Atoms and Photons
From Optical Pumping to Matter Waves

Claude Cohen-Tannoudji

Atom-photon interactions

Constant interplay between

- Fundamental interrogations

- Development of new tools, new methods of investigation resulting from a better understanding of the physical mechanisms

- New interrogations, new research fields whose emergence is made possible by the progress of experimental techniques

Purpose of this lecture

Present a brief survey of the important steps of the history of atomic physics.

Describe a few recent developments in the field of ultracold atoms:
- Laser cooling
- Bose-Einstein condensation

Try to identify a few trends of evolution, a few perspectives.

The renaissance of atomic physics after world war II

New sources of radiation in the RF and microwave domains (development of the radar)

RF spectroscopy
Molecular beam experiments

High precision measurements of the fine and hyperfine structure of atomic energy levels leading to a few important discoveries

Lamb shift
Electron spin anomaly g-2

Birth of Quantum Electrodynamics (QED)

Protoype of quantum field theories

Optical methods of RF spectroscopy
Double resonance - Optical pumping

A. Kastler, J. Brossel

Exciting atoms with polarized light

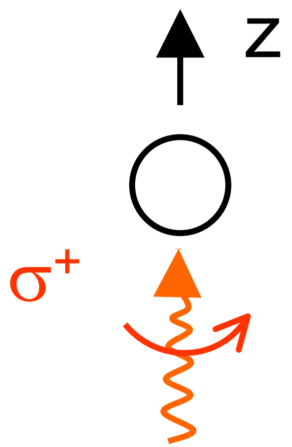
Transferring to atoms the angular momentum of polarized photons

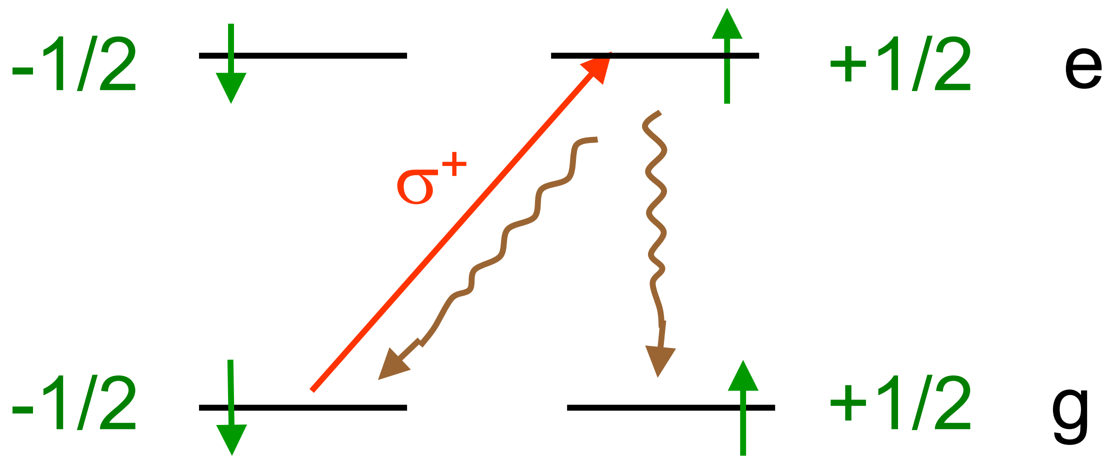
Detecting the polarized light emitted or absorbed by atoms

Monitoring the angular momentum state and its change induced by magnetic resonance or by relaxation processes

Very sensitive methods allowing precise measurements on very dilute systems

Optical pumping





- σ^+ photons have an angular momentum +1 along 0z.

Selective excitation of the transition

$$g, -1/2 \;\rightarrow\; e, +1/2$$

- The atom falls back in g, +1/2 and remains trapped there.

High degrees of spin polarization

at room temperature and in weak fields

Applications of optical methods

High resolution spectroscopy

- Fine and hyperfine structures
- Radiative lifetimes

Atom-photon interactions

- Multiphoton processes
- Light shifts

Quantum interference effects

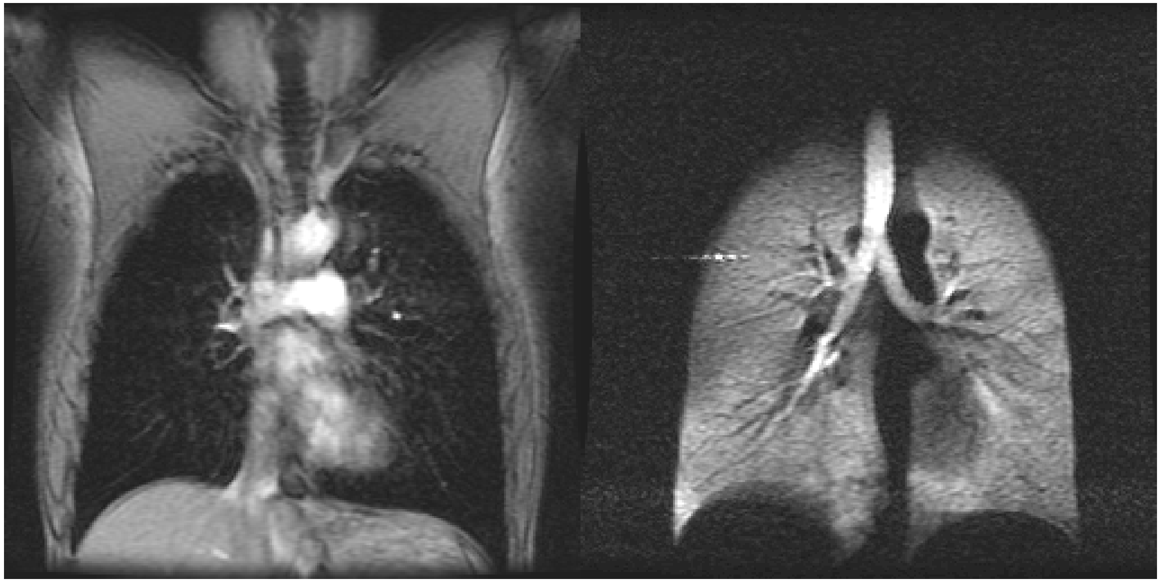
- Absorption and emission of light by an atom in a linear superposition of Zeeman sublevels
- Quantum beats. Coherent population trapping

Non equilibrium situations

- Relaxation processes
- Population inversions

A recent practical application: MRI of the lung

MRI Images of the Human Chest



Proton-MRI ^{3}He-MRI

Duke Univ., CAMRD
http://camrd4.mc.duke.edu/ (1997)

Human lung MRI centres :

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

About 10 more centres getting started

Masers and lasers

New sources of radiation

- using amplification by stimulated emission
- with spectacular performances (intensity, monochromaticity, coherence, pulsed operation, tunability...)

Increasing number of laser media

- Discharges, crystals, dyes, semiconductors...
- Devices becoming easier to operate, cheaper, smaller...

A new era for the physics of atoms and photons

Examples of new research fields opened by lasers

- Nonlinear spectroscopies
  - Saturated absorption
  - Doppler free two-photon absorption
- Time-resolved spectroscopies
  - Ultra-short pulses
  - Femtochemistry
- Nonlinear optics
  - Harmonic generation
  - Four wave mixing
- Terrawatt lasers
  - Relativistic effects
- Reduction of quantum noise
  - Squeezing

Laser cooling and trapping

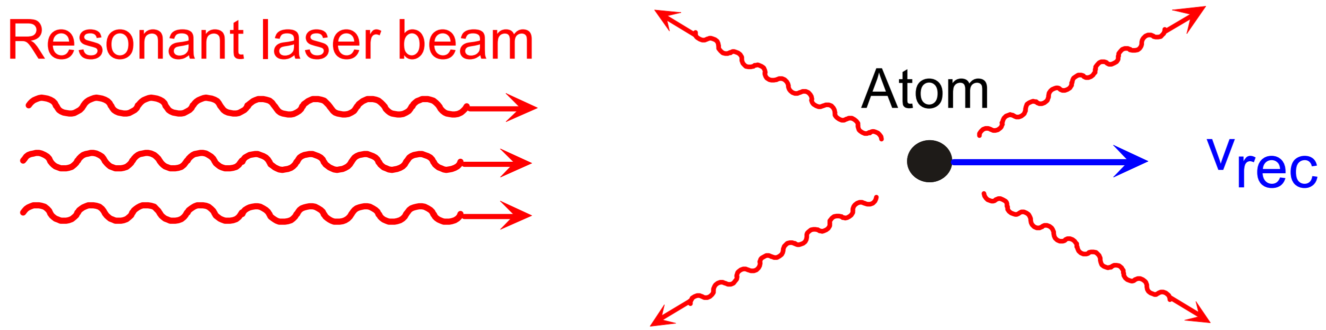
Using resonant exchanges of linear momentum between atoms and photons for controlling atomic motion with laser light

Radiative forces exerted by laser beams on atoms and allowing one to trap them and to cool them to very low temperatures, on the order of a few microkelvins

Applications

- Long observation times
  - High resolution spectroscopy
  - Atomic clocks
- Long de Broglie wavelengths (λ_{dB} increases if v decreases)
  - Atomic interferometry
  - Quantum degenerate gases
  - Bose-Einstein condensation

Radiation pressure force



After each fluorescence cycle, the atomic momentum increases on the average by an amount equal to the momentum $h\nu/c$ of the absorbed photon. Its velocity changes by an amount $v_{rec} = h\nu/Mc$ on the order of 10^{-2} m/s

<u>Mean number N of fluorescence cycles per second</u> : on the order of $1/\tau_R$ where τ_R is the radiative lifetime of e, about 10^{-8} s

<u>Acceleration a (or deceleration)</u>

a is on the order of $v_{rec} \times N$, i.e. on the order of $10^{-2} \times 10^{8}$ m / s^2 = 10^5 g

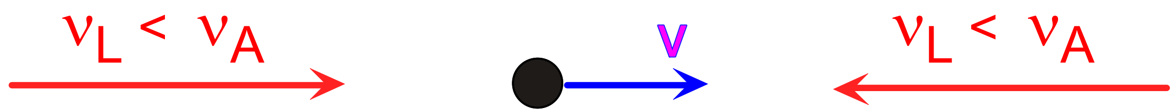
Laser Doppler cooling

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

2 counterpropagating laser beams

Same intensity

Same frequency, detuned to the red ($\nu_L < \nu_A$)



<u>Atom at rest (v=0)</u>

The two radiation pressure forces cancel each other out

<u>Atom moving with velocity v</u>

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"

