Research since April 2008

Shinji Mukohyama

January 3, 2010

Since I took up the position at IPMU on April 1, 2008, I have been working on various subjects in cosmology and gravitation such as braneworld cosmology, string cosmology, Higgs phase of gravity, gravity at a Lifshitz point, horizon thermodynamics to tackle the mysteries of the universe. In the following, I would like to explain some of my main research achievement at IPMU.

Cosmological implications of gravity at a Lifshitz point:

One of the biggest difficulties in attempts toward the theory of quantum gravity is the fact that general relativity (GR) is non-renormalizable. This would imply loss of theoretical control and predictability at high energies. In January 2009, Hořava proposed a new theory of gravity to evade this difficulty by invoking a Lifshitz-type anisotropic scaling at high energy. This theory, often called gravity at a Lifshitz point or Hořava-Lifshitz gravity, is power-counting renormalizable and is expected to be renormalizable and unitary. Having a new candidate theory for quantum gravity, it is important to investigate its cosmological implications. At least I cannot help doing so.

Since the high energy behavior of Hořava-Lifshitz gravity is very different from GR, there is a possibility that the theory does not recover GR at low energy. Indeed, in [5] I have shown that the theory does not recover GR but can instead mimic GR plus cold dark matter (CDM). The constraint algebra in this theory is smaller than GR since the time slicing is synchronized with the CDM rest frame in the theory level. A more recent preprint with an IPMU postdoc Keisuke Izumi (arXiv:0911.1814) supports this picture by proving that there is no static stellar solution in this theory: the "CDM" accretes toward a star and thus makes the stellar center dynamical. In [4], based on some simple examples, I conjectured that accreted "CDM" should bounce before forming caustics at microscopic scales. The existence of built-in "CDM" is an inevitable prediction of the theory and might solve the mystery of dark matter as mentioned in a recent article in the "Scientific American" magazine.

The anisotropic scaling at high energy is one of essential ingredients of the theory since the power-counting renormalizability stems from it. Based on the anisotropic scaling, I have proposed a new mechanism for generation of cosmological perturbations [9]. As confirmed by many authors, this mechanism can solve the horizon problem and generate scale-invariant cosmological perturbations without inflation.

I also worked on generation of primordial seed magnetic field with Satoshi Maeda and Tetsuya Shiromizu [2], and on other cosmological implications with Kazunori Nakayama, Fuminobu Takahashi (IPMU faculty) and Shuichiro Yokoyama [8].

Theoretical and cosmological aspects of Higgs phase of gravity:

From observational point of view, the paradigm of dark energy and dark matter is very successful to fit the data. However, from theoretical viewpoint, we do not know what they really are, despite the fact that there are many theoretical models. This situation has been a strong motivation for modification of gravity as an alternative to dark energy and dark matter: just changing behavior of gravity at long distance/time scales might be able to explain the observational data without introducing dark energy and dark matter. It is important to investigate theoretical consistencies and cosmological implications of modified gravity theories toward the future observations.

I recently revisited theoretical consistency of the ghost condensation scenario, which I had proposed in 2003 with Nima Arkani-Hamed, Hsin-Chia Cheng and Markus Luty [33]. Ghost condensation is an analogue of Higgs mechanism for gravity and modifies gravity at long distance/time scales in a theoretically controllable way. While this theory is known to be perfectly fine as a low-energy effective field theory, some authors challenged the possibility of UV completion by claiming that the generalized second law can be violated in ghost condensate backgrounds. In [12, 3], contrary to the previous considerations in the literature, I have shown that it is rather difficult to violate the generalized second law in ghost condensate backgrounds.

As for cosmological implications, along with Tomonori Furukawa, Kiyotomo Ichiki, Naoshi Sugiyama (IPMU principal investigator) and Shuichiro Yokoyama, I have been working on the possibility that ghost condensate may serve as an alternative to dark matter in the universe. The result will be published in a near future.

String cosmology and inflation:

Cosmic inflation not only solves various problems in the big-bang cosmology elegantly but also provides seeds for the rich structure in the universe. For this reason, inflation has been accepted by many researchers as a part of the standard theory of the universe. However, inflationary model building is known to be UV sensitive and the physical origin of the inflaton, a field driving inflation, has not yet been understood. String theory, as a candidate for the theory of everything, is expected to address this problem.

