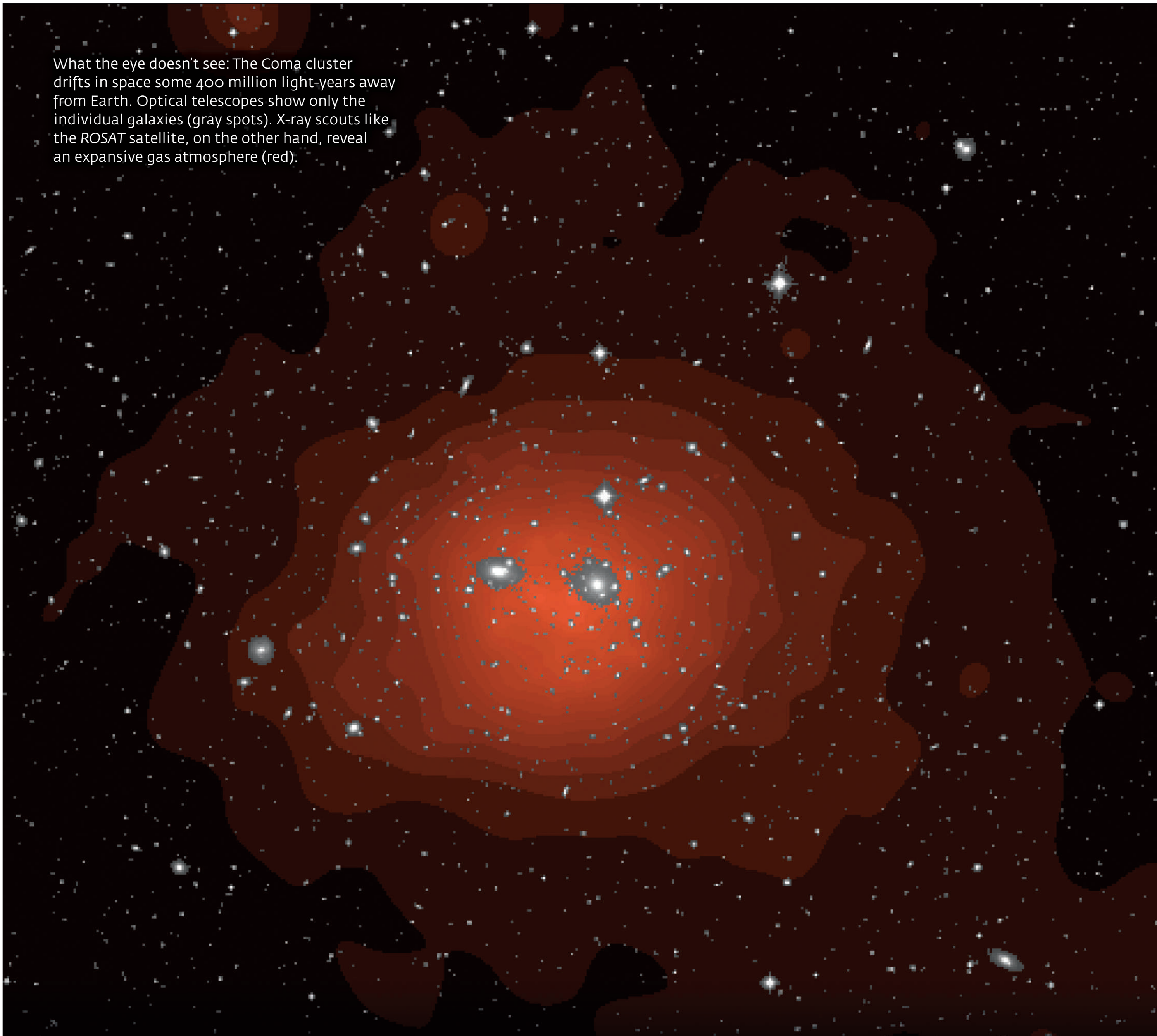


What the eye doesn't see: The Coma cluster drifts in space some 400 million light-years away from Earth. Optical telescopes show only the individual galaxies (gray spots). X-ray scouts like the *ROSAT* satellite, on the other hand, reveal an expansive gas atmosphere (red).

The Architecture **of Space**

The universe resembles an unfathomably large honeycomb. Gigantic galaxy clusters occupy the nodes of the waxy walls surrounding the cells composed of empty space. **Hans Böhringer** at the **Max Planck Institute for Extraterrestrial Physics** in Garching studies these conglomerations of galaxies, and in the process, encounters the invisible aspects of space.

