Research Experience

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It has been the aim of my research to deepen our understanding of various phenomena in the universe making free use of the universal laws of physics. In my opinion this is the real pleasure of theoretical physics and astrophysics. I have thus been working on cosmology and gravitation, focusing mainly on braneworld cosmology, string cosmology, Hořava-Lifshitz cosmology, dark energy and dark matter, modification of gravity at long distance and time scales, the effective field theory approach to gravity, the cosmological constant problem, black hole entropy, and so on. In the following I would like to explain some of my main contributions to the field. (The [number] corresponds to the number in the achievement list.)

Braneworld cosmology

Cosmology has recently been acquiring greater importance not only as our attempt towards better understanding of the universe but also as an ultimate testing ground of high energy physics. I consider it of particular interest to continue testing the predictions and ideas from string theory, that is considered as a candidate for the theory of everything, through cosmology. From this point of view, braneworld cosmology is one of important attempts to test the idea of extra dimensions predicted by string theory.

In a 5-dimensional braneworld scenario proposed by Randall and Sundrum, I found an exact solution that represents a general homogeneous and isotropic universe on the brane [233]. The effect of the extra-dimension is encoded in a concrete term in the evolution equation of the 4-dimensional universe on a brane and I named it dark radiation, which is a standard terminology in the field now. After finding a homogeneous and isotropic cosmological solution, I developed a formalism to analyze cosmological perturbations [230]. In the 5-dimensional braneworld cosmology the number of independent components of cosmological perturbations is greater than that of the standard cosmological perturbations in 4-dimensions, and we need to solve a set of coupled partial differential equations for them. Fortunately, I discovered a master variable, from which all components of cosmological perturbations in the 5-dimensional braneworld cosmology are derived by simply taking derivatives. I then completed the formalism by deriving a master equation for the master variable. The exact background solution and the master equation for perturbations form the foundation of the braneworld cosmology and provide a method to compare the theory with observations. A number of research groups applied the formalism to actual computation and obtained observable results such as the spectrum of cosmic microwave background anisotropies.

In the field of braneworld cosmology, I also investigated the global spacetime structure of the above mentioned exact solution [232], analyzed the linearlized gravity in a gauge-invariant way [221, 222], discovered new solutions that take into account quantum effects [227, 225], studied extensions to higher dimensions [209, 207, 205, 202], and proposed a new braneworld cosmology based on tachyon condensation [220, 218].

I received the Young Scientist Award from the Physical Society of Japan for the series of works in the braneworld cosmology. More recently, I used braneworld cosmology to tackle the cosmological constant problem, one of the most difficult problems in cosmology and theoretical physics [36].

String cosmology

The basic idea of string theory is as simple and ambitious as to describe everything in the universe by various oscillation modes of strings. For this reason it is often considered as the strongest candidate for the ultimate theory. Until 2002, however, an obstacle was standing in the way of string theory: there was no known solution in string theory that can describe the accelerated expansion of the 4-dimensional universe with the size and the shape of extra dimensions fixed. There were no-go theorems against construction of such a solution. Since there can be little doubt that the expansion of the universe is accelerating, the no-go theorems, if applicable to our universe, would drive string theory into a difficult situation. Fortunately, in 2003 such a solution was finally discovered by Kachru, Kallosh, Linde and Trivedi by evading the no-go theorems. When I heard about this breakthrough, I became certain that the age of string cosmology would come.

I thus started to work on early universe cosmology, in particular inflation, based on string theory. Why is our universe so big? Inflation can answer this question and also explain the origin of primordial fluctuations that seeded the rich structure in the universe such as galaxies and clusters of galaxies. However, while inflation is thought to be driven and ended by a field called inflaton, we do not really know what inflaton actually is. There are two kinds of strings in string theory: open string and closed string. A surface on which open strings end is a kind of soliton and is called D-brane. The possibility that a D-brane may be the origin of the inflaton has been attracting attention. Because of various structures in extra dimensions (such as warped throats due to fluxes of antisymmetric fields, other D-branes and anti D-branes, etc.), the D-brane moves in a nontrivial way. When the D-brane's potential energy changes slowly, our 4-dimensional universe may exhibit cosmic inflation.

