What does the World consist of?

Clemens Heuson

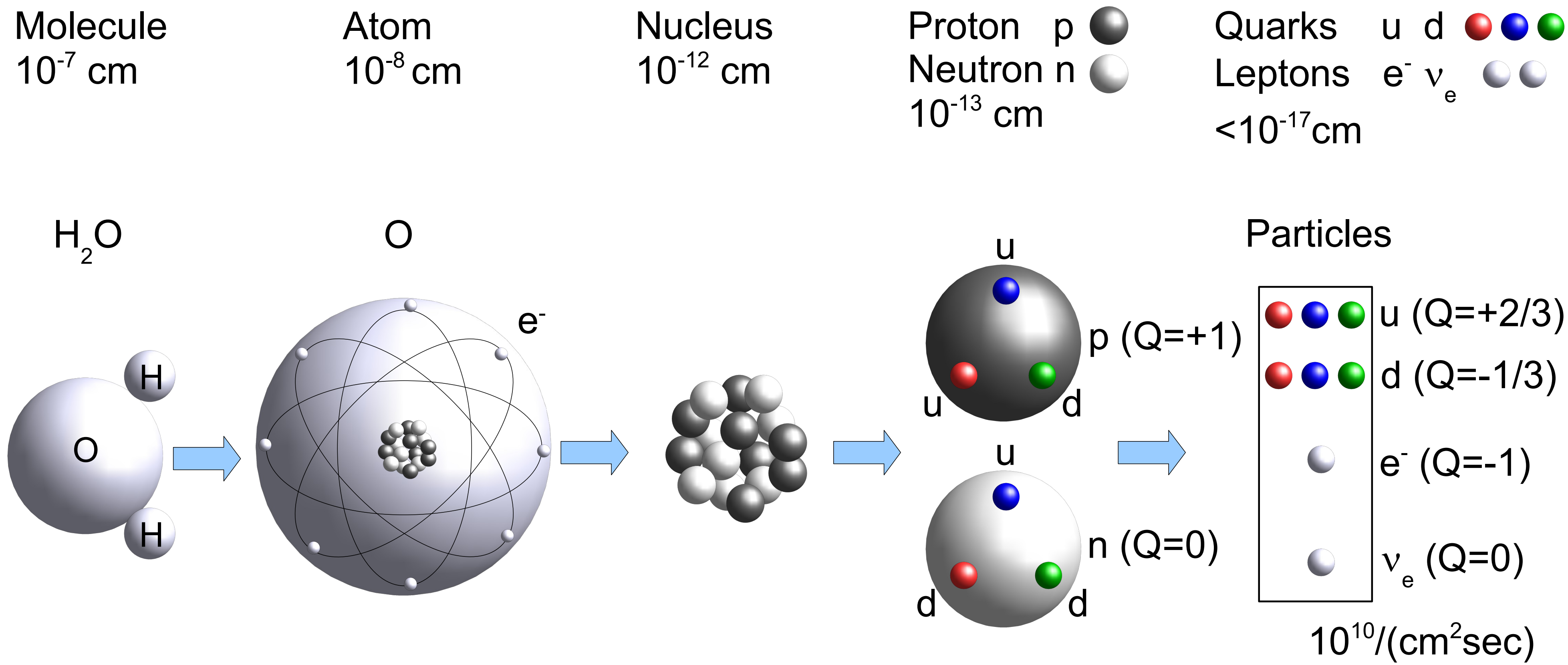
Which are the fundamental constituents of matter?

Which forces act between the fundamental constituents?

Why is the universe the way it is?

How did the universe begin and how will it end?

