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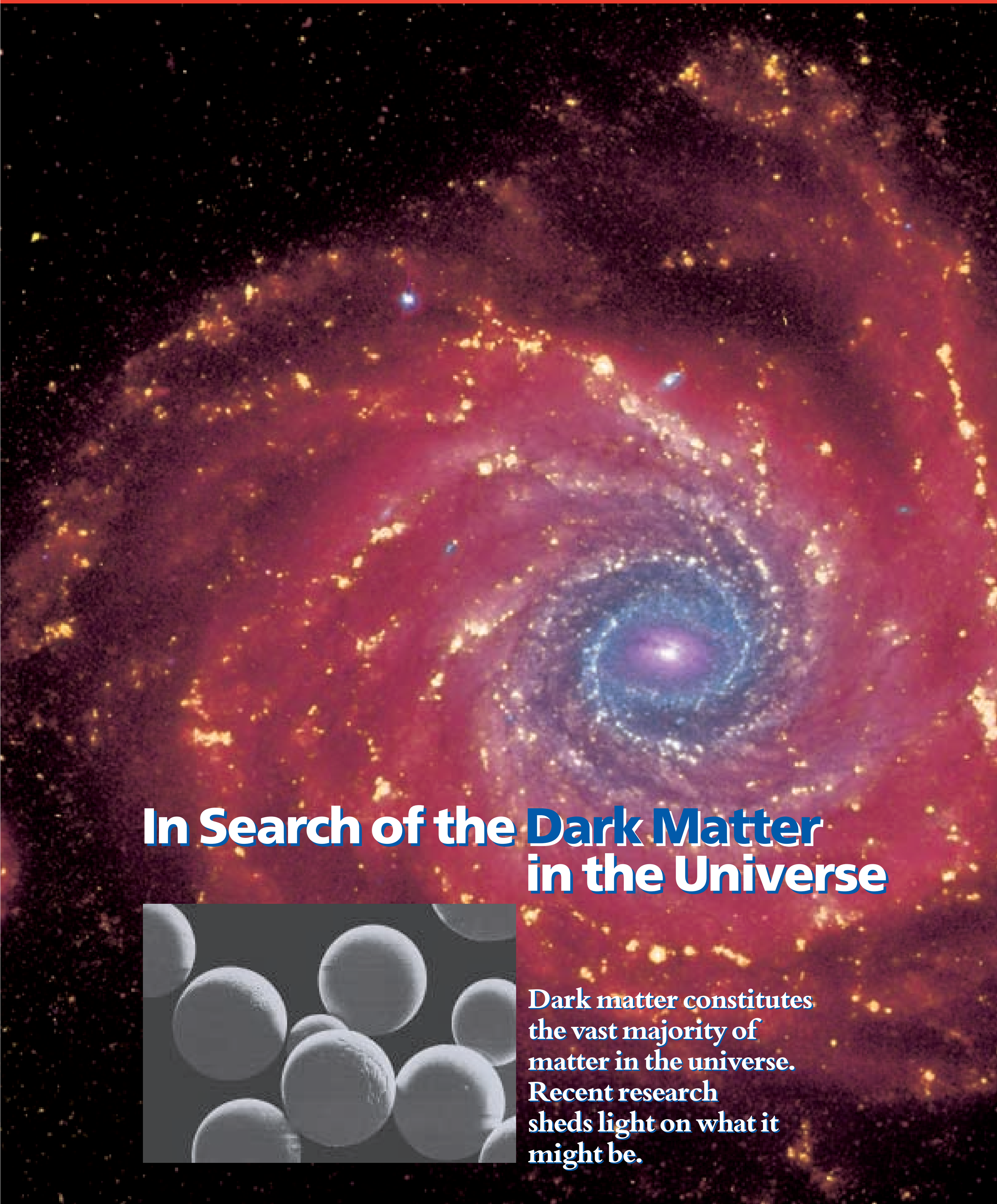

In Search of the Dark Matter in the Universe

Dark matter constitutes the vast majority of matter in the universe. Recent research sheds light on what it might be.

Editorial

Dark matter. Dark energy.
Dark is beautiful!

But it is not so easy to find the dark. It requires charting the unknown as was done some six hundred years ago with the terra incognita. Vague contours, however, are known. Dark matter manifests itself by gravitational effects on visible matter, giving a general direction for those who want to move on in the dark. But much more remains to be found out.

Dark matter is a playground for creative scientists. Imagination is required to define the unknown and formulate hypotheses, which will most likely be thrown out once sufficient scientific progress has been made. Karl Popper, the great Austrian philosopher, showed that rejection – not confirmation – of a theory is the creative step when it is followed by the formulation of a more comprehensive theory.

Dark matter is full of surprises. Dark matter is everywhere. Dark matter may even be found in the dark underworld of Bern. The author of this issue of Spatium, Professor Klaus Pretzl, head of the Laboratory for High Energy Physics of the University of Bern, knows where to find it. He is in charge of the ORPHEUS experiment, now in its final stage of implementation some thirty meters below the University of Bern. This complex set-up seeks to investigate a specific class of dark matter particles, the weakly interacting massive particles.

In March 2000 Professor Pretzl reported on his institute's fascinating search for dark matter to an interested Pro-ISSI audience. We are very grateful to Klaus Pretzl for his kind permission to publish herewith his lecture.

Dark is beautiful.

Hansjörg Schlaepfer
Bern, May 2001

Impressum

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Association Pro ISSI
Hallerstrasse 6, CH-3012 Bern
Phone ++41 31 631 48 96
Fax ++41 31 631 48 97

President
Prof. Hermann Debrunner,
University of Bern
Publisher
Dr. Hansjörg Schlaepfer,
legenda schläpfer wort & bild,
Winkel
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In Search of the Dark Matter in the Universe *)

Klaus Pretzl, Laboratory for High Energy Physics, University of Bern

Introduction

The story of the dark matter started in 1933, when the Swiss astronomer Fritz Zwicky published astonishing results from his studies of galactic clusters. In his paper he concluded that most of the matter in clusters is totally invisible. Zwicky argued that gravity must keep the galaxies in the cluster together, since otherwise they would move apart from each other due to their own motion. By determining the speed of motion of many galaxies within a cluster from the measurement of the Doppler-shift of the spectral lines he could infer the required gravitational pull and thereby the total mass in the cluster. Much to his surprise the required mass by far exceeded the visible mass in the cluster. His results were received with great scepticism by most astronomers at that time. It took another 60 years until he was proven to be right.

How much of this mysterious dark mass is there in the universe? Where do we find it? What is its real nature? Will we be able to directly detect it, since it does not radiate light or particles? It demonstrates its presence only by its gravitational pull on visible matter. These are the questions which intrigue astronomers, cosmologists, particle and nuclear physicists alike. In this talk I will try to give a short account of what we have learned about this mysterious kind of matter which dominates our universe.

How was matter created?

The very first instants

Our knowledge about the beginning of the universe is rather obscure, since it was born out of a state which is not describable by any physical law we know of. We simply call its indescribable moments of birth the Big Bang. After the Big Bang the universe rapidly expanded starting from an incredibly small region with dimensions of the order of 10^{-33} cm and an unthinkably high energy density of 10^{94} g/cm^3. Grand Unified Theories (GUT), which aim to describe the physical laws at this young age of the universe, tell us that physics was much simpler at that time, since there was only one force ruling everything. Today, however, we distinguish four fundamental forces: the force of gravity, which attracts us to the earth and the planets to the sun, the electromagnetic force, which keeps the negatively charged electrons in the outer shell of an atom attracted to the positively charged nucleus in the center, the weak force, which is responsible for the radioactivity we observe when unstable nuclei decay, and the strong force, which holds the protons and neutrons together in the nucleus. All these forces were unified in a single force at this early time. Physicists call this a state of symmetry, since the forces all have the same strength and are therefore indistinguishable from each other. However, while the universe was expanding rapidly this symmetry was quickly broken and gravity, the strong and the electro-weak forces appear today as separate forces with vastly different strength and reach.

