FEATURE

Masashi Hazumi
Professor, Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), and Kavli IPMU
Research Area: Experimental Physics

# Can We Observe the Universe before the Big Bang?*1

## Introduction

What did the exact moment of the birth of our universe look like? What are the fundamental laws of physics that governed the very beginning? Answering these questions is one of the grand challenges of science. It is also a research topic that invokes the sense of wonder even beyond science. When you pursue it, you might even encounter a problem like "how to originate existence from nothing."

How far can we go back in history and observe the primordial universe? It is often said that our universe at the beginning was in a hot dense state like a fireball, and the Big Bang, which is the expansion of the universe, occurred. Logically speaking, there is no state before the Big Bang if you define it as the true beginning of the universe. If, however, you define the Big Bang just as a state of the universe that is described by physical laws, you might admit that there should be a preparation period for the Big Bang.

Indeed, thanks to development of technology for observation, humankind is now about to start observing the universe before the hot fireball state, or before the Big Bang. Among several ways of observation that have been proposed, the most promising method is to observe the cosmic microwave background (CMB) polarization, about which there is a worldwide competition today.

*1 This article is revised from the following article written in Japanese: JAXA *ISAS News* 2016 Sep. (No.426) The Frontier of Space Science "Exploring the universe before the Big Bang with LiteBIRD."

## The Cosmic Microwave Background (CMB) and the Big Bang Cosmology

The CMB is the oldest radiation in the universe, which is coming from the entire sky nearly isotropically with the central frequency of approximately 160 GHz (or equal to the wavelength of about 2 mm). The CMB was discovered in 1964 (publication was in 1965) by Arno A. Penzias and Robert W. Wilson, who received the Nobel Prize in Physics in 1978.

The universe continued its expansion after the Big Bang, and was cooled down as a result. About 380 thousand years after the Big Bang, the Universe went through a huge transition in which electrons and protons, which were apart from each other by that time, bound together quickly to form hydrogen atoms. Photons (or radiation), which were frequently interacting with free electrons, started traveling the space freely as they encountered no charged particles anymore. This transition is called recombination ("Hare-agari" in Japanese, which means "(the sky) clearing up"), and the CMB is indeed radiation from the recombination. The temperature of CMB at the time of recombination was 3000 K (hereafter we use the absolute temperature unit, K, for Kelvin). On the other hand, we know that the temperature of the CMB now is about 2.7 K. The reason why the temperature is lower now is that the wavelength of CMB becomes longer due to the expansion of space itself, and the radiation with the longer wavelength means lower temperature. Since there is no other plausible

