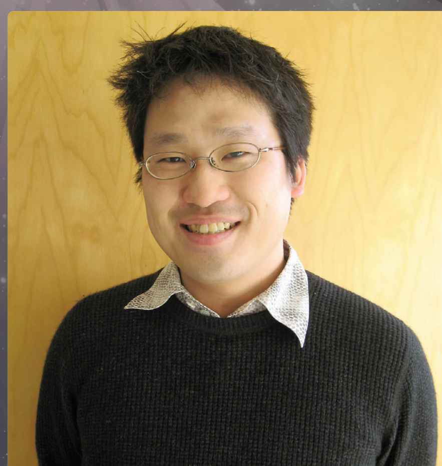
Looking back

Professor Eiichiro Komatsu at the University of Texas at Austin and Max-Planck-Institute for Astrophysics explains how he is testing the theories of cosmic inflation using analysis of non-Gaussian fluctuations to observe the early Universe



To begin, could you outline the main aims and objectives of your research?

The main goal of my research is to figure out what powered the Big Bang. Now we think that preceding the epoch of the Big Bang, when the Universe became hot, there was a period called 'cosmic inflation', during which the Universe is thought to have expanded exponentially. My research is focused on understanding the physics that drove cosmic inflation. A unique aspect of my research is that we are not solely relying on theoretical understanding of the physics of inflation: we use both theory and observations to approach the problem.

Could you explain the meaning of 'gaussianity' and how primordial density fields often experience non-linearity?

`Gaussianity' refers to the fact that the probability distribution of certain variables obeys Gaussian statistics. If we measure the temperature of the sky in many lines of sight, we can make a histogram of the values. Now, if this histogram shows a Gaussian distribution, which is bell-shaped (also known as the normal distribution), then we say that the probability distribution of the temperature on the sky is `Gaussian. If this histogram does not resemble Gaussian, then we say we see `non-Gaussianity', a departure from Gaussian statistics.

During the period of cosmic inflation, the Universe expanded exponentially, stretching microscopic scales to macroscopic scales, with regions the size of subatomic particles becoming the size of solar systems in a tiny fraction of a second. Initial fluctuations created as quantum fluctuations when the universe is tiny are stretched by inflation to macroscopic scales. Non-gaussianity usually arises when non-linearity exists in the system. Non-linearity arises in a few ways. Quantum fluctuations may generate non linearity by interacting with each other, as might the process by which these quantum fluctuations are turned into macroscopic fluctuations in space and time, seeding the large scale structure of the universe. Moreover, the subsequent evolution of macroscopic fluctuations may generate non linearity. All of these non-linearities (hence non-gaussianities) are expected to be small (in the order of one part in 1,000 to 100,000), but can be measured observationally if we use sensitive instruments.

What is the importance of heat in the study of cosmic physics?

As we know that the Universe had to become hot in order to synthesise helium nuclei by fusion, the temperature of the Universe had to be as high as a billion Kelvins when the Universe was about three minutes old. We now know that most of the helium nuclei that we see in the Universe came from the early Universe. It is likely that the temperature was much higher when the Universe was younger

Tackling the **big questions**

A **University of Texas** study into the statistical properties of quantum fluctuations generated during the inflationary period of the early Universe could pave the way for the next 10 years of research

SOME OF THE MOST compelling questions that mankind has ever contemplated concern the beginning of the Universe. When we look out at the cosmos, we find millions of galaxies containing untold billions of stars, continually exploding, colliding and expanding in a ceaseless cosmic dance, the mindboggling vastness of which we have only recently become aware.

In many places early civilisations are known to have painstakingly recorded the phenomena they encountered in the skies, quantifying and speculating on the nature of cosmic events such as comets and meteors, eclipses and supernovae; operating at the very limits of comprehension, and predisposed by evolution to prefer, in the face of uncertainty, a poor answer over no answer at all. It seems only natural that our primitive forebears would invoke the will of the gods to explain their observations. In the modern era, however, we have a sharper set of tools at our disposal, and little by little the layers of uncertainty surrounding these fundamental questions are being stripped back to reveal the truths that eluded our ancestors.