The enormous isotropy and homogeneity of the universe, which we encounter when looking at the distribution of galaxies throughout space, and which we obtain from measurements of the cosmic microwave background radiation (CMB), is very puzzling. This is because there are regions in the expanding universe which have never been in causal contact with each other, i.e. light never had sufficient time since the Big Bang to travel far enough to transmit information from one to the other of these regions. To solve this puzzle the astrophysicists A. Guth and A. Linde introduced a scenario according to which the universe experienced an exponentially rapid expansion during a very short period of time between 10^{-36} to 10^{-34} seconds after the Big Bang. During this period the universe was rapidly growing in size by about a factor of 3×10^{43}. Within this scenario of inflation it becomes possible to causally connect regions of the universe which seem to be otherwise disconnected from each other. Nevertheless, after that short period of inflation the universe continued its expansion with retarded speed. Inflation is very much favoured by most cosmologists and strongly supported by the recent observations of the cosmic microwave background

*) Pro ISSI lecture, Bern, March 15th 2000

radiation by the Boomerang and Maxima experiments (see also below).

According to this scenario the inflationary phase of the universe was abruptly ended by the creation of matter and radiation about 10^{-34} seconds after the Big Bang. At that time the universe contained all the basic building blocks of matter, the quarks, the gluons and the electrons, and their antiparticles. Nevertheless, most of the energy of the universe resided in radiation, mainly photons and neutrinos, etc... However, as the universe cooled by expansion, radiation lost its energy faster than matter and when the universe became about ten thousand years old the energy balance shifted in favour of matter.

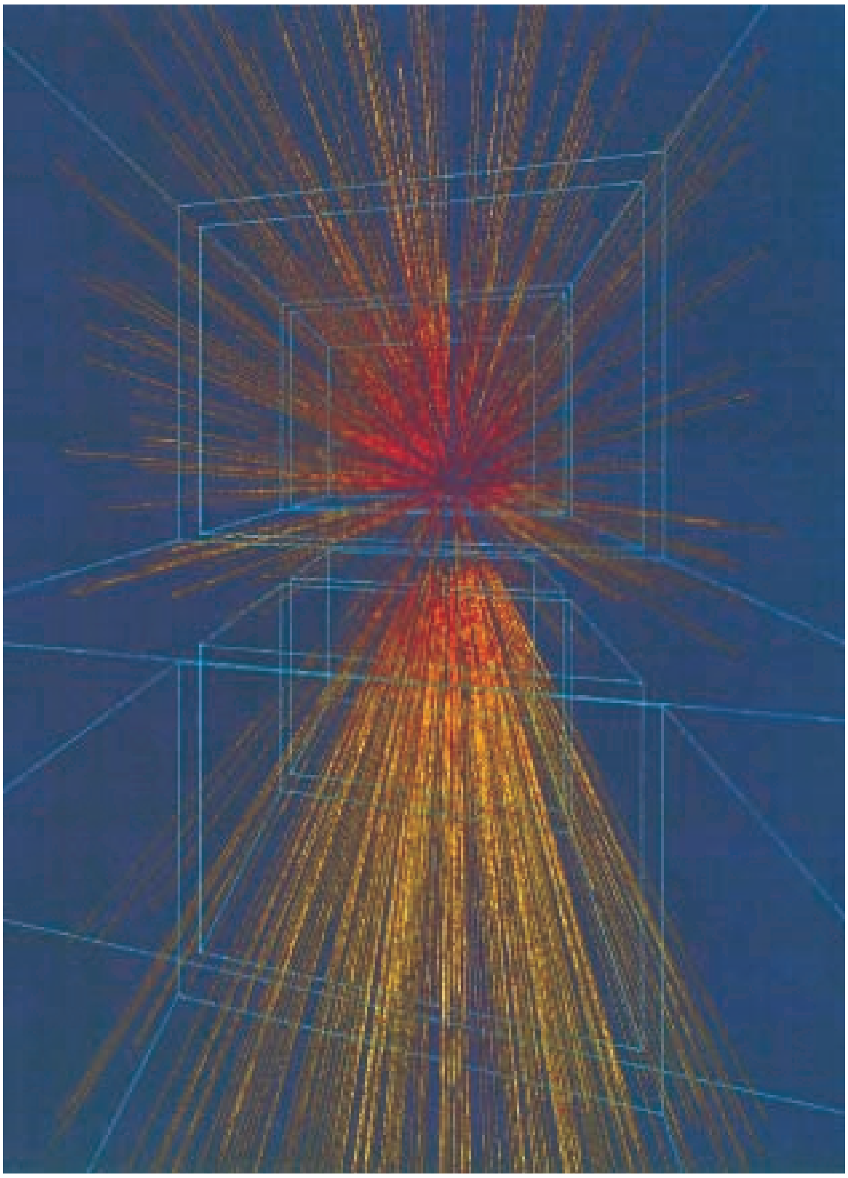

Figure 1
Temperatures of about 2 x 10^{12} were reached in this collision experiment at CERN. A lead target was bombarded with highly relativistic lead nuclei. At that temperature, the quark gluon plasma occurs. The picture shows the outburst of many particles which looks typical when transitions from the quark gluon to the nucleonic phase takes place. (NA49 experiment at CERN).

The quark gluon phase of matter ended about 10^{-6} seconds after the Big Bang, when the universe cooled to a temperature of 2 x 10^{12} Kelvin. At that temperature a phase transition from a quark gluon plasma to a nucleonic phase of matter took place **(Figure 1)**, where the protons and neutrons were formed. In this process three quarks of different flavour (so-called up-quarks and down-quarks) combine together to form a proton (two up-quarks and one down-quark) or a neutron (two down-quarks and one up-quark) and similarly antiprotons (two antiup-quarks and one antidown-quark) and antineutrons (two antidown-quarks and one antiup-quark). The gluons were given their name because they provide the glue for holding the quarks together in the nucleons. After this phase transition one would expect to end up with the same number of nucleons and antinucleons, which annihilate each other after creation, leaving us not a chance to exist. Fortunately this was not the case. The reason that we live in a world of matter with no antimatter is due to a very subtle effect, which treats matter and antimatter in a different way during