Sisyphus cooling

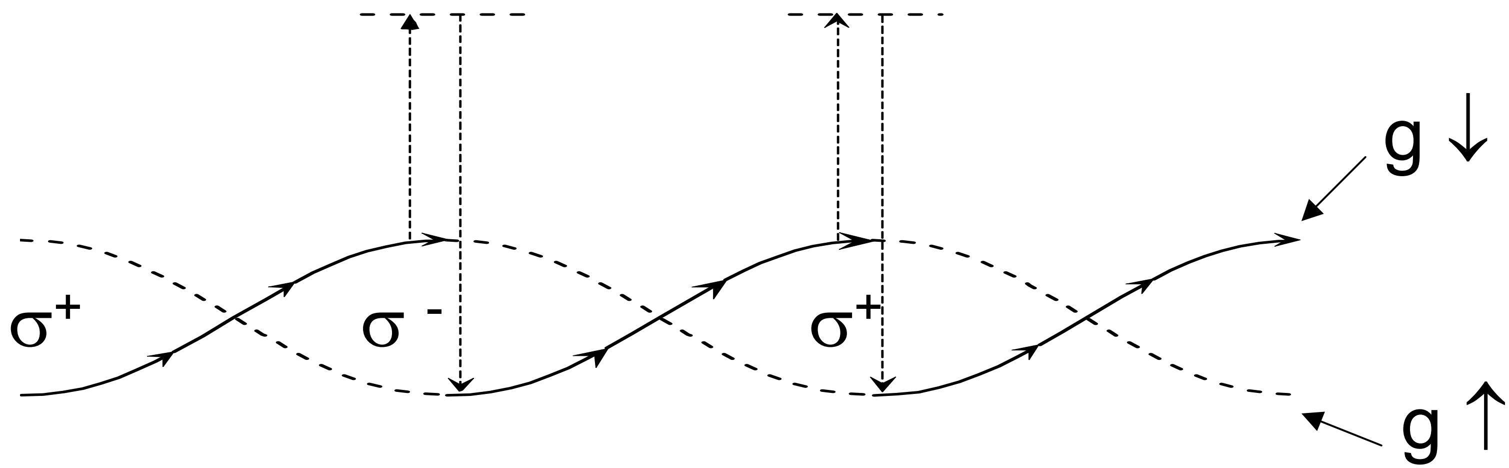
J.Dalibard, C.Cohen-Tannoudji

- Several ground state sublevels

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

❶- Spatially modulated shifts of g↑ and g↓ due to the laser light

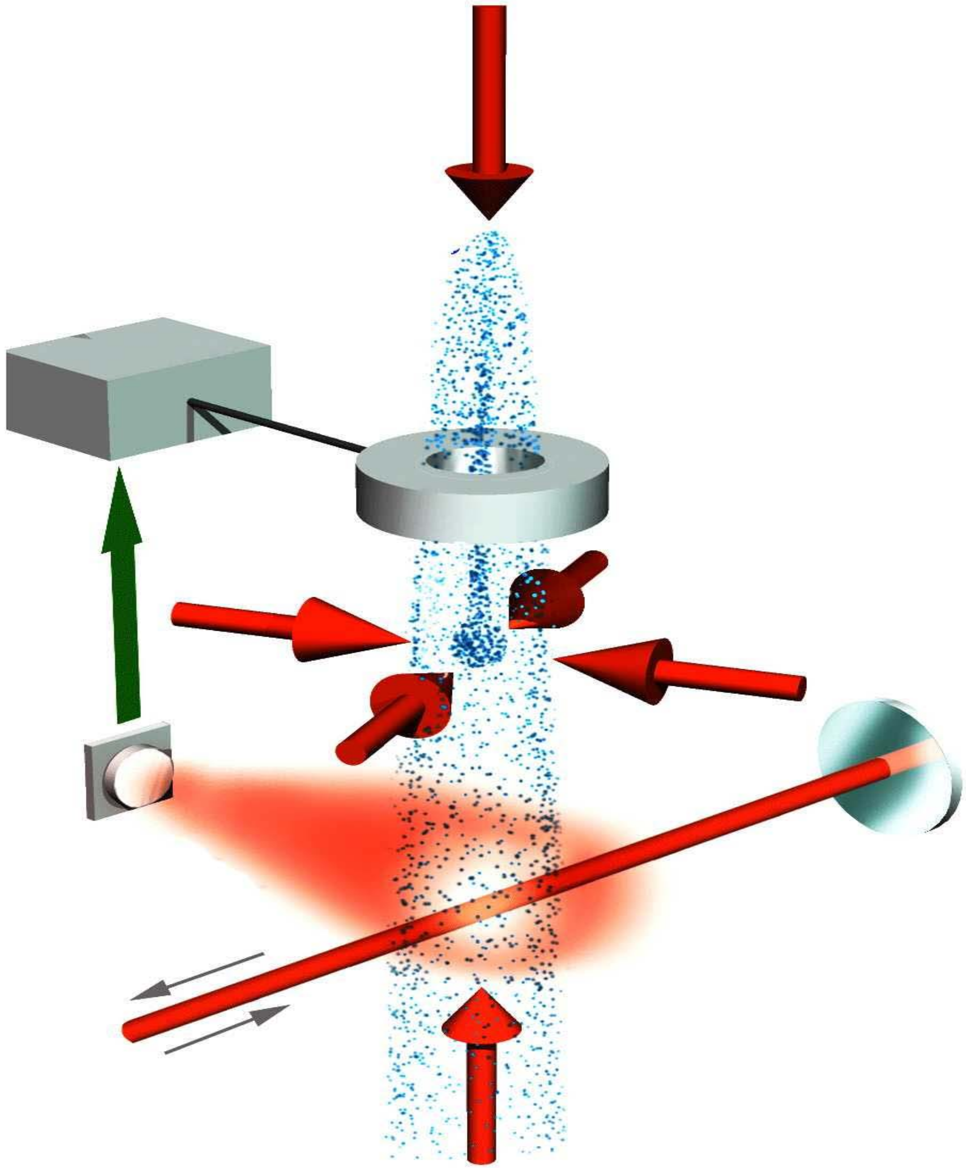
❷- Correlated spatial modulations of optical pumping rates g↑ ⇄ g↓



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

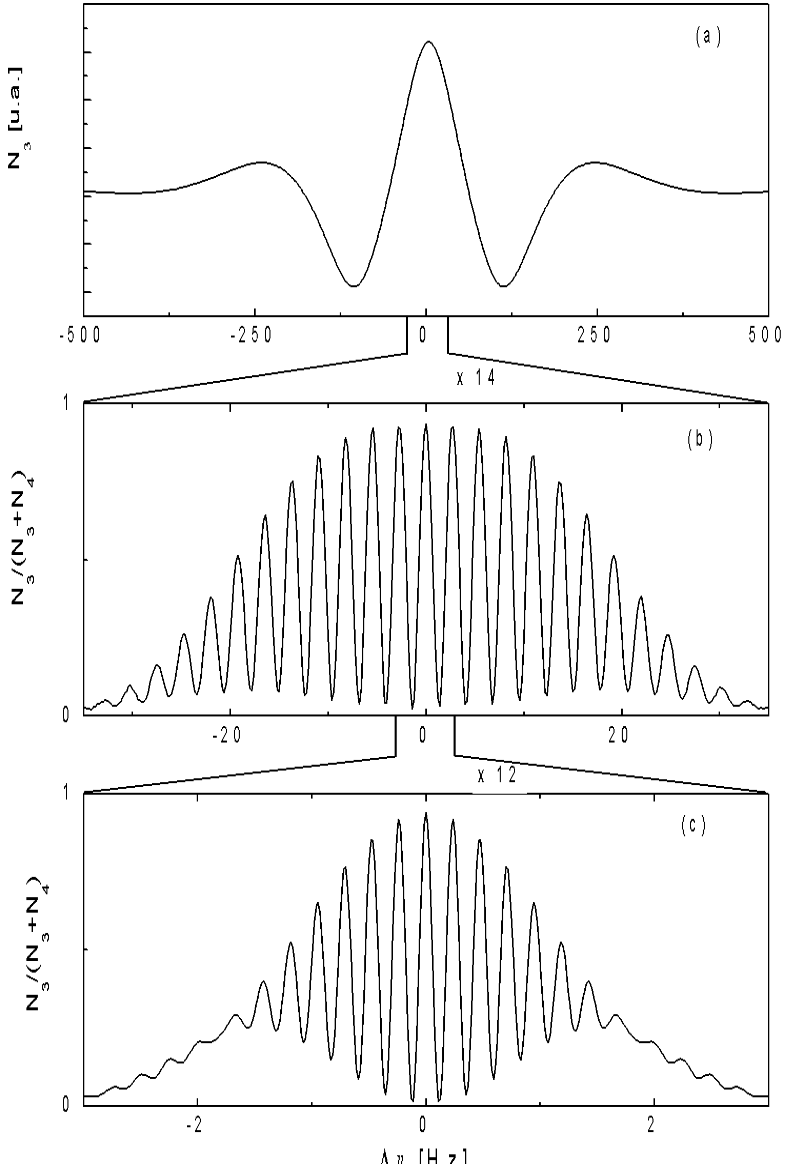
Very efficient cooling scheme leading to temperatures in the μK range

