LECTURE 2

BEC - reminder
Laser cooling techniques
Atomic BEC - few most remarkable results

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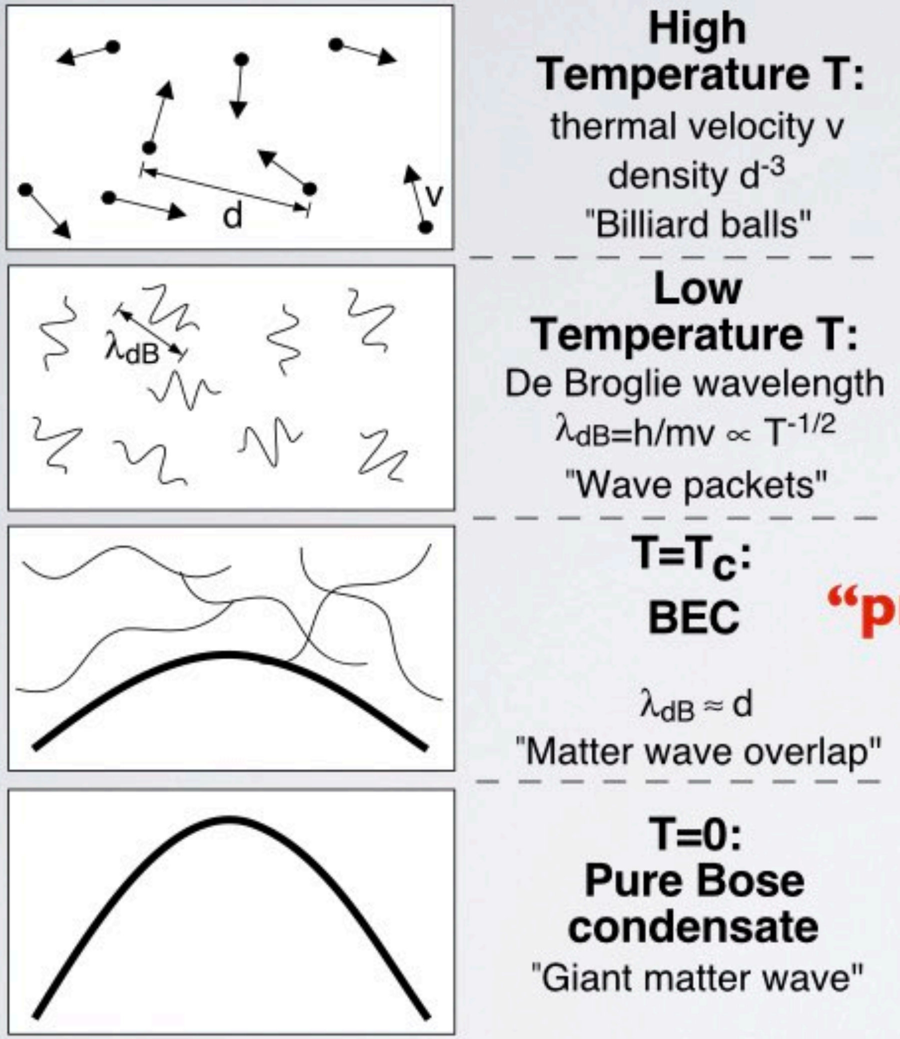
CONDENSATE (scheme)



Wysoka temperatura:
"kule bilardowe"

Niska temperatura:
"paczka falowa"

Temperatura krytyczna:
"przekrywanie się paczek falowych"
"zupa kwantowa" nierozróżnialnych cząstek

Zero bezwzględne:
"makroskopowa fala materii"

źródło: WHEN ATOMS BEHAVE AS WAVES: BOSE-EINSTEIN CONDENSATION AND THE ATOM LASER
W. Ketterle, Nobel Lecture, December 8, 2001

PHASE TRANSITION

CLASSICAL GAS $\xrightarrow{\textit{PHASE TRANSITION}}$ CONDENSATE

TEMPERATURE ↗

OR

DENSITY ↗

1ST ORDER PHASE TRANSITIONS

solid
liquid
gas

↑

discontinuity of the density

The existence of discontinuity (jump) the first derivative of the free energy (with respect to some thermodynamic variable)

The existence of discontinuity (jump) of the first derivative of the chemical potential with respect to the temperature

We supply heat - the temperature does not change until the phase change in the entire volume

2ND ORDER PHASE TRANSITIONS

„continuous phase transitions"

The first derivative of the specific heat is continuous.