Recent developments in string theory enabled us to calculate various corrections to the inflaton potential for warped brane inflation. It turned out that the inflaton, i.e. the brane position, generically has non-minimal couplings to spacetime curvature. Also, it is known that the inflaton in this setup has a nonlinear kinetic action called DBI action. Along with two IPMU postdocs Damien Easson and Brian Powell, I investigated observational signatures of these aspects of warped brane inflation [1].

Non-minimal coupling to spacetime curvature tends to spoil the slow-roll conditions for the inflaton potential and thus generically forces the inflaton to roll rapidly. Nonetheless, as Lev Kofman and I previously showed in [17], a rapidly-rolling inflaton with the conformal coupling (and with the standard canonical kinetic action) can naturally drive inflation. In this case, however, seeds for the structure in the universe should be generated not by inflaton but by other mechanisms such as the curvaton mechanism. As a concrete realization in string theory, Takeshi Kobayashi (IPMU visiting student) and I have developed a curvaton model from type IIB string theory compactified on a warped throat with approximate isometries [6]. Observational constraints on the rapid-roll inflation were investigated with Takeshi Kobayashi (IPMU visiting student) and Brian Powell (IPMU postdoc) in [13, 7].

I have also worked on other related topics. With Shunichiro Kinoshita, I have analyzed stability of Freund-Rubin flux compactifications in de Sitter background in [10]. In [15, 11], along with Shunichiro Kinoshita, Shin Nakamura and Kin-ya Oda, I investigated a holographic dual of Bjorken flow based on the AdS/CFT correspondence. I also investigated a field theory on the world-volume of a decaying D-brane with Tomoyoshi Hirata and Tadashi Takayanagi (IPMU faculty) [16].

Future Research

Shinji Mukohyama

January 3, 2010

In the forthcoming years, in order to tackle the mysteries of the universe, I will mainly work on string cosmology and alternative gravity theories.

String cosmology:

Modern cosmology has been ever developing, based on precision observational data. It is fair to say that many among those parameters describing our universe were determined, or at least are being determined, with good precision. However, physics behind the values of those parameters are still covered by a veil of mystery. For example, we do not know what dark energy and dark matter really are, although our universe is thought to be filled mostly with them. What made our universe so big? This question can be addressed by cosmic inflation, but again we do not know the physical origin of vacuum energy driving inflation. Three big mysteries, dark energy, dark matter and inflation, are standing in the way of cosmology which boasts precision observational data.

String theory is the strongest candidate for the theory of everything and, thus, is supposed to address these cosmological mysteries at least in principle. Thus, I will work on various cosmological issues in string theory. These include inflationary model building, investigation of reheating after inflation in multi-throat scenarios, analysis of gravity in braneworlds with co-dimension higher than two, investigation of properties of dark matter candidates, realization of Higgs phases of gravity, cosmological implications of the string landscape and so on.

A weakness of string theory is, if I have to point out, the lack of observational/experimental supports. It is therefore very important to seek observational/experimental signatures of the theory. From this point of view, I expect that signatures of tensor modes and non-Gaussianities in the cosmic microwave background should play important roles in coming years. Thus I will seek and investigate models of inflation which predict observable amplitudes of tensor modes and non-Gaussianities.

Alternative Gravity Theories:

Einstein's theory of relativity unifies a three-dimensional space and a one-dimensional time as a spacetime and describes gravity as a fabric of curved spacetime. This picture has been very successful in explaining and predicting many gravitational phenomena. Experimentally, however, we do not know how gravity behaves at distances shorter than ~ 0.01mm. At shorter distances, gravity may behave completely differently from what we expect. For example there may be hidden dimensions at short distances. In fact, many theories, including superstring theories and M-theory, require the existence of such extra dimensions. Extra dimensions may exist everywhere in our universe, but they are somehow hidden from us. One possibility recently investigated very actively is called the brane-world scenario. In this scenario our universe is supposed to be a three-dimensional surface, called brane, floating in higher-dimensional space. Although we cannot see extra-dimensions directly, we may hope to detect some indirect evidence of extra-dimensions in high-energy experiments or cosmological observations.

