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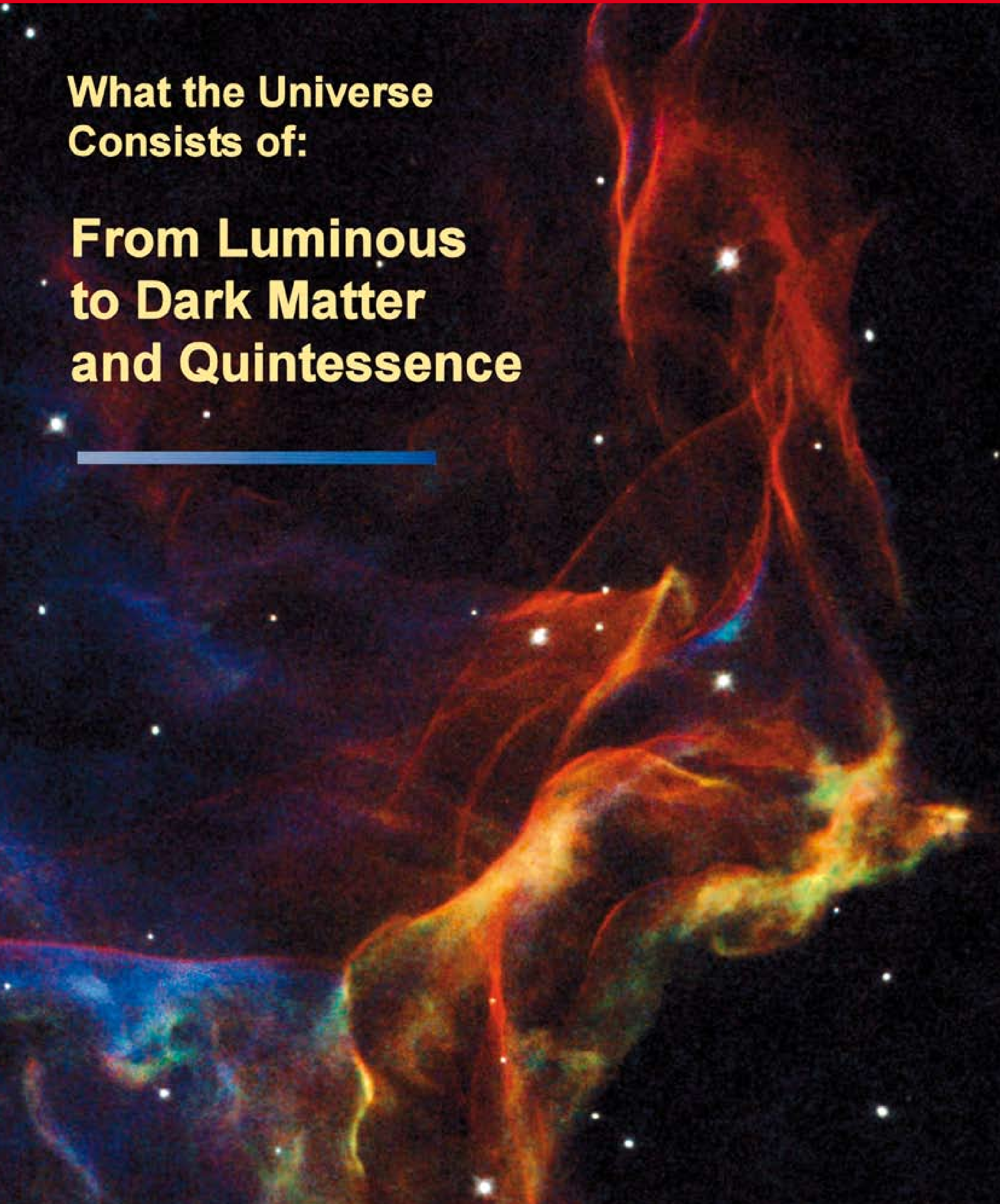
What the Universe Consists of:

From Luminous to Dark Matter and Quintessence



Editorial

Initially you were the most important entity all around. Later you began discovering your environment that quite naturally constituted the middle of your growing Universe. At school the grasp of your mind expanded rapidly. You learned about the Sun that is so important for your life that it henceforth quietly occupied the centre of your world. Later, you came to know that your beloved Sun is just a fairly small star at an arbitrary spot in a galaxy called the Milky Way that is by far not the centre of the Universe (which has none indeed). Even worse: you had to become accustomed to the idea of a Universe that has been expanding for billions of years at an unimaginable pace and the only open question was whether there is enough mass around for the big crunch to eventually happen or alternatively whether the Universe was to expand forever. Not enough, just a couple of decades ago scientists disclosed that beyond the stars we can see there must be much more hidden mass of unknown nature that by its sheer quantity rules the fate of our Universe. Tellingly, they called it dark matter. And recently they found that the Universe has started rushing out even more quickly than it had done before, driven by an unknown energy. Again, cosmologists found an appropriate designation for their discovery: dark energy, a term that does not hide our ignorance about its true nature.

The present issue of Spatium brings you gradually along this evolution and when you finally close its last page you will have reached that ultimate state of humbleness that Sokrates described so well: I know nothing except the fact of my ignorance. Fortunately though, this purgatory process is not without great reward: your mind will be purged and readied for all the fascinating news science will bring along in the years to come.

We owe much gratitude to Prof. Uwe-Jens Wiese, Director of the Institute for Theoretical Physics at the University of Bern, who authored the present text after his intriguing lecture for the Pro ISSI audience on 27 March 2007. And we congratulate you, dear reader, for the pertinacity to go with us the thorny way that leads to a refined degree of ignorance…

Hansjörg Schlaepfer
Brissago, November 2007

Impressum

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Front Cover
The Veil Nebula, one of the most spectacular supernova remnants in the sky, is seen here by the NASA/ESA Hubble Space Telescope. The supernova explosion presumably occurred some 5,000 to 10,000 years ago and could have been witnessed by ancient civilizations. (Credit: NASA / ESA)

What the Universe Consists of: From Luminous to Dark Matter and Quintessence[1]

Preface

In contrast to the saying that "there is no free lunch", according to Alan Guth from the Massachusetts Institute of Technology (MIT), the Universe is the ultimate free lunch. Luckily for us, the Universe has reached the rather old age of 13.7 billion years which gave us enough time to develop. Also it contains the type of matter that forms the material basis of life. Endowed with great curiosity, we urge to understand the deep meaning of it all. In particular, the curious mind asks questions such as: "Why did the Universe become so old?" and "What does the Universe consist of?". This article is an attempt to explain some of our current knowledge concerning these questions to interested laymen and laywomen.

Having stated this, it is obvious that no mathematical background should be required to understand this text. However, physics is a quantitative science, which is fascinating, in particular, because its results can be expressed in mathematical terms. Indeed, mathematics is the universal language that Nature has chosen to express herself in. Our human language, on the other hand, is often inadequate to accurately describe physical reality. For that reason, the author has decided not to avoid mathematical formulas completely. The formulas require no more mathematical apparatus than multiplication and addition, and are meant to deepen the understanding of some of the problems discussed here. Still, it is not necessary to understand the formulas in order to appreciate the rest of the article. In any case, the author likes to encourage the reader to try to understand the equations. Mathematics is such a beautiful language – even used by Nature herself – that we should not completely forget how to use it. Just as we cultivate the use of foreign languages, we may aim at "speaking" some mathematics as well.