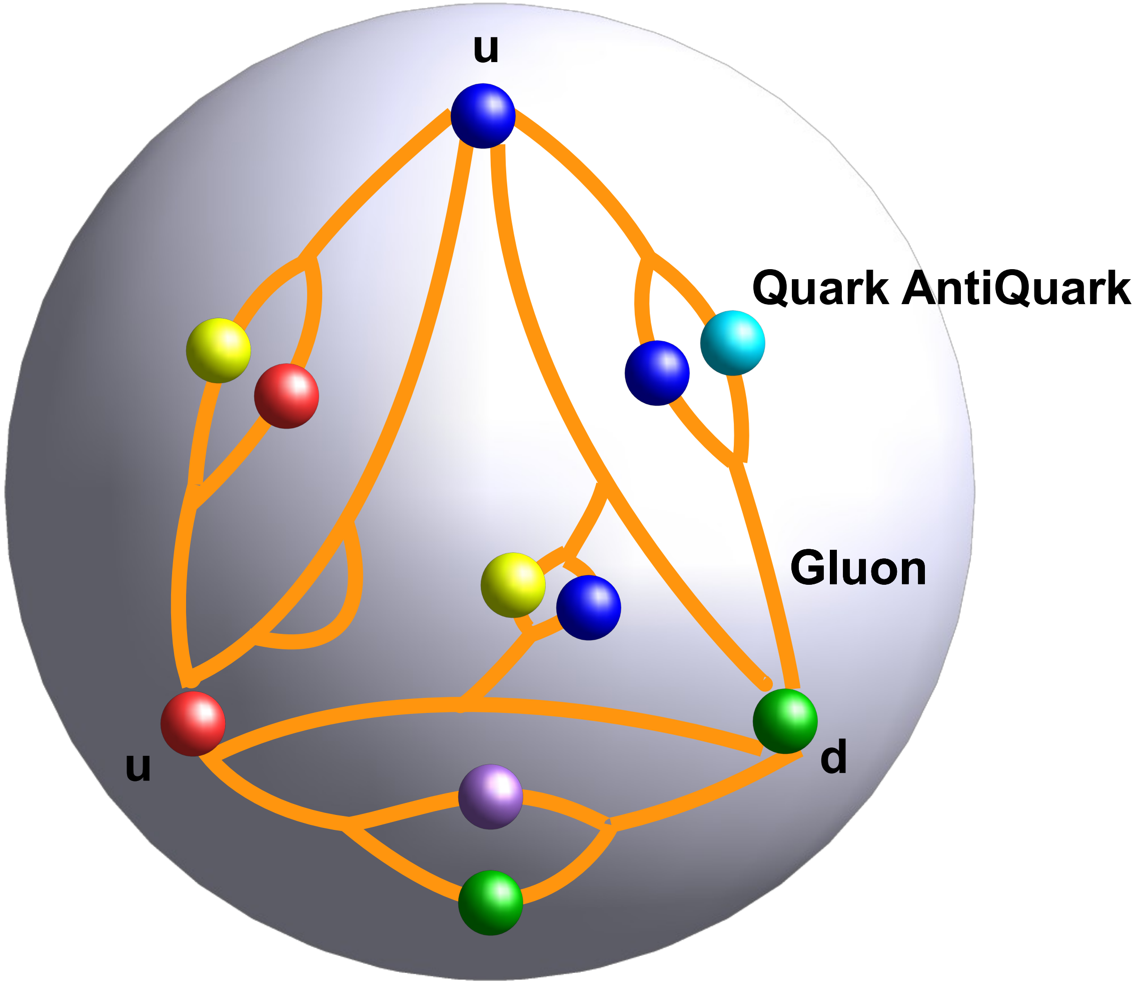
Structure of Matter



But things are not so simple, since a couple of additional particles exist: For every particle there is an antiparticle with equal mass and opposite charge. There exist particles mediating the forces between particles. Every particle has two heavier unstable cousins. Presumably there exist as yet undiscovered particles. Every second billions of neutrinos ν go through every square centimeter. Q is the electric charge in units of the elementary charge e.

Structure of the Proton

Proton Size 10^{-13} cm Quark Size $<10^{-17}$cm



The proton (or neutron) has a complicated inner live. The force between quarks is generated by the exchange of other particles, the so called gluons, which interact with each other and can be transformed into quark anti-quark pairs.

Classification of Particles

The matter surrounding us consists of the stable particles u, d, e^-, ν_e. Each of them has for unknown reasons two heavier unstable partners, giving three generations of particles. I: u d $e^-\nu_e$ II: c s $\mu^-\nu_\mu$ III: t b $\tau^-\nu_\tau$.
For every matter particle exists an antiparticle with the same mass but opposite charge. Every quark comes in three modifications called Red, Green, Blue and for antiquarks Anti-Red, Anti-Green; Anti-Blue. These are not conventional colours, but only names for the states. The quarks exist in nature only as bound states: mesons are quark antiquark states with colour and anti-colour, baryons are three quark states with the colours Red, Green, Blue or their Anti-Colours. The electron and neutrino together with its heavier partners are called leptons.

Leptons $l = e^-\nu_e\ \mu^-\nu_\mu\ \tau^-\nu_\tau$ The leptons $\mu^-\ \tau^-$ are unstable.

Quarks $q = u\ \ d\ \ c\ \ s\ \ t\ \ b$ The quarks $c\ \ s\ \ t\ \ b$ are unstable. $\bar{q}$ are AntiQuarks.

Mesons $M = q\bar{q}$ Examples: $\pi^+ = u\bar{d}\ \ K^0 = d\,\bar{s}$ All mesons are unstable.

Baryons $B = qqq\,,\overline{qqq}$ Examples: $p = uud\,,\ n = udd$ Other baryons are unstable.

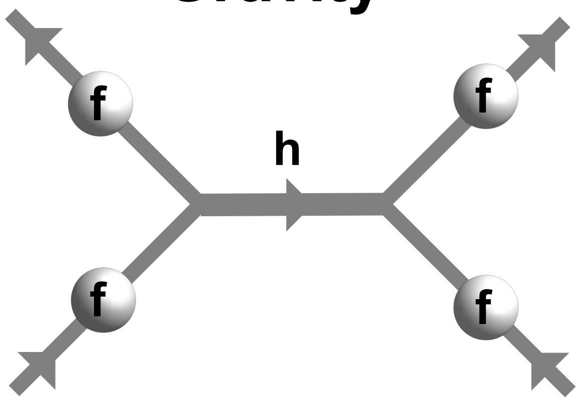
Classification of Forces

The world would be entirely different, if there were no forces between the objects in it.
Due to our present knowledge there are four fundamental forces between particles:
Gravity causes objects to fall, planets or stars orbiting, is neglegible for particles.
Weak force is responsible for particle decays and nuclear fusion in the sun.
Electromagnetic force attracts electrons to nuclei and repulses protons in nuclei.
Strong force binds quarks in the proton or neutron and keeps nuclei together.
The classical picture of a force is a field in spacetime acting on particles.
The quantum picture of a force is a force particle interacting with matter particles.