Atomic Fountain principle



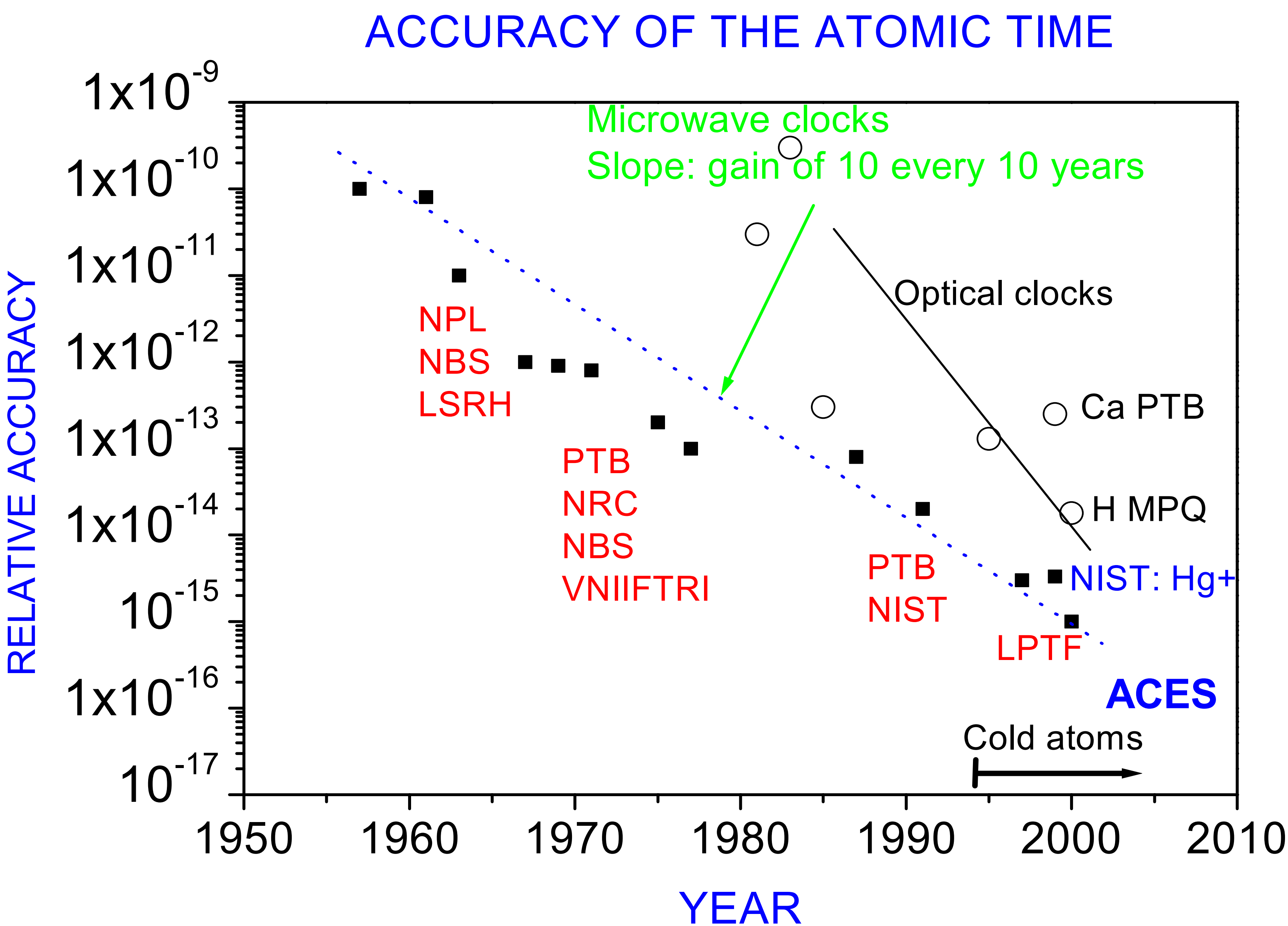
Atomic clocks with cold atoms

A.Clairon, C.Salomon (B.N.M./L.P.T.F.)



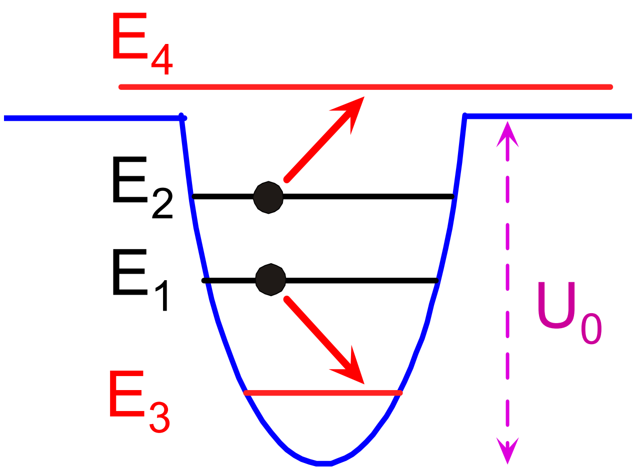
- Thermal beam :
  $v = 100$ m/s, $T = 5$ ms
  $\Delta\nu = 100$ Hz
- Fountain :
  $v = 4$ m/s, $T = 0.5$ s
  $\Delta\nu = 1$ Hz
- PHARAO :
  $v = 0.05$ m/s, $T = 5$ s
  $\Delta\nu = 0.1$ Hz

TESTS OF PHARAO WITH PARABOLIC FIIGHTS



ACCURACY OF THE ATOMIC TIME
RELATIVE ACCURACY
YEAR
1x10-9
1x10-10
1x10-11
1x10-12
1x10-13
1x10-14
10-15
1x10-16
10-17
1950
1960
1970
1980
1990
2000
2010
Microwave clocks
Slope: gain of 10 every 10 years
Optical clocks
Ca PTB
H MPQ
NIST: Hg+
NPL
NBS
LSRH
PTB
NRC
NBS
VNIIFTRI
PTB
NIST
LPTF
ACES
Cold atoms

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

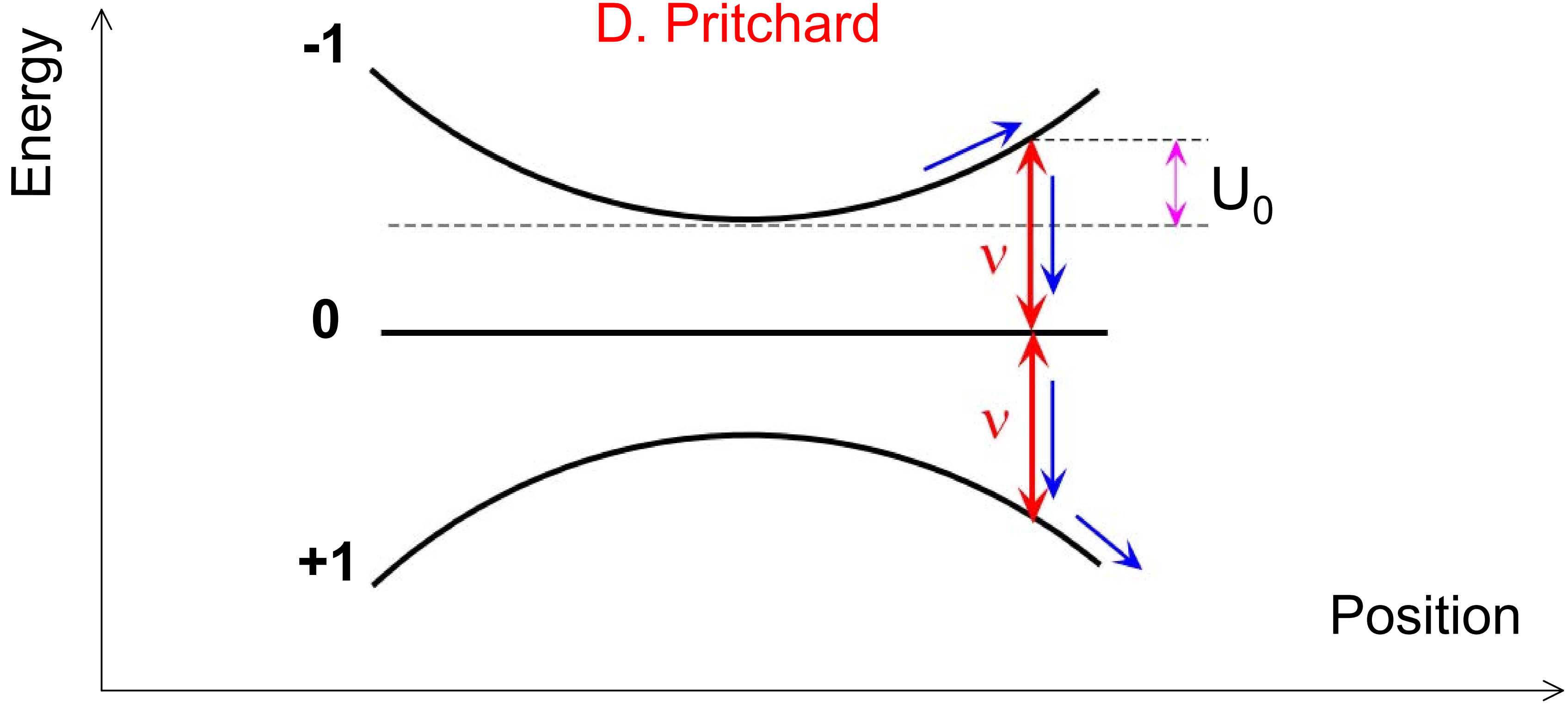
$$E_1 + E_2 = E_3 + E_4$$

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 rethermalisation of the atoms remaining trapped, the temperature of the sample decreases

RF Evaporation

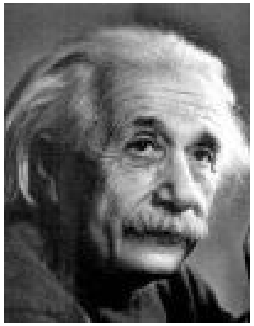
D. Pritchard



Decreasing the potential depth U_0 when the temperature decreases in order to maintain an efficient evaporation

The atom is transferred to an untrapped state with a RF field which is resonant when the energy of the atom reaches the value U_0

Bose-Einstein condensation



Bose-Einstein condensation (BEC)

At low enough temperatures and high enough densities, the de Broglie wavelength of the atoms becomes larger than the mean distance between atoms

Identical bosons in a trap are then predicted to condense in the ground state of the trap.
Macroscopic number of atoms in the same quantum state.
Macroscopic matter waves

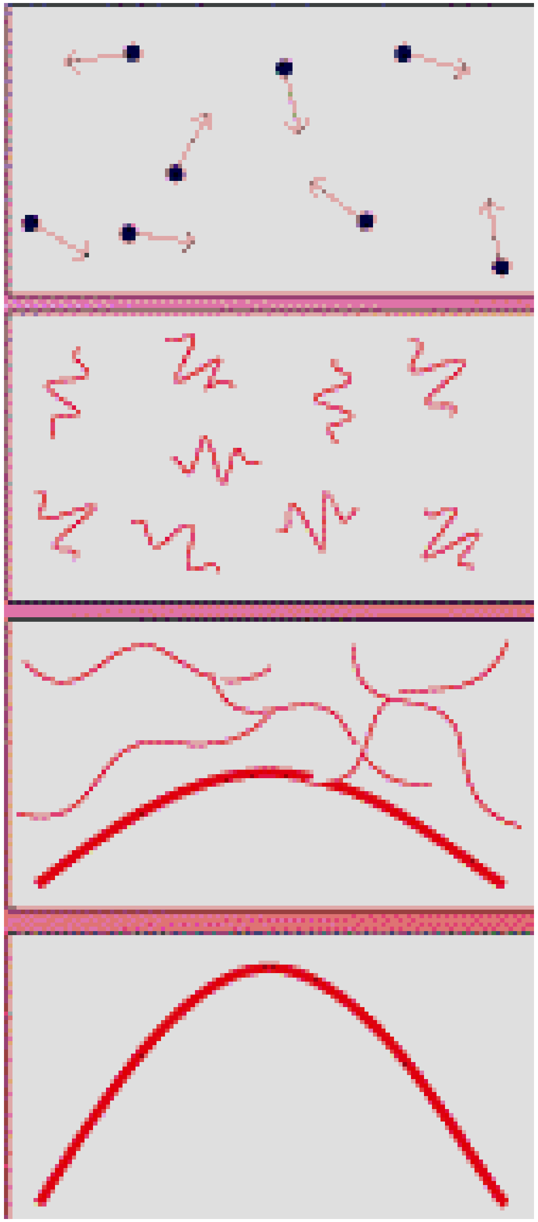
Combination of laser cooling and trapping with previously developed methods for studying spin-polarized Hydrogen (magnetic trapping, evaporative cooling) have led to the observation of BEC in alkali gases.