TEXT **HELMUT HORNUNG**

The photo is rather gloomy, with large portions glowing violet-black. But especially in the upper half, the image changes: there, millions of lights illuminate the scene. Most of them do not appear in isolation, but are strung together to form glittering chains, forming net-like patterns with bright splotches. The American space agency NASA published the photo, composed of individual shots taken by the satellite *Suomi NPP*, in early December 2012. It shows – the Earth by night.

The image arouses different associations in each viewer, and impressively reflects the north-south disparity on our planet: many lights mean large cities and dense settlement, such as in Europe and North America; Africa, with the exception of the southern tip, is nearly black. To an astronomer, in turn, the image may recall something unearthly – nothing less than the structure of space. After all, looking at the universe as a whole, it seems to be anything other than homogeneous. Instead, filaments traverse space and form a network that resembles the bubble walls of a cosmic bubble bath. Or the cell walls of a honeycomb. The light structures here mark the agglomeration areas of matter, while the dark ones are gigantic voids.

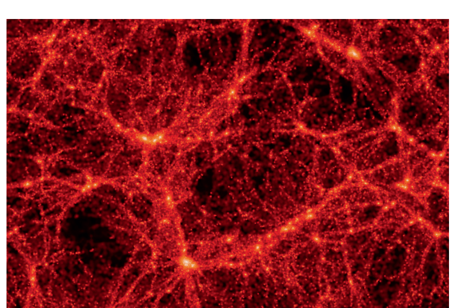
How does space come by such a honeycombed structure? To find out, Hans Böhringer at the Max Planck Institute for Extraterrestrial Physics in Garching does something like cosmography – cosmic geography: similar to the way the bright lights on the NASA images follow the contours of the continents, galaxy clusters trace the architecture of space. Accordingly, many of them would correspond to the metropolises. Our Milky Way, too, is part of a cluster: the Local Group. This cluster has some 40 members and resembles something more like a suburb; at least it belongs to a megacity, the Virgo Supercluster.

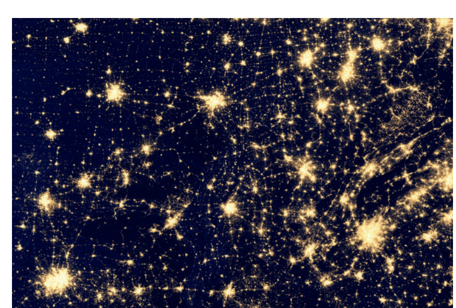
"Galaxy clusters are the largest clearly defined objects in the universe," says Böhringer. They comprise up to a few thousand galaxies, each of which is a system composed of billions of stars, gas and dust clouds. Our Sun is one of approximately 200 billion stars that, together with the interstellar matter, form such a galaxy. The gravity that causes a stone to fall on Earth binds the galaxies of a cluster together with invisible chains. "Invisible" – this word dominates Böhringer's research.

SPACE IS EMPTY – BY EARTHLY STANDARDS

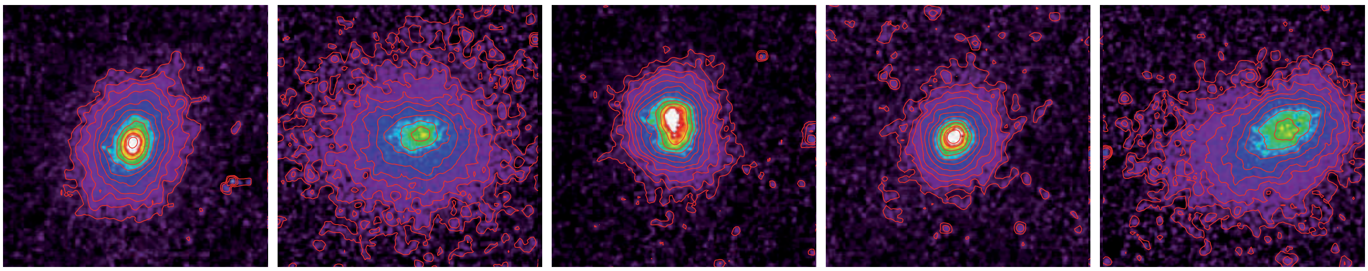
For one thing, there is dark matter, which makes up nearly a quarter of space. The first indications of this material, which remains a mystery even today, were discovered by Fritz Zwicky in 1933 while observing the Coma cluster, a galaxy cluster with more than 1,000 members and located more than 400 million light-years away. The Swiss astronomer estimated that it would require 400 times the visible mass to keep the structure as a whole in shape – but

Heaven and Earth: The cosmic network of filaments of matter (left) shares astonishing similarities with images of our planet by night (right). The bright nodes mark agglomeration areas – in one case matter, in the other, cities.





