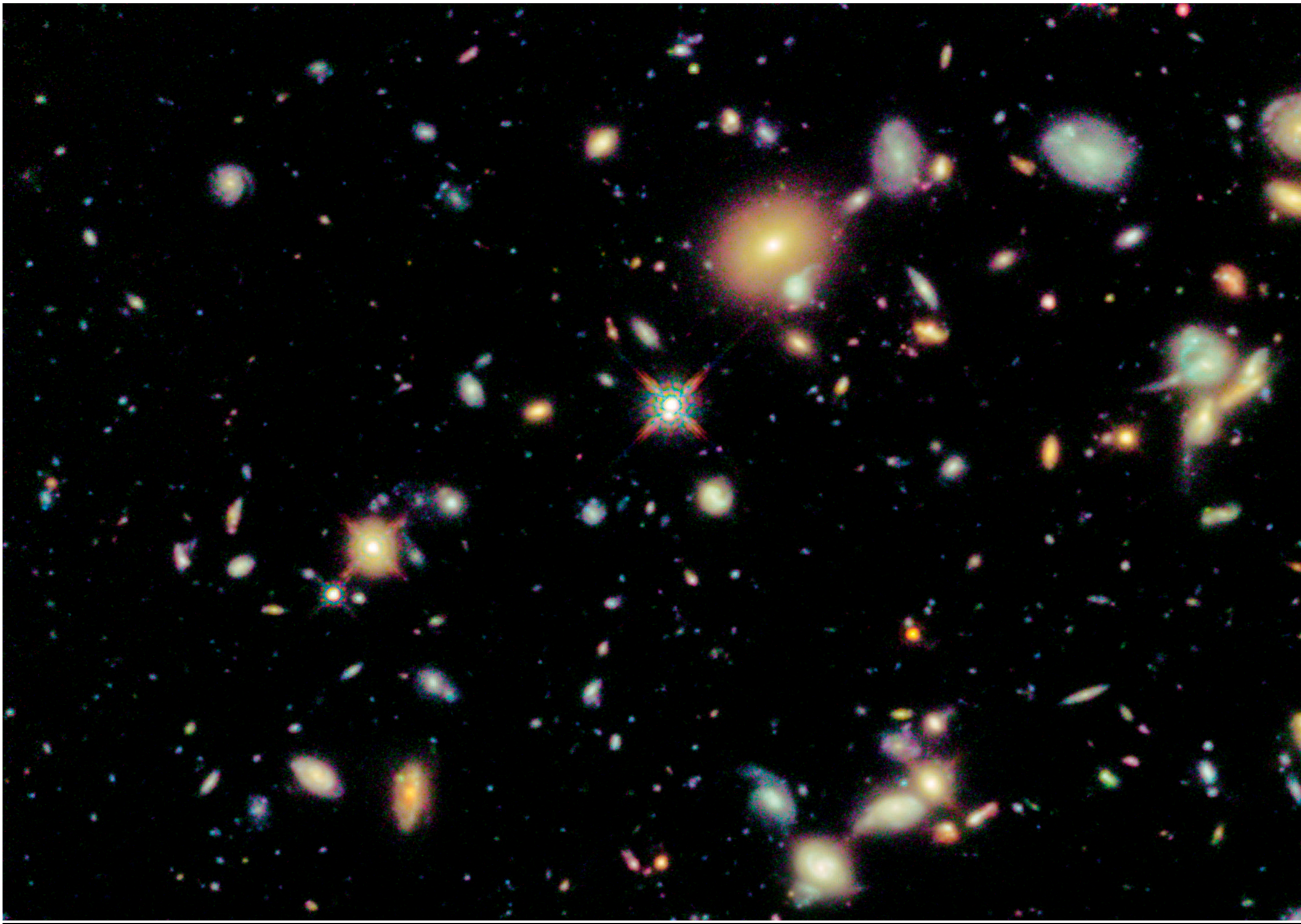


Star Factories
at the End of the World

When the universe came into being 13.7 billion years ago, there was initially only radiation. A few hundred million years later, however, the space was filled with galaxies – tremendously productive star factories that don't fit quite so well with the image of a gradual cosmic evolution. Researchers like **Fabian Walter** from the **Max Planck Institute for Astronomy** in Heidelberg are attempting to illuminate a dark epoch of the universe.

