The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2234-5

Meeting of Modern Science and School Physics: College for School Teachers of Physics in ICTP

27 April - 3 May, 2011

Quest to absolute zero and Bose condensation

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QUEST TO ABSOLUTE ZERO AND BOSE-EINSTEIN CONDENSATION

A. Buzdin

Condensed Matter Theory Group, University of Bordeaux I

and Institut Universitaire de France

Meeting of Modern Science and School Physics,
ICTP, Trieste, Italy
27 April - 3 May, 2011

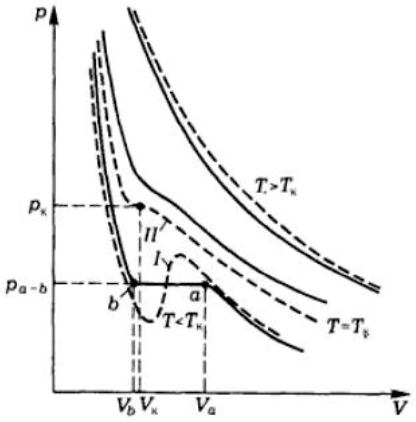
TEMPERATURE

$$\left(\frac{mV^2}{2}\right) = k_B T$$

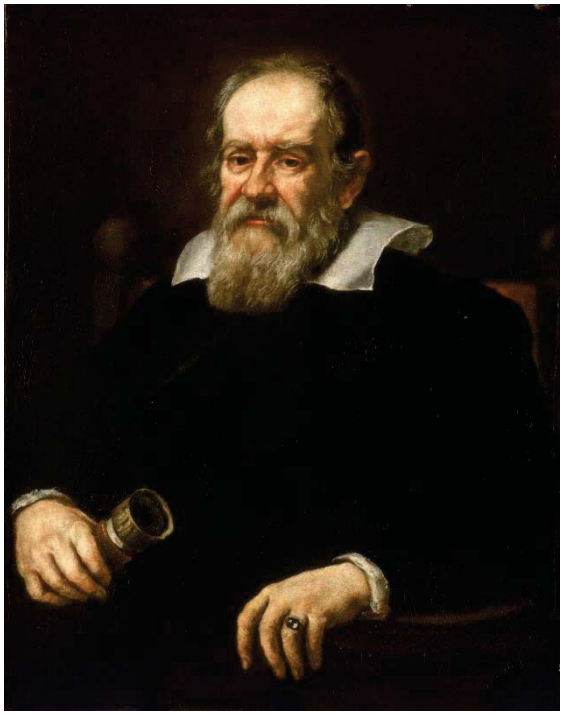
k_B= 1.380 6504×10^{-23} J K^{-1}

Boltzmann

$$pV = NkT$$

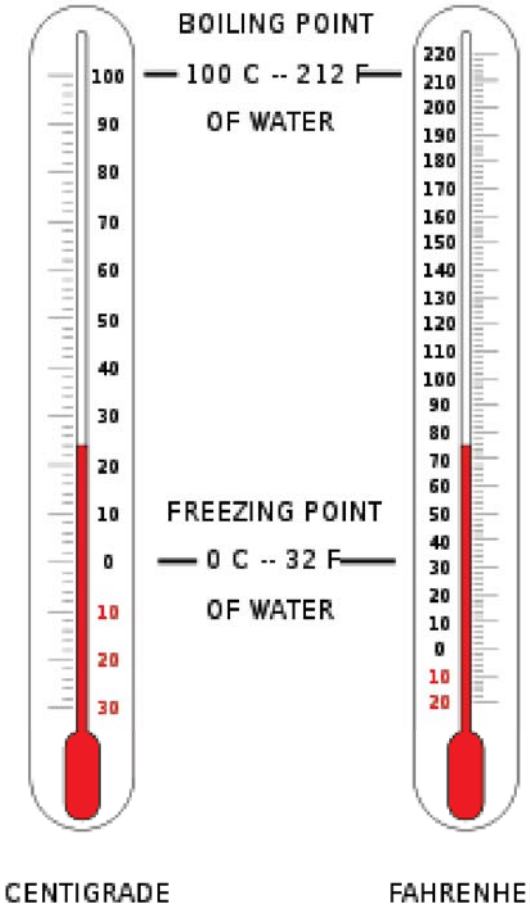


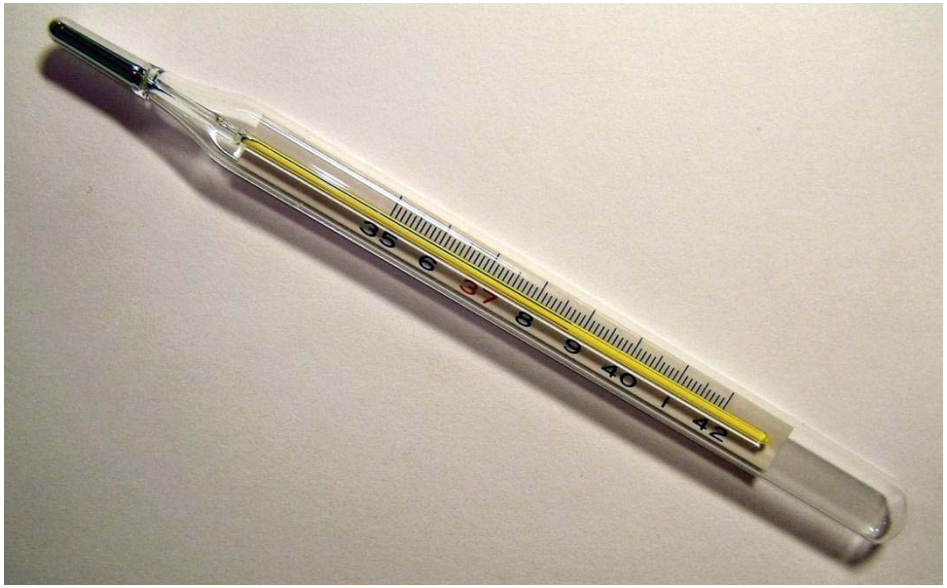
First thermometers - thermoscopes

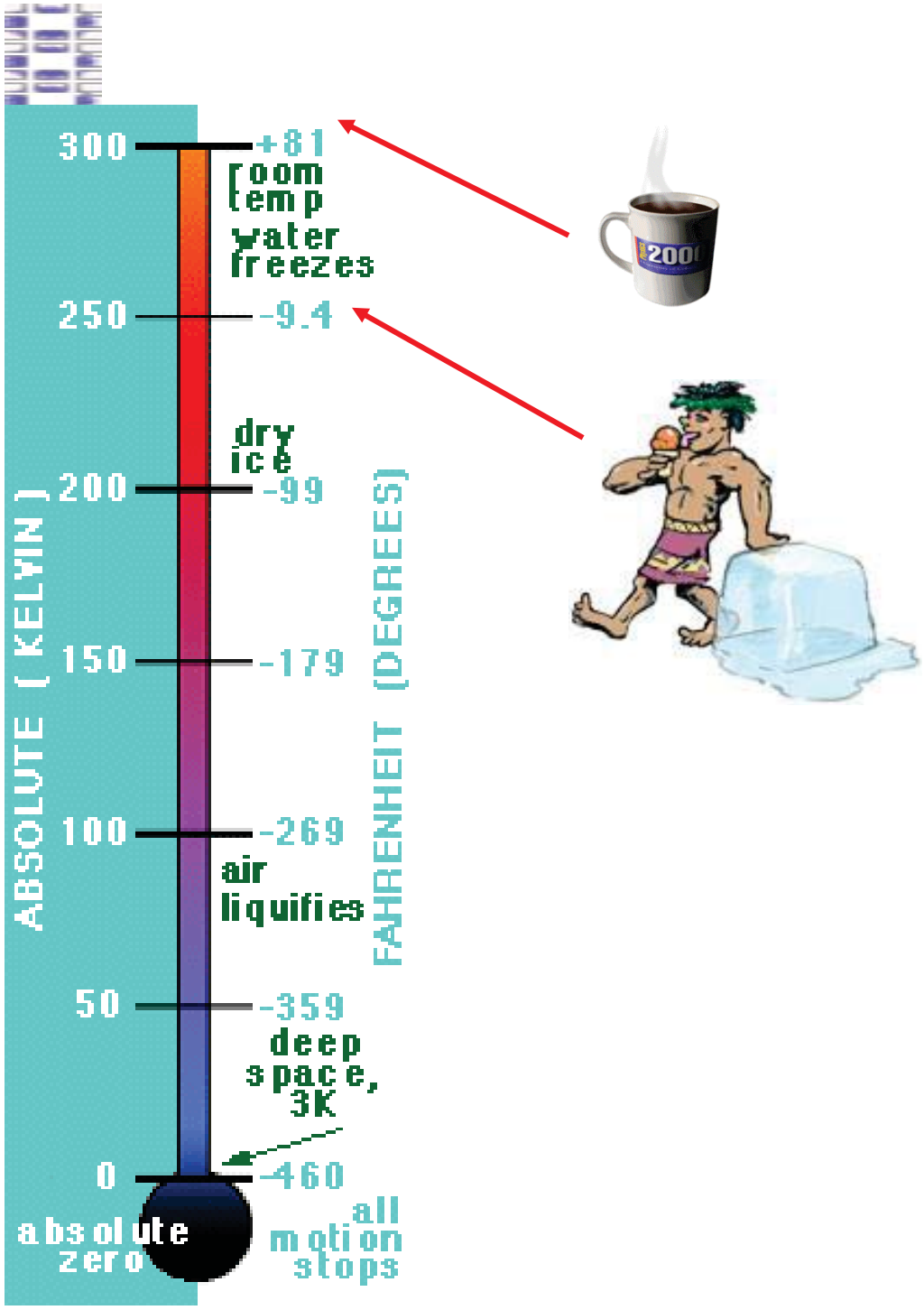


Galileo Galilei (1564 – 1642)

