# THERMAL & STATISTICAL PHYSICS
# SSP3133

# BOSE EINSTEIN CONDENSATION

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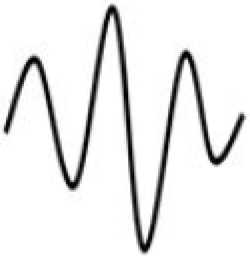
Acknowledgement : PROFESSOR DR RAMLI ABU HASSAN

De Broglie: all matter is composed of waves. Their wavelengths are given by

$$\lambda = \frac{h}{mv}$$



λ = de Broglie wavelength

h = Planck's constant

m = mass

v = velocity

At T~ 300 K : atoms are in many different energy states

At T ~ 0 K: some atoms go to the lowest quantum energy state and becomes **BE condensate**

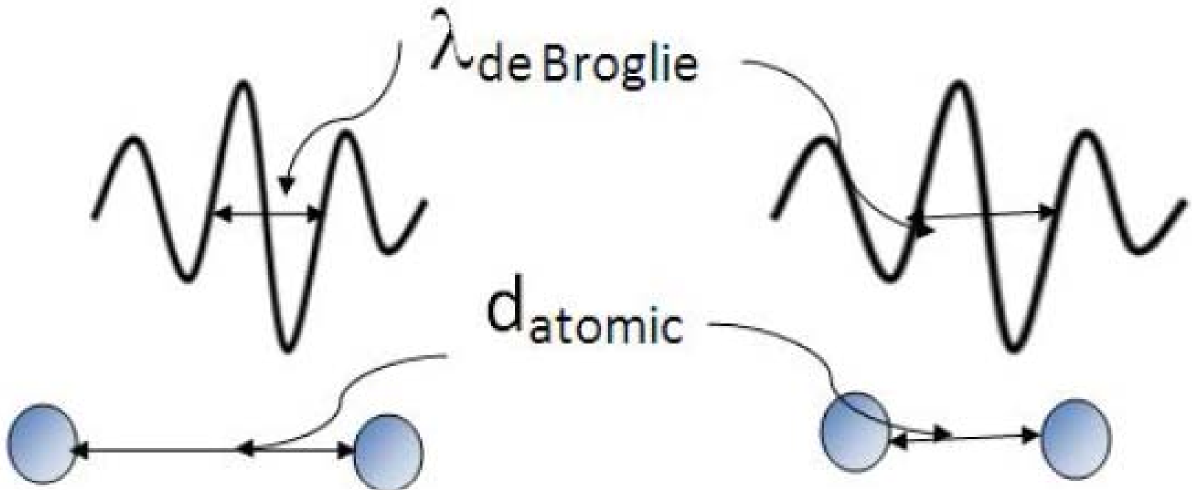
N total number of atoms: few hundred to ~ $10^{10}$

Densities range from $10^{11}/cm^3$ to $10^{15}/cm^3$

Temperature ranges from $10^{-9}$ K to $10^{-6}$ K.

At low T and ρ --atoms normally would solidify

--the condensate can exist for from few seconds to few minutes before solidification.




* $\lambda_{de\ Broglie} << d_{atomic}$ : atoms behave as particles.

* $\lambda_{de\ Broglie} \simeq d_{atomic}$ : wave nature of atoms noticeable

--at low T when atoms have low velocities.

--the wave nature of atoms will be described by quantum physics, e.g. discrete energy states (energy quantization).

# Fermions and Bosons

-Not all particles can have BEC -- related to the spin of the particles.

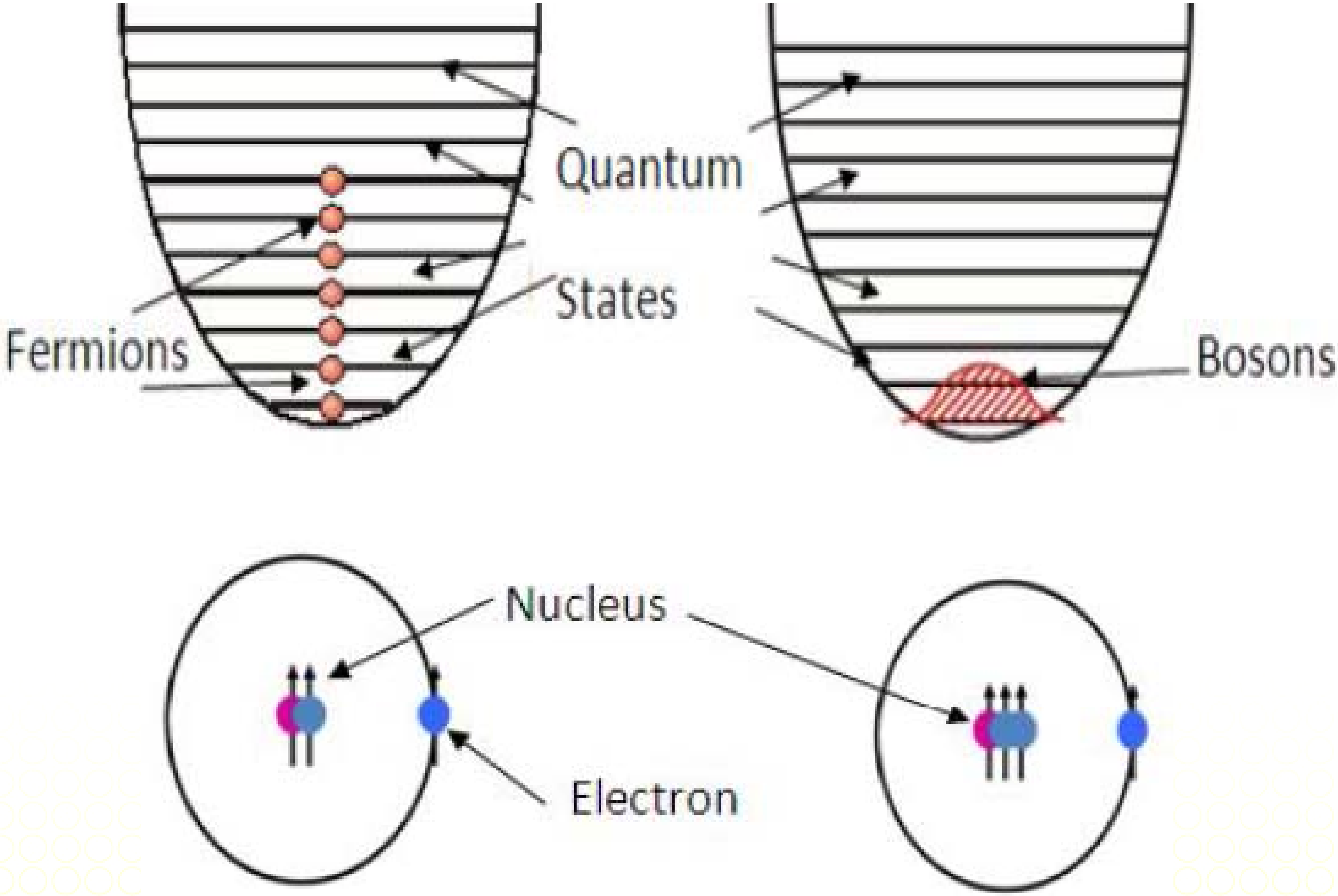
-The spin quantum number of a particle can be an integer or a half-integer.