TEXT **ALEXANDER STIRN**

A deeper view into the cosmos: This section from the *Hubble Ultra Deep Field* shows the galaxies at the edge of space and time. Huge numbers of stars are born in these young Milky Ways.

Photo: NASA, ESA, R. Ellis (Caltech) and the HUDF 2012 Team

Finding catchy designations for incomprehensible processes has never been a problem for astronomers: They call the era that begins just 380,000 years after the birth of the universe the Dark Ages. At that time, the positively charged ions emerging from the Big Bang set about catching the free electrons buzzing around – and the afterglow of the Big Bang fades. However, no stars that could bring light to the sudden darkness had formed yet.

This distant age isn't only a dark period cosmologically; science, too, has had a difficult time illuminating the processes of that time. There are hardly any observations surrounding the birth of the first stars. Researchers must thus rely on simulations and theoretical ideas. But this is slowly changing: "Because our telescopes are continually improving and becoming more sensitive, we see things today that we couldn't have observed ten years ago," says Fabian Walter, an astronomer at the Max Planck Institute for Astronomy in Heidelberg. There, the 41-year-old investigates how and when the first stars emerged, how productive the early galaxies were, and where exactly the stellar nurseries were located.

Time and time again throughout this process, he and his co-theoreticians have encountered unforeseen problems – and will probably continue to do so. "The study of galaxies in the early phase of the universe will develop into a main area of research for astronomers in the coming years," says Walter. It's still detective work – a laborious search that has practically nothing to do with the colorful photos that astronomy otherwise produces. Many of these typical, vivid photographs are hanging in the stairwell of the Heidelberg-based institute, a concrete structure located on the Königstuhl promontory high above the city. They show planetary nebulae, star clusters and spiral galaxies. In between all these stellar images hangs an unspectacular photograph, mostly black with many pixelated dabs of color. *Hubble Ultra Deep Field* is written below.

It is a view into the deepest depths of space. For many hundreds of hours, the *Hubble Space Telescope* directed its eyes to a region of the sky that would be only one square millimeter in size

> Especially molecular hydrogen is necessary for a star to be born. However, hydrogen can't be directly observed.

on a thumbnail at arm's length. Extremely old objects, themselves glowing extremely weakly, can still be made out on it. "Many of these galactic images are made up of only a couple hundred photons," says Walter and points to a reddish, shimmering spot.

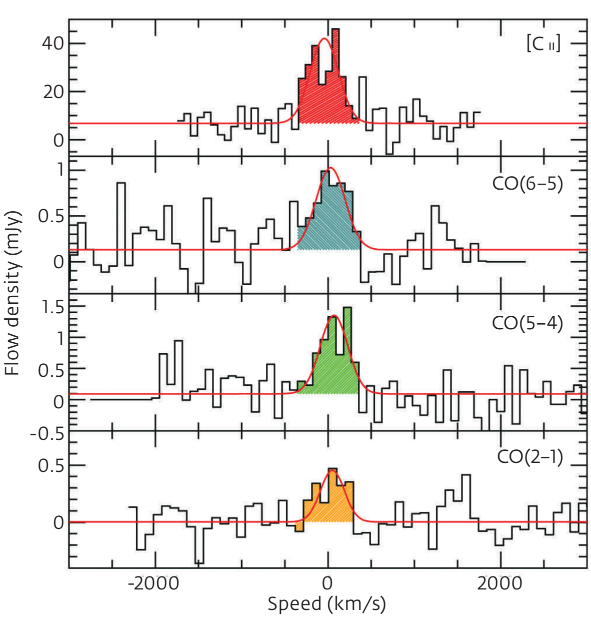
The color is no accident: the universe has been continuing to expand since the Big Bang. In the process, the particles of light called photons have been stretched as well. Their wavelengths were forced to extend – and all the more so the farther away the object that once sent them out was from the Earth.

