The fast and the slow: a new strategy for understanding the quantum world

INSPYRE 2018

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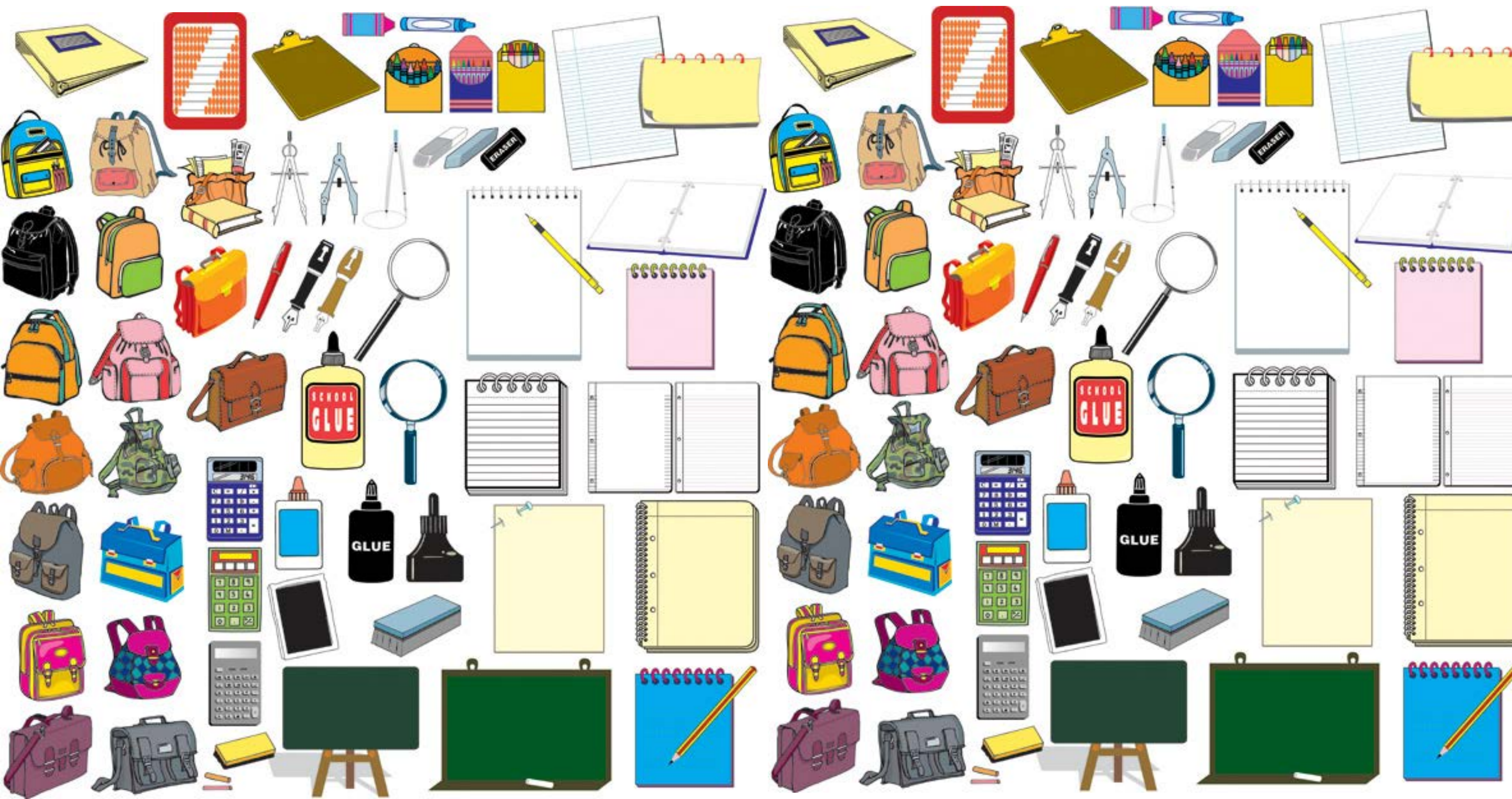
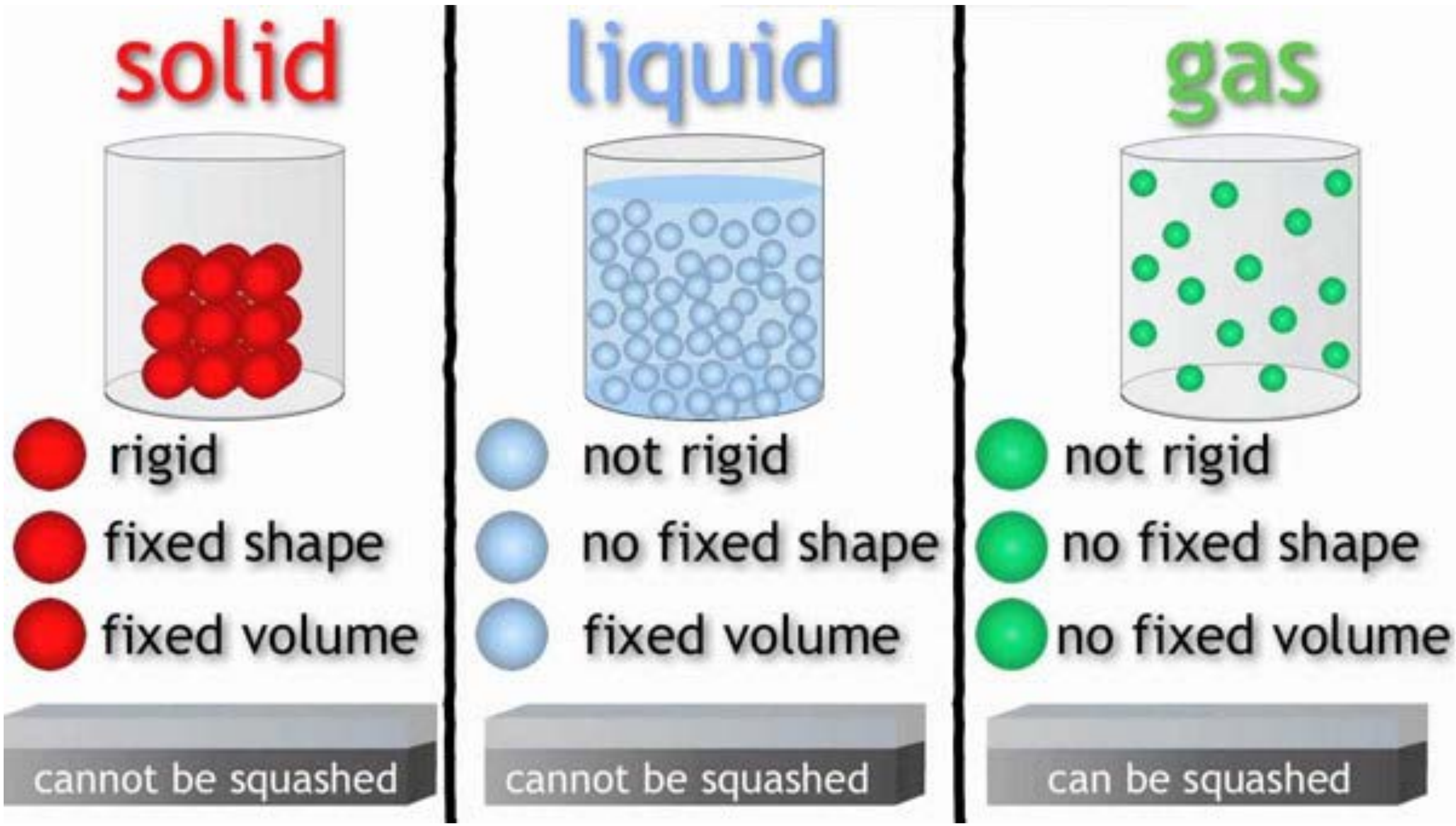
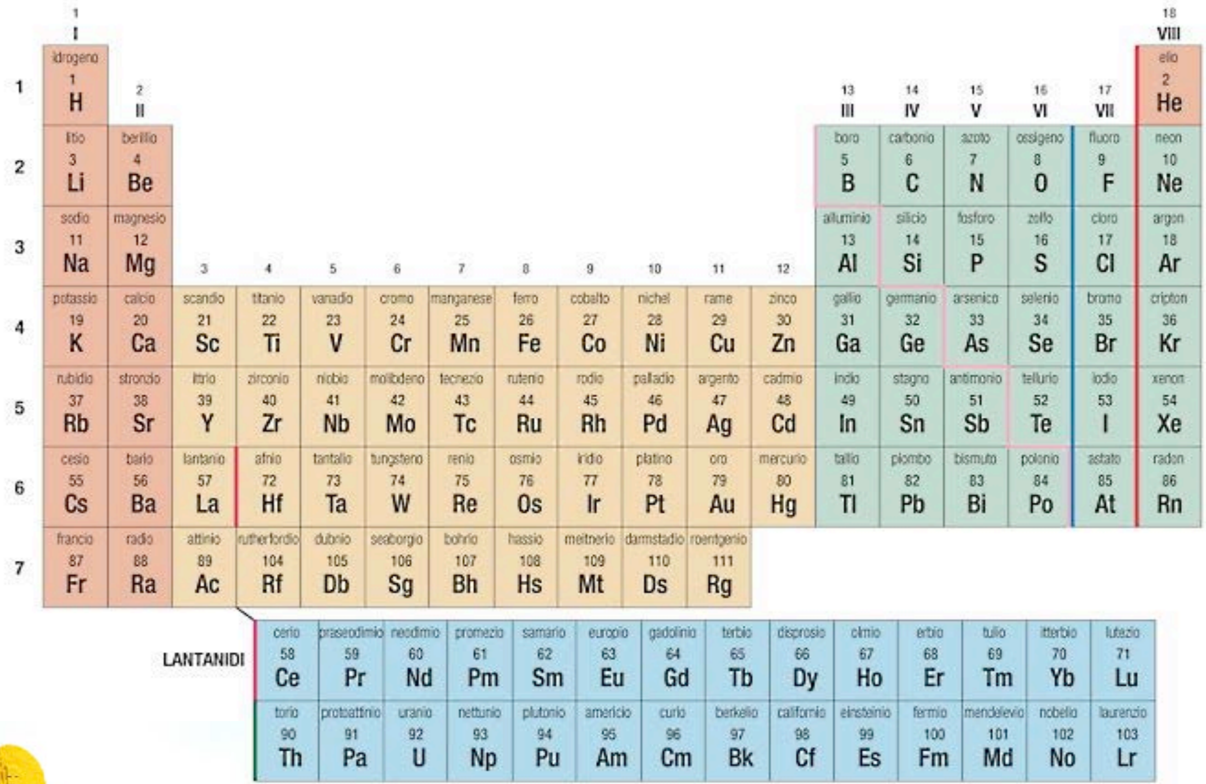
MATTER