Gravity at very long distances (for example, billions of light-years) may also be as weird as at short distances. Precision observational data recently revealed that the expansion of our universe is accelerating. If Einstein's theory is correct, this requires that more than 70% of our universe is filled with invisible, negative pressure, energy. This energy is named dark energy, but we do not know what it really is. This situation reminds us of a story in the 19th century: when the perihelion shift of Mercury was discovered, some people hypothesized the existence of an invisible planet called Vulcan, a so-to-speak dark planet, to explain the anomalous behavior of Mercury. However, as we all know, the dark planet was not real and the correct explanation was to change gravity, from Newton's theory to Einstein's. With this in mind, we wonder if we can change Einstein's theory at long distances to address the mystery of dark energy.

Concrete alternative gravity theories that I will work on include, but are not restricted to, braneworld scenarios, Higgs phases of gravity and gravity with Lifshitz-type anisotropic scaling. I will investigate both theoretical and observational aspects of those theories.

My attitude to the two subjects

Needless to say, my ultimate dream is to understand our universe. Toward this end, I will continue to challenge by using every possible means such as general relativity, particle physics and superstring theory. From this point of view, string theory (at least what is currently called string theory) is not just a theory but a rather big framework, in which we can hope to construct a theory of the universe. On the other hand, alternative gravity theories can be thought of as candidates for important parts, if not the whole, of ultimate description of the universe.

Since these two subjects are apparently very different from each other, here I think I had better provide an argument on why they can be compatible with each other at least in principle.

A recent example in which even two apparently exclusive subjects were actually shown to be compatible is cosmic inflation in string theory. Until 2002, there were no-go theorems claiming that there is no way to construct accelerating universe such as inflation in the framework of string theory. However, after a seminal work by Kachru, Kallosh, Linde and Trivedi in 2003, there appeared many models of inflation in the framework of string theory. Another example in which previously known no-go theorems were evaded is warped compactification in string theory, i.e. a stringy version of the Randall-Sundrum braneworld scenario. From these examples, I have learned that it is a rather healthy attitude to hope that apparently different subjects may in the end be related to each other in a consistent framework.

Therefore, I will continue to work on both subjects. For me, string cosmology and alternative gravity theories are not exclusive but complementary. Also, it is important to keep in mind that correctness of theories should be decided not by theoretical prejudice but by observations and experiments. Therefore, I will tackle any problems in cosmology, according to circumstances with theories and observations/experiments.

List of papers

Shinji Mukohyama

January 3, 2010

Papers in Refereed Journals

[1] D. A. Easson, S. Mukohyama and B. A. Powell, "Observational Signatures of Gravitational Couplings in DBI Inflation," accepted for publication in Physical Review D, arXiv:0910.1353 [astro-ph.CO].

[2] S. Maeda, S. Mukohyama and T. Shiromizu, "Primordial magnetic field from non-inflationary cosmic expansion in Horava-Lifshitz gravity," accepted for publication in Physical Review D, arXiv:0909.2149 [astro-ph.CO].

[3] S. Mukohyama, "Can ghost condensate decrease entropy?," accepted for publication in the open astronomy journal hot topic "Gravitational Alternative for Dark Energy and Inflation", arXiv:0908.4123 [hep-th].

[4] S. Mukohyama, "Caustic avoidance in Horava-Lifshitz gravity," JCAP **0909**, 005 (2009) [arXiv:0906.5069 [hep-th]].

[5] S. Mukohyama, "Dark matter as integration constant in Horava-Lifshitz gravity," Phys. Rev. D **80**, 064005 (2009) [arXiv:0905.3563 [hep-th]].

[6] T. Kobayashi and S. Mukohyama, "Curvatons in Warped Throats," JCAP **0907**, 032 (2009) [arXiv:0905.2835 [hep-th]].

[7] T. Kobayashi, S. Mukohyama and B. A. Powell, "Cosmological Constraints on Rapid Roll Inflation," JCAP **0909**, 023 (2009) [arXiv:0905.1752 [astro-ph.CO]].