Photos: MPI for Extraterrestrial Physics (left page); MPA Garching – Virgo Collaboration (left), NASA (right)



Gallery of galaxies: On the images of distant clusters, the scientists color-coded the radiation intensity of the X-ray halos. The gas – a plasma composed of ions and electrons – has extremely high temperatures of several dozen to 100 million degrees. The spectral analysis provides further important data on the intergalactic medium, such as its chemical composition.

the gravity of the visible galaxies isn't nearly sufficient for this. ("Hunting Down the Invisible," page 34 ff.)

For another thing, a galaxy cluster contains copious amounts of hot gas. The space between the individual galaxies is practically empty – but only by Earthly standards. "The density is many orders of magnitude lower than in a laboratory vacuum," says Böhringer. "Nevertheless, there are enough particles so that the total mass of the gas adds up to five times the mass of all galaxies." Simple physics is sufficient to understand the high temperatures of the galactic gas.

The material falls into the Coma cluster, for example, at a speed of 1,000 kilometers per second. During this nosedive, its potential energy is converted to kinetic energy. At supersonic speed, the falling gas crashes into gas that is already in the cluster between the galaxies. Upon colliding, the particles are slowed down, and motion turns into heat. The typical temperatures are around a few dozen up to 100 million degrees. And the mass of the material is not to be scoffed at, either: "In the Coma cluster, the gas mass is approximately that of a trillion Suns," says Hans Böhringer.

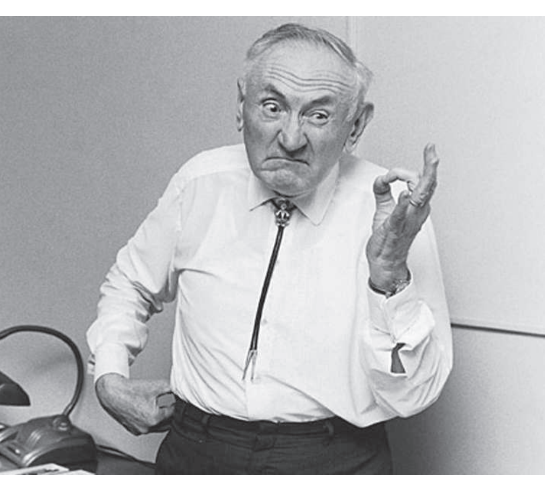
HIGH-ENERGY RADIATION WITH SHORT WAVELENGTHS

But Böhringer didn't weigh the Coma cluster. He didn't even see the gas – a plasma composed of ions and electrons – with his own eyes. As absurd as it may sound, it is invisible to optical telescopes. Rather, the hot matter emits largely high-energy radiation at extremely short wavelengths. And outside the Earth's atmosphere, this X-ray light can only be picked up with special detectors.

The *ROSAT* satellite developed at the Max Planck Institute for Extraterrestrial Physics was one such detector (MaxPlanckResearch 2/2012, page 94 f.). From June 1990 to February 1999, the scout detected nearly 125,000 X-ray sources. Behind 2,000 of the brightest sources are galaxy clusters, or more precisely, their halos. That is what astronomers call the galactic gaseous envelopes that sit between the individual galaxies in the cluster like atmospheres. Many findings can be derived from analyzing them, as researchers can thoroughly screen the halos in the X-ray light.

The halos are "optically thin" – that is, transparent – because the photons in the finely distributed gas can move about freely. These light particles thus transport the messages from all possible atomic processes to the outside unimpeded. If, for example, free electrons are accelerated or slowed down in the gas, they emit X-ray light; and if they collide with atoms, then spectral lines are emitted. These are just as characteristic for each element as fingerprints are for each person. To detect the lines, astronomers break the light down into spectra and obtain, among other things, information about the components of the gas. "Just as was to be expected, it consists of 80 percent hydrogen and helium, the most common elements in the cosmos," says Hans Böhringer.