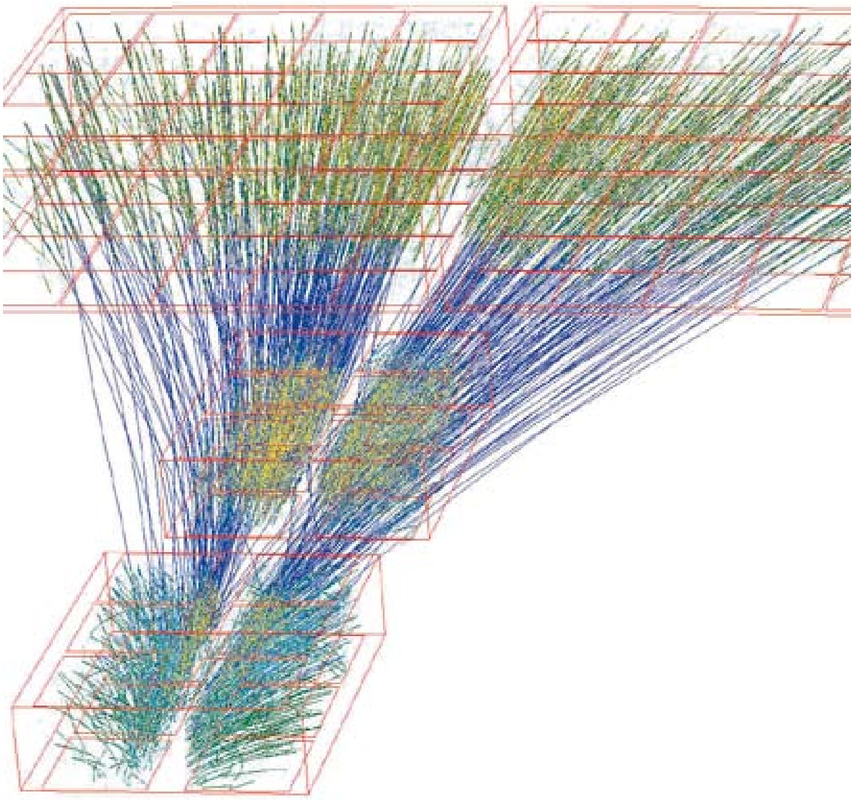


Fig. 1: One of the most fascinating results of modern physics is the fact that the fate of the Universe in its largest dimensions is intimately connected with the properties of elementary particles. Hence, the exploration of the smallest dimensions can provide us with indications regarding the future of the Universe. This picture portrays the result of the collision of a lead projectile on a lead nucleus at CERN, Geneva. (Credit: CERN)

[1] The present issue of Spatium contains a summary of the lecture by Prof. Uwe-Jens Wiese, Institute for Theoretical Physics, University of Bern, held for the Pro ISSI audience on 27 March 2007.

Introduction

The matter that we find on Earth has been investigated by humans ever since the dawn of scientific thinking. Ancient classifications into four essences – air, water, earth, and fire – have long been superseded by our modern understanding of atomic, nuclear, and particle physics. As we have known for about one hundred years, ordinary matter consists of atoms in which negatively charged electrons circle around a tiny positively charged nucleus. The electrons are bound to the nucleus by electric Coulomb forces. These forces are mediated by the electromagnetic field whose smallest quanta are photons – the particles that light consists of. Photons are coupled to any charged particle by the fundamental force of electromagnetism. Since they consist of charged particles, atoms can emit or absorb light. Also the matter in the Sun can emit light only because it contains charged particles. In particular, the luminous matter in the Sun and in other stars is made of the same stuff (namely electrons and nuclei) as the matter that we find on Earth.

Basics of Particle Physics I

Baryons are the family of subatomic particles which are made of three quarks. The family notably includes the proton and neutron, which make up the atomic nucleus, but many other unstable baryons exist as well. The term "baryon" is derived from the Greek barys (heavy), because at the time of their naming it was believed that baryons were characterized by having greater mass than other particles.

The **Large Hadron Collider (LHC)** is a new particle accelerator at the European Organization for Nuclear Research (CERN) in Geneva. It is due to start operations in 2008 and to probe deeper into matter than ever before. It will collide beams of protons at ultra-high energy which is about the equivalent of a flying mosquito, but the protons' energy will be squeezed into a space about a million million times smaller than a mosquito.

MACHOs (Massive Astrophysical Compact Halo Objects), candidates for baryonic cold dark matter.

WIMPs (Weakly Interacting Massive Particles), potential candidates for non-baryonic cold dark matter.

Atomic nuclei consist of positively charged protons and electrically neutral neutrons which in turn consist of quarks and gluons. Unlike electrons or photons, quarks and gluons have never been observed in isolation. They are subject to the strongest fundamental force in Nature – the so-called strong interaction – which permanently confines quarks and gluons inside protons and neutrons. Strongly interacting particles such as protons and neutrons are known as baryons. Since protons and neutrons are much heavier than electrons, the mass of atoms is dominated by baryons. For that reason, the ordinary matter that stars and planets consist of is known as baryonic matter.

Obviously, not all of the baryonic matter is actually luminous. For example, unlike stars, the Earth and the other planets are not sufficiently heavy to ignite nuclear fusion in their cores. Ordinary matter that does not actively shine is known as baryonic dark matter. Since the Sun is much bigger than the planets, most of the matter in the solar system is luminous. The biggest piece of baryonic dark matter in the solar system is the giant planet Jupiter. Dark matter objects such as Jupiter are classified as MACHOs (Massive Astrophysical Compact Halo Objects). Observations of distant galaxies imply that there must be a lot of dark matter in the Universe. In fact, there must be more dark matter than what can be attributed to MACHOs. Potential candidates for non-baryonic dark matter are so-called WIMPs (weakly interacting massive particles). Since these particles are electrically neutral, they cannot emit light and thus they are a form of dark matter. Also they do not participate in the strong interactions, and hence they are non-baryonic. Today there is a lot of indirect evidence for WIMPs, but they have never been detected directly. This may change when the Large Hadron Collider (LHC) at CERN starts operating in 2008.

As first observed by Edwin Hubble in the 1920s, the Universe is expanding, i.e. all galaxies are moving away from each other. Originally it was expected that the expansion would be slowed down due to gravitational attraction between the different galaxies. However, as we learned in 1998 from the observation of very distant supernova explosions, the expansion is actually accelerating. What counteracts the gravitational pull due to the luminous and dark matter inside the different galaxies? Currently, the best candidate is vacuum energy, i.e. energy that fills all of "empty" space, and that is not clustered in galaxies. The vacuum energy density is far too small to be directly detectable in a terrestrial experiment. However, since vacuum energy fills the entire Universe, it adds up to a large amount. Indeed, detailed observations of the cosmic microwave background radiation – a remnant of the hot big bang – indicate that vacuum energy dominates the Universe. The nature of the vacuum energy (which is sometimes also called dark energy) is a big puzzle. A static form of vacuum energy is a cosmological constant, as first introduced by Albert Einstein in general relativity. A dynamical form of vacuum energy is known as quintessence. Since we have learned a lot about air, water, earth, and fire, we may hope to also learn more about the nature of this fifth essence.

In the rest of this article we will take a closer look at luminous and dark matter as well as at quintessence. In particular, we will see that elementary particle physics – i.e. physics on the smallest length scales – has a big impact on cosmology – the physics on the largest scales. The composition of the Universe determines its evolution and is thus also essential for understanding our own existence.

Luminous Matter

In this section we will be concerned with the ordinary baryonic matter that we find on Earth and that has been studied extensively in countless atomic, nuclear, and particle physics experiments. We know that this form of matter exists everywhere in the observable Universe because we see the light that it emits. The light emitted from distant galaxies reaches us after a long journey through the expanding Universe. During this process, the wavelengths of the light are stretched because space itself is expanding. As a consequence, the frequencies are red-shifted. Still, the red-shifted spectra consist of the same spectral lines that are characteristic for the luminous matter here on Earth. In order to understand the structure of ordinary matter, we need to learn something about its constituents, electrons as well as protons and neutrons, which in turn consist of quarks and gluons.

Fundamental Forces

We distinguish four fundamental forces:

- the strong interactions
- the electromagnetic interactions
- the weak interactions
- and gravity.

The electromagnetic interactions, responsible for the binding of atoms, are mediated by the exchange of photons between charged particles such as electrons and nuclei. The strong interactions, responsible for the internal binding of nuclei and of the protons and neutrons themselves, are mediated by the exchange of gluons between quarks. Finally, the weak interactions, responsible for radioactive decay, are mediated by the exchange of heavy W- and Z-bosons **(see Basics II** on the next page). One expects that gravity is mediated by gravitons. However, since gravity is an extremely weak force, its quanta have never been detected. The four fundamental forces act on three types of matter particles – quarks, electrons, and neutrinos. The interactions that the different matter particles participate in are listed in **Basics II.**

The Structure of Matter

The matter that we find on Earth consists of atoms in which electrons orbit an atomic nucleus. The nucleus consists of protons and neutrons, which in turn consist of quarks confined together by gluons. Protons consist of two u-quarks and one d-quark, while neutrons consist of one u-quark and two d-quarks. The electric charge of a u-quark is $Q_u = \frac{2}{3}$ and that of a d-quark is $Q_d = -\frac{1}{3}$, such that the charges of proton and neutron result as

$$Q_p = 2Q_u + Q_d = 2\,\tfrac{2}{3} - \tfrac{1}{3} = 1$$
$$Q_n = Q_u + 2Q_d = \tfrac{2}{3} - 2\tfrac{1}{3} = 0. \qquad (1)$$

Protons and neutrons are tiny objects of a size of about 10^{-15} metres.

