Key concepts of particle physics

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Hubble Ultra Deep Field

Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team

STScI-PRC04-07a

The questions addressed by Particle physics are the same that guided the development of Natural Philosophy in the course of History

- How does the Universe work?
- Where does it come from?
- Where is it going?

- What are the ultimate components of matter?
- How do they "move"
- What "moves them"?

The most ambitious among all sciences!

Even the approach followed by ancient philosophers is similar to the one used by the modern physicist:

to indentify few fundamental principles, from which to derive the properties of all natural phenomena, both in the macrocosm (the sky, the Universe) and at the human scale

What has changed in the course of history is the perception of the true complexity of things, the ability to carry out quantitative measurements, and the epistemological criteria establishing the completeness of a given explanation and understanding

In common, the identification of two categories:

(a) The components of matter

(b) The forces that govern their behaviours

Example

Components:
air, water, fire, earth

Forces:
- air and fire pushed upwards
- earth and water pulled downwards

Judgement of correctness:
how come a tree falls in the water, but then gets pushed up and floats?

Reevaluation of the theory (Archimedes)
- **all** matter is pulled downwards, but with intensity proportional to its weight:

A body immersed in water receives a push upwards equal to the weight of the displaced water

Air is lighter than the rock, therefore it floats on top of it. Warm air is lighter than cold air, and by it it's pushed up.

Notice that there is no a-priori guarantee that Nature can be described by a limited number of principles, or that these apply everywhere and at all times.

For example Energy conservation had been put in doubt by the first quantitative studies of nuclear beta decays in the 1920-30's.

The great success of modern physics lies in its incredibly accurate unified description of the full multitude of observed natural phenomena

