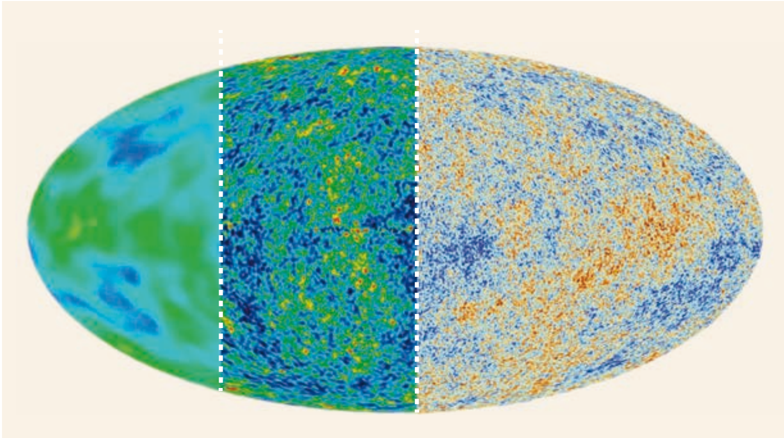
MAX-PLANCK-MEDAILLE

The Quantum Universe

Quantum fluctuations played a crucial role in the formation of the structure of our universe.

Viatcheslav F. Mukhanov

On March 21, 2013 something very remarkable happened. The Planck science team released a highly precise photograph of our universe when it was only few hundred thousand years old. This photograph is so detailed that it shows some major features that the universe acquired only 10^{-35} seconds after creation. Most strikingly, the observed nontrivial features in the portrait of such a young universe came in exact agreement with what had been predicted by the theorists more than thirty years ago, long before the experiment was carried out. Without any exaggeration one can say that by now it is experimentally proven that quantum physics, which is normally considered to be relevant in atomic and smaller scales, also played the crucial role in determining the structure of the whole universe, including the galaxies, stars and planets.



NASA/JPL-Caltech/ESA

The satellite missions COBE, WMAP and Planck successively revealed more and more details of the cosmic microwave background.

Of course scientists and philosophers have always been interested in the origin of our universe. However, cosmology only became a natural science less than a hundred years ago. It was not until 1923 that the American astronomer Edwin Hubble was able to resolve individual stars in the Andromeda Nebula and to conclude that for sure it is located outside of our own galaxy. This was the beginning of extragalactic astronomy. Today it is well established that there are about a hundred billion galaxies in our universe. Thus, the stars form galaxies with a size of about a hundred thousand light years. Moreover, the distance between neighboring galaxies is a few million light years. Observing the spectral lines of the galaxies, Hubble discovered that they are slightly redshifted. He interpreted this as a Doppler shift due to the relative motion of the other galaxies, which try to escape from us. Hubble also found that the spectral lines of galaxies further away show higher redshift. This means that they are escaping with higher velocities, proportional to the distance ($\vec{v} = H\vec{r}$) and thus the universe expands. This discovery was the beginning of scientific cosmology.

With Hubble's discovery it became clear that our universe is evolving as a whole. This did not come as a big surprise! In 1922 the Russian physicist Alexander Friedman had found that the generic solutions of the Einstein's equations describe either an expanding or a contracting Universe. Assuming that the total mass of the universe is about a hundred billion times larger than the mass of our galaxy, Friedman was even able to conclude that the universe must be about 10 billion years old. Thus, Hubble's discovery can be considered as a brilliant confirmation of the theoretical prediction by Friedman. The most important conclusion from Hubble's discovery was that the universe was created about several billions years ago. This extremely important discovery remained for many years the single experimentally established fact in cosmology. Only after more than thirty years the other piece of the puzzle was discovered.

In 1964 the two American radio astronomers Arno Penzias and Robert Wilson detected an unusual noise in their radio antenna. They found that there are radio waves coming from everywhere, from each part of the sky. Because their intensity does not depend on the direction, it was plausible to assume that they were not

IN SHORT

- The Cosmic Microwave Background radiation (CMB) represents a "photograph" of the universe, when it was only 100 000 years old.
- Tiny fluctuations in the temperature of the CMB correspond to inhomogeneities in the matter distribution which much later gave rise to galaxies and the structures we observe today.
- Ultimately the origin of the universe's structure are quantum fluctuations that were amplified during an inflationary expansion in the first roughly 10^{-30} seconds.
- The Planck satellite analyzed the CMB fluctuations with the highest precision so far and confirmed the theoretical predictions with an astonishing accuracy.