In the mid-1920s Monsignor Georges Lemaître first proposed his 'hypothesis of the primordial atom'; since then what would become known as the Big Bang theory has established itself as a commonplace of popular culture. Edwin Hubble's 1929 discovery that the distances to far off galaxies are generally proportional to their redshifts – meaning that the further away an object is, the faster it is travelling – confirmed Lemaître's prediction of a continually expanding universe. The most comprehensive explanation for the range of phenomena we are confronted with, the Big Bang theory is well supported by evidence, such as the increasingly detailed picture of the cosmic microwave background radiation (CMB). However, there are still many mysteries surrounding this event.

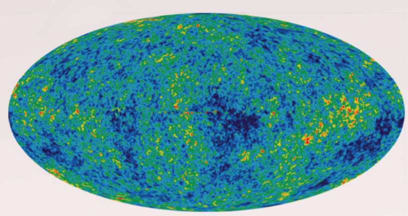


FIGURE 1. Full-sky map of temperature anisotropy of the cosmic microwave background obtained by the Wilkinson Microwave Anisotropy Probe (WMAP) collaboration. Red and blue regions indicate hot and cold regions on the sky.

AREAS OF UNCERTAINTY

Thanks to advances in technology and theoretical physics, observational data can be used to seek answers to questions such as what powered the Big Bang, and what happened prior to it. Observations indicate that, shortly after the universe was born, there was a period called 'cosmic inflation', during which the Universe expanded by a large factor – so large that the size of a subatomic particle would become the size of a solar system in a tiny fraction of a second. Several ingredients of the inflationary theory were discovered in the early 70s, and a relatively simple model was fleshed out in 1981 by cosmologist Alan Guth. This is now known as 'old inflation', having subsequently proved to be unworkable, but it played a profound role in the development of inflation cosmology, by showing how inflation could solve major problems such as the Universe's mysterious homogeneity.

One of the major successes of inflation is that it can explain the origin of structures in the Universe: galaxies, planets, even ourselves. However over the last three decades, it has become clear that vastly different physical models can achieve the exponential expansion, making it increasingly difficult to identify the physics driving it. Despite its success at providing explanations, the details of the physics of inflation – what drove it, how it happened and how it ended, along with many essential fundamental properties of inflation – are all still unknown, making inflation models very hard to falsify. With so many potential models, it seems they could explain virtually anything – which is another way of saying they explain nothing.

FALSIFYING THE THEORIES

A team of researchers at the University of Texas, led by Professor Eiichiro Komatsu, has made falsification a cornerstone of their methodology, focusing their attention on the specific statistical properties of quantum fluctuations generated during inflation, which would have had the effect of seeding the structures we see today.

than that, so heat had to play an important role in the evolution of the early universe.

Could you provide insight to the meaning of cosmological perturbation theory and how it underpins your research?

Cosmological perturbation theory plays an essential role in my research. It describes how perturbations such as density fluctuations evolve according to General Relativity. Using the evolution described by the theory, we can take the observed fluctuations and evolve them backward in time to study how they must have looked in the past, so cosmological perturbation theory even makes it possible to study the properties of fluctuations as they were generated during inflation.

Have you experienced difficulties in obtaining reliable observations or results? How do you minimise inaccuracy?

I have been a member of the Wilkinson Microwave Anisotropy Probe mission, a satellite mission to map the temperature and polarisation anisotropies of the cosmic microwave background (CMB). We have encountered many difficulties, especially for polarisation measurements, as polarisation is fainter than temperature by an order of magnitude. We think we have minimised systematic uncertainties to the level that they are insignificant compared to statistical uncertainties.

How will this investigation aid future study into the understanding of the cosmos?

I certainly hope this line of investigation adds to our understanding of the Universe at a fundamental level. The realisation that we can use both CMB and the large scale distribution of galaxies to study the physics of inflation in the period shortly after the birth of the Universe using observational means is truly a remarkable one.

INTELLIGENCE

THE PHYSICS OF INFLATION: NON-GAUSSIANITY, REHEATING AND PREHEATING

OBJECTIVES

This research focuses on non-Gaussianity of primordial fluctuations, and reheating and preheating after inflation. The Principal Investigator has developed and is continuing to develop new quantitative tests of inflation with non-Gaussianity. The project will focus on the higher correlation functions such as the Trispectrum (four-point function) which directly measures scattering effects and how they affect primordial non-Gaussianity, including non-linear effects such as scattering in the Boltzmann equation which describes the evolution of the fluctuations.