-Fermions: spin is ½ (e.g. protons, neutrons, electrons)

-Cannot be in the same quantum state –no BEC

-Boson: spin of whole number

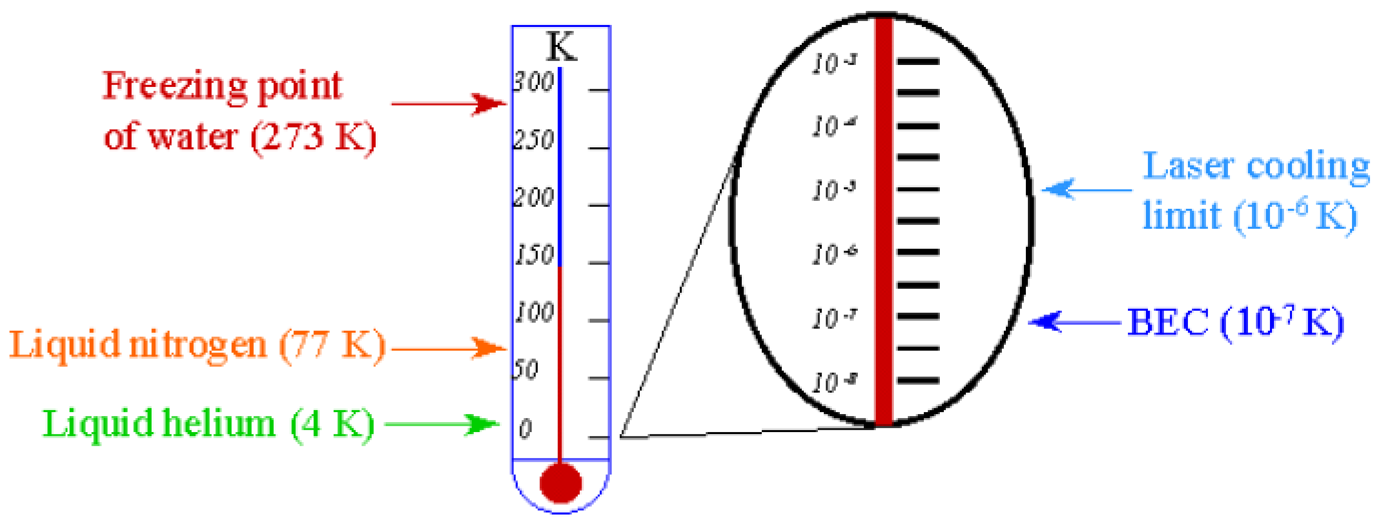
- Can be in the same quantum state – BEC


Quantum
States
Fermions
Bosons
Nucleus
Electron

In 1925 Bose and Einstein predicted

***The occupation of a single quantum state by a large fraction of bosons at low temperatures would be possible***

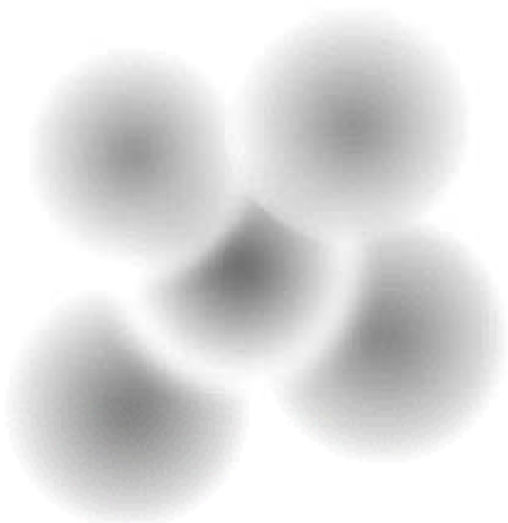
In 1995 -- was achieved --in a dilute atomic gas using laser and evaporative cooling to reach the ultra-cold temperatures of $10^{-7}$ K.



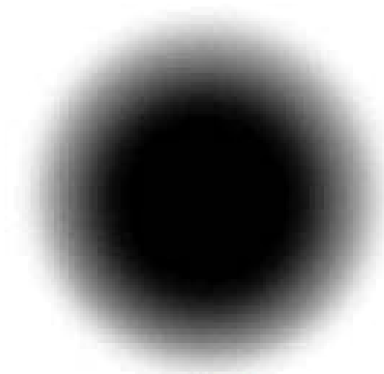
# Cooling Down the Atoms

-When T is high --describe the system by classical physics.

-When T is low --describe the system by quantum physics.



Some very cold atoms



Some atoms in a BEC condensate

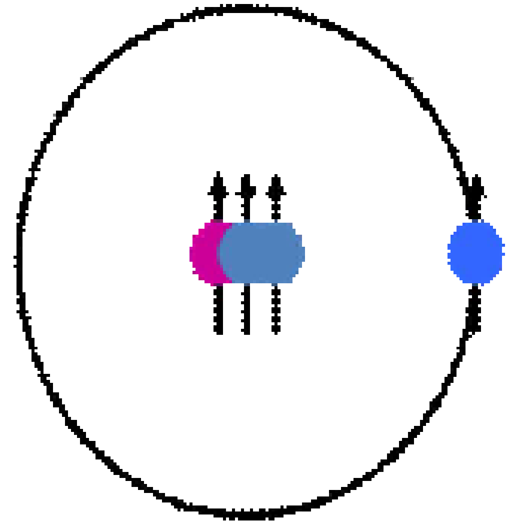
-When T is very low --atoms at the lowest energy state.

-This is called **Bose-Einstein condensation**.

-all the atoms are absolutely identical

# Making BEC

- **The Material for BEC**



BEC was found in alkali metals e.g. $^{87}Rb$, $^{23}Na$, $^{7}Li$ because:

-They are bosons.

-Each atom is a small magnetic compass, making magnetic cooling possible.

-The atoms have a small repulsion, do not liquefy or solidify down to a very low temperature.

