The Cosmic **Archaeologist**

He loves basketball and literature, but his real passion is cosmology. **Joe Hennawi** uses telescopes and supercomputers to investigate the largest structures in the universe at the **Max Planck Institute for Astronomy** in Heidelberg – in a research group called ENIGMA. Their aim is nothing less than to unravel the mysteries of the cosmic web.

TEXT **THOMAS BÜHRKE**

Quite a few careers in astrophysics begin with the purchase of a telescope as a teenager. At night, the budding young researcher looks in amazement at the rings of Saturn and the mountains on the moon. For Joe Hennawi, it was rather a series of fortunate incidents that led him to astrophysics; he could just as well have ended up as a writer or a professional basketball player. He now leads a research group bearing the apt name ENIGMA at the Max Planck Institute for Astronomy. Six years ago he received the Alexander von Humboldt Foundation's Sofja Kovalevskaja Award, one of Germany's most prestigious and highly endowed research awards, and he has recently caused quite a stir with several of his discoveries. But first things first.

His office at the Max Planck Institute atop the Königstuhl hill in Heidelberg doesn't reveal anything special – that is, if one ignores the hundred or so empty water bottles glinting in the sun on the window ledge. Astrophysics must make you thirsty. Joe Hennawi focuses on the structure of the universe and often has to cope with massive quantities of data that require efficient computer algorithms to interpret them. "Big data has become a fundamental issue in our field," he says, and adds: "I dedicate about a third of my time to theory, and the other two-thirds to observations using the largest telescopes in the world."

ENIGMA, the collective name of the 15 or so young people in his group, stands for Exploring the Nature of the Inter- and Circum-galactic Media. Even though the acronym is not self-explanatory at first glance, the research direction is clear: it's all about the gas that surrounds the galaxies and permeates the vast spaces in between them. It has a crucial impact on the evolution of the galaxies, our Milky Way included. This gas forms a gigantic cosmic web between the galaxies, and its structure provides us with information about how the universe has evolved since the Big Bang. Hennawi focuses on the big issues in cosmology. But it all began on a rather modest and small scale.

His parents emigrated from Egypt to the US. As Christians – their name means "family of John" – they didn't have the easiest time in their home country. "But they also emigrated for economic reasons," says Hennawi, who was born in 1976 in Salinas, California, not far from Monterey. Both his parents have a business degree, and his father later opened his own shop, where Joe also spent a lot of time.

He received good grades in high school, but he didn't take even one physics course. "Sports was my main focus back then," he recalls. After high school, he didn't apply for a big university, choosing instead to go to a community college in Salinas that had a de-

Photo: Thomas Hartmann

“I’m sticking with cosmology for the moment,” says Joe Hennawi, Research Group Leader at the Max Planck Institute for Astronomy in Heidelberg.

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cent reputation. Here, Joe enrolled in a broad range of courses, continued to play basketball, and even toyed with the idea of a professional career.

His physics teacher finally changed everything. "He was excellent and really inspiring, and we've stayed in contact and remain friends to this day." Joe said goodbye to his dream of being a basketball star and decided to study physics. And his parents? "They weren't too happy about physics. They would have preferred that I pursue a more pragmatic vocation, such as engineering," says Hennawi. His sister chose this path and is now an engineer. But Joe remained true to physics.

His good grades earned him a place at the renowned Stanford University – a huge opportunity. But he met with challenges early on: "I enrolled in a basic course on electromagnetism, and at the end of the first class I was completely frustrated: I thought, I don't know anything, I'm not well prepared for this." Time and again, he thought about giving up; he took a trip to Egypt to learn more about his roots. Ultimately, though, he fought his way through and obtained his master's degree.

THE OLDEST EVIDENCE FROM THE EARLY UNIVERSE

At Stanford he also became acquainted with Einstein's general theory of relativity, which would be a recurring theme in his subsequent work. He worked for a short time on the LIGO project – the detector involved in the spectacular discovery of gravitational waves in February 2016. "Perhaps I should have stuck with that after all," says Joe Hennawi with a grin.

