LIGHT AND MATTER

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Light and Matter

- **Understanding light, matter and their interactions**
  - **A central question in Physics**
  - **At the origin of conceptual and technological revolutions**
    - The relativistic revolution
    - The quantum revolution
    - The laser revolution
- **Light emitted by atoms: a source of information on the world around us**

  Spectroscopy
- **A new trend in Atomic Physics: Using light-atom interactions for manipulating atoms**
  - **How can one polarize atoms with light?**
  - **How can one cool atoms with laser light to extremely low temperatures?**
  - **What are the new research fields, the new applications opened by these advances?**

Outline

1 – Brief historical review

- Early models for light
- Wave theories versus particle theories
- Modern descriptions. Wave- particle duality

2 – Light: a source of information on atoms and on the cosmos

Spectroscopy

3 – Light: a tool for manipulating atoms

- Optical pumping
- Laser cooling
- Atomic clocks. Matter waves

4 – Conclusion

Euclid
300 bc

Aristotle
350 bc

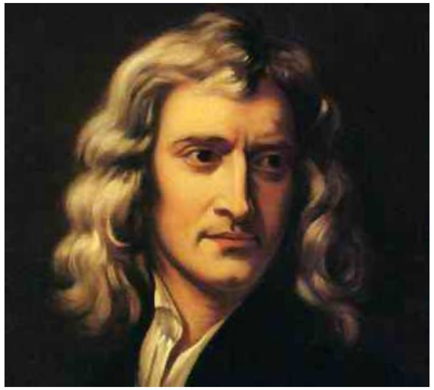
Ptolemy
200 ad

Alhazen (965-1040)

Iraqi scholar realizing for the first time that light is going from the object to the eye and not from the eye to the object

Light is a beam of particles

René Descartes
1596-1650



Isaac Newton
1643-1727

Light is a wave

Robert Hooke
1635-1703

Christiaan Huygens
1629-1695

Thomas Young
1773-1829

Augustin Fresnel
1788-1827

The triumph of wave theory
Maxwell's equations

James Clerk Maxwell
1831-1879

Heinrich Hertz
1857-1894

Unification of electricity, magnetism, optics, radio waves

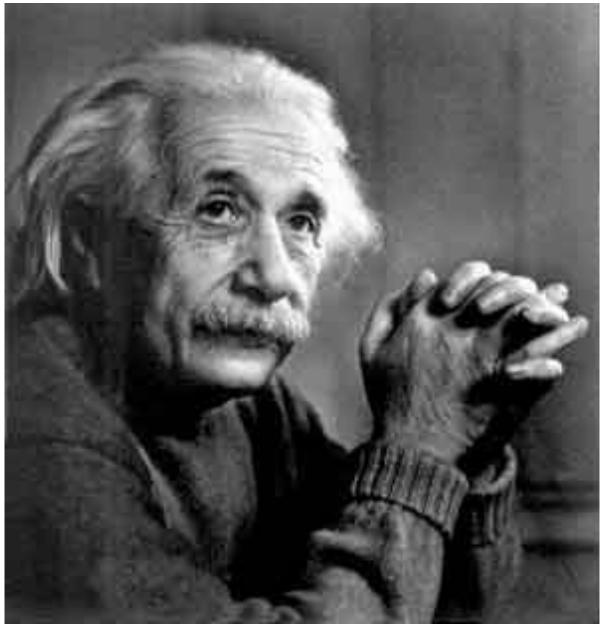
Two small "clouds"
at the end of the 19th century

1- Is light propagating through a medium called "ether"?

Failure to prove the existence of ether
(Michelson Morley experiment)

Solving this difficulty was at the origin of a conceptual revolution

Relativity of space and time



Albert Einstein
1879-1955

Two small "clouds"
at the end of the 19th century

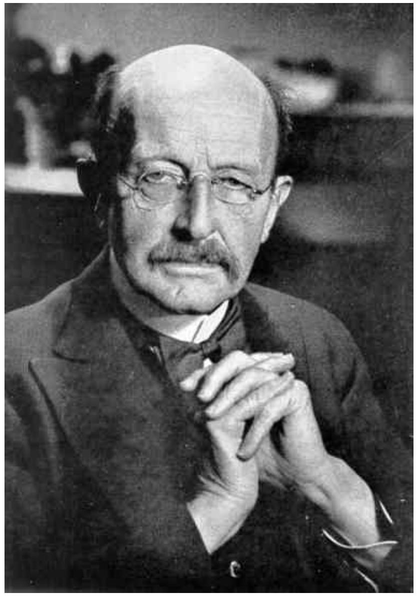
2- Frequency distribution of thermal radiation

Classical physics cannot explain this distribution

Solving this difficulty was at the origin of a second conceptual revolution

Quantization of the energy exchanges between light and matter (1900).
Birth of quantum physics

The light quantum
Einstein (1905)



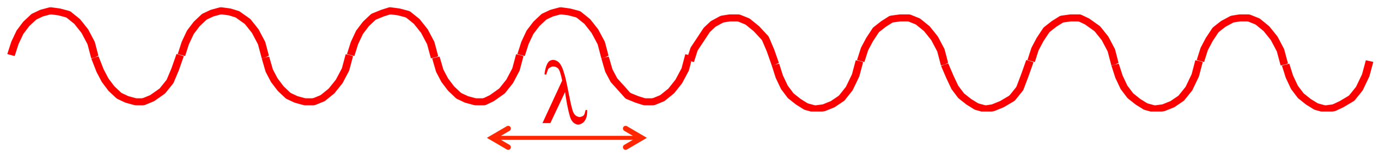
Max Planck
1858-1947

The modern description of light

Light is at the same time an electromagnetic wave

- with frequency ν, characterizing the color
- propagating in space with a velocity $c = 3 \times 10^8$ m/s

At a given time, sinusoidal wave whose spatial period is called the « wavelength » $\lambda = c / \nu$



And an ensemble of particles called « photons »

- with energy $E = h\nu$
- and momentum $p = h\nu / c$

h : Planck constant = 6.626×10^{-34} J.s

Both aspects are essential

Wave-particle duality

Wave-Particle Duality Extended to Matter (1924)

With every matter particle of mass M and velocity v is associated a wave with a wavelength λ_{dB} given by:

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

Louis de Broglie
1892-1987

<u>More generally,</u>

The state of a matter particle is described by a <u>wave function</u> obeying the <u>Schrödinger equation</u>

Only certain solutions of this equation are physically acceptable (analogy with the resonance frequencies of a music instrument)