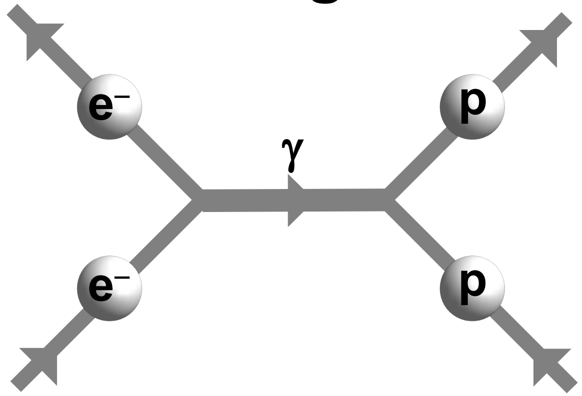
force	**relative strength**	**force particle**	**acts on**
Gravity	10^{-40}	graviton h (?)	all particles
Weak force	10^{-4}	W^+ W^- Z^0	quarks, leptons
El.magn. force	1	photon γ	charged particles
Strong force	50	8 gluons g	quarks, gluons

Forces (quantum picture)

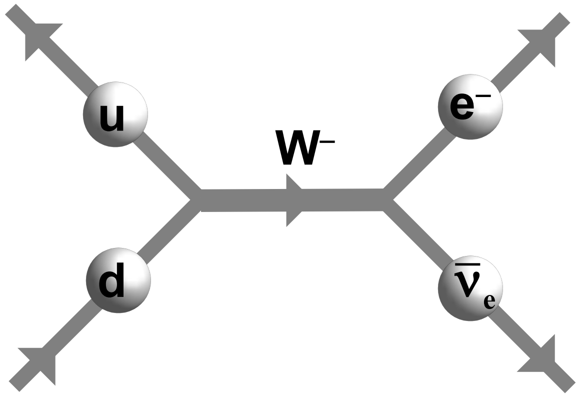
Gravity