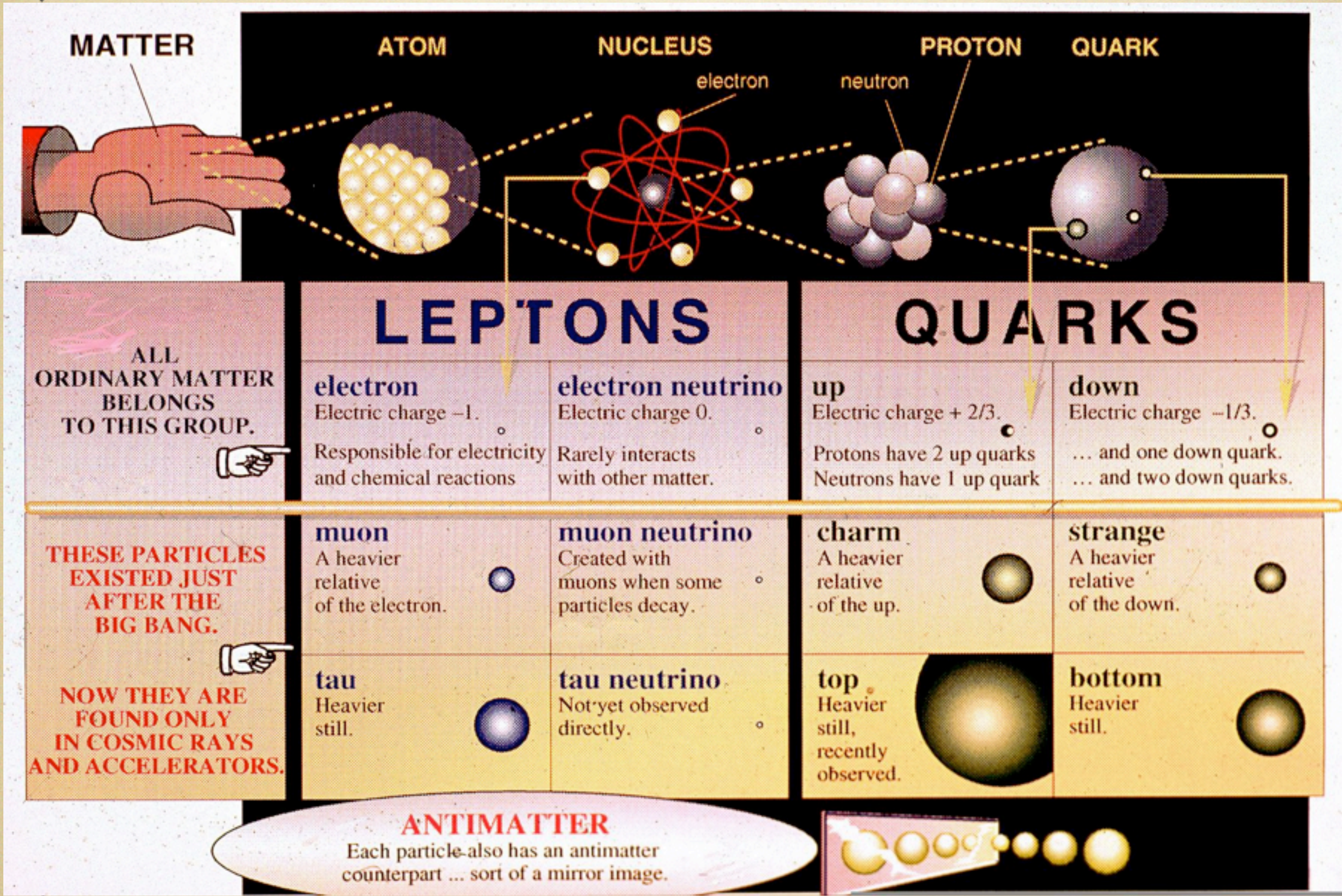

dark energy
73%
dark matter
23%
non-luminous atoms
(e.g. planets, dead
stars, dust, etc), ~4%
stars, neutrinos,
photons ~0.5%

- The understanding of the **Big Bang** and of what preceeded it requires the understanding of the behaviour of Nature in presence of gravitational fields of intensity similar to that of nuclear forces (Quantum Gravity).

- The sources of **Inflation** and of **Dark Matter** and **Dark Energy**, which, respectively, shaped and will determine the future of the large-scale structure of the Universe, have to be found within the spectrum of particles which will form our ultimate *"theory of everything"*.

Level 0: what? how?

- Are there fundamental building blocks?
- If so, what are they?
- How do they interact?
- How do they determine the properties of the Universe?


MATTER
ATOM
NUCLEUS
electron
neutron
PROTON
QUARK
LEPTONS
QUARKS
ALL ORDINARY MATTER BELONGS TO THIS GROUP.
electron
Electric charge –1.
Responsible for electricity and chemical reactions
electron neutrino
Electric charge 0.
Rarely interacts with other matter.
up
Electric charge + 2/3.
Protons have 2 up quarks
Neutrons have 1 up quark
down
Electric charge –1/3.
… and one down quark.
… and two down quarks.
THESE PARTICLES EXISTED JUST AFTER THE BIG BANG.
NOW THEY ARE FOUND ONLY IN COSMIC RAYS AND ACCELERATORS.
muon
A heavier relative of the electron.
muon neutrino
Created with muons when some particles decay.
charm
A heavier relative of the up.
strange
A heavier relative of the down.
tau
Heavier still.
tau neutrino
Not yet observed directly.
top
Heavier still, recently observed.
bottom
Heavier still.
ANTIMATTER
Each particle also has an antimatter counterpart ... sort of a mirror image.

Interactions (or "forces")

- Responsible for:
  - Formation of **bound states** (E<0):
    - Earth-Sun
    - Electron-Nucleus
  - **Scattering** (E>0):
    - Motion of an electron in a metal
    - Propagation of light
    - Deflection of charged particles moving through an electromagnetic field

e.g.protons in the LHC

  - **Transmutations**:
    - Atomic transitions (emission of radiation as an electron changes orbit)
    - Decays (n->p e neutrino, radioactivity)