- there is no latent heat of transition for any volume of the medium
- there is no energy barrier between the phases
- phases coexist and quite smoothly, without any excess of energy, pass one another

Discontinuity (jump) of the next derivative of the chemical potential with respect to the temperature

macroscopic fluctuations of the order parameter near the phase transition !!!

&

the appearance of long range order

CONDENSATE

Single particle wave-function satisfies the Gross-Pitaevskii time-dependent equation:

$$i\hbar \frac{\partial \psi(\vec{r},t)}{\partial t} = \left(-\frac{\hbar^2 \nabla^2}{2m} + V_{ext}(r) + g\,n\right)\psi(\vec{r},t)$$

$$n = \left|\psi(\vec{r},t)\right|^2$$

The condensate wave-function:

$$\psi(\vec{r},t) = \sqrt{n(\vec{r},t)}\, e^{i\theta(\vec{r},t)}$$

FEW FACTS

1. Typically 1 cm^3 contains 10^{22} molecules.
2. Molecules are in motion. Av. speed 570 m/s.
3. They collide billions of times. Phenomena: sound, pressure
4. Statistical description of the system.
5. Low temperature - possibility to find all particles in a quantum state, single and of the lowest energy.
6. Diluted gas limit (to avoid three-body collisions and allow only for elastic collisions). 10^{14}-10^{15} atoms/cm^3
7. B-E condensation.

MACROSCOPIC QUANTUM BEHAVIOR

phenomena

- Superconductivity
- Superfluidity
- Laser light
- BEC of atoms

MOST REMARKABLE EXAMPLE

Soon after the discovery of Einstein

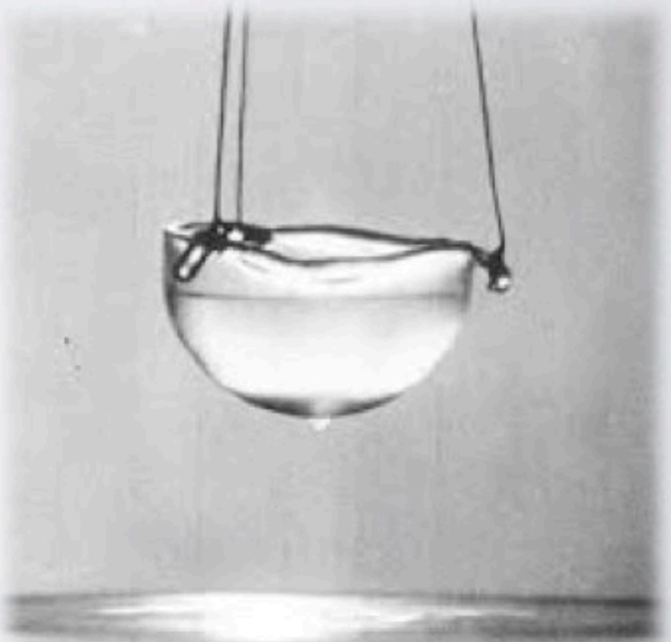
First example was helium $^{4}\mathbf{He}$ (further on ^{3}He)

Fritz London (1938) & Laszlo Tisza (1938)