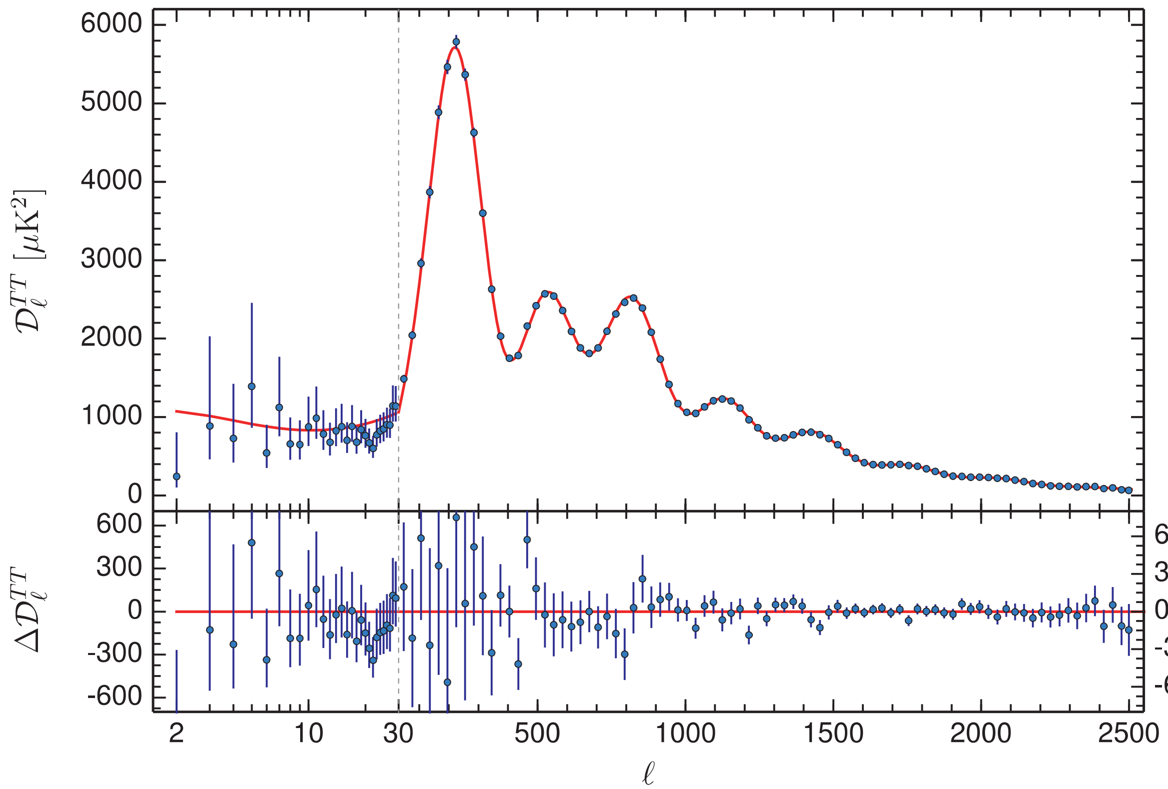


Fig. 1 Power spectrum of the CMB temperature fluctuation measured by the Planck satellite. The horizontal axis shows the wave number that corresponds to the fineness of the fluctuation pattern, while the vertical axis is the power of the fluctuation. The solid line is the result of the fit with the standard model of cosmology. The bottom panel shows the difference between the data and the fit result.

explanation for the existence of CMB, the discovery of CMB is regarded as key evidence of the Big Bang.

In 1989, NASA's COBE satellite started observation in orbit around the Earth. It was the beginning of the era of CMB precision measurements. The 2006 Nobel Prize in Physics was awarded to John C. Mather and George F. Smoot for their contributions to the measurements with COBE. In 2001, NASA's WMAP satellite, which was designed to measure the CMB with much better angular resolution, started observation at one of the Sun-Earth Lagrange points (L2).[*2] In 2009, the Planck satellite, with even better angular resolution and sensitivity than WMAP, was launched by the European Space Agency (ESA).

*2 See page 28.

Observations by these satellites have revealed the surprising facts of the universe with great precision, such as that the age of the universe is about 13.8 billion years, and that our universe is mostly filled by dark energy, which is not understood well.

Figure 1 shows a result from the observation by the Planck satellite announced in 2015. The solid line is the theoretical prediction, and the points with error bars are data. The figure is an example of the so-called spectral analysis, which uses precision data by Planck on the CMB temperature over the whole sky as the input, and shows how much unevenness (expressed as "fluctuation") is seen in a quantitative manner. The horizontal axis corresponds to the fineness of the scale of the fluctuation, while the vertical axis shows the magnitude of the fluctuation. One thing is surely seen from the figure even if you do not understand it, i.e., the theoretical prediction agrees quite well with data. This is a typical example of precision cosmology. The remarkable agreement is astonishing; humankind is able to uncover with precision what happened in more than 10 billion years ago!

The radiation consists of three entities, wavelength (color), intensity (brightness) and polarization (direction of oscillation). The frontier of CMB research after the observation by Planck is shifting to CMB polarization, which is not yet fully investigated. The primary motivation is that the CMB polarization, if observed with sufficient precision, will allow us to access the universe before the hot Big Bang. Humankind does not yet know what that looks like. We, however, know from all the cosmological observations done so far that the most promising idea is the cosmic inflation hypothesis.

## Cosmic Inflation Hypothesis

The cosmic inflation hypothesis was proposed in the early 1980s. Its basic idea is very simple; it states that the universe went through an enormous accelerating expansion before it became a hot dense state, or a fireball. Since it resolves several problems of the naïve Big Bang cosmology[*3] with one assumption only, it is regarded as the most promising hypothesis today. All the cosmological observations so far also indirectly support the hypothesis.

Given the explanation above, you might think that it is good enough to say that the cosmic inflation is the right answer. It is actually not that simple. The cosmic inflation contradicts the standard model of particle physics (the SM hereafter) we have today. The SM is a collection of most fundamental laws of physics. The universe follows the laws of physics with no exception. The problem is that the SM does not allow accelerating expansion of the universe; only deceleration is allowed. As long as we follow the SM, the universe should be like a car with brakes only; there is no accelerator you could press on.