Basics II

Fundamental forces and matter particles. The following table indicates which fundamental force acts on which matter particle:

Forces	Strong	Electro-magnetic	Weak	Gravity
Mediators	Gluon	Photon	W- and Z-Boson	Graviton
Quarks	yes	yes	yes	yes
Electrons	no	yes	yes	yes
Neutrinos	no	no	yes	yes

The **quarks** are basic constituents of matter, which participate in all fundamental forces including the strong interactions. The other constituents are electrons and neutrinos, which are not strongly interacting. It is quarks that make up protons and neutrons, with three quarks within each of these particles. Protons and neutrons as well as other particles consisting of three quarks are known as baryons.

The **gluon** is an elementary particle that causes quarks to interact, and is indirectly responsible for the binding of protons and neutrons together in atomic nuclei.

Quantum chromodynamics (QCD) is the theory of the strong interaction, one of the four fundamental forces. It describes the interactions of the quarks and gluons found in protons and neutrons. It is an important part of the standard model of particle physics.

The **W- and Z-bosons** are carrier particles that mediate the weak nuclear interactions, much like the photon is the carrier particle for the electromagnetic force.

The **neutrino** is an elementary particle travelling close to the speed of light. It lacks an electric charge, is able to pass through ordinary matter almost undisturbed, and is thus extremely difficult to detect. Neutrinos have a minuscule, but non-zero, mass too small to be measured currently.

Electrons have the electric charge $Q_e = -1$ and are, as far as we know, even point-like. The simplest atom – hydrogen – consists of a single proton that represents the atomic nucleus surrounded by a single electron, **see Fig. 2.** A hydrogen atom is hence electrically neutral because

$$Q_H = Q_p + Q_e = 1-1 = 0. \quad (2)$$

A helium atom consists of two protons and two neutrons forming the atomic nucleus surrounded by two electrons. Again, just as any other atom, the helium atom is neutral because

$$Q_{He} = 2Q_p + 2Q_n + 2Q_e = 2+0-2 = 0. \quad (3)$$

The luminous matter in the Sun is ionized, i.e. electrons are no longer bound to the nuclei. The light emitted from the Sun originates from the nuclear fusion of protons and neutrons to helium. When two protons and two neutrons form a helium nucleus, the mass of the nucleus is a bit smaller than the sum of the masses of protons and neutrons, i.e.

$$M_{He} = 2M_p + 2M_n - m. \quad (4)$$

According to Einstein's famous equation, the small mass deficit m corresponds to a binding energy $E = mc^2$ (where c is the velocity of light) which is liberated in the nuclear fusion process. This energy, which reaches us in the form of sunlight, is the source of life on Earth.

The Origin of Baryonic Mass

The mass of the baryonic matter (either luminous or dark) contributes to the gravitational pull between the galaxies that counteracts the cosmic expansion. Hence, to understand the evolution of the Universe, it is helpful to understand the origin of mass. As we know from Sir Isaac Newton, the gravitational force that attracts us to the planet is proportional to the mass of the Earth. Where does that mass originate from? Well, the Earth consists of baryonic matter whose mass is dominated by atomic nuclei. Since nuclei consist of protons and neutrons, we should ask where their mass comes from. In fact, pro-

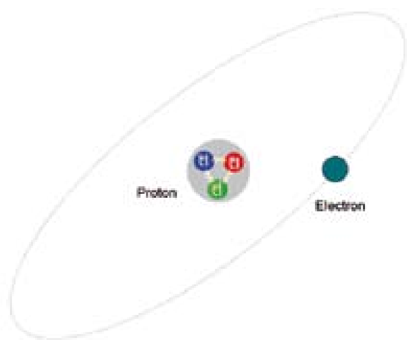


Fig. 2: The hydrogen atom consists of a proton that forms the atomic nucleus and an electron. The proton itself consists of two up-quarks (u), each with a charge of 2/3 and one down-quark (d) with a charge of –1/3. This results in a charge of 1 for the proton. The electron with its charge of –1 makes the hydrogen atom electrically neutral. The quarks in the proton are bound together by the gluons, represented here by the wave symbols between the quarks. The gluons mediate the strong interaction as detailed by the theory of quantum chromodynamics (QCD). This drawing is not to scale; rather the proton has a diameter of 10^{-15} m, while the orbit of the point-like electron is 10^5 times the proton's diameter.

tons and neutrons consist of almost massless quarks and gluons. As we have already seen for helium, the mass of a composite object may differ from the sum of the masses of its constituents due to binding energy. Since quarks and gluons are confined inside protons and neutrons by the strong force, binding energy is the main source of mass. The energy of bound quarks and gluons is described by quantum chromodynamics (QCD, **see Basics II**) – the theory of the strong interactions, which was developed by Harald Fritzsch from the Ludwig Maximilians University in Munich, Murray Gell-Mann from the Santa Fe Institute, Heiri Leutwyler from Bern University, Yoichiro Nambu from the University of Chicago, and by other physicists. Indeed, the strong binding energy of quarks and gluons inside protons and neutrons is the origin of baryonic mass.

The Feebleness of Gravity

We experience gravity as a rather strong force, just because we have the gigantic body of the Earth underneath us. Yet, gravity is much weaker than the other fundamental forces. To illustrate the feebleness of gravity, let us compare the electrostatic repulsive Coulomb force:

$$F_e = \frac{e^2}{r^2} \qquad (5)$$

between two protons at a distance r with the attractive gravitational force

$$F_g = \frac{GM_p^2}{r^2} \qquad (6)$$

between these particles. Here e is the basic electric charge unit and G is Newton's gravitational constant. In natural units of Geheimrat Max Planck's quantum $\hbar$ and the velocity of light c, the strength of electromagnetism is characterized by the so-called fine-structure constant **(see Basics III)**

$$\alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137}\,. \qquad (7)$$

Similarly, the strength of the strong interactions is characterized by a coupling α_s which is close to 1 at low energies. Since α is quite a bit smaller than 1, electromagnetism is a relatively weak force. In natural units of $\hbar$ and c, Newton's constant

$$G = \frac{\hbar c}{M^2_{Planck}} \qquad (8)$$

can be expressed through the Planck scale M_{Planck} **(see Basics III and V)**. Combining the equations (5), (6), (7), and (8), the ratio of the gravitational and the electrostatic force between two protons thus takes the form

$$\frac{F_g}{F_e} = \frac{GM_p^2}{e^2} = \frac{\hbar c}{e^2}\left(\frac{M_p}{M_{Planck}}\right)^2 \approx 137\left(\frac{M_p}{M_{Planck}}\right)^2. \qquad (9)$$

Hence, if the proton mass M_p would be of the order of the Planck scale M_{Planck}, gravity would be as strong as the electromagnetic interactions. However, the proton mass is much smaller than the Planck scale, namely $M_p/M_{Planck} \approx 10^{-19}$ such that gravity is, in fact, an incredibly weak force with

$$\frac{F_g}{F_e} \approx 10^{-36}. \qquad (10)$$

If we want to understand why gravity is so weak, we must hence understand why the proton is so much lighter than the Planck scale. As we discussed before, the proton mass can be derived from the theory of the strong interactions. As was pointed out by Frank Wilczek from MIT, the feebleness of gravity is a consequence of asymptotic freedom **(see Basics III)**, the fact that quarks and gluons interact only weakly at high energies. David Gross from the Kavli Institute in Santa Barbara, David Politzer from the California Institute of Technology (Caltech), and Wilczek won the Nobel prize in 2004 for explaining this property of QCD. Without asymptotic freedom, the proton and thus all baryonic matter in galaxies would be much heavier. Hence, the gravitational pull between the galaxies would be much stronger. In that case, the expansion of the Universe could come to a halt, and the Universe would re-collapse in a big crunch. This underscores how the physics of elementary particles determines the fate of the Universe.

Dark Matter

Based on the motion of galaxies in galaxy clusters, already in the 1930s the Swiss astronomer Fritz Zwicky concluded that besides the visible luminous matter there must be large amounts of hidden dark matter inside galaxies. In the 1970s, the existence of dark matter was confirmed by the measurement of the velocity of stars rotating around the centre of a galaxy. The velocity of a star can be inferred from the emitted light spectrum that is shifted due to the Doppler effect. The galaxy rotation curves show that stars at the edge of a galaxy have larger velocities than one would expect based on the luminous matter inside the galaxy, **see Fig. 3.** According to Newton's law of gravity, the velocity v of a star of mass m rotating around the centre of a galaxy at a distance r is determined by

$$F_g = \frac{GMm}{r^2} = m\frac{v^2}{r} \Rightarrow v^2 = \frac{GM}{r} \qquad (11)$$

Here M is the mass of the matter within the distance r from the centre of the galaxy. Hence, by measuring v through the Doppler effect, one can infer the mass M. If M is larger than the mass of the visible luminous matter, one will conclude that there is also dark matter – unless one concludes that Newton's law of gravity should be modified.