[8] S. Mukohyama, K. Nakayama, F. Takahashi and S. Yokoyama, "Phenomenological Aspects of Horava-Lifshitz Cosmology," Phys. Lett. B **679**, 6 (2009) [arXiv:0905.0055 [hep-th]].

[9] S. Mukohyama, "Scale-invariant cosmological perturbations from Horava-Lifshitz gravity without inflation," JCAP **0906**, 001 (2009) [arXiv:0904.2190 [hep-th]].

[10] S. Kinoshita and S. Mukohyama, "Thermodynamic and dynamical stability of Freund-Rubin compactification," JCAP **0906**, 020 (2009) [arXiv:0903.4782 [hep-th]].

[11] S. Kinoshita, S. Mukohyama, S. Nakamura and K. y. Oda, "Consistent Anti-de Sitter-Space/Conformal-Field-Theory Dual for a Time-Dependent Finite Temperature System," Phys. Rev. Lett. **102**, 031601 (2009) [arXiv:0901.4834 [hep-th]].

[12] S. Mukohyama, "Ghost condensate and generalized second law," JHEP **0909**, 070 (2009) [arXiv:0901.3595 [hep-th]].

[13] T. Kobayashi and S. Mukohyama, "Conformal Inflation, Modulated Reheating, and WMAP5," Phys. Rev. D **79**, 083501 (2009) [arXiv:0810.0810 [hep-th]].

[14] Y. i. Takamizu and S. Mukohyama, "Nonlinear superhorizon perturbations of non-canonical scalar field," JCAP **0901**, 013 (2009) [arXiv:0810.0746 [gr-qc]].

[15] S. Kinoshita, S. Mukohyama, S. Nakamura and K. y. Oda, "A Holographic Dual of Bjorken Flow," Prog. Theor. Phys. **121**, 121 (2009) [arXiv:0807.3797 [hep-th]].

[16] T. Hirata, S. Mukohyama and T. Takayanagi, "Decaying D-branes and Moving Mirrors," JHEP **0805**, 089 (2008) [arXiv:0804.1176 [hep-th]].

[17] L. Kofman and S. Mukohyama, "Rapid roll Inflation with Conformal Coupling," Phys. Rev. D **77**, 043519 (2008) [arXiv:0709.1952 [hep-th]].

[18] T. Kobayashi, S. Mukohyama and S. Kinoshita, "Constraints on Wrapped DBI Inflation in a Warped Throat," JCAP **0801**, 028 (2008) [arXiv:0708.4285 [hep-th]].

[19] S. Mukohyama, "Reheating a multi-throat universe by brane motion," Gen. Rel. Grav. **41**, 1151 (2009) [arXiv:0706.3214 [hep-th]].

[20] S. Kinoshita, Y. Sendouda and S. Mukohyama, "Instability of de Sitter brane and horizon entropy in a 6D braneworld," JCAP **0705**, 018 (2007) [arXiv:hep-th/0703271].

[21] S. Mukohyama, "Towards a Higgs phase of gravity in string theory," JHEP **0705**, 048 (2007) [arXiv:hep-th/0610254].

[22] Y. Sendouda, S. Kinoshita and S. Mukohyama, "Doubly covariant formula of deficit angle and its application to six-dimensional braneworld," Class. Quant. Grav. **23**, 7199 (2006) [arXiv:hep-th/0607189].

[23] S. Mukohyama, "An accelerating universe and cosmological perturbation in the ghost condensate," JCAP **0610**, 011 (2006) [arXiv:hep-th/0607181].

[24] S. Kawamura *et al.*, "The Japanese space gravitational wave antenna DECIGO," Class. Quant. Grav. **23**, S125 (2006).

[25] H. C. Cheng, M. A. Luty, S. Mukohyama and J. Thaler, "Spontaneous Lorentz breaking at high energies," JHEP **0605**, 076 (2006) [arXiv:hep-th/0603010].

[26] H. Yoshiguchi, S. Mukohyama, Y. Sendouda and S. Kinoshita, "Dynamical stability of six-dimensional warped flux compactification," JCAP **0603**, 018 (2006) [arXiv:hep-th/0512212].