The fundamental interactions:
vector bosons, spin=h/2π

FORCE	COUPLES TO:	FORCE CARRIER:
Electromagnetism	electric charge	photon (m=0)
"weak" force	"weak" charge	$W^{\pm}$ (m=80) Z^{0} (m=91)
"strong" force	"colour"	8 gluons (m=0)

tensor boson, spin=2 h/2π

gravity	energy	graviton (m=0)

scalar boson, spin=0

	mass	**Higgs (m~125)**

Main conceptual results

- ***Simplicity*** (of the building blocks and their interactions): complexity emerges from the large variety of combinations of large aggregates of elementary objects (like the LEGO sets!)
- ***Unity*** (of the laws of interaction)
- ***Unity*** (of the elements):

  "a proton is a proton is a proton"

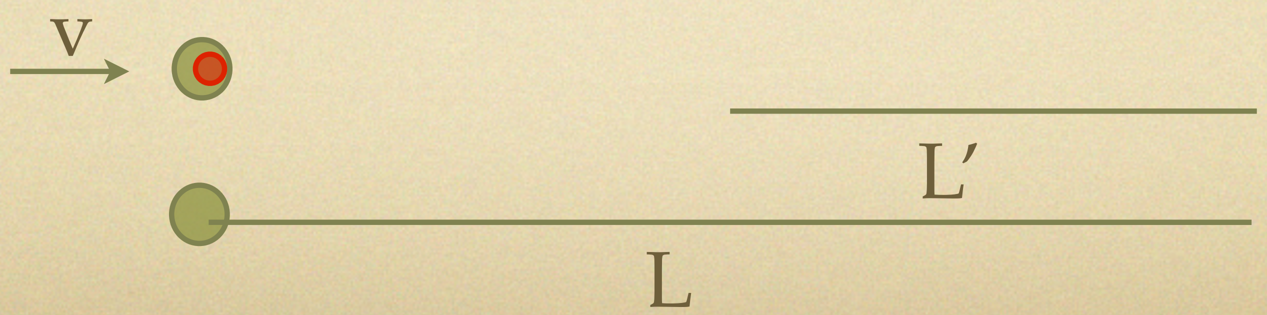
- ***Uniqueness*** (of the fundamental laws): independence from place, time and external conditions

The fundamental principles of Physics, and elementary particles

- Elementary particles are subject to the same fundamental principles that you teach in high school:
  - “F=ma”
  - causality (the cause precedes the effect)
  - conservation of energy (E), momentum (p) and angular momentum (L) (invariance of physical laws under space and time translations)
  - Einstein’s principle of special relativity
  - quantum mechanics (wave-particle duality, uncertainty principle, energy quantization, etc...)

Principles and consequences of special relativity

- No signal/information can propagate faster than light
- The laws of physics are the same in each two reference frames in constant relative motion
  - no preferred reference frame, no “center of the Universe”
  - light has the same speed in all frames
  - time is “relative”