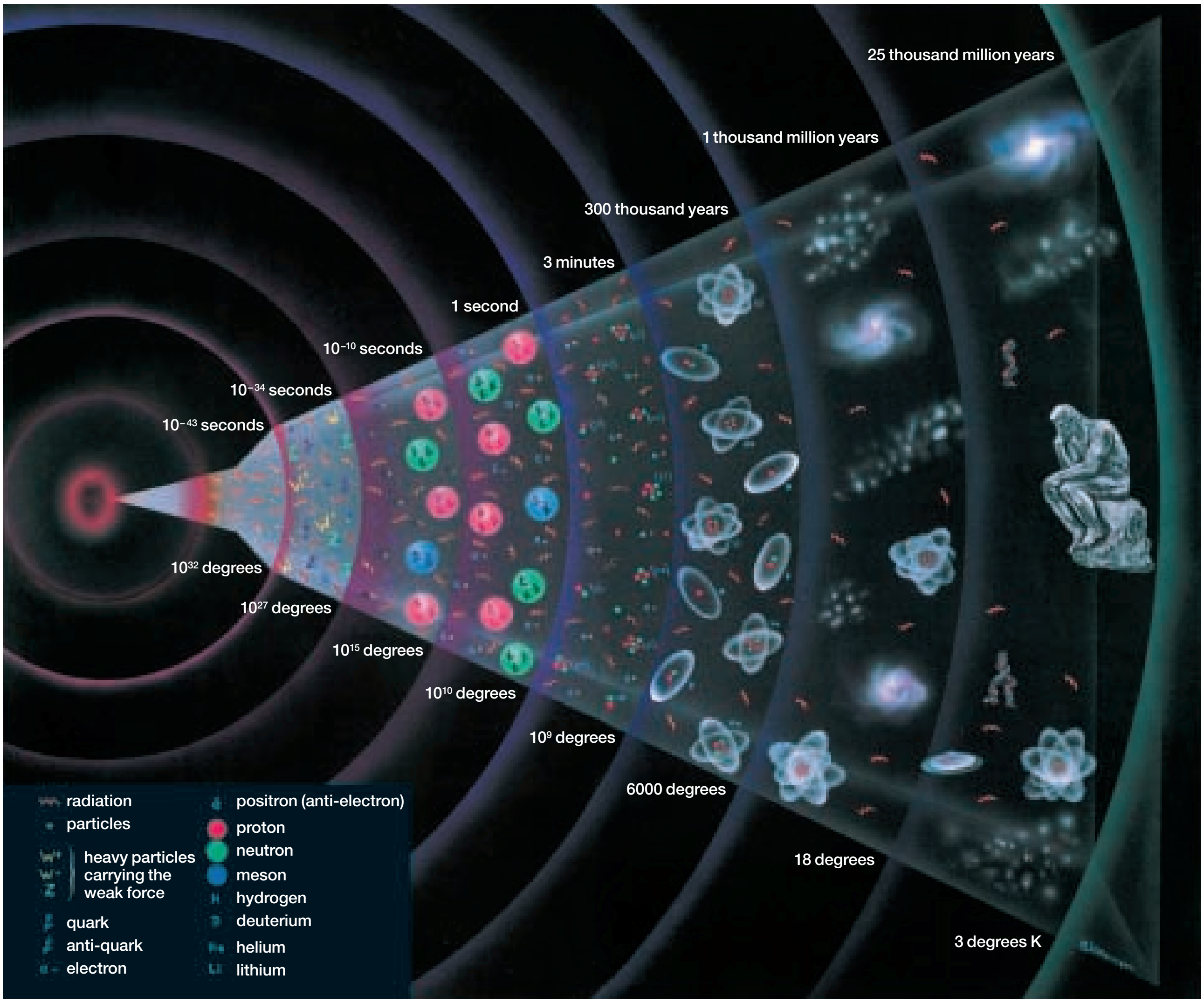

Figure 2
The evolution of the universe. Modern physics and experimental observations document the history of the universe from an incremental fraction of time after the Big Bang 15 billions of years ago up to its present state. Dark matter is seen today as having played a key role in the formation of stars and galaxies. (© CERN Publications, July 1991)

the phase of creation. This effect, which is known as CP-violation (Charge conjugation and Parity violation), was first discovered in an accelerator experiment by V. Fitch and J. Cronin in 1964, for which they got the Nobel prize in 1980, and was used by A. Sakharov to explain the matter antimatter asymmetry in the universe.

After further expansion the universe cooled to a temperature of 10^9 Kelvin, when protons and neutrons started to hang on to each other to form the light elements like helium, deuterium, lithium and beryllium. This phase of nucleosynthesis began a few seconds after the Big Bang. The heavier elements were only formed many million years later, mainly during star formation and supernova explosions. After their formation the light nuclei had hundred thousand years of time to catch electrons to build atoms.

The cosmic background radiation

About three hundred thousand years after the Big Bang radiation had not enough energy left to interact with matter and the universe became transparent for electromagnetic radiation. This radiation from the early universe was first discovered by R. Wilson and A. Penzias in 1965. They received the Nobel prize for this finding in 1978. Their discovery was made by chance, since they were on a mission from Bell Laboratories to test new microwave receivers to relay telephone calls to earth-orbiting communication satellites. No matter in what direction they pointed their antenna, they always measured the same noise. At first this was rather disappointing to them. But they happened to learn of the work of the astronomers R. Dicke and P. Peebles and they realised that the noise they were measuring was finally not the noise of the receiver, but rather the cooled down cosmic microwave background radiation (CMB) from the Big Bang. From the frequency spectrum and Planck's law of black body radiation the temperature of CMB was derived to be 2.7 Kelvin. Regardless which direction the cosmic radiation was received from, the temperature came out to be the same everywhere, demonstrating the enormous homogeneity of the universe. The most accurate CMB measurements come from the Cosmic Background Explorer satellite (COBE), which was sent into orbit in 1989. They found

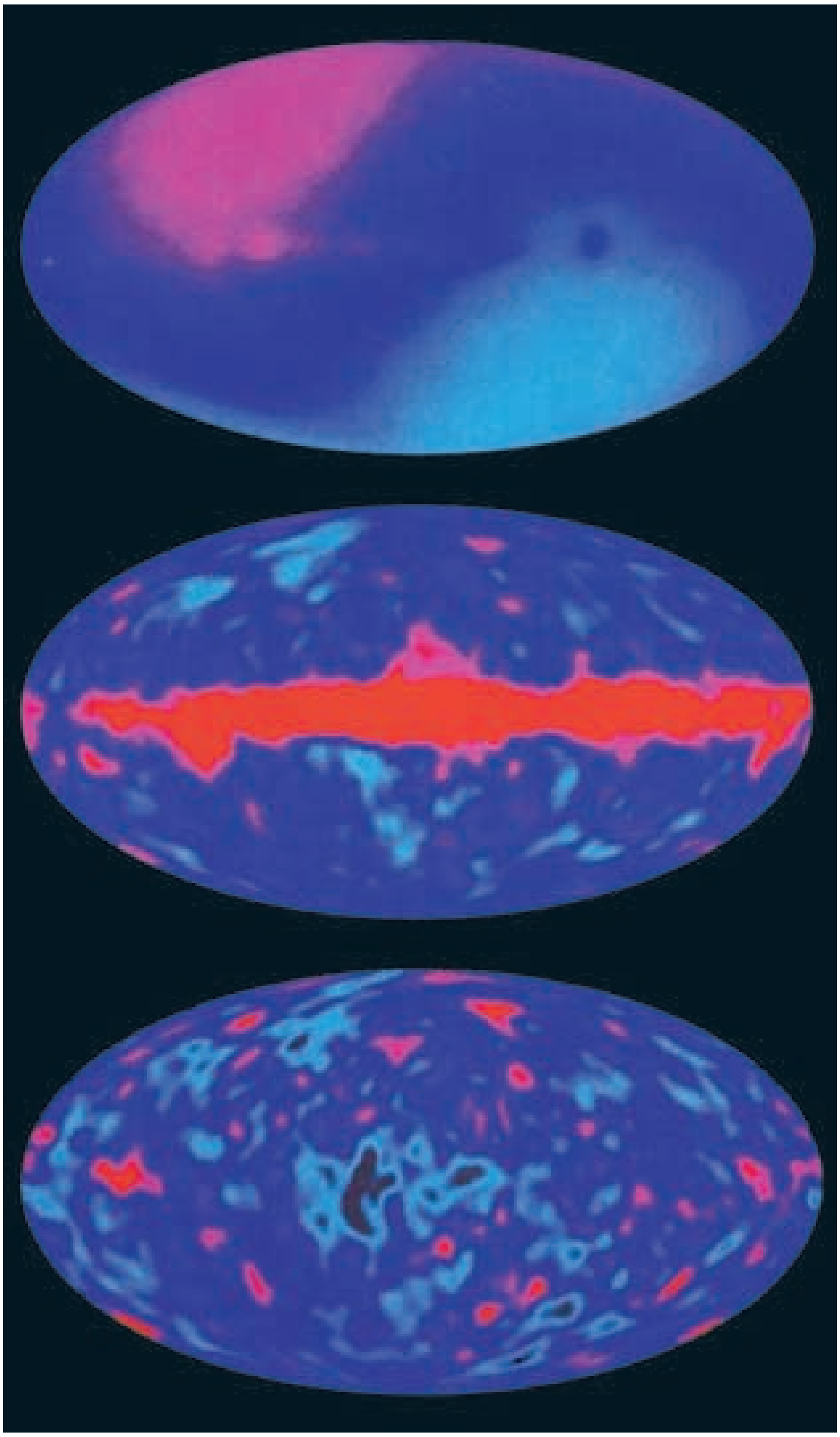

Figure 3
Full sky map of the cosmic background radiation as seen by the COBE mission. After subtraction of the dipol anisotropy (top) and our own galaxy's emission (center) temperature variation of 0.01% unveil matter density fluctuations in the very early universe (bottom). (© Physics Today)

temperature variations only at a level of one part in a hundred thousand.

Where does dark matter come from?

After this short description of the history of the universe and the creation of matter we ask ourselves: What about the dark matter? When and how was it created? A partial answer to this question is given to us by the COBE cosmic microwave background radiation measurements. They show islands of lower and higher temperatures appearing on the map of the universe which are due to density fluctuations of matter **(Figure 3)**. They were already present at the time radiation decoupled from matter, three hundred thousand years after the Big Bang, long before matter was clumping to form galaxies and clusters of galaxies. We have reasons to believe that these density fluctuations are due to the dark matter, which was probably created from quantum fluctuations during the inflationary phase of the universe. These tiny fluctuations expanded first through inflation and then retarded their expansion due to gravitational binding forces. They then formed the gravitational potential wells into which ordinary matter fell to form billion years later galaxies and stars. All galaxies and clusters of galaxies seem to be embedded into halos of dark matter.

How much matter is in the universe?

At first this question seems to be highly academic. It is not. The fate of our universe depends on its mass and its expansion velocity.

