The **Big Bang Clock**

It's the question of all scientific questions: How did the universe come into being? **Jean-Luc Lehners** at the **Max Planck Institute for Gravitational Physics** in Potsdam-Golm is addressing the question using state-of-the-art mathematical tools. In the process, he is also investigating the possibility that there was a precursor universe.

TEXT **THOMAS BÜHRKE**

In the beginning was the Big Bang. This foundation of our cosmic world view is as fundamental as it is incomprehensible. How can it have been possible for such an enormous quantity of matter – all the stars and planets, gas and dust nebulae – to be compressed into a single point? That suddenly exploded, creating space and time? It's an unimaginable scenario.

It is thus somehow immediately calming when even an established expert like Jean-Luc Lehners of the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) finds the birth of the universe "extremely mysterious." But this is precisely why he has spent years studying it. "The question of where everything originates has always fascinated me," says Lehners, whose paper-strewn desk looks like it has recently experienced a miniature Big Bang…

The circumstantial evidence in the case of the Big Bang is clear. In the 1920s, Georges Lemaître and Edwin Hubble discovered the expansion of the universe: it can be seen in the fact that almost all galaxies are moving away from us – and the further away a galaxy is, the faster it is moving. Cosmologists interpret this galactic flight in the context of Einstein's general theory of relativity. Accordingly, the universe – that is, space – is expanding and the galaxies are moving further away from each other – similar to raisins in a rising yeast dough.

THERE WAS NO TIME TO EXCHANGE INFORMATION

In his mind, Belgian mathematician and abbot Lemaître reversed this expansion and, in 1927, postulated the "birth of the universe from a primeval atom." Simple and logical. "However, we've known for a long time that it can't have been that simple," says Lehners. "Instead, the Big Bang occurred in numerous places simultaneously." This doesn't make the idea any easier, but Lehners can explain.

If we calculate the beginning of the expanding infant universe using Einstein's equations, we find that many regions couldn't have been in causal contact. There wasn't enough time for information to be exchanged between these regions, which is fundamentally limited to the speed of light. Yet the universe was astonishingly homogeneous.

This is demonstrated by the oldest tidings from this young universe that we are able to receive in the microwave range: cosmic background radiation. It reflects the temperature and density of the primeval gas 380,000 years after the Big Bang. Visible deviations from a mean value reach no more than hundredths of a part per thousand. But how could the universe be so uniform if numerous regions weren't in contact? Jean-Luc Lehners associates each of these regions with a Big Bang – the emergence of space and time from a quantum fluctuation. The remaining question is then: What coordinated these "Big Bangs"?

Lehners visualized the problem in the auditorium during a presentation at a Falling Walls conference. Ten members of the audience found a small bowl and a stick beneath their seats. Lehners then asked one of them to use these to make a sound. The gong represented a

Photo: CC0

Everything started with the Big Bang. According to cosmologists' theories, the universe originated in a single point. This singularity, however, is extremely mysterious even for experts.

» The inflationary universe theory states that, prior to the Big Bang, there was a state in which all particles were in mutual contact.

metaphorical Big Bang. Then the other nine observers were also asked to bang the bowl simultaneously. This functioned precisely only when Lehners dictated the rhythm. But who dictated the rhythm for the Big Bang?

There are two proposals on the table. The best known one was developed more than 30 years ago: the theory of the inflationary universe claims that prior to the Big Bang there was a state in which all particles were in mutual contact. This was then followed by a brief phase in which space expanded faster than the speed of light. This means that regions were separated to such an extent that they were no longer in contact. When this phase ended, the inflation energy transformed into radiation and matter – this moment is regarded as the Big Bang.

But there is a second possibility – one to which Lehners has devoted intensive research. It states that the Big Bang may have been a transition stage. Before that, there existed a different universe that eventually contracted and then expanded again in the Big Bang. "If we analyze such a contraction phase, we find that it probably occurred very slowly. This could have had the effect that the successor universe was homogeneous and isotropic," explains the Max Planck researcher. Here, the Big Bang corresponds to the swing from the contraction to the expansion phase, again producing radiation and matter.