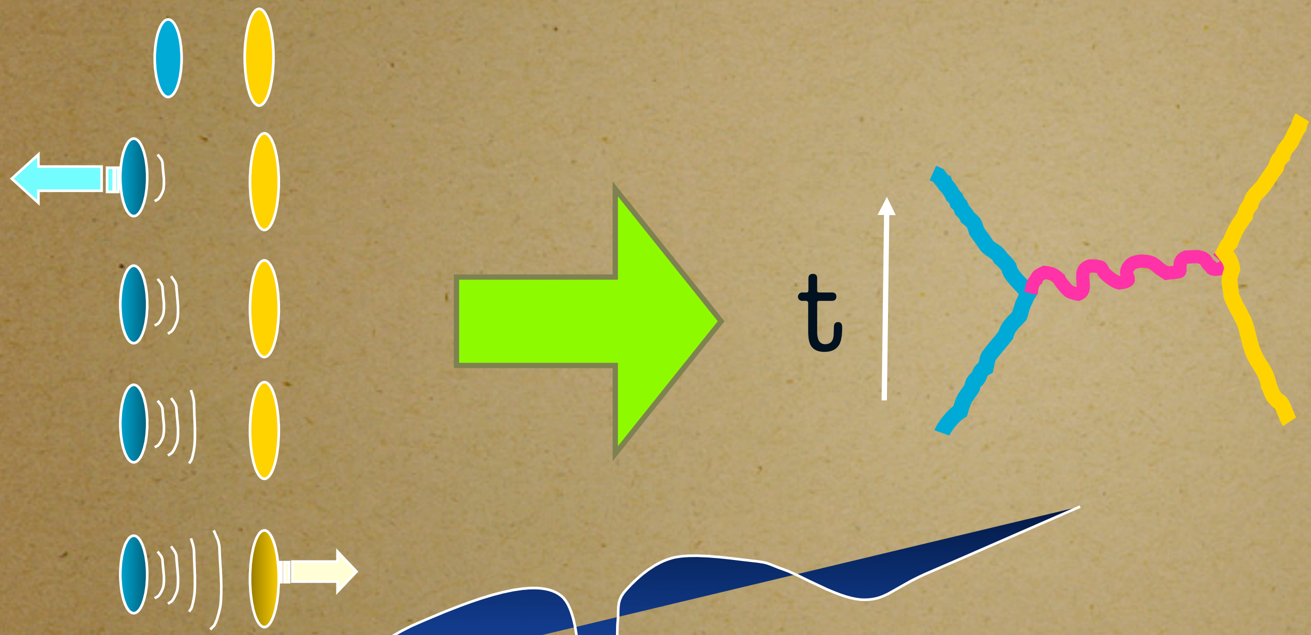
$T' = L'/c$

$T = L/c > T'$

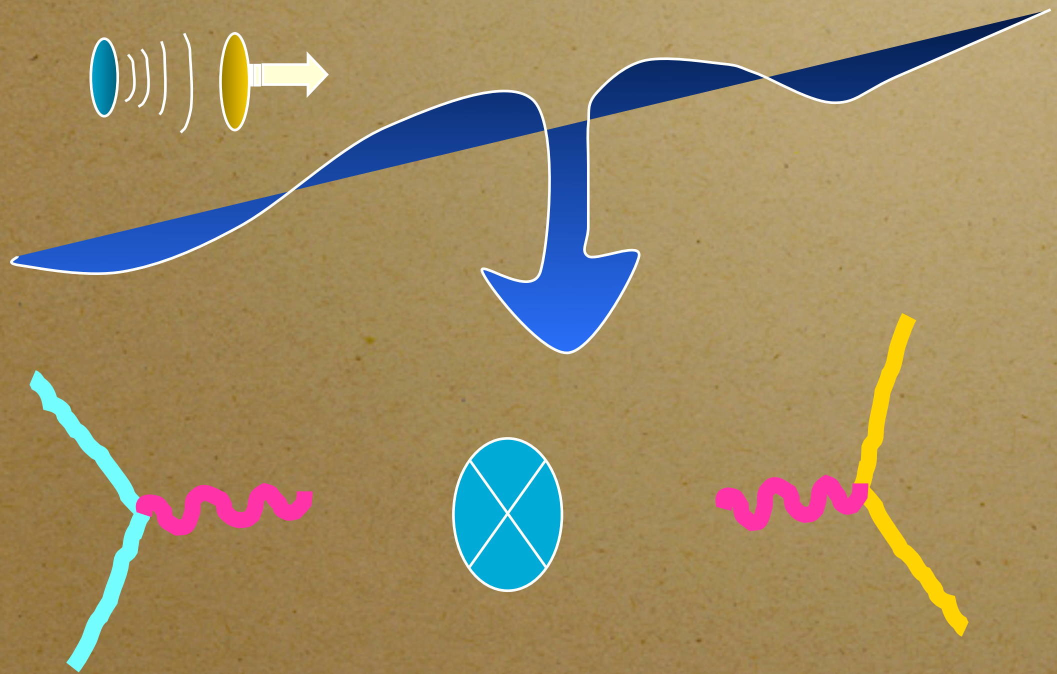
Role of Special Relativity

- Elementary particles have very tiny masses, and the forces present in the accelerators, as well as in the Universe, can easily accelerate them to speeds close to the speed of light. Relativistic effects are therefore essential, and the description of the behaviour of elementary particles should be consistent with the laws of special relativity.
- In particular, any model of interactions should fulfill the principle that forces cannot be transmitted over distances instantaneously

The representation of interactions



Feynman diagram



Locality

N.B.: in quantum mechanics waves and particles are different representations of the same object; therefore to the wave which transmits the signal of the interaction we should associate a particle.

