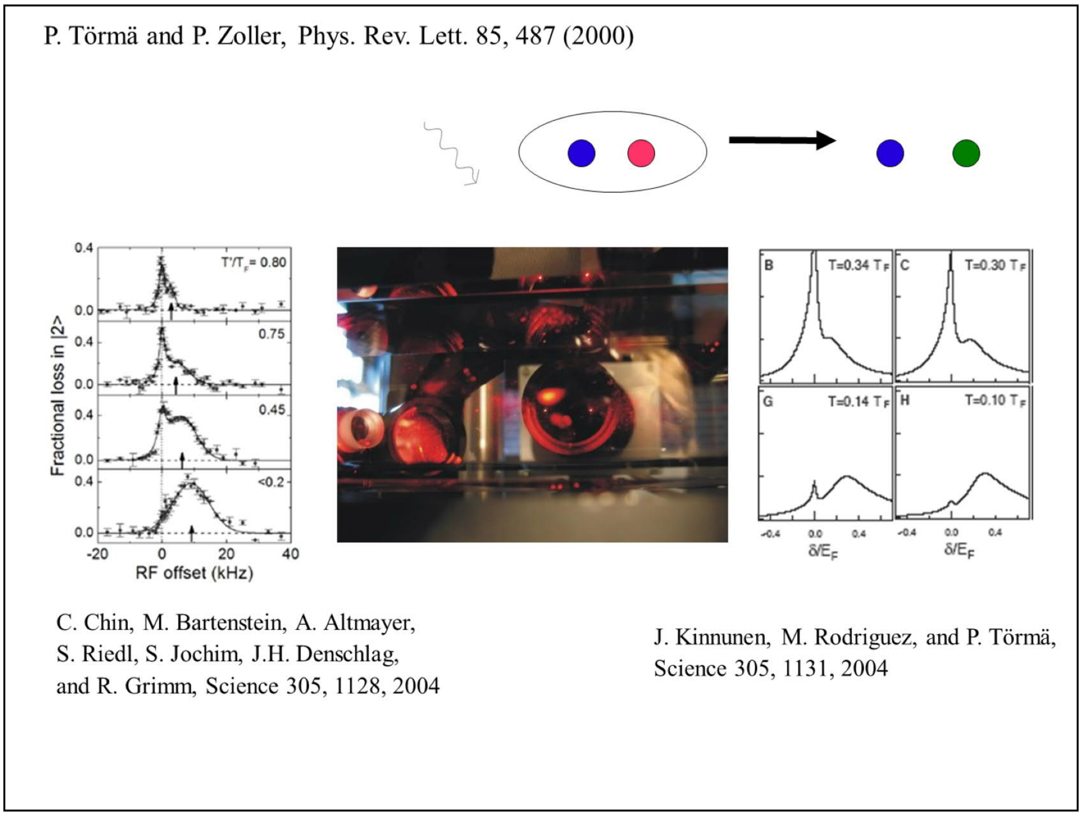
J. Kinnunen, M. Rodriguez, and P. Törmä,
Science 305, 1131, 2004