The energy of an atom cannot take any value. It is <u>quantized</u>

2nd excited state

1st excited state

Ground state

Energy spectrum

Elementary Interaction Processes Between Atoms and Photons

<u>Emission</u>

The atom goes from e to g by emitting a photon hν

<u>Absorption</u>

The atom goes from g to e by absorbing a photon hν

$$E_e - E_g = h\nu$$

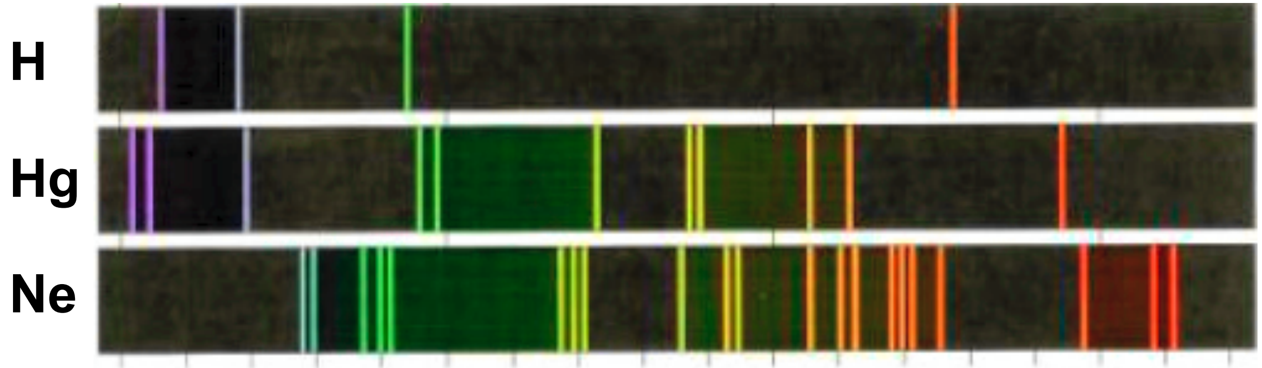
<u>Conservation of energy</u>

LIGHT
A SOURCE OF INFORMATION ON ATOMS

Light : a Source of Information on the Structure of Atoms

Measuring with a spectrometer the frequencies $(E_e\text{-}E_g)/h$ of the lines emitted by an atom allows one to reconstruct its energy diagram

A spectrum of lines characterizes an atom. It's a « finger print »



<u>Spectroscopy</u> : an essential source of information on various types of media, in particular in astrophysics

- **Galaxies, expansion of the universe**
- **Stellar and planetary atmospheres**
- **Interstellar molecules**
- **Plasmas, flames**
- **Detection of pollution (LIDAR)…**

LIGHT
A TOOL FOR MANIPULATING ATOMS

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 exciting it with conveniently prepared light beams

<u>First example</u> : Optical pumping

The absorption of polarized light can polarize atoms: all the atomic magnetic moments point along the same direction

Detection of magnetic resonance in dilute atomic gases

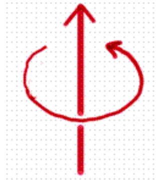
<u>Second example</u> : Laser cooling

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

Ultracold atoms

POLARIZING ATOMS

Atomic Angular Momentum



Atoms are « spinning tops »

They have an internal angular momentum J

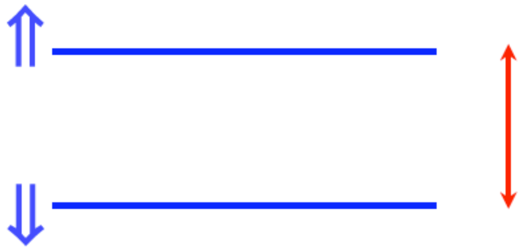
The projection J_z of J along the z-axis is quantized

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 $-M_zB$ proportional to *B*



Energy splitting Δ*E* proportional to *B*

$$\Delta E = h\nu_z$$

Magnetic resonance : transitions between the 2 spin states induced by a radiofrequency field of frequency ν_z

Optical pumping (A. Kastler, J. Brossel)

Atoms in thermal equilibrium at room temperatures, and in low magnetic field are weakly polarized.

Practically equal numbers of atoms ↑ and ↓

The magnetic resonance signals are proportional to the difference of populations in the 2 spin states.

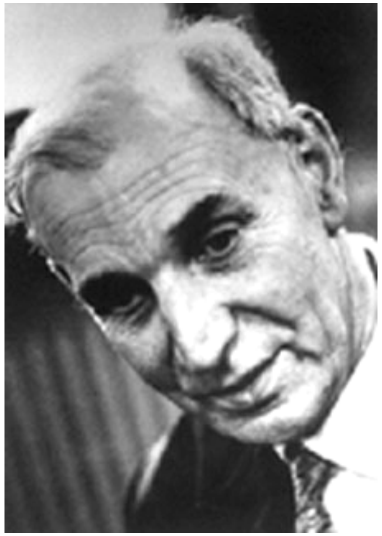
They are easy to observe only in dense systems (liquids, solids)

Polarization of atoms by light

Polarized photons have also an angular momentum and it is easy to polarize light

By absorbing polarized photons, atoms can gain the angular momentum of photons and become polarized.

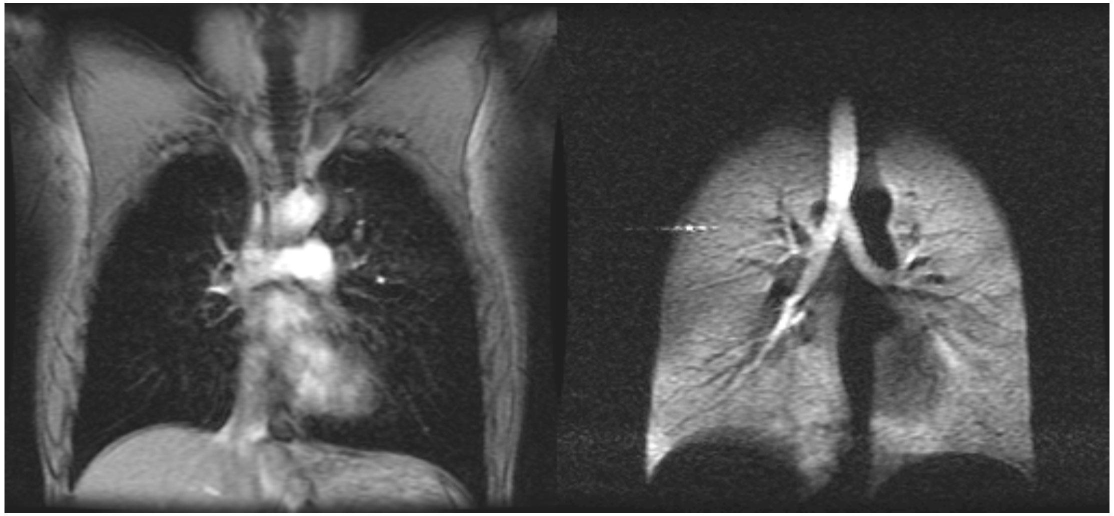
Gaseous samples with a high degree of polarization allowing a high resolution spectroscopy



