Researchers study a million galaxies to find out how the universe began

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Figure 1: An image obtained from observations of large-scale structure of the universe. The numerous objects shown in yellow to red all represent galaxies hundreds of millions of light years away from Earth. The galaxies come in a wide variety of colors and shapes, and are too numerous to count in the vastness of space. The spatial distribution and shape pattern of these galaxies are not random, but indeed have "correlations" originating from statistical properties of the seed primordial fluctuations as predicted by inflation. Credit: Subaru HSC

A team of researchers has analyzed more than 1 million galaxies to explore the origin of the present-day cosmic structures, as reported in a recent study published in *Physical Review D* as an Editors' Suggestion.

Until today, precise observations and analyses of the cosmic microwave background (CMB) and large-scale structure (LSS) have led to the establishment of the standard framework of the universe, the so-called ΛCDM model, where cold dark matter (CDM) and dark energy (the cosmological constant, Λ) are significant characteristics.

This model suggests that primordial fluctuations were generated at the beginning of the universe, or in the early universe, which acted as triggers, leading to the creation of all things in the universe including stars, galaxies, galaxy clusters, and their spatial distribution throughout space. Although they are very small when generated, fluctuations grow with time due to the gravitational pulling force, eventually forming a dense region of dark matter, or a halo. Then, different halos repeatedly collided and merged with one another, leading to the formation of celestial objects such as galaxies.

Since the nature of the spatial distribution of galaxies is strongly influenced by the nature of the primordial fluctuations that created them to begin with, statistical analyses of galaxy distributions have been actively conducted to observationally explore the nature of primordial fluctuations. In addition to this, the spatial pattern of galaxy shapes distributed over a wide area of the universe also reflects the nature of the underlying primordial fluctuations (Figure 1).

However, conventional analysis of large-scale structure has focused only on the spatial distribution of galaxies as points. More recently, researchers have started studying galaxy shapes, because it not only provides additional information, but it also provides a different perspective into the nature of the primordial fluctuations (Figure 2).