Boulder, MIT, Houston (1995)

Recent observation of BEC in Hydrogen (MIT, 1998) and in metastable Helium (Orsay, ENS, 2001)

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



$T >> T_C$

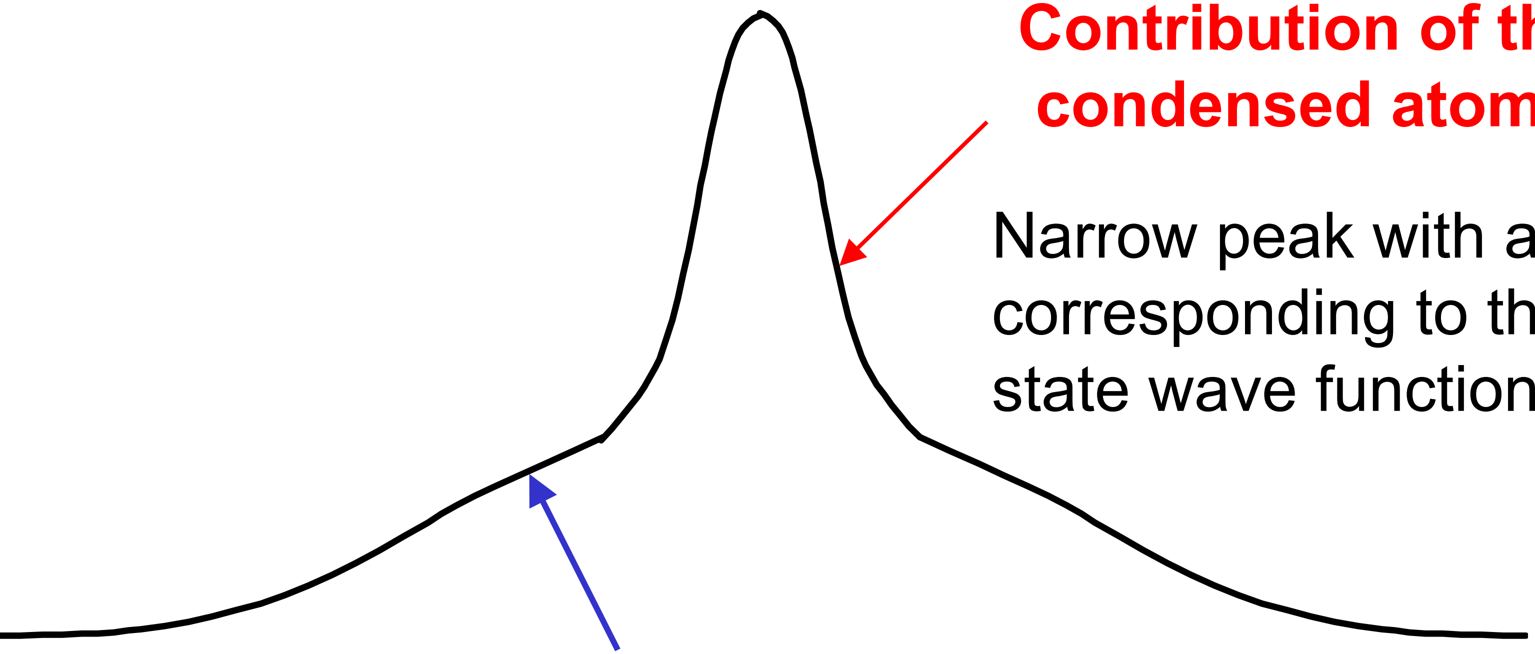
$T > T_C$

$T \sim T_C$

$T < T_C$

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 piedestal coming from atoms occupying excited states ot the well described by wave functions with a larger width

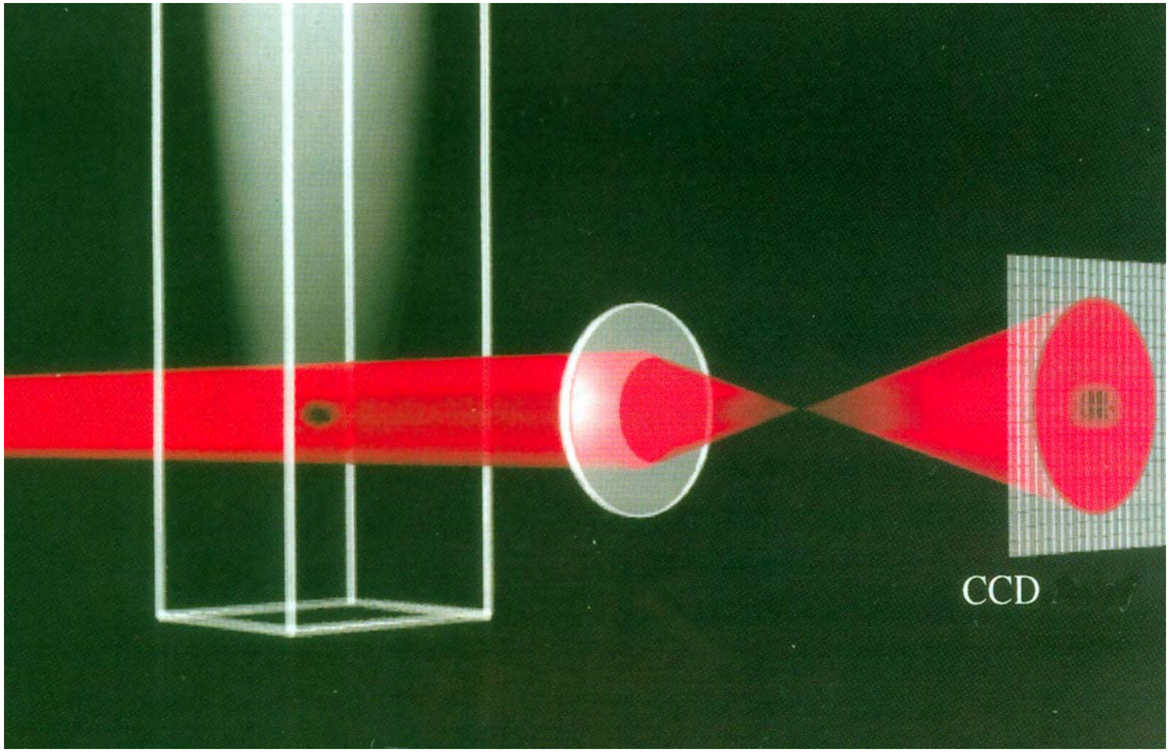
Different steps of the experiment

- Laser cooling and trapping of atoms coming from an atomic beam or from a vapour cell

  T = a few μK $N = 10^7$ to 10^8 atoms

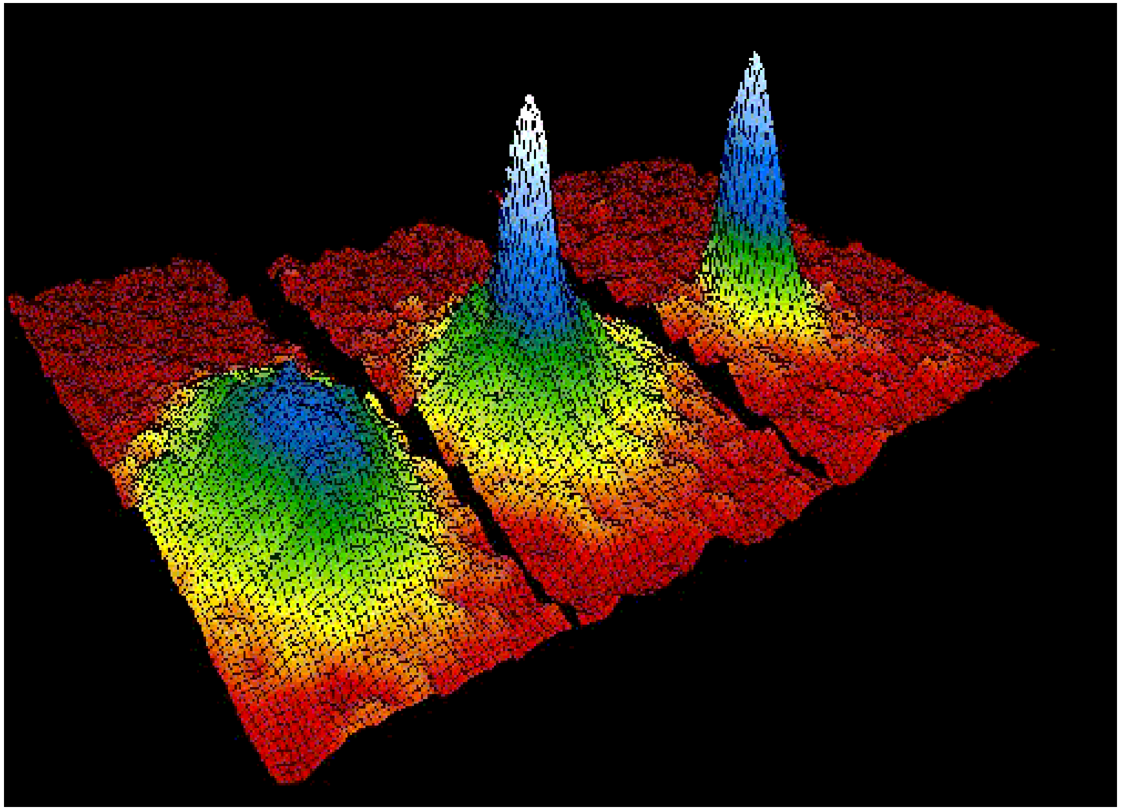
- The laser beams are switched off. A magnetic trap is switched on and the trap is compressed in order to increase the density and the elastic collision rate
- Evaporation with a ramp of radiofrequency field.The temperature decreases and the phase space density increases until the condensation threshold is reached.
- Switching off of the trap and optical detection of the cloud after a phase of balistic expansion (in order to increase the size of the cloud and to get images not limited by diffraction).