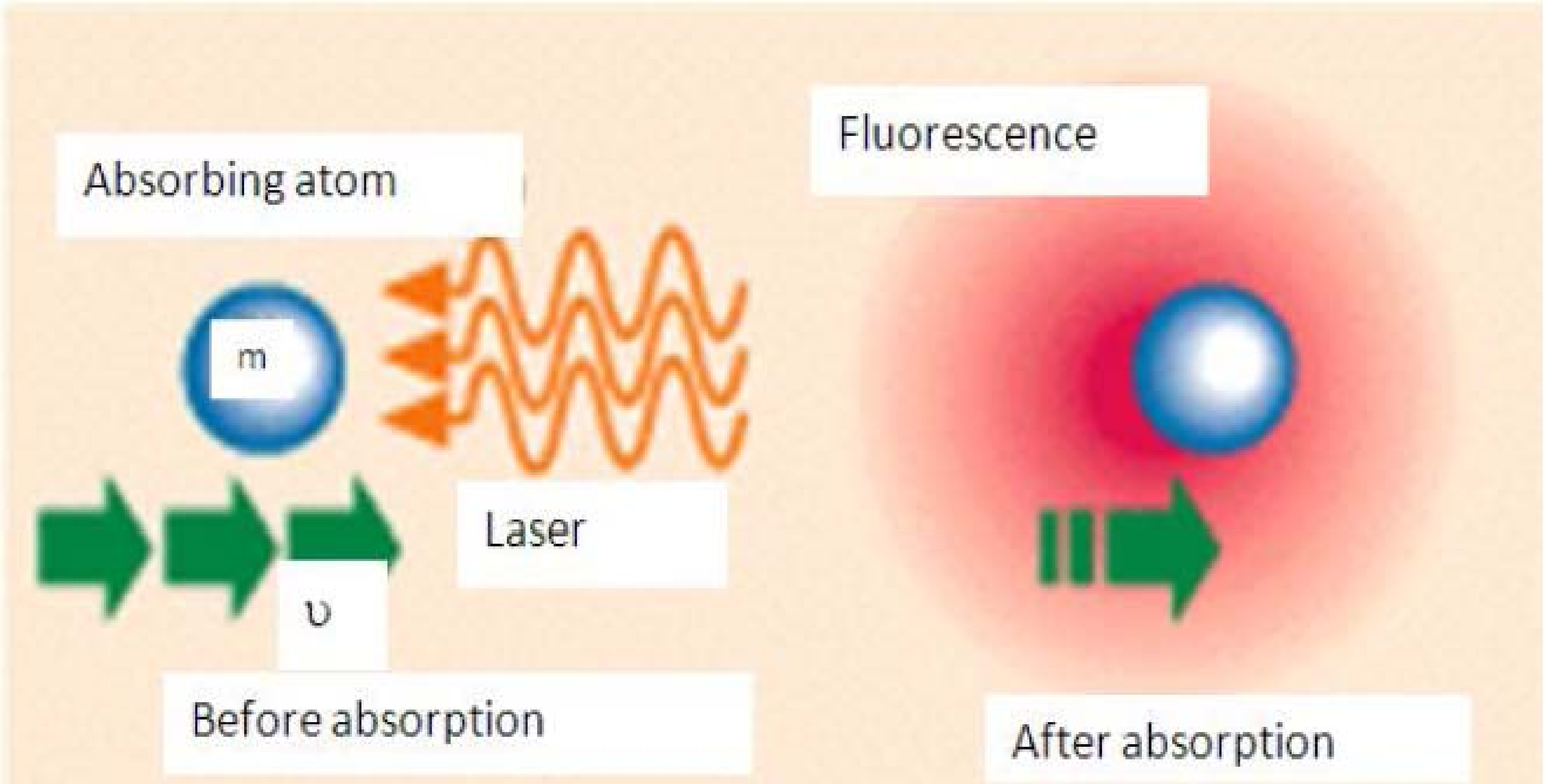
# • Atoms cooling

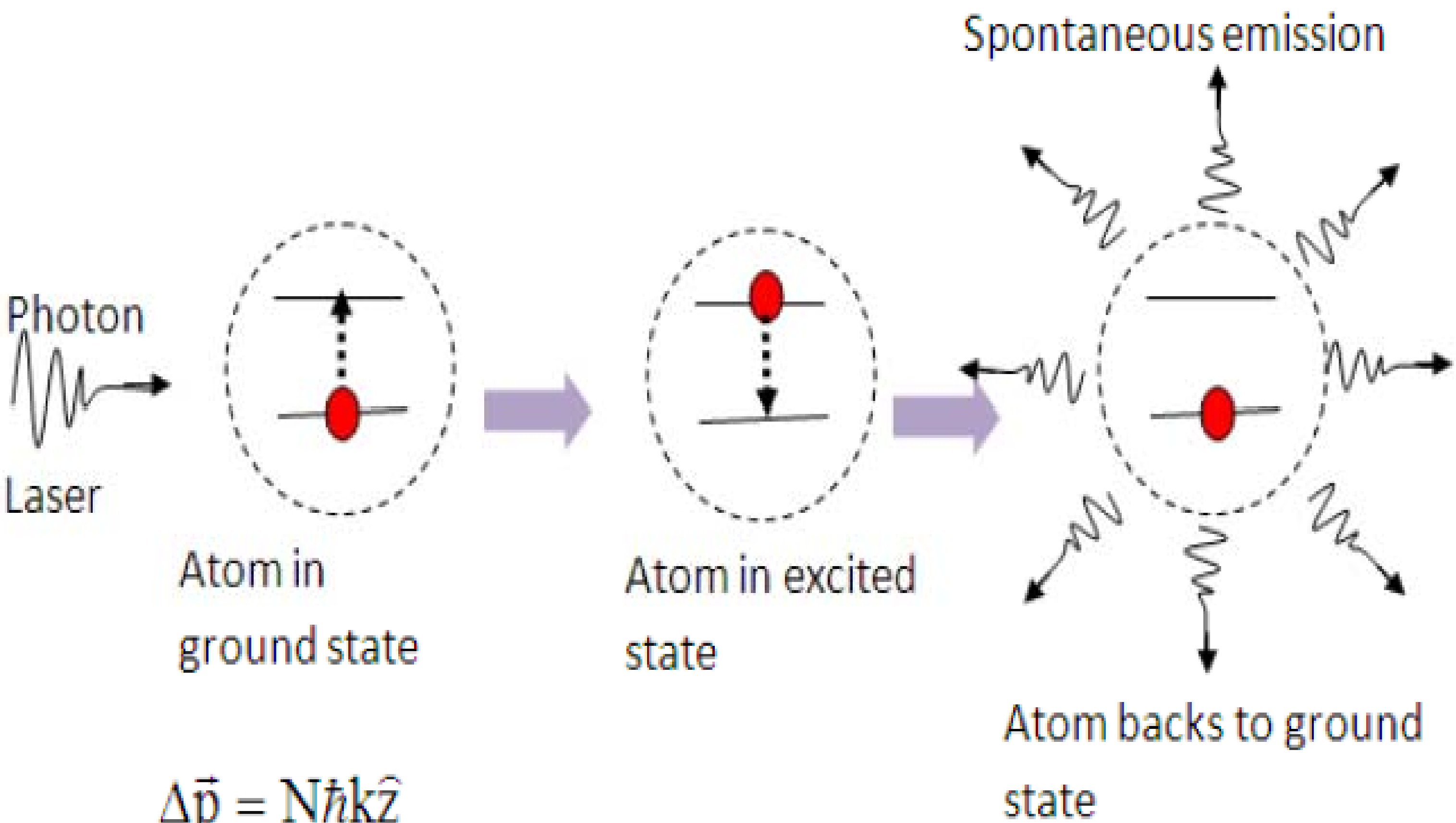
## Laser cooling

Laser cooling can get to the low temperature of 0.18μK

**The basic principle**

***--the conservation of energy and linear momentum during the absorption and emission of photon by the atom.***


Absorbing atom
m
Laser
υ
Before absorption
Fluorescence
After absorption




$$\Delta\vec{p} = N\hbar k\hat{z}$$

$$\langle \Delta\vec{p} \rangle = 0$$

-When the atom absorbs a photon, it suffers a momentum loss and slows down.