Alfred Kastler

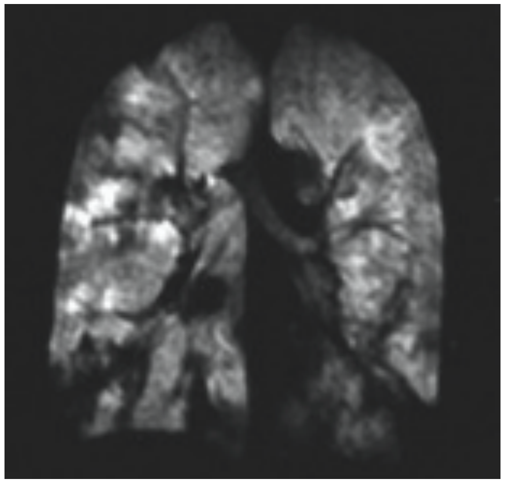
Jean Brossel

MRI Images of the Human Chest

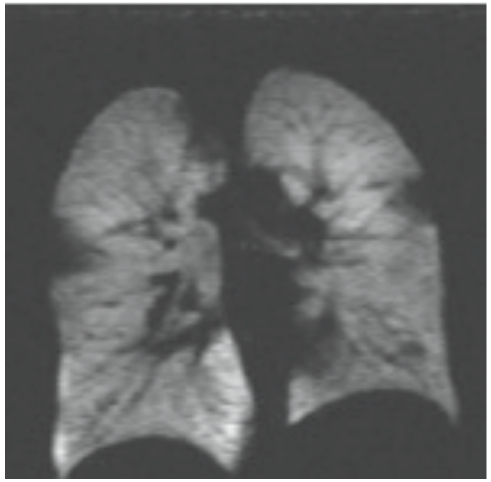


G.A.Johnson, L. Hedlund, J. MacFall Physics World, November 1998

Proton-MRI ^{3}He-MRI



Asthma



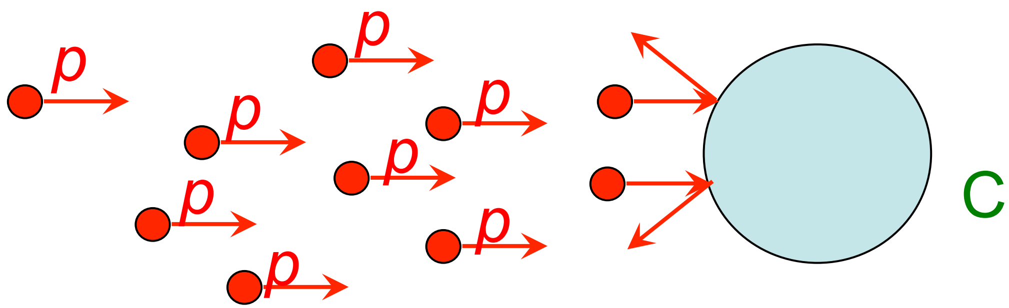
Smoker

LASER COOLING AND TRAPPING

Forces exerted by light on atoms

A simple example

Target C bombarded by projectiles *p* coming all along the same direction



As a result of the transfer of momentum from the projectiles to the target C, the target C is pushed

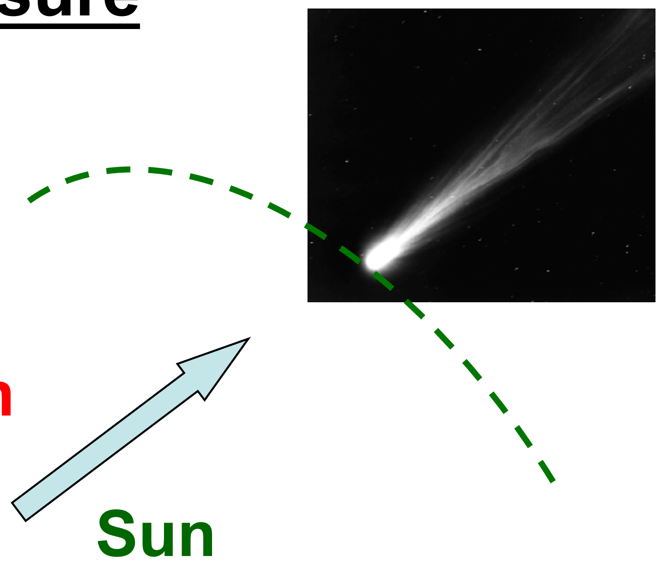
Atom in a light beam: radiation pressure

Analogous situation, the incoming photons, scattered by the atom C playing the role of the projectiles p

Explanation of the tail of the comets

In a resonant laser beam, the radiation pressure force can be very large

Accelerations (or decelerations) on the order of 100.000 g



Slowing down and cooling atoms with lasers

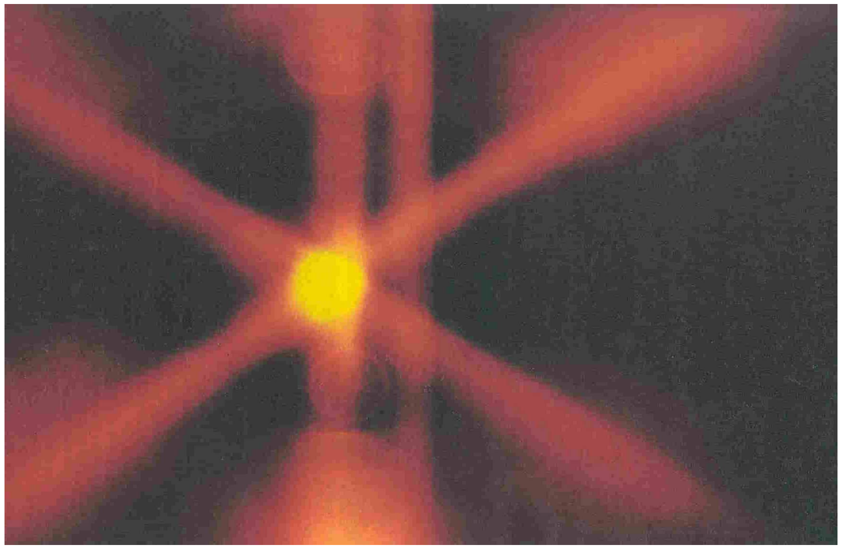
The forces exerted by laser beams on atoms allow one

- to reduce their mean velocity

  Slowing down atoms

- to reduce the velocity spread around the mean value, *i.e.* to reduce the disordered motion of the atoms