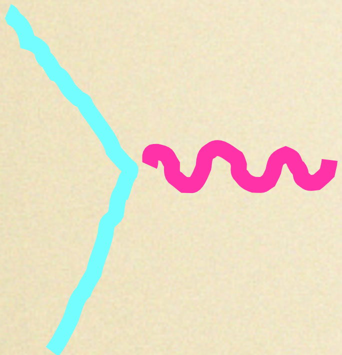
Properties of the interactions

- ***Locality*** (interaction properties only depend on the properties of the participants at a space-time point)

- ***Causality*** (the effect follows the cause. It cannot manifest itself before the time it takes for light to cover the distance between cause and effect.)

- ***Universality*** (the interaction between two particles factorizes in terms the independent properties (e.g. charges) of the individual particles

Simple ... but subtle!



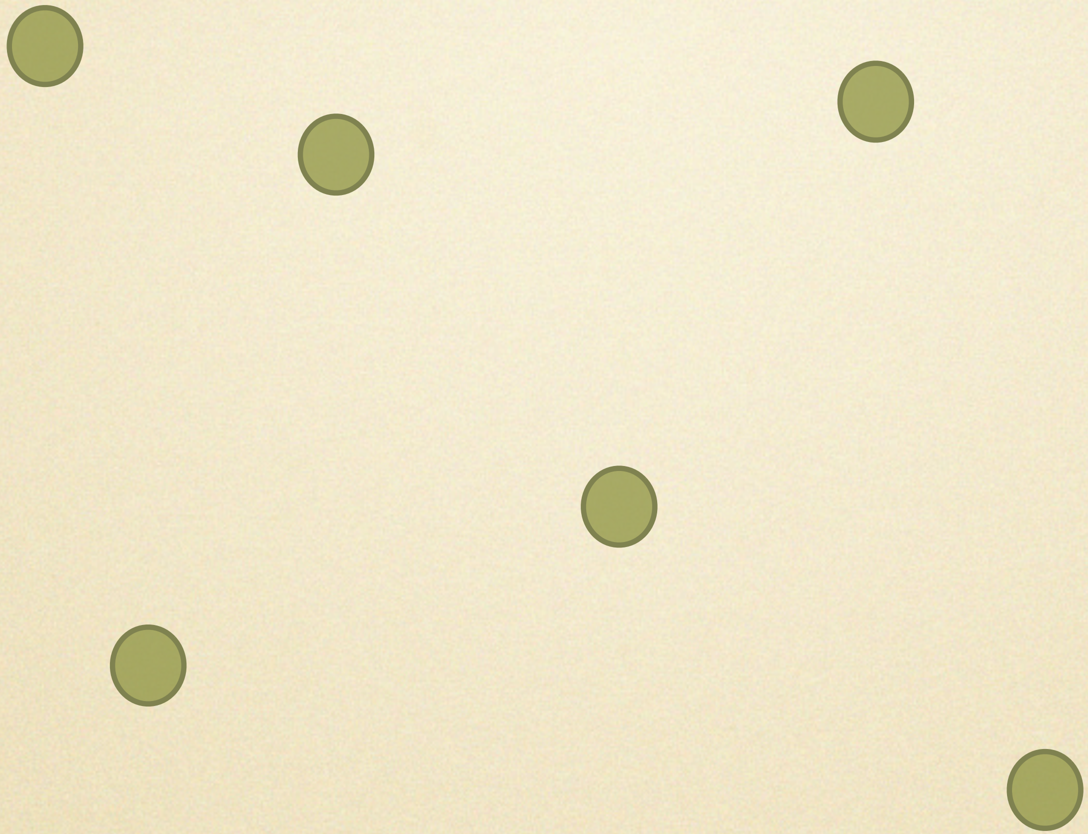
before: 

