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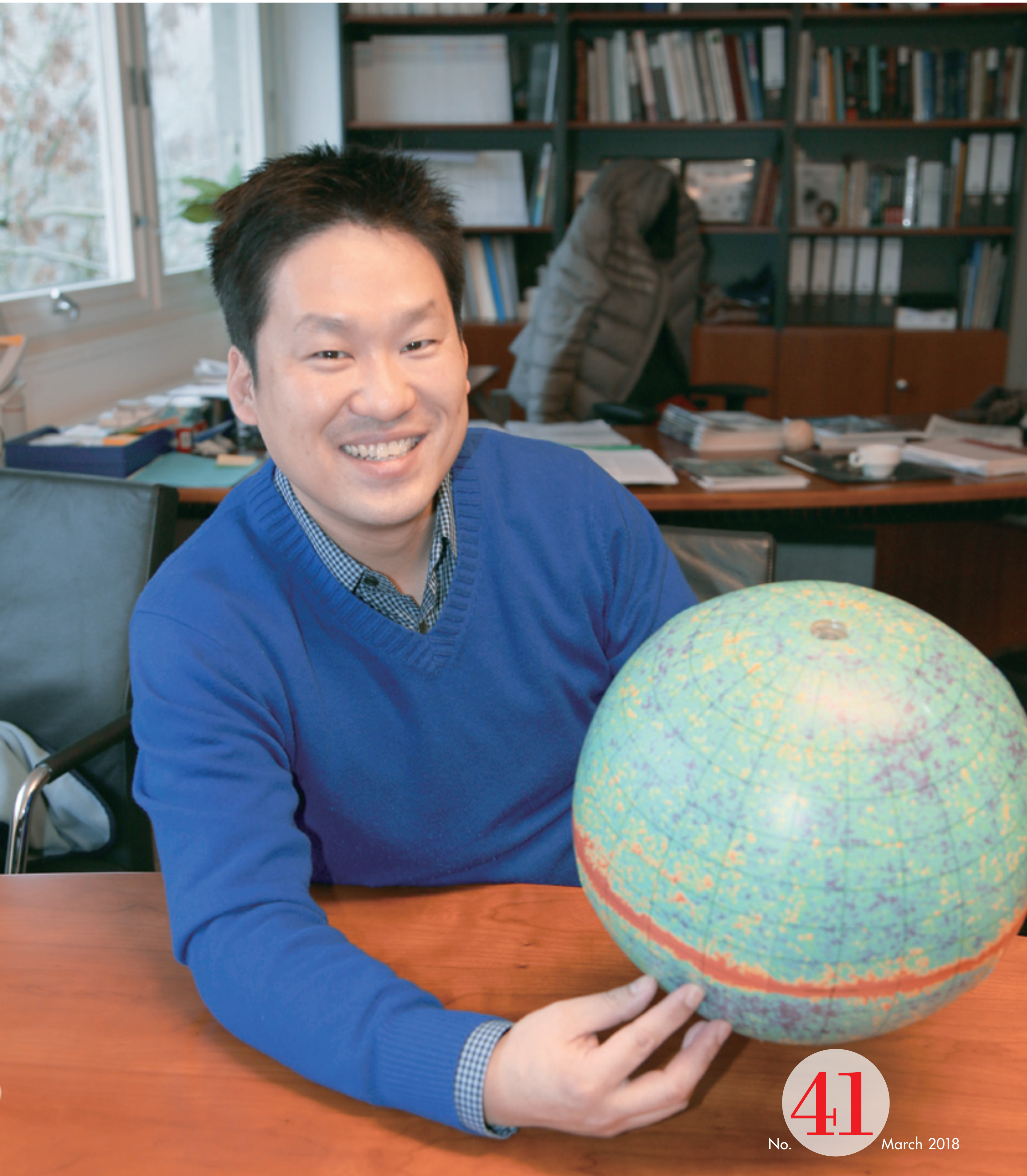
Feature
Quantum Fluctuation



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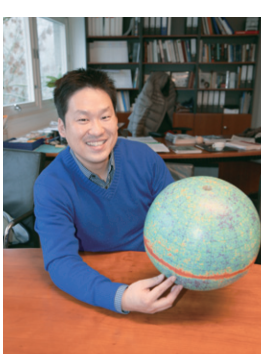