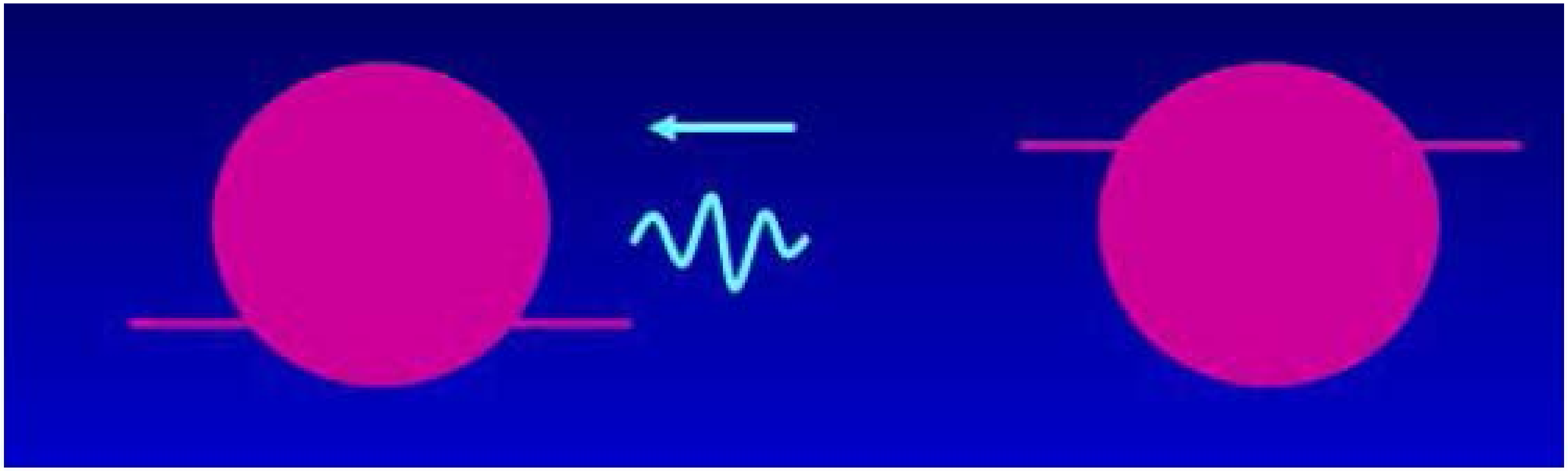
-The atom spontaneously emits a photon and returns to the ground state --$\Delta p = 0$, because the spontaneous emission has an isotropic angular distribution

-The total momentum change of the atom is in the direction of propagation of the laser.

-The atom's translational kinetic energy $KE = p^2/2m$ decreases and it cools.

-Laser cooling involves converting the atom's translational kinetic energy into optical energy carried away by spontaneously emitted photons.

