Big Bang and Origin of the Universe Part 3

Big Bang

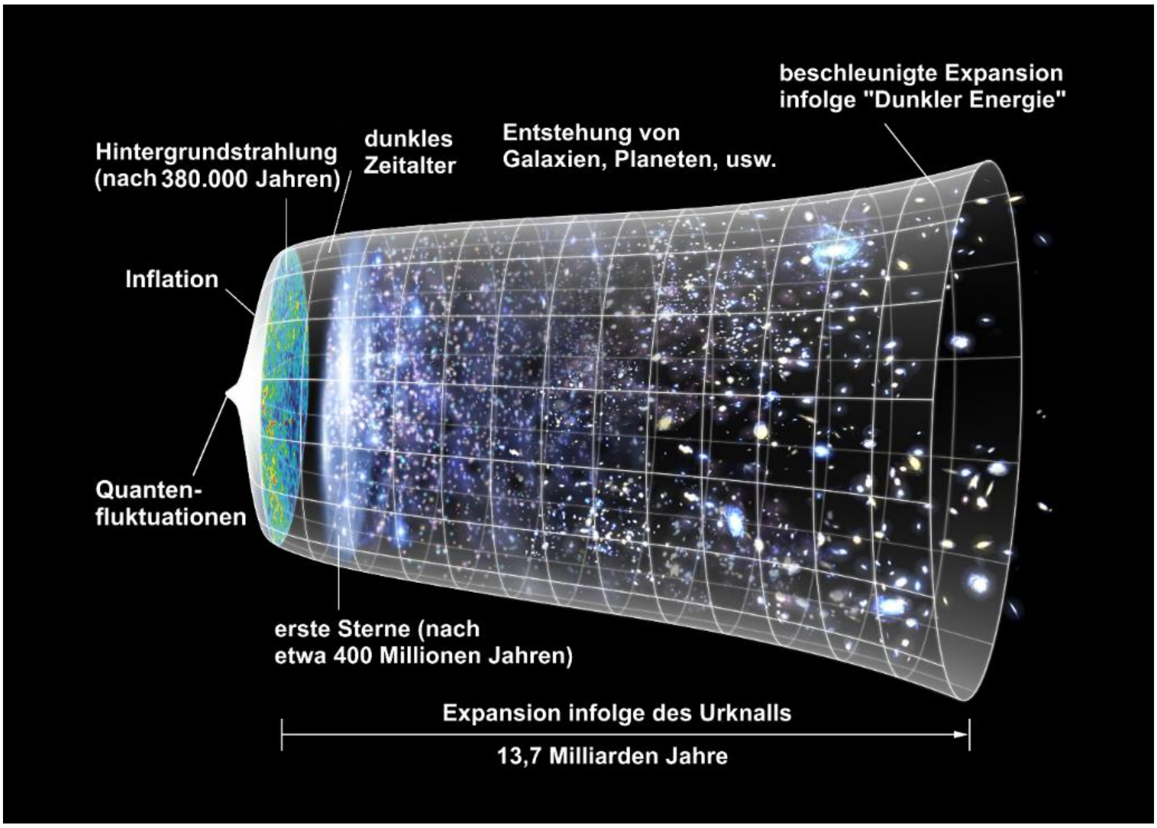


Fig. 1: Chronological sequence of the big bang.

The time zero, Planck length and quantum fluctuations

So we start with the beginning of the big bang. By the beginning, we mean that the point in time is zero.

The basic idea of Big Bang cosmology is that the universe evolved from a small, hot and dense state 13.7 billion years ago. Logically, it follows from this theory that at that time the universe began as a point of infinitely high density.

Points of infinite density like the one scientists assume was present at the beginning of the universe are called singularities.

But when scientists assume such extreme conditions, problems arise. These problems are partly related to the laws of quantum physics, the physics of very small things. Quantum physics states that it makes no sense to talk about distances smaller than the so-called Planck length, which is about 10^{-35} meters (corresponding to 0.00000000000000000000000000000000001 meters; Fig. 2).

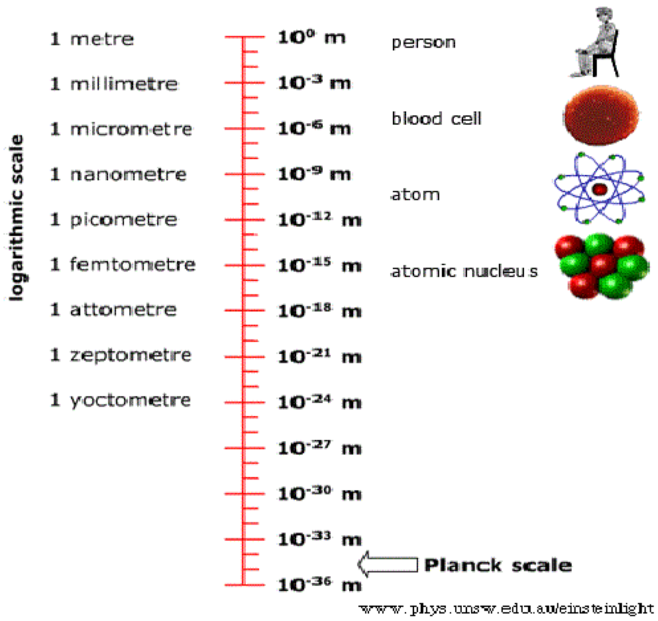


Fig. 2: Planck length

The reason lies in the Heisenberg uncertainty principle, which states that two complementary properties of a particle (e.g., its location and momentum) cannot be determined simultaneously with arbitrary precision. This "uncertainty" is an unavoidable consequence of the wave nature of matter (Fig. 3) and not a statement about the "accuracy of measuring instruments." Heisenberg's uncertainty principle can be regarded as an expression of the wave nature of matter. According to him, for example, an electron can have not only a particle character, but also a wave character. Heisenberg carried out a similar relation for the pair energy and time.