- Becomes superfluid below the lambda point 2.2K
- ^{4}He contains two electrons, two protons and two neutrons - it is boson (total spin zero)
- BEC as a possible mechanism underlying superfluidity (Landau did not share this opinion)
- From the critical temperature equation :

$$T_C = \frac{2\pi\hbar^2}{k_B m}\left(\frac{n}{2.612}\right)^{2/3}$$

- Tc = 3.1 K
- strongly interacting system



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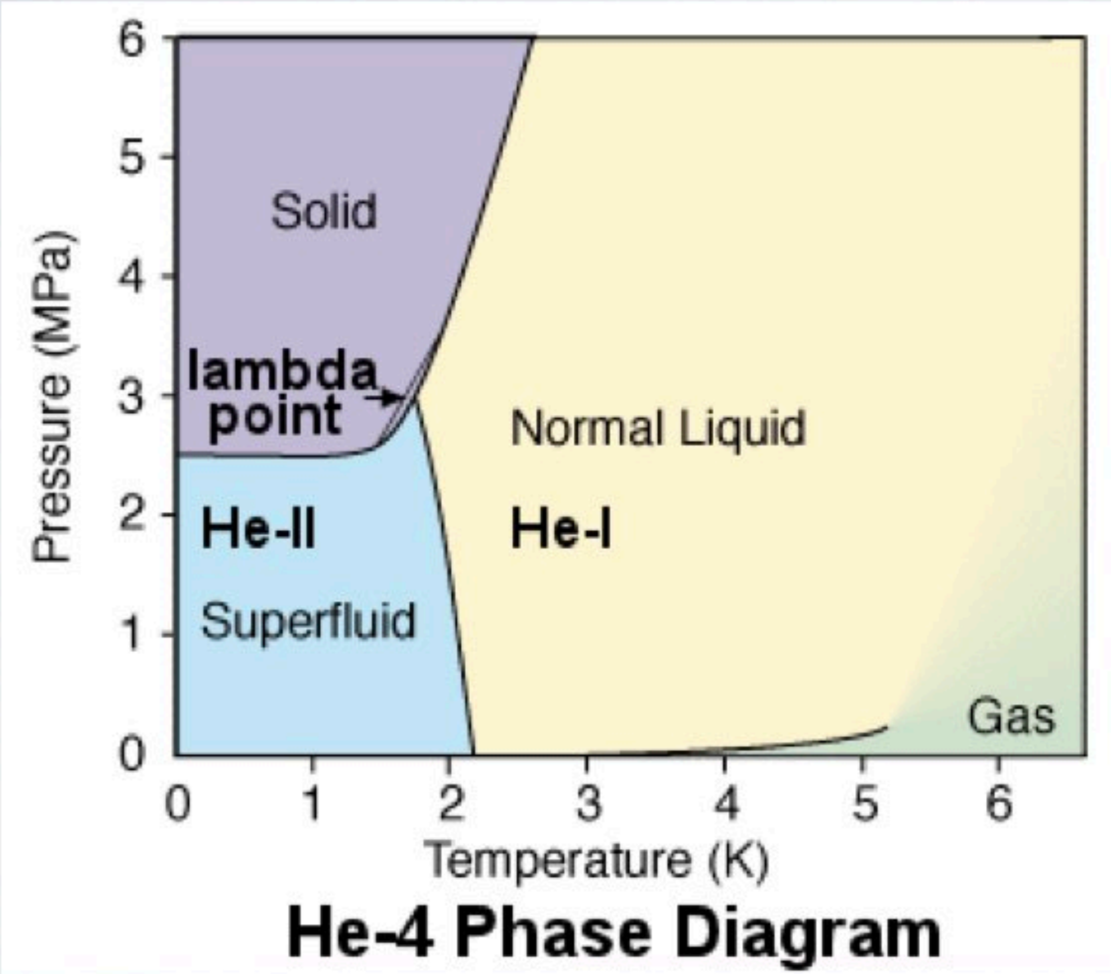