[27] N. Arkani-Hamed, H. C. Cheng, M. A. Luty, S. Mukohyama and T. Wiseman, "Dynamics of gravity in a Higgs phase," JHEP **0701**, 036 (2007) [arXiv:hep-ph/0507120].

[28] S. Mukohyama, Y. Sendouda, H. Yoshiguchi and S. Kinoshita, "Warped flux compactification and brane gravity," JCAP **0507**, 013 (2005) [arXiv:hep-th/0506050].

[29] S. Mukohyama, "anti-D-brane as dark matter in warped string compactification," Phys. Rev. D **72**, 061901 (2005) [arXiv:hep-th/0505042].

[30] S. Mukohyama, "Black holes in the ghost condensate," Phys. Rev. D **71**, 104019 (2005) [arXiv:hep-th/0502189].

[31] T. Shiromizu, S. Tomizawa, Y. Uchida and S. Mukohyama, "Kaluza-Klein bubble and celestial sphere in inflationary universe," Gen. Rel. Grav. **37**, 1823 (2005) [arXiv:hep-th/0406181].

[32] N. Arkani-Hamed, P. Creminelli, S. Mukohyama and M. Zaldarriaga, "Ghost inflation," JCAP **0404**, 001 (2004) [arXiv:hep-th/0312100].

[33] N. Arkani-Hamed, H. C. Cheng, M. A. Luty and S. Mukohyama, "Ghost condensation and a consistent infrared modification of gravity," JHEP **0405**, 074 (2004) [arXiv:hep-th/0312099].

[34] S. Mukohyama and A. Coley, "Scaling solution, radion stabilization, and initial condition for brane-world cosmology," Phys. Rev. D **69**, 064029 (2004) [arXiv:hep-th/0310140].

[35] S. Mukohyama, "Gravity in the dynamical approach to the cosmological constant," Phys. Rev. D **70**, 063505 (2004) [arXiv:hep-th/0306208].

[36] S. Mukohyama and L. Randall, "A dynamical approach to the cosmological constant," Phys. Rev. Lett. **92**, 211302 (2004) [arXiv:hep-th/0306108].

[37] S. Mukohyama, "Inhomogeneous tachyon decay, light-cone structure and D-brane network problem in tachyon cosmology," Phys. Rev. D **66**, 123512 (2002) [arXiv:hep-th/0208094].

[38] S. Mukohyama, "Non-locality as an essential feature of brane worlds," Prog. Theor. Phys. Suppl. **148**, 121 (2003) [arXiv:hep-th/0205231].

[39] S. Mukohyama, "Brane cosmology driven by the rolling tachyon," Phys. Rev. D **66**, 024009 (2002) [arXiv:hep-th/0204084].

[40] S. Mukohyama, "Brane gravity, higher derivative terms and non-locality," Phys. Rev. D **65**, 084036 (2002) [arXiv:hep-th/0112205].

[41] S. Mukohyama and L. Kofman, "Brane gravity at low energy," Phys. Rev. D **65**, 124025 (2002) [arXiv:hep-th/0112115].

[42] S. Mukohyama, "Doubly covariant action principle of singular hypersurfaces in general relativity and scalar-tensor theories," Phys. Rev. D **65**, 024028 (2002) [arXiv:gr-qc/0108048].

[43] S. Mukohyama, "Integro-differential equation for brane-world cosmological perturbations," Phys. Rev. D **64**, 064006 (2001) [Erratum-ibid. D **66**, 049902 (2002)] [arXiv:hep-th/0104185].

[44] S. Mukohyama, "Static solutions in the R**4 brane world," Phys. Rev. D **63**, 104025 (2001) [arXiv:hep-th/0101038].

[45] S. Mukohyama and W. Israel, "Moving-mirror entropy," Phys. Rev. D **62**, 121501 (2000) [arXiv:gr-qc/0009014].

[46] S. Mukohyama, "Quantum effects, brane tension and large hierarchy in the brane world," Phys. Rev. D **63**, 044008 (2001) [arXiv:hep-th/0007239].

[47] S. Mukohyama, "Perturbation of junction condition and doubly gauge-invariant variables," Class. Quant. Grav. **17**, 4777 (2000) [arXiv:hep-th/0006146].