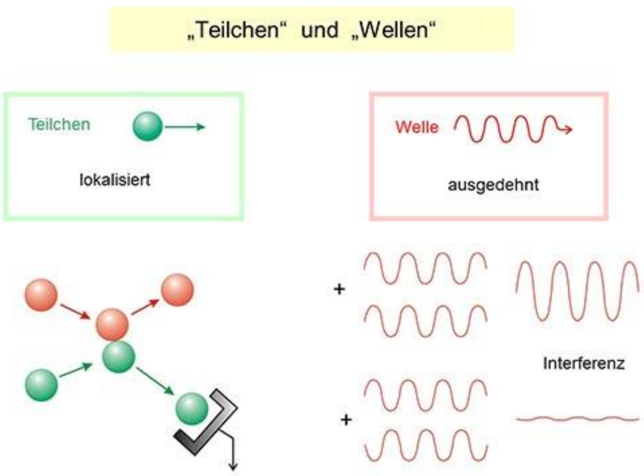
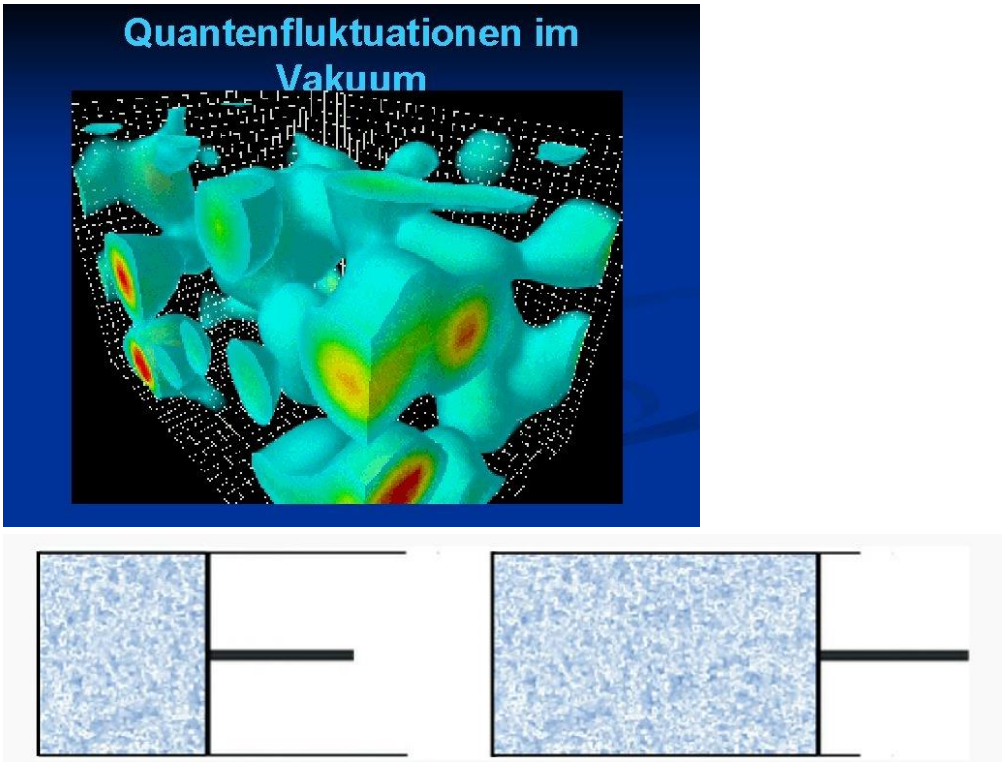


Fig. 3: Wave-particle duality

However, Heisenberg's uncertainty principle allows quantum fluctuations (fig. 4). A quantum fluctuation is a momentary change in the amount of energy at a point in space. Quantum fluctuations can produce particles and their antiparticles.



Quantenfluktuationen (blau) lassen sich durch Expansion nicht verdünnen, weil sich im zusätzlichen Volumen instantan neue Teilchen-Antiteilchen-Paare bilden.

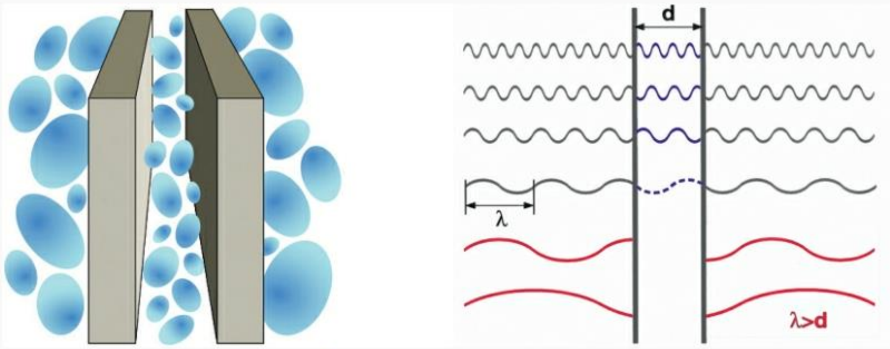
Fig. 4: Quantum fluctuations

This quantum mechanical possibility can be formulated in energy form something like this: The energy uncertainty multiplied by the time uncertainty must always be smaller than a natural constant, the (very tiny) Planck's quantum of action, in a small volume of space. Planck's quantum of action links particle and wave properties; it is the ratio of energy and frequency of a quantum of light and the ratio of mass, velocity and wavelength of any particle.

Quantum fluctuations occur when a particle-particle pair forms for a brief instant without violating this indeterminacy relation. Loosely speaking, the pair "borrows" energy for an extremely short time to form according to Einstein's mass-energy equivalence. If they don't separate in a flash, they then also immediately annihilate. Therefore the energy distribution in the space is a little bit uneven and can have been to germ cells of density increases, from which the galaxies formed later.

Scientists suspect that the first beginnings of structures in the universe occurred as small fluctuations in matter in the quantum realm.

This phenomenon of modern quantum physics occurs naturally in the atomic realm and is generally not noticeable in our everyday lives. Quantum fluctuation is reserved for particularly extreme situations: For example, one consequence of quantum fluctuation is that there cannot be an absolute vacuum. Even in a vacuum, particle-antiparticle pairs are constantly created (and vanish again, see Fig. 4). We find an experimental proof in the Casimir effect, where nearby metal plates exert forces on each other in vacuum (fig. 5). This force is based on the fact that the vacuum is a space full of virtual particles, which are subject to different conditions between the plates than in the rest of space. The effect was predicted by Hendrik Casimir in 1948 and also named after him. In 1956, the experimental confirmation was made by Yevgeny Lifschitz and colleagues in the Soviet Union.



2.9 Erzeugt man in einem Vakuum künstliche Randbedingungen, z. B. durch zwei leitende, parallele Platten, dann unterliegen die Quantenfluktuationen zwischen den Platten Einschränkungen, die es außerhalb nicht gibt. Offensichtlich wird dies, wenn man die Fluktuationen als Wellen darstellt (rechtes Bild). Zwischen den Platten finden nur Wellenlängen λ Platz, die ganzzahlig im Abstand d enthalten sind (blau), weil die Wellen an einer leitenden Oberfläche immer bei null beginnen und bei null enden. In der Folge sind zwischen den Platten weniger Quantenfluktuationen möglich als außerhalb und dieser Möglichkeitsdruck ist messbar – er steigt mit $1/d^4$.

Fig. 5: Casimir-Effect

If the universe started as a hot and small something, it would be interesting to know what temperature prevailed at that time. A good starting point - not to say the only starting point is 10^{-43} seconds after the big bang (0,0000000000000000000000000000000001 s). This point in time is called the Planck time.