The destiny of the universe

In the 1920s the famous astronomer Edwin Hubble demonstrated that all galaxies are moving away from us and from each other. His discovery was the foundation stone of modern cosmology, which claims that the universe originated about 15 billion years ago in an unthinkably small volume with an unthinkably high energy density, the so-called Big Bang, and is expanding ever since. However, this expansion is counteracted by the gravitational pull of the matter in the universe. Depending on how much matter there is, the expansion will continue forever or come to a halt, which subsequently could lead to a collapse of the universe ending in a Big Crunch, the opposite of the Big Bang. The matter density needed to bring the expansion of the universe to a halt is called the critical mass density, which today would be roughly the equivalent of 10 hydrogen atoms per cubic meter. This seems incredibly small, like a vacuum, when compared to the density of our earth and planets, but seen on a cosmic scale it represents a lot of matter.

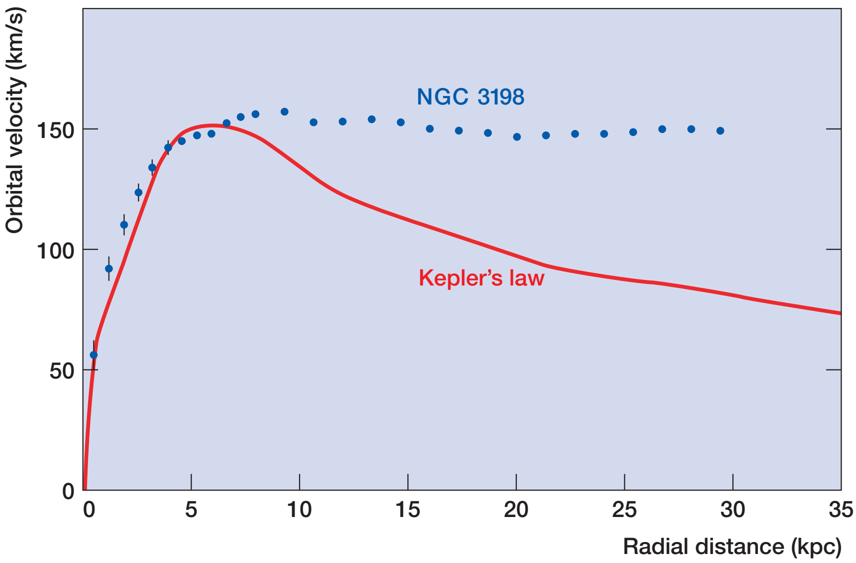

Figure 4
The observation of constant orbital velocities of stars around the galactic center (here the spiral galaxy NGC 3198) as a function of the radial distance provides convincing evidence for the presence of an extended halo of dark matter surrounding the galaxy. The expected curve from Kepler's law if there would be no dark matter is also shown.

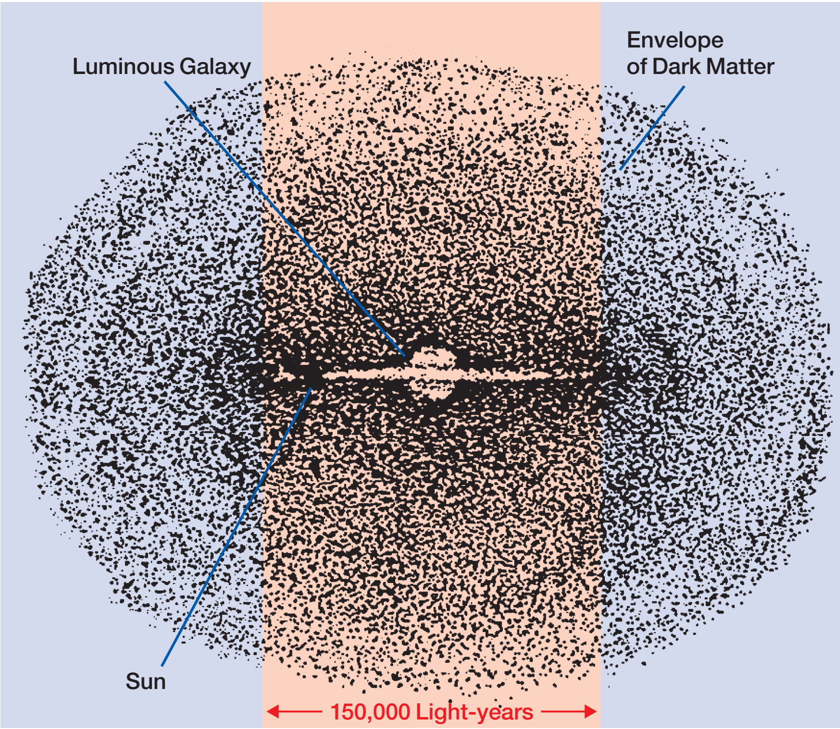

Figure 5
A galaxy as seen schematically from a distant point in the galactic plane. Dark matter forms a large halo extending far outside the outer edges of the galaxy.

and galaxies were the only matter in the universe, the universe would expand forever. We neglected here the amount of matter in form of planets, since they contribute not more than a few percent of the mass of a star. However, it came as a surprise when Vera Rubin and her team found out in the 1970s that the visible stars are not the only objects making up the mass of the galaxies. They measured the orbital speeds of stars around the center of spiral galaxies and found that they move with a constant velocity independent of their radial distance from the center **(Figure 4)**. This is in apparent disagreement with Kepler's law, which says that the velocity should decrease as the distance of the star from the galactic center increases, provided that all mass is concentrated at the center of the galaxy, which seems to

How can we find out how much matter there is? When estimating the visible matter in the universe, astronomers look in a very wide and very deep region in space and count the number of galaxies. Typical galaxies containing hundreds of billions of luminous stars have a brightness which is proportional to their mass. Thus, by simply counting galaxies over a large volume in space and by assuming that galaxies are evenly distributed over the entire universe, one can estimate the total mass they contribute in form of visible mass to the universe. However, it turns out to be only 1% of the critical mass of the universe. Therefore, if the visible matter in form of stars

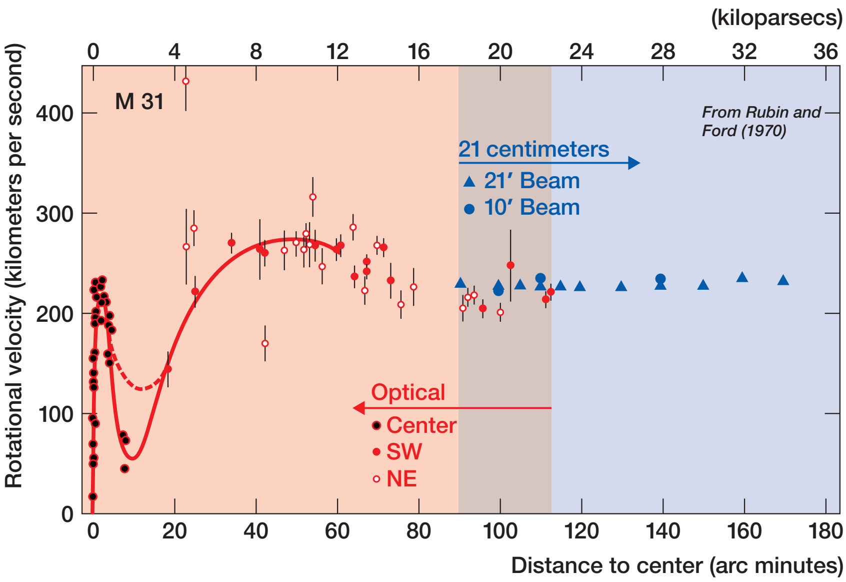

Figure 6
Experimental analysis of the rotational velocities in the Andromeda Galaxy M31 from optical observations (V. Rubin et al.) and radio observations at 21 cm wavelength (B. Roberts et al.).

be the case if only the luminous matter is considered. If however Kepler's law, which describes the orbital motion of the planets in our solar system very correctly, is valid everywhere in the universe, then the rotational velocities of the stars can only be explained if the mass of the galaxy is increasing with the radial distance from its center. Numerical calculations show that there must be at least an order of magnitude more matter in the galaxies than is visible. From their measurements, which they repeated on hundreds of different galaxies, they conjectured that each galaxy must be embedded in an enormous halo of dark matter, which reaches out even beyond the visible diameter of the galaxy **(Figure 5)**. Spiral galaxies are surrounded also by clouds of neutral hydrogen, which themselves do not contribute considerably to the mass of the galaxy, but which serve as tracers of the orbital motion beyond the optical limits of the galaxies. The hydrogen atoms in the clouds are emitting a characteristic radiation with a wavelength of 21 cm, which is due to a hyperfine interaction between the electron and the proton in the hydrogen atom and which can be detected. These measurements show that the dark matter halo extends far beyond the optical limits of the galaxies **(Figure 6)**. But, how far does it really reach out? Very recently gravitational lensing observations seem to indicate that the dark matter halo of galaxies may have dimensions larger than ten times the optical diameter. It is quite possible that the dark halos have dimensions which are already typical for distances between neighbouring galaxies within galactic clusters.