Eiichiro Komatsu is Director of the Max Planck Institute for Astrophysics. He also serves as a Principal Investigator of the Kavli IPMU. His research area is cosmology. He has been a member of the Wilkinson Microwave Anisotropy Probe (WMAP) Science Team. For his work on the analysis and interpretation of the WMAP data, in particular tests of the predictions of cosmic inflation, he received many prizes including the Nishinomiya Yukawa Memorial Award in 2010, Gruber Cosmology Prize in 2012, American Astronomical Society's Lancelot M. Berkeley - New York Community Trust Prize in 2013, Astronomical Society of Japan's Hayashi Chushiro Prize in 2015, Fellow of American Physical Society in 2015, and Breakthrough Prize in Fundamental Physics in 2017. After having received his Ph.D. from Tohoku University in 2001, he became WMAP Postdoctoral Research Fellow at Princeton University. In 2003, he moved to the University of Texas at Austin as an Assistant Professor. He became Associate Professor in 2008, Director of the Texas Cosmology Center in 2009, and Professor in 2010. He was appointed to the current position in 2012. On the cover: Photograph by Hiroto Kawabata.

小松英一郎：マックス・プランク宇宙物理学研究所ディレクター。Kavli IPMU主任研究員を兼ねる。専門は宇宙論。ウィルキンソンマイクロ波異方性探査機（WMAP）サイエンスチームのメンバーとして活躍。WMAPのデータの解析と科学的解釈、とりわけインフレーション理論の検証に関する業績により、2010年に西宮湯川記念賞、2012年にグルーバー宇宙論賞、2013年に米国天文学会のランスロット M. バークレー賞、2015年に日本天文学会林忠四郎賞と米国物理学会フェロー、2017年に2018基礎物理学ブレークスルー賞など、国内外の賞を多数授賞。2001年に東北大学から理学博士の学位を取得。同年プリンストン大学博士研究員、WMAPチームに参加、2003年テキサス大学オースティン校助教授、2008年同准教授、2009年同テキサス宇宙論センター所長、2010年同教授、2012年より現職。表紙写真提供：川端裕人氏。

Kavli IPMU Principal Investigator Eiichiro Komatsu
Research Area: Theoretical Physics

Quantum Fluctuation

The 20th century has seen the remarkable development of the Standard Model of elementary particles and fields. The last piece, the Higgs particle, was discovered in 2012. In the 21st century, we are witnessing the similarly remarkable development of the Standard Model of cosmology. In his 2008 book on "*Cosmology*" Steven Weinberg, who led the development of particle physics, wrote: "This new excitement in cosmology came as if on cue for elementary particle physicists. By the 1980s the Standard Model of elementary particles and fields had become well established. Although significant theoretical and experimental work continued, there was now little contact between experiment and new theoretical ideas, and without this contact, particle physics lost much of its liveliness. Cosmology now offered the excitement that particle physicists had experienced in the 1960s and 1970s."

The Standard Model of cosmology is known as the "ΛCDM model". This model contains some extraordinary ingredients, just like the Standard Model of elementary particles and fields once appeared to. The "Λ" denotes Einstein's cosmological constant, the simplest (but most difficult to understand) candidate of Dark Energy that accelerates the expansion of the Universe today. The "CDM" stands for "Cold Dark Matter", which accounts for 80% of the matter density in the Universe. The existence of Dark Matter and Dark Energy and their mysterious nature are well known to the public. They are among the most popular topics in cosmology.

However, the most extraordinary ingredient is not well known to the public. This ingredient is not contained in the name of ΛCDM, but is an indispensable part of the Standard Model of cosmology. It is the idea that our ultimate origin is the quantum mechanical fluctuation generated in the early Universe. However remarkable it may sound, this idea is consistent with all the observational data that have been collected so far for the Universe. Furthermore, the evidence supporting this idea keeps accumulating and is strengthened as we collect more data! It is likely that all the structures we see today in the Universe, such as galaxies, stars, planets, and lives, ultimately originated from the quantum fluctuation in the early Universe.

Borrowing energy from the vacuum

In quantum mechanics, we can borrow energy from the vacuum if we promise to return it immediately. The duration that we can borrow energy is inversely proportional to the amount we borrow. If you visit a bank without an appointment and ask to lend one million dollars for one day, they would not do it. However, if you ask to lend one million dollars for one second, they might do it because you would have to receive and return the money immediately. (And they will probably call a police because they think you are crazy.) You could borrow a lot of energy from the vacuum in the early Universe because the time was still very short. The quantum fluctuation has emerged randomly everywhere in space.