Then you might ask if the cosmic inflation hypothesis should be ruled out because of the SM. The answer is NO! Here is an interesting point. The research of physics is like pinning down the rules of chess just by watching games; it should be very hard to accomplish it if you do not know any of the rules of chess. We do know that the SM today is incomplete. Many physicists including myself think that the ultimate laws of physics, which we do not yet know today, are written in "the rulebook of the universe," which should be able to create the inflationary universe and derive the SM at the same time. We already have a few attractive proposals for the ultimate laws of physics, which await experimental/observational tests. A representative example is superstring theory, which boldly predicts that the world consists of higher dimensions than the well-known 4 dimensions (3 for space and 1 for time), and the most elementary objects are not particles but strings.

## Observation of Primordial Gravitational Waves (PGWs) through CMB Polarization

What observations will lead to a decisive test of the cosmic inflation hypothesis? Our answer is "primordial gravitational waves (PGWs)."[*4]

Generation of PGWs is the most important prediction of the cosmic inflation hypothesis. The gravitational wave is a phenomenon that the space-time distortion propagates as wave. The accelerating expansion of the cosmic inflation generates gravitational waves. To distinguish from ordinary gravitational waves due to motion of astronomical objects, the inflationary gravitational waves are often called "primordial" gravitational waves. As we cannot decisively prove the cosmic inflation without

[*3] See, for example, David Spergel "How Did the Universe Begin?" *Kavli IPMU News* Vol. 10 (Jun 2010), to see what problems can be solved by the cosmic inflation hypothesis.

[*4] See, for example, Katsuhiko Sato "Cosmic Inflation and Primordial Gravitational Waves," *Kavli IPMU News* Vol.26 (Jun 2014) p. 72.