Thermometers







Water

vapor

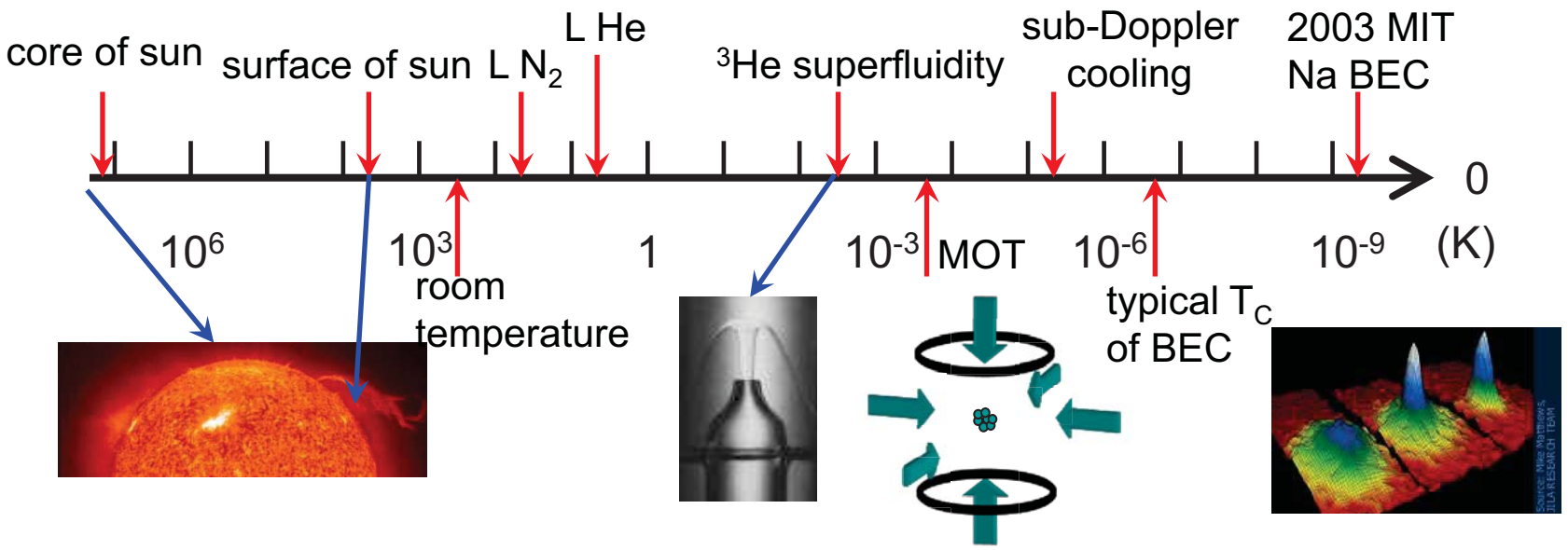
100°C

liquide

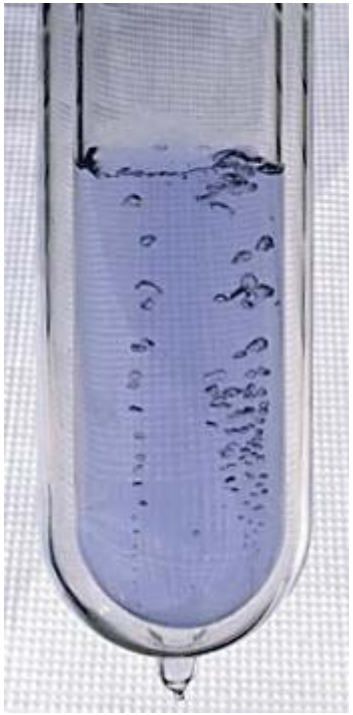
0°C

ice - solide

Temperature scale



By 1845, Michael Faraday had managed to liquefy most permanent gases then known to exist.

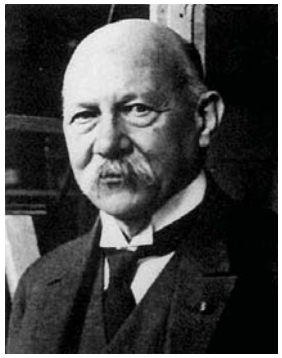


In 1877, Louis Paul Cailletet (1832–1913) in France and Raoul Pictet (1846–1929) in Switzerland succeeded in producing the first droplets of liquid air.

Nitrogen was first liquefied at the Jagiellonian University on 15 April 1883 by Polish physicists, Zygmunt Wróblewski and Karol Olszewski.

Quest to liquefy Helium

Helium-4 was first liquefied on 10 July 1908 by Dutch physicist Heike Kamerlingh Onnes.



Properties of liquid helium	Helium-4	Helium-3
Critical temperature[	5.2 K	3.3 K
Boiling point at 1 atm[	4.2 K	3.2 K
Minimum melting pressure	25 atm	29 atm at 0.3 K
Superfluid transition temperature at saturated vapor pressure	2.17 K	1 m K in zero magnetic field

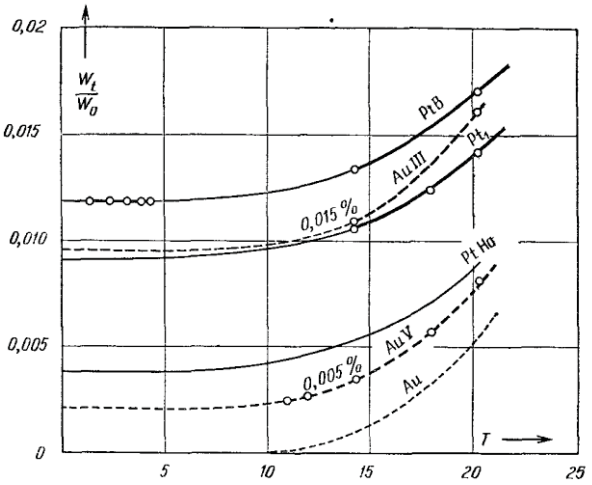


Рис. 4.3. Сопротивление двух образцов из платины и двух — из золота (тонкие пунктирные линии для образцов из золота — экстраполяция) [*Commun. Phys Lab. Univ Leiden*, № 119 (1911), лист III рис 3]

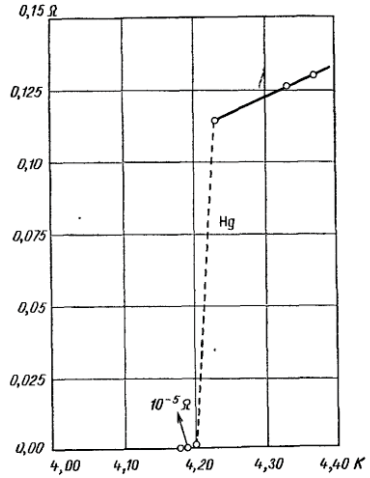
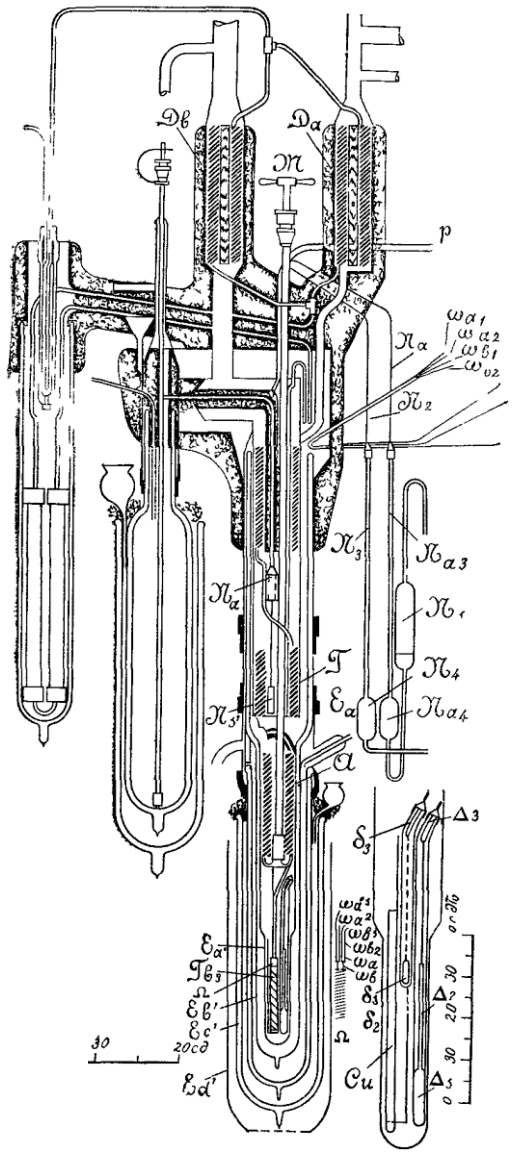
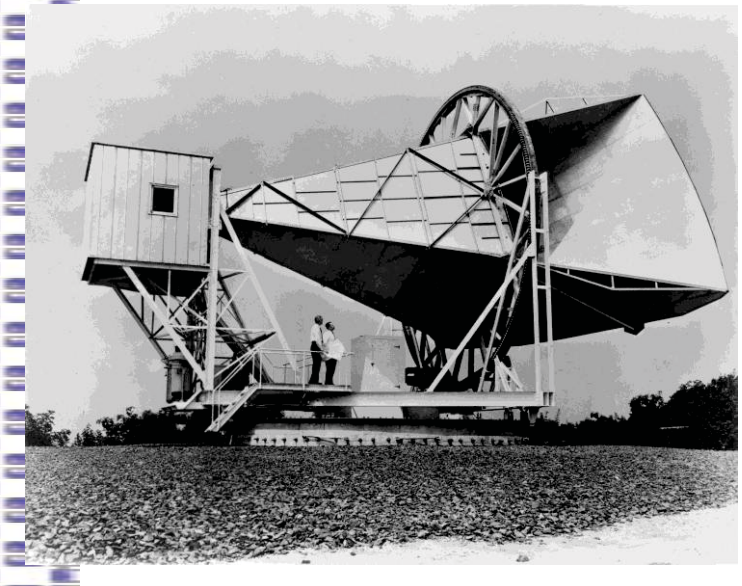
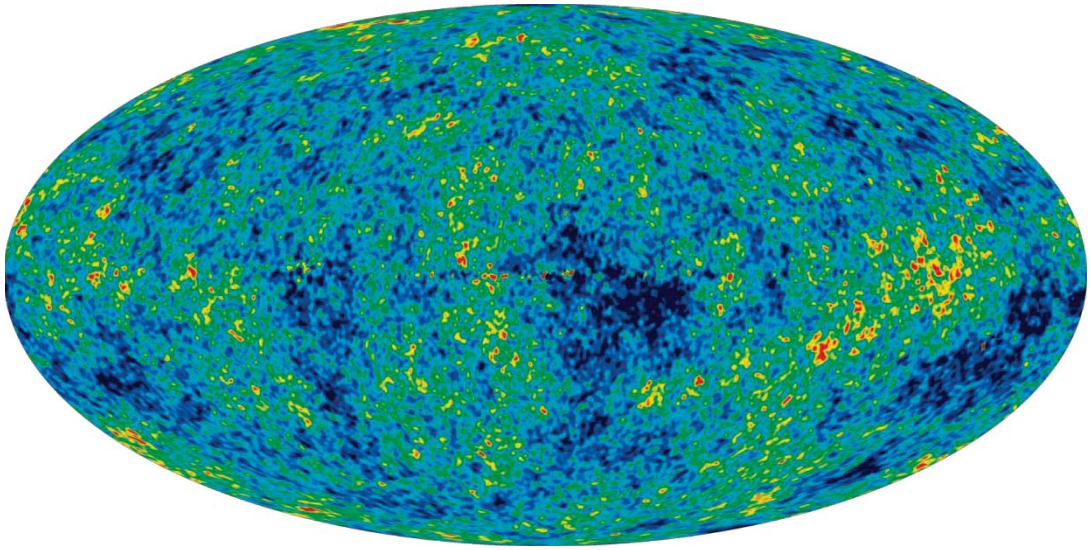


Рис. 4.5. Зависимость сопротивления образца ртути от температуры [*Commun. Phys. Lab. Univ. Leiden*, № 124 (1912), стр. 23, рис. без номера].



Physics of low temperature was born !