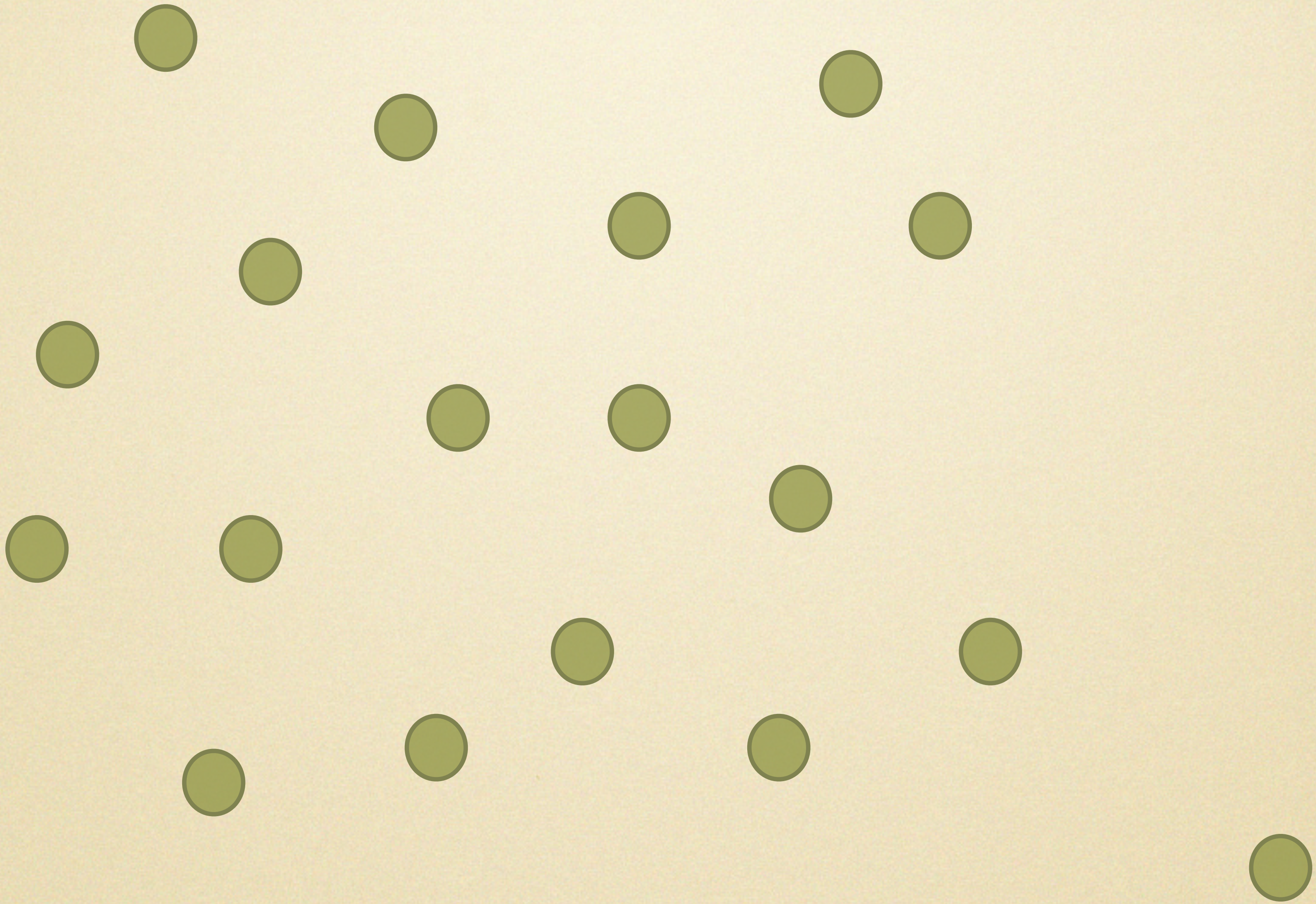
after:  + 

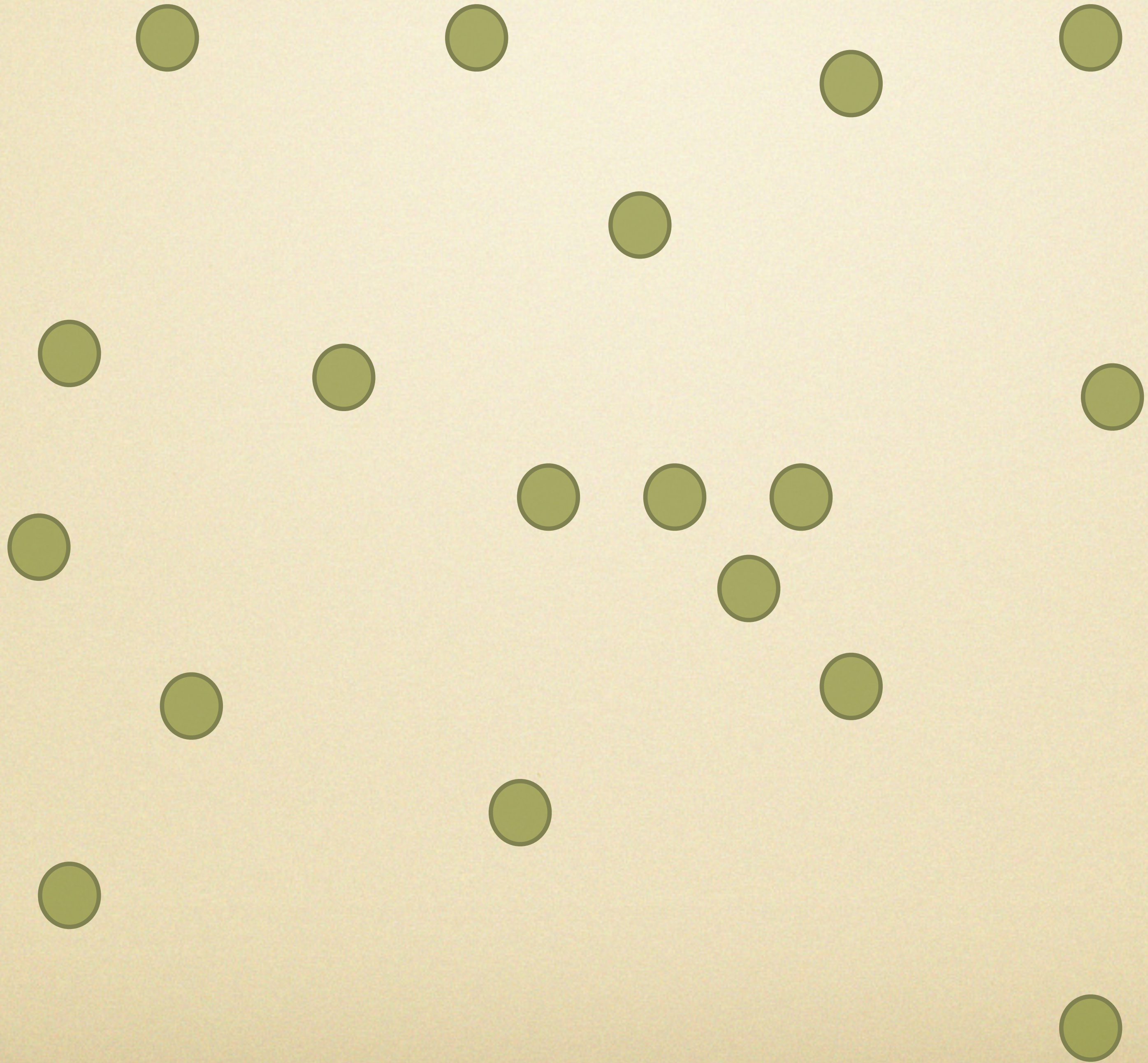
$$\boxed{\text{Energy(after)} \neq \text{Energy(before)}}$$

What happens to energy conservation ?!

