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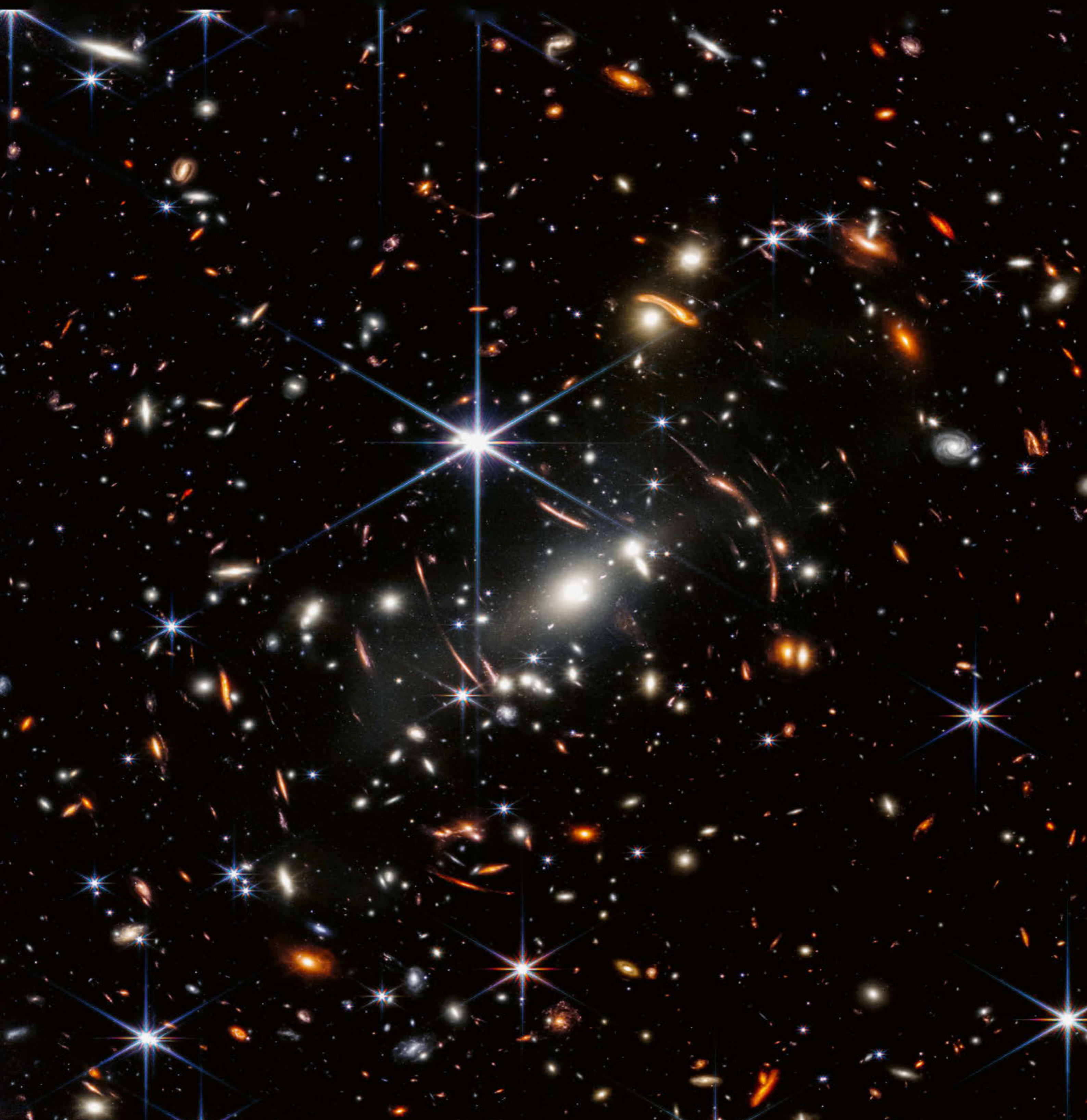
From the Present into the Past and Future - the Evolution of the Universe



Editorial

Cosmic history in the sense of the evolution of the Universe is a fascinating topic, and of course the cosmic future is similarly interesting. How has the world we are living in come to exist and how will it develop in future?

Naturally, the viewpoint for us as human beings is quite limited, the time and space scales in question are far from our imminent reach. With the techniques of today we have to find out about the far past and try to extrapolate to our best knowledge the possibilities of the future cosmic evolution.

Looking into space is looking back in time. Every telescope can be viewed as a time machine, and the further out it measures, the further back in time we can see. From plasma physics and elementary particle physics we have knowledge about the ratio of the earliest isotopes of hydrogen, deuterium and helium, having formed seconds to minutes after – after what…? After a singularity in space-time that can be considered the start of an evolution. This singularity, followed by a period of inflation, is called the "Big Bang". According to this model, our Universe started from a singularity, passed through a period of inflation and turned to accelerated expansion. It is the currently widely accepted model in cosmology.

The earliest images that we can receive are those of a time about 380 000 years after this point in space time, a time when photons could start to freely pass through space, and these photons we are still able to measure in the Cosmic Microwave Background. This ubiquitous cosmic radiation and its very faint spatial structure, the latter caused by temperature or density variations, also give hints to the expansion and the rate of expansion, the so-called Hubble constant (which is not really a constant, but only the current value of the expansion rate of the Universe). Another path to access the expansion rate leads via velocity and distance measurements, with special types of supernovae of known absolute brightness being used for extending the distance scale. The fate of the Universe is critically dependent on the action of gravity, acting against expansion. Will the Universe expand forever, will it stop and collapse in a "big crunch", or at a certain critical density asymptotically approach zero expansion rate and never collapse? The density is of course dependent on the total matter present in the Universe, including the dominating Dark Matter and Dark Energy – and although we have found "massive" evidence of its presence, we still have no real knowledge of the majority of the matter needed to sustain our Universe in its current manifestation. The search for Dark Matter and Dark Energy is still a very wide-open field. In a presentation for the Pro ISSI lecture series on 30 March 2022, Prof. Sabine Schindler summarised the current status of knowledge of our Universe's evolution. The material of the present issue of *Spatium* is based on this lecture.

The editor is grateful to Dr. Mark Sargent for careful reading of the manuscript.

Anuschka Pauluhn
Mönthal, December 2022

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Title Caption
The first scientific image by the James Webb Space Telescope that has been published shows the galaxy cluster SMACS 0723 as it appeared 4.6 billion years ago, with many more galaxies in front of and behind the cluster. The diffuse white objects are galaxies of the cluster. The elongated reddish objects are background galaxies, which appear distorted and magnified due to the gravitational lensing effect. The objects displaying spikes are nearby stars. This deep field, taken by Webb's Near-Infrared Camera (NIRCam), is a composite made from images at different wavelengths, totalling 12.5 hours – achieving depths at infrared wavelengths beyond the Hubble Space Telescope's deepest fields, which took weeks. Credit: NASA, ESA, CSA, and STScI.