  Cooling atoms

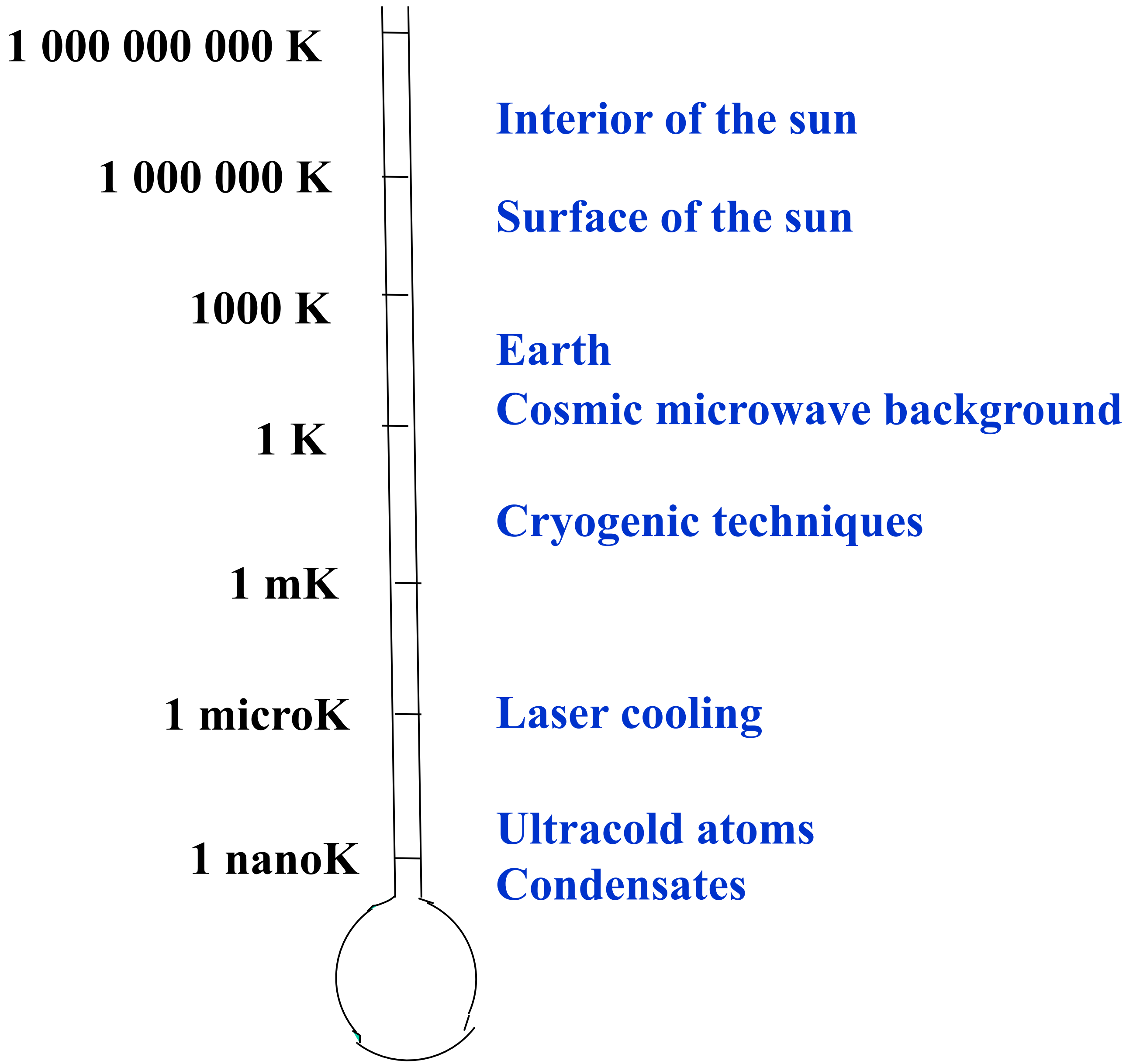


Obtaining temperatures on the order of a few 10^{-6} K and atomic velocities on the order of a few mm/s

At room temperatures (T = 300 K), atomic velocities are on the order of 1 km/s

Ultracold atoms; a rapidly expanding research field

Temperature scale (in Kelvin units)



A FEW APPLICATIONS OF ULTRACOLD ATOMS

Applications of ultracold atoms

1- Long observation times

Ultracold atoms are moving very slowly and can be kept during a much longer time T in the observation zone

The measurement of atomic frequencies becomes more and more precise when the T becomes longer and longer

More stable and more precise atomic clocks

Improvement of the GPS system

2- Long de Broglie wavelengths

$\lambda_{dB} = h/mv \qquad v \text{ small} \Rightarrow \lambda_{dB} \text{ large}$

The wave nature of atoms becomes easier to observe

(i) Atomic interferometry

Gyrometers, gradiometers using matter waves

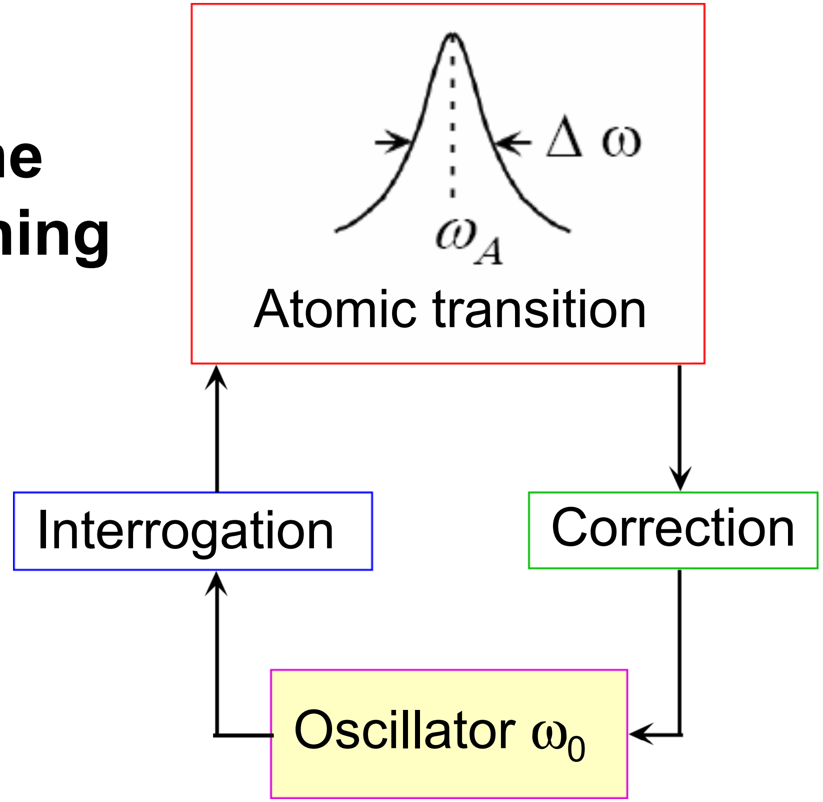
(ii) Ultracold quantum gases

Realization of new states of matter with macroscopic quantum properties: Bose-Einstein condensates

Measuring time with atomic clocks

Principle of an atomic clock

The correction loop locks the frequency of the oscillator to the frequency ω_A of the hyperfine transition of ^{133}Cs used for defining the second