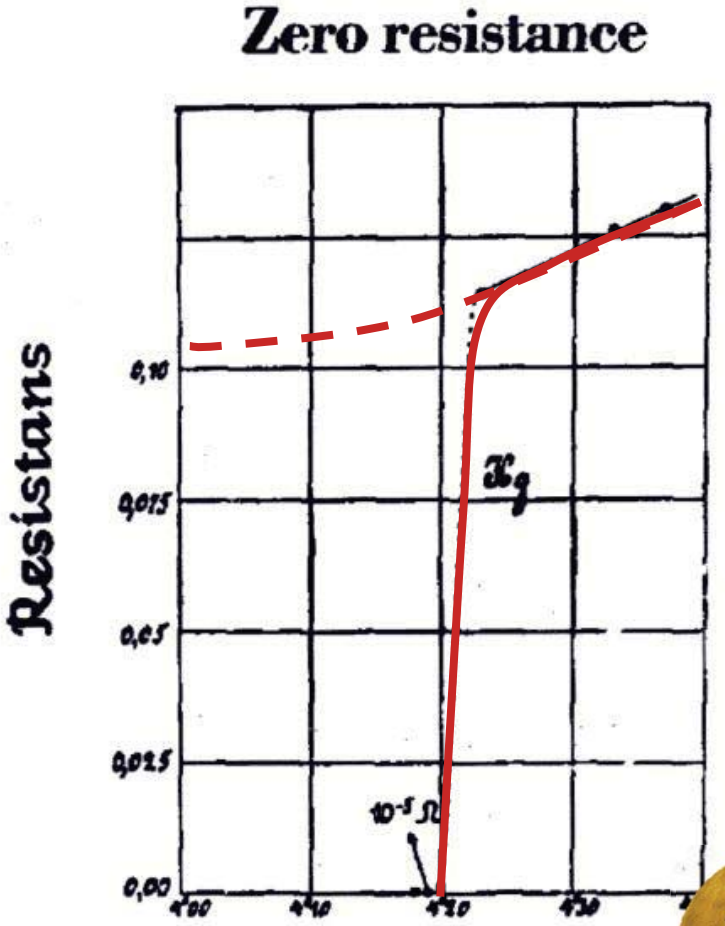
cosmic microwave background radiation
has a thermal black body spectrum at a temperature of 2.725 K

Arno Allan Penzias and Robert Woodrow Wilson

We may have the temperature below 2.7 K only in our laboratories.

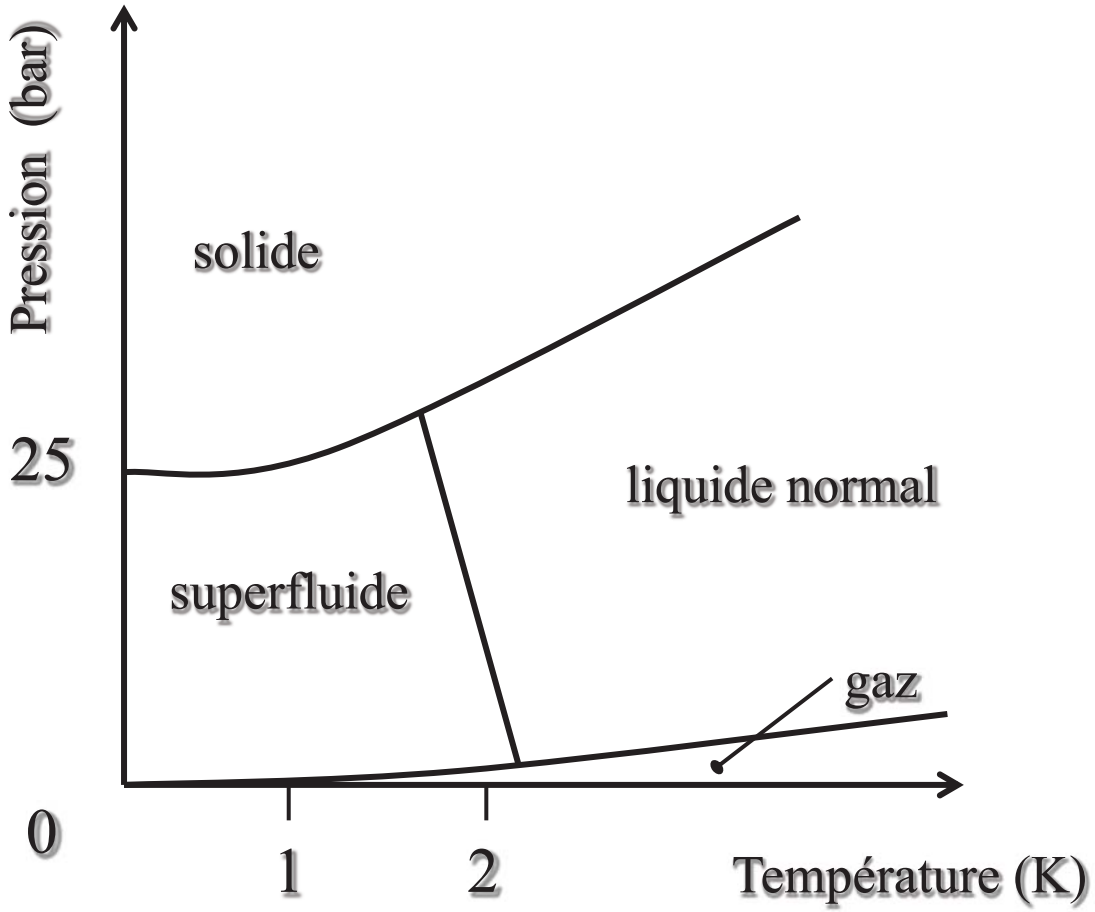
1911: discovery of superconductivity

- Discovered by **Kamerlingh Onnes** in 1911 during first low temperature measurements to liquefy helium
- Whilst measuring the resistivity of “pure” Hg he noticed that the electrical resistance dropped to zero at 4.2K
- In 1912 he found that the resistive state is restored in a magnetic field or at high transport currents

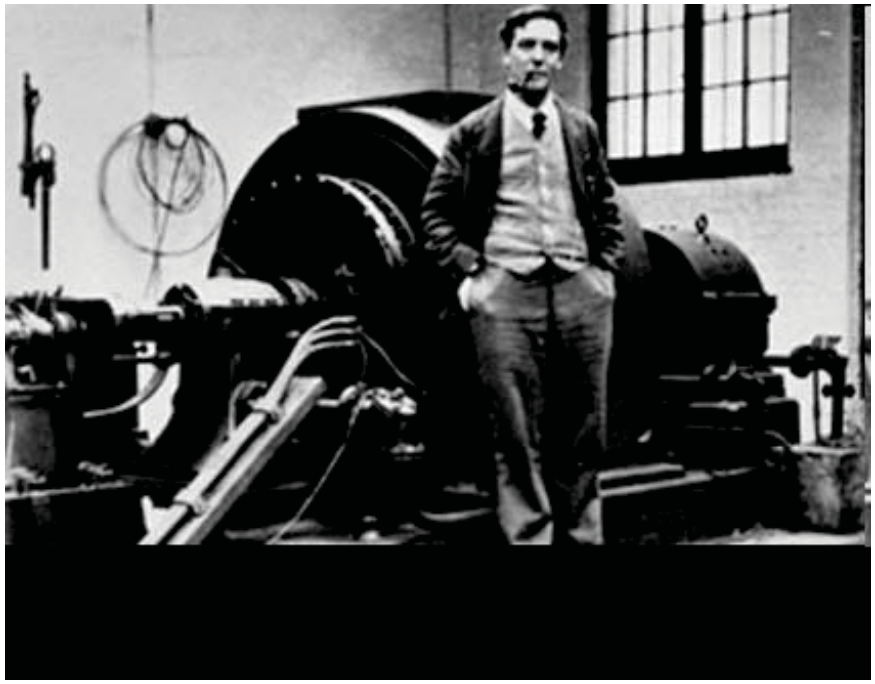


1913

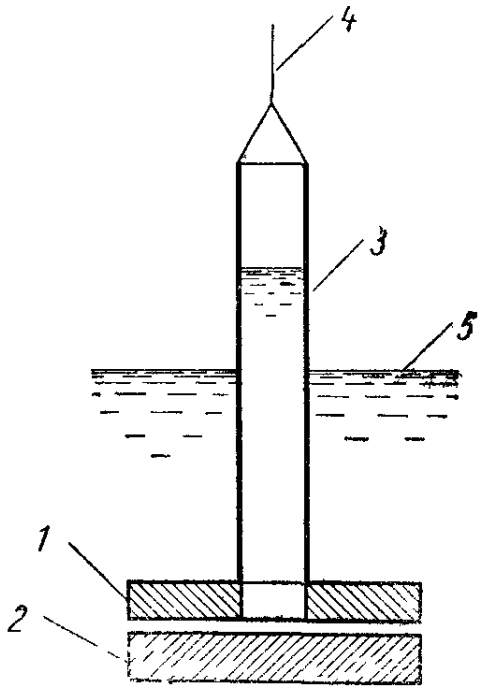
Phase diagram of He

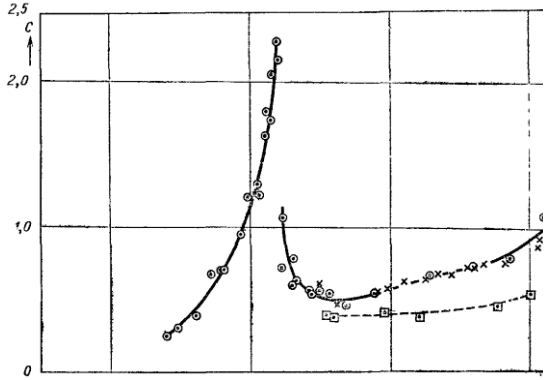


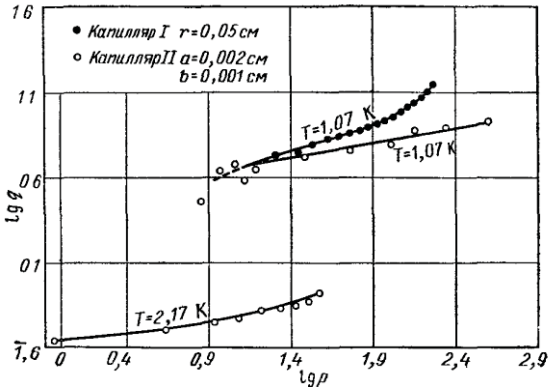
1937: Superfluidity of liquid He_4



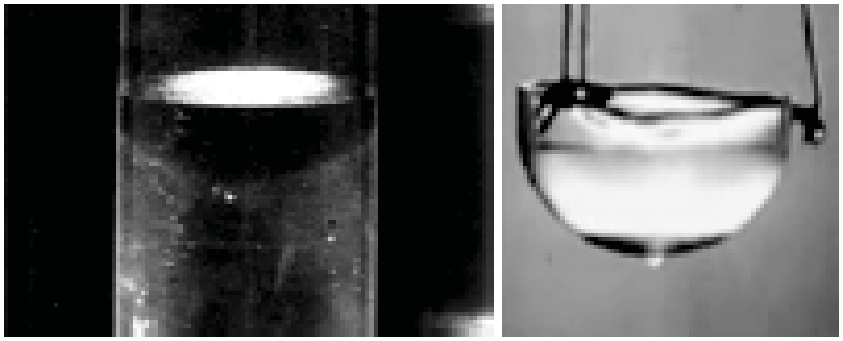
Piotr Kapitza



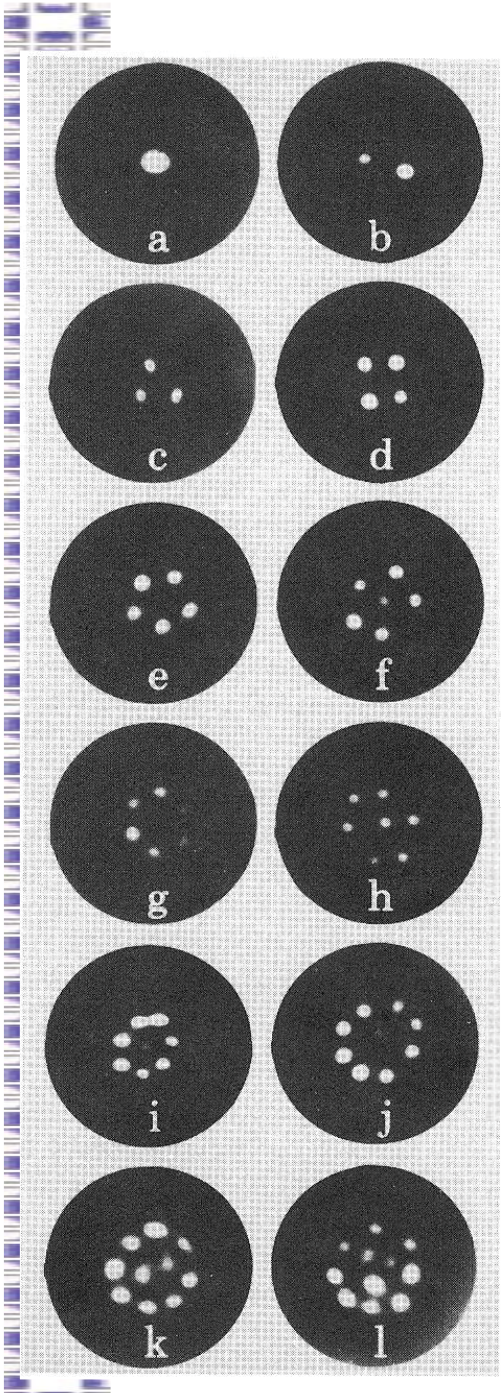




1978



Superfluidity in liquid Helium at 2.17?K, fluid without viscosity: No bubbles, no movement of liquid during circulation of its container