From the Present into the Past and Future – the Evolution of the Universe

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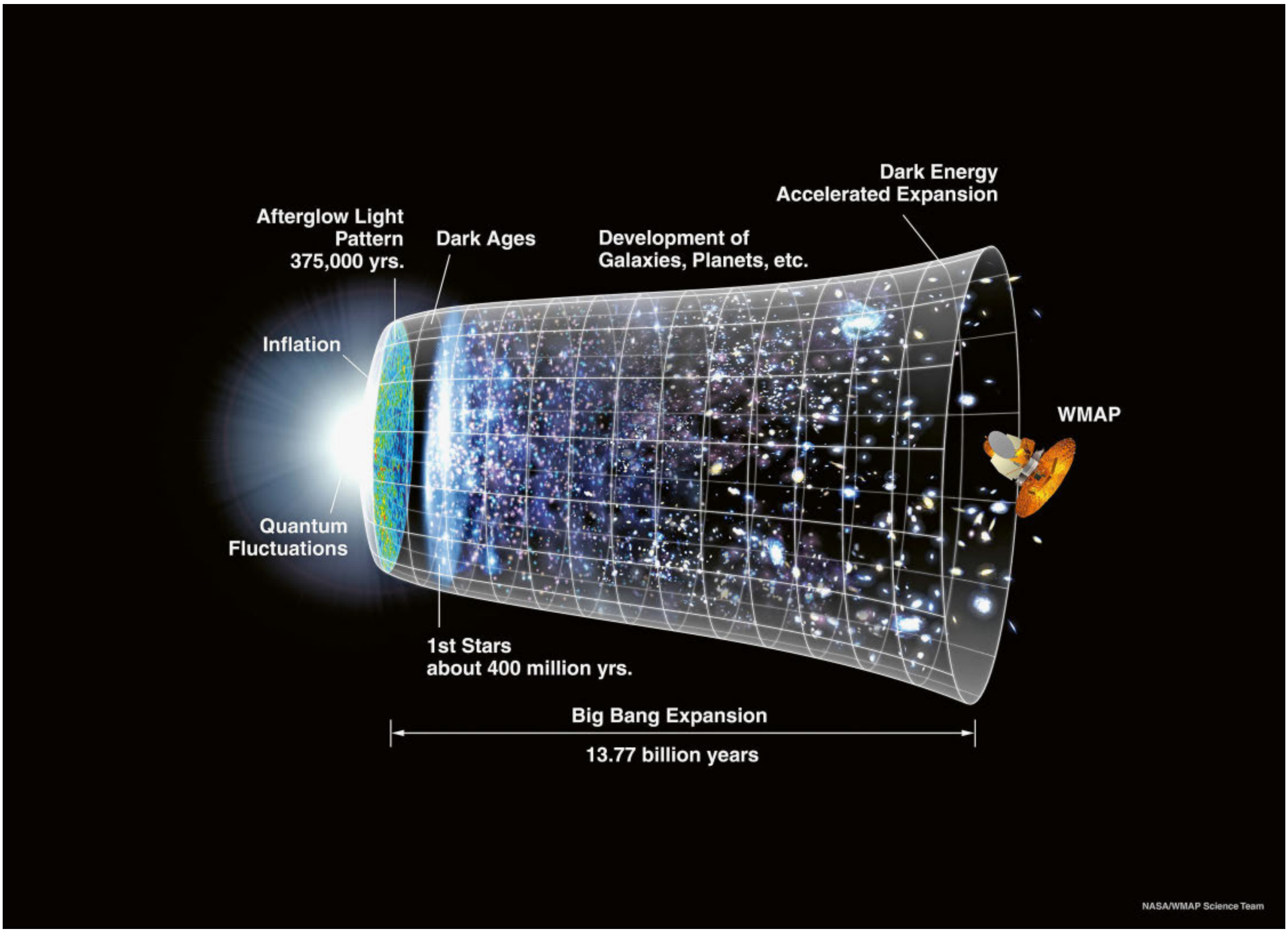
The Beginning of the Universe

For more than 13 billion years, the Universe has been expanding, after it formed in a so-called Big Bang. This is the commonly accepted model for the beginning and the evolution of the Universe, and it describes how it has developed from an initial state of extremely high density and temperature until now (**Figure 1**). With the expansion, its size increased and its temperature decreased. After about 300 000 years the Universe has cooled down sufficiently to allow the formation of the building blocks; from electrons and protons electrically neutral hydrogen atoms formed. With the elementary building blocks joined together, the Universe became transparent for the first time, and the radiation present at that time became apparent. Being then at a high temperature of about 3000 K, with expansion, the wavelength shifted from the visible and infrared to the millimetre range. This "stretched radiation" had been predicted by E. Regener already in 1933, and in the 1940s

Fig. 1: Illustration of the evolution of the Universe in the Big Bang model. (Credit: NASA/WMAP Science Team)



by G. Gamow and others. This is what can be observed now as the so-called Cosmic Microwave Background (CMB) radiation.[1] After even more cooling, stars and galaxies formed including planetary systems like the Solar System with the Earth. The Big Bang model provides a comprehensive explanation for a wide range of observed phenomena. Out of this multitude, four observations are presented here that speak convincingly for the Big Bang as a valid model.

Historically, the term "Big Bang" is ascribed to astronomer Fred Hoyle (1915–2001) who used it to distinguish this class of models from steady state models.[2] Although very catchy and figurative, it hardly conveys a correct "picture". Nevertheless, it might be just the right wording to describe something so abstract that it cannot be described nor visualised in any appropriate way. How to describe a singularity in time? Integrating Einstein's famous field equations backwards in time, at zero, one ends up with infinite density and all laws of physics as we know them, breaking down. Locating this "event" is even more impossible, for all objects move apart from each other in just the same way, and all find themselves at the centre and at rest. (The analogy of raisins in a rising dough used already in *Spatium* 3 by G.A. Tammann is very appealing.) It looks like the Big Bang has happened everywhere.

1. Cosmic Microwave Background Radiation

When the Universe was still hotter than about a few 1000 K, radiation was in constant exchange with matter. Photons hitting an atom were able to tear out an electron from the atom, a process called ionisation. Free electrons passing an ionised atom could be captured by the atom and this reverse process would emit a photon. Light and matter were in permanent interaction. However, with the cooling of the Universe the photons had less and less energy. At some point, they were not energetic enough anymore to detach electrons. As they were not able to interact with the atoms, they simply continued on their normal path through the Universe – and they are doing so until now. Thus, we still can detect these photons today. Due to the expansion of the Universe, their wavelength range has shifted to the microwave range of the spectrum. These photons reach us from all directions and they still carry the information on their last interaction with the atoms. Hence, they transmit the oldest picture of the Universe that we can get via photons.

In 1964, Arno Penzias and Robert Wilson detected this radiation for the first time, which convinced most astronomers of the Big Bang model. Of course, they were awarded the Nobel Prize for this discovery. The fundamentality of the CMB radiation was emphasised by the fact that the Nobel Prize was awarded for it even a second time – this time for the discovery of its anisotropy. **Figure 2** depicts measurements by the Planck satellite.