However, there are also other ingredients, such as carbon, oxygen and nitrogen, nickel, iron, magnesium, silicon and calcium. The expert is not particularly surprised by this, either,



Ingenious troublemaker: Fritz Zwicky (1898 – 1974) was considered difficult by his contemporaries. He served as the model for Friedrich Dürrenmatt's character Johann Wilhelm Möbius in the drama *The Physicists*. In 1933, Zwicky discovered dark matter while observing the Coma cluster.

Agglomeration areas: Held together by gravity, a few thousand galaxy systems stand side by side in the Coma cluster, which measures more than 20 million light-years in diameter. This photo in visible light shows the brightest ones, without revealing that the conglomerate of galaxies is embedded in hot gaseous clouds, or that dark matter accounts for 87 percent of its mass.

Photo: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

these being elements that massive stars have produced and, at the end of their life, released in a supernova. "In this way, we test models of star development."

From a line spectrum, researchers read the fingerprints of the individual elements, similar to securing evidence at a crime scene. Through this, they decipher not only the chemical composition, but also the physical state of the gas, such as density, temperature and mass. These values are related to one another. For example, at high temperatures, the particles move at great speeds. In order for a halo to nevertheless remain stable, it requires a lot of mass to keep the gaseous web in check with its strong gravity shackles.

Speaking of mass: Hans Böhringer and his colleagues confirm Fritz Zwicky's findings: the lion's share of the material in galaxy clusters is concentrated in dark matter. The numbers are far above those in the entire universe. "Dark matter accounts for a full 87 percent of the Coma cluster, while 11 percent is found in the gas halo and just 2 percent in the visible galaxies," says Böhringer.

RESEARCHERS EXPOSE UNKNOWN X-RAY SOURCES

The Coma cluster and, at a distance of 65 million light-years from us, the Virgo Cluster turn out to be ideal objects of study, particularly since they are relatively near and have long been known. As mentioned above, however, *ROSAT* detected some 2,000 further galaxy clusters whose halos obviously seem to be bright X-ray sources. But how do the astronomers know that there are actually galaxy clusters behind these sources?

First, Böhringer studies the existing catalogs of X-ray clusters and searches in directories that were compiled with optical telescopes. If the images show multiple suspicious objects – that is, galaxies – "in a cluster," then the astronomer takes the spectra and derives the respective distances from those. This is done using the cosmic redshift: the expansion of space pulls apart the waves of the objects embedded in space and shifts them into the red spectral range. The further away from us a galaxy is, the faster it is receding from us, and the higher the value of the redshift z is.

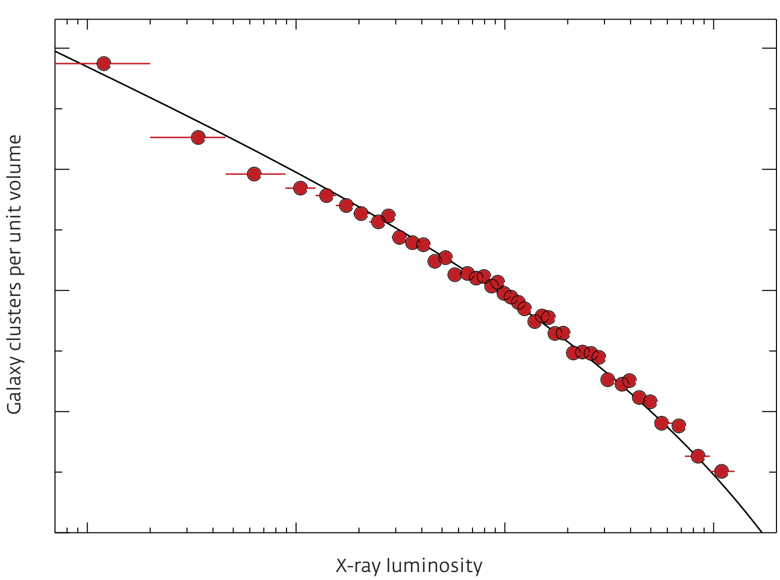
However, for very high values of z, the relationship between redshift and distance is complicated and is determined by the respective cosmological model being used. Astronomers thus prefer to speak of "look-back time" – the age an object had when its light set out on its journey. In any case, identical z values mean the same age and the same distance. If, for the suspicious galaxies mentioned, they are in agreement, then there is hardly any doubt that they all belong to one and the same cluster.