KEY COLLABORATORS

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EIICHIRO KOMATSU is a cosmologist who studies the origin and composition of our Universe. He has been Director of Max-Planck-Institut für Astrophysik since 2012. Before moving to Germany, he was Professor at the Department of Astronomy and Director of Texas Cosmology Centre at the University of Texas at Austin.

As different inflation models make specific, testable predictions for the statistical properties of quantum fluctuations, the statistical properties of the observed structures, such as fluctuations in the CMB and in the large scale distribution of matter, can be used to study the physics of inflation. By analysing the correlation functions of the CMB as well as those of galaxies at high redshifts, useful information about the origin and evolution of structures in the Universe can be obtained.

THE POWER SPECTRUM

The power spectrum is a measure of the correlation of the spatial distribution of galaxies – the larger the value is, the stronger the correlation. The power spectrum is a function of spatial scales, and thus it describes the correlation as a function of spatial scales. Cosmic inflation makes a specific prediction for the shape of the power spectrum – in other words, that the spatial correlation between galaxies has been set by the initial fluctuation during the inflation epoch. It follows that it is possible to study the correlation properties of initial fluctuations generated during inflation by analysing the measured shape of the power spectrum, as if the Universe knew where galaxies would form as soon as it was born.

THREE POINT FUNCTIONS

The tools used are N-point correlation functions; the power spectrum above uses correlations between two points in space, but the group is looking more at three and four point functions, the three point function being particularly useful as it vanishes for Gaussian fluctuations. Most inflation models predict that fluctuations obey Gaussian statistics, so the team is looking at the specific properties of 'non-Gaussianity', specifically the three point correlation function of fluctuations.

As connecting three points forms a triangle, one can measure three point correlations with a variety of triangular shapes. The so-called 'squeezed shape' is the most important, as this form cannot be produced by inflation models which are driven by one energy component. The team has investigated the extent to which this can be used to rule out some inflation models, finding that this is indeed a powerful way to exclude single component inflation. Moreover, they found that a slightly different version of the squeezed shape is sensitive to the initial state of quantum fluctuations, allowing us to look into the details of physics of inflation: namely, whether the initial state was a vacuum or already occupied by particles. The group also investigated whether it is possible to falsify inflation regardless of the number of energy components during inflation, finding that most inflation models should yield an inequality between the three and four point functions with specific shapes regardless of the number of energy components. Thus, detecting a violation of this inequality would challenge the inflationary paradigm as a mechanism for generating observed structures in the universe. All these hypotheses can be tested using observational data which will soon become available, such as CMB data from ESA's Planck satellite.

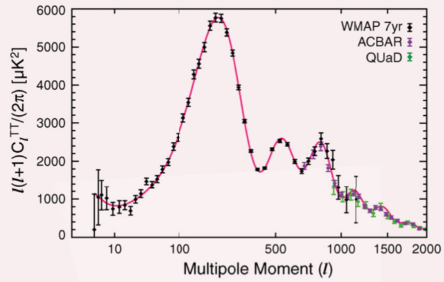

FIGURE 2. Power spectrum (two-point correlation function) of the map shown in Figure 1. The horizontal axis shows the angular wavenumber, l, which corresponds to 180 degrees divided by the angular separation on the sky (ie. larger values of l correspond to smaller angular separations on the sky). The vertical axis shows the strength of the fluctuation at a given angular wavenumber.

GREAT POTENTIAL

To date, observations of fluctuations in the CMB and the large scale structure of the Universe have focused largely on the Gaussian contribution as measured by the two point correlations of density fluctuations. However, an even greater amount of information is contained in non-Gaussianity, which can be measured with many observational probes, including CMB, large-scale structure, gravitational lensing, and the abundance of rare objects such as galactic clusters and high redshift galaxies. This maximises the science return from a range of present and future cosmological experiments, carrying great potential for important discoveries in the coming decade.

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