Manipulating Atoms with Light
Achievements and Perspectives

Claude Cohen-Tannoudji

CERN, 25 January 2006

Purpose of this lecture

- How to use atom-photon interactions and the basic conservation laws for manipulating atoms and for controlling their various degrees of freedom?
  - Internal degrees of freedom: Spin polarization
    Highly polarized gases
  - External degrees of freedom: Velocity, position
    Ultracold atoms (in the range of 10^{-6} K – 10^{-9} K)
- What are the new perspectives opened by these methods?
  - New research fields
  - New physical systems
  - New applications
  - New connections with other branches of Physics

Elementary interaction processes between atoms and photons

Emission

Absorption

$E_b - E_a = h\nu$

Conservation of energy

Measuring ν with a spectrometer gives $E_b - E_a$

Light is a source of information on the structure of atoms and a probe for detecting their presence in a medium

Light **A**mplification by **S**timulated **E**mission **R**adiation
in an atomic medium with inverted populations
New types of light sources: Lasers

Light is also a tool for manipulating atoms

When an atom absorbs and reemits a photon, it acquires some properties of the absorbed photon (energy, momentum, polarization)

One can thus modify the properties of an atom by sending on it conveniently prepared light beams

First example : Optical pumping

The absorption of polarized light can polarize atoms, i.e. orient all the atomic magnetic moments along the same direction

Detection of magnetic resonance in dilute atomic gases

Second example : Laser cooling

The absorption of photons coming all in the same direction can give rise to a radiation pressure force which changes their velocities

Ultracold atoms

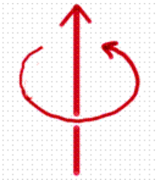
TRANSFER OF ANGULAR MOMENTUM FROM PHOTONS TO ATOMS

Optical pumping

Atomic angular momentum

Atoms are « spinning tops »

They have an internal angular momentum **J**

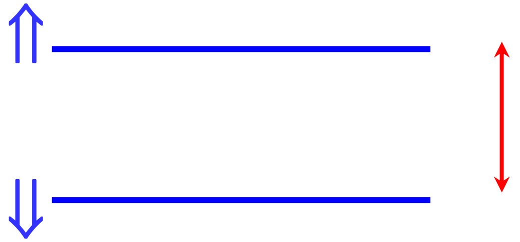


The projection J_z of **J** along the z-axis is quantized

For example, for a « spin 1/2 » atom, there are two possible values of J_z : **Spin up ⇑** **Spin down ⇓**

Atoms have also a magnetic moment M_z proportional to J_z

In a static magnetic field B, the 2 spin states have opposite magnetic energies proportional to B



Energy splitting ΔE proportional to B

$\Delta E = h \nu_z$

Magnetic resonance : transitions between the 2 spin states induced by a radiofrequency wave with frequency ν_z

Optical pumping (A. Kastler, J. Brossel)

At room temperatures and in low magnetic fields both spin states are nearly equally populated.
Very weak spin polarization

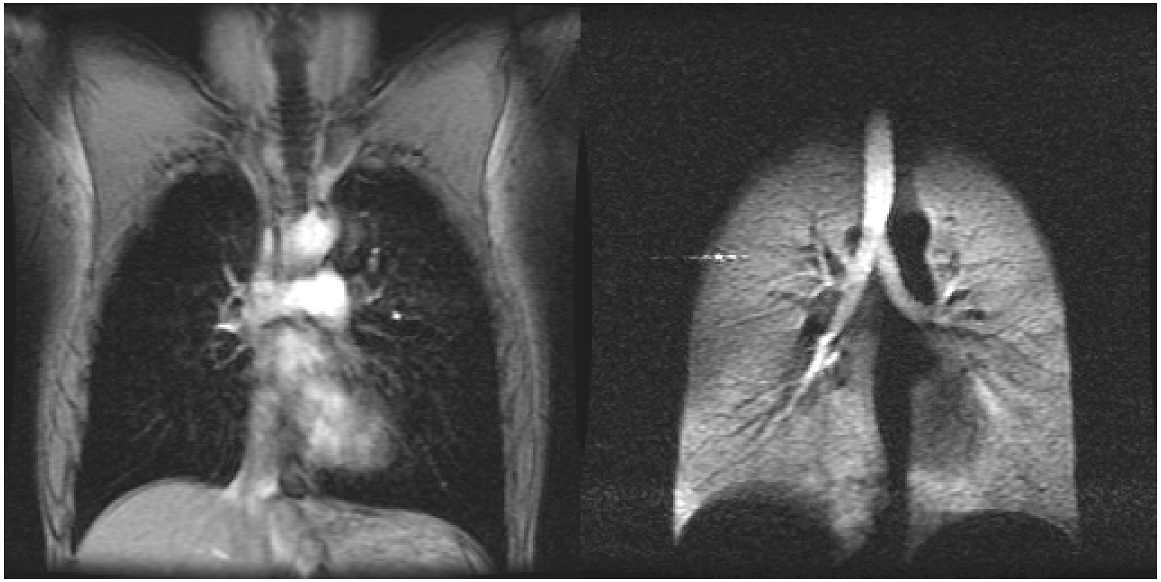
Magnetic resonance signals are proportional to the difference of populations between the 2 spin states.
Easy to observe only in dense systems (solids or liquids)

Polarized photons have also an angular momentum and it is easier to polarize light than atoms

By absorbing polarized photons, atoms can gain the angular momentum of these photons and become polarized.
Gaseous samples with large spin polarization

One can easily obtain in this way large signals of magnetic resonance with dilute gaseous samples

MRI Images of the Human Chest



Proton-MRI ^{3}He-MRI

G.A.Johnson, L. Hedlund, J. MacFall
Physics World, November 1998

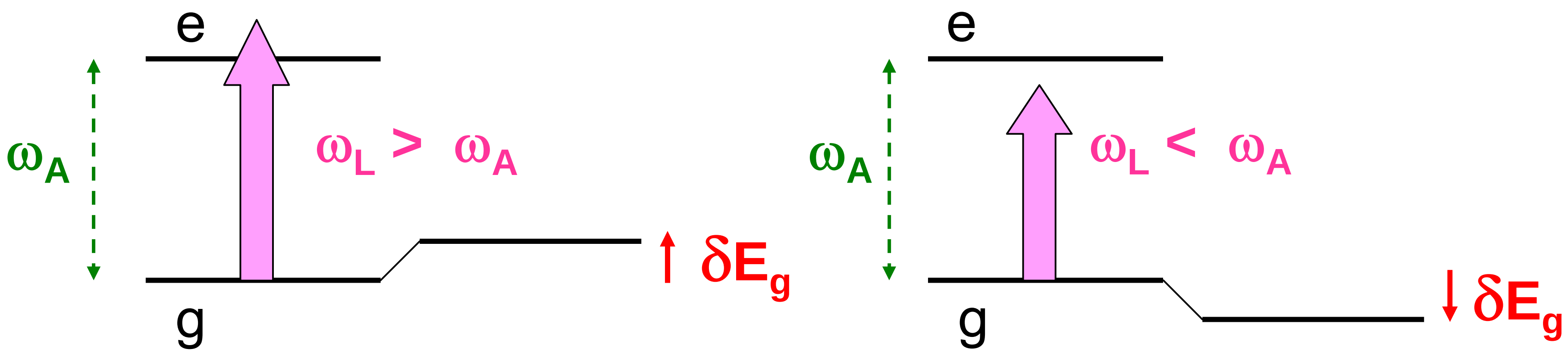
Human lung MRI centers :

- Princeton
- Mainz U., Paris-Orsay, Nottingham U
- Duke U., U. of Virginia, U. of Pennsylvania
- Boston B&W H., St Louis

About 10 more centers getting started

Light shifts (or ac-Stark shifts)

A non resonant light excitation displaces the ground state g



- δE_g is proportional to the light intensity
- δE_g has the same sign as $\omega_L - \omega_A$

Two Zeeman sublevels g_1 and g_2 have in general different light shifts depending on the light polarization.

→ Light shift of the magnetic resonance curve in g

C. Cohen-Tannoudji, C.R.Acad.Sci. **252**, 394 (1961)

This perturbation of atoms by light may be also useful!

Two examples given hereafter

TRANSFER OF LINEAR MOMENTUM FROM PHOTONS TO ATOMS

Radiation pressure force

Recoil of an atom absorbing a photon

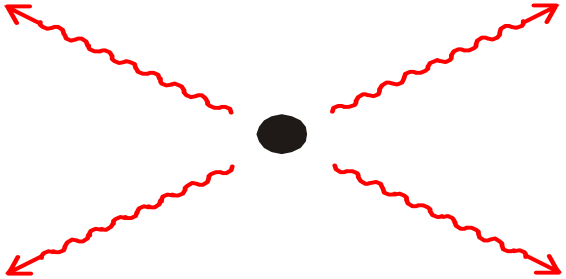
The atom, in the ground state g, absorbs a photon with momentum hν/c.

It jumps to the excited state e and gains this momentum hν/c.
It recoils with a velocity $v_{\mathrm{rec}} = h\nu / Mc$.

Spontaneous emission of a photon

After a mean time τ_R (radiative lifetime of e, of the order of 10^{-8} sec), the atom falls down in g by spontaneous emission of a photon, with equal probabilities in 2 opposite directions

On the average, the loss of momentum in the spontaneous emission process is equal to zero.



Mean velocity change δv in a fluorescence cycle

Absorption followed by spontaneous emission.

$\delta v = v_{rec} = h\nu / Mc$ on the order of $10^{-2} m/s$

Atom in a resonant laser beam

Mean number of cycles per second : W

$$W \approx 1 / \tau_R \approx 10^8 \, s^{-1}$$

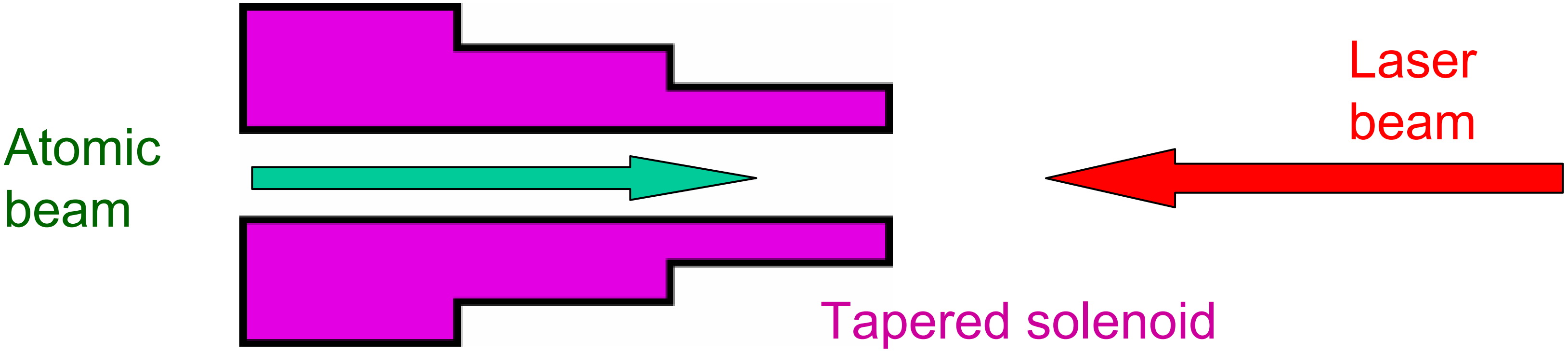
Mean acceleration a (or deceleration) of the atom

a = velocity change per second
= velocity change δv per fluorescence cycle
x number of cycles per second W
= $v_{rec} \times (1 / \tau_R)$

$$a = 10^{-2} \times 10^8 \, m/s^2 = 10^6 \, m/s^2 = 10^5 \, g$$

Huge radiation pressure force!