Dark Matter versus Alternative Theories of Gravity

As was pointed out by Sean Carroll from Caltech in one of his inspiring popular talks, the interplay between dark matter and theories of gravity has a long history. It had been known since the 1820s that the orbit of the planet Uranus was not completely accounted for by Newton's law applied to the Sun and the seven planets known at that time. In 1846 the mathematician Urbain Le Verrier explained the irregularities in the orbit of Uranus by predicting the existence of "dark matter": an eighth planet. It was a great triumph of Newton's law that Neptune was discovered almost exactly in the predicted position later in the same year. According to our modern classification, Neptune is a form of baryonic dark matter. In fact, the sunlight reflected from its surface is so dim that, in contrast to Uranus, Neptune cannot be seen with the naked eye.

Inspired by his success, Le Verrier also investigated the irregularities in the orbit of Mercury and predicted another planet which he called Vulcan. The many false claims of Vulcan's discovery ended only after Einstein had explained Mercury's perihelion shift as an effect of general relativity. In that case, there was indeed no hidden dark matter to be found. Instead, Newton's law of gravity had to be modified. One should keep in mind that, after the construction of general relativity, Newtonian gravity is not wrong – it is only incomplete. In fact, Newton's theory of gravity re-emerges from Einstein's general relativity in the limit of small velocities and weak gravitational fields.

After this brief discourse on the history of science, we might ask if the rotation curves of galaxies indeed imply the existence of dark matter. Moti Milgrom from the Weizmann Institute in Rehovot has challenged this standard view in his model of modified Newtonian dynamics (MOND). In MOND, Newton's law is modified such that the rotation curves of galaxies are described without the need for dark matter. However, unlike general relativity, MOND is not a fully satisfactory theory of gravity. It is designed to avoid dark matter, but it does not explain all the rest of gravitational physics. Indirect evidence for dark matter also comes from the analysis of the cosmic microwave background radiation to which we will turn later. Let us therefore adopt the generally accepted conclusion that, besides luminous matter, there must be large amounts of dark matter within galaxies.

Basics III

Asymptotic freedom is a property of some classes of physical theories in which the interaction between the particles, such as quarks, becomes arbitrarily weak at ever shorter distances, i.e. length scales that asymptotically converge to zero (or, equivalently, energy scales that become arbitrarily large).

The **fine-structure constant** is the fundamental physical constant characterizing the strength of the electromagnetic interaction. It is a dimensionless quantity, and thus its numerical value is independent of the system of units used.

The term **Planck scale** refers to a length scale in the neighbourhood of the Planck length 1.616×10^{-35} m, or a time scale in the neighbourhood of the Planck time 5.390×10^{-44} sec. At this scale, the usual concepts of space and time are expected to break down, as quantum indeterminacy becomes virtually absolute.

Dark Matter Candidates

As we said before, massive planets like Jupiter qualify as baryonic dark matter. By gravitational lensing, similar objects have been identified in the halo of our galaxy. MACHOs are definitely a viable dark matter candidate. However, their number is too small to account for all of the dark matter. Other dark matter candidates are WIMPs, **see Basics I**. In contrast to MACHOs, WIMPs are individual weakly interacting massive elementary particles. They should not participate in the strong or electromagnetic interactions. If they did carry an electric charge, they could scatter light and would thus be visible. Hence, WIMPs must be electrically neutral. If they did participate in the strong interactions, they would be bound inside exotic baryons, which have never been detected. Hence, WIMPs must be a non-baryonic form of dark matter. According to **Basics II**, neutrinos indeed do not interact strongly or electromagnetically. They only participate in the weak interactions and in gravity. Until recently, it was not known if neutrinos carry mass. However, due to tremendous recent progress in neutrino physics, we now know that neutrinos indeed have a small but non-zero mass. Indeed, besides the cosmic microwave background radiation of photons, there must be a similar background radiation consisting of an enormous number of neutrinos. Due to their large number, neutrinos are an important dark matter component. Since they are not very massive they are not classified as WIMPs. Because they are light and were produced with very high energies immediately after the big bang, neutrinos are a form of so-called hot dark matter. Hot dark matter alone would not lead to the structures observed in the galaxy distribution today. Hence, one expects that there are, in addition, large amounts of cold dark matter consisting of very massive weakly interacting elementary particles.

The standard model of the known elementary particles does not include a massive WIMP candidate. However, some extensions of the standard model, for example, those with supersymmetry (SUSY) predict the existence of such particles. If it is stable, the lightest SUSY particle is a WIMP and thus a good cold dark matter candidate. Using cryogenic detectors (including the ORPHEUS detector in Bern shown in **Fig. 5**[2]) one has tried to detect WIMPs which should be present everywhere in the galaxy. However, their interactions are so weak that none have been observed until now. In the near future, the Large Hadron Collider at CERN promises to provide enough energy to produce and detect WIMPs in a controlled collider experiment **(see Fig. 6).** Again, it is particle physics that holds the promise to teach us more about the composition of the Universe.

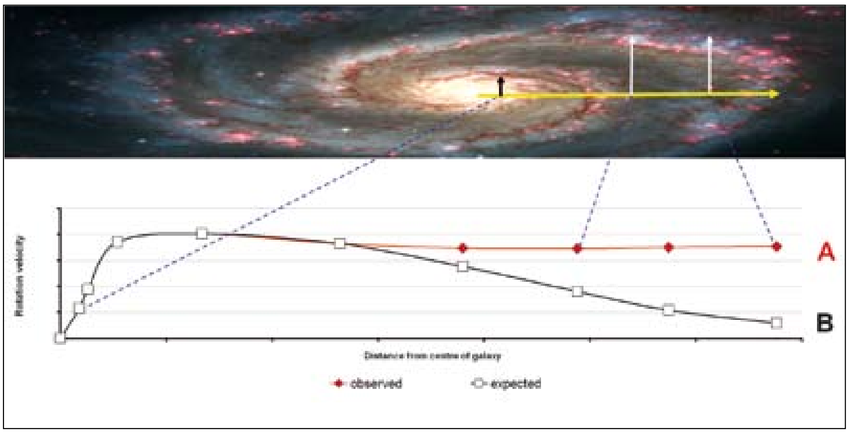


Fig. 3: Rotation curve of a spiral galaxy. The observed rotation velocity of stars at a large distance from the centre of the galaxy (A) is larger than one would expect based on the luminous matter (B). The discrepancy can be explained by the presence of dark matter.

Fig. 4 (on the next pages): ***Beautiful Universe.*** This Hubble Space Telescope view of the spiral galaxy NGC 1672 unveils details in the galaxy's star-forming clouds. Dust lanes extend away from the nucleus and follow the inner edges of the galaxy's spiral arms, where clusters of hot young blue stars form and ionize surrounding clouds of hydrogen gas that glow red. (Credit: NASA, ESA, and The Hubble Heritage Team)

[2] See also Spatium 7: In Search of Dark Matter in the Universe

Basics IV

The **Higgs field,** named after the British physicist Peter Higgs, is a postulated quantum field, which is believed to permeate the entire Universe. Its presence is required in order to explain the large mass of those particles which mediate the weak interactions (the W- and Z-bosons). The photon, which mediates the electromagnetic interactions, on the other hand, is massless.

The **cosmic microwave background radiation** is a form of electromagnetic radiation discovered in 1965 that fills the entire Universe. It is interpreted as the best evidence for the big bang model that stipulates the early Universe to be made up of a hot plasma of photons, electrons and baryons. As the Universe expanded, adiabatic cooling caused the plasma to cool until it became favourable for electrons to combine with protons and form hydrogen atoms. This happened at around 3,000 K or when the Universe was approximately 380,000 years old. At this point, the photons did not scatter off the now neutral atoms and began to travel freely through space. The photons have continued cooling ever since; they have now reached 2.725 K and their temperature will continue to drop as long as the universe continues expanding. Accordingly, the radiation from the sky we measure today comes from a spherical surface, called the surface of last scattering, from which the photons that decoupled from interaction with matter in the early Universe, 13.7 billion years ago, are just now reaching observers on Earth.

The inflaton is the generic name of the unidentified scalar field that may be responsible for an episode of inflation in the very early Universe. According to inflation theory, the inflaton field provided the mechanism to drive a period of rapid initial expansion that shaped the Universe immediately after the big bang. The name inflaton follows the convention of field names, such as photon field and gluon field, which end with „-on".