Prof. Dr. Viatcheslav F. Mukhanov, Arnold Sommerfeld Center for Theoretical Physics, Chair on Cosmology, Theresienstr. 37, 80333 München – Article on the occasion of the conferment of the Max-Planck-Medal 2015 at the DPG conference in Berlin.

 1617-9439/15/0909-41

emitted by some radio sources, but rather that they had survived since the creation of our universe. In this case they would carry minimal information and could be entirely characterized by their temperature. Measuring the intensity of the radiation at wavelengths of about a few centimeters, Penzias and Wilson found that this temperature must be somewhere between 2.5 and 4.5 Kelvin. The primordial Cosmic Microwave Background radiation (CMB for briefness) homogeneously pervades the space, while the baryonic matter is clustered mostly in galaxies. The number of quanta of the primordial radiation is much larger than the total number of baryons, namely, there is about a billion of photons per baryon.

A Snapshot of the Very Young Universe

The CMB discovery was the beginning of the hot Big Bang theory of the expanding universe. When the universe was a thousand times smaller than now and only a few hundred thousand years old, the CMB temperature was about 3000 Kelvin, which is enough to ionize all the atoms. This time is called recombination time. Before recombination there were a lot of free electrons, which were making the universe non-transparent for radiation. The electrons, baryons and photons were tightly coupled and only at recombination time, most of the free electrons were captured by nuclei and the universe became transparent for primordial radiation. Since then the overwhelming majority of the photons were never scattered by matter and hence they provide us at present with the "photograph" of the very young universe. This photograph, as taken by Penzias and Wilson, shows that although today we see the galaxies, stars etc., there was absolutely no structure when the universe was a few hundred thousand years old. The measured temperature was precisely the same in all directions of the sky; if the amount of matter had been different in various places, one would see temperature anisotropies.

Once again, the fact that the universe might have been hot in the past came not as a big surprise. In fact, Georg Gamov and his colleagues Ralph Alpher and Robert Herman, trying to explain the origin of the light chemical elements, already in 1948 suggested that the temperature in the very early universe might have been extremely high. From the observations of the intensity of the spectral lines it had been concluded that the most widespread elements in our universe are Hydrogen and Helium, which constitute about 75 and 25 percent, respectively. All the other more heavy chemical elements are present only in trace amounts. While heavy elements can still be produced in stars, as a result of nuclear reactions, the origin of Helium was difficult to understand. In fact, assuming that all Helium was synthesized in the stars one must conclude that the brightness of the sky should be about a hundred times greater than what we see in reality. On the other hand, if the Helium was formed in the hot universe when the temperature was very high, all radiation released would since have been thermalized and then cooled down by the expansion. Hence, the assumption that the universe was hot resolved the mystery with the origin of Helium. Although the actual calculations by Gamov, Alpher and Herman were not quite correct, they by fortuity even guessed the correct value for the temperature of radiation. The calculations by Robert Wagoner, William Fowler and Fred Hoyle in 1967 confirmed that the abundance of the light elements can really be explained with the theory of a hot Big Bang.

The Problem of Galaxy Formation

At the end of the seventies, when I took up cosmology, it was only known that the universe is expanding and, most likely, that it was very hot in the past. Although most cosmologists believed that we really see the remnant of the hot Big Bang it was not yet even a 99 percent established fact. To prove that the primordial radiation really survived from the very early universe, one needs to measure its spectrum with very high accuracy, and by the end of the seventies the balloon measurements were delivering contradicting results. Therefore the whole cosmology was entirely based on one and half experimental facts.

