Lecture 10: quantum physics, particle physics,

Content:

- quantum physics, further comments and info
- Heisenberg's uncertainty principle
- Copenhagen interpretation
- Schrödinger‘s equation
- orbital model of the atom
- basic parameters of particles
- particle physics, quarks
- the Standard model

quantum physics

Quantum mechanics gradually arose from Max Planck's solution in 1900 and Albert Einstein's 1905 paper which offered a quantum-based theory to explain the photoelectric effect.
Comment: Planck cautiously insisted that this was simply an aspect of the processes of absorption and emission of radiation and had nothing to do with the physical reality of the radiation itself, but Einstein interpreted Planck's quantum hypothesis realistically.

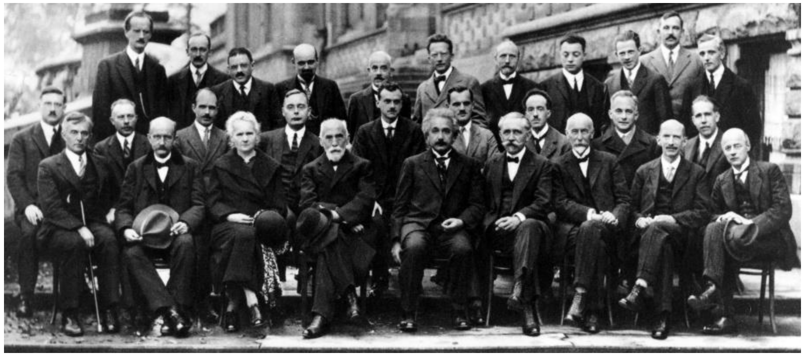
Early quantum theory was profoundly reconceived in the mid-1920s.

The reconceived theory is formulated in various specially developed mathematical formalisms. In one of them, a mathematical function, the wave function, provides information about the probability amplitude of position, momentum, and other physical properties of a particle.

Important applications of quantum mechanical theory include superconducting magnets, light-emitting diodes and the laser, the transistor and semiconductors such as the microprocessor, medical and research imaging such as magnetic resonance imaging and electron microscopy, and explanations for many biological and physical phenomena.

quantum physics

The foundations of quantum mechanics were established during the first half of the 20th century by Max Planck, Niels Bohr, Werner Heisenberg, Louis de Broglie, Arthur Compton, Albert Einstein, Erwin Schrödinger, Max Born, John von Neumann, Paul Dirac, Enrico Fermi, Wolfgang Pauli, Max von Laue, Freeman Dyson, David Hilbert, Wilhelm Wien, Satyendra Nath Bose, Arnold Sommerfeld, and others.
The Copenhagen interpretation of Niels Bohr became widely accepted (we will come in more detail to it later), important was also the Fifth Solvay Conference in 1927.



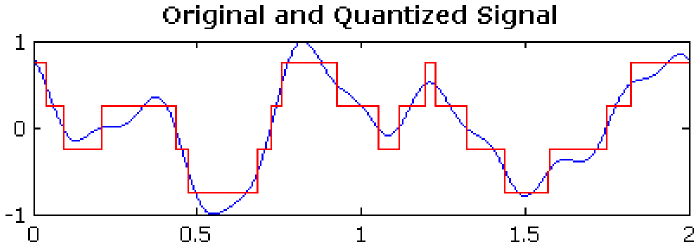
By 1930, quantum mechanics had been further unified and formalized by the work of David Hilbert, Paul Dirac and John von Neumann with greater emphasis on measurement, the statistical nature of our knowledge of reality, and philosophical speculation about the 'observer'. It has since permeated many disciplines including quantum chemistry, quantum electronics, quantum optics, and quantum information science.

quantum physics – four classes of phenomena (1/4)

Quantum mechanics is essential to understanding the behavior of systems at atomic length scales and smaller (< 10^{-10} m).

Broadly speaking, quantum mechanics incorporates four classes of phenomena for which classical physics cannot account:

- quantization of certain physical properties,
- quantum entanglement,
- principle of uncertainty,
- wave–particle duality.



1. Quantization:

Quantization is a process of transition from a classical understanding of physical phenomena to an understanding known as "quantum mechanics". It converts classical fields into operators acting on quantum states of the field theory.

There exist various methods of quantization (geometrical-, canonical-, loop-, path integral- quantization, etc....).

quantum physics – four classes of phenomena (2/4)

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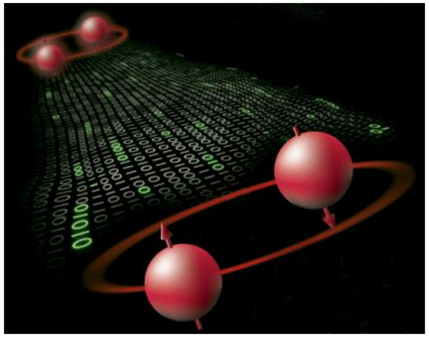

- quantization of certain physical properties,
- quantum entanglement,
- principle of uncertainty,
- wave–particle duality.

2. Quantum entanglement:

Quantum entanglement is a physical phenomenon that occurs when pairs or groups of particles are generated or interact in ways such that the quantum state of each particle cannot be described independently – instead, a quantum state must be described for the system as a whole.

For example, if a pair of particles are generated in such a way that their total spin is known to be zero, and one particle is found to have clockwise spin on a certain axis, then the spin of the other particle, measured on the same axis, will be found to be counterclockwise, as to be expected due to their entanglement.

This is connected with the so called EPR paradox (Einstein-Podolsky-Rosen paradox). We will come to it little bit later on.

quantum physics – four classes of phenomena (3/4)

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3. Principle of uncertainty:

Called also Heisenberg's uncertainty principle - is any of a variety of mathematical inequalities asserting a fundamental limit to the precision with which certain pairs of physical properties of a particle, known as complementary variables, such as position x and momentum p, can be known simultaneously.

Introduced first in 1927, by the German physicist Werner Heisenberg, it states that the more precisely the position of some particle is determined, the less precisely its momentum can be known, and vice versa.

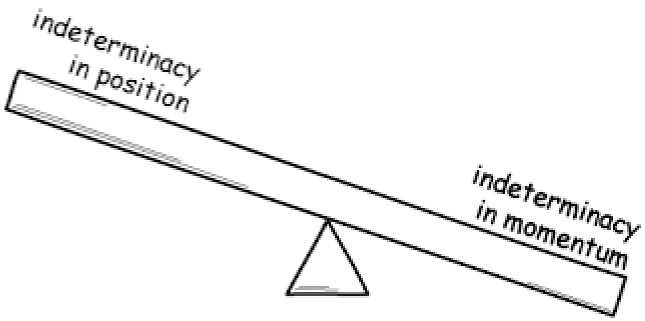
Heisenberg's uncertainty principle:

Later on it has been expressed in a form of following expression

(with standard deviation of position σ_x and stand. dev. of momentum σ_p):

$$\sigma_x \sigma_p \geq \frac{\hbar}{2}$$

($\hbar$ is the reduced Planck constant, $h / 2\pi$).



Historically, the uncertainty principle has been confused with a somewhat similar effect in physics, called the observer effect, which notes that measurements of certain systems cannot be made without affecting the systems.

But it has been shown that the uncertainty principle is inherent in the properties of all wave-like systems and that it arises in quantum mechanics simply due to the matter wave nature of all quantum objects.

Thus, the uncertainty principle actually states a fundamental property of quantum systems, and is not a statement about the observational success of current technology.

Hint: Let's say you want to find out where an electron is and where it is going. How would you do it? The very act of looking depends upon light, which is made of photons, and these photons could have enough momentum that once they hit the electron they would change its course!

Heisenberg's uncertainty principle:

W. Heisenberg wrote:

"Of course the introduction of the observer must not be misunderstood to imply that some kind of subjective features are to be brought into the description of nature. The observer has, rather, only the function of registering decisions, i.e., processes in space and time, and it does not matter whether the observer is an apparatus or a human being; but the registration, i.e., the transition from the "possible" to the "actual," is absolutely necessary here and cannot be omitted from the interpretation of quantum theory".

Something more from N. Bohr :
“ A quantum phenomenon is a process, a passage from initial to final condition, not an instantaneous "state" in the classical sense of that word.“

little bit from another kit:
„Why turbulence?“

quantum physics – four classes of phenomena (4/4)

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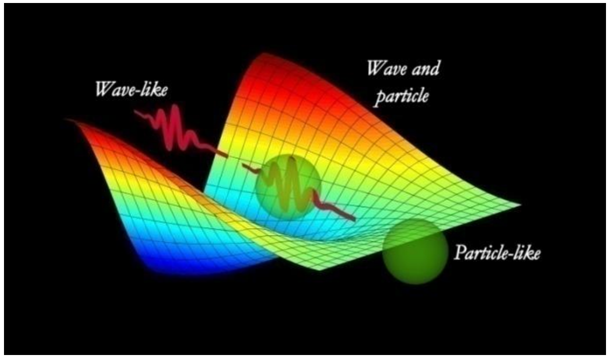


4. Wave–particle duality:

Wave–particle duality is the concept that every elementary particle or quantic entity may be partly described in terms not only of particles, but also of waves. It expresses the inability of the classical concepts "particle" or "wave" to fully describe the behavior of quantum-scale objects.

Although the use of the wave-particle duality has worked well in physics, the meaning or interpretation has not been satisfactorily resolved - there exist several interpretations in quantum mechanics.

interesting video:
https://www.youtube.com/watch?v=Xmq_FJd1oUQ

quantum physics

Interpretations of quantum mechanics deal with two problems:

a) how to relate the mathematical formalism of quantum mechanics to empirical observations; and
b) how to understand that relation in physical and metaphysical terms and in ordinary language.

The **Copenhagen interpretation** is an expression of the meaning of quantum mechanics that was largely devised in the years 1925 to 1927 by Niels Bohr and Werner Heisenberg. It remains one of the most commonly taught interpretations of quantum mechanics.

According to the Copenhagen interpretation, physical systems generally do not have definite properties prior to being measured, and quantum mechanics can only predict the probabilities that measurements will produce certain results. The act of measurement affects the system, causing the set of probabilities to reduce to only one of the possible values immediately after the measurement. This feature is known as wavefunction collapse.