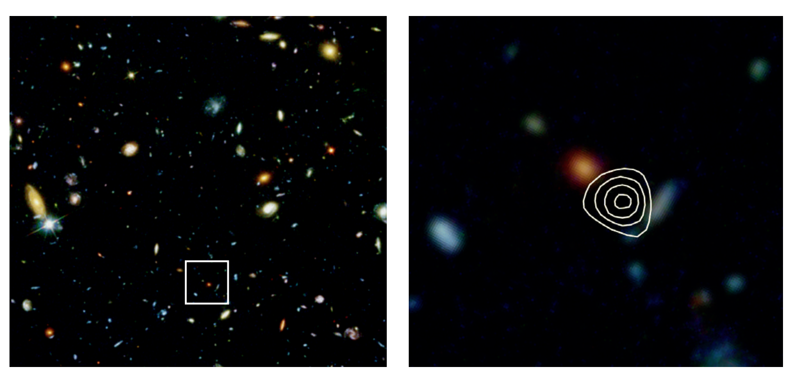
Astronomers call this effect "redshift." Its magnitude is described by the "z value." At z = 1, the wavelength is twice as large as for a stationary object, and with a value of 2, it has tripled, and so on. Because astronomers continually see distant objects at the point in time when the light began its journey, the redshift additionally serves as a metric for the age of a galaxy. The light from an object with z = 10 started its trip at about the time when the universe was just 500 million years old. With an assumed age of the universe of around 13.7 billion years, the light was thus under way for 13.2 billion years.

"Very remote objects quickly become dramatically dark due to redshift – most especially in the visible light range," says Fabian Walter. However, the Heidelberg-based astronomer is only marginally interested in the light of galaxies that can be seen in the *Hubble Deep Field (HDF)*. This light largely originates from fully formed stars. The birth of new suns happens elsewhere – in the interior of dense clouds of dust and gas. "Without gas, no stars," says Walter.

Especially molecular hydrogen is necessary for the stellar offspring to be born; however, hydrogen can't be directly observed. It is only possible through an indirect route of a gas that is closely related to the amounts of hydrogen: carbon monoxide. Its molecule emits a characteristic signal that normally lies in the infrared region of the spectrum.

Due to the redshift, it arrives at Earth with wavelengths of a few millimeters – that is, just below the micro-





A galaxy pops up: The object known as HDF850.1 can't be seen at all in the *Hubble Deep Field* (photo left). In contrast, this distant galaxy becomes visible in the submillimeter wavelength region (light contour lines, photo right). The light from HDF850.1 took 12.5 billion years to reach us and is extremely weak. Nevertheless, a team of astronomers headed by Fabian Walter succeeded in analyzing the emissions of the galaxy. The spectra (left) show characteristic lines of carbon that indicate a high stellar birth rate.

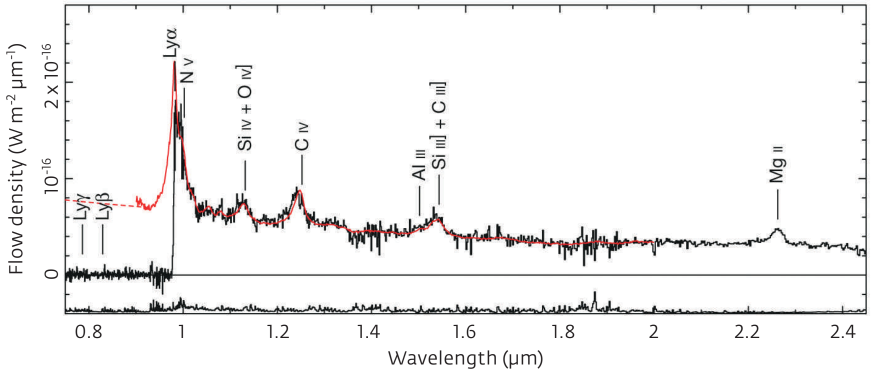
Graphic: Nature 2012; photos: STScI/NASA, F. Walter (MPIA), Nature 2012

wave range. At the very least, the brightest of these ancient regions of star formation can be found by modern millimeter-wavelength telescopes, such as the observatory of the Institut de Radioastronomie Millimétrique (IRAM) in the French Alps (see box on page 31).