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

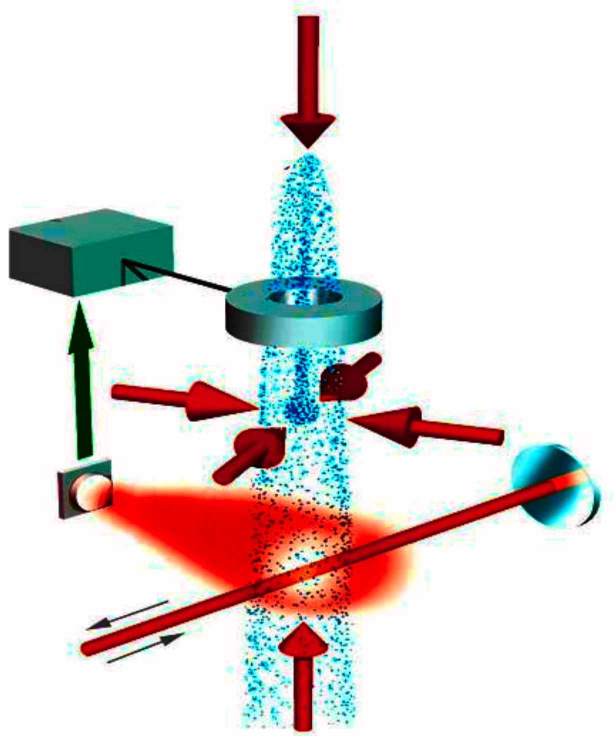
$$\Delta\omega \approx 1 / T$$

T : Observation time

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

Examples of atomic fountains

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



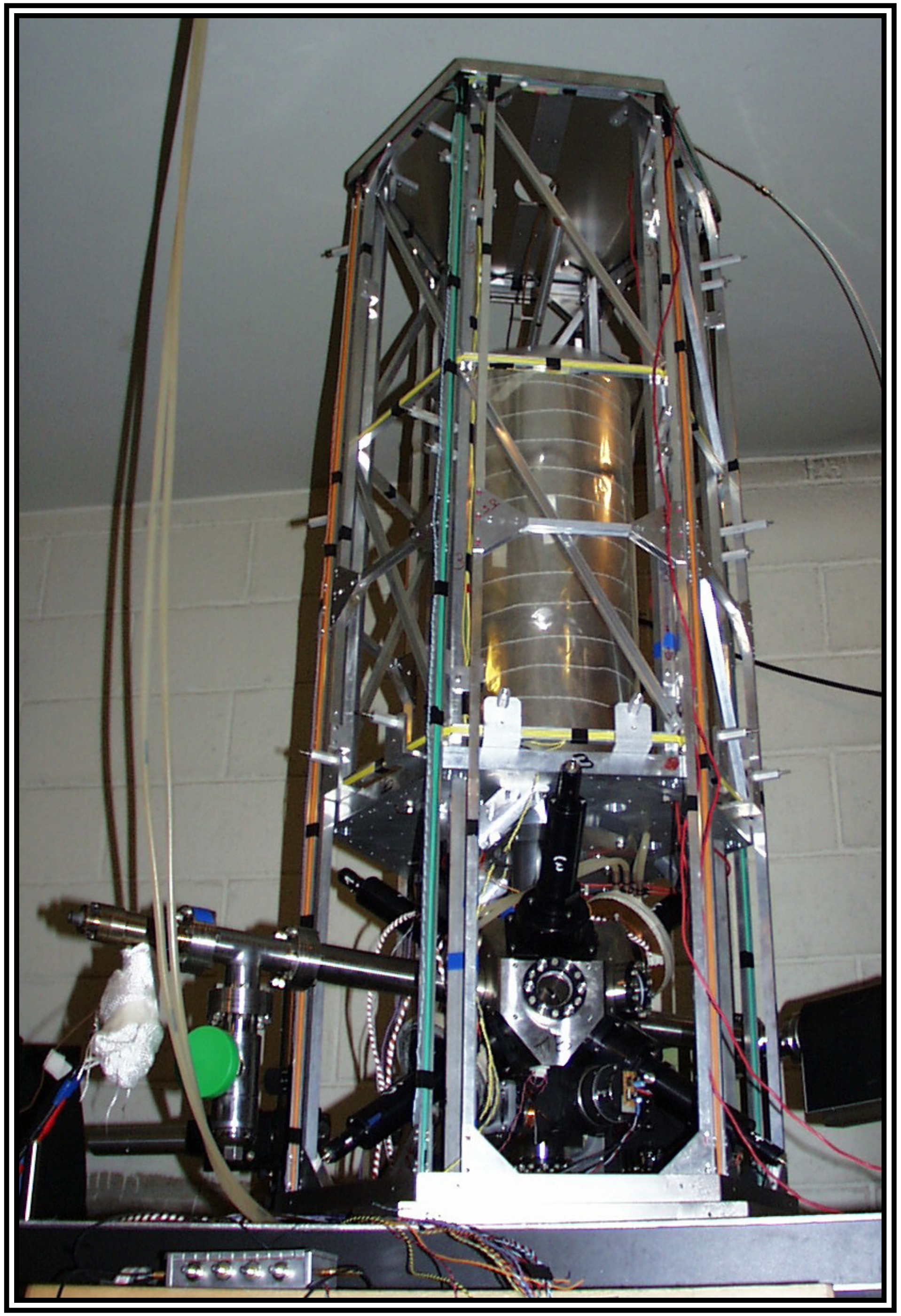
Christophe Salomon

André Clairon

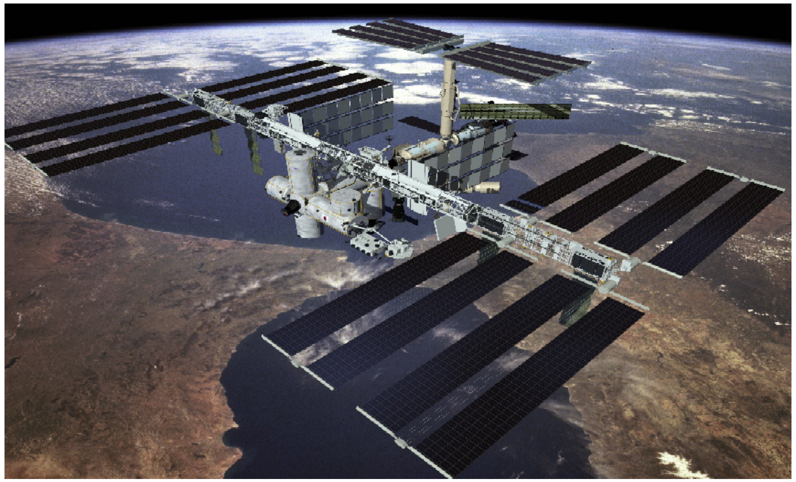
Stability: 1.6 x 10^{-16} for an integration time 5 x 10^{4} s
Accuracy: 3 x 10^{-16}