What does the anisotropy mean, and why is it so important? Anisotropy means that the CMB radiation is not exactly the same in all directions. The photons coming from some directions have slightly higher energies, meaning that the temperature there was slightly hotter than in other directions. This is an indication that the matter distribution at the time of the last interaction was not exactly homogeneous, but there were very small density differences, which are called density fluctuations. Assuming a completely homogeneous matter distribution, all gravita-

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[1] The prefix "micro-" in the Term Cosmic Microwave Background does not imply wavelength in the micrometre range (10^{-6} m), but electromagnetic radiation from metre to millimetre range, corresponding to radio frequencies between 300 MHz and 300 GHz, respectively. The CMB is strongest between 50 GHz and 500 GHz.

[2] A steady state model assumes the "perfect" cosmological principle, isotropy and homogeneity of the entire spatial mass distribution. The density of matter would stay constant in an expanding Universe due to continuous creation of matter. Detection of bright radio sources only at large distance or the fluctuations in the CMB have rendered these models improbable. Although having no objections against an expanding Universe, Fred Hoyle preferred steady state models, as he did not believe in a "beginning".

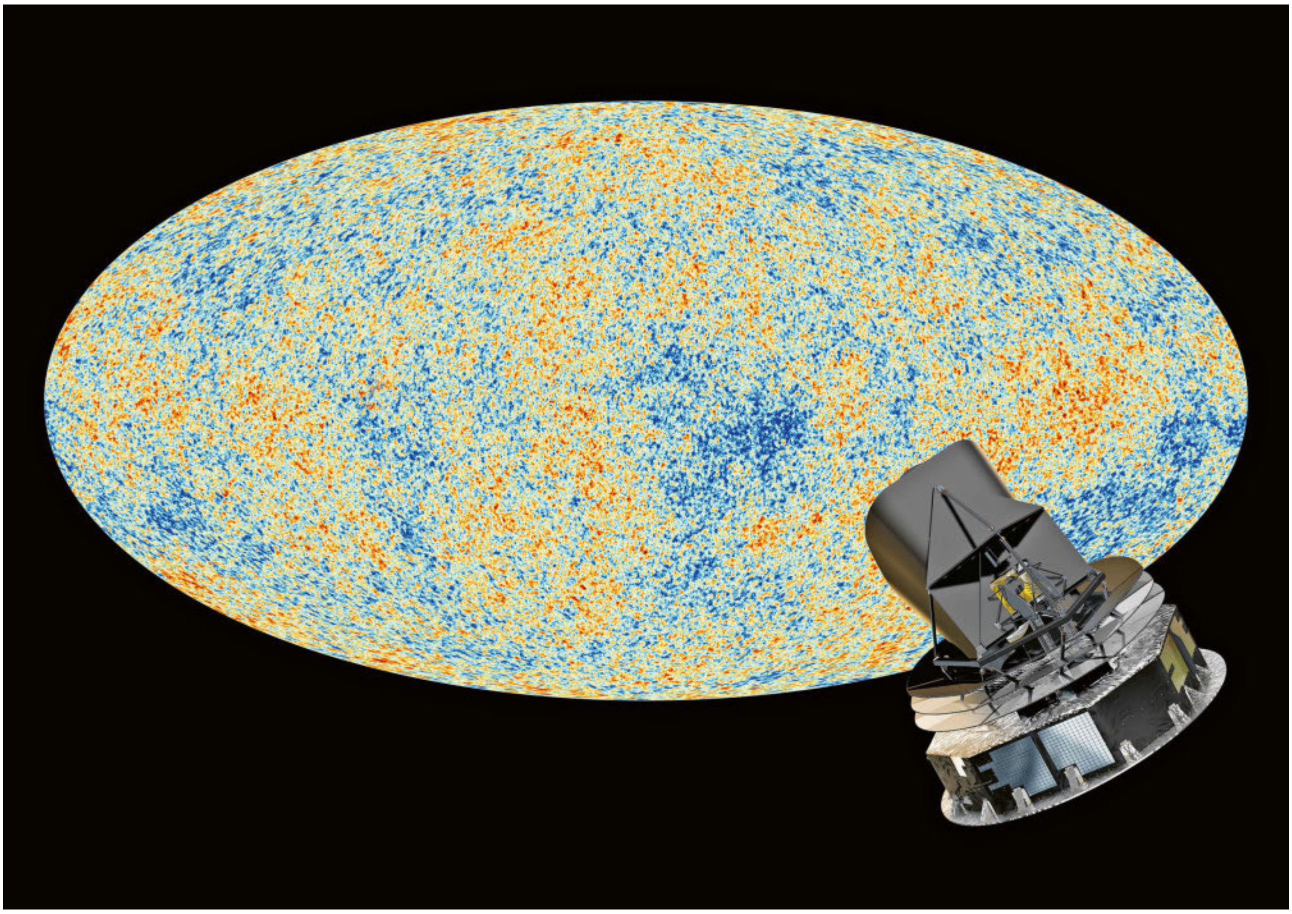


Fig. 2: The CMB radiation as observed by the Planck Satellite, which is shown in the foreground. The complete sky is projected here in a similar way as the Earth is projected onto a plane. Fluctuations in temperature, on the order of 10^{-5}, (shown in colour) indicate that there were density fluctuations in the early Universe. (Credit: ESA and the Planck Collaboration, D. Ducros)

tional forces cancel each other and there are no remaining forces, consequently neither movement nor change. Therefore, a completely homogeneous matter distribution would always remain the same homogeneous matter distribution. However, this is not at all, what is observed today. The detection of the anisotropies was such an important proof of the model that the Nobel Prize was awarded to George Smoot and John Mather in 2006 for it. What can be measured today are indeed large density contrasts in the large-scale structure of the Universe (see **Figure 3**). These are the next important observation that needs to be mentioned.

2. Large-Scale Structure

Galaxies can be observed out to large distances, and they can be observed in all directions, tracing the large-scale structure of the Universe. We find regions with high galaxy density (clusters of galaxies with hundreds and thousands of galaxies, and filaments between them) and regions with low galaxy density (so-called voids). Obviously, matter is not distributed homogeneously in the Universe; instead, there are huge density variations.

These large variations in density can be explained in a universe that has started out with tiny density fluctuations (just as observed in the

CMB radiation[3]) and gravity working over the age of the Universe. In regions with just a little bit more matter than in the surroundings, there is a small gravitational attraction. This attraction causes matter to move towards these regions, which in turn contain even more matter after a while. The opposite happens to regions, which are slightly underdense at the beginning. Matter is withdrawn from there. They end up at being almost empty – the voids. Therefore this process, and with it the density contrast, is becoming stronger and stronger with time. In numerical simulations based on the Big Bang model (with the correct initial conditions), one finds the same large-scale structure as in observations. This is another indication that the Big Bang model describes the Universe well.