The Origin of Non-Baryonic Mass

As we have seen, the origin of the mass of baryonic dark matter is well understood in terms of strong interaction energy of quarks and gluons inside protons and neutrons. We have also seen that neutrinos and WIMPs are candidates for hot and cold non-baryonic dark matter. What is the origin of this non-baryonic mass? For example, what is the origin of the neutrino masses? In the original minimal version of the standard model of elementary particle physics, neutrino masses were even zero. After the discovery of non-zero neutrino masses, we know that we must use an extended version of the standard model. In this model the neutrino masses are free parameters, which are at least naturally small due to a mass hierarchy mixing mechanism (known as the see-saw mechanism) first discussed by Peter Minkowski from Bern University. Also the masses of electrons and quarks are free parameters not predicted by the theory. These parameters are related to couplings to the so-called Higgs field **(see Basics IV)**, which has a non-zero value in the vacuum as a result of electroweak symmetry breaking. The dynamics of the Higgs field thus affects the masses of the other elementary particles. One major goal of the Large Hadron Collider is to produce a quantized oscillation of the Higgs field – the so-called Higgs particle – which is the last still unobserved particle in the standard model. The search for the Higgs particle may also shed some light on the dynamics of electroweak symmetry breaking and thus on the origin of the masses of the other particles. If SUSY WIMPs will

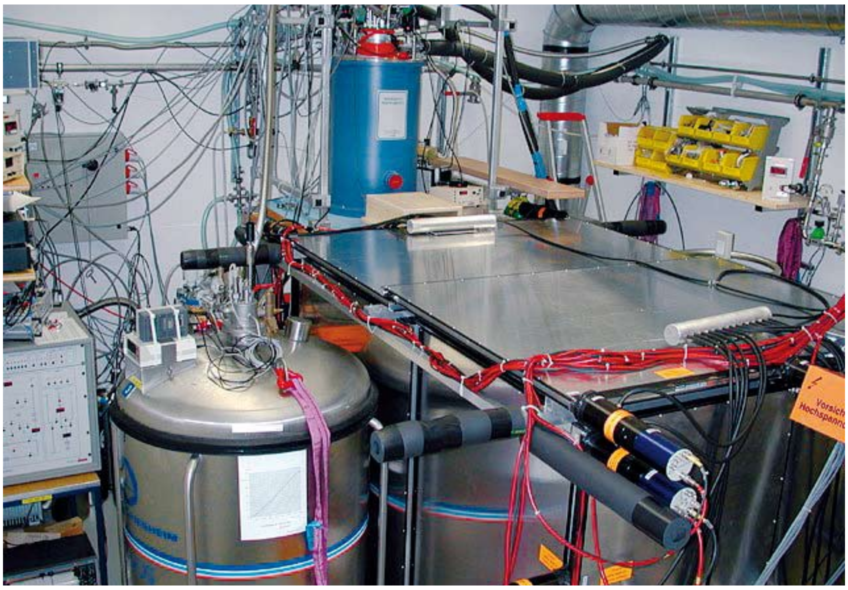


Fig. 5: The cryogenic ORPHEUS detector in the underground laboratory at Bern University has been used in the search for WIMPs. Due to their very weak interactions, the detection of WIMPs is extremely difficult and has not yet been achieved. See also Spatium-7: In Search of Dark Matter in the Universe.

be produced at the LHC, their mass should result from supersymmetry breaking which is a highly speculative subject. Hence, in contrast to baryonic matter, the origin of the mass of non-baryonic dark matter is presently much less well understood. It will require an enormous amount of experimentation at very high energies to make progress on these exciting questions. The LHC is a first giant leap in this direction.

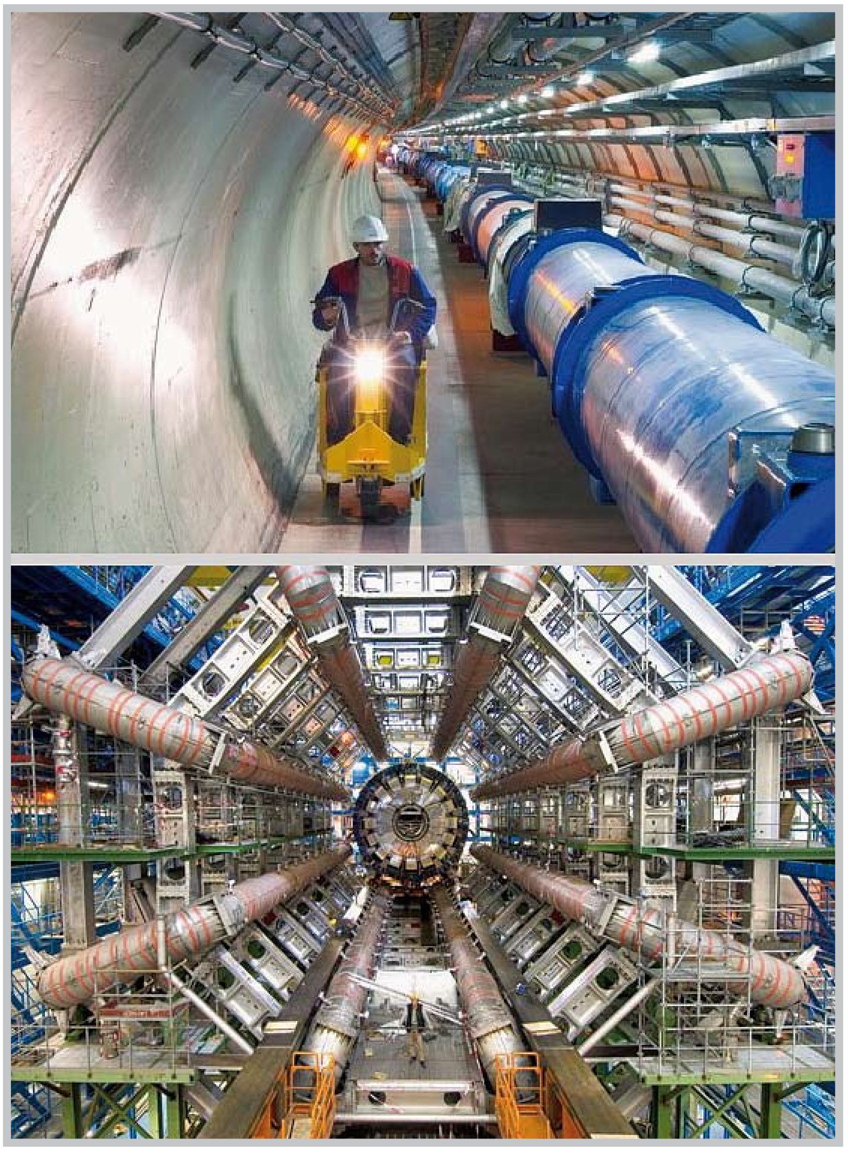


Fig 6: The Large Hadron Collider (LHC) experiment at CERN: The upper plate shows a section of the 27 km long underground ring-tunnel in which protons will be accelerated and collided with each other at the highest energies ever reached in any collider experiment. The lower table shows the gigantic ATLAS (A Toroidal LHC ApparatuS) detector built by an international collaboration including the Laboratory for High-Energy Physics at Bern University. The detector will be used to search for Higgs particles, WIMPs, and other as yet undiscovered elementary particles.

Vacuum Energy

As observations of very distant supernova explosions and detailed investigations of the cosmic microwave background radiation have shown, luminous and dark matter alone cannot explain the composition of the Universe. Indeed, there is evidence for vacuum energy which, unlike luminous or dark matter, does not cluster inside galaxies but fills all of space homogeneously. This form of energy counteracts the gravitational pull of the matter and leads to an accelerated expansion of the Universe. Vacuum energy may be represented by a static cosmological constant or by dynamical quintessence. In the framework of the inflationary Universe, vacuum energy also plays a central role immediately after the big bang.

Evidence for Vacuum Energy

Supernova explosions are among the most violent events in the Universe, **see front cover**. When a large star runs out of nuclear fuel, it collapses under its own gravity. The resulting shock wave expels most of the mass of the star in a gigantic explosion. One distinguishes different types of supernova explosions. Those of type Ia are events that emit a well-defined amount of energy and follow a standard pattern of luminosity change over time. When a distant supernova of type Ia is observed on Earth, it serves as a standard candle whose distance can be inferred from its apparent luminosity because the actual brightness is known. At the same time, the velocity of the emitting galaxy resulting from the expansion of the Universe can be deduced from the red-shift of the emitted light spectrum. In 1998 two international collaborations, the supernova cosmology project and the high-z supernova search team, found that distant supernovae are fainter than one would expect for a Universe whose expansion is decelerated by gravitational pull, **Fig. 7.** Consequently, very distant supernovae of type Ia provide evidence that the expansion of the Universe is actually accelerating. A sufficient amount of positive vacuum energy can indeed counteract the gravitational pull of the matter and give rise to an accelerated expansion of the Universe.