In this way, the researchers at the Max Planck Institute for Extraterrestrial Physics compile two catalogs: *Noras II* includes 934 galaxy clusters in the northern sky, and *Reflex II* covers 919 clusters in the southern firmament. The large amount of data means a lot of work for Hans Böhringer – but in a surprisingly different way than one would at first expect.

The scientist leads his visitor out of his office, through a labyrinth of hallways and stairs into a long corridor where a wooden chest the size of a rabbit hutch stands against one wall. The front is covered with a sheet of glass. Böhringer switches on the light, and hundreds of orange circles light up inside the chest. They appear to float freely in space. "Here you see around 900 galaxy clusters, precisely arranged in their actual positions in space," says Böhringer. The galaxy clusters are store-bought adhesive dots.

Close-up: Hans Böhringer displays the objects of his research at the Max Planck Institute for Extraterrestrial Physics – in the form of a showcase that he fitted with 900 galaxy clusters (orange adhesive dots).

"There are three sizes, corresponding to their absolute luminosity." The dots are mounted on 38 parallel plates of antireflective glass set up one behind another. The researcher painted the paper galaxy clusters with fluorescent paint, and UV lamps illuminate them. "Some day, when I have time, I have to stick on another 900 dots," says Böhringer. The content needs to be updated to reflect the current status of *Noras II* and *Reflex II*, which comprise a good 1,800 X-ray clusters.



Simple relationship: The diagram shows the luminosity function of galaxy clusters, or their number per unit volume at a certain X-ray luminosity. The graphic shows clearly that the clusters with the highest luminosities and the largest masses are very rare. This corresponds to the distribution of matter in young space, where there were many small fluctuations and few large ones.

The peep show is far more than scientific play. After all, it shows a true-to-nature section of the universe – a cube with an edge length of four billion light-years. In it, each galaxy cluster is recorded not only with two celestial coordinates – similar to how one can precisely specify the position of a location on Earth by indicating the geographical longitude and latitude – but also with its distance. This is what makes the map three-dimensional and provides a true-to-scale likeness of the natural relationships.

At first glance, even a layperson can see that the broad distribution of the galaxy clusters is by no means homogeneous. In fact, on this scale, the net-like structures mentioned above start to become evident. Astronomers use various methods to study this cosmic honeycomb in detail.

"An important instrument is the mass spectrum," says Hans Böhringer. This has nothing to do with a conven-

Photo: Axel Griesch; graphic: MPI for Extraterrestrial Physics

> Inflation abruptly pulled apart tiny fluctuations in the original quantum vacuum and spread them across the melon-sized space.

tional spectrum, where a prism or a grating separates the light of an object into a rainbow. A mass spectrum provides information on how the galaxy clusters are distributed according to their mass. Or to put it another way: How many galaxy clusters of a certain mass are there per unit volume?

To understand why answers to this question are of fundamental importance, we must take a little excursion to the roots of all existence. Today, most cosmologists, who trace the birth and development of the universe, accept the inflationary model of the Big Bang. This theory holds that space emerged from a quantum vacuum 13.7 billion years ago. In the incredibly short timespan of 10^{-34} to 10^{-32} seconds after the Big Bang, the cosmos is thought to have expanded by 30 orders of magnitude at faster than the speed of light, from the Planck length (10^{-35} meters) to the diameter of a melon.

AFTER THE BIG BANG, THE COSMIC SEED SPROUTS

This inflation not only made space extremely smooth, but also abruptly pulled apart tiny fluctuations in the original quantum vacuum and spread them across the now melon-sized space. Because the cosmos expanded further – and is still expanding today – also the initial (primordial) density fluctuations grew. From this, a few hundred million years after the Big Bang, extensive structures developed in the form of net-like filaments: the germ cells of galaxy clusters, galaxies and stars.

There are various possibilities for determining the mass of a cluster. In one method, researchers merely establish its X-ray luminosity. Before this, they must measure many galaxy clusters and take numerous statistical distortions into account. And they must determine one or the other mass with an independent method, such as with the aid of a gravitational lens (MAX-

NEW X-RAY SCOUT PREPARED TO LAUNCH

X-ray astronomers are excited: The Russian satellite *Spectrum-Roentgen-Gamma* (SRG) is set to launch from Baikonur in 2014. The main instrument on board is known as *eROSITA*, and is expected to conduct the first complete celestial scan in the central X-ray range up to 10 kiloelectron volts with never before achieved spectral and spatial resolution.

eROSITA will trace the dark sides of the universe, dark matter and dark energy. The latter could be the vacuum energy that corresponds to the cosmological constant in Einstein's general theory of relativity; however, it could also be a time-variable energy field. The solution to this question will play a fundamental role for physics.