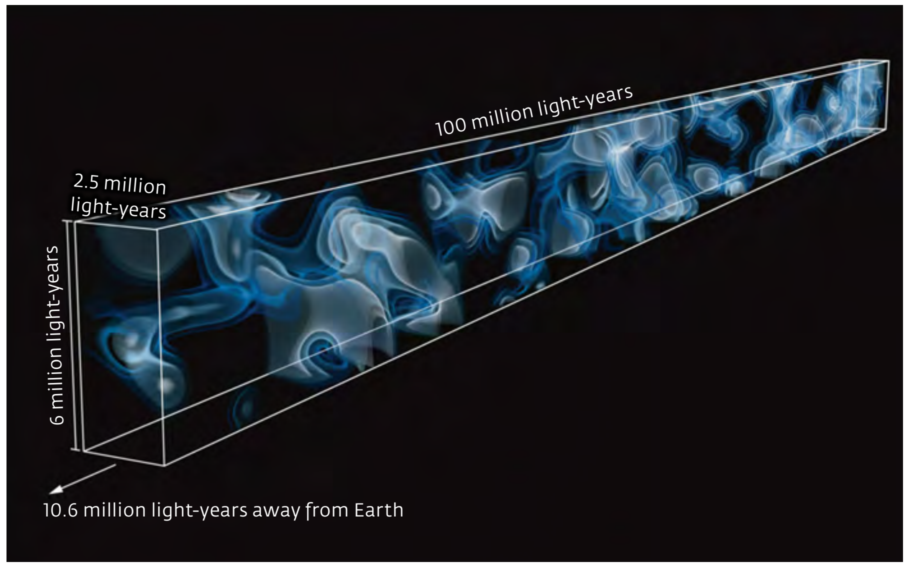
Offered a full scholarship, he moved to the equally renowned Princeton University. This is where Albert Einstein worked until his death, and where there was also a strong cosmology group. Joe Hennawi's doctoral supervisor, David Spergel, was working on observational data from a space telescope known as the Wilkinson Microwave Anisotropy Probe (WMAP), which was being used to investigate the cosmic background radiation. This radiation is considered to be the oldest evidence of the early universe – and it contains a plethora of information about the beginnings of the universe: groundbreaking cosmology in its purest form.

At Princeton, Hennawi worked on the theory of the background radiation, which again involves the general theory of relativity. The cosmic background radiation, relic radiation produced 380,000 years after the Big Bang, fills the entire universe and can be seen in all directions on the sky. It

Photo: Thomas Hartmann

Left page The universe on a computer: Joe Hennawi investigates the largest structures in the universe – on his laptop in a quiet corner of the Institute.

Right Cross-section through the past: Joe Hennawi and his team identified the hydrogen absorption lines of the cosmic web in the spectra of 24 faint galaxies and used them to reconstruct a three-dimensional map that shows a small part of the universe when it was not quite three billion years old. The lighter the color, the higher the density of the hydrogen gas.



thus traveled through the universe for almost 14 billion years before arriving at astrophysicists's telescopes. It went through a lot on this long journey: it traversed gas clouds, either inside galaxies or between them, and was deflected from its straight line of propagation by gravity, as predicted by Einstein's theory.

This cosmic background radiation is thus slightly distorted when it arrives on Earth; it is like looking at it through a pane of translucent glass. On the one hand, this is annoying, as it distorts the information from the early universe; but on the other hand, it also offers a unique opportunity to learn something about the galaxies and the intergalactic matter between them. And this is what Hennawi studied during his PhD at Princeton.

As his doctoral studies drew to a close, he received his first opportunity to undertake astronomical observations himself. "But I wasn't observing at a telescope perched on a mountaintop – I was in the basement of our astronomy department," he remembers, somewhat wistfully. Hennawi operated the telescope in New Mexico via remote control. But things are different now. Today, Joe Hennawi travels to the biggest observatories on Earth in Hawaii and Chile.