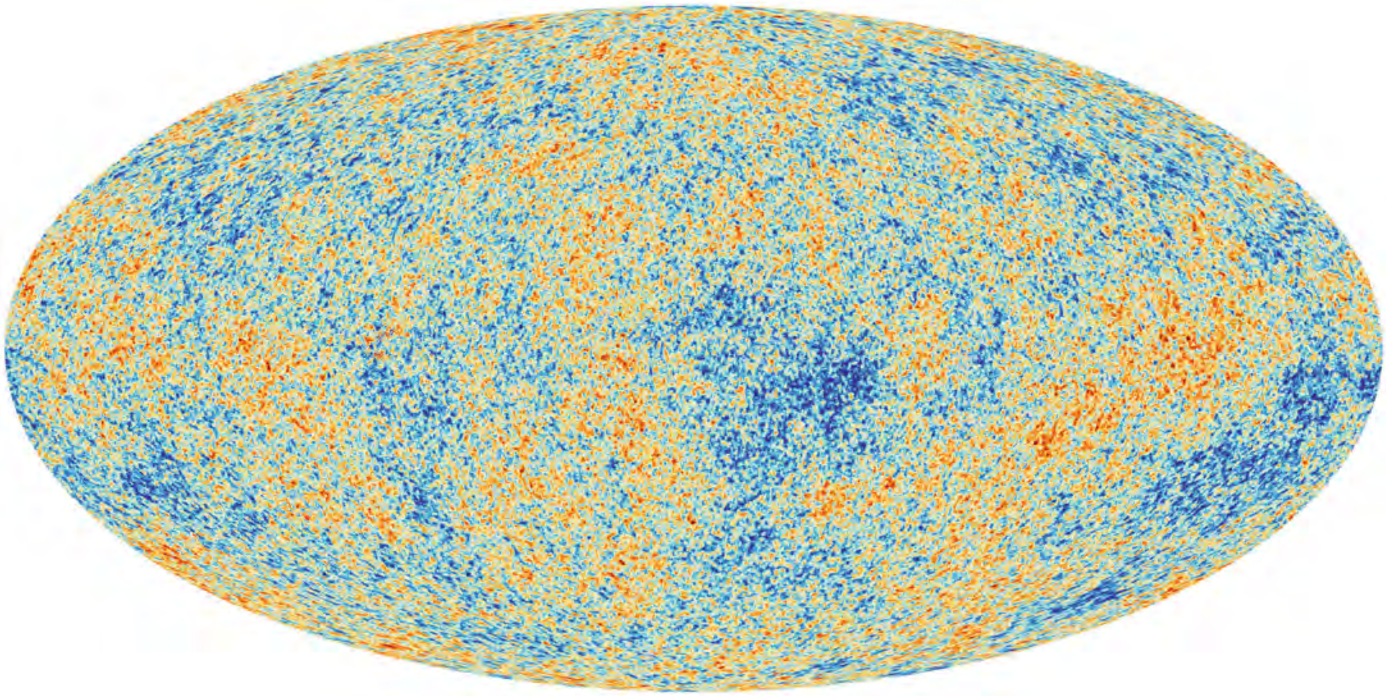
EXISTING MATTER DOESN'T ADMIT OF A REBOUND

The concept of such a cyclic universe seems appealing, echoing ancient Hindu and Buddhist myths. But does this scenario really reflect reality? Jean-Luc Lehners tackled this question – with the sobering result that the matter existing in the universe today doesn't admit of such a rebound. There would have to have been an unknown energy field that caused matter to swing. Could the recently discovered Higgs particle have played a role here?

As is common in quantum physics, the Higgs particle is associated with a

A view into the distance: This section from the Hubble Ultra Deep Field shows galaxies at the edge of space and time. Because of cosmic expansion, all of these galaxies appear to be moving away from us – the further away they are, the faster they are receding from us.

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



A baby picture of space: Around 380,000 years after the Big Bang, the universe became transparent to radiation. The *Planck* satellite recorded this microwave background with great precision. The map shows minute temperature fluctuations in regions of slightly differing density, from which stars and galaxies emerged.

space-filling field. However, the currently known strength of this field would be insufficient to initiate a matter rebound. "I investigated whether, at extremely high densities, the Higgs or a similar field could have had different properties than in today's universe, but with little success," says Lehners. So things aren't looking too good for the concept of a cyclic universe.

However, the scientist doesn't intend to give up on this idea that easily. He is currently investigating a different approach that was already proposed back in the 1920s but that wasn't pursued intensively. It's based on the fact that specific particles, such as electrons, twist the space around them slightly. This is caused by what is referred to as their spin, which can be imagined as similar to the rotation of a spinning top. The rotation in space caused by the spin is so small that it is completely irrelevant under normal conditions.