To read more:
https://en.wikipedia.org/wiki/Copenhagen_interpretation

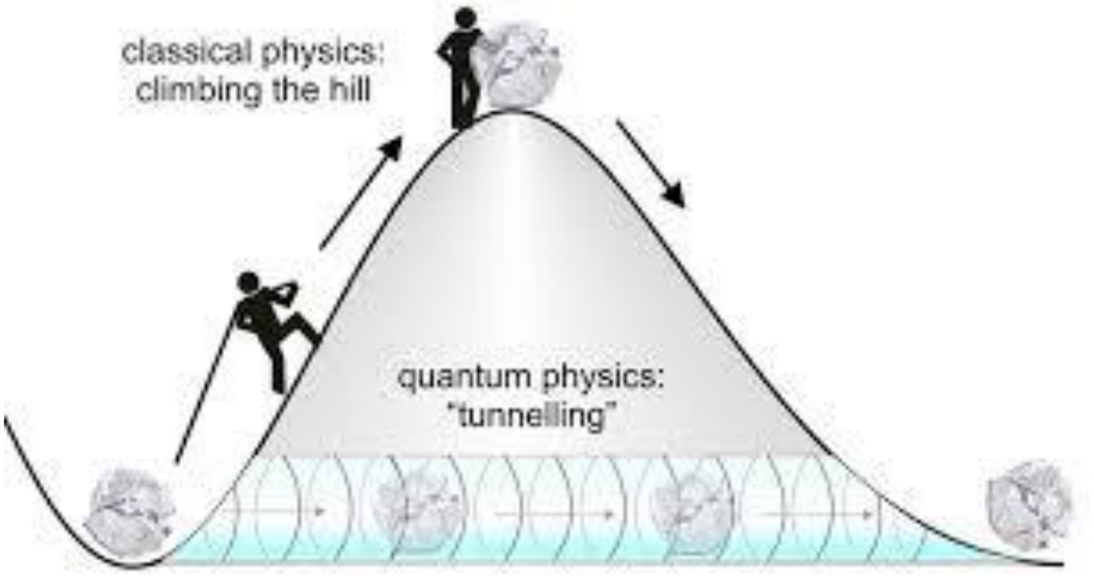
other or alternative interpretations (short overview):
https://en.wikipedia.org/wiki/Interpretations_of_quantum_mechanics

quantum physics

Ideas to self-study topics:

Effects, which can be explained by means of quantum mechanics principles:

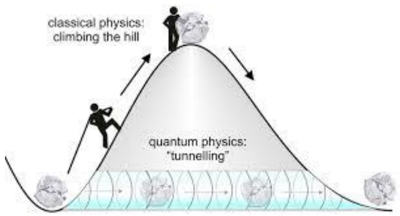
- tunneling effect
- Compton - effect
- Raman - effect
- Zeeman – effect.



tunneling effect:
https://www.youtube.com/watch?v=K64Tv2mK5h4

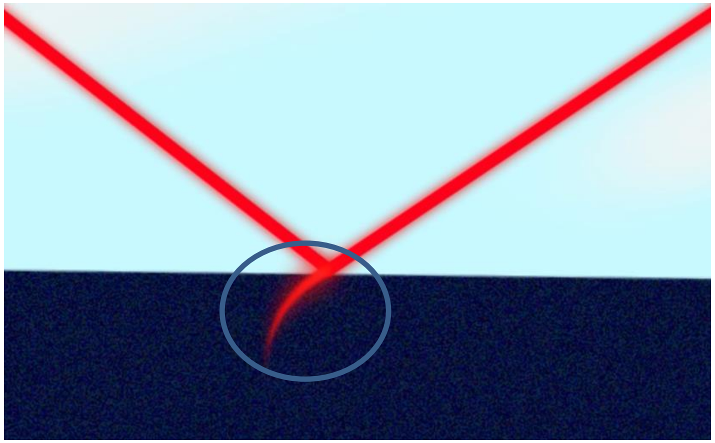
https://www.youtube.com/watch?v=WPZLRtyvEqo

• tunneling effect

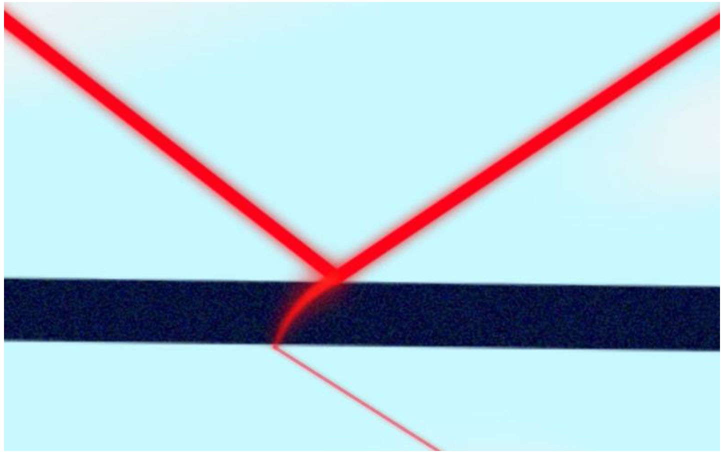


Can be explained, using the properties of light during the total reflection:

During a total reflection of light a small part of the light penetrates into the second medium (so called evanescent wave) – this can be shown mathematically by solving Maxwell equations…



evanescent wave



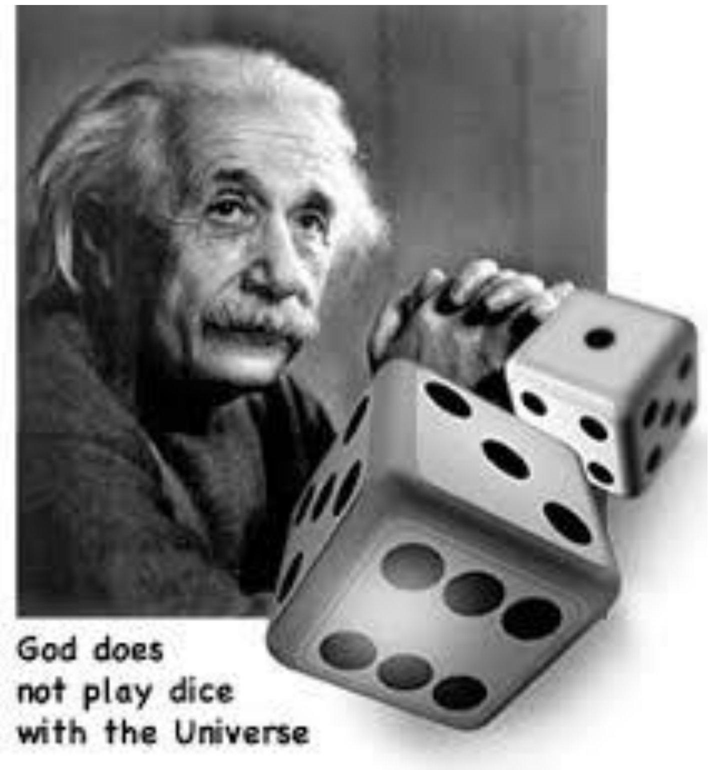
evanescent wave is resulting into so called frustrated total internal reflection

frustrated total internal reflection – simple experiment:
https://www.youtube.com/watch?v=aC-4iSD2aRA

quantum physics

Copenhagen interpretation – cricitism

Many physicists and philosophers have objected to the Copenhagen interpretation, both on the grounds that it is non-deterministic and that it includes an undefined measurement process that converts probability functions into non-probabilistic measurements.
Einstein's comments "I, at any rate, am convinced that He (God) does not throw dice." and "Do you really think the moon isn't there if you aren't looking at it?" exemplify this.
Bohr, in response, said, "Einstein, don't tell God what to do".

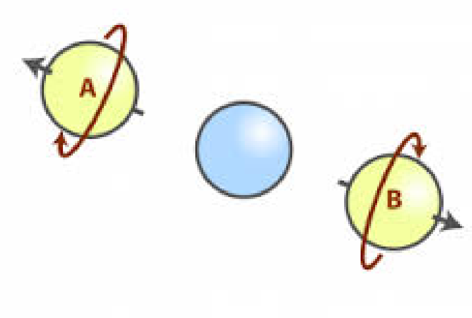


Copenhagen interpretation – cricitism

EPR = Einstein - Podolsky – Rosen argument (paradox)

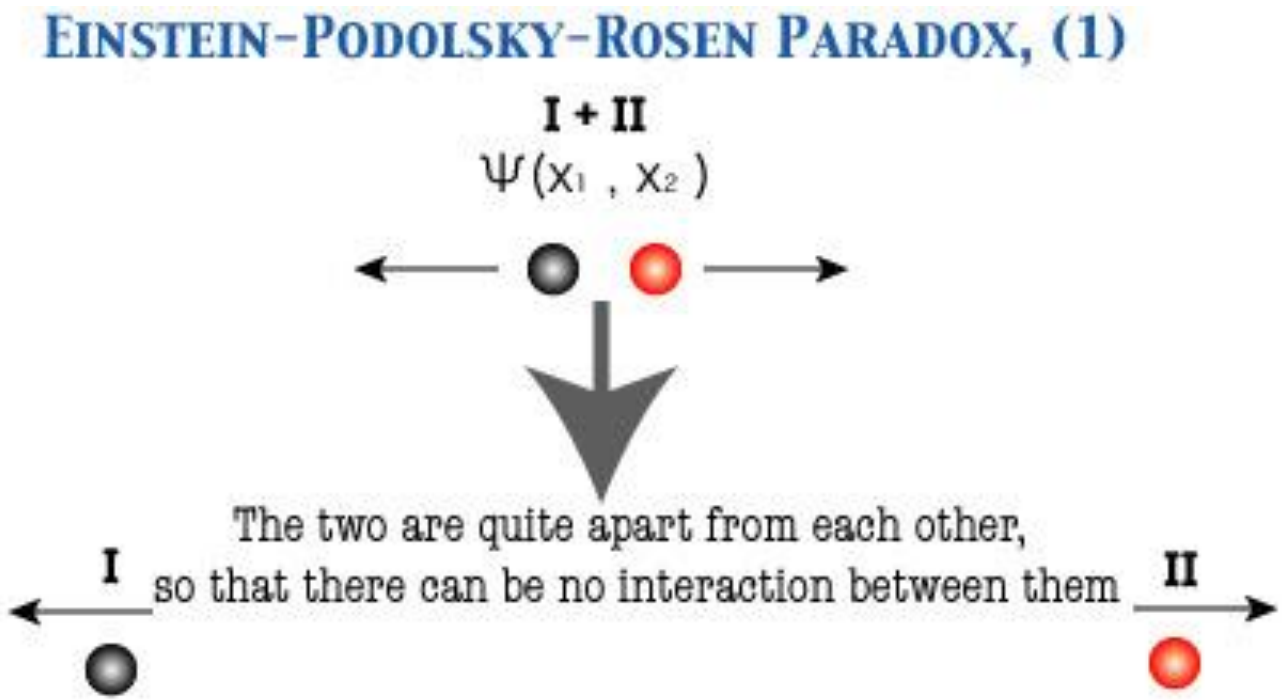
The EPR paradox of 1935 is a thought experiment in quantum mechanics with which A.Einstein and his colleagues B. Podolsky and N. Rosen claimed to demonstrate that the wave function does not provide a complete description of physical reality, and hence that the Copenhagen interpretation is unsatisfactory.
The essence of the paradox is that particles can interact in such a way that it is possible to measure both their position and their momentum more accurately than Heisenberg's uncertainty principle allows.

Bohm‘s version (1951) of the paradox is easier to understand (it is connected with the quantum entanglement) – it works with two separated atoms (the spin of each is exactly opposite to that of the other). In this situation, the angular momentum of one particle can be measured indirectly by measuring the corresponding vector of the other particle. This would involve information being transmitted faster than light as forbidden by the theory of relativity.
Thanks to so called Bell's inequalities (Bell 1964), this phenomenon can be tested in laboratory experiments.