Rotaion of superfluid: vortices

helium

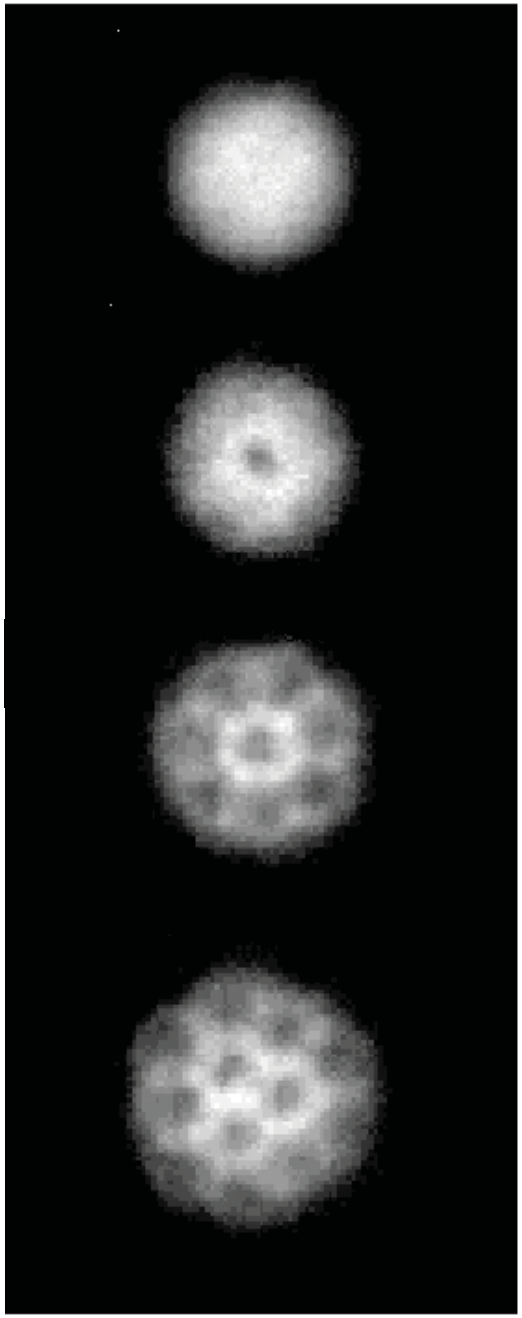
at 1979 :

E.J. Yarmchuk, M.J.V. Gordon et R.E. Packard

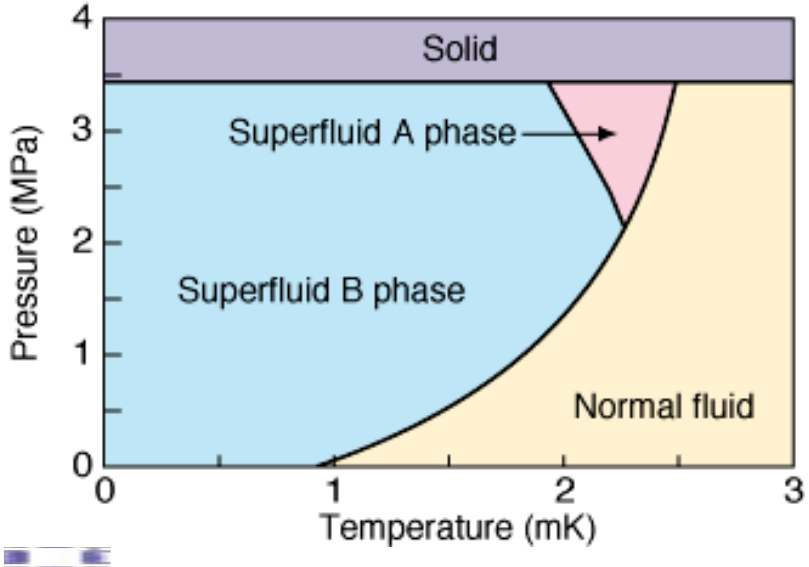
et le rubidium gazeux

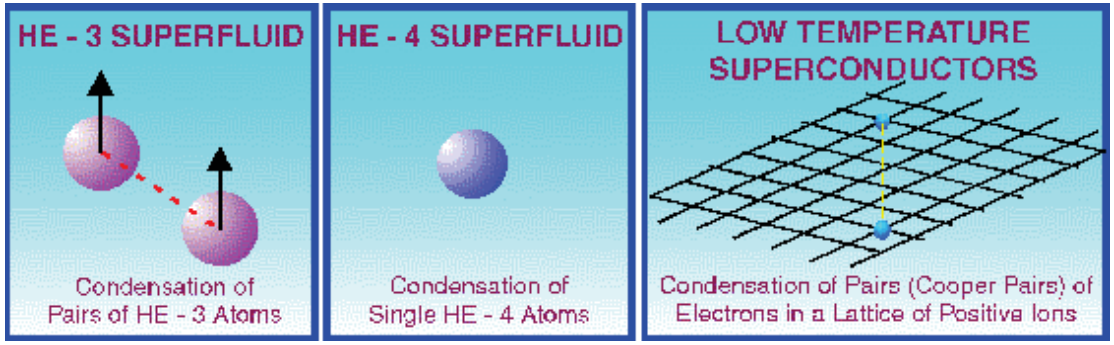
en 2000 :

KW Madison, F. Chevy, W. Wohlleben et J. Dalibard



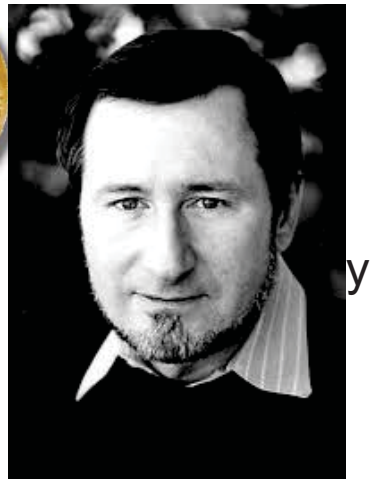
1973: Superfluidity in liquid He_3





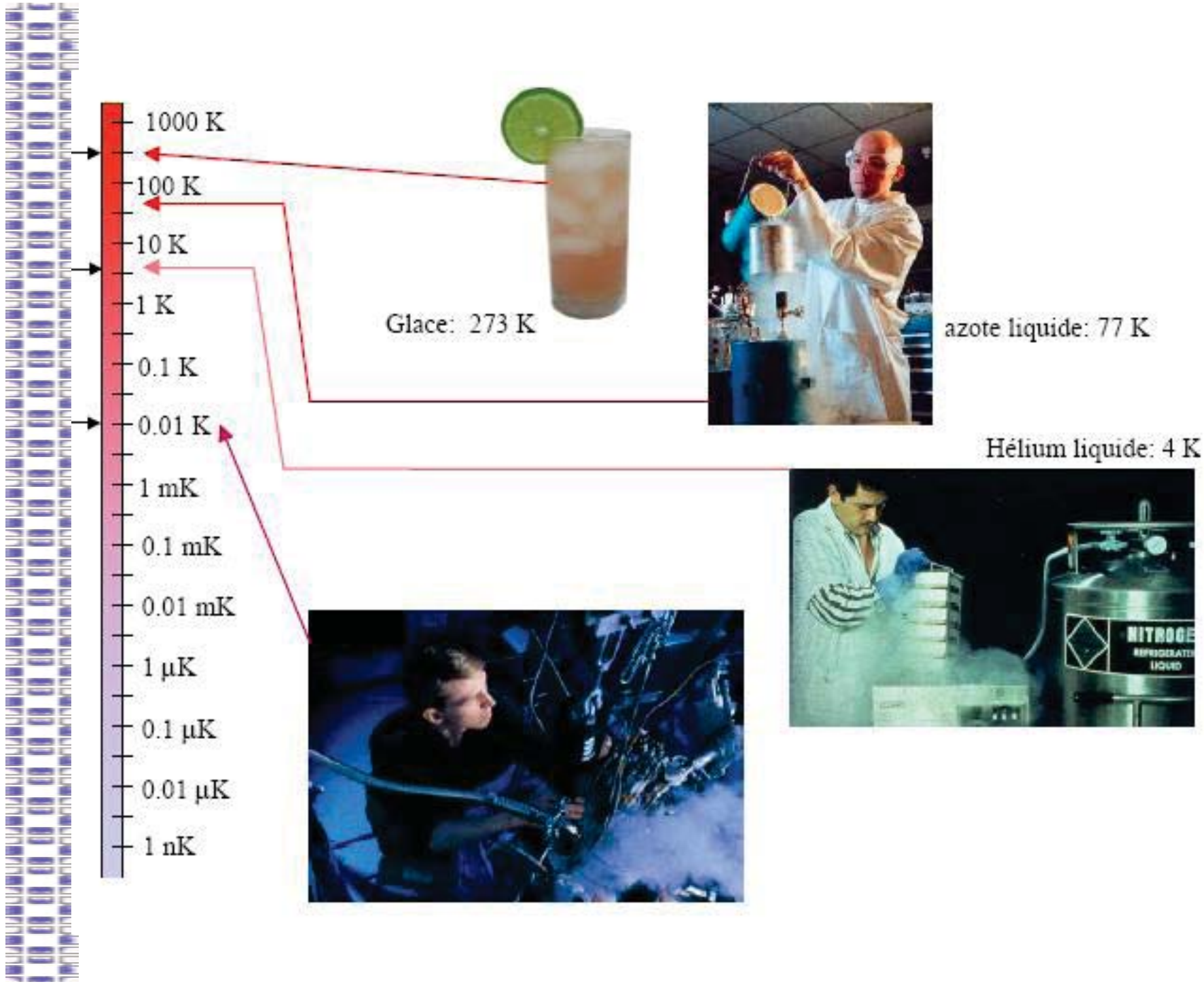
David M. Lee, **Douglas Dean Osheroff and** Robert C. Richardson