But this idea suggested that perhaps, under the extreme conditions before the rebound, this twisted space developed a force that protected the compacting matter from total collapse and reversed the compression to expansion. We can perhaps imagine this as resembling twisted rubber bands that, in trying to untangle, exercise an outward-directed force.

This kind of theoretical research requires an amalgamation of the general theory of relativity, which describes the physics of space and time in variables, and quantum physics, which is responsible for the particle microcosmos. For decades, the aim has been to unify the two fields in an overarching theory of quantum gravity. It may then be possible to understand and describe extreme states – such as the Big Bang or the inner workings of black holes.

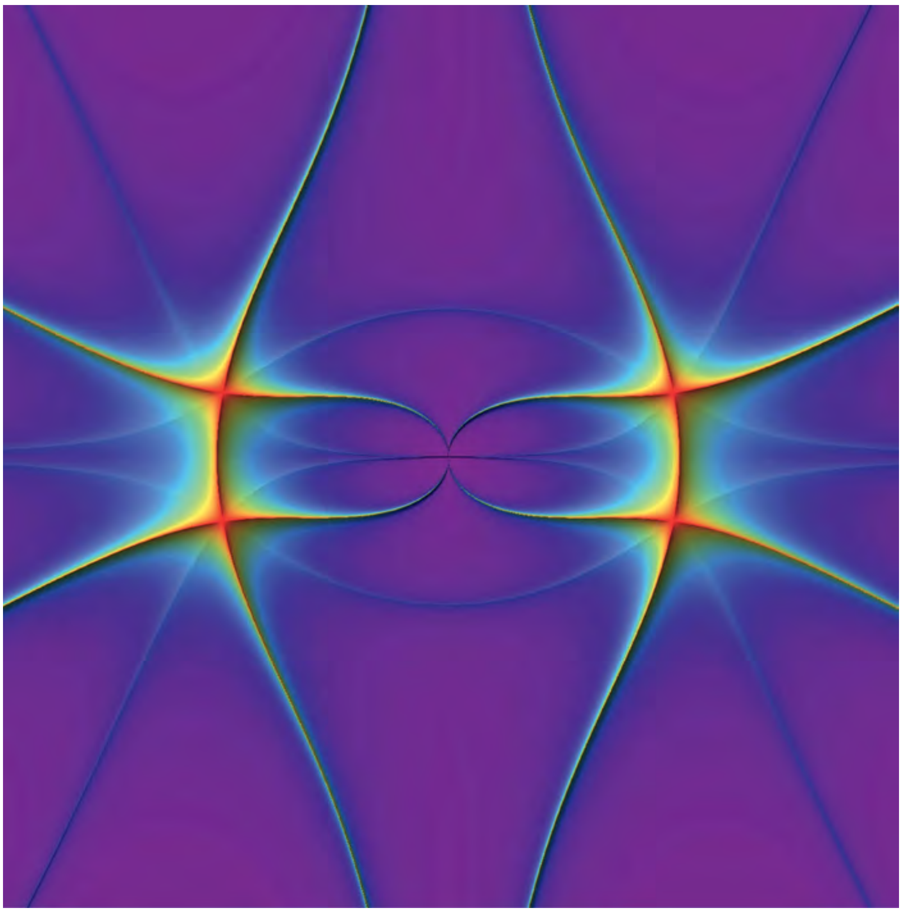
Until this aim has been achieved, theoreticians must apply insights from the one theory to the other and determine the effects. It approximates a "theory of everything," although it is never quite clear how closely one has approached the truth. This could perhaps be compared to an attempt to completely dissolve oil in water, and because that doesn't work, one instead studies what happens if a drop of oil (a particle) falls into water (space and time). Analyses like this require not only excellent knowledge of the two fundamental pillars of physics, but also strong familiarity with mathematical methods that would drive most physicists to despair.

SUPERGRAVITY AS A DOCTORAL THESIS TOPIC

Native Luxembourger Jean-Luc Lehners acquired these skills in world-class institutions. Leading up to his doctoral degree, he alternated between Imperial College London and Stephen Hawking's group at Cambridge University. In his doctoral thesis, Lehners studied the topic of supergravity, which is an attempt to transfer a certain symmetry from particle physics to the theory of relativity.