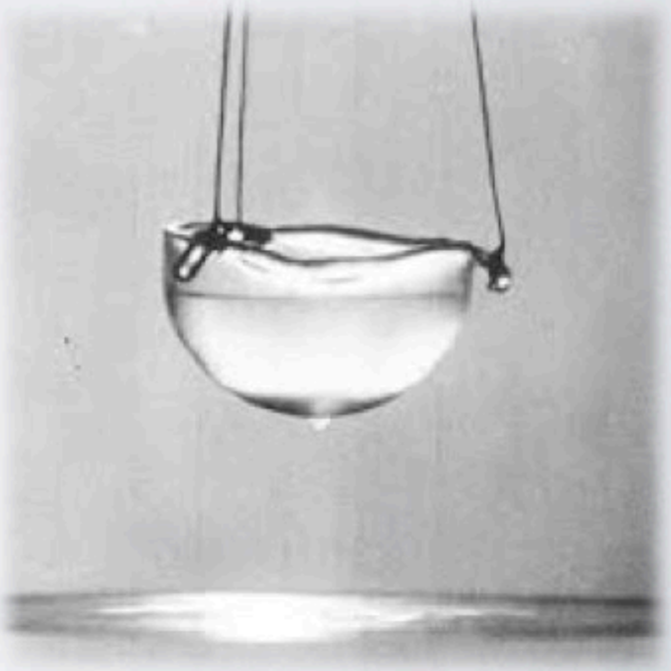

HISTORY of experimental realization

Steven Chu
Claude Cohen-Tannoudji
William D. Philips

Laser cooling techniques :
Nobel Prize 1997

first works on laser cooling at 1985

to reach temperatures as low as 10^{-7}K = 100 nK

HISTORY of experimental realization

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Laser cooling techniques :
Nobel Prize 1997

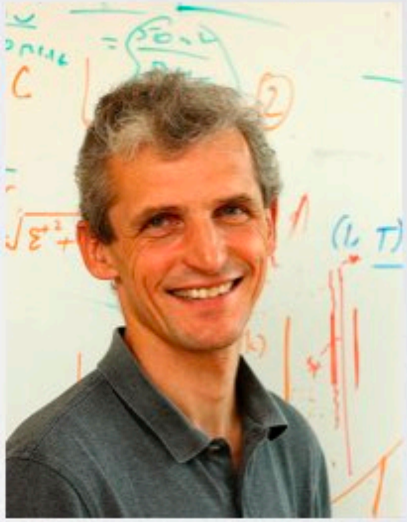
70 years after works of Bose & Einstein... 1995

Carl Wieman
Eric Cornell
University of Colorado at Boulder NIST-JILA

Rubidium atom gas
cooled to 170nK !!!

4 months later 1995

Sodium atom gaz
(100 times more atoms)



Wolfgang Ketterle
Massachusetts Institute of Technology

Nober Prize 2001

LASER COOLING TECHNIQUES

- Radiative forces acting on atoms:
  - are velocity dependent (radiation pressure, Doppler cooling, optical molasses)
  - can be position dependent (magneto-optical trap)

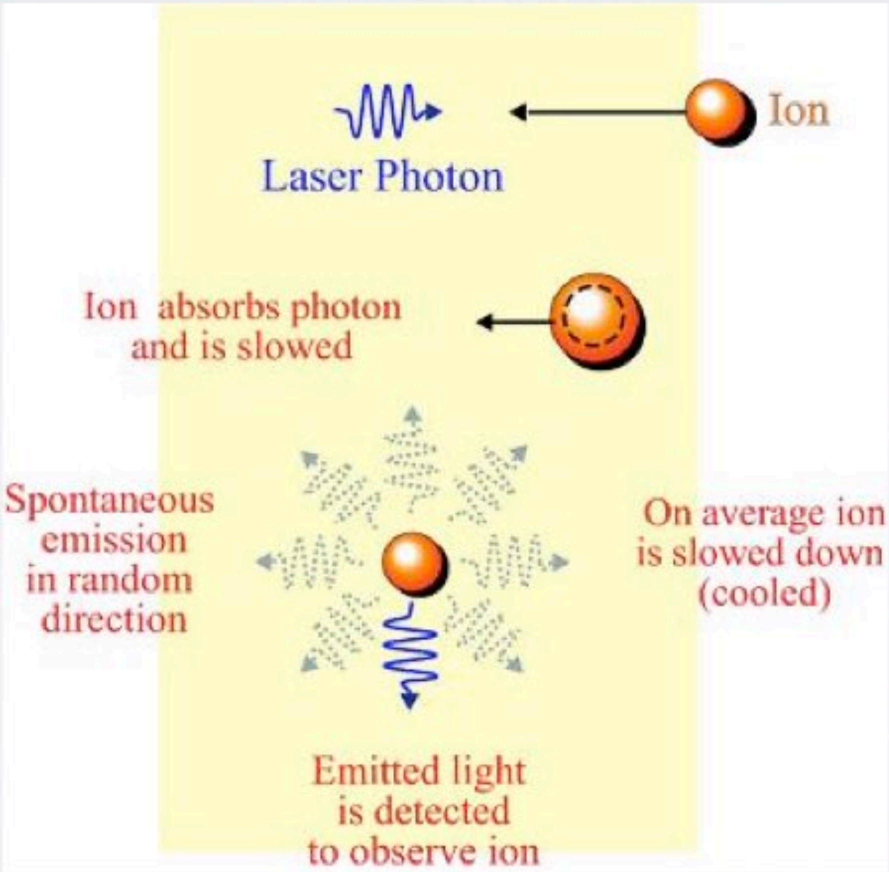
- Effect of light on the atomic **external** state (center of mass motion)