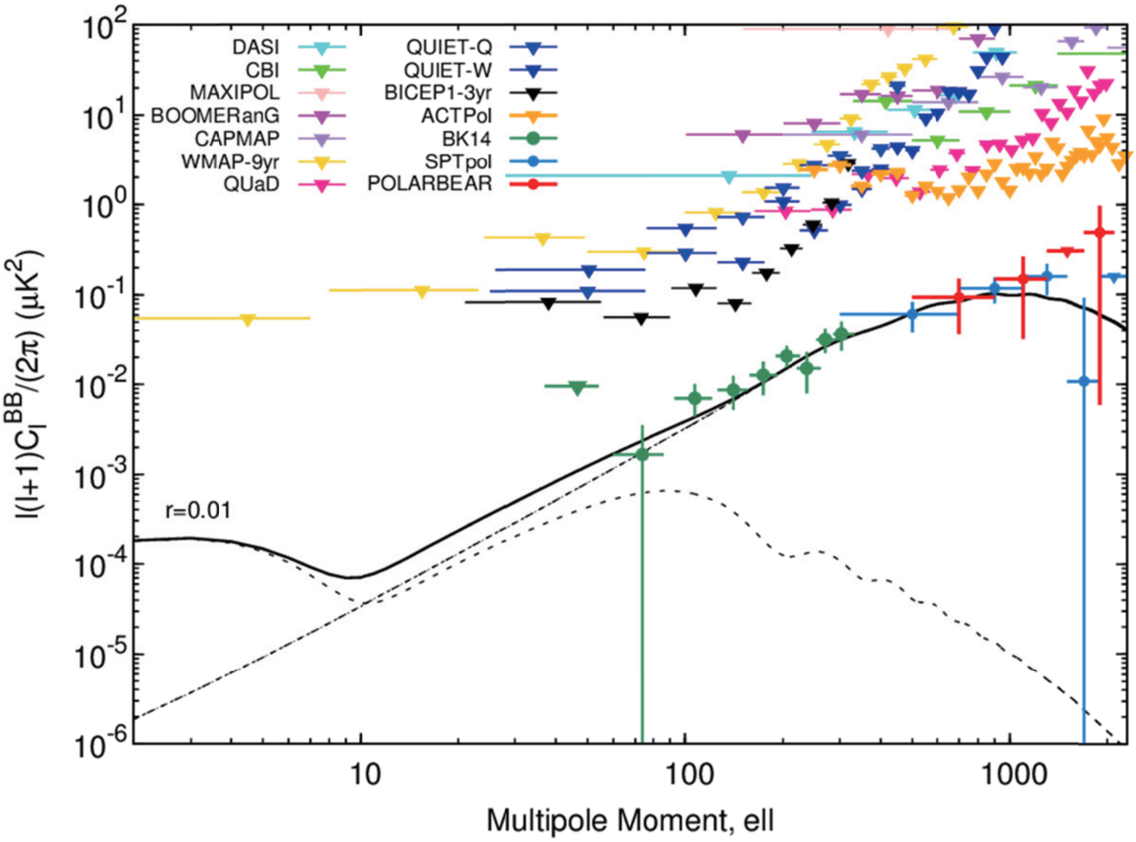


Fig. 2 The current status of CMB B mode measurements. The definitions of the horizontal and vertical axes are the same as those in Fig. 2. Circles (triangles) show the central values (upper limits). The dashed line is a theoretical prediction of the B mode signal due to the PGWs, which has not been confirmed by observation. An apparent B mode seen as the dot-dashed line is due to gravitational lensing of the CMB radiation, which has already been observed. The solid line shows the total from these two contributions. (Figure: courtesy of Dr. Yuji Chinone of Kavli IPMU and UC Berkeley)



detecting the PGWs, it is of crucial importance to observe them.

Let us explain the principle of the detection of PGWs with CMB polarization. It is predicted that PGWs, after generated during cosmic inflation, filled in the universe at the time of recombination and imprinted special curl pattern called "the B mode" in the distribution of CMB polarization on the sky (often called "the map"). Detection of the B mode in the polarization map is "smoking-gun" evidence for cosmic inflation. You might think that the method is analogous to detection of fingerprints.

Nowadays, there is a world competition on the CMB polarization measurements for discovery of the PGWs. It looks like "the warlord era of CMB." There are several ground-based telescopes and balloon-borne instruments that are observing CMB polarization, or are in preparation. In Japan also, researchers at KEK and Kavli IPMU participate in an international collaboration and are observing CMB with a telescope in Atacama, Chile. If you want to know more about this ground-based project, named POLARBEAR, I suggest you read, for example, my book entitled "The Cosmic Microwave Background – in search for the signal from the universe before the Big Bang" (SHUEISHA paperback).

Figure 2 summarizes all the major results of the hunts for PGWs. As in Figure 1, which shows the outcome of the spectral analysis of the temperature fluctuation, Figure 2 shows the results of the spectral analyses of the B-mode fluctuation. There are a lot of data (circles for central values and triangles for upper limits), but the point is that none of the results have indicated the signal of PGWs, which should appear as the dashed line from the prediction of the cosmic inflation hypothesis. To discover PGWs, one needs to carry out observations that are more sensitive than the results today at least by an order of magnitude. At the POLARBEAR project, for example, we plan to deploy three telescopes in total for higher sensitivities from the ground, which is called the Simons Array project.

To perform a decisive and ultimate measurement, one needs to cover the whole sky without contamination due to atmosphere. This means we need a dedicated satellite. In Japan, by reading the trends correctly, the CMB group at KEK started conceptual studies for a relatively small satellite already in 2008. This was the beginning of the LiteBIRD working group.

## LiteBIRD Satellite

The LiteBIRD satellite was proposed to ISAS, JAXA in February 2015, and passed the initial down-selection. There have been more than 130 researchers who joined the working group for the conceptual design from KEK, Kavli IPMU, JAXA, Okayama Univ., National Astronomical Observatory of Japan, UC Berkeley, Max-Planck Institute for Astrophysics, etc. The group includes CMB experimenters, and X-ray and infrared astrophysicists.

Figure 3 shows an overview of LiteBIRD. It is the ultimate instrument for measurements of B-mode fluctuation as faint as a nano-Kelvin. Let me add more explanations for those who love instruments; from the sky side toward the detector system, the satellite consists of 1) a rotating half-wave plate system that modulates CMB polarization to reduce systematic bias due to imperfection of the instrument, 2) a reflective cryogenic telescope at around 4 K, which consists of a primary mirror of about 80 cm in diameter and a secondary mirror, and a supplemental small refractive telescope dedicated to high-frequency measurements, 3) arrays of superconducting detectors with the base temperature of 100 mK, 4) readout system, 5) Joule-Thomson coolers and Stirling coolers, and 6) adiabatic demagnetization refrigerators. As WMAP and Planck did, we plan to send LiteBIRD to one of the Sun-Earth Lagrange points, L2, which is about a million miles away from the earth. With a scan strategy that looks like a spinning top with precession, we are able to survey the entire sky with great uniformity. Our superconducting detector arrays will observe the sky with 15 frequency bands between 40 GHz and 400 GHz. The general strategy of LiteBIRD is to have sufficient feasibility by using the detector technology that has been used in ground-based observations as proof-of-principle, and the cryogenic system as well as components for the satellite bus system that have high technology readiness levels based on past satellite missions.