A BLACK SPOT ON A BLACK BACKGROUND

With the help of those regions, astronomers have discovered an entire series of such sources over the past years. One of the most important of these is simply called HDF850.1. The galaxy is no more than a black spot on a black background in the classic *Hubble Deep Field*, but it lights up strongly in the submillimeter wavelength region. Carbon monoxide molecules that once absorbed radiation, converted it into rotational oscillations, and finally emitted it at clearly defined frequencies (spectral lines) are especially visible there.

Together with researchers from the Max Planck Institute for Radio Astronomy in Bonn and other colleagues, Fabian Walter succeeded in determining the redshift of HDF850.1 in 2012. It lies at a z-value of 5.2. Accordingly, the light of the galaxy was on its way to Earth for 12.5 billion years, and permits a glimpse into a time when the universe was a mere 1.2 billion years old.



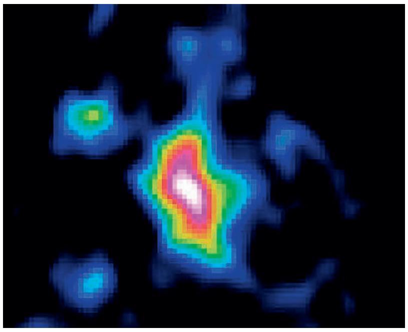
Keys to the early developmental phase of the universe: Quasars are some of first objects formed a few hundred million years after the Big Bang. In the heart of these young galaxies are gigantic black holes that spew matter in the form of jets into space (illustration above). The spectra of these objects reveal a great deal about their internal workings, especially about the processes of stellar formation. Here the spectrum of the record holder (z = 7.1), which looks just like any quasar in the vicinity of Earth.

However, the study, which was published in the journal Nature, reveals even more: characteristic spectral lines of carbon – particularly of atoms that are missing an electron – indicate high stellar activity. These spectral lines not only reveal that new stars are being

Graphic: ESO – M. Kornmesser (top), Nature 2011 (bottom)

In the labor ward of suns: The Orion Nebula (above) is one of the most picturesque subjects in our firmament. You can see a faint spot in the sword hilt of Orion even with the unaided eye.

A telescope reveals a majestic cloud of dust and gas where stars are born. In the Orion KL region of the formation (black rectangle), located about 1,350 light-years away, the stellar birthrate is close to that of Galaxy J1148+5251 (below), though calculated over a much greater volume. After all, this remote star factory in the early universe is as large as a hundred million Orion regions together.



produced hidden behind thick clouds of dust and gas deep in the distant Milky Way, but they also provide clues about the course of this process.

A GALAXY WITH AN AMAZINGLY HIGH BIRTH RATE

According to this, a galaxy like HDF850.1 produces a trillion times as much energy as our Sun. That is possible only if stars with around a thousand solar masses form there, year after year. By contrast, a normal galaxy like our Milky Way manages only one one-thousandth of this amount. "Galaxies must have already existed shortly after the Big Bang that were able to produce incredible numbers of stars," says Fabian Walter.

However, this contradicts the conventional models, according to which the first stars and galaxies should form rather more leisurely: Until now, theoreticians have assumed that the elements formed in the Big Bang needed many hundreds of thousands of years to slowly agglomerate – supported by a force that astronomers call dark matter and about whose nature they still can say hardly anything. The gaseous elements – primarily hydrogen, helium and lithium – collected in the disks of the first galaxies, condensed under the influence of their mutual gravitational force, and began to collapse. At some point, the molecular clouds were finally dense enough to ignite the fire of nuclear fusion.

These first suns – theoreticians speak of Population III stars – must have been immense. They burned out, exploded and, in the process, hurled the heavier elements that they had produced during nuclear fusion out into space. The components from which today's stars and galaxies are made accrued in this manner, bit by bit – a slow, continuous process, actually.

» Galaxies like HDF850.1 aren't the only risk for the contemporary model of the early universe. Surprising data comes from quasars, as well.