P. Törmä and P. Zoller, Phys. Rev. Lett. 85, 487 (2000)

C. Chin, M. Bartenstein, A. Altmayer,
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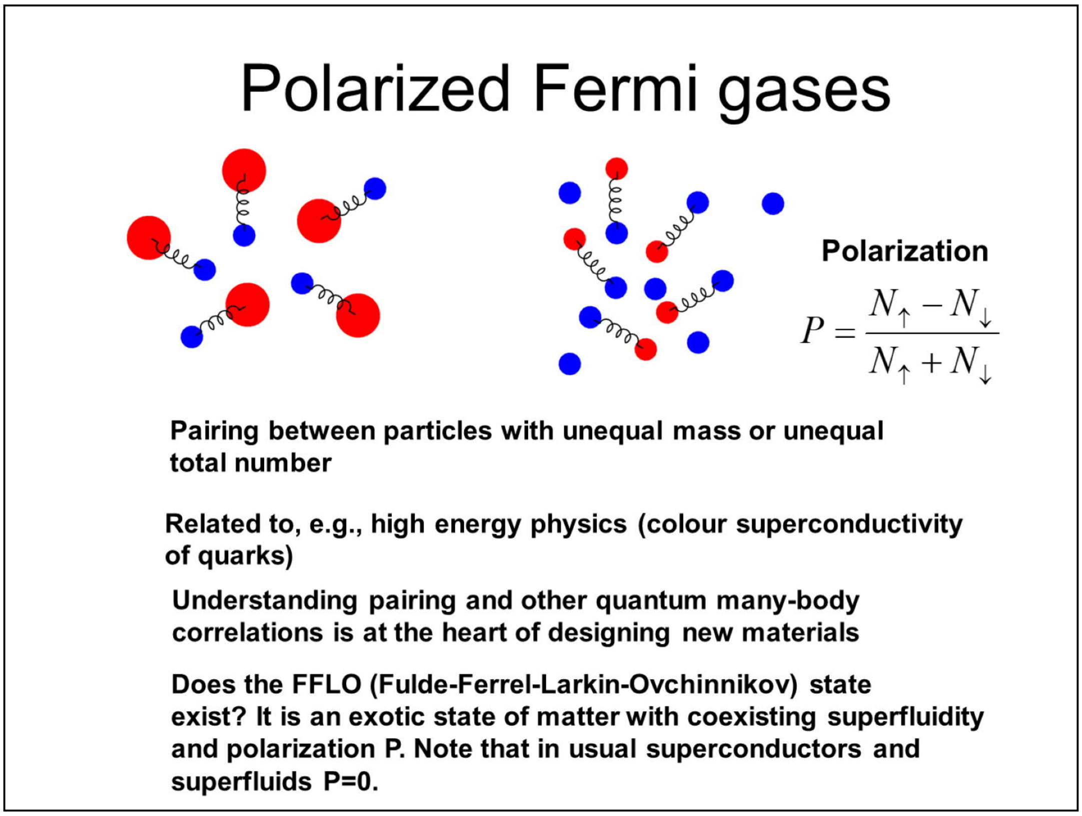
J. Kinnunen, M. Rodriguez, and P. Törmä,
Science 305, 1131, 2004

The existence of many-body pairing was demonstrated by a shift in the rf-spectrum of the Fermi gas (left picture). When temperature becomes lower, pairing is stronger and the pairing peak appears and shifts to higher energies. The fact that the gas is trapped in a harmonic trapping potential causes a double peak structure, as explained in the theory work (right picture). This type of probing of pairing was theoretically suggested by P. Törmä and P. Zoller in Phys. Rev. Lett. 85, 487 (2000). In the middle is a picture of the glass vacuum chamber where the atom cloud lives. The glass cell is few centimeters in each dimension. The atom cloud is visible to naked eye due to fluorescence, even when the actual size of the cloud is in the micrometer scale.