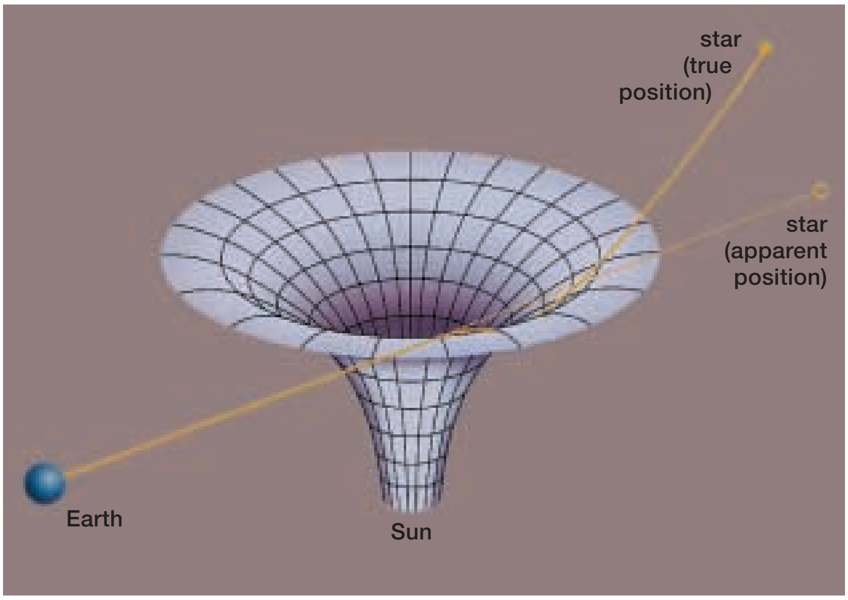

Figure 7
Space is curved by gravity. The light rays from a distant star are bent by the gravity field of the sun. The distant star therefore appears at a different position. (Spektrum der Wissenschaft)

Determining the mass in the universe

The effect of gravitational lensing is a consequence of Einstein's general relativity. It was first observed in 1919, when an apparent angular shift of the planet Mercury close to the solar limb was measured during a total solar eclipse. This was the first, important proof for the validity of Einstein's theory, according to which light coming from a distant star is bent when grazing a massive object due to the space curvature caused by the gravity of the object **(Figure 7)**. It was Fritz Zwicky in 1937 who realized that the effect of gravitational lensing would provide the means for the most direct determination of the mass of very large galactic clusters, including dark matter. But it took more than 50 years until his suggestion was finally realized and his early determination of the mass of the COMA cluster, in 1933, was confirmed. With the Hubble telescope in space and the Very Large Telescopes (VLT) at the Southern Observatory in Chile astronomers now have very powerful tools, which allow them not only to explore the visible, but also the dark side of the universe with gravitational lensing.

An observer sees a distorted multiple image of a light source in the far background, when the deflecting massive object in the foreground is close to the line of sight. The light source appears to be a ring, the so-called Einstein-Ring,

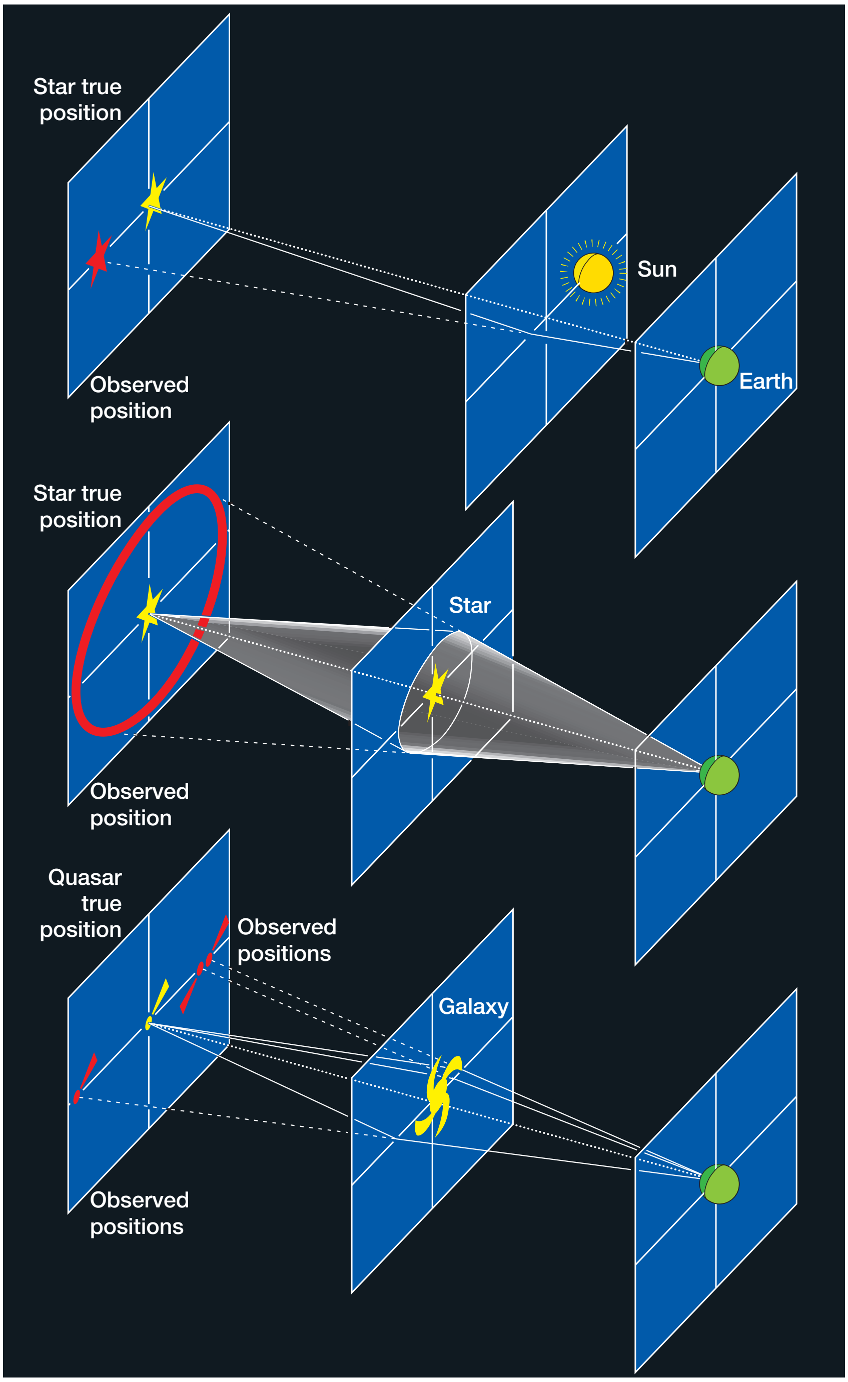

Figure 8
Gravitational lensing occurs when the gravity field of a massive celestial object bends the path of light emitted by a distant source. Einstein predicted the deflection of starlight by the sun (top) and the ring that would appear if the star and the celestial body were aligned perfectly (center). Lens systems found to date result from the alignment of extra-galactic quasars and galaxies (bottom). (© Scientific American, July 1988)

when the object is exactly in the line of sight **(Figure 8)**. If one knows the distance of the light source and the object to the observer one is able to infer the mass of the object from the lensing image. With this method it was possible to determine the mass of galactic clusters, which turned out to be much larger than the luminous matter. It seems that the gravitational pull of huge amounts of dark matter is preventing individual galaxies from moving away from each other and is keeping them bound together in large clusters, like for example the famous Coma cluster. By adding the total matter (dark and luminous matter) in galaxies and clusters of galaxies one ends up with a total mass which corresponds to about 30% of the critical mass of the universe. With only 1% luminous mass this would mean that there is 30 times more dark mass in the universe. In addition, the universe would be growing forever, since its total mass is subcritical to bring the expansion to a halt. But as we will see, this seems not to be the full story.