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

Atomic Fountain BNM-SYRTE



From terrestrial clocks to space clocks



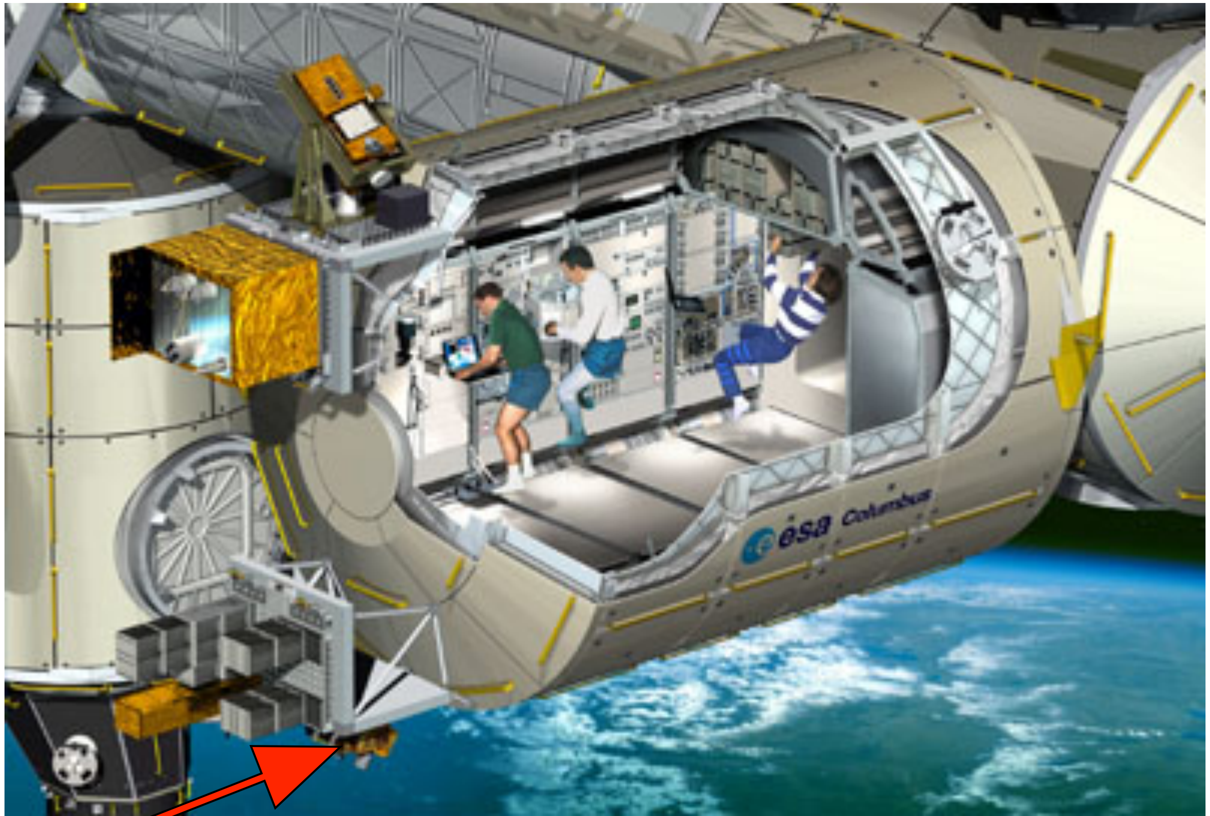
ACES project

Test of Einstein's gravitational shift

$\Delta\omega / \omega = \Delta U / c^2$

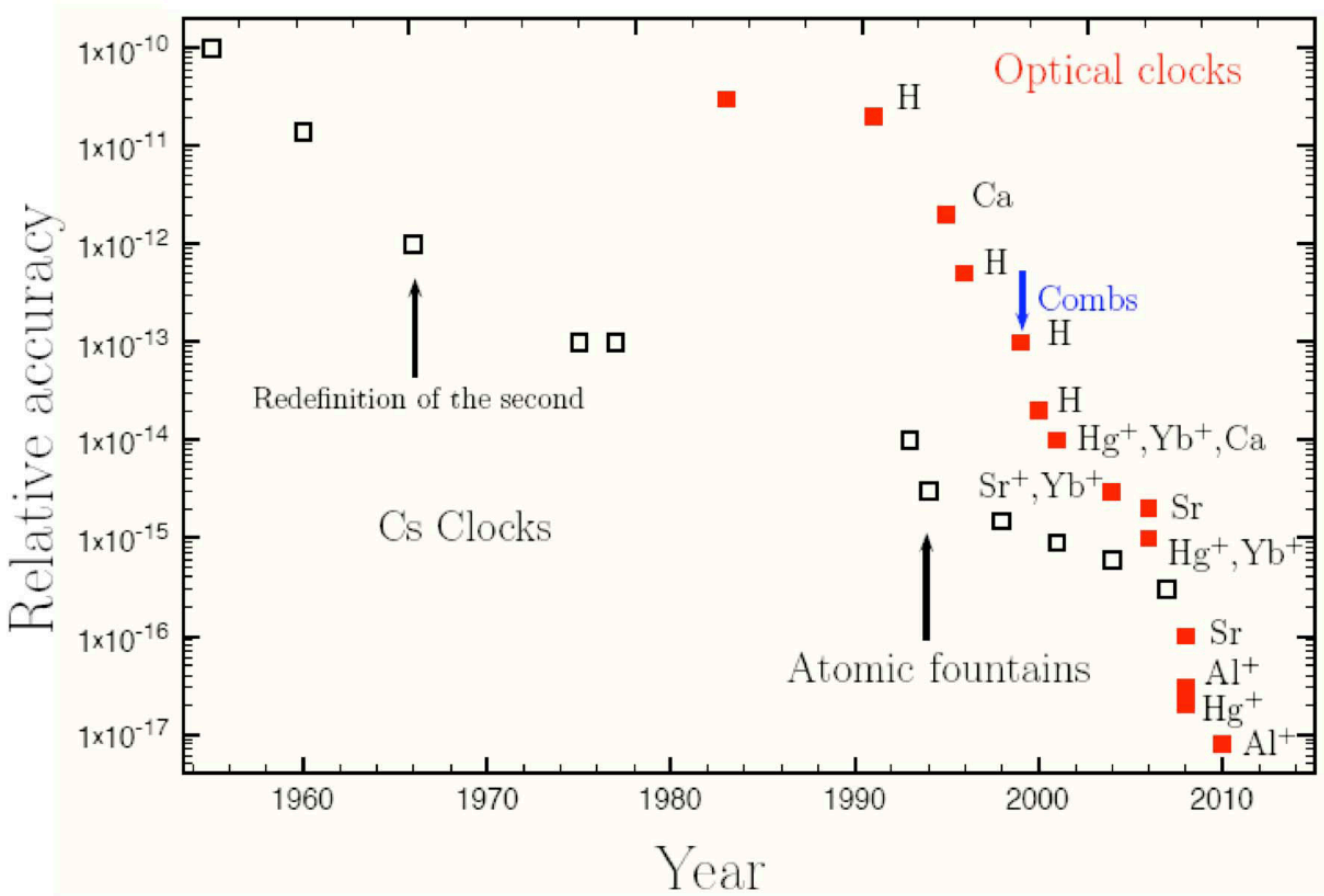
C. Salomon
A. Clairon

ACES ON COLUMBUS EXTERNAL PLATFORM



ACES

M = 227 kg P = 450 W



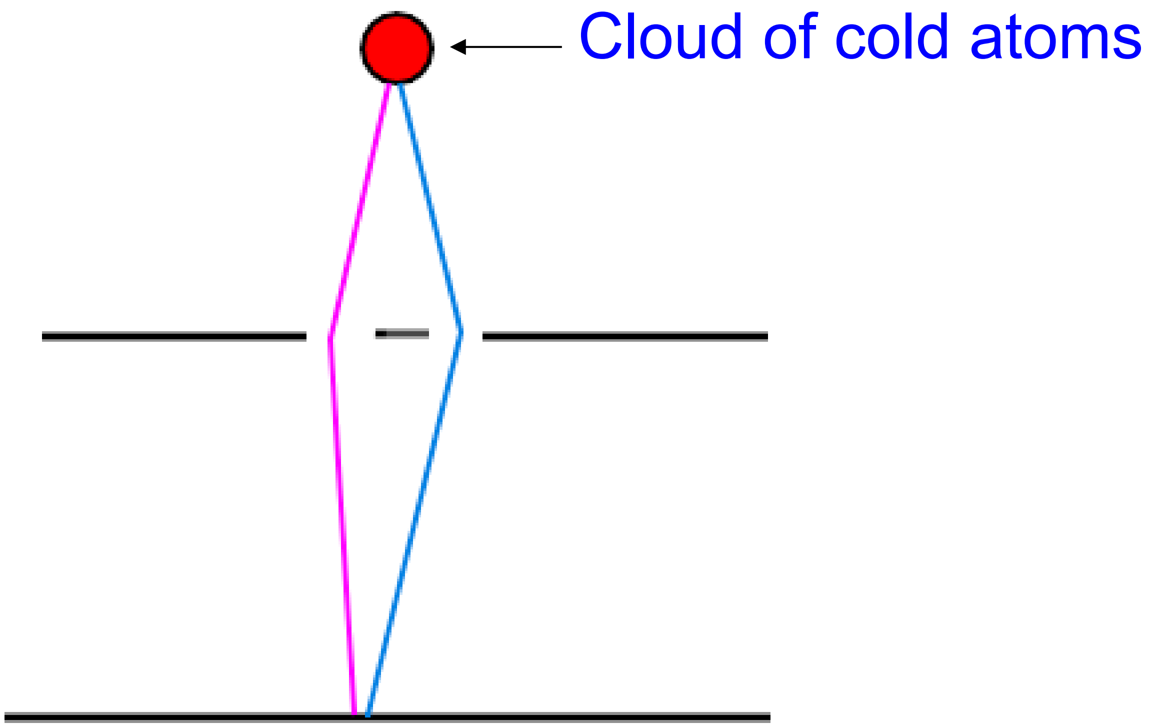
A stability of 10^{-17} corresponds to

- an error smaller than 1 second in 3 billion years

- to a sensitivity of 10 cm for the gravitational red shift