Basics V

Man-made versus Natural Units

The most basic physical quantities – length, time, and mass – are measured in units of metres (m), seconds (sec), and kilogrammes (kg). Obviously, these are man-made units appropriate for the use at our human scales. For example, a metre is roughly the length of an arm, a second is about the duration of a heart beat, and a kilogramme comes close to the mass of a heavy meal. Expressed in man-made units, Nature's most fundamental constants are: the velocity of light:

$$c = 2.9979 \times 10^{8}\, m/\mathrm{sec},$$

Planck's quantum

$$\hbar = 1.0546 \times 10^{-34}\, kgm^{2}/\mathrm{sec},$$

and Newton's gravitational constant

$$G = 6.6720 \times 10^{-11}\, m^{3}/kg\ \mathrm{sec}^{2},$$

Appropriately combining these fundamental constants, Nature provides us with her own natural units (also known as Planck units): the Planck length

$$l_{Planck} = \sqrt{G\hbar/c^{3}} = 1.6160 \times 10^{-35}\, m,$$

the Planck time

$$t_{Planck} = \sqrt{G\hbar/c^{5}} = 5.3904 \times 10^{-44}\, \mathrm{sec},$$

and the Planck mass

$$M_{Planck} = \sqrt{\hbar c/G} = 2.1768 \times 10^{-8}\, kg.$$

Planck units are not too practical in our everyday life. For example, an arm has a length of about 10^{35} l_{Planck}, a heartbeat lasts roughly 10^{44} t_{Planck}, and our body weighs about 10^{10} M_{Planck}. Still, l_{Planck}, t_{Planck}, and M_{Planck} are the most fundamental basic units that Nature provides us with. It is interesting to ask why we exist at scales so far removed from the Planck scale defined by these three fundamental units. For example, why does a kilogramme correspond to about 10^{8} M_{Planck}? In some sense, this is a historical question. The amount of platinum-iridium alloy deposited near Paris about a hundred years ago, which defines the kilogramme, obviously is an arbitrarily chosen man-made unit. If we assume that the kilogramme was chosen because it is a reasonable fraction of our body weight, we may rephrase the question as a biological one: Why do intelligent creatures weigh about 10^{10} M_{Planck}? If biology could explain the number of cells in our body and (perhaps with some help of chemistry) could also explain the number of atoms necessary to form a cell, we can reduce the question to a physics problem. Since atoms get their mass from protons and neutrons, we are led to ask: Why is the proton mass given by $M_p \approx 10^{-19}$ M_{Planck}? This physics question is addressed in the main text.

The cosmic microwave background radiation consists of photons that originated from a mass extinction of matter and antimatter about one second after the big bang. The early Universe contained a gas of charged particles and was thus opaque. Only when the Universe had sufficiently expanded and cooled down could atoms form, thus neutralizing the matter. At that time, about 380,000 years after the big bang, the Universe became transparent, and the cosmic photons decoupled from the matter. Hence, the red-shifted cosmic photons that we observe today still carry detailed information about the Universe at the decoupling time. Remarkably, the temperature of the cosmic background radiation is uniform to a degree of 1 in 100,000. The small deviations from uniformity were measured with very high accuracy by the Wilkinson microwave anisotropy probe (WMAP) satellite in 2003, **Fig. 8,** upper table. The WMAP data allow us to reconstruct the composition of the Universe. The total amount of energy in the Universe determines if, on the largest scales, space is curved or flat. It is flat only if the energy density ρ assumes a critical value ρ_c. For a flat Universe one thus obtains the ratio

$$\Omega = \frac{\rho}{\rho_c} = 1. \qquad (12)$$

The WMAP data indicate that $\Omega = 1$ and hence that, on the largest scales, space indeed is flat. The matter fraction $\Omega_M = \Omega_b + \Omega_{nb}$ consists of a baryonic and a non-baryonic contribution, Ω_b and Ω_{nb}, and the vacuum contribution is denoted by Ω_Λ. As illustrated in **Fig. 8**, lower table, the best fit to the WMAP data corresponds to an energy cocktail of only about 5 percent of ordinary baryonic (luminous or dark) matter (i.e. $\Omega_b = 0.05$), about 20 percent of non-baryonic dark matter ($\Omega_{nb} = 0.20$), and 75 percent vacuum energy ($\Omega_\Lambda = 0.75$). Altogether, we thus obtain

$$\Omega = \Omega_M + \Omega_\Lambda = \Omega_b + \Omega_{nb} + \Omega_\Lambda = 0.05 + 0.20 + 0.75 = 1. \qquad (13)$$

Interestingly, the amount of dark matter that one infers from the observation of galaxy clusters is consistent with $\Omega_M = \Omega_b + \Omega_{nb} = 0.25$. Furthermore, the observed abundances of light nuclei such as helium and lithium, which were produced in the primordial nucleosynthesis a few minutes after the big bang, also imply $\Omega_b = 0.05$. Finally, the amount of vacuum energy inferred from type Ia supernova explosions is again consistent with $\Omega_\Lambda = 0.75$.

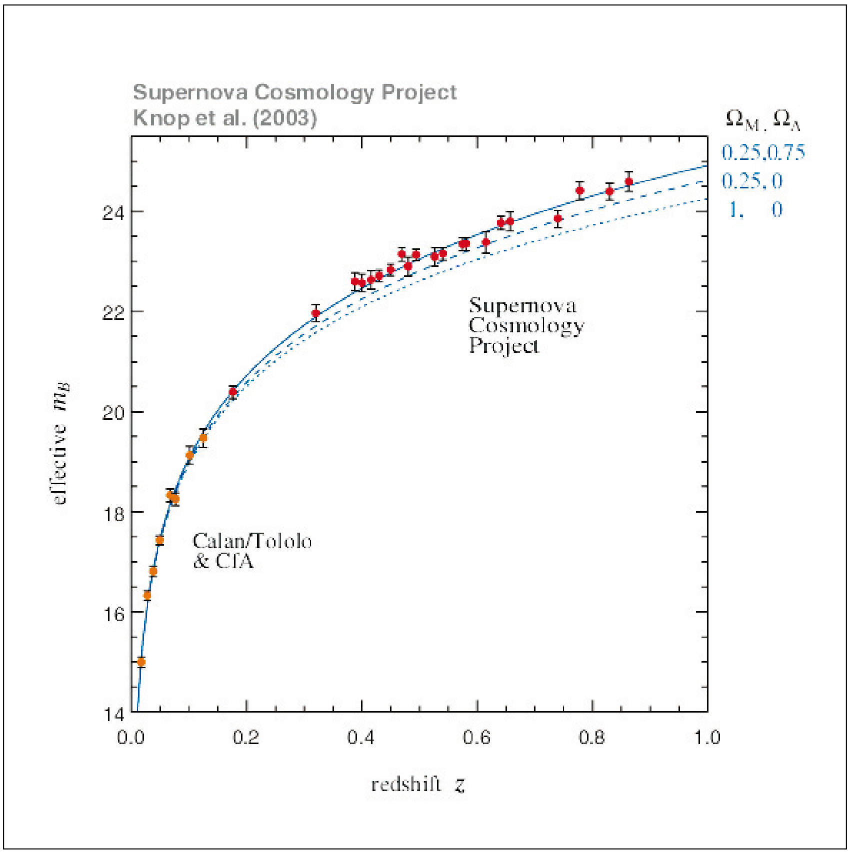
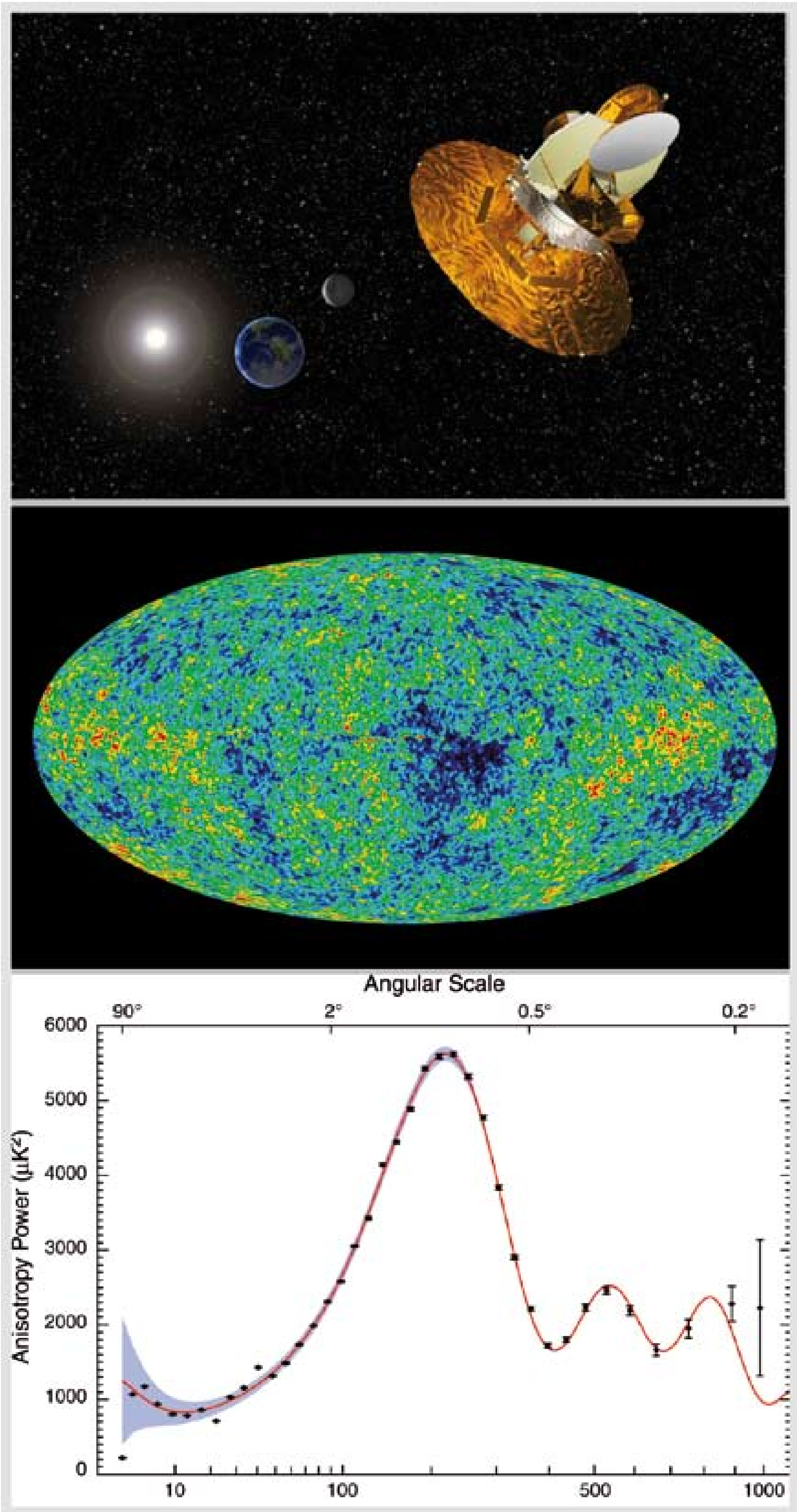