Visualization of the atomic cloud



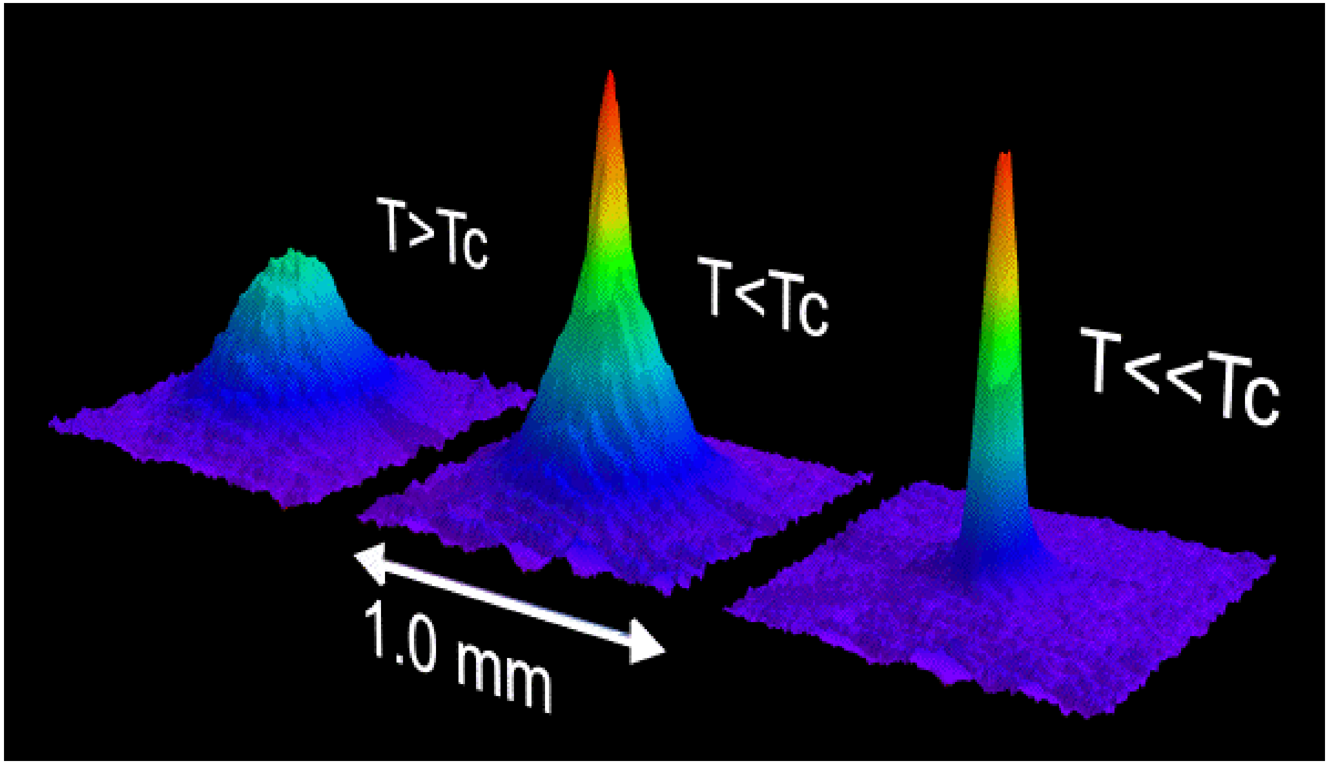
Spatial dependence of the absorption of a laser beam by the cloud

Bose-Einstein condensation of Rubidium 87
JILA - Boulder



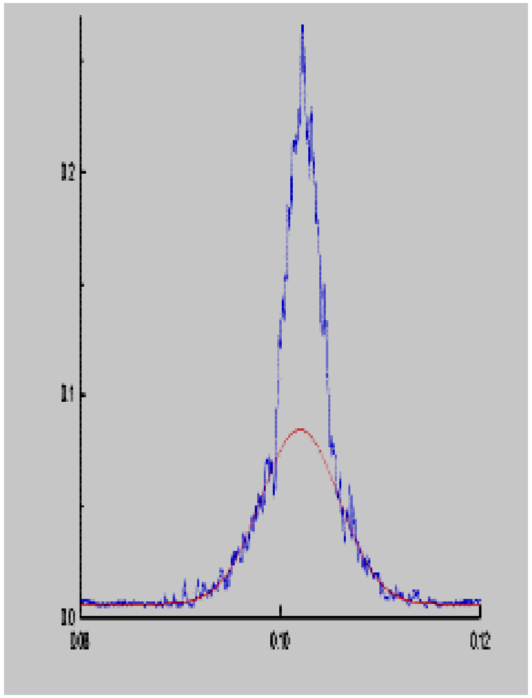
Science, 269, 198 (1995)

Bose-Einstein condensation of Sodium
MIT



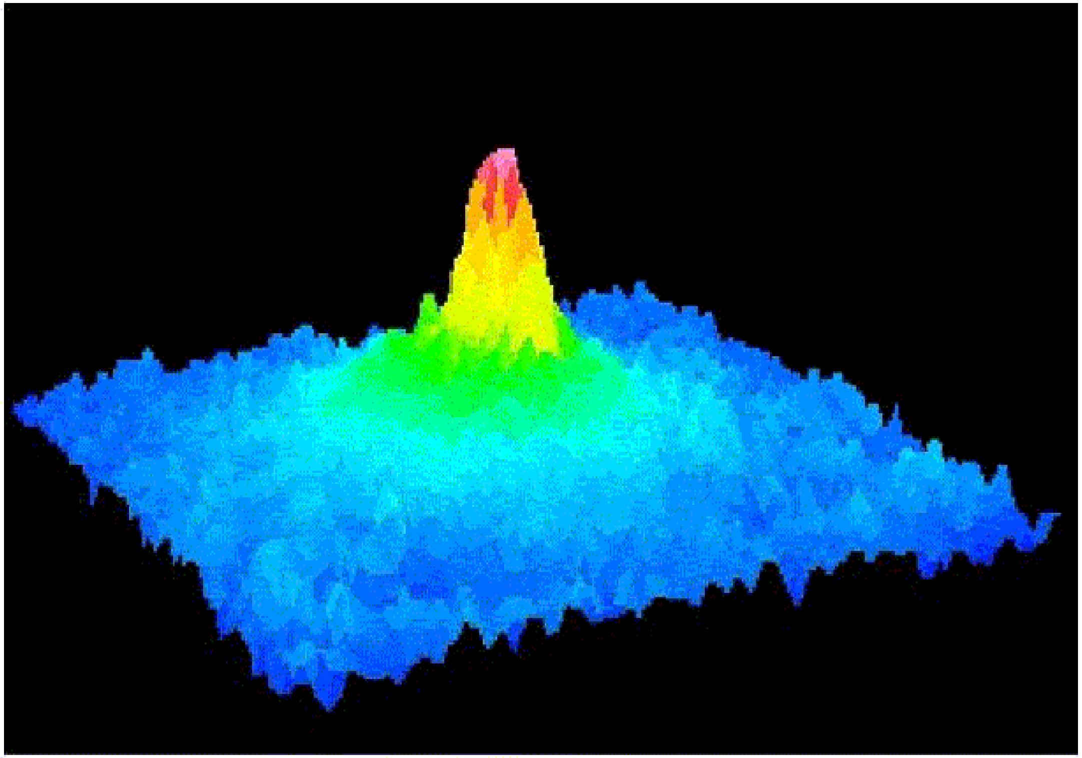
Phys. Rev. Lett. 75, 3969 (1995)

Bose-Einstein condensation of metastable helium
IOTA - Orsay



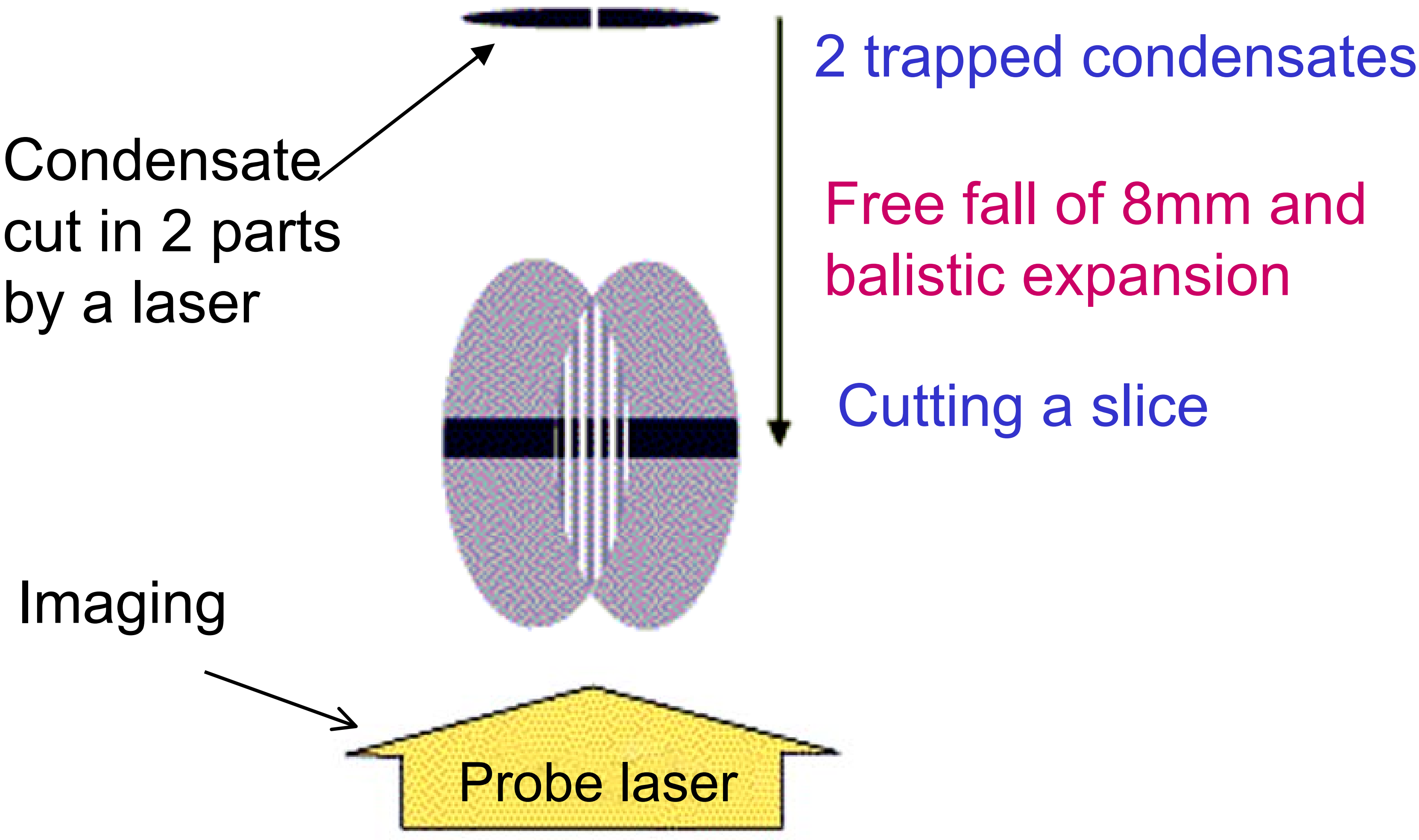
A. Robert, O. Sirjean, A. Browaeys, J. Poupard, S. Nowak, D. Boiron, C. Westbrook, A. Aspect, Science, <u>292</u>, 461 (2001)