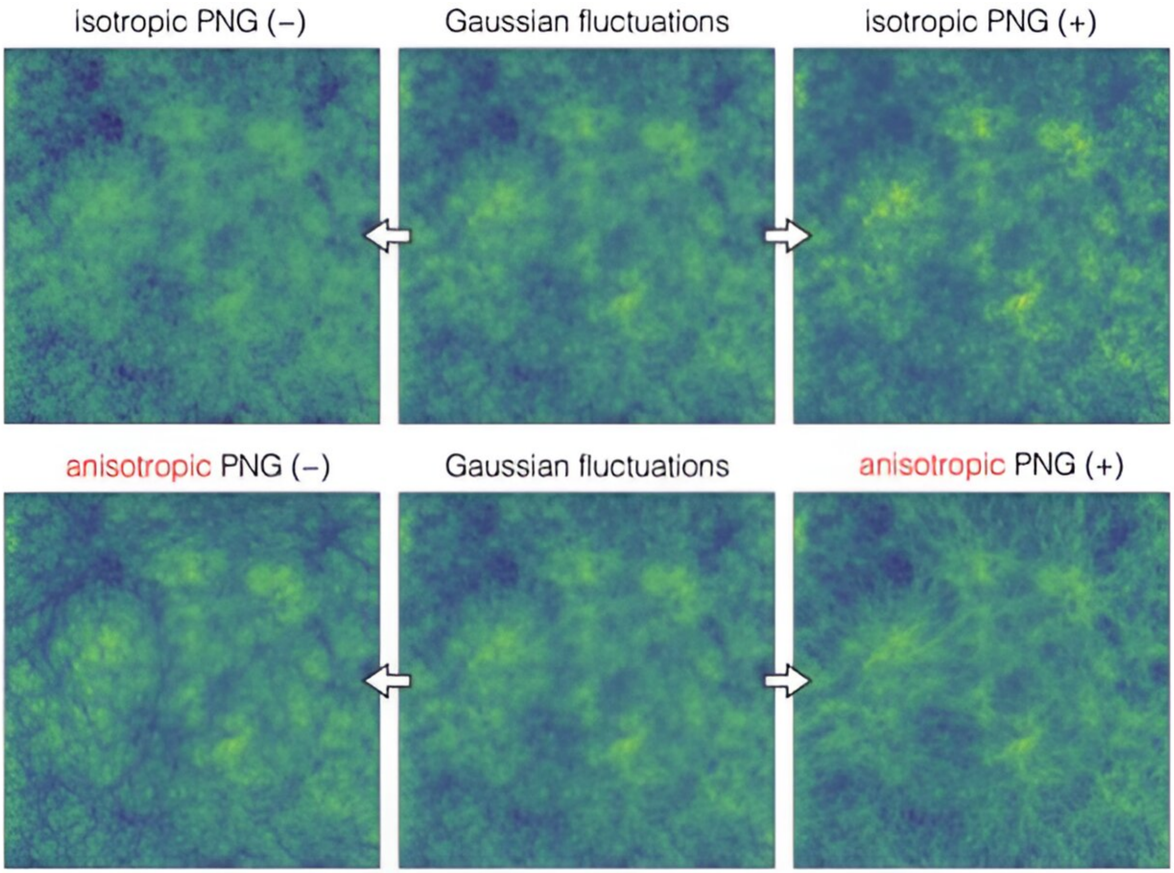

Figure 2: Visualization of how the "different" primordial fluctuations of the universe lead to the different spatial distribution of dark matter. The central figure (common to both the upper and lower rows) shows the fluctuations in the reference Gaussian distribution. The color gradation (blue to yellow) corresponds

to the value of the fluctuation at that location (low to high density regions). The left and right figures show fluctuations that deviate slightly from the Gaussian distribution, or are non-Gaussian. The sign in parentheses indicates the sign of the deviation from Gaussianity, corresponding to a negative (-) deviation on the left and a positive (+) deviation on the right. The top row is an example of isotropic non-Gaussianity. Compared to the central Gaussian fluctuation, the left figure shows an increase in large negative (dark blue) regions, while the right figure shows an increase in large positive (bright yellow) regions. It is known that we can search for such isotropic non-Gaussianity using the spatial distribution of observed galaxies. The lower panel shows an example of anisotropic non-Gaussianity. Compared to the isotropic case in the upper panel, the overall brightness and darkness is unchanged from the Gaussian fluctuation in the central panel, but the shape of each region has changed. We can search for this "anisotropic" non-Gaussianity from the spatial pattern of galaxy shapes. Credit: Kurita ▯ Takada

A team of researchers, led by at-the-time Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU) graduate student Toshiki Kurita (currently a postdoctoral researcher at the Max Planck Institute for Astrophysics), and Kavli IPMU Professor Masahiro Takada developed a method to measure the power spectrum of galaxy shapes, which extracts key statistical information from galaxy shape patterns by combining the spectroscopic data of spatial distribution of galaxies and imaging data of individual galaxy shapes.

The researchers simultaneously analyzed the spatial distribution and shape pattern of approximately 1 million galaxies from the Sloan Digital Sky Survey (SDSS), the world's largest survey of galaxies today.

As a result, they successfully constrained statistical properties of the primordial fluctuations that seeded the formation of the structure of the entire universe.

They found a statistically significant alignment of the orientations of two galaxies' shapes more than 100 million light years apart (Figure 3). Their result showed correlations exist between distant galaxies whose formation processes are apparently independent and causally unrelated.