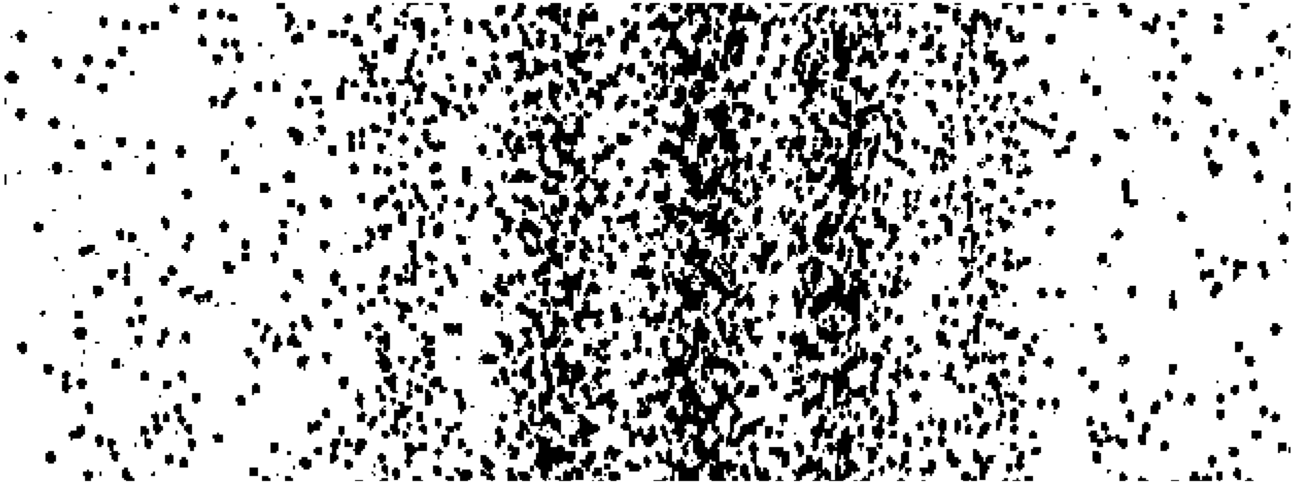
ATOMIC DE BROGLIE WAVES

Interference fringes obtained with the de Broglie waves associated with metastable laser cooled Neon atoms



F.Shimizu, K.Shimizu, H.Takuma Phys.Rev. **A46**, R17 (1992)

Experimental results



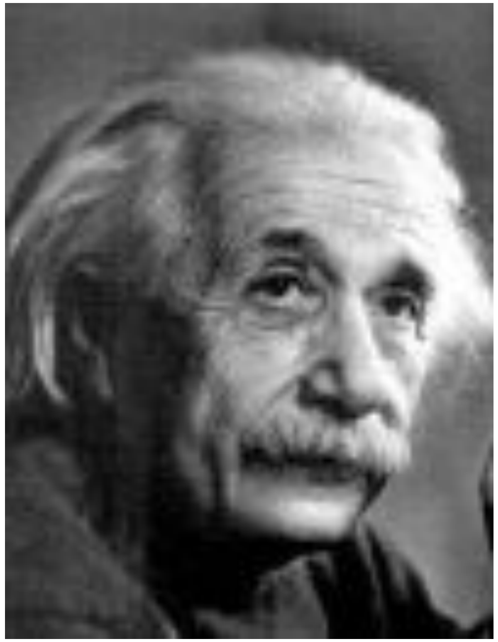
Each atom gives rise to a localized impact on the detector
The spatial repartition of the impacts is spatially modulated

Wave-particle duality for atoms

The wave associated with the atom allows one to calculate the probability to find the atom at a given point