1996



y

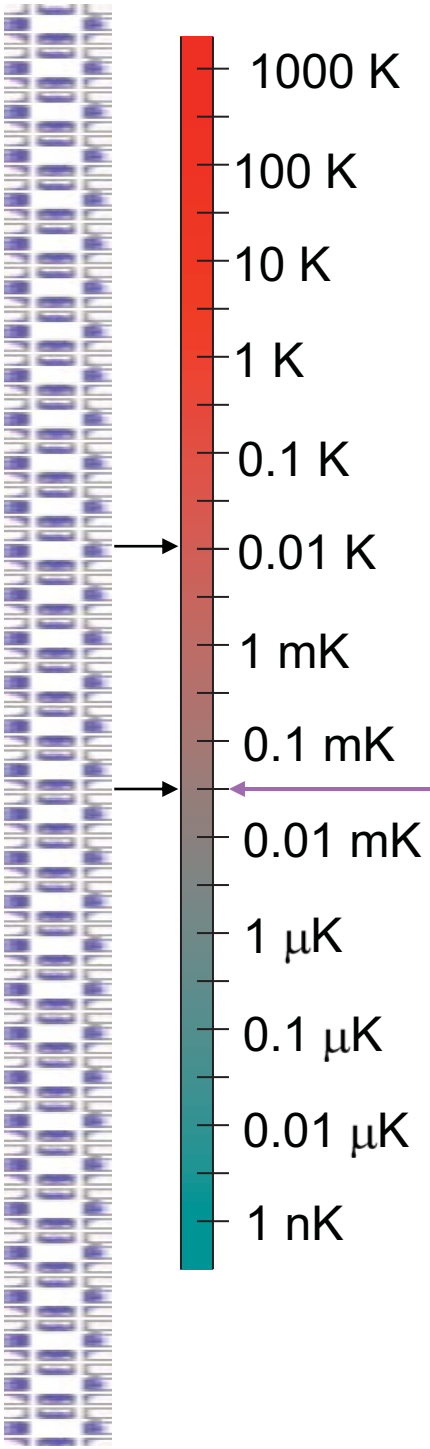
2003

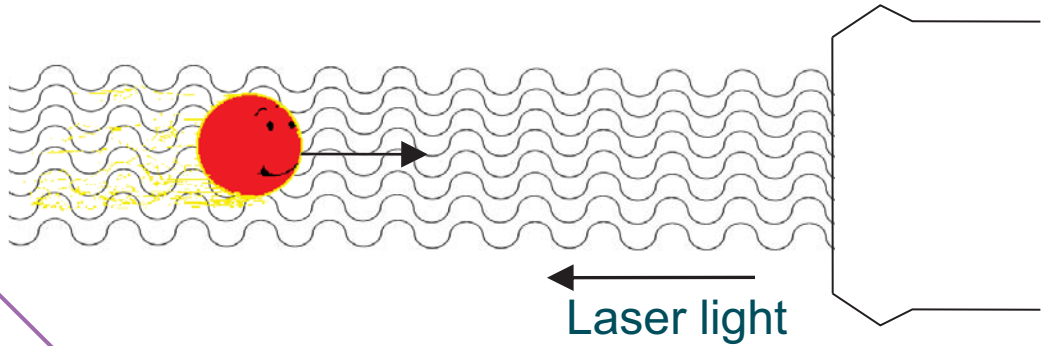

1000 K
100 K
10 K
1 K
0.1 K
0.01 K
1 mK
0.1 mK
0.01 mK
1 µK
0.1 µK
0.01 µK
1 nK
Glace: 273 K
azote liquide: 77 K
Hélium liquide: 4 K

Laser cooling

Chu, Cohen-Tannoudji et Phillips – Nobel Prize 1997

"for development of methods to cool and trap atoms with laser light".

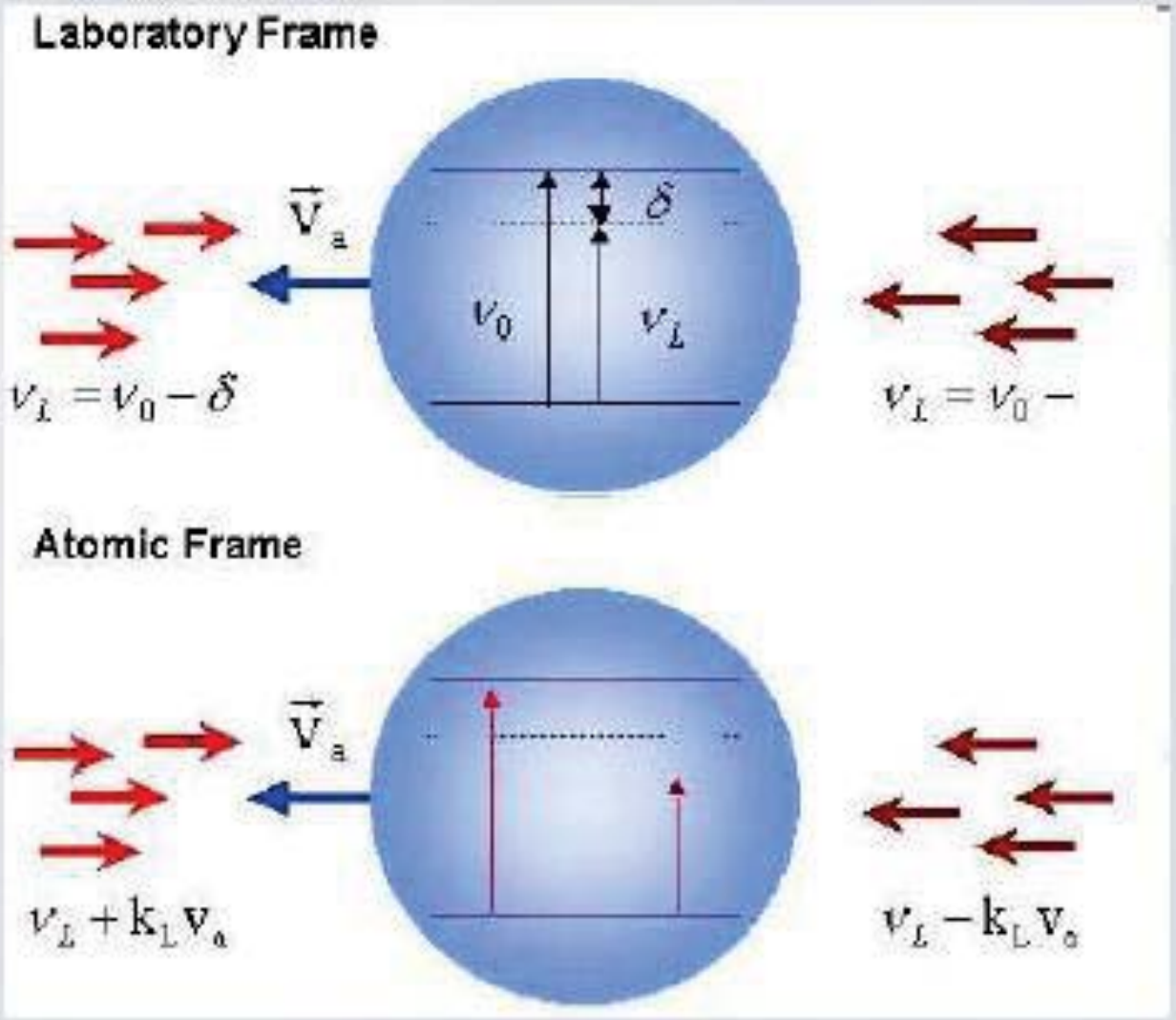


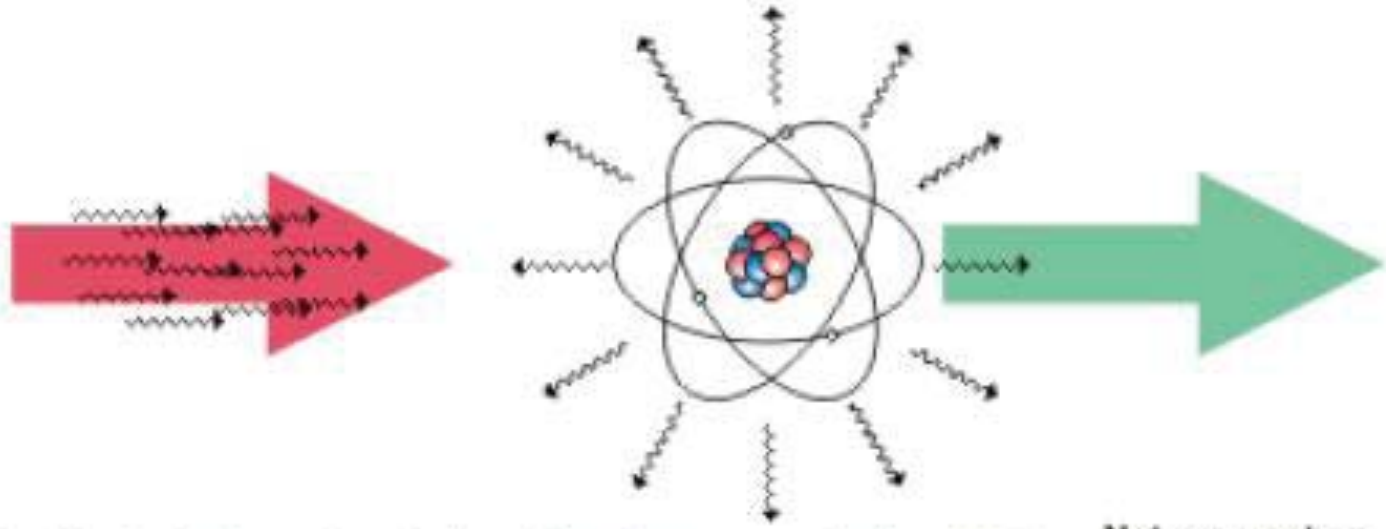


10-100 microkelvin
= 0.00001 - 0.0001 K

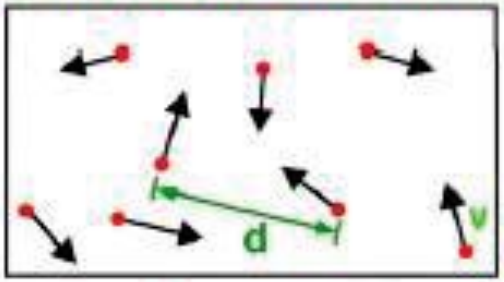
demo

Laser cooling

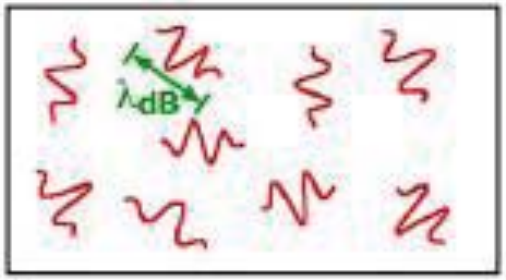



Incident photons absorbed:
momentum transfer = ħk
Spontaneous emission: total
momentum transfer = 0
Net momentum
transfer to atom in
direction of laser

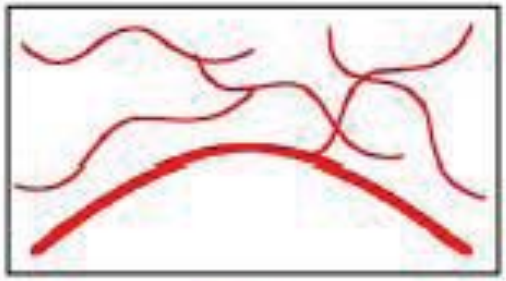
What is Bose-Einstein condensation (BEC)?