That an enormous star factory like HDF850.1 must have existed a billion years after the Big Bang doesn't fit very well with this picture. "In many areas of astronomy, we are discovering that several things at the beginning of the universe must have run their course much more quickly than we thought," says Walter about the dilemma between theory and practice.

The observational data still isn't sufficient for a definitive deduction. In his search for especially remote galaxies, it is quite possible that Fabian Walter has captured those that are brightest and most active – and therefore the easiest to observe. These are perhaps outliers, or perhaps just lucky hits. And the data possibly doesn't allow for any conclusions to be drawn about the true conditions of the universe in its childhood. "If we're honest, we have no idea how many of these kinds of objects there are. We've really only investigated one in detail so far," says Walter. "If, however, thousands of them exist, then the theoreticians have a problem with their simulations."

Galaxies like HDF850.1 aren't the only risk for the contemporary model of the early universe. Surprising data comes from quasars, as well – active black holes that sit in the center of most galaxies and continuously draw matter in. Gas and dust are forced into spiraling orbits, accelerated, and heated intensely. Shortly before the matter disappears into the cosmic chasm, it lights up brightly.

Quasars represent some of the visually brightest objects in space. "That makes them ideal research tools for studying physical processes and the

THE IRAM INTERFEROMETER

At an altitude of 2,550 meters on the Plateau de Bure in the French Alps stands one of the highest-performance telescopes for millimeter radiation: the observatory of the Institut de Radioastronomie Millimétrique, or IRAM for short. There are six radio telescopes in the joint German-French-Spanish project, each having a diameter of 15 meters and connected together in what is known as an interferometer (photo). This results in each individual telescope dish – due to their individualized locations – receiving the radio waves from deep space at a slightly different time. The signals are subsequently superposed and algorithms compute a high-resolution image from the differences for the objects observed. In this way, astronomers can look with sharper focus and more deeply into the cosmos than would be possible with a single telescope. Until 2018, the observatory on the Plateau de Bure will be modernized and expanded to 12 telescopes, funded on the German side by the Max Planck Society.

Photo: IRAM – Rebus

» ALMA, an unsurpassed millimeter-wavelength telescope, will soon go into operation in Chile. The facility will comprise 66 antennas.

chemical composition in remote regions," says Walter. Even a few hours' observation time with IRAM is sufficient to coax the secrets from quasars.

The brightly glowing objects have one great disadvantage, though: they occur extremely rarely – at least during the early periods of the universe – and are correspondingly difficult to find. Walter and his colleagues are therefore relying on a systematic scrutiny of the sky with the aid of a telescope in Hawaii: Pan-STARRS *(Panoramic Survey Telescope & Rapid Response System)* automatically sifts through the entire firmament above the Pacific island for points of light whose signatures could match that of quasars. "We have already found two quasars this way," says Walter. "That's not great, but it demonstrates that the method works, and we can continue with a sense of confidence."

TELESCOPE PROBES THE CHILDHOOD OF SPACE

One cosmic beacon that has long been known is called J1148+5251. It provides insight into a time less than a billion years after the Big Bang. In 2009, the astronomers in Heidelberg and Bonn were already able to demonstrate, with the aid of IRAM, that an extremely large number of stars are being formed in this galaxy as well. The rate even lies at the upper limit of what is physically possible – even more stars, and the energy of the large number of births would blow up the 5,000-light-year diameter nursery.

"In our Milky Way, these extreme conditions are found only in much smaller regions around parts of the Orion nebula," says Walter. However, J1148+5251 is as large as a hundred million Orion regions together – and that not even a billion years after the birth of the universe.

And yet another observation that Walter and his colleagues have made in relation to quasars shortly after the Big Bang is an enigma: Although the objects are extremely young, their black hole is already similar in mass to today's galaxies. The dynamic mass that is distributed all around it, however, is miniscule by comparison, totaling merely twenty or thirty times that of the center. With contemporary galaxies, this value is significantly higher and lies at around one thousand times.

This could suggest that, in the early universe, the black holes originated right away. They drew in more and more dust and gas, which ultimately led to the birth of the first stars in the immediate vicinity of the galactic center. "That is very speculative though," warns Fabian Walter. He thus concentrates on taking the measurements. His theoretical astronomy colleagues are the ones who have to wrack their brains over what it all means.