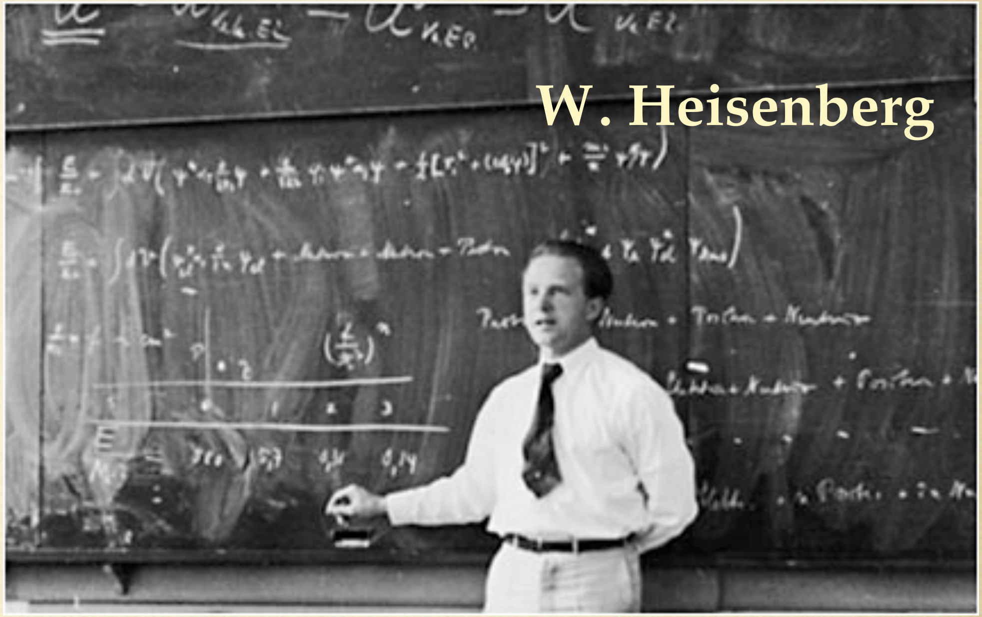
Count fast!





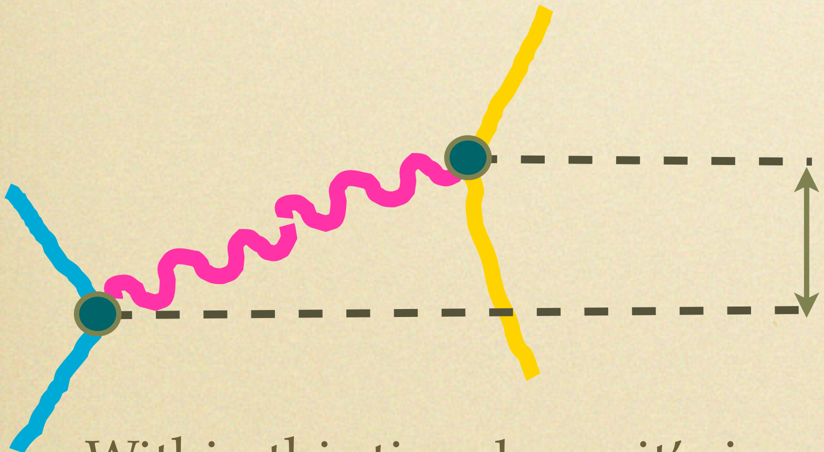


Quantum mechanics



Heisenberg uncertainty principle:

an energy measurement performed within a short time **Δt** can at best reach a precision **ΔE ≥ 1/Δt**



Δt < 1/ΔE

Within this time lapse it's impossible to determine whether energy is conserved or not, since we can't measure it accurately enough. Therefore it's possible to "cheat" nature, and allow the exchange of energy between the two particles