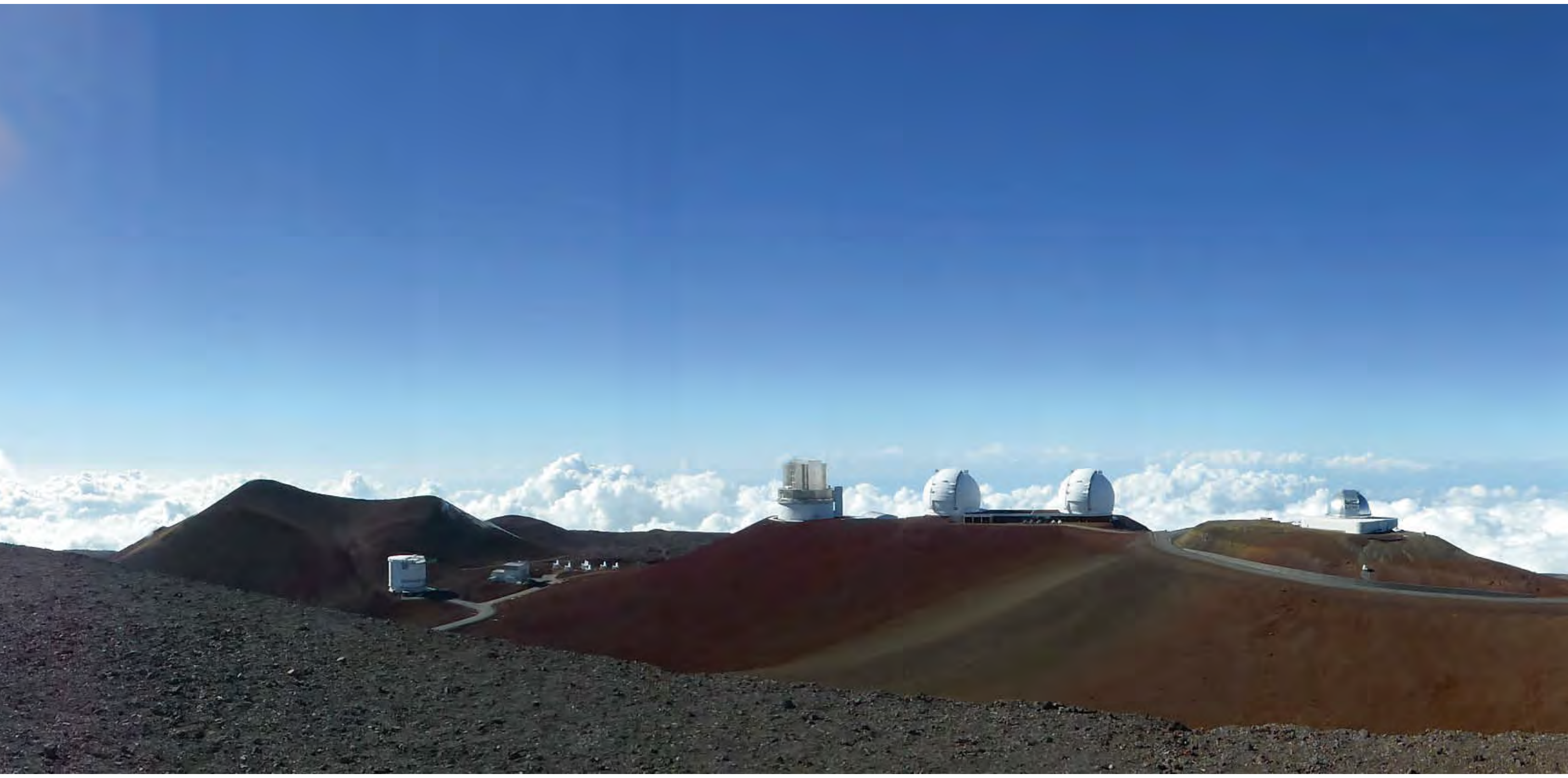
SWIRLING GAS HEATS UP TO SEVERAL MILLION DEGREES

Even though the telescope he used in New Mexico was on the small side, he still discovered celestial bodies that still occupy his attention today: quasars. When they were discovered in the 1950s, they were known as quasistellar objects, as they appeared to be point-like, similar to stars. However, a great many other characteristics indicated that they couldn't be stars. Astronomer Maarten Schmidt solved the puzzle in 1963, and showed that quasars are actually among the brightest and most distant objects in the known universe.

A theory soon emerged about how the huge amounts of radiation could be produced. The idea is that quasars reside at the center of young galaxies that possess a supermassive black hole. These attract gas from their surroundings, which accumulates in a large disk around the black hole before gradually plunging in – like water gurgling into a drain and disappearing. As it falls onto the black hole, the gas heats up to several million degrees and shines incredibly brightly. A quasar shines a thousand times more brightly than the light emitted by everything else in the galaxy – up to hundreds of billions of stars – combined.