Stopping an atomic beam



Atomic beam

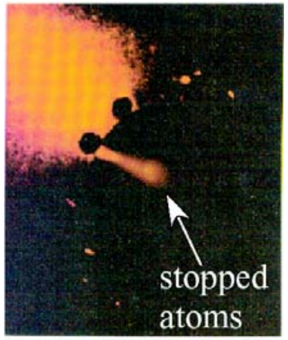
Laser beam

Tapered solenoid

Atoms coming from an oven with a velocity $v_0 = 10^3$ m/s are decelerated by the radiation pressure force exerted by the laser and stop after a time $t = v_0/a = 10^3/10^6 = 10^{-3}$s . They travel over a distance $L = v_0^2 / 2a = 0.5$ m

<u>Zeeman slower</u> J. Prodan, W. Phillips, H. Metcalf, P.R.L. <u>49</u>, 1149 (1982)

The Doppler detuning due to the deceleration of the atoms is compensated by a spatially dependent Zeeman shift



<u>Another solution</u> : chirp of the laser frequency

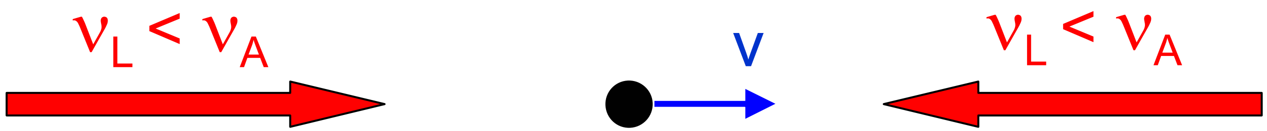
Laser Doppler cooling

T. Hansch, A. Schawlow, D. Wineland, H. Dehmelt

Theory : V. Letokhov, V. Minogin, D. Wineland, W. Itano

2 counterpropagating laser beams

Same intensity   Same frequency ν_L ($\nu_L < \nu_A$)



$\nu_L < \nu_A$ v $\nu_L < \nu_A$

Atom at rest (v=0)

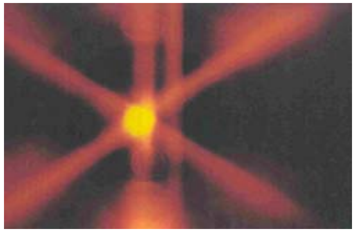
The two radiation pressure forces cancel each other out

Atom moving with a velocity v

Because of the Doppler effect, the counterpropagating wave gets closer to resonance and exerts a stronger force than the copropagating wave which gets farther

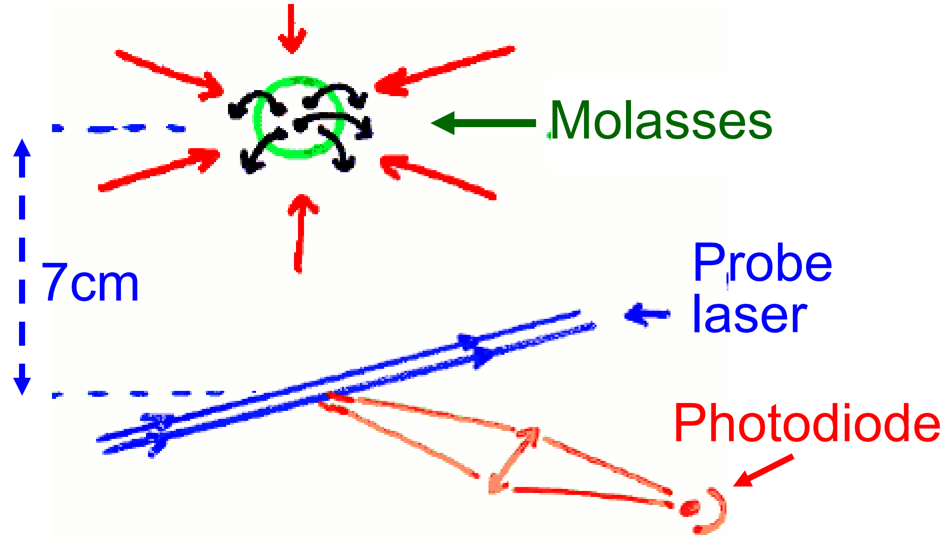
Net force opposite to v and proportional to v for v small

Friction force   "Optical molasses"



Measurement of the temperature

Time of flight method



The time of flight signal depends on:

- the acceleration due to gravity
- the initial position distribution (which can be deduced from a photo of the molasses)
- the initial velocity distribution (which is determined by the temperature)

Experimental results

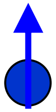
They don’t agree with the predictions deduced from the theory of Doppler cooling and they are about 100 times lower than the lowest possible temperatures predicted by such a theory!

P. Lett, R. Watt, C. Westbrook, W. Phillips, P. Gould, H. Metcalf
Phys. Rev. Lett. 61, 169 (1988)

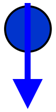
“Sisyphus” cooling

J. Dalibard
C. Cohen-Tannoudji

Several ground state sublevels



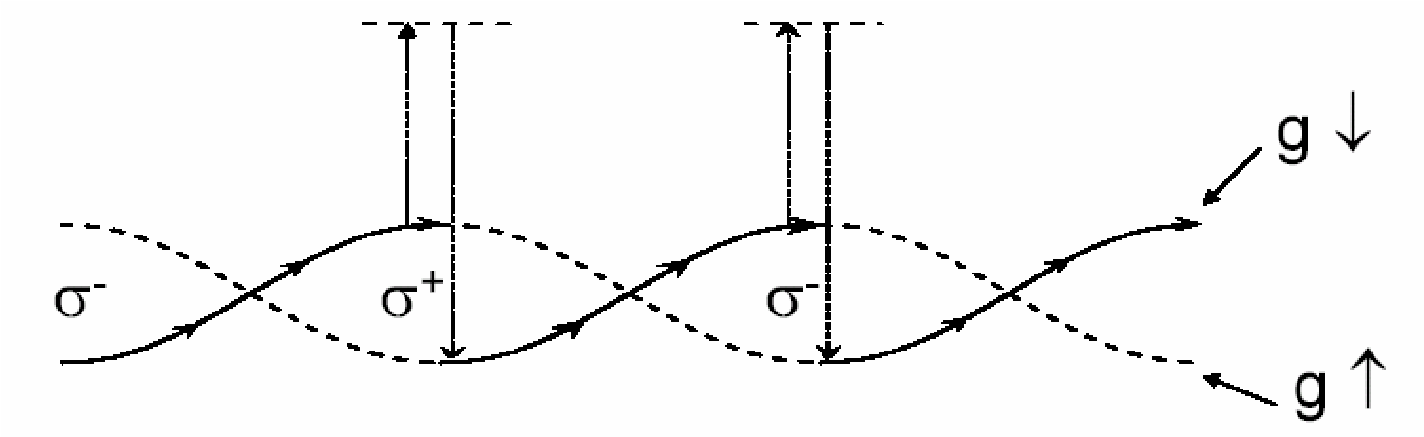
Spin up



Spin down

In a laser standing wave, spatial modulation of the laser intensity and of the laser polarization

- Spatially modulated light shifts of g↑ and g↓ due to the laser light
- Correlated spatial modulations of optical pumping rates g↑ ↔ g↓

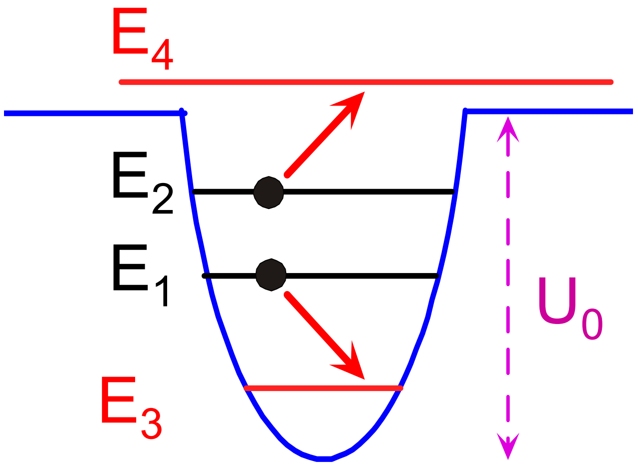


The moving atom is always running up potential hills (like Sisyphus)!