# Tuning the laser

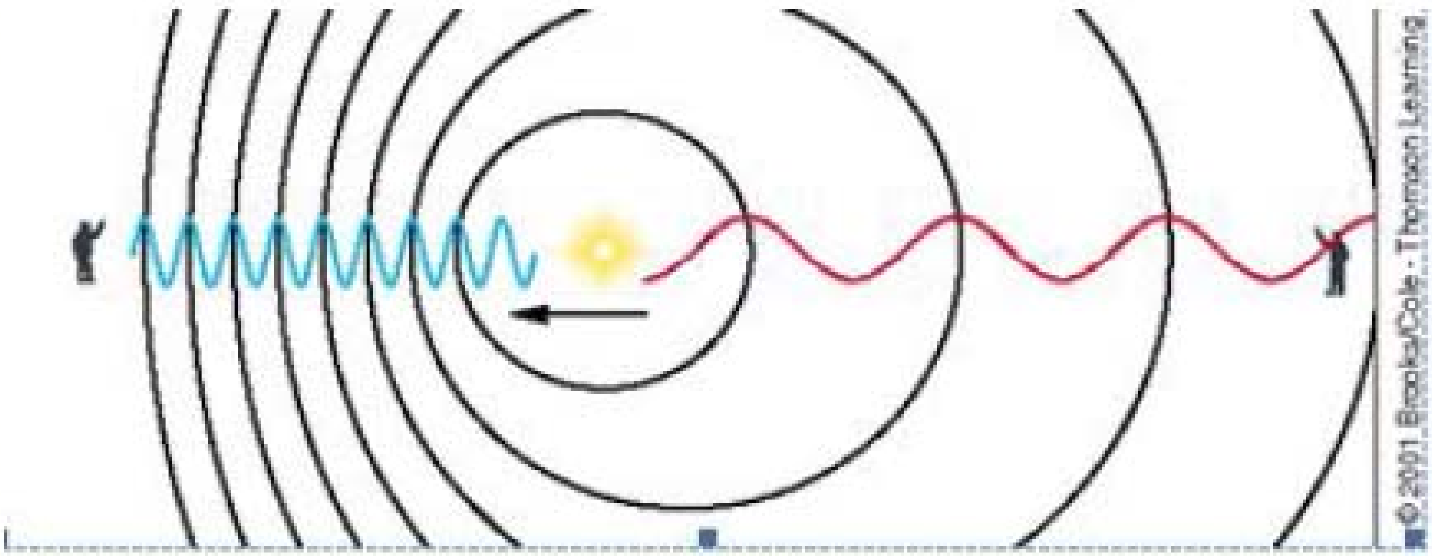


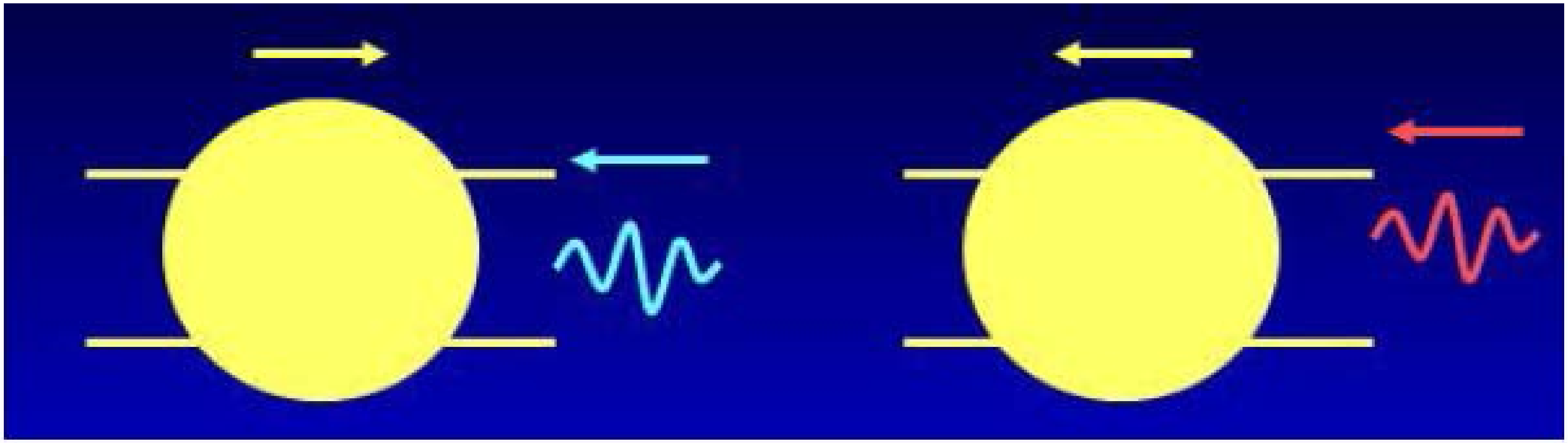
-Only laser light with the correct colour (frequency) can be absorbed by the atoms.

-If the colour is wrong, the atoms cannot absorb the photons.

Problem: The laser can slow the approaching atoms, but it can also blast off the receding ones

Solution: Use Doppler shift





-the atom is moving away from the laser source, the wavelength is lengthened and there is a **redshift**.

-the atom is approaching the laser source, the wavelength is shortened and there is a **blueshift**.

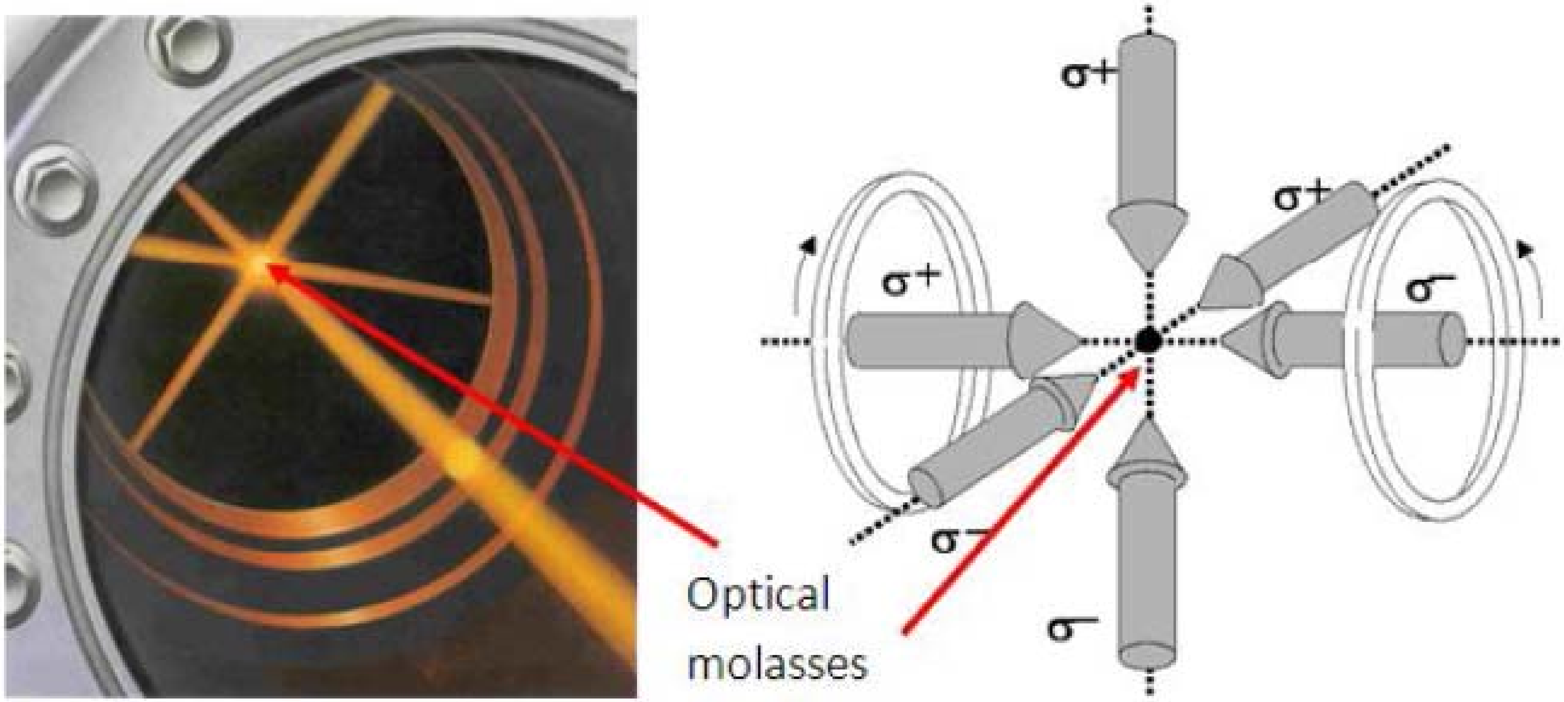
# Laser Trapping

-Atoms absorb photon at certain frequency (colour) and loose momentum –slow down

-The slow-down atoms need photon at other colour (because of Doppler Effect) for absorption to further slow-down.

-When lasers are sent in from all the different directions, the atoms can get cold very quickly

This is called **laser trapping**, and the trapped atoms form an **optical molasses**




Note:

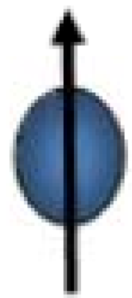
-Laser cooling can cool the atoms down to 10μK, because atoms can spontaneously emit the absorbed photon.

-This is still too hot for BEC

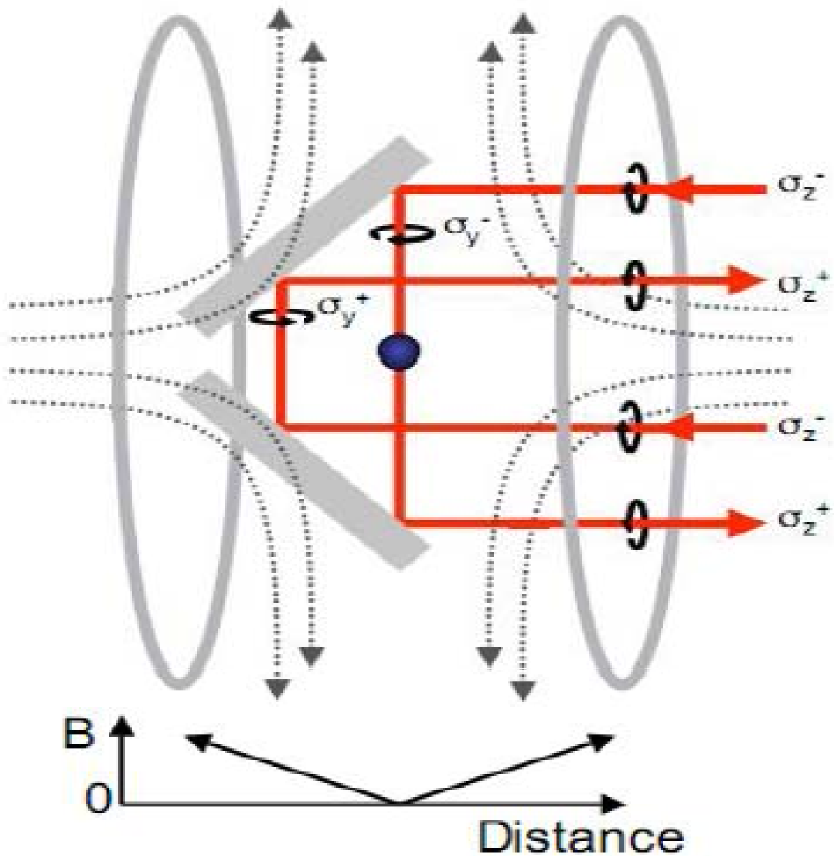
-Further cooling -- ***Evaporative cooling***