Thus, every discussion of the expanding universe begins only at the Planck time, when the universe possessed an expansion of the just mentioned size of the Planck length of 10^{-35} m. In the period before the Planck time our present physical models are not suitable.

A shorter time is not accessible, because only with the Planck time time and space can be determined at all. It is senseless to ask the question according to the state of knowledge up to now, what was before, because there was no before. The question about the before is here as senseless as the question what is more northern than the north pole.

Planck Epoch and Epoch of the Great Unification

What happened now in the Planck epoch (10^{-43} seconds after the big bang)? The temperature at this time was 10^{32} K (100,000,000,000,000,000,000,000,000,000 K!). It is almost impossible to imagine anything hotter. The temperatures in our sun are just "only" 15 million °K.

In the Planck epoch, the four fundamental forces were still united into one force (Fig. 6). The search for quantum gravity is the search for the particle that would mediate the singular force. Hence, it is sometimes referred to as the "theory of everything." Particle accelerators cannot yet reach this incredible energy.

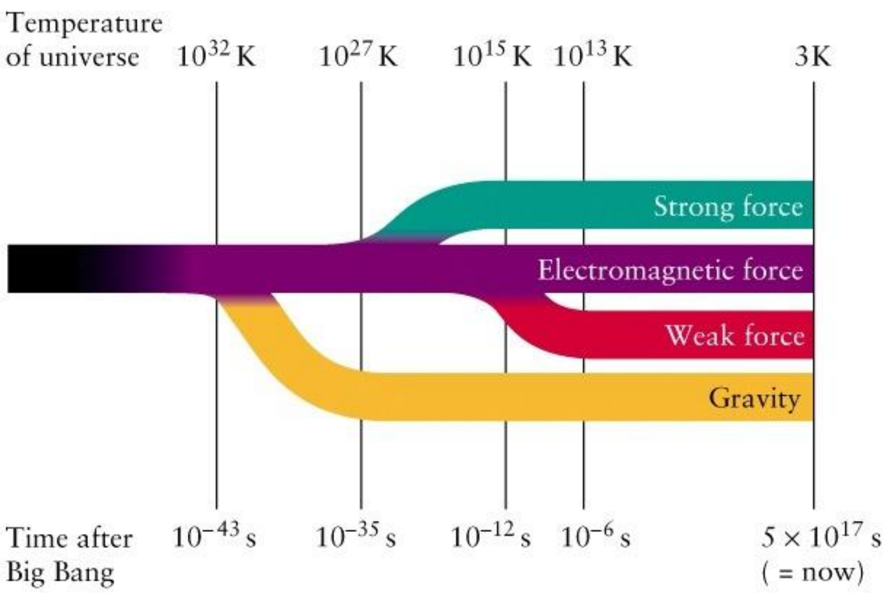


Fig. 6: Separation of the fundamental forces of physics after the big bang.

But in the time between 10^{-43} and 10^{-36} seconds, called the epoch of the Great Unification, temperatures cool down to 10^{29} K. This allows gravity to separate from the other three fundamental forces. These still unified fundamental forces (electromagnetic, strong and weak force) are also summarized as electro-strong force. The splitting off of gravitation from the other basic forces is described by the "Grand Unified Theory". This splitting off of forces from other forces is the result of symmetry breaking, a phenomenon that can occur when extreme temperatures fall below certain transition temperatures. In 1979, Sheldon Glashow, Steven Weinberg and Abdus Salam were awarded the Nobel Prize in Physics for this work. In this way, we can understand that all the different elementary particles in the universe were once part of the same whole, which only manifested as distinct objects through a series of successive symmetry breaking during the cooling of the universe.

Next, we enter the era from 10^{-36} to 10^{-32} seconds. This is called the electroweak epoch. It is defined by the decoupling of the strong nuclear force from the other two fundamental forces. The remaining weak nuclear force and electromagnetic force are called the electroweak force. This is possible because the universe has cooled down to 10^{28} °K.

Epoch of Inflation

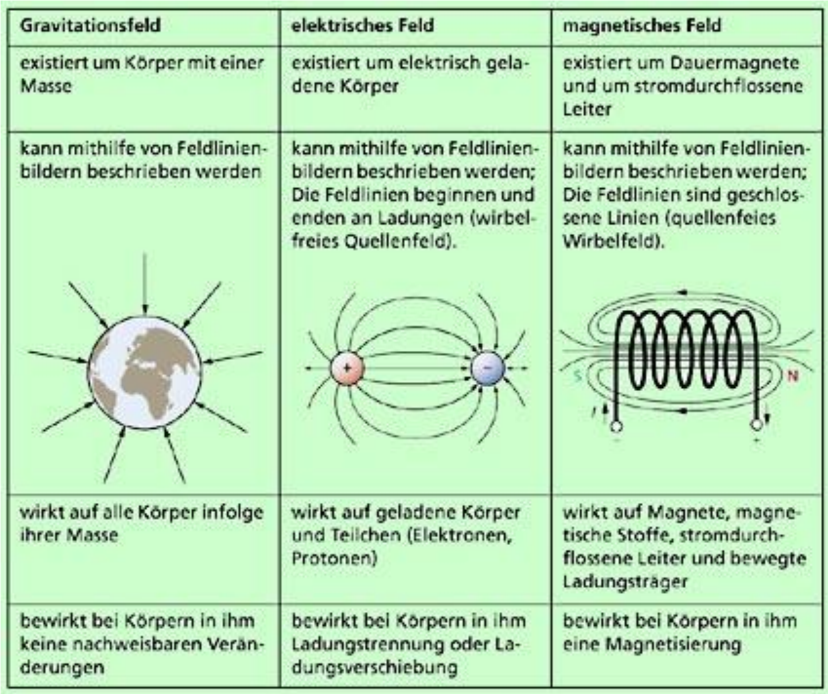
Around the same time, the epoch of inflation took place. This was a short period of time in which the universe expanded by a factor of 50. This inflation was triggered by the separation of the strong nuclear force and the electroweak force. It was developed by Alan Guth and later extended by other scientists such as Alexei Starobinsky and Stephen Hawking.

Before inflation, the universe was much smaller than a proton. At the end of the inflation period, the universe was about the size of an apple. From then on it went on "normally" with the slower (but still fast) expansion of the universe.

The reservoir of energy that drives inflation comes from the vacuum. According to quantum theory, the vacuum of space is anything but empty. It is constantly creating and annihilating particles and antiparticles through quantum fluctuations. Tapping into this energy provided the explosive energy of the Big Bang and the radiation that was created along with it.

The vacuum has another bizarre property. It can exert a repulsive gravitational force that, instead of pulling two objects together, pushes them apart; this is also known as antigravity.