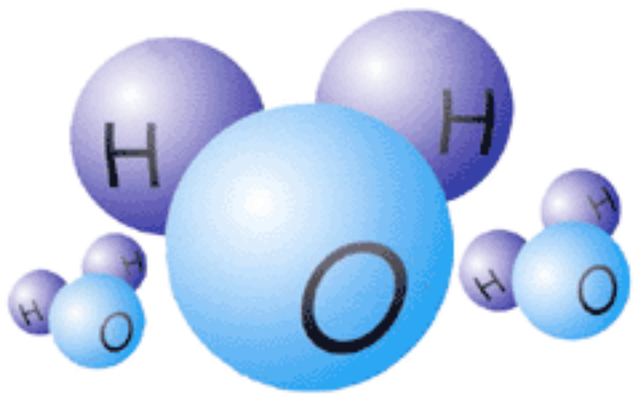
Matter is made of atoms

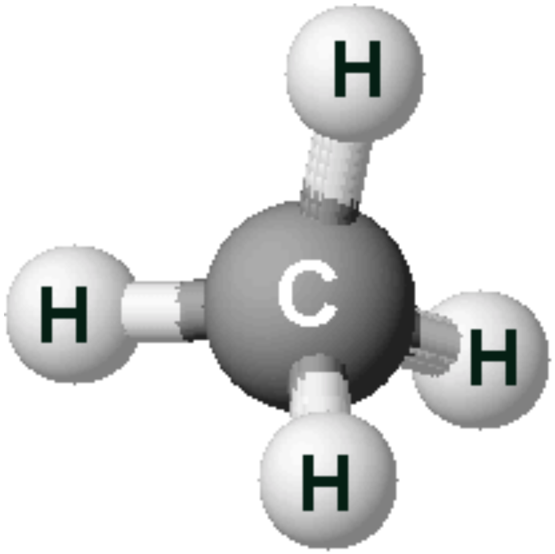


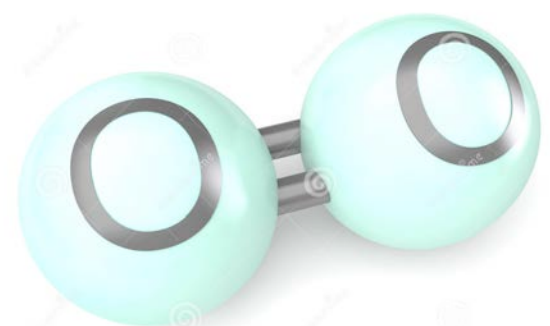
Matter is made of FEW atoms



Atom form simple molecules···





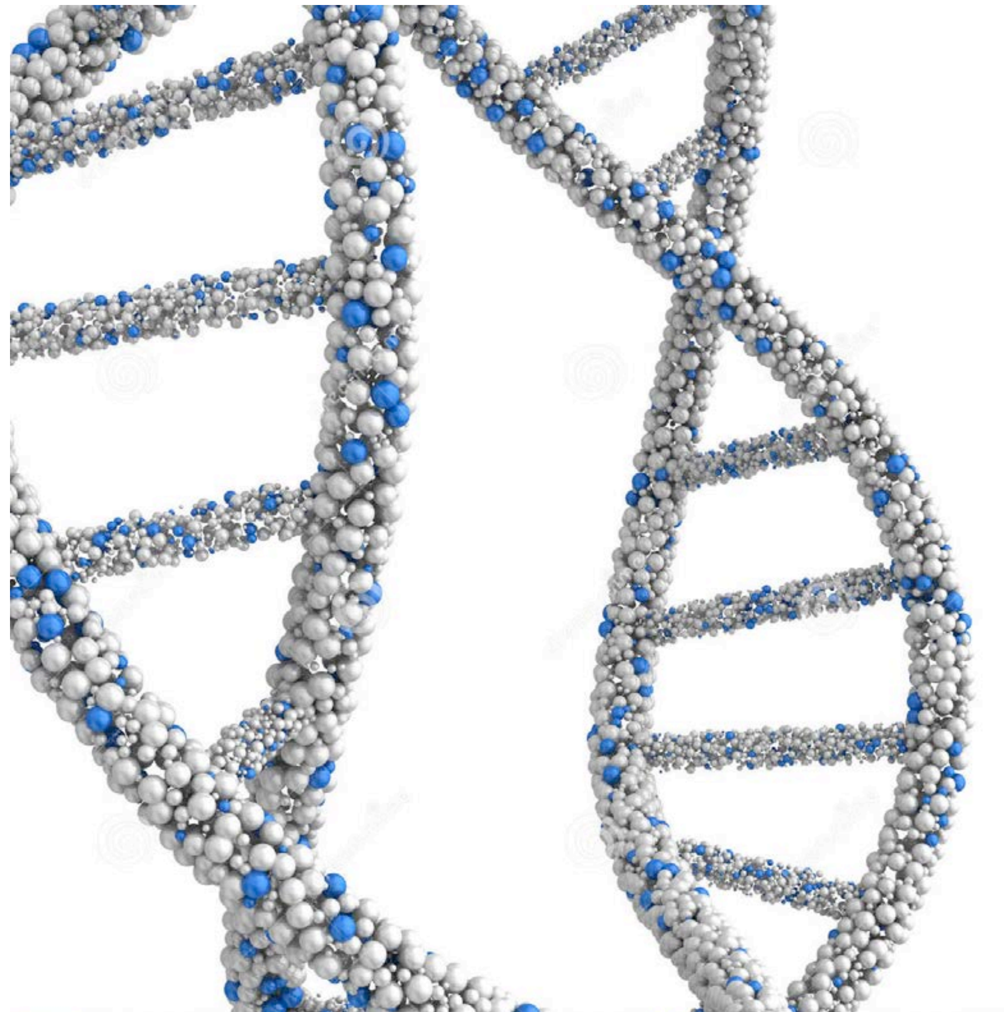


···as well as more complex molecules

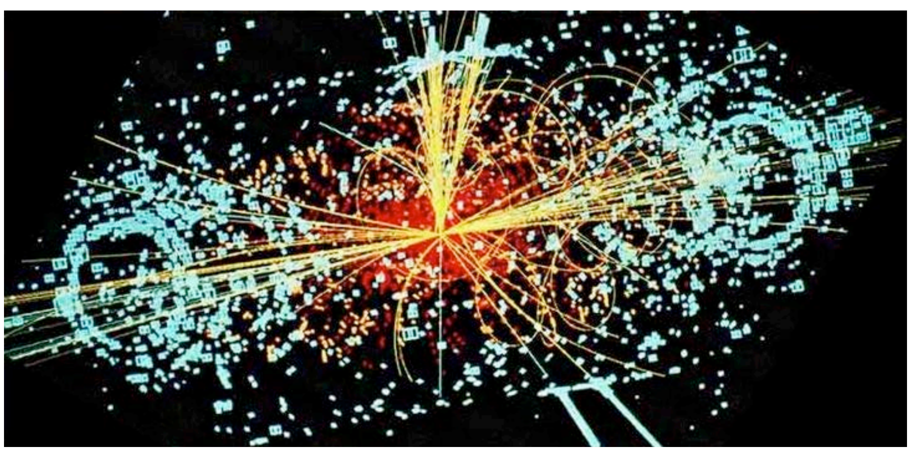
DNA
Life

The length of human DNA in each single cell is 2 meters.

It contains over 200 billion atoms. Same as the number of galaxies in the universe.



How do we study atoms?

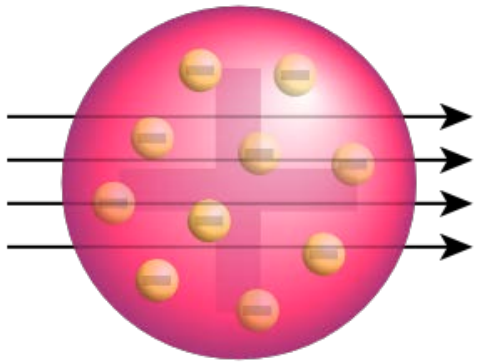


Physicists **break matter** and see what there is inside

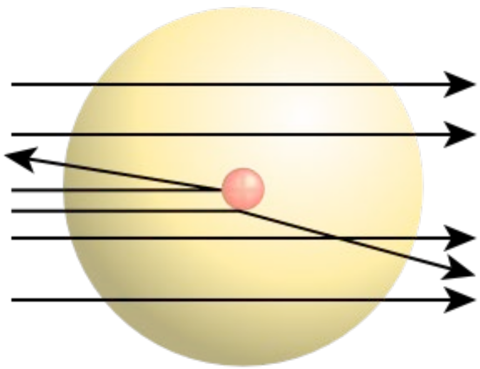
(modern accelerators)

Rutherford model for the atom (1911)