Very efficient cooling scheme leading to temperatures in the μK range

A first example of the usefulness of light shifts

Evaporative cooling



Atoms trapped in a potential well with a finite depth U_0

2 atoms with energies E_1 et E_2 undergo an elastic collision

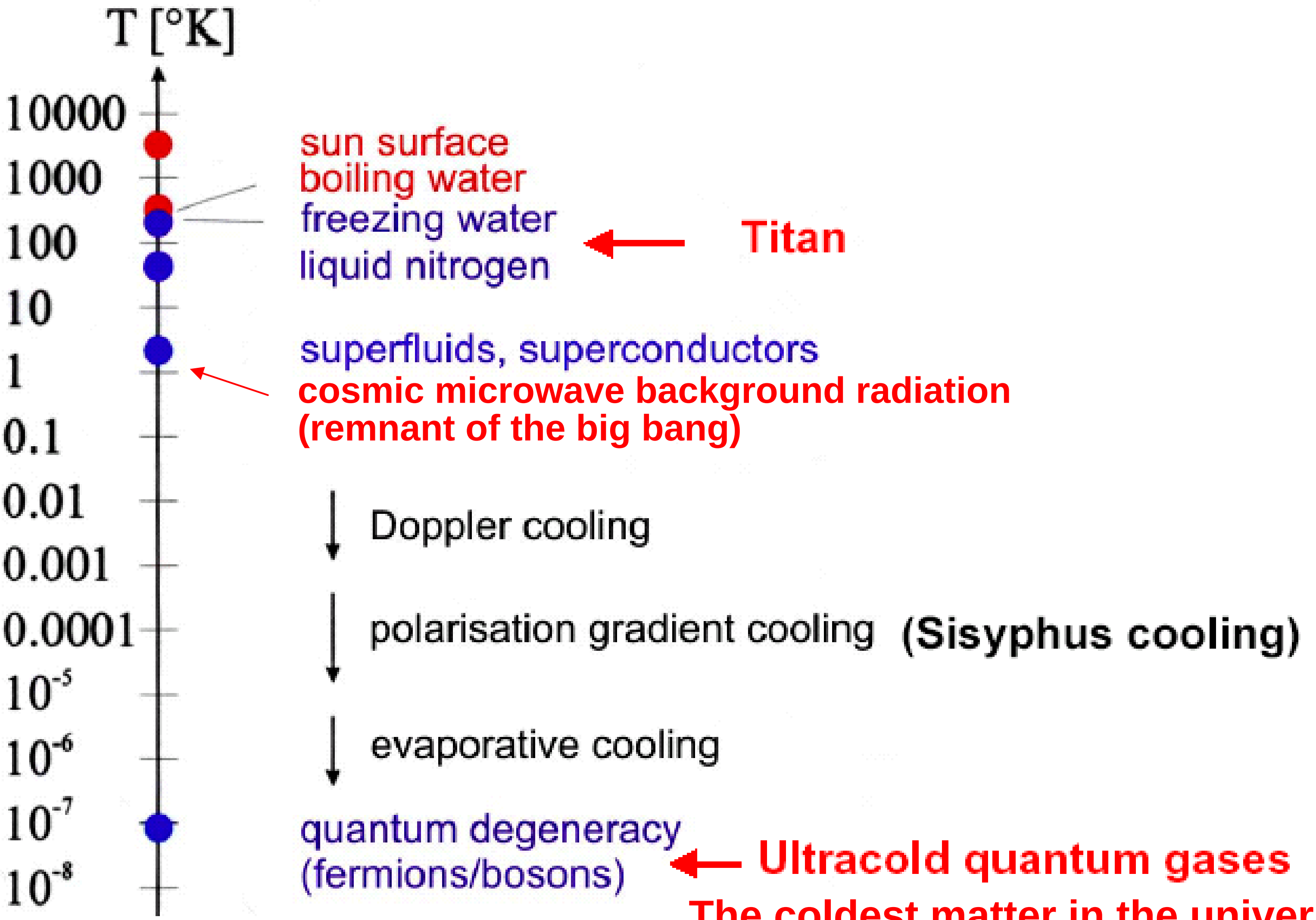
After the collision, the 2 atoms have energies E_3 et E_4, with

$$E_1 + E_2 = E_3 + E_4$$

If $E_4 > U_0$, the atom with energy E_4 leaves the well

The remaining atom has a much lower energy E_3. After rethermalization of the atoms remaining trapped, the temperature decreases

Temperature scale (in Kelvin units)



Titan

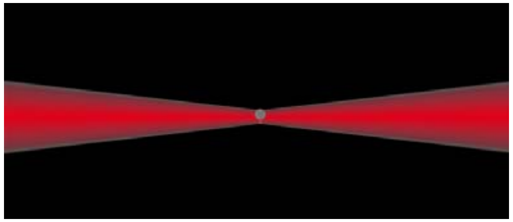
cosmic microwave background radiation (remnant of the big bang)

(Sisyphus cooling)

Ultracold quantum gases

The coldest matter in the universe

Traps for neutral atoms

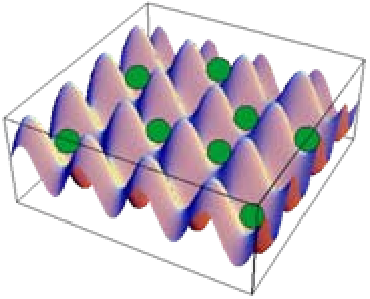


"Optical Tweezers"

Spatial gradients of laser intensity

Focused laser beam. Red detuning ($\omega_L < \omega_A$)

The light shift δE_g of the ground state g is negative and reaches its largest value at the focus. Attractive potential well in which neutral atoms can be trapped if they are slow enough



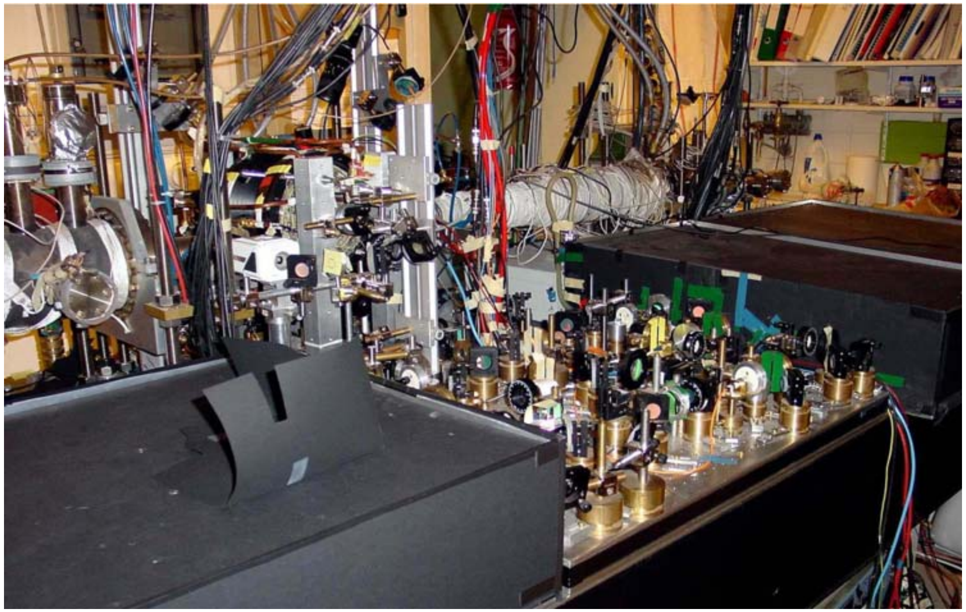
"Optical lattice"

Spatially periodic array of potential wells associated with the light shifts of a detuned laser standing wave

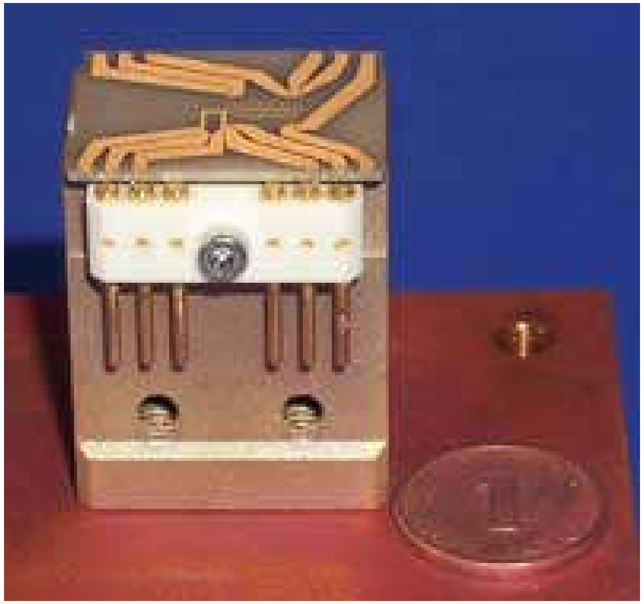
A second example of the usefulness of light shifts

Other types of traps using magnetic field gradients or magnetic field gradients combined with the radiation pressure of properly polarized laser beams ("Magneto Optical Traps")

A typical cold atom experiment



Cold atom "chip"



APPLICATIONS
OF ULTRACOLD ATOMS

Why are ultracold atoms interesting

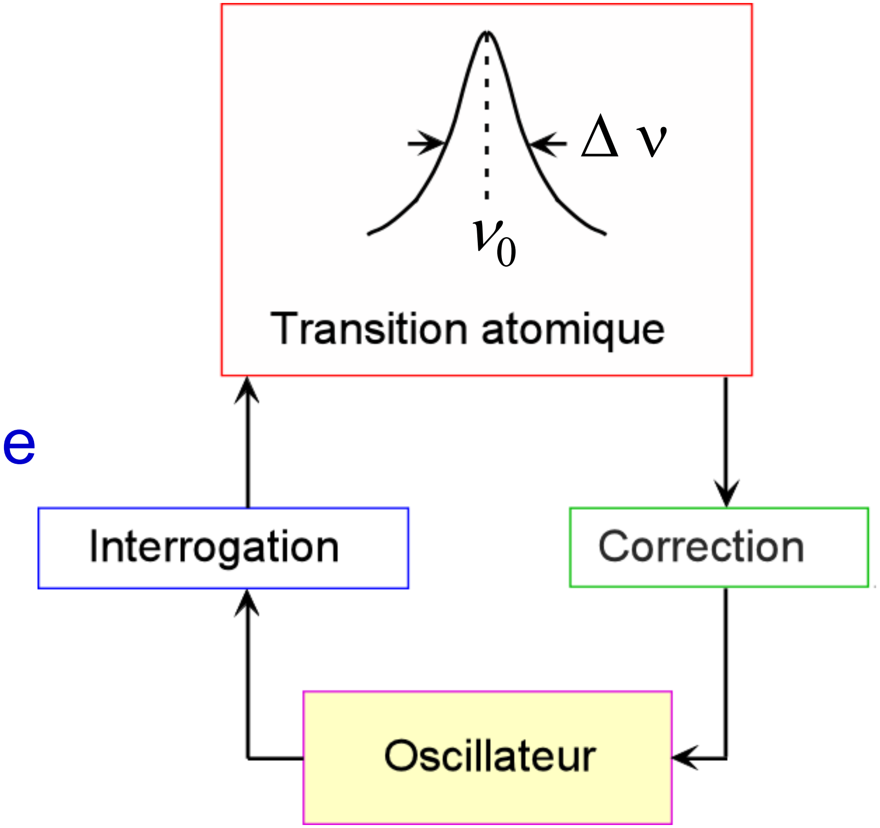
1- Long observation times for atomic clocks

The correction loop locks the frequency of the oscillator to the frequency ν_0 of the hyperfine transition of ^{133}Cs

The narrower the atomic line, *i.e.* the smaller $\Delta\nu$, the better the locking of the frequency of the oscillator to ν_0.