Fig. 7: The Hubble diagram based on very distant type Ia supernovae observed at high redshift obtained by the international supernova cosmology project. The observed luminosity is smaller than originally expected, which implies that the expansion of the Universe is accelerating. The best fit to the data is obtained for $\Omega_M = 0.25$ and $\Omega_\Lambda = 0.75$, indicating that 25 percent of the energy of the Universe is due to (luminous or dark) matter, while 75 percent is vacuum energy.

The Cosmological Constant

What is the nature of the vacuum energy? Unlike the energy of MACHOs or WIMPs that is clustered in galaxies, vacuum energy homogeneously fills all of space. In order to obtain a static Universe, Einstein had included a cosmological constant Λ in the equations of general relativity. Once Hubble had observed the cosmic expansion, Einstein is quoted as considering the introduction of Λ his biggest blunder. In quantum field theory the vacuum fluctuations of the fields do give rise to vacuum energy. However, that energy is formally divergent. Naive attempts to make it finite lead to the estimate $\Lambda = M^4_{Planck} c^5/h^3$ which is a factor of 10^{120} bigger than the amount of vacuum energy necessary to explain the observed accelerated cosmic expansion. This shows drastically that we have presently no idea how to compute the tiny but non-zero vacuum energy density. Indeed, the cosmological constant problem is one of the greatest puzzles in physics today. At present we do not have an established theory of quantum gravity, and hence we do not even know the rules from which one could perhaps derive the value of Λ. We have seen that the property of asymptotic freedom of quantum chromodynamics explains naturally why the proton mass is very much smaller than the Planck scale. Perhaps the correct theory of quantum gravity has a similar property that guarantees the same for Λ.



Inflation and Quintessence

A dynamical form of vacuum energy plays a central role in Guth's inflationary early Universe. Putting aside the cosmological constant problem, he postulates that Λ is indeed zero in the true vacuum – the state of absolute lowest energy. However, he then assumes that in the moment of the big bang the Universe started out in a false vacuum in which the quantum fields did not have their final vacuum values. In particular, a yet unidentified inflaton field **(see Basics IV** on page 12) is suggested to be slowly rolling towards its true vacuum value, **Fig. 10.** The energy of the inflaton field in the false vacuum then acts like vacuum energy. As a consequence, the inflationary Universe

Fig. 8: The antennae of NASA's Wilkinson microwave anisotropy probe (WMAP) point away from the Sun and detect photons of the cosmic microwave background radiation (upper table). These photons were generated immediately after the big bang and have been travelling through the expanding Universe for about 13.7 billion years. The middle plate shows tiny 1 part in 100,000 variations in the temperature of the cosmic microwave background radiation as a function of the angular position in the sky. This radiation carries detailed information about the physical conditions about 380,000 years after the big bang. In the lower plate the intensity distribution of the cosmic microwave background radiation is analysed as a function of angular scale. It contains detailed information about the composition of the Universe. The best fit to the data is obtained for $\Omega_b = 0.05$, $\Omega_{nb} = 0.20$, and $\Omega_\Lambda = 0.75$, indicating that only 5 percent of the energy of the Universe is due to ordinary (luminous or dark) baryonic matter, while 20 percent is due to non-baryonic dark matter, and 75 percent is vacuum energy.

undergoes an accelerated exponential expansion. The idea of inflation solves many problems of the standard big bang cosmology. First, Guth predicted that $\Omega = 1$, long before this was confirmed by the WMAP data. In this way, inflation explains why the Universe is old and flat. Second, it also solves the horizon problem: Why do the cosmic photons coming from opposite ends of the Universe have almost exactly the same temperature? This is a puzzle because they originated from regions separated by two times the horizon distance and should thus not have been in causal contact. In the inflationary Universe, space is stretched so much that those regions indeed were in causal contact very early on. Third, inflation even explains the 1 part in 100,000 deviations from uniformity in the temperature of the cosmic background radiation, which formed the seeds for structure formation in the Universe. These initial fluctuations are attributed to the quantum fluctuations of the inflaton field. Finally, inflation also explains why magnetic monopoles (isolated magnetic north or south poles), which unavoidably arise in grand unified theories, are no longer to be found in the Universe today. They simply got extremely diluted by the inflationary expansion. Interestingly, inflation includes a mechanism by which it can naturally end. This happens when the inflaton field finally reaches its true vacuum value. While inflation has been a very attractive theoretical speculation for a long time, the WMAP data have recently confirmed it in great detail.

In 1987, long before there was observational evidence for vacuum energy, Christof Wetterich from Heidelberg University applied the idea of dynamical vacuum energy to today's Universe. Again, he assumed that some quantum field – in this case called a cosmon field – has not yet reached its true vacuum value. This provides us with dynamical vacuum energy – known as quintessence – which may drive the ac-

Fig. 9: The European Space Agency's Planck mission is scheduled for launch in 2008. It aims at probing the cosmic microwave background radiation with the highest resolution so far. The cosmic background was discovered accidentally by Penzias and Wilson in 1965 by means of a terrestrial microwave receiver. In 1992, the NASA cosmic background explorer COBE delivered the first detailed maps of the temperature distribution of the cosmic background. In 2002, NASA's Wilkinson microwave anisotropy probe (WMAP) charted the cosmic background even more precisely (Fig. 8). The Planck spacecraft will go a step forward by mapping the cosmic microwave background anisotropies with a temperature resolution of the order of 10^{-6}. The Swiss space industry led by Oerlikon Space of Zurich contributed the entire payload module structural subsystem, seen here in the company's clean room. (Credit: Oerlikon Space, Zurich)