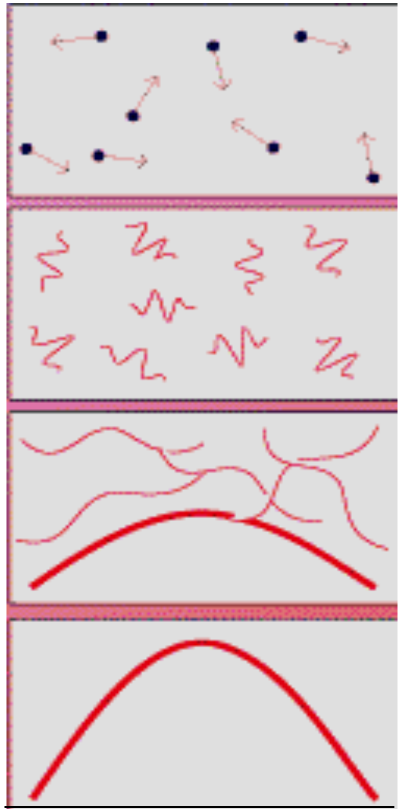
Bose-Einstein Condensation

Satyendra Nath Bose



Albert Einstein

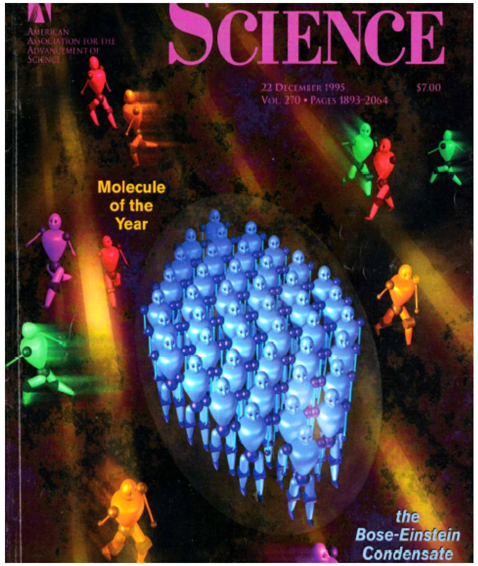
Bose Einstein condensation



When the temperature decreases, the de Broglie wavelength increases and the atomic wave packets become more and more extended.

When they overlap, they interfere and all atoms se condense in the ground state of the trap which contains them.

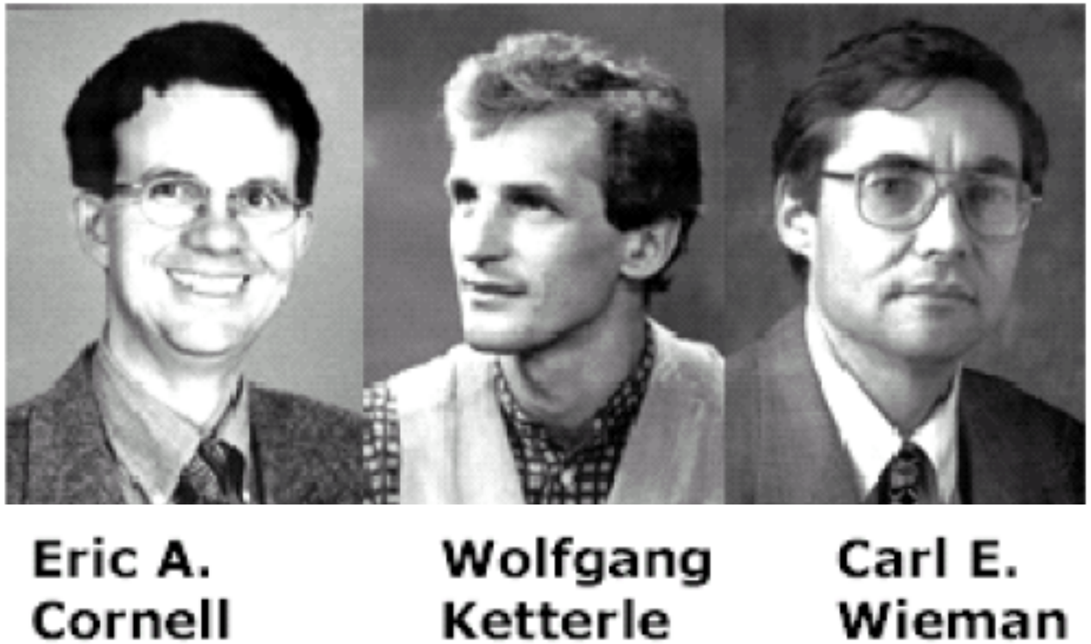
They form a macroscopic matter wave

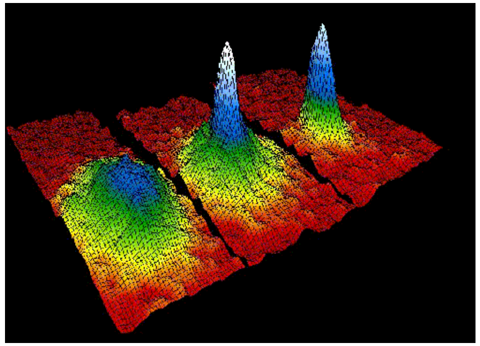


All atoms are in the same quantum state and they evolve in a coherent way like the soldiers of an army marching in lockstep

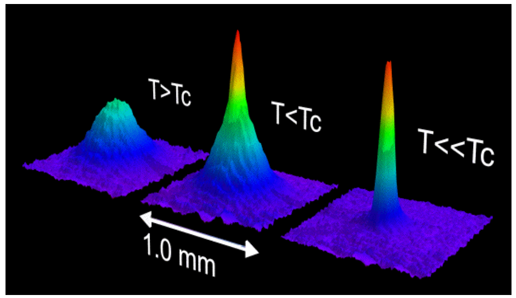
These gaseous condensates, discovered in 1995, are macroscopic quantum systems with properties (superfluidity, coherence) which make them very similar to other systems only found up to now in liquids or solids (liquid helium, superconductors)

Experimental observation (1995)





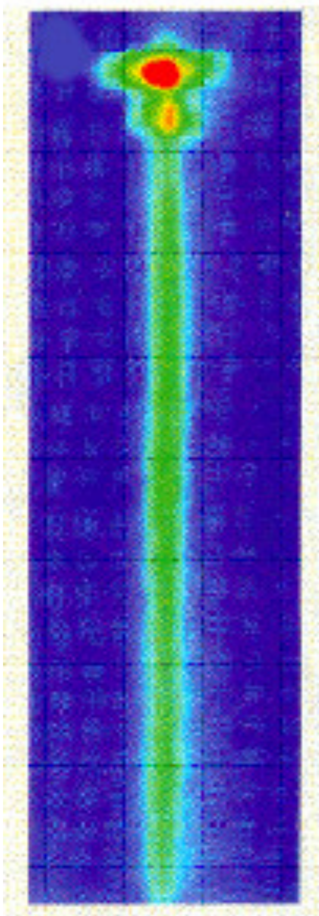
JILA ^{87}Rb



MIT ^{23}Na

Many others atoms have been condensed
^{7}Li, ^{1}H, ^{4}He*, ^{41}K, ^{133}Cs, ^{174}Yb, ^{52}Cr…

Example of application



Atom laser : coherent beam of atomic de Broglie waves extracted from a Bose Einstein condensate

Conclusion

The better understanding of light-matter interactions has allowed several important advances:

- **invention of new light sources, the lasers**
- **invention of new schemes (optical pumping, laser cooling) for manipulating atoms**

These advances are opening new research fields and allow us to ask new questions and to investigate new systems, new states of matter, like macroscopic matter waves which share many common features with light waves

The history of light and matter shows that basic research

- **changes our vision of the world by introducing conceptual revolutions (relativity, quantum physics)**
- **leads to a wealth of unexpected practical applications**

Science is a fascinating adventure which should attract young students who want to explore new fields and find new solutions for improving our living conditions on earth