Structure formation in the Universe proceeds according to Einstein's gravitational field equations and the equations of motion for matter and energy components that constitute the Universe. Once initial conditions are given, the subsequent evolution is deterministic. And now modern cosmology, which is rooted firmly in a lot of observational data, tells us that the initial conditions were chosen randomly by quantum mechanics. Einstein said, "God does not play dice with the Universe" when he criticized the probabilistic aspect of quantum mechanics. Indeed, which galaxies form in what places in the Universe was determined by rolling dice!

"Missing link" between micro- and macroscopic worlds

But, the quantum fluctuation operates only in a microscopic world. How come it became a seed for an enormous structure like a galaxy? What is the missing link between microscopic and astronomical length scales? The most promising idea, which constitutes a pillar of the Standard Model of cosmology, is "cosmic inflation". The Universe underwent a period of rapid, exponential expansion right after its birth, and a short wavelength of the quantum fluctuation was stretched exponentially to become an astronomical length. In a typical model of inflation, the Universe expanded by at least 26 orders of magnitude within a trillionth of a trillionth of a trillionth (10^{-36}) of a second. That is to say, the size of an atomic nucleus became the size of Solar System within a tiny fraction of a second. Who would believe this? Despite tremendousness of the idea, the statistical properties of cosmic structures predicted by inflation are consistent with all the data we have collected so far. As I describe later, I have spent most of my career testing the predictions of inflation with the cosmic microwave background data. Every time I confirm the prediction with better precision I say to myself, "Geez, I am such an ordinary researcher! Those who came up with this crazy idea (Sato, Guth, Starobinsky...)—the idea that might actually be correct—are too extraordinary."

Didn't we have to return energy to the vacuum immediately? Something strange happens when the wavelength of the quantum fluctuation is stretched by inflation to a macroscopic scale: it starts to behave as if it were a classical fluctuation despite that it is still quantum. If we had to use the analogy with a bank again, it would be like "we do not have to return the money due to inflation (in economics)," which makes no sense. A better metaphor would be like this: Space between you and a person of the bank counter expands exponentially as soon as you borrow one million dollars, and the distance becomes so large that the communication between them is no longer possible.

Researchers have been wondering about a physical mechanism by which the quantum fluctuation became classical during inflation. Just because the wavelength was stretched does not mean that the fluctuation became classical. It just means that the fluctuation became nearly indistinguishable from a classical fluctuation. I always get a question about this "classicalization" of the quantum fluctuation during inflation whenever I give a talk on inflation in front of physicists. I reply by saying, "we do not yet understand the physical mechanism of classicalization, so perhaps it is a good topic for a Ph.D. thesis." However, at the conference on "*General Relativity and Gravitation*: *A Centennial Perspective*" held at Penn State University in June 2015, Abhay Ashtekar, a leading researcher on quantum gravity, said to me, "Eiichiro, the fluctuation never became classical. This world is still fully quantum!" I was like, "haha, that is funny." But he was serious. Indeed, as it is nearly indistinguishable from a classical fluctuation, perhaps we do not have to be adamant that the fluctuation had to become truly classical. The conversation with him made me realize again that I am an ordinary researcher with little imagination. I was glad that I could broaden my view on this profound issue of inflation.

We need a new energy component to accelerate the Universe, as the known components such as matter and radiation must always decelerate it. The Λ

of the “ΛCDM” denotes Dark Energy that accelerates the Universe today, and we need something similar in the early Universe too. The technical term for this energy component in the early Universe is an “inflaton field”. Researchers working on inflation were encouraged very much when the Higgs particle was discovered, as the basic property of the Higgs field is similar to that of an inflaton field. However, the Higgs field in the Standard Model of elementary particles and fields cannot be an inflaton field for a technical reason that the Higgs potential is too steep. Therefore, we need a field that is similar to the Higgs but has a flat potential. Alternatively, we may introduce a new element to the Standard Model called a “non-minimal coupling of the Higgs field to gravity”.

To summarize: According to an inflationary scenario, the Universe underwent a period of accelerated expansion at the rate at which the size of an atomic nucleus could become the size of Solar System in a tiny fraction of a second. A microscopic wavelength of the quantum fluctuation was stretched enormously to a macroscopic wavelength, seeding all the structures we see today in the Universe. Astronomers often say, “we are stardust,” referring to the fact that the elements that make up our bodies originate from nucleosynthesis in stars. Cosmologists would say, on the other hand, “we originate from the quantum fluctuation.”