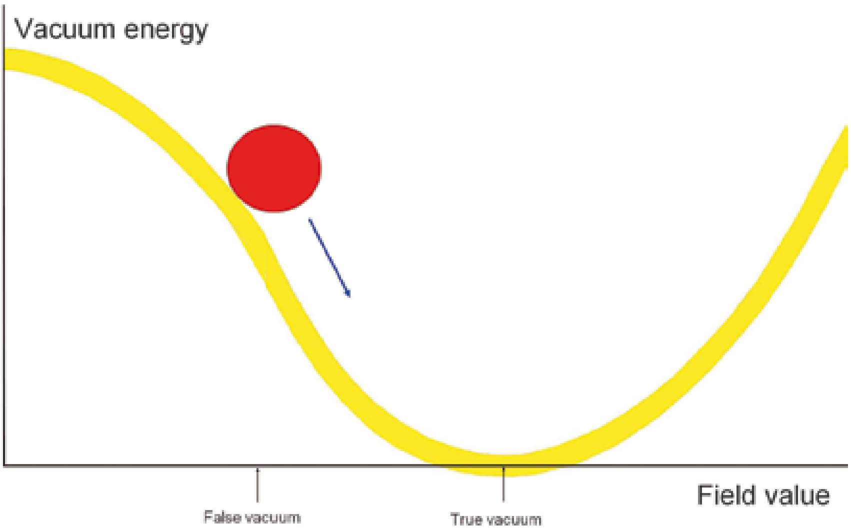


Fig. 10: Vacuum energy as a function of the value of an inflaton field. Immediately after the big bang, the field is displaced from its true vacuum value. The energy of the inflaton field in the false vacuum leads to an exponential expansion of the Universe. The inflationary epoch ends when the inflaton field rolls down to its true vacuum value.

celerated expansion of the Universe today. We then arrive at the following picture of the cosmic evolution. Immediately after the big bang, the Universe was dominated by dynamical vacuum energy in the form of an inflaton field rolling down to its true vacuum value. When this value is reached, inflation ends and the energy stored in the inflaton field is released in the form of an extremely hot gas of elementary particles. The Universe then becomes radiation dominated. It keeps expanding (although no longer at an exponential rate) and, consequently, the hot gas cools down. As a result, particles and antiparticles in the gas annihilate almost completely (at about 1 second after the big bang) thus producing the enormous number of photons and neutrinos in the cosmic background radiations. Only a tiny surplus of matter survives the mass extinction of particles and antiparticles and constitutes all the matter that we find in the Universe today. Once the gas has cooled so much that neutral atoms form (at about 380,000 years after the big bang) the cosmic photons decouple and the Universe becomes transparent. Around that time the Universe begins to be matter dominated. The atoms then form large structures and the first stars are born (at about 500 million years after the big bang). After about 10 billion years of expansion, the matter is diluted so much that vacuum energy (of a much smaller magnitude than during the inflationary epoch) again becomes noticeable. By now (at 13.7 billion years after the big bang) vacuum energy has begun to dominate over the matter. If the vacuum energy exists in the form of a cosmological constant, the Universe will from now on expand forever at an exponential rate. If the vacuum energy is dynamical and exists in the form of quintessence, i.e. if it is carried by a cosmon field, the exponential expansion may eventually come to an end. This will happen when the cosmon field finally reaches its true vacuum value. All this happens over time scales of billions of years. It is interesting to ask why we happen to exist around a time when matter dominance is being replaced by vacuum dominance.

Life in the Multiverse

Once we adopt inflation as a paradigm for cosmology, we must accept that it is a never ending process. In other regions of space the inflaton field may not yet have reached its true vacuum value and thus new exponentially expanding Universes are constantly being created at an astounding rate. This process will practically not be detectable from our own Universe, but the idea of inflation naturally leads to the concept of a very large Multiverse, containing our Universe as just one part.

If the value of the vacuum energy is determined by the value of a cosmon field, the same could be true for other physical "constants" such as the fine-structure constant α or the masses of quarks, electrons, and neutrinos. If so, there is no reason why these parameters should necessarily have the same values in other regions of the Multiverse. In our Universe, the quark masses seem to be fine-tuned so that nuclear physics happens in a very peculiar way. Similarly, chemistry would work totally differently if the fine-structure constant α or the electron mass were only slightly different. Why do we live in a Universe in which all those parameters are so well suited for the development of life? Similarly, we might ask why we are not living on the surface of the Sun. Obviously, the conditions there are inappropriate for the development of life. If we contemplate the existence of other Universes with other physical conditions, we should not be surprised that we developed in one that is hospitable to life. We may in turn use the anthropic principle, i.e. the fact of our own existence, to "explain" the particular values of various fundamental parameters: they are simply what they must be in order to allow life to develop. The question why we live in a transition period between matter and vacuum dominance may perhaps also be answered by the anthropic principle: at much earlier or much later times the world might not be hospitable for life.

As tempting as it may seem, the anthropic principle should only be used as a last resort when all other possible explanations fail. For example, we could have used the anthropic principle to argue that hydrogen or helium behave just the way they do, simply because this is necessary for our own existence. Such argumentation could, in fact, have stopped us from developing atomic or nuclear physics. Fortunately, as some interesting consequence of the laws of Nature, we are endowed with great curiosity and we can understand things at a very deep level. The anthropic principle should not stop us from figuring out everything that can possibly be understood.

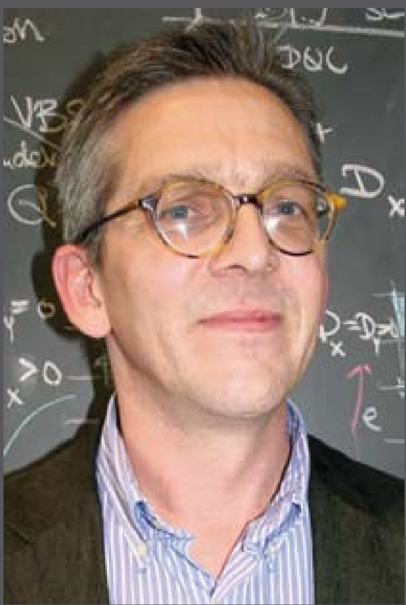
Conclusions

Consistent observations of galaxy clusters, the abundances of light nuclei, distant type Ia supernova explosions, and the cosmic microwave background radiation have revolutionized our understanding of the composition of the Universe and lead to the following conclusions. The ordinary baryonic matter that we find here on Earth and that we understand well constitutes only about 5 percent of the energy of the Universe. Other 20 percent are non-baryonic dark matter of a yet unidentified type. We may hope to soon produce this matter in the form of WIMPs at the LHC. Still, the majority of 75 percent of the energy in the Universe is vacuum energy filling space homogeneously. The nature of this energy, if it is a static cosmological constant or dynamical quintessence, is very much unclear. We live in a Universe that provides physical conditions suitable for our own existence, and that may be part of a much larger Multiverse. Other parts of the Multiverse may be inhospitable to life but are very far away and practically impossible to investigate. Although human endeavour may thus be naturally limited, and we may never find ultimate truth, there is no doubt that there are numerous open questions and many exciting things to explore in our Universe for current and future generations of curious minds.

Acknowledgements

I like to thank the Association Pro ISSI for inviting me to give the talk on which this text is based. Very special thanks go to Hansjörg Schlaepfer for numerous discussions about the main text, as well as for contributing beautiful figures and clear explanations in the boxes concerning the basics. I am also indebted to Heiri Leutwyler for a careful reading of the manuscript and for a number of very useful suggestions.

The Author



Uwe-Jens Wiese received his diploma in physics at Hannover University in 1984 and the Ph.D. degree in Theoretical Particle Physics in 1986. He completed his studies during several post-doctoral positions at Hamburg University, the DESY Höchstleistungsrechenzentrum in Jülich and at the University of Bern. In 1993, he completed his habilitation at the Rheinisch Westphälische Technische Hochschule (RWTH) Aachen.

From 1994 to 1999 Uwe-Jens Wiese was an Assistant Professor at the Massachussetts Institute of Technology (MIT). In 1999 he was promoted to an Associate Professor and later to a Full Professor at MIT. In 2001 he followed a call from the University of Bern to succeed Hans Bebie. Currently he is the director of the Institute for Theoretical Physics at the University of Bern. Although he loved working at MIT, Uwe-Jens Wiese also appreciates the attractive academic environment in Bern. Even compared to the world-famous MIT, the quality of the work performed in Bern is compatible, only the variety of subfields that are being covered is smaller. His research interests focus on the dynamics of quarks and gluons in particle physics and of strongly correlated electron systems in condensed matter physics. He uses analytic methods as well as numerical simulations to gain insight into these fascinating and very active fields of research.

Uwe-Jens Wiese is actively engaged in the public outreach of physics; he is an active member of the organization committee for "Physik am Samstag", a series of public lectures given by leading scientists at the University of Bern that are addressed to high school students and their teachers.

When asked what fascinates him about physics, he says: "I find it very intriguing that the basic laws of Nature can be formulated in mathematical terms. Indeed, the fundamental constituents of matter are an embodiment of mathematics – the universal language that Nature has chosen to express herself in. In some sense, by evolving the human subspecies of the theoretical physicist, the Universe is thinking about itself. Being part of this process together with colleagues all around the world is a fascinating and most rewarding experience."