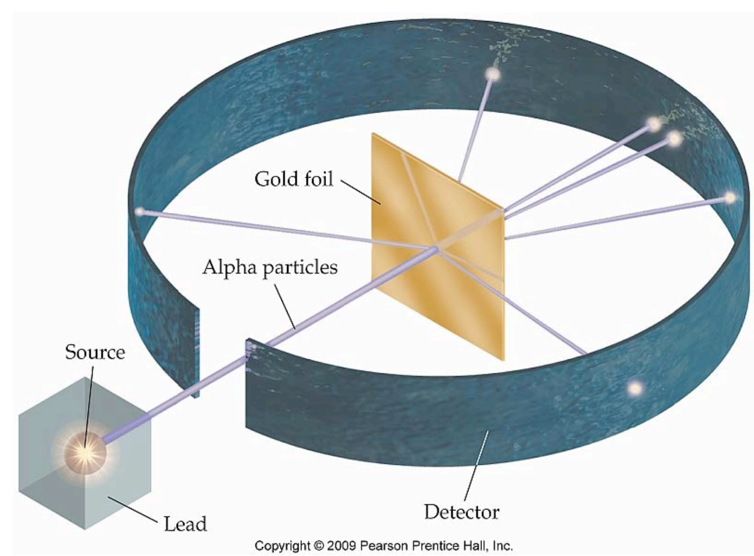
Two models for the atom



1. Plum pudding model

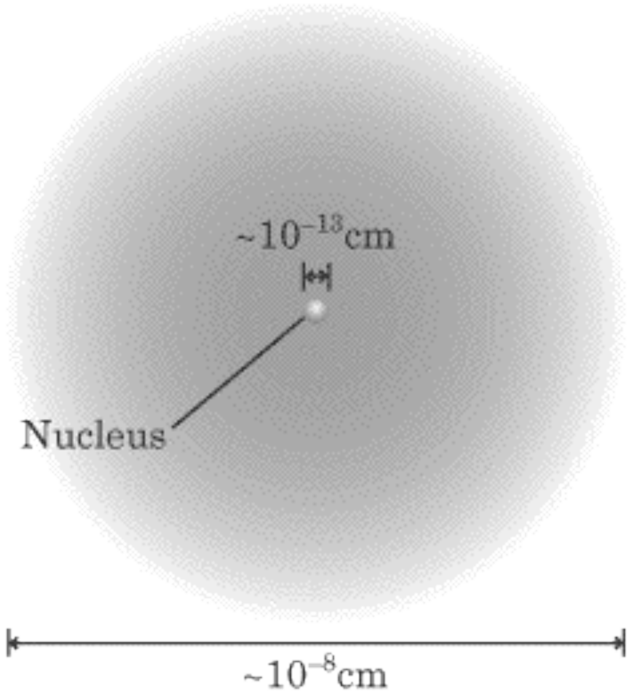


2. Planetary model



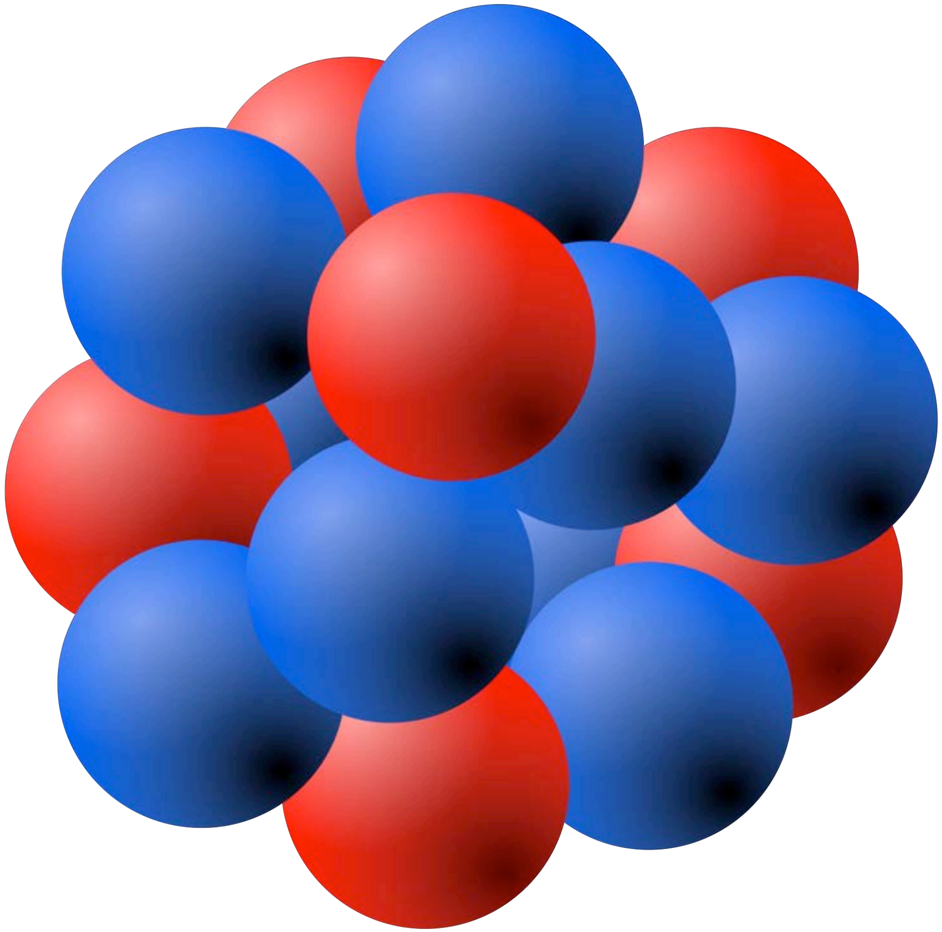
Experiment➔
The planetary models wins

The atom today

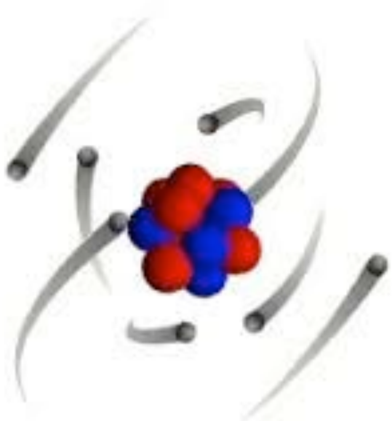


A compact nucleus with positive charge, surrounded by electrons with negative charge

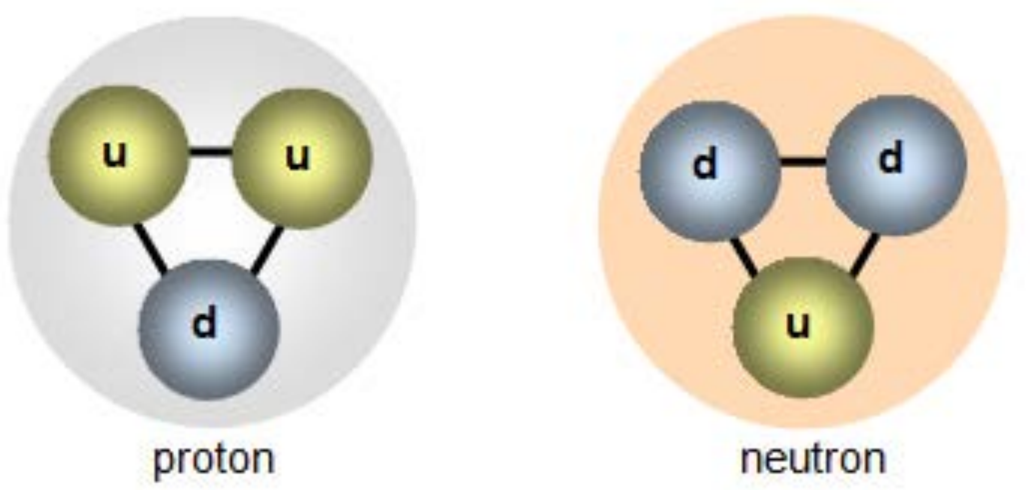
Inside the atom: the nucleon



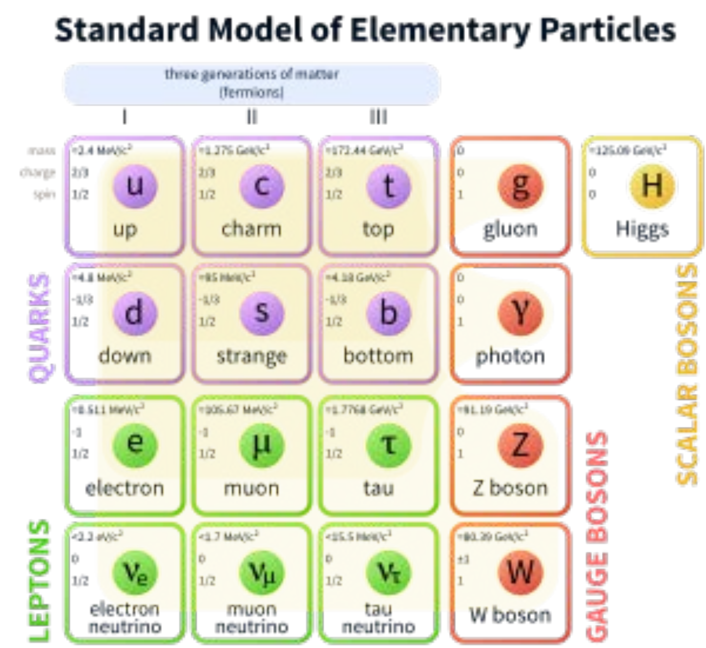
The **nucleus** is made of **protons**, with positive charge, and **neutrons**, which are neutral. They are called **nucleons.**



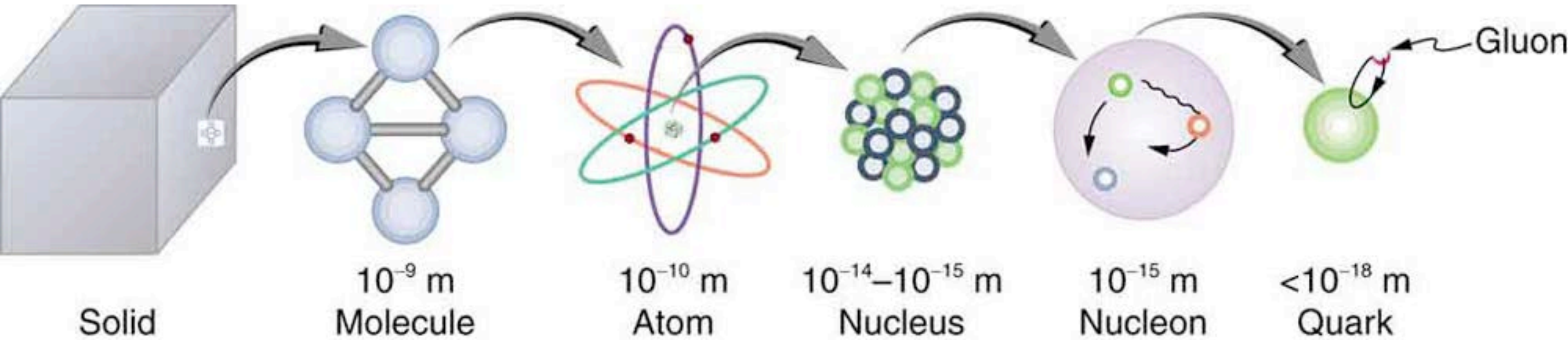
Inside the nucleon: the quarks



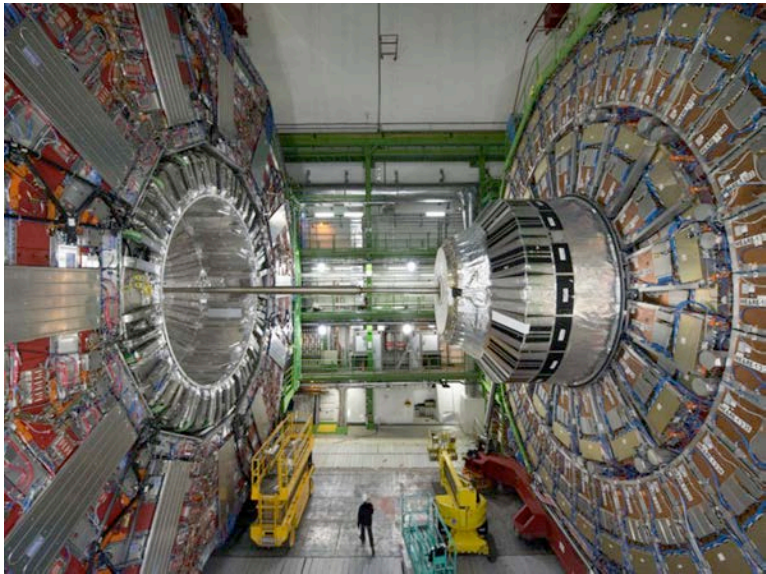
Quarks are of different types and are strongly interacting. It takes a lot of energy to see them "separately"