Polarized Fermi gases

Polarization

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

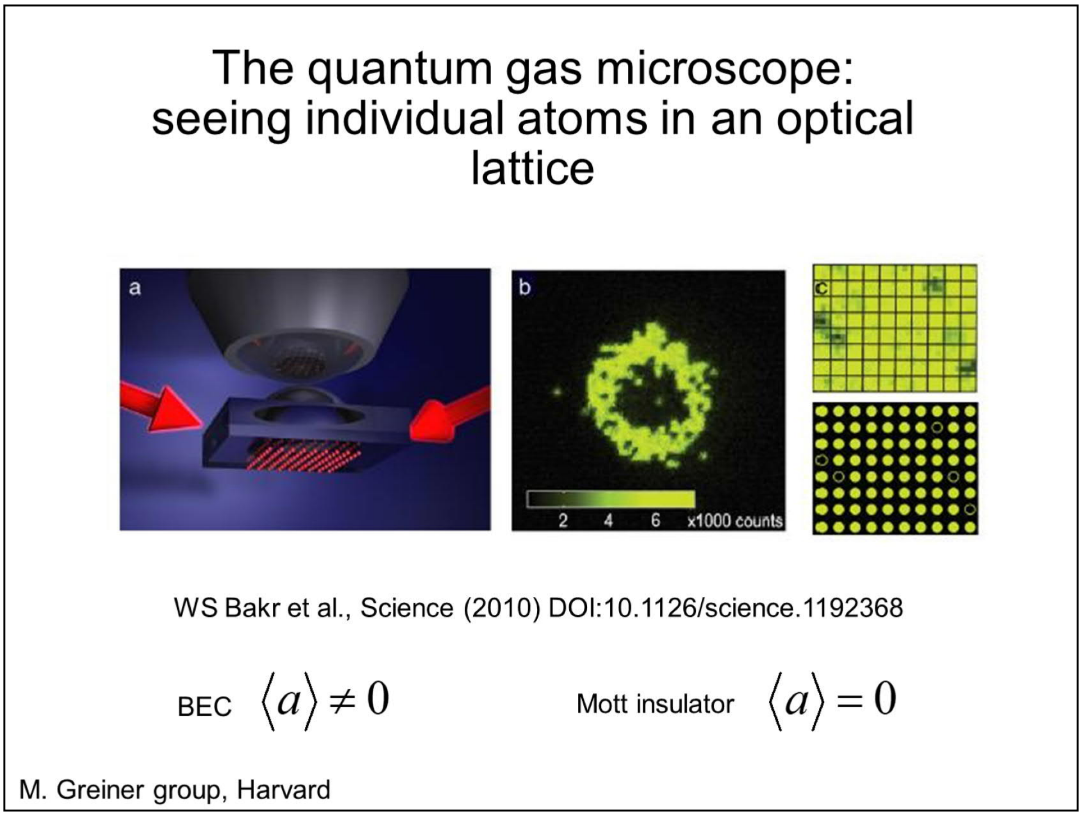
Pairing between particles with unequal mass or unequal total number

Related to, e.g., high energy physics (colour superconductivity of quarks)

Understanding pairing and other quantum many-body correlations is at the heart of designing new materials

Does the FFLO (Fulde-Ferrel-Larkin-Ovchinnikov) state exist? It is an exotic state of matter with coexisting superfluidity and polarization P. Note that in usual superconductors and superfluids P=0.

Polarized Fermi gases, i.e. gases with different number of the two fermion types, typically two different hyperfine states of an atom (or two types of fermions of different masses, e.f. Li and K) have been under intensive investigation in recent years, and are continuing to be so.



The quantum gas microscope: seeing individual atoms in an optical lattice

WS Bakr et al., Science (2010) DOI:10.1126/science.1192368

BEC $\langle a \rangle \neq 0$ Mott insulator $\langle a \rangle = 0$

M. Greiner group, Harvard

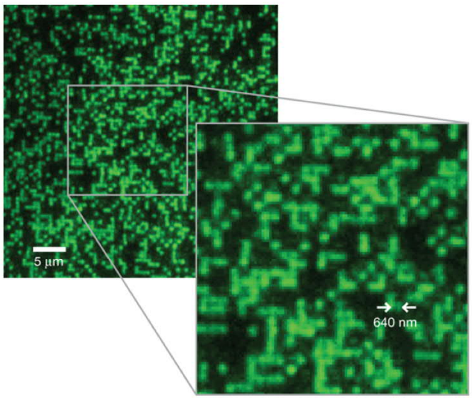
The quantum gas microscope is a major breakthrough in the field of ultracold gases. The microscope resolves single atoms in a lattice. It takes a snapshot of one single realization of the quantum state of the gas. The gas can be initialized in exactly the same way several times, and each measurement gives a picture of the particle number in one preparation of the gas. Averaging these results, one obtains the expectation values of quantities in the system. But not only that: from the different realizations one can also extract all kinds of fluctuations and correlations in the state! These are often the crucial characteristics of the many-body states. For instance, the difference in the particle number fluctuations in the BEC and Mott insulator states has been observed directly with single-site resolution! In the next lecture, you will learn the BEC – Mott insulator quantum phase transition. Then you can come back to this picture and think which one you see in the picture: a BEC or a Mott insulator?

The quantum gas microscope: seeing individual atoms in an optical lattice

Site-resolved imaging of single atoms on a 640-nm-period
optical lattice, loaded with a high density Bose–Einstein condensate.