Lehners has a simple answer to the question of why he ultimately ventured into this difficult territory: "I thought, if I don't learn the theory now, I never will." He then went to Princeton University, Einstein's former academic home, and after a short stopover at the Perimeter Institute in Can-

Photo: ESA and Planck Collaboration



Complex mathematics: This image symbolizes the response of the integral over time if a quantum theory is developed about the scale factor of the universe (that is, about its size). This integral must be regarded as a sum across possible universes that all require different times to advance to today's state. In a quantum theory of the cosmos, the time required by the universe to arrive at today from the time of creation isn't predetermined. In this model, the most probable evolutionary paths of the universe occur at the points in the image where the lines meet.

ada, moved to the Max Planck Institute in Potsdam-Golm where he has led the Theoretical Cosmology Research Group since 2010.

The approximation methods employed by quantum cosmology often lead to a multitude of possible solutions. It is only when certain assumptions that appear physically plausible are brought into play that this diversity is limited to such an extent that, ideally, only a few solutions remain. "But what is plausible when it comes to the Big Bang, anyway?" Lehners remarks, highlighting the limitations of the method. Ultimately, astronomical observations must decide whether a possible solution accurately describes nature.

Cosmologists now find themselves in the unique situation of being able to look into the past. The reason is the very fast, but nonetheless finite, speed of light. For example, the radiation from galaxies that can be observed today had to travel for approximately 13 billion years before reaching our telescopes. Astronomers thus see these star systems in a stage of development as they were 13 billion years ago, or 800 million years after the Big Bang.

THE CONTRACTION OF SPACE WAS A SEDATE AFFAIR

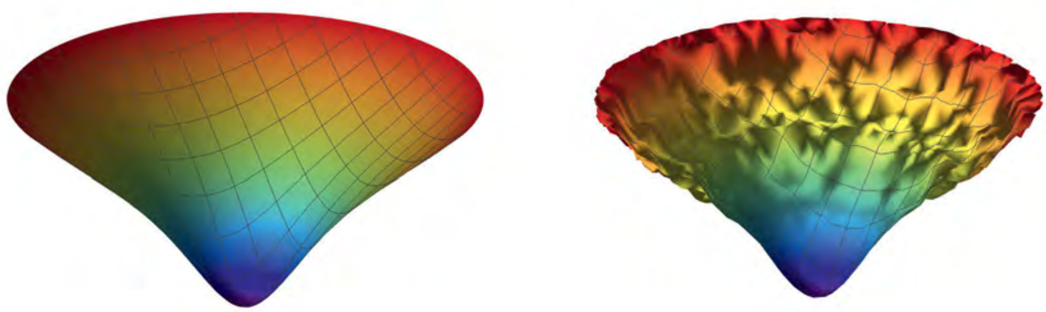
However, the researchers can't look back to just any distance they want. The oldest tidings are those of the cosmic background radiation mentioned above. It originated when the hot primeval gas became transparent, which happened around 380,000 years after the Big Bang – a relatively short period on the cosmic timescale. This radiation field thus also contains information on the Big Bang and the postulated inflationary phase. It is said to have given rise to strong gravitational waves – fluctuations that compress and stretch space in waves. We can picture this as being similar to ripples on the surface of a pond.

These gravitational waves are thought to have "blueprinted" themselves in a certain pattern onto the cosmic background radiation. Physicists say the radiation is polarized in a very characteristic way, meaning that it oscillates predominantly in one plane. In the cyclic universe theory, no – or only very weak – gravitational waves were generated, because the contraction of the precursor universe was more sedate, and space-time not as strongly agitated as assumed.

Observing polarization in the cosmic background radiation thus affords the great opportunity of differentiating between the inflationary and cyclic universe theories. However, the signal was probably extremely weak and overlain by other effects.

It therefore caused a sensation when, in spring 2014, a team of researchers from the Harvard-Smithsonian Center for Astrophysics claimed they had identified precisely this polarization pattern using the BICEP2 telescope operating at the South Pole. Some cos-

Graphic: Jean-Luc Lehners/MPI for Gravitational Physics



The wrong way out: Stephen Hawking (photo below) and James Hartle's no-boundary proposal avoids the singularity of the Big Bang. The quantum fluctuation from which the universe arose was finite (blue) and was subjected to inflationary expansion from there (cone expansion). However, the no-boundary proposal didn't pass a stress test: quantum fluctuations, which become stronger with time (right), prevent a stable universe such as ours.

mologists could already see the Nobel Prize within reach.