[48] Y. Morisawa, K. Uzawa and S. Mukohyama, "Excitation of Kaluza-Klein modes of U(1) field by parametric resonance," Phys. Rev. D **62**, 104019 (2000) [arXiv:gr-qc/0005029].

[49] S. Mukohyama, "Gauge-invariant gravitational perturbations of maximally symmetric spacetimes," Phys. Rev. D **62**, 084015 (2000) [arXiv:hep-th/0004067].

[50] S. Mukohyama, T. Shiromizu and K. i. Maeda, "Global structure of exact cosmological solutions in the brane world," Phys. Rev. D **62**, 024028 (2000) [Erratum-ibid. D **63**, 029901 (2001)] [arXiv:hep-th/9912287].

[51] K. Uzawa, Y. Morisawa and S. Mukohyama, "Excitation of Kaluza-Klein gravitational mode," Phys. Rev. D **62**, 064011 (2000) [arXiv:gr-qc/9912108].

[52] S. Mukohyama, "Brane-world solutions, standard cosmology, and dark radiation," Phys. Lett. B **473**, 241 (2000) [arXiv:hep-th/9911165].

[53] S. Mukohyama, "Is the brick wall model unstable for a rotating background?," Phys. Rev. D **61**, 124021 (2000) [arXiv:gr-qc/9910013].

[54] T. Shimomura and S. Mukohyama, "Does the generalized second law require entropy bounds for a charged system?," Phys. Rev. D **61**, 064020 (2000) [arXiv:gr-qc/9906047].

[55] S. Mukohyama and S. A. Hayward, "Quasi-local first law of black-hole dynamics," Class. Quant. Grav. **17**, 2153 (2000) [arXiv:gr-qc/9905085].

[56] S. Mukohyama, "The Hartle-Hawking state is a maximum of entanglement entropy," Phys. Rev. D **61**, 064015 (2000) [arXiv:gr-qc/9904005].

[57] S. A. Hayward, S. Mukohyama and M. C. Ashworth, "Dynamic black-hole entropy," Phys. Lett. A **256**, 347 (1999) [arXiv:gr-qc/9810006].

[58] S. Mukohyama, "On the Noether charge form of the first law of black hole mechanics," Phys. Rev. D **59**, 064009 (1999) [arXiv:gr-qc/9809050].

[59] S. Mukohyama and W. Israel, "Black holes, brick walls and the Boulware state," Phys. Rev. D **58**, 104005 (1998) [arXiv:gr-qc/9806012].

[60] S. Mukohyama, "Comments on entanglement entropy," Phys. Rev. D **58**, 104023 (1998) [arXiv:gr-qc/9805039].

[61] S. Mukohyama, M. Seriu and H. Kodama, "Thermodynamics of entanglement in Schwarzschild spacetime," Phys. Rev. D **58**, 064001 (1998) [arXiv:gr-qc/9712018].

[62] S. Mukohyama, "Excitation of a Kaluza-Klein mode by parametric resonance," Phys. Rev. D **57**, 6191 (1998) [arXiv:gr-qc/9711058].

[63] S. Mukohyama, "State after quantum tunneling with gravity," Phys. Rev. D **56**, 7638 (1997) [arXiv:gr-qc/9709040].

[64] T. Chiba, S. Mukohyama and T. Nakamura, "Anisotropy of the cosmic background radiation implies the violation of the strong energy condition in Bianchi type I universe," Phys. Lett. B **408**, 47 (1997) [arXiv:gr-qc/9707043].

[65] S. Mukohyama, M. Seriu and H. Kodama, "Can the entanglement entropy be the origin of black-hole entropy ?," Phys. Rev. D **55**, 7666 (1997) [arXiv:gr-qc/9701059].

[66] S. Mukohyama, "D-brane configuration and black hole thermodynamics," Mod. Phys. Lett. A **11**, 3035 (1996) [arXiv:hep-th/9611052].

[67] S. Mukohyama, "New proof of the generalized second law," Phys. Rev. D **56**, 2192 (1997) [arXiv:gr-qc/9611017].