A problem with the D-brane inflation is that an inflaton has a conformal (or an almost conformal) coupling to the spacetime curvature. This stems from the fact that the background spacetime is approximately anti de Sitter and thus the existence of the (almost) conformal coupling is rather universal. It had thus been thought that the contribution of this kind of coupling to the inflaton mass needs to be canceled with other effects by fine-tuning. With L. Kofman, however, I found that inflation can occur under a certain condition without need for a severe fine-tuning (conformal rapid-roll inflation) [199, 196, 188]. In this model it is not the inflaton but another field called curvaton that is responsible for generation of primordial cosmological perturbations. The role of the conformally coupled inflaton is to provide a background expansion suitable for the curvaton. Along with T. Kobayashi, I then proposed a model of curvaton based on another D-brane in warped extra dimensions, and showed that there are regimes of parameters consistent with observational data [189]. My collaborators and I investigated two types of curvaton models, one originated from a physical degree of freedom on the inflaton D-brane and the other from a degree of freedom outside the inflaton D-brane, and showed that they predict distinct inflationary observables [122].

In a paper with T. Kobayashi and S. Kinoshita [200], I also proposed a model of inflation driven by a D-brane wrapped over a part of extra dimensions. In this model we derived a relation between non-Gaussianities of cosmological curvature perturbations and the Euler number of a Calabi-Yau manifold. This work thus illustrates not only a concrete model building of the inflationary scenario within string theory but also the possibility that cosmological observational data may in principle tell us something about properties of extra dimensions. I also proposed a dark matter candidate from anti D-branes [210], and a reheating scenario based on brane motion [201].

More recently, along with collaborators, I have also studied the Swampland and Trans-Planckian conjectures in superstring theory. For example, we have successfully extended the de Sitter swampland conjecture to a form applicable to a scalar field with a nonlinear kinetic term [86]. Given that the action describing a D-brane in string theory has a nonlinear kinetic term and that such an action is used in a variety of cosmological scenarios, such an extension is intrinsically important for connecting physics at the smallest scale (string theory) and the largest scale (cosmology). Based on the Trans-Planckian conjecture, we also gave an upper bound on the inflationary scale independent of model details and discussed the observability of gravitational waves originating from inflation based on superstring theory [81]. I have also studied cosmology based on double field theory, which preserves the $O(D,D)$ symmetry (D is the space-time dimension) in superstring theory at the level of field theory [87].

Cosmology based on Hořava-Lifshitz gravity

Gravity and particle physics are successfully described by general relativity and quantum field theory, respectively, in a vast range of scales. However, in extreme situations such as the beginning of the universe, both of them fail to work. We thus need a theory of quantum gravity.

I have been working on cosmology based on string theory, which is the strongest candidate for the theory of quantum gravity. However, string theory is not the only candidate. Actually, a gravity theory proposed by Hořava in 2009, often called Hořava-Lifshitz gravity has been thought to realize renormalizability and unitarity and was recently proved to do so indeed. Thus Hořava-Lifshitz gravity is also a strong candidate for the theory of quantum gravity.

One day in 2009, I took one look at the Hořava's paper for the first time and knew instinctively that this theory would lead to a novel cosmology. What I noted was a property called anisotropic scaling, which is the essential reason why the theory is renormalizable. I soon found that the anisotropic scaling renders quantum fluctuations at short distances scale-invariant and thus thought that this may lead to a novel mechanism for generation of cosmological perturbations. I thus proposed a new scenario of the early universe that can solve the horizon problem and generate scale-invariant cosmological perturbations without need for inflation [191]. This scenario can be applied to all versions of Hořava-Lifshitz gravity that have been proposed so far.

Based on the so called projectable version of the Hořava-Lifshitz gravity, I also proposed a scenario that can mimic behaviors of dark matter without dark matter [190, 186], and a scenario that can amplify the amplitude of stochastic gravitational waves [187].