BEC

$$\langle a \rangle \neq 0$$



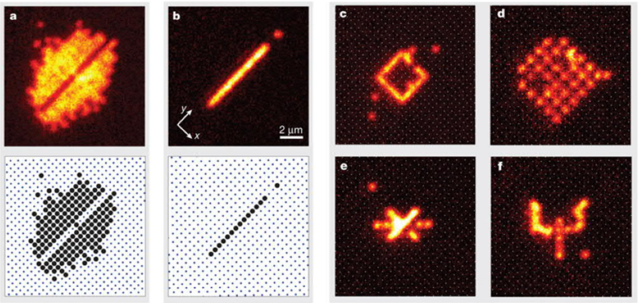
WS Bakr *et al.* *Nature* **462**, 74-77 (2009) doi:10.1038/nature08482

nature

M. Greiner group, Harvard

ULTRACOLD GASES: QUANTUM SIMULATORS OF MANY-BODY PHYSICS, WITH DIRECT ACCESS TO IMAGING CORRELATIONS AND DYNAMICS

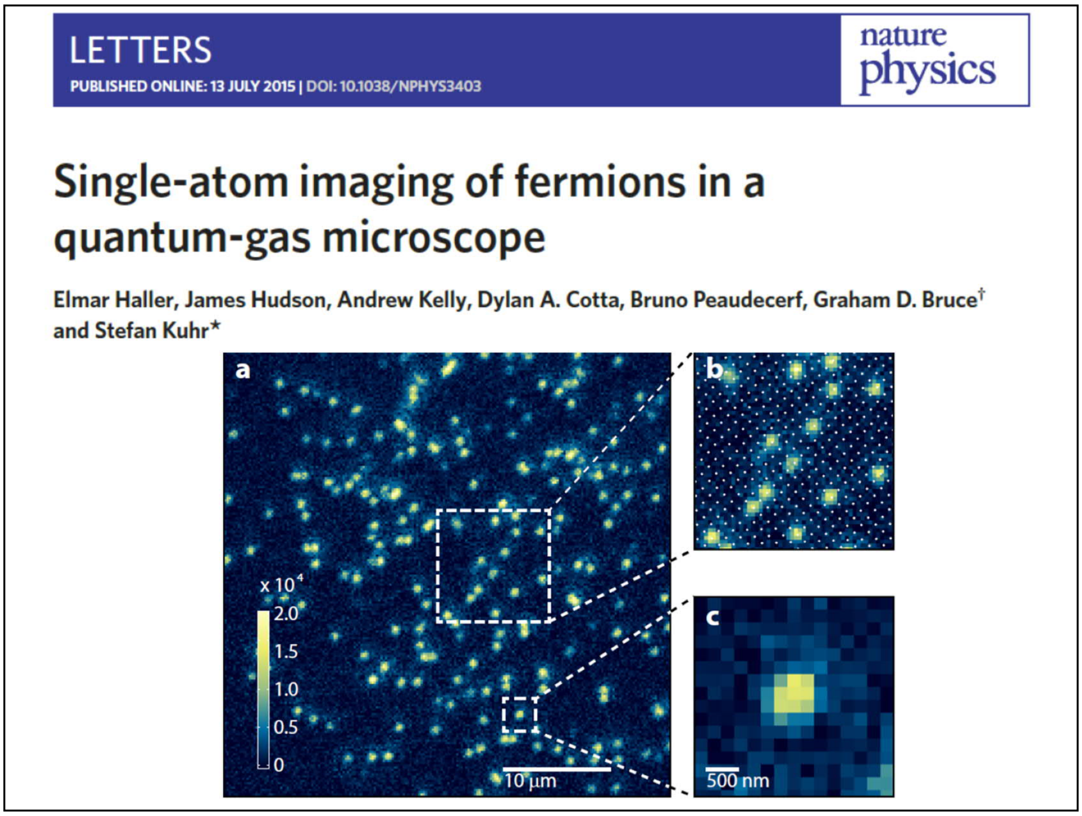
Not only single-site imaging but also single-site addressing/manipulation is possible.