One of the problems that seriously occupied cosmologists at that time was the problem of galaxy formation. From the CMB observations it followed that the universe had no structure when it was a thousand times smaller, and the natural question was how the galaxies could be formed in this case? The key idea here is that they were formed as a result of gravitational instability. Because gravity is an attractive force, it works towards making the distribution of matter more and more clumpy even if it was originally nearly homogeneous. Places with larger concentrations of matter attract matter from nearby less dense regions, and finally the universe becomes very clumpy with nearly all baryons ending up in the galaxies and their clusters. However, to get a clumpy distribution of matter today we have to assume that in the early universe there were some initial small inhomogeneities. The answer to the question as to how large these initial inhomogeneities should be depends on the rate with which they grow.

At the beginning of the last century James Jeans found that in a non-expanding media, gravitational instability is extremely efficient and happens exponentially fast. However, in 1946 Evgeny Lifshitz showed that in an expanding universe and on scales larger than the size of causally connected regions, the inhomogeneities do not grow at all because they have no chance to communicate, while when the age of the universe increases and the communication becomes possible, they grow only in direct proportion to the size of the expanding universe. This means that at the galactic scales all initial inhomogeneities were frozen until the universe became about a hundred thousand years old, and only after that they increased by a factor of a few thousand.

Thus, to explain the structure of the universe one needs to assume that the matter density was differing by about 0.01 percent from place to place at the time of recombination. These variations should be accompanied by variations of the radiation temperature. Hence the main cosmological puzzle was why we do not see these small temperature variations (of about 0.01 percent) on the "photograph" of the universe aged a few hundred thousand years? If the radiation has really survived since this time then the temperature fluctuations must be there!

The first theoretical estimates for the expected temperature fluctuations, made by Rashid Sunyaev, Yakow Zeldovich, James Peebles and Jer Yu in 1970, were not so robust and one could explain the apparent absence of said fluctuations by the low sensitivity of the detectors. However, it was also clear that if the theory of a hot expanding universe was correct then finally, after increasing the sensitivity of the detectors, we would inevitably discover these primordial temperature fluctuations. This observational situation also explains why at that time there were so many theories of galaxy formation. Concerning the nature of perturbations one could assume that the radiation and the baryons were both distributed in a slightly inhomogeneous way, while the number of photons per baryon was exactly the same everywhere. This was the essence of the theory of adiabatic perturbations, which was put forward mainly in the Soviet Union and was not so well accepted in the West. Instead, the most popular in US theory, advocated by Peebles, was to assume that initially baryons were distributed slightly inhomogeneously on a completely homogeneous background of photons. Not even the cosmological turbulence theory, explaining the rotation of galaxies, was completely dead at that time. In addition, it was absolutely unclear whether the initial inhomogeneities were completely random (so called Gaussian perturbations) or if some extra information (non-Gaussianity) was encoded in them. For instance, the later developed theories of cosmic strings and textures were predicting very large non-Gaussianity.

This explains why I preferred a more academic topic, which had nothing to do with observations at that time. Assuming that the hot Big Bang was correct, my collaborator Gennady Chibisov and I were going to investigate the possible origin of primordial inhomogeneities, which could later have produced the galaxies. Taking for granted that for some yet unknown reason the universe was created in a completely homogeneous state, we were going to investigate whether quantum fluctuations could in principle be responsible for the origin of the universe's structure. In the middle of 1979 when we began our work on this topic we had nothing to build on. The first task we faced was to quantize the cosmological perturbations. The quantization of the linearized gravitational waves was well known, but nobody before had tried seriously to consider the quantum gravitational field induced by quantum matter. The Heisenberg uncertainty relation inevitably leads to a minimal level of inhomogeneities in the matter distribution. We wanted to use these inhomogeneities to produce galaxies. At first glance the idea looks a bit crazy as quantum effects are significant only on the scale of atoms or smaller. However one should not forget that after the creation of the expanding universe all matter in our galaxy was concentrated within scales smaller than even the atomic scale. This is why quantum mechanics might be significant on those scales which today have become huge, due to the expansion of the universe. If we were right, the expansion would provide us with a missing link between atomic and galactic scales, relating micro and macro physics. In the spring of 1980 the theory of quantum cosmological perturbations was essentially completed. The first thing we proved was that in a decelerating expanding universe the quantum fluctuations can never be amplified to the required level. Therefore, the only remaining possibility was to consider a universe which in the very remote past went through a stage of accelerated expansion (known today as cosmic inflation). This worked! Thus, by the end of 1980 we had completed the theory of the quantum origin of the universe's structure. The theory makes very definite predictions, which in principle can be experimentally verified. Namely, we have found that if the primordial inhomogeneities originated from the initial quantum fluctuations they should be a) adiabatic, b) Gaussian, and c) the amplitude of the gravitational potential resulting from these inhomogeneities should logarithmically grow to larger scales. Let me elaborate a bit on these predictions. Adiabaticity means that although the density of the baryons and dark matter could slightly vary from place to place, the number of photons per baryon (or cold dark matter particle) must be strictly the same throughout space. The metric of the slightly inhomogeneous Friedmann universe can be written as