# Evaporative cooling

-The atoms behave as tiny compasses. They can be pulled by magnetic fields.

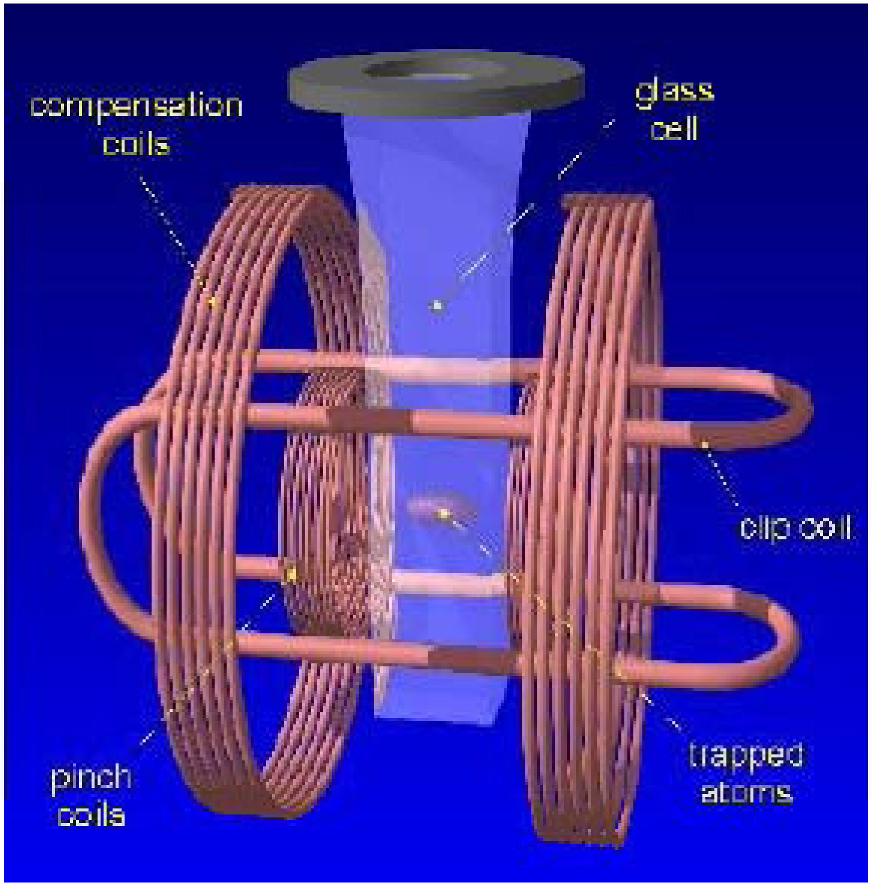


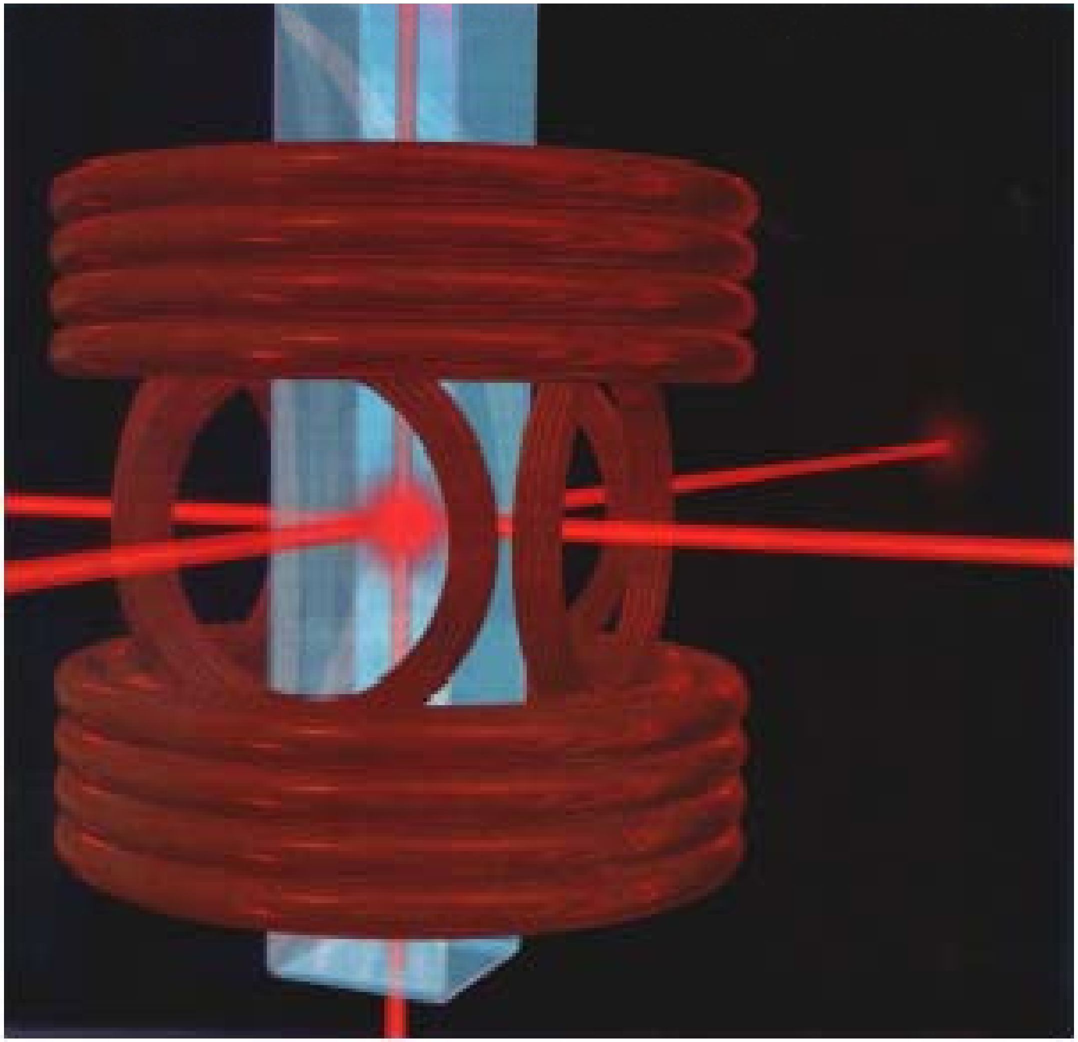
-A magnetic field can be designed to push the atoms inwards from both sides, forming a ***magnetic trap***