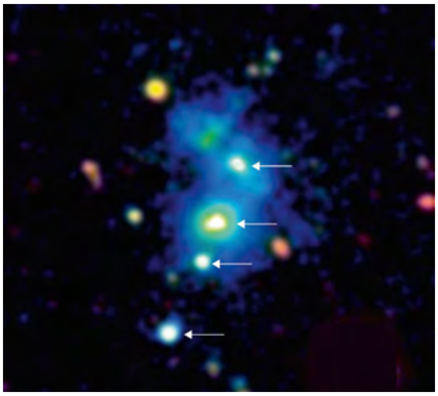
This explanation of quasars is accepted as standard today. And since our current knowledge states that there is a central, supermassive black hole at the center of almost every galaxy, this suggests that every galaxy must also be a quasar – but this is by no means the case. Quite the contrary: quasars tend to be extremely rare, because the quasar activity lasts for only around ten million years. Compared with the typical age of a galaxy of more than ten billion years, this is a very short period of time. It is therefore an improbable stroke of luck if astronomers see a galaxy when it is actually in its quasar phase.

Joe Hennawi continued his work on quasars at the University of California, Berkeley from 2004-2009, where he received a prestigious Hubble Fellowship



Top Above the clouds: Joe Hennawi uses data from the world's largest telescopes for his work – like these on the summit of Mauna Kea in Hawaii. The two white domes (image on this page) conceal the two Keck telescopes, each with mirrors measuring ten meters in diameter.

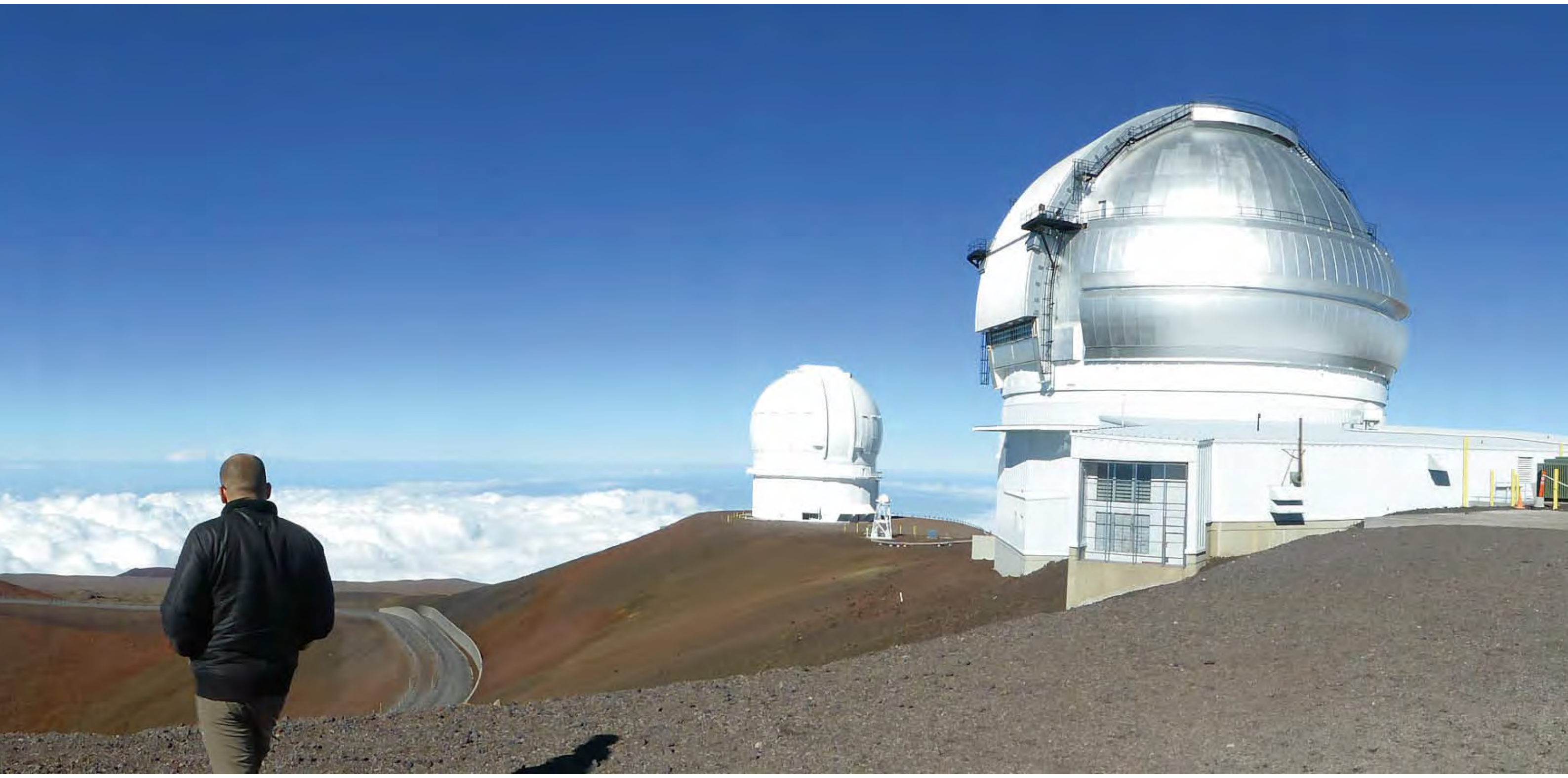
Below Rare shots: Left, a section of the cosmic web (turquoise) stretching over roughly two million light-years, which was observed in the immediate vicinity of the quasar UM 287. The gas glows thanks to the same effect to which fluorescent tubes owe their light. Somewhat smaller, namely around one million light-years, is the nebula in which the four quasars (arrows) in the photo on the right are embedded. The quartet is a rarity; its light needs ten billion years to reach us.