C Weitenberg *et al. Nature* **471**, 319-324 (2011) doi:10.1038/nature09827

nature

I. Bloch group, Max Planck Institute for Quantum Optics, Garching



LETTERS

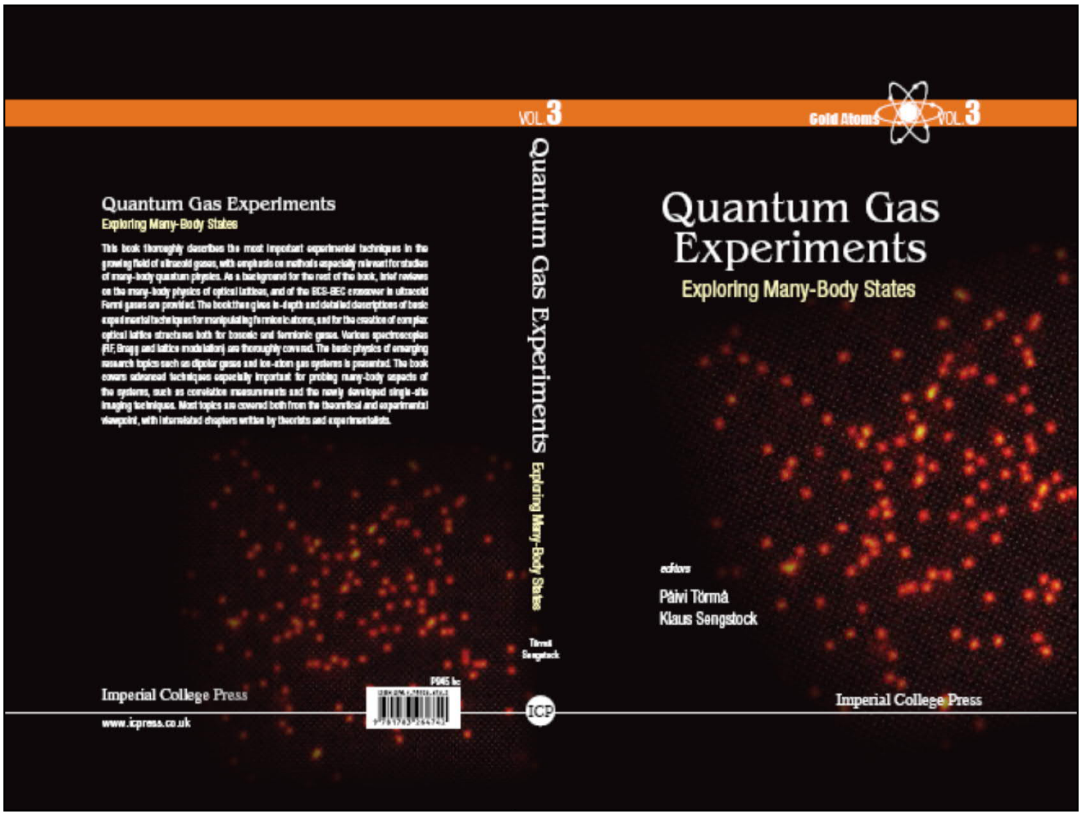
PUBLISHED ONLINE: 13 JULY 2015 | DOI: 10.1038/NPHYS3403

nature physics

Single-atom imaging of fermions in a quantum-gas microscope

Elmar Haller, James Hudson, Andrew Kelly, Dylan A. Cotta, Bruno Peaudecerf, Graham D. Bruce[†]
and Stefan Kuhr*

In 2015, the first quantum gas microscopes for fermions have been reported!