Forces are exerted on particles that can be represented in physical fields. Examples are magnetic, electric or gravitational fields (Fig. 7). Along with matter, they are a form of matter that have certain properties at certain points in space. The value of a field at a particular location is called field strength in some cases. Field strength can be vividly defined in terms of the force effect that the field exerts on a body. For example, the stronger a magnetic field, the higher its attraction or repulsion.



Gravitationsfeld	elektrisches Feld	magnetisches Feld
existiert um Körper mit einer Masse	existiert um elektrisch geladene Körper	existiert um Dauermagnete und um stromdurchflossene Leiter
kann mithilfe von Feldlinienbildern beschrieben werden	kann mithilfe von Feldlinienbildern beschrieben werden; Die Feldlinien beginnen und enden an Ladungen (wirbelfreies Quellenfeld).	kann mithilfe von Feldlinienbildern beschrieben werden; Die Feldlinien sind geschlossene Linien (quellenfeies Wirbelfeld).
wirkt auf alle Körper infolge ihrer Masse	wirkt auf geladene Körper und Teilchen (Elektronen, Protonen)	wirkt auf Magnete, magnetische Stoffe, stromdurchflossene Leiter und bewegte Ladungsträger
bewirkt bei Körpern in ihm keine nachweisbaren Veränderungen	bewirkt bei Körpern in ihm Ladungstrennung oder Ladungsverschiebung	bewirkt bei Körpern in ihm eine Magnetisierung

Fig. 7: Physical fields

Scientists assume that in the early universe, when the energy levels were enormously high, matter was in the form of scalar fields, which are similar to electric and magnetic fields, with the difference that they have no direction. The Higgs field, which gives particles their mass, is an example of such a scalar field. The scalar field that triggered inflation is called the inflaton field. Guth's idea was that the inflaton field at the beginning of the universe was in a state called a false vacuum. This means that it was very energetic, but that its energy level was unable to transition to a lower state (Fig. 8). In this false vacuum state, the inflaton field exerted a large negative pressure. This pressure has the effect of creating a repulsive gravitational field that repels objects from each other instead of attracting them. Thus, a powerful presence of negative pressure was the force that drove inflation.

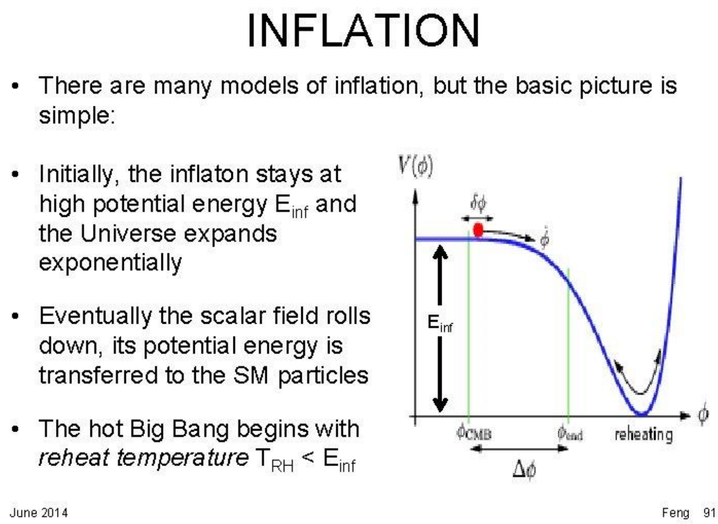


Fig. 8: Theory of inflation

Guth's ideas were refined and updated by a number of other physicists. To describe these in detail would be too complex and detailed. For us, however, the following is crucial: this almost instantaneous expansion distributed the earliest fundamental particles fairly evenly in a much larger volume, whereupon the immense potential energy from inflation was released and a hot plasma of quarks, anti-quarks, and gluons was created. Before exploring what happens next, it is useful to add that inflation is capable of solving a number of problems in cosmology. Some will be presented.

The homogeneity problem (Fig. 9): The period of inflation shifted tiny regions that were once in close contact out to far-flung corners of the universe. As a result, the cosmos looks similar everywhere, no matter which direction an observer's telescope points. This is called homogeneous (appearing the same everywhere) and isotropic (appearing the same in all directions).

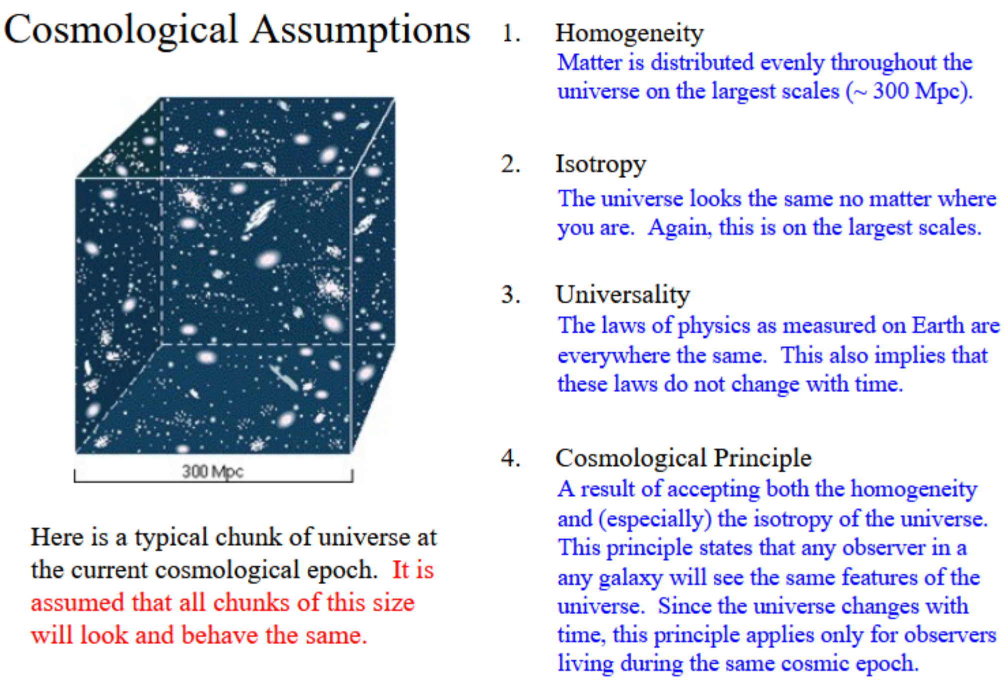


Fig. 9: cosmological assumptions

This gigantic growth spurt captured random subatomic energy fluctuations and inflated them to macroscopic proportions. By conserving and magnifying these quantum fluctuations, inflation produced areas with slight density variations. Some areas contained more matter and energy on average than others. This corresponds to the cold and hot spots in the temperature of the cosmic background radiation. Over time, gravity shaped these variations into the spider web of galaxy clusters and giant voids that fill the universe today. Inflationary theory also makes predictions about what such fluctuations should look like. Some of these predictions have been confirmed by measurements from the Wilkinson Microwave Anisotropy Probe (WMAP). The data show minute temperature differences in the background radiation due to density fluctuations in the universe when it was 380,000 years old. According to the models of inflation, these density fluctuations arose much earlier, when inflation was still emitting minute quantum fluctuations that expanded into nuclei for future structures.