$$\Delta\nu \approx 1 / T$$

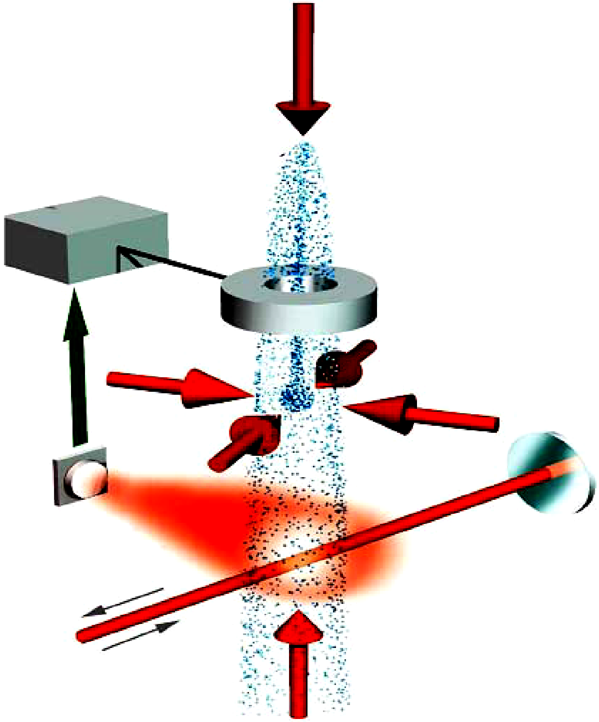
T : Observation time

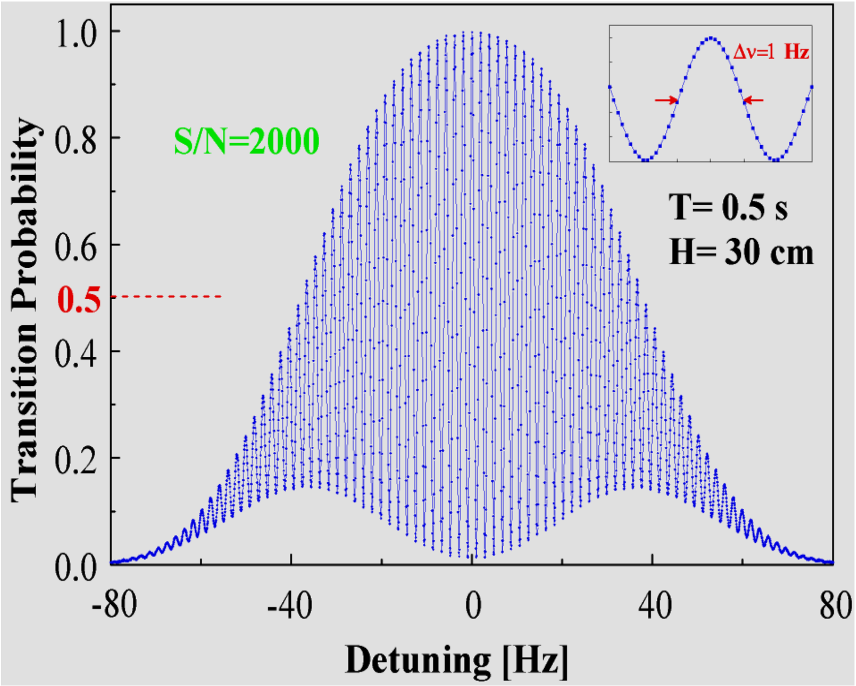


It is therefore interesting to use slow atoms in order to increase T, and thus to decrease $\Delta\nu$

Atomic fountains

- Sodium fountains : Stanford S. Chu
- Cesium fountains : BNM/SYRTE C. Salomon, A. Clairon





Stability : 1.6 x 10^{-16} for an integration time 5 x 10^{4} s

Accuracy : 7 x 10^{-16}

A stability of 10^{-16} corresponds to an error smaller than 1 second in 300 millions years

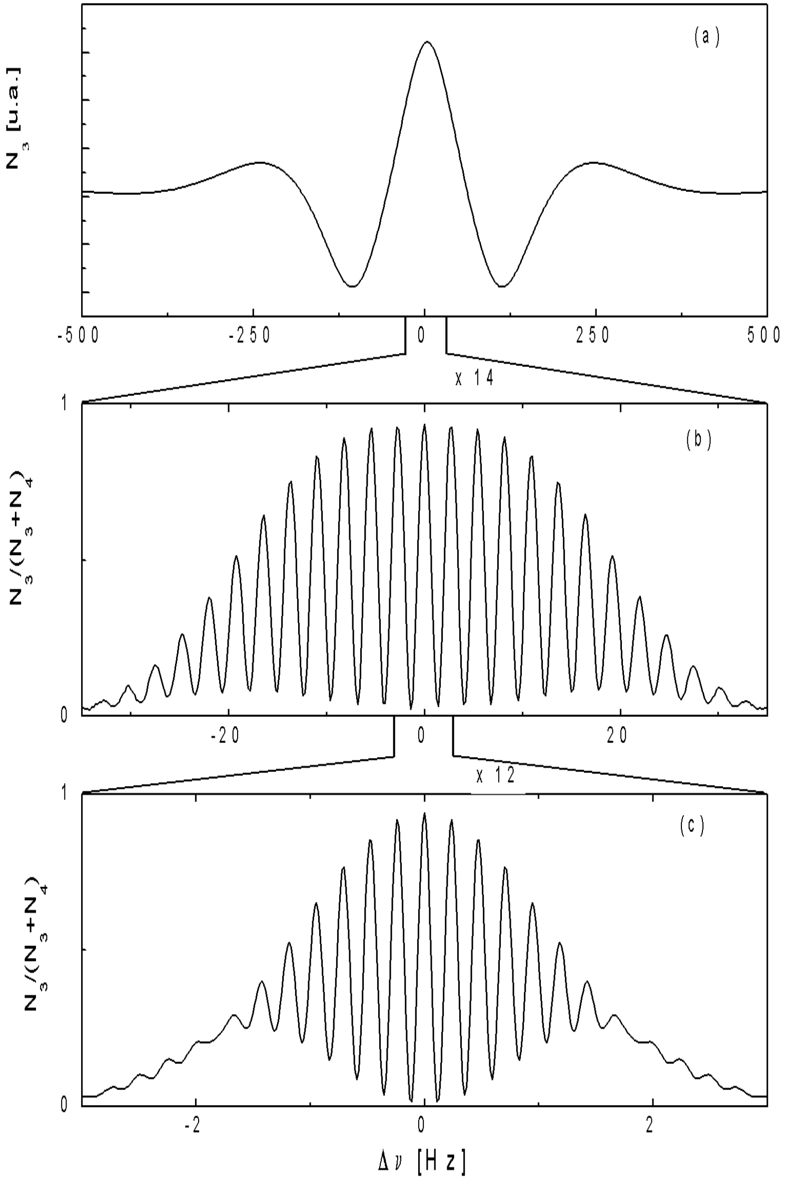
Parabolic flights

Atomic Clock Ensemble in Space

CENTRE NATIONAL D'ETUDES SPATIALES

- A cold atom Cs standard in space
- Fundamental physics tests
- Worldwide access

Sensitivity gains



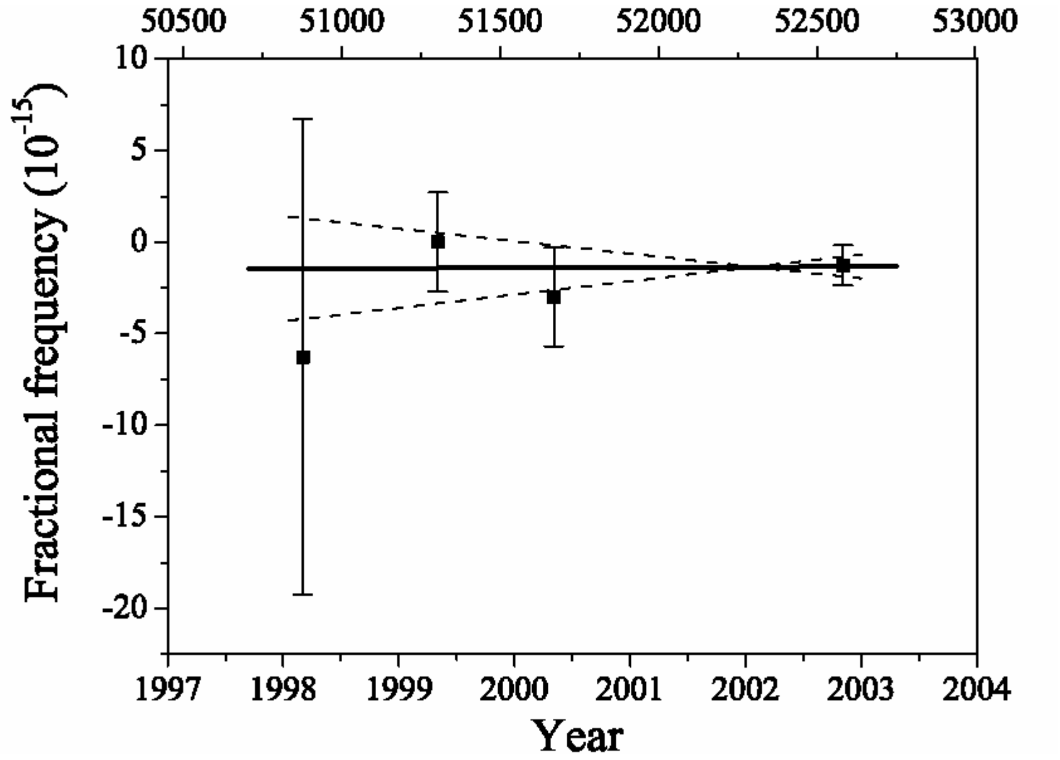
- Thermal beam :
  v = 100 m/s, T = 5 ms
  Δν = 100 Hz

- Fountain :
  v = 4 m/s, T = 0.5 s
  Δν = 1 Hz

- Clock in zero-g flight :
  v = 0.05 m/s, T = 5 s
  Δν = 0.1 Hz

Looking for possible variations of fundamental constants

Measurement of the ratio of the frequencies
of the 2 hyperfine transitions of Rb and Cs



H. Marion *et al*
Phys. Rev. Lett.
90, 150801 (2003)

$$\frac{d}{dt}\ln\left(\frac{\nu_{Rb}}{\nu_{Cs}}\right) = \left(0.2\pm7\right)\times10^{-16}\,/\,\mathrm{an}$$

$$\frac{\dot{\alpha}}{\alpha} = \left(-0.4\pm16\right)\times10^{-16}\,/\,\mathrm{an}$$

Why are ultracold atoms interesting (continued)?