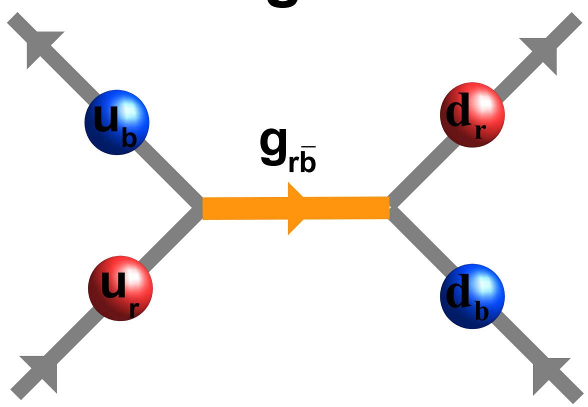
ElectroMagnetism



Weak Force

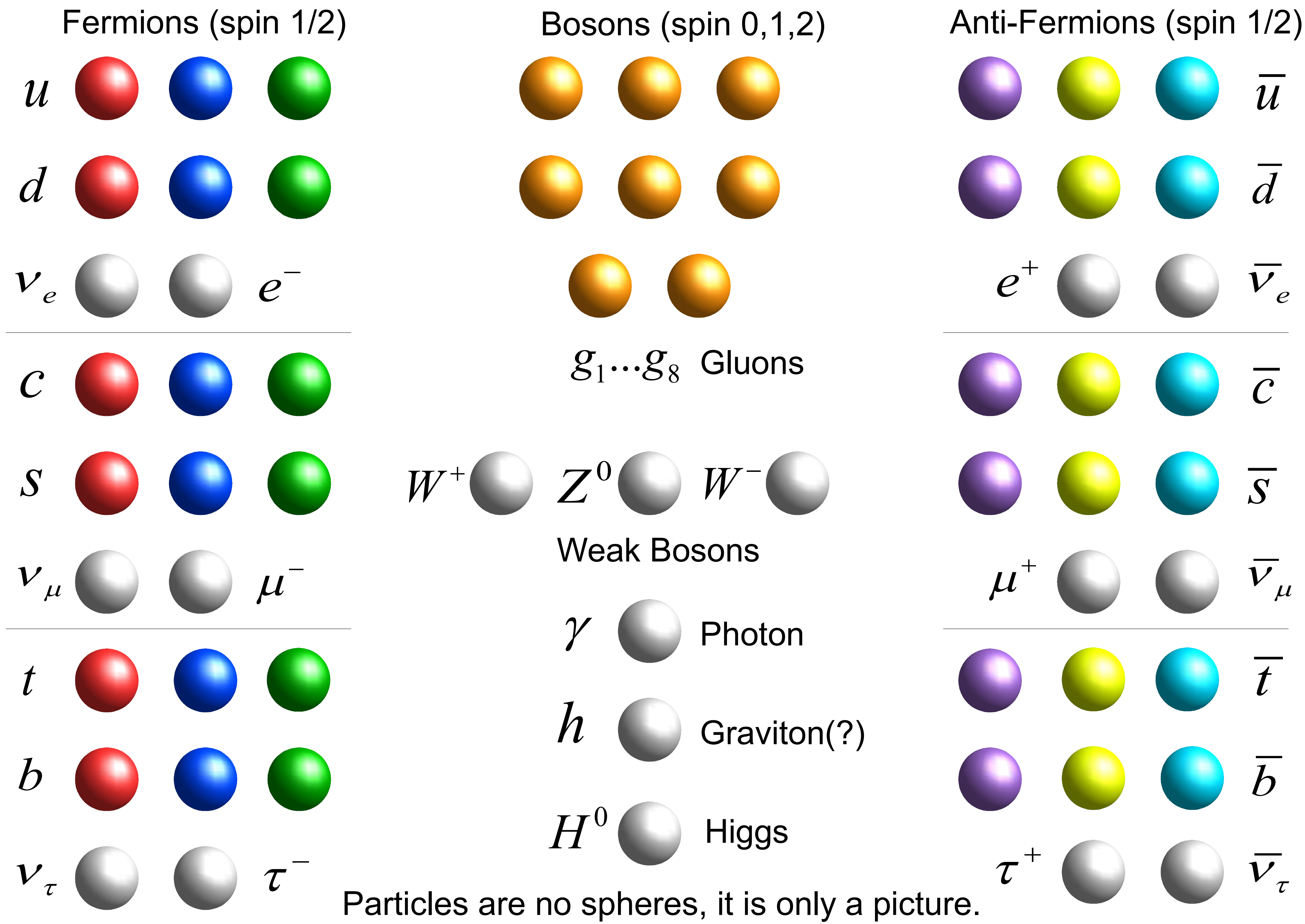


Strong Force



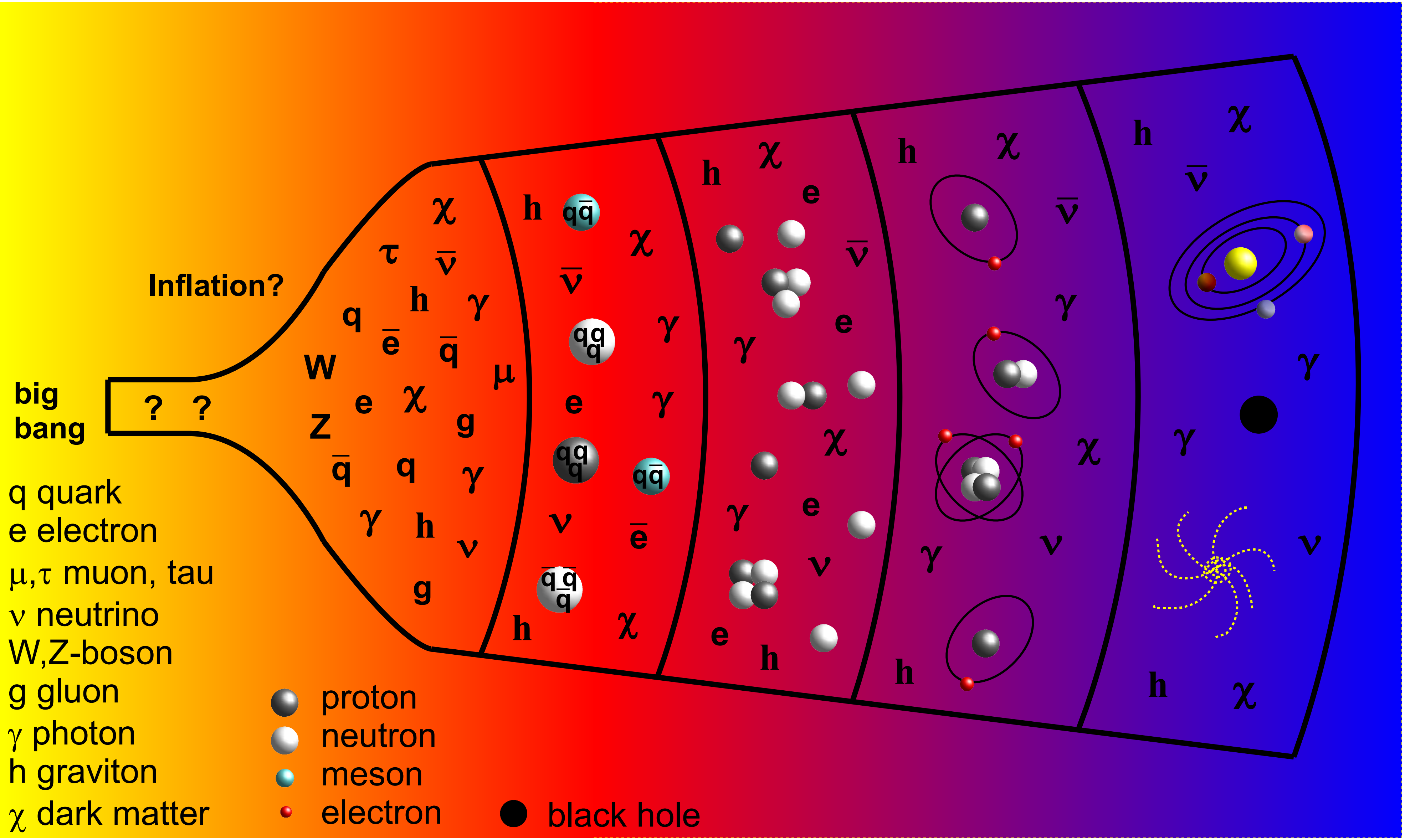
A matter particle (fermion) emits a force carrier particle (boson), which can be absorbed by another distant matter particle influencing its movement. Forces are called interactions.