The flatness problem: The inflation process would have imposed another condition on the universe: It would have made it flat. Already in 1922, Alexander Friedmann had shown that a homogeneous and isotropic universe (what we have) can have only three possible shapes: closed, open or flat (fig. 10).

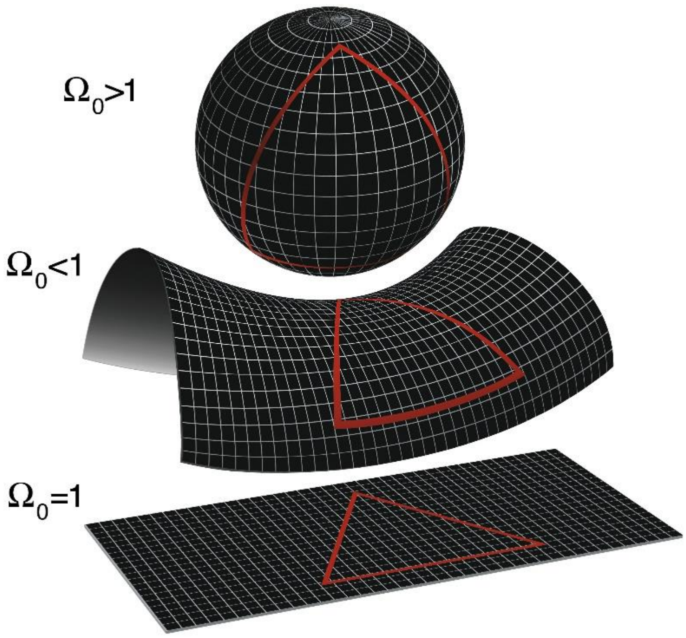


Fig. 10: Geometry of the universe

Decisive for this is the critical density of the universe (fig. 11). The sum of the energy of matter, dark matter and dark energy in our universe results exactly in the so-called critical density. This makes the universe Euclidean. This is the familiar geometry of angles and lines that we drew on a piece of paper in school. In a Euclidean universe, two photons shot on parallel paths fly parallel forever. Neither they come closer to each other, nor do they move further away from each other. The relation between measured and critical energy density is represented by Ω. In a Euclidean universe, Ω=1. If the density of the universe were greater than this critical value, the pull of gravity would be great enough to reverse the expansion and eventually cause the universe to collapse. Such a universe would be closed, have the surface of a sphere, and a spaceship traveling in a straight line would end up exactly where it started.

If the density were smaller than the critical value, gravity could never overcome the expansion and the universe would continue to grow forever. A universe with a density smaller than the critical value would have a negative curvature with a shape resembling a horse saddle. Since today's measurements give a value for Ω very close to 1.0, the universe started out perfectly or nearly perfectly with Ω=1, to within fifteen decimals. Guth's inflation theory yields the desired Ω=1 because the gravitational field perfectly balances the energy produced.

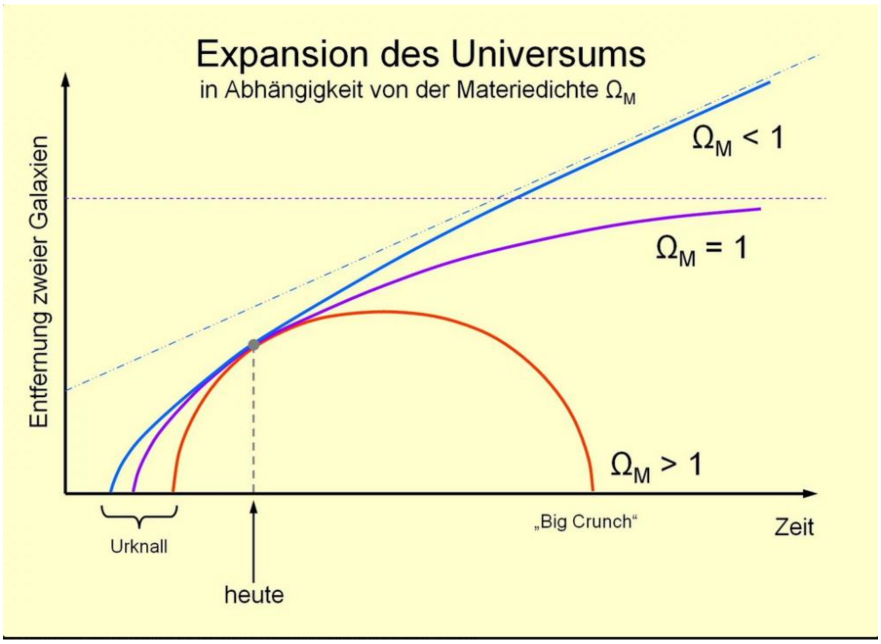


Fig. 11: Depending on the value of the matter density ΩM relative to a critical density (usually normalized to 1), the universe meets a different fate. For ΩM > 1 (closed universe), the initial expansion eventually reverses and ends in a "reverse big bang", the "big crunch". If ΩM < 1 (open universe) the universe expands eternally and strives towards a constant expansion speed > 0 (slanted dashed line). If ΩM = 1 (flat universe), there is a borderline case, where the universe just does not collapse, but strives towards an expansion speed of 0. Note that the age of the universe since the big bang is different if the expansion speed is the same today.

From the epoch of quarks to primordial nucleosynthesis

The epoch of inflation is followed by the epoch of quarks in the period between 10^{-32} to 10^{-6} seconds. Here it became cool enough for the electromagnetic and weak forces to separate and the elementary particles to acquire observable properties. During this time, the Higgs field gives the elementary particles their mass. However, the temperatures are still too hot for protons and neutrons to form. A quark-gluon plasma and electrons fill space (fig. 12).