Kavli IPMU plays a central role in moving ahead on the conceptual development of LiteBIRD. You might tend to think that Kavli IPMU is just for theoretical physics, mathematics, computer-based research and so on. We do have experimental facilities on the 1st floor of our IPMU building at Kashiwa campus, where we are doing R&D on instruments for LiteBIRD. Professor Matsumura, who is a world expert of the rotating half-wave plate system, is leading development and Dr. Sakurai is working on various measurements in the lab. Professor Sugai is investigating materials for reflective mirrors and plans for the test and verification of the optics. Professor Katayama is instrumental in introducing new instruments in our laboratory, and promoting collaborations with other research groups of the University of Tokyo. Of course studies with computer simulations are quite active. The current focus is on the method of separating foreground radiations from CMB. Dr. Eiichiro Komatsu, the director of Max-Planck Institute for Astrophysics and a new

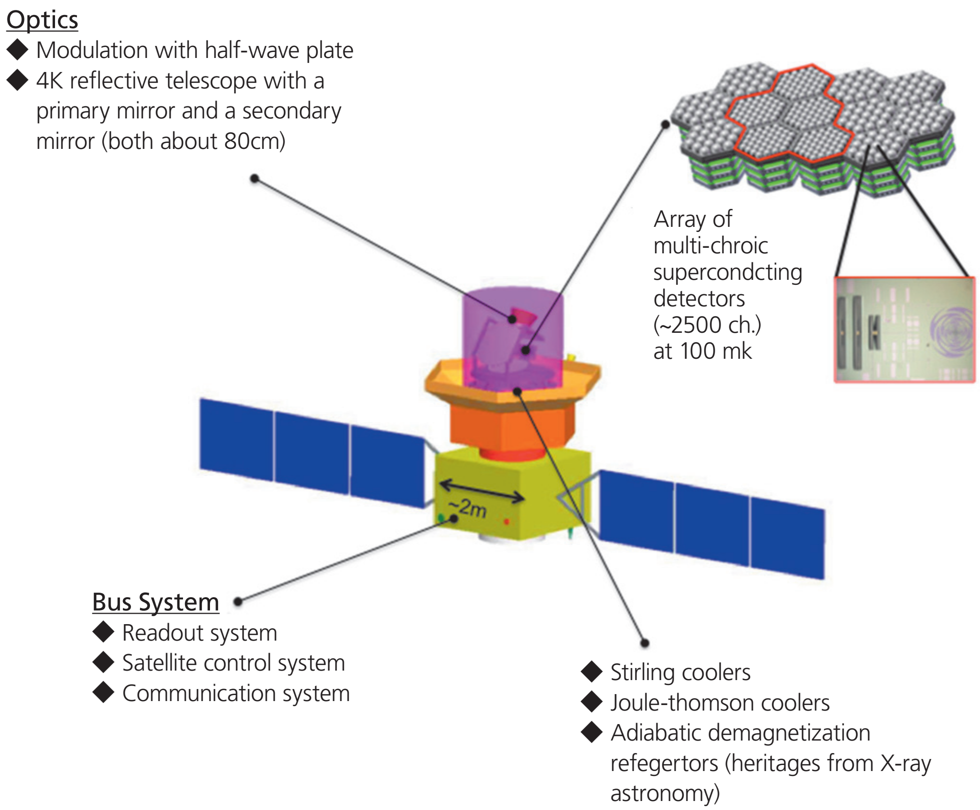


Fig. 3 Overview of the LiteBIRD satellite.

PI of Kavli IPMU, is conducting research on this important problem. At Kavli IPMU, there are several more researchers and visiting graduate students who are involved in R&D on LiteBIRD.

## Conclusion

While two Nobel Prizes have already been awarded on the observations of cosmic microwave background, it is often said that beyond them the discovery of primordial gravitational waves will be a huge achievement. After all, it is the signal from the universe before the Big Bang! Observations from space by a satellite will play a key role in testing the proposals for the ultimate laws of physics, such as superstring theory. It is true that it is a challenging experimental project. The members of LiteBIRD are working hard to improve the design as much as possible to pursue "the beginning of everything," which invokes a great sense of wonder. Stay tuned!