The discovery of dark energy

The big surprise came in 1998 from a supernovae type1a survey performed by the Super Cosmology Project (SCP) and the High z-Supernova Search (HZS) groups. Supernovae type1a are a hundred thousand times brighter than ordinary stars. They are still visible at very great distances for which their light needed several million years to travel until it reached us. In principle we experience now super-

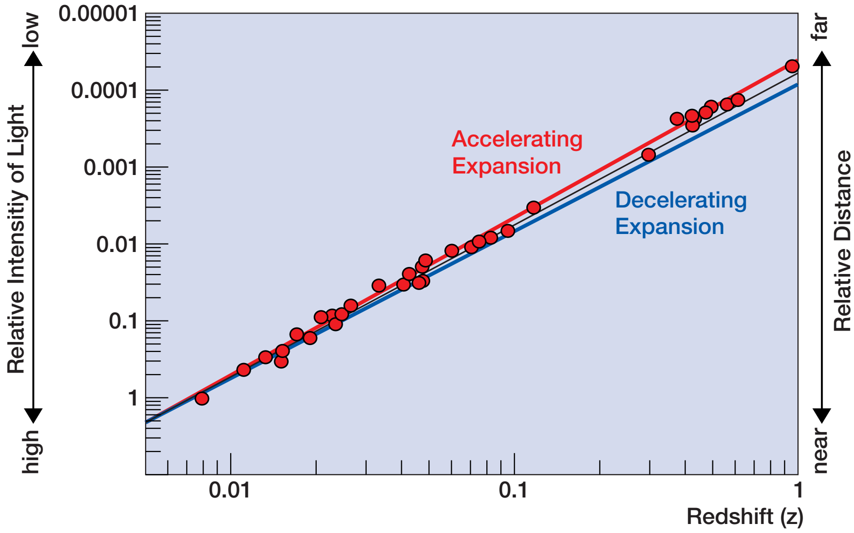

Figure 9
Recent supernovae distance measurements show that the expansion of the universe is accelerating rather than decelerating as assumed before. This observation suggests the presence of dark energy. (© Scientific American, January 1999)

novae explosions which happened several million years ago. Since in every supernova type1a explosion there is always the same total amount of energy released, they all have the same brightness and therefore they qualify as standard candles in the cosmos. Their distance from us can then be inferred from the measurement of their apparent brightness. By probing space and its expansion with supernovae distance measurements astrophysicists learned that the universe has not been decelerating, as assumed so far, but has rather been expanding with acceleration **(Figure 9)**. More measurements are still needed to corroborate these astonishing findings of the supernovae survey. But it already presents a surprising new feature of our universe, which revolutionizes our previous views and leaves us with a new puzzle. In order to speed up the expansion of the universe a negative pressure is needed, which may be provided by some unidentified form of dark energy.

This ubiquitous dark energy amounts to 70% of the critical mass of the universe and has the strange feature that its gravitational force does not attract, on the contrary it repels. This is hard to imagine since our everyday experience and Newton's law of gravity tell us that matter is gravitationally attractive. In Einstein's law of gravity, however, the strength of gravity depends not only on mass and other forms of energy, but also on pressure. From the Einstein equation, which describes the state of the universe, it follows that gravitation is repulsive if the pressure is sufficiently negative and it is attractive if the pressure is positive. In order to provide enough negative pressure to counterbalance the attractive force of gravity, Einstein originally introduced the so-called cosmological constant to keep the universe in a steady state. At that early time all observations seemed to favour a steady state universe with no evolution and no knowledge about its beginning and its end. When Einstein learned about the Hubble expansion of the universe in 1920 he discarded the cosmological constant by admitting that it was his biggest blunder. For a long time cosmologists assumed the cosmological constant to be negligibly small and set its value to zero, since it did not seem to be of any importance in describing the evolution of the universe. This has changed very recently, since we know about the accelerated expansion of the universe. However, there remain burning questions like why is the cosmological constant so constant over the lifetime of the universe and did not change similar to the matter density, and what fixes its value. Besides the cosmological constant, other forms of dark energy are also discussed by cosmologists, like for example vacuum energy, which consists of quantum fluctuations providing negative pressure, or quintessence, an energy source which, unlike vacuum energy and the cosmological constant, can vary in space and time.

In contrast to dark matter, which is gravitationally attractive, dark energy cannot clump. Therefore it is the dark matter which is responsible for the structure formation in the universe. Although the true nature of the dark energy and the dark matter is not known, the latter can eventually be directly detected, while the former cannot.

What is the nature of the dark matter?

Baryonic dark matter

Before speculating with exotic matter, the obvious thing is to look for non-luminous or very faint ordinary matter in form of planetary objects like jupiters or brown dwarfs for example. If these objects represent the dark matter, our galactic halo must be abundantly populated by them. Since they may not be visible even if searched for with the best telescopes, B. Paczynski suggested to look for them by observing millions of individual stars in the Large and the Small Magellanic Cloud to see whether their brightness changes with time due to gravitational lensing when a massive dark object is moving through their line of sight **(Figure 10)**. Several research groups, so-called MACHO, EROS and OGLE followed Paczynski's idea – Paczynski himself was member of the OGLE group – to look for these so-called Massive Astrophysical Compact Halo Objects (MACHOs) using gravitational lensing. They found some of these dark objects with masses smaller than the solar mass, but by far not enough to explain the dark matter in the halo of our galaxy. Other objects like black holes or neutron stars could also have been detected by this method, but we knew

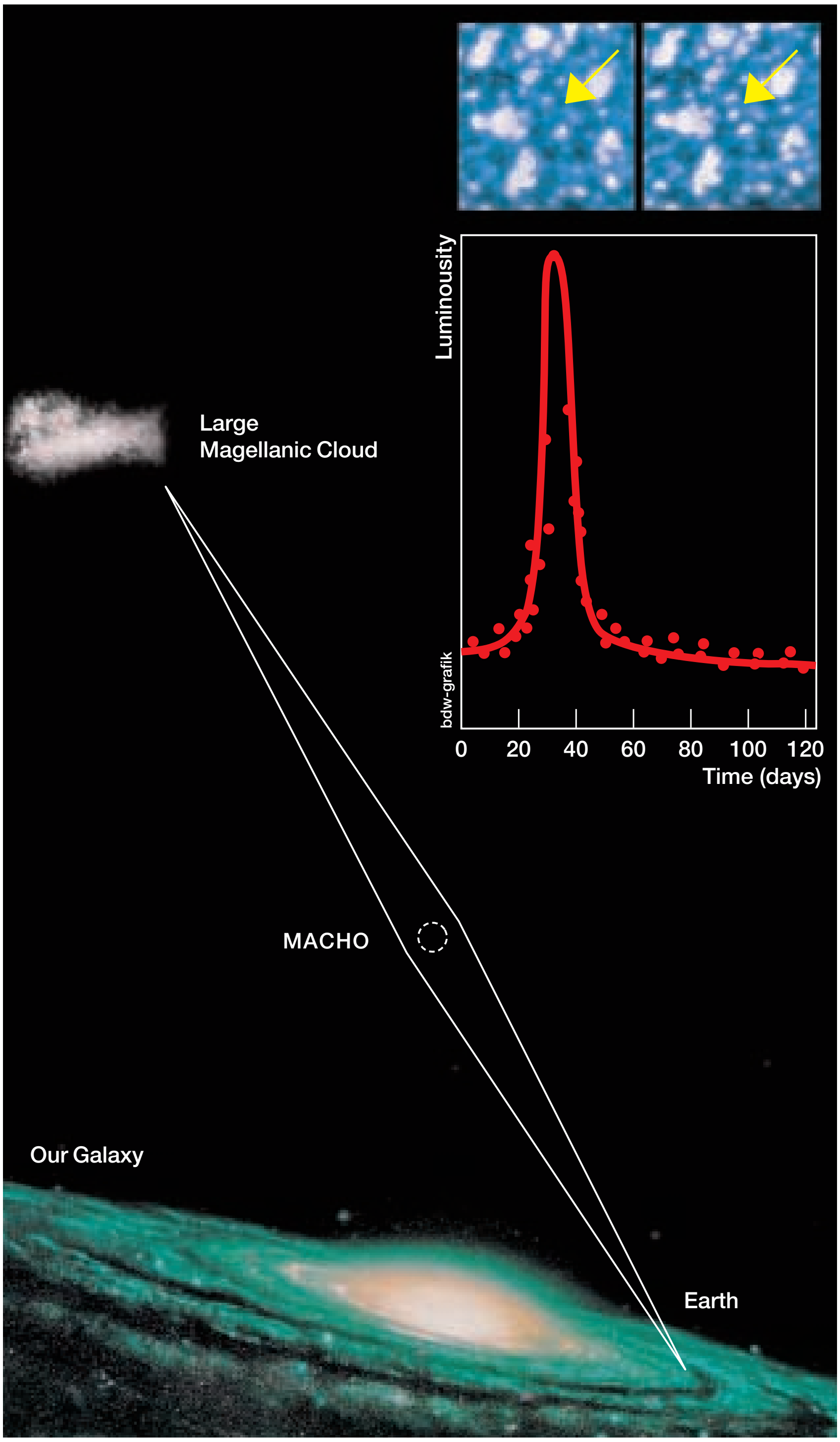

Figure 10
Massive dark objects (Massive Astrophysical Compact Halo Objects MACHOs) moving through the line of sight between the observer and a distant star in the Large Magellanic Cloud cause the apparent luminosity to change. (© Bild der Wissenschaft, 2/1997)

already that there are not many of them in the galactic halo.