When I say something like this at public lectures, the audience would not believe it. Their reaction is completely normal. I worry more about astrophysics graduate students believing in this so easily. In my opinion, the public tends to take the cosmology research as a kind of a fairy tale. While they enjoy hearing about it, they seem to think, “This is a very interesting story, but most of it is a speculation of astronomers.” This could be because researchers giving a public lecture do not always make a clear distinction between the solid facts based on observational data and more speculative results. In any case, we must have convincing observational evidence to claim that we originate from the quantum fluctuation.

Observational evidence

The observational evidence came from measurements of the cosmic microwave background (CMB). Fluctuations in the photon energy density obey a certain probability distribution, which depends on physics of the creation of quantum fluctuations. One important question is as to which field's quantum fluctuation was mainly responsible for the seeds of cosmic structure formation. In the simplest picture, the quantum fluctuation of the inflaton field, the field that drove inflationary expansion, became the seeds. For technical reasons, the inflaton field has a flat potential, which implies that the interaction of the inflaton field must be weak. The probability distribution of quantum vacuum fluctuations of a free, non-interacting field is a Gaussian distribution; thus, the CMB temperature fluctuations are also expected to obey a Gaussian distribution.

I joined the science team of NASA’s Wilkinson Microwave Anisotropy Probe (WMAP) mission shortly after the launch in 2001 and worked mainly on the analysis and cosmological interpretation of the WMAP data until the final data release in 2012. Testing inflation has been one of my main focus topics. We have found that the distribution of the temperature fluctuations (Figure 1) is consistent with a Gaussian distribution. In the final data release on December 21, 2012, we obtained a stringent 95% upper limit of 0.2% on a deviation from a Gaussian distribution. The science team of ESA’s Planck mission used our method to improve the upper limit to 0.04%. This is the most precise Gaussian distribution I have ever seen for the data on the Universe (except instrumental noise). Not only are these results consistent with the quantum mechanical origin of CMB temperature fluctuations, but also with the prediction of “single-field inflation models” in which the quantum fluctuation originates from the inflaton field while contributions from other fields are unimportant.

The quantum fluctuation kept being generated, and its wavelength kept being stretched throughout

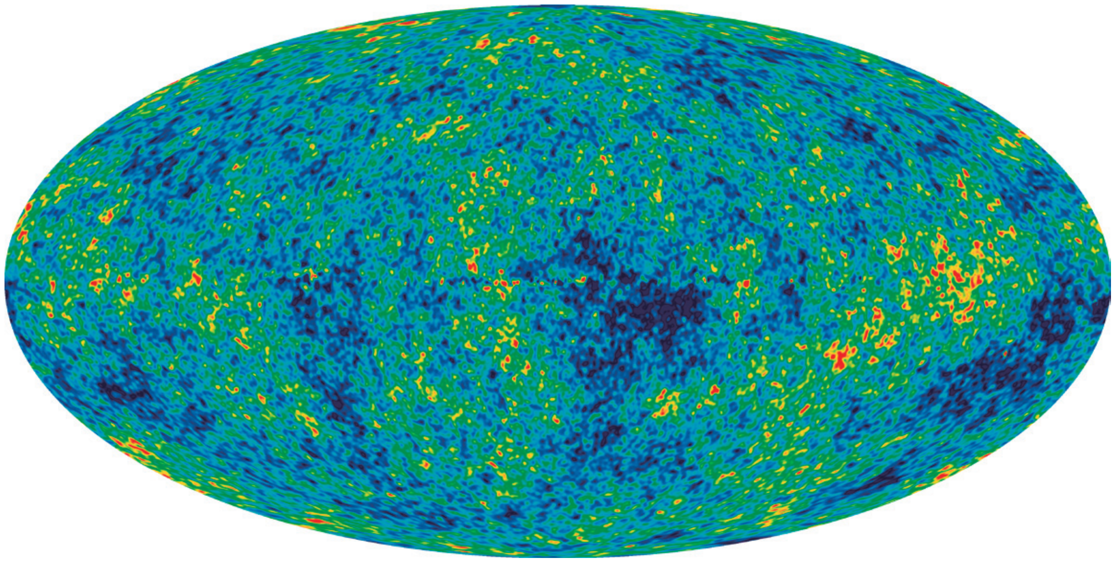

Figure 1: Full-sky map of the CMB temperature fluctuation in the Mollweide projection, obtained from 9-year observations of the WMAP. The distribution of the temperature fluctuation is consistent with a Gaussian distribution. (Credit: WMAP Science Team)

inflation. The earlier the fluctuation was generated during inflation, the longer its wavelength has become because it had more time to be stretched until the end of inflation. In the CMB data, the fluctuation generated earlier during inflation would appear on large angular scales. The amplitude of the quantum fluctuation we can borrow from the vacuum is inversely proportional to the time we borrow. The convenient quantity is the "Hubble expansion rate", which is the number of e-folds of expansion per unit time. The expansion rate is thus in units of $[\text{time}]^{-1}$, and we can show that the amplitude of the quantum vacuum fluctuation in the inflaton field is proportional to the Hubble expansion rate.