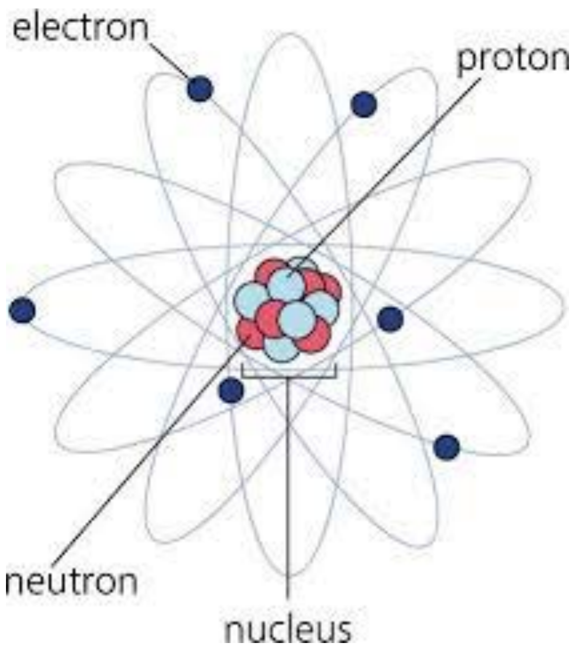
To summarize



Its takes higher and higher energies to see smaller and smaller objects

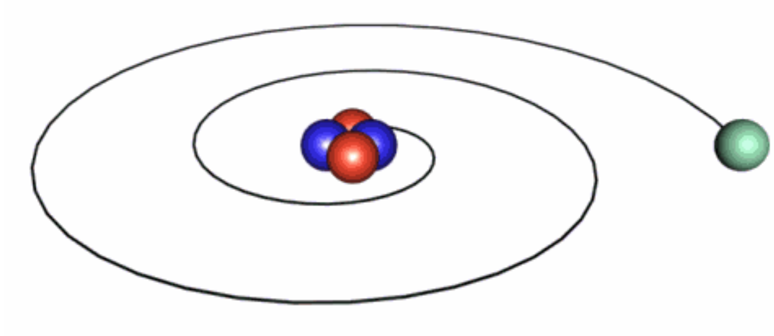


Quantization of matter: Bohr's atom (1911-13)



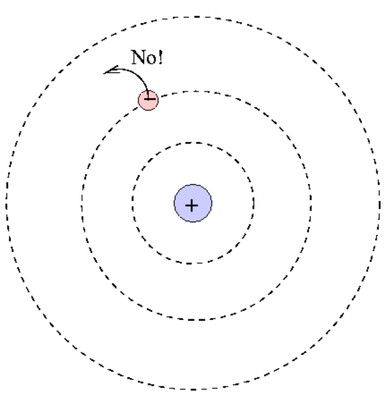
Classical Atom

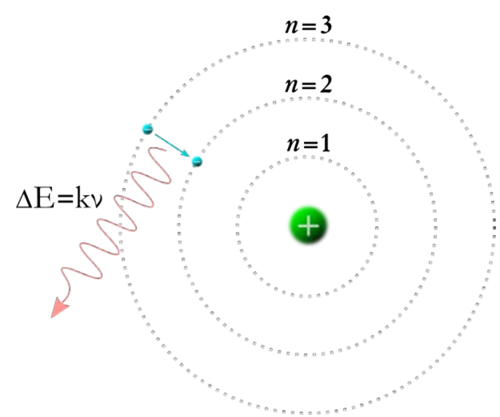
Like the solar system.
However… it is unstable (why?)
(t = 10^{-11}s)



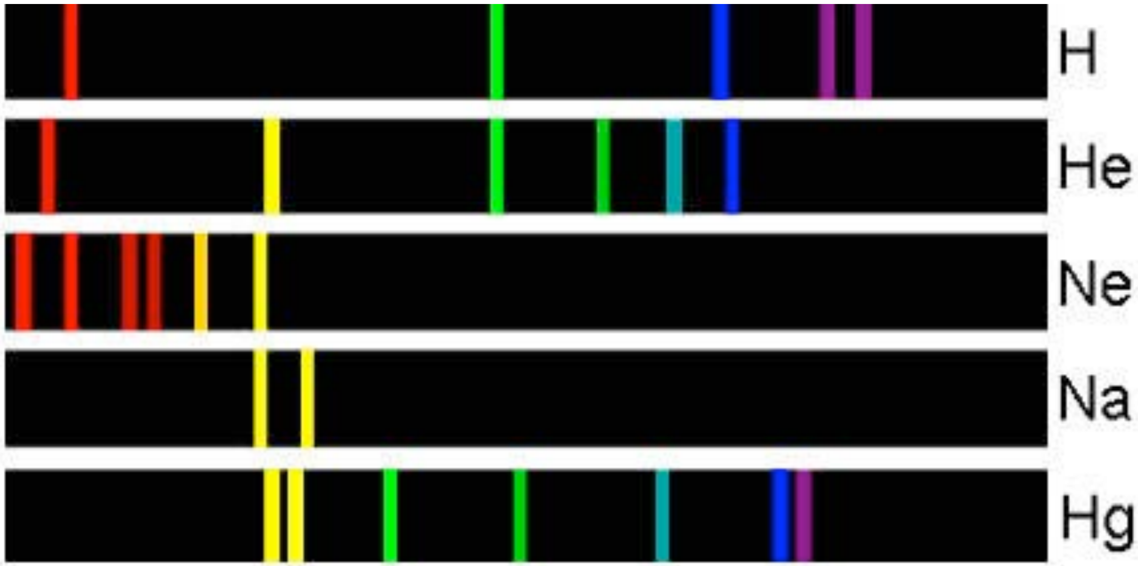
Bohr's atom

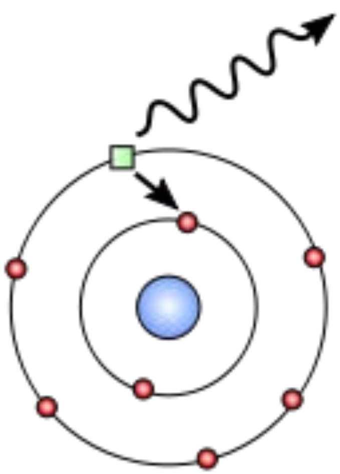
Only specific (= **quantized**) orbits are allowed. On these orbits, electrons are **stable**. **Jumps** are possible, with the **emission** of radiation.





Every atom has its own ID card





The frequency of the light depends on the jump. The size of the jump depends on the type of atom.

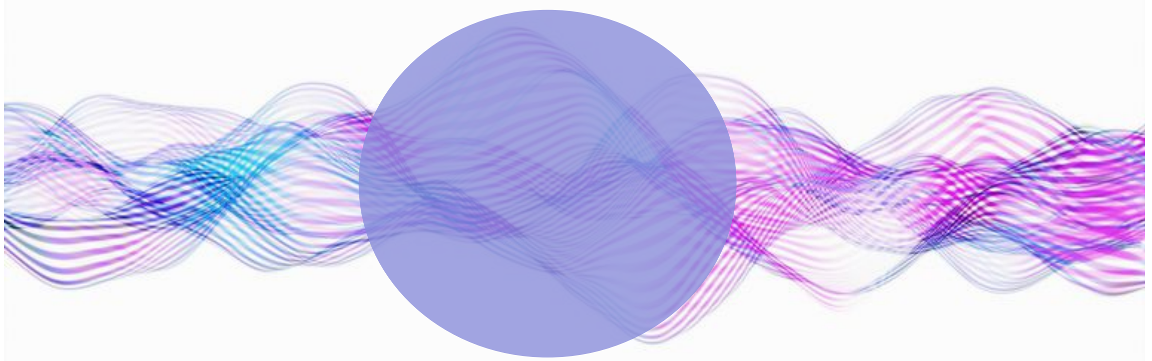
Very important in spectroscopy, study of galaxies···

Quantization of matter: de Broglie's hypothesis (1924)

Motivation: Light seems to have a double nature, particle and wave.

Hypothesis: Also matter has a **double nature**, particle a wave. A particle moving with velocity **v** is associated a wave with wavelength