2- Large de Broglie wavelengths

At very low temperatures atoms do not behave simply as particles. They behave also as waves because their de Broglie wavelength proportional to 1/v becomes very large.

de Broglie waves

$$\lambda_{dB} = \frac{h}{M\,v}$$

Louis de Broglie 1924

The colder the atom, the smaller v, the larger λ_{dB} which can reach values of the order of tens of microns

New research fields

- Atomic interferometry

  Extension to atomic de Broglie of interference experiments previously performed with light (gyrometers, gradiometers)
- Gaseous Bose Einstein condensates: a new state of matter
- Fermi degenerate gases

Bose Einstein condensation for a perfect gas of bosonic atoms

N identical bosonic atoms in a trap, in thermodynamic equilibrium at temperature T

One lowers the temperature T. The de Broglie wavelength λ_{dB} of the atoms increases. When T becomes lower than a certain critical value T_c, a macroscopic number N_0 of bosons accumulates in the ground state of the trap and they are all described by the same 3D wave function

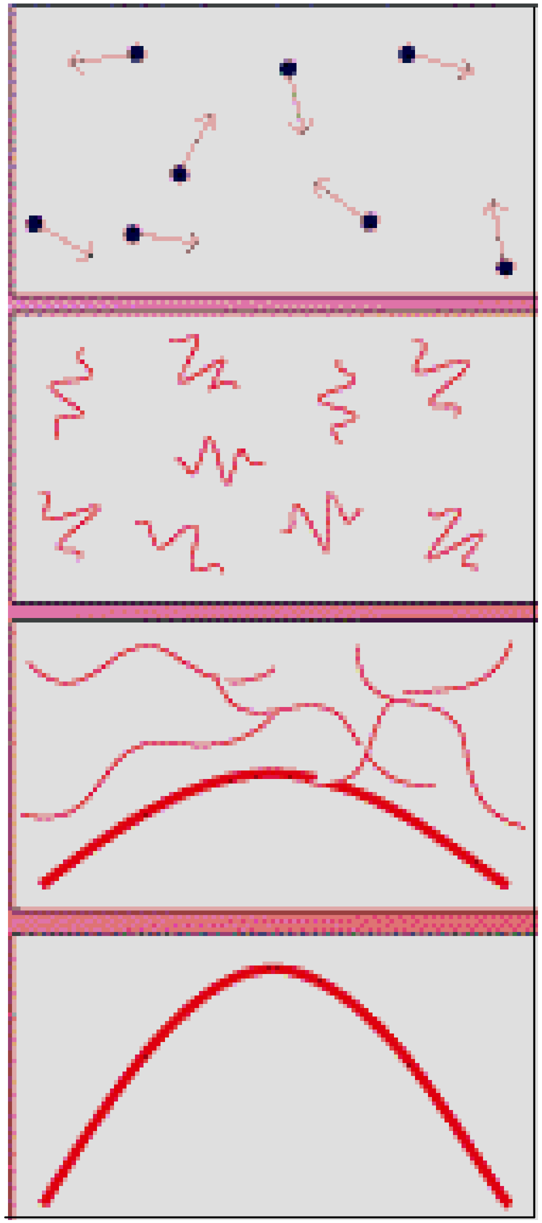
« Giant » matter wave

The critical temperature T_c corresponds to a situation where the de Broglie wavelength of the atoms becomes of the order of the mean distance between atoms.

The de Broglie waves of the various atoms then overlap and interfere.

Sketch of the waves associated with the trapped atoms

Evolution of these waves when T decreases from a value much higher than T_C to a value much lower



$T >> T_C$

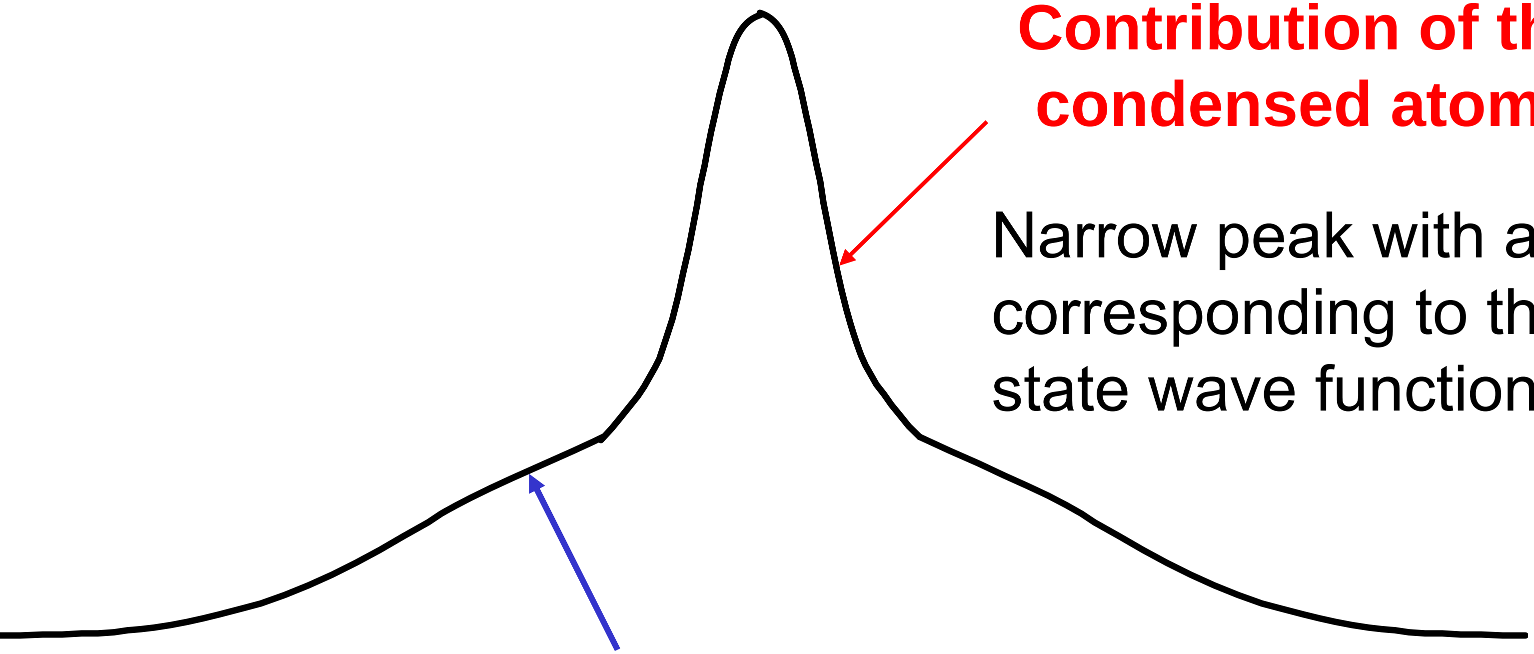
$T > T_C$

$T \sim T_C$

$T < T_C$

W. Ketterle

Bimodal structure
of the spatial distribution of bosons



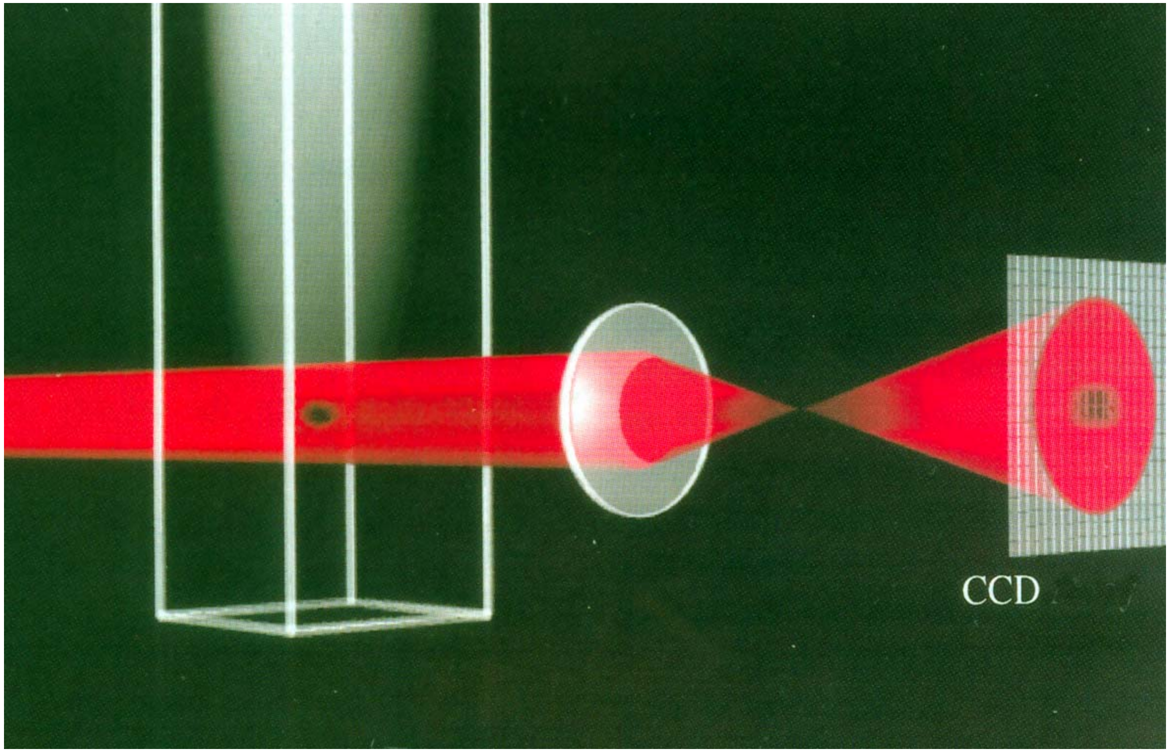
Contribution of the condensed atoms

Narrow peak with a width corresponding to the ground state wave function of the well

Contribution of the non condensed atoms

Broad pedestal coming from atoms occupying excited states of the well described by wave functions with a larger width

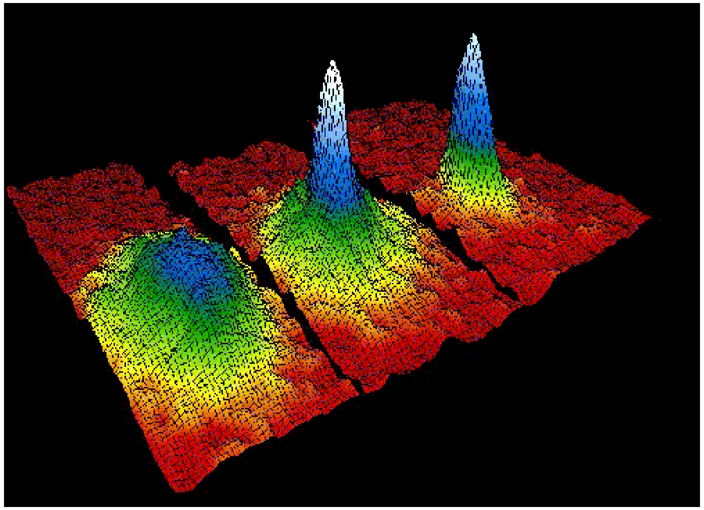
Visualization of the atomic cloud



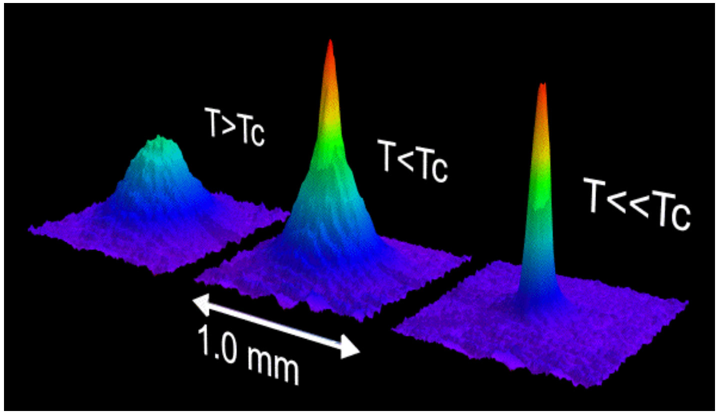
Spatial dependence of the absorption
of a laser beam by the cloud