Copenhagen interpretation – cricitism

EPR = Einstein - Podolsky – Rosen argument (paradox)



Suppose you measure the momentum of the black particle (I); then you can know the momentum of the red particle (II) as well. Likewise, if you measure the position of the black, then you can know the position of the red as well. In both cases, the measurement can be done **without disturbing** the red (since there can be **no interaction** between the black and the red).

quantum physics

Schrödinger‘s equation:

One of the most important equations in quantum mechanics.
It is a wave equation in terms of the wavefunction which predicts analytically and precisely the probability of events or outcome. The detailed outcome is not strictly determined, but given a large number of events, the Schrodinger equation will predict the distribution of results.

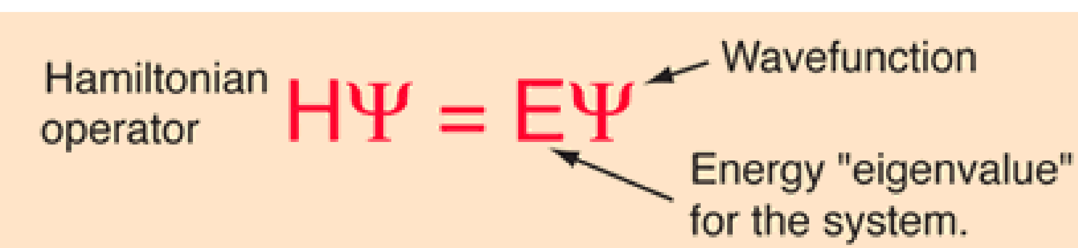
$$i\hbar \frac{\partial}{\partial t}\psi(\mathbf{r},t) = -\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{r},t) + V(\mathbf{r},t)\psi(\mathbf{r},t)$$

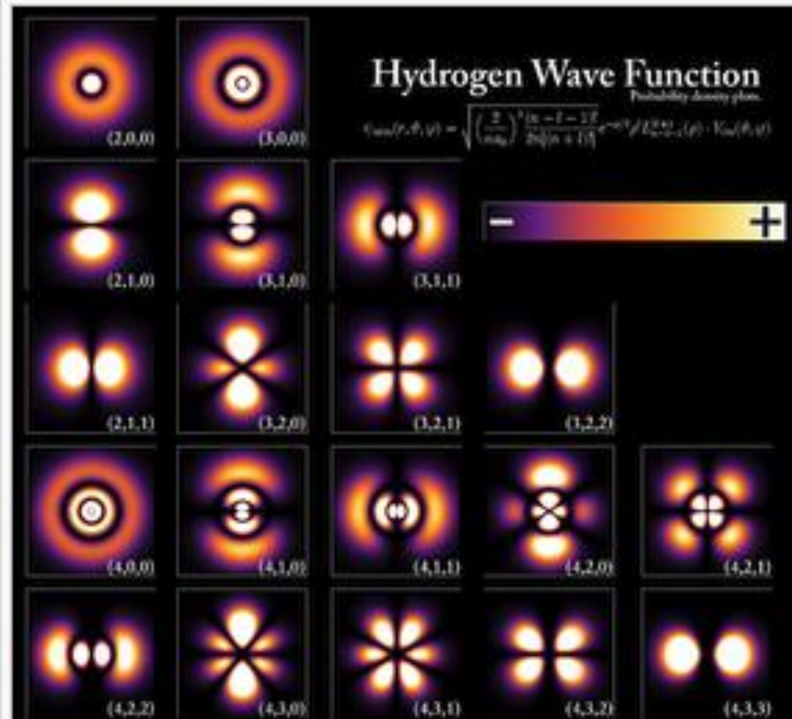
i is the imaginary number, $\sqrt{-1}$.
$\hbar$ is Planck's constant divided by 2π: 1.05459×10^{-34} joule·second
$\psi(\mathbf{r},t)$ is the wave function, defined over space and time.
m is the mass of the particle.
∇^2 is the Laplacian operator, $\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$.
$V(\mathbf{r},t)$ is the potential energy influencing the particle.

quite good explanation:
https://www.youtube.com/watch?v=QeUMFo8sODk&list=PL1lNrW4e0G8WmWpW846oE_m92nw3rlOpz

Schrödinger's equation:

In the Copenhagen interpretation of quantum mechanics, the wave function is the most complete description that can be given of a physical system. Solutions to Schrödinger's equation describe not only molecular, atomic, and subatomic systems, but also macroscopic systems, possibly even the whole universe.
The Schrödinger equation, in its most general form, is consistent with both classical mechanics and special relativity, but the original formulation by Schrödinger himself was non-relativistic.





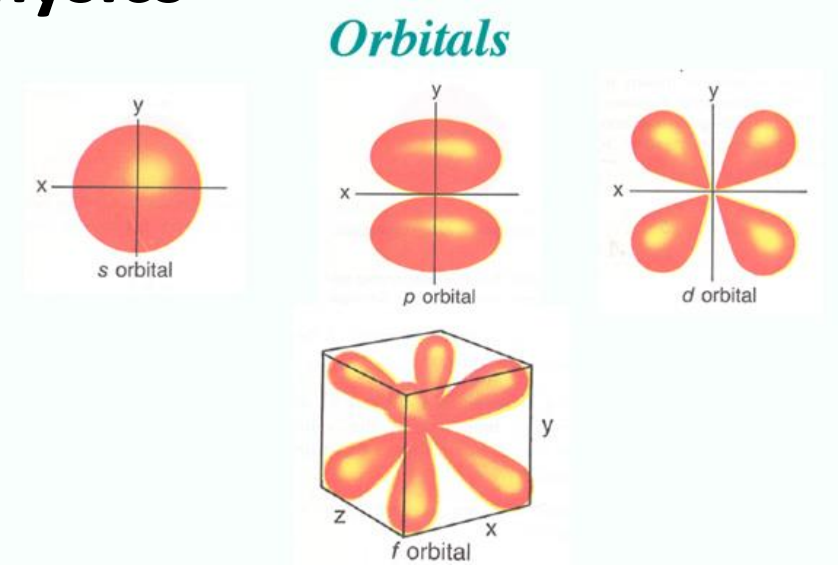
Solution to Schrödinger's equation for the hydrogen atom at different energy levels. The brighter areas represent a higher probability of finding an electron

quantum physics

Orbital model of the atom:

An atomic orbital is a mathematical function that describes the wave-like behavior of either one electron or a pair of electrons in an atom.

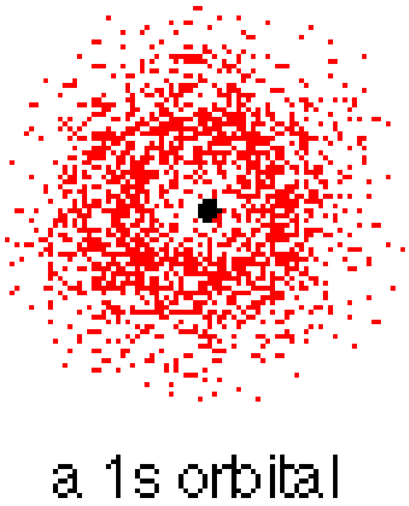
Derived from the latin word „orbita“ (track).



Summary of Principal Energy Levels, Sublevels, and Orbitals		
Principal energy level	**Number of sublevels**	**Type of sublevel**
$n = 1$	1	1*s* (1 orbital)
$n = 2$	2	2*s* (1 orbital), 2*p* (3 orbitals)
$n = 3$	3	3*s* (1 orbital), 3*p* (3 orbitals), 3*d* (5 orbitals)
$n = 4$	4	4*s* (1 orbital), 4*p* (3 orbitals), 4*d* (5 orbitals), 4*f* (7 orbitals)

Orbital model of the atom:

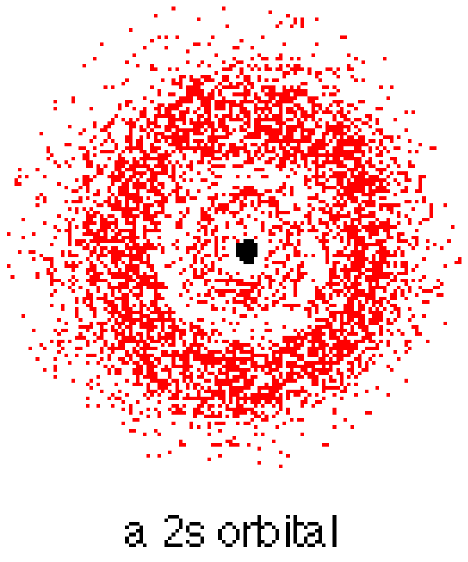
1s Orbital



- sphere around the nucleus

  (the one tells you that the electron is in the orbital closest to the nucleus)
- S tells you about the shape

2s Orbital

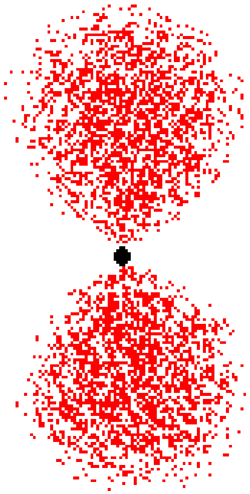


- similar to 1s except the electron is most likely in the region farther from the nucleus