$$ds^2 = \mathrm{a}^2(\eta)[(1+2\Phi)\,d\eta^2 - (1-2\Phi)\,d\vec{x}^2]$$

where $\mathrm{a}(\eta)$ is the scale factor which characterizes the expansion of the universe and Φ is the gravitational potential due to the small inhomogeneities. Since the primordial fluctuations were obtained as a result of the amplification of initially Gaussian quantum fluctuations by the external classical source (they acquired energy from the Hubble expansion), the resulting gravitational potential must be described by a Gaussian random field up to the second order corrections due to the nonlinearity of the Einstein equations, that is,

$$\Phi = \Phi_{\mathrm{gauss}} + f_{\mathrm{NL}}\Phi^2_{\mathrm{gauss}},$$

where the non-Gaussianity parameter f_{NL} must be of order unity, that is, $f_{\mathrm{NL}} = O(1)$. Because the gravitational potential is of order $O(1) \times 10^{-5}$ the admixture of non-Gaussianity must be extremely small and not exceed 10^{-9}. The most striking prediction concerns the spectrum of the inhomogeneities. As we have discovered, the spectrum right after the stage of the accelerated expansion must be logarithmic

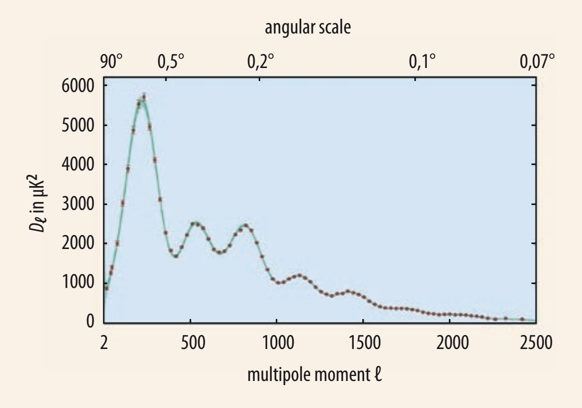


Fig. 1 The temperature fluctuations of the CMB as function of angular separation between antennas. The experimental results (red points) are in very good agreement with the theoretical prediction (green curve).

$$\Phi(\lambda) \propto \ln(\lambda/\lambda_0)$$

that is, the amplitude of the gravitational potential must grow slightly with the scale of perturbation λ. The physical reason for this logarithmic growth is the necessity to have a graceful exit from the stage of accelerated expansion. Within the range of scales we can observe today, this logarithm can be approximated as

$$\Phi(\lambda) \propto \lambda^{1-n_s},$$

with the spectral index n_s equal to 0.96! Soon it became also clear that if the universe had gone through a stage of accelerated expansion then it should inevitably be flat today, i.e. its geometry should be Euclidean.

Thus, the theory makes four very nontrivial predictions. Obviously the next step in falsifying this theory would be the experimental verification of the predictions above. However, the state of observational cosmology at the beginning of the eighties was rather poor and it was impossible even to imagine that these predictions could ever be verified, even many hundred years from now. Moreover, in the eighties and even in the nineties, the astronomical observations seemed to be in complete contradiction with the predictions above. In fact, until about 1998 all astronomical observations were forcefully pointing out that there is not enough matter in the universe to make it flat and it should appear to have a Lobachevskian geometry on cosmological scales. The adiabatic, Gaussian perturbations were also not the most favorable, from the point of view of observations. Many astrophysicists thought that entropy perturbations or cosmic topological defects described the observations much better than adiabatic, Gaussian perturbations. The accuracy of the observations was not allowing even to dream to find the predicted tiny logarithmic variations of the initial inhomogeneities on the different cosmological scales. Only because of the bad quality of the astrophysical data the theory of quantum cosmological perturbations was not abandoned right away. At this time even the Cosmological Principle was not yet proven, the spectrum of cosmic radiation was not yet fully established and moreover nobody had ever seen the expected temperature variations in the sky. Clearly, under these circumstances, one could put in doubt the hot expanding universe, but on the other hand nobody could say that our theory was for sure wrong either.