Gold Atoms VOL. 3

Quantum Gas Experiments

Exploring Many-Body States

editors

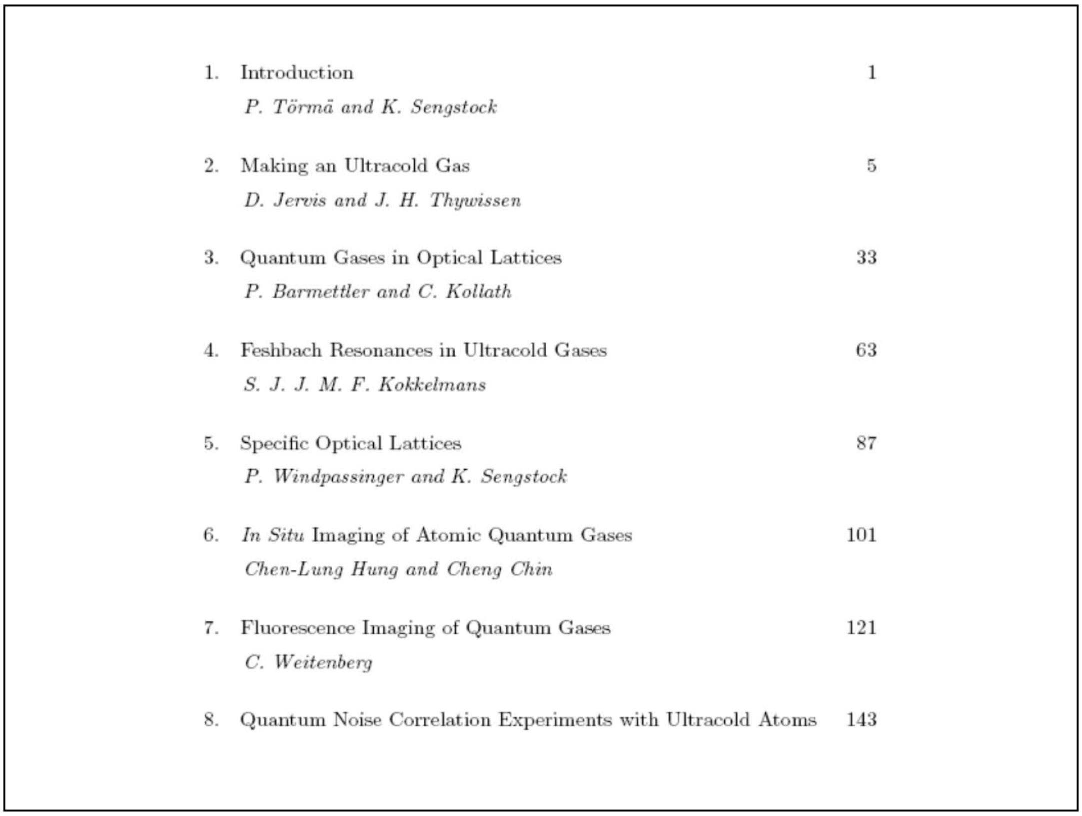
Päivi Törmä

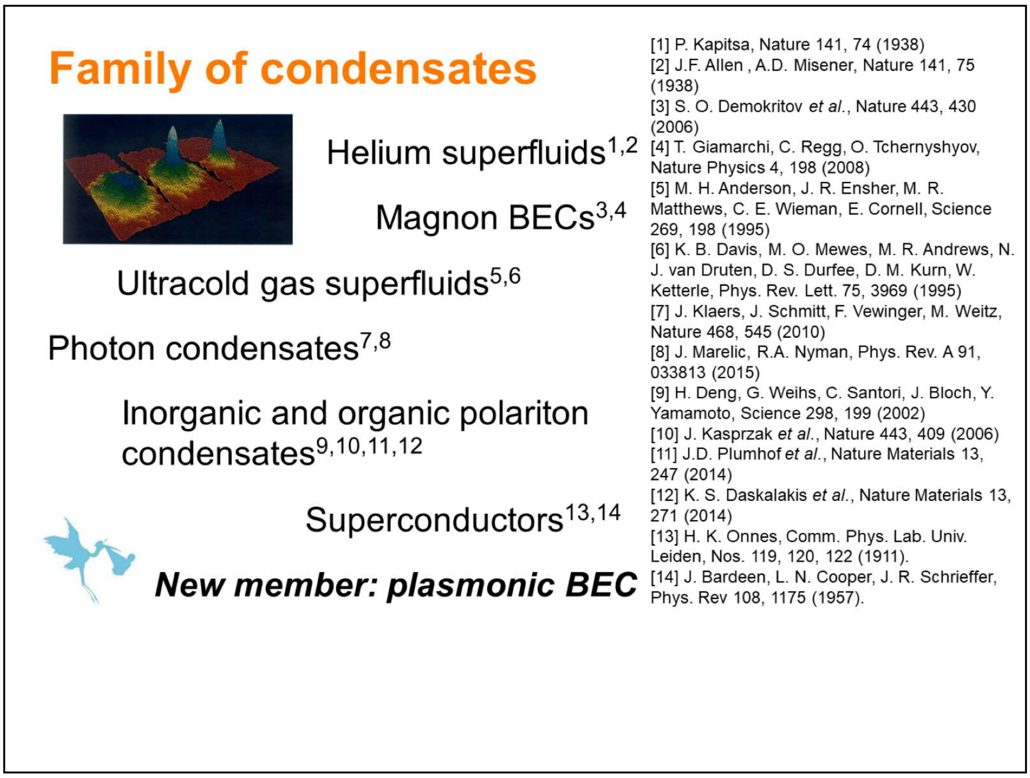
Klaus Sengstock

Imperial College Press

www.icpress.co.uk

Chapters 3., 9. and 10. from this book will be used during the rest of the course. Moreover, chapter 4. gives a nice and pedagogical presentation of Feshbach resonances, the topic of the previous lecture. For anybody interested in the quantum gas microscopes, chapters 6. and 7. are useful.