In 2010, I was invited to write a review article on cosmology in Hořava-Lifshitz gravity [176]. The article was selected as one of Highlights of 2010-2011 in the journal. I was then appointed as an Editorial board member of Classical and Quantum Gravity. I have been serving as an Advisory panel member since January 2018.

Recently, along with collaborators, I have been working on quantum cosmology based on Hořava-Lifshitz theory. First, for the DeWitt boundary condition, one of the three famous boundary conditions for the wave function of the universe, we proved the no-go theorem that a consistent wave function cannot be obtained in general relativity once not only the homogeneous and isotropic background universe but also tensor perturbations are taken into account [40]. In the Hořava-Lifshitz quantum gravity theory, on the other hand, we showed for the first time in the world that this problem can be avoided by actually constructing a wave function that describes both a homogeneous and isotropic universe and tensor perturbations and that satisfies the DeWitt boundary conditions [27]. I also studied the remaining two types of (no-boundary and tunneling) boundary conditions by the Lorentzian path integral [9].

In addition, I have worked on the recovery of Lorentz symmetry in Hořava-Lifshitz theory [101], a perturbative proof of the black hole no-hair in the low-energy effective theory of Hořava-Lifshitz theory [115], the derivation of the Boltzmann equation for a Lifshitz scalar [90], and black hole perturbations in Hořava-Lifshitz theory [54]. In the Einstein-Aether theory, which is closely related to the low-energy limit of the Hořava-Lifshitz quantum gravity theory, I have successfully analyzed black hole formation by gravitational collapse using numerical simulations [100]. In addition, we have scrutinized the observational constraints on the Einstein-Aether theory following the observation of the gravitational wave event GW170817, among others [106].

So far I have described some of my research subjects in which developments of gravitational theories at short distances led to novel views on our universe. Experimentally, we do not know how gravity behaves at distances shorter than about 0.01 mm. At such short distances, gravity may behave completely differently from what we naively expect. From theoretical viewpoints as well, many researchers consider it necessary to modify general relativity one way or another to treat gravity consistently as a quantum theory. In this sense gravity at short distances is one of frontiers in theoretical physics.

Effective field theory approach to gravity

Gravity at cosmological scales is also considered as yet another frontier since gravity at such long distances has never been probed directly.

The latest observational data suggests that the universe today is mostly filled with unknown energy and matter. These energy and matter are called dark energy and dark matter, respectively, and it is thought that they fill more than 90 percent of the universe. Nonetheless, we do not know what they really are. Along with N. Arkani-Hamed, H. C. Cheng and M. Luty, I thus started to reconsider the question "Do we really need dark energy and dark matter?" When the perihelion shift of Mercury was discovered in the 19th century, some people tried to explain this interesting phenomenon by introducing an unknown planet, so to speak dark planet. Some people even "discovered" it. As we all know, however, the right answer was not a dark planet but to change gravity, from Newton's theory to Einstein's general relativity. This was indeed the beginning of the success of the new theory. We thought that the mystery of the accelerated expansion of the universe might be similar. We thus started to ask "Can we change general relativity at long distance or/and time scales instead of introducing dark energy or/and dark matter?" In the end we decided to apply the Higgs mechanism, that plays an important role in the standard model of particle physics, to gravity and reached a completely new idea called ghost condensation [213]. In ghost condensation the structure of the low energy effective field theory (EFT) is determined by the symmetry breaking pattern and thus general relativity is modified at long distance and time scales in a theoretically consistent way.

The systematic method of construction of the low energy EFT that we developed is universal and thus can be applied or/and extended to different setups. For example, Cheung, Creminelli, Fitzpatrick, Kaplan and Senatore extended our construction of the EFT to a general homogeneous and isotropic background to construct what is currently known as EFT of inflation. This formulation, called Effective field theory (EFT) of inflation, was also adopted by ESA's Planck team to help analyze the non-Gaussian nature of the fluctuations. The same kind of EFT was later applied to late-time acceleration to construct what is called EFT of dark energy. It has become one of the mainstays of theoretical research on dark energy and modification of gravity at long distances as a bridge between observation and theory. It was also used by Dubovsky to construct a new class of massive gravity theories.