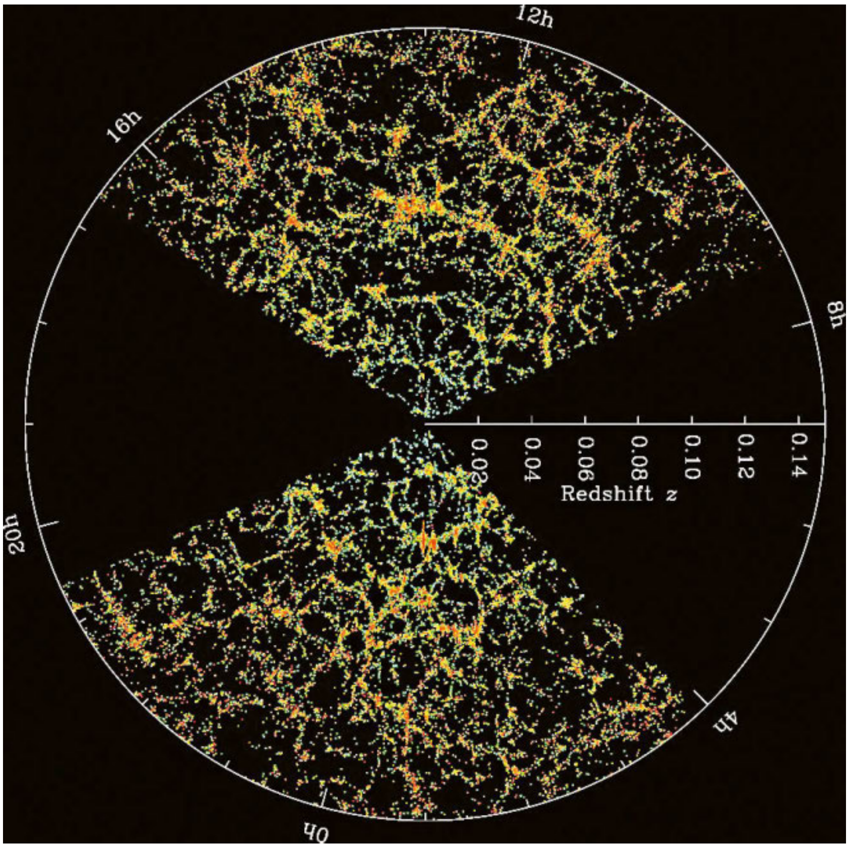


Fig. 3: The galaxy distribution as observed by the Sloan Digitized Sky Survey (SDSS). Each dot is a galaxy – the redder the region, the higher the galaxy density. It is obvious that the large-scale structure traced by galaxies is very inhomogeneous, with voids, filaments and clusters of galaxies at the meeting points of the filaments. Only two sectors are observed in directions perpendicular to the disc of the Milky Way, in order to avoid too much contamination by Milky Way stars. (Credit: M. Blanton and SDSS)

3. Synthesis of Elements in the Early Universe

After having had a look at two very different observations – the radiation from the very early Universe and the galaxy distribution on large scales –, we are considering now a third, again very different, quantity: the elements that have formed during the Big Bang. Elements can only form under special conditions with high energies and high densities. Nowadays, elements are formed inside stars and during supernova explosions. In the early Universe, the conditions were such that the formation of elements, the so-called primordial nucleosynthesis, took place everywhere. However, the nucleosynthesis did not proceed very far. The synthesis begins with the lightest atomic nucleus – the hydrogen nucleus, which is actually simply a proton. Starting from this nucleus, it is easy to produce helium with relatively simple reactions. The protons can react with each other to form a nucleus with two nucleons, which in turn can react with

[3] The density variation in the CMB itself, however, reflects the variations of density of the baryonic matter (i.e., matter as we know it), and can only explain part of the observed density structure today. A significantly larger fraction of today's structure must be due to Dark Matter perturbations (see next chapter), that had already grown to 10 to 100 times the amplitude of the baryonic density fluctuation at that time.

another proton. Through further reactions, very stable helium nuclei are formed consisting of four nucleons. To move on to heavier elements, the required reactions are more complicated. A simple combination of two helium nuclei or one helium nucleus and one hydrogen nucleus does not lead to a stable nucleus. Therefore, the nuclei with more than four nucleons have a much lower probability to be formed, i.e., hardly any heavier element than helium has been formed in the early Universe.

With all the knowledge that we have from plasma physics and from nuclear physics one can calculate – assuming the Big Bang model – the ratio between helium and hydrogen. Similarly, the ratio between hydrogen and the other low-abundance elements can be inferred (see **Figure 4**). In order to compare the results of these calculations with the real Universe, one requires observations of the abundances in regions of the Universe that have not been contaminated by stellar nucleosynthesis products. As in stars, many elements are produced and dispersed into space by supernova explosions, they would distort the result. If these regions are strictly avoided in the observations, one indeed finds the element abundances as predicted by the Big Bang model: 75% hydrogen and 25% helium. This is a third, very strong indication that the Big Bang model is actually a good model.

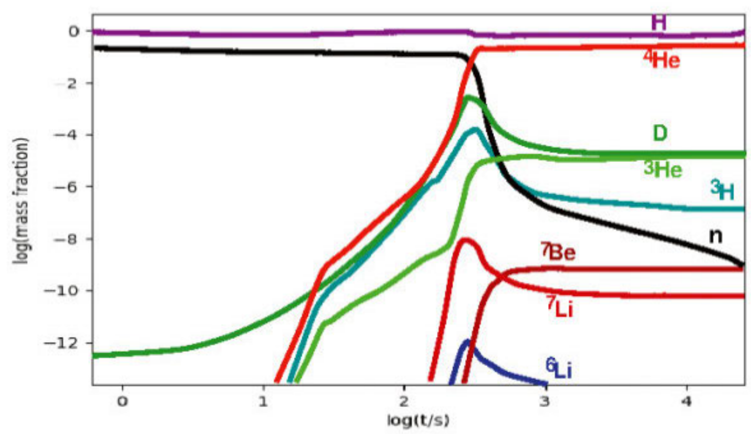


Fig. 4: The calculated mass fractions (abundances relative to hydrogen) of various isotopes are shown versus time. At the beginning, the isotopes are dominated by hydrogen with some neutrons being present. The reactions take place mainly in the interval between 100 and 1000 seconds after the Big Bang.
After 1000 seconds, there is mainly hydrogen and helium left. Of all the other nuclei only traces are formed. Note the logarithmic scale on both axes!

4. Expansion of the Universe

The discovery of the expansion of the Universe of course provided another strong indicator for the Big Bang model. The earliest evidence for expansion was already found one hundred years ago, based on a relatively simple measurement. Vesto Slipher, Edwin Hubble, Henrietta Leavitt and others measured the distances and the motion of galaxies. They used the well-known Doppler effect that is known from a passing ambulance: you hear a change in the sound pitch, when the ambulance is passing, because there is a change in the frequency of the sound that is arriving at your ear. The Doppler effect does not only exist in sound but also in light. Therefore, we can measure the velocity of galaxies by measuring their spectral distribution and find shifts in the spectral lines. In this way, it was discovered that almost all galaxies are moving away from us – the farther away the galaxies are, the faster they recede from us. Their recession speed is proportional to their distance – the so-called Hubble's law. This is true for every position in the Universe, as it is expanding everywhere in the same way.