and then a National Science Foundation Fellowship to continue his groundbreaking research. "This is where I learned to handle big data," he recalls. Big data has become a fundamental theme in modern astronomy and astrophysics, as many telescopes record massive amounts of data from large areas of the sky night after night, detecting copious numbers of faint stars and galaxies.

One of these surveys, the Sloan Digital Sky Survey (SDSS), has been running since the year 2000 at the Apache Point Observatory in New Mexico. It uses a custom-designed telescope and has so far imaged billions of celestial objects covering about half of the night sky through multi-color filters, and recorded more than three million spectra of these objects. The result is the most detailed three-dimensional map of the universe ever made. The Max Planck Institute for Astronomy has been involved in the SDSS project since it began, and Joe Hennawi mines this treasure trove of data for his research.

After five years at Berkeley, Hennawi moved to the Max Planck Institute for Astronomy in Heidelberg in 2009. He initially found the charming town a bit small, and chose to live in the bustling metropolis of Frankfurt in-



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stead and commute. From the beginning, it was important to him to learn German, and he enrolled in a two-year German language course that the Humboldt Society offers its award recipients. Eventually Hennawi can even read German literature, from the likes of Max Frisch and Hermann Hesse to Franz Kafka. “But I find Günter Grass too difficult to read in German,” he says, adding “If I hadn’t become an astrophysicist, I probably would have gone into creative writing.”

After less than a year at the Max Planck Institute, he was awarded the Humboldt Foundation Sofja Kovalevskaja Award. He used the prize money of almost 1.5 million euros to expand his research group. Scientific success soon followed.

Around three years ago, his team, together with colleagues from the University of California, Santa Cruz, discovered a quasar surrounded by an unusual nebula. One of its peculiarities was that it extended over roughly two million light-years, so its light couldn’t be attributed to the galaxy hosting the quasar at its center. “We succeeded in detecting part of the cosmic web,” explains Joe Hennawi (MaxPlanckResearch 2/2014, p. 41).

Cosmological models predict that the universe is permeated by a complex web-like network of matter with voids or holes, similar to Swiss cheese. Its walls are filaments of hydrogen gas and dark matter. Galaxies such as our Milky Way, and also quasars, reside primarily at the nodes connecting the filaments of this web. But the gas in this so-called cosmic web is so rarefied that it was never possible to image it directly before. In the case of Hennawi’s nebula, however, the quasar acts like a flashlight that excites the surrounding hydrogen gas to emit light, thus making part of the web visible. The editors of the journal Physics World, published by the British Institute of Physics, chose this discovery as one of the “Top Ten Breakthroughs” of 2014.