I have been working on properties and applications of ghost condensation, such as the possibility for it to replace dark energy and dark matter [213], a new model of inflation [214], accretion to a black hole [211], the formulation of cosmological perturbation theory [204], the gauged version of ghost condensation as a partial UV completion [206], the consistency with the generalized second law [193, 185] and the de Sitter entropy bound [131], and so on. I also formulated a cosmological perturbation theory [204].

Recently, together with young researchers, I succeeded for the first time in the world in extending these EFTs (EFT of ghost condensation, EFT of inflation, and EFT of dark energy) to arbitrary backgrounds with timelike scalar field profiles [35]. Then, we applied the general EFT to black holes in scalar-tensor theory and succeeded for the first time in the world in investigating background solutions and in deriving the generalized Regge-Wheeler equation describing odd-parity perturbations [25]. As an application of the generalized Regge-Wheeler equation, we calculated the quasi-normal mode frequencies of the black hole solution with a timelike scalar profile [15]. I believe that this general EFT will lead to many future research projects that take full advantages of the universality of the effective field theory approach, such as formulation and calculation of the tidal Love number of black holes, extensions to even-parity perturbations, extensions to rotating black holes, accretion to black holes, and applications to the process of black hole formation by gravitational collapse. This effective field theory is expected to serve as a bridge between observations of gravitational waves, cosmological-scale observations, and gravitational theories.

By extending the above-mentioned gauged version [206] of ghost condensation from flat spacetime to the expanding universe, we have also succeeded in constructing an effective field theory that can universally describe all vector-tensor theories in cosmological backgrounds [39] and arbitrary backgrounds [7]. These effective field theories will be useful to constrain dark energy models based on vector-tensor theories from observations of cosmology and gravitational waves.

Massive gravity

Spins and masses are among those important properties that characterize particles. It is easy to give a mass to a spin-0 particle, by simply adding a mass term to the Lagrangian of a scalar field. For a spin-1 particle, we know the Higgs mechanism and one can give a mass to a vector field by postulating a state that spontaneously breaks the gauge symmetry of the theory. Until very recently, however, we did not know whether we can give a mass to a particle with spin-2 in a theoretically consistent way.

Massive gravity, the possibility that the graviton, a spin-2 field, may have a non-vanishing mass, has a long history since Fierz and Pauli proposed a linear theory in 1939. However, in 1972 Boulware and Deser pointed out an instability at nonlinear level. Since then for a long time it had been thought that a graviton cannot have a non-zero mass. It took almost 40 years until de Rham, Gabadadze and Tolley finally found a theory of massive gravity, often called dRGT theory, that avoids the problem of the Boulware-Deser instability.

With a consistent theory of massive gravity found in 2010, it is natural to apply it to cosmology in order to solve the riddles of the universe such as cosmic acceleration. Dark energy is necessary if general relativity is correct. However, it may be unnecessary if the behavior of gravity is modified from general relativity at long distance or/and time scales. Along with collaborators, I thus investigated cosmological solutions and their stability systematically. Concretely, we first found a homogeneous and isotropic, self-accelerating cosmological solution [170], analyzed gauge-invariant cosmological perturbations around it [168], discovered a new type of nonlinear instability [165], found a new class of cosmological solutions that is expected to produce statistical anisotropy of perturbations [166, 156], and so on. We have also been studying extensions of dRGT theory. In 2013, I acted as the editor of "CQG Focus Issue on Massive Gravity" in Classical and Quantum Gravity to summarize the progresses and future prospects of the field.

In 2014 I received the Lagrange Award from Institut Lagrange de Paris for the series of works on massive gravity and other subjects of gravity.