Cosmology as Precision Science

The situation with cosmological observations started to change drastically only at the beginning of the nineties. In 1992 the first results of the COBE (Cosmic Background Explorer) space mission were released. According to the Nobel Prize Committee citation, these results marked "the starting point for cosmology as a precision science". I would even say: this was the beginning of scientific cosmology. In fact, in 1987 a Japanese-American team announced a substantial deviation from the black body spectrum in CMB (Cosmic Microwave Background) in their sounding rocket experiment. If they were right this would be the end of the theory of hot Big Bang. Therefore, everybody was eagerly awaiting the results of COBE, which was expected to say the final word.

COBE contained two instruments: FIRAS (Far-InfraRed Absolute Spectrophotometer, Principle Investigator: John Mather) and DMR (Differential Microwave Radiometer, PI: Georg Smoot). Due to an ingenious idea FIRAS was supposed to measure the spectrum of CMB with exquisite precision, while DMR was going to look for the tiny variations in the CMB temperature. The results of the measurements were sensational. It was found that the CMB had the most perfect thermal spectrum with the temperature of 2.726 Kelvin. Thus the primordial origin of the CMB and the hot universe became a fact beyond any doubt. The DMR instrument made an even more revolutionary discovery. For the first time it had detected the anticipated tiny variations in the temperature in different directions on the sky, which were of order 0.0001 degree. Thus we finally could see the "galaxy embryos" in a few hundred thousand years old universe. From this picture we also could easily restore the rough portrait of a much younger universe when it was only a tiny fraction of a second old.

Indeed, from the Einstein theory of gravity it follows that the inhomogeneities on the scales much larger than the size of causal region are not developing at all when the universe decelerates. Therefore, irrespective as to how early they were produced, the "galaxy embryos" survive completely frozen and unchanged until the universe becomes about a hundred thousand years old. This is the power of gravity! It does not care about other unknown physics at extremely high energies when it goes about creation of the whole world! The galaxy embryos "wake up and begin to develop" only when the universe becomes about a hundred thousand years old. But at this time we know all physics behind and we can take complete control of the further evolution of the "embryos".

Thus, the COBE results have proven that we really live in a hot expanding universe and even provided us with the picture of the primordial "seeds". This picture nevertheless was not yet detailed enough to draw any conclusion about the origin of the initial inhomogeneities. In fact the resolution of DMR was not too high and the "number of pixels" on the photograph of the universe at a hundred thousand years was not allowing us to see the detailed structure of the "embryos of galaxies". Therefore, although the COBE results were not contradicting the quantum perturbations theory, they were also consistent with the other theories, as, for example, cosmic strings, textures and even entropy perturbations. Since then the main task has been in improving the resolution of the CMB measurements.