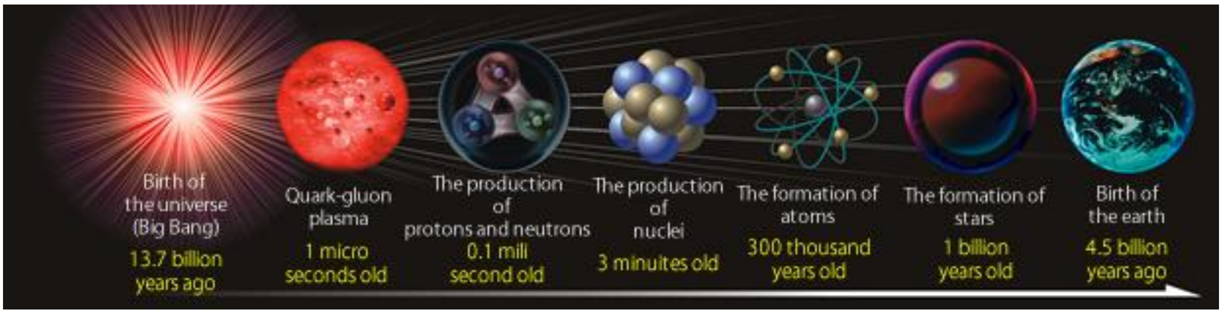


Fig. 12: Evolution of matter from the quark-gluon plasma to the birth of the Earth.

In the time from 10^{-6} to 1 seconds we enter the epoch of hadrons. Temperatures are cool enough for the quark-gluon plasma hadrons to form. Hadrons are composed of quarks and form protons and neutrons (Figs. 12, 13).

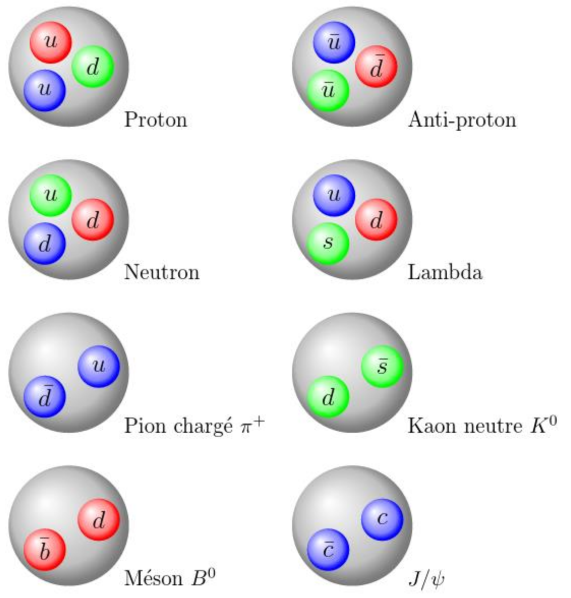


Fig. 13: Hadrons

From second 1 to second 10 after the Big Bang comes the epoch of leptons. Hadrons and anti-hadrons annihilate each other for the most part, so that leptons and anti-leptons dominate. Also leptons and anti-leptons annihilate each other.

We remember: To every elementary particle there is a so-called antiparticle. It has exactly the same properties as the corresponding elementary particle, but an opposite charge.

After a few seconds, however, the universe had cooled down so much that only particle-antiparticle pairs annihilated, but no new ones were created. But because matter-particles had a slight surplus, in the end these still remained (fig. 14).

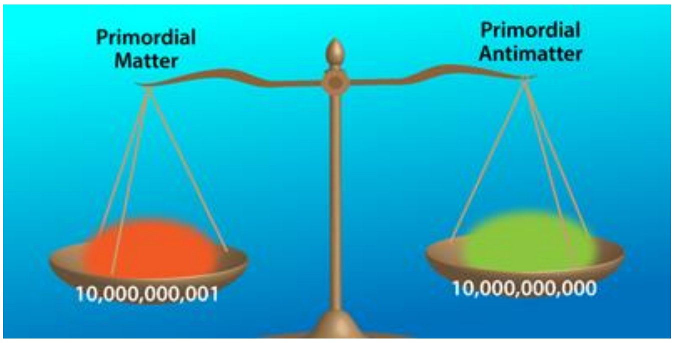


Fig. 14: the slight excess of matter

After this the epoch of photons begins. For about 17 minutes the universe is cool enough that the baryons (i.e. protons and neutrons) are stable enough, but warm enough that they can also fuse. The first atomic nuclei form. This important step is primordial nucleosynthesis and led to the formation of hydrogen, helium, and lithium nuclei, the three lightest elements in our universe. After that, the temperature and density of the universe fell below the critical values necessary for nuclear fusion. Only the light elements (atomic mass numbers A = 2, 3, 4, 7) could be fused: heavy hydrogen (deuterium nuclei or ^{2}H), which has a proton and a neutron in its nucleus; helium (^{3}He and ^{4}He); and traces of lithium (^{7}Li). Hydrogen atom nuclei in the form of protons were already present before fusion, as mentioned above (Fig. 15). The short period of time explains on the one hand why heavier elements did not form already at the big bang and on the other hand why reactive light elements like deuterium could remain.

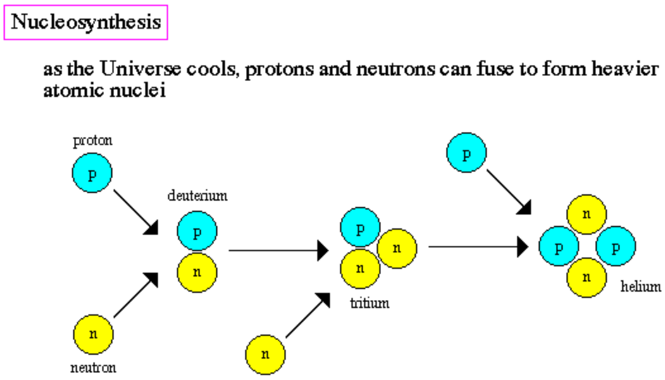


Fig. 15: Primordial nucleosynthesis

The idea for primordial nucleosynthesis dates back to work by physicist George Gamow in 1946. In 1950, the Japanese Chushiro Hayashi described the neutron-proton equilibrium processes for the production of the light elements, and in 1966 Ralph Alpher created a model of ^{4}He synthesis. Initially, neutrons and protons had a 1:1 ratio, but because neutrons are quite unstable and decay into a proton, electron, and anti-neutrino within 15 minutes, the ratio changed in favor of protons. To escape this fate, the neutrons must form a bond with a proton (they then become bound neutrons).

5 minutes after the Big Bang, the particle density and thus the temperature of the universe had dropped to the point where primordial nucleosynthesis had essentially ended. The result of primordial nucleosynthesis was, in addition to ^{4}He, traces of deuterium and tritium nuclei and helions (^{3}He nuclei) as intermediates of ^{4}helium synthesis, as well as the protons that had not found neutrons as reaction partners. The remaining free neutrons decayed in the course of the next minutes, the tritons in the course of further decades.

Theory predicts a mass ratio of 75% hydrogen (protons) to 25% helium. The excess of hydrogen protons is a consequence of the instability of neutrons. This value agrees extremely well with observations of the oldest stars, which is one reason for the wide acceptance of this theory. Especially for 4He measurements have been made also outside our Milky Way, which confirm the result. Also the relative abundances of deuterium, ^3He and lithium are very well explained by the theory.