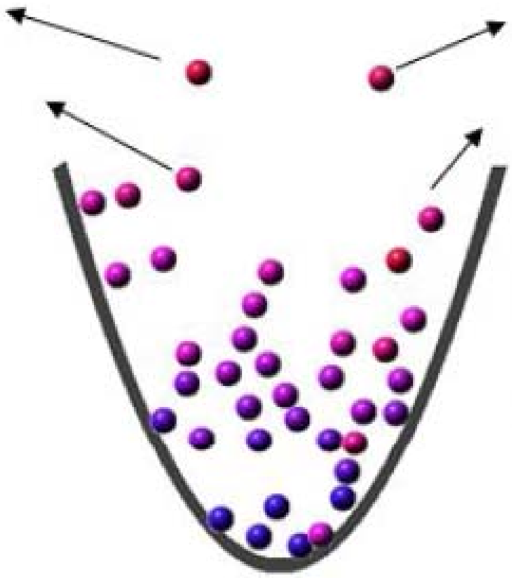



-Helmholtz coils --create a harmonic oscillator type magnetic potential.

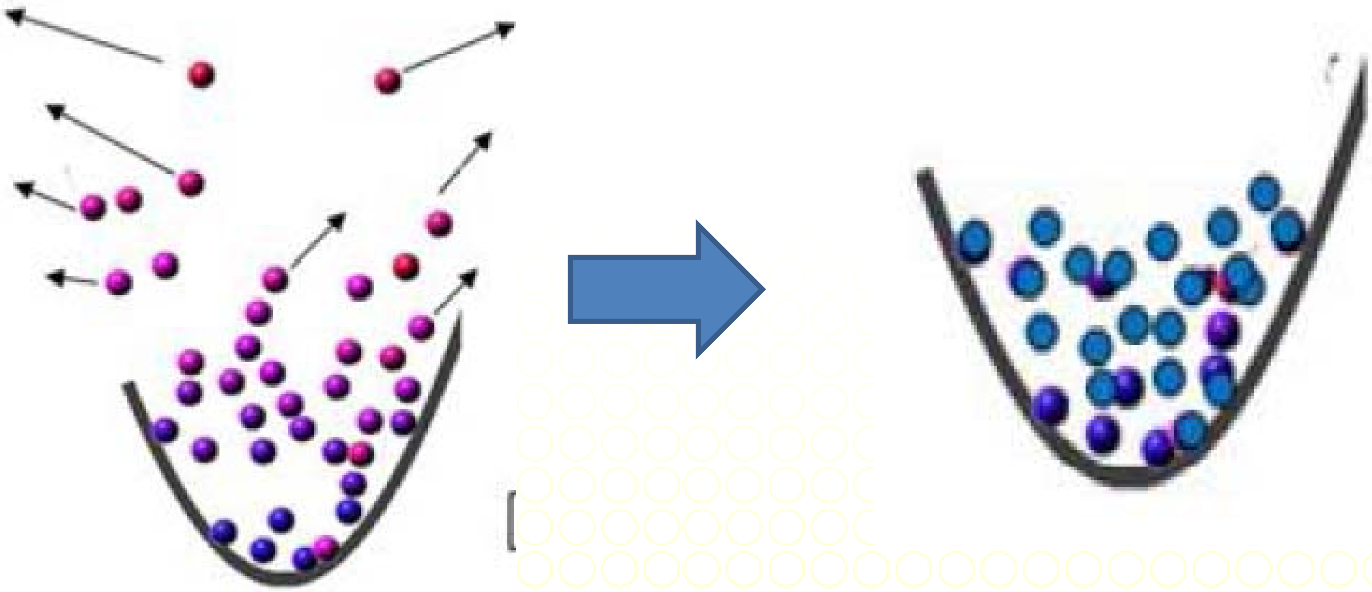
-The atoms, due to their spins, are confined to the local minimum of the magnetic field


compensation coils
glass cell
clip coil
pinch coils
trapped atoms





Each atom that leaves the trap carries away more than the average amount of energy and so the remaining gas gets colder.



Lower the height of the trap quickly, so that there are still enough atoms left in the trap

When the magnetic coils are energized,

-the magnetic field further confines most of the atoms while allowing the energetic ones to escape.

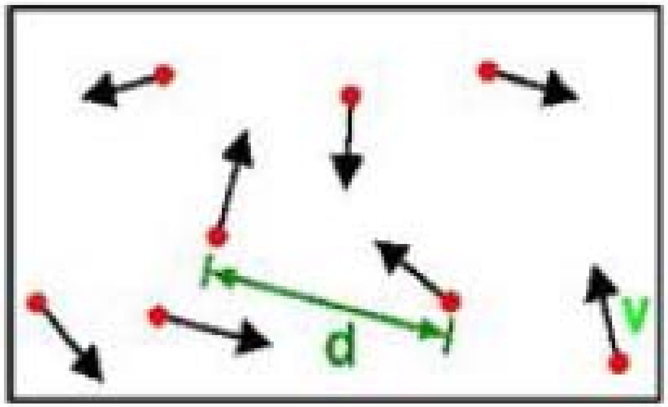
-decreasing the average energy of the remaining atoms

- Ultimately, many of the atoms attain the lowest possible energy state allowed by quantum mechanics and become a single entity known as a *Bose-Einstein condensate*

Note:

Evaporative cooling has no fundamental lower limit and temperatures below 10nK have been reached in magnetic traps.