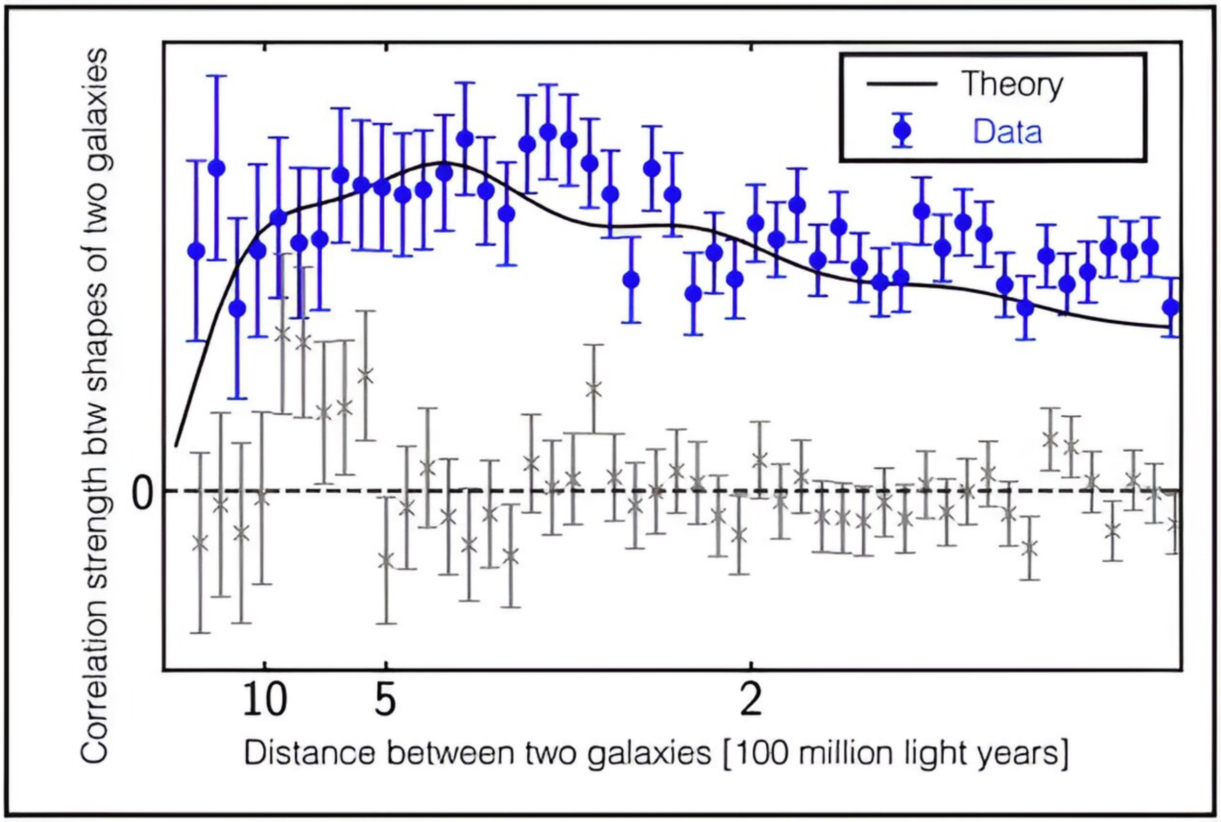

Figure 3: The blue dots and error bars are the values of the galaxy shape power spectrum. The vertical axis corresponds to the strength of correlation between two galaxy shapes, i.e., the alignment of the galaxy shape orientations. The horizontal axis represents the distance between two galaxies, with the left (right) axis representing the correlation between more distant (closer) galaxies. The gray dots indicate non-physical apparent correlations. The fact that this value is zero within error, as expected, confirms that the blue measured points are indeed astrophysically origined signals. The black curve is the theoretical curve from the most standard inflationary model, and it is found to be in good agreement with the actual data points. Credit: Kurita & Takada

"In this research, we were able to impose constraints on the properties of the primordial fluctuations through statistical analysis of the 'shapes' of numerous galaxies obtained from the large-scale structure data. There are few precedents for research that uses galaxy shapes to explore the physics of the early universe, and the research process, from the construction of the idea and development of analysis methods to the actual data analysis, was a series of trial and error.

"Because of that, I faced many challenges. But I am glad that I was able to accomplish them during my doctoral program. I believe that this achievement will be the first step to open up a new research field of cosmology using galaxy shapes," said Kurita.

Furthermore, a detailed investigation of these correlations confirmed they are consistent with the correlations predicted by inflation, and do not exhibit a non-Gaussian feature of the primordial fluctuation.

"This research is the result of Toshiki's doctoral dissertation. It's a wonderful research achievement in which we developed a method to validate a cosmological model using galaxy shapes and galaxy distributions, applied it to data, and then tested the physics of inflation. It was a research topic that no one had ever done before, but he did all three steps: theory, measurement, and application. Congratulations! I am very proud of the fact that we were able to do all three steps. Unfortunately, I did not make the great discovery of detecting a new physics of inflation, but we have set a path for future research. We can expect to open up further areas of research using the Subaru Prime Focus Spectrograph," said Takada.

The methods and results of this study will allow researchers in the future to further test inflation theory.

More information: Toshiki Kurita et al, Constraints on anisotropic primordial non-Gaussianity from intrinsic alignments of SDSS-III BOSS galaxies, *Physical Review D* (2023). DOI: 10.1103/PhysRevD.108.083533. On *arXiv*: DOI: 10.48550/arXiv.2302.02925

Provided by Kavli Institute for the Physics and Mathematics of the Universe, The University of Tokyo

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