In the nineties there was a tremendous progress in observational extragalactic astronomy due to the new and much more advanced telescopes like the 2.4-meter Hubble Space Telescope, the two 10-meters Keck telescopes on Hawaii, the Very Large Telescope in Chile with four mirrors, 8 meters each, and many others. The telescopes allowed us to increase drastically our knowledge of the present state of the universe. There were some results that were extremely important for cosmology. Already in the eighties a lot of data had been collected, all pointing out that there must be dark matter in the universe that is invisible to telescopes; otherwise it was simply impossible to explain the rotational curves of galaxies and the dynamics of their clusters. The main puzzle was: what constitutes this dark matter? Already in the eighties the deuterium abundance was strongly indicating that the baryons can perhaps not constitute this invisible matter. However, the idea that the dark matter may be made of new unknown particles, never seen on accelerators before, was only taken seriously much later. In the mid-nineties all astronomical observations were indicating that the amount of this dark matter in galaxies and clusters was obviously not enough to make the universe flat as predicted. If that result would persist then it would be the end of the theory of quantum perturbations and inflationary cosmology, irrespective of how beautiful the idea may be.[1] Fortunately, the missing matter required to make the universe flat was finally found, and first in astronomical observations. In 1998 two research teams led by Saul Perlmutter and Brian Schmidt, Adam Riess observing supernovae at very large distances found strong indications that now the universe accelerates again and therefore it should be dominated by dark energy. In distinction from dark matter, this dark energy anti-gravitates and it is spread homogeneously around the whole universe. Therefore we could not see too much of it in the clusters. Thus was discovered the missing matter, which was able to make the universe flat and hence to save the theory. Among other astronomical observations that were crucial for cosmology I would also like to mention the Sloan Digital Survey. In this survey the 2.5-meter telescope was collecting the redshifts of more than a million galaxies. As a result, the Cosmological Principle, which tells us that on large scales the universe is homogeneous and isotropic, was finally robustly proven and became a fact.

Unlike astronomy, the CMB observations do not suffer so much from uncontrollable systematic errors and provide us with a picture of the young universe when it was much less sophisticated than now. Therefore we can learn much more about its creation from these observations. Because of the enormous progress in sensitivity of the detectors after COBE, it also became possible to measure the temperature variations with balloons and even from the ground. These experiments were of course limited because they could provide only a relatively small part of the whole picture, taking it in the most clean, transparent directions of the sky. However, the resolution of these experiments was at least ten times better than with COBE. Therefore, they could provide us with a more refined pattern of the galactic embryos that started to develop around that time. In fact, when the universe got a hundred thousand years old, the inhomogeneities which were frozen before, evolve like standing sound waves. As a result the temperature difference between two antennas depends on their angular separation, and for adiabatic perturbations there must be many maxima (called Doppler peaks) for various angular separations. The location and strength of these maxima depend not only on the initial pattern of inhomogeneities but also on the composition and geometry of the universe. In the case of a flat universe the first Doppler peak must be at one angular degree separation between antennas. This was a first big triumph of the theory, when in 1999 in two ground-based experiments in Saskatoon (a city in Canada) and MAT/TOCO (Cerro Toco is a mountain in Chile), led by Lyman Page, it was discovered that this peak is really located at one degree and therefore the universe must be flat. Thus, it was established that dark energy really provides the missing matter in exactly the right amount. Within several months this result was confirmed in the great Italian-American balloon experiment Boomerang, led by Paolo de Bernardis and Andrew Lange. In addition, Boomerang detected for the first time the second and third Doppler peaks. This very strongly favored the theory of adiabatic perturbations compared to cosmic strings, textures and entropy

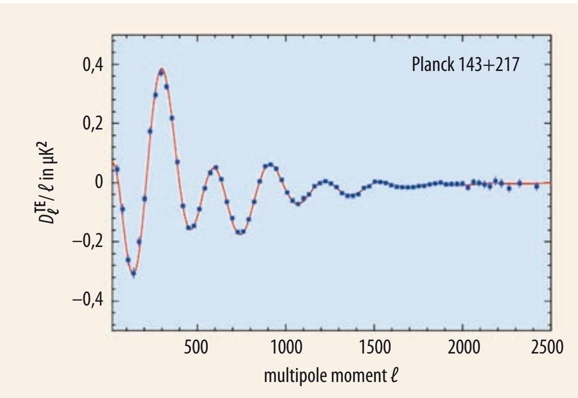


Fig. 2 The Planck results for the correlation between temperature and polarisation (blue points) are in excellent agreement with the theoretical prediction (red curve).

1) The aesthetic value of a theory cannot be used as a proof of its correctness, contrary to the belief of many theoretical physicists nowadays. Only experiment can decide the fate of the theory! Even Einstein made a mistake when he called the introduction of the cosmological constant, which was spoiling the beauty of his theory, the "greatest blunder of my life". Contrary to Einstein, the Nature seems to like this constant.

perturbations, and allowed us to establish robustly that the dark energy really constitutes most of the matter within the universe. After that there were a few dozens of other great ground based and balloon experiments with even better resolution, which fully confirmed the results of Saskatoon, MAT/TOCO and Boomerang. Thus at the beginning of this century the quantum perturbations theory lost its competitors, but still it was not yet 100 percent proven.