Do we know how much ordinary matter exists in the universe? Under ordinary matter or so-called baryonic matter (barys meaning strong or heavy in ancient Greek) we understand matter in form of chemical elements consisting of protons, neutrons and electrons. About 3 minutes after the Big Bang the light elements, like hydrogen, deuterium and helium, were produced via nucleosynthesis. From the measurement of their present abundances we can estimate the total amount of the baryonic matter density in the universe. This amounts to not more than 6% of the critical mass density of the universe. It shows that most of the baryonic matter is invisible and most of the dark matter must be of non-baryonic nature.

Non-baryonic dark matter

The most obvious candidates for non-baryonic matter would be the neutrinos, if they had a mass. Neutrinos come in three flavours. If the heaviest neutrino had a mass of approximately 10^{-9} times the mass of a hydrogen atom, it would qualify to explain the dark matter. This looks like an incredibly small mass, but the neutrinos belong to the most abundant particles in the universe and outnumber the baryons by a factor of 10^{10}. For a long time it was assumed that neutrinos have no mass. The standard model of particle physics includes this assumption. All experimental attempts to determine the mass of the neutrinos ended in providing only upper limits. However, in 1998 an underground detector with the name SUPER-Kamiokande in Japan observed anomalies in the atmospheric neutrino flux which is highly suggestive that neutrinos have indeed a mass. These observations will have to be corroborated by planned accelerator experiments, like K2K in Japan, MINOS in the USA and OPERA in Europe. The OPERA experiment will be constructed in the underground Gran Sasso laboratory, which is located about 100 km north east of Rome. For this experiment, a neutrino beam will be sent from CERN to the Gran Sasso laboratory. If neutrinos have a mass they would change their flavour during their journey over the 735 km distance from CERN to the Gran Sasso. They would start as muon-neutrinos at CERN and would arrive as tau-neutrinos at the Gran Sasso. This change of flavour can be detected by the OPERA experiment, in which our group in Bern is also participating. The future will show whether neutrinos will be able to contribute significantly to the missing mass in the universe. Massive neutrinos may also provide the solution to the puzzle of the missing neutrinos from our sun.

A cocktail of non-baryonic dark matter

Computer models allow us to study the development of small and large scale structures under the hypothesis of various non-baryonic dark matter candidates. Two main categories are distinguished, namely the so-called hot and cold dark matter. Neutrinos would qualify under the category hot dark matter, since their velocities were very large when they decoupled from matter, a few milliseconds after the Big Bang. Because of their speed they were not able to clump on small, typical galactic scales, but their gravitational force would still allow for clustering on very large, typical supercluster scales. Thus in a hot dark matter dominated universe only the formation of large scale superclusters would be favoured. In such a model superclusters would fragment into smaller clusters at a later time. Hence galaxy formation would be a relatively recent phenomenon, which however is in contrast to observation. Cold dark matter candidates, on the other hand, would have small velocities at early phases and therefore would be able to aggregate into bound systems at all scales. A cold dark matter dominated universe would therefore allow for an early formation of galaxies in good agreement with observations, but it would overpopulate the universe with small scale structures, which does not fit our observations. Questions like, how much hot and how much cold or only cold dark matter, are still not answered. Some computer models yield results which come closest to observations when using a cocktail of 30% hot and 70% cold dark matter.

Neutralinos

Exotic particles like neutralinos are among the most favoured cold dark matter candidates. Neutralinos are stable elementary particles which are predicted to exist by Super Symmetry (SUSY), a theory which is an extension of the Standard Model of elementary particles. Thus if they exist, they would solve two problems at the same time: namely the dark matter as well as SUSY, which is a prerequisite for the unification of all forces in nature, the so called grand unification theory (GUT). Experiments at the Large Hadron Collider (LHC) at CERN, which is under construction and will be operational in 2005, will also search for these particles.

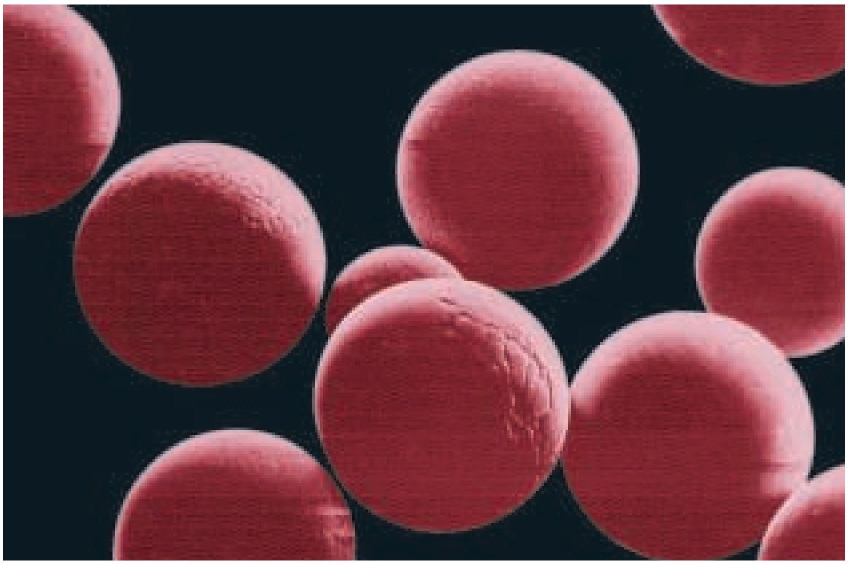

Figure 11
The ORPHEUS detector contains billions of small tin granules with a diameter of 30 micrometers. They are cooled down to –273 °C, where they are in a superconducting state. An interacting WIMP may generate enough heat in a granule to cause a phase transition from the superconducting to the normal conducting state. This phase transition of the granule can be measured with a sensitive read-out system.

Weakly interacting particles

If the dark matter consisted of neutralinos, which would have been produced together with other particles in the early universe and which would have escaped recognition because they only weakly interact with ordinary matter, special devices would have to be built for their detection. These detectors would have to be able to measure very tiny energies which these particles transfer in elastic scattering processes with the detector material. Because of the very weak coupling to ordinary matter these particles are also called WIMPs, for Weakly Interacting Massive Particles. They would abundantly populate the halo of our galaxy and would have a local density in our solar system which would be equivalent to one hydrogen atom in 3 cm^3. Since they would be bound to our galaxy allowing for an average velocity of 270 km/s, their flux (density times velocity) would be very large. However, because they only weakly interact with matter, the predicted rates are typically less than one event per day per kilogram detector material.

WIMPs can be detected by measuring the nuclear recoil energy in the rare events when one of these particles interacts with a nucleus of the detector material. It is like measuring the speed of a billiard ball sitting on a pool table after it has been hit by another ball. Because of the background coming from the cosmic rays and the radioactivity of the material surrounding the detector, which yield similar signals in the detector as the WIMPs, the experiment must be carried out deep underground, where cosmic rays cannot penetrate, and must be shielded locally against the rest radioactivity of materials and the radioactivity in the rock.