Edwin Hubble created the famous Hubble diagram by plotting the distance versus the velocity of the galaxies. The straight line fitted through the data points, the slope, yields the so-called Hubble constant. Many researchers tried to determine the Hubble constant over the course of decades, because this is what is required to measure distances of cosmological objects.

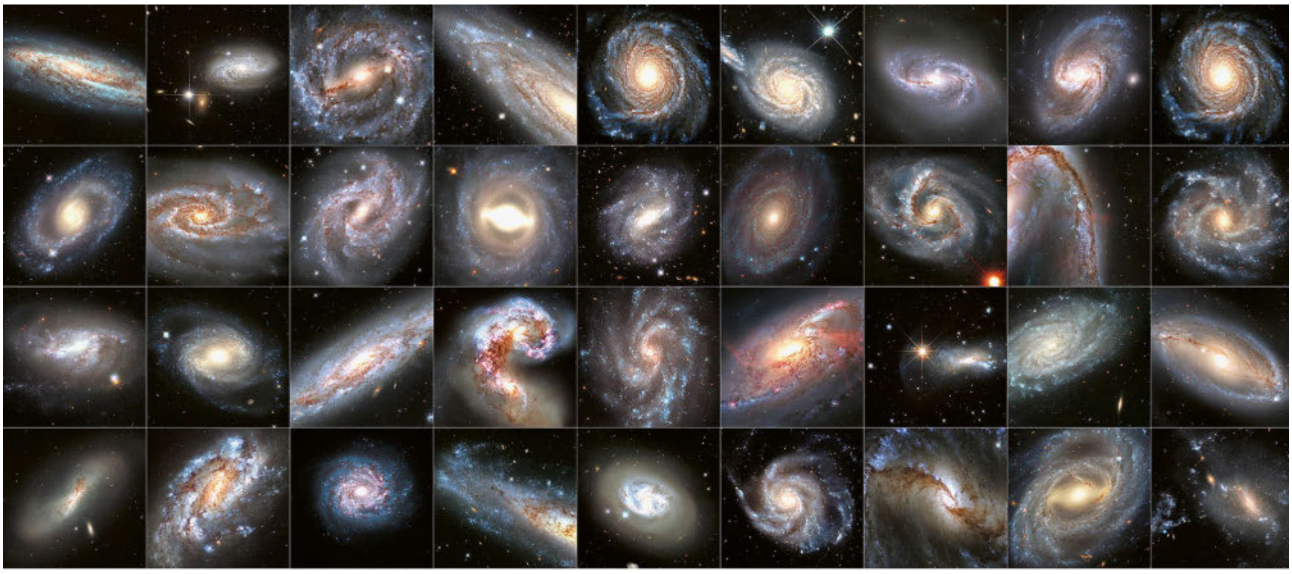


Fig. 5: This collection of images from the Hubble Space Telescope features 36 galaxies that are all host to Cepheid variables as well as supernovae (cf. Riess et al. 2022). Both are crucial tools used to calibrate the astronomical distance ladder, and have been used to refine measurements of the expansion rate of the Universe. (Credit: NASA, ESA, Adam G. Riess)

However, the measurement of this slope is not easy. While it is simple to determine the velocity via the Doppler effect, the determination of the distance is difficult. For a long time the results were disagreeing, with differences in the value of the Hubble constant of up to a factor of two. Gradually the results approached a common value only to disagree again recently (see, e.g., *Spatium* 47). **Figure 5** shows 36 galaxies that have been included in recent studies of the "cosmic distance ladder".

The differences are much smaller than before (less than 10%); however, the measurement precision is so much higher now that the results do not agree within the uncertainties of each of the methods. In particular, values that are obtained by methods starting from nearby distances yield higher values than methods that use the CMB radiation. It is speculated that these discrepancies could point to some imperfection of the model – maybe "new physics".[4]

Summarising, all these measurements of the expansion support the Big Bang model, and consequently this is the model commonly accepted by cosmologists. **Figure 6** presents the time line of the cosmic evolution according to the currently agreed-on theory.

[4] While the data from the Planck cooperation suggest values around 67.5 km/s/Mpc for H_0, the present Hubble parameter, measurements using combinations of Cepheid variables and SN1a measurements yield higher values of around 73.3 km/s/Mpc. Thus, currently there is a 5 σ difference between direct and cosmological routes to determining H_0.