Family of condensates

Helium superfluids[1,2]

Magnon BECs[3,4]

Ultracold gas superfluids[5,6]

Photon condensates[7,8]

Inorganic and organic polariton condensates[9,10,11,12]

Superconductors[13,14]

New member: plasmonic BEC

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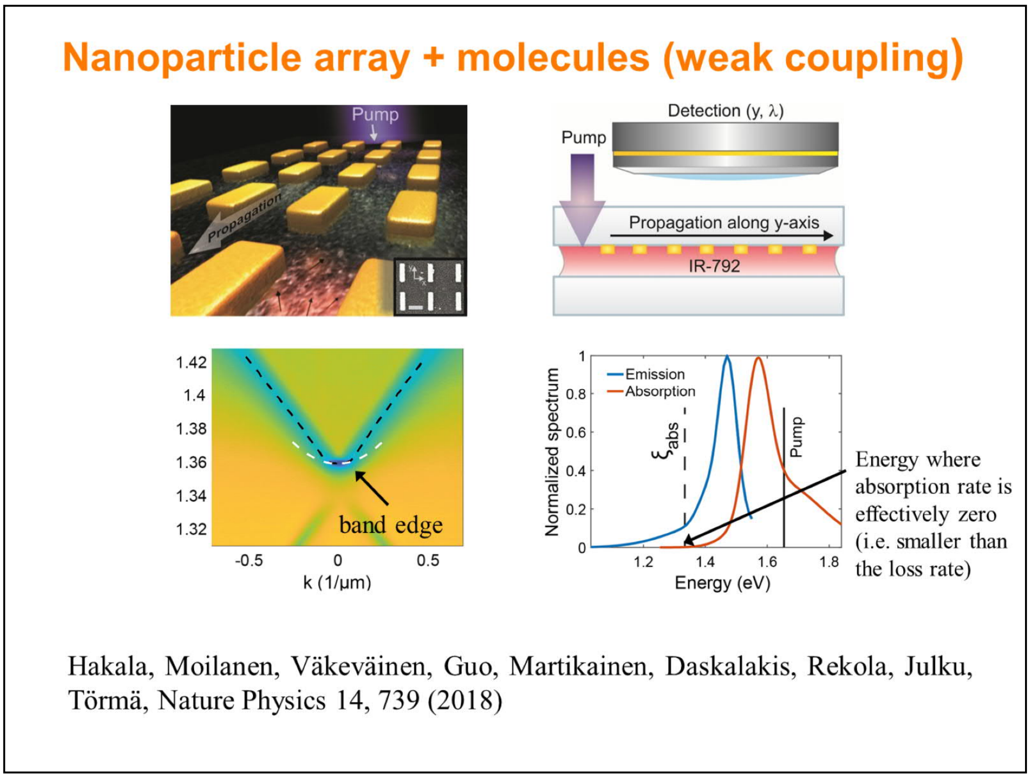
Bose-Einstein condensates have been experimentally realized in various systems (not only ultracold gases).