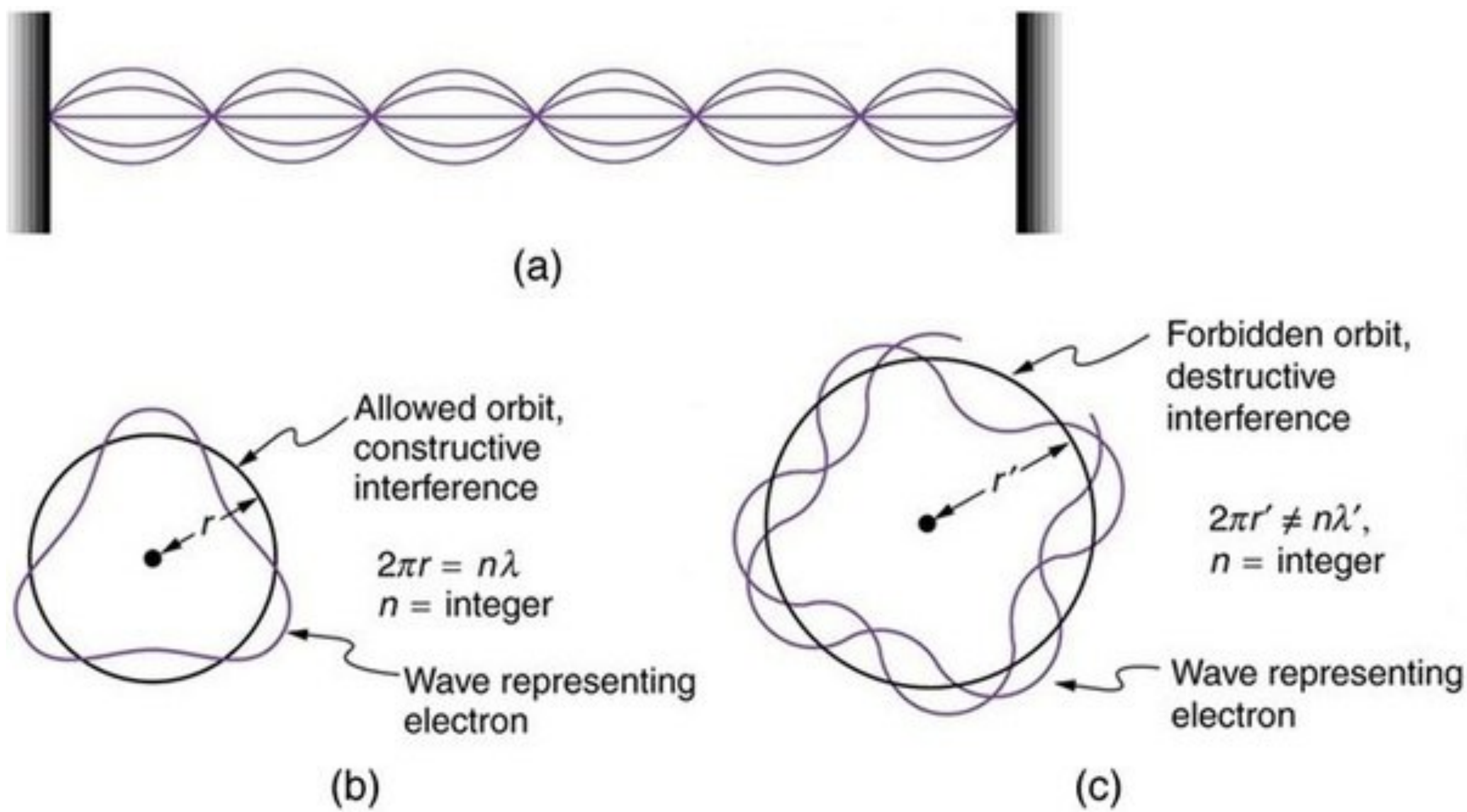
$$\boldsymbol{\lambda = h/p = h/mv}$$



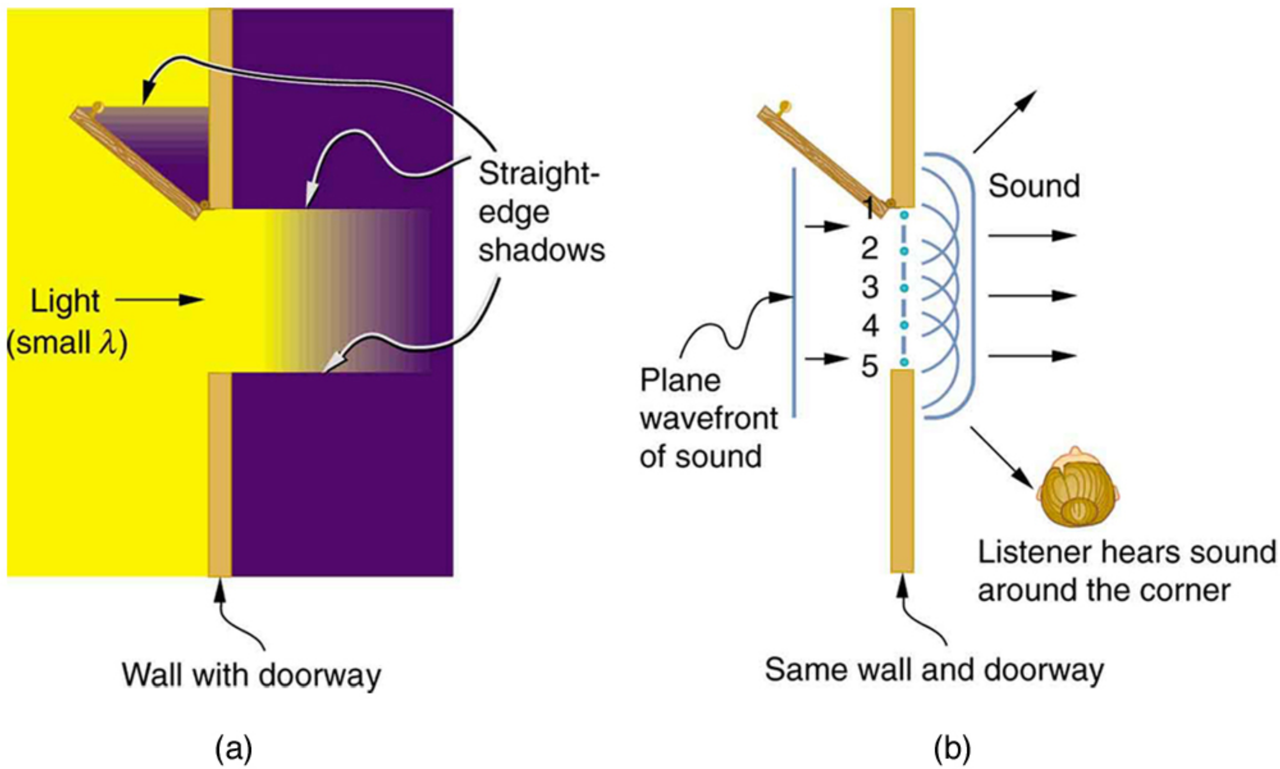
The de Broglie wave length of macroscopic matter is so small that it cannot be detected (classical behaviour). That of small particles, like electrons, can (quantum behaviour).

de Broglie and Bohr’s atom

De Broglie’s hypothesis explains why orbits in atoms are quantized



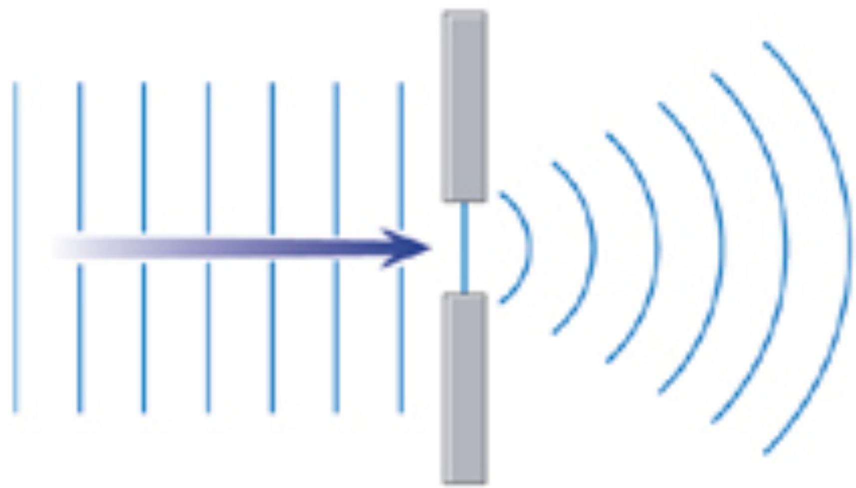
How do we see a wave behaviour?



Light: λ = 400-700nm, much smaller than the width of the doorway ➔ No diffraction

Sound: λ = 0.33m (1000Hz), comparable to the width of the doorway ➔ Diffraction

Condition for Diffraction



Diffraction occurs when

$$\frac{F^2}{L\lambda} \ll 1$$

F = Size of the slit / dimension of the diffracting object

L = Distance from the aperture

λ = wavelength

Two examples

Macroscopic system: m = 1g, v = 1m/s

$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34} J \cdot s}{1 \times 10^{-3} Kg \times 1 m/s} = 6.63 \times 10^{-31} m$$

L = 10m (max for a lab). Then
F < 10^{-15} m (size of proton).
Impossible!

Very small, impossible to detect!

Microscopic system: electrons (m = 9.11 x 10^{-31} Kg),

E = 54 eV = 8.65 x 10^{-18} J.

Then v = $(2E/m)^{1/2}$ = 4.36 x 10^6 m/s

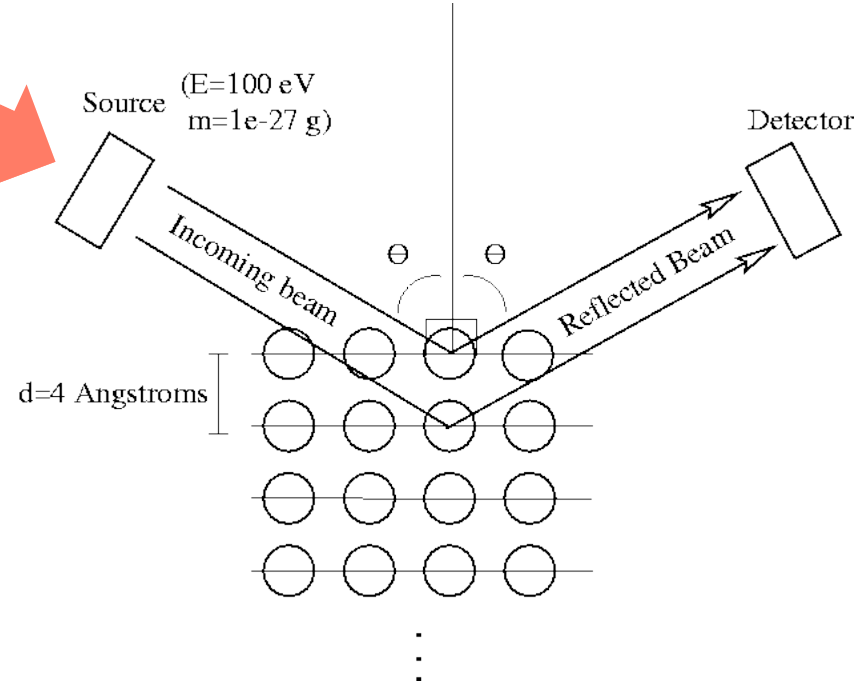
L = 1m.
Then
F < 10^{-5} m. Easy
F = 10^{-10}m
(crystals)

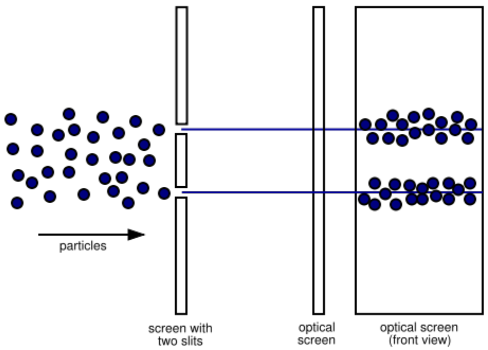
$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34} J \cdot s}{9.11 \times 10^{-31} Kg \times 4.36 \times 10^{6} m/s} = 1.67 \times 10^{-10} m$$

Wave nature of matter: the experiment of Davisson & Germer (1927)