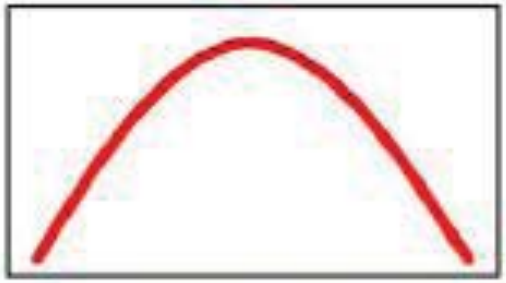
High Temperature T:
thermal velocity v
density d^{-3}
"Billiard balls"



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"

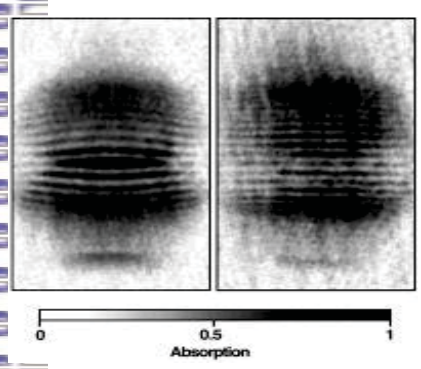
$$\lambda = \frac{h}{\sqrt{2\pi mkT}}$$

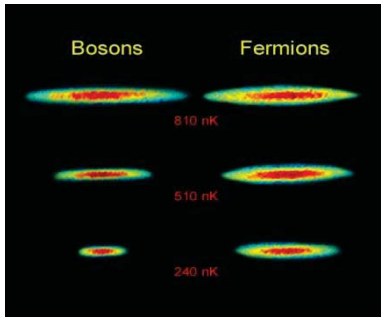
$$T_c = \left(\frac{n}{\zeta(3/2)}\right)^{2/3} \frac{2\pi\hbar^2}{mk_B} \approx 3.31 \frac{\hbar^2 n^{2/3}}{mk_B}$$

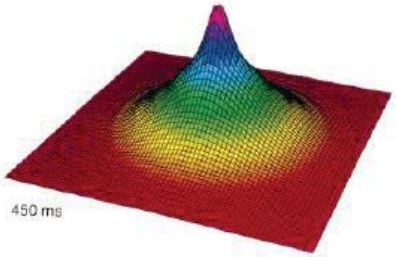
Particles are tranformed to waves…

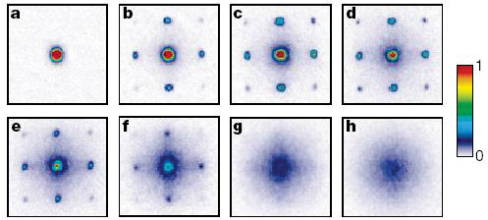
- World of Quantum Mechanics
  - Wave nature of matter, interference, tunneling, resonance

    $\lambda = h/\sqrt{2\pi m k_B T}$ ~1μm for Na @ 100nk
  - Quantum statistics
  - Uncertainty principle, zero-point energy
  - Quantum phase transition









Experimental observation of Bose-Einstein condensation

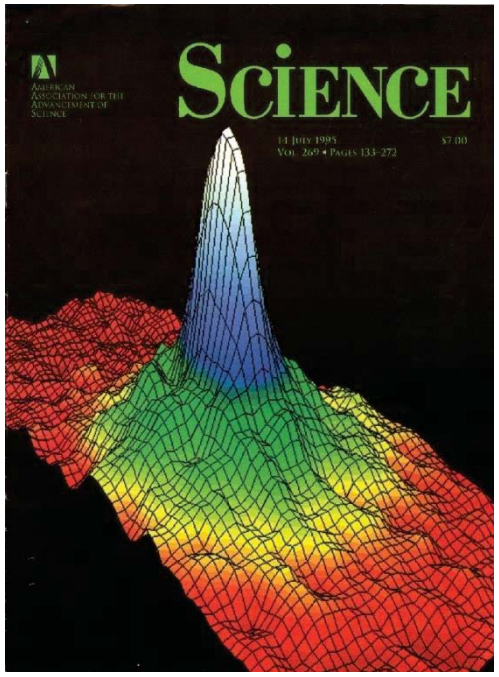
Nobel Prize 2001

E. Cornell, W. Ketterle and C. Wieman

"for the achievement of Bose-Einstein condensation **in dilute gases of alkali atoms**, and for early fundamental studies of the properties of the condensates"

The first condensates at en 1995

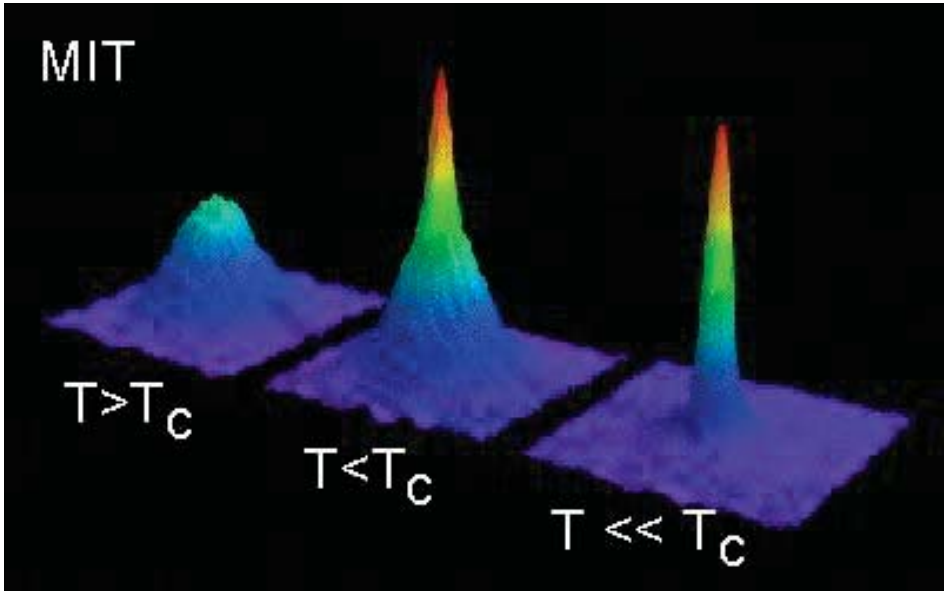
$T_c \sim 0{,}0000001$ K !!!!!!!!!!!!



Rubidium

C. Wieman et E. Cornell

Boulder, Colorado

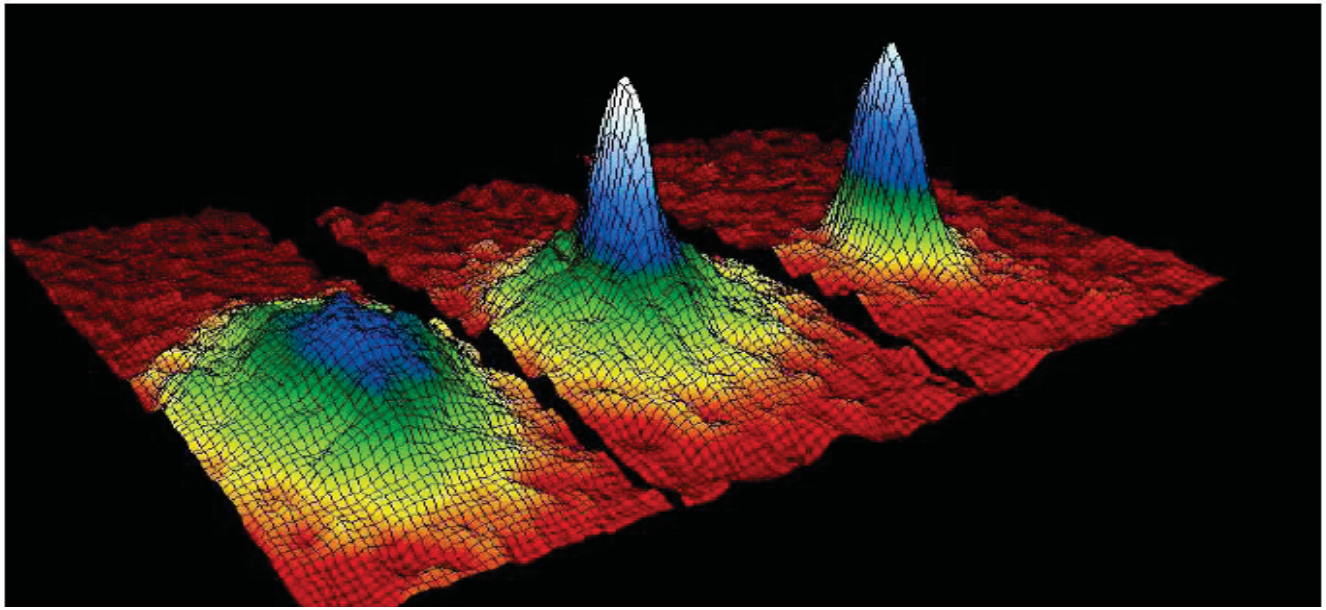


Sodium

W. Ketterle

MIT

Bose-Einstein condensation of weakly interacting atoms



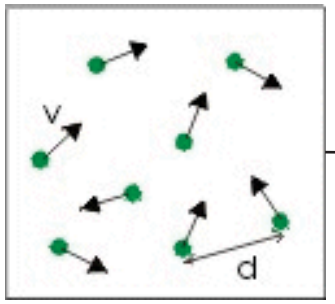
Typical distance between atoms	300 nm
Typical scattering length	10 nm

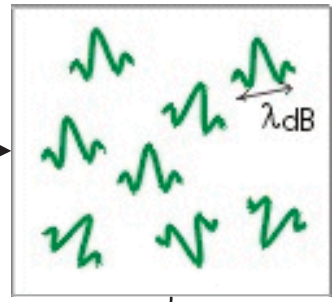
$$T_{\mathrm{BEC}} \sim 1\mu\mathrm{K}$$

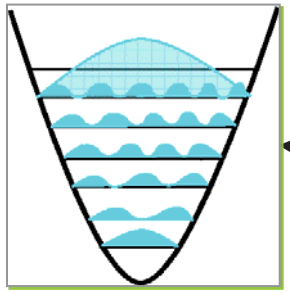
Scattering length is much smaller than characteristic interparticle distances.
Interactions are weak