Following an analysis of the observational data recorded by the European Planck space telescope, the sobering conclusion was that the researchers had missed something: the polarization pattern didn't originate from gravitational waves, but from dust within our Milky Way, through which the background radiation had passed on its way to us. Nothing more than a misinterpretation, then! Because of the enormous importance of this observation for cosmology, background radiation measurements are now being carried out with greater sensitivity.

Discovering the polarization signal would be something akin to finding the Holy Grail of cosmology. But for theoreticians such as Lehners, even after this success, the question would remain: How can we understand and describe the singularity of the Big Bang, with its physically senseless, infinitely high density and temperature? Thirty-five years ago, Stephen Hawking and his then-colleague James Hartle caused a stir by proposing a possible solution, which they named the no-boundary hypothesis.

The idea is based on several assumptions about how to unite quantum physics and the general theory of relativity in a single Big Bang model and avoid the singularity. One of the most critical steps was that Hawking and Hartle described time as a complex variable. Time, now imaginary, thus formally becomes a fourth spatial coordinate, and space and time have become indistinguishable.

AN ELEGANT HYPOTHESIS – BUT UNFORTUNATELY WRONG

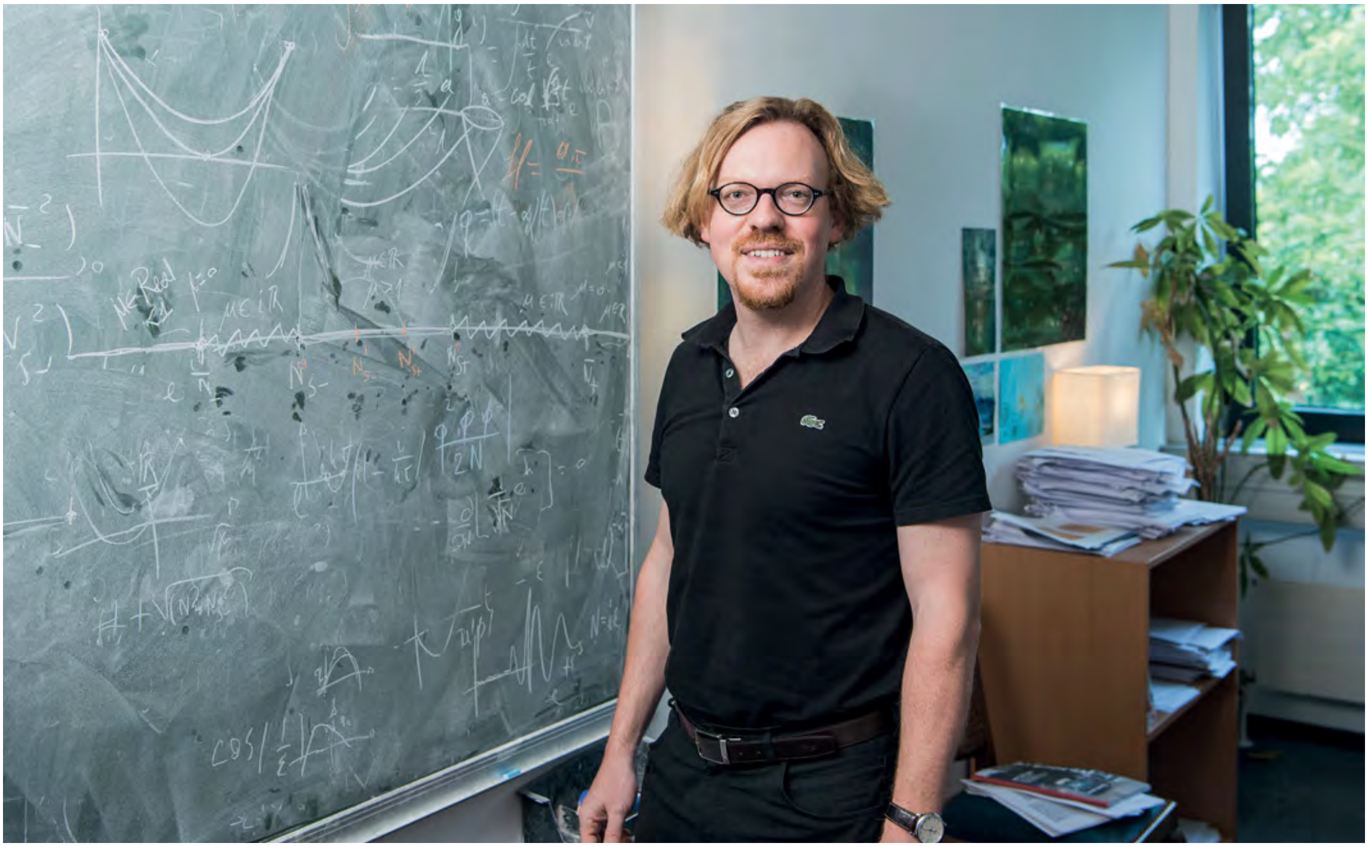
"One can no longer truly speak of space and time. Rather, the universe is now a quantum state or a quantum fluctuation," says Jean-Luc Lehners. In this description, the universe may have been self-contained, like a sphere. It thus had no edge, but was unbounded, similar to how, in principle, one can circumnavigate the Earth without encountering an edge or a boundary. Nor did it possess a singularity – a location with physically senseless variables.