More recently, along with A. de Felice, I proposed a new theory of massive gravity (minimal theory of massive gravity) [137, 134]. This theory has only two physical degrees freedom and serves as a stable nonlinear completion of the above mentioned self-accelerating cosmological solution that I had found in dRGT theory with other collaborators [170]. Along with collaborators, I have also worked on observational constraints on massive gravity [46, 6], analysis of background gravitational waves in the context of massive gravity [163], a novel mechanism to enhance inflationary gravitational waves to an observable level by massive gravity [95, 82], and the chameleon bigravity that extends the applicability of bimetric theories [117, 108]. Furthermore, we were the first to discover the minimal theory of bigravity (MTBG), a theory of bigravity that eliminates all fatal instabilities [55]. MTBG is applicable to a variety of situations, including the early universe, and the graviton mass term in MTBG can substitute for dark energy and accelerate the cosmic expansion. In addition, MTBG provides a theoretical basis for testing massive gravitons with gravitational wave observations and a theoretical foundation for spin-2 dark matter [112, 21].

Cosmological constant problem

The cosmological constant (cc) problem, or "Why is the cosmological constant so small?" is considered one of the most difficult problems in theoretical physics and cosmology. The observational upper bound on the cc is smaller than what is naively expected quantum mechanically by 120 orders of magnitude. At present there is no theory that can convincingly explain this small value. For this reason, some researchers show a tendency to rely on the anthropic principle. However, I consider it premature to give up seeking a solution without the anthropic principle. We should not give up attempting difficult problems.

Therefore, along with L. Randall, I proposed a cosmological model towards a solution to the cc problem [216, 217]. We scceeded in making the cc sufficiently small. The remaining problem was how to reheat the universe. Even though we can make the cc small, we would end up with an empty universe if there was no reheating. Our model thus needs to be extended so that the universe is sufficiently reheated, with the cc kept small. If successful, this will be a significant progress towards a solution to the cc problem. Fortunately, recent research has successfully extended this cosmological model to obtain sufficient reheating while keeping the cosmological constant small [28]. In this extended model, the reheating process is repeated periodically, with the value of the cosmological constant becoming a little smaller each time the reheating occurs. Repeating this process over and over again results in a hot big-bang universe with a sufficiently small cosmological constant that is consistent with observations.

More recently, I have also been studying a completely different cosmological scenario to address the cosmological constant problem in the context of braneworld cosmology [36].

Black hole entropy

The theory of black holes has a collection of properties analogous to thermodynamics and it is often called black hole thermodynamics. I have been interested in black hole thermodynamics and, in particular, the microscopic origin of black hole entropy.

With W. Israel, I revisited a long-debated problem in the brick wall model for the origin of black hole entropy [240]. In this model, black hole entropy is considered to be originated from a thermal atmosphere near the black hole horizon. However, many people including 'tHooft himself, who had proposed this model, pointed out the problem of strong backreaction due to large positive energy and considered it as a fatal defect of this model. Contrary to the "lore", by identifying the correct ground state of the system in the brick wall model, we showed that the problematic large positive energy is canceled by negative energy of the ground state and that the backreaction is actually weak enough.

I have also worked on various other aspects of black hole entropy. These include validity of the generalized second law [248, 235], other proposals for the origin of black hole entropy such as D-brane description in superstring theory [247] and entanglement entropy [246, 242, 241, 237], extensions of the first law of black hole thermodynamics to general covariant theories of gravity [239] and to dynamical processes [238, 236], and so on.

More recently, I have been working on extensions of the covariant entropy bound to theories of gravity beyond general relativity [67], reconsideration of the information loss problem [48, 12, 8], and so on.

Other subjects

- With collaborators including experimentalists, I studied high energy phenomena beyond the Planck scale by using polarization data of gamma-ray bursts. If the dispersion relation of photons receive corrections due to quantum gravity effects then the propagation of photons is modified. For example, if the CPT is broken at extremely high energy then polarization of photons from gamma ray bursts will be depleted. This effect is locally negligible but can be observable if integrated over cosmological distances as photons travel. In other words, if polarization of a gamma ray burst at a cosmological distance is observed then it implies that the CPT symmetry holds at high energy. By using the observational data we have shown that the CPT symmetry holds at energies all the way up to at least 10^{15} times the Planck scale [162]. This was the most stringent bound on the CPT violation at that time and gave a strong constraint on quantum gravity theories such as loop quantum gravity.