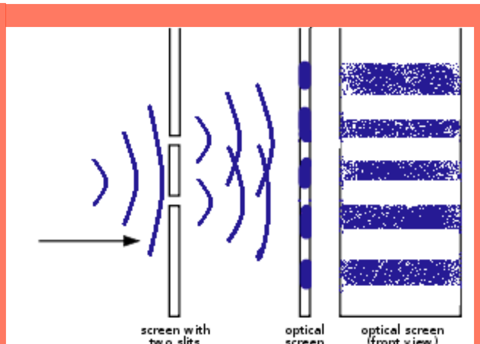
Diffraction of electrons by a crystal

A more complicated version of the d**ouble-slit experiment**

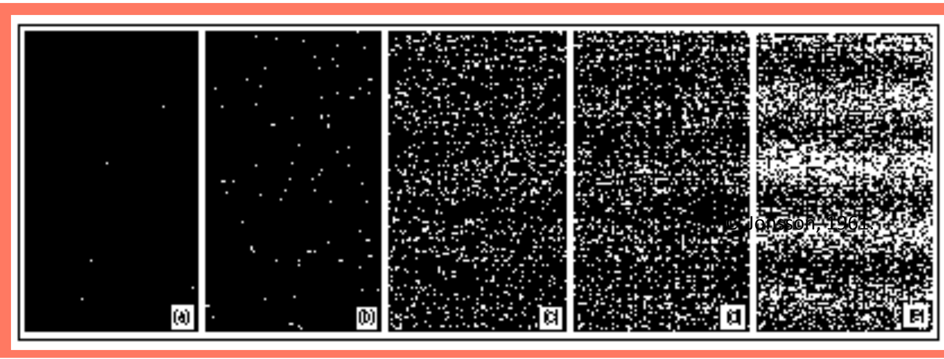




Particle behaviour

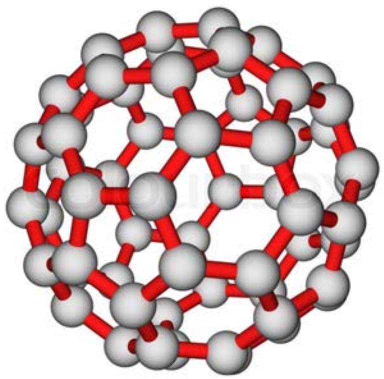


Wave behaviour

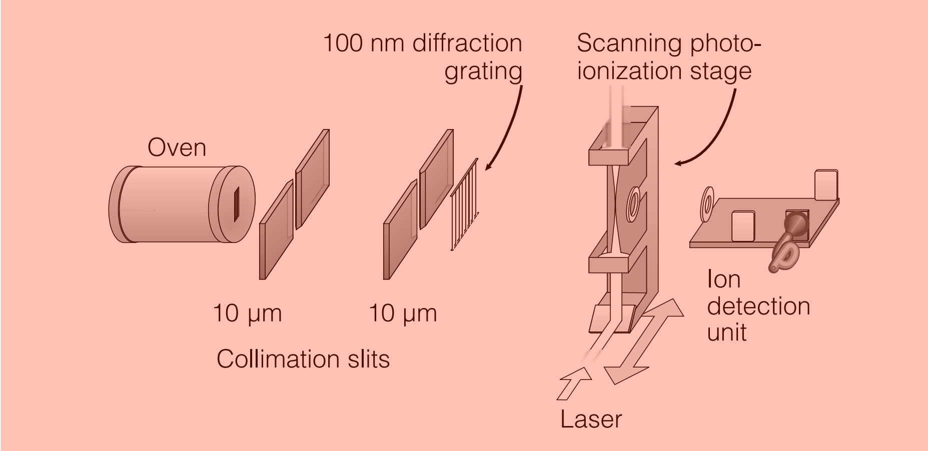


Modern Experiment with molecules (1999)

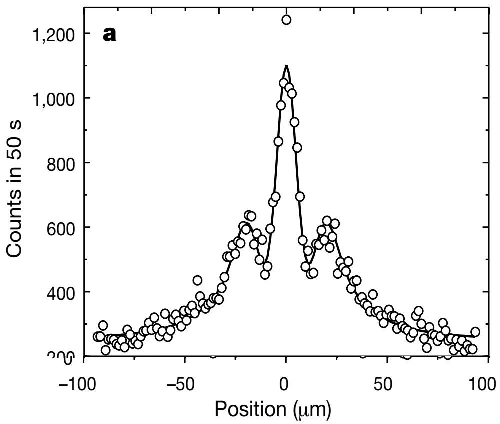
Diffraction of Fullerene (C_{60})



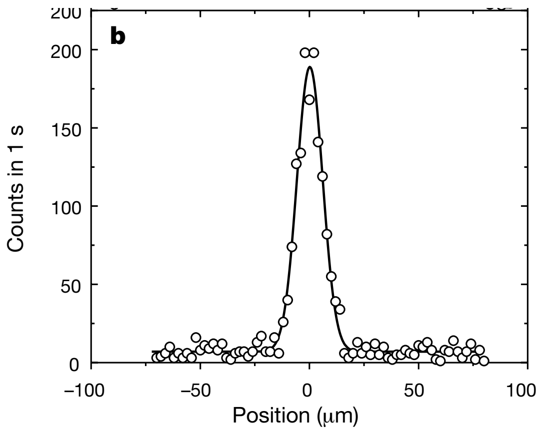
The experiment



The result



With grating



Without grating

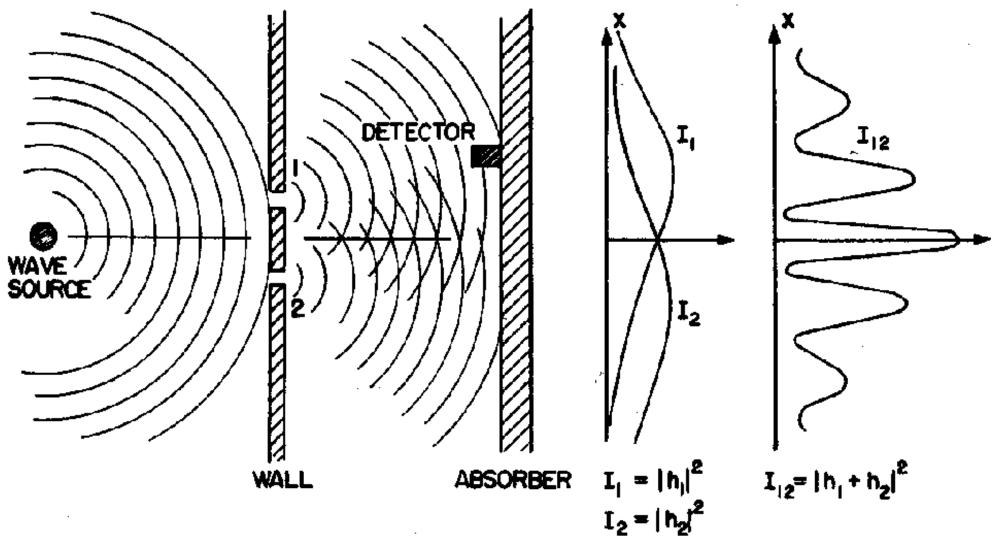
Some numbers

Mass = 60 x 12 x 1,68 x 10^{-27} Kg = 1,21 x 10^{-24}Kg = 10^{6} larger than the mass of the electron.

Velocity = 220 m/2

λ = 2.49 pm = 10^{-2} smaller than that of electrons

How far can we push it?



$$\frac{F^2}{L\lambda} = \frac{(100nm)^2}{1,25m \times 2,49pm}$$

$$= 3,21 \times 10^{-3} \ll 1$$

But particles fall while traveling

$$t = \frac{L}{v} = \frac{1,25m}{220m/s} = 5,68 \times 10^{-3}s$$

$$d = \frac{1}{2}gt^2 = \frac{1}{2} \times 9,81m/s^2 \times (5,86 \times 10^{-3}s)^2 = 0,16mm$$

How far can we push it?

The Fraunhofer condition constraints the product

$$\frac{F^2}{L\lambda} \ll 1$$

The size of slits cannot be significantly decreased, due to technological limitations and because molecules would get stuck.

The size of the experiment cannot be enlarged too much.

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

Therefore the de Broglie wave length cannot change too much.

So if we want to increase the mass, we need to decrease the velocity.

$$t = \frac{L}{v}$$

But then the **time of flight increases.**

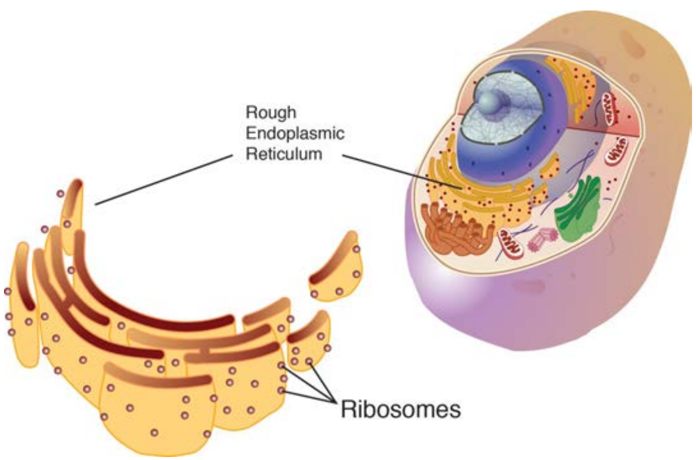
And the molecule **falls more in gravity.**

$$d = \frac{1}{2}gt^2$$

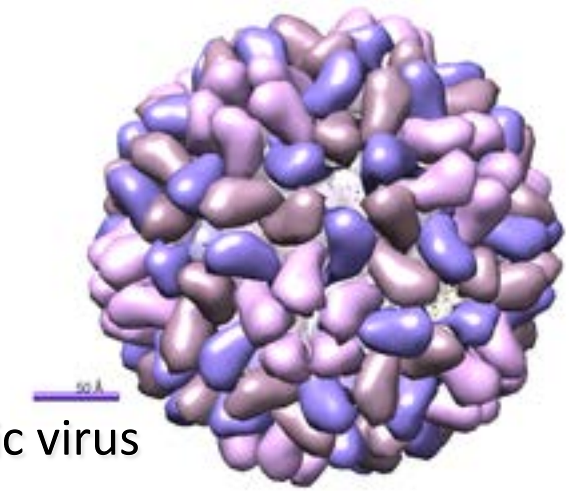
By **increasing the mass by 3 orders of magnitude**, the distance of free fall also increases by 6 order of magnitude, from 0,1mm to 100m. This is too much!

How far can we push it?

So we can go up to masses of 10^{-21}Kg = attogram



Ribosome



Brome mosaic virus

Although technologically very challenging, these object are still very small.

Performing diffraction experiments with small **viruses** would represent the first type of experiment with a **living object.**

It’s time for Space

In outer space one can create conditions of almost **0 gravity**.