Particles of the Standard Model



Particles are no spheres, it is only a picture.

History of the Universe



History of the Universe

Big Bang: From the movement of far galaxies we know, that the universe is expanding and cooling down. Therefore 14 billion years ago it must have been in an extremely hot and dense state called big bang. We don't know, why this big bang happened nor the physical laws at extremely high energies. One possibility is that the universe evolved out of a previous collapsing universe. A speculation shared by many is, that after the big bang there happened an exponential superluminal expansion of the universe (inflation), making it so homogeneous and isotropic on very large scales, as we observe now.

Hot particle soup: At particle energies comparable to those we generate in particle accelerators, there must have been a very hot soup of all particles we know: quarks, leptons, bosons and possible dark matter particles.

Protons and neutrons: Particles and antiparticles annihilate and for unknown reasons an excess of particles remains. After further expansion and cooling down, quarks bind to mesons and baryons. Mesons and many baryons decay leaving protons, neutrons, electrons, neutrinos and photons.

Primordial Nucleosynthesis: Protons and neutrons combine to deuterium and helium and other light nuclei by nuclear fusion, explaining that nowadays 75% of normal matter is hydrogen and 24% helium.

Decoupling of photons: Nuclei and electrons combine to neutral atoms and the photons decouple from matter, giving the cosmic microwave background observed today, which was at first discovered as perturbation in radio antennas.

Stars, galaxies, black holes: Inhomogeneities in the soup of particles presumably driven by dark matter particles lead to the formation of the first stars and galaxies. Very massive stars after exhausting their amount of hydrogen and helium by nuclear fusion collapse and explode as supernovas leaving black holes or neutron stars. By fusion and collapse all heavier elements of the periodic table were generated and blown out in the universe. The next generations of stars were born in gas clouds together with planets orbiting them. Black holes absorb matter and fuse giving large black holes with many solar masses in the centre of galaxies. About 4 billion years ago our solar system and the earth were formed and on the earth live evolved, including humans.

Dark Matter and Dark Energy: From the movement of stars in galaxies with constant velocity and from gravitational lensing, one concludes that there must be large amounts of dark matter around galaxies. From precision measurements of the cosmic microwave background and from the recently discovered accelerating expansion of the universe one concludes, that there must be an additional stuff (vacuum energy, dark energy) filling the universe. Normal matter makes 5% of the universe, dark matter 25% and dark energy 70%. It is a big challenge for science to find out, what really constitutes 95% of the universe and how this stuff is connected to normal matter made from quarks, leptons and bosons.

Future of universe: The future of the universe is uncertain, due to the fact, that we don't understand dark matter and dark energy and many unsolved problems of particle physics. It may expand forever or collapse again. Perhaps the observed universe is only a part of something larger or other universes exist.