- Effect of light on the atomic **internal** state (electronic motion relative to nucleus)

LASER COOLING TECHNIQUES

1. Doppler coolig

from ~500 K to~100 microK
N ~ 10^9
further on random emission and absorption processes



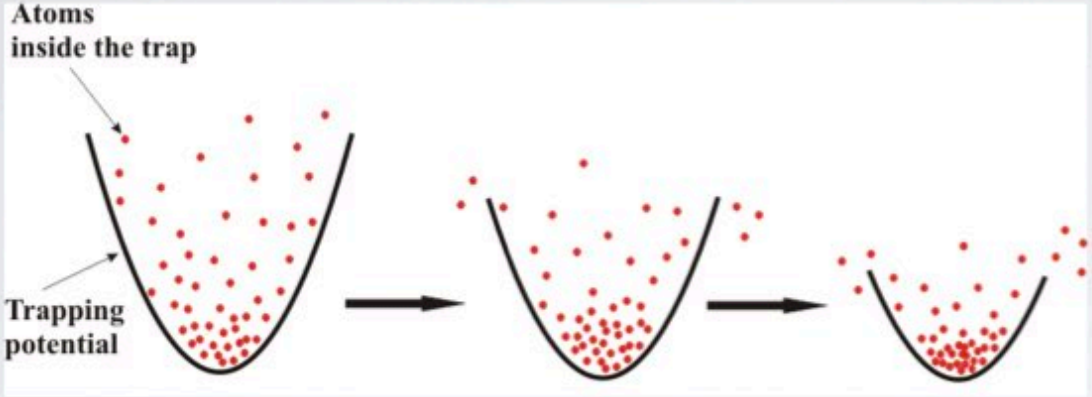
http://publish.ucc.ie/boolean/2011/00/Russell/42/en

LASER COOLING TECHNIQUES

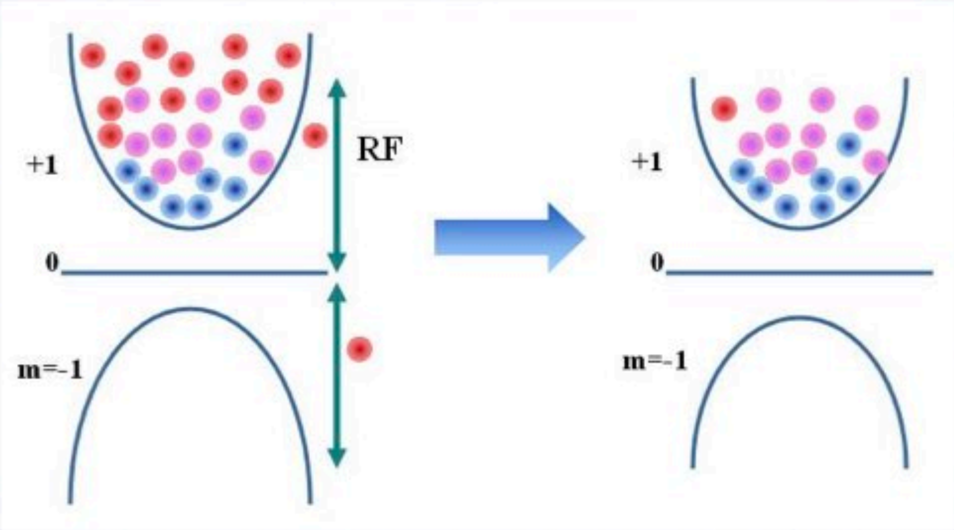
2. Evaporative cooling

rate of elastic collisions > inelastic collisions

from ~100 microK to ~100nK
N ~ 10^7



Radio-frequency cooling:



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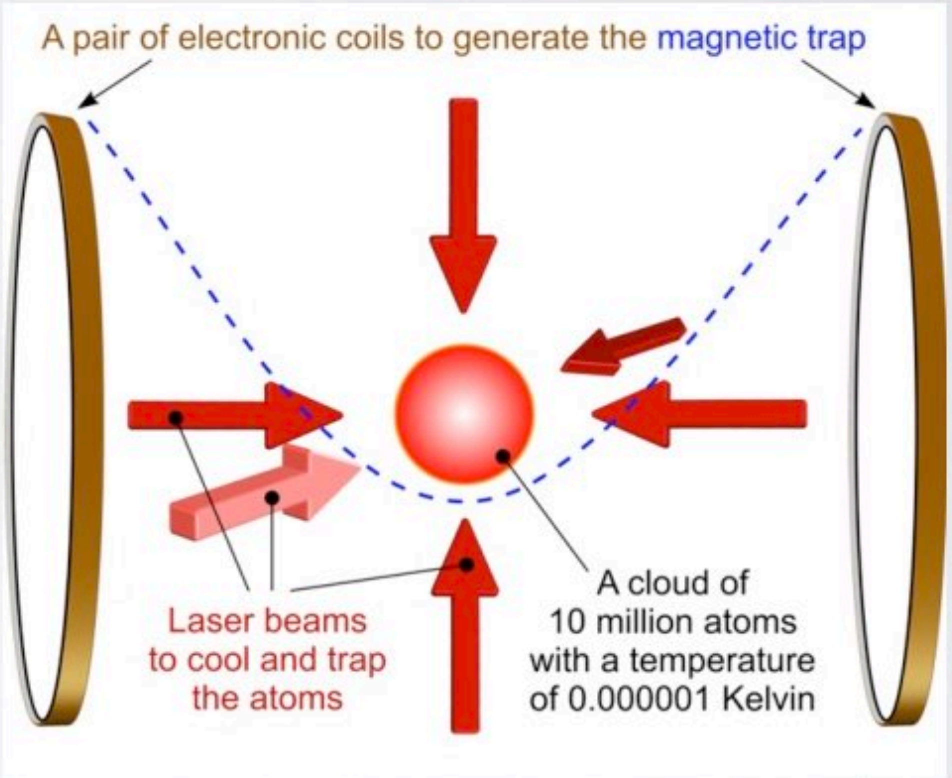
LASER COOLING TECHNIQUES

2. Optical trap - **light shift**

3. Magneto-optical trap
MOT

The six laser beams cool the atoms and push them to the intersection point while the magnetic trap (generated with a pair of electronic coils) confines the atoms.