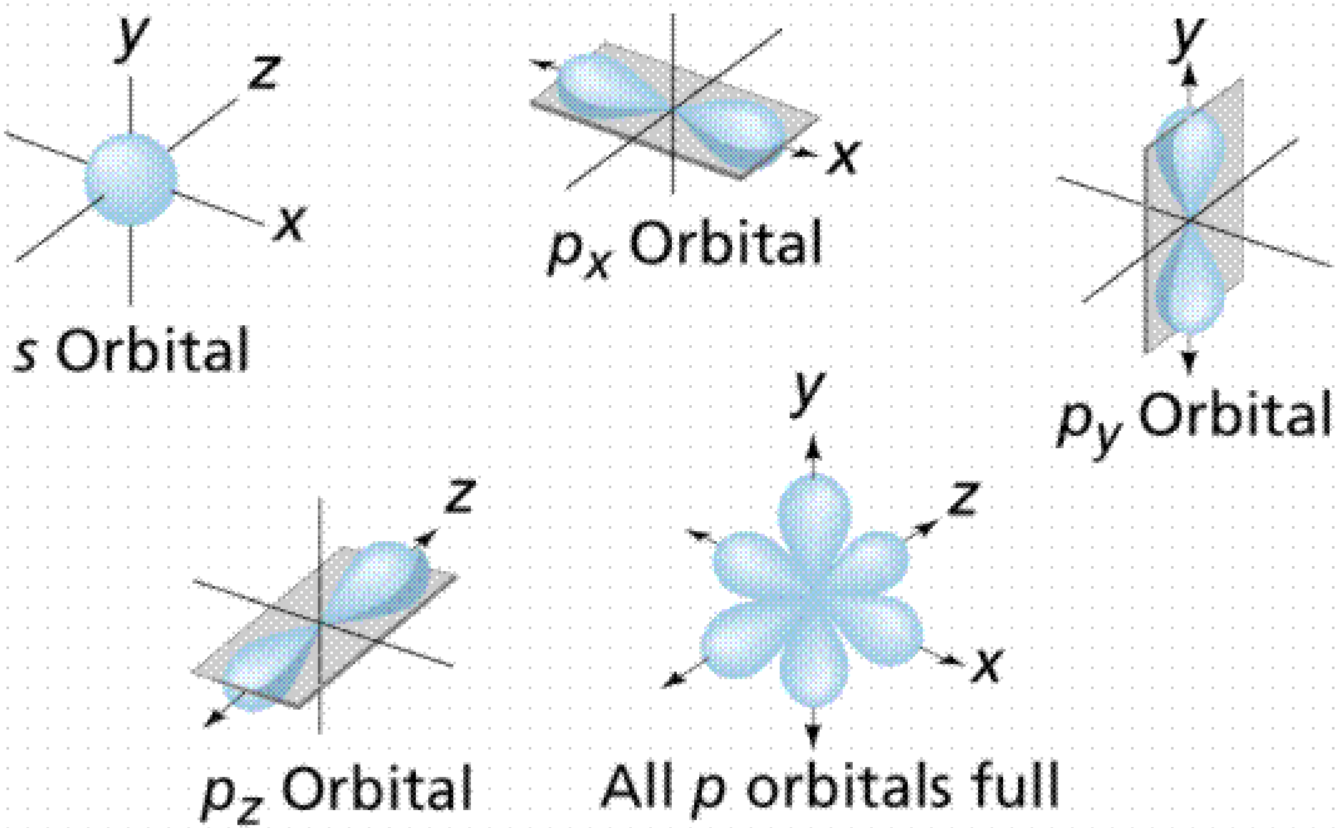
Orbital model of the atom:

p Orbitals

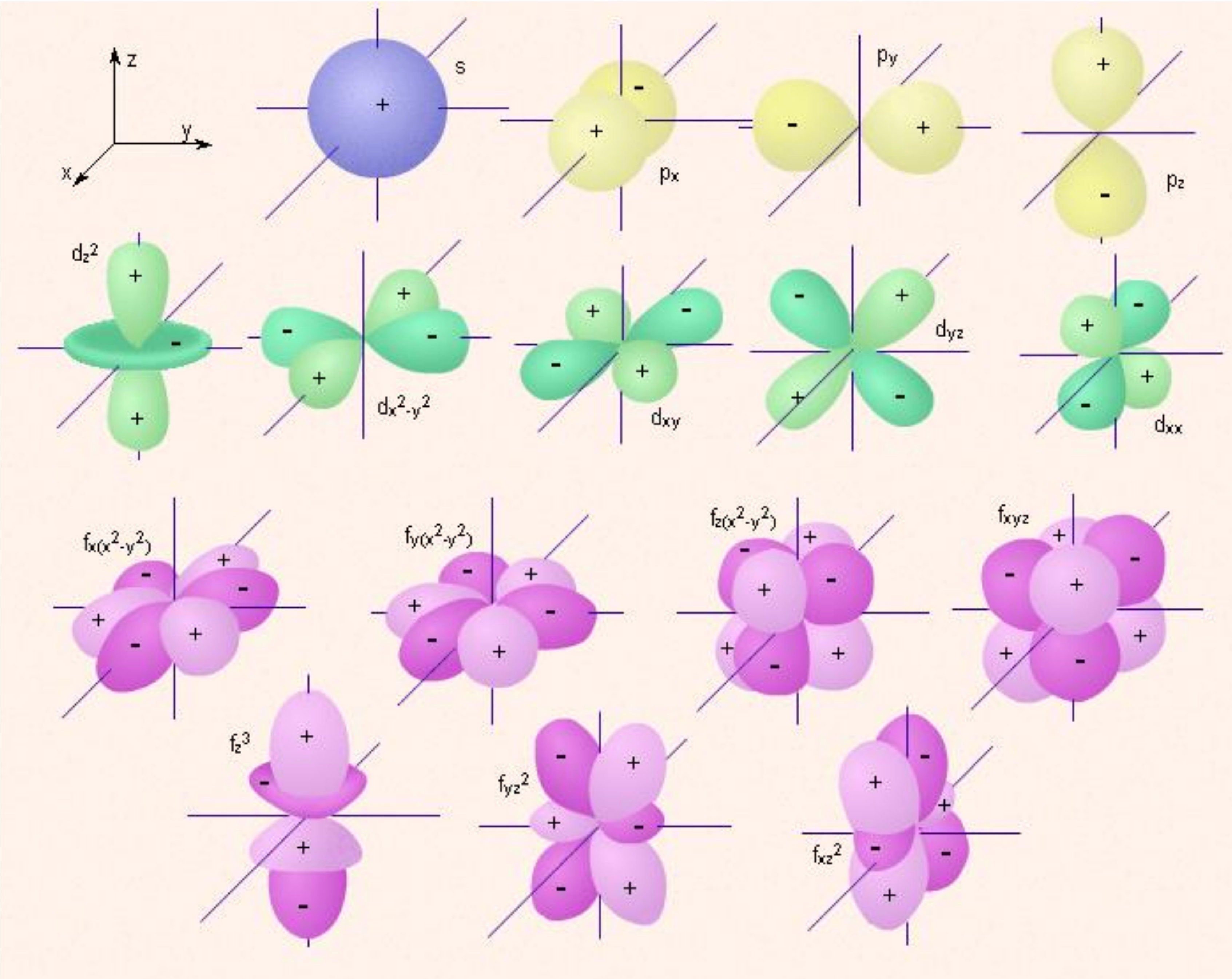
- at the first energy level there is only the 1s orbital, after the second energy level there are 2p orbitals
- look like dumbbells
- oriented in the three directions



a p orbital



Orbital model of the atom:



Orbital model of the atom:

There are 3 important principles:

1. Aufbau priciple - electrons occupy energy levels with lowest energy first,
2. Pauli's exclusion principle - if 2 electrons occupy the same energy level they must have opposite spins,
3. Hund’s rule - electrons that occupy orbitals of the same energy will have the maximum number of electrons with the same spin.

max number of electrons in an energy elevel

ENERGY LEVEL	MAX # OF ELECTRONS
1	2
2	8
3	18
4	32
5	50

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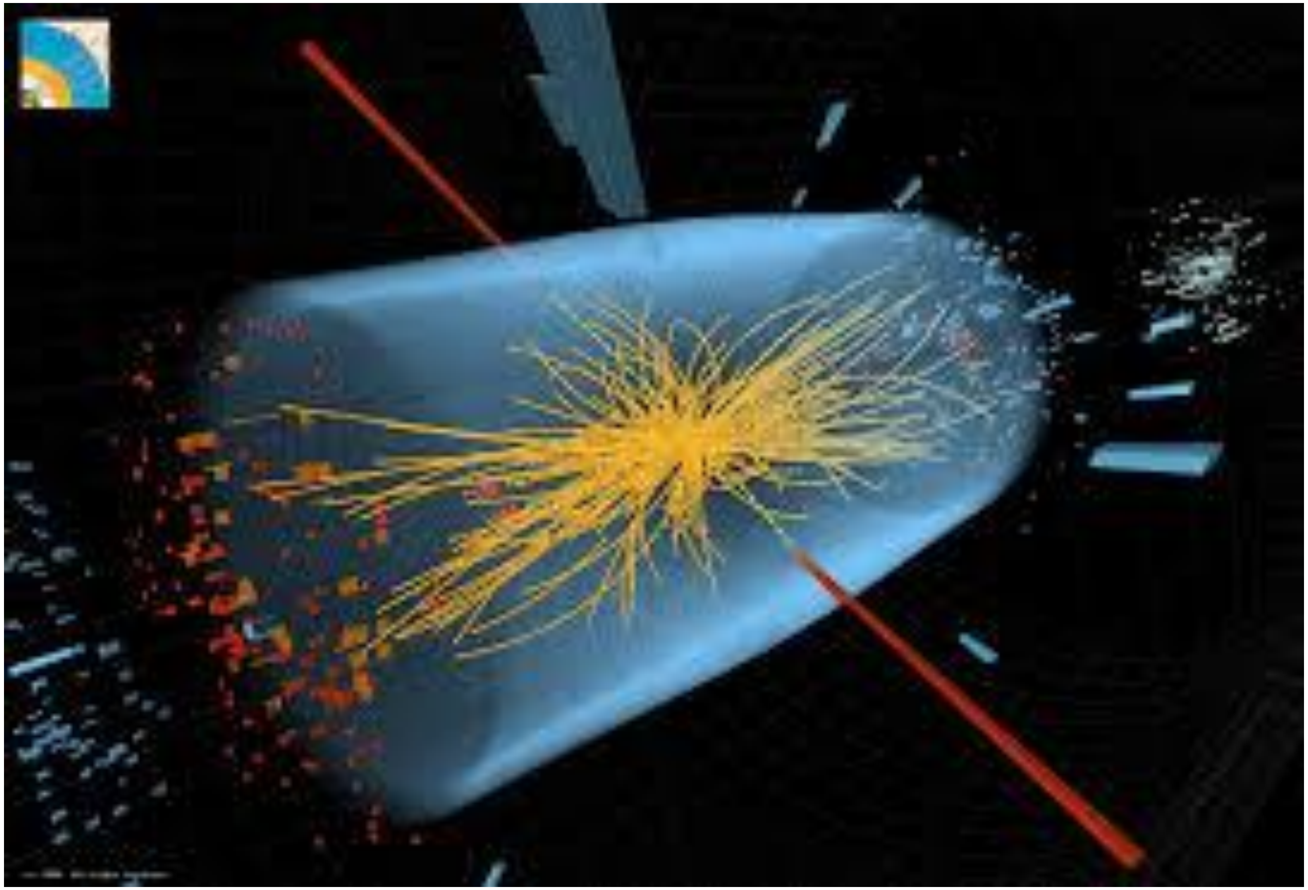
- basic parameters of particles
- particle physics, quarks
- The standard model
- dark matter

particle physics



particle physics - quarks

In the today state-of-the art level of knowledge in physics, the fundamental constituent of matter is quark.

The word quark comes from the standard English verb quark, meaning "to caw, croak," and also from the dialectal verb quawk, meaning "to caw, screech like a bird.„, which comes from a poem from James Joyce (M. Gell-Mann was motivated by this poem).

Murray Gell-Mann at TED in 2007. Gell-Mann and George Zweig proposed the quark model in 1964.

In 1932 W. Heisenberg formulated a theory that nucleons could exchange some kind of particles (in order to manage forces). In 1935 H.Yukawa formulated a next hypotesis that these particles are so called mesons.
The quark model was independently proposed by physicists M. Gell-Mann and G. Zweig in 1964.