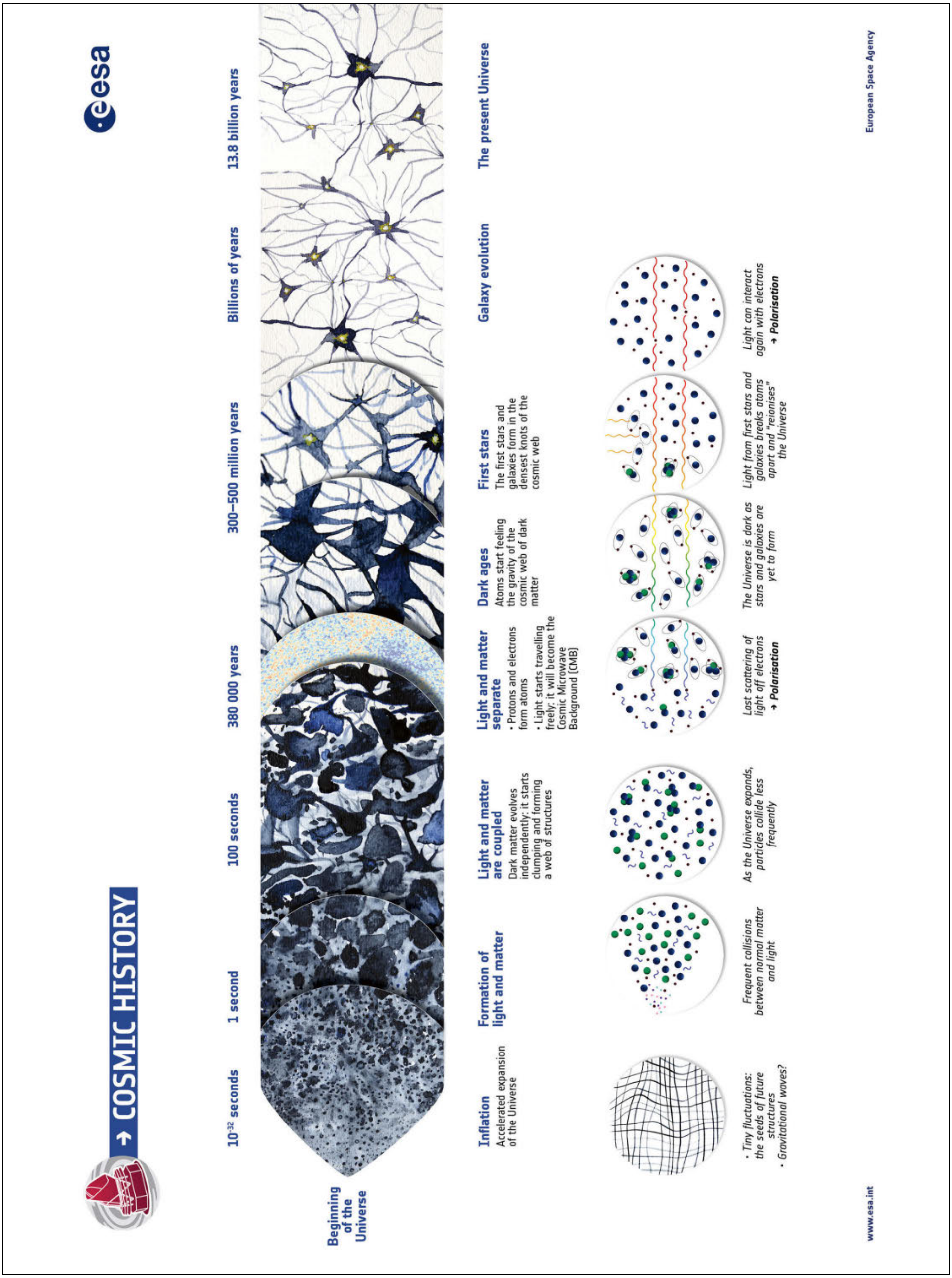


Fig. 6: The time line of the evolution of light and matter – the "cosmic history". (Credit: ESA)

The Future of the Universe

After having looked at the past of the Universe, we try now to find out something about its future. The future expansion is determined by the amount of attractive and repulsive components in the Universe. Gravity is acting on all types of matter in an attractive way. Therefore, the amount of matter in the Universe plays an important role. In **Figure 7**, the effects of various matter densities Ω_m on the mean distance between galaxies are shown. All curves meet at the current expansion rate shown as "today", because this is the expansion rate that we currently measure.

In a universe with density $\Omega_m = 1$ (the so-called critical density, shown as blue line) the expansion would become slower and slower and eventually it would come to a hold. With higher matter densities, the gravitational attraction would be stronger, resulting in a lower expansion rate that would even turn around at some point. In this model, the Universe would eventually collapse in a "big crunch" (purple line). In a universe with a matter density Ω_m less than the critical density the expansion would slow down, and the expansion would continue forever (green line). When repulsive components are considered, the expansion rate would even increase with time resulting in an accelerated expansion (red line).

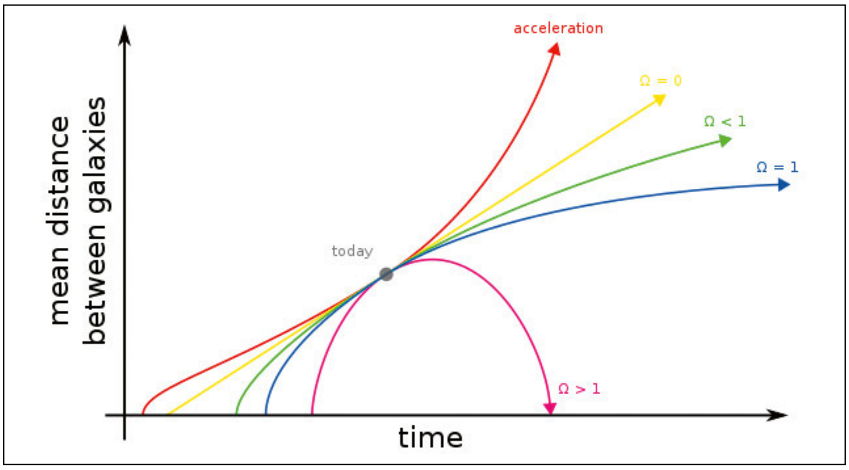


Fig. 7: Evolution of the distance between galaxies in model universes with various densities (Ω) and Dark Energy effects. (Source: Wikipedia, public domain)

The question is now, which of these models is the correct model of our Universe. Unfortunately, we cannot look into the future – not even with the largest telescopes. Nevertheless, we can look into the past, because the speed of light is finite. Light that has been emitted from distant galaxies is reaching us after millions and billions of years, so that we can see these distant objects now as they have been in the early Universe. That means it is possible to make measurements to the left of the "today" marker in the diagramme. When we can determine, with measurements of the past, which of the curves represents our Universe best, we can follow the curve to the right and infer how the Universe will evolve in the future.

If we would make measurements too close to "today", that means measuring only nearby objects, we would not be able to distinguish between the curves, because they are too close together. Hence, no useful prediction for the future could be made. Therefore, we need to observe objects that are very far away.

As mentioned before, the distance measurements of far-away objects are not easy. Various sophisticated methods have been developed to measure distances. One of the methods uses the concept of "standard candles". Imagine you are standing on a road in the dark and you see an approaching light. It could be the headlamp of a bicycle or the headlamp of a motorbike. If you know what kind of vehicle it is, you know by experience how bright the headlamp is, and from the light you see, you can estimate the distance. This principle is used in cosmology. Of course, you first need to know how bright the object of your choice is intrinsically. Thus, this method requires objects that all have the same known intrinsic brightness. Secondly, you need objects that are very bright so that you can see them out to very large distances in order to look back into the distant past.

When Edwin Hubble determined distances, he used variable stars. There is a type of variable stars called Cepheids that have a well-determined period-luminosity relation.[5] With an easily measurable period, one can infer the luminosity. Unfortunately, most stars do not emit a lot of radiation, so that they are visible only at short distances.

For cosmological purposes, objects that are more luminous have to be used. The objects of choice are so-called supernovae type Ia. These particular supernova (SN) explosions are not caused by a single star at the end of its life. Single stars can have various masses so that the explosions result in different of brightness, which makes them useless objects for this purpose. However, a supernova Ia is caused by a binary system consisting of a white dwarf and a red giant. A simplified description of a SN type Ia is the following: the red giant is expanding so that matter is flowing from the red giant to the white dwarf. Hence, the white dwarf is getting more and more massive, and at some point, it is so massive, that it is not stable anymore and explodes as a supernova Ia. The stability limit is reached when the white dwarf has a mass of 1.4 solar masses. Consequently, it is always the same mass that is exploding. Therefore, the explosion always develops in the same way, has always the same luminosity and can be used as a standard candle.[6]

With this method, two groups have measured the expansion rate of the Universe in the 1990s. They found that the Universe has an accelerated expansion (corresponding to the red curve in **Figure 6**). For this discovery, the Nobel Prize in Physics 2011 was awarded to Saul Perlmutter, Brian P. Schmidt and Adam G. Riess "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae". It is remarkable that it is possible to obtain cosmological results – results on the Universe as a whole – by using the knowledge of explosions of relative small objects like stars. This is a fascinating example of sophisticated methods that are used in astronomy.

1. What Matters?

So far, we can identify two parameters, which determine the expansion of the Universe. The first parameter is matter. Matter is acting in an attractive way due to gravity. The second parameter manifests itself as a repellent component. This component has been called Dark Energy. It is responsible for the accelerated expansion. If one wants to know the future of the Universe, it is necessary to measure, how much of these two components is present in the Universe. In the following, some methods are described to determine the amount of these two components.