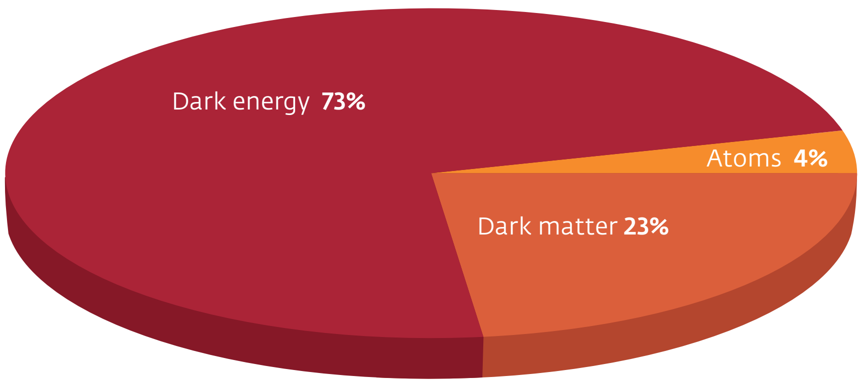
The main scientific goals of the mission:

- To observe the hot intergalactic medium of 50,000 to 100,000 galaxy clusters and galaxy groups, and the gas halos with which they reveal themselves in the X-ray image. Researchers want to use this to map the expansive structures of the universe and study their development.
- To systematically examine all black holes in nearby galaxies and many new (up to three million), distant active galactic cores.
- To study in detail the physics of X-ray sources in our galaxy, such as supernova remnants, X-ray binary star systems and pre-main-sequence stars.

The *eROSITA* telescope consists of seven identical mirror modules. To achieve the required sensitivity, each module includes 54 nested mirror dishes developed by a team working with Peter Predehl at the Max Planck Institute for Extraterrestrial Physics. Scientists working with Lothar Strüder designed the cameras at the Max Planck Society's semiconductor laboratory in Munich.

Spy in the kingdom of darkness: The X-ray observatory *eROSITA*.

Photo: MPI for Extraterrestrial Physics



Unknown substance: Observations indicate that approximately 96 percent of the universe is invisible. The baryonic matter of which humans, planets, stars and galaxies consist constitutes just 4 percent of the mass.

PlanckResearch 1/2011, page 64 ff.). At the end is a diagram that shows the luminosities on the y-axis and the masses on the x-axis. A curve passes through the measuring points. Entering the newly determined luminosity of a galaxy cluster on this curve immediately yields its mass. The more brightly the cluster shines in the X-ray light, the greater its mass is.

Hans Böhringer and his colleagues use such a mass spectrum to conduct a cosmic census. As with Earthly surveys, their interest is not limited to the result for a certain point in time. Governments, for example, conduct censuses again and again and compare the results. This gives them valuable insights into the demographic development of their country. “When we astronomers determine the number of galaxy clusters per unit volume for different epochs, we gain insight into the evolution of the universe,” says Böhringer.

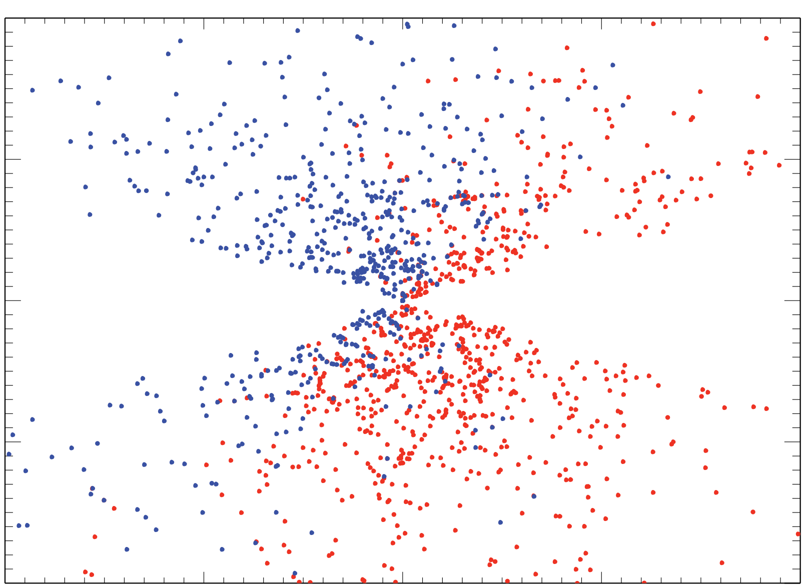
After the Big Bang, space grew and developed, from the simple to the complex, from the initially tiny fluctuations to the large structures. Accordingly, the number of galaxy clusters should fluctuate over time. And because their distribution and density, in turn, depend on the cosmological models, Böhringer’s observations should be a touchstone for the theory.