Atomic gazes

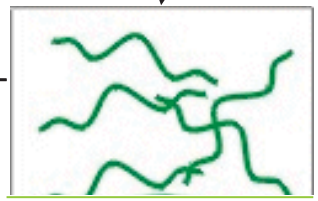
Theory of ideal classic gaz



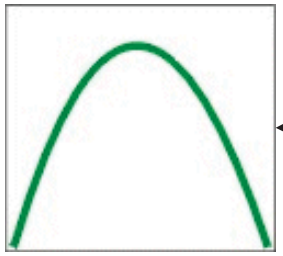




Das Pauli-verbot



$\Delta p \cdot \Delta x > \hbar$



Condensation of non interacting atoms

S.N. Bose and other Bosons

Bose-Einstein condensate

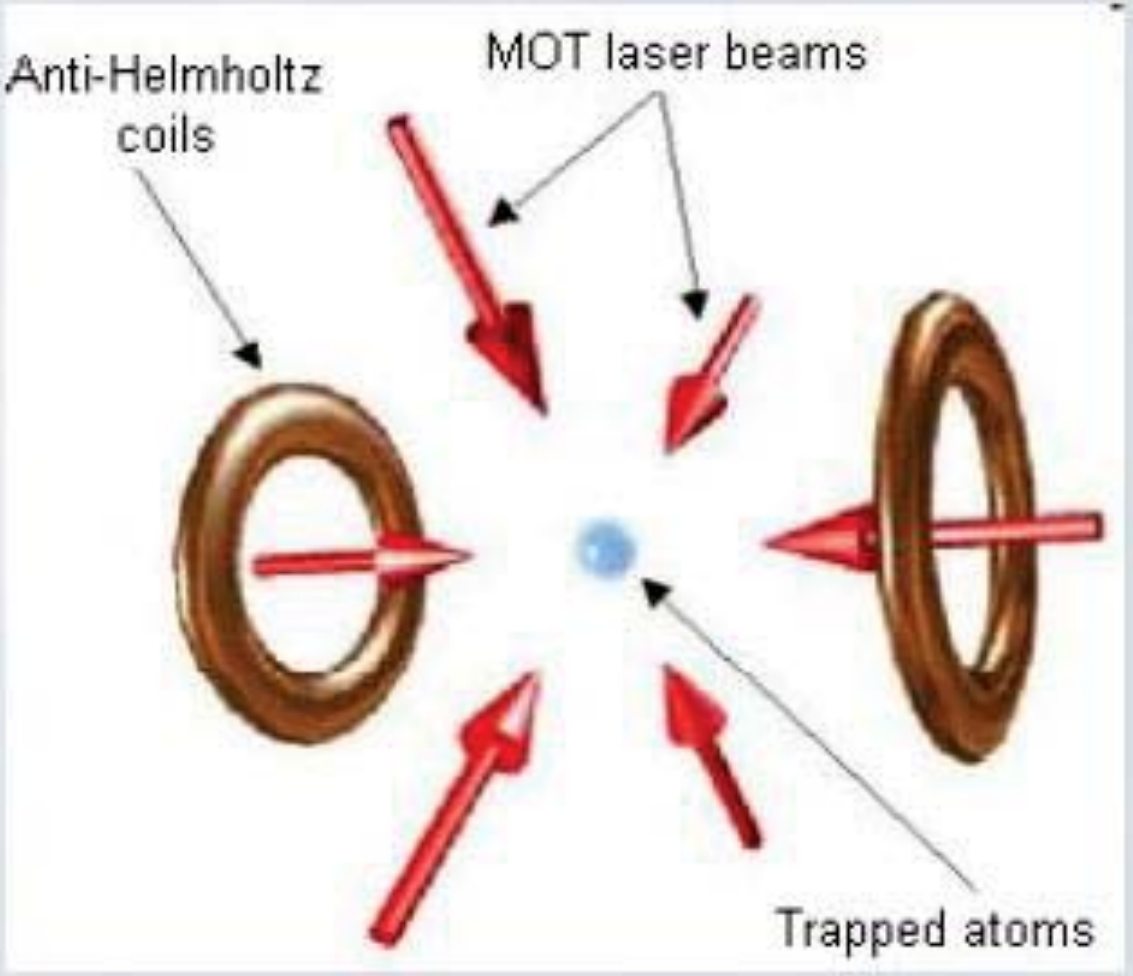
$T<T_c$

$T>T_c$

vs.

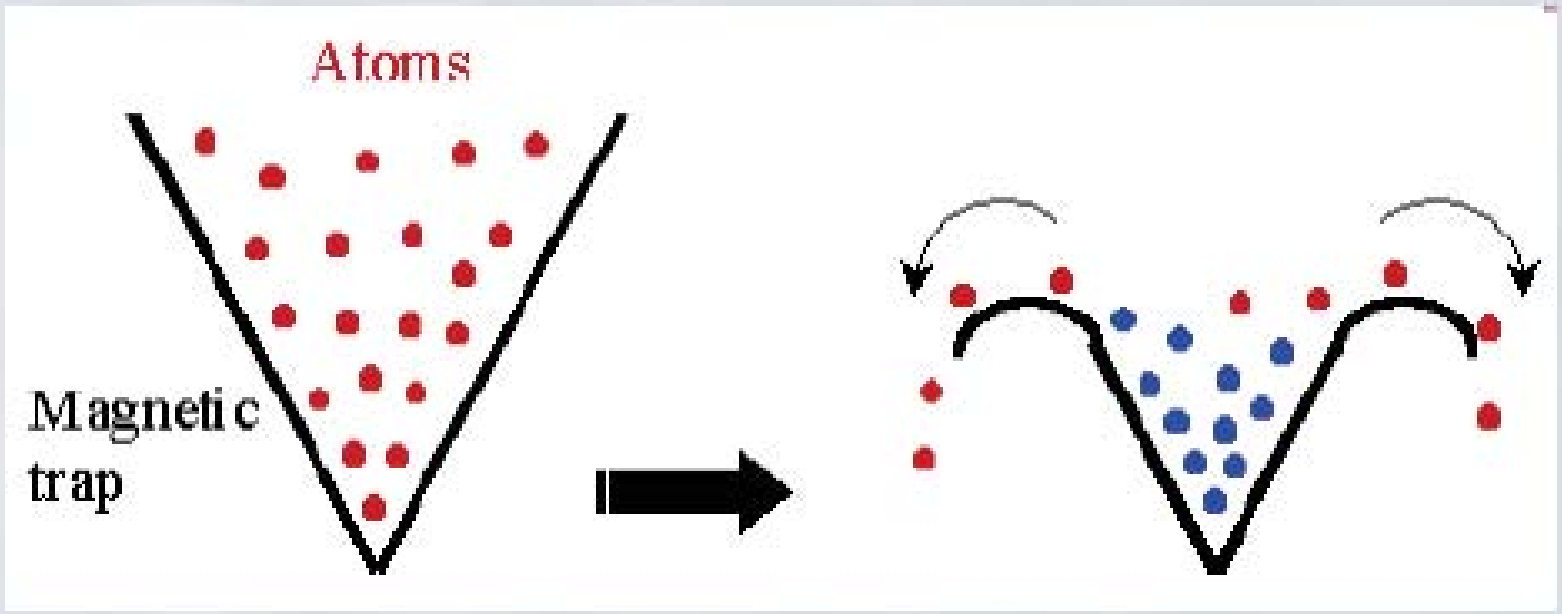
cf. le laser atomique

Magneto-Optical trap



Evaporative Cooling

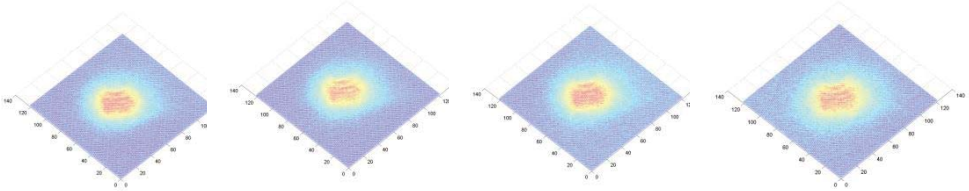
Magnetic Evaporative cooling



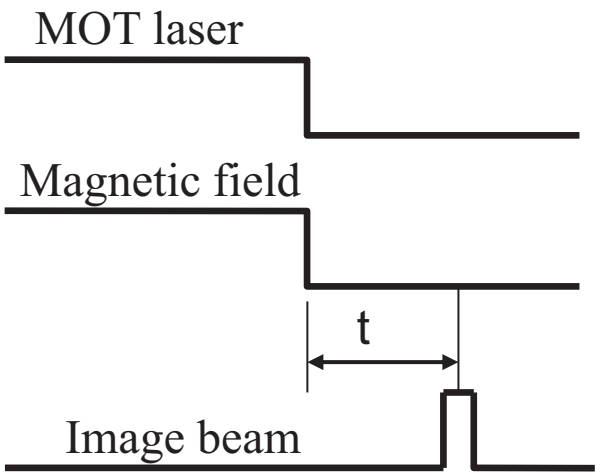
How to determine the temperature?

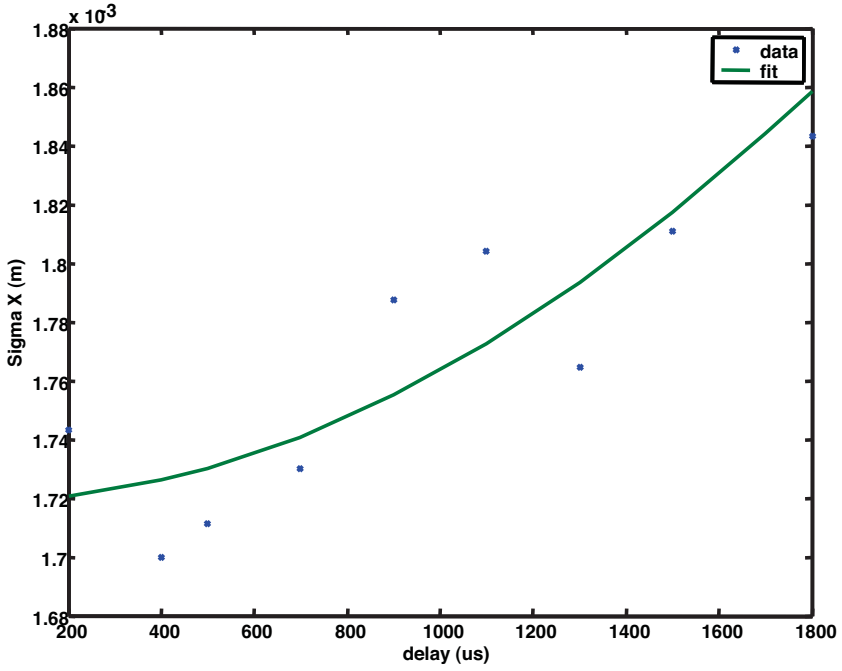
$$\sigma^2(t) = \sigma_0^2 + \bar{v}^2 t^2$$