- Magnetic fields in the universe are observed at various scales. Recently a lower bound on the magnitude of magnetic fields in void regions were obtained by observation of TeV and GeV gamma rays. Along with T. Fujita, I thus started to work on scenarios of magnetogenesis during cosmic inflation. We then obtained a universal upper bound on the scale of inflation from the observational lower bound on the magnitude of the magnetic field, independently of details of theories [167]. Also, motivated by the suggestion in the literature that supercurvature modes of magnetic field may help magnetogenesis in open inflationary scenarios, we studied the $U(1)$ gauge field with unbroken or broken gauge symmetry in open de Sitter spacetime and proved that there is no supercurvature mode [148]. These results provide conditions to be imposed on early universe scenarios of magnetogenesis. Also, by taking into account possible nonlinear interactions of the $U(1)$ gauge field and its non-minimal coupling to gravity, I found a family of stable exact solutions that represent a homogeneous universe with a finite magnetic field [123]. I then studied the stability of the solution [93] and the evolution after inflation [72].

- Rich structures in the universe such as galaxies and clusters of galaxies are thought to be formed due to gravitational instability from quantum fluctuations generated during inflation. I have been studying inflationary cosmological perturbations by using both perturbative [183, 188, 196] and non-perturbative (gradient expansion) [195, 178] approaches complementarily.

- There are a number of mysteries in cosmology, such as dark energy, dark matter, inflation as well as initial singularity and cosmic magnetic field. Some of those mysteries may be solved by modification of gravity. On the other hand, modification of gravity is allowed only to the extent that is consistent with experiments and observations. The parameterized post-Newtonian (PPN) formalism can be applied to various gravity theories and has been playing important roles in interpreting results of gravitational experiments at the solar system scales in a universal way. Along with collaborators, I pointed out that the conventional PPN formalism cannot be applied directly to the low energy limit of Hořava-Lifshitz gravity. We then extended the formalism by introducing a new parameter to make it possible to compare the theory with gravitational experiments at the solar system scales [150, 164].

- Many attempts to modify general relativity at long cosmological scales are strongly constrained by tests of gravity at solar system scales. Mechanisms that shield extra physical degrees of freedom, e.g., through nonlinear effects, are known as a way to pass these constraints. As another possibility, my collaborators and I have constructed a theory of minimally modified gravity (MMG) with no extra physical degrees of freedom, i.e., 2 local physical degrees of freedom [111, 75], and investigated the properties of the theory and its solutions [92, 88, 61, 60, 41, 31, 11]. We then studied the possibility of modifying general relativity at long distances on the cosmological scale while evading the observational constraints on the solar system scale [70, 59].

- In quantum gravity the concept of time is not fundamental but is emergent in the sense that it is encoded in correlations among observables. In order to understand the origin of time in the system with gravity, J.-P. Uzan and I proposed a novel mechanism by which a Lorentzian theory emerges from a Riemannian, i.e. locally Euclidean, theory without the concept of time [158]. Based on this scenario, I proposed a new theory of gravity that is power counting renormalizable [157]. The theory was later proved to be renormalizable by other authors.

- Superstring theory is not only a strong candidate for the ultimate theory of the universe but also serves as a useful tool to analyze gauge theories. This is because the AdS/CFT correspondence often translates difficult problems in gauge theories to less difficult problems in gravity. Along with collaborators, I constructed a black hole spacetime that is dual to a situation closely related to the actual QGP experiments [197, 194]. This is an example of the AdS/CFT correspondence in a time-dependent situation.

- As mentioned above, I have proposed scenarios for the origin of dark matter, including those based on superstring theory [210] and those based on massive gravitons [128, 112, 21]. I have also studied the origin and generation mechanism of dark matter from different viewpoints. For example, along with collaborators I have proposed a new scenario in which vector dark matter, i.e., dark photon dark matter, is produced during inflation [63, 58]. We have also proposed a scenario in which dark matter is generated from entropy perturbations [43]. Recently, I studied the possibility of observationally distinguishing the spins of ultralight dark matter using gravitational wave interferometers [5]. Also, I have reconsidered the observational constraints on the QCD axion as a dark matter candidate by correctly accounting for the non-equilibrium evolution of the stochastic distribution function during inflation [3].