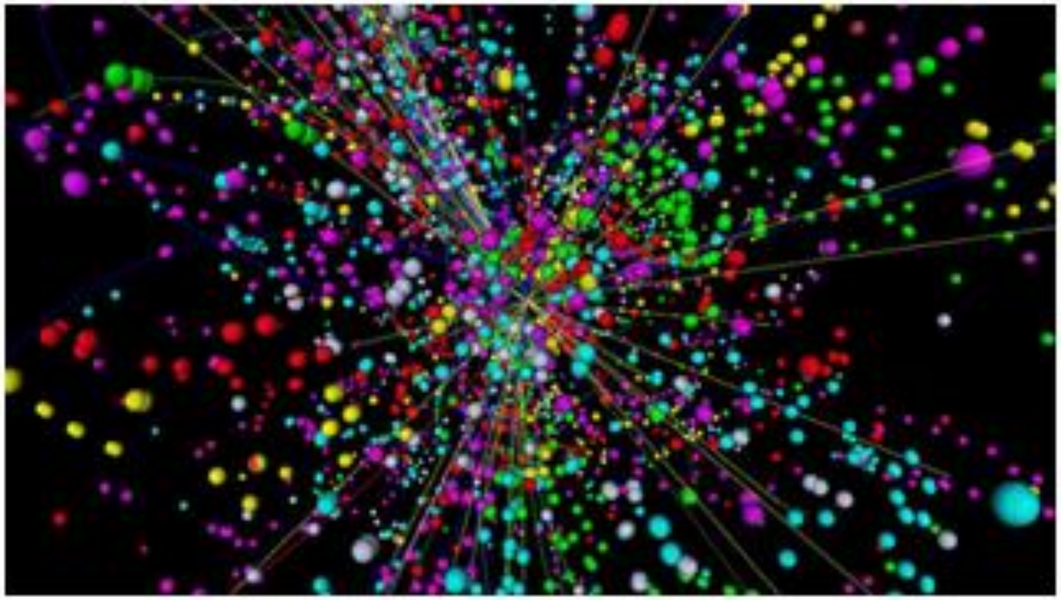
They posited that they were not elementary particles, but were instead composed of combinations of quarks and antiquarks. Their model involved three flavors of quarks, up, down, and strange, to which they ascribed properties such as spin and electric charge.
One year later S.L. Glashow and J. Bjorken predicted the existence of a fourth flavor of quark, which they called charm. Later on Top/Bottom flavors were added.

particle physics - quarks

Quarks make up all matter, but have never been seen by themselves.
The first problems with what were considered "fundamental" particles started springing up in the 1960s, when scientists shooting electrons at matter saw them veer off in different directions, seemingly for no reason.

Looking at how and when the electrons changed direction, scientists concluded that the nucleus had to be made up of smaller parts, some of which the electrons were "running into.“

These parts were smaller than the protons (had to be inside the protons).



particle physics

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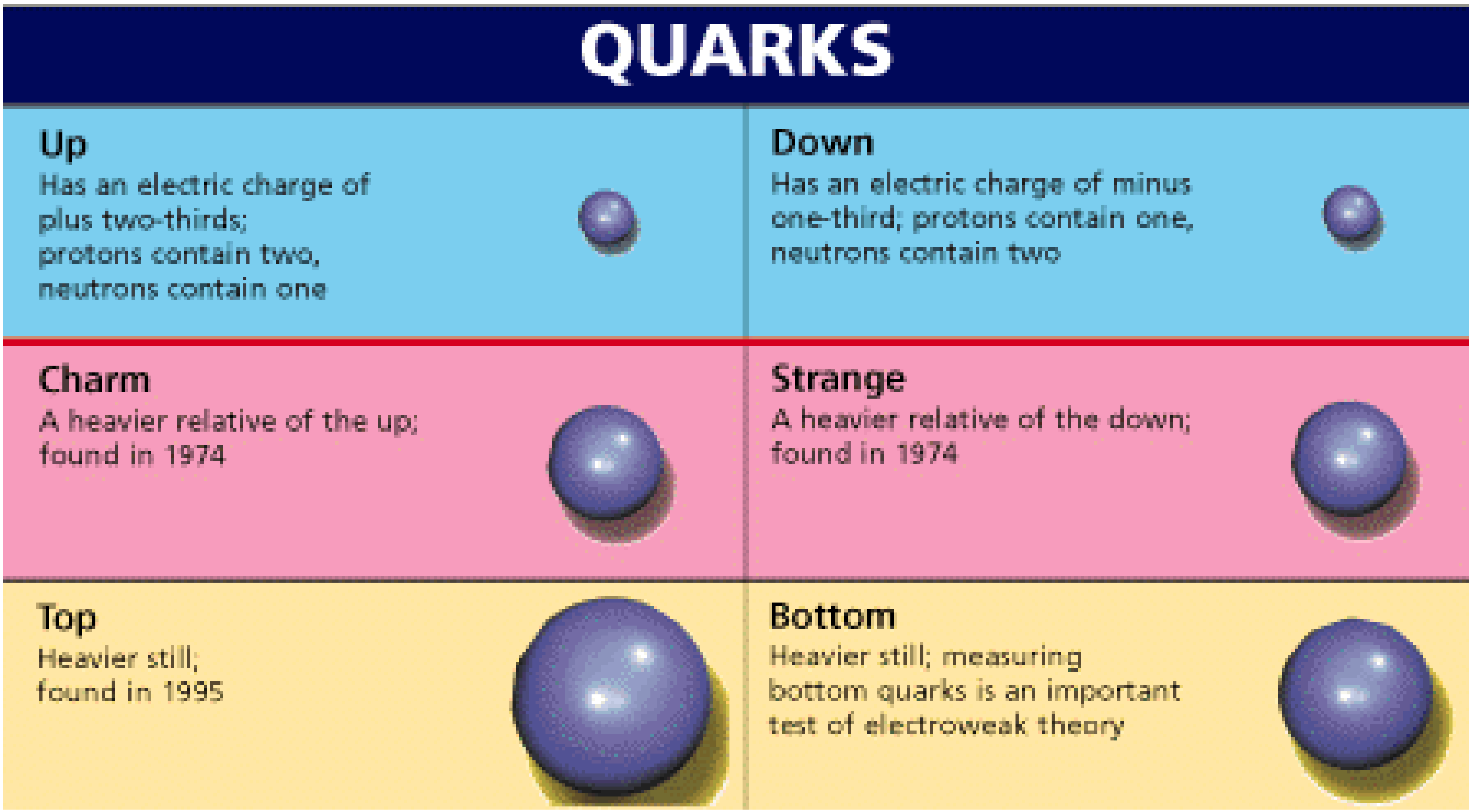
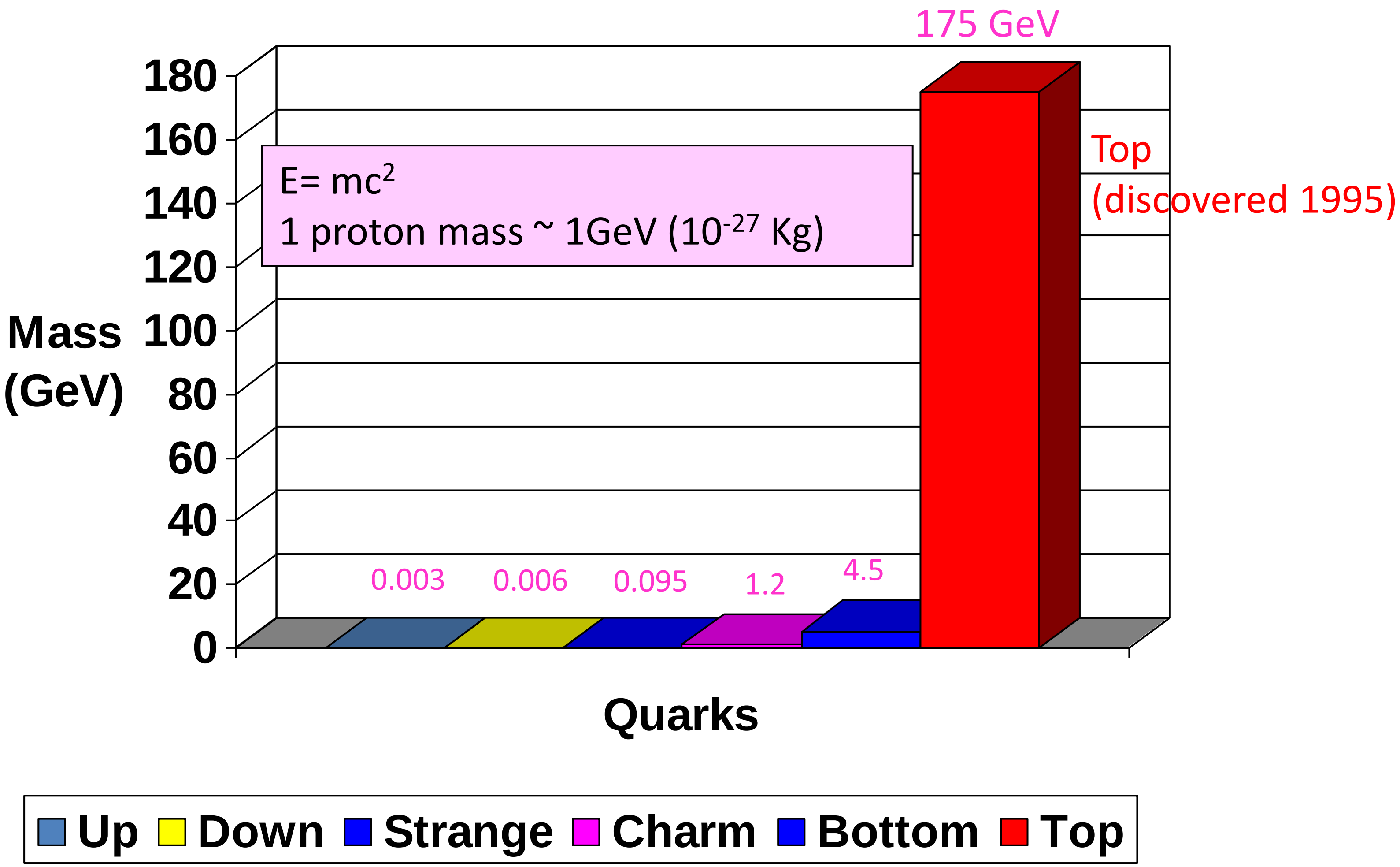


quark masses



quarks

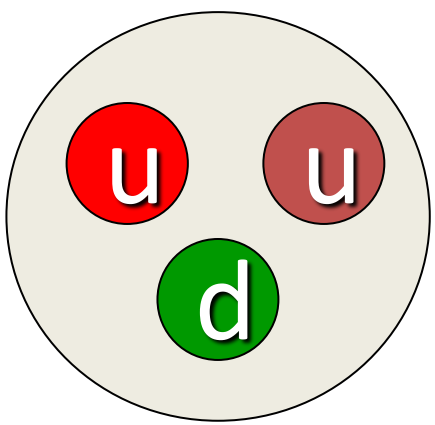
Quarks combine to form composite particles called hadrons, the most stable of which are protons and neutrons, the components of atomic nuclei.
up quark or u quark (symbol: u) is the lightest of all quarks,
down quark or d quark (symbol: d) is the second-lightest of all quarks,

Quarks have fractional electric charge!