THE QUASAR LIGHT TRAVELED TEN BILLION YEARS

In 2015, Hennawi and his colleagues pulled off another feat: they chanced upon a quasar quartet, which was similarly surrounded by a giant nebula of hydrogen gas (MaxPlanckResearch 3/2015, p. 44). To understand the excitement this generated, it must be understood that, although we now know of around half a million quasars, they are spread over vast regions of the sky. It is extremely unusual to find two quasars very close to each other. We currently know of only a hundred quasar pairs,

Research dialog: Joe Hennawi discusses the latest results with his PhD student Anna-Christina Eilers. What fascinates him about cosmology is that it is cleanly and clearly described by the equations of the general theory of relativity.

and just a single quasar triplet. "The probability of a chance coincidence of four quasars in such a small region of space is one in ten million," explains Hennawi, who hence named the quartet the "Jackpot Nebula." Finding this constellation was by no means a mere stroke of luck, as the surrounding region of space also contains several hundred times more galaxies than the researchers expected. They had stumbled upon a rare massive structure in the early universe.

This discovery also attracted significant attention. The US magazine ASTRONOMY ranked it fourth in its top five discoveries – just behind the Horizon probe flyby of the dwarf planet Pluto. To put Hennawi's discovery into perspective, consider that the light from these quasars had been journeying through space for ten billion years before it reached us. This allows researchers to see the universe as it looked more than ten billion years ago, less than four billion years after the Big Bang. In a way, the astronomers are doing cosmic archaeology.

USING NORMAL GALAXIES AS COSMIC LIGHTHOUSES

But there is yet another way of getting to the bottom of the cosmic web, which is spread out over billions of light-years. It bears a remote resemblance to computer tomography, so-called CT scans, in which X-rays are used to scan the inside of the human body from different directions.

To achieve this, the astronomers exploit the fact that the light – from a distant quasar, for example – traverses the walls and filaments of the cosmic web several times as it journeys toward us. Each time it does so, the hydrogen gas absorbs a small amount of the light. If the quasar light is dispersed into its spectral components, the hydrogen absorption appears as a dark line in the spectrum at a very special wavelength.

The fact that space is continuously expanding causes this hydrogen line to shift toward ever longer wavelengths the further the absorbing cloud is away from us. If the quasar light has traversed ten such clouds on its journey, then there will be ten absorption lines at different wavelengths; their positions in the spectrum can be used to determine the distance of the cloud. It is thus possible to determine the spatial distribution of the cosmic web and the density of the hydrogen gas that permeates it.

Since quasars are rare objects distributed all over the sky, aside from the few rare exceptions of multiple systems, researchers can study only single points through the web. However, it would be a different story if one were to use, not quasars, but the much more abundant normal galaxies as the "cosmic light-

Photo: Thomas Hartmann

houses." This seemed to be impossible, because galaxies at these enormous distances are extremely faint. It thus came as a tremendous surprise when Hennawi and his postdoc Khee-Gan Lee tackled this project – with success.

Using the giant 10-meter reflecting telescope known as Keck I on the summit of Mauna Kea in Hawaii, they recorded spectra from 24 faint galaxies and showed how one could identify the hydrogen absorption to construct a map of the cosmic web. "This is the first time we've been able to reconstruct a three-dimensional map of a small part of the universe that stretches back to a time when the universe wasn't even three billion years old," explains Joe Hennawi. This project to map the cosmic web continues. Since their groundbreaking discovery, the scientists have extended their method to large volumes of the universe using a hundred galaxies.

What's next for Hennawi after so many success stories? "I'm sticking with cosmology for the moment," he says. "The Universe is a well-defined physical system that is cleanly and clearly described by the equations of the theory of relativity, but it still offers enough puzzles to keep me busy." The nature of dark matter could be the next frontier: "It turns out that observations of the cosmic web can be used to constrain its quantum mechanical properties," says the Heidelberg-based Max Planck researcher. "The role massive neutrinos play in forming structure in the universe also interests me." In other words, the really big questions. Which, of course, doesn't leave much time for basketball. ◂

GLOSSARY

Cosmic background radiation: Also known as the cosmic microwave background or CMB, as it is observed in the microwave range. It formed around 380,000 years after the Big Bang, when the universe became transparent, protons and electrons bonded together, and light particles (photons) were henceforth able to fly unhindered through space. The background radiation bears the signature from the era in which it was formed and is thus a valuable tool for studying the structure and physical properties of the very young universe.

Wilkinson Microwave Anisotropy Probe: The US satellite, WMAP for short, was launched in 2001 and sent data to Earth until 2010. Its task was to map the irregularities in the cosmic background radiation. Researchers used the measurements to determine the composition of the universe: 4.6 percent normal matter, 23 percent dark matter, and 72 percent dark energy. These values were corrected slightly by its successor, the Planck satellite.