Over the next 380,000 years or so, the universe continued to expand and the density of protons in space became too low that the formation of He did not continue. Between the atomic nuclei moved the free electrons and other elementary particles. The universe was in a so-called plasma state. After about 380,000 years, the universe had cooled down enough for the electrons to join the atomic nuclei of H and He, so the first atoms were formed (Fig. 16).

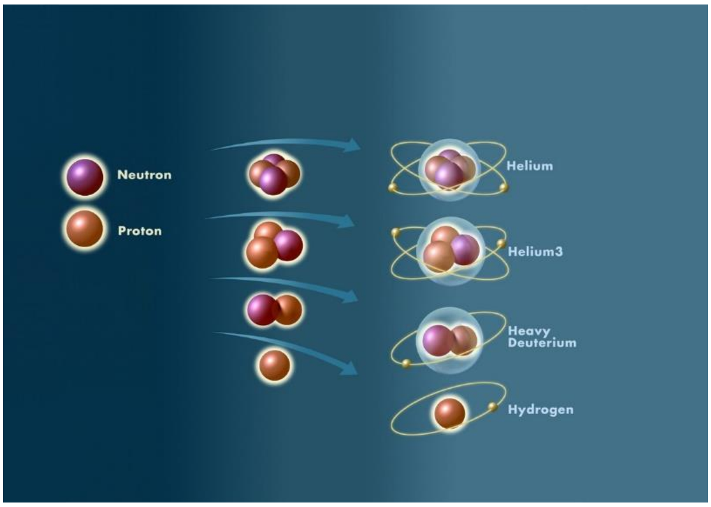


Fig. 16: Formation of the first atoms

The electrons are captured, get a lower energy level and thus emerge photons (fig. 17). The free photons divide the space and provide the present cosmic background radiation. Instead of plasma, we now have a transparent universe. It is no longer impermeable, but permeable, in that electromagnetic radiation can move freely. Not much happens in the next 150 million years. There is plenty of hydrogen and helium in the universe and photons move freely through space, but no stars formed yet. Temperatures dropped from 4,000 to 300 to 60 °K. Slowly, however, the hydrogen and helium clouds gathered together due to gravity, so that the first clumps of matter formed. After 30 million years the first stars and other heavy elements are formed. But we will deal with this in the next article.

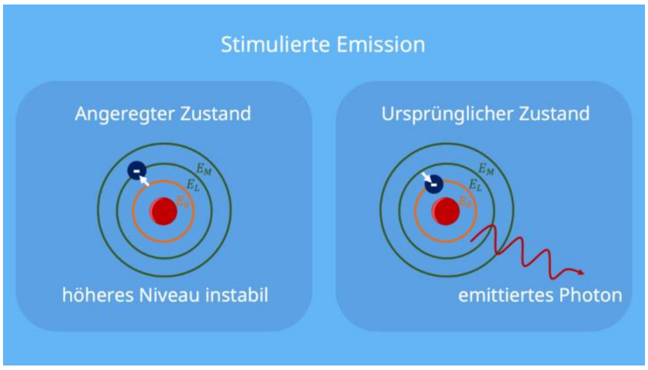


Fig. 17: Photon at lower energy state

Conclusion and open questions

So much for the basics of the Standard Model, the circumstantial evidence for the Big Bang and its temporal sequence. Still by far not all questions are clarified. The standard model of particle physics has been tested and investigated extensively and describes excellently the building blocks of the world and their interactions. However, there are also a number of open questions that it cannot answer. For example, it does not account for gravity. So far, the interaction particle for gravity has not been proven. Furthermore, about a quarter of the universe consists of dark matter. This substance cannot be explained with the particles of the standard model.

The first indication that there must be something other than visible matter in the universe was provided as early as 1933 by astronomical observations and calculations of gravitational effects. Scientists observed, for example, that light flying past galaxies was deflected more strongly than the mass calculations for these galaxies predicted - so there had to be more than the known mass attracting the light. Since this form of matter appears through its gravity but is not visible, it was called "dark matter."

The rotation speeds of stars in galaxies could also not be explained if the galaxies consisted only of visible matter. They are also held together by the gravitation of an invisible matter. Measurements have shown that our universe consists of about 25 percent dark matter (Fig. 18). The existence of dark matter is inferred on the basis of its gravitational influence on visible matter. From this, there are two possibilities: Either dark matter exists or our understanding of gravity is incorrect.

Observations of distant supernovae showed that the expansion of the universe has been accelerating over the last billion years. Scientists blame this on so-called dark energy, which must surround us uniformly everywhere in the universe. Unlike ordinary mass, it has a repulsive rather than an attractive effect in the universe - the universe is expanding at an ever-increasing rate. This accelerated expansion can be measured. We have shown that due to the critical density of the universe, as well as the knowledge of relativity, the universe is flat. However, measurements on the total amount of matter (dark matter and visible matter) show that it accounts for only about 30% of the critical density. Dark energy accounts for the remaining 70% (Fig. 18).

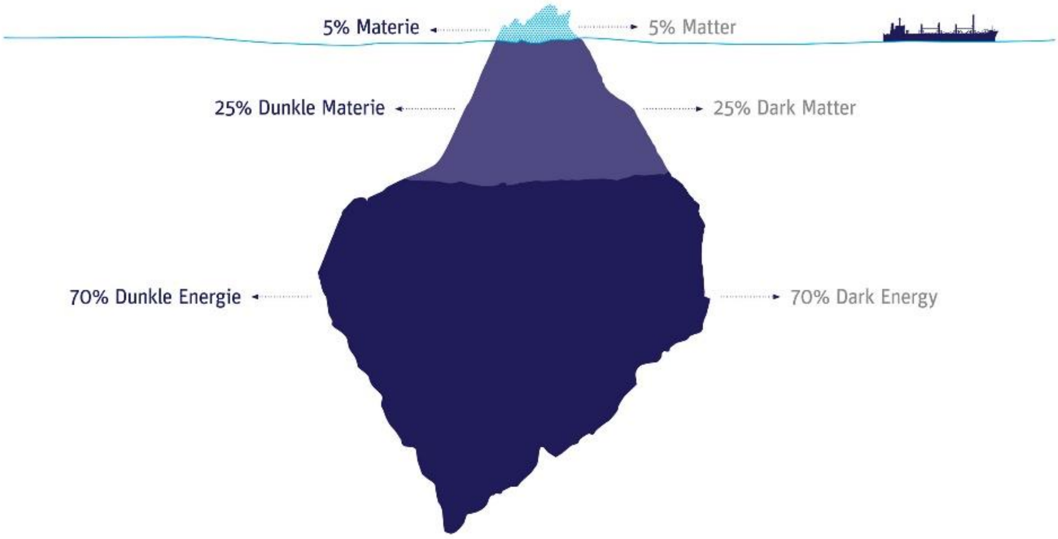


Fig. 18: Proportion of matter, dark matter and dark energy in the universe.