Nor is that the only challenge that Walter and his colleagues are confronting the theoreticians with: The light that the astronomers have captured from the ancient quasars is spread over the various wavelengths very similarly to the light of contemporary galaxies. "There's hardly a difference between a quasar that we see 800 million years after the Big Bang and one that we see in the today's universe," says Walter.

SIMPLE MEASUREMENTS RUIN MODELS

However, that also means that the characteristic spectral lines of metals like iron or magnesium can be found even in the early quasars – elements that cannot form in the Big Bang, but instead must first be produced by the stars, bit by bit. One of the conventional models of stellar formation indeed predicts that iron, as the heaviest element, could be formed solely in stars that were at least two billion years old. "With simple measurements, these models have been thrown into disarray," says Walter. But he isn't disappointed because of this – just the opposite: "I find it fascinating."

Nevertheless, as previously with the galaxies in the *Hubble Deep Field*, the number of quasars that have been investigated is still too few to allow a statistically valid prediction about the processes in the young universe. That could soon change: ALMA, an unsurpassed millimeter-wavelength telescope, will soon go into operation in Chile. Instead of six antennas like IRAM, ALMA has 66 at its disposal. And instead of being at an altitude of 2,550 meters in the French Alps, it stands at more than 5,000 meters in the Atacama Desert, one of the driest and clearest regions on Earth.

1 | Scout above a sea of clouds: The telescope of the Pan-STARRS on Maui (Hawaii) sifts through the firmament for points of light and searches for the fingerprints of quasars, among other objects.
2 | Journey in space: Astronomer Fabian Walter has worked for many years on the Very Large Array in Socorro, New Mexico.

Fabian Walter becomes very excited when he thinks about it: "ALMA is absolutely gigantic," says the astronomer. "This is a telescope that overshadows everything that has gone before it. It's a great leap, like going from the human eye to Galileo's telescope."

Compared to its predecessors, ALMA combines several qualities at once: the telescope isn't only significantly more sensitive, its individual dishes can be separated from one another by up to sixteen kilometers. Submillimeter sources from the extremely young universe can be found more easily this way and the distribution of their light and their masses can be observed in greater detail.

That much progress will take five to ten years, though. "We are therefore still dependent on models and simulations," says Fabian Walter. With every new observation, regardless of whether it is made now with IRAM or in the future with ALMA, a new opportunity opens up for the astronomers to adapt their models to the realities of that time a little bit better – and to bring more light to a dark age of the universe. ◂

TO THE POINT

- **The universe was born about 13.7 billion years ago in the Big Bang. Just a few hundred million years later, there were already stars and galaxies.**
- **Several of the first galaxies were unimaginably productive: stars on the order of about a thousand solar masses apparently formed year after year within them. In contrast, a normal galaxy like our Milky Way manages a mere one one-thousandth of this amount.**
- **The high rate of production doesn't match up with the theoretical models. Astronomers are attempting to collect as much data as possible about the early period of the cosmos.**
- **Observations of young galaxies and remote quasars should help us understand what processes ran their course in the interior of the first gigantic star factories.**

GLOSSARY

Redshift: For objects receding from Earth at high speed, this is a metric for the shift of the wavelengths toward the red region of the spectrum and is represented by the value z.

Look-back time: At very large distances, the redshift depends not only on the speed of a receding object (Doppler effect). The expansion of all of space lengthens the light much more. Nor can the distance to the object therefore be deduced simply from this cosmological redshift; it depends on the respective cosmological model applied, among other things. Astronomers prefer to speak of the look-back time – the time that the light from the object took to reach us and that indicates the age of the universe when the light started its journey.

Big Bang: Cosmologists' preferred model for the birth of the universe. Accordingly, the cosmos originated 13.7 billion years ago from an unimaginably dense and hot initial singularity that can't be described physically. Today, the classical Big Bang model has been extended by inflation – the sudden expansion of the extremely young cosmos.

Photos: Rob Ratkowski (left), private (right)