THE UNIVERSE AS AN ORDERLY EXPERIMENT

Just as a demographer uses every statistical trick in the book to study the population, the Max Planck researcher uses sophisticated mathematical methods like the power spectrum to determine the distribution of the galaxy clusters. “It turns out that the chance of finding a galaxy cluster near another cluster is greater than at any other point,” says Böhringer, explaining the finding. In other words: “The distribution of the cluster is clumped.” And this applies likewise to dark matter. That, according to scientists’ understanding, is what must be behind the galaxy clusters – like an unlit metropolis on the satellite photo of Earth. Only when the lights are turned on do the contours of the city become visible.

Now simulations come into play: Today, cosmologists manage to reconstruct the evolution of space using supercomputers. Ultimately, six parameters are sufficient for this, such as the value at which space expands (Hubble constant), or the density of dark energy, which apparently accounts for 73 percent of the universe; this dark energy is driving space apart at an increasing rate. So the scientists feed their electron brain with half a dozen ingredients, start shortly after the Big Bang, and then let it calculate millions and billions of years into the future.

These simulations give rise to expansive structures that depend on the parameters entered at the outset. “If we vary these parameters, the struc-



Cosmic pattern: Researchers used data from the X-ray satellite *ROSAT* to compile a three-dimensional map of the galaxy clusters. In addition to the positions in the sky, for each cluster, they indicated the redshift as a measure of the distance, thus giving the graphic depth. The different colors stem from different scans; no data is available from the regions without dots. Even without elaborate statistical analysis methods, it appears that the clusters tend to form chains or clumps.

Graphic: designergold (top), MPI for Extraterrestrial Physics (bottom) tures change, too," says Hans Böhringer. "The whole thing runs like a neat, orderly experiment." In this way, it is possible to trace back which initial conditions must have prevailed in the very young cosmos and which parameters must have had which values.

A viable cosmological model naturally offers close agreement between simulation and observation. The described scenario of the inflationary Big Bang does quite a decent job. Also the suspected shares of dark energy (73 percent) and dark matter (23 percent) in the total energy density of the universe appear to fit quite well – "normal" baryonic matter apparently accounts for just 4 percent. Nevertheless, many questions are still unanswered. This doesn't scare Hans Böhringer – on the contrary: "What would be most interesting is if we were to discover something surprising." ◂

TO THE POINT

- **Galaxy clusters are the largest structures in the universe. Most of them are located in a hot gaseous envelope; this halo shows up in X-ray light.**
- **From their analysis of the X-ray halos, astronomers conclude the components of the gas and the total mass of the galaxy cluster. The unknown dark matter makes up more than 80 percent of the mass of a cluster.**
- **Because galaxy clusters trace the expansive structures, they are valuable indicators of the distribution of matter in the universe. They also serve to validate cosmological models.**

GLOSSARY

Baryonic matter: This is generally understood to be the matter that we know and of which the visible world consists. In the narrower sense, baryons are particles that are made up of three quarks, so for instance protons. A distinction is also made between leptons (electrons, for example) and unstable mesons (quark-antiquark pairs).

Plasma: Electrically conductive gas consisting completely of free charge carriers, or in other words, ions and electrons. The ions are atoms that have either more or fewer electrons than in the normal state. Of the baryonic matter in space, 99 percent is in the form of plasma.

Supernova: If a star has more than eight solar masses at the end of its life, and if its internal source of energy (nuclear fusion) has dried up, then the outward-acting radiation pressure can no longer withstand the force of gravity: the sphere collapses and the star explodes. In another type of supernova, a small, burnt-out star (white dwarf) explodes because it is fed with matter by a larger one and, under this excessive intake of food, finally collapses.