Bose-Einstein condensation of metastable helium
ENS -Paris



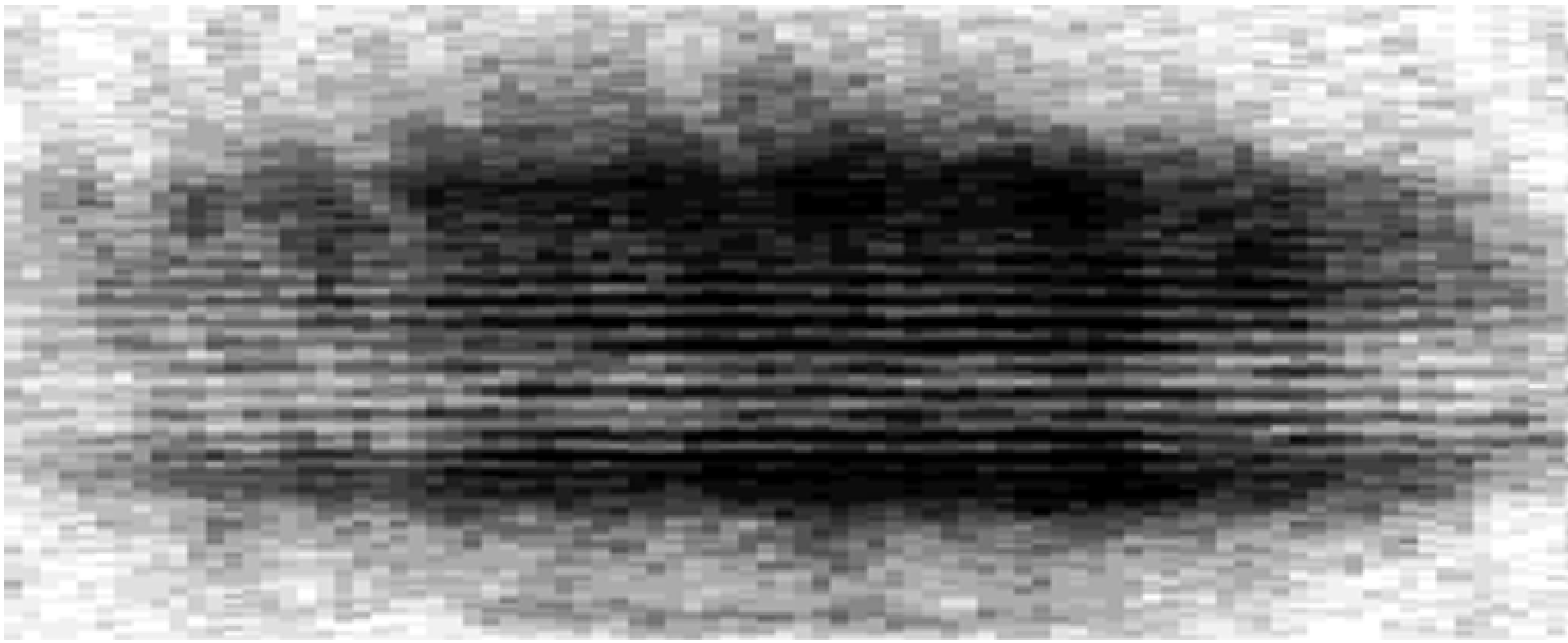
F. Pereira Dos Santos, J. Léonard, J. Wang, C. Barrelet,
F. Perales, E. Rasel, C. Unnikrishnan, M. Leduc,
C. Cohen-Tannoudji, Phys. Rev. Lett. 86, 3459 (2001)

Interferences between 2 condensates
Principle of the M.I.T. experiment



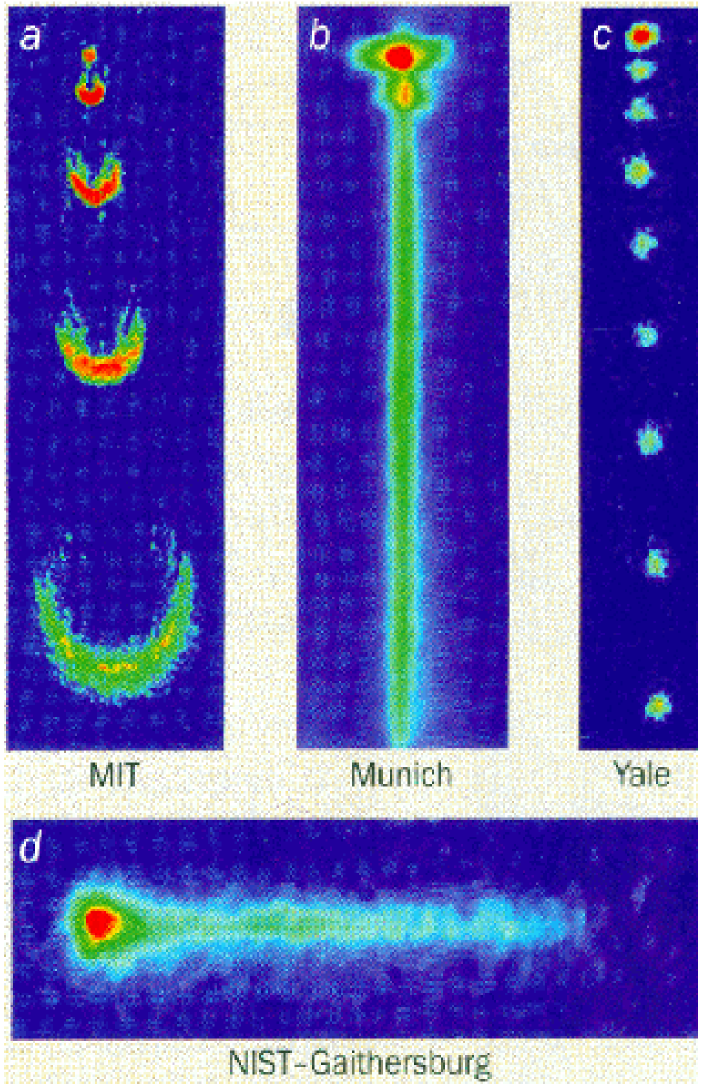
M.R.Andrews, C.G.Townsend, H.-J. Miesner, D.S. Durfee, D.M.Kurn, W.Ketterle, Science, 31 Janvier 1997

Observed interference fringes

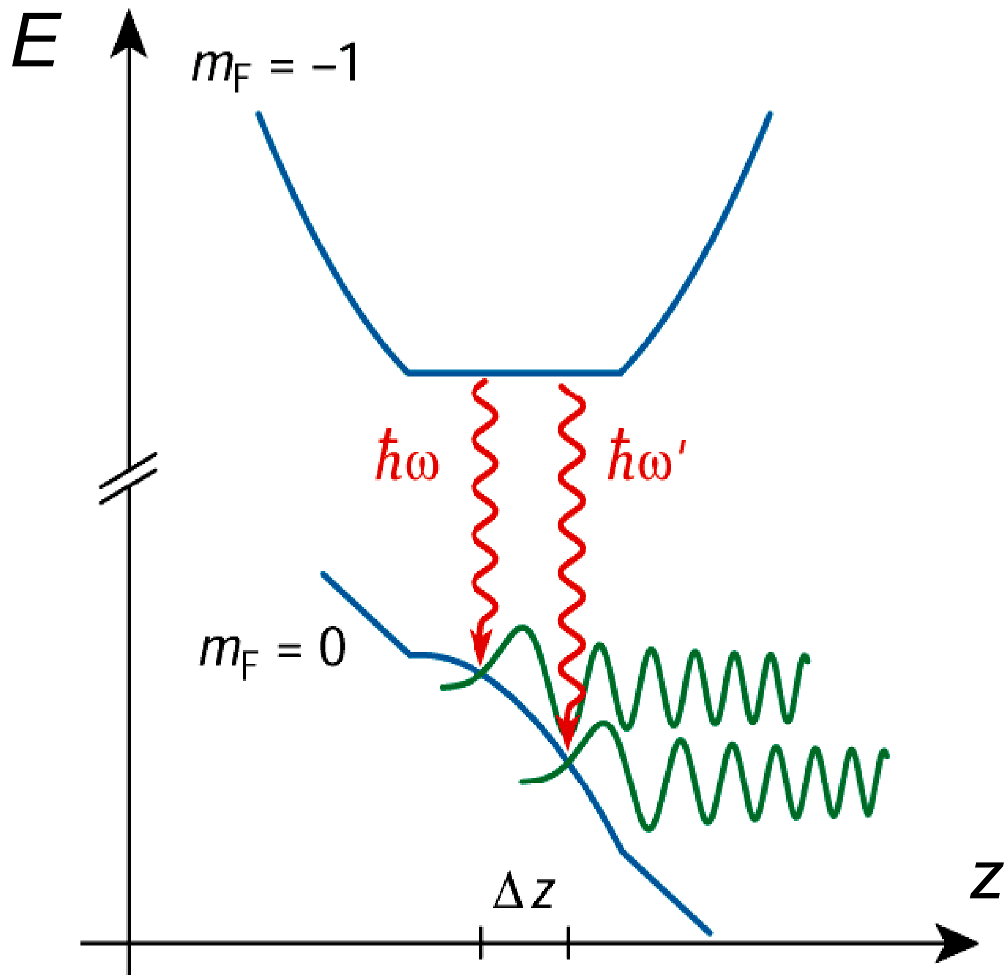


M.R.Andrews, C.G.Townsend, H.-J. Miesner, D.S. Durfee,
D.M.Kurn, W.Ketterle, Science, 31 Janvier 1997