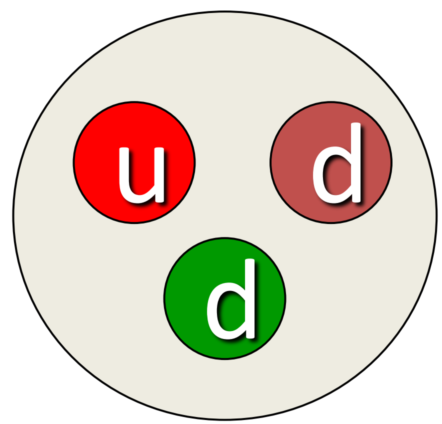
u electric charge + 2/3

d electric charge −1/3

proton (charge +1)



neutron (charge 0)

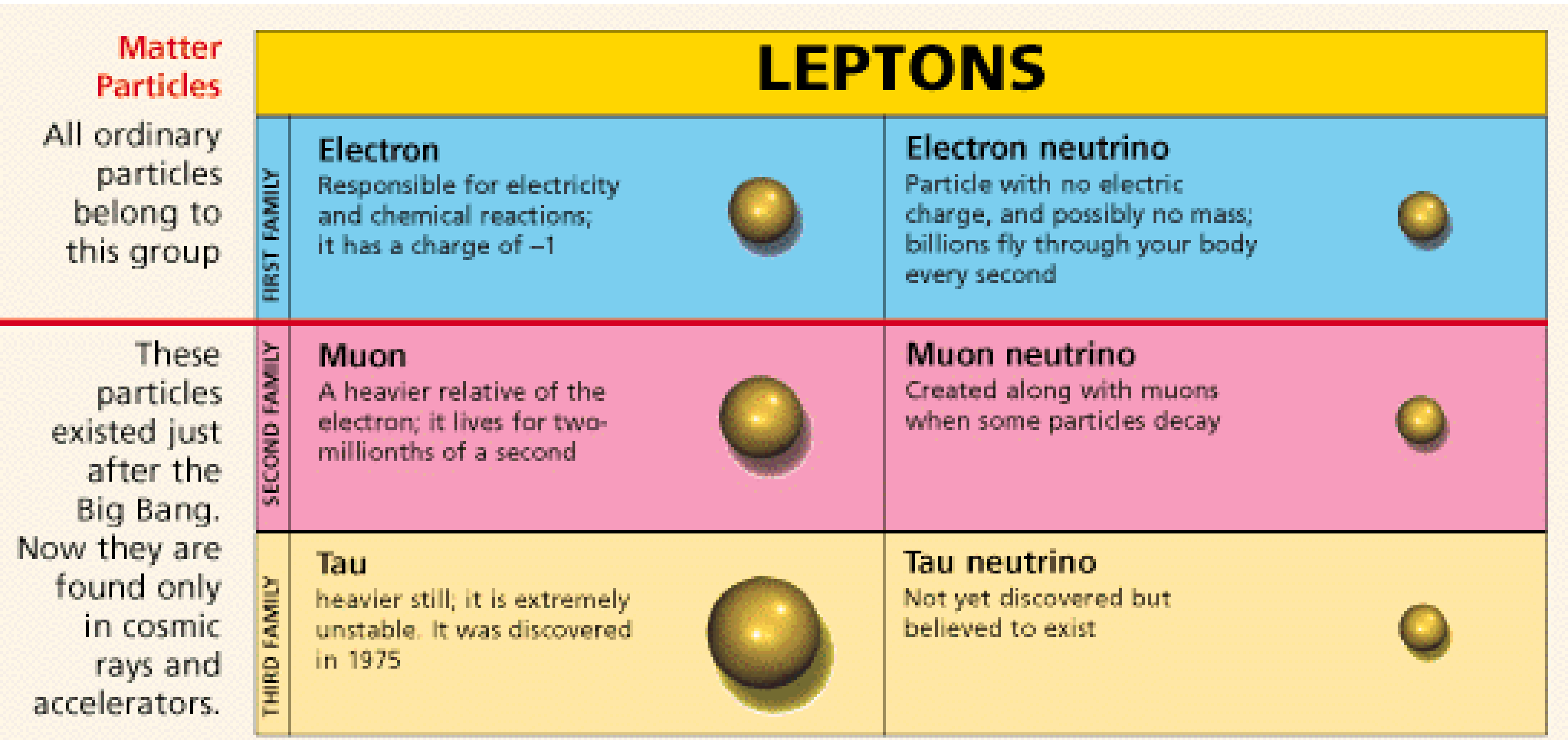


$$u\left(+\frac{2}{3}\right)u\left(+\frac{2}{3}\right)d\left(-\frac{1}{3}\right)=p(+1)$$

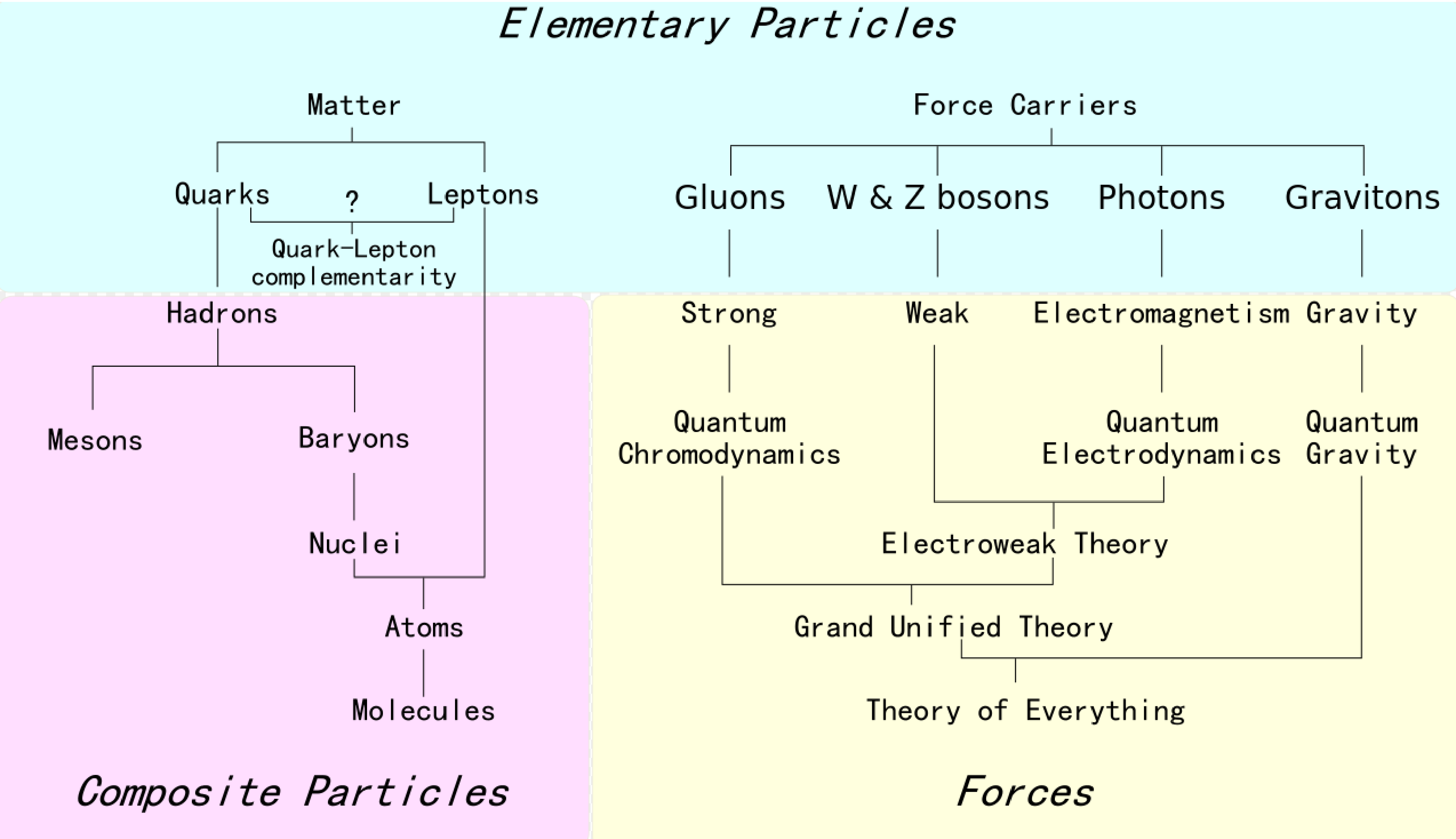
$$u\left(+\frac{2}{3}\right)d\left(-\frac{1}{3}\right)d\left(-\frac{1}{3}\right)=n(0)$$

leptons

In 1960's several particles were reclassified: electrons, muons, and neutrinos were grouped into a new group of particles – the leptons.
A lepton is an elementary, half-integer spin (spin 1⁄2) particle that does not undergo strong interactions.

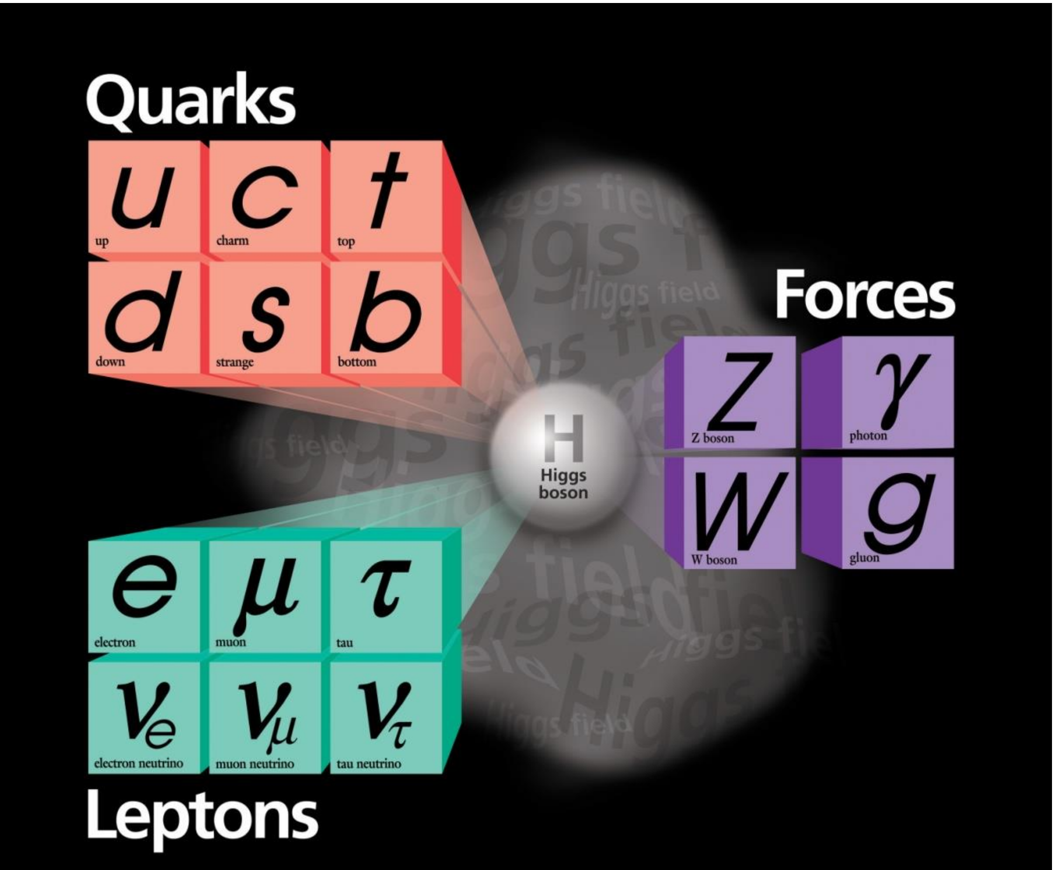


The standard Model



leptons = electrons, neutrinos and muons

The Standard Model



H= the missing ingredient: the Higgs Boson

Framework which includes:

Matter
- 6 quarks
- 6 leptons

Grouped in three generations

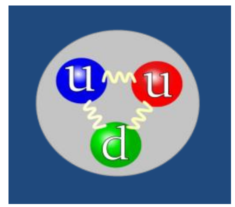
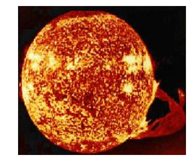
Forces
- Electroweak:
  - γ (photon)
  - Z^0, $W^\pm$
- Strong
  - g (gluon)

Not gravity! No quantum field theory of gravity yet..

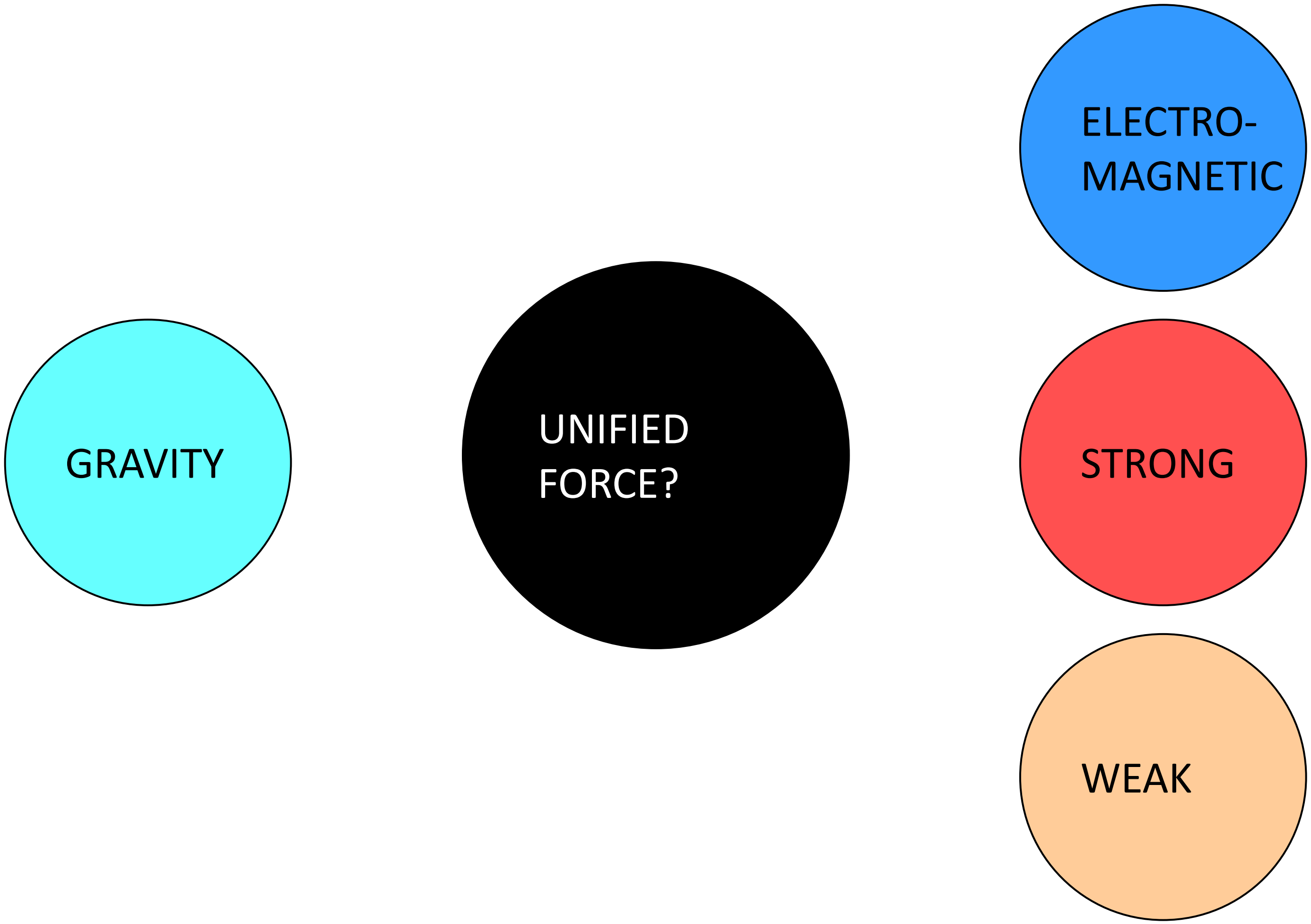
Very successful to describe all observed phenomena in the subatomic world so far. But there ought to be more..

main forces particles

Particles interact and/or decay thanks to forces.
Forces are also responsible of binding particles together

Strong: gluons quark binding  	Weak: W^+, W^-, Z^0 leptons and quarks 
Electromagnetic:γ quarks and charged leptons (no neutrinos) 	Gravity: graviton? Still to be discovered Negligible effects on particles 

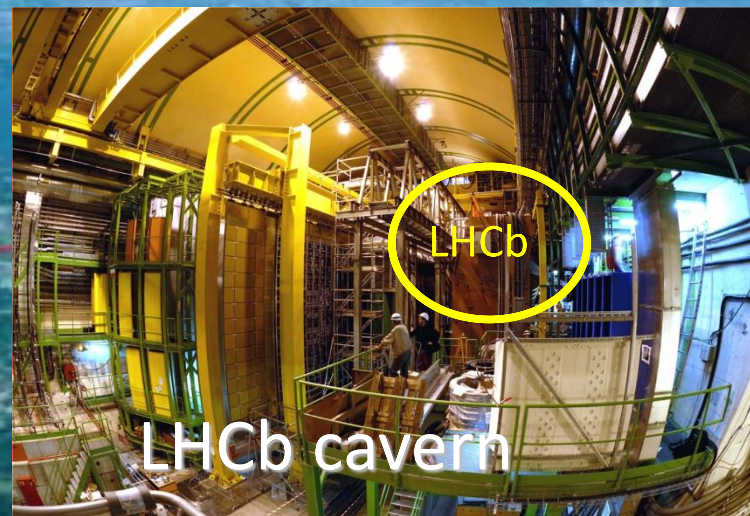
beyond The Standard Model: Unification of forces