2. Dark Matter

When looking at objects like galaxies or clusters of galaxies, one finds that their constituents have quite high velocities. The stars in galaxies are moving either in circular orbits in a plane (in spiral galaxies) or they are just moving around uncoordinatedly (in elliptical galaxies), but always at high speed. Galaxy clusters are accumulations of thousands of galaxies. They have masses of around 10^{15} solar masses and diameters of several millions of light-years. This makes them the largest bound objects in the Universe. The galaxies in the clusters are moving around uncoordinatedly with velocities of about 1000 km/s. It was suspected already a long time ago, that there is not only luminous matter in these objects but also some other kind of matter providing enough gravity in order to keep them as bound objects. If there was only

5 In 1908, Henrietta Swan Leavitt identified a direct and linear relationship between the luminosity of Cepheid variable stars and the logarithm of their pulsation period.

6 Of course, not all SNe Ia have exactly the same luminosity, as the white dwarfs have slightly different element compositions. Furthermore, not all the emitted light reaches our telescopes, because some fraction of the light is scattered by dust and gas on the way to us. These and various other effects have to be taken into account and calibrated for.

the luminous matter, the constituents would disperse quickly due to their large velocities, and quickly there would be no more galaxies or galaxy clusters left in the Universe. Actually, there has to be a lot more of the so-called Dark Matter in the Universe than luminous matter to hold the constituents together. As Dark Matter is obviously such an important component, several independent methods have been developed to determine the amount of Dark Matter in galaxy clusters. Three of them are shown here.

The first method used was the measurement of the velocity of galaxies in clusters. This method uses the above-mentioned Doppler effect. This effect is easy to measure, and Fritz Zwicky already applied it as early as 1933. He concluded that there is not enough luminous mass in the member galaxies to account for the total mass of the galaxy cluster. He termed it then "the missing mass problem" – describing the same portion of mass that we nowadays call Dark Matter.

In a second method, X-ray observations are used. The space between the galaxies in a cluster is filled with hot gas (10^7 °C to 10^8 °C). The temperatures are so high that the gas is not emitting in visible wavelengths but in X-ray wavelengths. The reason for the gas being so hot is that it has fallen into the deep potential well of the galaxy cluster. During this process, the gas has gained a lot of energy, which results in an increase of temperature. This hot gas traces the size and the depth of the potential well, hence the mass and the mass distribution of the cluster. By measuring the gas density and the gas temperature distribution, one can infer the mass distribution. Therefore, a combination of an X-ray image and an X-ray spectrum is used for these kind of mass determinations. As X-rays are absorbed by the Earth's atmosphere, X-ray telescopes have to be placed on satellites. In **Figure 8** a combination of an optical image and an X-ray image of the Coma cluster, taken by the X-ray satellite XMM-Newton, is shown.

A third method involves the gravitational lensing effect (see for example *Spatium* 32). Analogue to optical glass lenses, also mass distributions influence the light path. This is an effect of general relativity and was predicted already by Albert Einstein. The gravitational lensing effect causes light coming from distant galaxies to be bent by the mass of a foreground galaxy cluster. In this way, we can observe magnified, distorted images of these distant galaxies. As the bending angle depends on the mass of the cluster, it can be used as a measure for the mass. If the elongated images of a few very prominent background galaxies are used, the method is called "strong lensing". The lensed elongated background galaxies seen in the cluster SMACS 0723 in the first published James Webb Space Telescope (JWST) image (which is shown on the title page of this issue) are wonderful

Fig. 8: Overlay of an optical image (galaxies) and an X-ray image (colours) of the Coma cluster of galaxies obtained with XMM-Newton. The X-ray emission of the hot gas is shown in false colours (red corresponds to higher intensity of X-ray emission, blue to lower intensity). (Credit: ESA)

examples for this strong lensing. In addition to the mass of the cluster, other features can be studied, e.g., the structure and the properties of the background galaxies can be investigated in detail.

Another way to use gravitational lensing for cluster mass determination is the so-called weak lensing. All the distortions of the background galaxies are used – even if they are very small. From these distortions, the mass distribution and the mass of the foreground cluster are inferred.

The results obtained by all three methods agree quite well: there is much more Dark Matter in a cluster than ordinary luminous matter – about four times more. As clusters are huge objects, that have collected matter from volumes of millions of light-years across, they can be regarded as being representative for the entire Universe. Therefore, the clusters are considered to have the same ratio of Dark Matter to luminous matter as the Universe as a whole.

So far, it is not clear what Dark Matter is made of. It is certainly not present as big objects, but it is rather made of elementary particles. However, none of the elementary particles that we know so far are useful candidates. Currently, several experiments are actively trying to measure new candidate particles for Dark Matter.

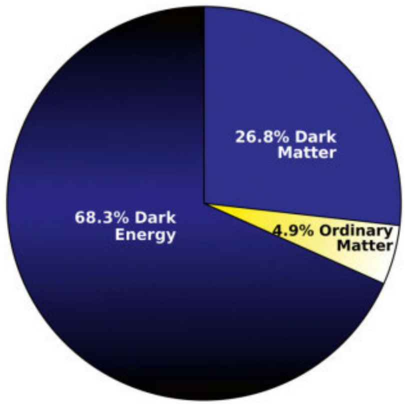
Although there is so much Dark Matter present, in total (as sum of luminous and Dark Matter) there is still not enough matter in the Universe to turn around the expansion. There is only about 30% of the matter present that would be required to finally stop the expansion. We call this matter density $\Omega_m = 0.3$.

3. Dark Energy

Already Albert Einstein introduced a term in his field equations of the Universe that has a repelling effect – the so-called cosmological constant, often denoted by Λ. He introduced it in order to compensate for the attracting effect of gravity, because, at the time Einstein wrote the equations, the Universe was assumed static. Later, when the expansion of the Universe was discovered, he called the cosmological constant his "greatest blunder". The constant was assumed zero for several decades. Unfortunately, Einstein did not live to see that it was not a blunder, but that we have now a similar concept, that we do not call cosmological constant but Dark Energy – as it was coined by Michael Turner in 1998. Dark Energy is assumed a component in the Universe that has a repellent effect.

Since the supernova observations in the 1990s, the results of an accelerated expansion have been confirmed by several independent measurements, for example by measurements of large-scale structure as traced by galaxies and galaxy clusters. Still, the nature of the Dark Energy is not known so far. Several experiments are currently going on to study Dark Matter in more detail, e.g., measurements of large-scale wave patterns of the mass density in the Universe[7]. In particular, an ESA space mission named Euclid is planned to be launched in 2023, which will explore the evolution of the dark Universe. It will construct a three-dimensional map of the Universe (with time as the third dimension) by observing billions of galaxies out to ten billion light-years, across

Fig. 9: Diagramme of the composition of the Universe. The smallest sector is visible, ordinary matter – the matter that our surroundings and we are made of. There is a lot more Dark Matter than visible matter in the Universe, but the largest sector is the one of Dark Energy. (Source: Wikipedia, public domain)



[7] In technical terms, these large-scale fluctuation patterns are called Baryon Acoustic Oscillations (BAO).

more than a third of the sky. In this way, Euclid will reveal how the Universe has expanded and how structure has formed over cosmic history.