Exemples of atom lasers



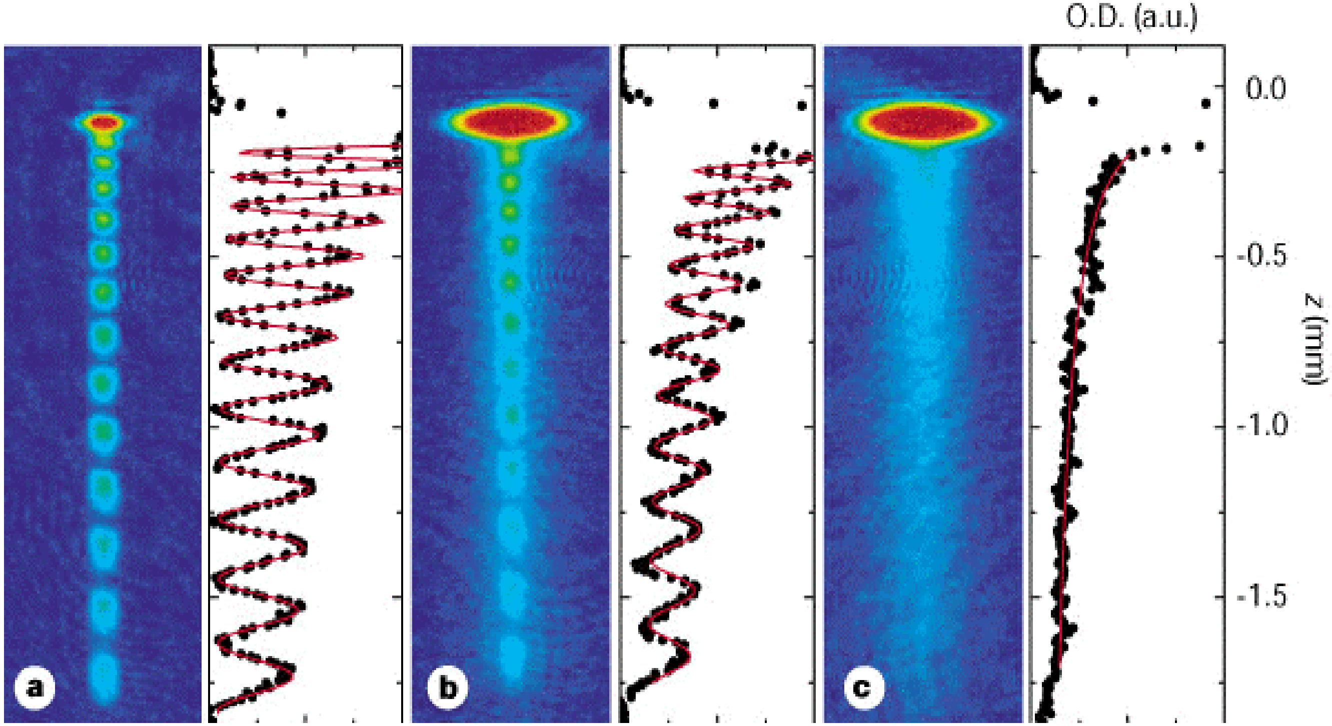
Extraction of 2 matter waves from a Bose-Einstein condensate



I. Bloch, T.W. Hänsch, T. Esslinger
Nature, 403, 166 (2000)

Interférences between 2 matter waves extracted from a Bose-Einstein condensate

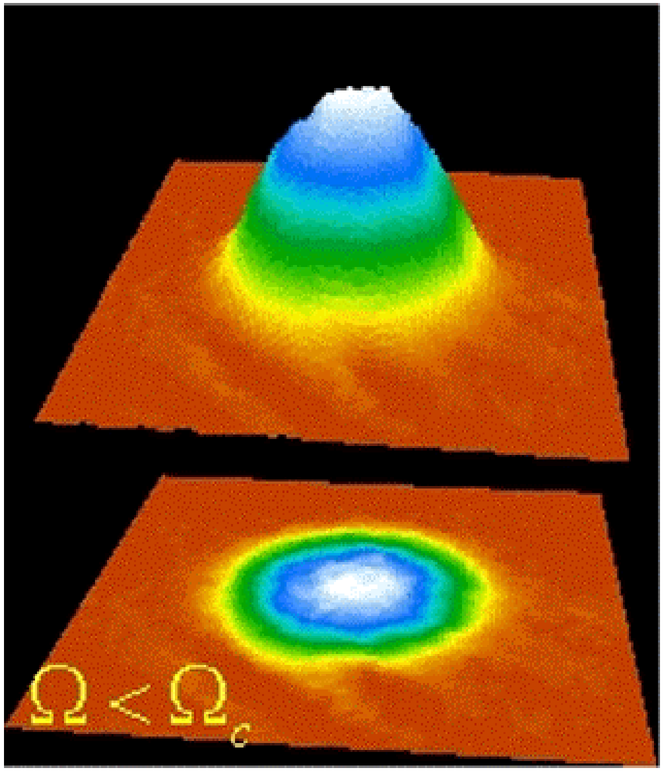
$T < T_C$ $T \approx T_C$ $T > T_C$

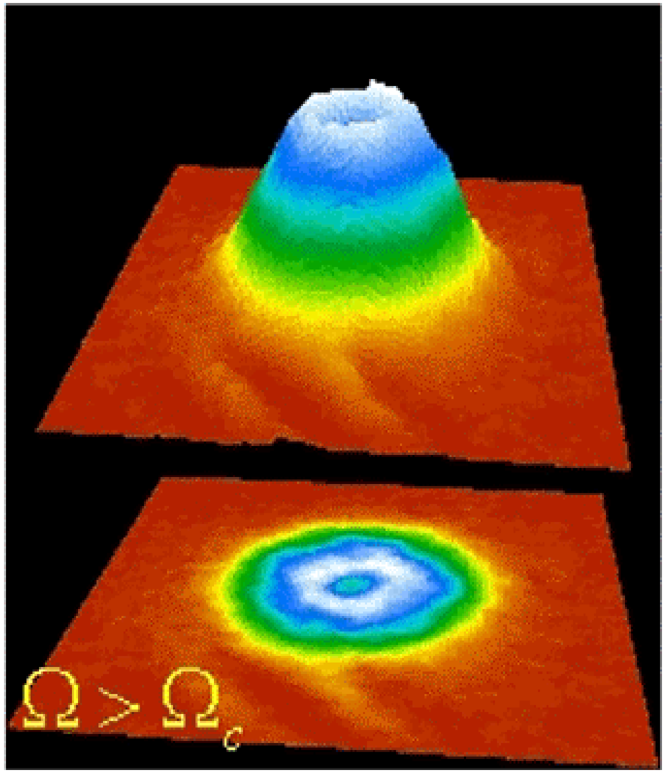


I. Bloch, T.W. Hänsch, T. Esslinger
Nature, 403, 166 (2000)

Quantized vortex in a condensate of Rubidium 87

ENS – Paris

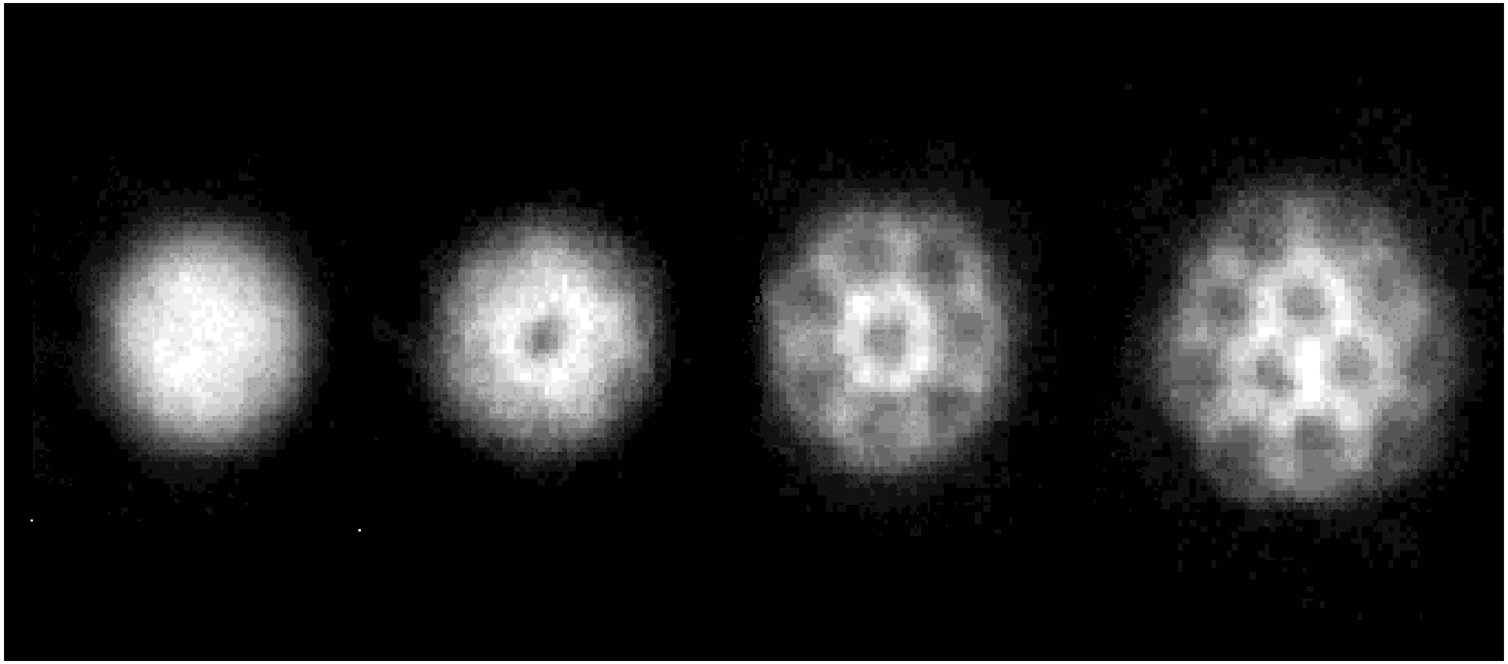




K.W. Madison, F. Chevy, W. Wohlleben, J. Dalibard
Phys. Rev. Lett. 84, 806 (2000)

Lattice of vortices in a condensate of Rubidium 87

ENS – Paris



K.W. Madison, F. Chevy, W. Wohlleben, J. Dalibard
Phys. Rev. Lett. 84, 806 (2000)