Physicists, on the other hand, would like to see a theory that not only takes into account phenomena such as gravity and dark matter, but that also establishes a direct relationship between matter particles and force particles. Theoretical physicists have developed, among other things, supersymmetry, an elegant extension of the Standard Model.

Julius Wess and Bruno Zumino were the first to formulate a theoretical model of supersymmetry - SUSY for short - in 1973 (Fig. 19). It associates fermions with bosons and provides each known particle with a supersymmetric partner whose spin differs by ½ from that of the Standard Model particles. That is, to fermions with half-integer spin exist supersymmetric particles with integer spin, and to bosons with integer spin exist supersymmetric particles with half-integer spin. Accordingly, the theory of supersymmetry connects the world of matter particles with that of force particles. Since a supersymmetric partner exists for every particle in the Standard Model, the number of particles doubles.

Supersymmetric particles could be the key to the study of dark matter. Thus, the lightest of the supersymmetric particles could be its main component. However, the experimental confirmation of this theory is still pending.

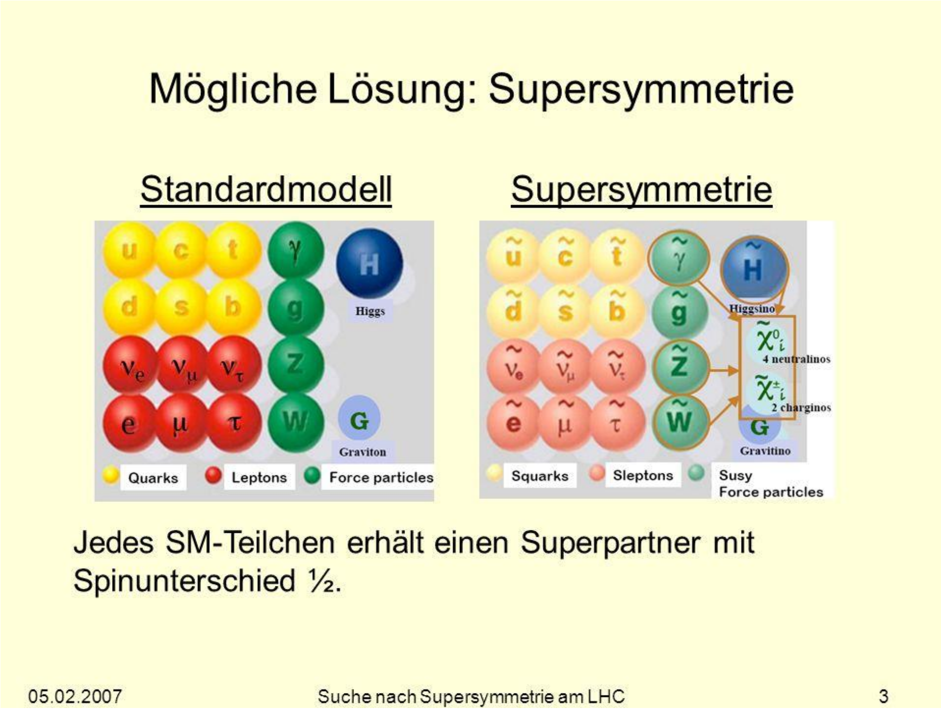


Fig. 19: Supersymmetry

Other scientists criticize inflation or dark energy. Again, other scientists reject the Big Bang model completely and present other hypotheses. In 1993, for example, Hoyle and colleagues proposed the theory of the quasi-stationary state. According to this theory, the universe has always existed and will always exist. According to this theory, matter is constantly produced with a low background rate, but in addition with occasional bursts of large amounts of matter - quasi a series of small big bangs within the universe (Fig. 20). The cosmic background radiation is thereby explained as the residual of burned out stars. But this theory is confronted with the problem of not having observed such small big bangs.

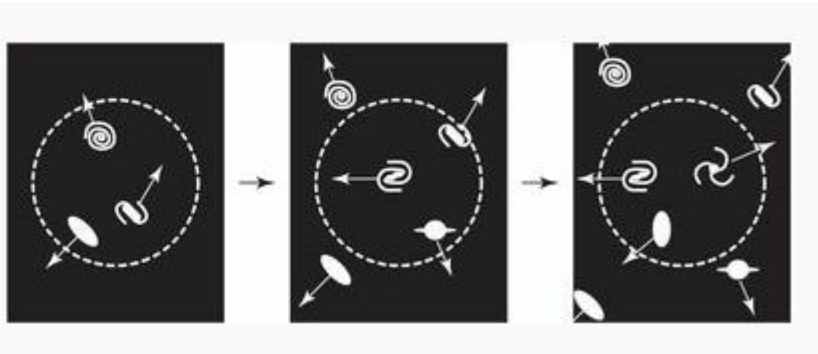


Fig. 20: Steady-state hypothesis.

I lack the expertise to evaluate whether the alternative explanations describe the universe better than the Big Bang model. Just as little I have the expertise to form an opinion about the existence of inflation, dark matter and dark energy. Therefore I decided to give the "Standard Model" - quite compressed and by no means clarifying all details. By far not all questions are clarified and further research results will certainly provide more clarity. But the decisive is: it explains the origin of our universe without the help of divine beings.

Literatur

Bennett, J. Donhaue, M., Schneider, N., Voit, M. (2020): Astronomie die kosmische Perspektive. Pearson Verlag, 9. Auflage

Guth, A. H. (1981): Inflationary Universe, a possible solution to the horizon and flatness problems, Phys. Rev. D23, 347

Heise online: Die Kosmische Inflation und die Suche nach Raum-Zeit-Fossilien https://www.heise.de/tp/features/Die-Kosmische-Inflation-und-die-Suche-nach-Raum-Zeit-Fossilien-4109978.html

Lesch, H., Gaßner, J. M. (2020): Urknall, Weltall und das Leben. Verlag Komplett-Media, 4. Auflage

Lifshitz, E. M. (1956): The Theory of Molecular Attractive Forces Between Solids. Soviet Physics 2, 73.

Maran, S. M. (2008): Astronomie für Dummies. Wiley VCH Verlag, 3. Auflage

Oschmann, W. (2016): Evolution der Erde. Utb

Pincock, S., Frary, M. (2009): Ursprung des Universums für Dummies. Wiley VCH Verlag, 1. Auflage

Prothero, D. (2021): The Evolving Earth. Oxford University Press

Spektrum Inflation https://www.spektrum.de/lexikon/astronomie/inflation/197

Weltmaschine: Physik https://www.weltmaschine.de/physik/dunkle_energie/

Hendrik Casimir: On the attraction between two perfectly conducting plates. Proc. Kon. Nederland. Akad. Wetensch. B51, 793 (1948)