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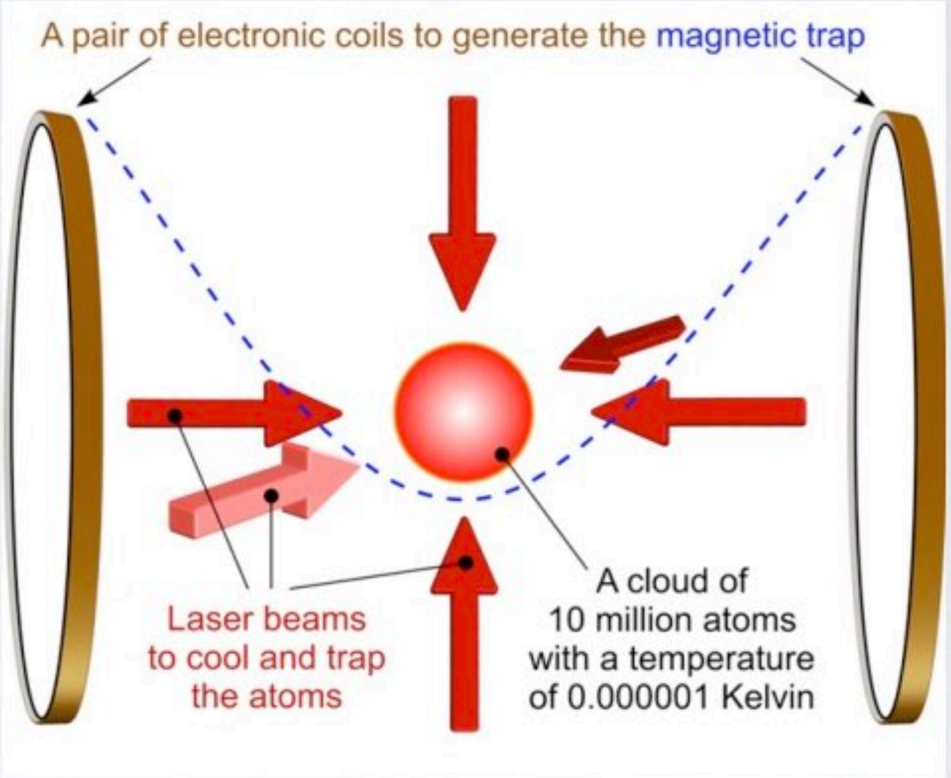

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LASER COOLING TECHNIQUES

2. Evaporative cooling - advances in magnetic trap

Atom on a chip

Observation:
Trapping forces are proportional to the magnetic field gradient

Realization:
Microchip created lithographically

Purpose:
Wave-guides and beamsplitters of coherent matter in restricted geometry; ultra-sensitive sensors

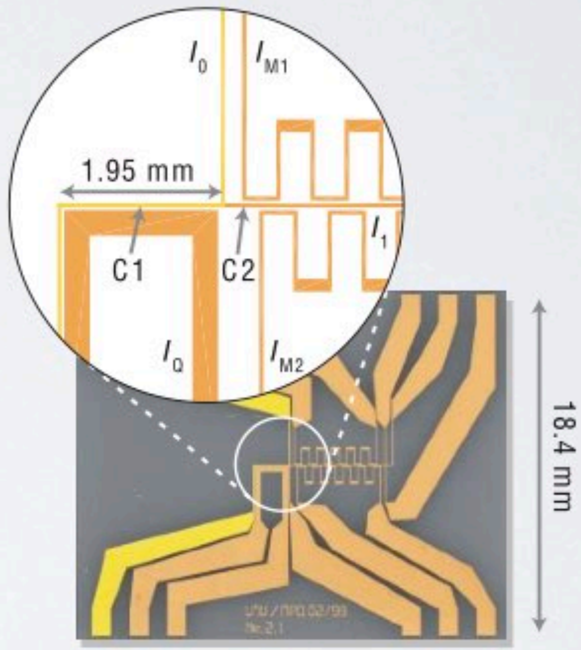


Figure 1 Atom chip. Bose–Einstein condensates (BECs) were created in magnetic traps formed by tiny gold wires that were created lithographically on a substrate[16,17]. The figure shows the pattern used by researchers at the Ludwig-Maximilians University in Munich[17]. Atoms were trapped at positions C1 and C2.

Bose - Einstein condensation of atomic gases
J. R. Anglin, W. Ketterle, Nature **416**, 211 (2002)

Bose Einstein Condensate Coldest Place in the Universe

A short video explaining how a Bose-Einstein Condensate of sodium atoms is created in lab at MIT by Martin Zwierlein. Using highly focused, single frequency .