Experiments can be run for longer times (**< 100s** technological limit).

Masses **larger by 2-3 orders of magnitude** (femtogram) can be used

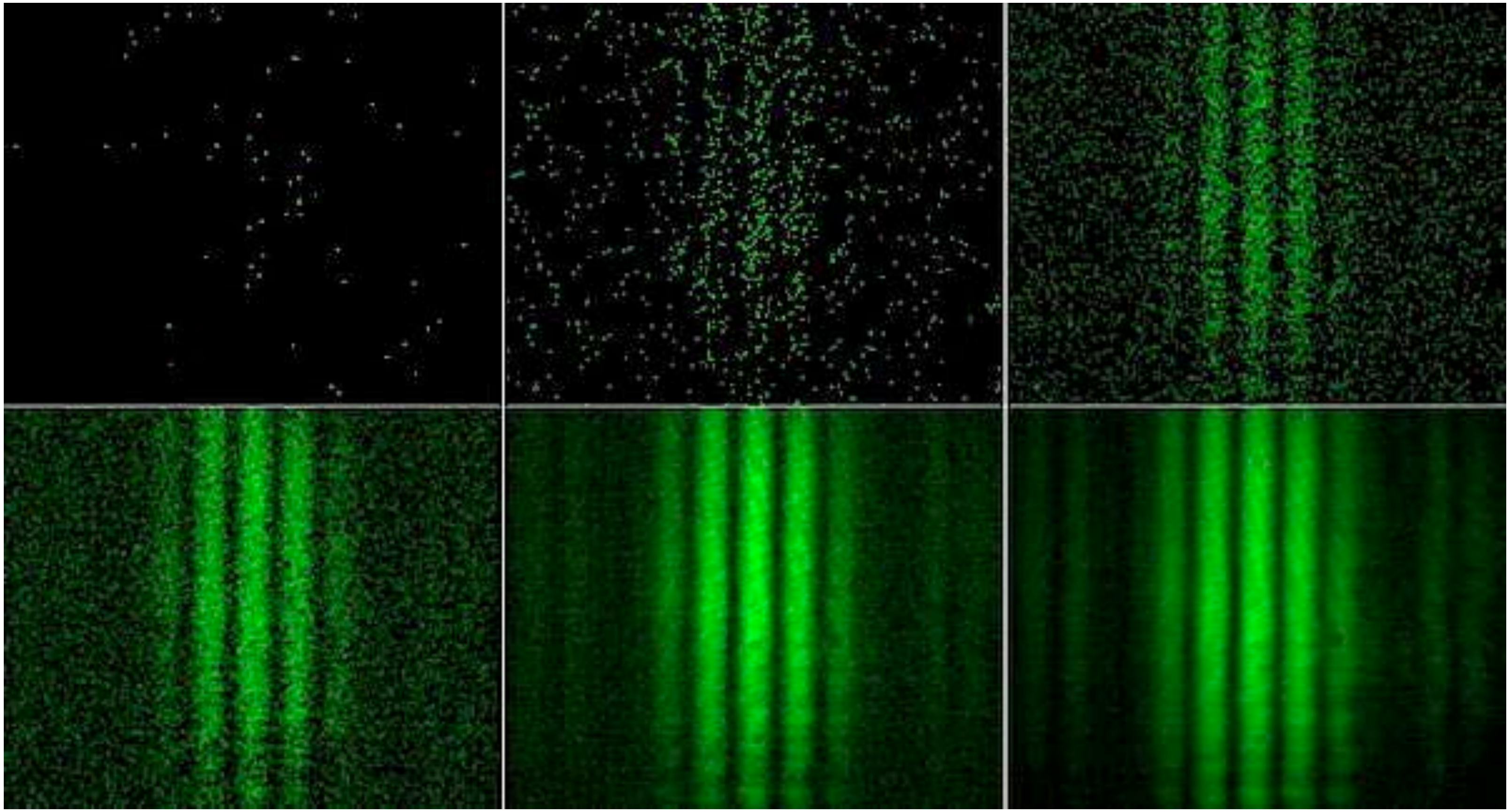
Quantization of matter: summary

Matter behaves like a **particle**

Matter behaves like a **wave**

What's going on? Is it a particle or a wave?

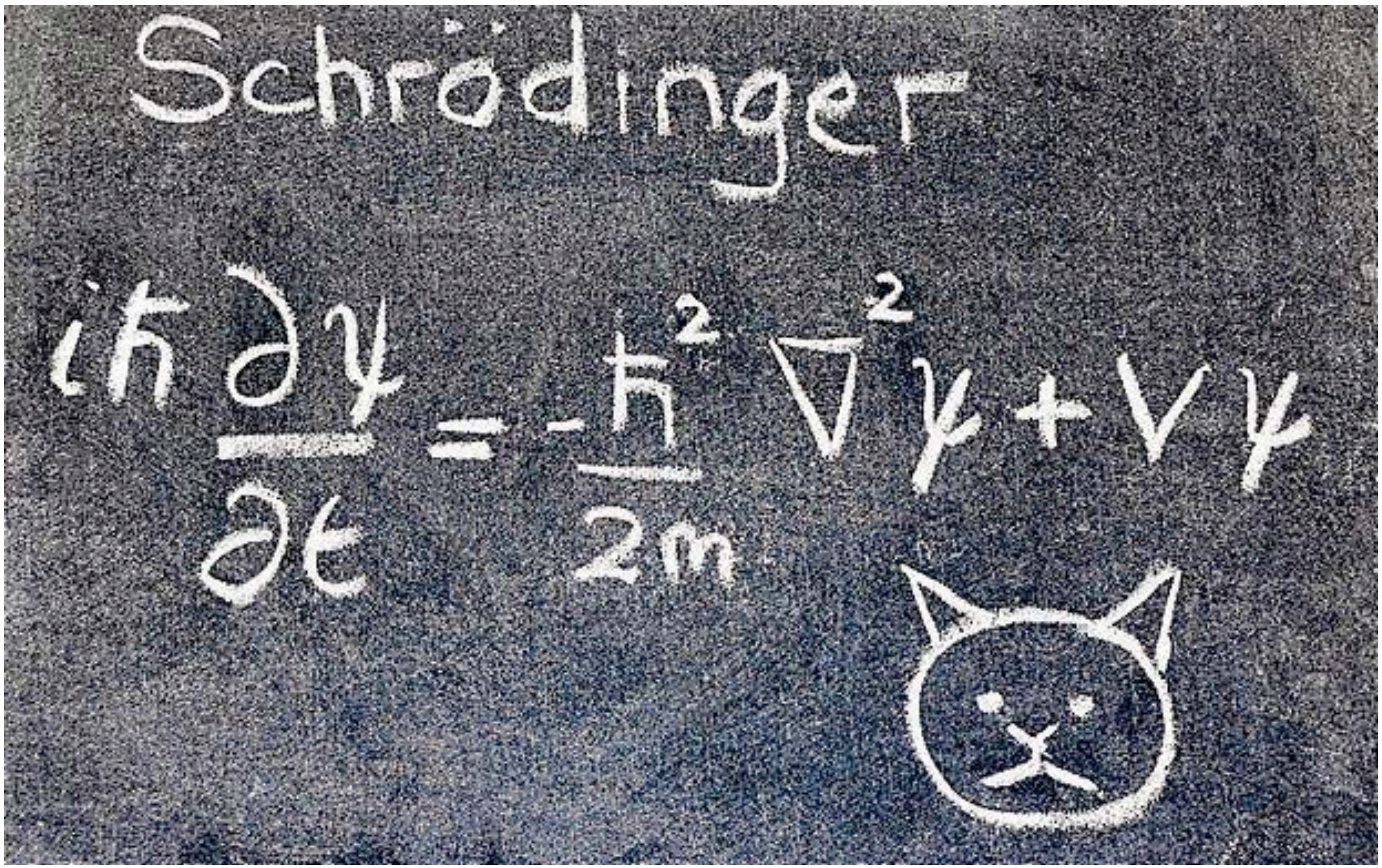
The problem



Each single atom atom hits the screen in a precise point and one can count them (➔ **particle**) but at the same time they arrange themselves according to an interference pattern (➔ **wave**). How do we describe this?

Birth of Quantum mechanics (1926)

In 1926, Schrödinger suggests to associate a wave function to every physical system. This wave function is solution of of an equation − the Schrödinger equation − which determines its time evolution.



… but there is a problem

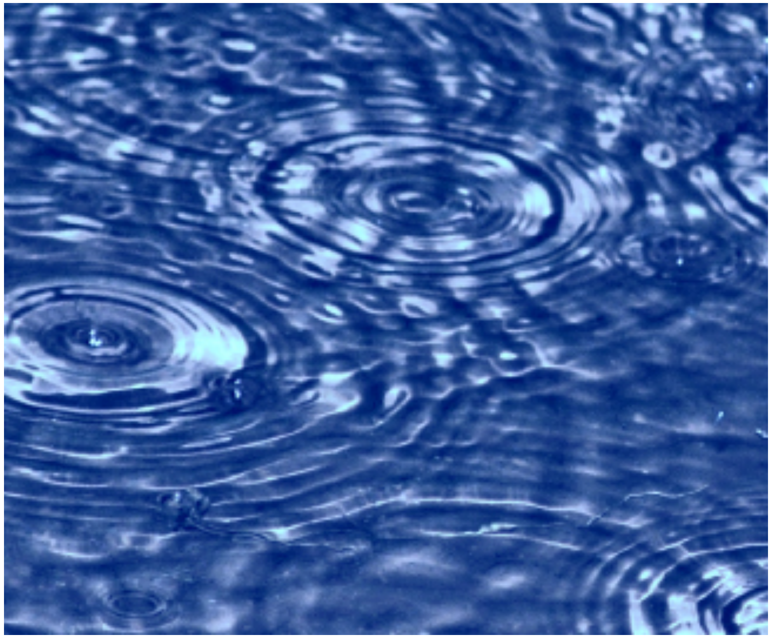
«At an early stage, [Schrödinger] had tried to replace ‘particles’ with wavepackets. But wavepackets diffuse. And the paper of 1952 ends, rather lamely, with the admission that Schrödinger does not see how, for the present, to account for particles tracks in track chambers … nor, more generally, for the definiteness, the particularity, of the world of experience, as compared with the indefiniteness, the waviness, of the wavefunction».

(*“Are there quantum jumps*?”, in: J.S. Bell, “*Speakable und unspeakable in quantum mechanics”*, Cambridge University Press, 1987, p. 201).

A wave function explains all wave properties of matter.

But when measured, particles are always found in a precise location in space, not spread out like waves!

The particle properties are not explained.