As inflation has to end, the Hubble expansion rate decreases over time; thus, the earlier the fluctuation was generated during inflation, the stronger its amplitude would become. In the CMB data, the amplitude of the temperature fluctuation on large angular scales would be stronger than that on small angular scales. In practice, a perturbation to a photon fluid of the CMB creates sound waves, and the amplitude of the CMB temperature fluctuation oscillates as a function of angular scales. This oscillation must be modeled before extracting information on the primordial fluctuations with "the amplitude on large angular scales being stronger than that on small angular scales". This modeling is not difficult because the physics of sound waves is well understood.

Mukhanov and Chibisov predicted this effect in 1981. Finding it has been the dream of researchers working on inflation. If we write that the amplitude of the primordial fluctuation is proportional to the wavelength to the power of $1 - n_s$, the Mukhanov-Chibisov prediction is $n_s < 1$. We want to measure this. In December 2012, we used the WMAP 9-year data in combination with the other ground-based CMB data and the galaxy survey data from the Sloan Digital Sky Survey to measure $n_s = 0.958 \pm 0.008$ with the 68% confidence level. We were able to finally discover $n_s < 1$ with more than 5 standard deviations. Three months later, the Planck team combined the Planck and WMAP data to measure $n_s = 0.960 \pm 0.007$. This is an important confirmation of our result because it is based on the CMB data only. These results provide the strongest ever support for inflation and the quantum origin of the cosmic structures.

WMAP could have found primordial gravitational waves

Carl Sagan said, "Extraordinary claim requires extraordinary evidence." In the pursuit of definitive evidence for inflation, CMB researchers are working hard to discover "primordial gravitational waves" generated during inflation. LIGO detects gravitational waves from collisions of binary black holes, whose wavelength is a few thousand kilometers. On the other hand, the wavelength of the primordial gravitational waves has been stretched by inflation to billions of light years! As astrophysical bodies cannot generate gravitational waves with such extreme wavelengths, their discovery would provide definitive evidence for inflation.

As gravitational waves stretch and contract space, they also stretch and contract the wavelength of the CMB light, generating temperature fluctuations. The WMAP could have measured this effect.

Back then, a monomial potential of the inflaton field ϕ was thought to be among the most plausible. A quartic potential (ϕ^4) was considered natural in particular. I certainly learned this view from my former thesis advisor at Tohoku University, Toshifumi Futamase, and the fact that the potential of the Higgs field is quartic for a large field value ϕ made this potential attractive. The quartic potential yields the amplitude of gravitational waves large enough for WMAP to detect. In the meantime, Keiichi Maeda at Waseda University and Toshifumi showed that the quartic potential model would become even more attractive when we include the so-called "non-minimal coupling of ϕ to gravity", as it would allow the Higgs field to drive inflation. (This coupling does not exist in the Standard Model of elementary particles and fields.) Inspired by their idea, I calculated the expected amplitude of gravitational waves from this model. To my surprise, the model prediction for n_s hardly changed, but the amplitude of gravitational waves became 100 times smaller! I thus concluded in January 1999 that the non-minimal coupling to gravity would be required if no gravitational wave was found despite $n_s < 1$.

In 2006, we ended up ruling out the minimal ϕ^4 model by the WMAP data. I trembled. I certainly did not expect this to happen, though this result was foreseen in my 1999 paper. At the time of writing (April 2018), no primordial gravitational wave has been found. The ϕ^4 model with non-minimal coupling to gravity is called "Higgs inflation" nowadays and remains one of the best-fitting models to the CMB data (Figure 2).