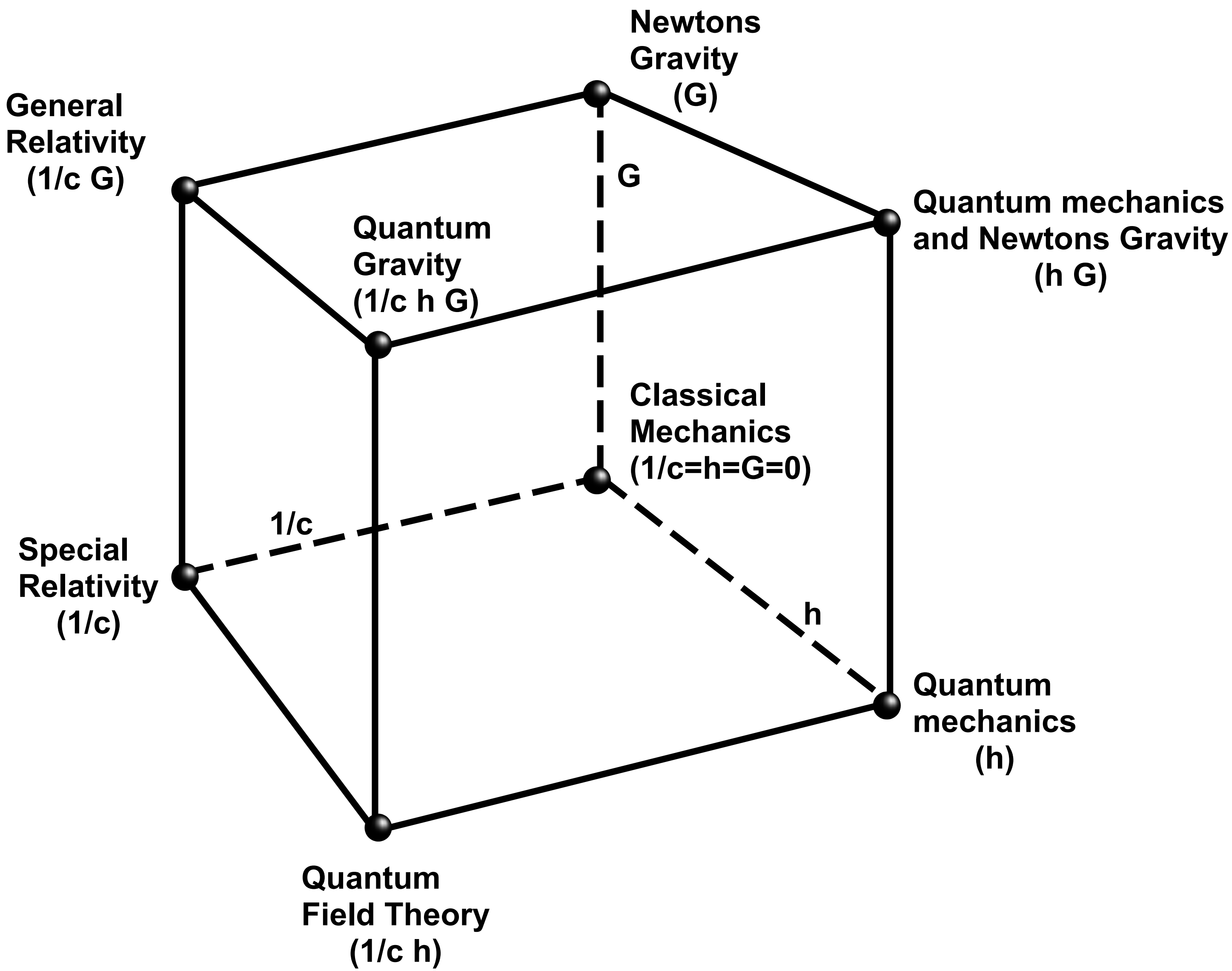
Theoretical Foundations of Particle Physics

The fundamental physical theories can be classified by the appearance of three fundamental constants of nature. An unsolved problem is, why the fundamental constants of nature have the observed values.

gravitational constant *G*	speed of light *c*	Plancks constant *h*
Newtons law of gravity	equivalence of mass and energy	energy frequency relation of particles
$F = \frac{G\, m_1\, m_2}{r^2}$ $G = 6.674 * 10^{-11} \frac{m^3}{s^2\, kg}$	$E = m\, c^2$ $c = 2.998 * 10^{8} \frac{m}{s}$	$E = h\, f$ $h = 6.626 \times 10^{-34} \frac{kg\, m^2}{s}$

"The Book of Nature is written in the language of mathematics." Galileo Galilei

The Cube of Physical Theories



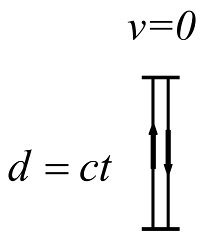
Special Relativity (SR)

- Constancy of the speed of light *c* in all systems moving with constant velocity.
- Laws of nature are invariant under Lorentz transformations.
- Time elapses slower in a moving system compared to a system in rest.
- New relations between energy *E*, momentum *p*, velocity *v* containing the Newton ones in the limit for $c \to \infty$.

$$E = mc^2 / \sqrt{1 - v^2 / c^2} \qquad p = mv / \sqrt{1 - v^2 / c^2} \qquad E^2 = p^2c^2 + m^2c^4$$

- There exist particles with mass zero (photon, gluons), moving with c.
- Equivalence of mass and energy $E=mc^2$ (nuclear bomb, nuclear fusion).

Light clock and time in a moving frame

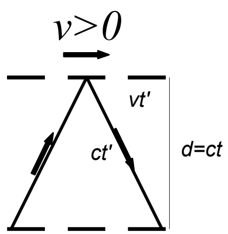


Pythagoras:

$$d^2 = c^2t'^2 - v^2t'^2$$

$$d = ct'\sqrt{1 - v^2 / c^2}$$

$$t' = t / \sqrt{1 - v^2 / c^2}$$



A light clock consists of two mirrors and a light ray bouncing between them. The light ray needs a longer time in the moving light clock, as observed from a rest frame, i.e. time elapses slower in a moving system.

Lorentz Transformation

$$t' = \gamma(t - \frac{v}{c^2}x)$$

$$x' = \gamma(x - vt)$$

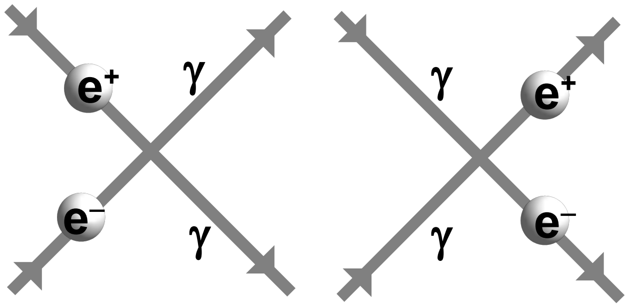
$$\gamma = 1 / \sqrt{1 - v^2 / c^2}$$

Determines, how space *x* and time *t* are changed in a system moving with velocity *v*.

"Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality." Hermann Minkowski

Quantum Field Theory (QFT)

- Unification of SR and QM: seperate equations for particles of different spins.
- Quantisation of classical fields: electrons are quanta of the electron field, photons are quanta of the photon field etc. All particles of one type are therefore absolutely identical. Particles and fields are unified to quantum fields.
- There exist particles and antiparticles, with same mass but opposite charge, pair annihilation in bosons and pair creation occur. Energy can be converted in particles.
- Interaction between matter particles (fermions) is mediated by the exchange of force particles (bosons) of the forces (strong, weak, electromagnetic, gravitational).
- Graphical description of interactions by Feynman diagrams.
- The strength of forces depends on distance (energy): the strength of electromagnetism increases because of the screening by virtual particle antiparticle pairs for smaller distance (or higher energy), while the strength of the strong force decreases because of the contribution of gluons.



annihilation   pair creation

Lagrangian of the standard model
for the calculation of particle interactions

$$\mathcal{L} = i\hbar\bar{\Psi}\gamma^{\mu}D_{\mu}\Psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\Psi}Y\Psi\Phi + \left|D_{\mu}\Phi\right|^{2} - V(\Phi)$$

Paul Dirac's shortest story of the world: young man meets young antigirl, kiss, end.

A new Paradigm of QFT: Spinors

1983 Parke and Taylor found a surprisingly simple formula for special scattering amplitudes (from which the cross section can be obtained) using computers to evaluate about 200 Feynman diagrams. People immediately wondered, why Feynman diagrams are so complicated, while the final result is so simple – something must be wrong with the previous picture. 1987 three chinese physicists Xu, Zhang and Chang described massless spin 1 bosons by massless spinors (spin 1/2 particles), which simplified the calculation of amplitudes considerably ("chinese magic"). These discoveries led to a couple of further developments by Bern, Dixon, Kosover and many others for calculating amplitudes much more efficiently. In Feynman diagrams massless spin 1 bosons as the photon and gluon are represented by a vector with four components and the massless spin 2 graviton by a symmetric tensor with 10 components. This requires some invariances, which now appear as a redundancy of description and not as fundamental principles, in order to reduce the degrees of freedom to the two necessary ones. Later on by Schwinn, Weinzierl, Arkani-Hamed, Huang and Huang this was extended to massive spinors (quarks and leptons), described by a pair of massless spinors. Amplitudes are now expressed by massless spinors with positive or negative helicity (projection of spin on the momentum) or by massive spinors. One very surprising consequence of this is, that (gravity amplitude) = (gluon amplitude)^2. It is really astonishing, that interactions between particles can be described by such simple formulas. These new methods presumably lead into an entirely new territory of particle physics including quantum gravity.

$\vert i\rangle, \vert i] \,.\, \vert \mathbf{i}\rangle, \vert \mathbf{i}]$	Massless spinors with negative, positive helicity. Massive spinors (**bold**).
$\mathcal{A} = \dfrac{\langle i\, j\rangle^4}{\langle 1\,2\rangle\langle 2\,3\rangle..\langle n\,1\rangle}$	Parke Taylor formula for n gluon scattering (couplings and other constants are omitted).
$\varepsilon_i^- = \dfrac{\vert i\rangle[q\vert}{[i\,q]} \,,\, \varepsilon_i^+ = \dfrac{\vert i]\langle q\vert}{\langle i\,q\rangle} \,.\, \varepsilon_i = \dfrac{\vert \mathbf{i}\rangle[\mathbf{i}\vert}{m}$	Massless Spin 1 boson i with negative, positive helicity (chinese magic). Massive spin 1 boson.
$\mathcal{A} = x\langle \mathbf{1}\,\mathbf{2}\rangle \,,\, \mathcal{A} = x^2\langle \mathbf{1}\,\mathbf{2}\rangle \,,\, x = \dfrac{\langle \varsigma\,\mathbf{2}\rangle[\mathbf{2}\,3]}{m\langle \varsigma\,3\rangle}$	Amplitude: massive fermions **1**, **2** interacting with gluon, graviton 3.
$\mathcal{A} = \dfrac{\langle 1\,2\rangle^3}{\langle 2\,3\rangle\langle 1\,3\rangle} \,,\, \mathcal{A} = \left(\dfrac{\langle 1\,2\rangle^3}{\langle 2\,3\rangle\langle 1\,3\rangle}\right)^2$	Amplitude: interacting gluons (1, 2, 3), interacting gravitons.

What is the Spin of Particles?

Classical Physics: Spin is the intrinsic angular momentum of rotating objects. A wheel turning around a fixed axis has spin, given by mass x mean distance to axis x velocity, which is conserved, if there is no torque influencing the rotation. Analogously a freely rotating spinning top or the earth rotating around it's axis (thus generating day and night) have a spin, whose modulus can take all possible values greater or equal than zero.

Quantum Physics: For a pointlike particle (electron, quark, photon etc) there exists no rotating mass with a distance from an axis. Therefore the spin of quantum particles is defined by the behaviour of the wavefunction under rotation of the coordinate system. By a mathematical derivation one obtains, that the spin of particles is quantised, i.e. can only take values, which are half integer or integer multiples of $\hbar$ (Planck's constant $h/2\pi$).