- Because of their extremely weak interactions, gravitational waves are expected to play important roles in probing the early universe era before recombination of hydrogen atoms. There are many observational projects and theoretical ideas to detect gravitational waves and to use them as probes of the universe and new physics. I worked on ideas to test cosmological scenarios such as inflation driven by a pseudo scalar [161], particle production due to oscillations of a pseudo scalar [68] and massive gravity [163] by stochastic background gravitational waves. I have also proposed a scenario in which the amplitude of the stochastic background gravitational waves is increased by modified cosmic expansion due to quantum gravity effects [187] and, as mentioned above, another scenario to generate observable inflationary gravitational waves based on massive gravity [95, 82].
- Gravitational waves are expected to play a role not only in elucidating astronomical phenomena such as the formation of a black hole and in probing the early universe era, but also in testing general relativity in a strong gravitational field, which is directly related to the foundations of physics. I have been studying the physics of gravitational waves and their applications. Recently, in addition to the construction of an effective field theory of black hole perturbations with timelike scalar profile [35] and the analysis based on it [25, 15], I have studied, for example, gravitational wave propagation [24] and memory effects [30] in scalar tensor theory, gravitational lensing of gravitational waves in general relativity [10], stability of quasinormal mode frequencies against small deformations of the potential [29], and test of Lorentz symmetry by black hole ringdown [1].

Future Research

Shinji Mukohyama

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Cosmology, the physics of the largest scales, has been rapidly developing, based on precision observational data. It can now be said that many of the parameters describing the universe have been determined, or at least are being determined, with considerable precision. However, much of what the values of those parameters mean is still veiled. In fact, we do not know the true nature of the dark energy and dark matter that are thought to occupy most of the universe today. And why is the universe so big? Inflation is thought to explain a large part of it, but we still do not know the physical origin of the field driving (and ending) inflation. Dark energy, dark matter, and inflation are three major mysteries that stand in the way of cosmology, which boasts a wealth of precise observational data. I will continue to challenge these three great mysteries of the universe by all possible means, including general relativity, statistical physics, particle physics, and superstring theory.

One of the greatest aims of theoretical physics is to construct the theory of quantum gravity. This is an attempt to unify quantum mechanics and Einstein's theory of general relativity. I expect that in the process of finding the theory of quantum gravity, research of cosmology and black hole will play important roles. Hence, I will cope with any problems to understand the origin and the dynamics of the universe and black holes with great interest, including all research fields in which I have been working. If we take into account the fact that superstring theory, as a strong candidate for the theory of everything, is gradually revealing its non-perturbative, whole structure and if we compare this exciting situation with the history of the development of quantum mechanics, it is probably very effective to tackle concrete problems like cosmology and black hole. I thus strongly believe that cosmology and black hole will play as important a role in the development of quantum gravity as the black body radiation and the hydrogen atom did in the development of quantum mechanics.

In order to make robust predictions in cosmology and theoretical physics, there are (at least) two approaches. One is to develop quantum mechanically stable arguments, based on symmetry or symmetry breaking pattern in a low energy effective theory. The other is to go back to a more fundamental theory and to extract its predictions. I will proceed with my research by using the two approaches complementarily.

In the following, I would like to describe my future research, focusing on four themes.

Cosmology based on quantum gravity

In the universe, physical phenomena of various scales are constantly occurring, influencing each other. I believe that the physics of the largest scale, or cosmology, must be connected to the physics of the smallest scale. This is because the newborn universe is in an extreme state of ultra-high energy, which makes microscopic physics essential. In particular, in a situation such as the creation of the universe, where both gravity and quantum effects are significant, both general relativity, which describes gravitational phenomena, and quantum field theory, which describes the world of elementary particles, would fail. Therefore, a theory of quantum gravity, which avoids this theoretical breakdown and reconciles gravity and quantum theory, is necessary in order to discuss the creation of the universe. Superstring theory is the most promising candidate, but there are other candidates such as the Hořava-Lifshitz theory. I expect that quantum gravity theory will provide hints for solving various mysteries in cosmology. I will extend my research to construct a cosmological scenario that is consistent with observations, based on quantum gravity theories such as superstring theory and the Hořava-Lifshitz theory. By directly connecting with observations such as cosmic background radiation, I would like to explore the possibility that observations on the largest scales can elucidate physics on the smallest scales.