The race for WIMPs

Several groups in the USA, in Europe and in Japan are searching for WIMPs employing different techniques. However, in order to be sensitive to very small nuclear recoil energies, innovative new cryogenic detectors have been developed. At temperatures near the absolute zero point, at –273 °C, where the heat capacity is very small, a very tiny recoil energy can be transformed into a measurable signal. One of these innovative detection systems has been developed by our group at the University of Bern. The detector is called ORPHEUS in analogy to Greek mythology. However, we the experimentalists spend a lot more time underground than Orpheus ever did, because our detector is situated in an underground laboratory 30 meters below the University of Bern. The detector consists of billions of small superconducting tin grains with a diameter of a few micrometers, which are cooled down to –273 °C where they are in a superconducting state **(Figure 11)**. When an incoming WIMP hits a granule it can lead to a minute temperature increase of the granule, which can be just sufficient to cause a phase transition from the superconducting to the normal state. This phase transition of an individual granule can be detected by a pick-up loop which measures the magnetic flux change due to the disappearance of the Meissner effect. The ORPHEUS detector, consisting of about 0.5 kg of superconducting tin granules, just started to be operational **(Figure 12)**. It will however take some time before the background is sufficiently understood and true WIMP signals can be detected. Nevertheless, there is still the possibility that the dark matter does not consist of WIMPs, in which case we would not find any signals and other strategies would have to be developed in order to disclose the mystery of the dark matter in our universe.

Conclusions

Despite many interesting candidates, we still do not know what the dark matter is made of. Intensive experimental work is going on by trying to directly detect this abundant matter in our own galaxy or by learning about it through indirect methods. Recent studies of the Cosmic Background Radiation lead us to believe that the dark matter was present long before the chemical elements were created and was responsible for the fascinating architecture of our observable universe, providing also the necessary conditions for life to develop. Without the attractive pull of the dark matter, the universe would be extremely dull today. There would be no galaxies, no stars, no planets and no life. The total amount of dark matter and dark energy will determine the destiny of our universe. From all we have learned so far, it looks as if the universe will not end in a Big Crunch, instead it will expand forever.

In the coming years we are eagerly awaiting new insights into the dark side of the universe. I would like to close with a quote from Shakespeare: There is no darkness, only ignorance.

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Figure 12
Cross sectional view of the ORPHEUS dark matter detector. The detector is horizontally connected via a side axis with a dilution refrigerator, which cools it down to a temperature of –273 °C. It is surrounded by shielding material and scintillation counters to protect against background from particles other than WIMPs.

The author

Klaus Pretzl was born in Munich, Germany, in 1940. From 1941 to 1956 his family lived in Schliersee, south of Munich in the Bavarian Alps, where he also went to primary school. In 1956 he returned to Munich, where he made his Matura at the Wilhelms-Gymnasium.

His fascination for physics was inspired by public lectures about quantum physics given by Professor Auer, a former director of the Deutsches Museum in Munich. As a result he studied physics at the Technische Hochschule in Munich and wrote his diploma thesis in nuclear physics under Prof. H. Meyer Leibnitz and Prof. P. Kienle. He also gained a scholarship from EURATOM to work at the Centre des Recherches Nucléaires in Strasbourg.

His interest turned from nuclear physics to elementary particles, the fundamental building blocks of matter. For this reason he went to CERN in Geneva, where he met Prof. W. Paul (Nobel Prize winner 1989), who offered him to work on an experiment to study meson nucleon backward scattering at high energies. This work was the subject of his PhD thesis, which he submitted to the faculty of the University of Munich in 1968.

After receiving his PhD, Klaus Pretzl went to the USA for 4 years, where he worked at Fermi-Lab, near Chicago, under Prof. R. Wilson on the construction of the world's largest particle accelerator at that time. During the construction time of the accelerator, Klaus Pretzl conducted several experiments studying strong interaction processes at the nearby Argonne National Laboratory. When the construction of the Fermi-Lab accelerator was completed, he was involved in the first experiments to explore physics at the very highest energies.

In 1973 Klaus Pretzl returned to Europe and joined the Max Planck Institute for Physics in Munich. There he first worked at the e^+ - e^- - storage ring DORIS at DESY (Deutsches Elektron Synchrotron), in Hamburg, with the so-called DASP (Double Arm Spectrometer) experiment, which lead to the discovery of the charmonium states. Later he performed several experiments at CERN studying QCD (Quantum Chromo Dynamic) processes. In 1982 he became interested in the topic of dark matter and started to study new concepts for its direct detection.

In 1988 he became professor of physics and head of the Laboratory for High Energy Physics at the Bern University. There he started a new group with the aim to develop cryogenic detectors for a dark matter experiment, which is now in operation in the Bern Underground Laboratory and is called ORPHEUS. Klaus Pretzl and his group are also involved in the ATLAS experiment at the Large Hadron Collider (LHC) at CERN and in the long baseline neutrino oscillation experiment OPERA at the Gran Sasso Laboratory in Italy.

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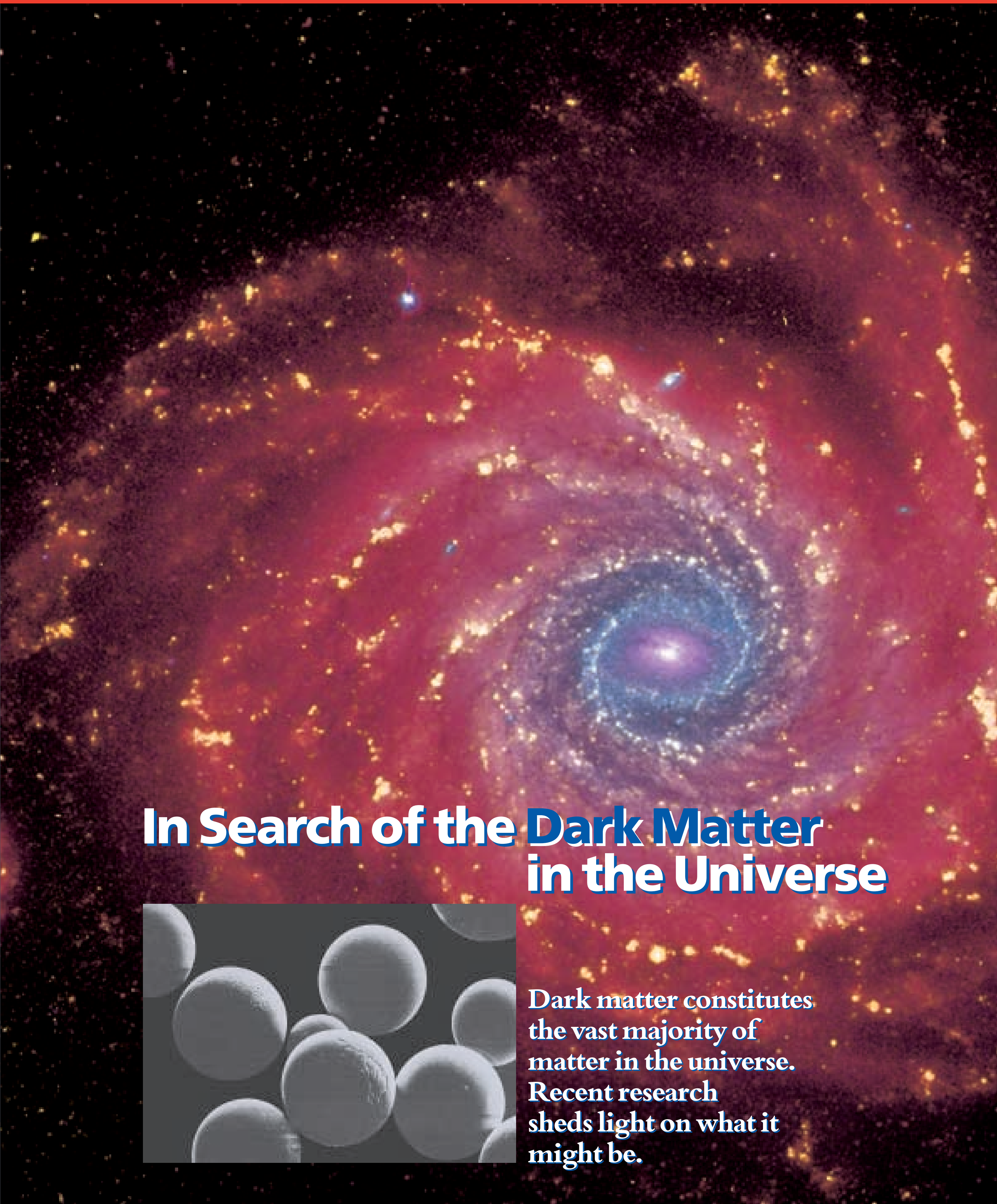

In Search of the Dark Matter in the Universe

Dark matter constitutes the vast majority of matter in the universe. Recent research sheds light on what it might be.