Particles with half integer spin 1/2, 3/2.. are called fermions (matter particles).
Particles with integer spin 0, 1, 2.. are called bosons (force particles).

For bosons of spin 1(2) the wavefunction remains unchanged after a rotation by 360°(180°), examples are for spin 1 an arrow, for spin 2 a double arrow. For fermions of spin 1/2 the wavefunction remains unchanged after a rotation by 720°. Examples for this are the balinese cup trick or Dirac's belt trick: see internet. Fermions don't like themselves, i.e. you never find two identical fermions in the same quantum state, whereby the structure of the electronic shells in atoms can be explained. Bosons like themselves, i.e. they prefer to be in the same quantum state, an example are the photons in a laser.

History of Particle Physics

500 B.C.	**Anaxagoras** introduces an unlimited multiplicity of entities, causing the change of substances. **Empedokles** introduces the four elements: earth, water, air, fire.
400 B.C.	**Leukipp** and **Demokrit** were teaching, that the universe consists of empty space and a huge number of invisible and undivisible particles (**atoms**). The atoms differ in form and are undestroyable. All objects are explained by different arrangements of atoms and events in the world by joining and splitting of atoms.
1700	**Isaac Newton** develops classical mechanics, describing the motion of bodies through the influence of forces and the theory of gravitation. Light consists of particles. Matter consists of small particles, and they again consist of smaller particles with increasingly stronger forces between the particles.
1800	**Thomas Young** describes light as waves, measures it's wave length and performs double slit experiments showing interference.
1800	**John Dalton** develops his atom theory. All atoms of an element are identical. Atoms of an element can bind with other atoms to molecules.
1820	**Hans C. Oersted** discovers the magnetic effect of electric currents.

1905	**Albert Einstein** introduces light quanta (**photons**) as particles. **Special relativity** explains the dependence of distance and time on the reference frame, as well as the equivalence of mass and energy.
1909	**Ernest Rutherford** performs scattering experiments with alpha-particles (nuclei of Helium) on gold foils and observes single alpha particles scattered under large angles. Thereby one derives the existence of a small, positive charged centre in the atom, the nucleus.
1913	**Niels Bohr** develops a model of atomic structure, explaining the discrete energy spectrum of light emitted by atoms.
1916	**Albert Einstein** proposes **general relativity**, which explains gravitation by the curvature of space-time through matter and energy. **Friedmann, Lemaitre** and others apply the theory successfully to the entire universe. The unification with quantum mechanics is still unsolved.
1920	**Ernest Rutherford** finds first hints for the existence of the **proton** as the nucleus of the hydrogen atom.
1923	**Arthur Compton** confirms with his scattering experiments the particle nature of photons, as postulated by Einstein 1905.

1964	**Murray Gell-Mann, George Zweig** and **Andre Petermann** propose **quarks** as subparticles. Mesons are composed of quark antiquark pairs and baryons of three quarks, which are called **u, d, s** = **up, down, strange**. The quarks have spin 1/2 and carry electric charges of 2/3, -1/3, -1/3 e.
1964	**Peter Higgs, Francois Englert, Robert Brout** and others postulate a field, which endows other fundamental particles with mass, and whose quantum is later called **Higgs particle**. Now it is possible to give mass to the weak bosons as well as to quarks and leptons.
1964	**James Cronin**, **Val Fitch** and collaborators show in an experiment, that in weak interactions the particle antiparticle symmetry (C) and the mirror symmetry (P), together called CP, are violated.
1965	**Oscar Wallace Greenberg** and others introduce the additional quark property of colour to explain the existence of certain baryons, which would else violate the Pauli principle. Thereby every quark exists in three modifications, called red, green, blue, The observed mesons or baryons are colour neutral, i.e. a combination of colour and anticolour or of red, green and blue quarks.
1967	**Steven Weinberg** and **Abdus Salam** unify the electromagnetic and weak to the electroweak interaction. The theory requires the existence of three weakly interacting bosons, called $\mathbf{W^{+,-}}$, $\mathbf{Z^0}$ today. The Higgs boson is also introduced. The second quantum field theory is born.

2010	**Start of the LHC:** hope for new physics, explaining the standard model as well as dark matter and dark energy by finding new particles like Higgs, WIMPS, magnetic monopoles etc.
2010	**Tetra- and Penta-quarks at LHC:** several particles consisting of four quarks (exotic mesons) and of five quarks (exotic baryons) are discovered at the LHC.
2012	**Higgs particle at LHC:** discovery of the Higgs boson with a mass of about 125 GeV. Further investigations must reveal the detailed properties of this particle.
2015	**LHC with 13-14 TeV:** The LHC (Large Hadron Collider) runs again with higher energy. One hopes for new phenomena beyond the standard model.
2016	**Gravitational waves** emitted by the fusion of black holes or neutron stars were discovered with the new detectors Ligo and Virgo. The waves emitted from two coalescing neutron stars were detected nearly simultaneously with a gamma ray burst, which means that gravitational waves and gamma rays travel at the same speed to a very high precision. In the mean time a couple of further gravitational waves were observed, which openes a new window into the universe and confirmed the predictions of general relativity.
2019	**LHC upgrade:** The LHC will be upgraded to higher luminosity in the next years.