Mixture of Lithium isotopes
Bosons with Fermions

F. Schreck
L. Khaykovich

K.L. Corwin
G. Ferrari
C. Salomon

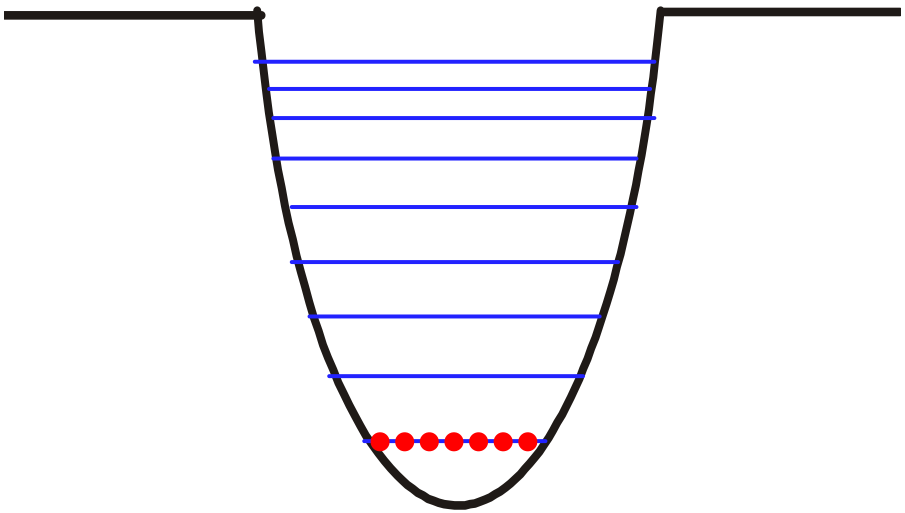
T. Bourdel
J. Cubizolles

E.NS. Paris

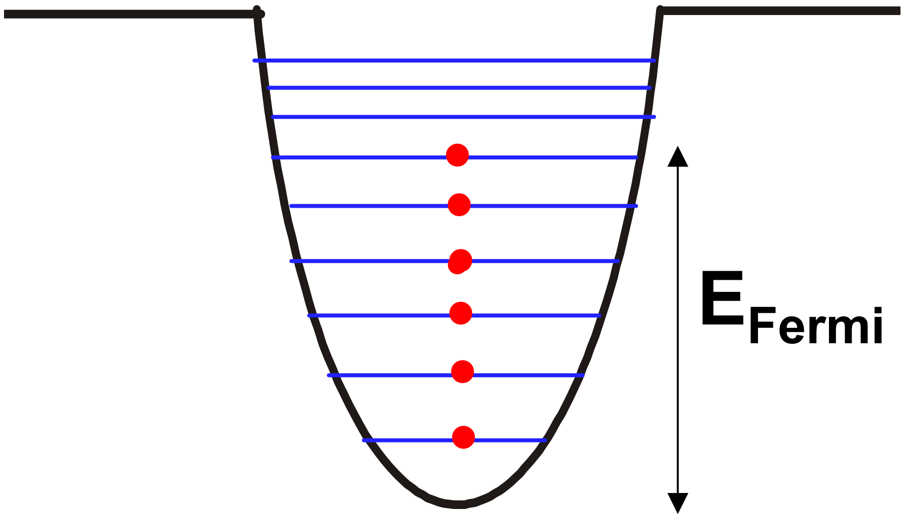
- Mixture of ^{7}Li (bosons) and ^{6}Li (fermions) in a magnetic trap
- ^{6}Li atoms are cooled sympathetically by ^{7}Li
- Coexistence of two quantum degenerate gases

See also groups of D. Jin, NIST, Colorado
R. Hulet, Rice University, Houston
W. Ketterle, MIT

Bosons versus Fermions at very low T



Bosons



Fermions

Critical temperature T_C for BEC

$$k_B T_C = \hbar\omega\left(0.83\,N\right)^{1/3}$$

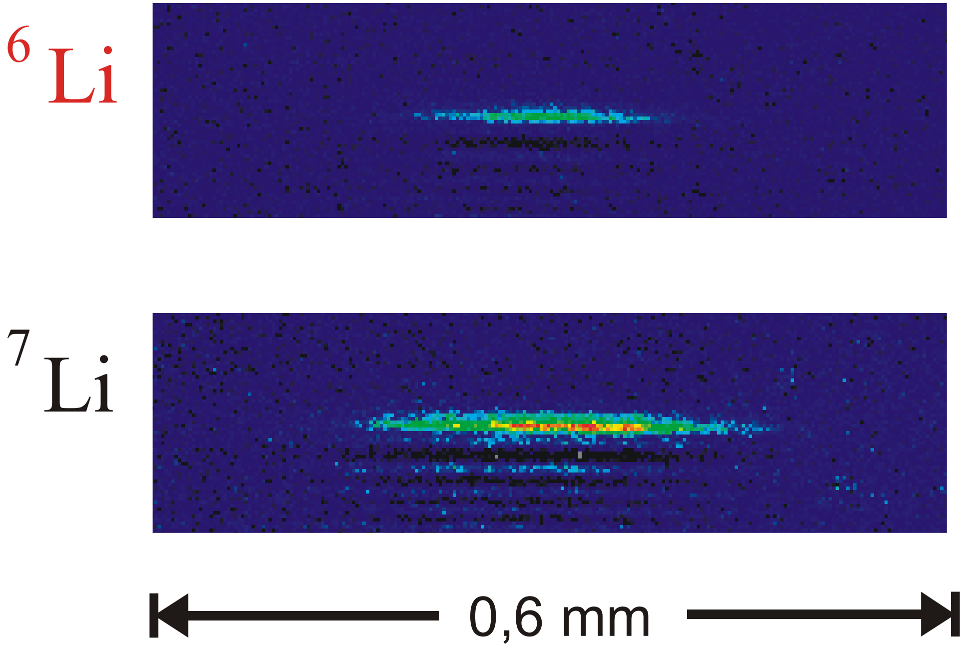
Fermi temperature T_F

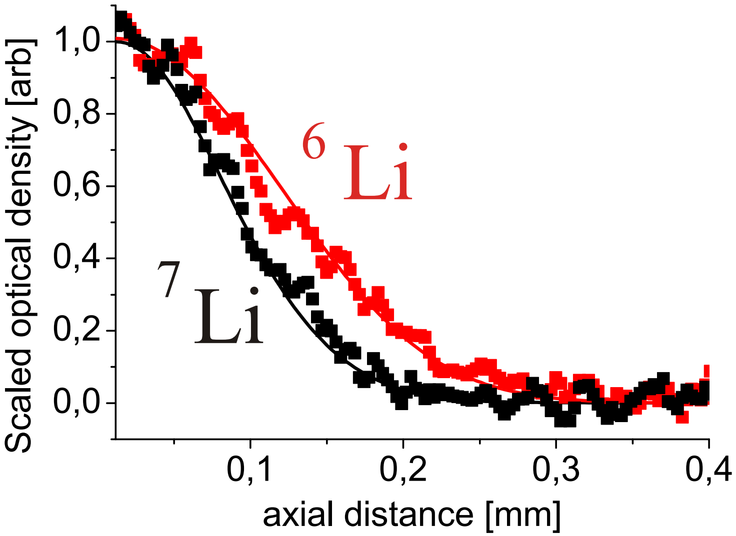
$$k_B T_F = E_{\mathrm{Fermi}} = \hbar\omega\left(6\,N\right)^{1/3}$$

- **Bosons condense in the ground state**
- **Each state is occupied by a single Fermion**

Fermi degeneracy is achieved when $T \leq T_F$

Fermi pressure



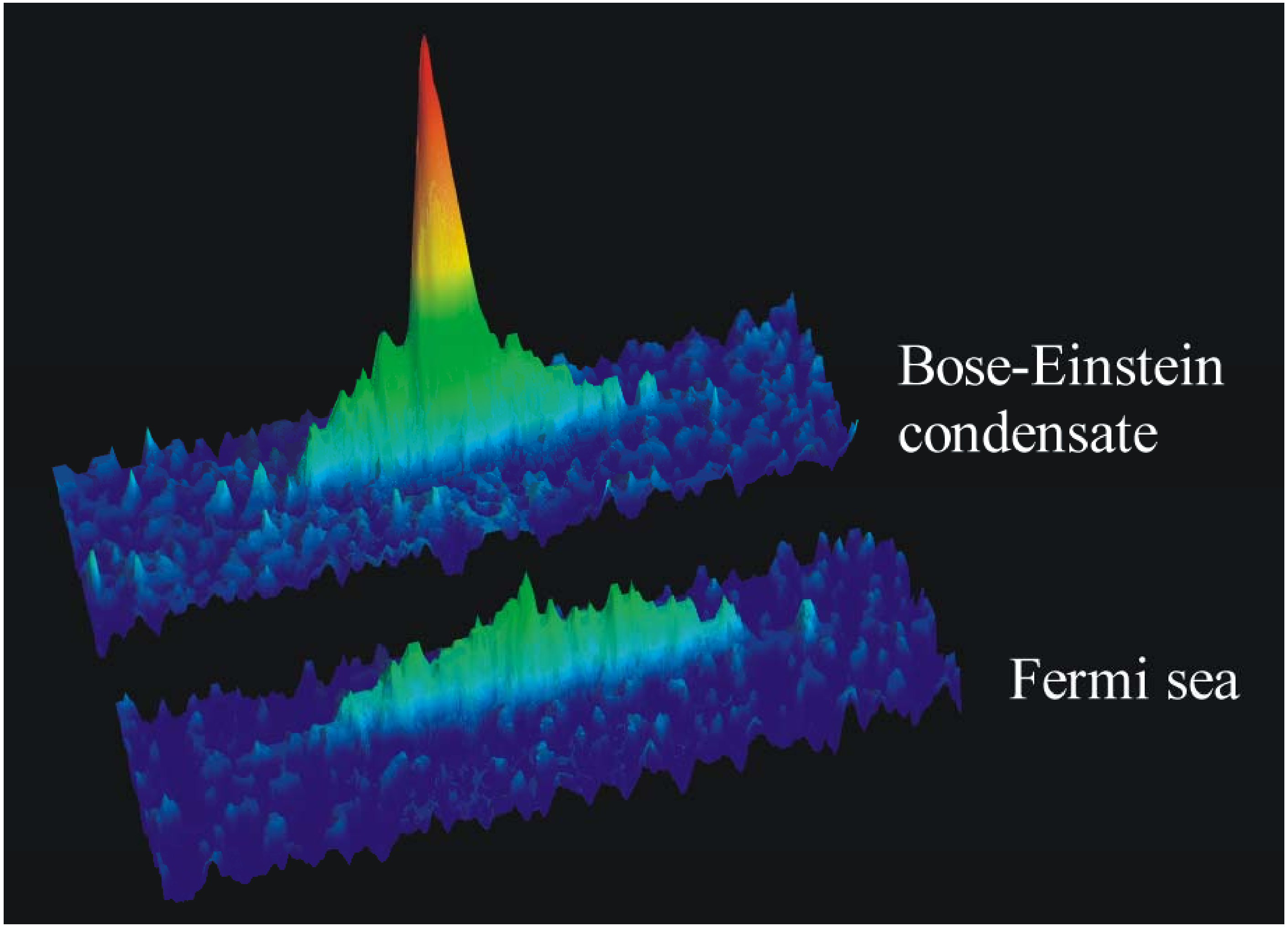


2.7 10^4 bosons at T = 0.97 µK

8.1 10^4 fermions with T_F = 4.38 µK

$\Rightarrow$ $T/T_F = 0.22$

BEC of ^{7}Li in a Fermi sea of ^{6}Li



F. Schreck, L. Khaykovich, K.L. Corwin, G. Ferrari, T. Bourdel, J. Cubizolles, and C. Salomon, Phys. Rev. Lett. 87, 080403 (2001)

A few perspectives

Fermi degenerate gases with ultracold atoms

Pairing of fermionic atoms?

BCS with atoms?

Nonlinear atom optics

Microcondensates on microchips

Cavity quantum electrodynamics

Quantum information

Entangled states

Quantum cryptography

Teleportation