Experimental observation

JILA
^{87}Rb
1995



MIT
^{23}Na
1995

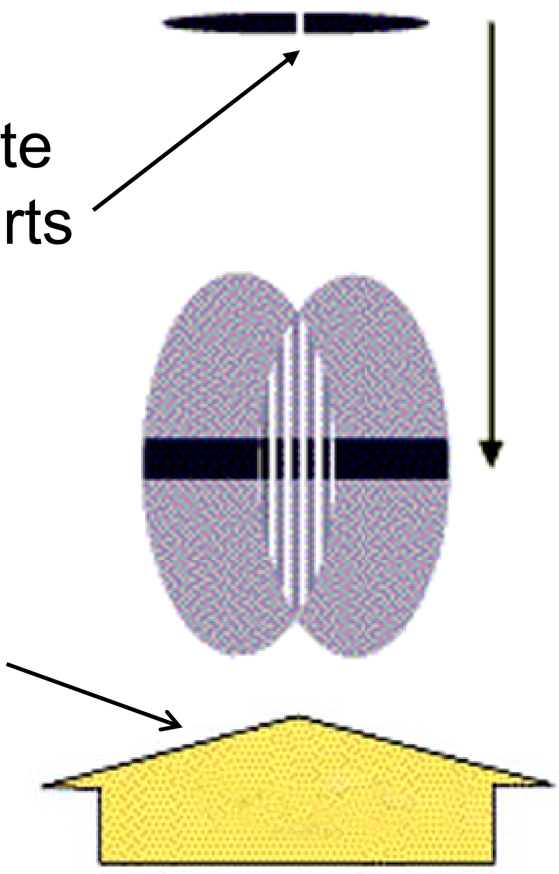


All atoms are in the same quantum state

They form a macroscopic matter wave

Other subsequent observations in ^{7}Li, ^{1}H, ^{4}He*, ^{41}K, ^{133}Cs, ^{174}Yb, …

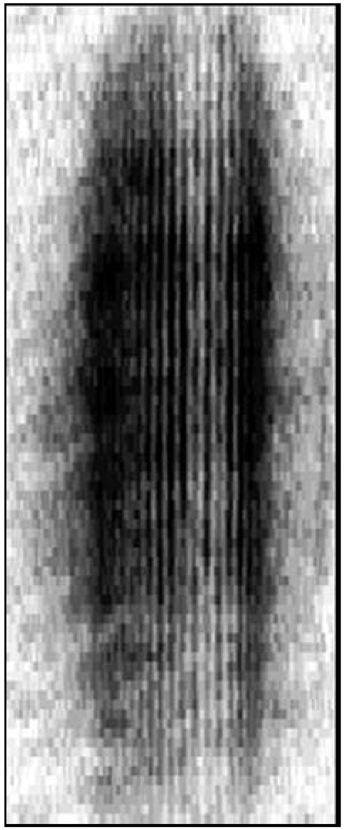
Interference between 2 condensates



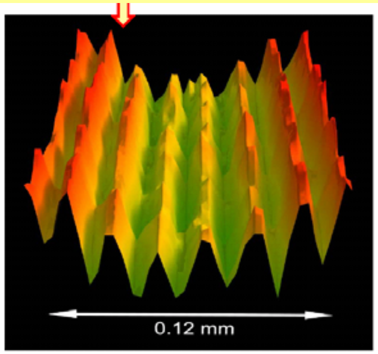
Condensate cut in 2 parts by a laser

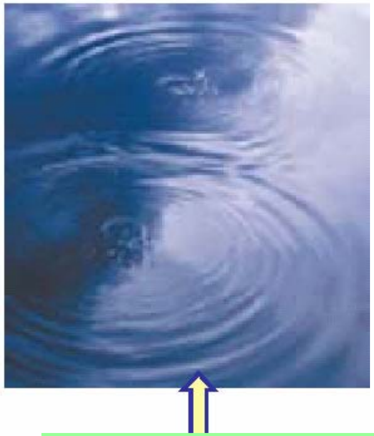
Imaging

Probe laser



Interferences between 2 condensates

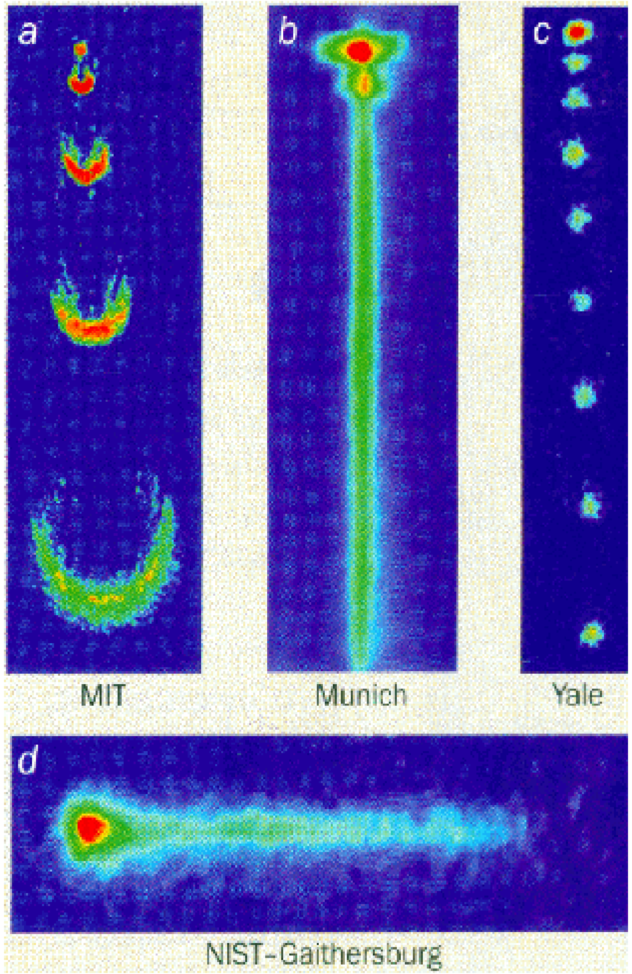




Interferences in water

M.R.Andrews, C.G.Townsend, H.-J. Miesner, D.S. Durfee, D.M.Kurn, W.Ketterle, Science, 275, 637 (1997)

Atom lasers



Coherent beam of atomic de Broglie waves extracted from a condensate

Very promising system for atom optics

Superfluidity

An object moving through a condensate does not feel any friction as long as its velocity remains smaller than a certain critical value.
Experimental observation of this effect at MIT.

Behavior similar to the one observed in superfluid He

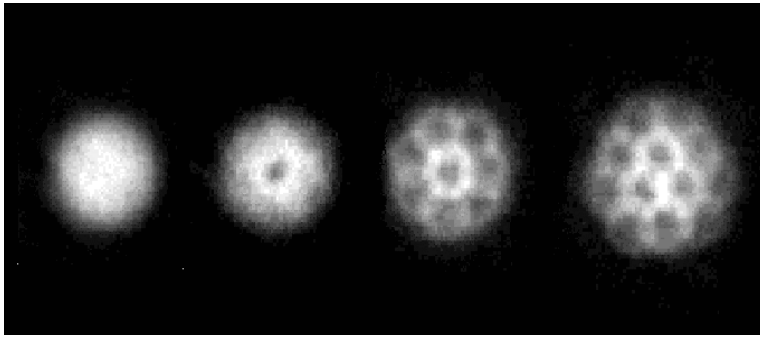
Quantized vortices

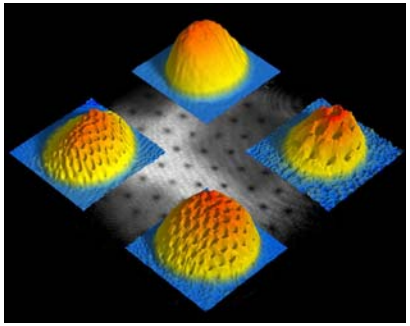
If the trap containing the atoms is rotating, it does not drag the condensate with it as long as the angular velocity is lower than a certain critical value.
Above this value, vortices appear. The density vanishes along the axis of the vortex and the circulation of the velocity along a contour around the axis is quantized

Vortices analogous to those observed in superconductors

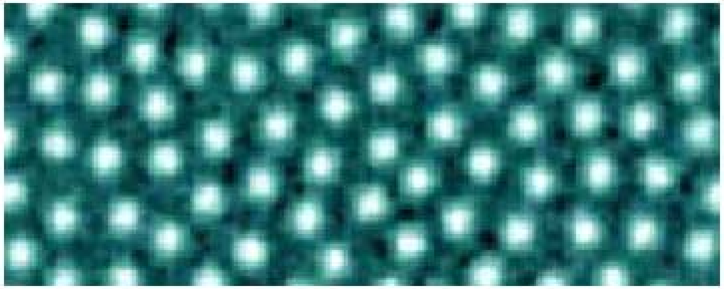
Lattice of vortices in a Bose Einstein condensate

Paris



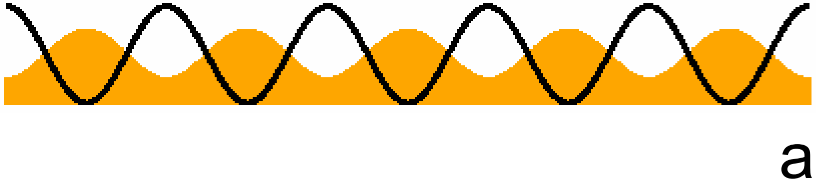


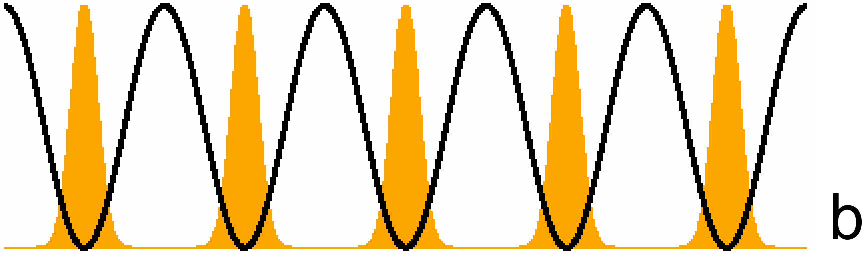
MIT



Analogy with Abrikosov lattices in type II superconductors

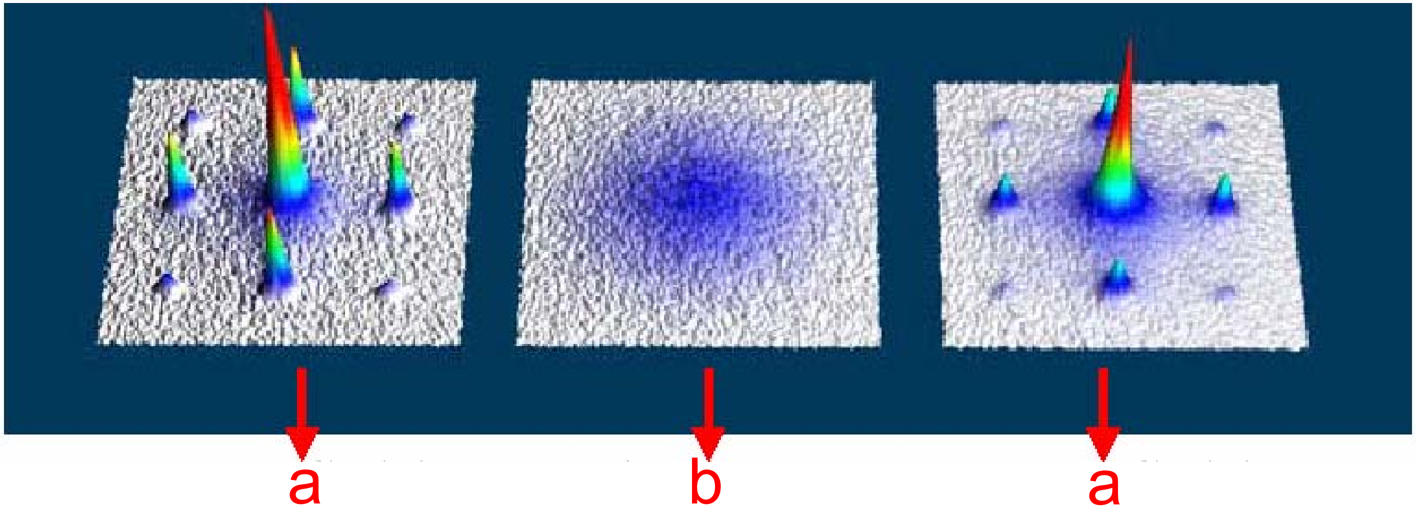
BEC in a periodic optical potential
Superfluid – Mott insulator transition





a – Small depth of the wells. Delocalized matter waves.
Superfluid phase

b - Large depth of the wells. Localized waves. Insulator phase



Importance of gaseous Bose Einstein condensates

Matter waves have very original properties (superfluidity, coherence,…) which make them very similar to other systems only found, up to now, in condensed matter (superfluid He, superconductors)