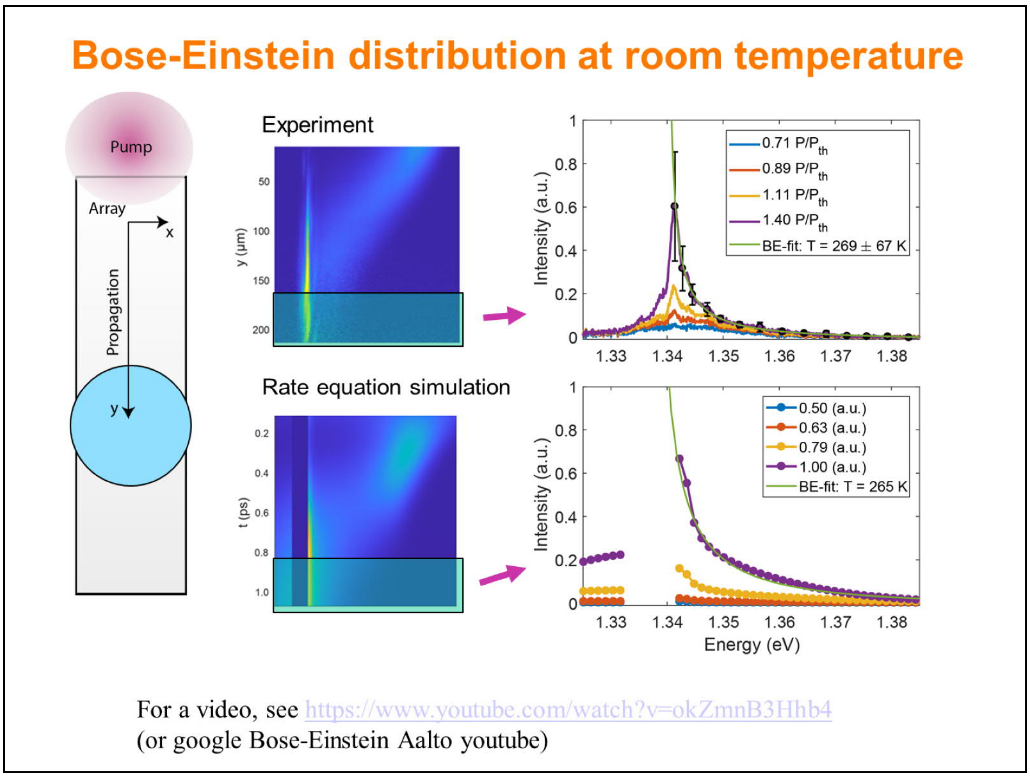


Nanoparticle array + molecules (weak coupling)

Energy where absorption rate is effectively zero (i.e. smaller than the loss rate)

Hakala, Moilanen, Väkeväinen, Guo, Martikainen, Daskalakis, Rekola, Julku, Törmä, Nature Physics 14, 739 (2018)

Recently, a new type of Bose-Einstein condensate: a condensate of surface plasmon polaritons and light, was experimentally realized in a gold nanoparticle array at Aalto University. The nanoparticle array has dispersive modes and a band edge. The array is combined with fluorescent molecules, which are pumped to the excited state, but only at one end of the array. The excitations of light and plasmons start to propagate from the end of the array. Along the propagation, some of them scatter out and are monitored. In this way, time evolution maps into spatial location, and it is possible to observe the sub-picosecond dynamics of the system.



Bose-Einstein distribution at room temperature

For a video, see https://www.youtube.com/watch?v=okZmnB3Hhb4
(or google Bose-Einstein Aalto youtube)

It was observed that due to the interaction of the excitations with the molecules, they lose energy during the propagation (the light redshifts). If the band edge energy is chosen correctely, the redshifted population condenses at the band edge and follows the Bose-Einstein distribution.