The main disadvantage of the ground based and balloon measurements is that they can provide only a small part of the photograph of the early universe. To get the whole picture we still need to go into space, with much more expensive space missions. In 1996 NASA selected a space mission devoted to CMB: the Wilkinson Microwave Anisotropy Probe (WMAP), led by Charles Bennett and Lyman Page. It was launched in June 2001. WMAP was about forty times more sensitive and had thirty times better resolution compared to COBE. It was collecting data for about nine years and has provided us with an excellent full sky map of the early universe. Already after the first release in 2003 it became clear that the data were in very good agreement with the predictions of the theory of quantum fluctuations. With more data coming in, this became even more obvious. These data were strongly favoring the Euclidean universe with adiabatic, Gaussian perturbations that slightly grow towards the larger scales. However, there still were many sceptics doubting the Gaussianity and scale dependence of the amplitude of inhomogeneities in the early universe. The final word here was said by the Planck experiment. Although the Planck mission was selected by the European Space Agency (ESA) around the same time as WMAP, its launch was delayed until May 2009. The Planck mission is the ESA satellite project, combining two experiments (PIs Jean-Loup Puget and Nazzareno Mandolesi). It was a hundred times more sensitive and had about five times better resolution than WMAP. Therefore it is not surprising that it delivered the most perfect available all-sky maps of the early universe, released on March 21, 2013 and in February of this year. From these maps we have learned that our thirty-five-year-old predictions are confirmed at an astonishing 99.9999999... percent level of confidence. In particular, it was found that the universe is flat with an accuracy better than half a percent, the adiabatic perturbations are perfectly Gaussian with amazingly high accuracy ($f_{NL} = 0.8 \pm 5$), better than one over ten thousand of the value of the temperature fluctuations. Finally, the spectral index of inhomogeneities was found to be 0.965 ± 0.005 (my prediction with Chibisov in 1981 was 0.96). Along with numerous recent astrophysical observations, as for example baryon acoustic oscillations, direct deuterium abundance measurements and others, CMB experiments nicely put "all pieces of the puzzle together" and establish the picture of the quantum origin of the universe structure beyond any doubt.

Conclusion

By now we know that we live in a universe where the baryons that we are made of constitute only five percent of the total matter. The rest is dark and it is composed of two components: dark matter and dark energy. The amount of dark energy is two and half times larger than the amount of dark matter. In distinction from dark matter, which gravitates, the dark energy anti-gravitates. Its role is not quite clear at present, but in a very remote past a similar substance may have been responsible for the amplification of quantum fluctuations. Any theory explaining the origin of galaxies is now based on the quantum theory of cosmological perturbations, the predictions of which were so brilliantly confirmed by the CMB measurements. For the quantum origin of the universe's structure there is no alternative anymore.

Thus, from cosmology we have established that Einstein's General Relativity is valid nonperturbatively, on scales much larger than the curvature scale. Moreover, we have found that gravity is the most universal force, which has been experimentally tested on scales spreading over a huge range: from those which are a billion times smaller than the ones probed in accelerators to those ranging over many billion light years. Finally we have learned that we all originate from tiny quantum fluctuations.

References

[1] *G. V. Chibisov* and *V. F. Mukhanov*, Galaxy Formation and Phonons, Lebedev Phys. Inst. Preprint No. 162 (1980); MNRAS **200**, 535 (1982)

[2] *V. F. Mukhanov* and *G. V. Chibisov*, JETP Letters **33**, 532 (1981)

THE AUTHOR

Jan Röhl

Viatcheslav F. Mukhanov (left, with DPG president E. Krubasik) studied physics at the Institute for Physics and Technology in Moskau where in 1982 he also earned his PhD in physics and mathematics working under Vitaly Ginzburg. After some time at the Institute for Nuclear Research in Moskau Mukhanov was appointed lecturer at the ETH Zürich (1992 – 1997). Since 1997 he holds the chair for cosmology at Ludwig-Maximilians-University Munich.