In the Big Bang, this boundaryless quantum state expanded, and space and time as we know them today were created. Interestingly, this scenario requires an energy field for the initial no-boundary state – just as the theory of inflationary expansion does. "An inflationary universe would therefore automatically develop from the initial state," says Lehners. An elegant hypothesis, then, and it would have solved two problems at once: the initial singularity of the Big Bang would have been avoided and the cause of inflation identified.

But even Hawking had pointed out that the no-boundary hypothesis was merely a proposal and couldn't be derived from any underlying principle. In particular, due to the mathematical difficulties, this scenario was always analyzed using extreme simplifications, and nobody knew how realistic they were.

Jean-Luc Lehners, together with his colleagues Job Feldbrugge and Neil Turok from the Perimeter Institute in Canada, recently subjected Hawking's model to a stress test using improved

Graphic: Jean-Luc Lehners/MPI for Gravitational Physics; photo: Mike Hutchings/Reuters



Search for the answer: How was the universe created? This question has occupied humanity for millennia. At the Max Planck Institute for Gravitational Physics in Potsdam-Golm, Jean-Luc Lehners is addressing this problem using state-of-the-art mathematical tools.

mathematical methods – with an interesting result: it didn't work! The theoreticians investigated the stability of the initial quantum fluctuation and discovered that, the greater the fluctuation, the more chaotic it is. If we regard them as oscillations in spacetime, this means that the oscillations become stronger and stronger and prevent a stable universe such as ours from developing. And the greater the fluctuation is, the greater is the probability of its occurrence.

"There is no upper limit," says Lehners. That is, the probability that a sufficiently small quantum fluctuation occurred from which our universe could develop is zero. "We were amazed that the effects we had identified practically turned the Hawking and Hartle model on its head," says Lehners: "It didn't yield any sensible solutions."

The researcher doesn't consider this unpleasant result to be negative by any means. Rather, it shows him the path along which he wants to continue. "Today, we have better mathematical methods to continue questioning," he says. Right now, nobody knows when or whether this path will even lead to a final result. Ultimately, though, this is the greatest question that humans can ask: How was our world created? ◂

TO THE POINT

- **The birth of the universe in the Big Bang is undisputed among cosmologists. What is less clear, however, is what exactly happened at time zero.**
- **The most popular hypothesis assumes an inflationary, faster-than-light expansion of the infant universe. However, the possibility of a gentler transition from a precursor universe has not been ruled out.**
- **Recently, Jean-Luc Lehners and two colleagues brought down the no-boundary hypothesis with which Stephen Hawking and James Hartle had tried to avoid the initial singularity.**

GLOSSARY

Expansion of the universe: After Belgian Georges Lemaître had discovered the expansion of the universe in theory in 1927, US astronomer Edwin Hubble confirmed it in practice in 1929. Hubble observed the flight of the galaxies, which appeared as a redshift in the spectral lines of galactic systems. This galactic redshift, in turn, had already been found by American researcher Vesto Slipher in 1912.

Planck space telescope: This European space probe, launched in 2009, produced the most precise cosmic background radiation map to date before the mission ended in 2013. With the aid of the satellite, the researchers determined that the universe was 13.82 billion years old. In addition, they derived its composition very accurately: today it comprises 68.3 percent dark energy, 26.8 percent dark matter and 4.9 percent baryonic matter (atoms).

Photo: Andreas FranzXaver Süß

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