Next frontier: Polarization of the CMB

The amplitude of the gravitational waves from Higgs inflation is too small to be detected in the temperature data of WMAP and Planck. Therefore, the CMB researchers have turned their attention to the polarization of the CMB. CMB becomes polarized when electrons scatter the CMB temperature fluctuation generated by gravitational waves. The CMB researchers around the world are competing to find this polarization signal. I am a part of the international team led by Masashi Hazumi at KEK and Kavli IPMU, working with JAXA to develop the next-generation CMB satellite mission called "LiteBIRD" (*Kavli IPMU News* No. 36). While the LiteBIRD has not been selected for flight yet (we are in the middle of Phase A1), we are expecting to hear the result of JAXA's selection by the end of this Japanese fiscal year. Fingers crossed. We really want to fly LiteBIRD to measure primordial gravitational waves.

In 2014, a group of researchers at American institutions reported a discovery of CMB polarization from primordial gravitational waves. This turned out to be a false alarm because they mistook polarization from thermal dust emission within our Galaxy for the CMB. While they are responsible for the false alarm, the news media also made two mistakes. First, they ignored cautionary remarks from CMB experts who were not involved in the discovery and sensationalized the news. (There were also researchers who actively contributed to the hype.) Second, they jumped to a conclusion that this

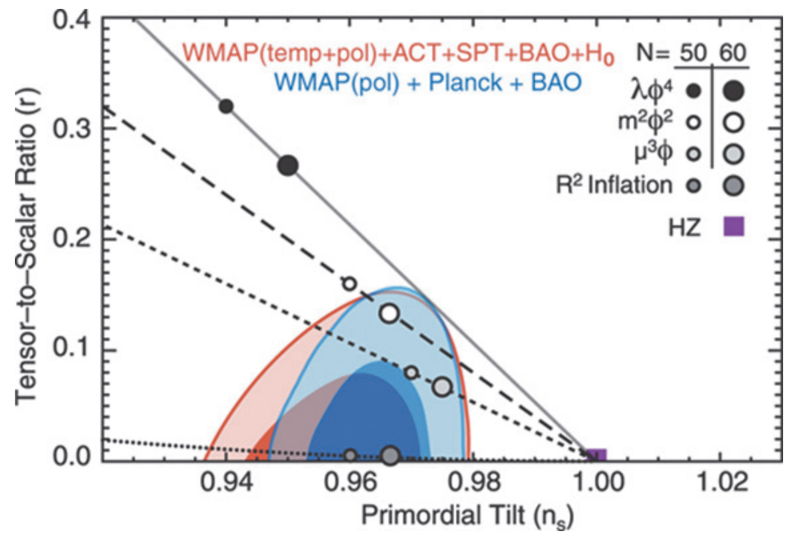

Figure 2: Constraints on inflation models. The vertical and horizontal axes show the amplitude of gravitational waves and n_s, respectively. The red contours show the 68% and 95% confidence levels of the WMAP final data release in December 2012, while the blue contours show those of the Planck data release in March 2013. The black circles in the top show the range of predictions from the minimal ϕ^4 model, whereas the dark grey circles in the bottom show those from the ϕ^4 model with non-minimal coupling to gravity. Adopted from Komatsu et al., *PTEP*, 06B102 (2014).

discovery is the evidence for quantum gravity. Let me comment on the latter.

The reason for this claim is the following. Gravitational waves are ripples of spacetime, and thus their quantum fluctuation would be a quantized deformation of spacetime; hence quantized gravity. While this claim is correct in principle, to make this profound claim we must *show* that the statistical property of the detected gravitational waves is consistent with that of the quantum fluctuation. That is to say, we must make sure that the distribution of CMB polarization is consistent with a Gaussian. This test has never been done, even today.

Do primordial gravitational waves originate from the quantum fluctuation in spacetime?

Frustrated by this situation, I started a campaign with my collaborators in our recent research articles and presentations at conferences. It is natural to expect that there were other matter fields as well as the inflaton field during inflation. The energy density of the other fields must be much smaller than that of the inflaton field because the CMB temperature fluctuation is close to a Gaussian. Nonetheless, their energy density can be large enough to produce detectable amplitudes of gravitational waves in the CMB polarization. The probability distribution of gravitational waves from the matter fields can be strongly non-Gaussian. The CMB polarization data would then be a superposition of contributions from the quantum fluctuation in spacetime and the matter fields. We do not know which contribution dominates until we analyze the data.

It is essential to test Gaussianity of the probability distribution of primordial gravitational waves. If it is consistent with a Gaussian, and the wavelength dependence of the gravitational wave amplitude agrees with the expectation, we may declare discovery of evidence for the quantum fluctuation in spacetime. What if it is not a Gaussian? It would be the beginning of a new era in which particle physics of inflation makes a big leap!