Documentary on the Bose-Einstein Condensate work done in Wolfgang Ketterle's lab. By Stephen Craft, Lauren Maurer and Fangfei Shen. A production of the .

https://youtu.be/5S3BTgFsT0w

EXPERIMENTAL PROCEDURE

1. Atoms are released from a source.
$N = 10^{10} - 10^{12}$ atoms.

2. Atoms are trapped in a magnetooptical trap. (MOT)

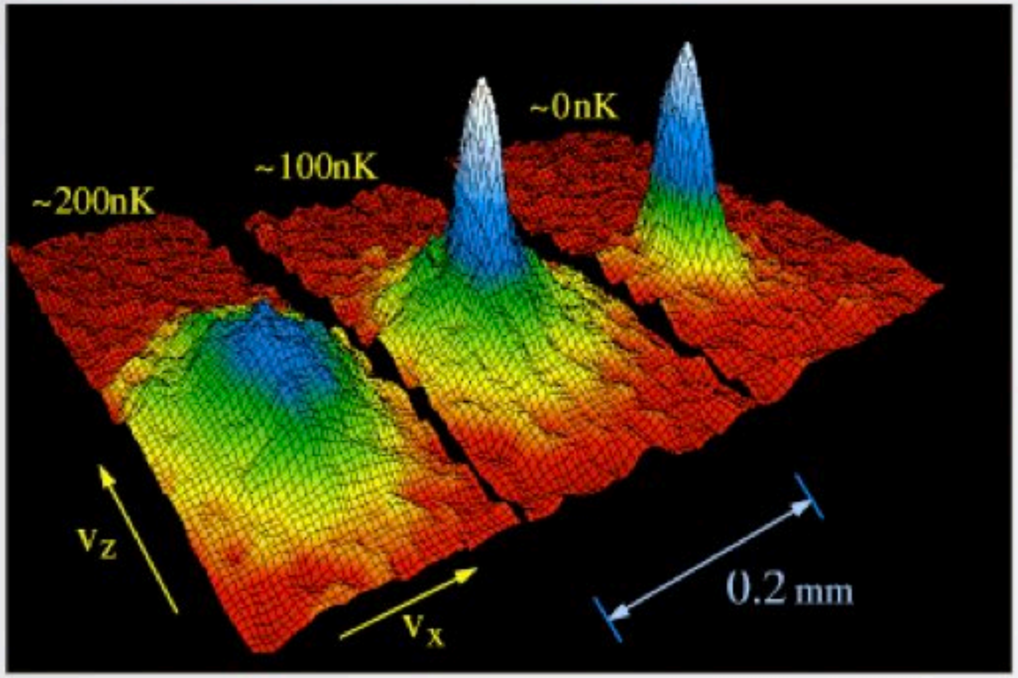
3. Doppler cooling. $N = 10^9$ atoms. $T = 100$ mikroK.

4. Atoms are trapped in a magnetic trap.

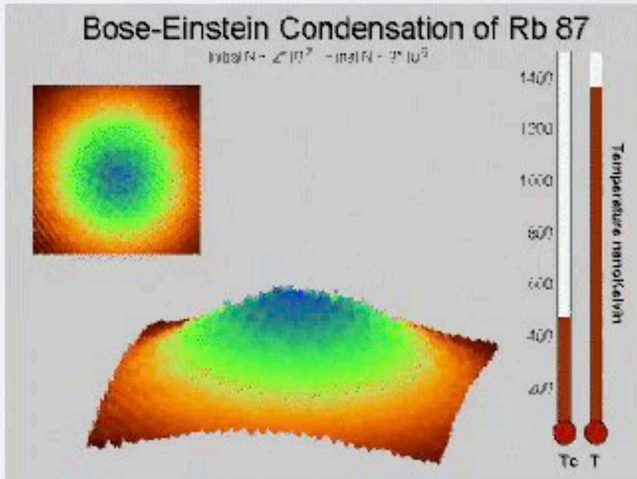
5. Evaporative cooling. $N = 10^7$ atoms. $T = 100$ nanoK.

HISTORY
experimental results

2 D velocity distributions



^{87}Rb



Velocity distribution of gas of Rb atoms.

M. H. Anderson et al., Science **269**, 198 (1995)

E. Cornell et al. JILA, 1995

http://www.colorado.edu/physics/2000/bec/images/evap2.gif