$$\bar{v} = \sqrt{\frac{2k_B T}{m}}$$

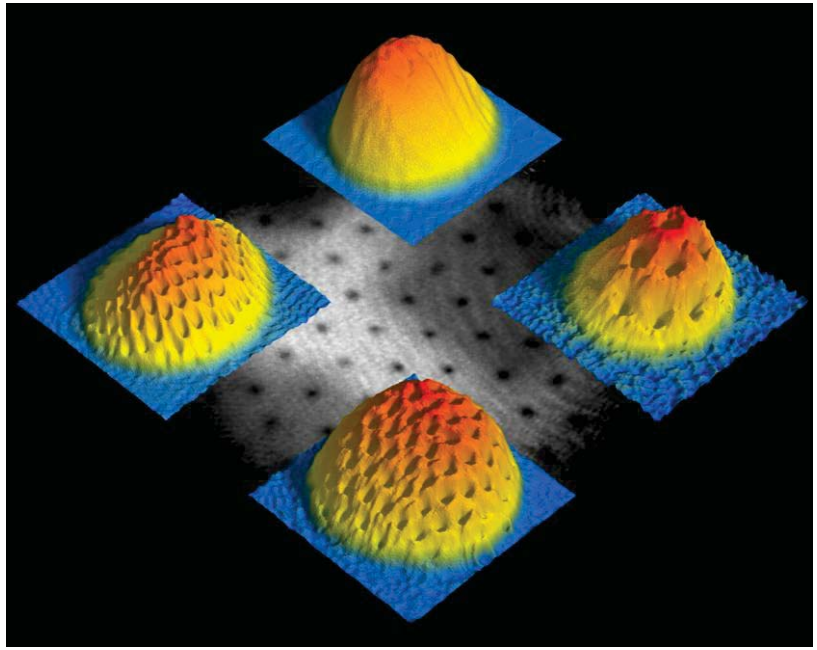


t=200 μs t=500 μs t=1000 μs t=2100 μs

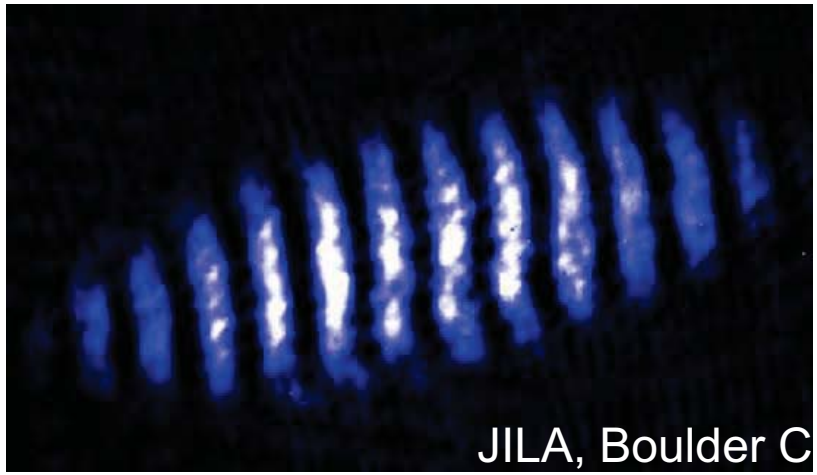




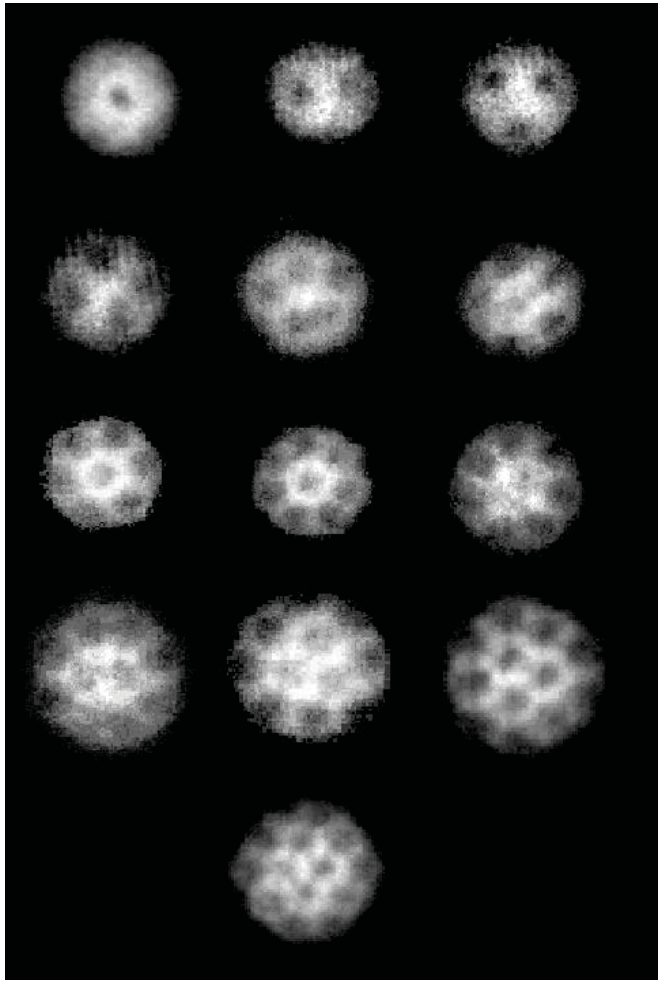
Rotating condensate and vortices



MIT, Cambridge MA, USA

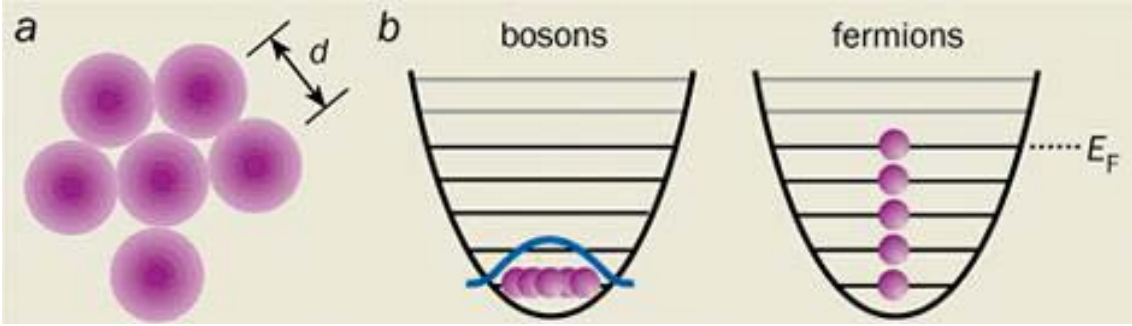


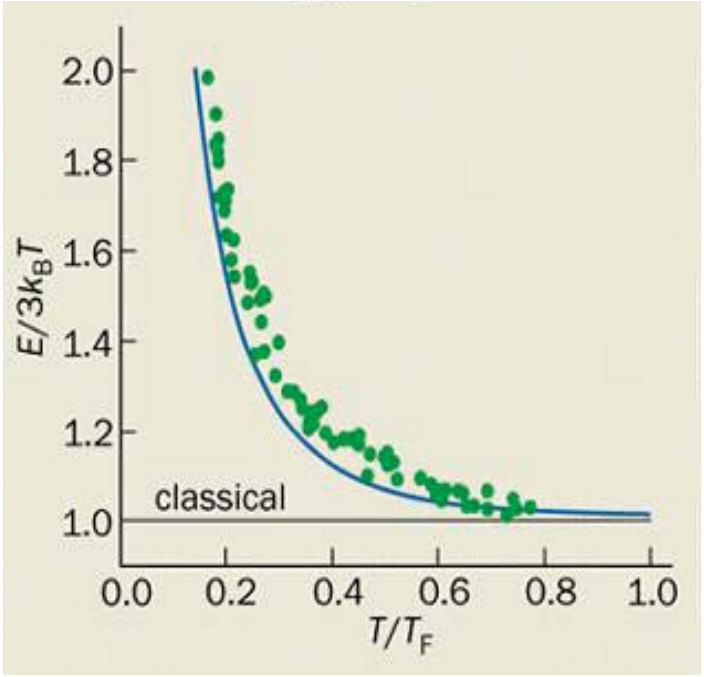
JILA, Boulder C

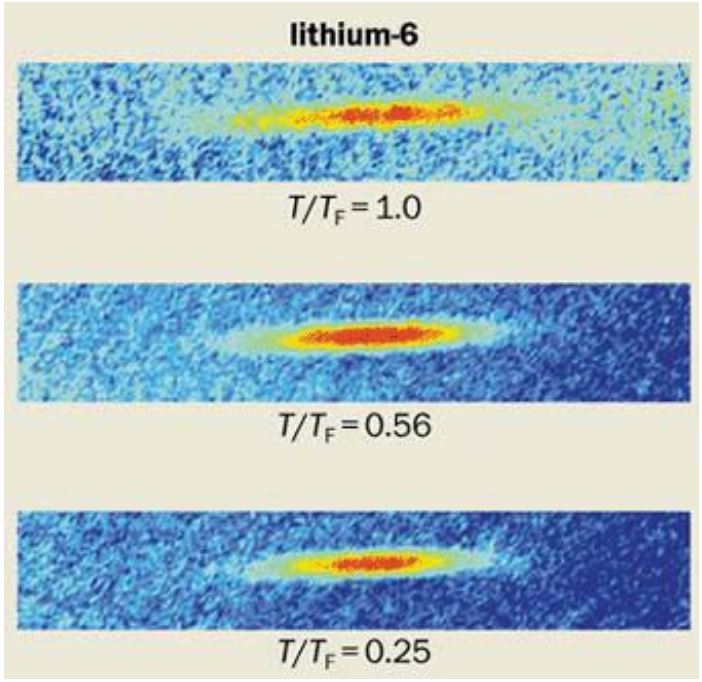


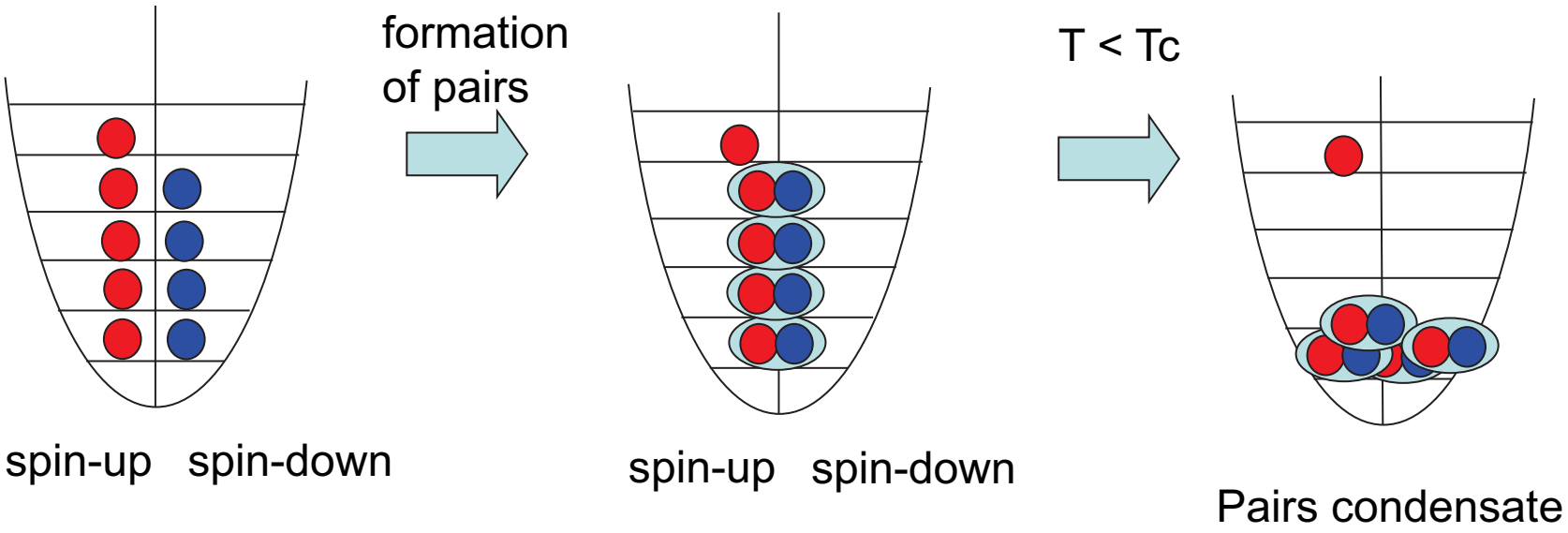
ENS, Paris, France

Fermions


a
d
b
bosons
fermions
E_F


2.0
1.8
1.6
1.4
1.2
1.0
$E/3k_BT$
classical
0.0
0.2
0.4
0.6
0.8
1.0
T/T_F


lithium-6
$T/T_F = 1.0$
$T/T_F = 0.56$
$T/T_F = 0.25$


formation
of pairs
T < Tc
spin-up spin-down
spin-up spin-down
Pairs condensate

Further quest to absolute zero ?

What are the applications of the cold gazes and BEC ?