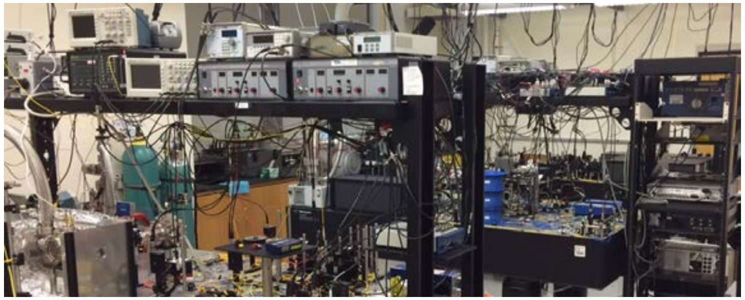
The official solution (Born - 1926)

One cannot ask where particles are, or what properties they have. One can only speak only of **outcomes of measurements**, the only thing one has access to. The wave function therefore does not describe the particle and its properties, but only the probability of outcomes of measurements (through the square modulus)

Classical Physics

Direct access to the system under study

Quantum Physics



No direct access to the system under study

Quantum Mechanics

Axiom1. Every physical system is associated a wave function $\Psi(x,t)$

Axiom 2. The wave function evolves in time according to the Schrödinger equation.

Axiom 3. The probability of finding a particle at **x** at time **t** is:

$$P(x,t) = |\Psi(x,t)|^2$$

Note that the wave function does not refer to properties of the system. This explains the **wave** properties of matter (and light)

Axiom 4. After the measurement, the wave function collapse around the point where the particles as been found **(collapse process).**

This explains the **particle** properties of matter (and light)

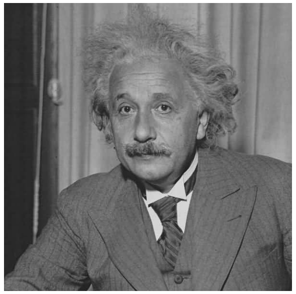
The debate at those times

W. Pauli

«As O. Stern said recently, one should no more rack one's brain about the problem of whether something one cannot know anything about exists all the same, than about the ancient question of how many angels are able to sit on the point of a needle. But it seems to me that Einstein's question are ultimately always of this kind».

(from a 1954 letter to M. Born, in: "*The Born-Einsten Letters*" Walker, New York, p. 223)

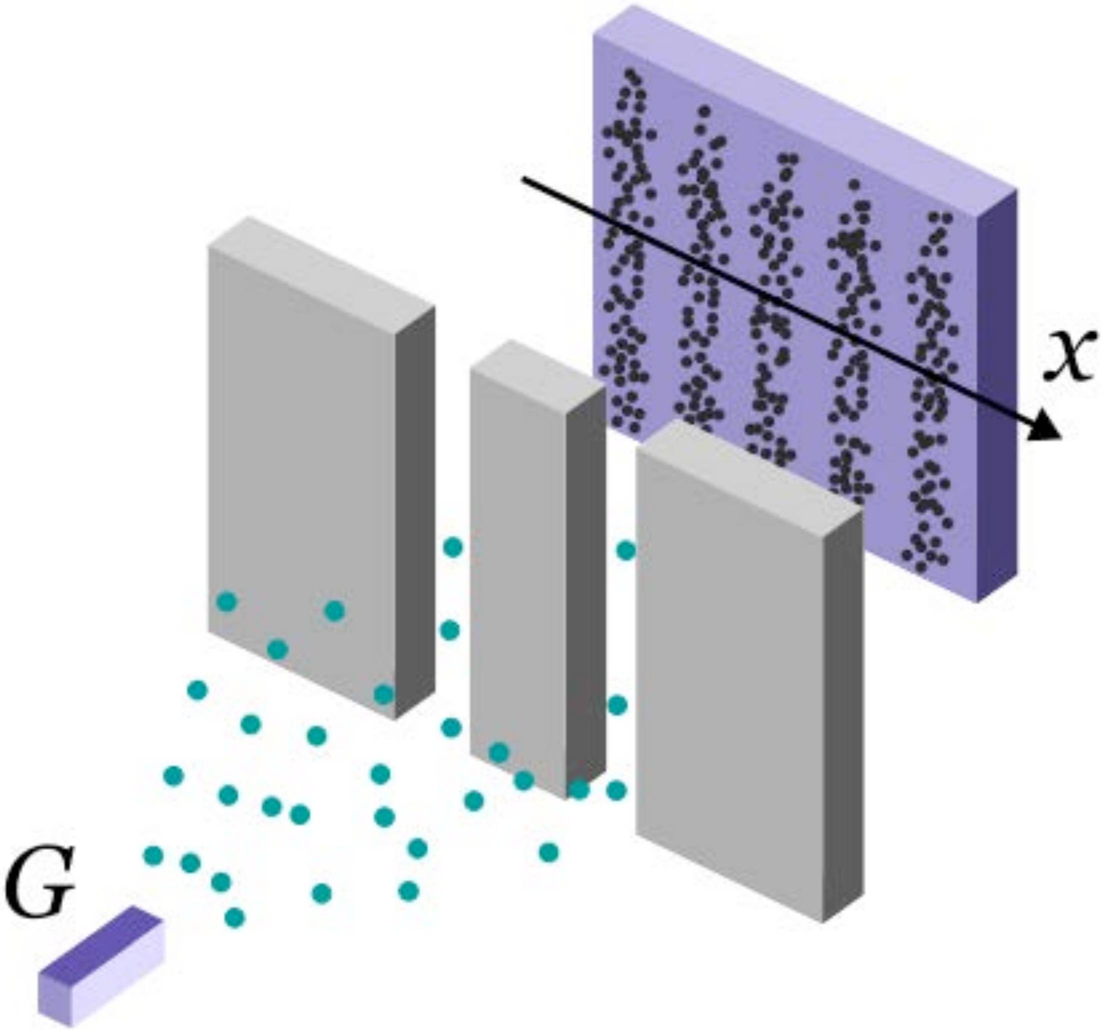
A. Einstein



«What I dislike in this kind of argumentation is the basic positivistic attitude, which from my point of view in untenable».

(in: "*Albert Einstein: philosopher-scientist"*, p. 668)

There is still an open problem



Question: which slit does each particle go through?

Official answer: it is not a legitimate question. One can only speak about outcomes of measurements, in this case, where particles hit the screen.

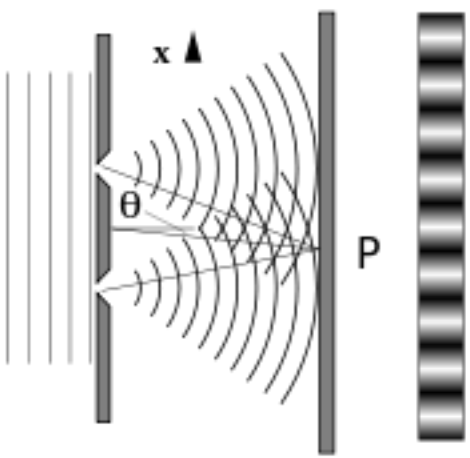
During the measurement, we can only say that the wave function describing the system interferes with itself while passing through both slits. This is called a **superposition state**

Quantum superpositions

A system being described by a wave function, which is the sum of two states

$$\Psi(x,t) = \Psi_1(x,t) + \Psi_2(x,t)$$

Particle passing through one slit + Particle passing through the other slit

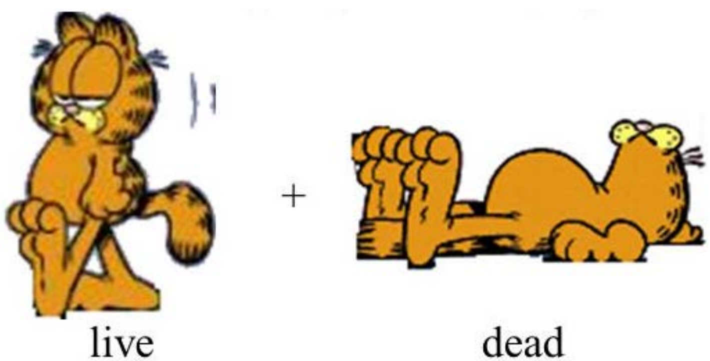


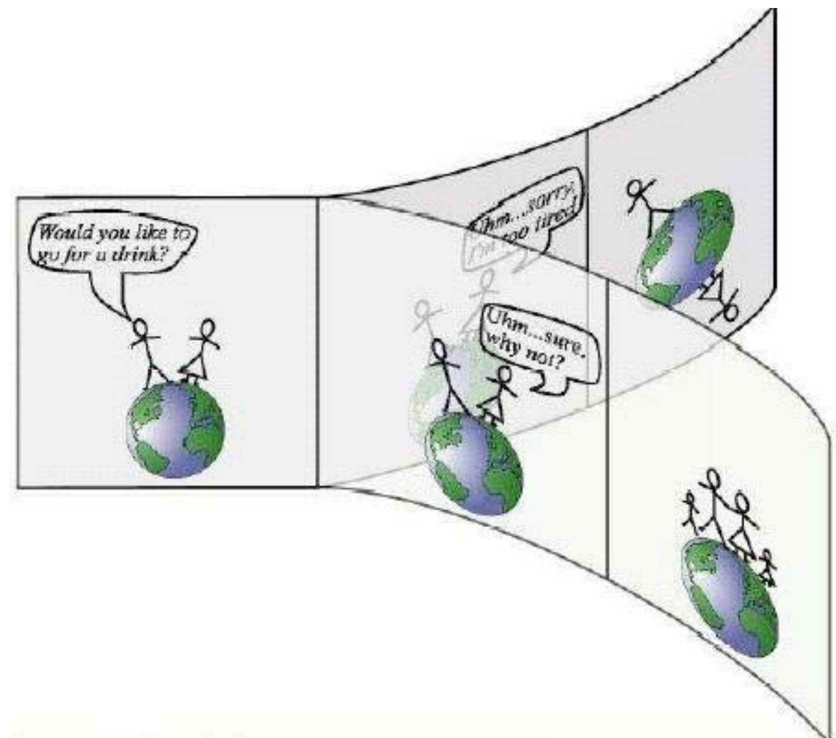
Quantum superpositions are the characteristic properties of quantum systems, which marks the most profound difference with respect to classical physics.

They are the basis of future **quantum technologies (quantum information, computation, cryptography, sensing···)**

Schrödinger's cat (1935)

There is no reason why quantum superpositions should be possible only for microscopic systems. Why not thinking of macroscopic quantum superpositions? Macroscopic systems are made of atoms, which are quantum. Therefore they should also be quantum.





What does it mean? Why don't we see them in everyday life? Quantum Mechanics faces a problem when applied to macroscopic object. **The debate is still open!**