Cosmological constant problem and dark energy

The cosmological constant problem, one of the most difficult questions in modern theoretical physics and cosmology, has two aspects. The first is the question, “Why is it small?” The cosmological scenario that I proposed with L. Randall allows the cosmological constant to be small enough, and more recent work has succeeded in extending it so that sufficient reheating can be realized while keeping the cosmological constant small. In the future, I hope to draw out observable predictions such as primordial fluctuations in this scenario. The second aspect is “’Why non-zero?” and “Why this value now?” This is the mystery of dark energy itself. I would like to make full use of ghost condensation, which I have proposed, and the effective field theory of dark energy, which was developed from it, to tackle this problem. Essentially, the second problem, the mystery of dark energy, should be discussed after the first problem, “Why is it small?” is solved. On the other hand, the progress of observations of dark energy has been remarkable. Therefore, I believe that a valid strategy is to study the two problems in parallel. I will pursue my research in a complementary manner and aim for a final solution.

Black hole entropy and information loss problem

Microscopic black holes created in the early universe are thought to lose their masses and possibly evaporate due to Hawking radiation. Where does the information captured in a black hole go after evaporation? This is the information loss problem. If the information is really lost, then it means that the gravitational effect will cause the breakdown of the quantum unitary evolution. Therefore, this problem is an essential issue in the integration of quantum theory and gravity theory. Many researchers, including myself, believe that information is recovered without information loss. However, how it is recovered has not been elucidated. I would like to address the issue of information loss through the study of black hole entropy. The entropy of a black hole should reflect the number of microscopic degrees of freedom, and is expected to be closely related to the amount of information captured by the black hole. Therefore, the entropy of black holes, which I have been studying, should be an important key to solving the information loss problem.

Tests of gravity

Gravitational waves, first directly detected by Advanced LIGO in 2015, are expected to play a role in testing general relativity; images of black hole shadows by the Event Horizon Telescope, released in 2019, have also been used to test the Kerr black hole geometry of general relativity. In addition, as experiments and observations continue, new phenomena may be discovered that cannot be explained by general relativity, and a new theory of gravity may become necessary. The discrepancy between observational data and the standard cosmology, called H_0 tension or S_8 tension, which has been actively discussed recently, may be such a sign. In my recent work, together with young collaborators, I have successfully extended the effective field theory of ghost condensation, the effective field theory of inflation, and the effective field theory of dark energy to an arbitrary background with a timelike scalar profile, for example, black holes, as well as cosmology. By extending these recent studies, I hope to develop a framework for testing deviations from general relativity, making full use of observational data from gravitational waves, black holes, and cosmology.

Other subjects

In addition to the four themes mentioned above, I would like to develop various other themes that I have been working on. Of course, I will not hesitate to tackle new themes. I will continue my research in a flexible manner according to progresses in theory and observation/experiment.

Postscript

If I self-analyze my style of research in the past, there is a tendency that new developments in fundamental theories inspired me to find novel pictures of our universe. By continuing this style of research, I would like to pursue the true picture of our unvierse from the viewpoints of fundamental theories. I will also make effort to extend this style to broaden our knowledge on fundamental theories through attempts to solve the mysteries in cosmology. I will keep these in mind and cotinue research, in cooporation with researchers in related fields.

Publication List

Shinji Mukohyama

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Papers Submitted to Journals

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[2] M. Minamitsuji, S. Mukohyama and S. Tsujikawa, “Angular and radial stabilities of spontaneously scalarized black holes in the presence of scalar-Gauss-Bonnet couplings,” [arXiv:2403.10048 [gr-qc]], accepted for publication in Phys. Rev. D.

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