The structure in the CMB radiation suggests that the sum of the densities of (dark and visible) matter and Dark Energy is unity. As mentioned above, the total matter density constitutes about 30%, which leaves about 70% for Dark Energy density Ω_Λ (see **Figure 9**). The picture of the composition of the Universe is thus a diagramme with a very small sector for visible matter, a larger sector for Dark Matter, and an even larger sector for Dark Energy.

Outlook — JWST and Beyond

We are living in exciting times. Not only have we witnessed the discovery of new features of the Universe in the last years, but also there are more discoveries to be expected in the near future. In the past, every jump in technology brought surprises and unexpected findings. There are now several large telescopes that have just been launched, are under construction or are being planned, together with new technology and improved detectors.

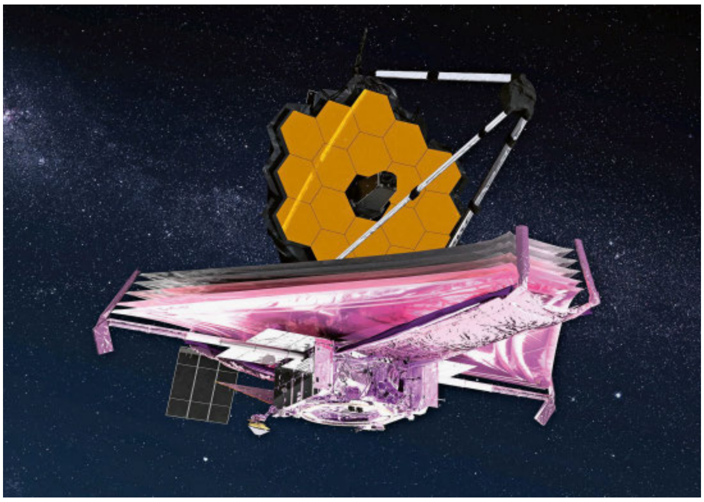
Examples of great new facilities are ground-based telescopes like the Extremely Large Telescope (ELT, see **Figure 10**) or the Square Kilometer Array (SKA) in radio wavelengths. Many new results are also expected from new space-based telescopes like, e.g., the James Webb Space Telescope (JWST) that has been launched in December 2021, shown in **Figure 11,** from Euclid and from new X-ray telescopes. Finally, yet importantly, gravitational wave detectors in space will provide very interesting data from this new window to the Universe.

These telescopes will surely lead to observations that are even more spectacular. For example first comparisons of data from JWST with corresponding ones from earlier missions give an impression on how the resolution has improved, see **Figures 12** and **13.**

The measurements of these new instruments will very likely solve many of the current questions – and will probably raise completely

Fig. 10: An artistic rendering of how the Extremely Large Telescope (ELT) will look like on top of Cerro Armazones. (Credit: ESO)

Fig. 11: An artistic rendering of the James Webb Space Telescope (JWST) that has been launched in December 2021. (Credit: NASA/Goddard Space Flight Center/CIL/Adriana Manrique Gutierrez)



new ones. Let us see, whether the Big Bang model, the concept of Dark Matter and Dark Energy, and the models for the formation of galaxies and the large-scale structure will stay as they are now or whether they have to be refined in the future.

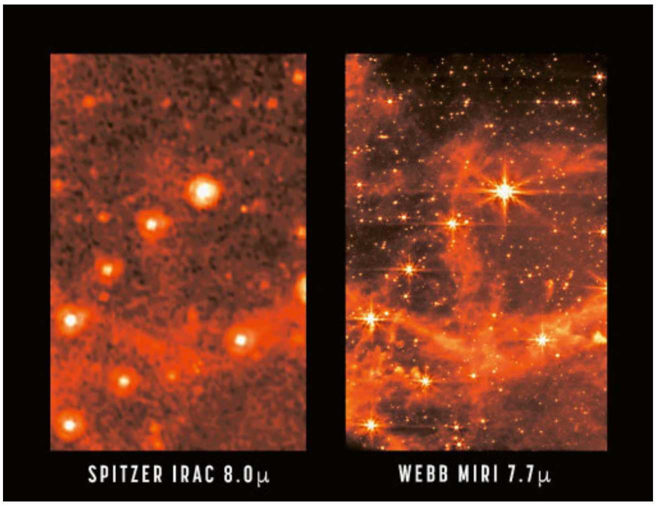


Fig. 12: Comparison of IR images of a part of the Magellanic Cloud.
(Credit: Spitzer: NASA/JPL-Caltech; MIRI: NASA/ESA/CSA/STScI)

Fig. 13: Comparison of Hubble and JWST images of the so-called Pillars of Creation, a star-forming region in the Eagle Nebula, 6 500 light-years away. It shows newly formed stars near columns of gas and dust. Left-hand side: Hubble's view in visible light (2014), right-hand side: JWST's new near-infrared view (2022).
(Credit: NASA/ESA/CSA/STScI)

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Web resources

The ISSI Game Changer Online Seminar Series on Cosmology: https://www.issibern.ch/publications/game-changers-seminars/

Information on the James Webb Space Telescope: https://webb.nasa.gov/

SPATIUM

The Author

Prof. Dr. Sabine Schindler studied physics at the University Erlangen-Nürnberg. In 1992, she obtained her PhD from the Ludwig Maximilians University Munich and the Max Planck Institutes for Astrophysics and for Extraterrestrial Physics Garching. From 1992 to 1993, she was a postdoc at the University of California in Santa Cruz with a Feodor Lynen Research Fellowship of the Alexander von Humboldt Society. In the following years, she worked at the Max Planck Institutes for Astrophysics and for Extraterrestrial Physics Garching. From 1998 to 2002, she was staff scientist at the Astrophysics Research Institute, Liverpool John Moores University.

Since 2002, Prof. Schindler is full professor at the University of Innsbruck. From 2004 to 2012, she served as head of the Institute for Astro- and Particle Physics in Innsbruck, and from 2012 to 2017 she was Vice President for Research at the University of Innsbruck. From 2014 to 2020, she was President of the private University for Health Sciences, Medical Computer Sciences and Technology in Hall. In 2020, she was awarded with the Johannes Geiss Fellowship of the International Space Science Institute in Bern.

Her first years in Innsbruck were characterised by her efforts as figurehead for the accession of Austria to ESO, which finally succeeded in 2009. Subsequently, Prof. Schindler was member of the ESO Council. At the University of Innsbruck, she was the head of the interdisciplinary university focal point Scientific Computing. Furthermore, she was member of the executive committees of the European Astronomical Society, the Austrian Society for Astronomy and Astrophysics and the Austrian Private University Council as well as of evaluation commissions of institutes in many countries. She has always conducted various activities to support and encourage women in science. Prof. Schindler is elected member of the Austrian Academy of Sciences and the International Academy of Astronautics, and she was awarded with the Tyrolean Eagle Medal in Gold for her merits in science and research.

Her research is centred around clusters of galaxies – studying their evolution, physical processes, their use for cosmology, interaction of constituents and their masses.