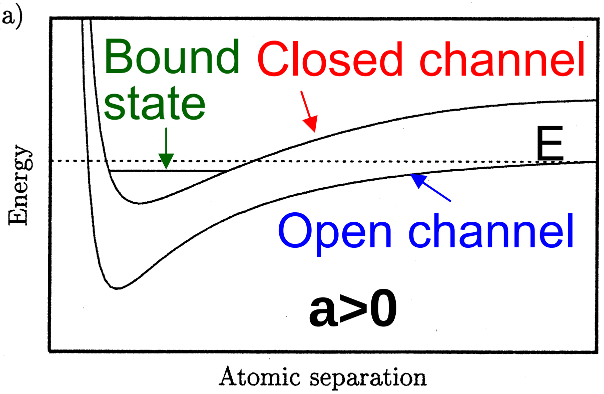
The new feature is that these properties appear here in very dilute systems, about 100000 times more dilute than air. Atom-atom interactions have then a much smaller effect which can be calculated more precisely

Furthermore, these interactions can be modified at will, in magnitude and in sign (attraction or repulsion), using « Feshbach resonances » obtained by sweeping a static magnetic field

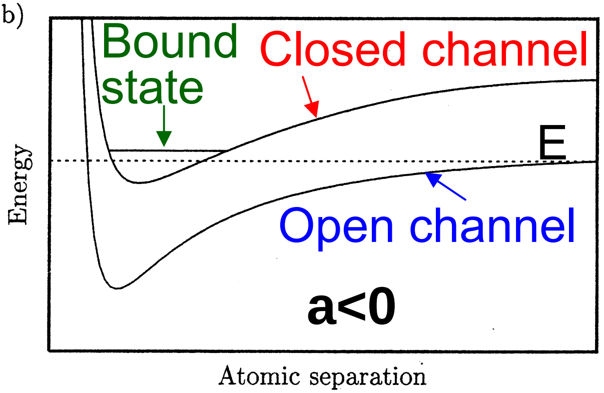
Feshbach Resonance

Resonance between a free state in an open channel
and a bound state in a closed channel

(a)

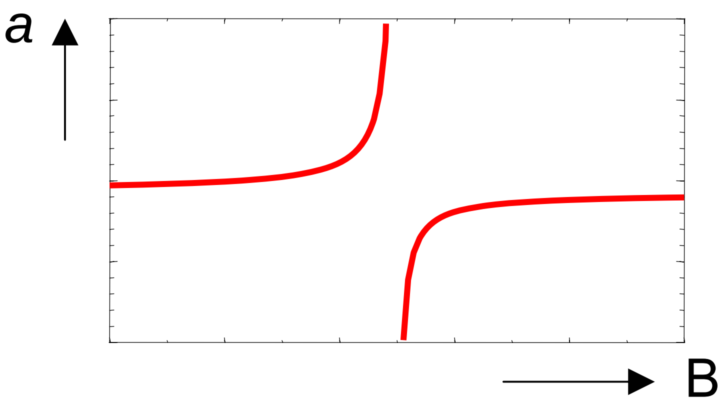


(b)



The 2 channels correspond to 2 different relative orientations of the spins of the 2 atoms

Their energy difference can be varied by sweeping a magnetic field B, leading to resonant variations of the scattering length *a* which fully characterizes collisions at very low T

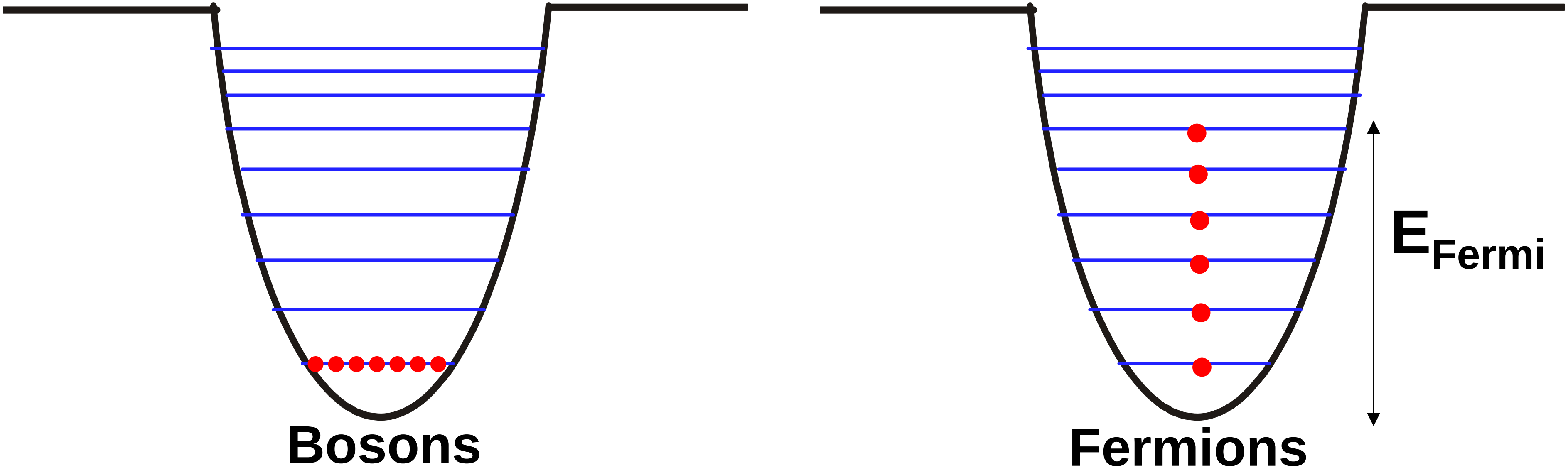


In the region of B where the scattering length a is positive and large, the 2 atoms can form a bound state with a weak binding energy.

In the region where a is negative, there is a long range attractive force

QUANTUM DEGENERATE FERMIONIC GASES

Bosons versus Fermions at very low T



Bosonic atoms condense in the ground state of the trap

Fermionic atoms pile up with one atom per level

The energy of the highest level occupied by a fermion is called the Fermi energy E_F which can be written $E_F = k_B T_F$

k_B : Boltzmann constant T_F : Fermi temperature

The Fermi gas is degenerate if $T < T_F$

Is it possible to cool fermions down to the quantum degeneracy?

Evaporative cooling does not work well

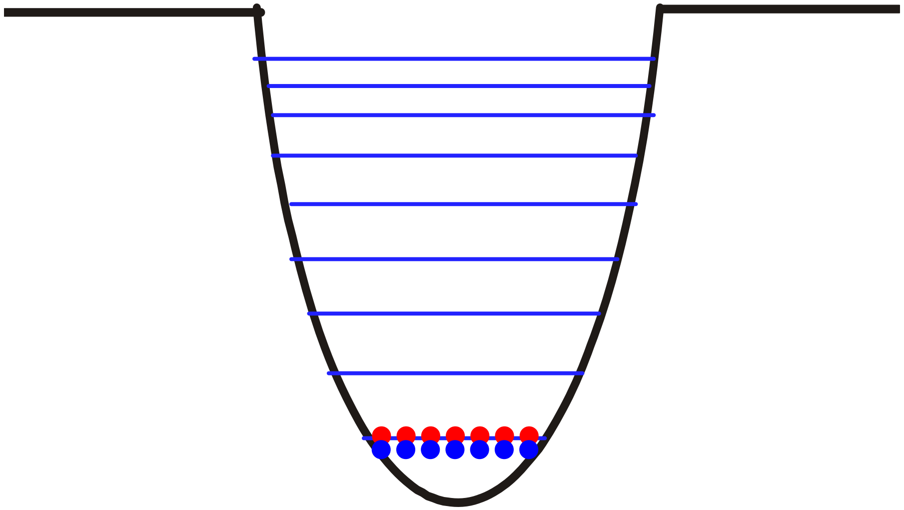
2 polarized fermions (in the same spin state) cannot collide in a s-wave (Pauli principle) → very low elastic collision rates at low T

Solution : Sympathetic cooling

Collisions between polarized fermions and other distinguishable atoms which can be evaporatively cooled

Pairs of Fermions

When 2 fermions form a pair, the pair contains an even total number of electrons, protons and neutrons.