# What Does a Bose-Einstein Condensate Look Like?

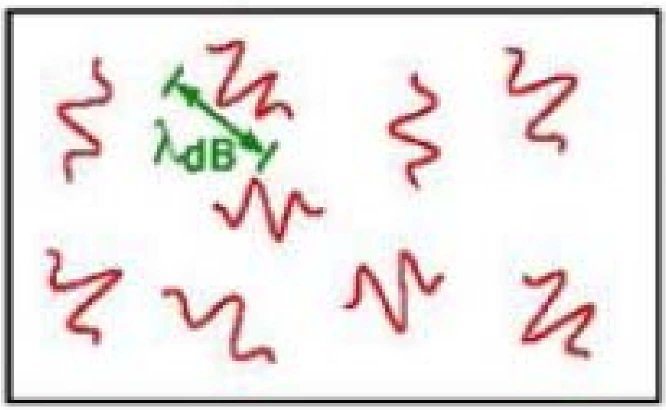



**High Temperature T:**

thermal velocity v

density $d^{-3}$

"Billiard balls"

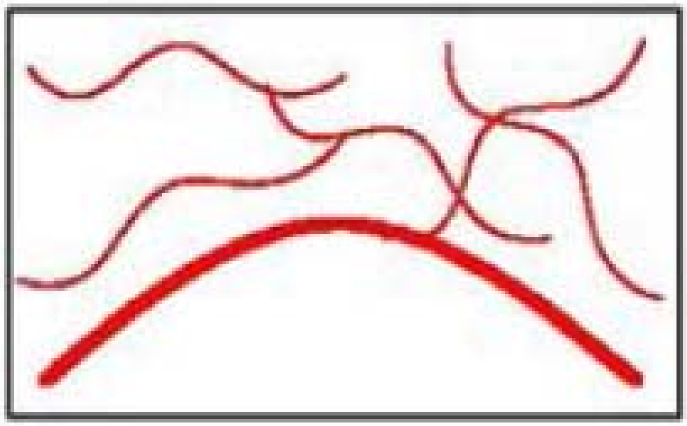


**Low Temperature T:**

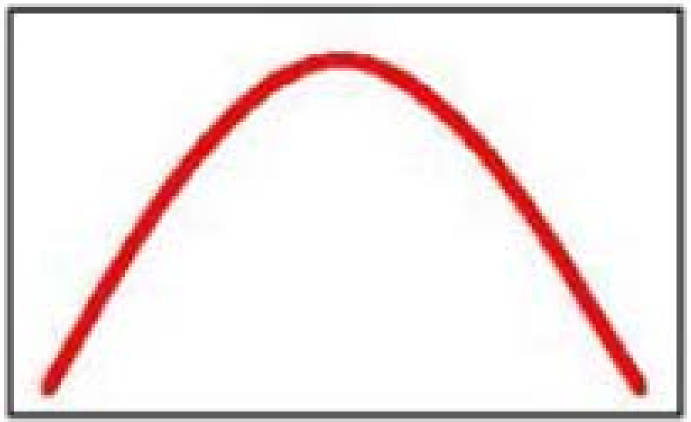
De Broglie wavelength

$\lambda_{dB} = h/mv \propto T^{-1/2}$

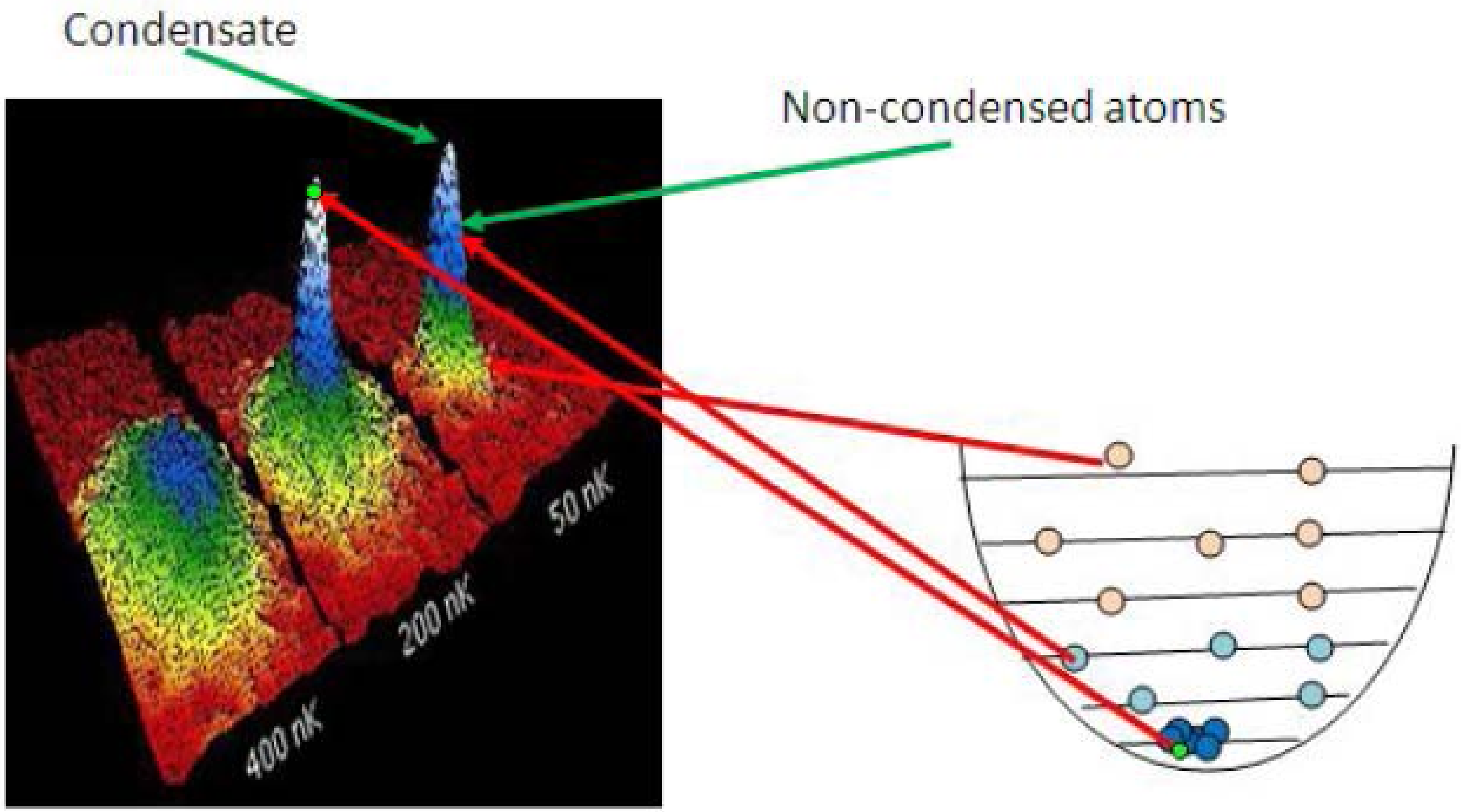
"Wave packets"



**$T=T_{crit}$:**
**Bose-Einstein Condensation**
$\lambda_{dB} \approx d$
"Matter wave overlap"



**T=0:**
**Pure Bose condensate**
"Giant matter wave"




-There is a drop of condensate at the centre.

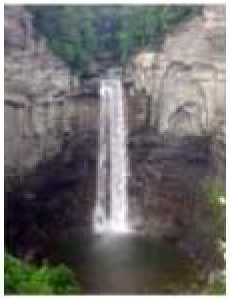
-The condensate is surrounded by uncondensed gas atoms.

# States of matter

BOSE-EINSTEIN CONDENSATE

SOLIDS

LIQUIDS



GASES

PLASMAS (only for low density ionized gases)

Lower Temperature ⟷ Higher Temperature

# THE END

REFERENCES:

1. REAF, F : “Fundamentals Of  Statistical And Thermal Physics”, McGraw-Hill.

2. KITTEL & KROMER: “Thermal Physics”, W.H. Freeman & Company.