Looking for a simple elegant unified theory

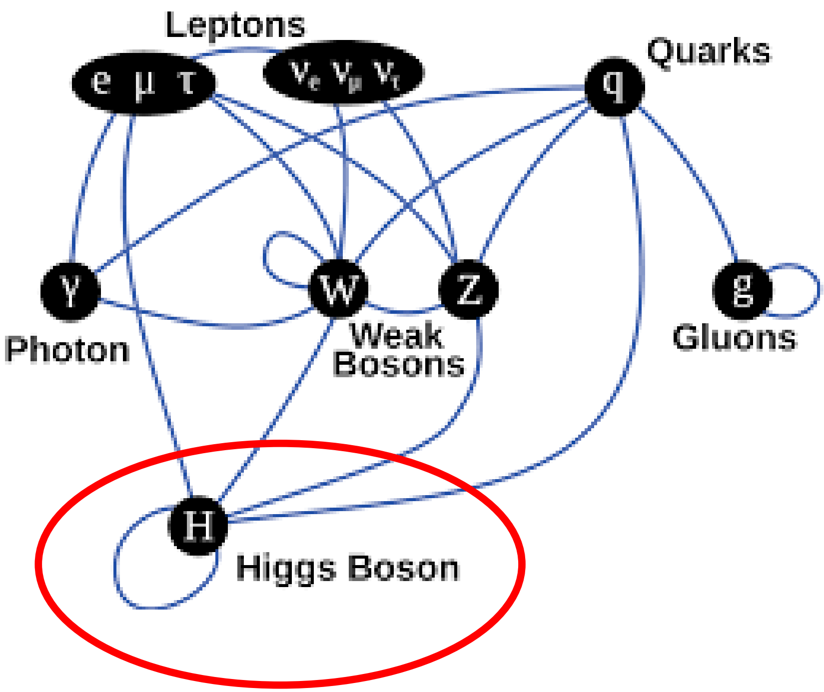
Large Hadron Collider - LHC

LHCb experiment:
700 physicists
50 institutes
15 countries

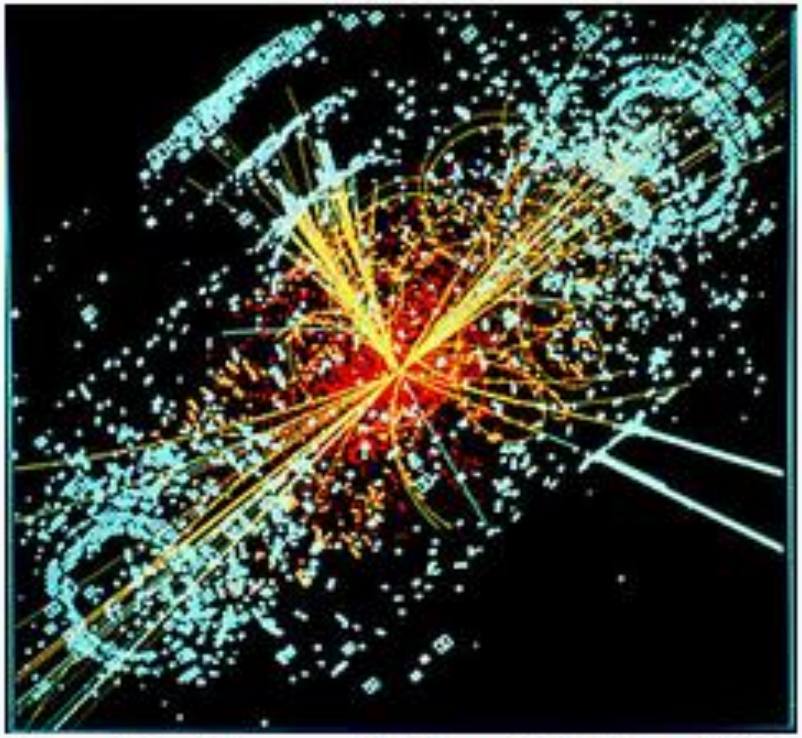


CERN
ATLAS

Large Hadron Collider - LHC

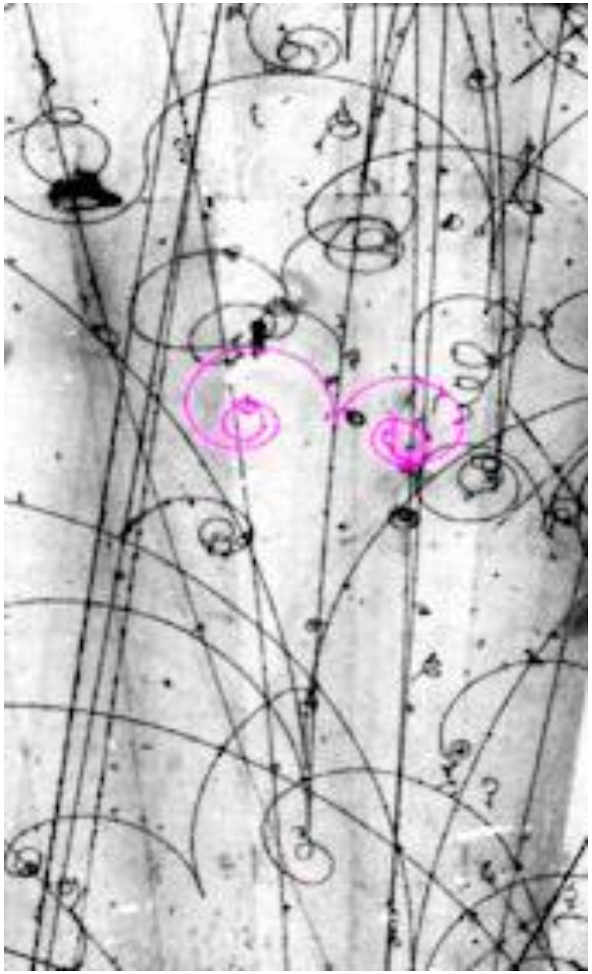


Beyond the Standard Model



Simulated **Large Hadron Collider** CMS particle detector data depicting a Higgs boson produced by colliding protons decaying into hadron jets and electrons

matter-antimatter pair creation



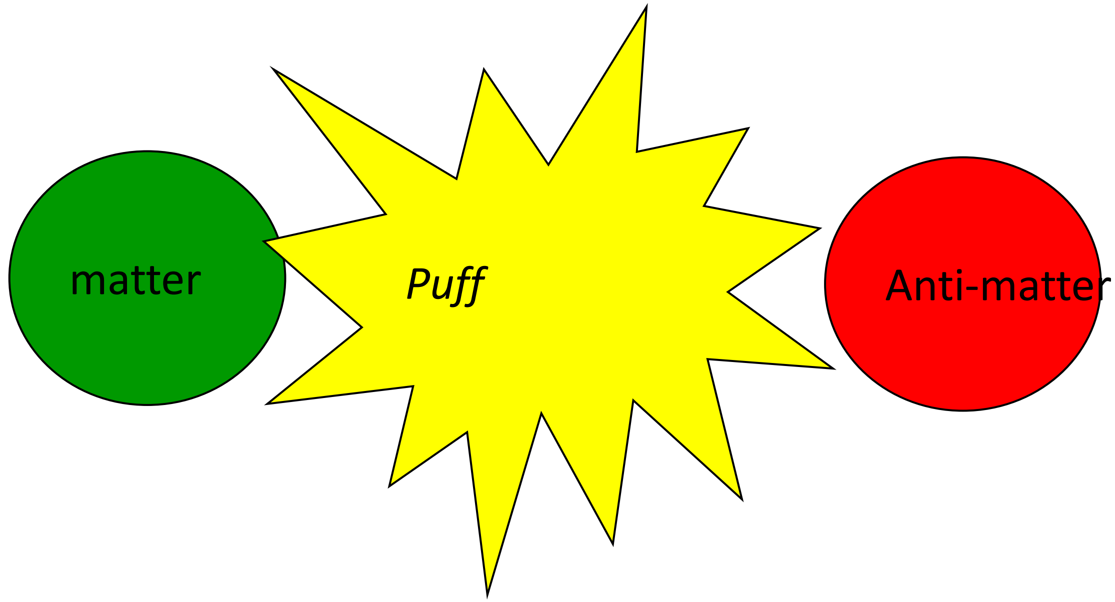
• electron-positron pair created out of photons hitting the bubble-chamber liquid

• example of conversion of photon energy into matter and anti-matter

• matter and anti-matter spiral in opposite directions in the magnetic field due to the opposite charge

• energy and momentum is conserved

Why has all the anti-matter gone?



Good thing for us that there is no antimatter around!

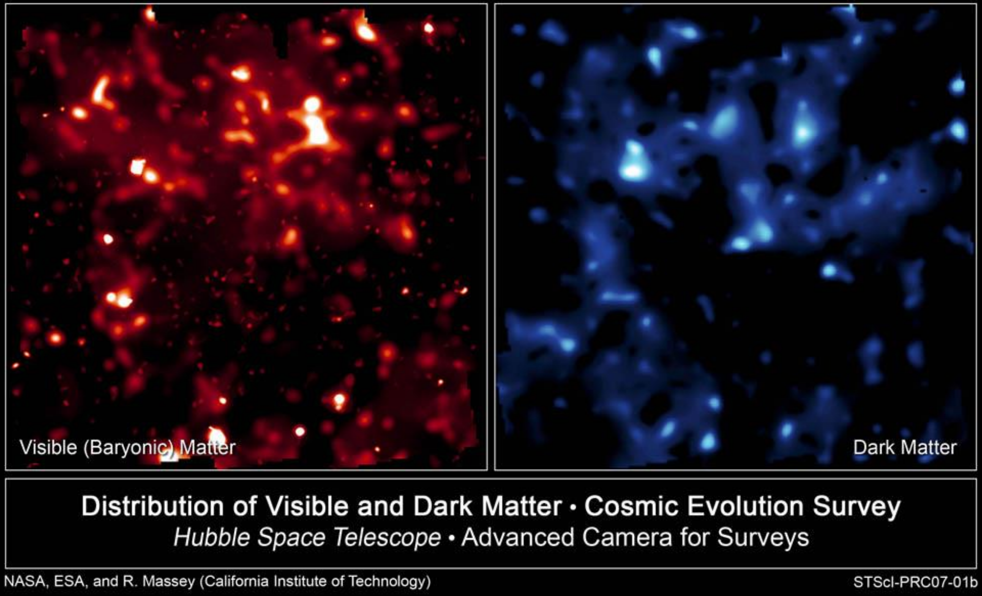
The development of the Universe containing matter and no antimatter requires that **matter and antimatter behave differently**

Another open question:

What is the Dark Matter?

- Astronomical observations have shown that “observable” mass represent less than 4% of the Universe!

Visible Matter   Dark Matter

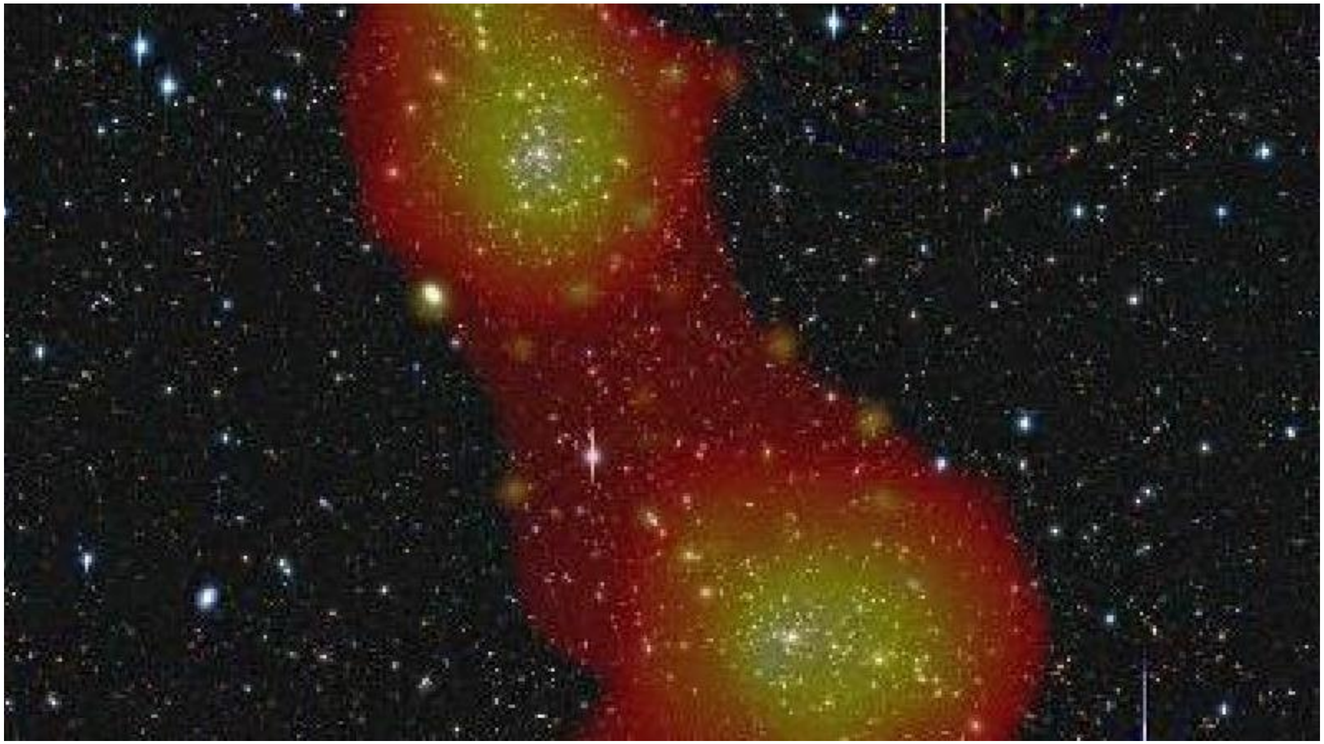


False-color images
The brightness of clumps corresponds to the density of mass.

- What is dark matter? We don’t really know …
  - Perhaps partially composed of neutrinos, or possibly neutralinos particles predicted by super-symmetric theories beyond the Standard Model?

very important contribution,

Norbert Werner (born in Slovakia, today: Stanford university), 2011



He has contributed to the experimental check of so called "cosmic web" theory (from 1999) - on X-ray photos of galaxies he detected a thread of hot gas between two groups of galaxies Abell 222 and Abell 223.

Maybe that up to 50% of all visible matter could be concentrated in such threads!

"Young man, if I could remember the names of these particles, I would have been a botanist!"

E.Fermi to his student

L. Lederman (both Nobel laureates)

the particle physicist's "bible":

Particle Data Book

https://pdg.lbl.gov

Most particles are not stable and can decay to lighter particles..