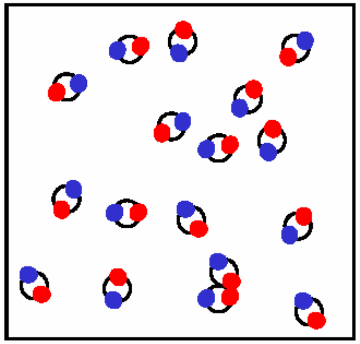
A pair of 2 fermions is therefore a boson

These pairs of fermions can condense and form a superfluid phase of fermion pairs

Pairs of ultracold fermionic atoms

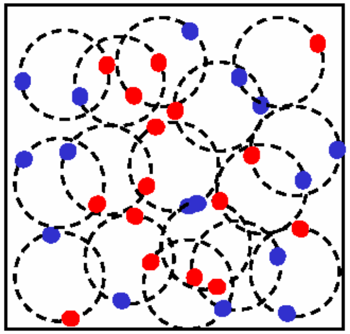
2 types of pairs have been produced

1 – Molecules formed with 2 fermionic atoms



Bound state of 2 fermionic atoms
In different spin states in the interaction potential of the 2 atoms.
These short-range molecules condense in a molecular BEC

2 – Cooper-type pairs formed with 2 fermionic atoms



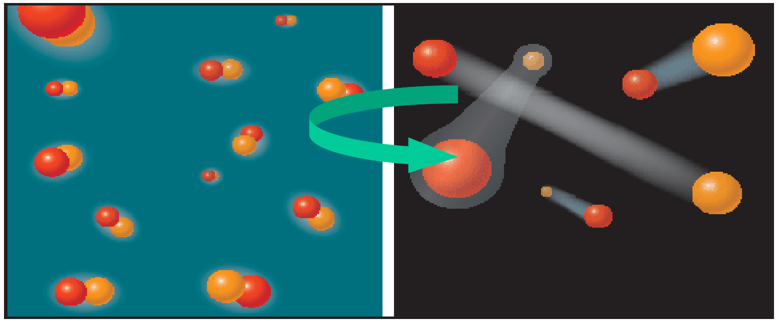
Long-range pairs of 2 fermionic atoms
In different spin states due to long-range weak interactions between the 2 atoms and to many-body effects.
These pairs condense in a superfluid phase analogous to the BCS phase

BEC-BCS crossover observed with ultracold fermions

By varying the magnetic field around a Feshbach resonance, one can explore 3 regions

- Region a>0 (strong interactions). There is a bound state in the interaction potential where 2 fermions with different spin states can form molecules which can condense in a BEC
- Region a<0 (weak interactions). No molecular state, but long range attractive interactions giving rise to weakly bound Cooper pairs which can condense in a BCS superfluid phase
- Region a=∞ (center of the resonance). Strong interactions Strongly correlated systems with universal properties.

Recent observation at MIT (W. Ketterle et al) of quantized vortices in all these 3 zones demonstrating the superfluid character of the 3 phases



a>0
BEC

a=∞

a<0
BCS

Molecules formed with 2 atoms in different spin states in the region a > 0

The lifetime of molecules formed with fermionic atoms is much longer than the lifetime of molecules formed with bosonic atoms. Fermionic molecules are much less sensitive to collisions which could destroy them.

Advantage of fermionic molecules

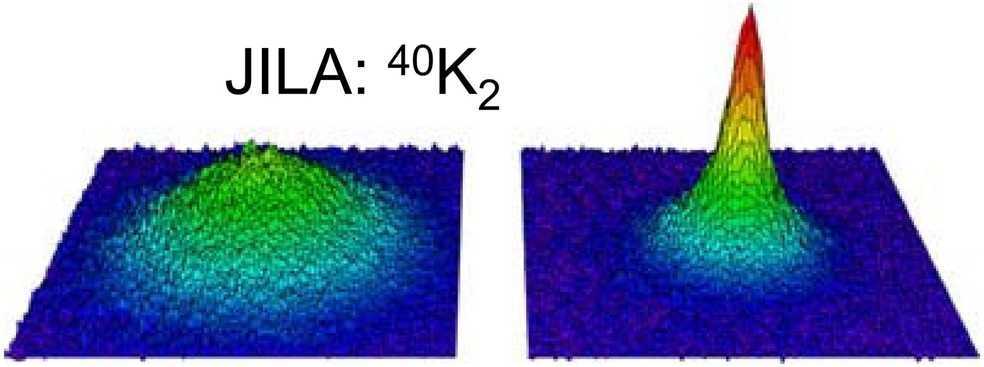
Very long lifetime of the molecular state ↑↓ because Pauli principle prevents short distance collisions between a molécule ↑↓ and an atom ↑ or ↓, which are responsible of the decay of the molecules.

Possibility to get high enough densities of molecules allowing one to reach the Bose Einstein condensation threshold.

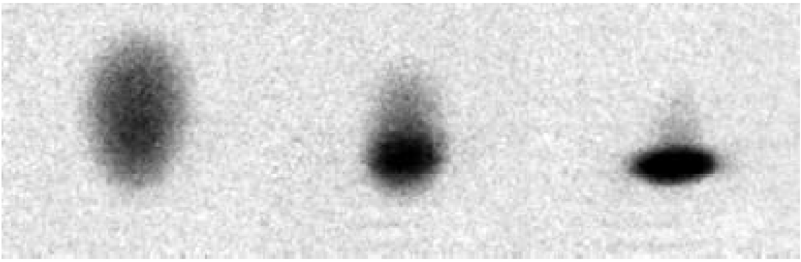
5 different groups have obtained molecular condensates.

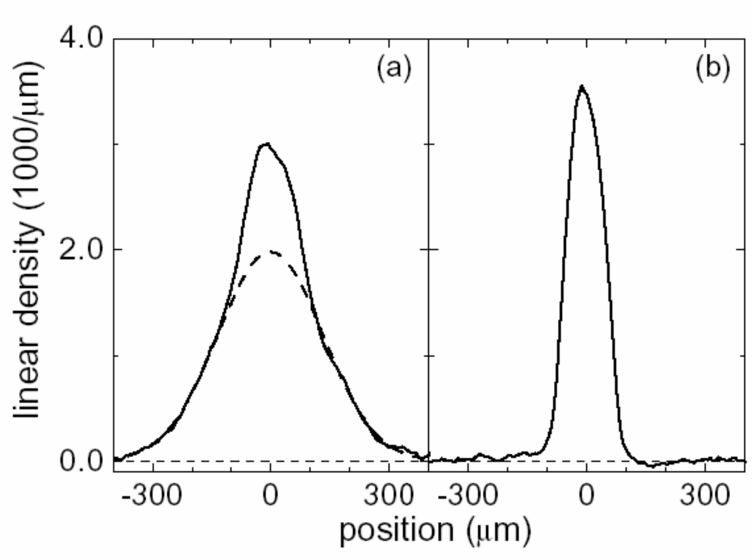
Molecular condensates

JILA: $^{40}K_2$



MIT $^{6}Li_2$

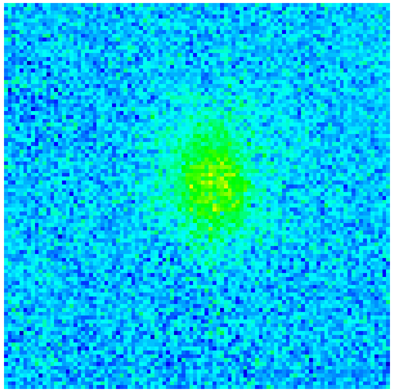


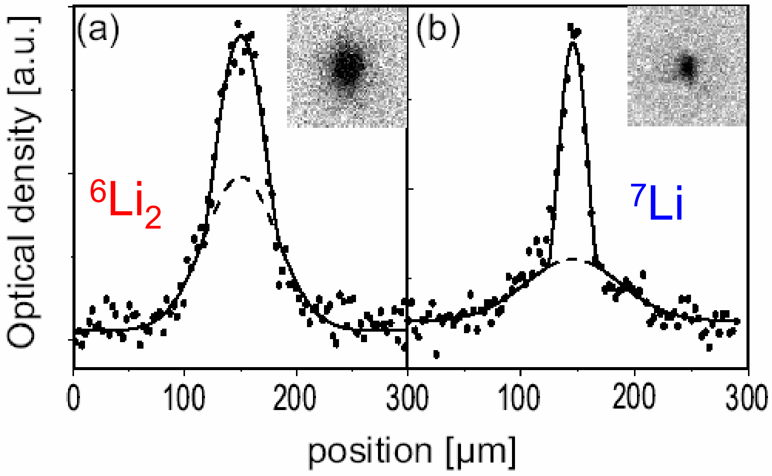


$^{6}Li_2$:Innsbruck

Rice $^{6}Li_2$

ENS $^{6}Li_2$



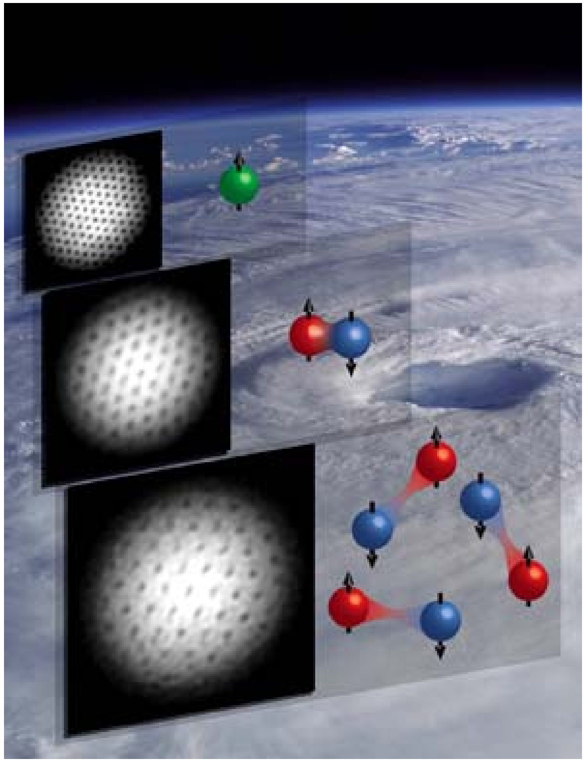


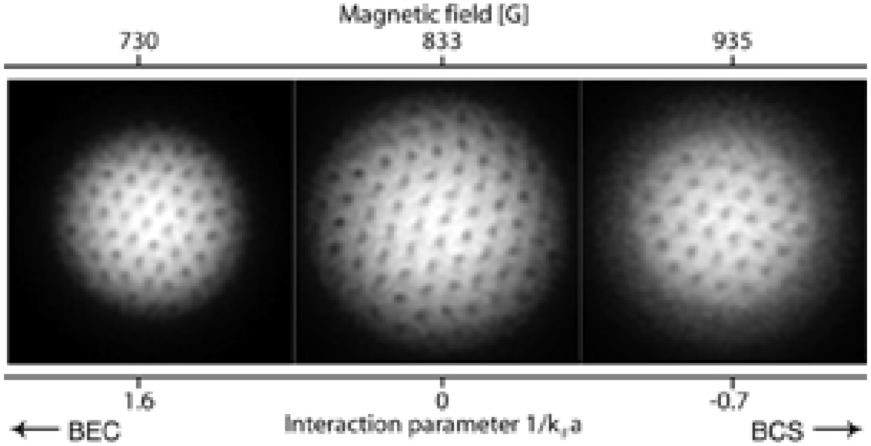
Gallery of vortices observed at MIT on Li

Atoms →

Molecules →

Cooper pairs →





a>0

a=∞

a<0

M.Zwierlein, J.Abo-Shaeer, A.Shirotzek, C.Schunck, W.Ketterle
Nature, **435**, 1047 (2005)
cond-mat/0505635

Conclusion

Our ability to control and to manipulate quantum systems (atoms, ions, electrons) has considerably increased during the last few decades

This is opening completely new research fields and allows us to ask new questions and to investigate new systems, new states of matter.

The most recent developments indicate that ultracold atoms provide simple models in fully controllable conditions allowing one to get a better understanding of more complicated many body problems found in other branches of physics:

- Superfluid Mott-insulator transition
- BEC-BCS cross-over
- High T_C superconductors
- Quantum information